

# One Lecture on Jets

## From Physics to Algorithms

Jesse Thaler



8.701 — November 12, 2019

# Outline

Jets in the Big Picture (cartoons)

Dynamics of Jet Formation (more cartoons)

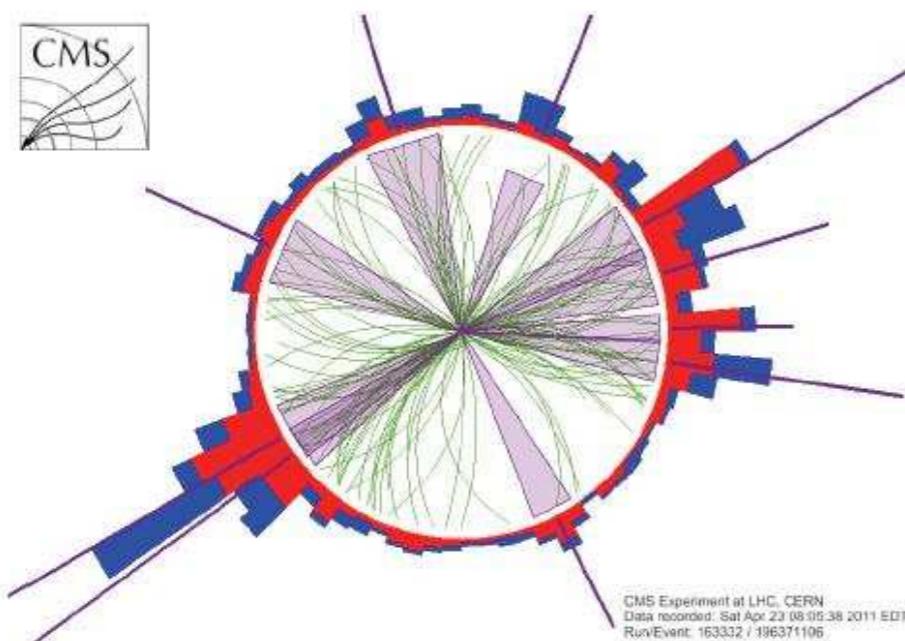
The Shape of Jets (algorithms)

Parting Thoughts (inspiration)

# What is a Jet?

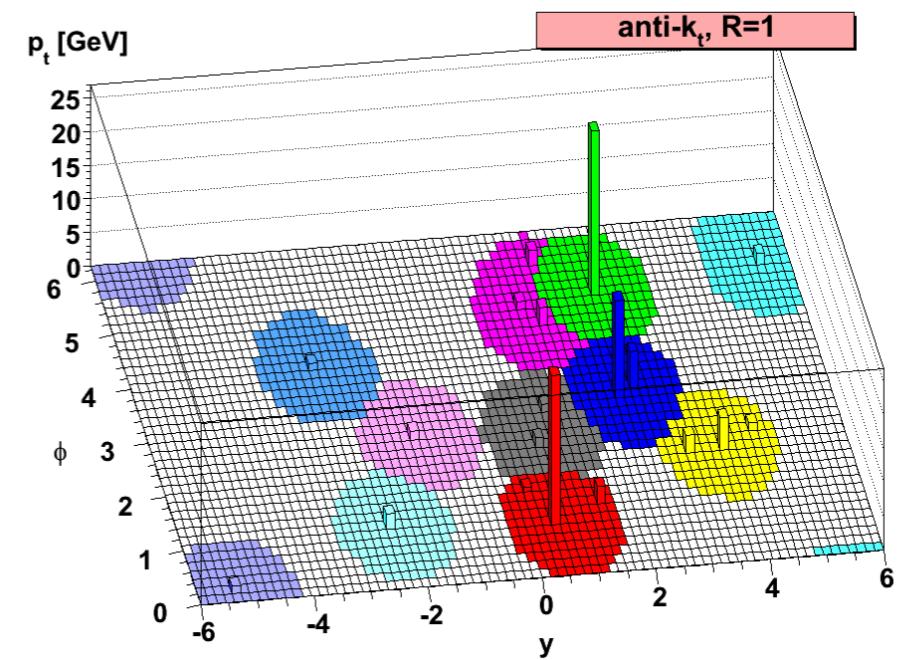
A physical phenomena:

*Emergent feature of  
confining gauge theories*



An analysis technique:

*Method to interpret  
hadronic final states*

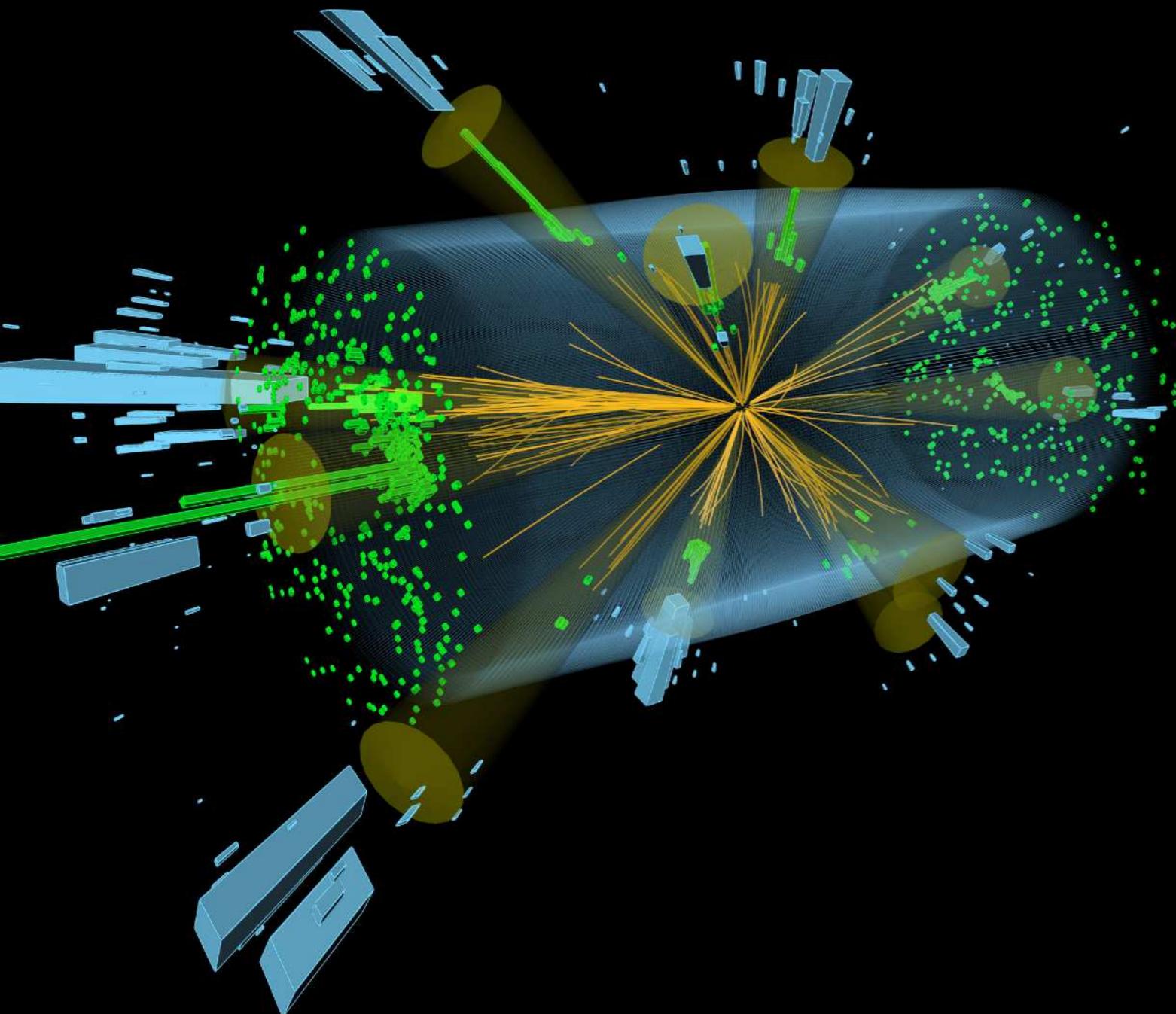


*Freedom to use  
different analysis strategies for  
different physical questions*

# *Jets in the Big Picture*

# Collider Event

Collection of points in (momentum) space



T E H M

 $\gamma$ 

photon

 $e^+$ 

electron

 $\mu^+$ 

muon

 $\pi^+$ 

pion

 $K^+$ 

kaon

 $K_L^0$ 

K-long

 $p/\bar{p}$ 

proton

 $n/\bar{n}$ 

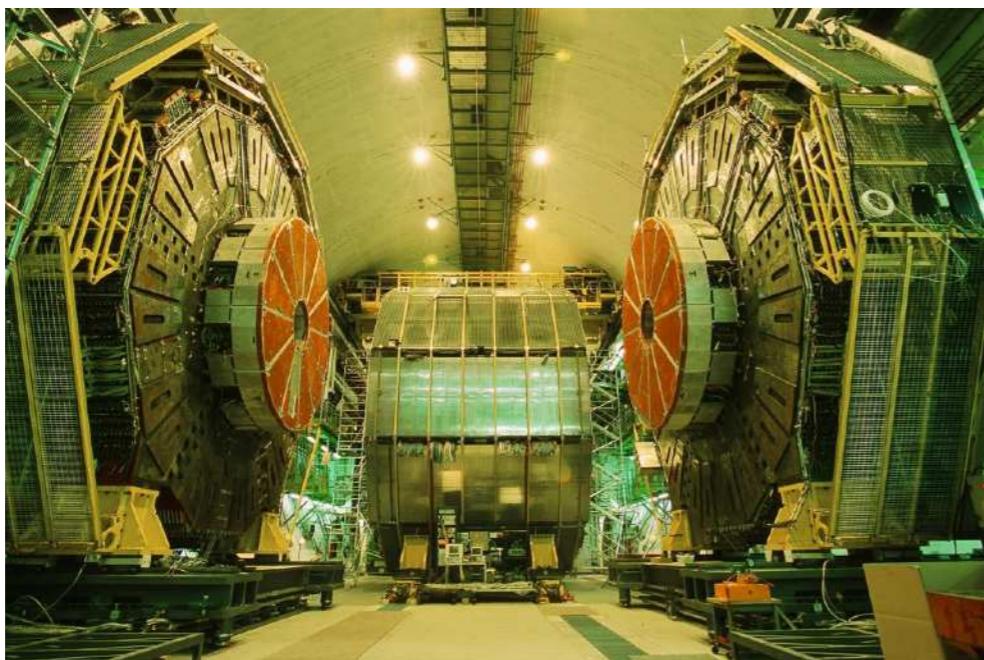
neutron

elementary

composite

JOSHUA BATSON SCIENCE 01.23.15 6:45 AM

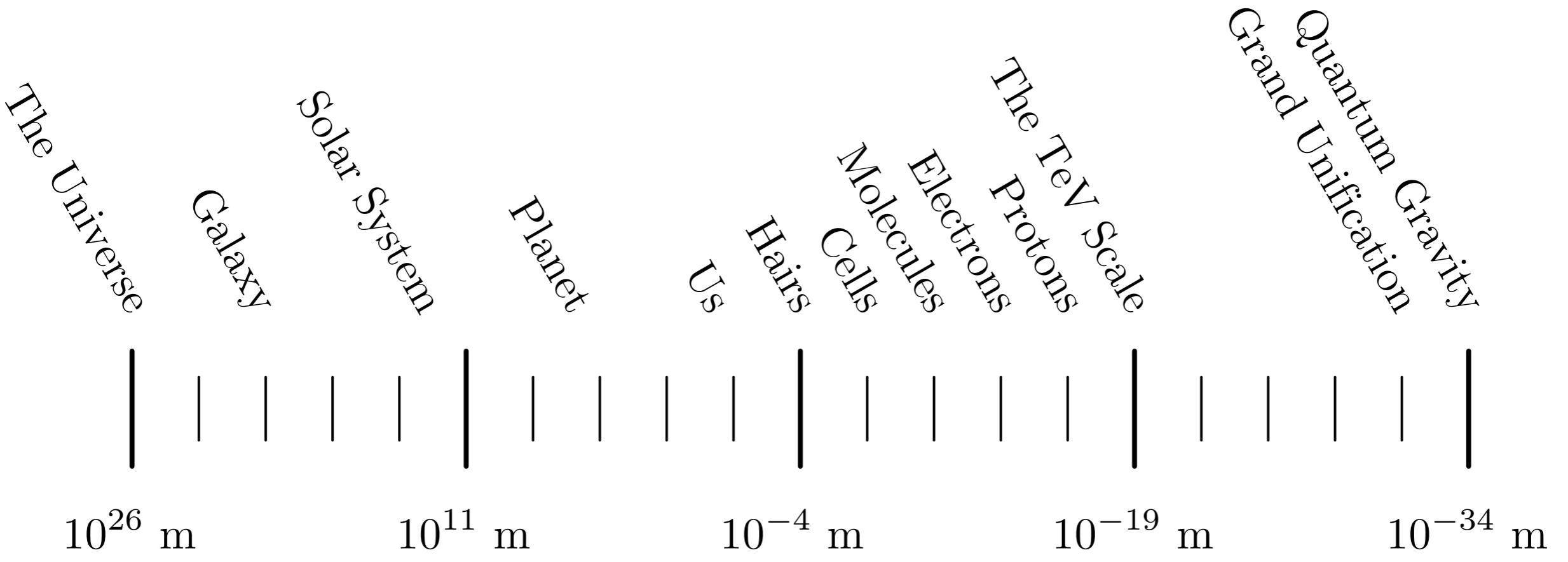
## HOW THREE GUYS WITH \$10K AND DECADES-OLD DATA ALMOST FOUND THE HIGGS BOSON FIRST



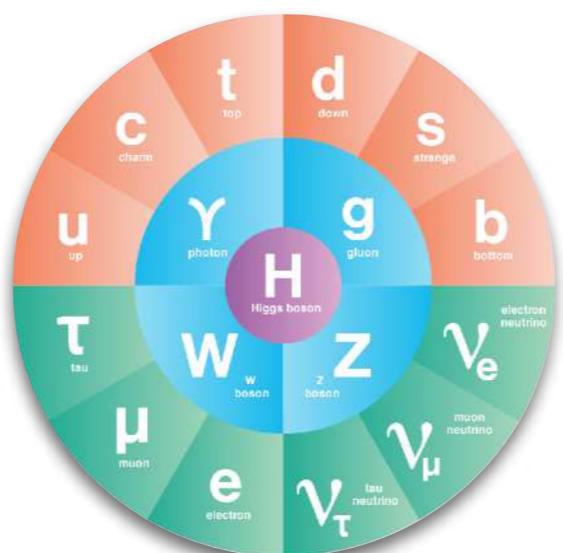
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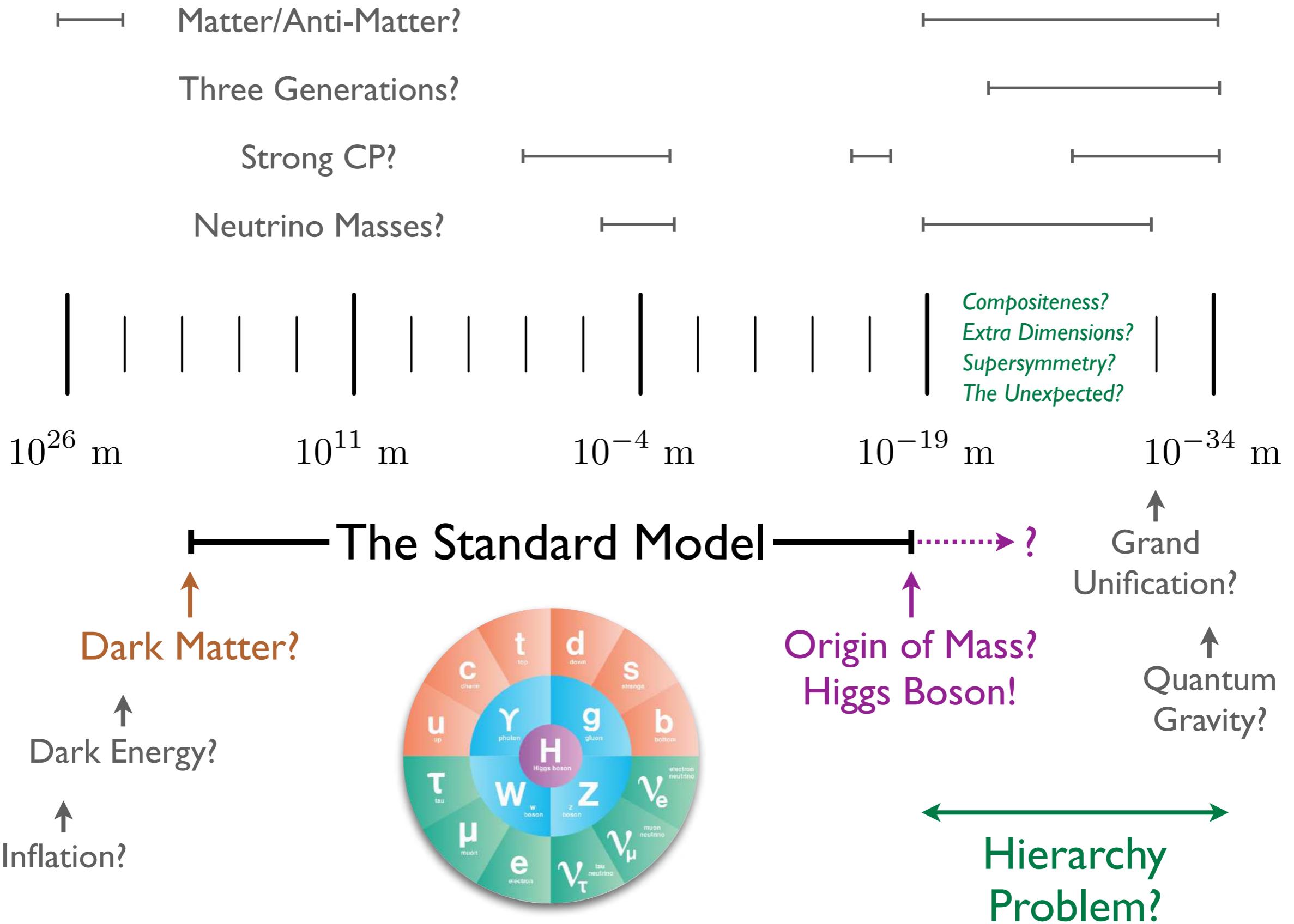
**“Figuring out what happened in a collider is like trying to figure out what your dog ate at the park yesterday. You can find out, but you have to sort through a lot of shit to do it.”**

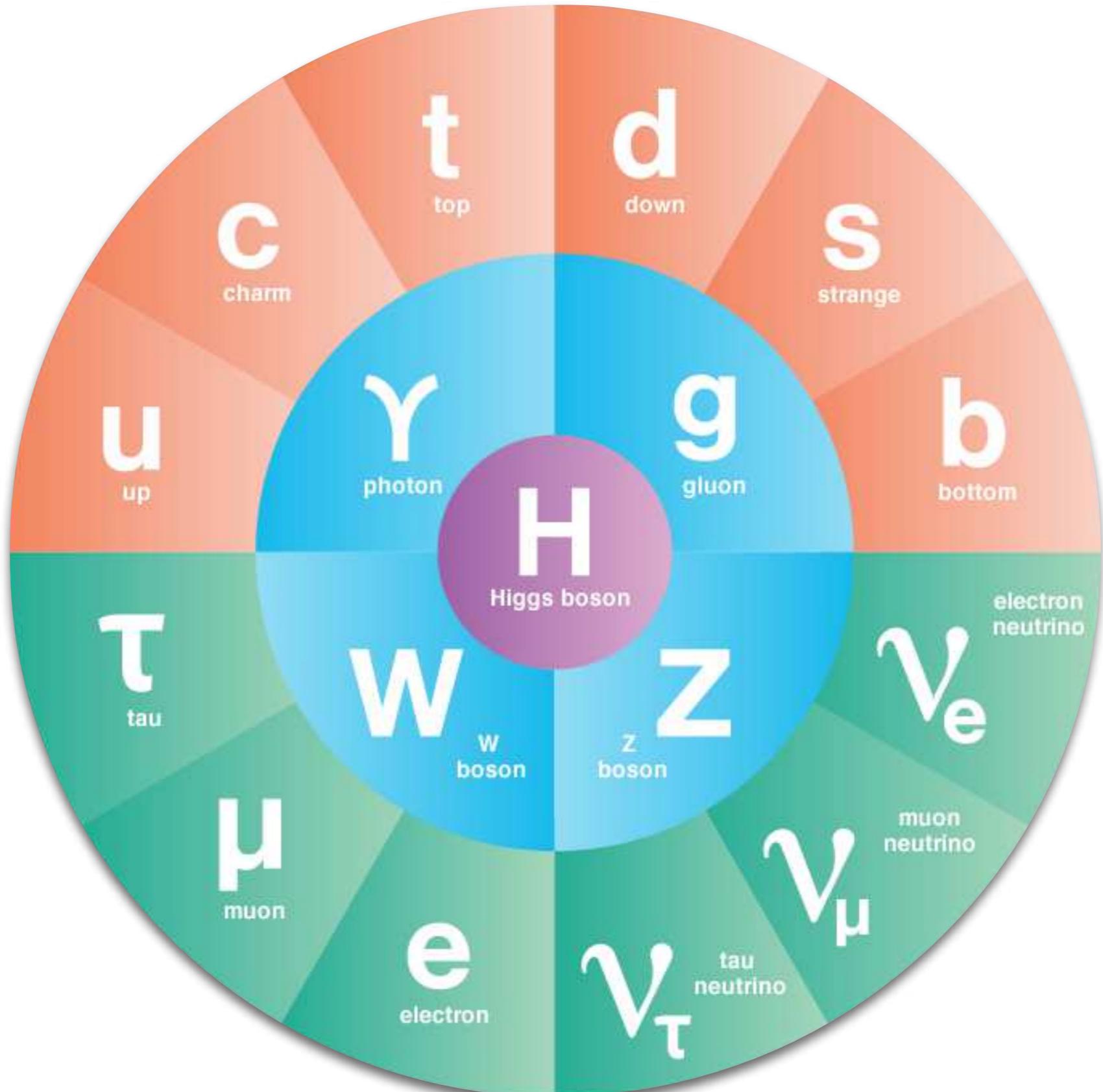
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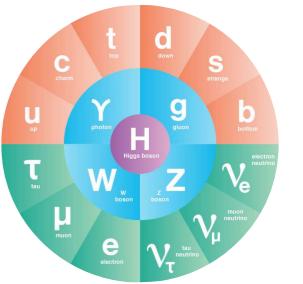


## The Standard Model



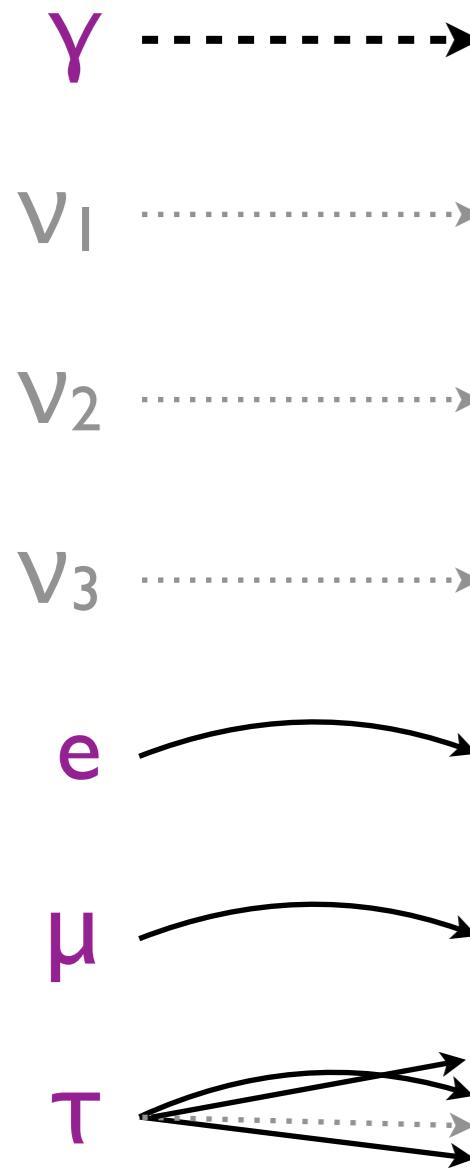




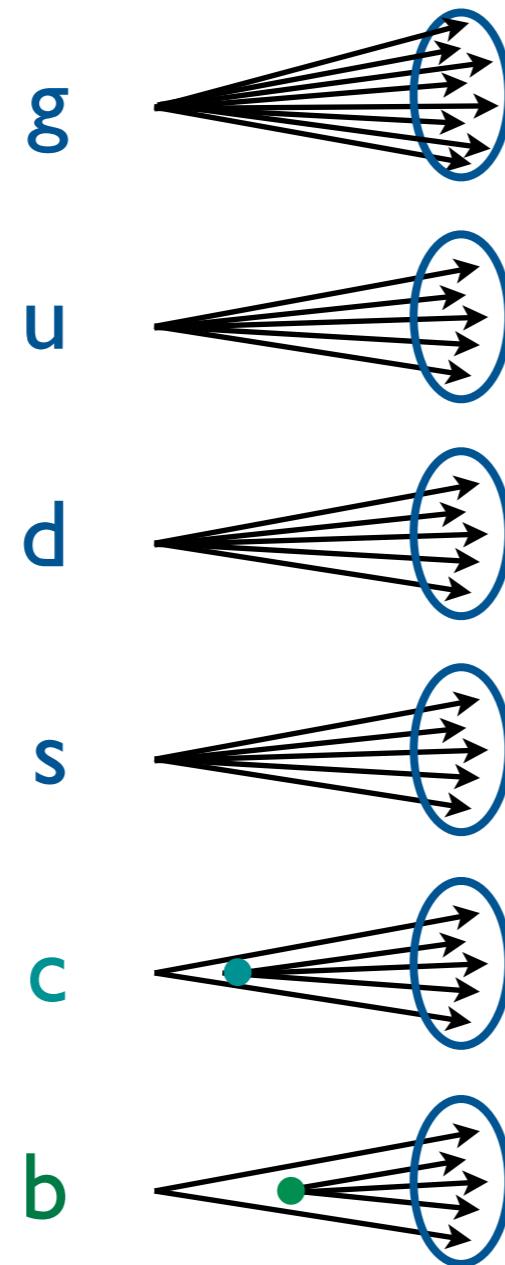


# Particles as Probes

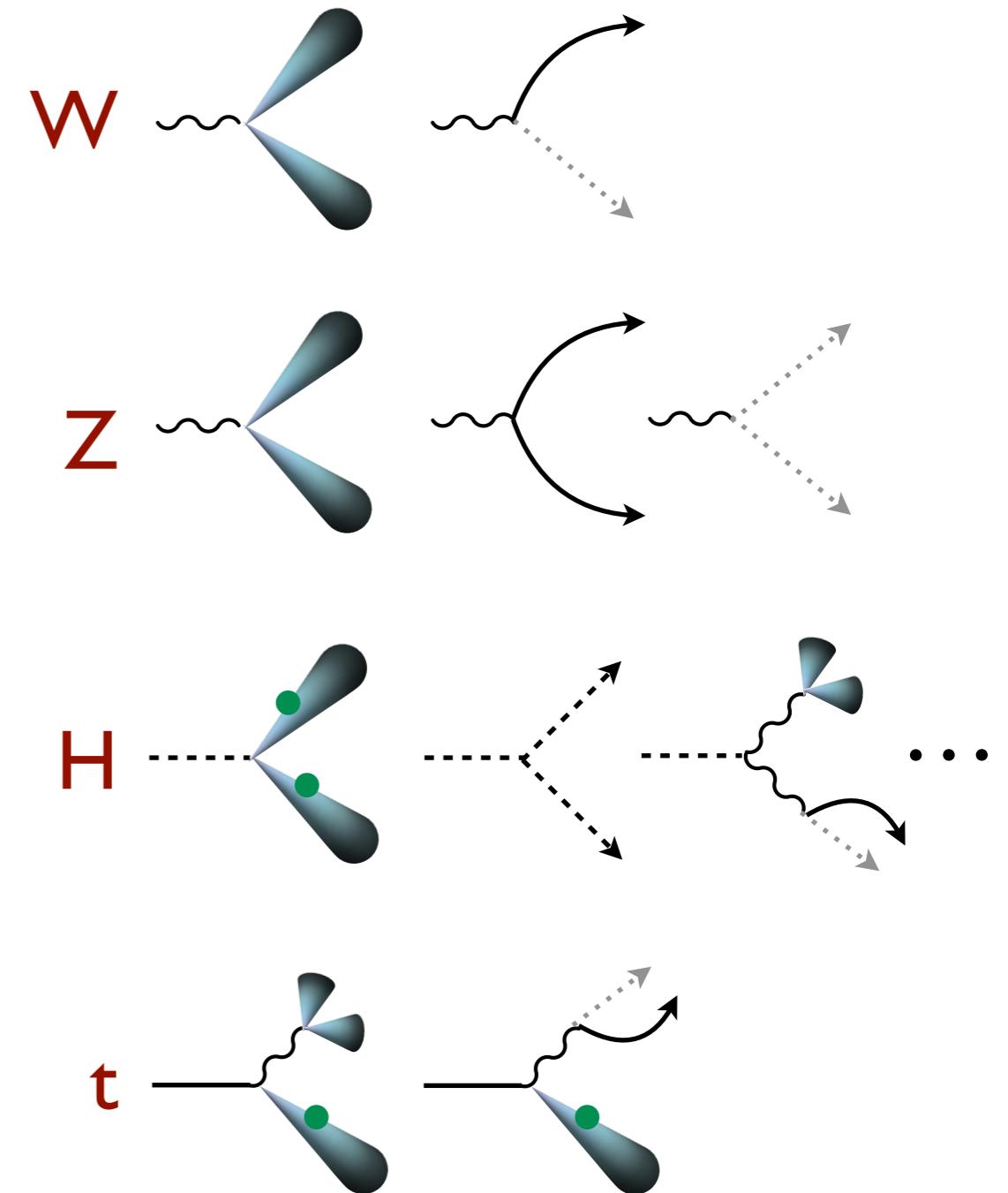
Not Jets



Jets



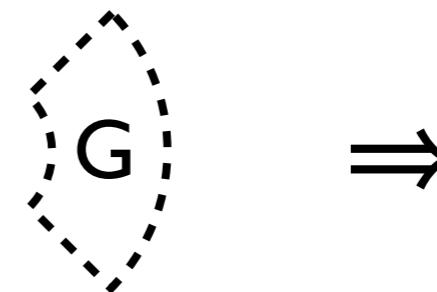
Multi-Jets (or Not)



