

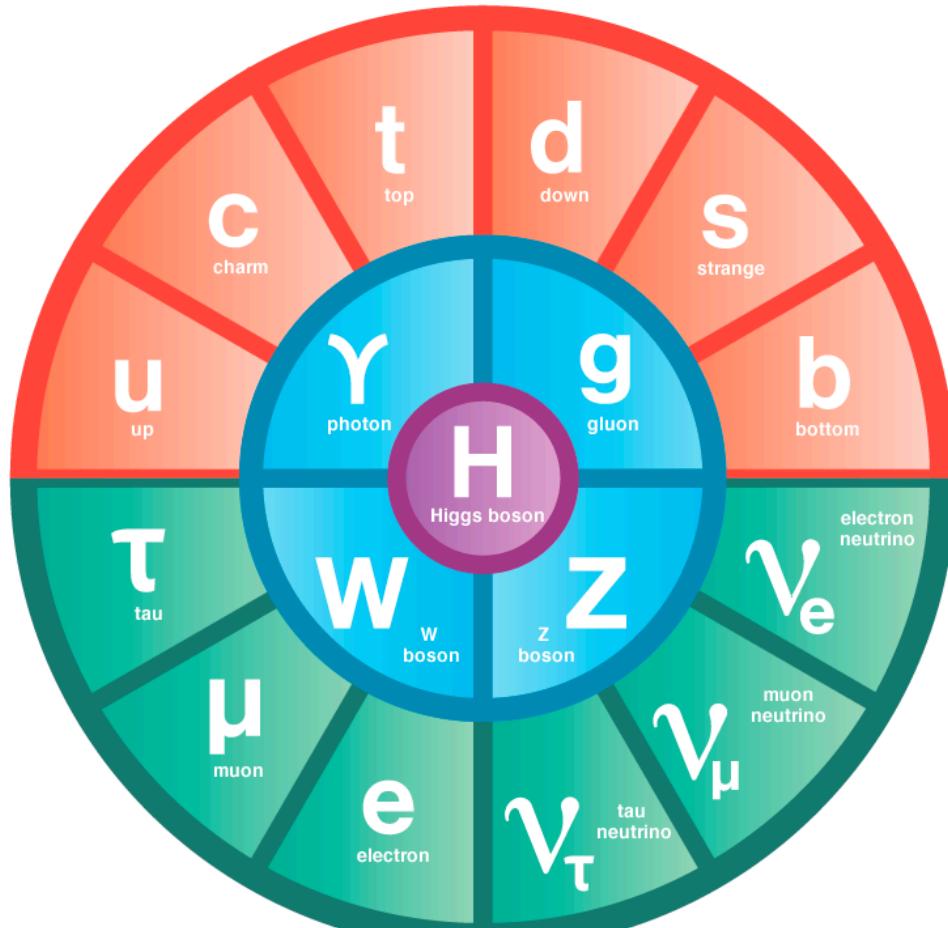


Lecture 7

Understanding Jets

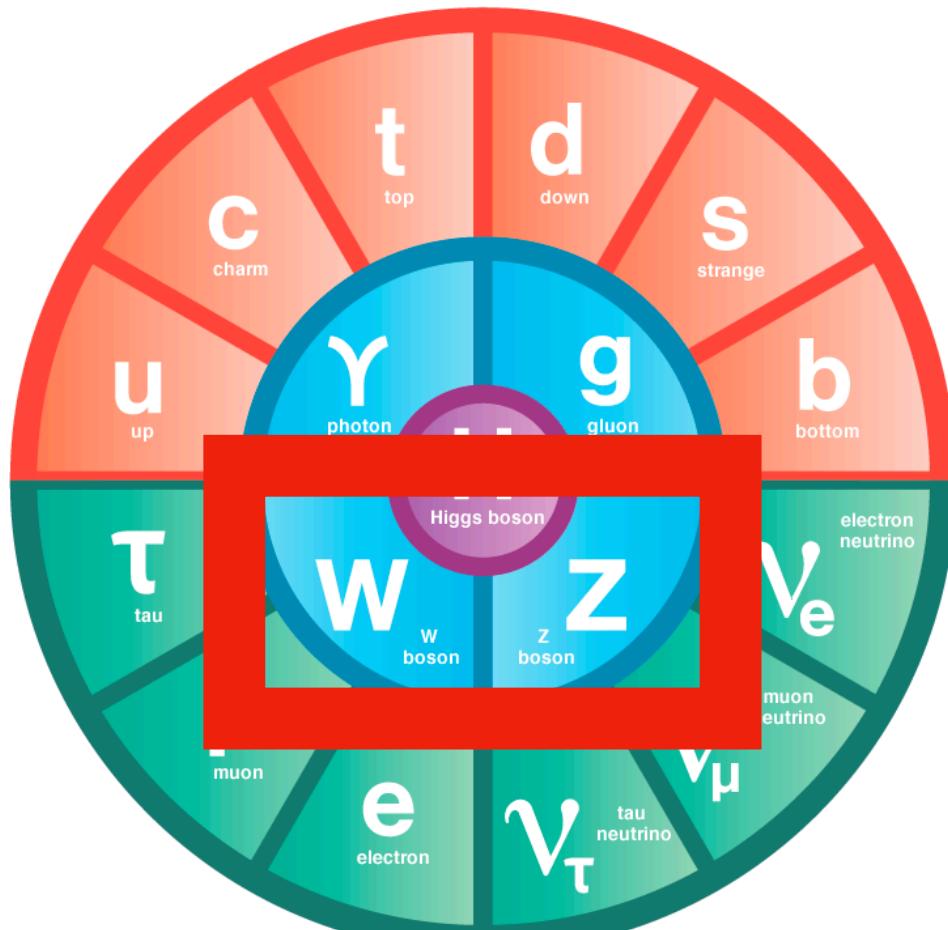
Laboratory

- The challenge of this lab is to fin the W and Z boson



Laboratory

- The challenge of this lab is to fin the W and Z boson
 - These are the particles that cover the Weak Boson Interaction



Fundamental Forces

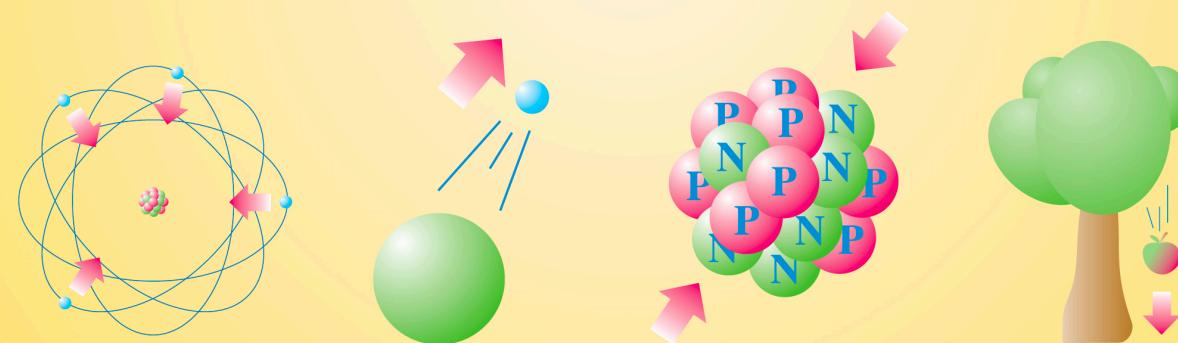
The Four Fundamental Forces of Nature

Electro-magnetism

Weak Interaction

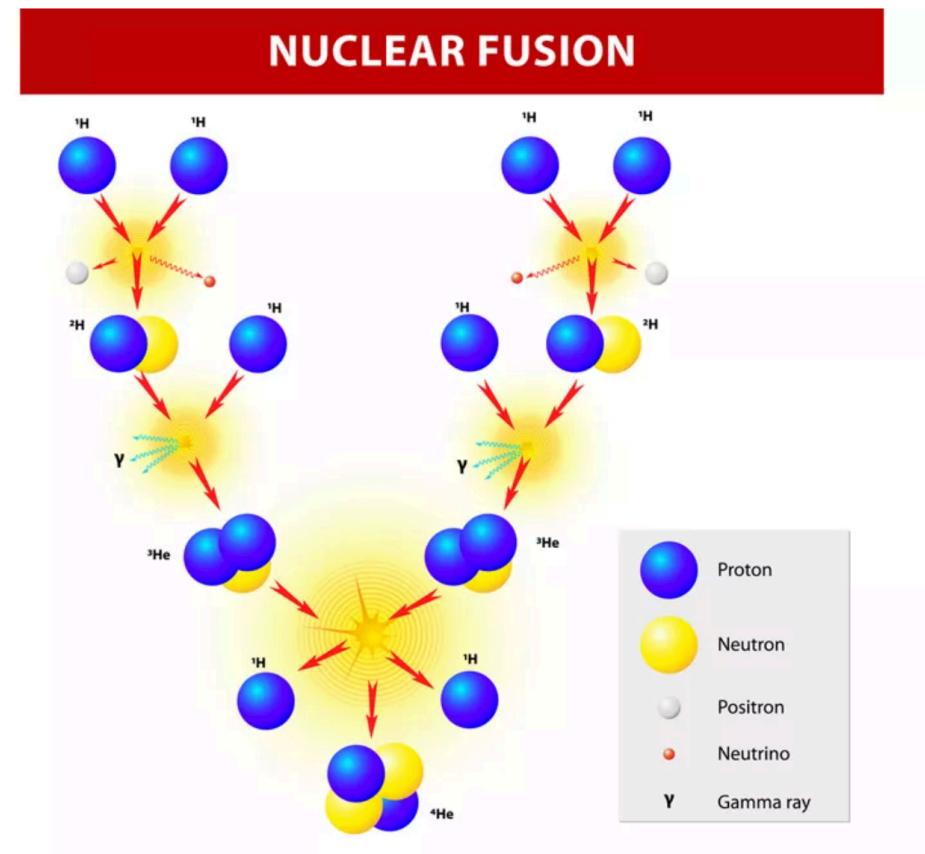
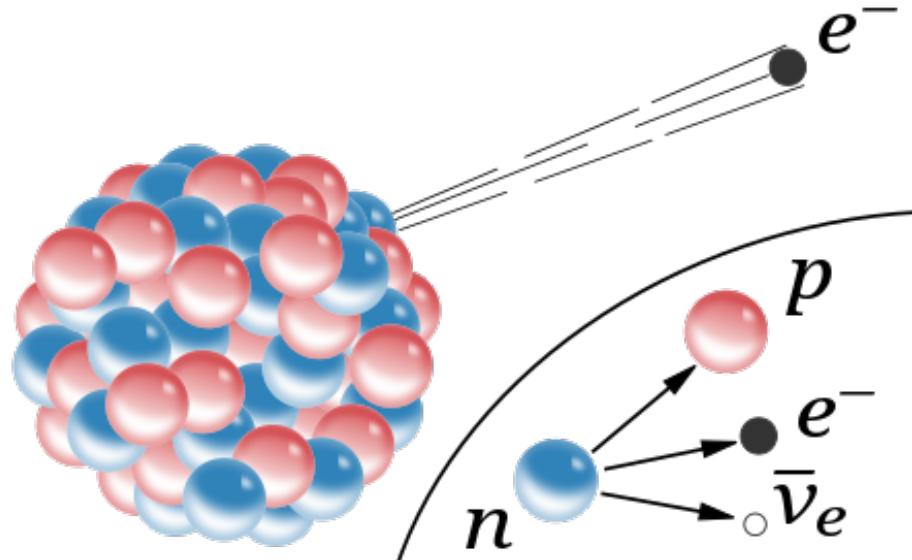
Strong Interaction

Gravitation



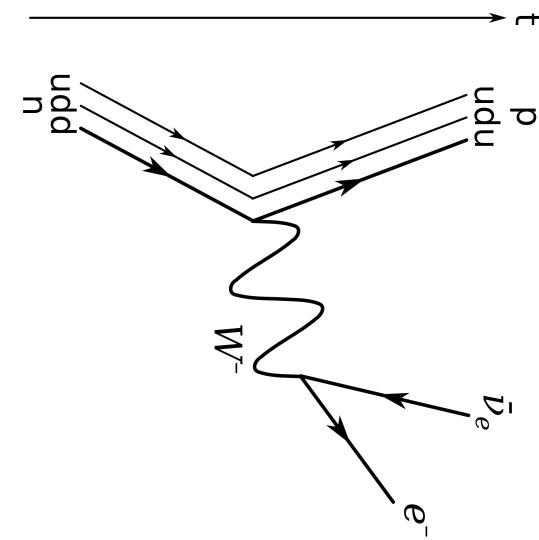
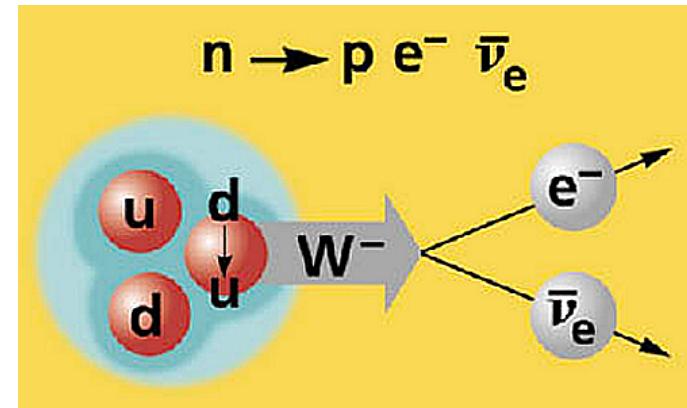
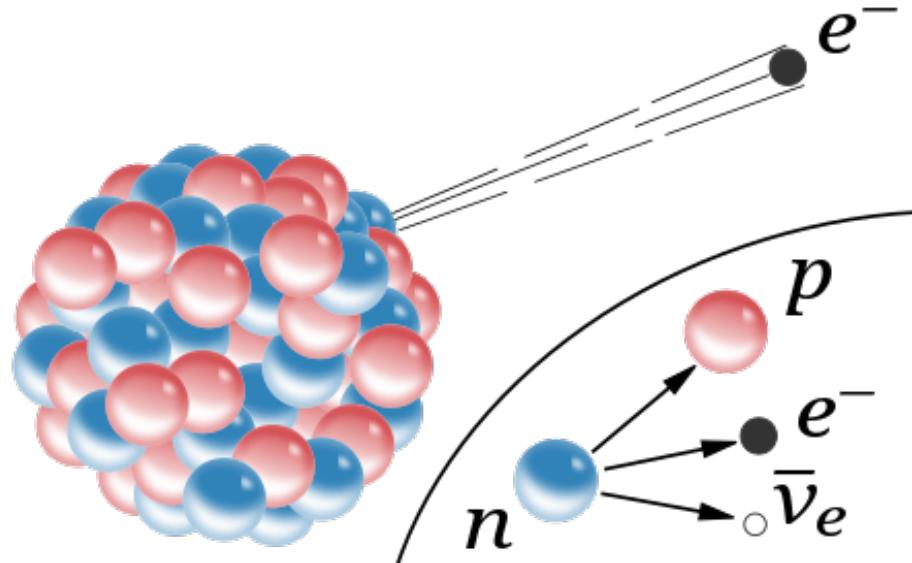
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Weak Interactions



- The Weak interaction is described by W and Z bosons

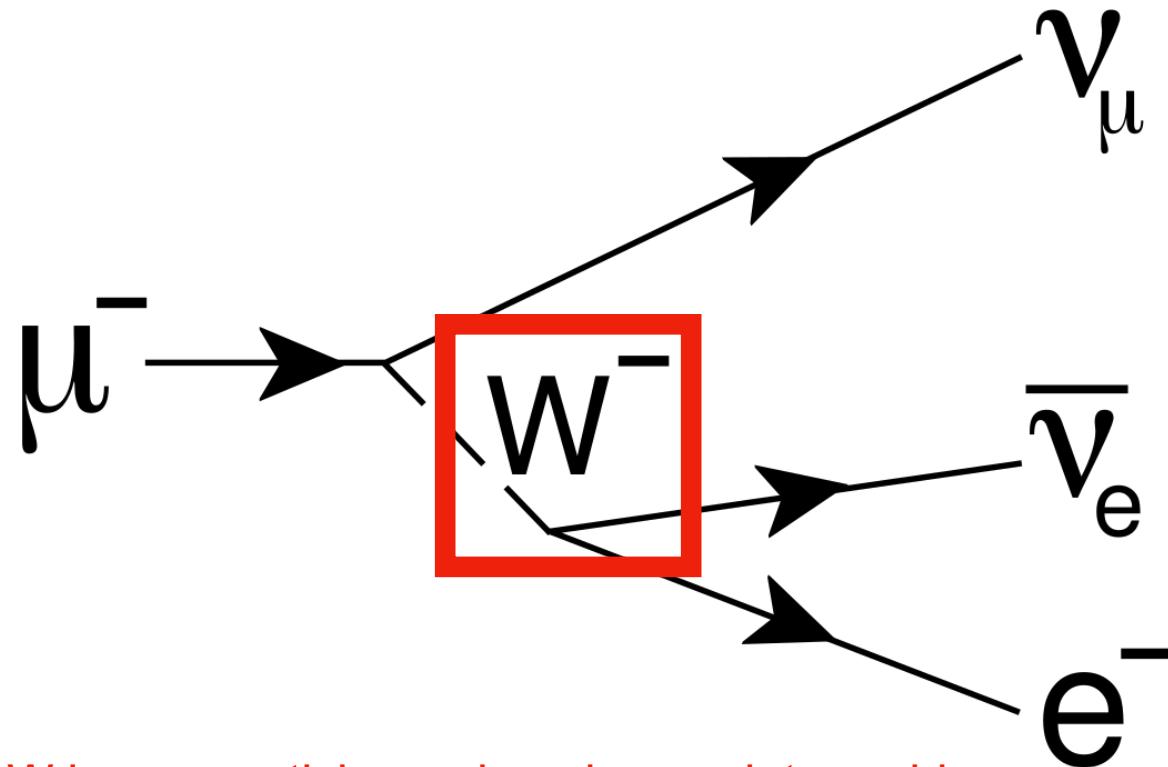
Weak Interactions



- The Weak interaction is described by W and Z bosons

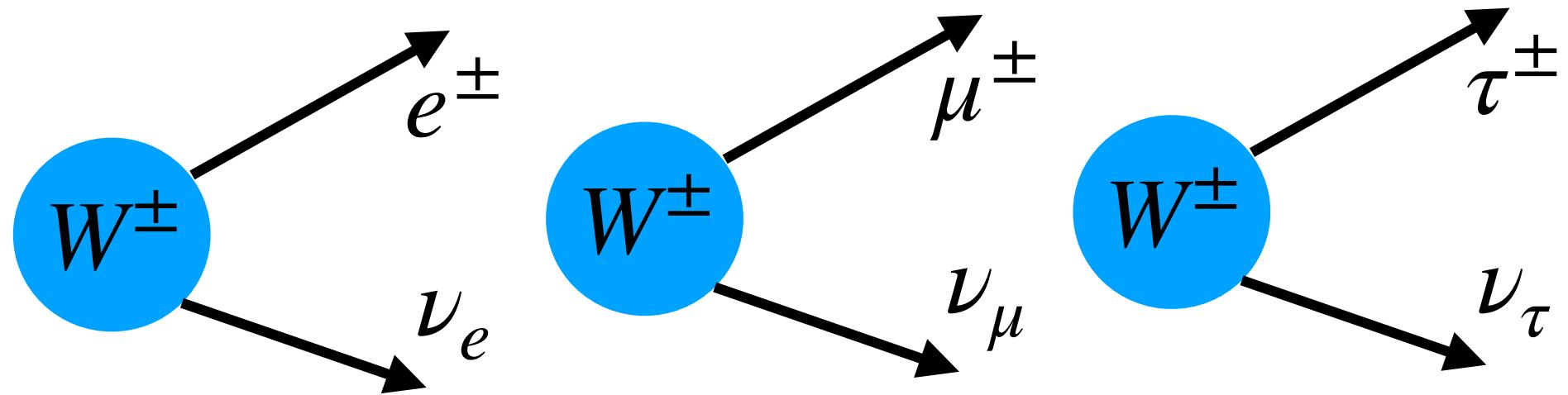
What really is this?

- Weak interaction is actually a very strong interaction
 - Its just mediated by a heavy particle



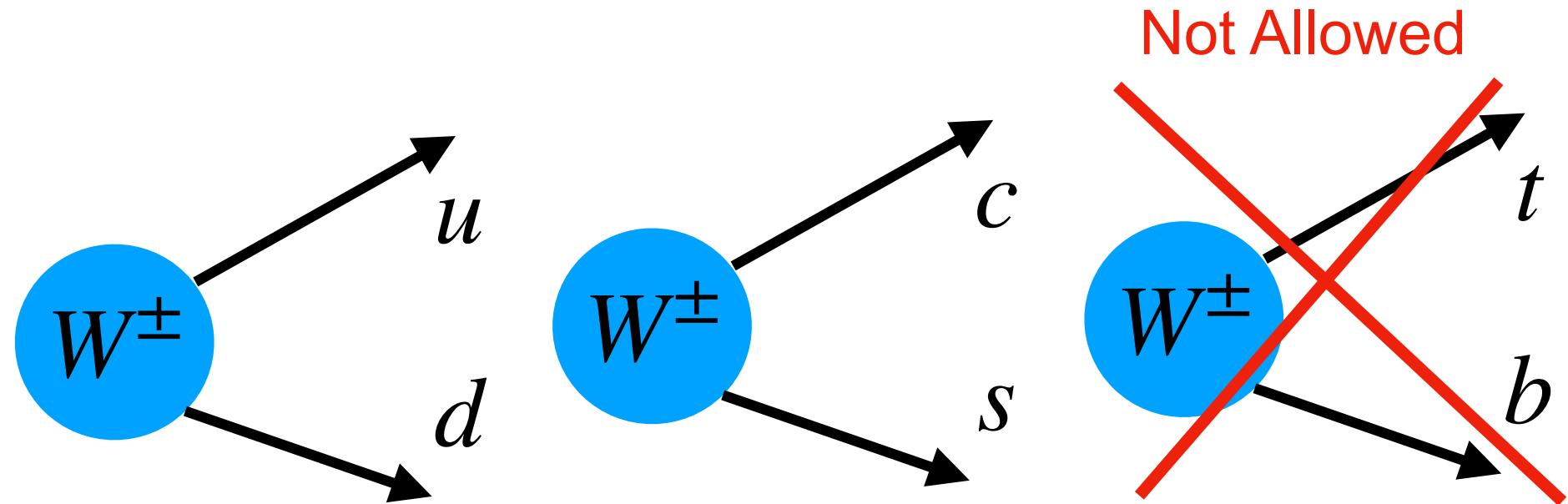
Heavy W boson particle produced as an intermediary

W boson Properties



- W boson interacts with many different particles

W boson Properties

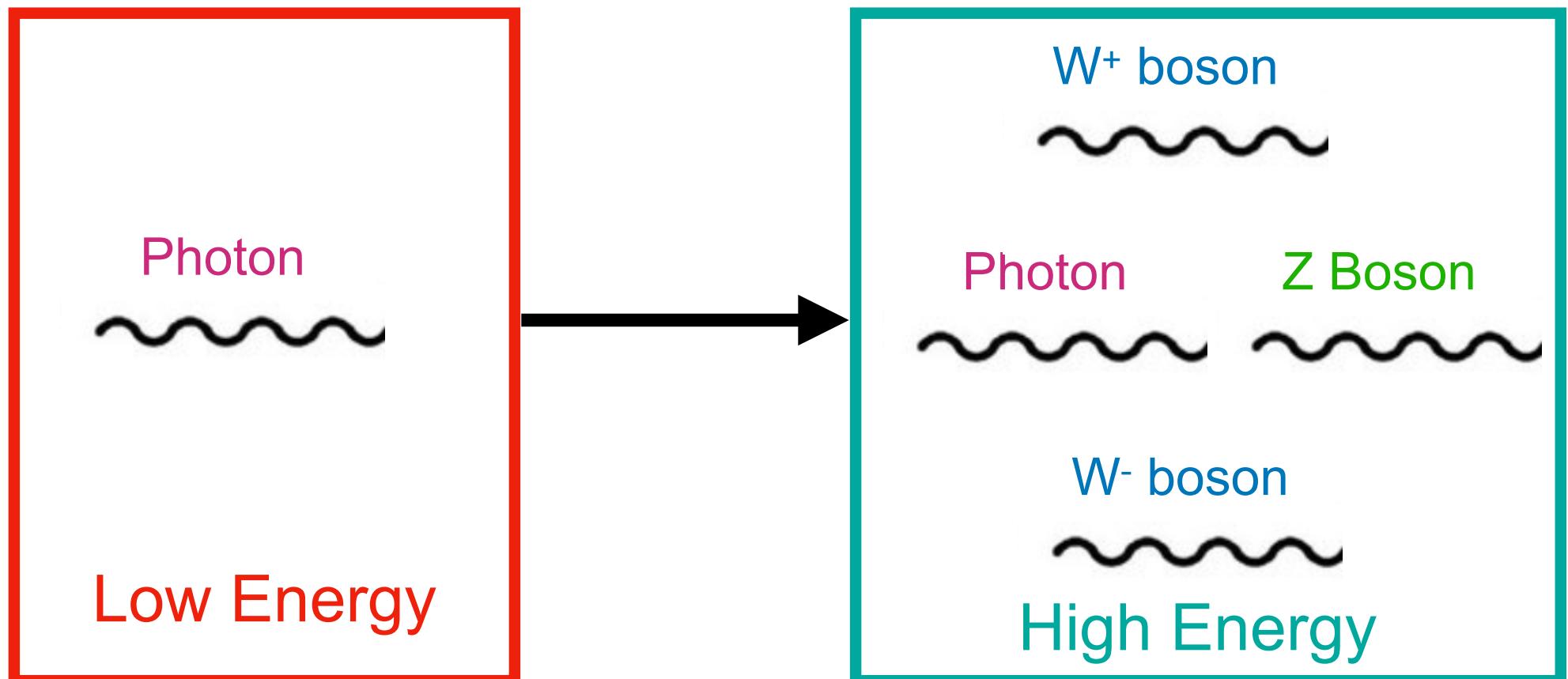


$$M_W < m_t + m_b$$

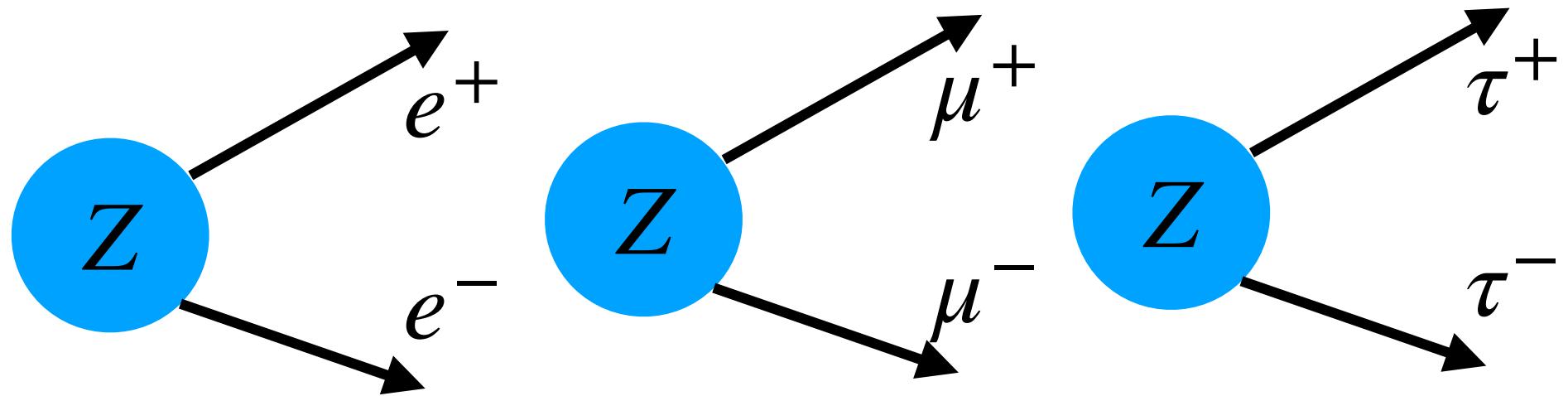
- W boson interacts with many different particles
 - These don't happen frequently b/c W boson is heavy

Electroweak Bosons

- Weak force is combined with EM forces to be electroweak
 - Practically, from low to high energy new forces turn on



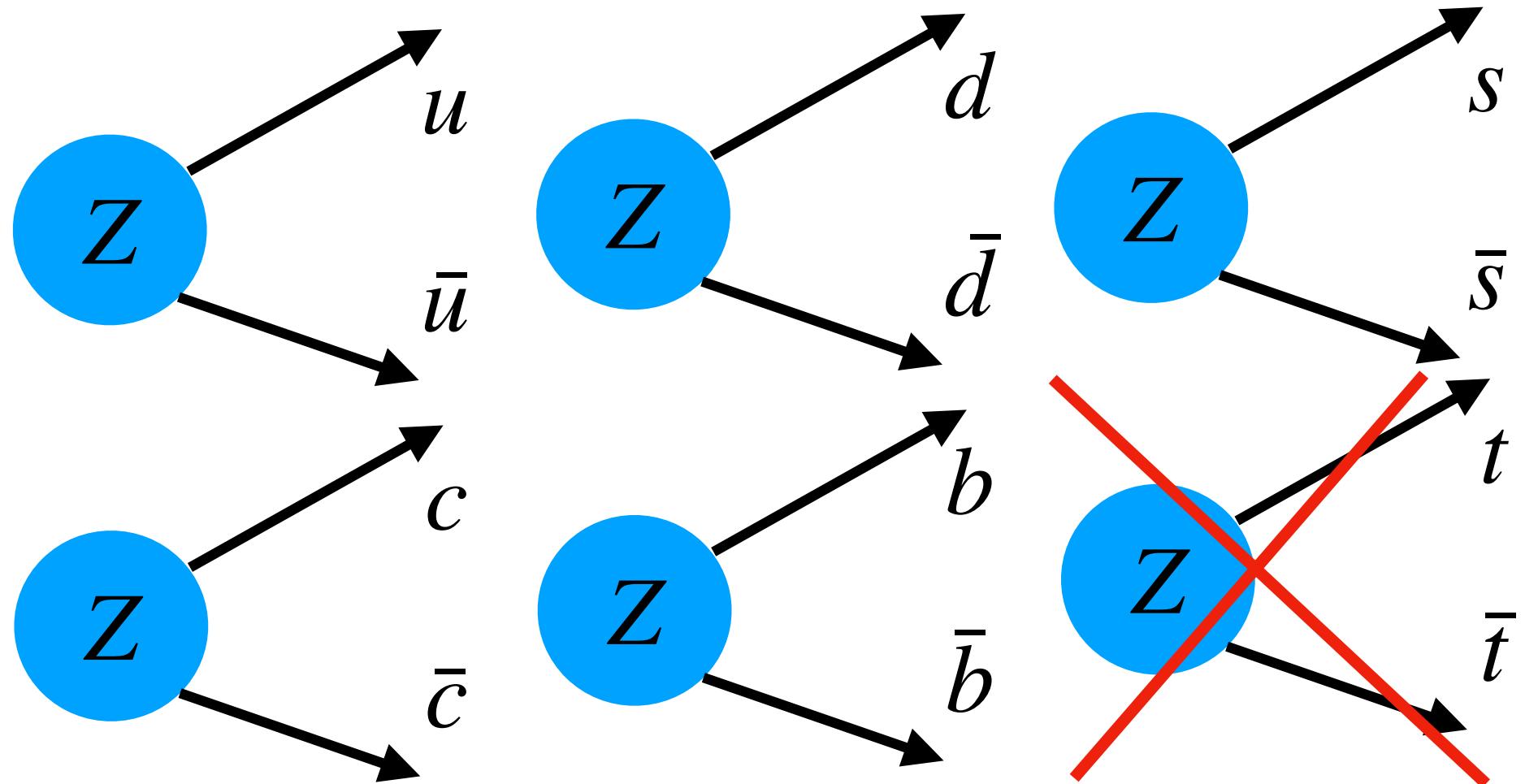
Z boson Properties



- Z boson is like a heavy photon (no charge, but heavy)
- Can decay to leptons

Z boson Properties

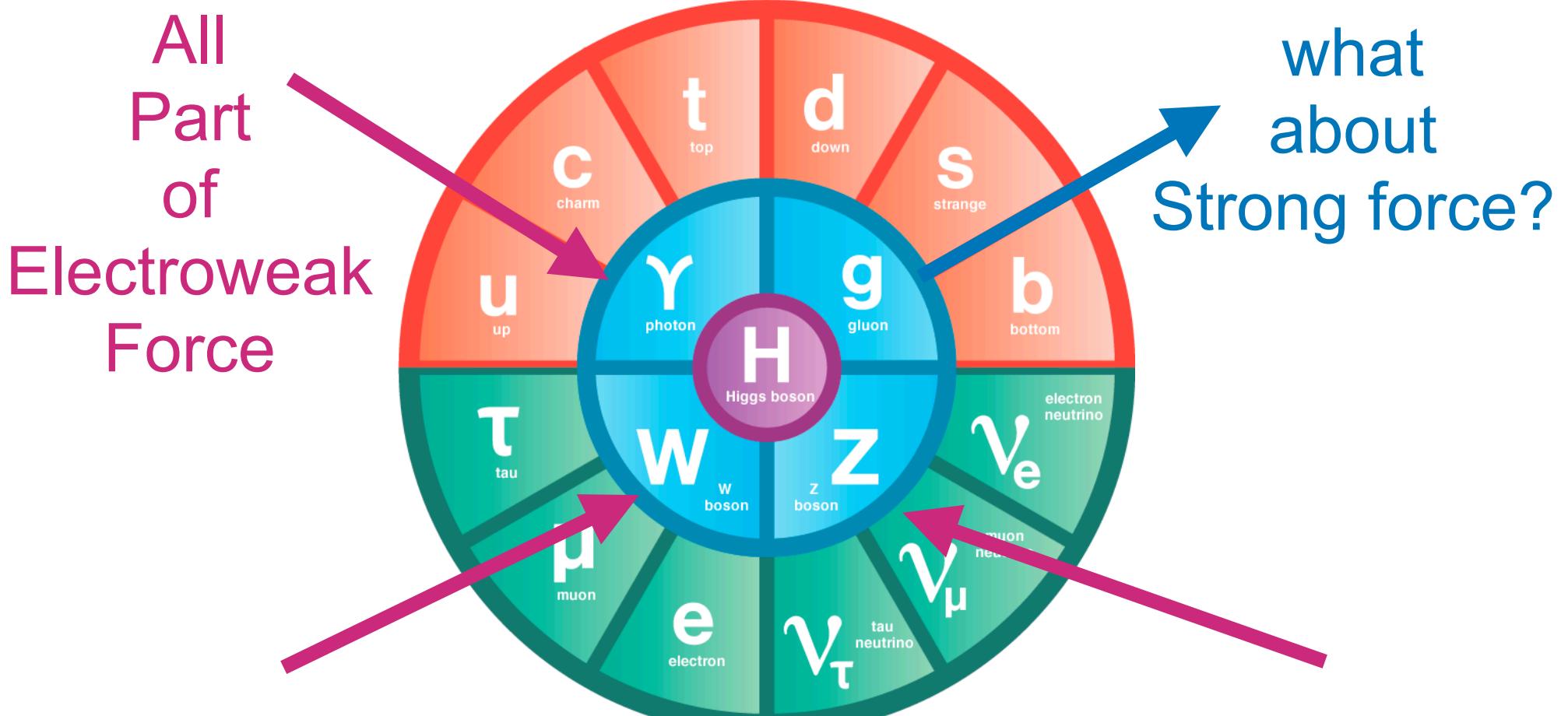
Decays to all quarks, except top



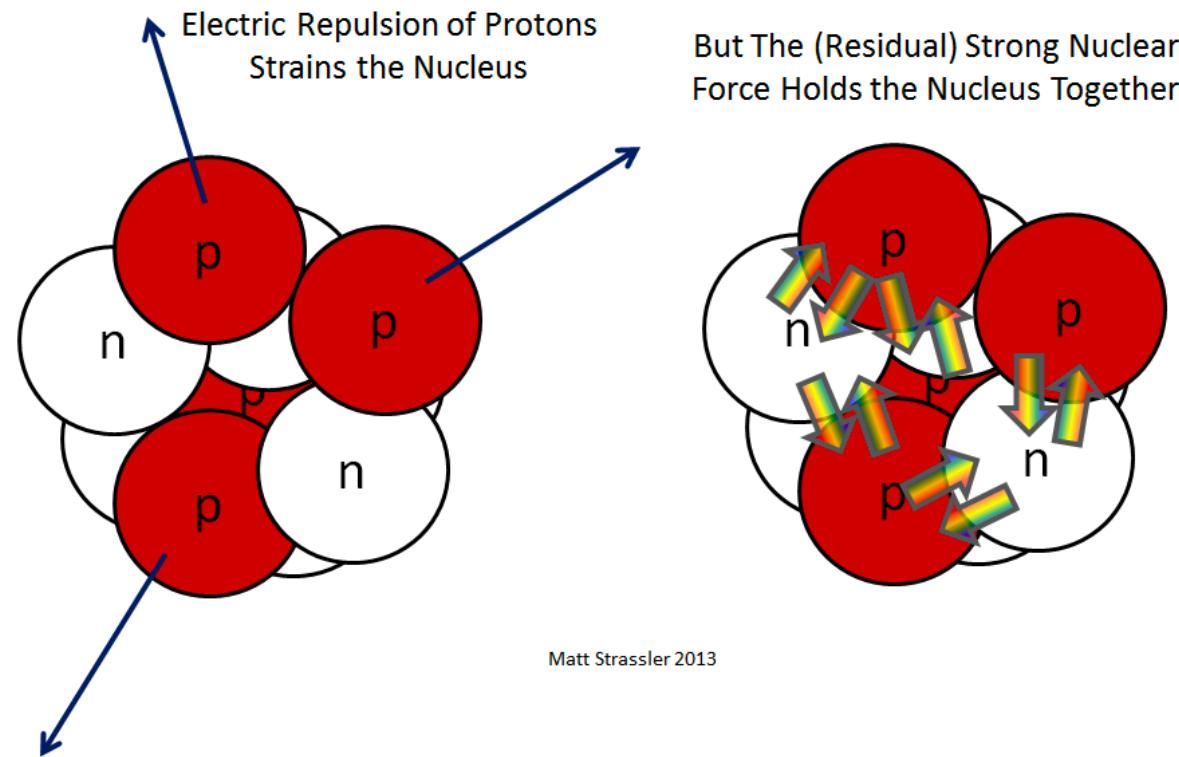
- Z boson is like a heavy photon (no charge, but heavy)

The Forces

- The challenge of this lab is to fin the W and Z boson
 - These are the particles that cover the Weak Boson Interaction

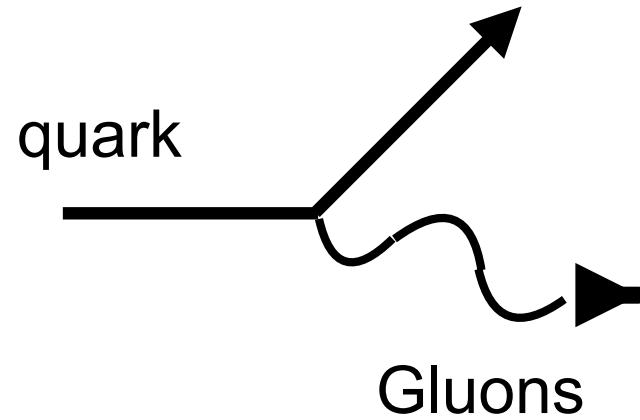


Strong Force



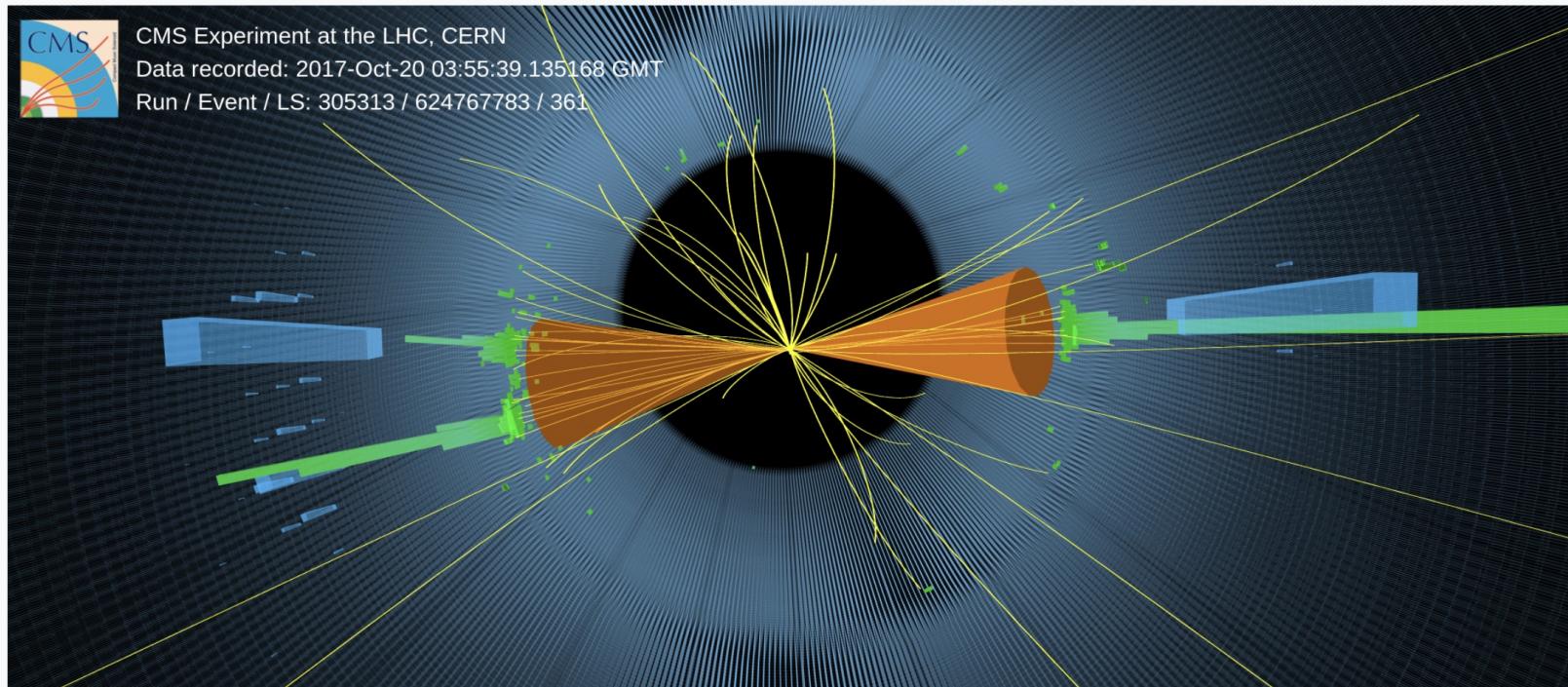
- Strong force is what bins quarks together
 - This is how we get protons

Strong Force Production



- Strong force
 - At high energy quarks can get produced which radiate gluons

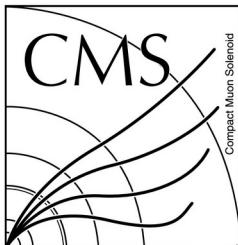
Jet Physics



Phil Harris (MIT)



MIT 8.S50



Understanding Jets

cabbage

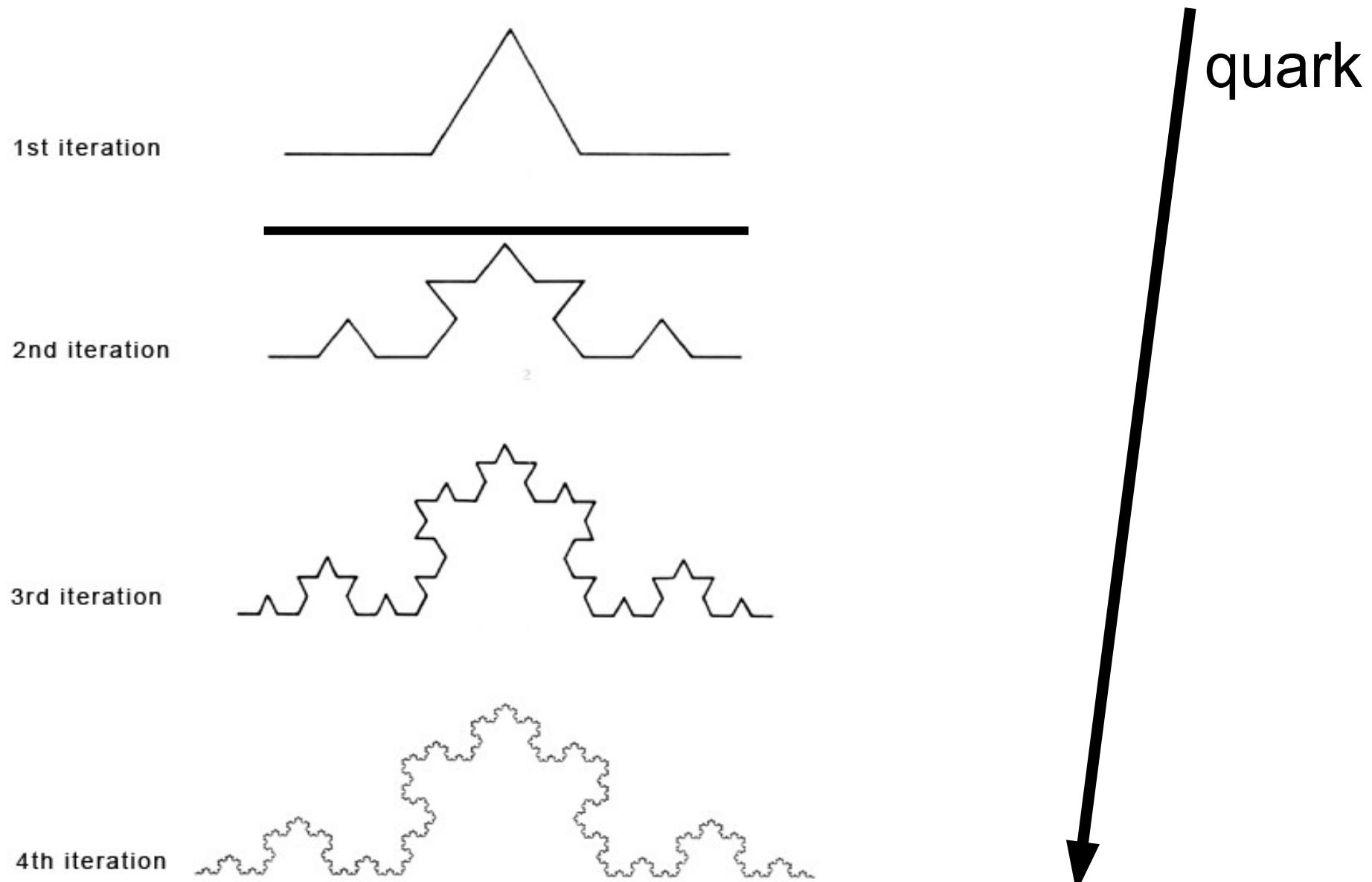


Understanding Jets

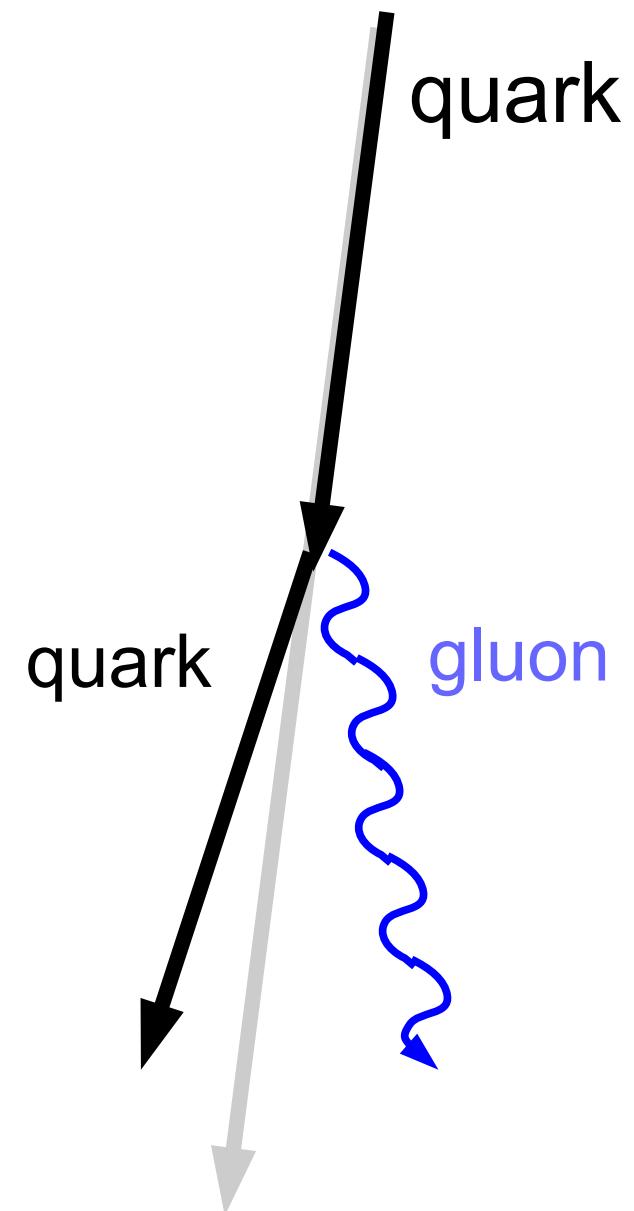
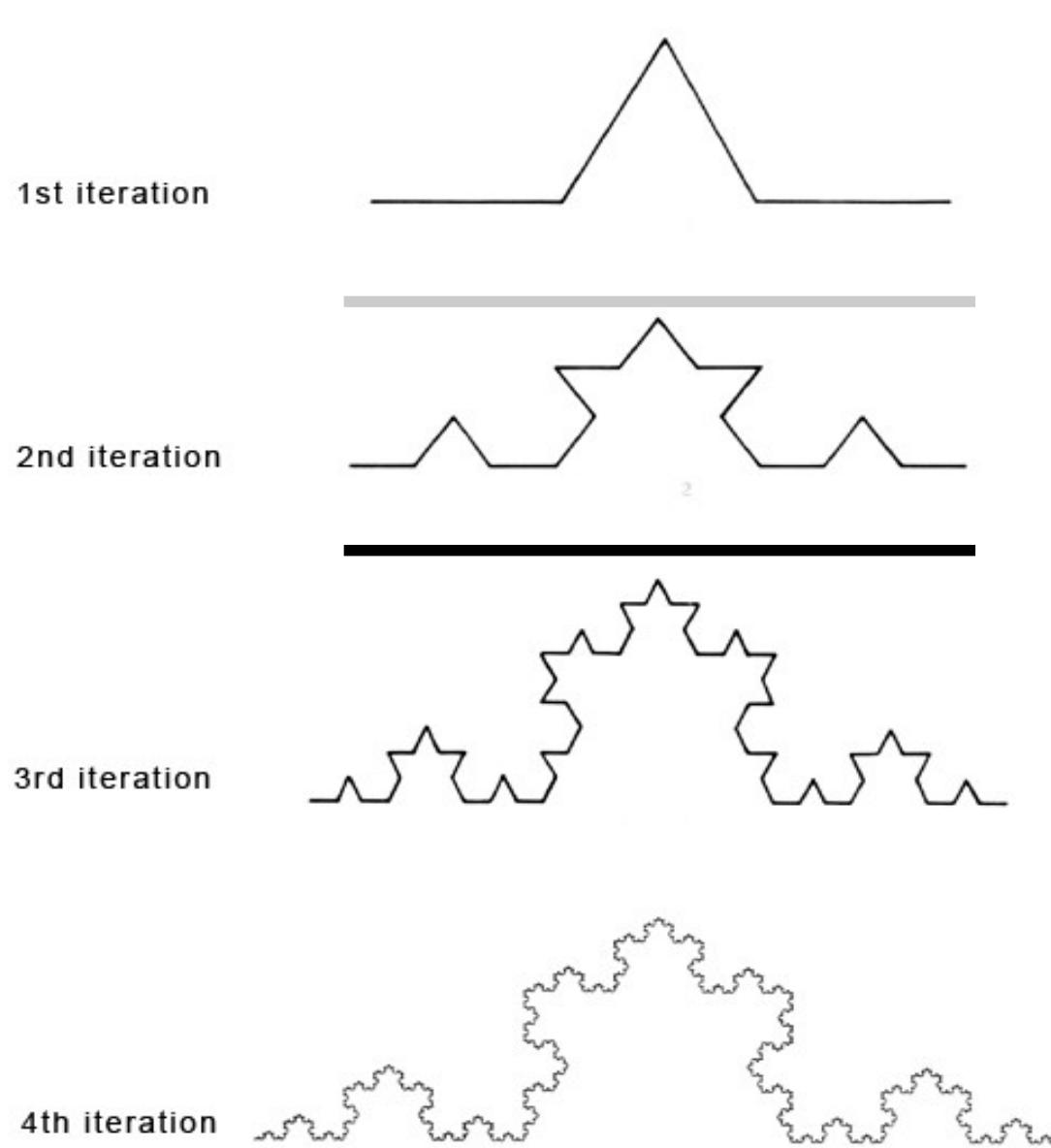
(modern view)



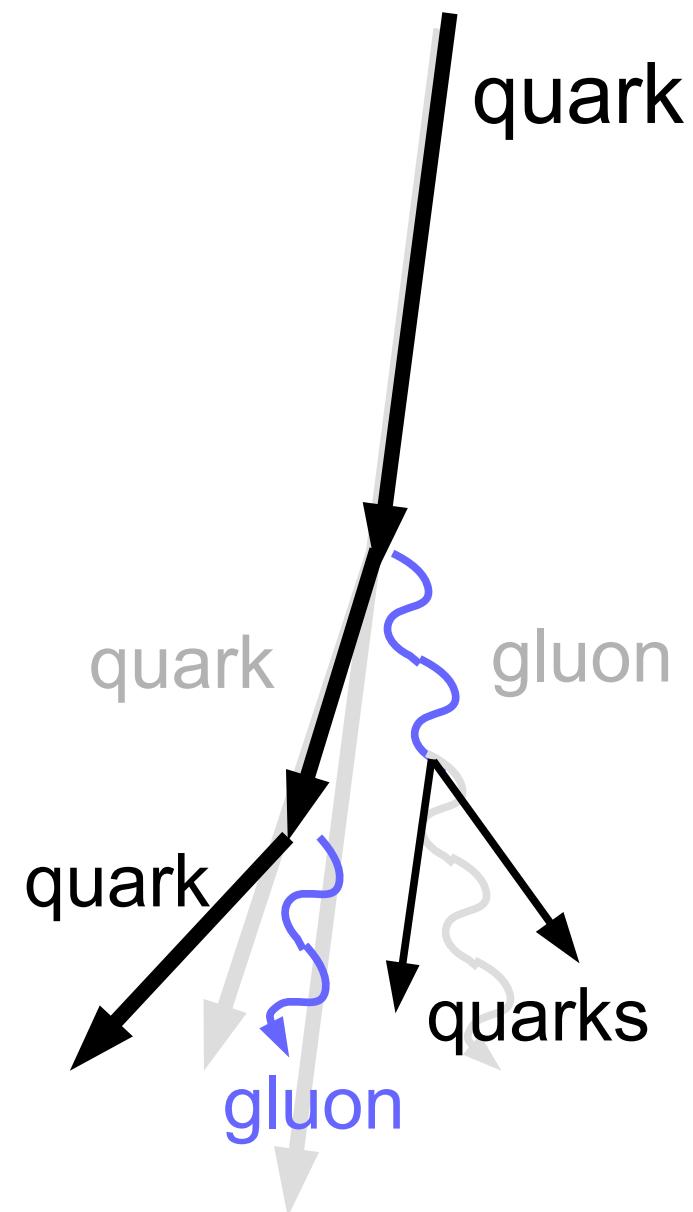
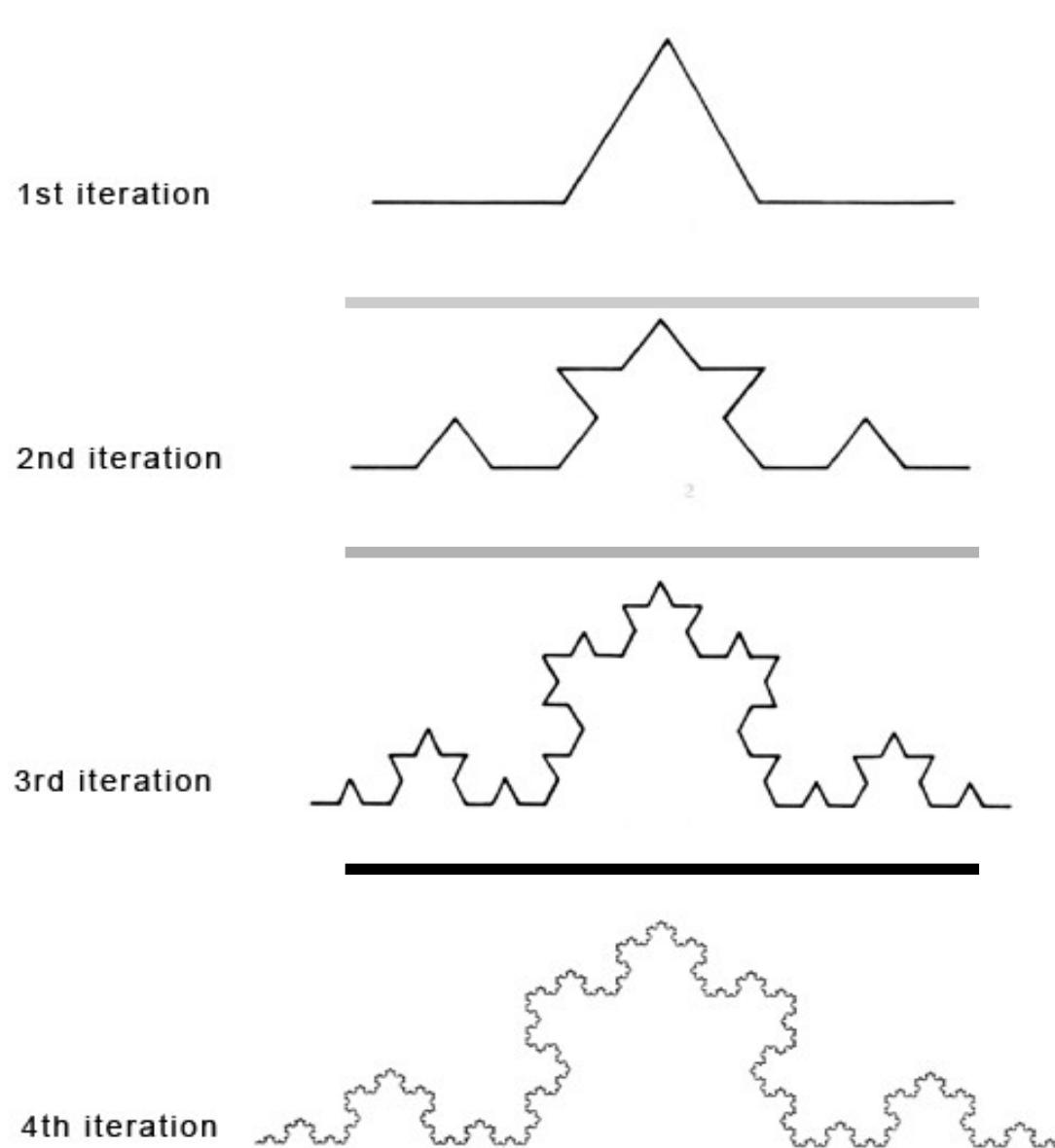
How does this cluster appear?



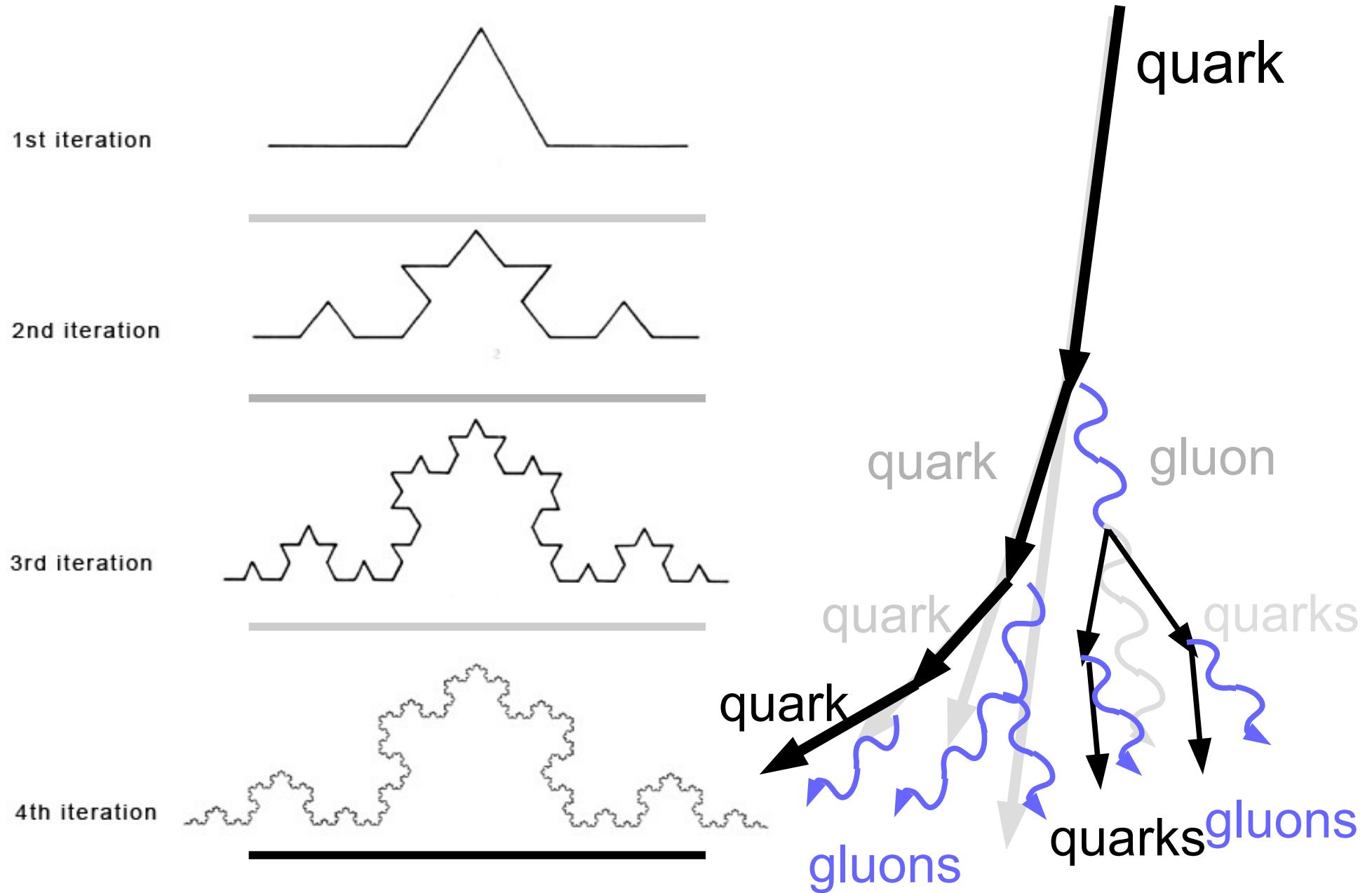
How does this cluster appear?



How does this cluster appear?

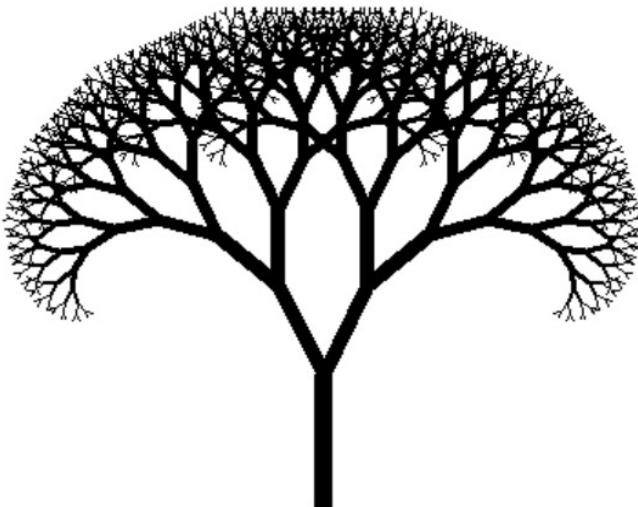


How does this cluster appear?



A fractal

- The repeated branching structure gives a fractal



Branches



Norway coastline



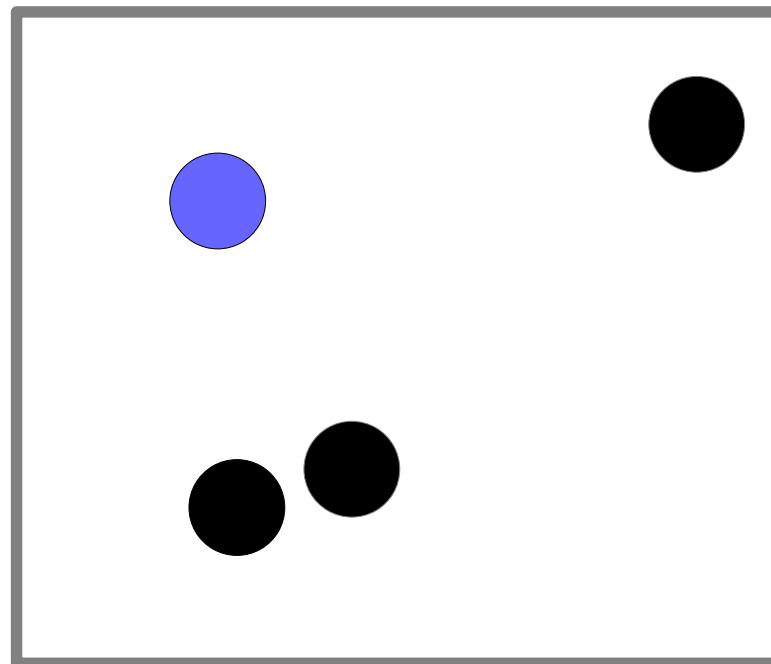
Romenesco cauliflower

Lets use this property to make a simple observable?
What is the scaling dimension of a jet

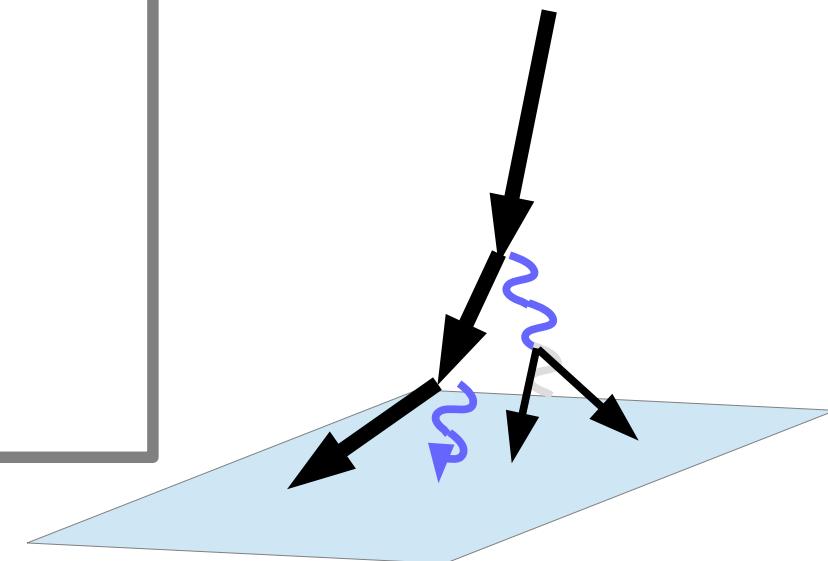
Box Counting(Hausdorff Dimension)

For a given distance scale :

What number of boxes are needed to describe a jet



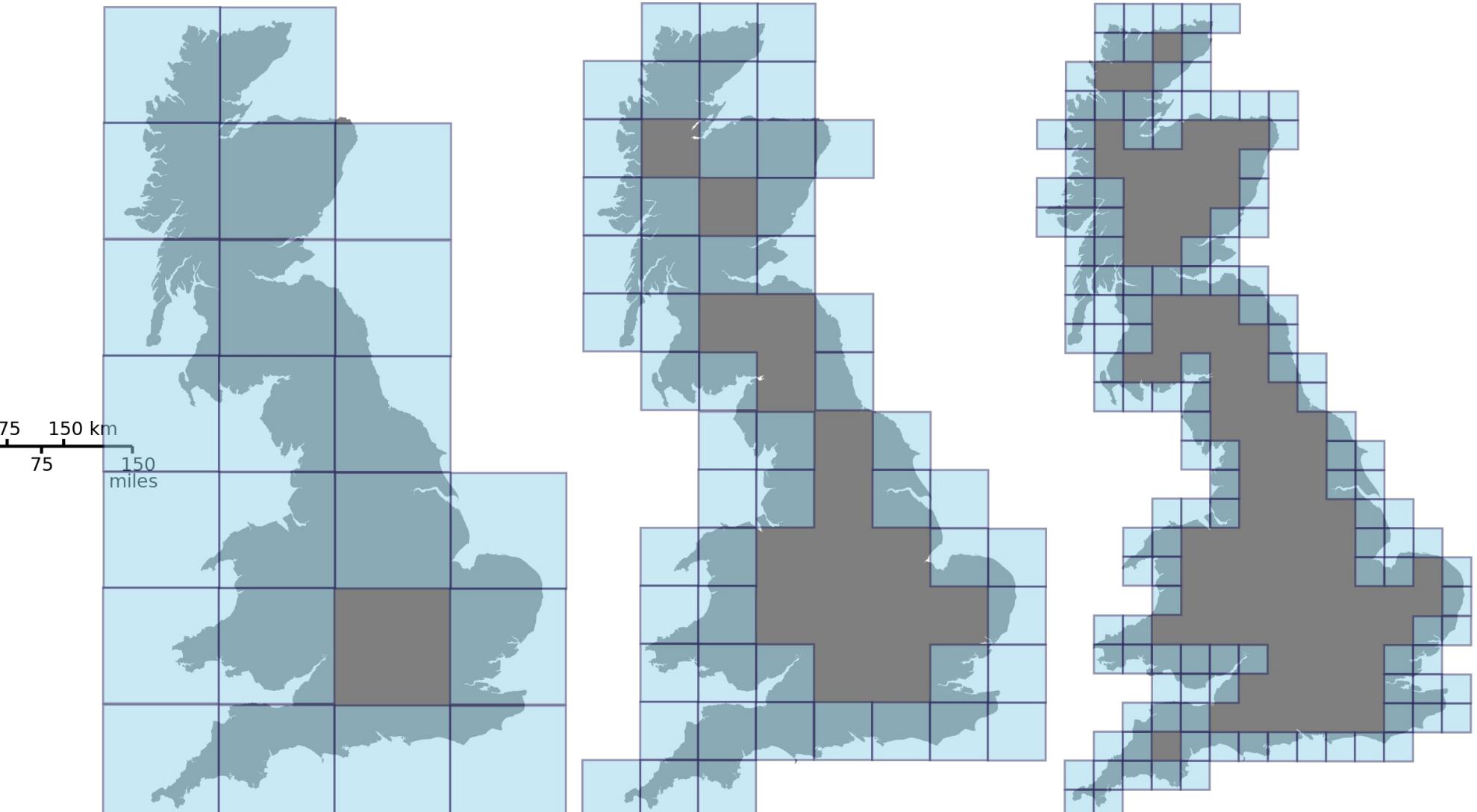
Same jet from 2 slides ago



$$\text{(Fractal) Dimension} = \lim_{D(\text{istance}) \rightarrow 0} \frac{\log(N_d^{\text{boxes}})}{\log(\text{Distance})}$$

Can we characterize this?

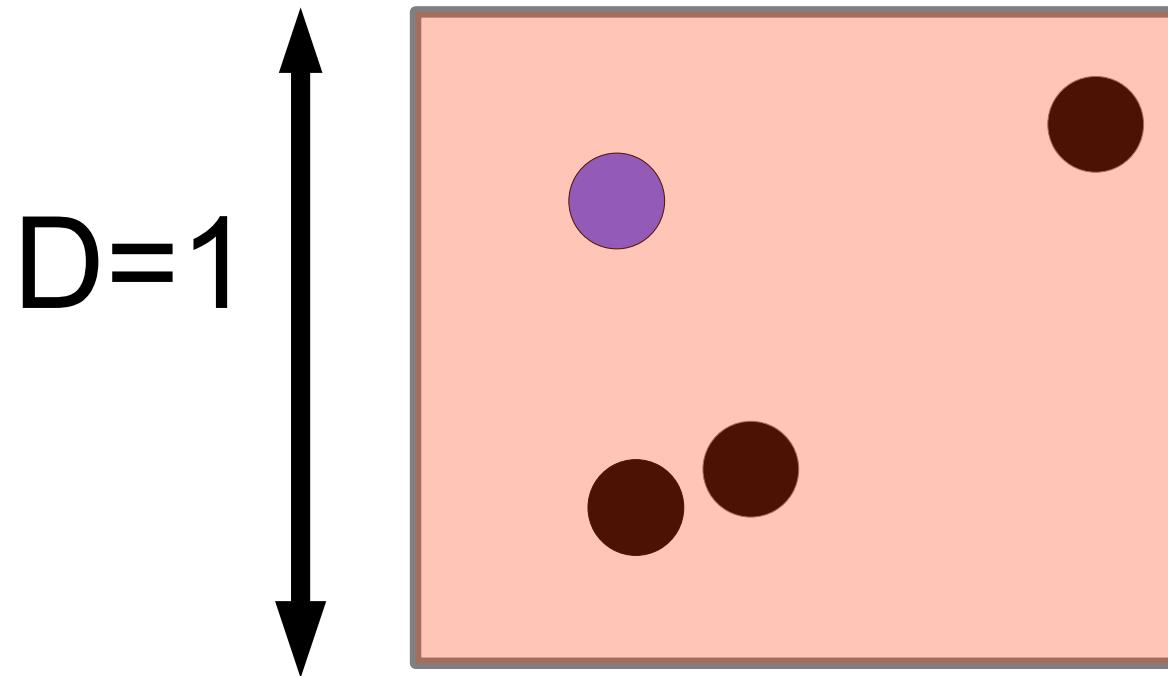
- Measuring fractals:



Coastline of Great Britain is $D=1.25$

$$\text{Dimension} = \lim_{D \rightarrow 0} \frac{\log(N_D^{\text{boxes}})}{\log(D)}$$

Box Counting

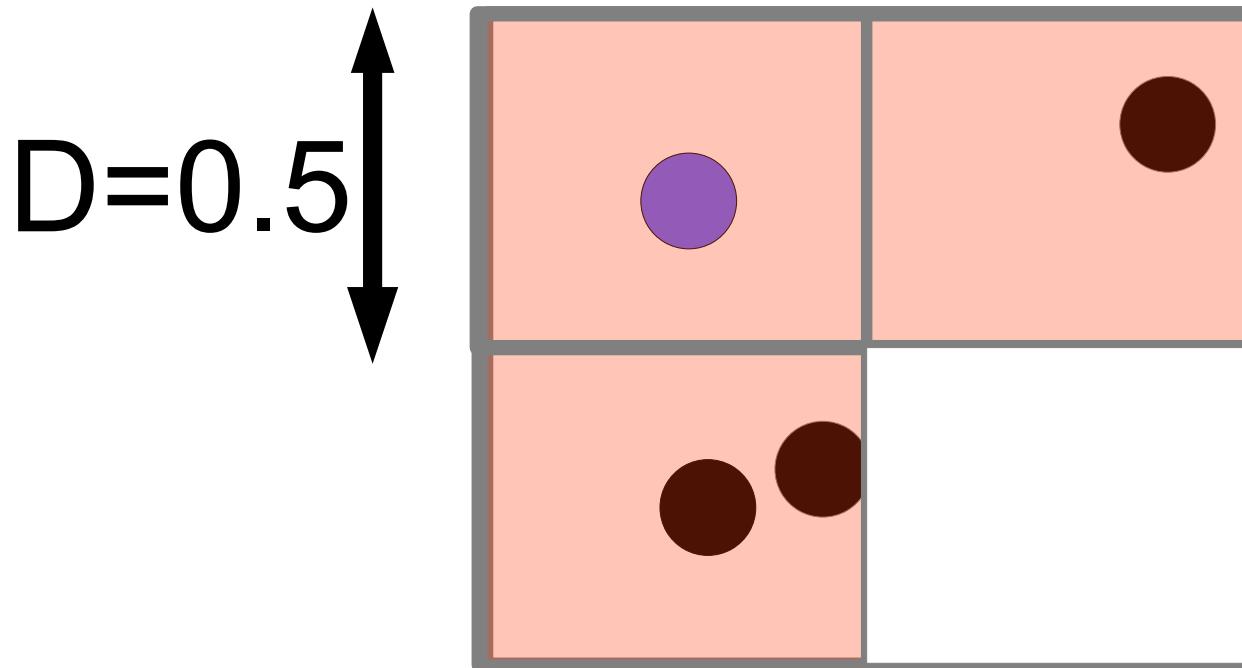


1 Box with distance=1 covers all points

Number of boxes to cover per size defines dimension

$$\text{Dimension} = \lim_{D \rightarrow 0} \frac{\log(N_D^{\text{boxes}})}{\log(D)}$$

Box Counting



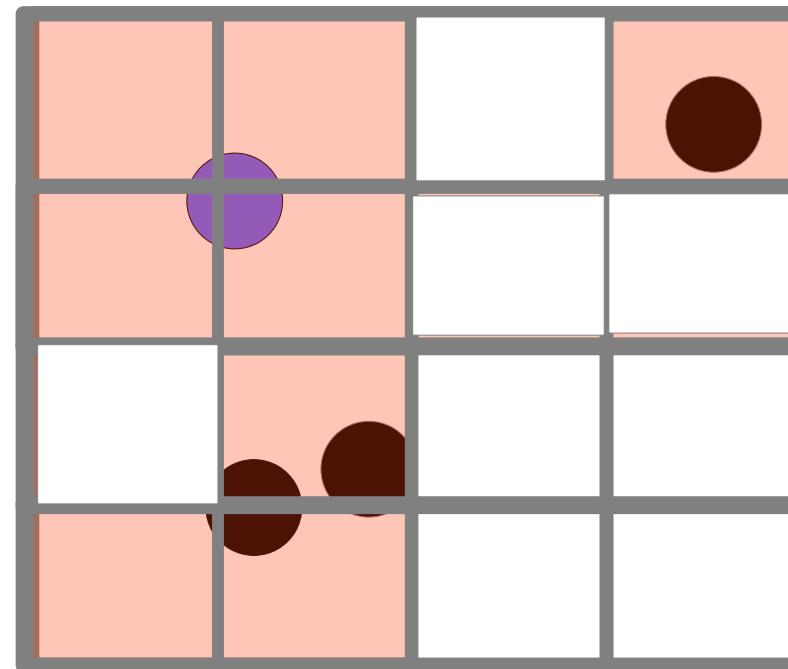
3 Boxes with distance=0.5 cover all points

Number of boxes to cover per size defines dimension

$$\text{Dimension} = \lim_{D \rightarrow 0} \frac{\log(N_D^{\text{boxes}})}{\log(D)}$$

Box Counting

$D=0.25$ ↑

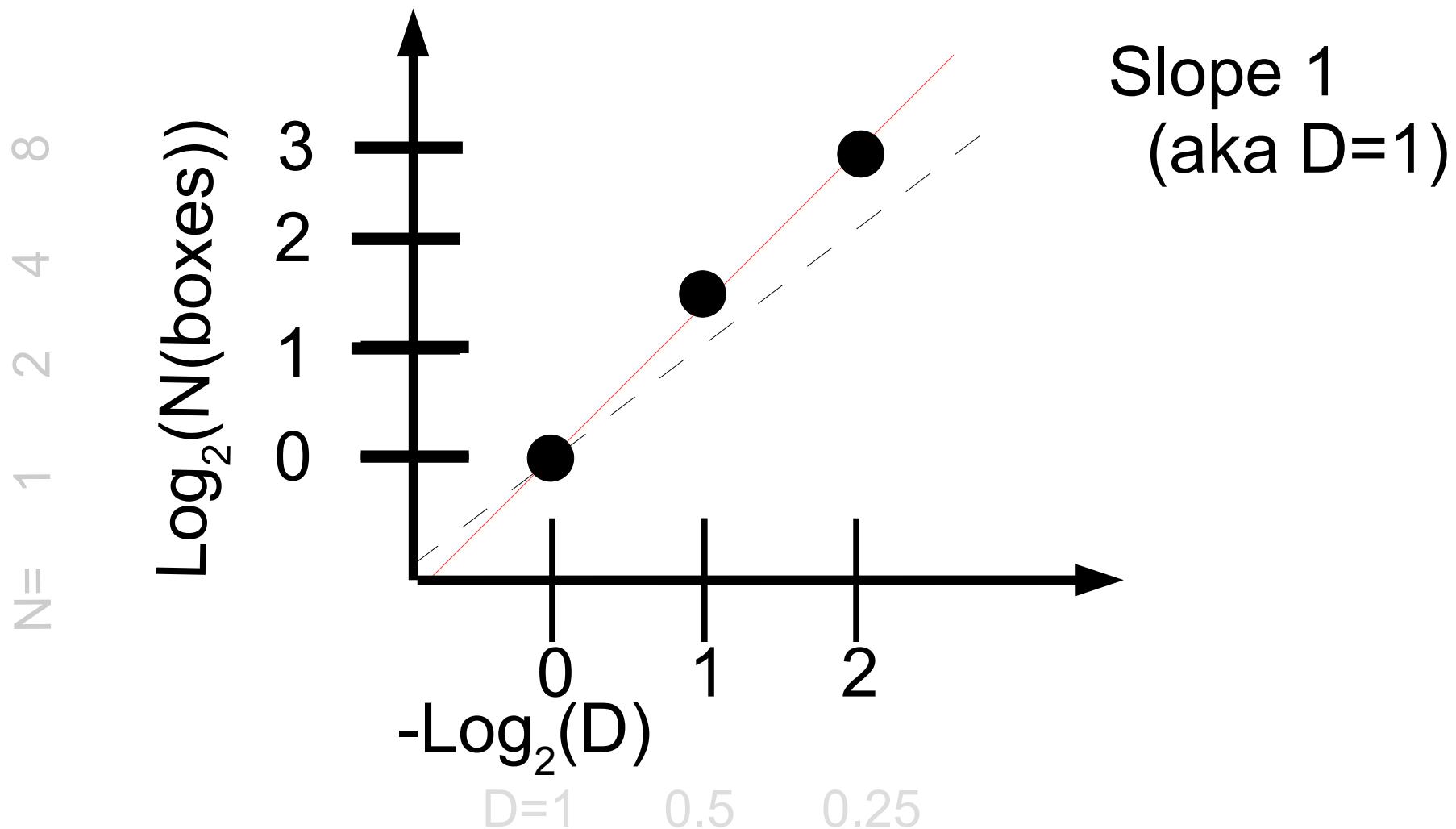


8 Boxes with distance=0.25 cover all points

Number of boxes to cover per size defines dimension

Dimension=Lim_{D→0} $\frac{\text{Log}(N_D^{\text{boxes}})}{\text{Log}(D)}$

Box Counting



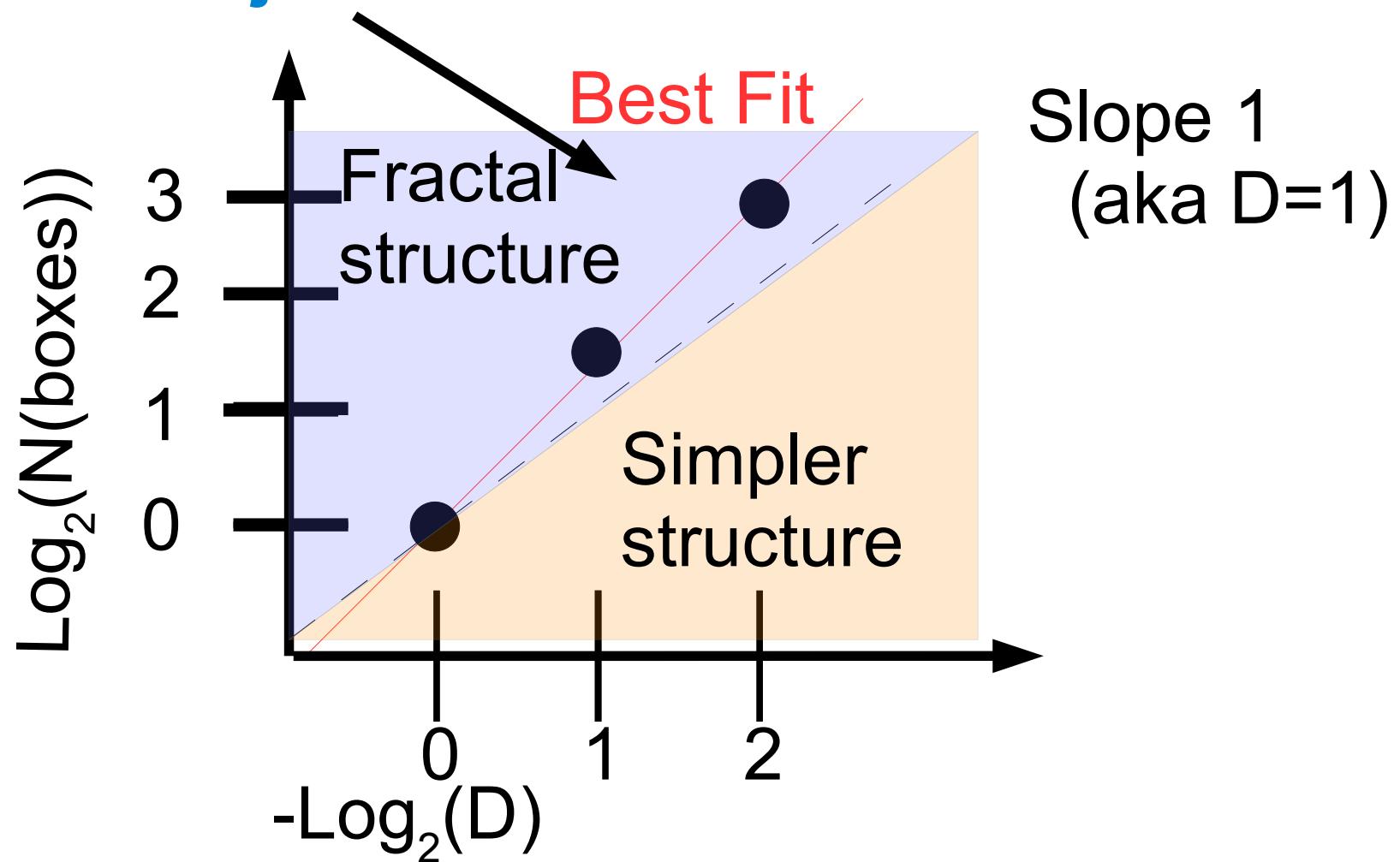
Slope 1
(aka D=1)

Number of boxes to cover per size defines dimension

$$\text{Dimension} = \frac{\log(N_D^{\text{boxes}})}{\log(D)} \quad (D \rightarrow 0)$$

Box Counting

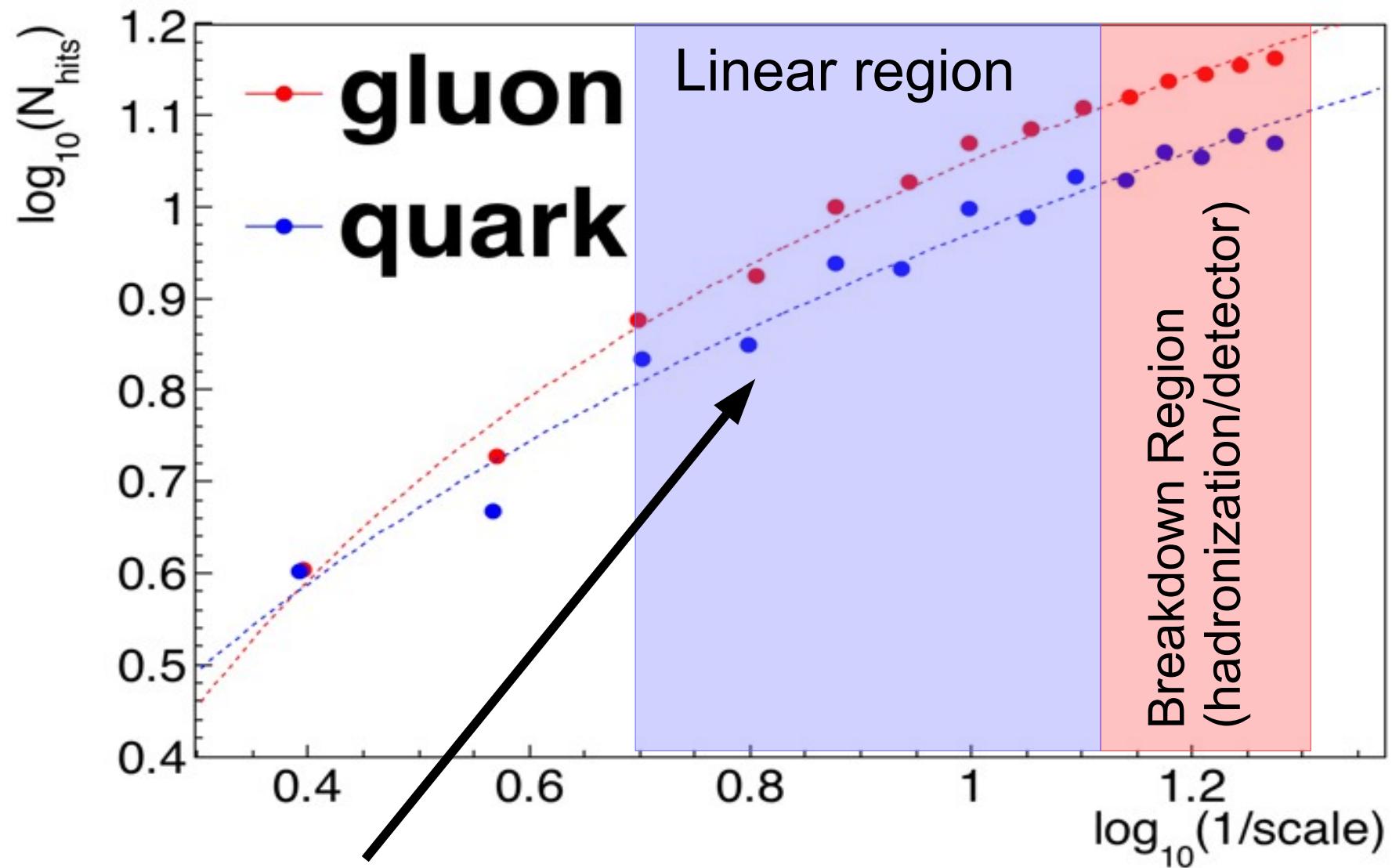
Our 4 particle jet is fractal like



Slope 1
(aka D=1)

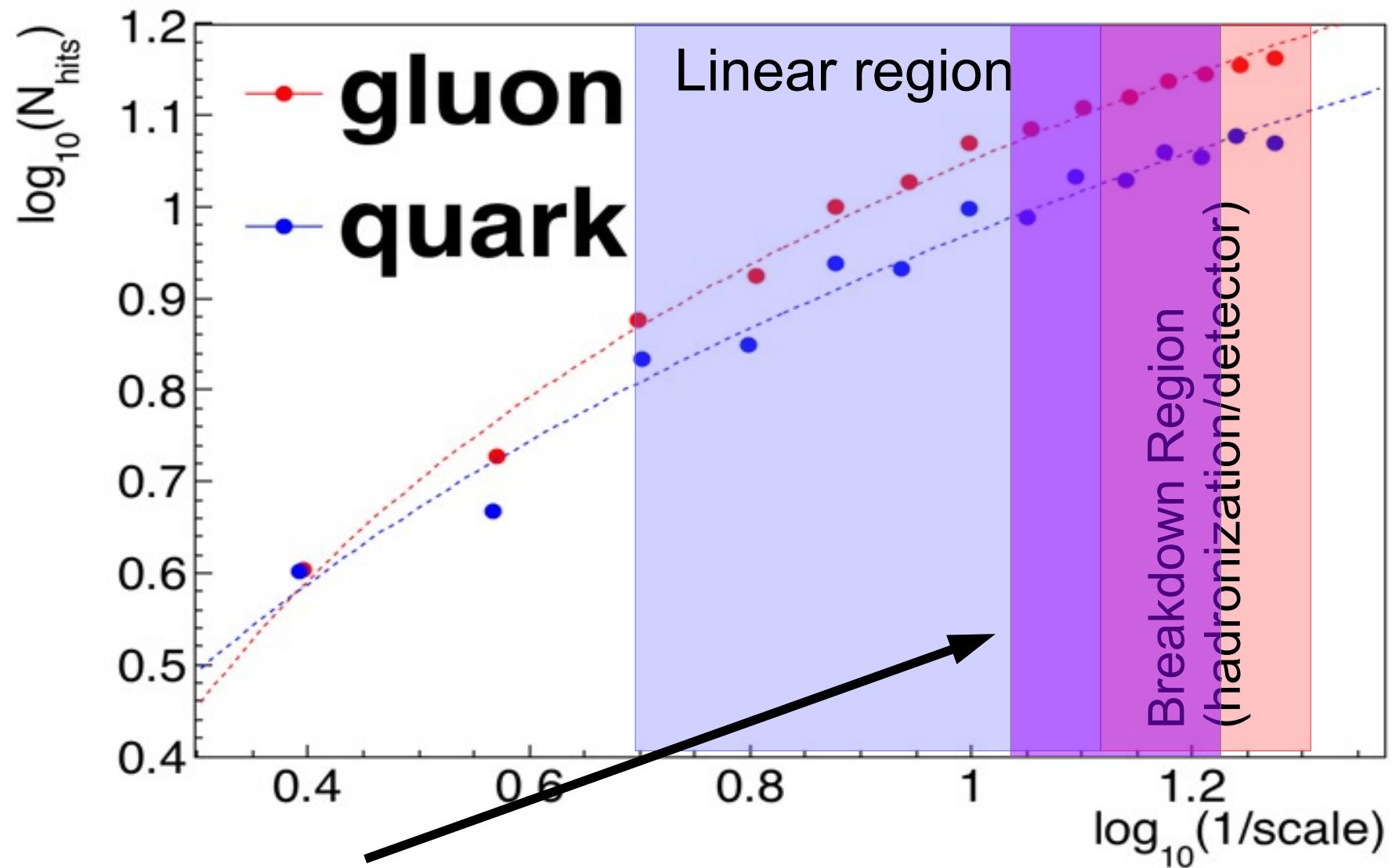
Number of boxes to cover per size defines dimension

What about a real jet?



