# Jet Tools

Phil Harris (CERN/MIT)

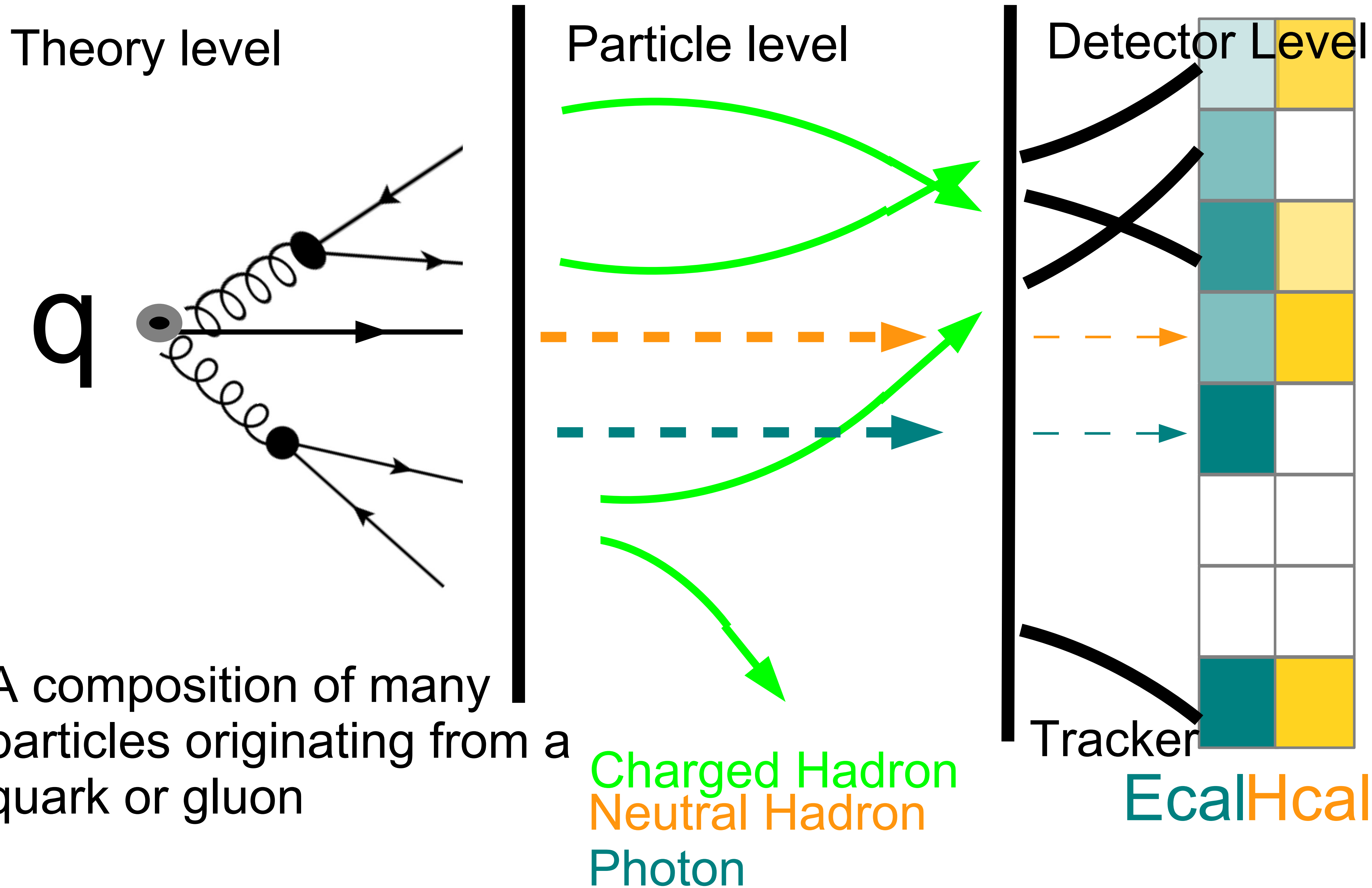
# (from a pp perspective)

# Disclaimer

- This talk is overview from a review last year 2016
  - It has been slightly revamped at the end for new tech
    - The end is a bit disjoint
    - I am moving at the end of the week to the US
  - This review was for the pp community
    - The aim was to introduce this to jet reconstruction beginners
    - So bear with me at times

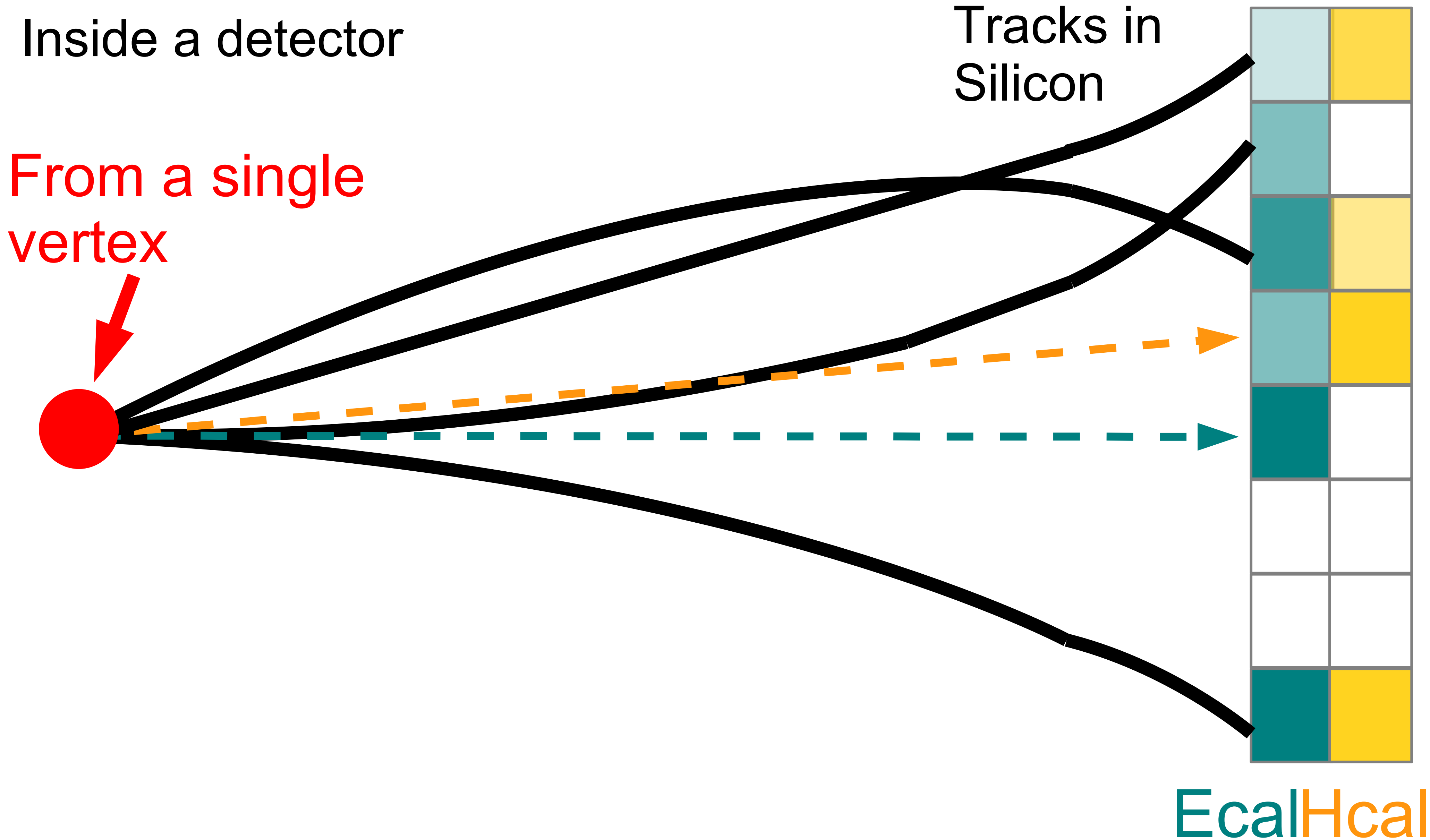
- I am a pp physicist
  - I have done some work in HI
  - I don't speak fluent HI
  - I am familiar with the tools

# What is a jet?



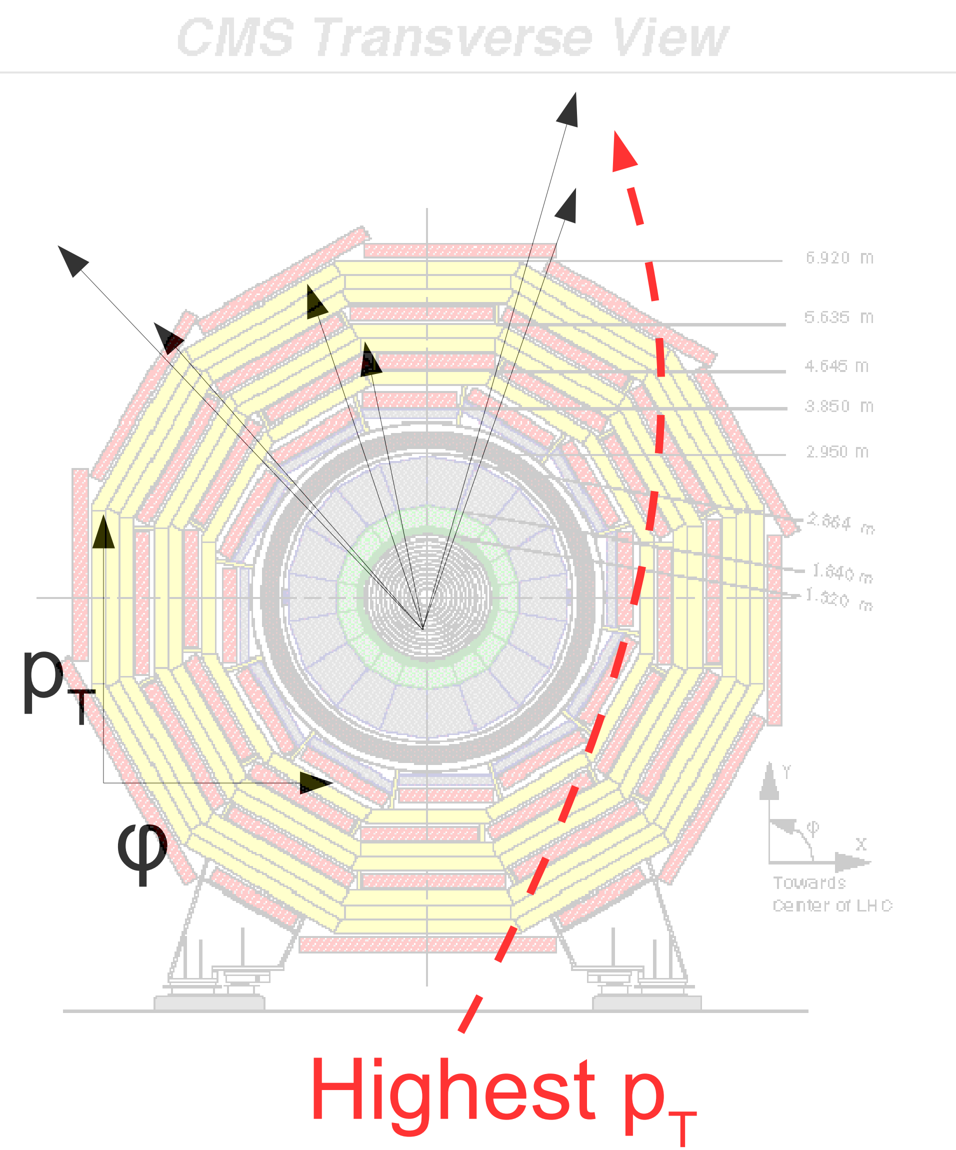

A composition of many particles originating from a quark or gluon

# What is a jet?


Inside a detector
Tracks in Silicon
From a single vertex
EcalHcal

# Jet Reconstruction

- Itrerate over two




Take smallest

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

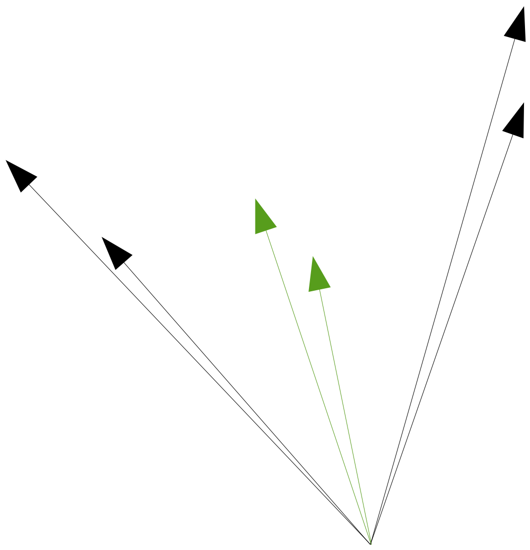
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

# Jet Reconstruction

- Itrerate over two



Start small

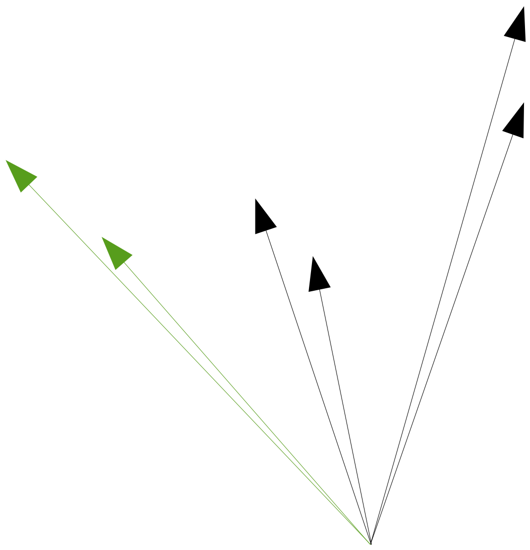
Take smallest

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

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

# Jet Reconstruction

- Itrerate over two



Start Close

Take smallest

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

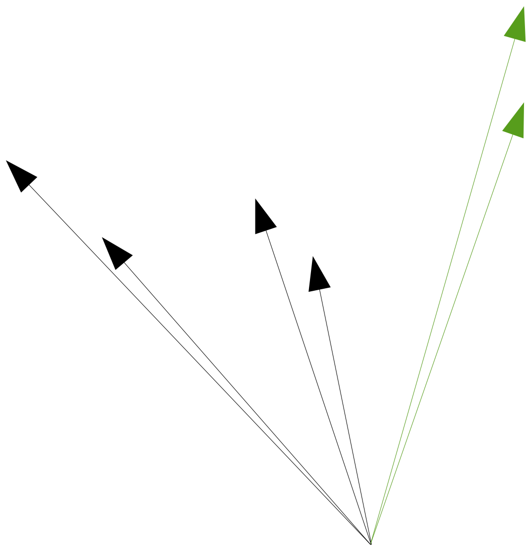
$\alpha=1$ kT

$\alpha=0$ Cambridge Aachen

$\alpha=-1$ Anti-kT

# Jet Reconstruction

- Itrerate over two



Start Big

Take smallest

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

$\alpha=1$ kT
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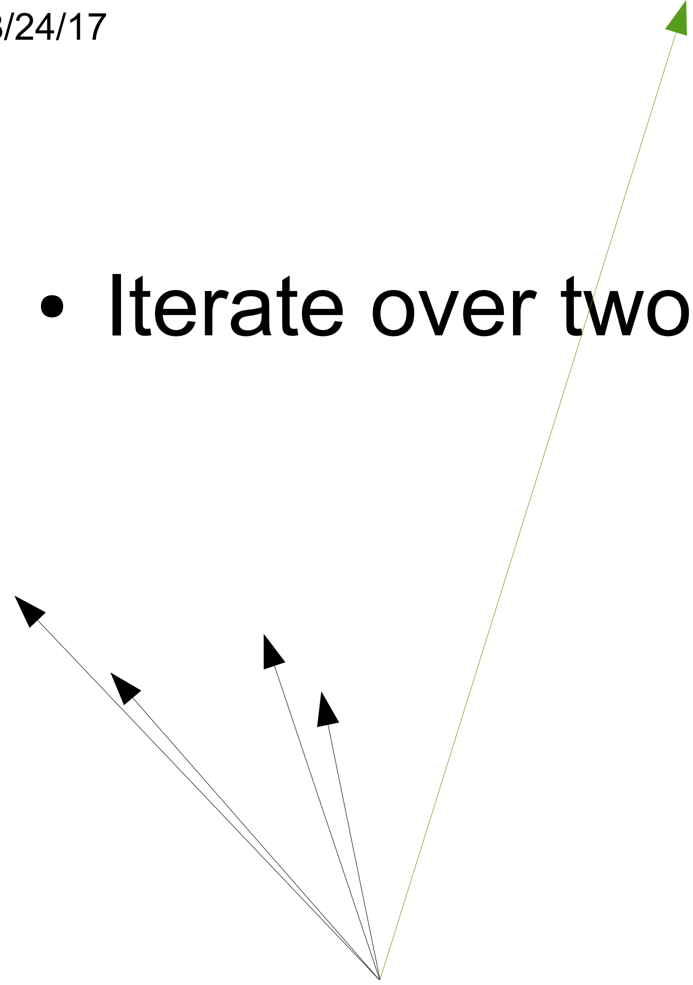
# Jet Reconstruction

- Iterate over two



Now merge initial into a particle

Take smallest

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

α=1 kT
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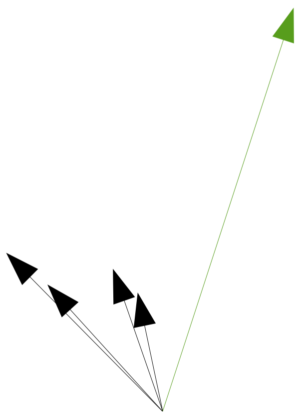
α=-1 Anti-kT

# Jet Reconstruction

- Iterate over two



Zooming out

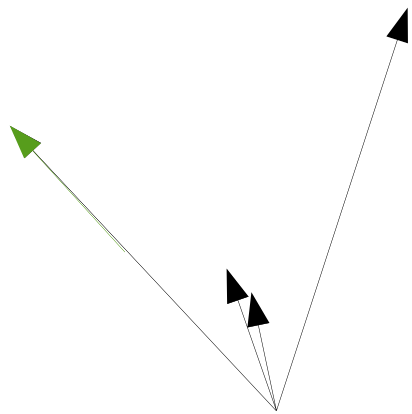
Take smallest

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

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

# Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

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

α=1 kT
α=0 Cambridge Aachen
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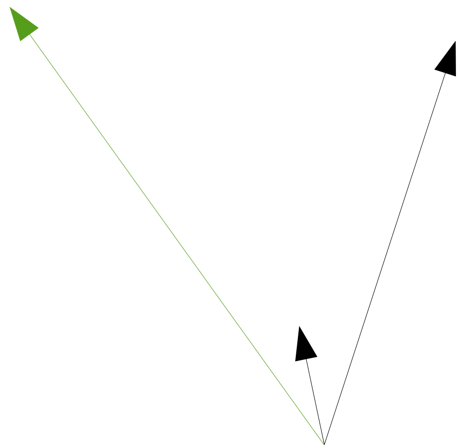
# Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

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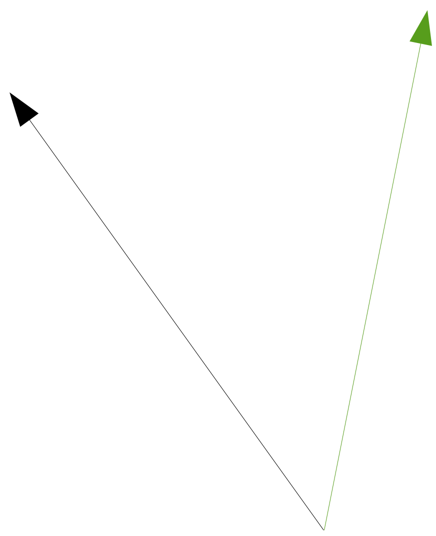
# Jet Reconstruction

- Iterate over two



Merge next set

Take smallest

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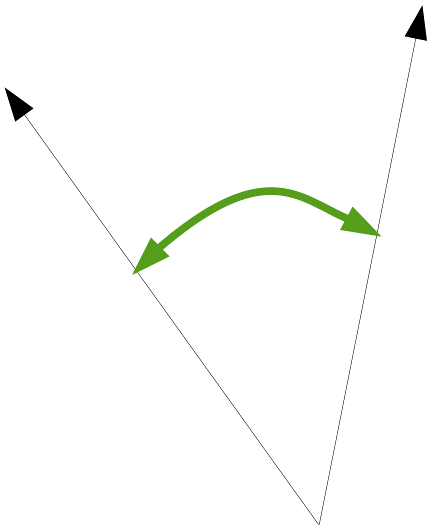
# Jet Reconstruction

- 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
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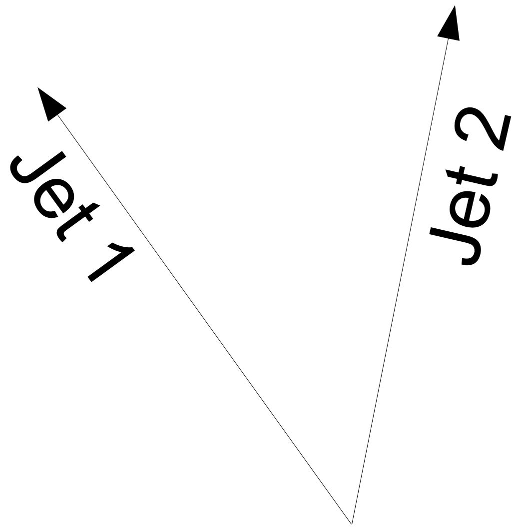
# Jet Reconstruction

- Iterate over two




Done

Take smallest

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

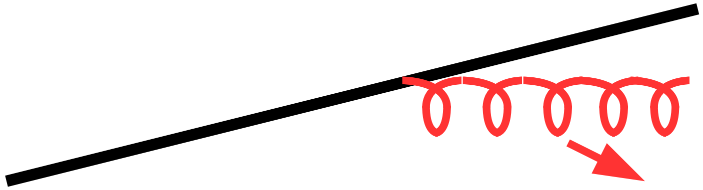
α=1 kT
α=0 Cambridge Aachen
α=-1 Anti-kT

# 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 $\Delta R \to 0$

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

When $\Delta R \to 0$

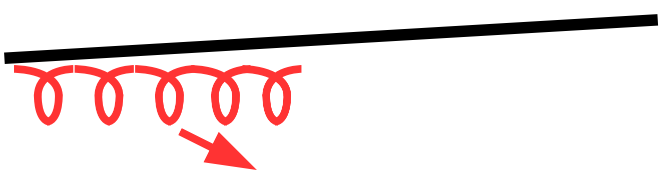
*Wesley Smith

# 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?

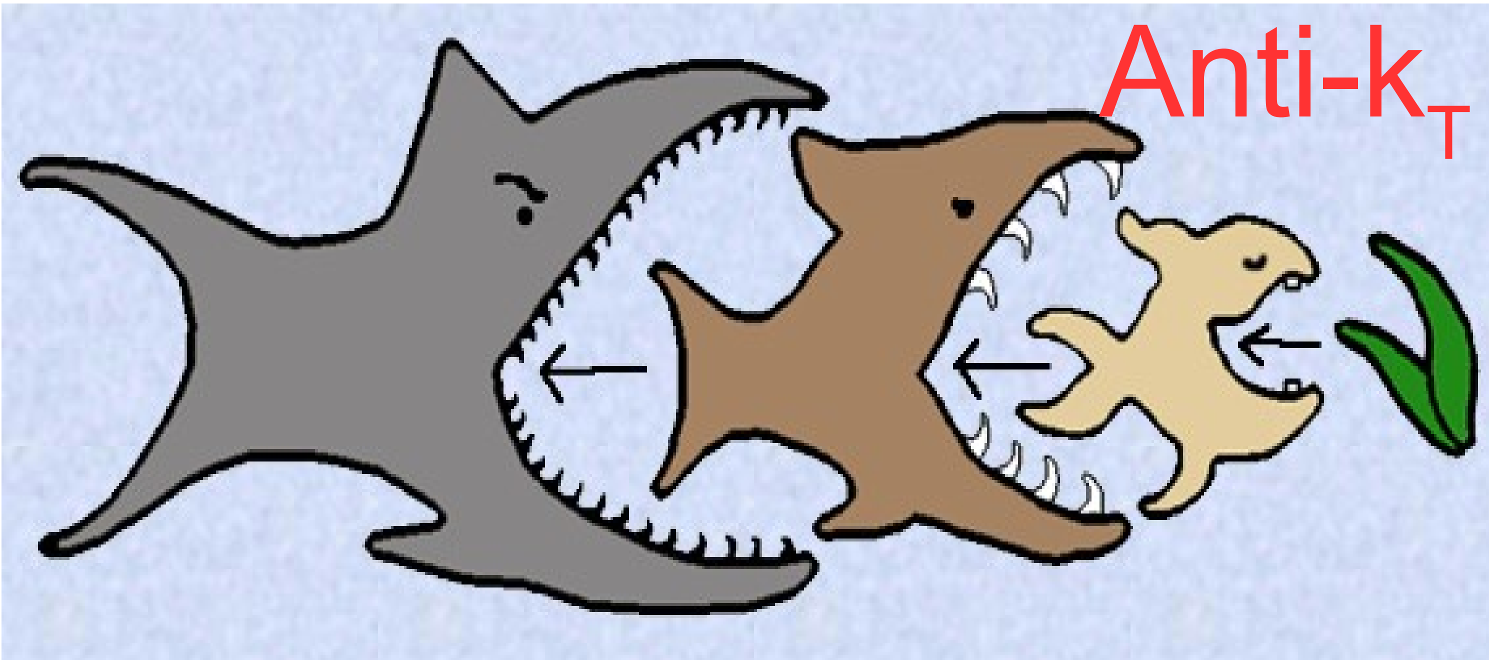

*

To calculate anything with a jet we need to observe :

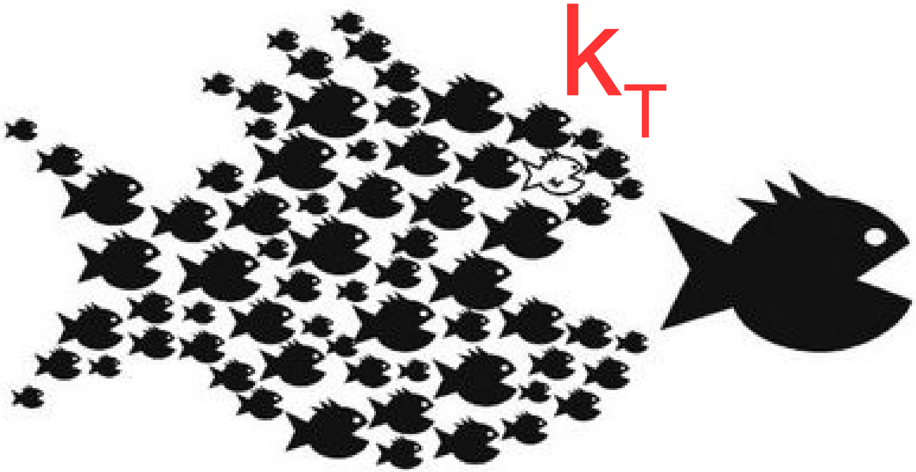
Infrared safety : invariance with random particle w/E→0
Collider safety : invariance with random split ΔR→0

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

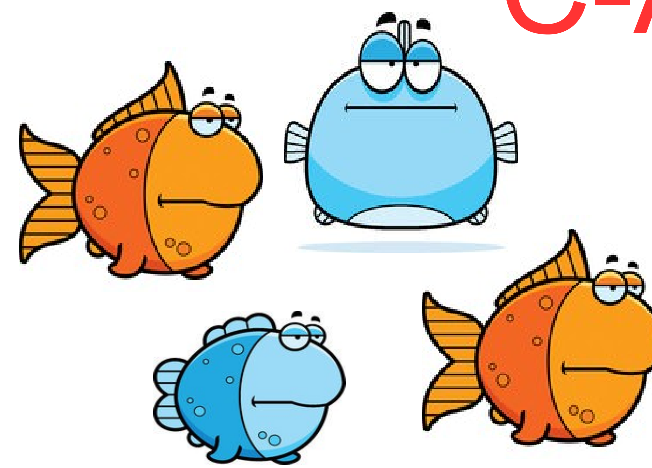
# Recap



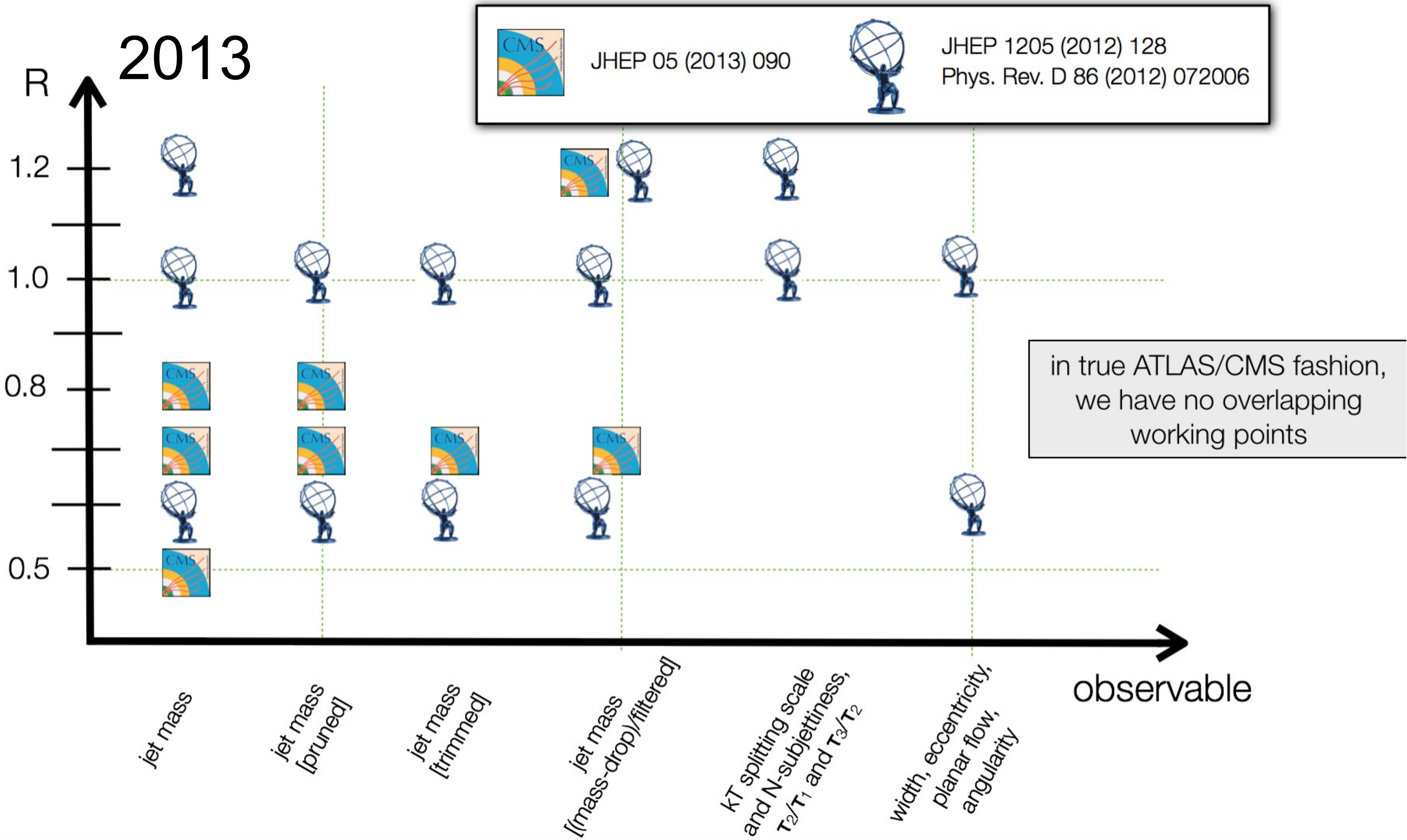

$k_T$



C-A

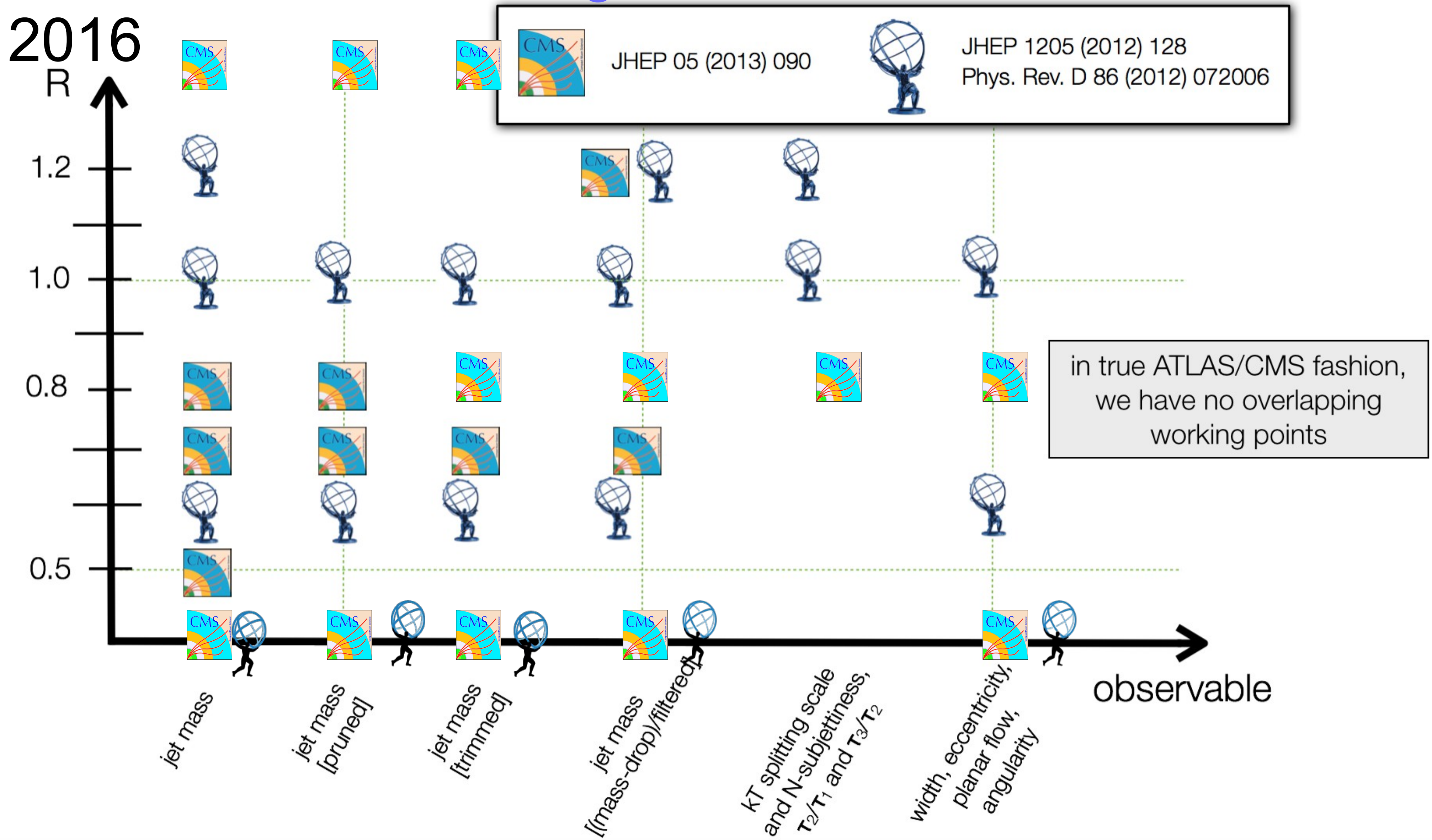


# Whats the right cone size?

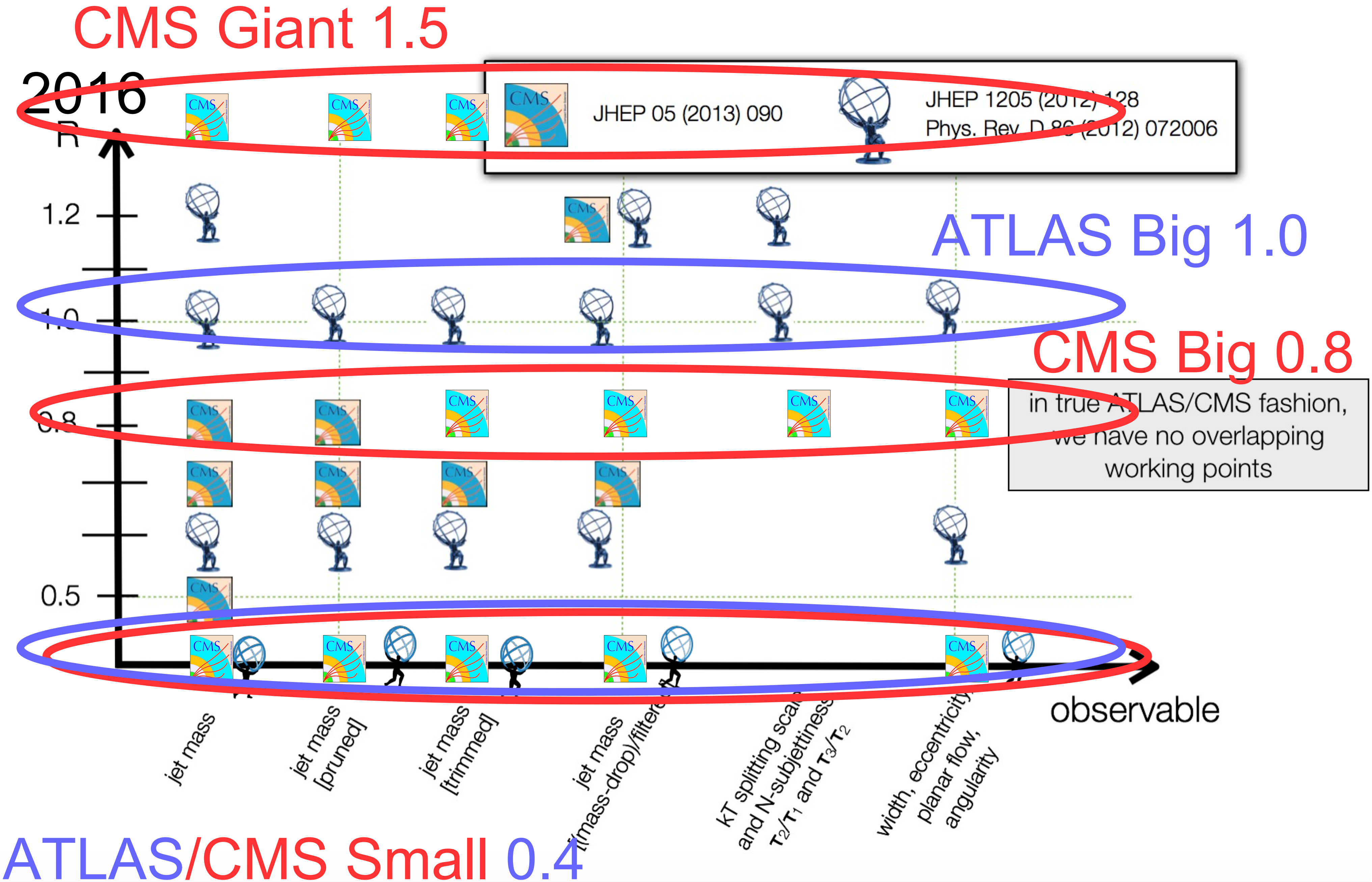


# Whats the right cone size?

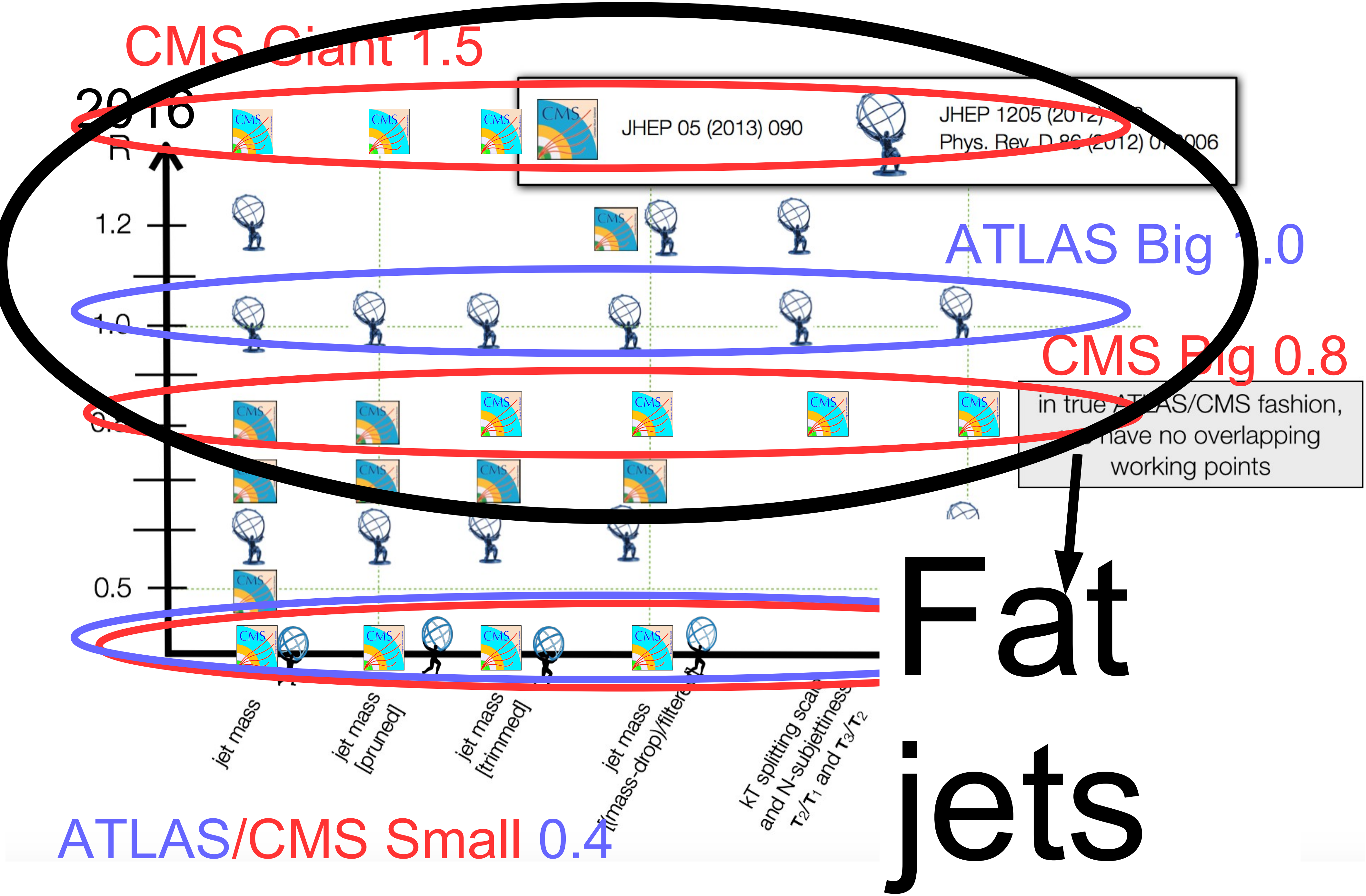
## There is no right cone size



# Current Defaults at LHC

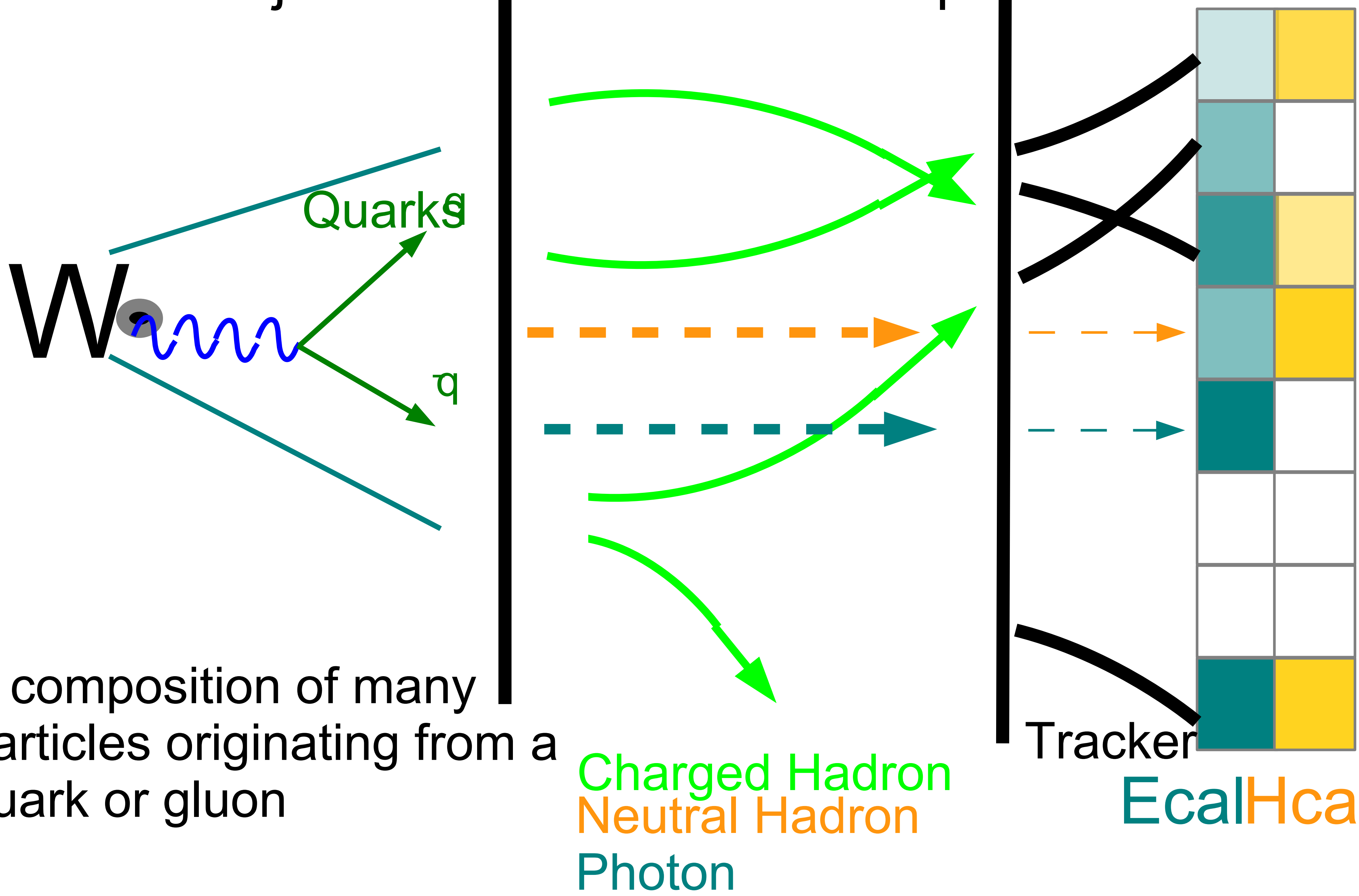


# Current Defaults at LHC



# Why do we have different defaults?

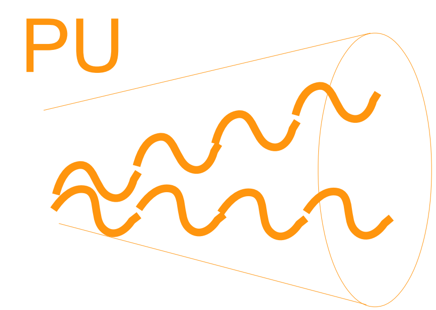
- We don't just care about the initial quark



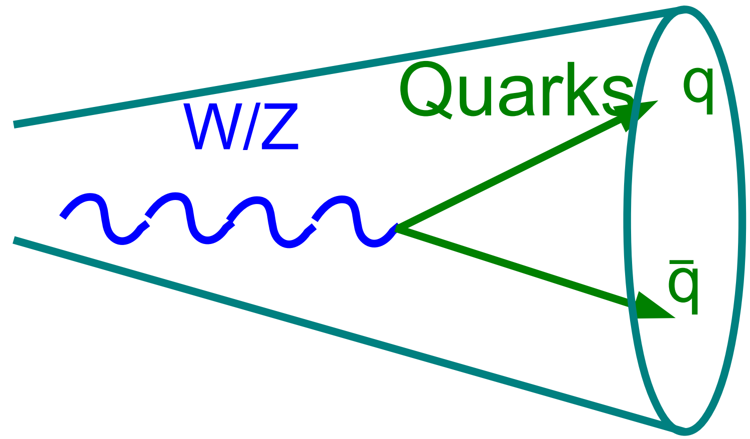

A composition of many particles originating from a quark or gluon

# Many Phases of Jets

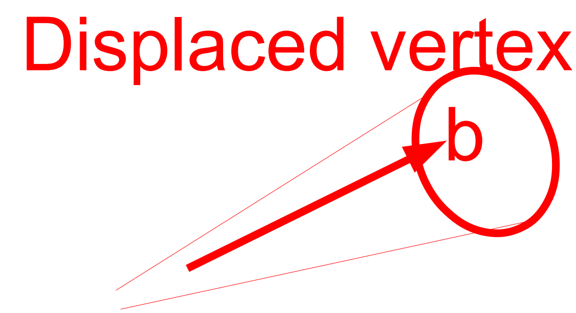
## Pileup Jet



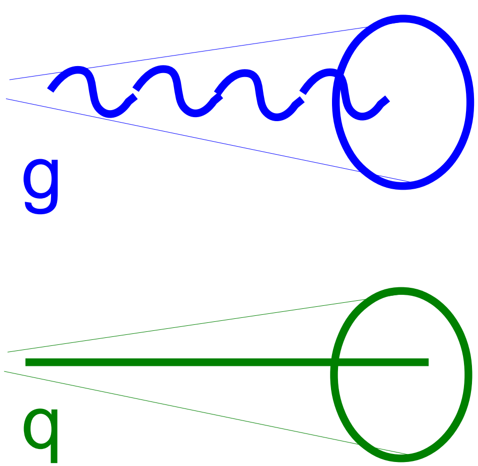

## V Boson Jet



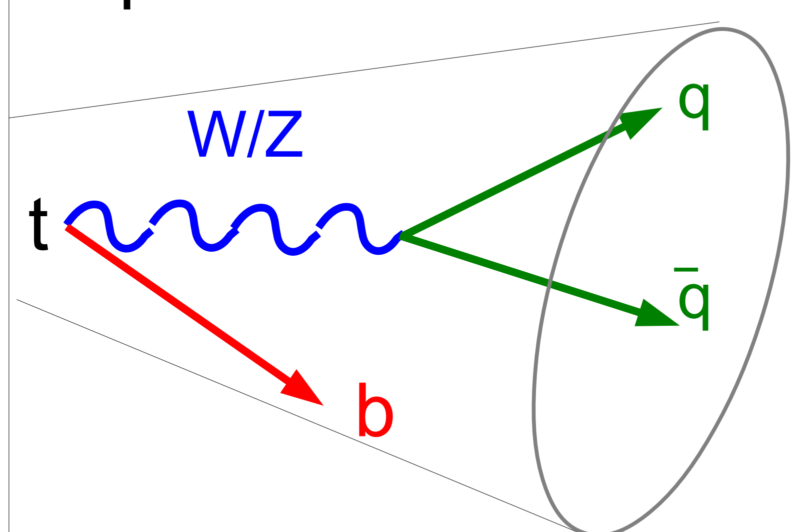

## B-quark Jet



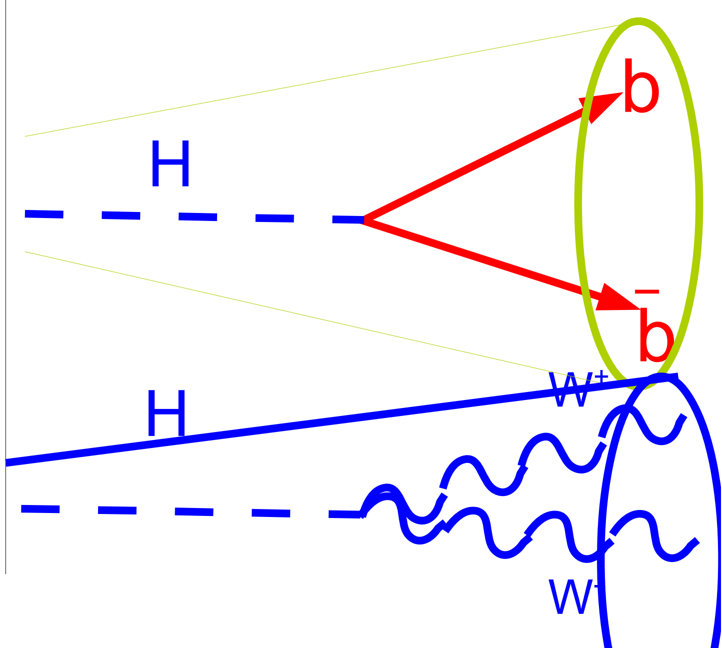

## Quark/Gluon Jet




## Top Jet

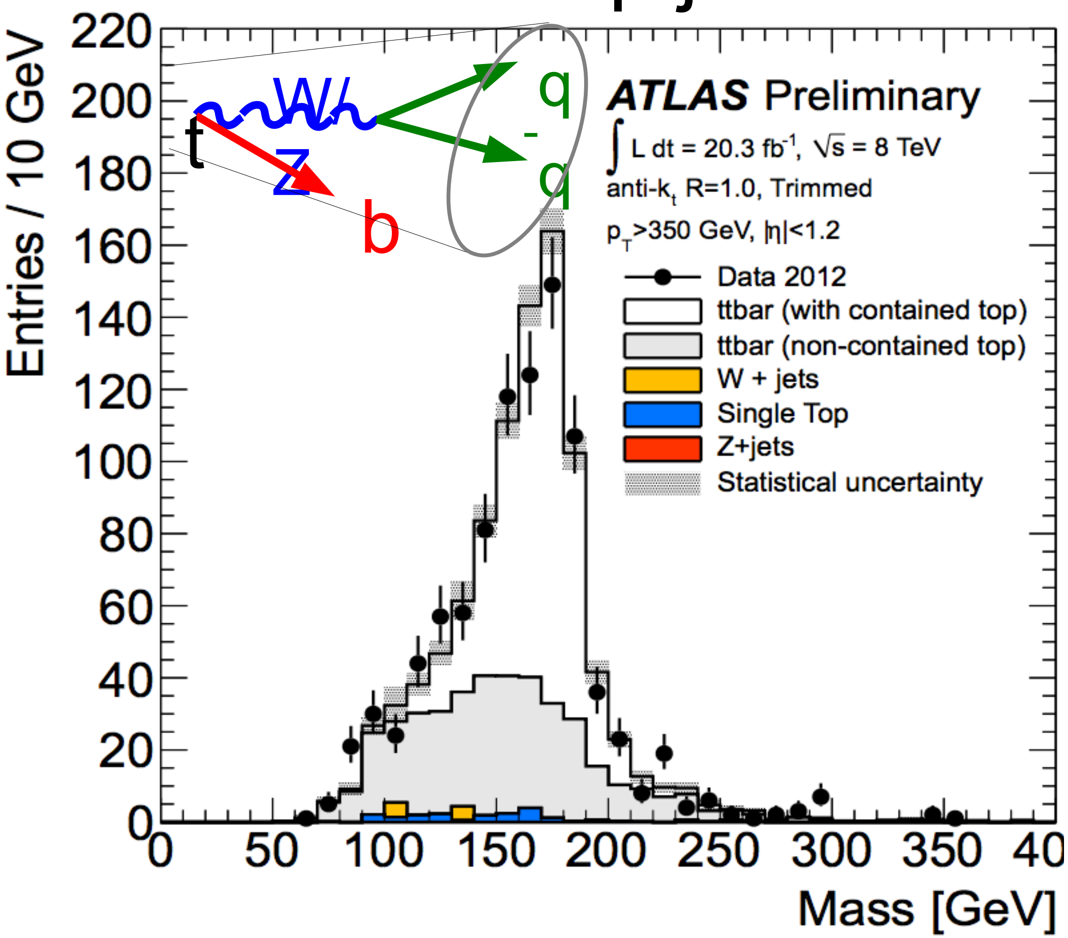



## Higgs Jet

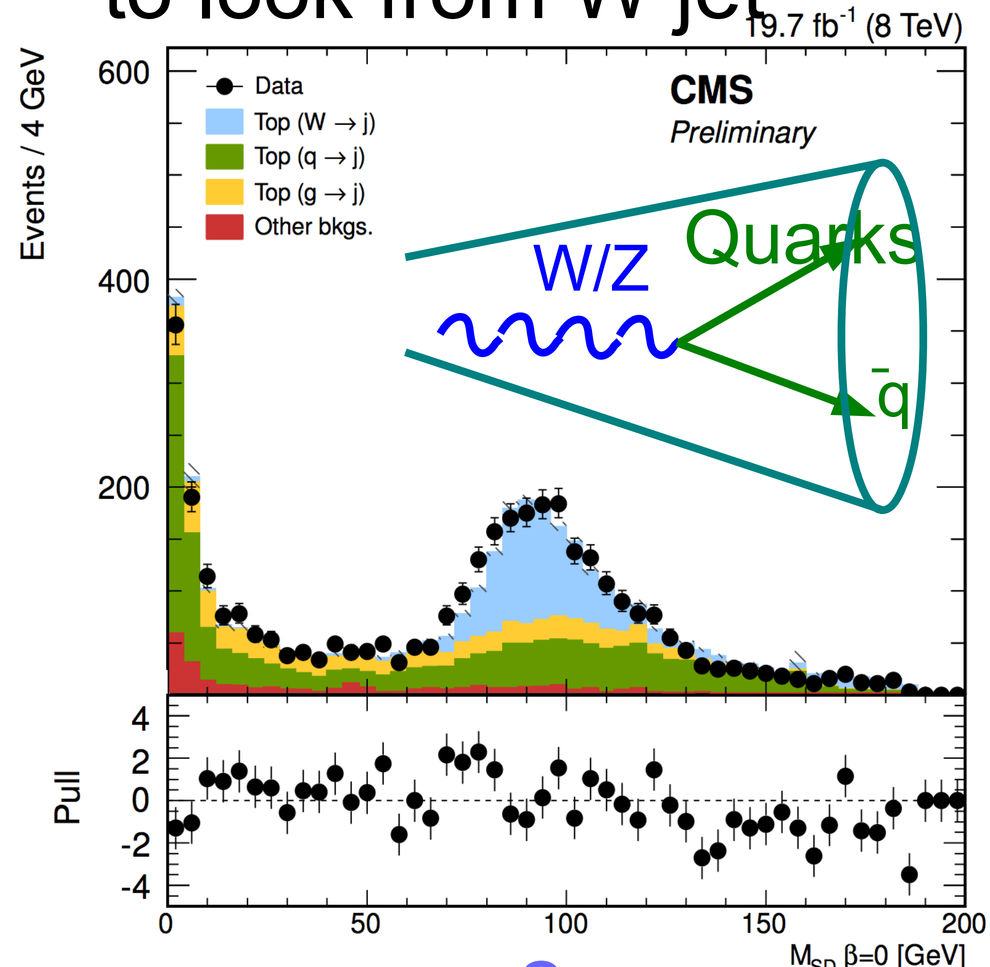


# Each cone focus on a different object

Larger cone allows us to look from top jet




Smaller cone allows us to look from W jet

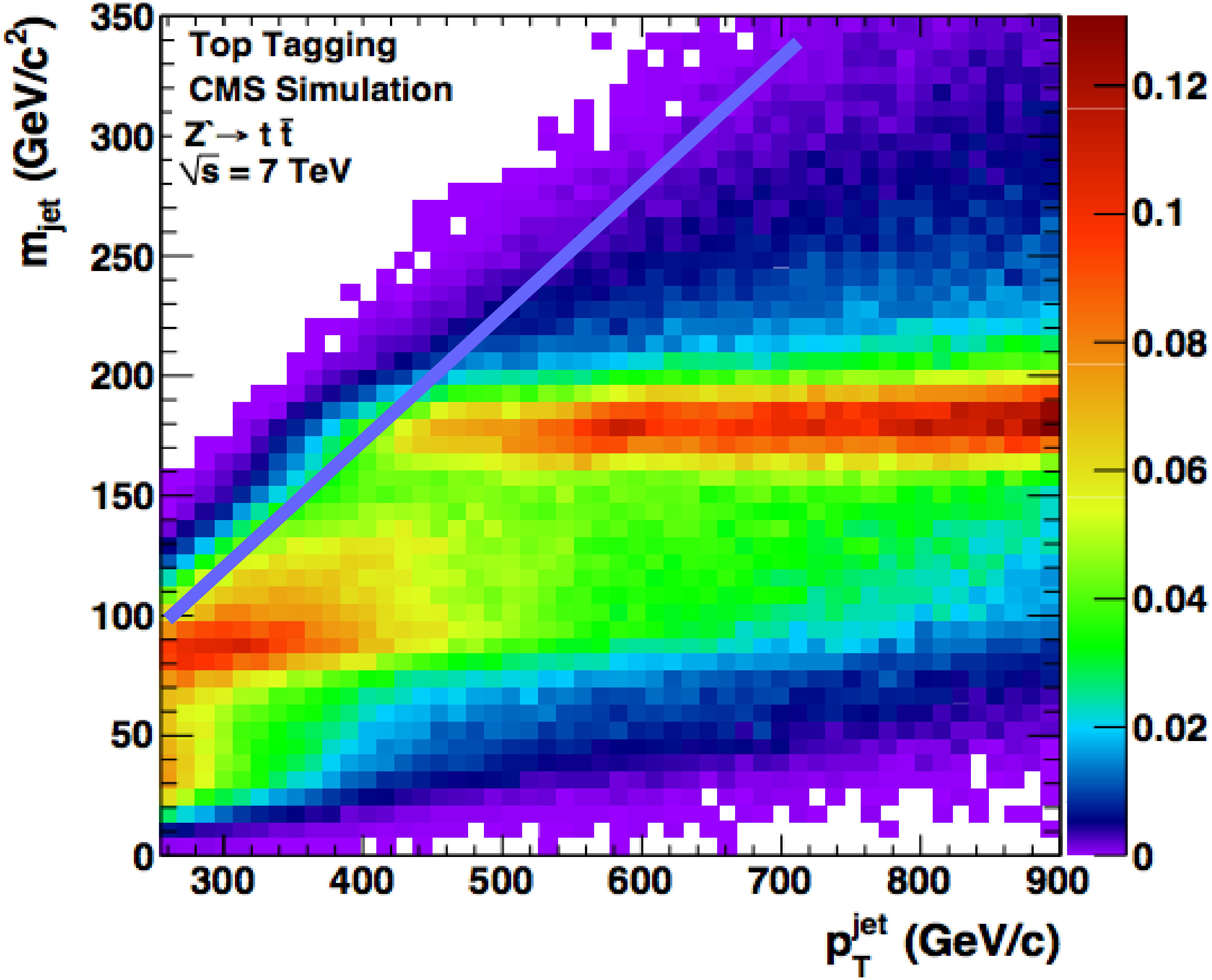



Master formula for heavy object : $\Delta R = \frac{2m}{p_T}$

# Each cone focus on a different object

Larger cone allows us to look from top jet

Smaller cone allows us to look from W jet



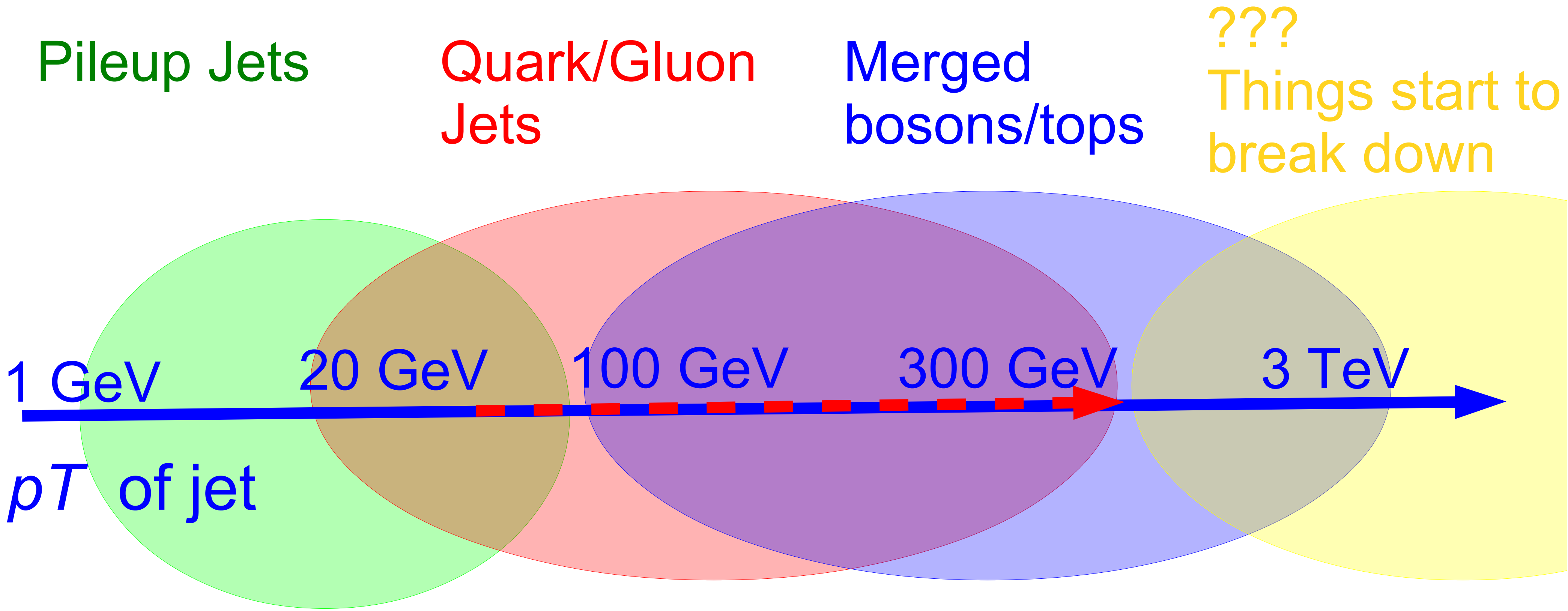

Fix $\Delta R \rightarrow 0.8$

$$\frac{2m}{p_T} = 0.8$$

$m = 0.4\ p_T$

# Spectrum of Jet Substructure

Substructure has been leading to a change in how we view jets



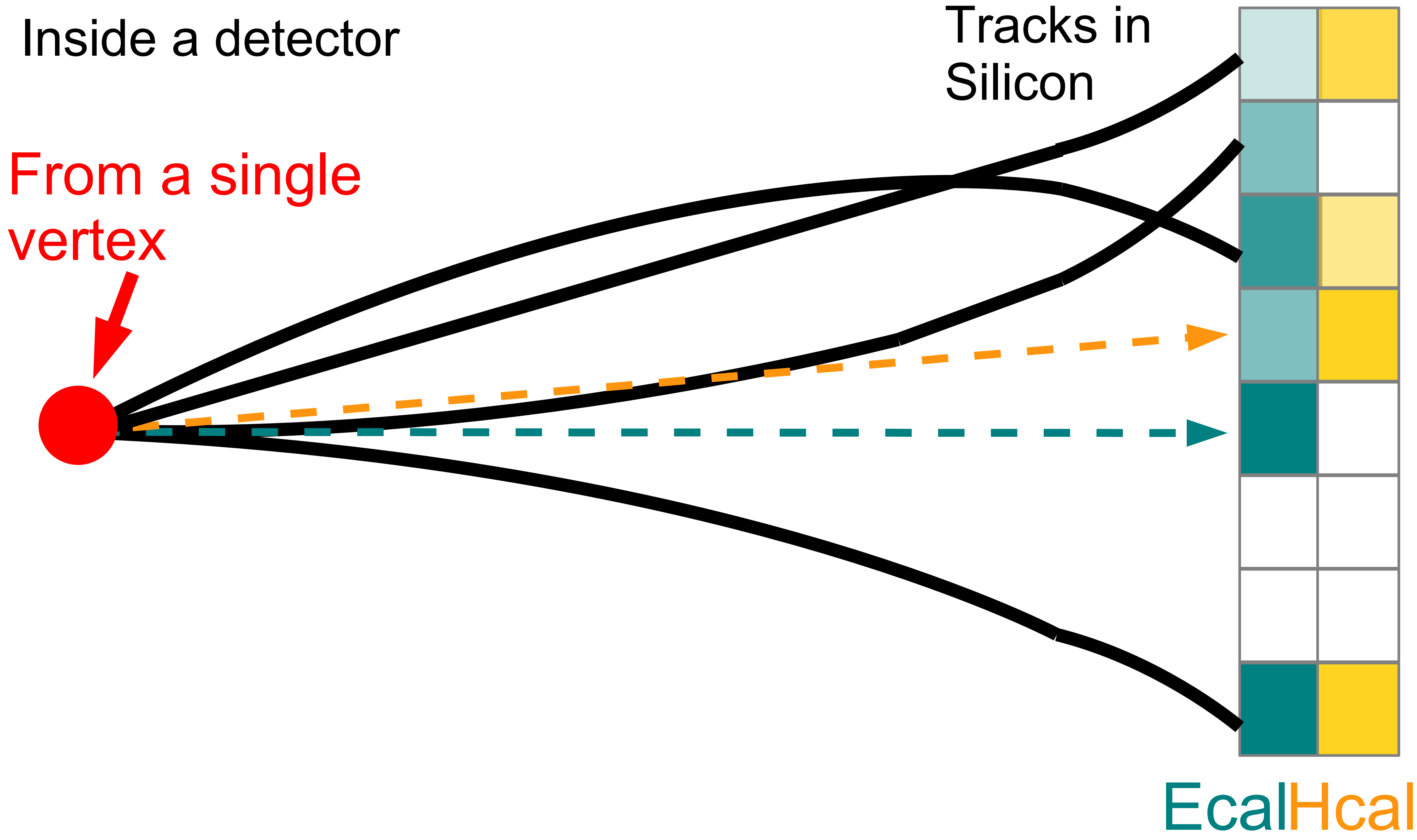

Pileup treated with Pileup Jet Id at low *pT*

At high *pT* Pileup subtraction the most important

At 1 TeV Reconstruction effects limit substructure (we will not talk about this here)

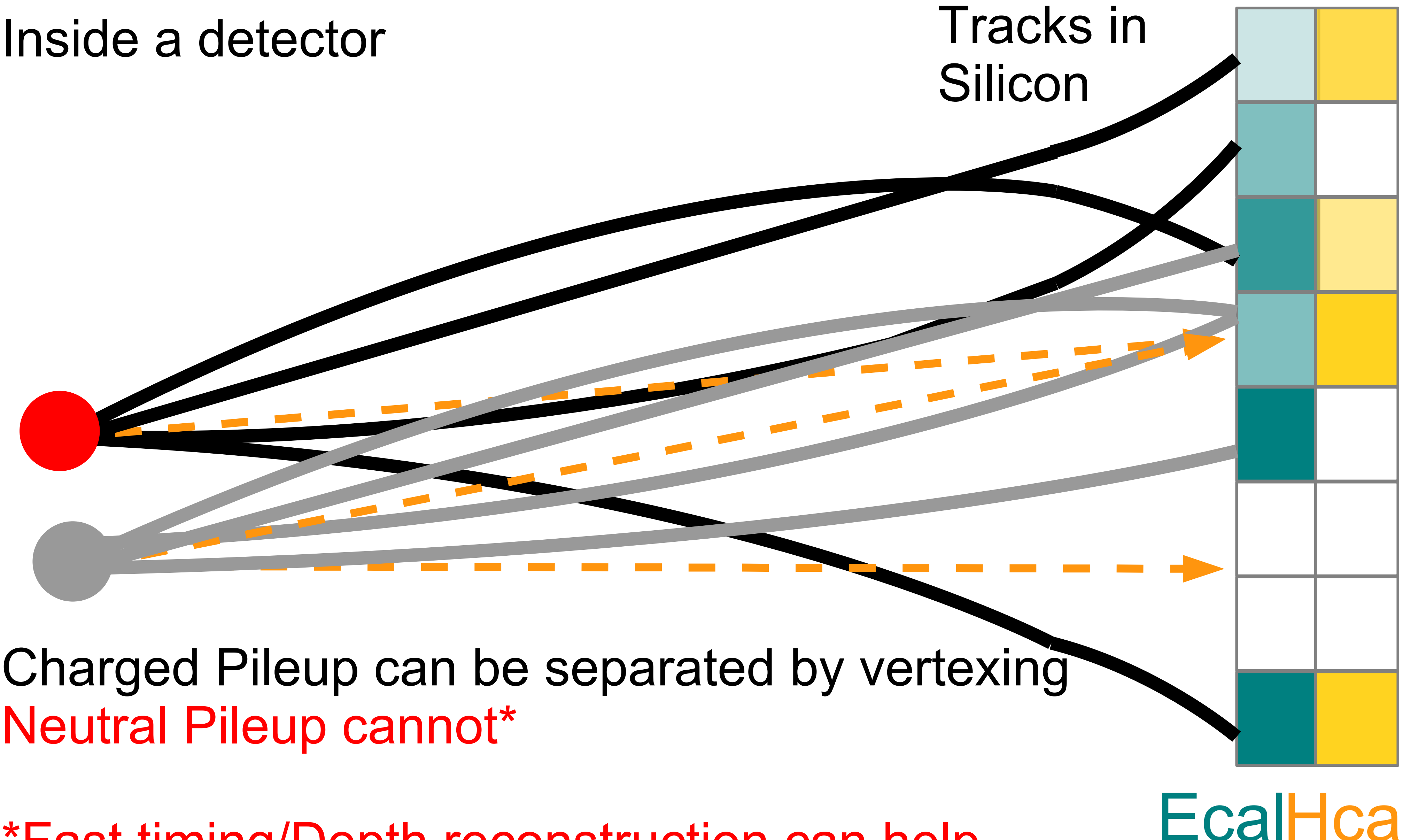
# What is a jet?

