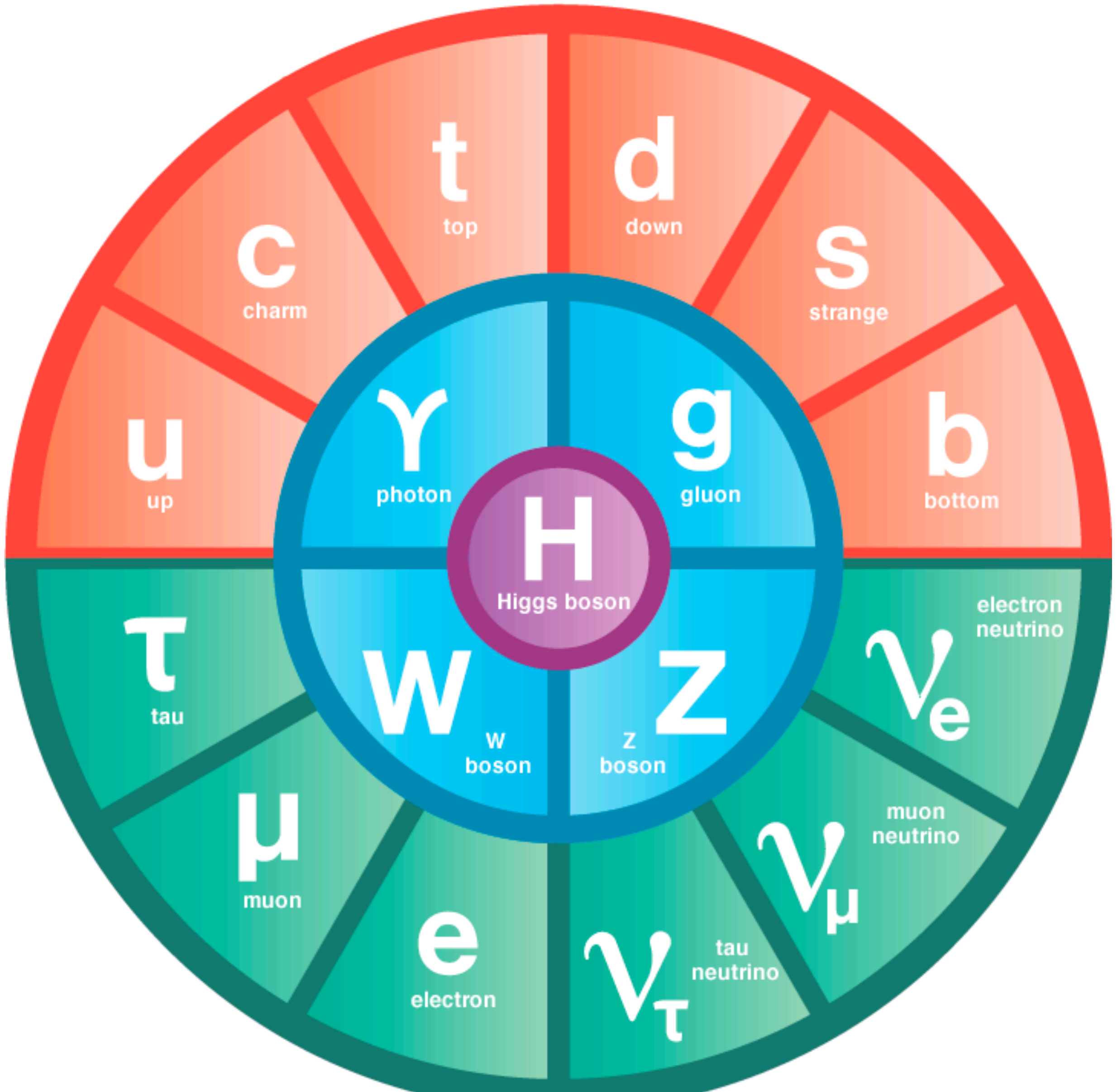
Lecture 8
Understanding Jets

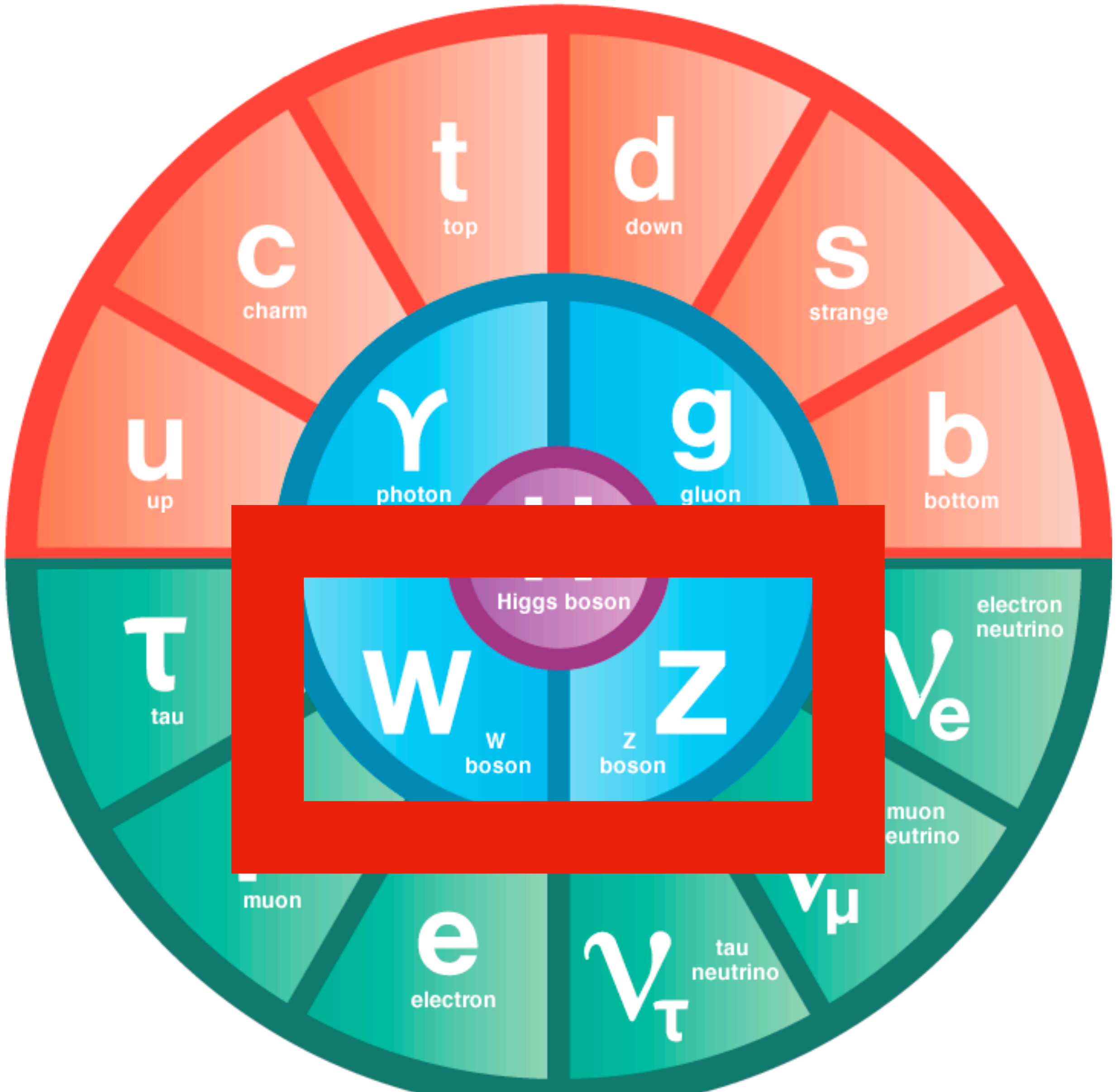
Laboratory

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



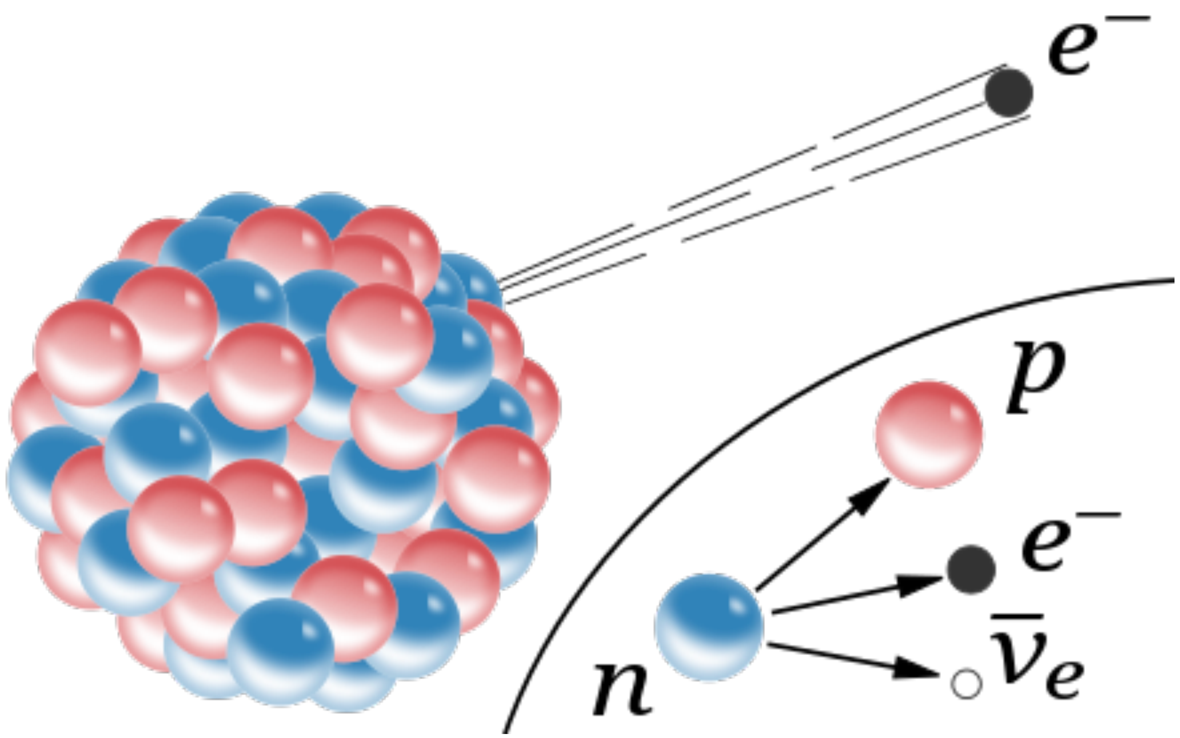
Laboratory

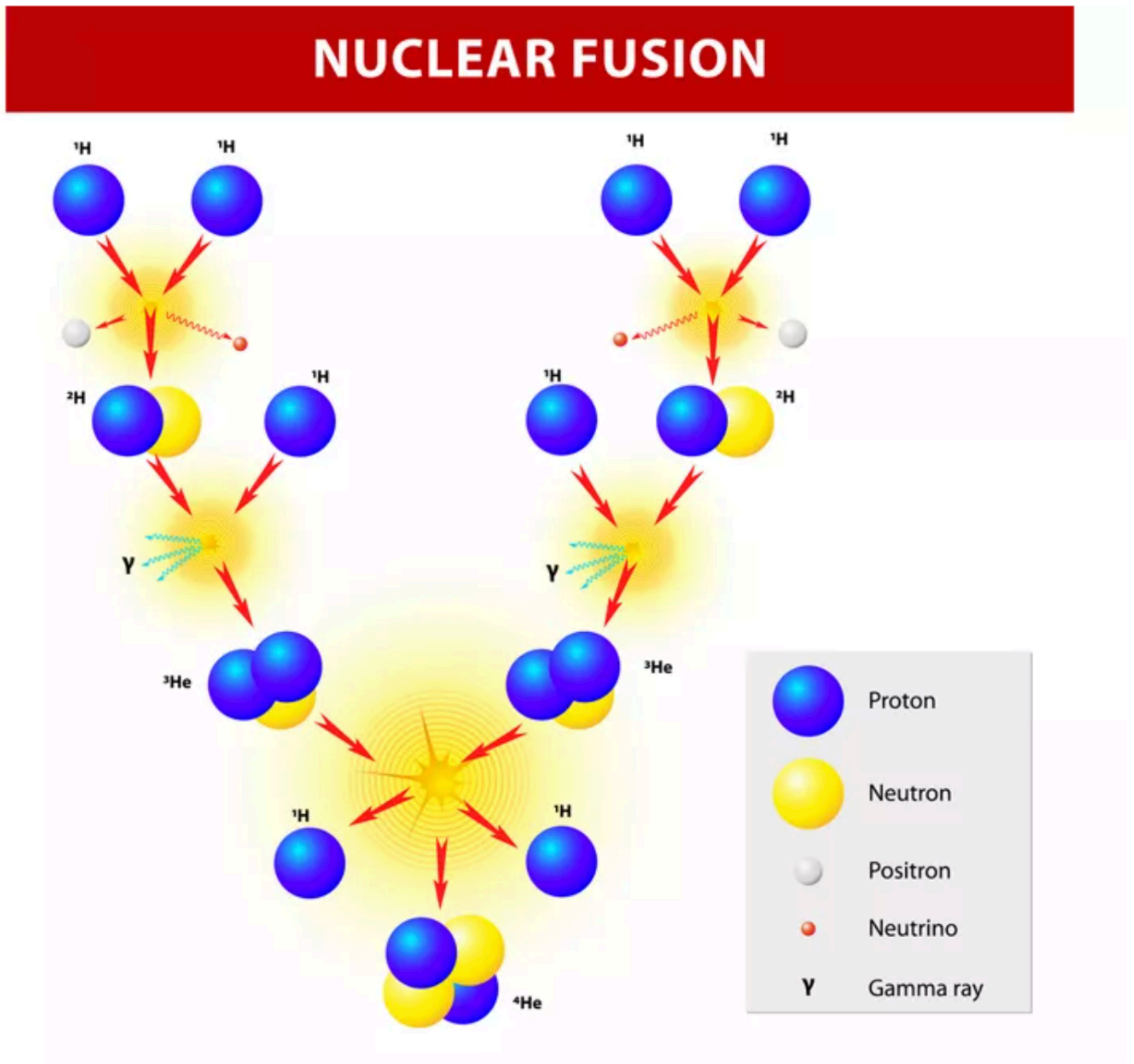
- The challenge of this lab is to fin the W and Z boson
  - These are the particles that cover the Weak Boson Interaction



Fundamental Forces

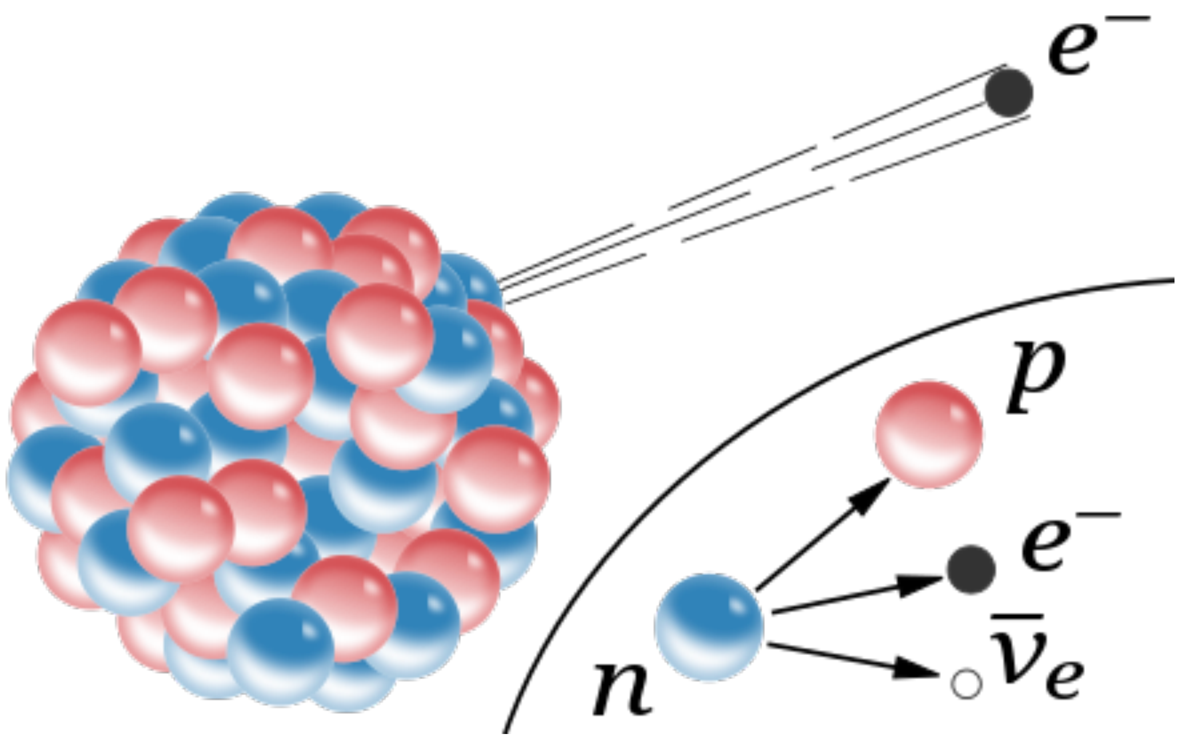
Weak Interactions

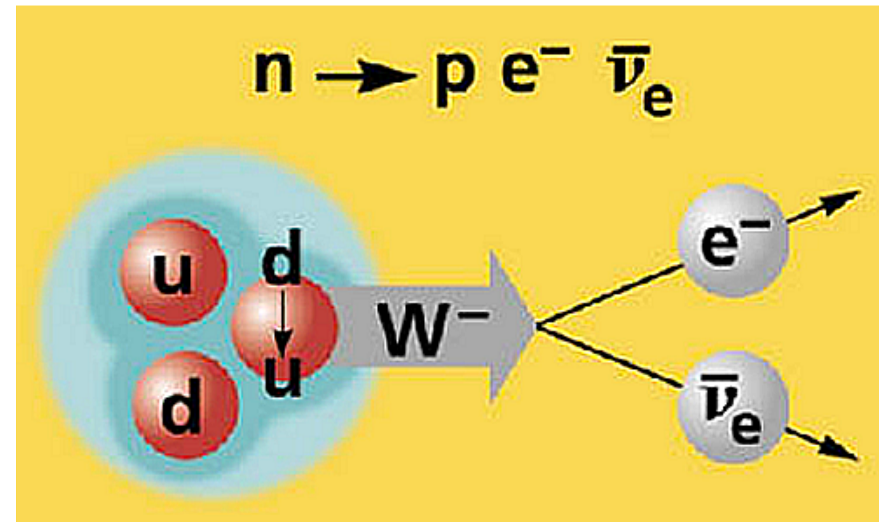


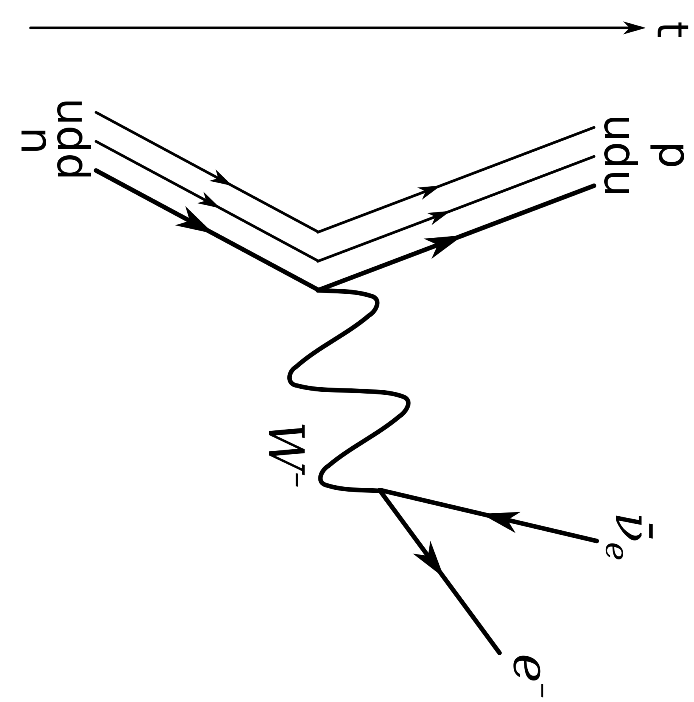


- The Weak interaction is described by W and Z bosons

Weak Interactions



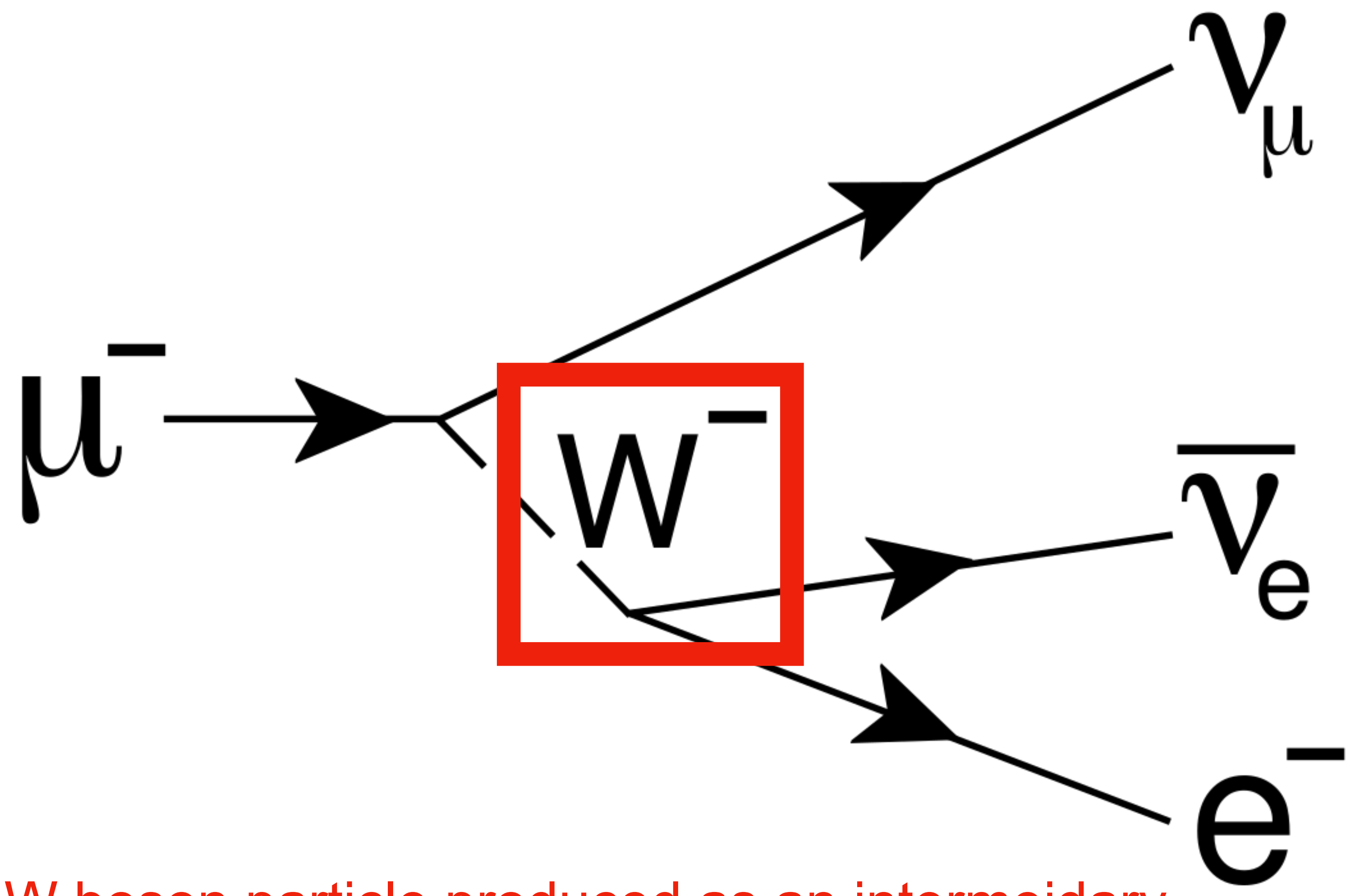




- The Weak interaction is described by W and Z bosons

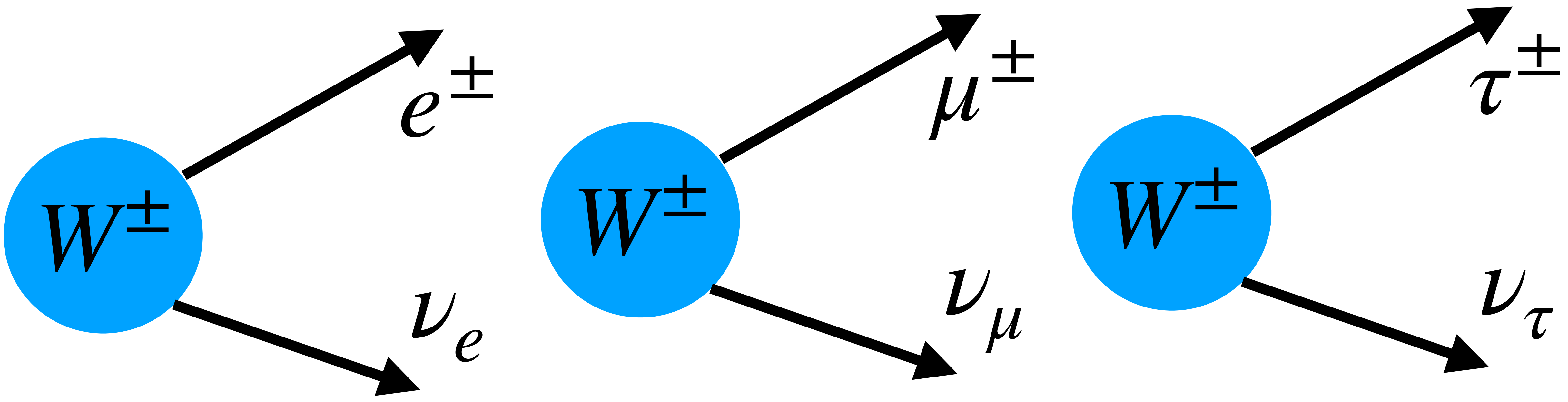
What really is this?

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



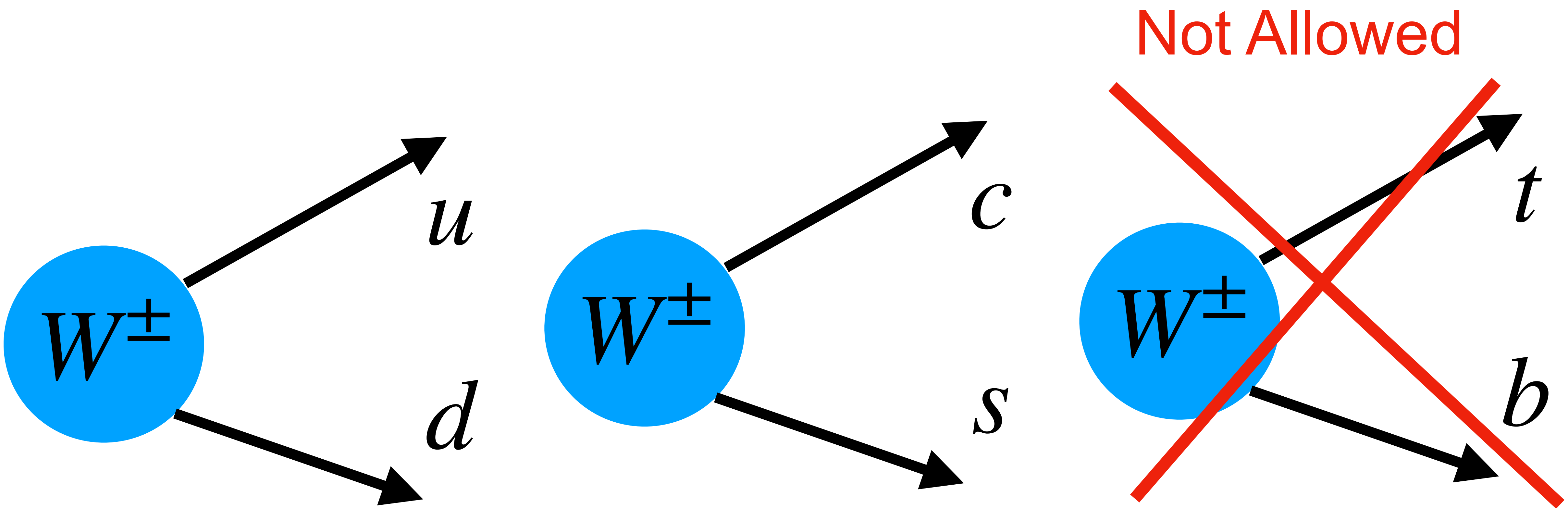
Heavy W boson particle produced as an intermeidary

W boson Properties



- W boson interacts with many different particles

W boson Properties

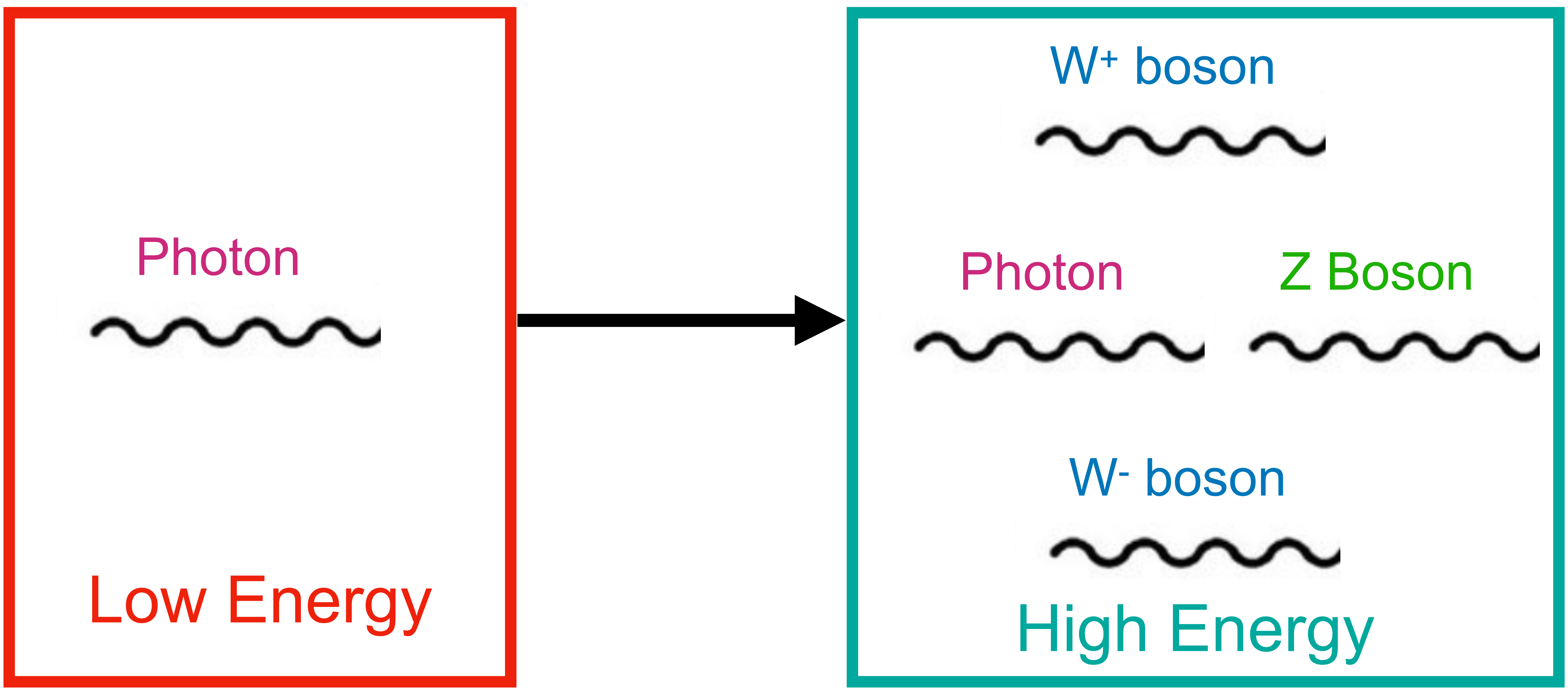


$$M_W < m_t + m_b$$

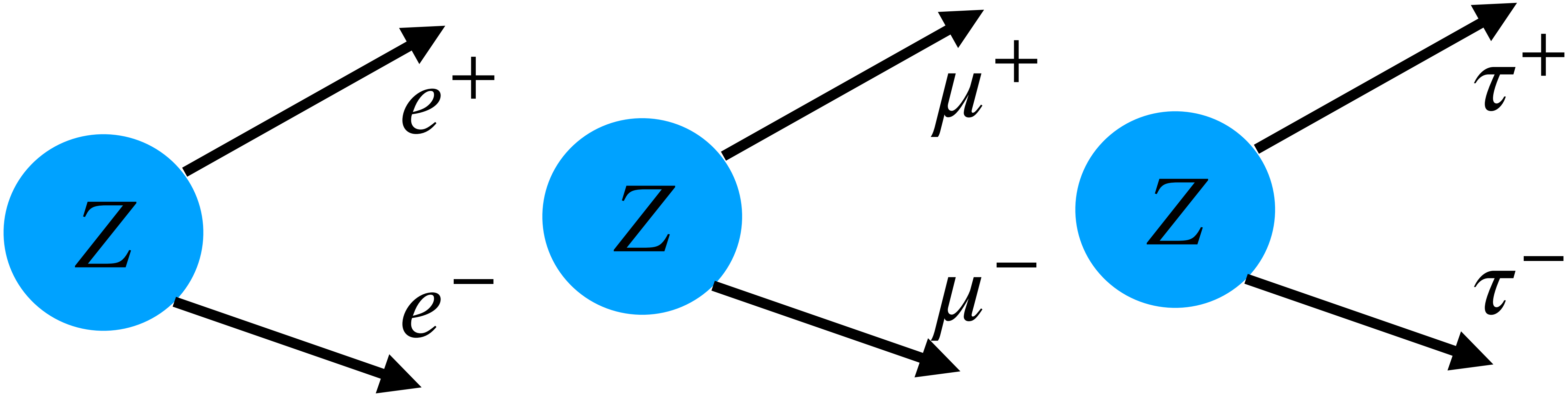
- W boson interacts with many different particles
  - These don’t happen frequently b/c W boson is heavy

Electroweak Bosons

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



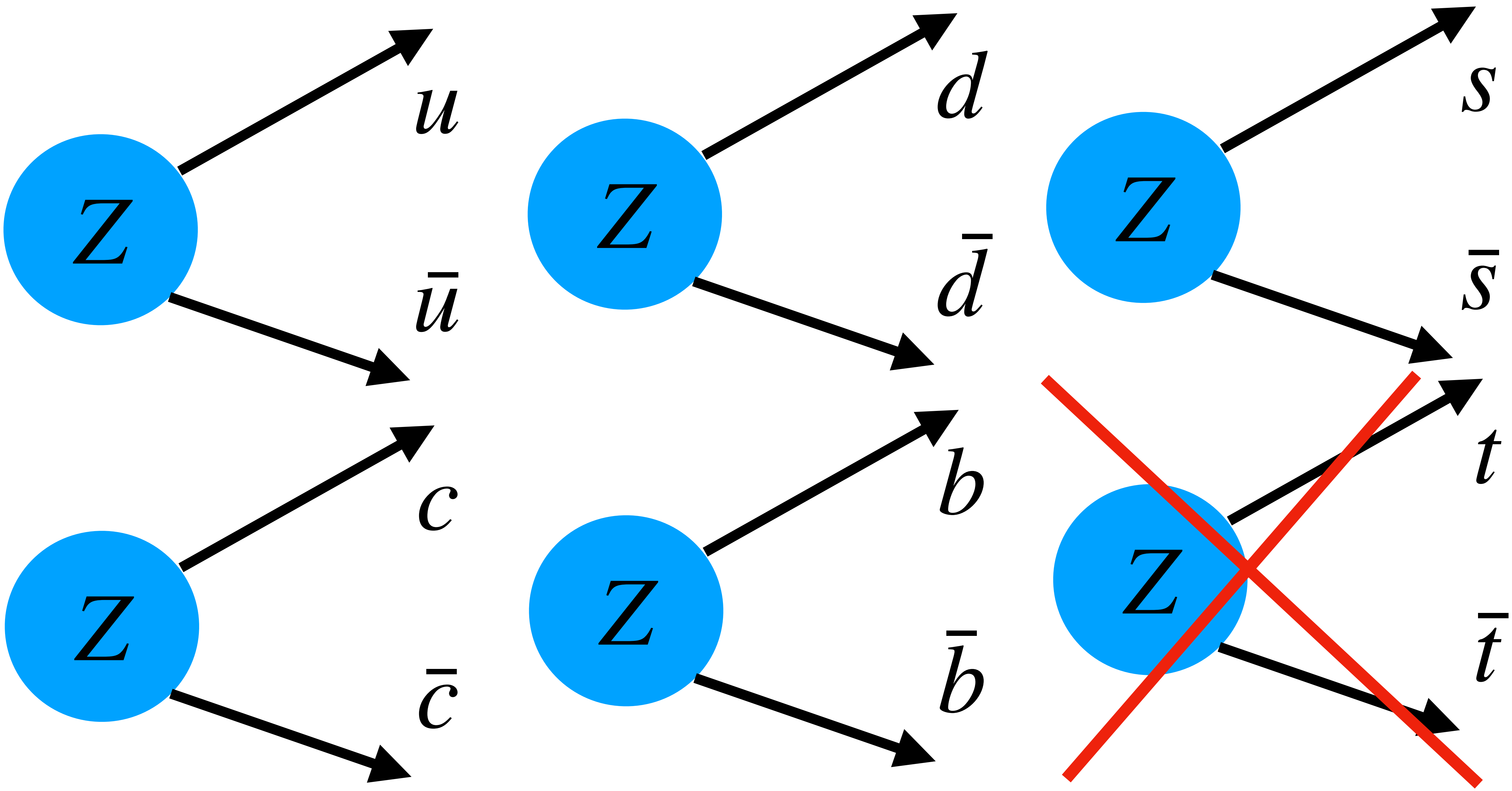
Z boson Properties



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

Z boson Properties

Decays to all quarks, except top

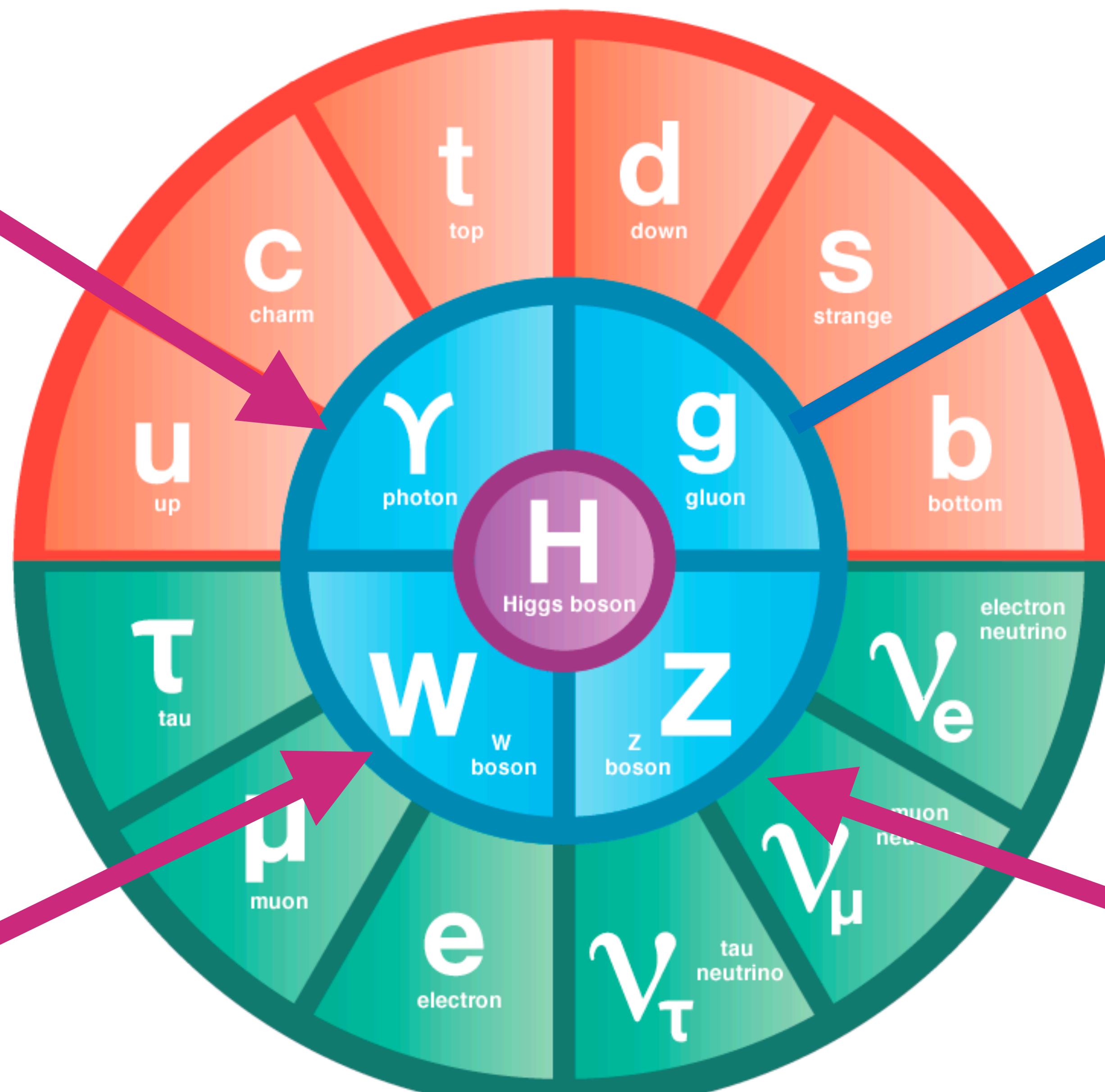


- Z boson is like a heavy photon (no charge, but heavy)

The Forces

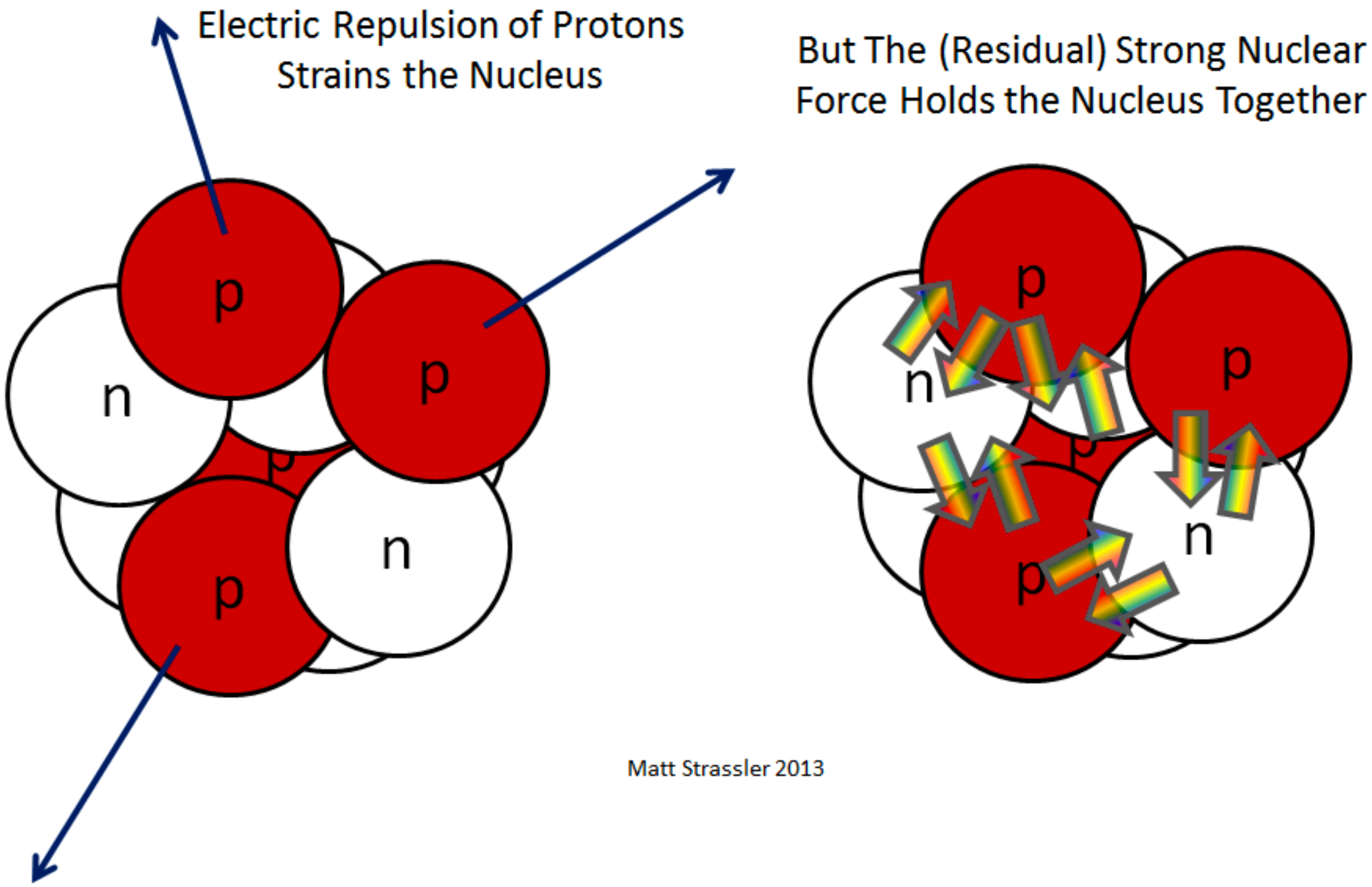
- The challenge of this lab is to fin the W and Z boson
  - These are the particles that cover the Weak Boson Interaction

All
Part
of
Electroweak
Force



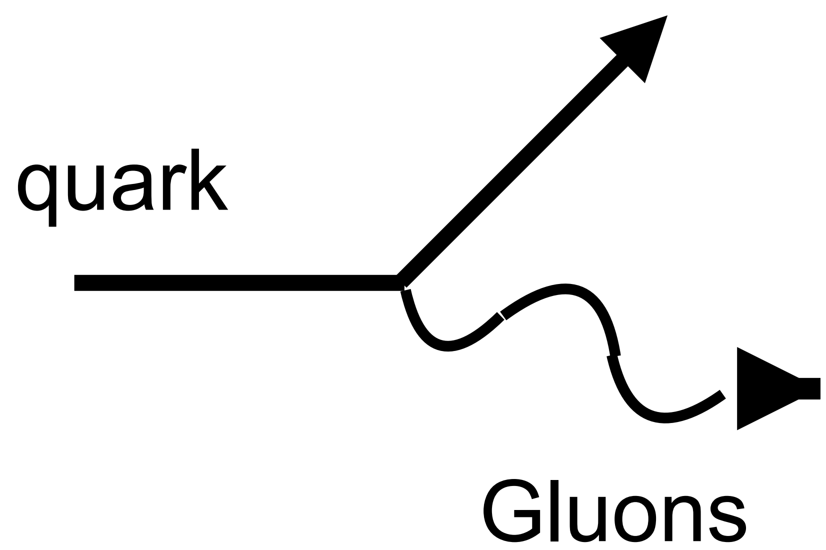
what
about
Strong force?

Strong Force



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

Strong Force Production

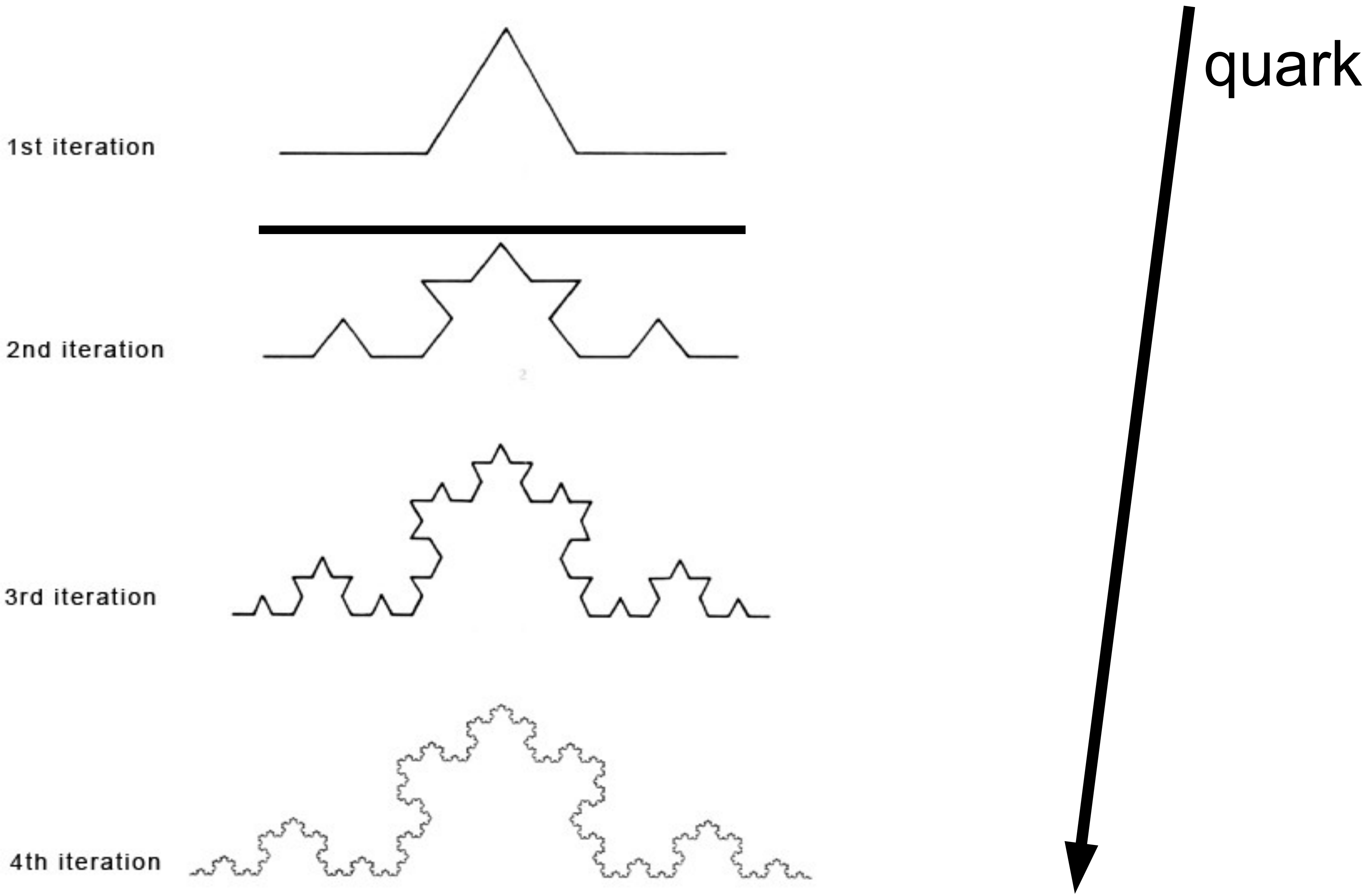


- Strong force
  - At high energy quarks can get produced which radiate gluons

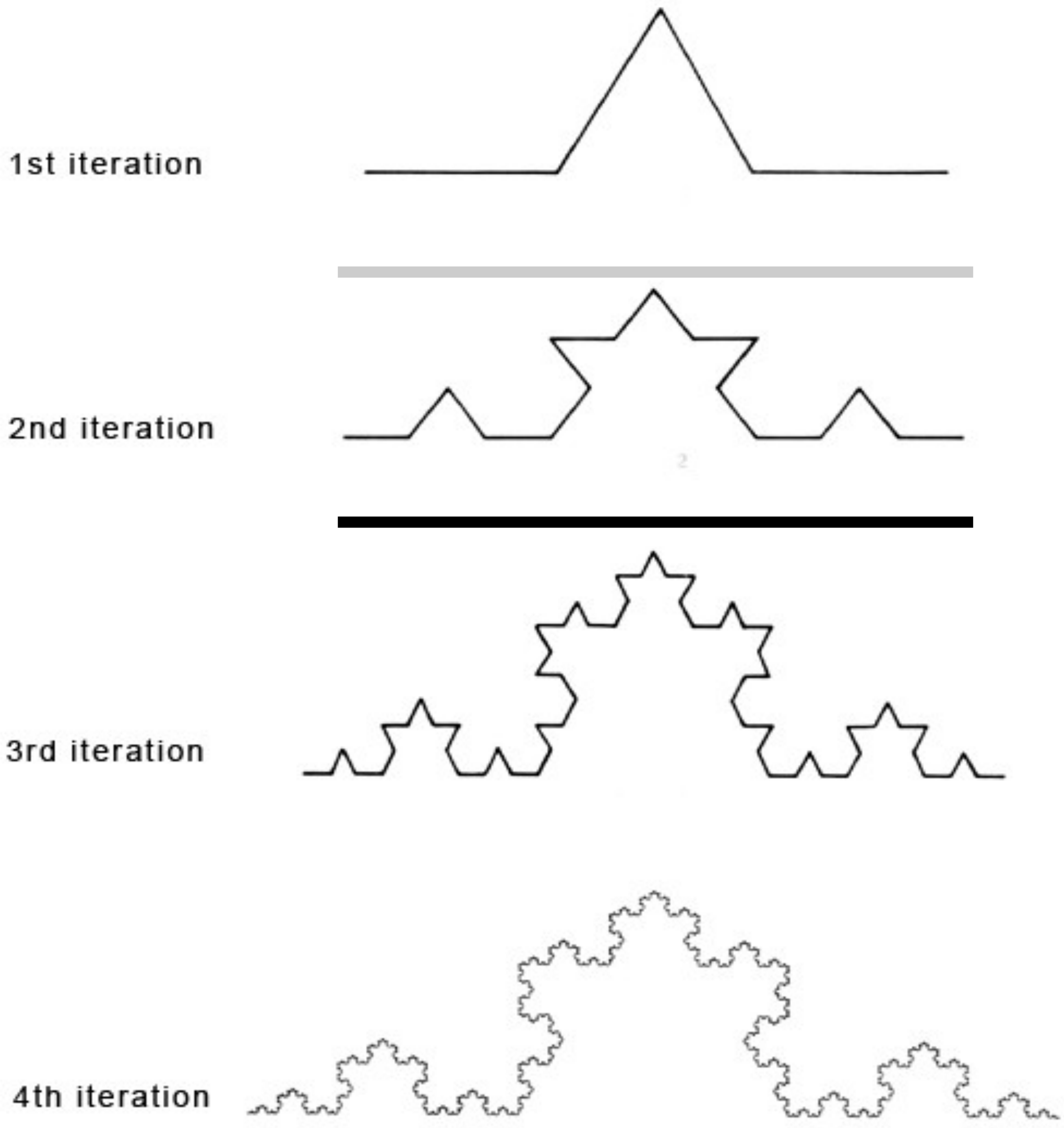
Understanding Jets

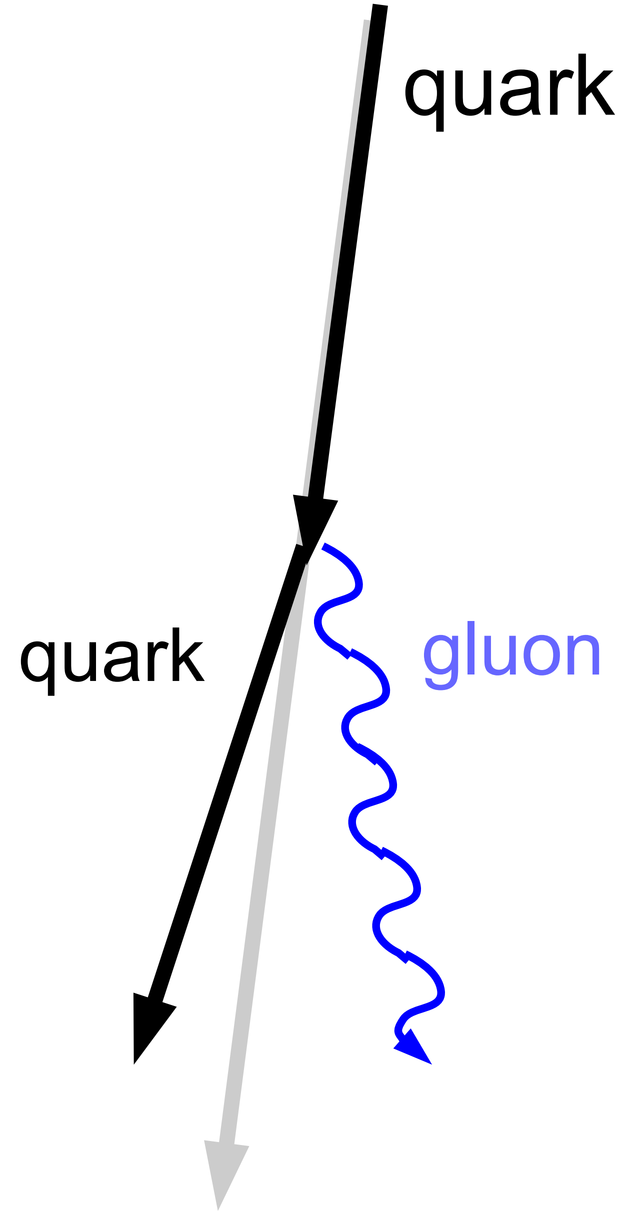
Understanding Jets (modern view)

How does this cluster appear?

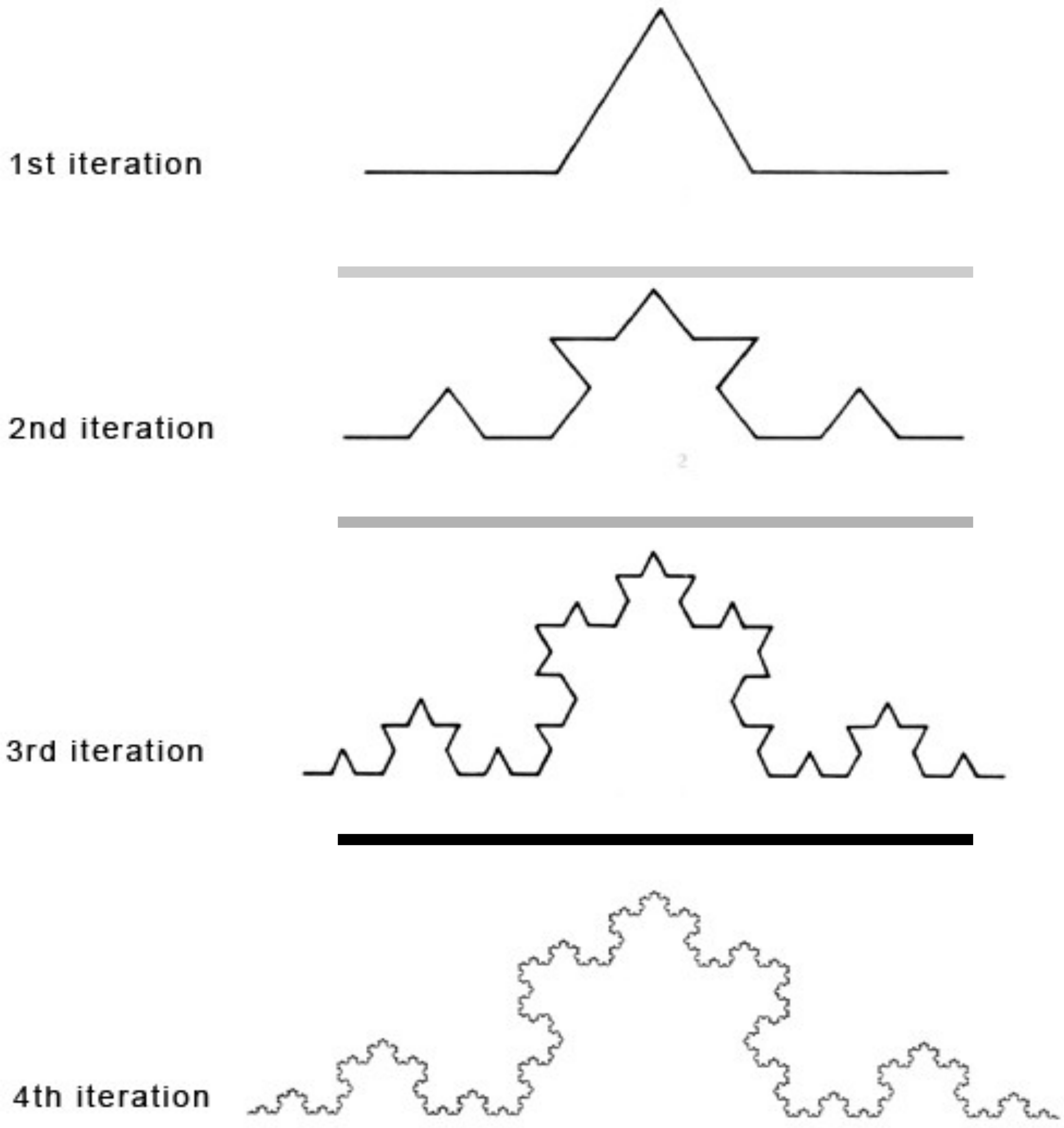


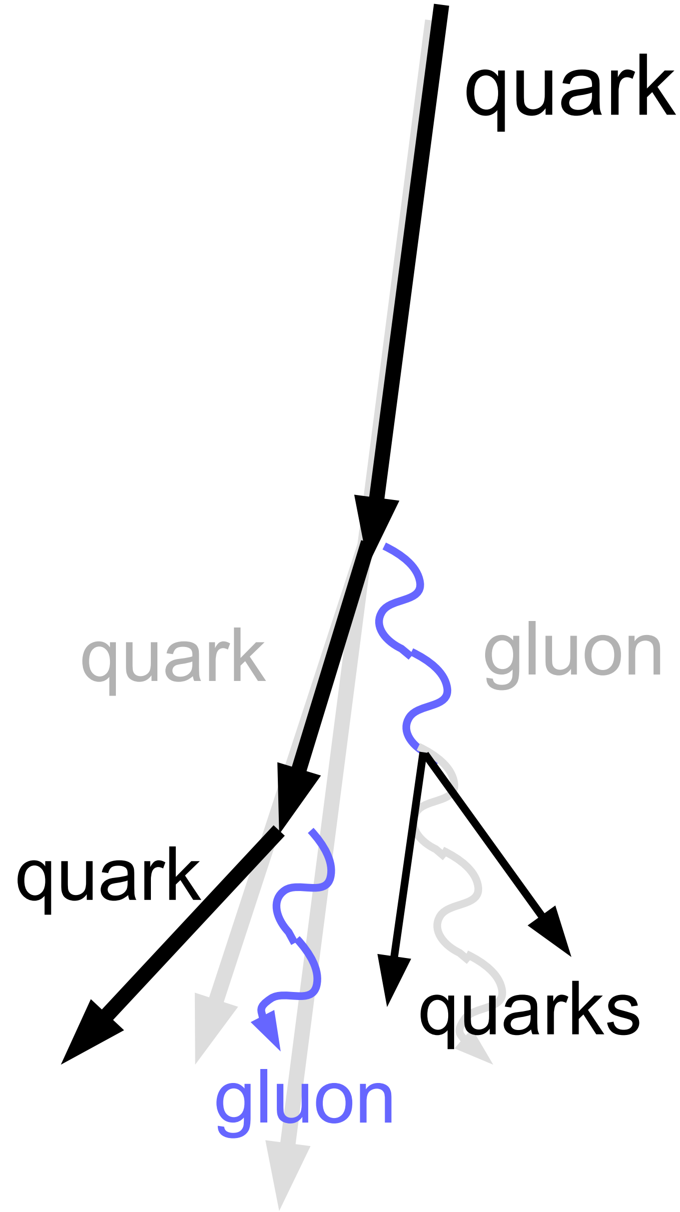
How does this cluster appear?





How does this cluster appear?





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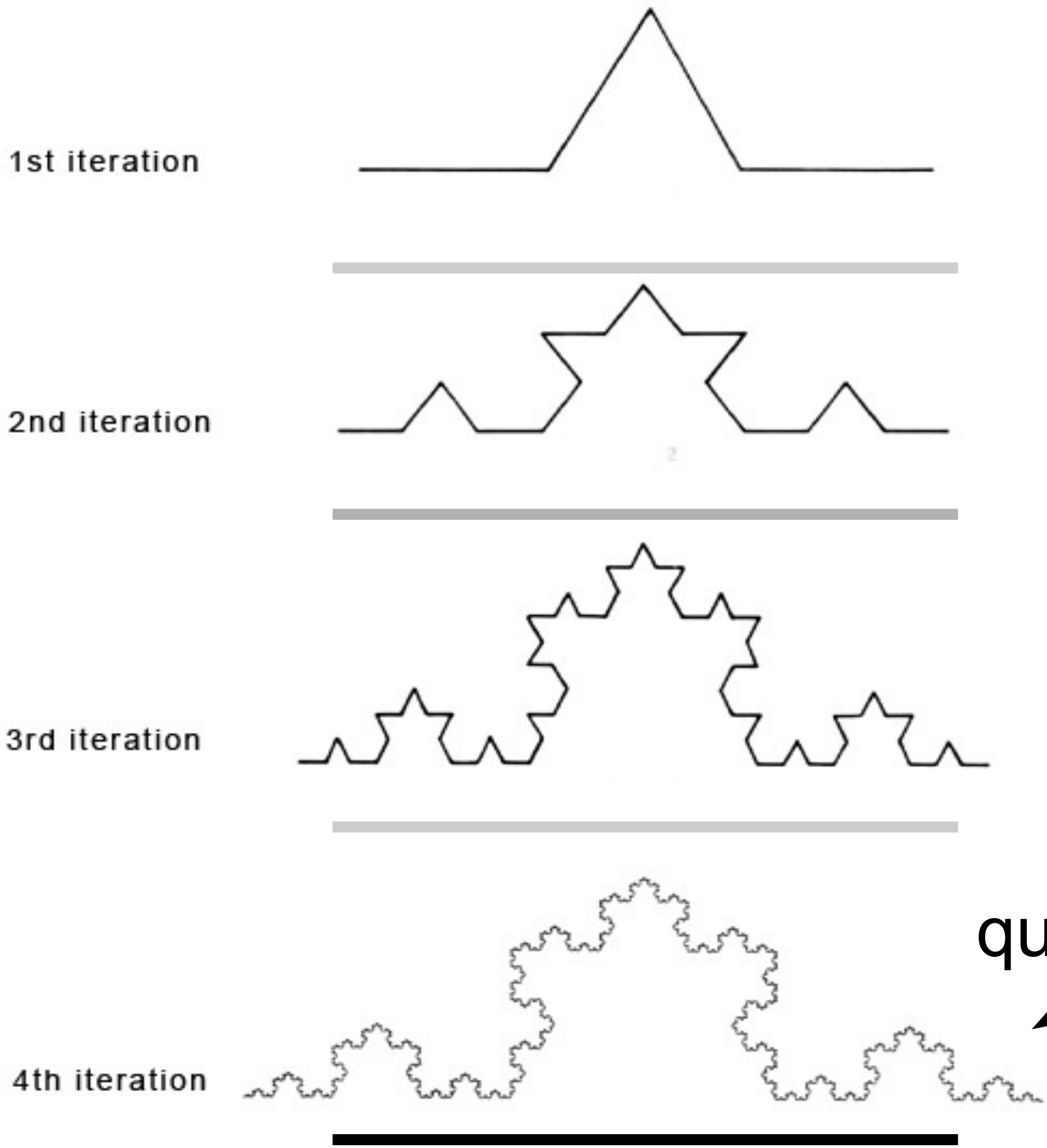
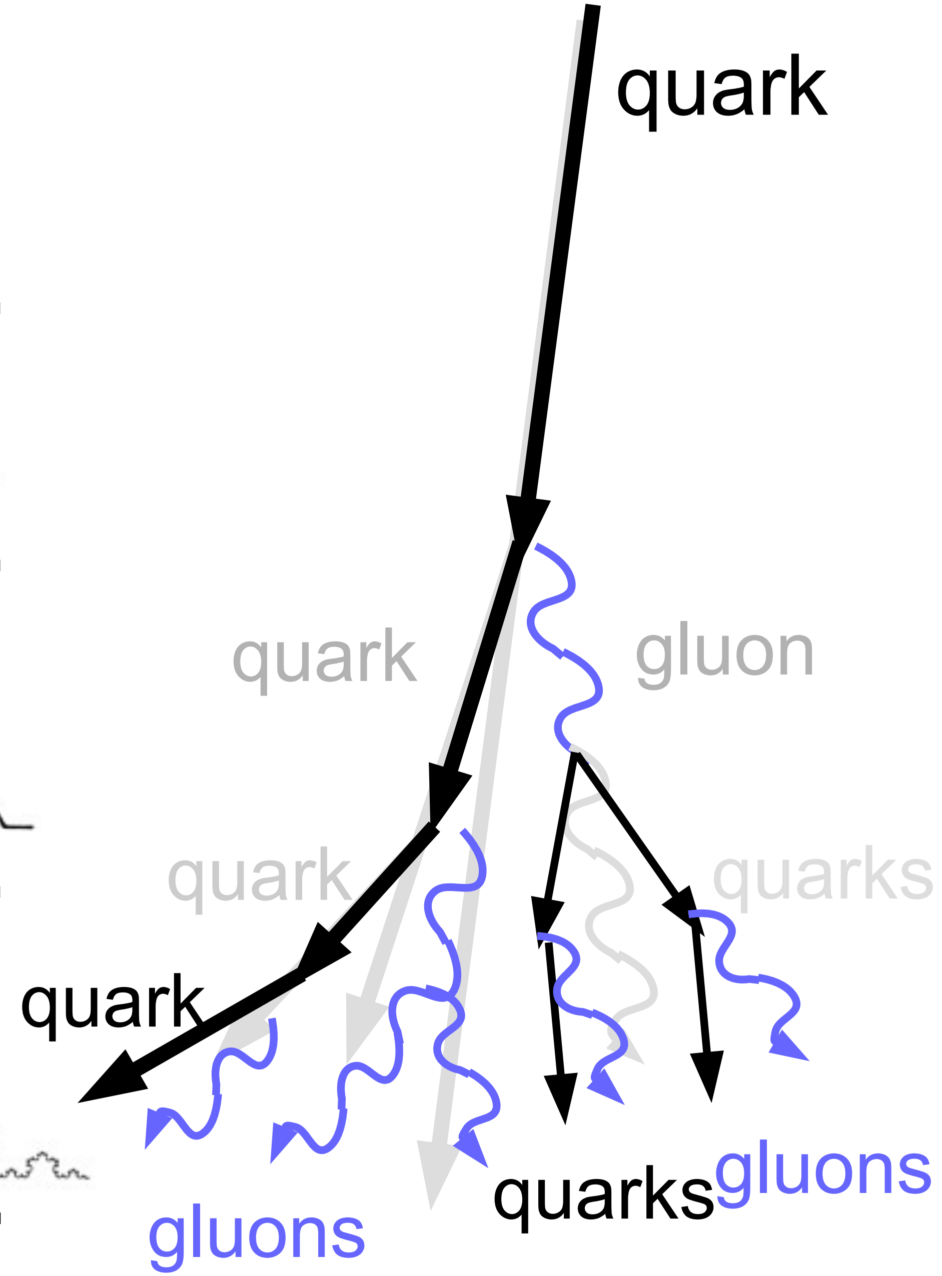
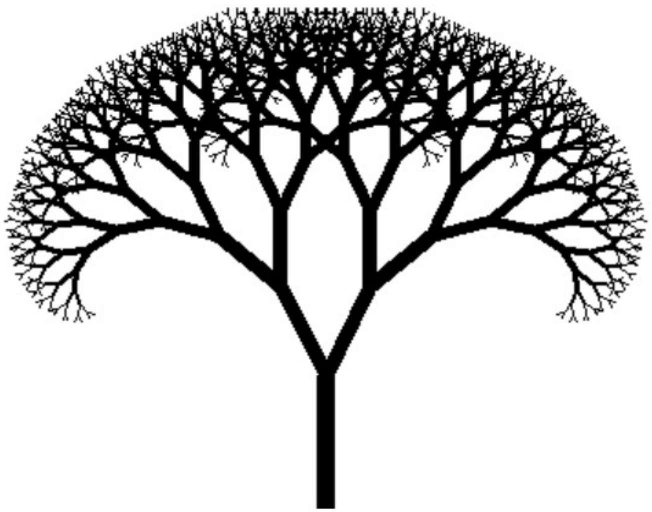




A fractal

- The repeated branching structure gives a fractal



Branches

Norway coastline

Romensco cauliflower

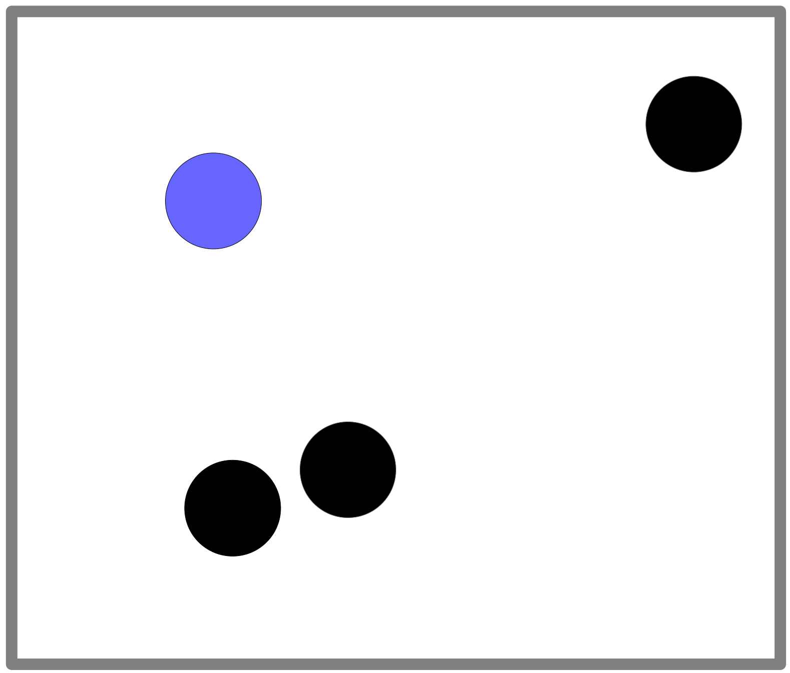
Lets use this property to make a simple observable?

What is the scaling dimension of a jet

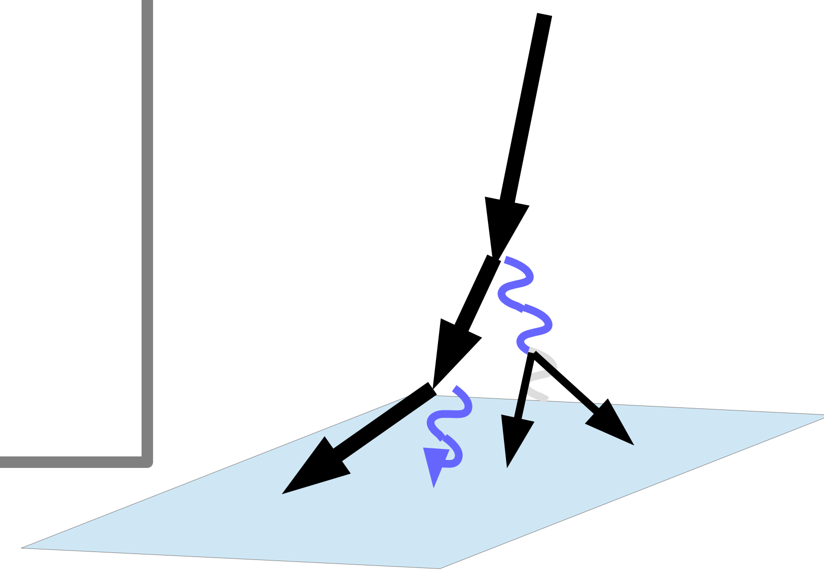
Box Counting(Hausdorff Dimension)

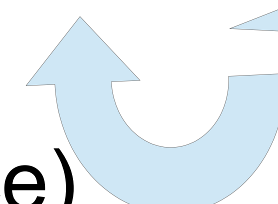
For a given distance scale :

What number of boxes are needed to describe a jet



Same jet from 2 slides ago



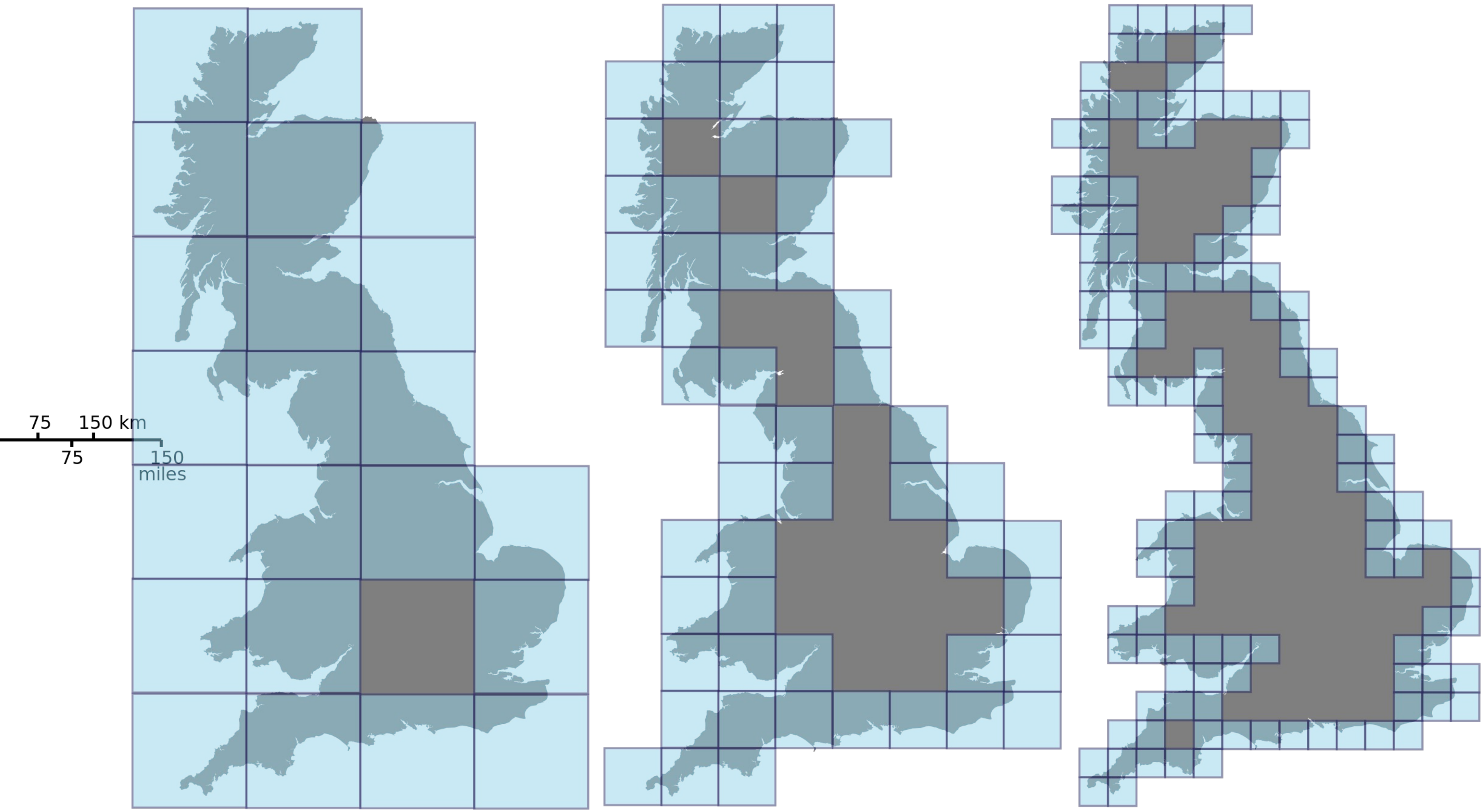


$$\text{(Fractal) Dimension} = \lim_{D(\text{istance}) \to 0} \frac{\text{Log}(N_d^{\text{boxes}})}{\text{Log}(\text{Distance})}$$

Project with CERN summer student 2014

Can we characterize this?

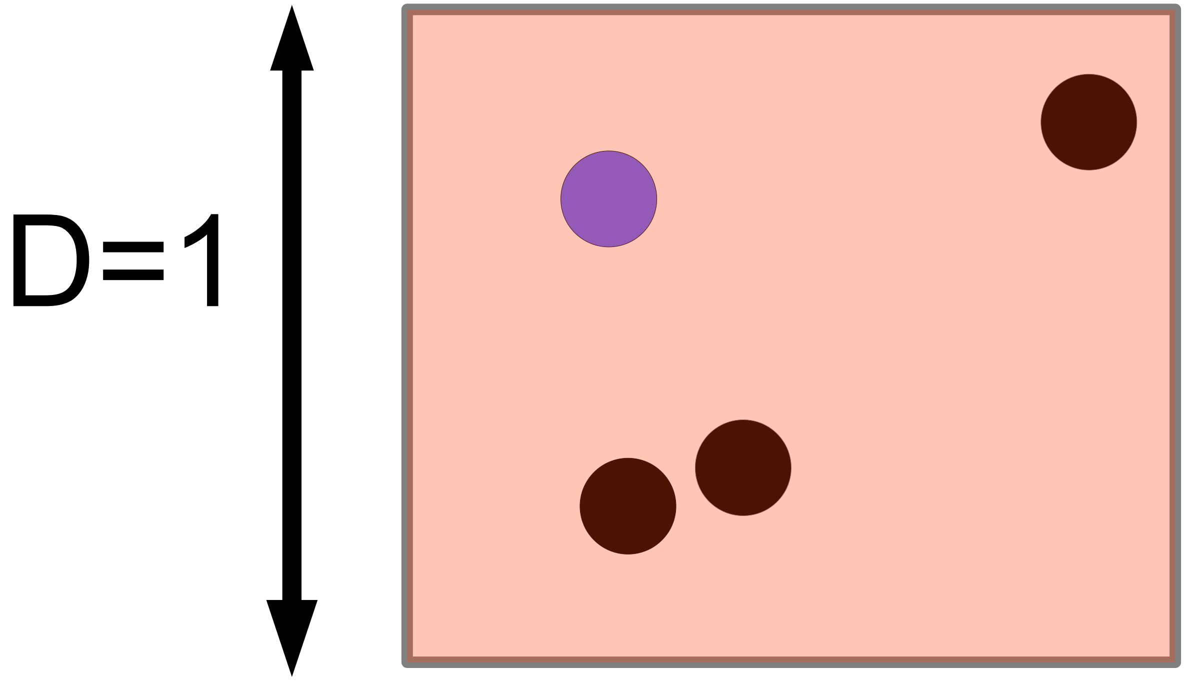
- Measuring fractals:



Coastline of Great Britain is D=1.25

Box Counting

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

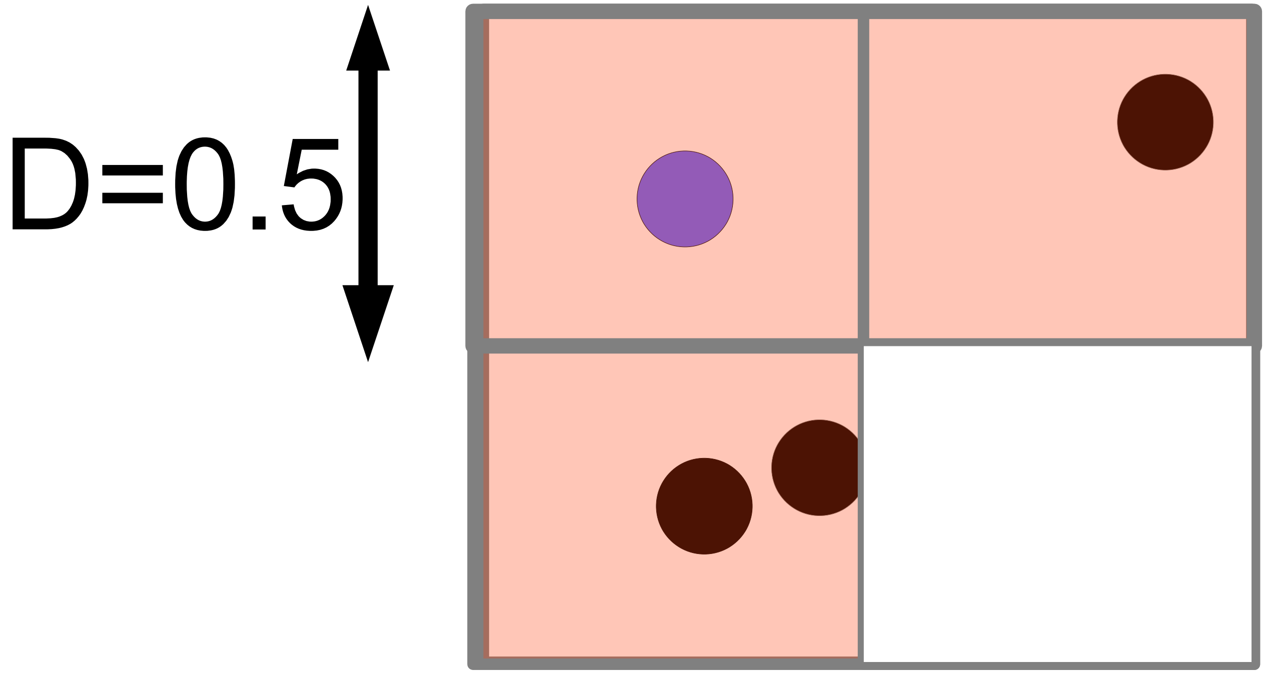


1 Box with distance=1 covers all points

Number of boxes to cover per size defines dimension

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

Box Counting



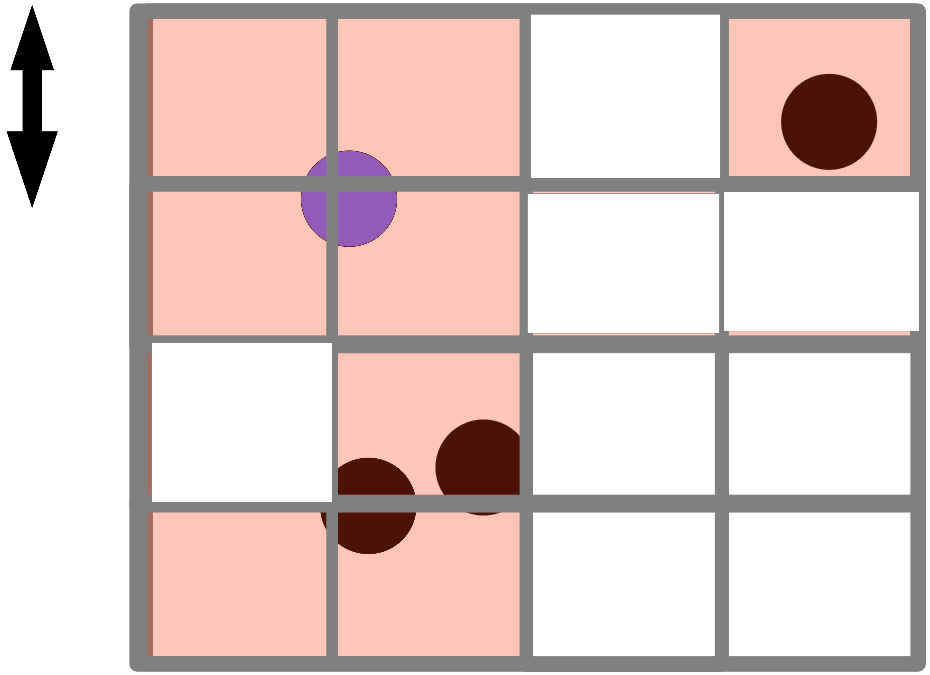
3 Boxes with distance=0.5 cover all points

Number of boxes to cover per size defines dimension

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

Box Counting

D=0.25

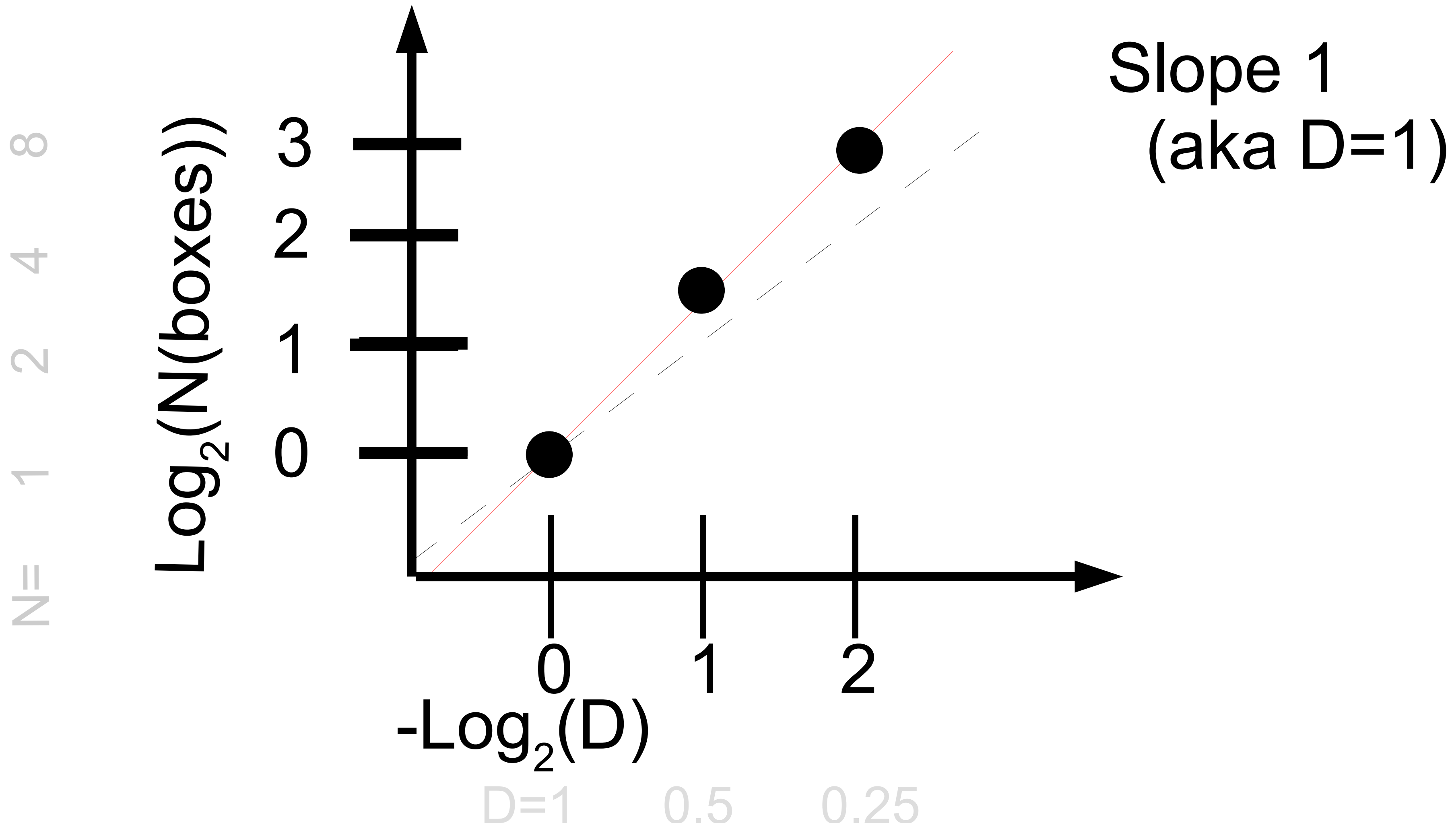


8 Boxes with distance=0.25 cover all points

Number of boxes to cover per size defines dimension

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

Box Counting

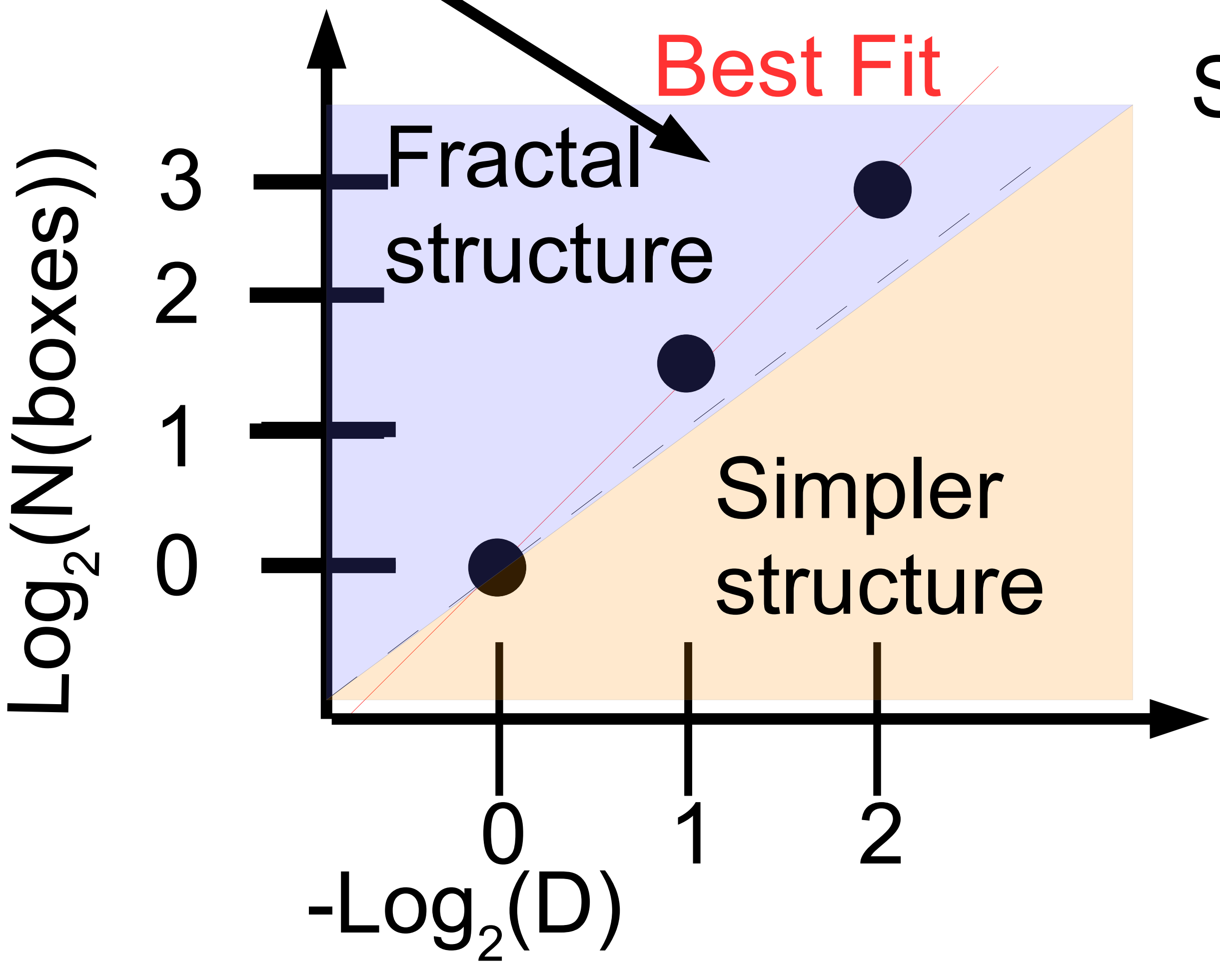


Number of boxes to cover per size defines dimension

Box Counting

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

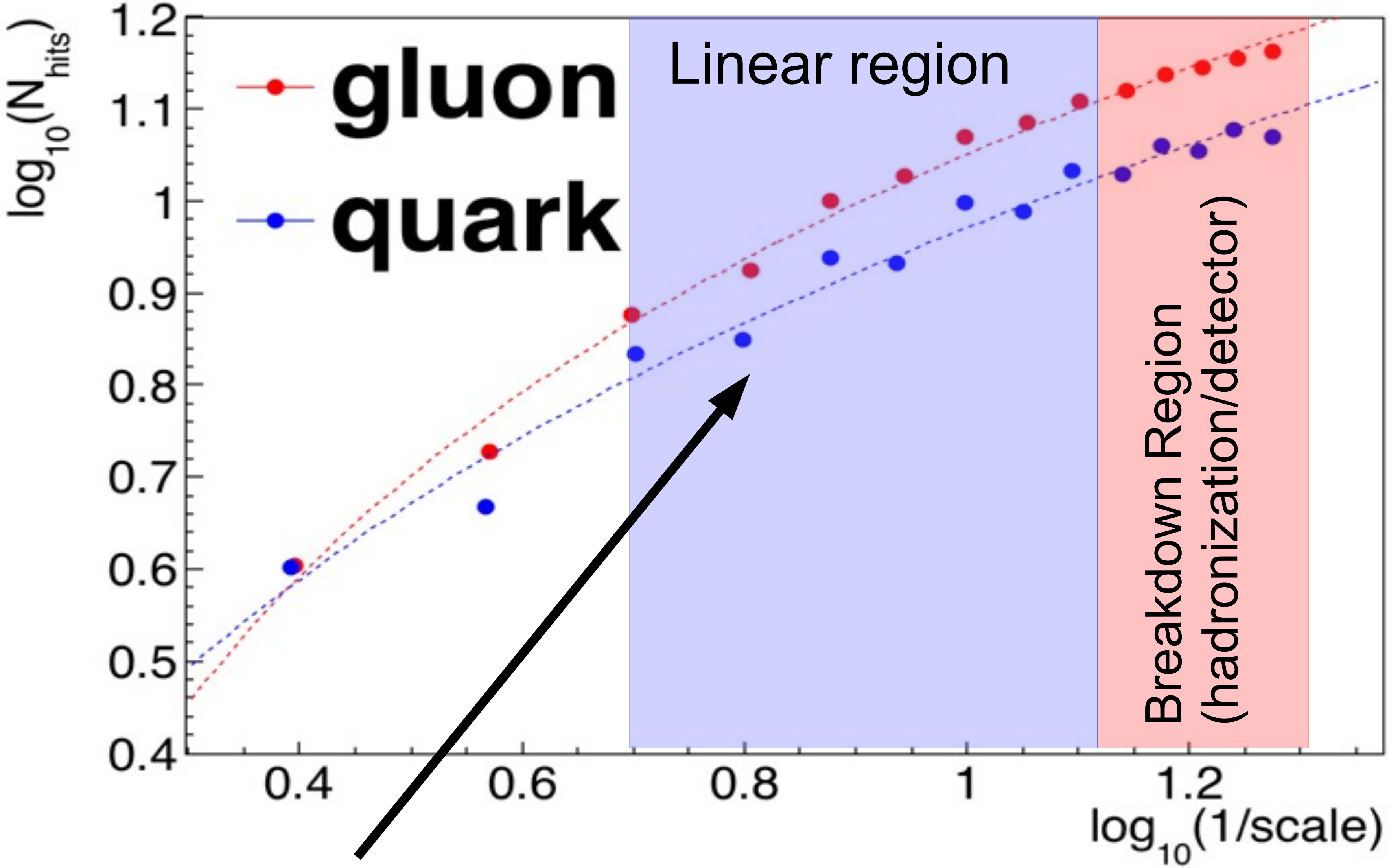
Our 4 particle jet is fractal like



Slope 1 (aka D=1)

Number of boxes to cover per size defines dimension

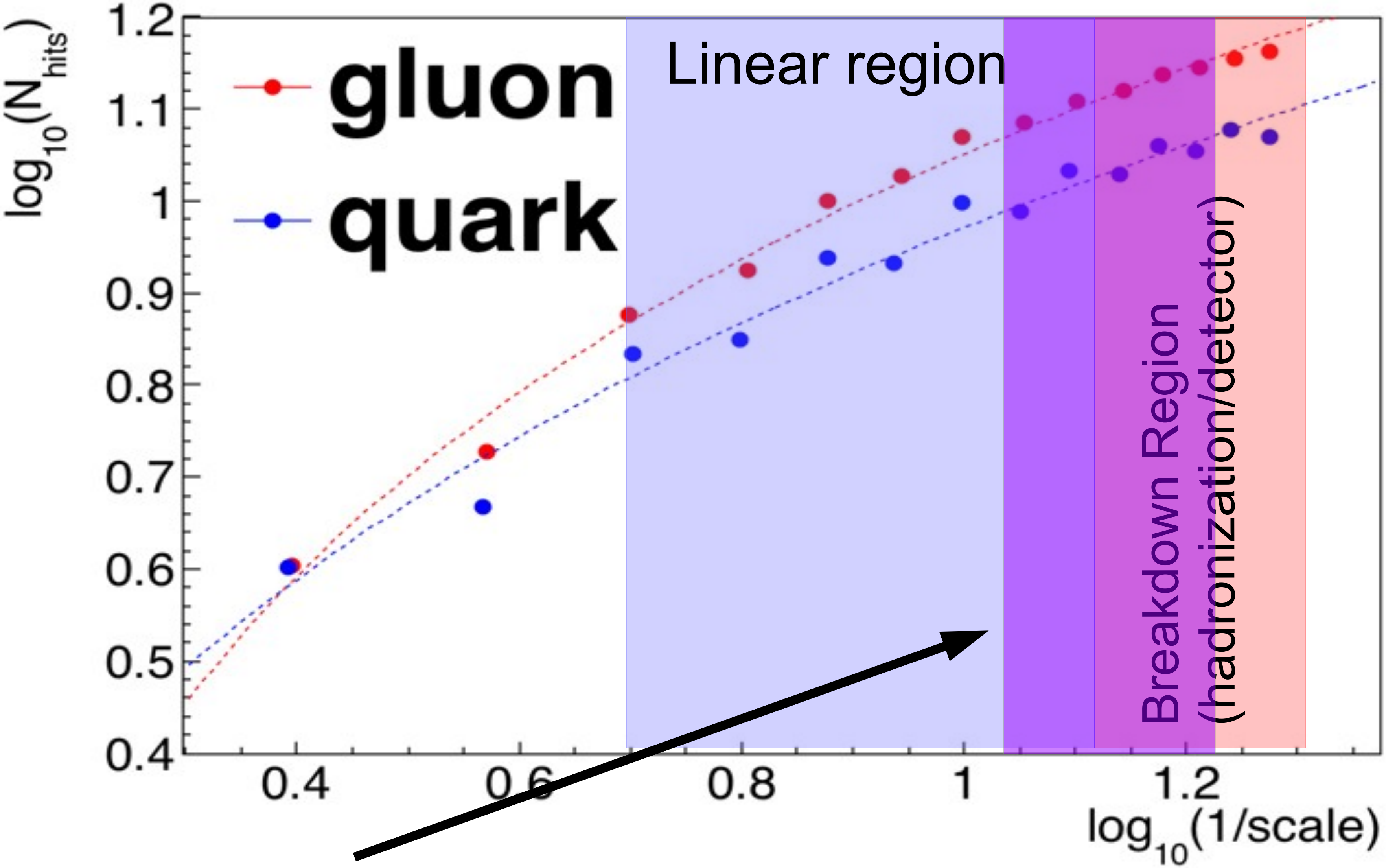
What about a real jet?