Roughly linear scalar separation between quarks and gluons
arxiv/sometime soon

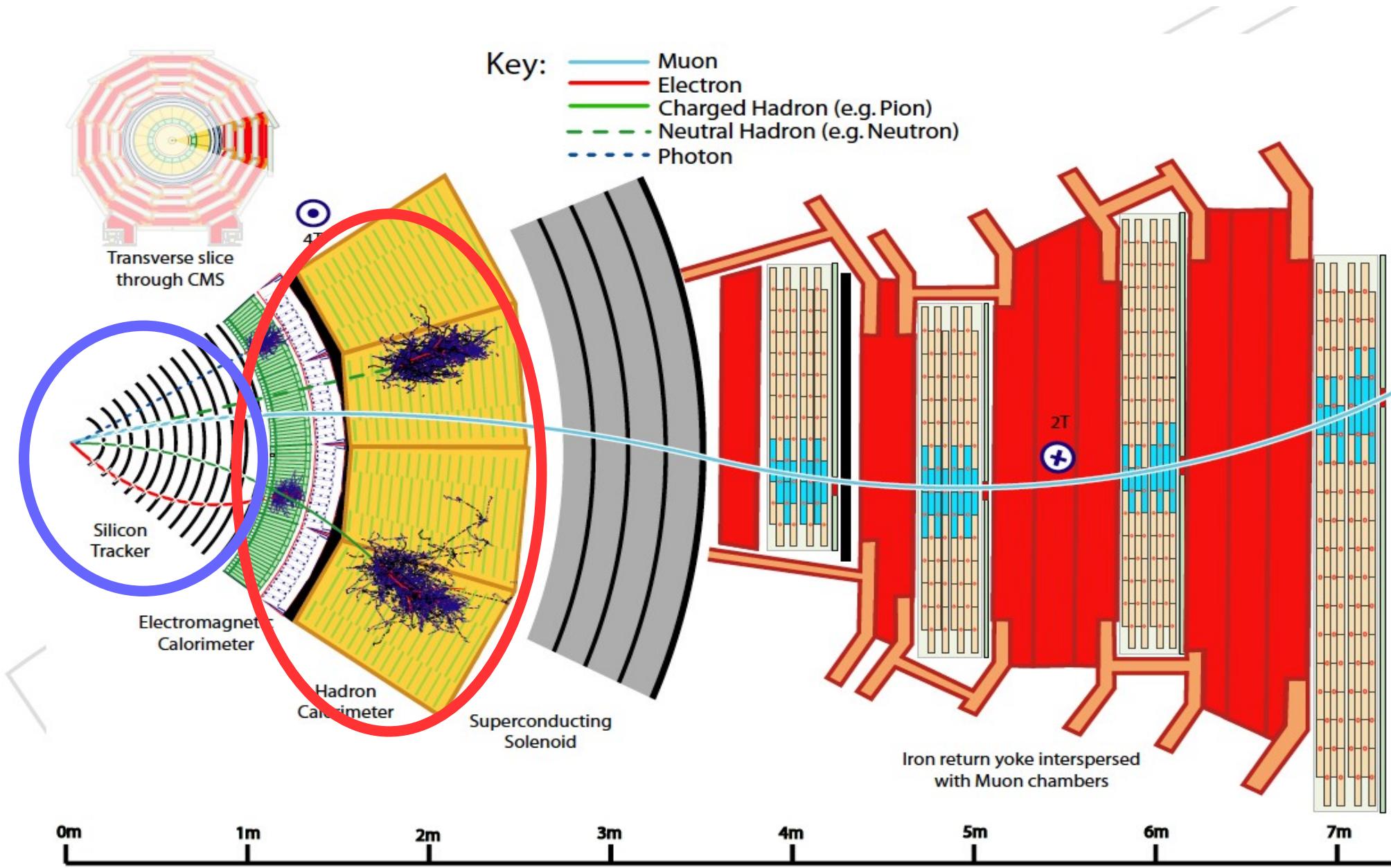
What about a real jet?



Effects from the heavy ion medium can modify this region
arxiv/sometime soon

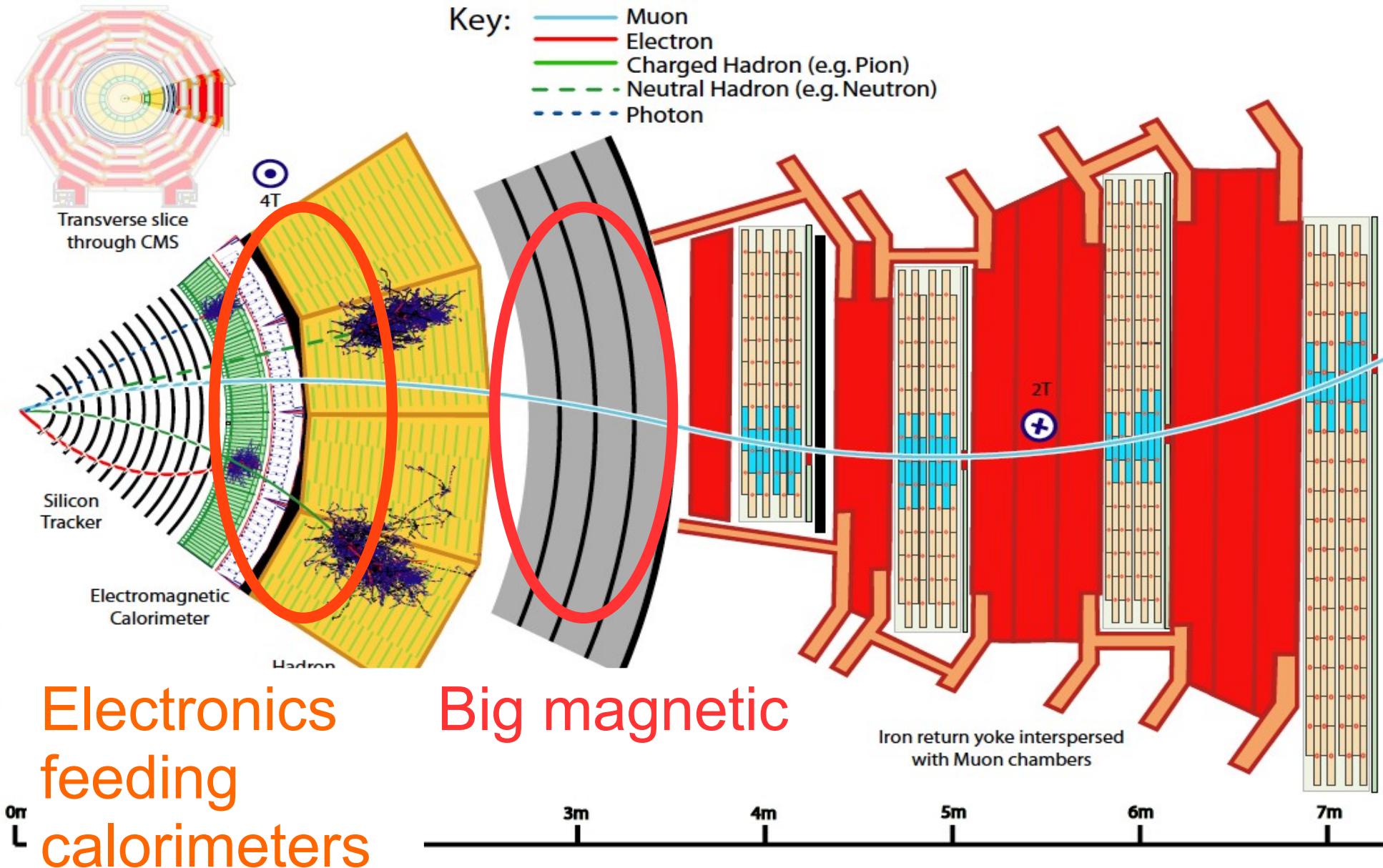
In Our Detector

Over the past week you have seen the individual components

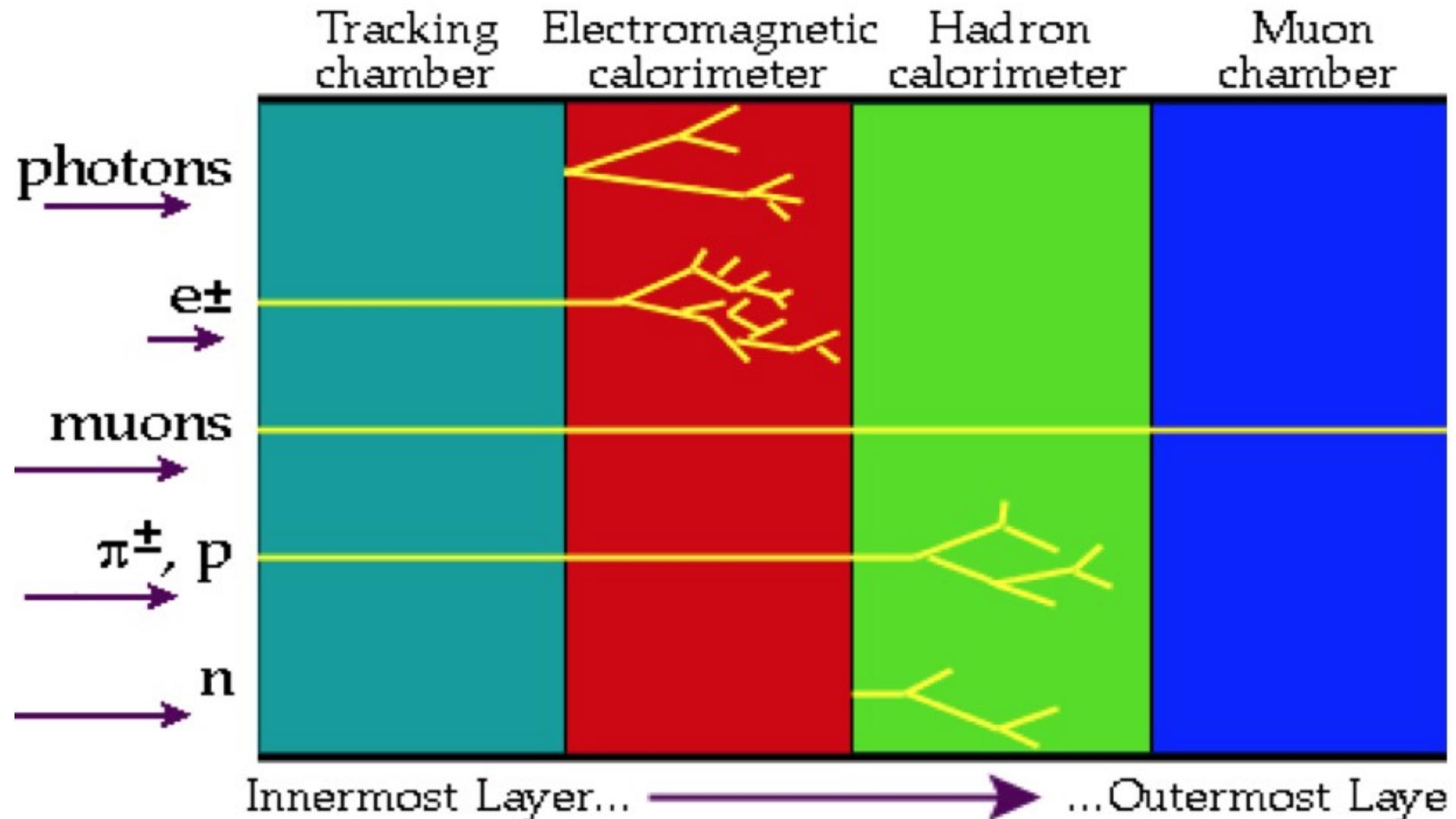


What if we start to link things together?

We have to account for the other detectors



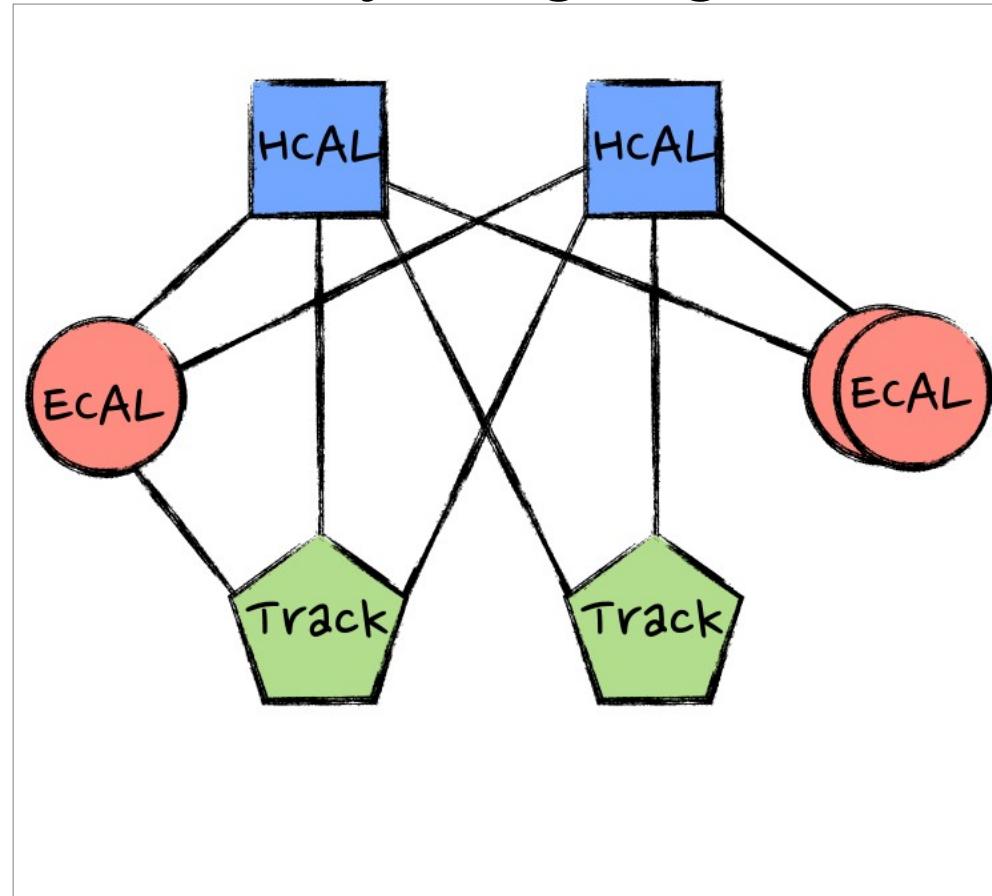
Particle Identification Basics



Credit: Particle Data Group (LBNL)

Particle Flow

Link everything together



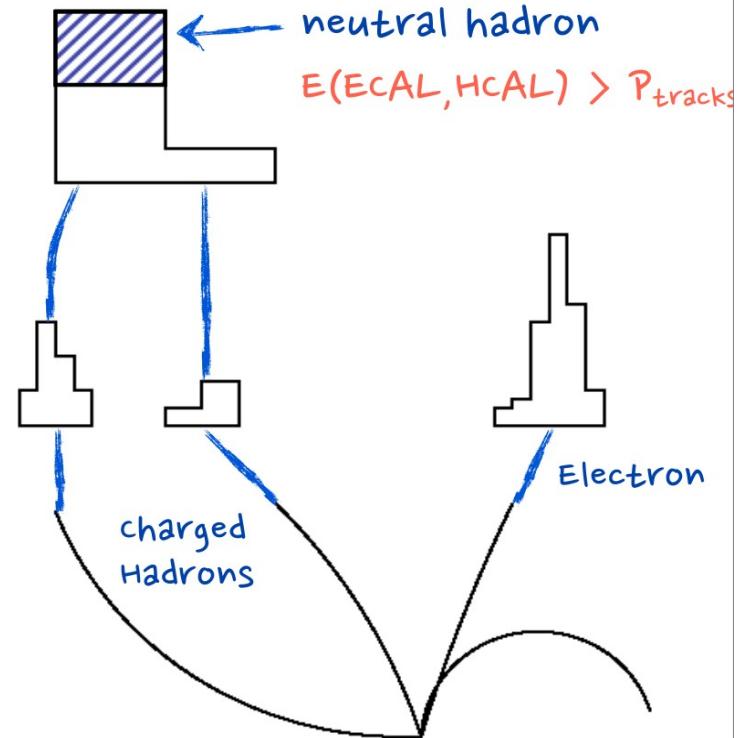
Make Particles

Finally Apply Particle ID & Separation

HCAL
clusters

ECAL
clusters

Tracks



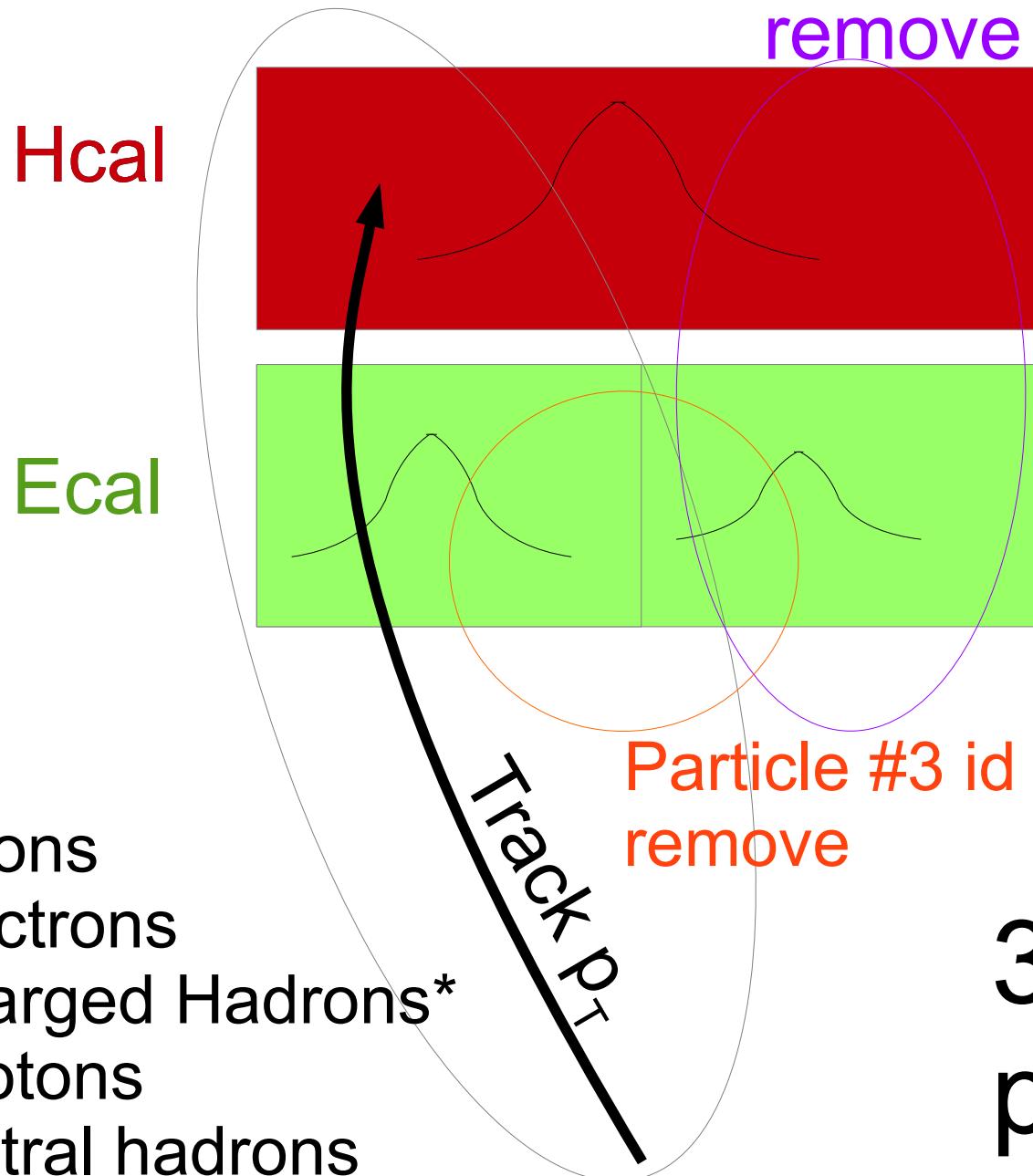
We get 5 classes of particles

Are we missing any?

Particle #1 (Id) & remove
(expected)deposit

Ordering is key

Particle #2 (Id) &
remove



Particle #3 id &
remove

3 overlapping
particle event

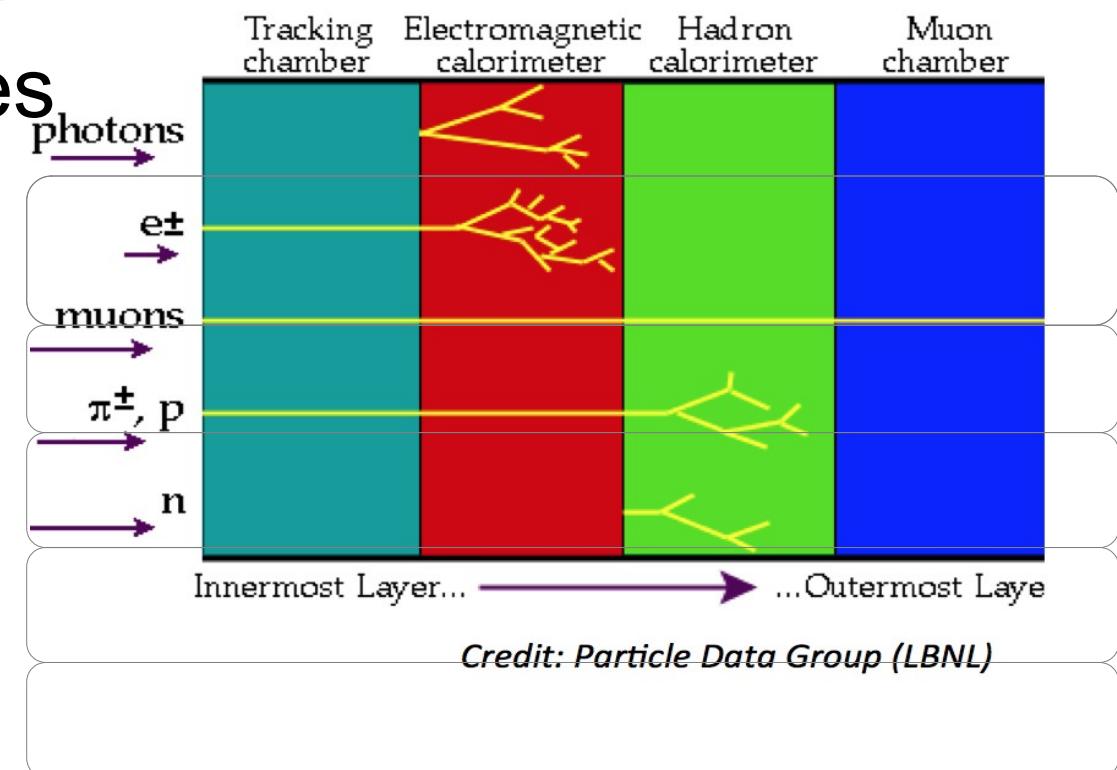
Resulting Components

- `Std::vector<ParticleFlowCandidates>`

- `ParticleFlowCandidate`

- Particle id
- Mass
- p_T
- Eta
- Phi

5 types

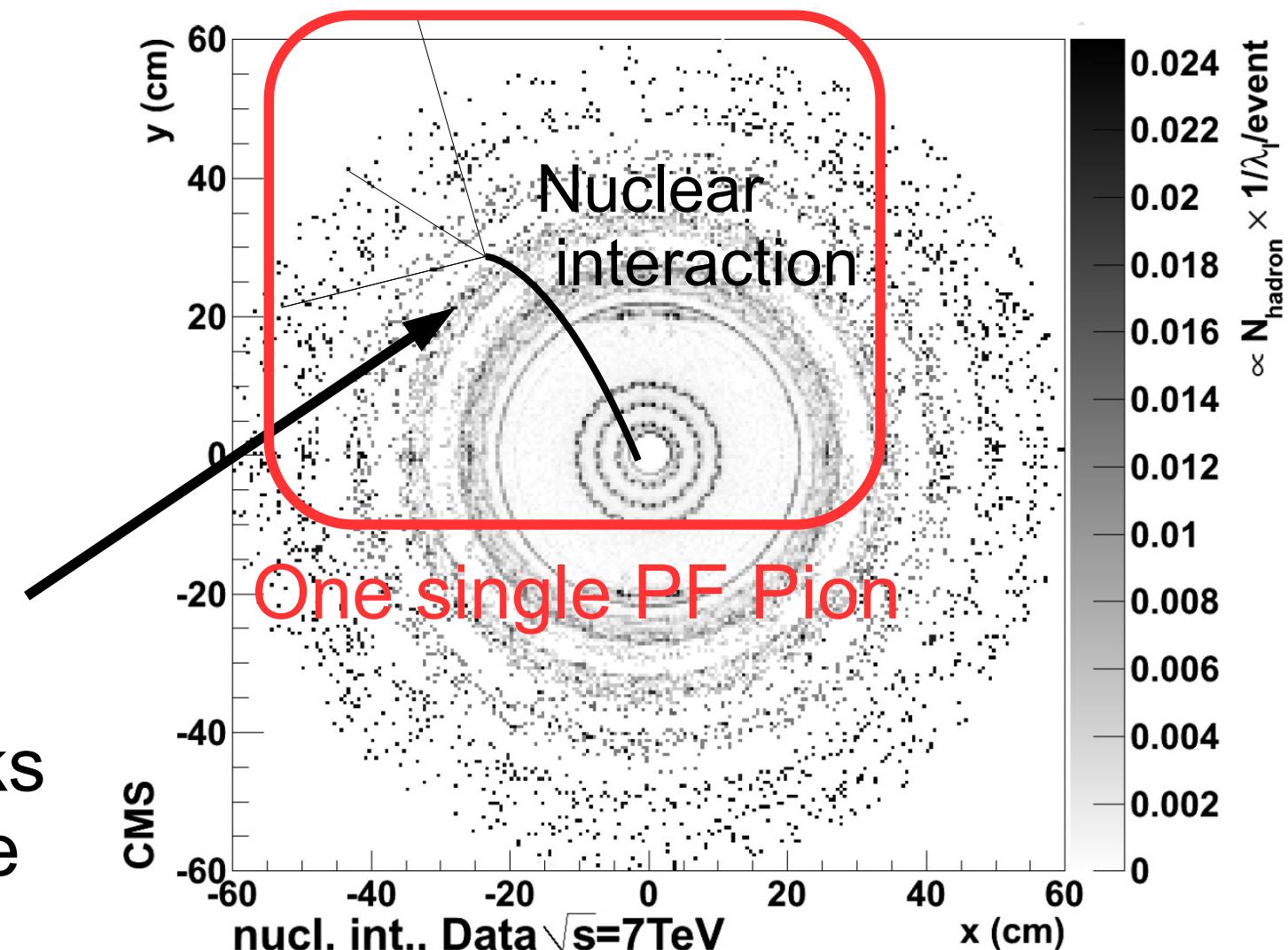


ATLAS does not (yet) link charged particles w/calorimeters

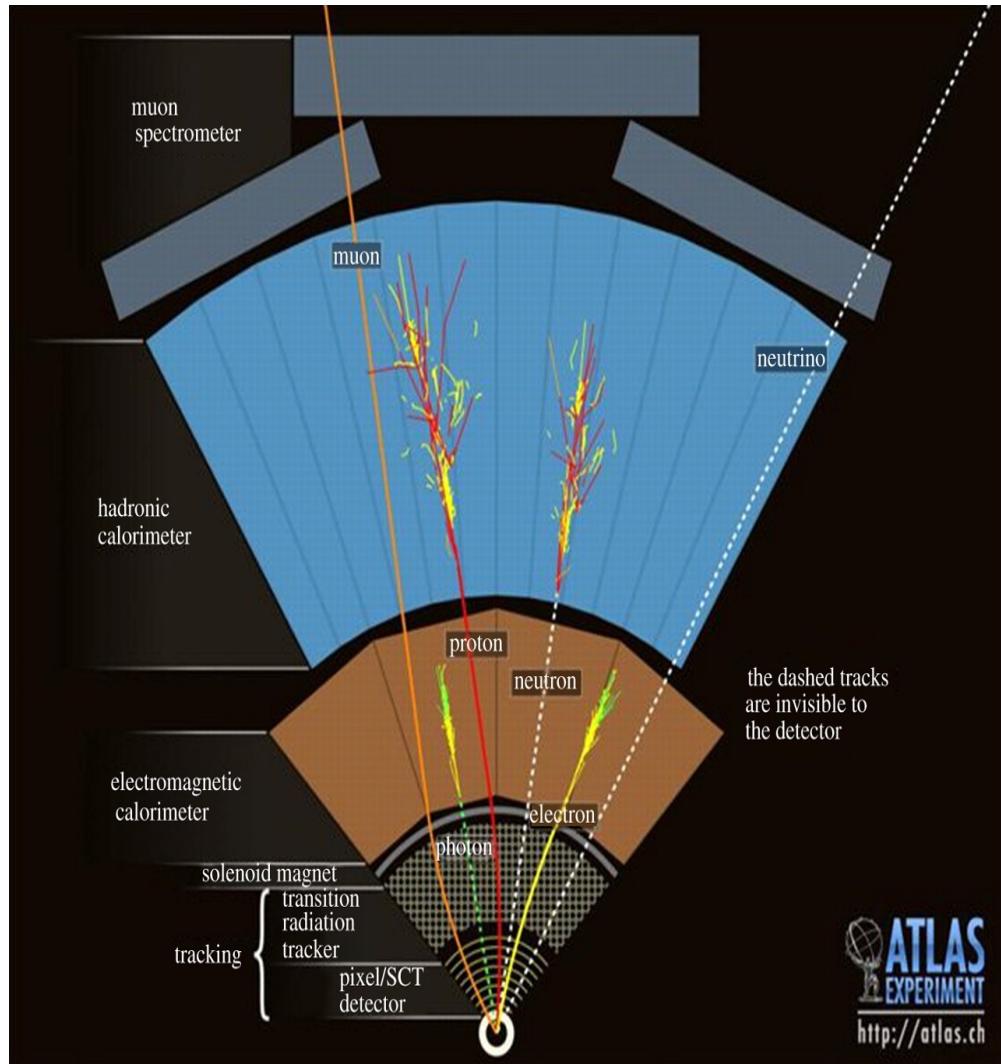
A lesser known point

- Embedded in particle flow are nuclear interaction

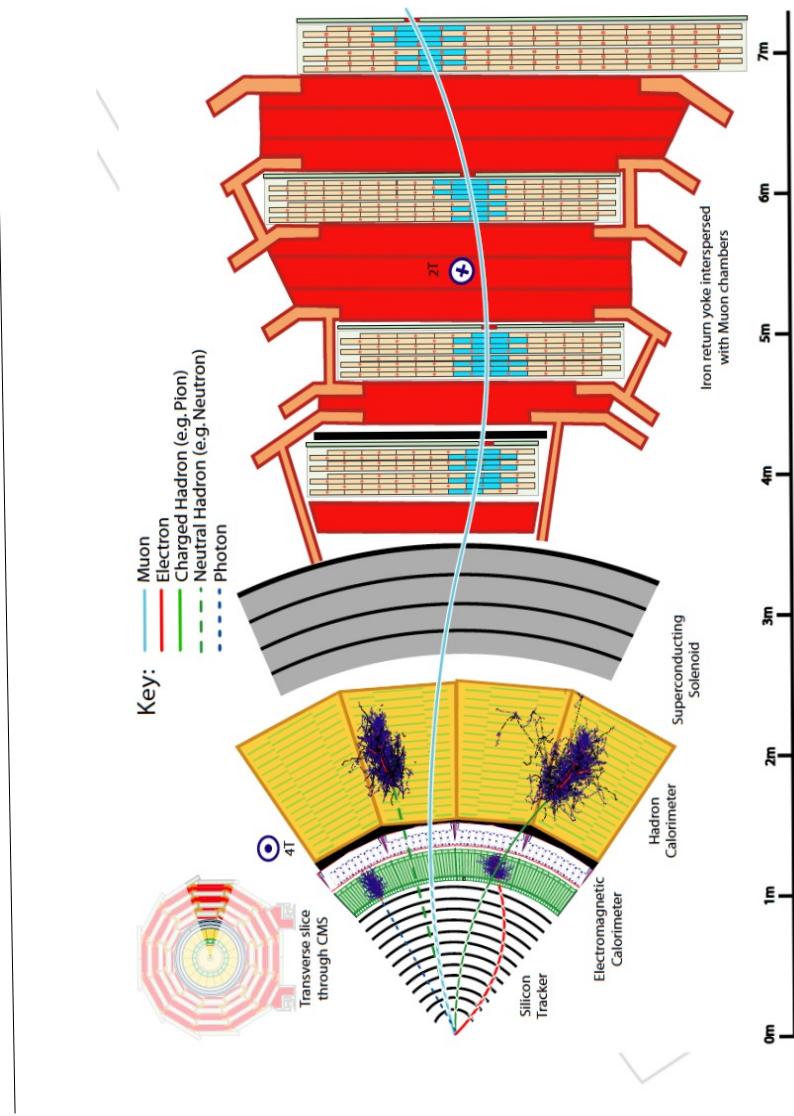
Particle flow looks for displaced secondary vertices and merges tracks into 1 particle



Any complication for PF in ATLAS?

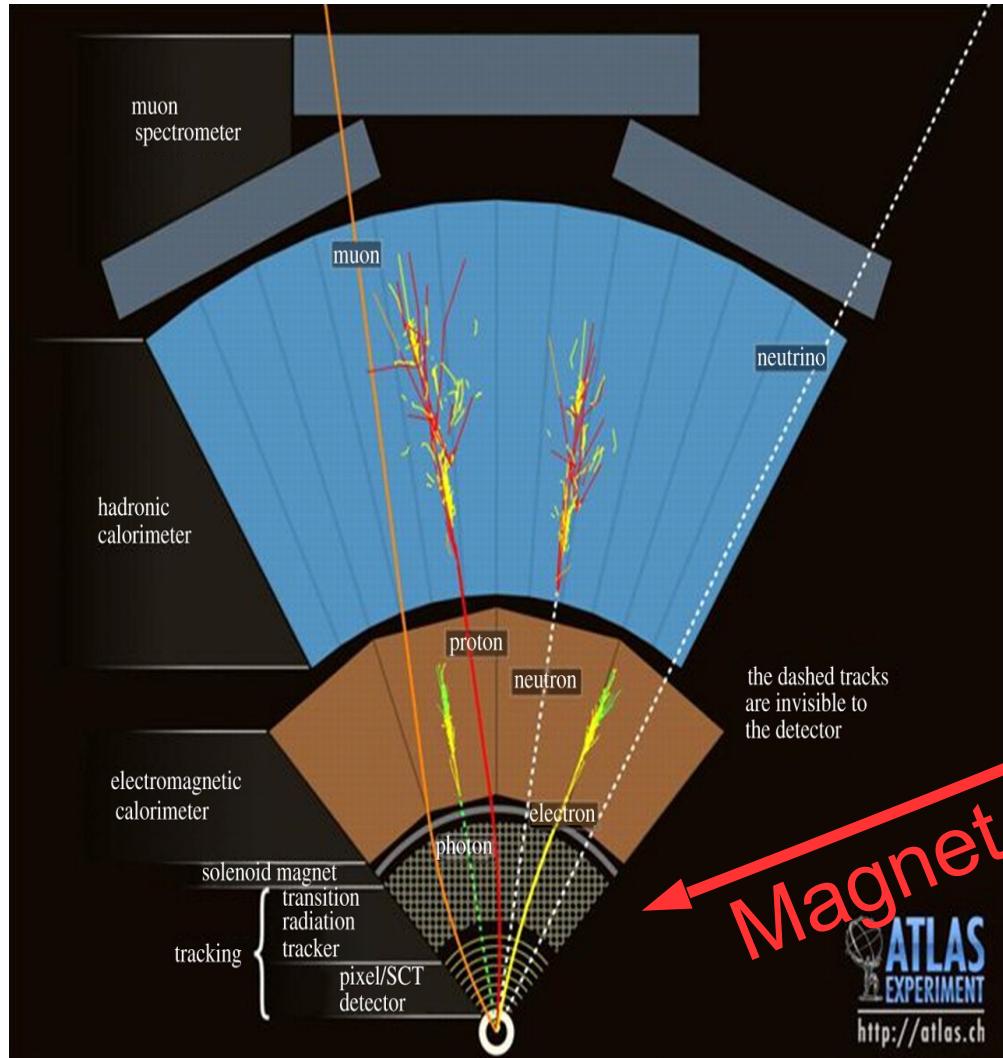


ATLAS



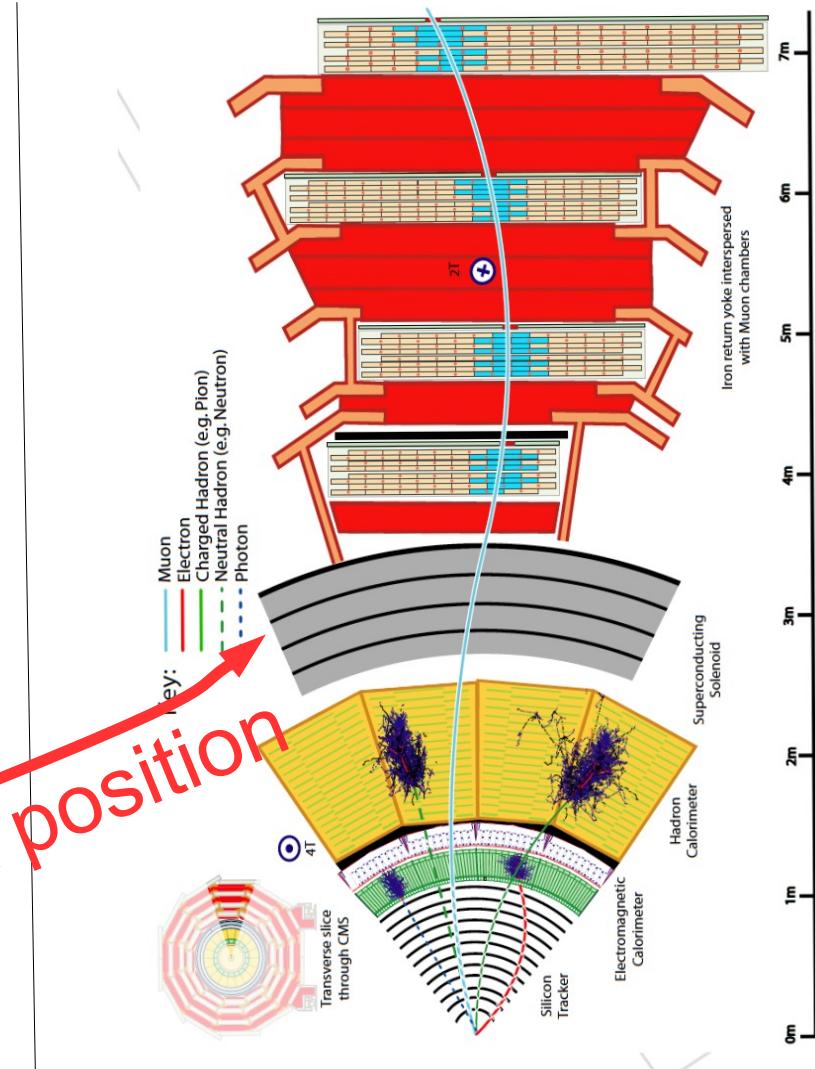
CMS

Any complication for PF in ATLAS?



ATLAS

Need to correct for the
energy loss



CMS

Using the particles

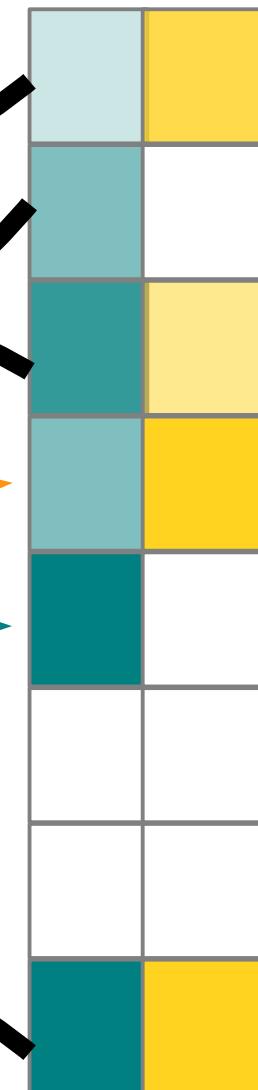
Inside a detector

From a single
vertex



Now we can
classify these
guys

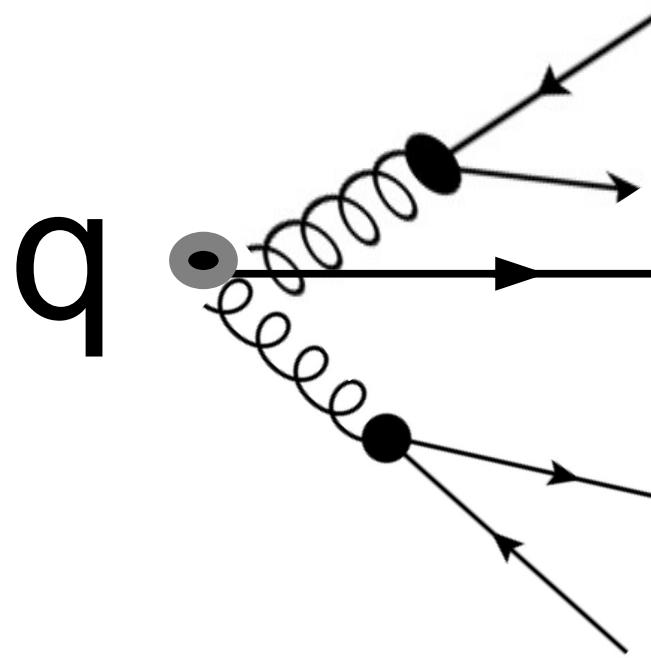
Tracks in
Silicon



EcalHcal

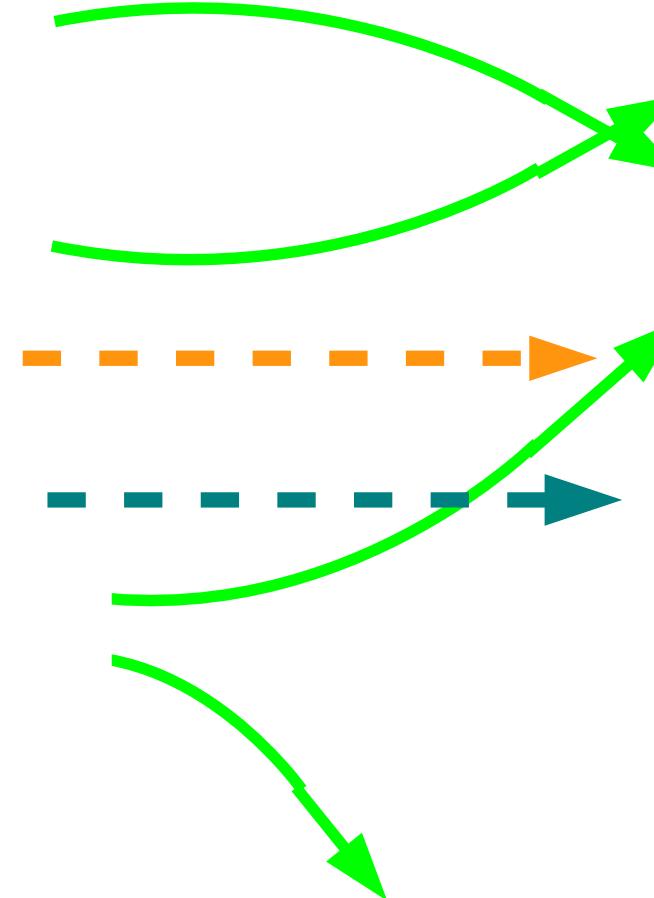
What is a jet?

Theory level



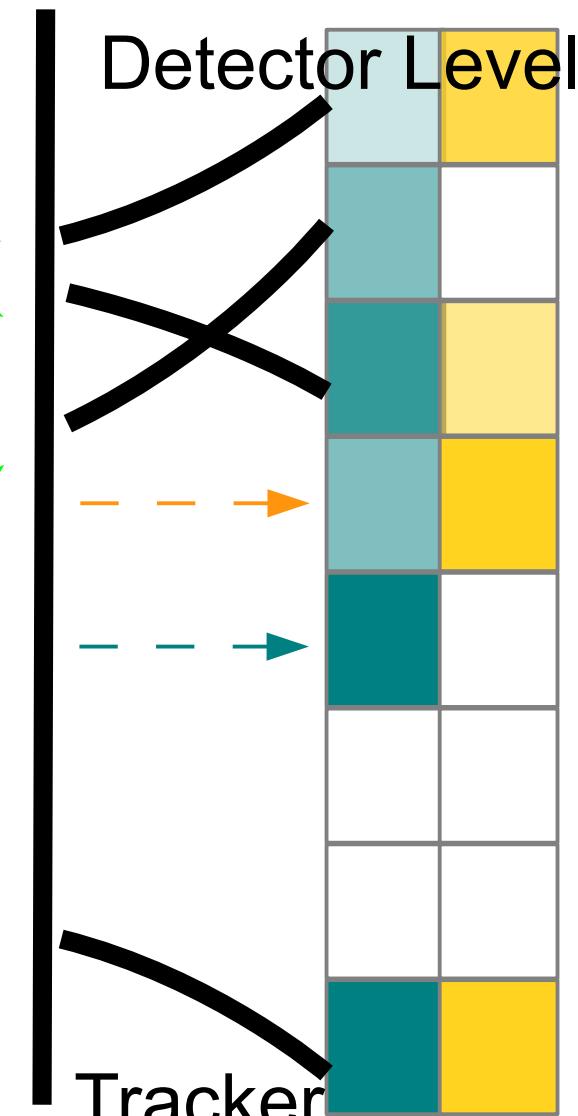
A composition of many particles originating from a quark or gluon

Particle level



Charged Hadron
Neutral Hadron
Photon

Detector Level



EcalHcal

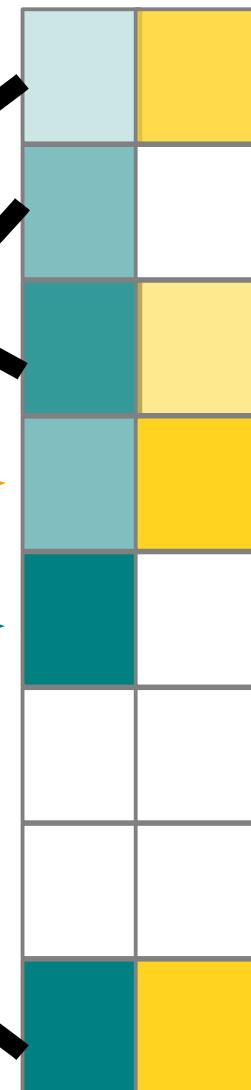
What is a jet?

Inside a detector

From a single
vertex



Tracks in
Silicon

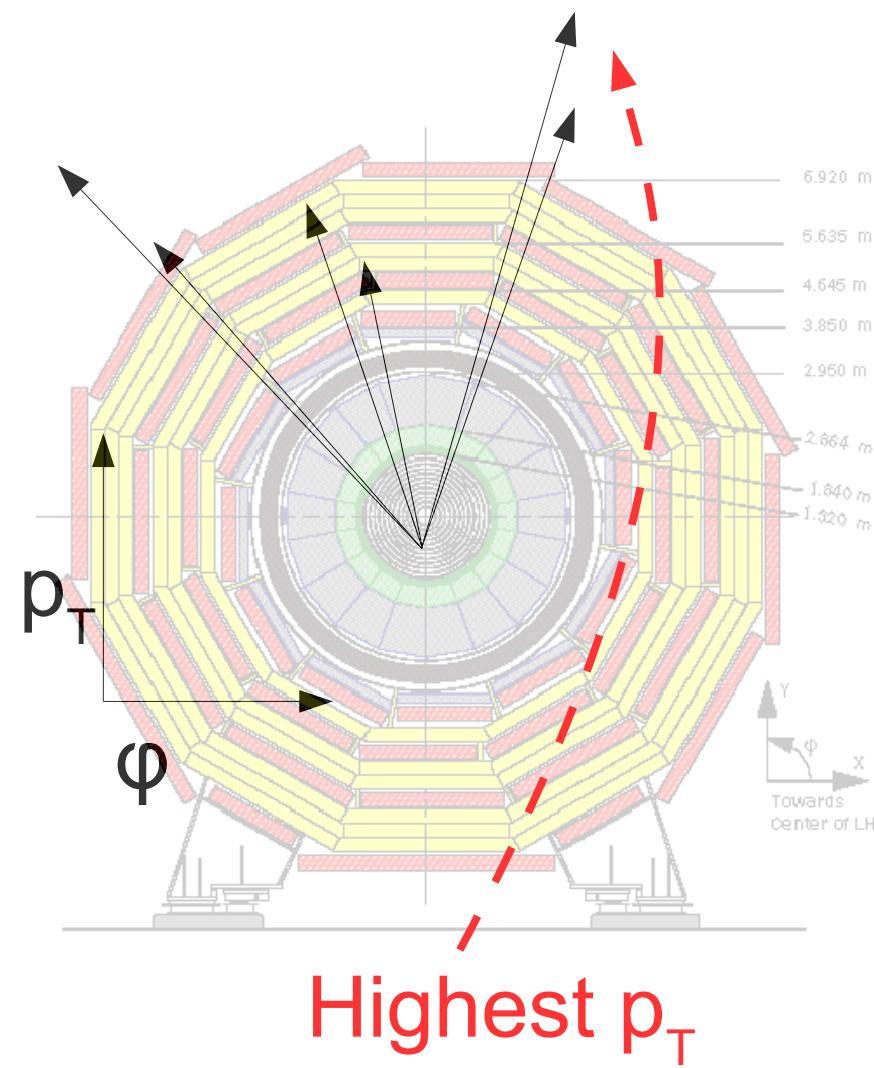


Ecal Hcal

Jet Reconstruction

- Iterate over two

CMS Transverse View



Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

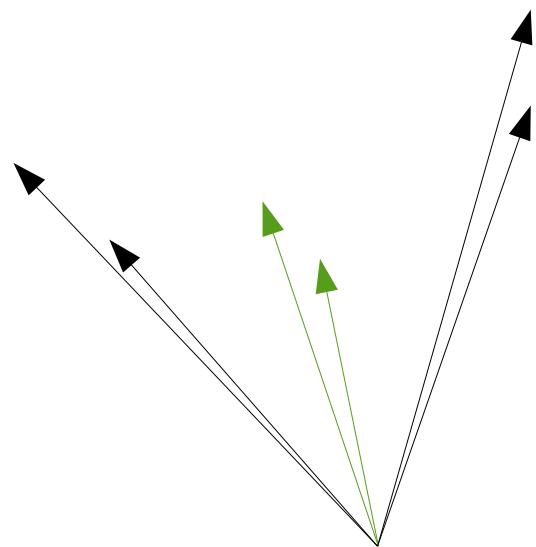
$$\alpha = 1 \text{ kT}$$

$$\alpha = 0 \text{ Cambridge Aachen}$$

$$\alpha = -1 \text{ Anti-kT}$$

Jet Reconstruction

- Itrerate over two



Start small

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

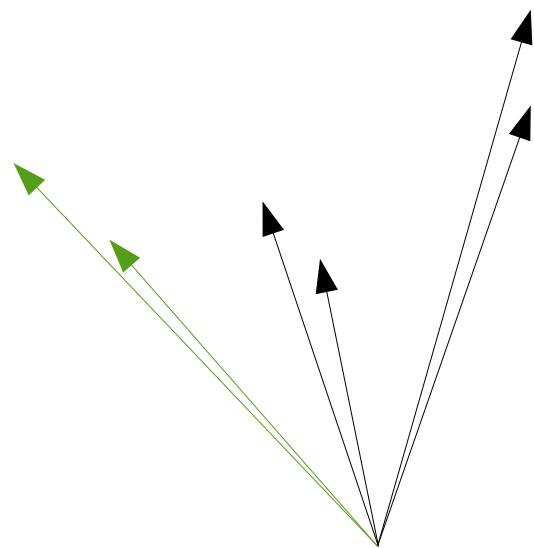
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

Jet Reconstruction

- Itrerate over two



Start Close

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

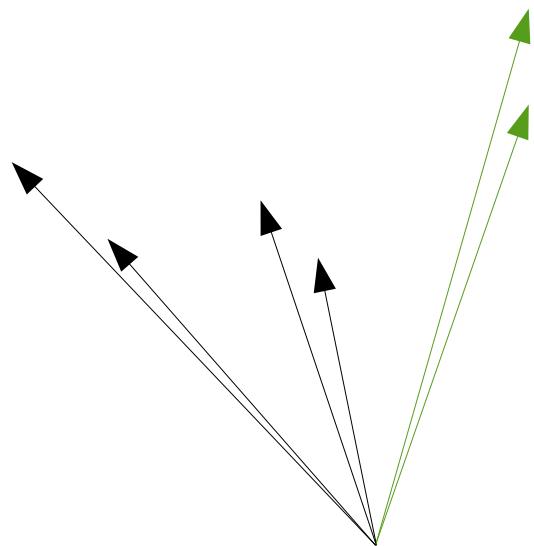
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti- kT

Jet Reconstruction

- Itrerate over two



Start Big

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

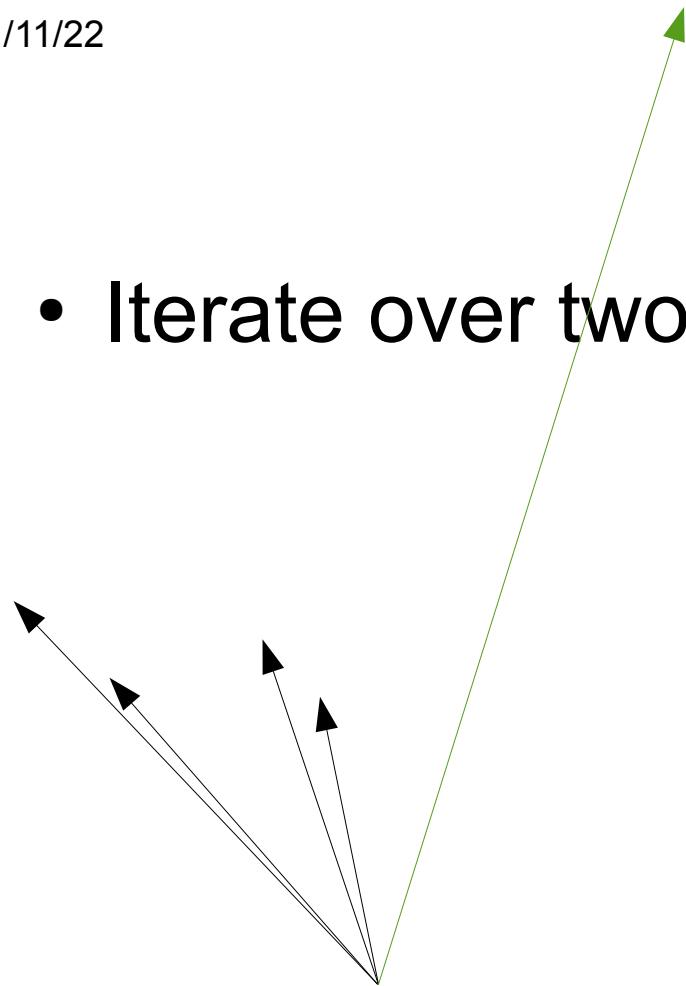
$\alpha = 1$ kT

$\alpha = 0$ Cambridge Aachen

$\alpha = -1$ Anti- kT

Jet Reconstruction

- Iterate over two



Now merge initial into a particle

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

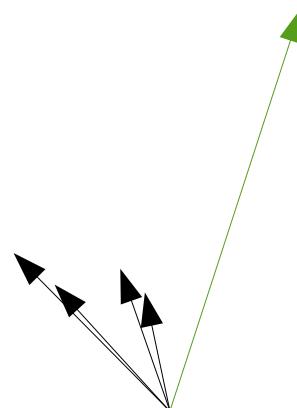
$$\alpha=1 \text{ kT}$$

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

Jet Reconstruction

- Iterate over two



Zooming out

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

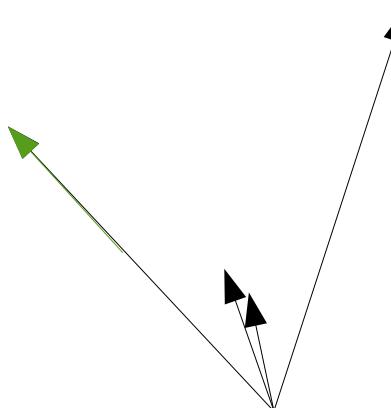
$$\alpha = 1 \text{ kT}$$

$\alpha = 0$ Cambridge Aachen

$\alpha = -1$ Anti-kT

Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

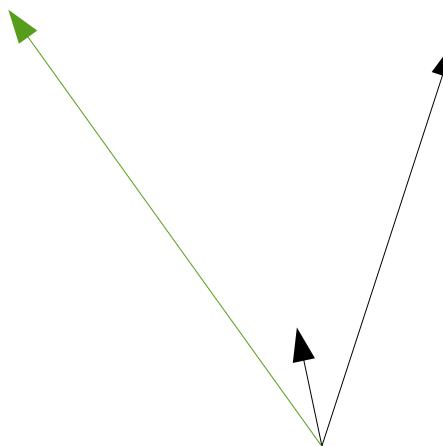
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

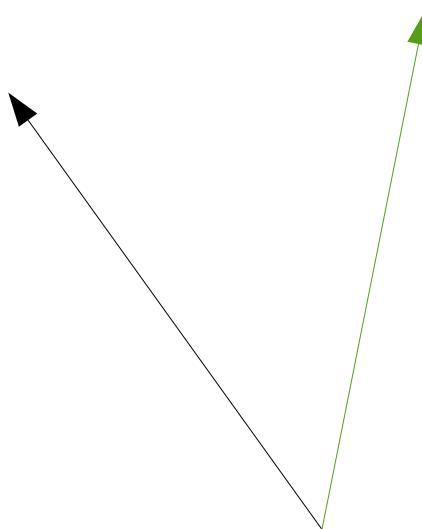
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti- kT

Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

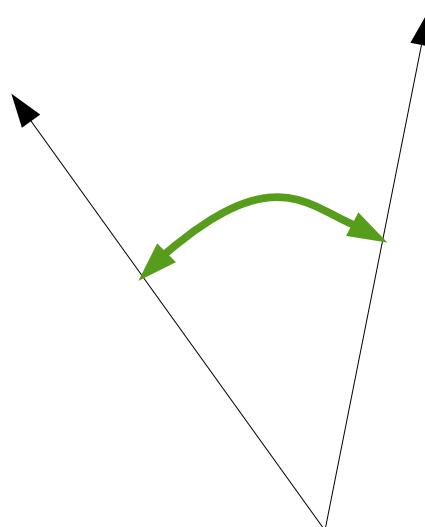
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

Jet Reconstruction

- Iterate over two



If distance > X (stop)
 $X=0.4, 0.8, \dots$

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

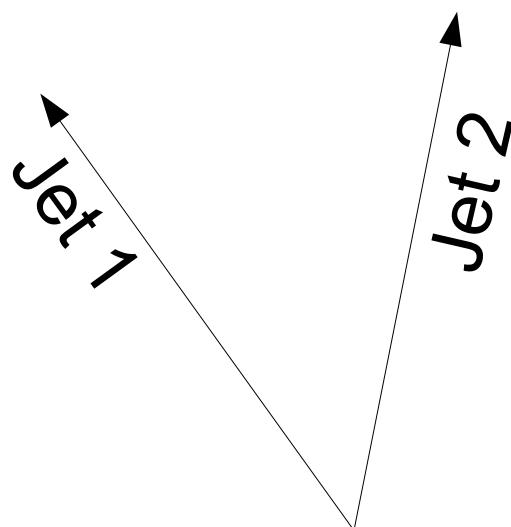
$\alpha = 1$ kT

$\alpha = 0$ Cambridge Aachen

$\alpha = -1$ Anti-kT

Jet Reconstruction

- Iterate over two



Done

Take smallest

$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

$$\alpha = 1 \text{ kT}$$

$$\alpha = 0 \text{ Cambridge Aachen}$$

$$\alpha = -1 \text{ Anti-kT}$$

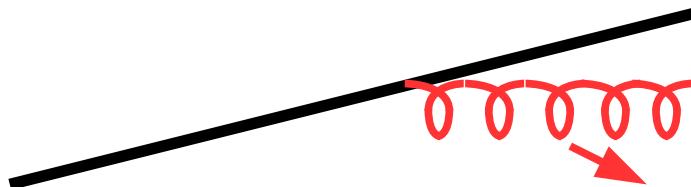
Why do we use these algorithms?



$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

Need to be able to calculate these with QCD

Collinear safety



$\Delta R \min(p_T^1, p_T^2)^\alpha \rightarrow 0$
When $\Delta R \rightarrow 0$

Can Randomly
happen? When $\Delta R \rightarrow 0$

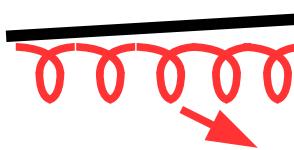
Why do we use these algorithms?



$$\Delta R \min(p_T^1, p_T^2)^\alpha$$

Need to be able to calculate these with QCD

Infrared safety



Can Randomly
happen? When $E \rightarrow 0$

*Wesley Smith

$$\Delta R \min(p_T^1, p_T^2)^\alpha \rightarrow 0 \quad (p_T \rightarrow 0)$$

For $\alpha=0$ gluon gets combined with nearest particle $p_T^i \rightarrow p_T^i + E(\rightarrow 0) = p_T^i$

Why do we use these algorithms?



To calculate anything with a jet we need to observe :

Infrared safety : invariance with random particle $w/E \rightarrow 0$

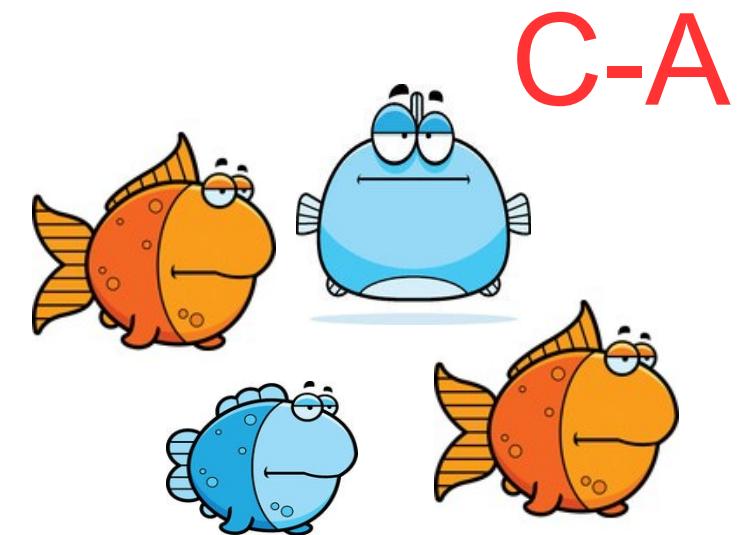
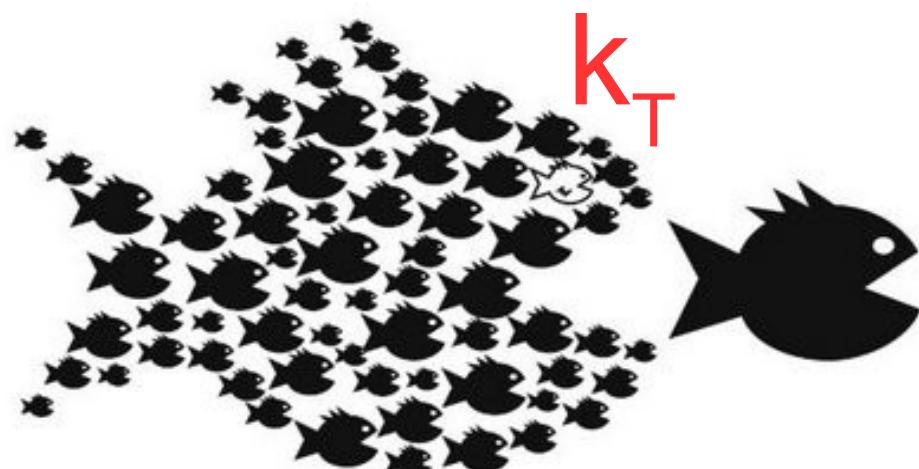
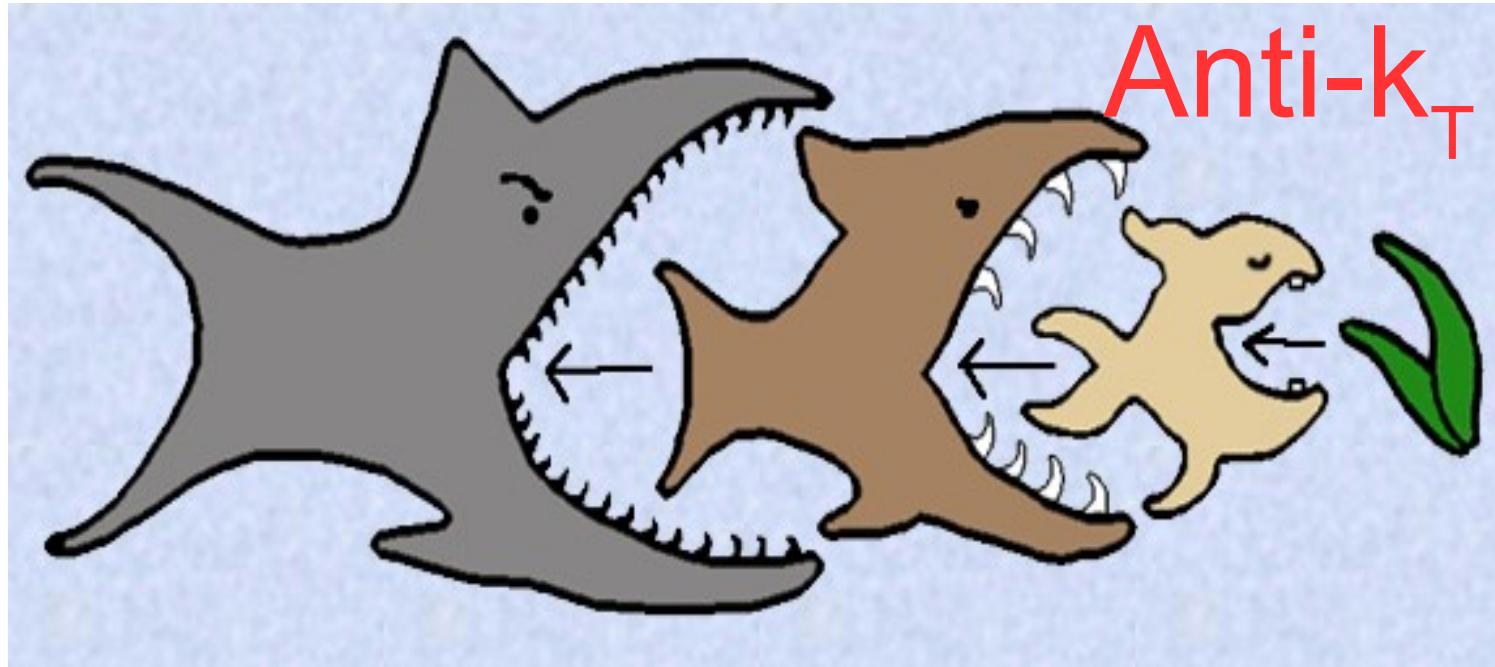
Collider safety : invariance with random split $\Delta R \rightarrow 0$

This applies to jet substructure observables too!

.....Well maybe

can you think of a example that breaks IR safety?

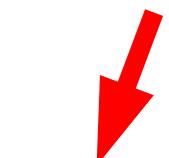
Recap



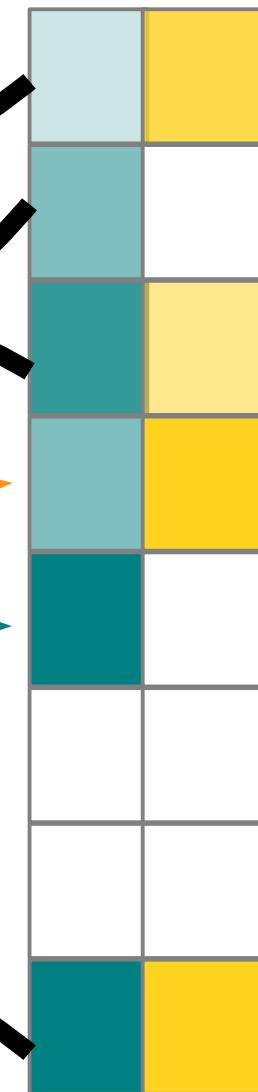
What is a jet?

Inside a detector

From a single
vertex



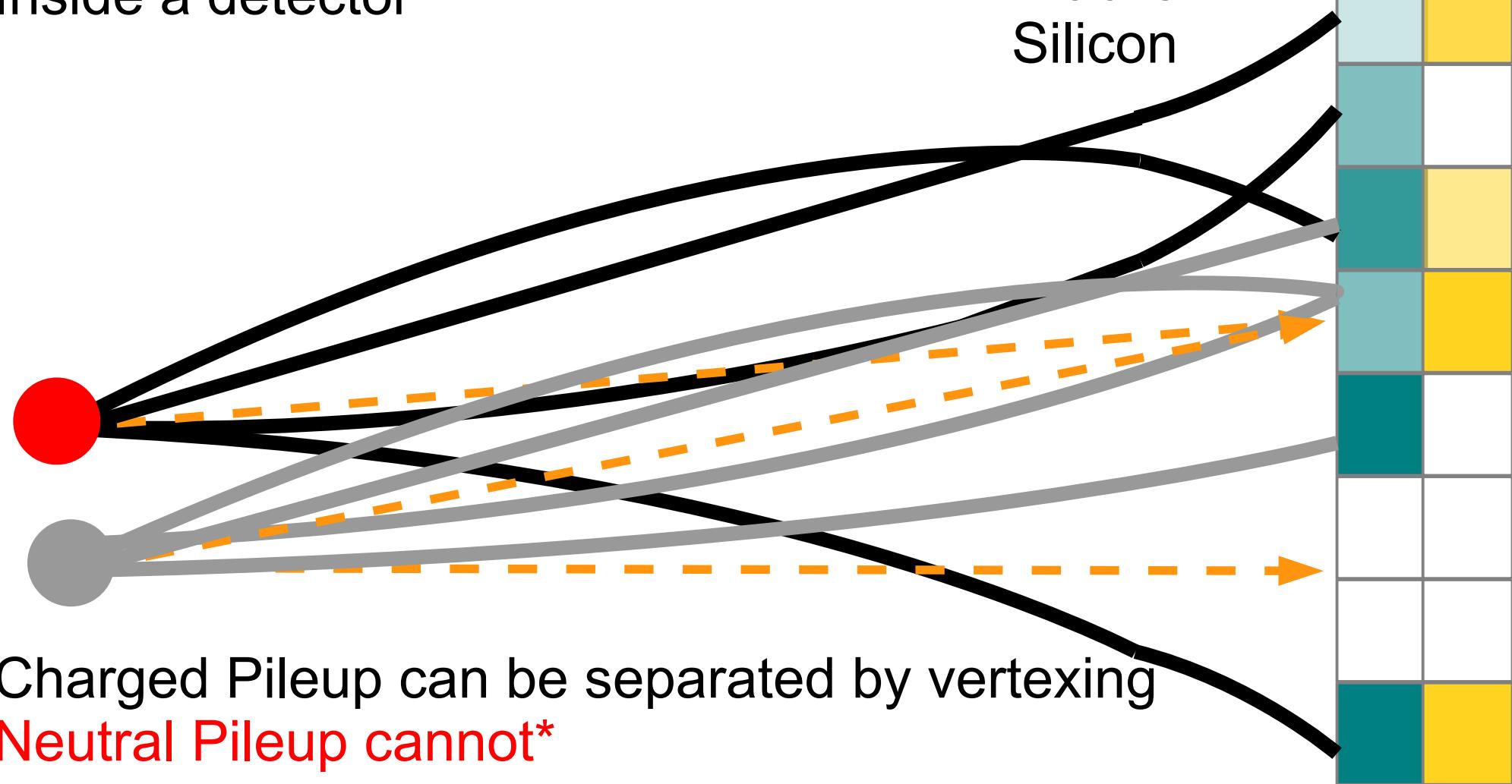
Tracks in
Silicon



Ecal Hcal

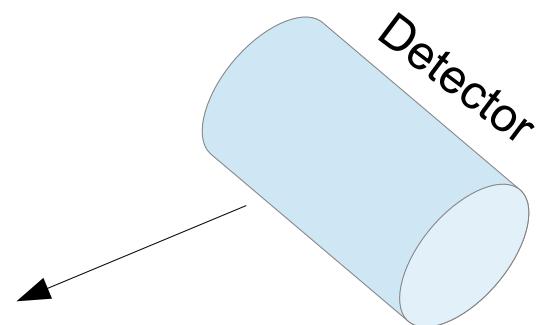
What is a Jet?

Inside a detector

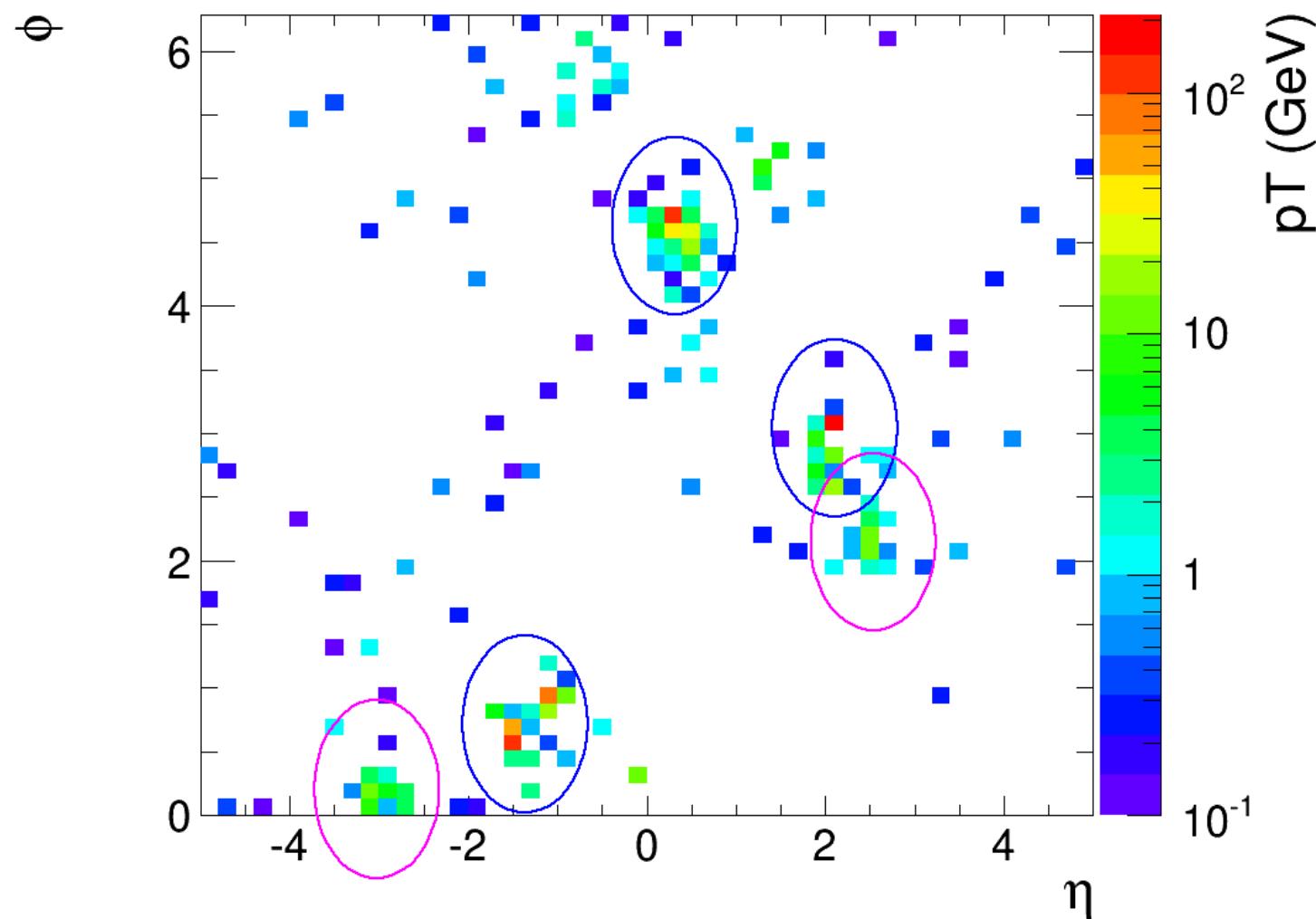


Charged Pileup can be separated by vertexing
Neutral Pileup cannot*

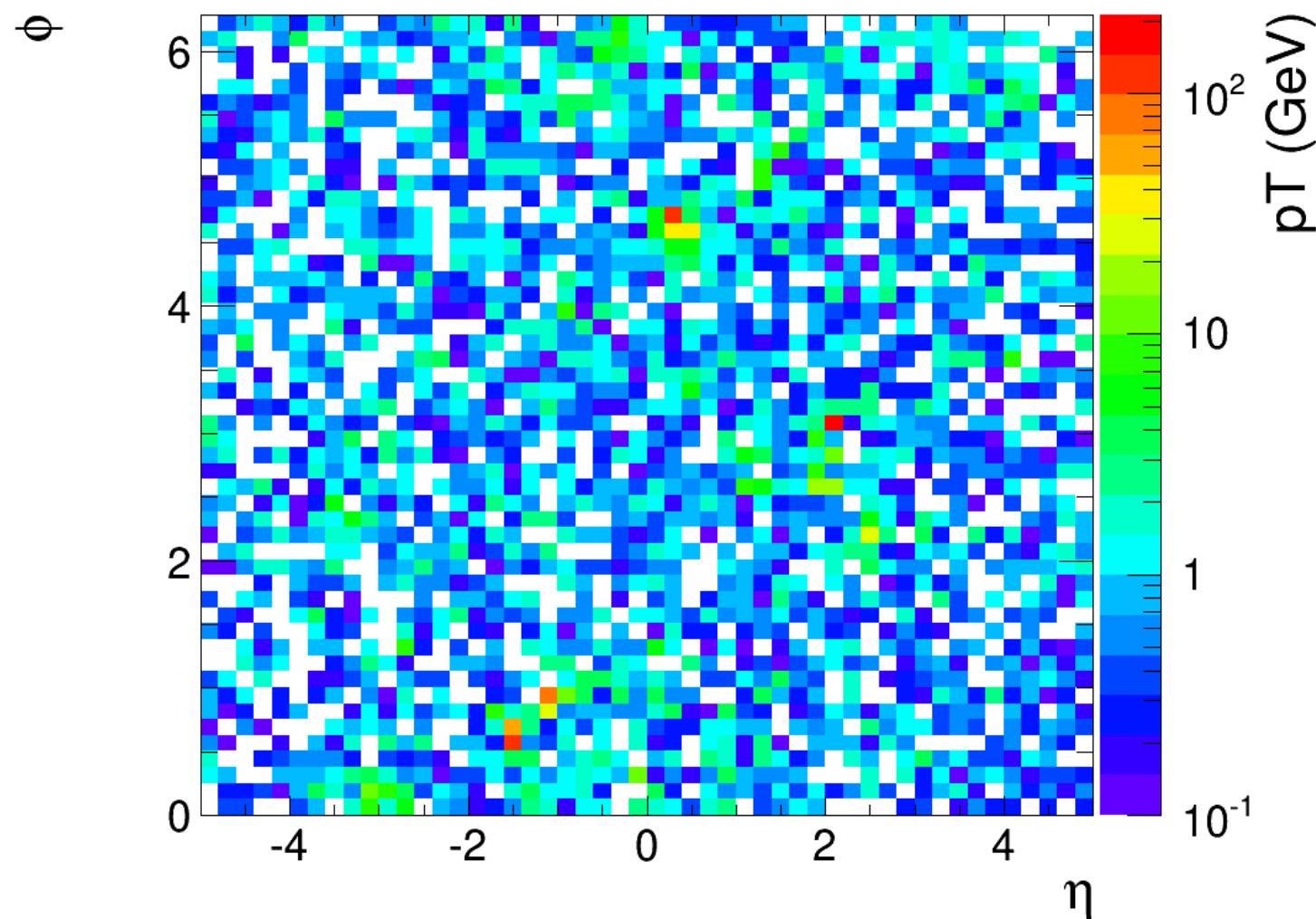
*Fast timing/Depth reconstruction can help



Detector Surface

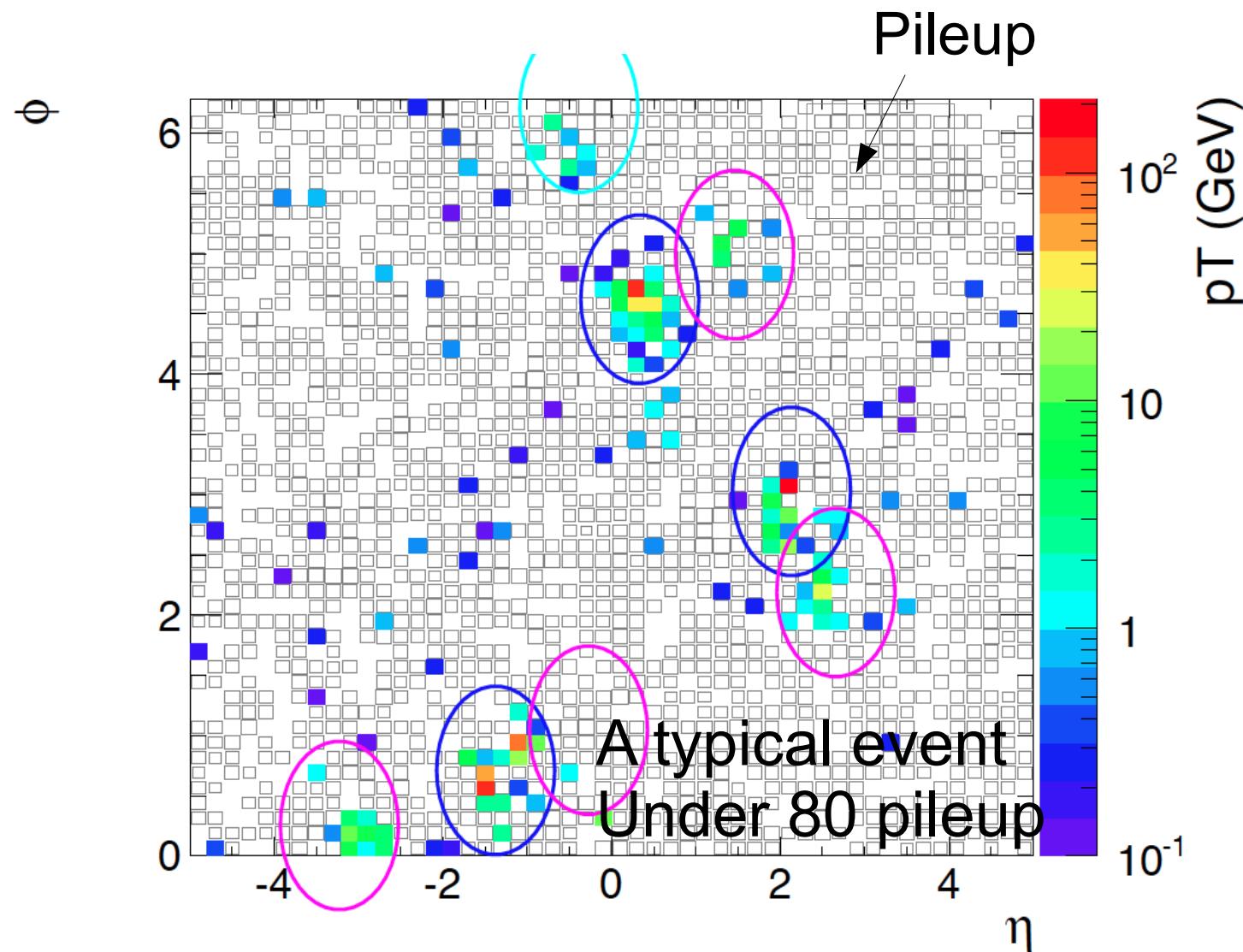


We also have pileup



We also have pileup

- Filtering the interesting info

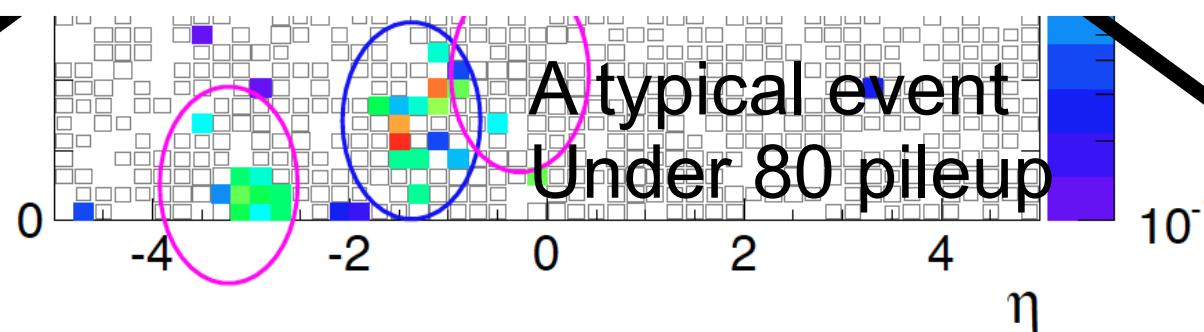


We also have pileup

- Filtering the interesting info

↳ While Pileup in pp has some differences

Many of the properties of pileup are similar to UE fluctuations



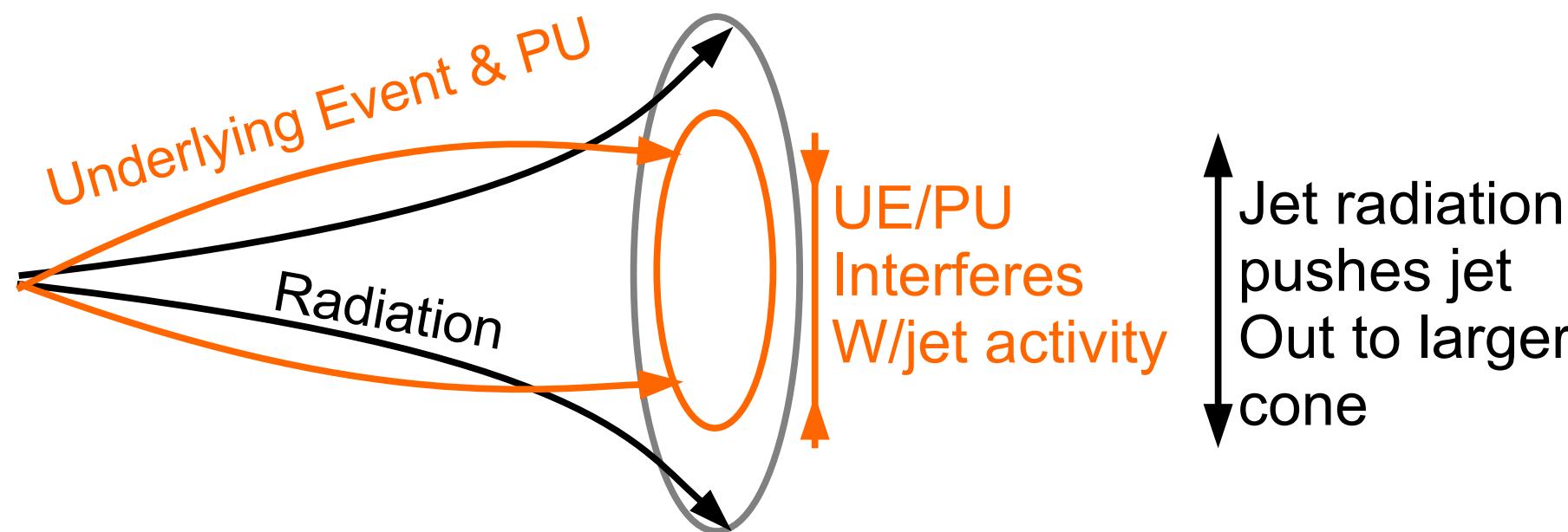
>200 GeV

50-200 GeV

25-50 GeV

Jet Energy Correction

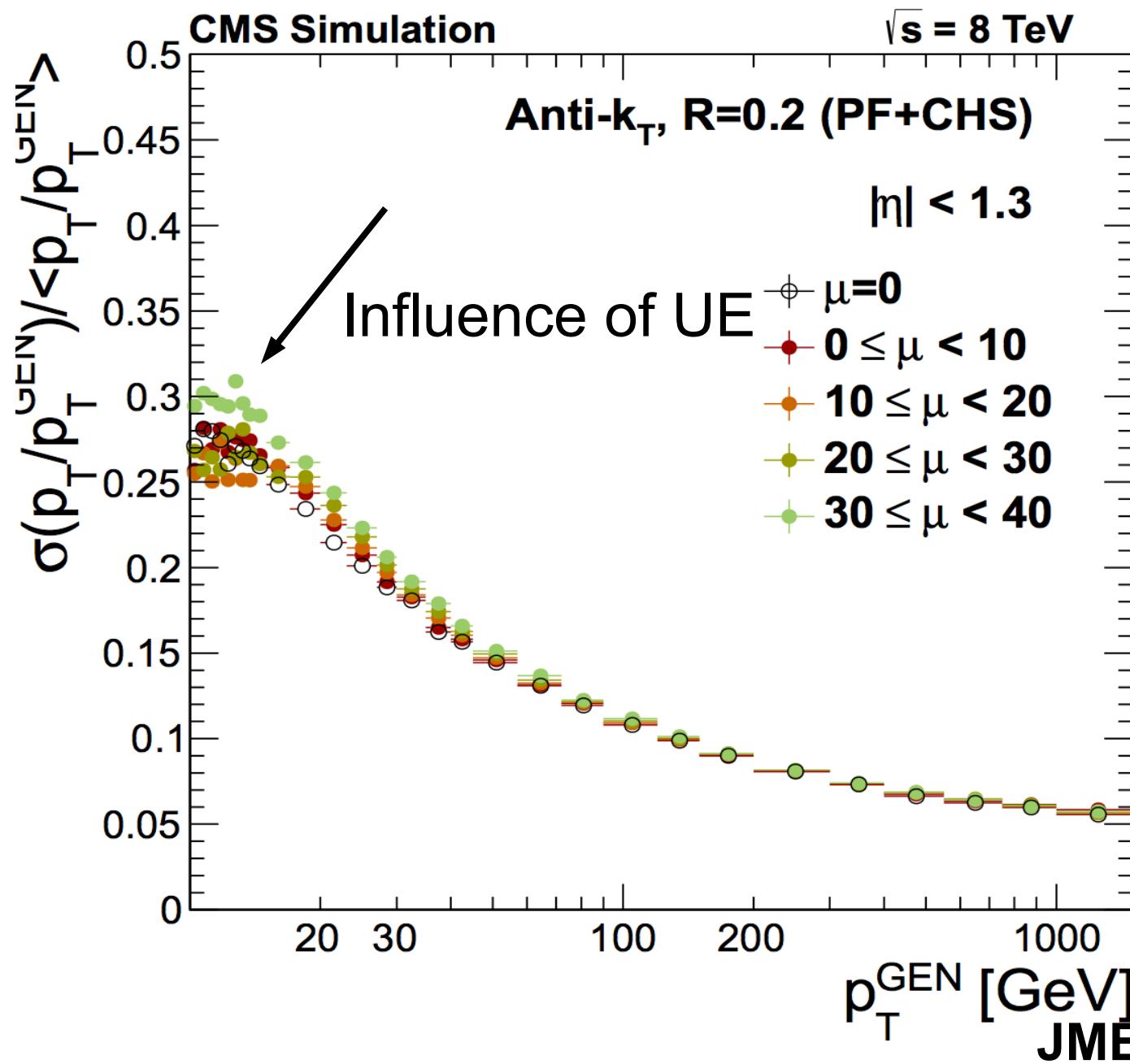
- Correcting to truth



How do we shape our jet against the UE?
Why did CMS switch to AK4?