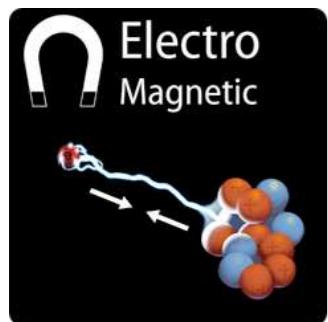
# Particles and Fundamental Forces



massless spin-2 graviton



GR  
 $G_N$



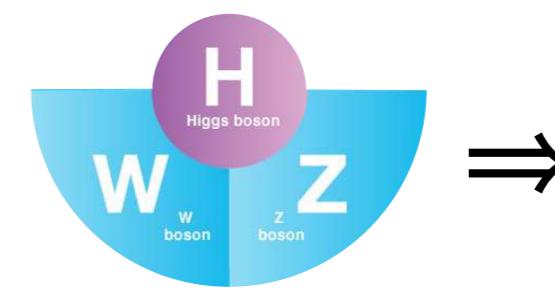
massless spin-1 photon



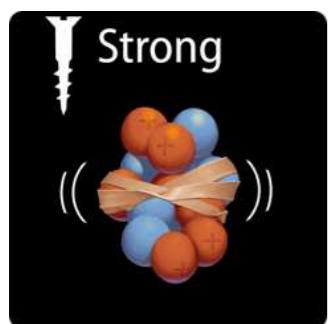
QED  
 $\alpha_{EM}$



3 massive spin-1 W/Z bosons  
+ massive spin-0 Higgs boson



Puzzles  
16+



8 massless spin-1 gluons



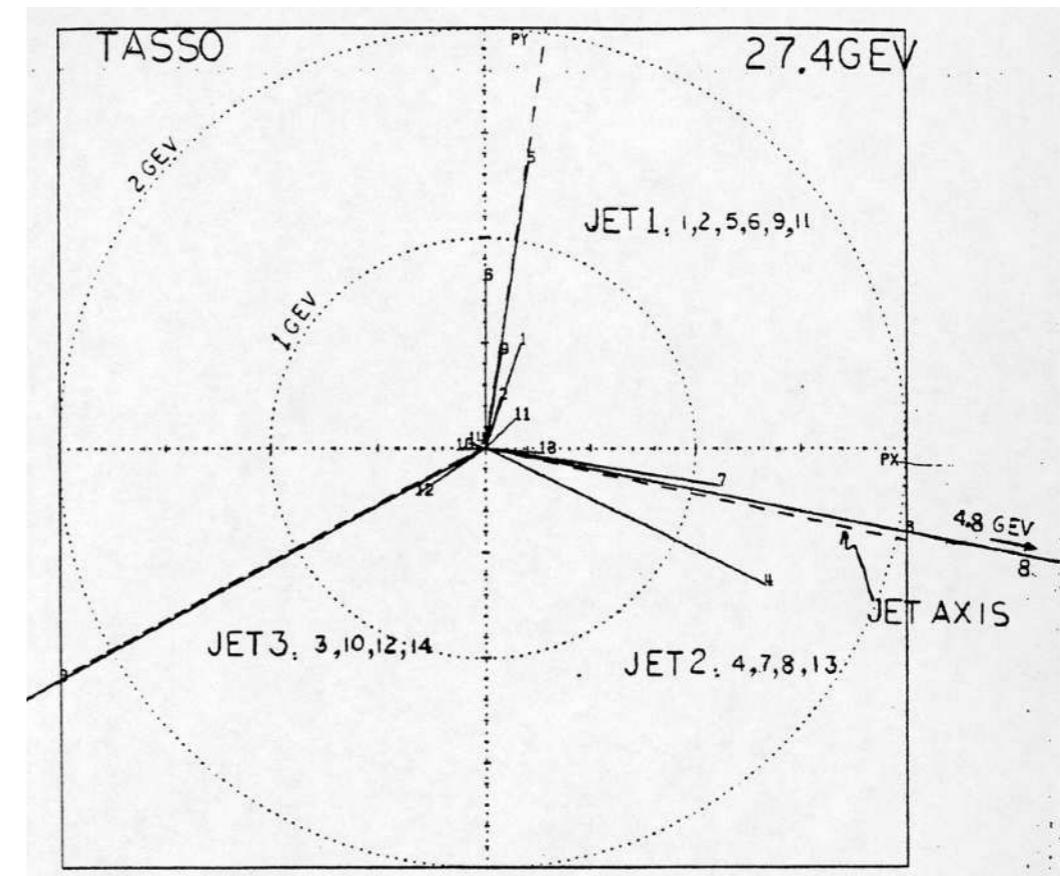
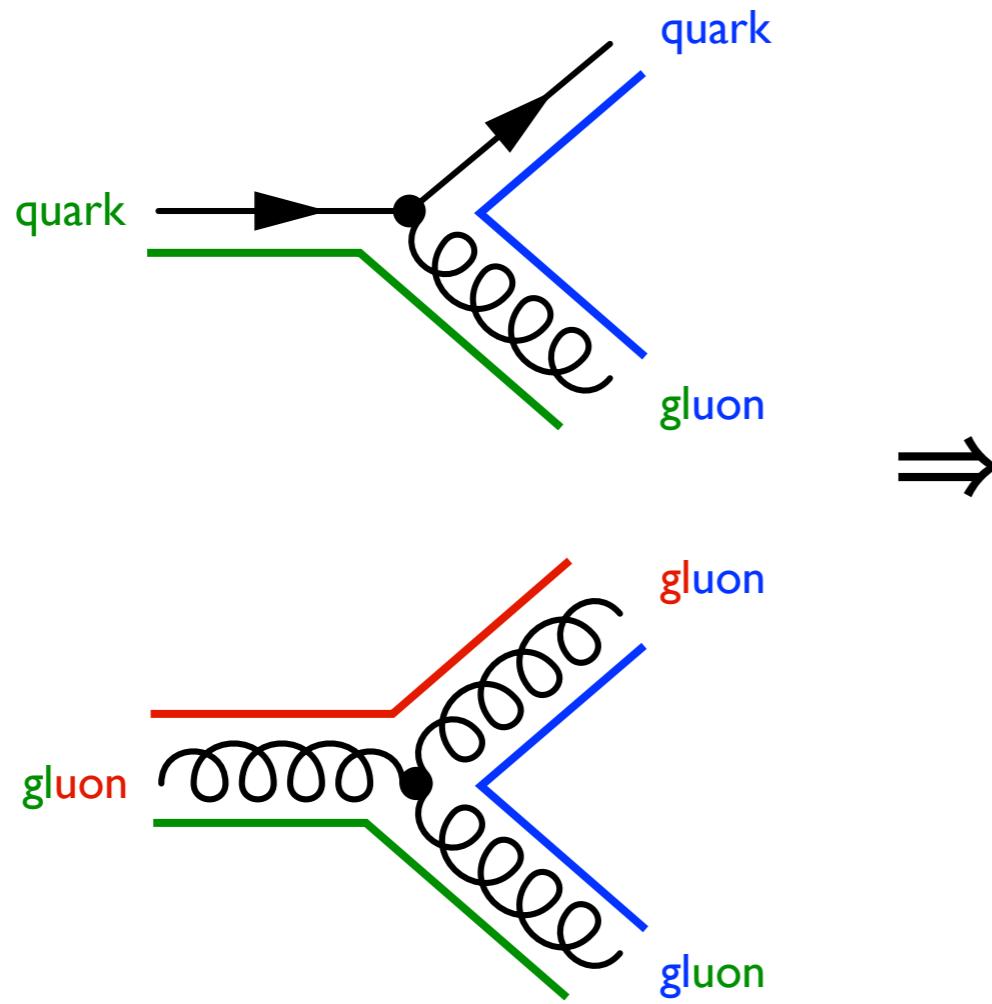
QCD  
 $\alpha_s$   
 $\text{plus } \theta_{QCD} \approx 0$

$$\mathcal{L} = \frac{1}{4g^2} G_{\mu\nu}^\alpha G_{\mu\nu}^\alpha + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

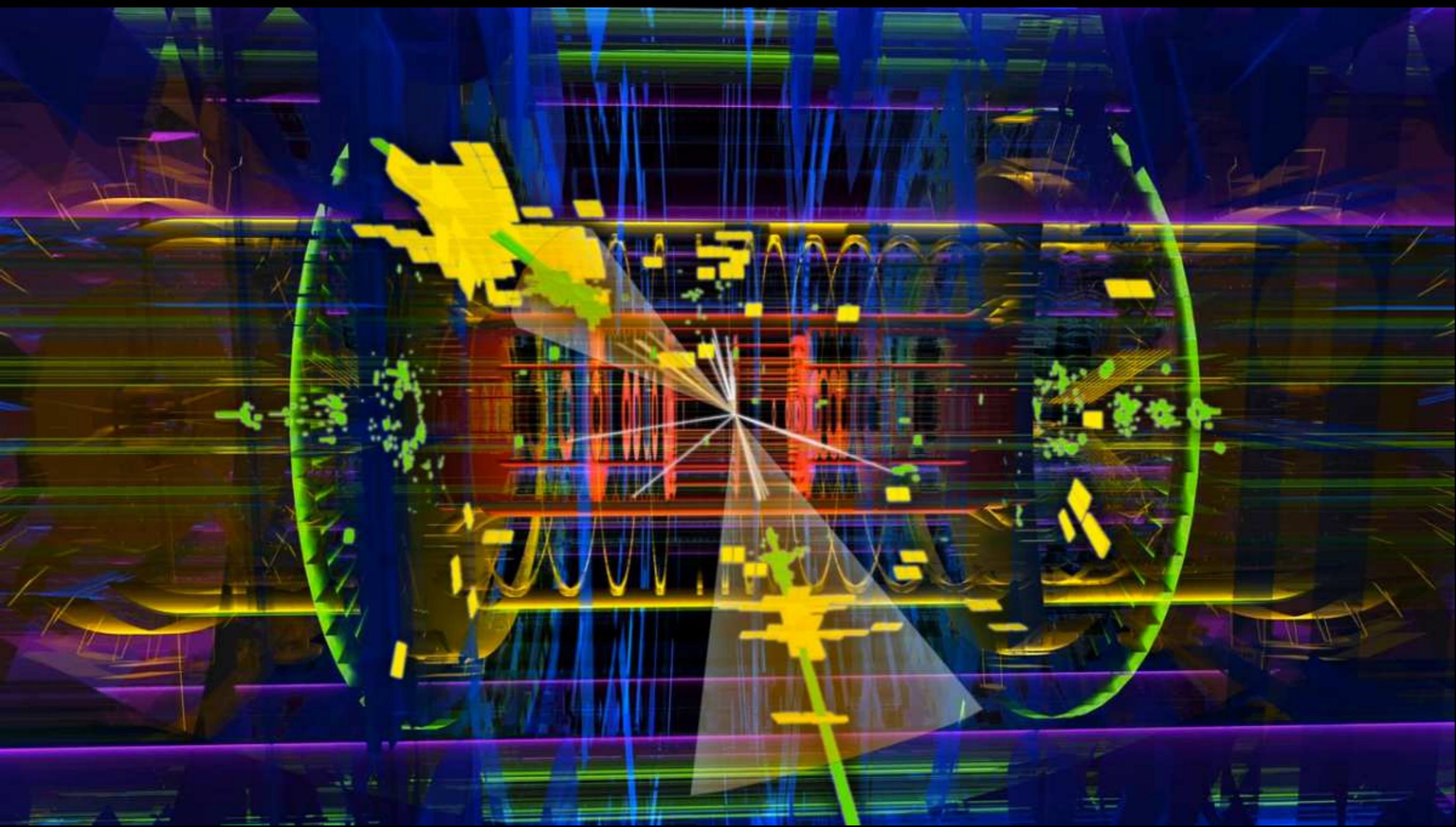
where  $G_{\mu\nu}^\alpha = \partial_\mu A_\nu^\alpha - \partial_\nu A_\mu^\alpha + i f_{\beta\gamma}^\alpha A_\mu^\beta A_\nu^\gamma$

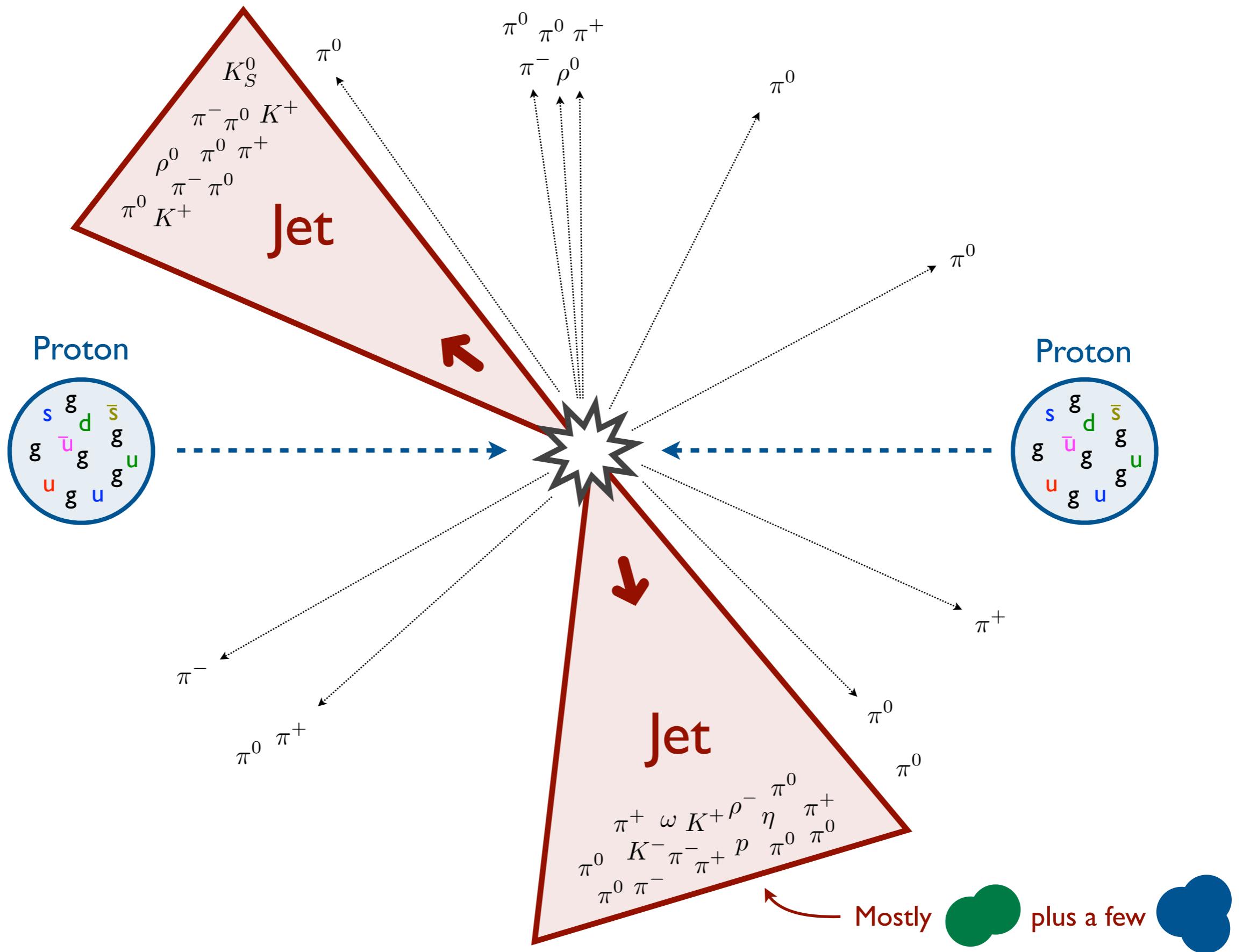
and  $D_\mu \equiv \partial_\mu + i t^\alpha A_\mu^\alpha$

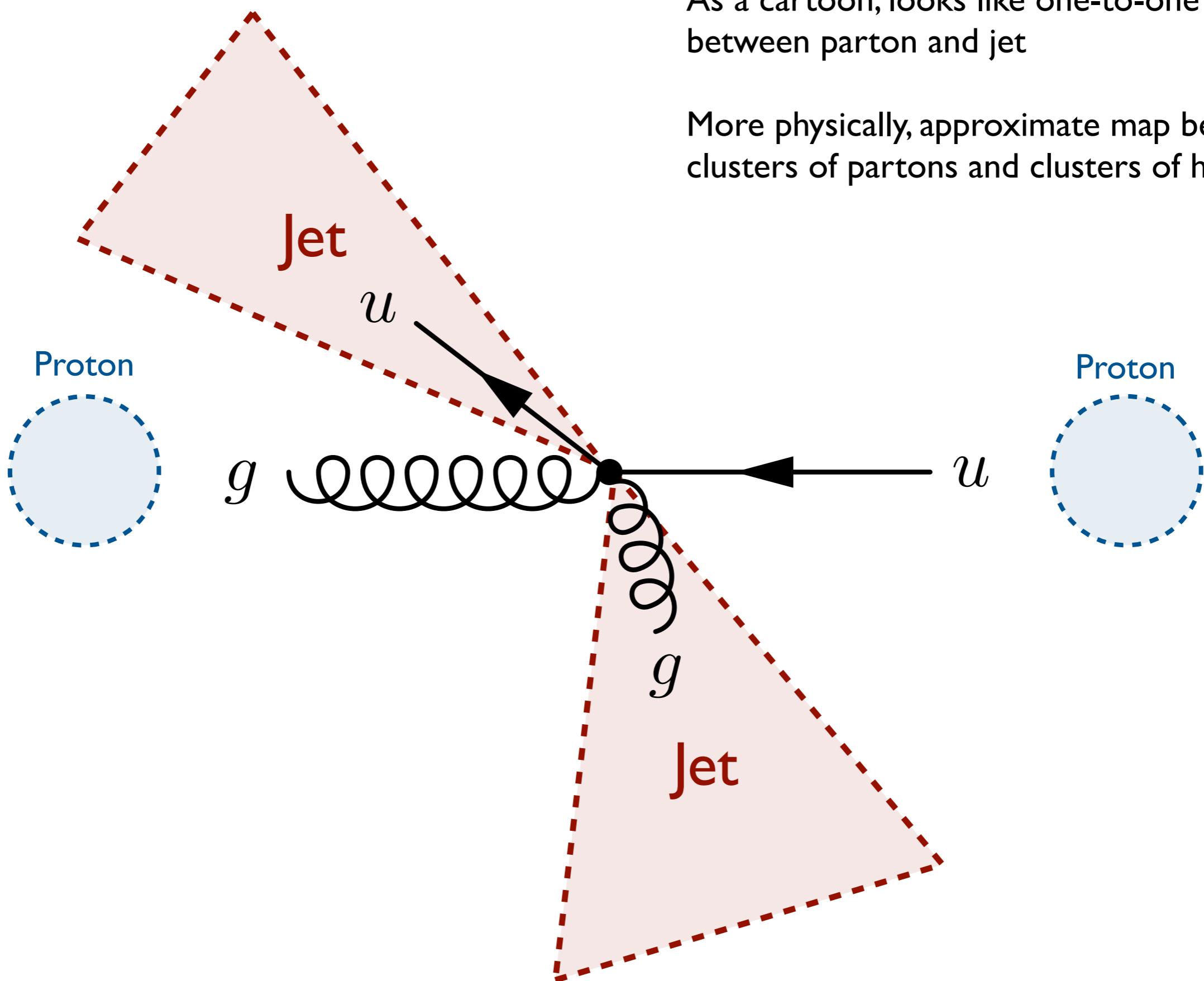
That's it!



[TASSO @ PETRA @ DESY, 1979]

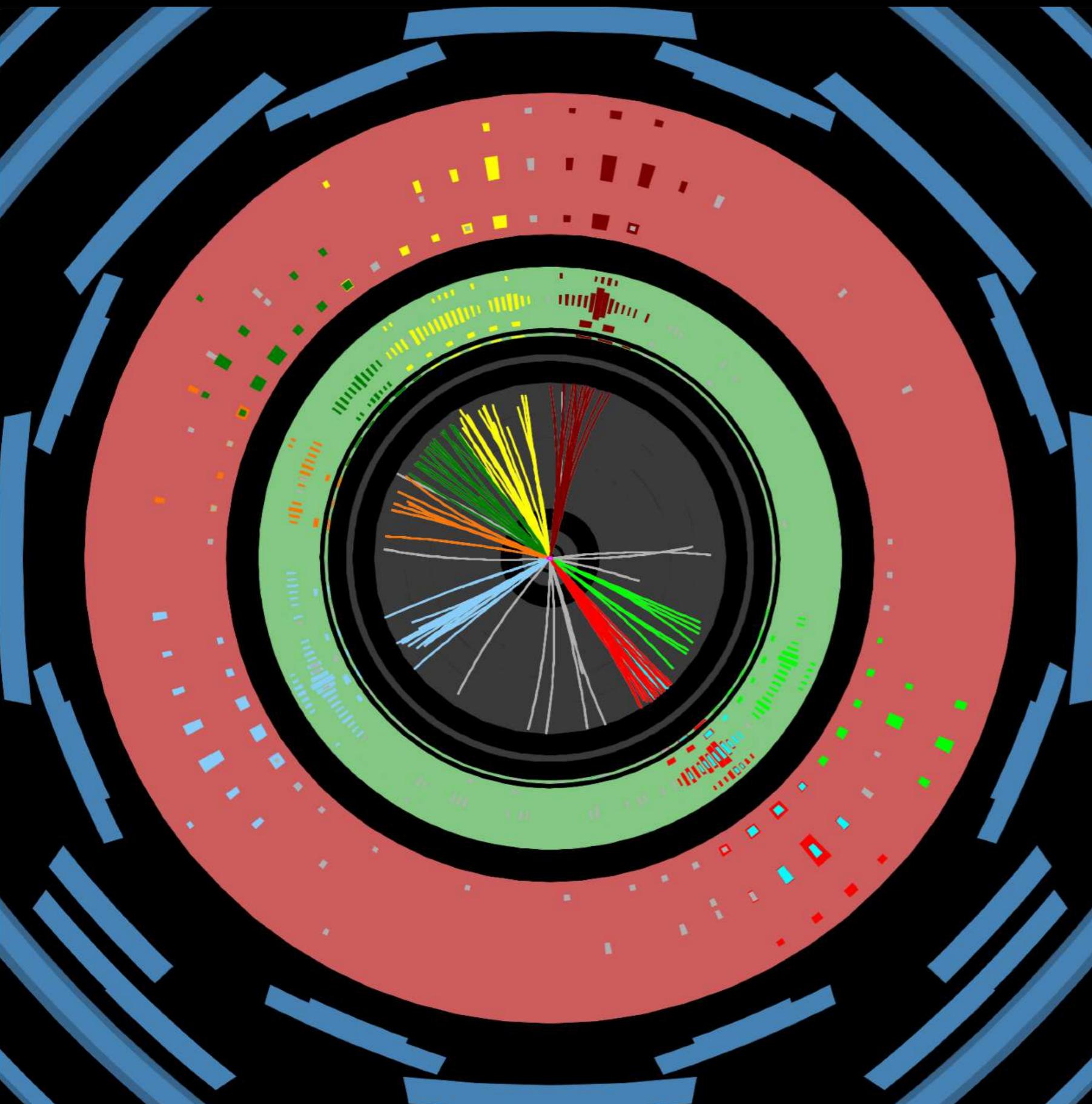






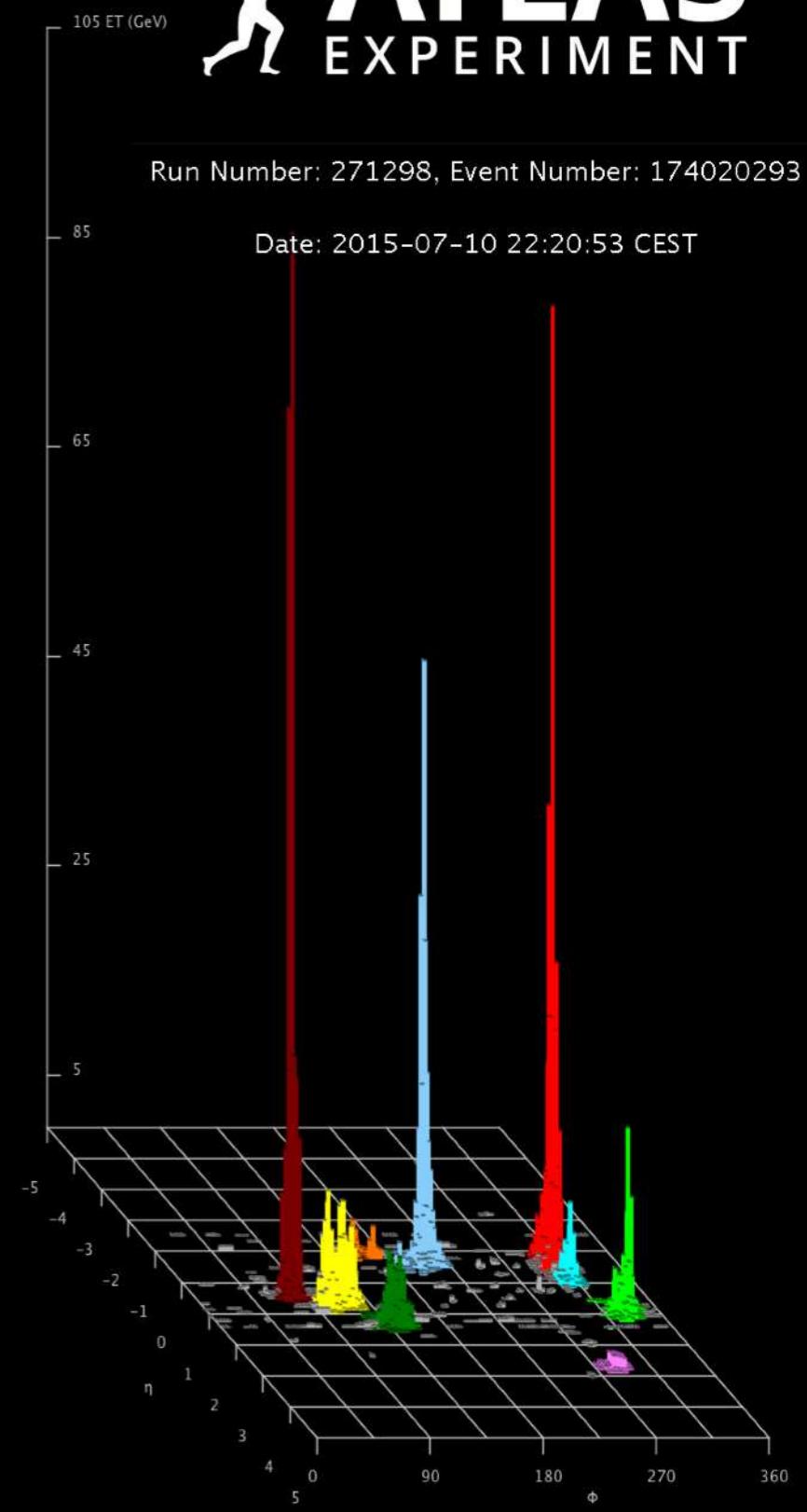
As a cartoon, looks like one-to-one map  
between parton and jet