Inside a detector



# What is a Jet?

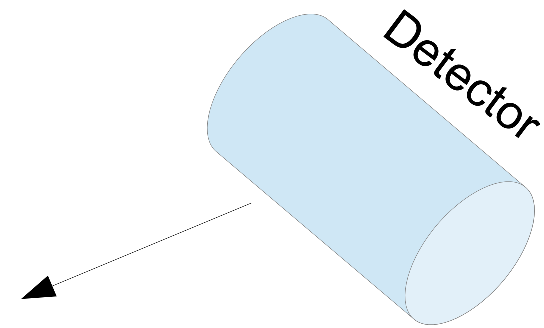
Inside a detector



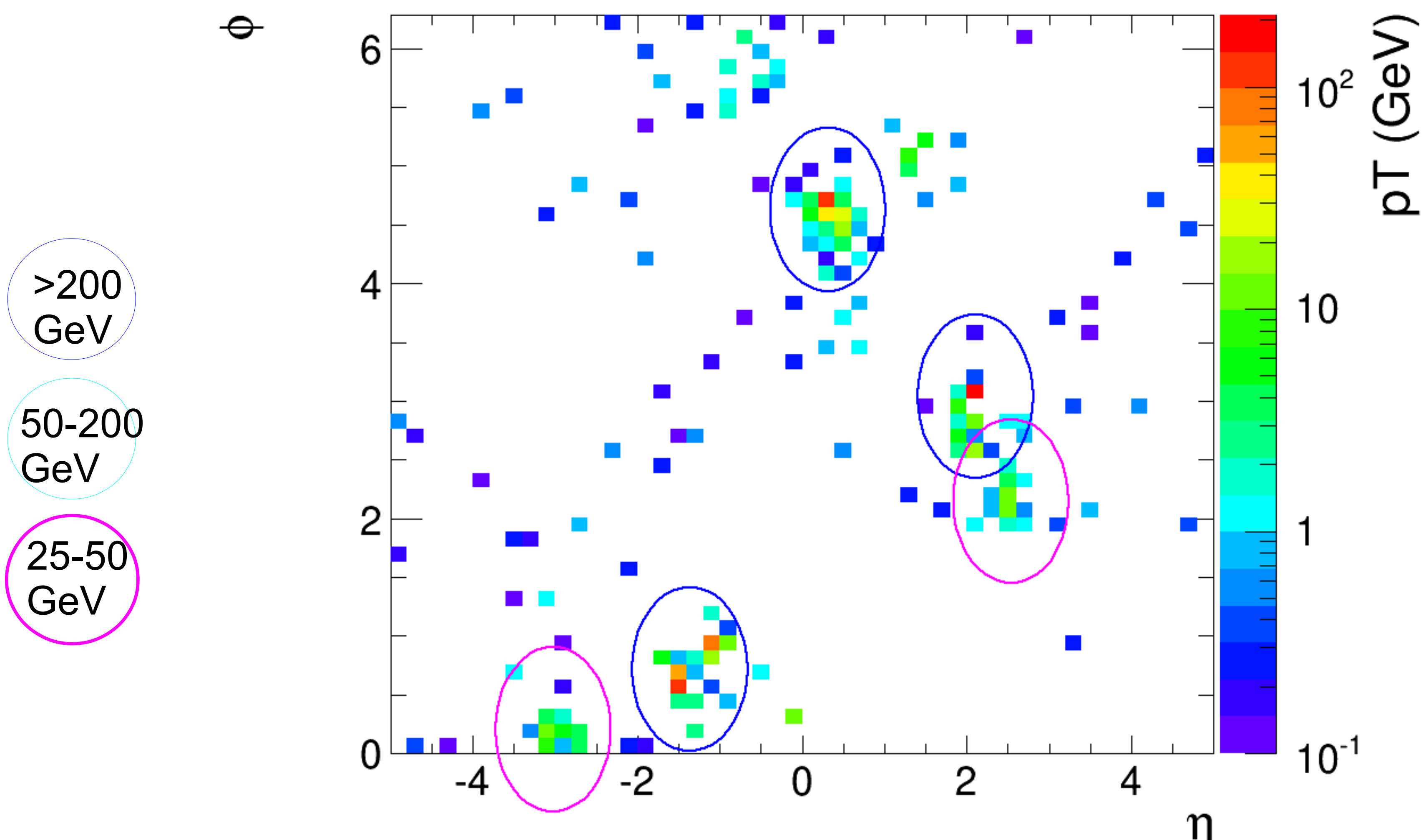

Charged Pileup can be separated by vertexing

Neutral Pileup cannot*

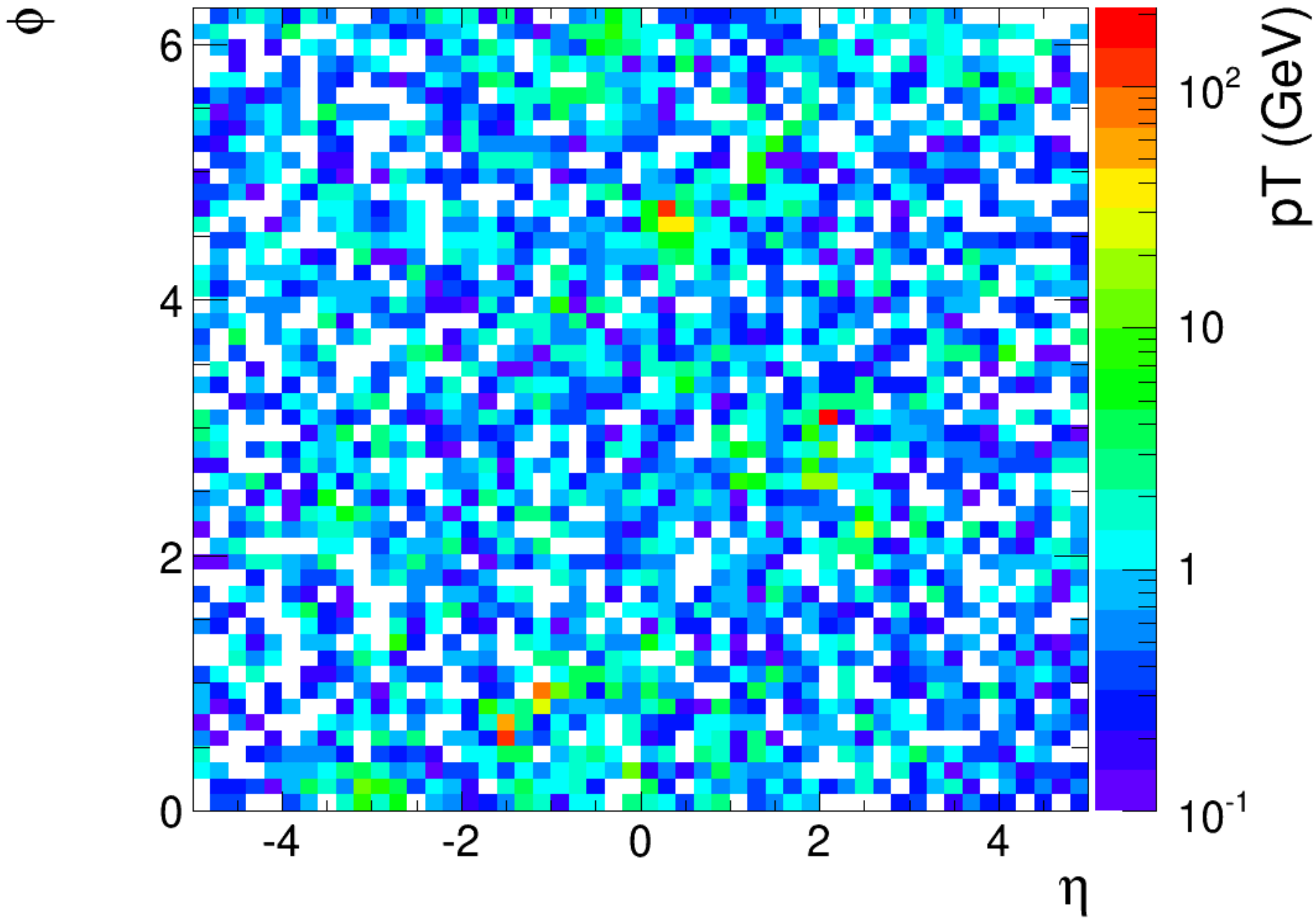
*Fast timing/Depth reconstruction can help




# Detector Surface



# We also have pileup



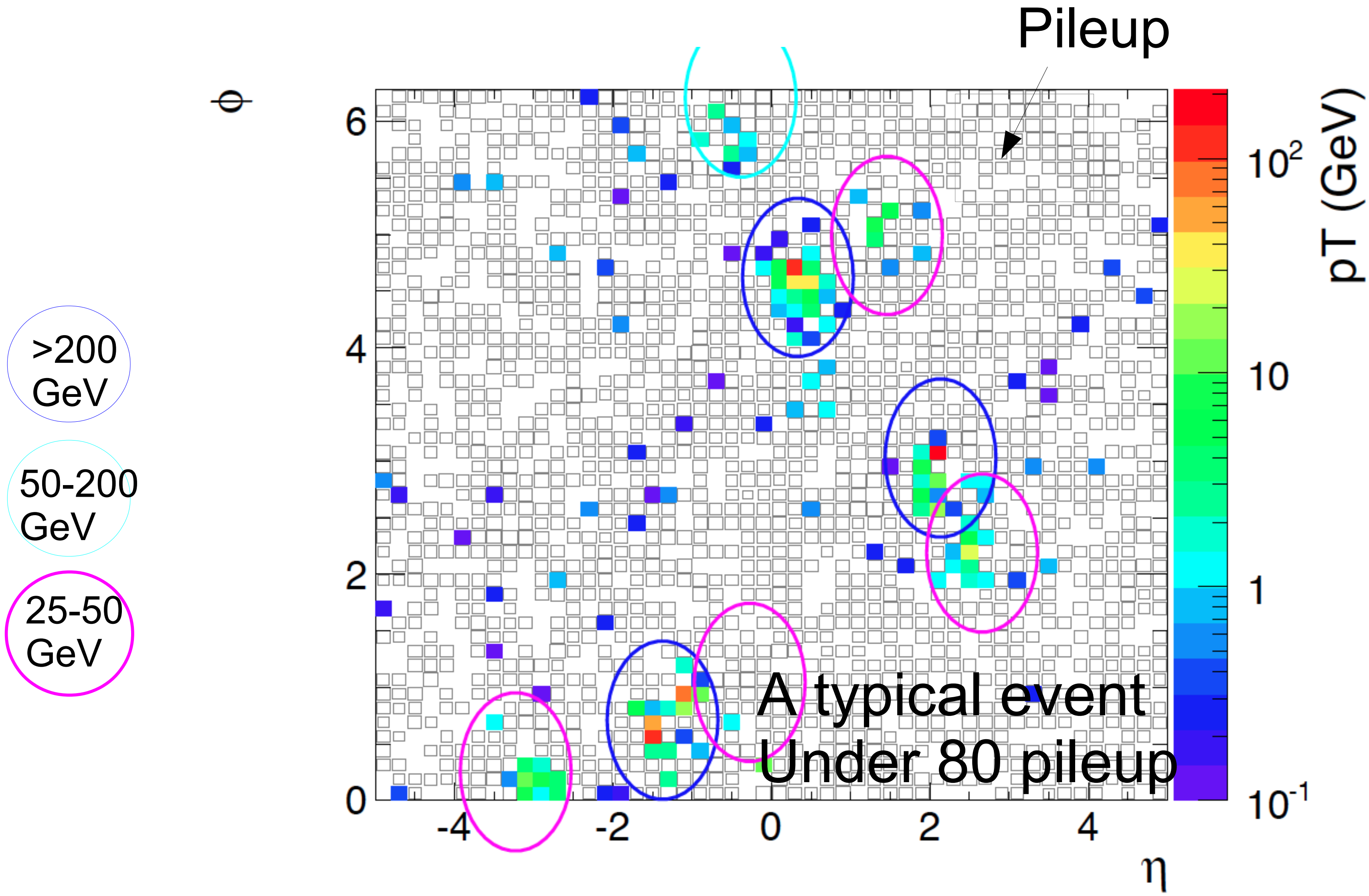

>200 GeV

50-200 GeV

25-50 GeV

# We also have pileup

- Filtering the interesting info



# We also have pileup

- Filtering the interesting info

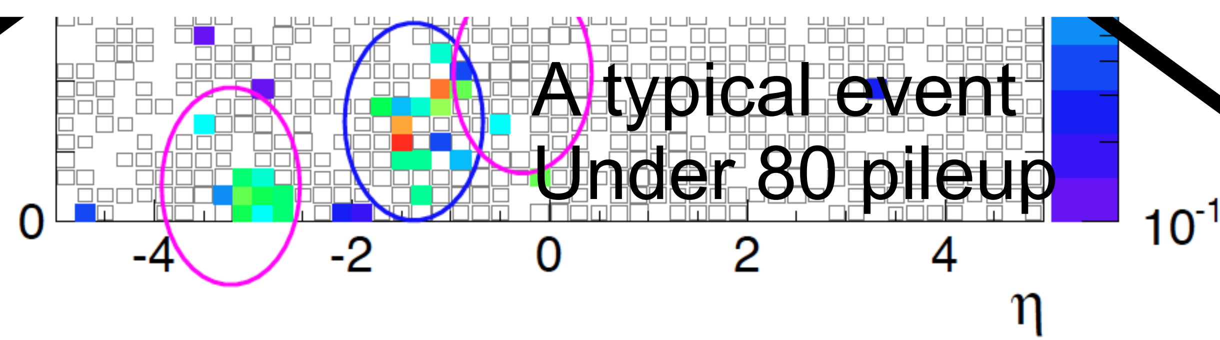
Pileup

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

>200 GeV

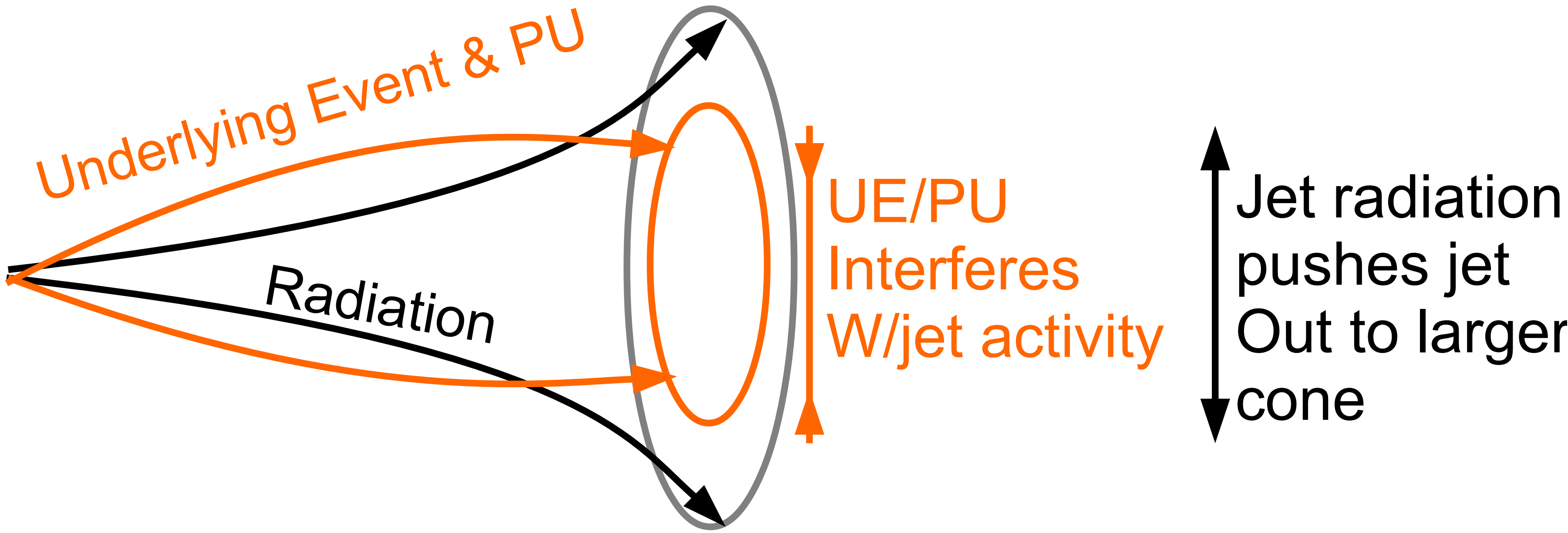
50-200 GeV

25-50 GeV



# Jet Energy Correction

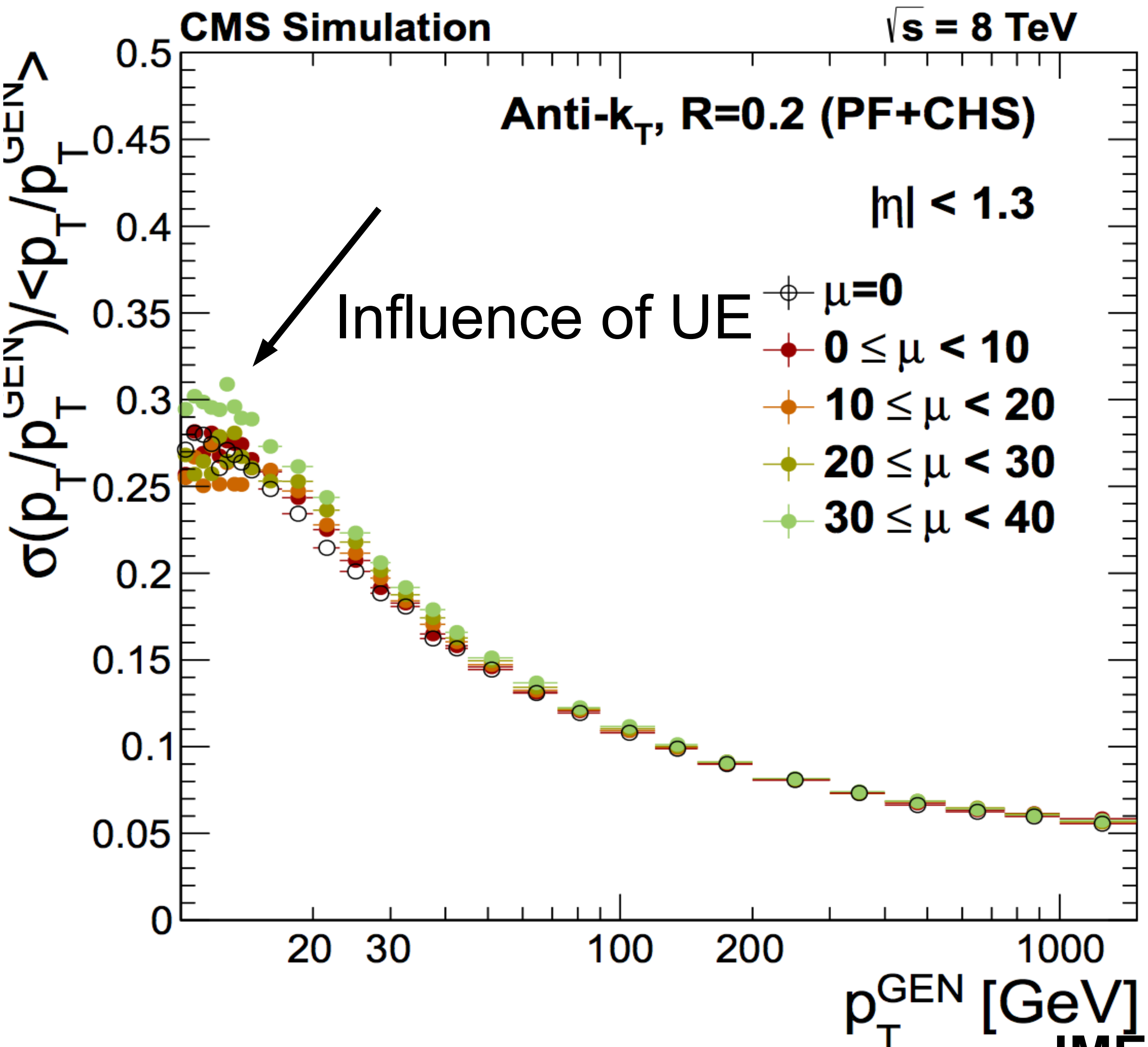
- Correcting to truth




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

# Jet Energy Correction

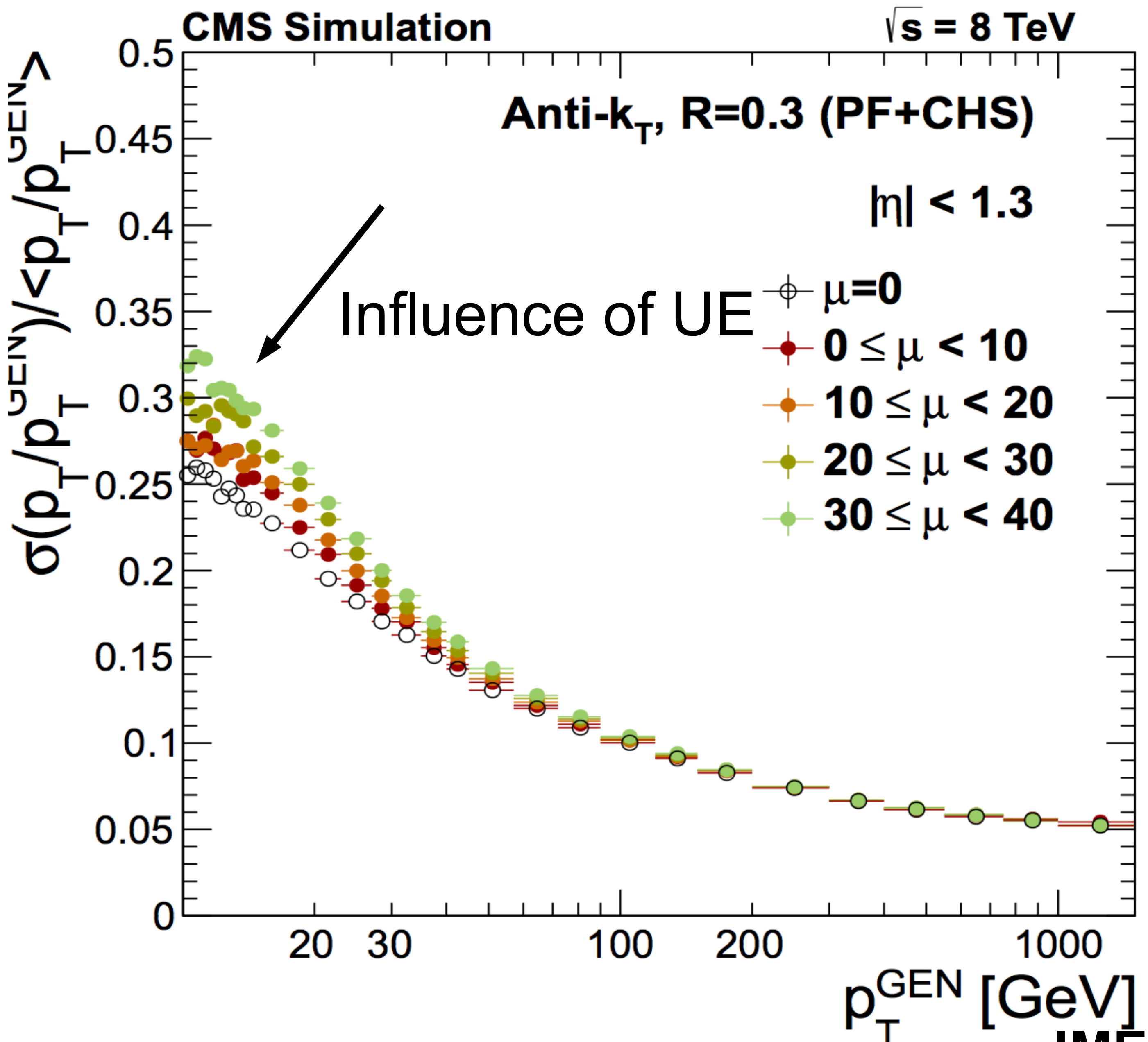
- AK2




JME-DP-14/037

# Jet Energy Correction

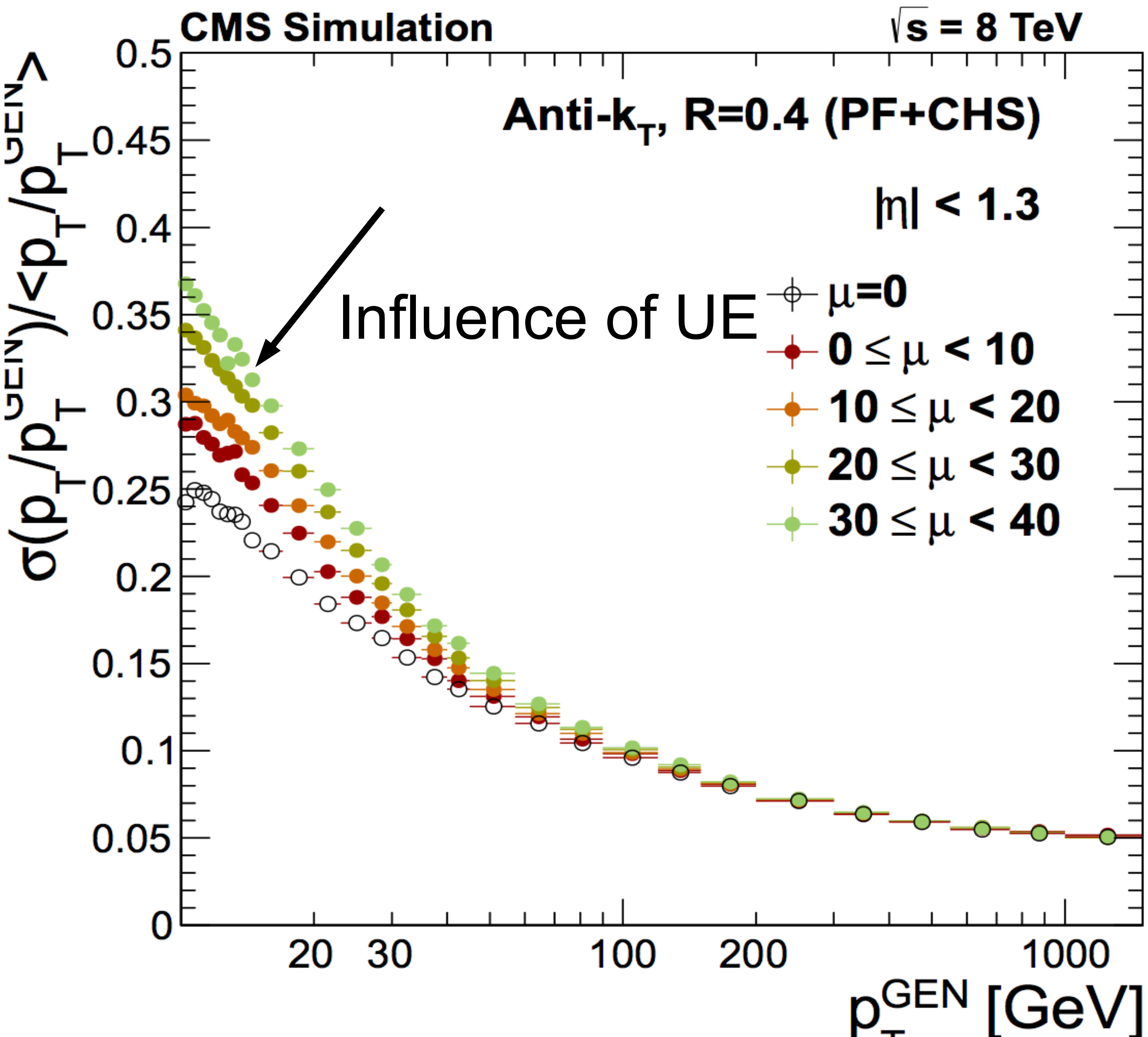
- AK3




JME-DP-14/037

# Jet Energy Correction

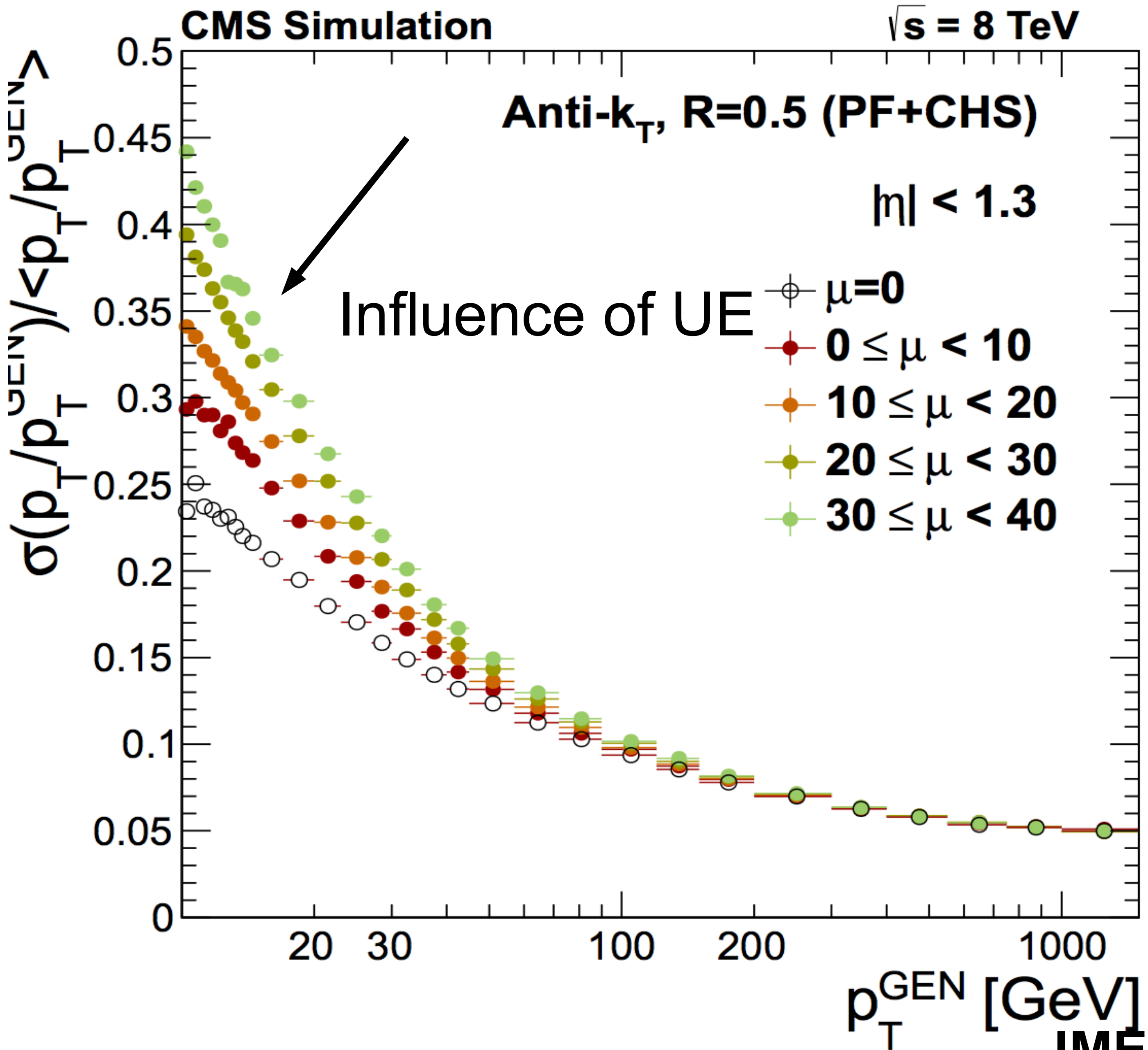
- AK4




JME-DP-14/037

# Jet Energy Correction

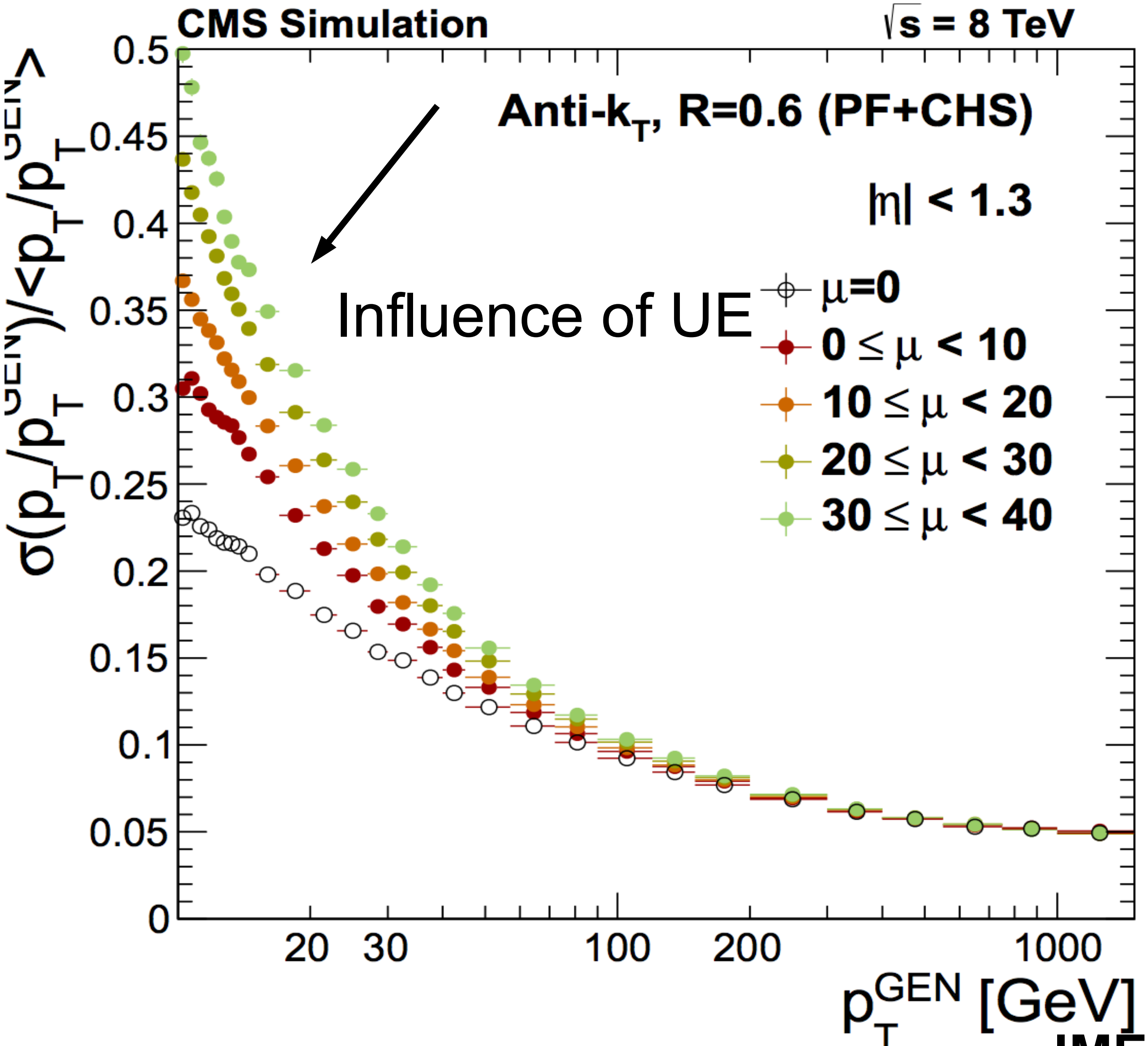
- AK5




JME-DP-14/037

# Jet Energy Correction

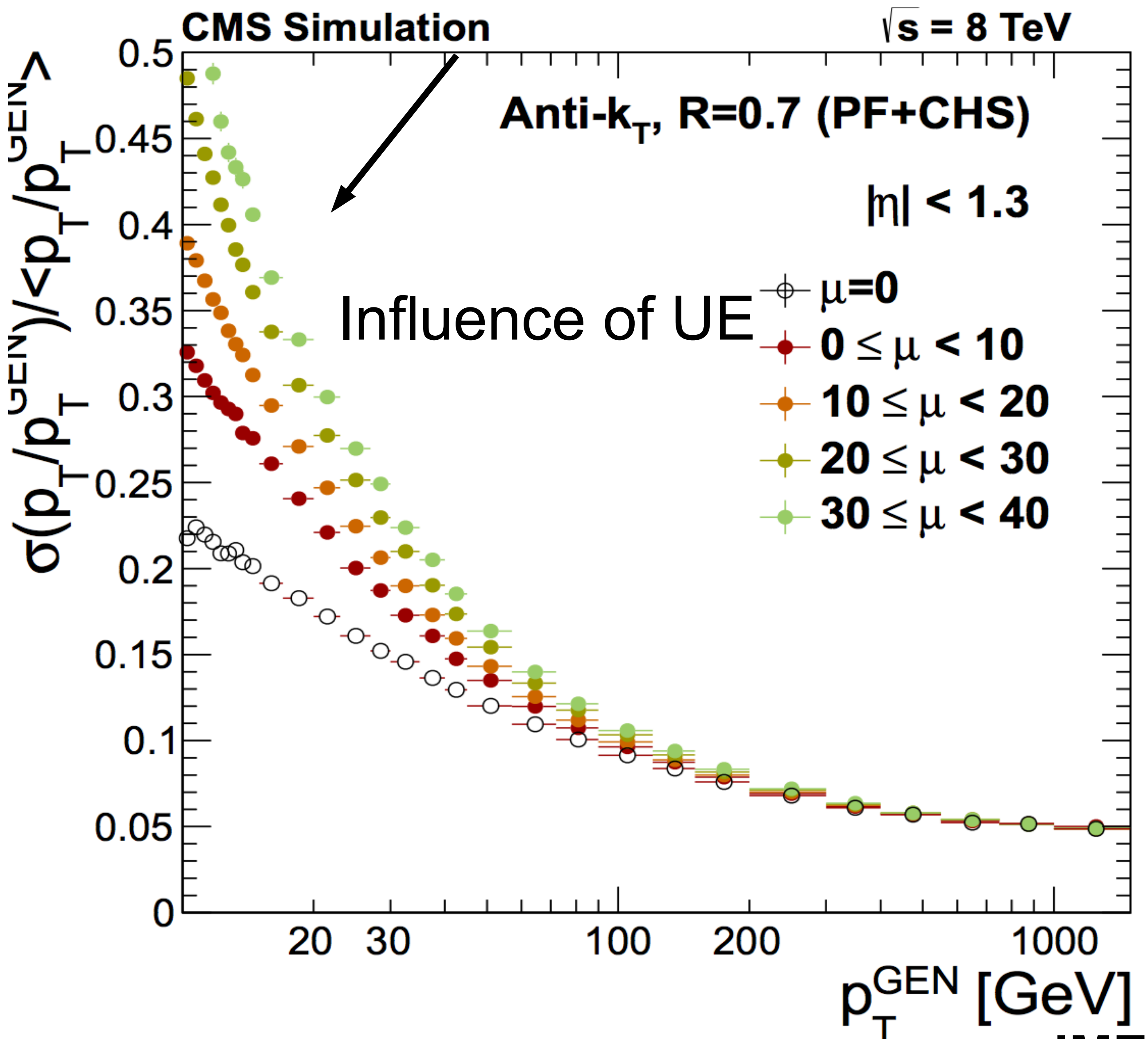
- AK6




JME-DP-14/037

# Jet Energy Correction

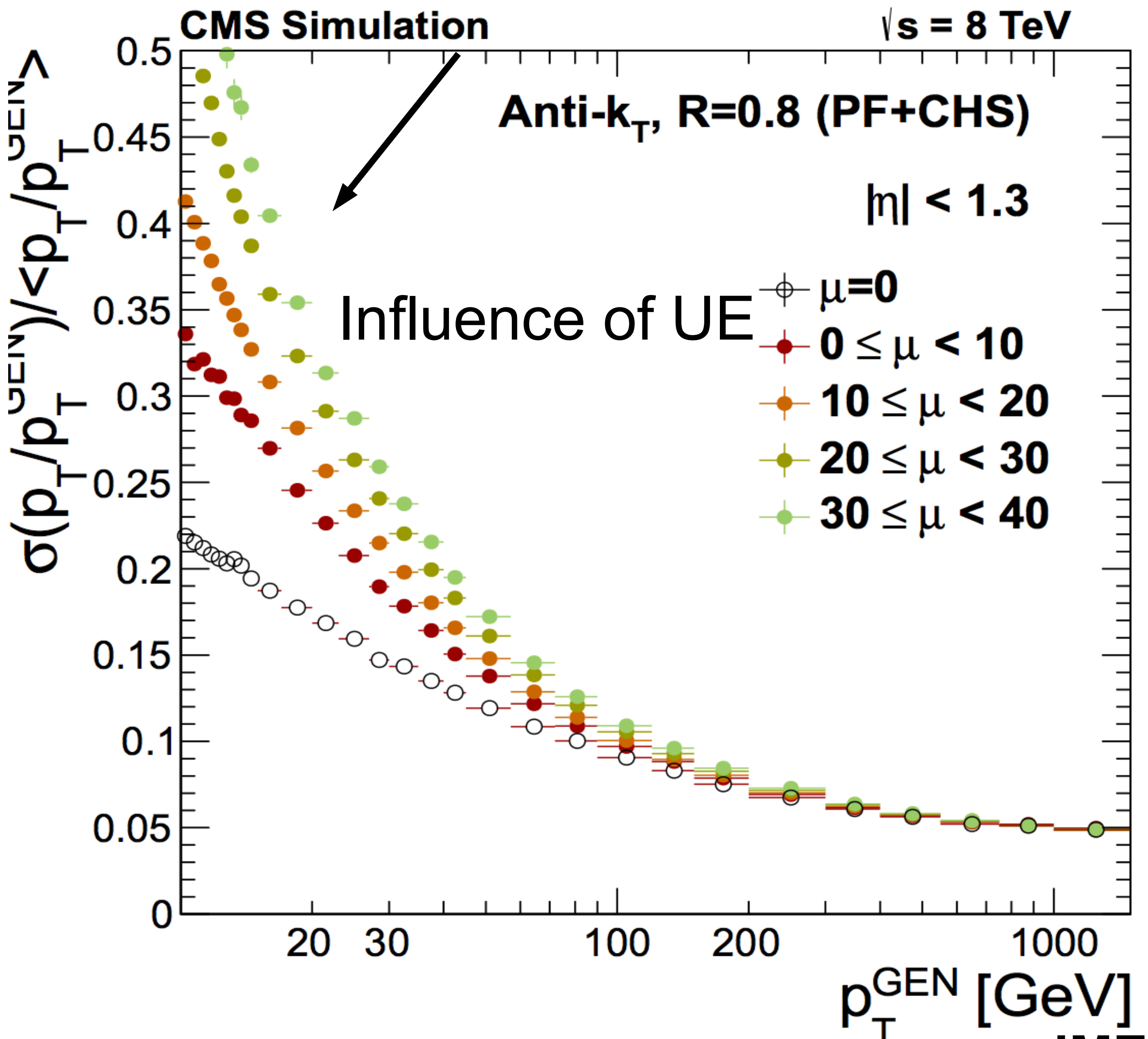
- AK7




JME-DP-14/037

# Jet Energy Correction

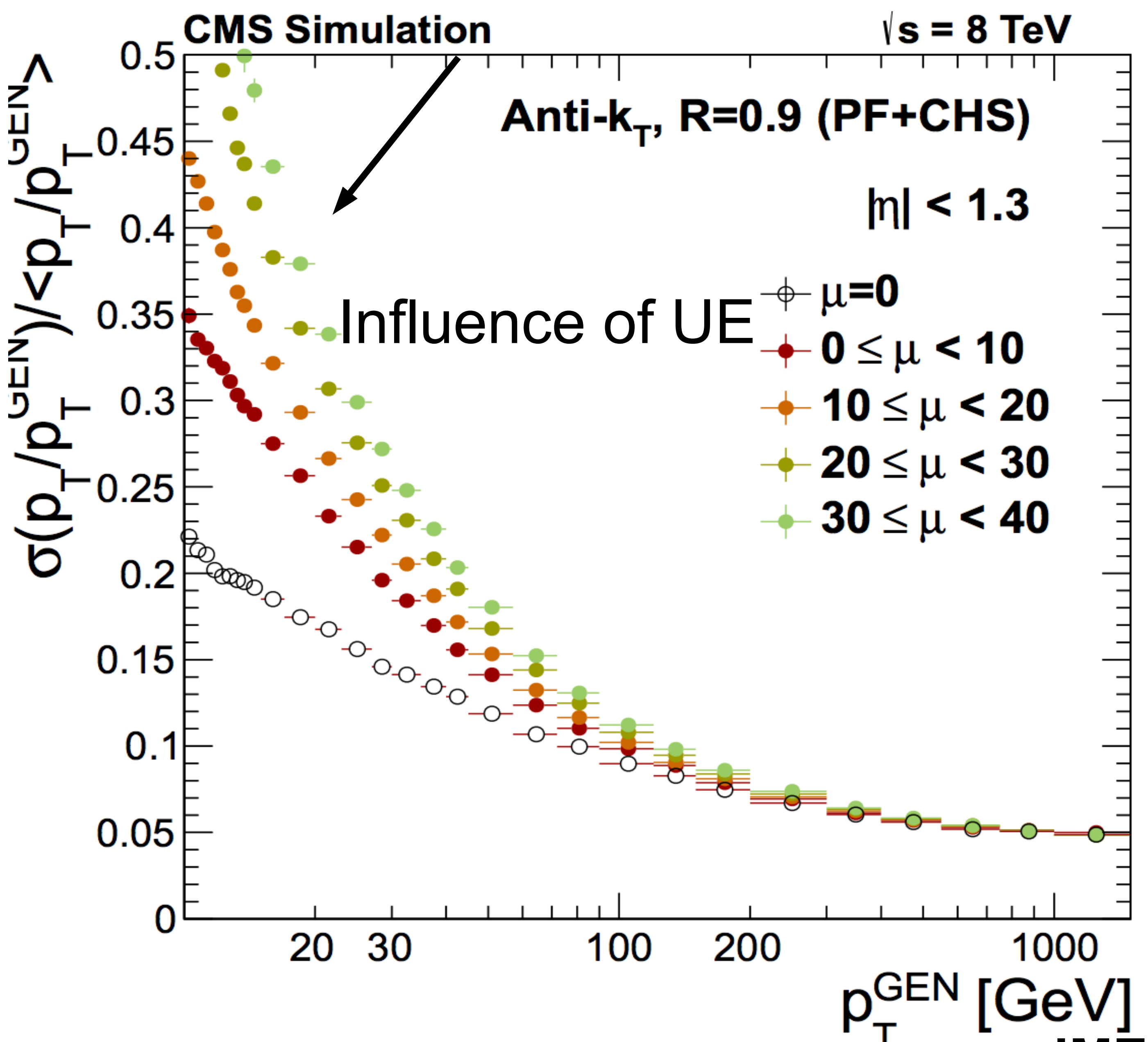
- AK8




JME-DP-14/037

# Jet Energy Correction

- AK9

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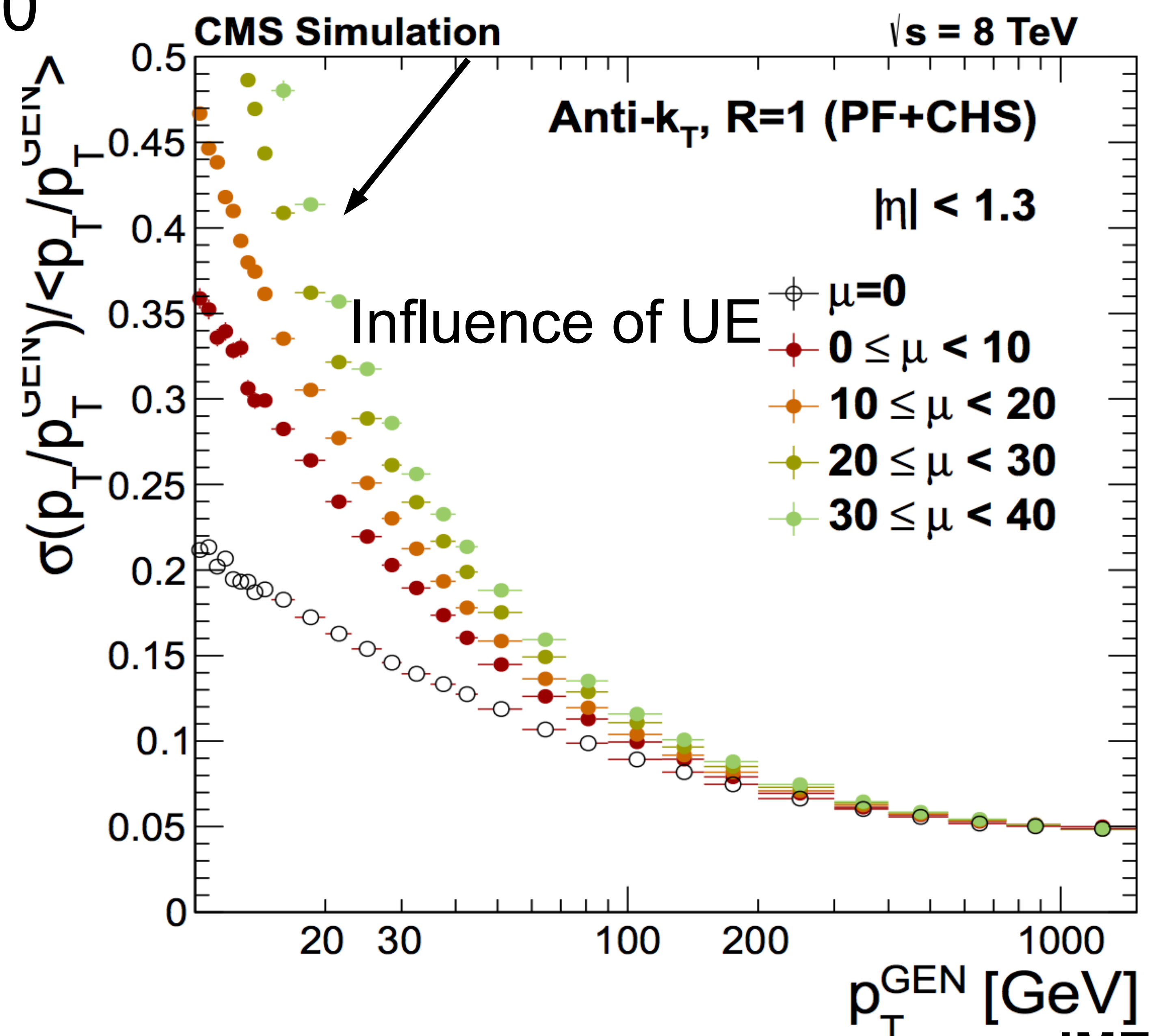
# Jet Energy Correction

- AK1.0




JME-DP-14/037

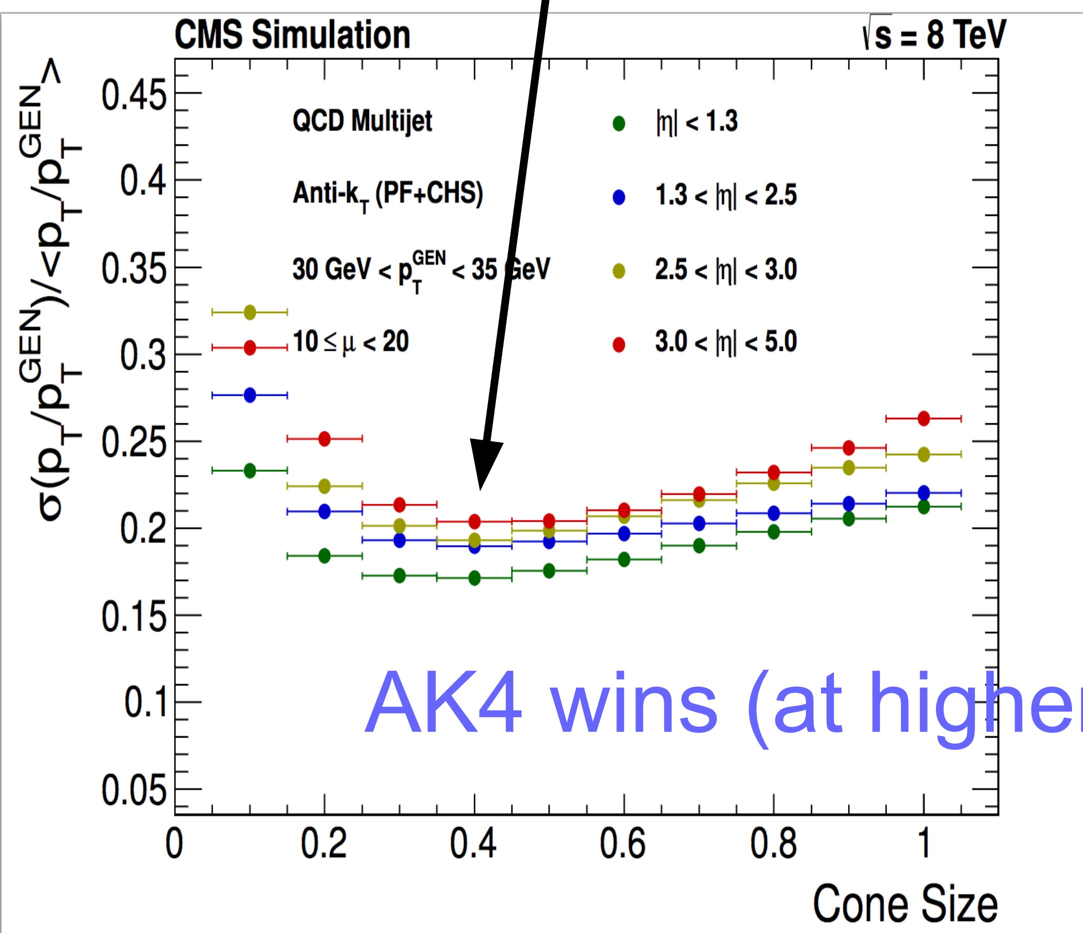
# Jet Energy Correction

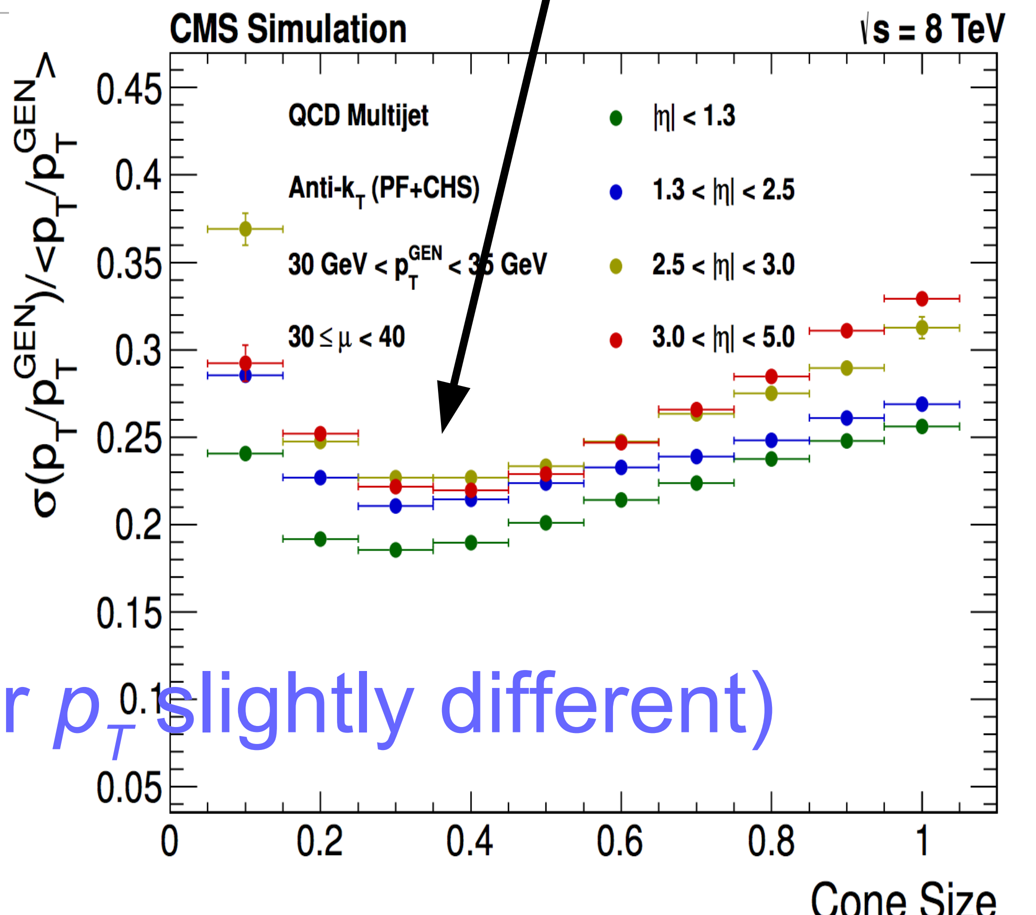
- Executive Summary :

We switch to AK4

Run I PU

Run II PU




AK4 wins (at higher $p_T$ slightly different)

**JME-DP-14/037**

# Jet Energy Correction

- Executive Summary :

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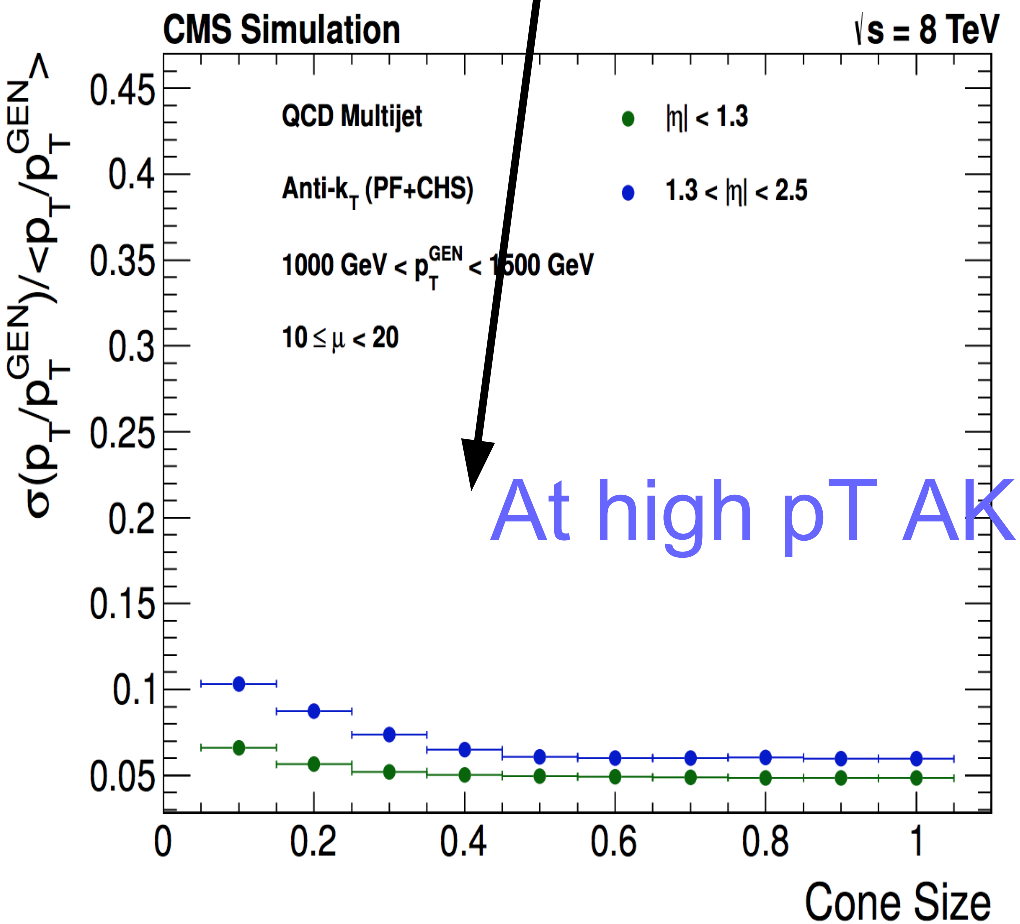
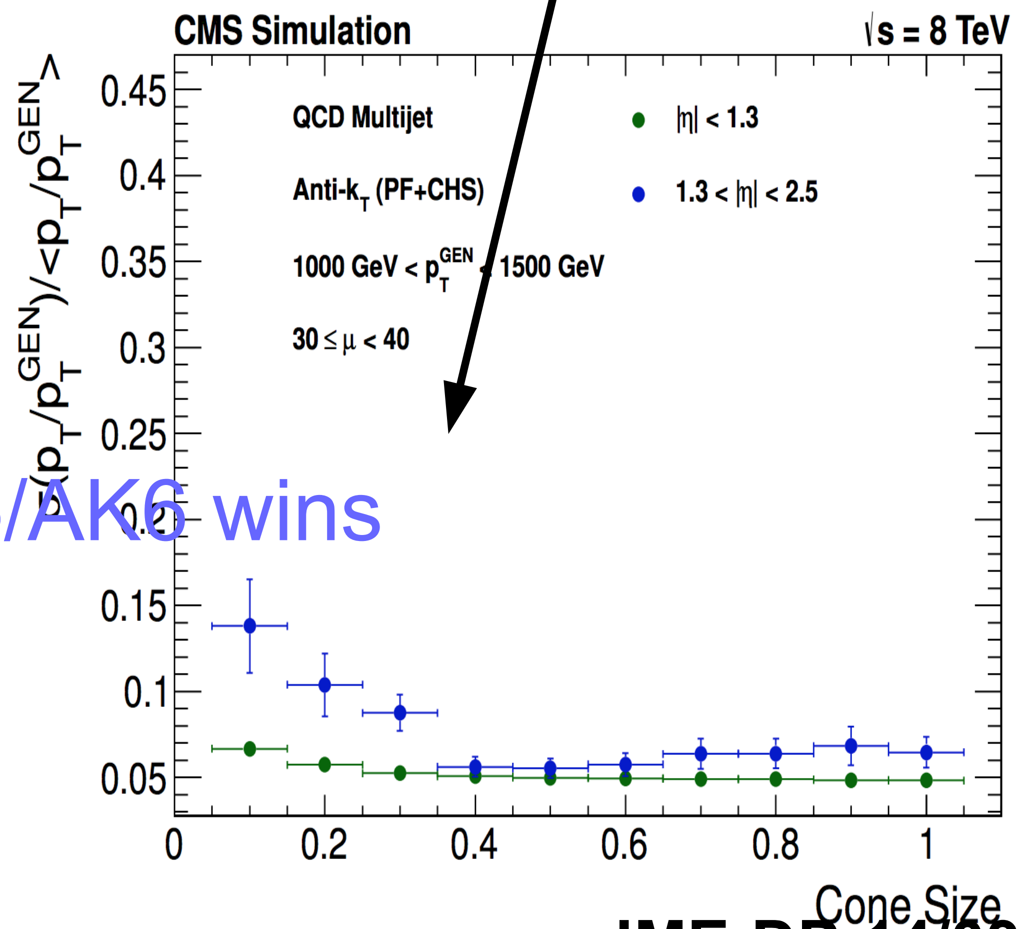
Run II PU




At high pT AK5/AK6 wins

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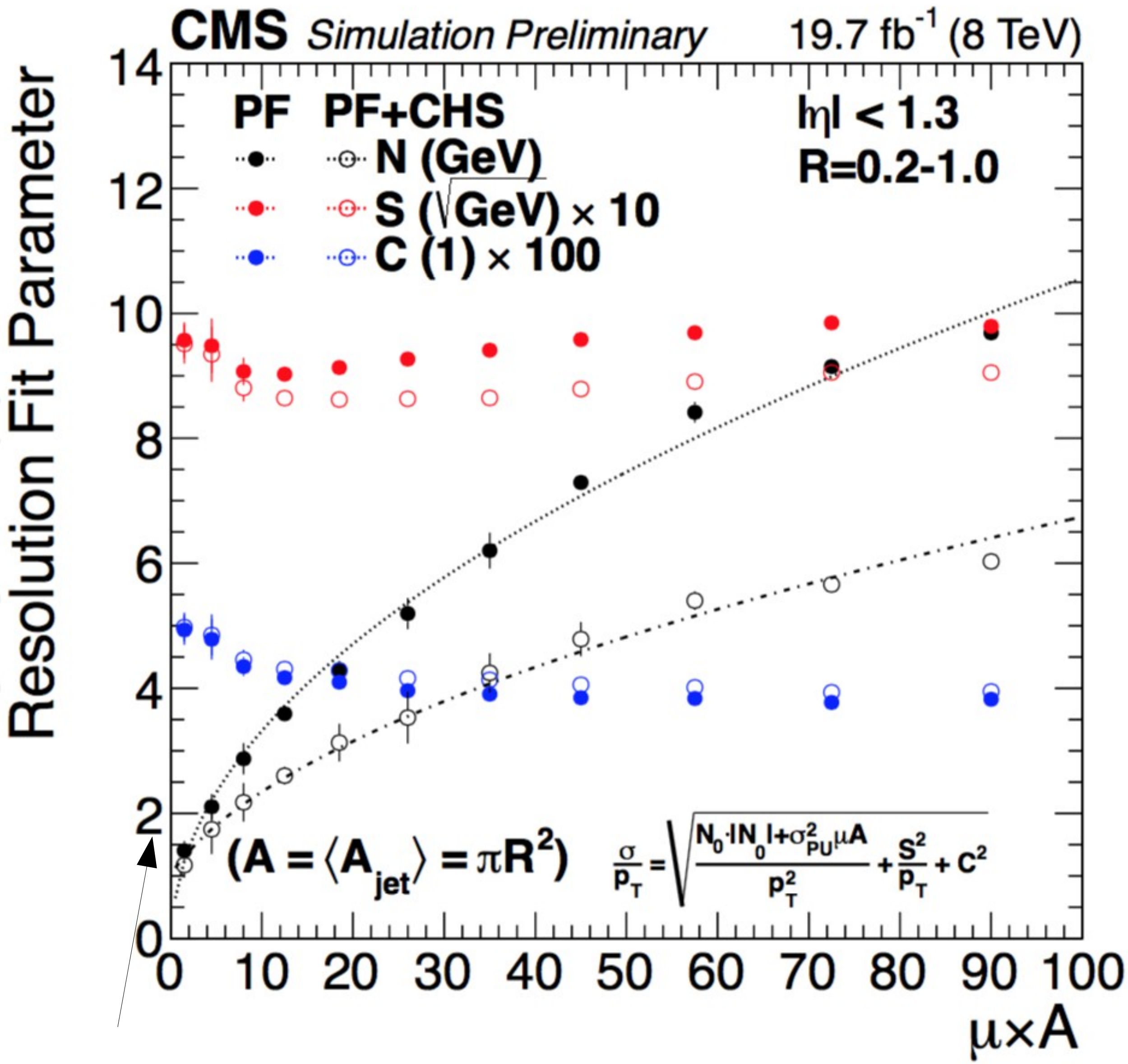
# Stability of our detector

- Using all the jet cones allows plots like this:



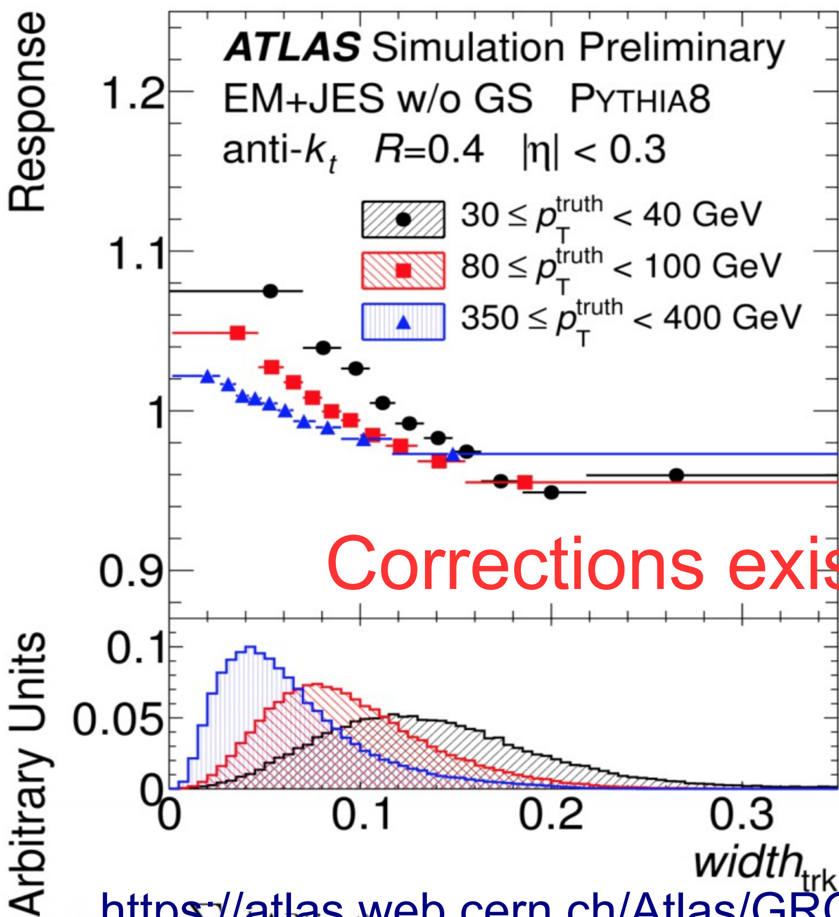

Generically ATLAS doesn't have this scaling

**JME-DP-14/037**

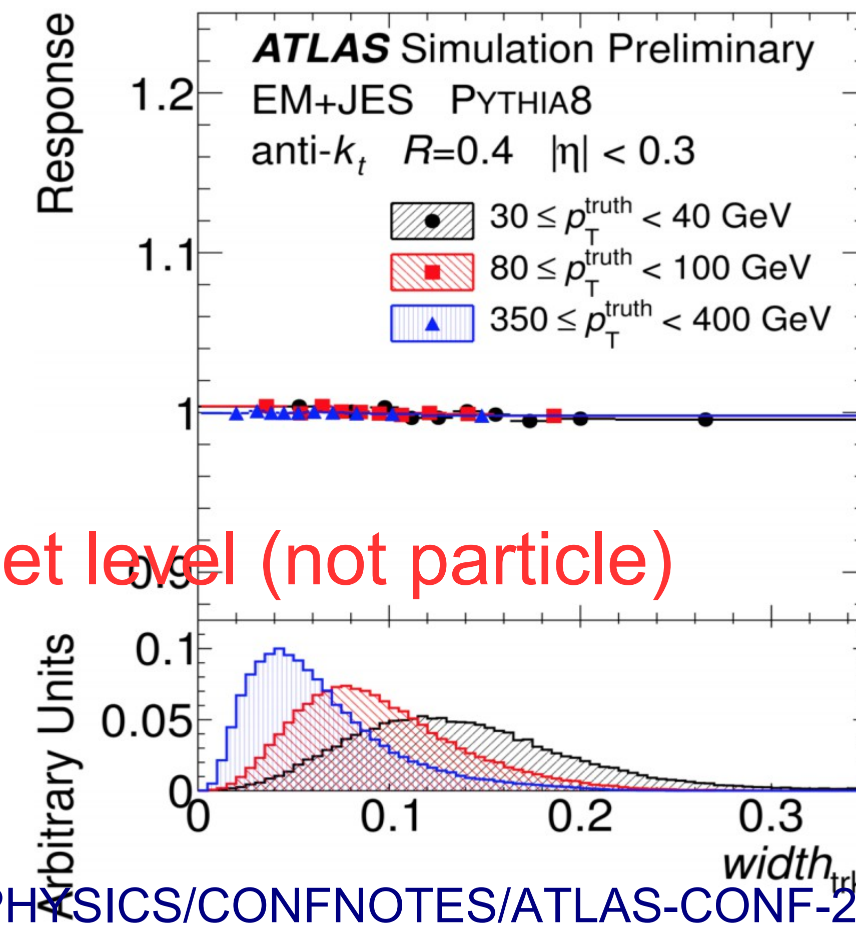
# Improvements form ATLAS

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

Before GSC



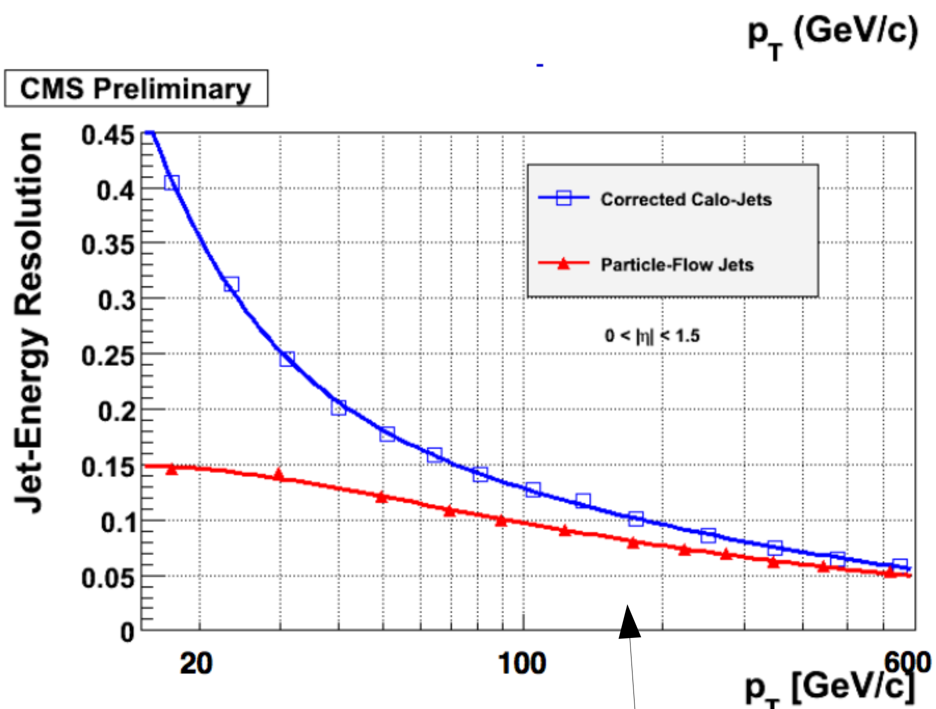

After GSC

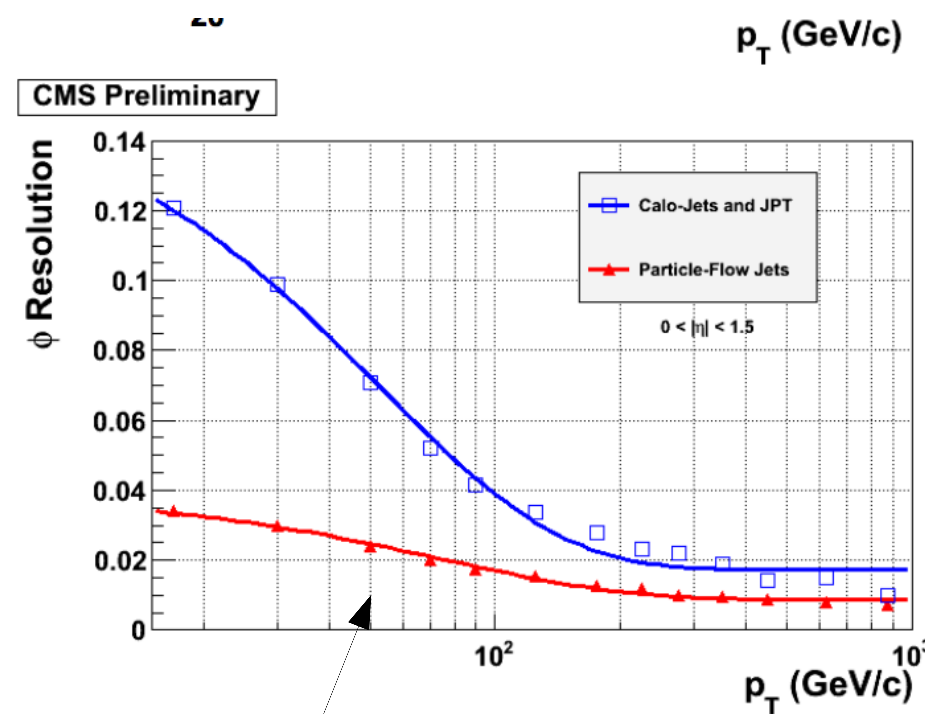



Corrections exist at jet level (not particle)

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

# Visualizing the PF impact

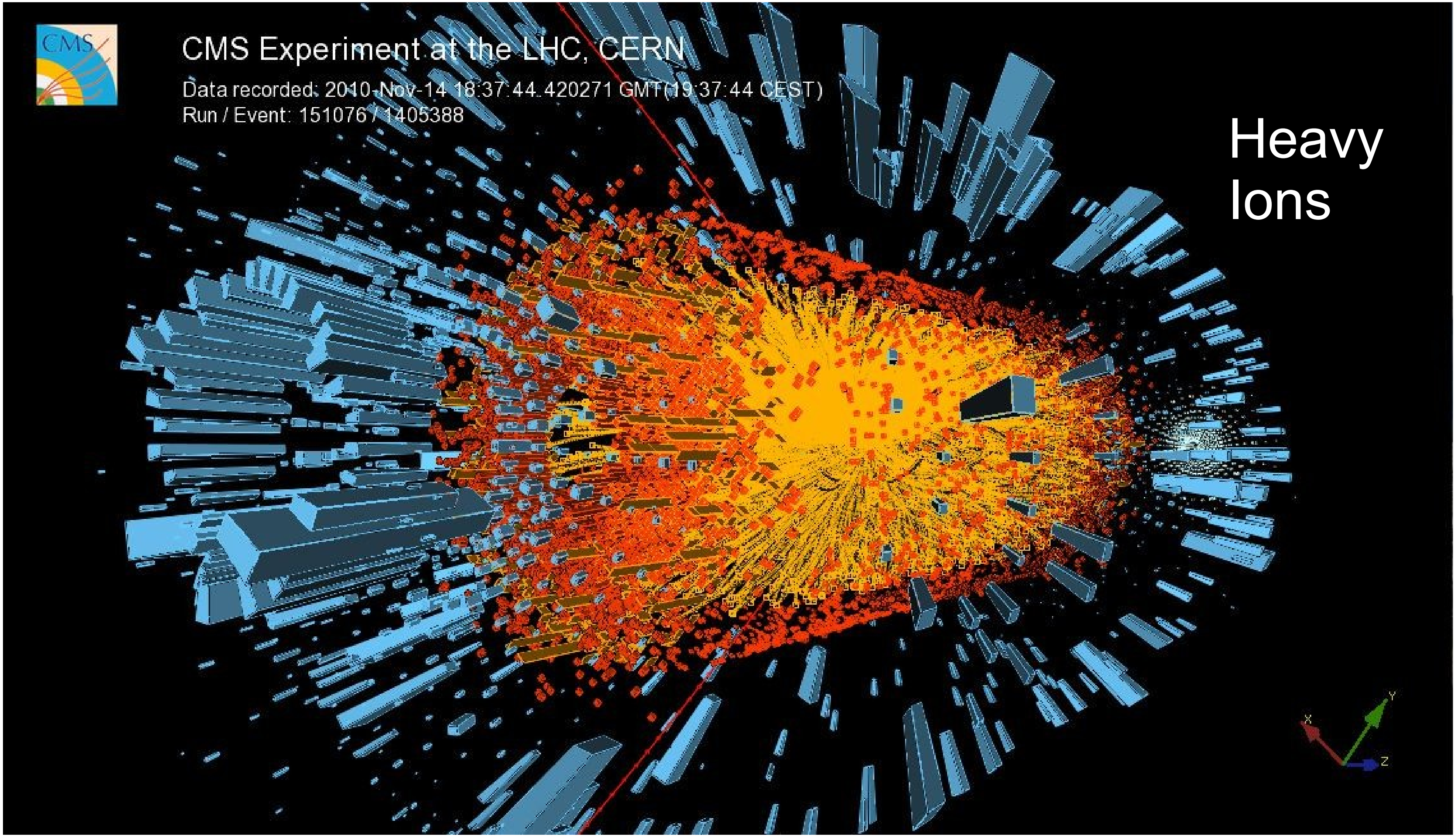



Angular information from the tracks improves the resolution of the jet shape internals

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

# Dense Environment

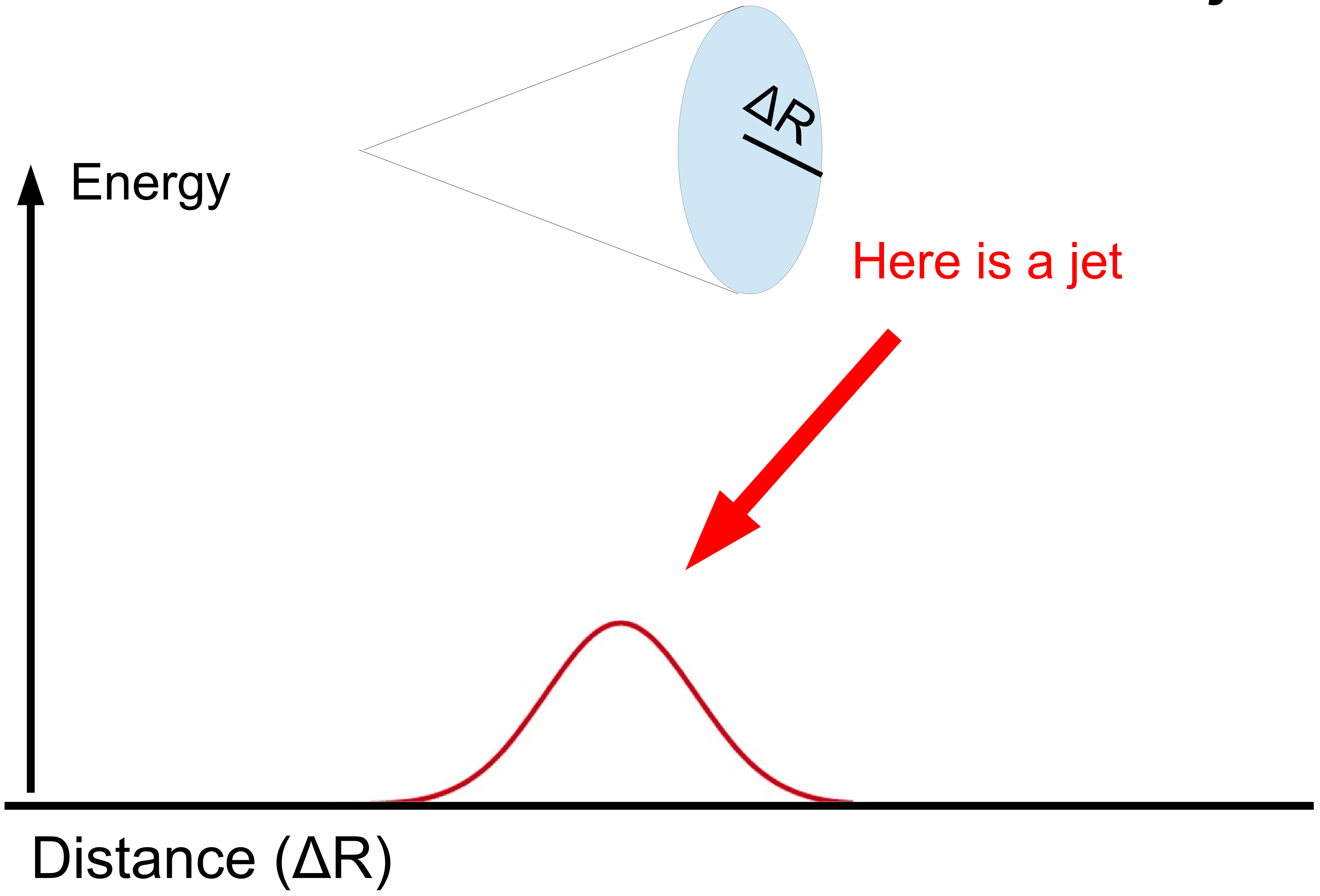


# Dealing w/~~PU~~ UE:

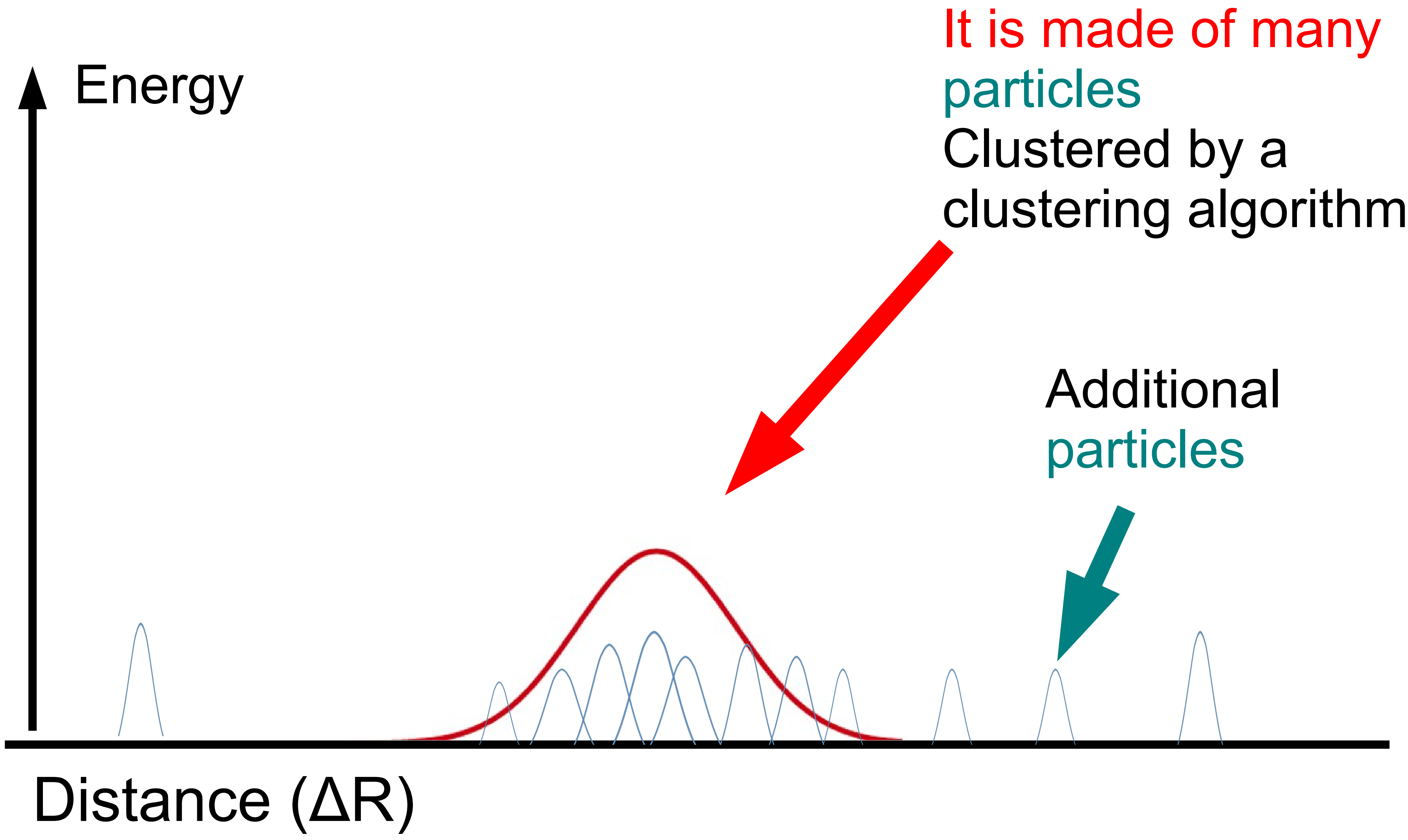
Key questions :

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

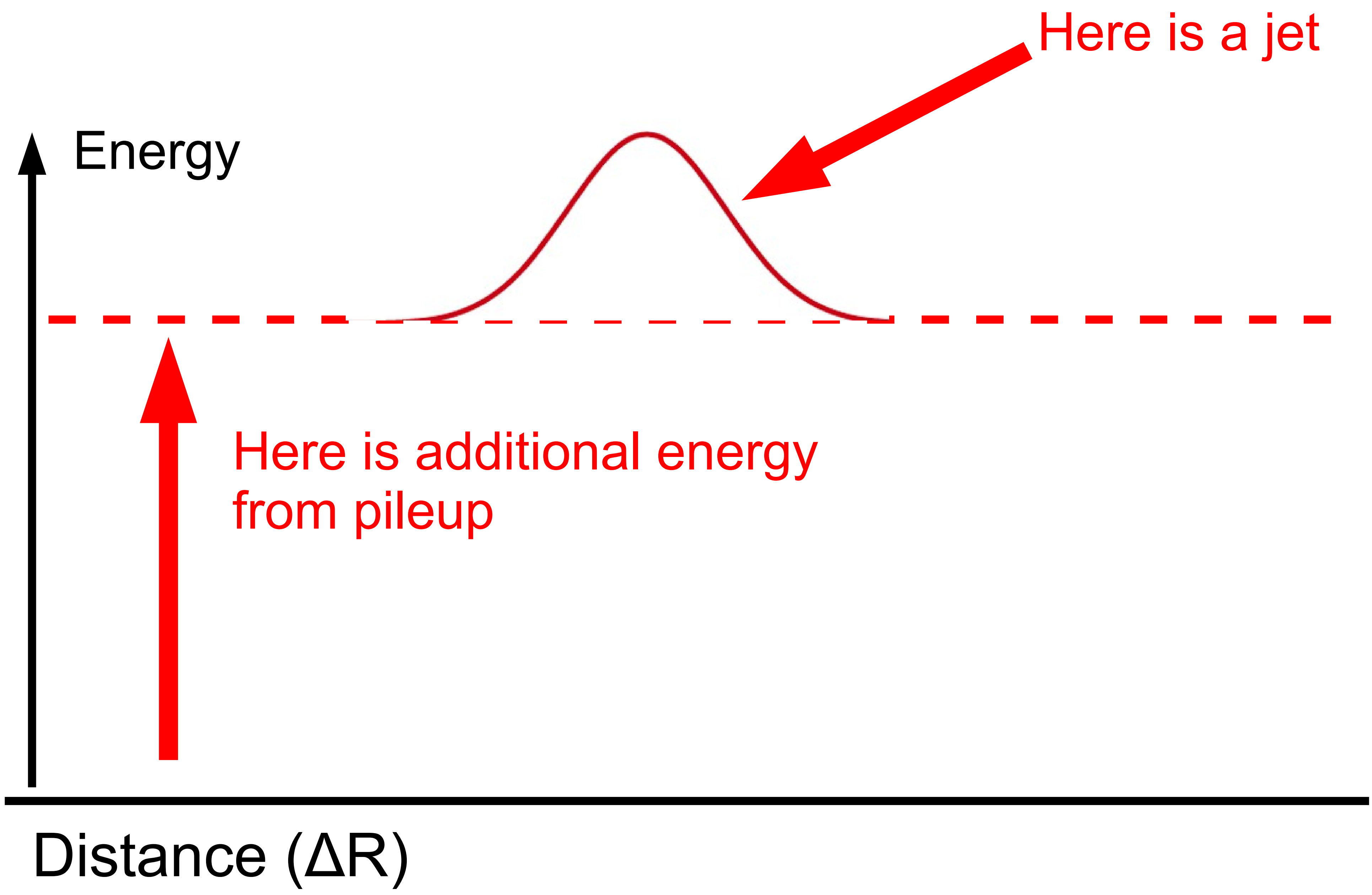
# Consider a jet



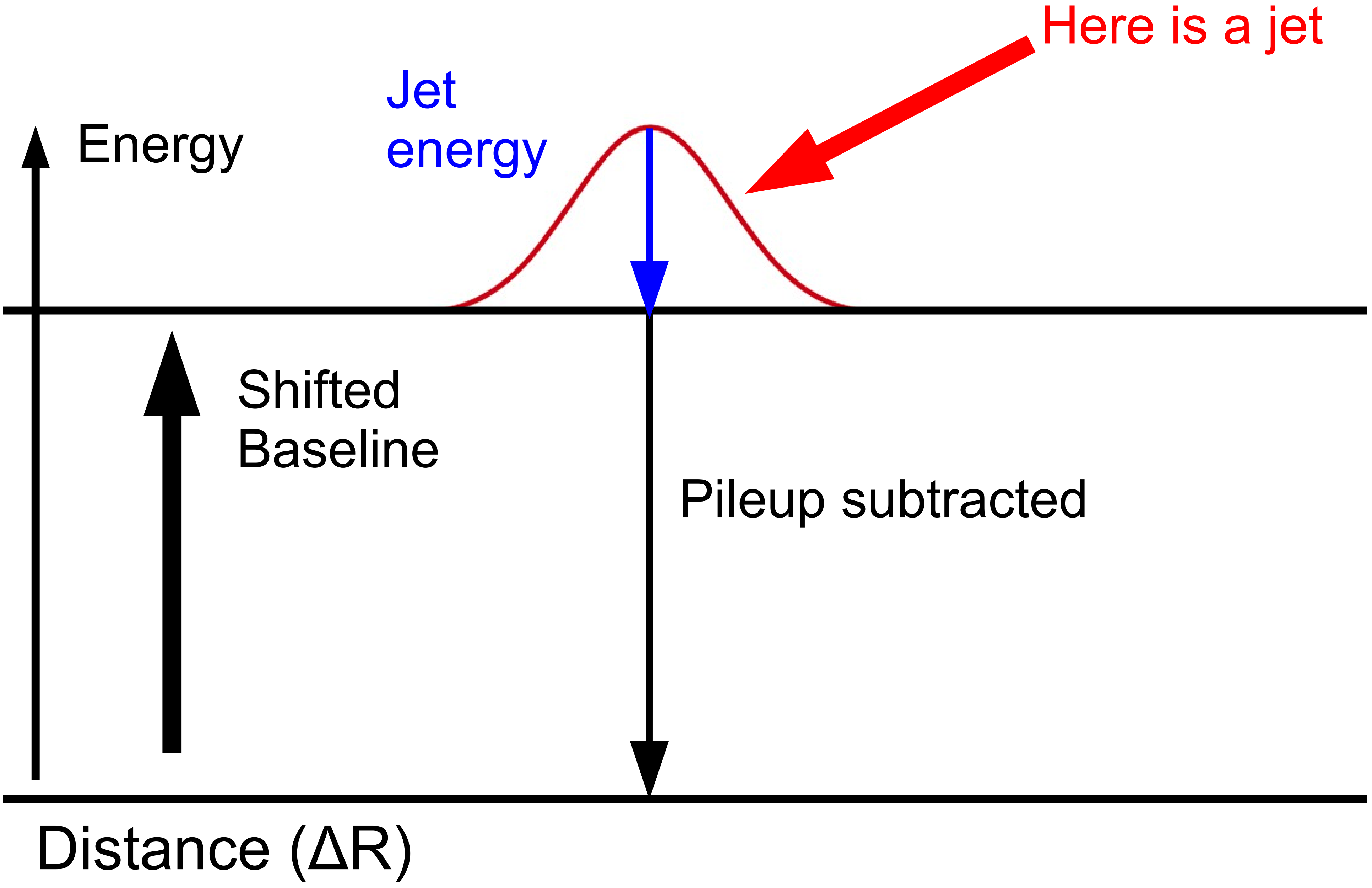
# Consider a jet



# Consider a jet in high pileup

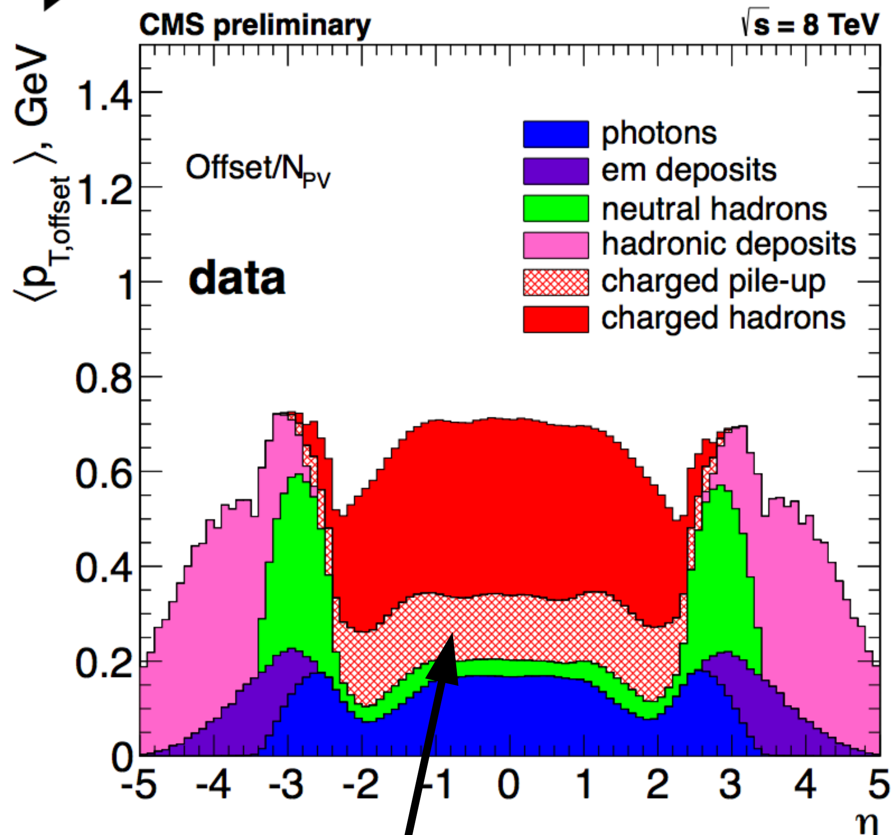


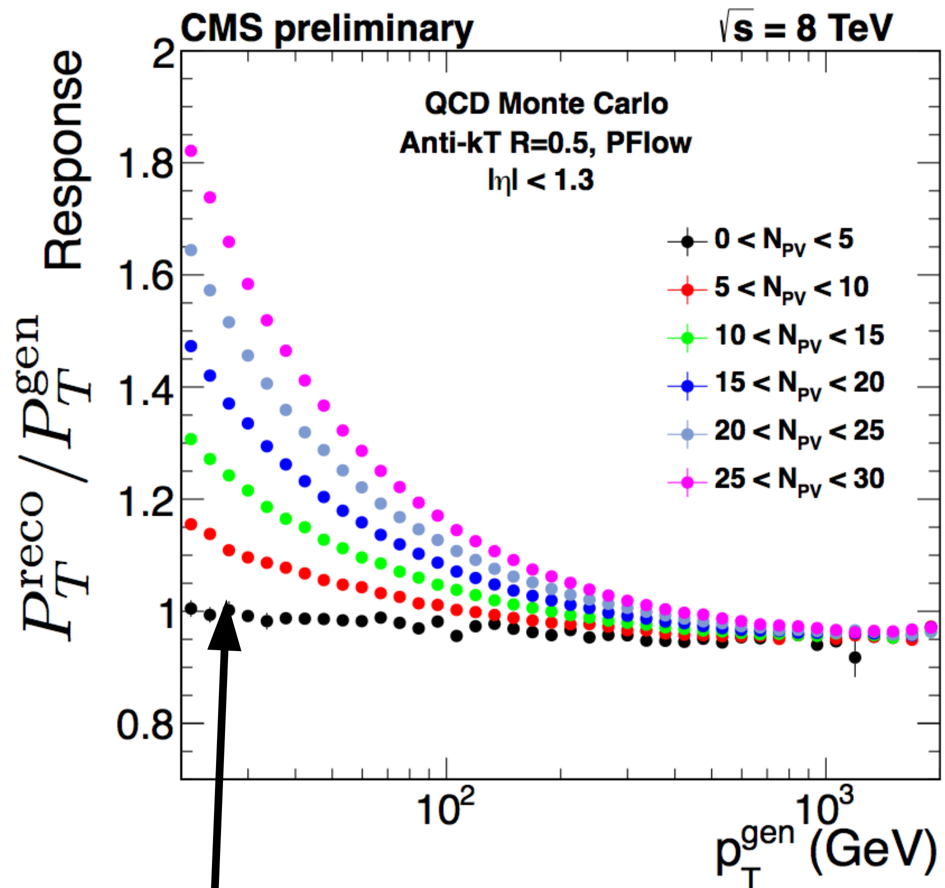
# Consider a jet in high pileup



# Pileup removal in action

PT offset / unit area / # of vertices

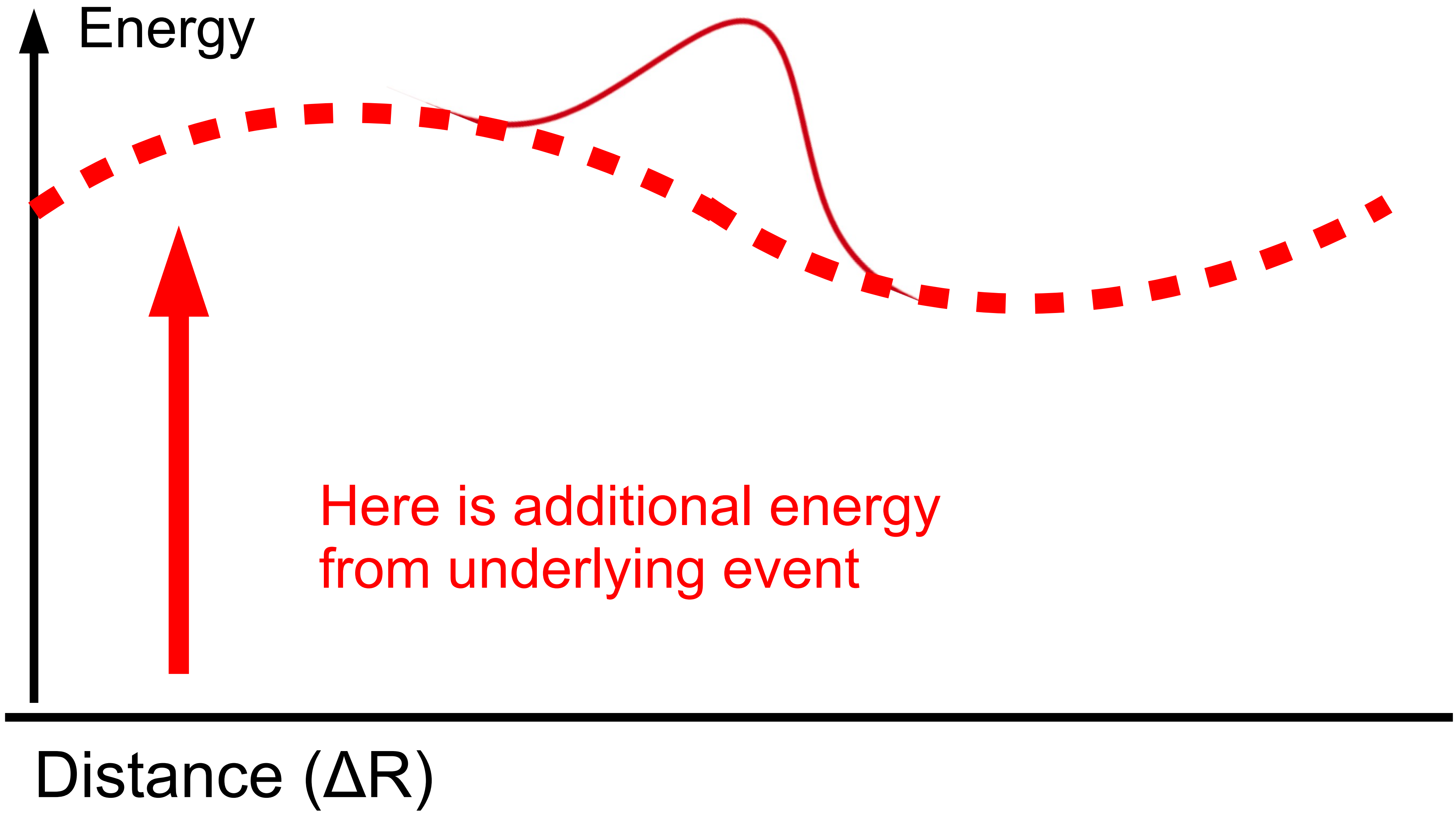


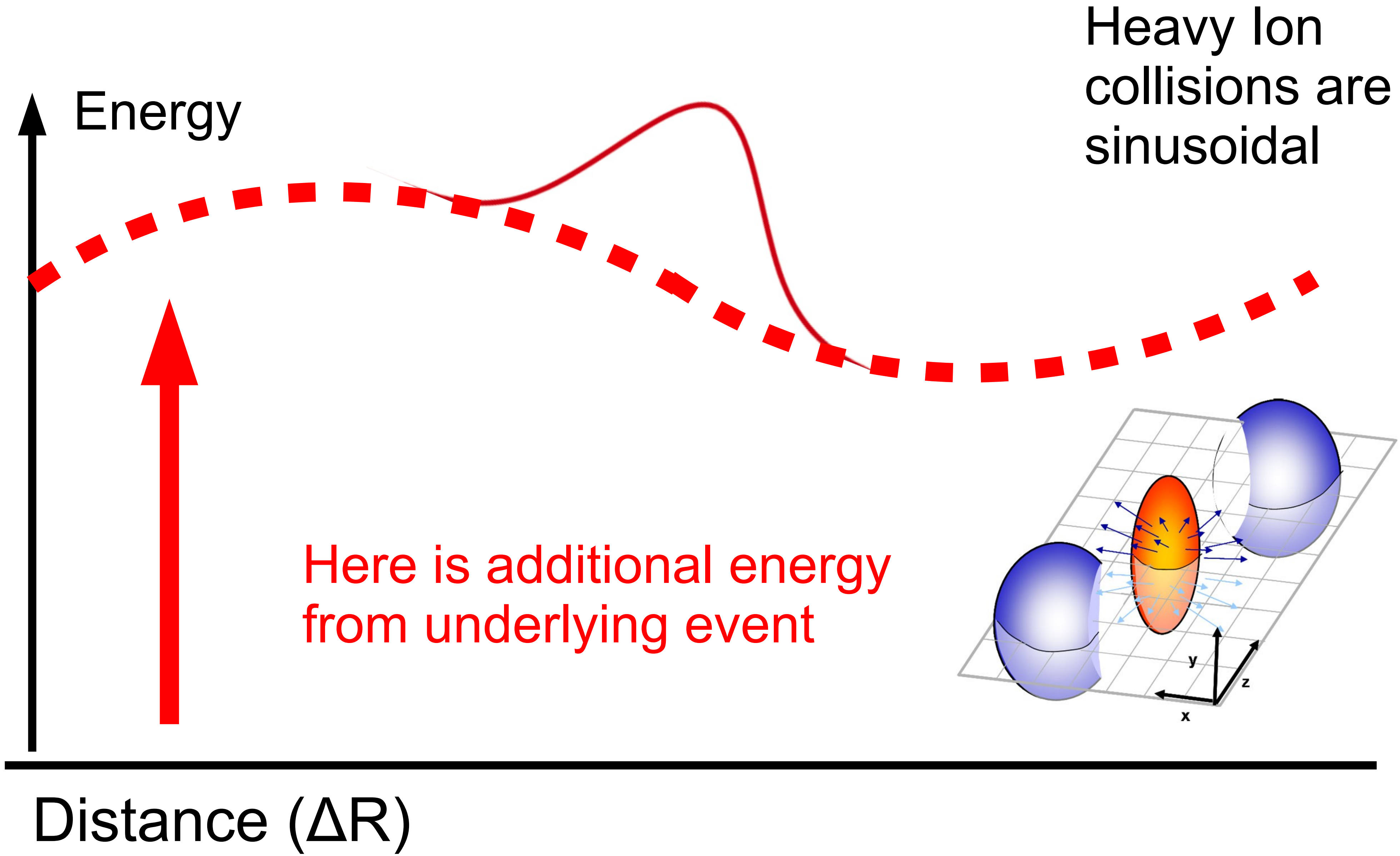

Average subtraction/Pileup

Change in response post subtraction

# Consider a jet in Heavy Ions

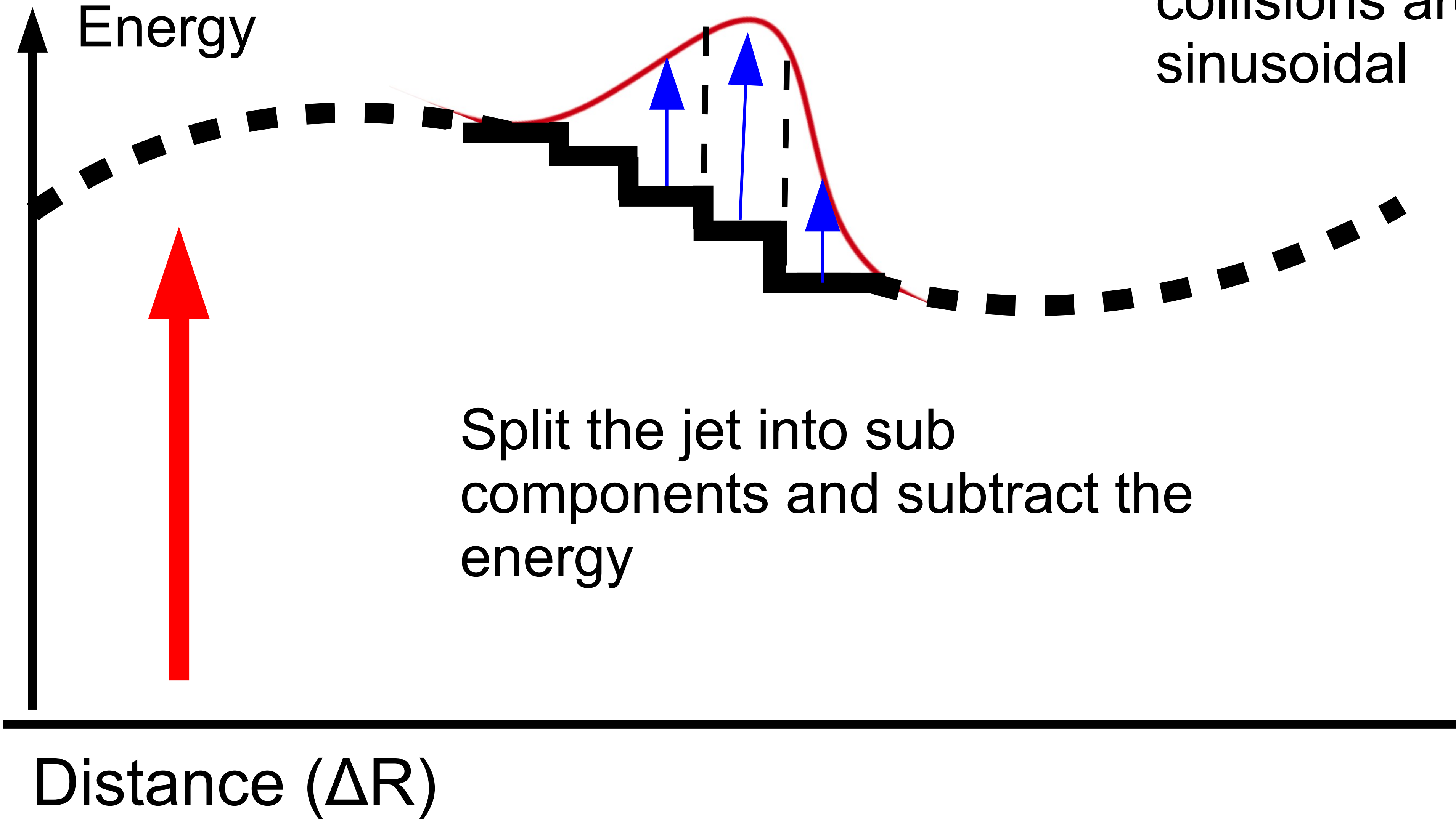


# Consider a jet in Heavy Ions



# Consider a jet in Heavy Ions

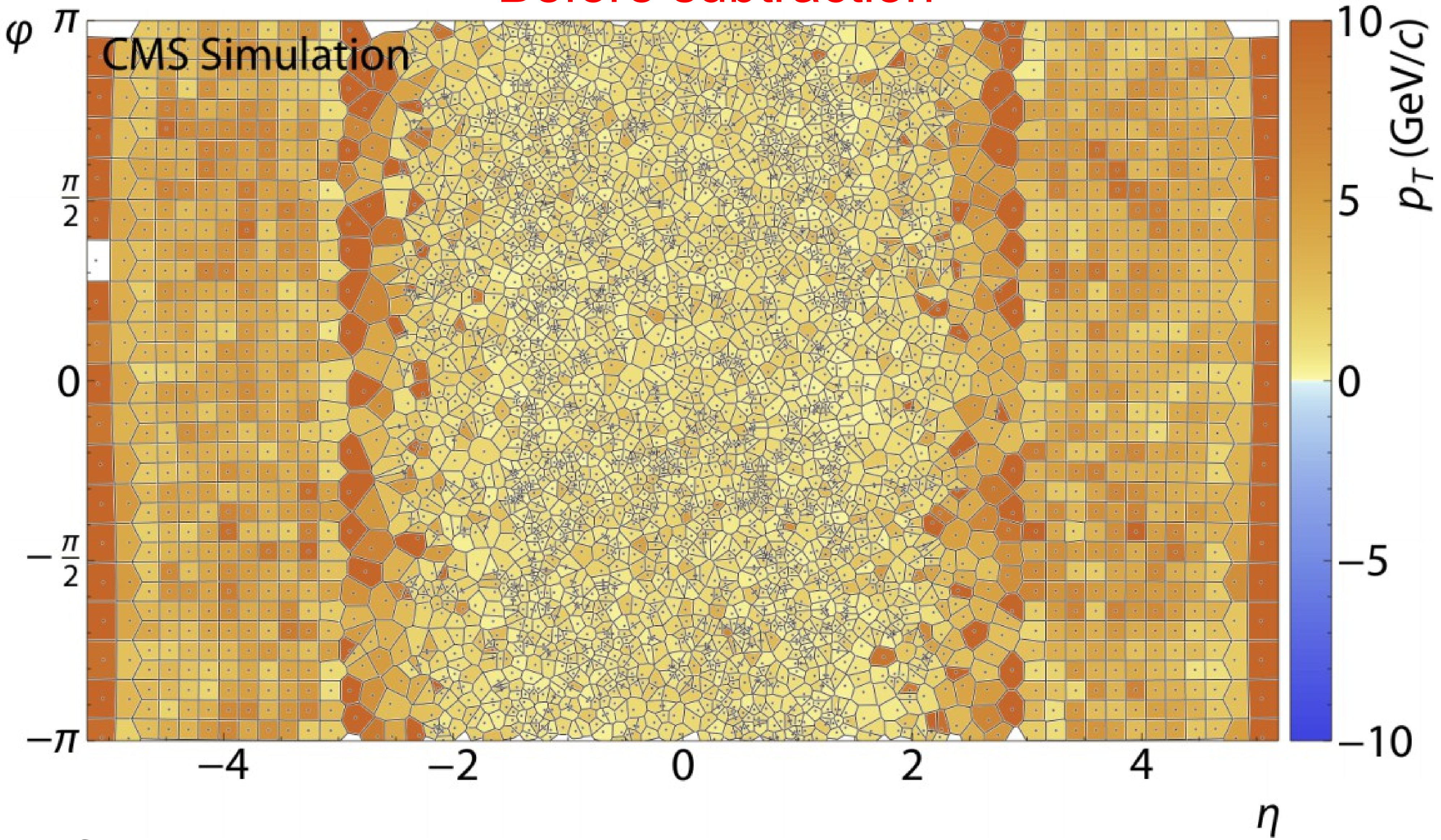
Heavy Ion collisions are sinusoidal




Split the jet into sub components and subtract the energy

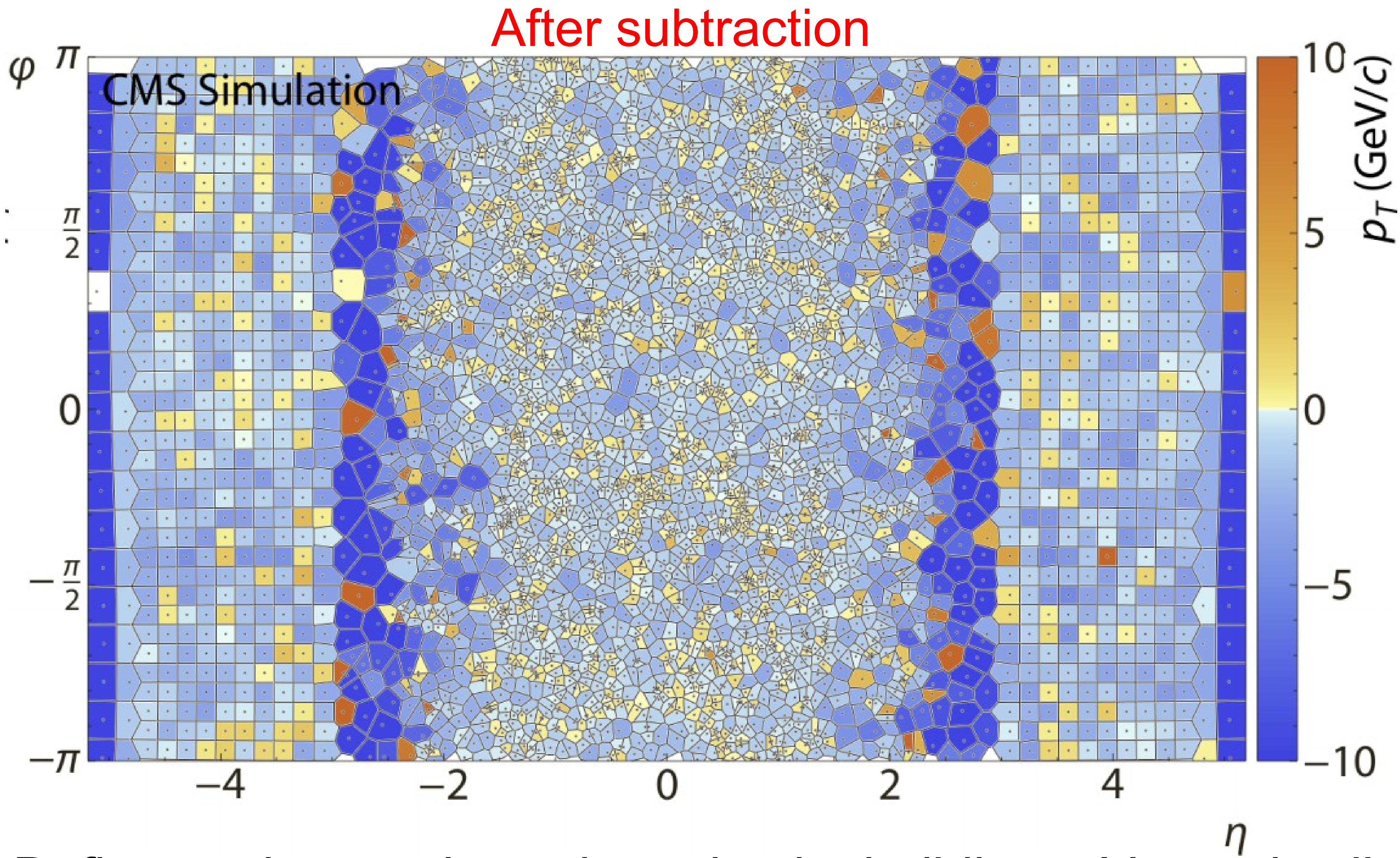
# Led to HF/Voronoi Method

Before subtraction



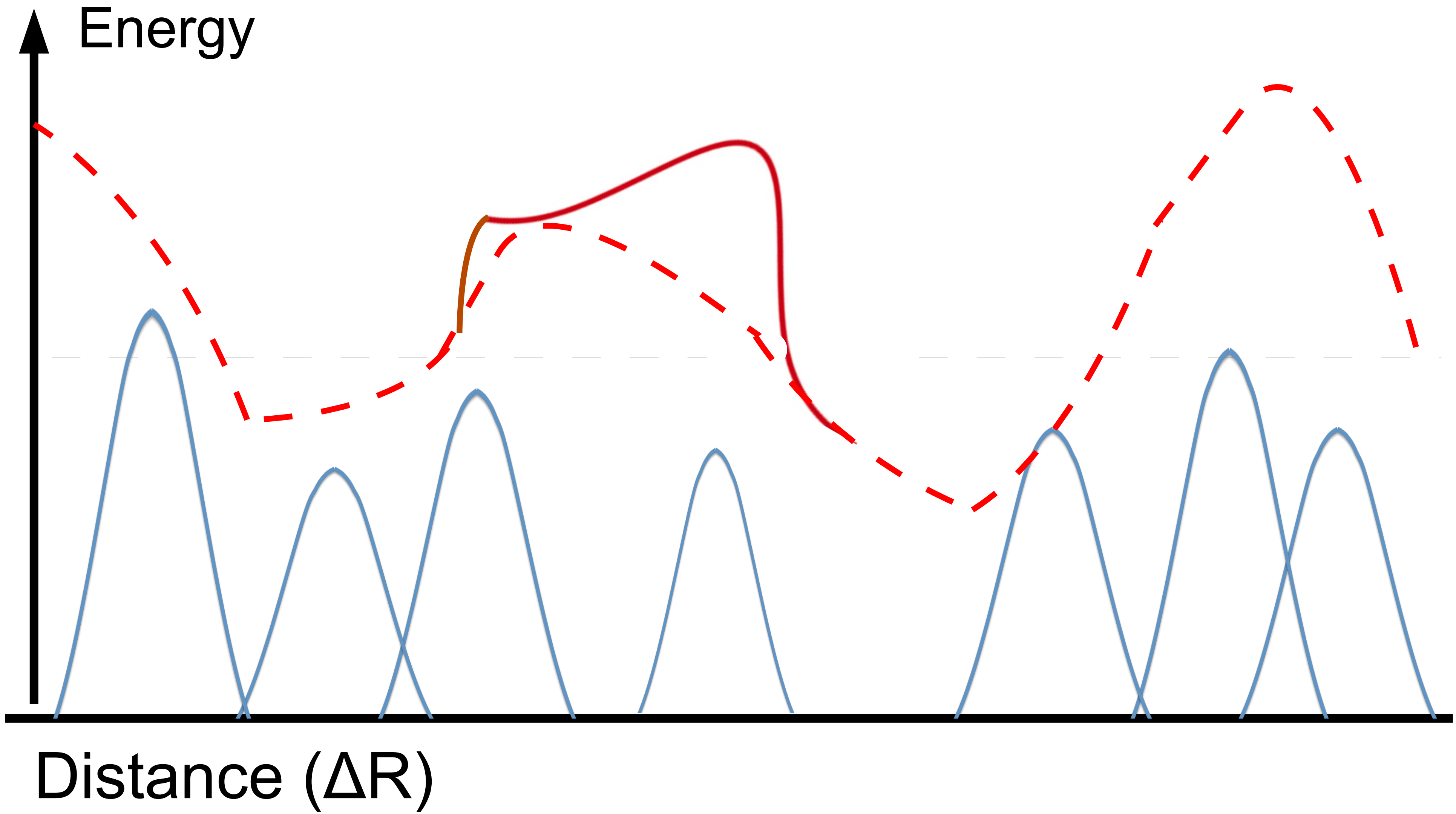

Define each stepwise subtraction by building a Voronoi cell

# Led to HF/Voronoi Method

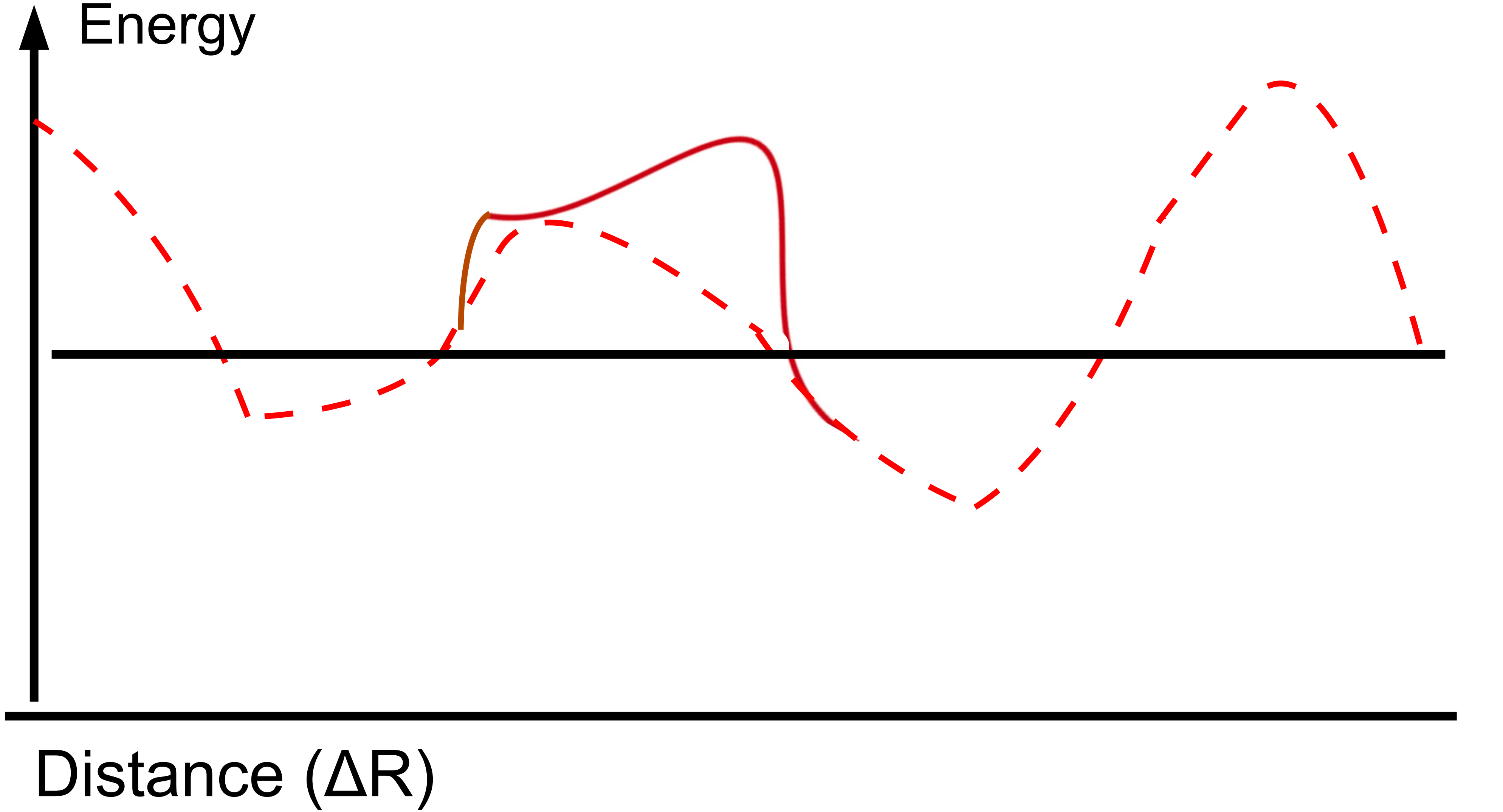



Define each stepwise subtraction by building a Voronoi cell

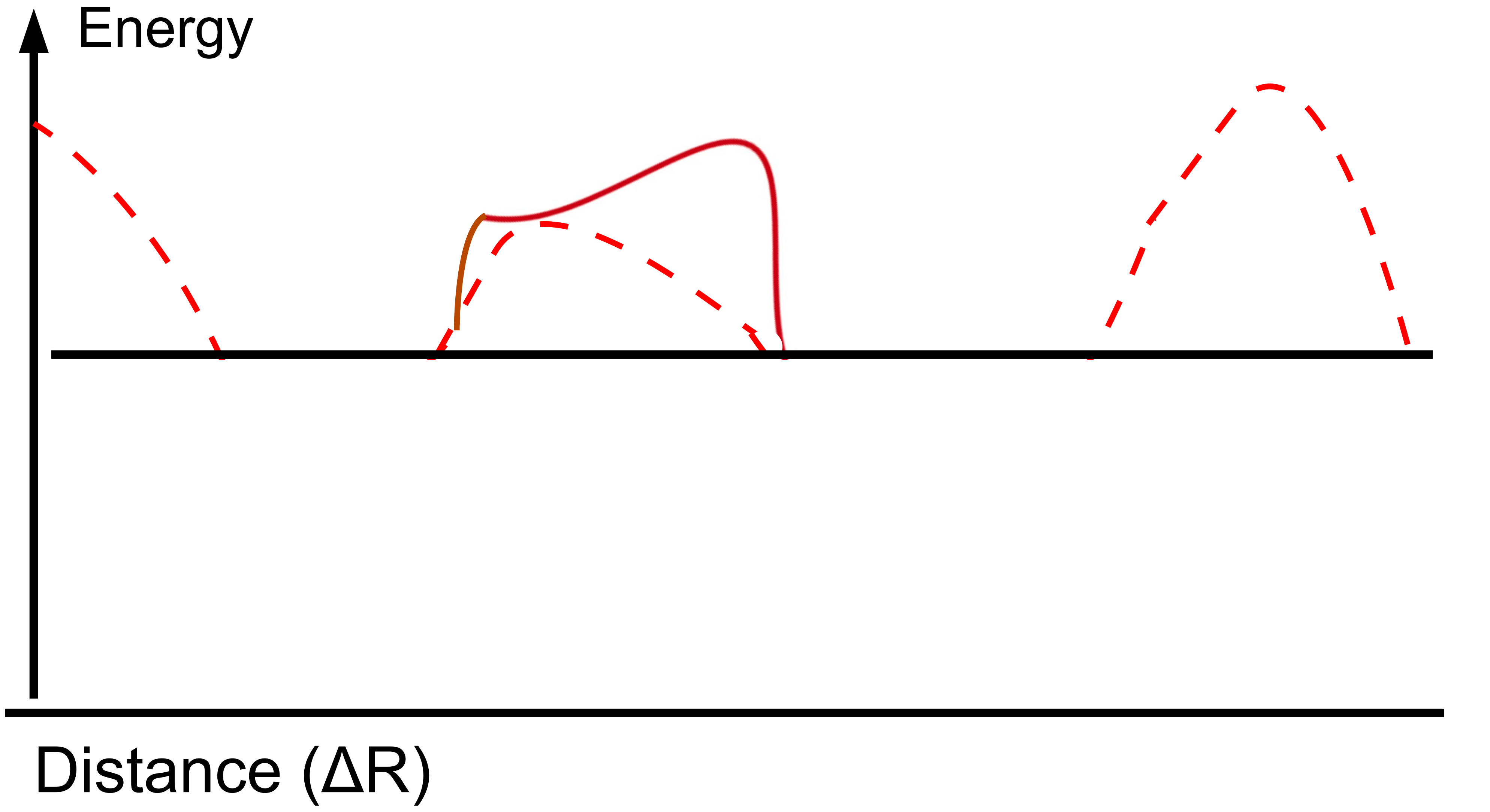
# A jet in realistic pileup



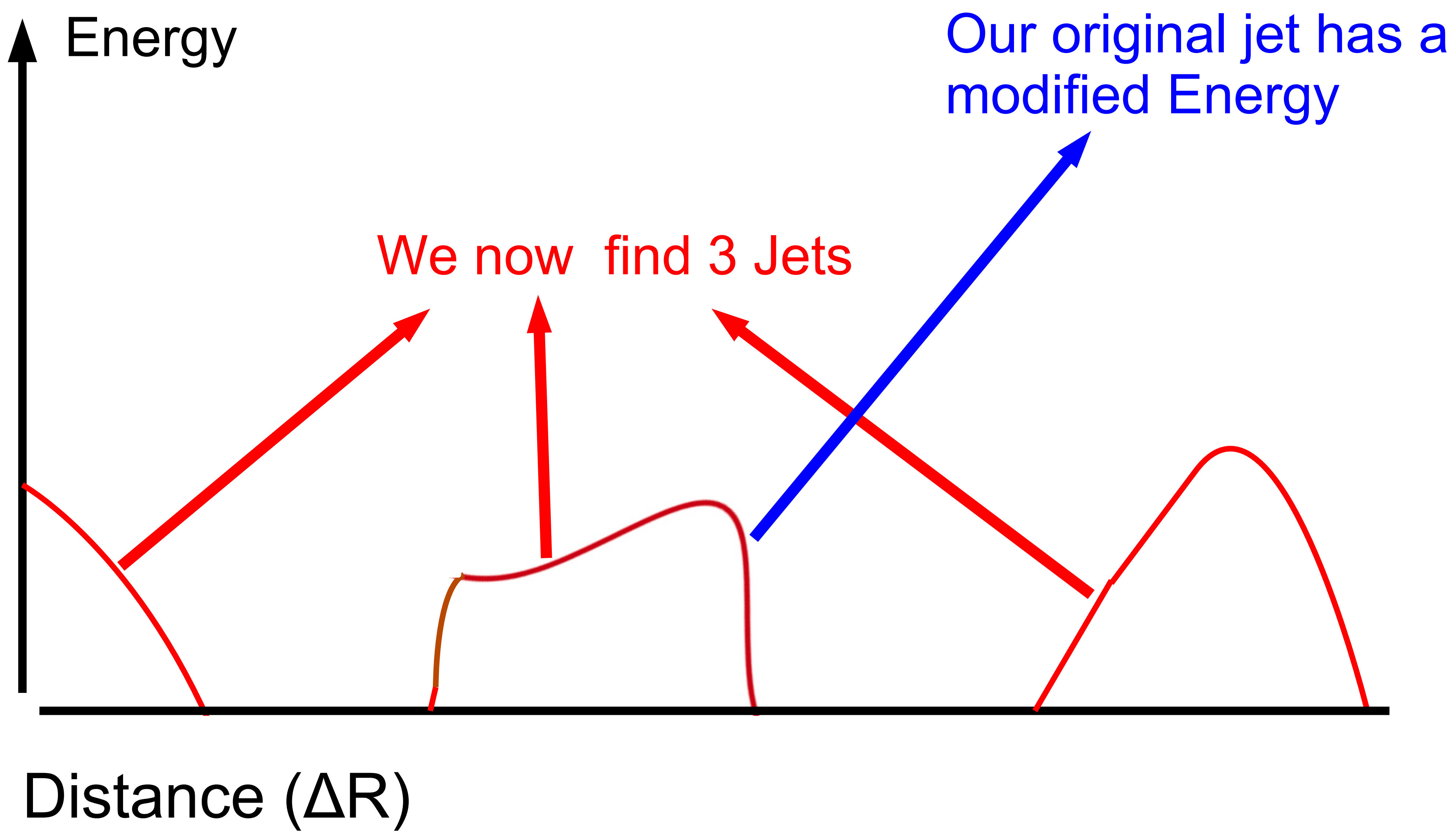
# Conventional subtraction



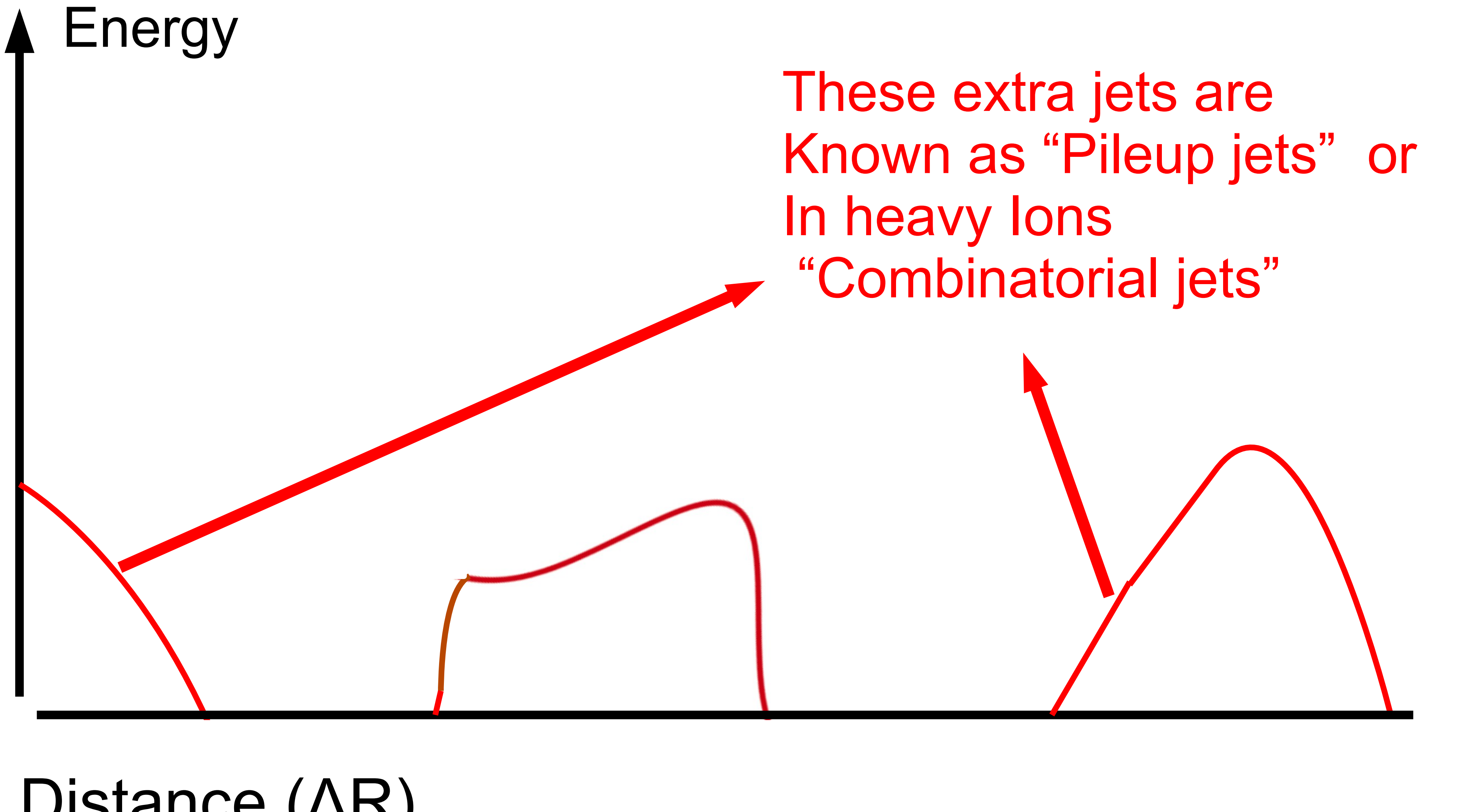
# Conventional subtraction



# Conventional subtraction

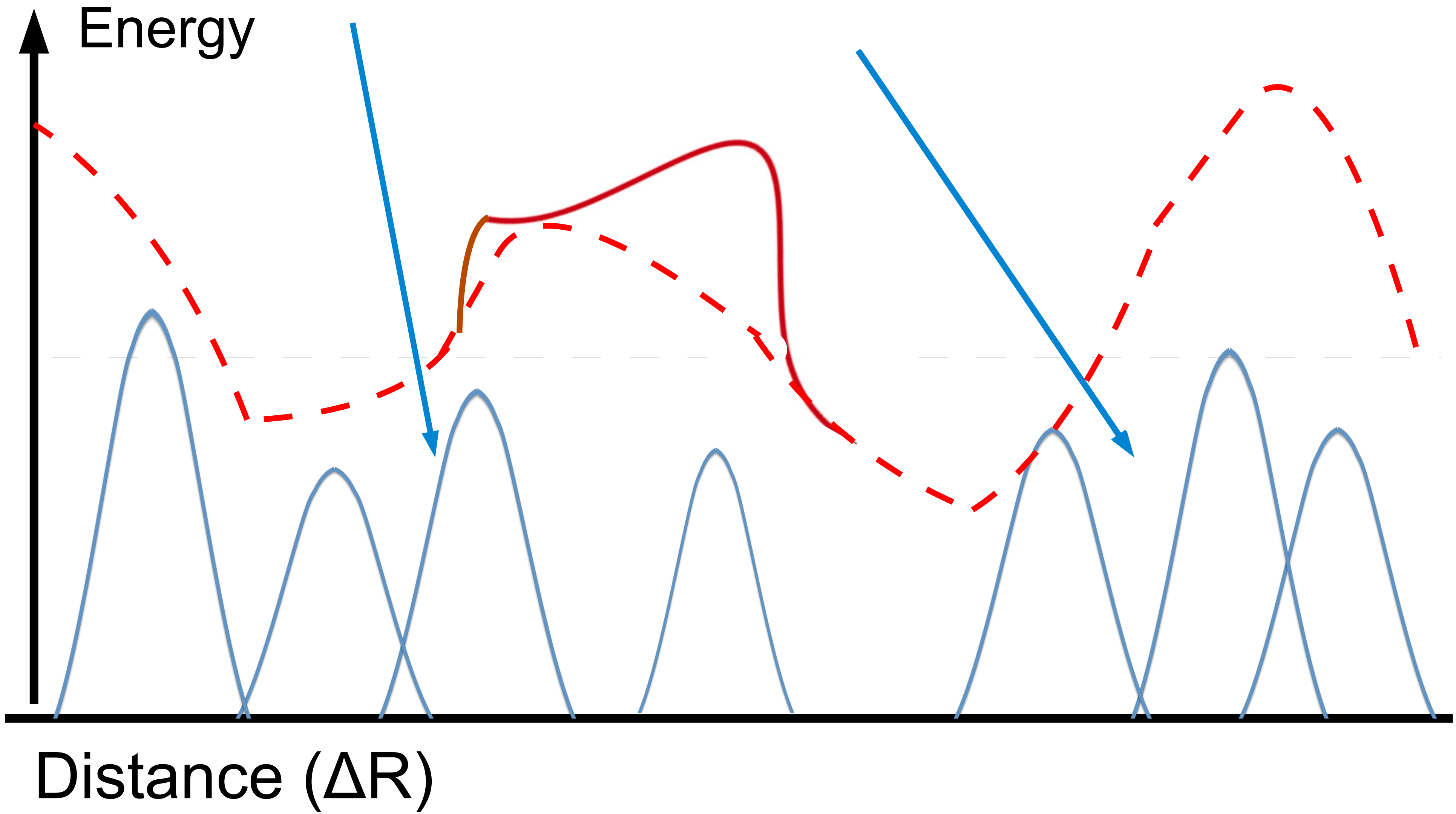


# Conventional subtraction



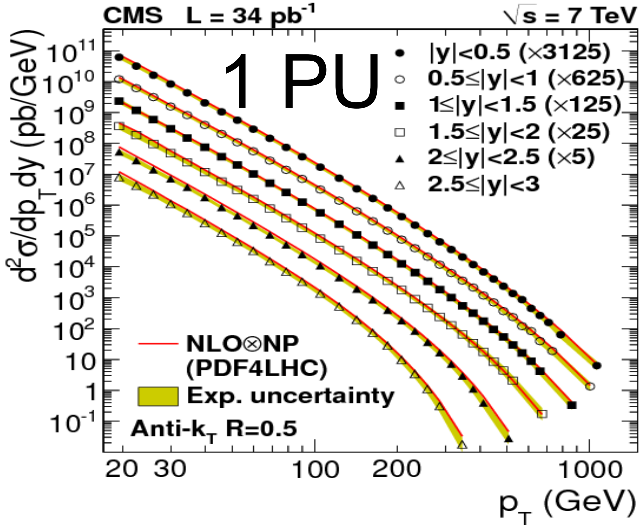
# Lets back track

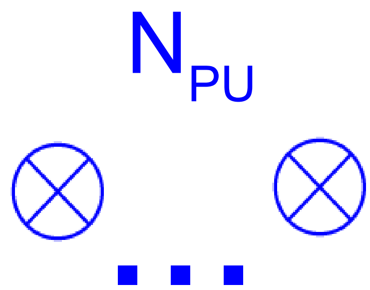
What is the composition of the pileup?