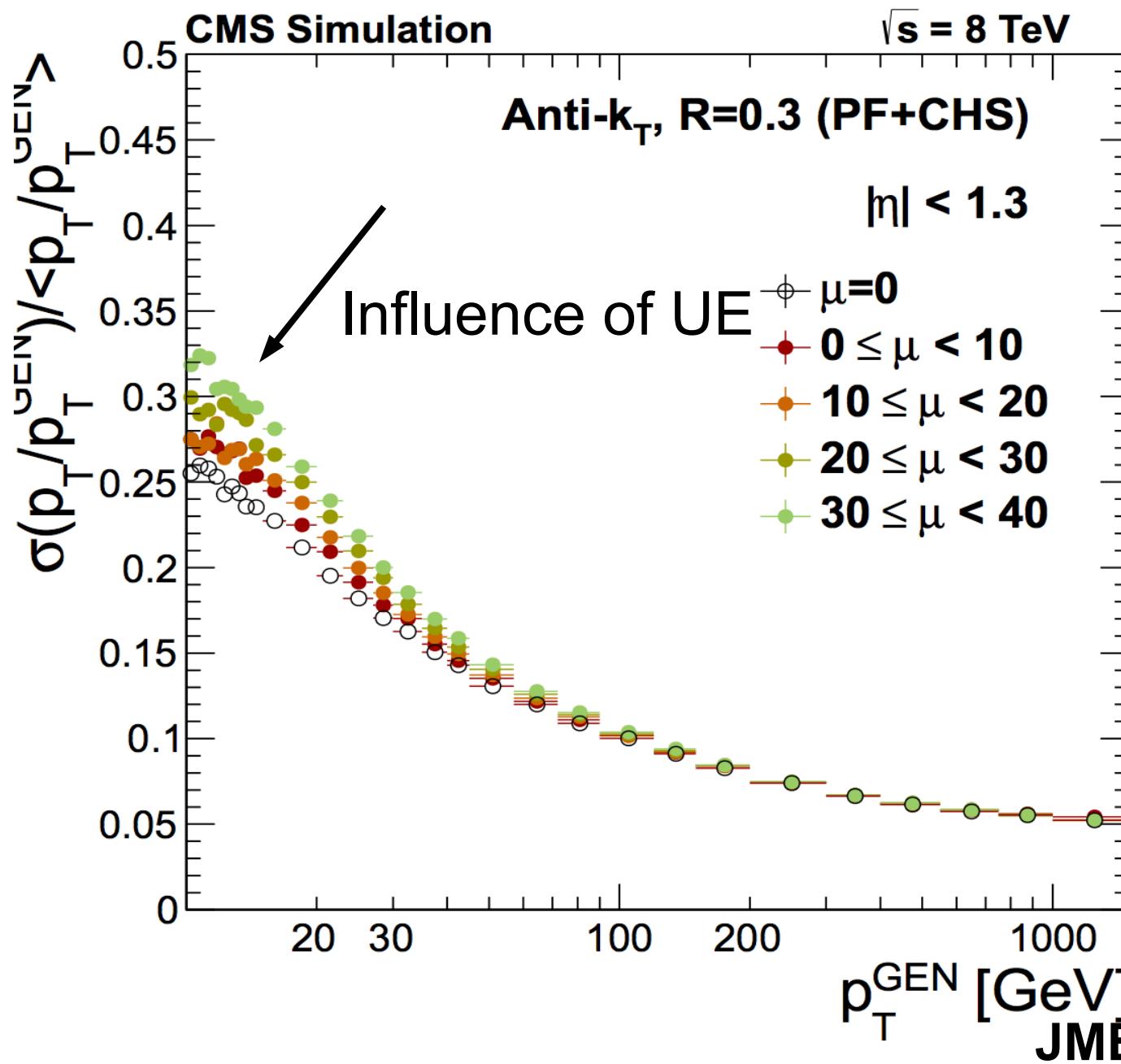
Jet Energy Correction

- AK2



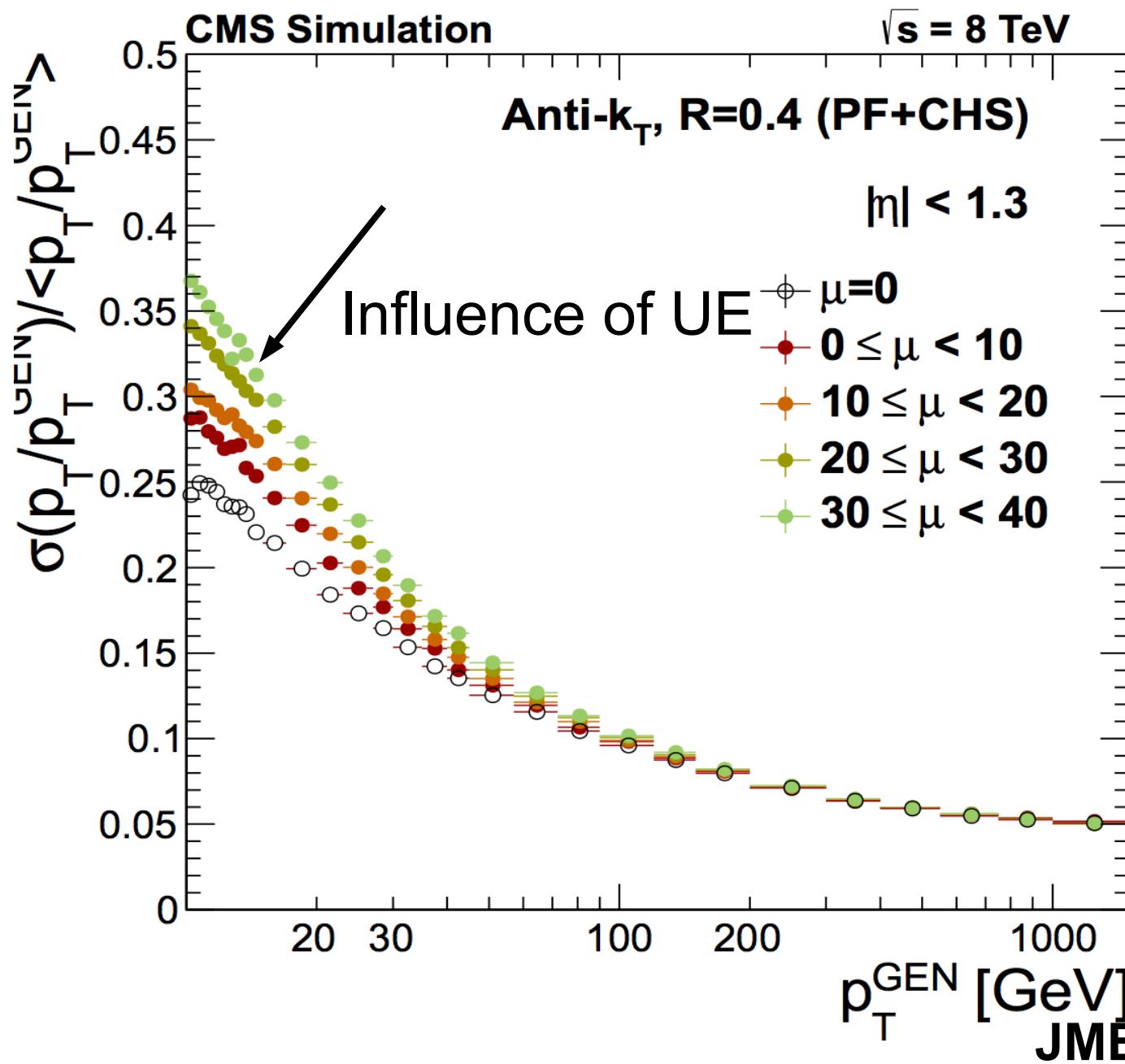
Jet Energy Correction

- AK3



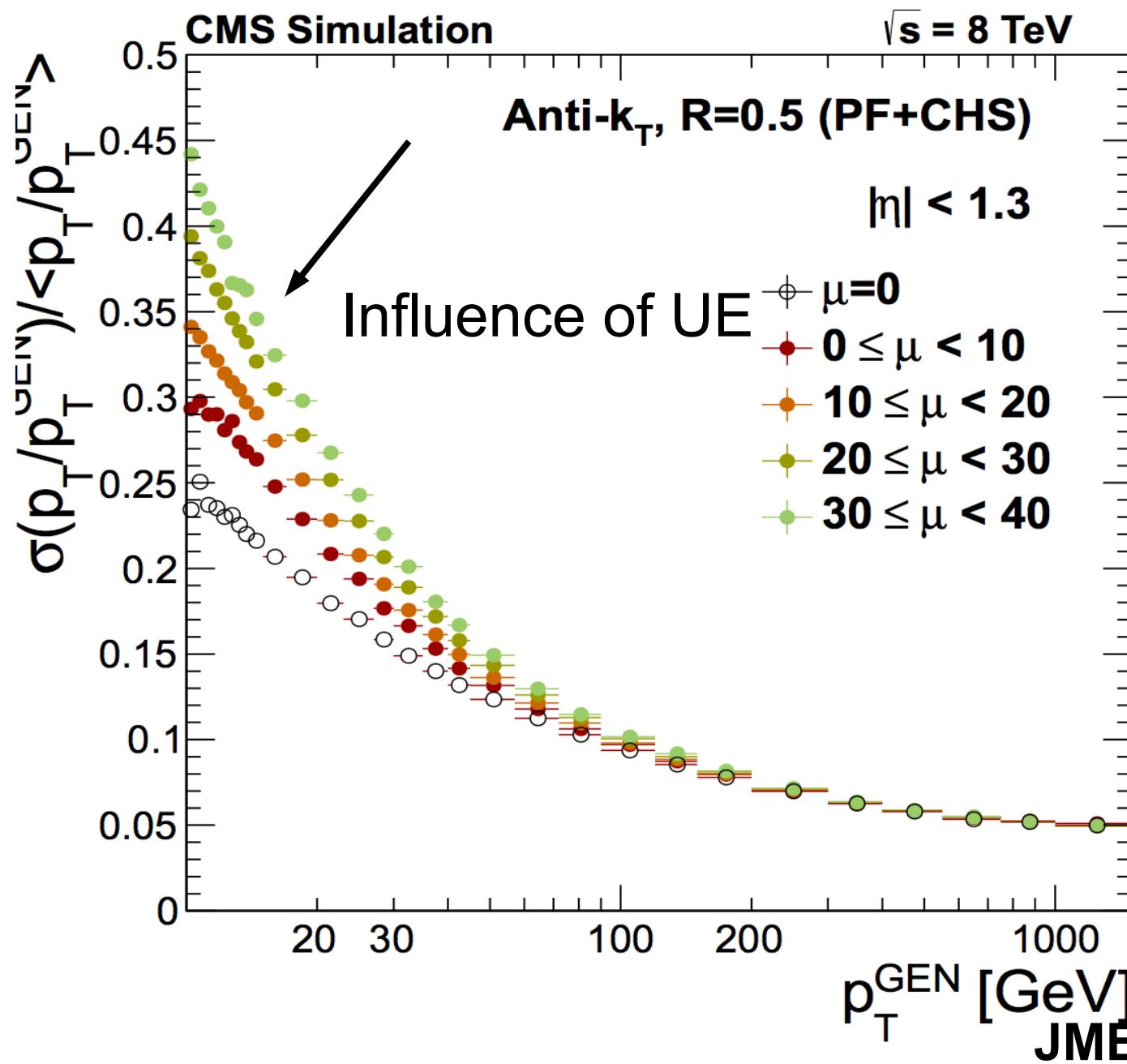
Jet Energy Correction

- AK4



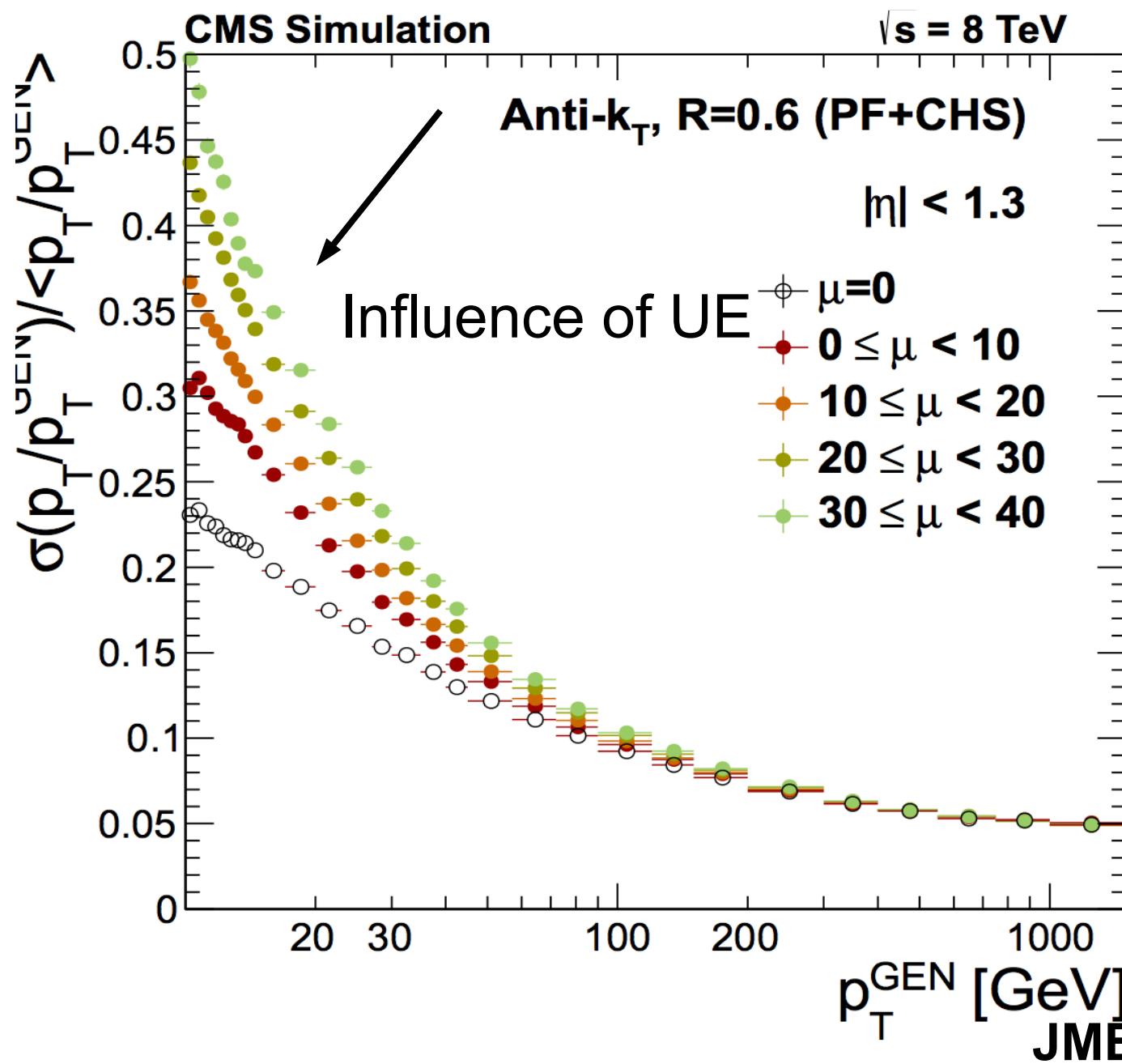
Jet Energy Correction

- AK5



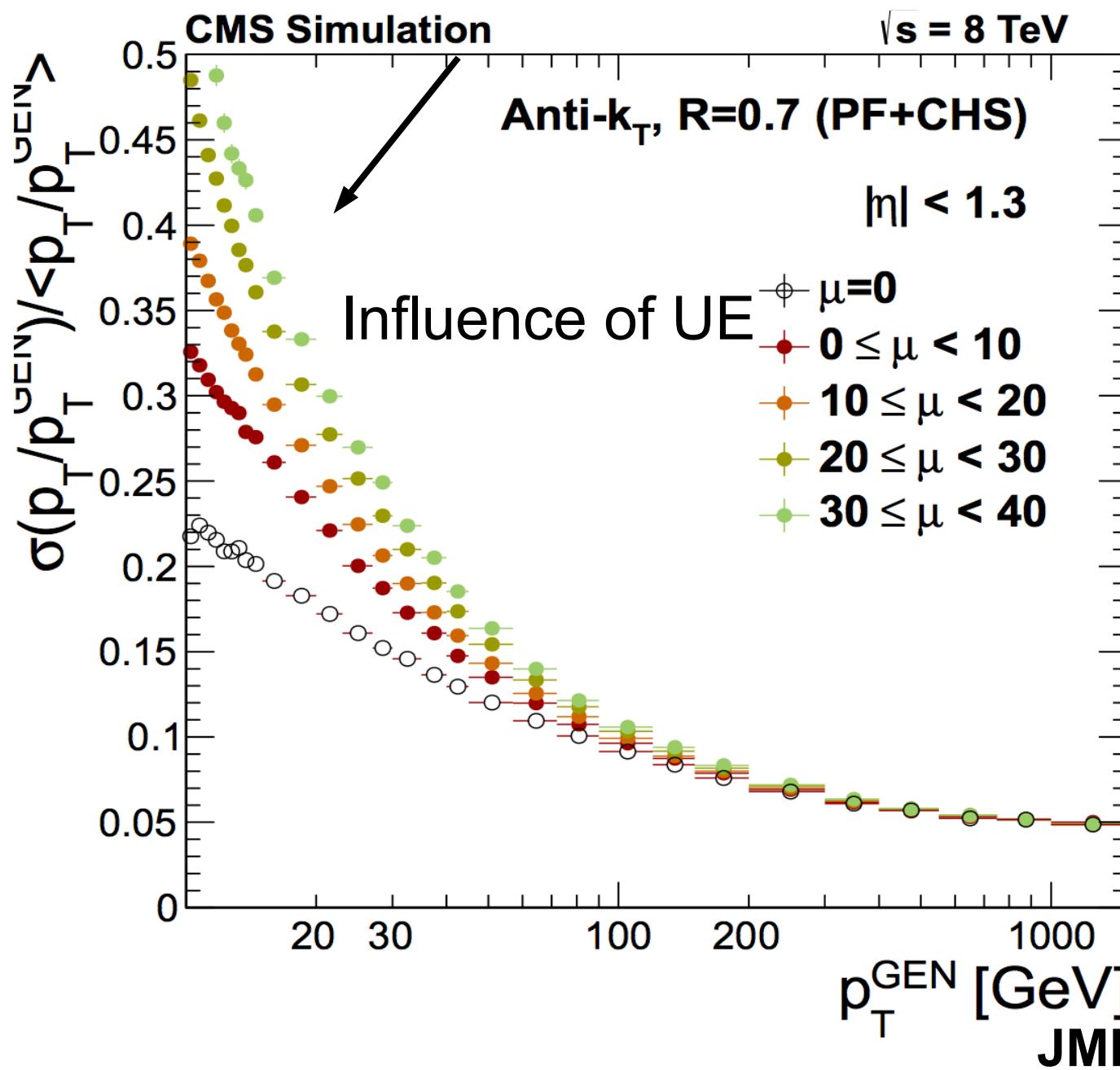
Jet Energy Correction

- AK6



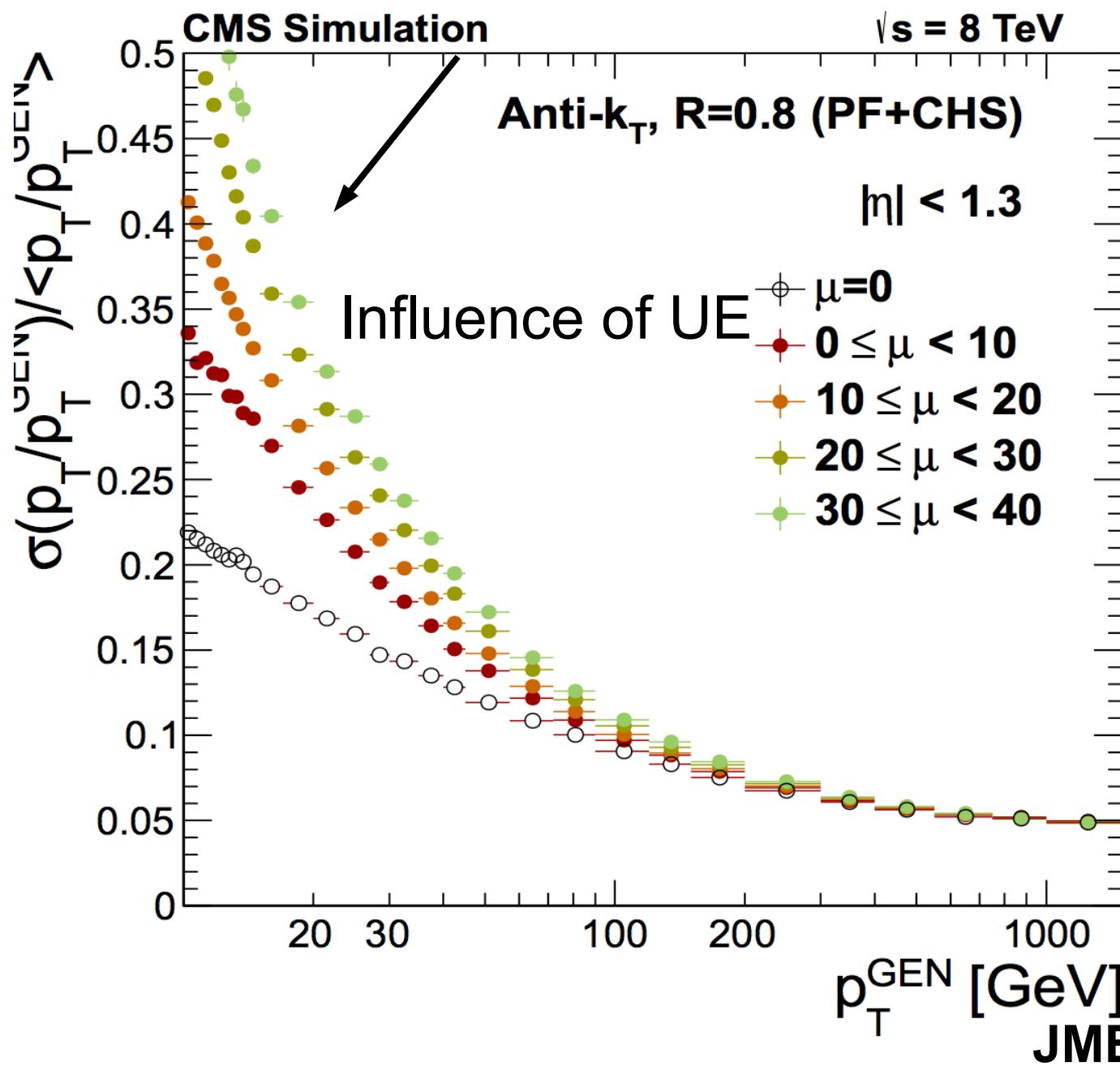
Jet Energy Correction

- AK7



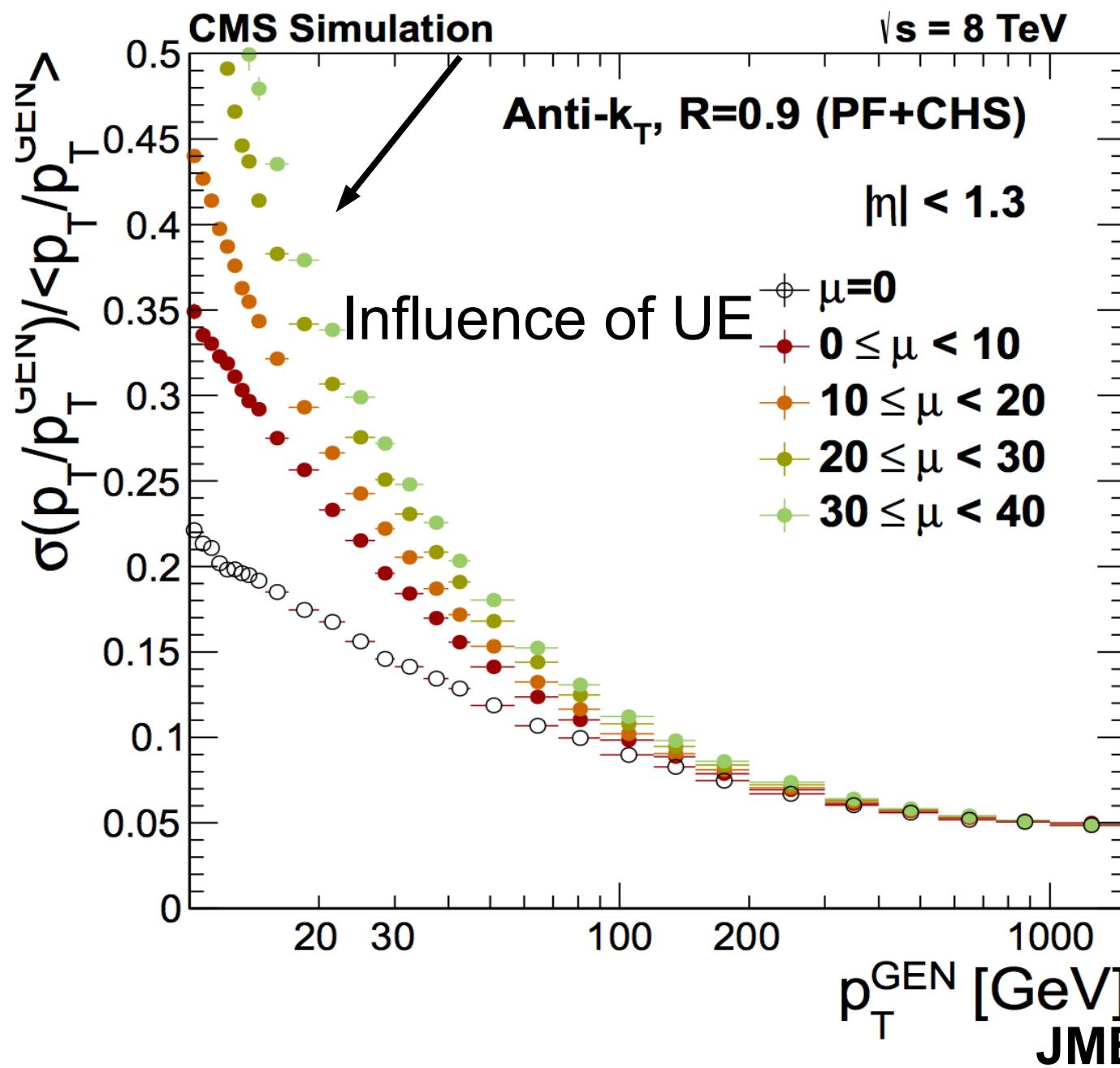
Jet Energy Correction

- AK8



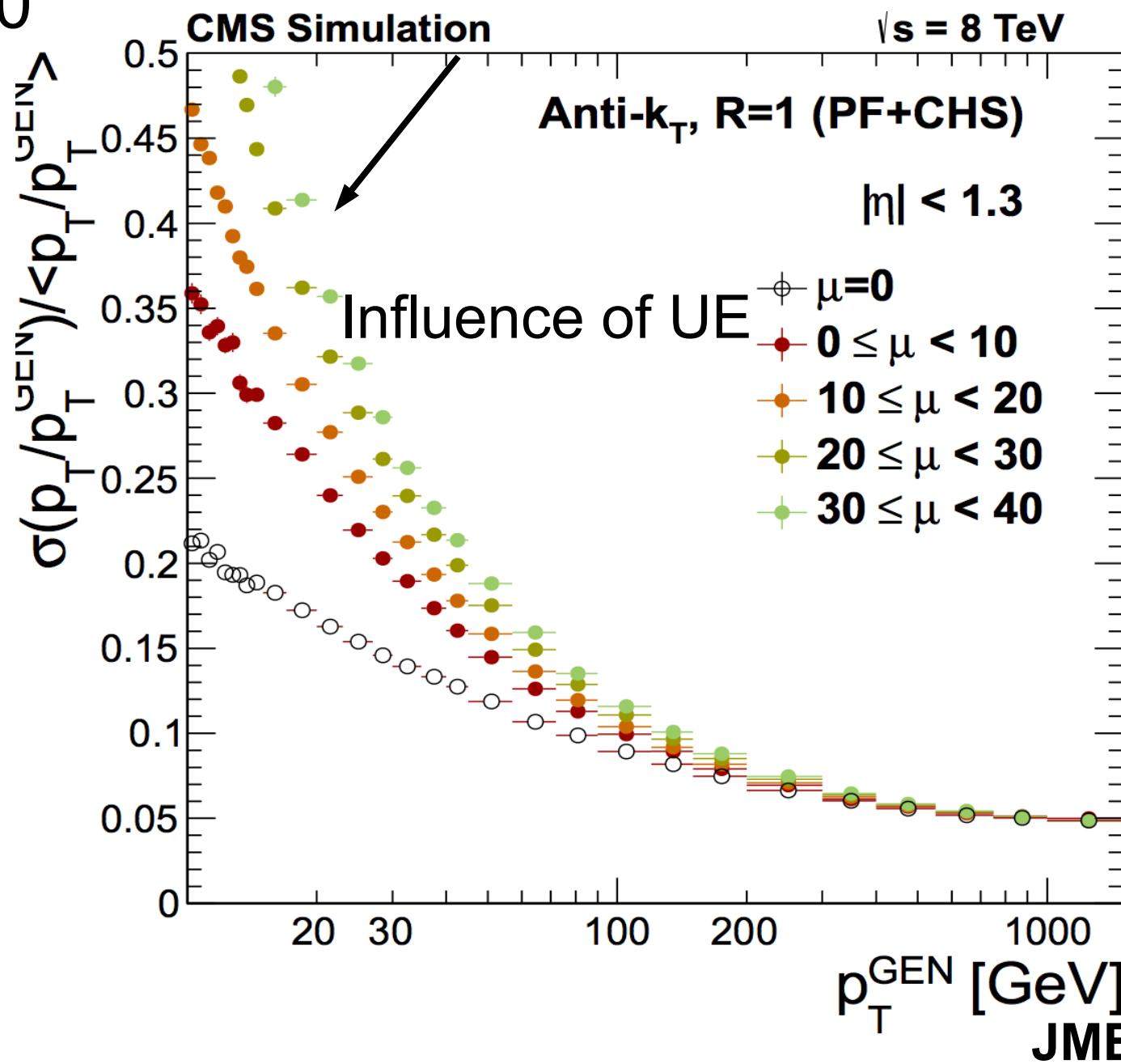
Jet Energy Correction

- AK9



Jet Energy Correction

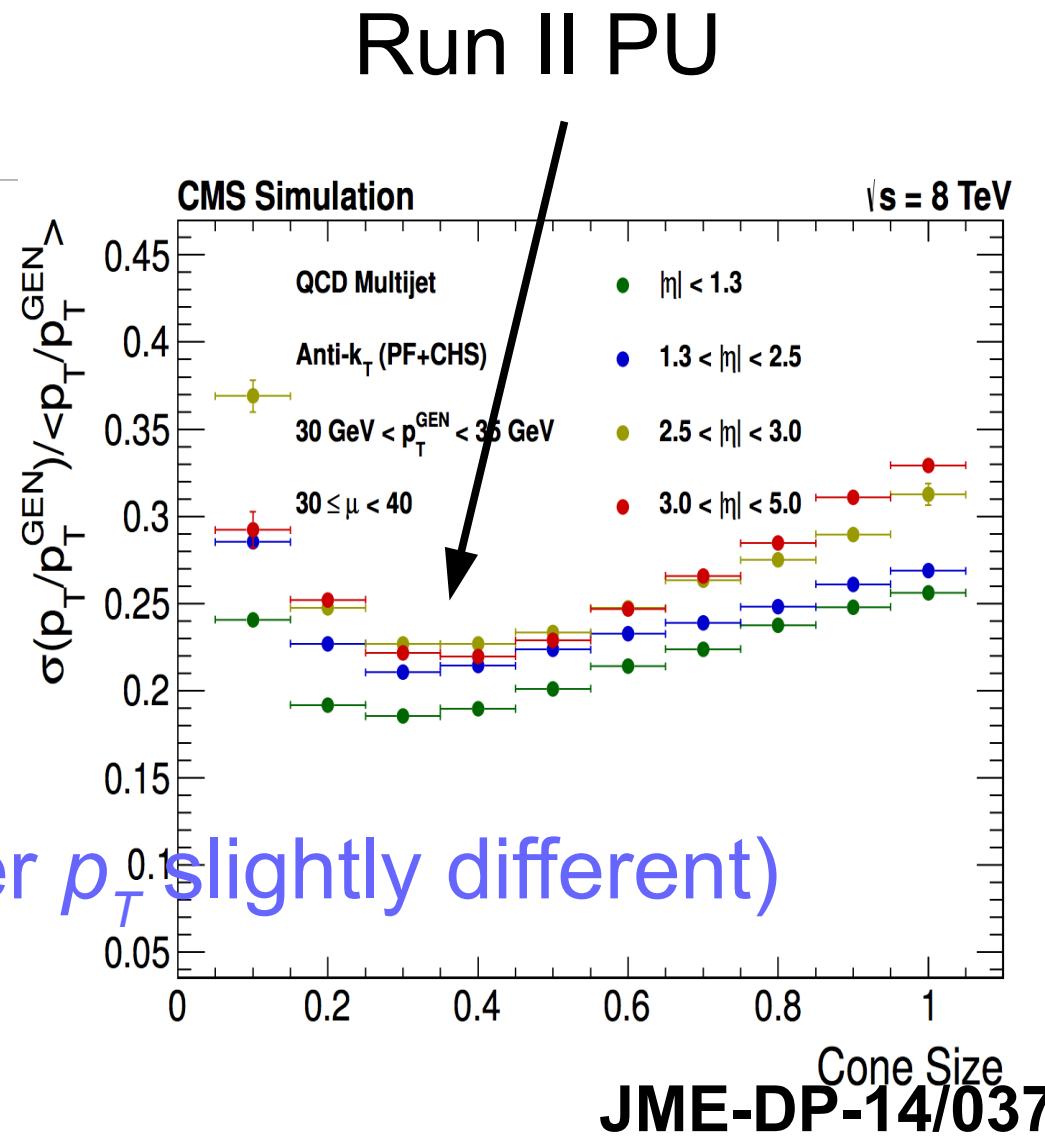
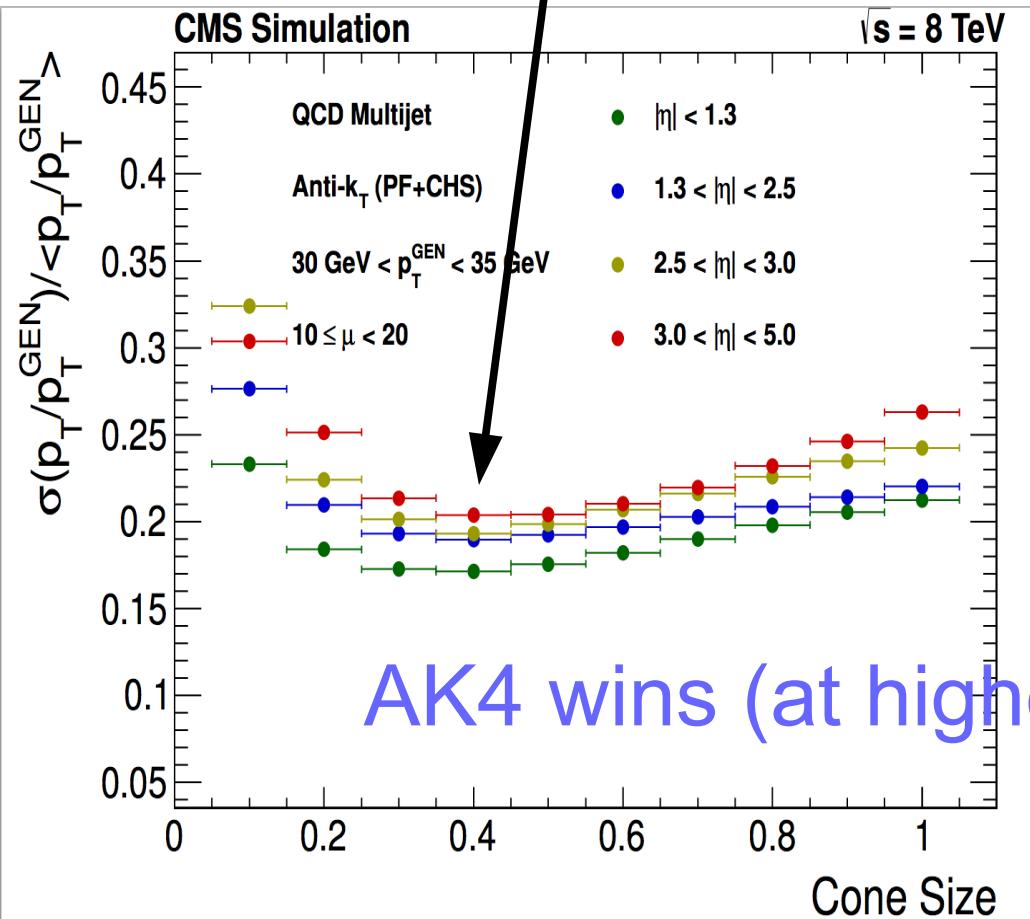
- AK1.0



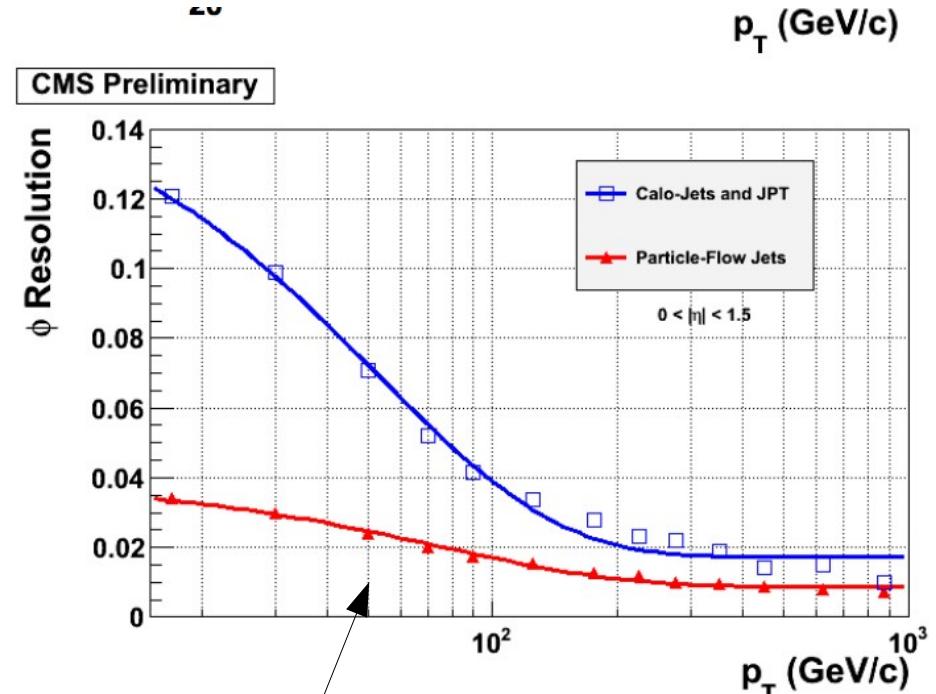
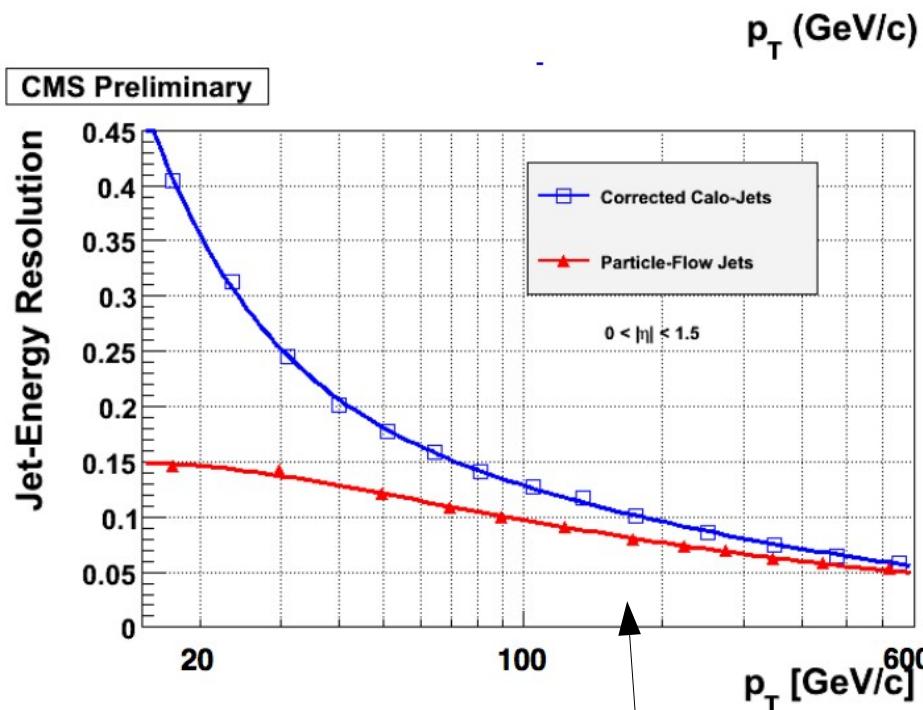
Jet Energy Correction

- Executive Summary :

We switch to AK4
Run I PU

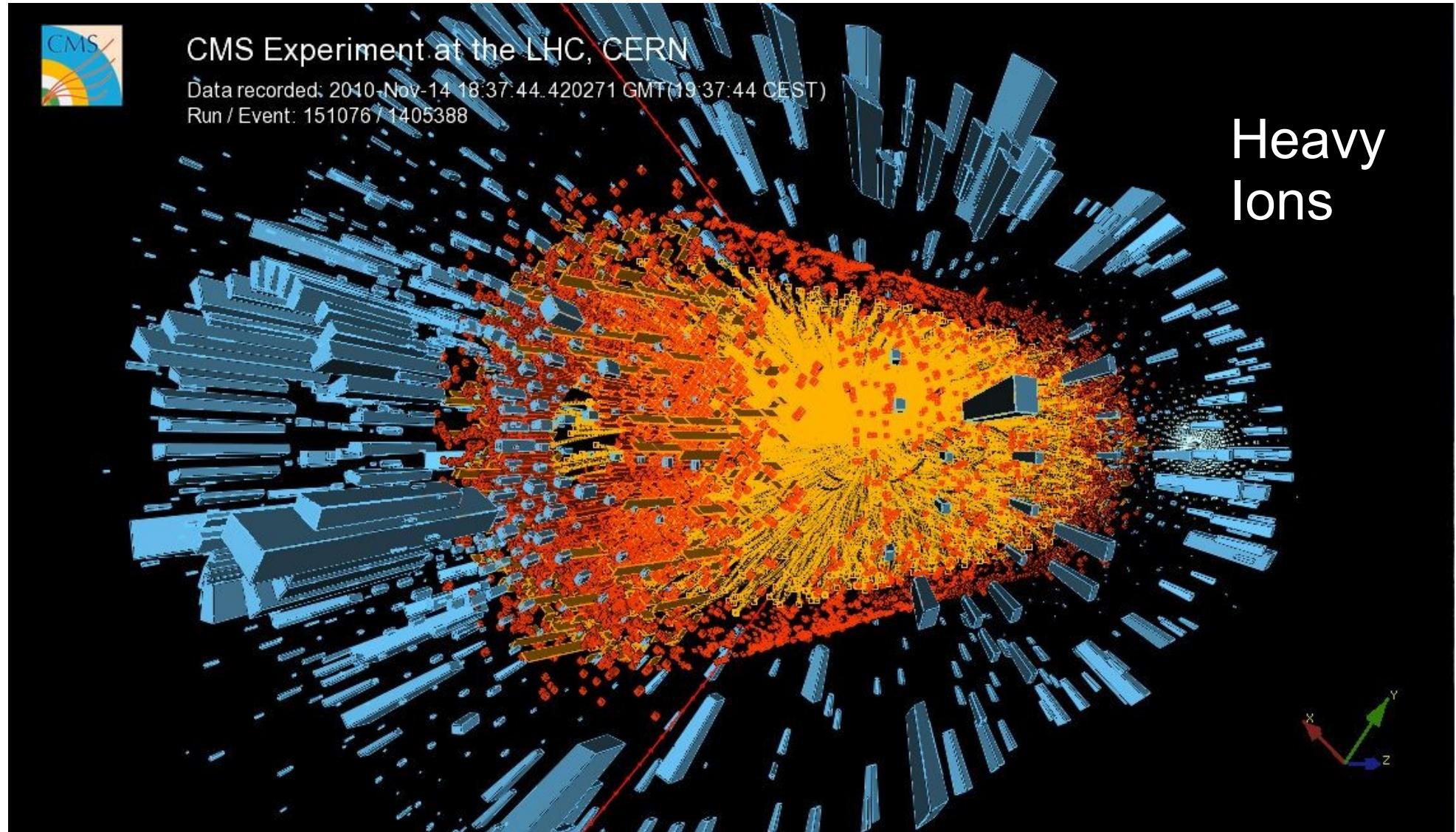


Visualizing the PF impact



Angular information from the **tracks** improves the resolution of the jet shape internals
 (Don't need to correct for jet shape *a posteriori*)

Dense Environment

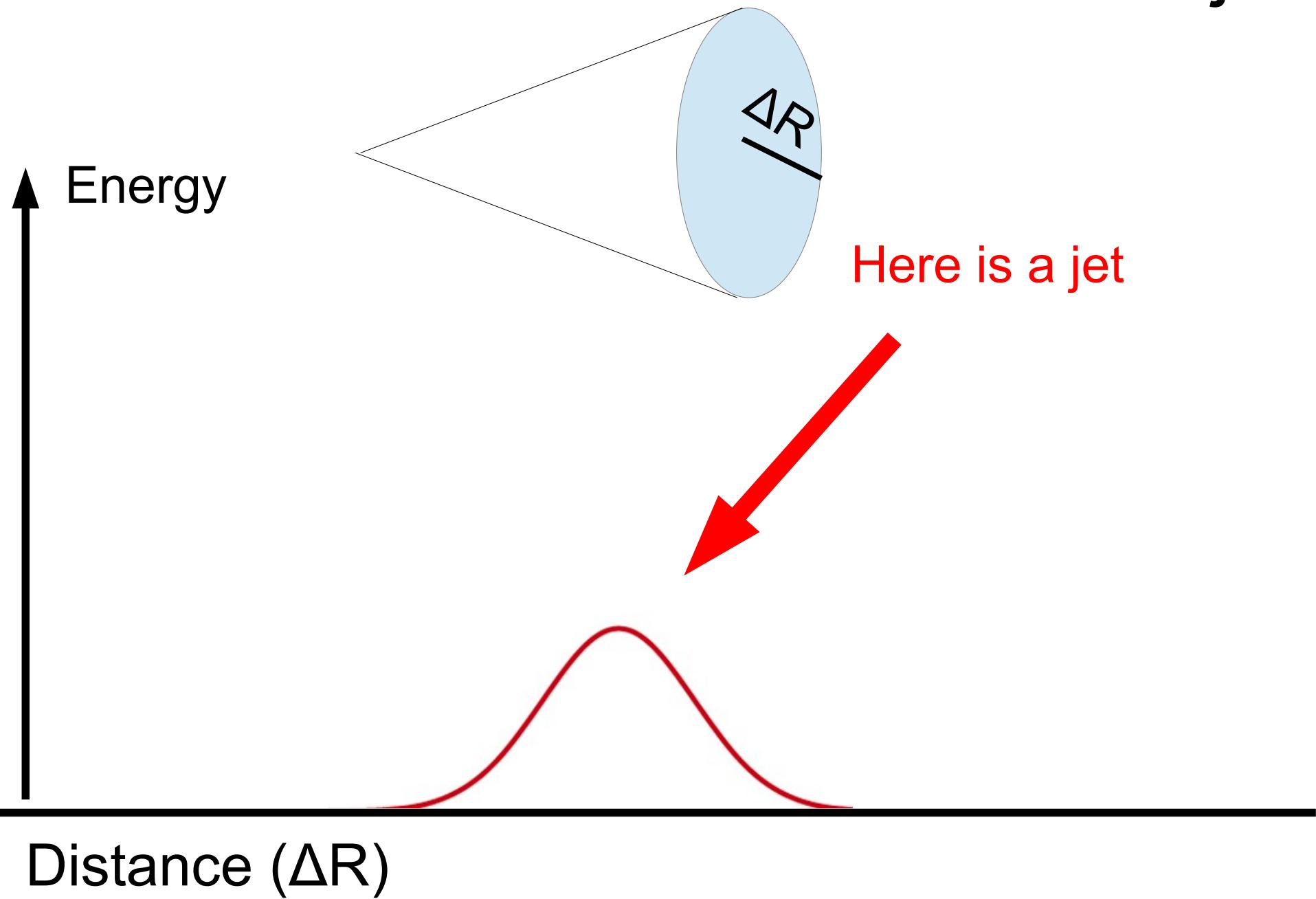


Dealing w/PU-UE:

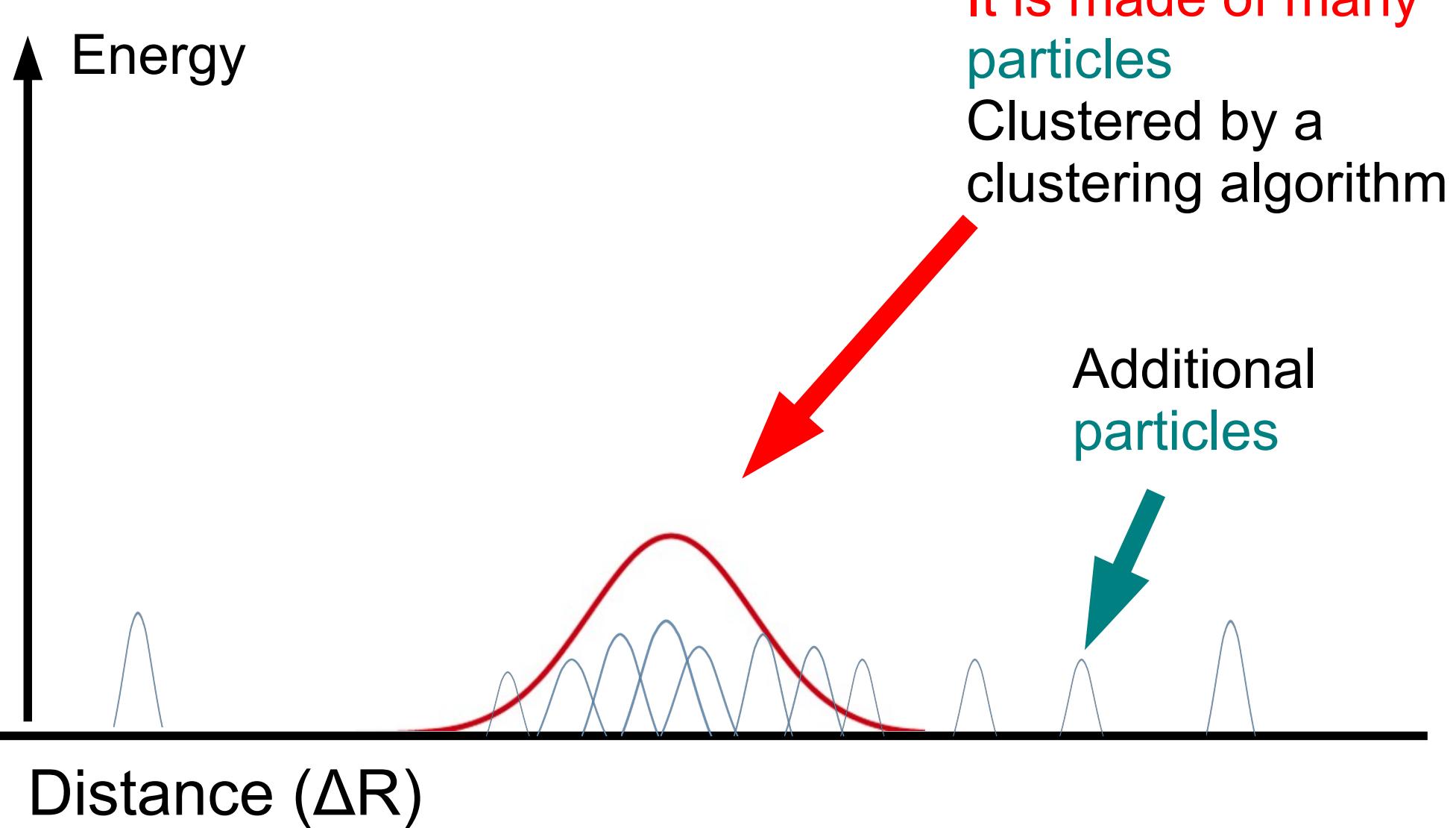
Key questions :

- What happens to a jet in pileup?
- What is the composition of pileup?

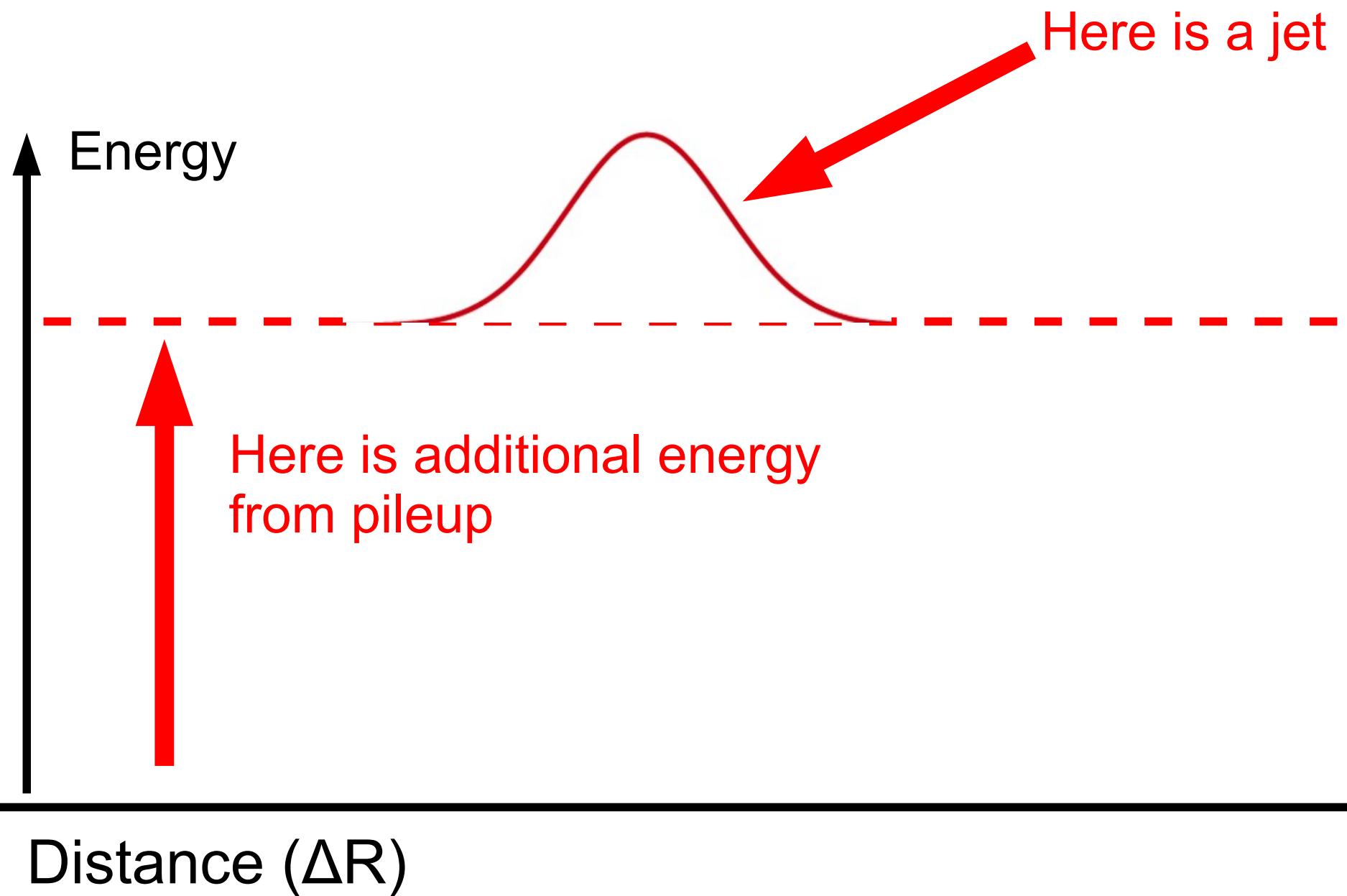
Consider a jet



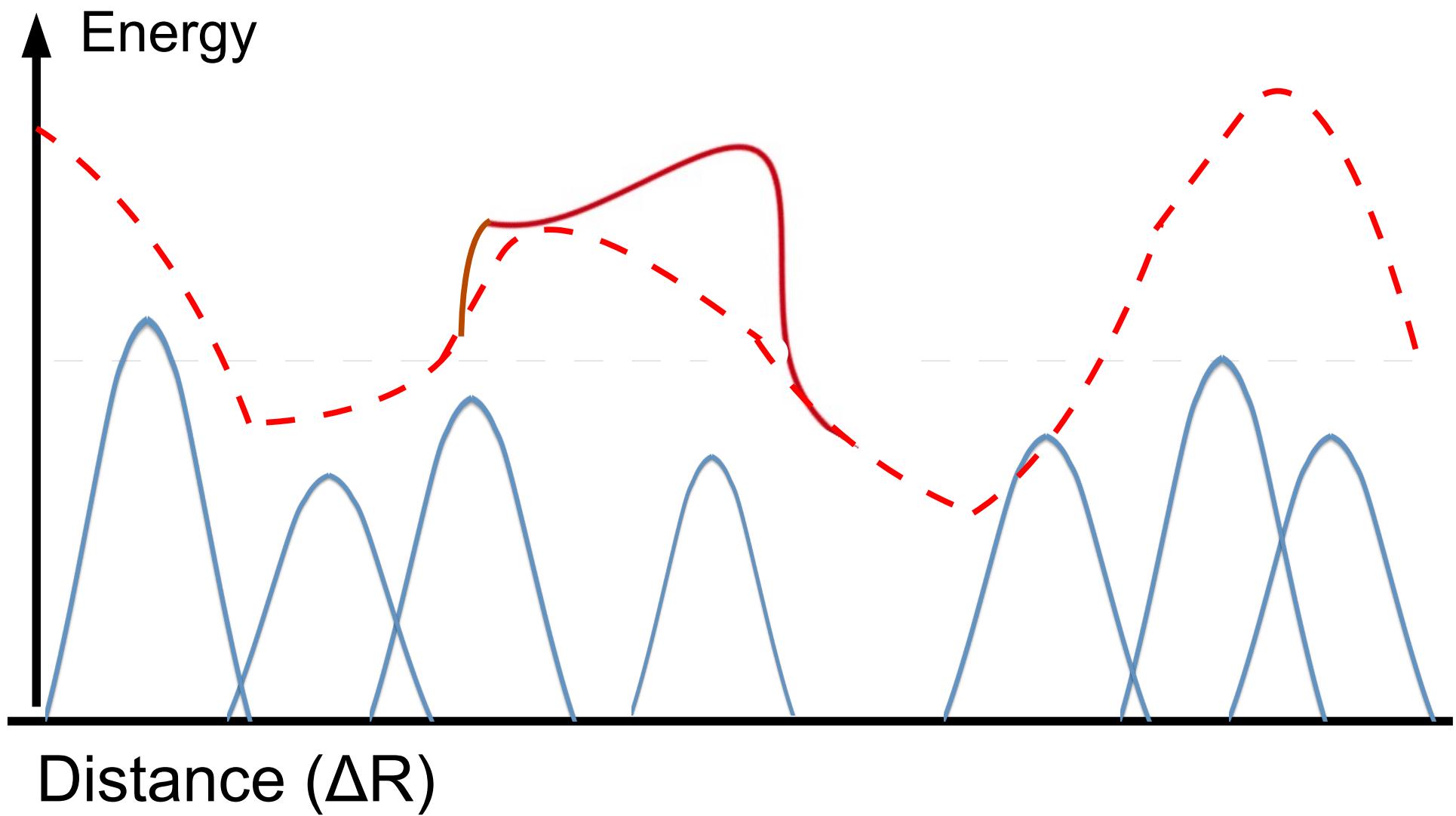
Consider a jet



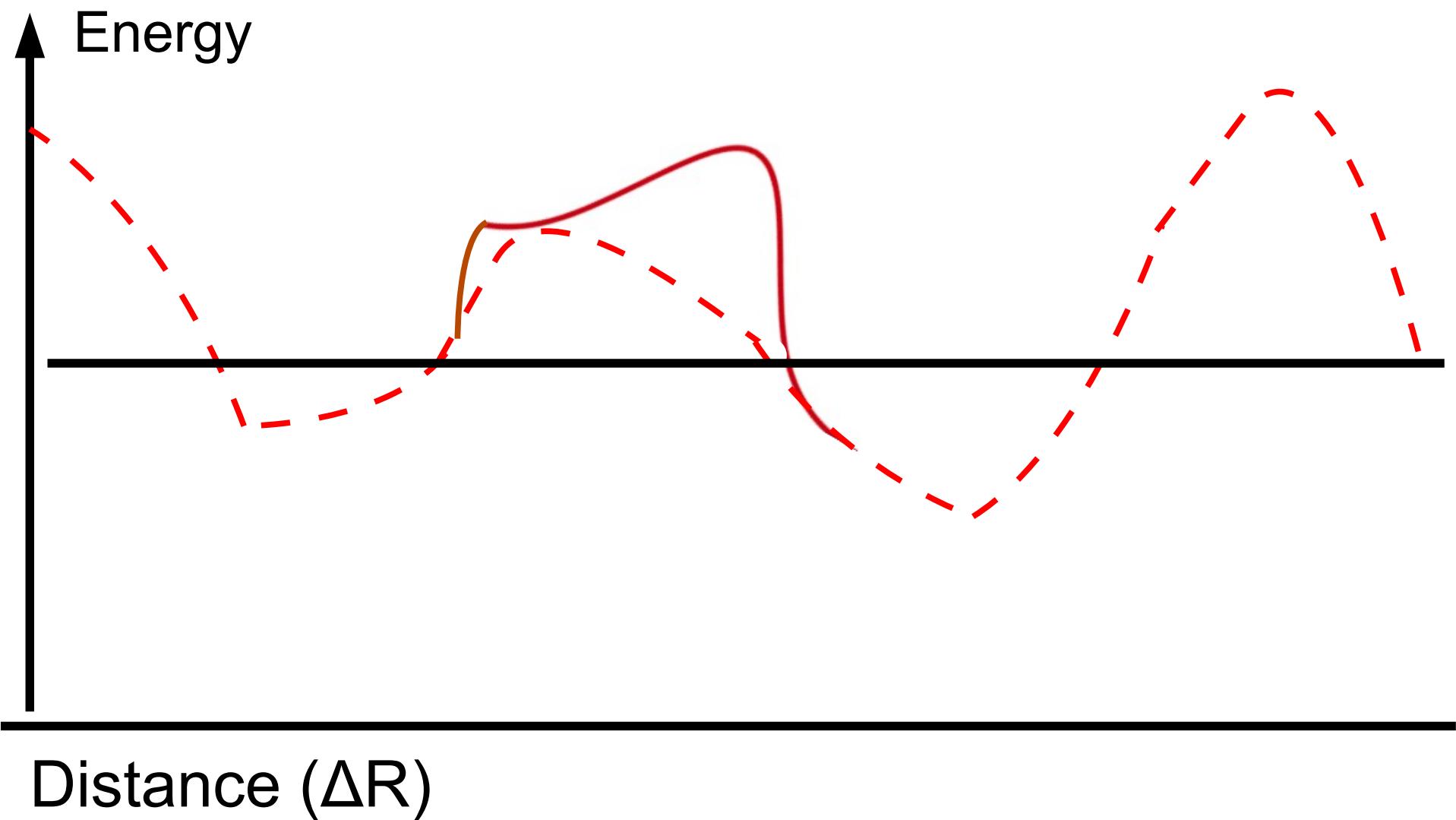
Consider a jet in high pileup



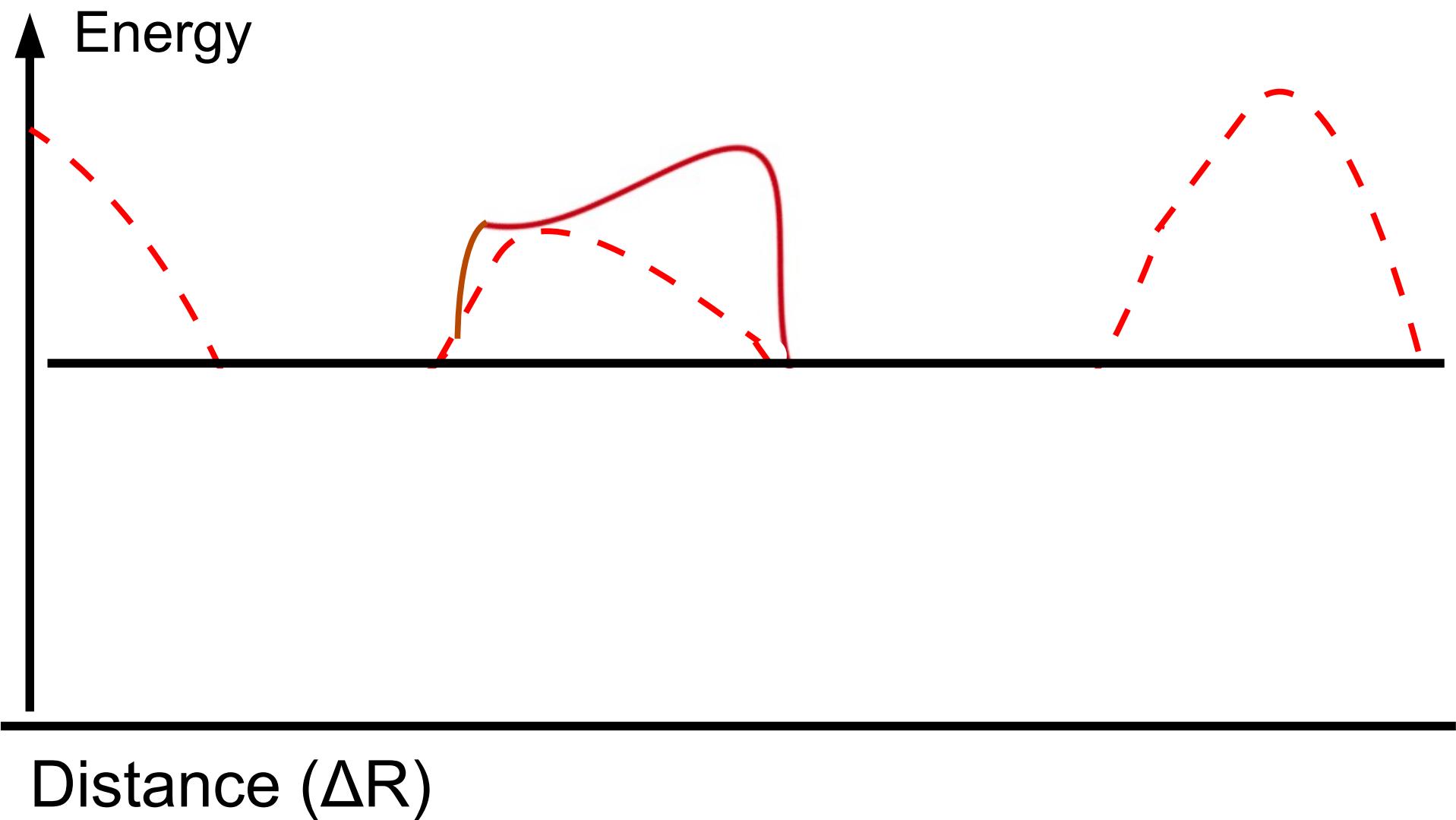
A jet in realistic pileup



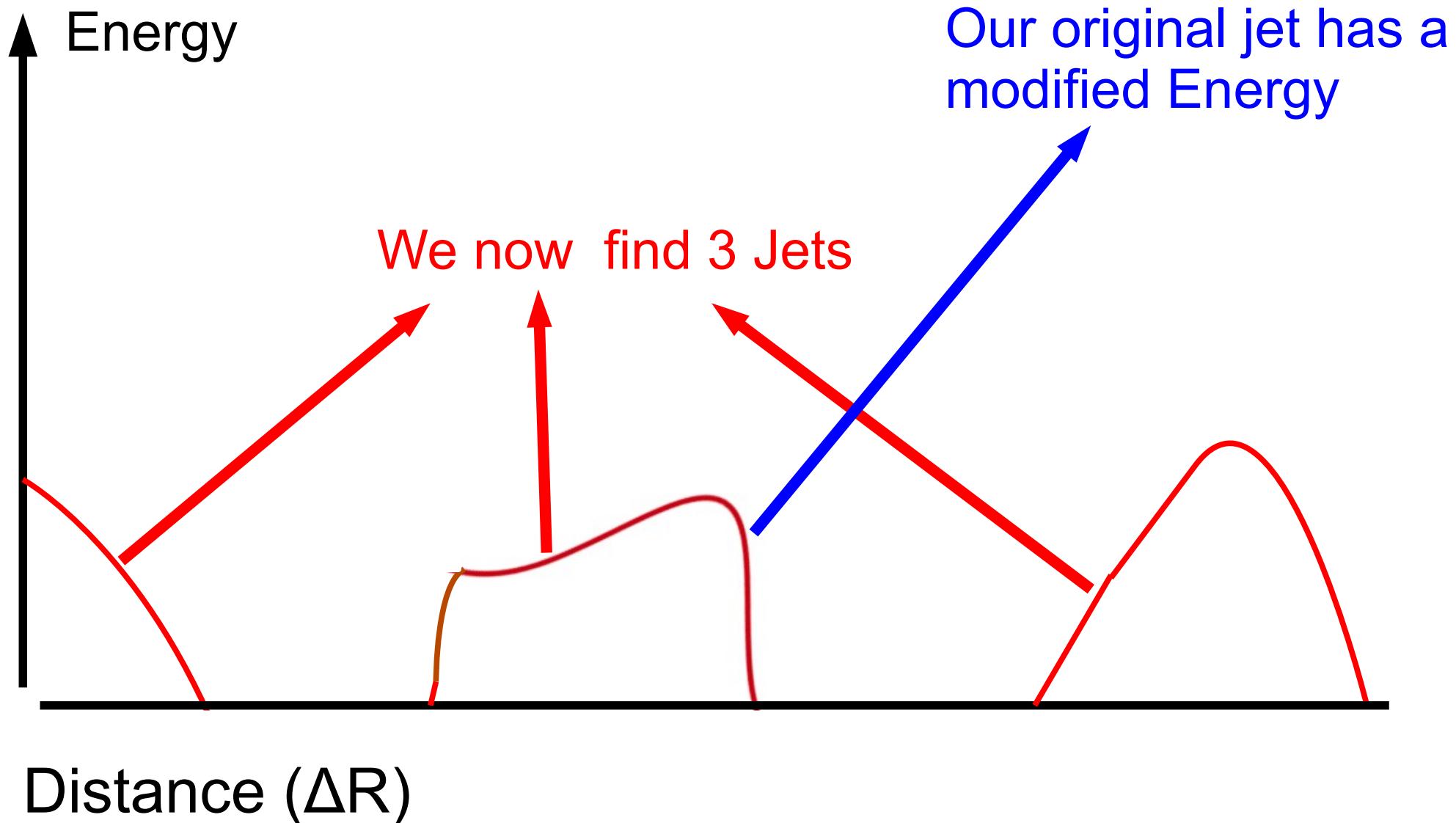
Conventional subtraction



Conventional subtraction



Conventional subtraction

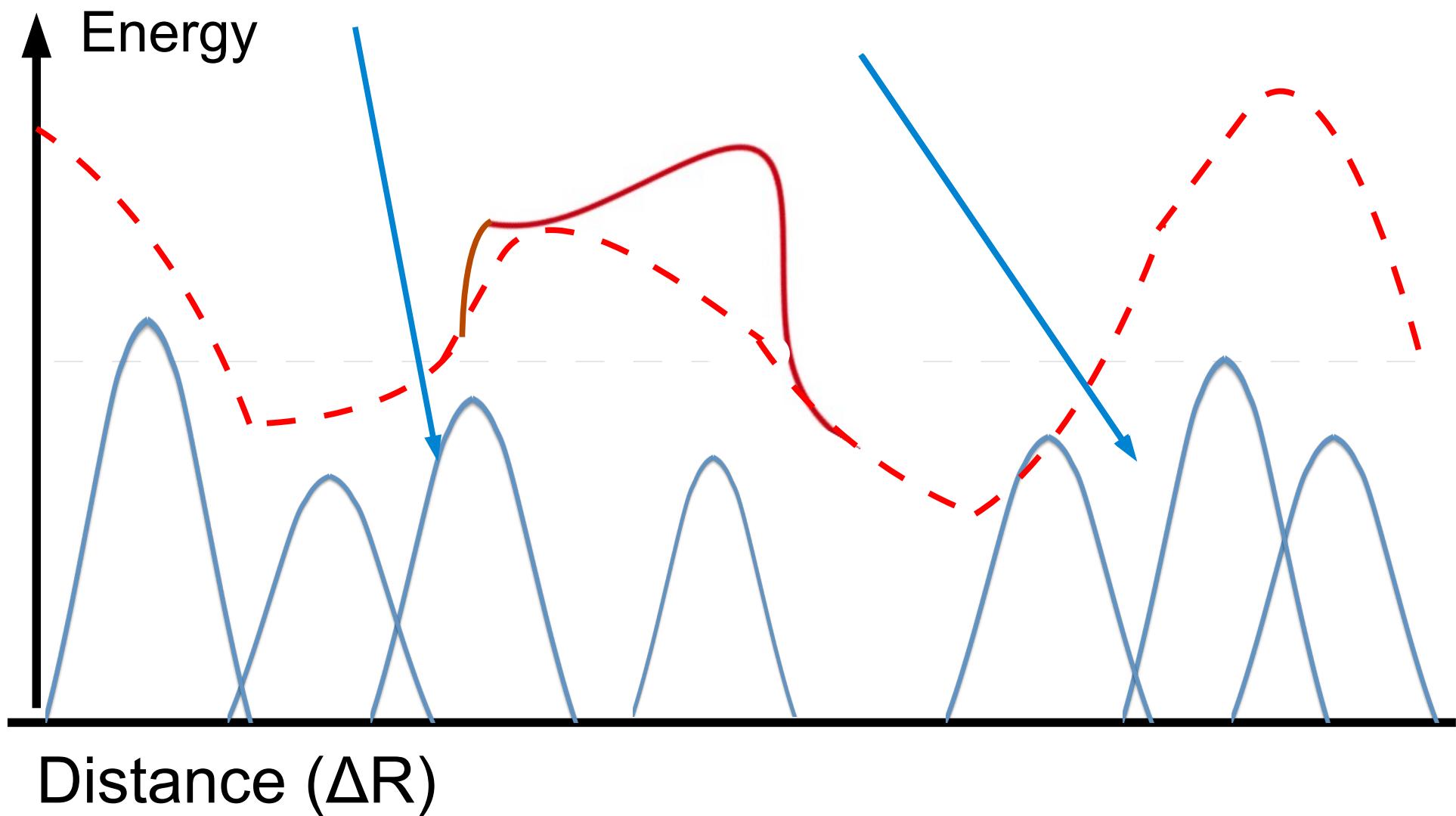


Conventional subtraction



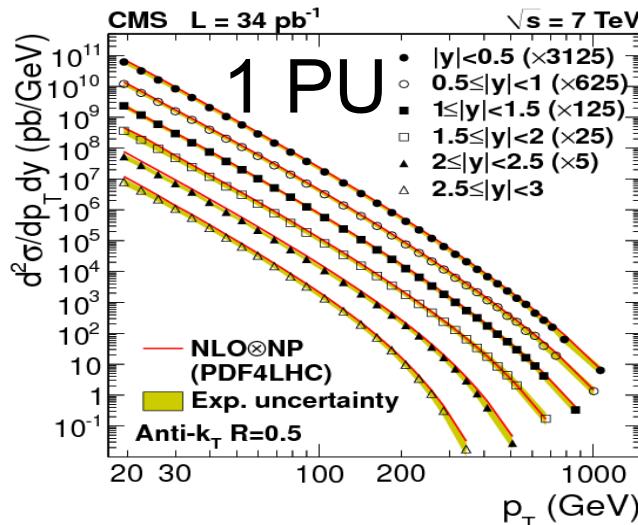
Lets back track

What is the composition of the pileup?



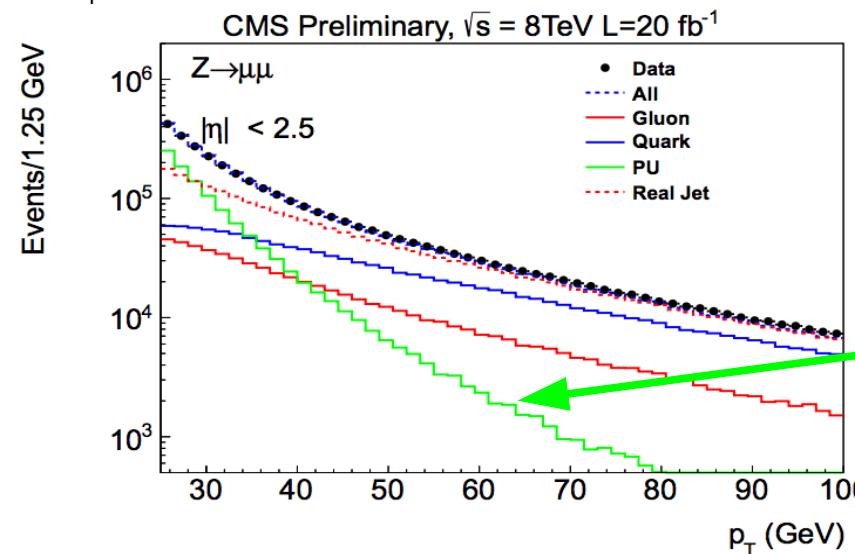
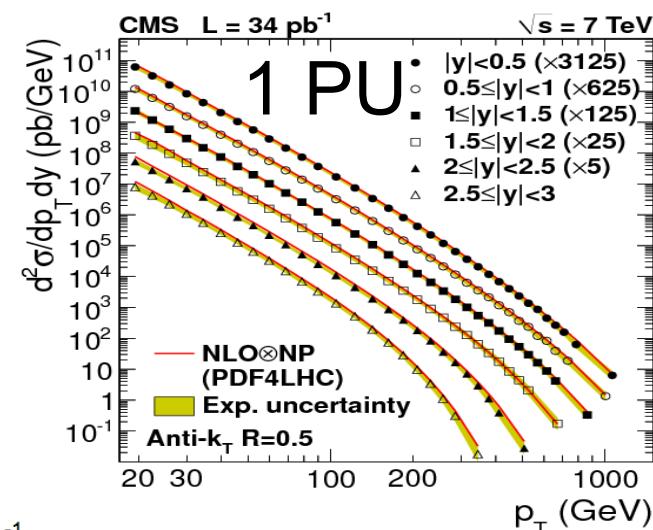
Composition of pileup

- Every collision starts with quarks
 - This leads to jets in the final state
 - Now combine many different collisions together



N_{PU}

■ ■ ■

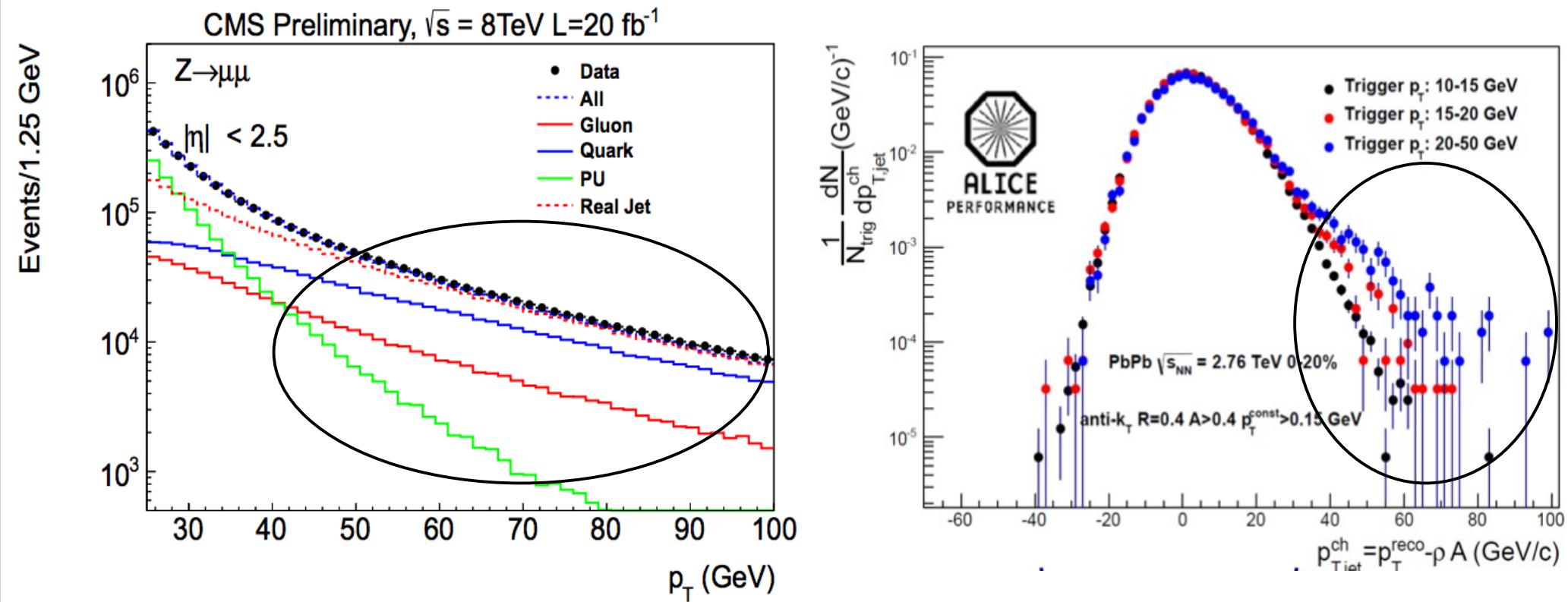


Jets overlapping
Gives up pileup jets

Pileup Jets or “Fake” Jets

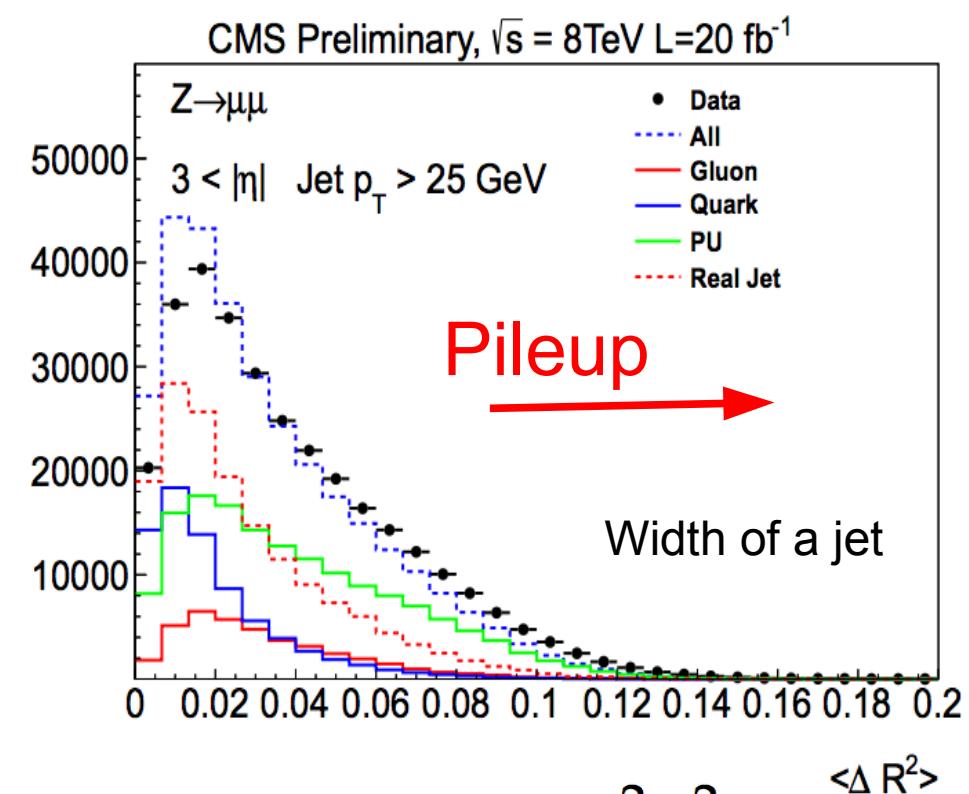
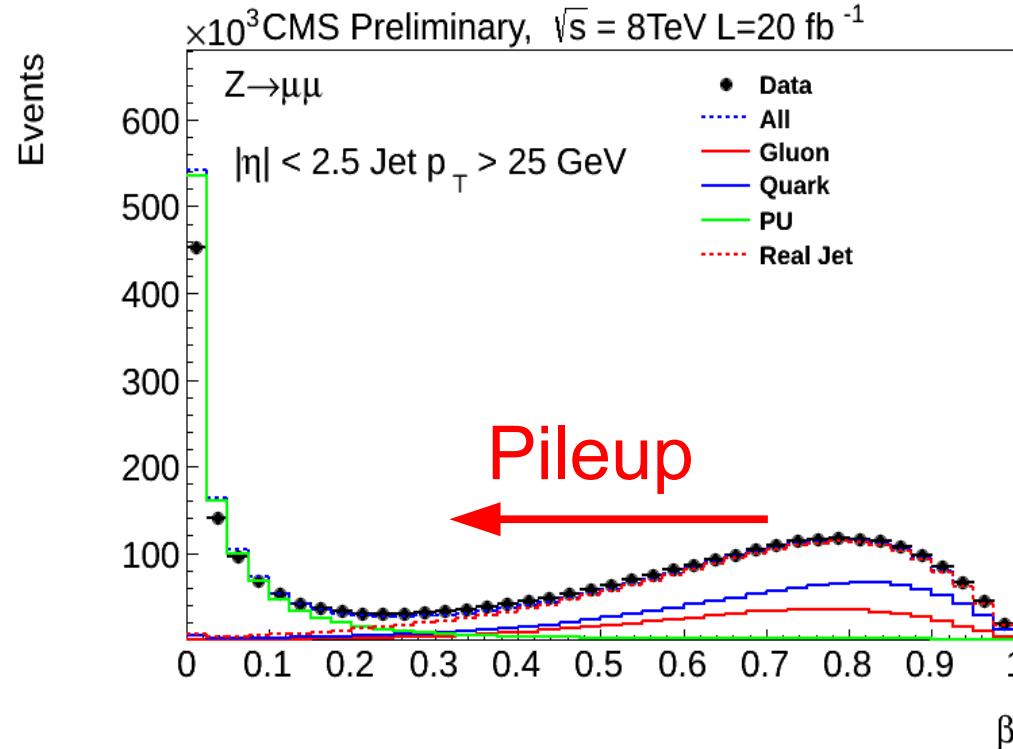
- For all classical purposes
 - Pileup jet can be viewed as overlapping low p_T jets
 - **Consider the Jet substructure of such an object?**

$$P(\text{overlap}|pT) \approx C N_{\text{pu}}^2 a_{\text{jet}}^2 pT^{-6.2} \text{ Real Jets} \approx pT^{-5}$$



Identifying pileup jets

- Can identify pileup jets by :
 - Jets that are associated to the primary vertex
 - Looking for objects that are wide(overlapping)



$$\beta = \frac{\sum_{i \in PV} p_{Ti}}{\sum_i p_{Ti}}$$

$$\langle \Delta R^2 \rangle = \frac{\sum_i \Delta R_i^2 p_{Ti}^2}{\sum_i p_{Ti}^2}$$

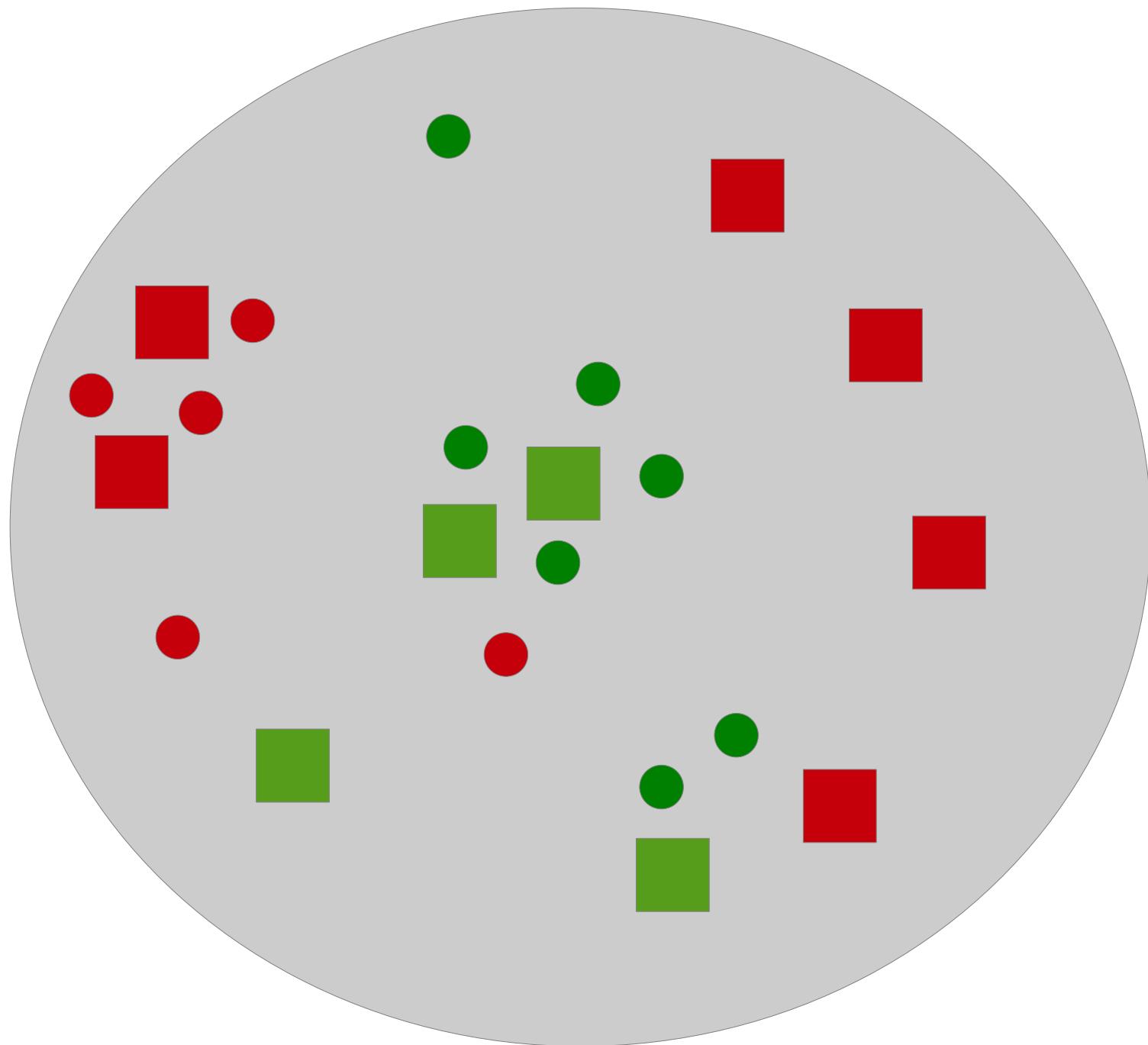


Current Technology

Consider a jet

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed



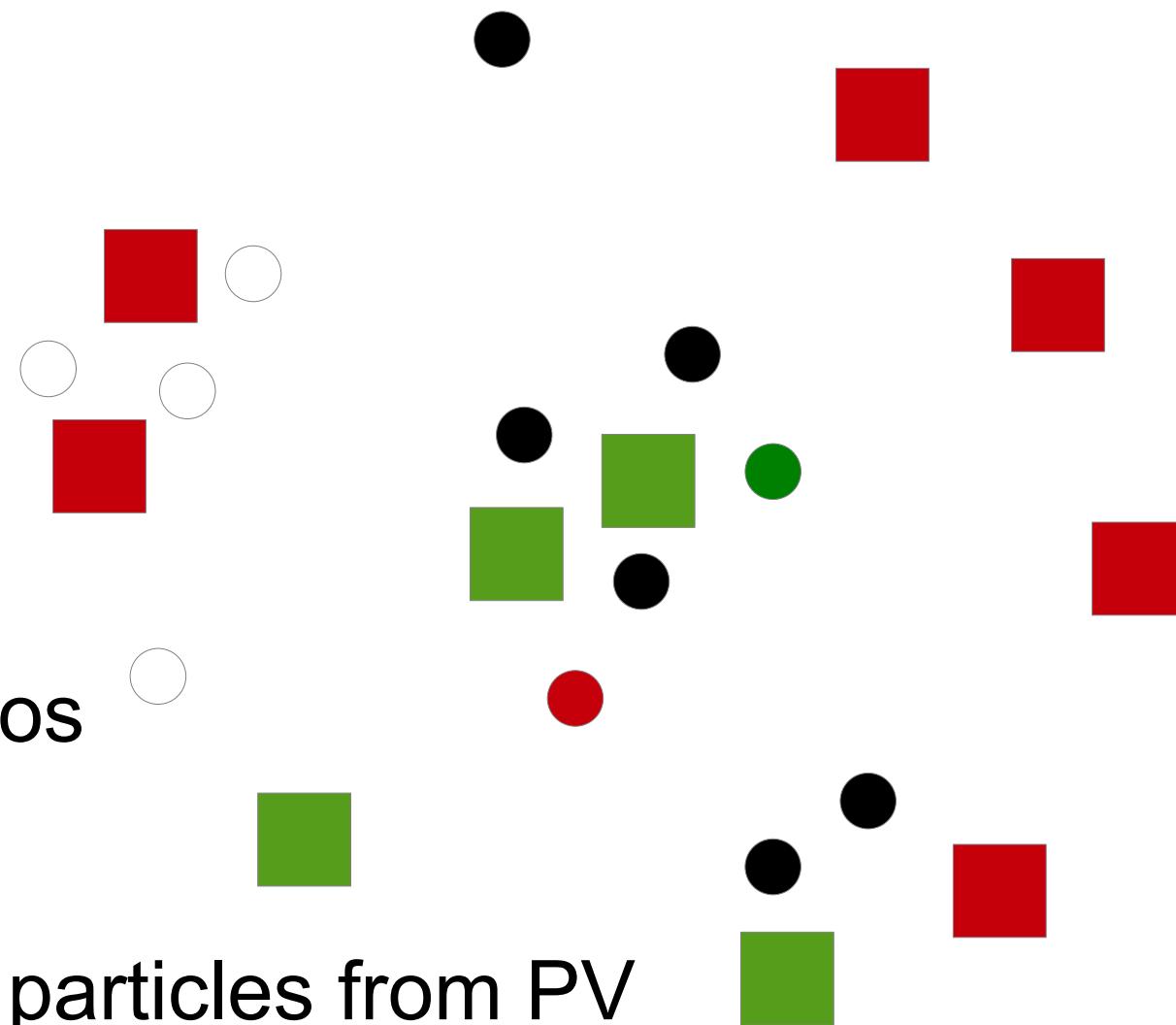
Charge Hadron Subtraction

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

Step 1 of all Algos
CHS

Choose charge particles from PV
Remove charged particles not



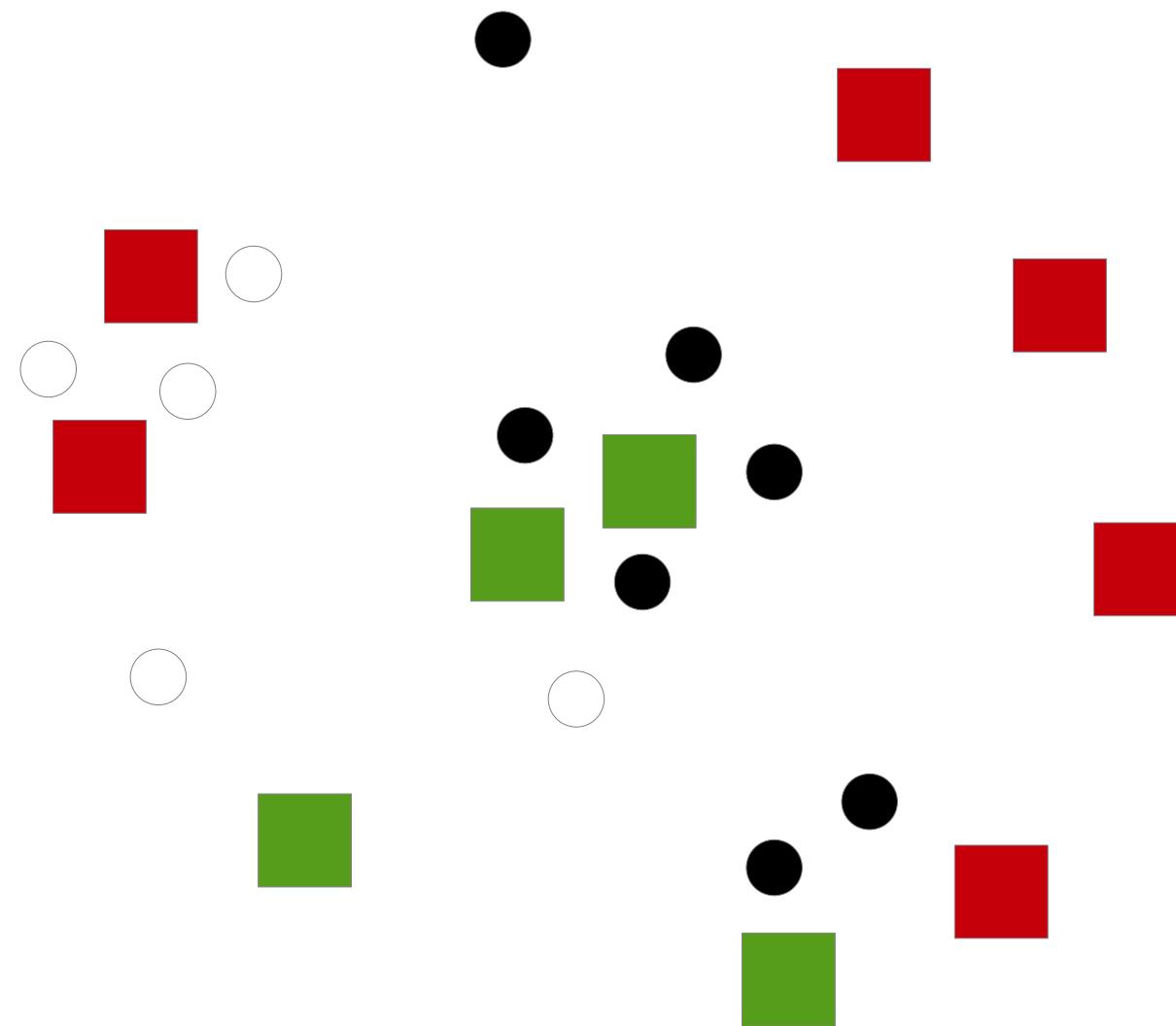
Puppi algorithm

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

Step 1

Tracks can point
to PU vertices
w/high efficiency

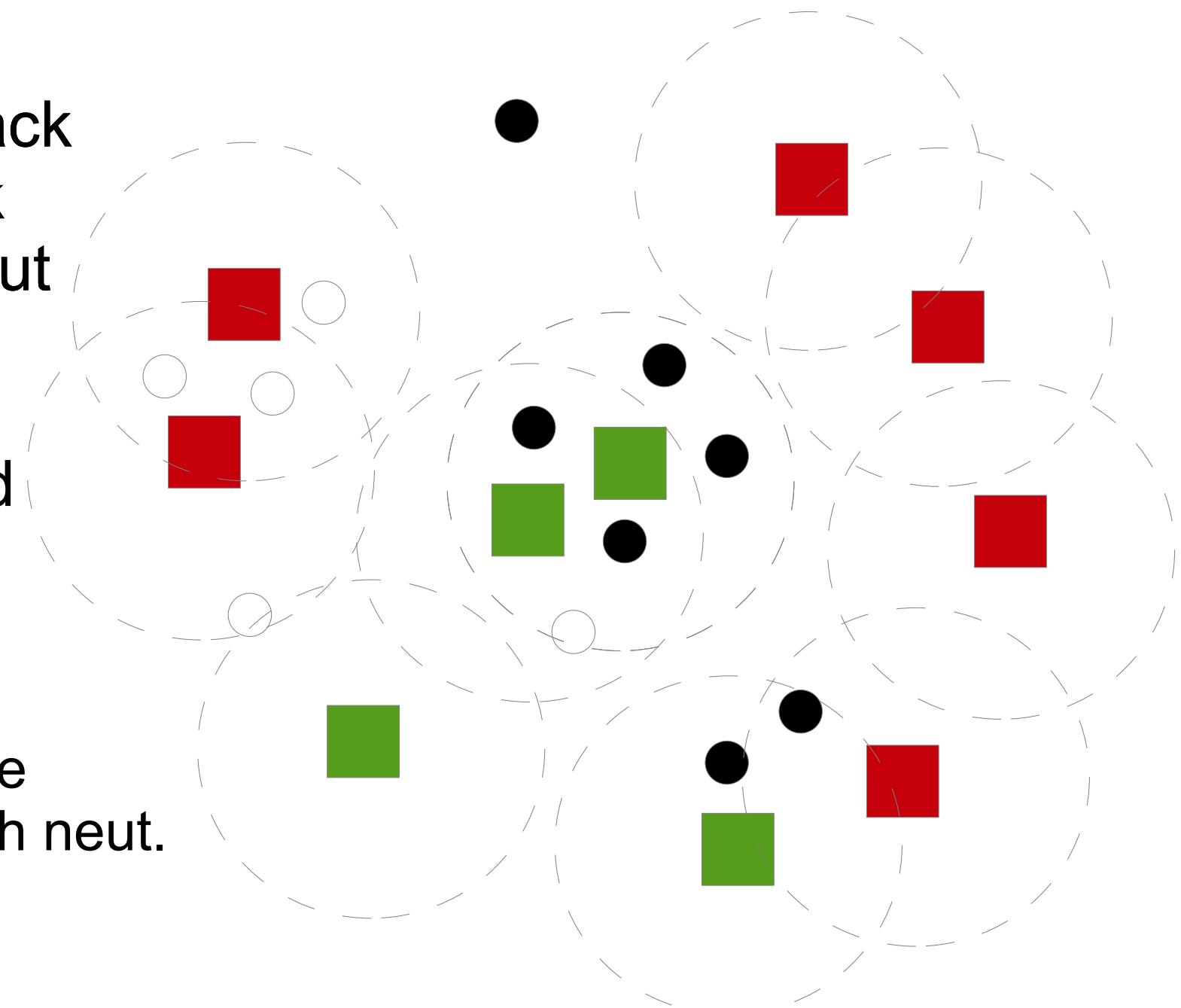


Puppi algorithm

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

Step 1
Vertexing
Step 2
Draw a cone
About each neut.