More physically, approximate map between  
clusters of partons and clusters of hadrons

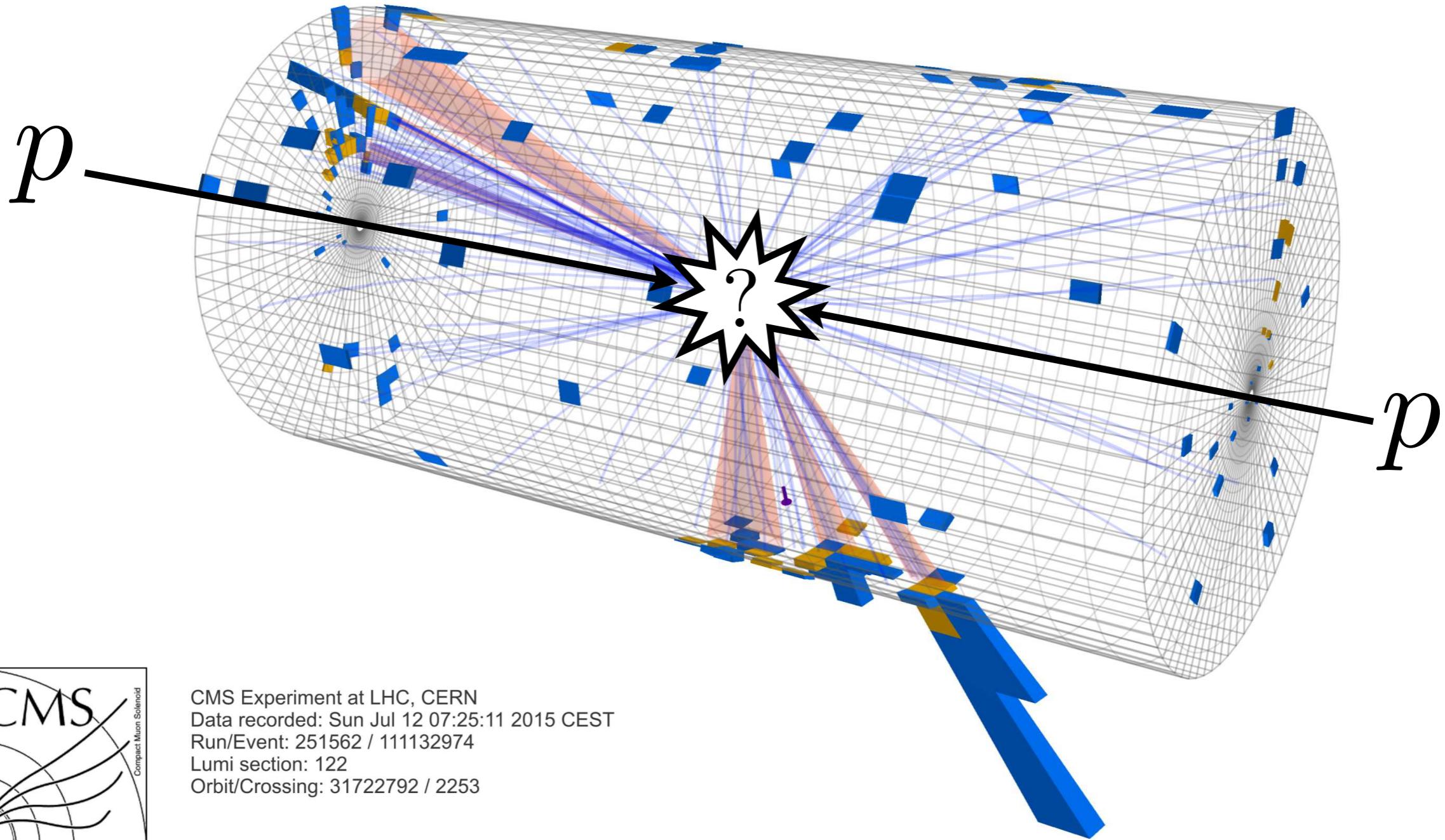


Run Number: 271298, Event Number: 174020293

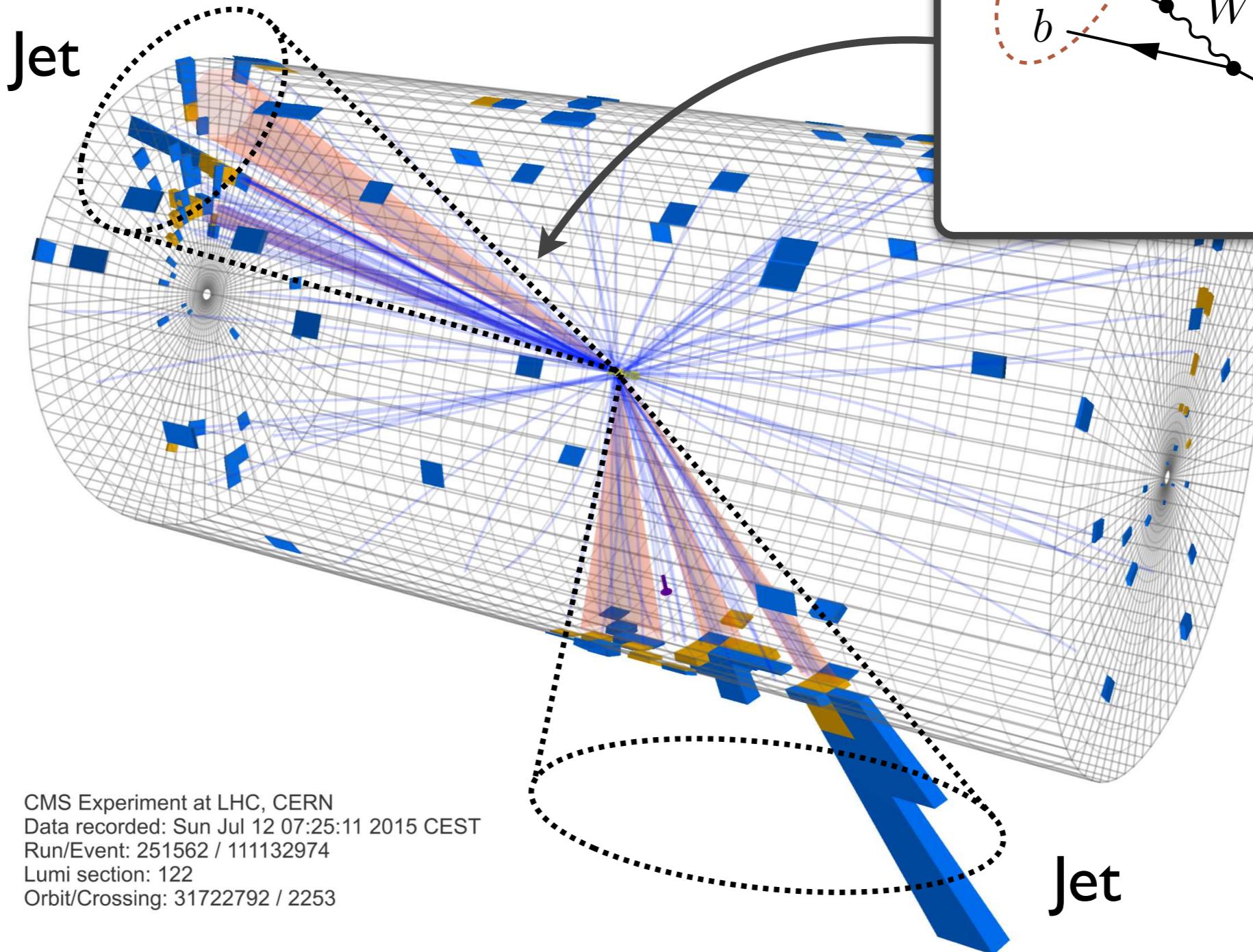
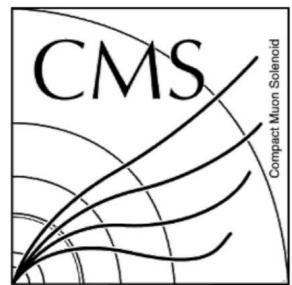
Date: 2015-07-10 22:20:53 CEST



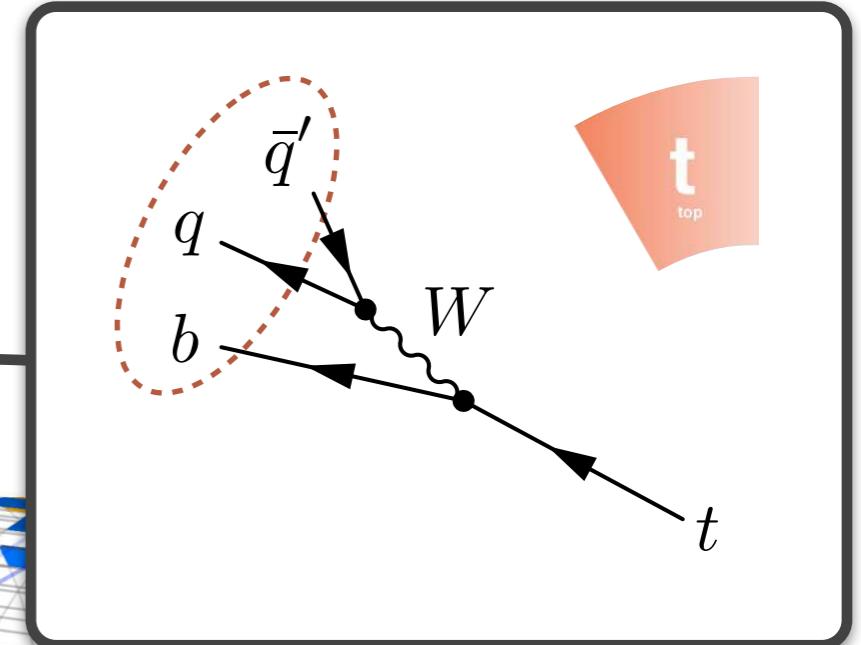
# The Rise of Jet Substructure



# The Rise of Jet Substructure



CMS Experiment at LHC, CERN  
Data recorded: Sun Jul 12 07:25:11 2015 CEST  
Run/Event: 251562 / 111132974  
Lumi section: 122  
Orbit/Crossing: 31722792 / 2253



# If you ain't Boostin', you ain't Livin'...

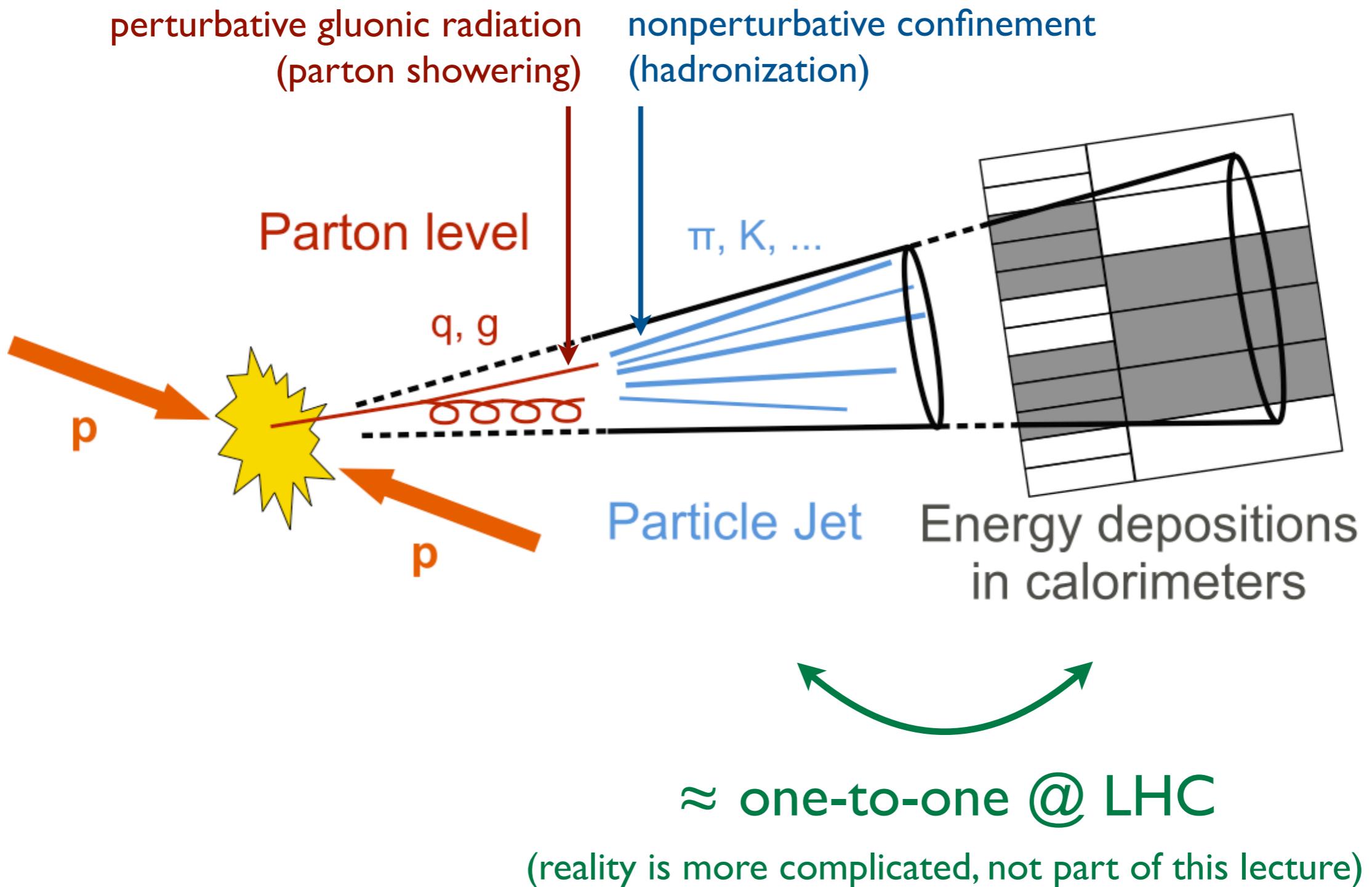
11th International Workshop on Boosted Objects



[see reviews in Larkoski, Moult, Nachman, [arXiv 2017](#);  
Asquith, Delitzsch, Schmidt, et al., [arXiv 2018](#);  
Marzani, Soyez, Spannowsky, [LNP 2019](#)]

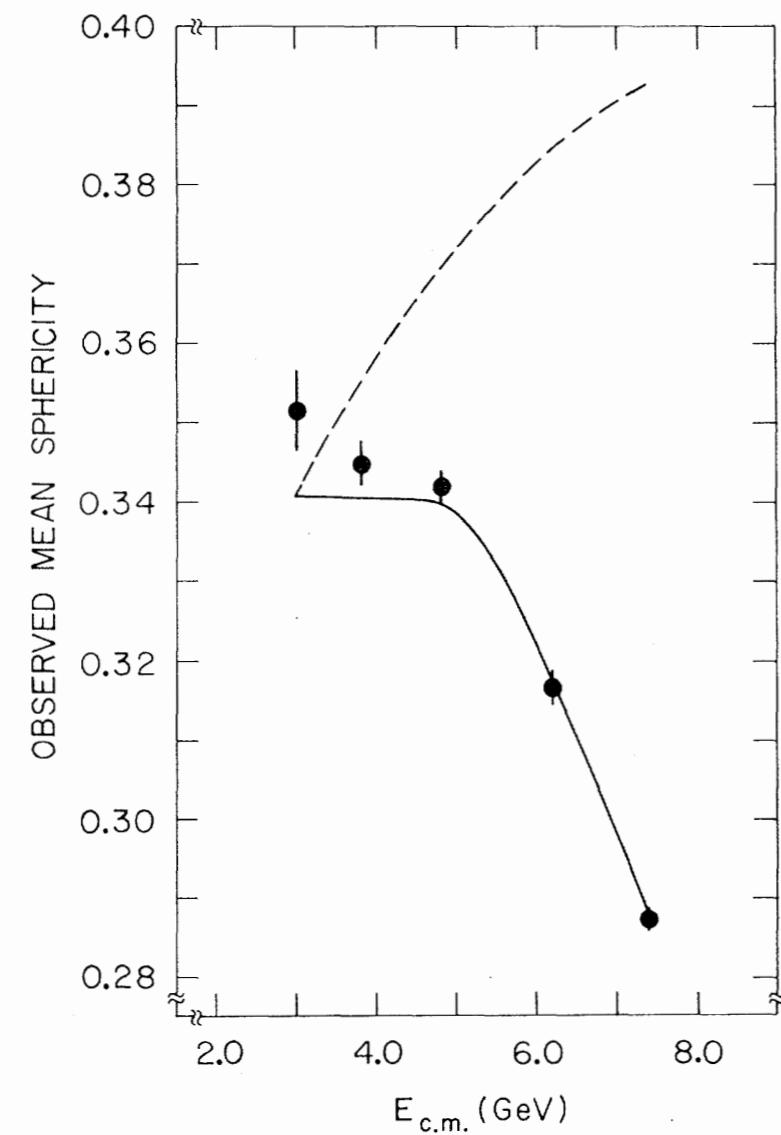
# *Dynamics of Jet Formation*

# From Partons to Hadrons to Detection

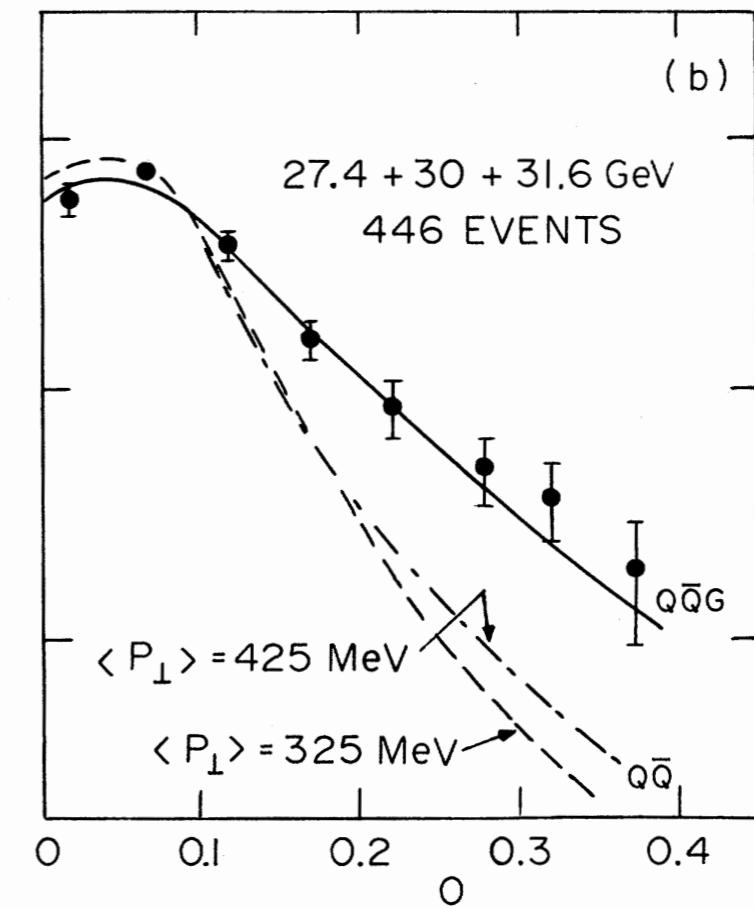


# First Light on Jets

*Jets @ SPEAR, 1975*

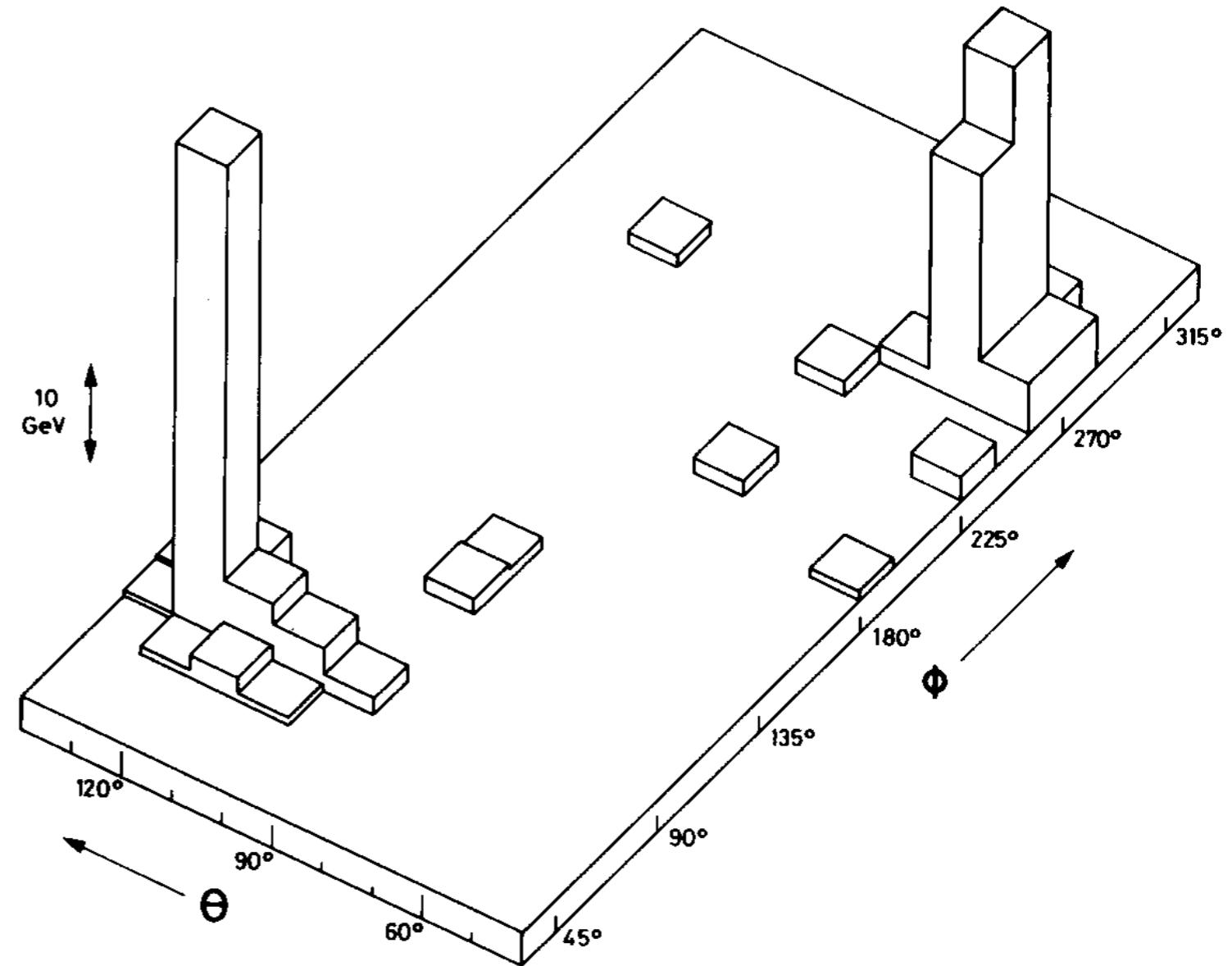
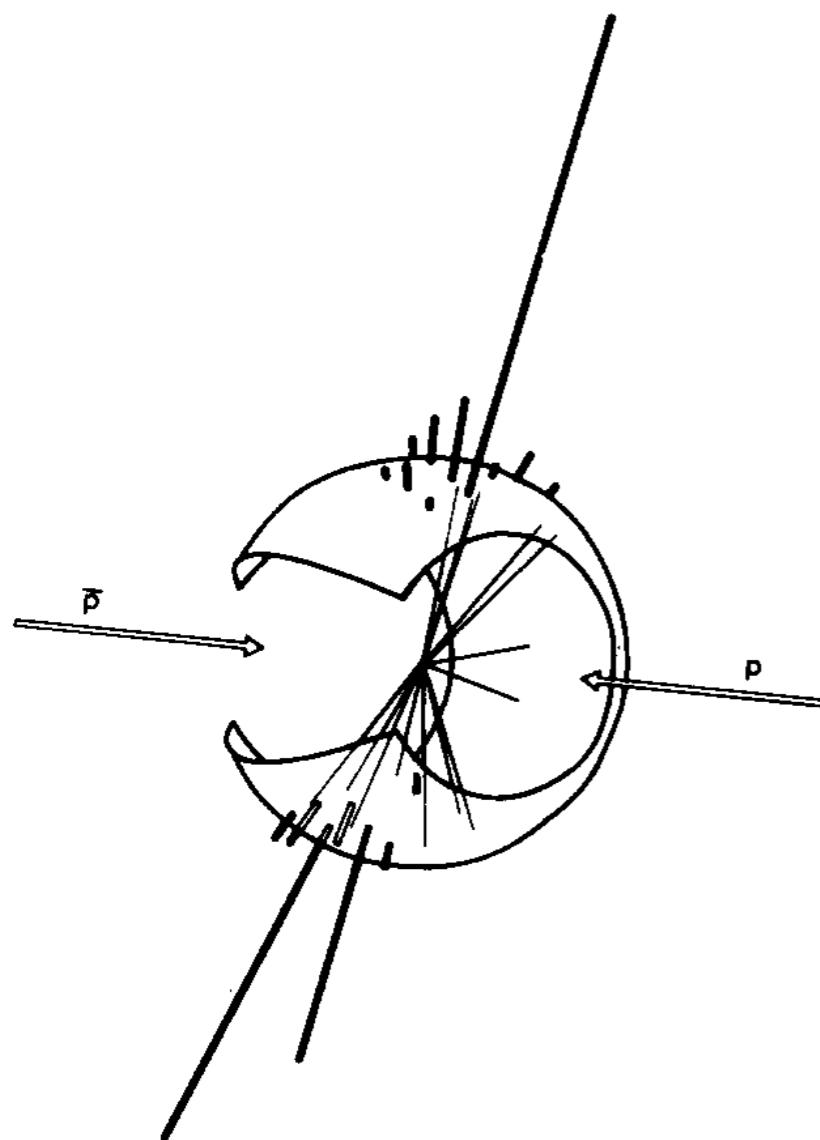
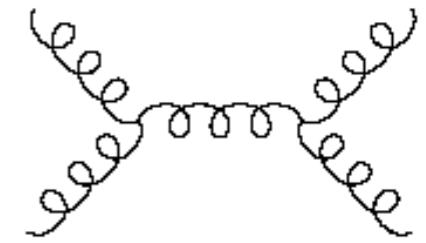