Roughly linear scalar separation between quarks and gluons

arxiv/sometime soon

What about a real jet?

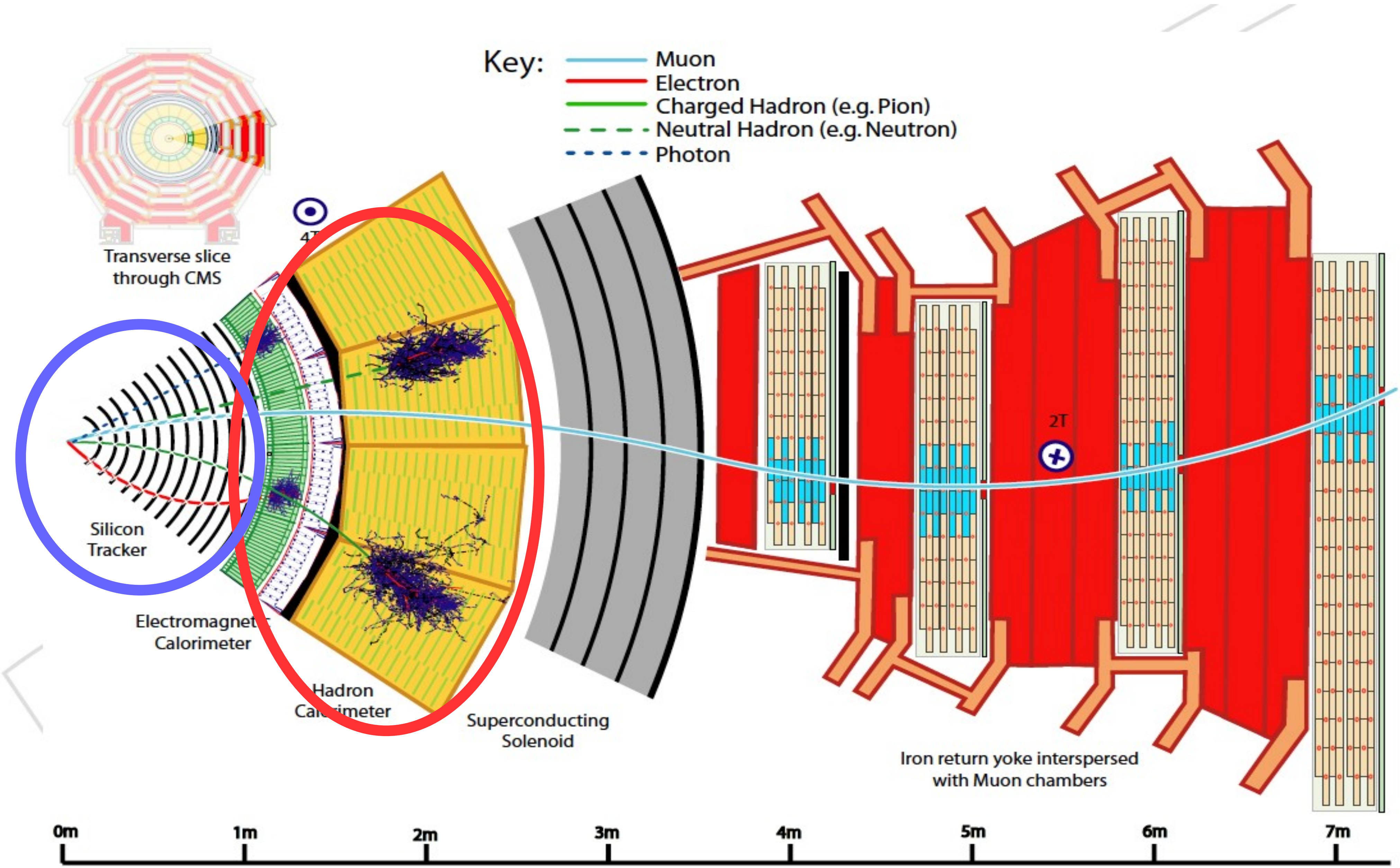


Effects from the heavy ion medium can modify this region

arxiv/sometime soon

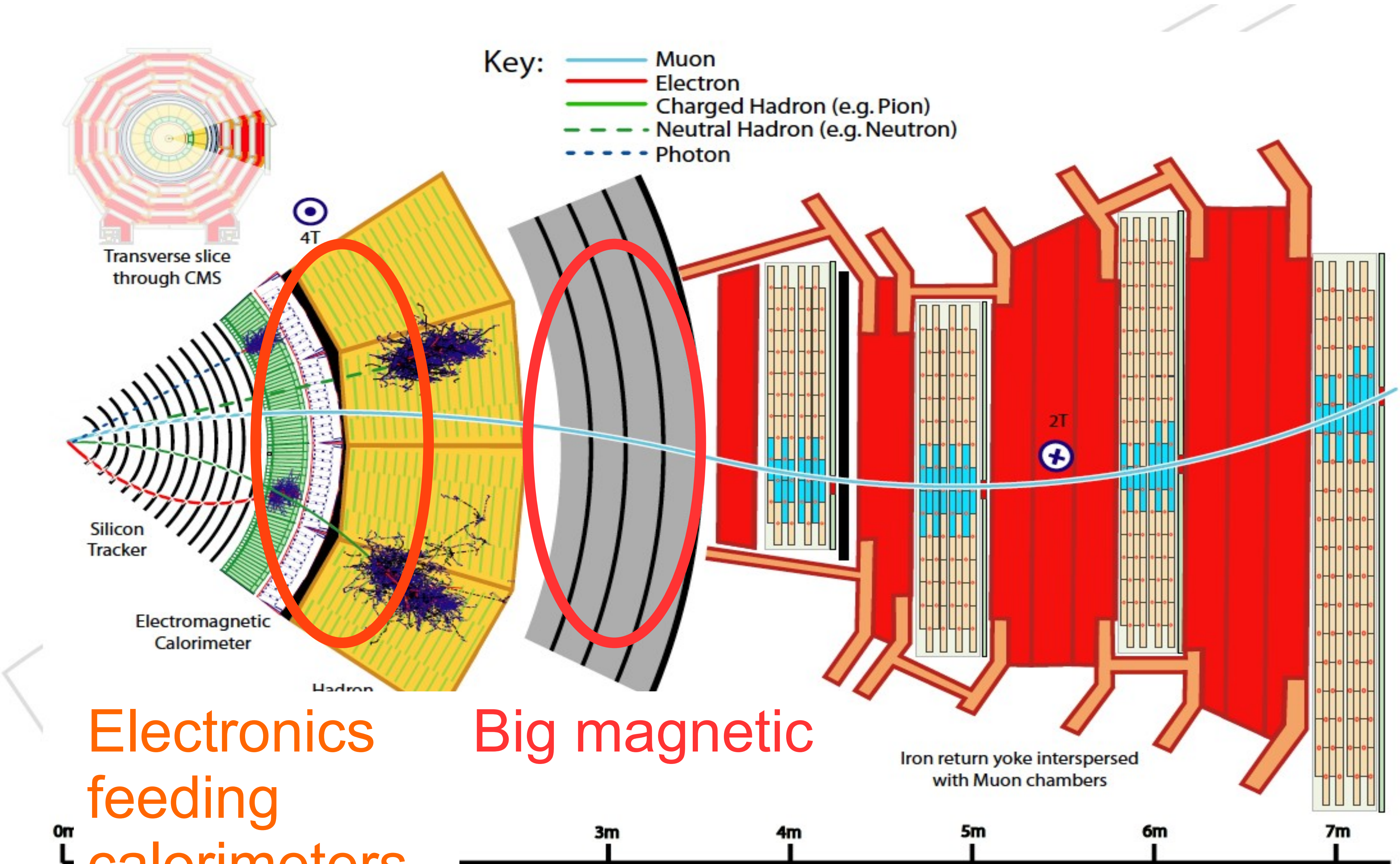
In Our Detector

Over the past week you have seen the individual components



What if we start to link things together?

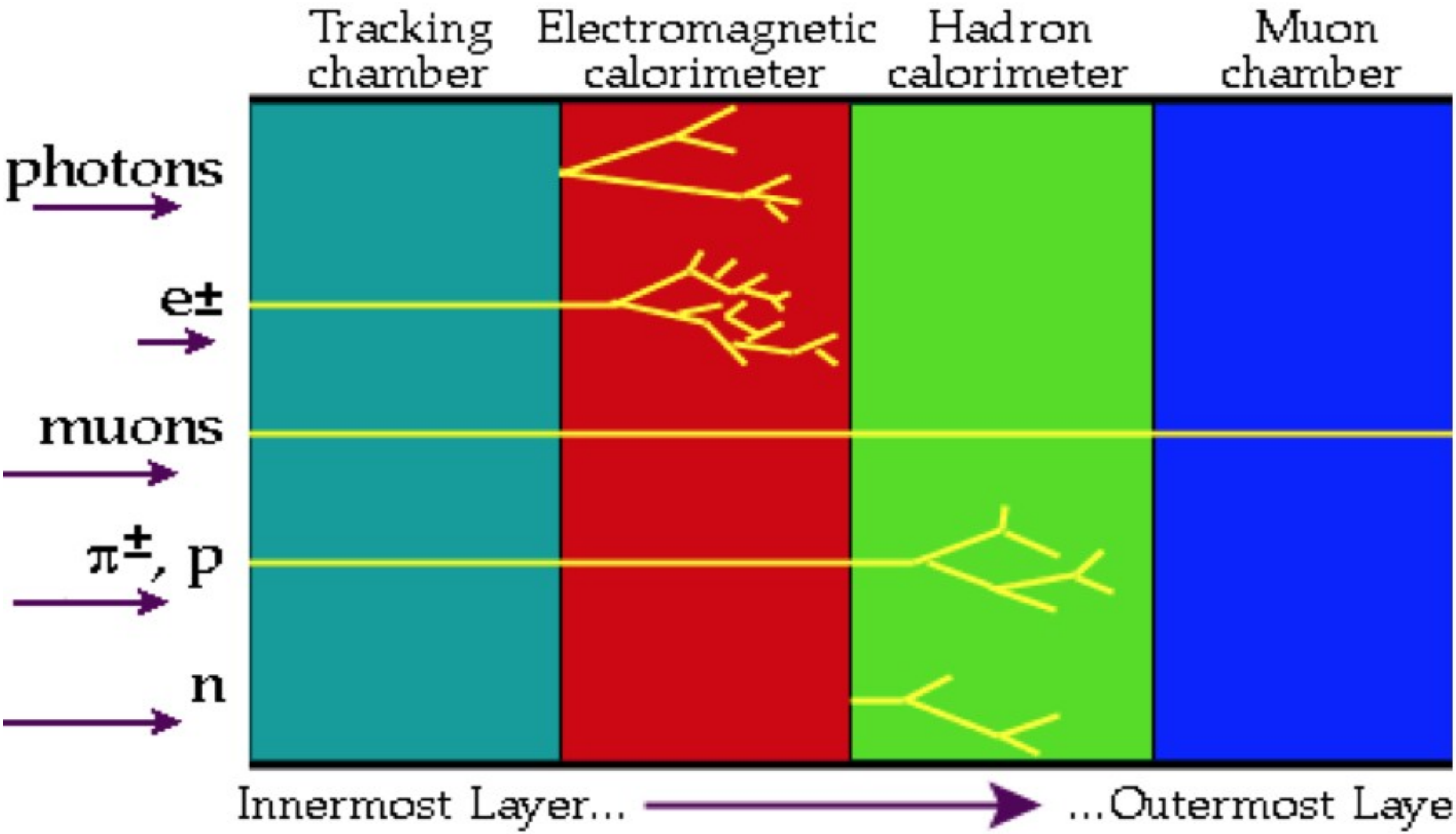
We have to account for the other detectors



Electronics feeding calorimeters

Big magnetic

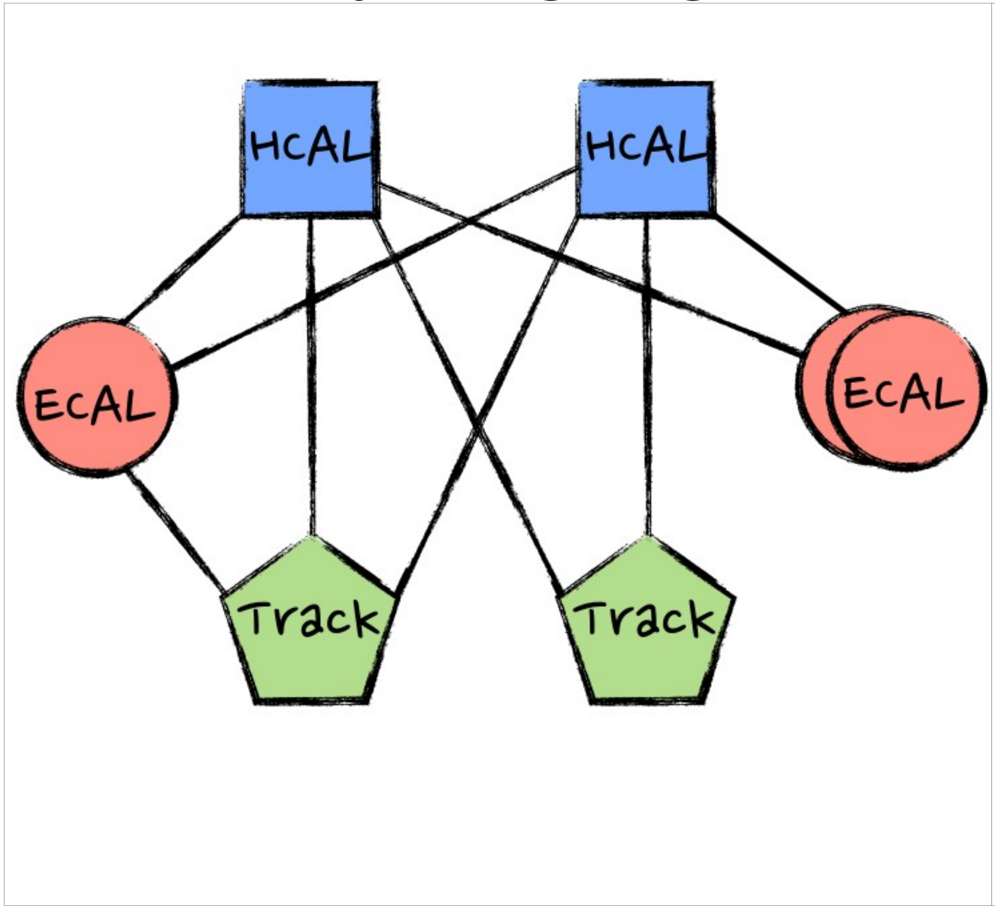
Particle Identification Basics



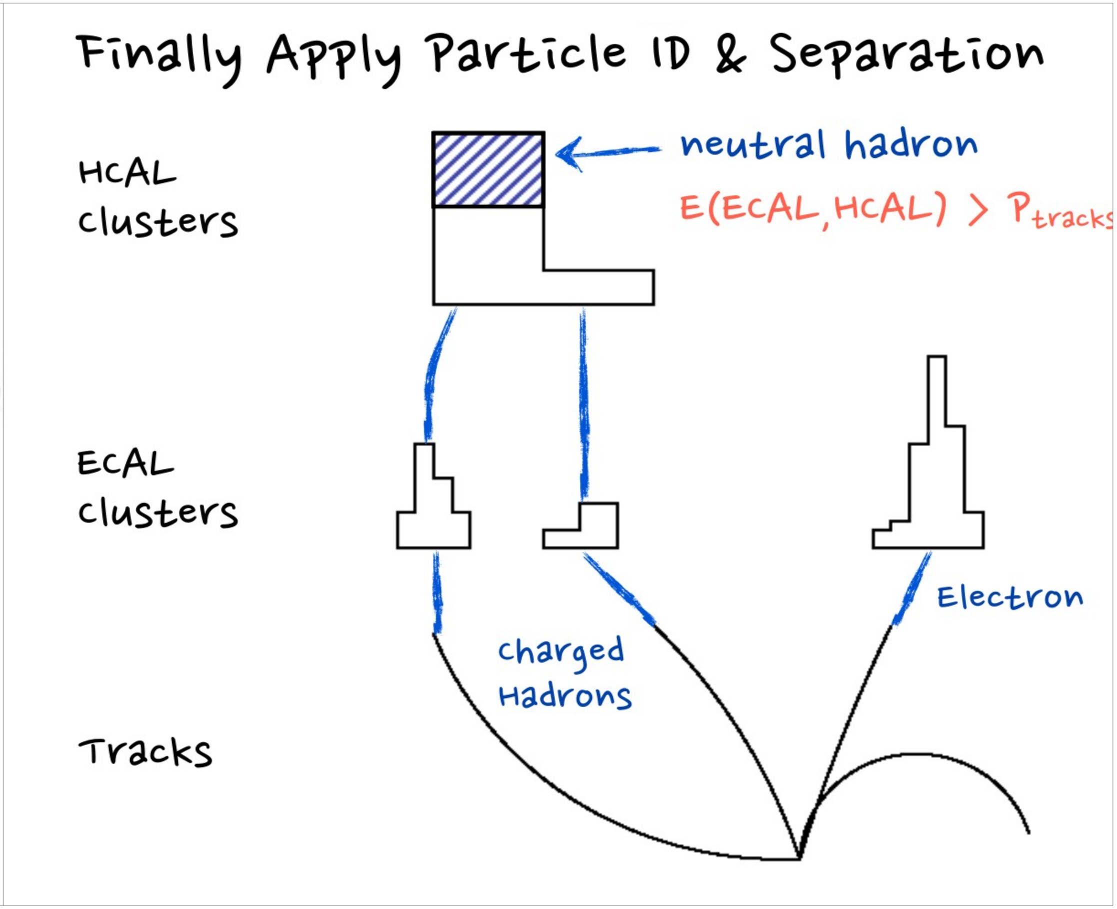
Credit: Particle Data Group (LBNL)

Particle Flow

Link everything together



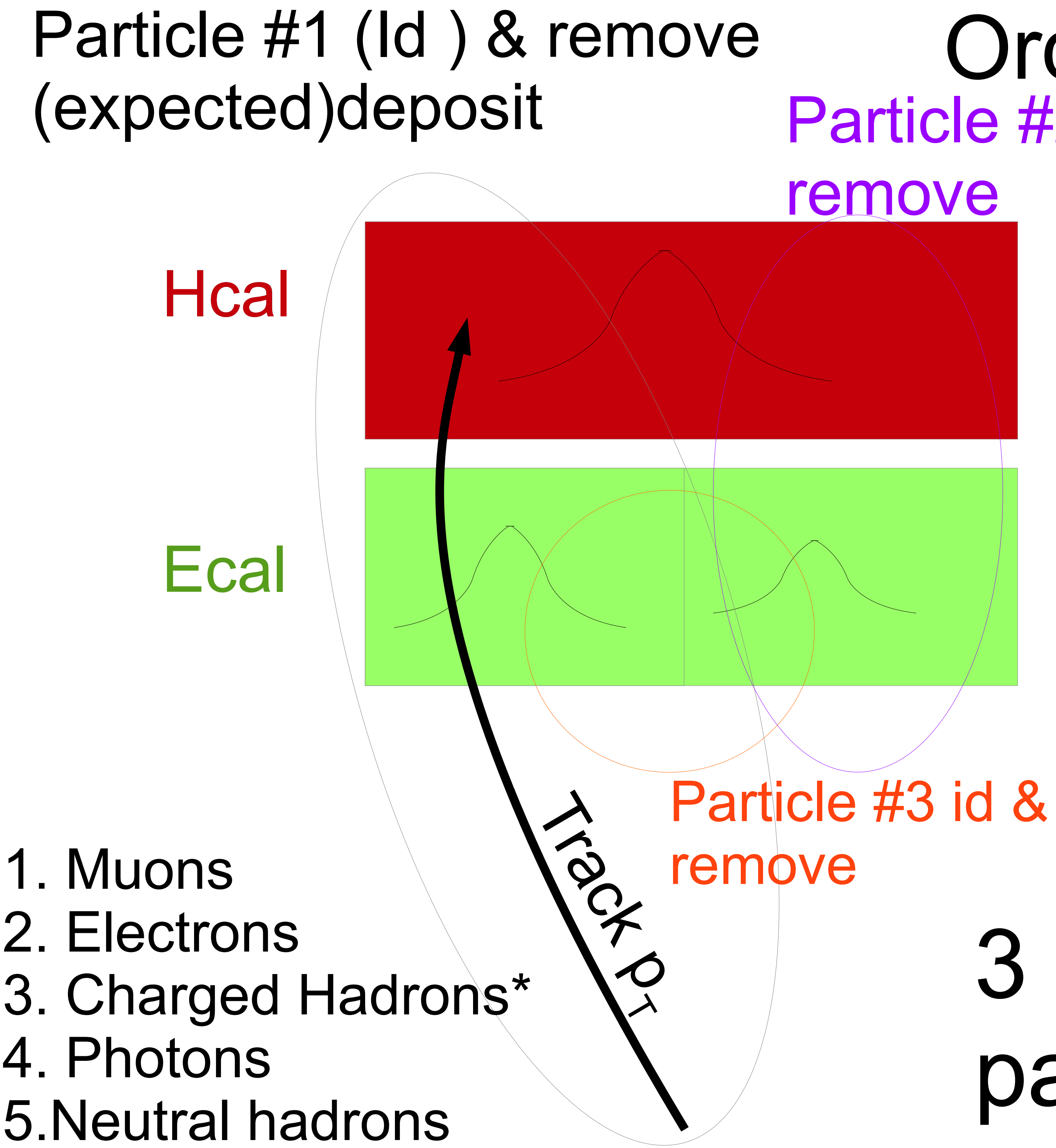
Make Particles



We get 5 classes of particles

Are we missing any?

Ordering is key



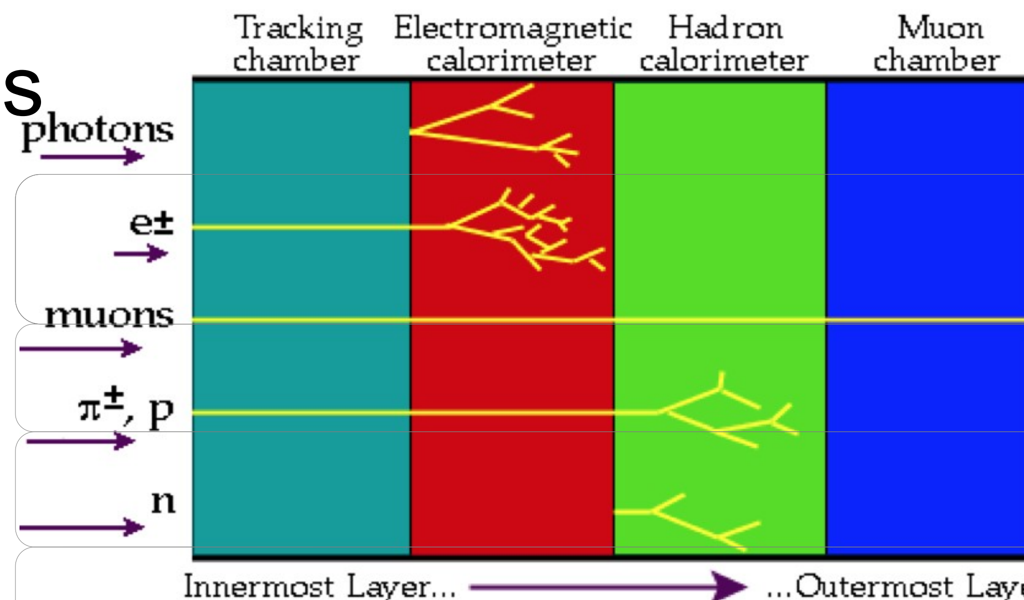
1. Muons
2. Electrons
3. Charged Hadrons*
4. Photons
5. Neutral hadrons

3 overlapping particle event

Resulting Componnets

- Std::vector<ParticleFlowCandidates>
- ParticleFlowCandate :
  - Particle id
  - Mass
  - p_T
  - Eta
  - Phi

5 types



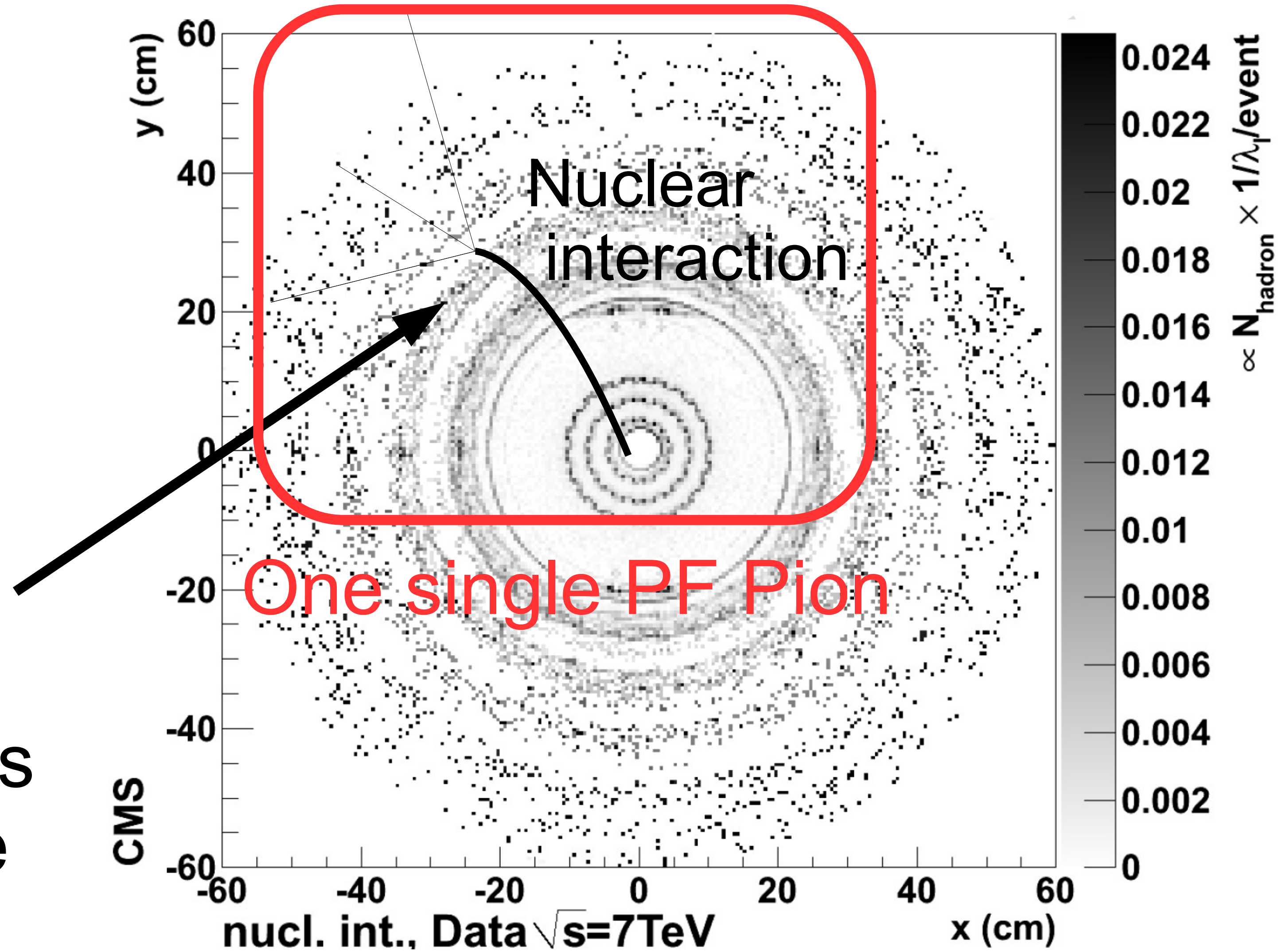
Credit: Particle Data Group (LBNL)

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

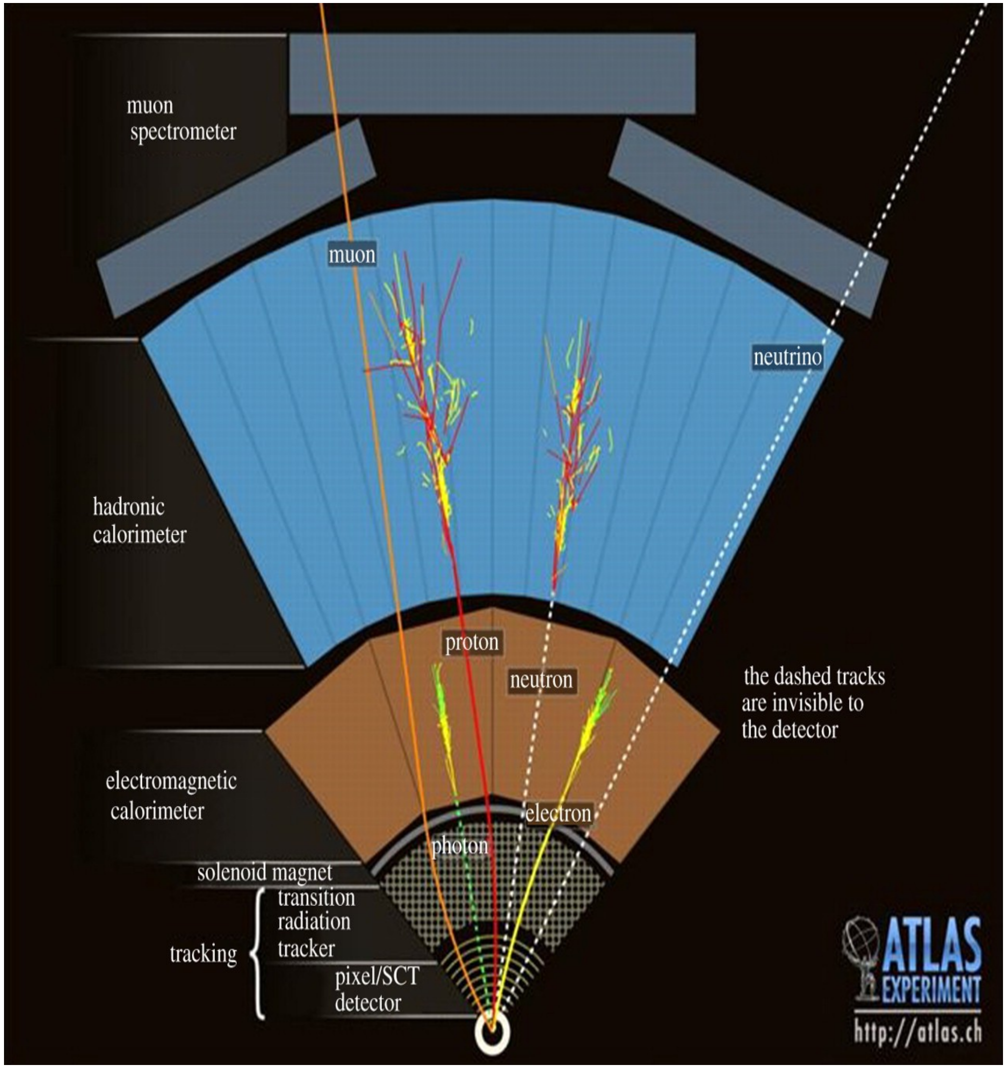
A lesser known point

- Embedded in particle flow are nuclear interaction

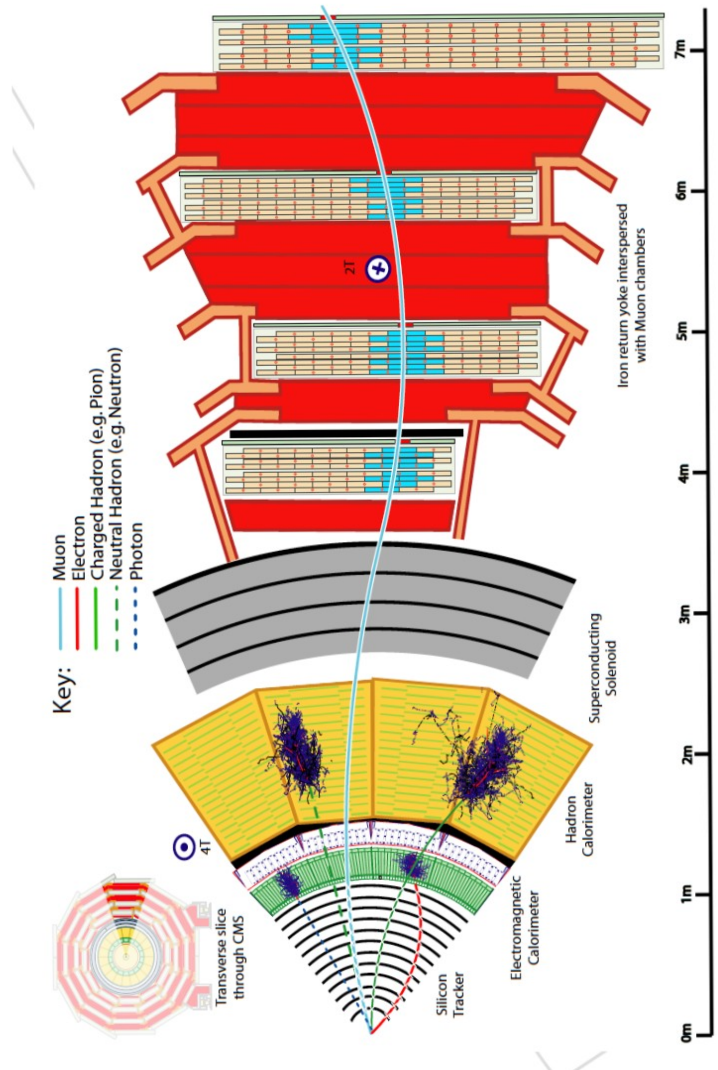
Particle flow looks for displaced secondary vertices and merges tracks into 1 particle



Any complication for PF in ATLAS?

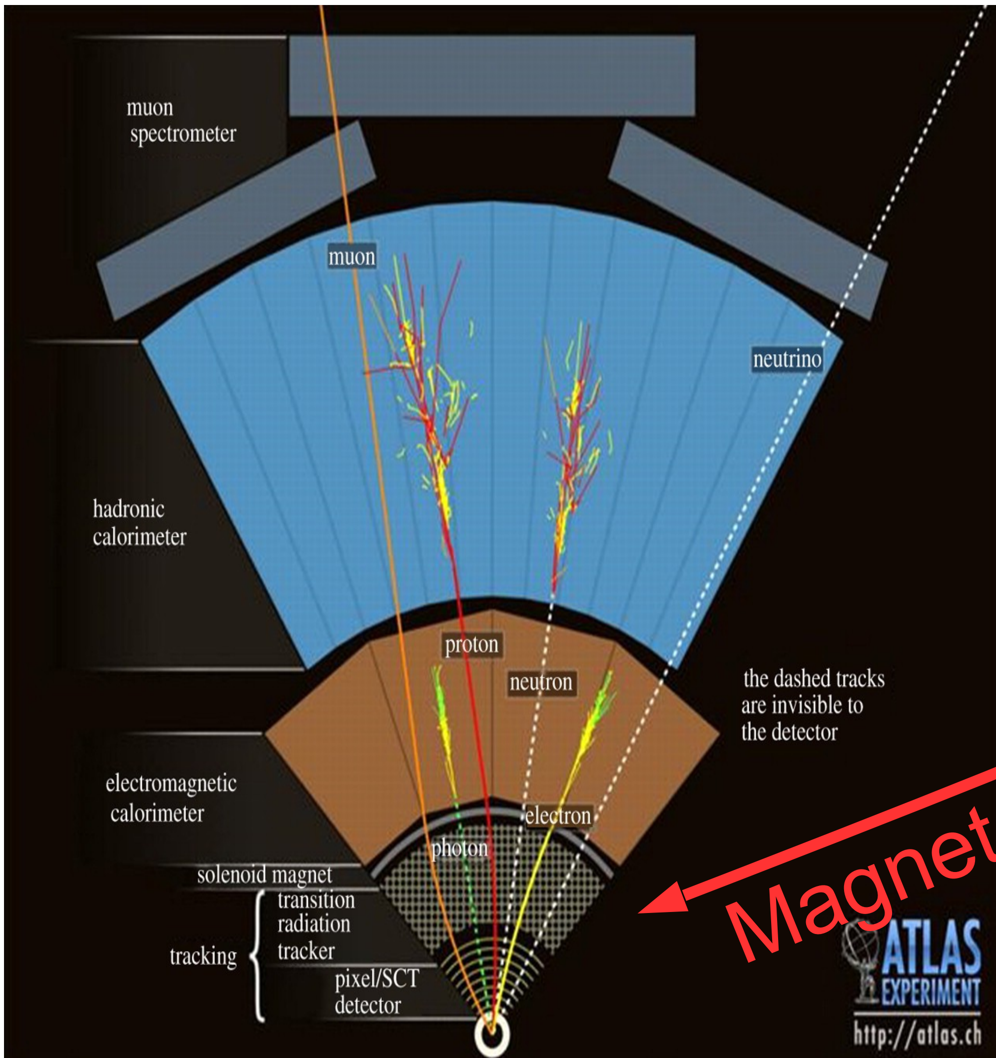


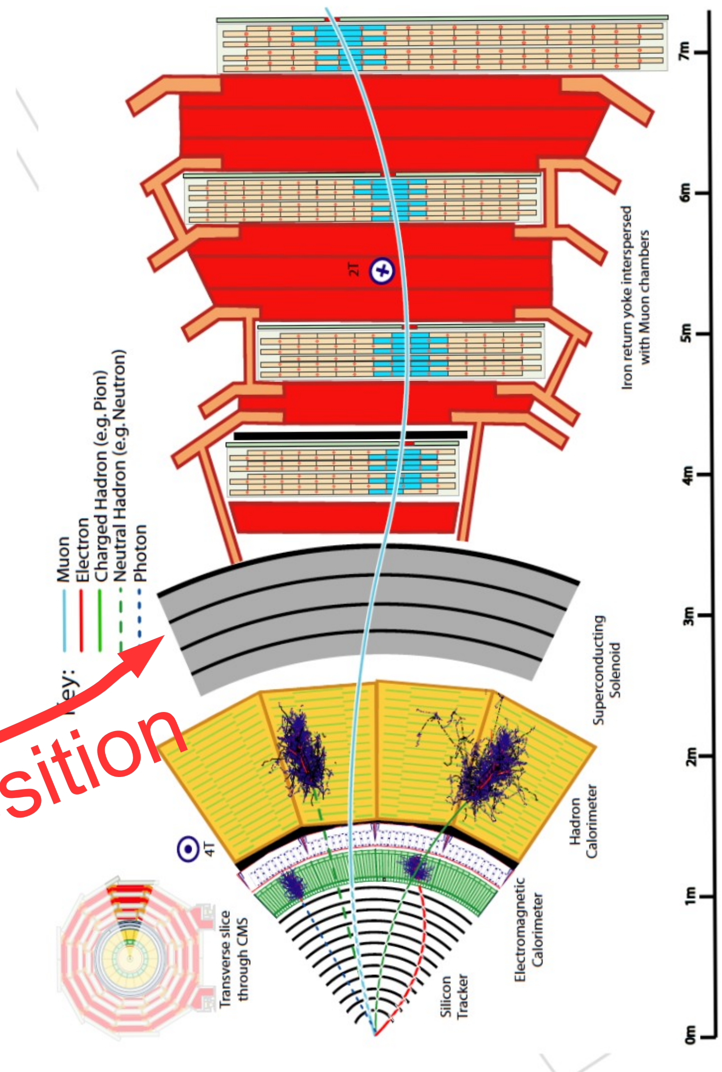
ATLAS



CMS

Any complication for PF in ATLAS?





Magnet position

ATLAS

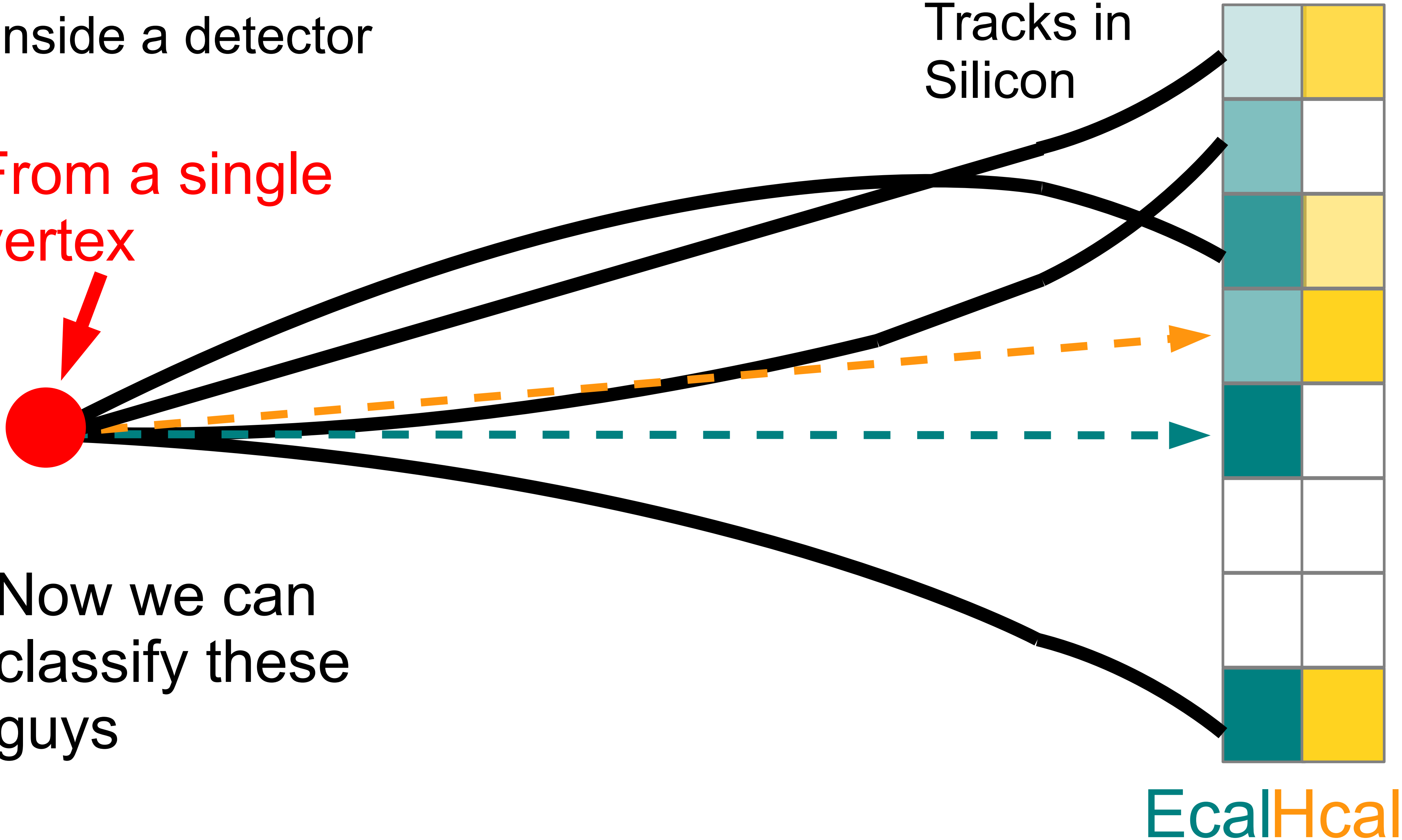
Need to correct for the energy loss

CMS

Using the particles

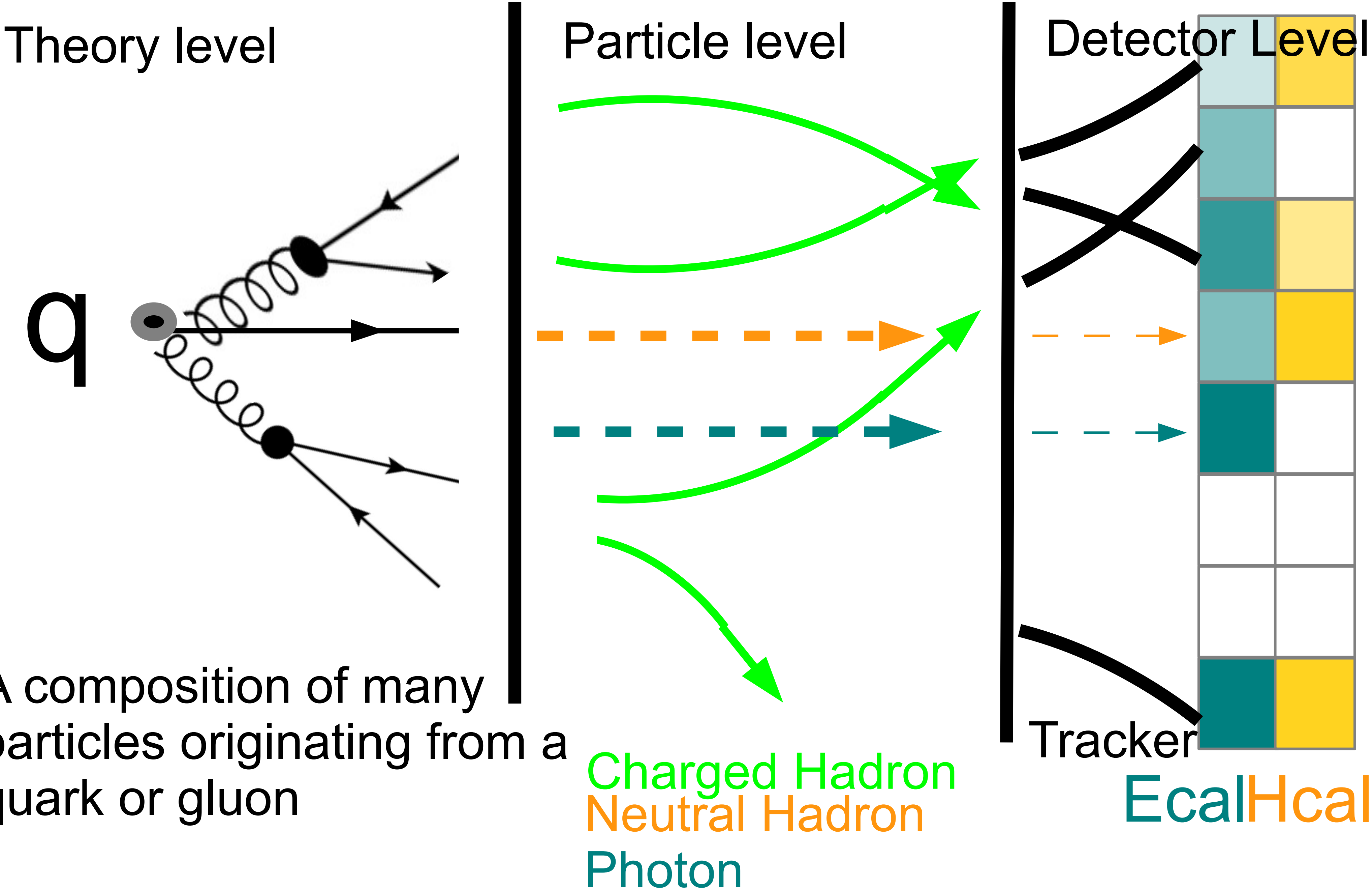
Inside a detector

From a single vertex



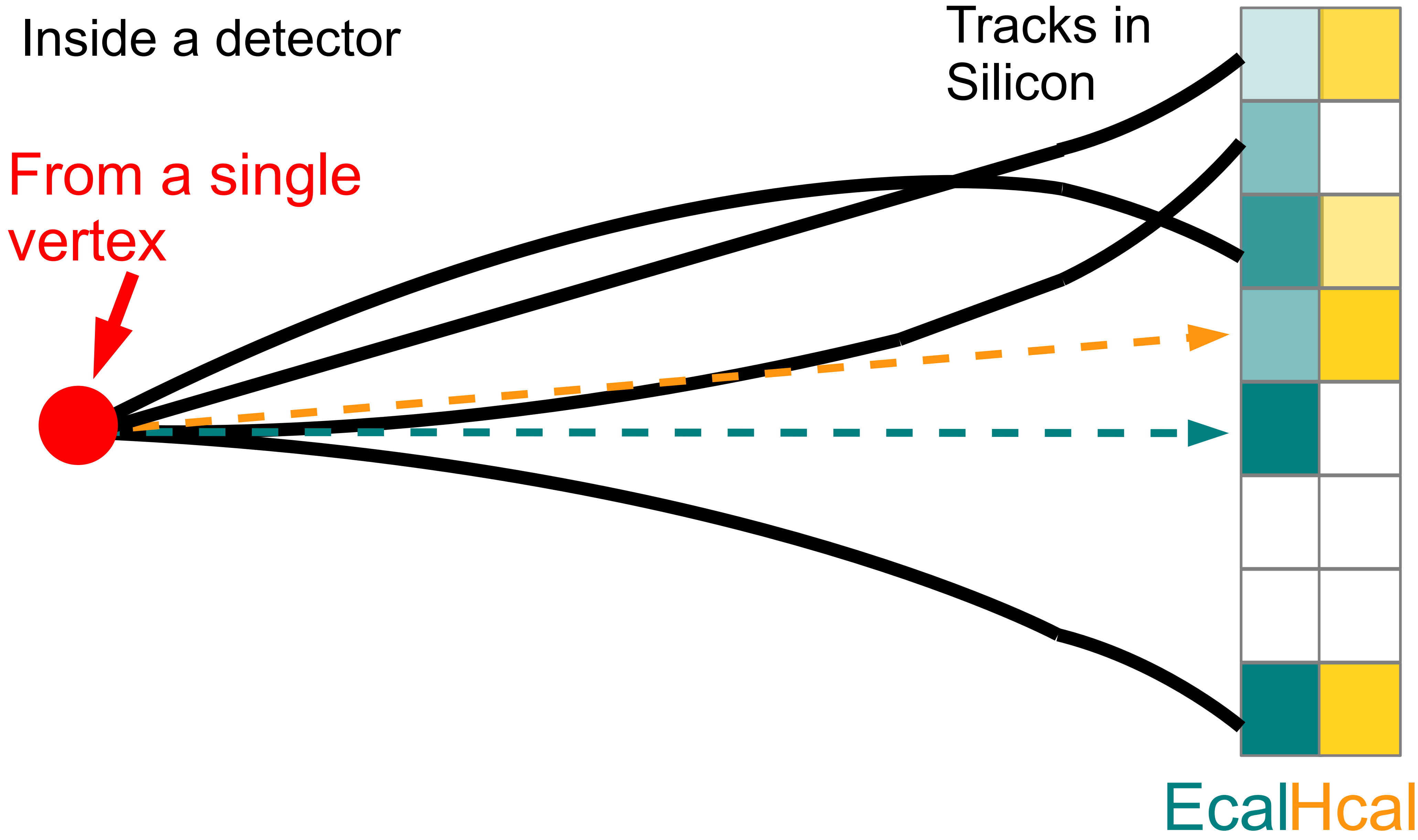
Now we can classify these guys

What is a jet?



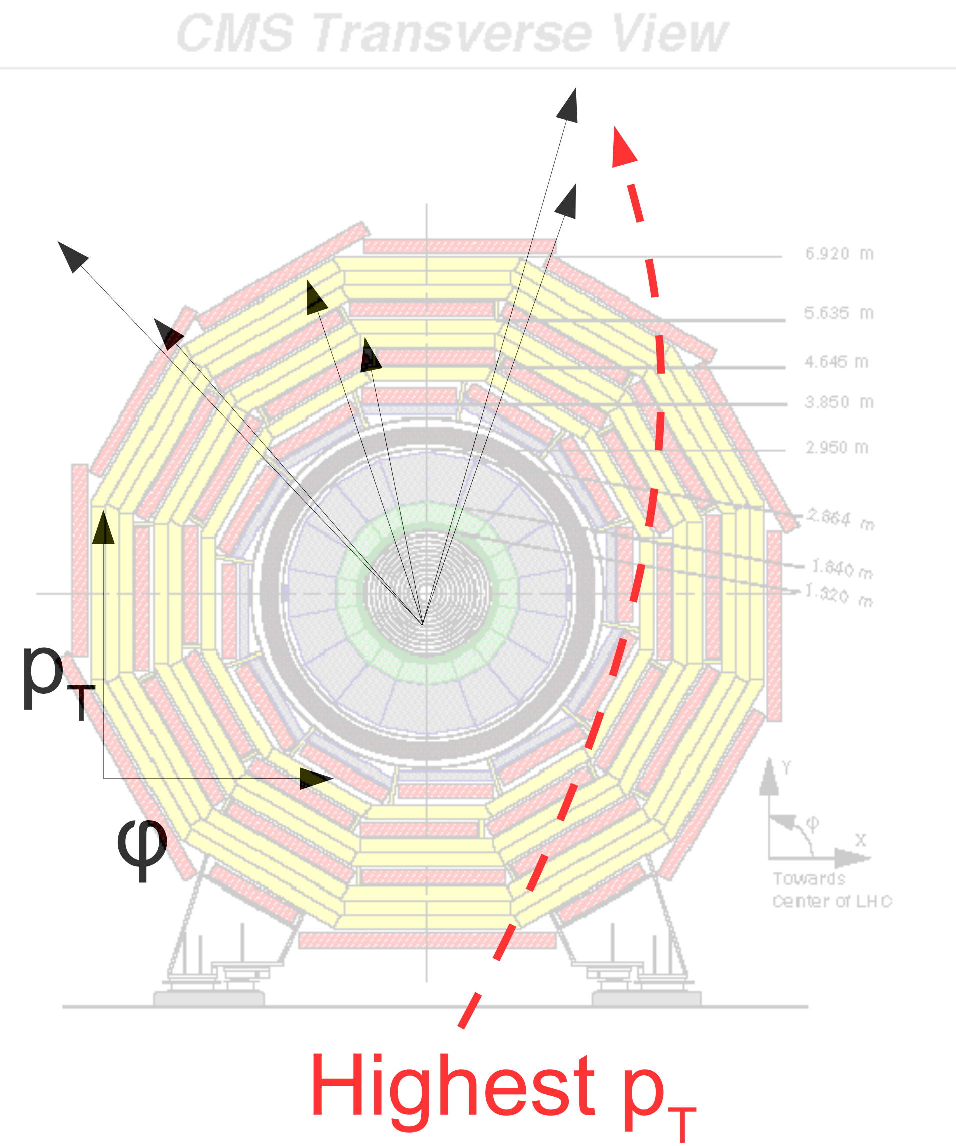
A composition of many particles originating from a quark or gluon

What is a jet?


Inside a detector
Tracks in Silicon
From a single vertex
EcalHcal

Jet Reconstruction

- Itrerate over two



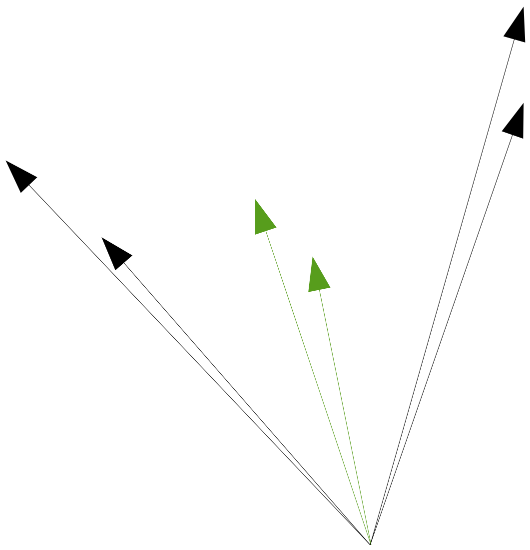
Take smallest

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

α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

Jet Reconstruction

- Itrerate over two



Start small

Take smallest

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

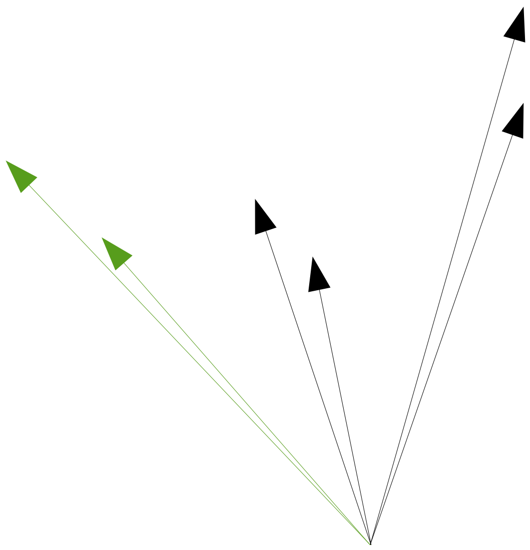
α=1 kT

α=0 Cambridge Aachen

α=-1 Anti-kT

Jet Reconstruction

- Itrerate over two



Start Close

Take smallest

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

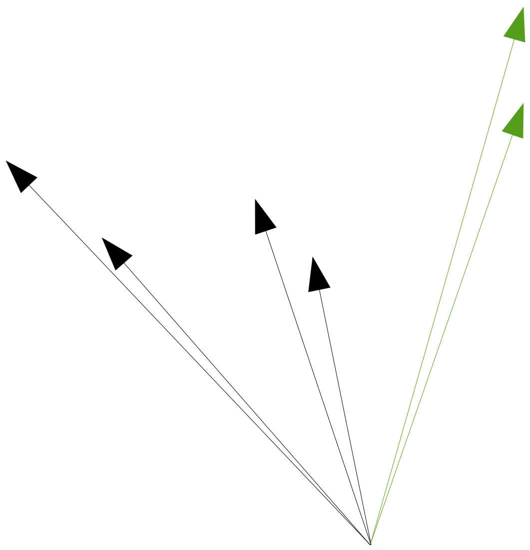
α=1 kT

α=0 Cambridge Aachen

α=-1 Anti-kT

Jet Reconstruction

- Itrerate over two



Start Big

Take smallest

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

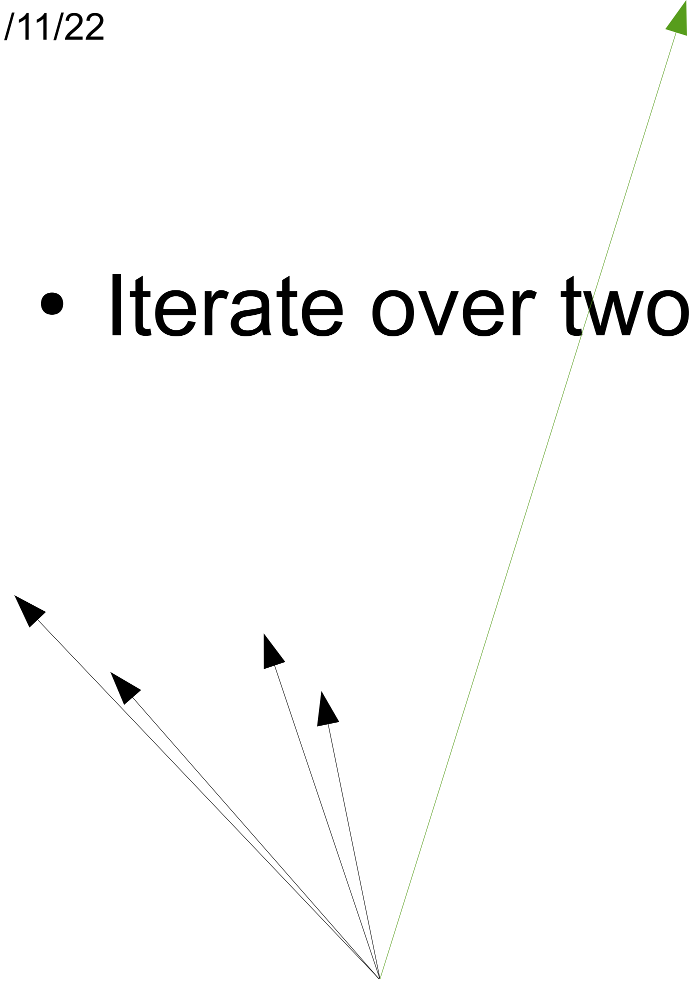
α=1 kT

α=0 Cambridge Aachen

α=-1 Anti-kT

Jet Reconstruction

- Iterate over two



Take smallest

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

$\alpha=1$ kT

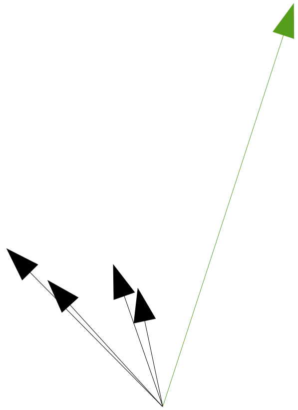
$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

Now merge initial into a particle

Jet Reconstruction

- Iterate over two



Zooming out

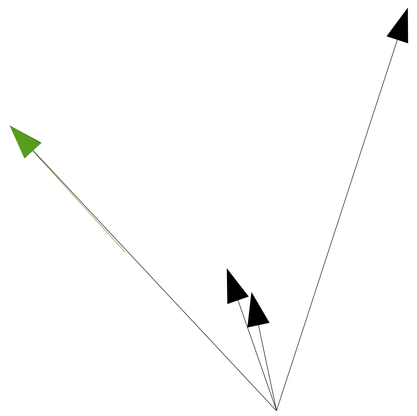
Take smallest

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

α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

Jet Reconstruction

- Iterate over two



Merge next set

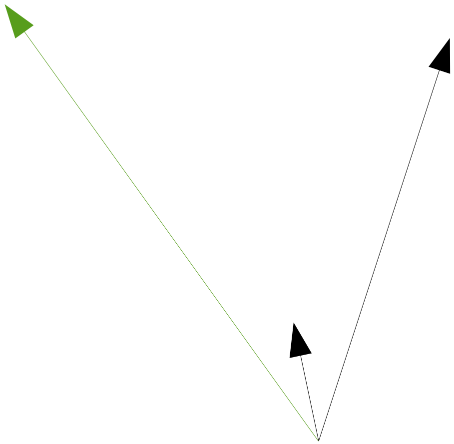
Take smallest

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

$\alpha=1$ kT
$\alpha=0$ Cambridge Aachen
$\alpha=-1$ Anti-kT

Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

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

α=1 kT
α=0 Cambridge Aachen
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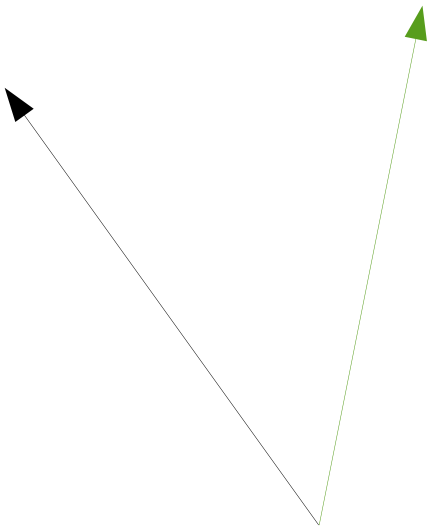
Jet Reconstruction

- Iterate over two



Merge next set

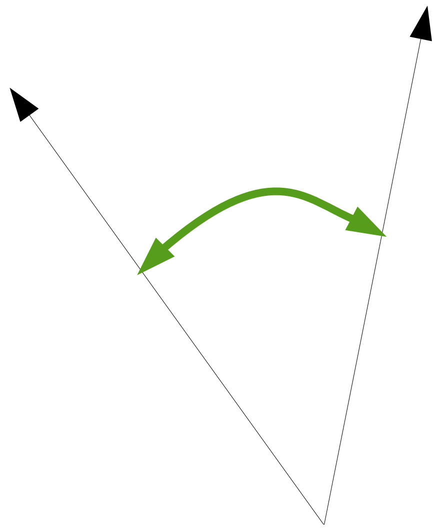
Take smallest

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

α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

Jet Reconstruction

- Iterate over two



If distance > X (stop)
X=0.4,0.8,...

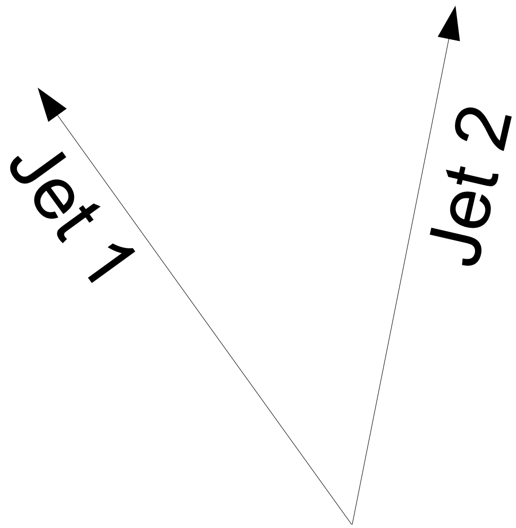
Take smallest

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

α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

Jet Reconstruction

- Iterate over two



Done

Take smallest

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

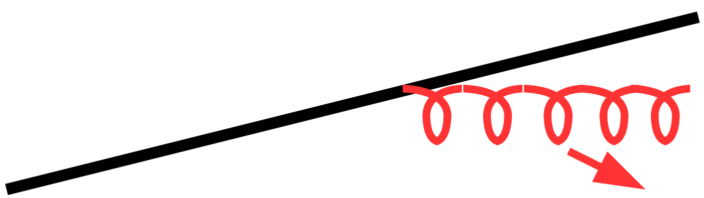
α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

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



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

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

When $\Delta R \rightarrow 0$

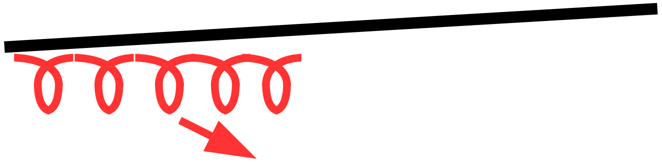
*Wesley Smith

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 $E \rightarrow 0$

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

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

*Wesley Smith

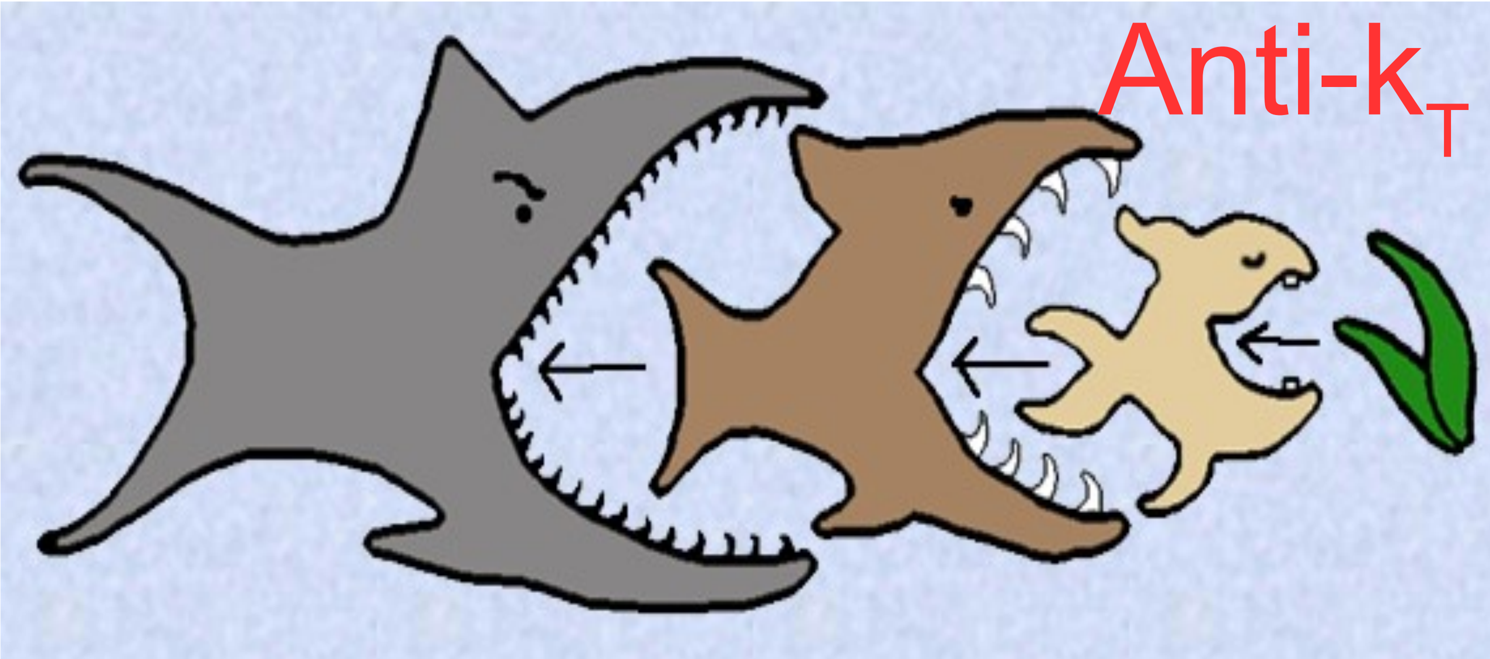
Why do we use these algorithms?

To calculate anything with a jet we need to observe :

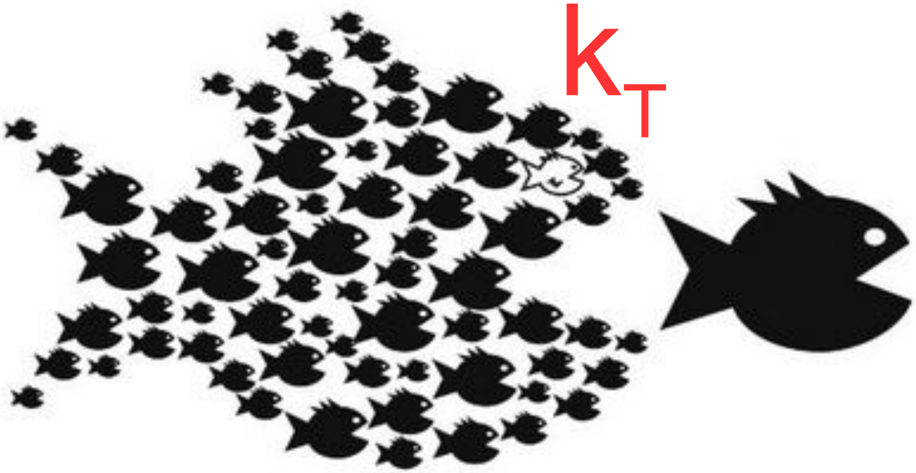
Infrared safety : invariance with random particle w/E→0
Collider safety : invariance with random split ΔR→0

This applies to jet substructure observables too!
…..Well maybe
can you think of a example that breaks IR safety?

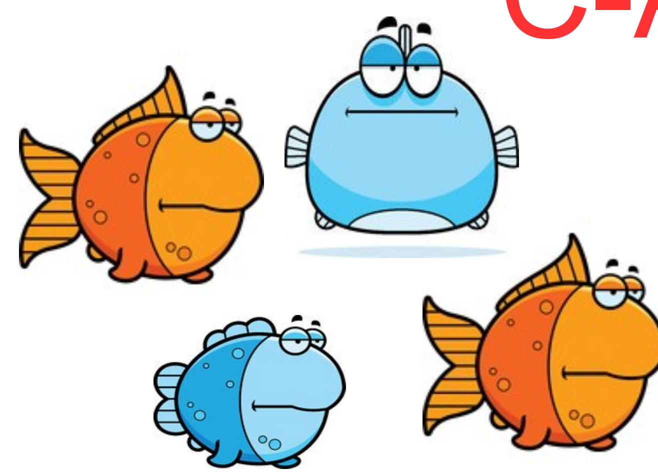
Recap



Anti-k_T

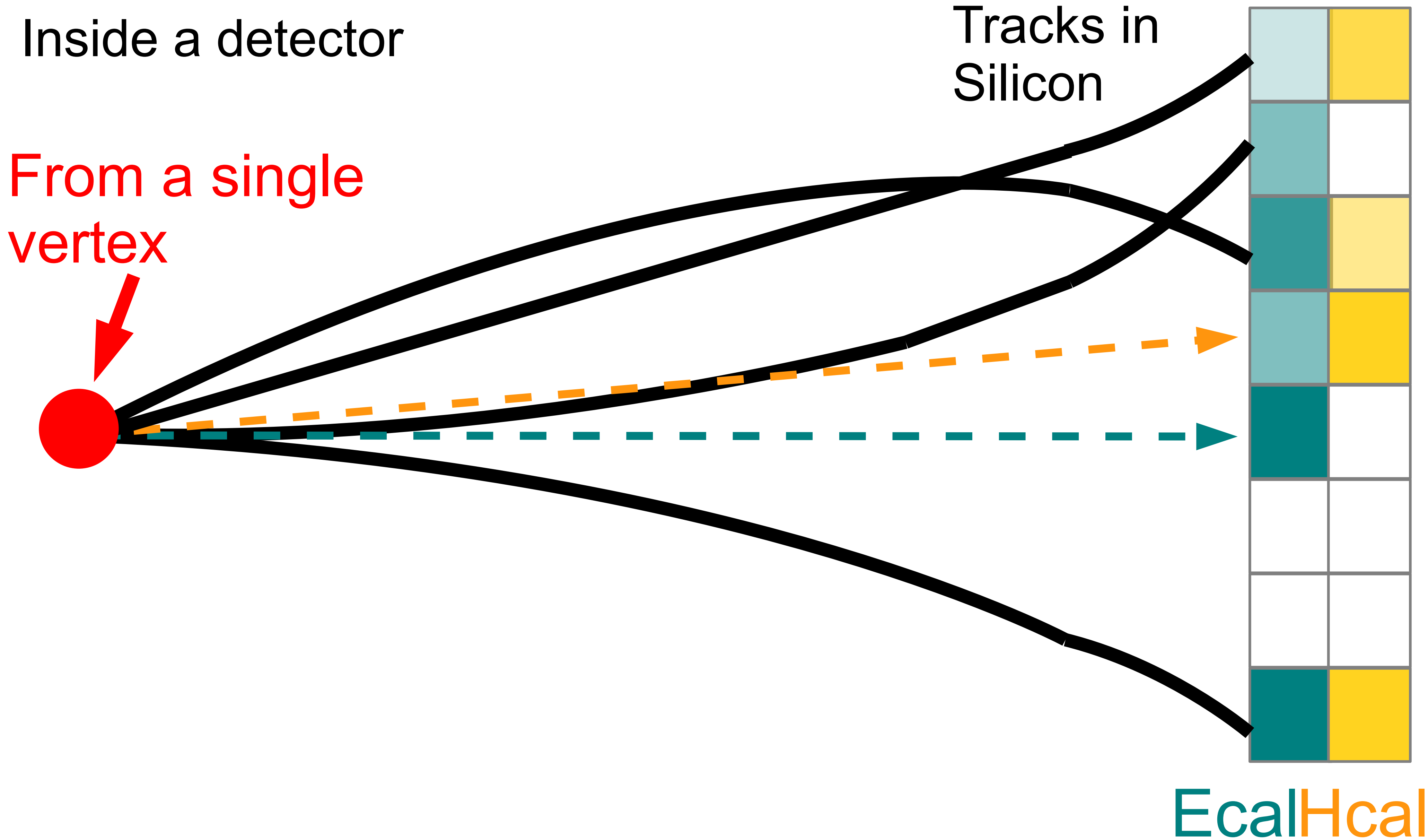


k_T



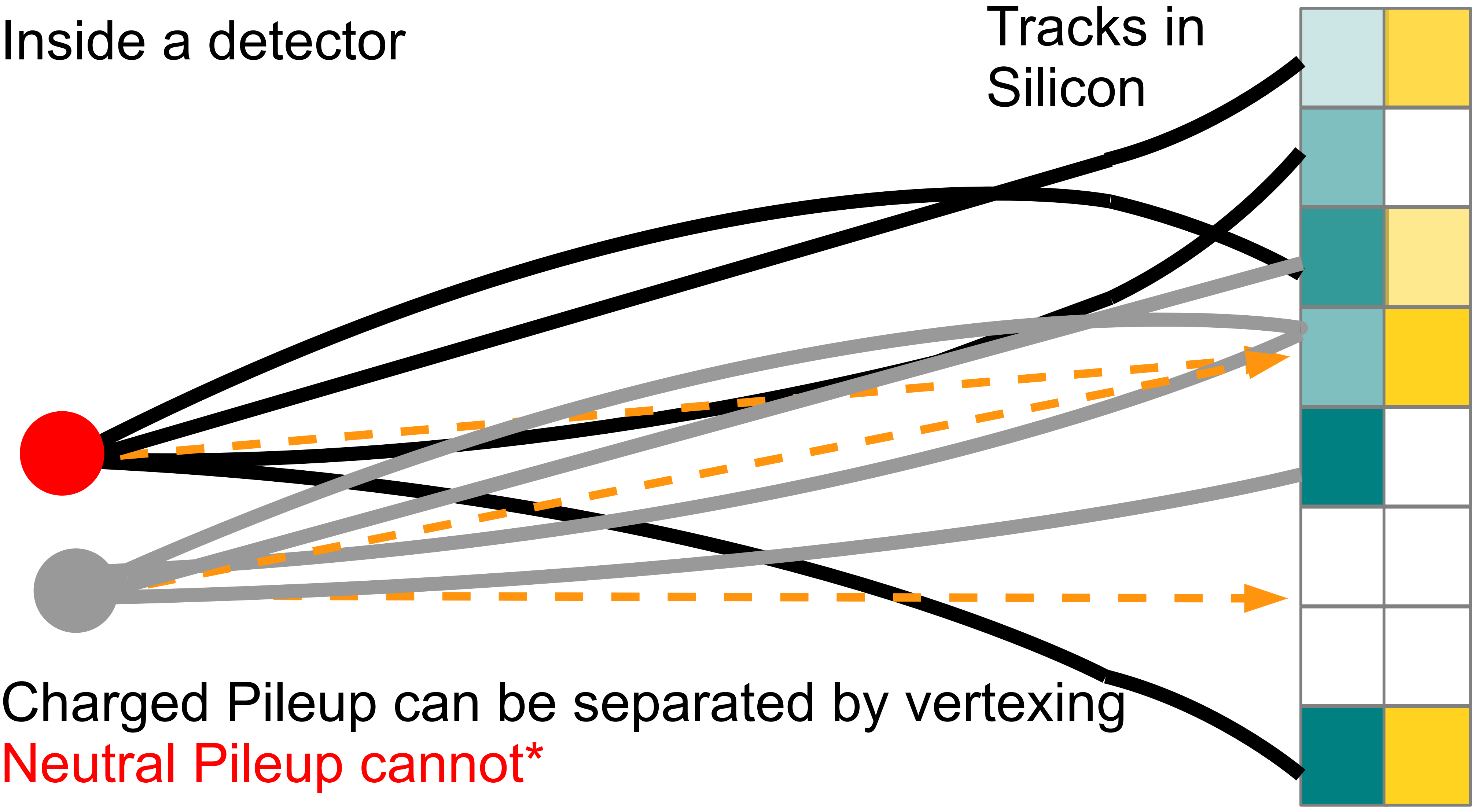
C-A

What is a jet?


Inside a detector
Tracks in Silicon
From a single vertex
Ecal
Hcal

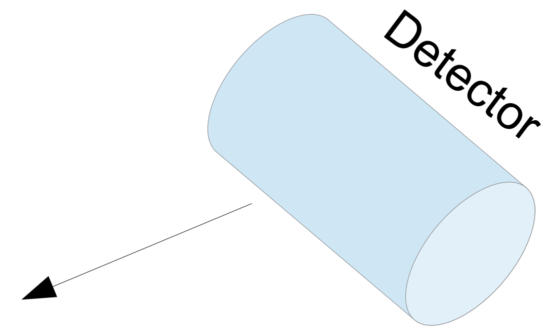
What is a Jet?

Inside a detector

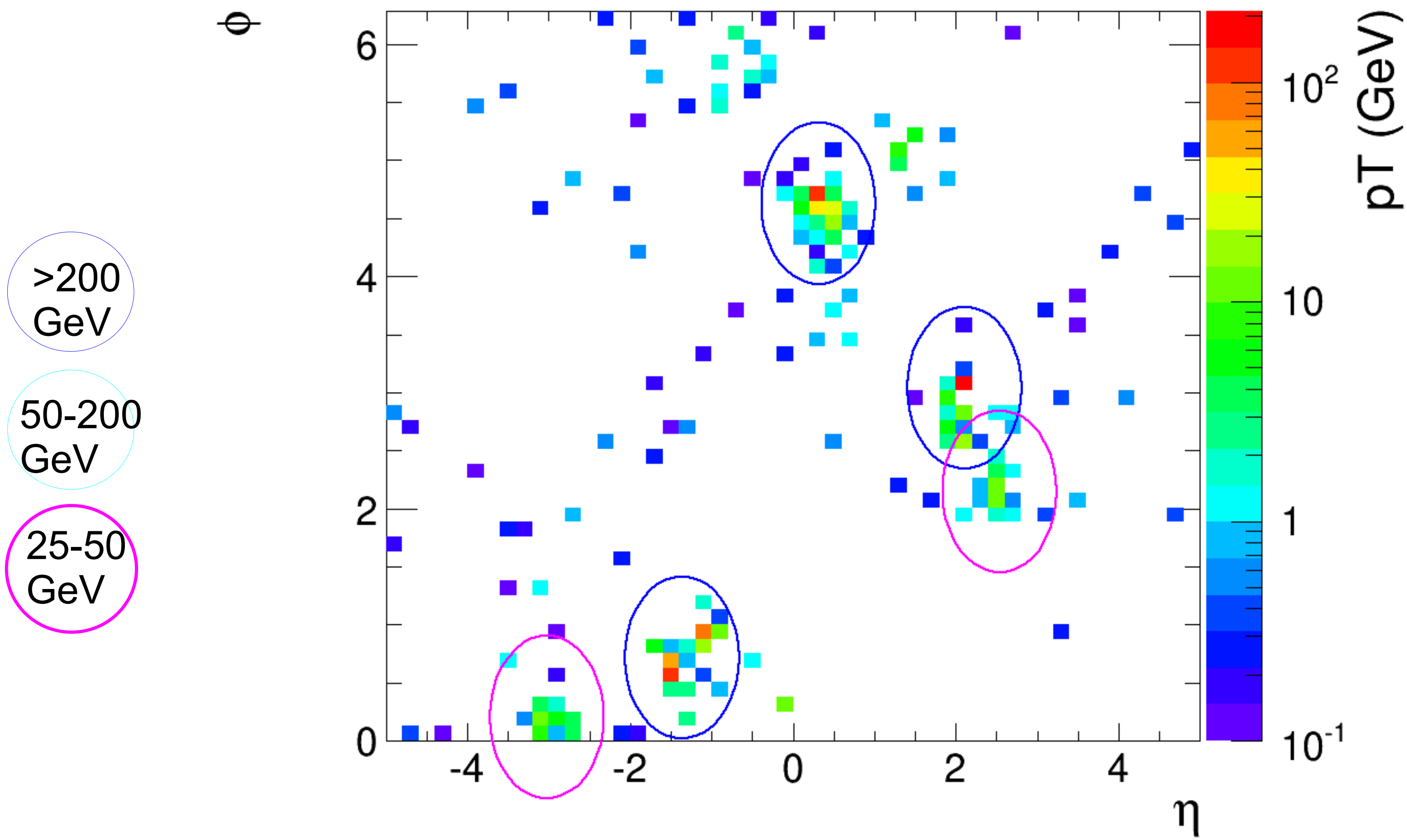


Charged Pileup can be separated by vertexing
Neutral Pileup cannot*

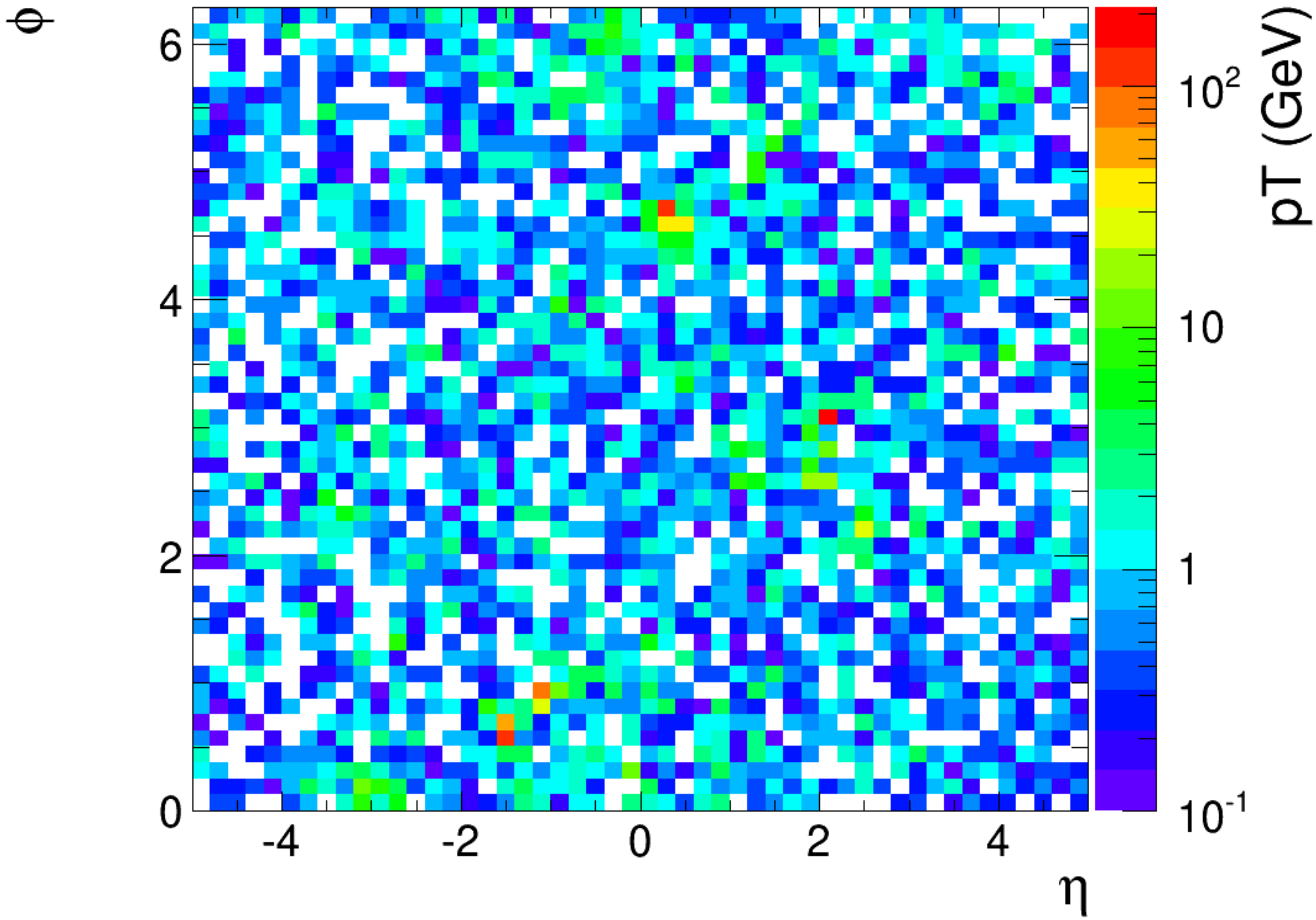
*Fast timing/Depth reconstruction can help



Detector Surface



We also have pileup



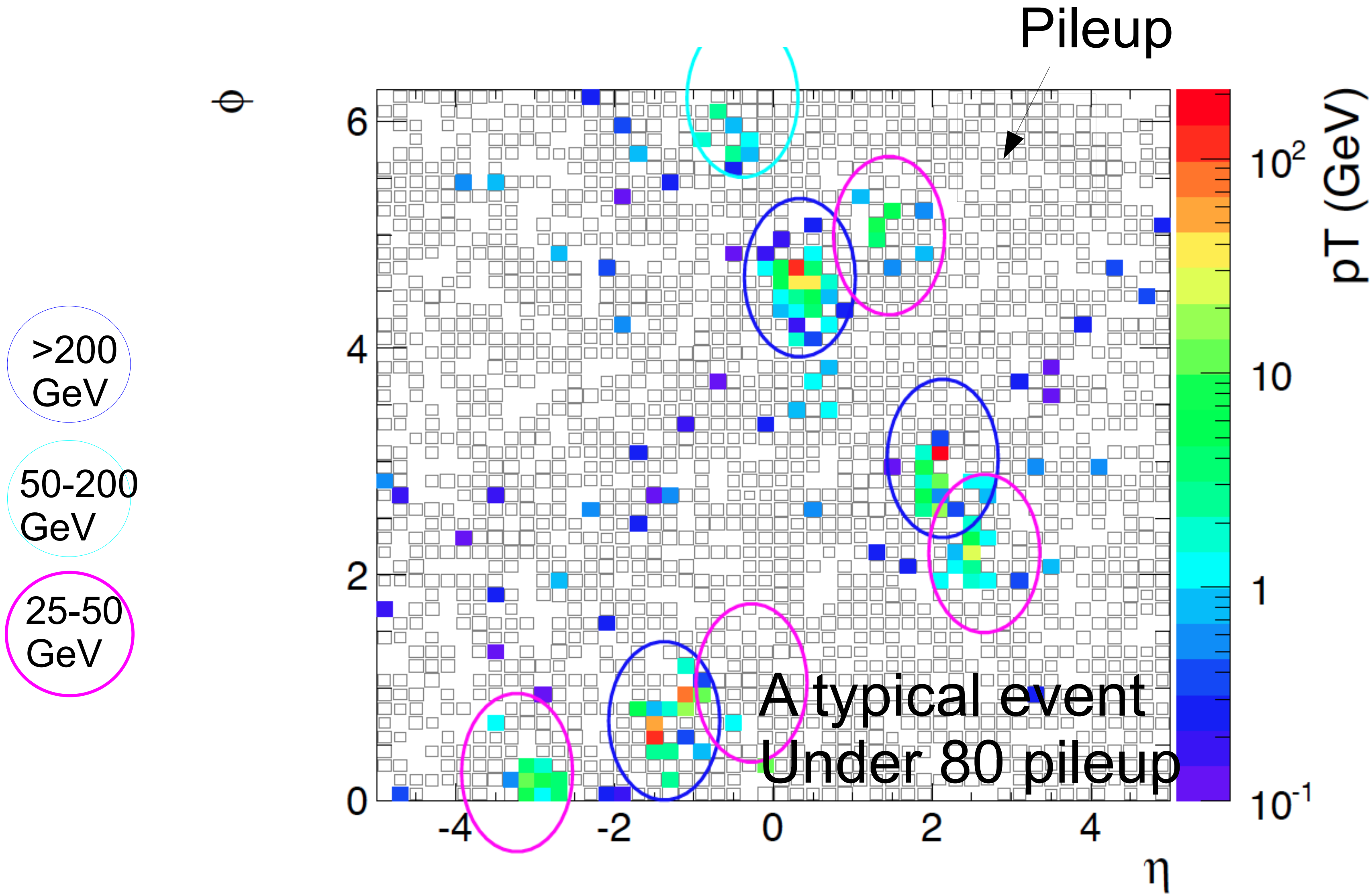
>200 GeV

50-200 GeV

25-50 GeV

We also have pileup

- Filtering the interesting info



We also have pileup

- Filtering the interesting info

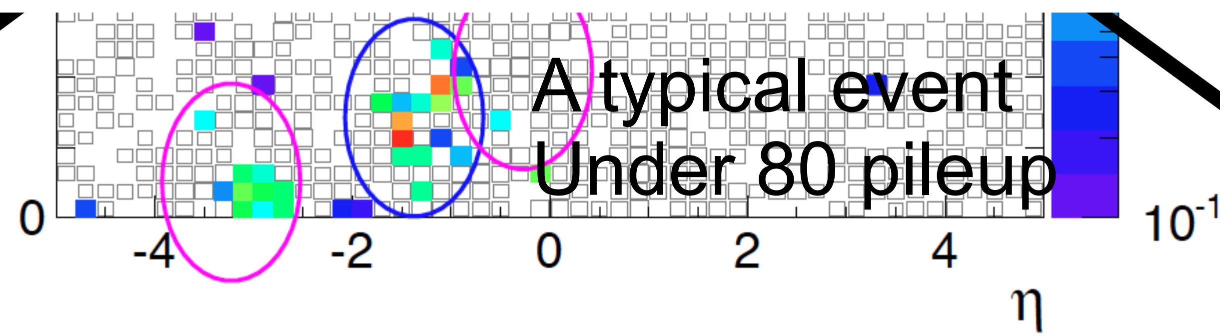
Pileup

While Pileup in pp has some differences
Many of the properties of pileup are similar to UE fluctuations