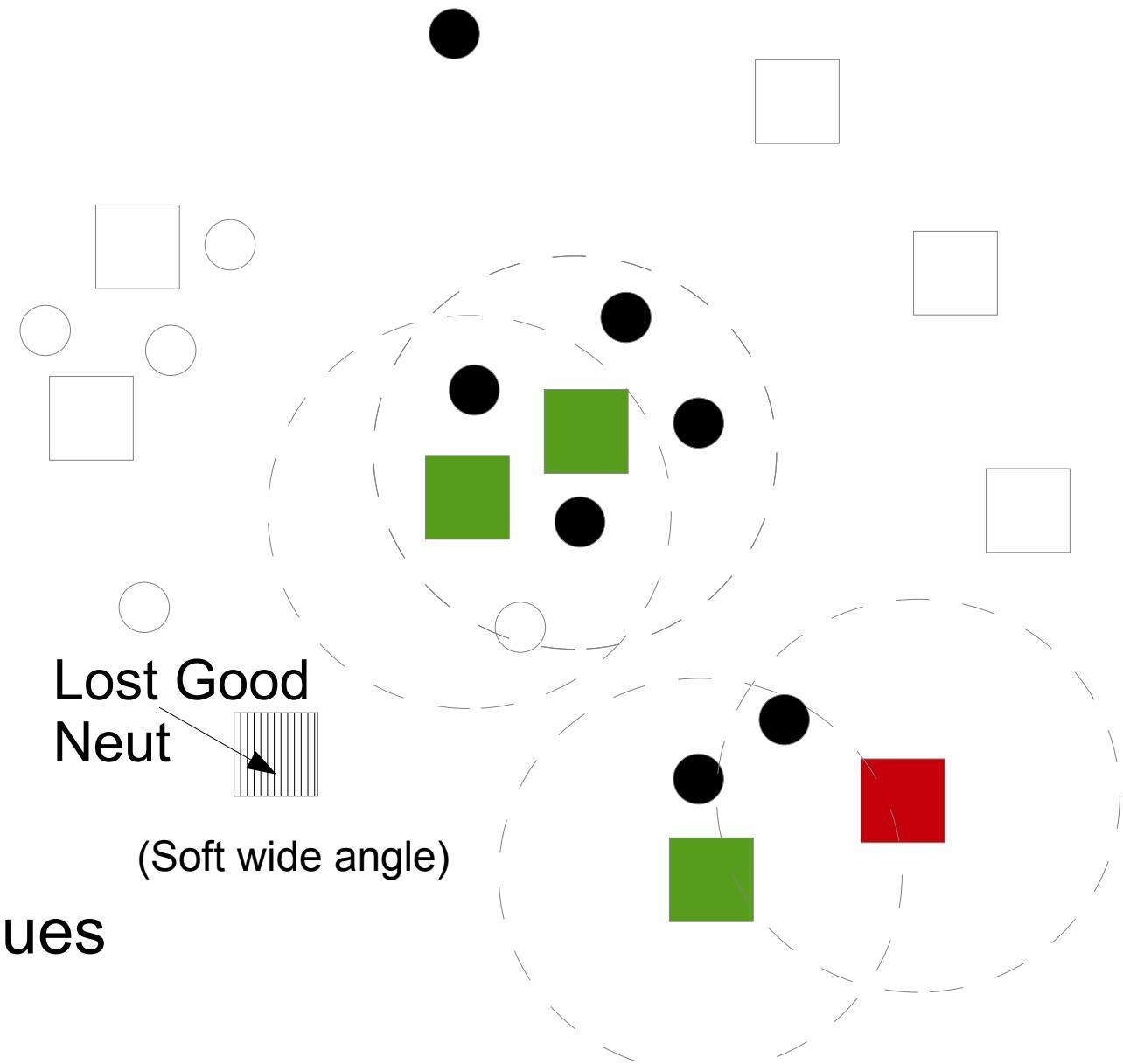


Puppi algorithm

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

- Step 1
Run CHS
Step 2
Draw a cone
Step 3
Remove all 0 values

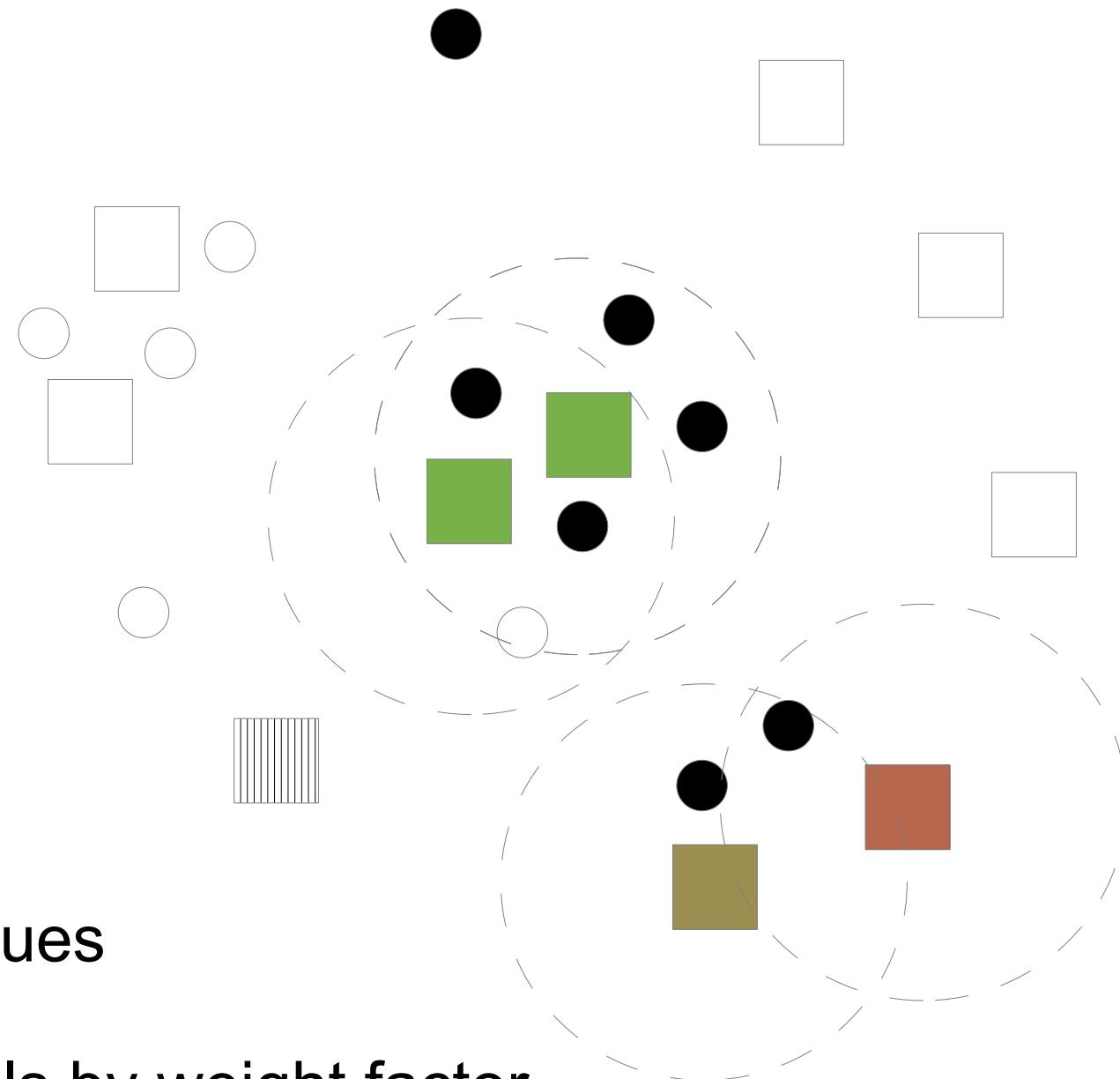


Puppi algorithm

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

- Step 1
Vertexing
Step 2
Draw a cone
Step 3
Remove all 0 values
Step 4
Reweight Neutrals by weight factor

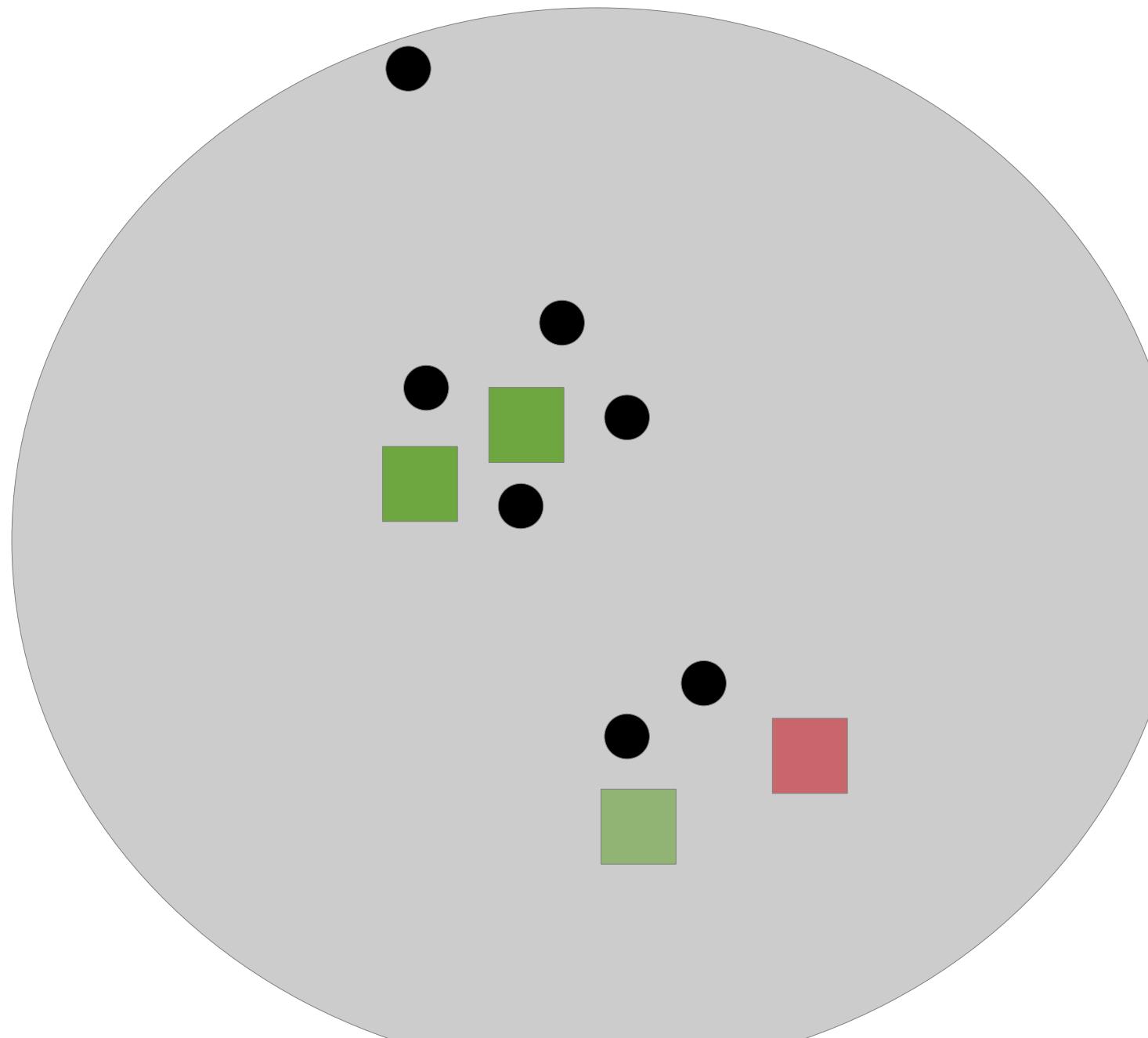


After Puppi

Key

- Good Track
- PU Track
- Good Neut
- PU Neut
- Chosen
- Removed

Step 5
Re-interpret evt
(Re-cluster)



The weight factor

- For each particle consider in a cone :

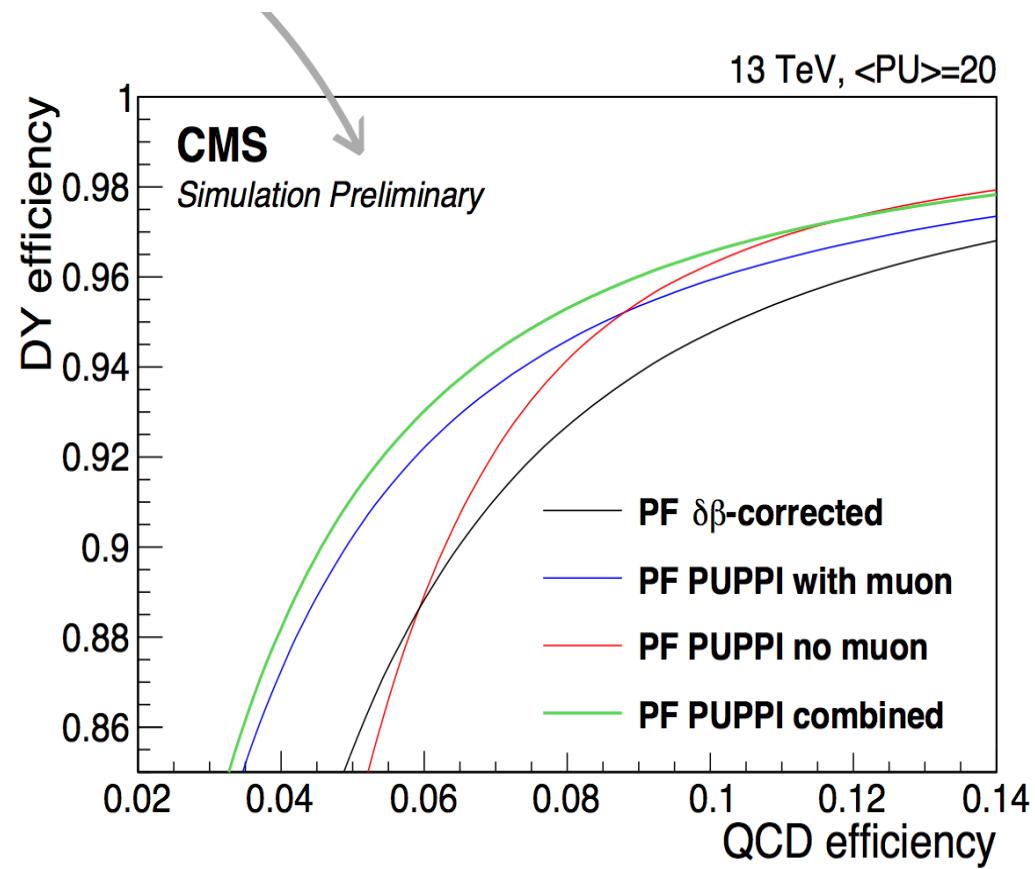
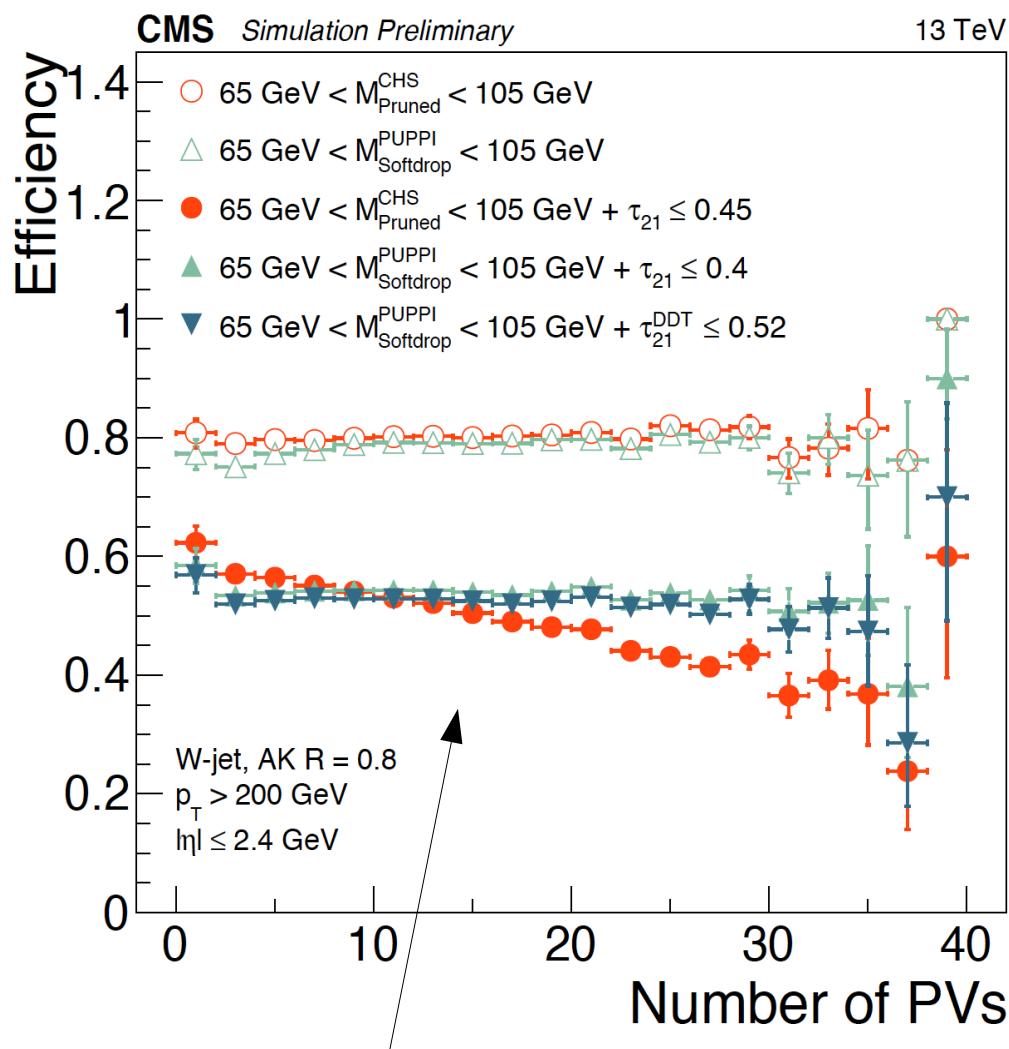
$$\log \sum_{\substack{j \in R_{\min} \leq \Delta R_{ij} \leq R_0}} \frac{p_T j}{\Delta R_{ij}}$$

↑ Hard collinear particles
↓ Soft wide angle particles

Variable roughly gaussian → build likelihood
 Translate to weight (w_i) applied to each candidate

Apply a cut on weighted $w_i p_T > A + B N_{PV}$

PUPPI Performance

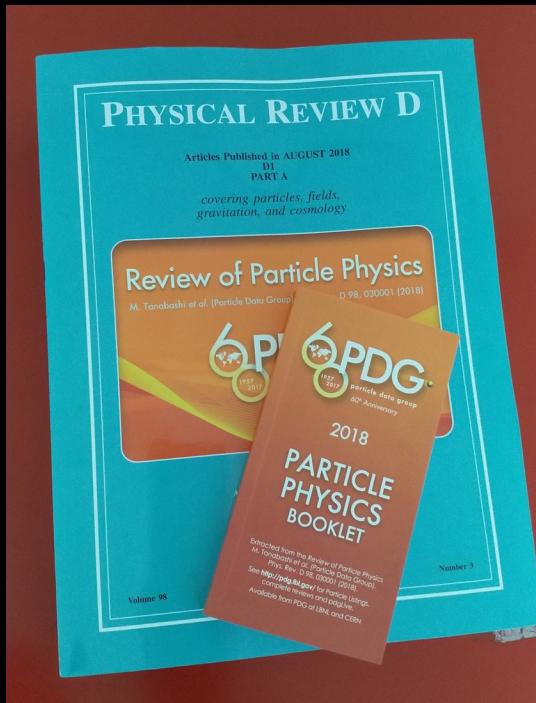


Particle level properties
like Isolation & MET
improve substantially

PUPPI+Soft drop now the standard
in CMS for boosted jets

Part 1

Hadronic Resonances



Part 1

Hadronic Resonances

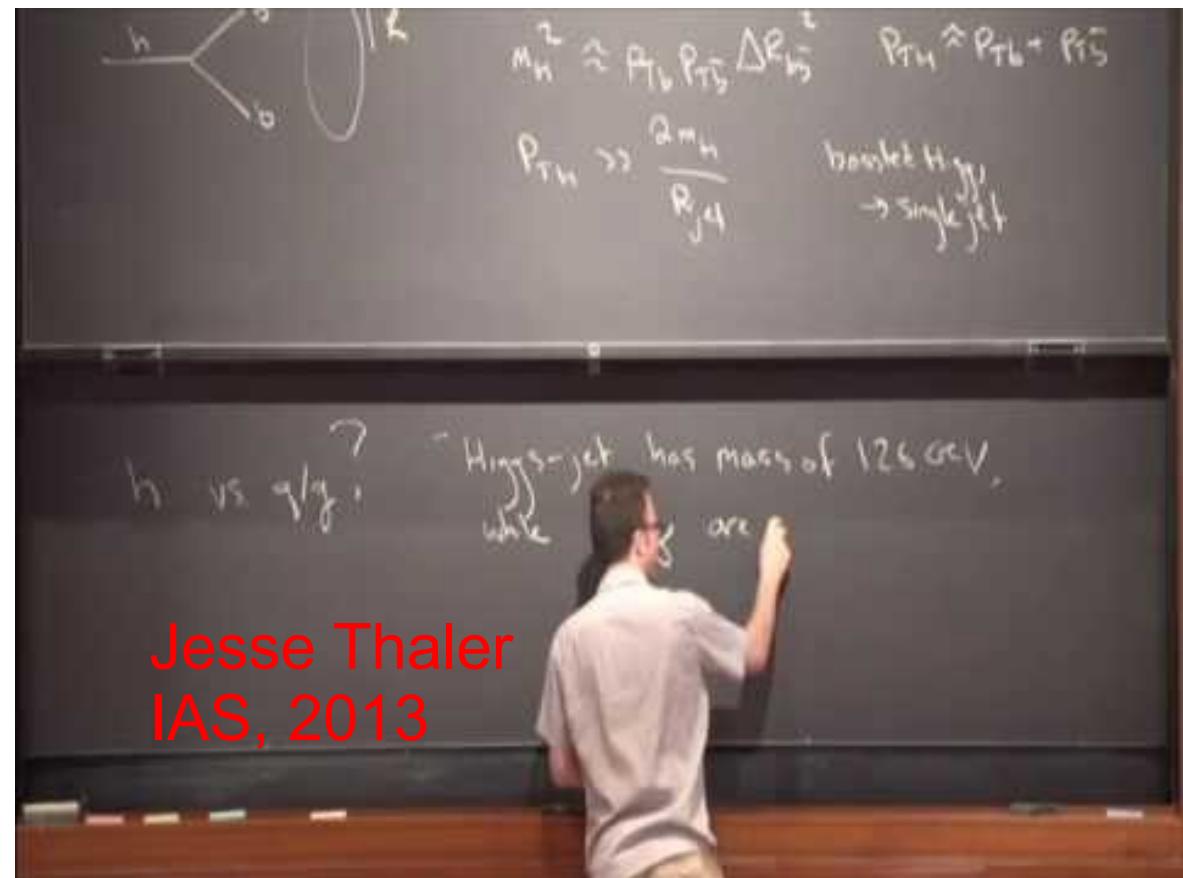
III.4.2. $H \rightarrow b\bar{b}$

The production mode $gg \rightarrow H$ with $H \rightarrow b\bar{b}$ is overwhelmed by the background from the inclusive production of $p\bar{p} \rightarrow b\bar{b} + X$ via the strong interaction. The associated

Particle Data Group 2016
(High Energy Physics Handbook)

History

- With the first generation of substructure
 - We were able to resolve overlapping objects
 - In regions where clear signatures were expected
 - Found them and characterized the
- Led to a
 - Wealth of new physics bounds
 - **Transformative** in our approach to LHC

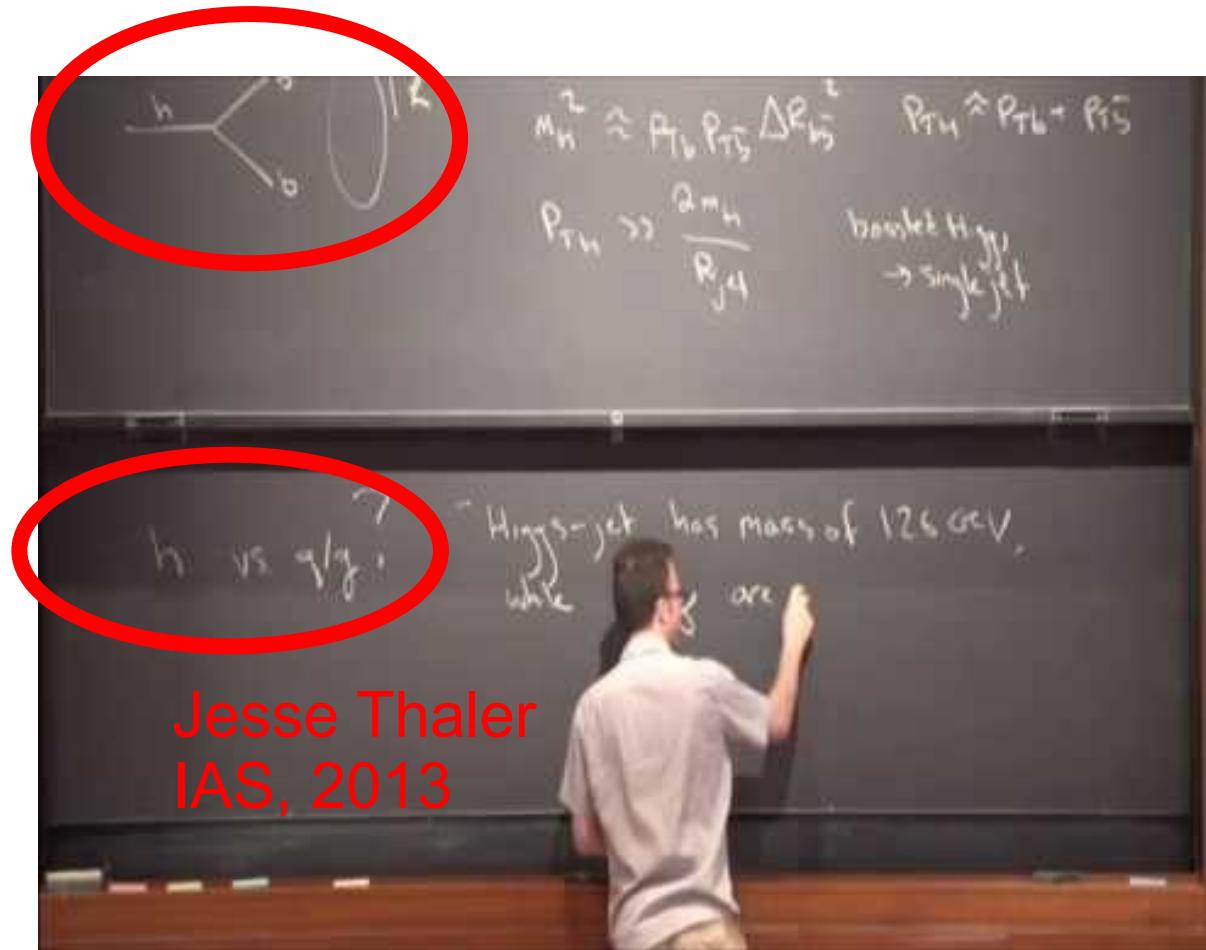


A few Questions remained uncertain

- If you look closely
 - Jesse is setting up the beginning of a problem
 - The same problem **that PDG said was impossible**

In the rest of this talk
**Explain how we
solved this problem**

Standing on the
shoulders of giants



EVENT DISPLAYS!

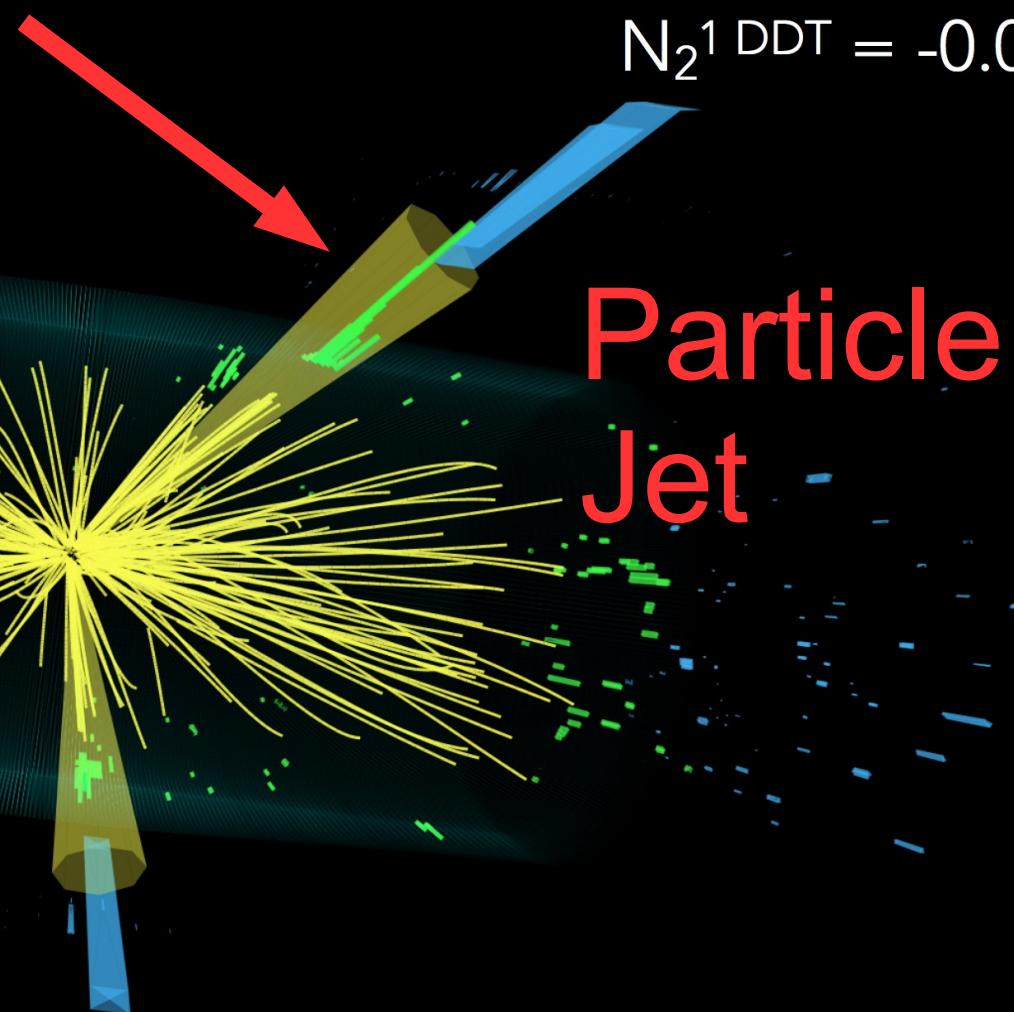
This is actually what it looks like in the detector

$p_T = 466 \text{ GeV}$
 $\text{double-}b = 0.95$
 $m_{SD} = 126.2 \text{ GeV}$
 $N_2^{1 \text{ DDT}} = -0.07$



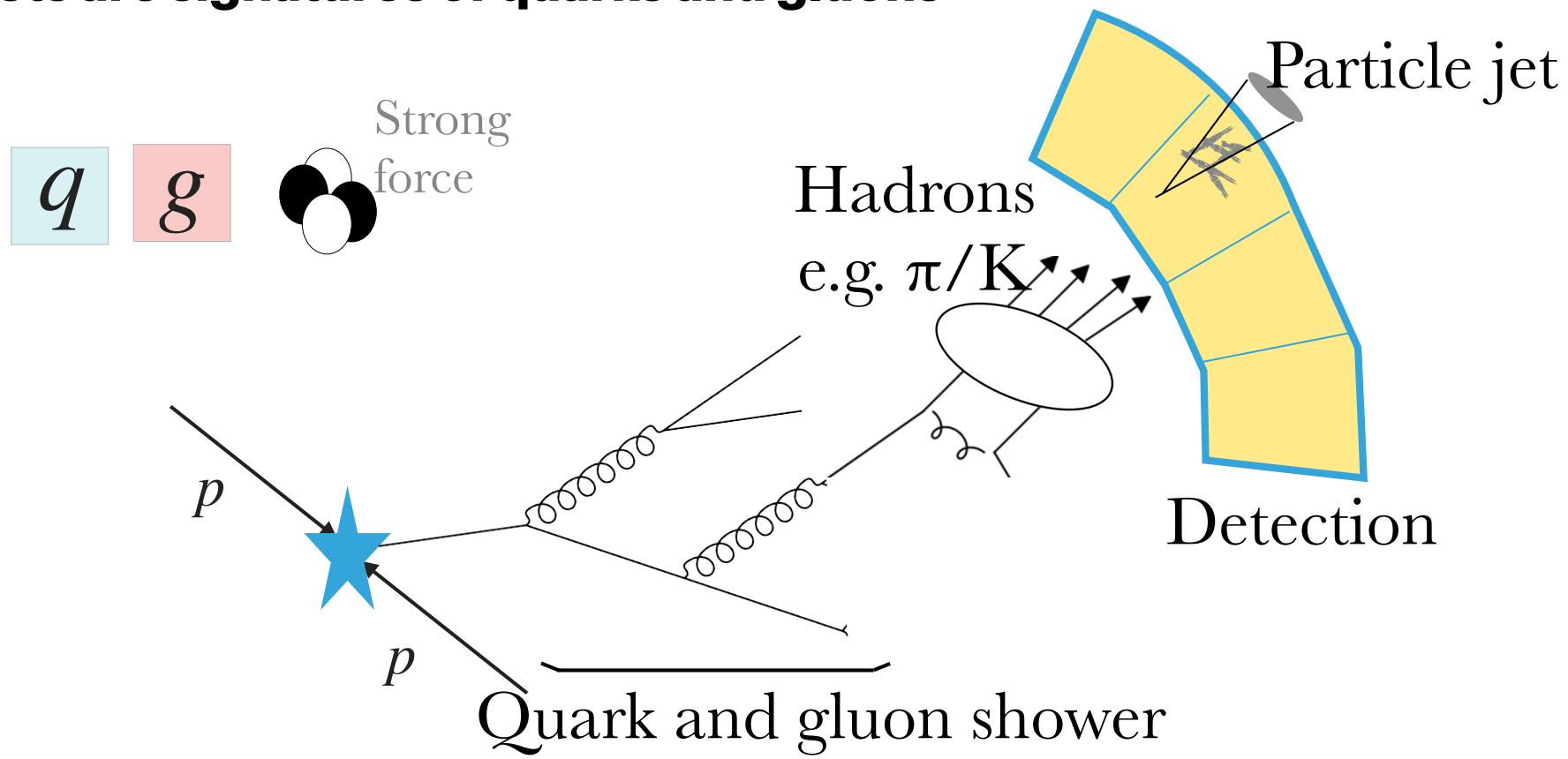
CMS Experiment at the LHC, CERN
Data recorded: 2016-Aug-15 04:31:20.039252 GMT
Run / Event / LS: 278822 / 1778731024 / 1026

$p_T = 357 \text{ GeV}$



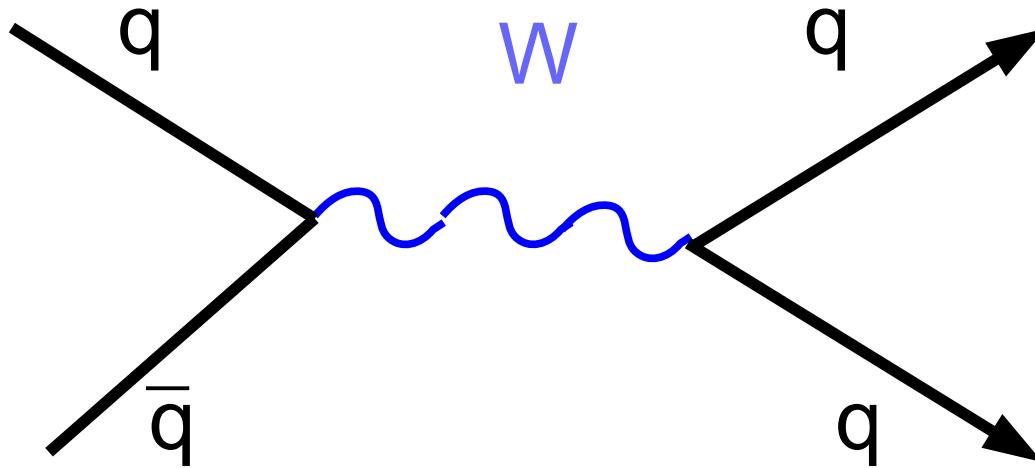
What you know now:

Jets are signatures of quarks and gluons



Lets go back and try again?

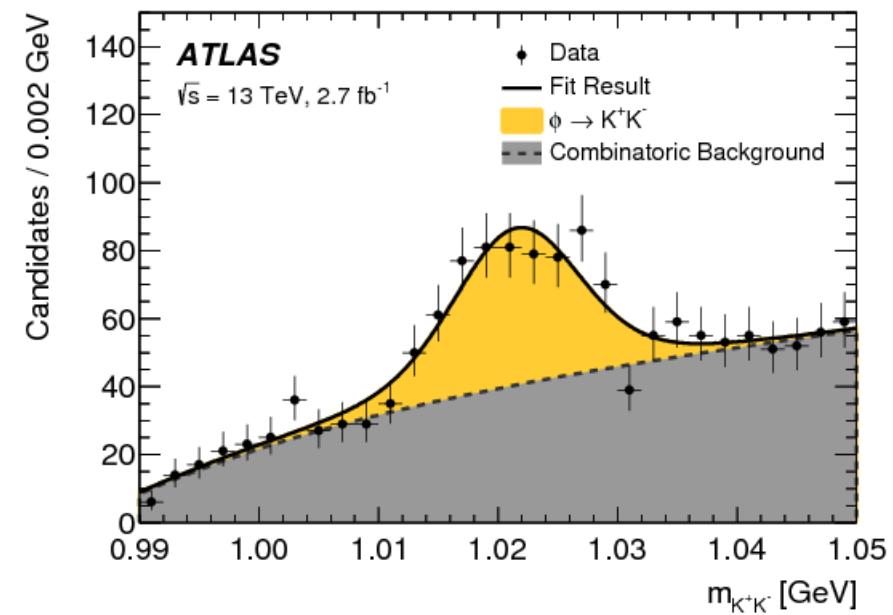
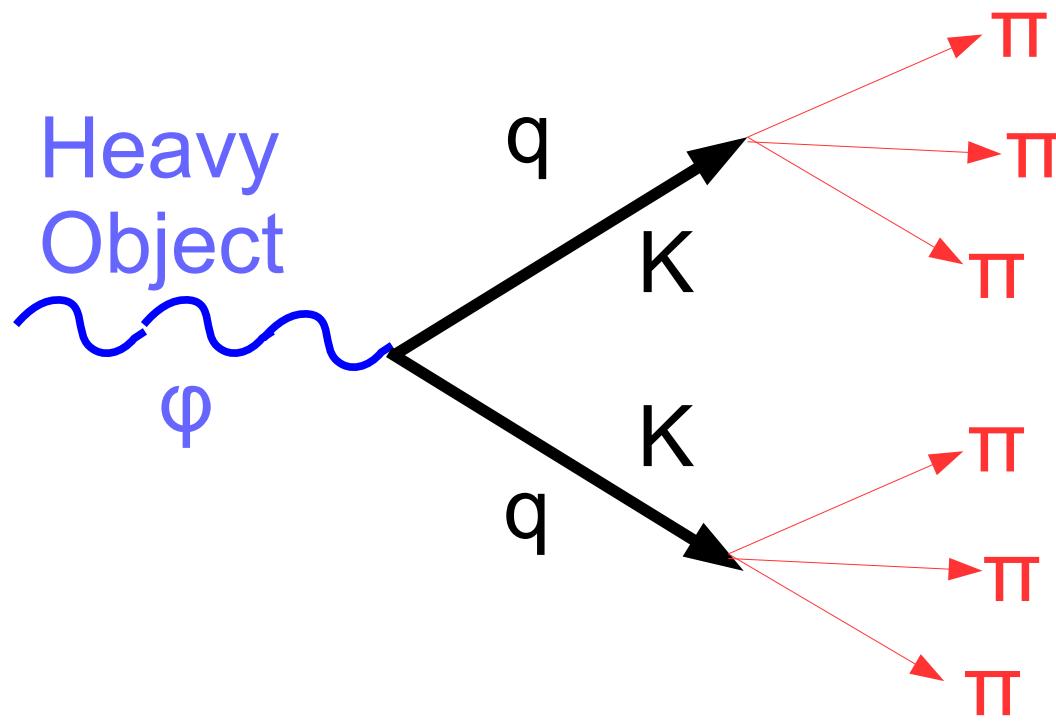
To see if its useful lets target a core process:



A W boson decaying to quarks

What is a hadronic resonance?

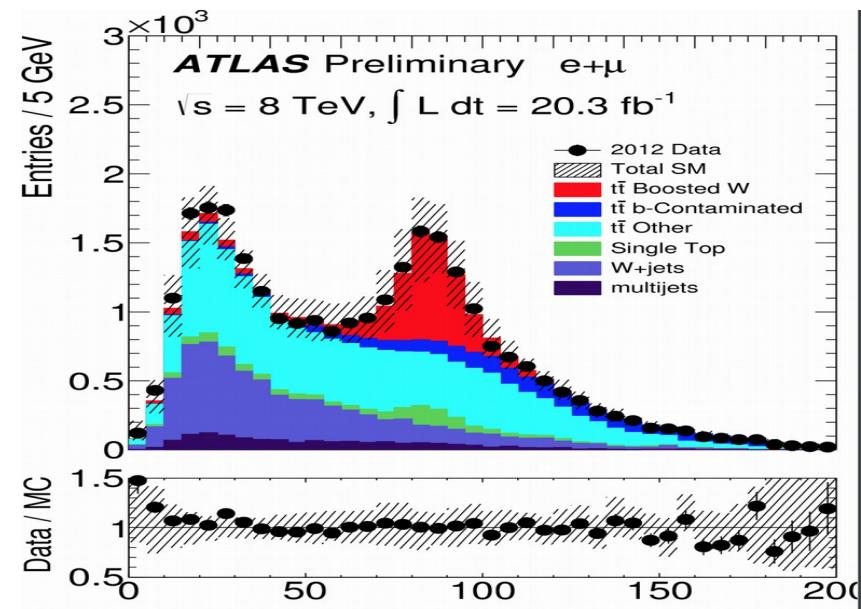
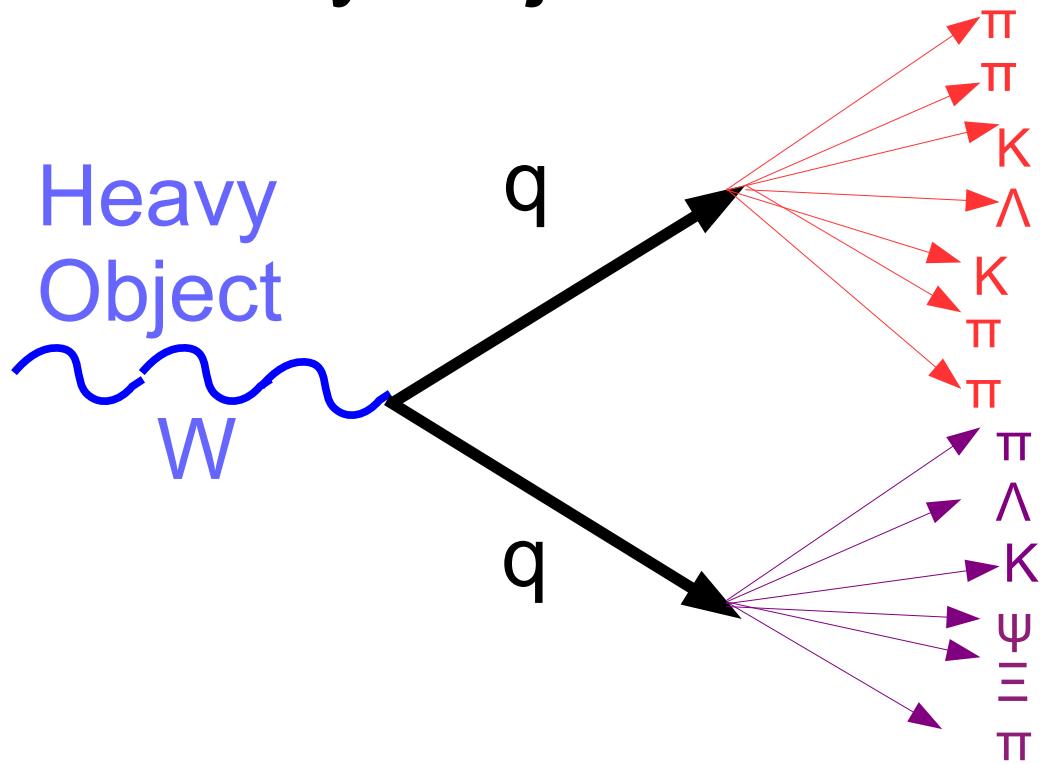
A Heavy Object that decays to quarks:



A simple example is a ϕ to Kaons
Kaons decay to 3 Pions

What is a hadronic resonance?

A Heavy Object that decays to quarks:



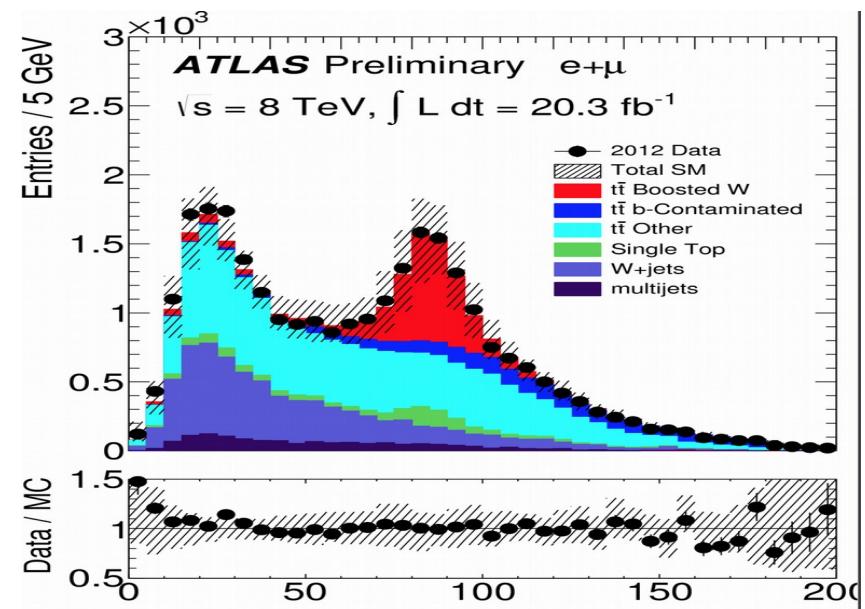
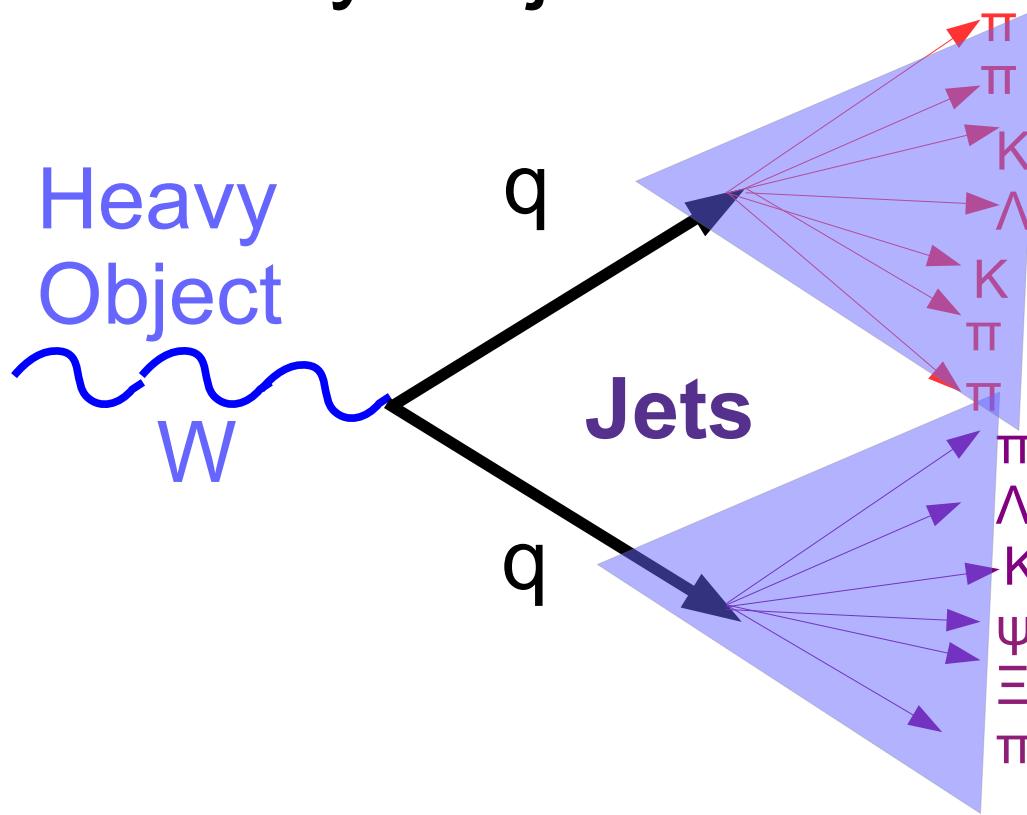
a complicated example is a W boson to quarks

High energy quarks decay to a shower of particles

What makes this hard?

What is a hadronic resonance?

A Heavy Object that decays to quarks:

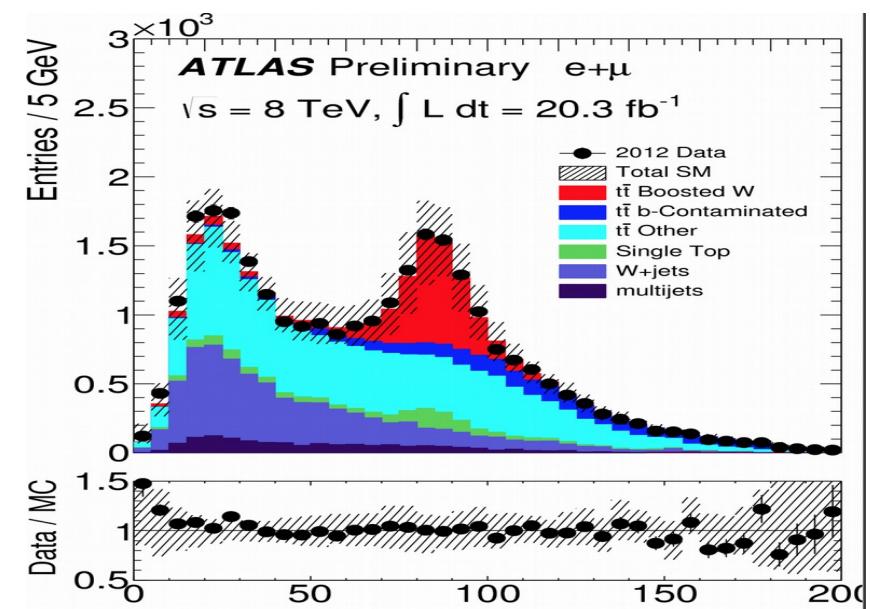
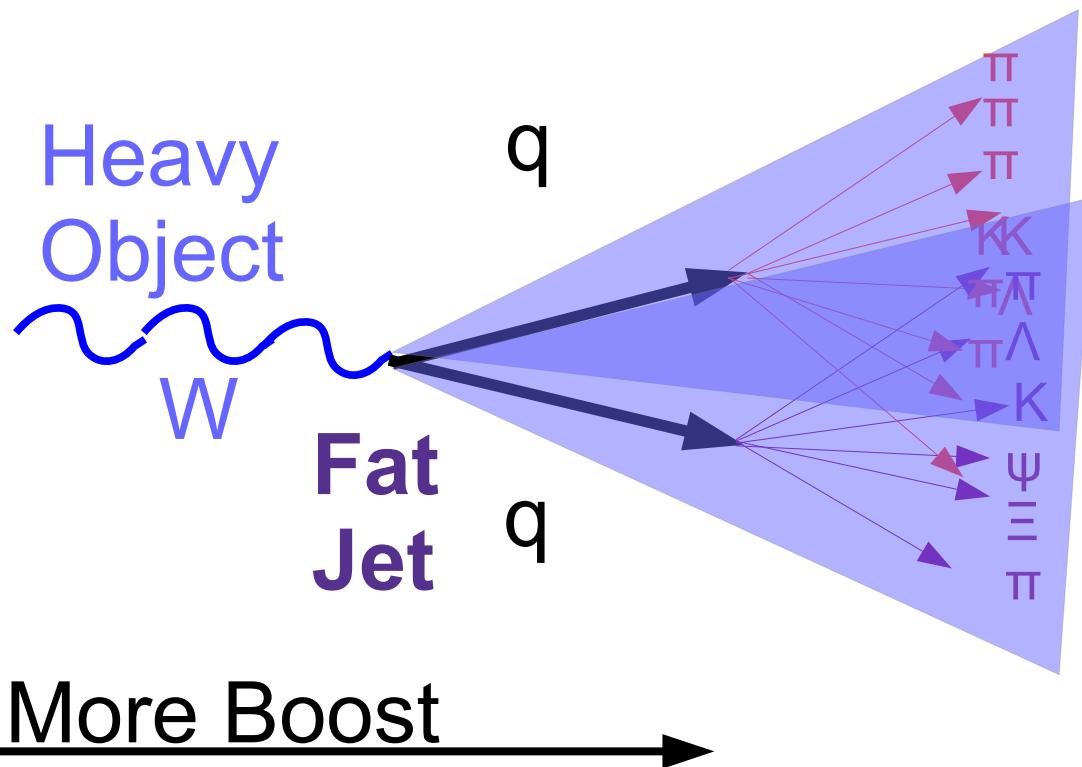


a complicated example is a W boson to quarks
 High energy quarks decay to a shower of particles

What makes this hard?

What is a hadronic resonance?

A Heavy Object that decays to quarks:

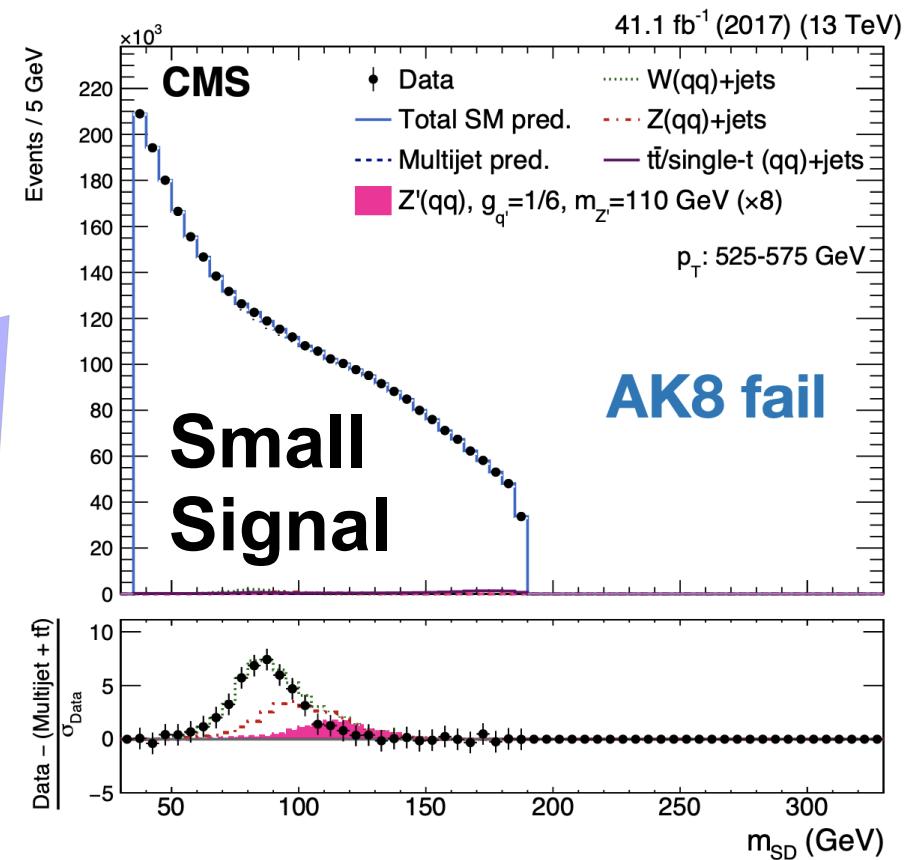
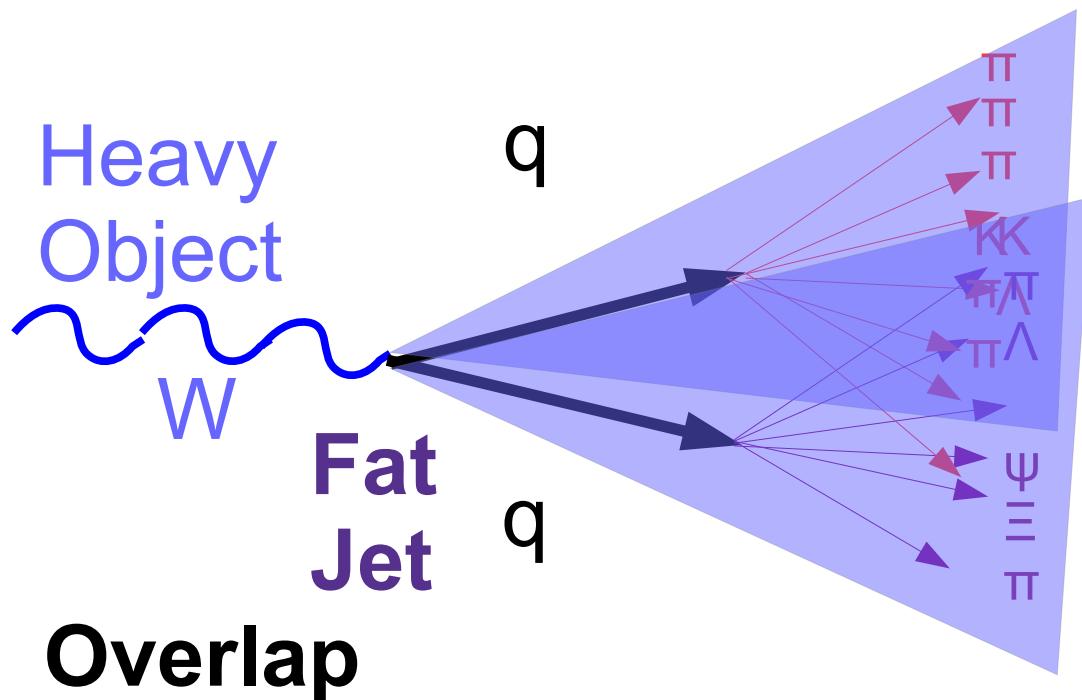


a complicated example is a W boson to quarks
High energy quarks decay to a shower of particles

What makes this hard?

What makes it Hard?

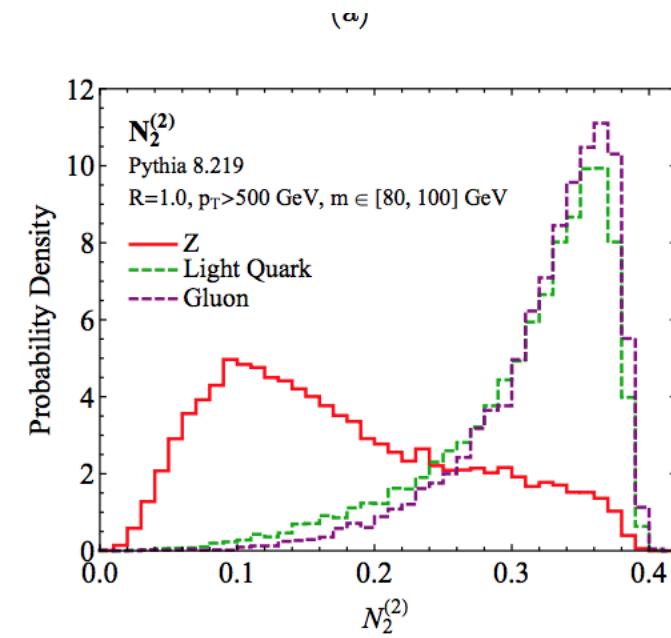
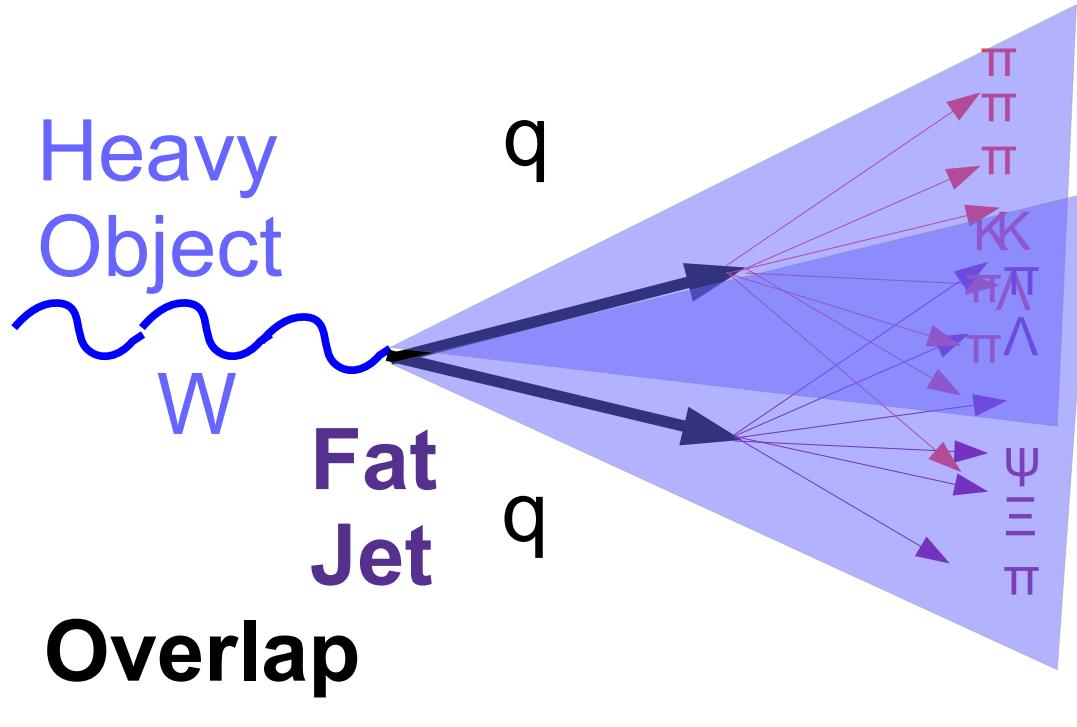
Two main things:



Trying to select Heavy Ws to quarks is hard
Need a way to remove the background

What makes it Hard?

Two main things:

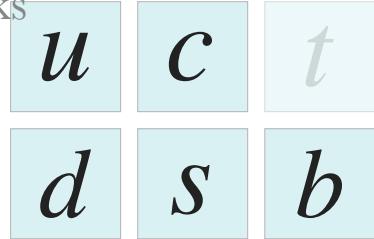


$$\begin{aligned}
 e_3^{(\beta=2)} &= \sum_{i < j < k \in \text{jet}} z_i z_j z_k \theta_{ij}^2 \theta_{ik}^2 \theta_{jk}^2 \approx \sum_{i < j} z_i z_j \theta_{ij}^2 \theta_i^2 \theta_j^2 \\
 &\approx \sum_{i < j} z_i z_j \max(\theta_i^2, \theta_j^2) \theta_i^2 \theta_j^2 \approx \sum_{i < j} \rho_i \rho_j \max(\theta_i^2, \theta_j^2),
 \end{aligned}$$

To resolve the overlap we resort to aggregate combinations of particles

What you know now: Jets of the Standard Model

Quarks



The Higgs boson

Leptons



W boson

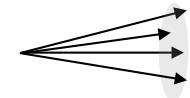


Z boson



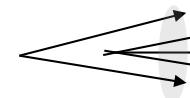
Force carriers

quark jet
 u, d, s



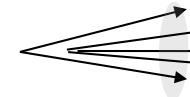
100 MeV
+ gluon radiation

b-jet



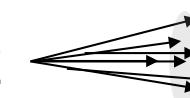
4.2 GeV
+ gluon radiation

c-jet



1.3 GeV
+ gluon radiation

gluon-jet



0 GeV
+ gluon radiation

pileup jet

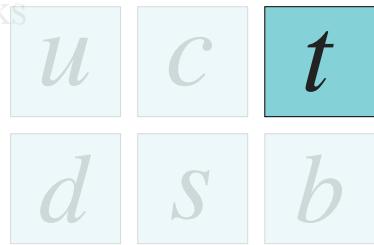


1 GeV

What you know now:

Jets of the Standard Model

Quarks



The Higgs boson



W boson

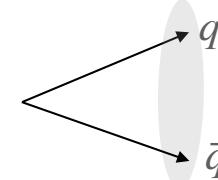


Z boson



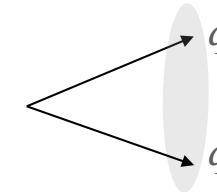
Force carriers

W-jet
~70%



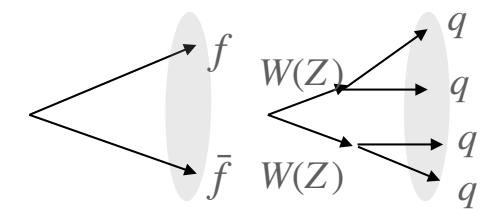
80.4 GeV

Z-jet
~70%



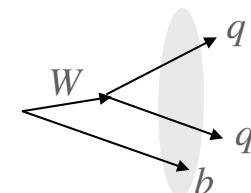
90 GeV

Higgs jet
~60%



125 GeV

Top jet
~70%

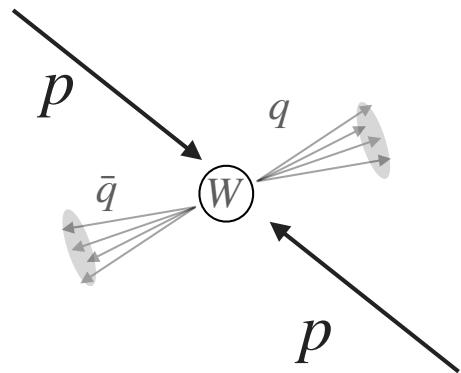


173 GeV

High boost

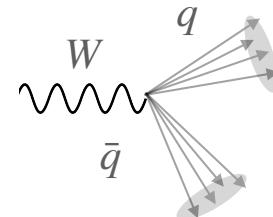
Let's consider a W-decay

$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



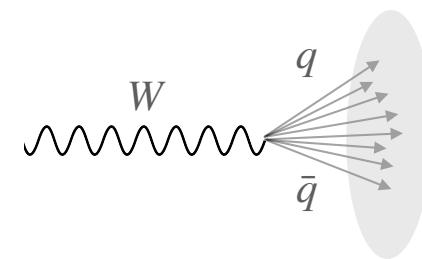
At \sim rest

$$\Delta R(q\bar{q}) \approx \pi$$



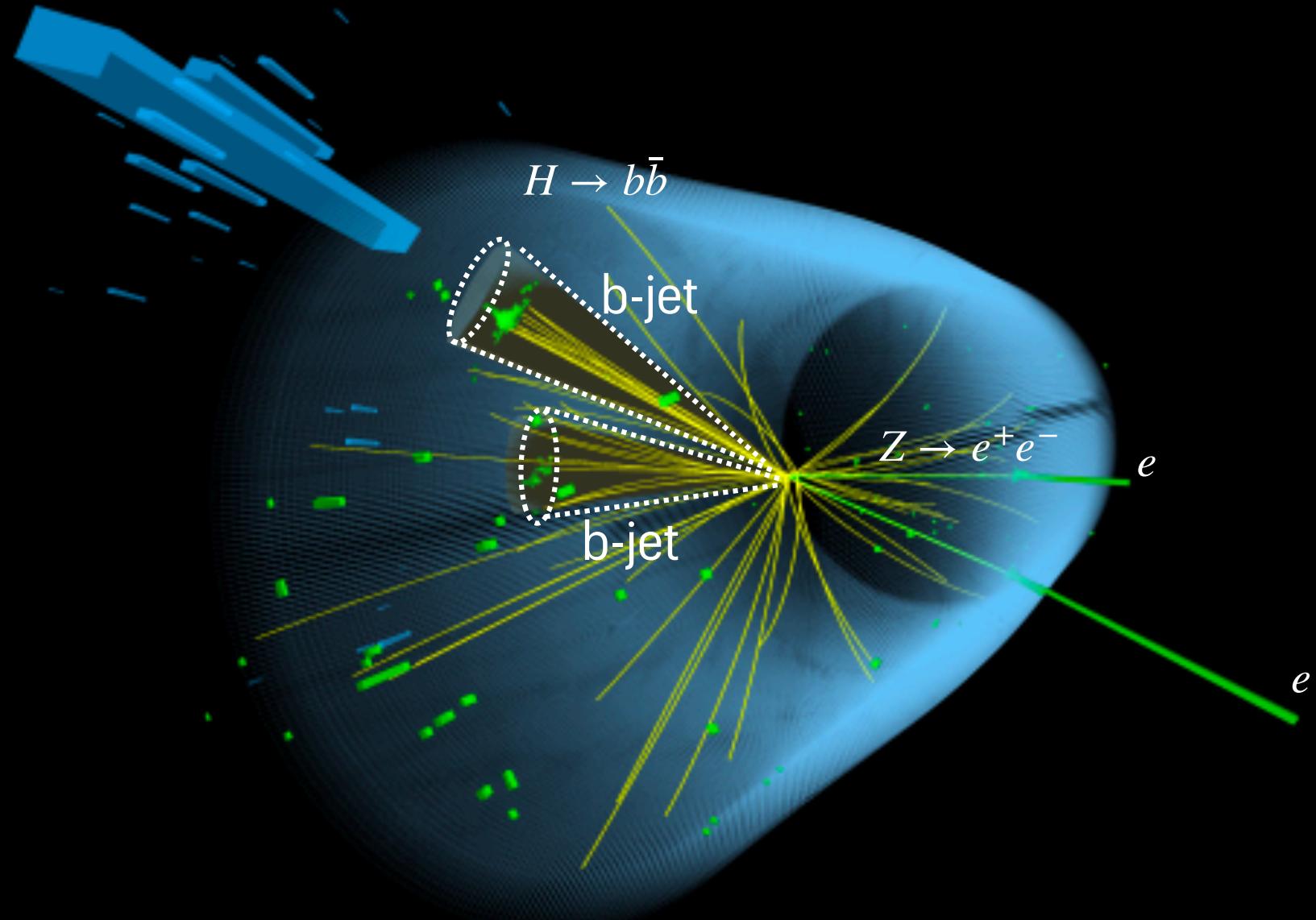
low W-momentum
($p_T \sim 100$ GeV)

$$\Delta R(q\bar{q}) \approx \pi/2$$



high **boost**
($p_T > 200$ GeV)

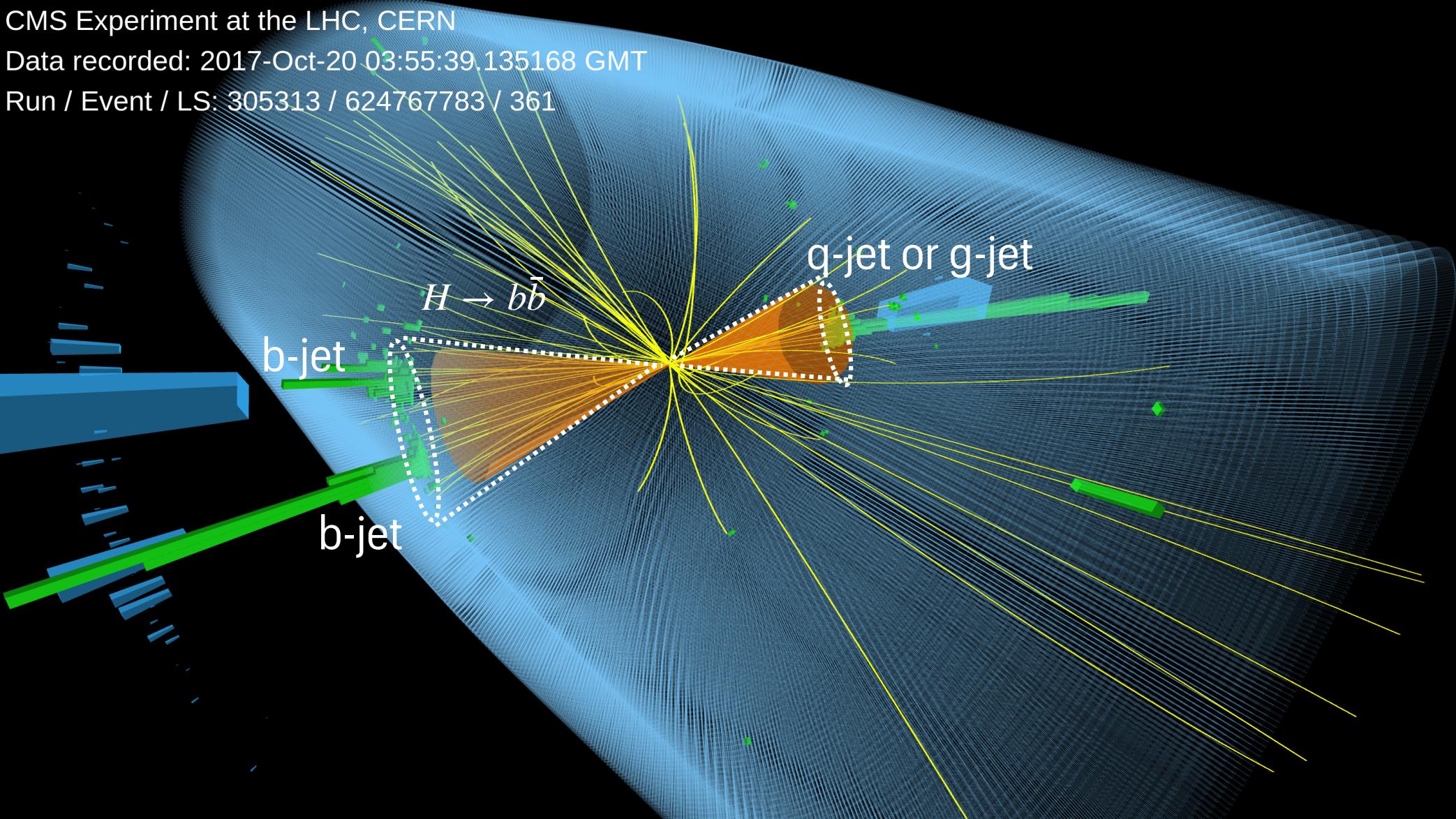
$$\Delta R(q\bar{q}) < 0.8$$



CMS Experiment at the LHC, CERN

Data recorded: 2017-Oct-20 03:55:39.135168 GMT

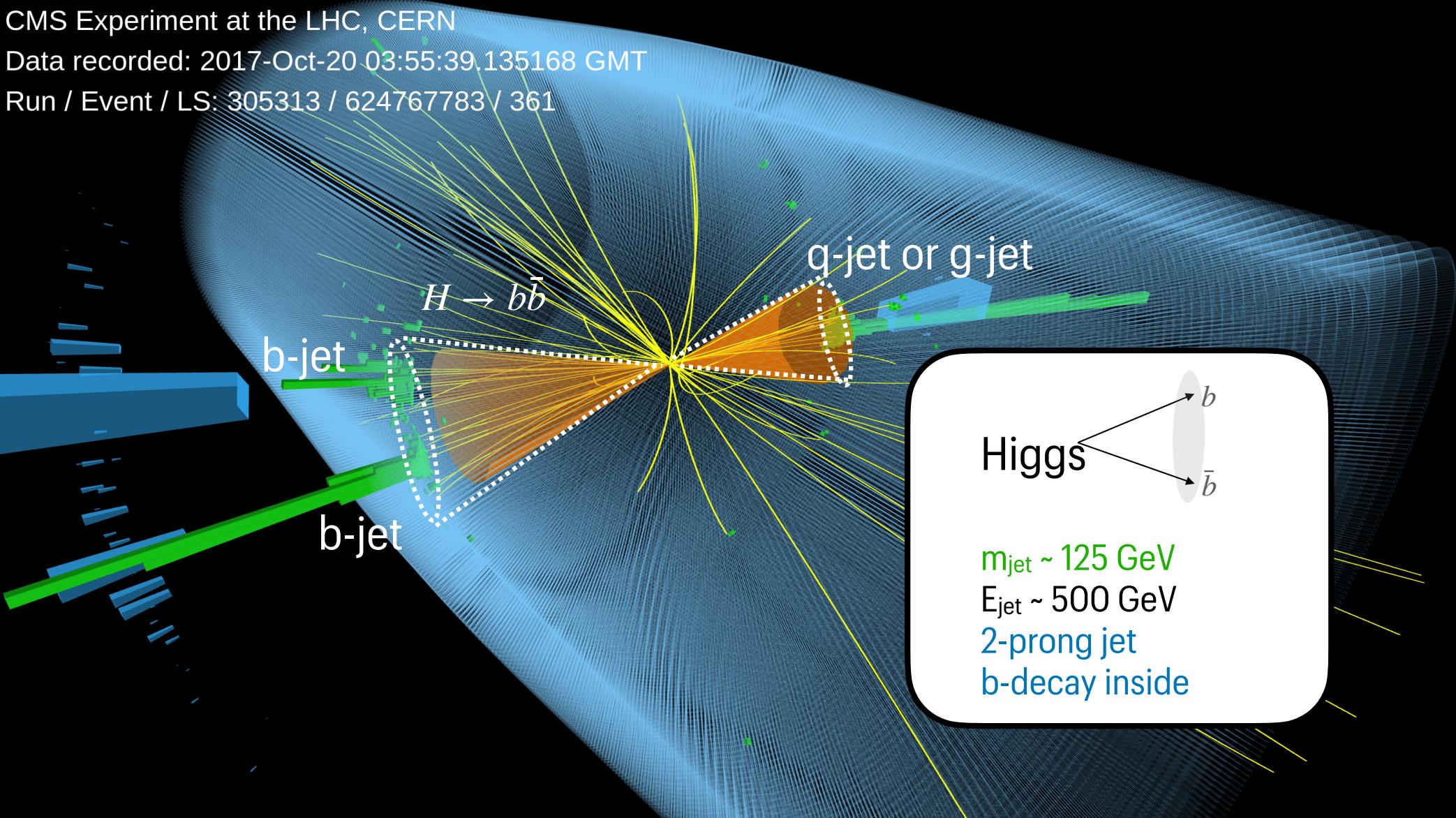
Run / Event / LS: 305313 / 624767783 / 361



CMS Experiment at the LHC, CERN

Data recorded: 2017-Oct-20 03:55:39.135168 GMT

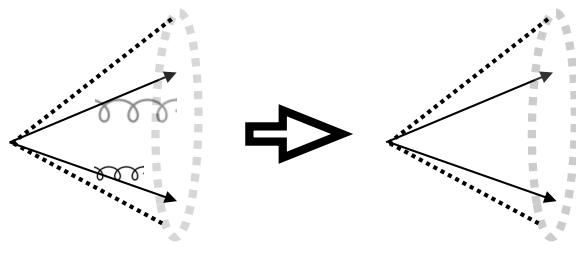
Run / Event / LS: 305313 / 624767783 / 361



Jet substructure

Resolving emissions within the jet

Jet grooming



Jet tagging



Higgs
 b
 \bar{b}

$m_{\text{jet}} \sim 125 \text{ GeV}$
 $E_{\text{jet}} \sim 500 \text{ GeV}$
2-prong jet
b-decay inside

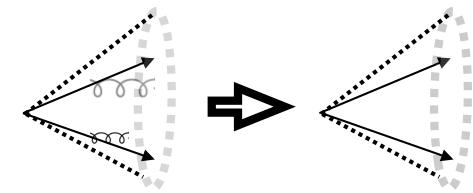
Jet grooming



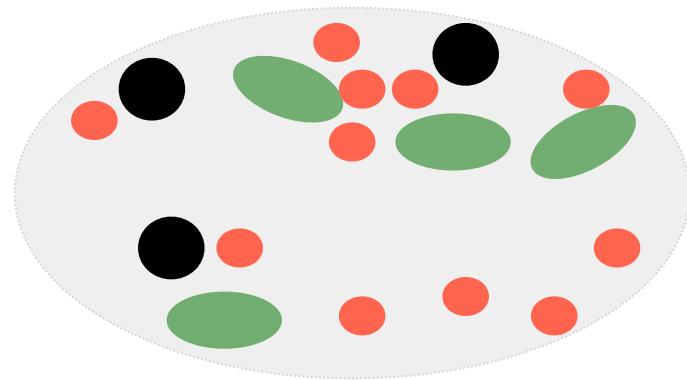
© dak

Removing a jet's soft and wide-angle radiation

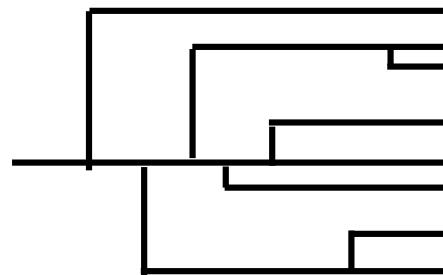
Grooming declustering



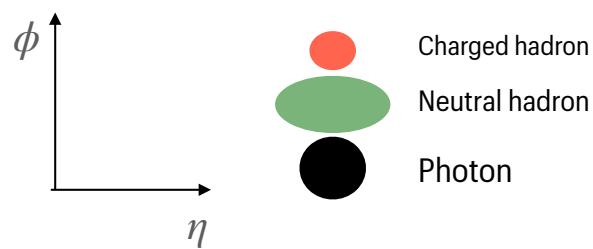
Original jet



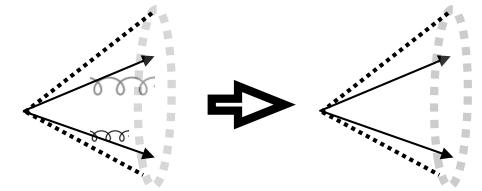
In a clustering tree



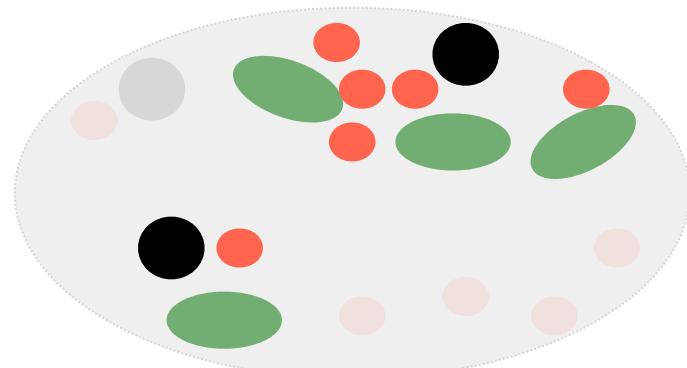
=



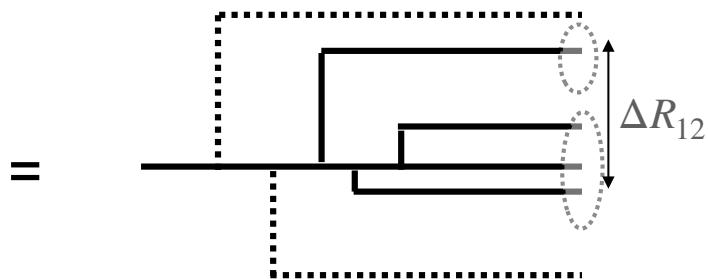
Grooming declustering



Groomed jet

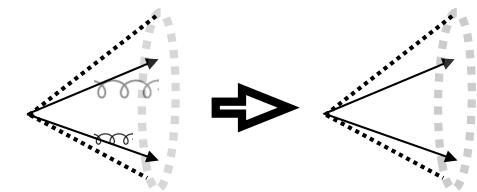


Groomed clustering tree

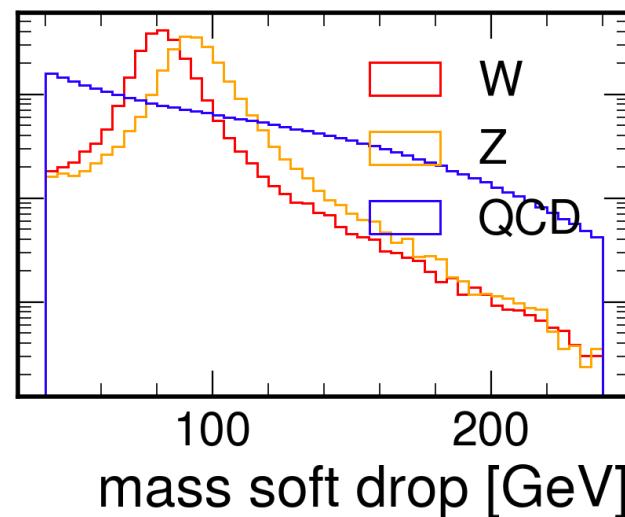
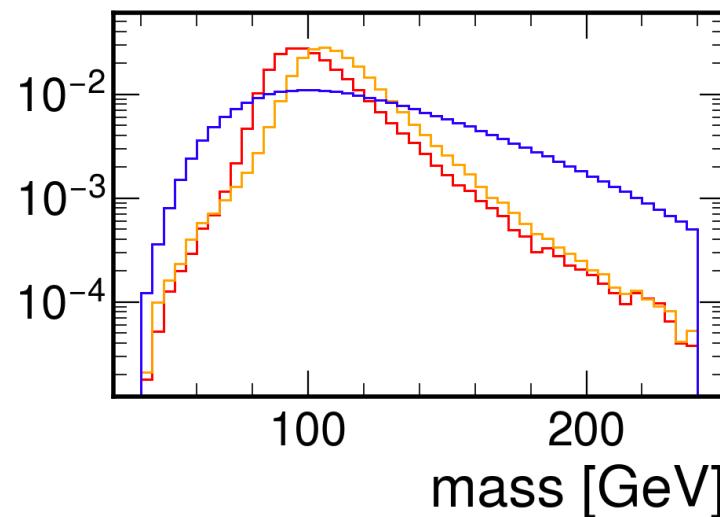


- Grooming algorithms iteratively decluster a jet
- The soft-drop algorithm removes lowest p_T sub-jets failing pairwise condition $z > z_{cut} \left(\frac{\Delta R_{12}}{R} \right)^\beta$ with $z = \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2}$

Calculating groomed mass

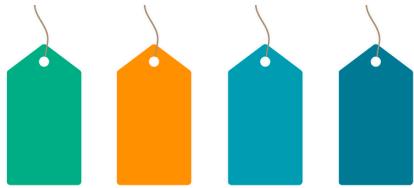


27



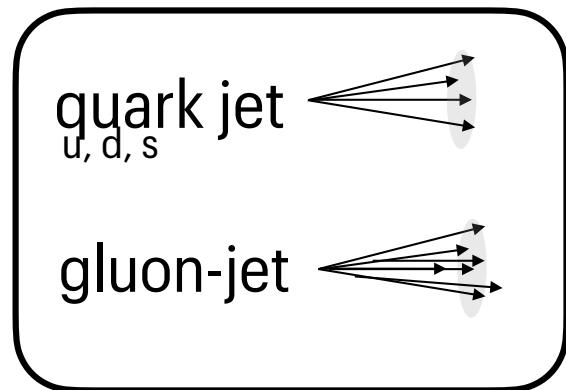
- Improves the mass *resolution* of a jet (removes away excess radiation)
- Brings the mass of background jets (QCD) to low mass

Jet tagging

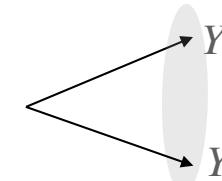


Characterizing a jet's internal decay

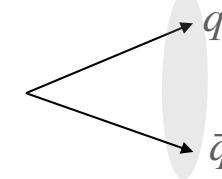
Signatures:



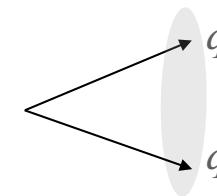
X-jet



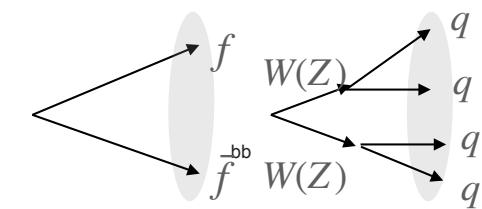
W-jet



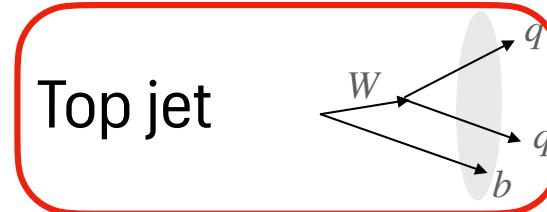
Z-jet



Higgs jet

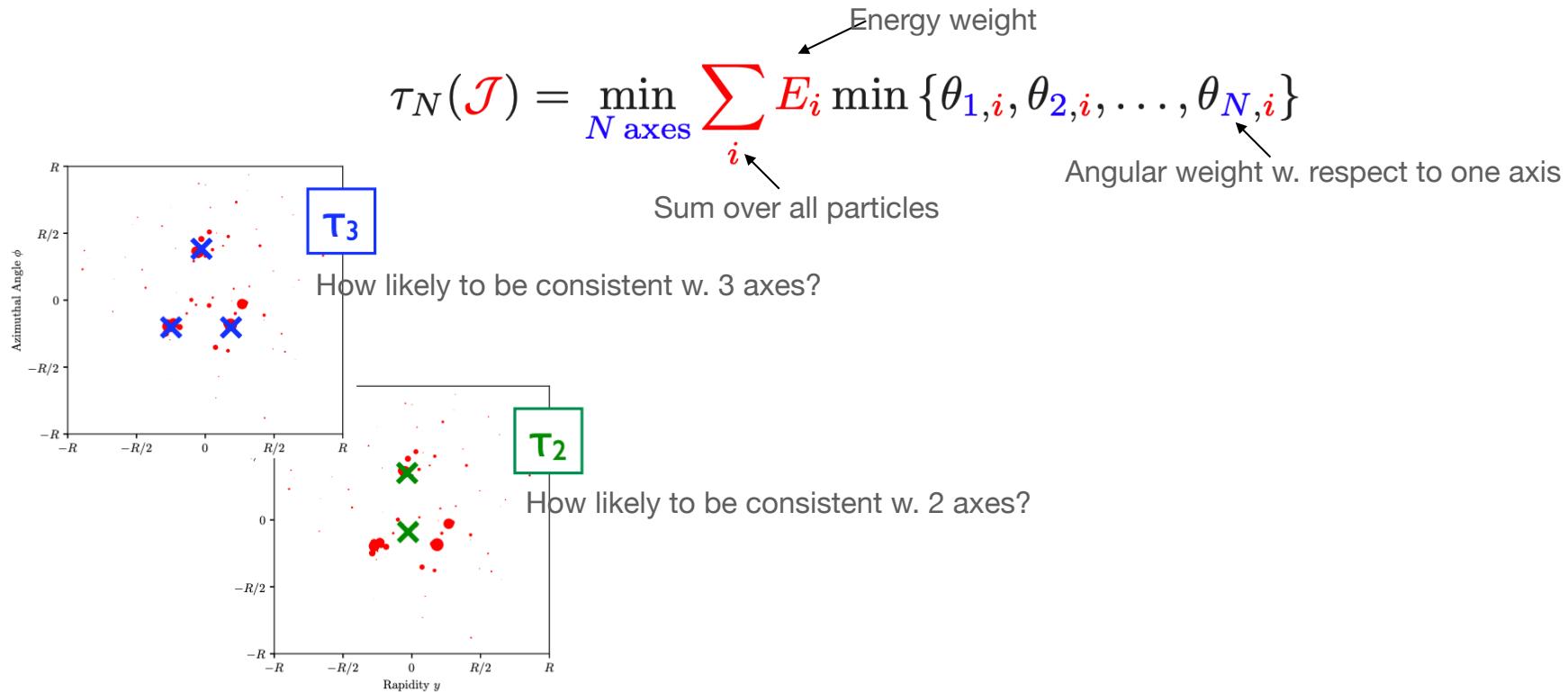


Top jet



N-subjettiness

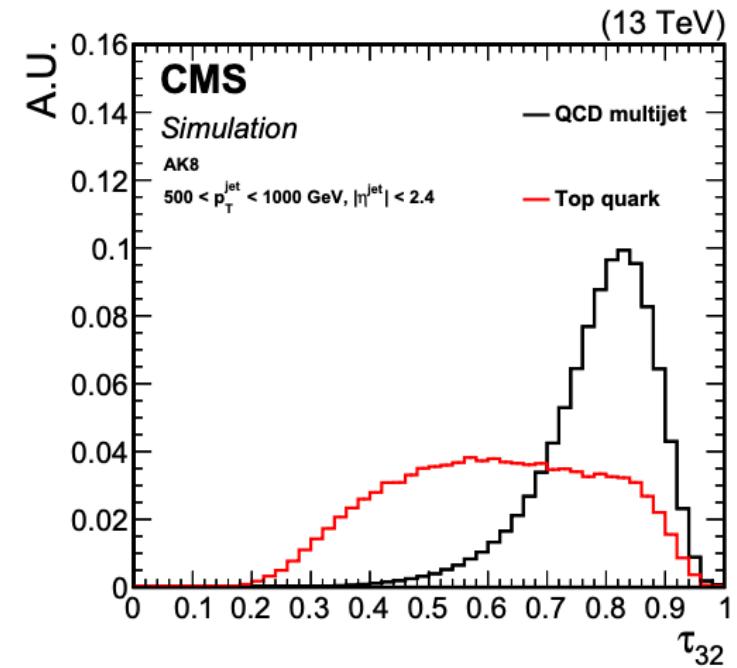
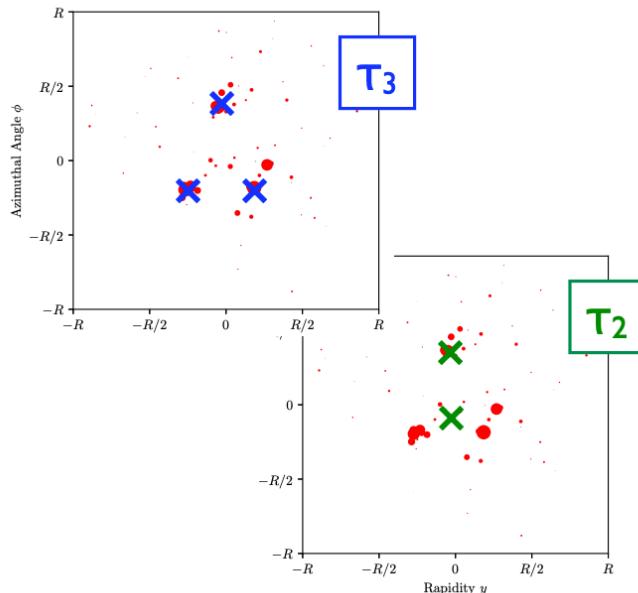
Counting the number of “prongs” for almost a decade



N-subjettiness

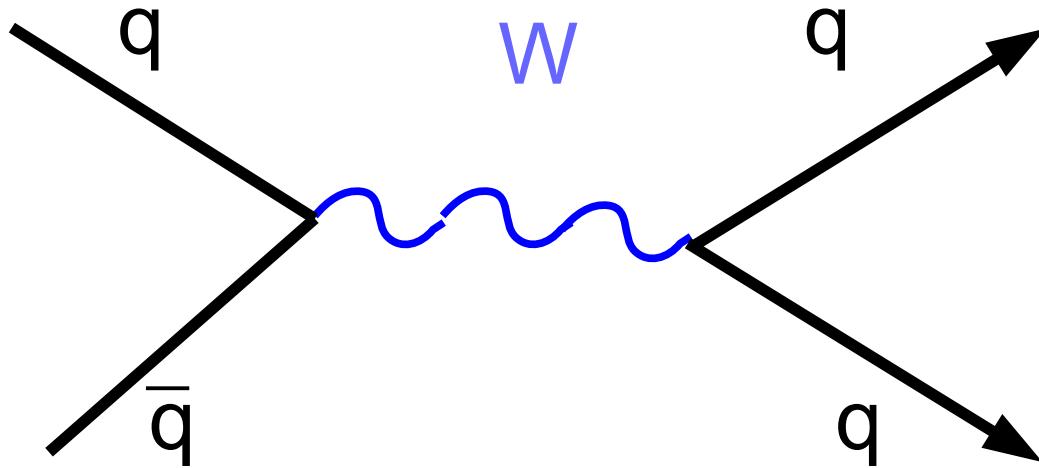
Counting the number of “prongs” for almost a decade

$$\tau_N(\mathcal{J}) = \min_{N \text{ axes}} \sum_i E_i \min \{\theta_{1,i}, \theta_{2,i}, \dots, \theta_{N,i}\}$$



Lets go back and try again?