*Gluons @ PETRA, 1979*



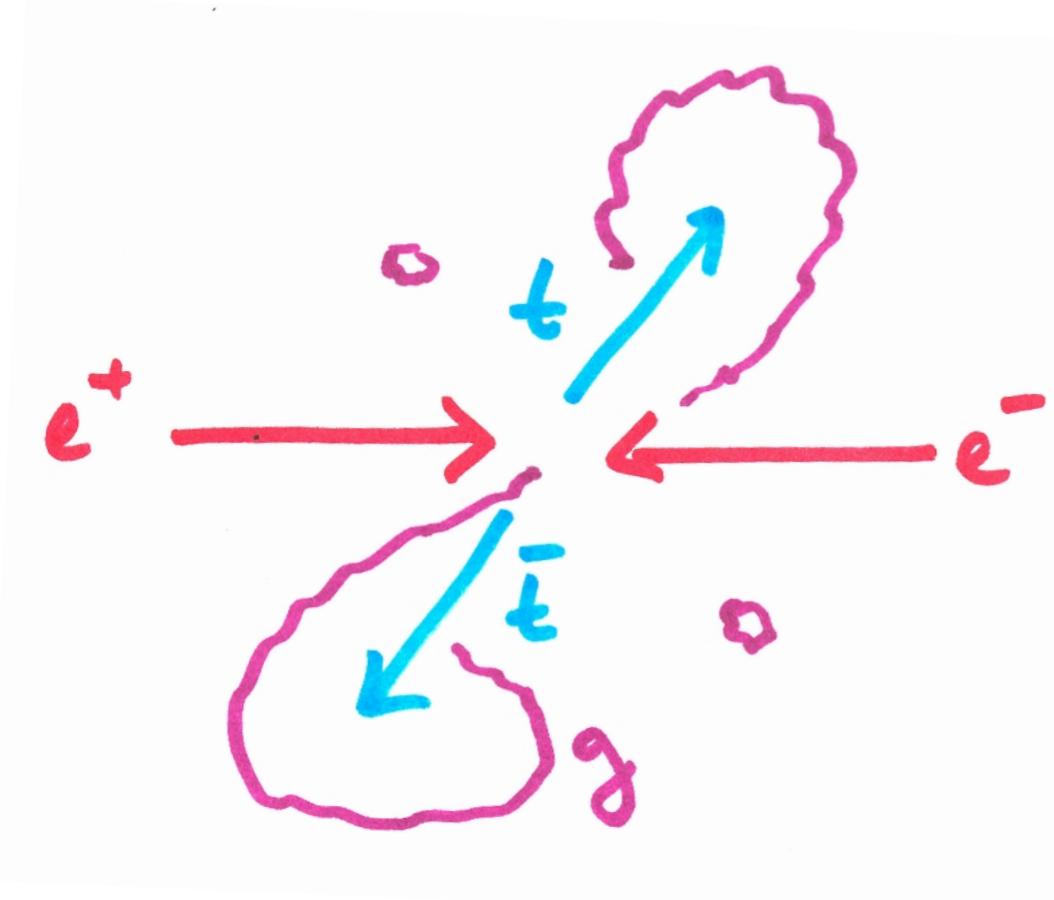
# Four Decades of Jets and QCD

UA2, 1982



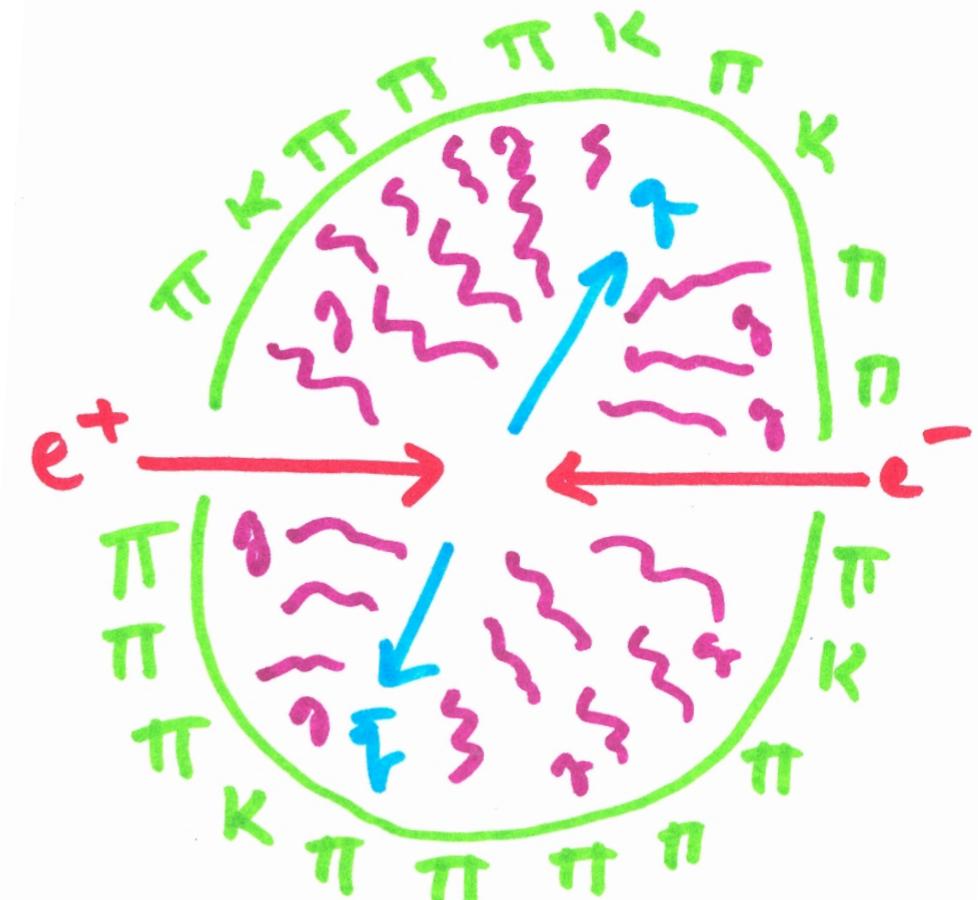
# Jets are not automatic!

## Quirky World (QCD with only top quark)



Can't break color flux tubes!  
Just “toponium” and glueballs!

## Quasi-Conformal World ( $\beta \approx 0, g \approx 4\pi$ )



No hierarchy of scales!  
All “spherical” events!

# Jets are emergent property of QCD

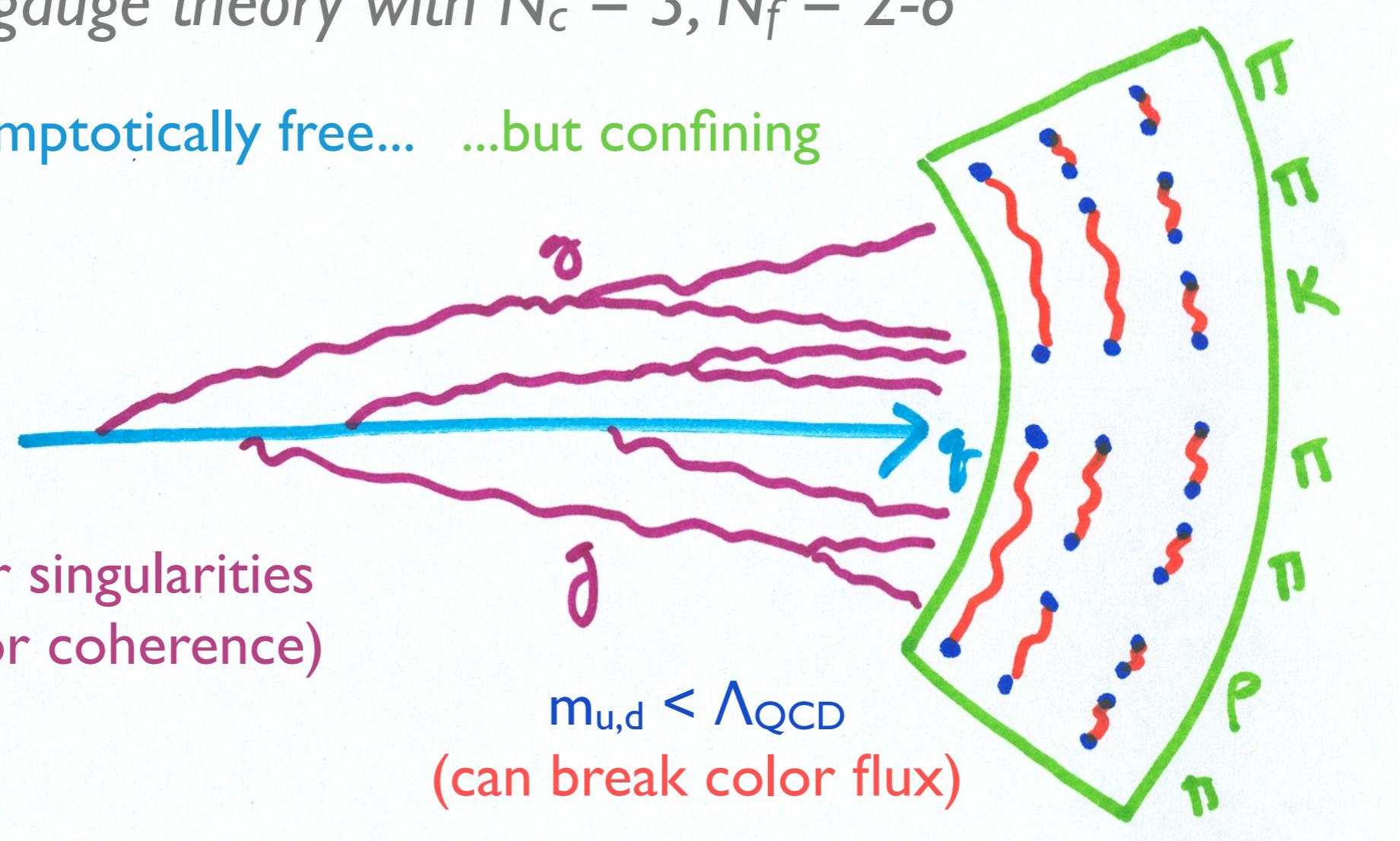
Non-abelian gauge theory with  $N_c = 3, N_f = 2-6$

Asymptotically free... ...but confining

Collinear singularities  
(and color coherence)

$$m_{u,d} < \Lambda_{\text{QCD}}$$

(can break color flux)



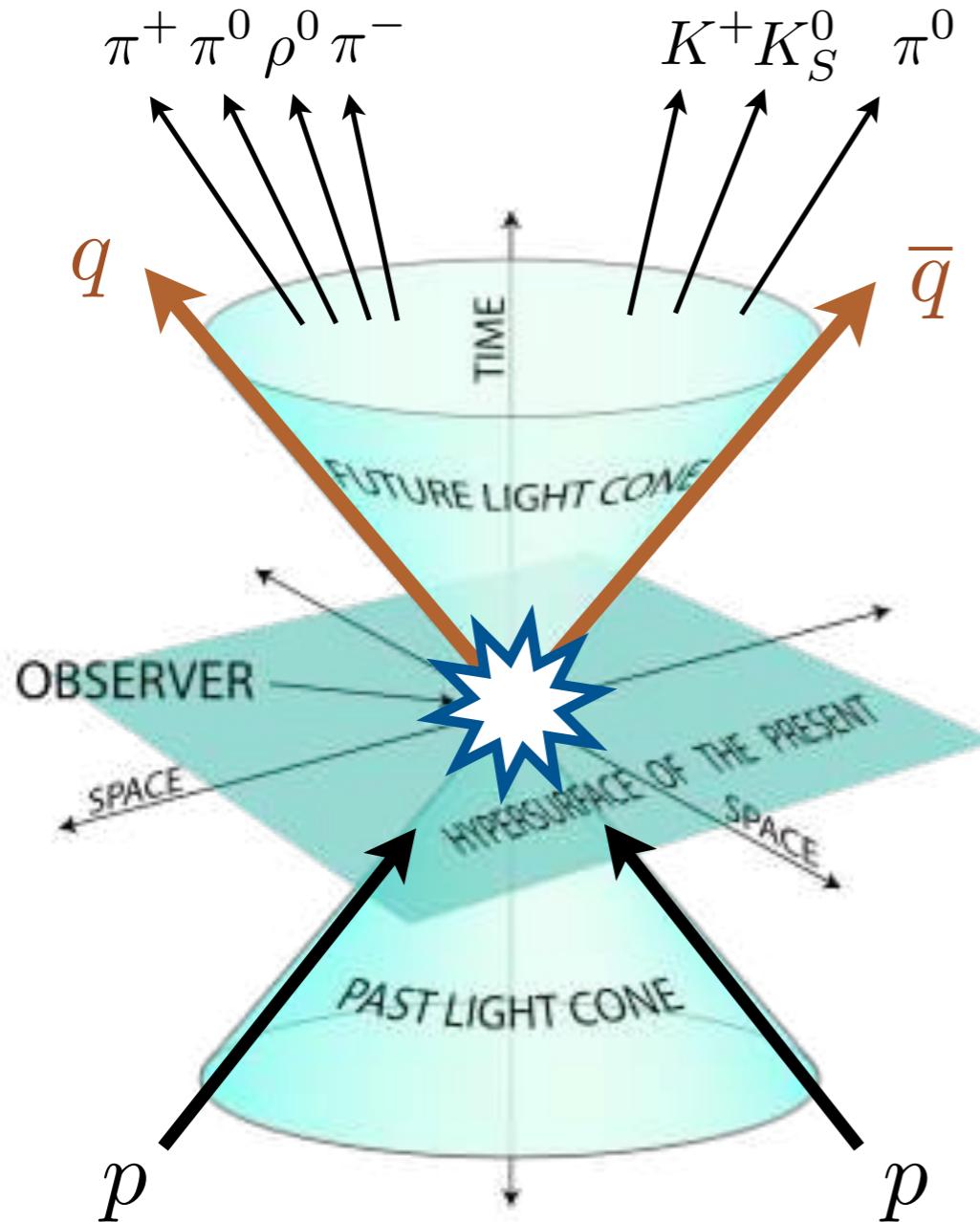
Energy flow in UV  
(where partons go)



Energy flow in IR  
(where hadrons go)

Jet = quark/gluon + radiation + ambiguities ( $m_j \approx 10\% p_{Tj}$ )

# Jet formation is a dynamic process



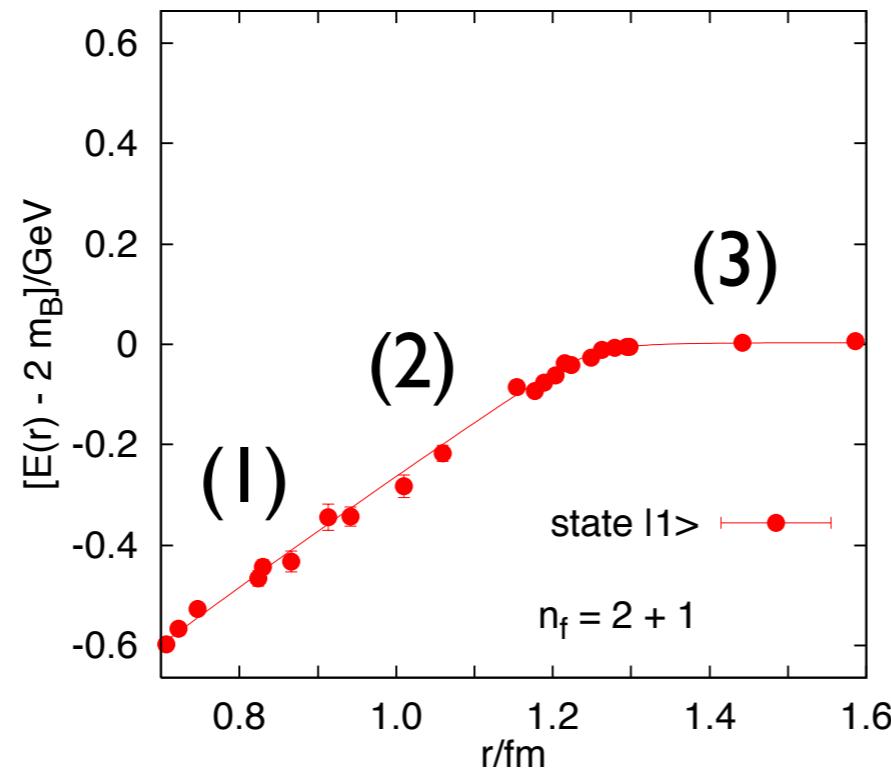
The dynamics of hadronization is one of the deepest mysteries in modern physics

How do short-distance quarks and gluons on the light cone turn into long-distance hadrons off the light cone?

We should be thinking more about this question

For this lecture, you'll have to live with cartoons

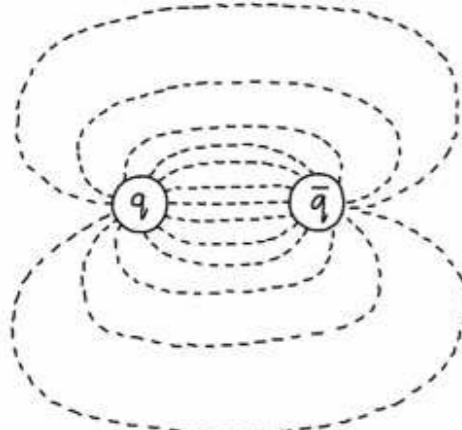
# Confinement/Liberation



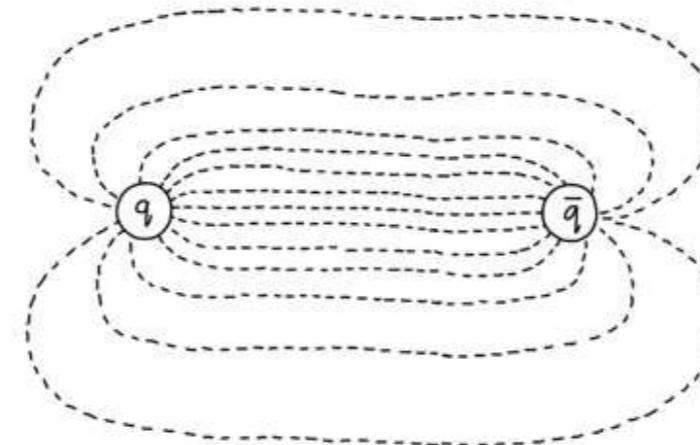
Potential between  
two heavy quarks  
(from lattice calculation)

[SESAM, 2005]

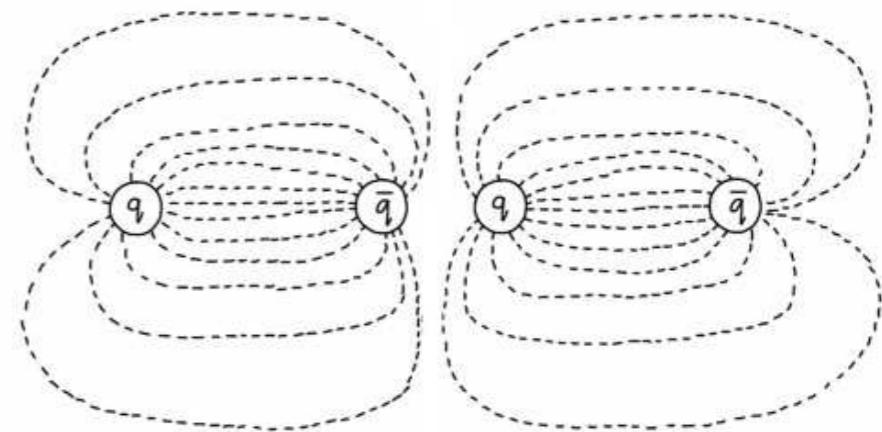
(1)



(2) = linear confinement



(3) = string breaking



[pictures from [coffeeshopphysics.com](http://coffeeshopphysics.com)]

# String picture gives jet basics

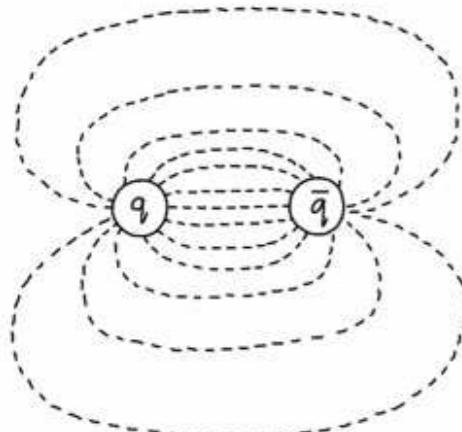
String breaks easily: Quark/gluon direction  $\approx$  Jet direction

String has energy density: Massless quarks/gluons  $\rightarrow$  Massive jet

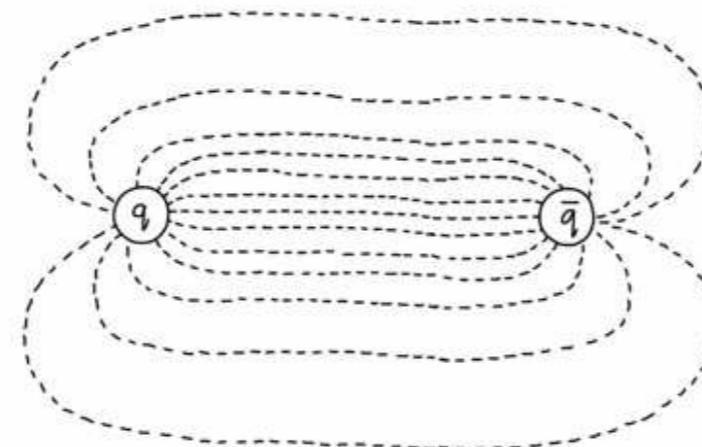
String breaks by popping quarks: Jets are mostly  $q\bar{q}$  bound states (mesons)

String is color singlet: Jets are fundamentally ambiguous

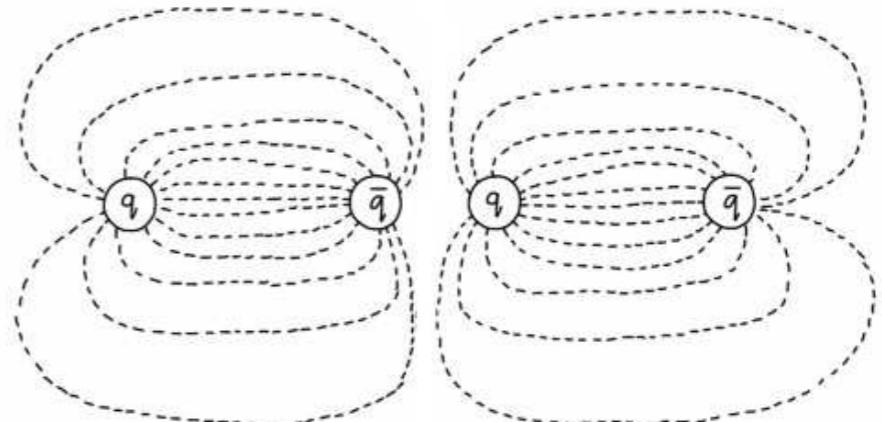
(1)