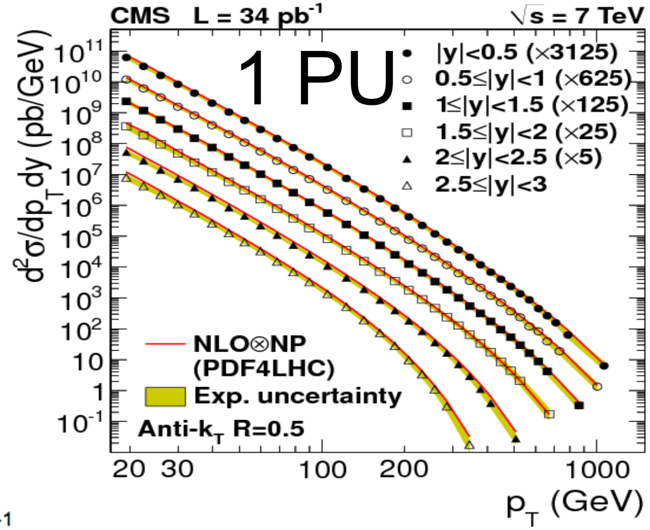


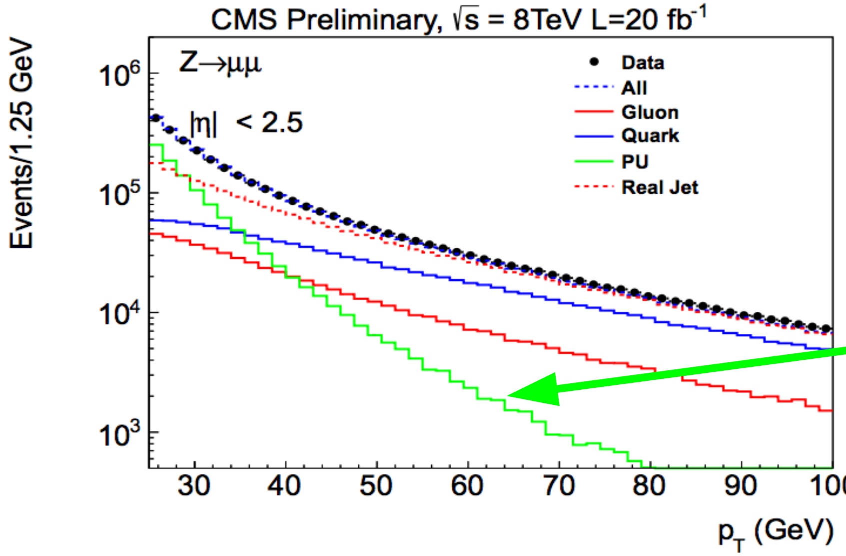
# Composition of pileup

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



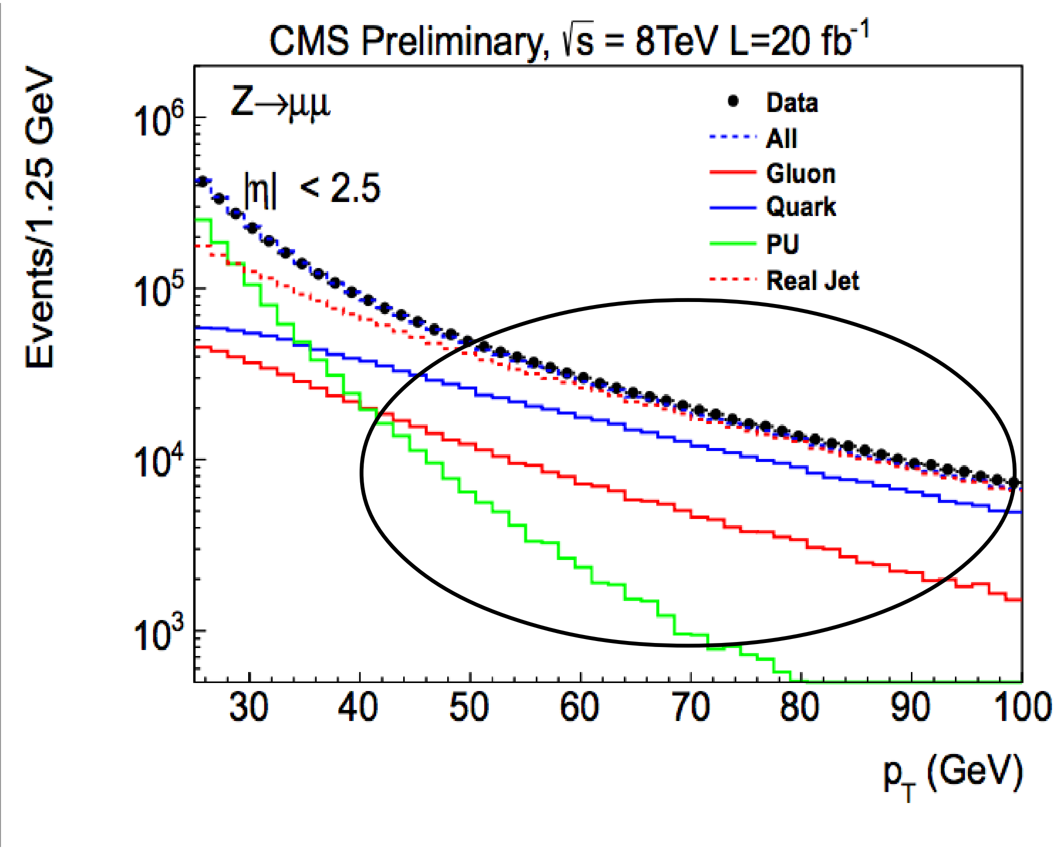



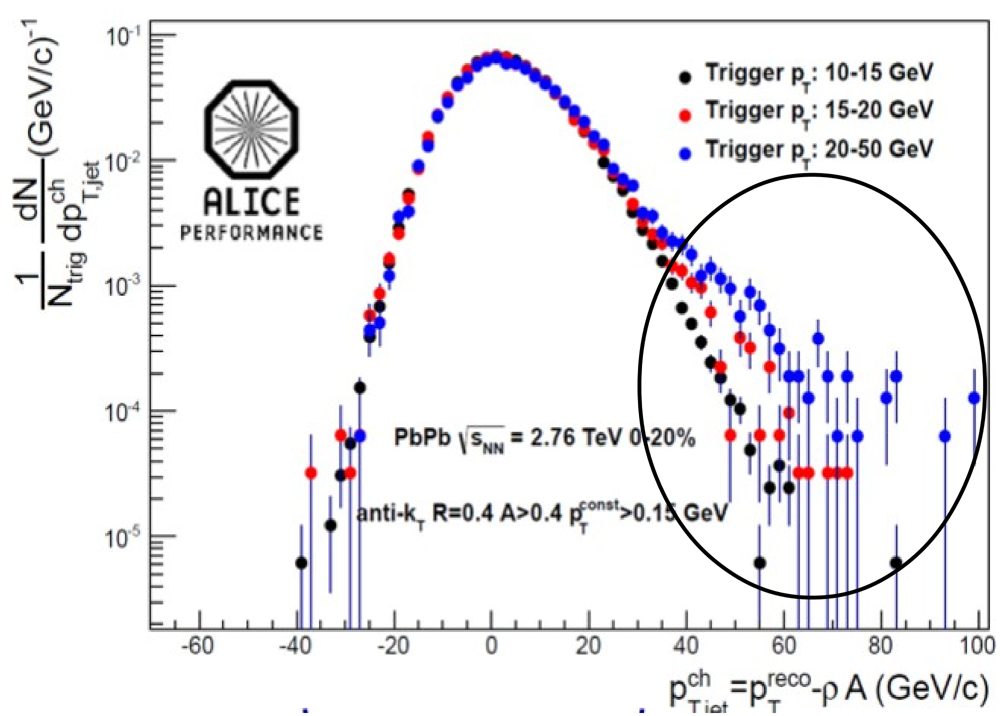

Jets overlapping
Gives up pileup jets

# 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?**

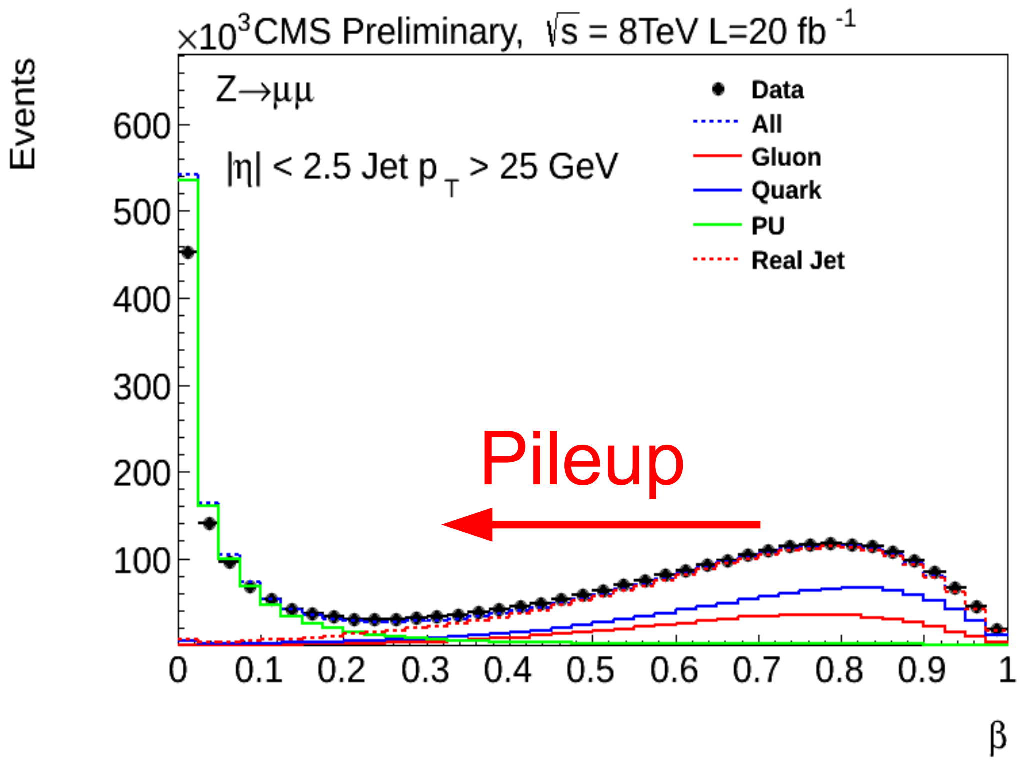
$P(\text{overlap}|pT) \approx C\, N^2_{pu}\ a^2_{jet}\, pT^{-6.2}$ Real Jets $\approx pT^{-5}$

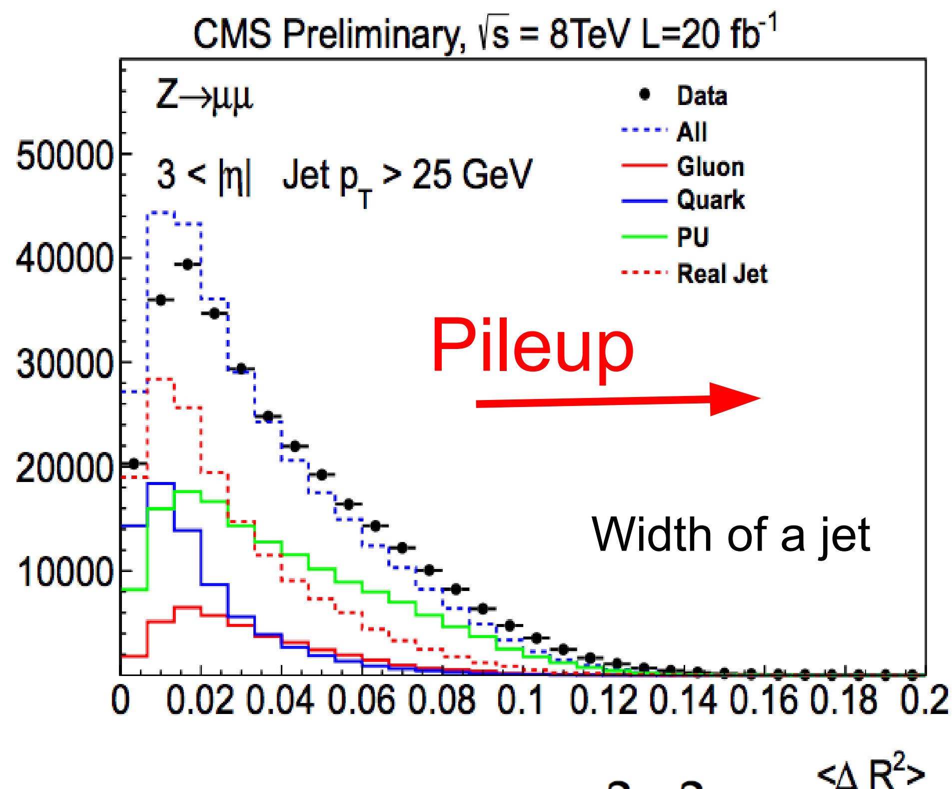


# Identifying pileup jets

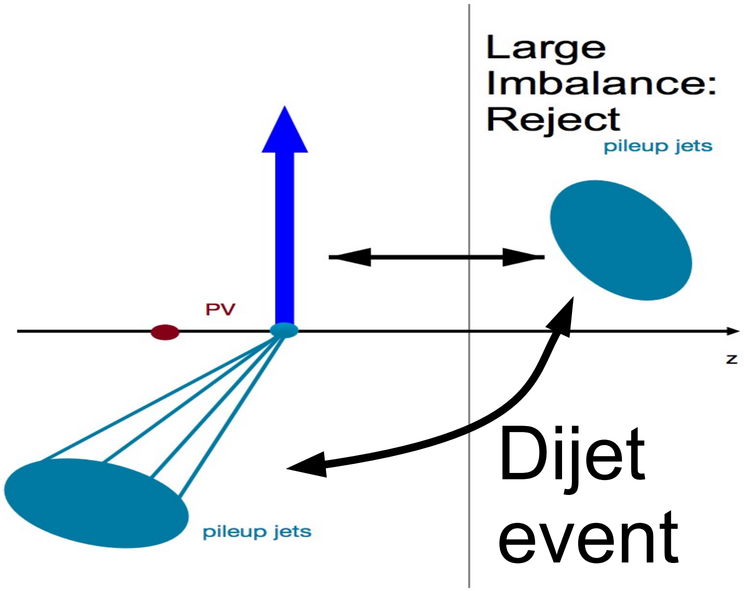
- Can identify pileup jets by :
  - Jets that are associated to the primary vertex
  - Looking for objects that are wide(overlapping)



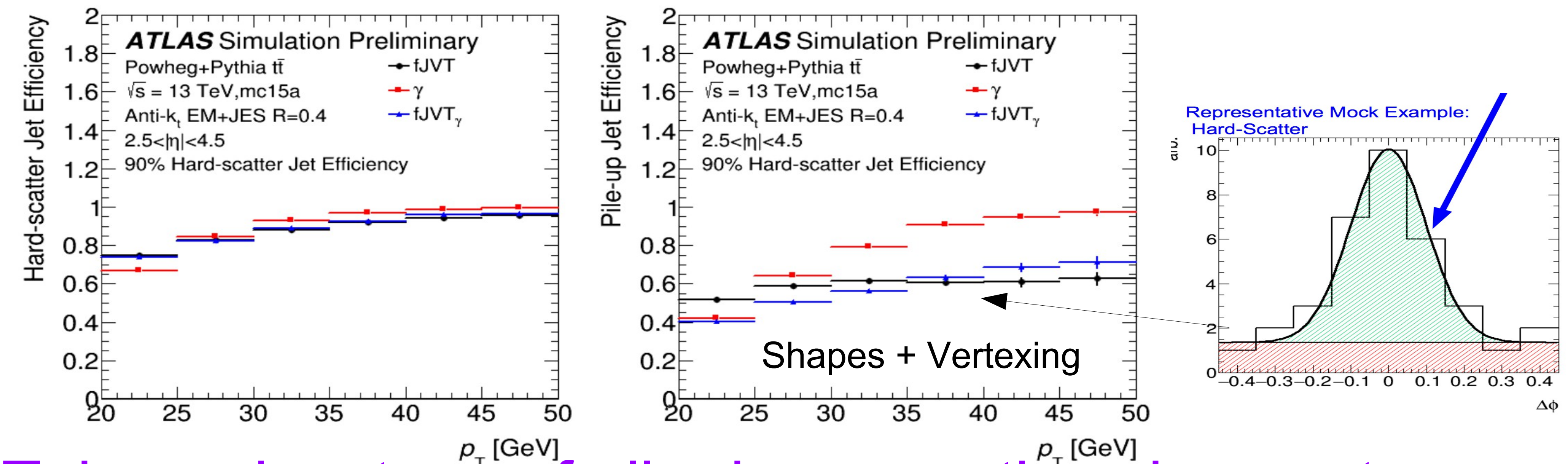

$$\beta = \frac{\sum_{i \in PV} p_{Ti}}{\sum_i p_{Ti}} \qquad \langle \Delta R^2 \rangle = \frac{\sum_i \Delta R_i^2 p_{Ti}^2}{\sum_i p_{Ti}^2}$$

# Ideas from ATLAS on PU Jets (fwd id)




Take an imbalanced PU vertex
look for forward recoiling jet

(works: PU Jet mostly from 1 jet)



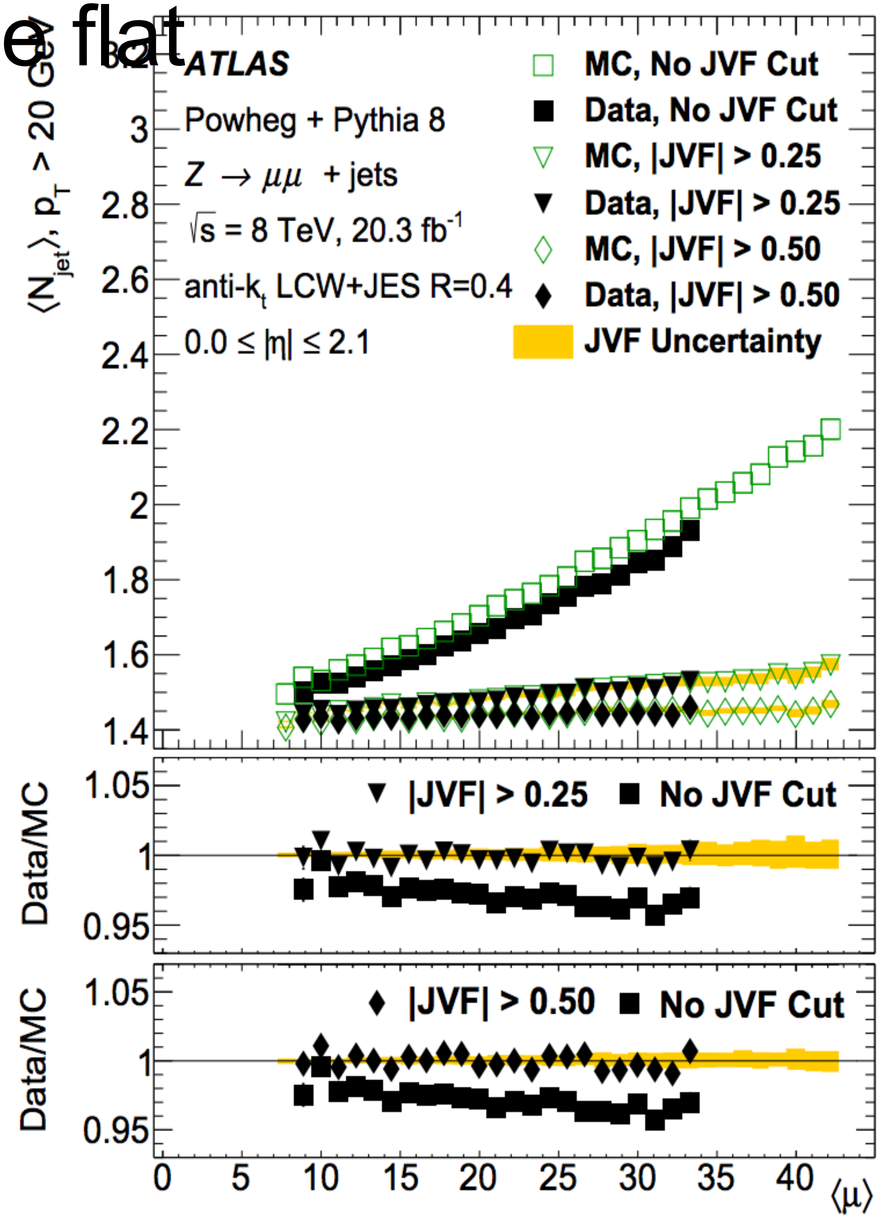

Takes advantage of all primary vertices in event

Arxiv/1705.02211

# Pileup Jet Id

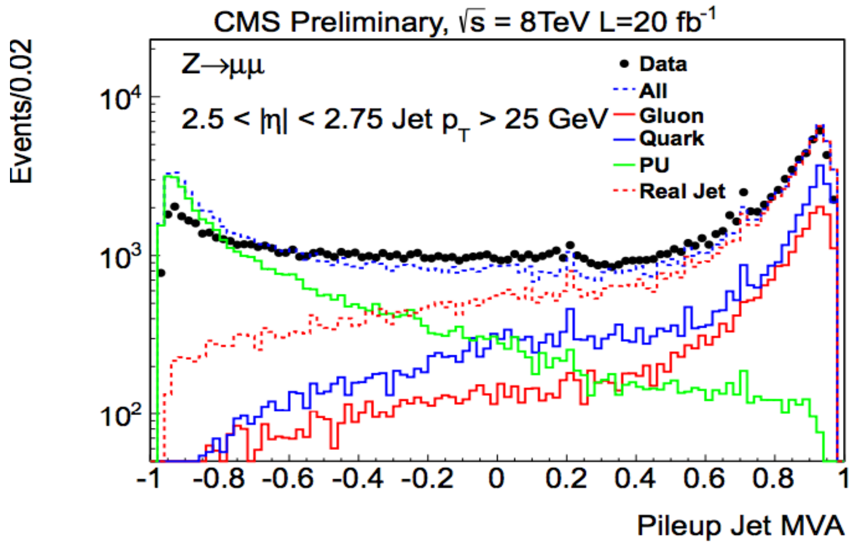
## ATLAS

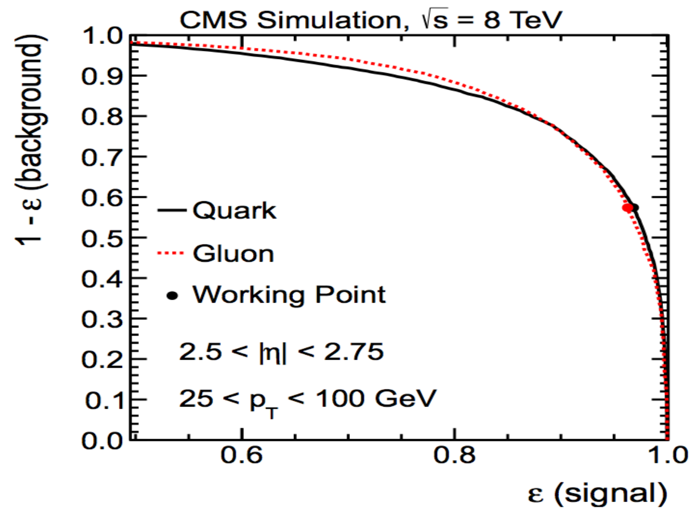
Cut on tracking tuned to be flat




## CMS

Put 10 tracking/shape variables in an MVA



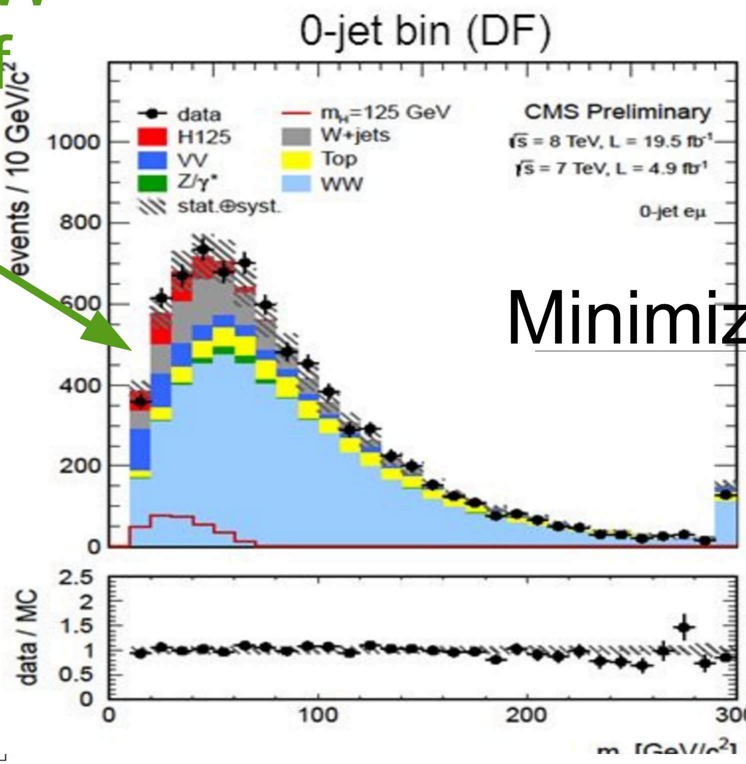
# Why is it so important?

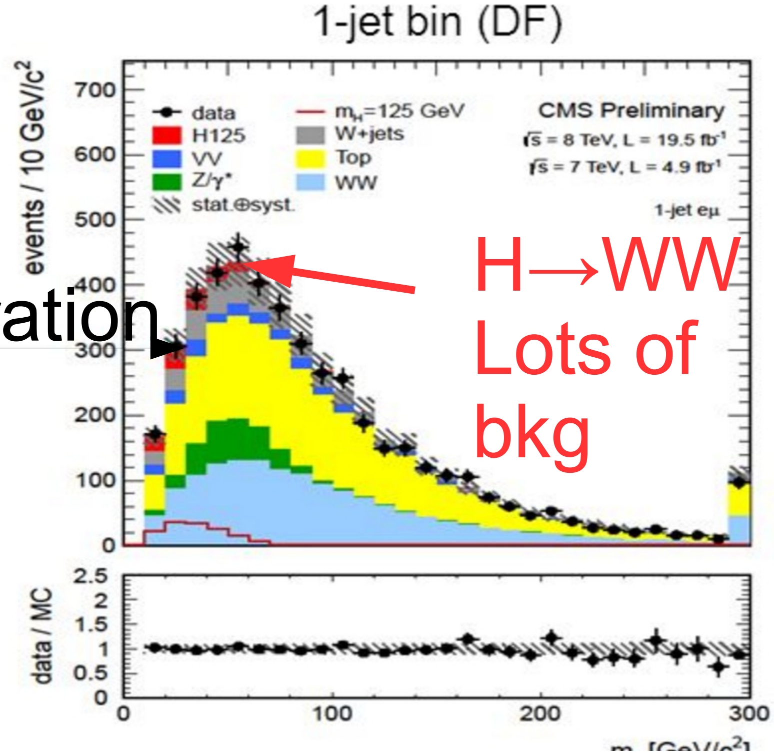


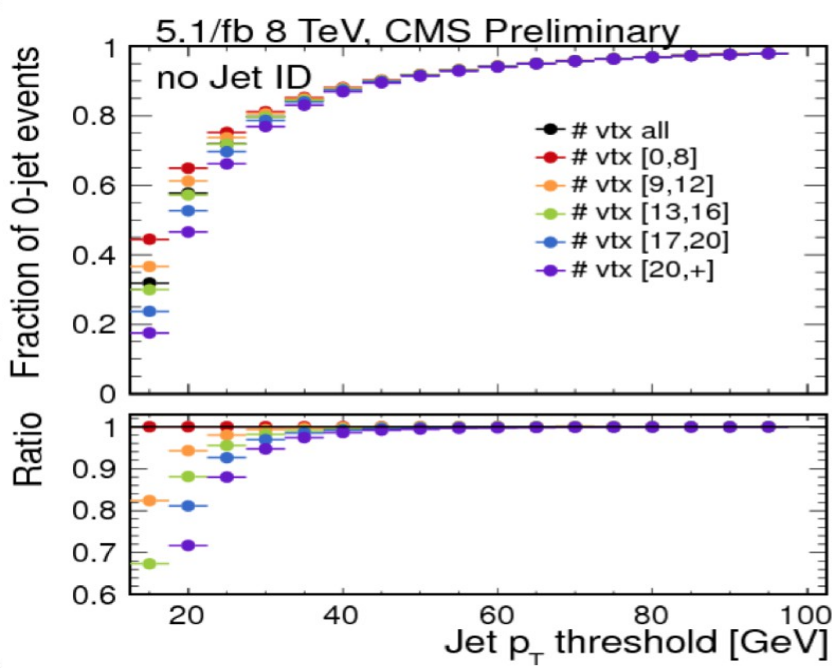
H→WW
Lots of
higgs

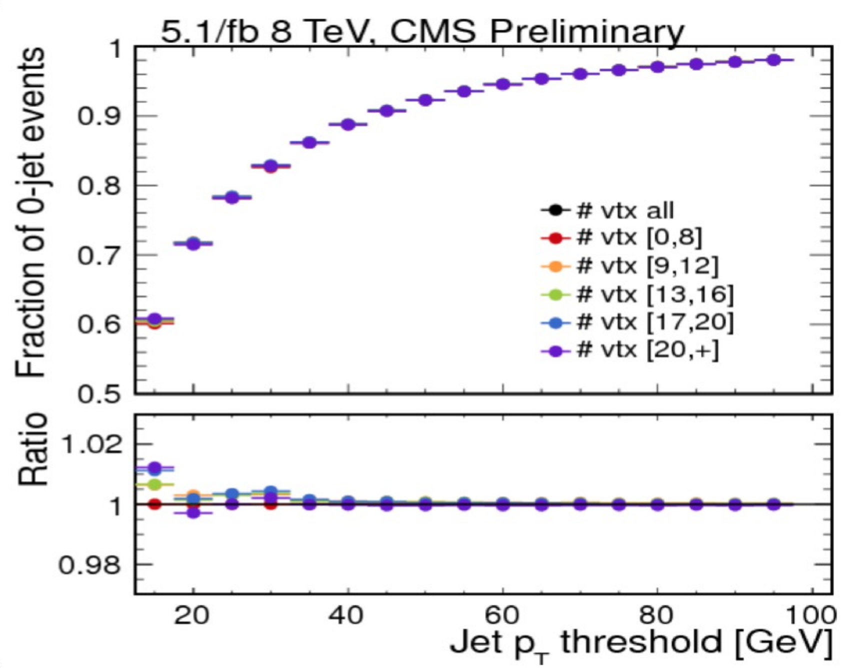
Minimize migration

H→WW
Lots of
bkg

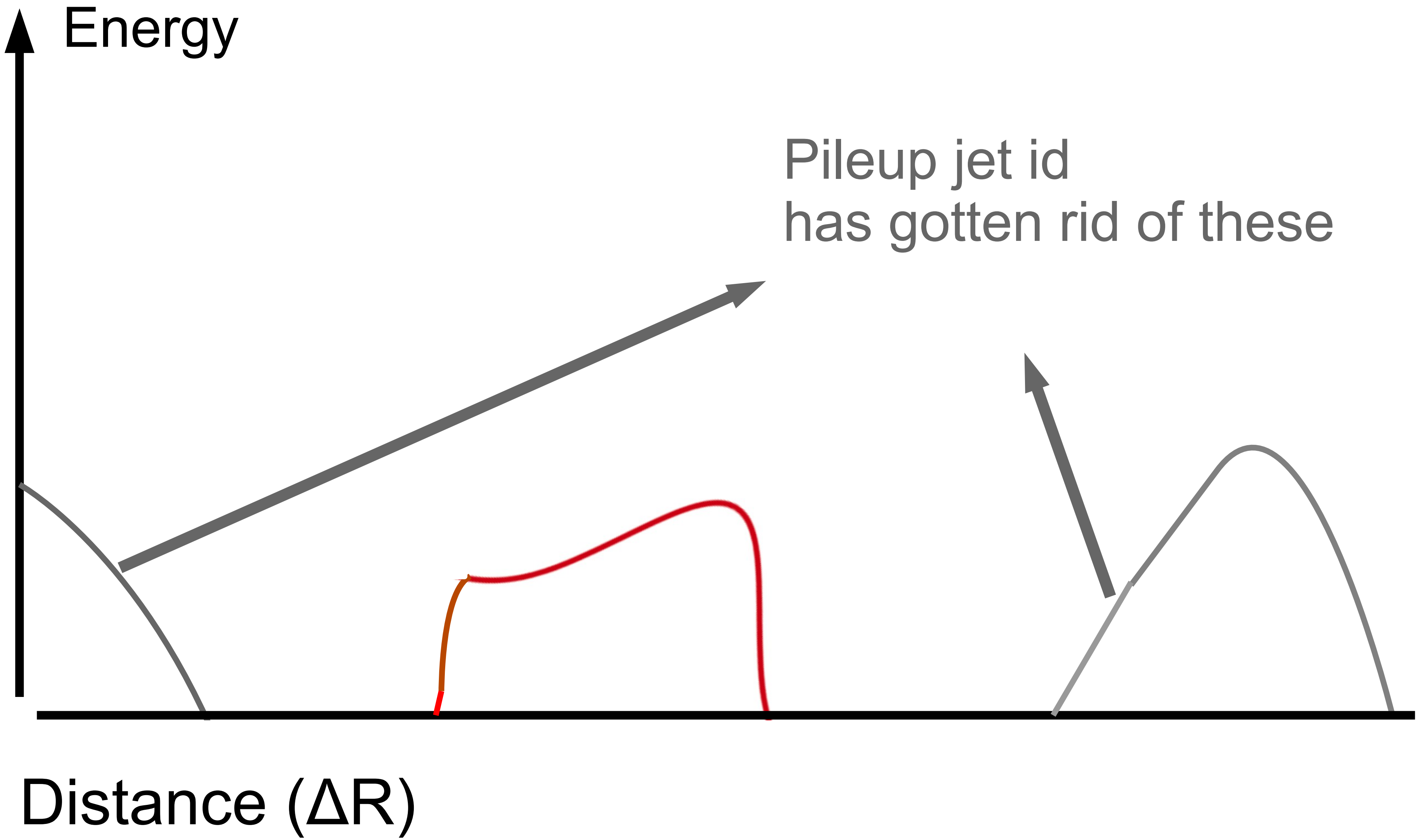


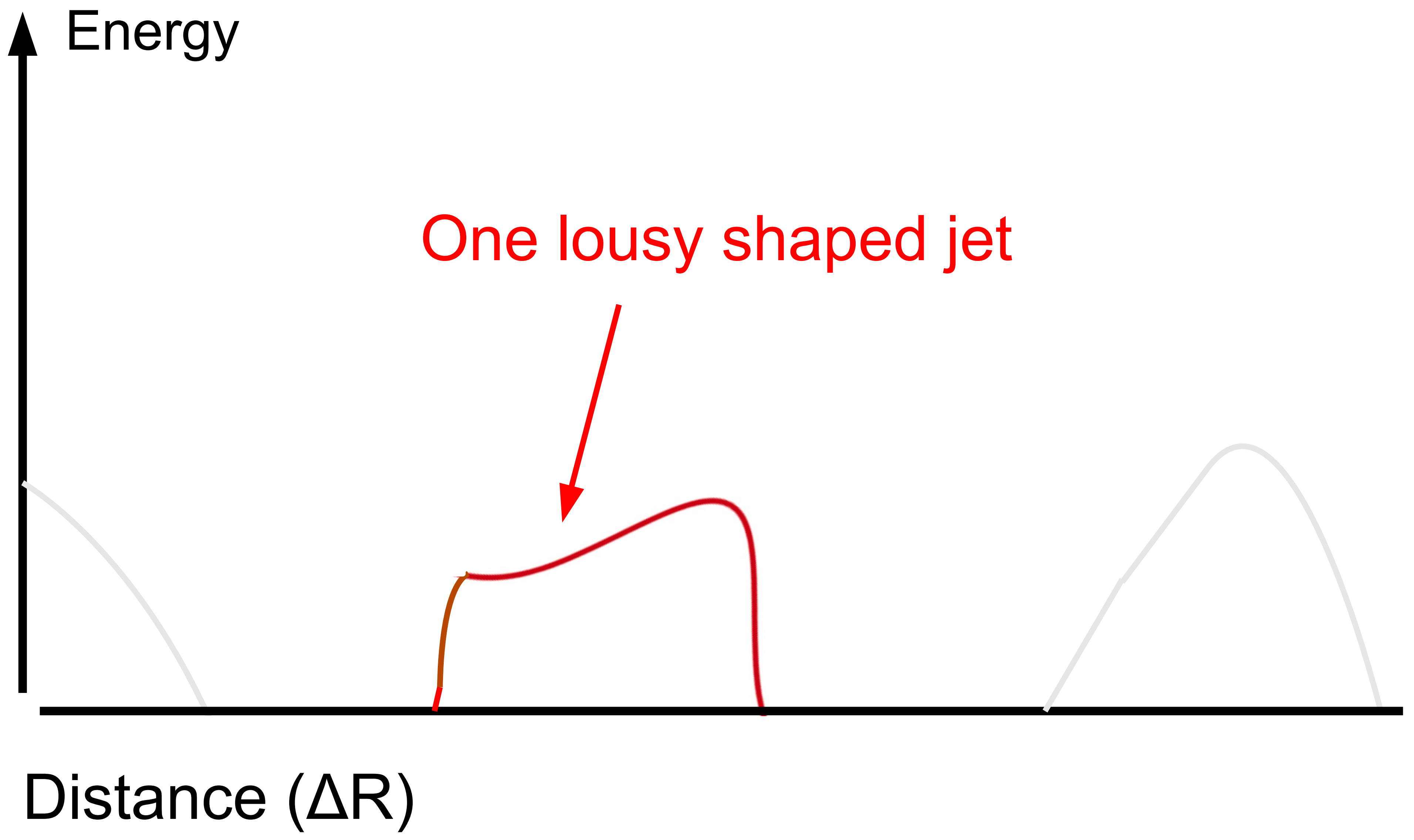



# Pileup Jet Id Effect



# State of the art 3 years ago



# Observations

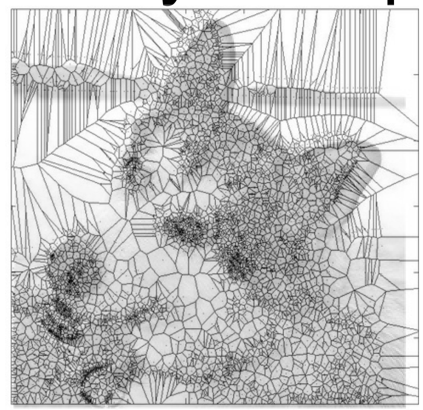
- A flat baseline subtraction at the jet level:
  - Solves the the issue of producing an unbiased jet $p_T$
  - Yields pileup jets
    - Requires a Pileup jet id to remove these
  - Does not clean up the internals of a jet
    - Neither does it clean up MET or isolation
- Resolving internals of jet require particle approach
  - Subtract pileup from the particle level
  - 4 main approaches exist for this :
    - Jet grooming, Constituent subtraction, Soft killer, PUPPI

# Current Technology

# Evolution of PU Subtraction

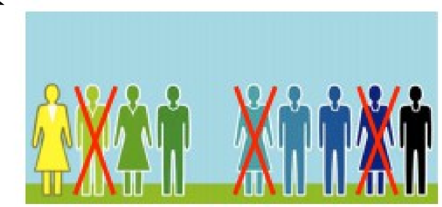
Aim is to remove pileup
at particle level

Heavy Ion approach



**HF Voronoi**
Per-particle subtraction
Using voronoi cells

**PUPPI**
PU Jet id @particle level



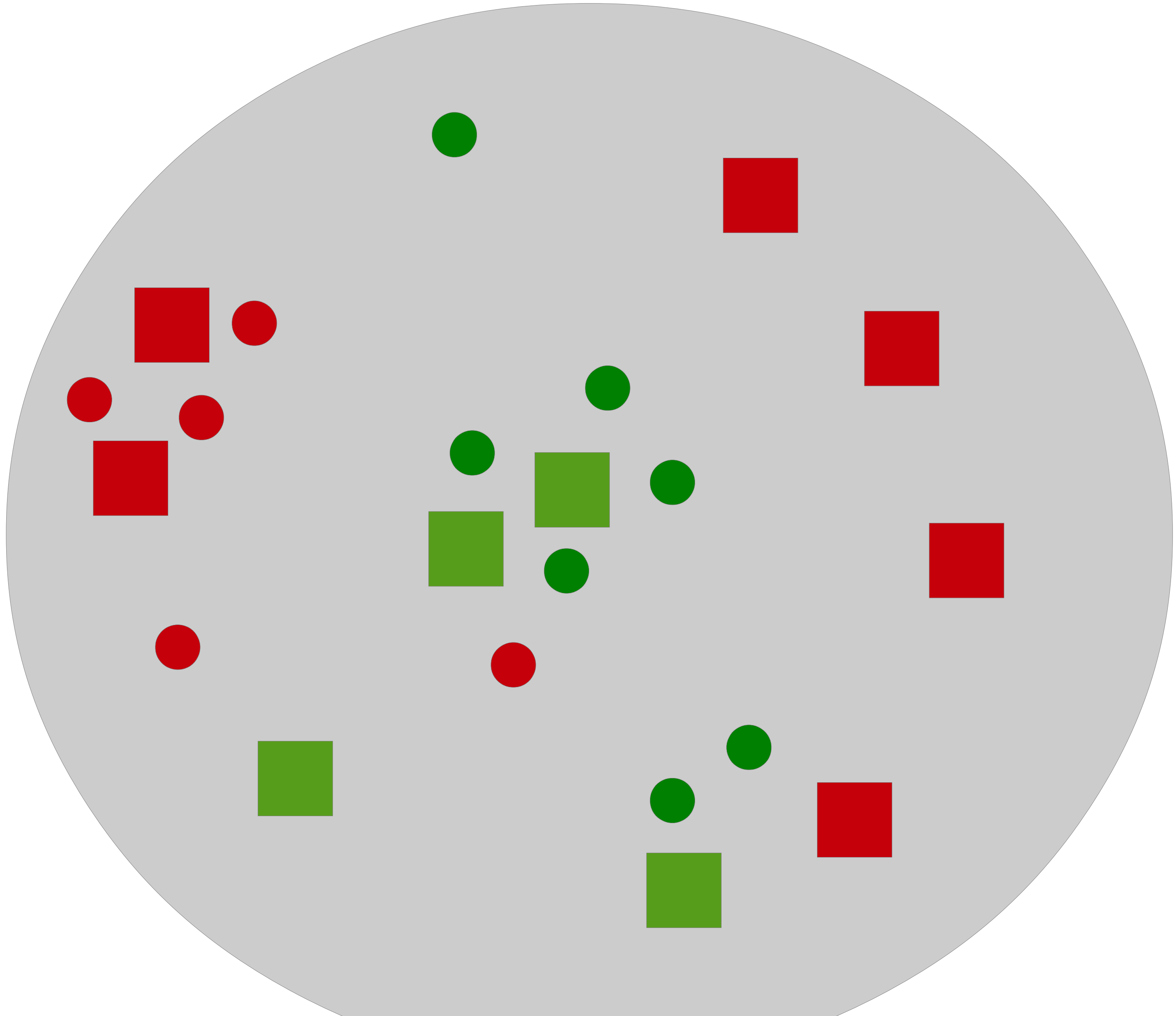
**Constituent Subtraction**
ρA correction per particle

**Soft Killer**
Median ρ removal
Per particle

**JME-DP-13-018**
**JME-14-001**

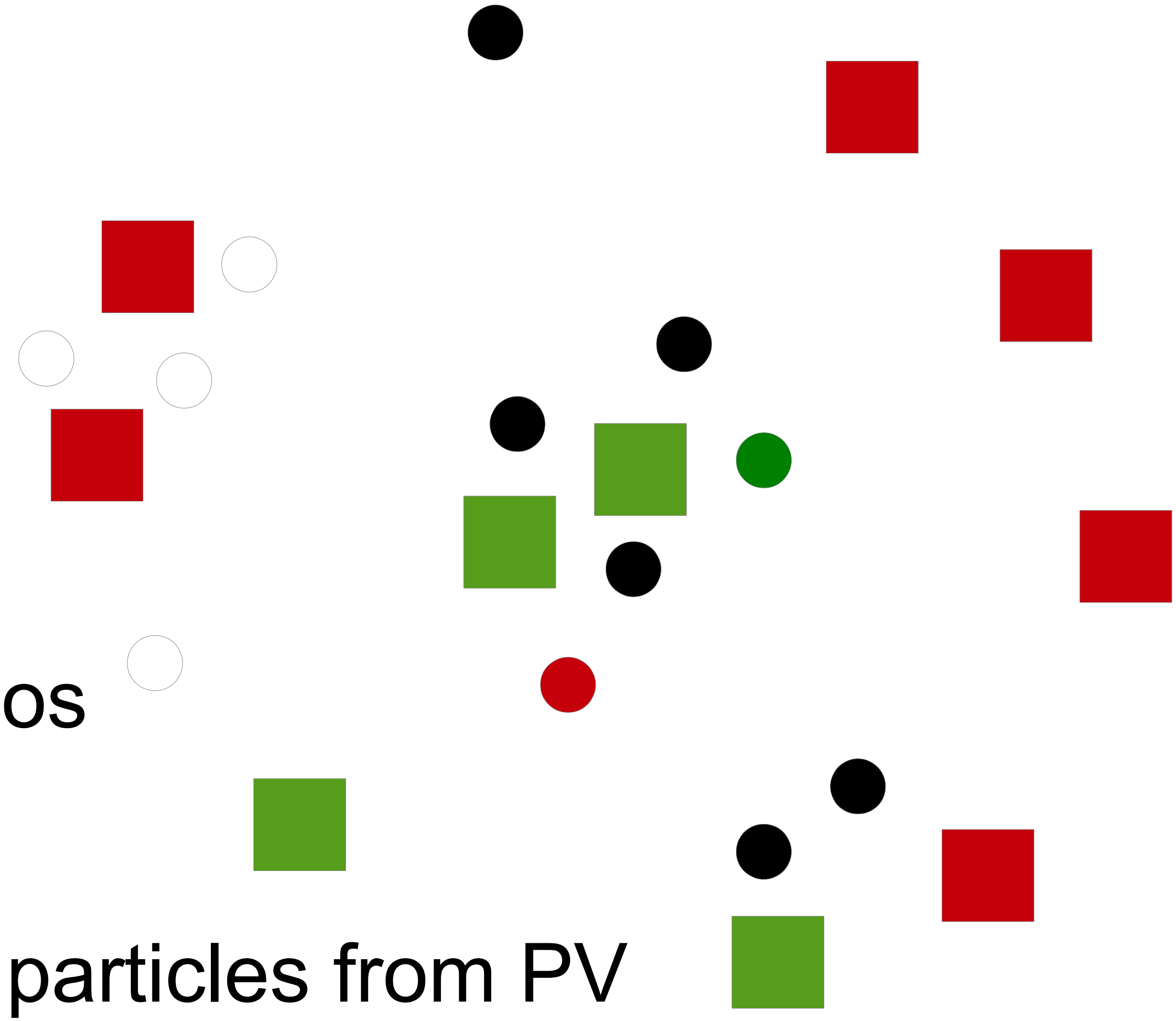
# Consider a jet

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



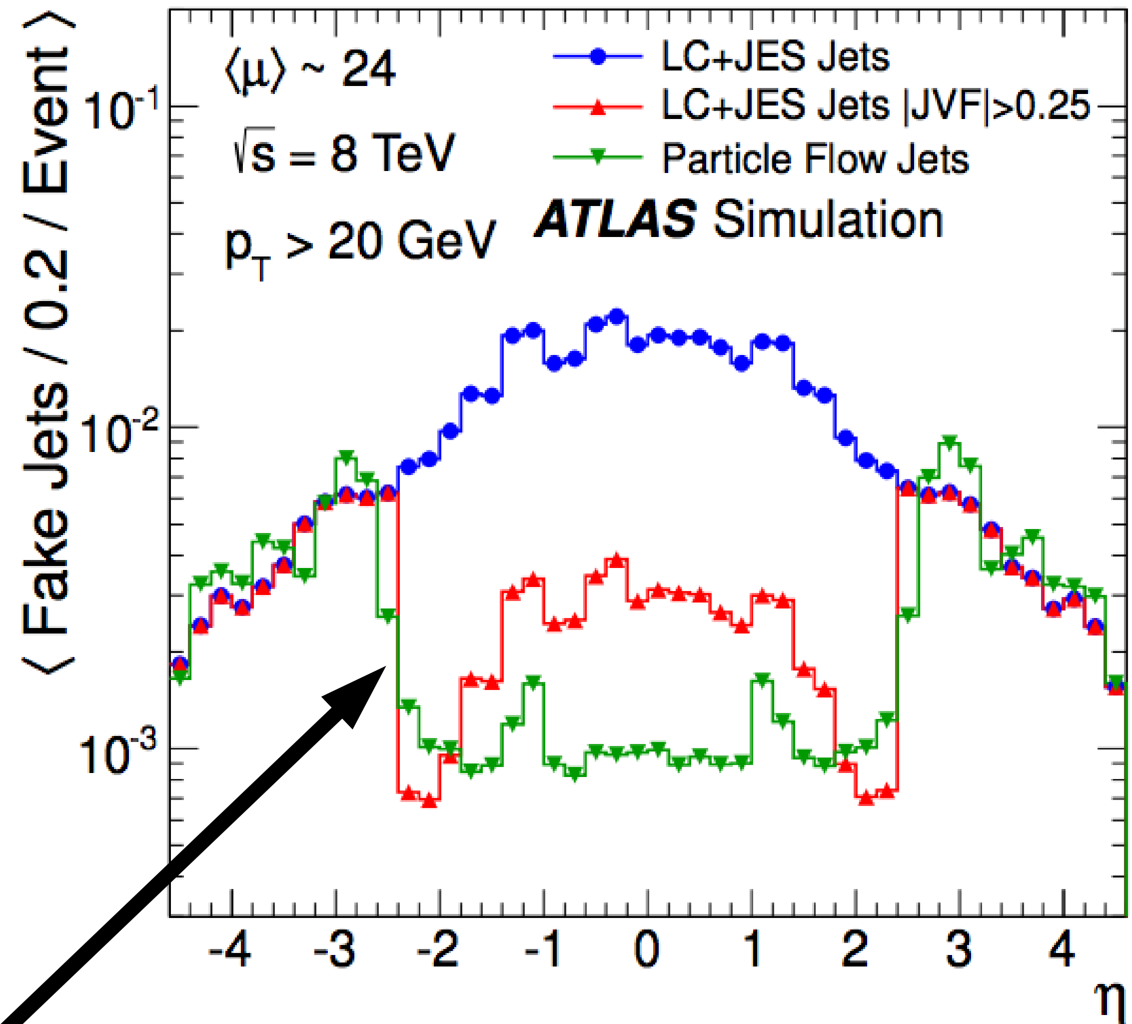
Step 1 of all Algos
CHS

Choose charge particles from PV
Remove charged particles not

# Charge Hadron Subtraction

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

Step 1 of all Algos
CHS



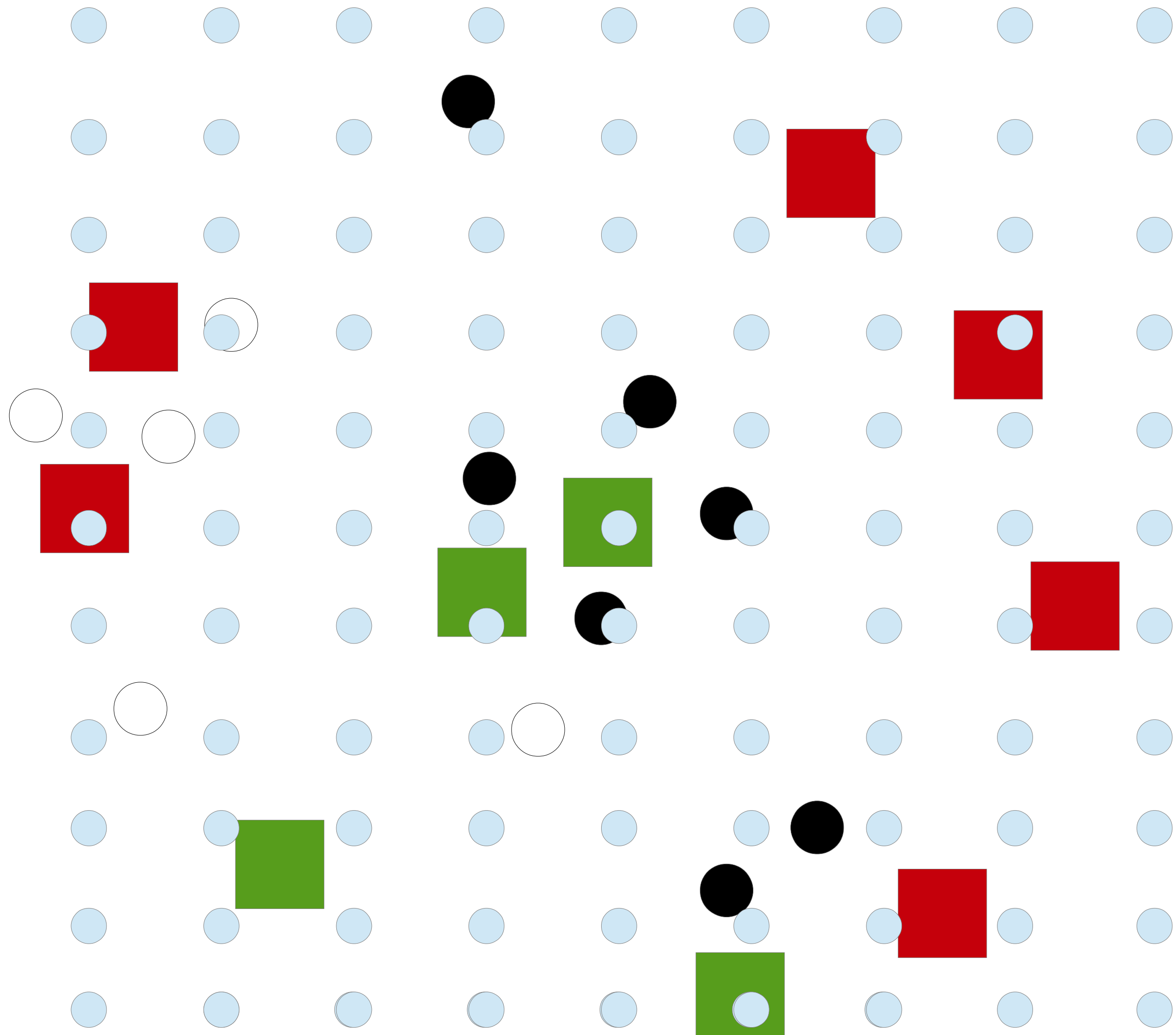

ATLAS can now do it!

Arxiv/1703.10485

# Constituent Subtraction

Key

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

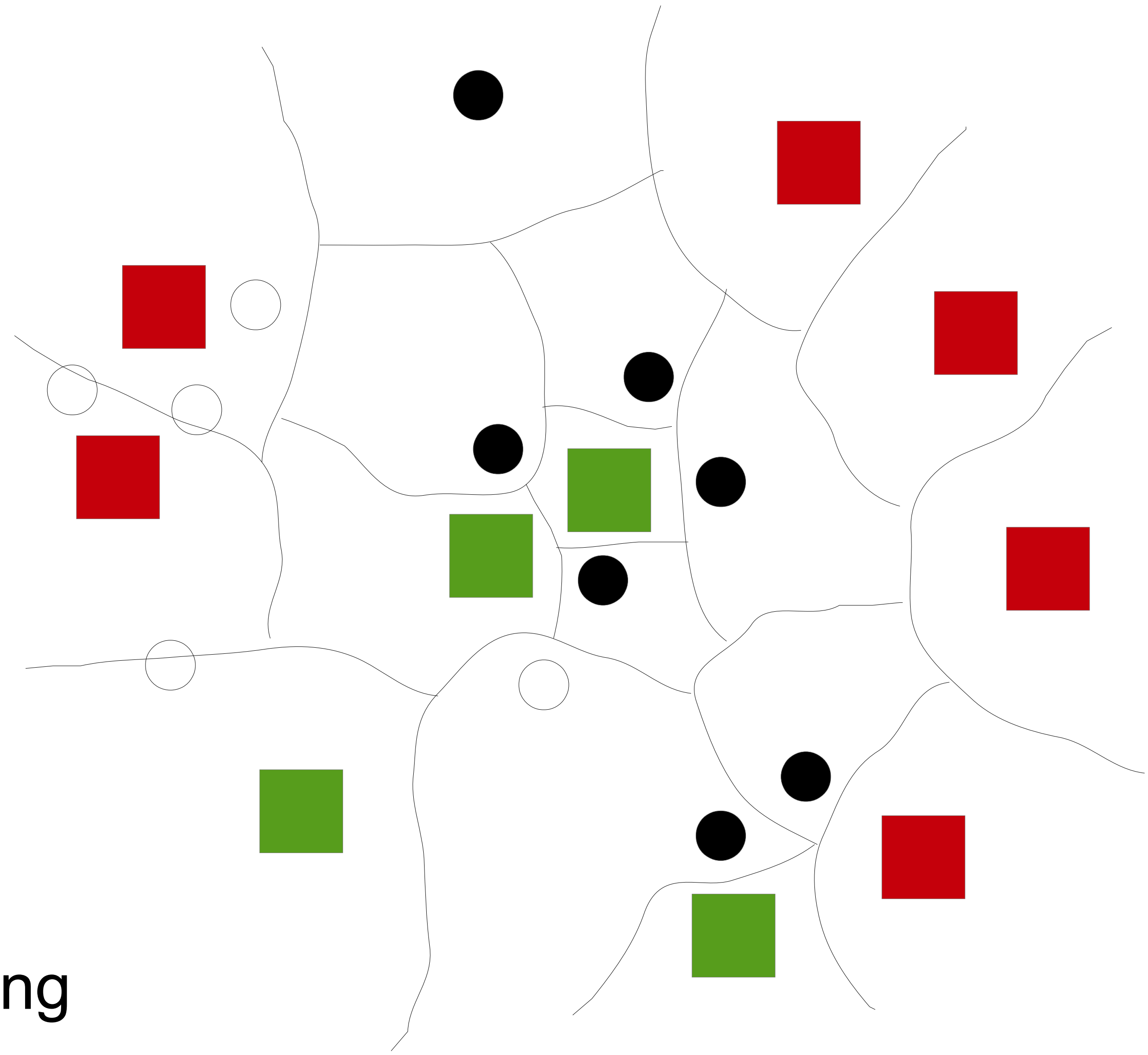


Step 1
Run CHS
Step 2
Compute Area around each particle clustering ghosts

Arxiv/1403.3108

# Constituent Subtraction

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



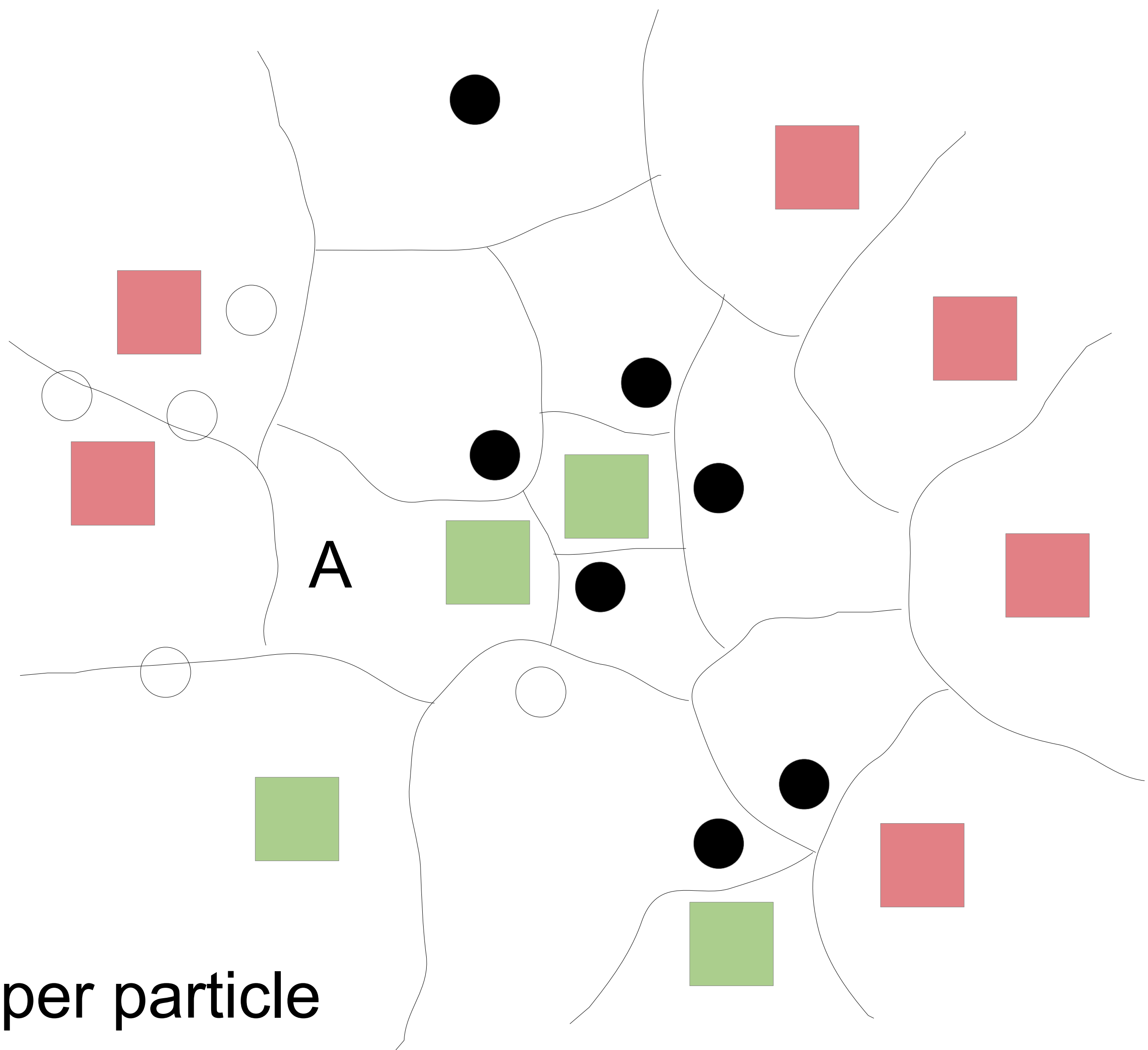
Step 1
Run CHS
Step 2
Compute Area around each particle clustering ghosts