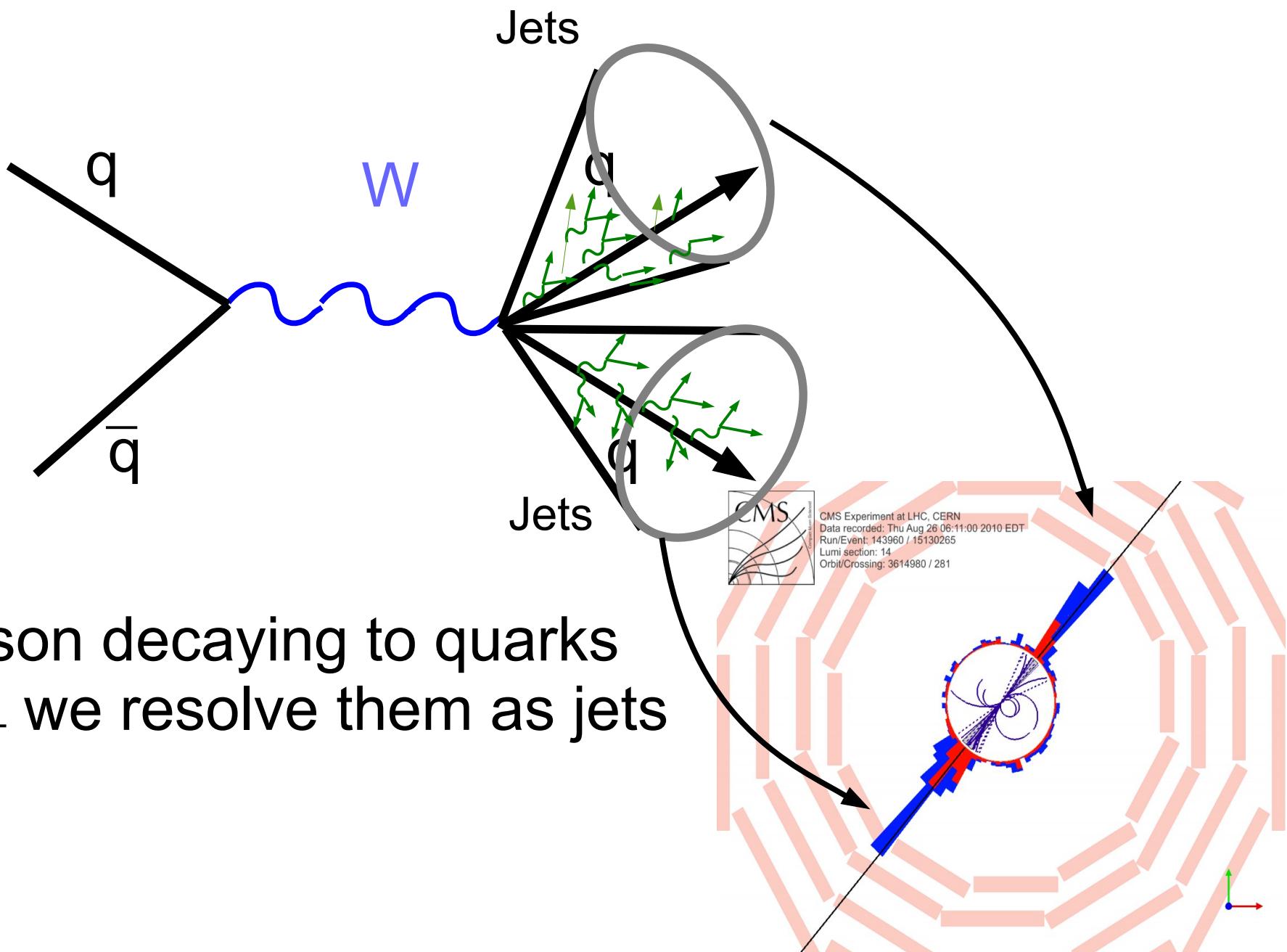
To see if its useful lets target a core process:



A W boson decaying to quarks

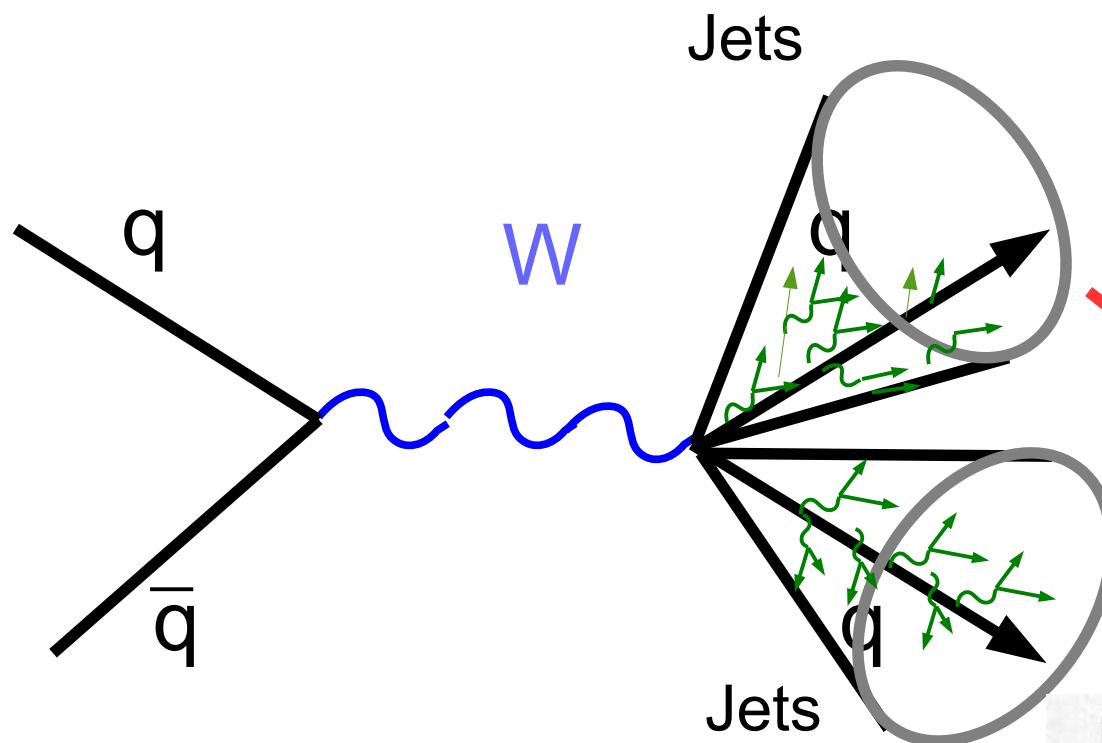
In an experiment

Find:



In an experiment

Find:



Resolved as a tiny
bump on a huge
background

A W boson decaying to quarks
A low p_T we resolve them as jets

Was last observed 30 years
Result was not very convincing
Have not seen this since

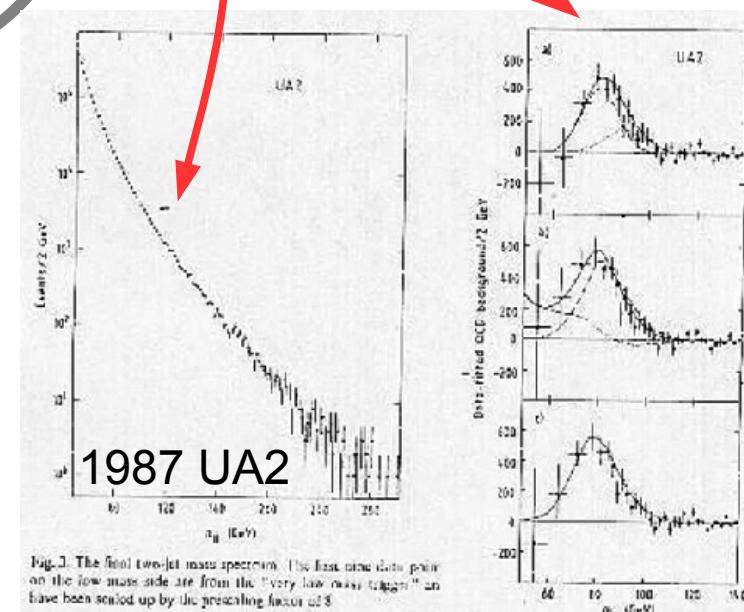
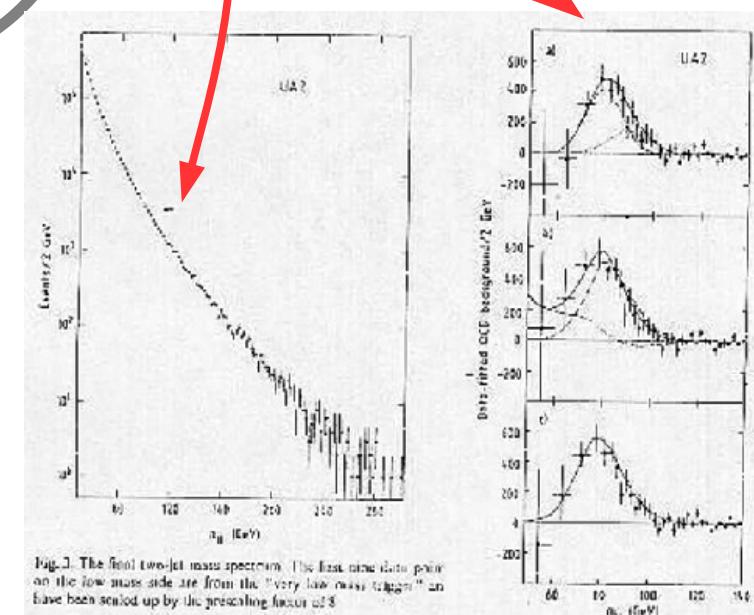
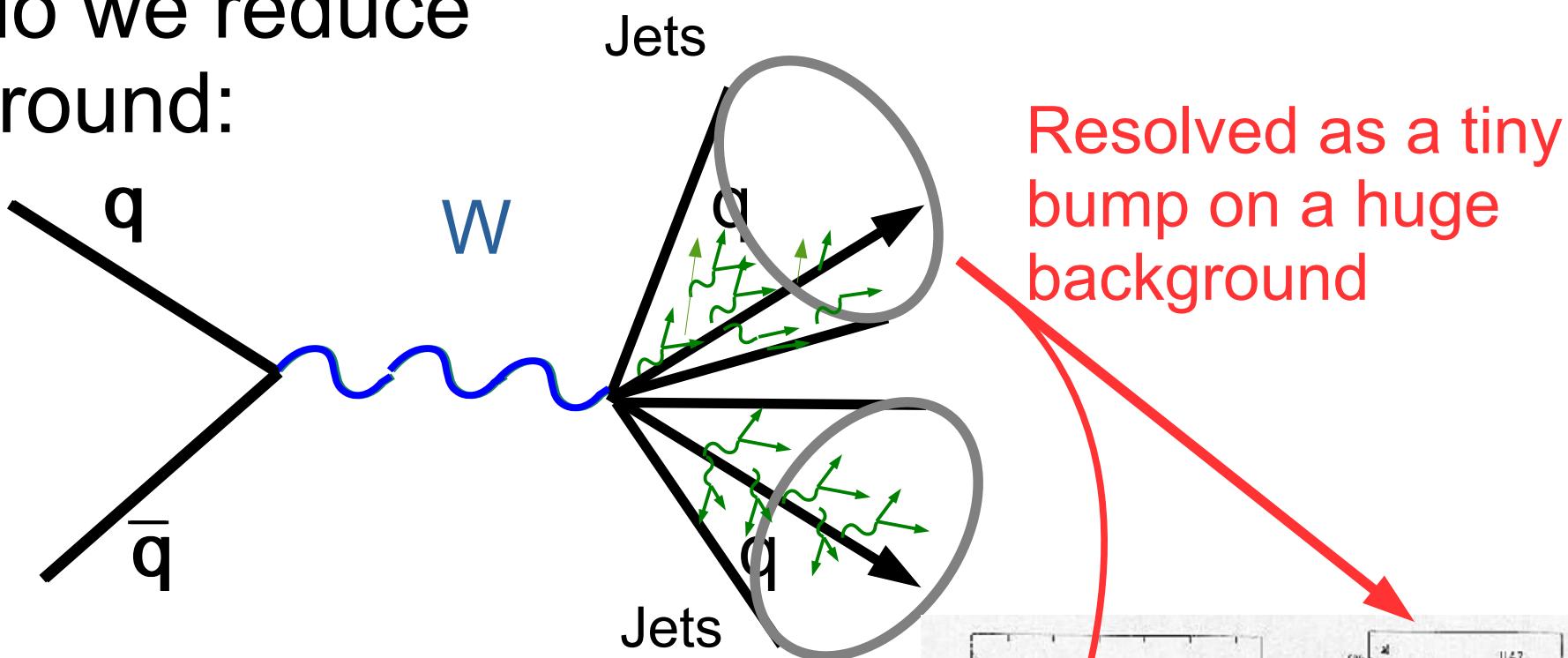


Fig. 3. The final two-jet mass spectrum. The last nine data point on the low-mass side are from the "very low mass trigger" and have been scaled up by the pre-scaling factor of 3.

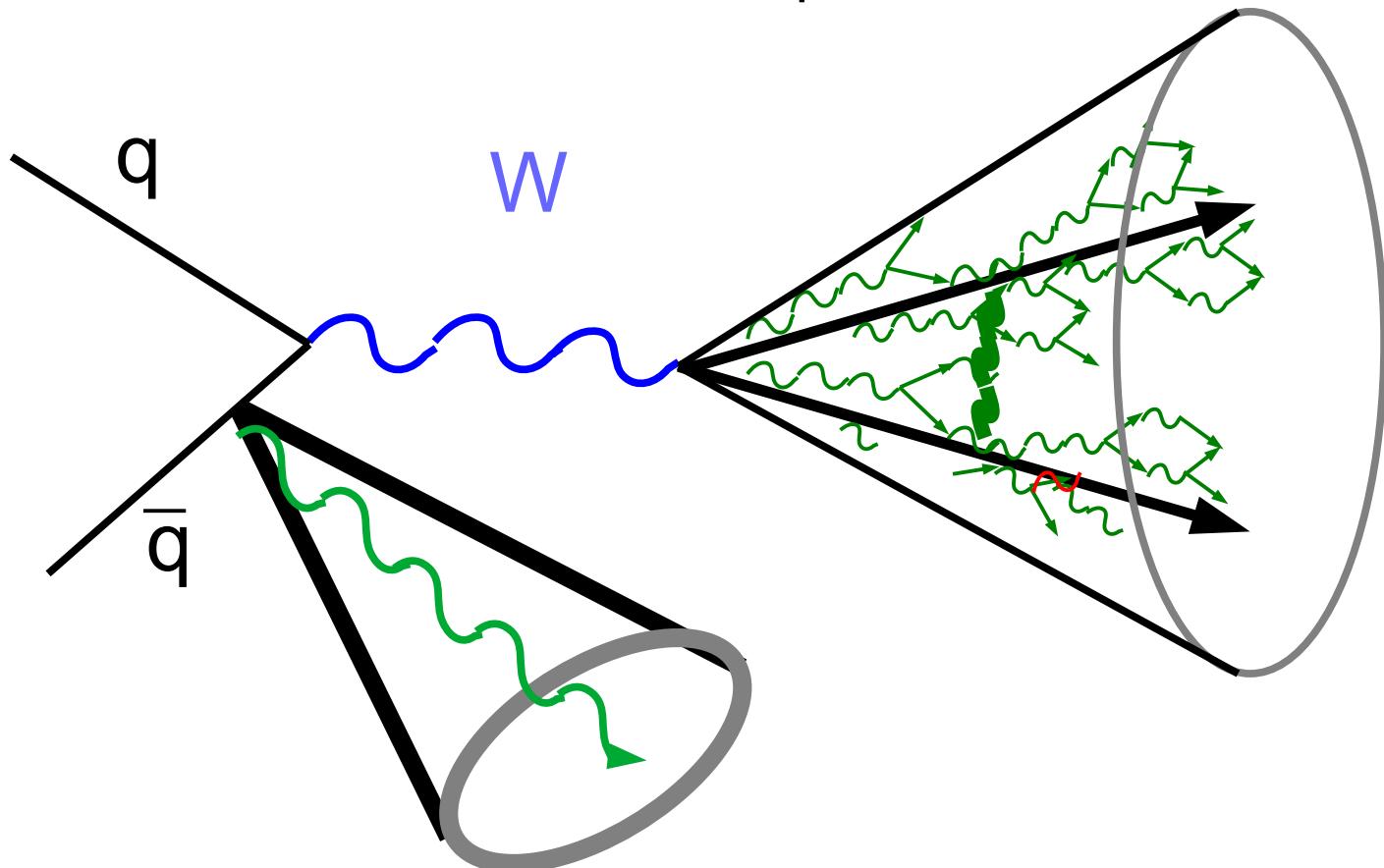
1988

How do we reduce background:



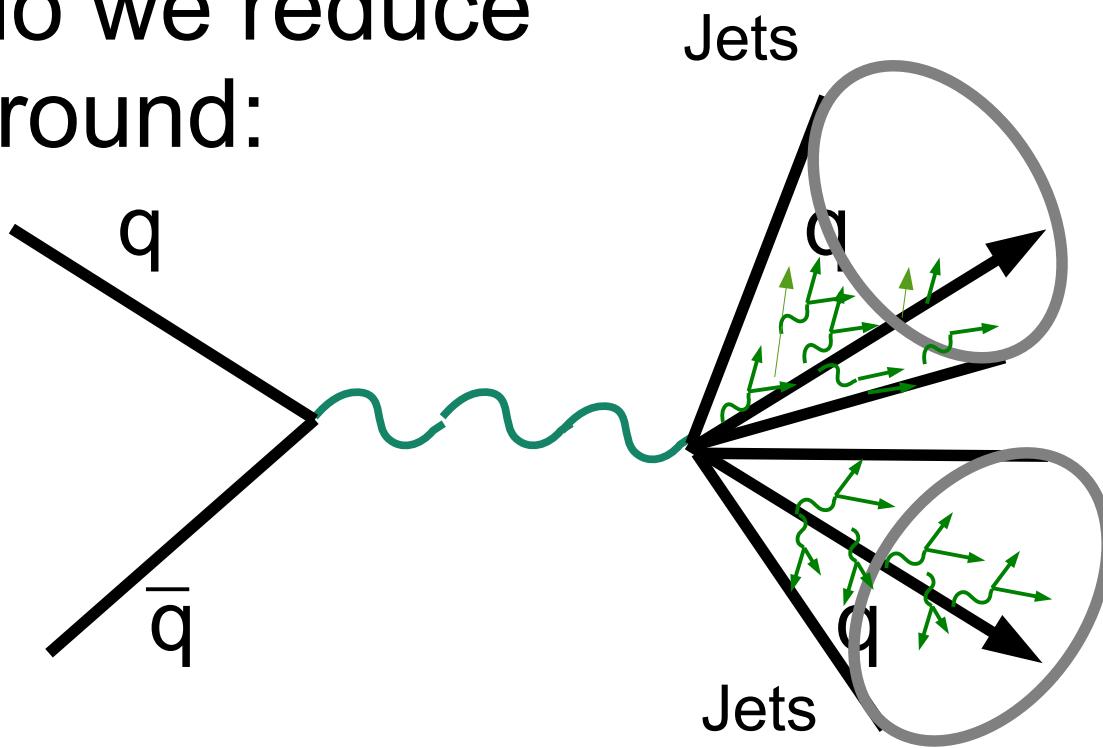
Whats the first goal?

Require W to be a high p_T



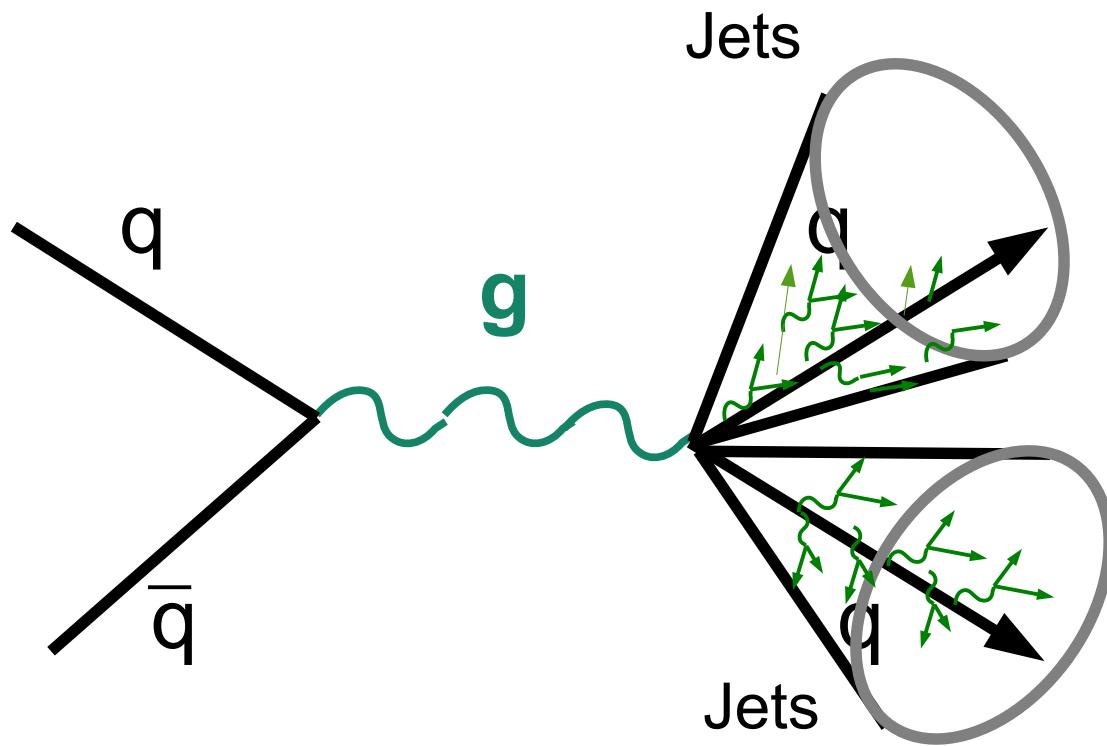
Isolating the W

How do we reduce background:



The core issue is that the background is too large
Quark and gluon interactions are large!

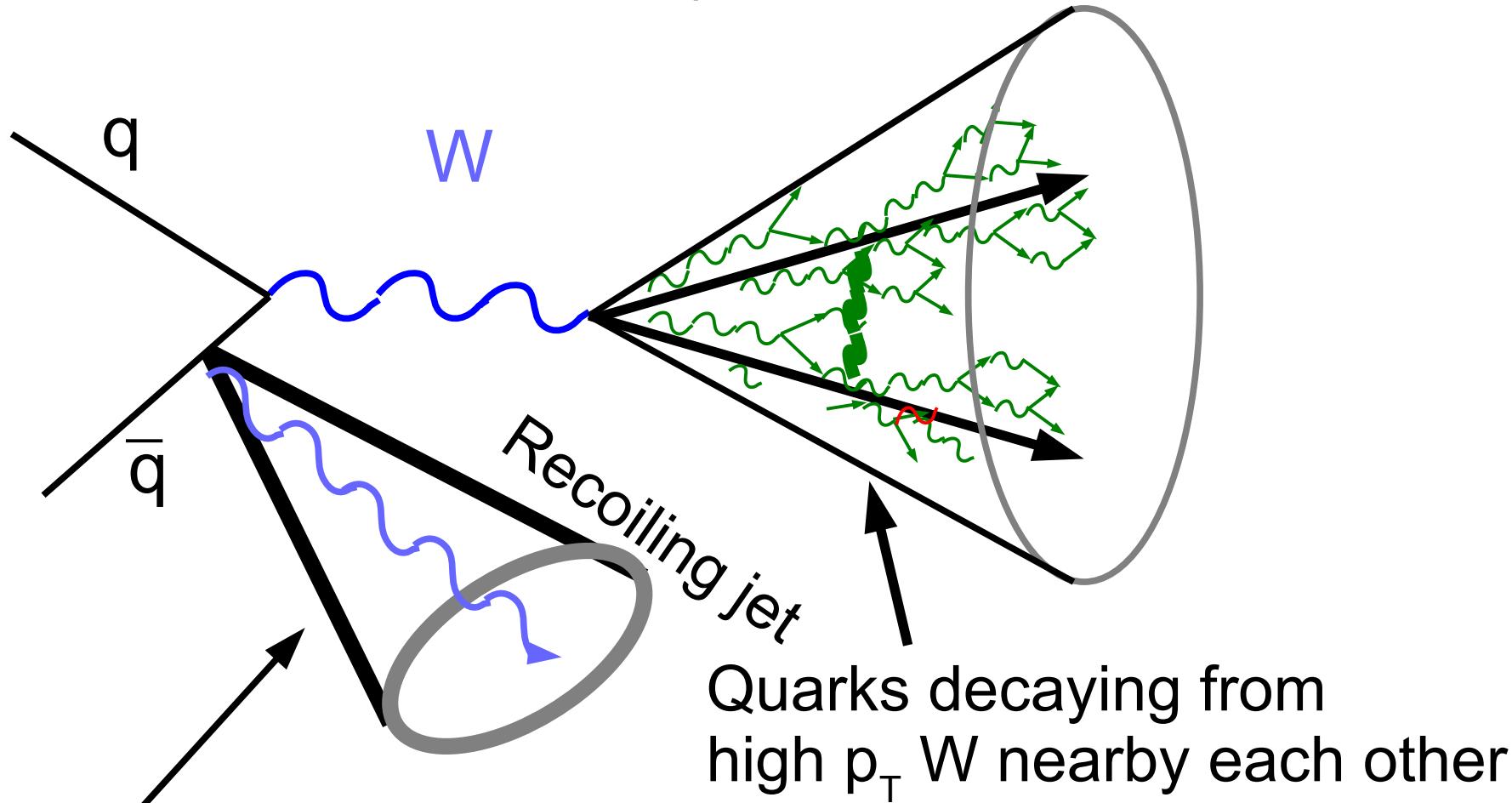
Isolating the W



The core issue is that the background is too large

Whats the first goal?

Require W to be a high p_T

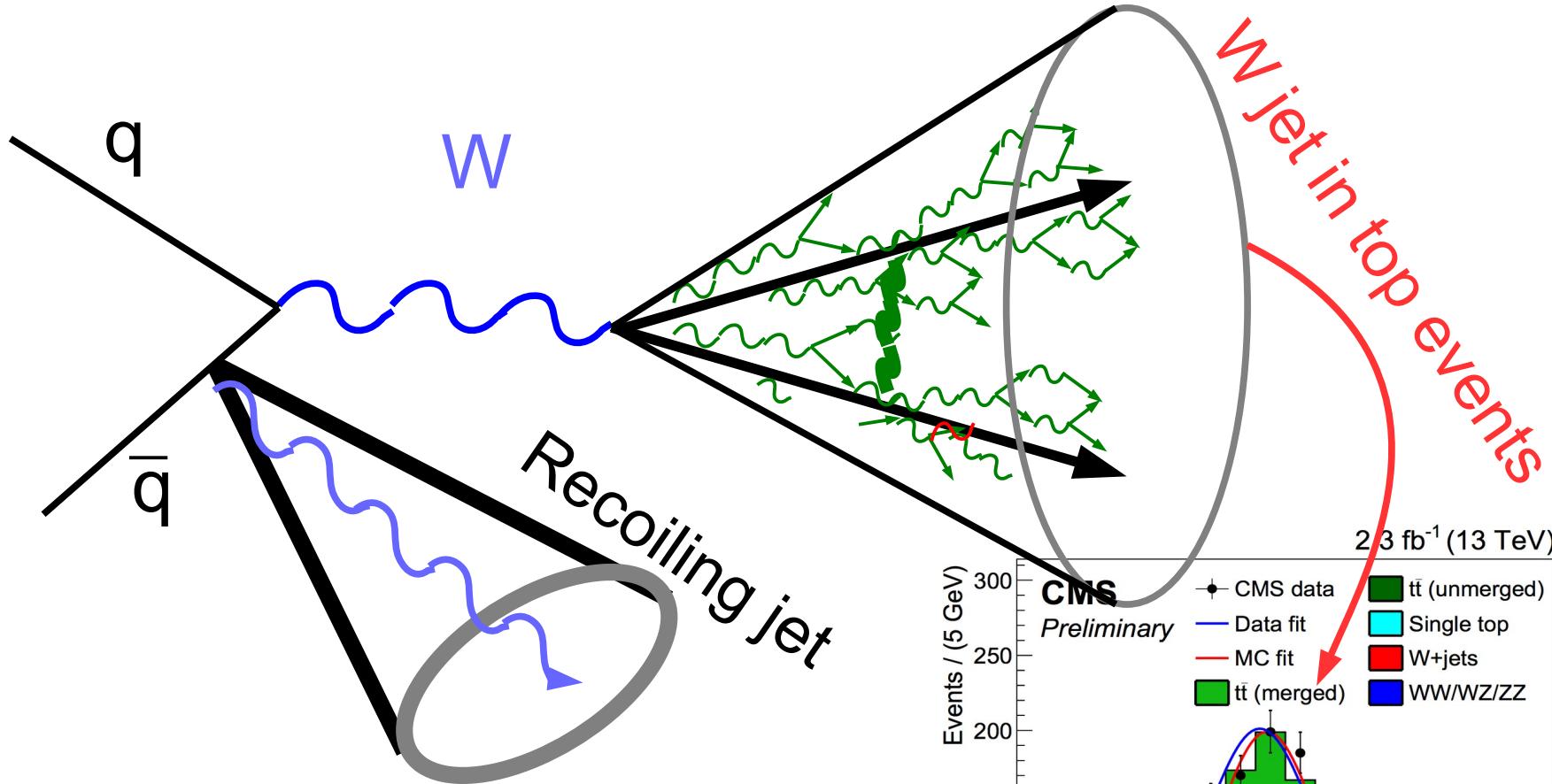


Recoiling jet off W gives the
 W high p_T

Quarks decaying from
high p_T W nearby each other
Resolve this as a single jet

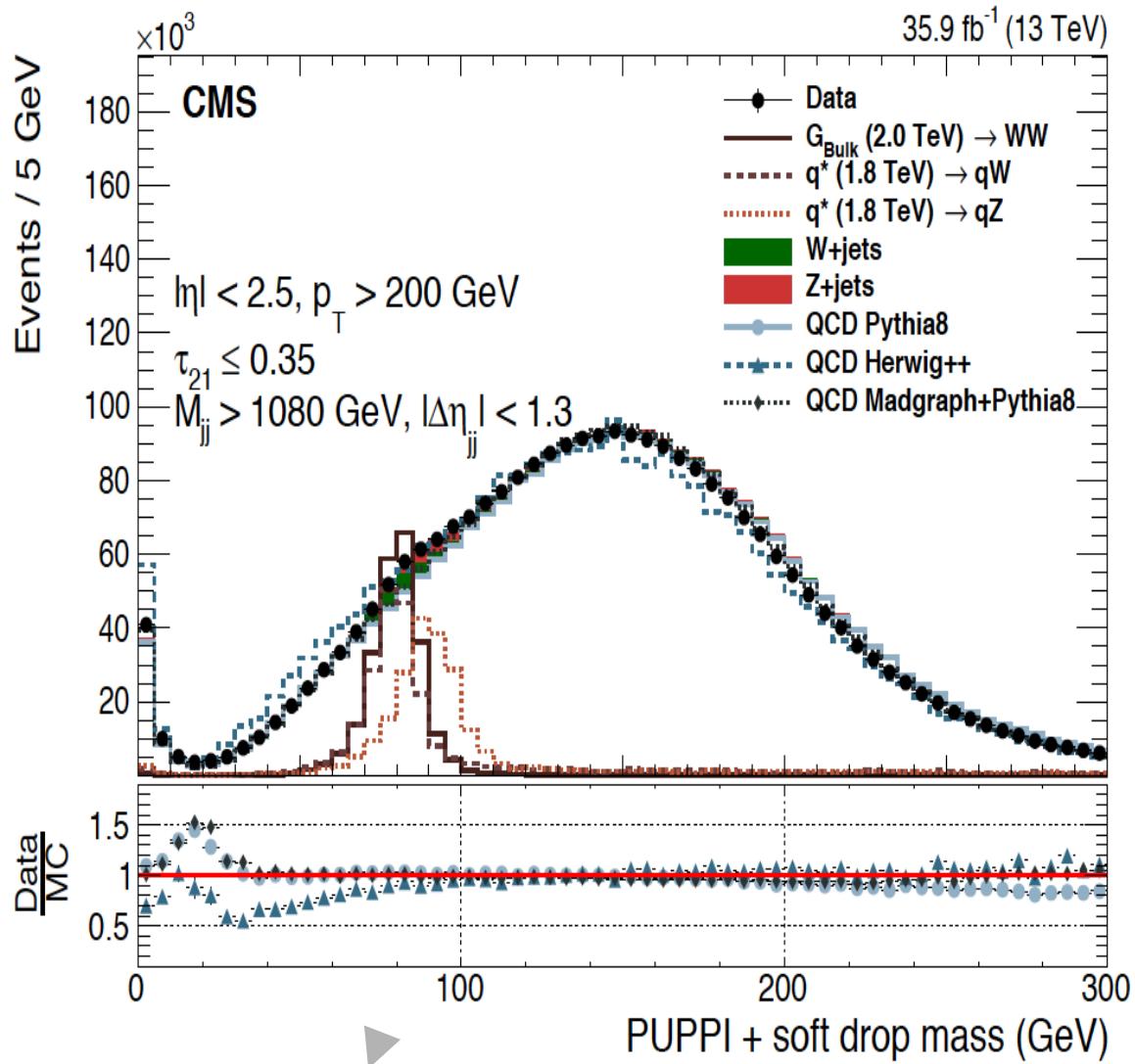
Whats the first goal?

Require W to be a high p_T



Have not observed a single W jet boson event from SM produce
(Have only seen W jets in top events)

Performing a basic selection



Tools developed with the first rounds of jet substructure did not lead to a significant signature

Hard to convince anybody that bump is at 80
With another big bump at a higher mass

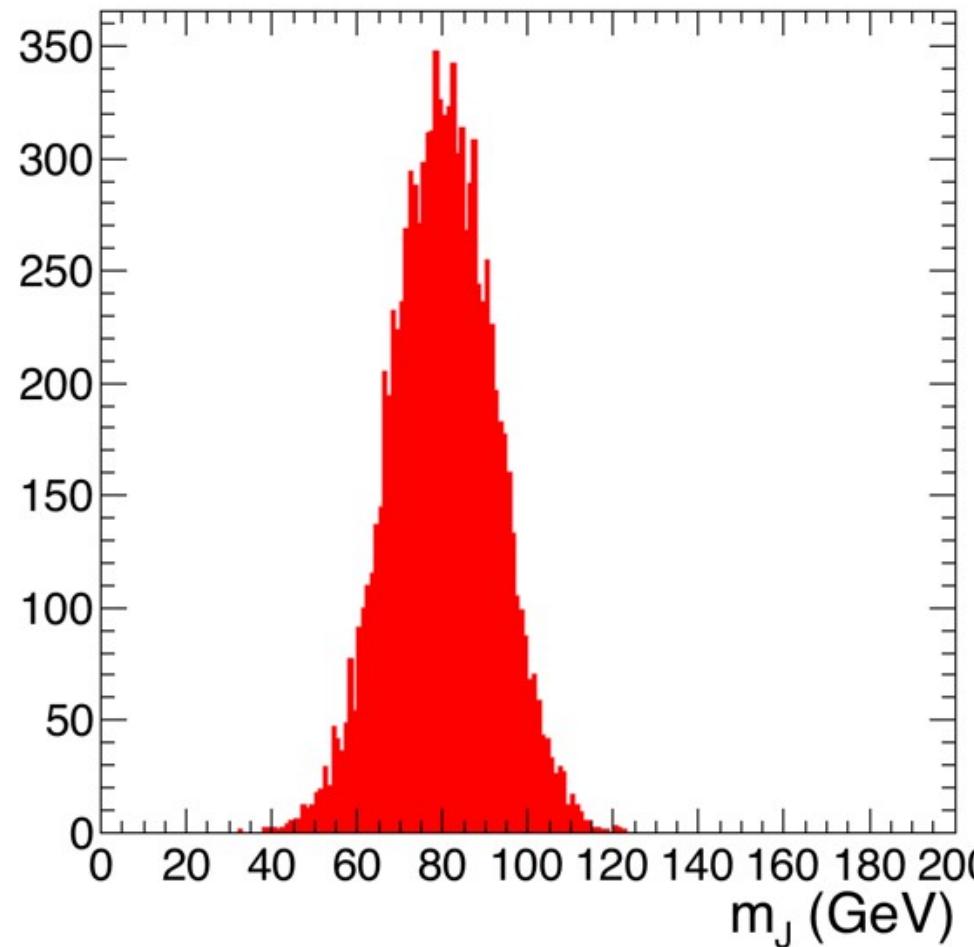
Part 2

Decoding Data

A Game

Lets play a game

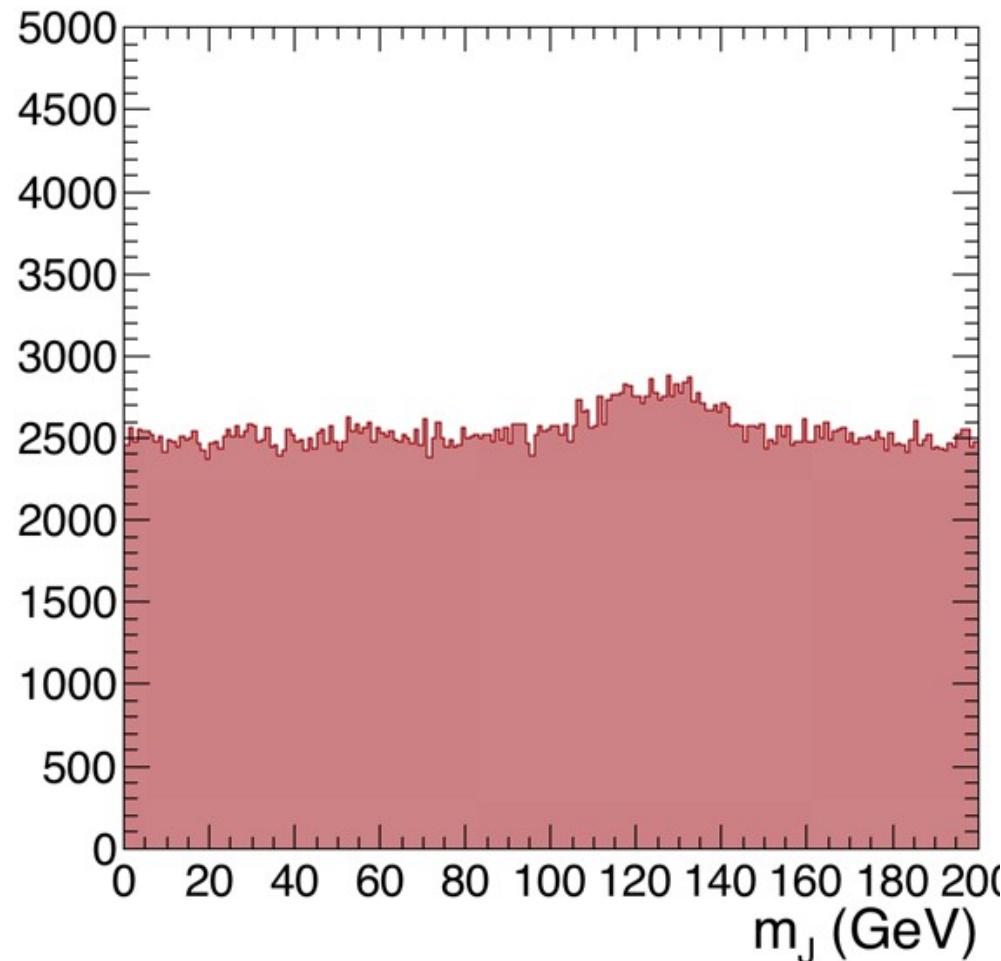
- Lets try to inject a signal like this



Into a background 50 times larger than this
This signal looks very much like a W peak

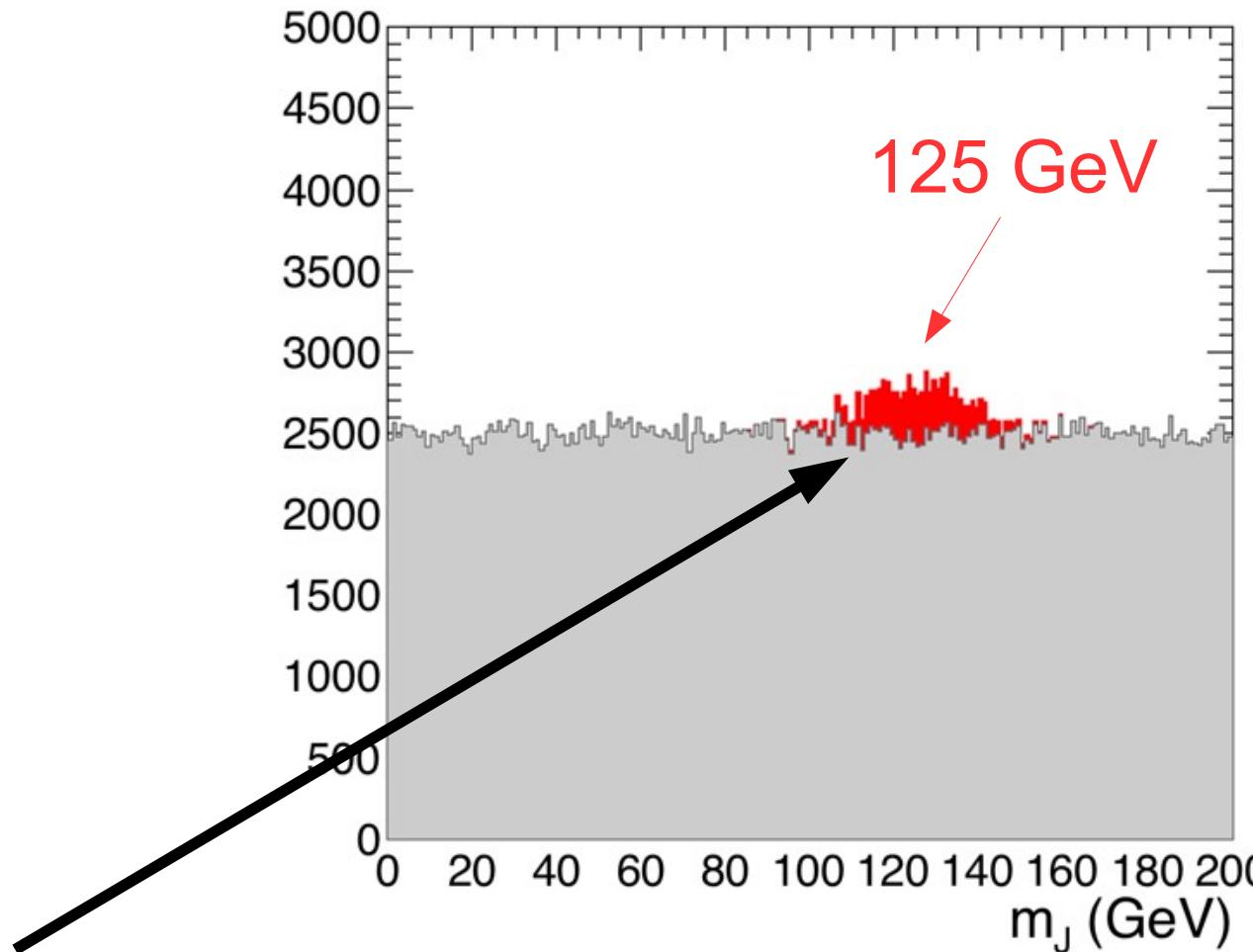
Find the signal

- Can you see the signal?



Find the signal

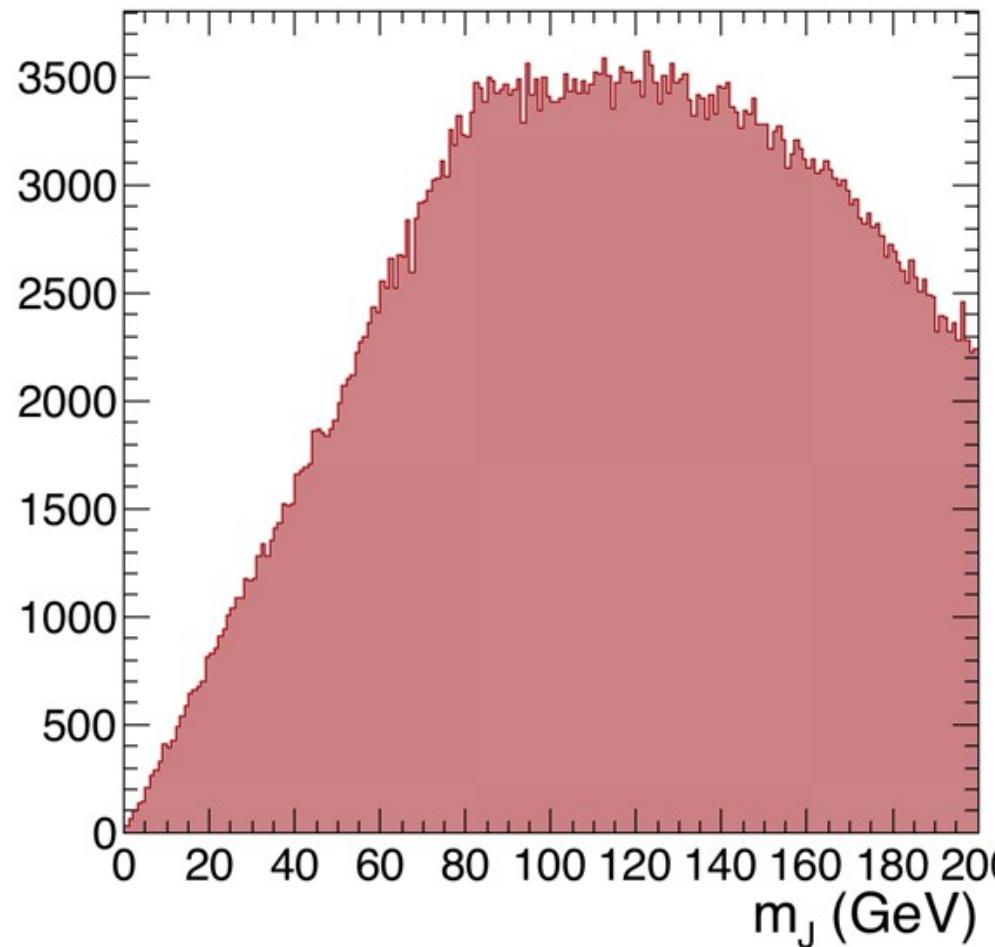
- Can you see the signal?



Here is the signal at 125 GeV on a flat background
That was an easy one!

Find the signal

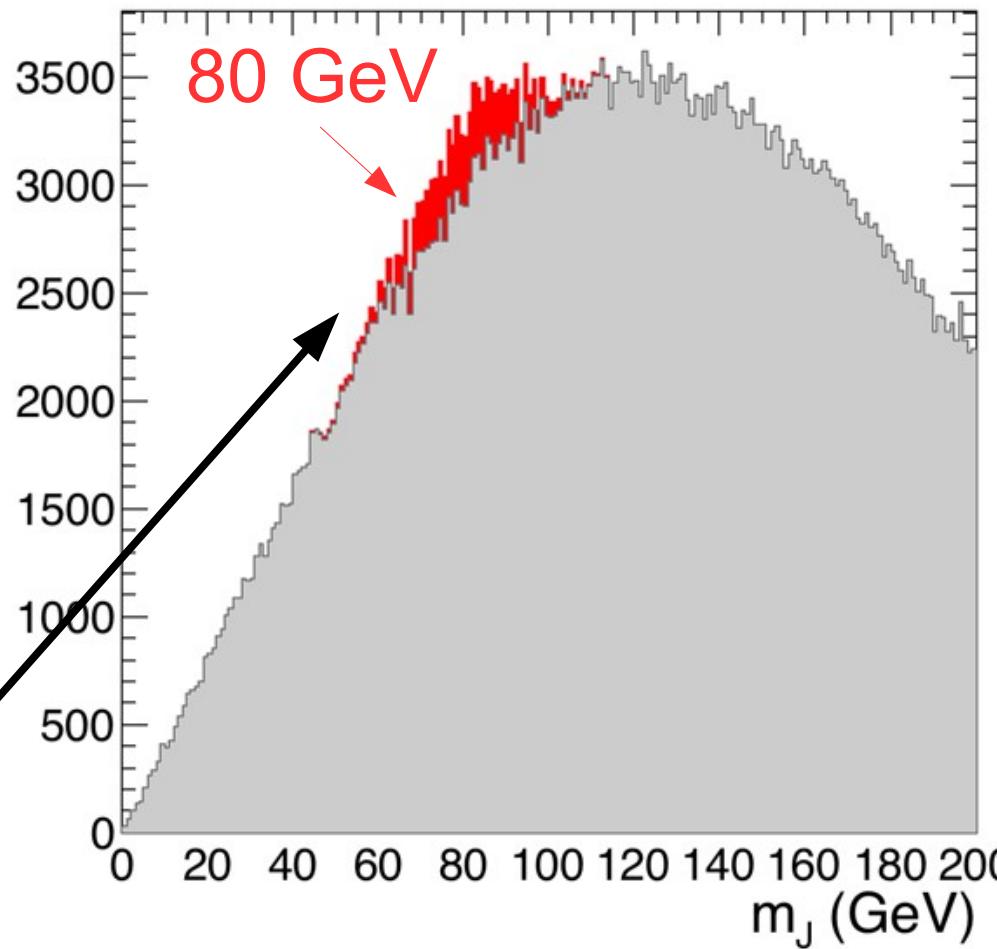
- Can you see the signal?



Here is the signal at 125 GeV on a flat background
Now the background peaks just after the signal

Find the signal

- Can you see the signal?

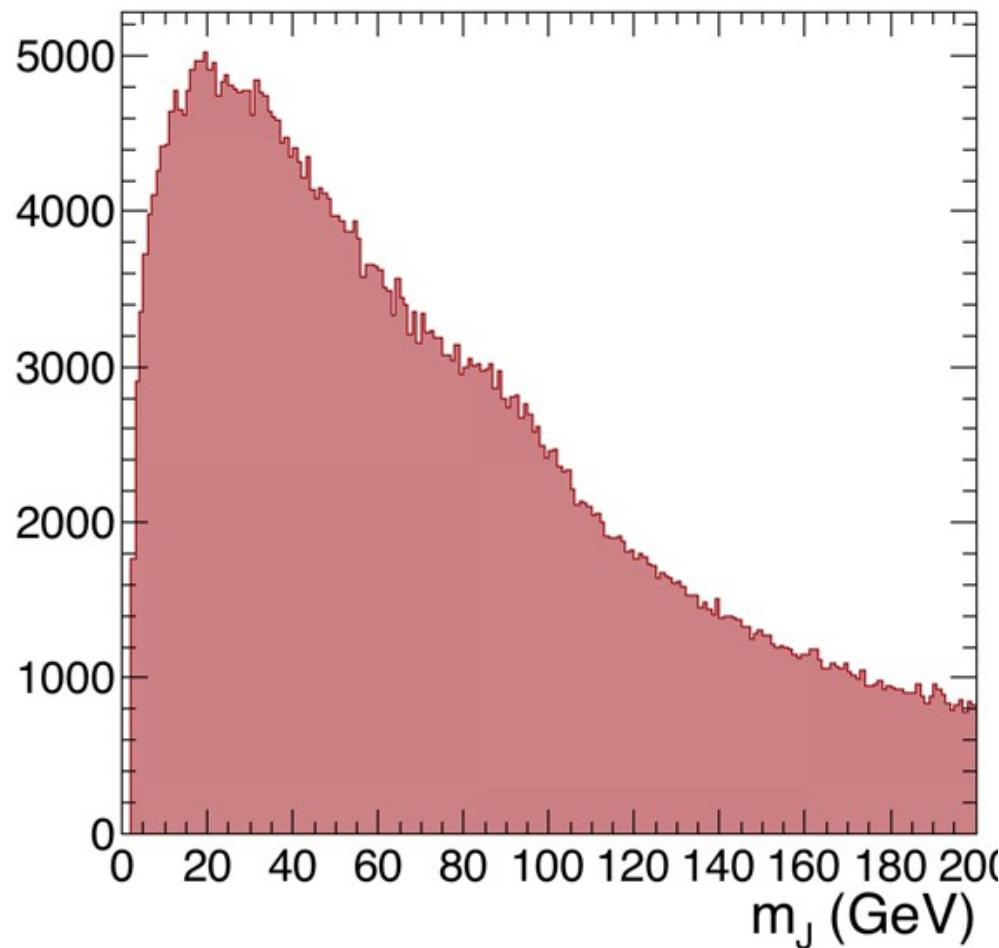


Here it is. This one is a bit harder.

Note exact same amount of background and signal

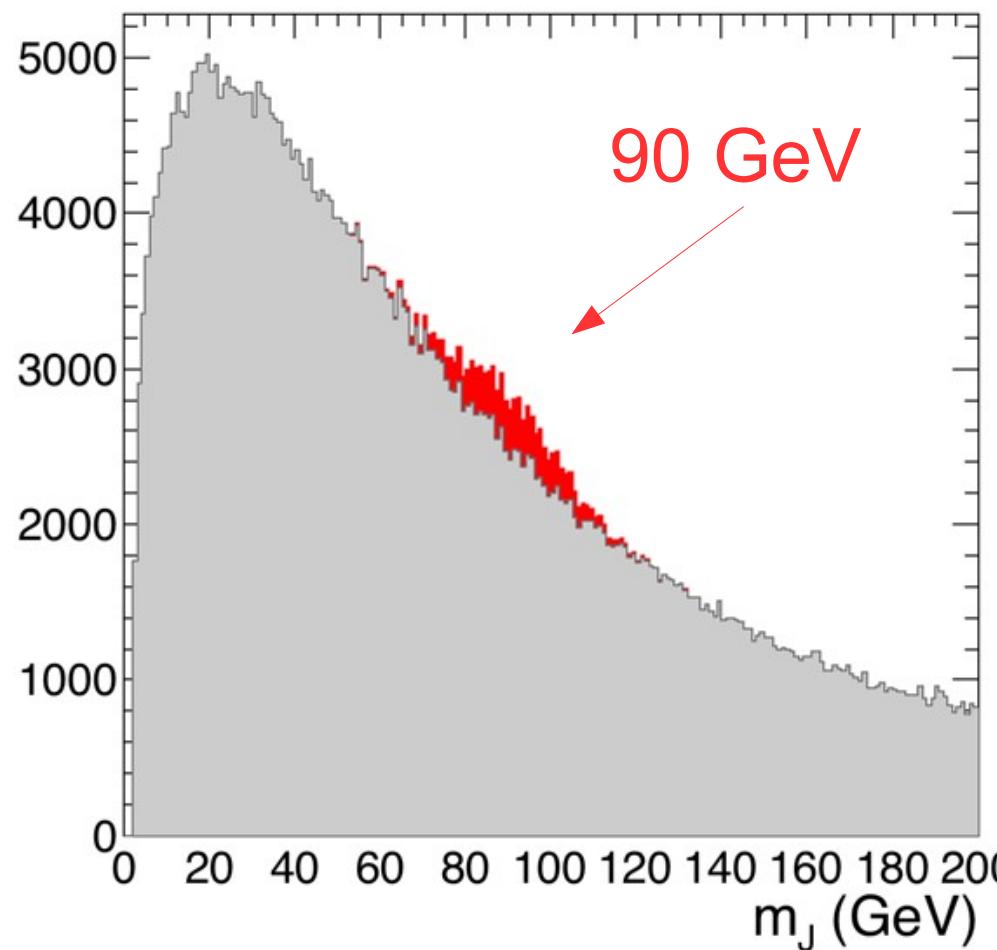
How about now?

- Can you see the signal?



How about now?

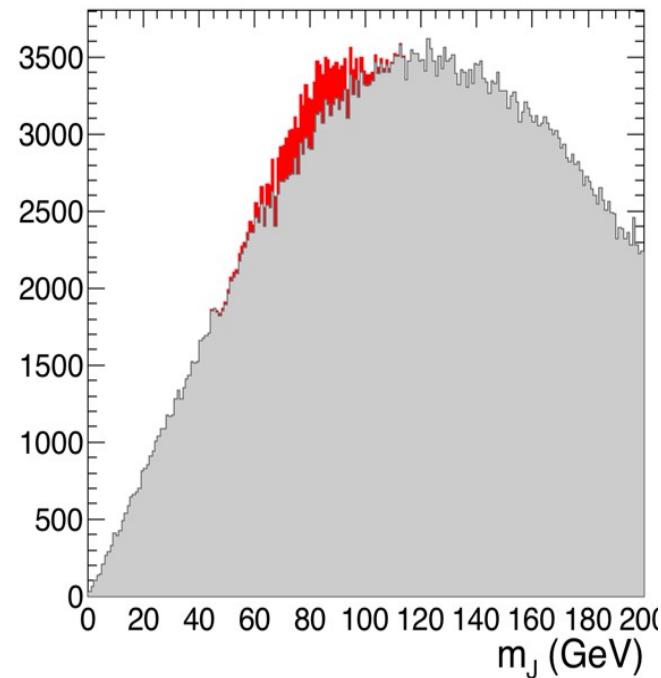
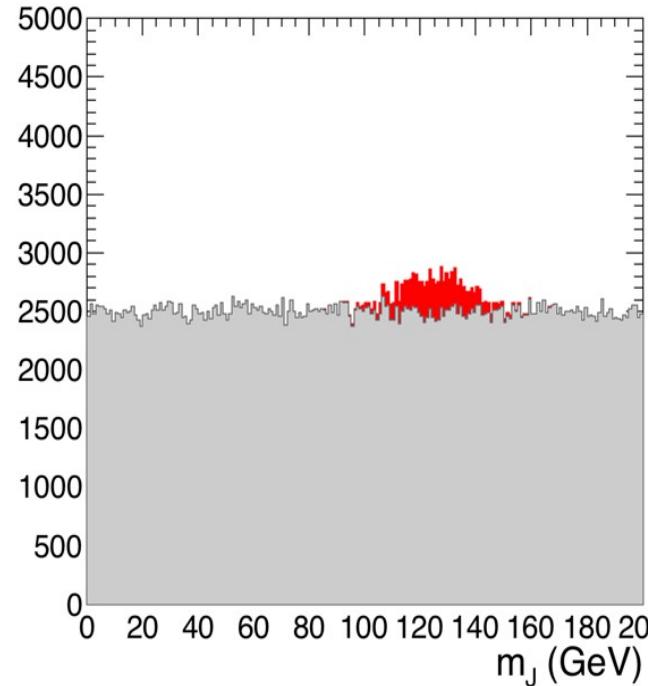
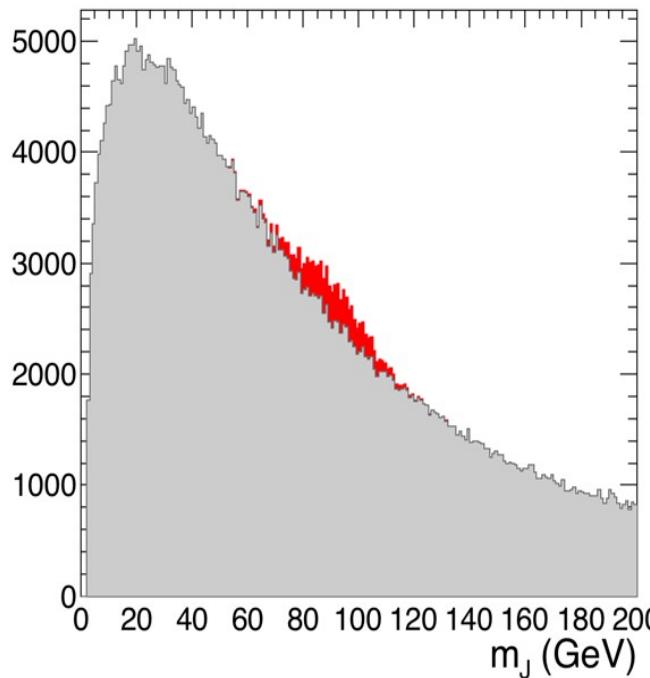
- Can you see the signal?



Background

Note exact same amount of background and signal

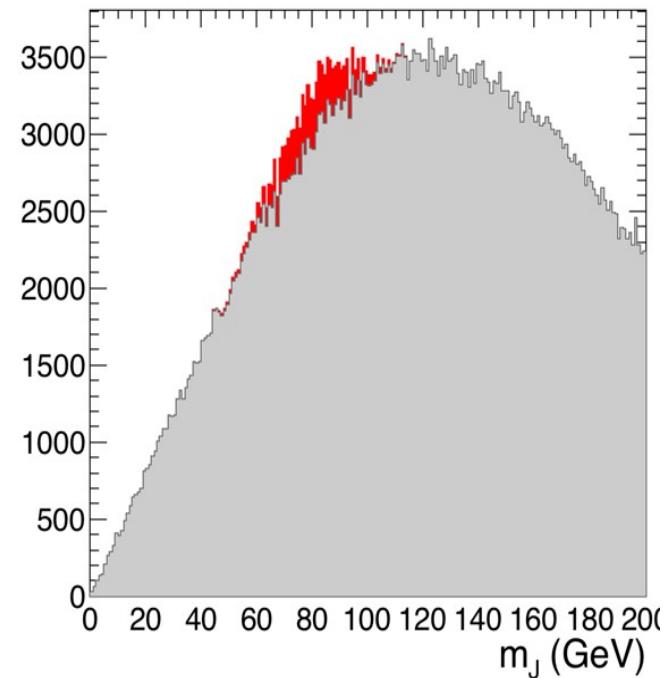
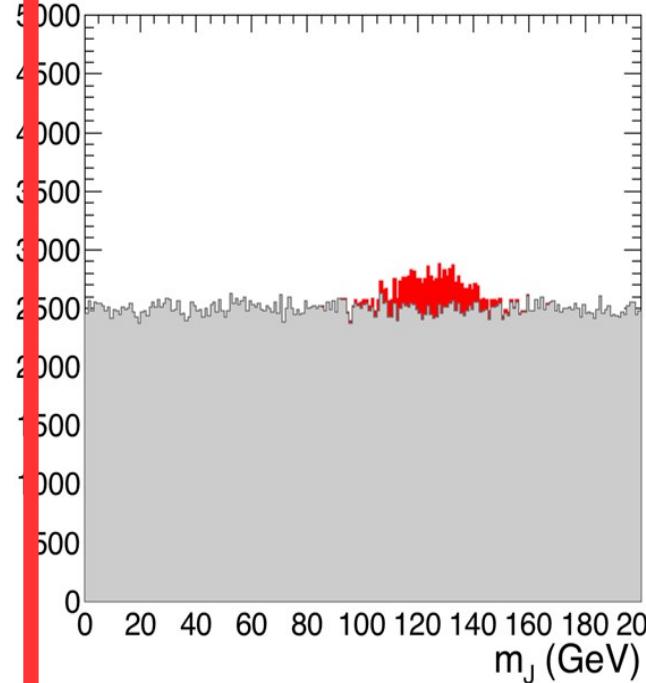
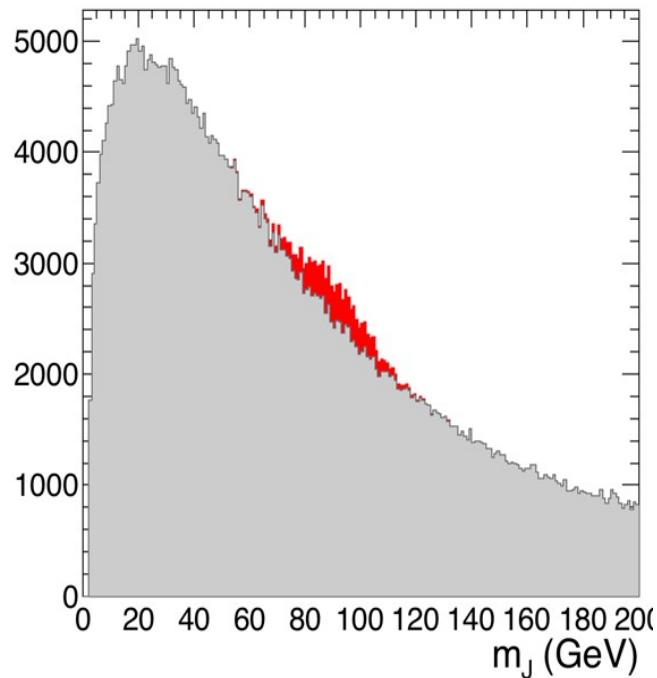
What's best background?



All variables yield roughly the same performance
Exactly the same background yield
Exactly the same signal yield

What if we could tune background shape to what we want?
What would be our best choice of shape?

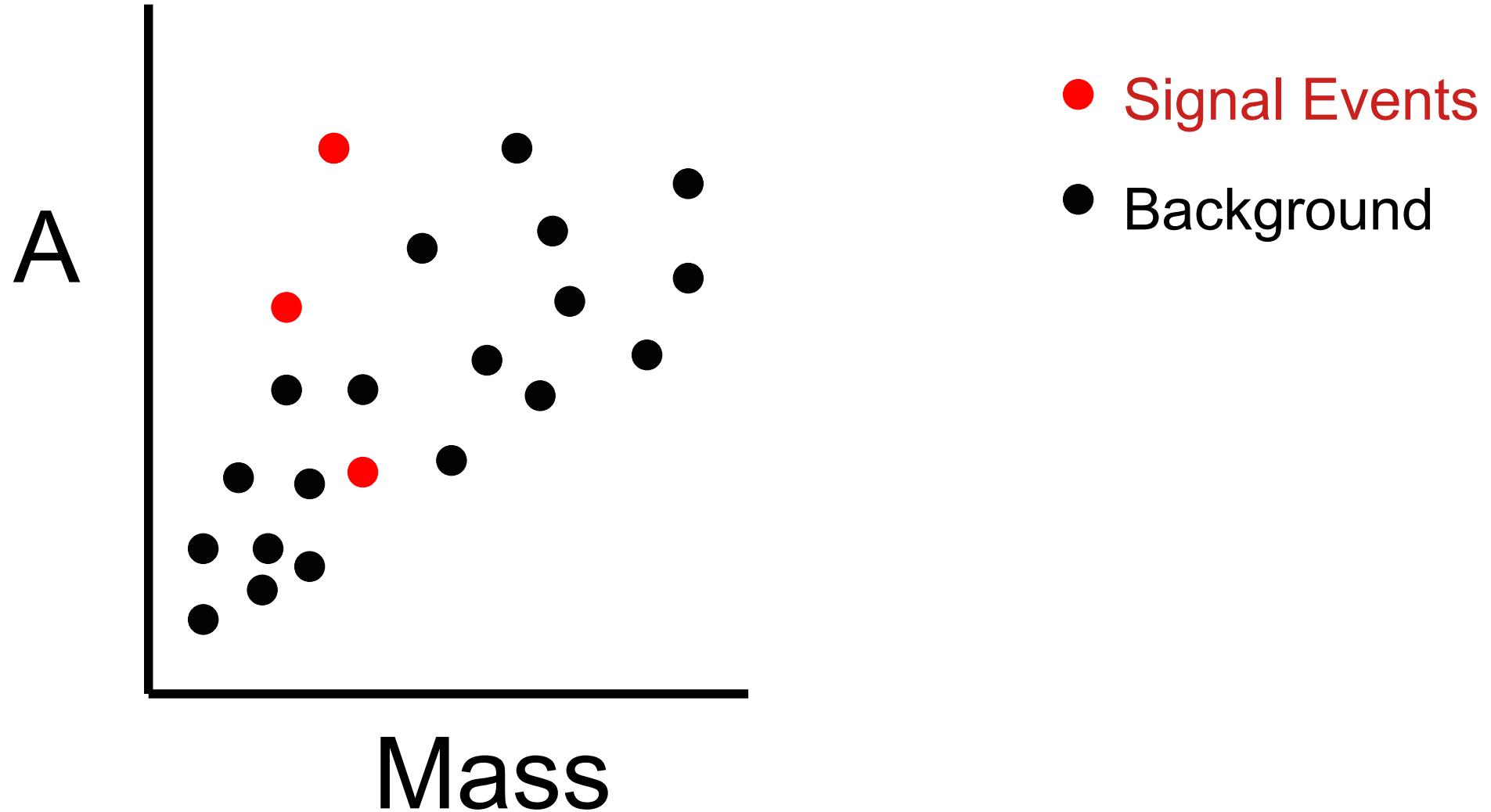
What's best background?



All variables yield roughly the same performance
Exactly the same background yield
Exactly the same signal yield

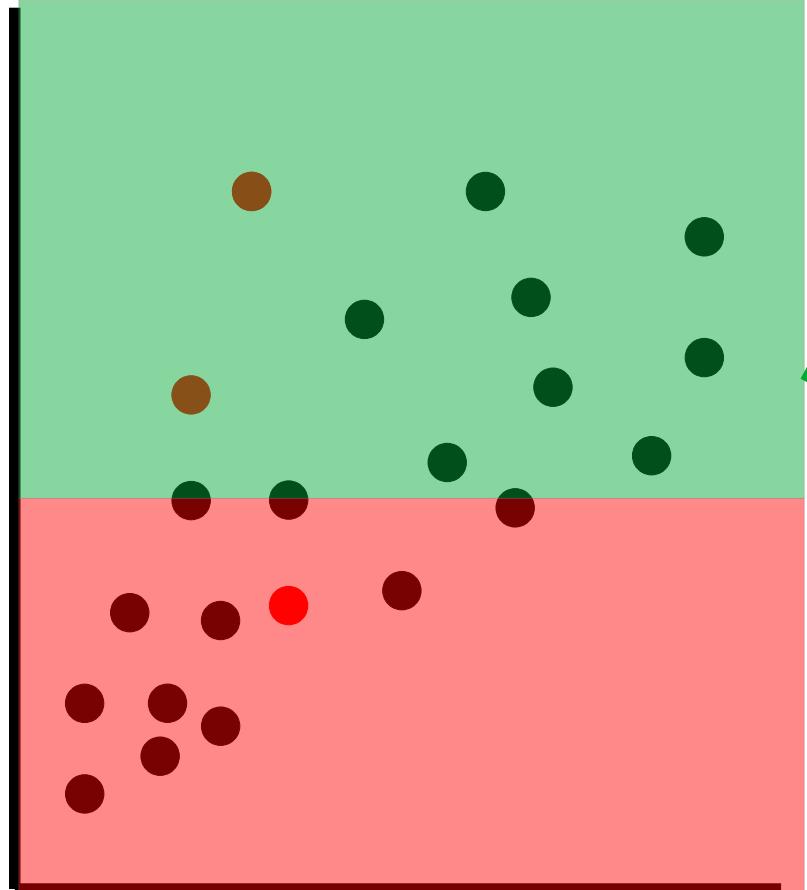
What if we could tune background shape to what we want?
What would be our best choice of shape?

Consider trying to isolate a signal



Extracting a Signal

A

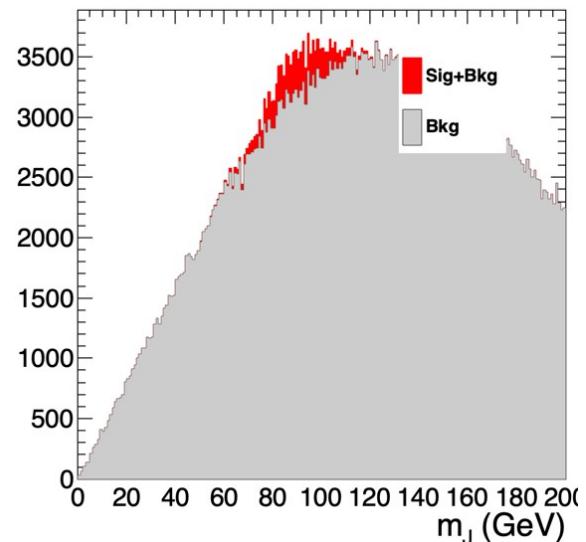


Not Good Enough!

● Signal Events

● Background

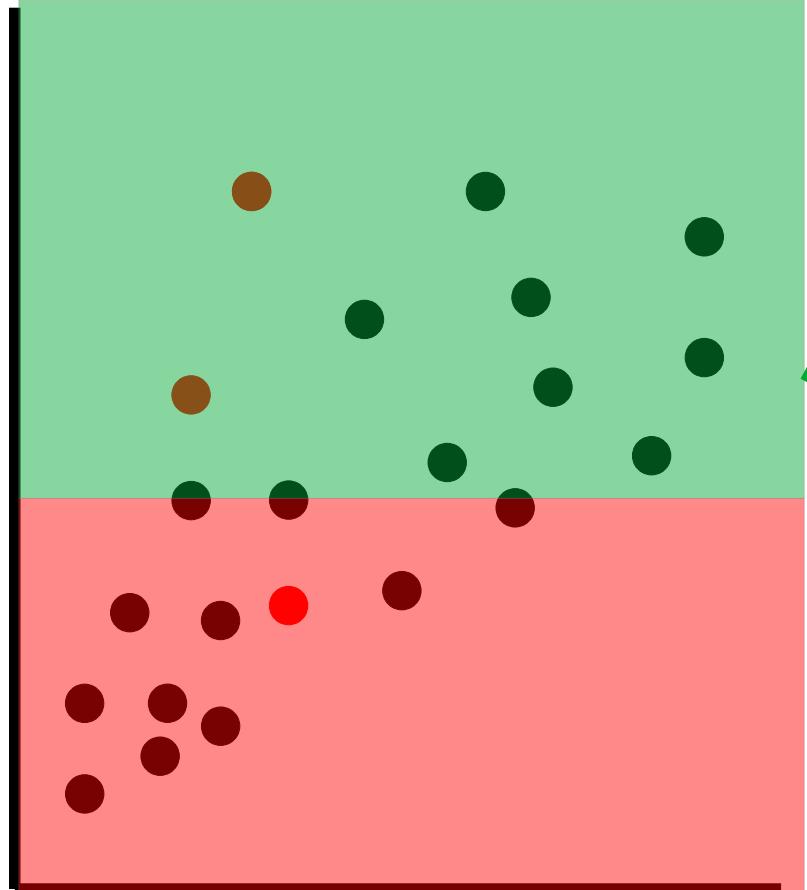
Select Events



And Fit Mass

Extracting a Signal

A



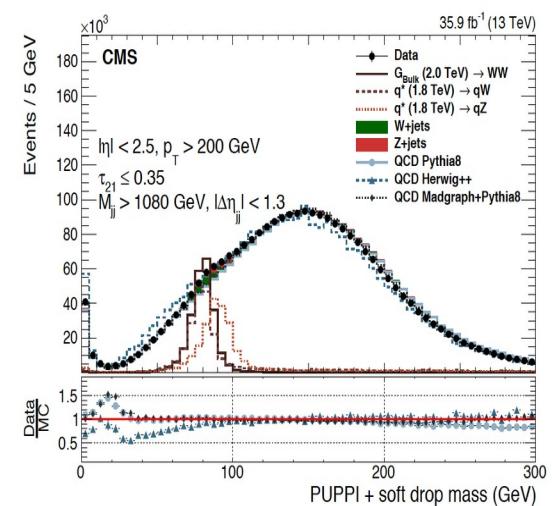
Mass

Cut tighter!

- Signal Events

- Background

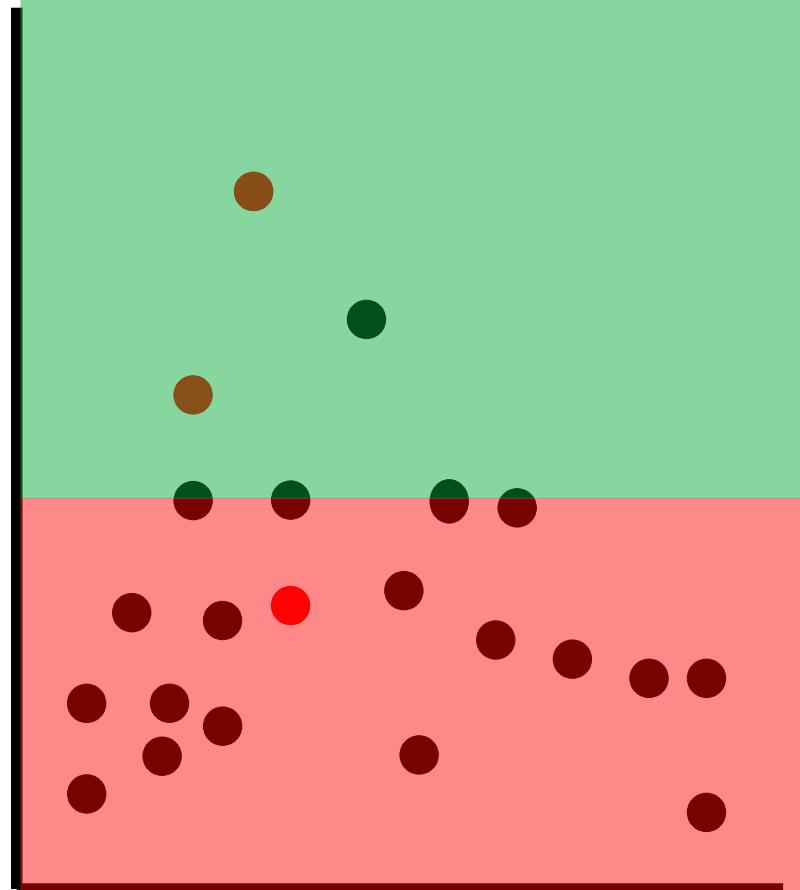
Select Events



And Fit Mass

Use Deep Learning

DNN(....)

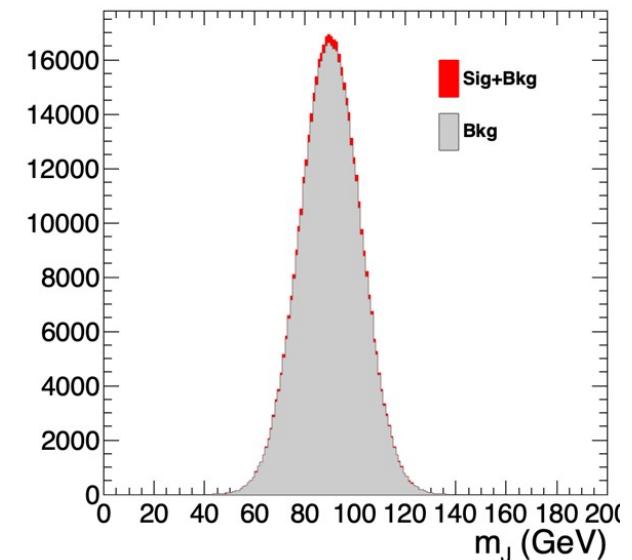


Still Not Enough!

● Signal Events

● Background

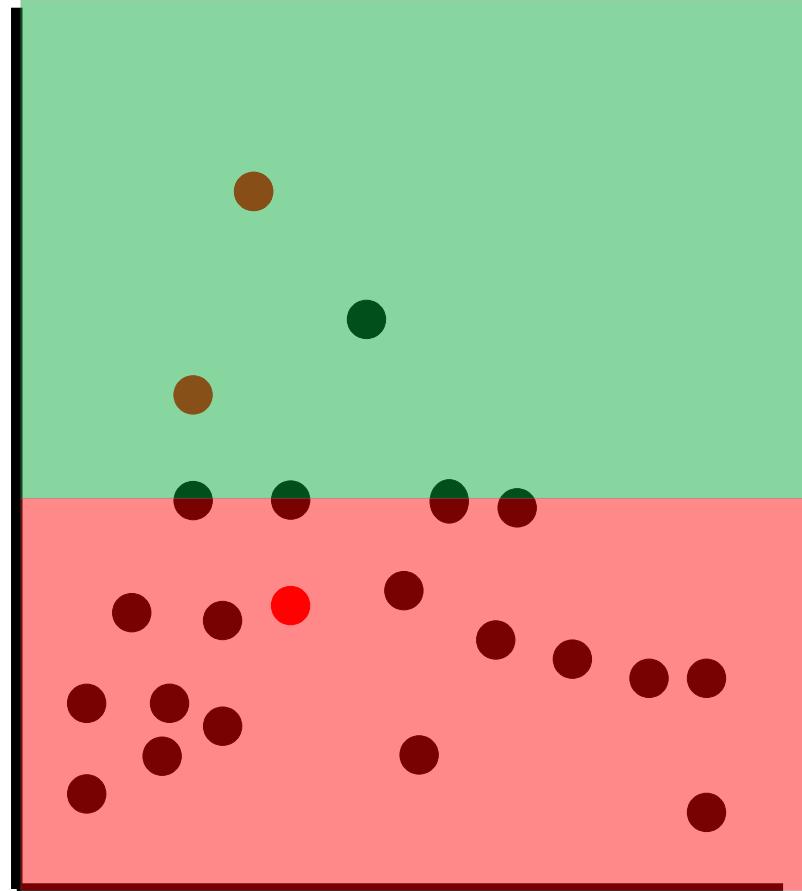
Select Events



And Fit Mass

Use Deep Learning

DNN(....)



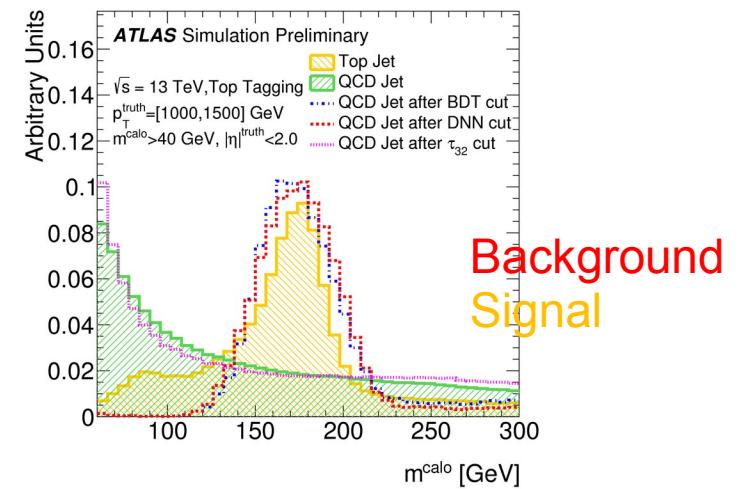
Mass

Can't separate sig+bkg

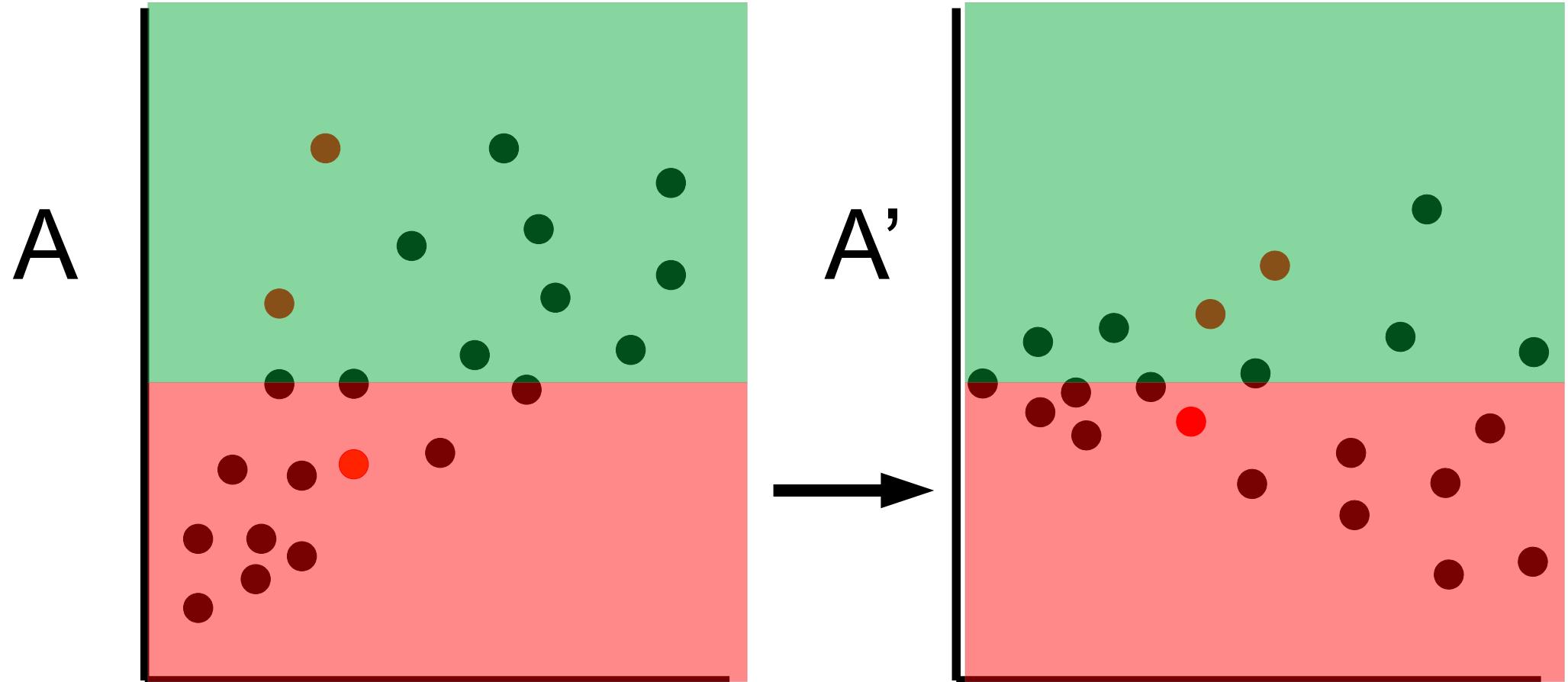
And Fit Mass

- Signal Events
- Background

Select Events

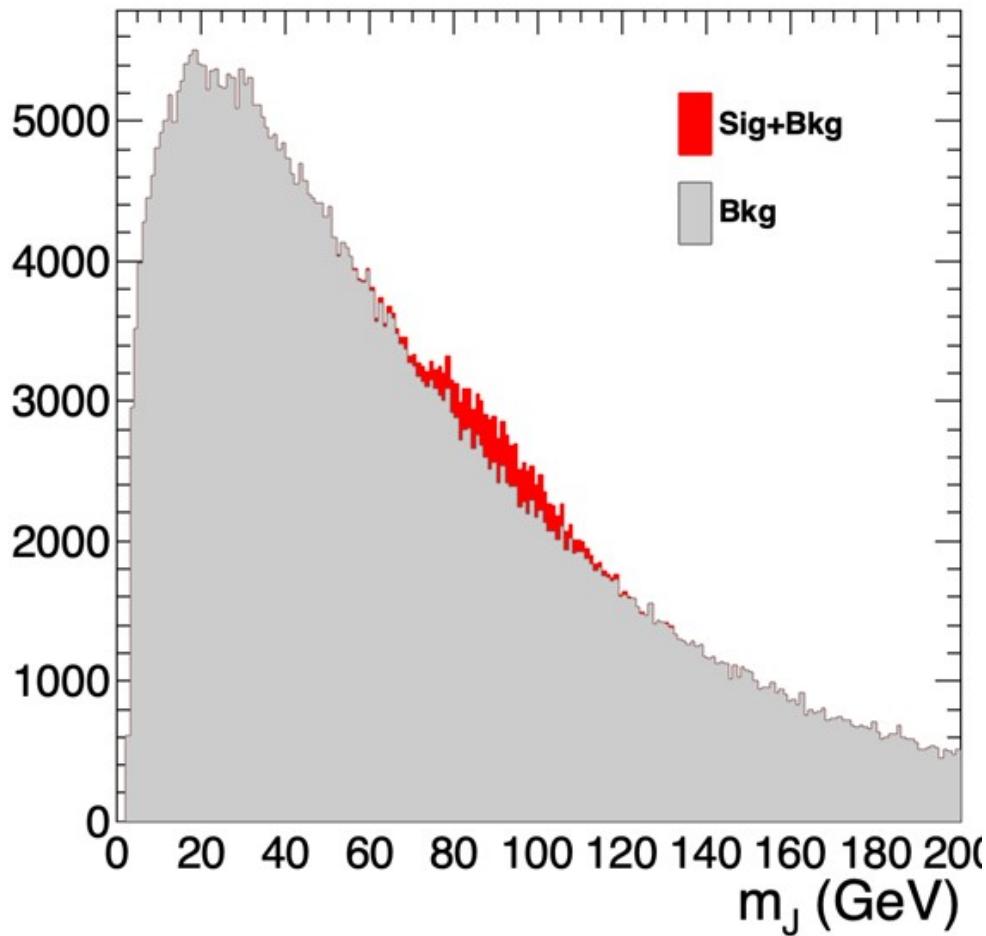


Conceptually what was done?