(2) = linear confinement

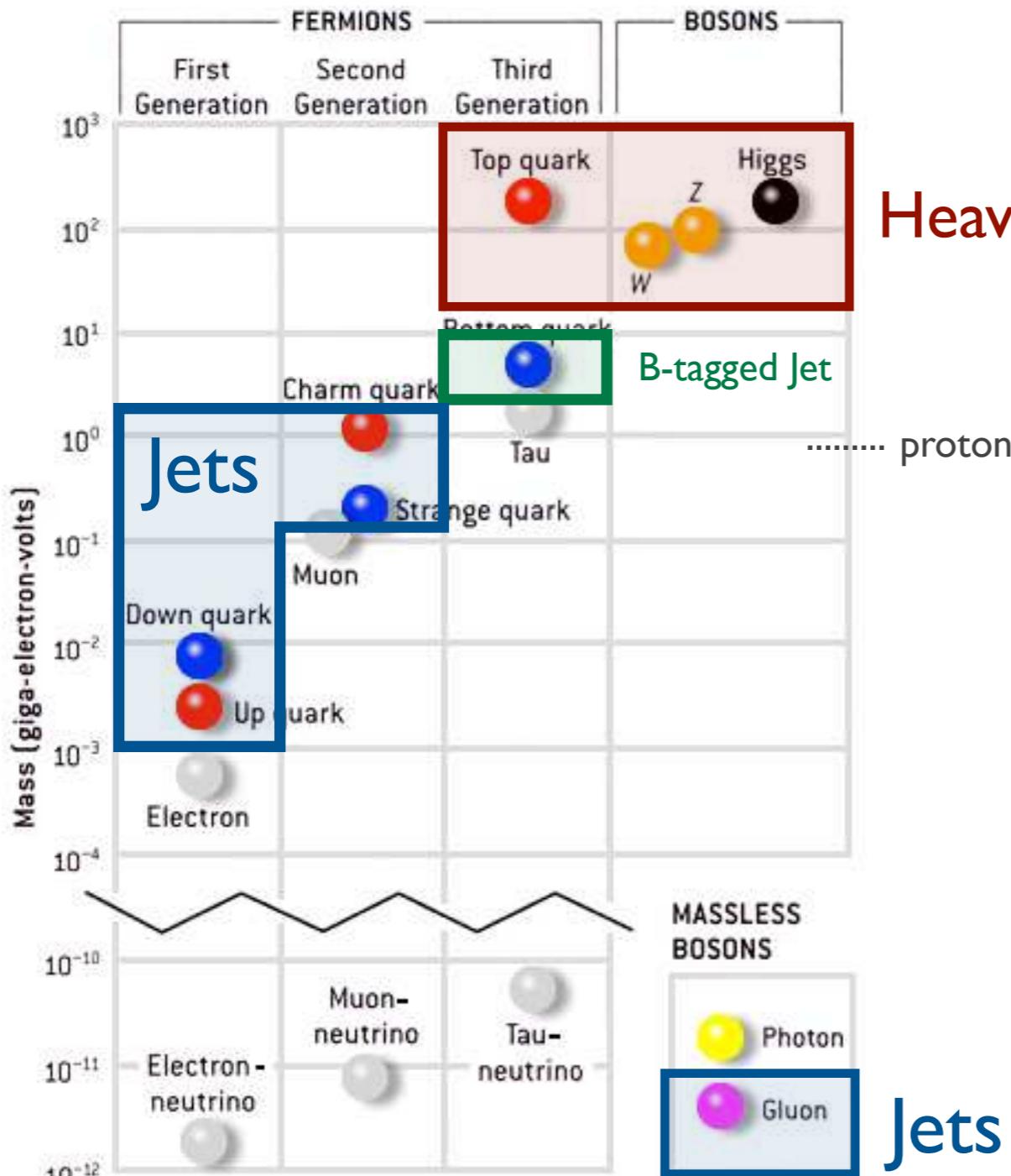


(3) = string breaking

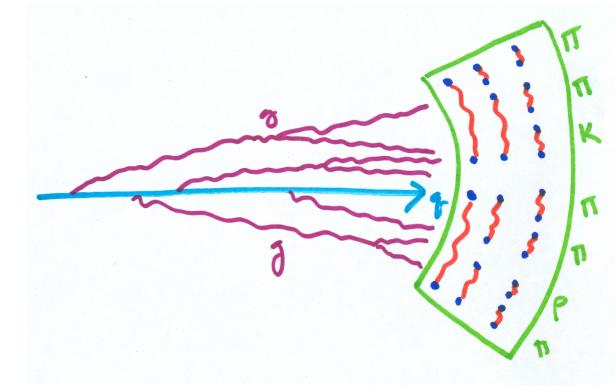
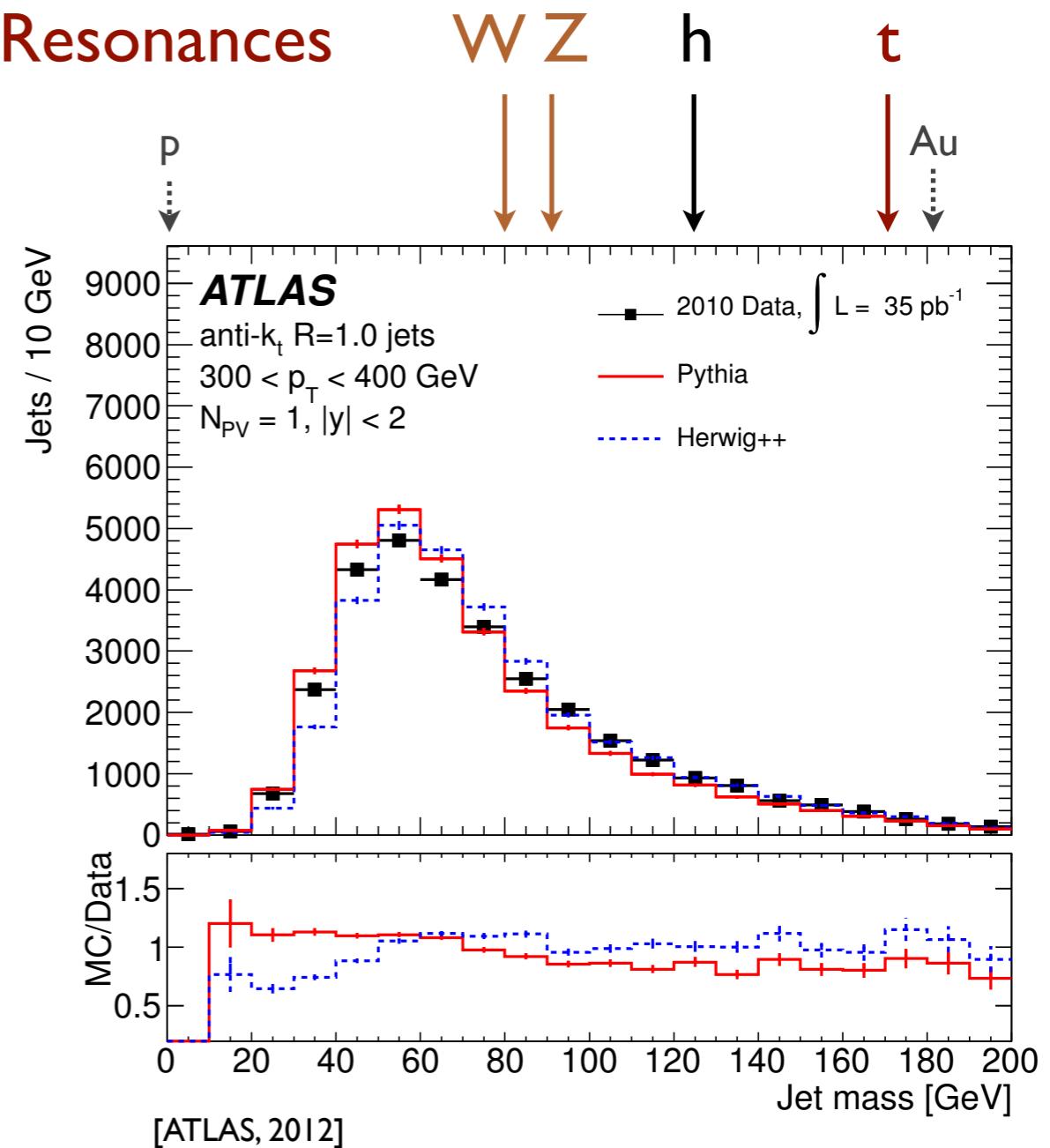


[pictures from [coffeeshopphysics.com](http://coffeeshopphysics.com)]

# Yes, jets really are massive

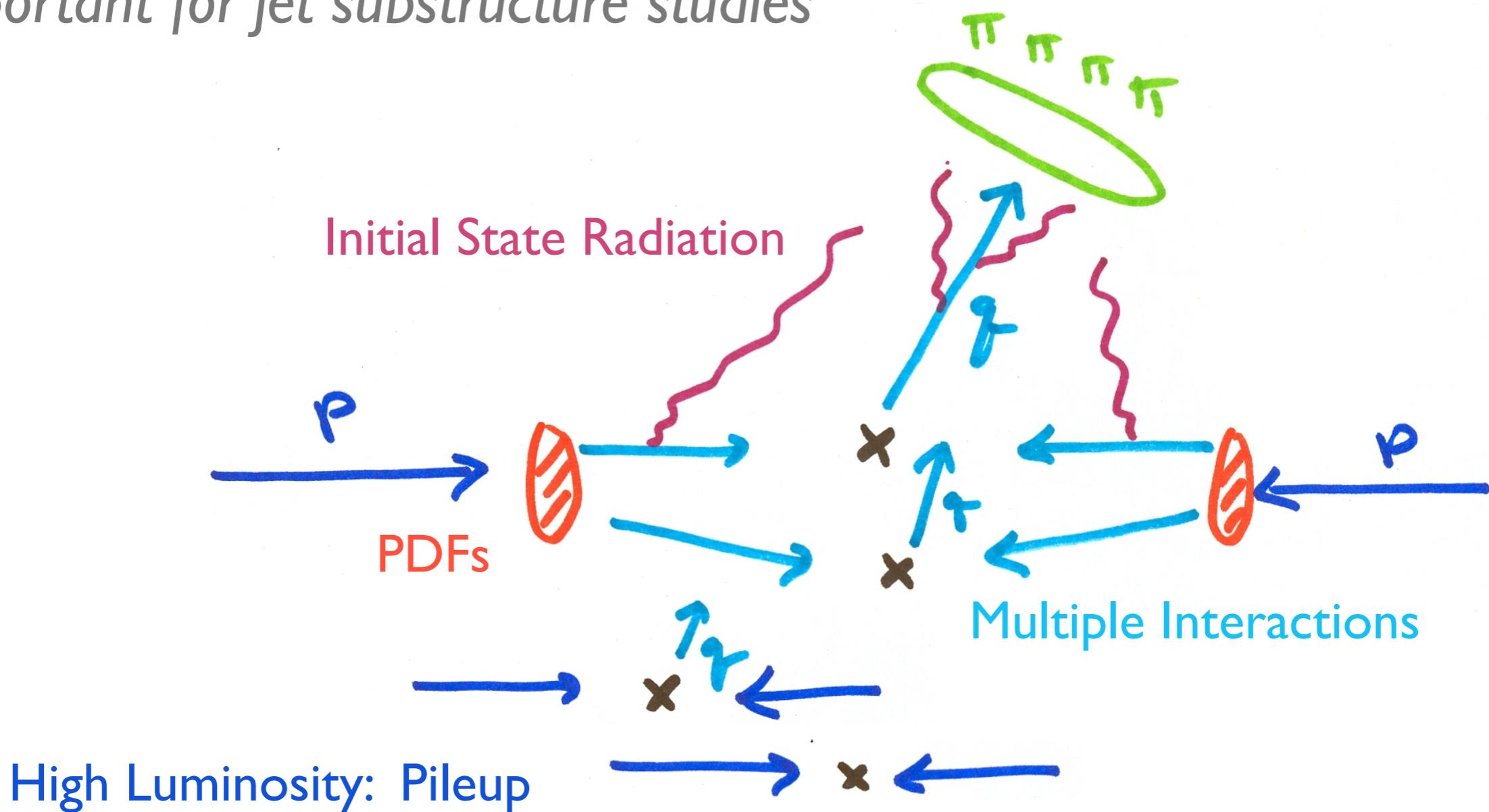


## Heavy Resonances



# Messiness is also a property of QCD

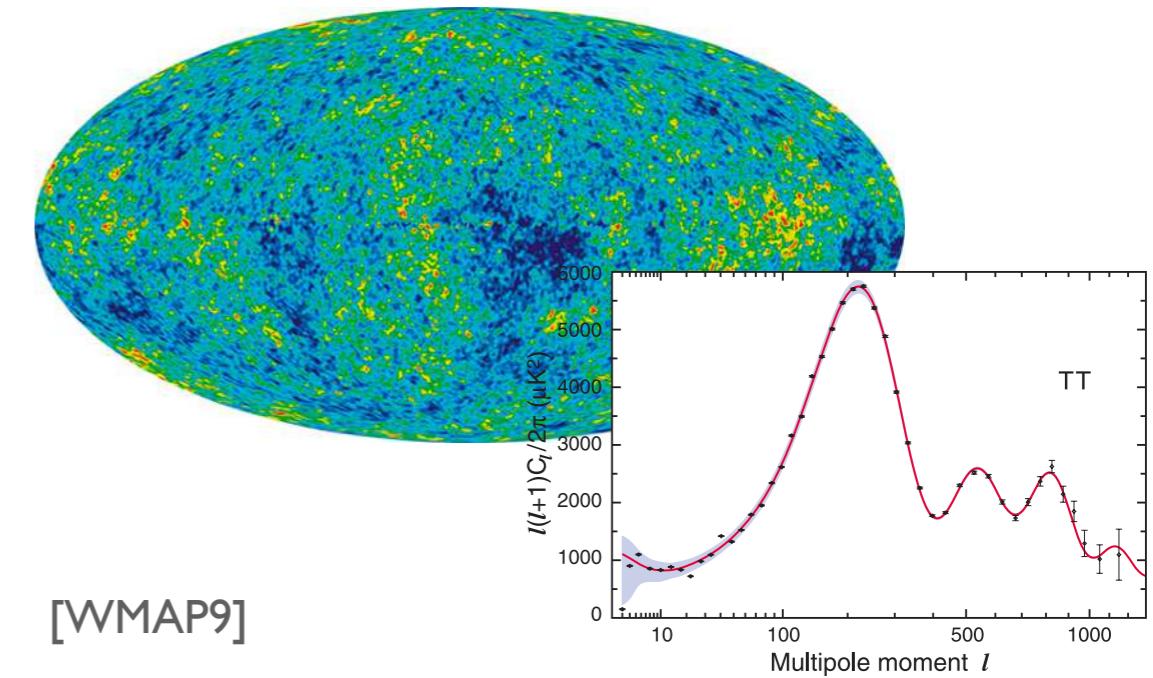
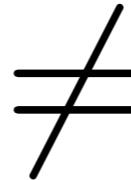
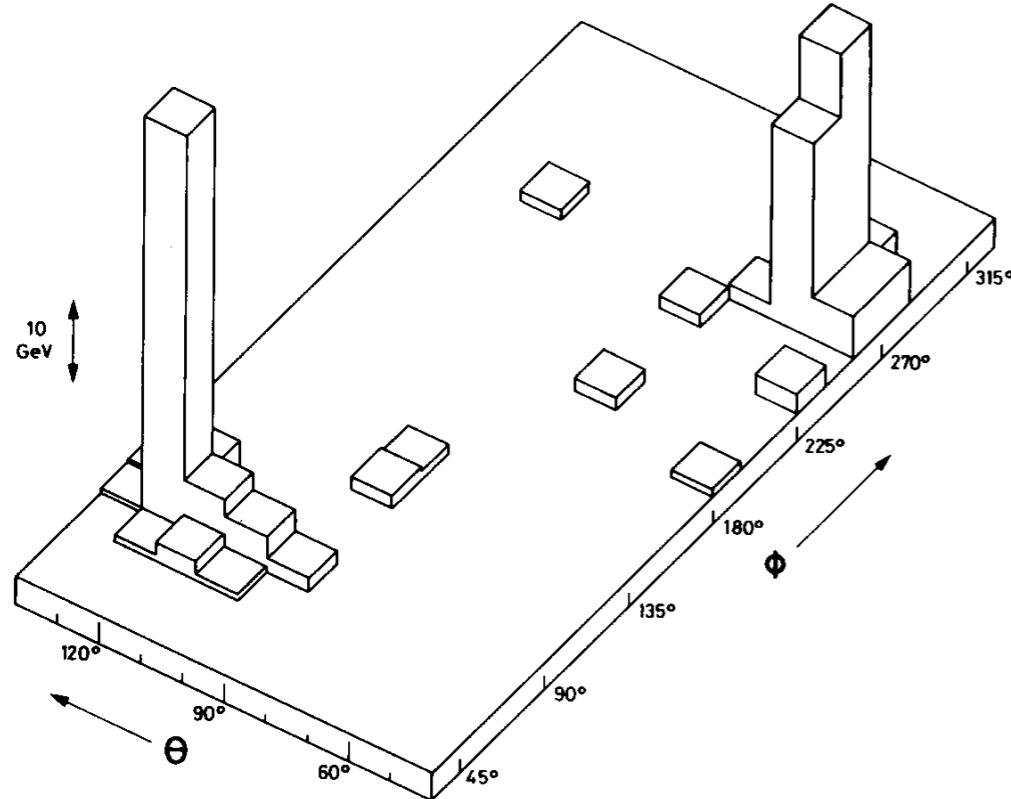
*Important for jet substructure studies*



Jet = desired radiation from hard quark/gluon  
+ additional contamination

# *The Shape of Jets*

# Identification of Jets



[WMAP9]

By eye, jets are collimated along specific directions  
Need “image processing”, not “Fourier decomposition”

(Though my views on this are evolving...)

# Generic Jet Algorithm

Inputs:

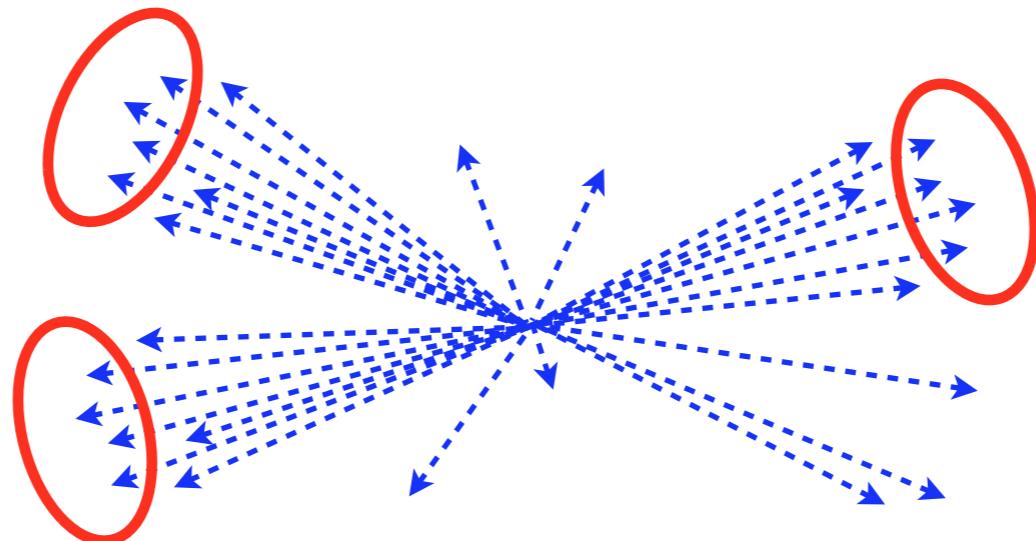
$$\{p_1, p_2, \dots, p_k\}_{\text{hadrons}} \Rightarrow \{p_1, p_2, \dots, p_N\}_{\text{jets}}$$

Unless otherwise stated:

$$\sum_{i \in \text{jet}} p_i = p_{\text{jet}}$$

Outputs:

(aka “E-scheme recombination”,  
other schemes also plausible)



Remember,  
jets are massive:

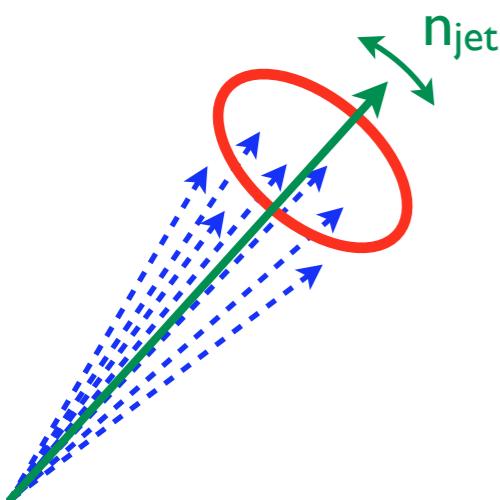
$$p_{\text{jet}}^2 = \left( \sum_{i \in \text{jet}} p_i \right)^2 \geq \sum_{i \in \text{jet}} m_i^2 \geq m_{\text{quark/gluon}}^2$$

# Simple Option: Cone Jets

$$\{p_1, p_2, \dots, p_k\}_{\text{hadrons}} \Rightarrow \{p_1, p_2, \dots, p_N\}_{\text{jets}}$$

## I. Stable Cone:

Collection of hadrons within radius  $R$ , such that  
jet axis ( $n_{\text{jet}}$ ) parallel to jet momentum ( $p_{\text{jet}}$ )



2. Cluster that maximizes:  $E_{\text{jet}} - \frac{1}{R^2} \frac{m_{\text{jet}}^2}{E_{\text{jet}}}$

3. Axis that minimizes:  $\sum_{i \in \text{event}} \min \left\{ E_i, \frac{2n \cdot p_i}{R^2} \right\}$

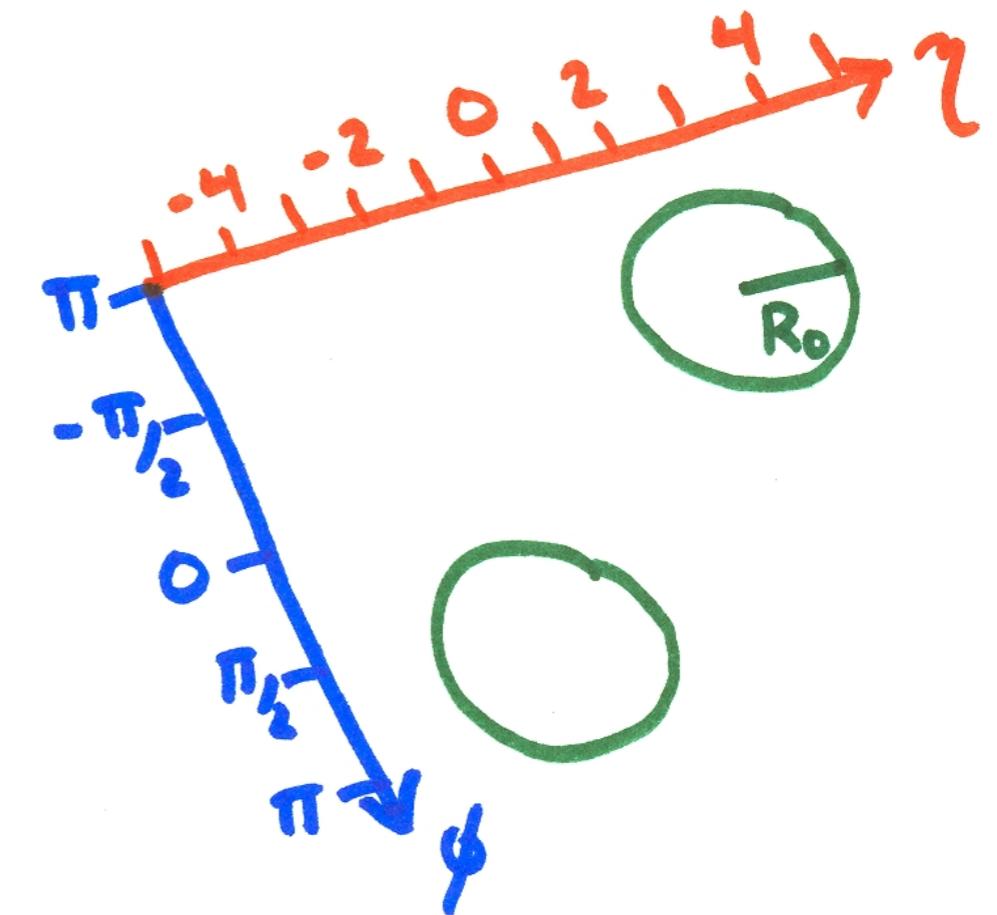
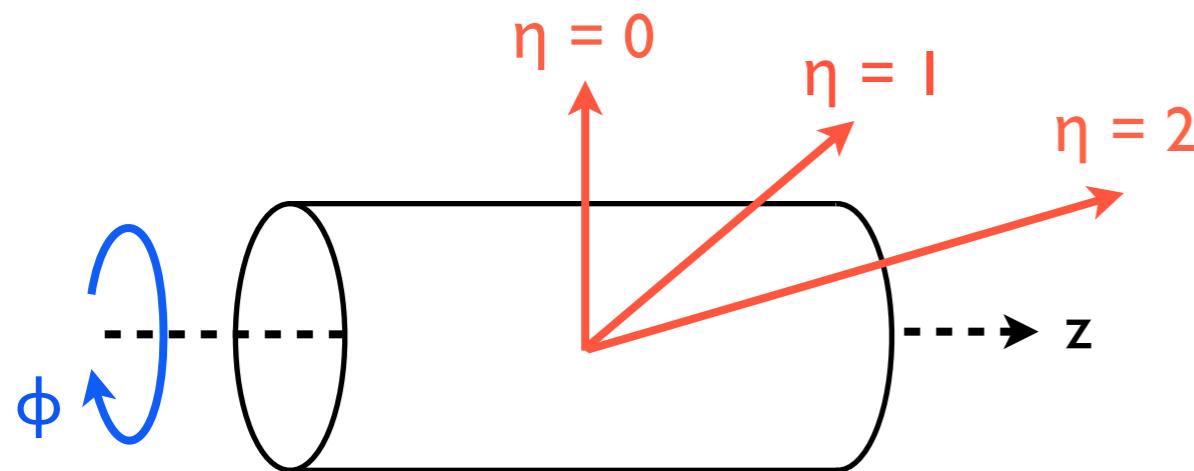
These are all fine (and essentially equivalent) algorithms  
Complications when multiple overlapping cones (split/merge headaches)  
Not used very often; worth revisiting with modern understanding

[JDT, PRD 2015; see also Wei, Naik, Harrow, JDT, arXiv 2019]

# Coordinate System for Jets

*Invariant to longitudinal boosts along beam direction*

$$p_T = \sqrt{p_x^2 + p_y^2} \quad \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Cone Jet Algorithms: Punch holes of radius  $R_0$

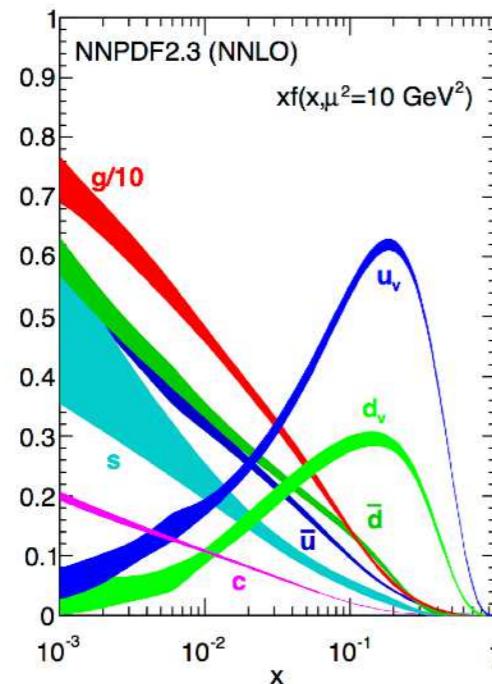
# Why $p_T$ & $R$ (instead of $E$ & $\theta$ )?