**Arxiv/1403.3108**

# Constituent Subtraction

Key

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




Step 1

Run CHS

Step 2

Compute Area

Step 3

Subtract $p_T$-ρA per particle

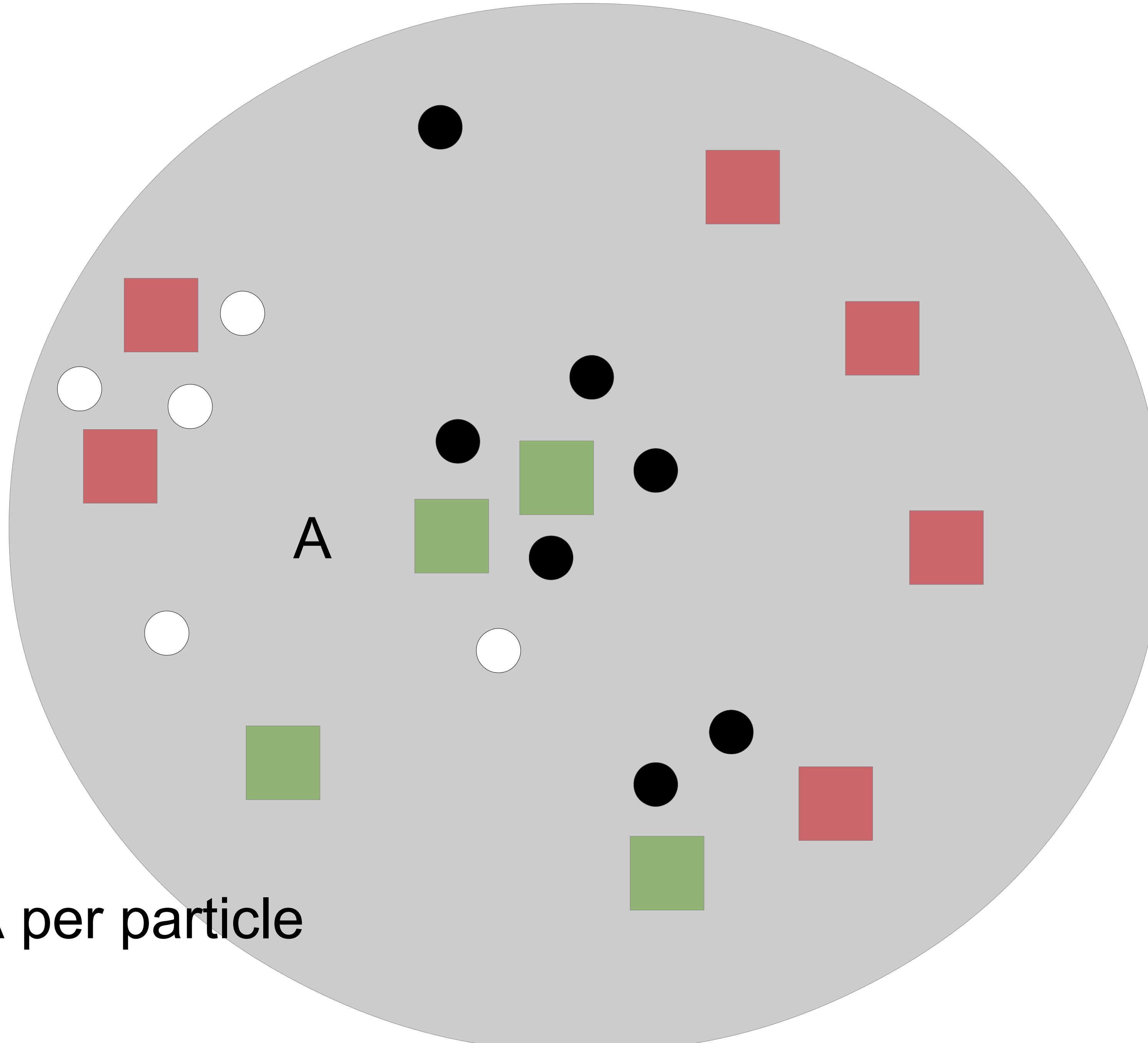
If $p_T < 0$ remove particle

Arxiv/1403.3108

# Constituent Subtraction

Key

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




Step 1
Run CHS

Step 2
Compute Area

Step 3
Subtract $p_T$-ρA per particle

Step 4
Cluster

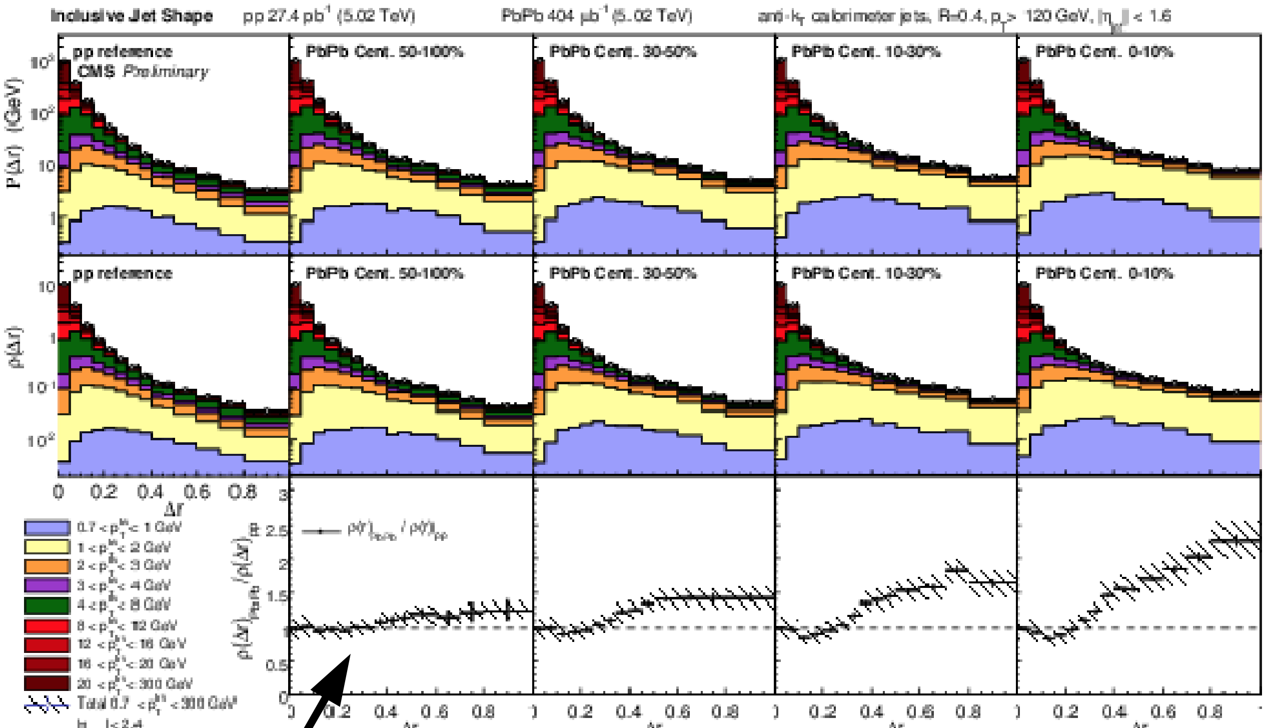
Arxiv/1403.3108

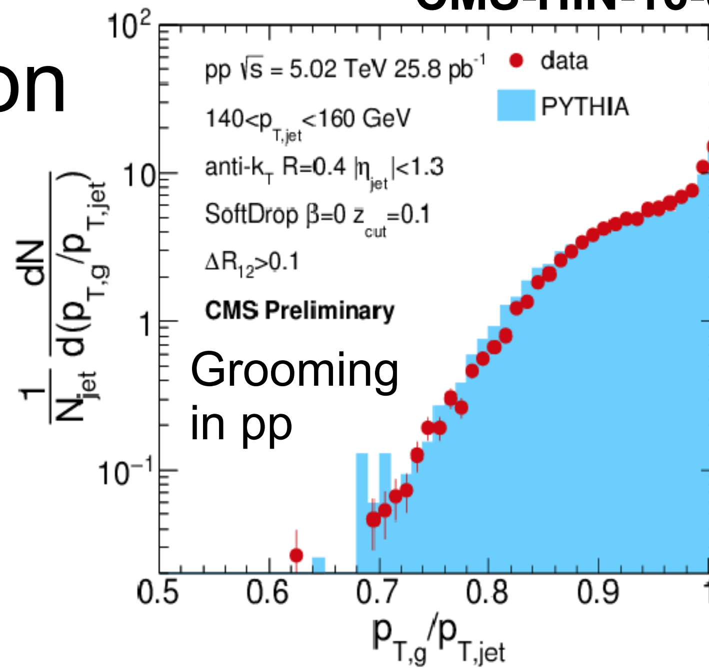
CMS-HIN-16-020

# Constituent Subtraction in CMS

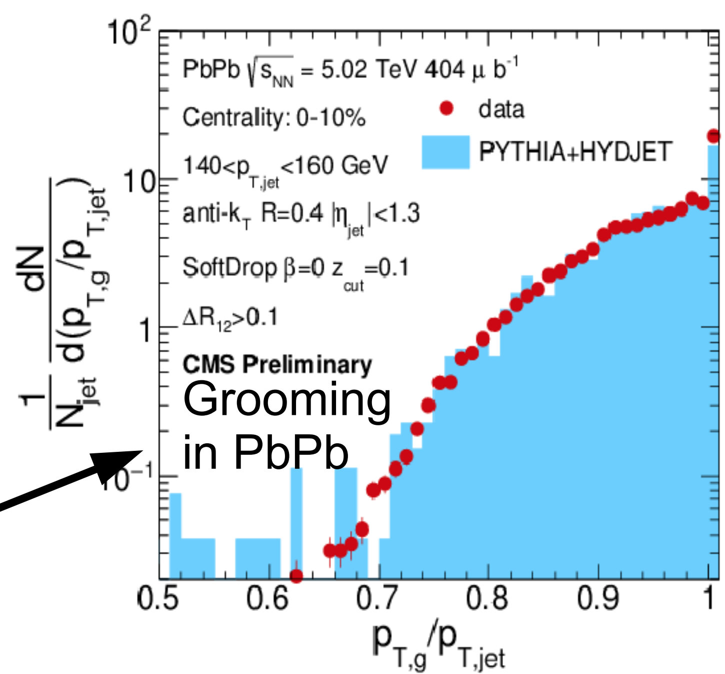
CMS-HIN-16-006

- Default Heavy Ion reconstruction




CMS developed first consistent subtraction with voronoi cells

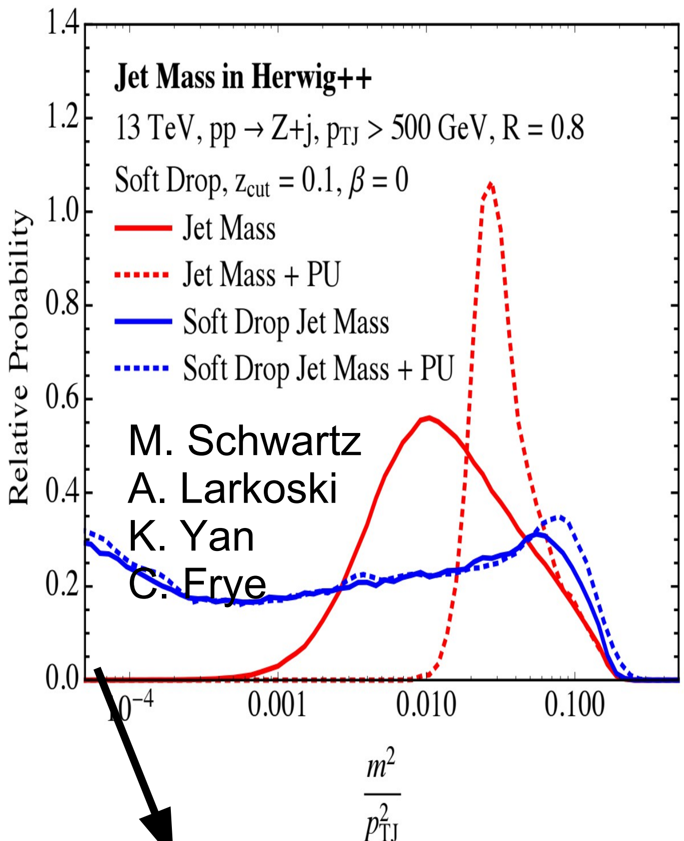


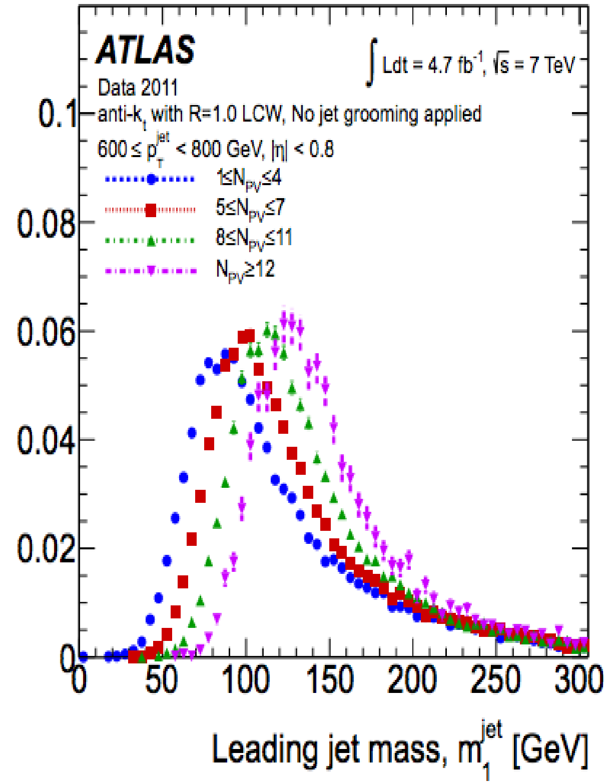

Now we use the fastjet default

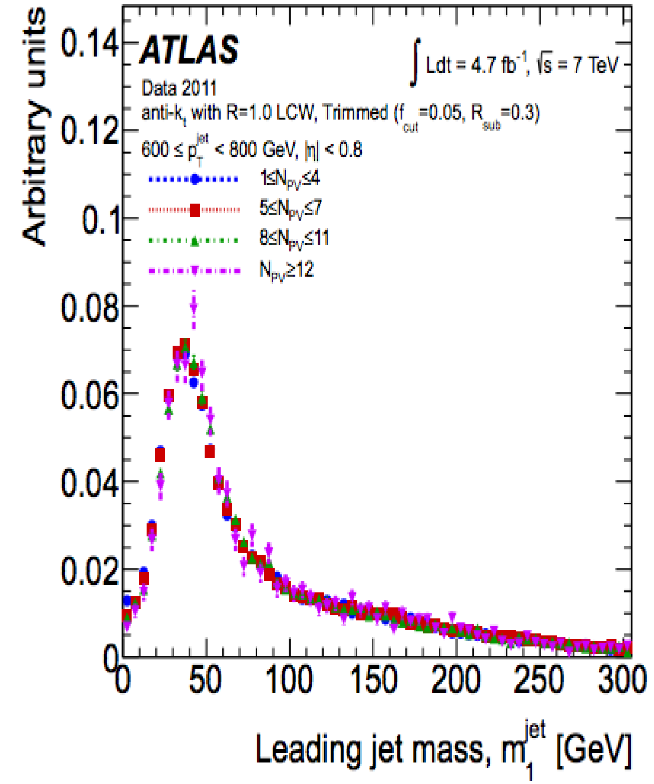
We also do grooming

# Using Local Info Grooming

- Grooming can substantially reduce pileup



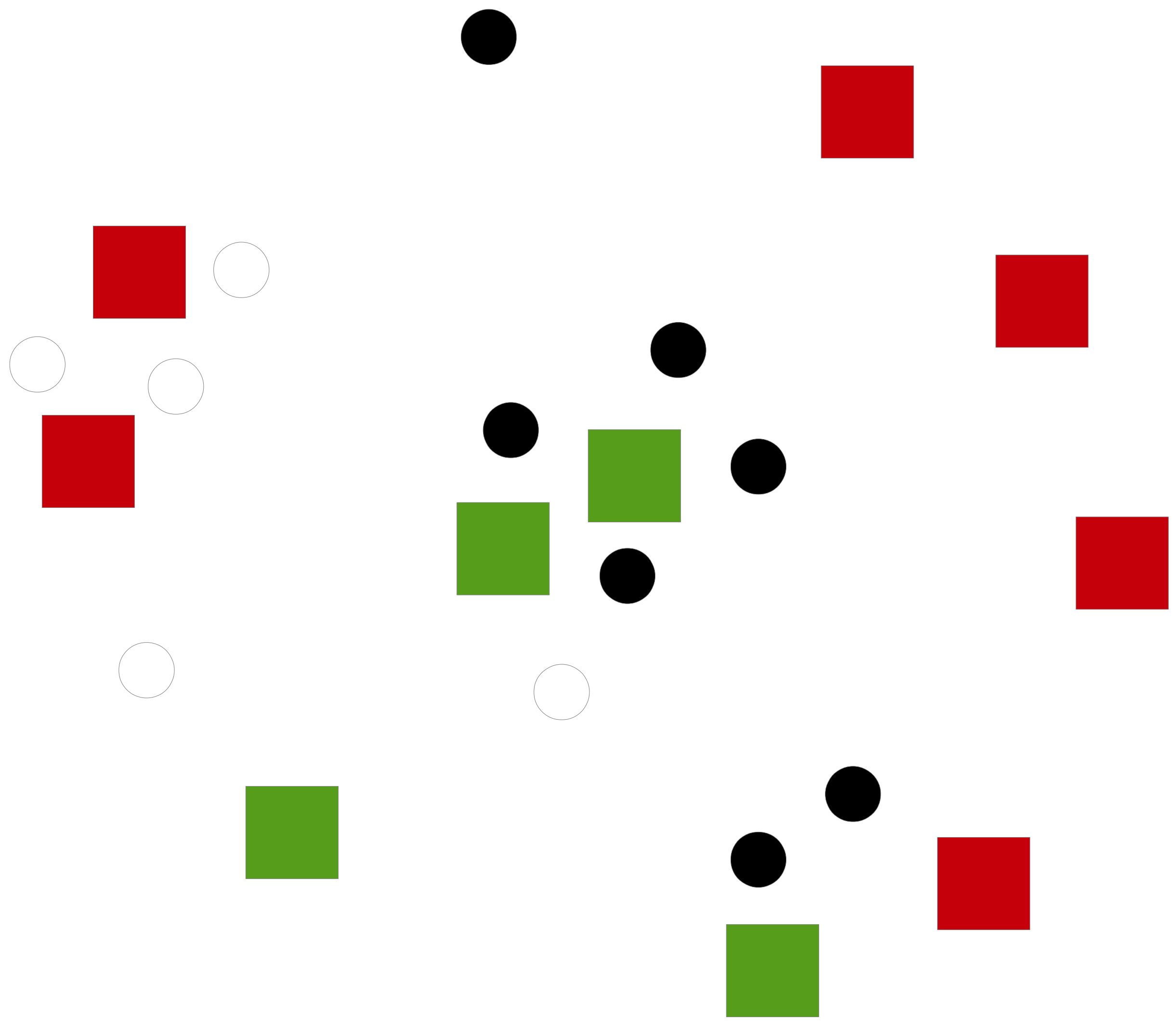




Supporting calculations from theorists indicate :
core QCD properties are preserved

**arxiv:1510.03823**
**arxiv:1603.06375**

# Puppi algorithm

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



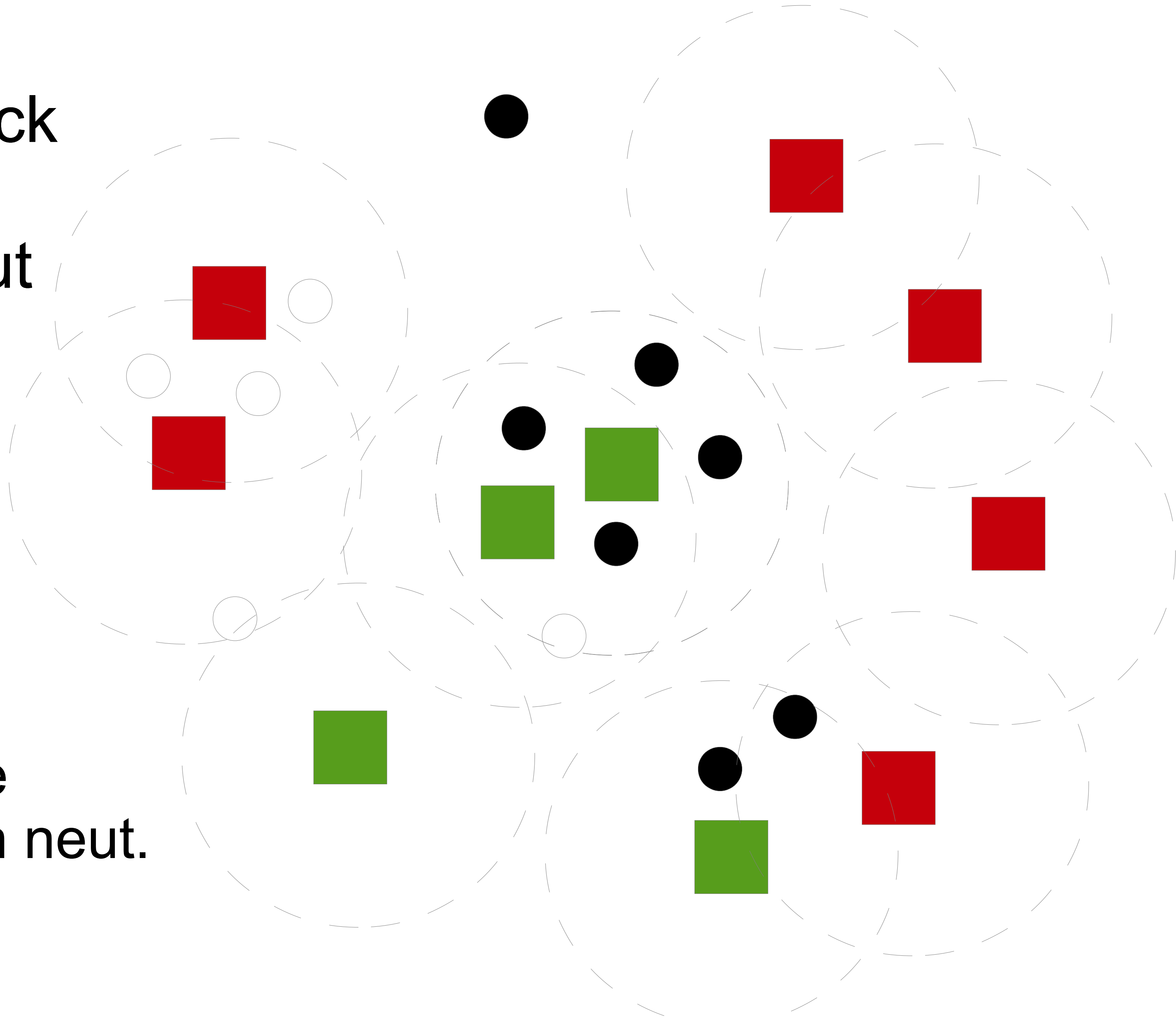
Step 1
Tracks can point to PU vertices w/high efficiency

Arxiv/1407.6013

# Puppi algorithm

## Key

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



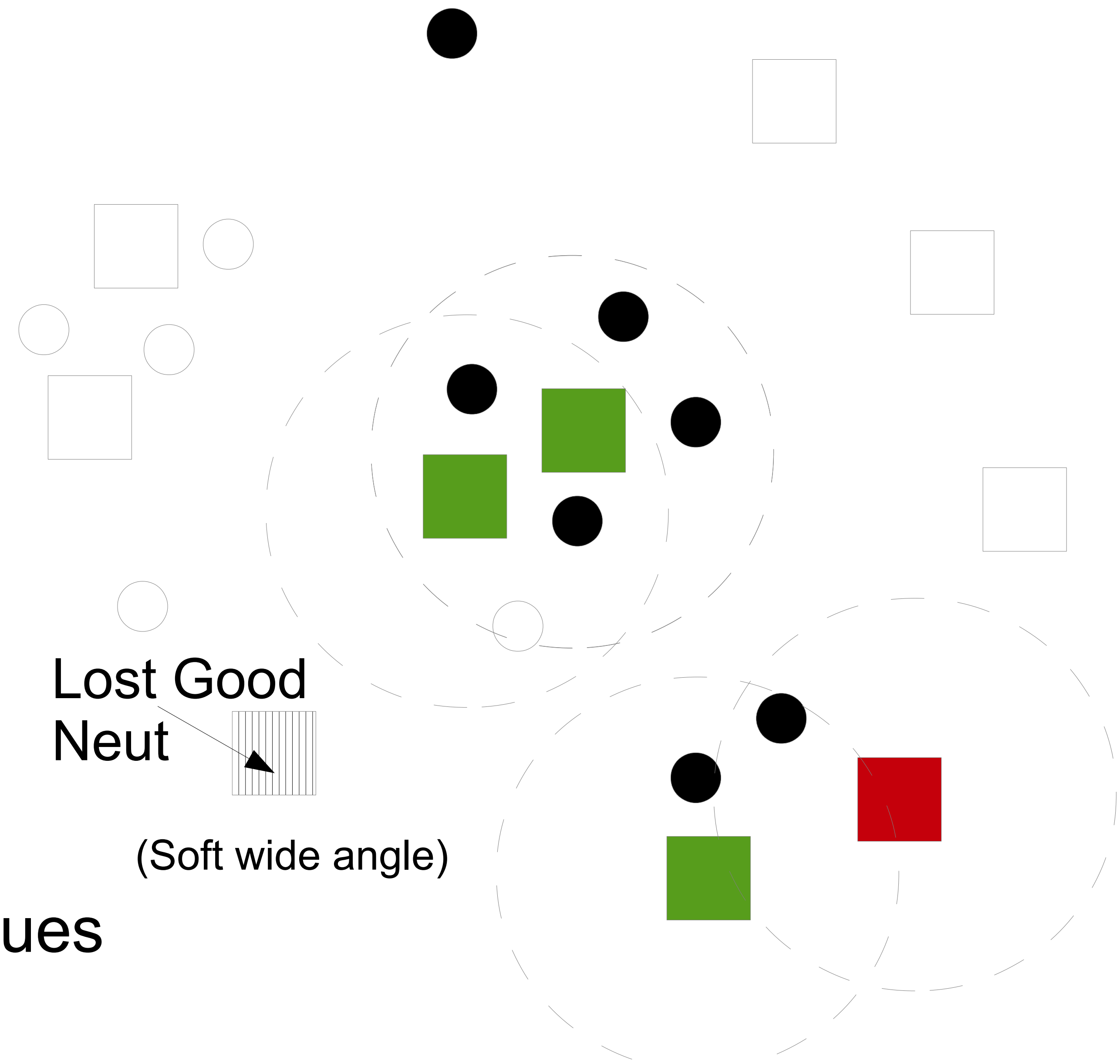
Step 1
 Vertexing
Step 2
 Draw a cone
 About each neut.

**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

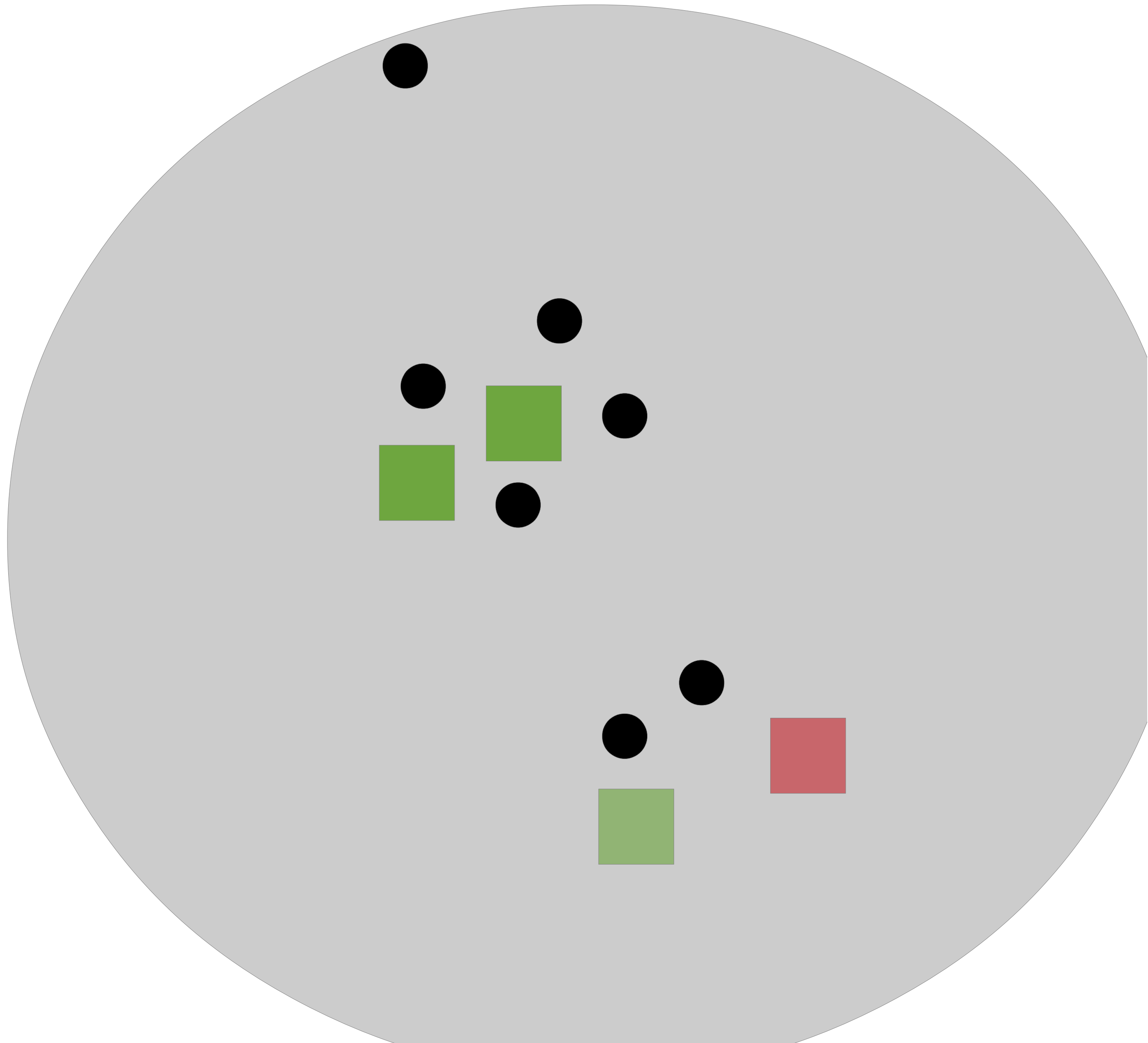
Step 1
 Vertexing
Step 2
 Draw a cone
Step 3
 Remove all 0 values
Step 4
 Reweight Neutrals by weight factor

**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

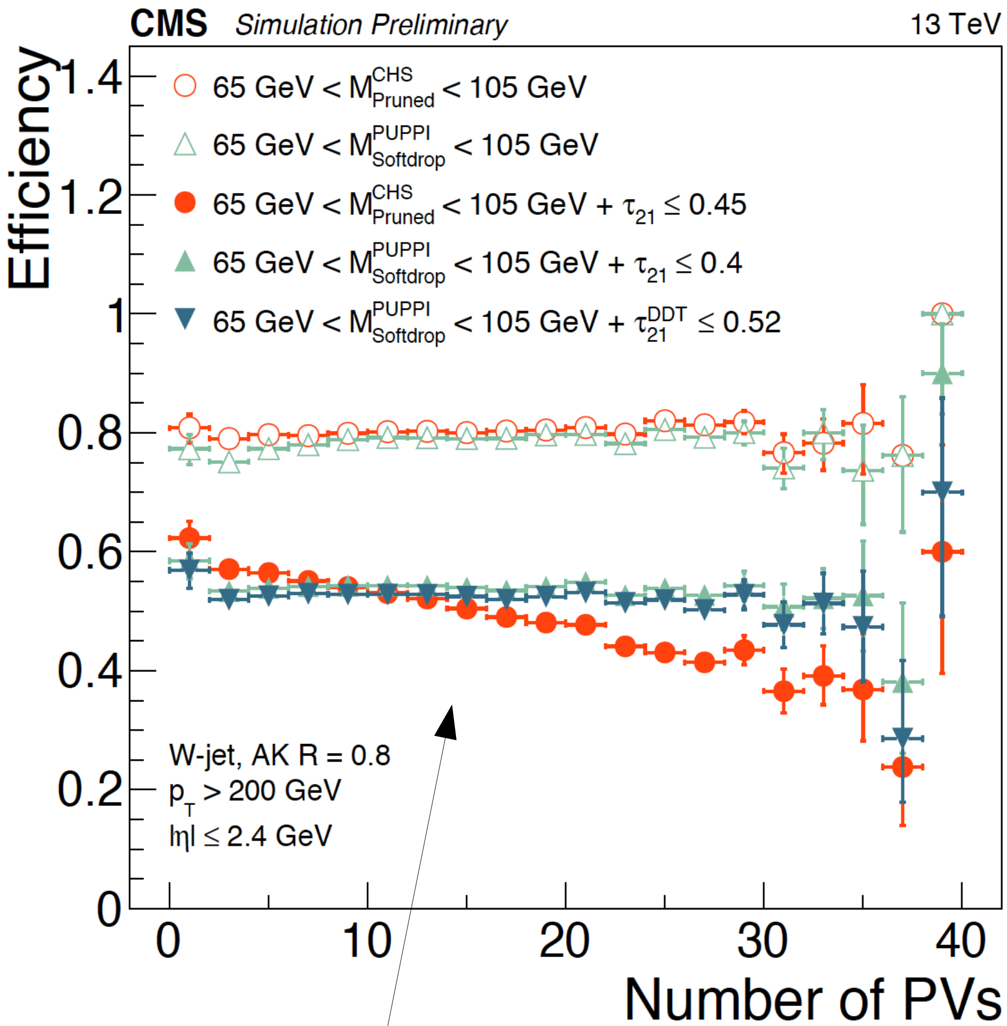
Variable roughly gaussian→ build likelihood

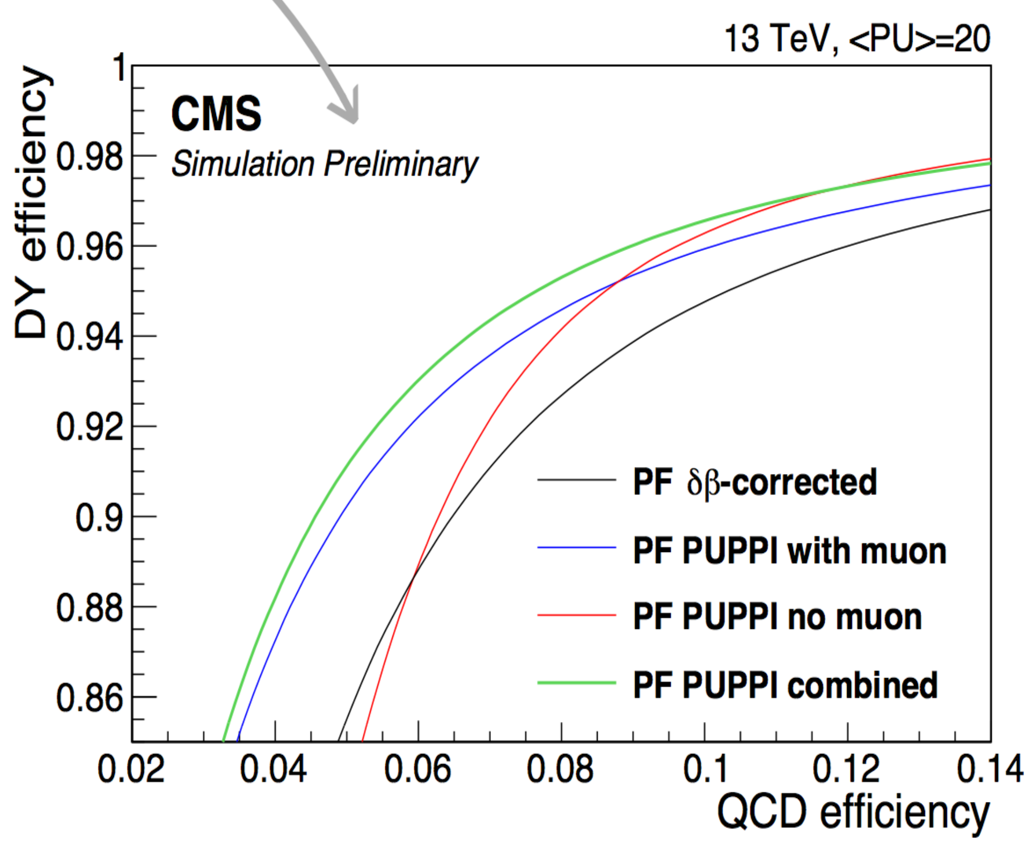
Translate to weight ($w_i$) applied to each candiate

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

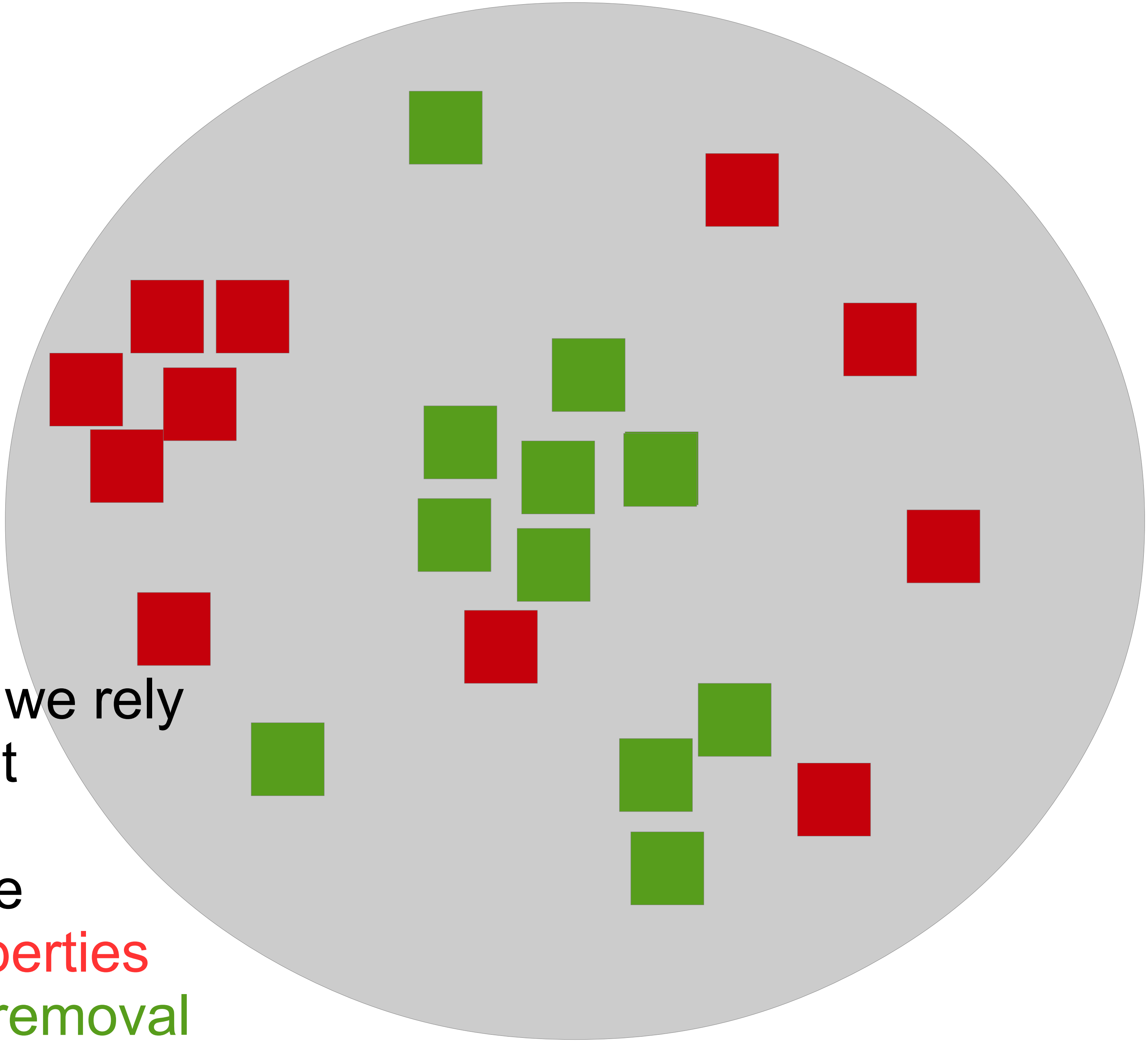
CMS-JME-16-003

CMS-DP2015-034

# Puppi No Tracking

Key

Good Neut
PU Neut
Chosen
Removed



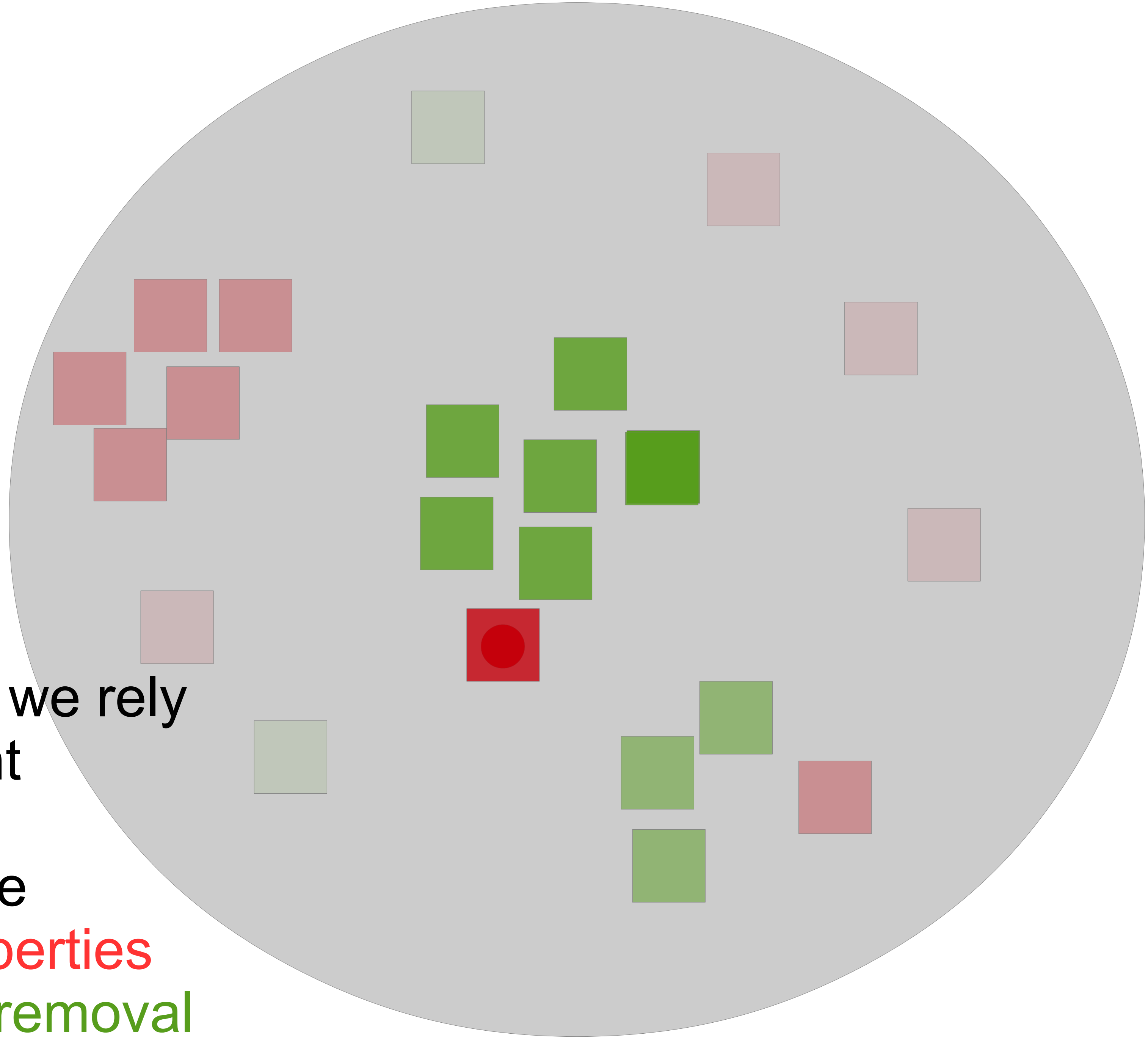
Without tracking we rely heavily on weight

Can induce some
biases in jet properties
Good for PU jet removal

# Puppi No Tracking

Key

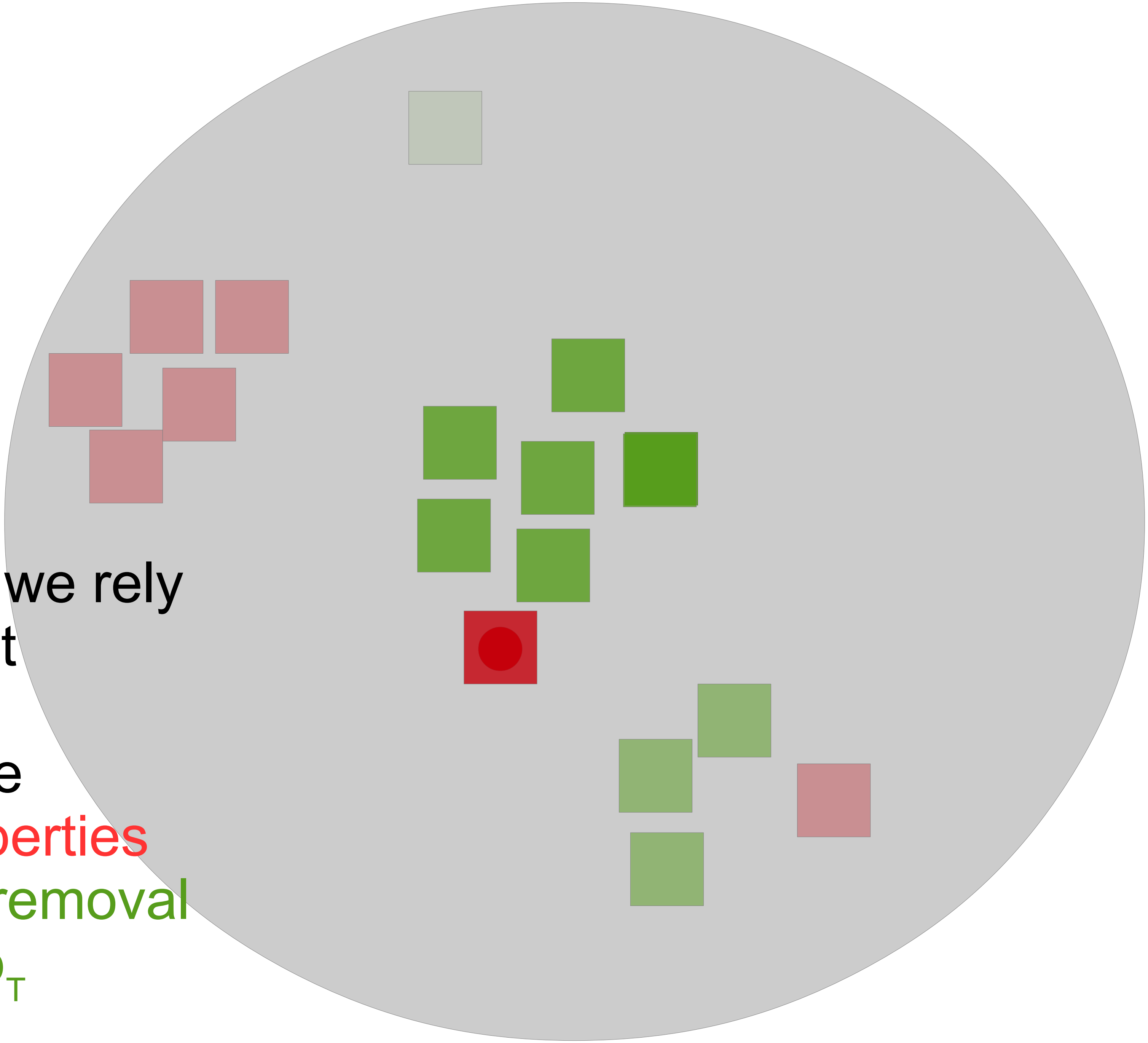
Good Neut
PU Neut
Chosen
Removed



Without tracking we rely heavily on weight

Can induce some
biases in jet properties
Good for PU jet removal

# Puppi No Tracking



Key

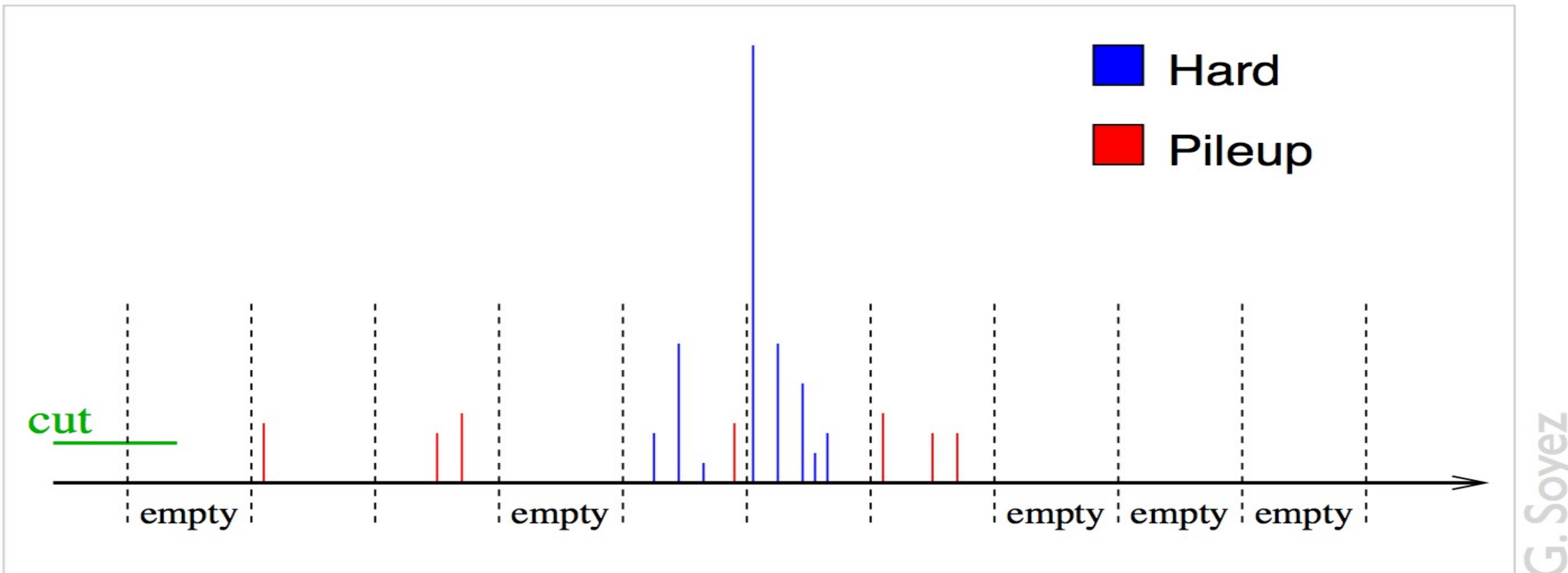
Good Neut
PU Neut
Chosen
Removed

Without tracking we rely heavily on weight

Can induce some
biases in jet properties
Good for PU jet removal
Apply cut on $w_i\ p_T$

# Soft Killer

$$p_t^{cut} = \underset{i \in \text{patches}}{\text{median}} \{p_{ti}^{max}\}$$



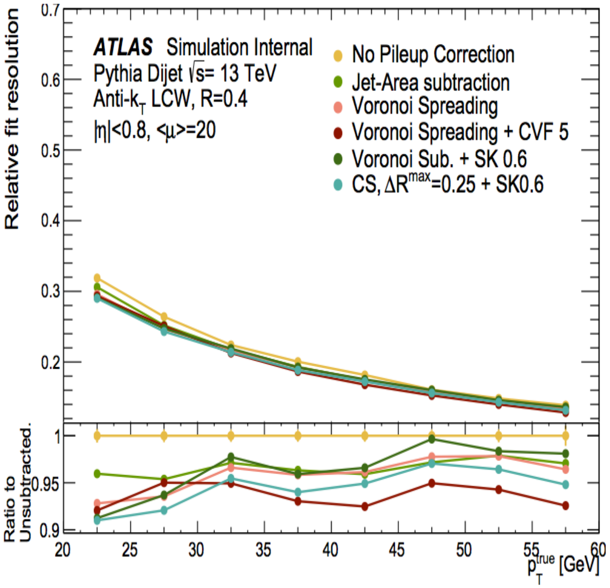

**Half of the event is empty ⇒ ρ = 0 (because it's the median)**

Soft killer is a dynamic $p_T$ cut adjusted  to get grid ρ to be 0

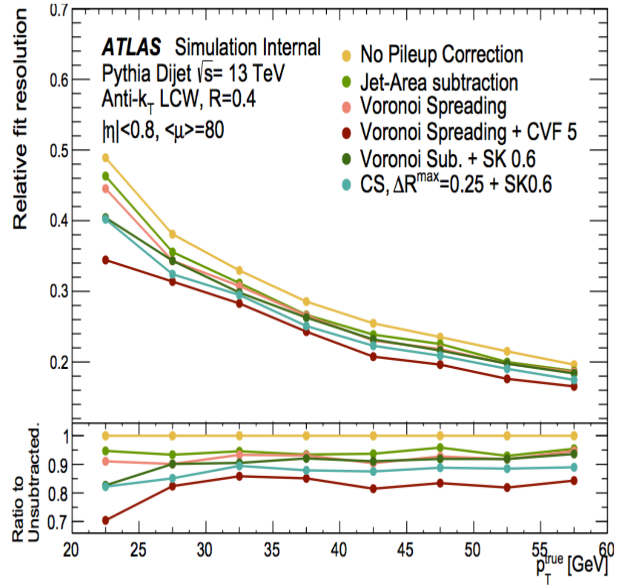
Grid size is a tunable parameter

Soft killer presents a particle level alternative to PUPPI w/o use of angular informaiton

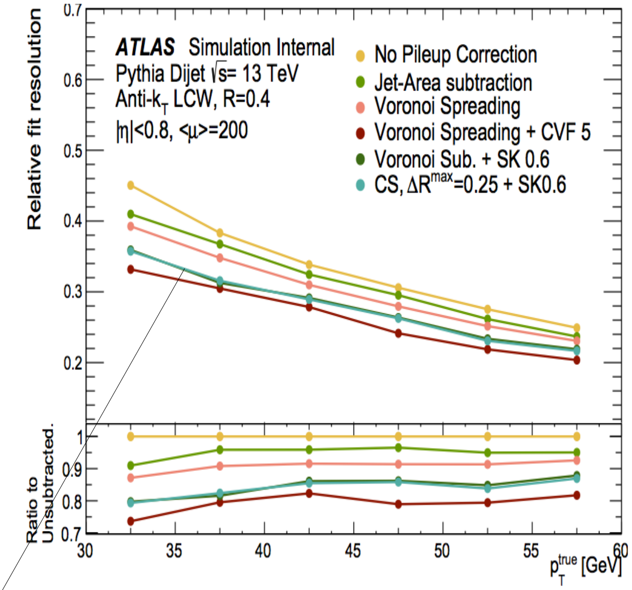
# Comparing Performance




$\langle\mu\rangle$ = 20




$\langle\mu\rangle$ = 80




$\langle\mu\rangle$ = 200

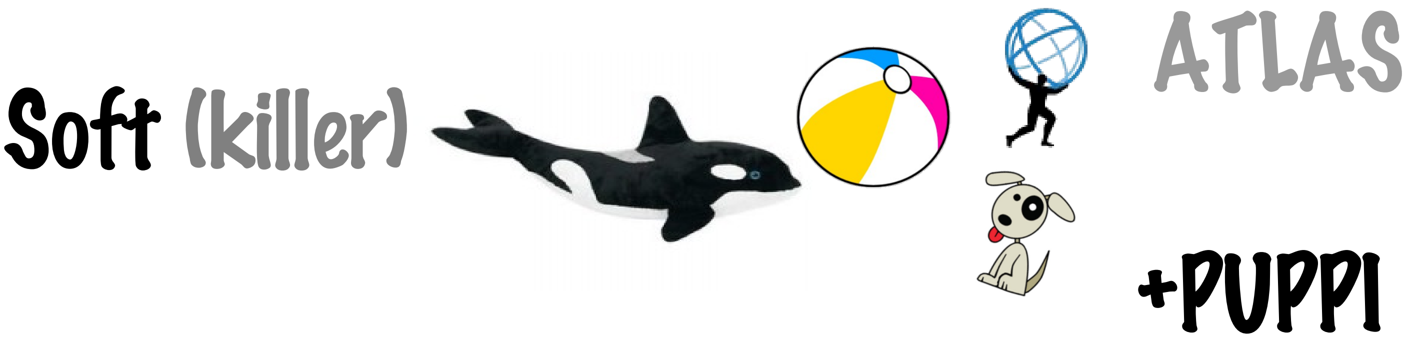
Combined hybfid of Consitiuent subtraction and Soft Killer
Currently the most performant on ATLAS (note : no PF)

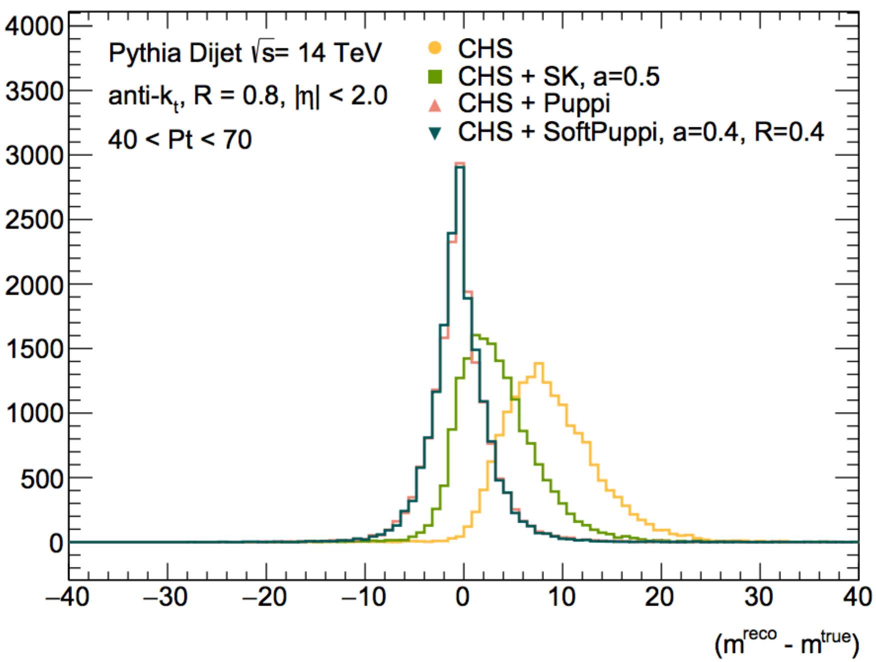
# The future of PUPPI

- A big criticism of PUPPI has been
  - Puppi needs to be tuned
  - This is true but :
    - We don't expect to retune it very often
    - Tunes mostly about determining the right detector geometry
  - NB: Current ρ subtraction in CMS is highly tuned
- What do we tune :
  - Weighted pT cut : $w\, p_T > C + B\, N_{PV}$
  - Additional parameters (not changed):
    - Cone-size,Algorithm,Using charged or not
    - Only adjusted with detector geometry (tracking or not)
- Can we minimize the amount of tuning?

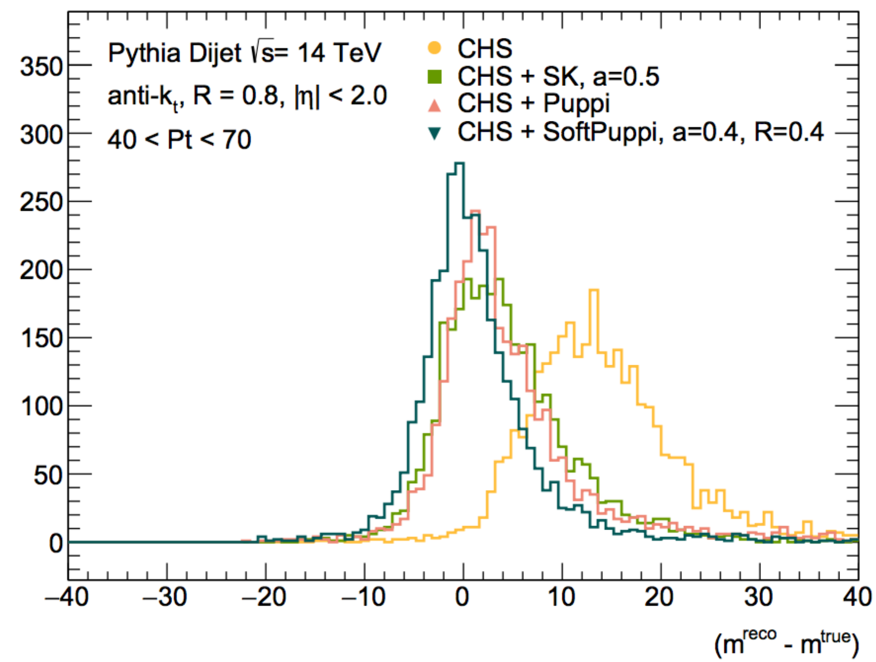
# A new idea

- Can we replace the weighted neutral cut?
  - Try to combine the best of Soft killer w/ PUPPI
  - **P.Harris,N.Tran,J.Roloff,G.Salam,G.Soyez,M.Cacciari**




NPU = 20




NPU = 100

# Pileup subtraction Tools

Global ⟷ Jet Shape Info ⟷ Local

Global ρ
MVA *MET*
JA(F) *MET*

Jet Grooming
Differential ρ
Const. Subtraction
HF/Voronoi
Safe Subtraction
NpC
Jet Cleansing
Pileup Jet ID
...

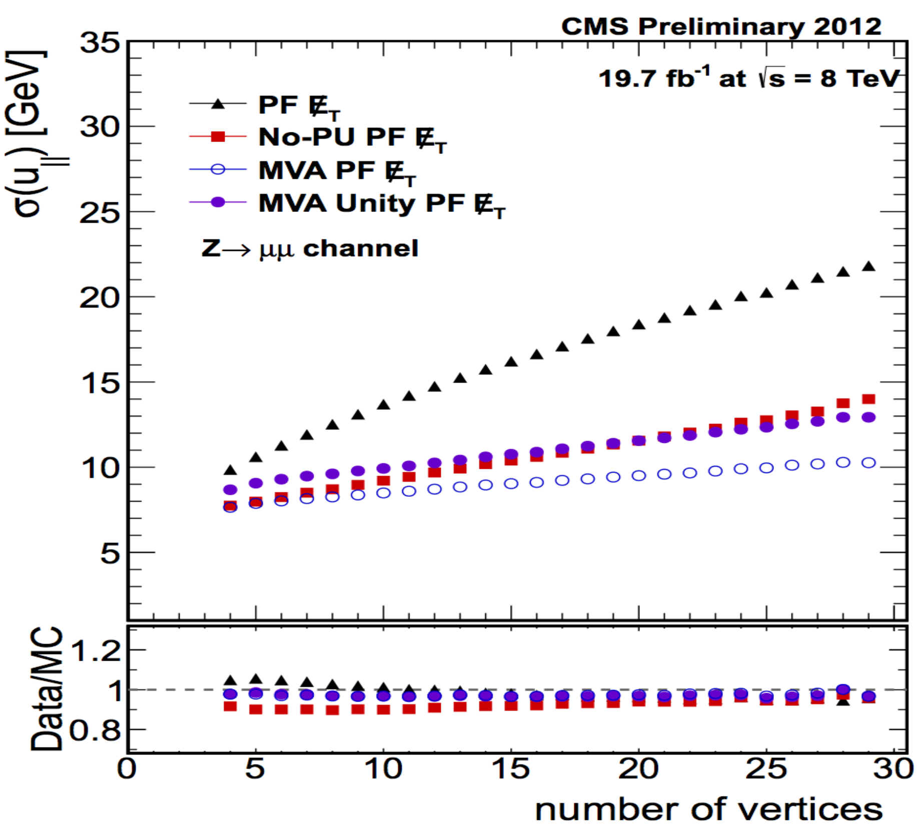
Vertexing (CHS)
Timing
Depth Segmentation
TopoClustering
Soft Killer ($p_T$)
Wavelet
...

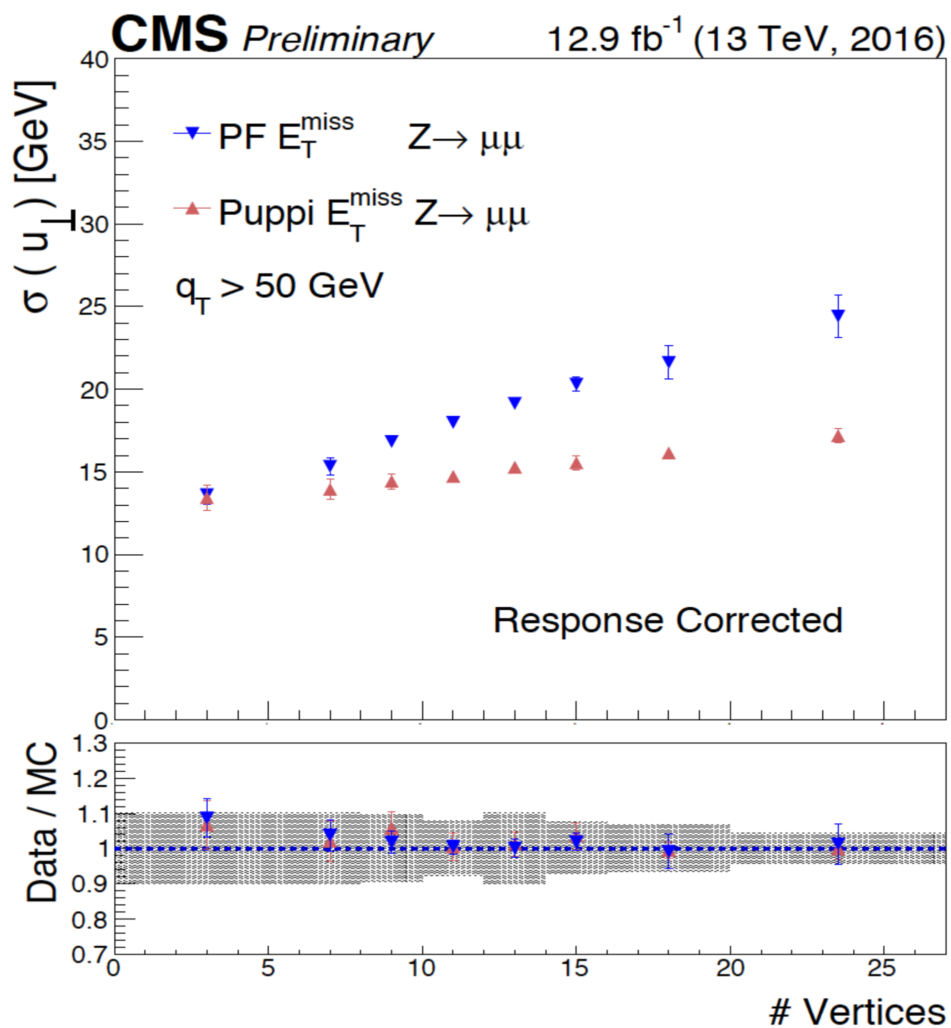
# Looking Forwards

## (And Backwards)

# MVA Approaches

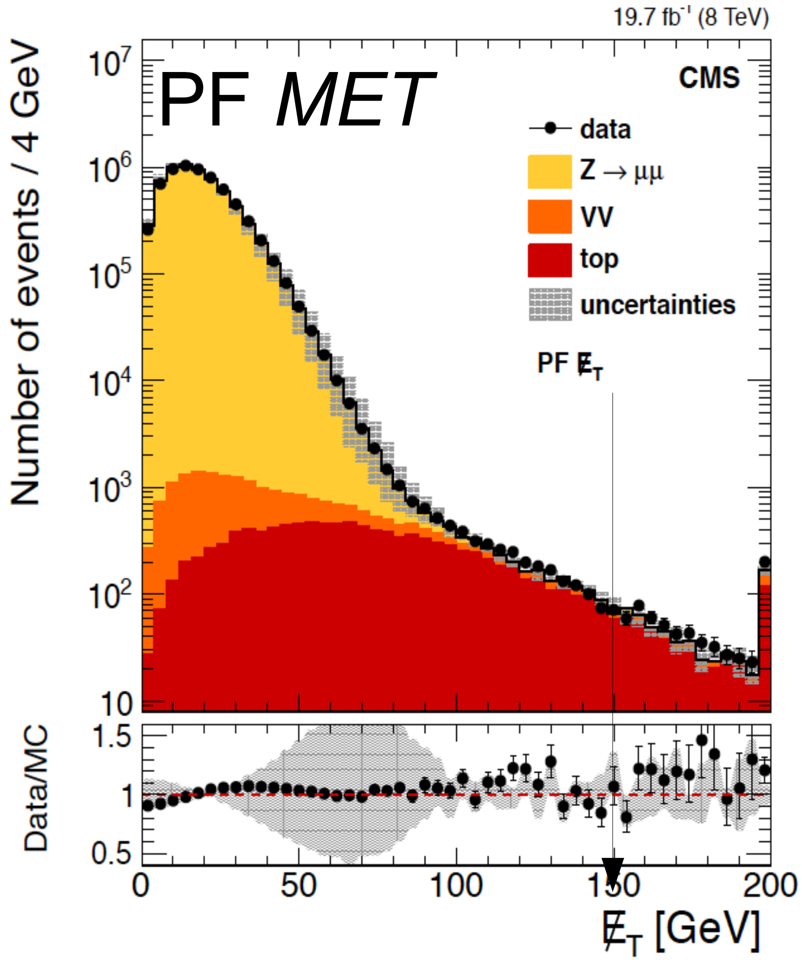
One of the biggest MVA successes in LHC was
using it to reduce Pileup in *MET*

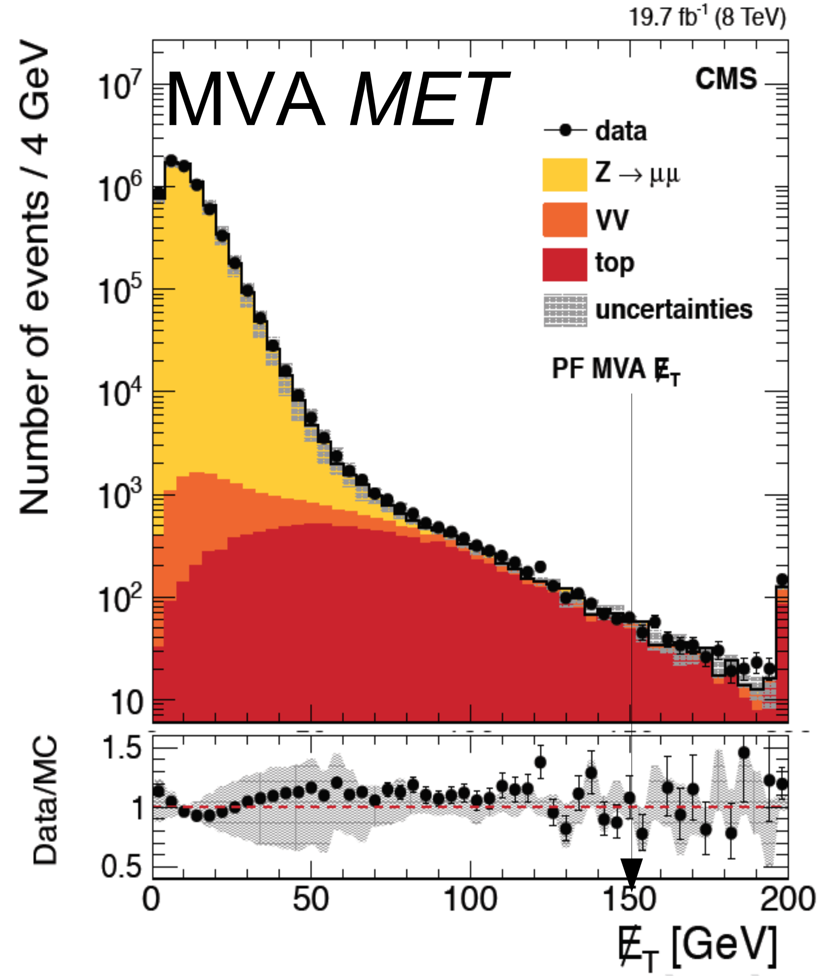



Now almost descoped : PUPPI gives a similar performance

# Best at getting Tails



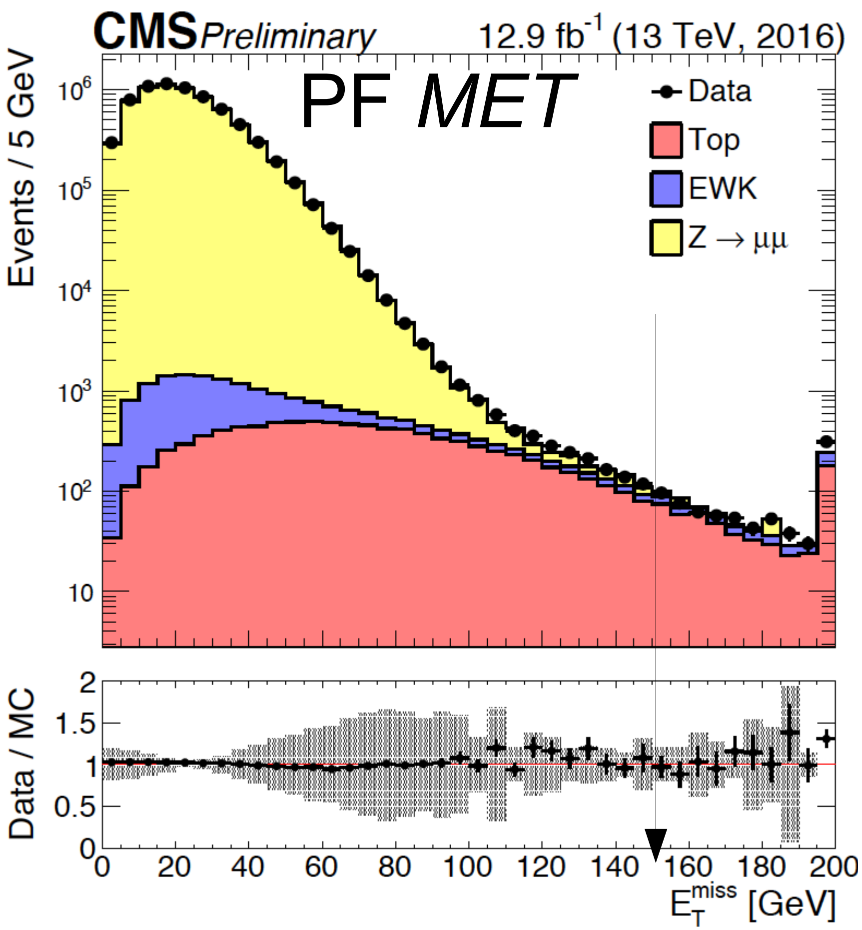



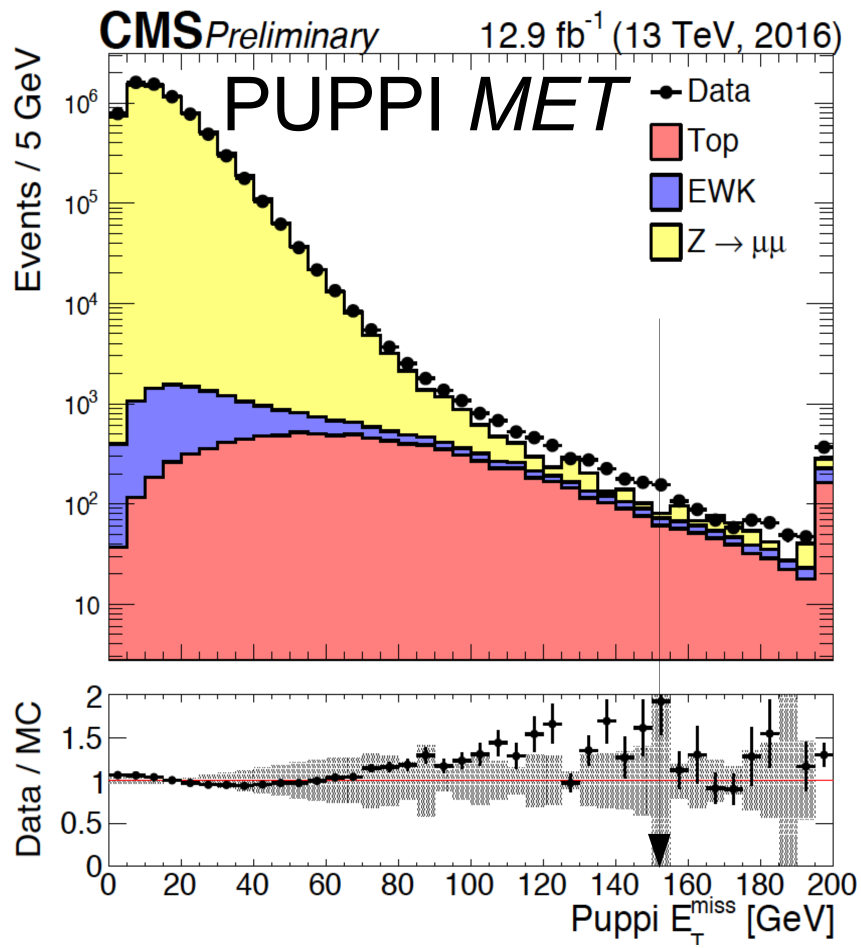

The biggest advantage of MVA *MET* was reduced tails

Consistently improve the *MET* across the full range

Remains today as the best performing *MET* at LHC

# Best at getting Tails




With PUPPI we gain the resolution improvement

However there is some contamination in the tails

Much of tail comes from jets at |η| of 2.4 (can be fixed)

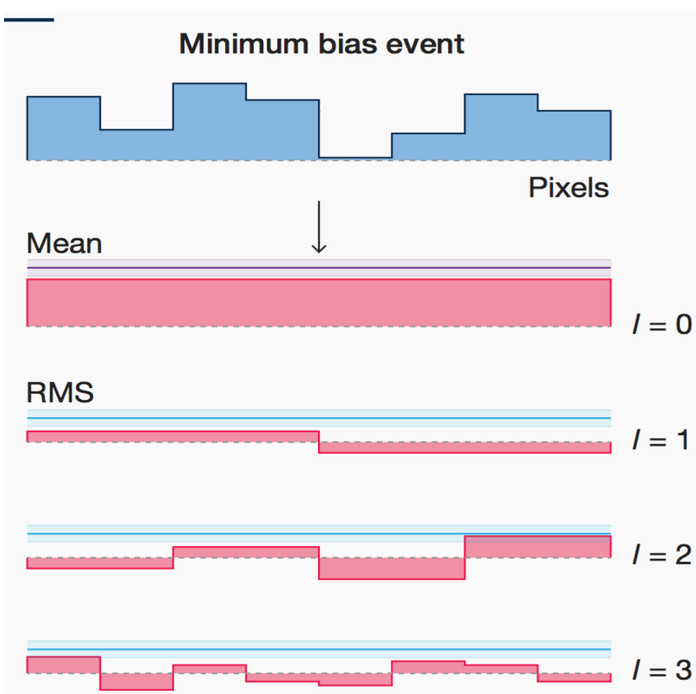
Fine touches like this are what really make MVAs useful