Mass
Now its good!

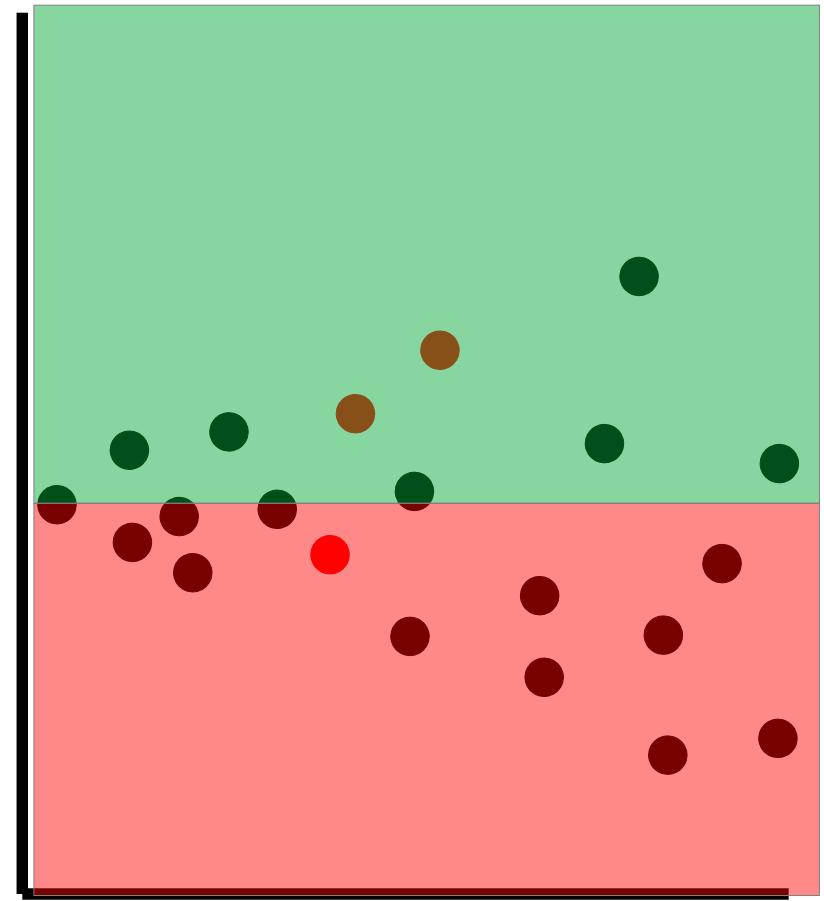
Conceptually what was done?



Mass

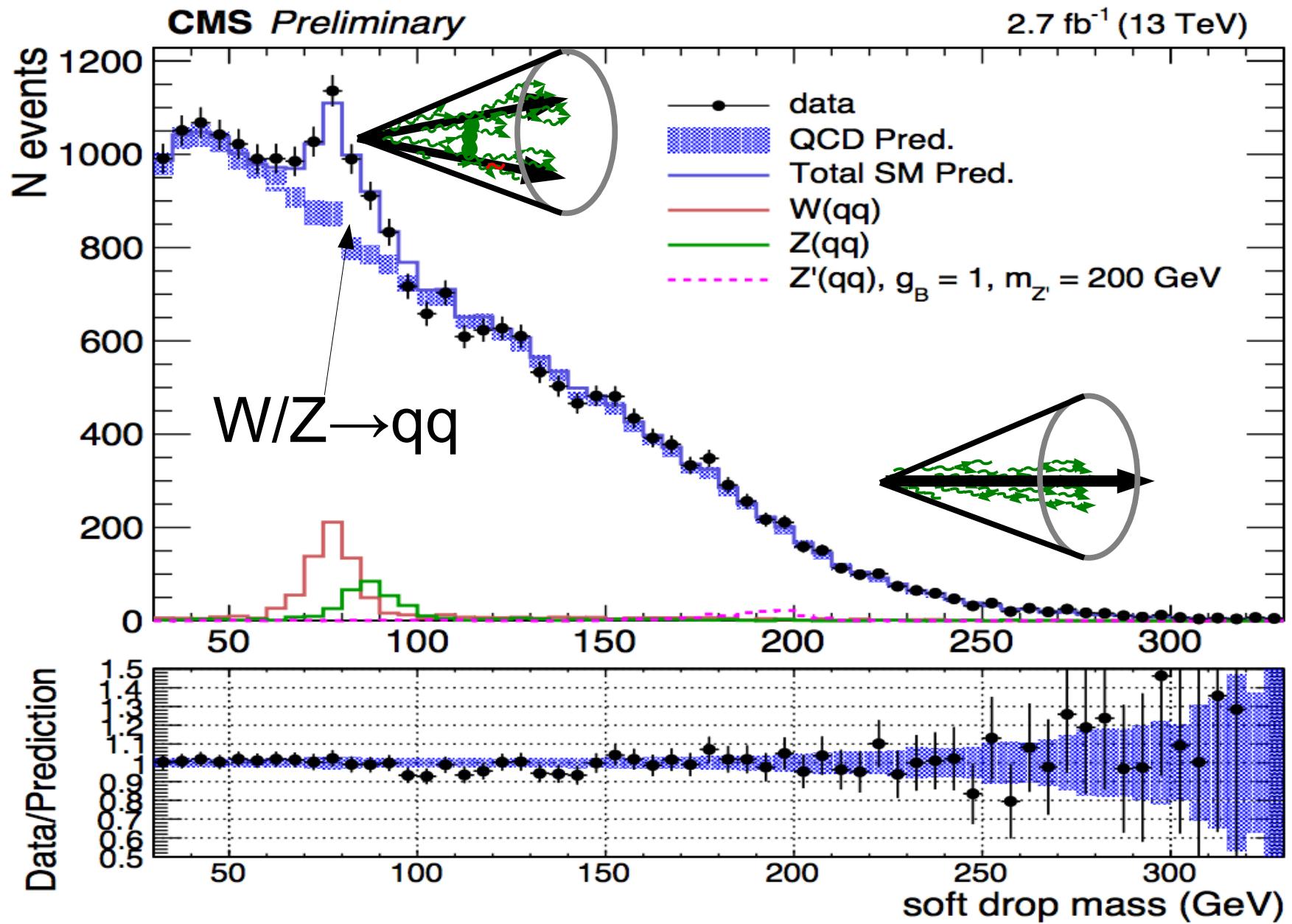
Now its good!

A'



Mass

Jet Mass distribution

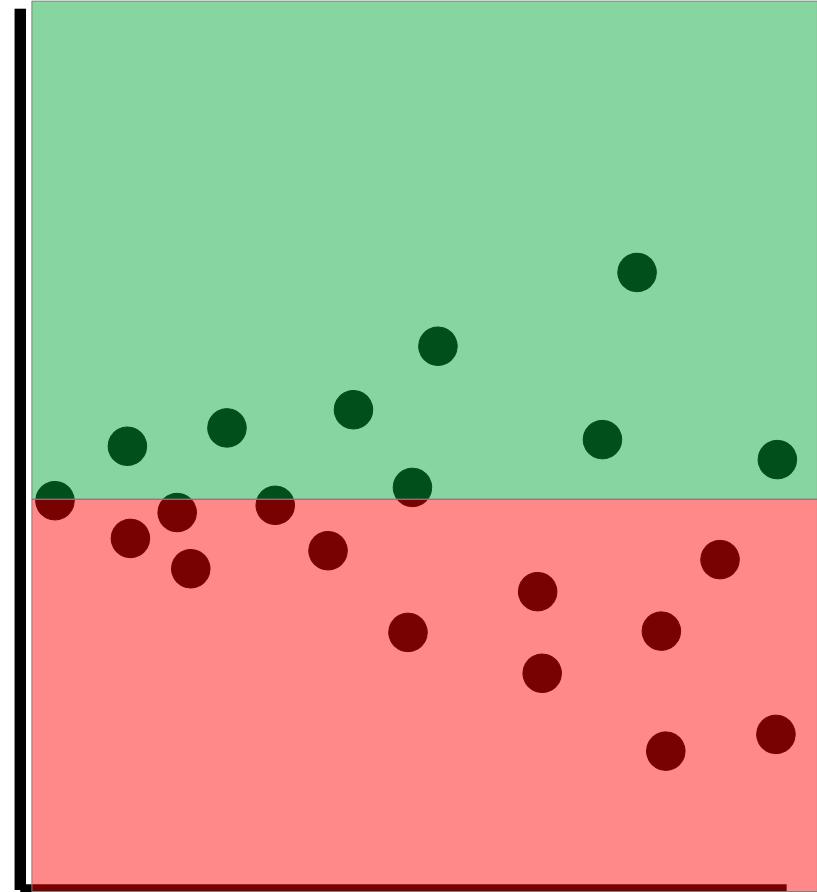


What makes this complicated?

$A'(\text{in}_1, \text{in}_2, \dots, \text{in}_{1000})$

The actual variable we cut on can be a function of 1000 different variables

No Joke
(I will get back to that)



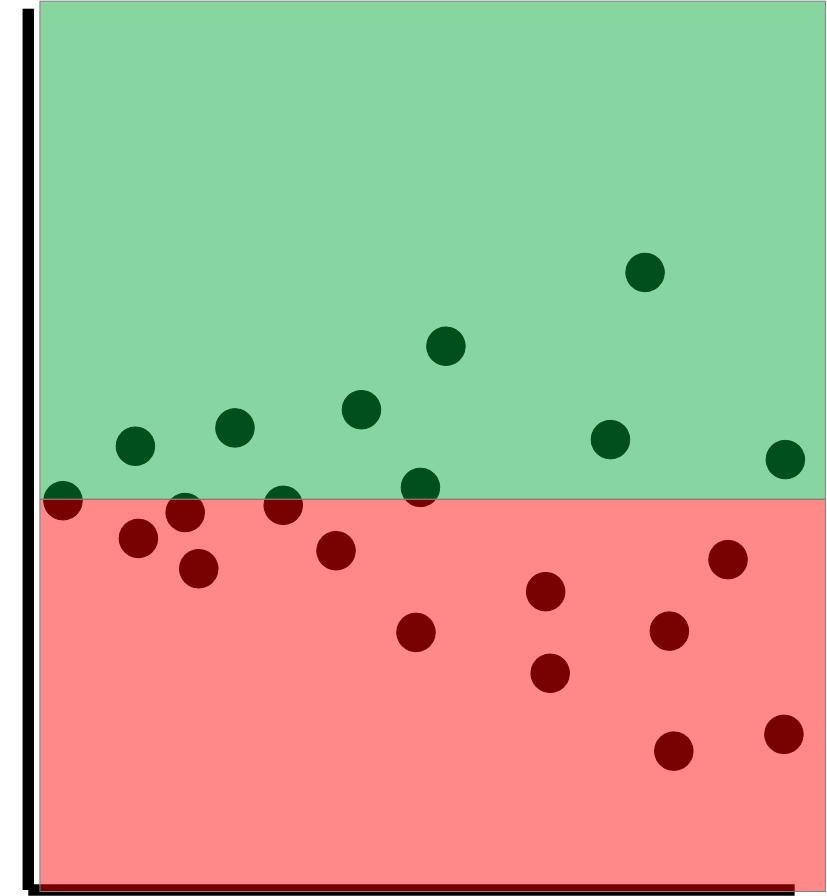
What makes this complicated?

To start with we relied
on a standard:

$$A'(\text{in}_1, \text{in}_2, \dots, \text{in}_{1000})$$

$$= \tau_2 / \tau_1$$

+Brute force
decorrelation



Mass

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min \{ \Delta R_{1,k}, \Delta R_{2,k}, \dots, \Delta R_{N,k} \}$$

What makes this complicated?

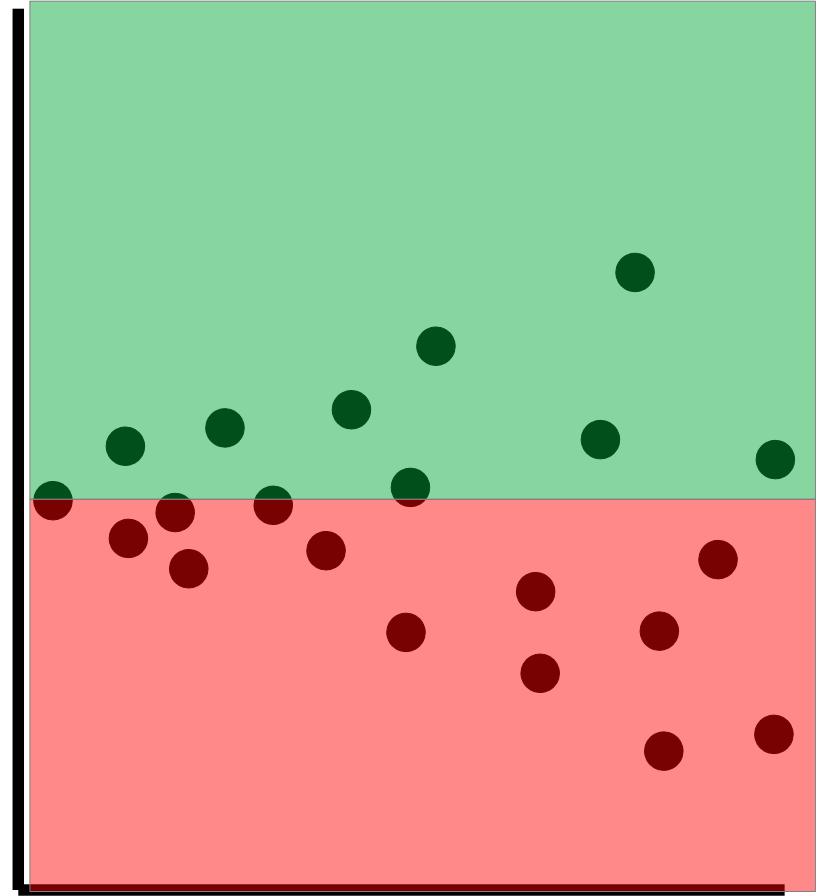
After Jesse's paper we switched to:

$$A'(\text{in}_1, \text{in}_2, \dots, \text{in}_{1000})$$

$$= \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^2} (N_2)$$

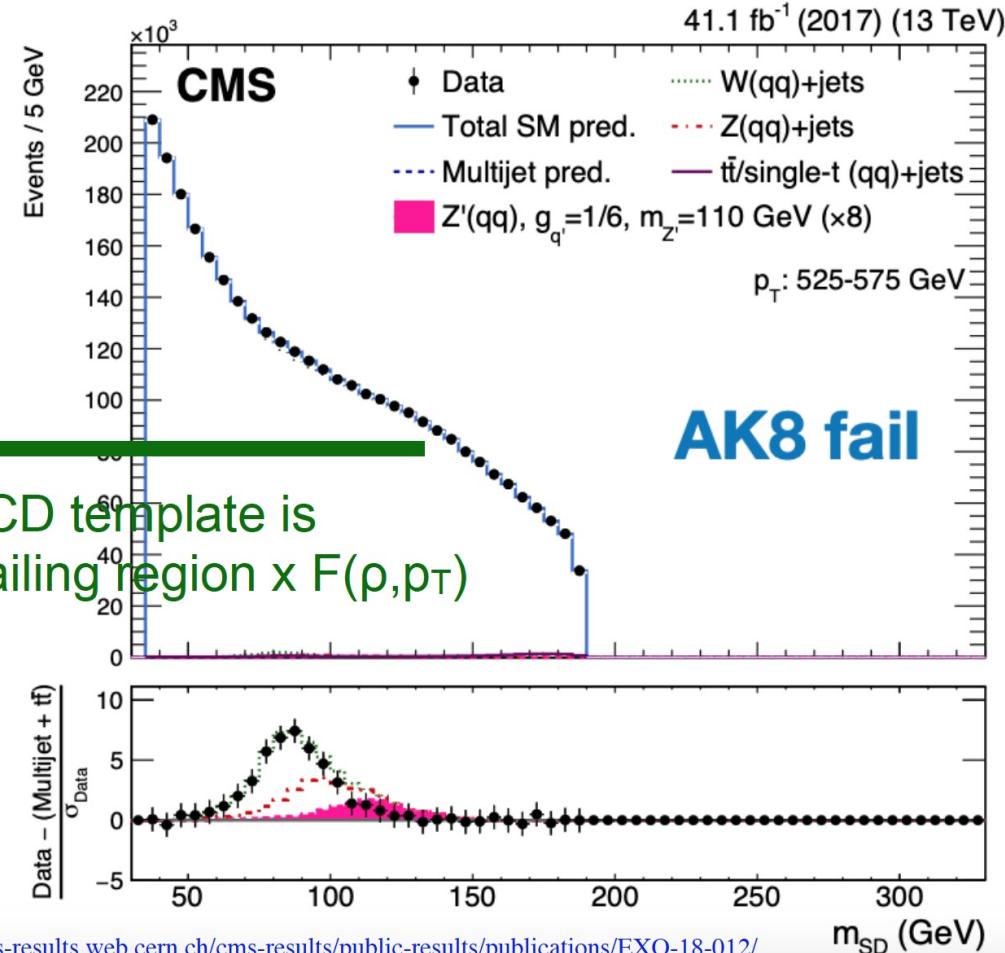
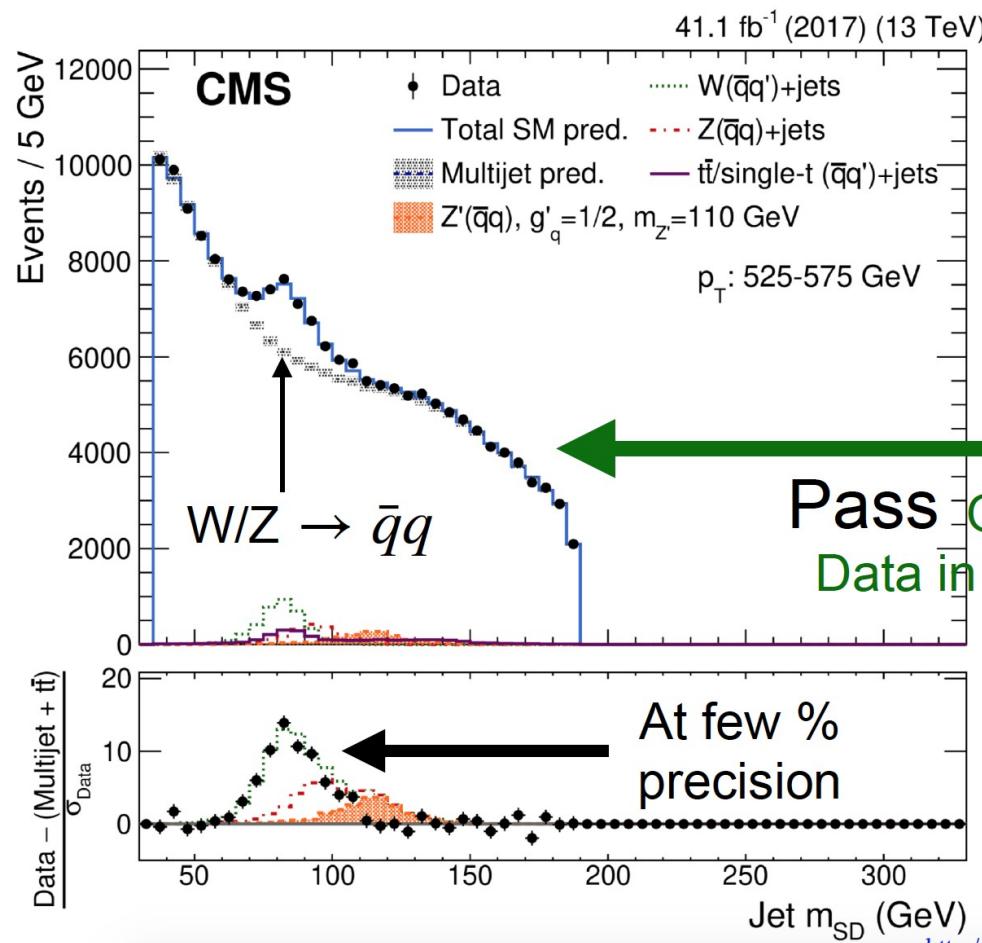
+Brute force
decorrelation

$$\begin{aligned} e_3^{(\beta=2)} &= \sum_{i < j < k \in \text{jet}} z_i z_j z_k \theta_{ij}^2 \theta_{ik}^2 \theta_{jk}^2 \approx \sum_{i < j} z_i z_j \theta_{ij}^2 \theta_i^2 \theta_j^2 \\ &\approx \sum_{i < j} z_i z_j \max(\theta_i^2, \theta_j^2) \theta_i^2 \theta_j^2 \approx \sum_{i < j} \rho_i \rho_j \max(\theta_i^2, \theta_j^2), \end{aligned}$$



Mass

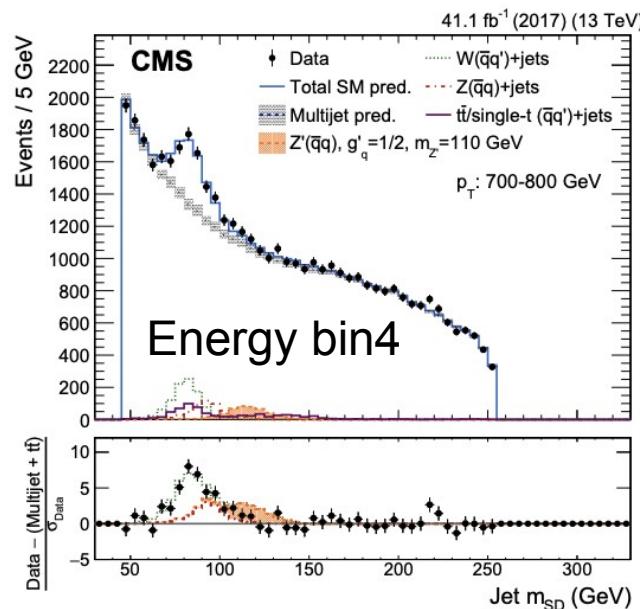
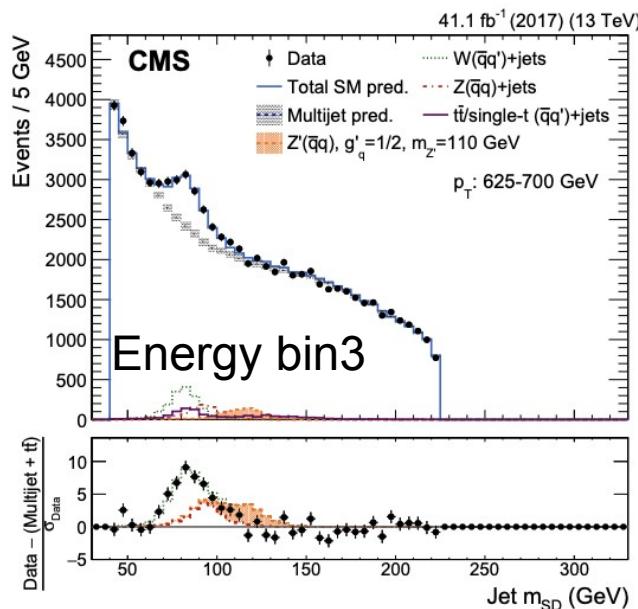
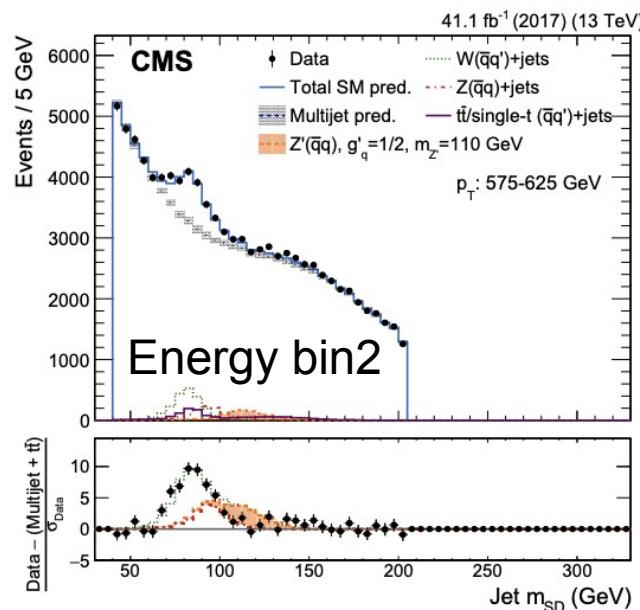
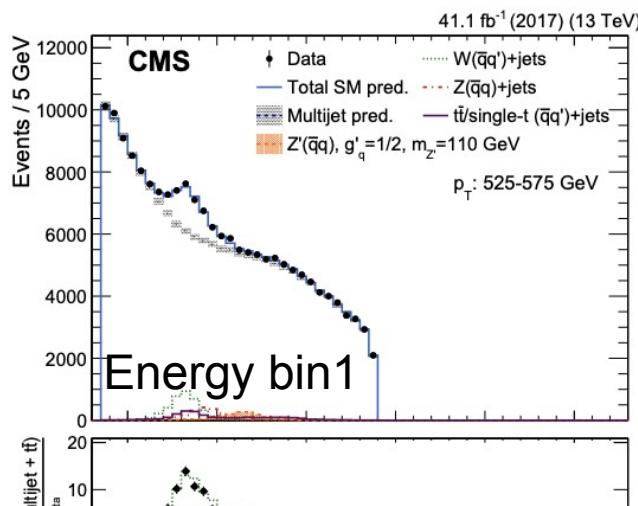
Our current result



Only through above strategies could we get here
Ultimately it meant we could safely cut tighter

<http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-18-012/>

Our Current Result

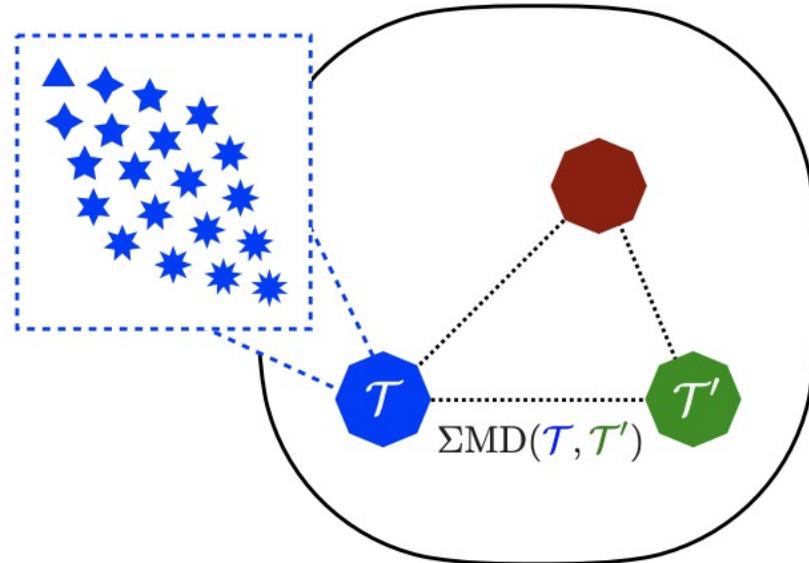
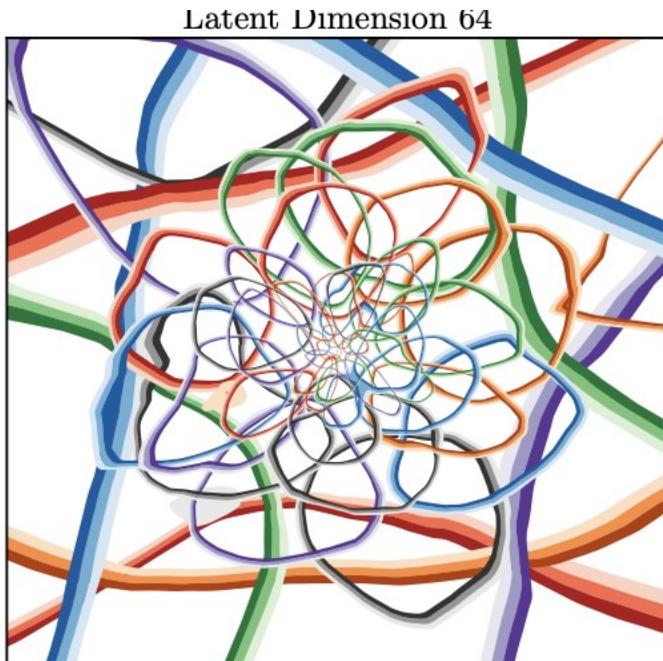


Starting to get real precision

Whats the deal with deep learning?

There are 30-200 entangled particles In a jet

$$\begin{aligned} \mathcal{C}_N &= \sum_{k=0}^N \binom{N}{k} \sum_{i_1=0}^1 \cdots \sum_{i_k=0}^1 \lambda^{\sum_{a=1}^k i_a} (1-\lambda)^{k-\sum_{a=1}^k i_a} E_1^k \\ &\quad \times \sum_{i_{k+1}=2}^M \cdots \sum_{i_N=2}^M C_{i_1 \dots i_N}(\hat{p}_{i_1}^\mu, \dots, \hat{p}_{i_N}^\mu) \prod_{j=k+1}^N E_{i_j} \\ &= \sum_{k=0}^N \binom{N}{k} \sum_{\ell=0}^k \binom{k}{\ell} \lambda^\ell (1-\lambda)^{k-\ell} E_1^k \\ &\quad \times \sum_{i_{k+1}=2}^M \cdots \sum_{i_N=2}^M C_{\underbrace{0 \dots 0}_{\ell} \underbrace{1 \dots 1}_{k-\ell} i_{k+1} \dots i_N}(\hat{p}_1^\mu, \dots, \hat{p}_1^\mu, \hat{p}_{i_{k+1}}^\mu, \dots, \hat{p}_N^\mu) \end{aligned}$$

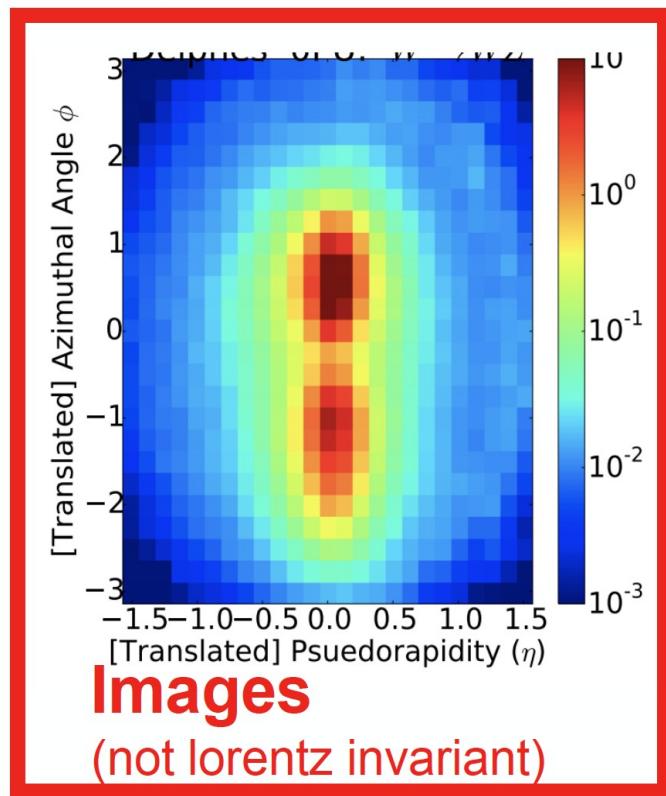


Deep Learning has made it possible to decode some of the finer features of a jet

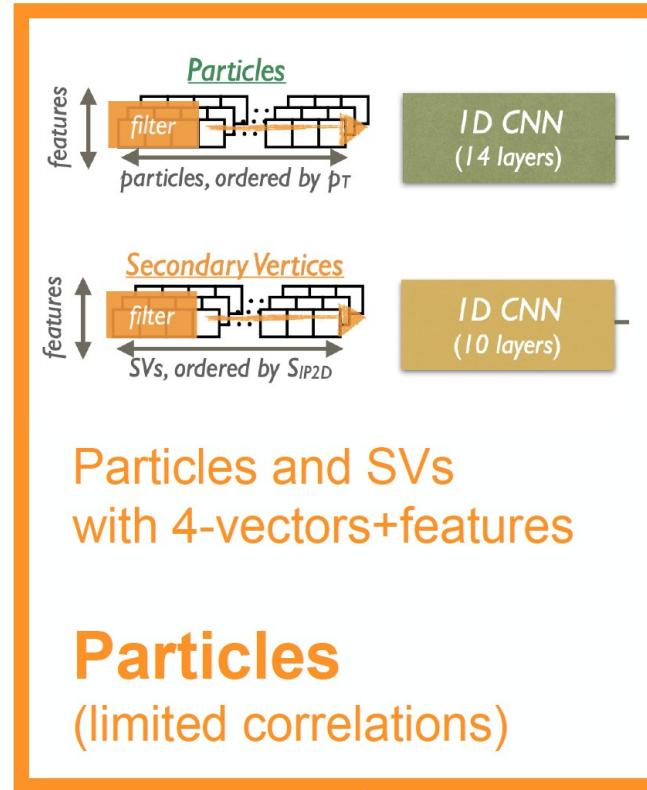
How it's evolved over time

- Deep learning for substructure is rapidly growing field

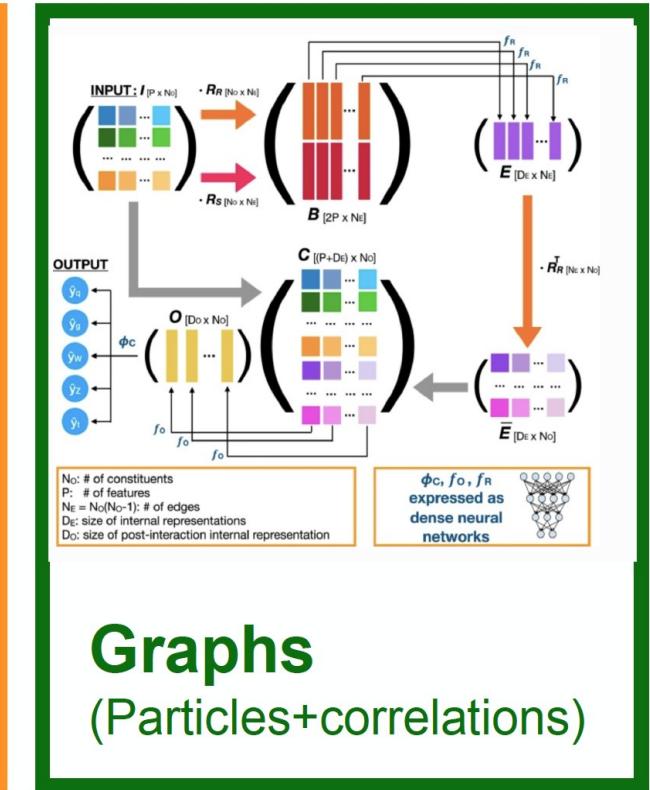
2016



2018



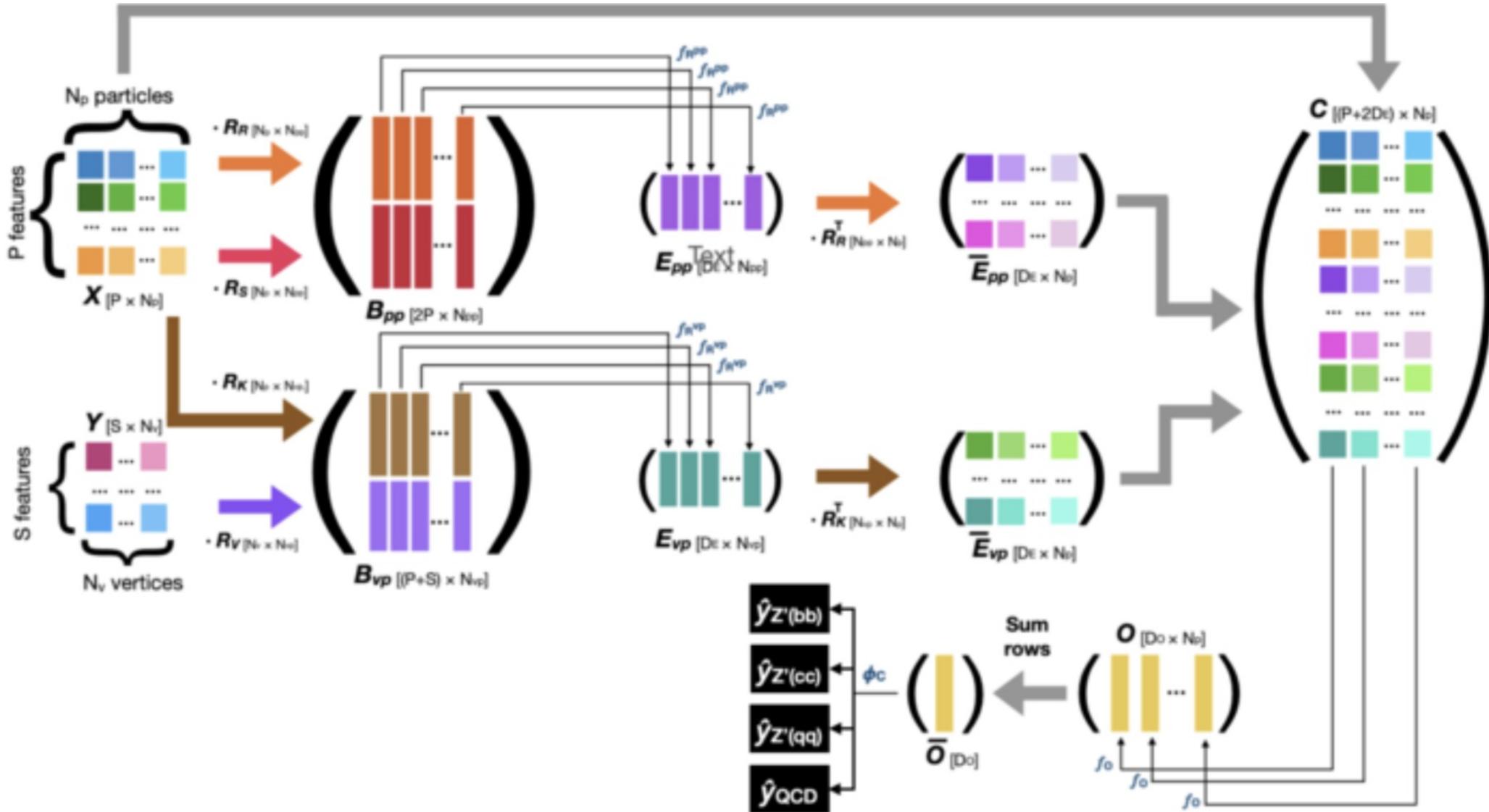
2020



Current collaboration results

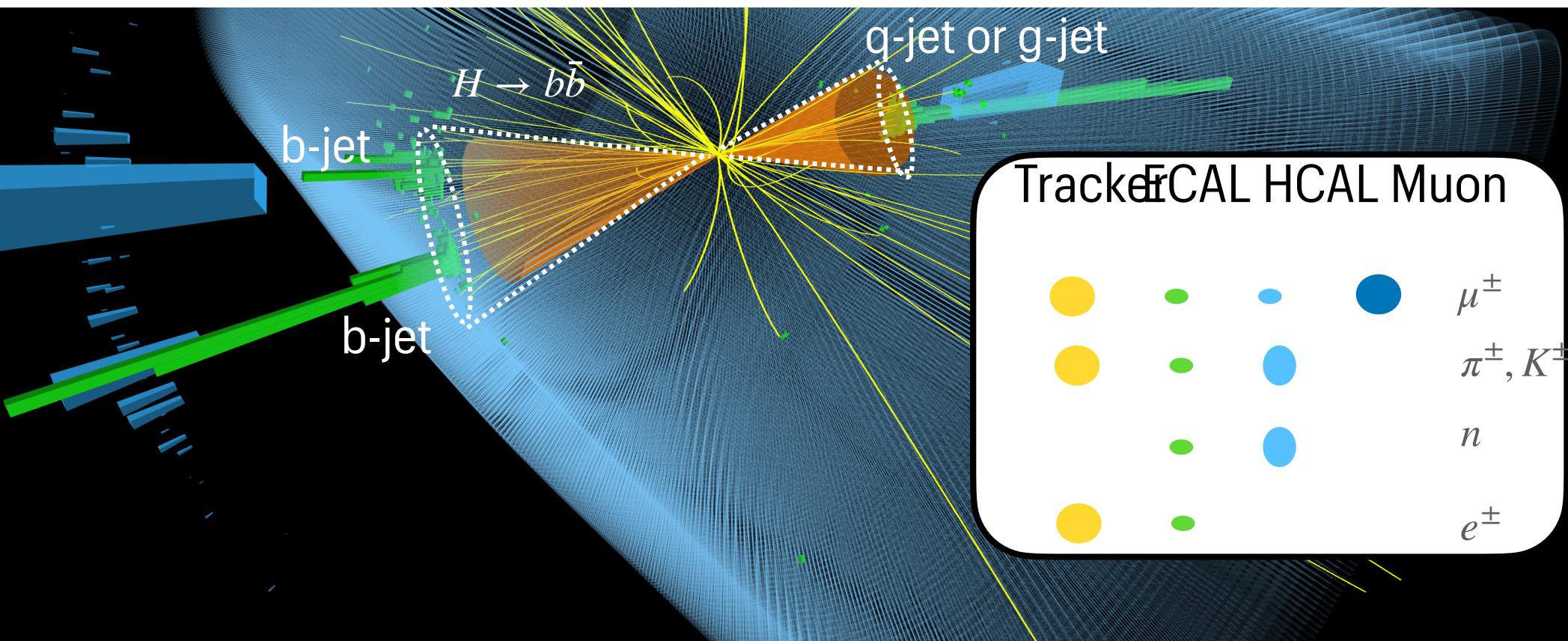
Progressively moving towards use of more info

Why are we so excited?



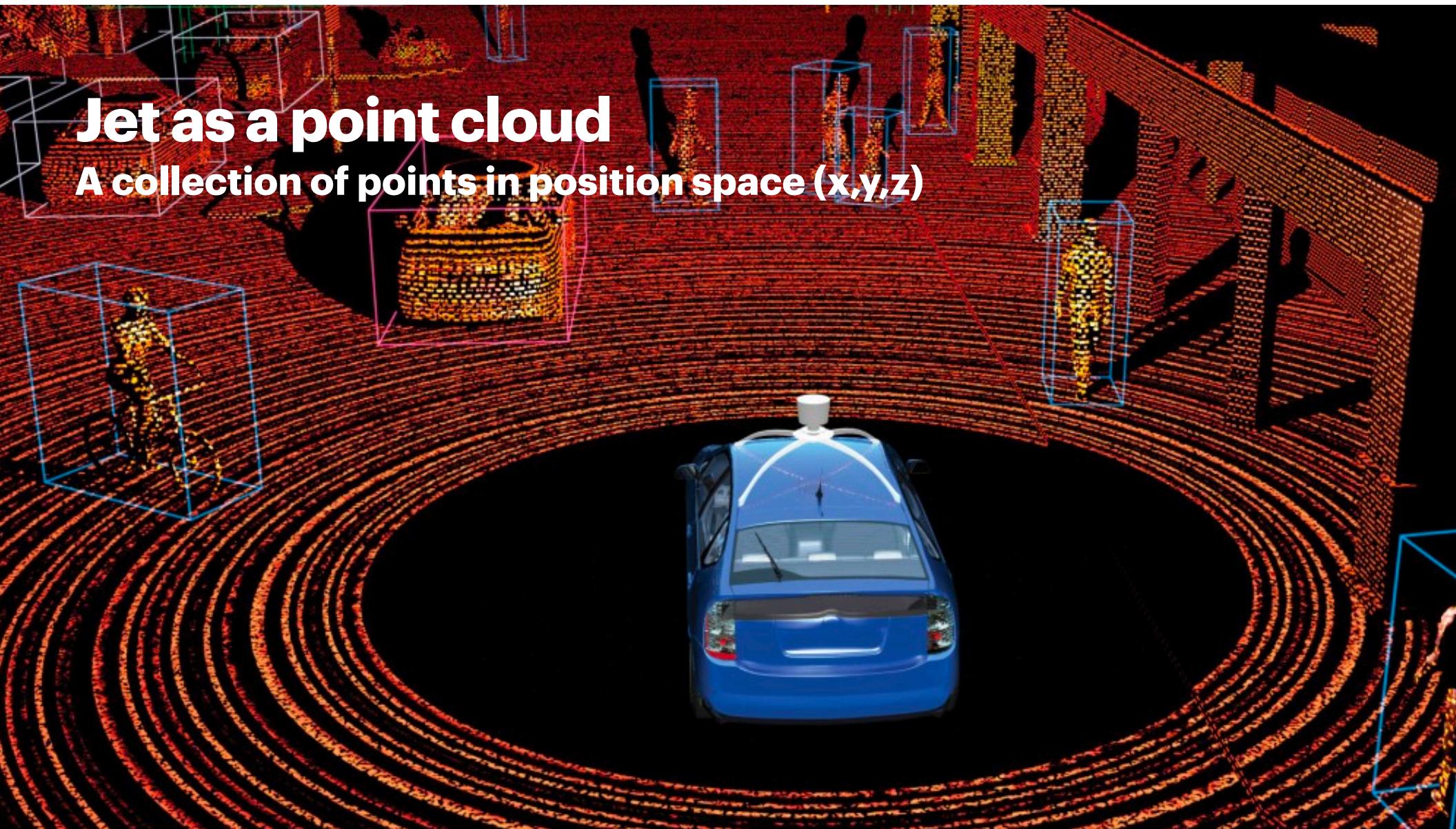
A collision event

A collection of particles in momentum space



Jet as a point cloud

A collection of points in position space (x,y,z)

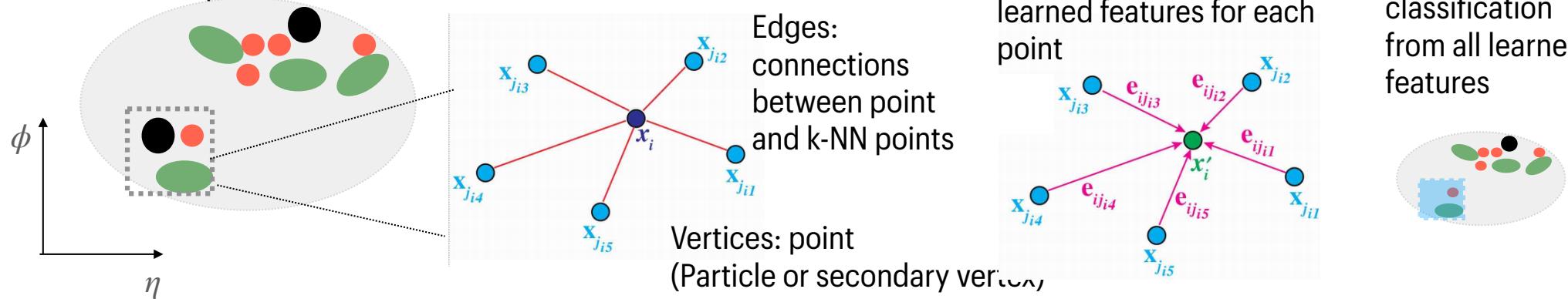


Particle-Net

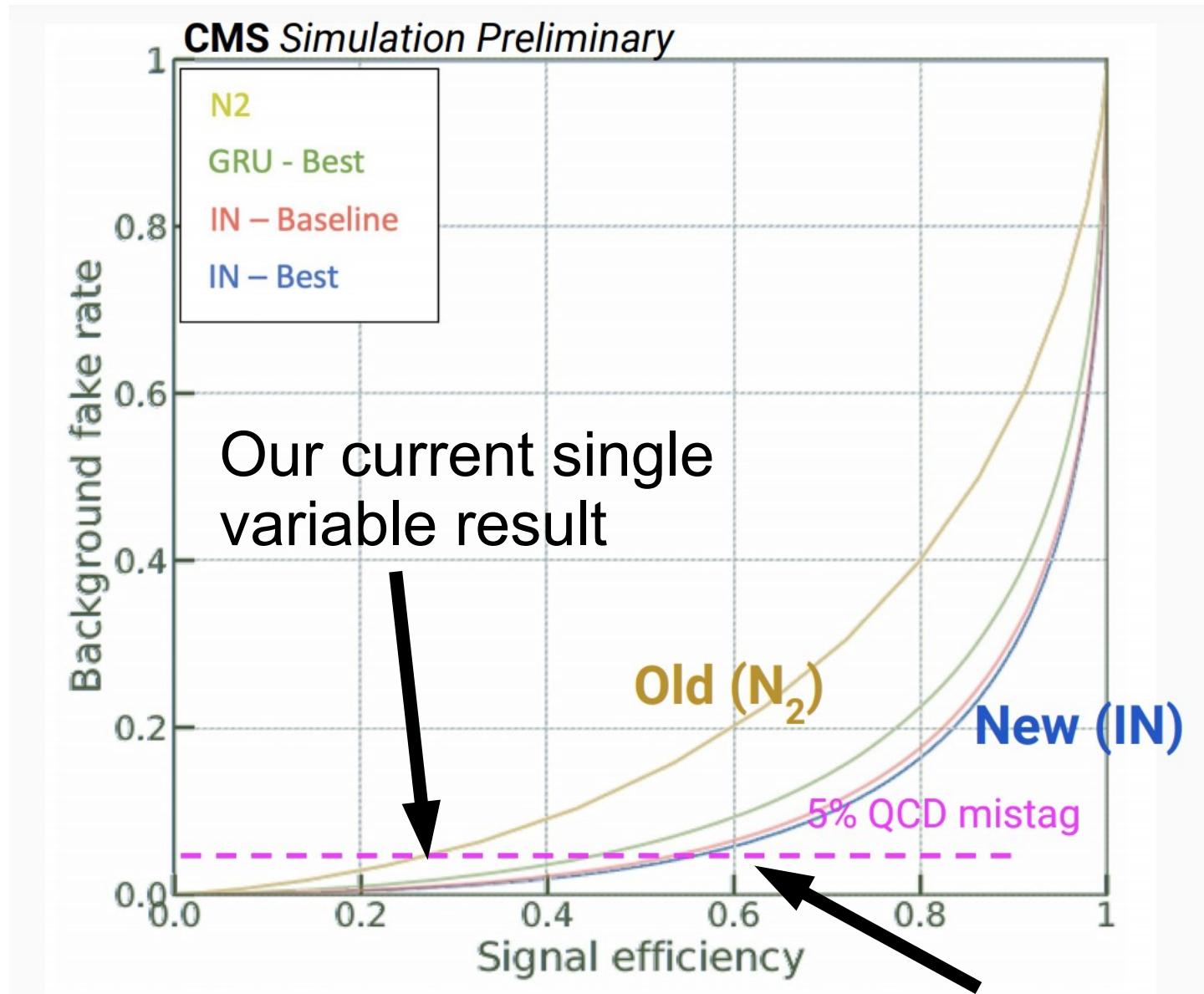
A graph neural network using particle-clouds

- For a jet: we have 2D information of particles, but also energy/momenta, charge/particle ID, track quality/impact parameter, etc.

Jet as a particle cloud Each cloud is a graph Perform convolution Get ID
Unordered representation



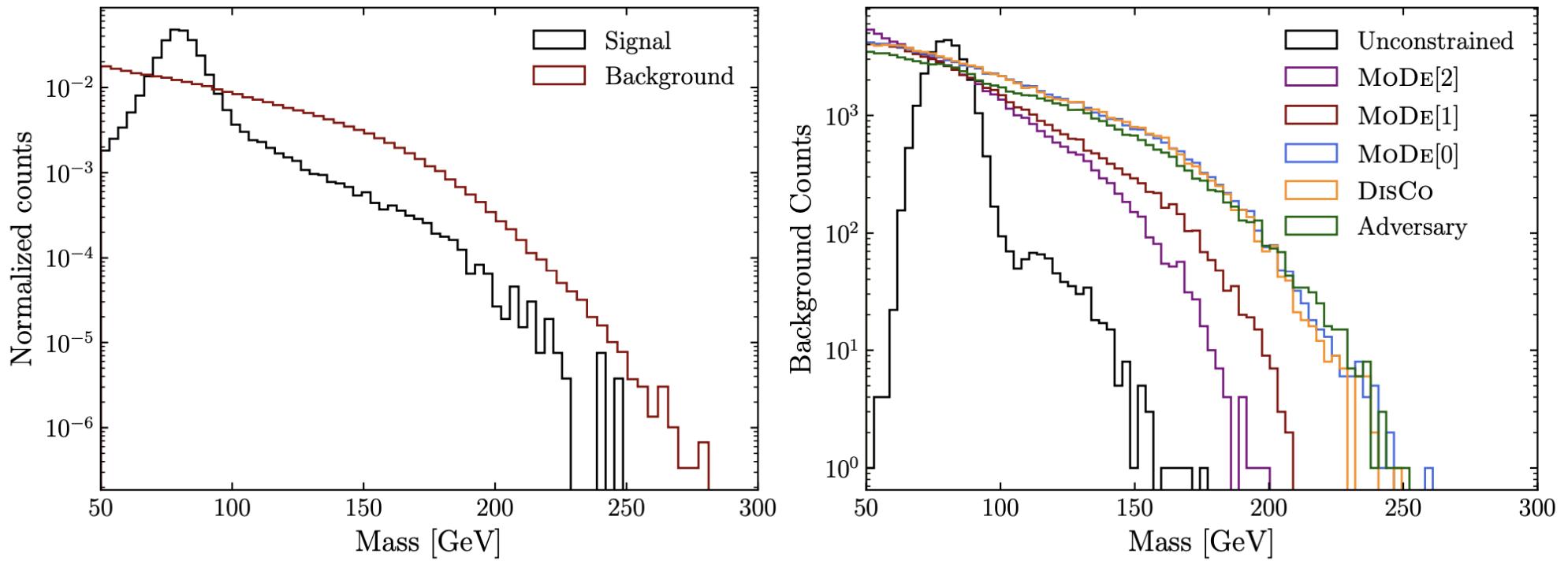
Why are we so excited?



Our future result: 2x sensitivity!

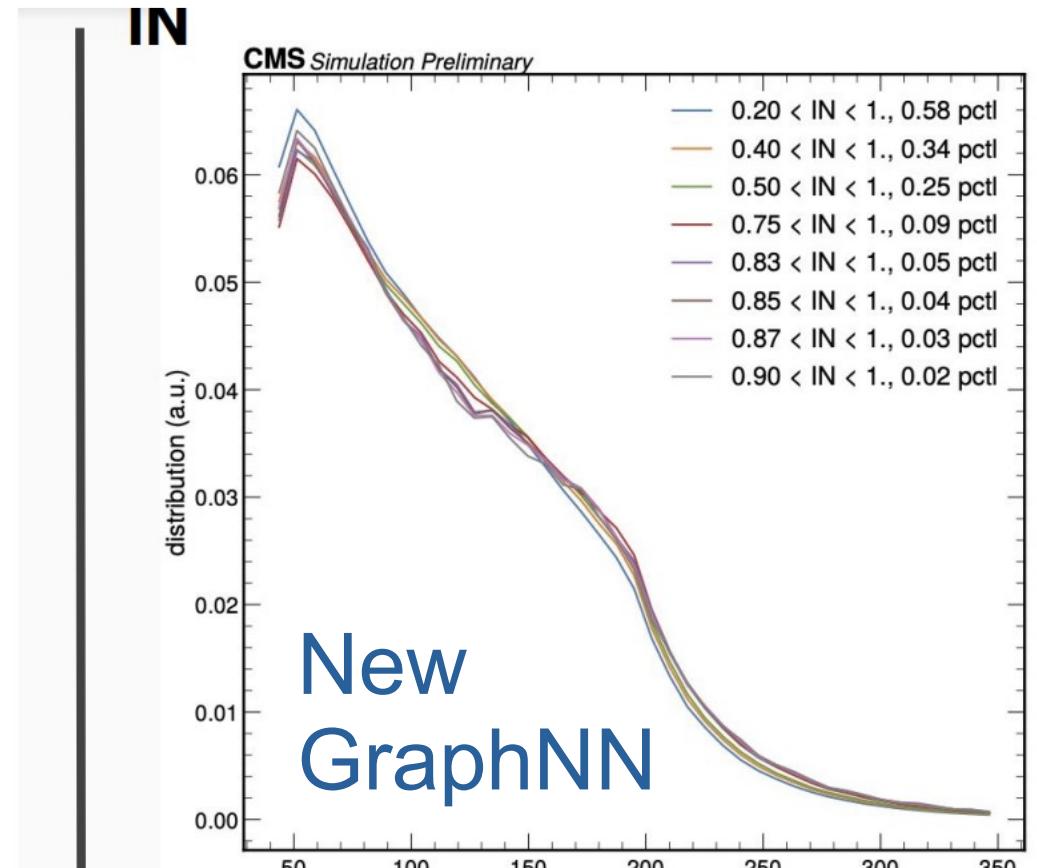
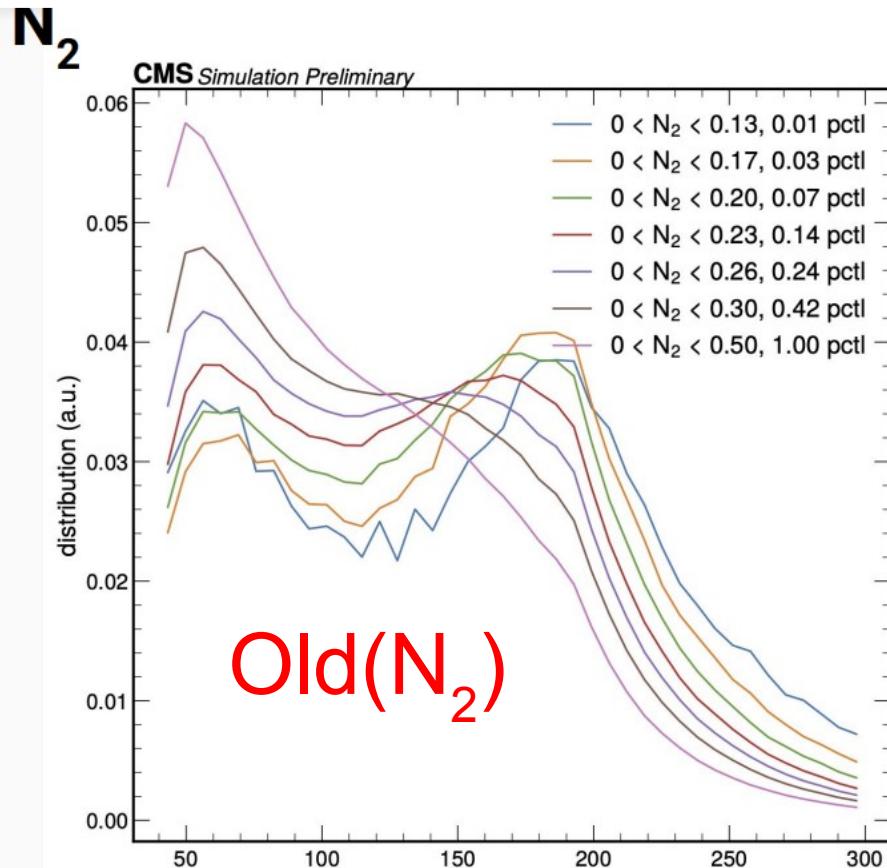
What about decorrelation?

After we first pointed out this was critical for jets
An industry of papers have been built off of this



A lot of people have been trying to modify networks/ to enforce decorrelation
This only goes so far

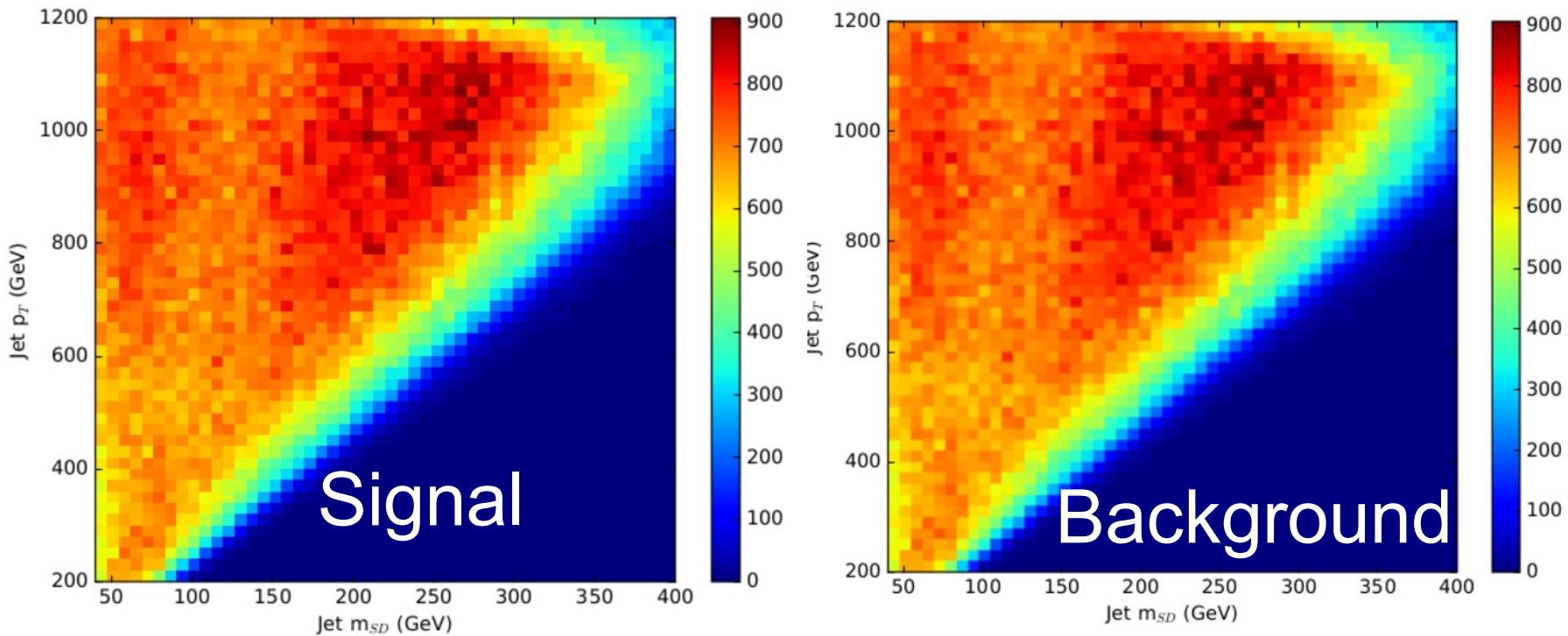
What about decorrelation?



With some clever(unpublished) tricks
Our newest NNs are fully decorrelated

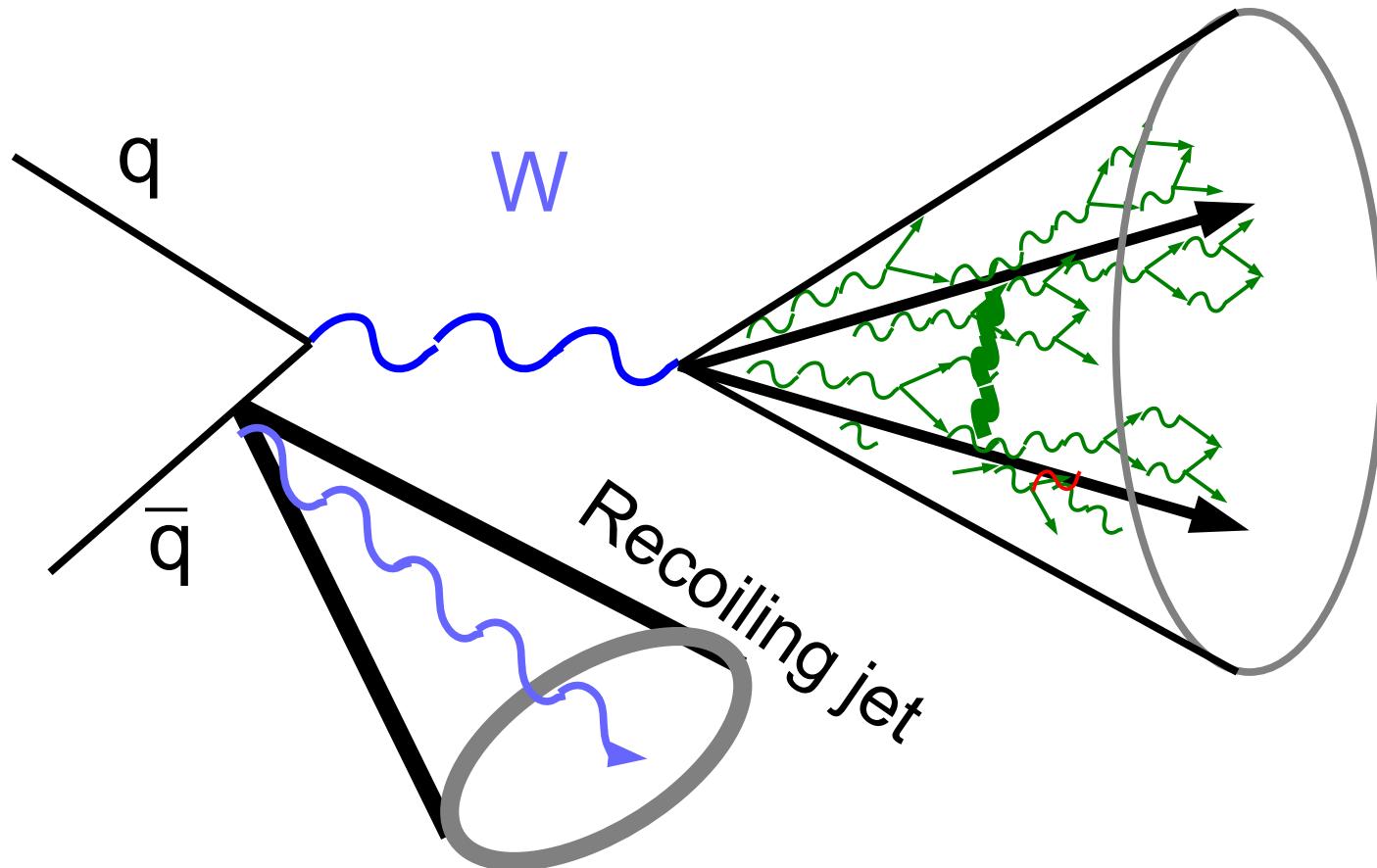
How did we de-correlate so well?

- Modified the matrix elements of our samples
 - Made a resonance with an infinite width
 - Also made this resonance have a flat p_T distribution
 - Matched the signal and background distributions



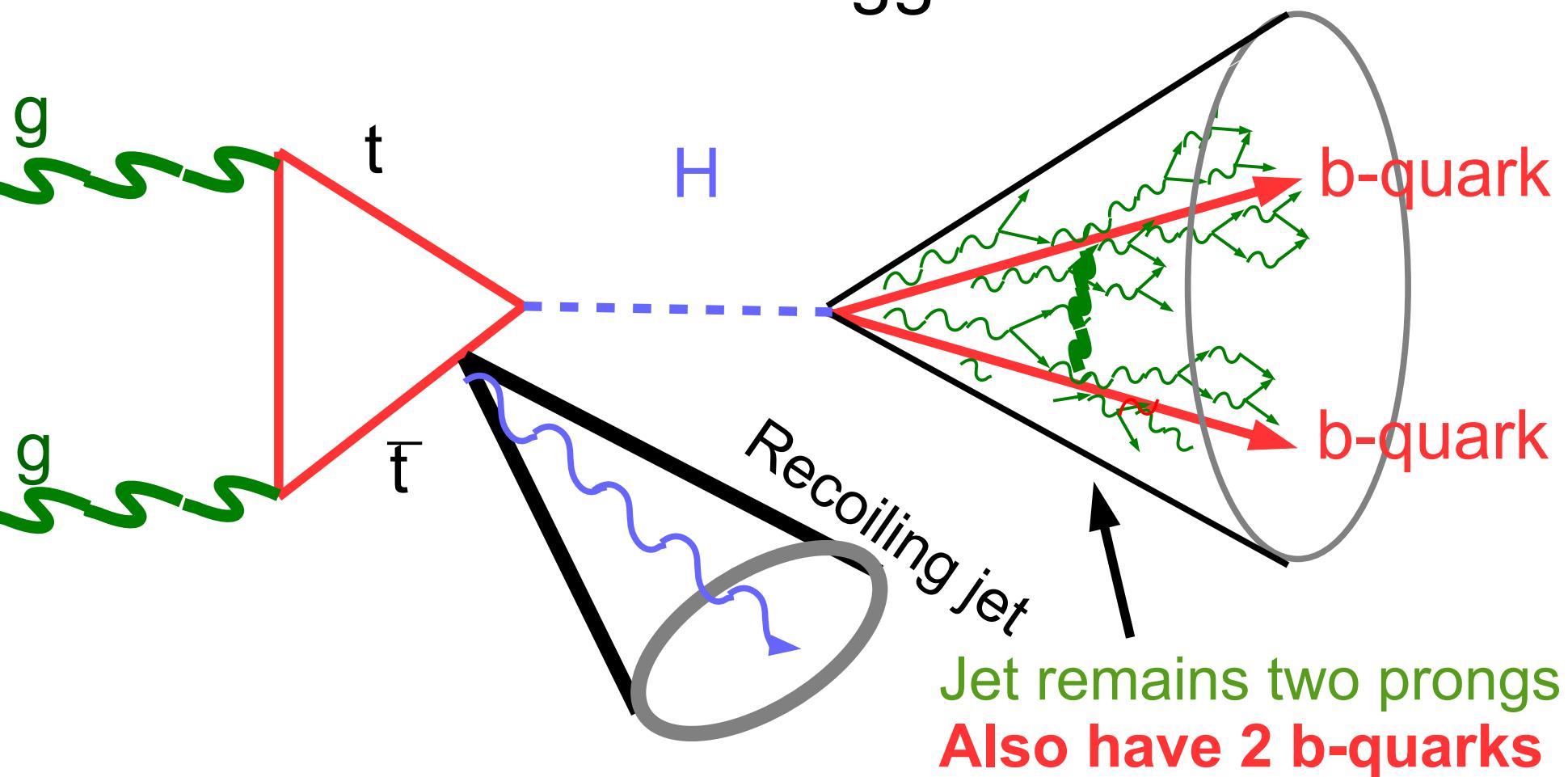
Changing Gears

We started with W production



How do things change for Higgs

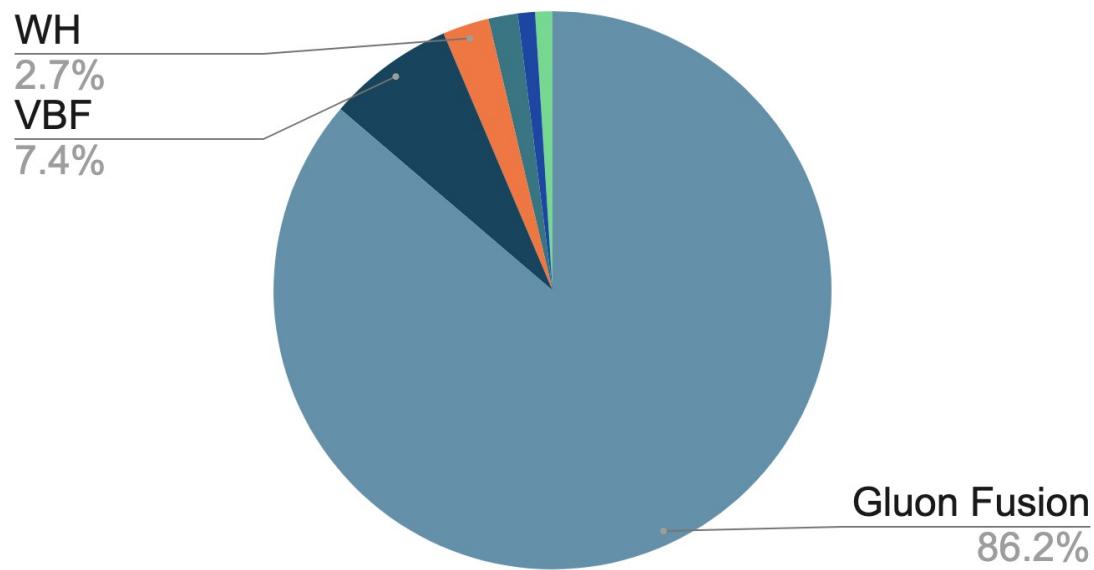
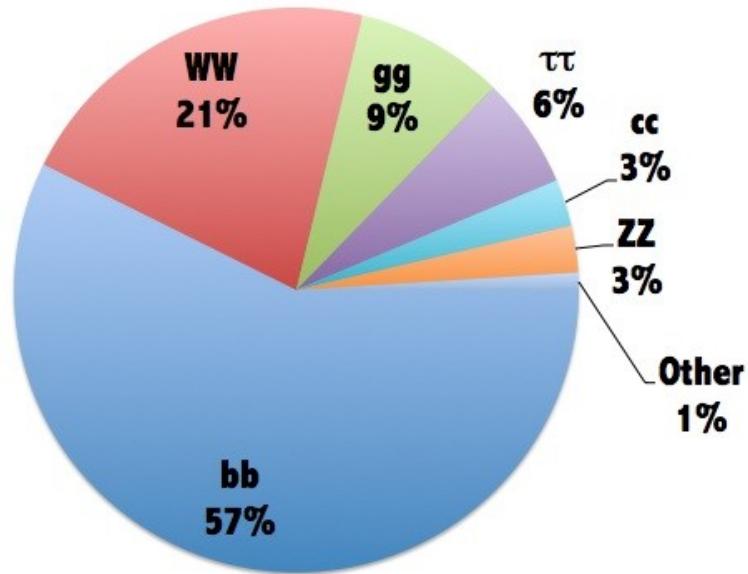
Now we can look for Higgs



Machine Learning has been the key to identifying b-quarks

What is so special about this?

Higgs decays at $m_H=125\text{GeV}$



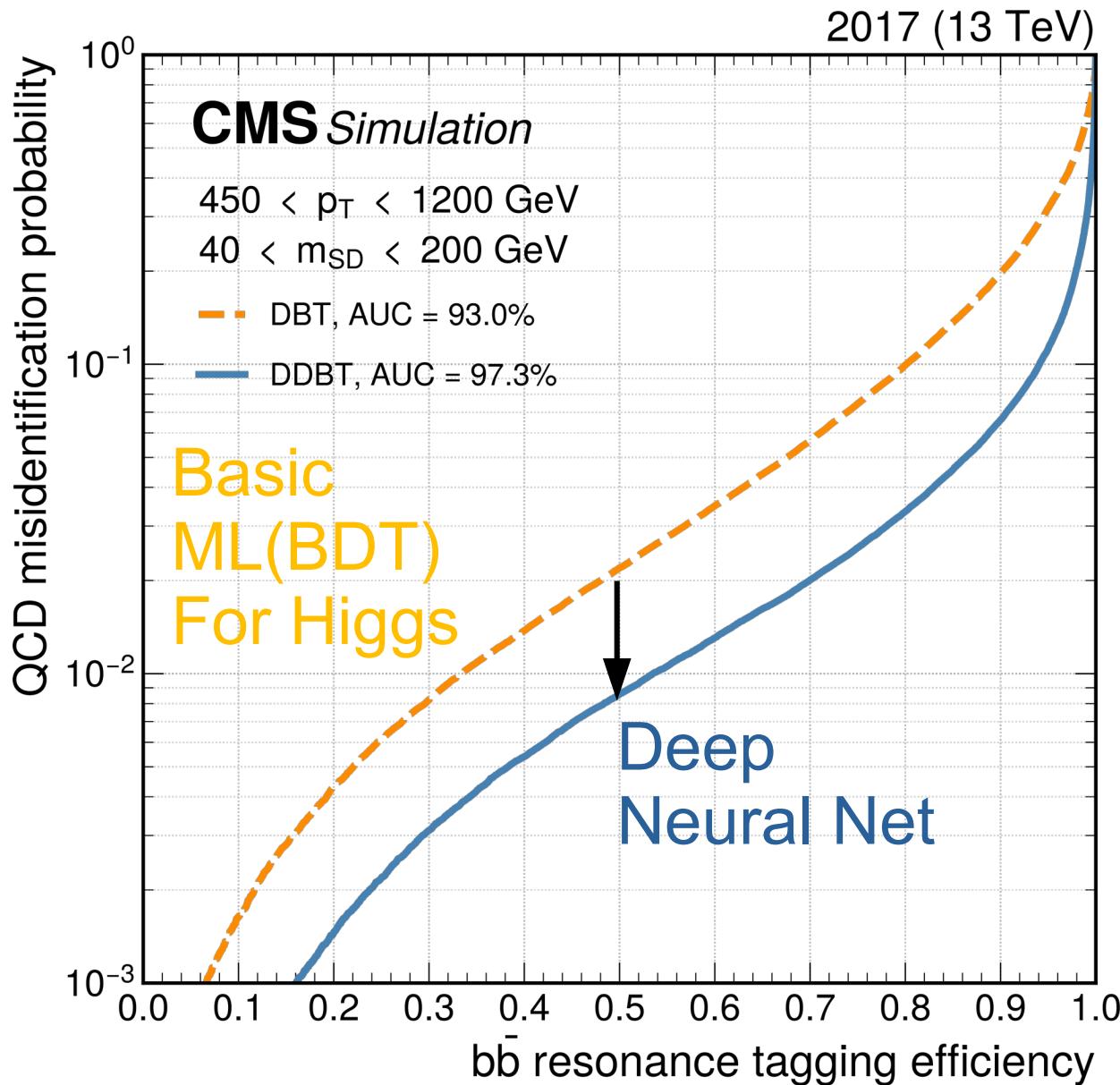
Higgs decays to b-quarks 58% of the time

Higgs is produced by gluon fusion 86% of the time

Highest single production mode (by $\times 10$)

Yet this channel was deemed to be impossible

What about the Higgs?

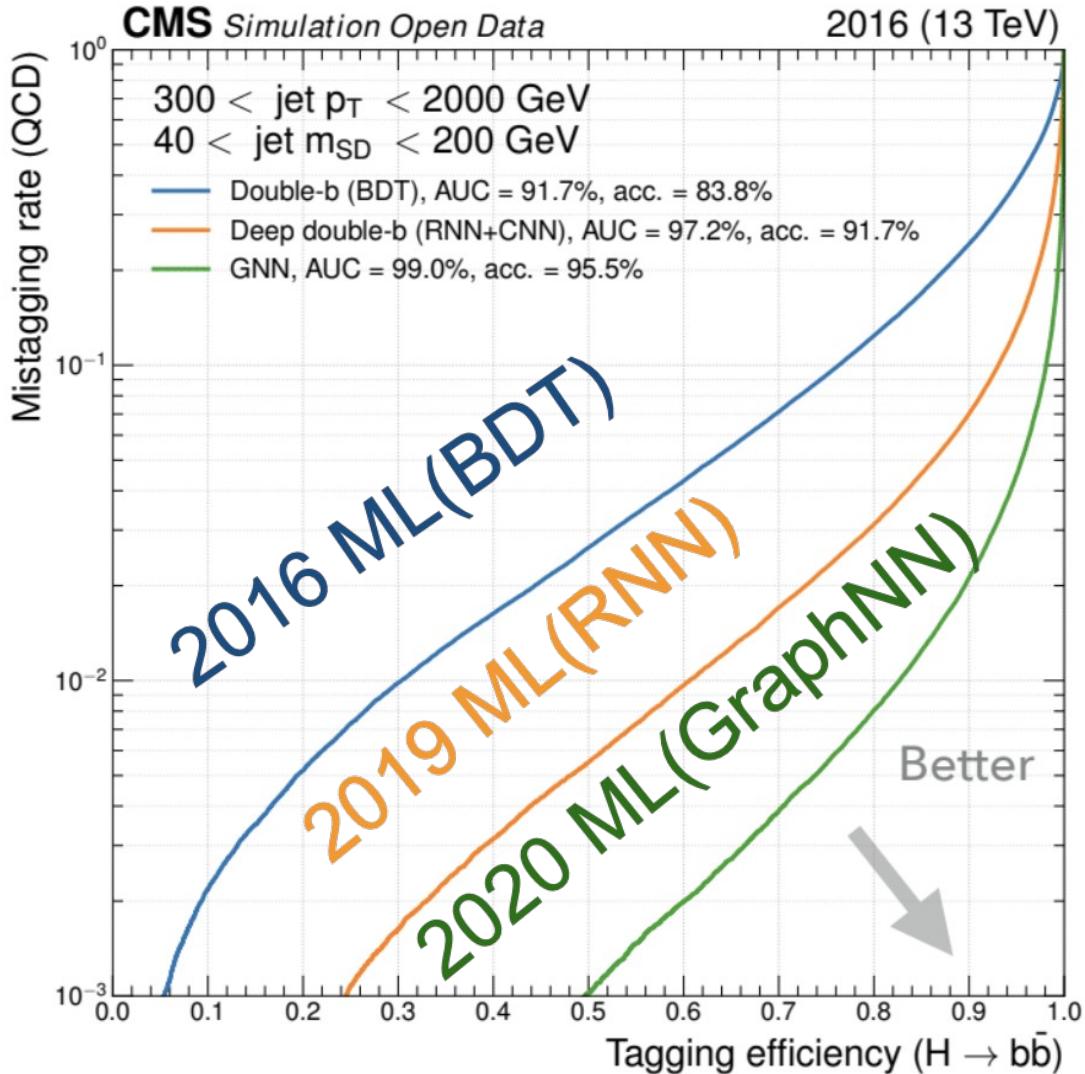


To identify the Higgs boson we need to remove background by even more

Key has been to use machine learning

Without these tools we could not have gotten there

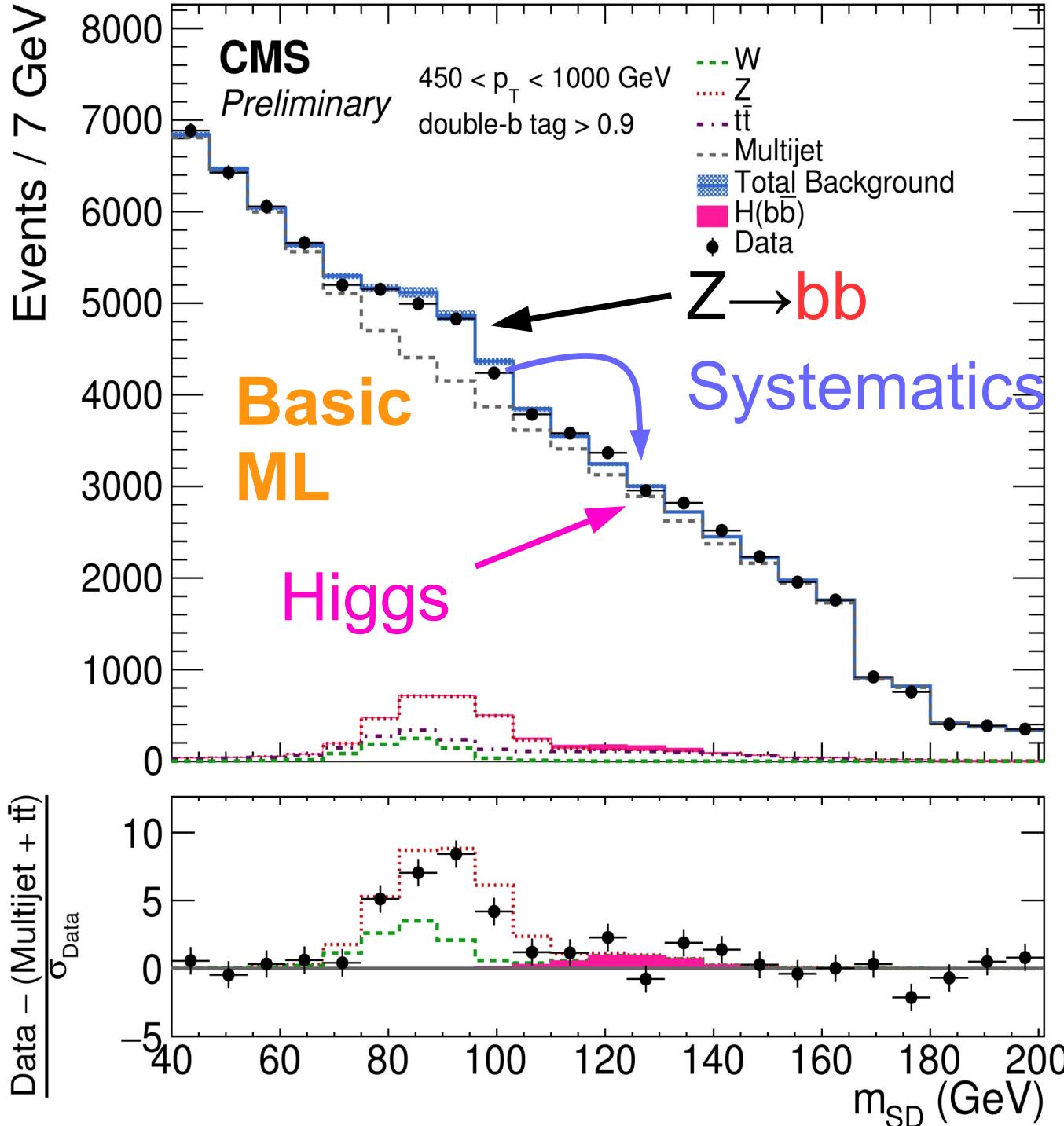
Deep Learning Revolution and Higgs



To identify the Higgs boson we need to remove background by even more

Key has been to use machine learning

Without these tools we could not have gotten there

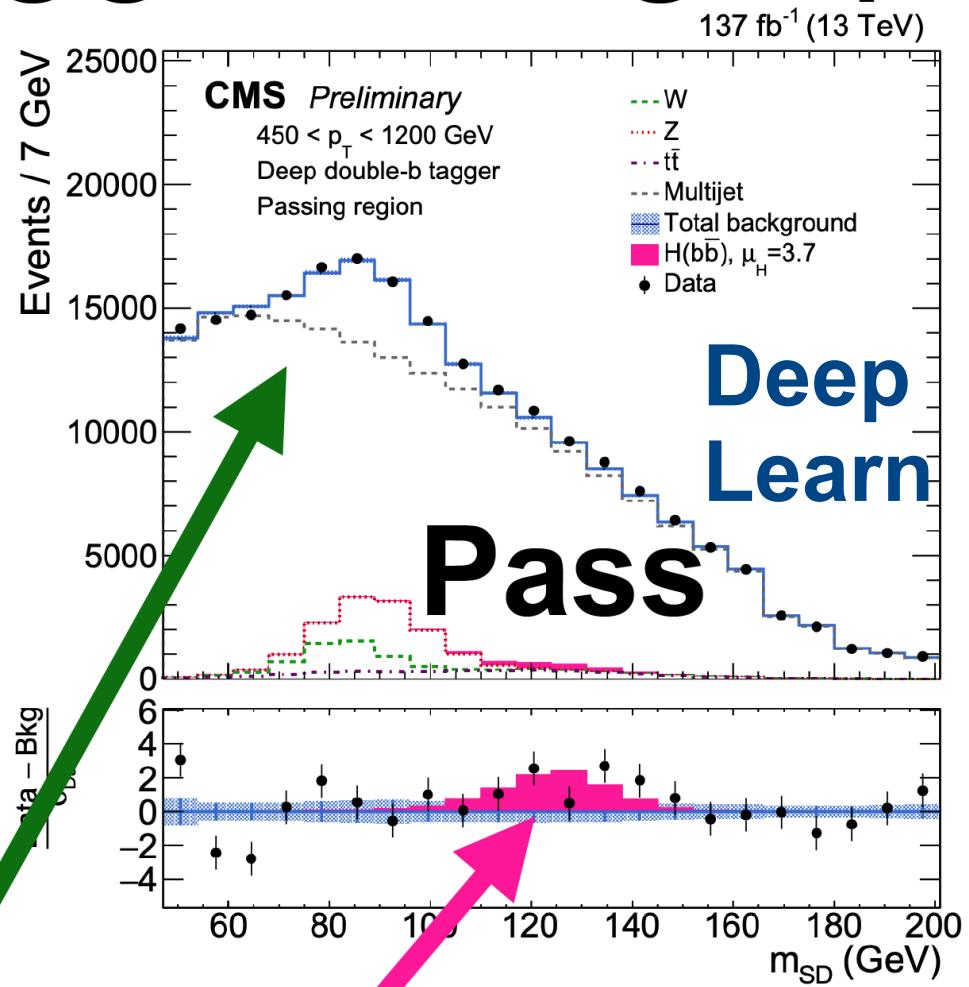
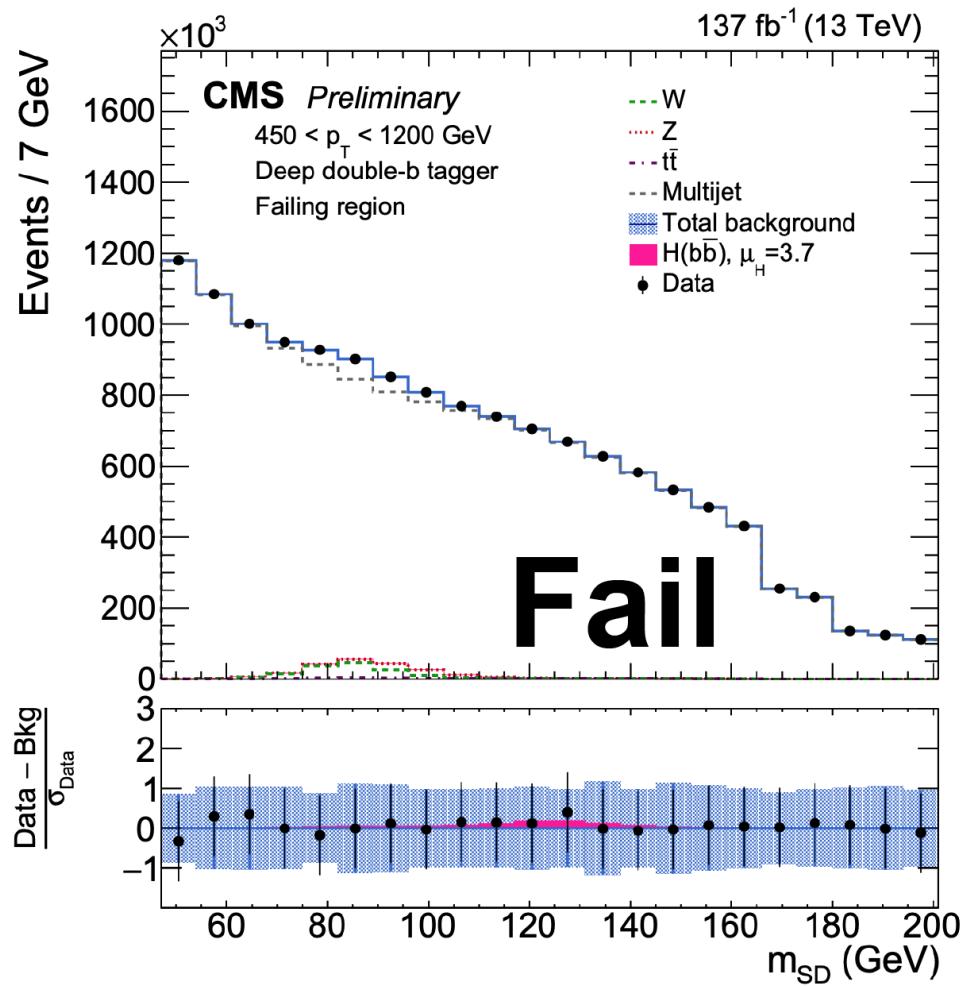
35.9 fb^{-1} (13 TeV)

First Result

The large $Z \rightarrow b\bar{b}$
Allows us to
calibrate our
signal

Z peak
Allows us to
calibrate Higgs

Higgs at high p_T



Relied on the Z to perform
Calibration $\mu_Z = 1.01^{+0.24}_{-0.20}$

Large Excess at Higgs mass $\mu_H = 3.7^{+1.6}_{-1.5} (2.5\sigma)$

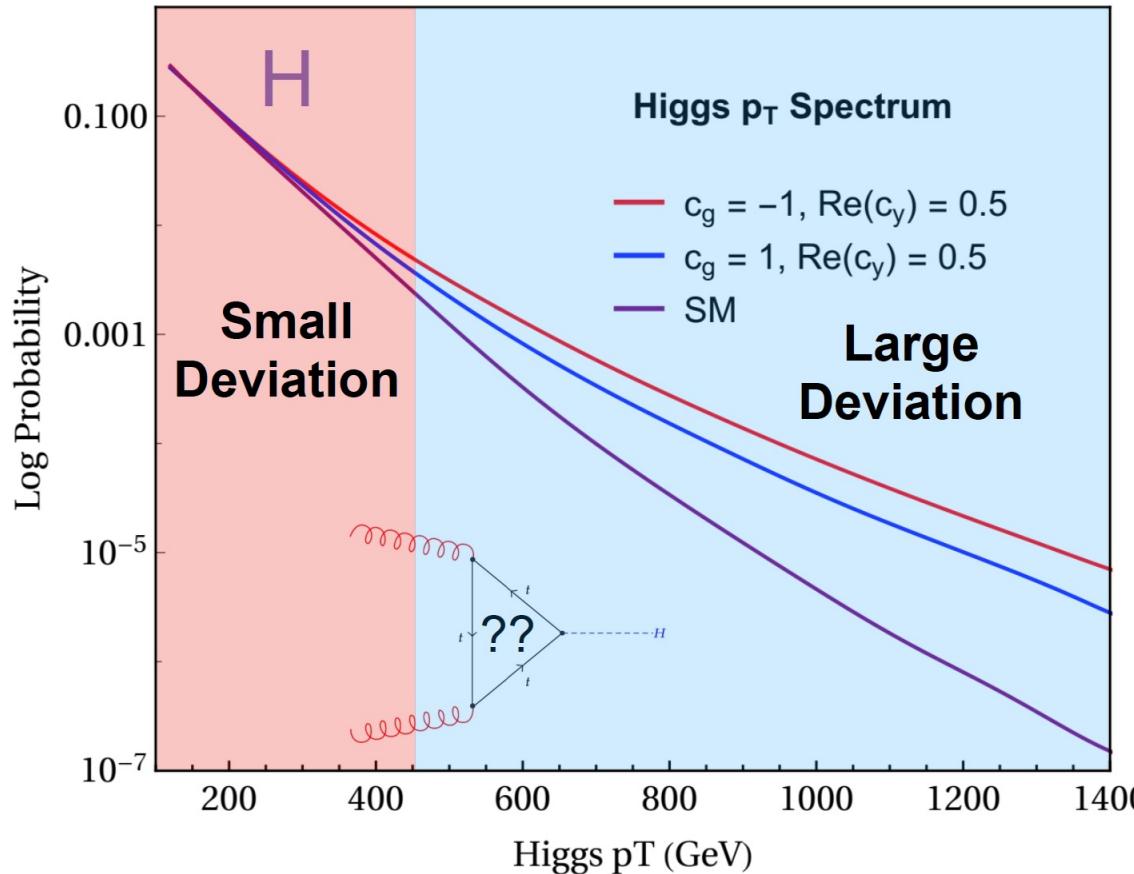
μ is wrt to LHC Higgs WG

Physics Implications

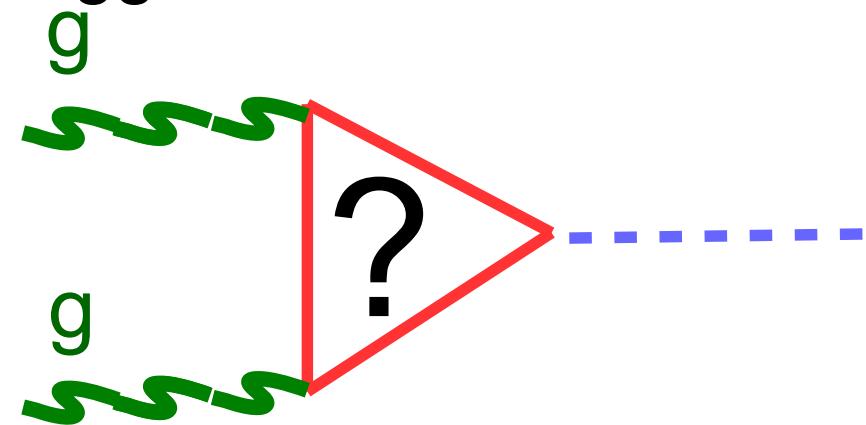
advantage of the harder transverse momentum spectrum of the $gg \rightarrow H$ production mode with respect to the QCD background, a search for high p_T Higgs boson decaying to a pair of b quarks in association with an energetic Initial State Radiation (ISR) jet, has been performed by ATLAS [155] and CMS [156]. For this analysis with the Run 2 data, ATLAS and CMS require jets clustered with

Particle Data Group 2020
(High Energy Physics Handbook)

Higgs at High Energy



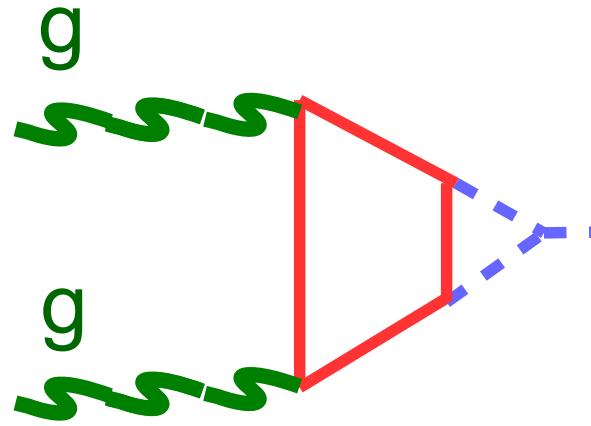
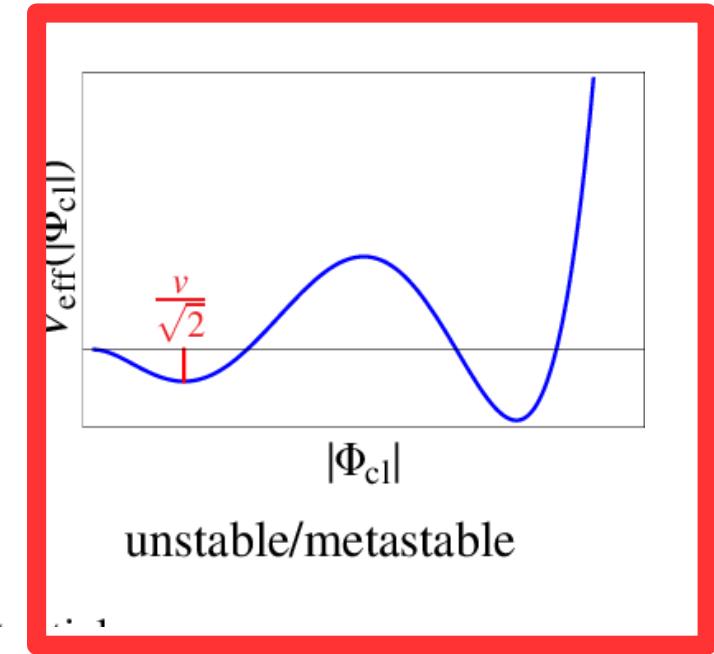
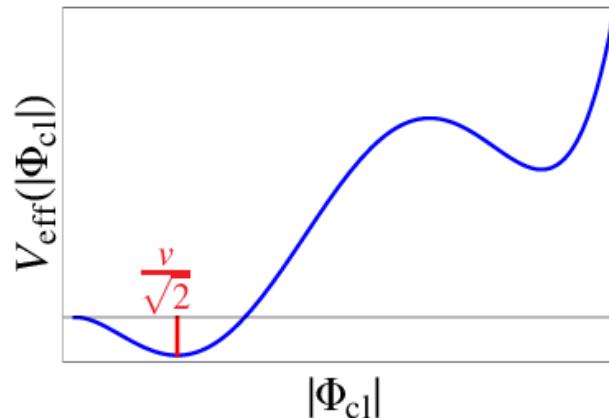
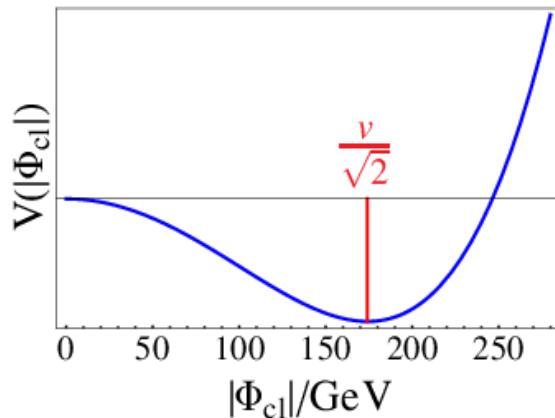
Process with the most events is the best at probing highest energy Higgs bosons



Can now measure Higgs process in the blue region
 Could not before
 Note: The prediction in this region is not well known

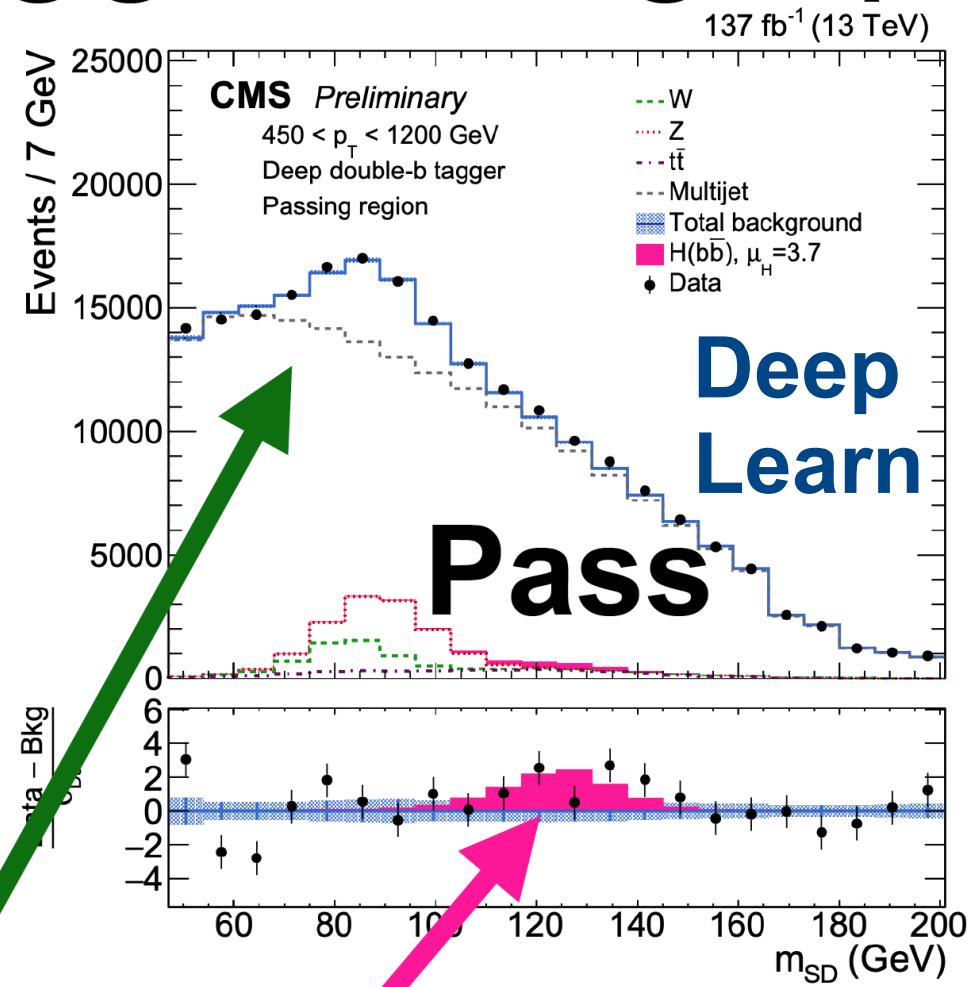
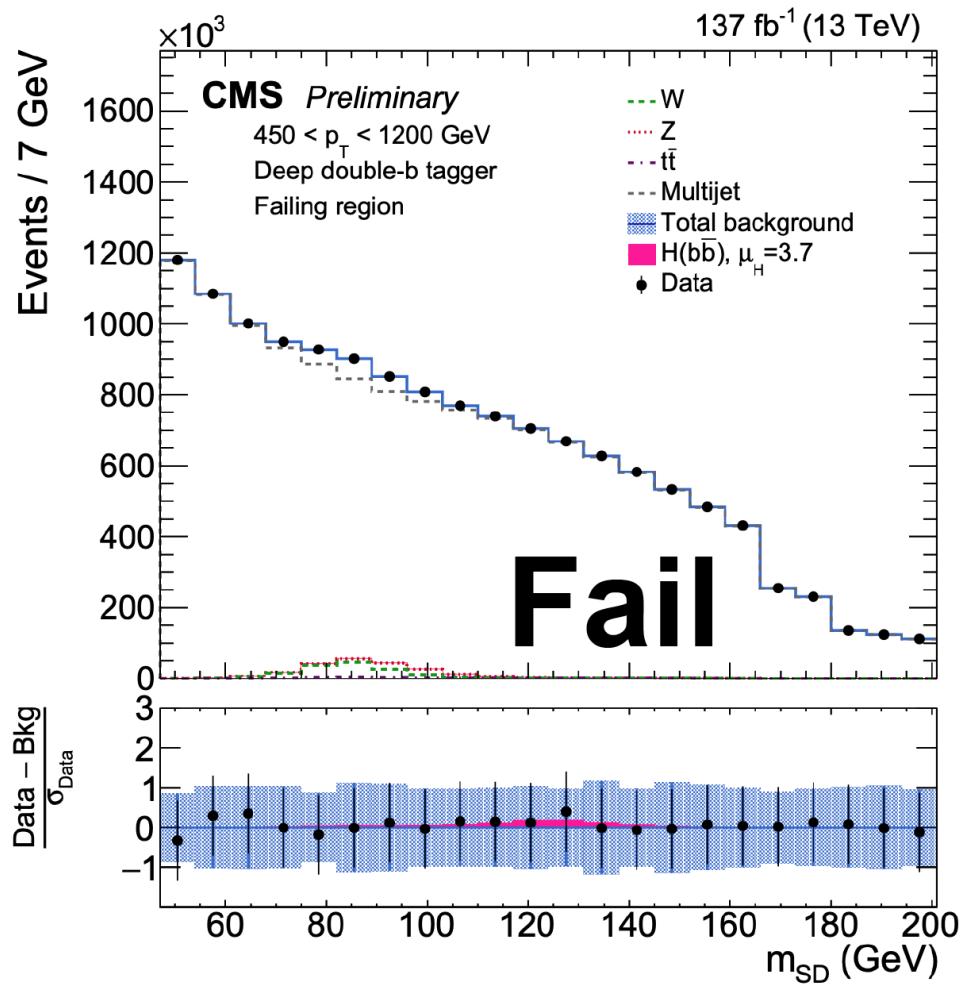
State of the Universe

- What does this have to do with it?