*Invariant to longitudinal boosts along beam direction*

$$p_T = \sqrt{p_x^2 + p_y^2}$$

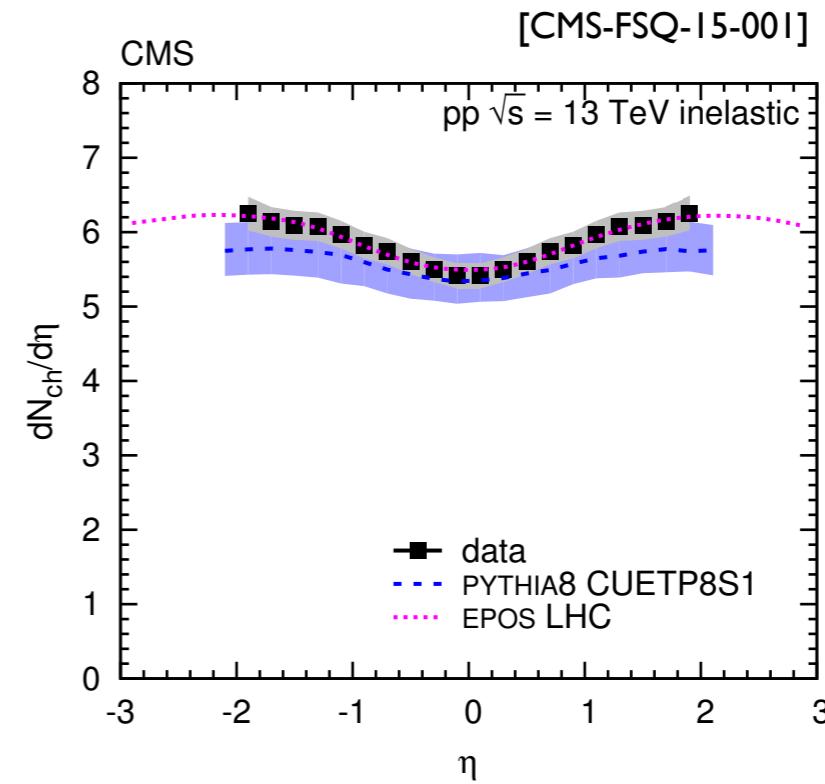
$$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$

Usual Answer: PDFs



Unknown longitudinal momentum fraction of colliding quarks/gluons  
→ longitudinally-boost-invariance

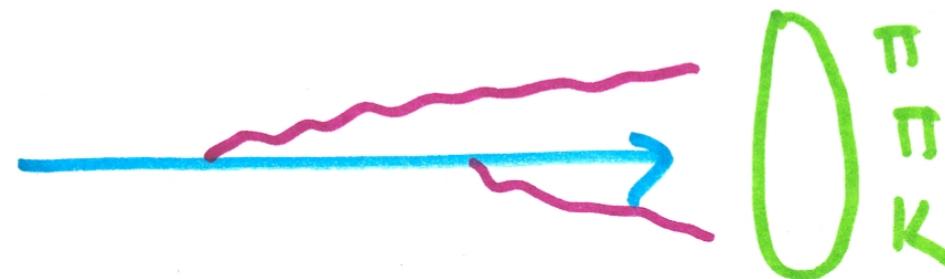
Better Answer: Rapidity Plateau



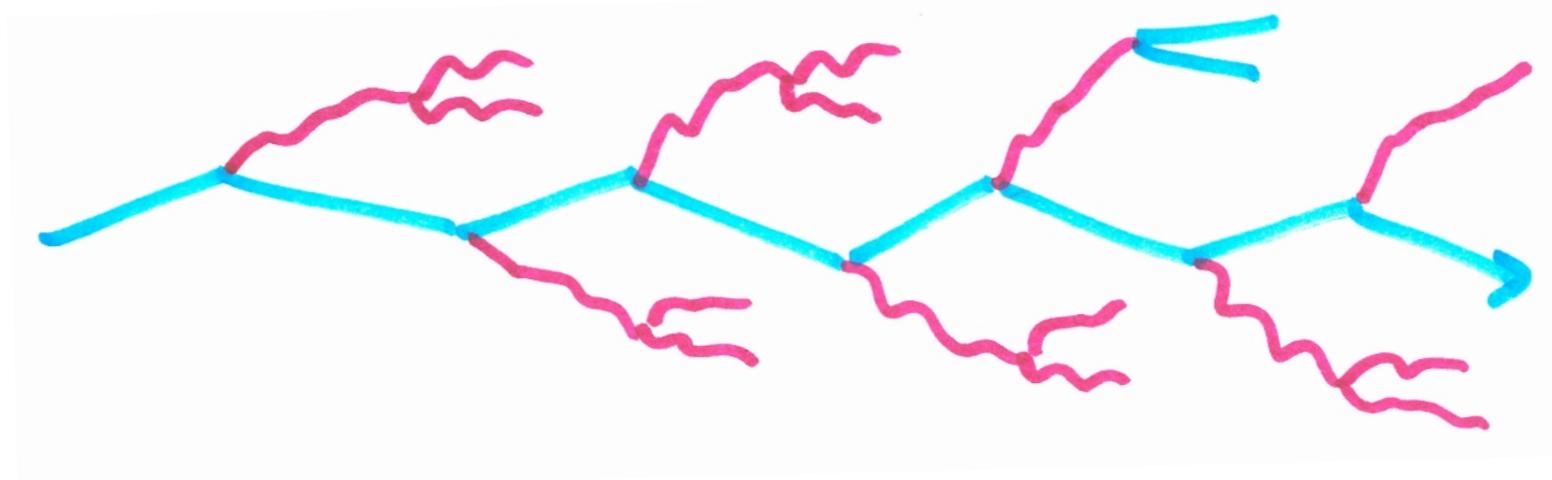
Roughly uniform underlying event as a function of  $\eta$   
A requirement we should probably revisit

# Goal of Jet Algorithm

*Cluster observed hadrons to approximate short-distance partons*



Clustering that mimics fragmentation  $\leftrightarrow$  Parton shower picture

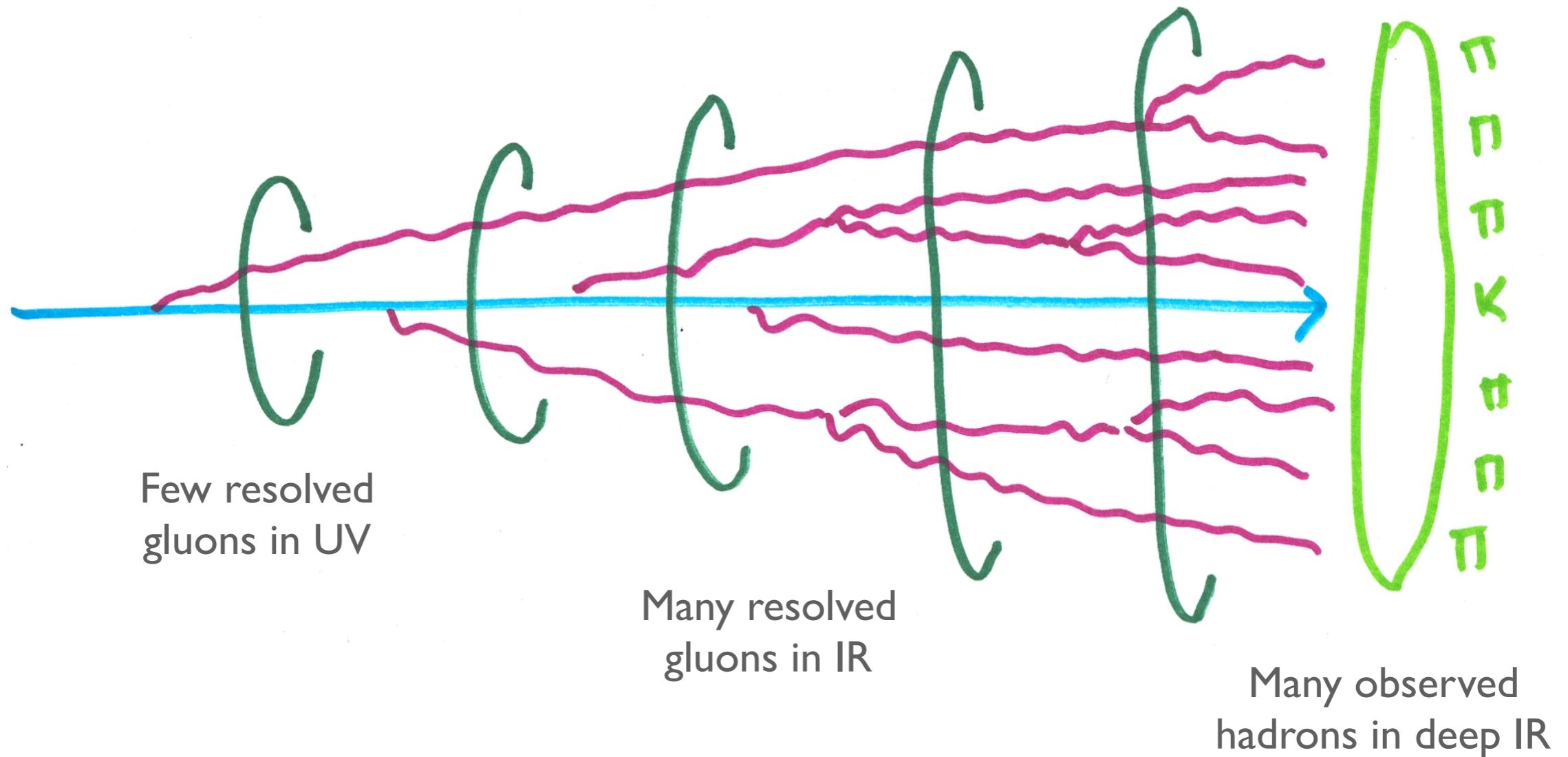


$$dP_{i \rightarrow ig} \simeq \frac{2\alpha_s}{\pi} C_i \frac{d\theta}{\theta} \frac{dz}{z}$$

 Collinear    Soft

# “Fractal” Jets

*Intuitively, jets at long distances  $\approx$  jets at short distances*



“Resolved” gluon emissions should not change jet structure  
Cone algorithms scale pretty well from UV (partons) to IR (hadrons)  
Recursive clustering algorithms attempt to mimic flow from UV to IR

# Recursive Jet Algorithms

*Workhorse of modern jet physics*



- 1) Make list of protojets
- 2) Calculate all  $d_{ij}$  and  $d_i$
- 3) If  $d_{ij}$  smallest:  
combine  $i + j$       If  $d_i$  smallest:  
 **$i$  is finished**
- 4) Repeat until nothing left

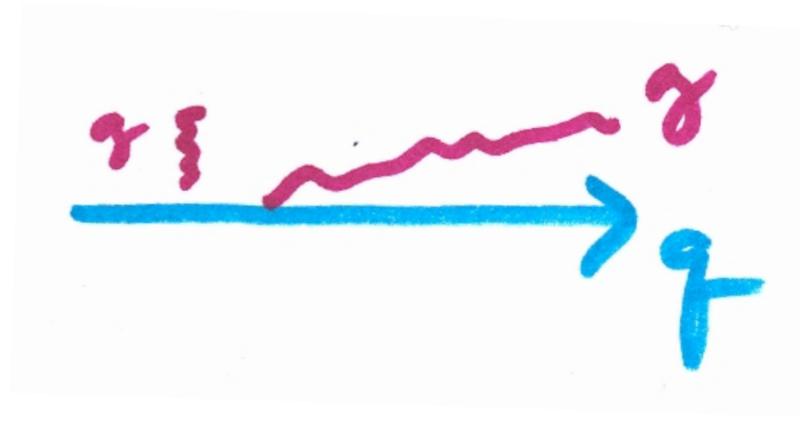
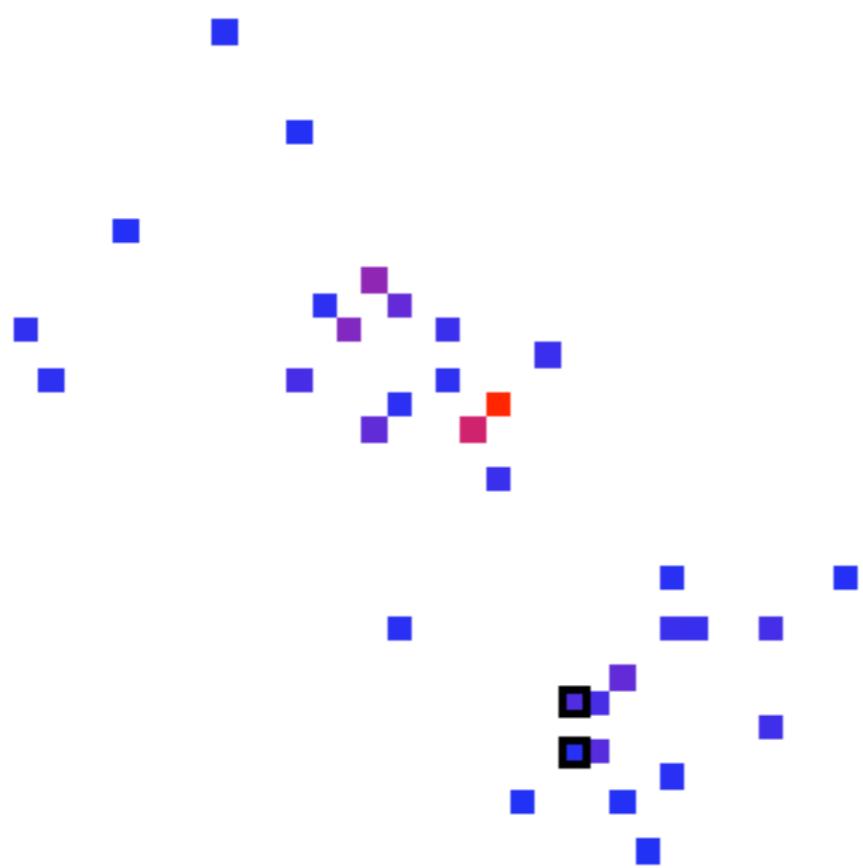
Works the same on  
calorimeter cells,  
hadrons & partons

Computationally efficient,  
flexible, defined to all  
orders in  $\alpha_s$ , (mostly)  
pathology free

[starting with JADE; Durham, ...]

# $k_T$ Measure

*Jet built from soft/collinear singularities of QCD*



$$d_i = p_{Ti}^2$$

$$d_{ij} = \min [p_{Ti}^2, p_{Tj}^2] \frac{R_{ij}^2}{R_0^2}$$

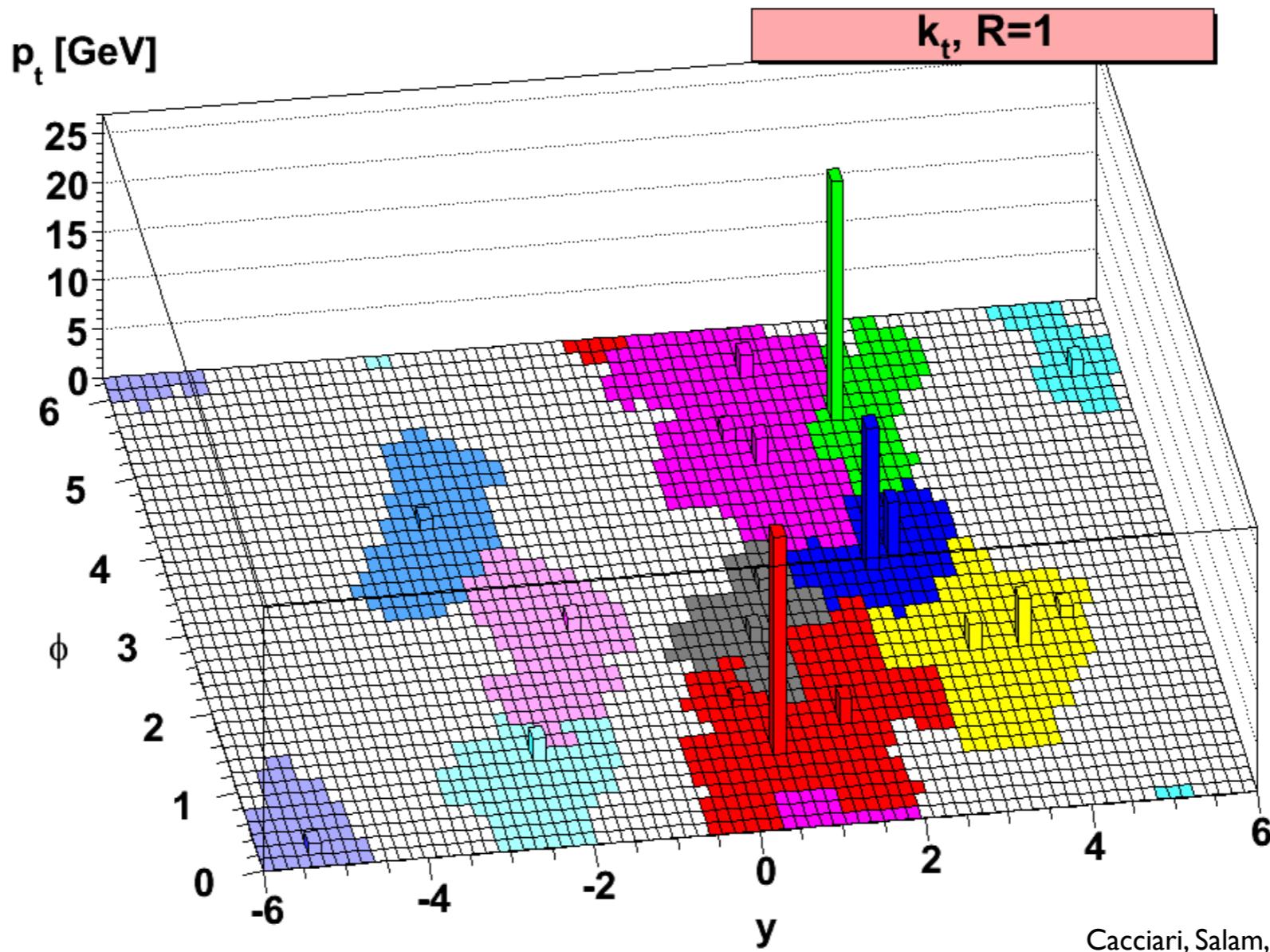


Animation from Jon Walsh  
& Chris Vermilion

[Catani, Dokshitzer, Seymour, Webber, 1993;  
Ellis, Soper, 1993]

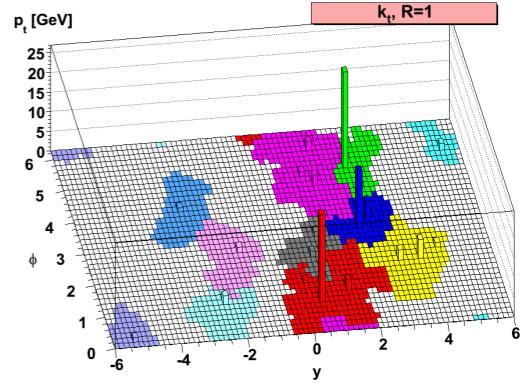
# $k_T$ Measure

*Jet built from soft/collinear singularities of QCD*

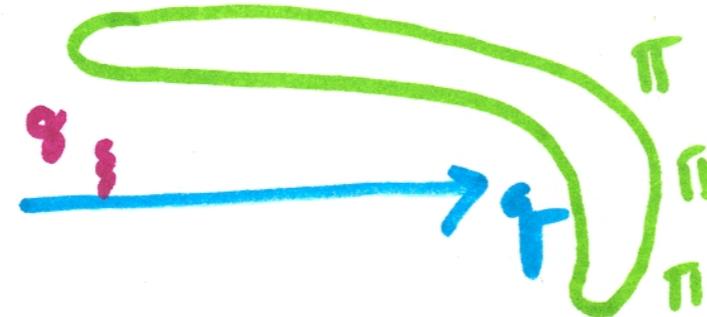


Funny looking jets, but calculable in pQCD

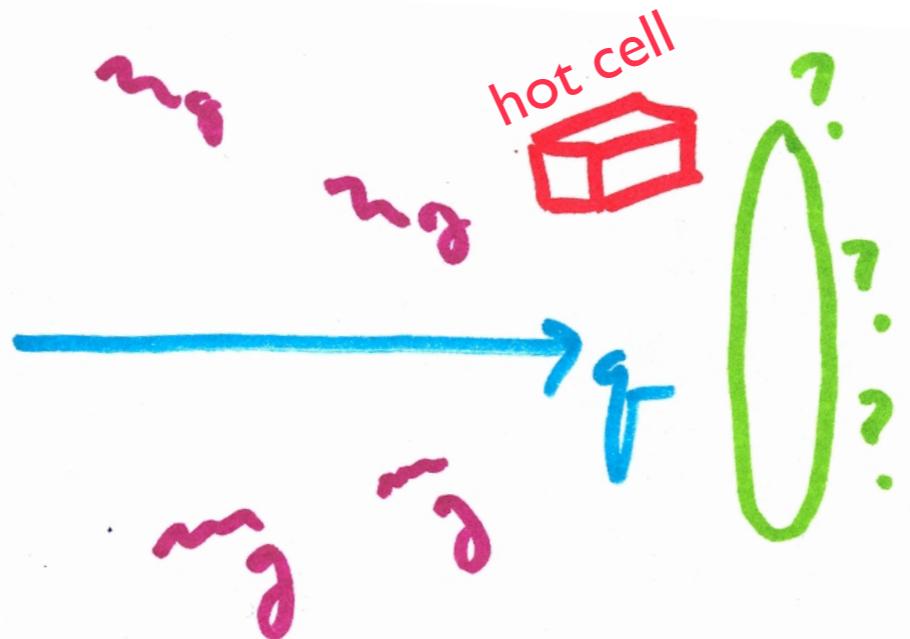
# Amoeba Jets?



QCD has soft singularity...



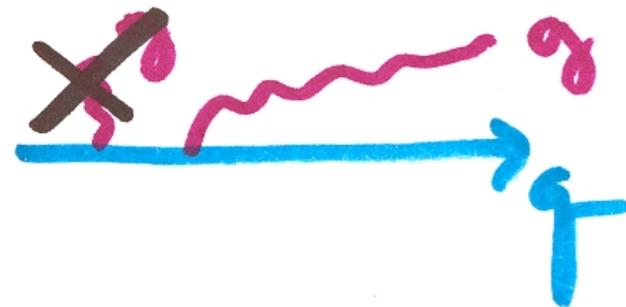
...but ISR/Multiple Interactions/Pileup/Detector Noise also soft



Nothing intrinsically wrong with  $k_T$ -style clustering,  
but (over-)emphasizes soft physics

# Cambridge/Aachen Measure

Uses only angular information, ignores soft singularity

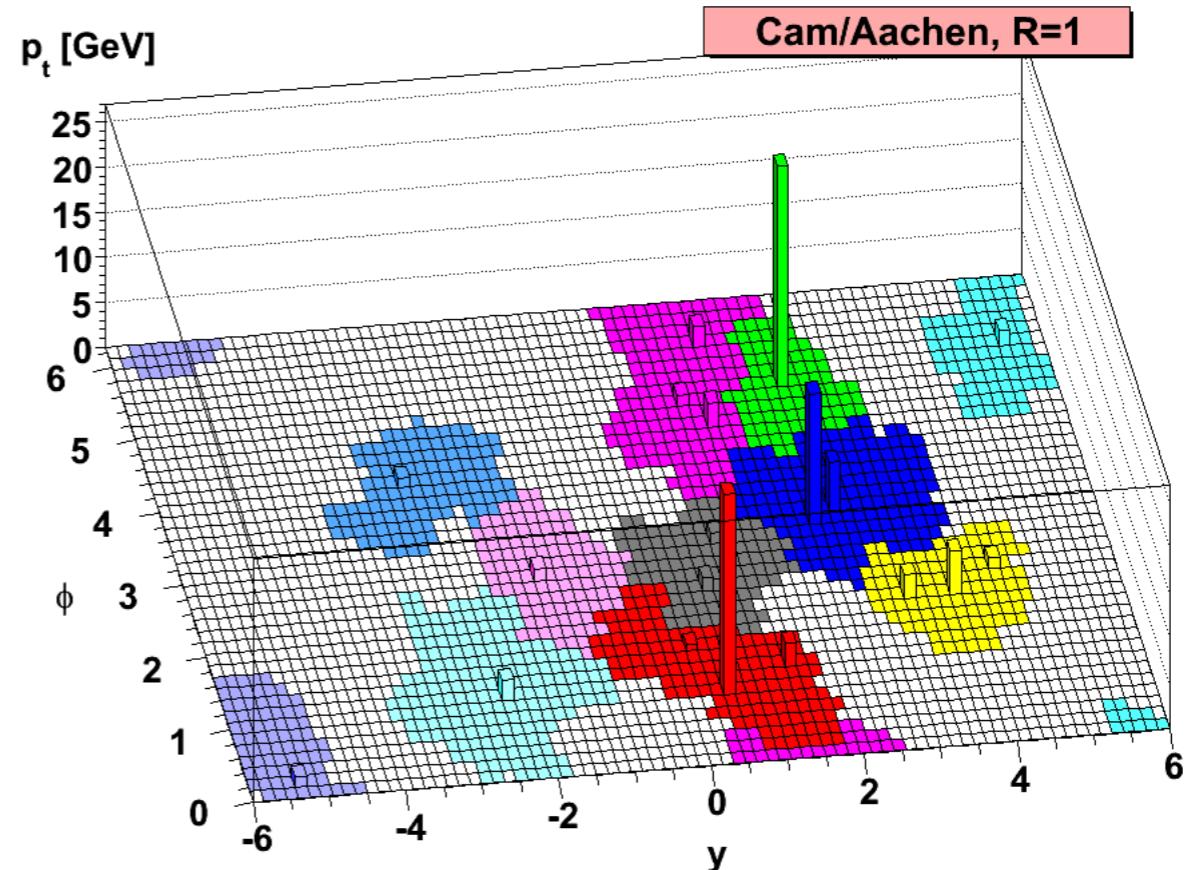


$$d_i = 1$$

$$d_{ij} = \frac{R_{ij}^2}{R_0^2}$$

Just Collinear

[Dokshitzer, Leder, Moretti, Webber, 1997;  
Wobisch and Wengler, 1998]

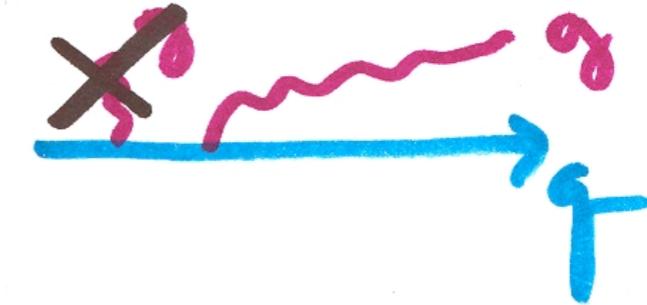
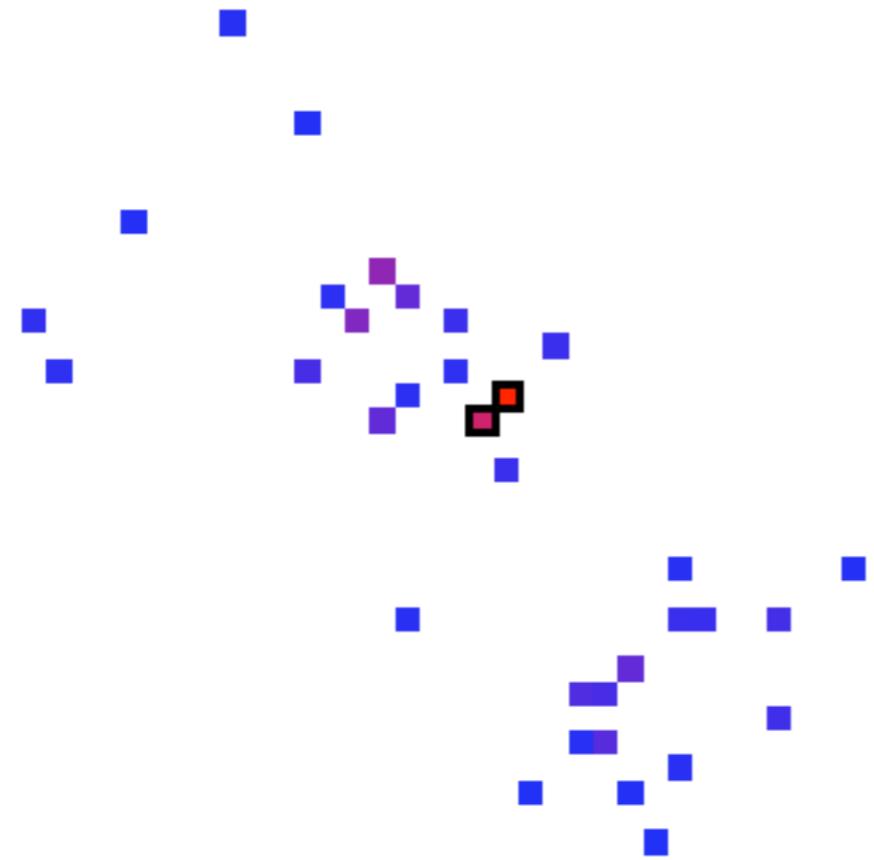


[figure from  
Cacciari, Salam, Soyez, JHEP 2008]

Still amoeba jets...