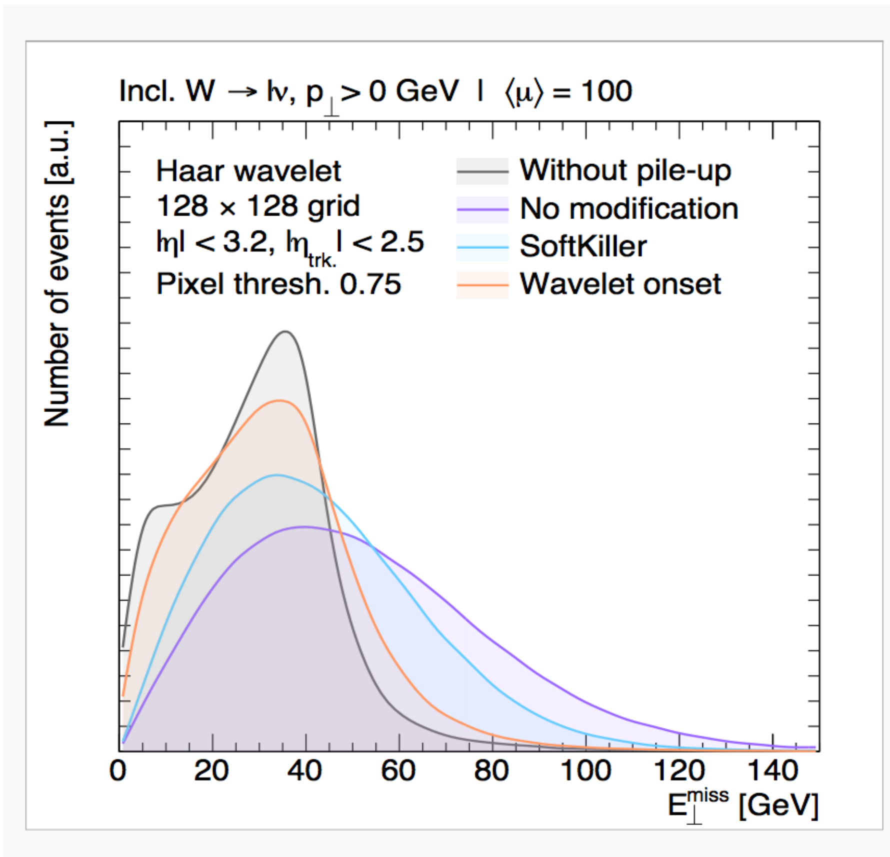
# *MET* reduction with Wavelets

Aim to exploit local energy density

1. Use Wavelets to deduce nearby energy density vector
2. Take inner product of region with primary vertex vector

Similar idea in spirit to PUPPI instead using wavelet deco

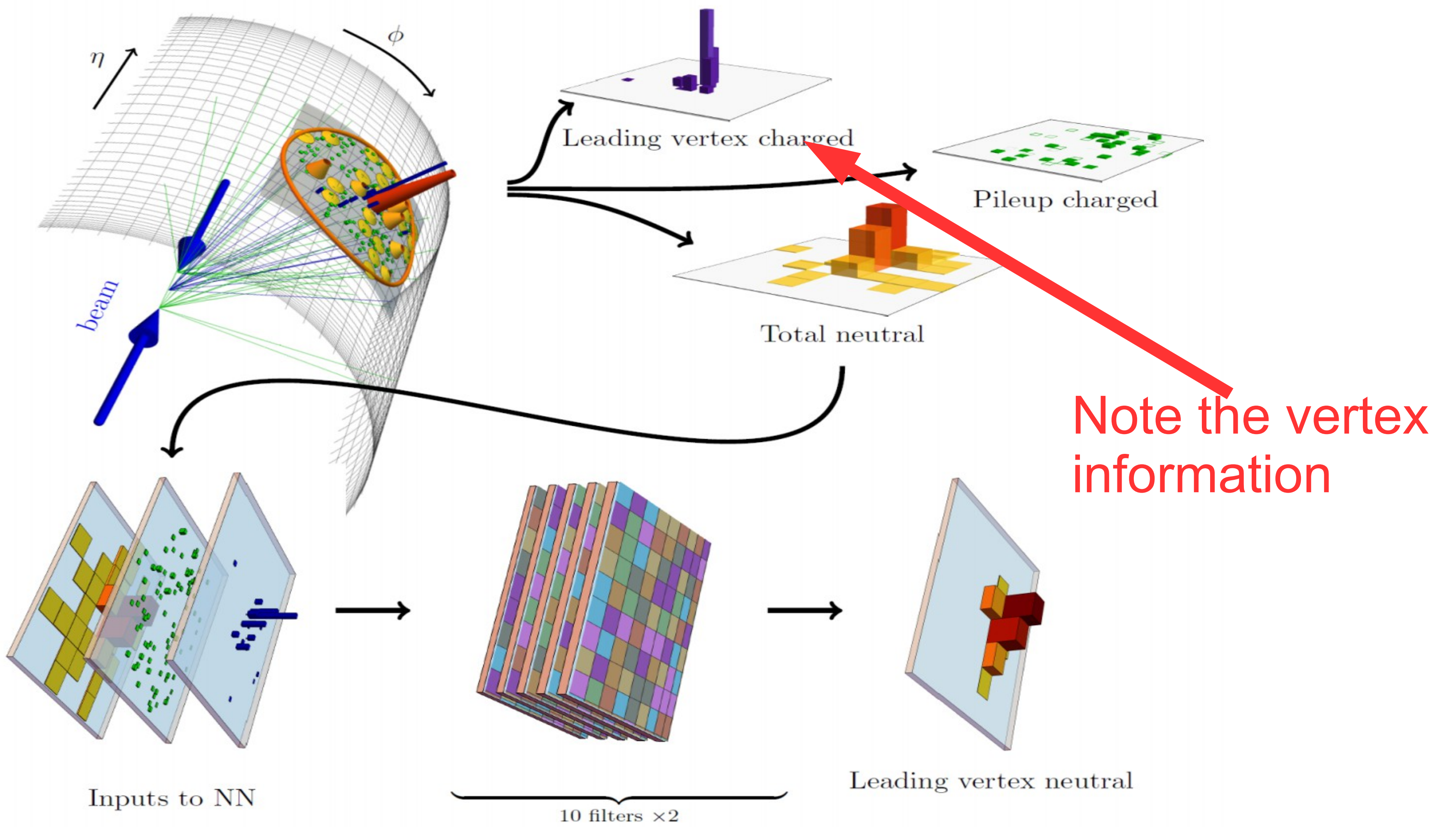


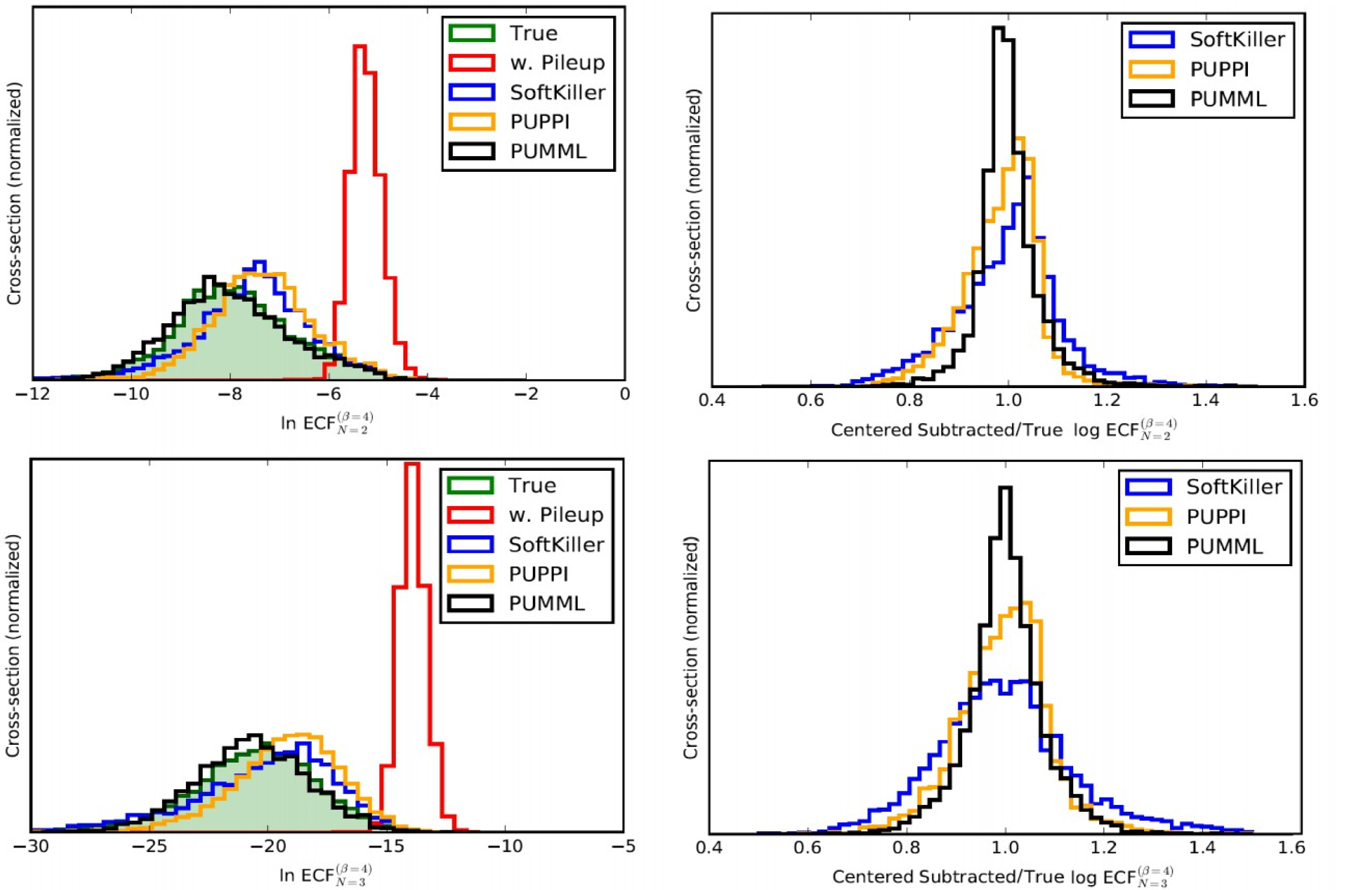

**Andreas Sogaard**

# PUMML : PU mitigation w/ML

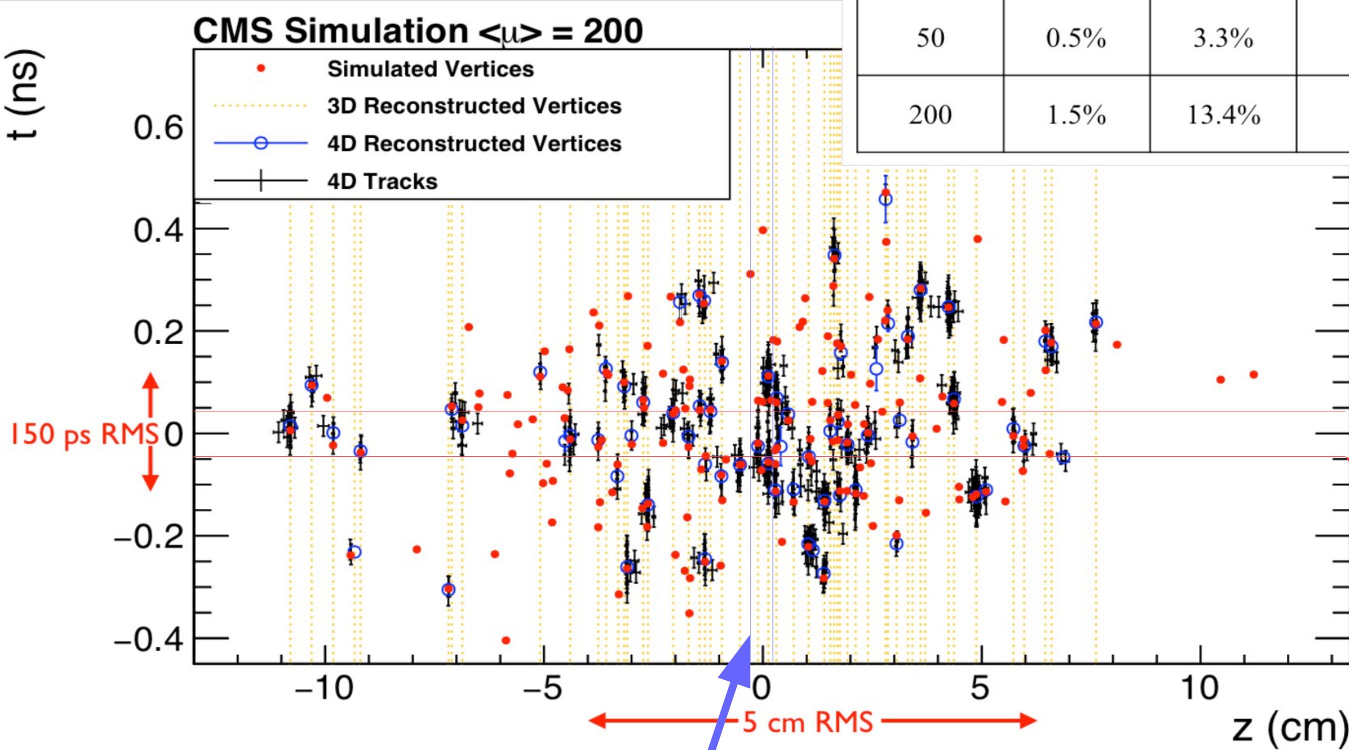
- PUMML is a similar concept to PUPPI
  - Uses region information as an image fed to a DNN



# PUMML : PU mitigation w/ML



# Other technology




CMS Simulation

| <μ> | 4D Merged Vertex Fraction | 3D Merged Vertex Fraction | Ratio of 3D/4D |
|---|---|---|---|
| 50 | 0.5% | 3.3% | 6.6 |
| 200 | 1.5% | 13.4% | 8.9 |

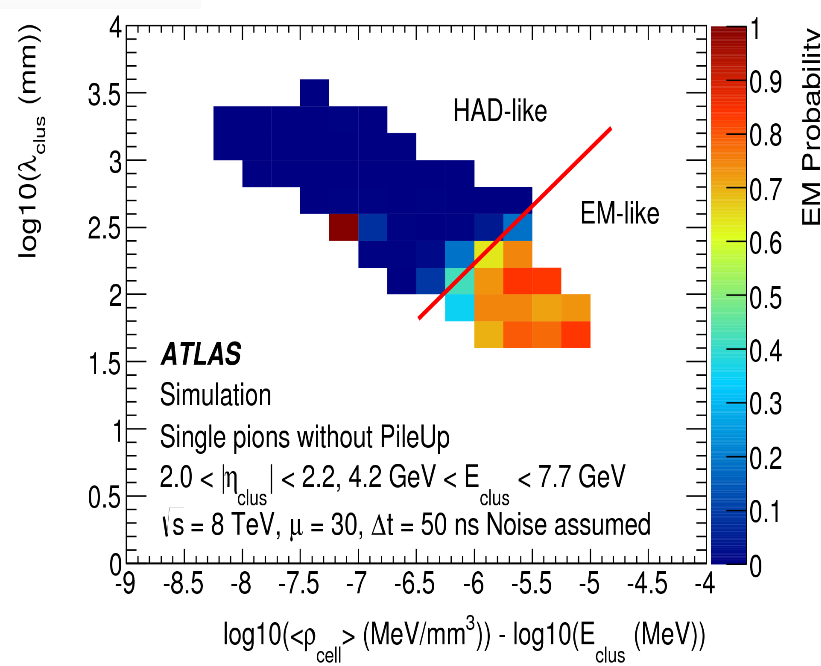
Fast timing

Reduces window for vertexing

Timing resolution

Tracking resolution

- Depth Segmentation
  - Pileup doesn't go as deep
  - ATLAS uses this in cluster reco
    - Layered energy thresholds

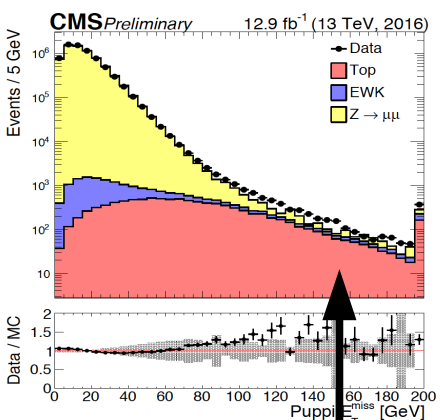


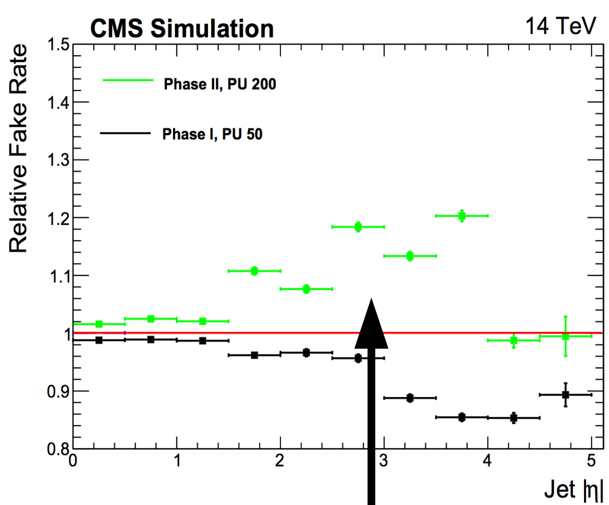

CMS-DP2016-008
arXiv:1603.02934

# Do we hit a wall?

- No

- ….but there is room where we can gain



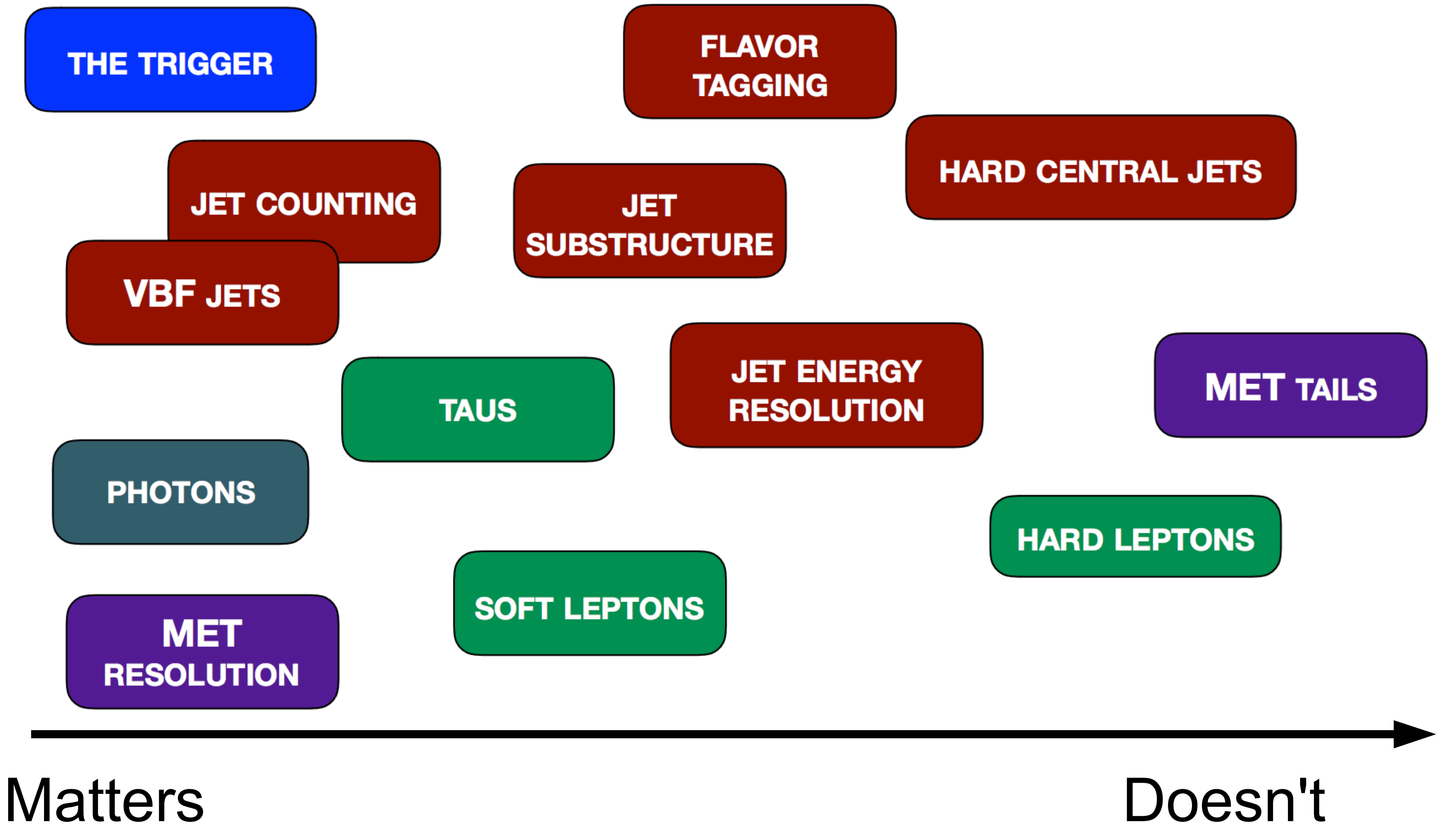




Tails of the *MET*
We know what to do

Jets in forward region

Trigger?!
(does not exist)

# When does UE subtraction matter

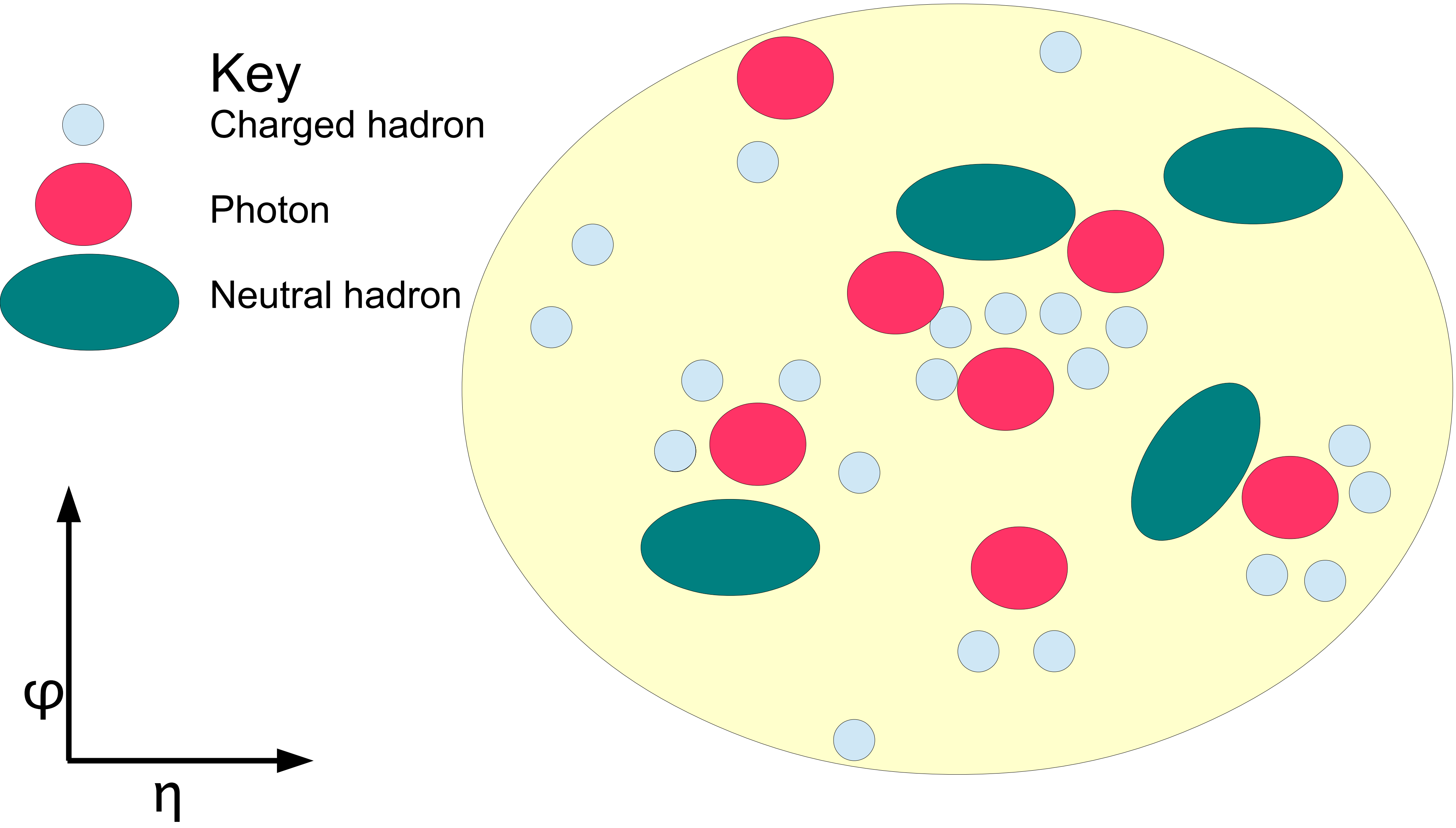


A depiction of Jet Grooming :
0912.0033,1402.2657,0912.1342,/0802.2470

# Jet Grooming

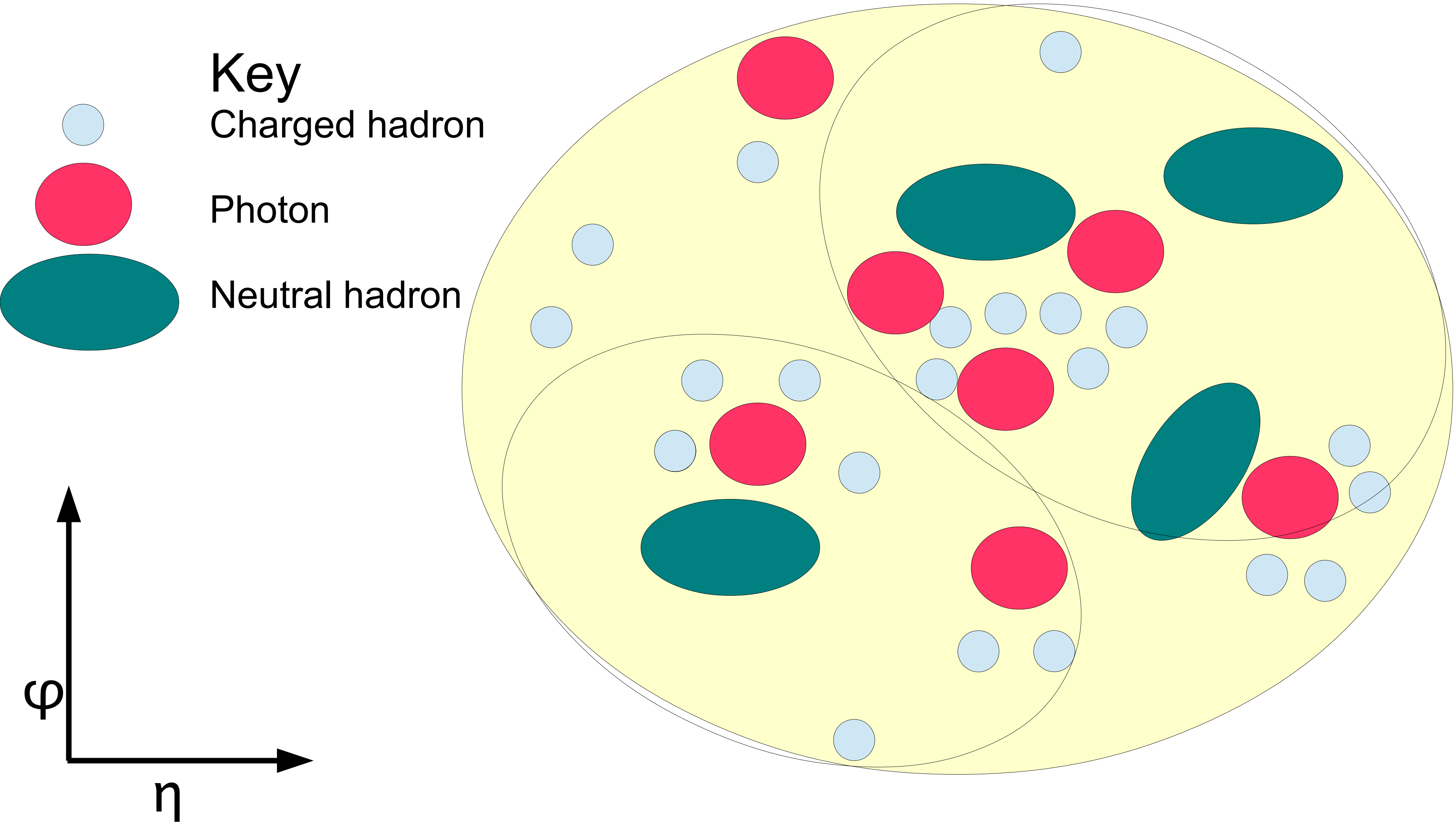
# Jet Grooming

Imagine the surface of a jet



# Jet Grooming

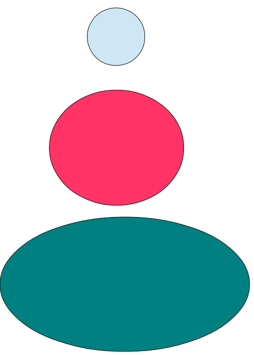
## All Jet groom starts with de-clustering (using CA)

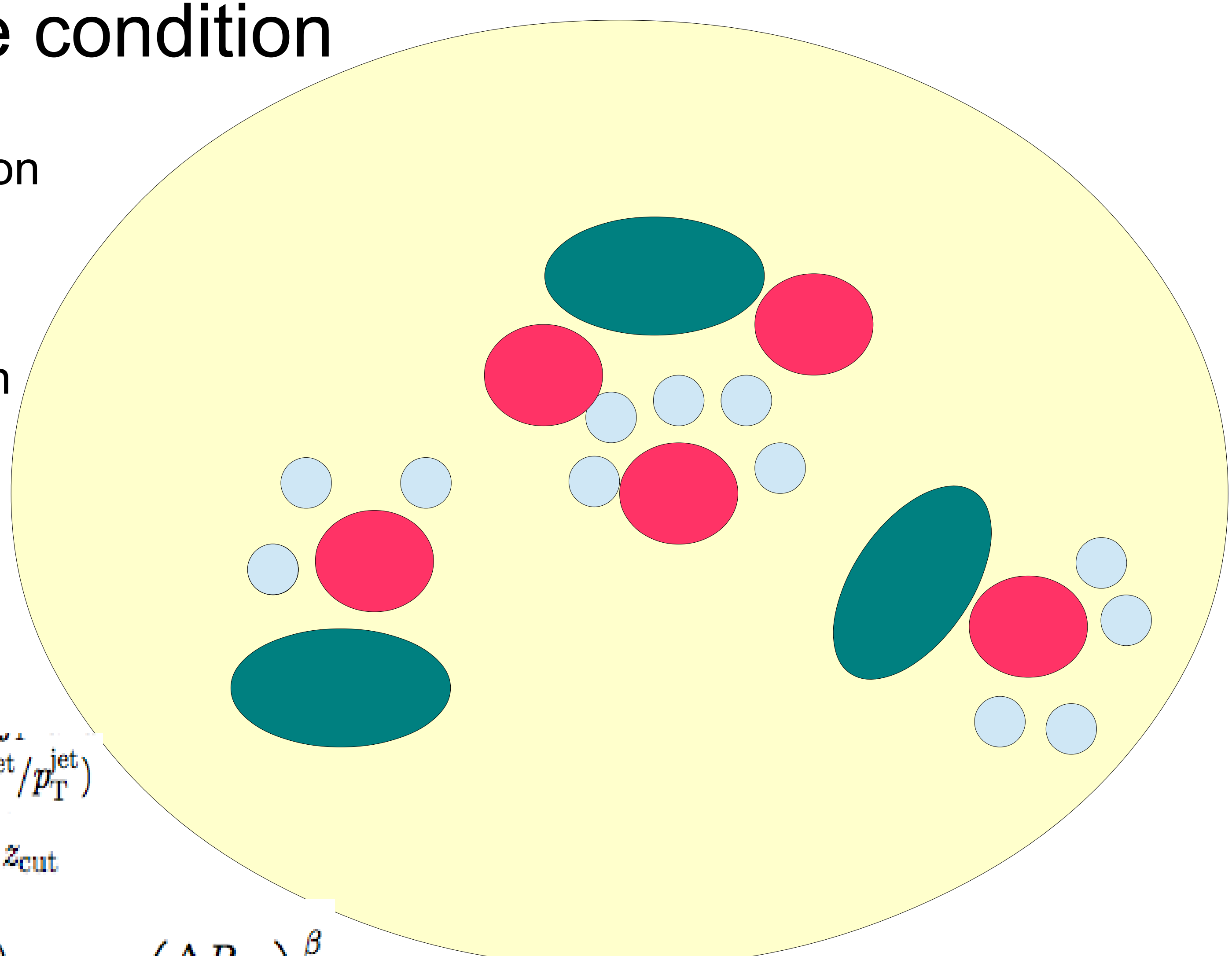


# Jet Grooming : Pruning/Soft Drop

Iteratively decluster jet removing lowest $p_T$ subjet failing pairwise condition

Key



Approaches are generally more aggressive

Pruning : $\Delta R_{j_1,j_2} < R_{\text{cut}} \times (2m^{\text{jet}}/p_{\text{T}}^{\text{jet}})$, $p_{\text{T}}^{j2}/p_{\text{T}}^{j1+j2} > z_{\text{cut}}$

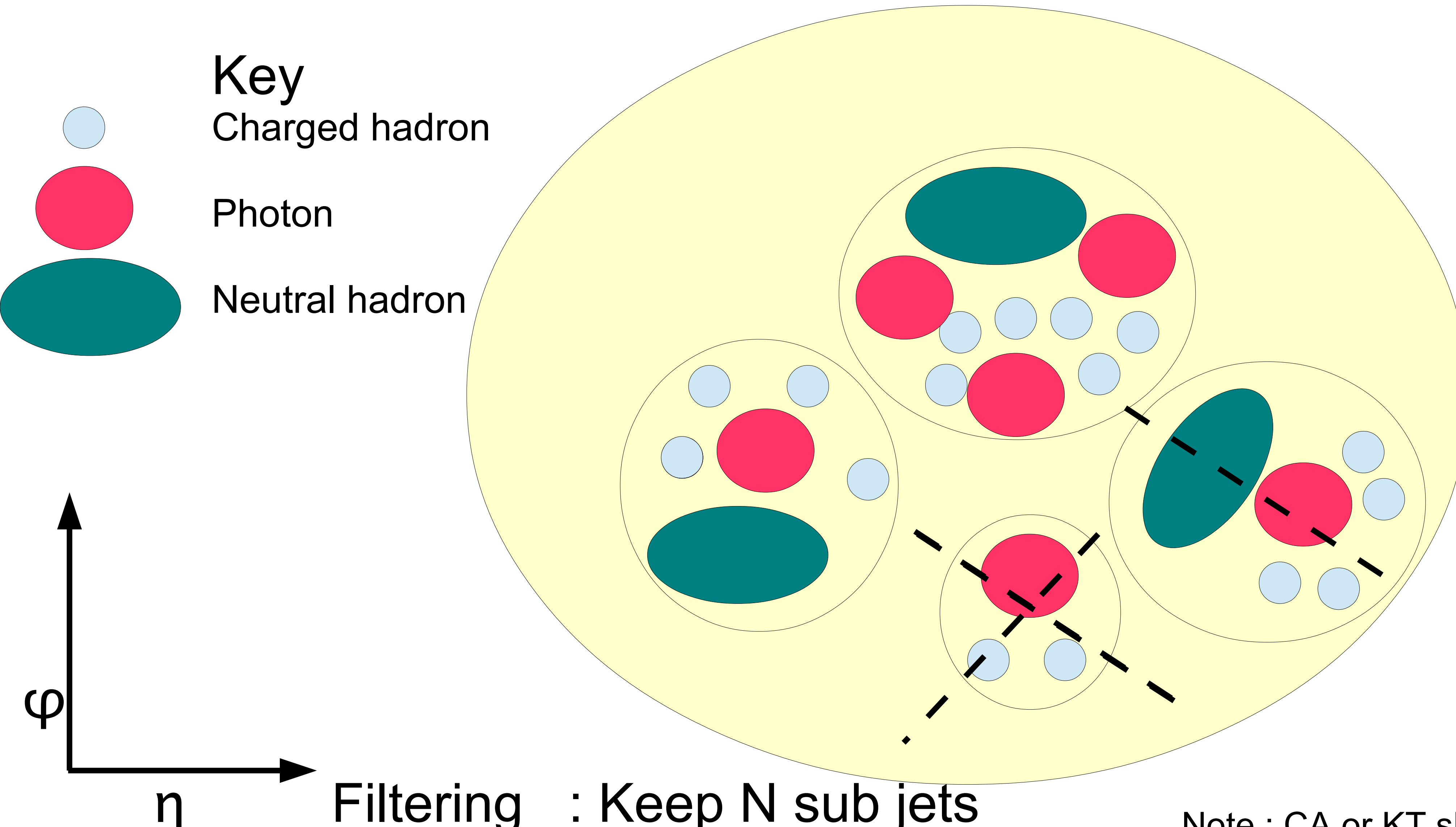
Soft Drop: $$\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} > z_{\text{cut}}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$$

Only first clustering

Note : CA or KT shoul be used to de-cluster

# Jet Grooming : Filtering/Trim/SD

## Decluster jet and take only subjets




Filtering : Keep N sub jets

Trimming : Keep $pT_i/pT_{jet}$ jets

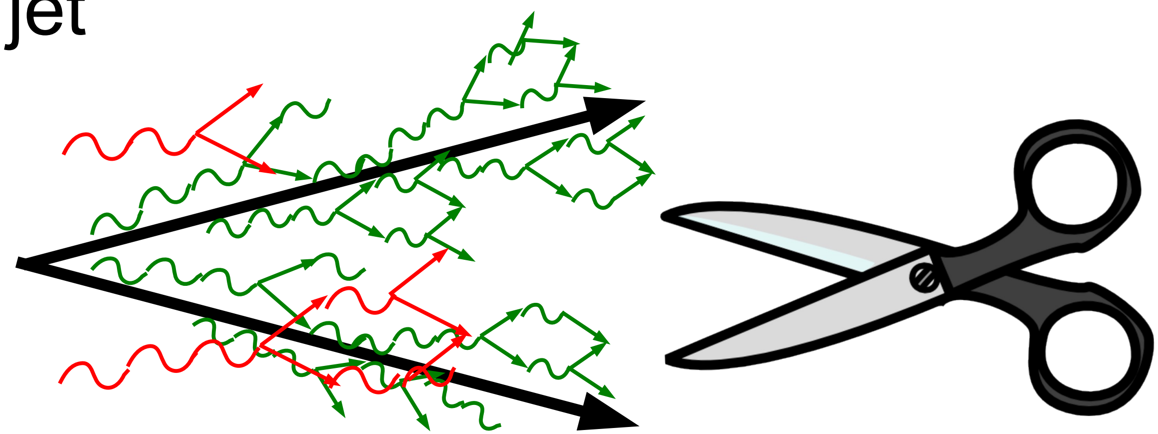
Note : CA or KT should be used to de-cluster

# Jet grooming : a highlight

- Improving the mass resolution on of a jet
  - Requires pruning/trimming away excess radiation

1 jet

W→qq



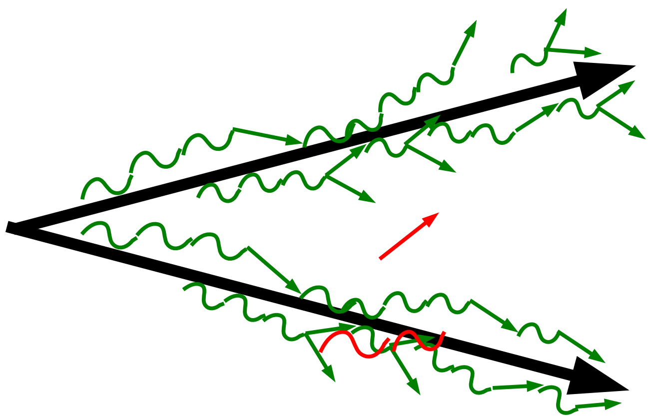
High W $p_T$

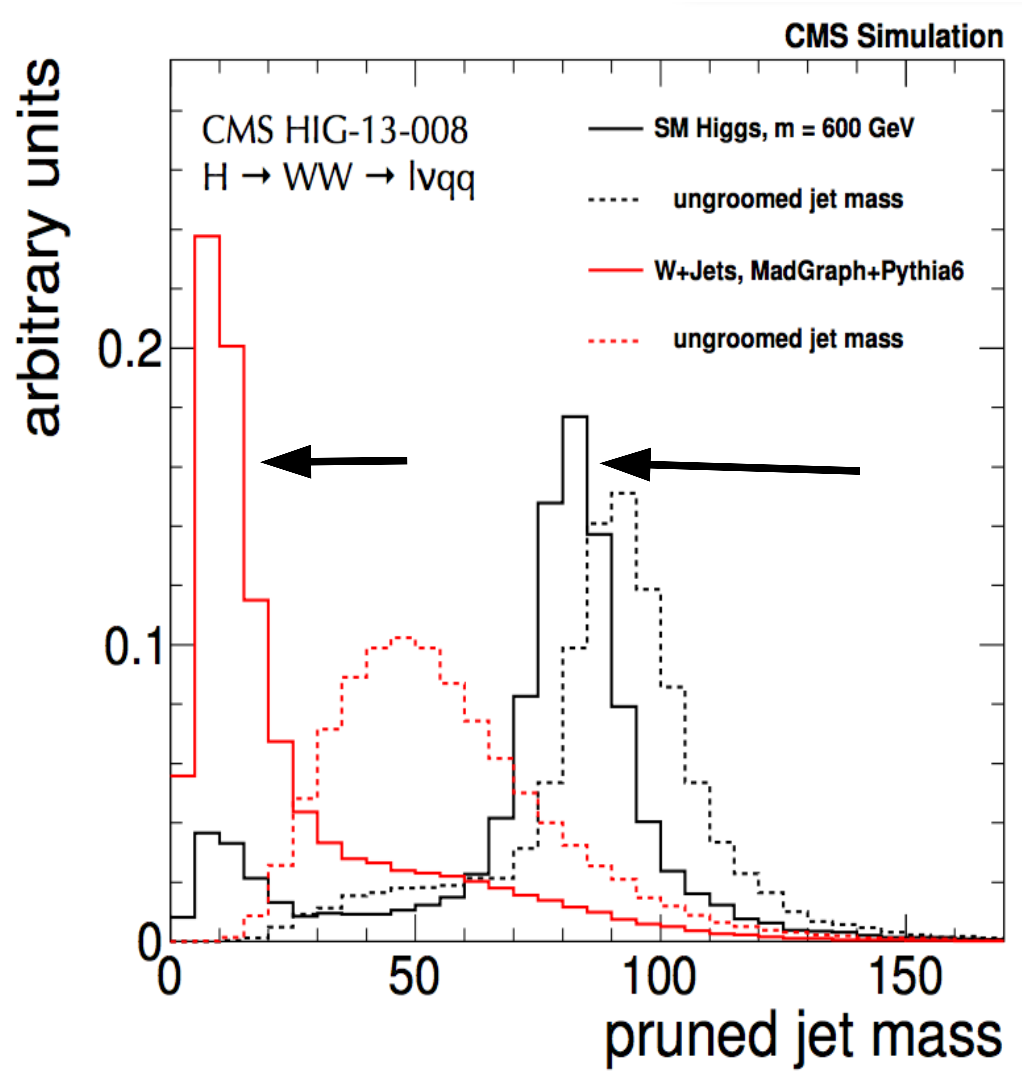
Pileup/QCD radiation

# Jet Grooming : a Highlight

- Improving the mass resolution on of a jet
  - Requires pruning/trimming away excess radiation

W→qq





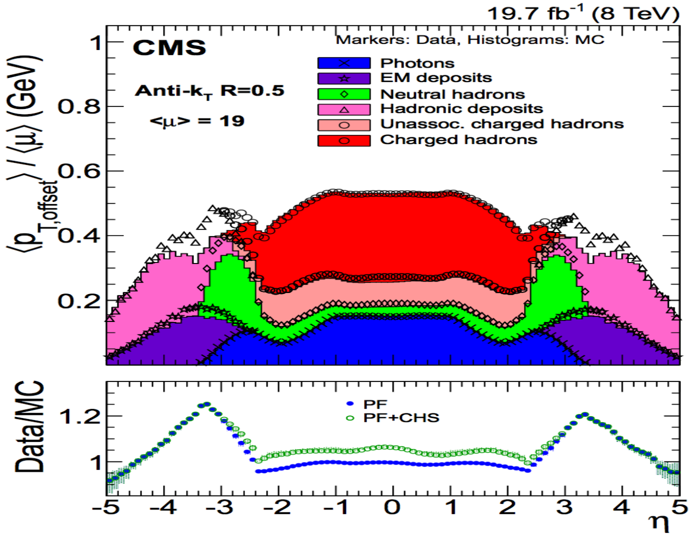

Jet grooming improves the resolution of jets

Pileup/QCD radiation

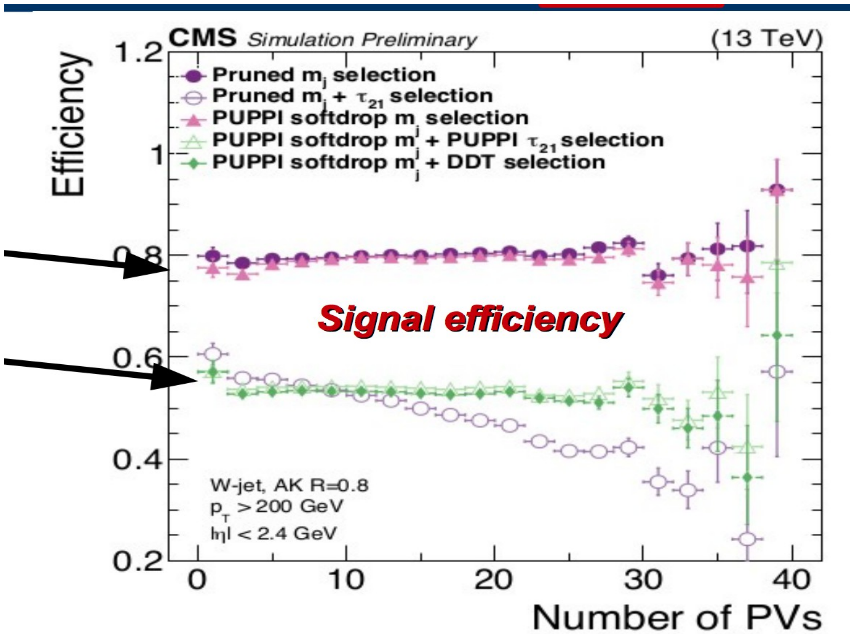
# PU : ATLAS vs CMS

CMS

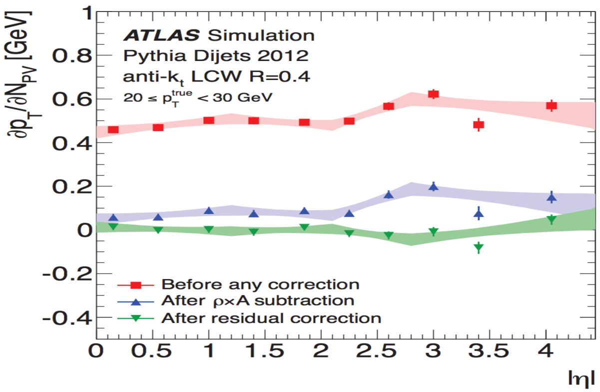
## Small jets : Area sub



## Large jets : PUPPI

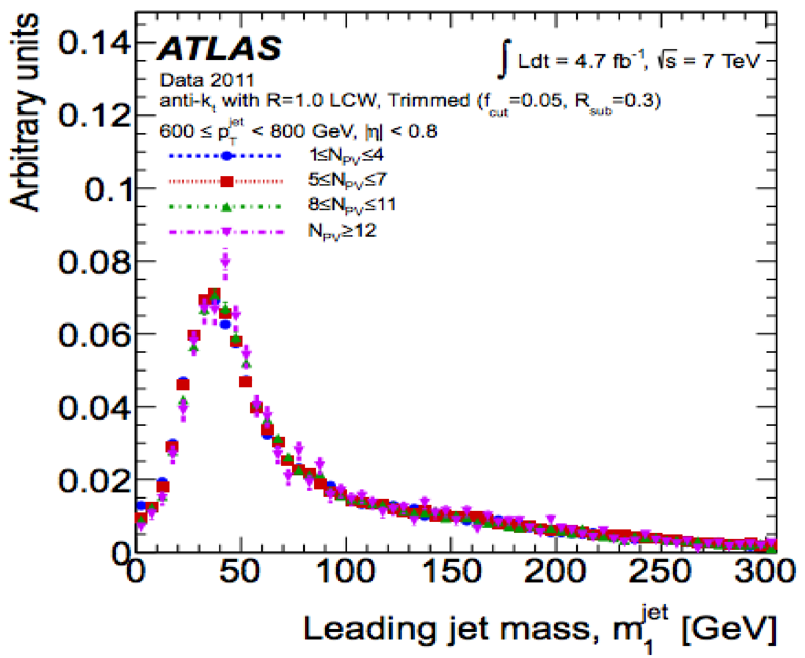


## Small jets : Area subtraction



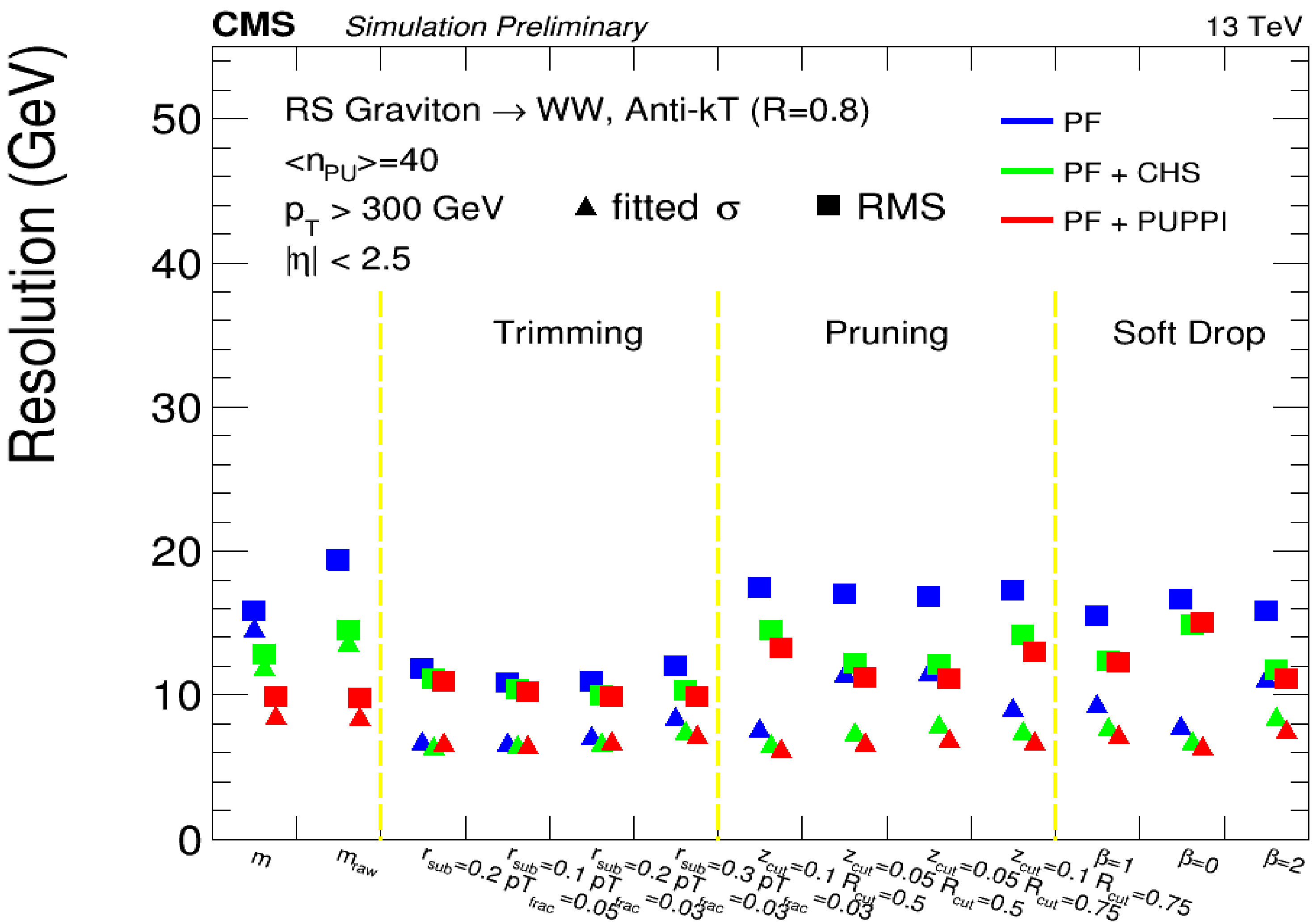
ATLAS

## Fat jets : using trimming On whole jet



# Grooming and UE subtraction

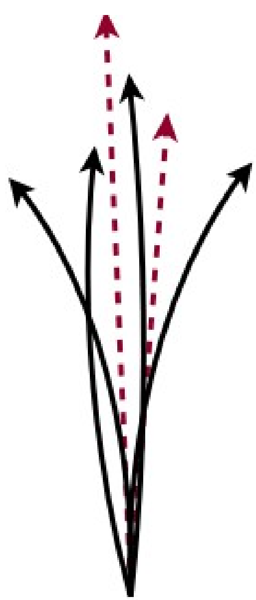
- Grooming is going after the jet structure
  - UE subtraction is going after other effects : use both



# Quark Gluon Discrimination

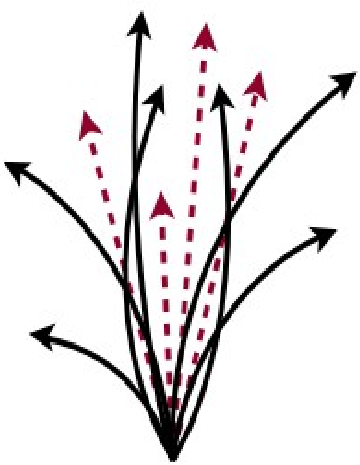
- Goal : Separate quarks and gluons
  - New technique for modeling of discriminant in data
  - Application : AK5 Jets
  - Potential application to many other approaches

**Quark jets:**



Narrow
Have less particles
High $p_T$ core
Enhanced in Z/γ+jets

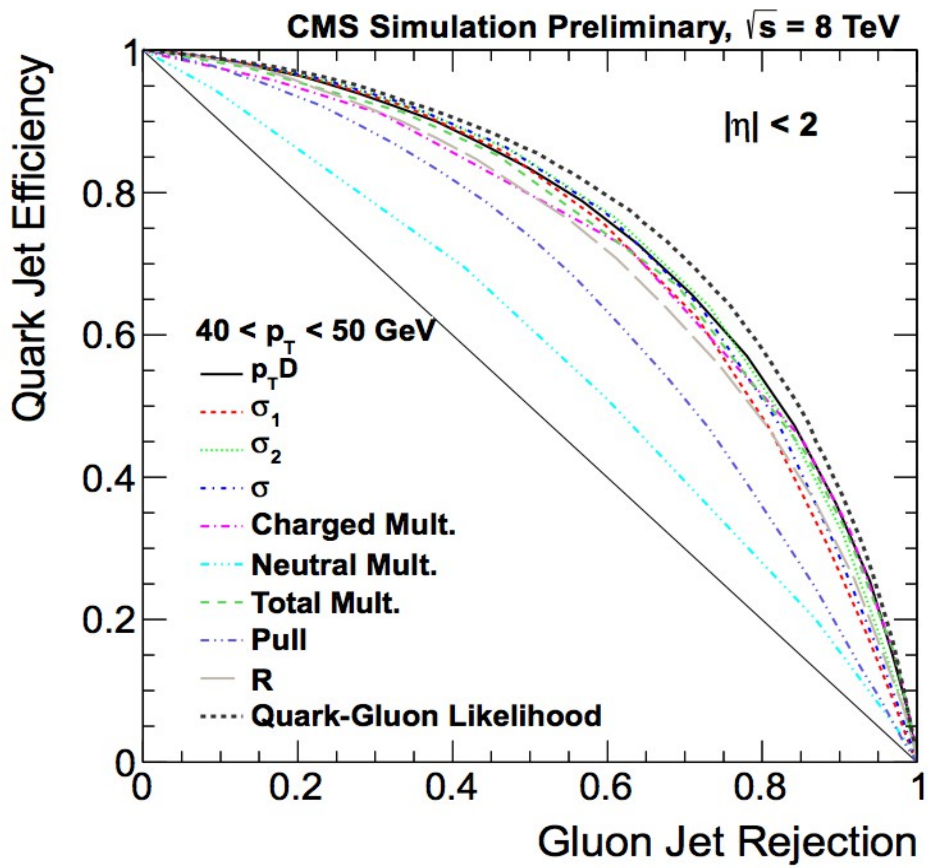
**Gluon jets:**

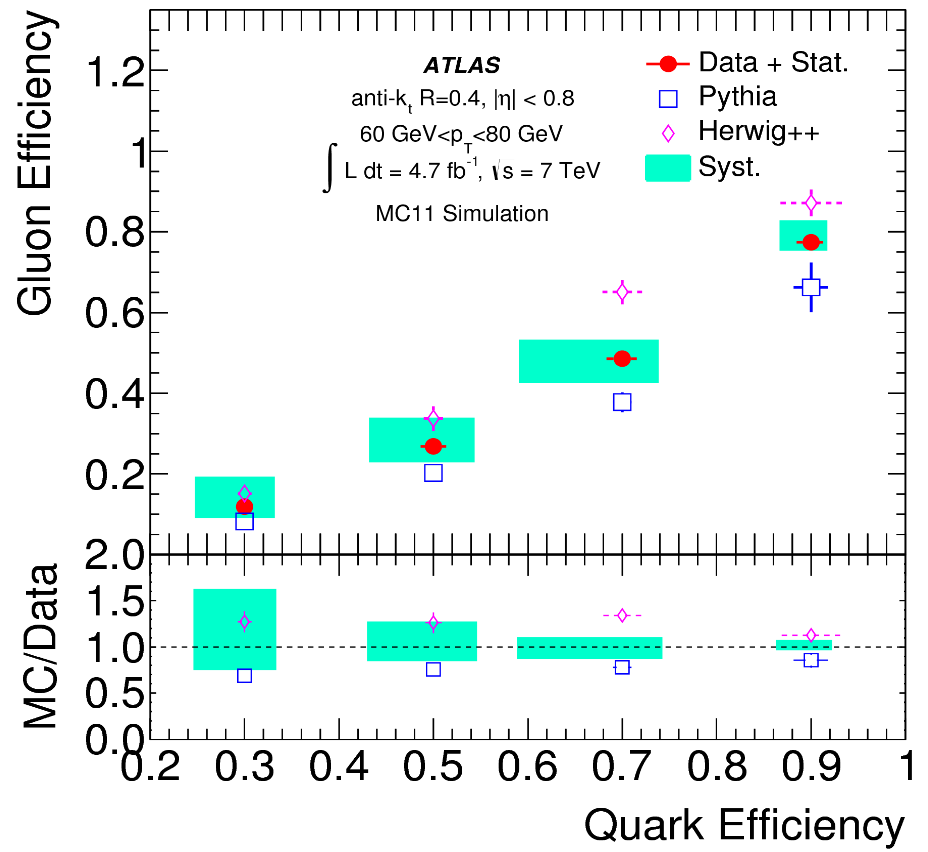


Wide
More particles
Lower $p_T$
Enhanced in dijet

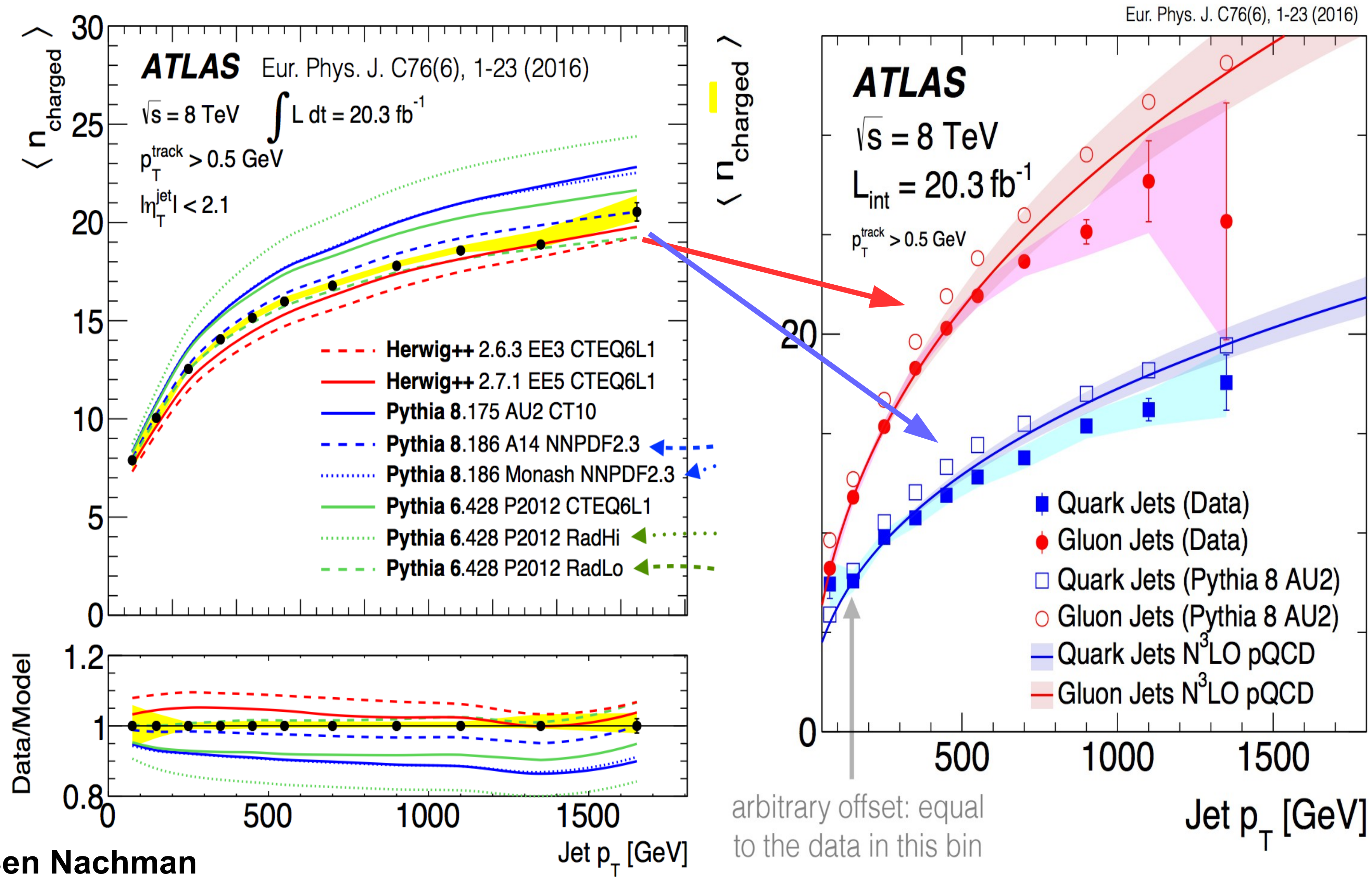
# Quark Gluon Performance

- CMS has better performance
  - Gain from use of $p_T D$ variable (also not just using tracks)
  - ATLAS relies on tracks in place of all pf candidates
    - Also maintain large uncertainties from generator differences



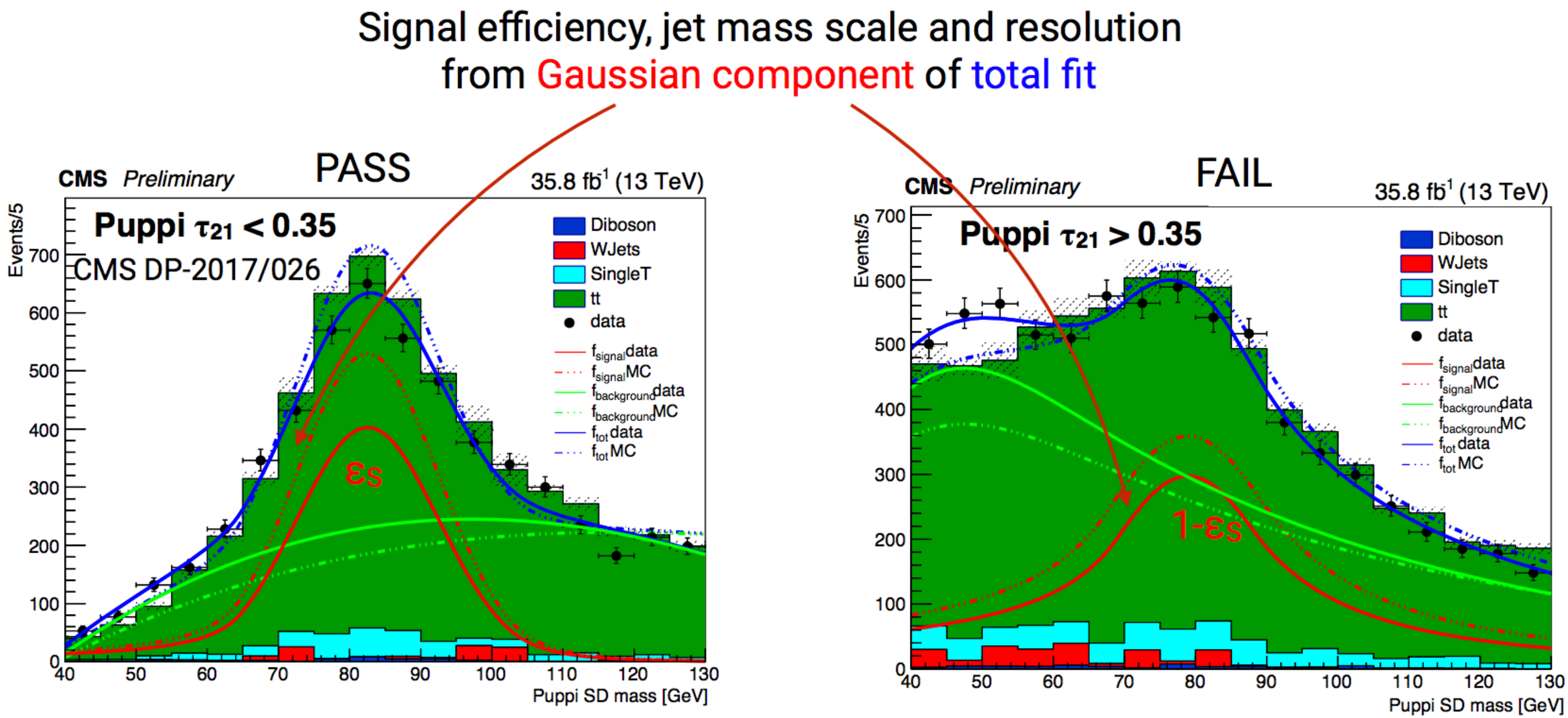
# Measuring Quark and Gluon Mult.