>200 GeV

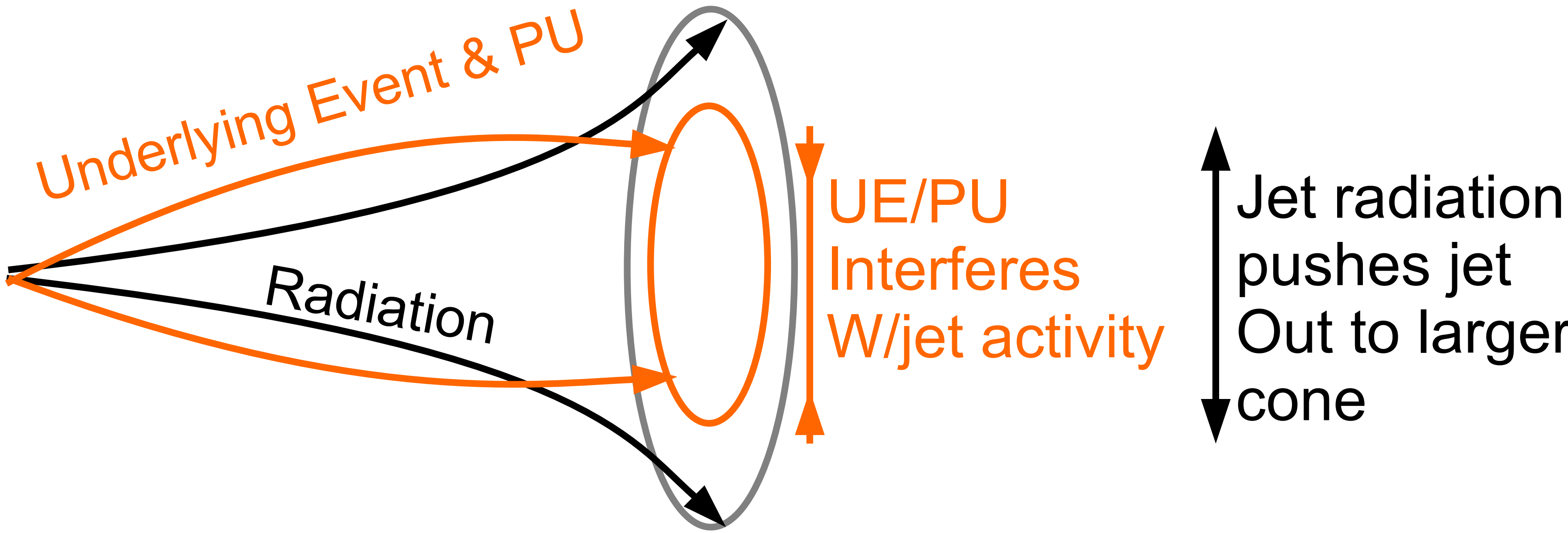
50-200 GeV

25-50 GeV



Jet Energy Correction

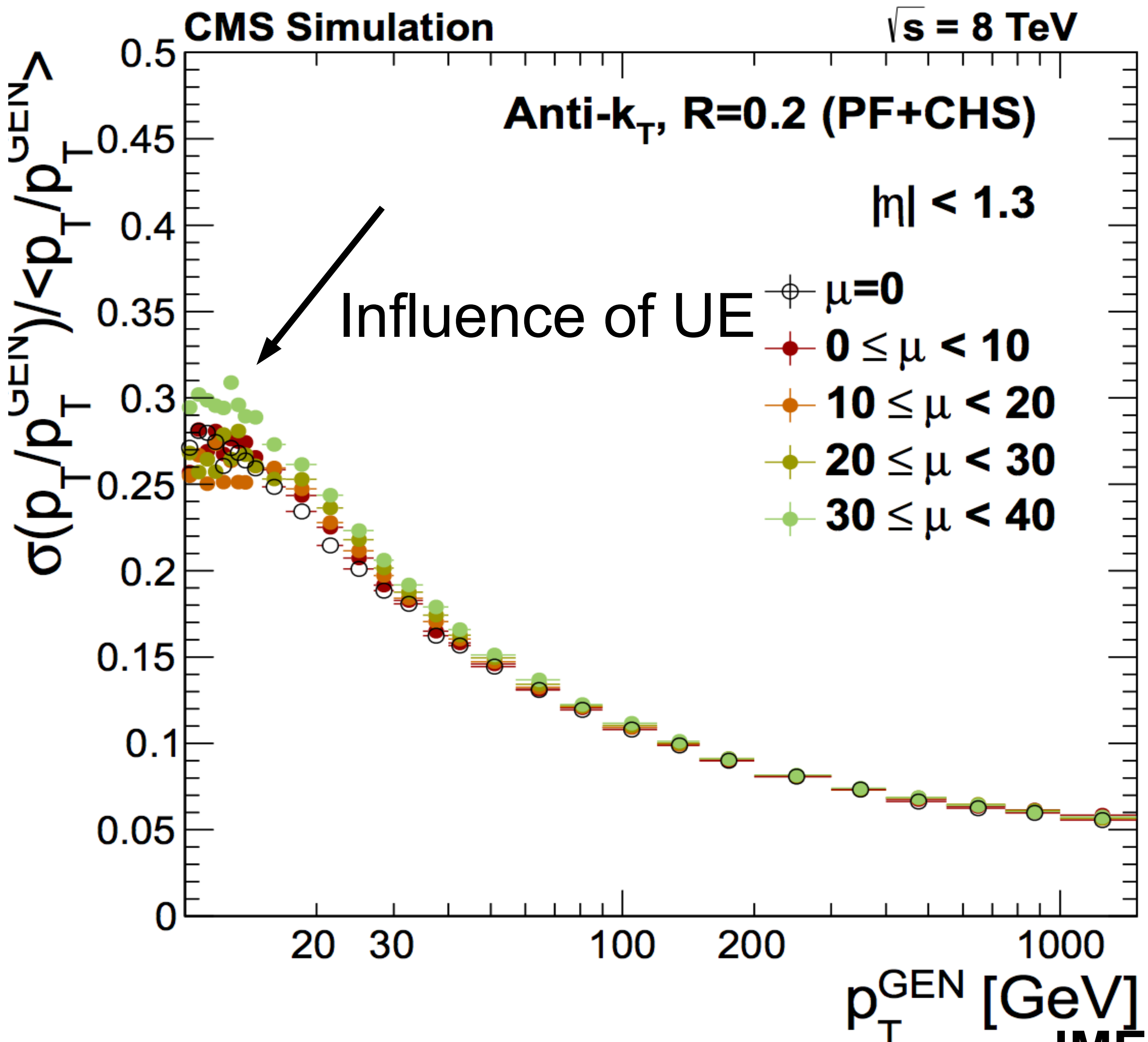
- Correcting to truth



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

Jet Energy Correction

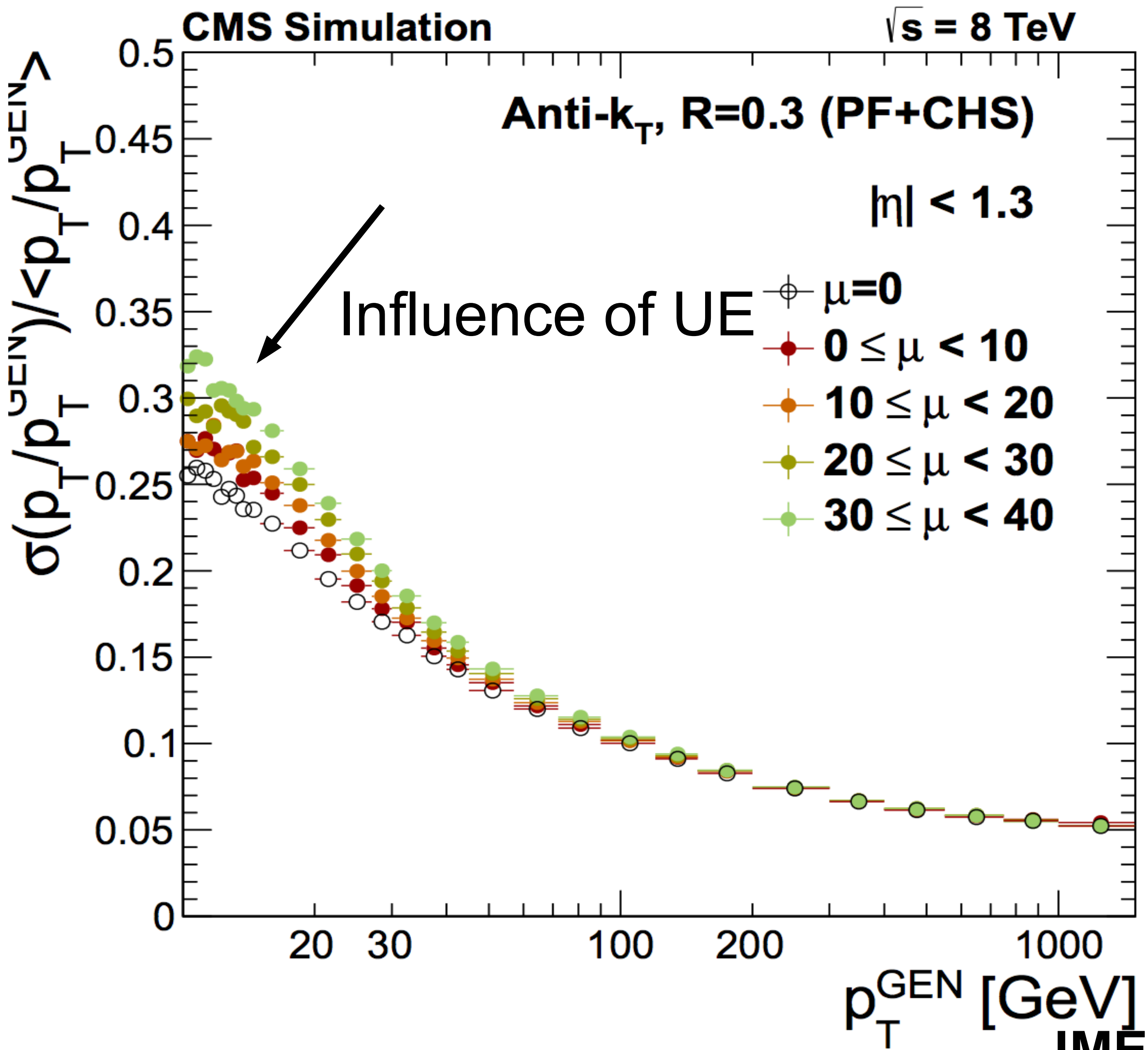
- AK2



JME-DP-14/037

Jet Energy Correction

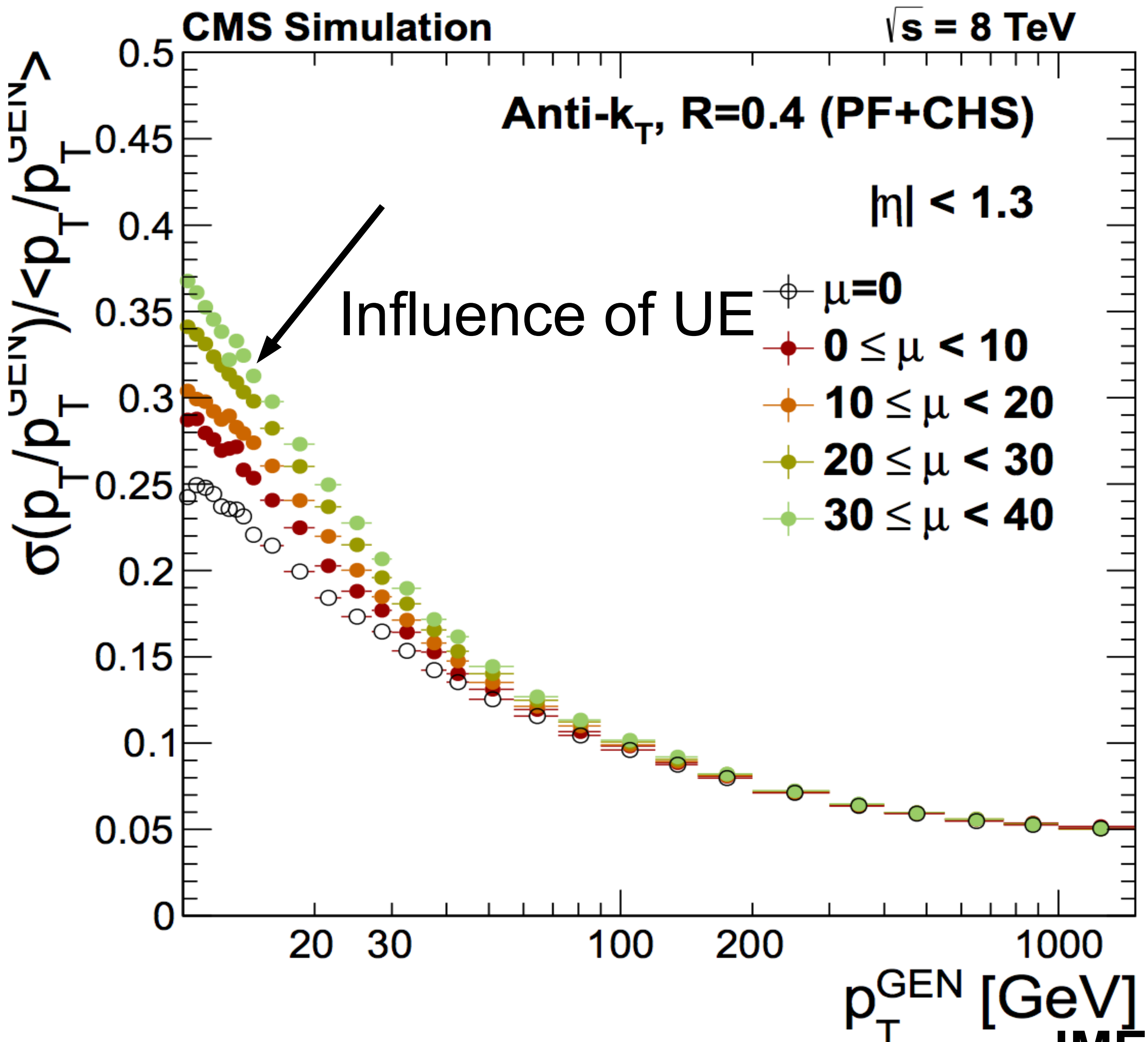
- AK3



JME-DP-14/037

Jet Energy Correction

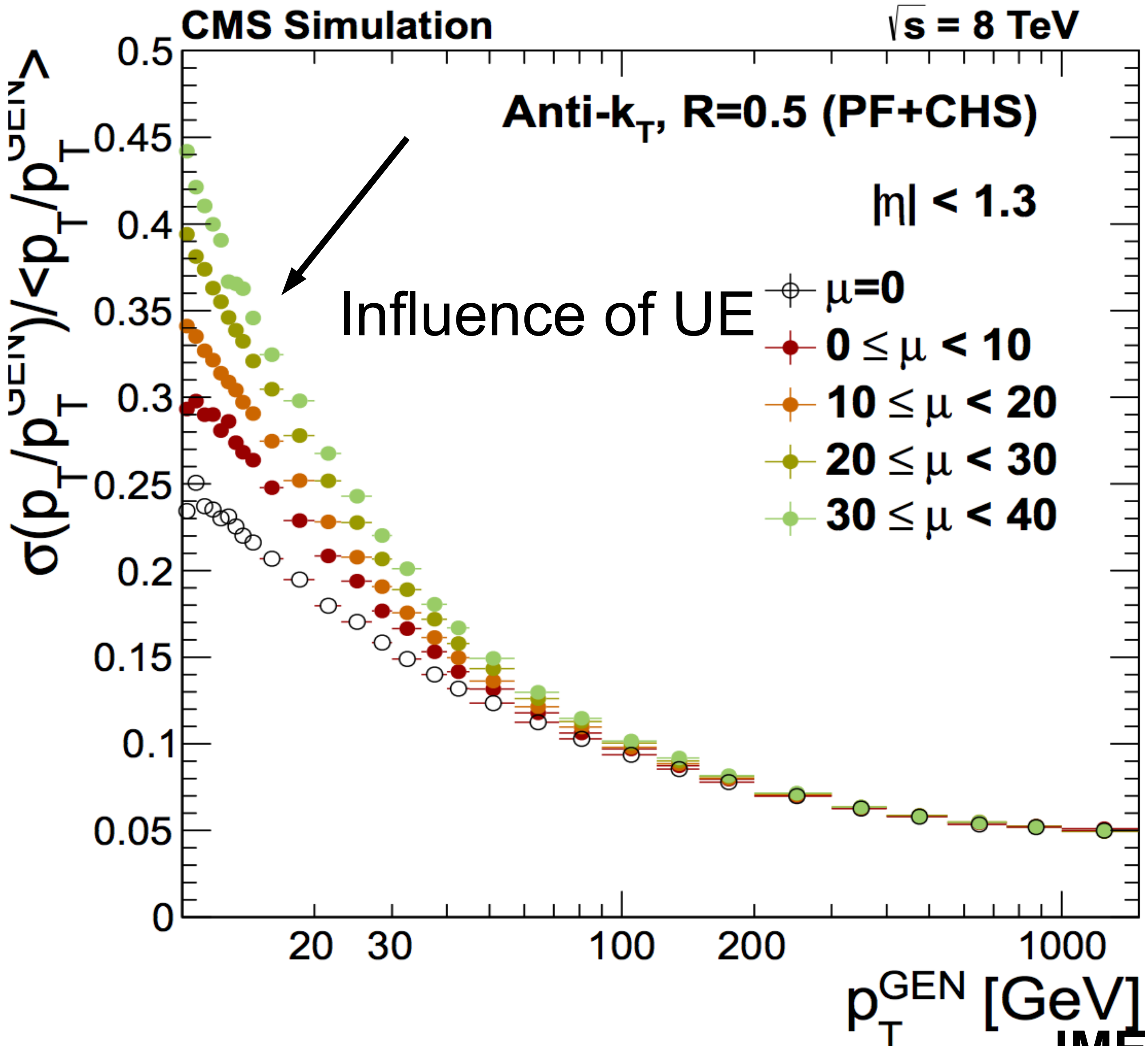
- AK4



JME-DP-14/037

Jet Energy Correction

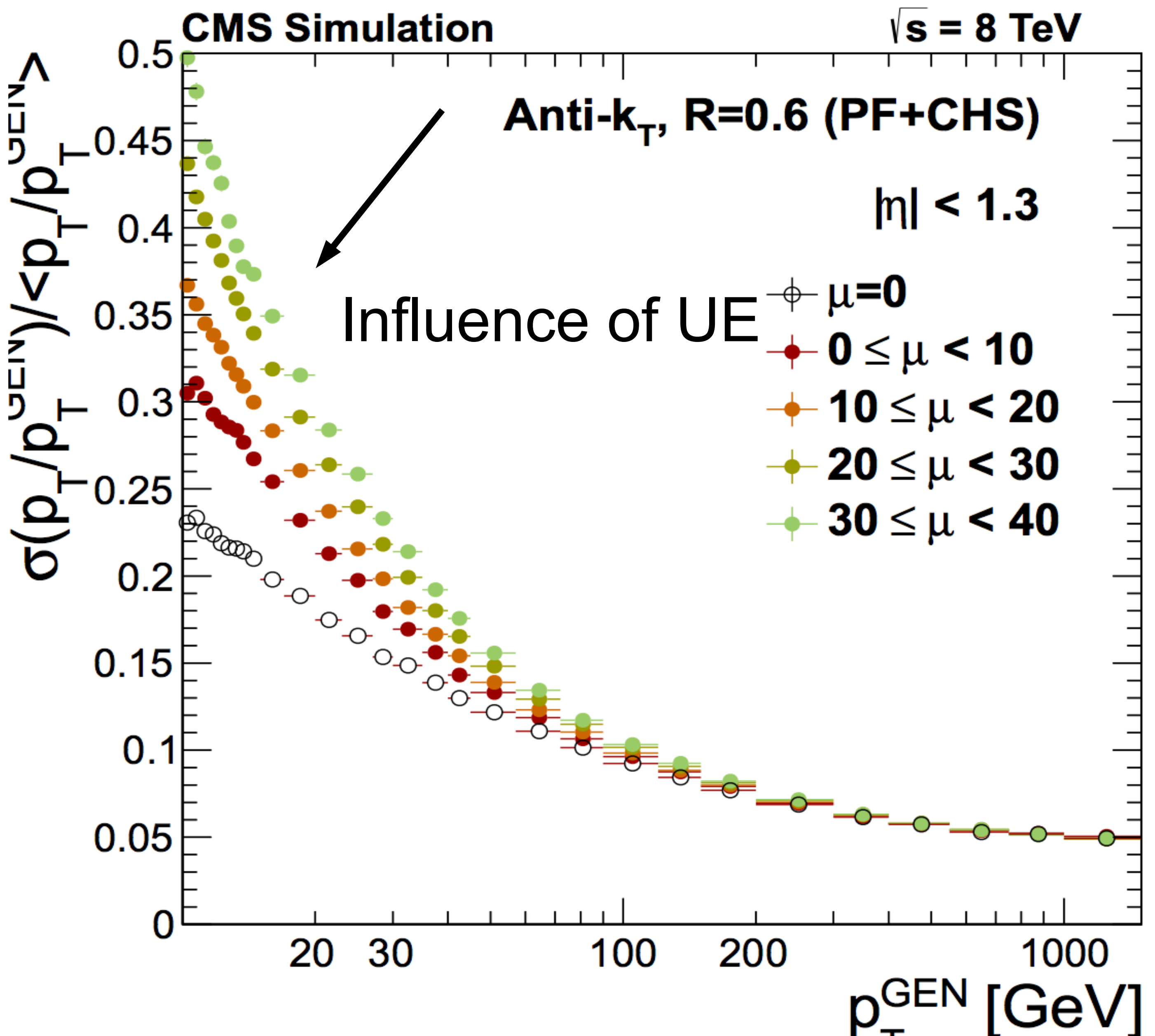
- AK5



JME-DP-14/037

Jet Energy Correction

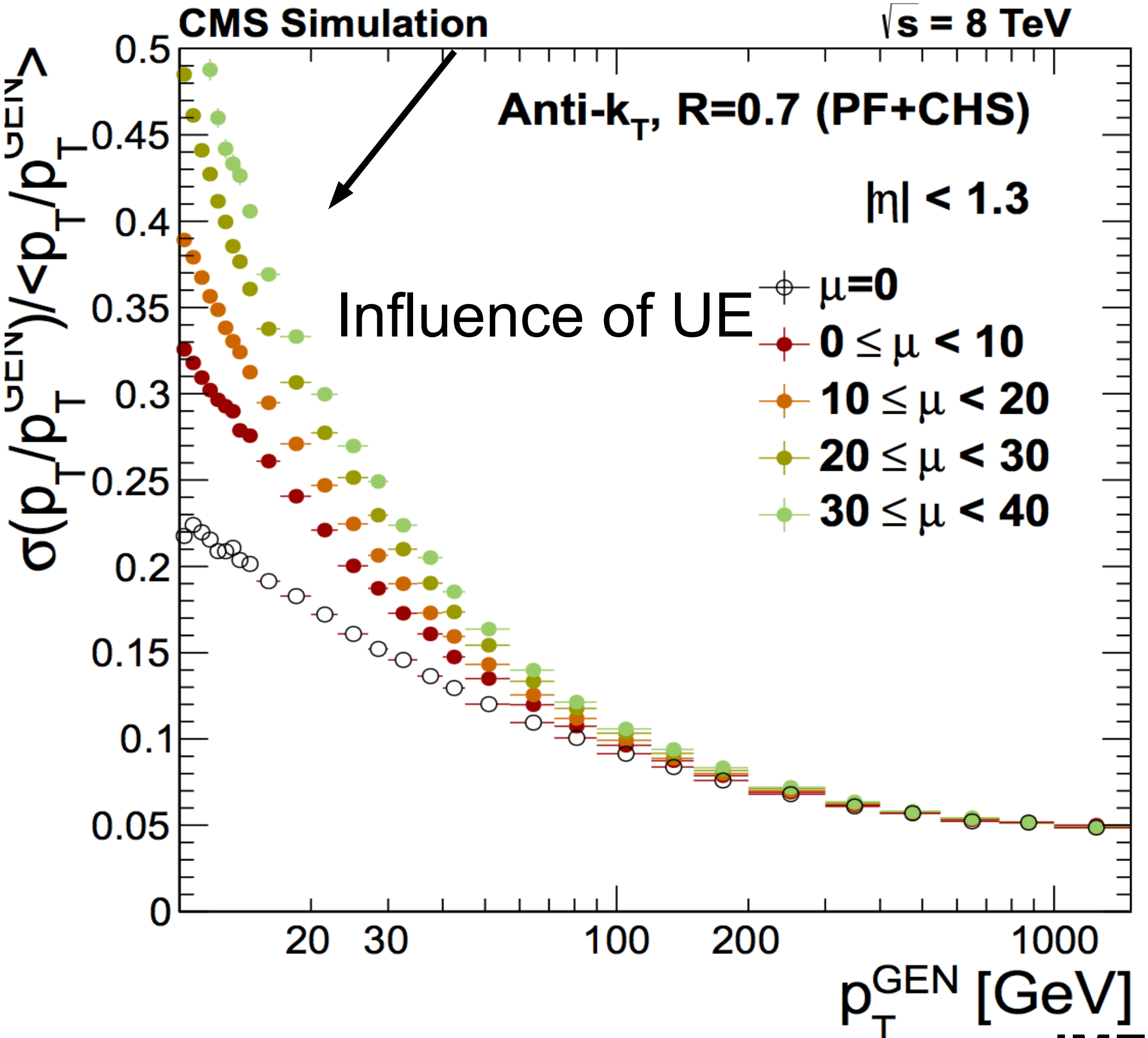
- AK6



JME-DP-14/037

Jet Energy Correction

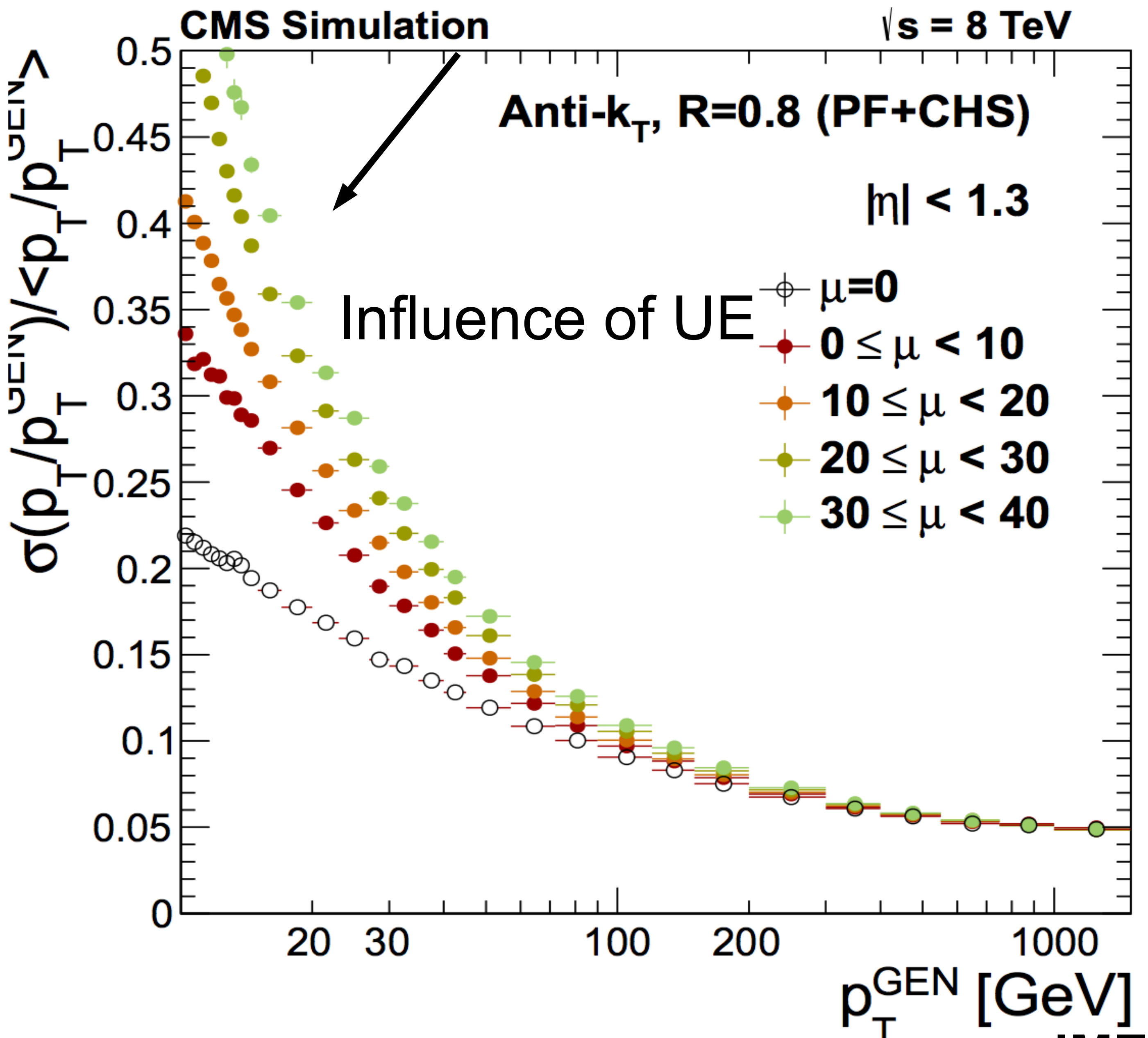
- AK7



JME-DP-14/037

Jet Energy Correction

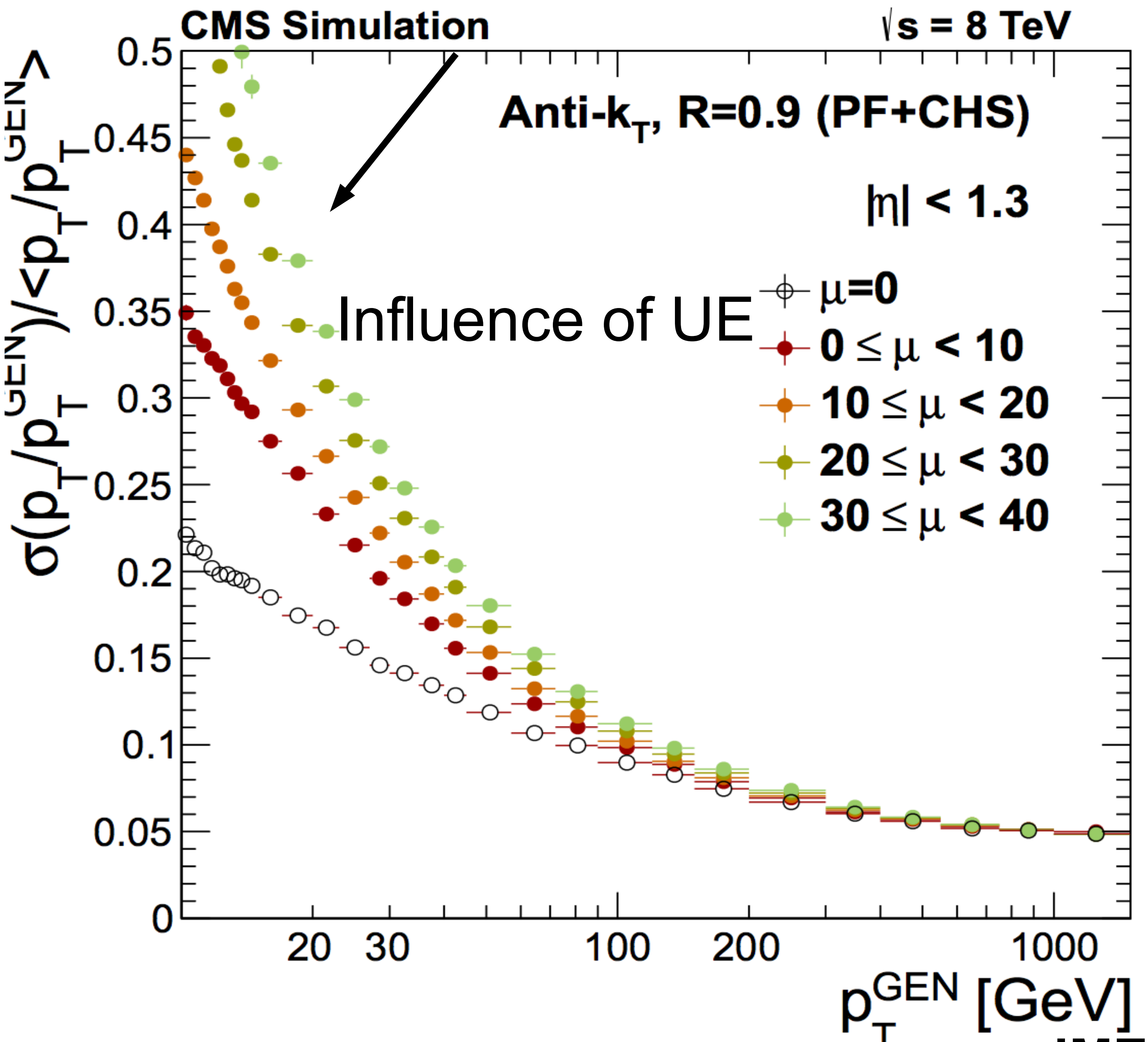
- AK8



JME-DP-14/037

Jet Energy Correction

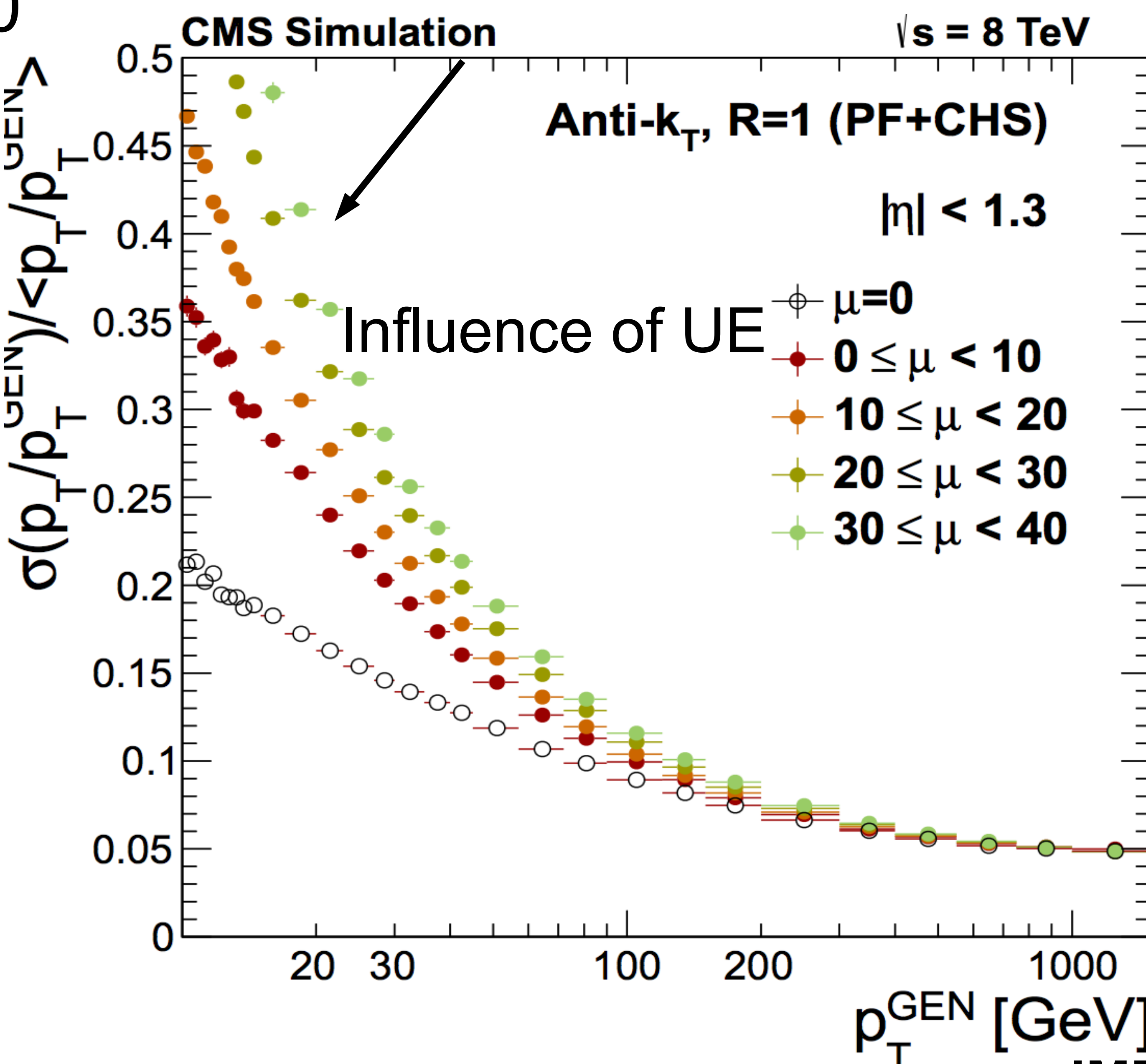
- AK9



JME-DP-14/037

Jet Energy Correction

- AK1.0



JME-DP-14/037

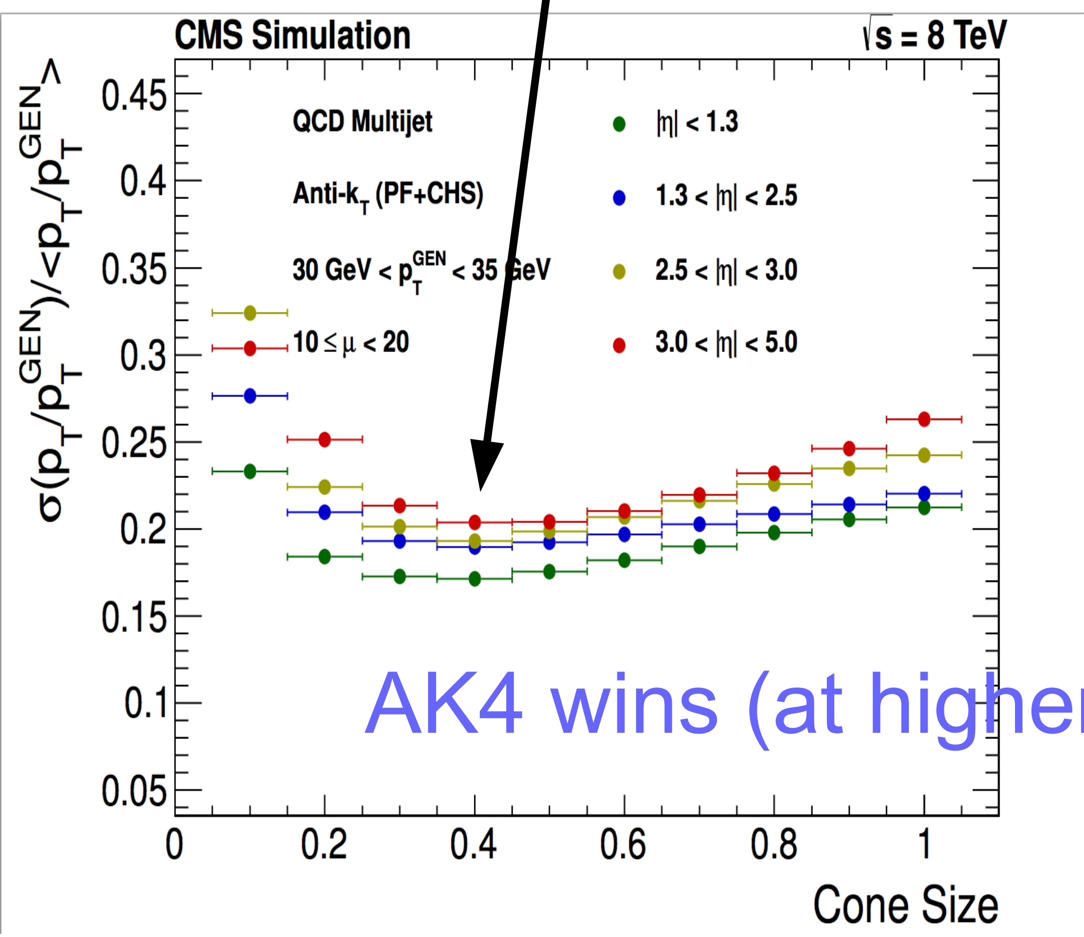
Jet Energy Correction

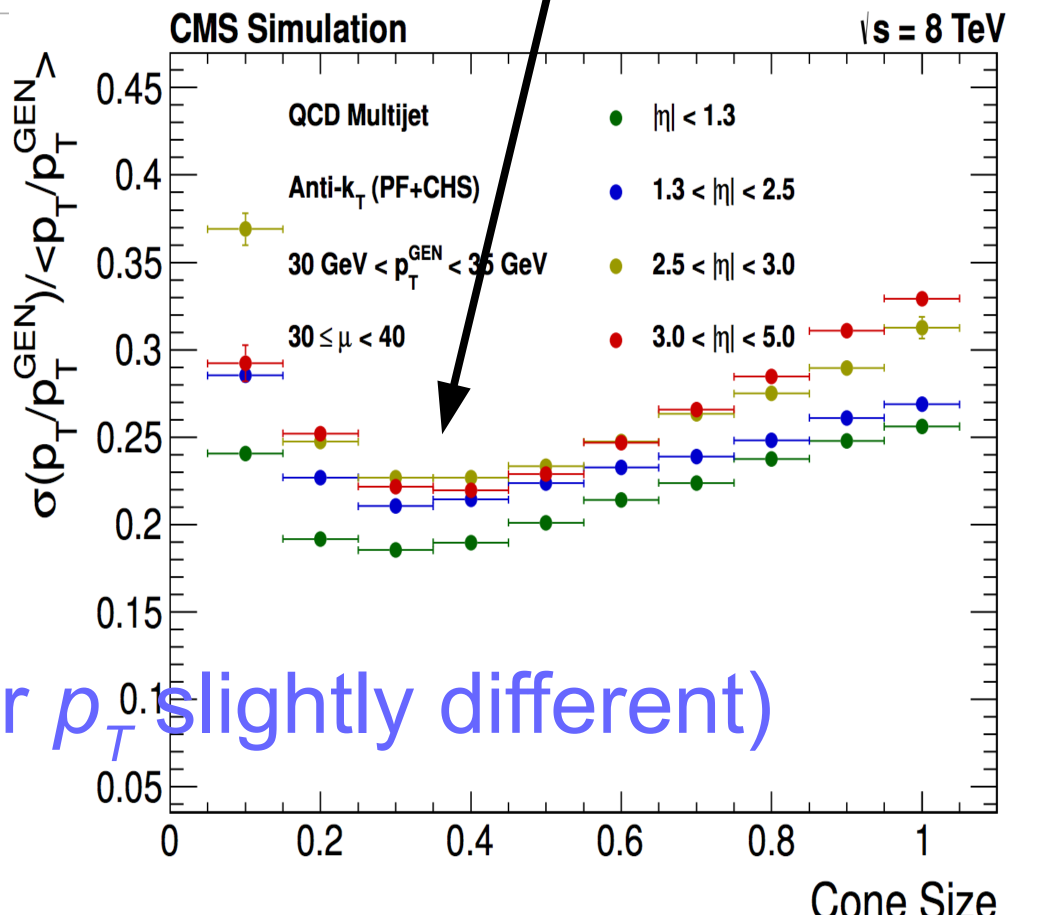
- Executive Summary :

We switch to AK4

Run I PU

Run II PU

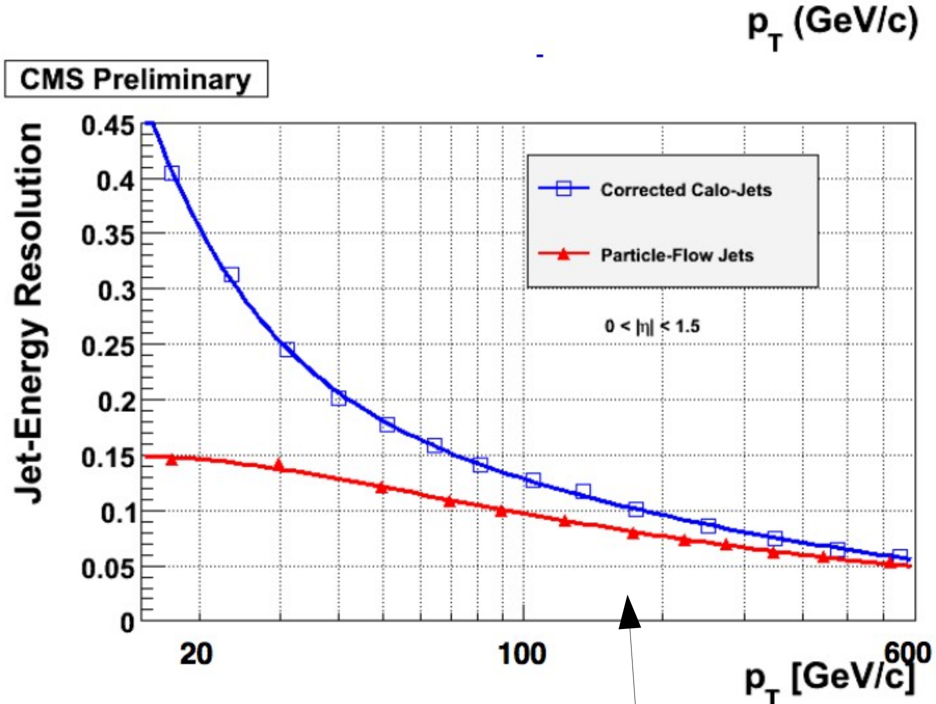


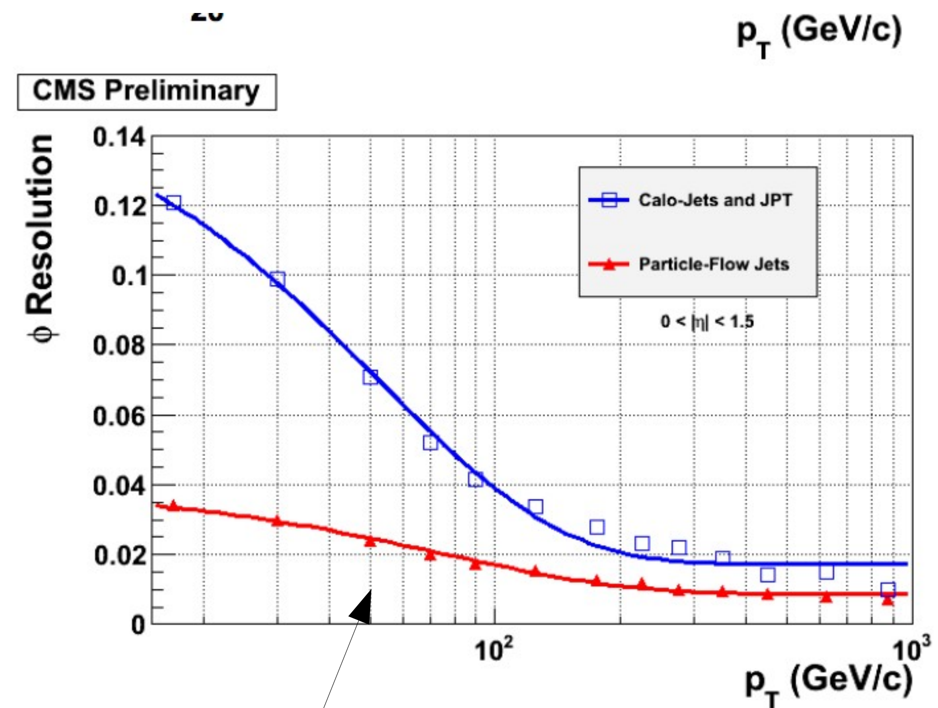


AK4 wins (at higher p_T slightly different)

JME-DP-14/037

Visualizing the PF impact

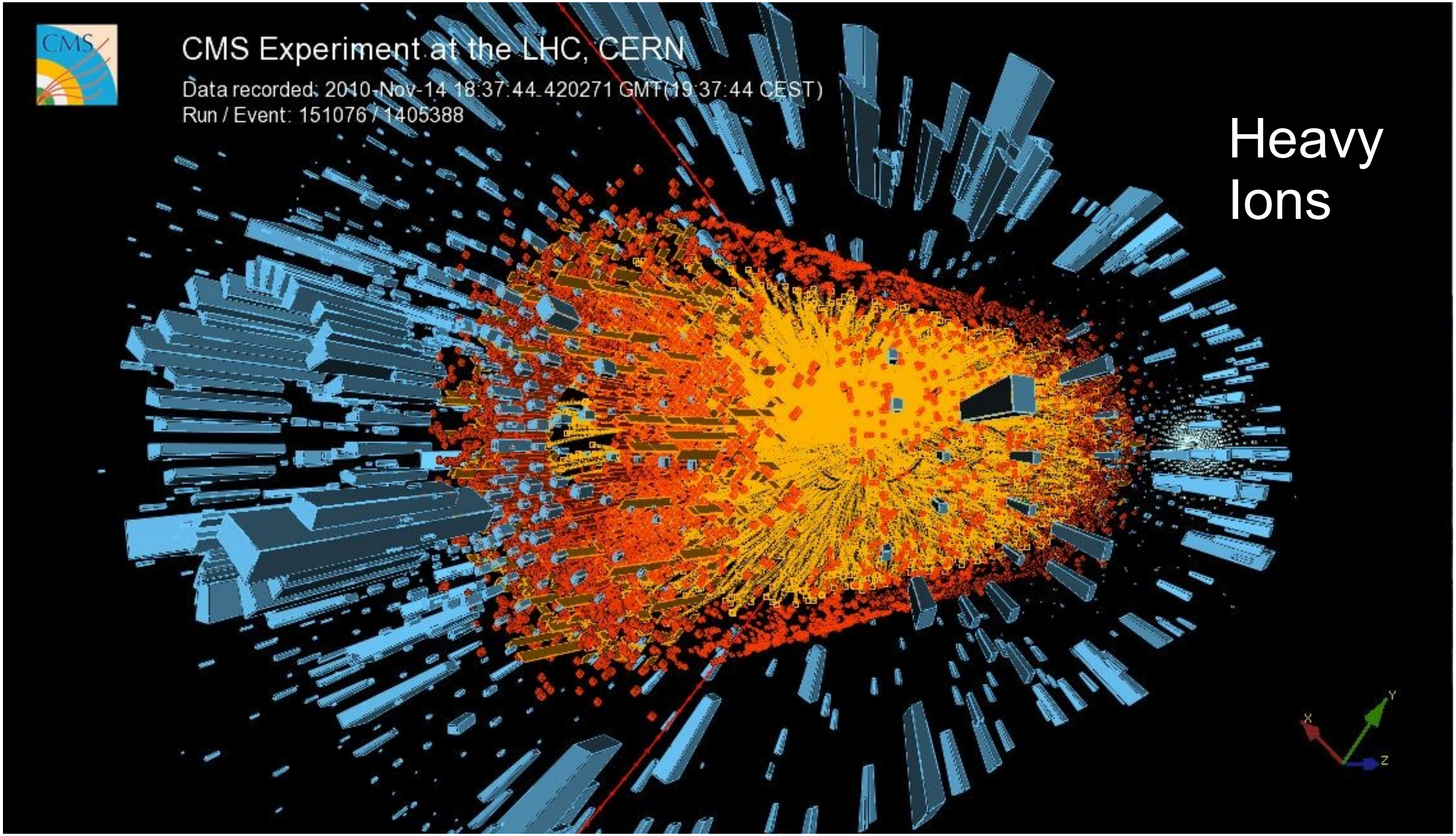




Angular information from the tracks improves the resolution of the jet shape internals

(Don't need to correct for jet shape aposteriori)

Dense Environment

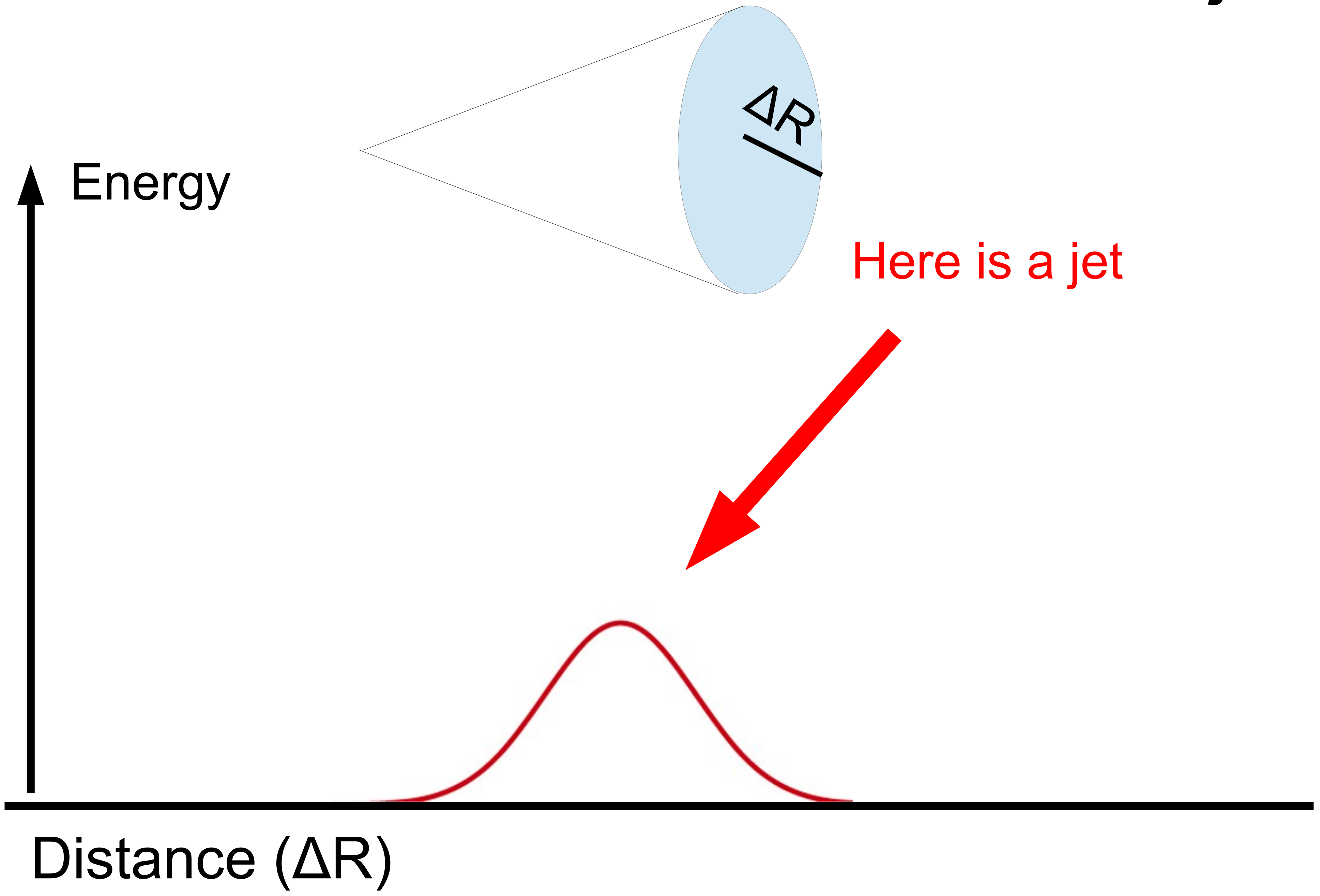


Dealing w/PU-UE:

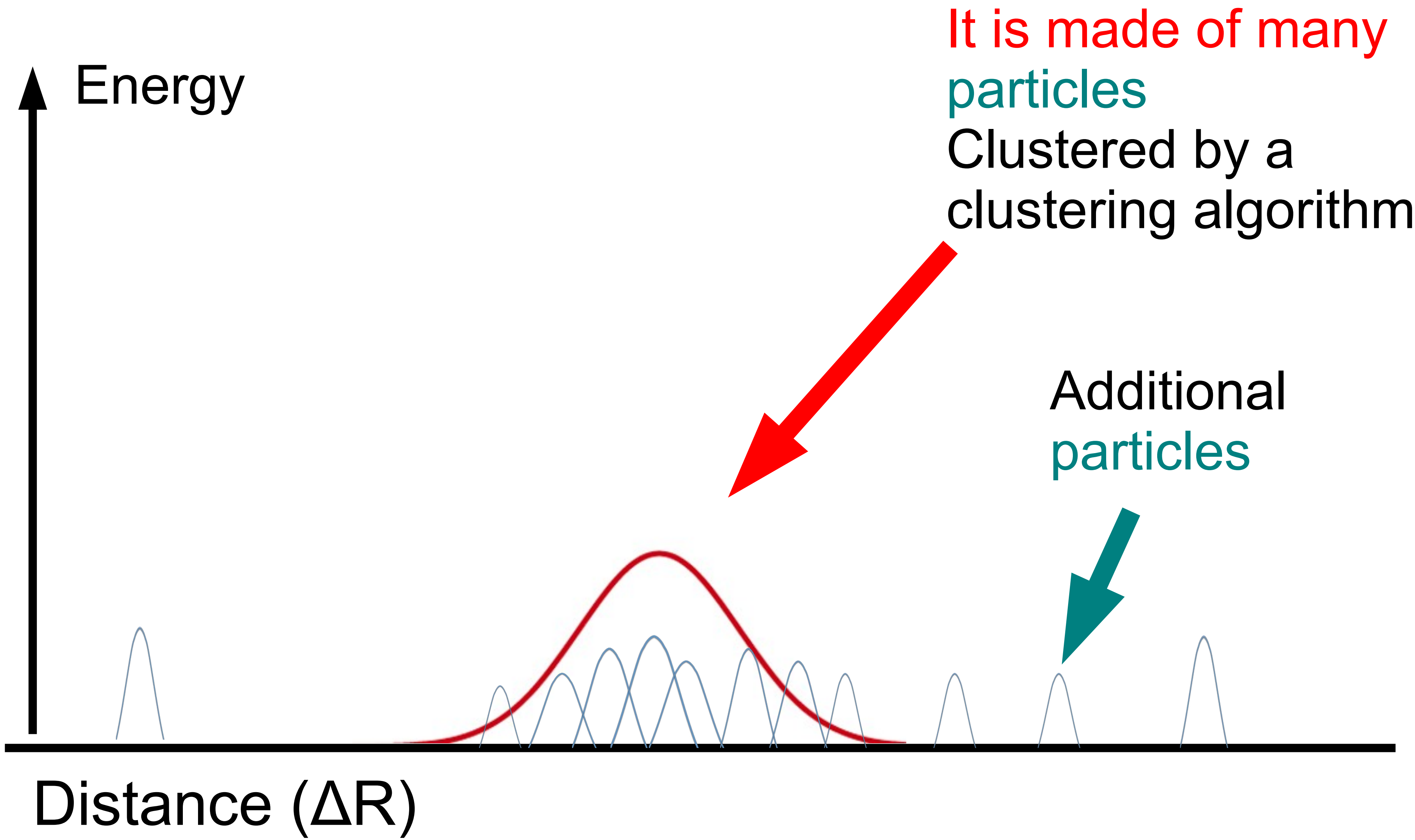
Key questions :

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

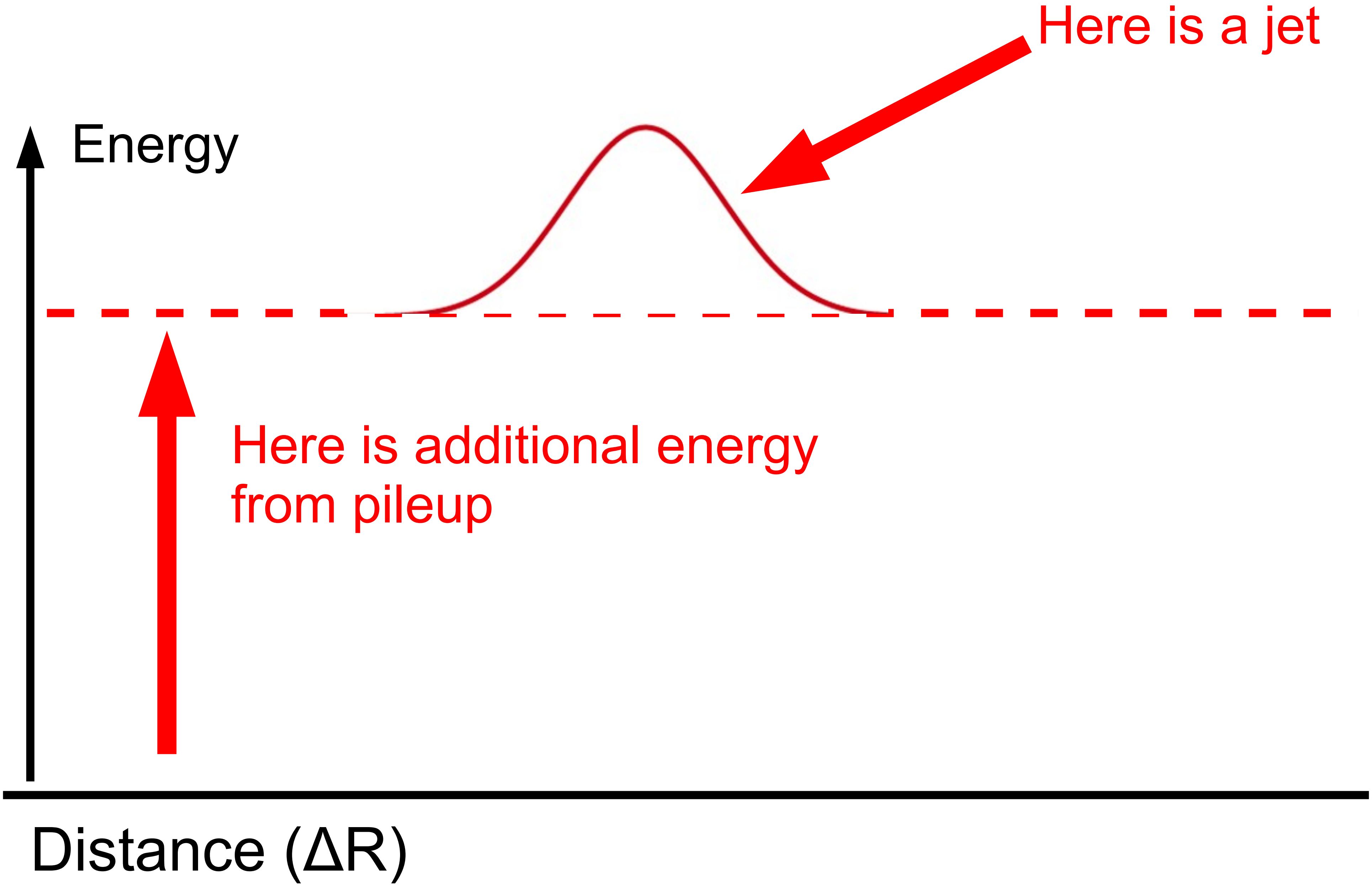
Consider a jet



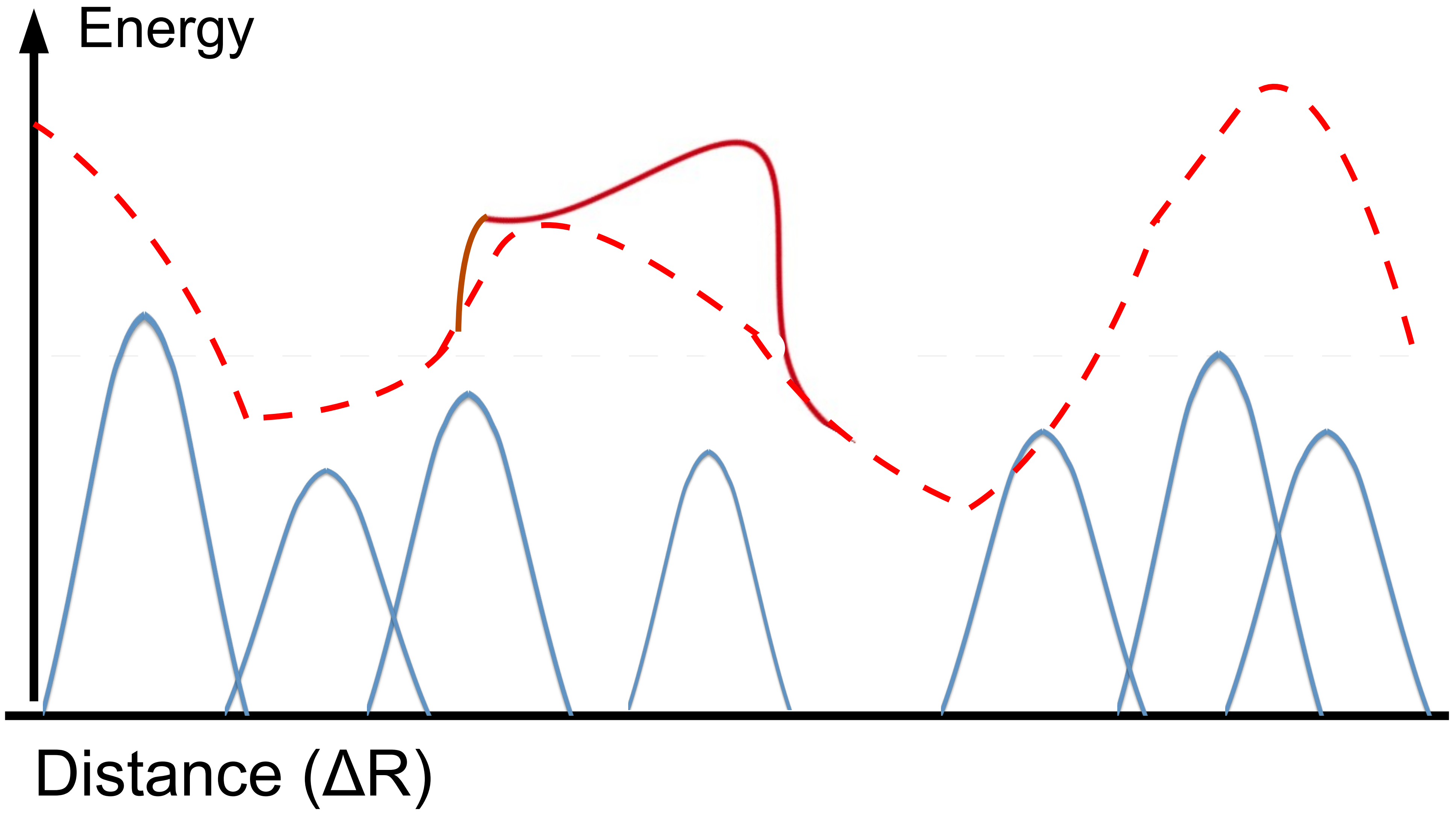
Consider a jet



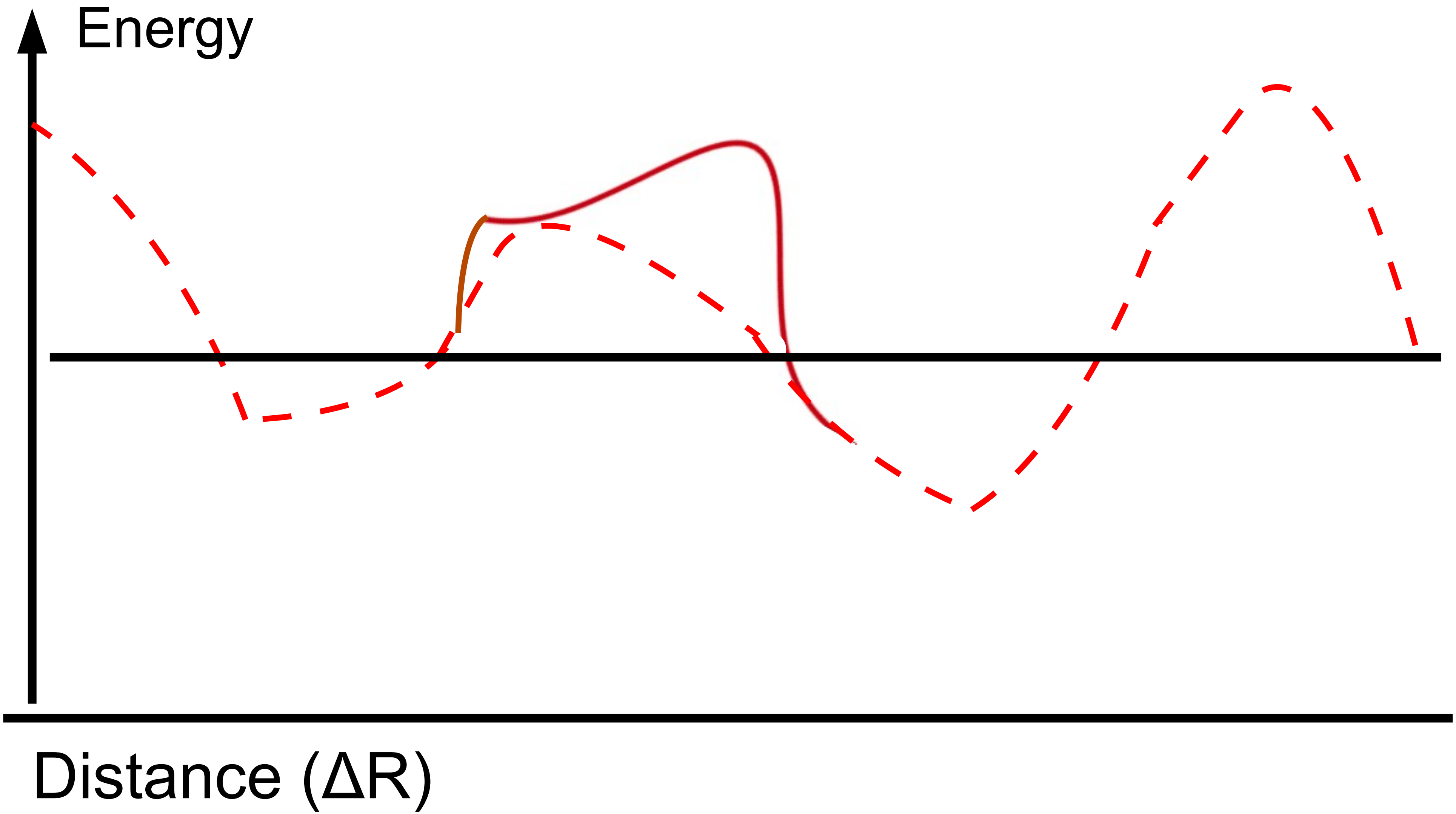
Consider a jet in high pileup



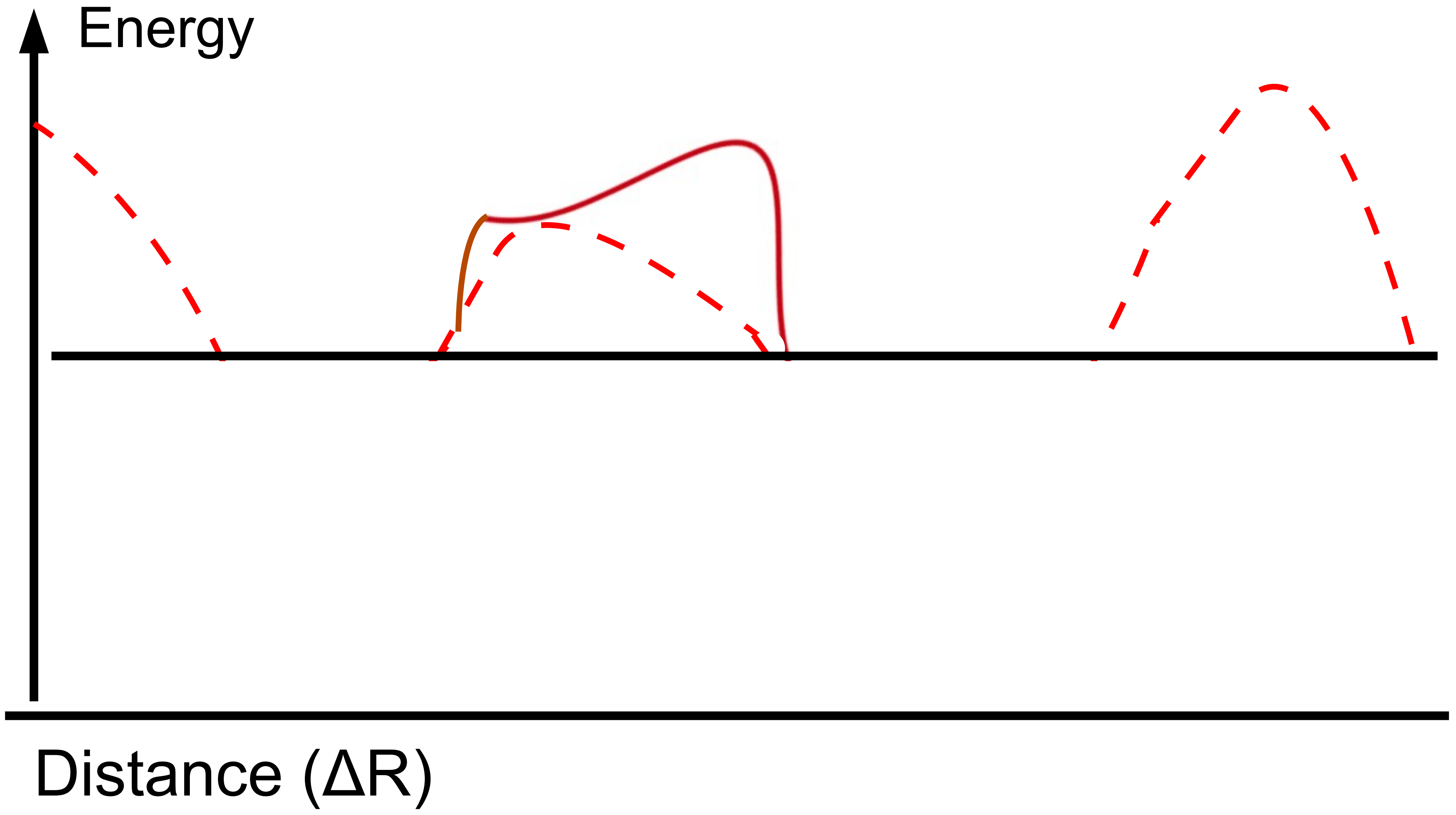
A jet in realistic pileup



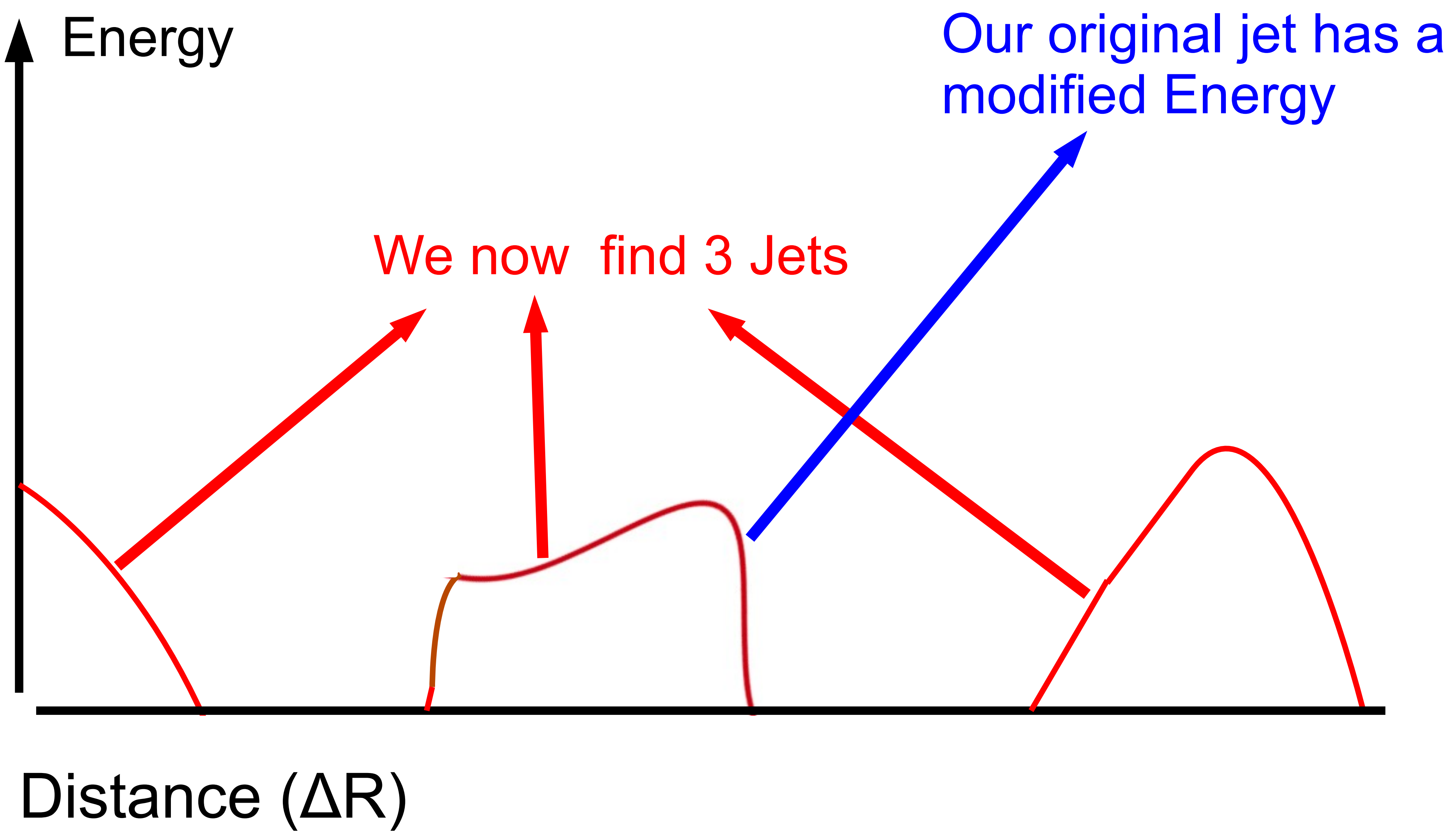
Conventional subtraction



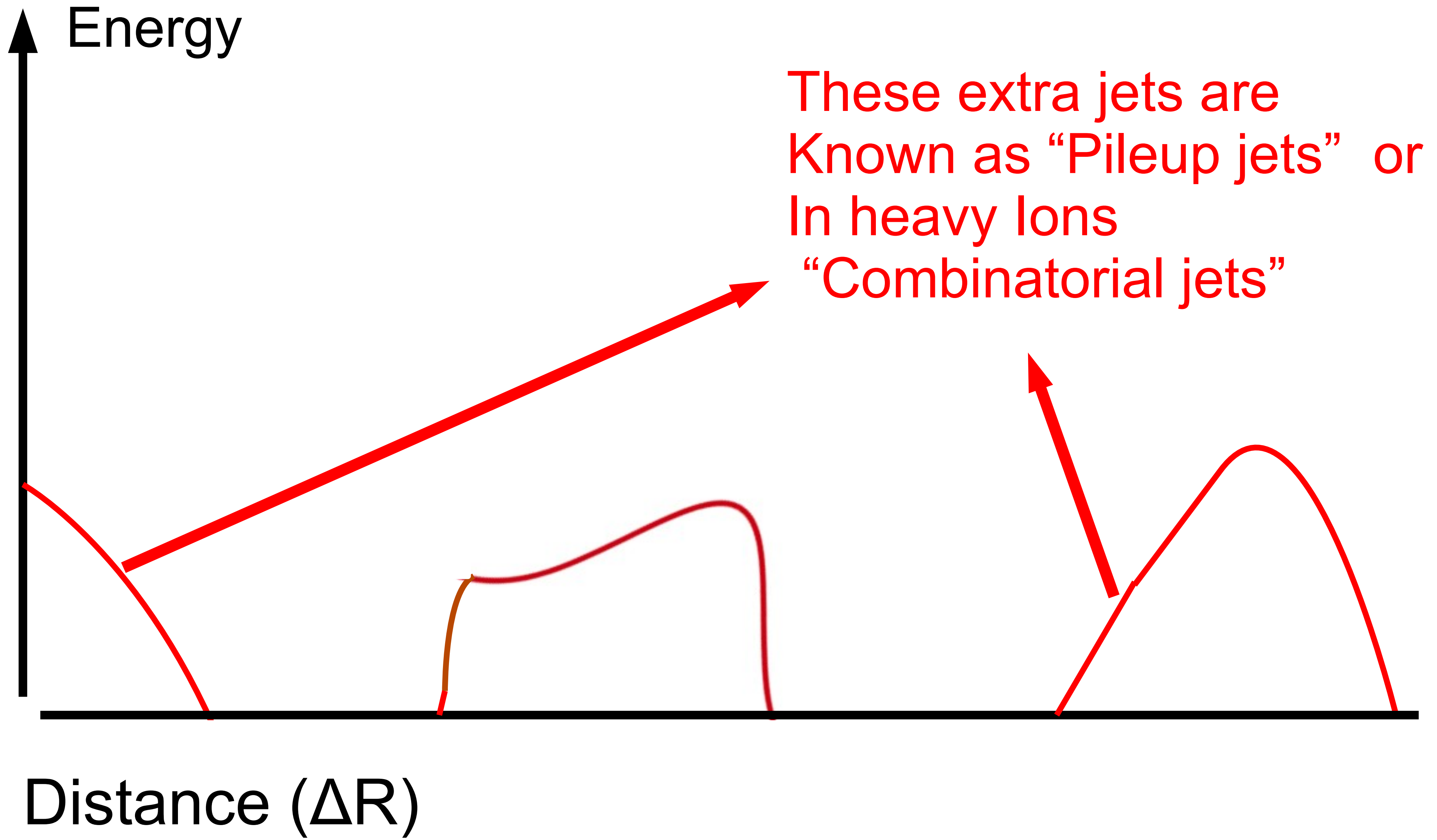
Conventional subtraction



Conventional subtraction

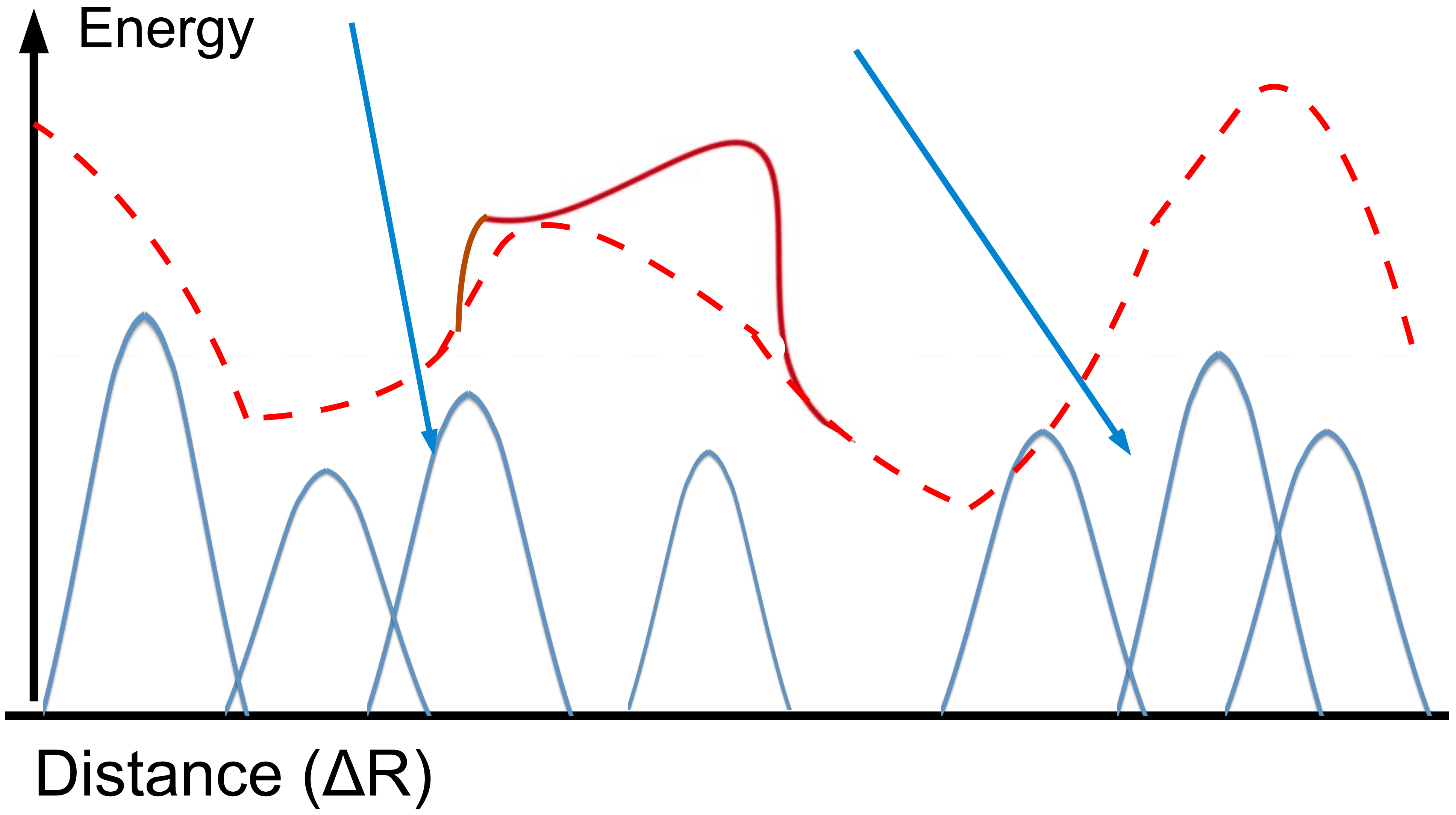


Conventional subtraction



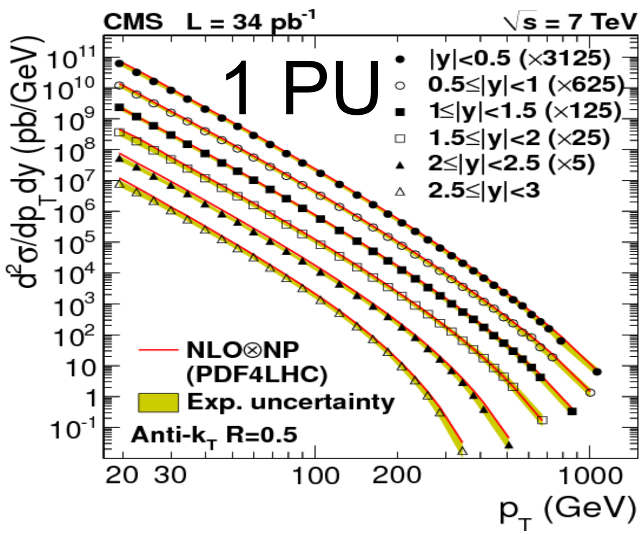
Lets back track

What is the composition of the pileup?



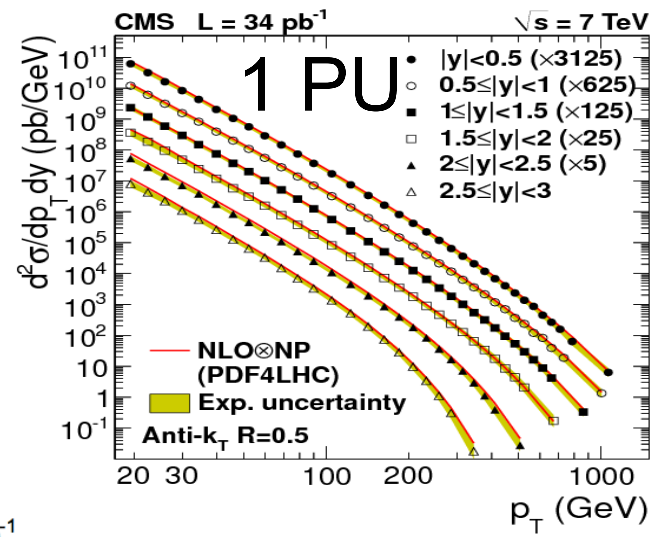
Composition of pileup

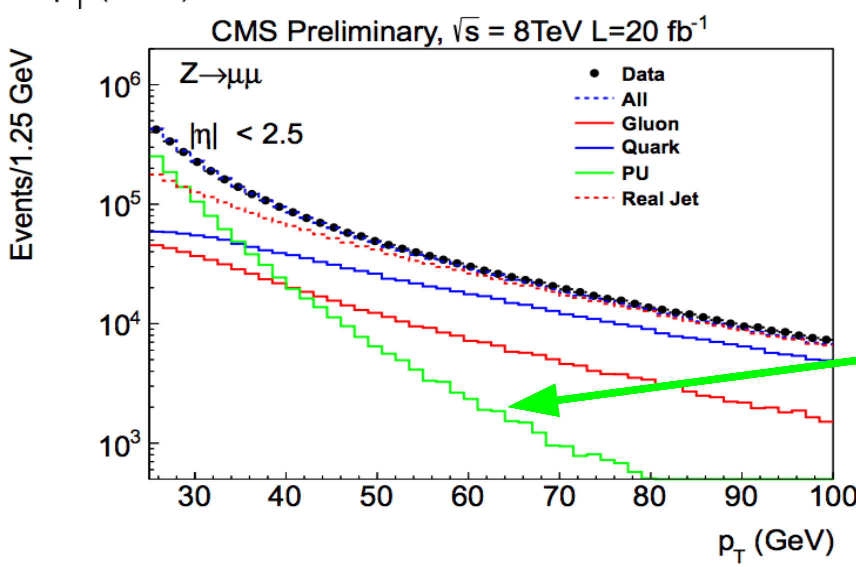
- Every collision starts with quarks
  - This leads to jets in the final state
  - Now combine many different collisions together



N_{PU}

...



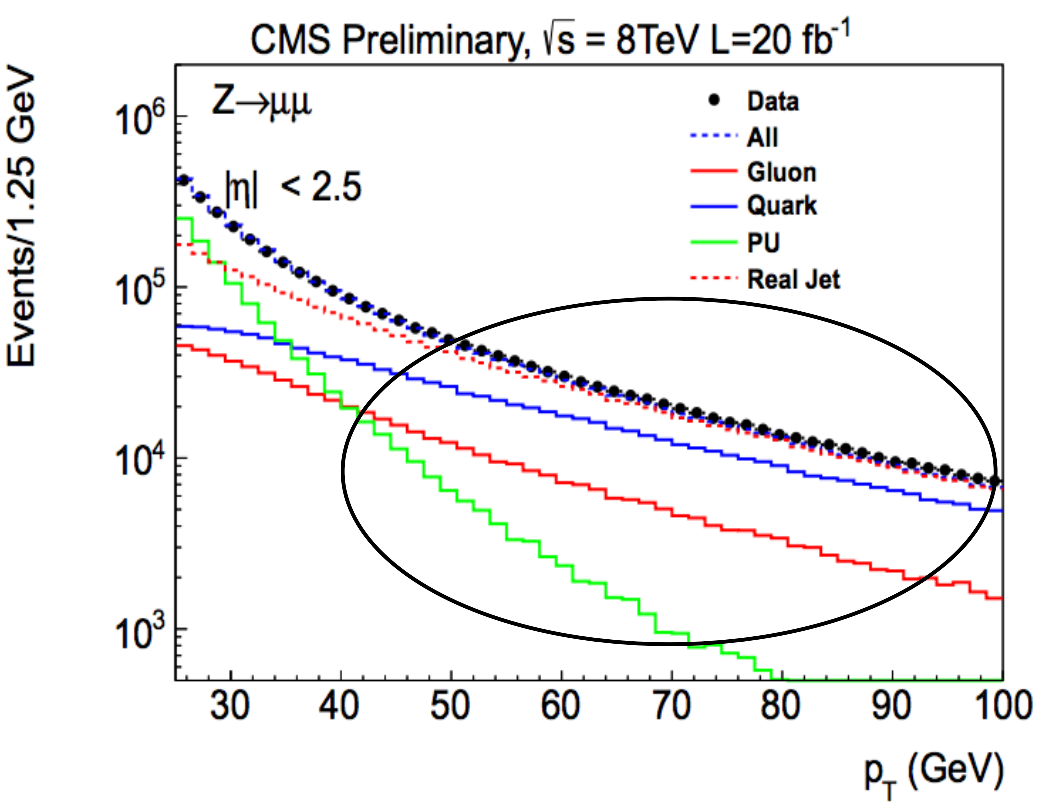


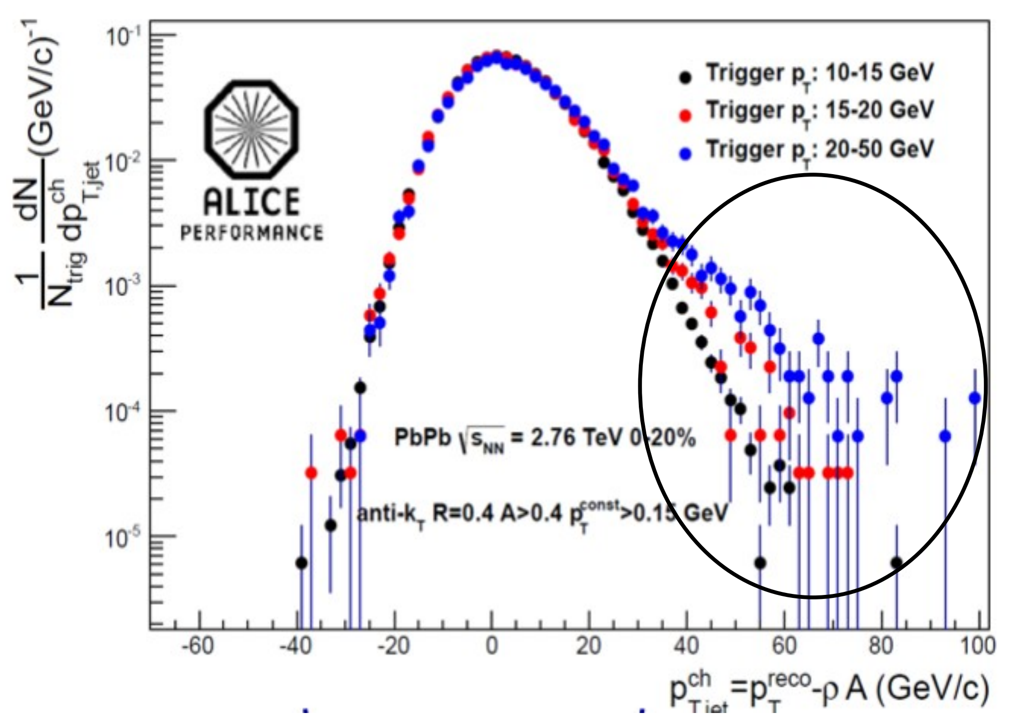
Jets overlapping
Gives up pileup jets

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?**

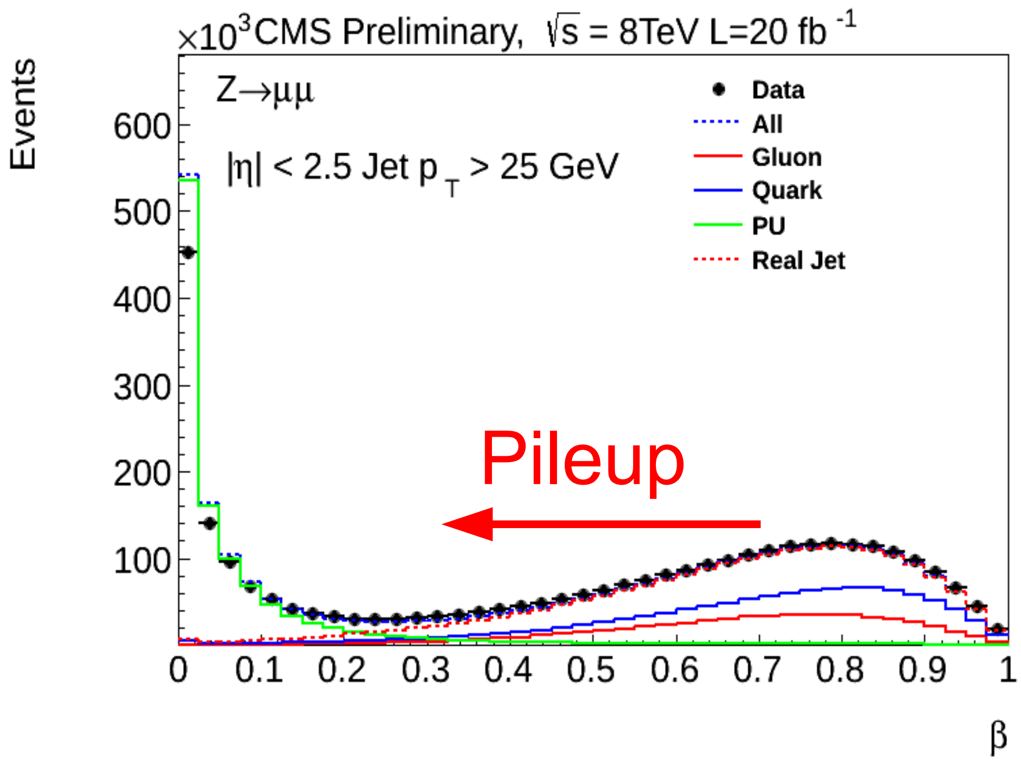
$P(\text{overlap}|pT) \approx C\, N^2_{pu}\, a^2_{jet}\, pT^{-6.2}$ Real Jets $\approx pT^{-5}$

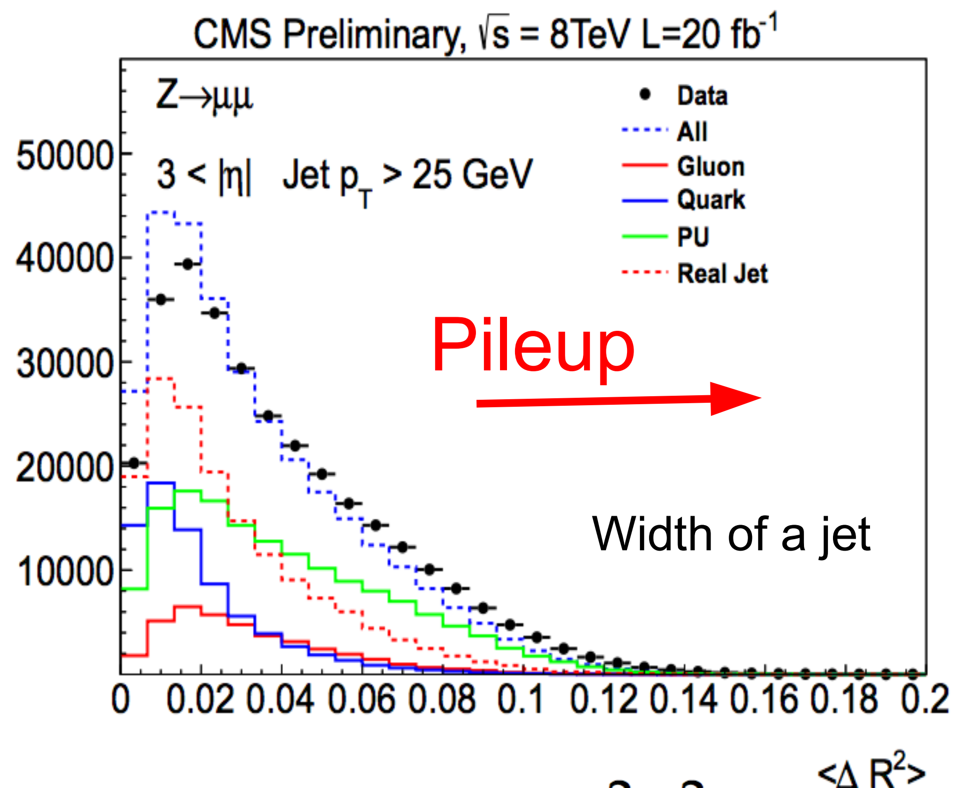




Identifying pileup jets

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





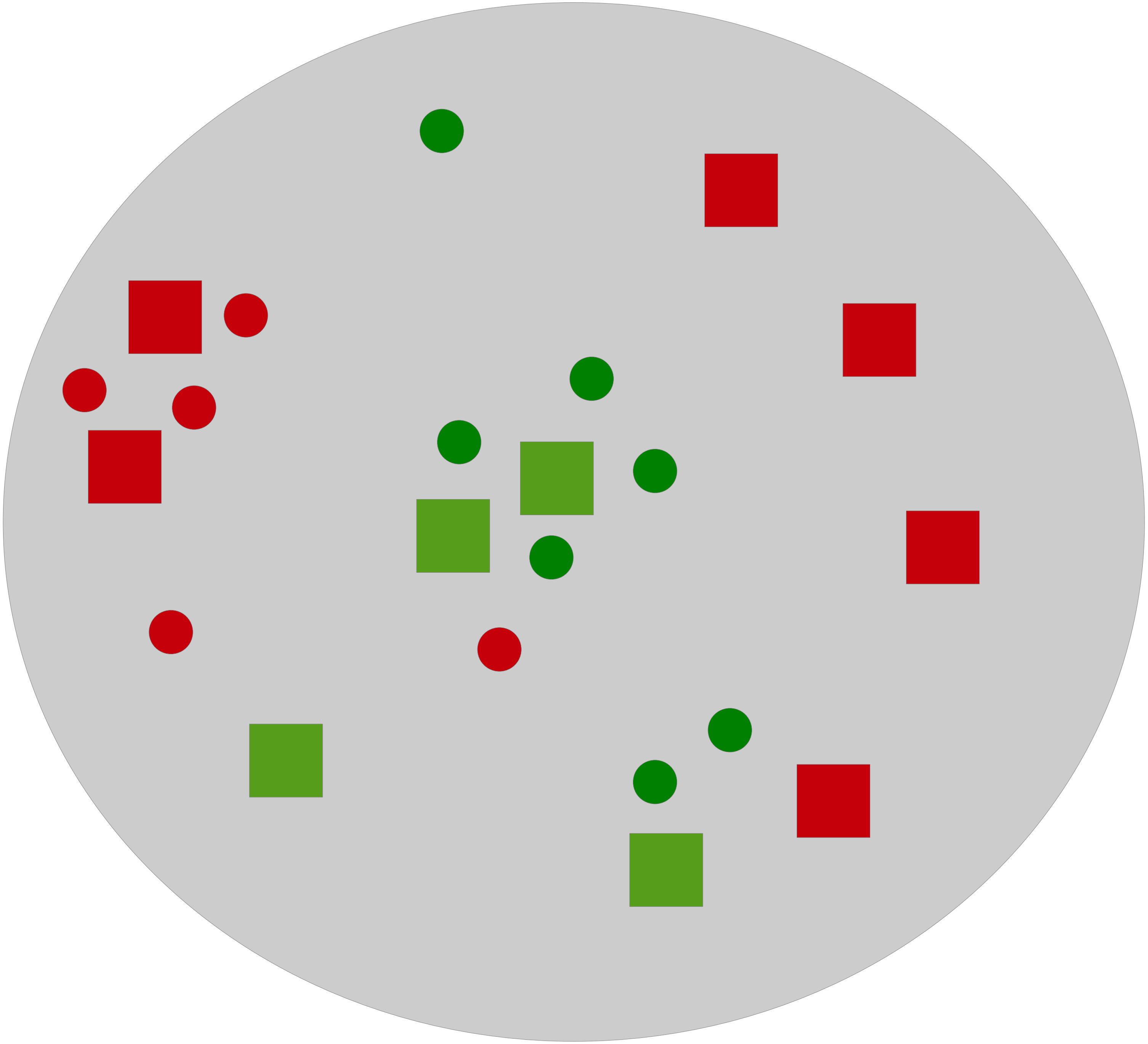
$$\beta = \frac{\sum_{i \in PV} p_{Ti}}{\sum_i p_{Ti}} \qquad \langle \Delta R^2 \rangle = \frac{\sum_i \Delta R_i^2 p_{Ti}^2}{\sum_i p_{Ti}^2}$$