# Anti- $k_T$ Measure

“Invert” soft singularity, build jets from hard to soft



$$d_i = \frac{1}{p_{Ti}^2}$$

$$d_{ij} = \frac{1}{\max [p_{Ti}^2, p_{Tj}^2]} \frac{R_{ij}^2}{R_0^2}$$



Animation from Jon Walsh  
& Chris Vermilion

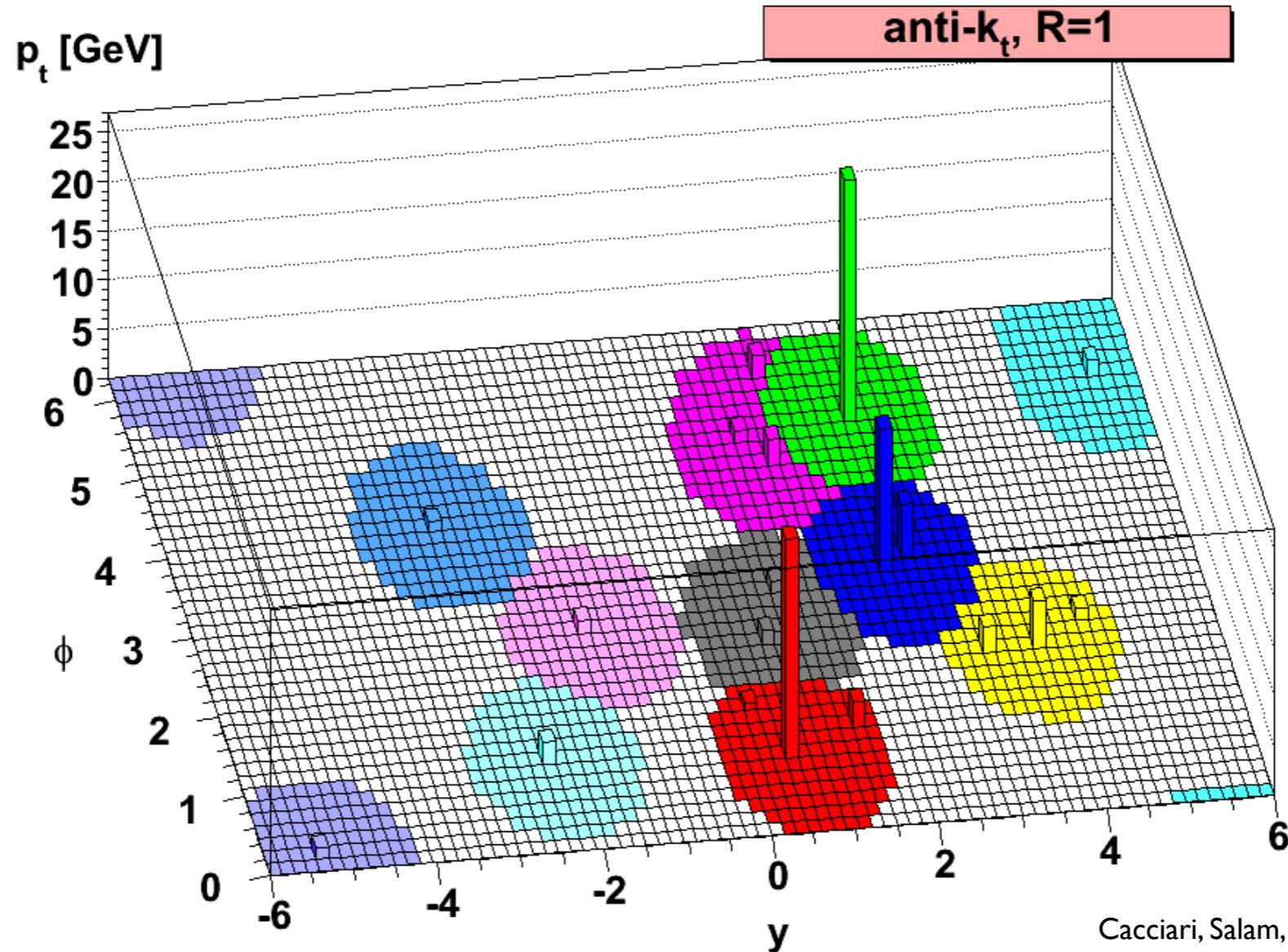
[Cacciari, Salam, Soyez, JHEP 2008]



when I was a postdoc @ Berkeley

# Anti- $k_T$ Measure

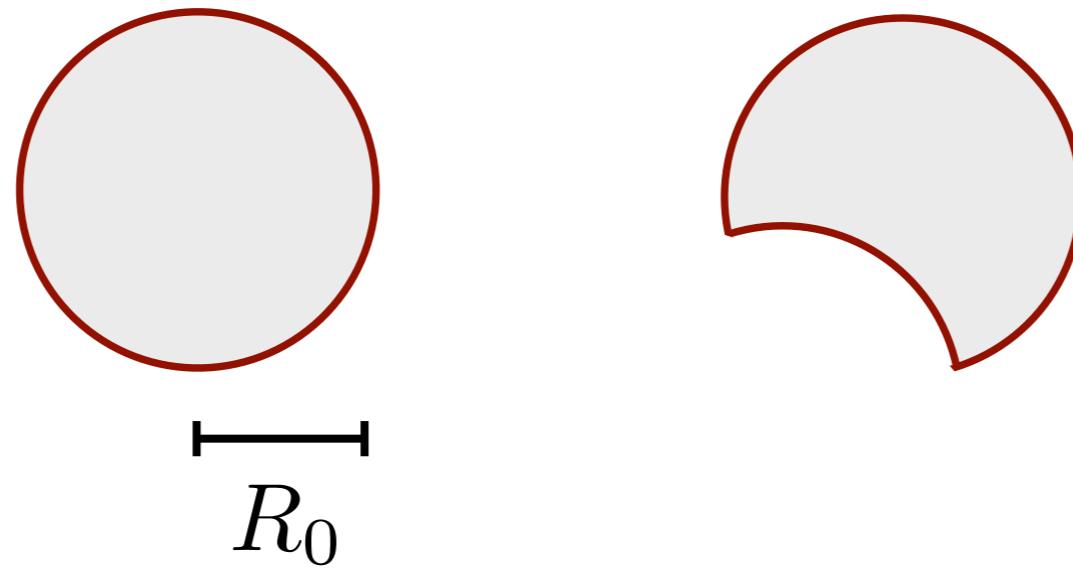
*Ignore soft singularity, and build jets from hard to soft*



Recursive, calculable, soft-insensitive, conical  
(essentially equivalent to stable cone finding in eikonal limit)

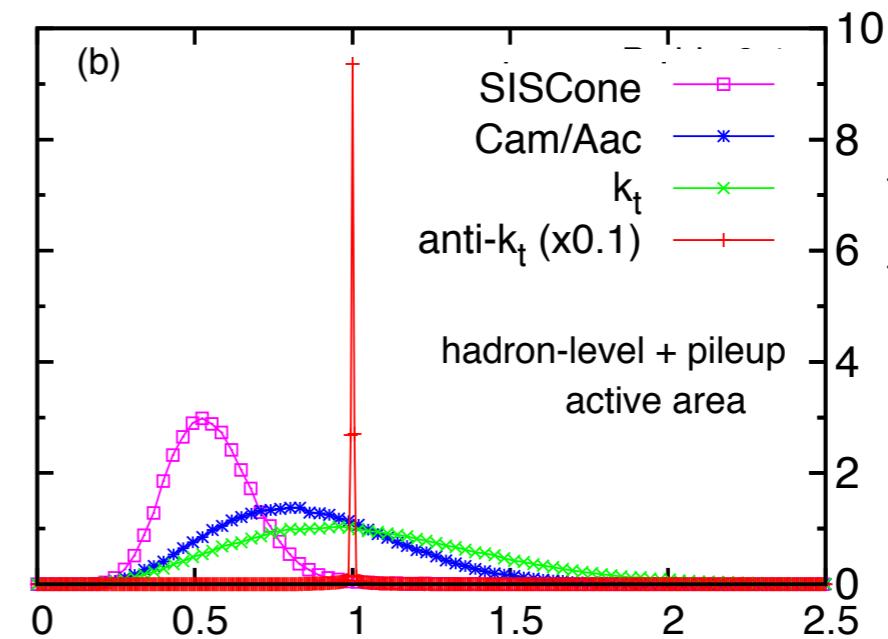
# The Current Shape of Jets

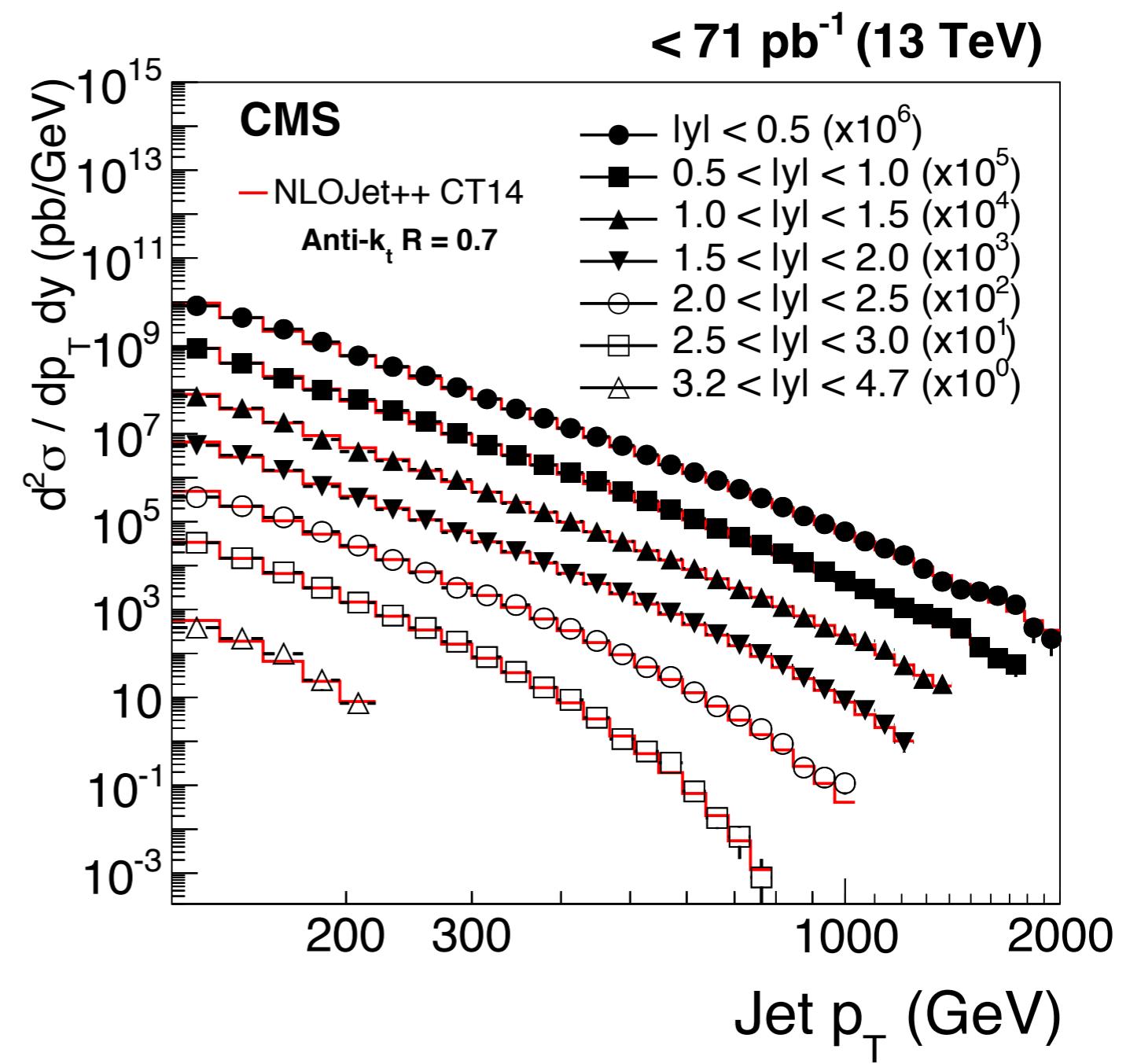
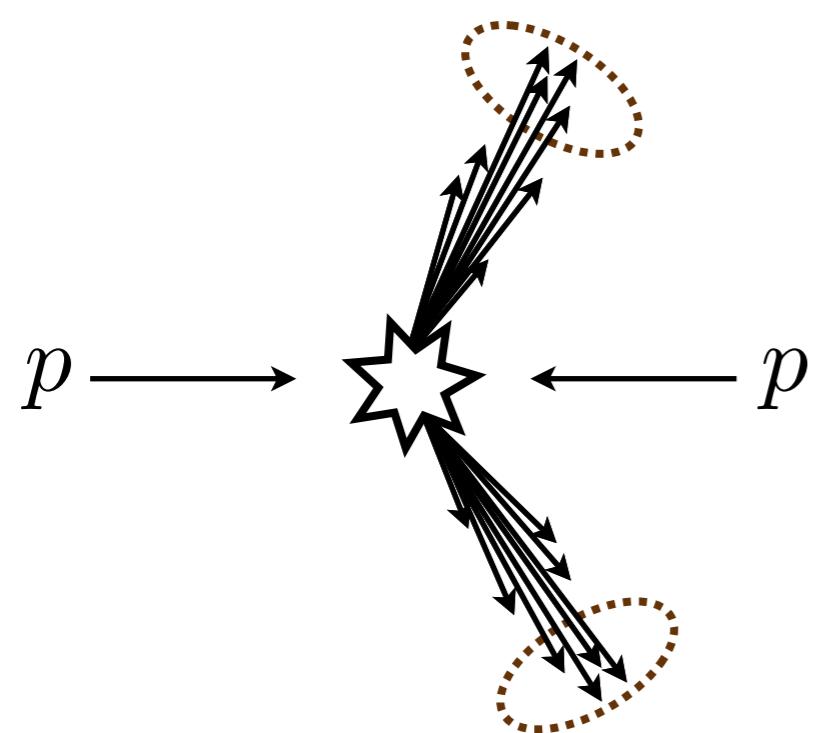
*Almost every analysis at the LHC uses anti- $k_T$*

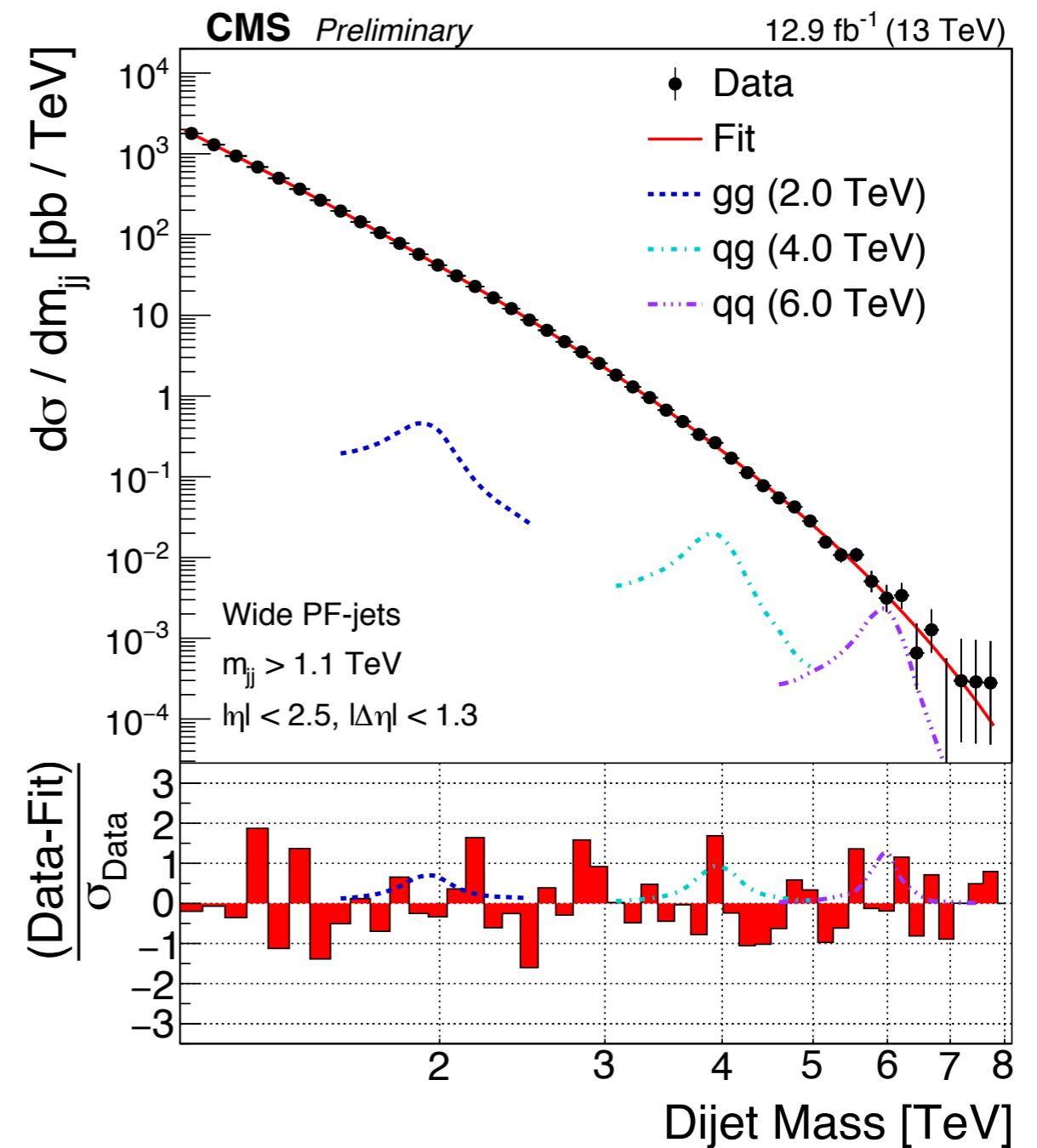
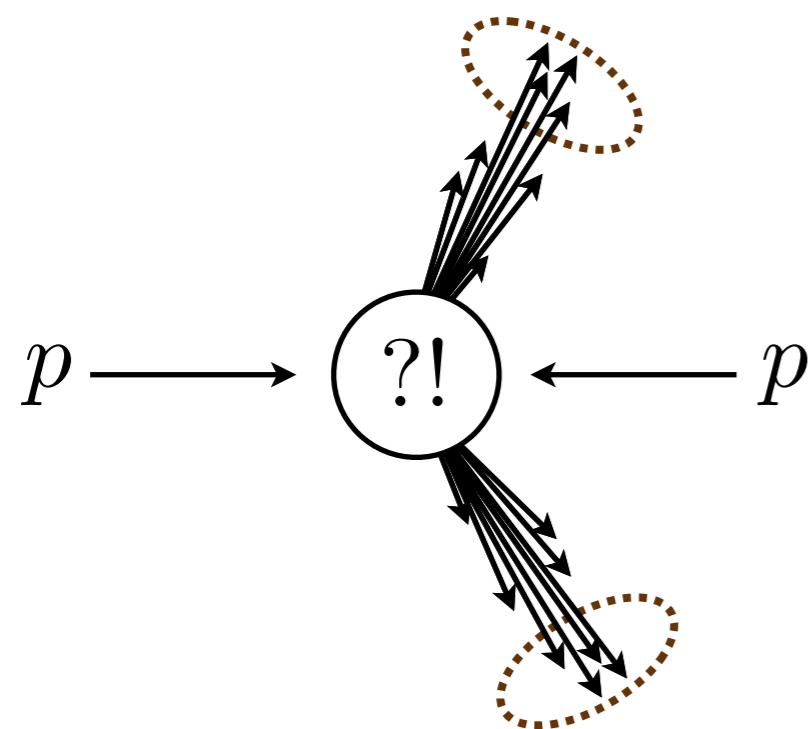


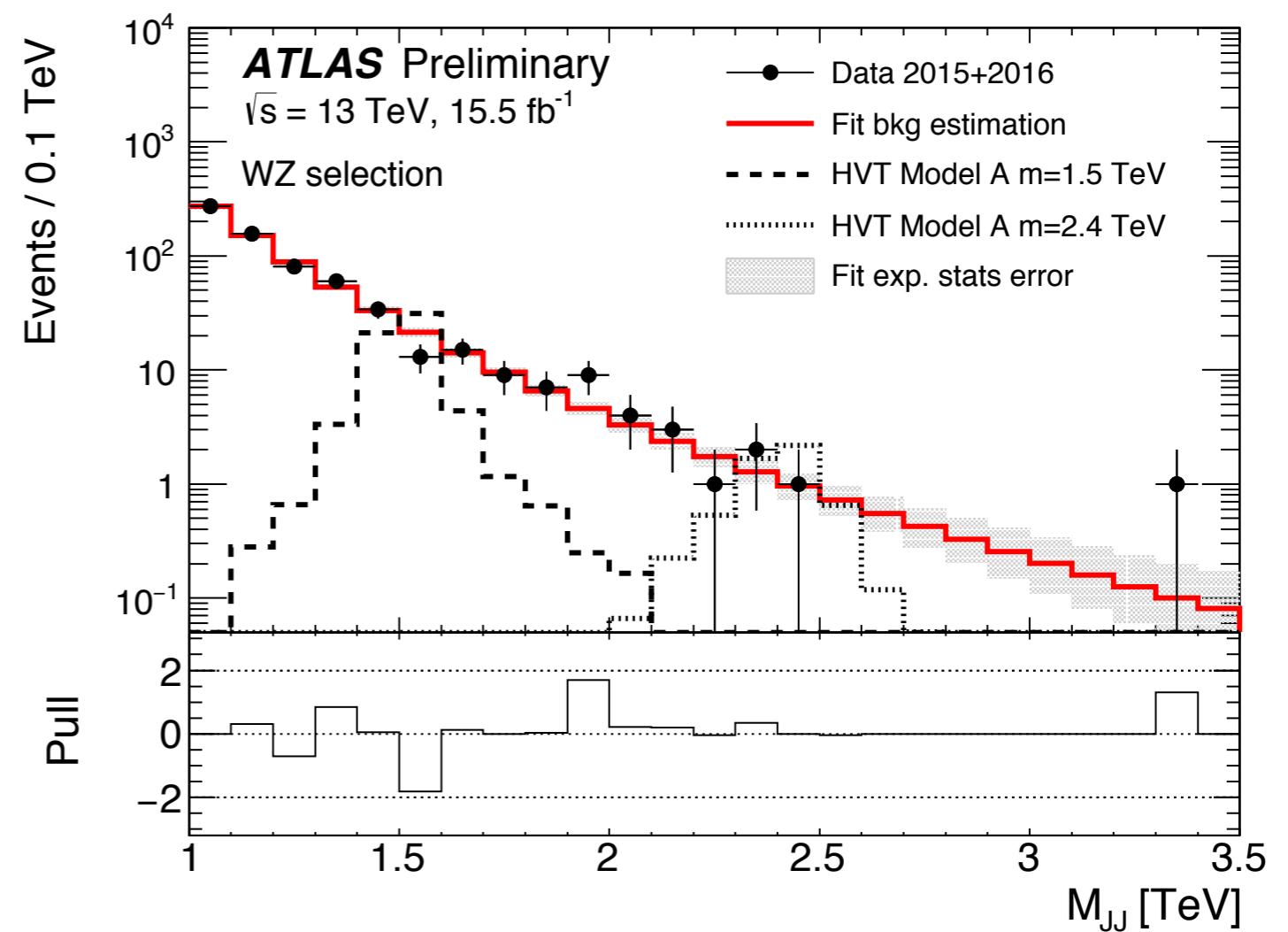
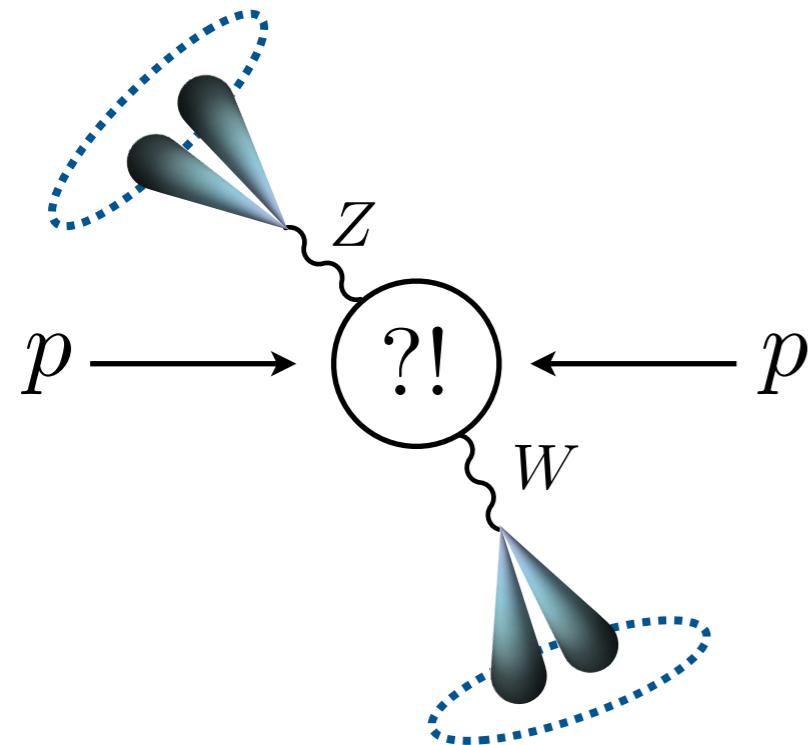
**Nice feature:  
uniform catchment area  
(just like idealized cones!)**

[Cacciari, Salam, Soyez, JHEP 2008, see also JHEP 2008]









$m_{jj} = 7.5 \text{ TeV}$   
(out of 13 TeV)



Run: 302347  
Event: 753275626  
2016-06-18 18:41:48 CEST

# *Parting Thoughts*

# Standard lore should be revisited periodically

*It is your job to challenge your elders!*

Longitudinal boost invariance (i.e.  $p_T$  &  $R$  vs.  $E$  &  $\theta$ )

Manifest energy-momentum conservation

Fixed jet radius

Unique assignment of hadrons to jet clusters

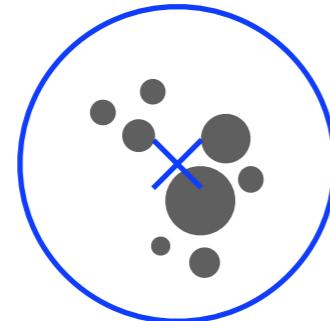
Unique jet reconstruction per event

Hierarchical clustering vs. global optimization

...

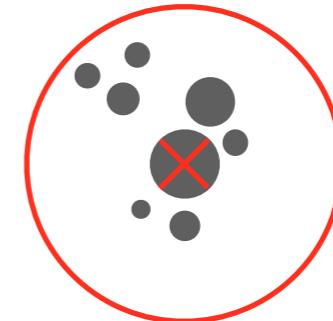
# Change the jet axis?