**Ben Nachman**

# Tagging

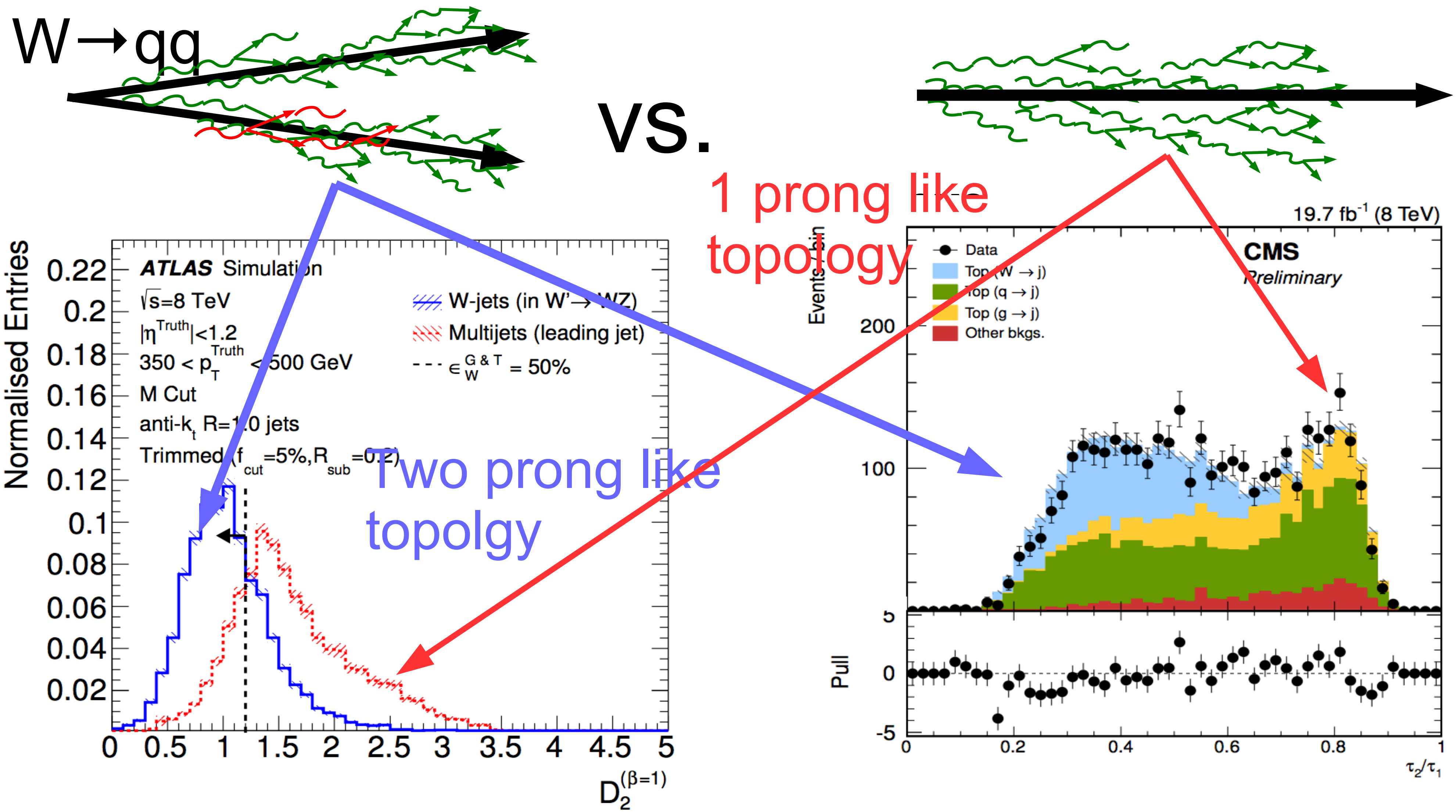
- pp has a wealth of tops and Ws to help calibrate




Classic tag and probe on W jets using N-subjettiness

# Tagging

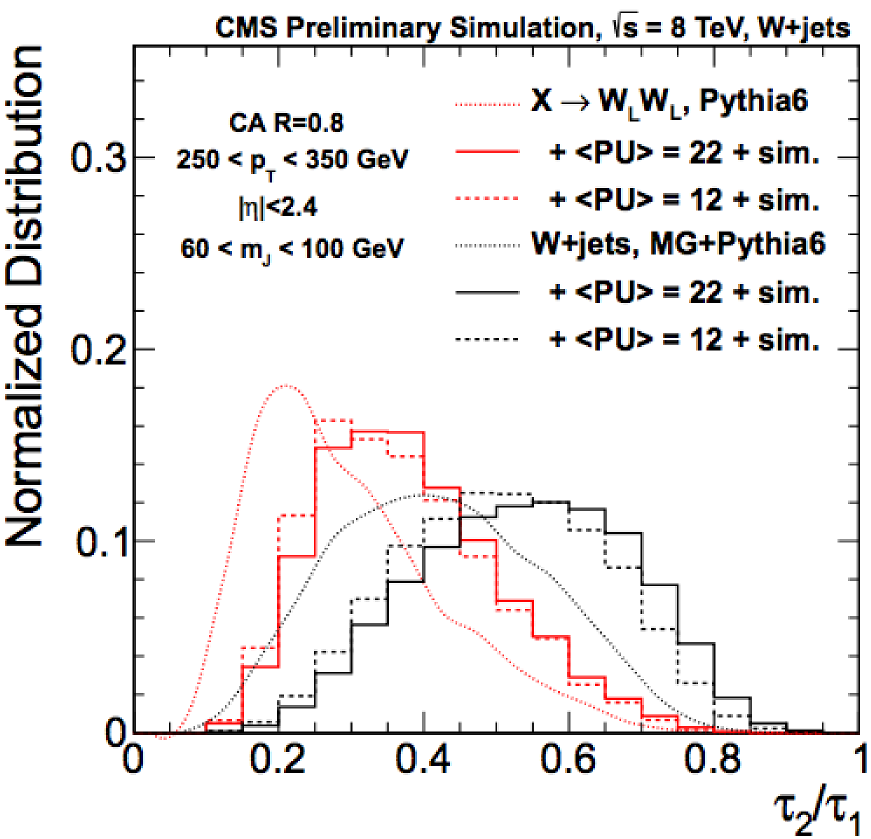
- In addition to grooming we use a tagger

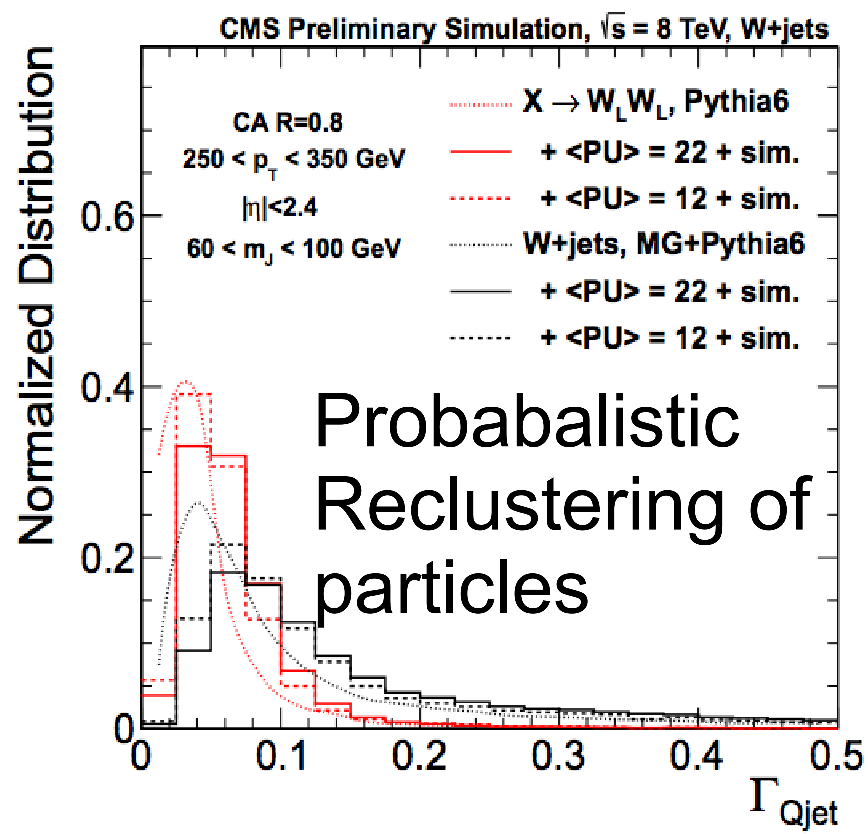


# N-subjettiness/Q-Jets

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

- Measures of number of prongs




Probabalistic Reclustering of particles

# Energy Correlation functions(ECFs)

## Generalized ECFs

- Extension of original ECFs to allow for different angular orders:

$$e(o,N,\beta) \equiv {}_oe_N^\beta = \sum_{i_1<i_2<\cdots<i_N\in J}\left[\prod_{1\leq k\leq j} z_{i_k}\right] \times \min\left\{\prod_{k,l\in\text{pairs}\{i_1,\ldots,i_N\}}^{o} \Delta R_{kl}^\beta\right\}$$

- e.g.

$${}_2e_3^1 = \sum_{a<b<c\in J} z_a z_b z_c \times \min\{\Delta R_{ab}\Delta R_{ac}, \Delta R_{ab}\Delta R_{bc}, \Delta R_{bc}\Delta R_{ac}\}$$

- Summary of parameters:
  - $N =$ order of the correlation function. An $N$-pronged jet should have $e_N \gg e_M$, for $N < M$
  - $o =$ order of the angular factor.
  - $\beta =$ angular power
    - Tunes the relative importance of the angular factor and the energy factor
    - Weights the impact of small angles (assuming $\Delta R < 1$)

# New Substructure Observables

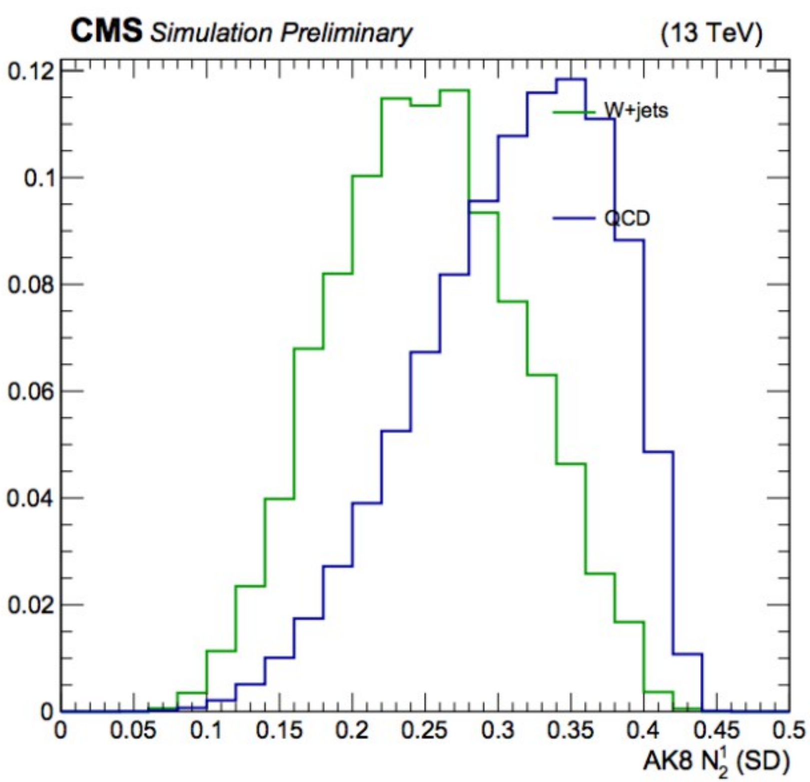
$$N_2(\beta) = \frac{{}_2e_3^{\beta}}{(e_2^{\beta})^2}$$

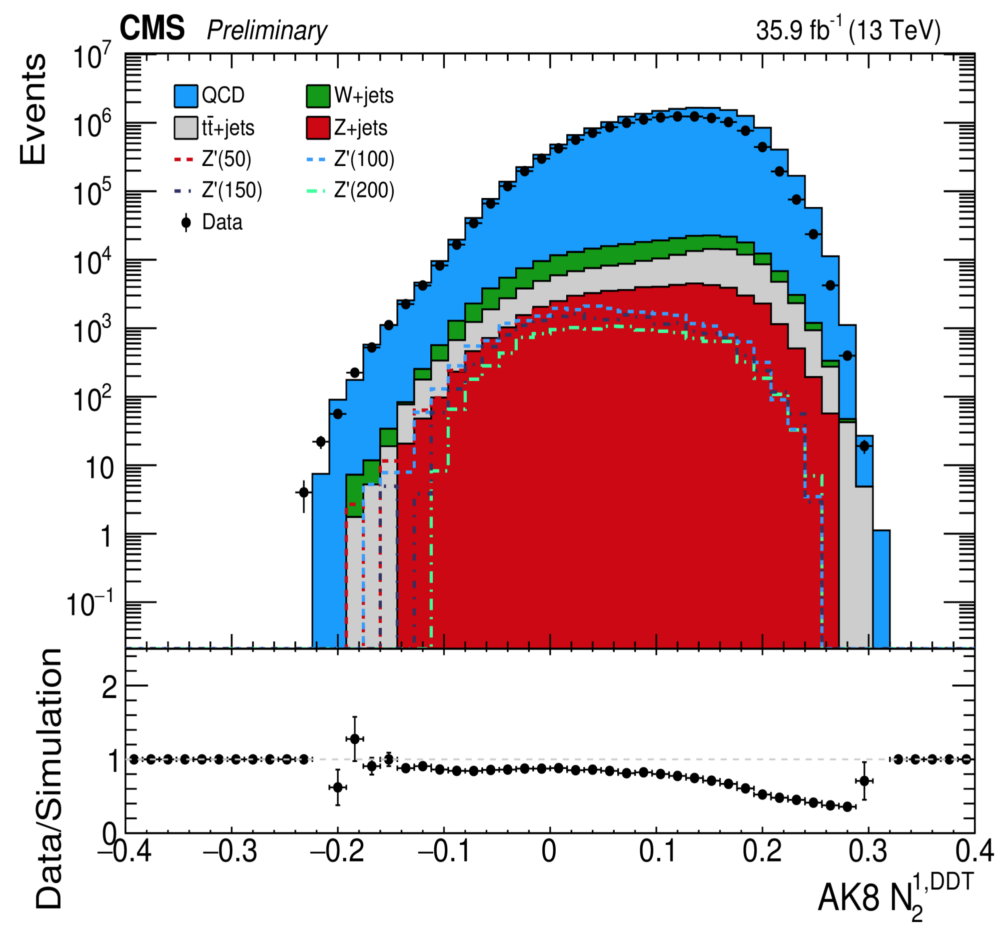
$${}_1e_2^{\beta} = e_2^{\beta} = \sum_{1 \le i < j \le n_J} z_i z_j \Delta R_{ij}^{\beta}$$

$$z_i \equiv \frac{p_{Ti}}{\sum_{j \in \text{jet}} p_{Tj}}$$

$${}_2e_3^{\beta} = \sum_{1 \le i < j < k \le n_J} z_i z_j z_k \min\{\Delta R_{ij}^{\beta}\Delta R_{ik}^{\beta}, \Delta R_{ij}^{\beta}\Delta R_{jk}^{\beta}, \Delta R_{ik}^{\beta}\Delta R_{jk}^{\beta}\}$$

Using AK8 PUPPI jets




Arxiv/1609.07483

We use $N_2$ to see the W peak

# Crrorelation functions

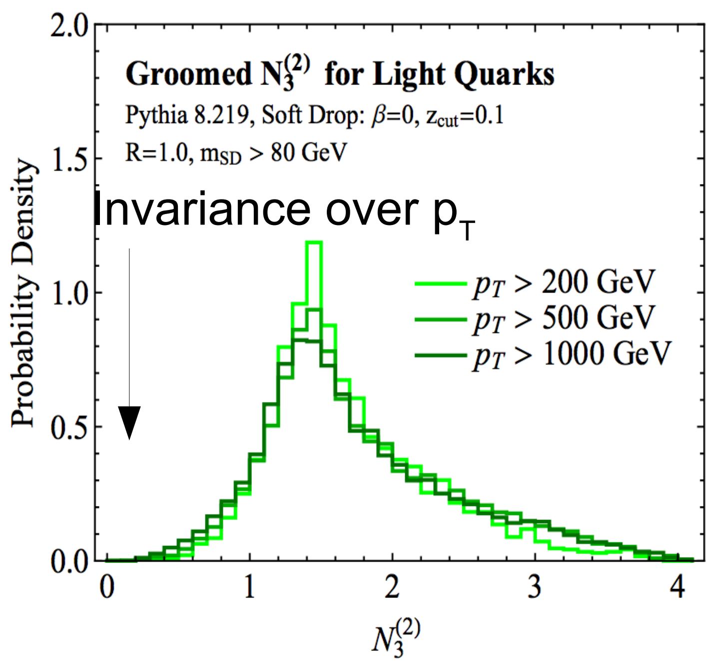
- Theorists decided to build in the scale invariance

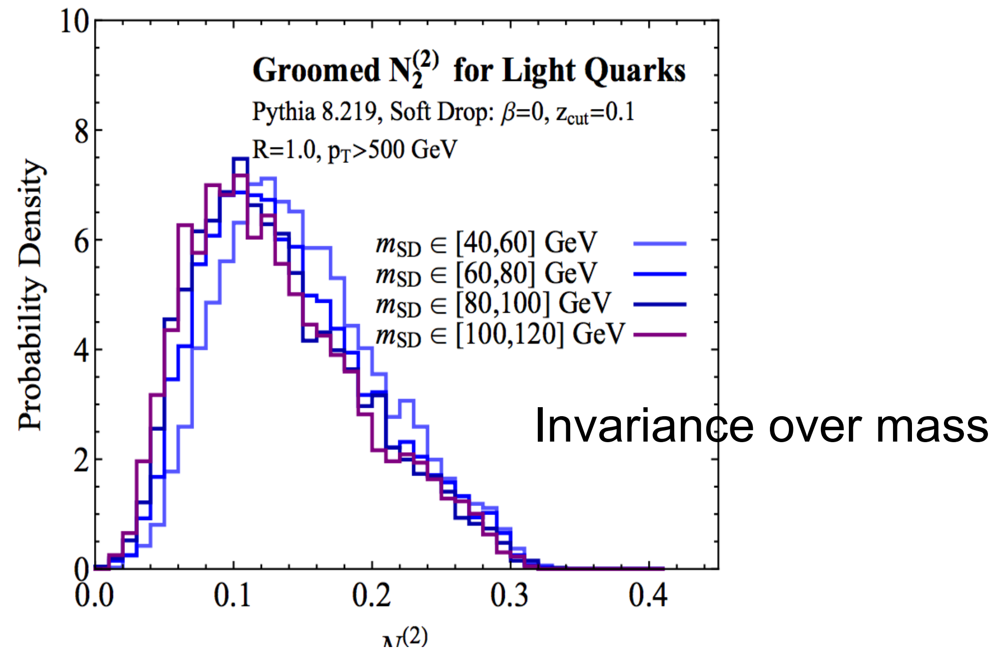
**New Angles on Energy Correlation Functions**

Ian Moult, Lina Necib, Jesse Thaler

*(Submitted on 23 Sep 2016)*

  - Into a new set of substructure observables
  - Guiding principles are to exploit invariances in QCD



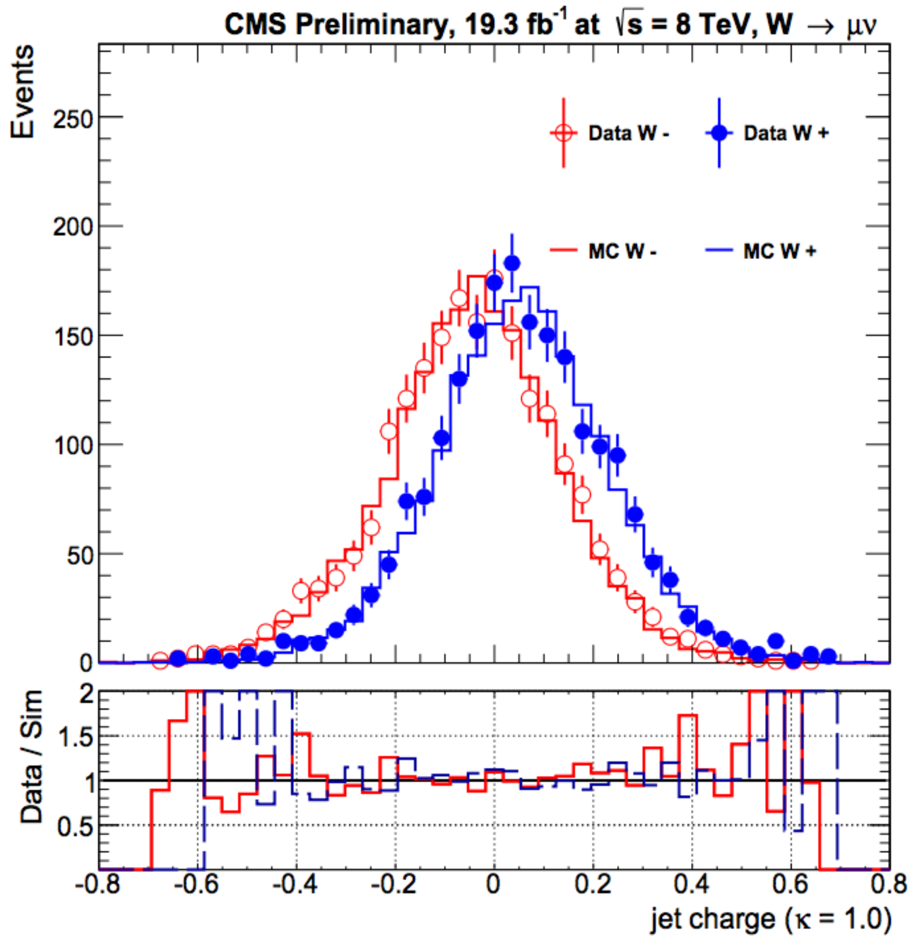



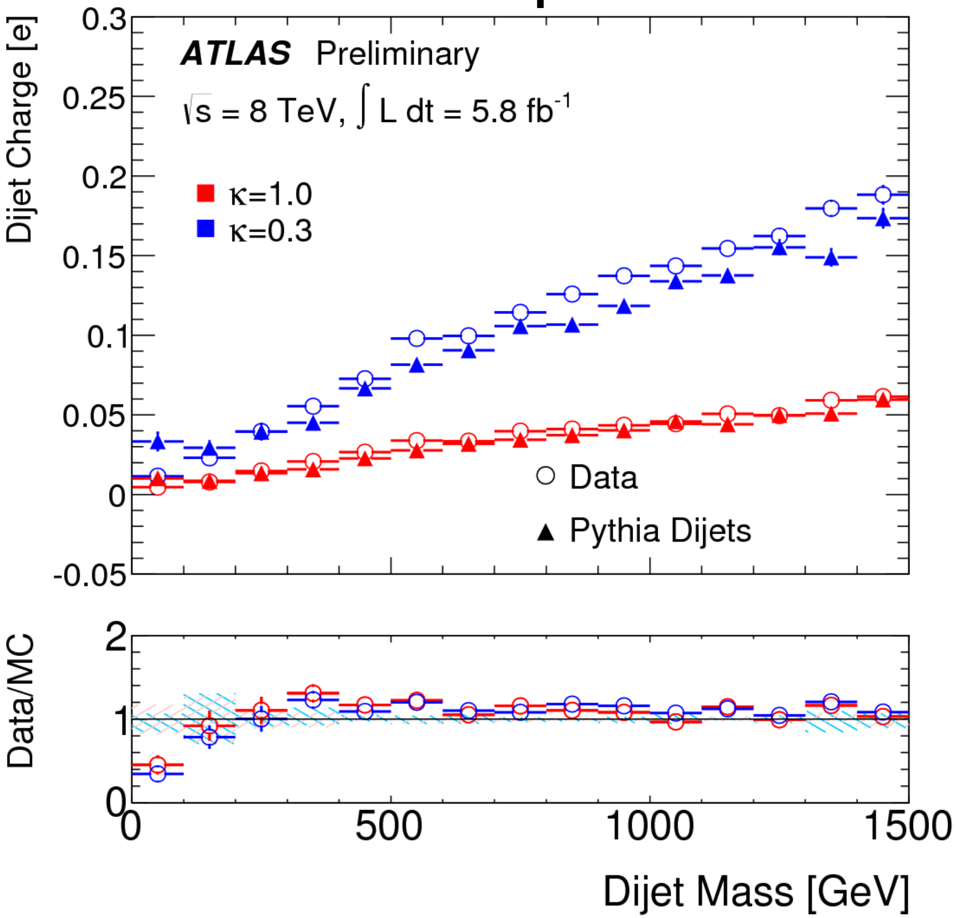
# Jet Charge

$$Q^\kappa = \frac{\sum_i q_i (p_T^i)^\kappa}{(p_T^{jet})^\kappa}$$

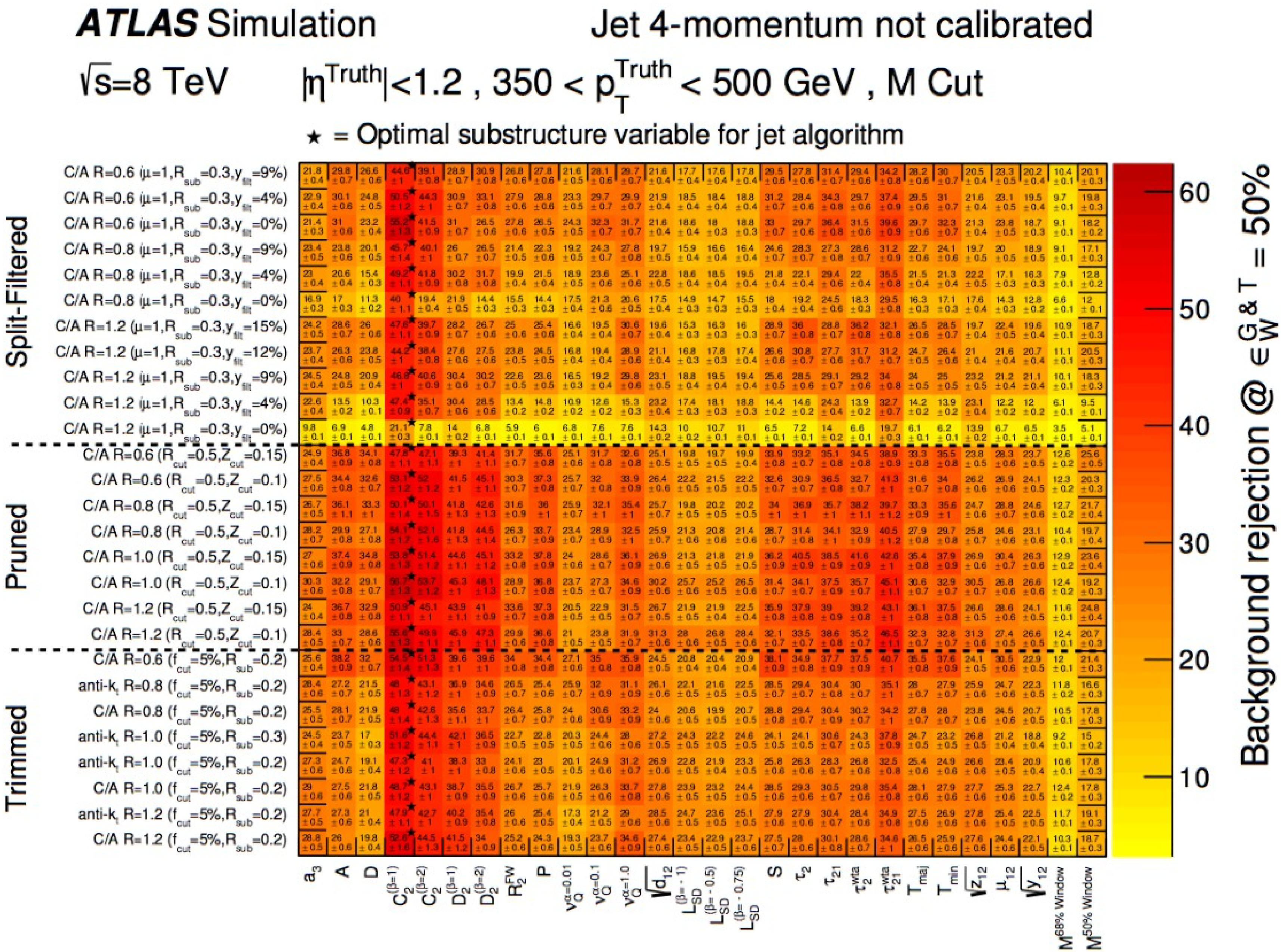
- It works, but its not great :

Charge rise shows valence quarks



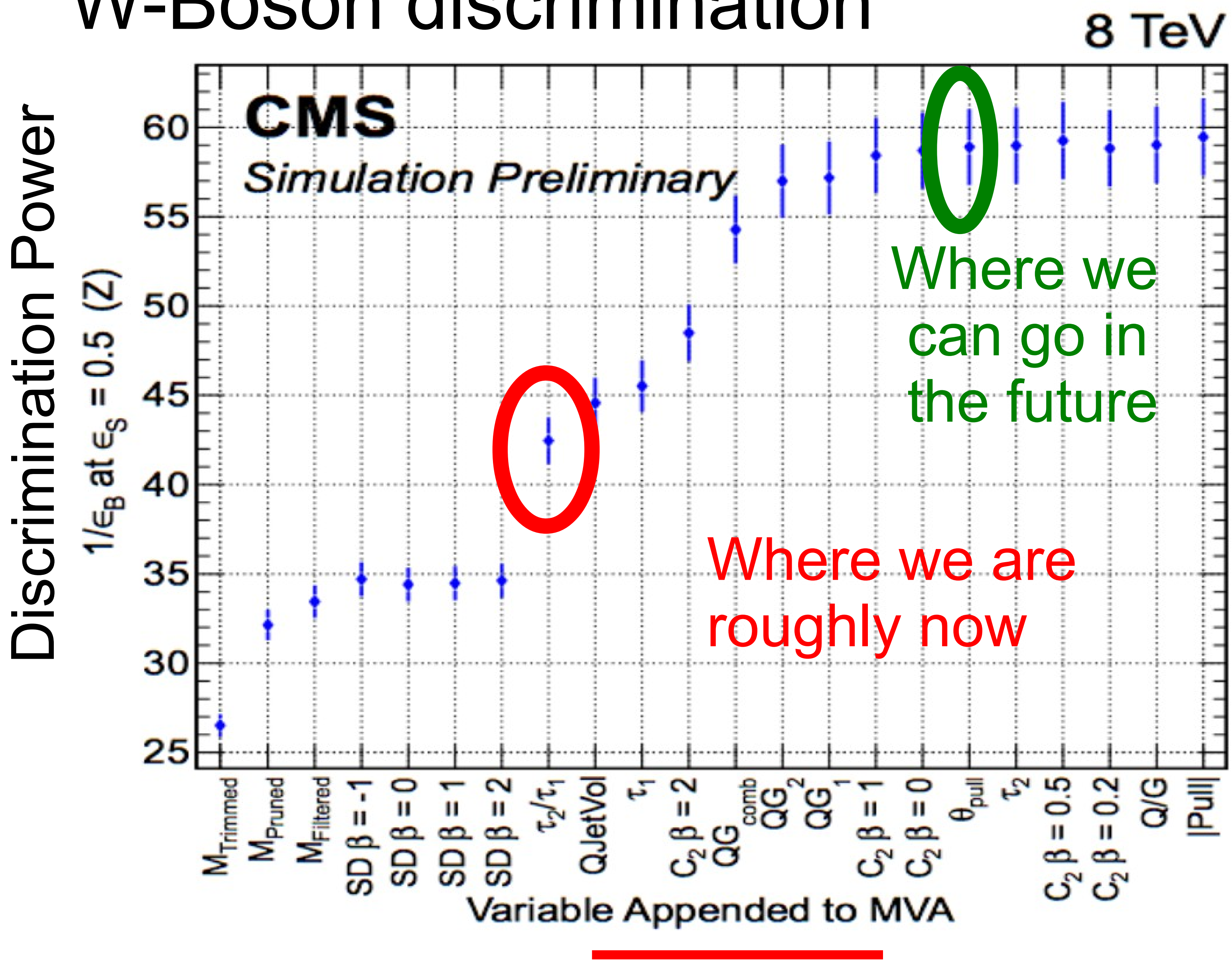



# How did we scan these?



# Pushing it to the Limits

## W-Boson discrimination




We are not even done with ideas yet!

# Executive Summary for W-tagging

- CMS :
  - Past : Pruning + $\tau_2/\tau_1$
  - Present : Soft Drop + PUPPI + $\tau_2/\tau_1^{(DDT)}$
- ATLAS :
  - Past : Trimmed Mass + $\sqrt{y_{12}}$
  - Present : Trimmed Mass + Smoothed $D_2$+Variable R
- Both are commissioned on data
  - Mass scale and efficiency

# Executive Summary for Top tagging

- CMS :
  - Past : Mass + CMS/HEP Top Tagger
  - Present : Soft Drop + PUPPI + $\tau_3/\tau_2$ + subjet b-tag
- ATLAS :
  - Past : Trimmed Mass + $\sqrt{d_{12}}$
  - Present : Trimmed Mass +$\tau_3/\tau_2$ + b-tag (MV2C)
- Both are commissioned on data
  - Mass scale and resolution (ATLAS)

# Closer to state of the art

Simplified
Partial
Perturbative
Calculable

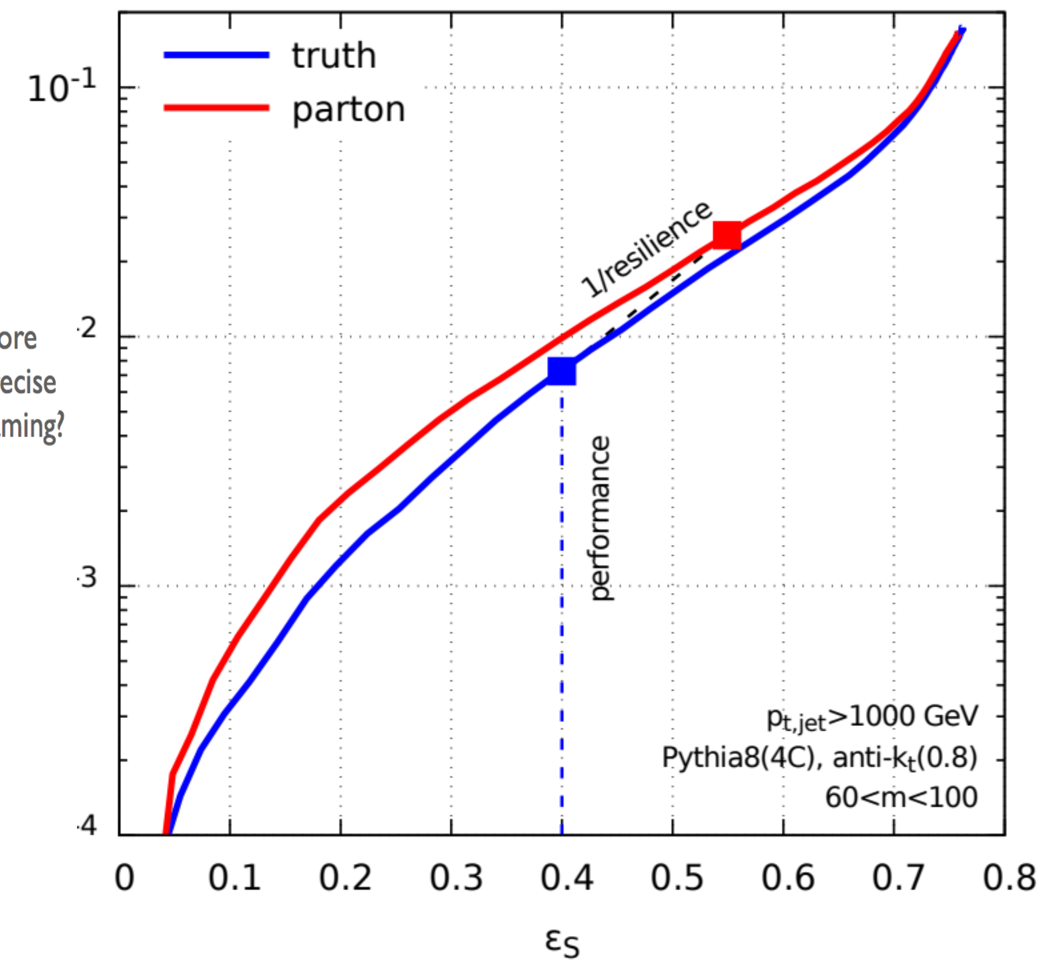
More Idealized ↑ | More Realistic ↓

Complex
Complete
Nonperturbative
Machine Learnable

- Parton (after shower)
- Hadron (without MPI)
- Particle (with MPI)
- Detector
- Pileup

More precise naming? (Parton, Hadron, Particle)

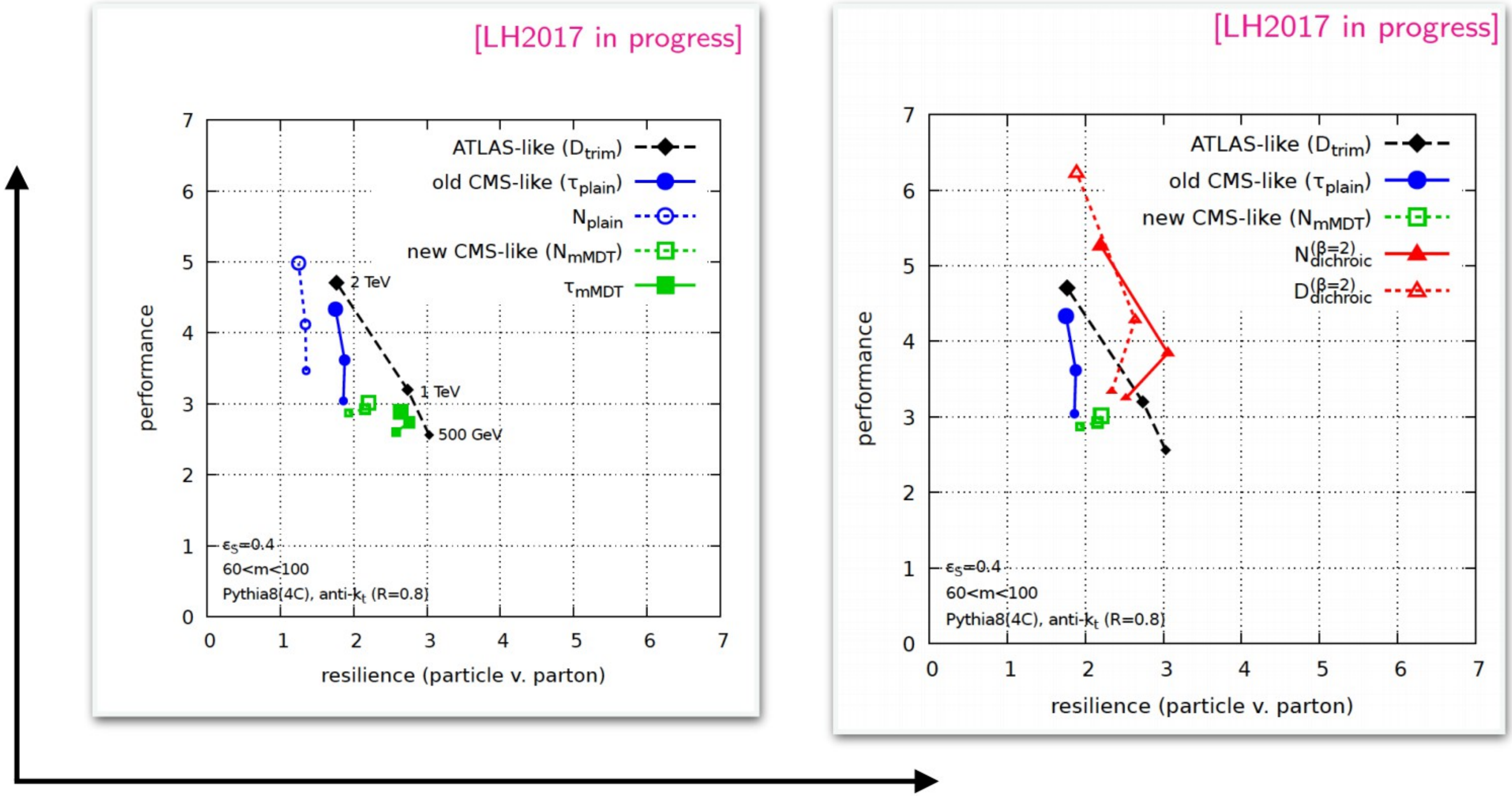
performance-oriented (particle v. parton)




Much of focus now is to understand differing conclusions
Serves as a gauge for our total understanding

# Closer to state of the art

## V-tagging stability vs. performance study

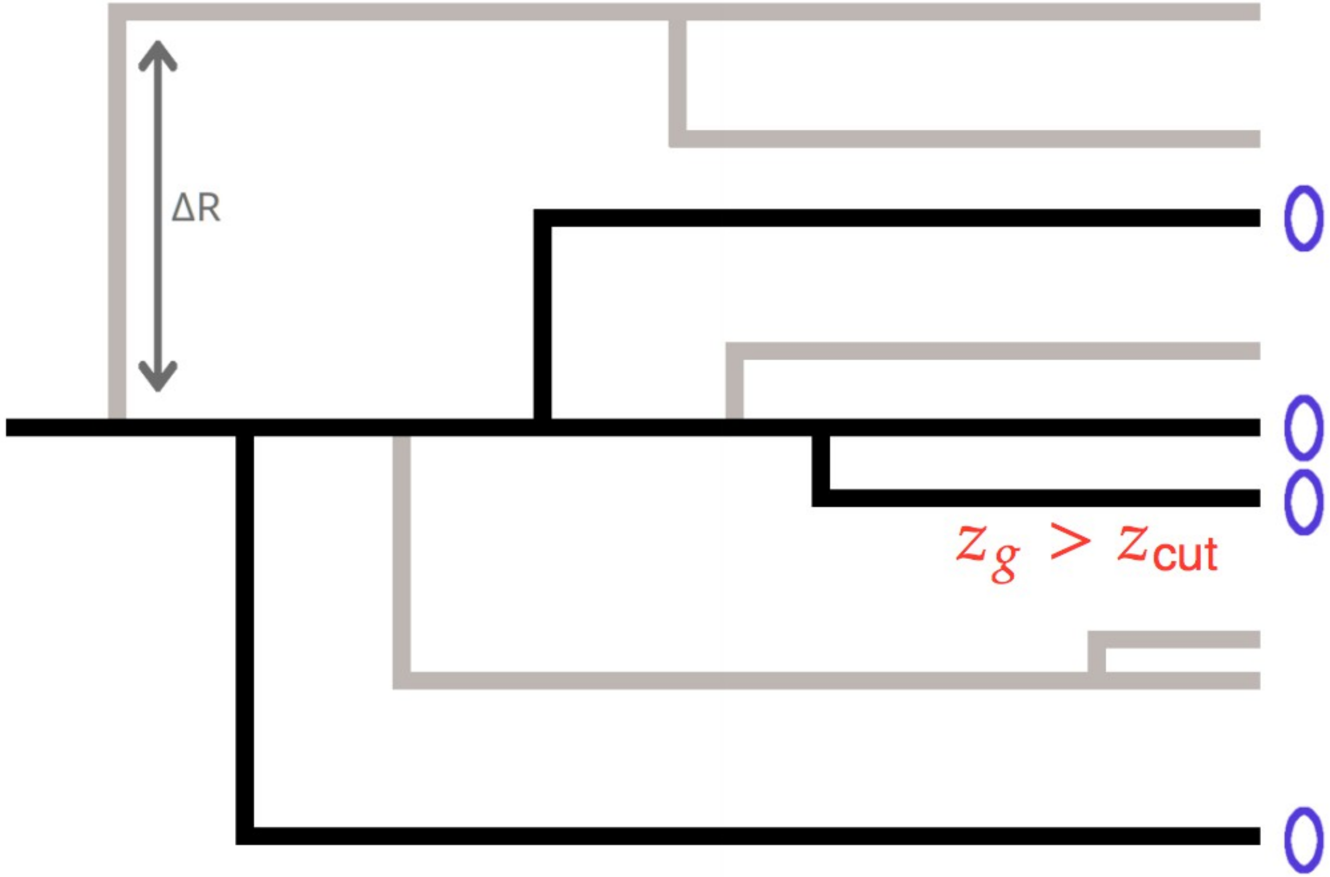


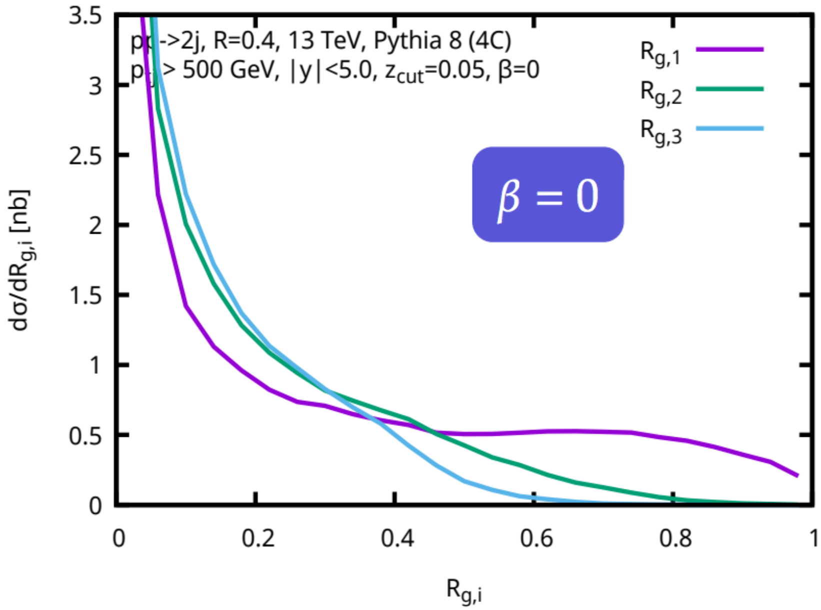

better!

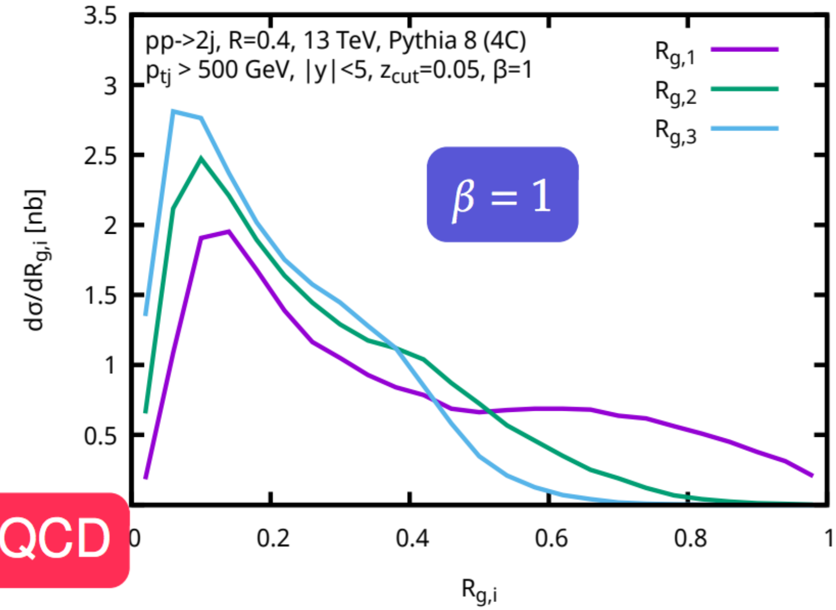
*new di-chroic taggers?*

# Closer to state of the art

$N = 3$



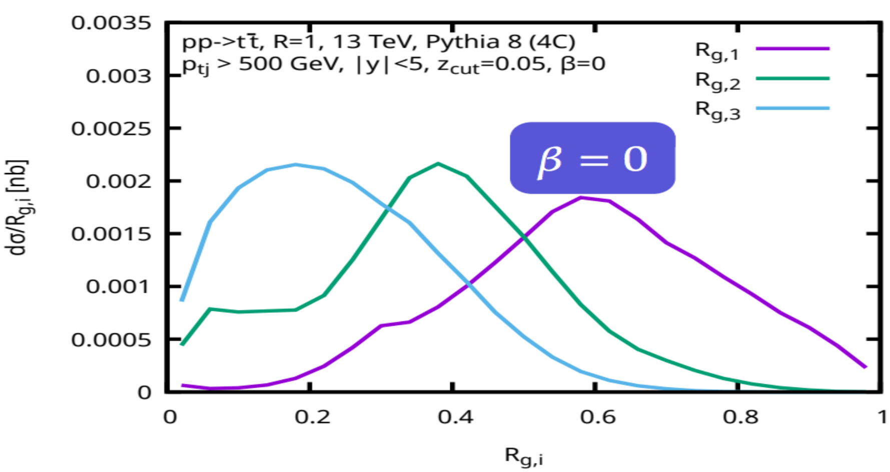


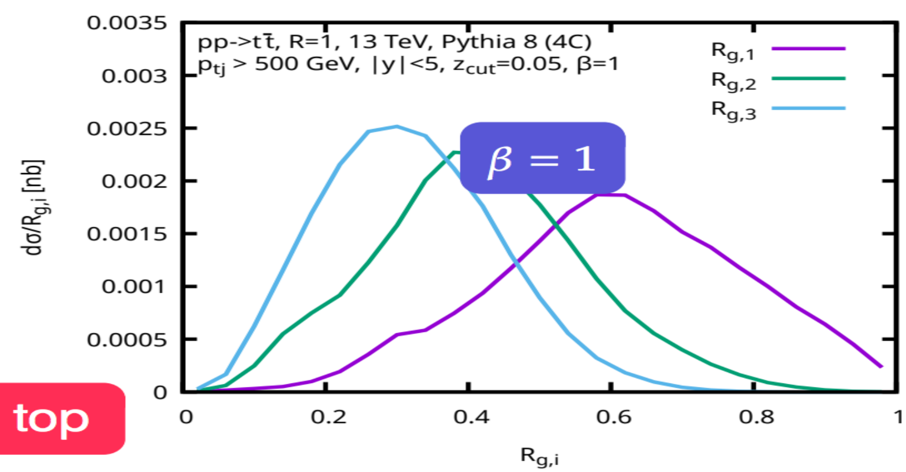




QCD

At each iteration passing the Soft Drop condition, define

$$R_{g,i} = \Delta R_{12}\,, \qquad z_{g,i} = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}}$$




top

Provides information on jet structure.

# Iterated soft drop

see Frederic Dreyer's talk for "recursive soft drop"

algorithm's parameters: $z_{\rm cut}$ , $\beta$ , $\theta_{\rm cut}$
used to define variables: $z_n$ , $\theta_n$

- begin at trunk of C/A clustering tree with $n = 1$
- at branching into subjets i,j require

$$\theta_{ij} > \theta_{\rm cut}$$

otherwise terminate algorithm

- if soft drop criterion is satisfied

$$z_{ij} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$

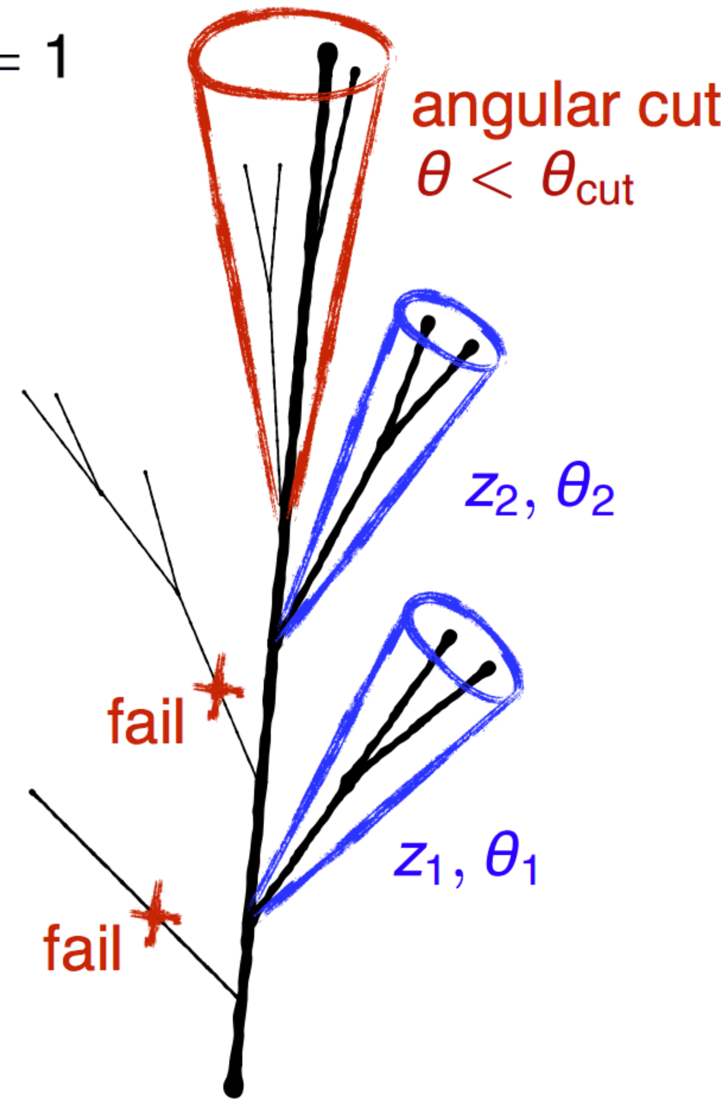
then

$$z_n = z_{ij}$$

$$\theta_n = \theta_{ij}$$

$$n \to n + 1$$

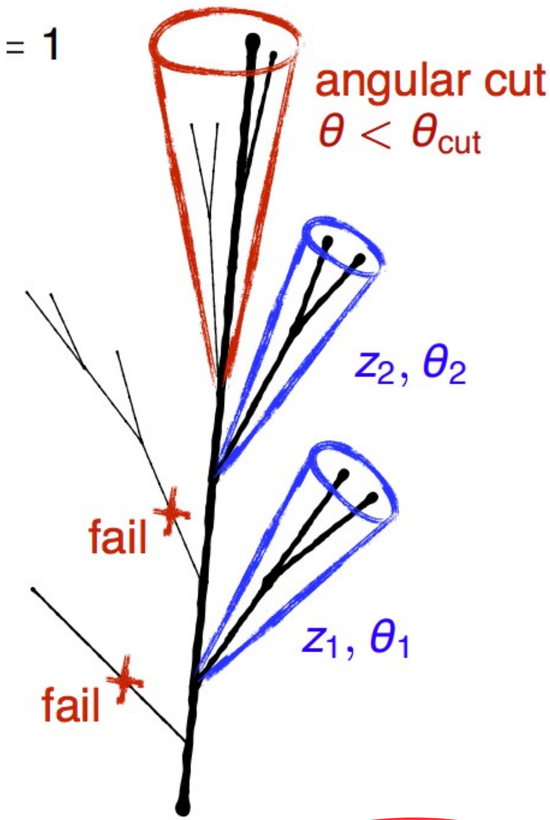
- follow harder subjet i or j and recurse

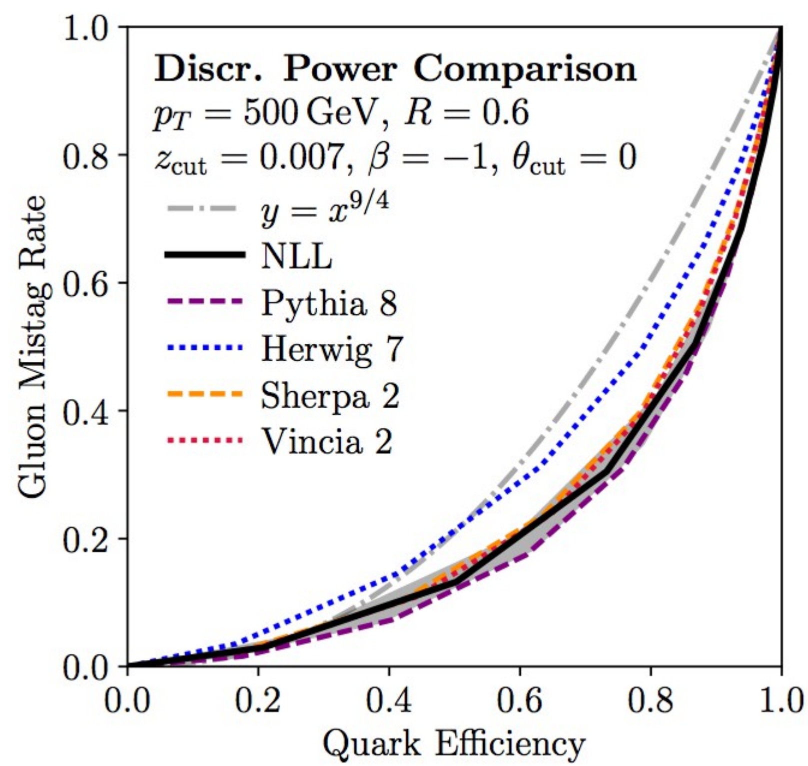



Larkoski, Marzani, Soyez, Thaler
JHEP 1405 (2014) 146

# Slide from Gregory Soyez's 2017 Boost Summary

## Iterative SoftDrop [Christopher's talk]




- Great performance
- Calculability
- Still large Pythia/Herwig differences

(Herwig 7.1 to come)

Starting to explore multiple emissions deep in the jet

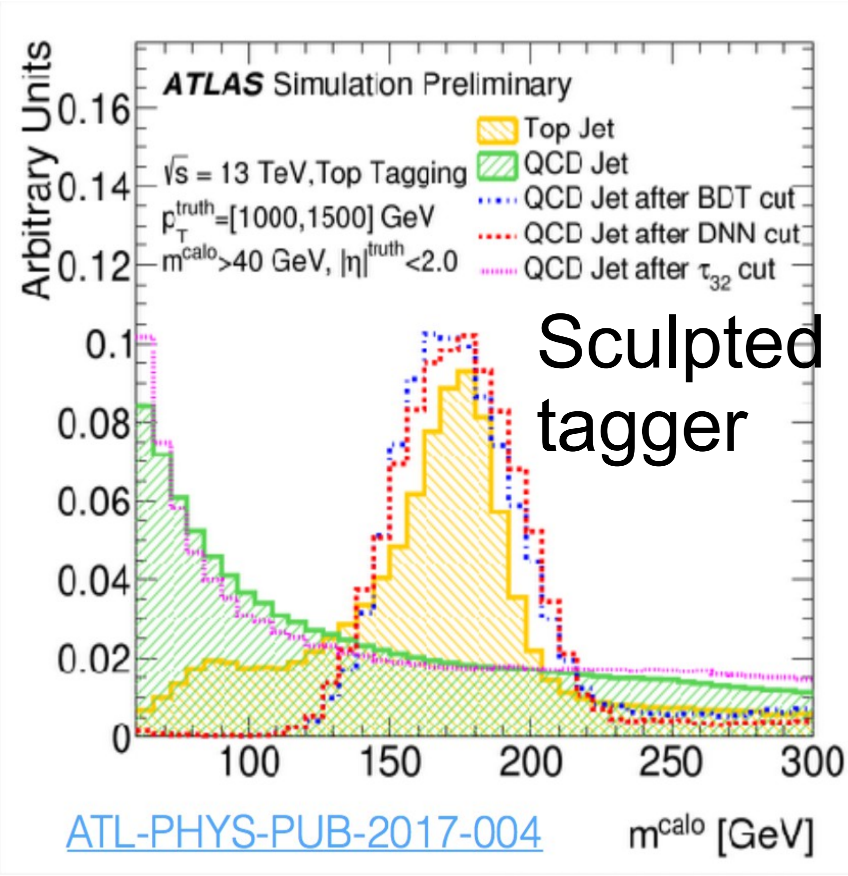
"Deep Deep Thinking"

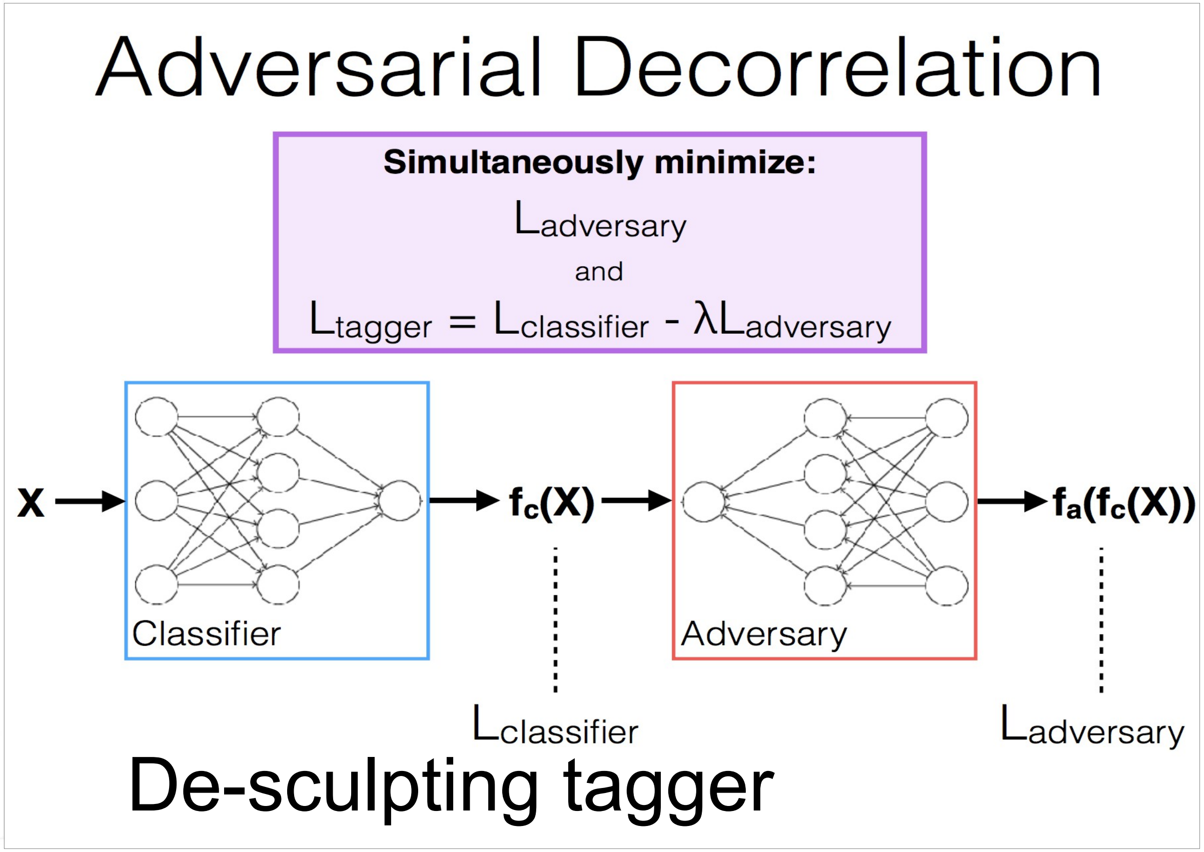
This is the state of pp

We are just starting on multiple emissions

# New Directions

- Key concept was modifying jet substructure

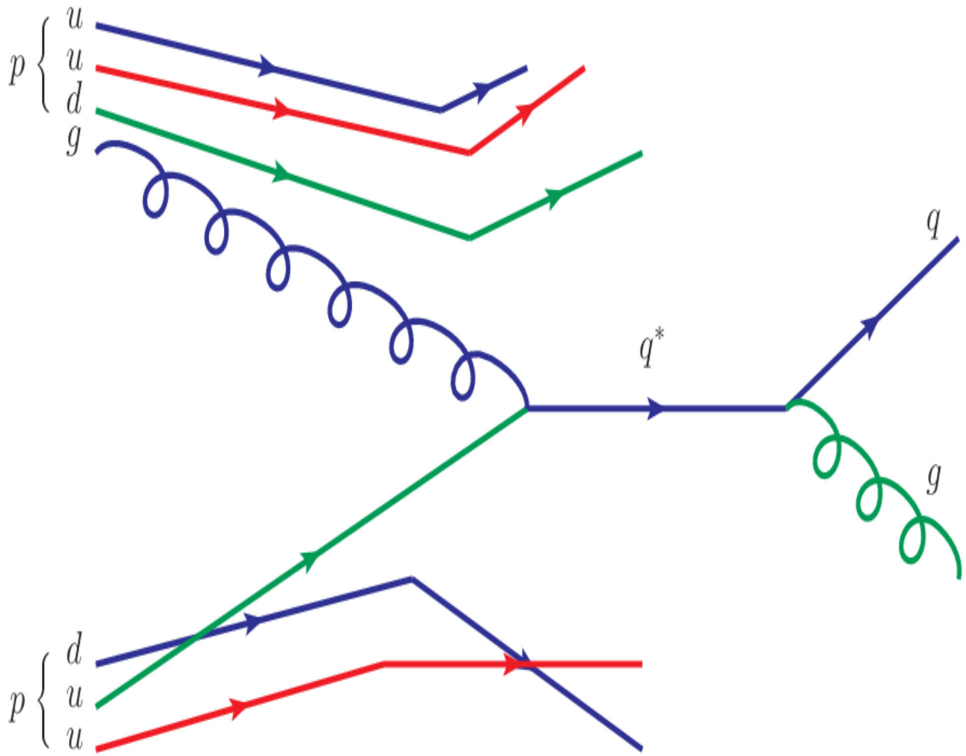


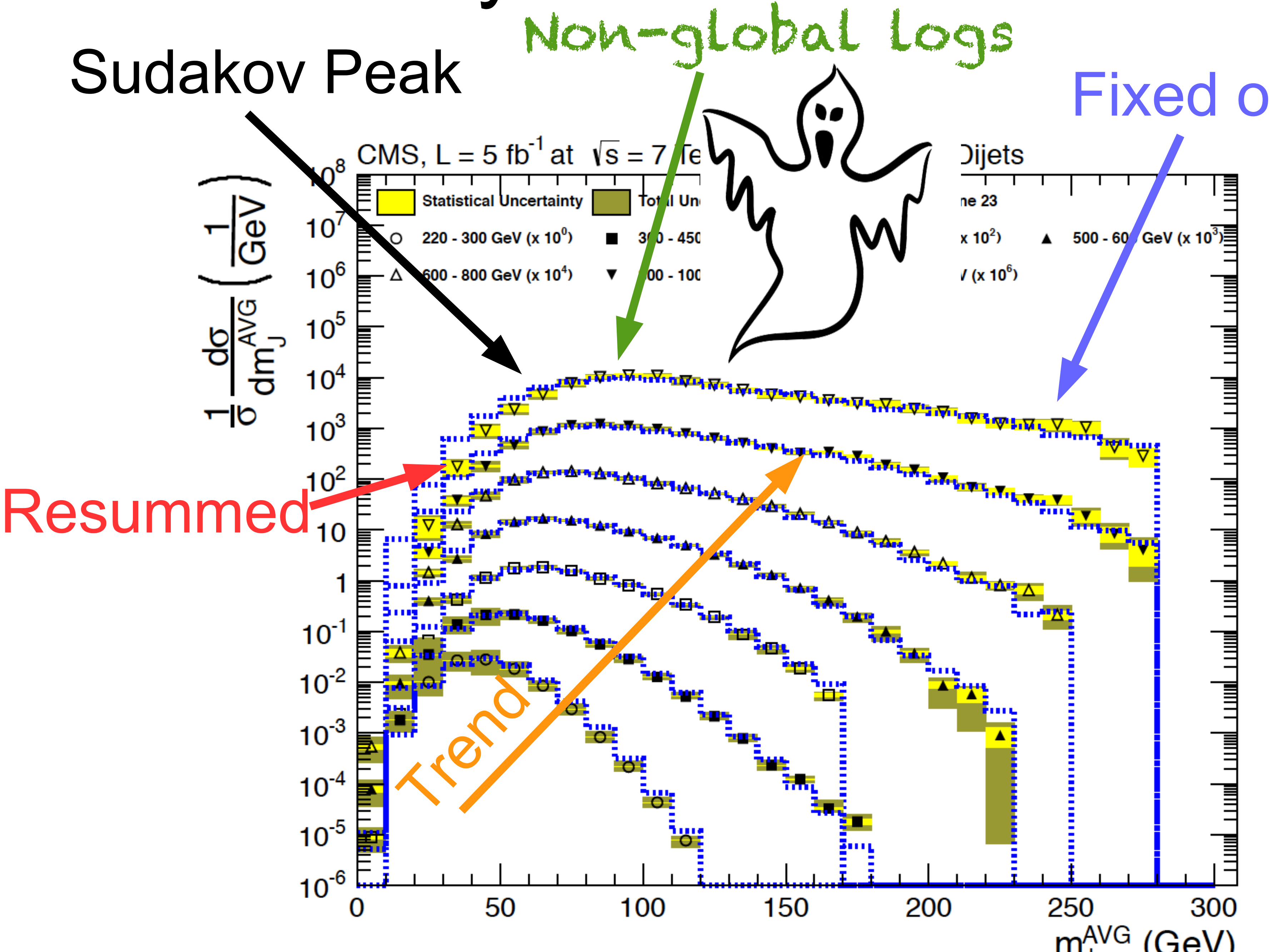

New approaches w/deep learning can decorrelate observables

Some of these taggers have 1000s of inputs

# QCD Jet Mass in PP: A case study

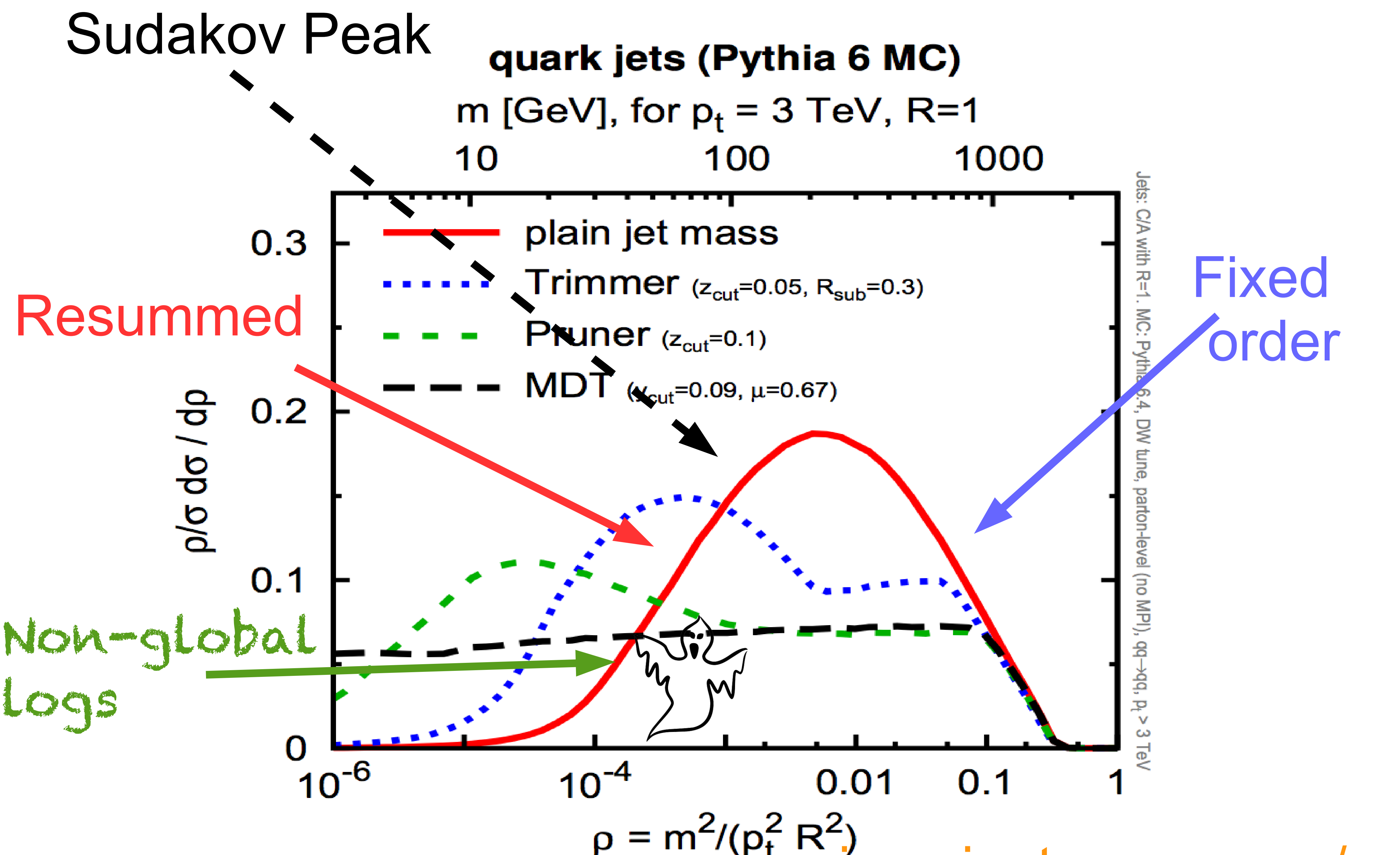


# Anatomy of Quark/Gluon Jet Mass




Jet Mass is a hearty brew of QCD physics

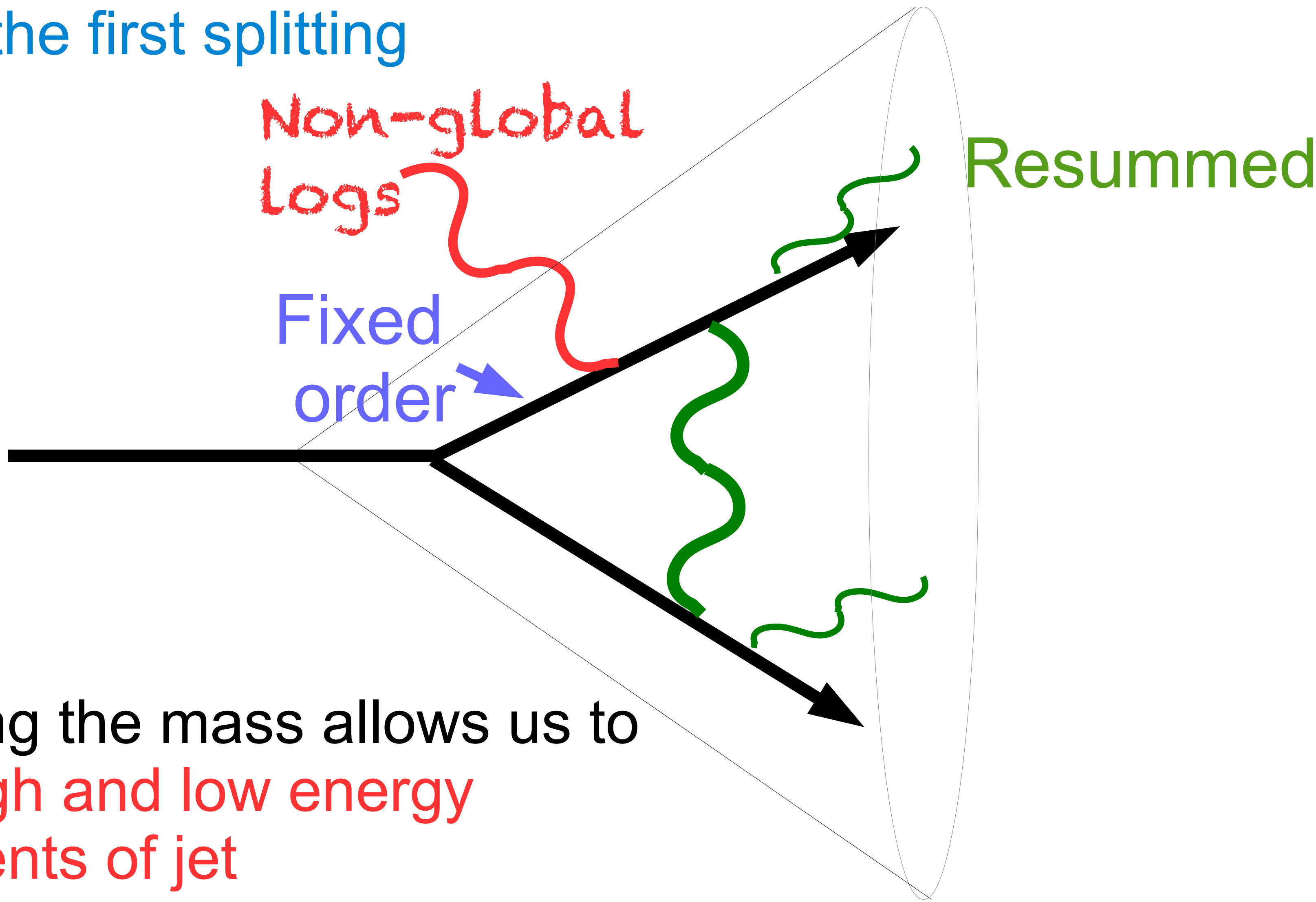
# Anatomy of Jet Mass: Theory




Calculate in $\rho$ ———— invariant over mass/$p_T$

# Visualizing Jet Mass

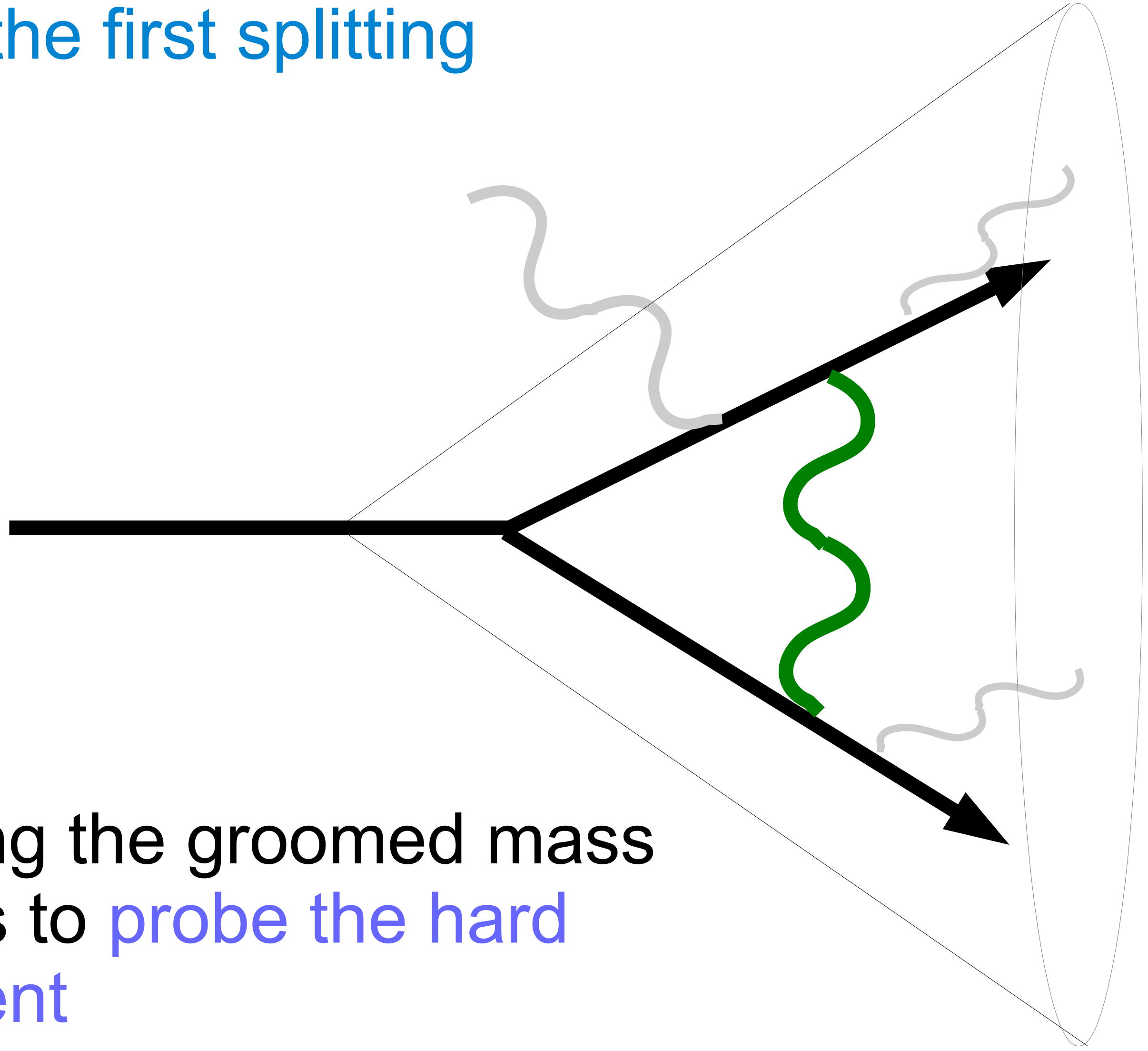
Consider the first splitting in jet




Measuring the mass allows us to probe high and low energy components of jet

# Visualizing Jet Mass

Consider the first splitting in jet

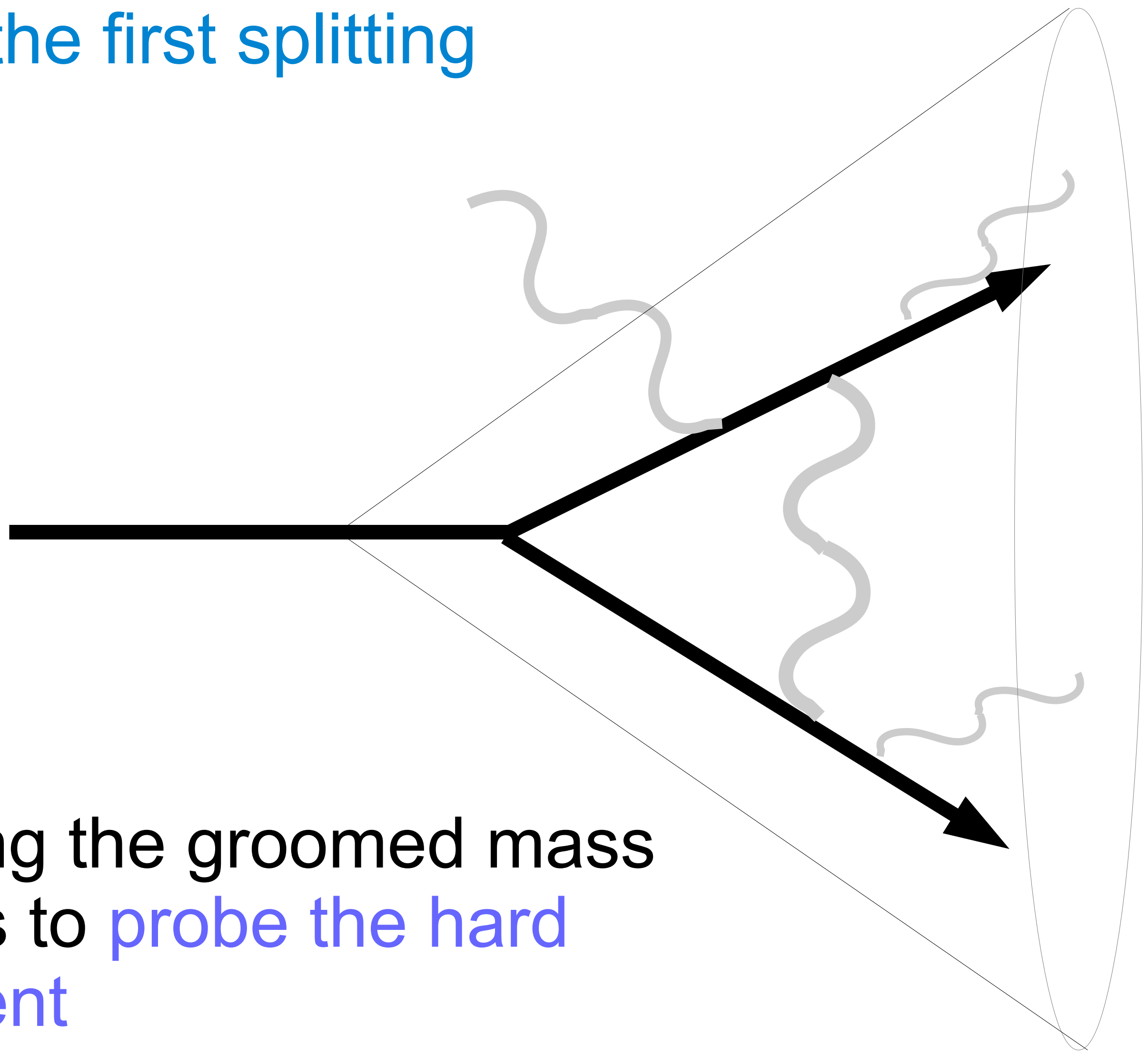


Measuring the groomed mass allows us to probe the hard component

This allows us to look at the first splitting
We can also avoid non-global logs

# Visualizing Jet Mass

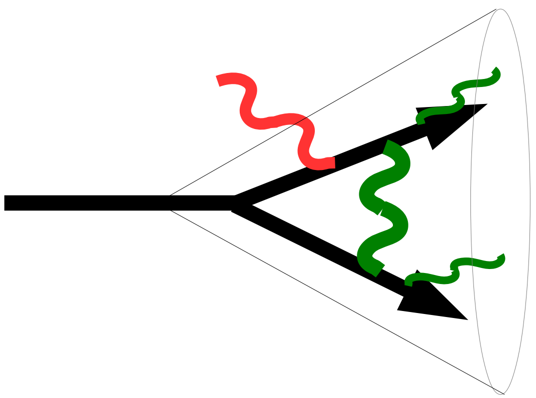
Consider the first splitting in jet

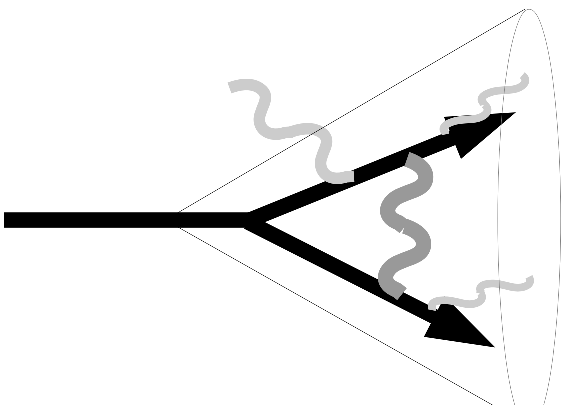


Measuring the groomed mass allows us to probe the hard component

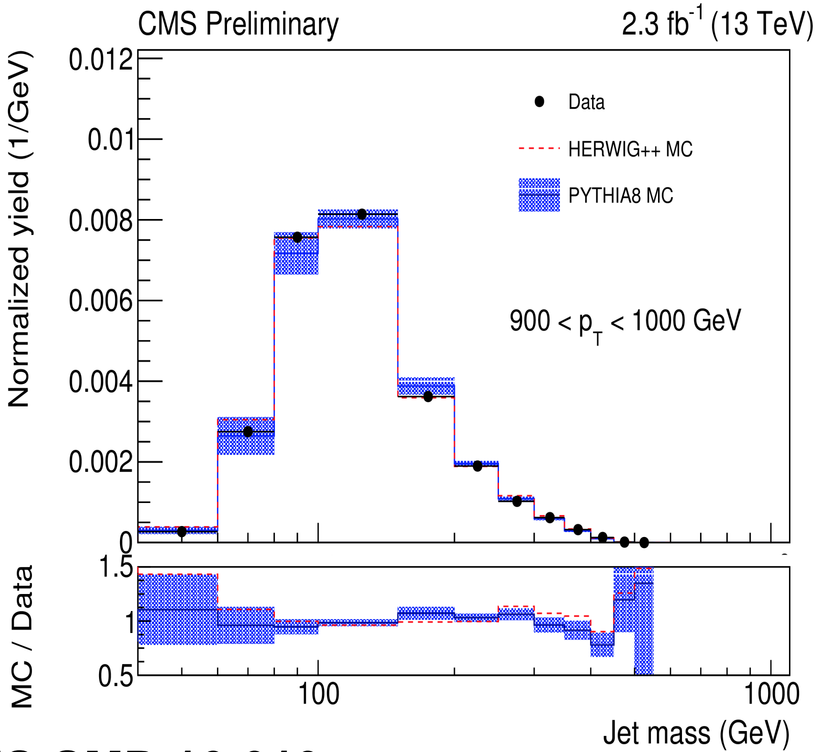
For mMDT(soft drop β=0) the first splitting approximate the fragmentation