Current Technology

Consider a jet

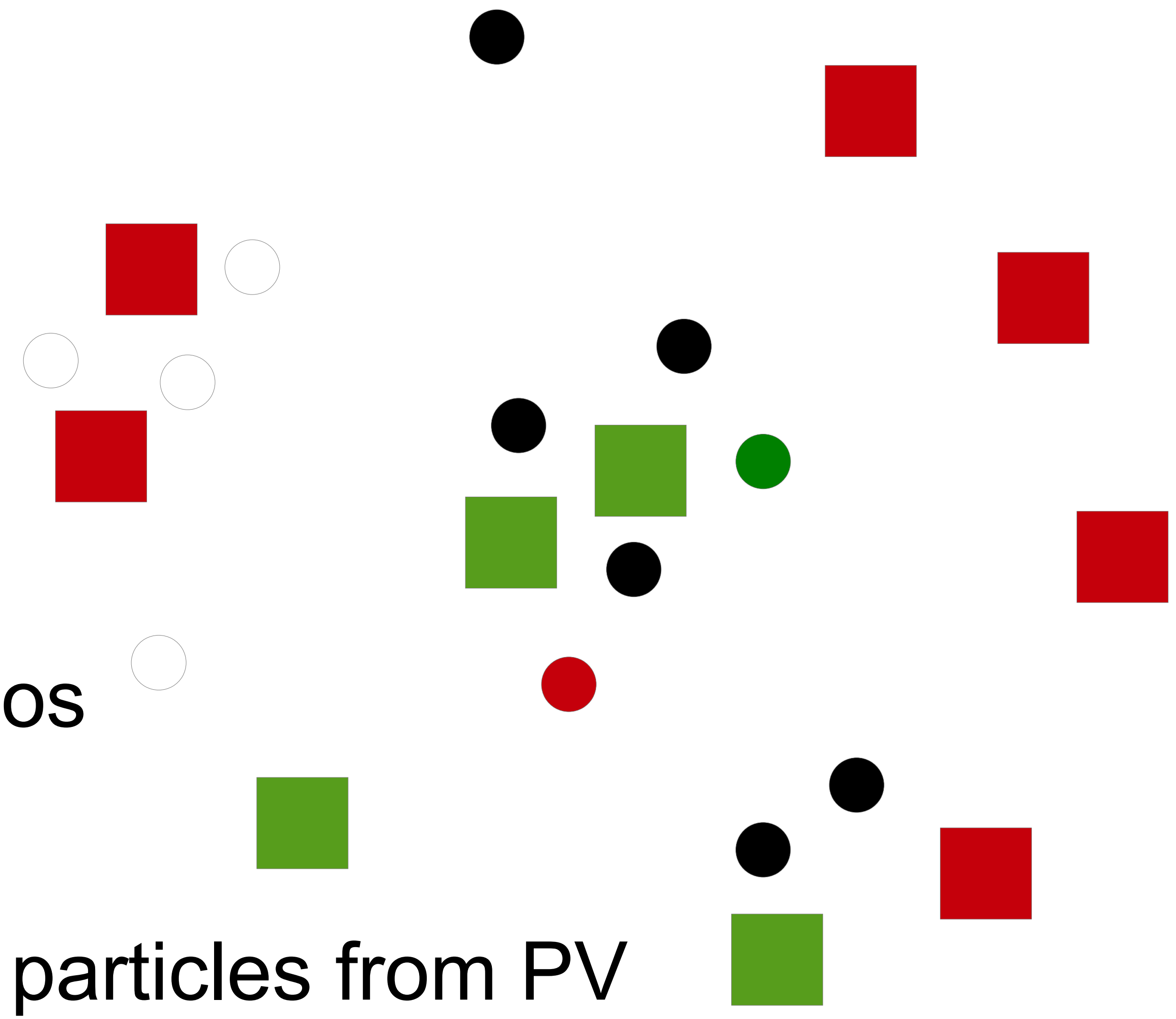
Key

- 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

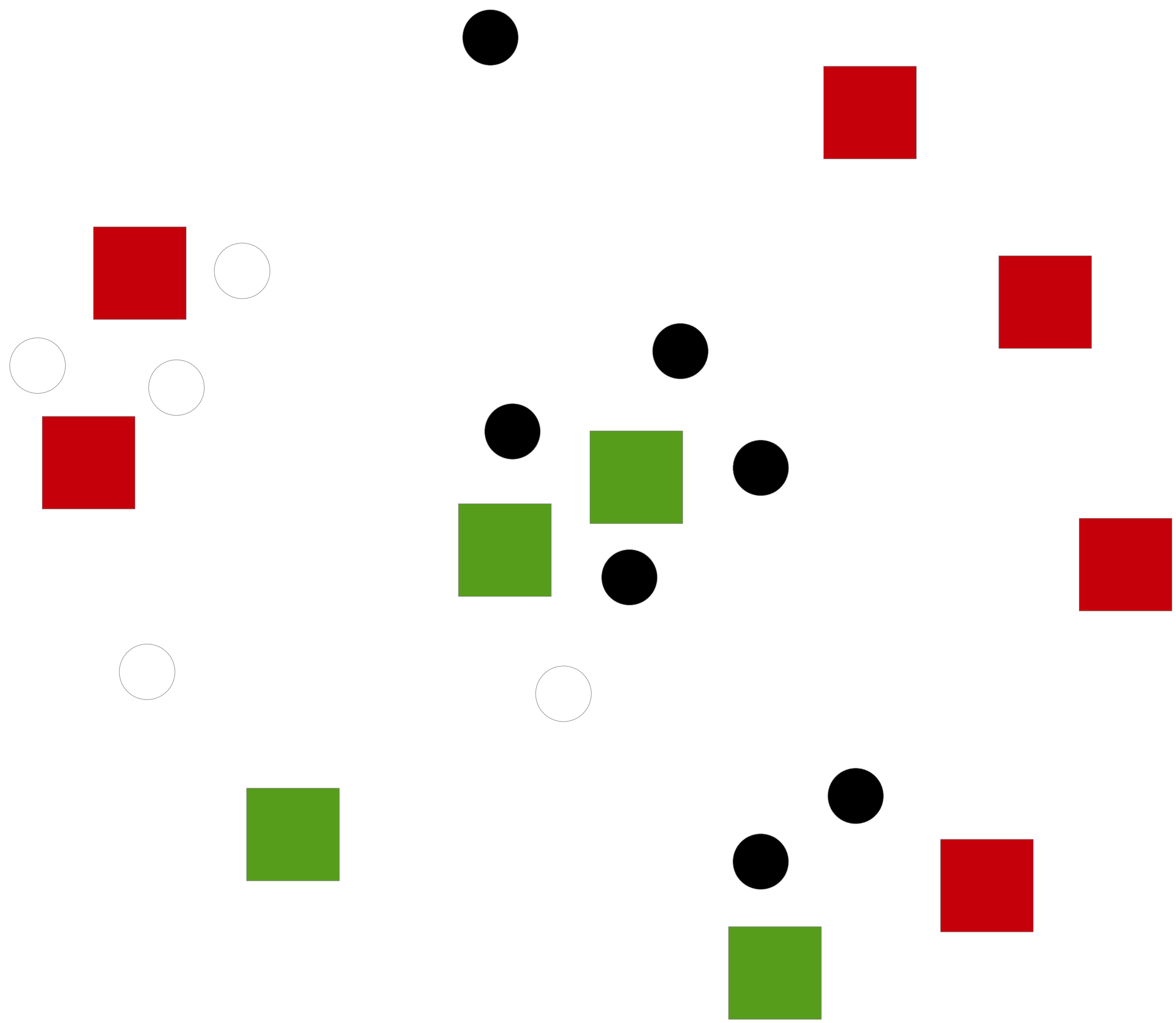
PU Neut

Chosen

Removed

Step 1

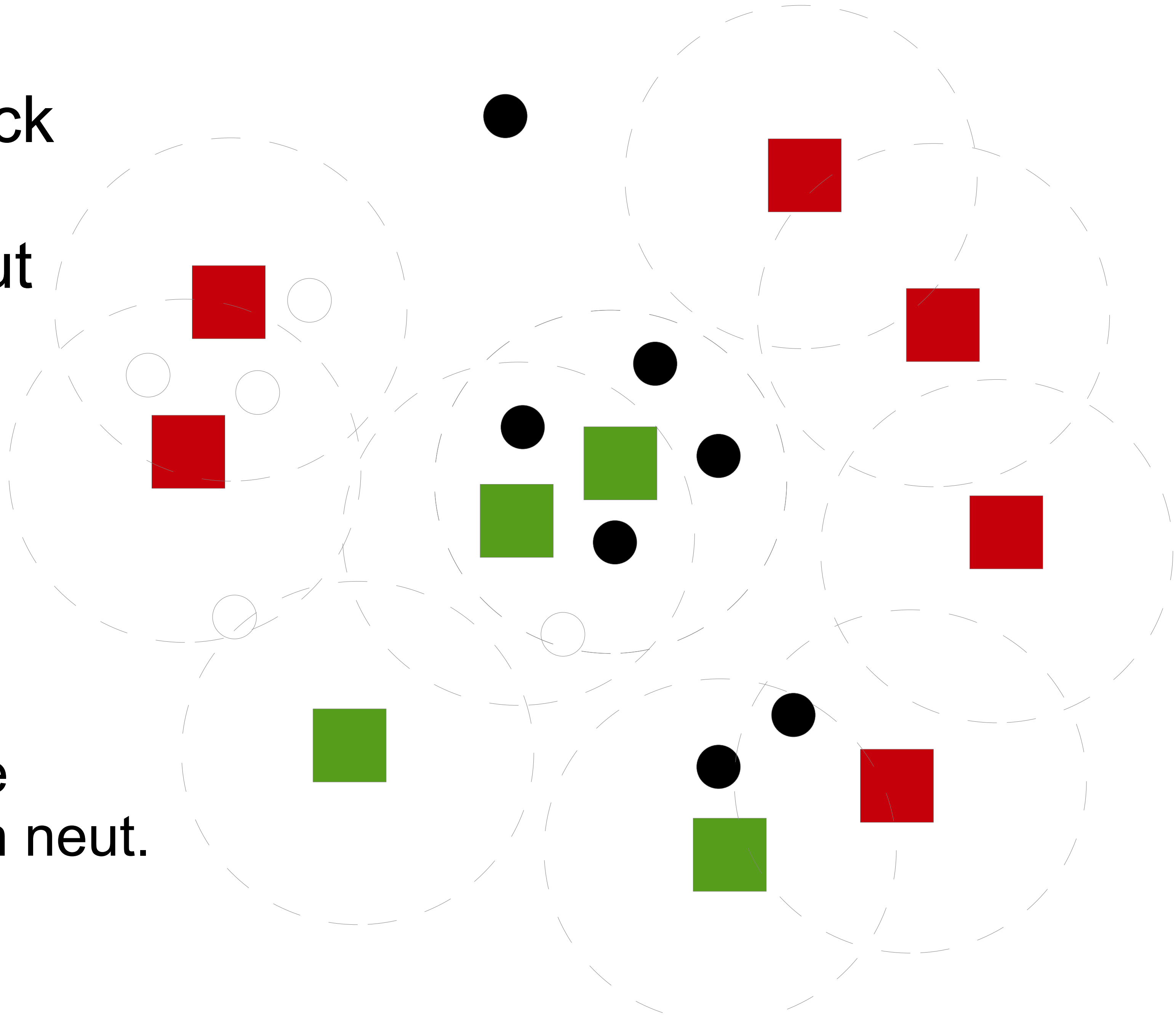
Tracks can point to PU vertices w/high efficiency



Arxiv/1407.6013

Puppi algorithm

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



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

Arxiv/1407.6013

Puppi algorithm

Key

Good Track

PU Track

Good Neut

PU Neut

Chosen

Removed

Step 1

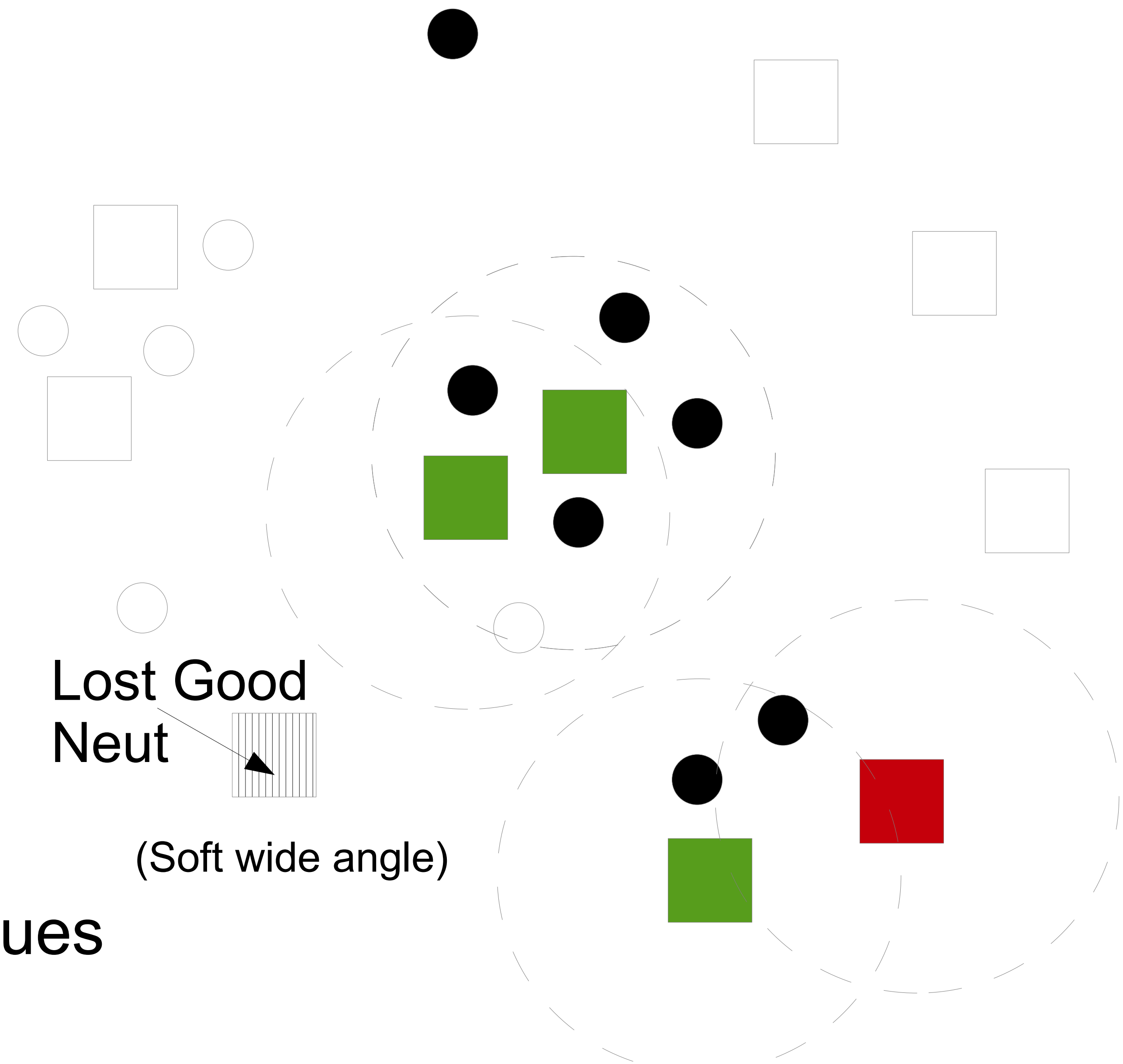
Run CHS

Step 2

Draw a cone

Step 3

Remove all 0 values



Arxiv/1407.6013

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

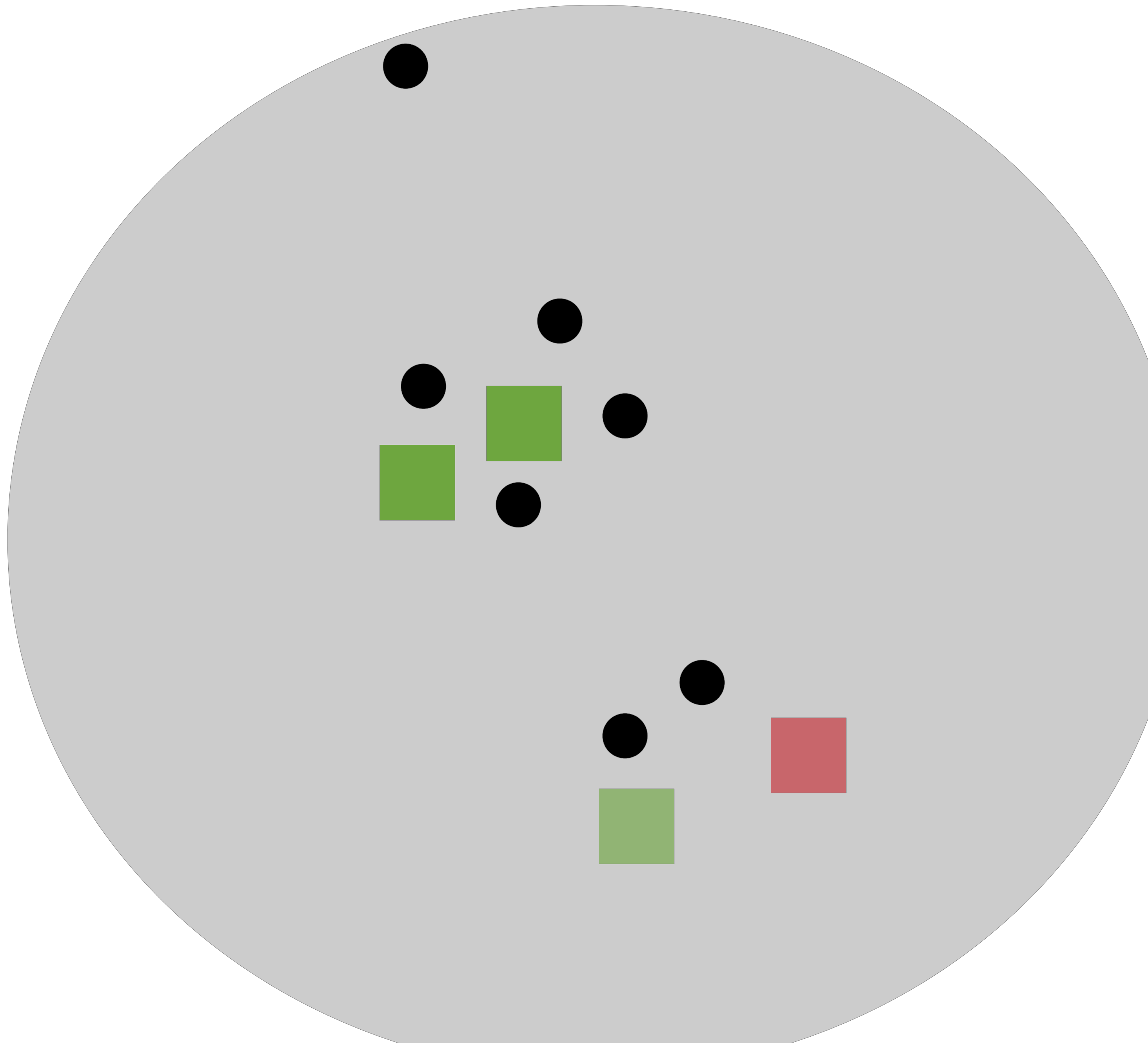
Arxiv/1407.6013

After Puppi

Key

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

Step 5
Re-interpret evt
(Re-cluster)



Arxiv/1407.6013

The weight factor

- For each particle consider in a cone :

$$\log \sum_{j \in R_{\min} \leq \Delta R_{ij} \leq R_0} \frac{p_{Tj}}{\Delta R_{ij}}$$

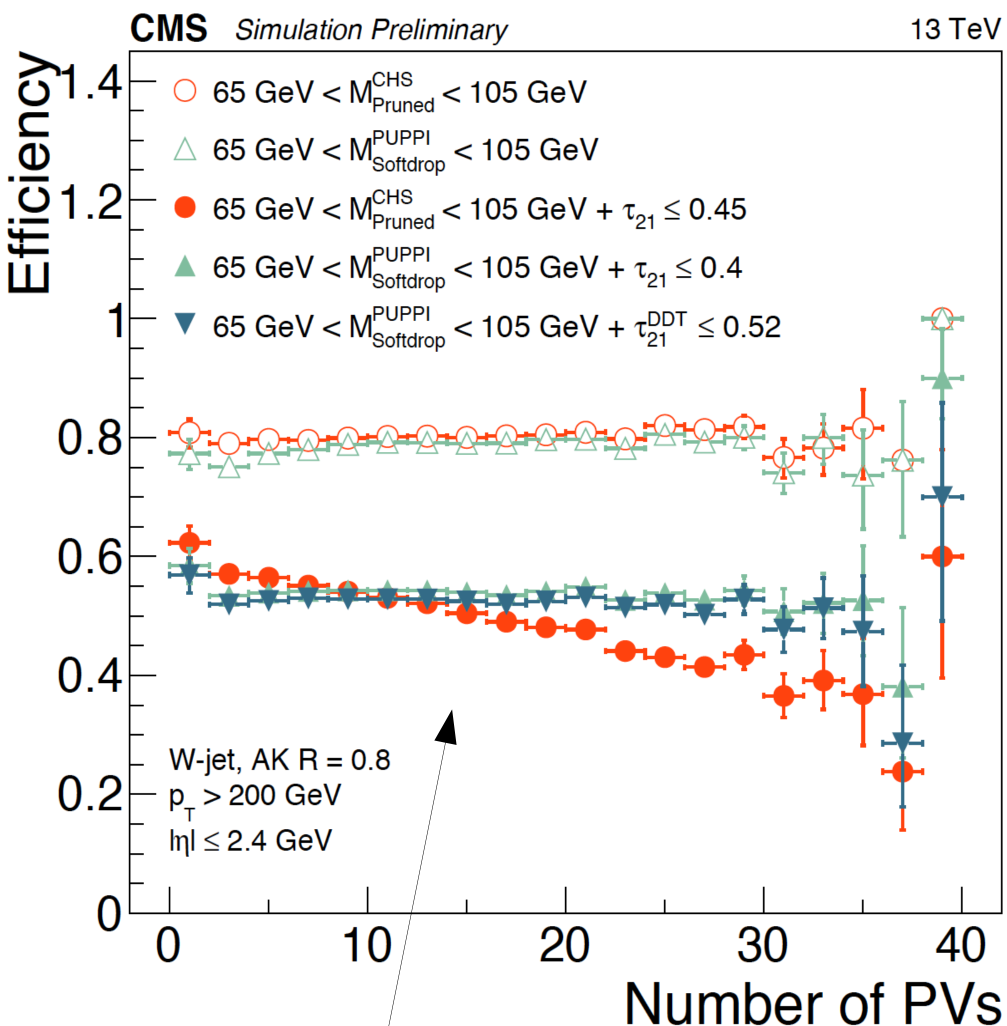
Hard collinear particles

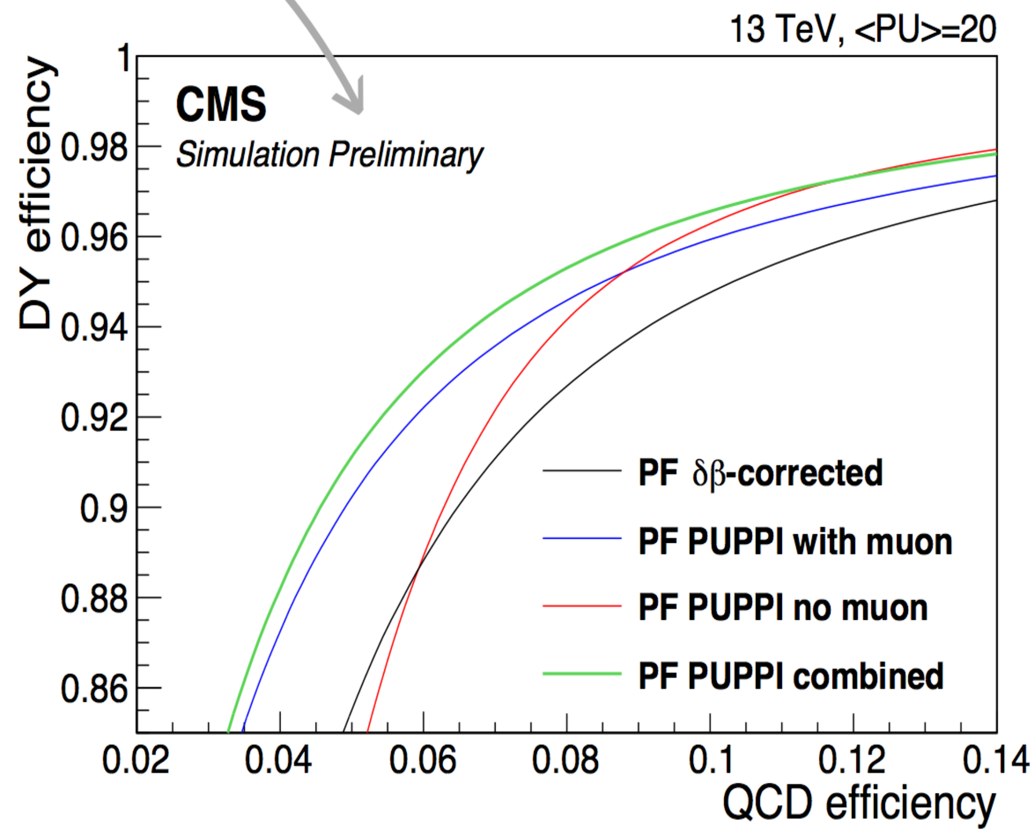
Soft wide angle particles

Variable roughly gaussian→ build likelihood
Translate to weight (w_i) applied to each candiate
Apply a cut on weighted $w_i p_T > A + B\ N_{PV}$

Arxiv/1407.6013

PUPPI Performance





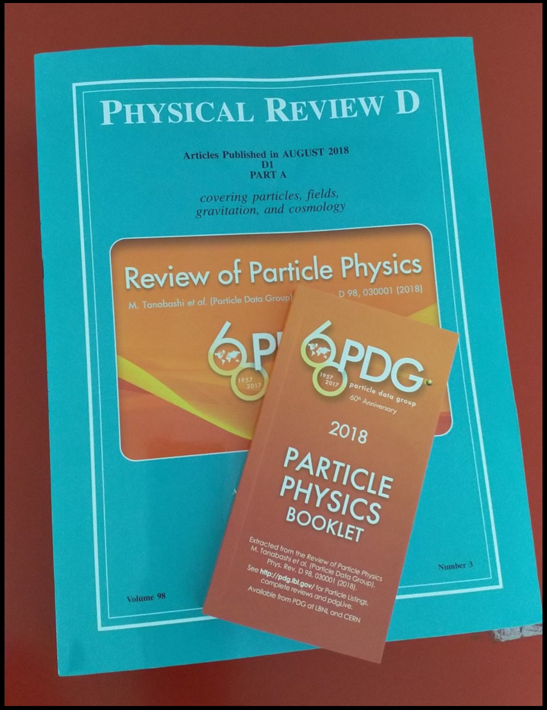
Particle level properties like Isolation & *MET* improve substantially

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

CMS-JME-16-003

CMS-DP2015-034

Part 1
Hadronic Resonances



Part 1
Hadronic Resonances

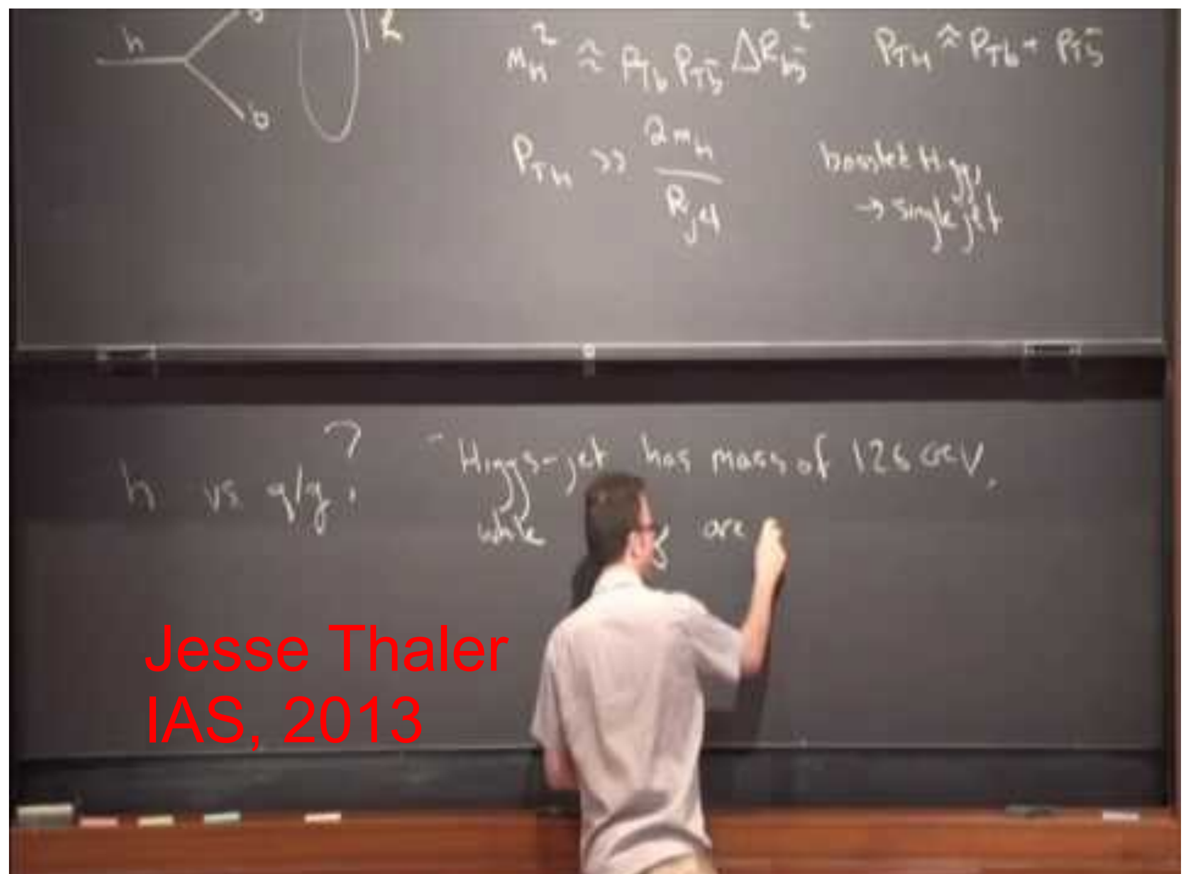
III.4.2. $H \rightarrow b\bar{b}$

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

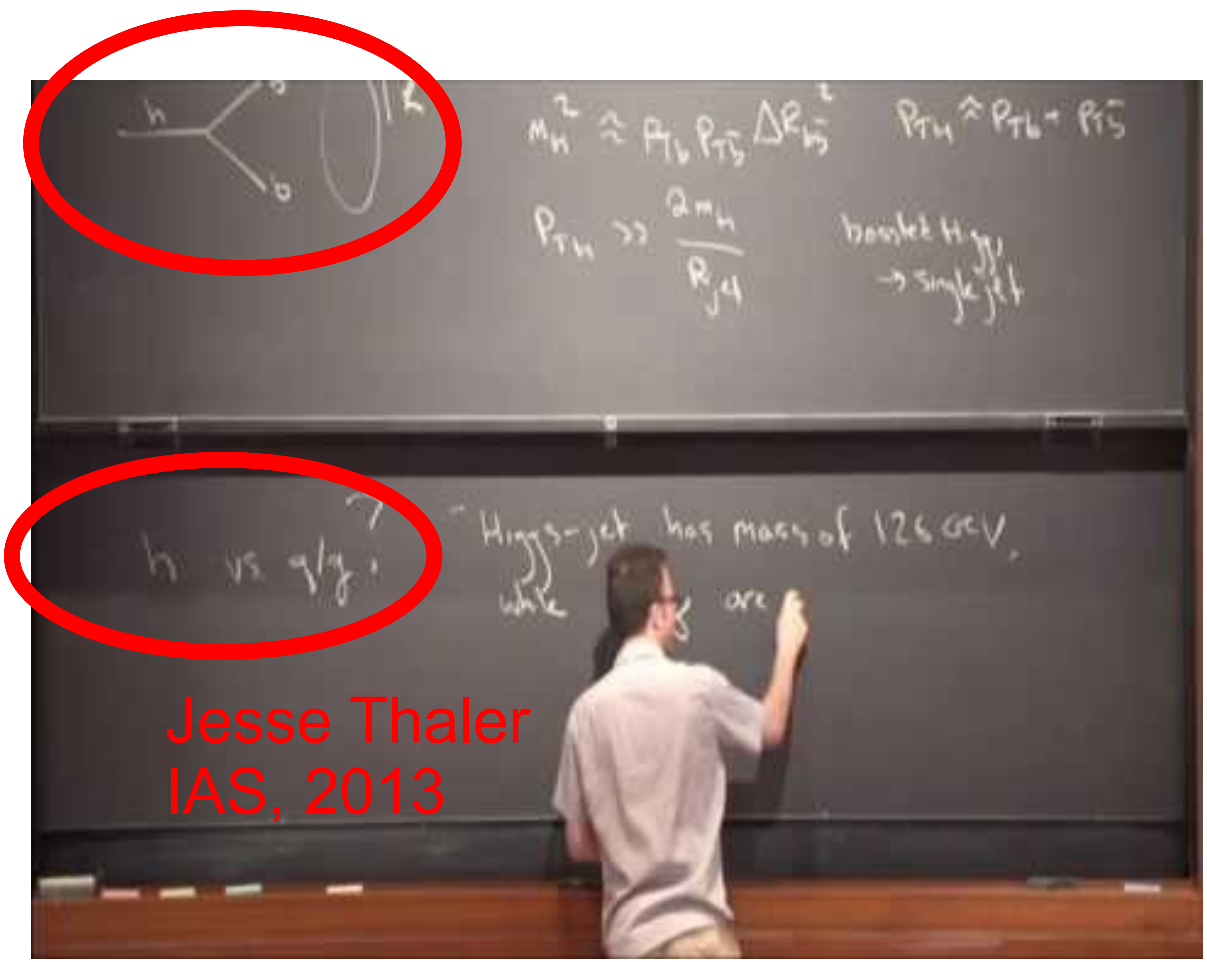


A few Questions remained uncertain

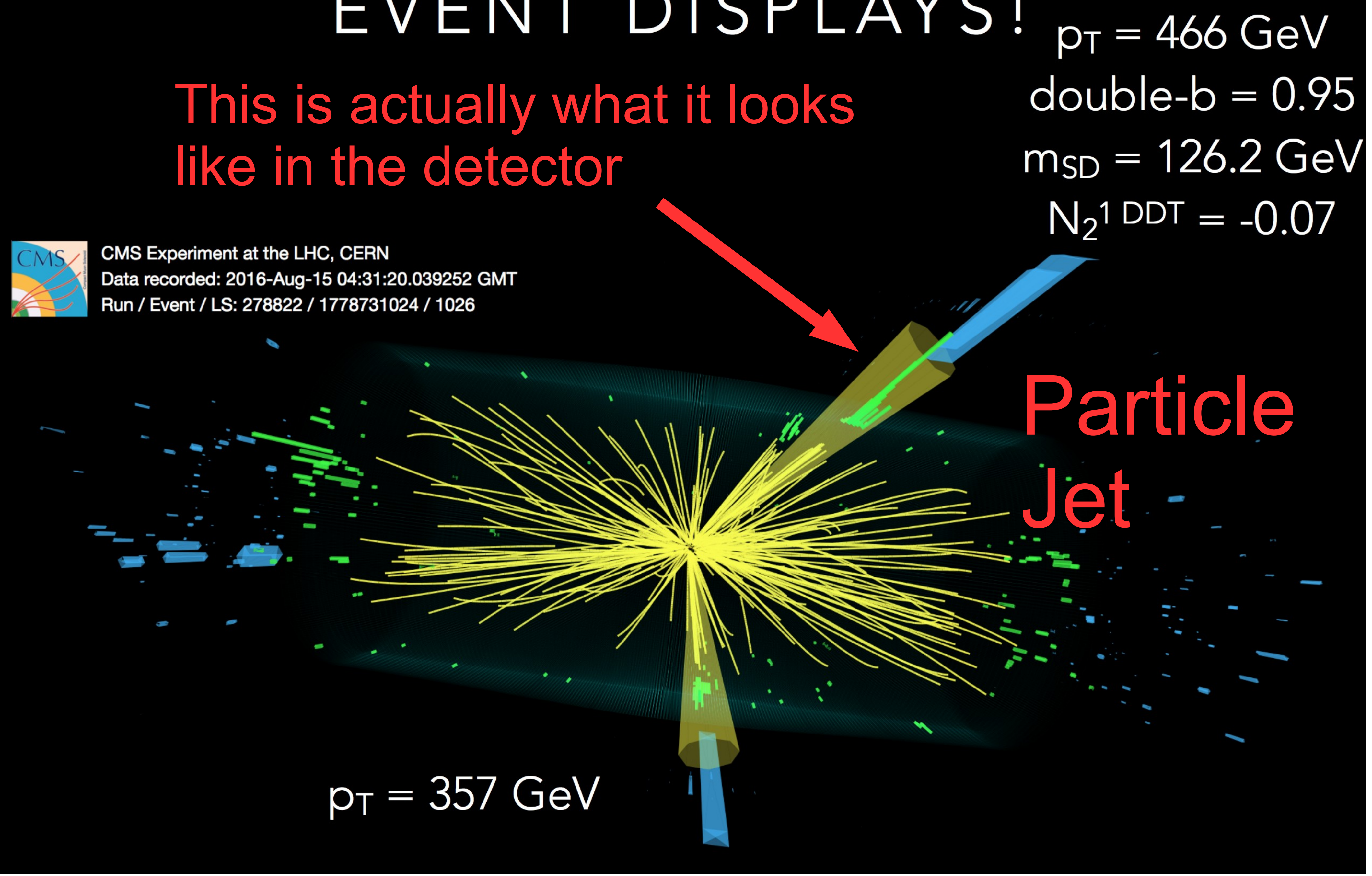
- If you look closely
  - Jesse is setting up the beginning of a problem
  - The same problem that PDG said was impossible

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

Standing on the
shoulders of giants

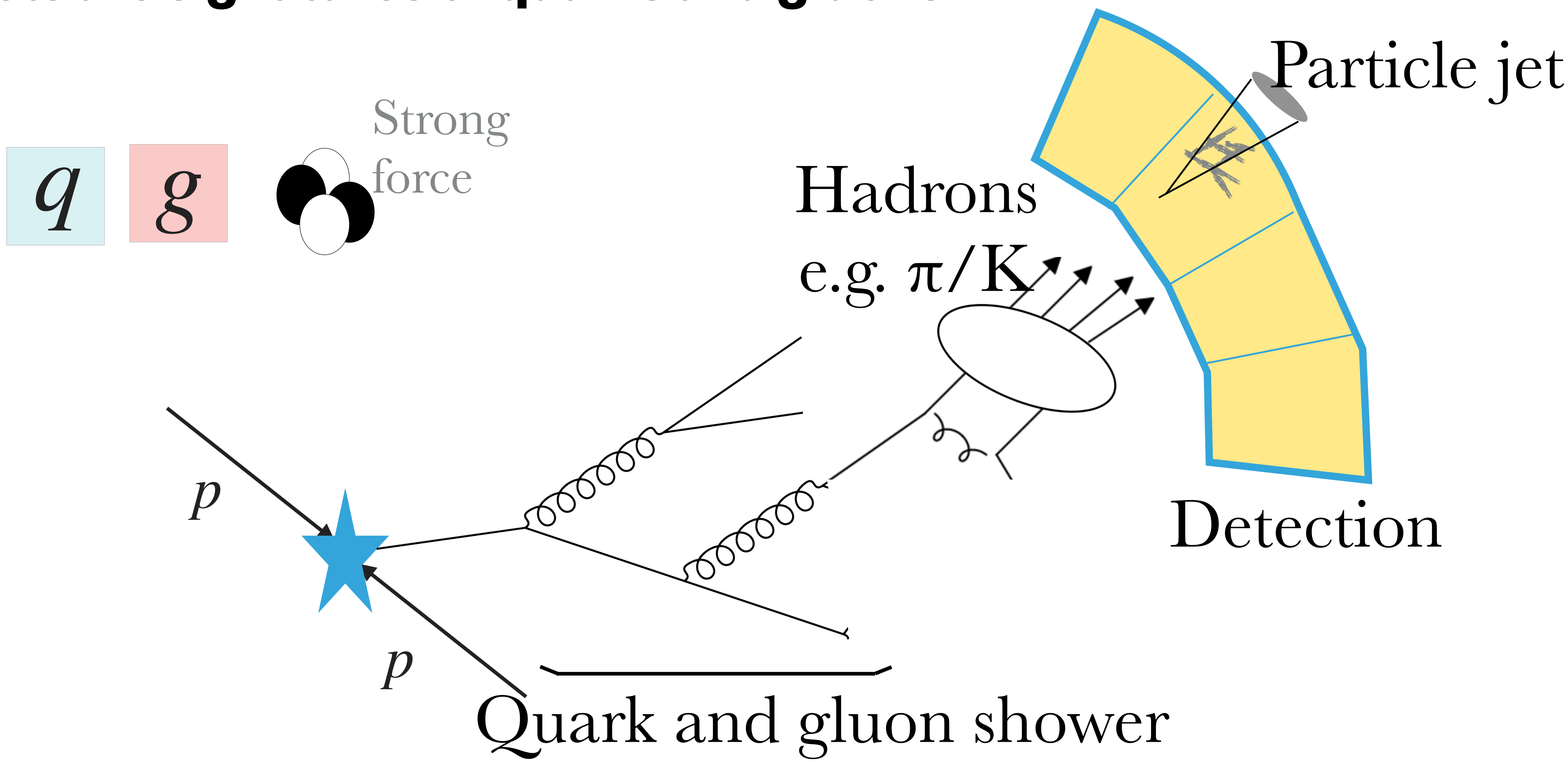


EVENT DISPLAYS!



What you know now:

Jets are signatures of quarks and gluons



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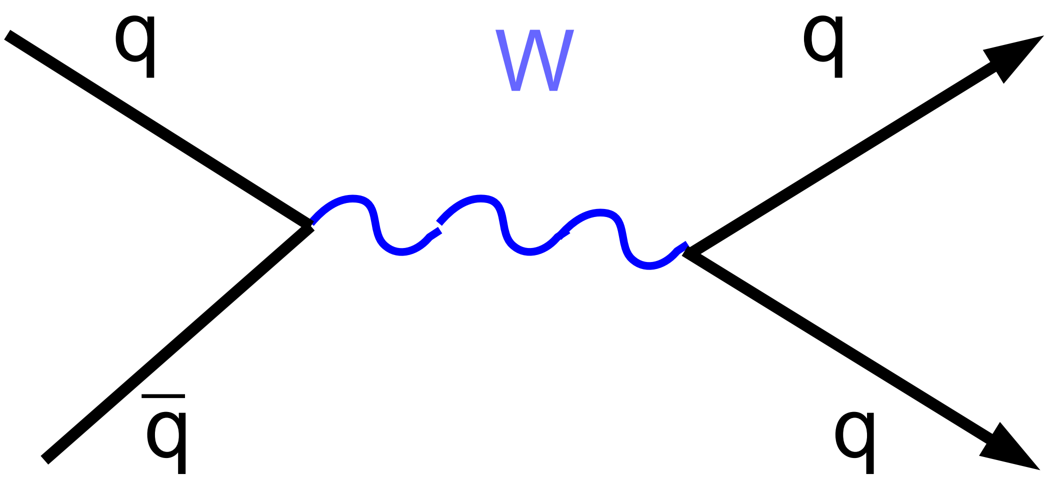
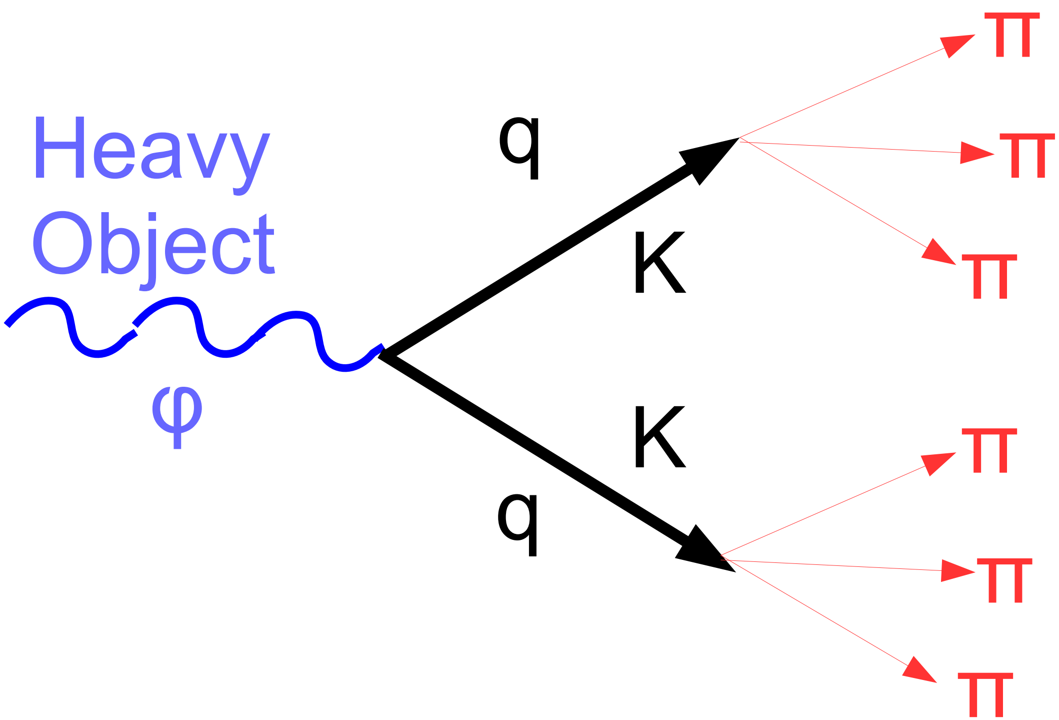
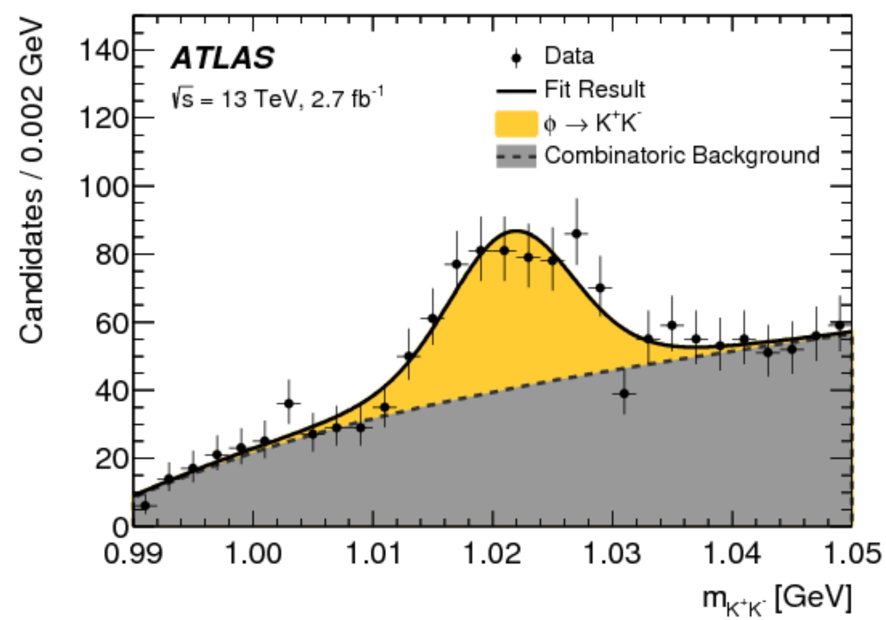


A W boson decaying to quarks

What is a hadronic resonance?

A Heavy Object that decays to quarks:



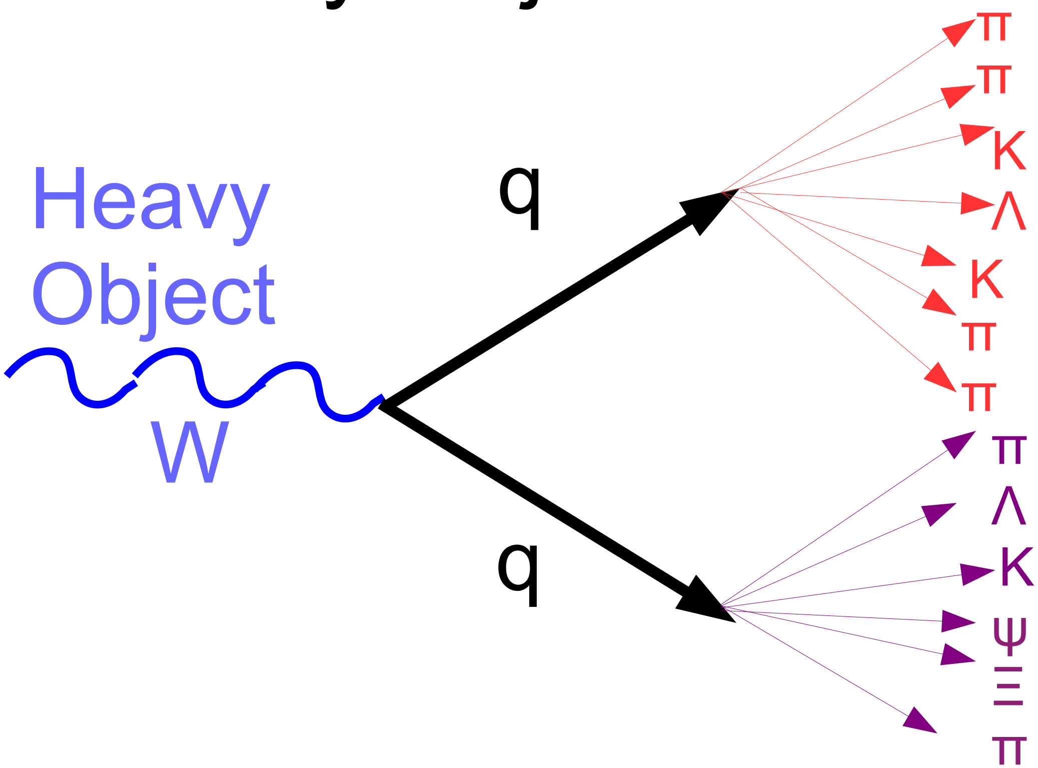


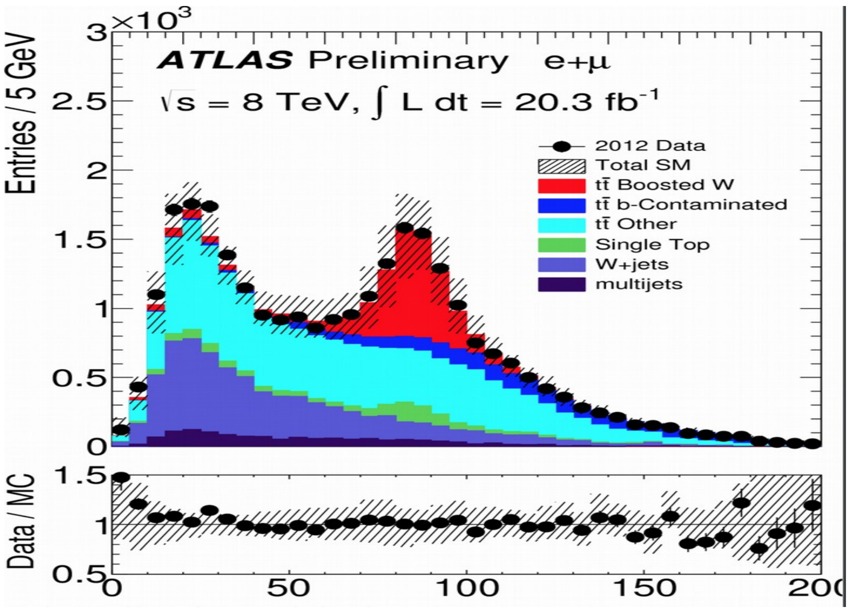
A simple example is a φ to Kaons

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 paricles

What makes this hard?

What is a hadronic resonance?

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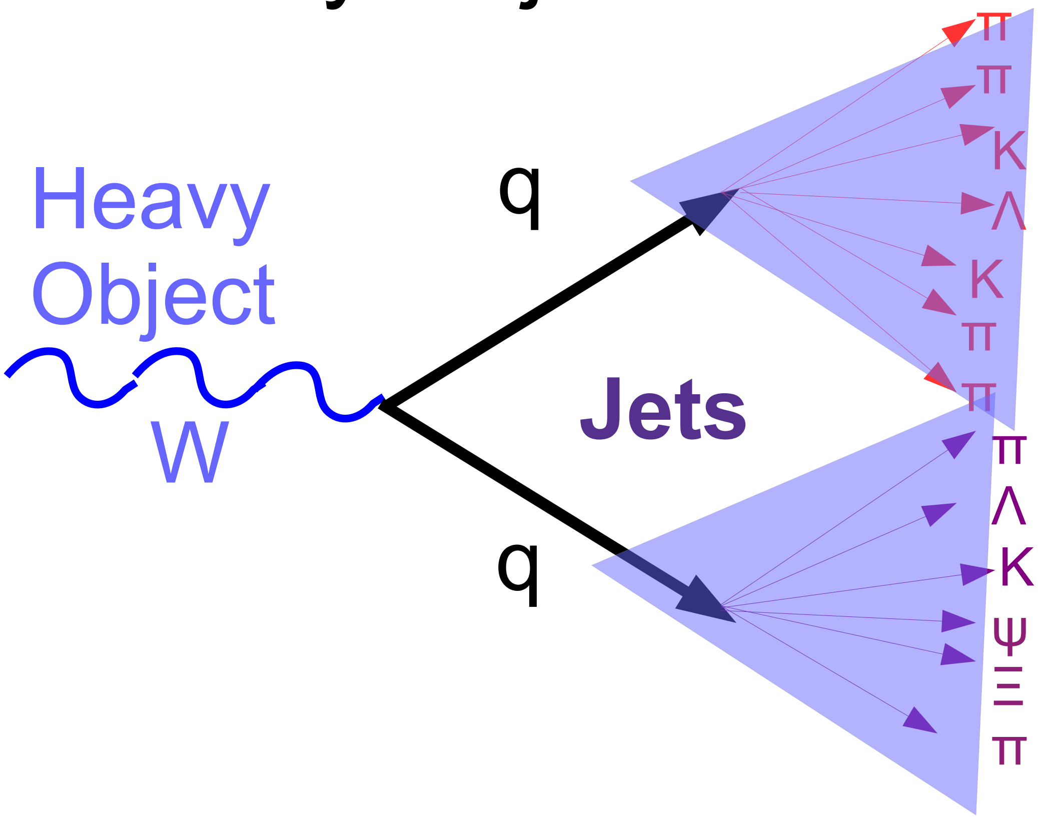

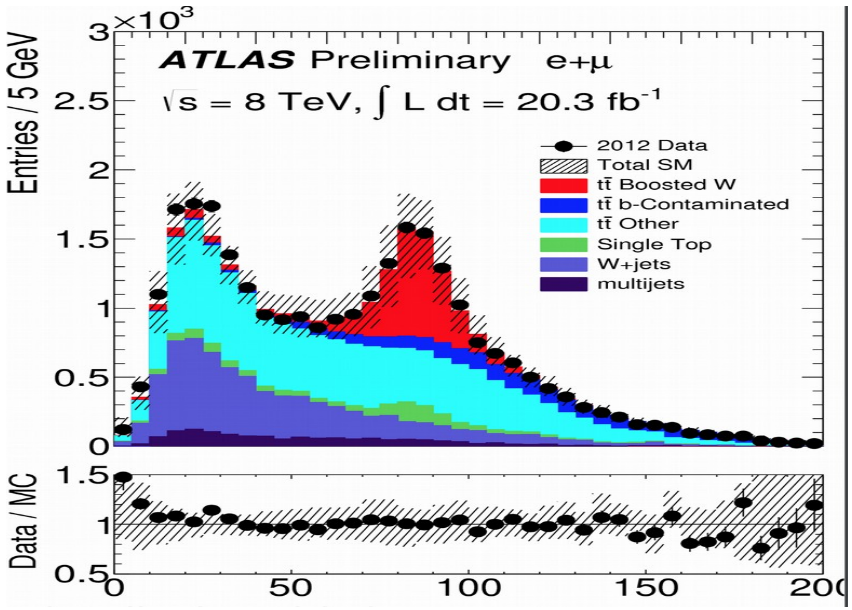

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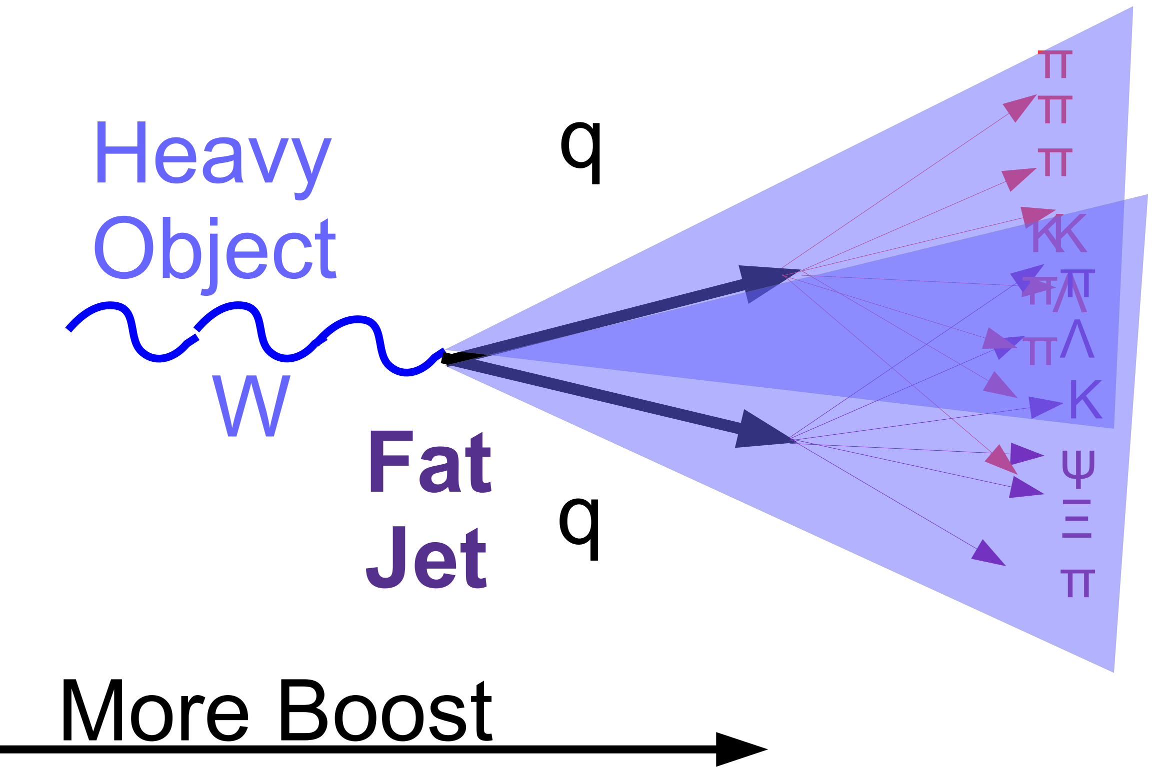

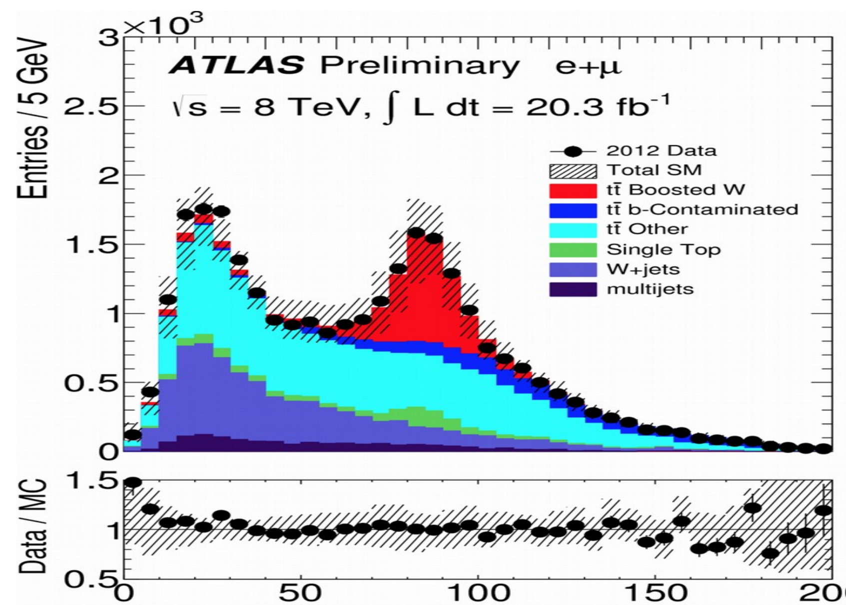

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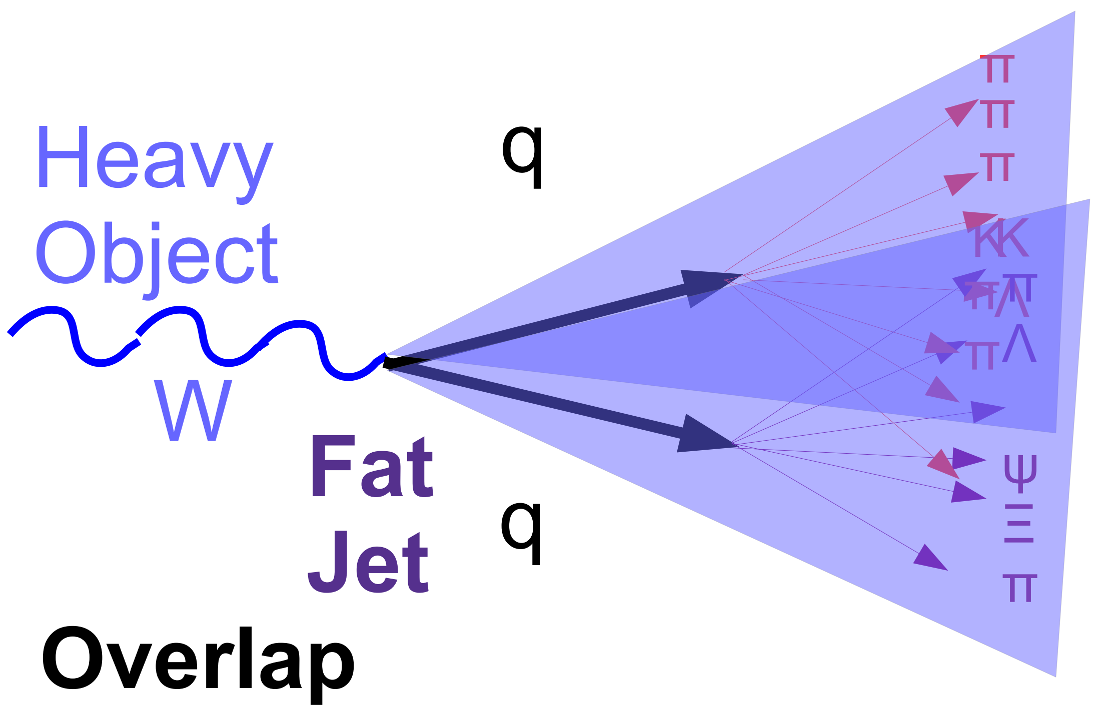
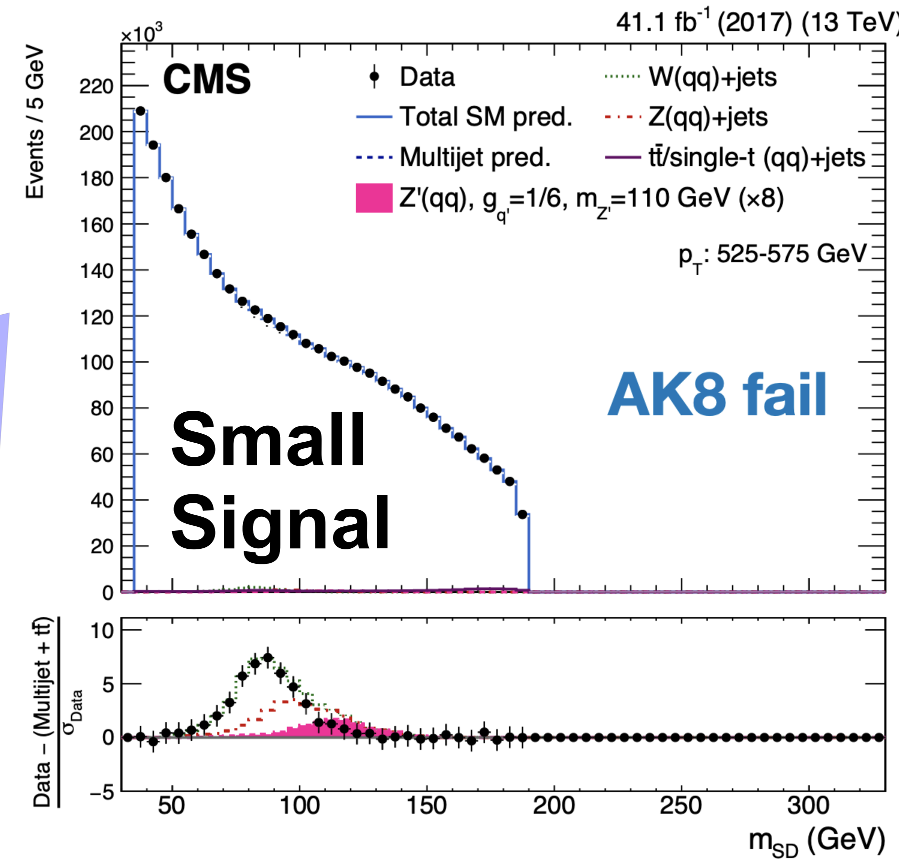
High energy quarks decay to a shower of paricles

What makes this hard?

What makes it Hard?

Two main things:

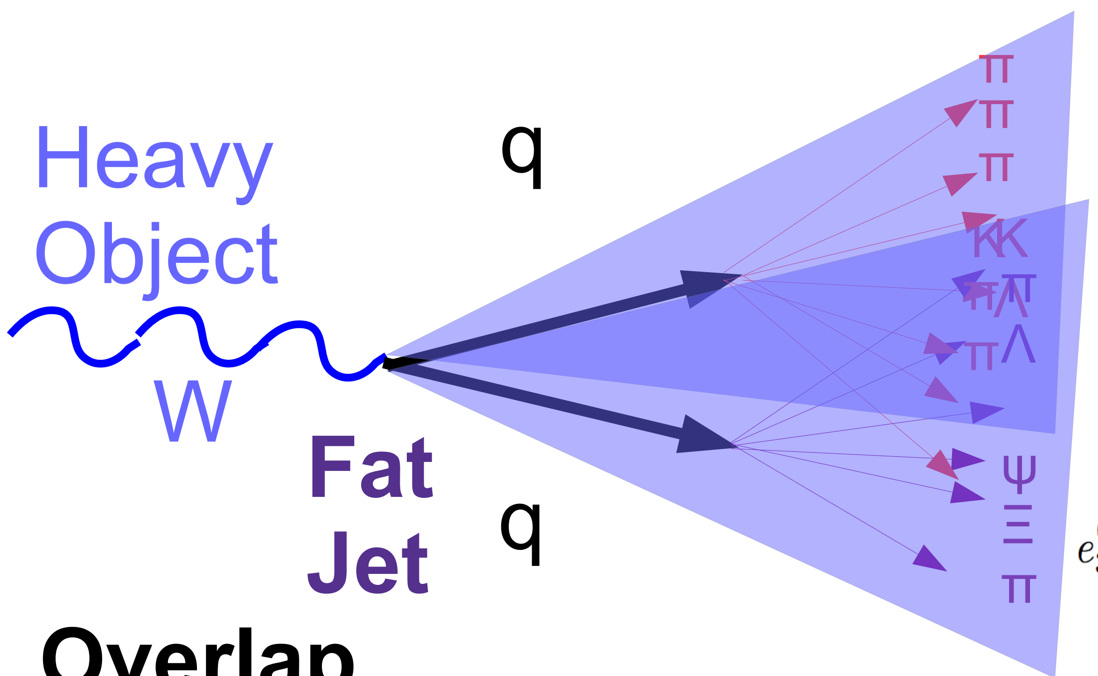


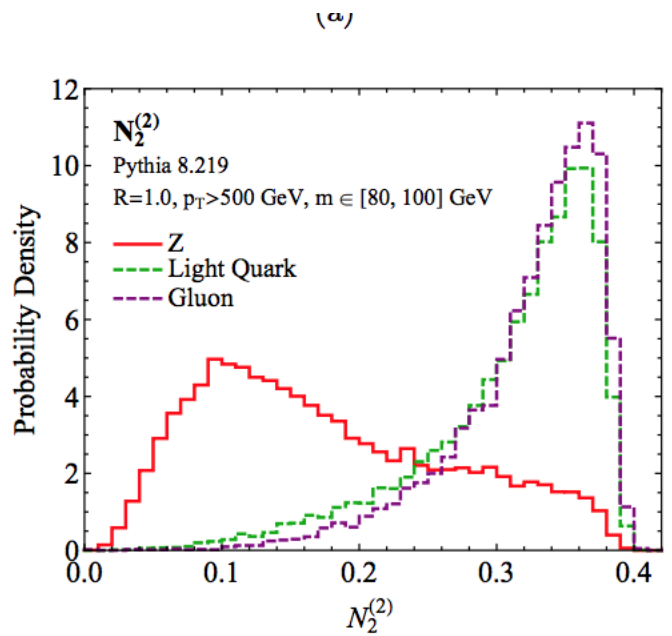


Trying to select Heavy Ws to quarks is hard
Need a way to remove the background

What makes it Hard?

Two main things:





$$e_3^{(\beta=2)} = \sum_{i<j<k\in \text{jet}} z_i z_j z_k \theta_{ij}^2 \theta_{ik}^2 \theta_{jk}^2 \approx \sum_{i<j} z_i z_j \theta_{ij}^2 \theta_i^2 \theta_j^2$$

$$\approx \sum_{i<j} z_i z_j \max(\theta_i^2, \theta_j^2) \theta_i^2 \theta_j^2 \approx \sum_{i<j} \rho_i \rho_j \max(\theta_i^2, \theta_j^2),$$

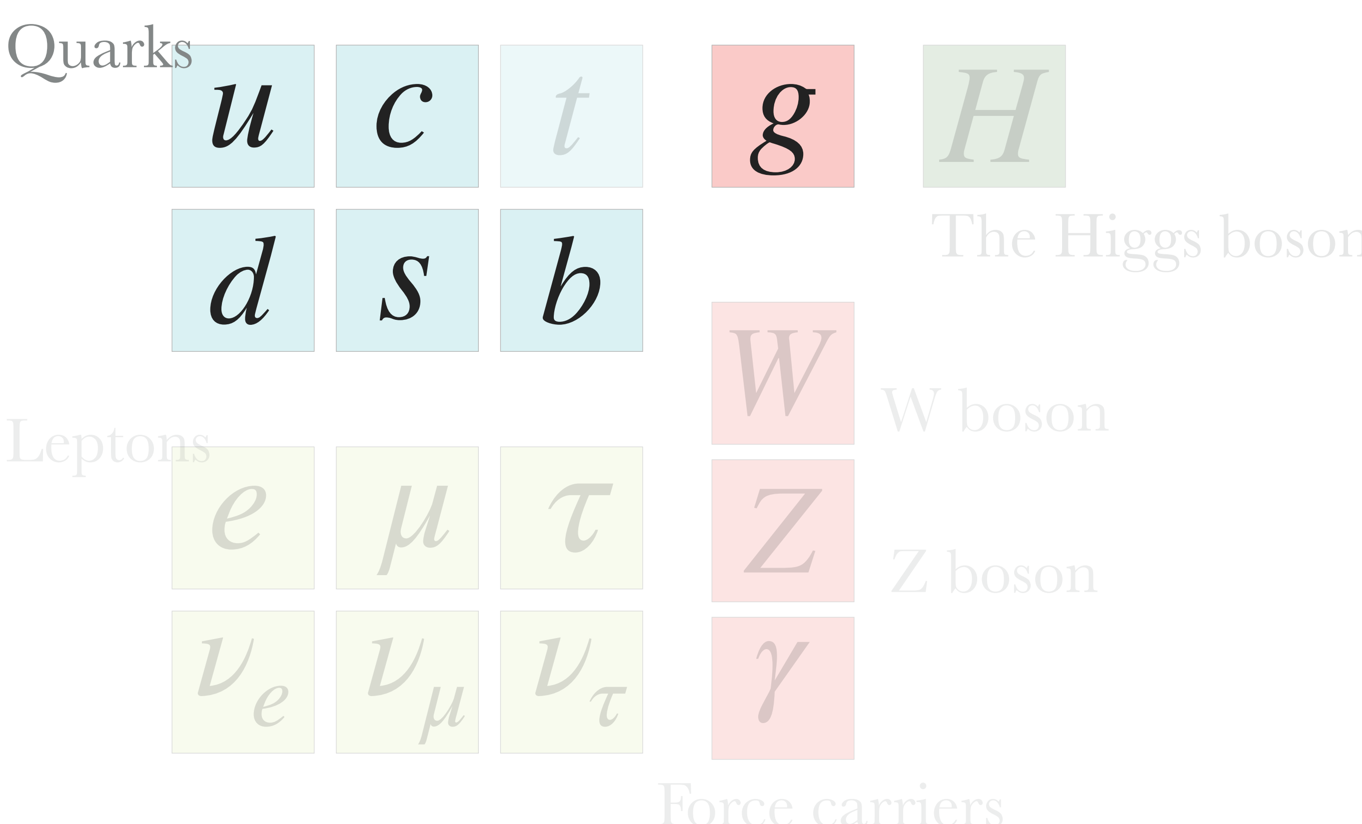
Overlap

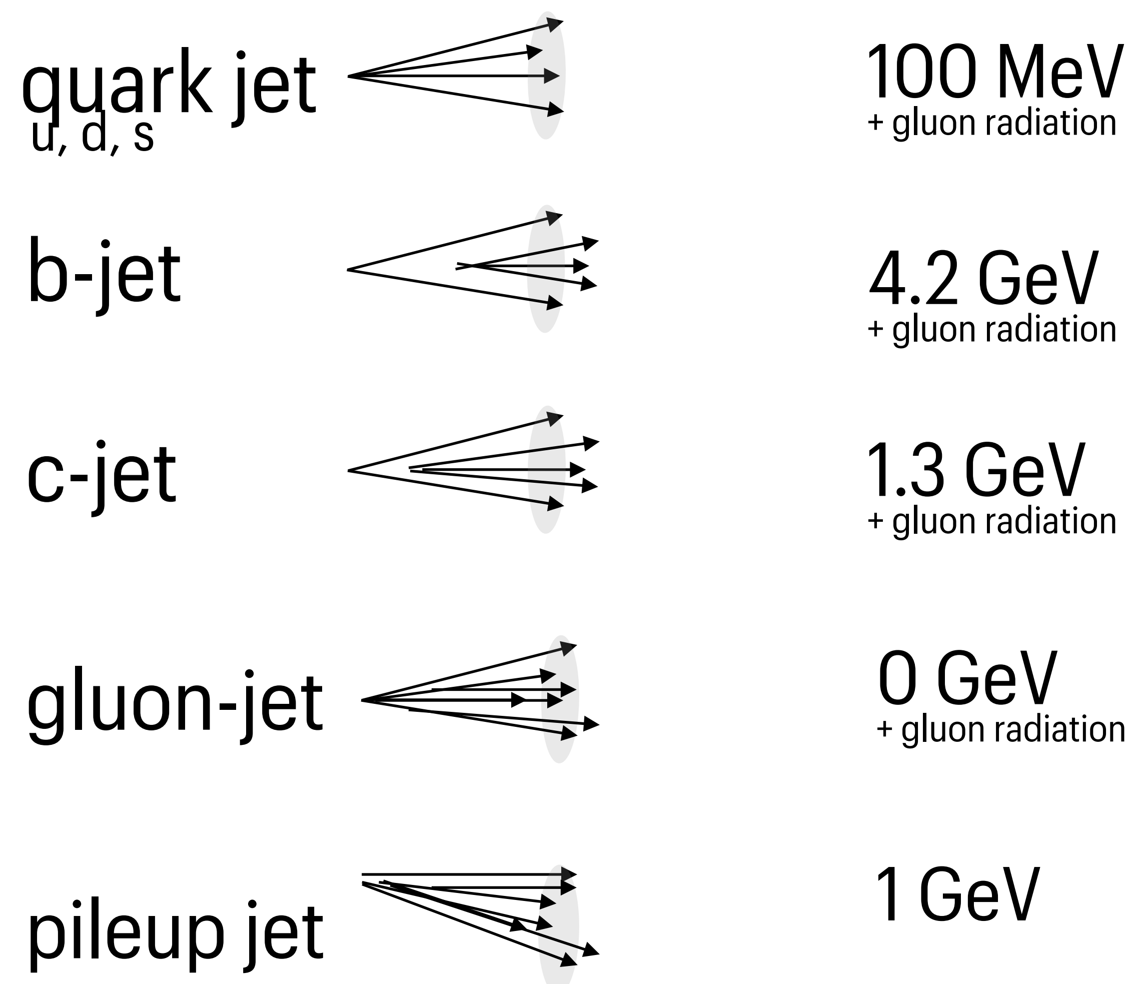
To resolve the overlap we resort to aggregate combinations of particles

From J. Thaler

What you know now:

Jets of the Standard Model





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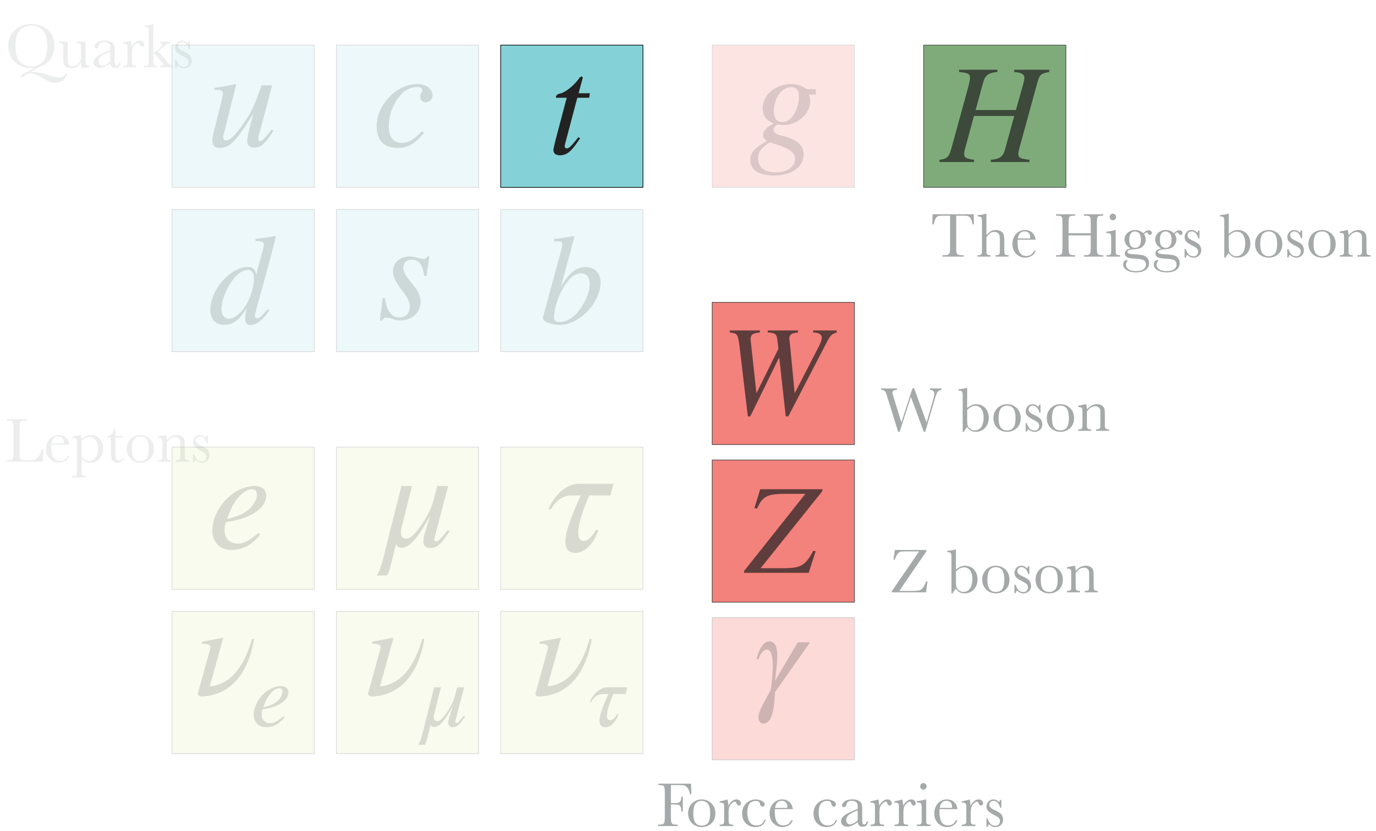
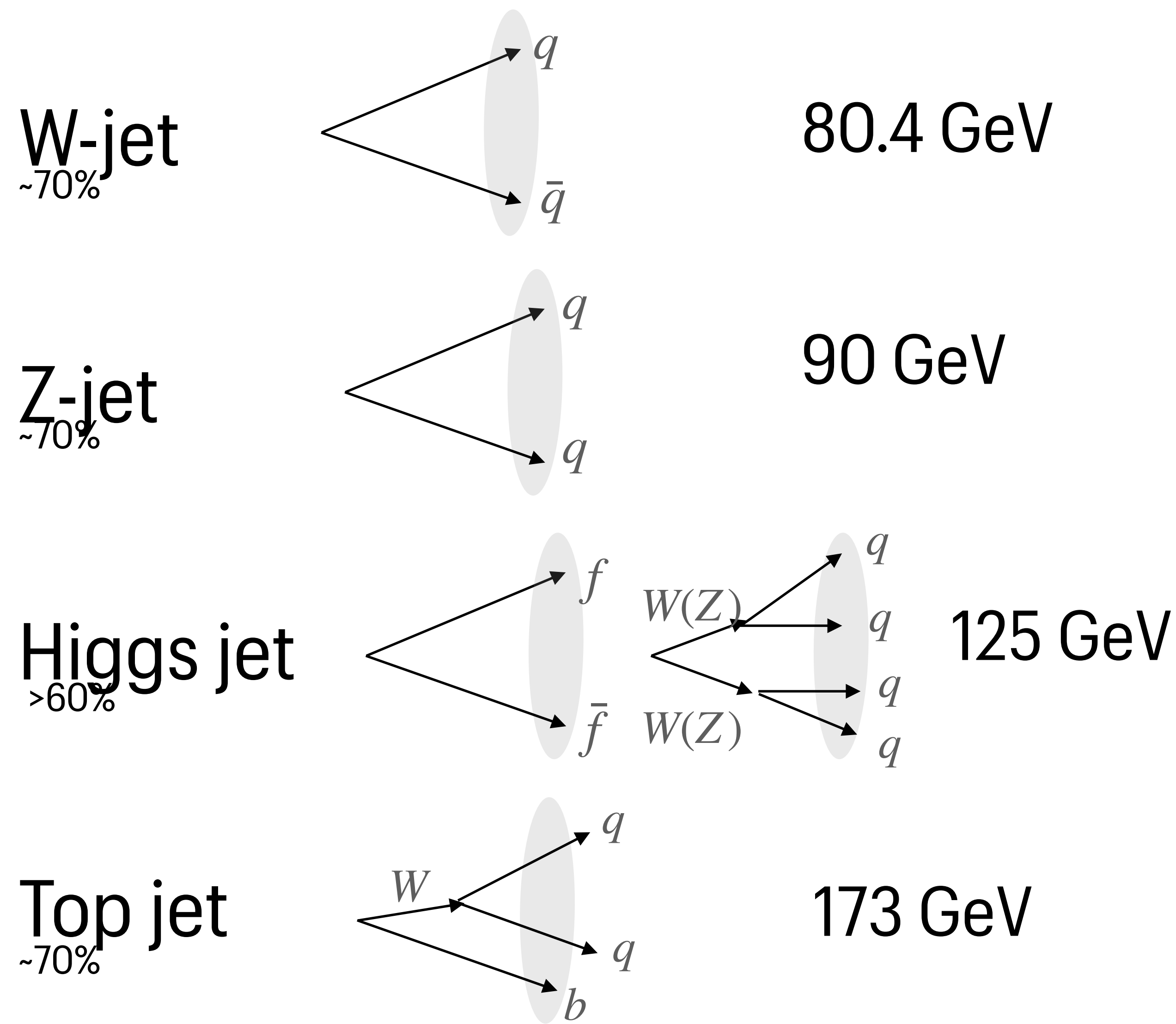
Jets of the Standard Model

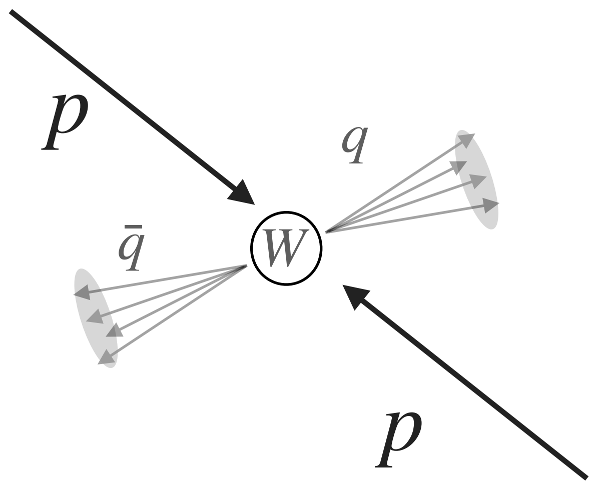


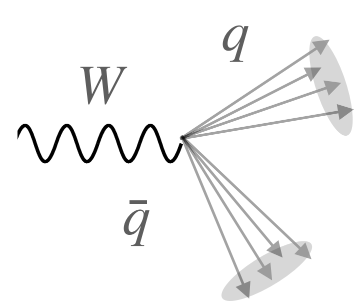


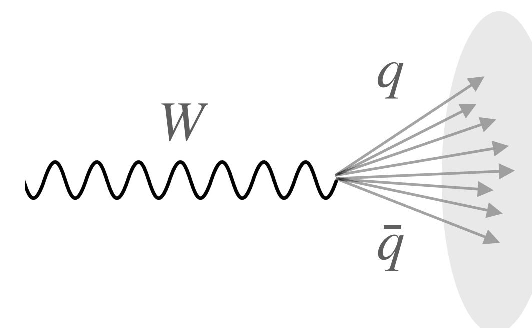
High boost

Let's consider a W-decay

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







At ~rest

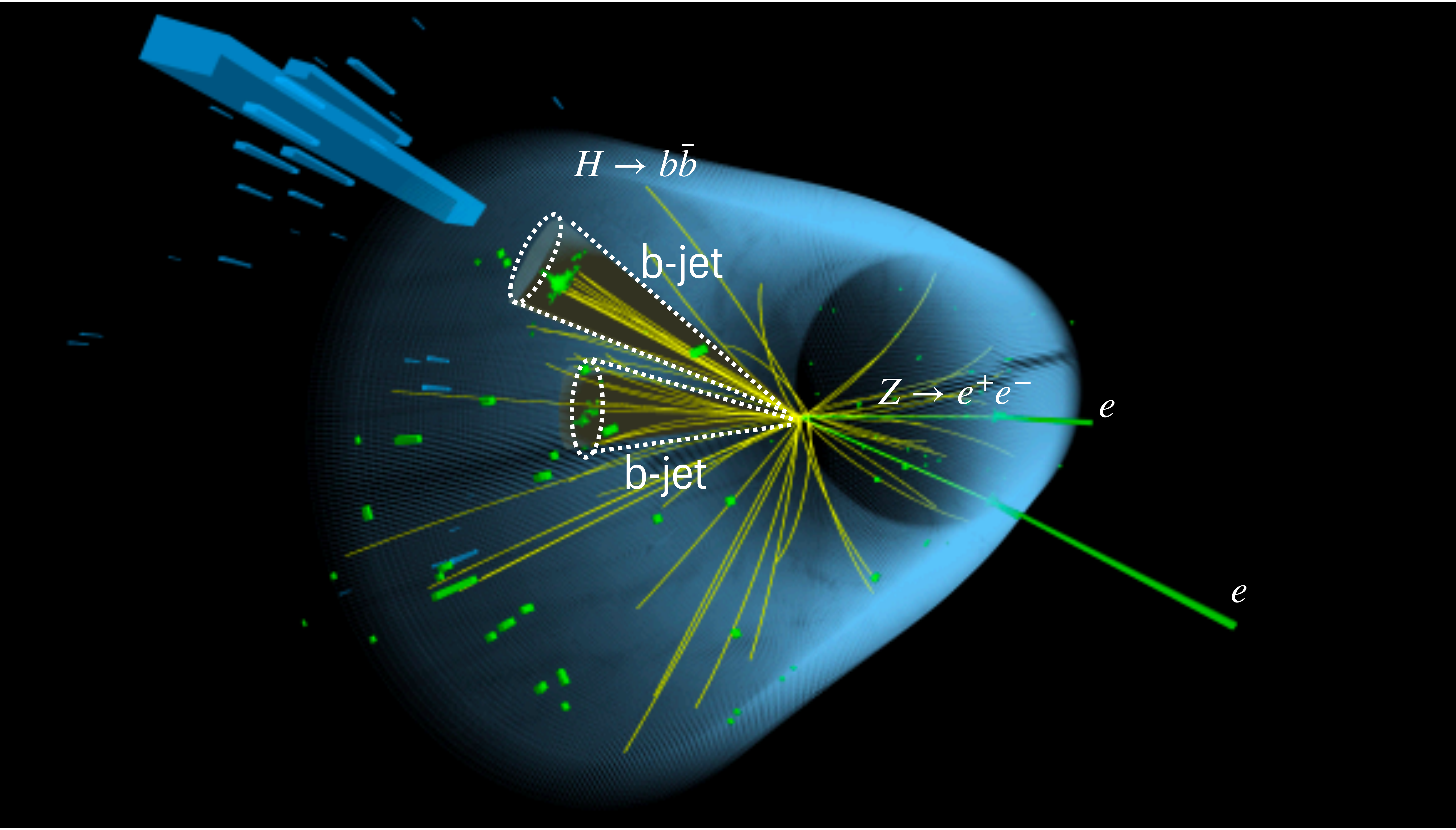
low W-momentum (p_T~100 GeV)

high boost (p_T>200 GeV)

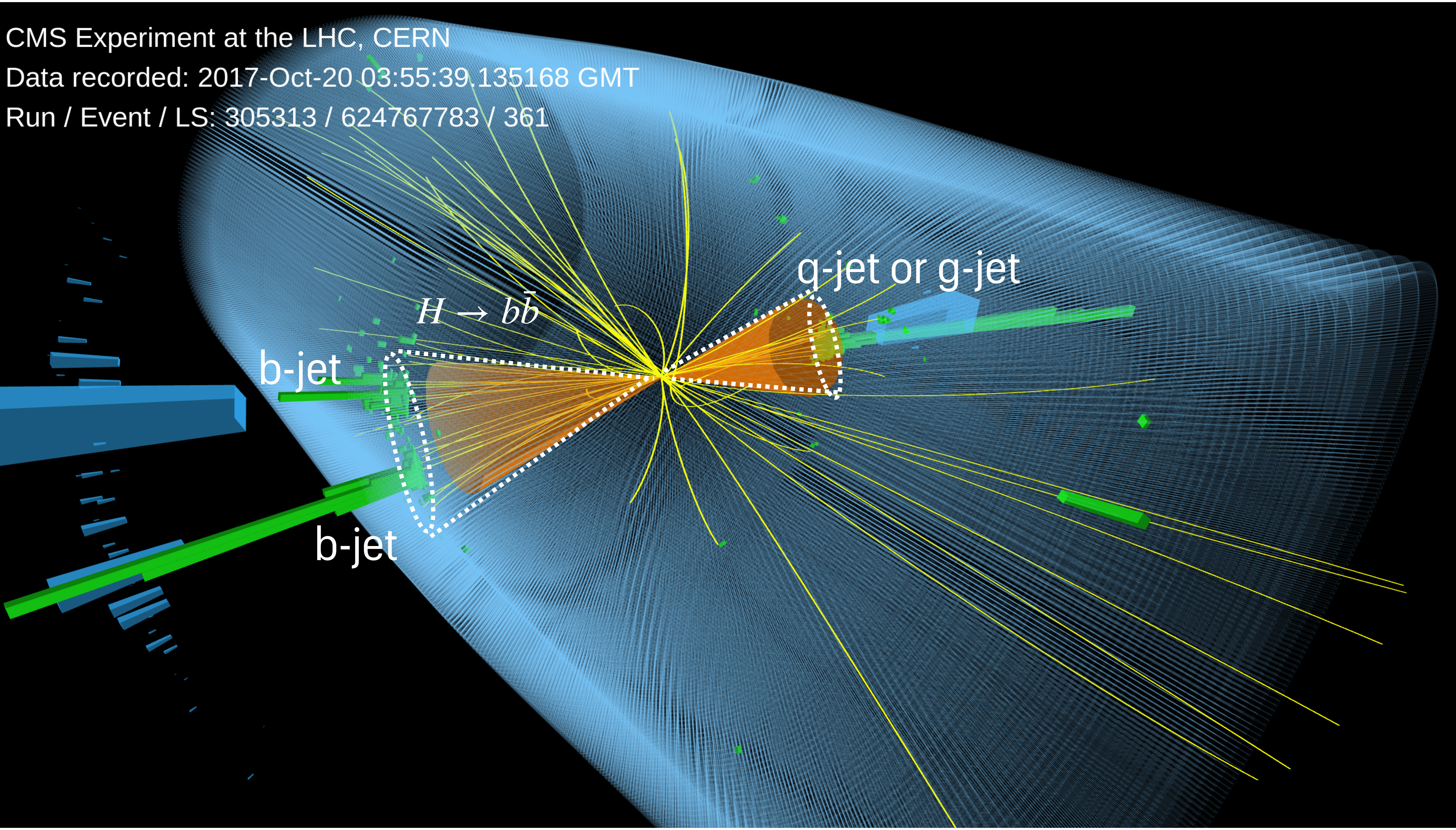
$\Delta R(q\bar{q}) \approx \pi$

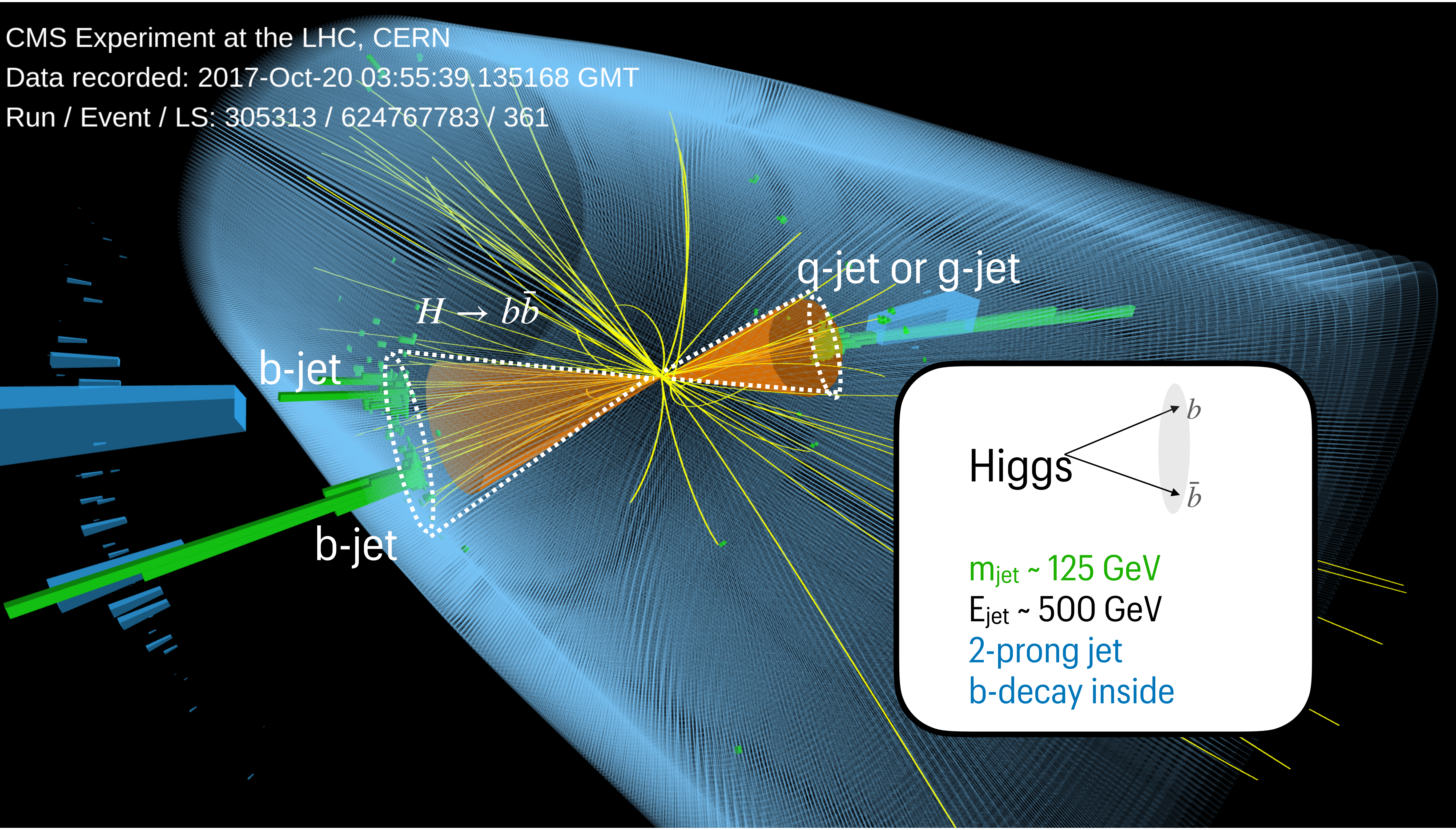
$\Delta R(q\bar{q}) \approx \pi/2$

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



$H \to b\bar{b}$
b-jet
b-jet
$Z \to e^+e^-$
e
e


CMS Experiment at the LHC, CERN
Data recorded: 2017-Oct-20 03:55:39.135168 GMT
Run / Event / LS: 305313 / 624767783 / 361
q-jet or g-jet
$H \to b\bar{b}$
b-jet
b-jet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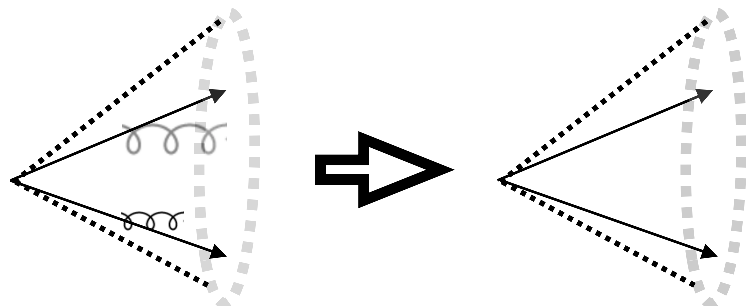
q-jet or g-jet
$H \to b\bar{b}$
b-jet
b-jet
Higgs
b
$\bar{b}$
m_{jet} ~ 125 GeV
E_{jet} ~ 500 GeV
2-prong jet
b-decay inside

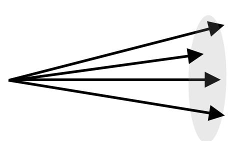
Jet substructure

Resolving emissions within the jet

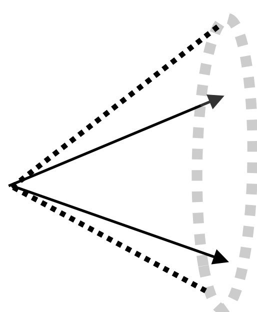
Jet grooming

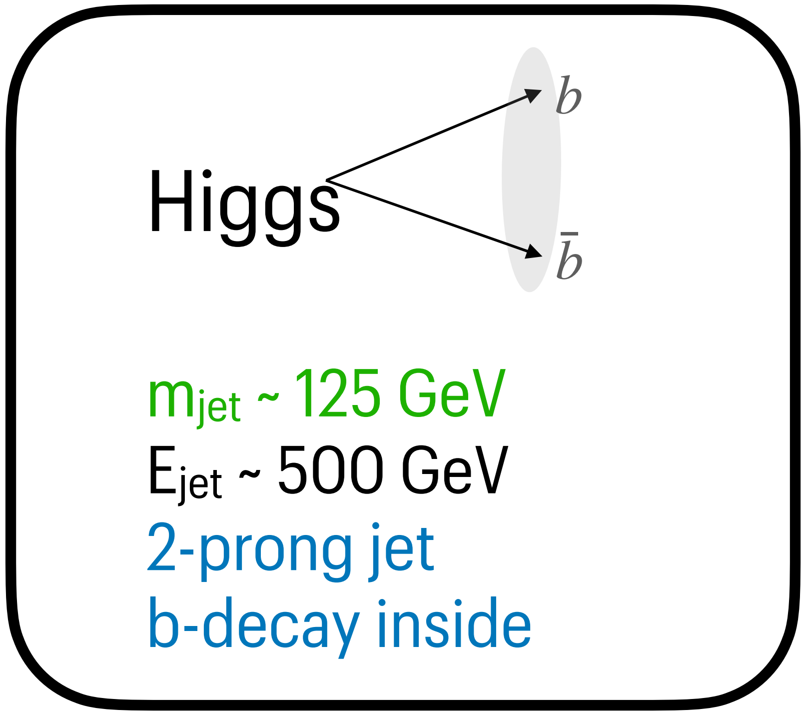


Jet tagging



vs.