## Jet Momentum Axis



“Mean”  $\approx$  minimizes sum of  $|distance|^2$   
(sensitive to outliers)

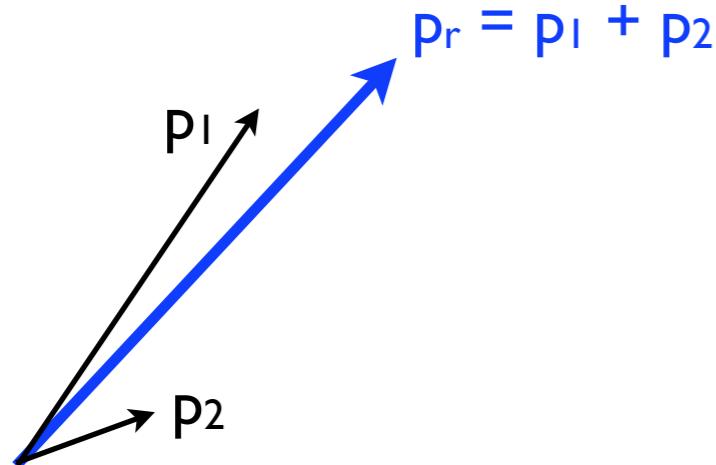
## Winner-Take-All Axis



“Median”  $\approx$  Minimizes sum of  $|distance|$   
(insensitive to outliers)

vs.

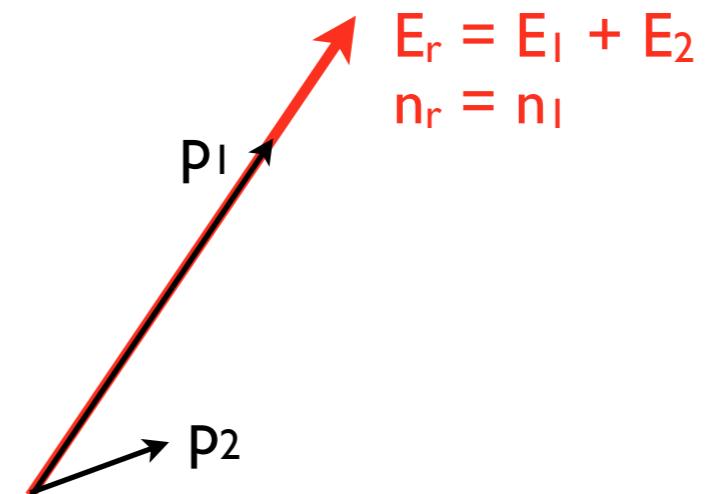
## E-scheme Recombination



$\Rightarrow$

One line of code  
in FastJet 3.1

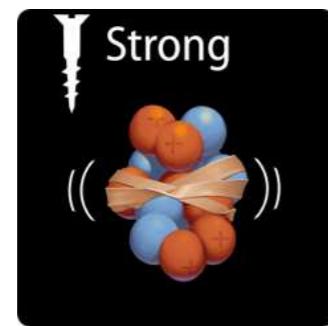
## WTA Recombination



[Bertolini, Chan, JDT, JHEP 2014; Larkoski, Neill, JDT, JHEP 2014; see also JDT, Van Tilburg, JHEP 2012]

# A Jet/QCD Renaissance

c. 2008–present



**LHC**  
Higher Energy  
Higher Luminosity  
Finer Segmentation

*vs. Tevatron*

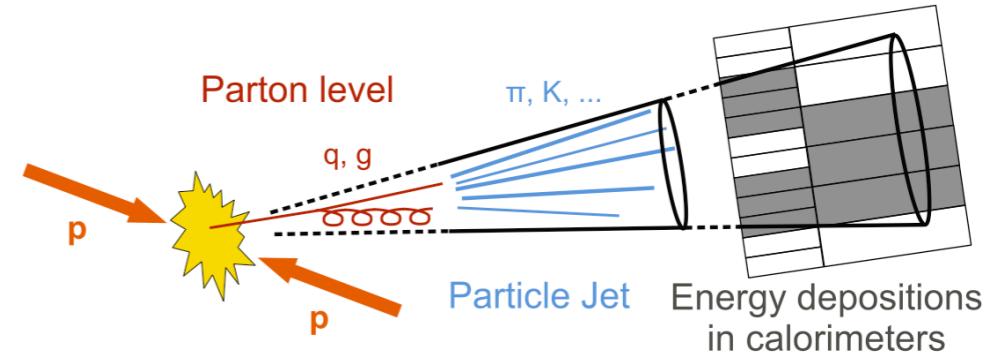
$\approx x3.5\text{--}7$   
 $\approx x10\text{--}20$   
 $\approx x5$



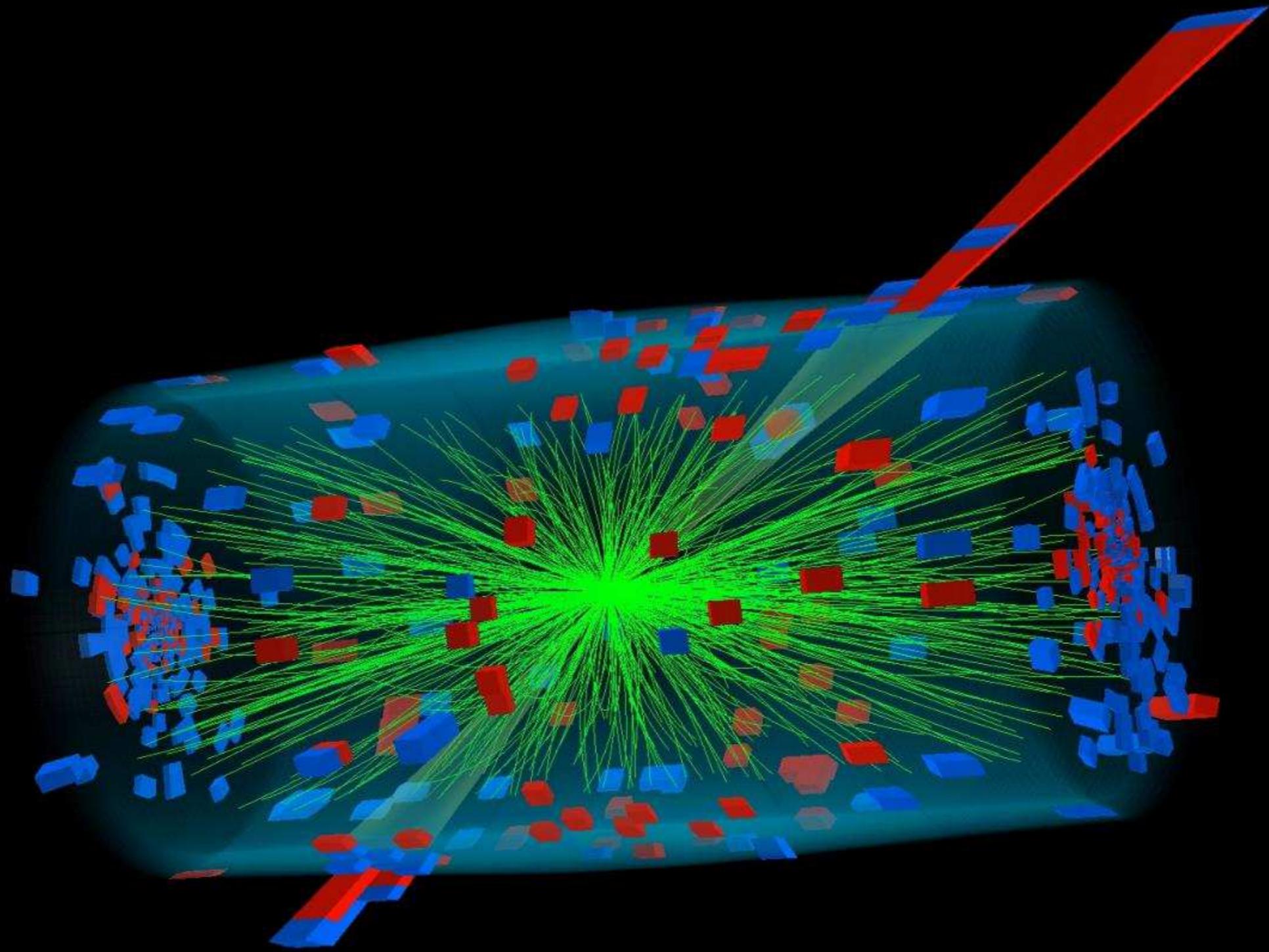
## Theoretical Progress

New Jet Algorithms  
Loop/Leg/Log Explosion  
Jet Substructure

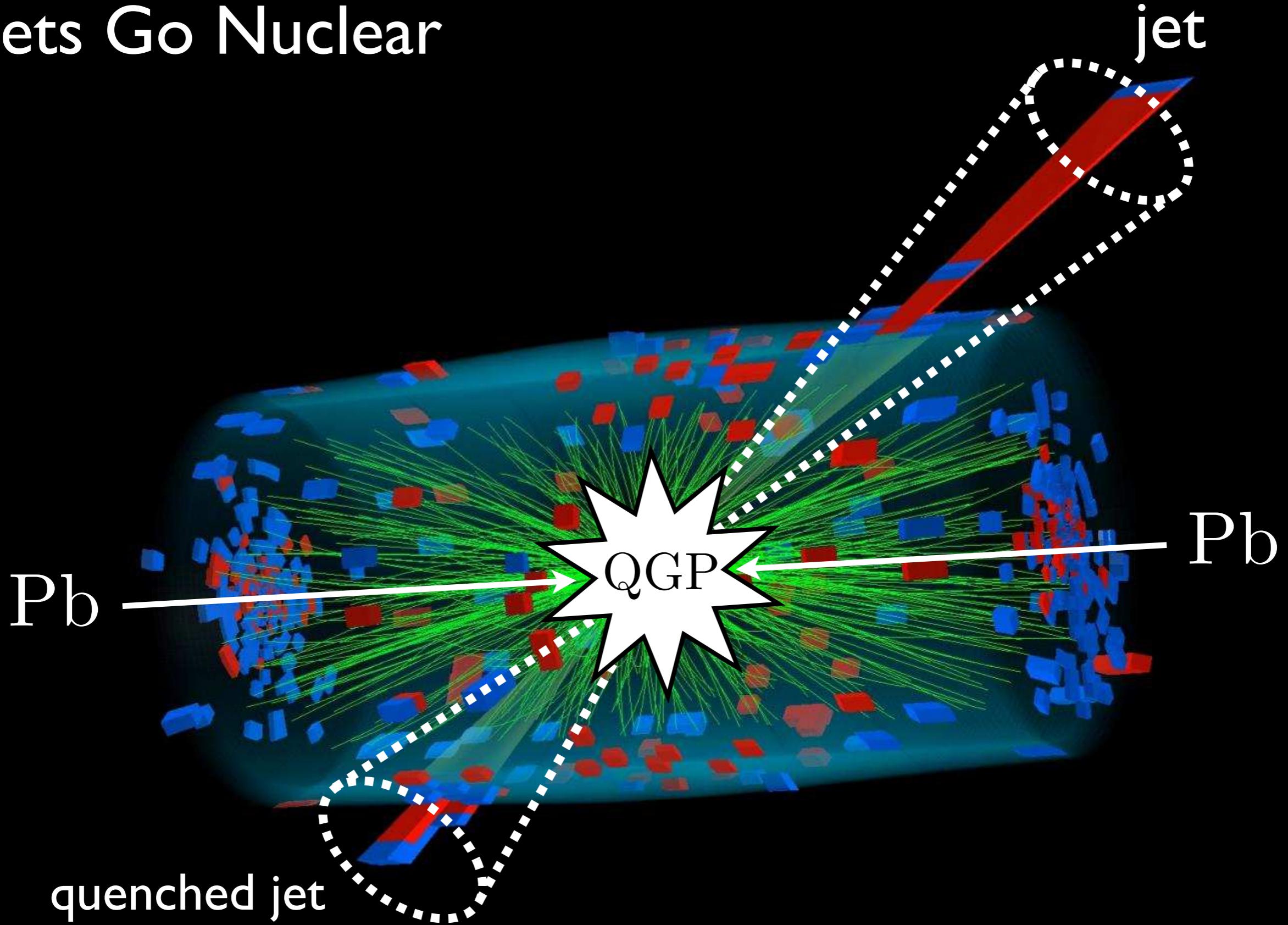
[Anti- $k_T$ : Cacciari, Salam, Soyez, 2008; see also Delsart, 2006]  
[BDRS: Butterworth, Davison, Rubin, Salam, 2008; see also Seymour, 1991, 1994]



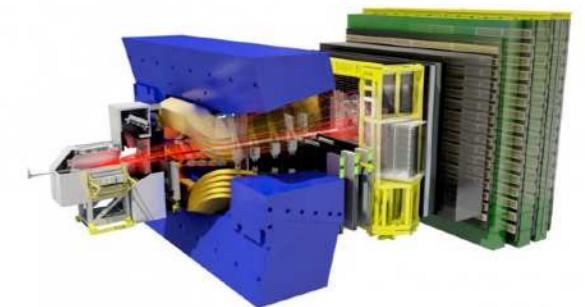
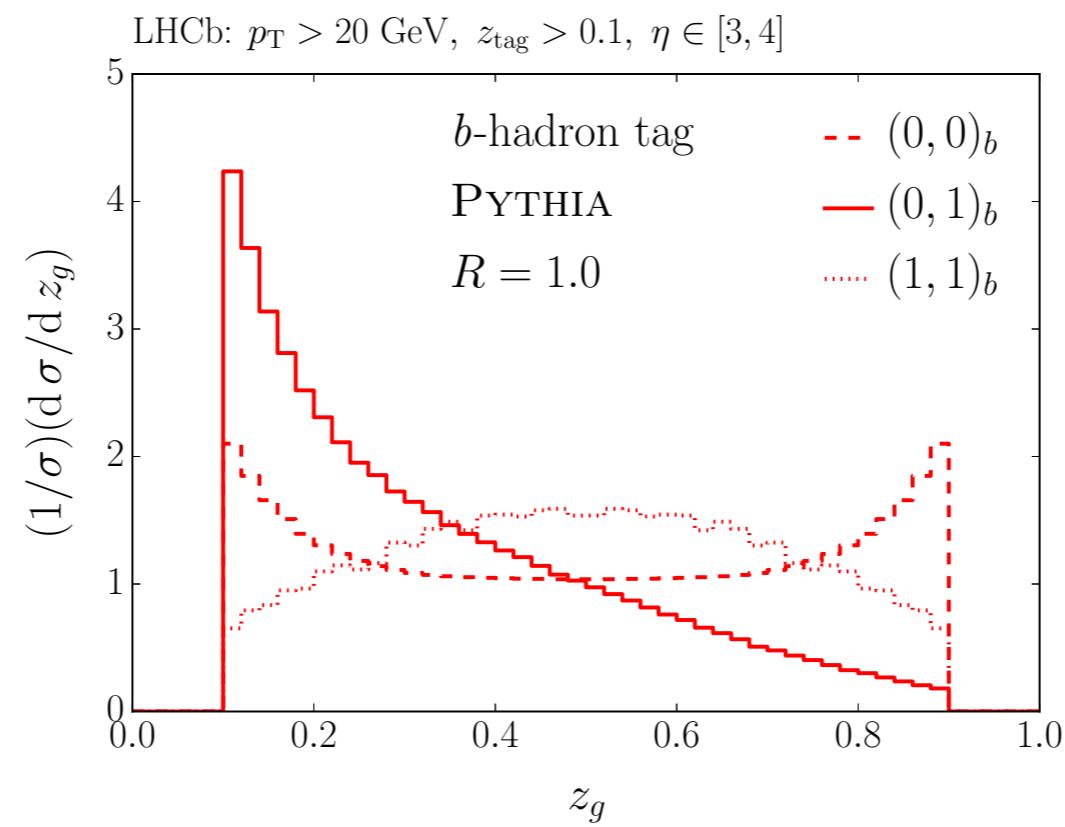
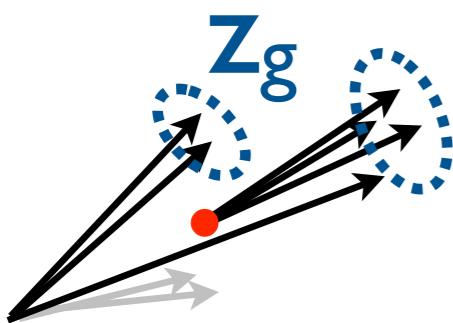
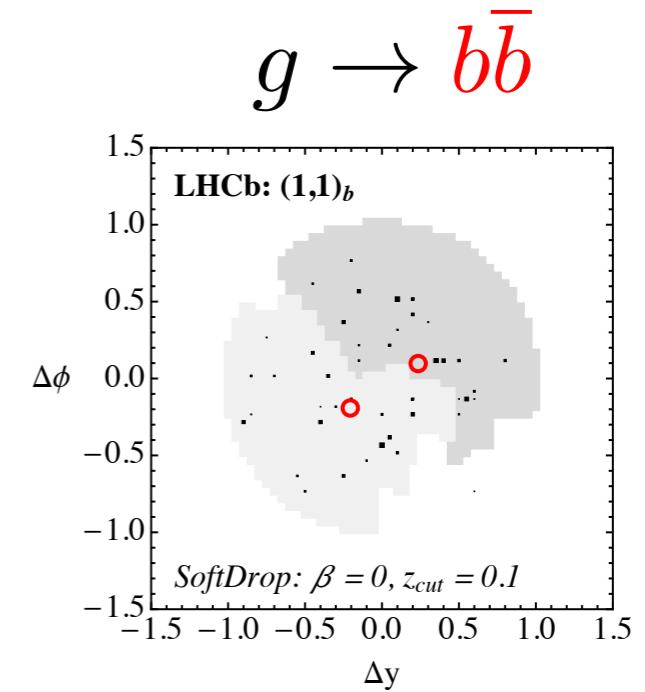
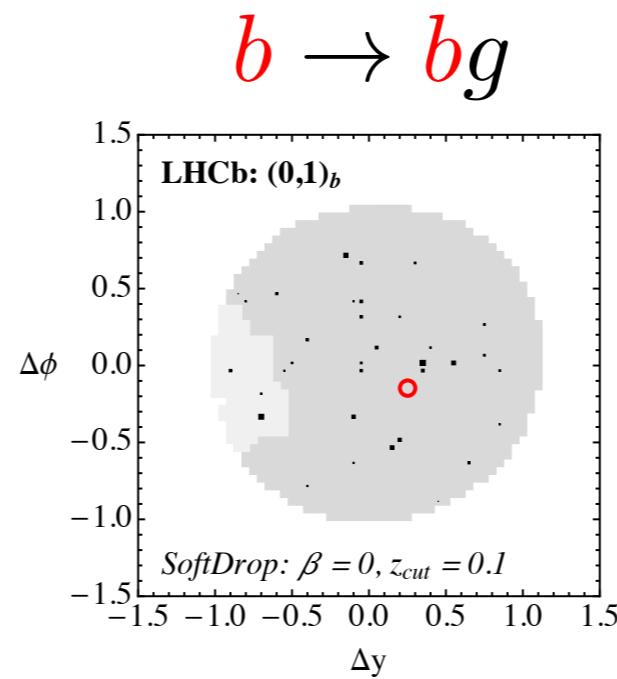
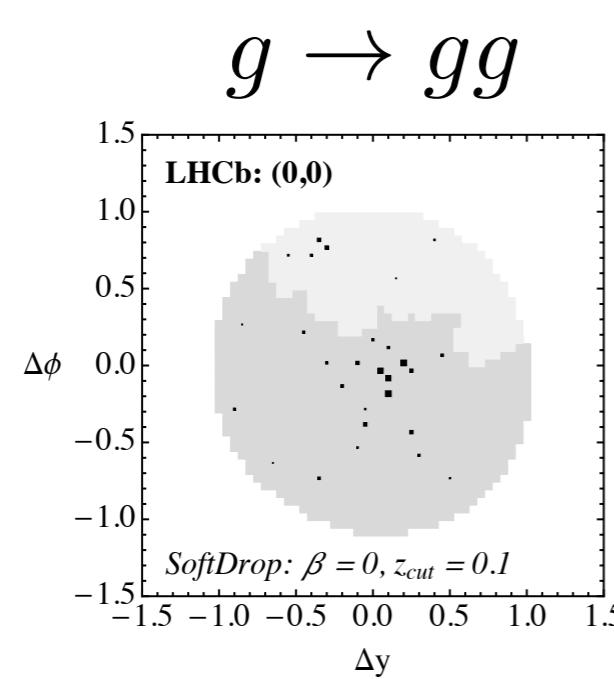
# Jets Go Nuclear



# Jets Go Nuclear



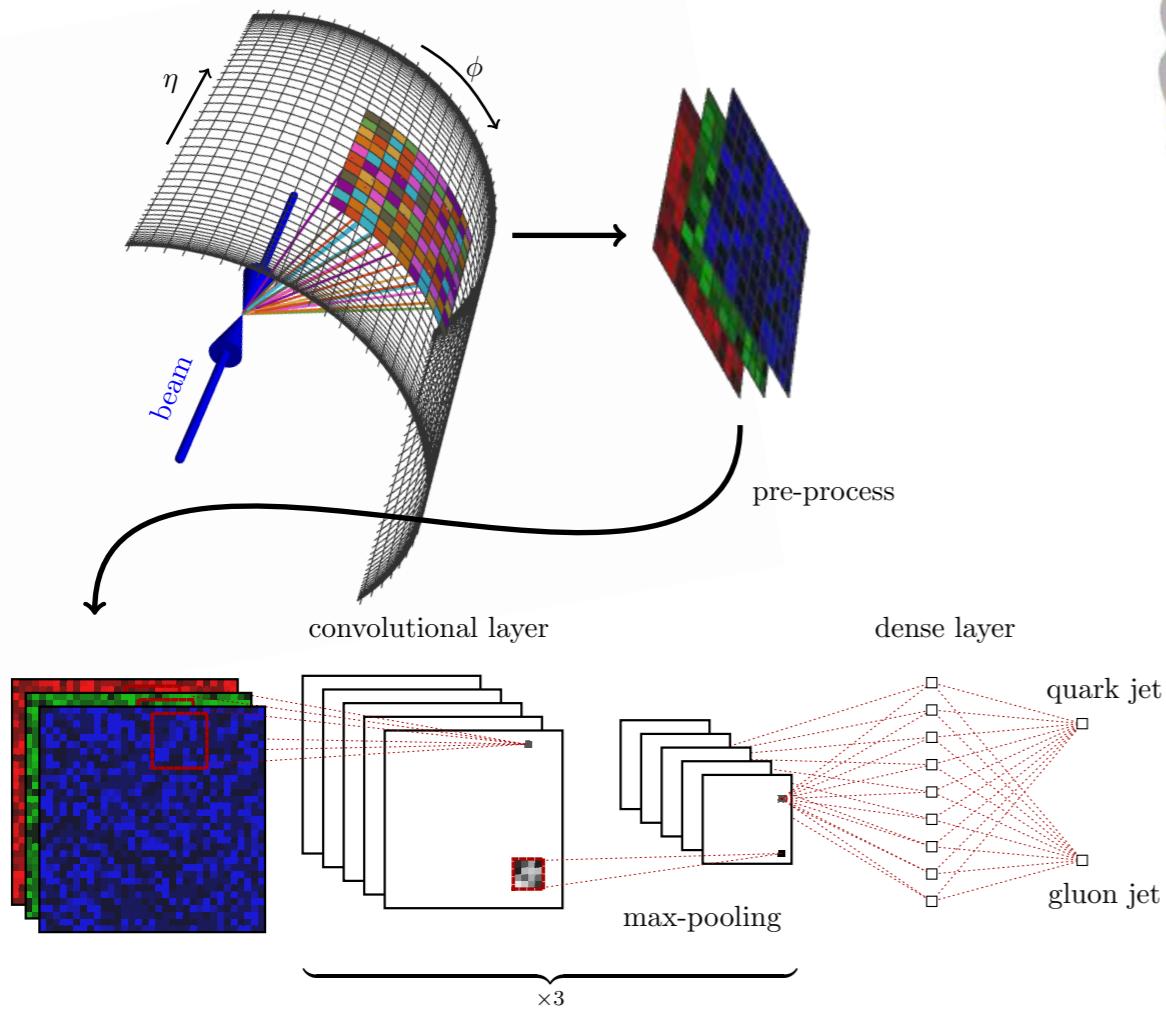
# Jets Get More Flavorful



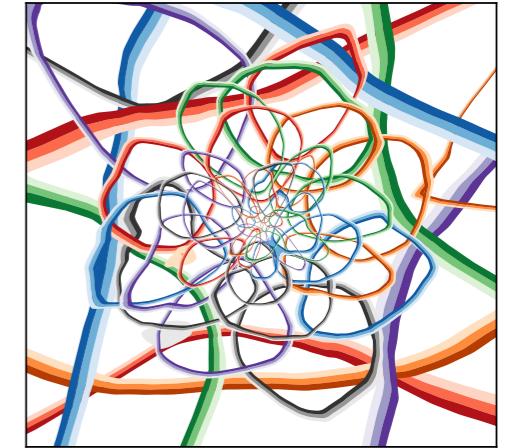
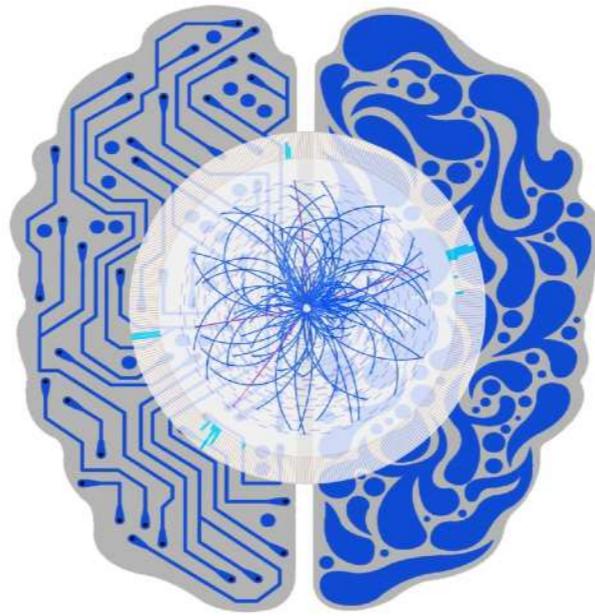
[Ilten, Rodd, JDT, Williams, PRD 2017]

# The Rise of Machine Learning

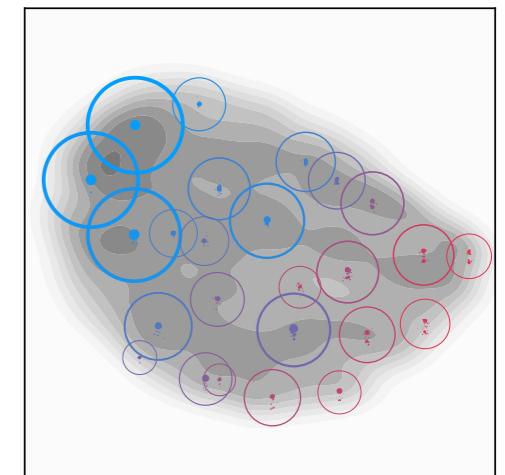
c. 2015–present



[figure from Komiske, Metodiev, Schwartz, JHEP 2017;  
reviews in Larkoski, Moult, Nachman, arXiv 2017; Guest, Cranmer, Whiteson, ARNPS 2018;  
ML4Jets Workshop Series, next iteration at NYU, January 2019]



[Komiske, Metodiev, JDT, JHEP 2019]



[Komiske, Mastandrea, Metodiev, Naik, JDT, arXiv 2019;  
based on Komiske, Metodiev, JDT, PRL 2019]

Run Number: 159224, Event Number: 3533152

Date: 2010-07-18 11:05:54 CEST