High energy regime
potentially tells us about the
stability of the Higgs potential

Higgs at high p_T

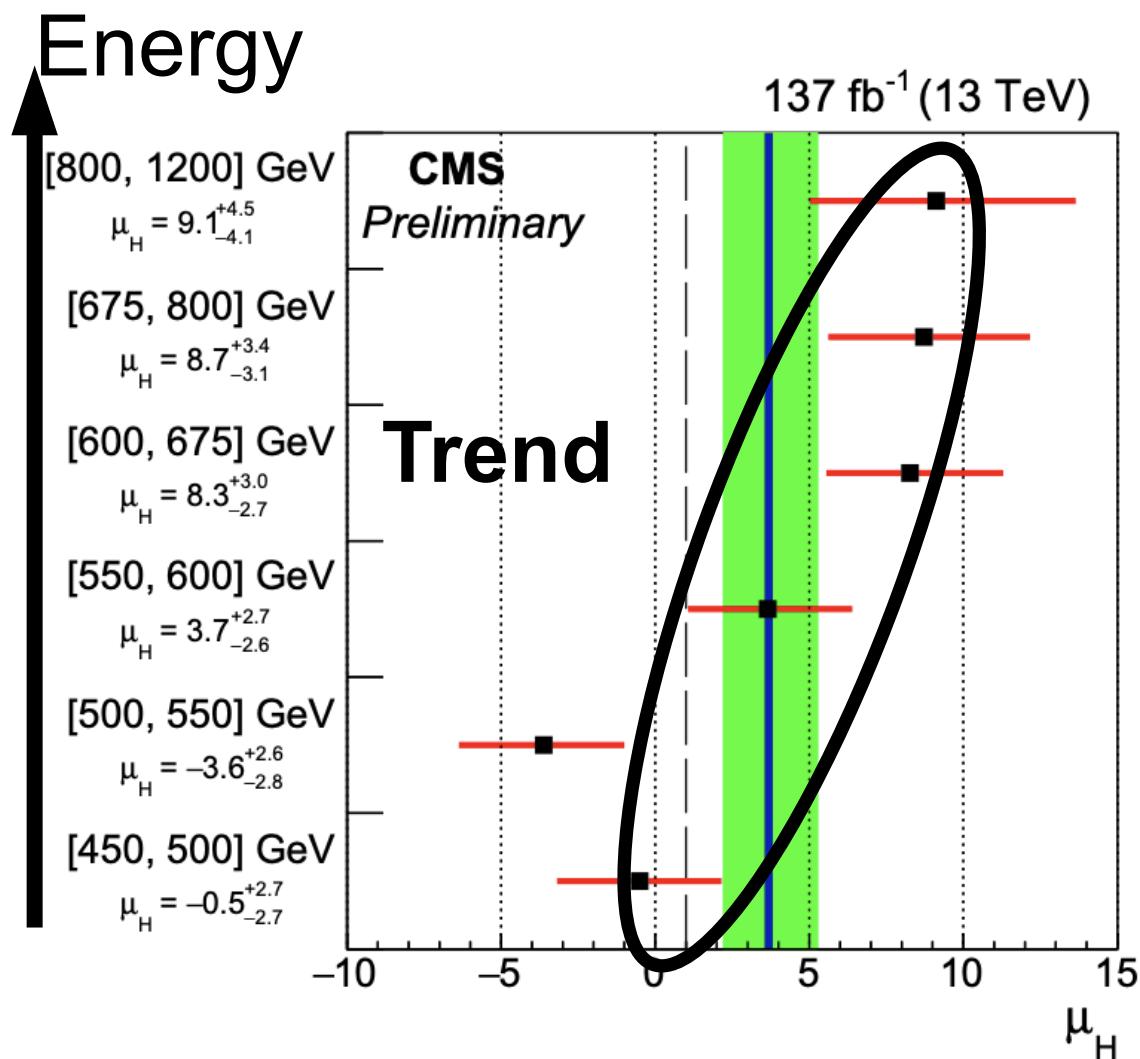


Relied on the Z to perform
Calibration $\mu_Z = 1.01^{+0.24}_{-0.20}$

Large Excess at Higgs mass $\mu_H = 3.7^{+1.6}_{-1.5} (2.5\sigma)$

μ is wrt to LHC Higgs WG

Delving in more detail



Trend toward higher Energy

Consistent with modified coupling

This regime is difficult to calculate

Large excess shows an interesting trend

What does this mean?

Large excess with a trend means.....

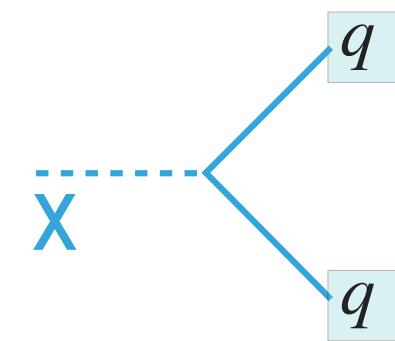
Our prediction for high energy Higgs bosons is off
Higgs boson production at high energy is HARD

There is the potential of some new physics

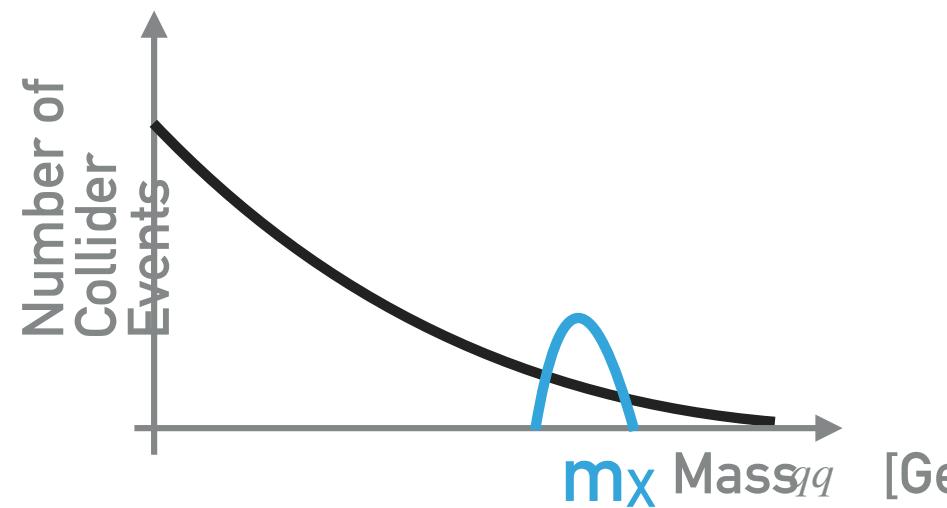
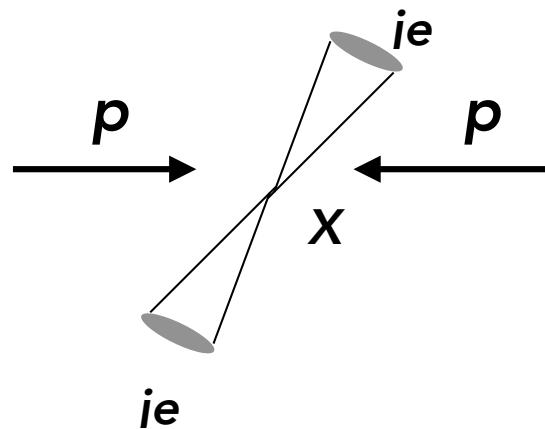
We are not yet at the point where we can make a significant claim

Low mass (qq) resonances

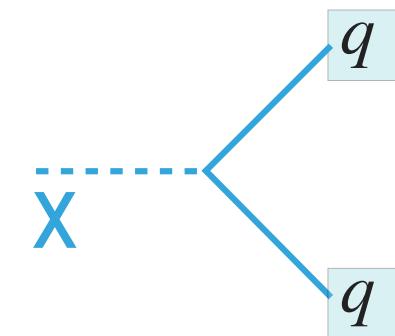
Looking for a resonance At the LHC



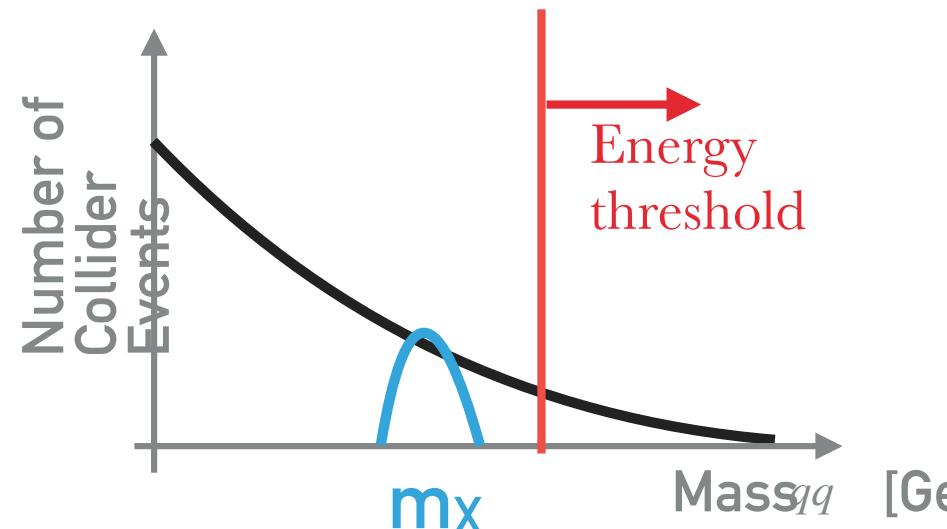
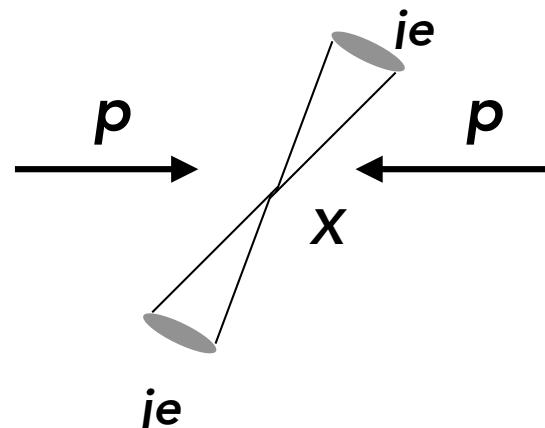
$p_T < 200 \text{ GeV}$
 $m_X > 500 \text{ GeV}$



If $m_X < 500 \text{ GeV}$, event does not get saved
LHC has tight energy thresholds (mass thresholds)

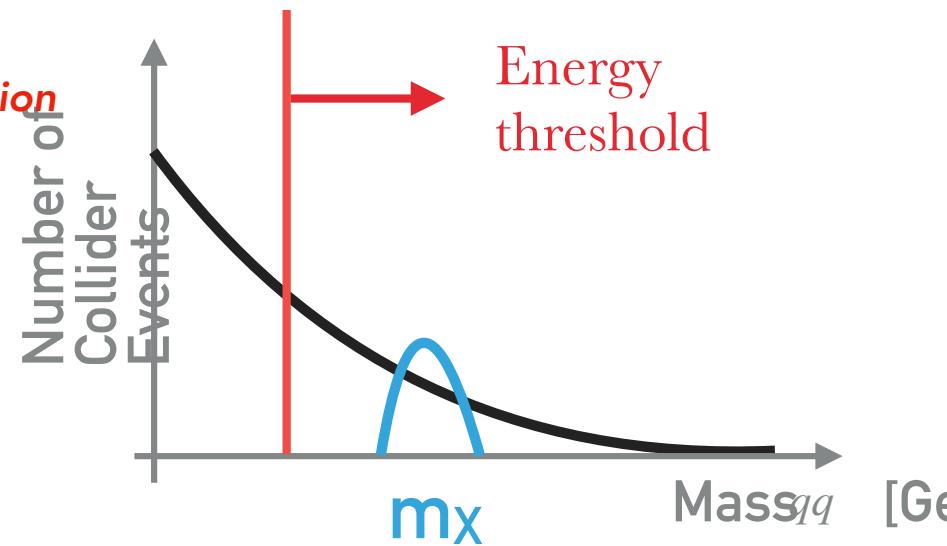
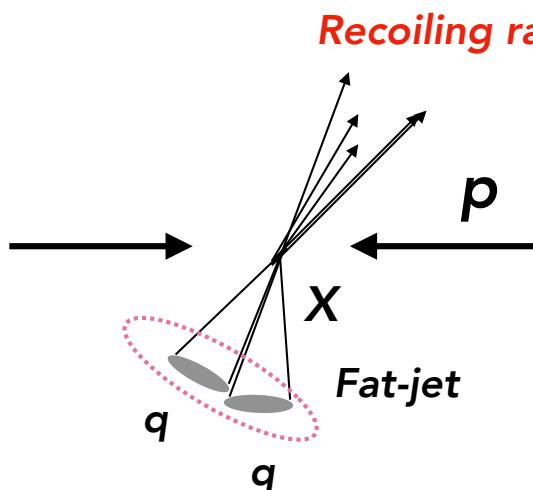
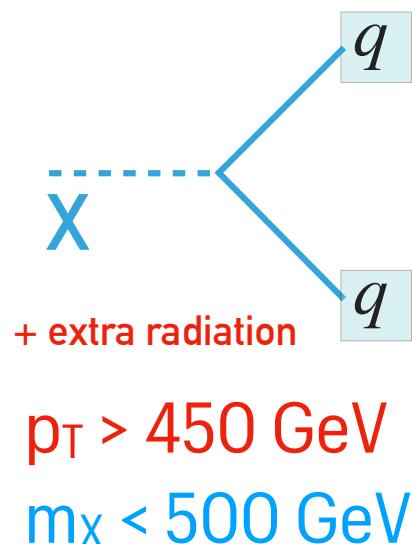


$p_T < 200 \text{ GeV}$
 $m_X < 500 \text{ GeV}$



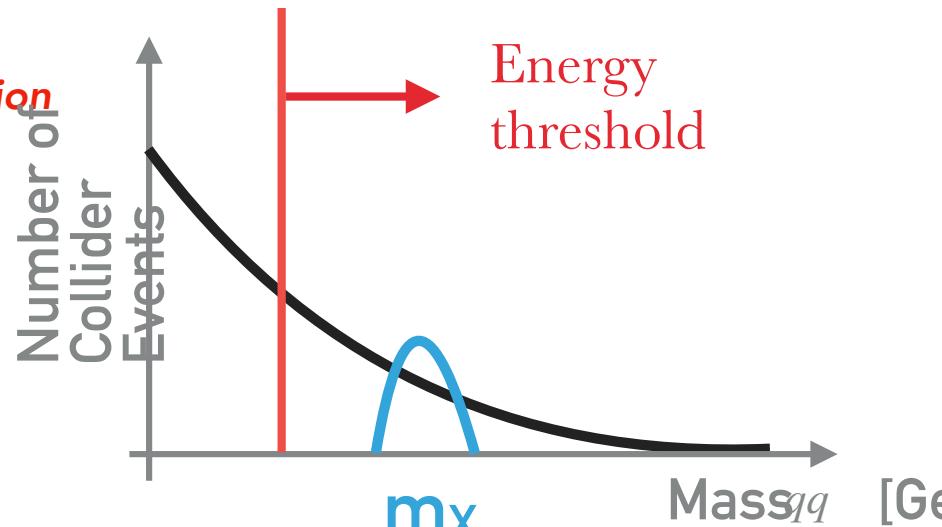
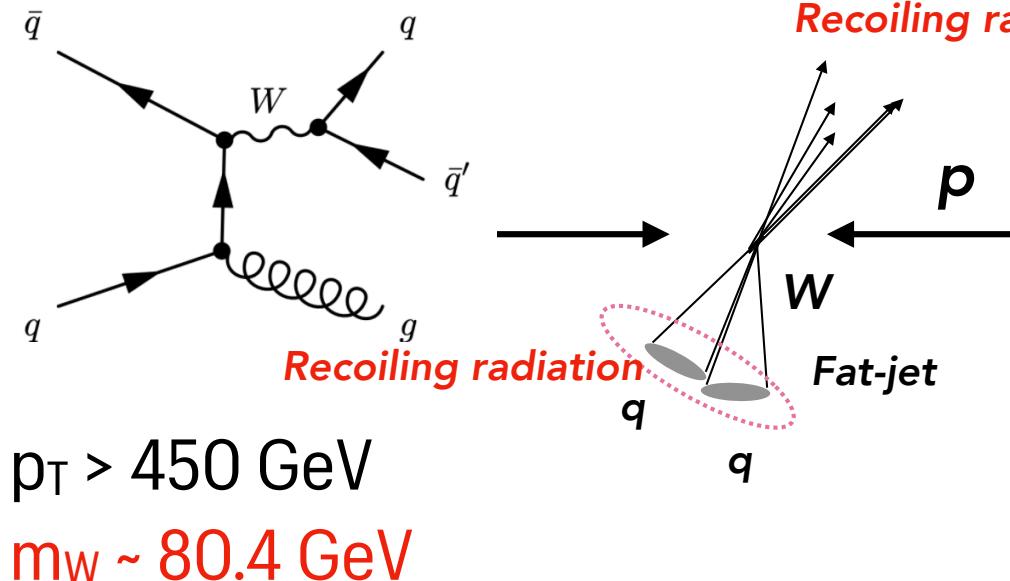
How to save these events

Boost them!



What the process looks like

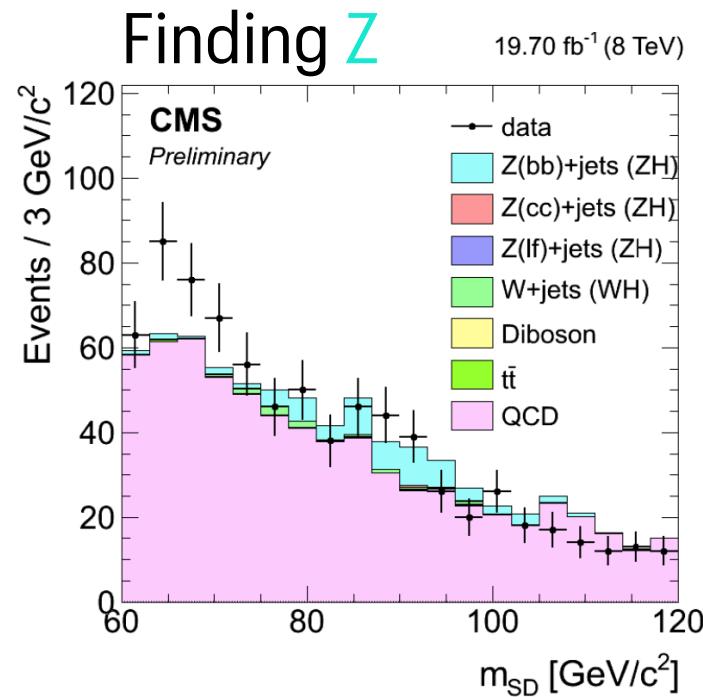
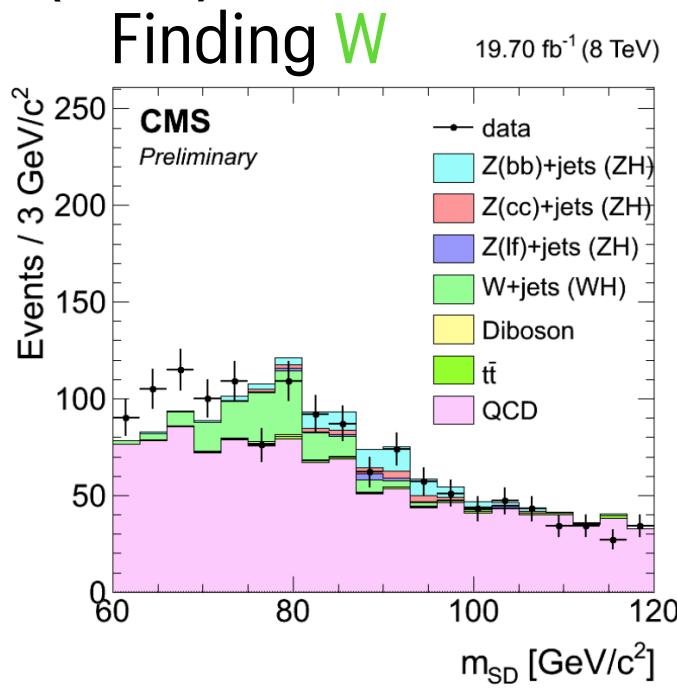
And what you'll be looking for



Your goal: reproduce LHC results (or improve them)

With 8 TeV data

@ 8 TeV (2015)

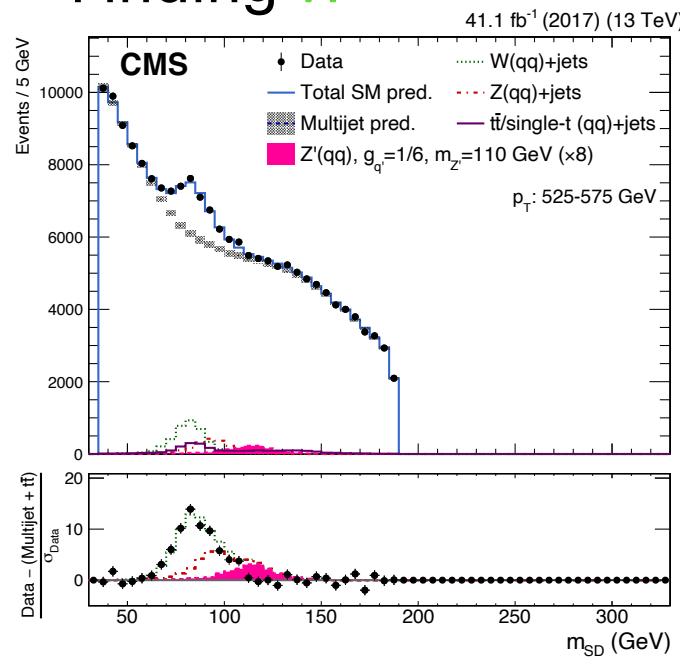


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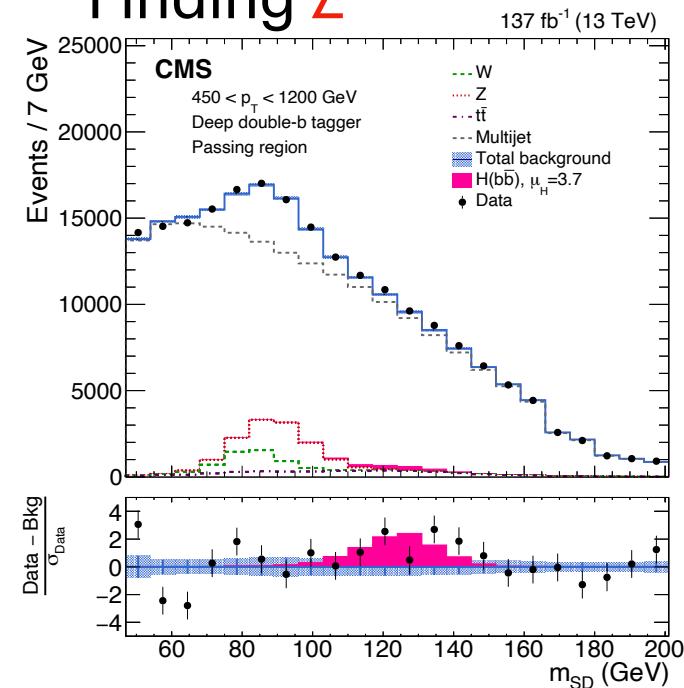
With 8 TeV data

@ 8 TeV (2015)

Finding W

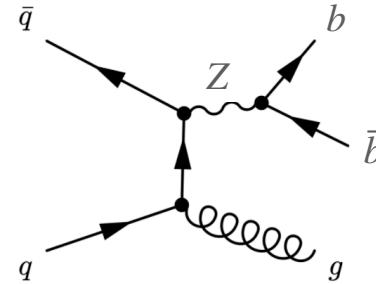
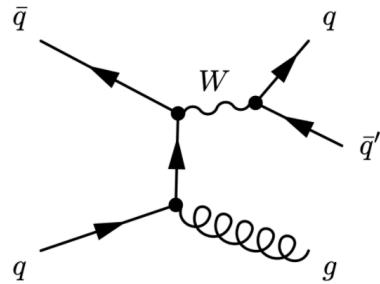


Finding Z



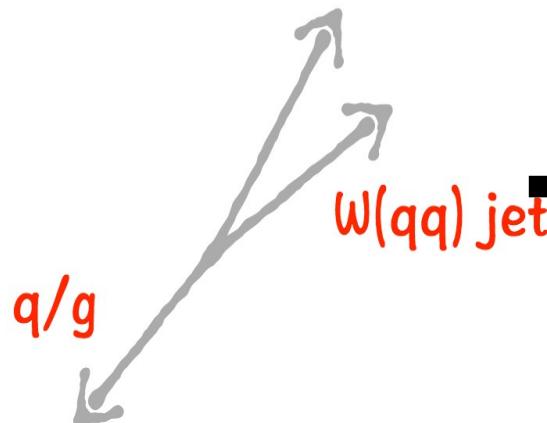
Project 2

Finding W(qq) and Z(qq) in 8 TeV LHC data

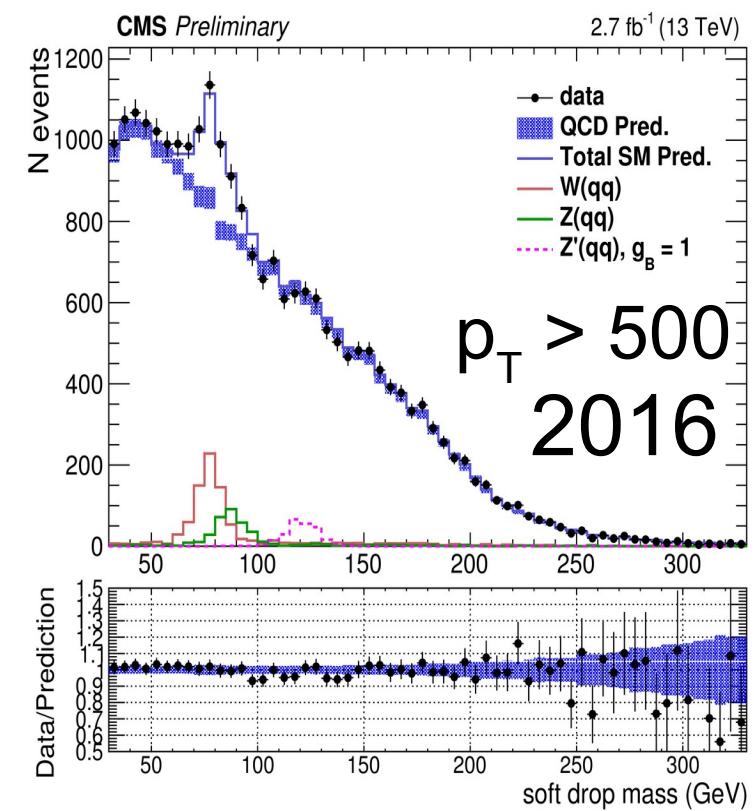
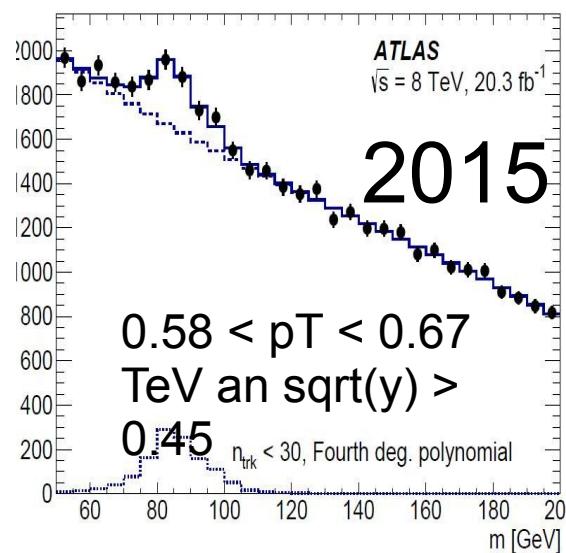
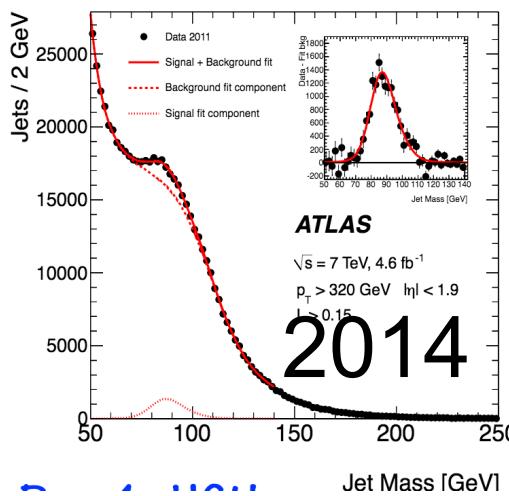


Introduction

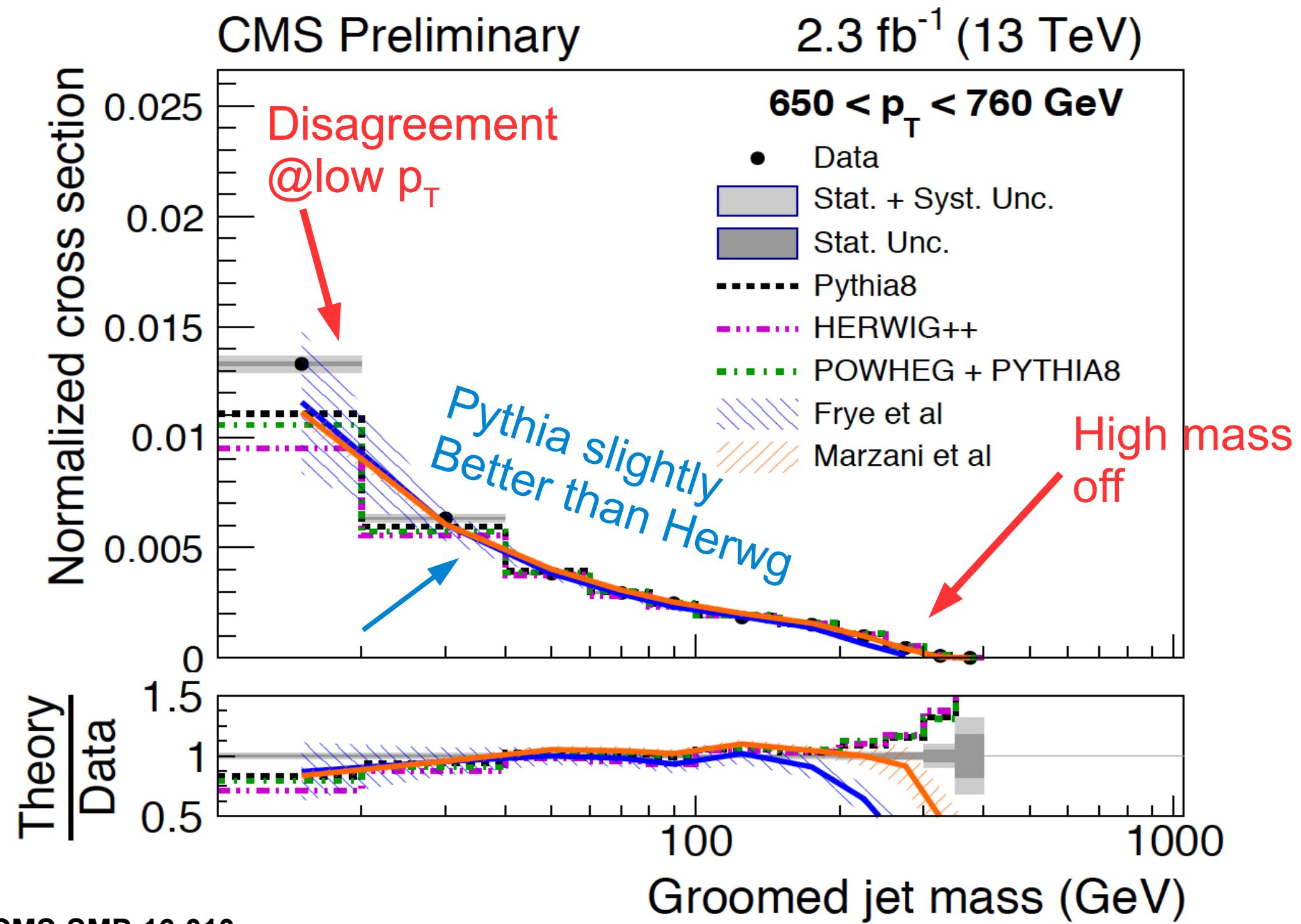
In this lab we will investigate W bosons produced in the LHC's 8 TeV proton proton collisions. These samples were produced 4 years ago in a fun experiment that opened up the option of performing low mass resonance searches at the LHC. The studies done then have led to a wealth of results from both LHC experiments, ATLAS and CMS. To understand how this study works, we first need to introduce a few concepts.



Thanks!

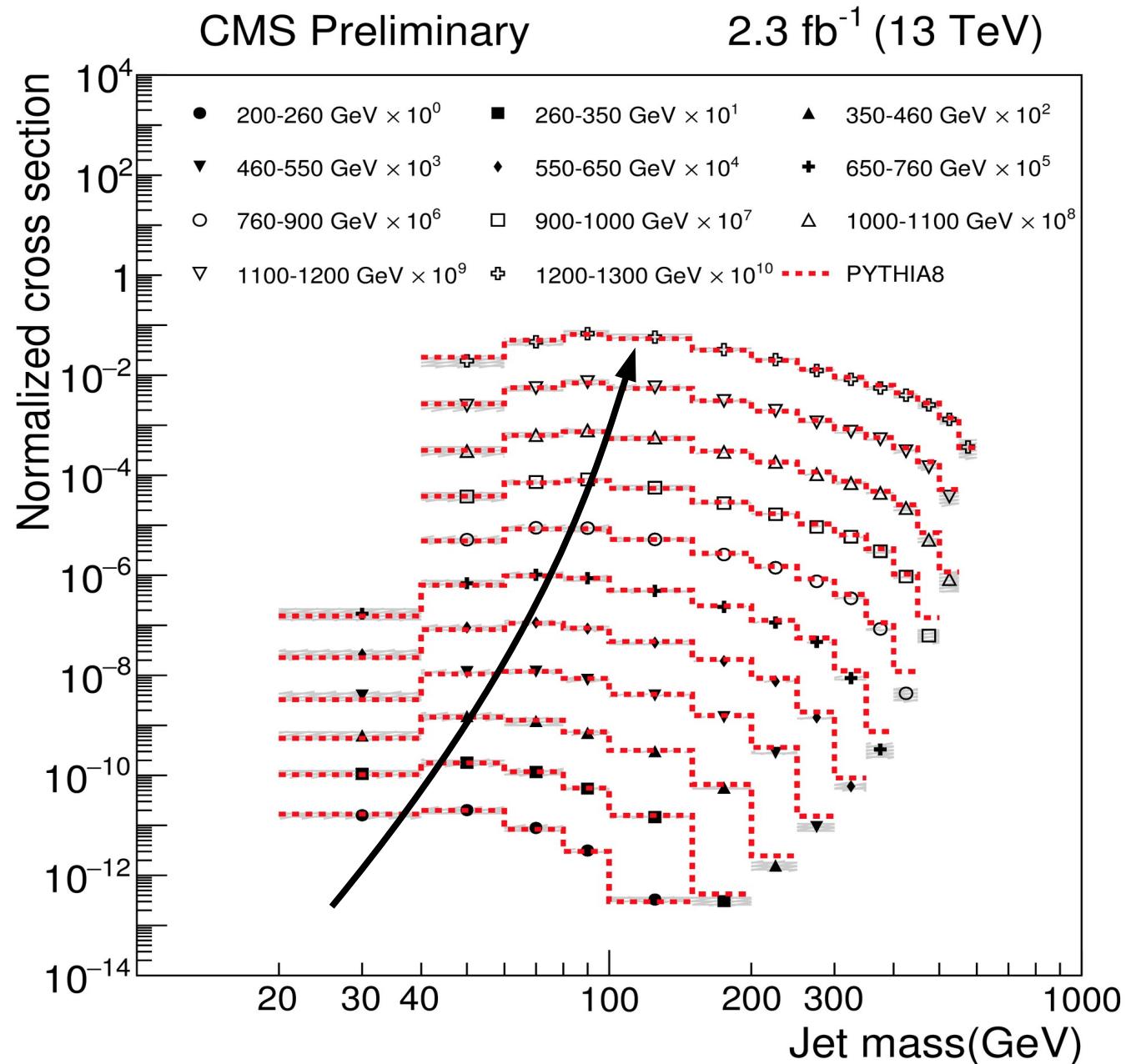


This peak has only been observed over past 2 years



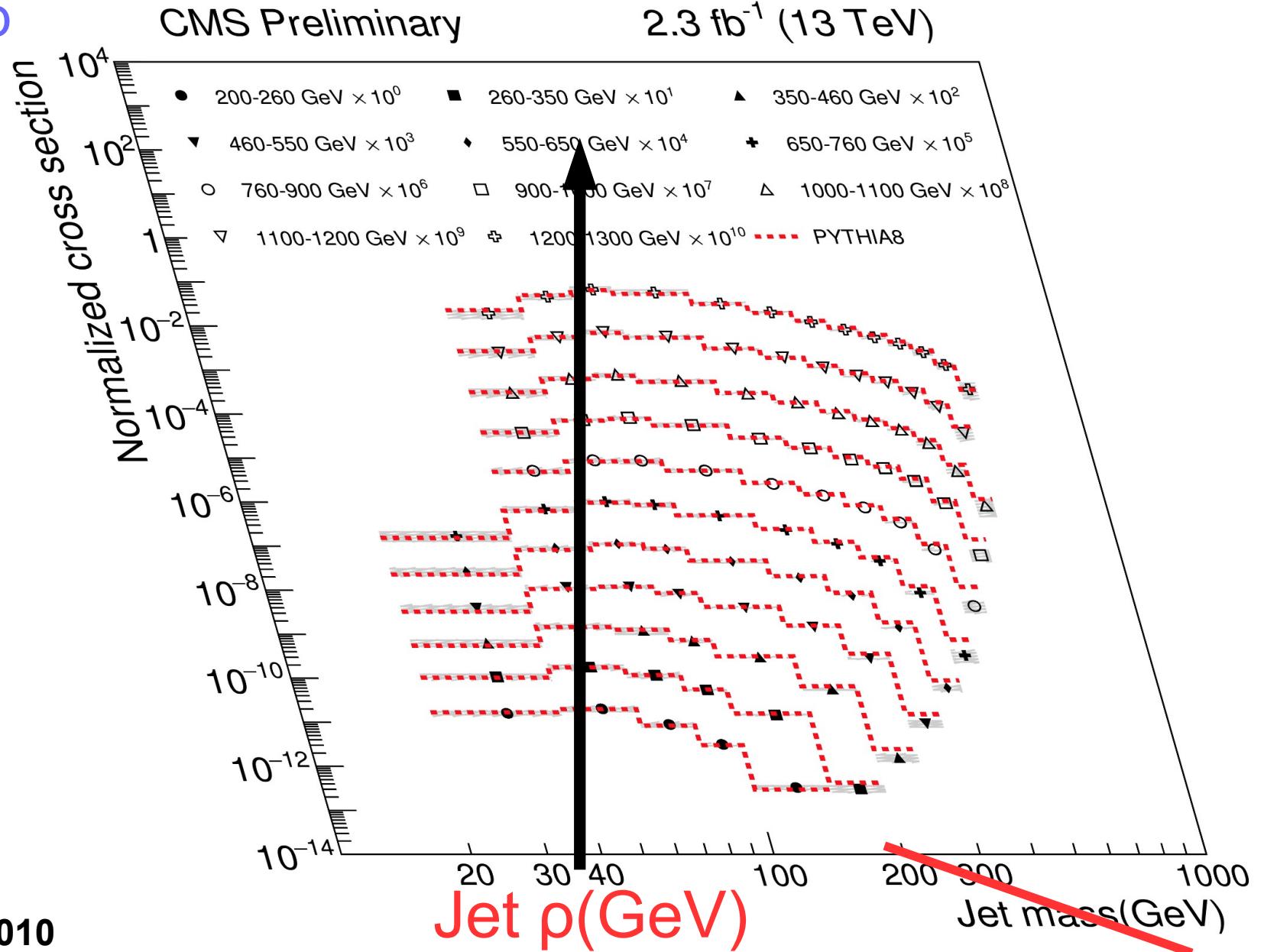
Evolution of Mass Peak

Clear trend in observed mass



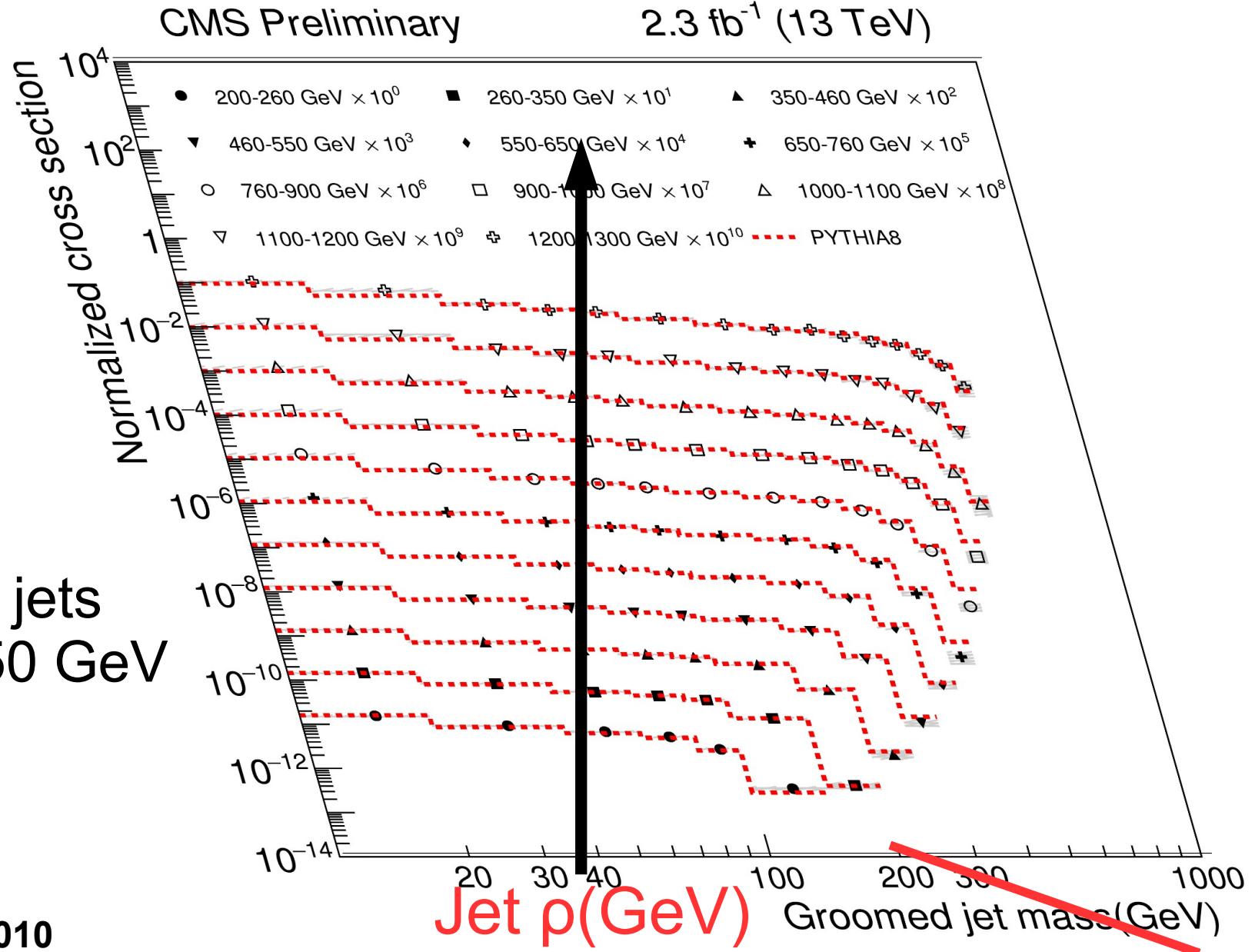
Trend becomes straight
When transform from
mass \rightarrow p

Evolution of Mass Peak



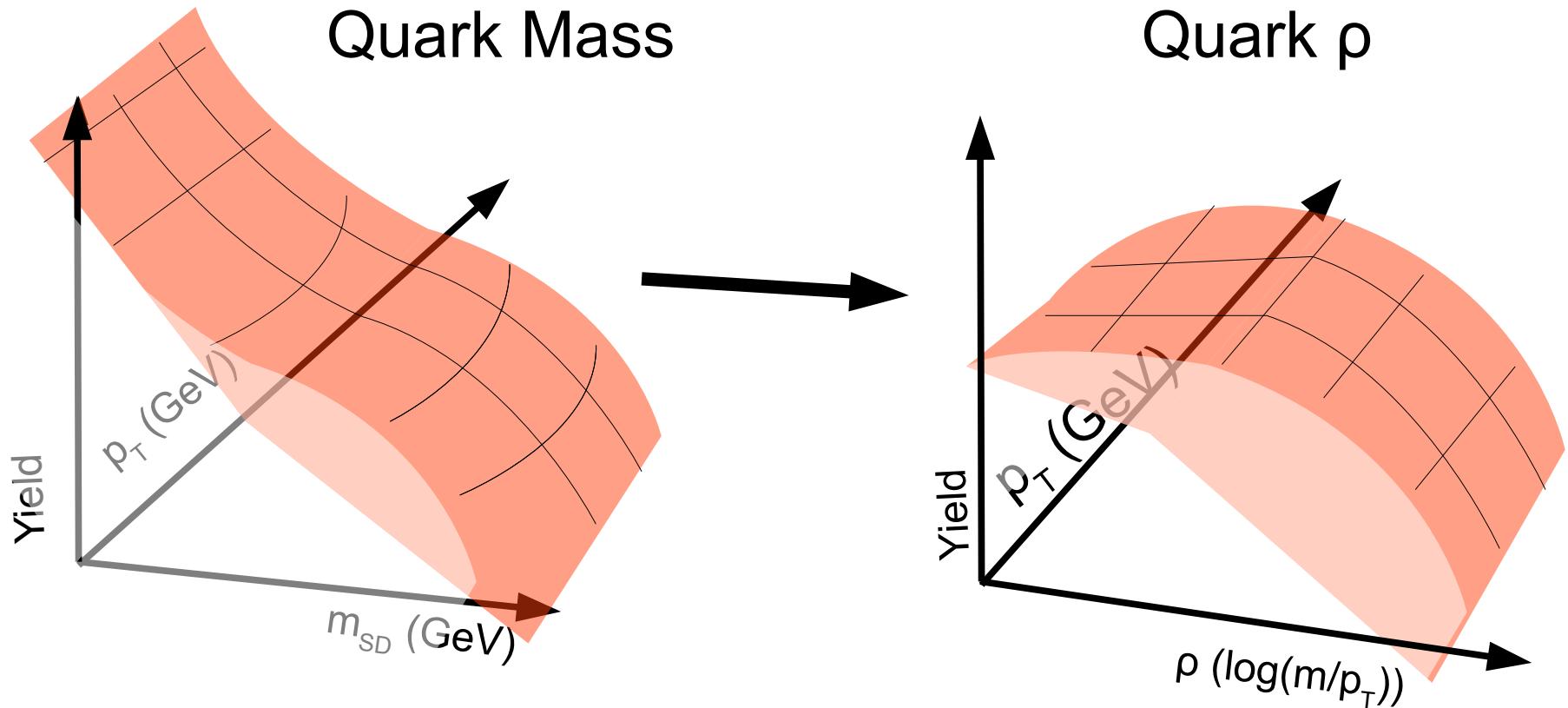
Groomed Evolution

When grooming the mass becomes even flatter in ρ



Merging with ρ

- Merging to ρ makes imposes invariance over p_T

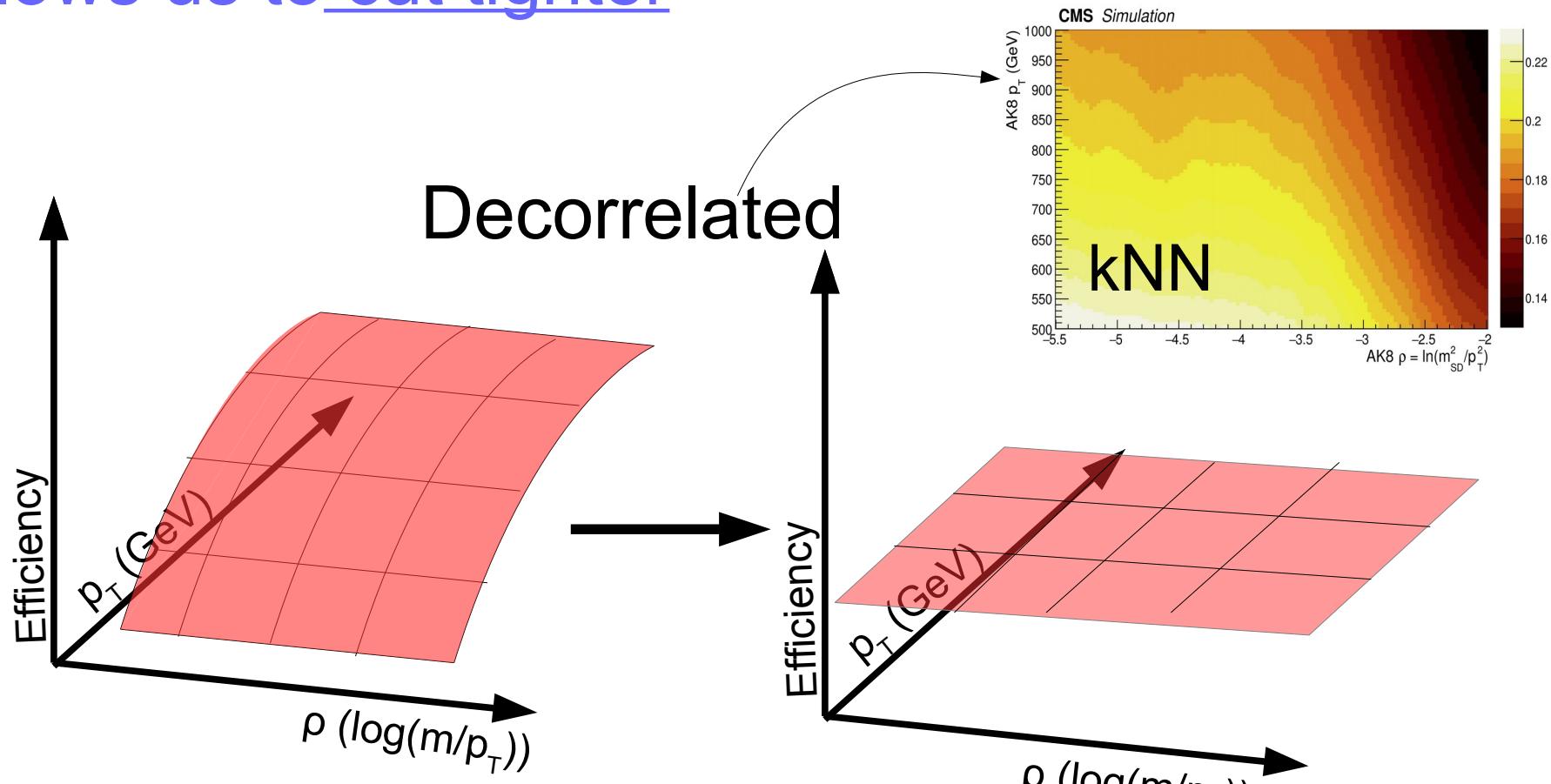


When translating to ρ distributions over p_T are also invariant

This allows us to extend our fit from 1D mass to 2D p_T and ρ

Design a transform to decorrelate against mass and p_T

Decorrelating avoid mass sculpting
allows us to cut tighter

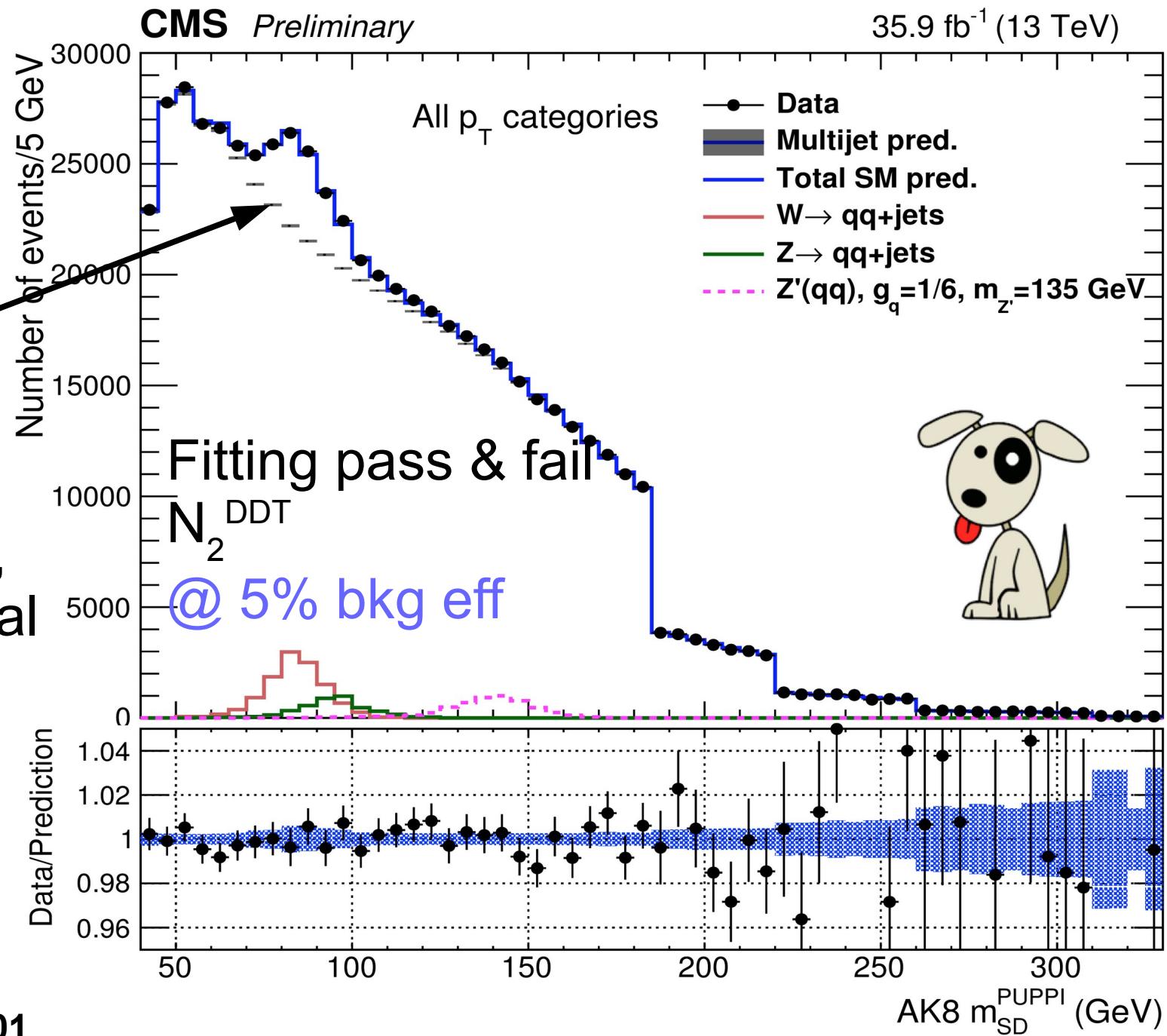


As a first example decorrelate $N_2 \rightarrow N_2^{DDT} = N_2 - \varepsilon(x\%)$

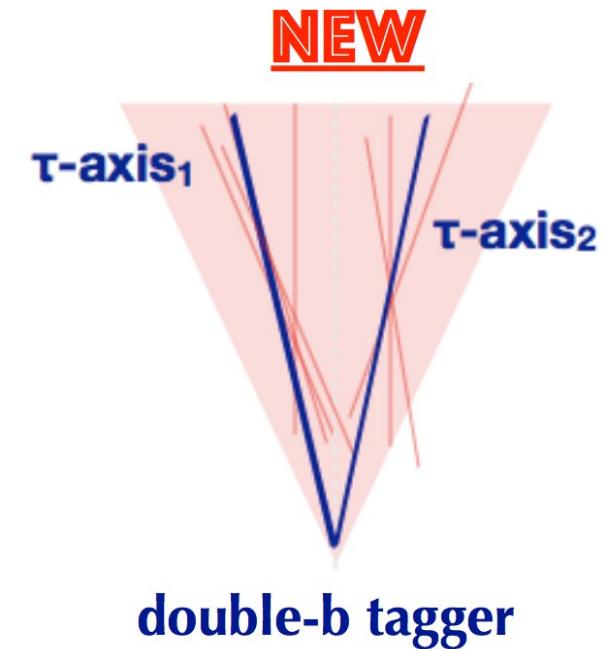
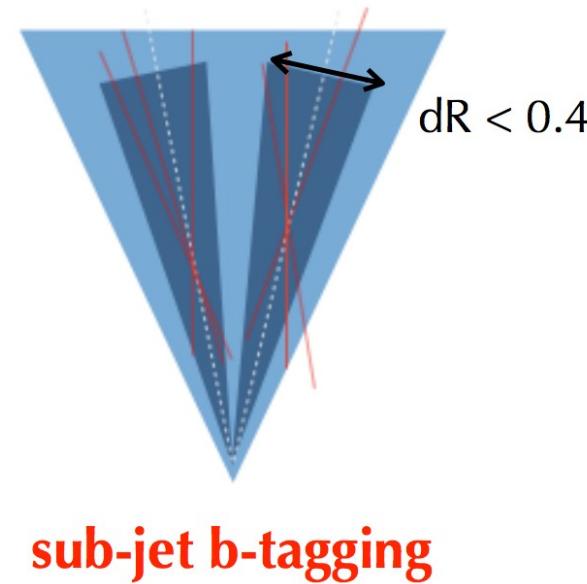
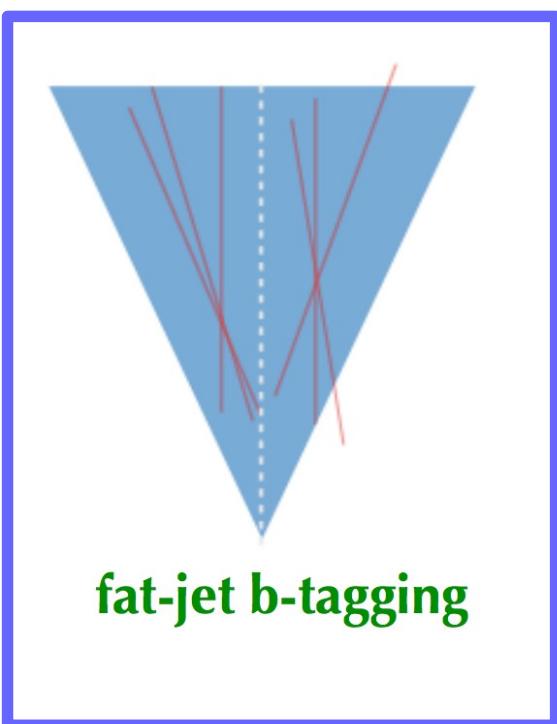
arXiv:1603.00027

Without B-tagging

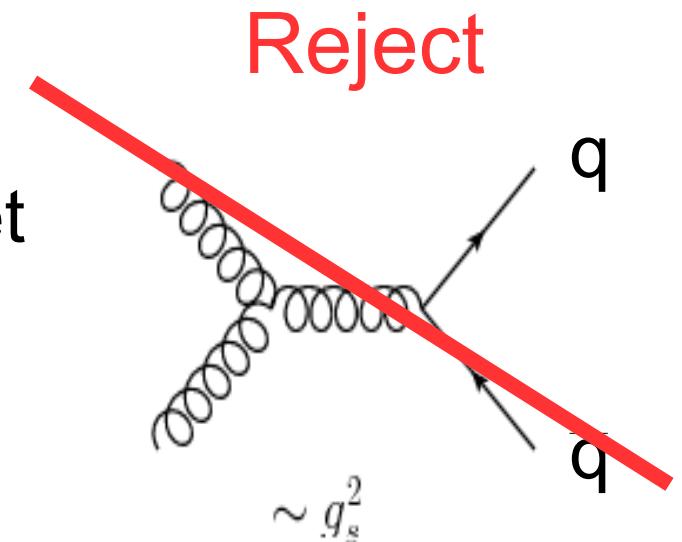
W/Z peak
 Fit at the
 7% σ unc.
 QCD NLO,
 EWK critical



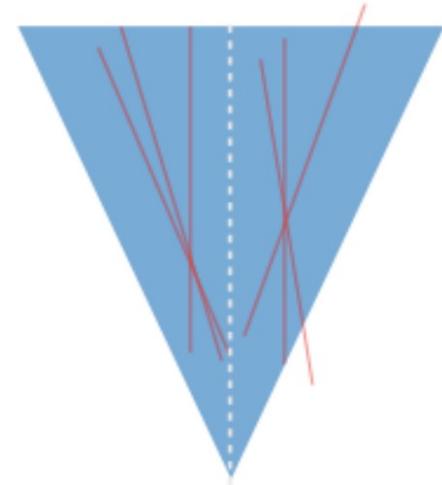
Double-b tagging Concept #1



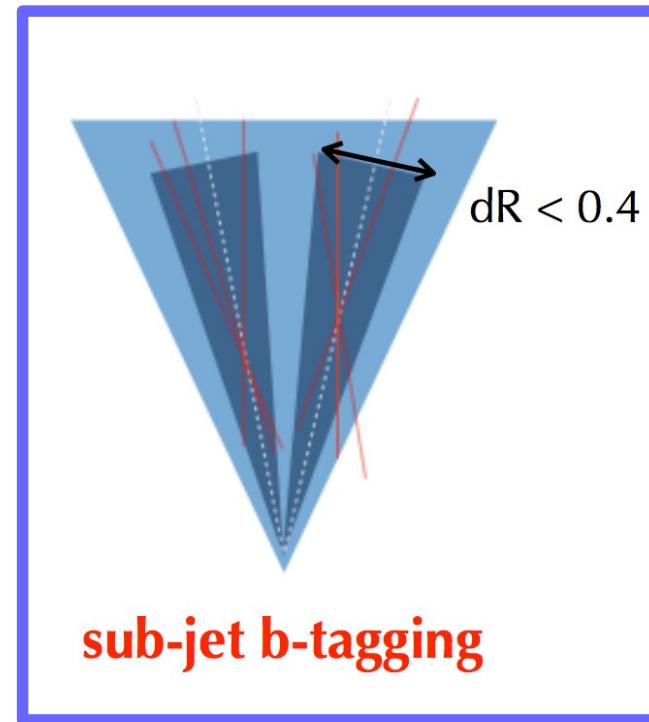
Apply standard b-tagging on the whole jet
 Best at identifying Higgs against a jet
 composed of light quarks



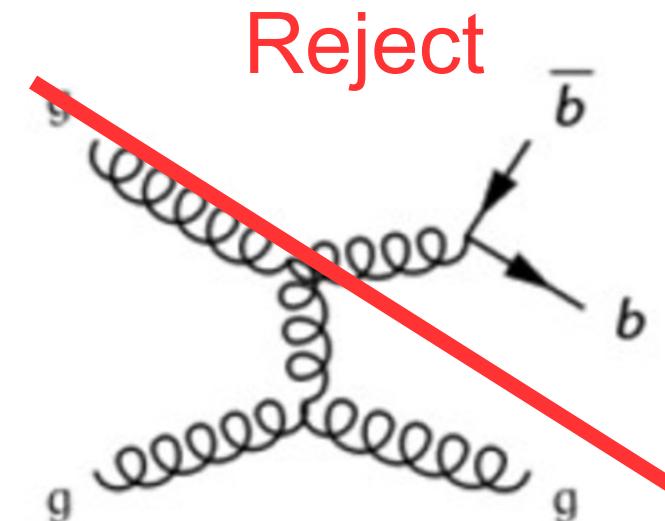
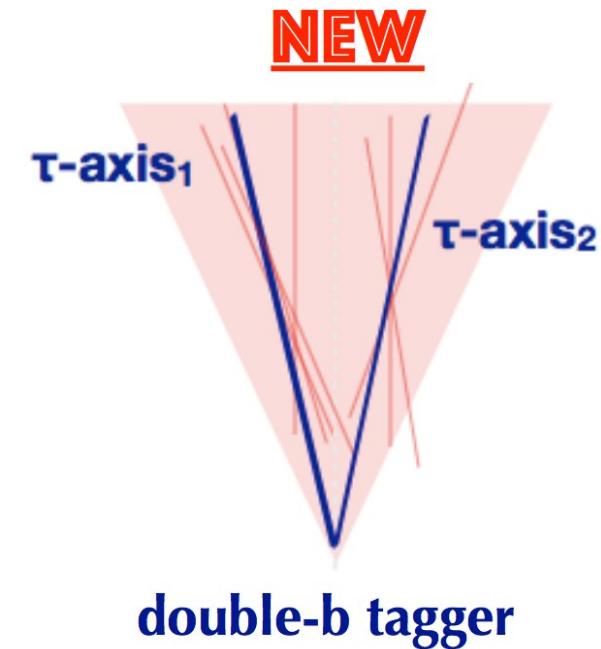
Concept #2



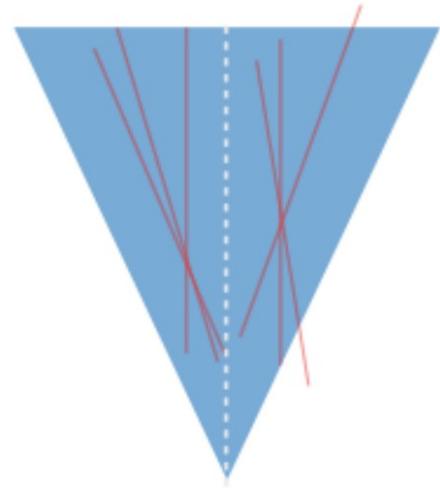
fat-jet b-tagging



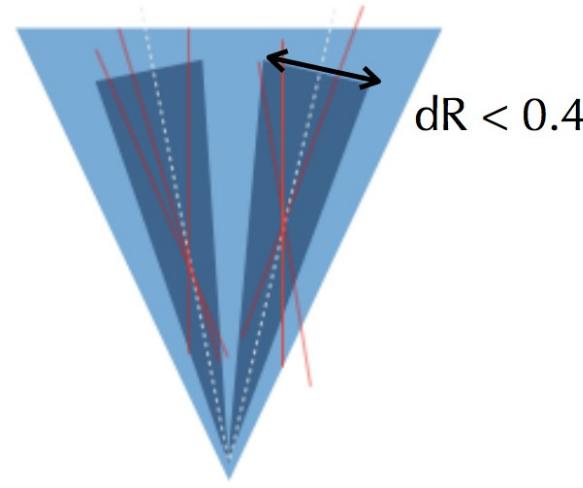
Apply b-tagging on the subjet
 Best at identifying Higgs
 Against a jet from a gluon splitting



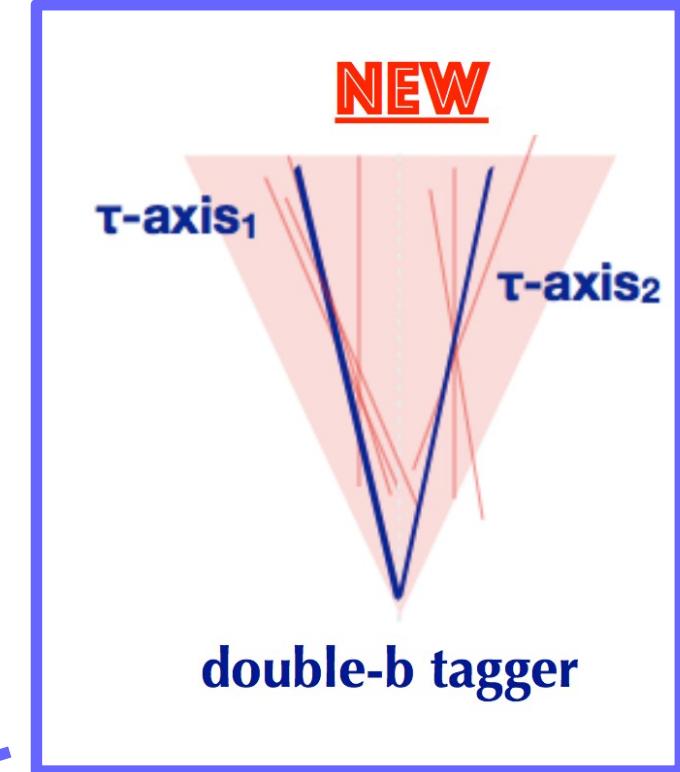
Concept #3



fat-jet b-tagging

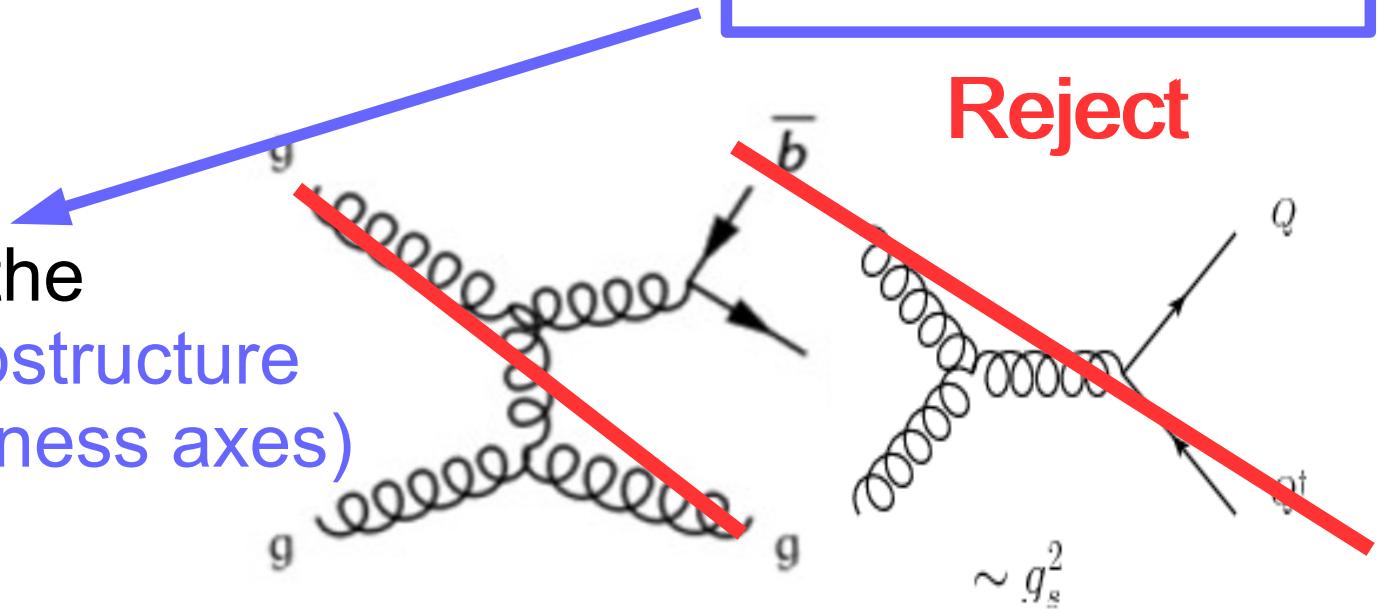


sub-jet b-tagging

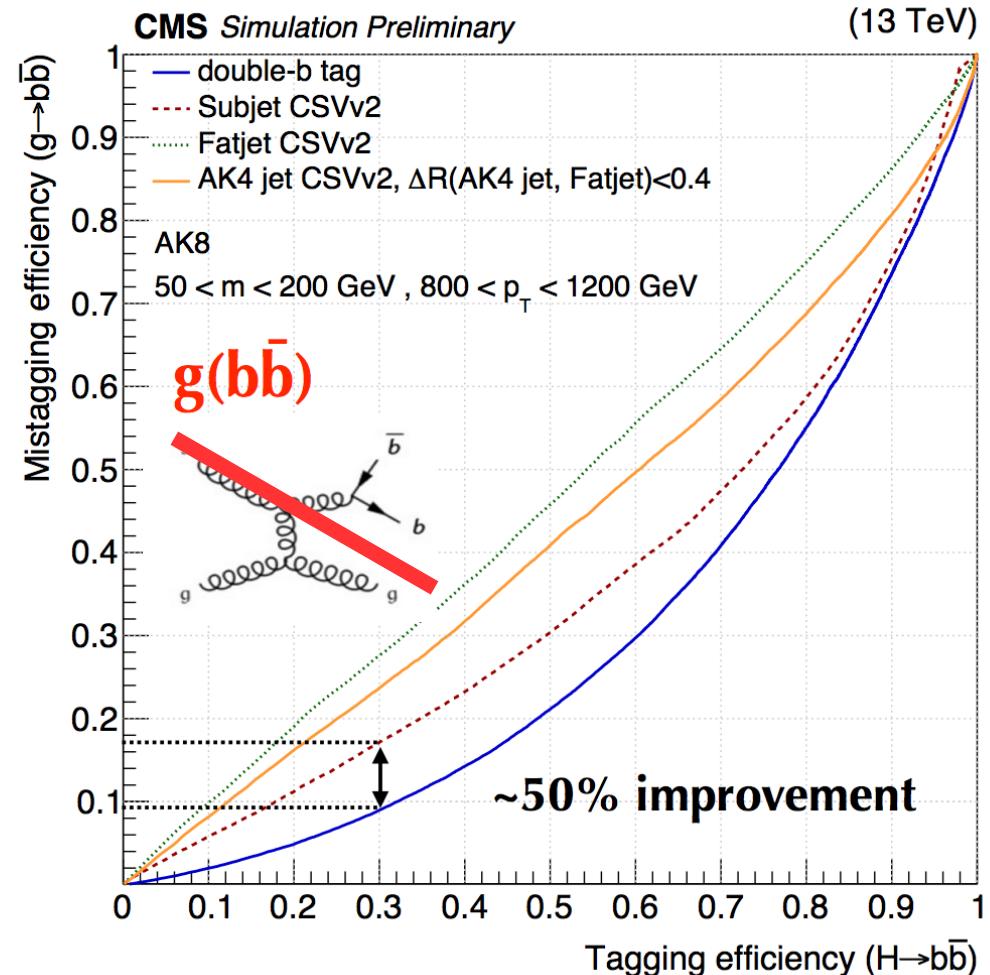
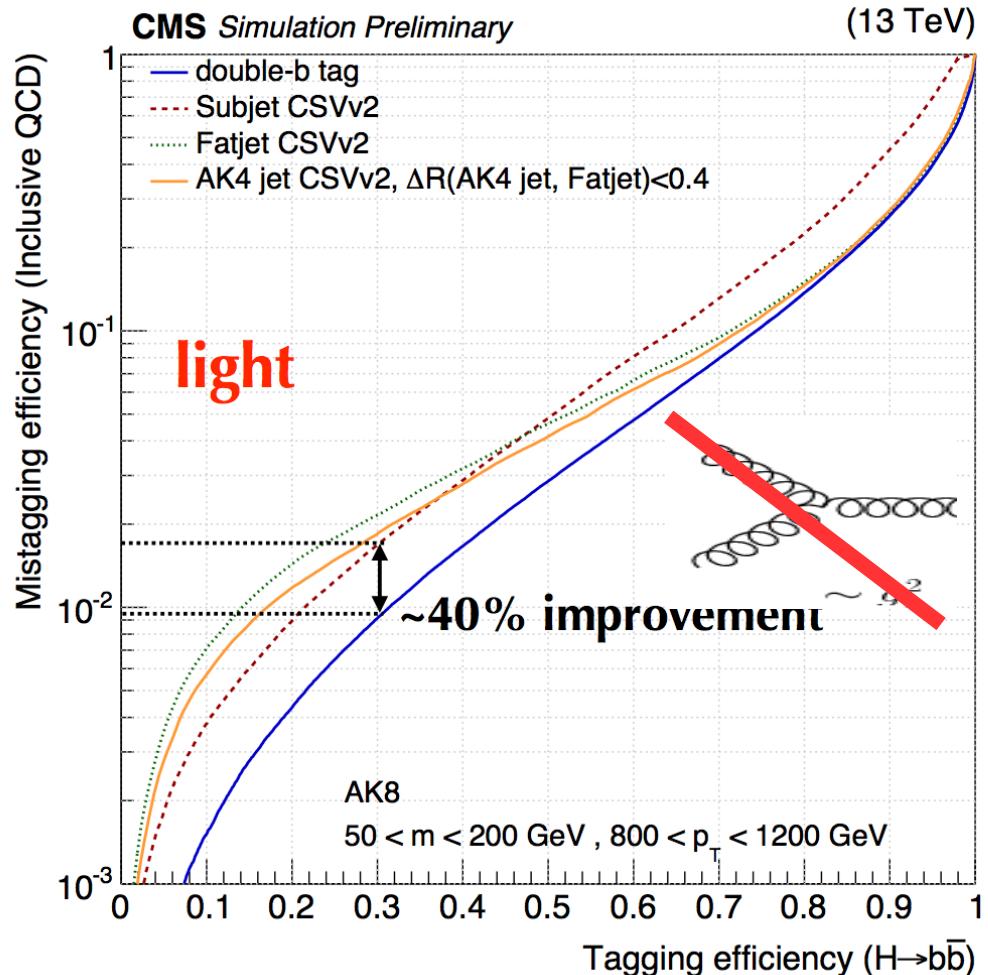


double-b tagger

Apply b-tagging on the
Whole Jet using substructure
Variables (n-subjettiness axes)
1-pass kT

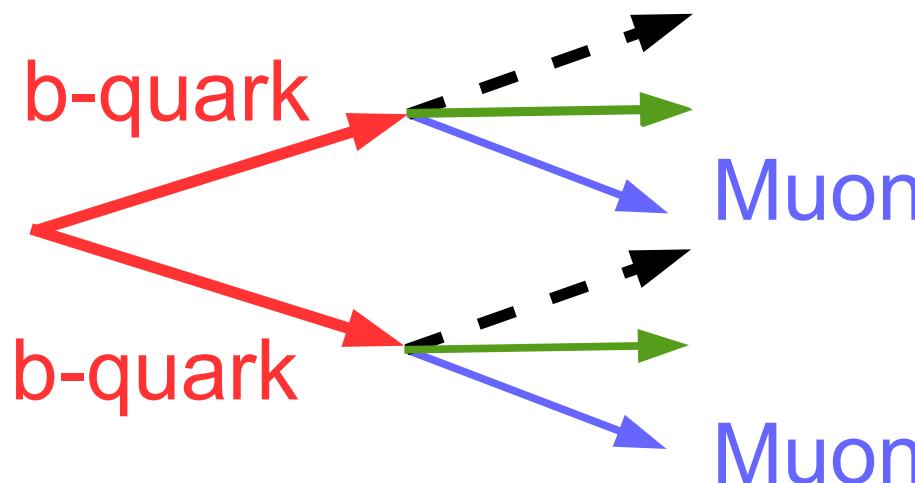


Double B-tagger

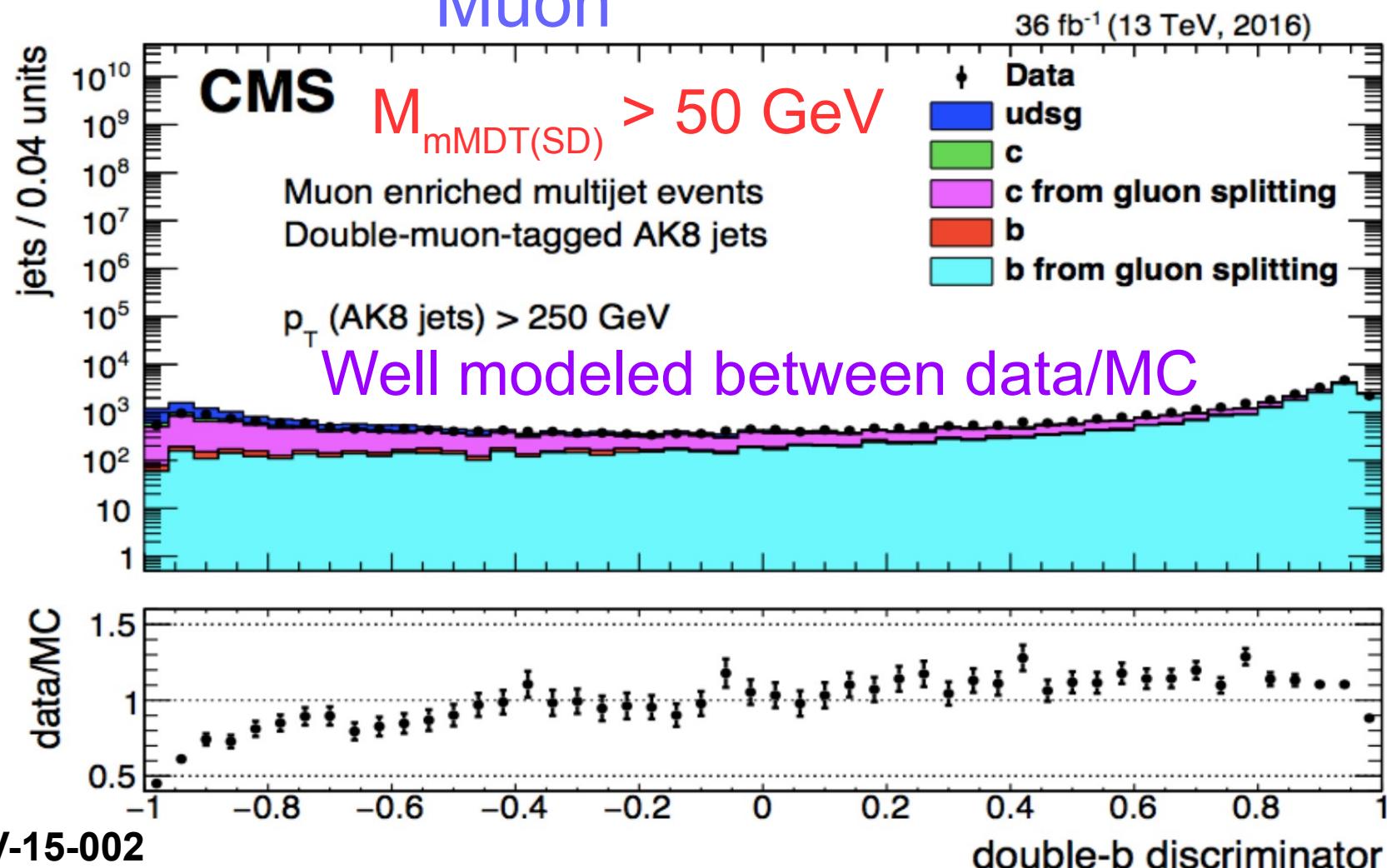


Resulting combination gives 50% improvement over previous

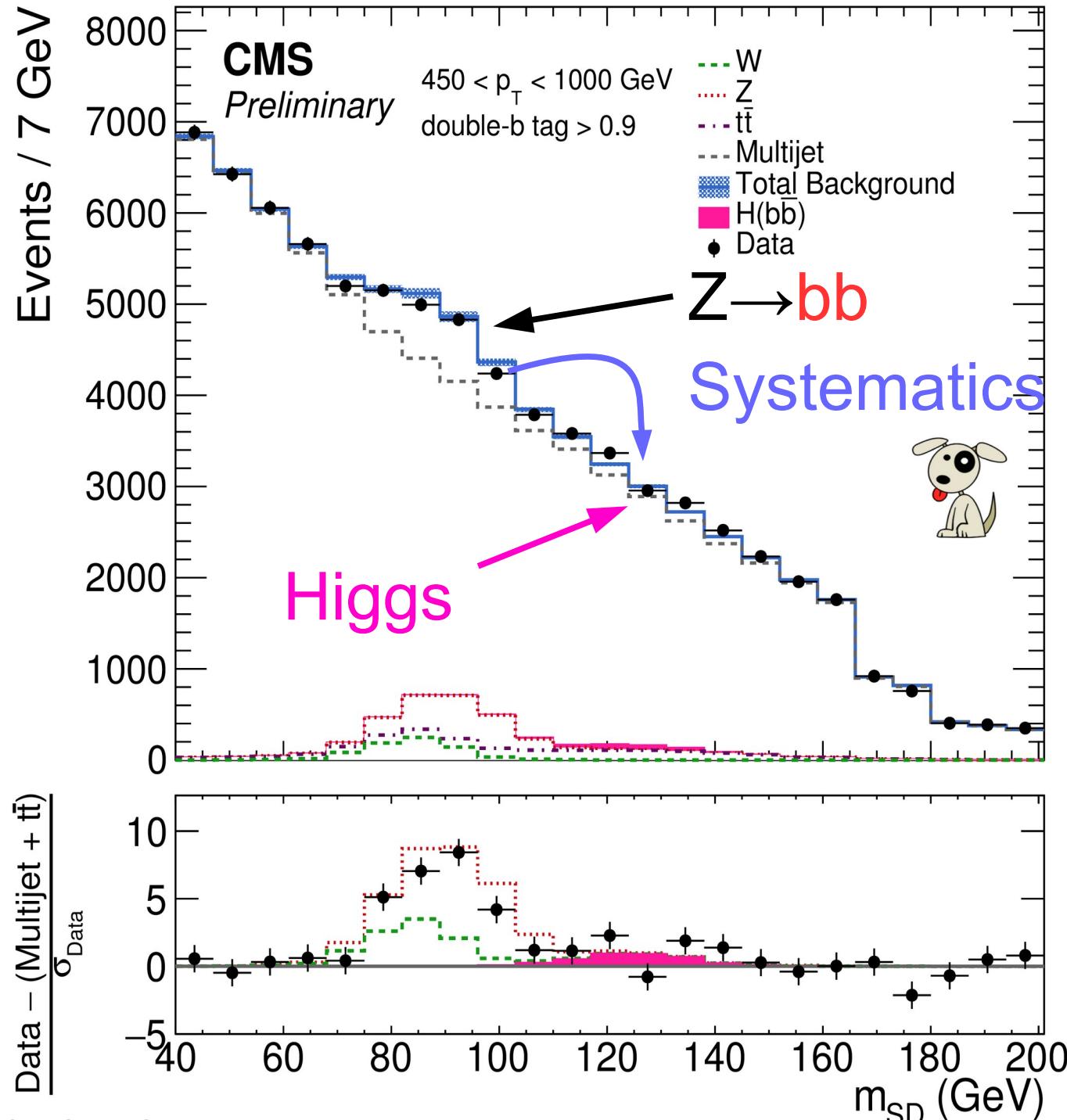
What about data/MC



Tag two muons in a jet
Use this to infer signal-like
2 b-quarks in a jet



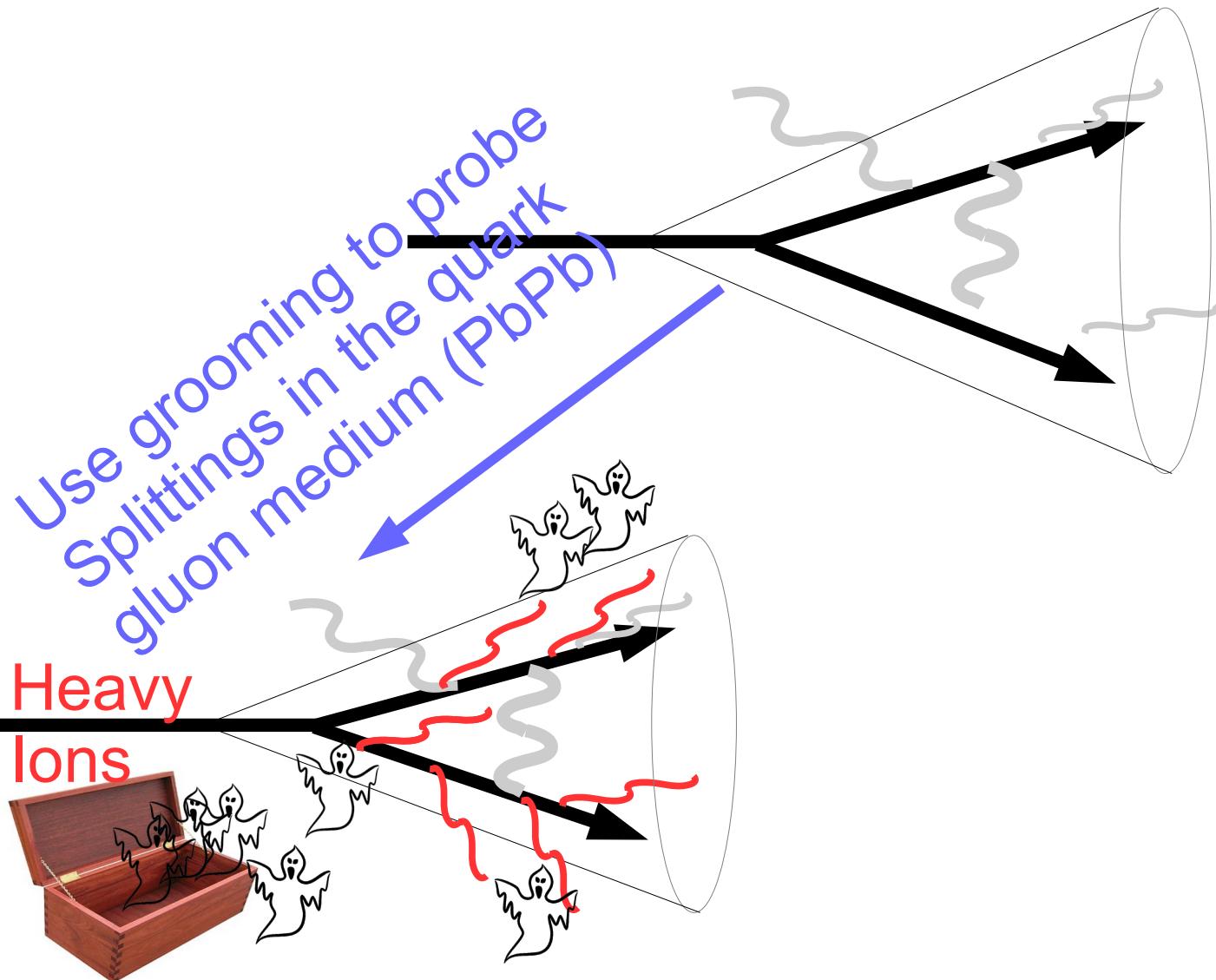
Result



The large $Z \rightarrow bb$
Allows us to
calibrate our
signal

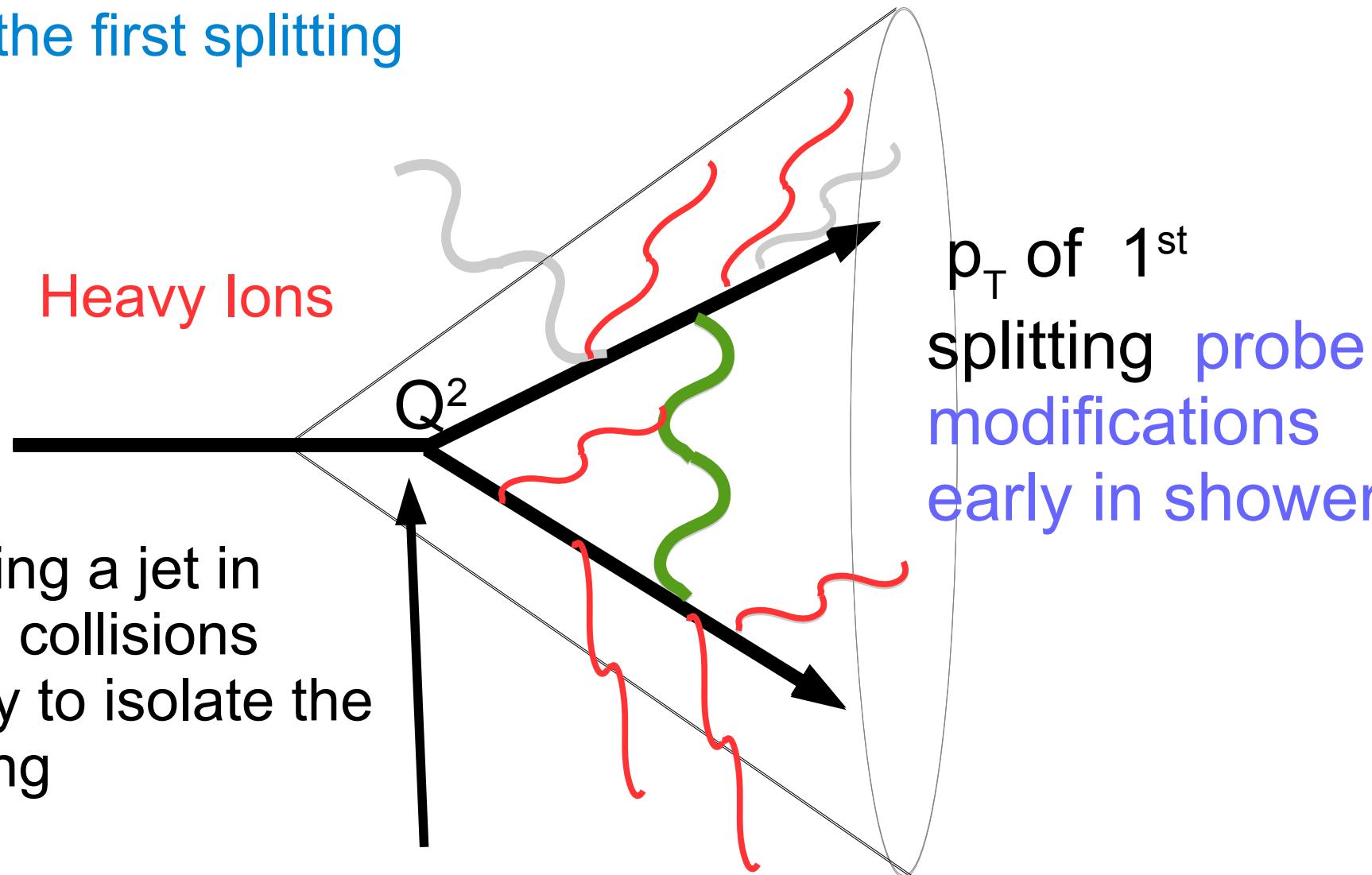
Z peak
Allows us to
calibrate Higgs

Where do we go from here?