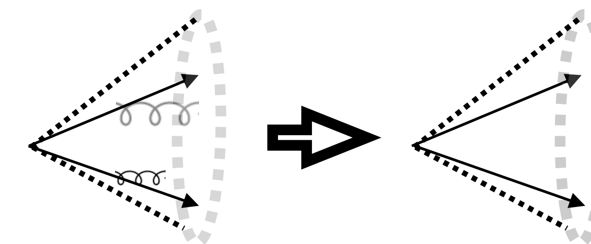




Jet grooming

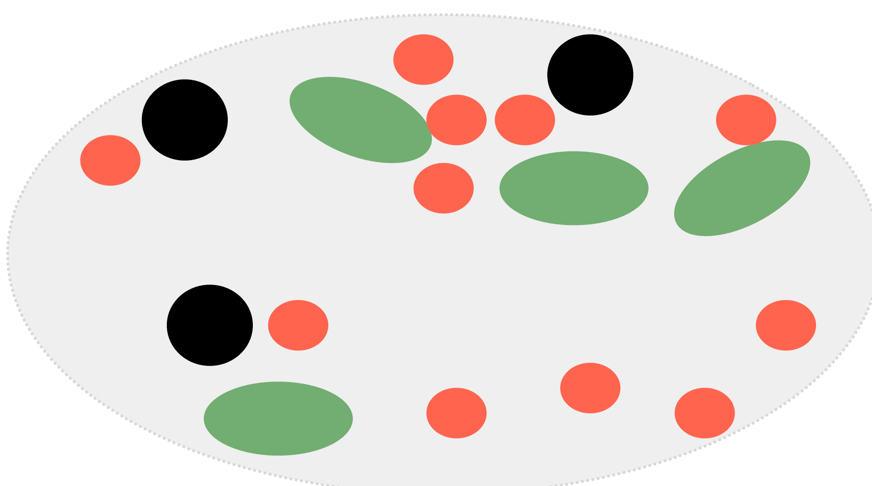
Removing a jet’s soft and wide-angle radiation

Grooming declustering

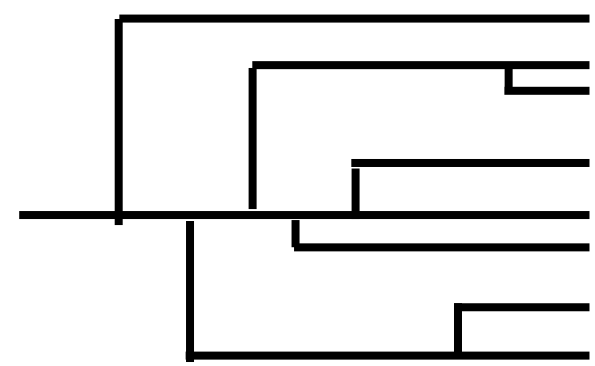


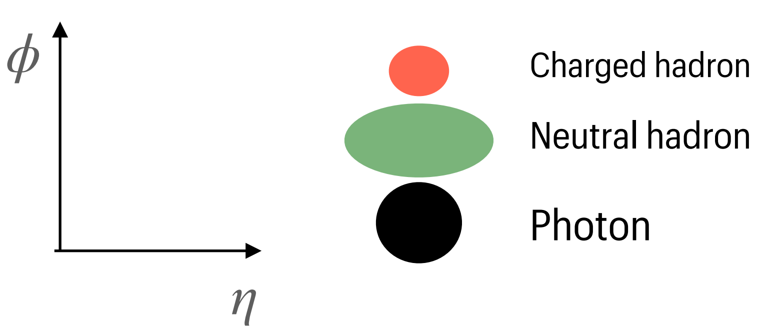
Original jet

In a clustering tree

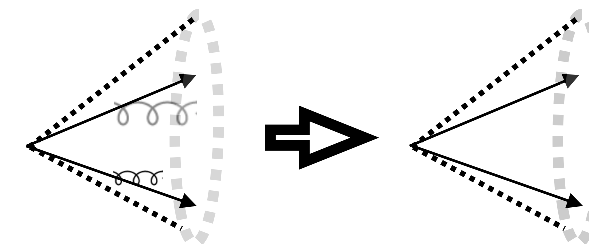


=



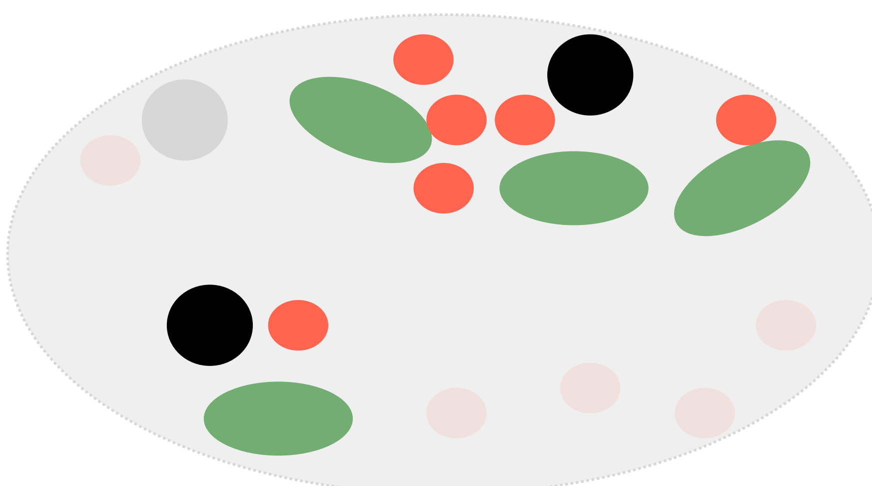


Grooming declustering



Groomed jet

Groomed clustering tree



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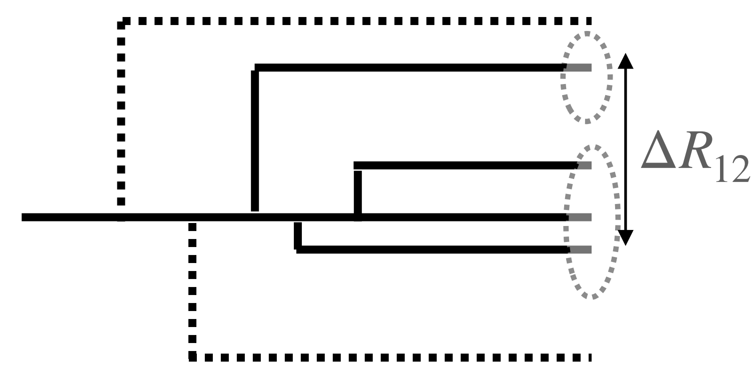
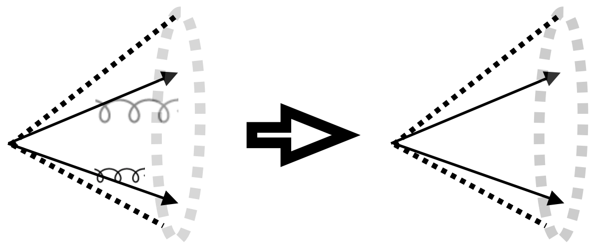
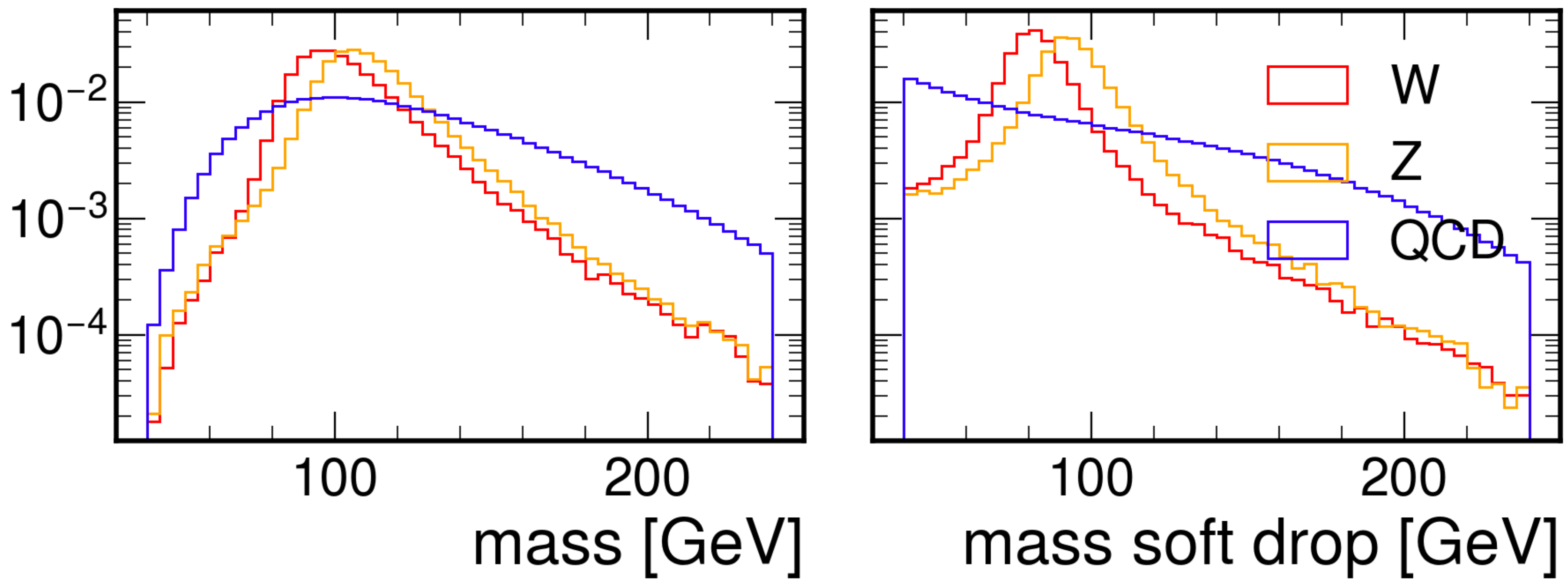


- Grooming algorithms iteratively decluster a jet
- The soft-drop algorithm removes lowest p_T sub-jets failing pairwise condition

$$z > z_{cut} \left(\frac{\Delta R_{12}}{R}\right)^{\beta} \quad \text{with} \quad z = \frac{\min(p_T^1, p_T^2)}{p_T^1 + p_T^2}$$

Calculating groomed mass



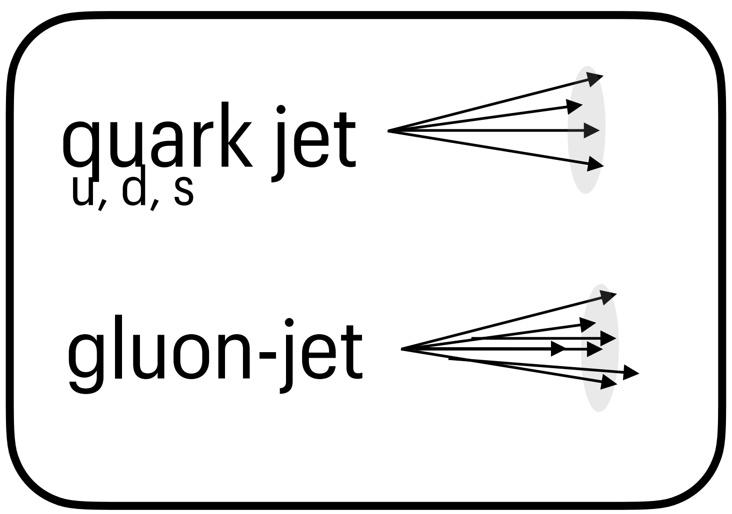


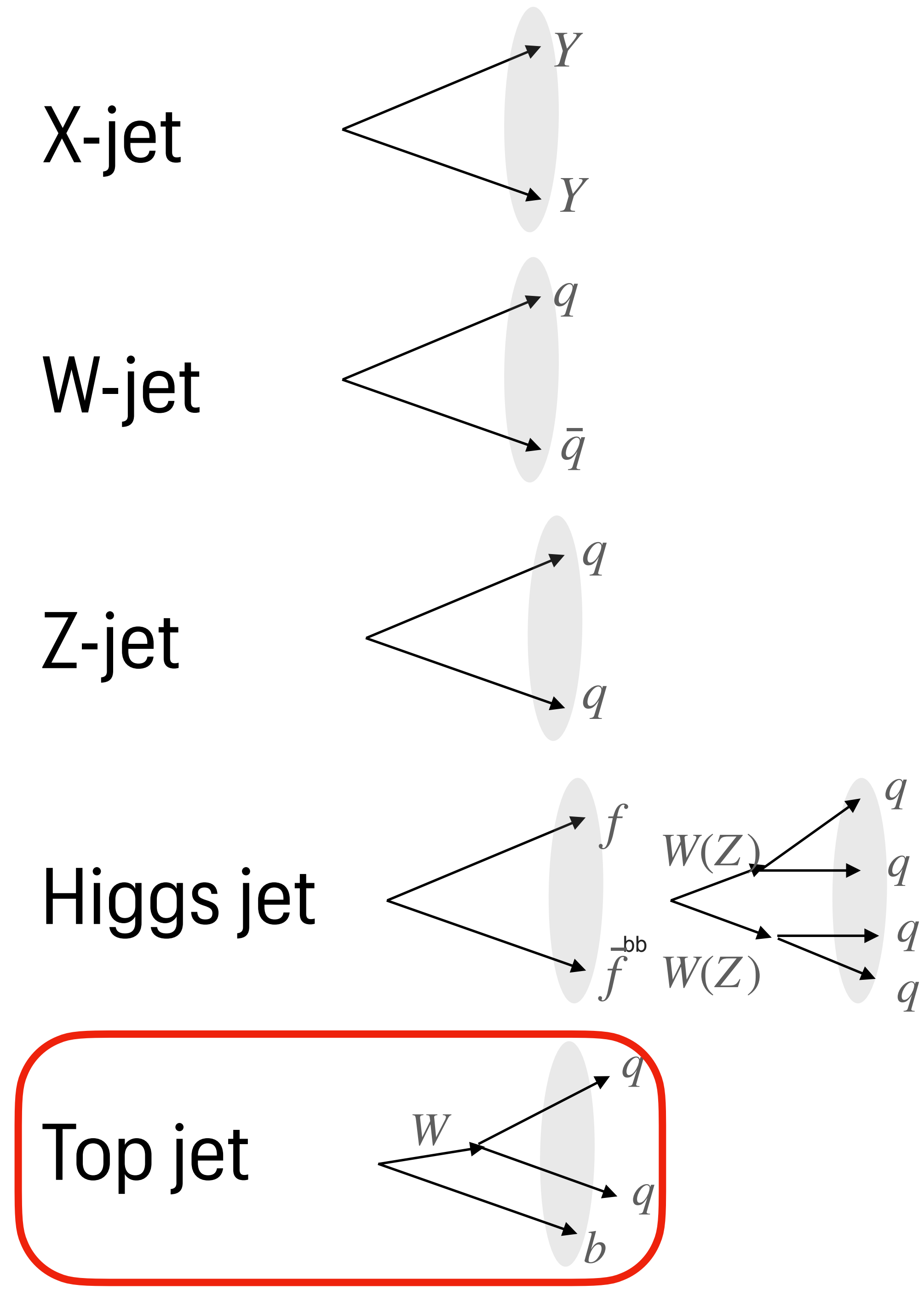
- Improves the mass *resolution* of a jet (removes away excess radiation)
- Brings the mass of background jets (QCD) to low mass

Jet tagging

Characterizing a jet's internal decay

Signatures:


quark jet
u, d, s
gluon-jet


X-jet
Y
Y
W-jet
q
q̄
Z-jet
q
q
Higgs jet
f
bb
f̄
W(Z)
W(Z)
q
q
q
q
Top jet
W
q
q
b

N-subjetiness

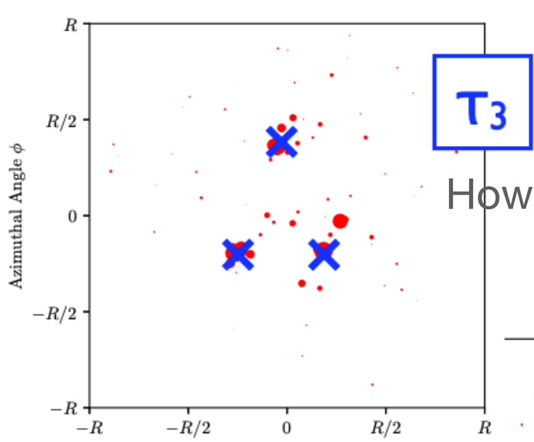
Counting the number of “prongs” for almost a decade

Energy weight

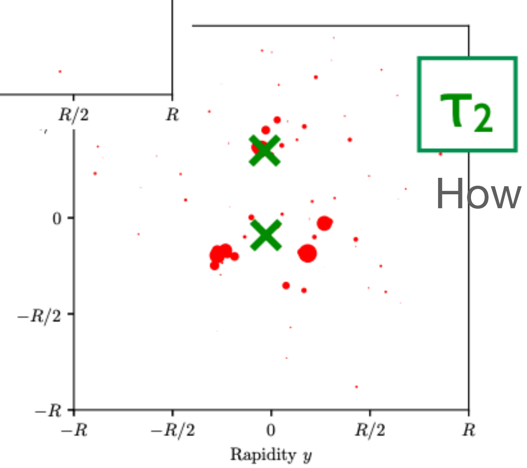
$$\tau_N(\mathcal{J}) = \min_{N\text{ axes}} \sum_i E_i \min\left\{\theta_{1,i}, \theta_{2,i}, \ldots, \theta_{N,i}\right\}$$

Angular weight w. respect to one axis

Sum over all particles



How likely to be consistent w. 3 axes?

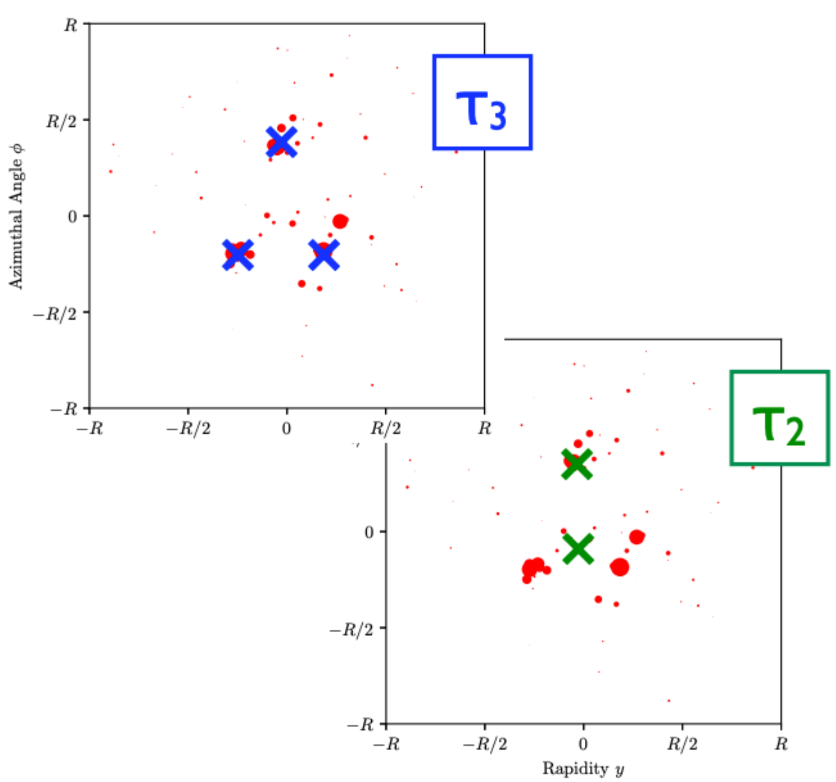


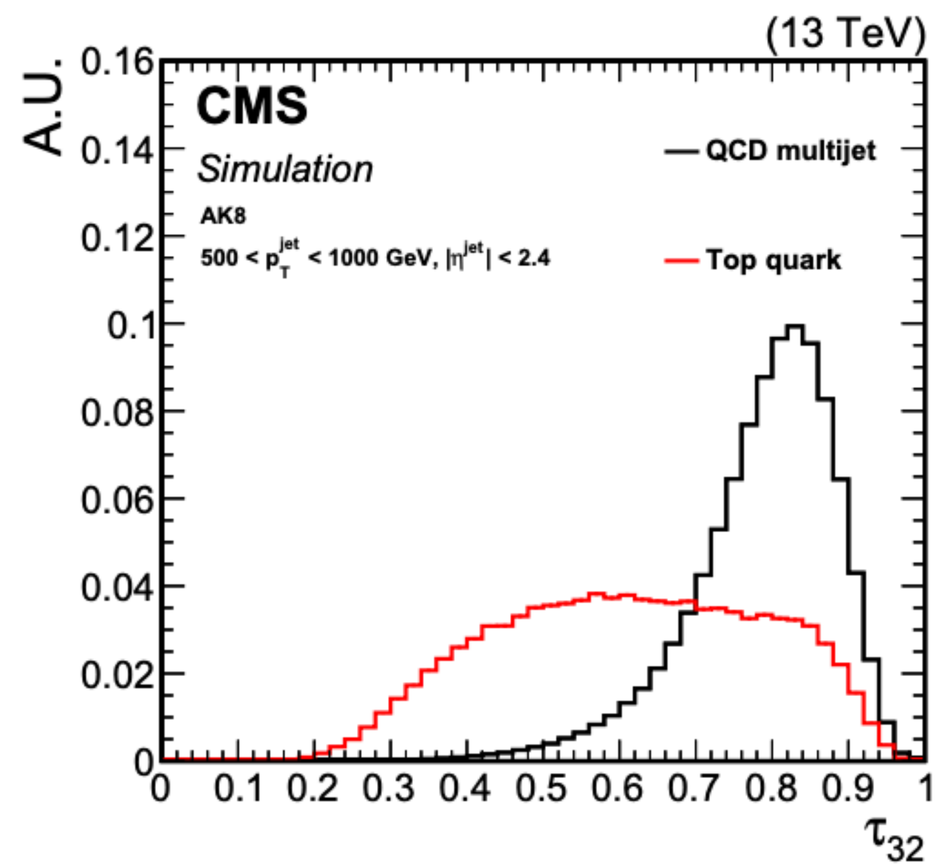
How likely to be consistent w. 2 axes?

N-subjetiness

Counting the number of "prongs" for almost a decade

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





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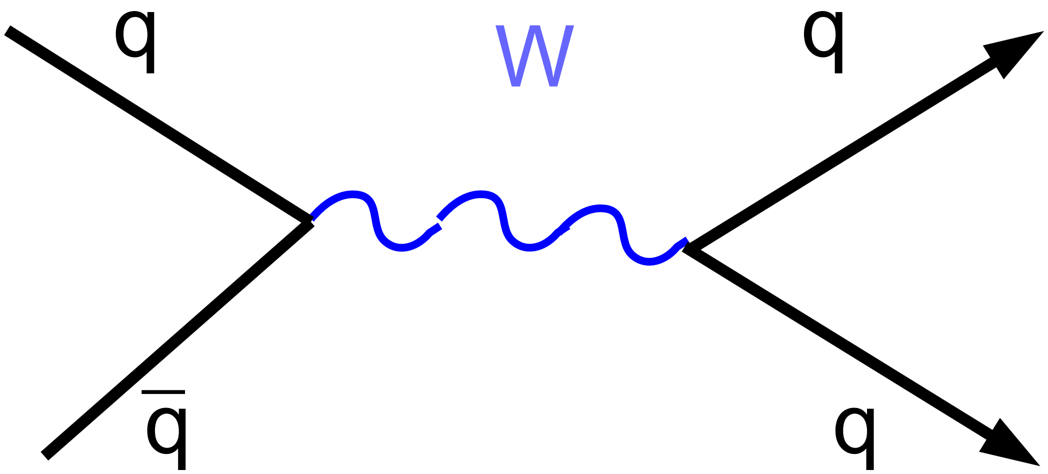
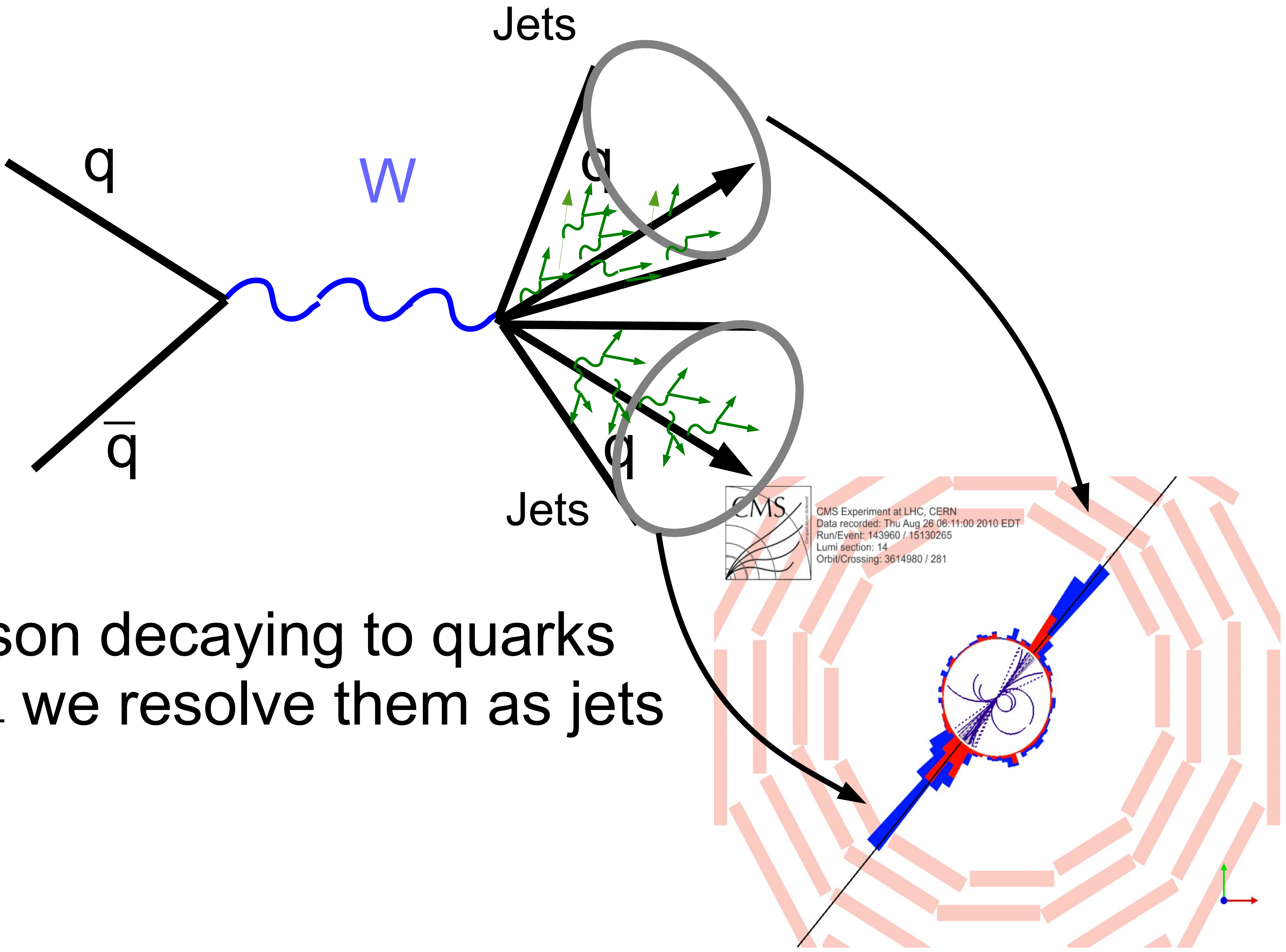


A W boson decaying to quarks

In an experiment

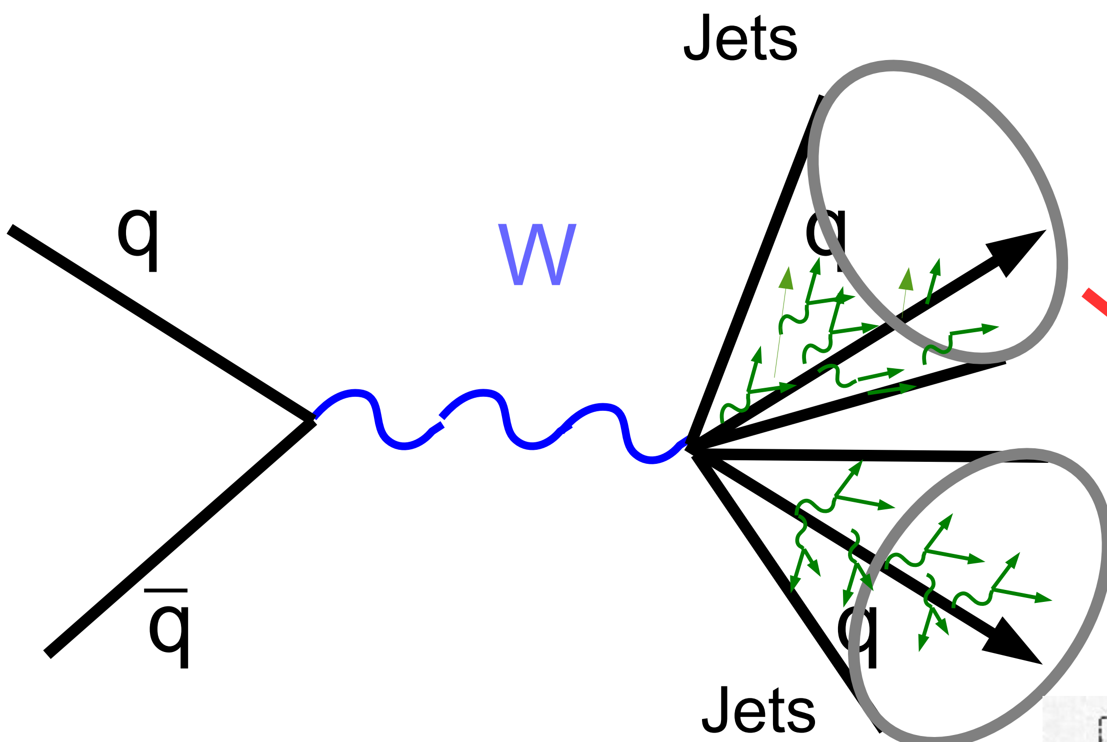
Find:



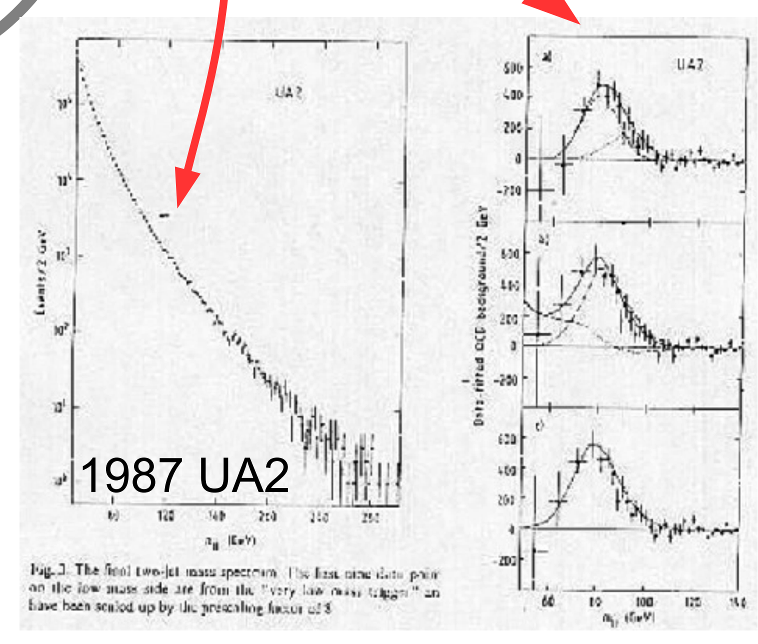
A W boson decaying to quarks
A low p_T we resolve them as jets

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

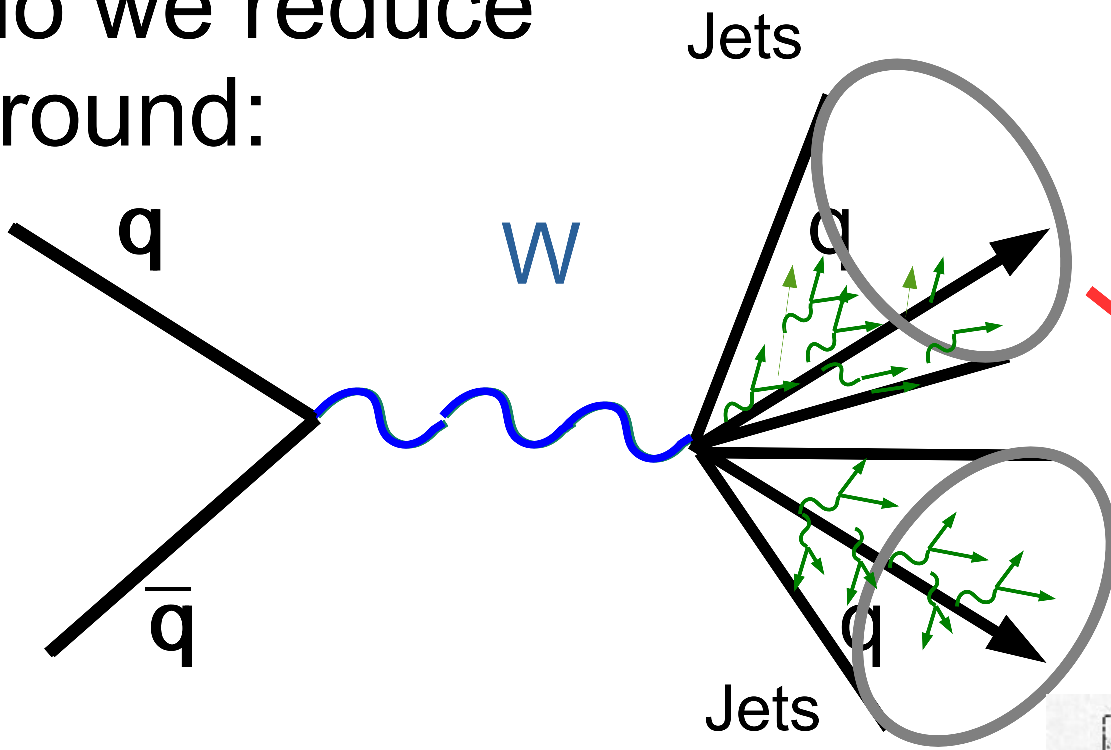
Was last observed 30 years

Result was not very convincing

Have not seen this since

1988

How do we reduce background:



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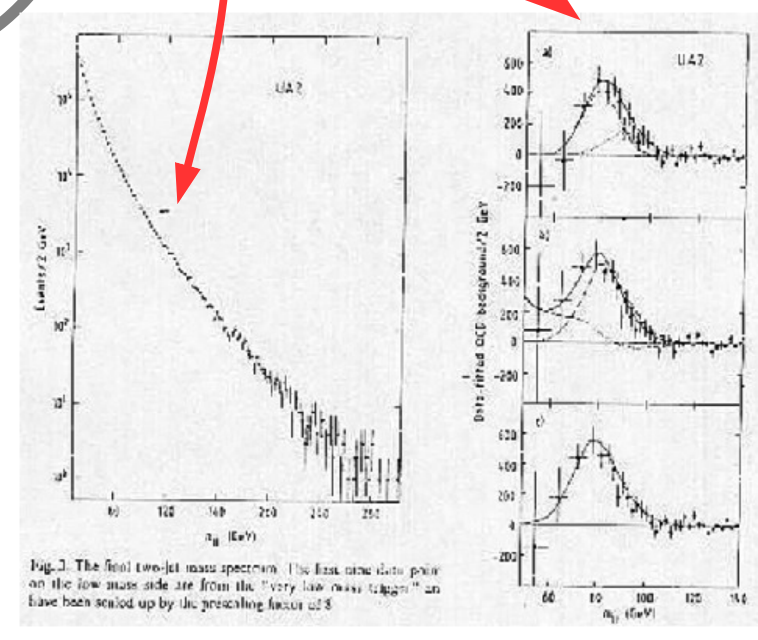
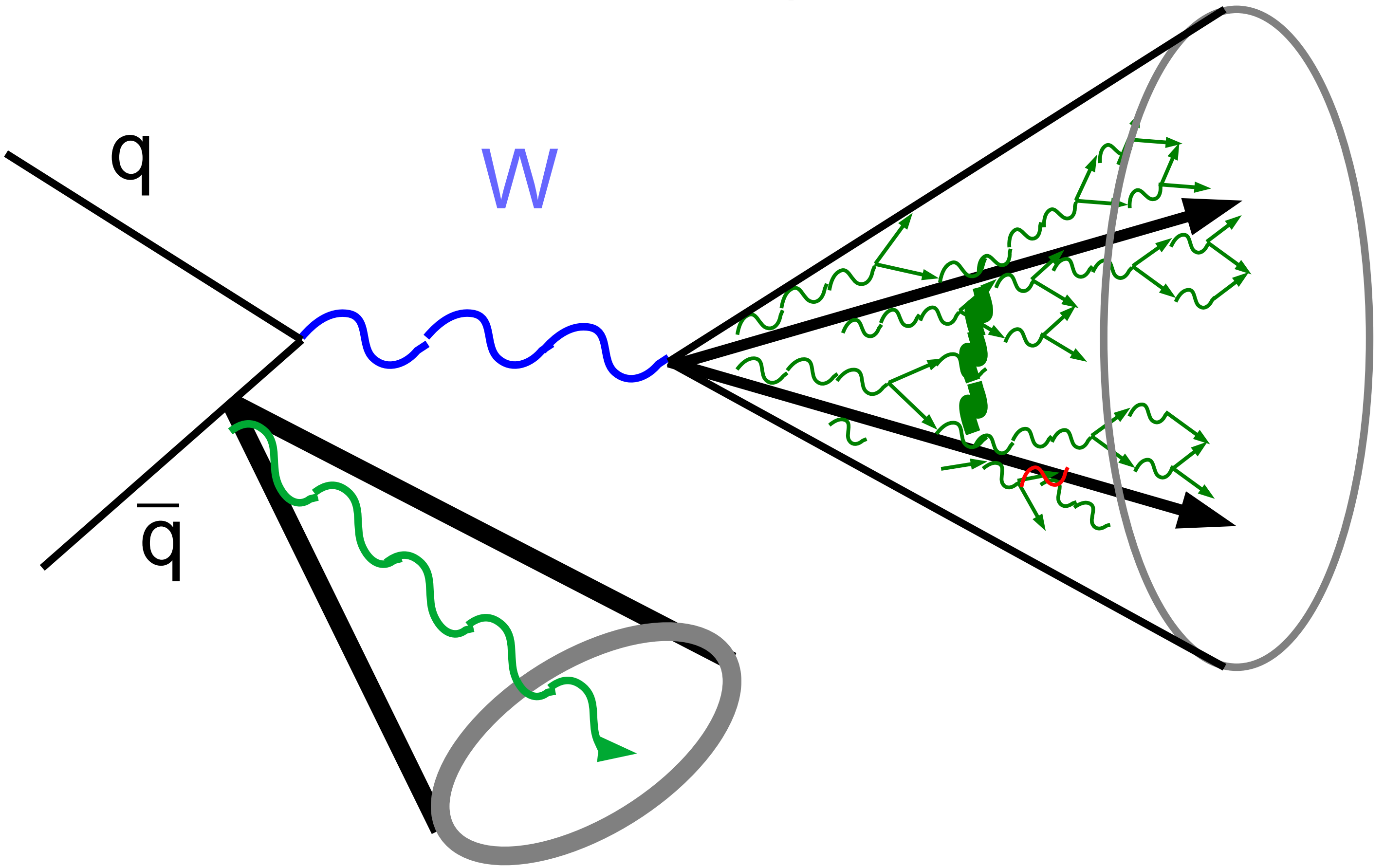


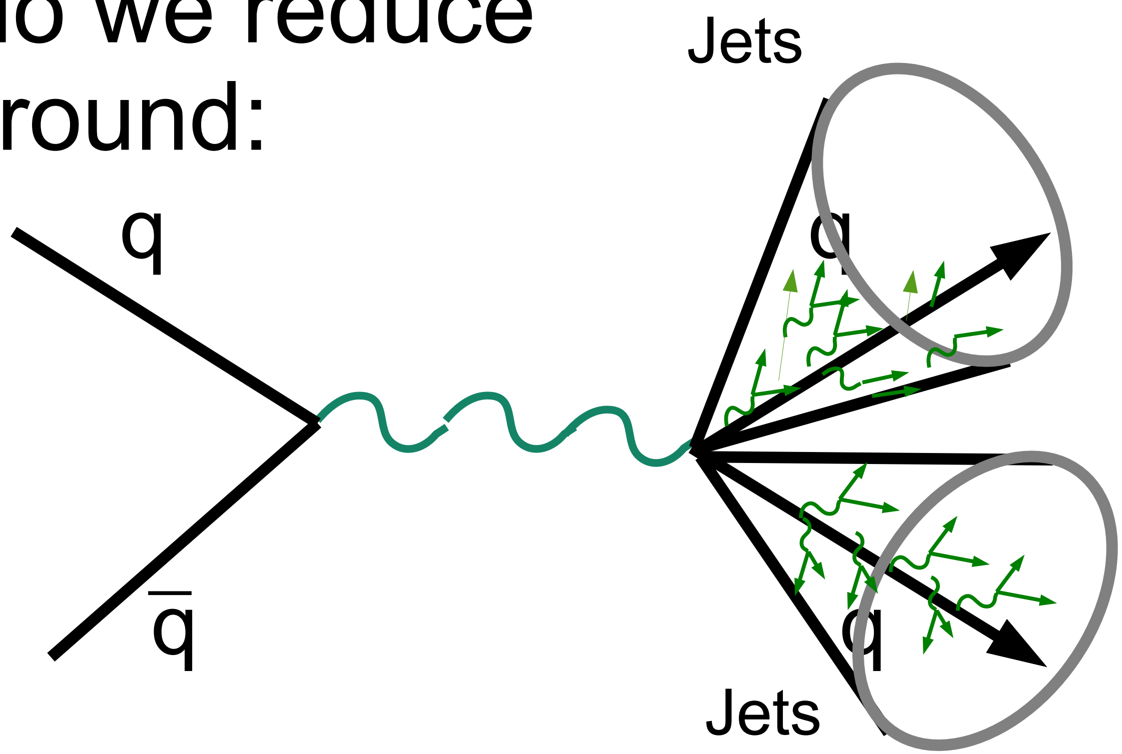
Whats the first goal?

Require W to be a high p_T



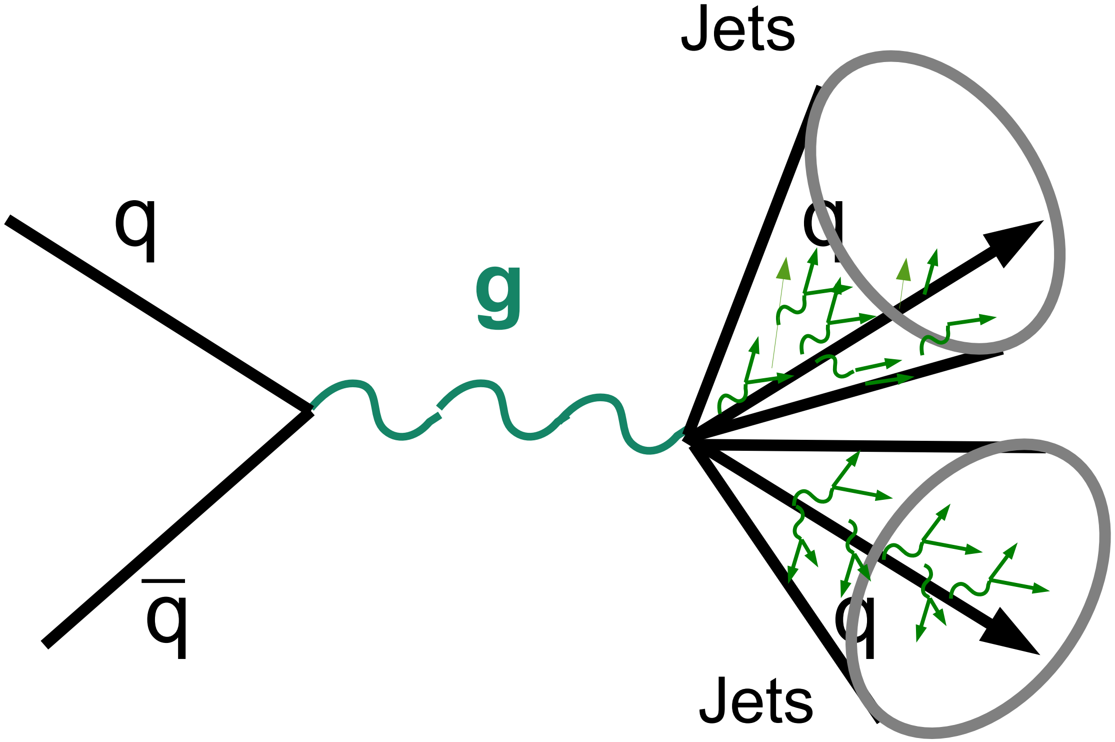
Isolating the W

How do we reduce background:



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

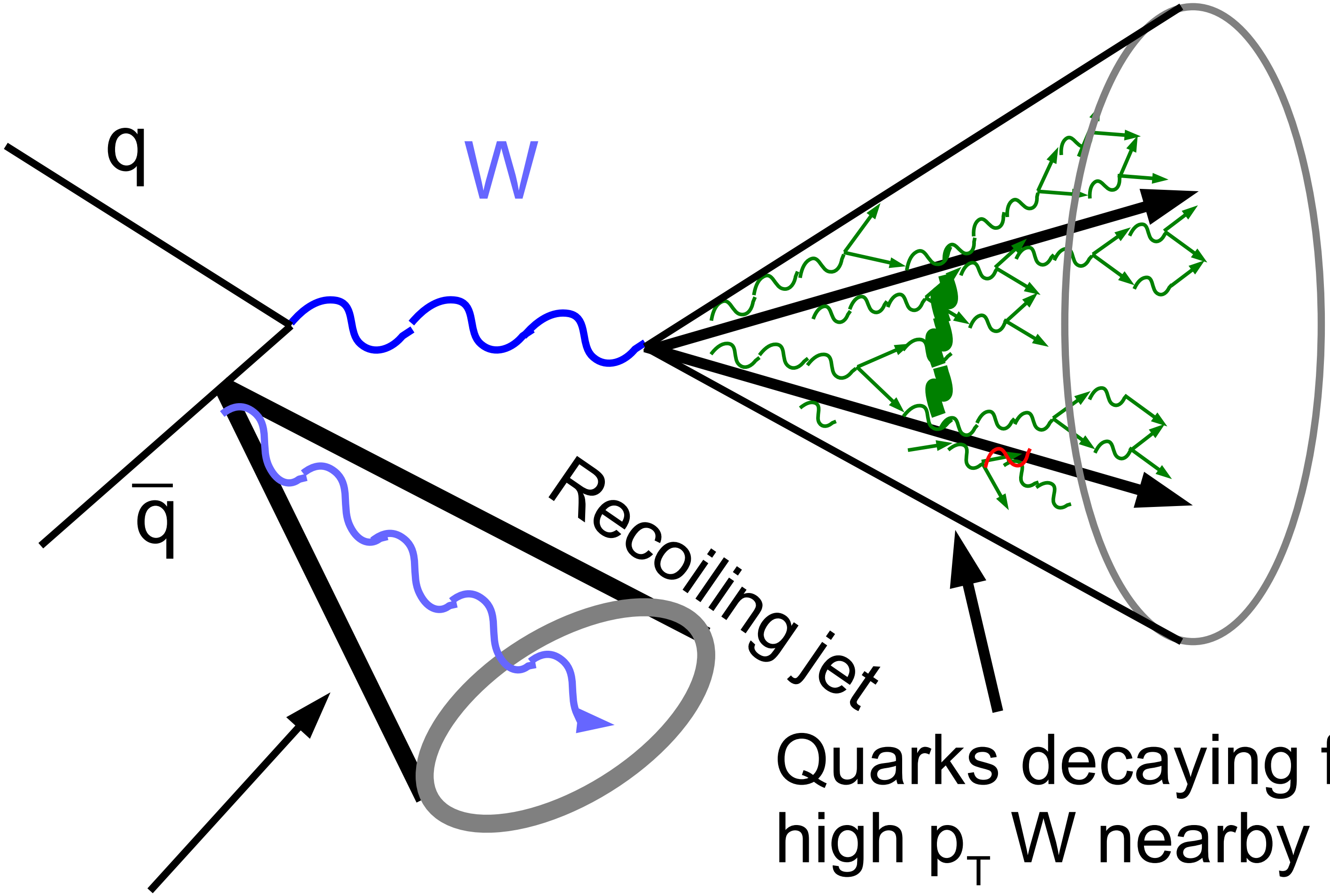
Isolating the W



The core issue is that the background is too large

Whats the first goal?

Require W to be a high p_T



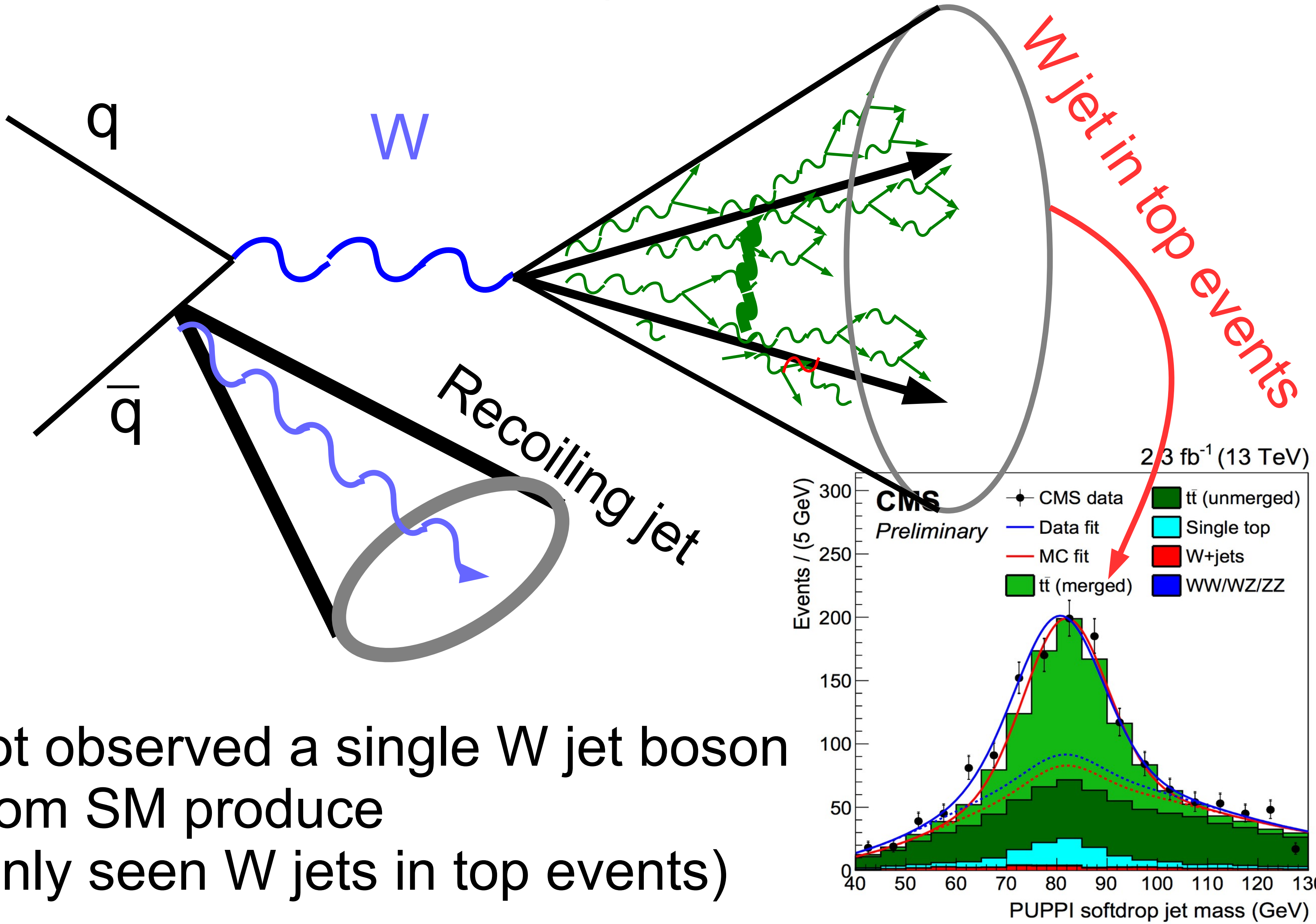
Quarks decaying from high p_T W nearby each other

Resolve this as a single jet

Recoiling jet off W gives the W high p_T

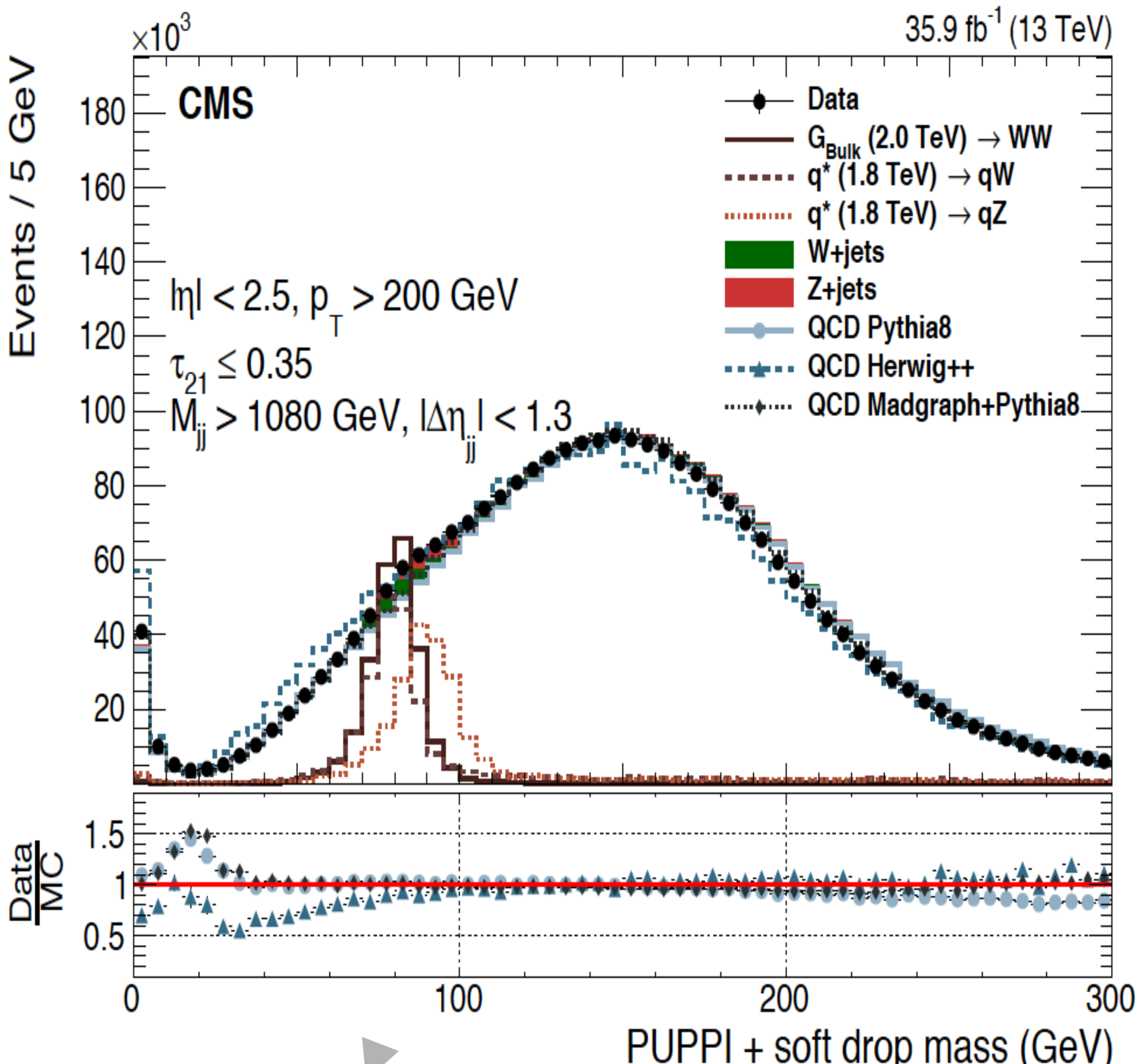
Whats the first goal?

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

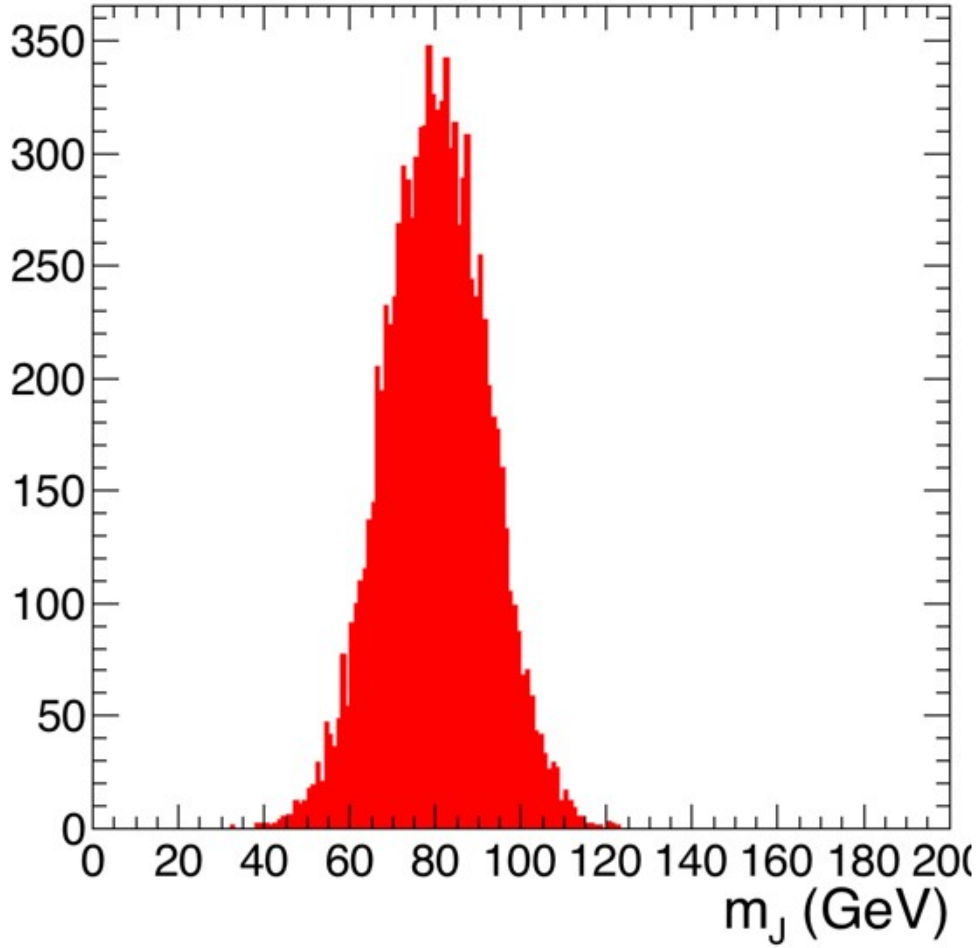
Hard to convince anybody that bump is at 80
With another big bump at a higher mass

Part 2
Decoding Data

A Game

Lets play a game

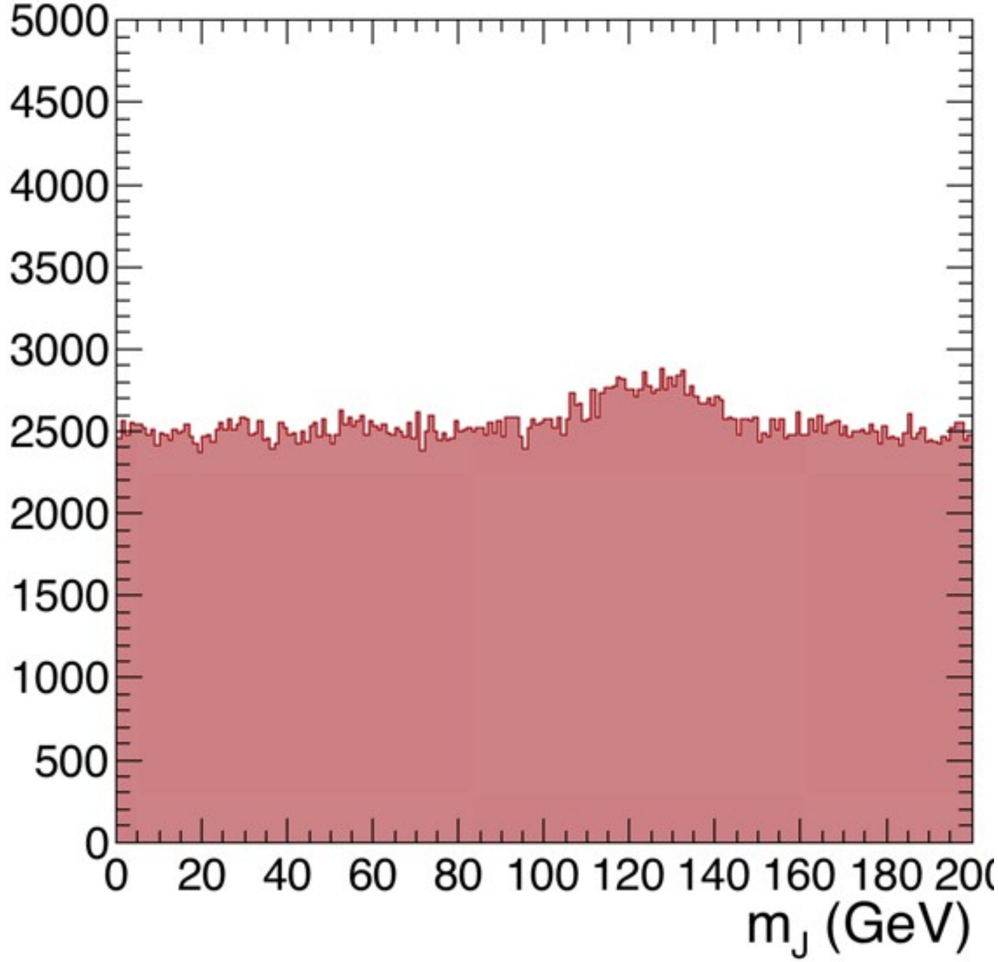
- Lets try to inject a signal likes this



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

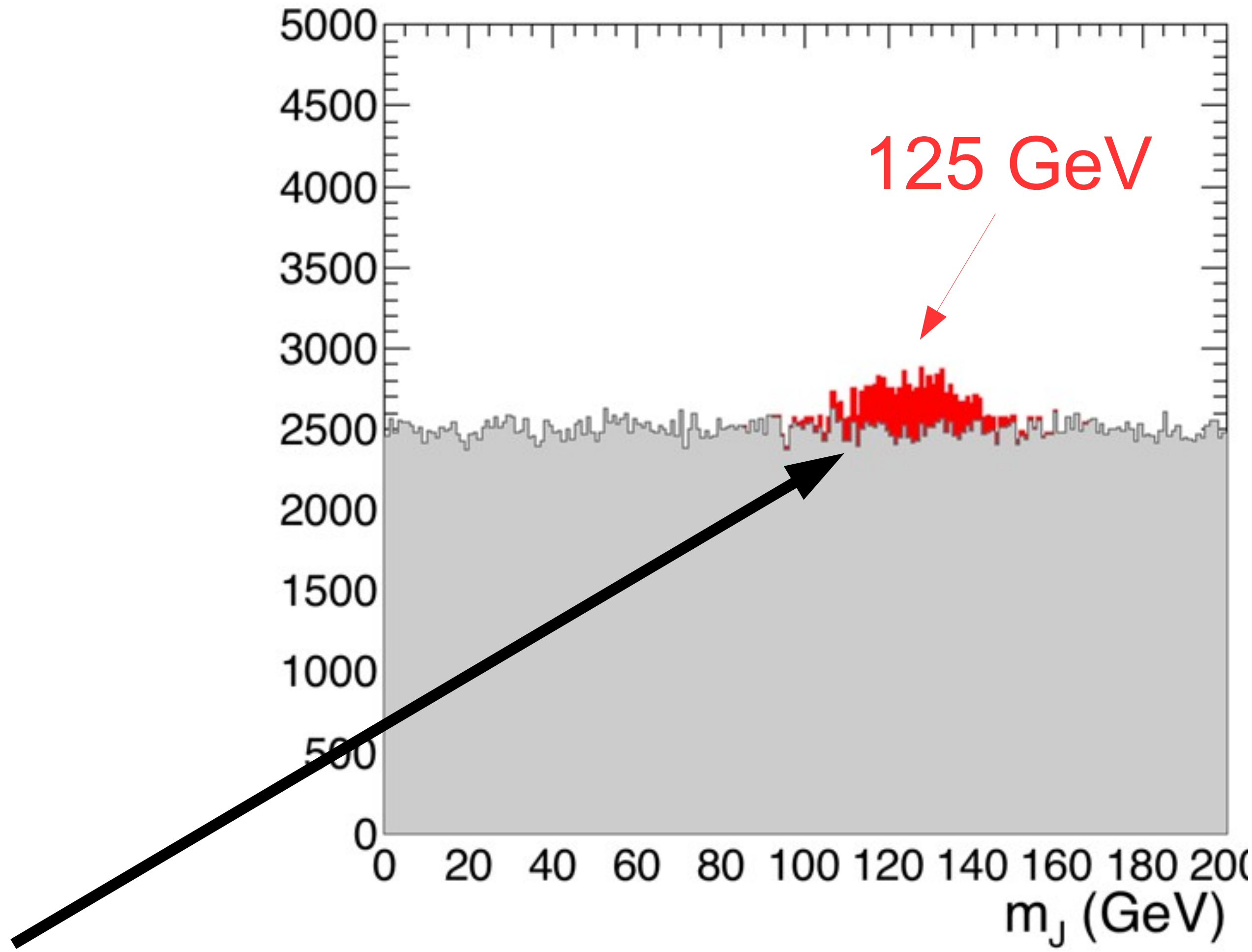
Find the signal

- Can you see the signal?



Find the signal

- Can you see the signal?

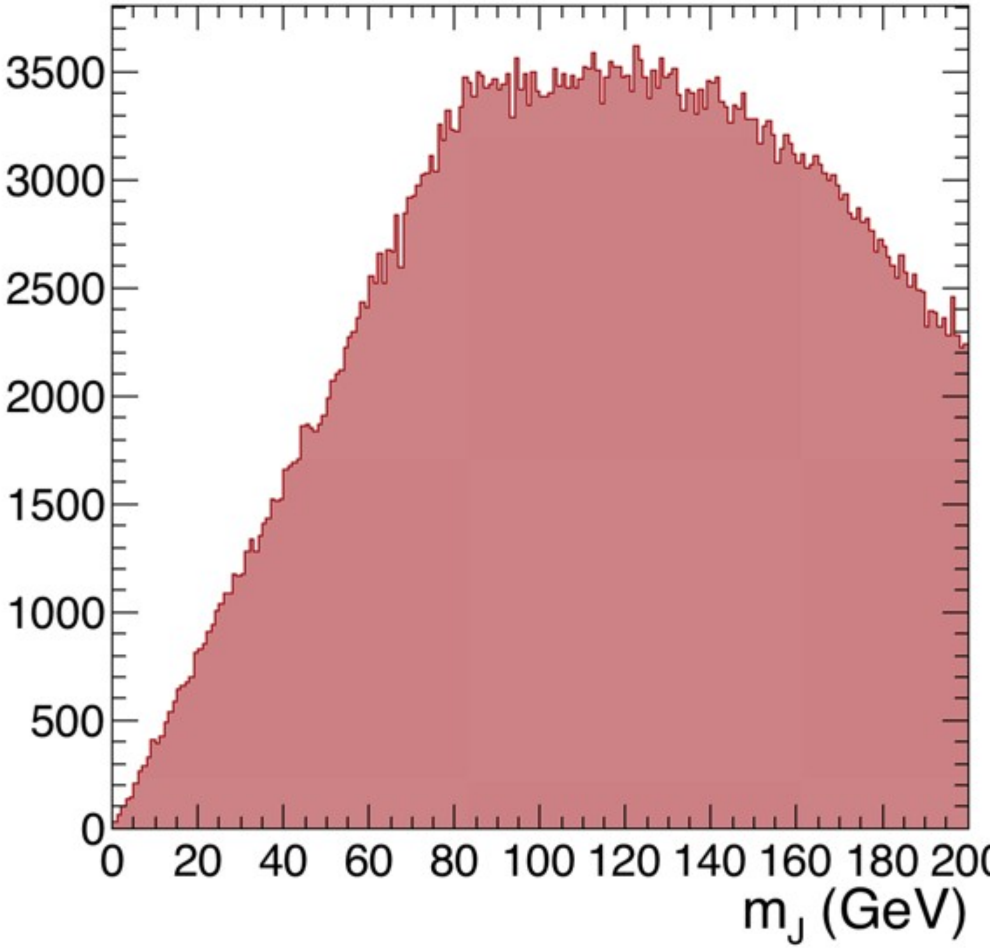


Here is the signal at 125 GeV on a flat background

That was an easy one!

Find the signal

- Can you see the signal?

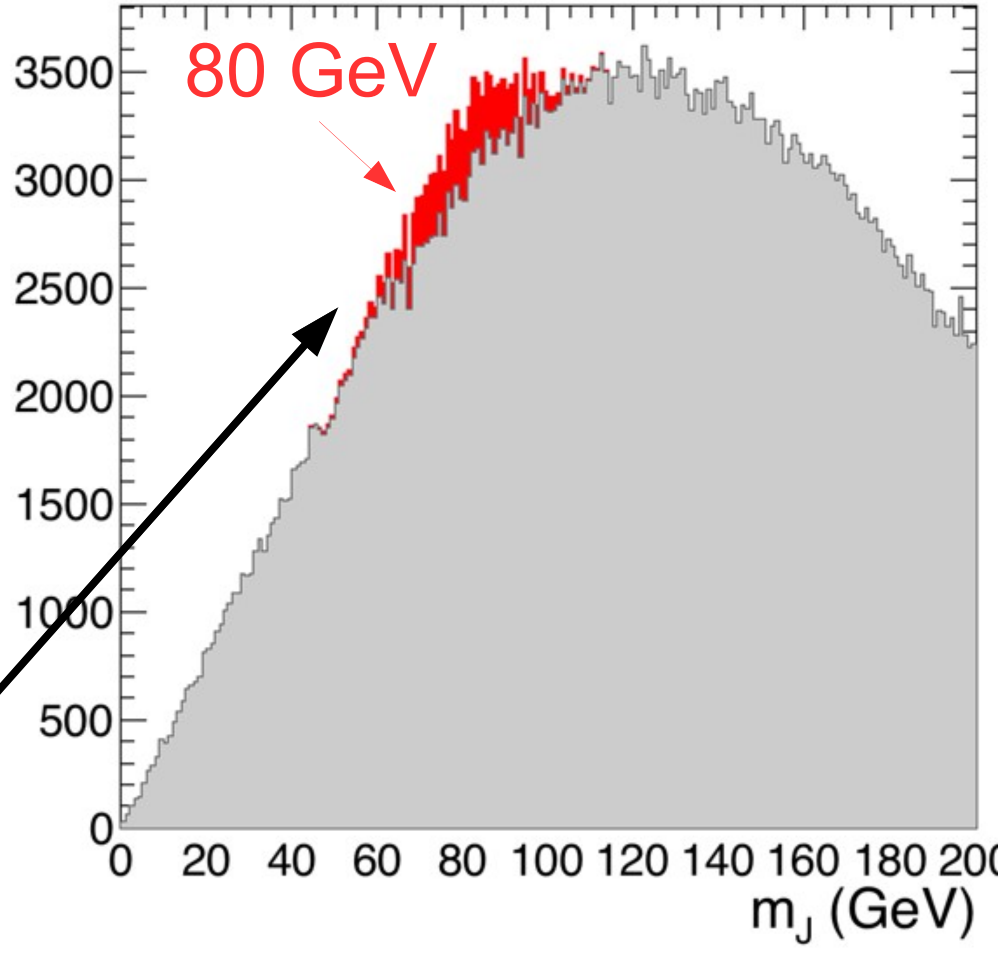


Here is the signal at 125 GeV on a flat background

Now the background peaks just after the signal

Find the signal

- Can you see the signal?

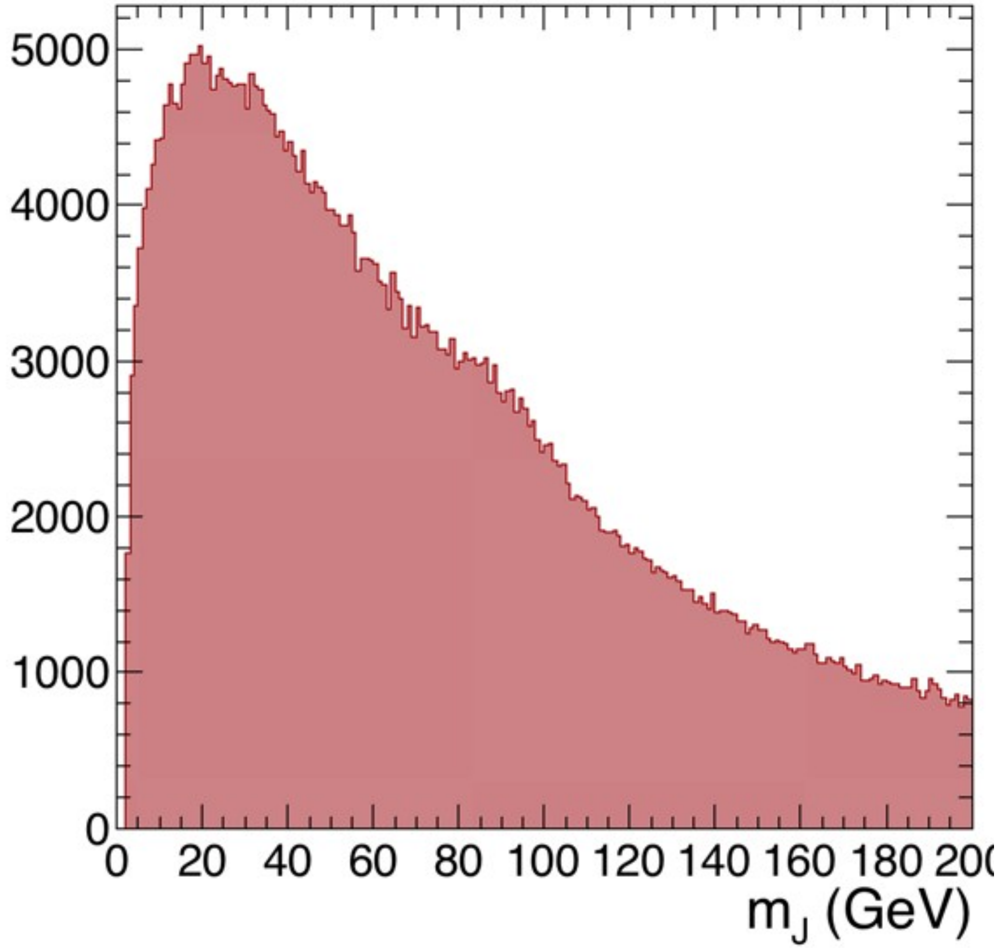


Here it is. This one is a bit harder.

Note exact same amount of background and signal

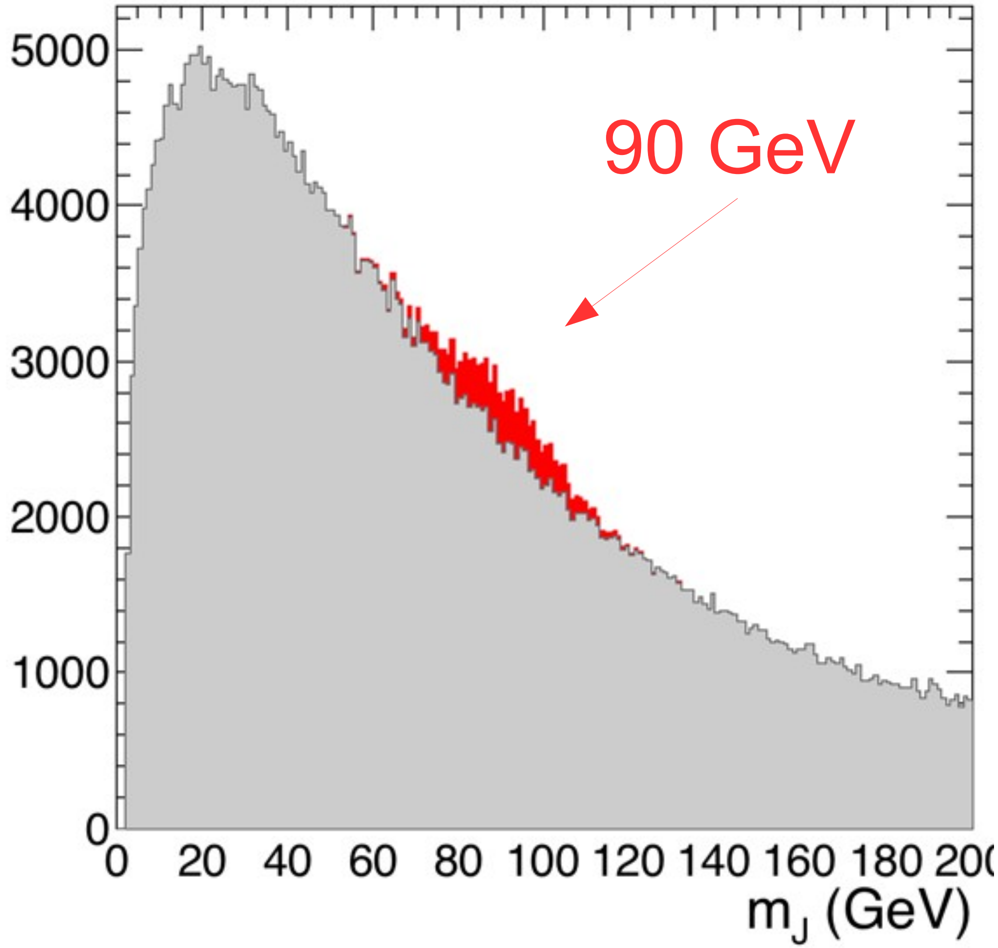
How about now?

- Can you see the signal?



How about now?

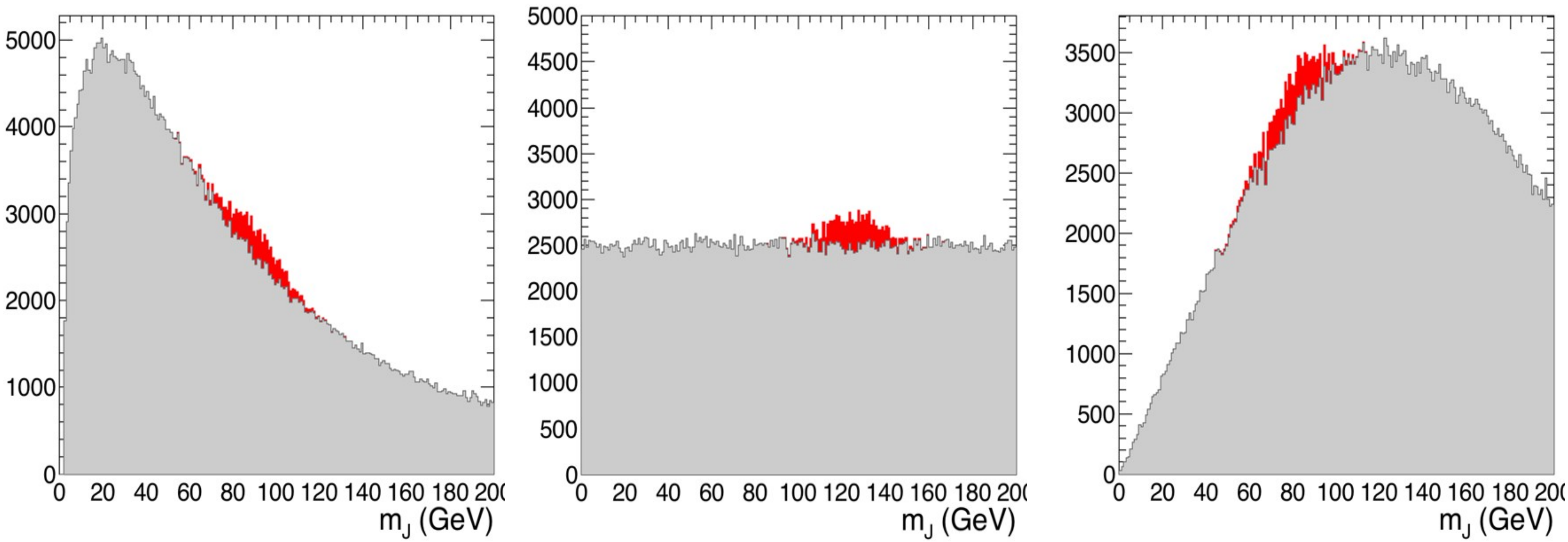
- Can you see the signal?



Background

Note exact same amount of background and signal

Whats best background?



All variables yield roughly the same performance

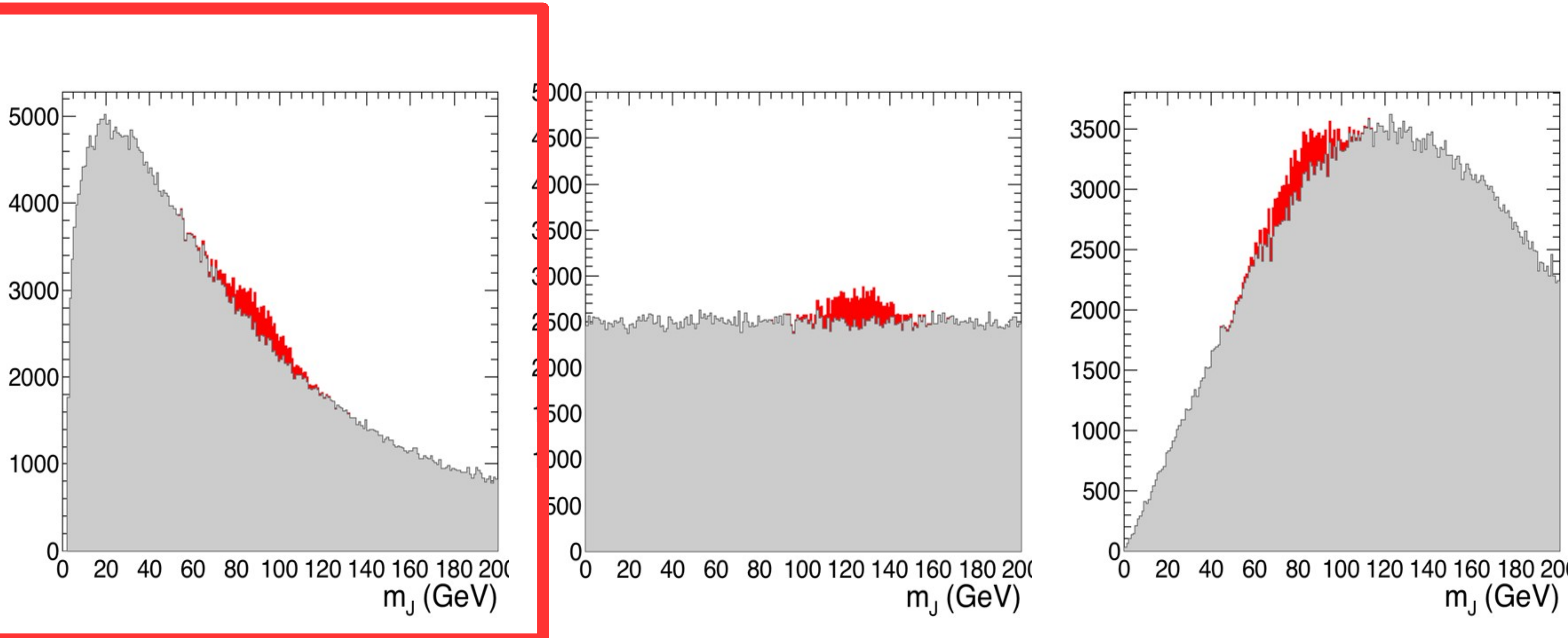
Exactly the same background yield

Exactly the same signal yield

What if we could tune background shape to what we want?

What would be our best choice of shape?

Whats best background?



All variables yield roughly the same performance

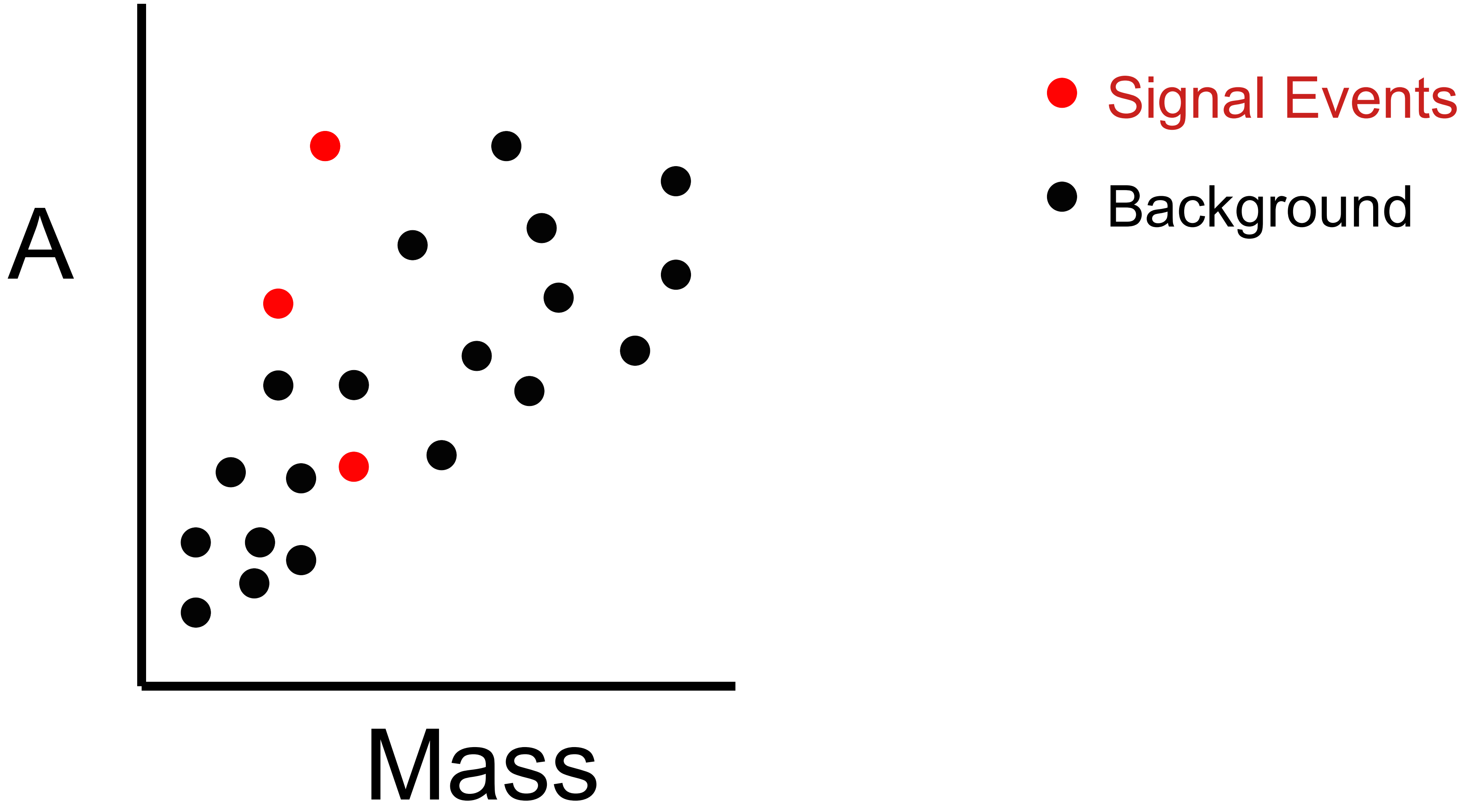
Exactly the same background yield

Exactly the same signal yield

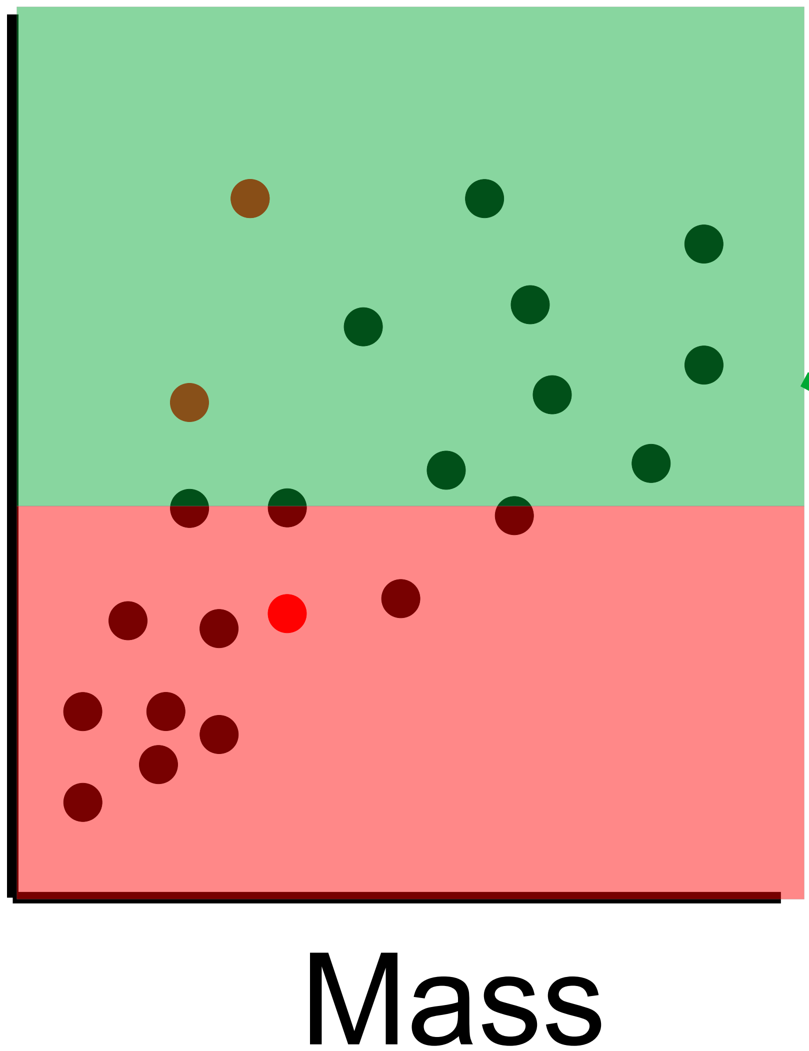
What if we could tune background shape to what we want?

What would be our best choice of shape?

Consider trying to isolate a signal



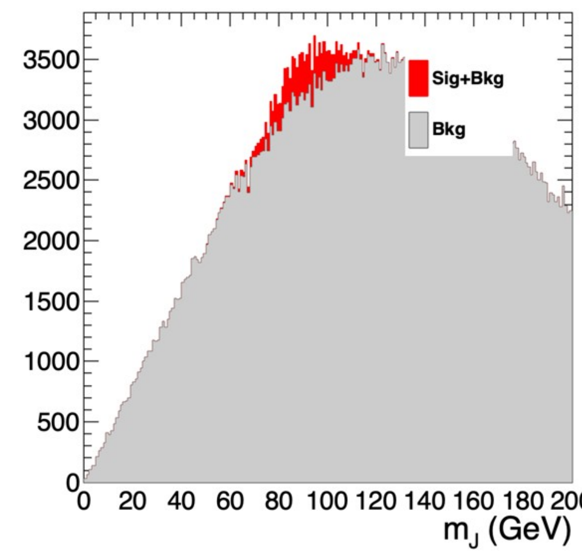
Extracting a Signal



● Signal Events

● Background

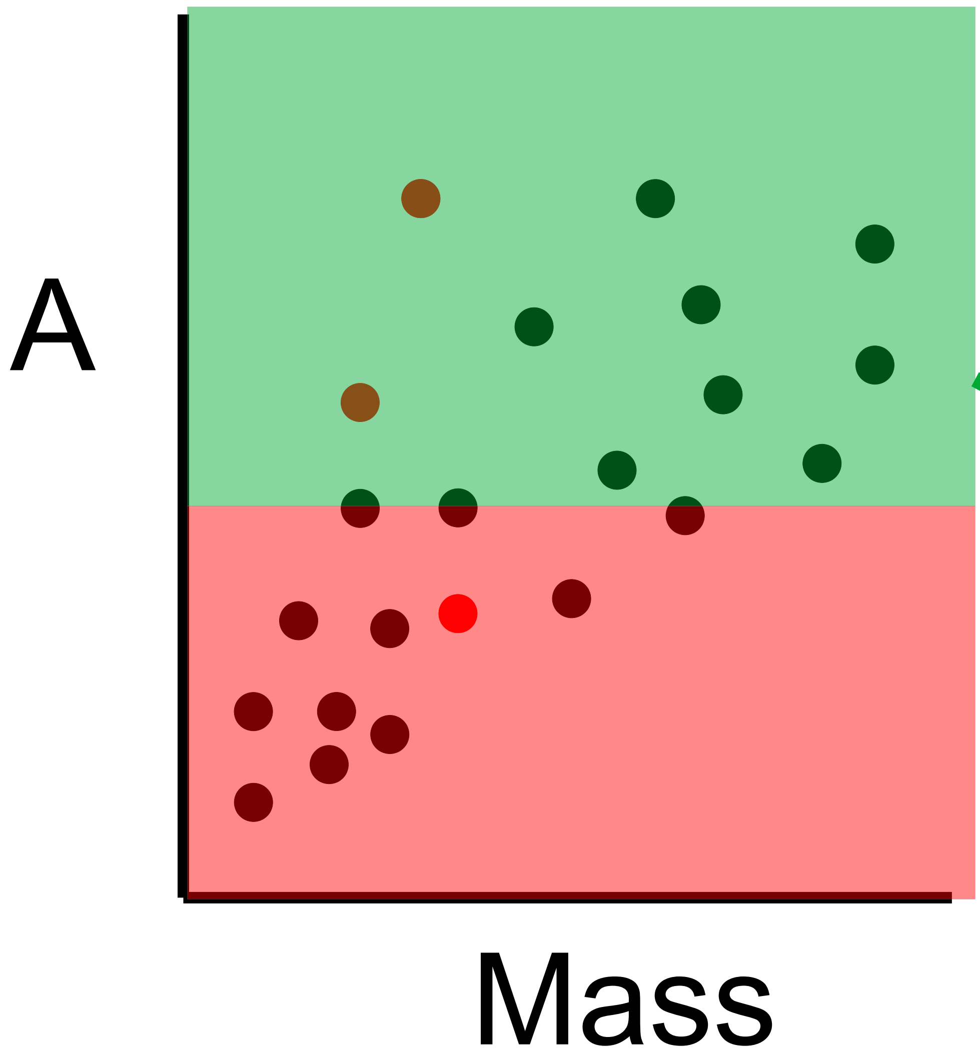
Select Events



And Fit Mass

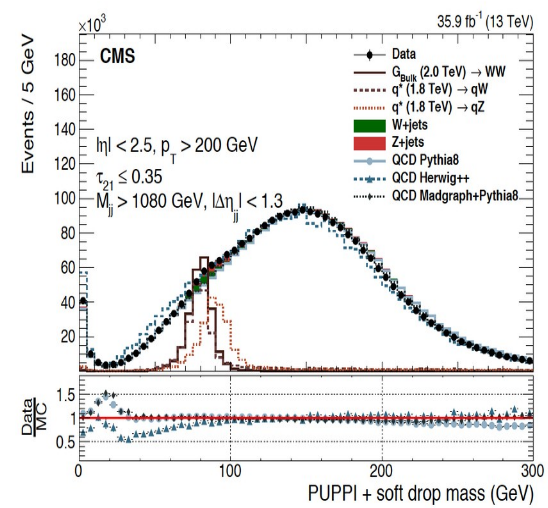
Not Good Enough!

Extracting a Signal



- Signal Events
- Background

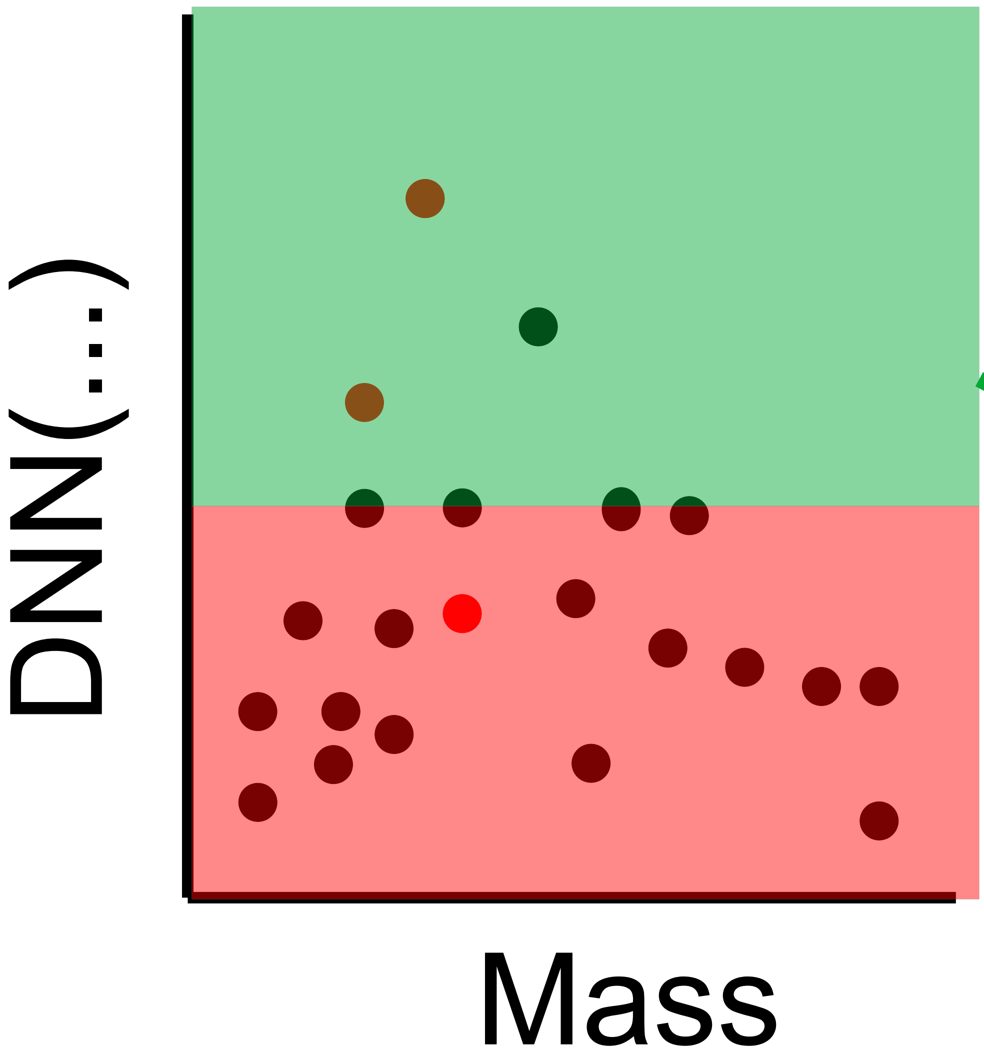
Select Events



Cut tighter!

And Fit Mass

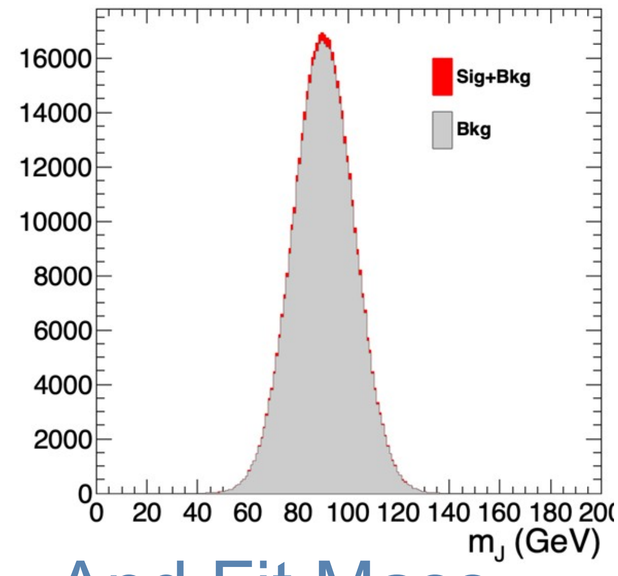
Use Deep Learning



Signal Events

Background

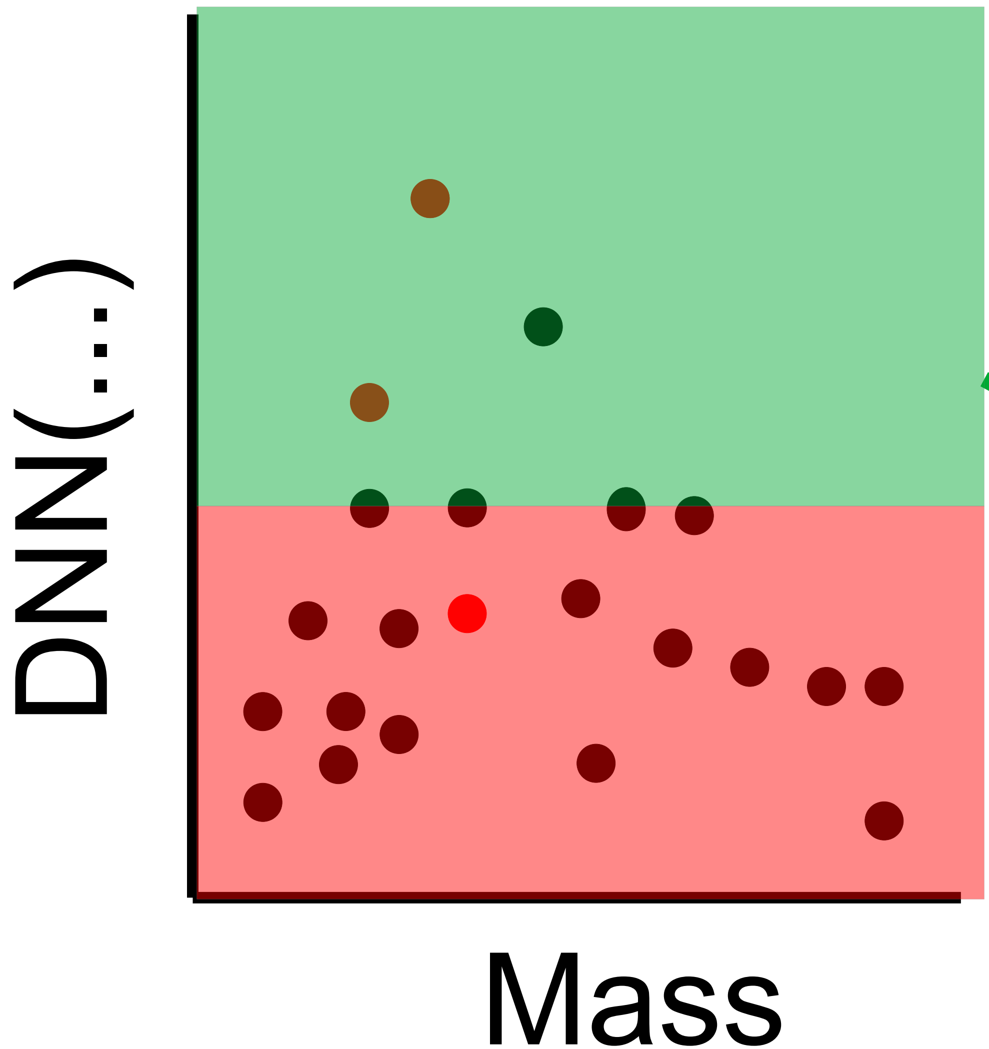
Select Events



And Fit Mass

Still Not Enough!

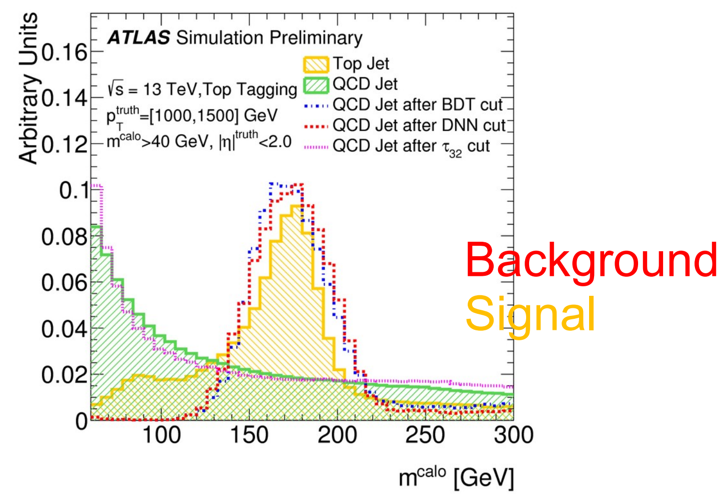
Use Deep Learning



Signal Events

Background

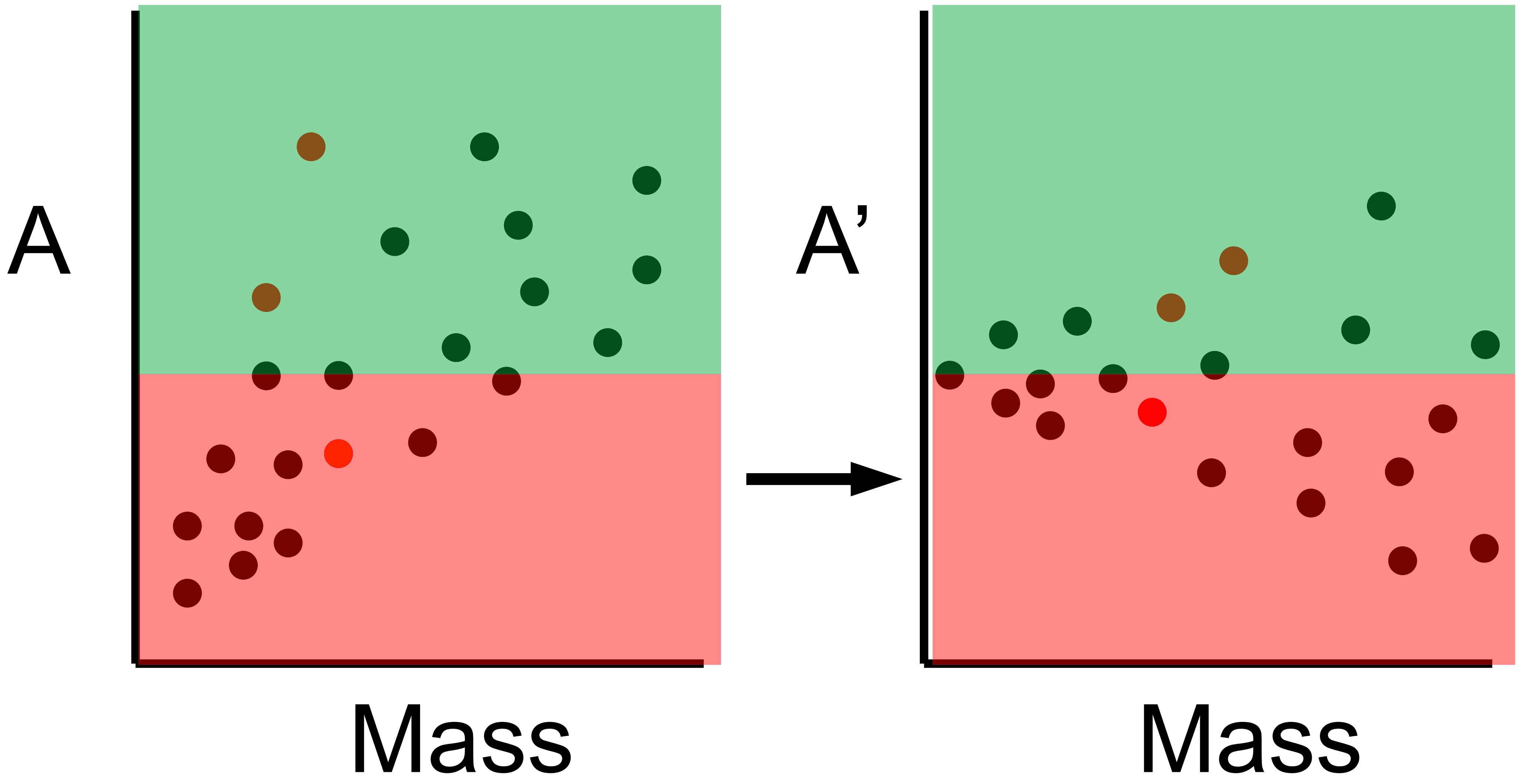
Select Events



Can’t separat sig+bkg

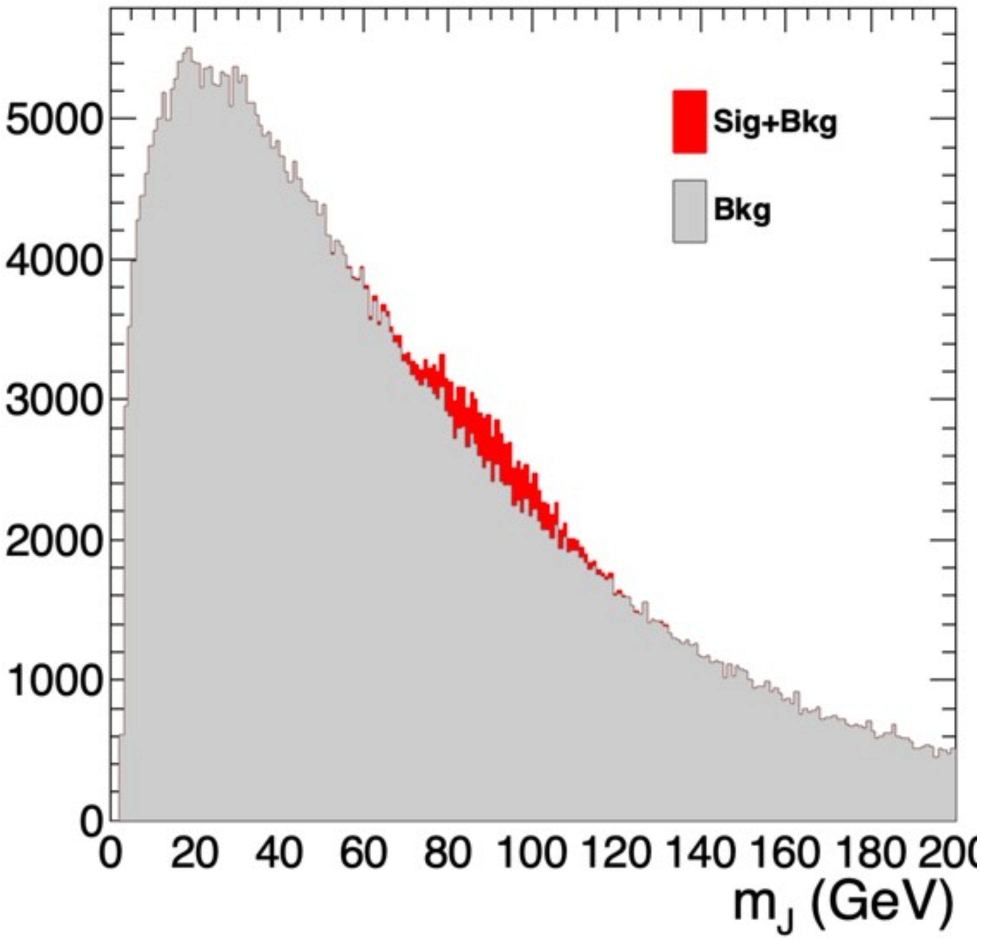
And Fit Mass

Conceptually what was done?

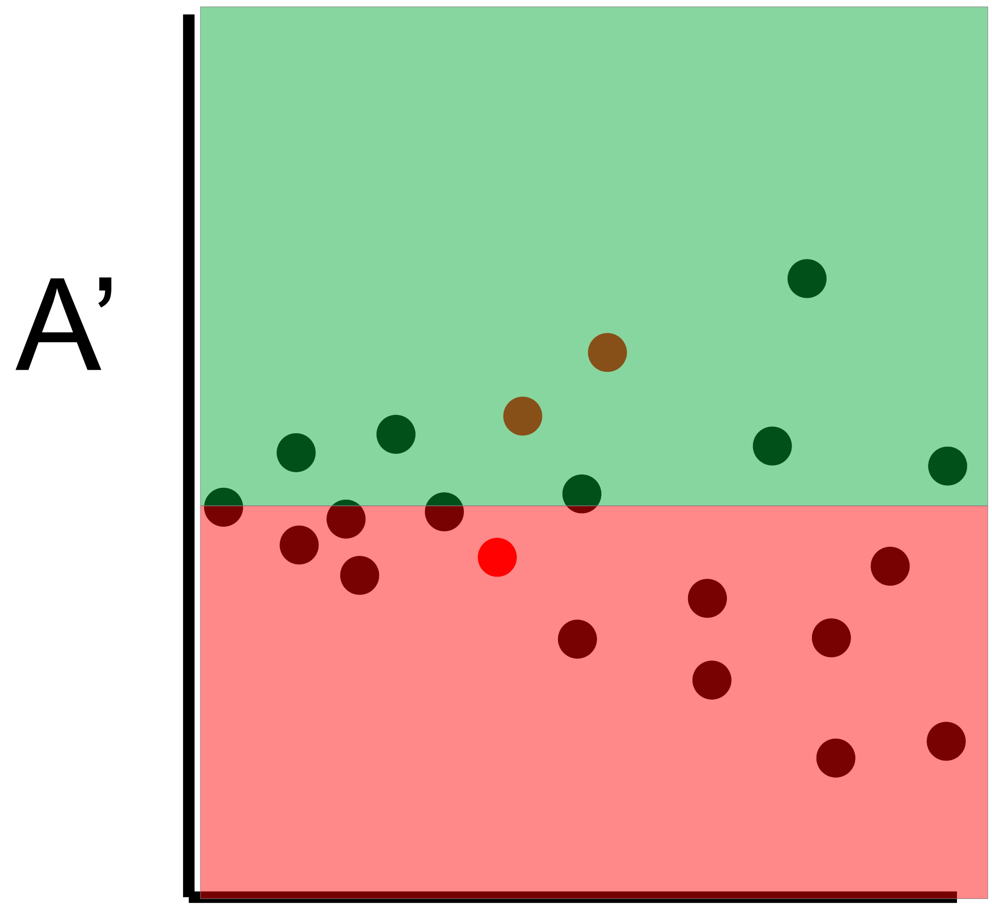


Now its good!

Conceptually what was done?



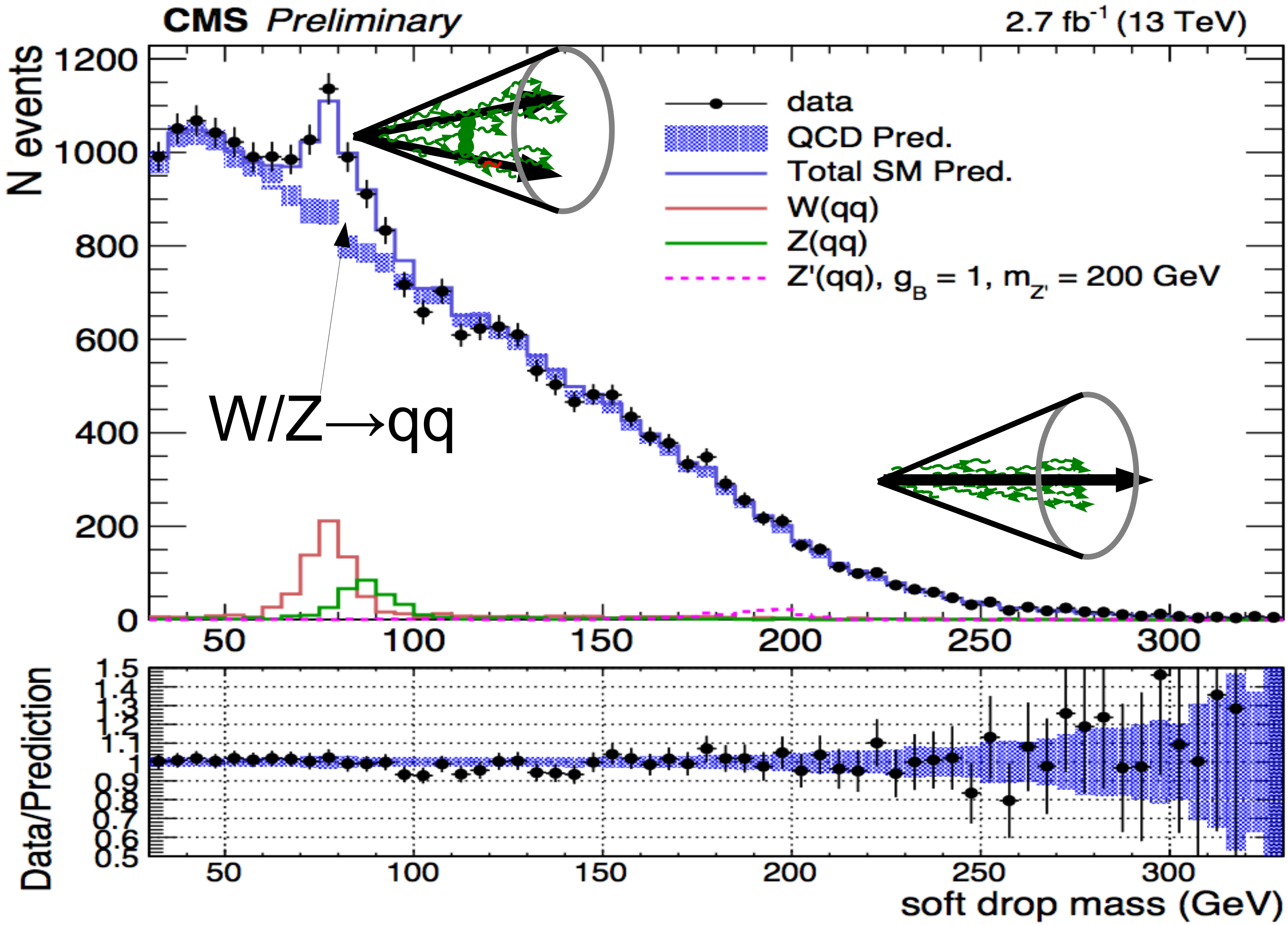
Mass



Mass

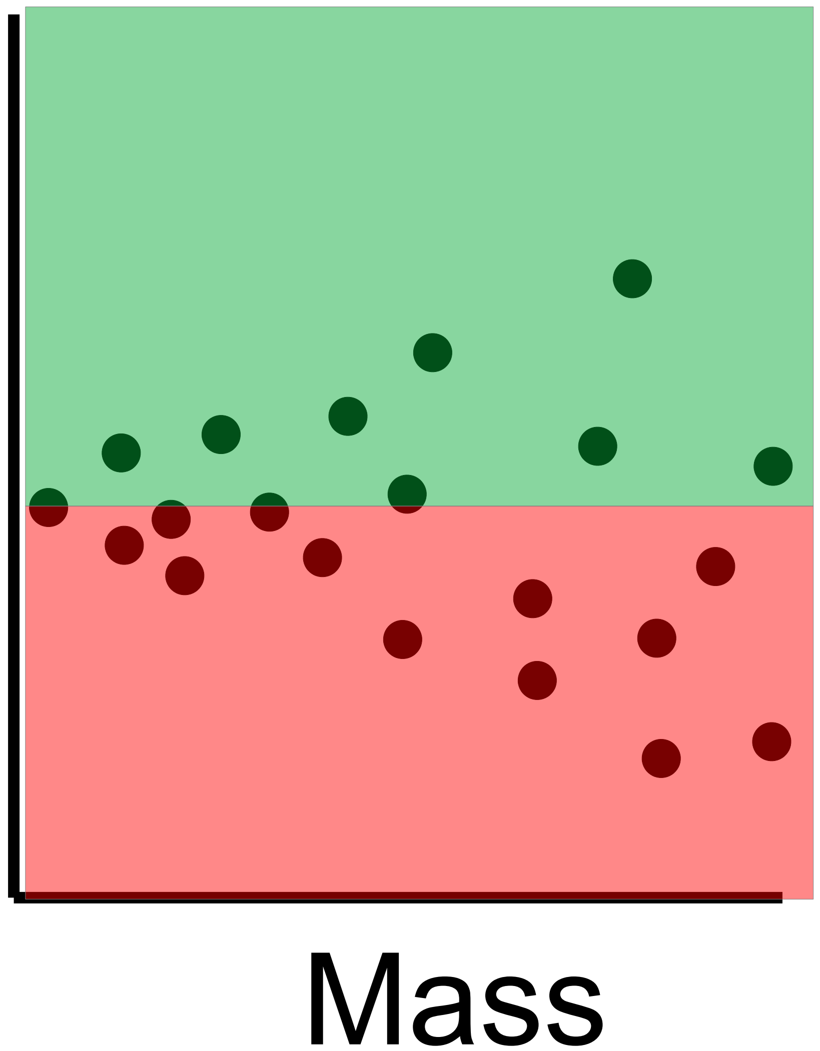
Now its good!

Jet Mass distribution



What makes this complicated?

$$A'(in_1, in_2, \ldots, in_{1000})$$



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

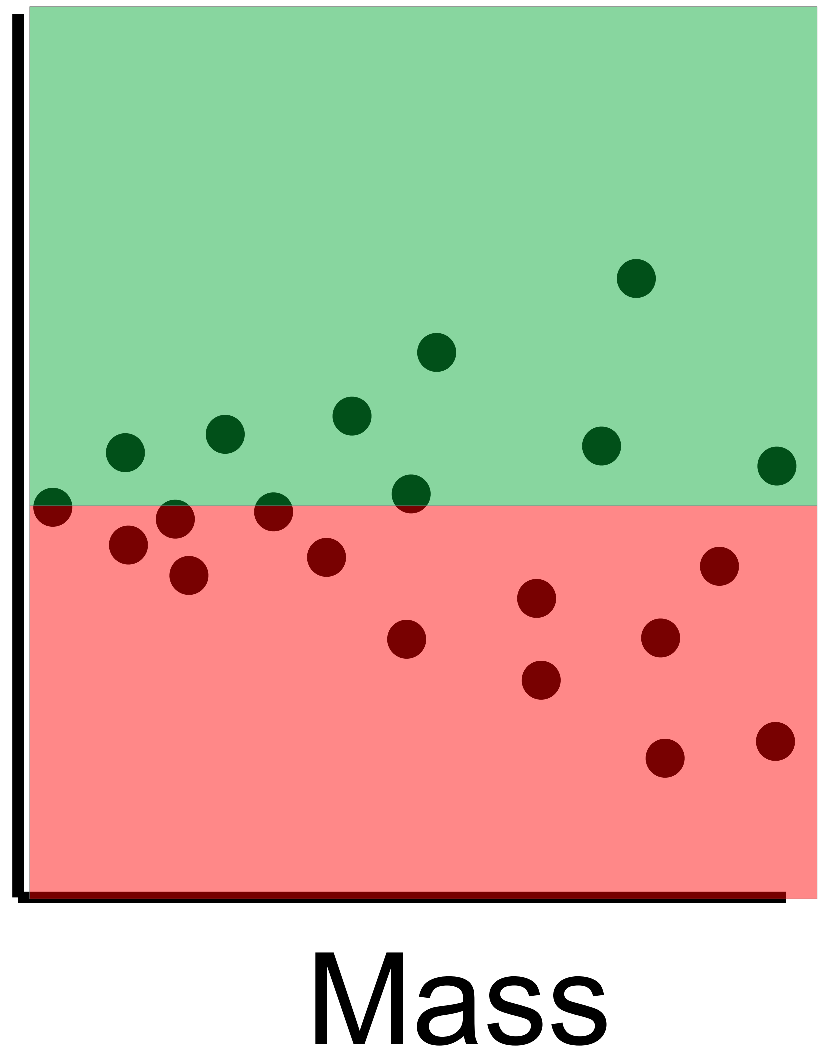
No Joke
(I will get back to that)

What makes this complicated?

To start with we relied on a standard:

$A'(in_1, in_2, \ldots, in_{1000})$
$= \tau_2/\tau_1$

+Brute force decorrelation



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

What makes this complicated?

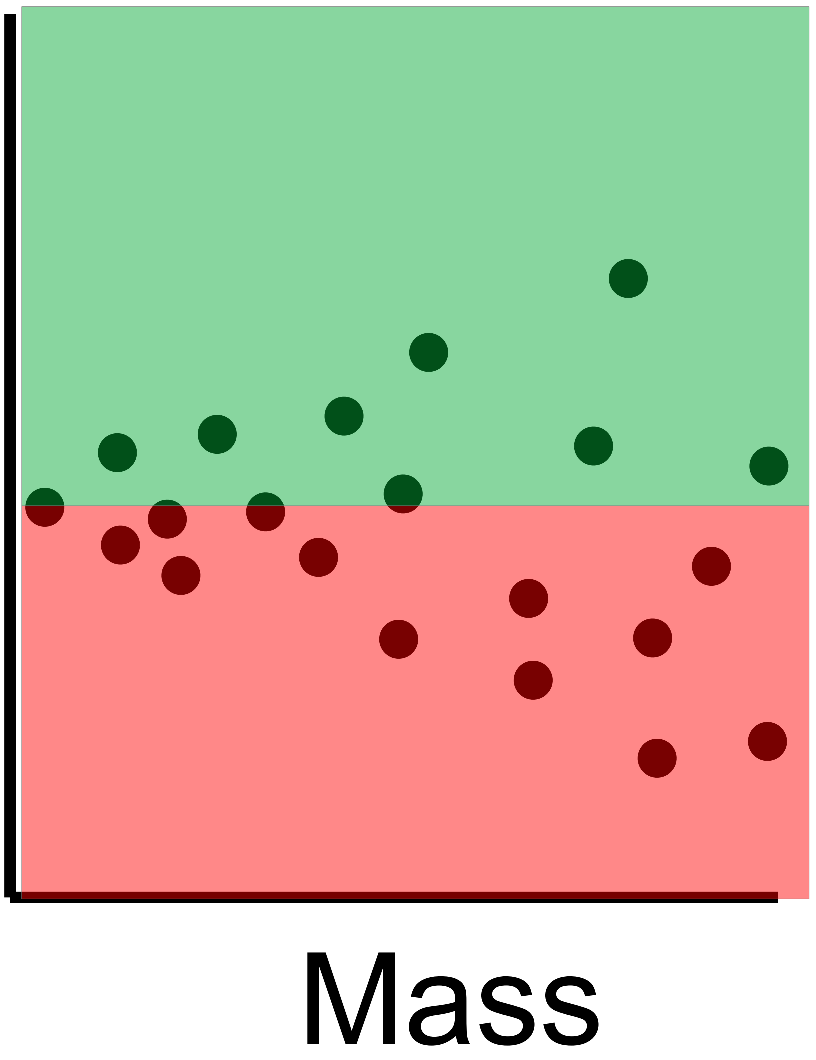
After Jesse's paper we switched to:

A'(in$_1$,in$_2$,…,in$_{1000}$)

$$= \frac{{}_2e_3^{(\beta)}}{\left(e_2^{(\beta)}\right)^2}\,(N_2)$$

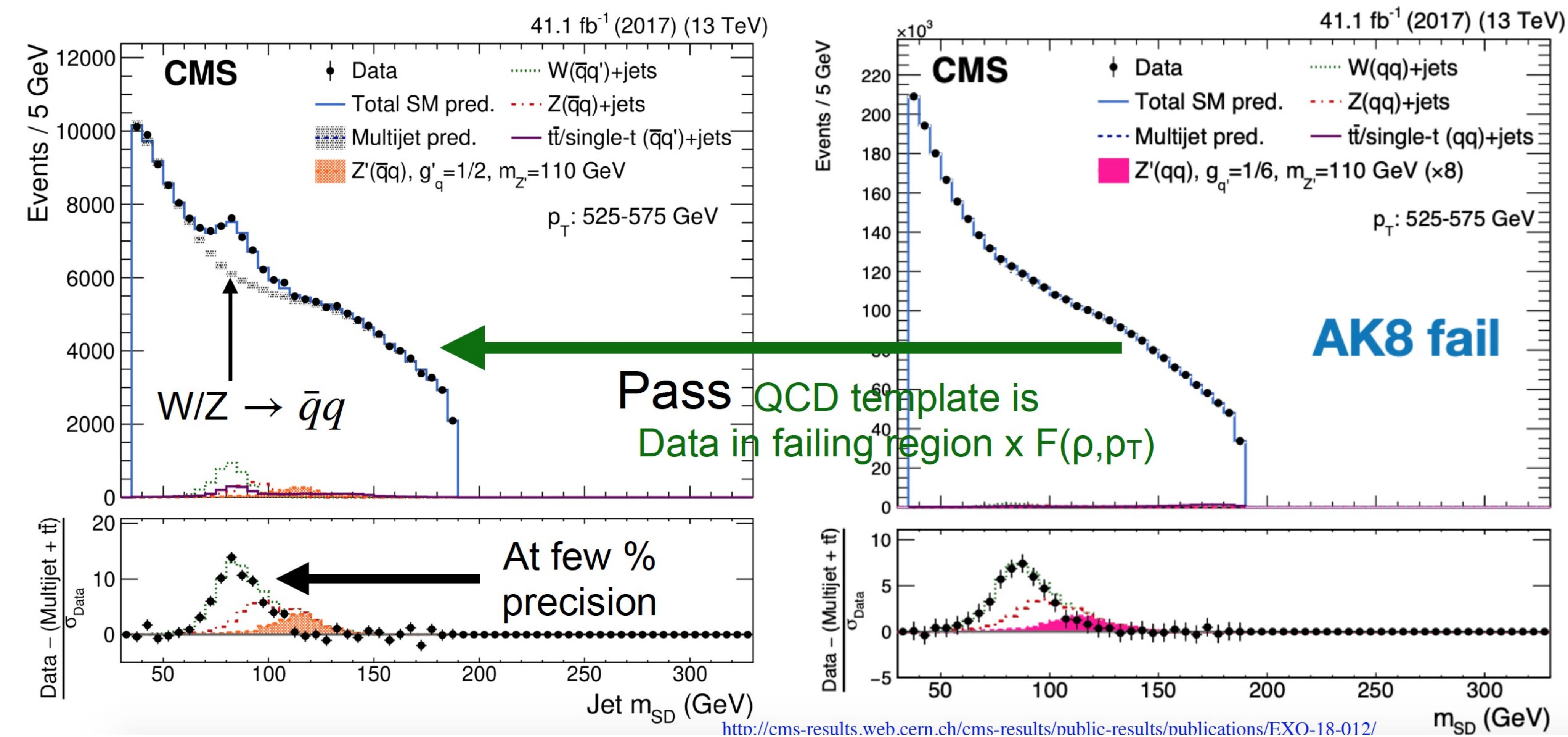
+Brute force decorrelation

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



J.Krupa

Our current result



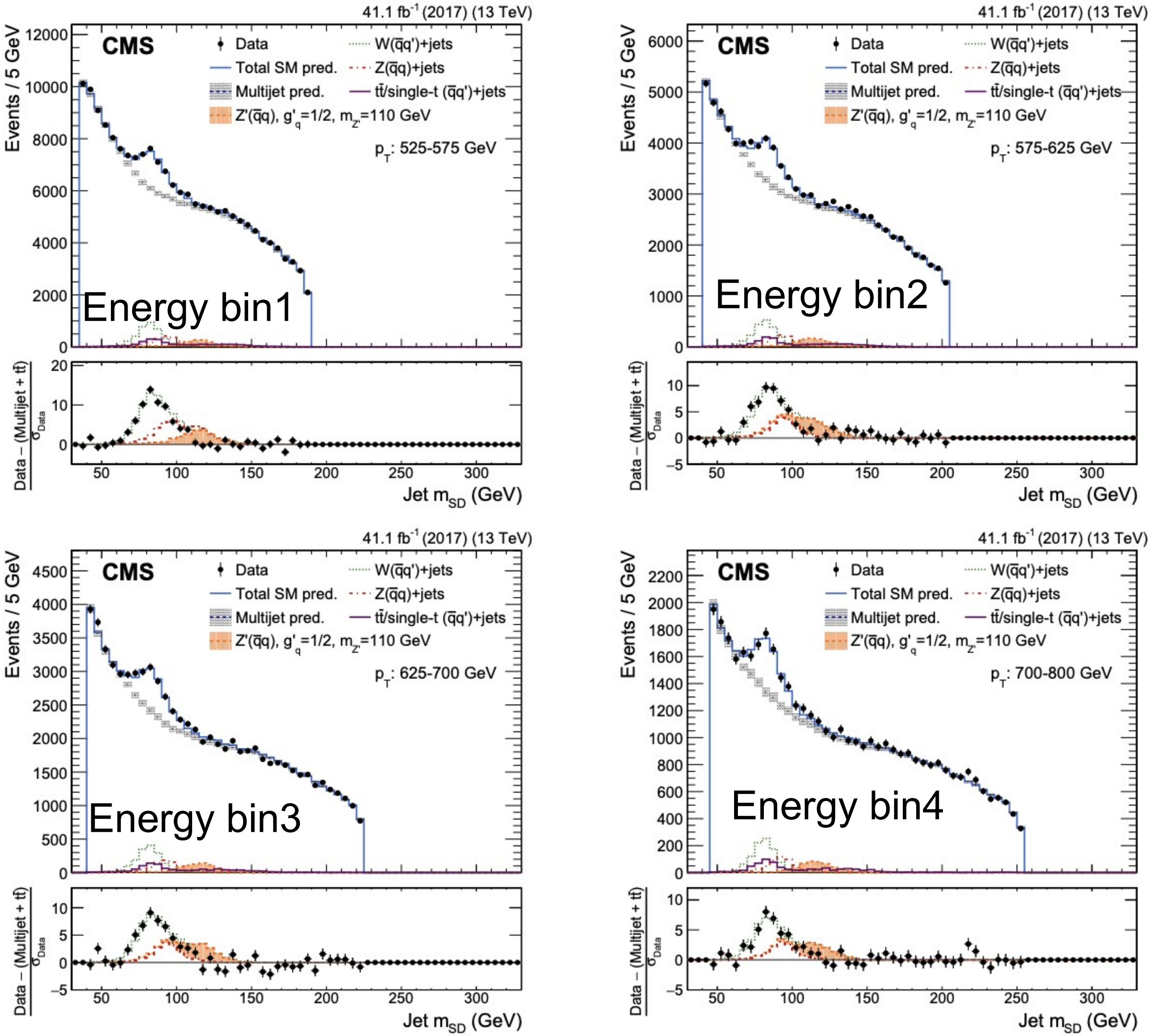
http://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-18-012/

Only through above strategies could we get here

Ultimately it meant we could safely cut tigher

J.Krupa

Our Current Result

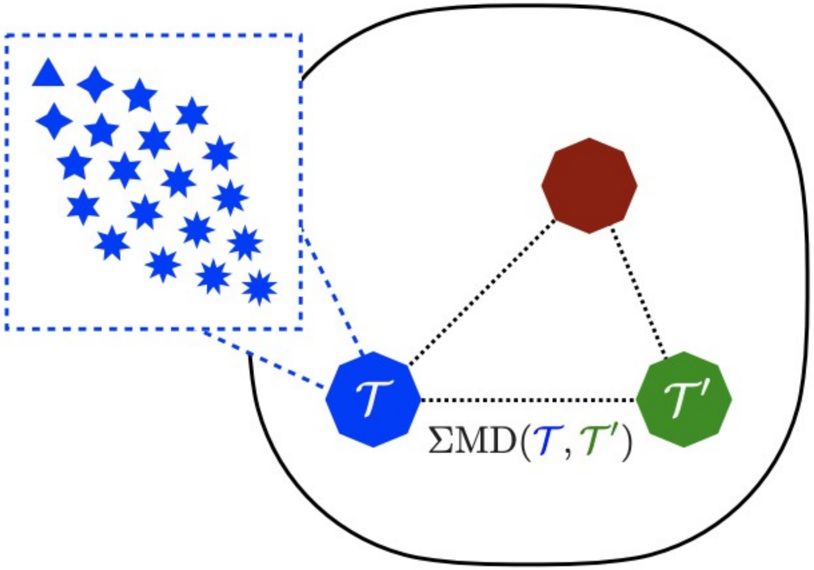


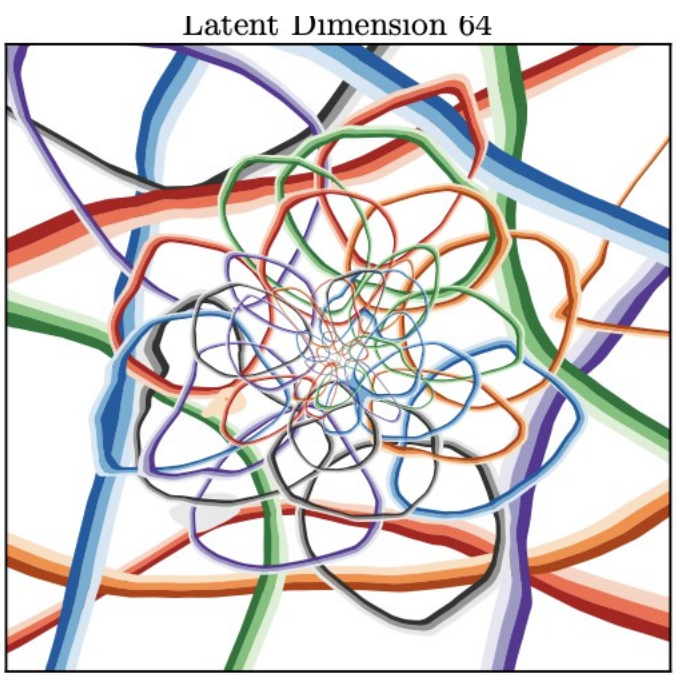
Starting to get real precision

Whats the deal with deep learning?

There are 30-200 entangled particles In a jet

$$
\begin{aligned}
\mathcal{C}_N &= \sum_{k=0}^{N} \binom{N}{k} \sum_{i_1=0}^{1} \cdots \sum_{i_k=0}^{1} \lambda^{\sum_{a=1}^{k} i_a} (1-\lambda)^{k-\sum_{a=1}^{k} i_a} E_1^k \\
&\quad \times \sum_{i_{k+1}=2}^{M} \cdots \sum_{i_N=2}^{M} C_{i_1 \cdots i_N}(\hat{p}^\mu_{i_1}, \ldots, \hat{p}^\mu_{i_N}) \prod_{j=k+1}^{N} E_{i_j} \\
&= \sum_{k=0}^{N} \binom{N}{k} \sum_{\ell=0}^{k} \binom{k}{\ell} \lambda^\ell (1-\lambda)^{k-\ell} E_1^k \\
&\quad \times \sum_{i_{k+1}=2}^{M} \cdots \sum_{i_N=2}^{M} C_{\underbrace{0\cdots0}_{\ell}\,\underbrace{1\cdots1}_{k-\ell}\, i_{k+1}\cdots i_n}(\hat{p}^\mu_1, \ldots, \hat{p}^\mu_1, \hat{p}^\mu_{i_{k+1}}, \ldots, \hat{p}
\end{aligned}
$$



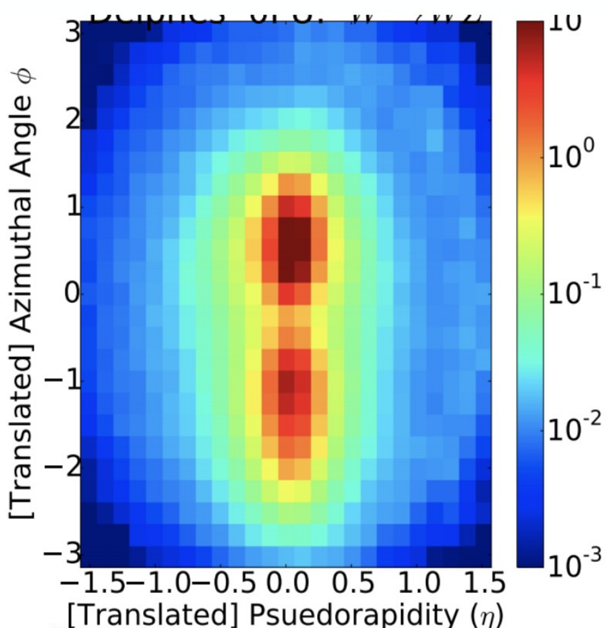


Deep Learning has made it possible to decode some of the finer features of a jet

How its evolved over time

- Deep learning for substructure is rapidly growing field

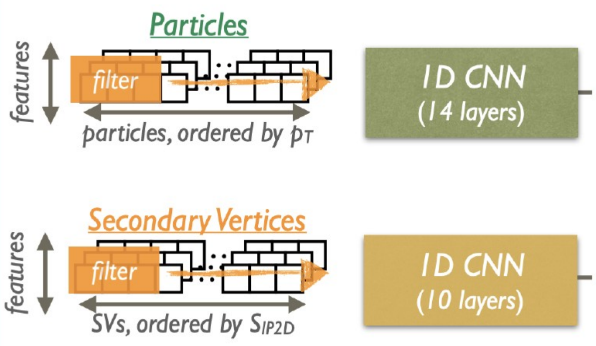
2016



Images

(not lorentz invariant)

2018

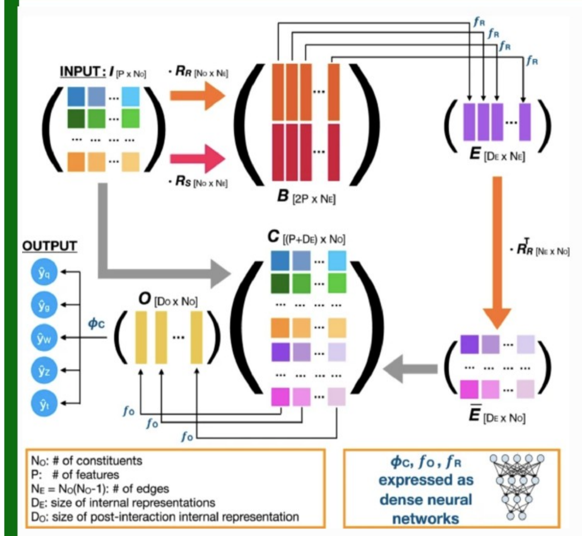


Particles and SVs
with 4-vectors+features

Particles

(limited correlations)

2020



Graphs

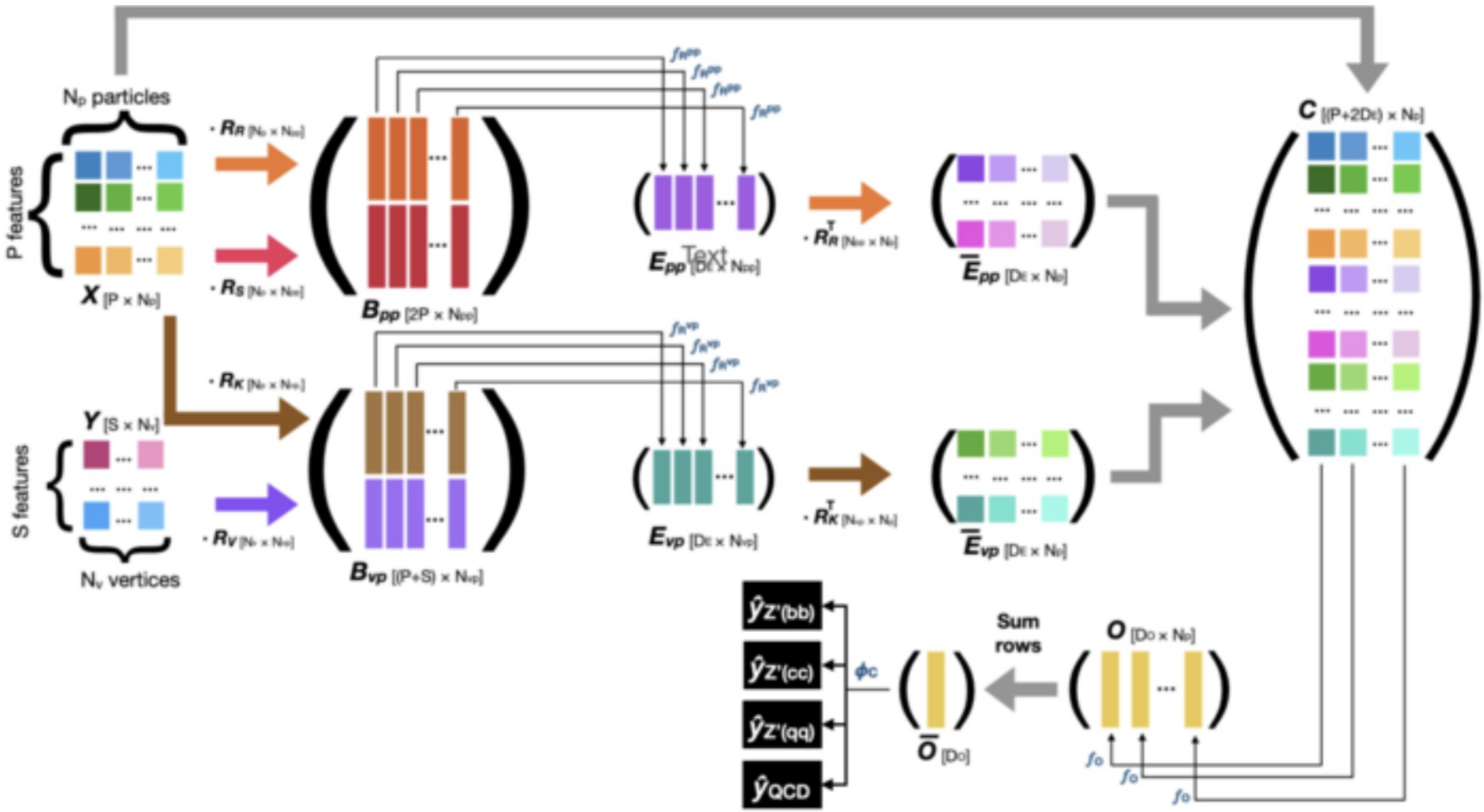
(Particles+correlations)

Current collaboration results

Progressively moving towards use of more info

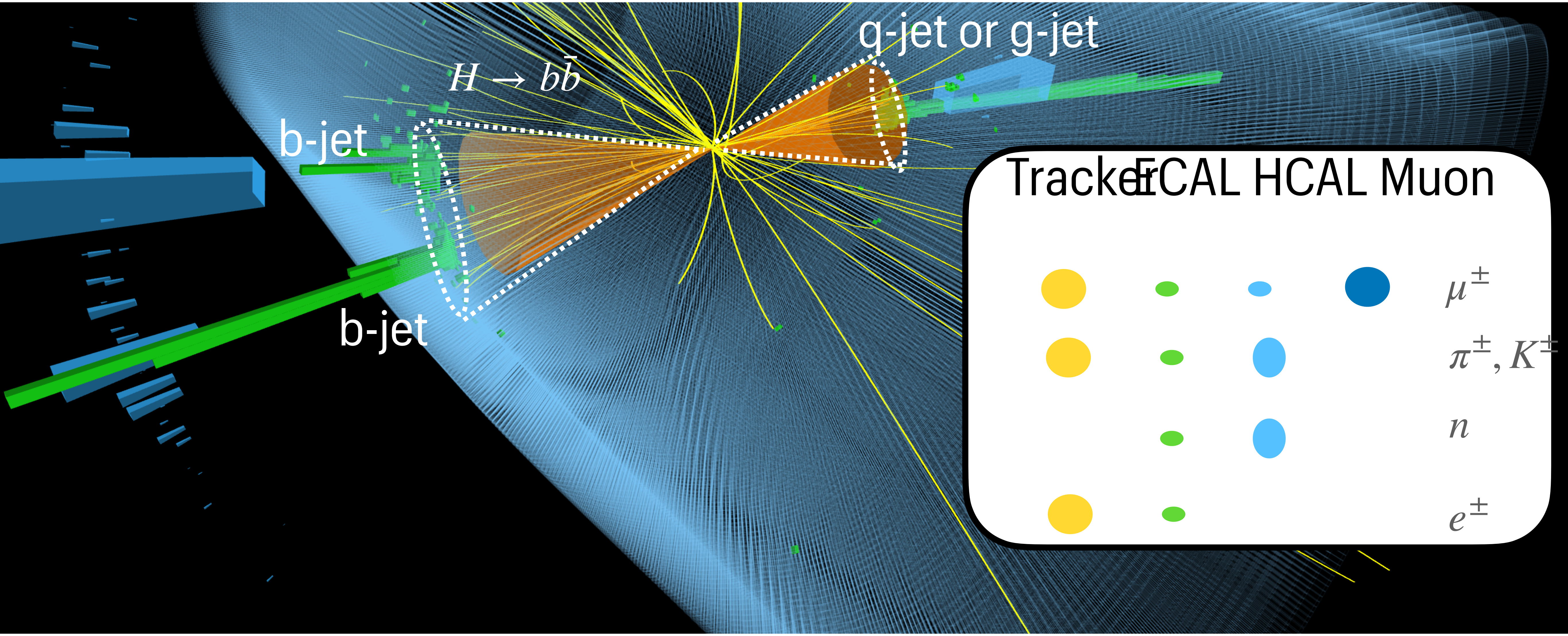
J.Krupa, D. Rankin, S. Siegel (UROP),K. Llewellen

Why are we so excited?



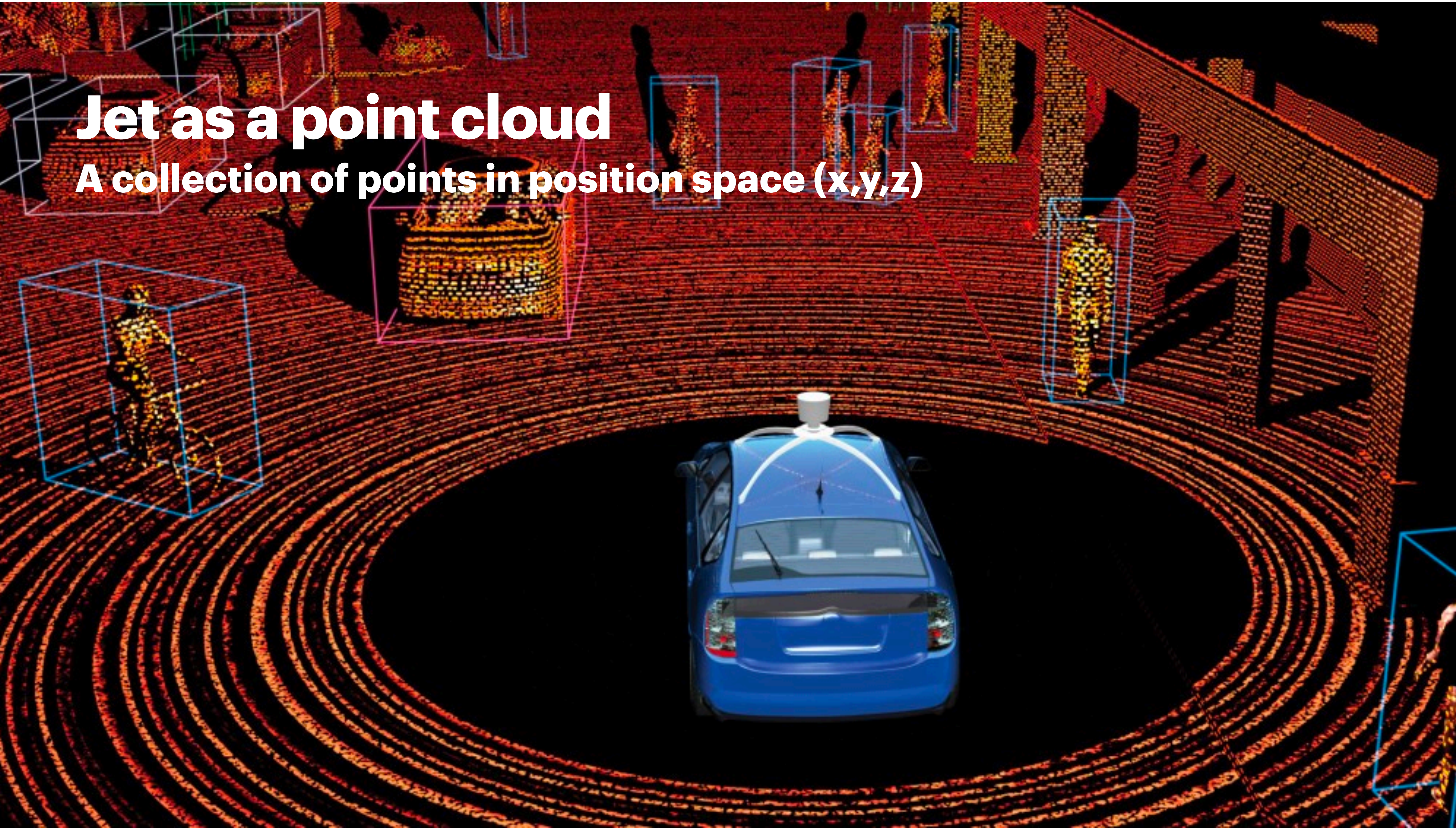
A collision event

A collection of particles in momentum space



Jet as a point cloud

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



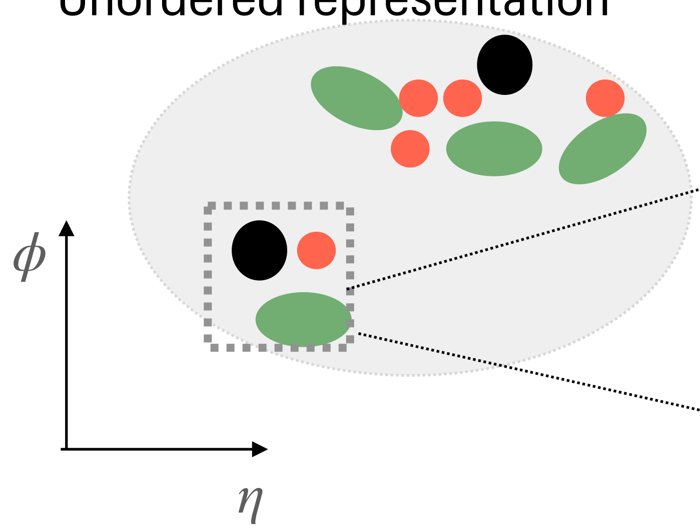
Particle-Net

A graph neural network using particle-clouds

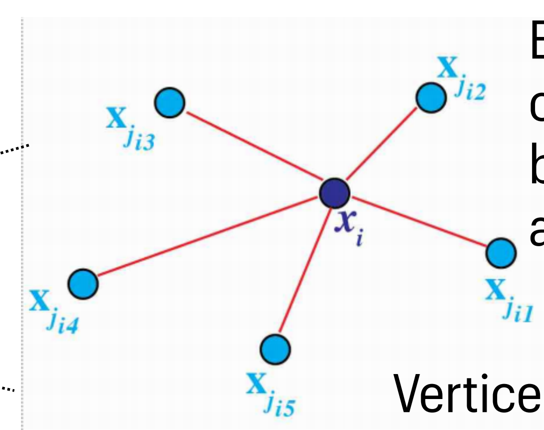
- For a jet: we have 2D information of particles, but also energy/momenta, charge/particle ID, track quality/impact parameter, etc.

Jet as a particle cloud

Unordered representation



Each cloud is a graph

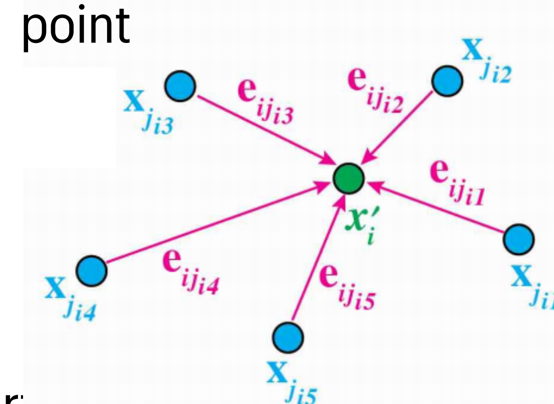


Edges: connections between point and k-NN points

Vertices: point (Particle or secondary vertex)

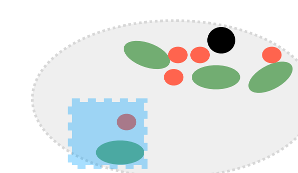
Perform convolution

EdgeConv outputs a set of learned features for each point



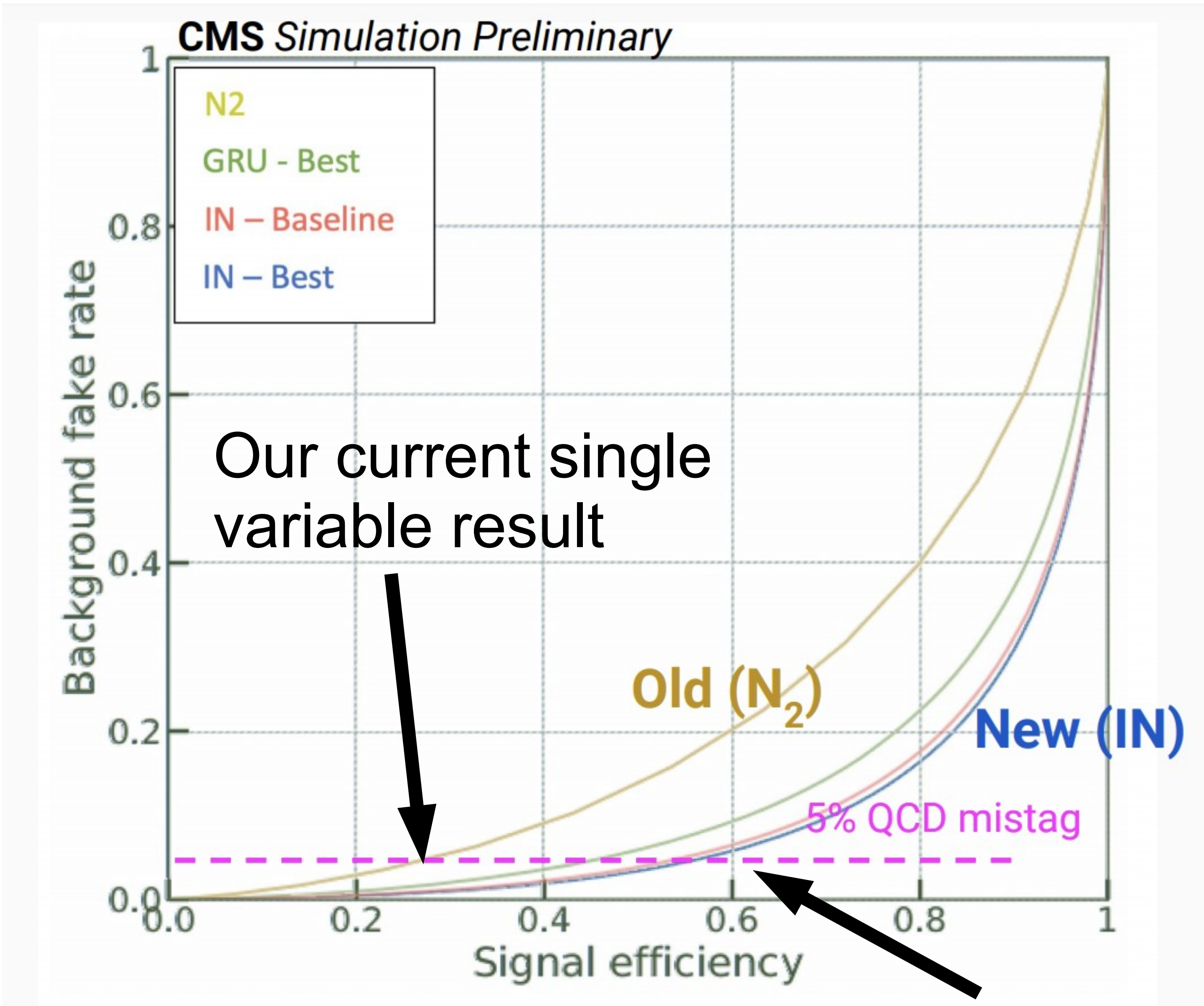
Get ID

Binary classification from all learned features



J.Krupa, D. Rankin, S. Siegel (UROP),K. Llewellen

Why are we so excited?



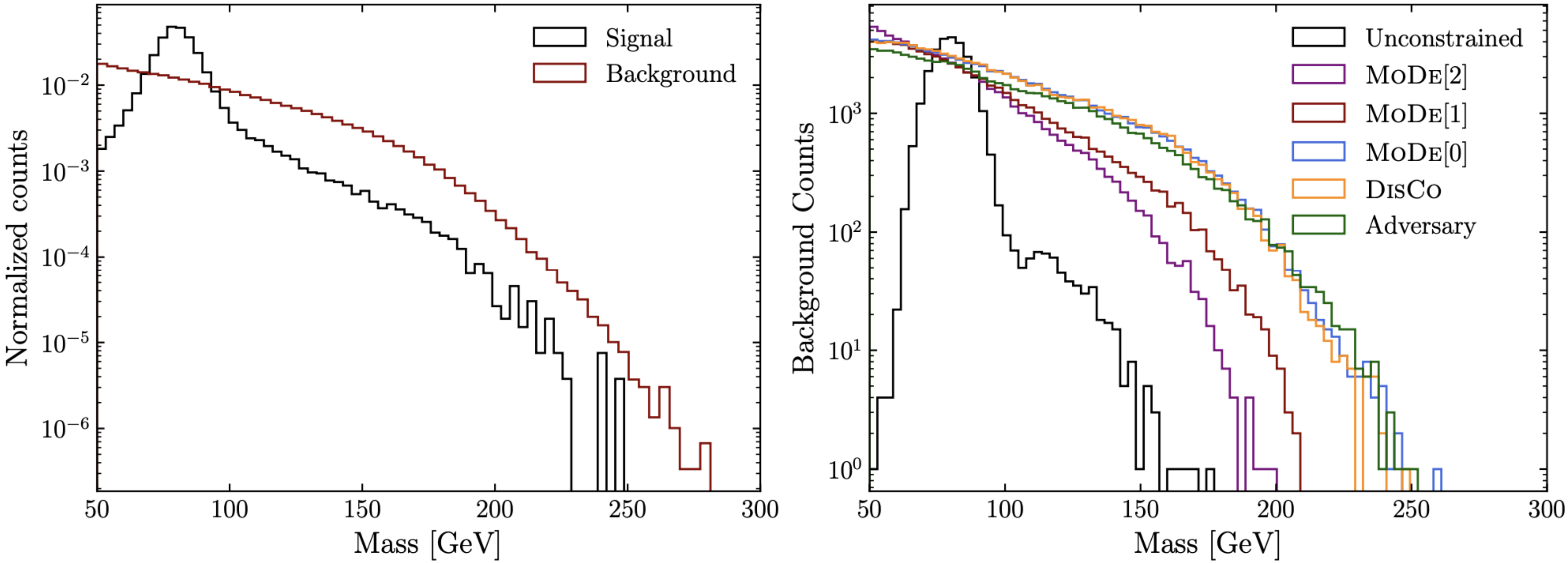
Our current single variable result

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

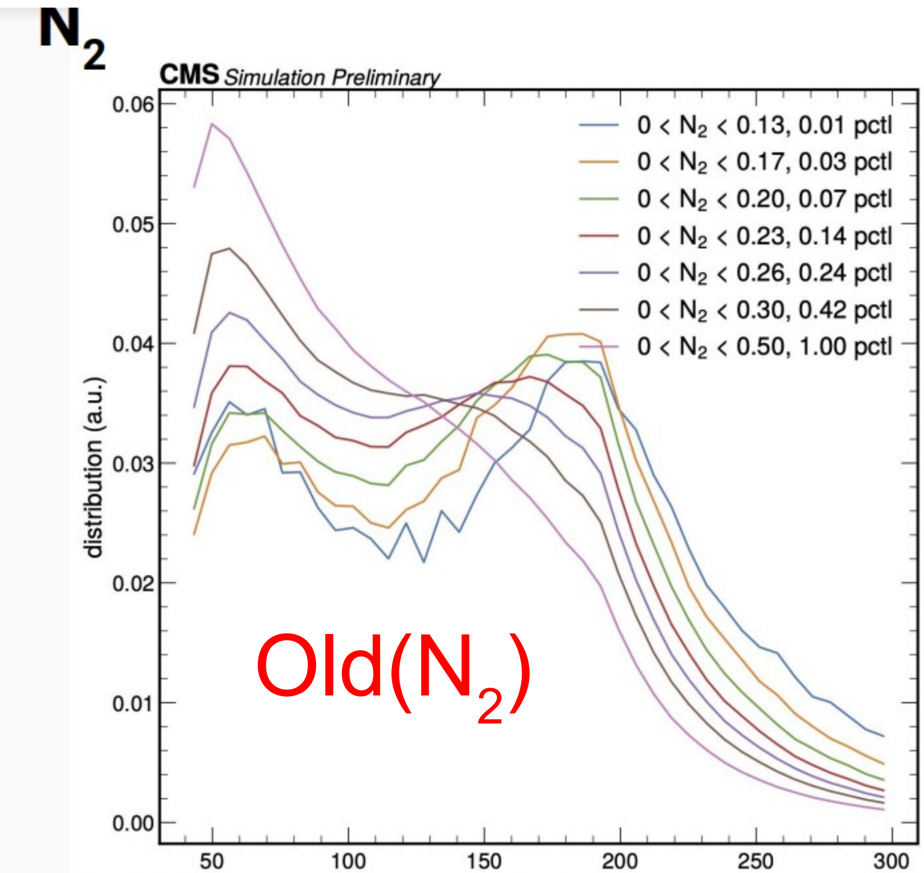


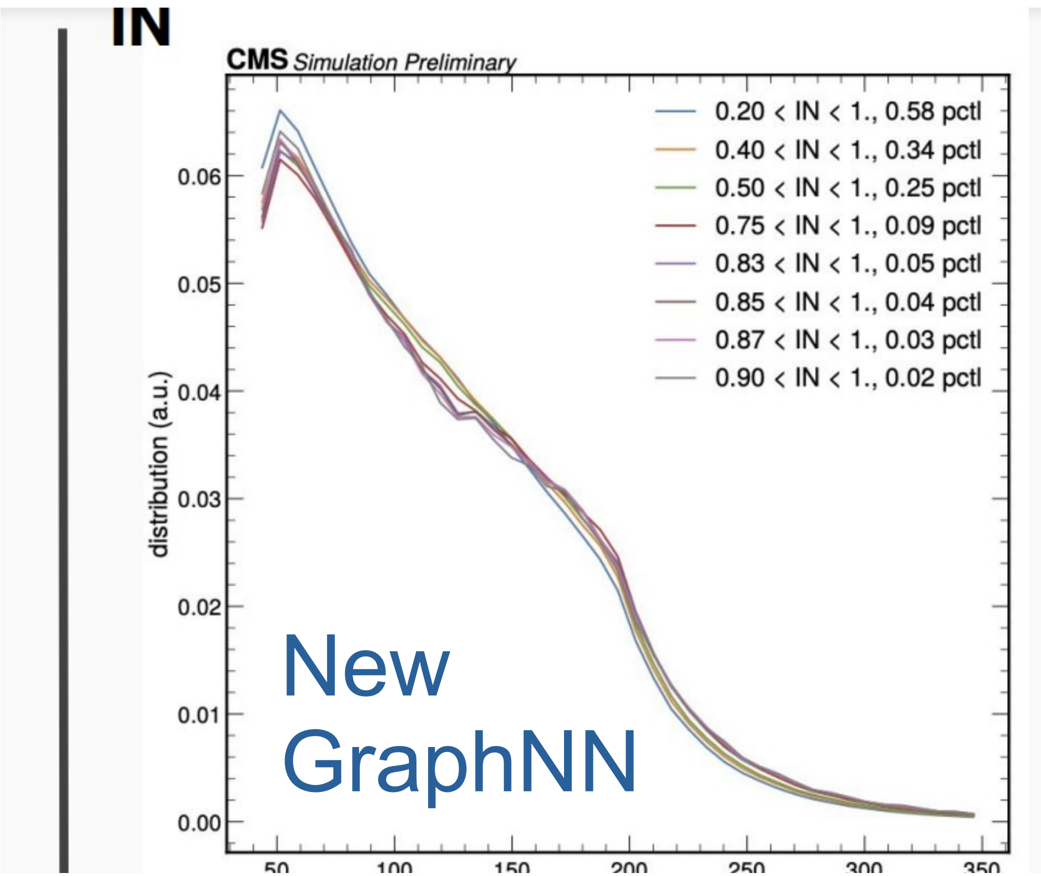
A lot of people have been trying to modify networks/ to enforce decorrelation

This only goes so far

J.Krupa, D. Rankin, S. Siegel (UROP),K. Llewellen

What about decorrelation?

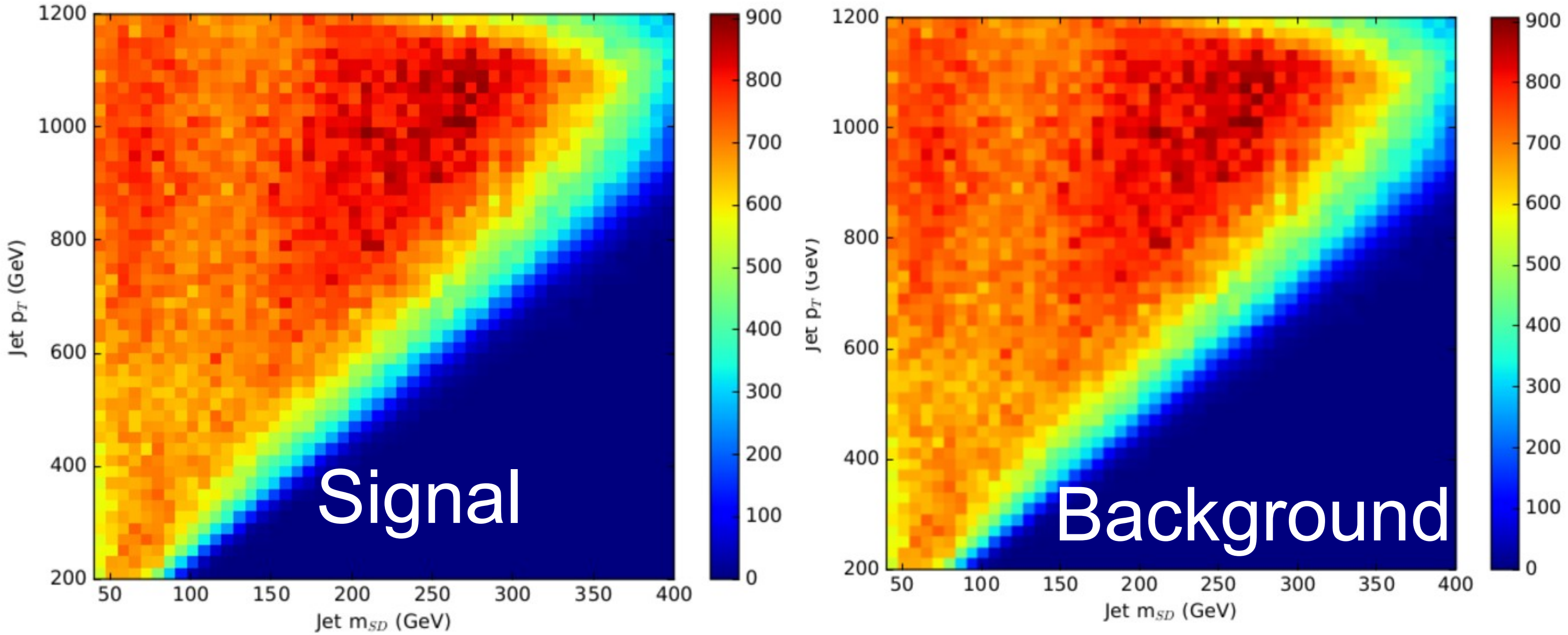




With some clever(unpublished) tricks
Our newest NNs are fully decorrelated

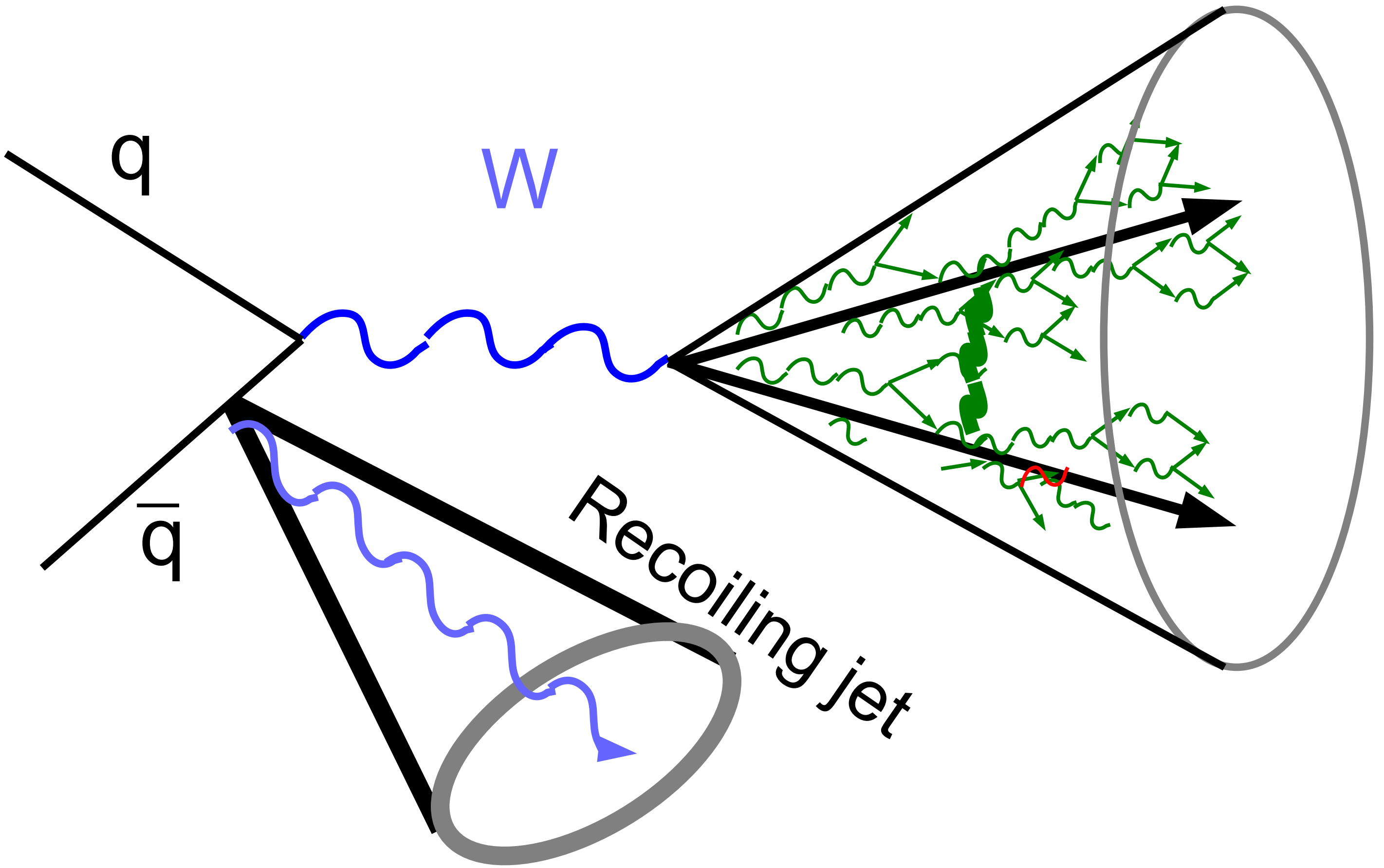
How did we de-correlate so well?

- 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



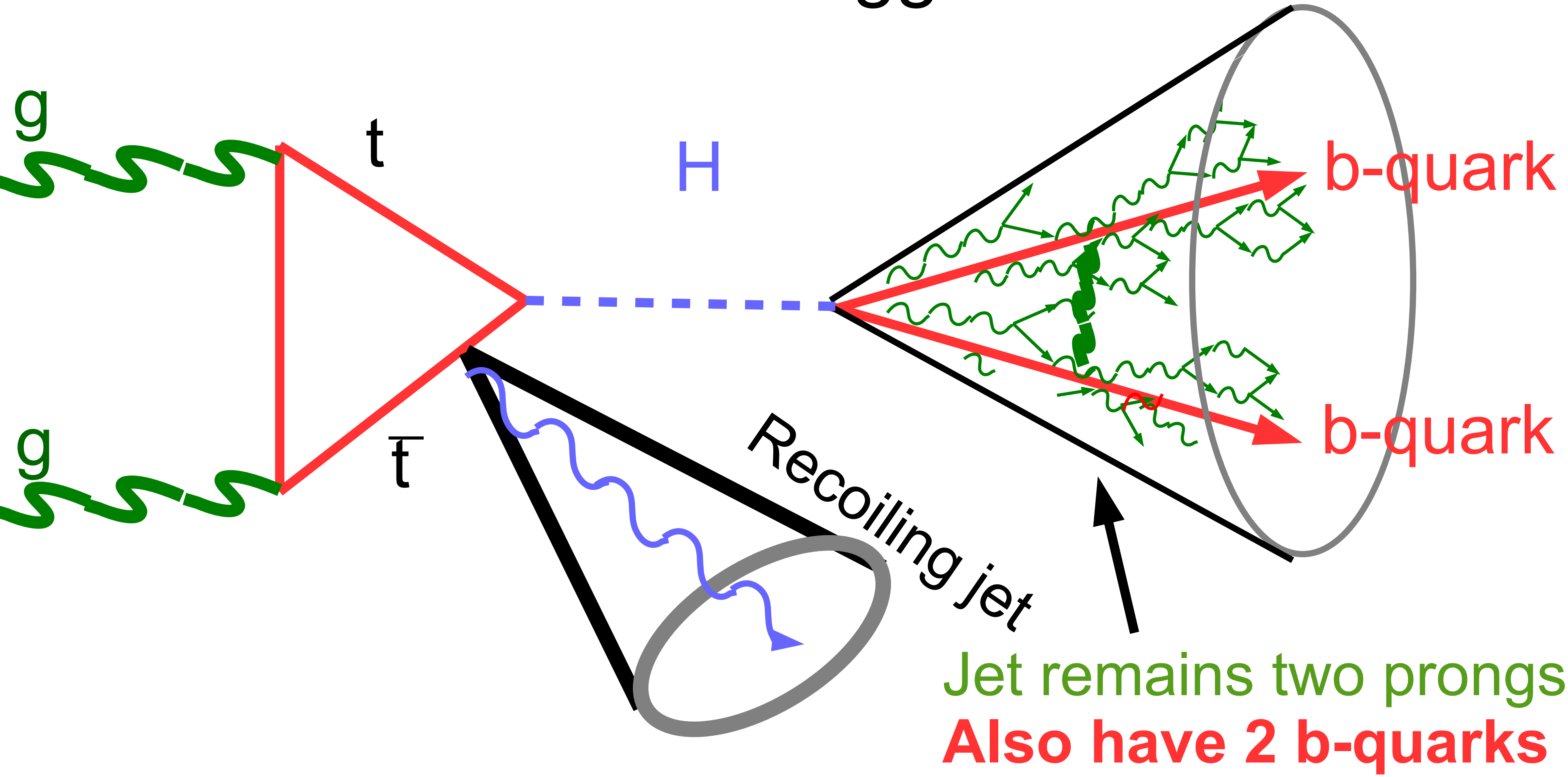
Changing Gears

We started with W production



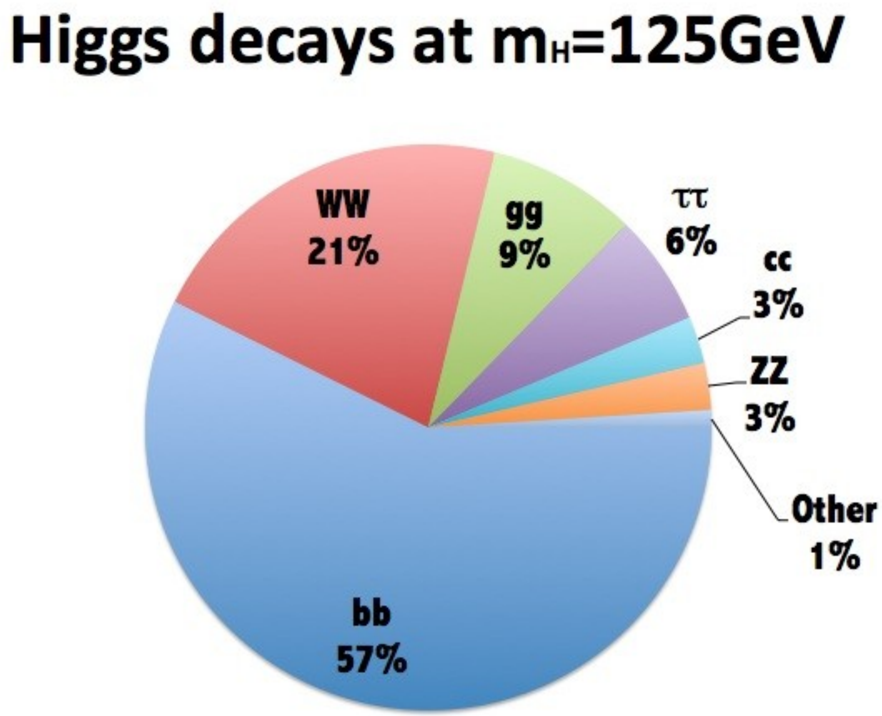
How do things change for Higgs

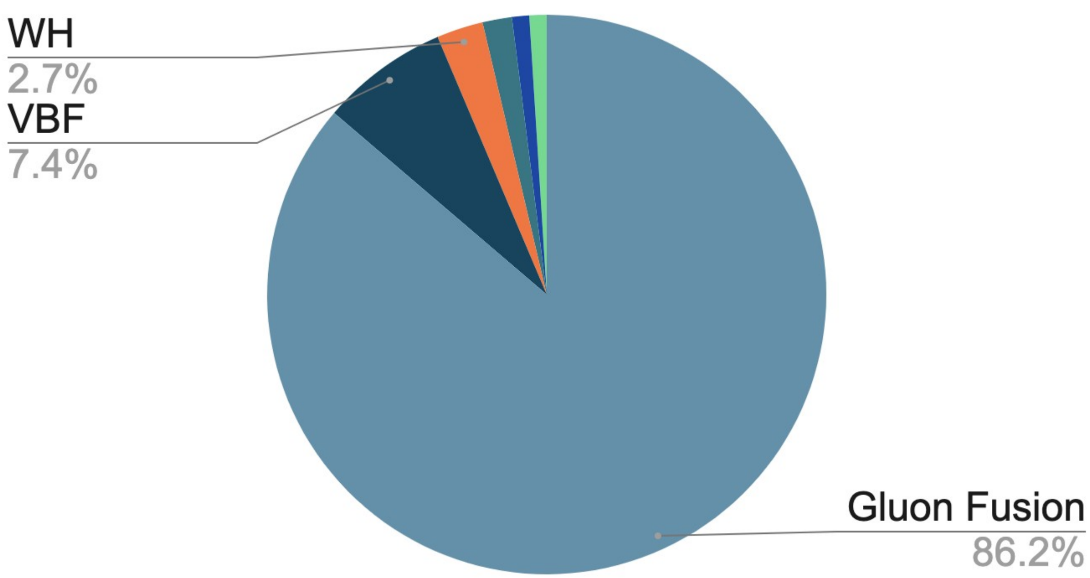
Now we can look for Higgs



Machine Learning has been the key to identifying b-quarks

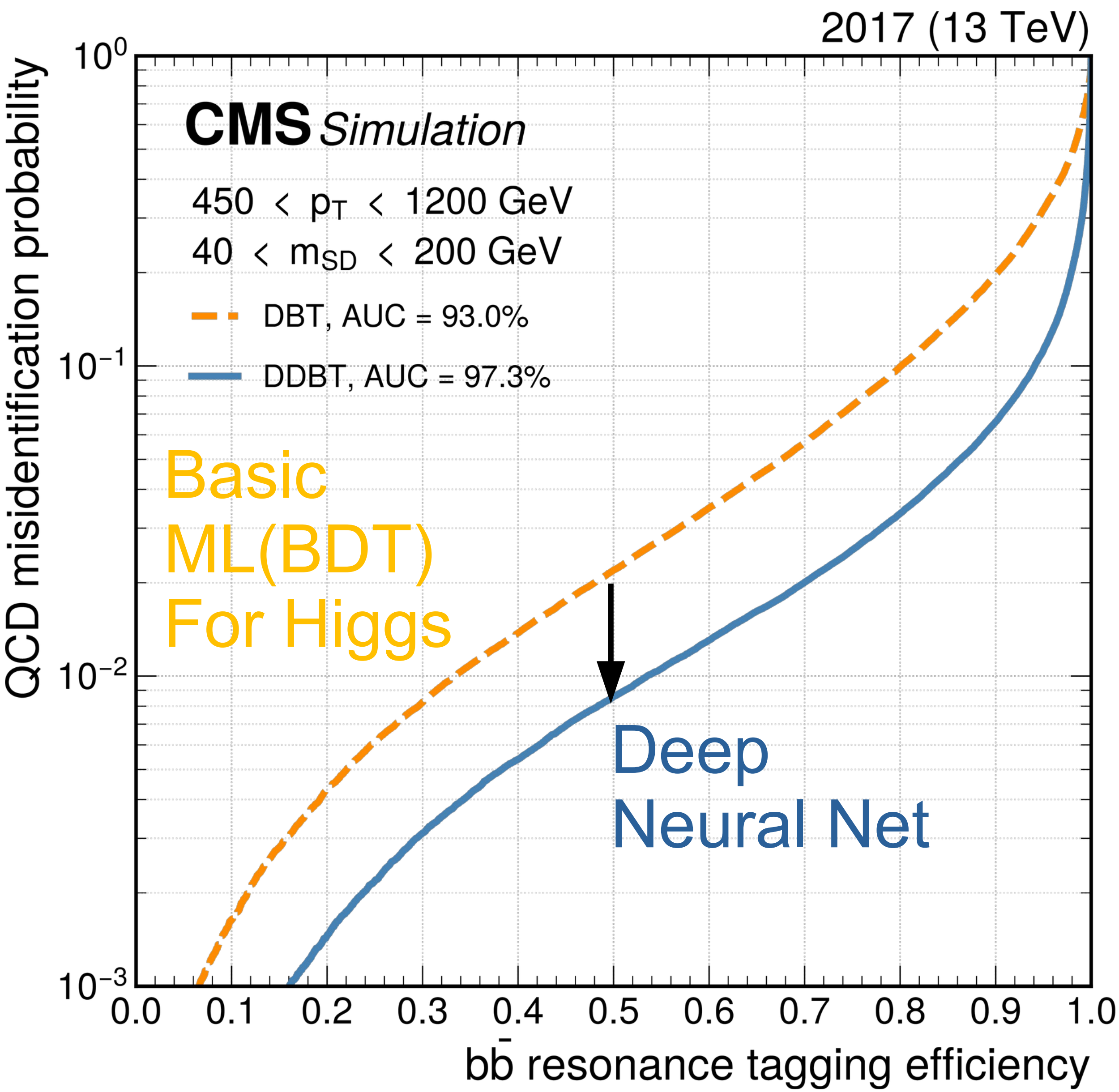
What is so special about this?





Higgs decays to b-quarks 58% of the time
Higgs is produced by gluon fusion 86% of the time
Highest single production mode (by x10)
Yet this channel was deemed to be impossible

What about the Higgs?

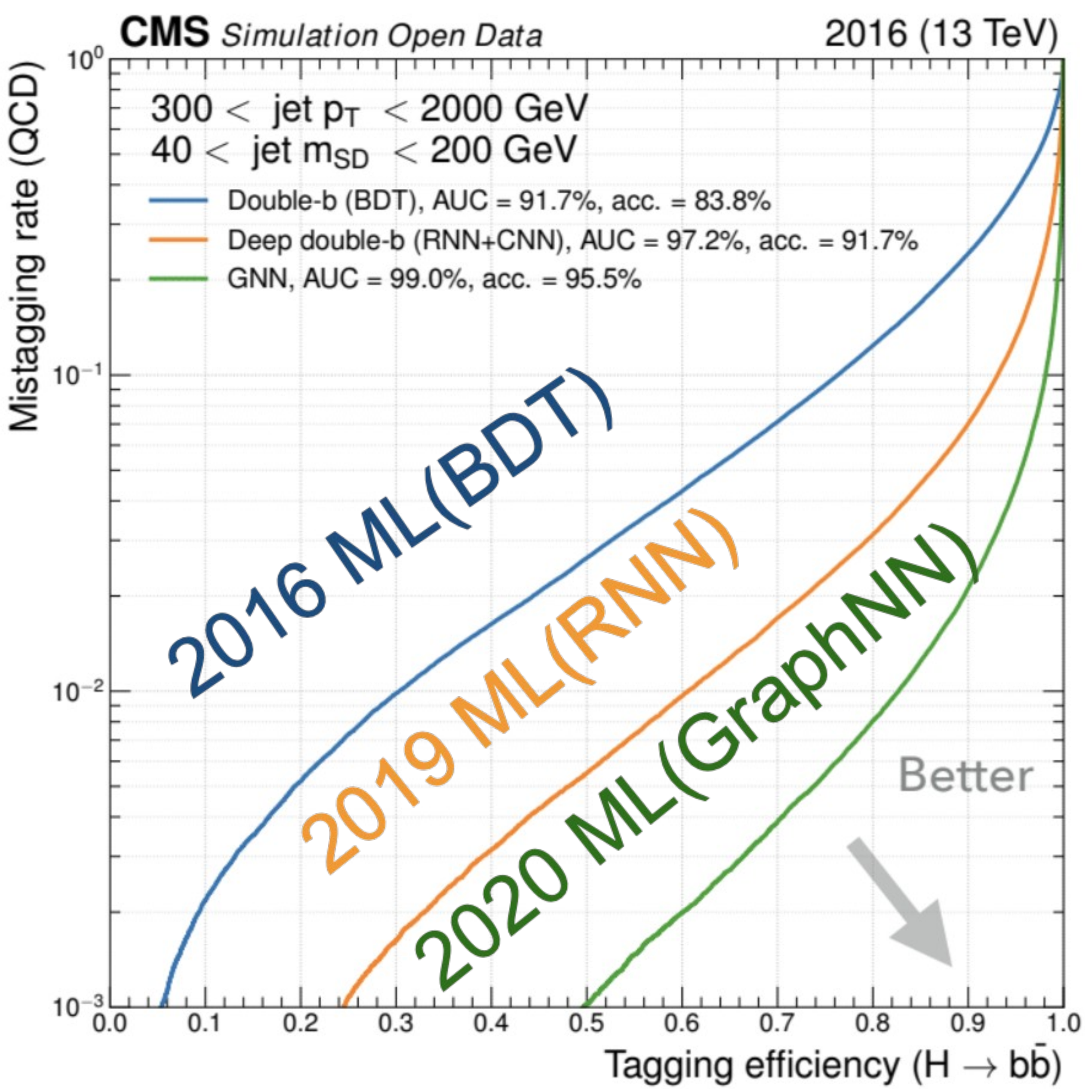


To identify the Higgs boson we need to remove background by even more

Key has been to use machine learning

Without these tools we could not have gotten there

Deep Learning Revolution and Higgs



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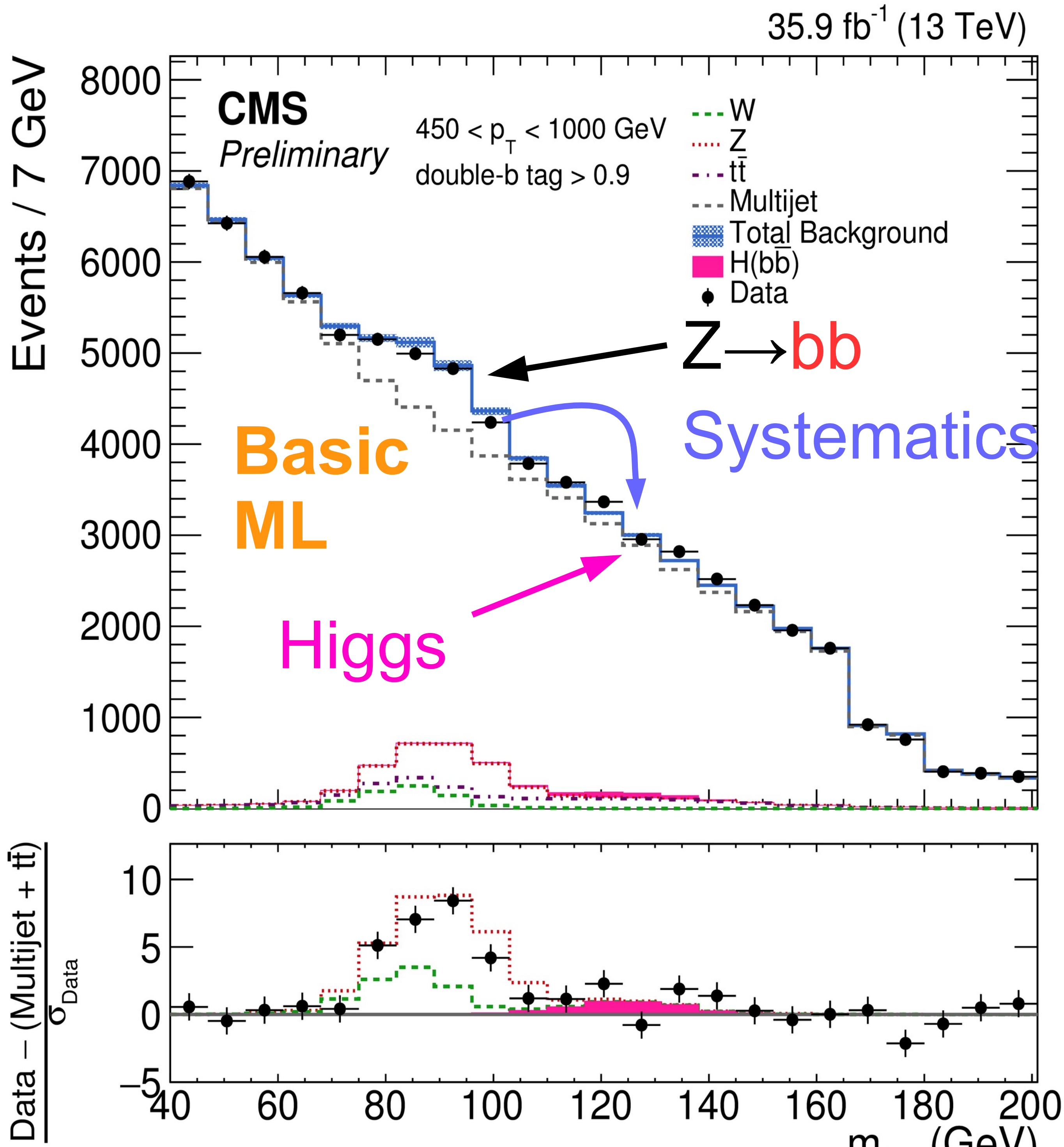
Without these tools we could not have gotten there

First Result

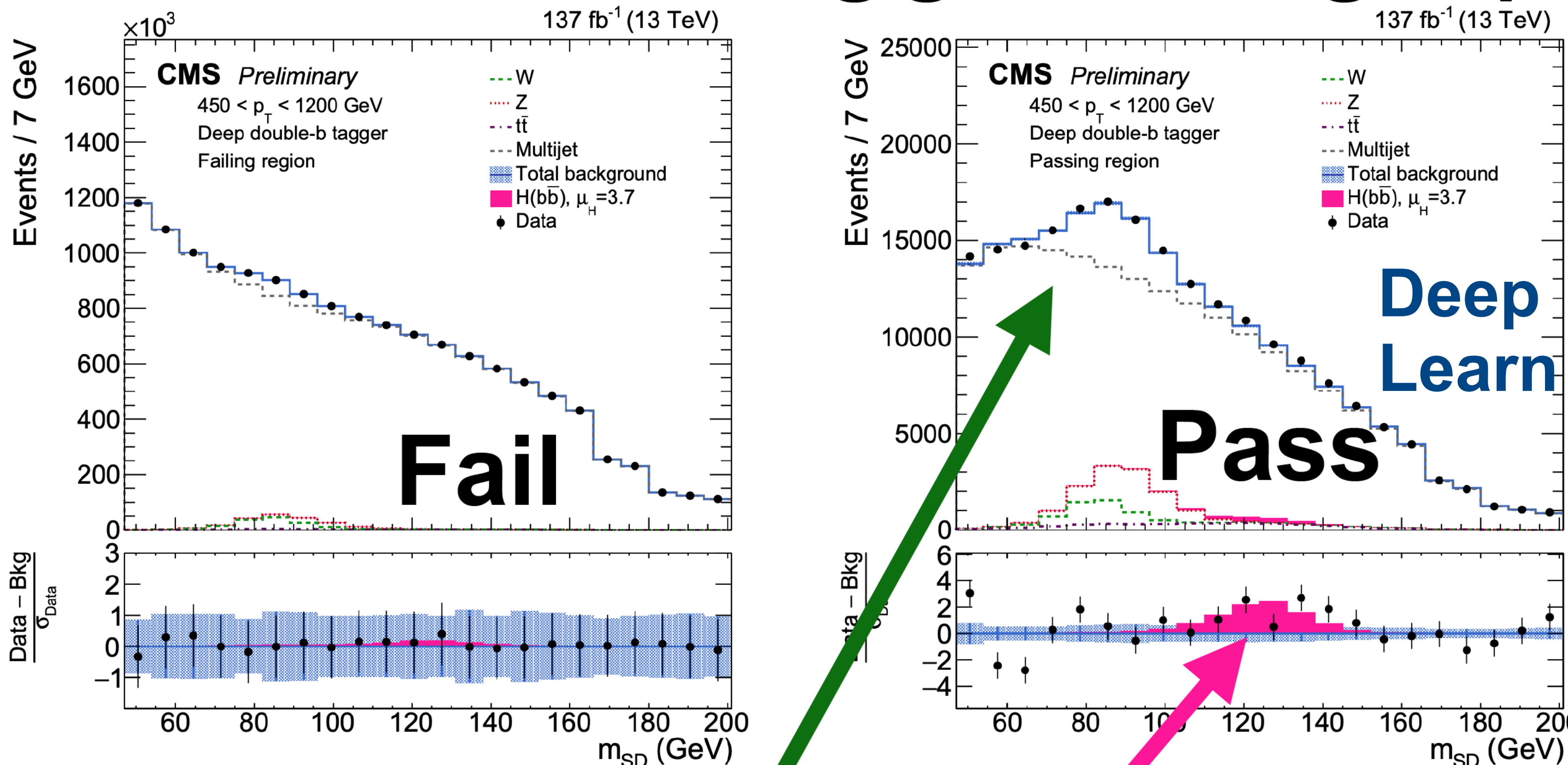


The large Z→bb Allows us to calibrate our signal

Z peak Allows us to calibrate Higgs

D. Rankin, S.E. Park

Higgs at high p_T



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

μ is wrt to LHC Higgs WG

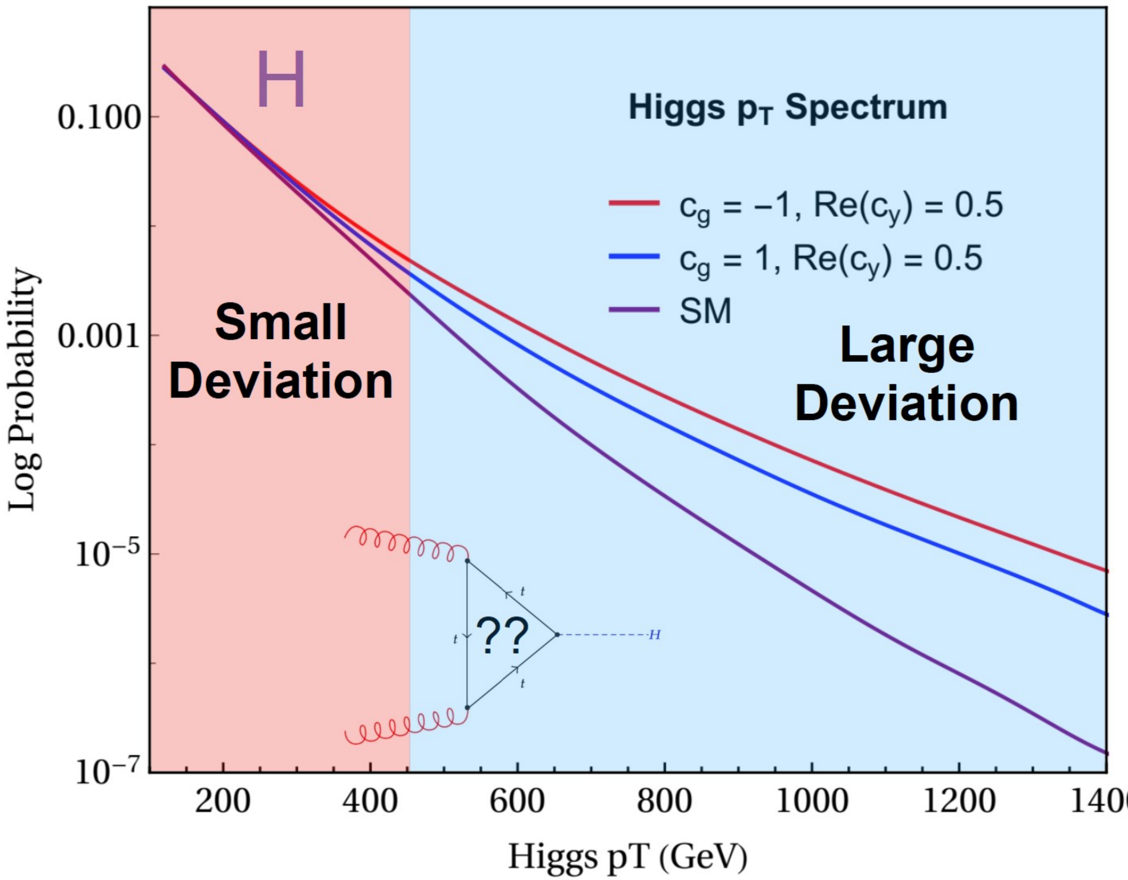
Large Excess at Higgs mass $\mu_H=3.7^{+1.6}_{-1.5}$ (2.5σ)

Physics Implications

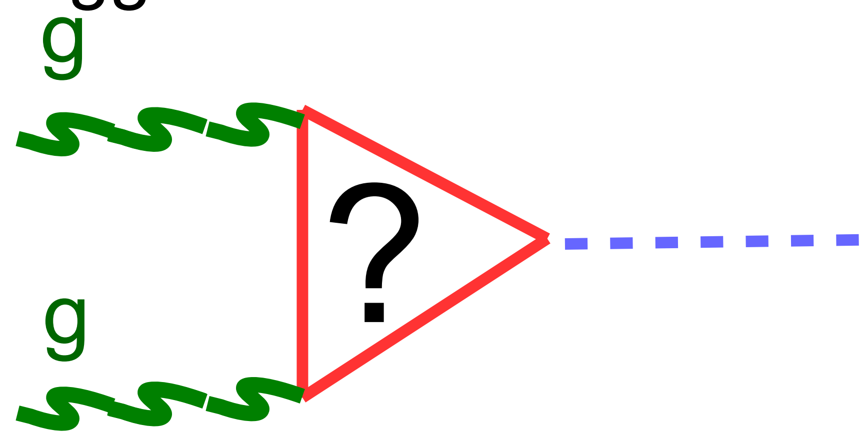
advantage of the harder transverse momentum spectrum of the $gg \to H$ production mode with
respect to the QCD background, a search for high p_T Higgs boson decaying to a pair of b quarks in
association with an energetic Initial State Radiation (ISR) jet, has been performed by ATLAS [155]
and CMS [156].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



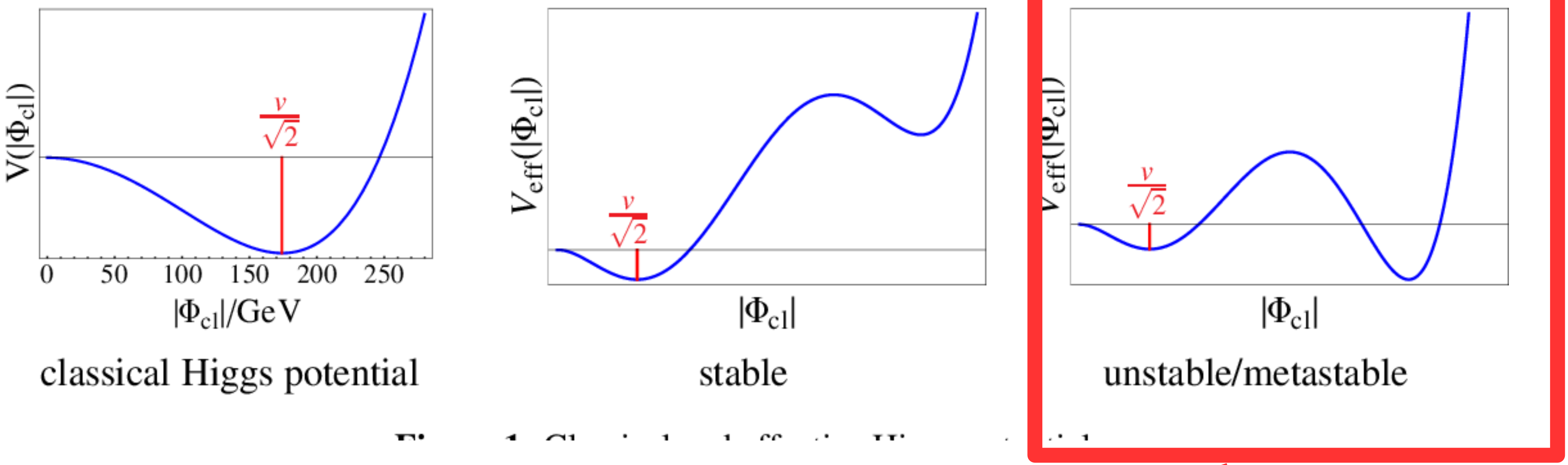
Can now measure Higgs process in the blue region

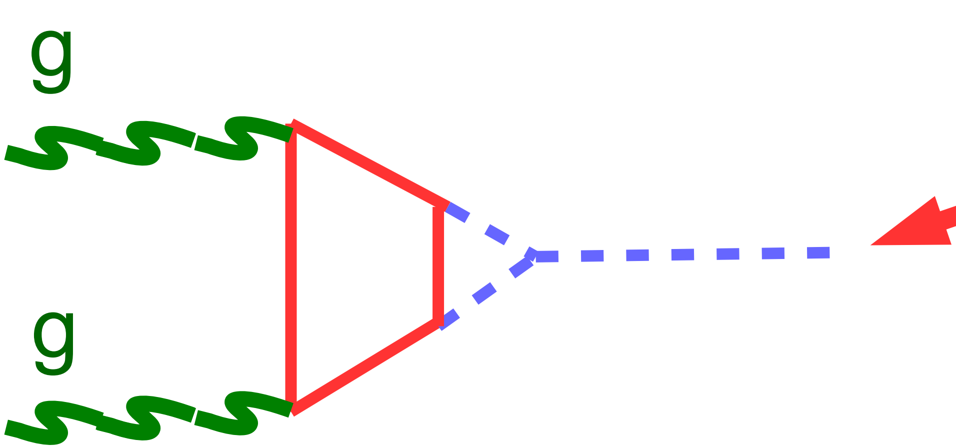
Could not before

Note: The prediction in this region is not well known

State of the Universe

- What does this have to do with it?