Heavy Ion Collisions

Consider the first splitting
in jet



By grooming a jet in
Heavy ion collisions
We can try to isolate the
first splitting

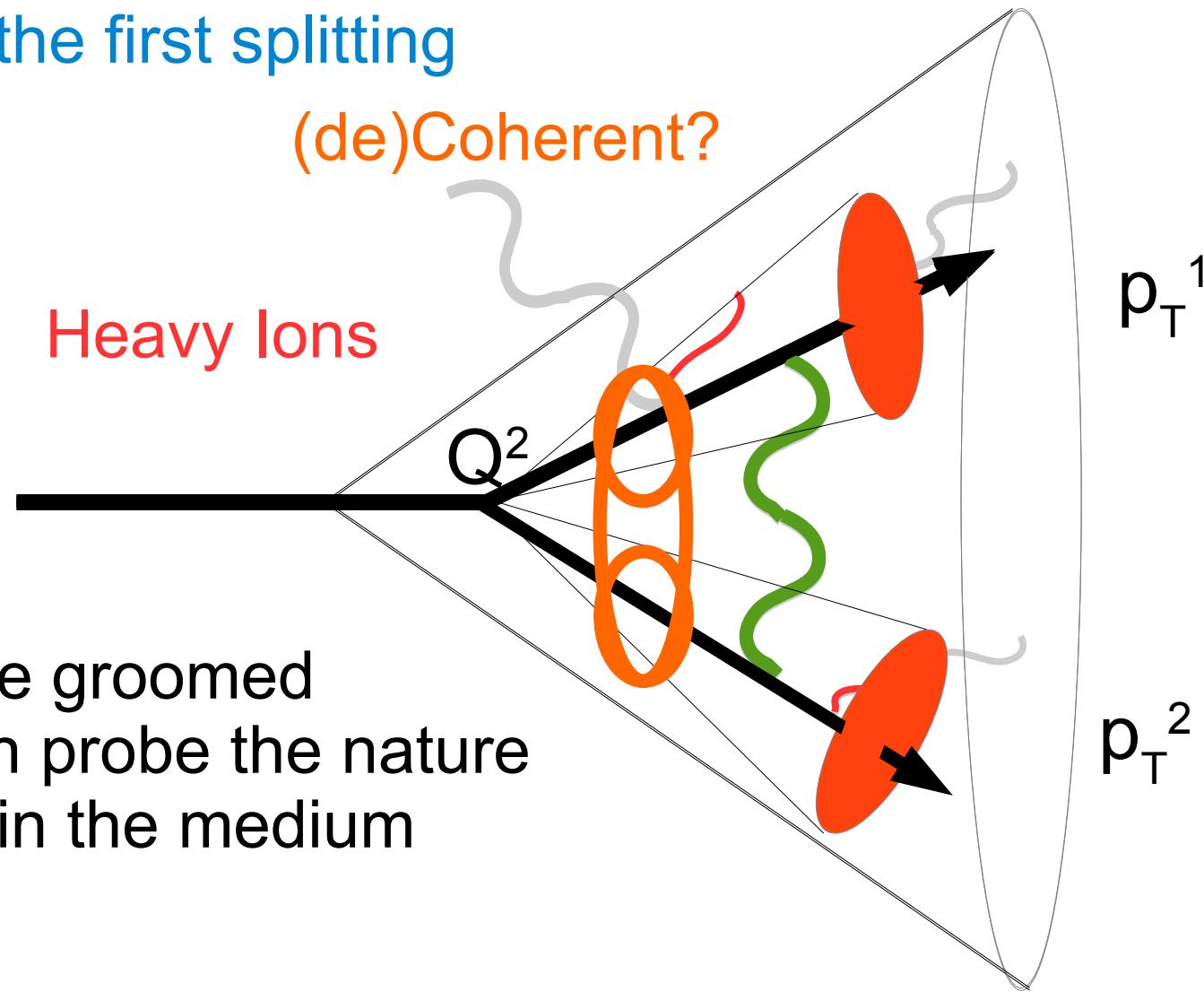
p_T of 1st
splitting probe
modifications
early in shower

The scale of the splitting acts as a gauge
for the virtuality of medium modifications

Heavy Ion Collisions

Consider the first splitting
in jet

(de)Coherent?



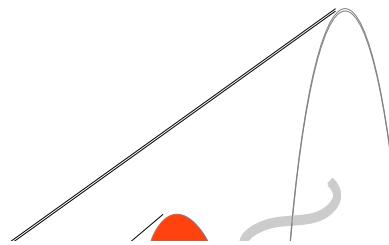
Isolating the groomed
Subjets can probe the nature
of the loss in the medium

$$z_g = \frac{p_T^2}{p_T^1 + p_T^2}$$

Probes coherence of the energy loss in
the medium

Heavy Ion Collisions

Consider the first splitting
in jet



Confidence in the first splitting in pp
is fairly recent, yet it has been
discussed for a long time

$$M^2 \sim p_1 p_2 \Delta R_{12}^2$$

ΔR_{12} Probes the nature of the loss in the medium
(quark/gluonic how it loses...)



Summary

- Field of jet substructure is well developed
 - With a lot of tools

Very Busy Boost \Rightarrow summary of summary (take home messages)

My Boost is solid

- amazing understanding
- precision calculation
- theory uncertainties

My Boost is opened

- New ideas
 - still proposed
 - still welcome

My Boost is expanding

- fast progress in calculations
- expand towards MC
- expand towards HI

Thanks Sal & Simone for
Beautiful Outstanding Organisation and Superb Time

Gregory Soyez Boost 2017 Summary

Summary

- Community is starting to think about HI as well

Very Busy Boost \Rightarrow summary of summary (take home messages)

My Boost is solid

- amazing understanding
- precision calculation
- theory uncertainties

My Boost is opened

- New ideas
- still proposed
 - still welcome

My Boost is expanding

- fast progress in calculations
- expand towards MC
- expand towards HI

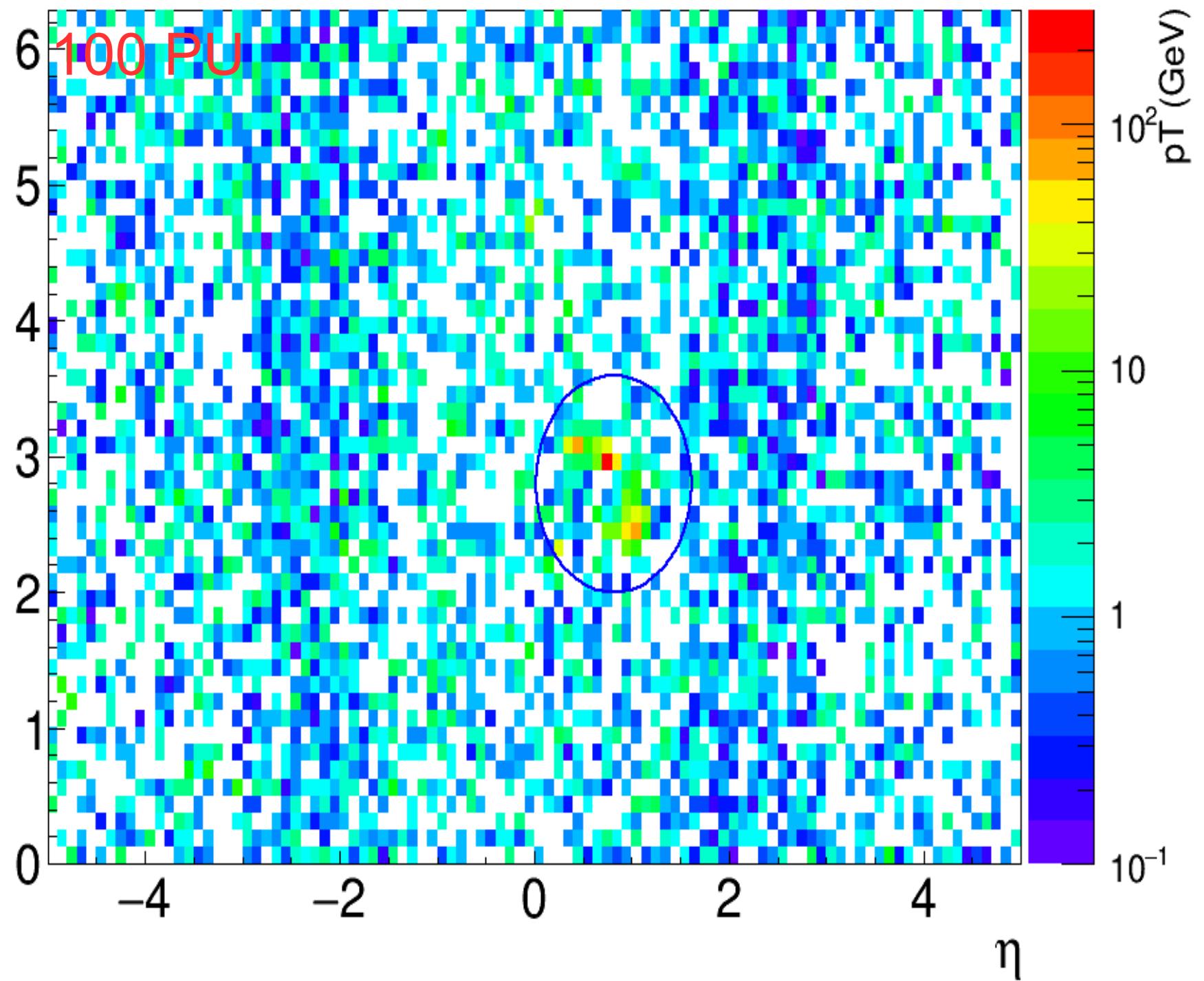
Thanks Sal & Simone for
Beautiful Outstanding Organisation and Superb Time

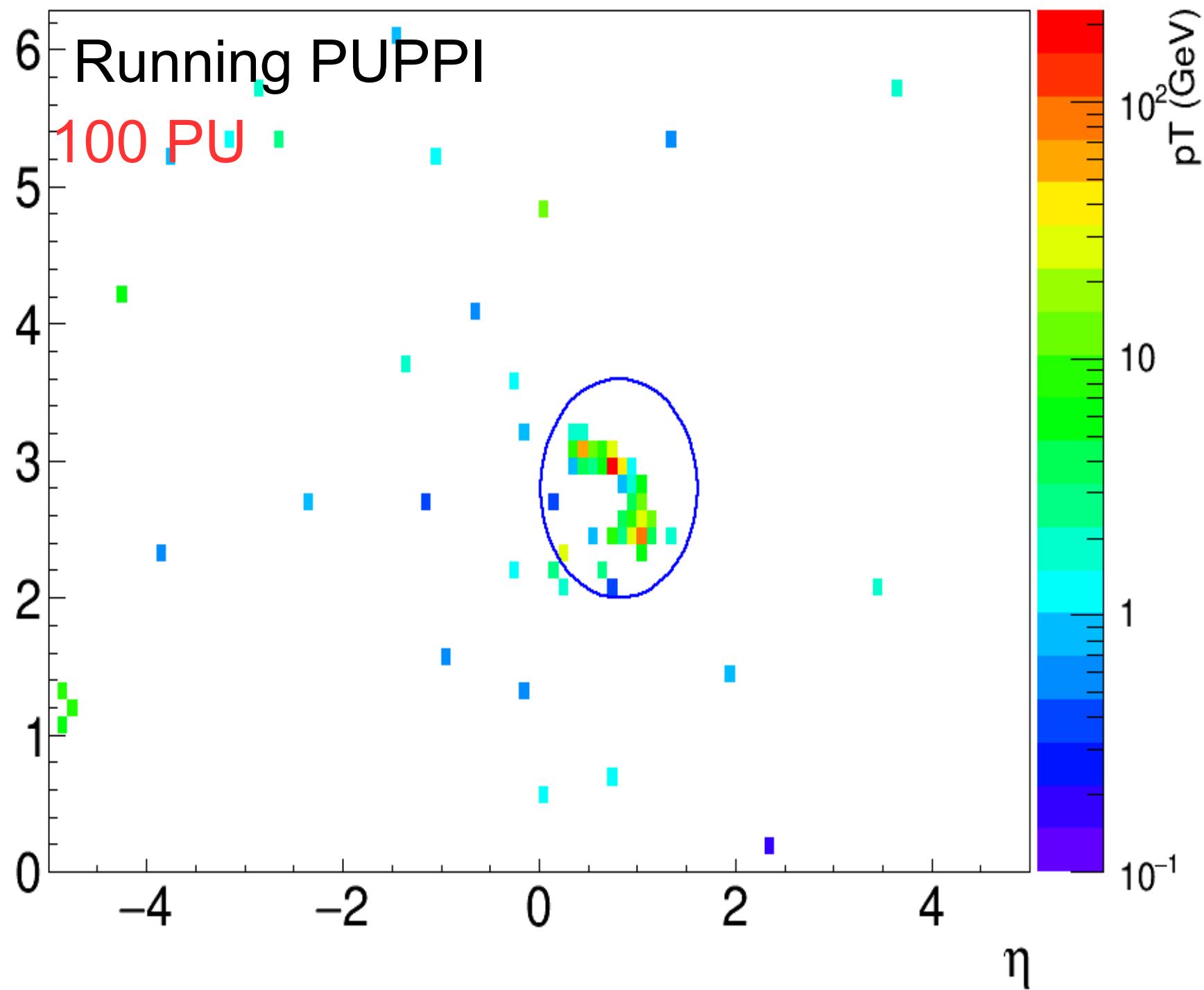
Gregory Soyez Boost 2017 Summary

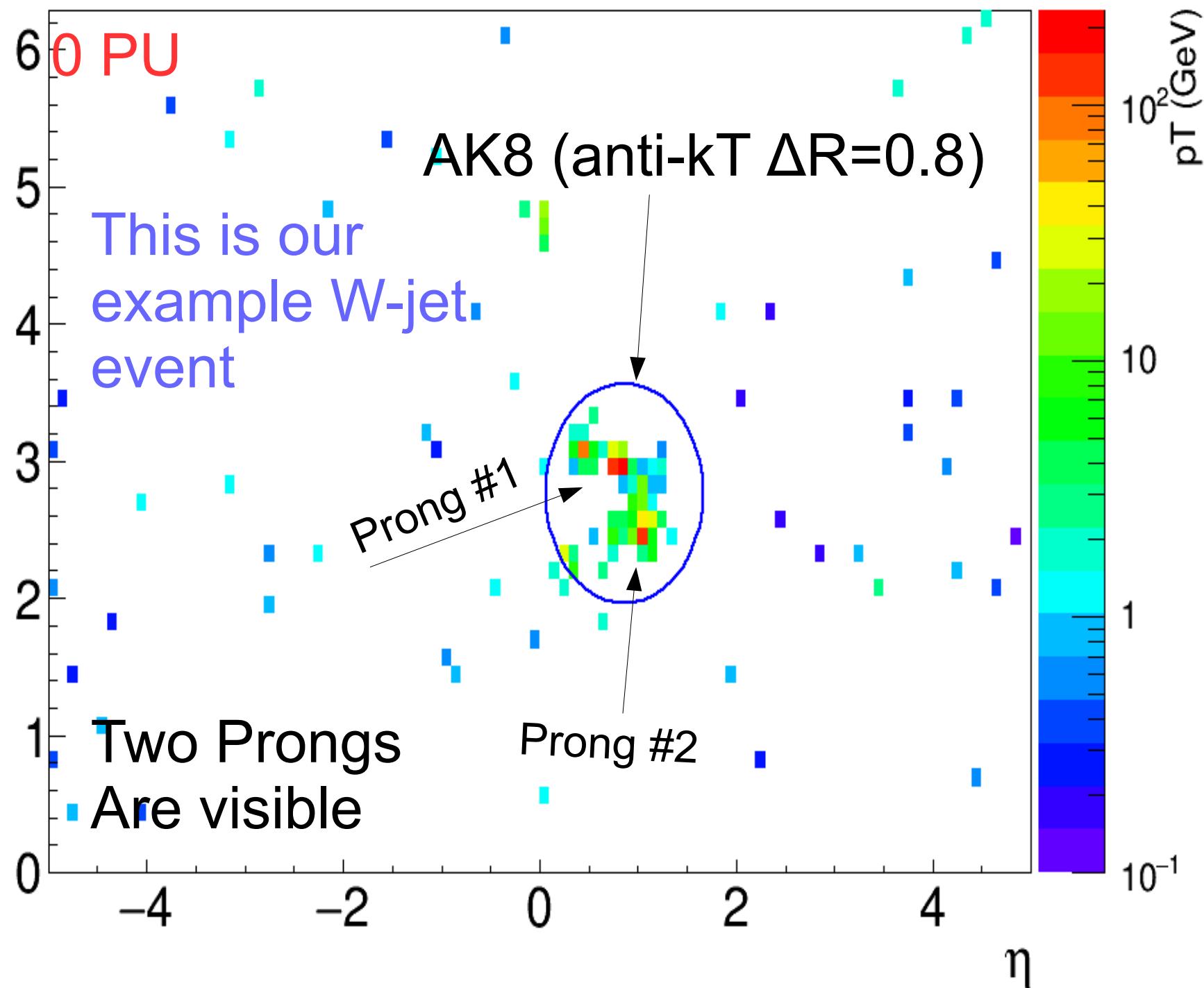


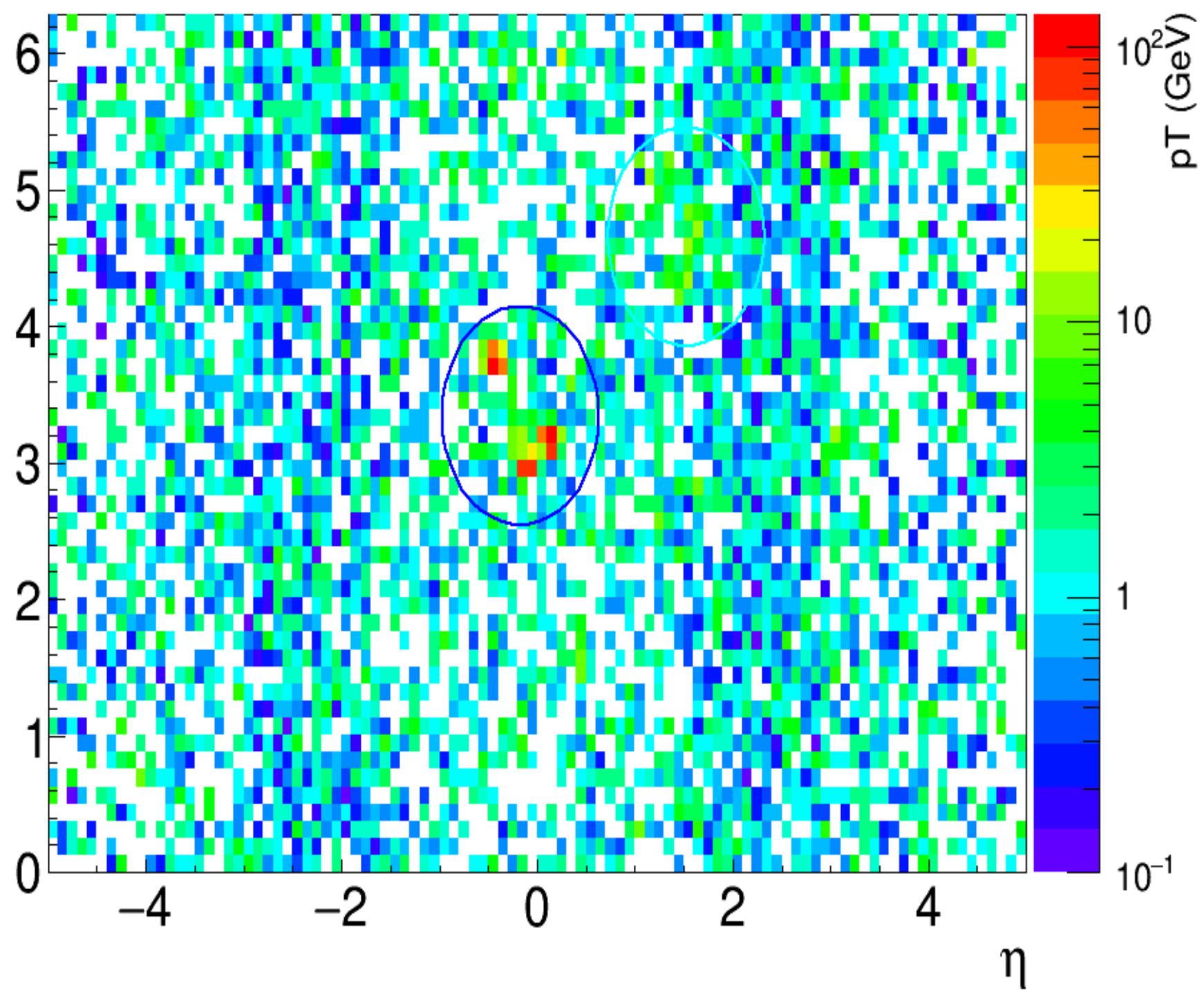
Thanks!

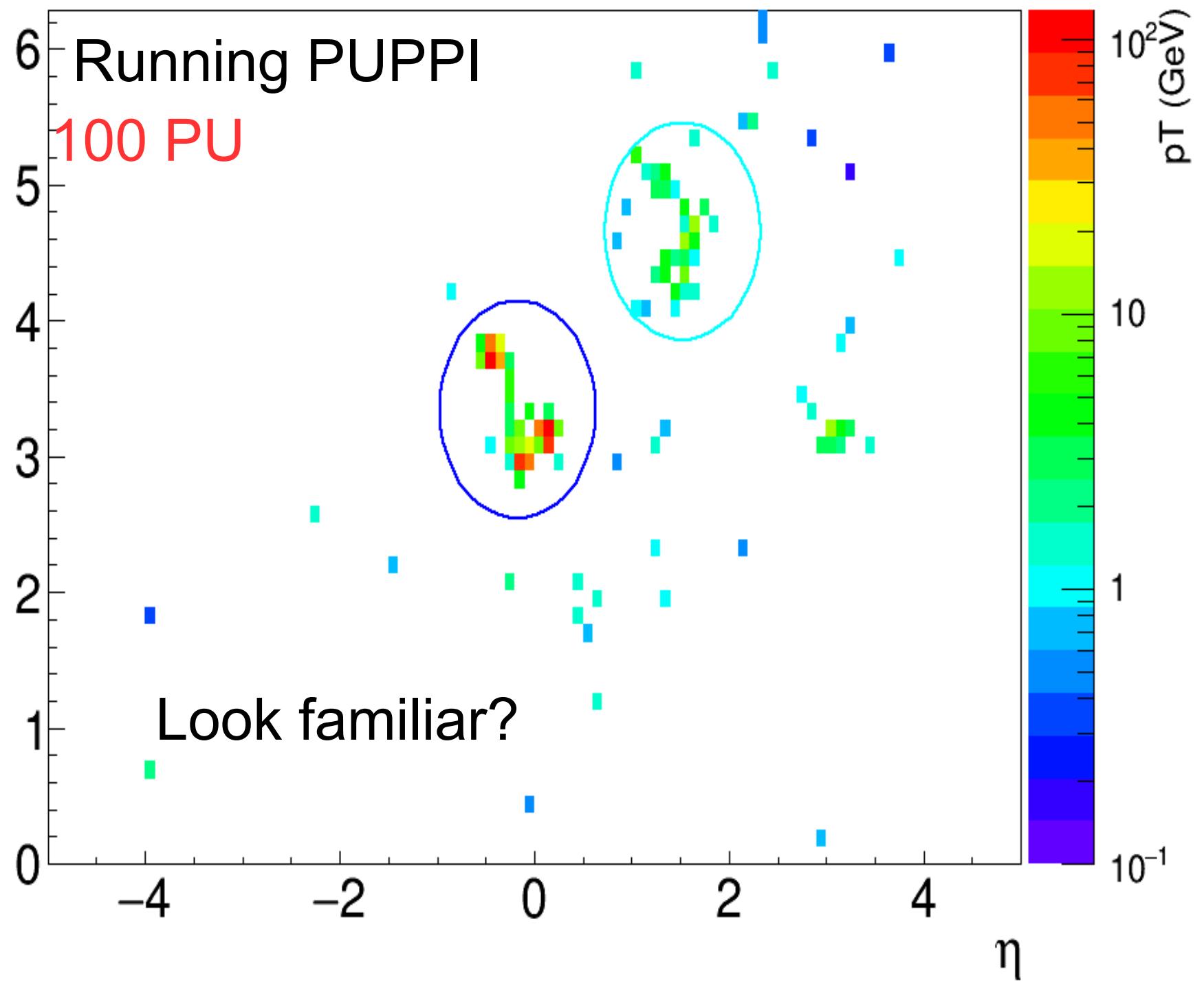
Now @ 100 PU
(Next year)



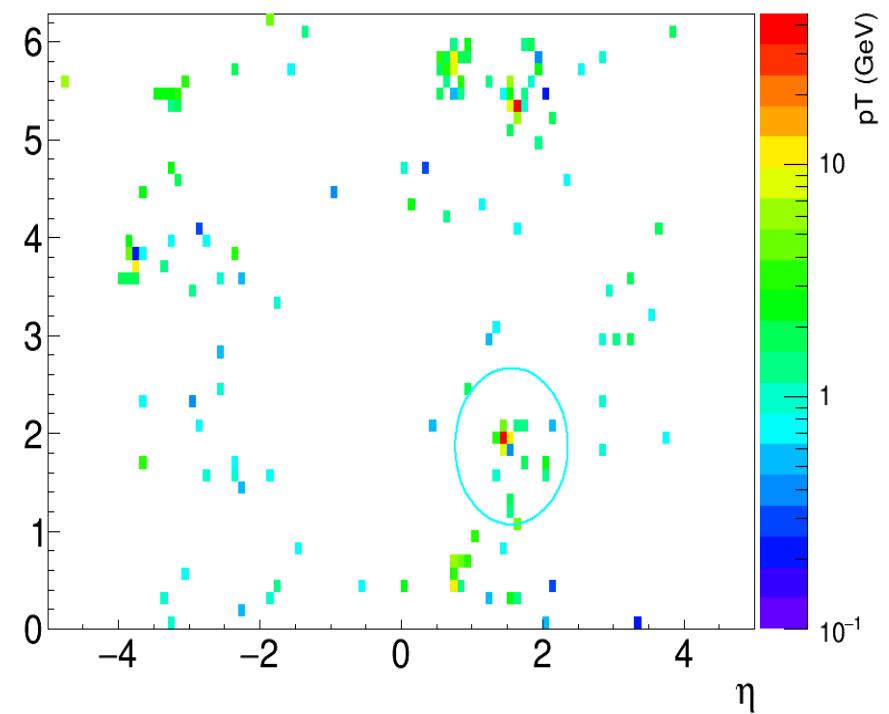
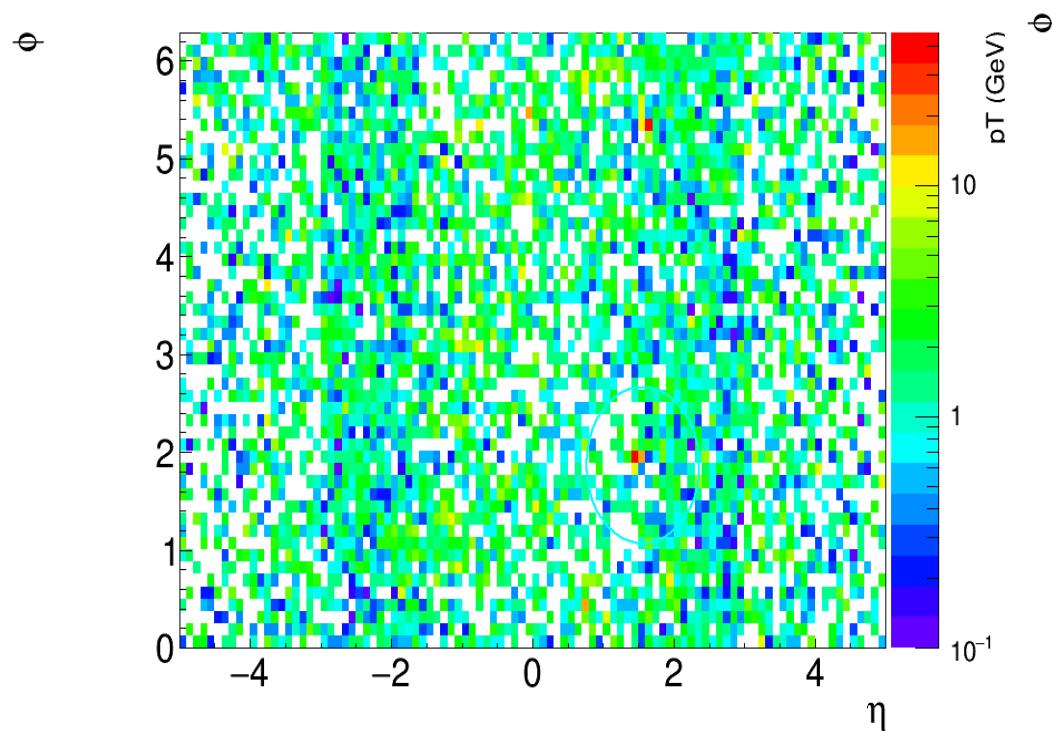
ϕ 



ϕ 



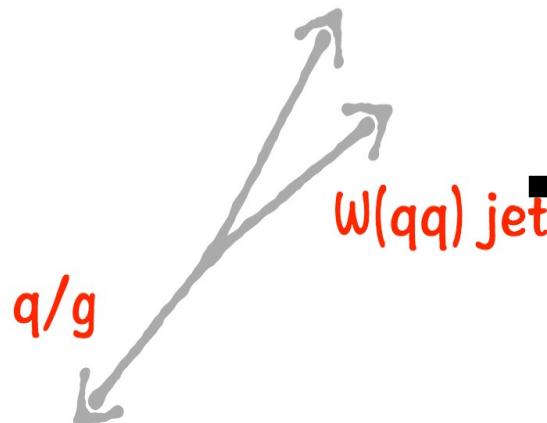
Any guesses?



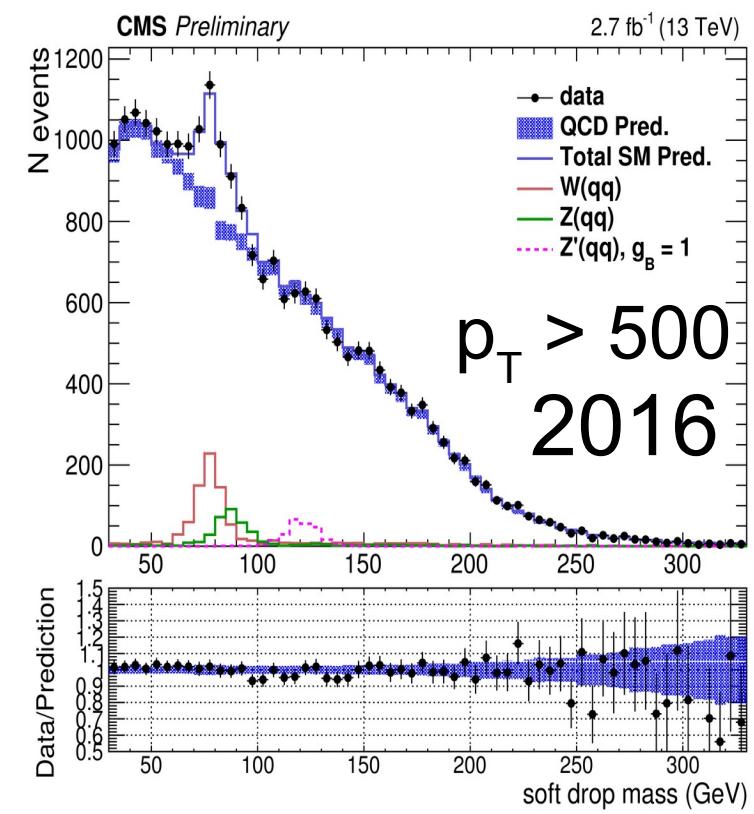
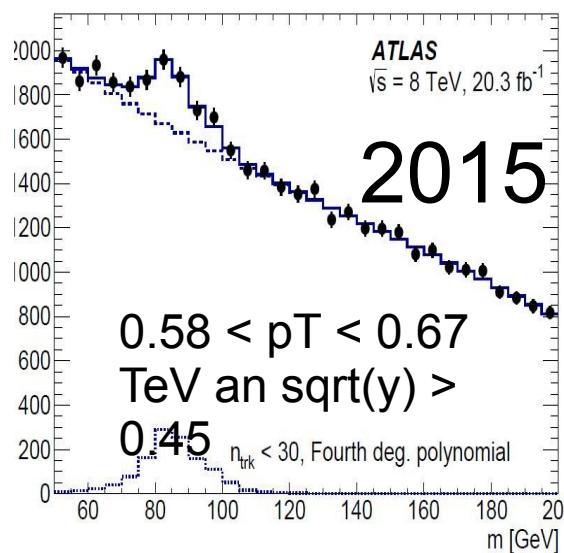
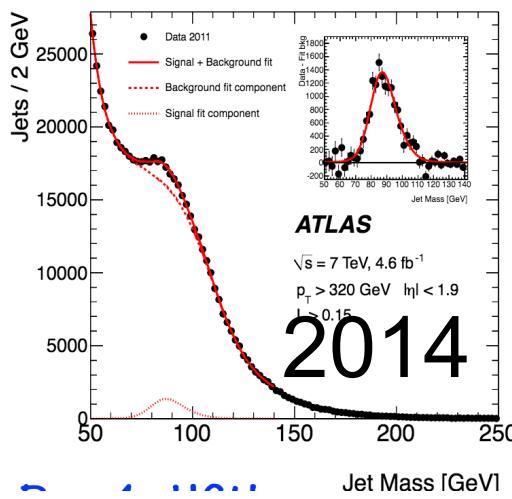
See backup

Recap

- Actual analyses are on objects combining deposits
- Particle flow combines the deposits to particles
 - Takes into account many features (Brem/Nuclear Int)
- Hadronic τ decays are composite “particle” objects
 - Find the decays and rely heavily on isolation
- Jets have rich & interesting identification features
 - Pileup an important aspect that needs to be addressed
- MET relies heavily on everything else
 - To reconstruct nothing you have to know everything



Thanks!

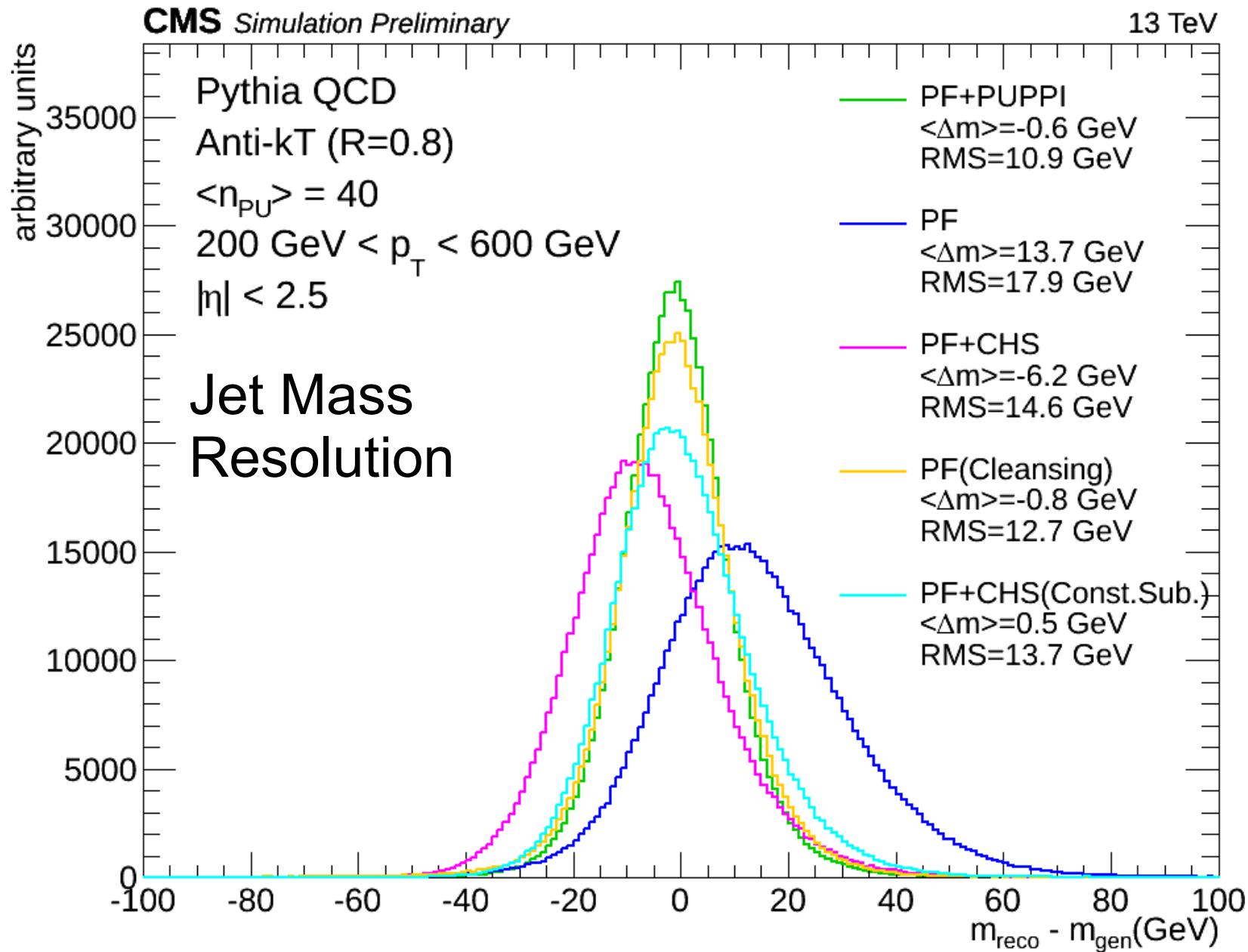


This peak has only been observed over past 2 years

Thanks to the
Organizers!

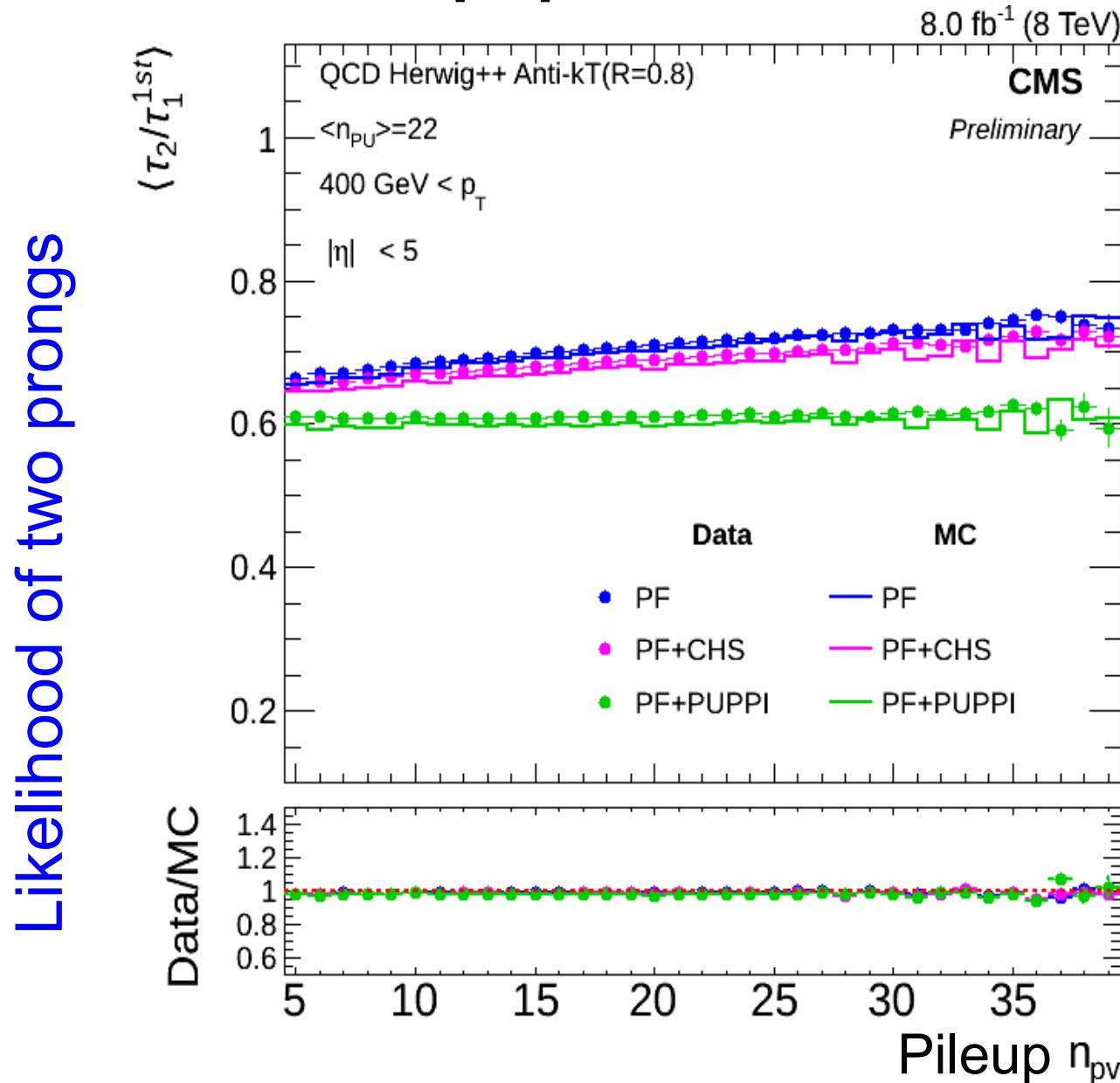
Have a good trip
back

Jets in CMS



Mass resolution shows clear improvement (40 PU)

Pileup performance in data

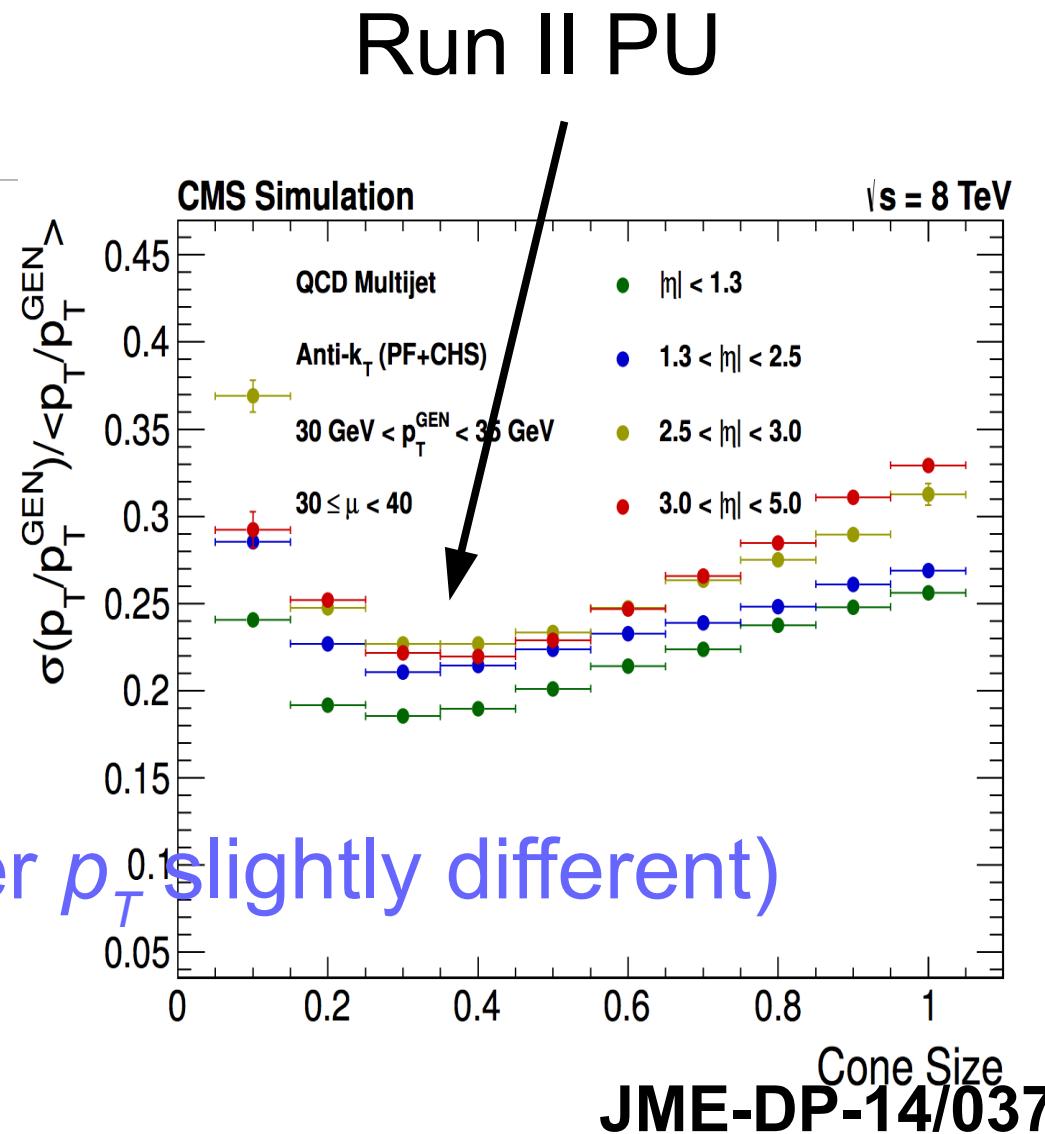
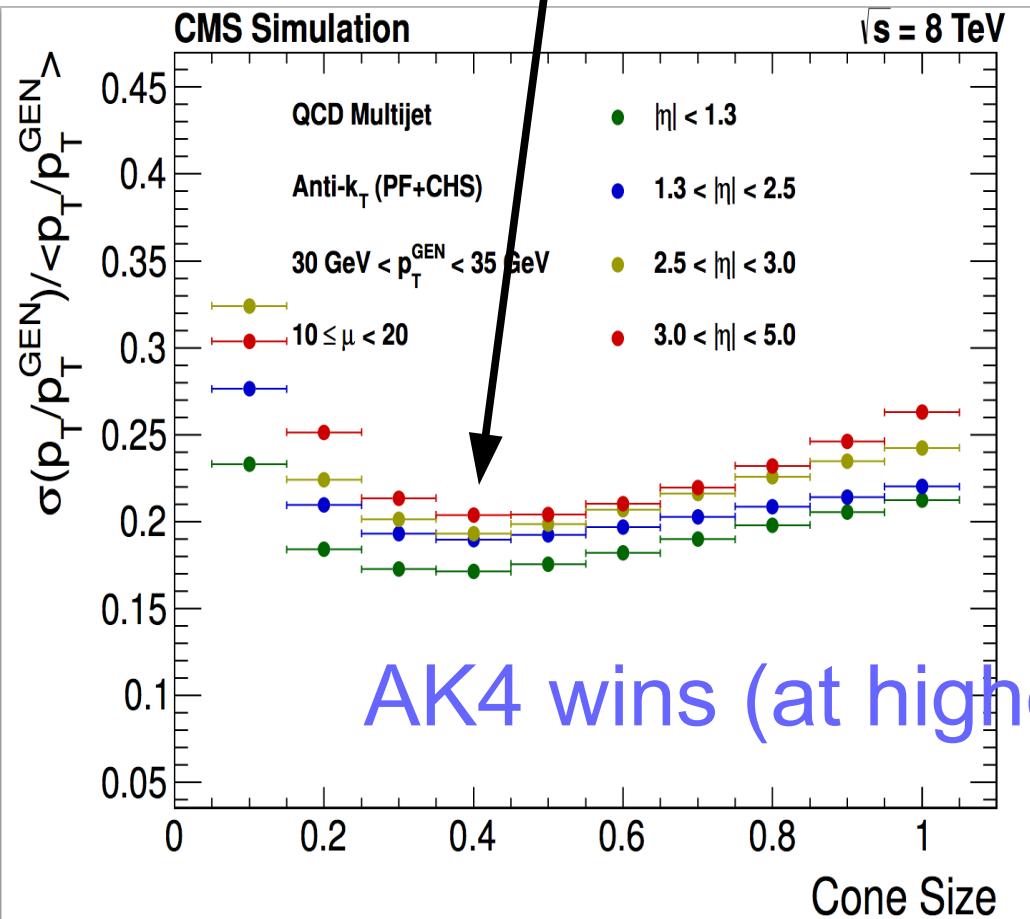


- No more trends in pileup with Puppi

Jet Energy Correction

- Executive Summary :

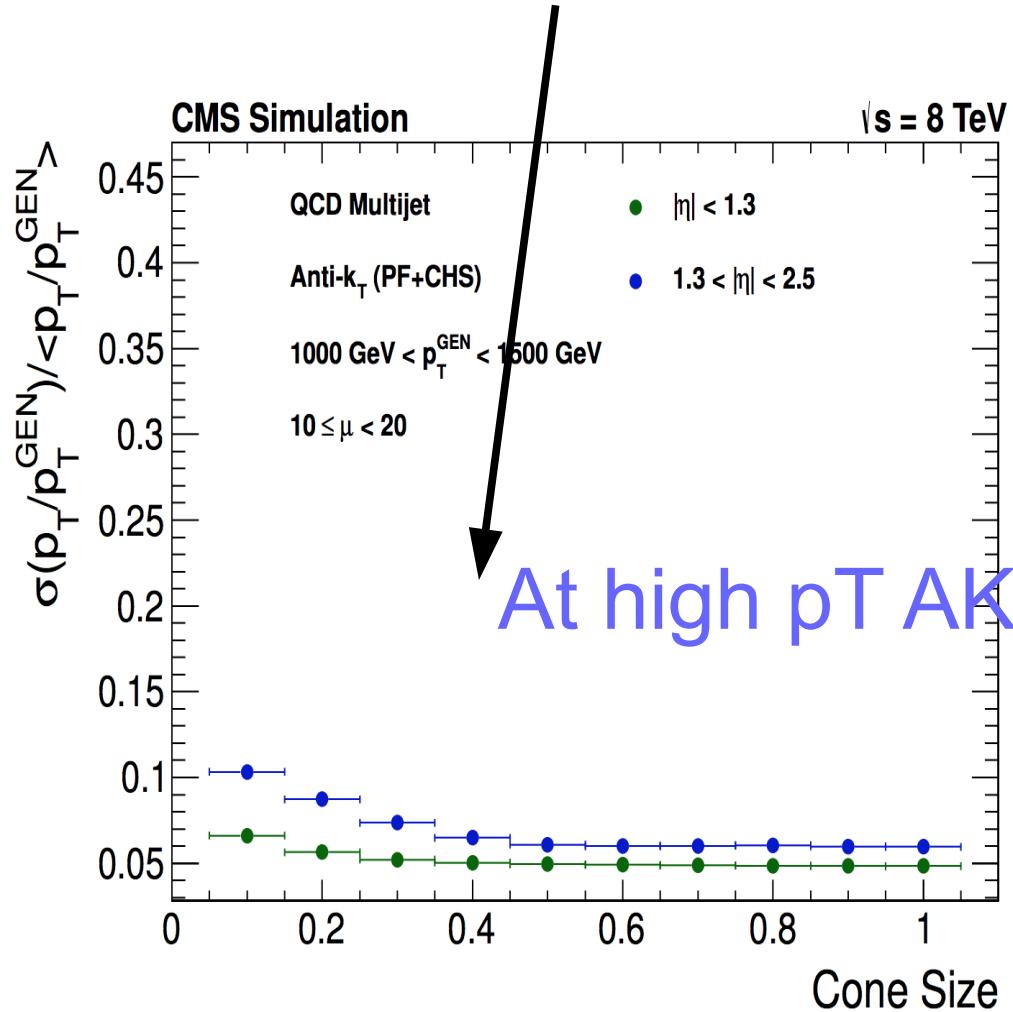
We switch to AK4
Run I PU



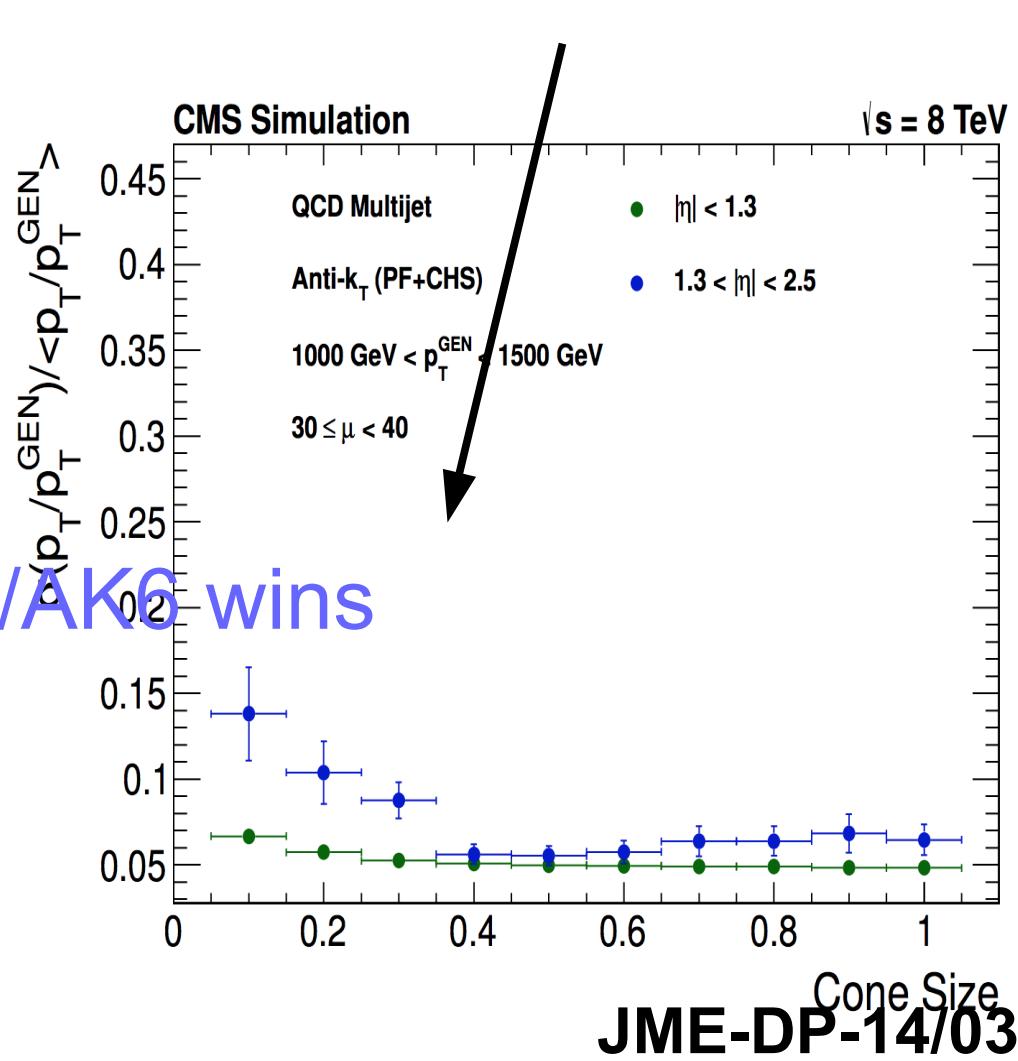
Jet Energy Correction

- Executive Summary :

We switch to AK4
Run I PU



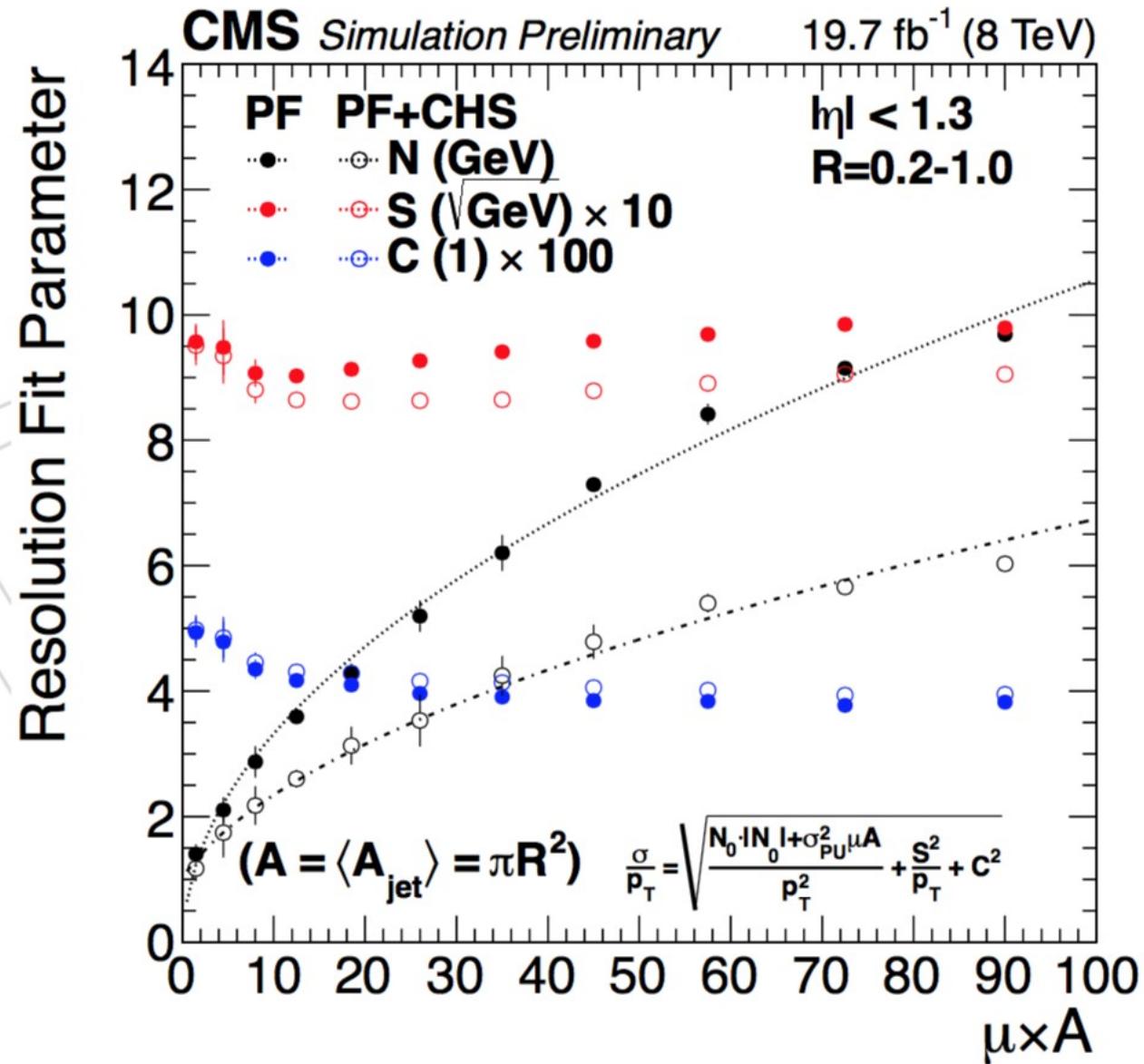
Run II PU



At high p_T AK5/AK6 wins

Stability of our detector

- Using all the jet cones allows plots like this:



What does it take for E-flow?

- Need to reconstruct a jet and **correct it**

ATLAS

Cluster+correct
Calorimeter
Cells
(Topoclusters)

Cluster
Topoclusters
To
jets

(ρ) PU
Correction
+Global
Correction
Of Jet
($p_T + \eta$)

Residual
Correction of
Jet (using
width/tracks)
GSC

CMS

Cluster
Calorimeter
Cells
(pf clustersr)

Link
Tracks to
Pfclusters
(pf particles)

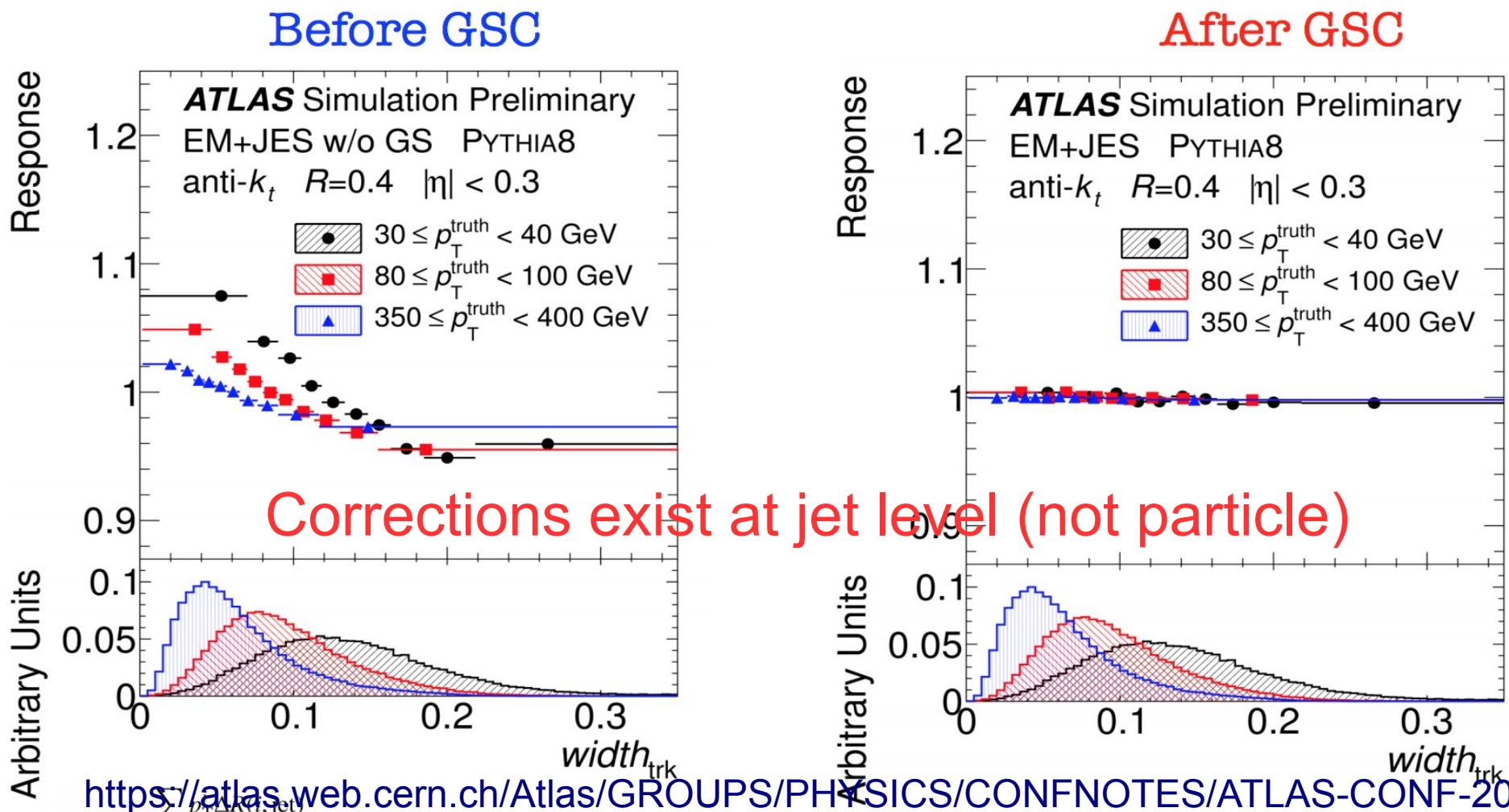
Correction
Of
PF
Candidate
($p_T + \eta$)

(ρ) PU
Correction +
Global
Correction of
Jet ($p_T + \eta$)

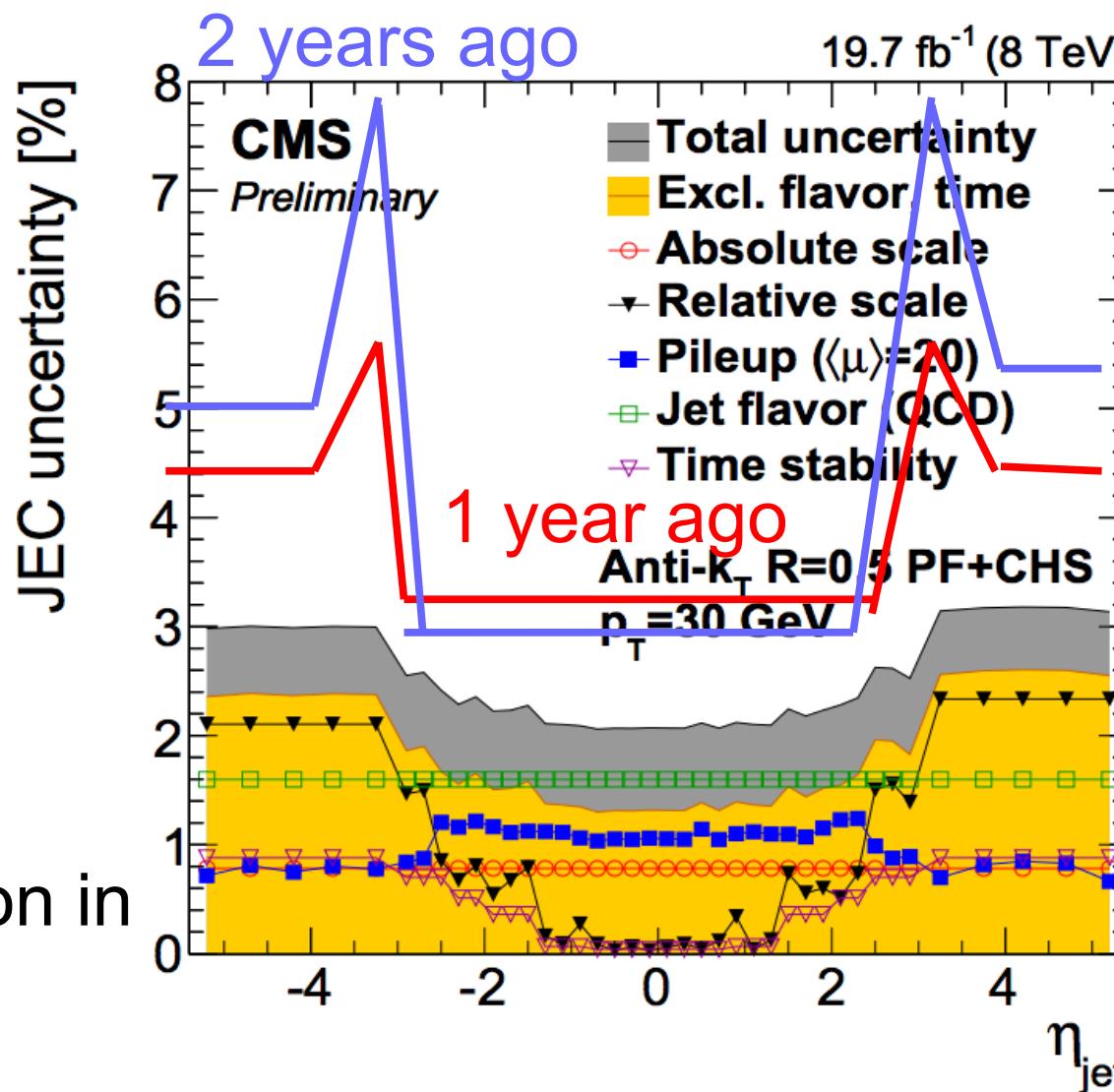


Jet-Level in ATLAS

- While ATLAS does not use pflow
 - Yields resol. loss(Charged parts)+worse granularity
 - Compensates w/improved aranularity through GSC



Jet Energy Scale

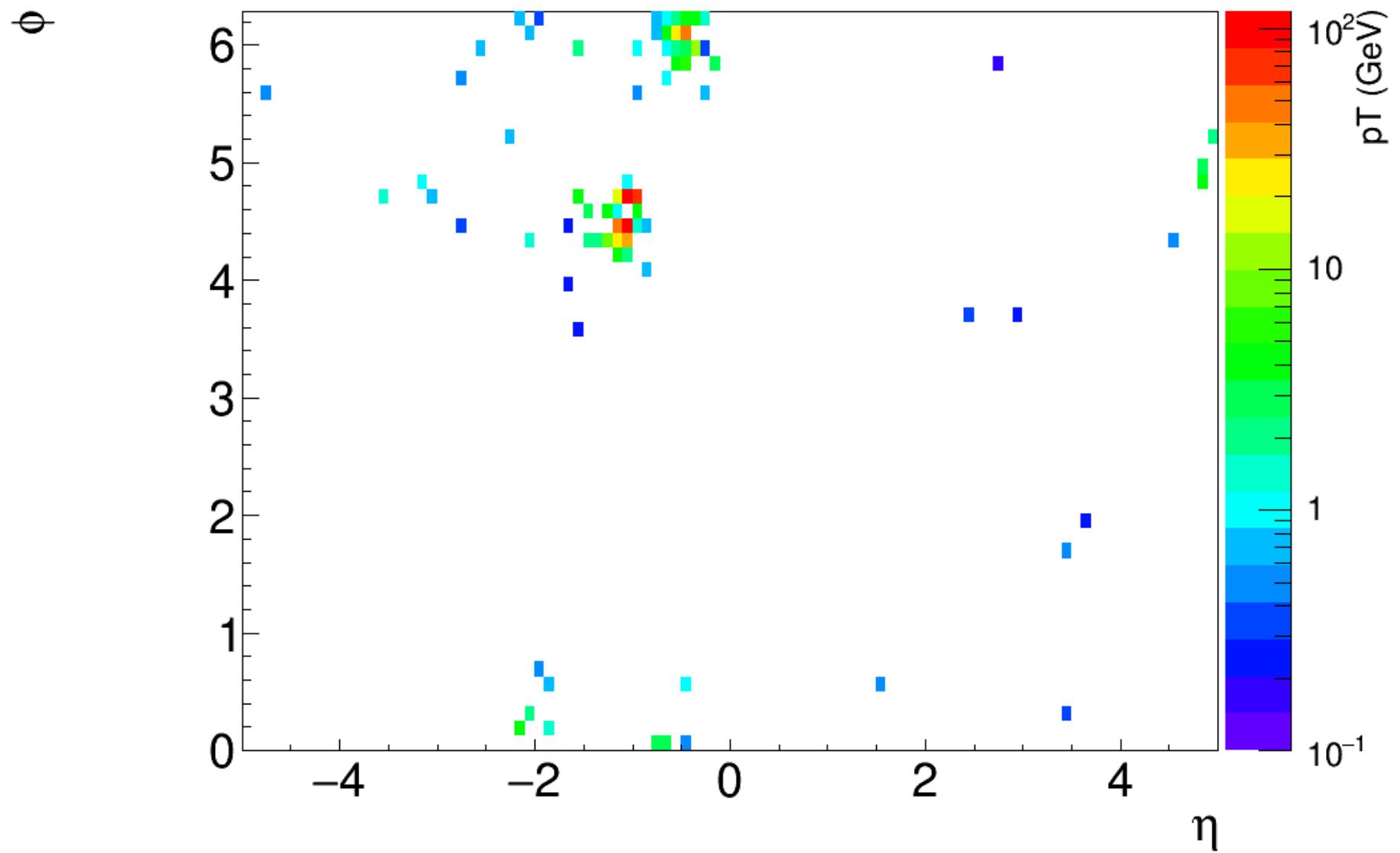


Understanding
of JEC
Steadily improved

As we dealt with
detector effects

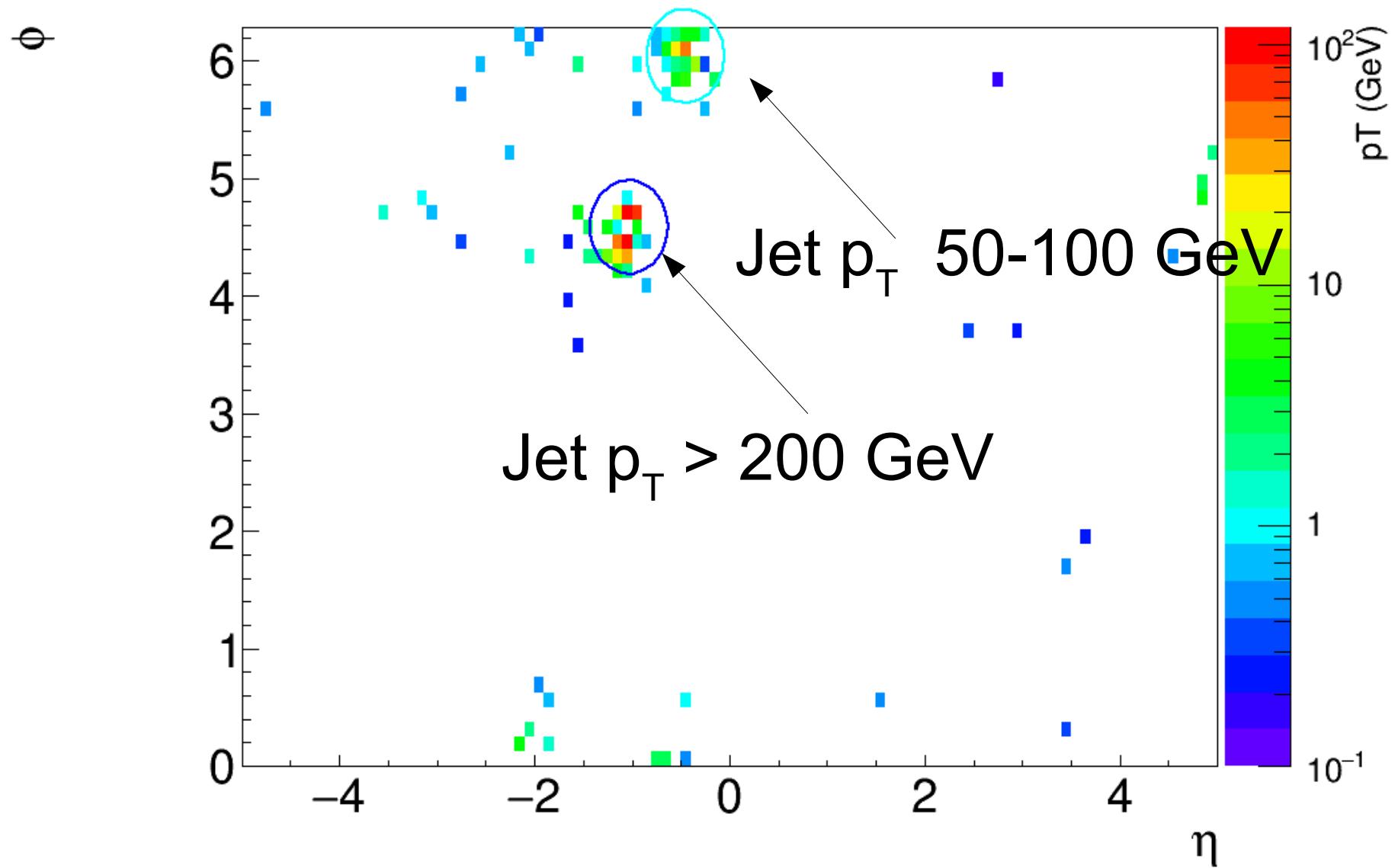
- Run II: expect same trend with a faster timescale
- We are now down to 3% uncertainty at 30 GeV!

What is it?

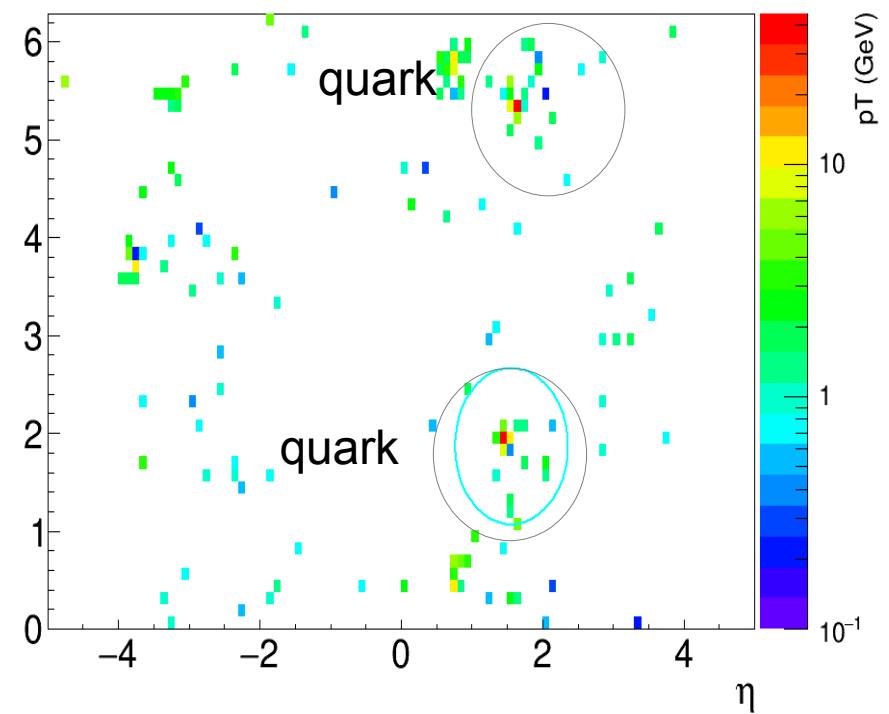
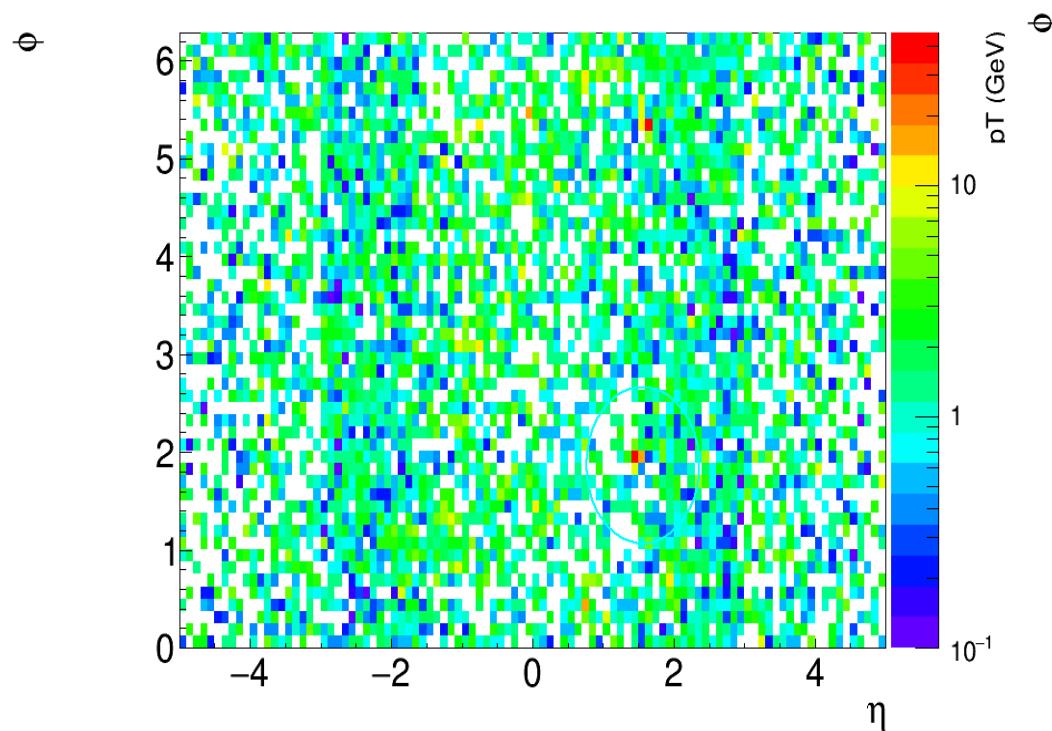


What is it?

Run Jet reco



Any guesses?



Its a low pT W boson



Pileup outside of jets

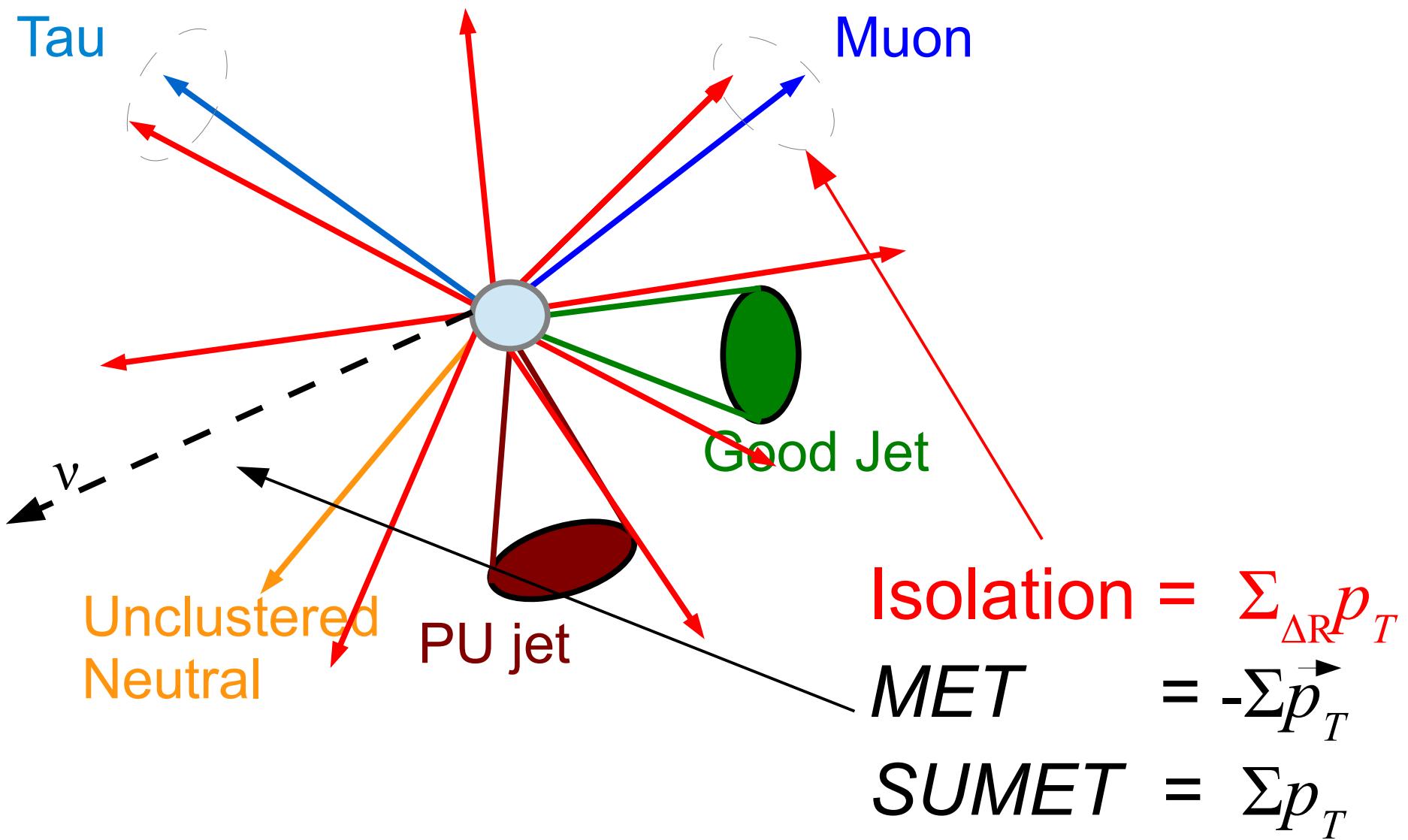


Lets look at objects outside of the jet!

Puppi affects everything

- It does not just work on jets!

PU Particle



Puppi affects everything

- It does not just work on jets!

PU Particle