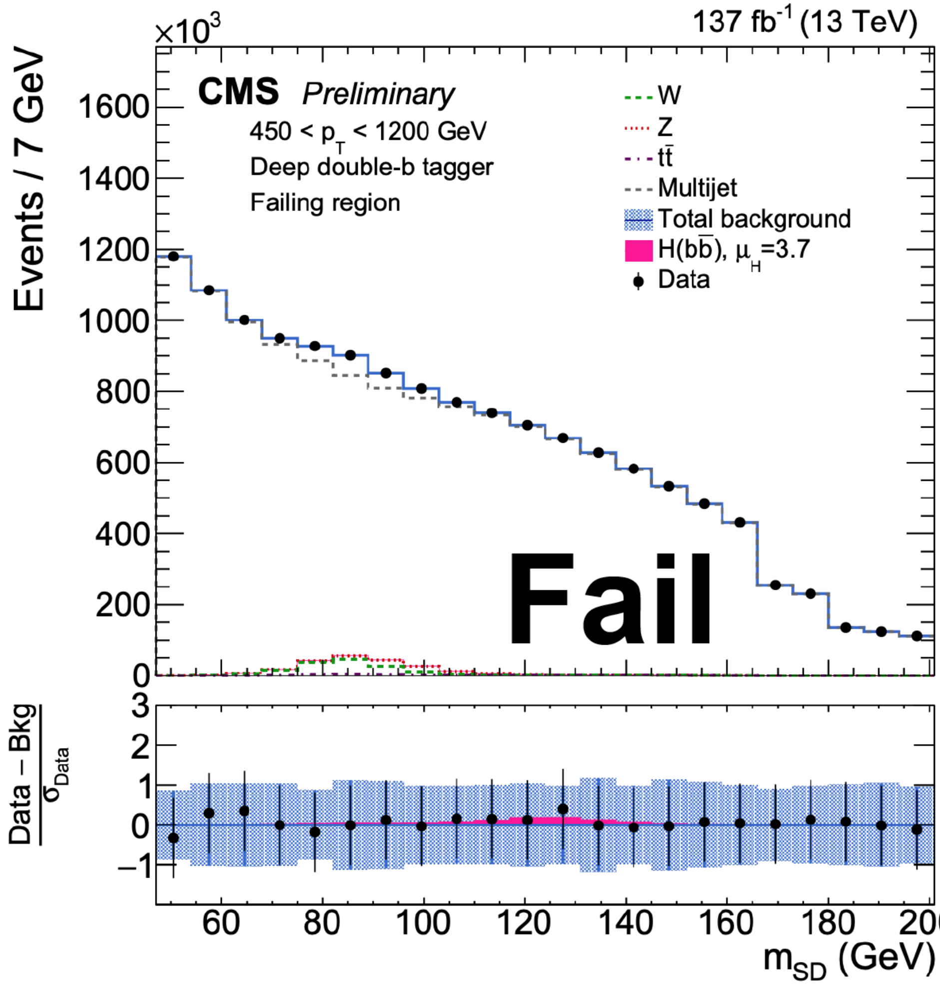


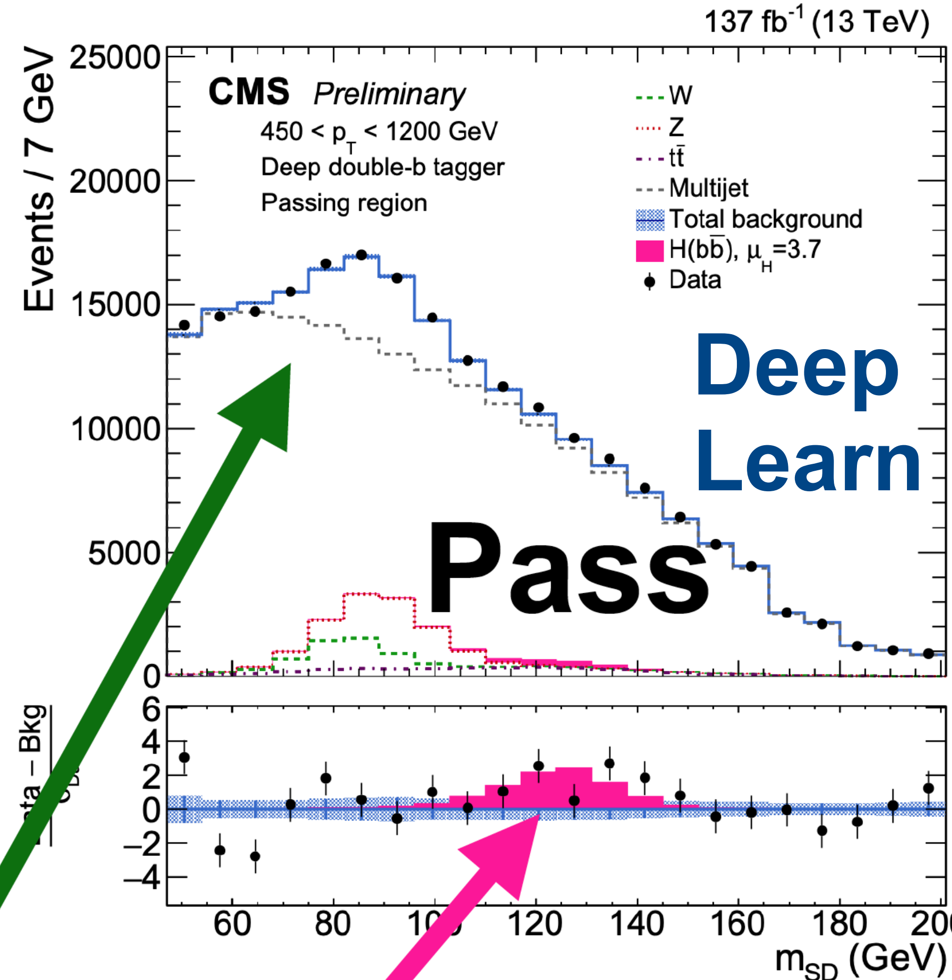


High energy regime *potentially* tells us about the stability of the Higgs potential

D. Rankin, S.E. Park

Higgs at high p_T





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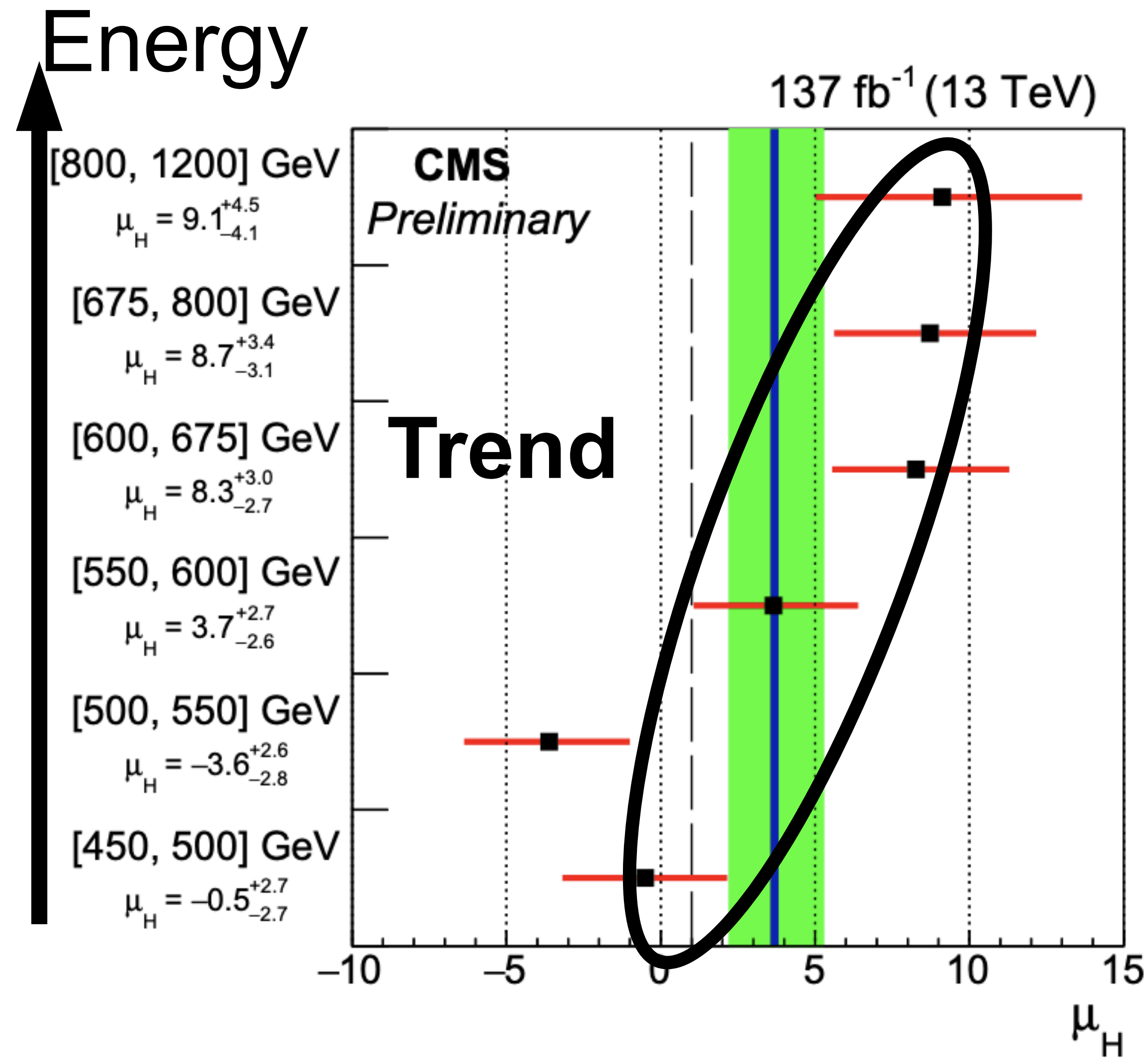
Large Excess at Higgs mass $\mu_H=3.7^{+1.6}_{-1.5}$ (2.5σ)

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…..

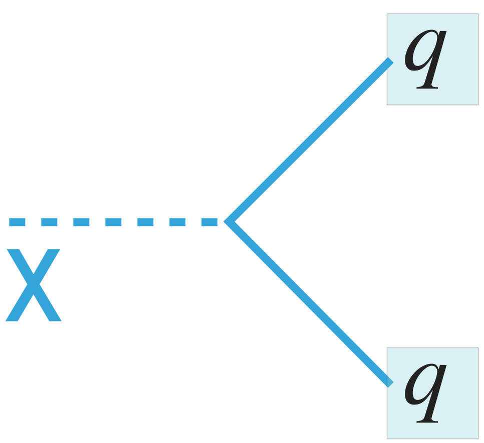
Our prediction for high energy Higgs bosons is off
Higgs boson production at high energy is HARD

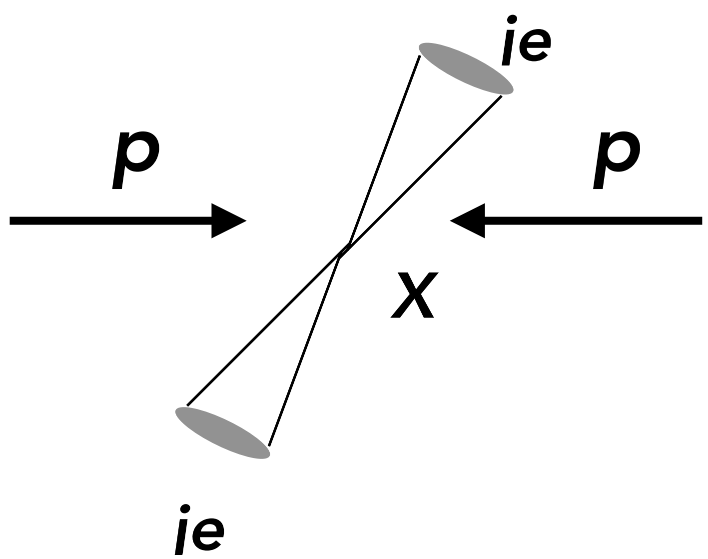
There is the potential of some new physics

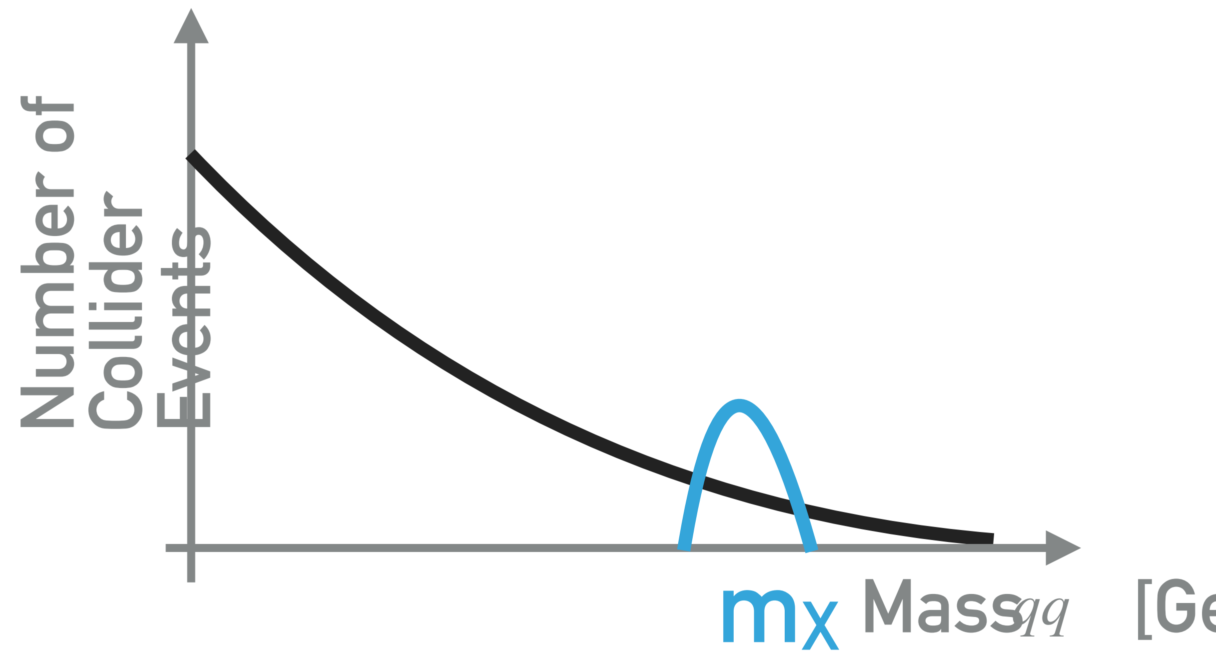
We are not yet at the point where we can make a significant claim

Low mass (qq) resonances

Looking for a resonance
At the LHC





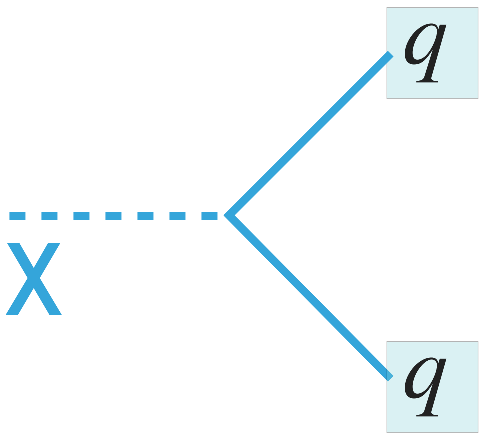


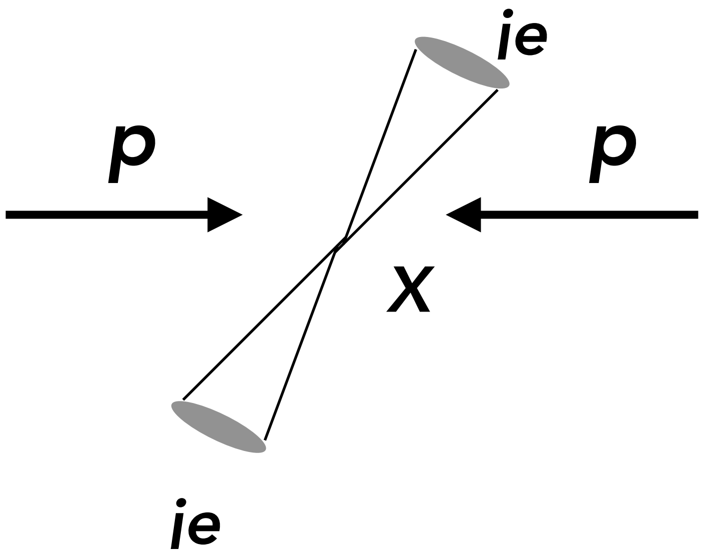
p_T < 200 GeV

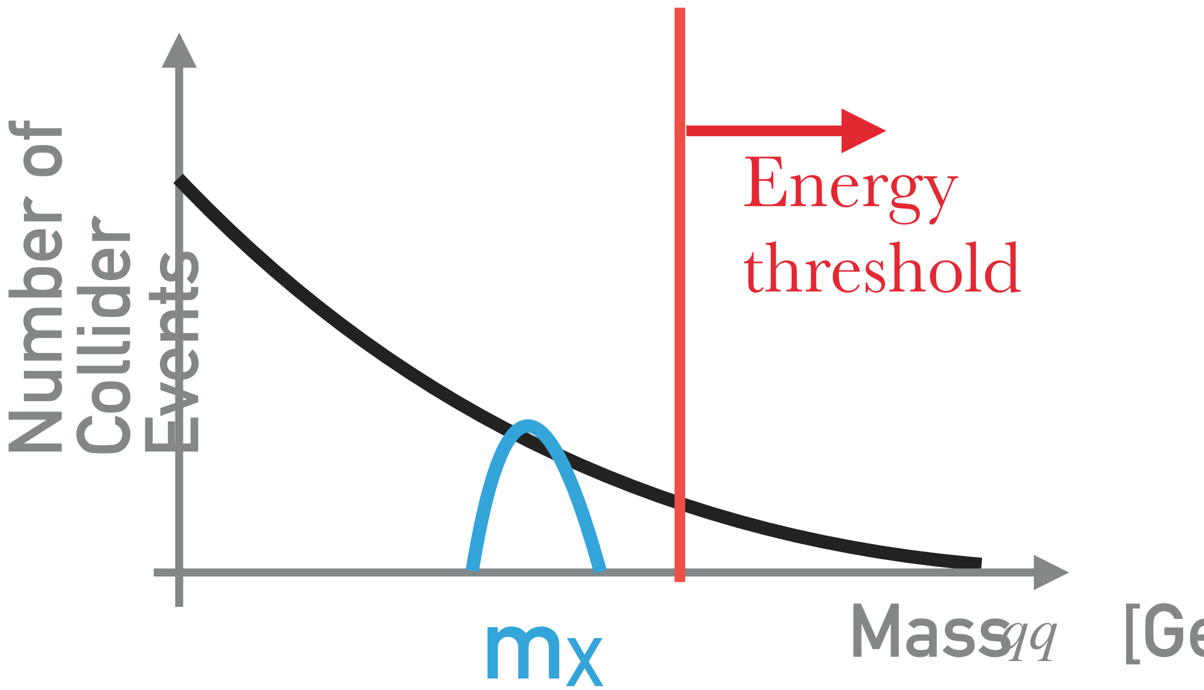
m_X > 500 GeV

If m_X < 500 GeV, event does not get saved

LHC has tight energy thresholds (mass thresholds)





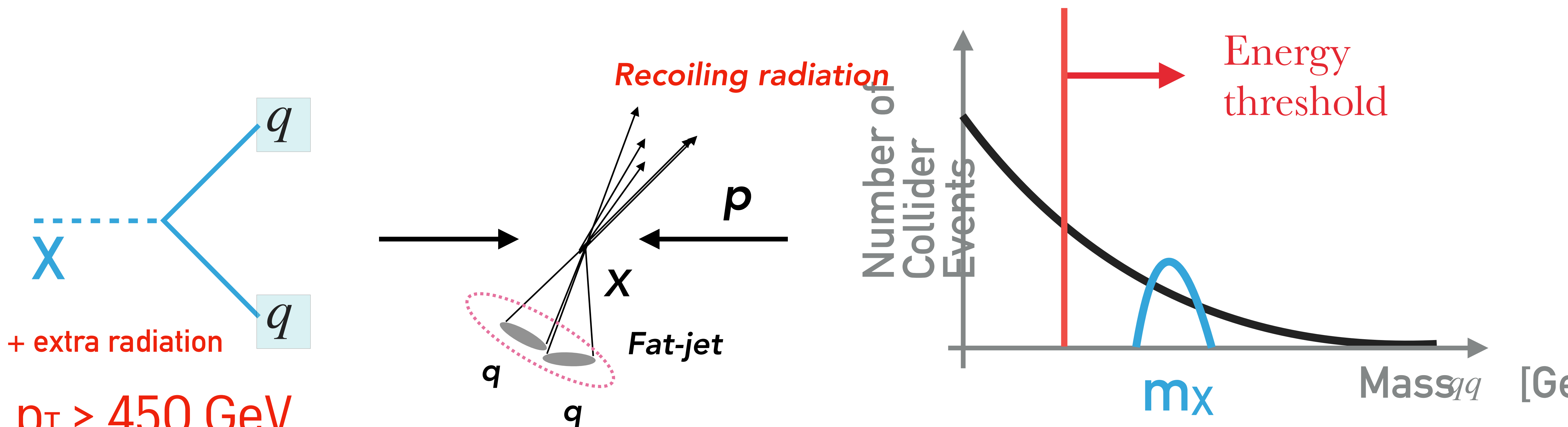


p_T < 200 GeV

m_X < 500 GeV

How to save these events

Boost them!

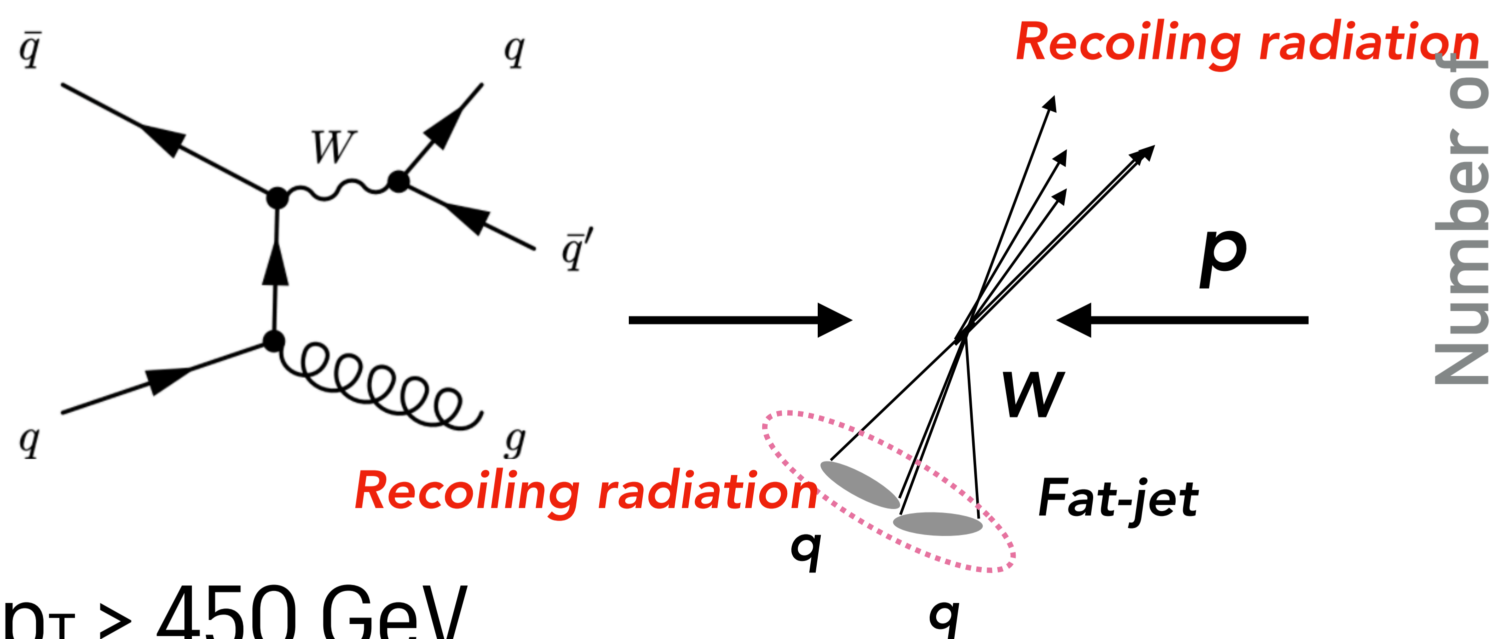


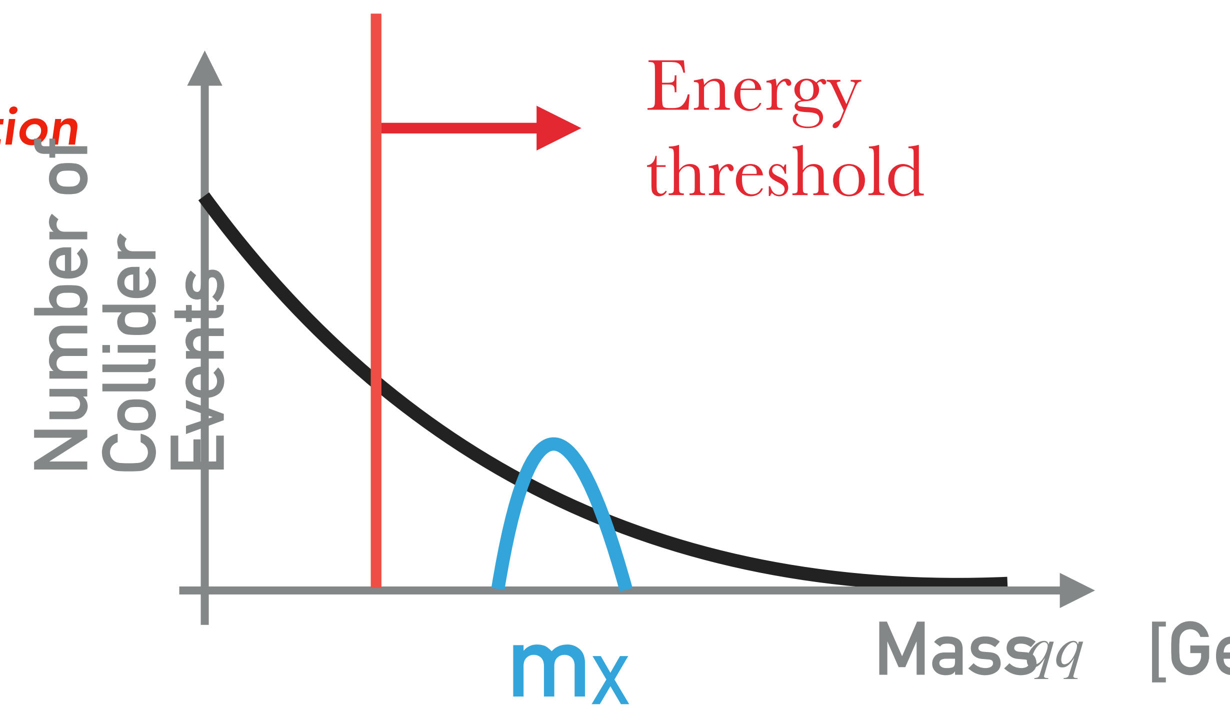
p_T > 450 GeV

m_X < 500 GeV

What the process looks like

And what you'll be looking for





p_T > 450 GeV

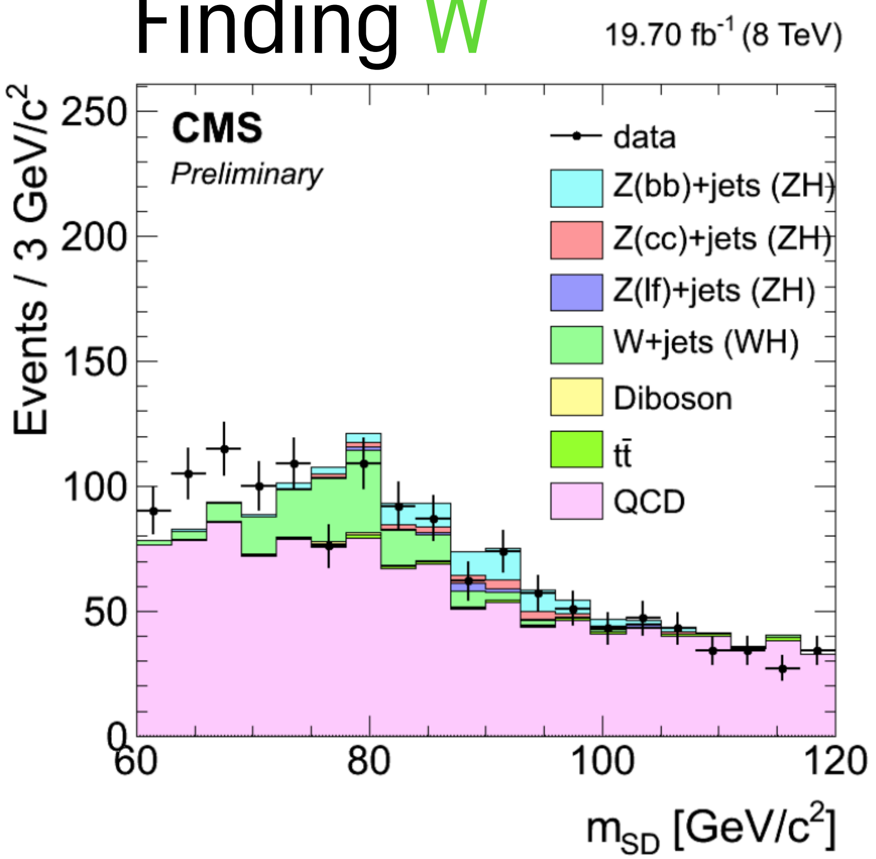
m_W ~ 80.4 GeV

Your goal: reproduce LHC results (or improve them)

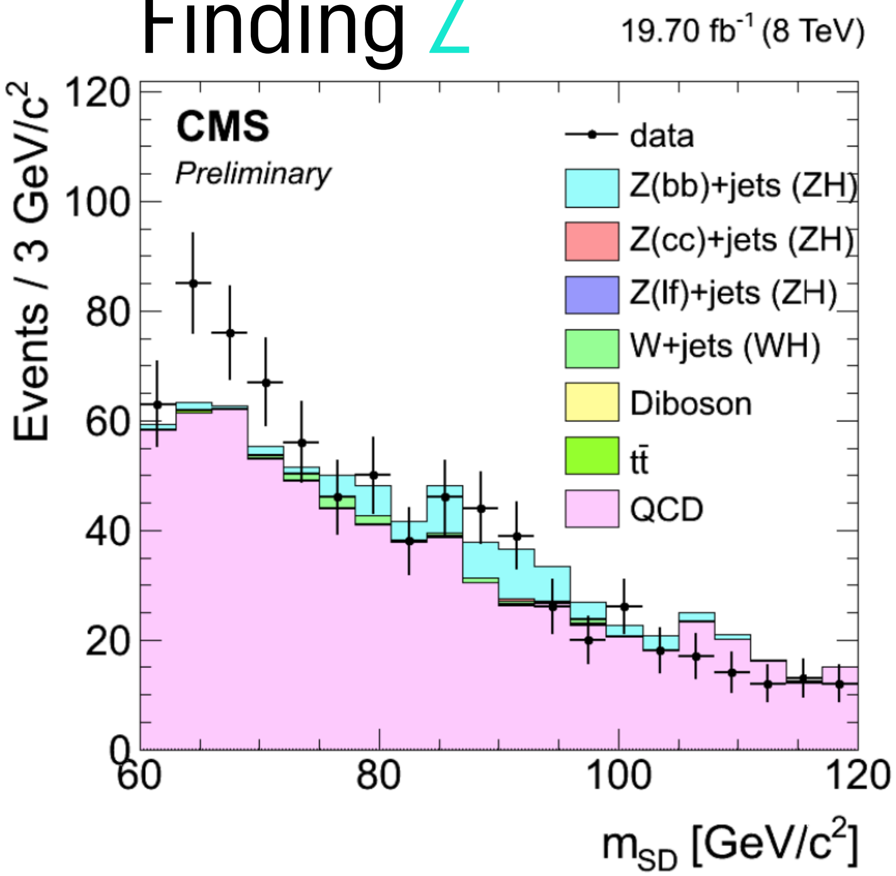
With 8 TeV data

@ 8 TeV (2015)

Finding W



Finding Z

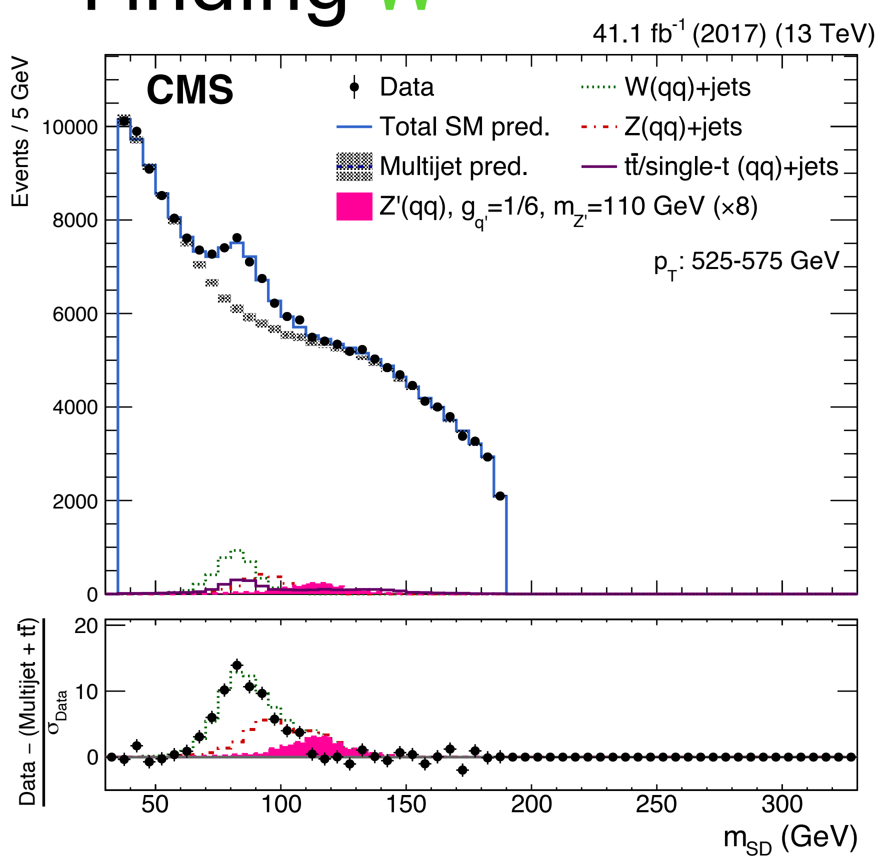


Your goal: reproduce LHC results (or improve them)

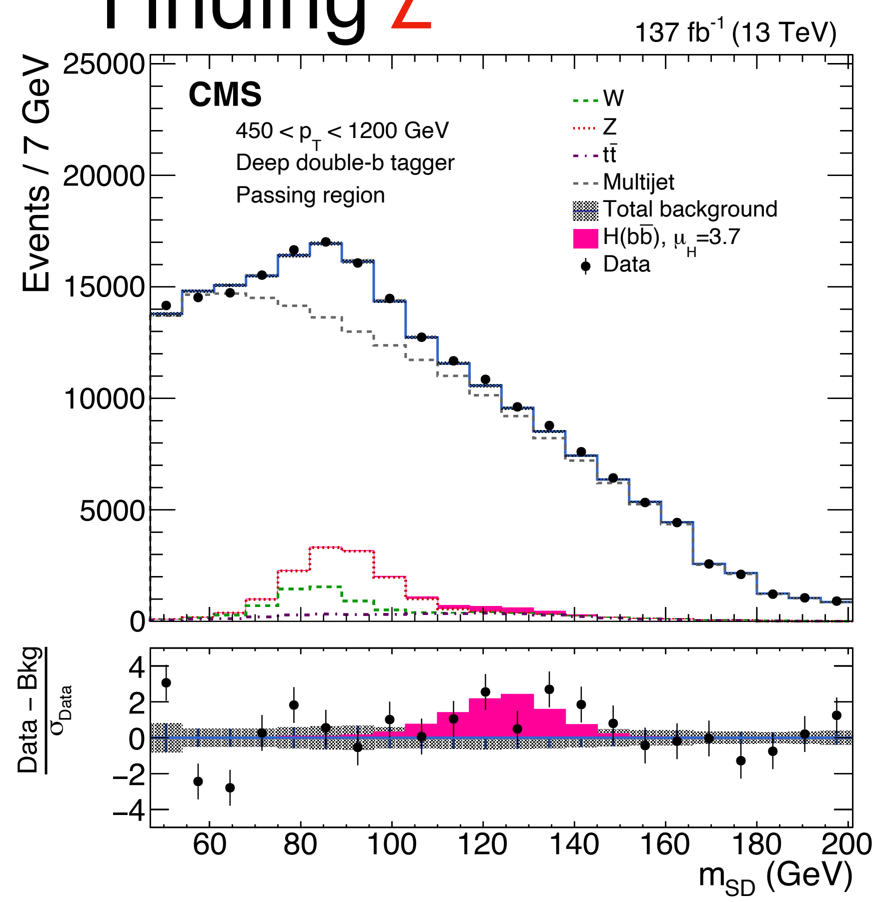
With 8 TeV data

@ 8 TeV (2015)

Finding W

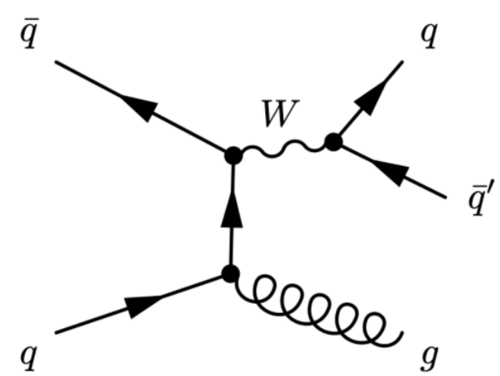


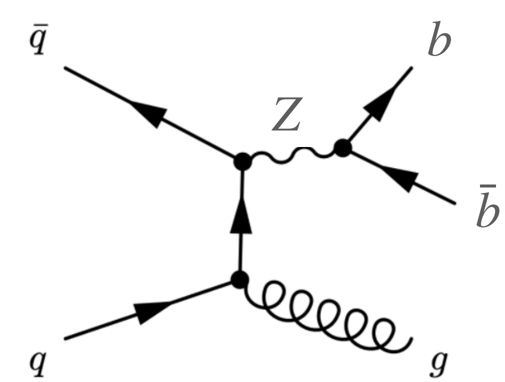
Finding Z



Project 2

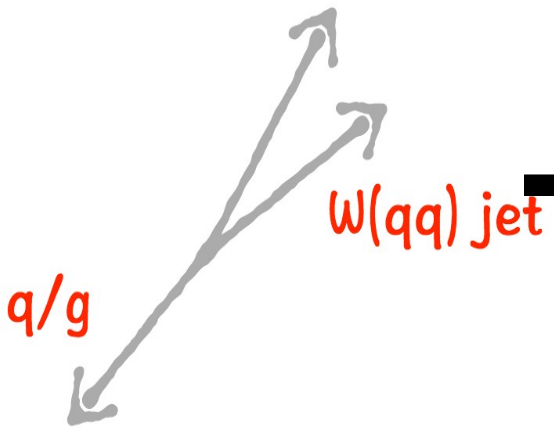
Finding W(qq) and Z(qq) in 8 TeV LHC data



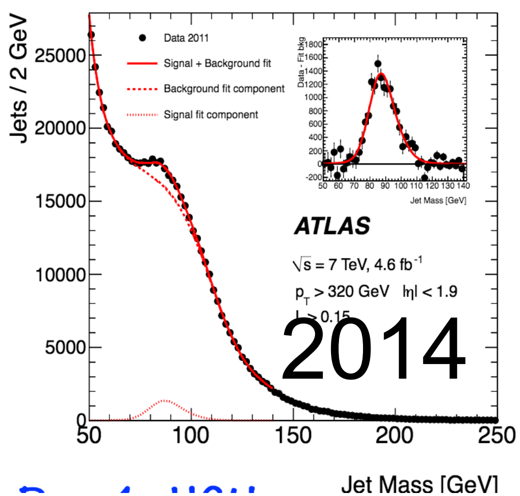


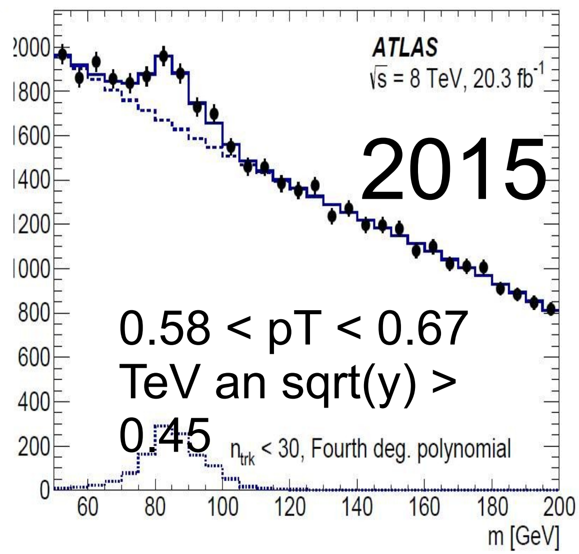
Introduction

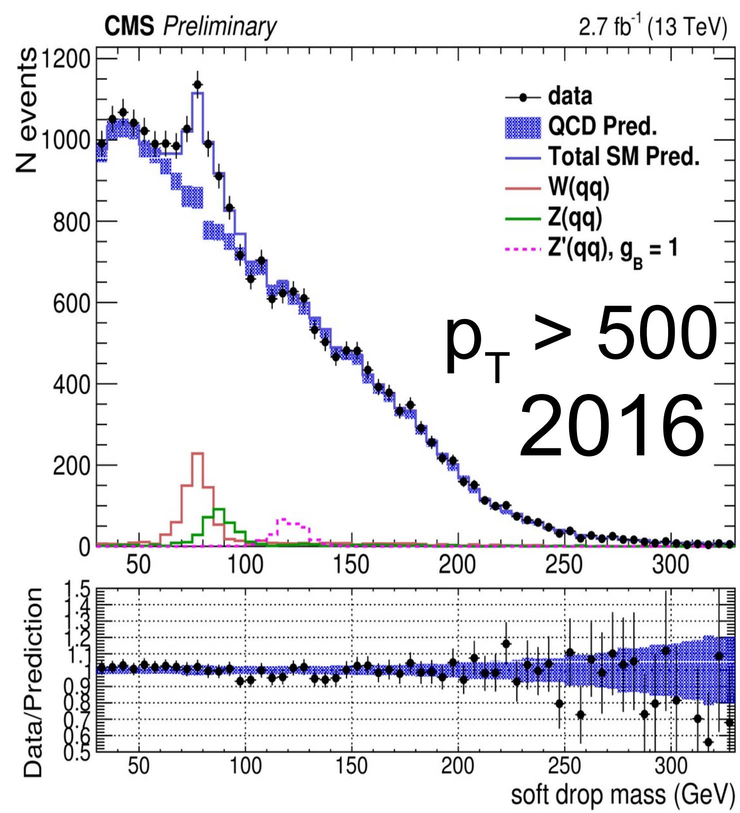
In this lab we will investigate W bosons produced in the LHC's 8 TeV proton proton collisions. These samples were produced 4 years ago in a fun experiment that opened up the option of performing low mass resonance searches at the LHC. The studies done then have led to a wealth of results from both LHC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



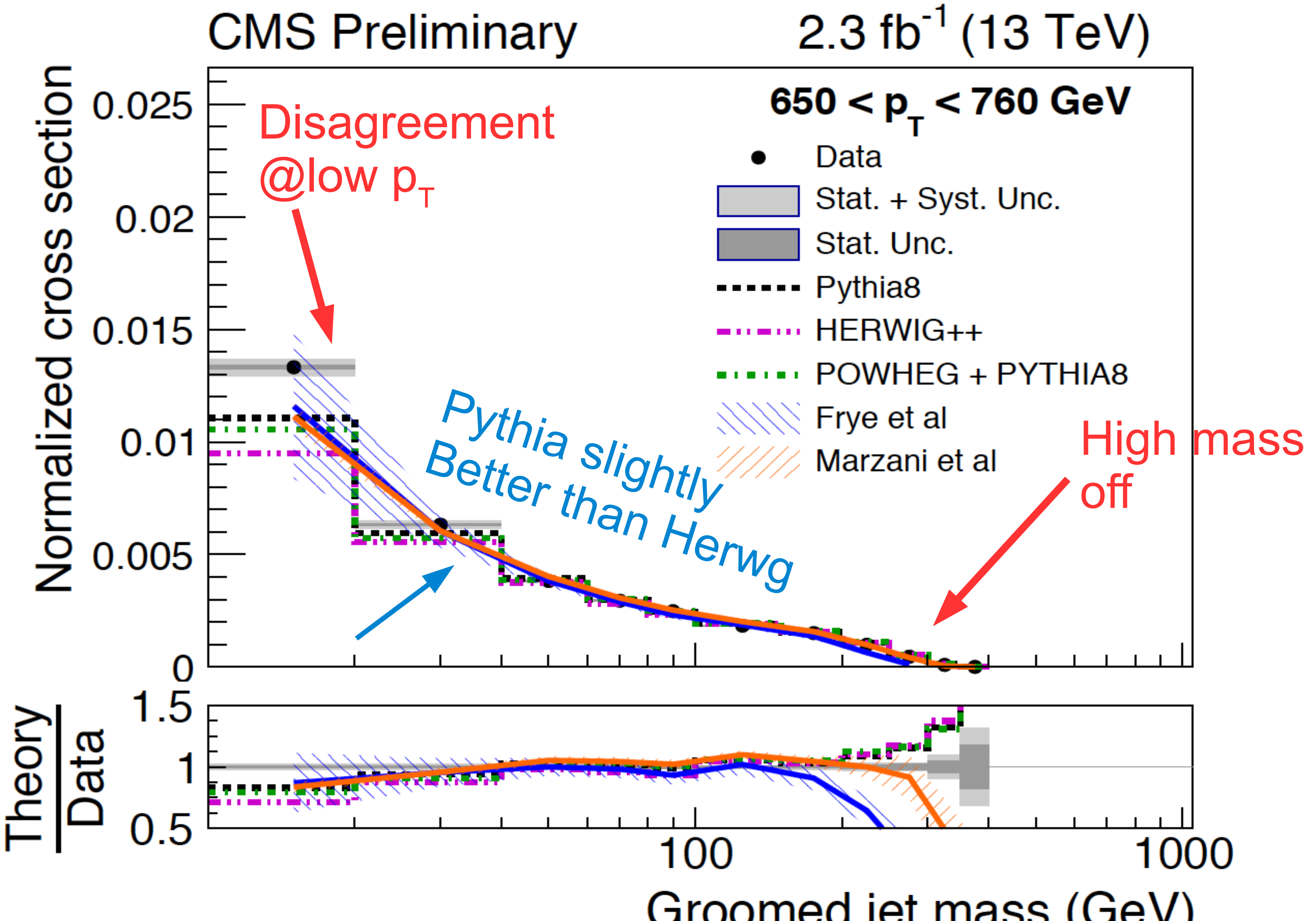
Thanks!







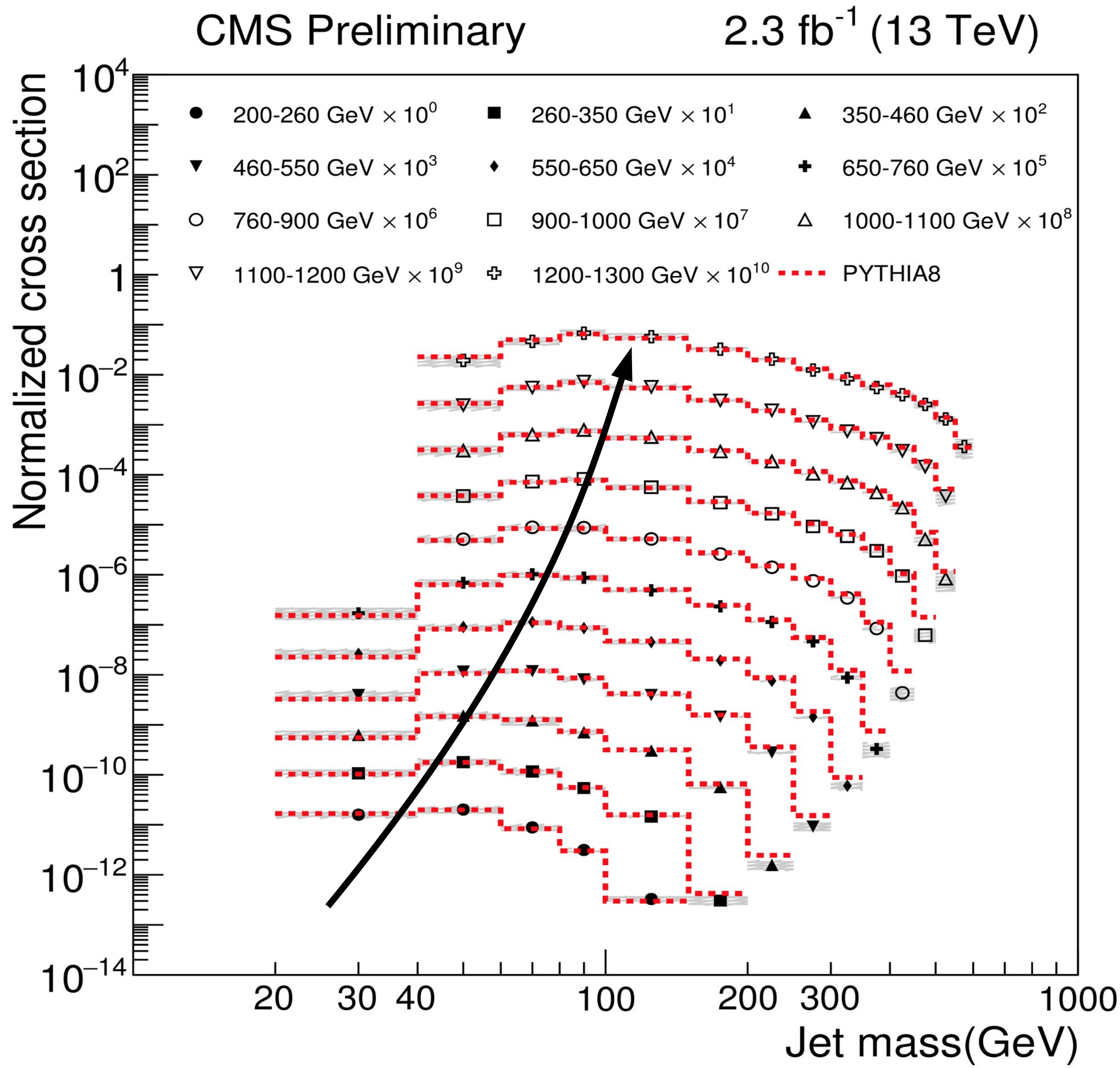
This peak has only been observed over past 2 year



CMS-SMP-16-010

Evolution of Mass Peak

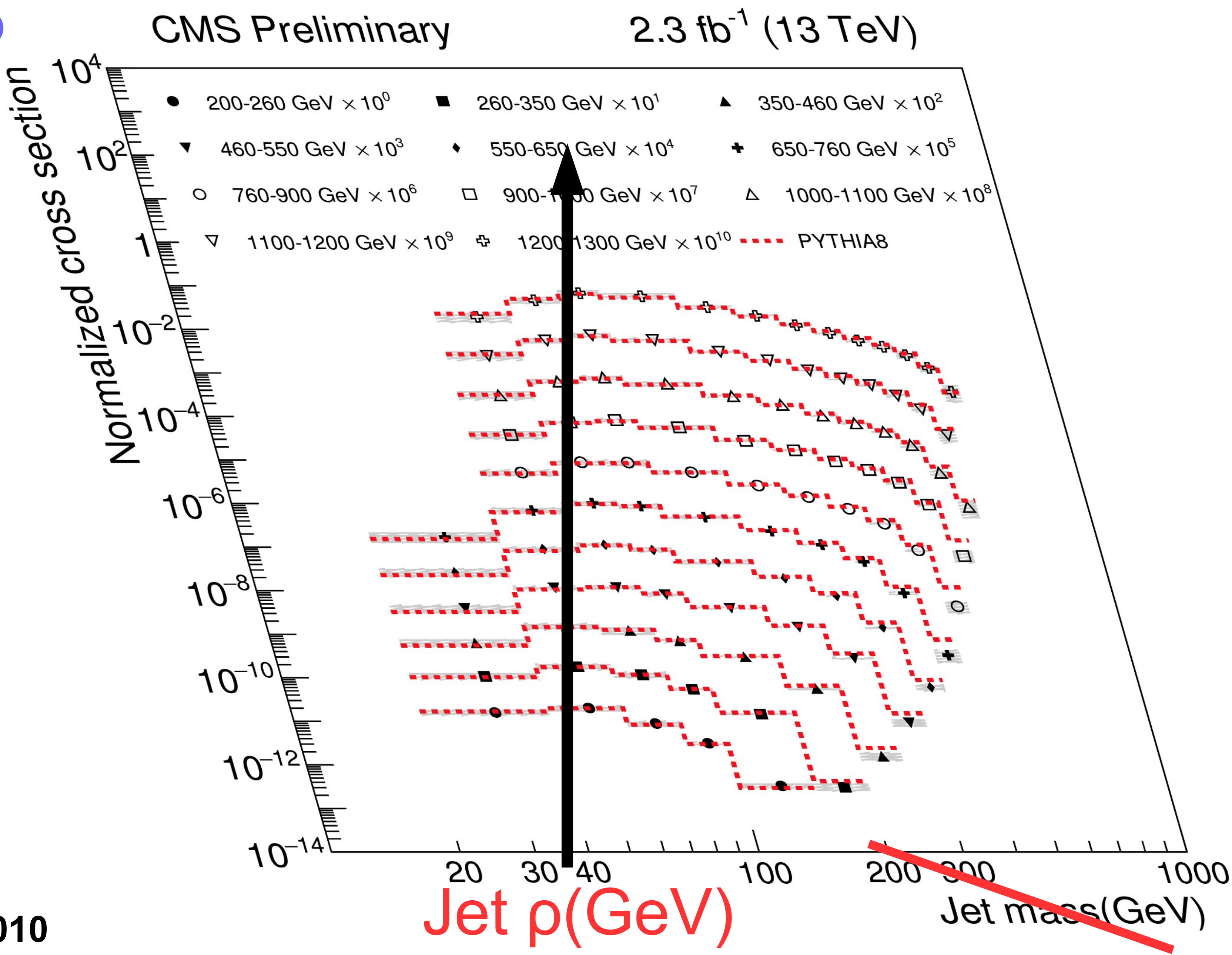
Clear trend in observed mass



CMS-SMP-16-010

Evolution of Mass Peak

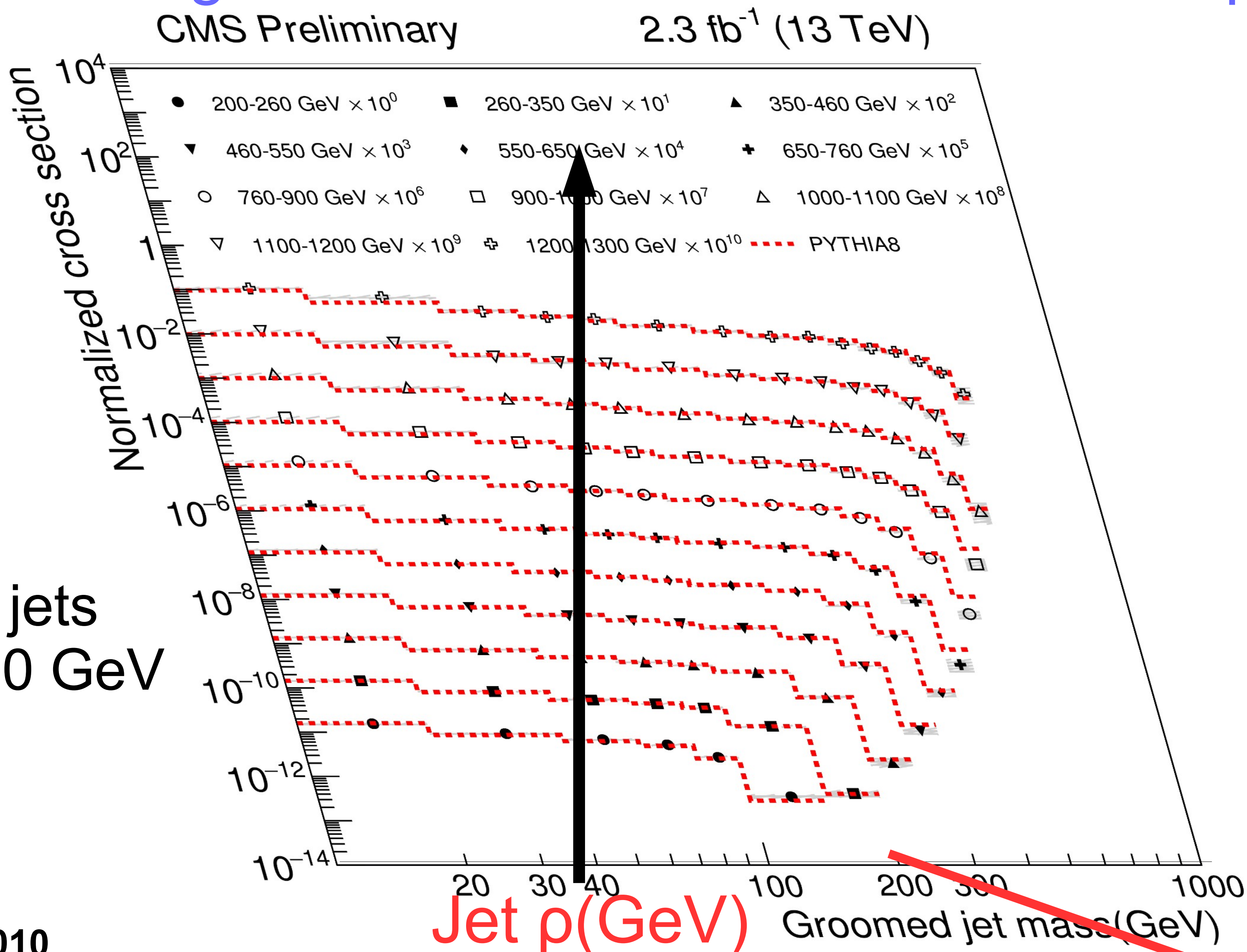
Trend becomes straight
When transform from
mass→ρ



CMS-SMP-16-010

Groomed Evolution

When grooming the mass becomes even flatter in ρ

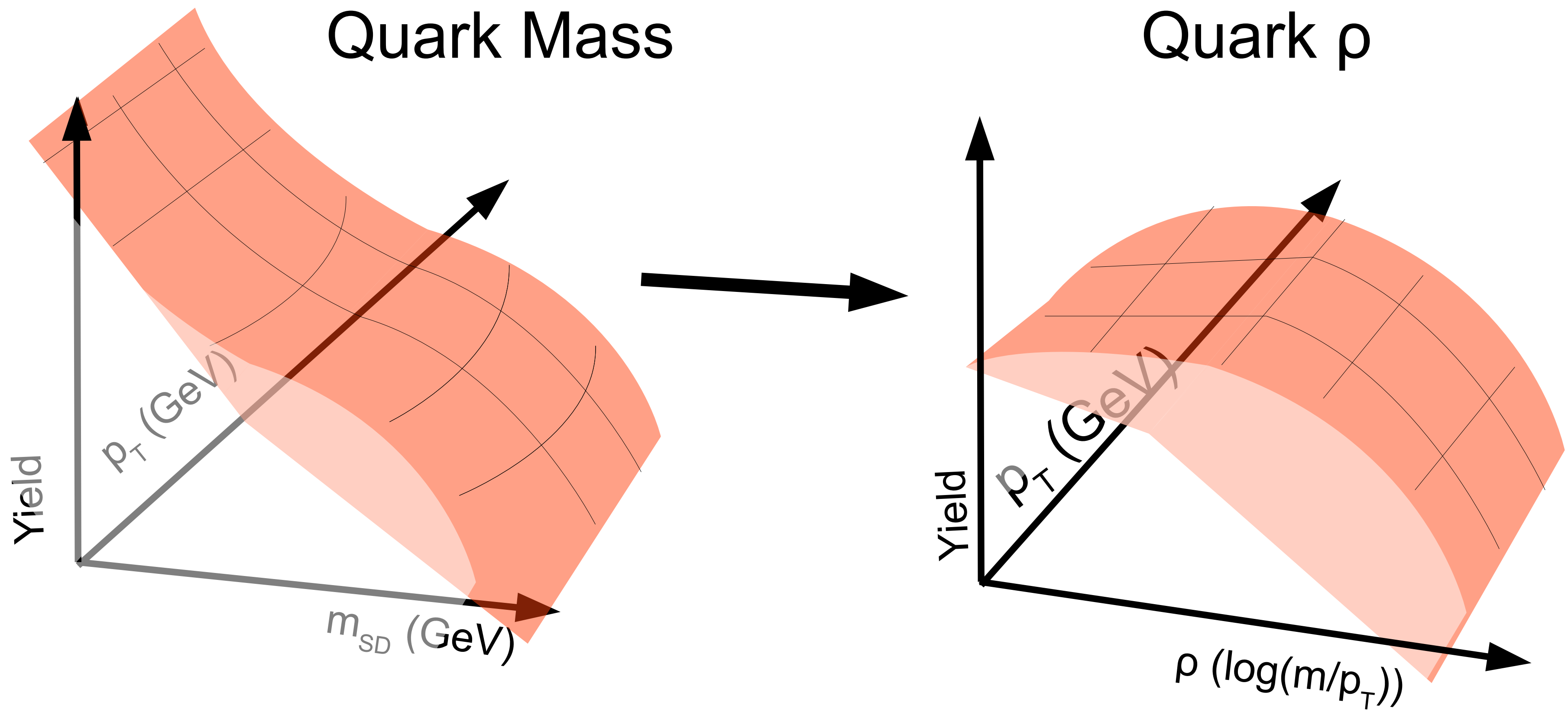


Consider jets w/p_T > 450 GeV (trigger)

CMS-SMP-16-010

Merging with ρ

- Merging to ρ makes imposes invariance over p_T

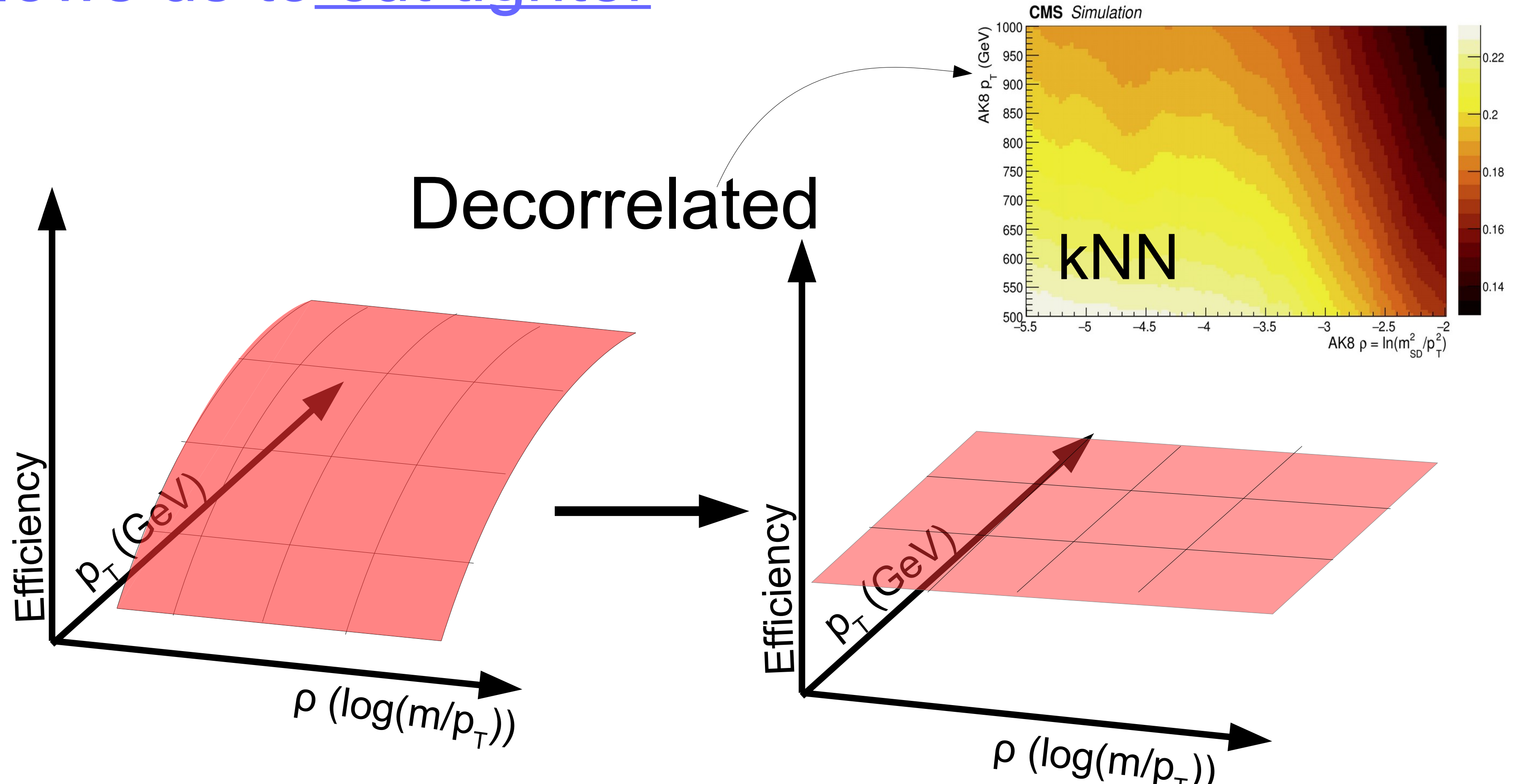


When translating to ρ distributions over p_T are also invariant

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



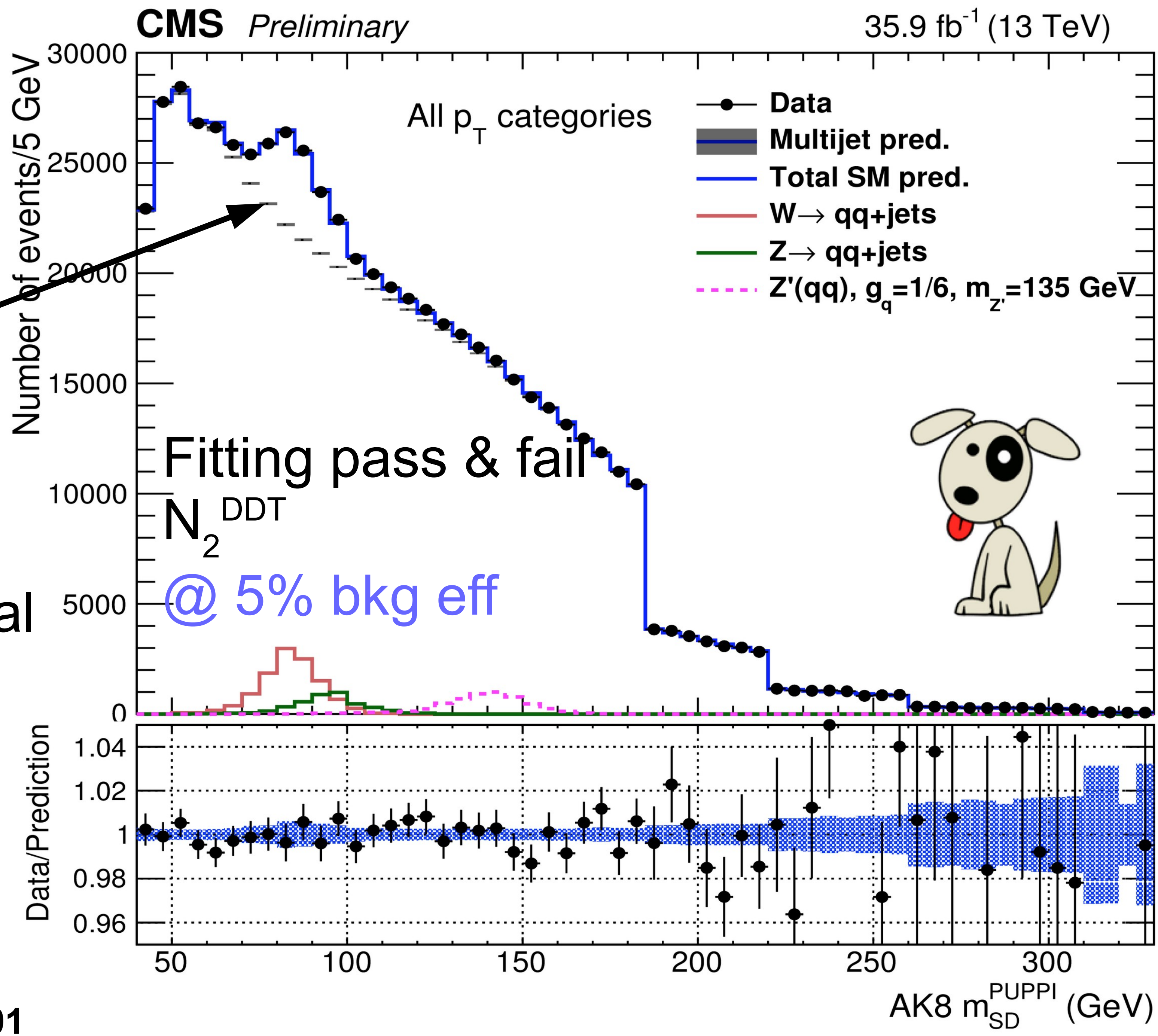
As a first example decorrelate $N_2 \rightarrow N_2^{DDT} = N_2 - \varepsilon(x\%)$

arXiv:1603.00027

Without B-tagging

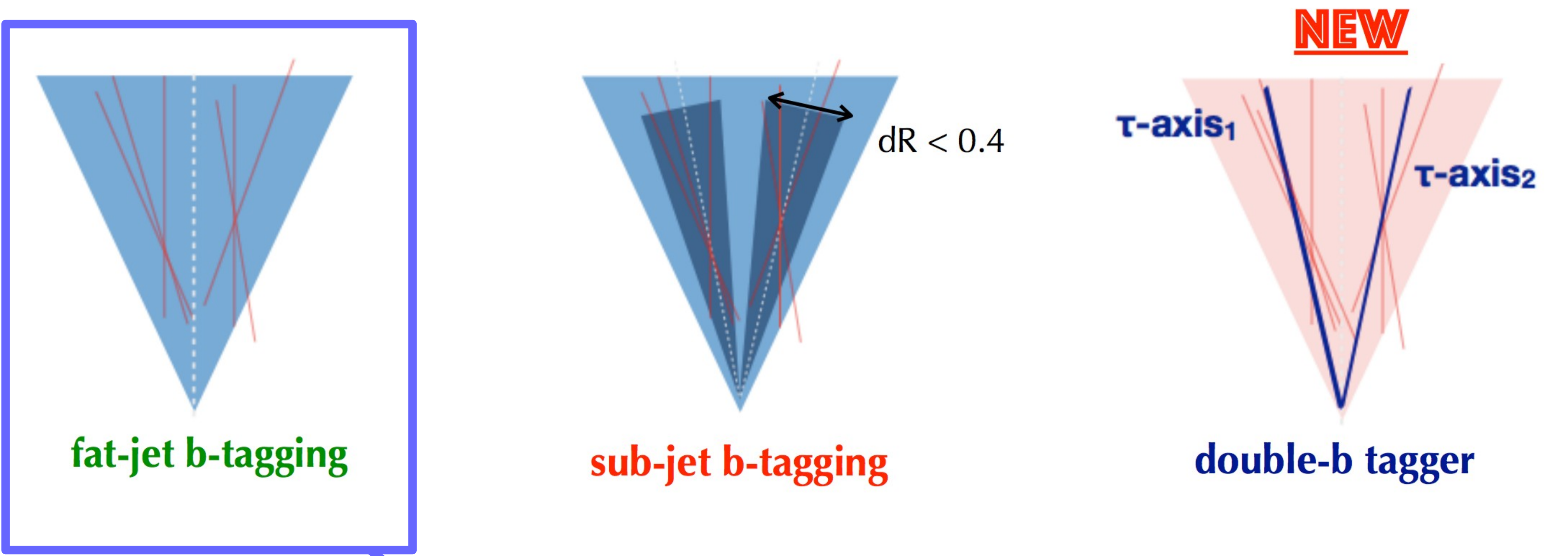
W/Z peak
Fit at the
7% σ unc.

QCD NLO,
EWK critical

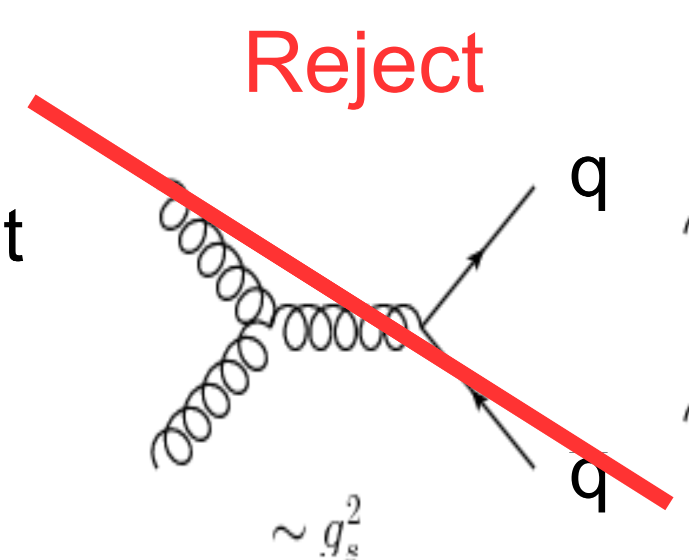


CMS-EXO-17-001

Double-b tagging Concept #1

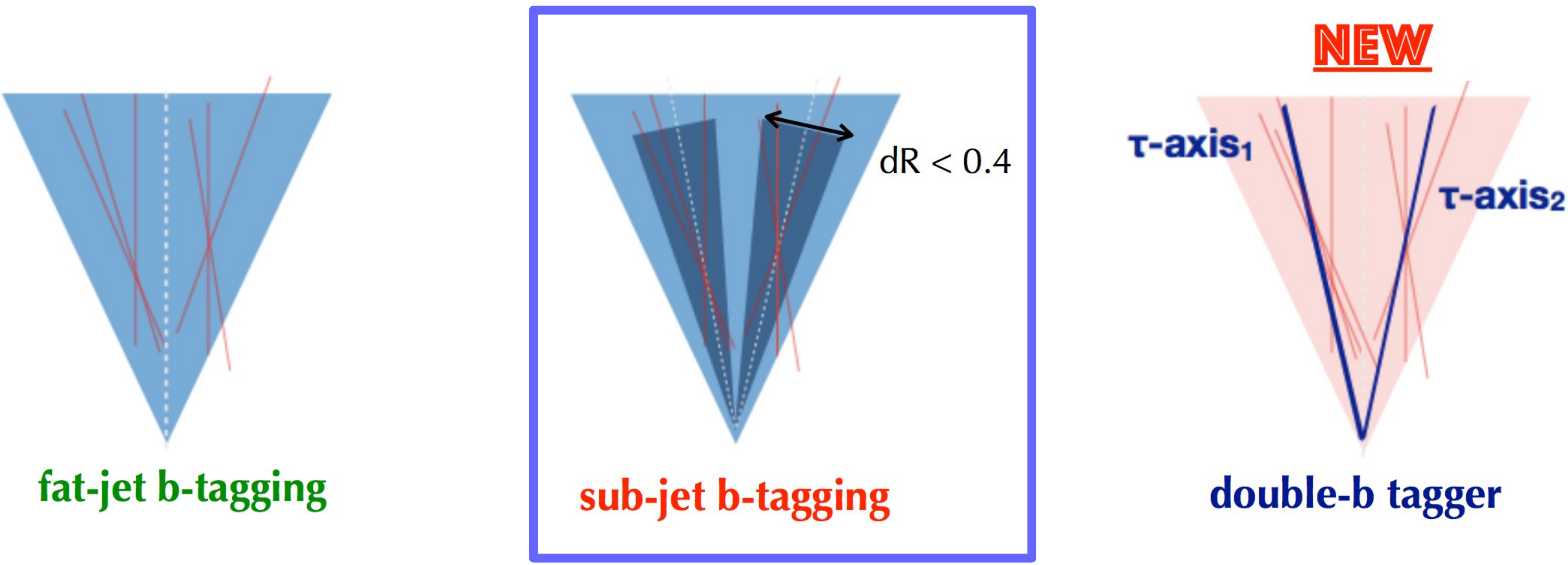


Apply standard b-tagging on the whole jet
Best at identifying Higgs against a jet composed of light quarks

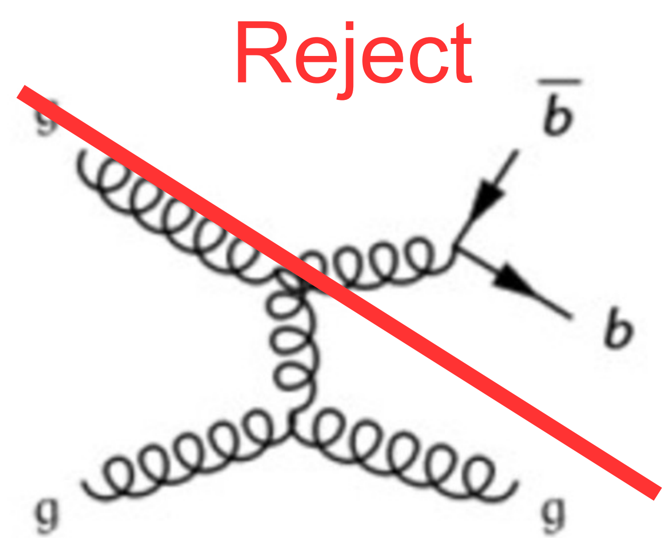


CMS-BTV-15-002

Concept #2

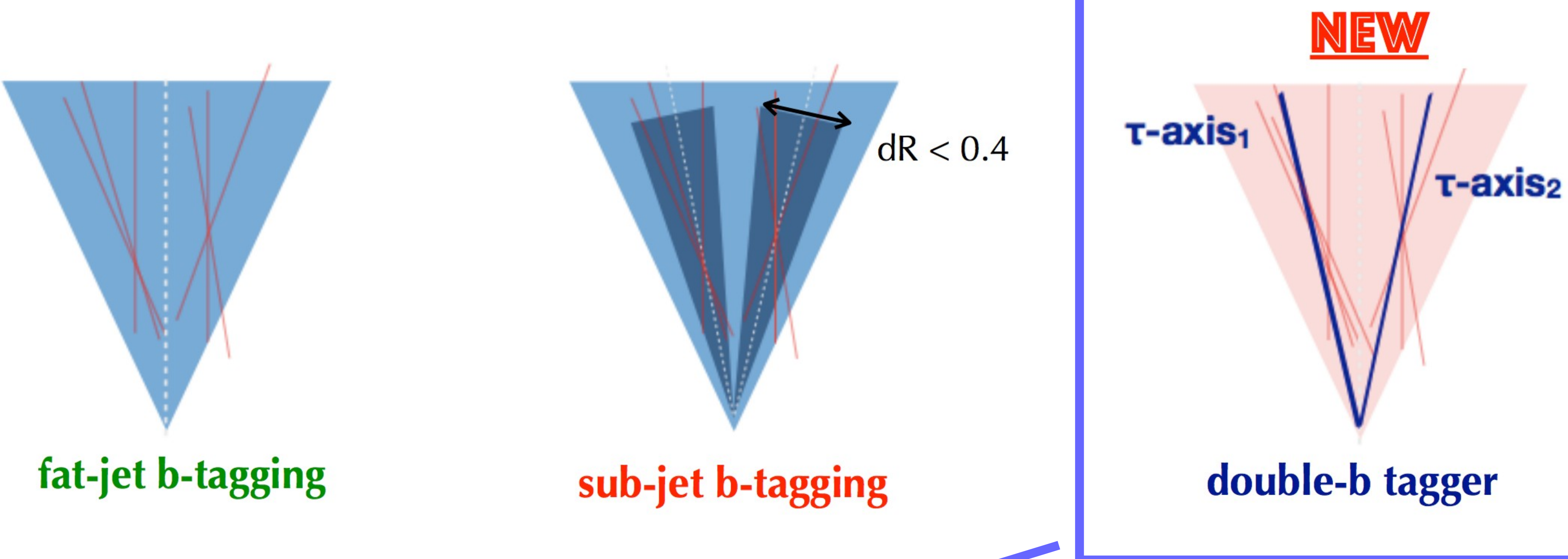


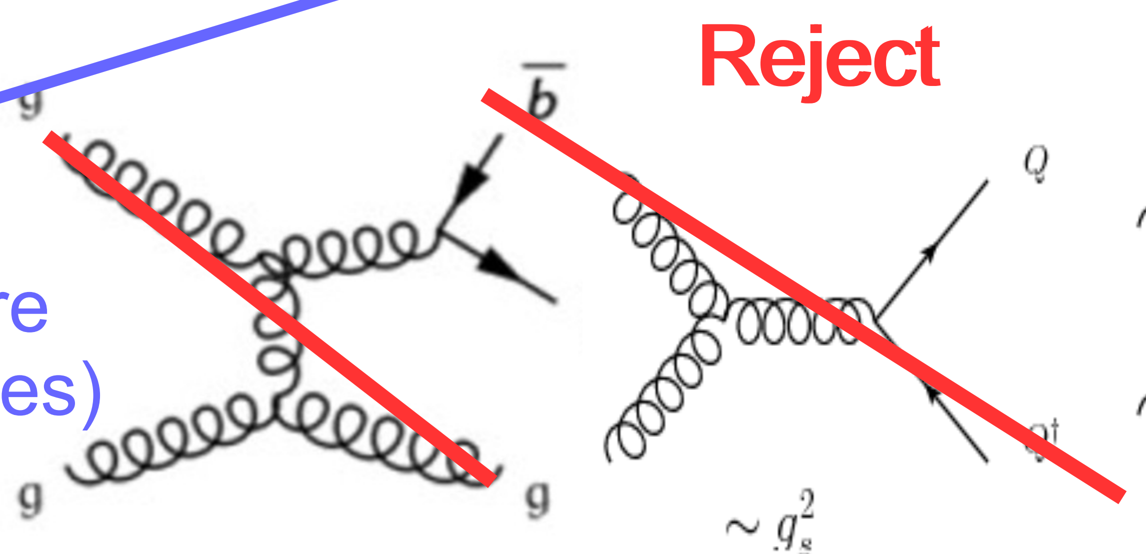
Apply b-tagging on the subjet
Best at identifying Higgs
Agains a jet from a gluon splitting



CMS-BTV-15-002

Concept #3

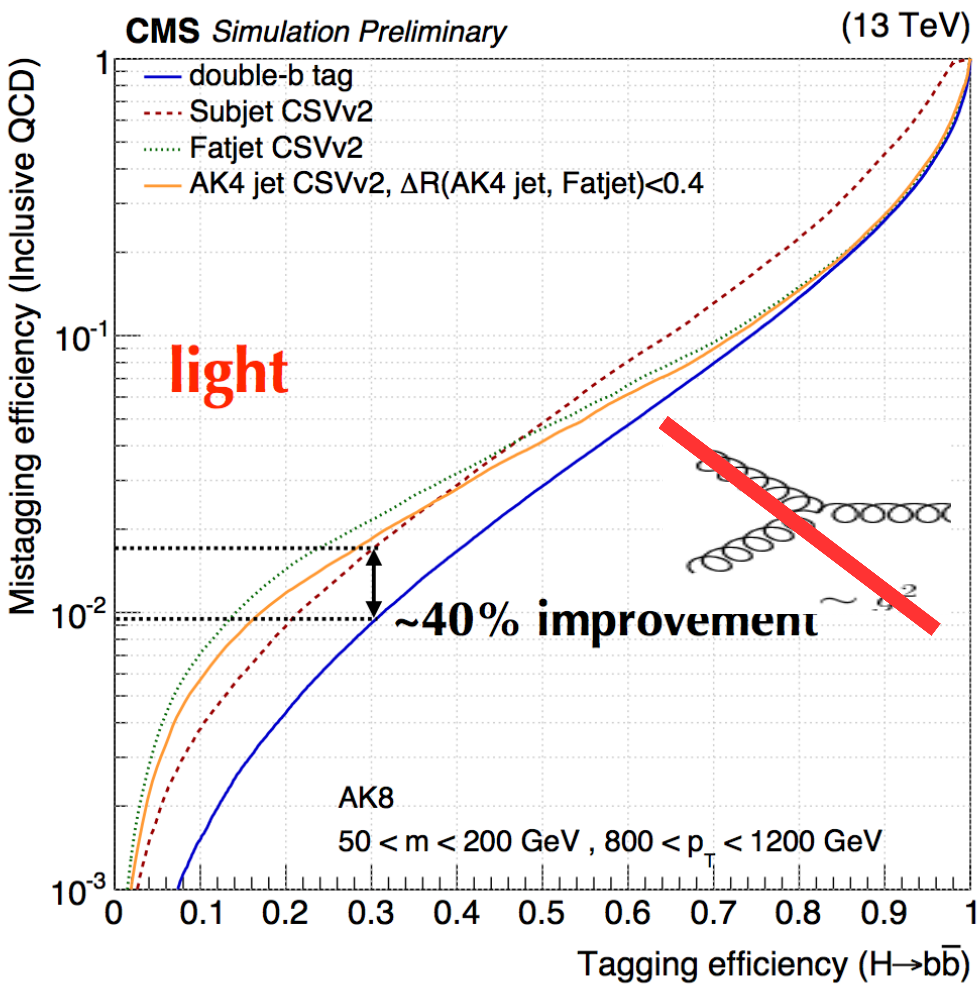


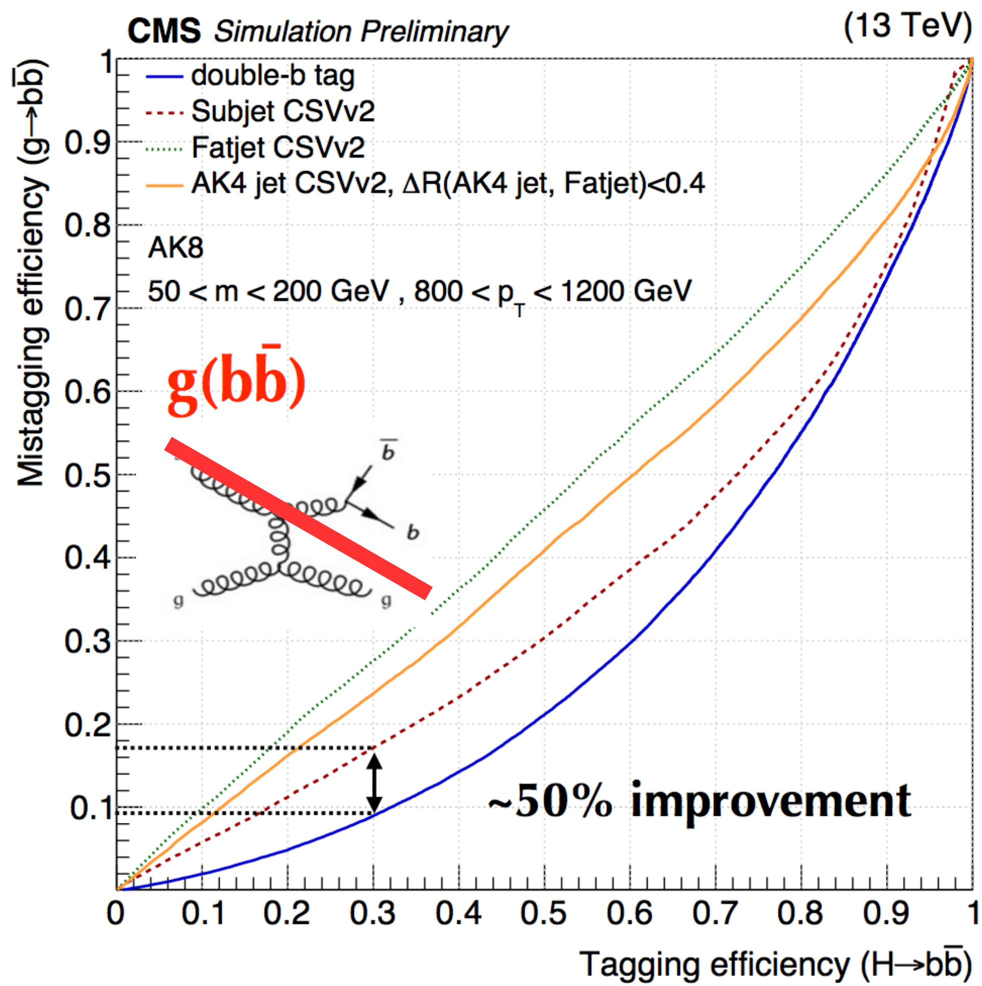


Apply b-tagging on the
Whole Jet using substructure
Variables (n-subjettiness axes)
1-pass kT

CMS-BTV-15-002

Double B-tagger

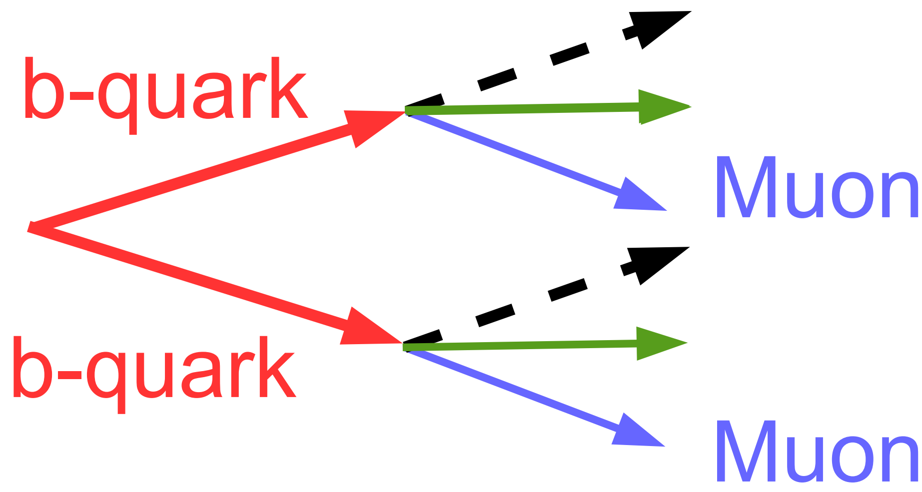




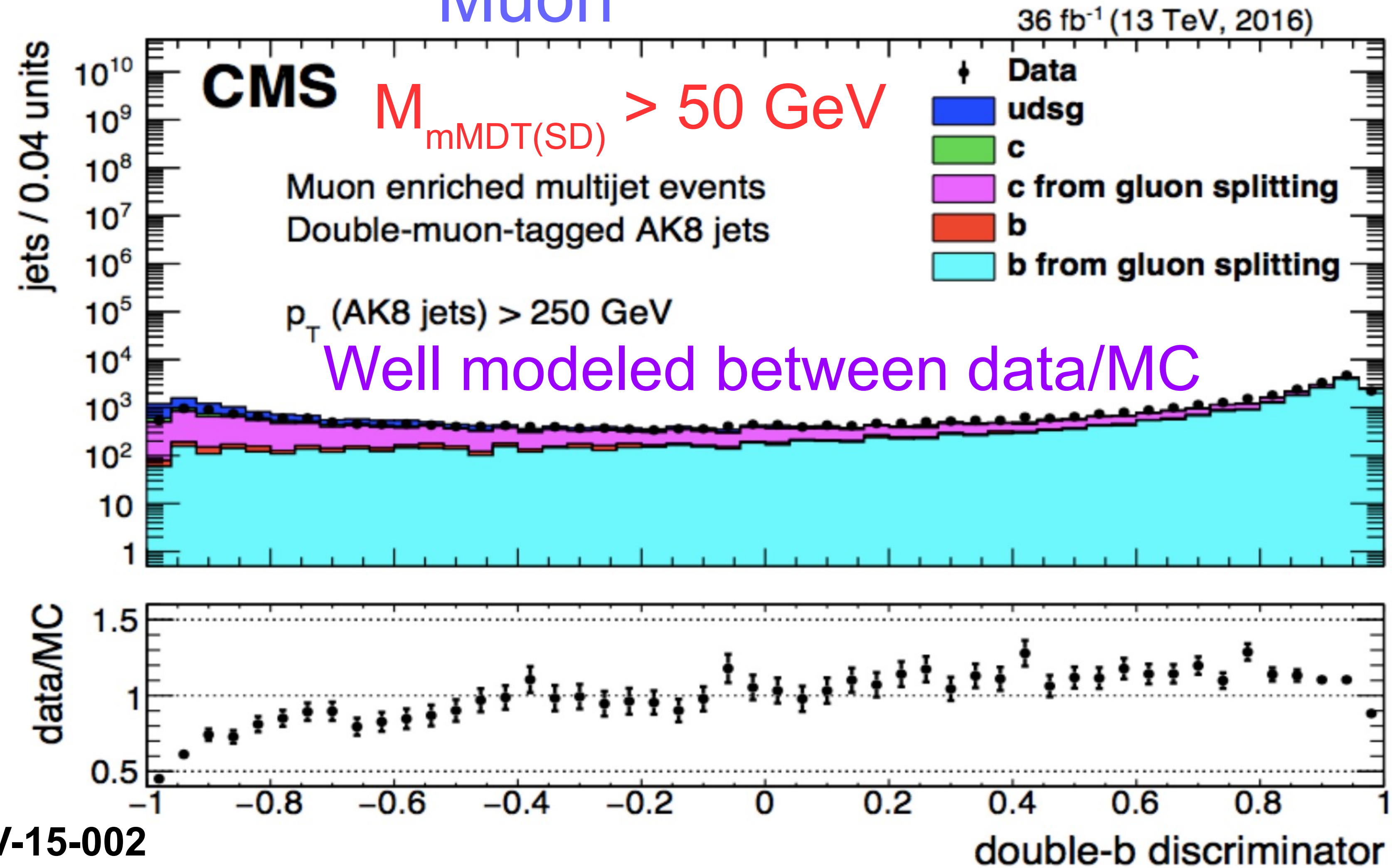
Resulting combination gives 50% improvement over previous

CMS-BTV-15-002

What about data/MC

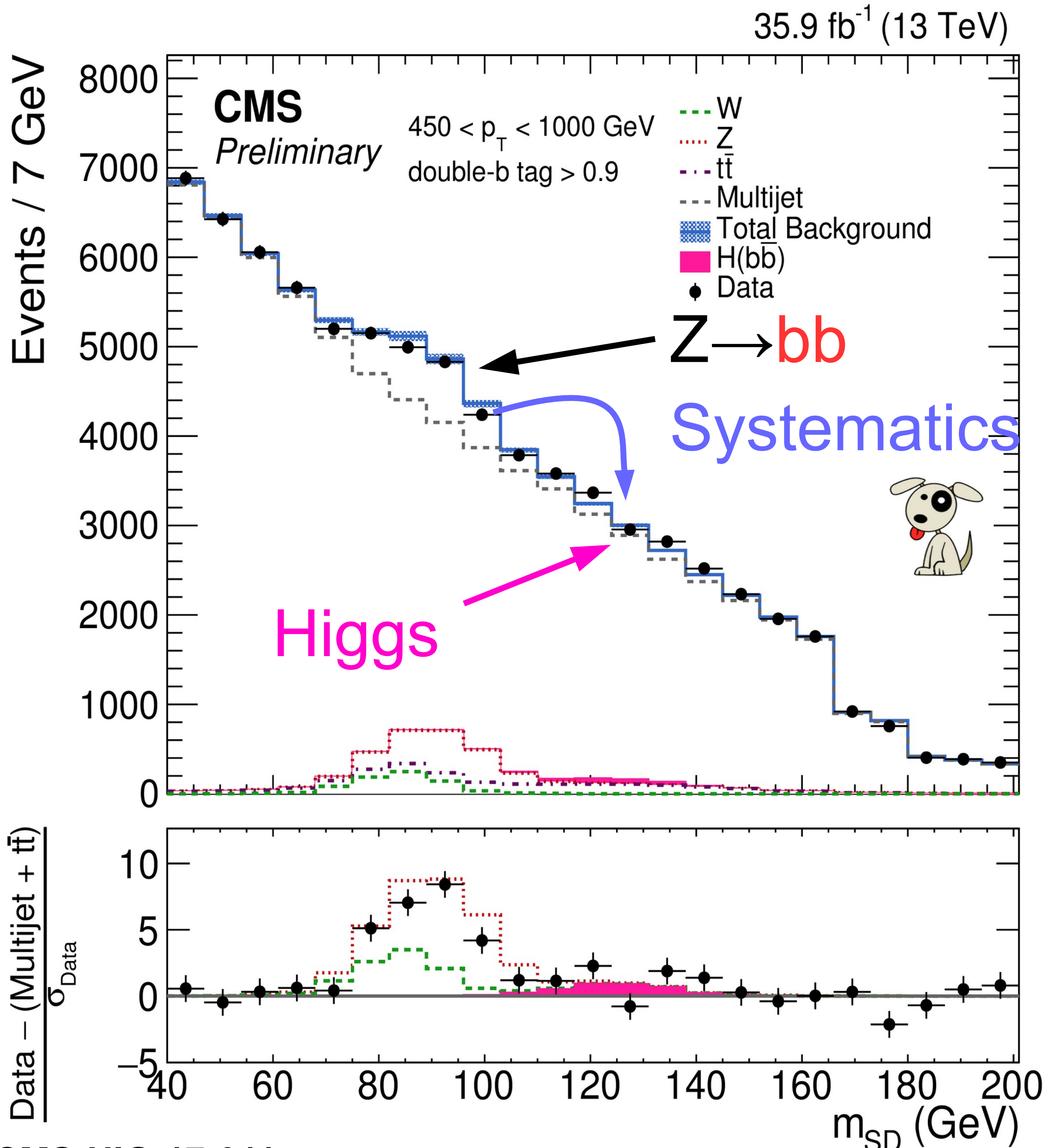


Tag two muons in a jet
Use this to infer signal-like
2 b-quarks in a jet



CMS-BTV-15-002

Result

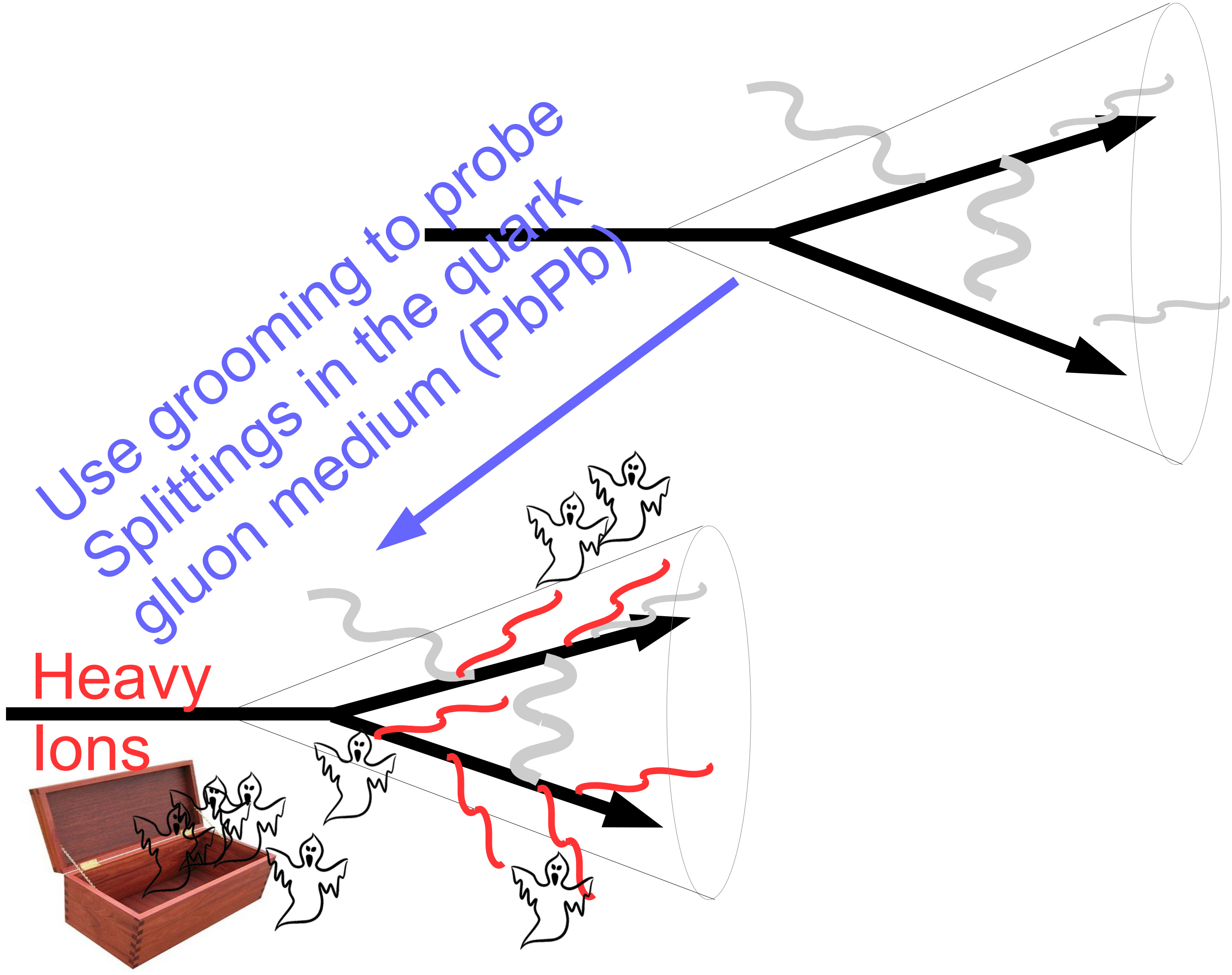


CMS-HIG-17-011

The large Z→bb Allows us to calibrate our signal

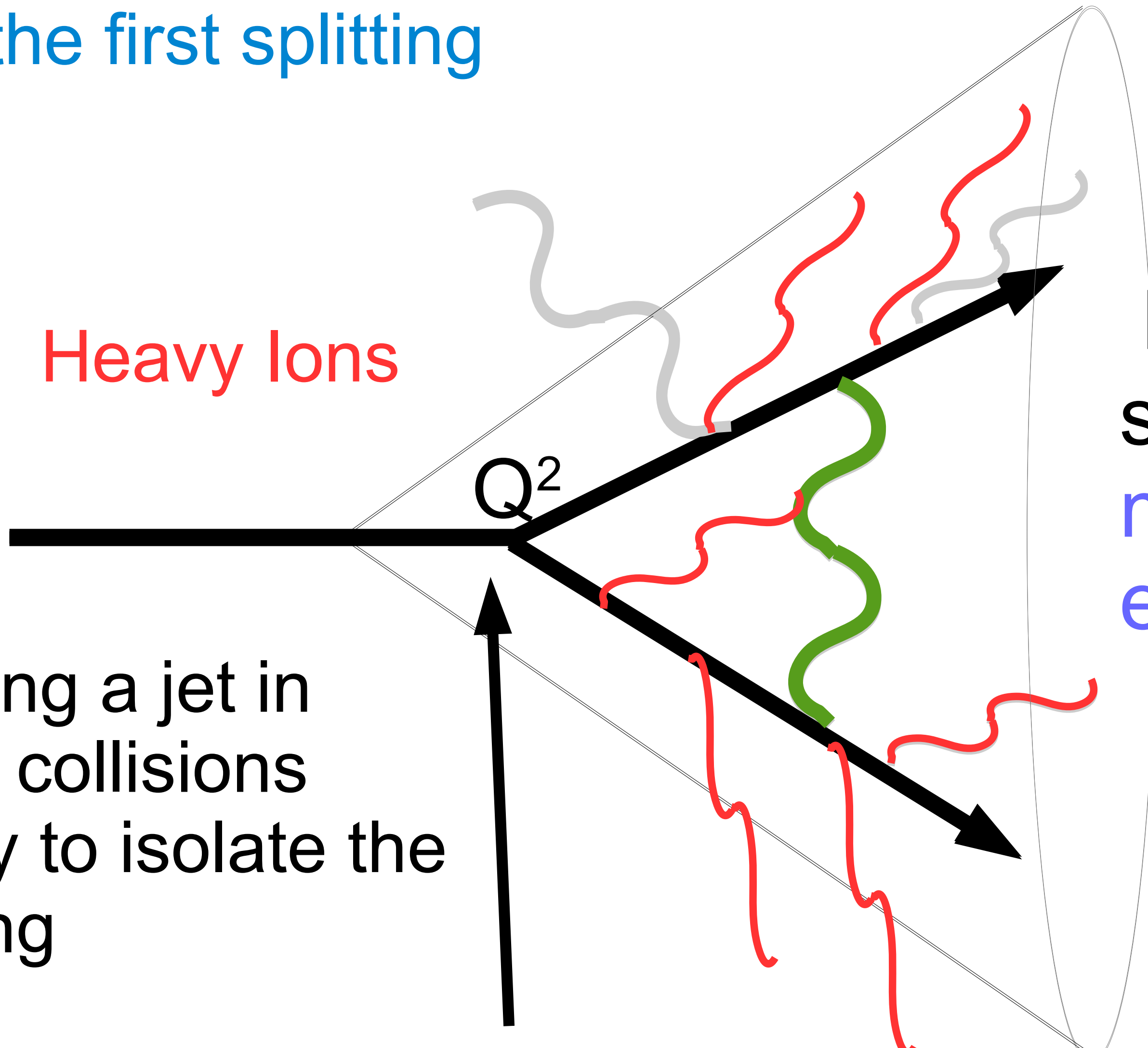
Z peak Allows us to calibrate Higgs

Where do we go from here?



Heavy Ion Collisions

Consider the first splitting in jet



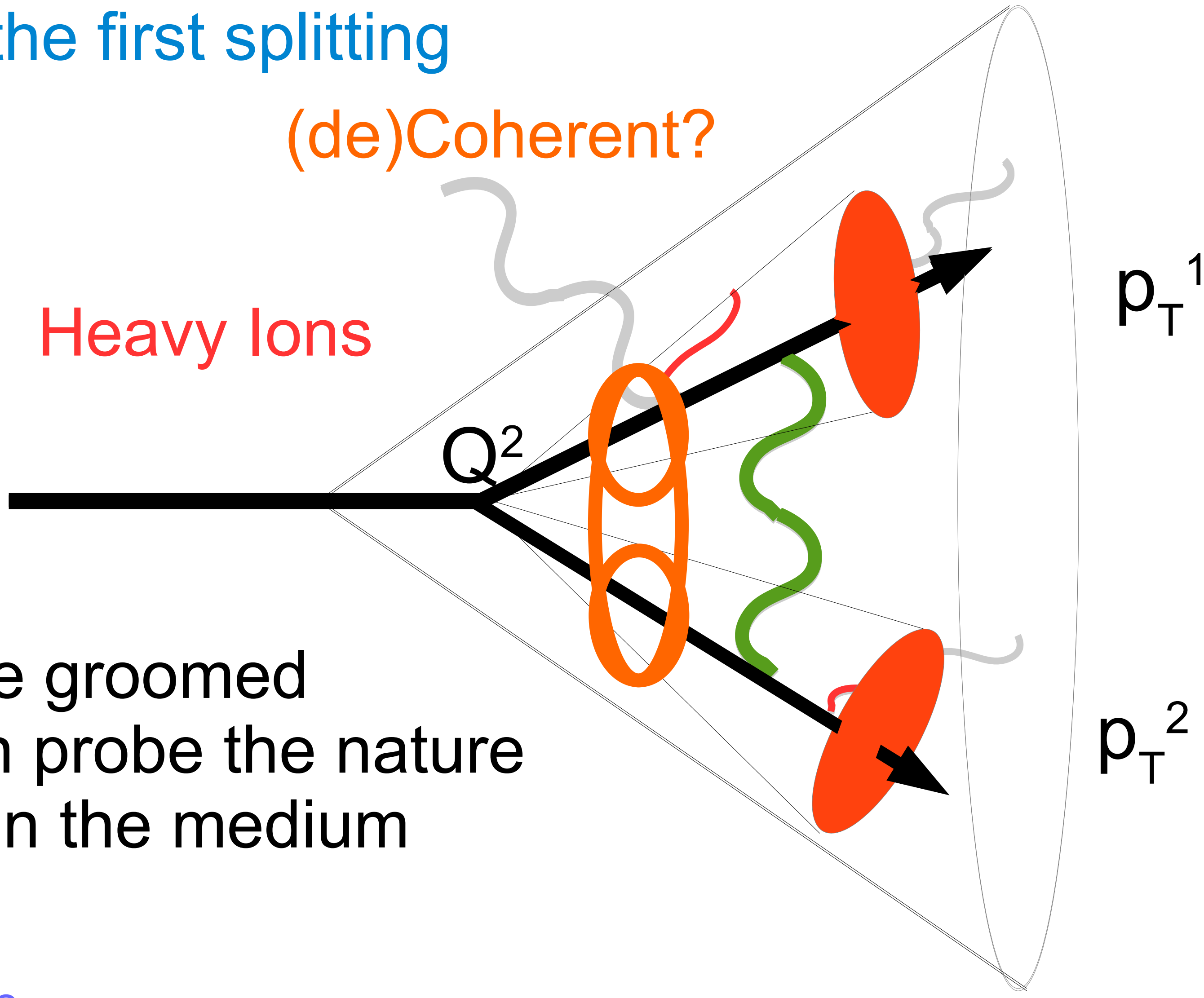
p_T of 1^{st} splitting probe modifications early in shower

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

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

Heavy Ion Collisions

Consider the first splitting in jet



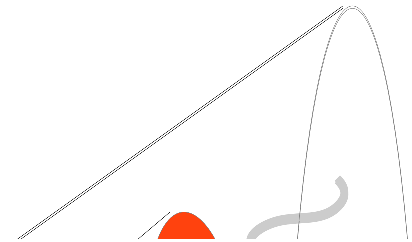
Isolating the groomed Subjets can probe the nature of the loss in the medium

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

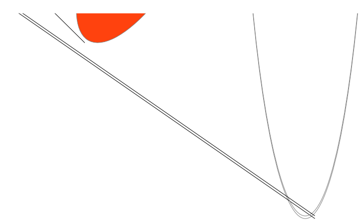
Probes coherence of the energy loss in the medium

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



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

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 ⇒ 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

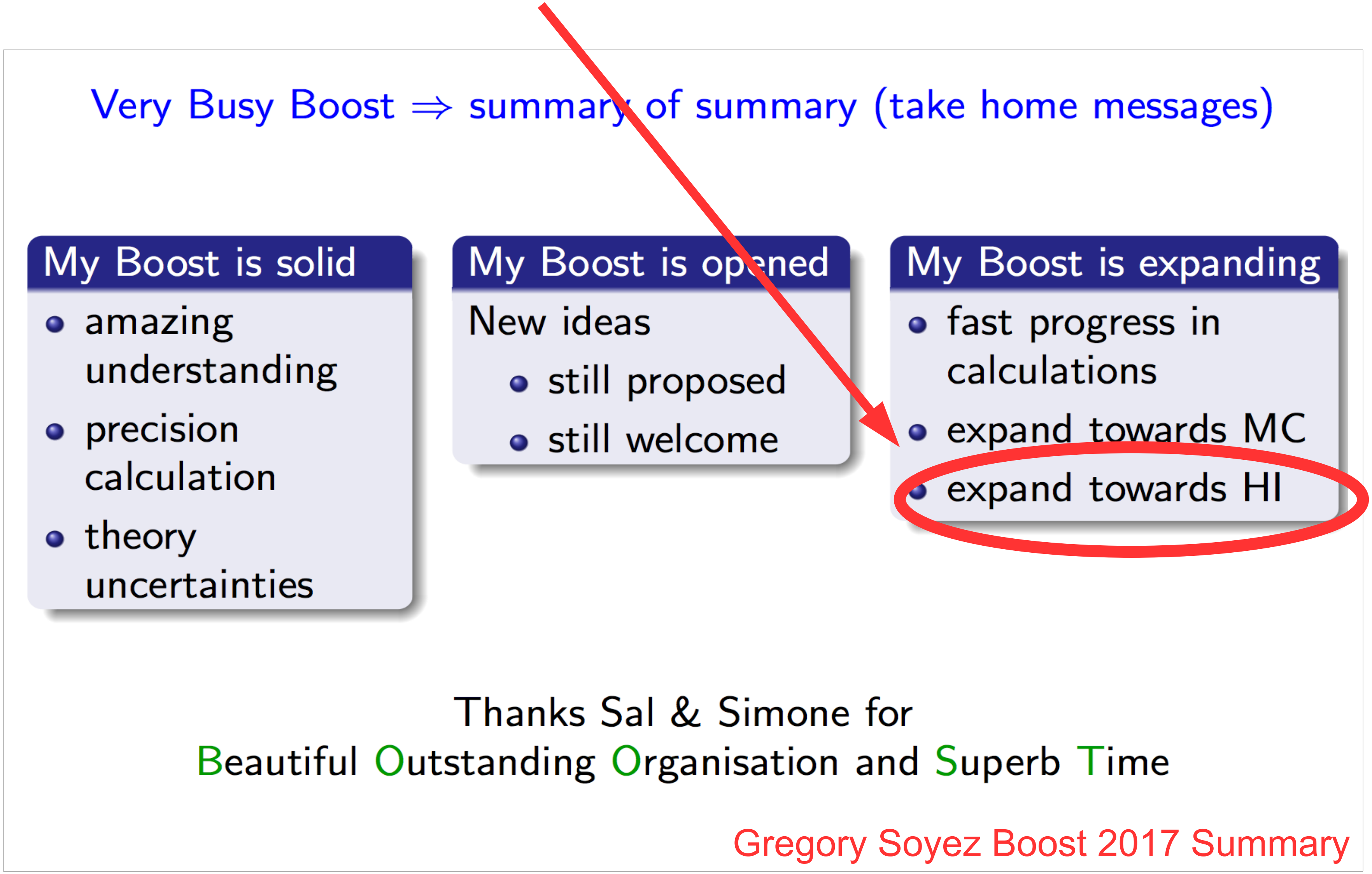
Thanks Sal & Simone for

Beautiful Outstanding Organisation and Superb Time

Gregory Soyez Boost 2017 Summary

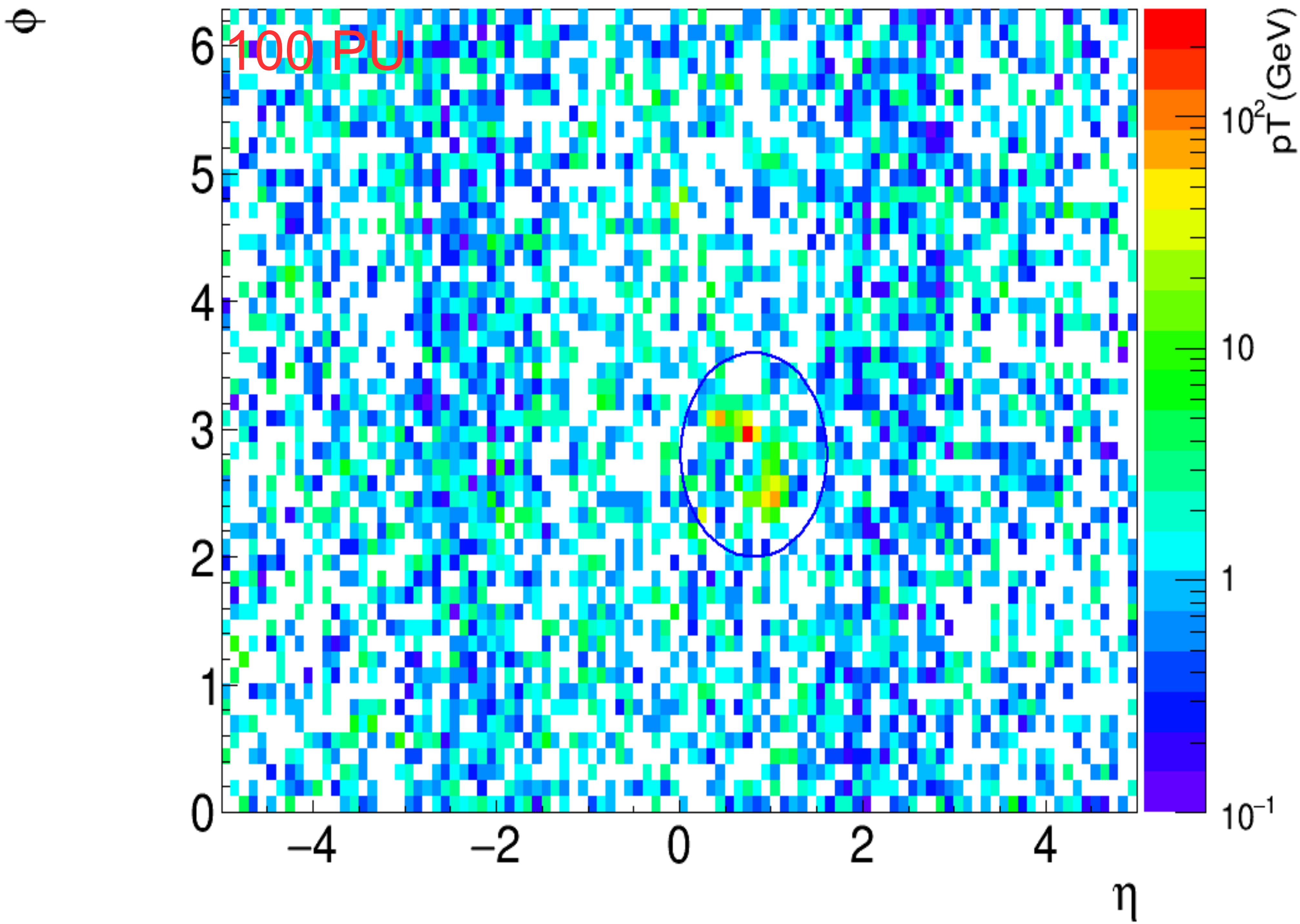
Summary

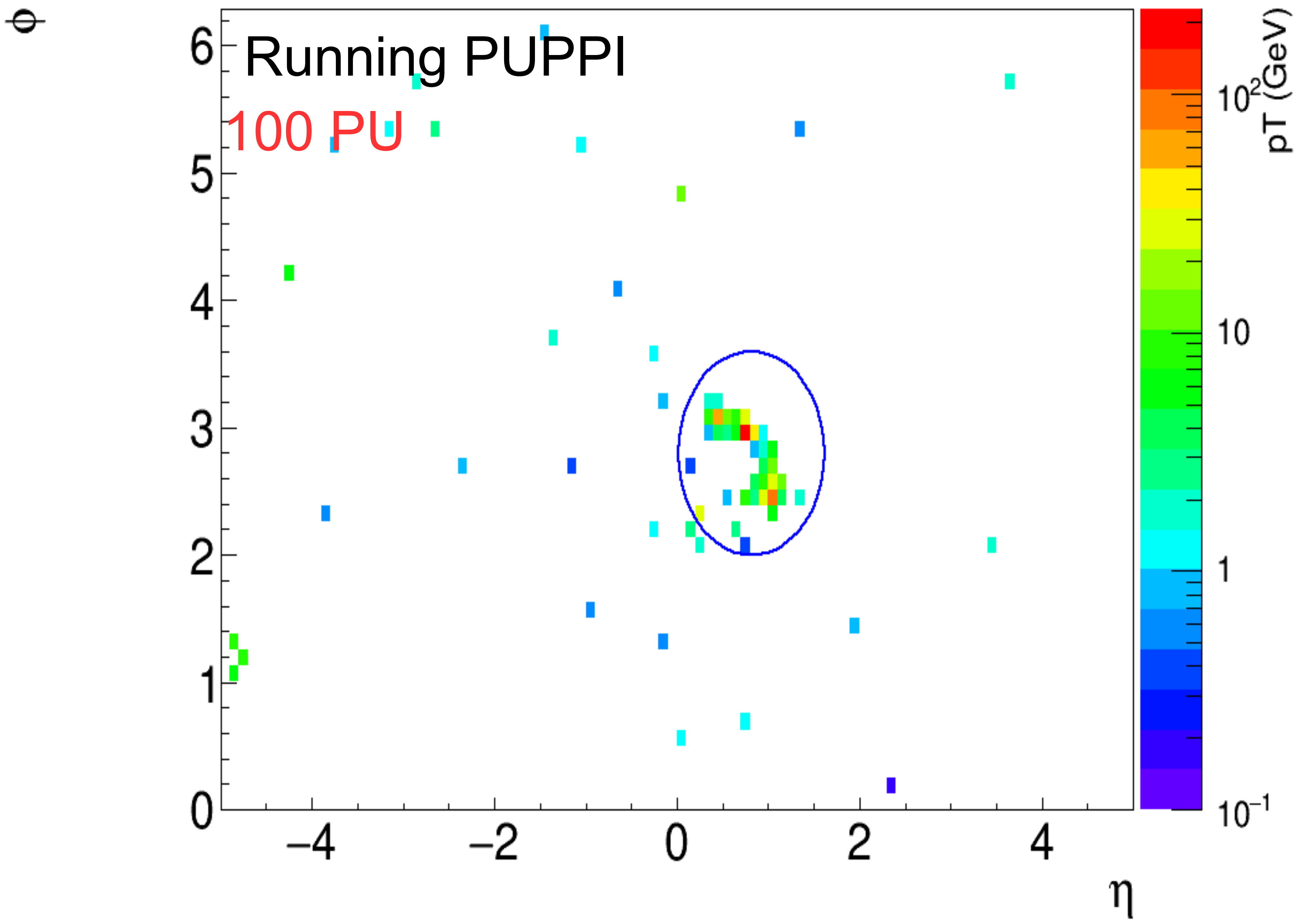
- Community is starting to think about HI as well



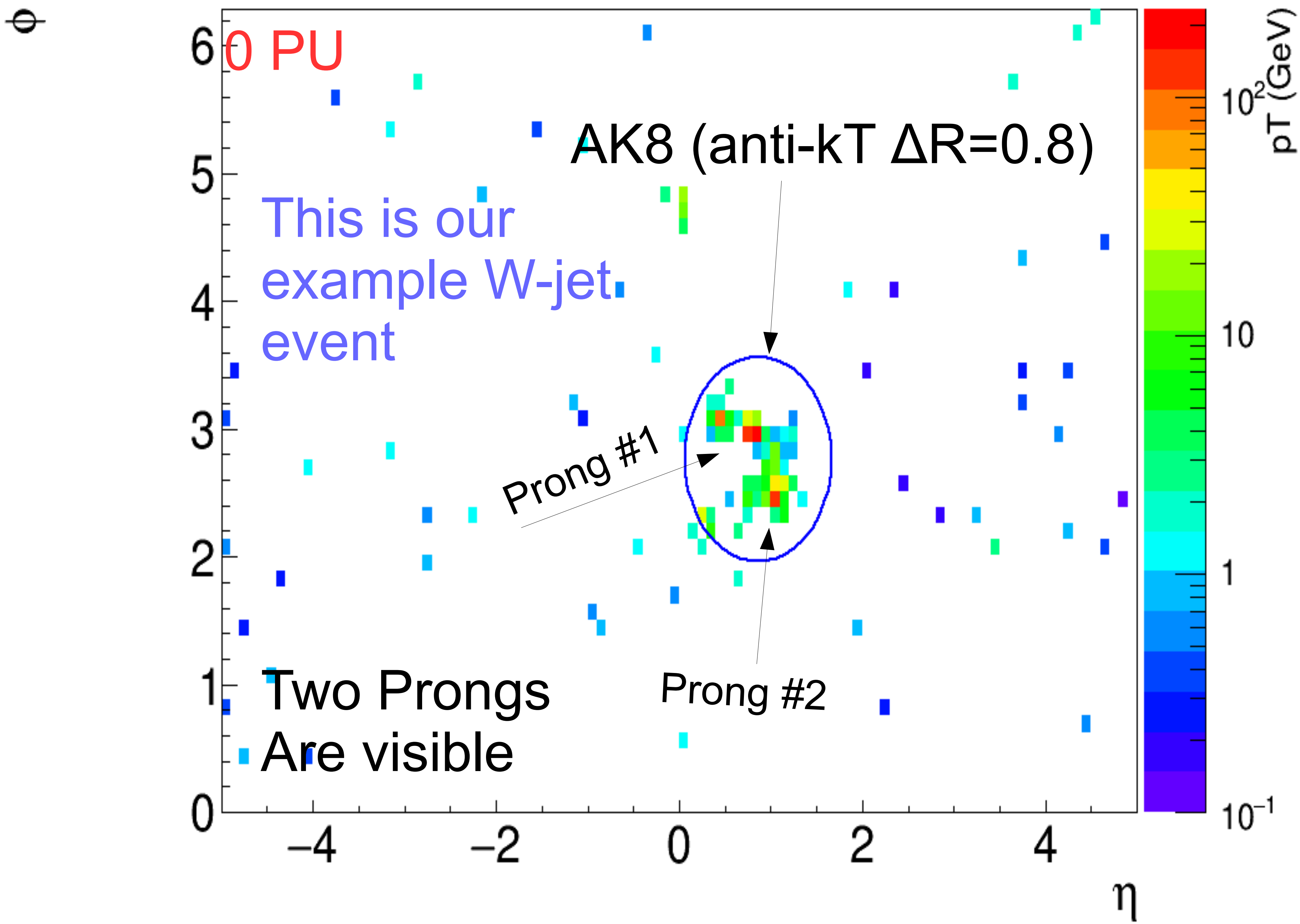
Thanks!

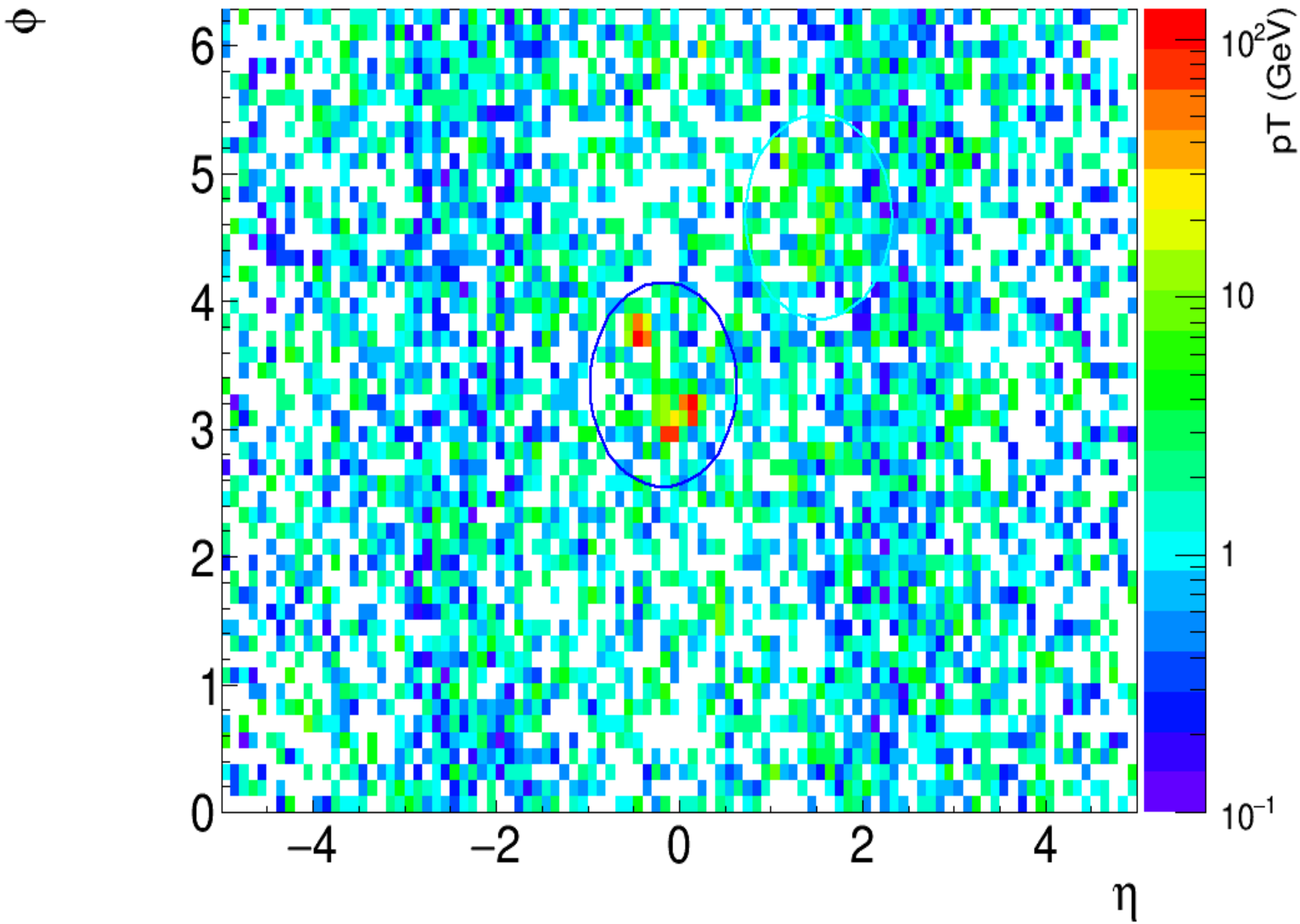
Now @ 100 PU (Next year)


100 PU
φ
η
pT (GeV)
10^2
10
1
10^{-1}
0
1
2
3
4
5
6
−4
−2
0
2
4

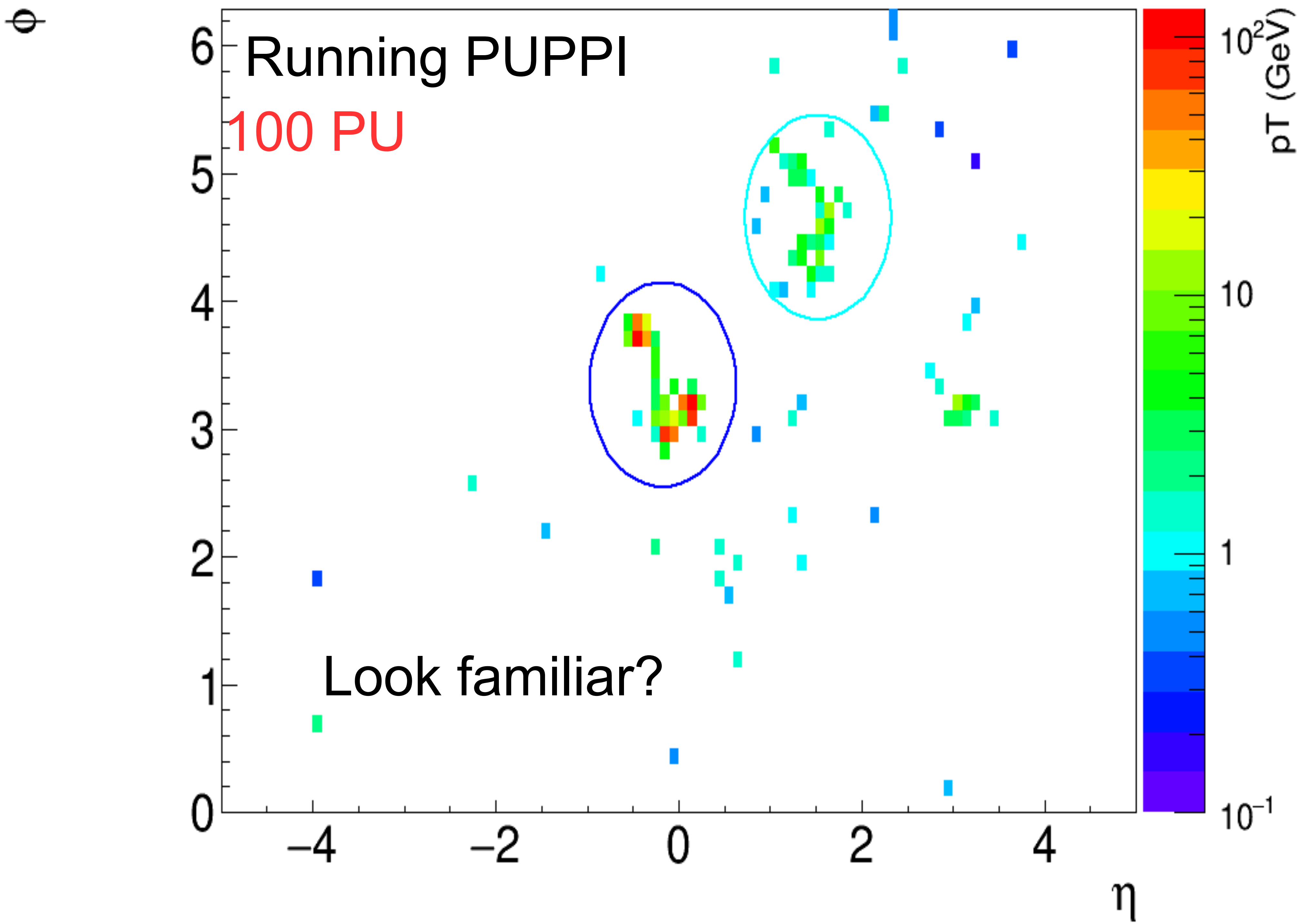


Running PUPPI
100 PU
φ
η
pT (GeV)
0
1
2
3
4
5
6
−4
−2
0
2
4
10^{-1}
1
10
10^2

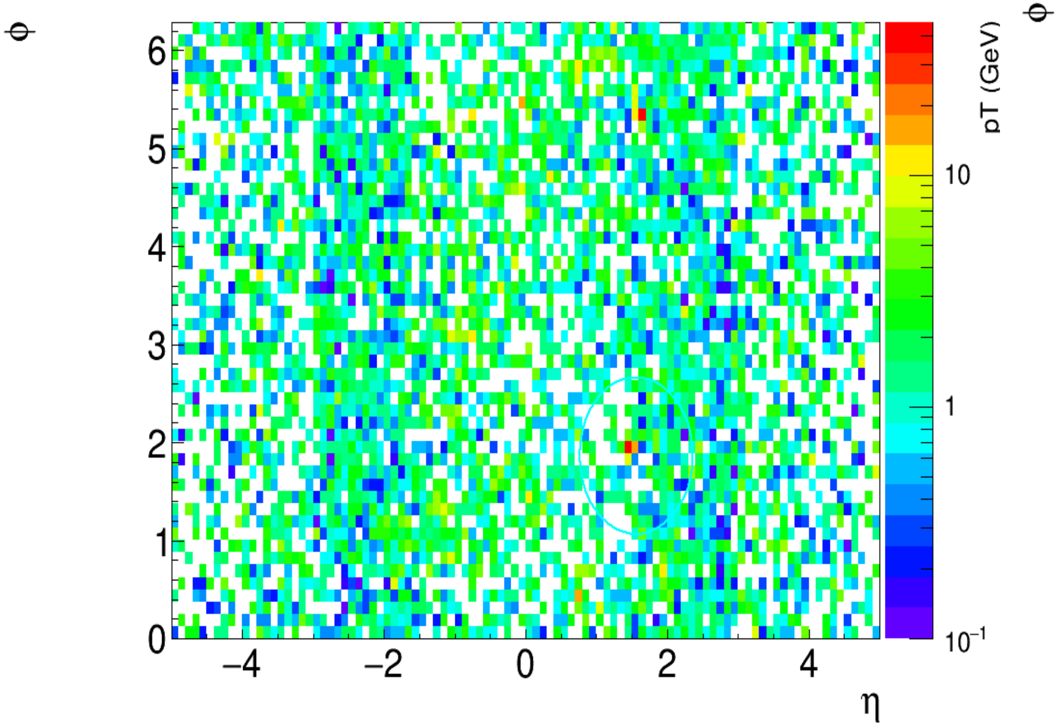

0 PU
AK8 (anti-kT ΔR=0.8)
This is our example W-jet event
Prong #1
Prong #2
Two Prongs Are visible
φ
η
pT (GeV)

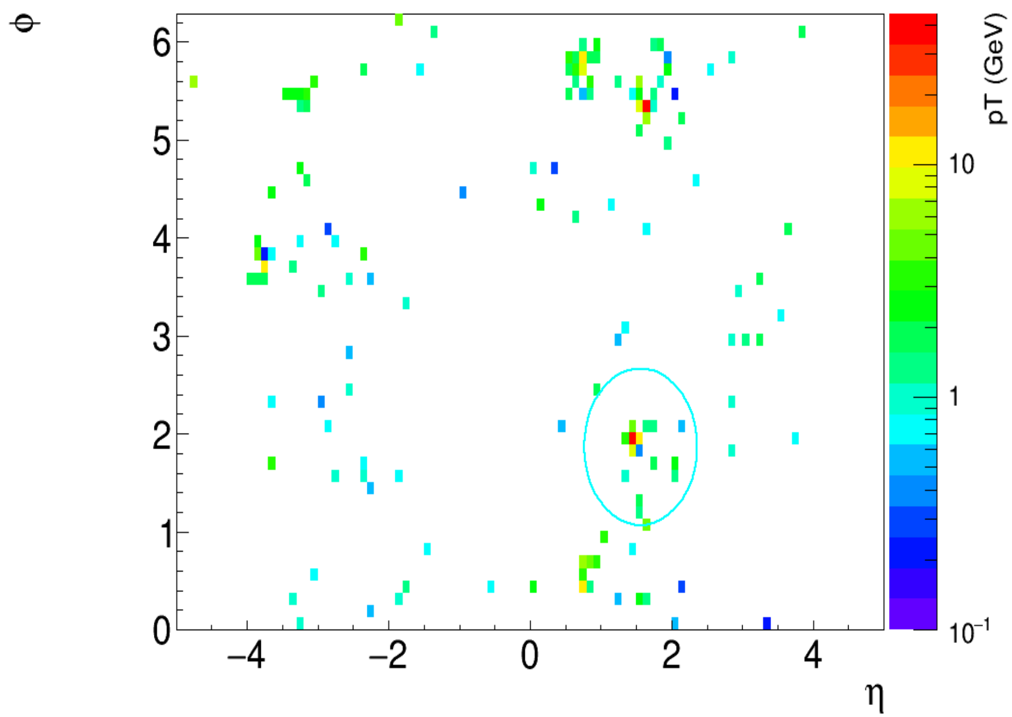


φ
0
1
2
3
4
5
6
−4
−2
0
2
4
η
pT (GeV)
10^{-1}
1
10
10^2


Running PUPPI
100 PU
Look familiar?
ϕ
η
pT (GeV)
0
1
2
3
4
5
6
−4
−2
0
2
4
10^{-1}
1
10
10^2

Any guesses?

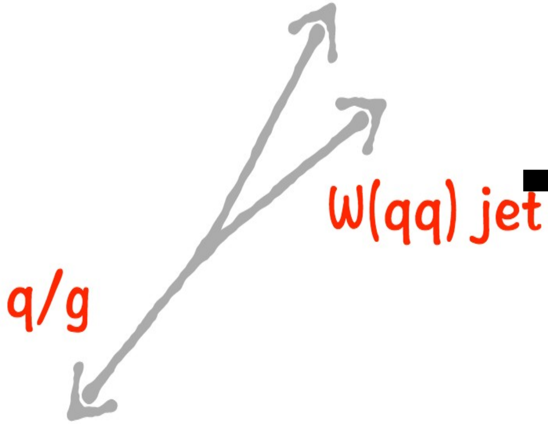




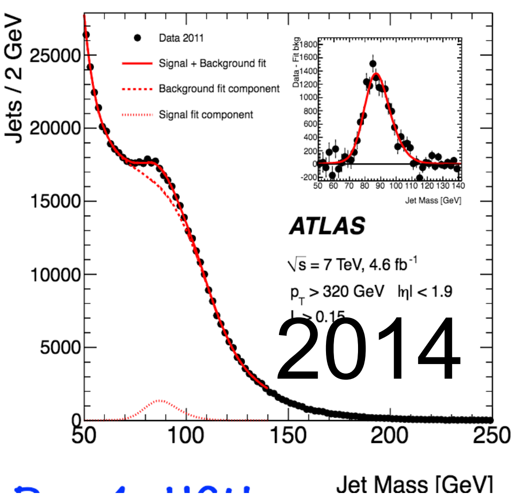
See backup

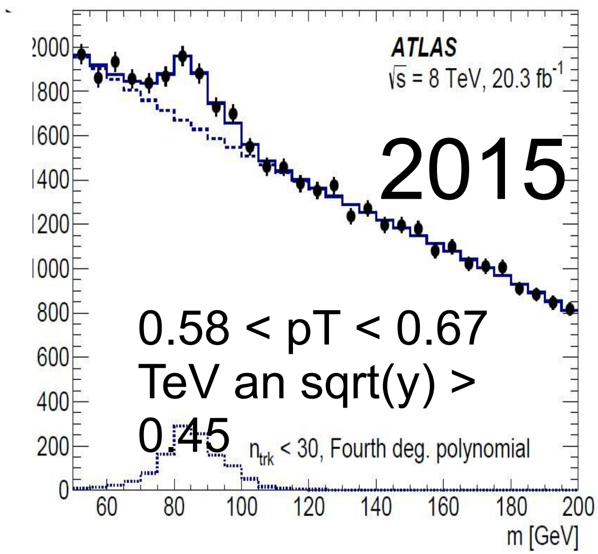
Recap

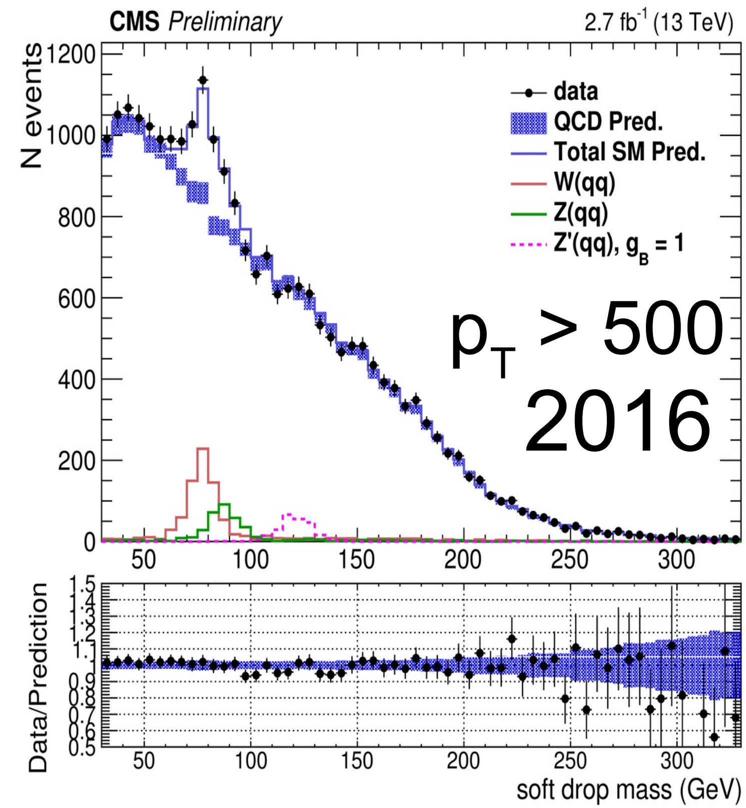
- Actual analyses are on objects combining deposits
- Particle flow combines the deposits to particles
  - Takes into account many features (Brem/Nuclear Int)
- Hadronic τ decays are composite "particle" objects
  - Find the decays and rely heavily on isolation
- Jets have rich & interesting identification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



Thanks!



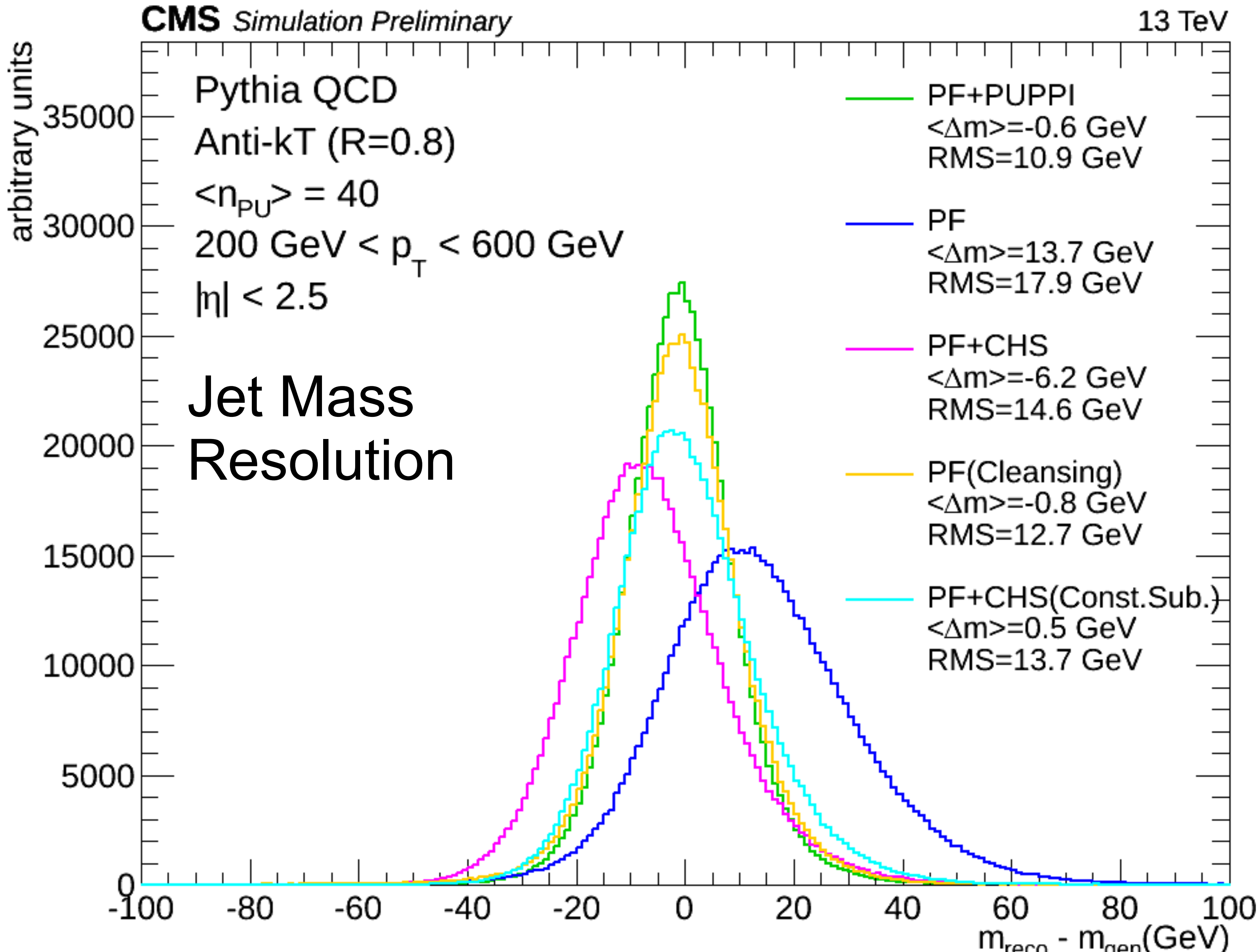




This peak has only been observed over past 2 year

Thanks to the Organizers! Have a good trip back

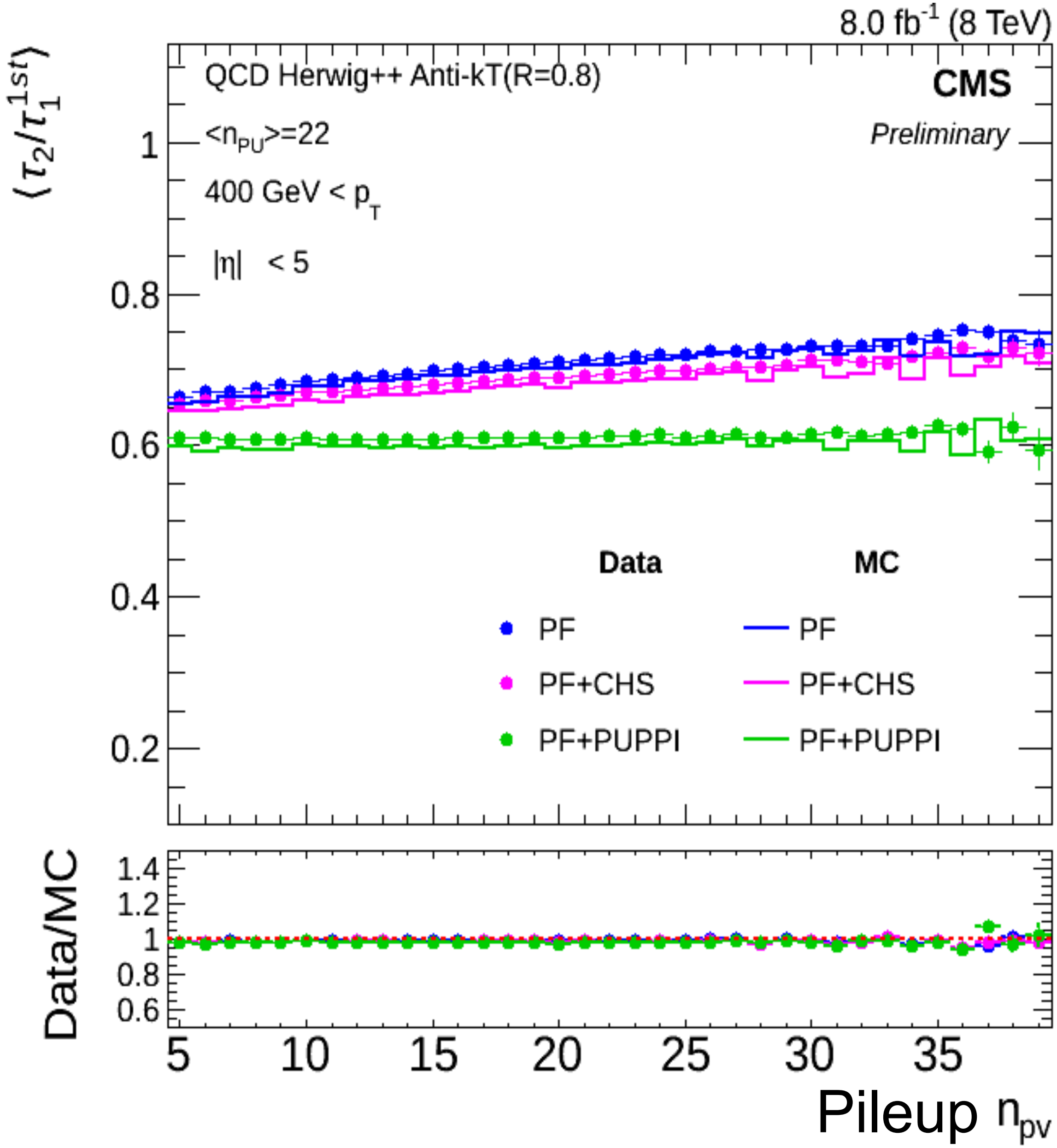
Jets in CMS



Mass resolution shows clear improvement (40 PU)

Pileup performance in data

Likelihood of two prongs



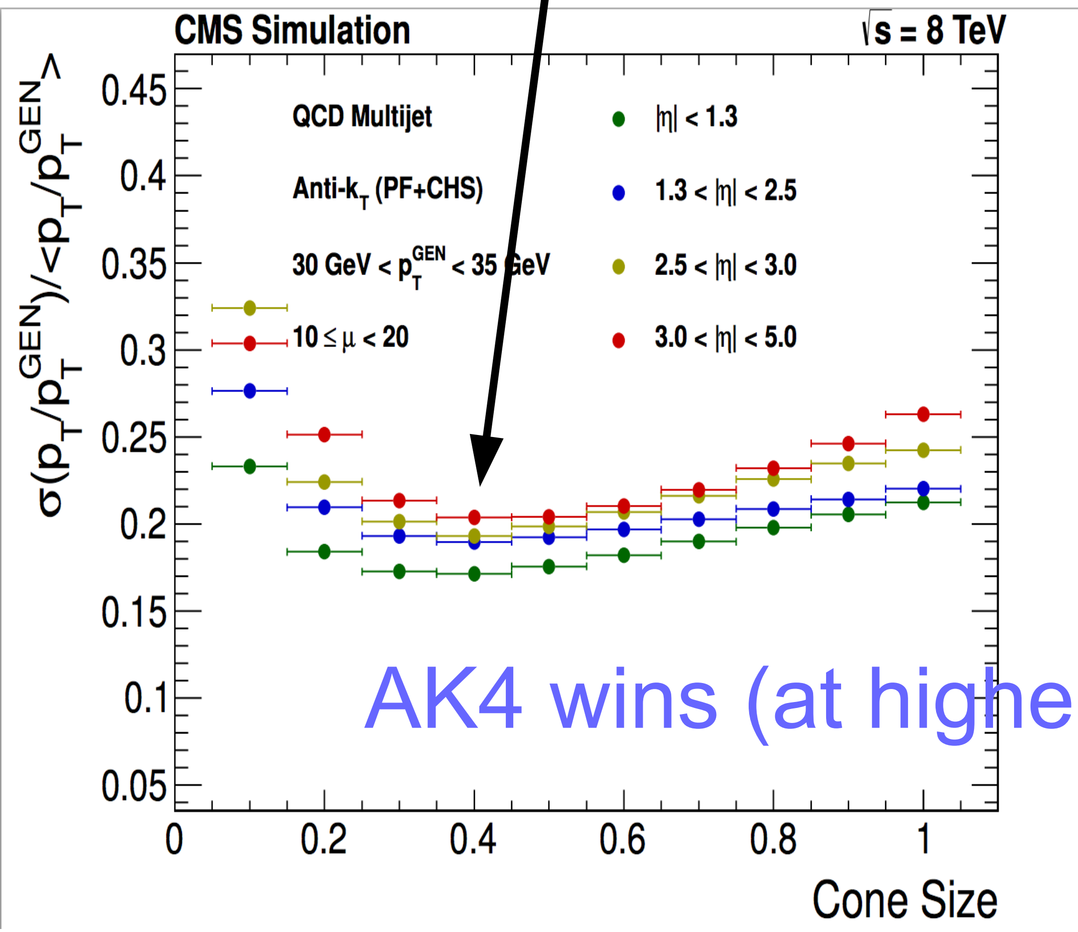
- No more trends in pileup with Puppi

Jet Energy Correction

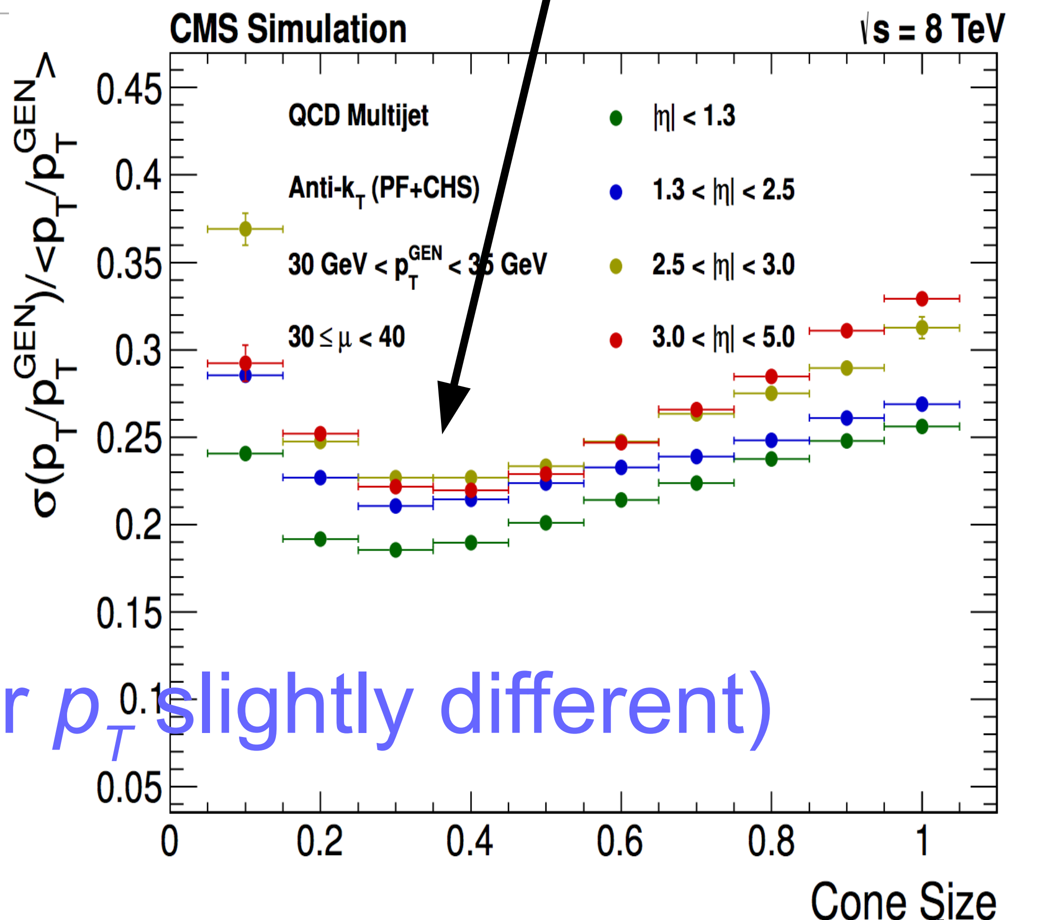
- Executive Summary :

We switch to AK4

Run I PU



Run II PU



AK4 wins (at higher p_T slightly different)

JME-DP-14/037

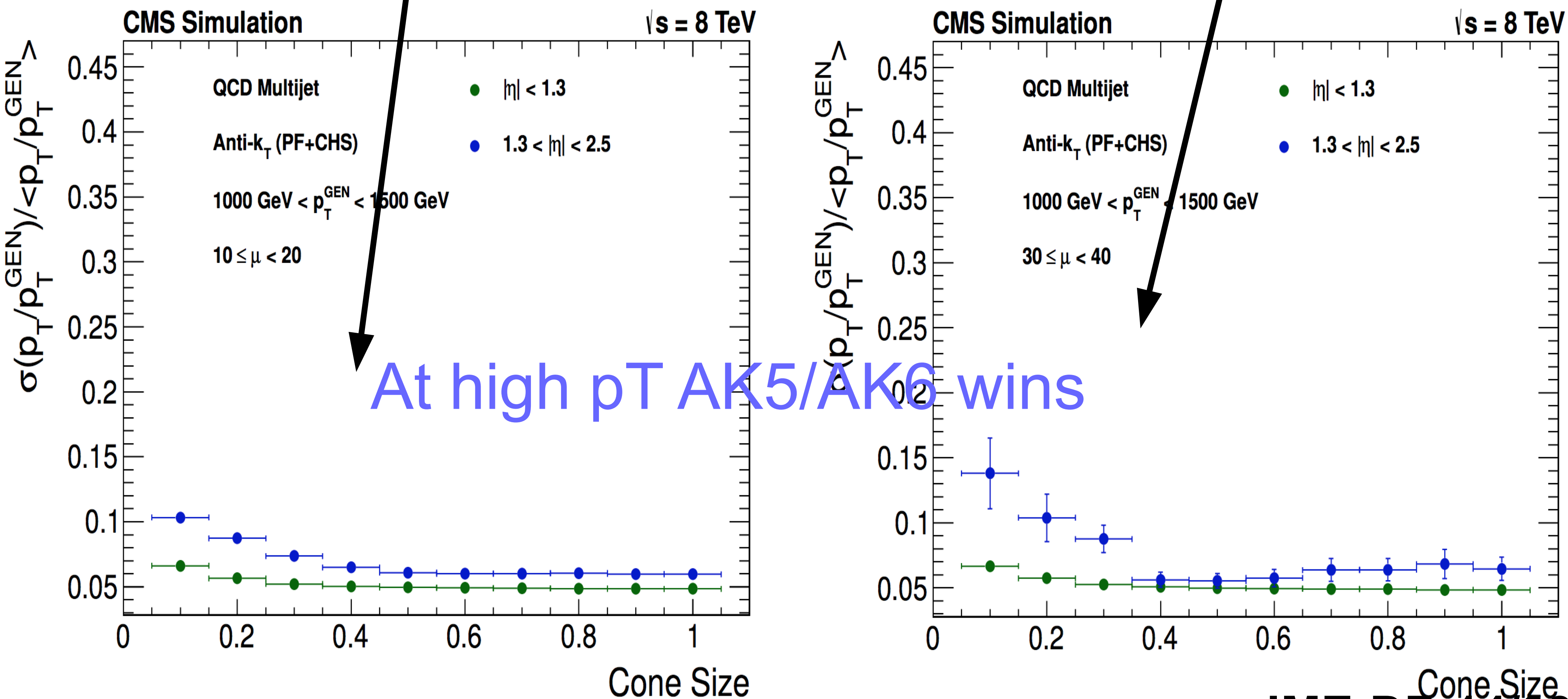
Jet Energy Correction

- Executive Summary :

We switch to AK4

Run I PU

Run II PU

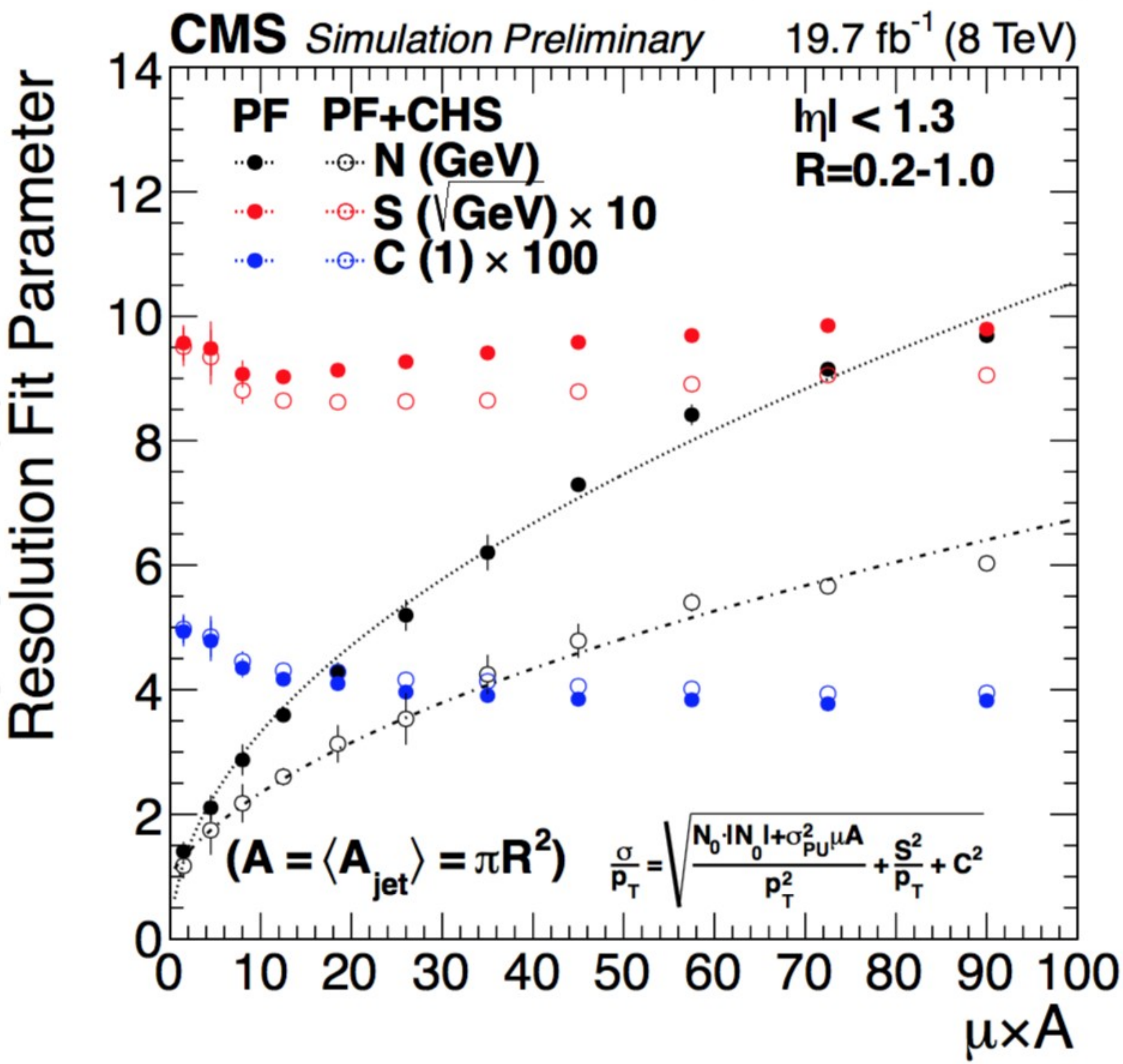


At high pT AK5/AK6 wins

JME-DP-14/037

Stability of our detector

- Using all the jet cones allows plots like this:



JME-DP-14/037

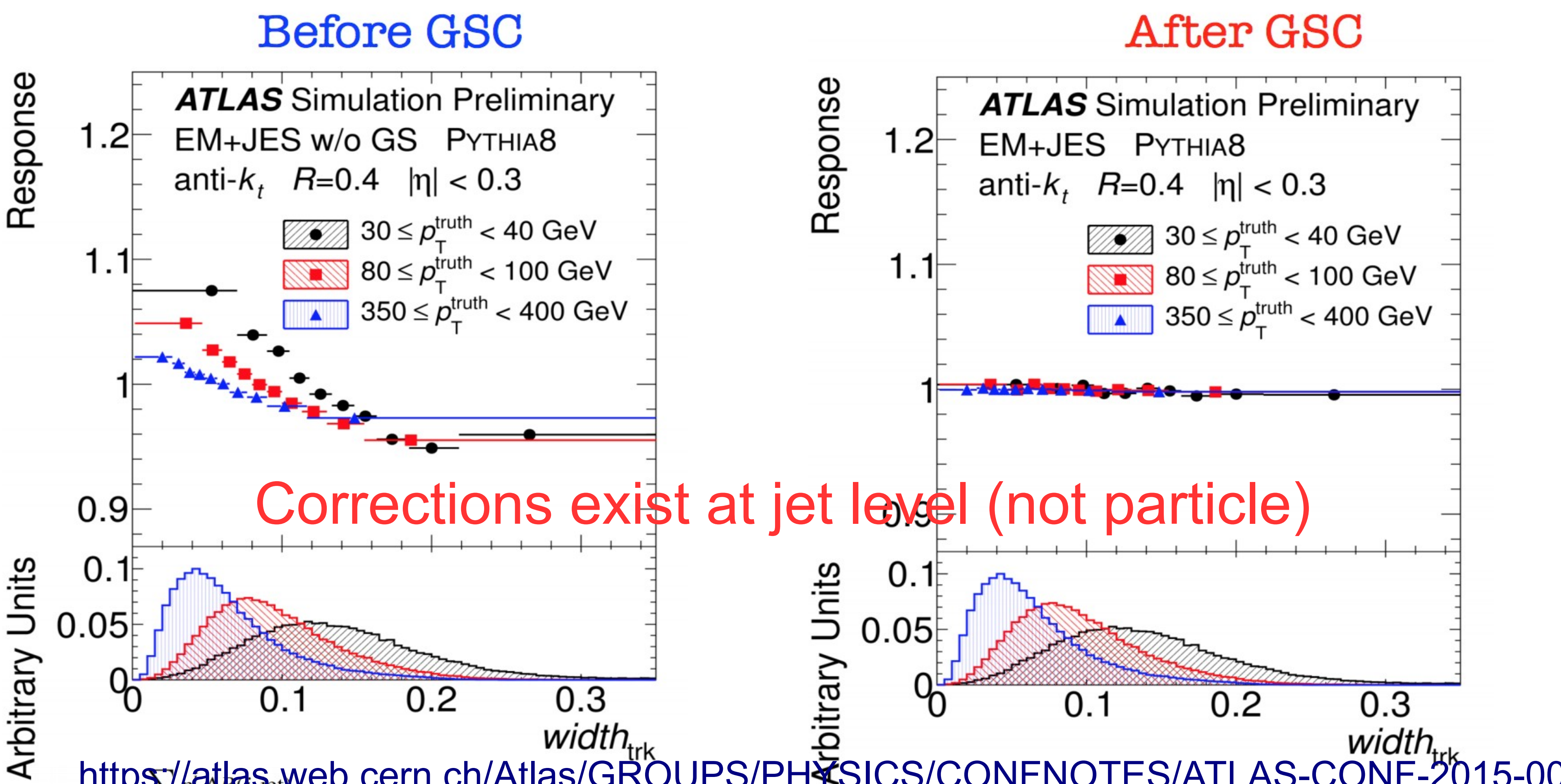
What does it take for E-flow?

- 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+η)	Residual Correction of Jet (using width/tracks) GSC
CMS Cluster Calorimeter Cells (pf clustesr)	Link Tracks to Pfclusters (pf particles)	Correction Of PF Candidate (p_T+η)	(ρ) PU Correction + Global Correction of Jet (p_T+η)

Jet-Level in ATLAS

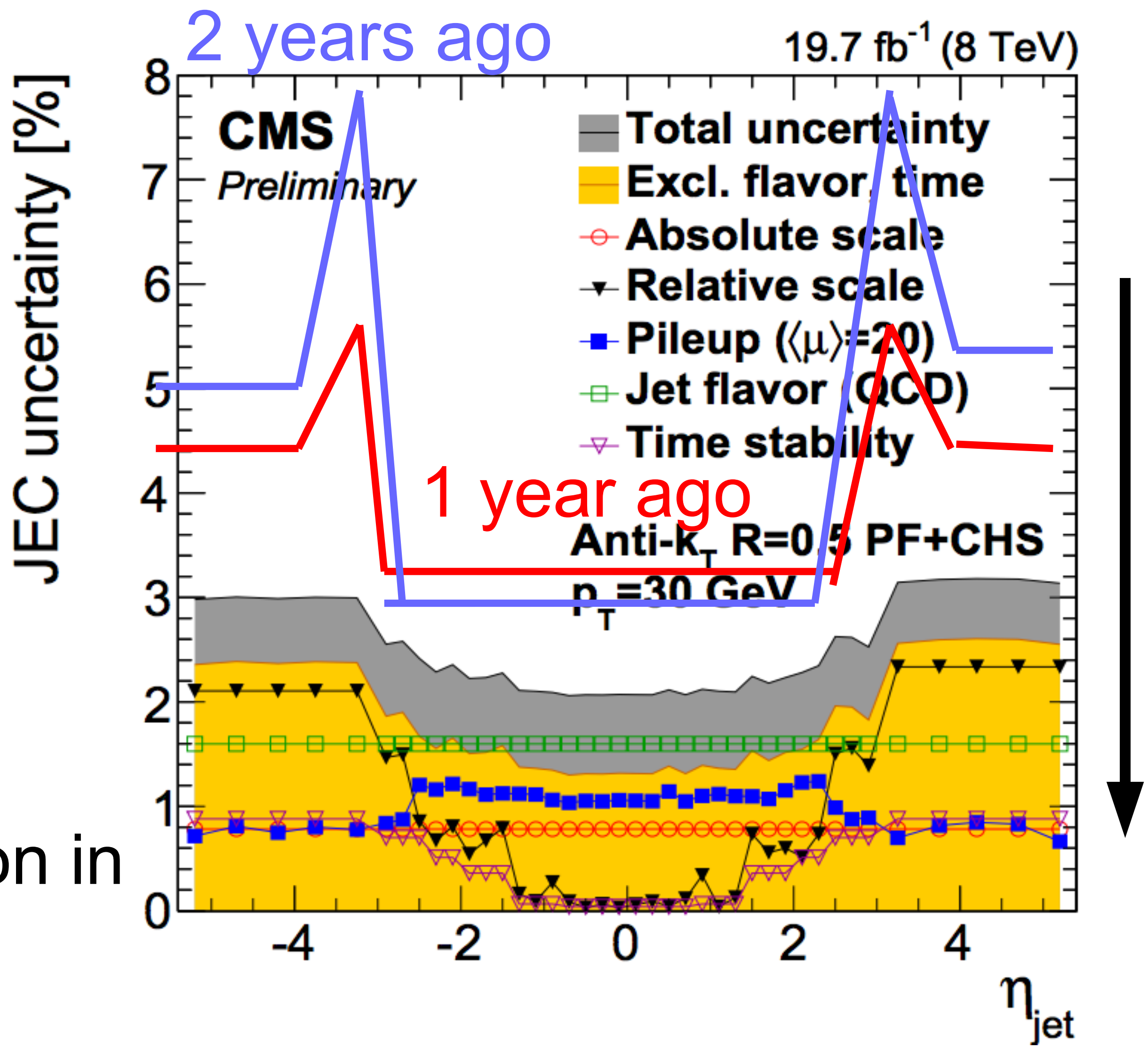
- While ATLAS does not use pflow
  - Yields resol. loss(Charged parts)+worse granularity
  - Compensates w/improved granularity through GSC



Corrections exist at jet level (not particle)

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-00

Jet Energy Scale



Understanding of JEC Steadily improved

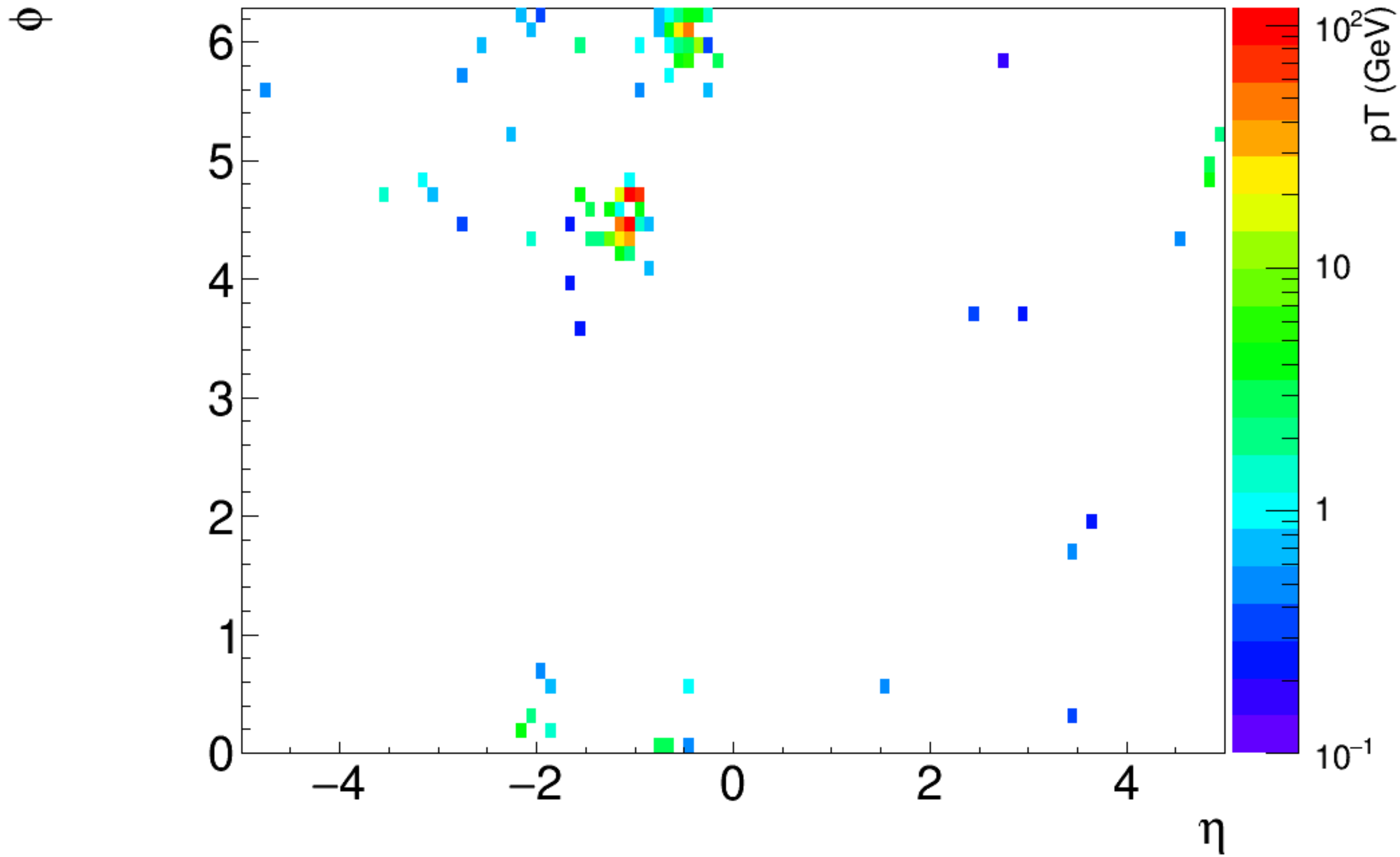
As we dealt with detector effects

Similar progression in ATLAS

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

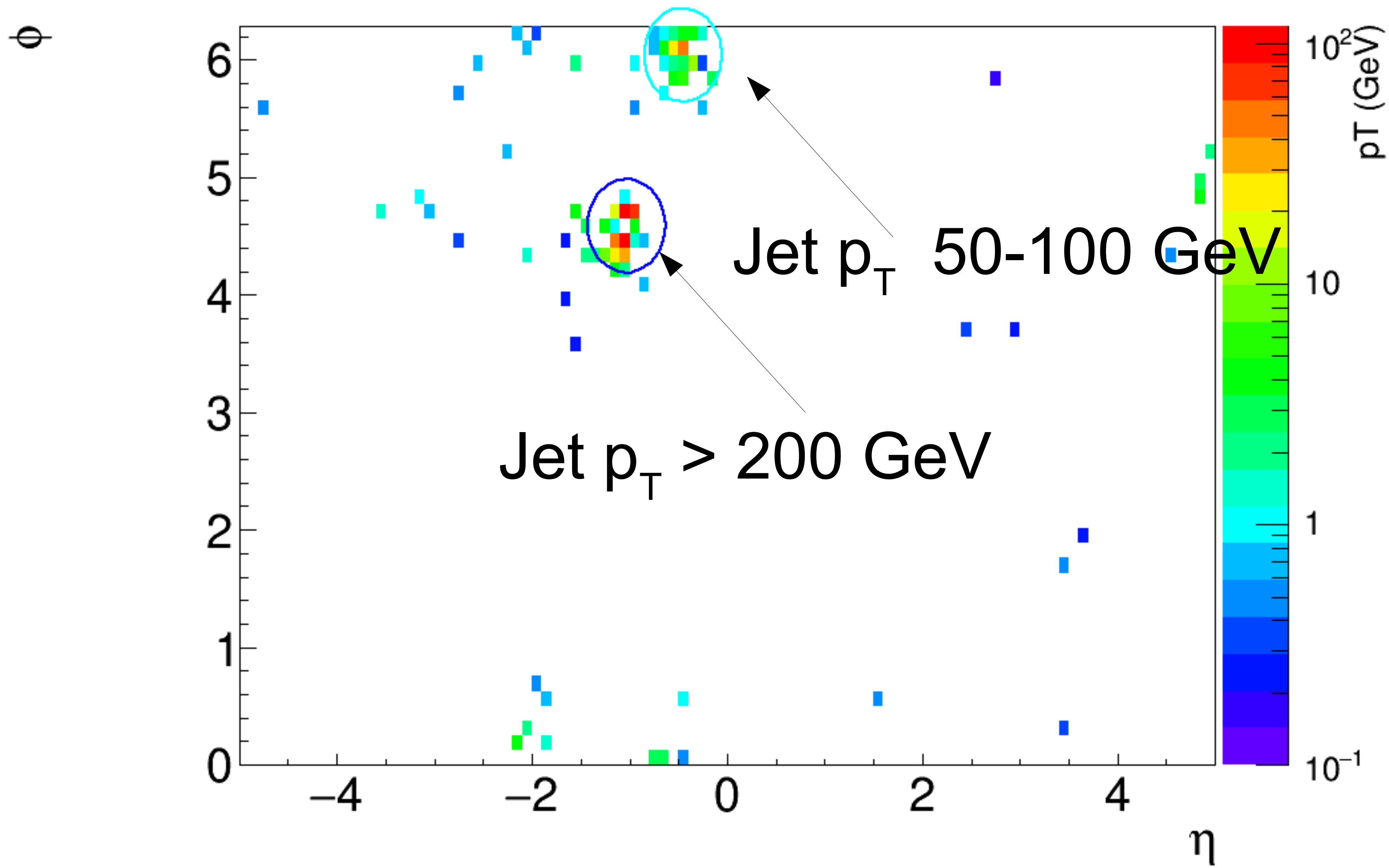
JME-13-004

What is it?

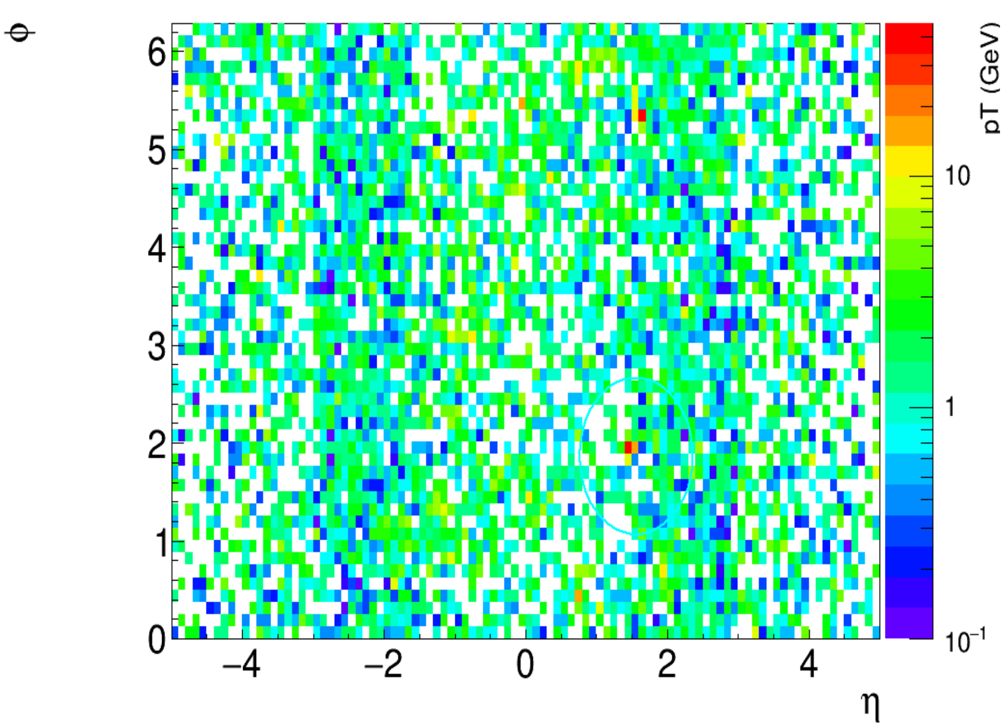


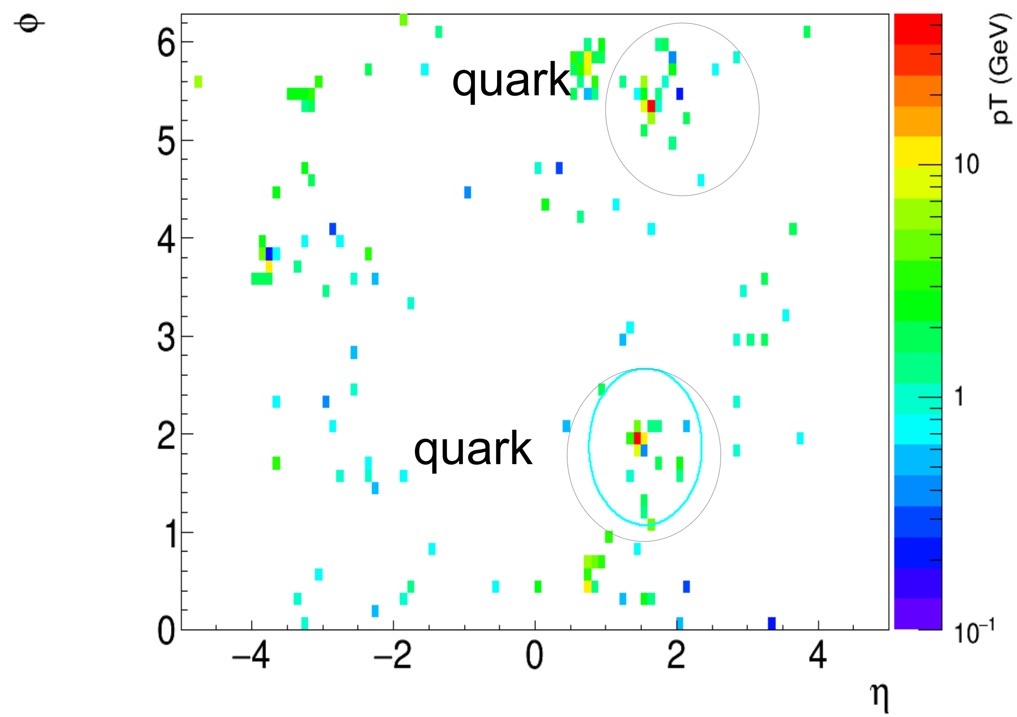
What is it?

Run Jet reco

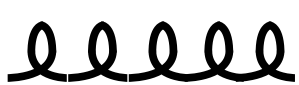


Any guesses?





Its a low pT W boson

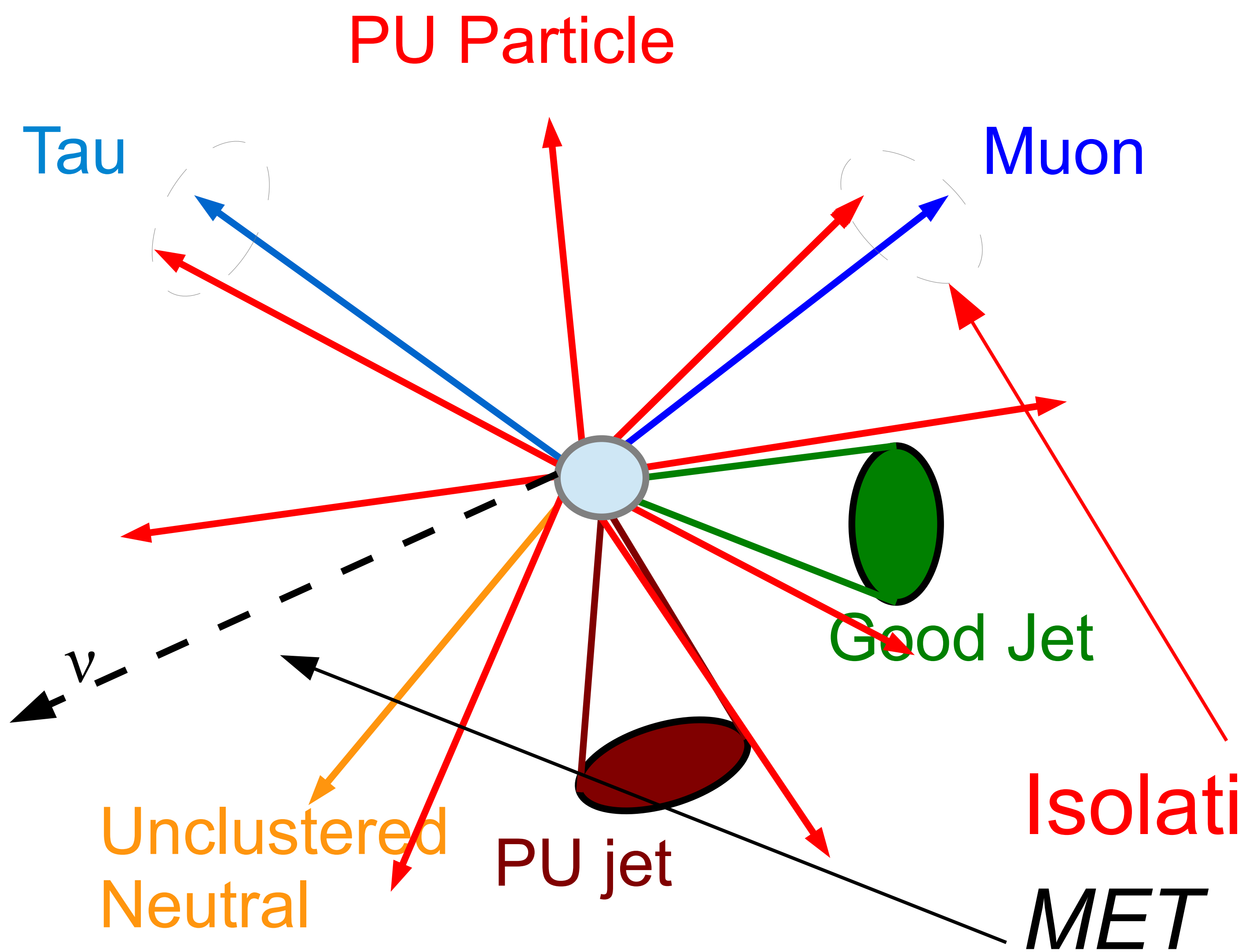


Pileup outside of jets

Lets look at objects outside of the jet!

Puppi affects everything

- It does not just work on jets!



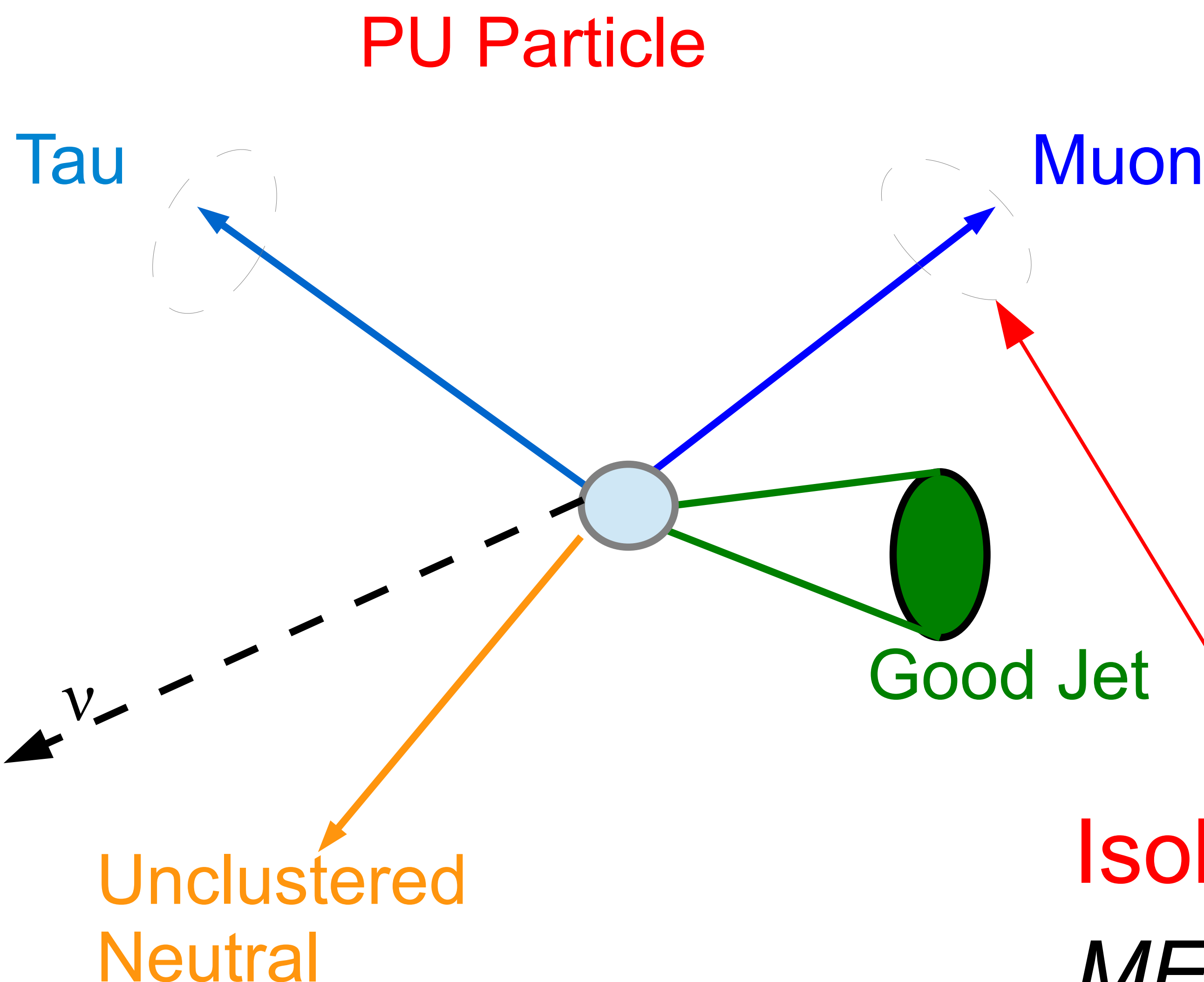
$$\text{Isolation} = \Sigma_{\Delta R} p_T$$

$$MET = -\Sigma \vec{p}_T$$

$$SUMET = \Sigma p_T$$

Puppi affects everything

- It does not just work on jets!



Apply the Puppi Weights w

$$\text{Isolation} = \Sigma_{\Delta R} p_T w$$

$$MET = -\Sigma \vec{p}_T w$$

$$SUMET = \Sigma p_T w$$