# Spectra of Measurements

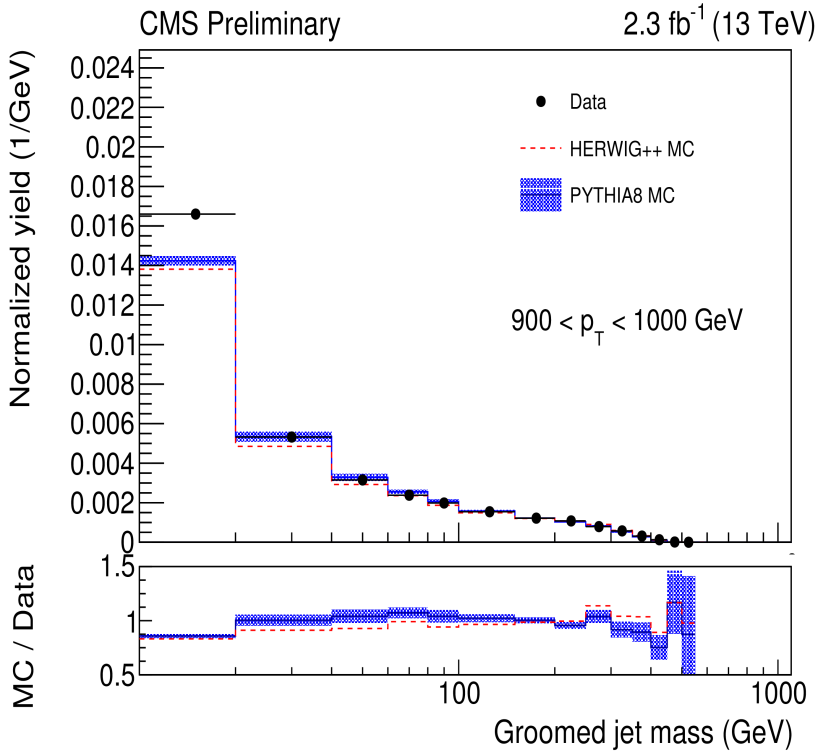




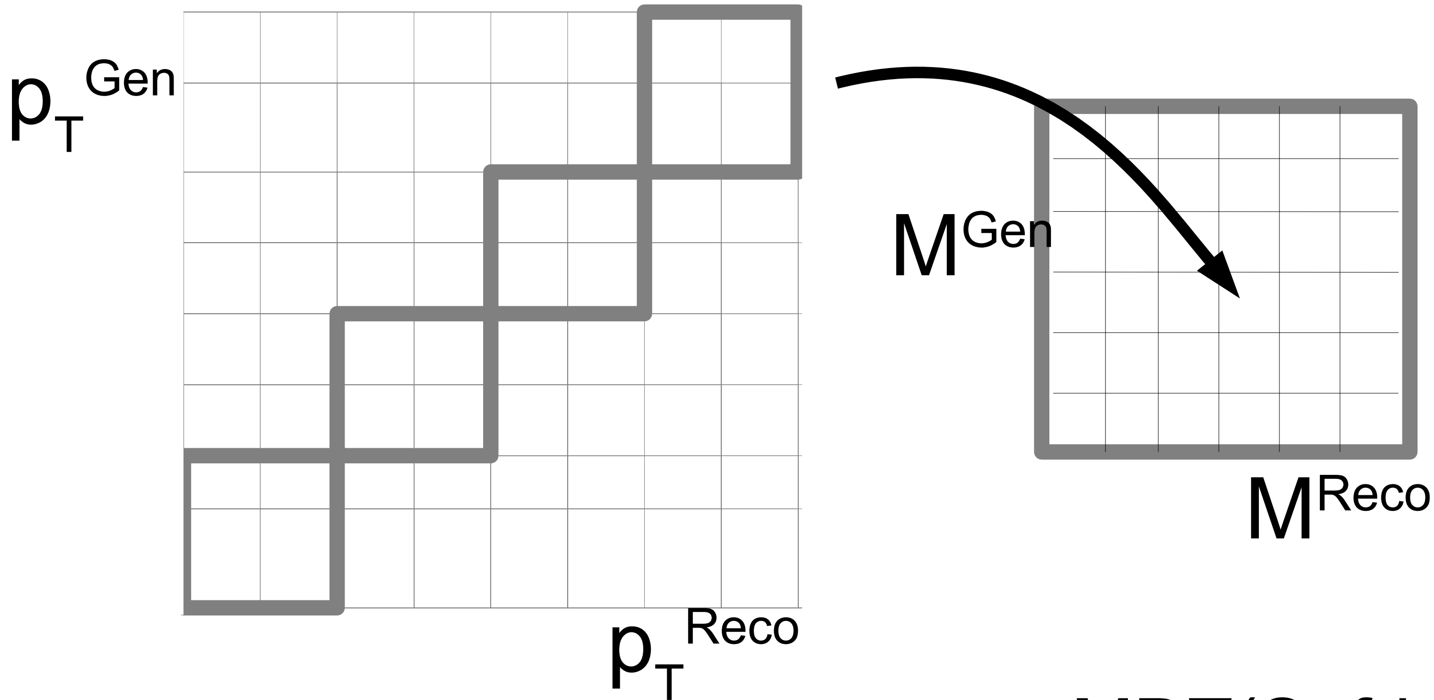
## Ungroomed jet mass




## mMDT(Sofdrop β=0) jet mass




**CMS-SMP-16-010**



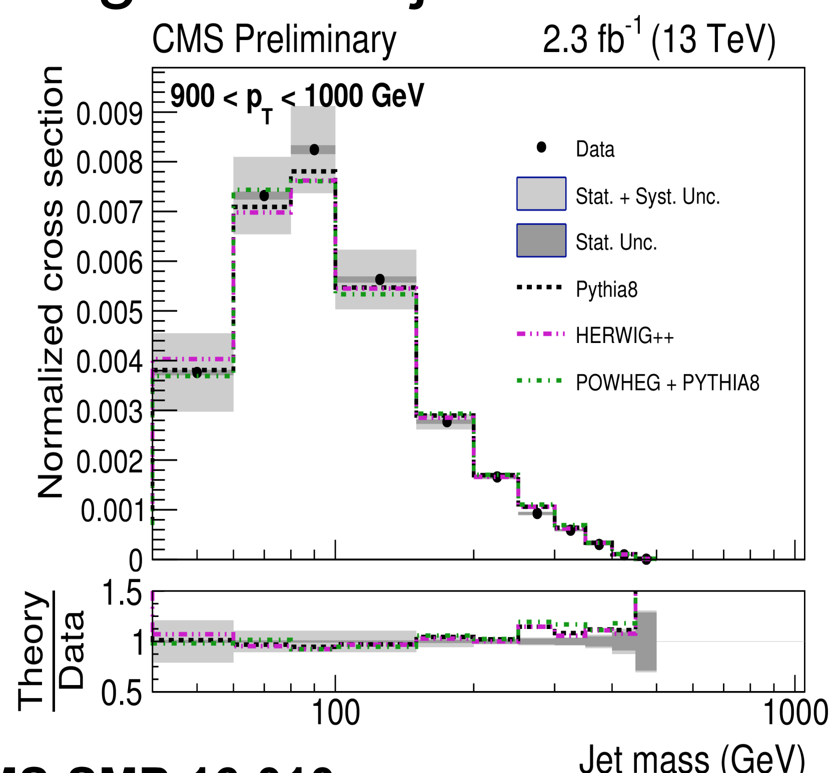

# Unfolded

4D unfolding

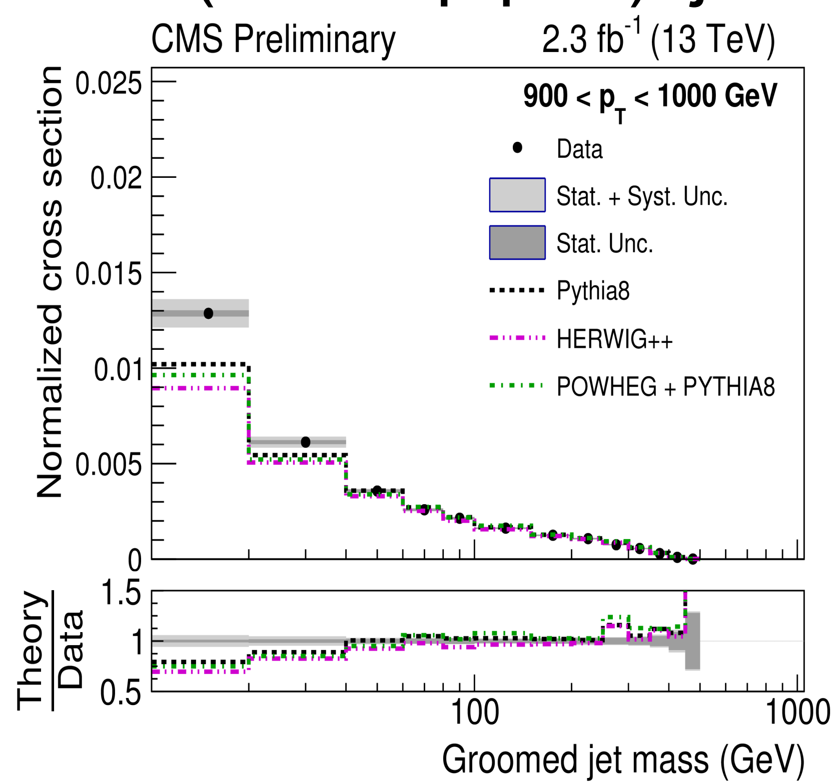
$M^{reco}, p_T^{reco}$ to

$M^{Gen}, p_T^{Gen}$

## Ungroomed jet mass



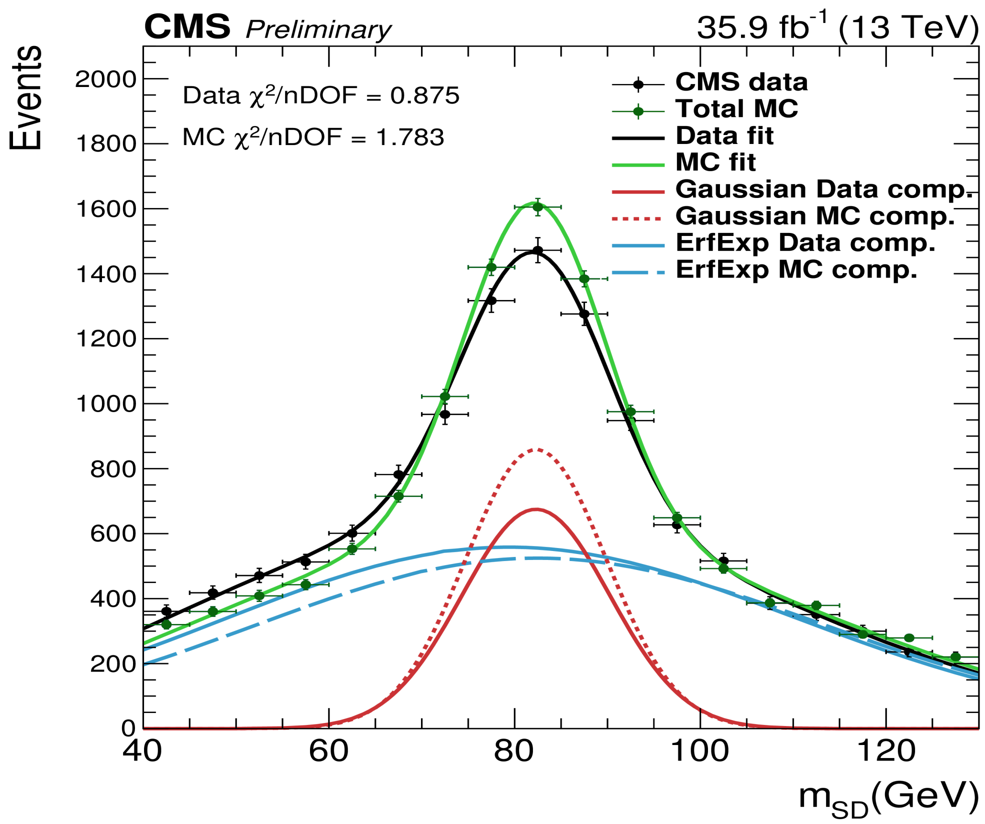

## mMDT(Sofdrop β=0) jet mass




**CMS-SMP-16-010**

# Jet Mass Resolution

- Mass resolution obtained with top events

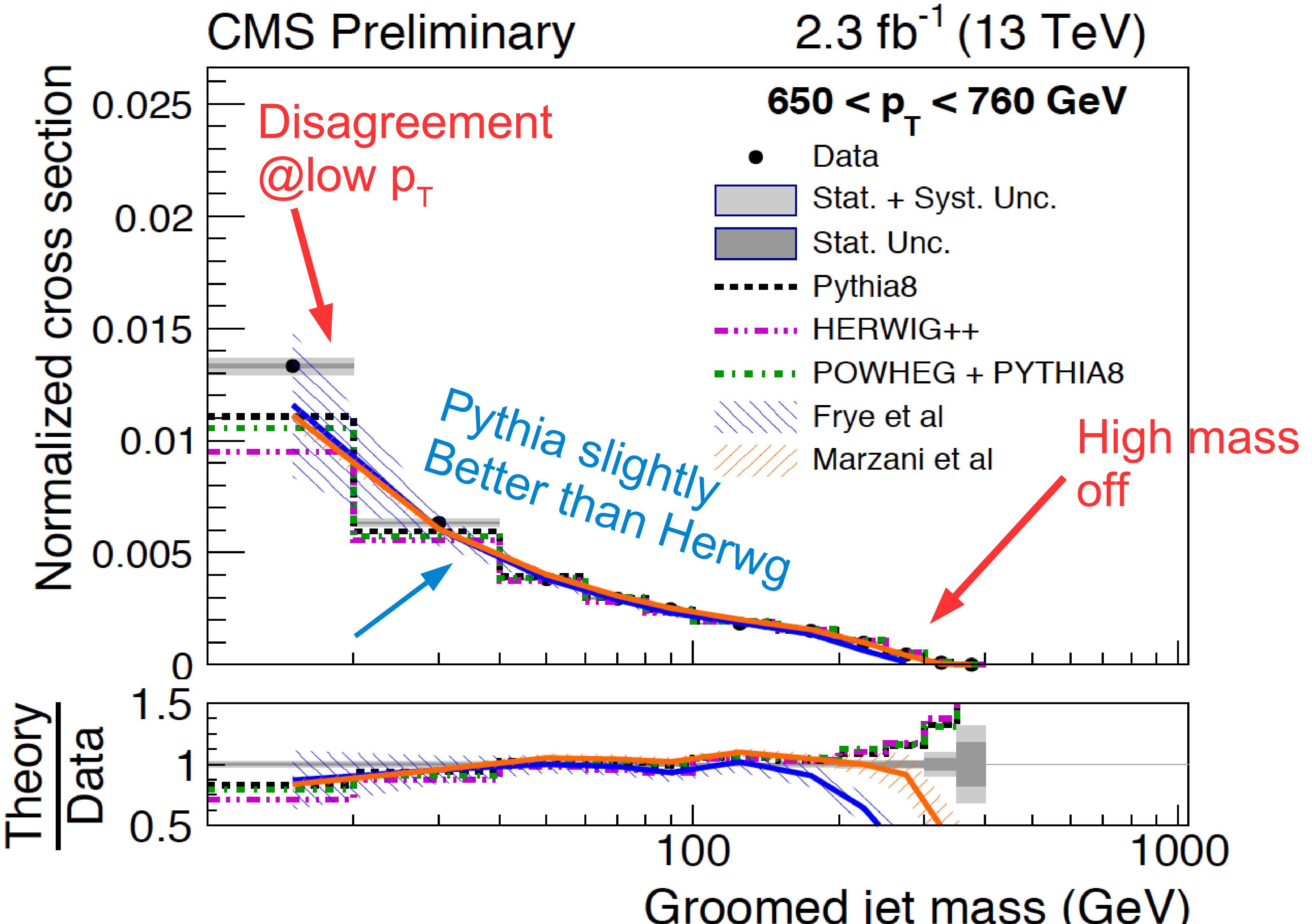



Jet mass and resolution calibrated on W peak in ttbar events

Unc extrapolated to all phase space

In addition compute uncertainty based :
Jet energy corrections/resoultion,Pileup,
PDF and Physics model

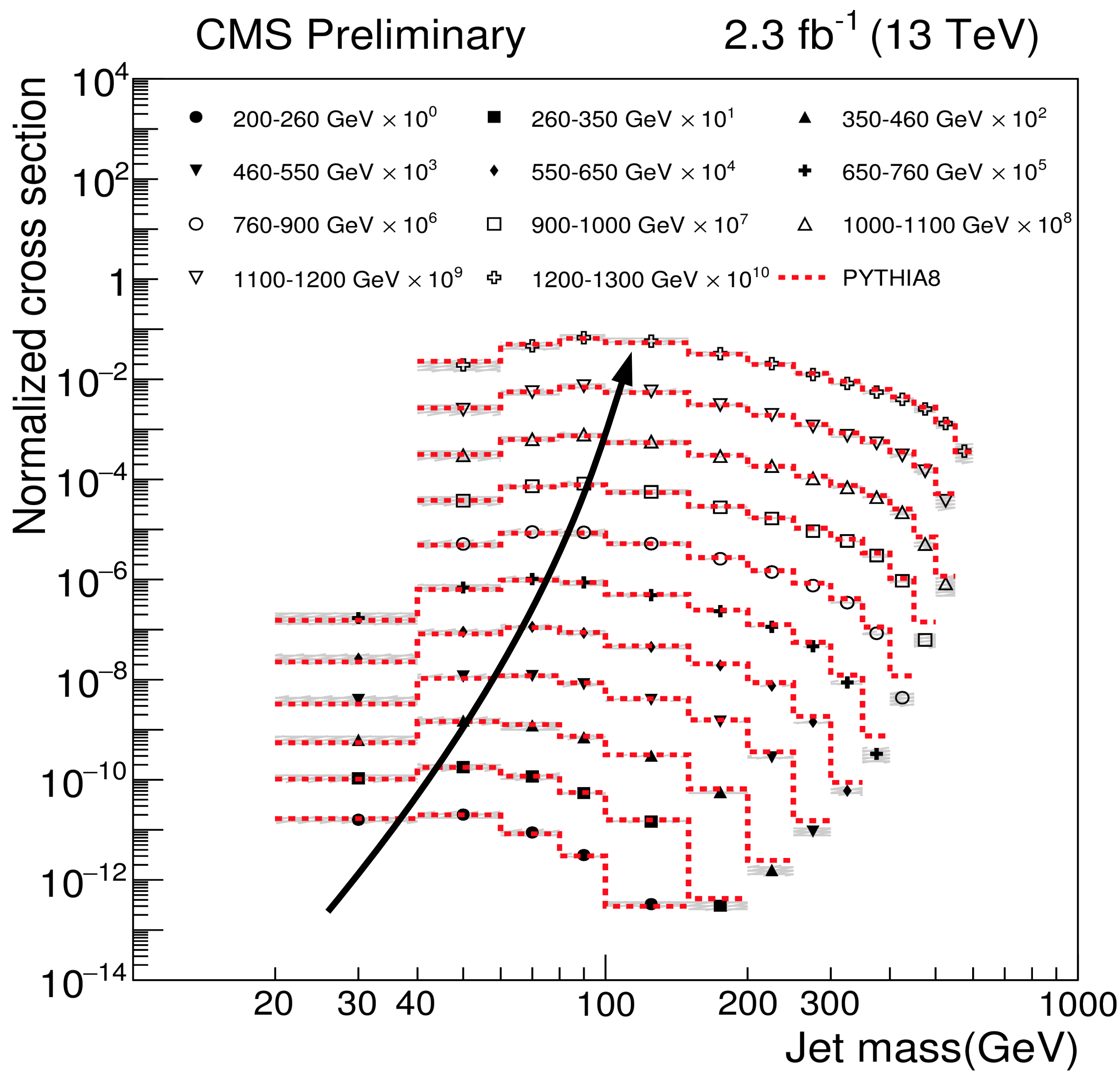
CMS-SMP-16-010




CMS-SMP-16-010

# Evolution of Mass Peak

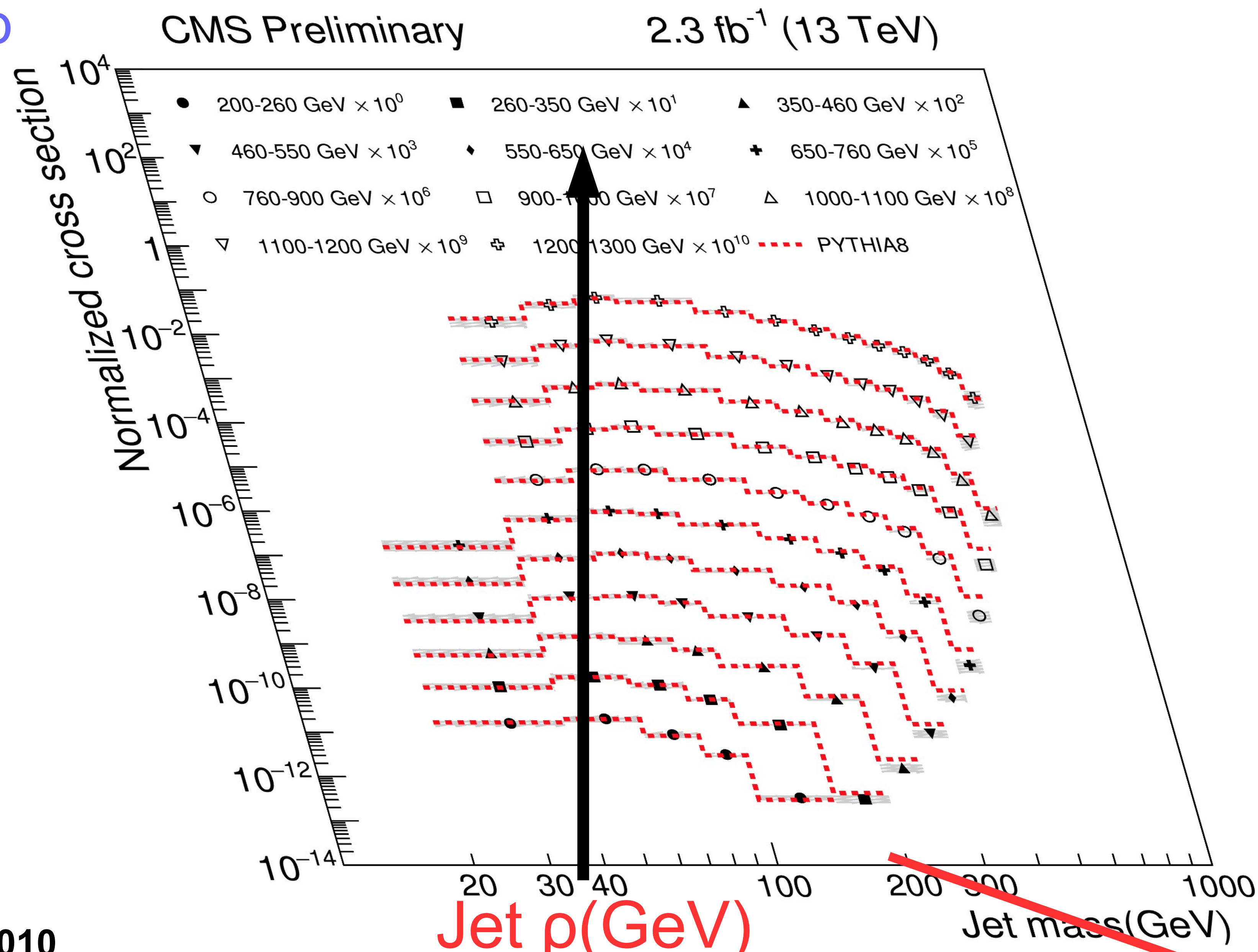
Clear trend in observed mass




**CMS-SMP-16-010**

# Evolution of Mass Peak

Trend becomes straight
When transform from
mass→ρ

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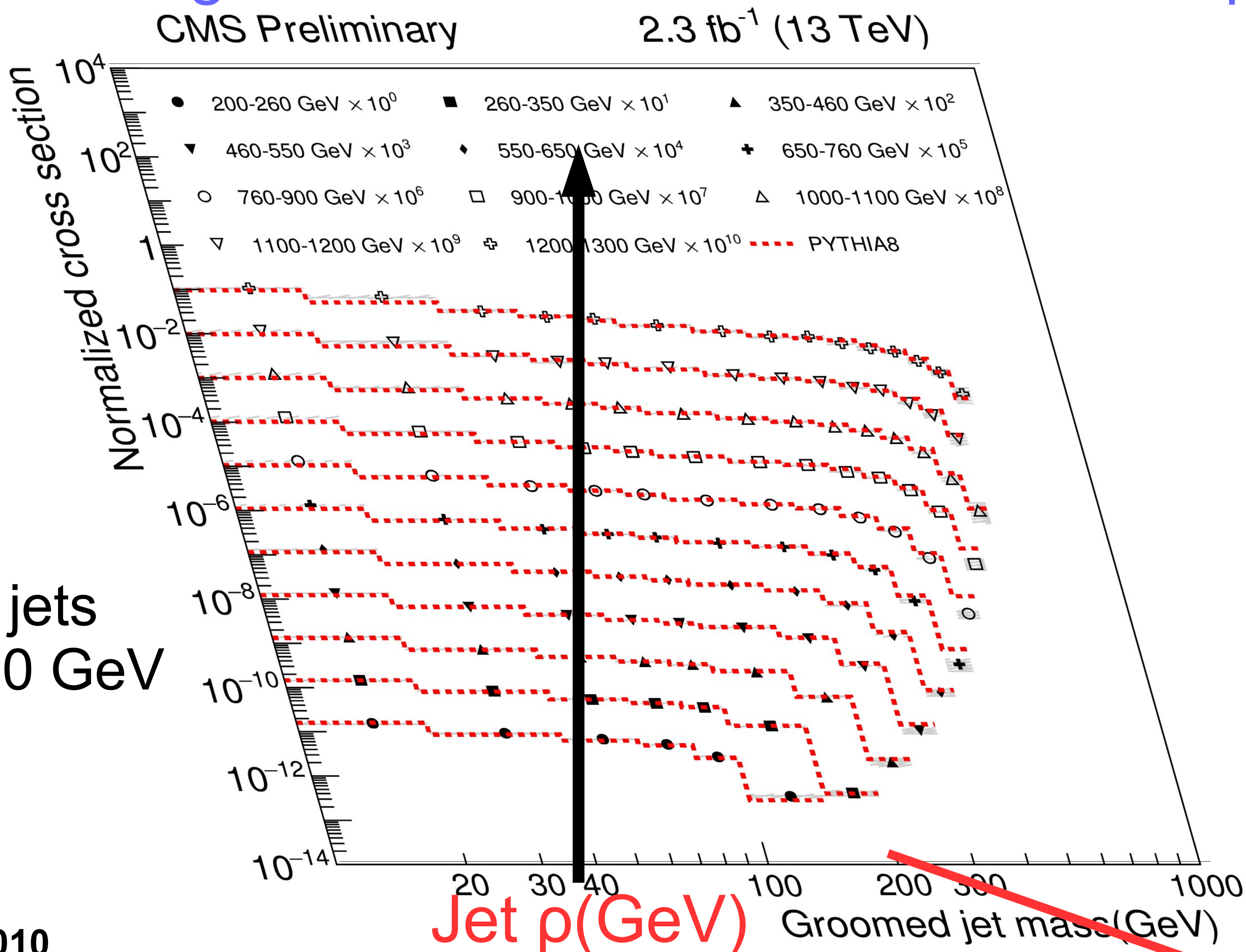
# Groomed Evolution

When grooming the mass becomes even flatter in ρ

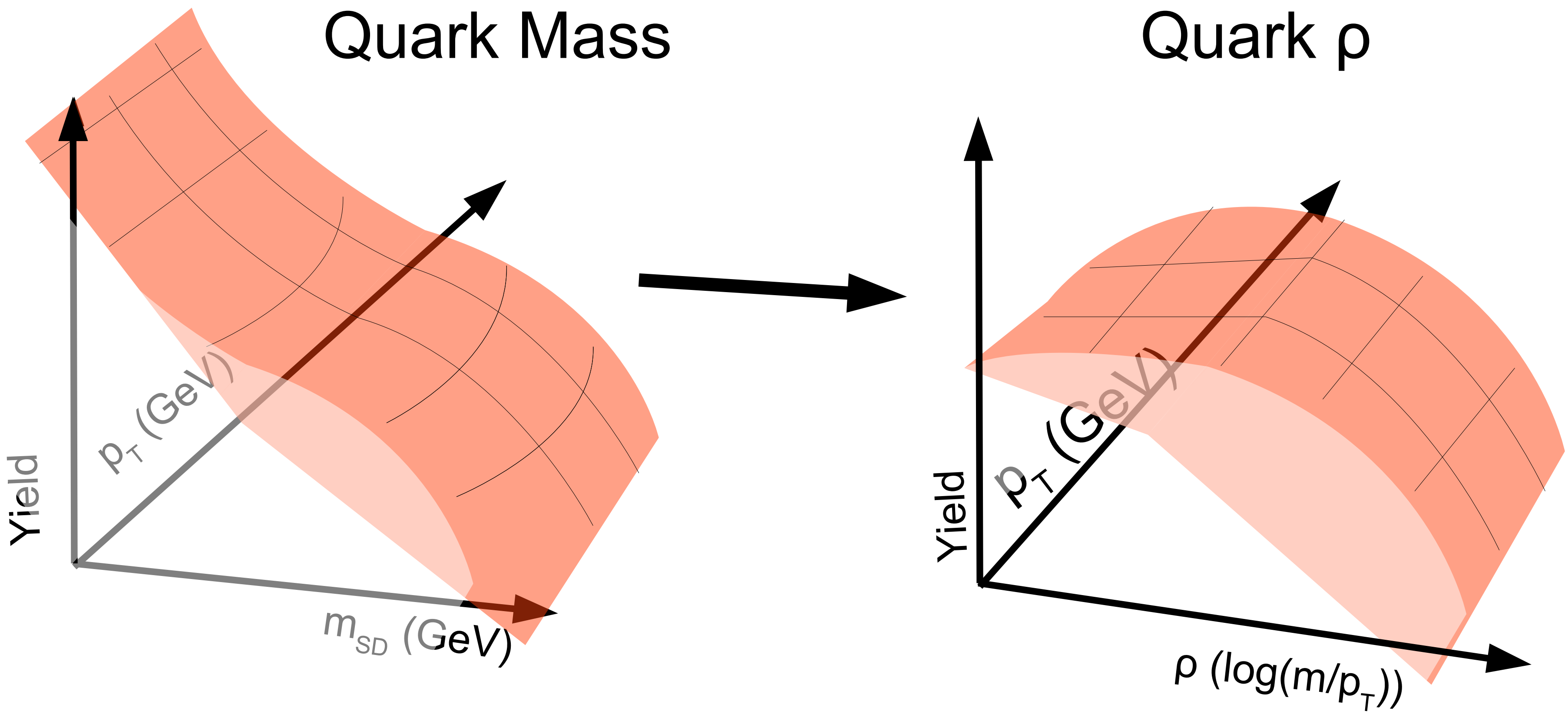



Consider jets w/$p_T$ > 450 GeV (trigger)

CMS-SMP-16-010

# Merging with ρ

- Merging to ρ makes imposes invariance over $p_T$

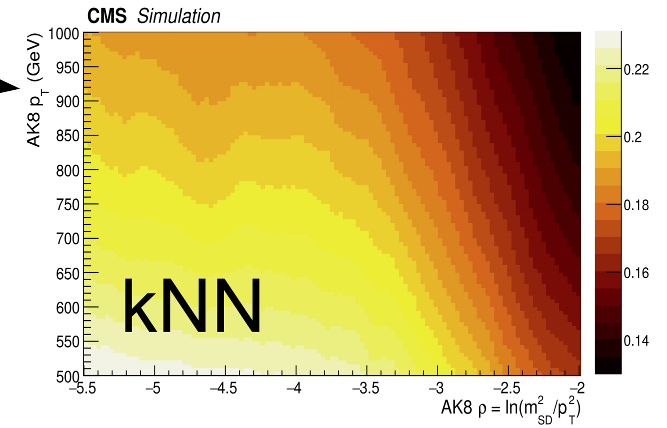



When translating to ρ distributions over $p_T$ are also invariant

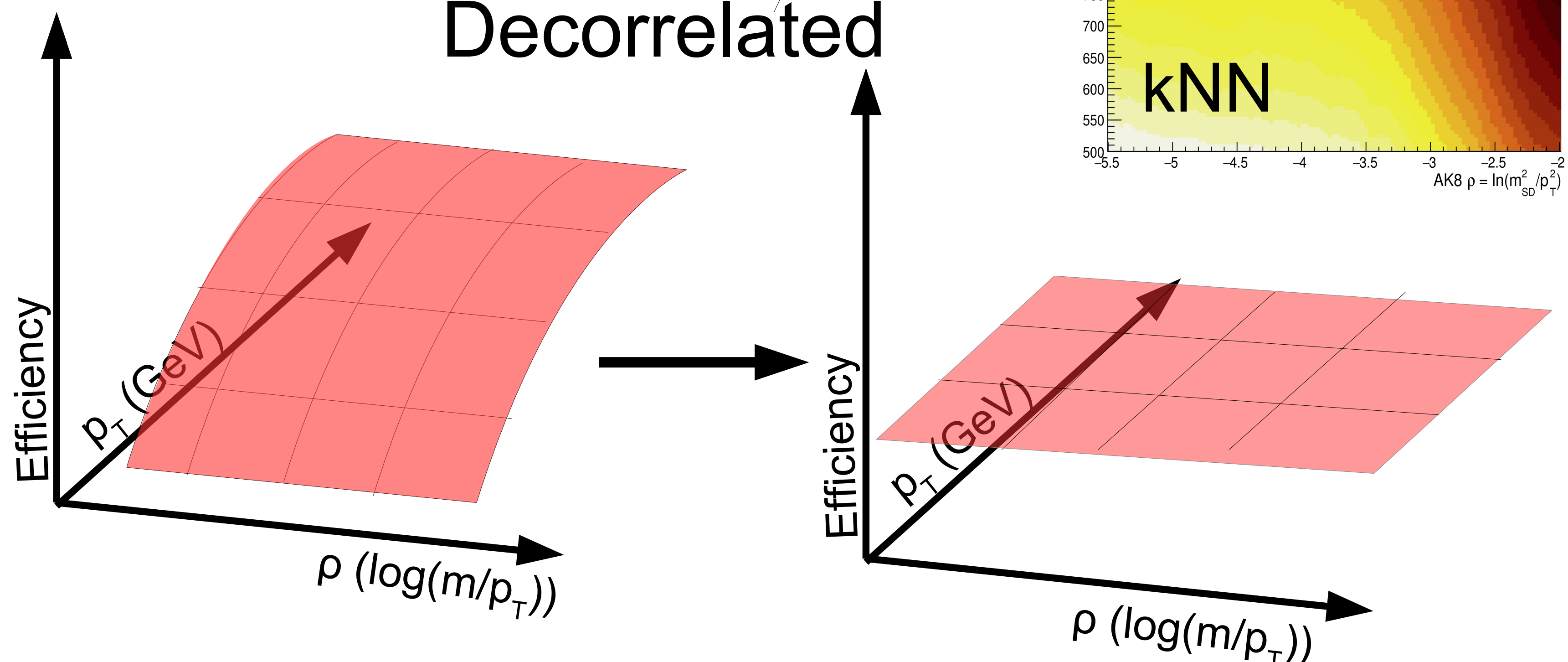
This allows us to extend our fit from 1D mass to 2D $p_T$ and ρ

# Design a transform to decorrelate against mass and $p_T$

Decorrelating avoid mass sculpting allows us to cut tighter




Decorrelated



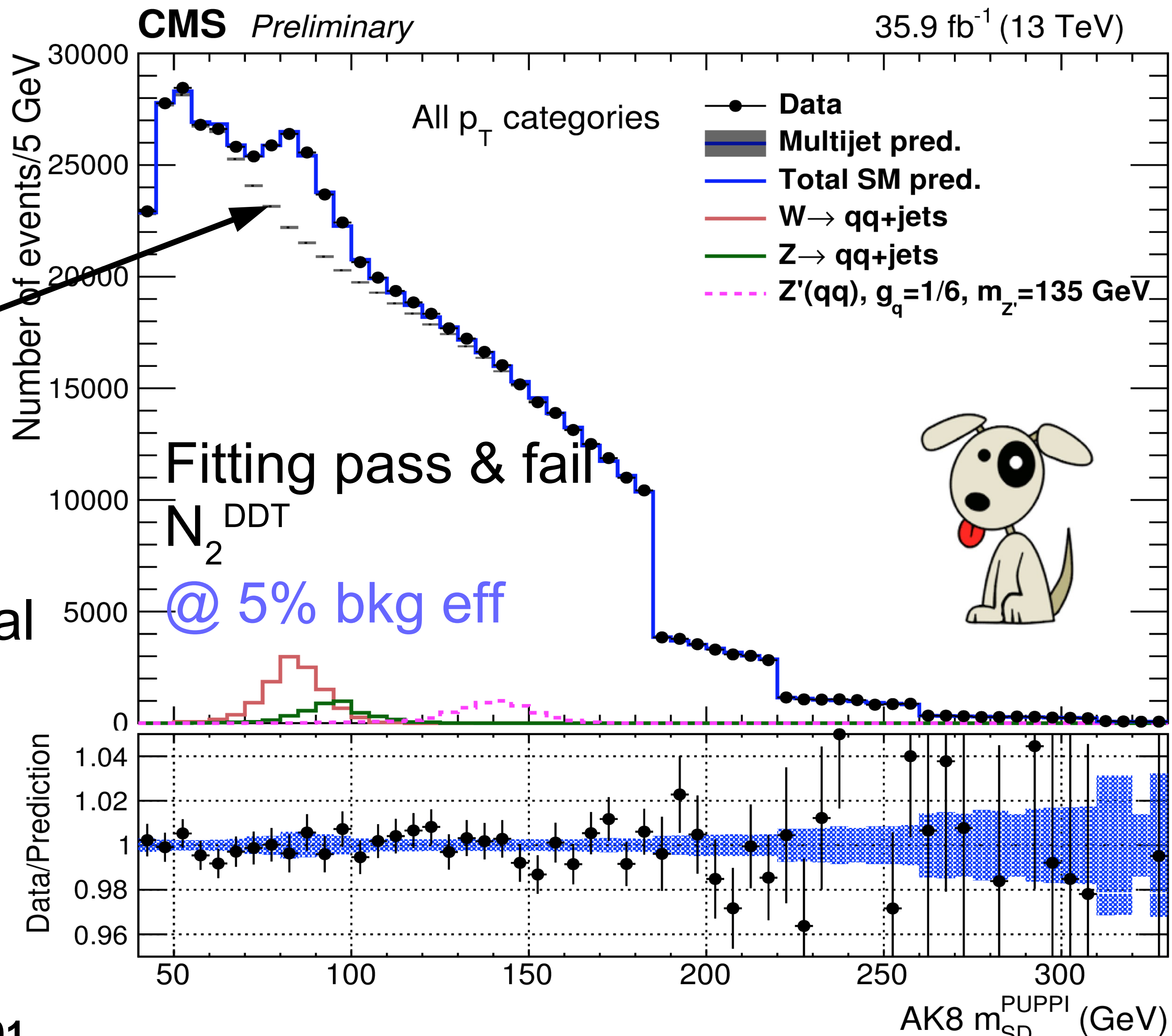

As a first example decorrelate $N_2 \rightarrow N_2^{DDT} = N_2 - \varepsilon(x\%)$

arXiv:1603.00027

# Without B-tagging

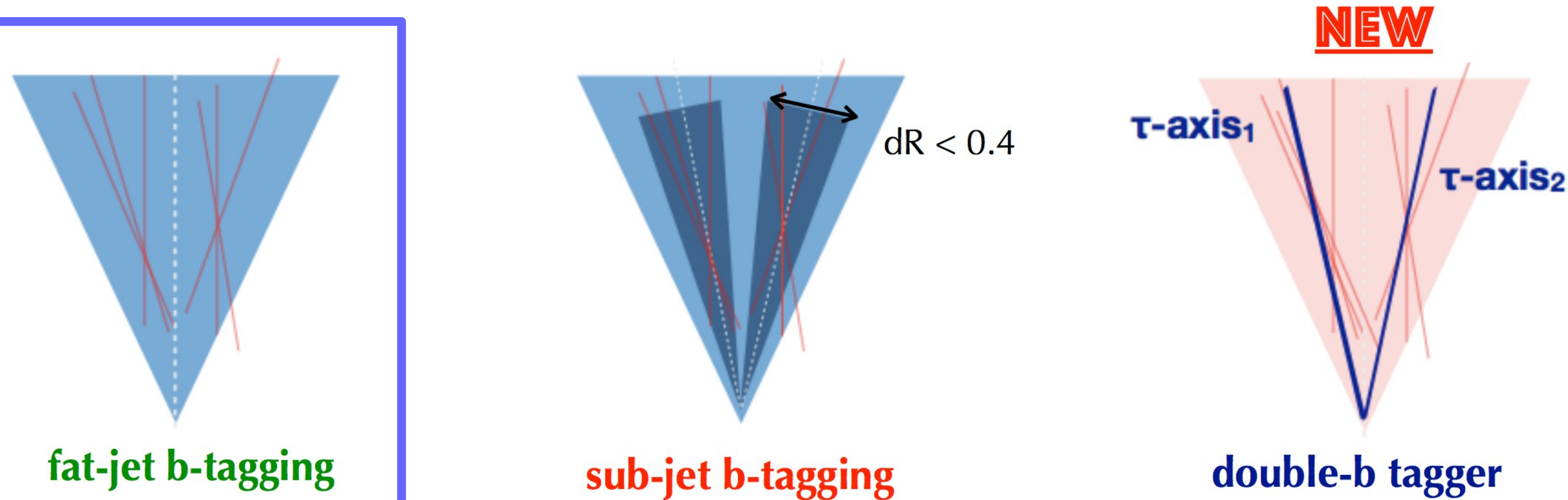
W/Z peak
Fit at the
7% σ unc.

QCD NLO,
EWK critical



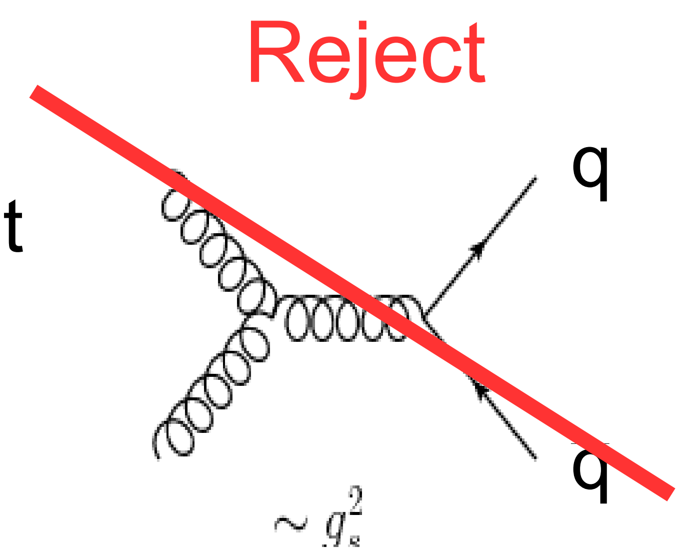

CMS-EXO-17-001

# Double-b tagging Concept #1



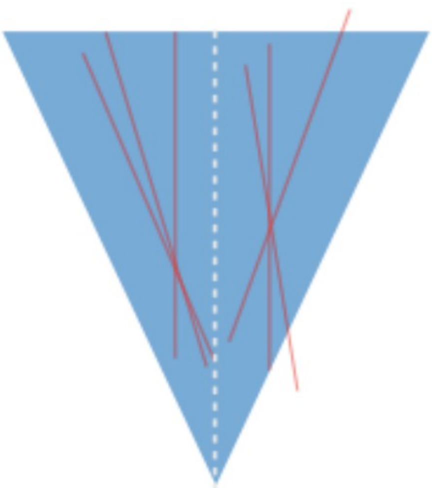

Apply standard b-tagging on the whole jet

Best at identifying Higgs against a jet composed of light quarks

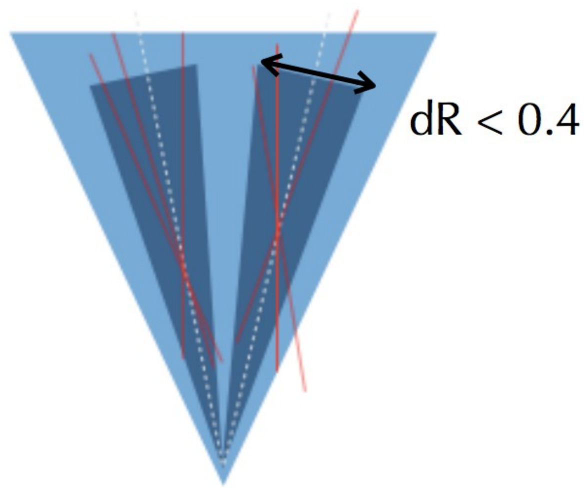



**CMS-BTV-15-002**

# Concept #2

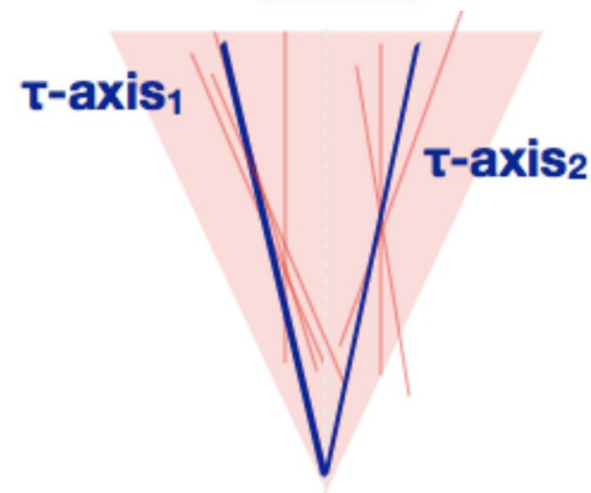


fat-jet b-tagging



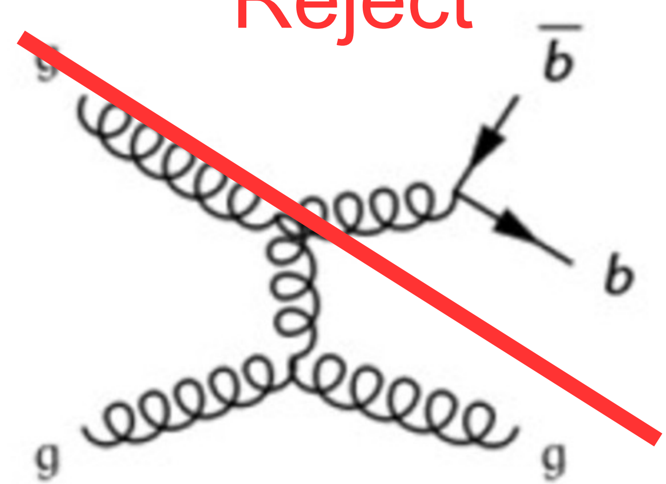

sub-jet b-tagging

NEW




double-b tagger

Reject



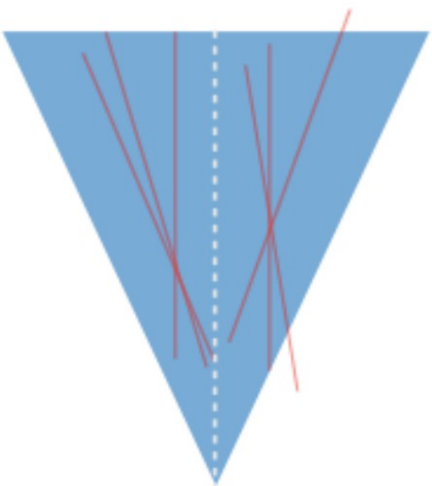

Apply b-tagging on the subjet

Best at identifying Higgs

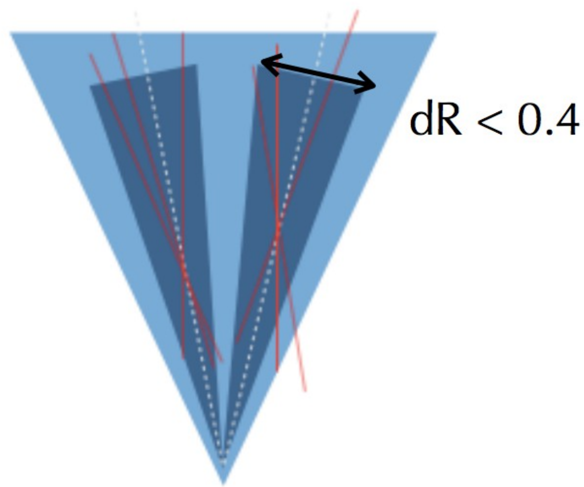
Agains a jet from a gluon splitting

**CMS-BTV-15-002**

# Concept #3

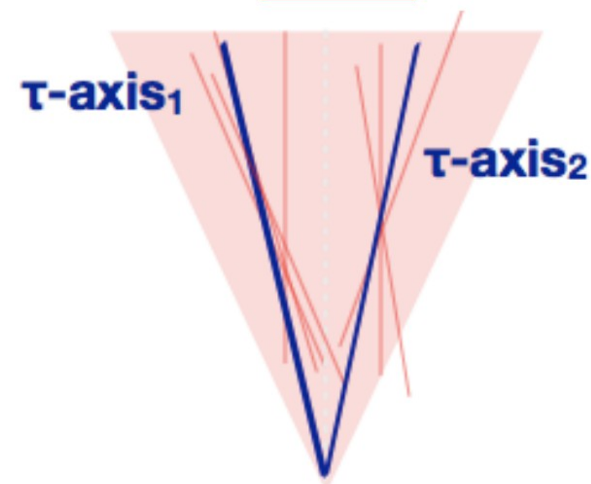


**fat-jet b-tagging**



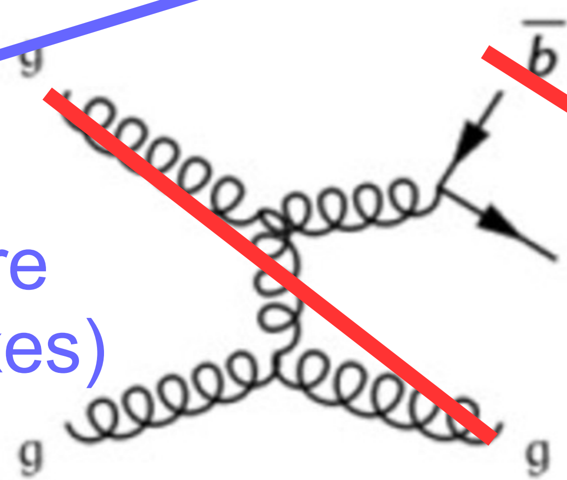

**sub-jet b-tagging**

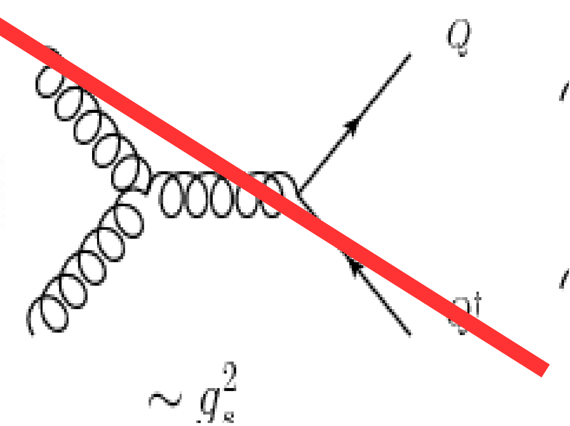
**NEW**




**double-b tagger**

**Reject**

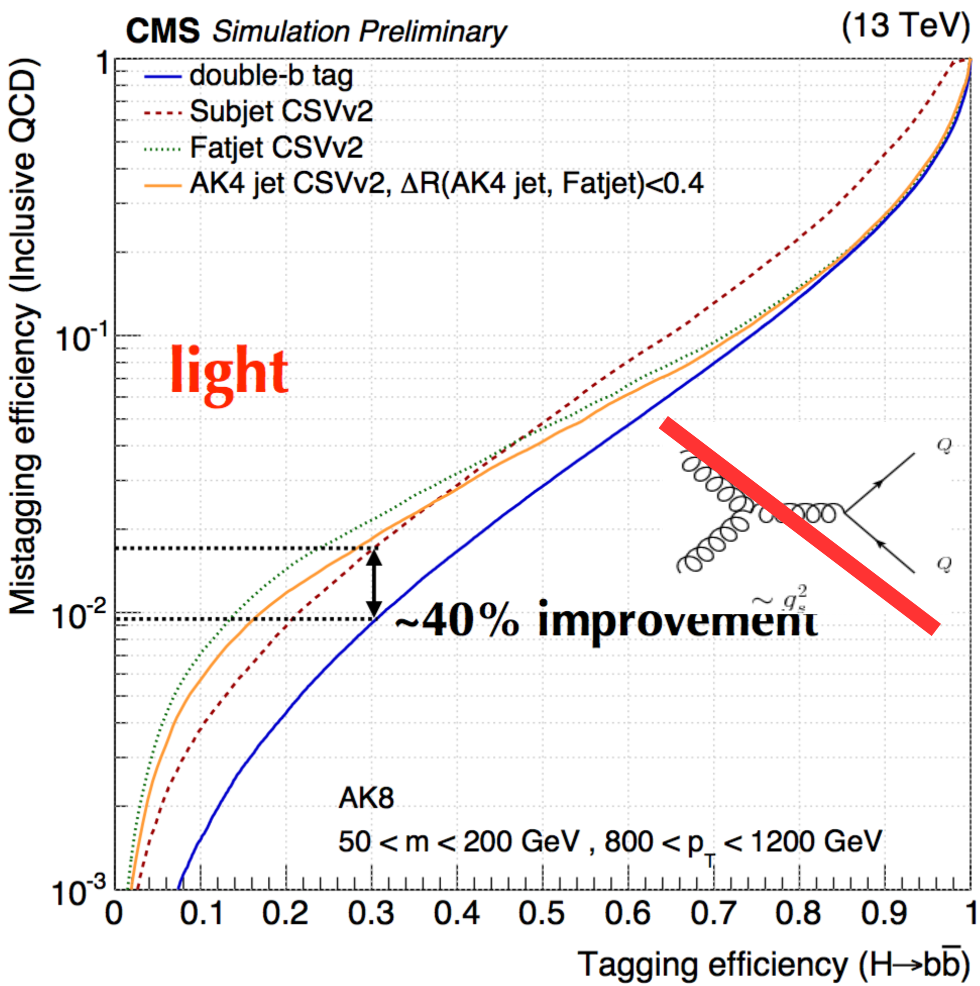


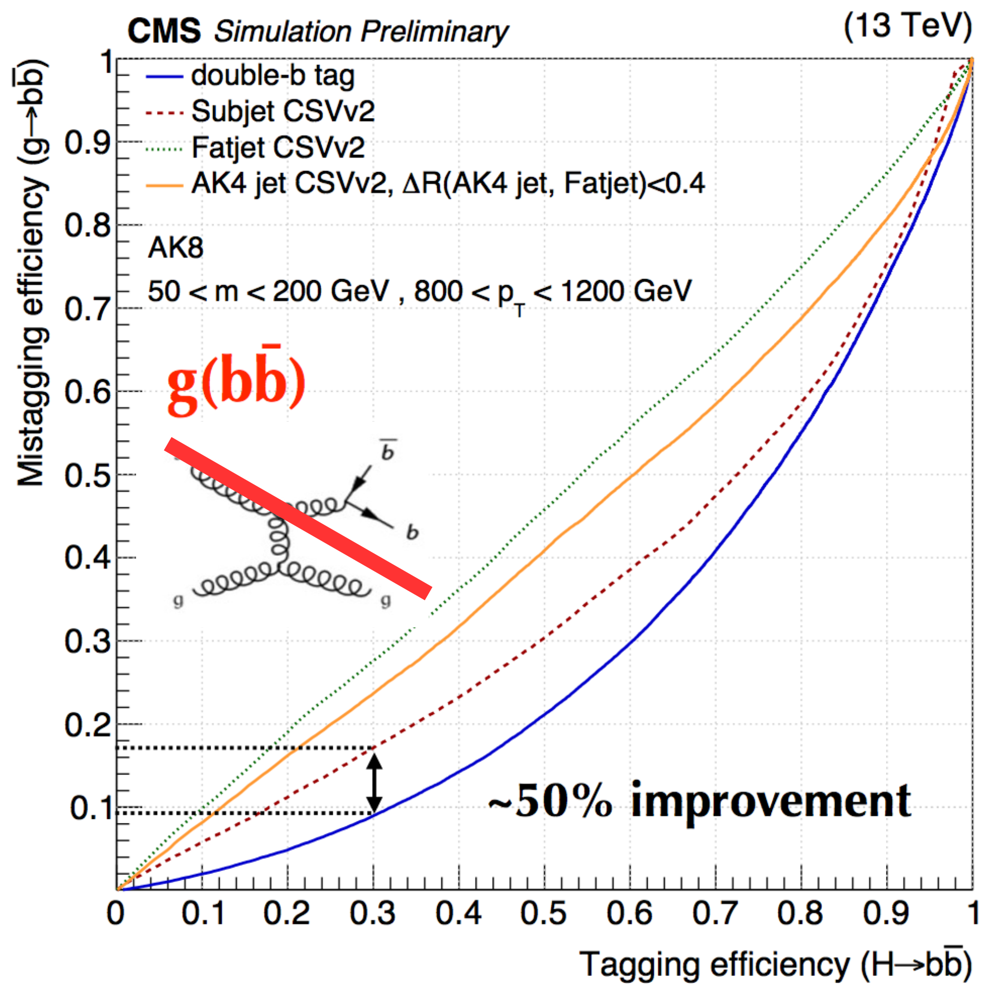




Apply b-tagging on the
Whole Jet using substructure
Variables (n-subjettiness axes)
1-pass kT

**CMS-BTV-15-002**

# Double B-tagger

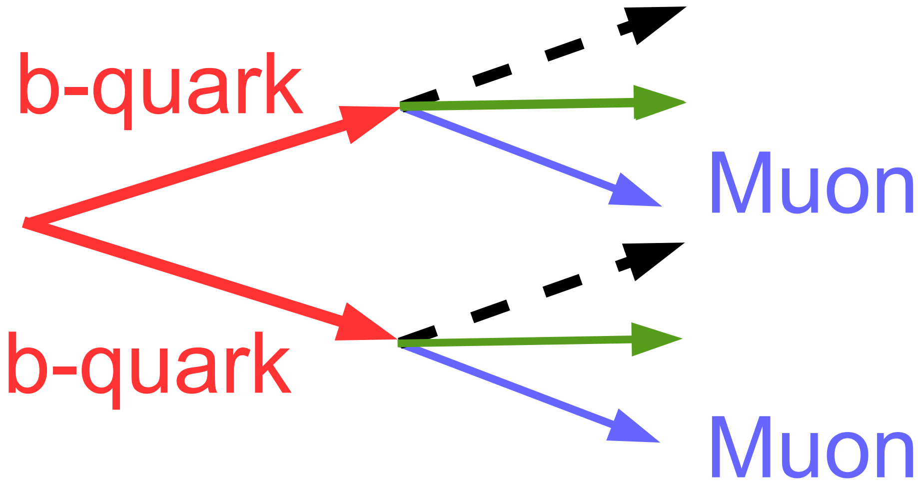


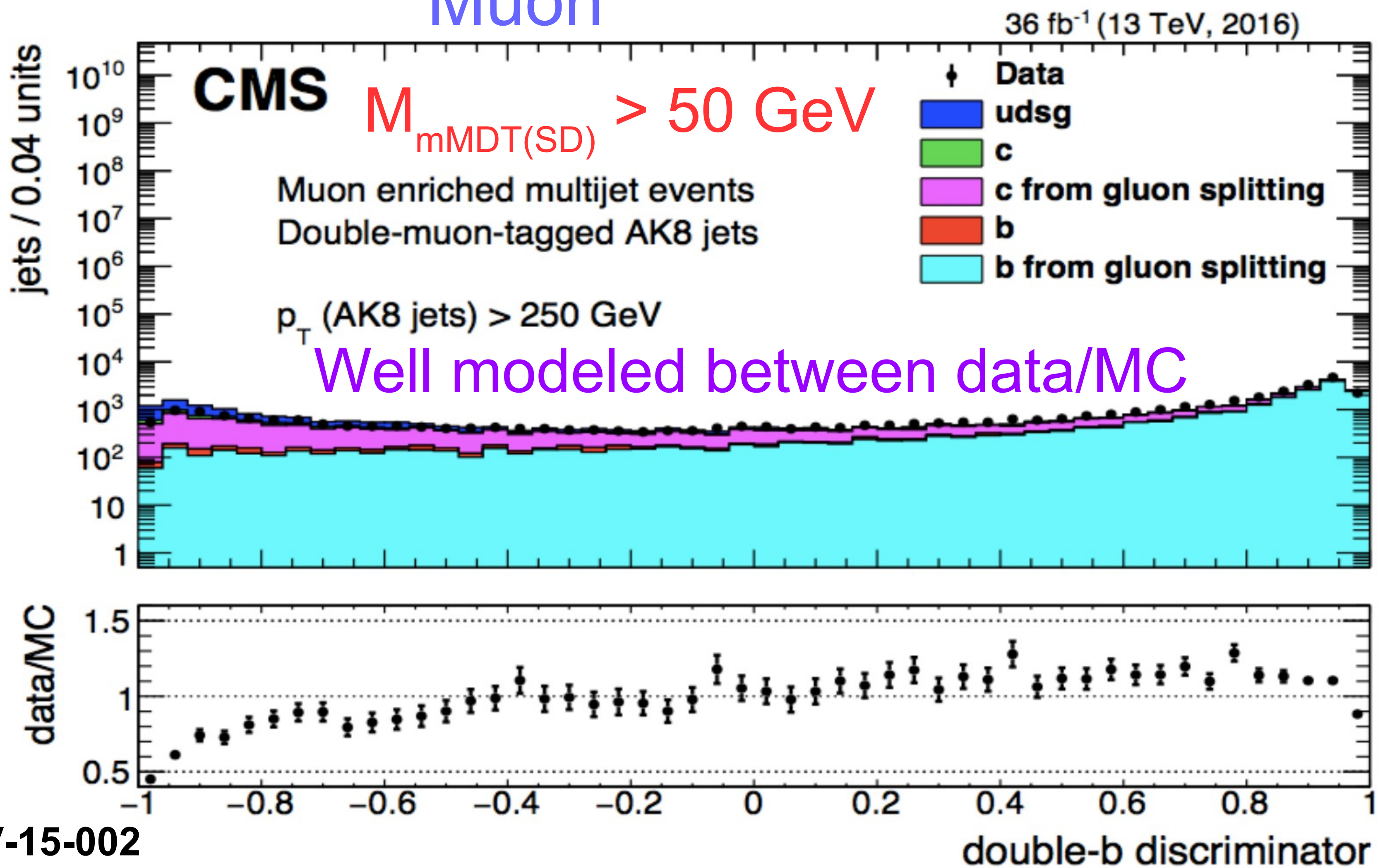

Resulting combination gives 50% improvement over previous

**CMS-BTV-15-002**

# What about data/MC

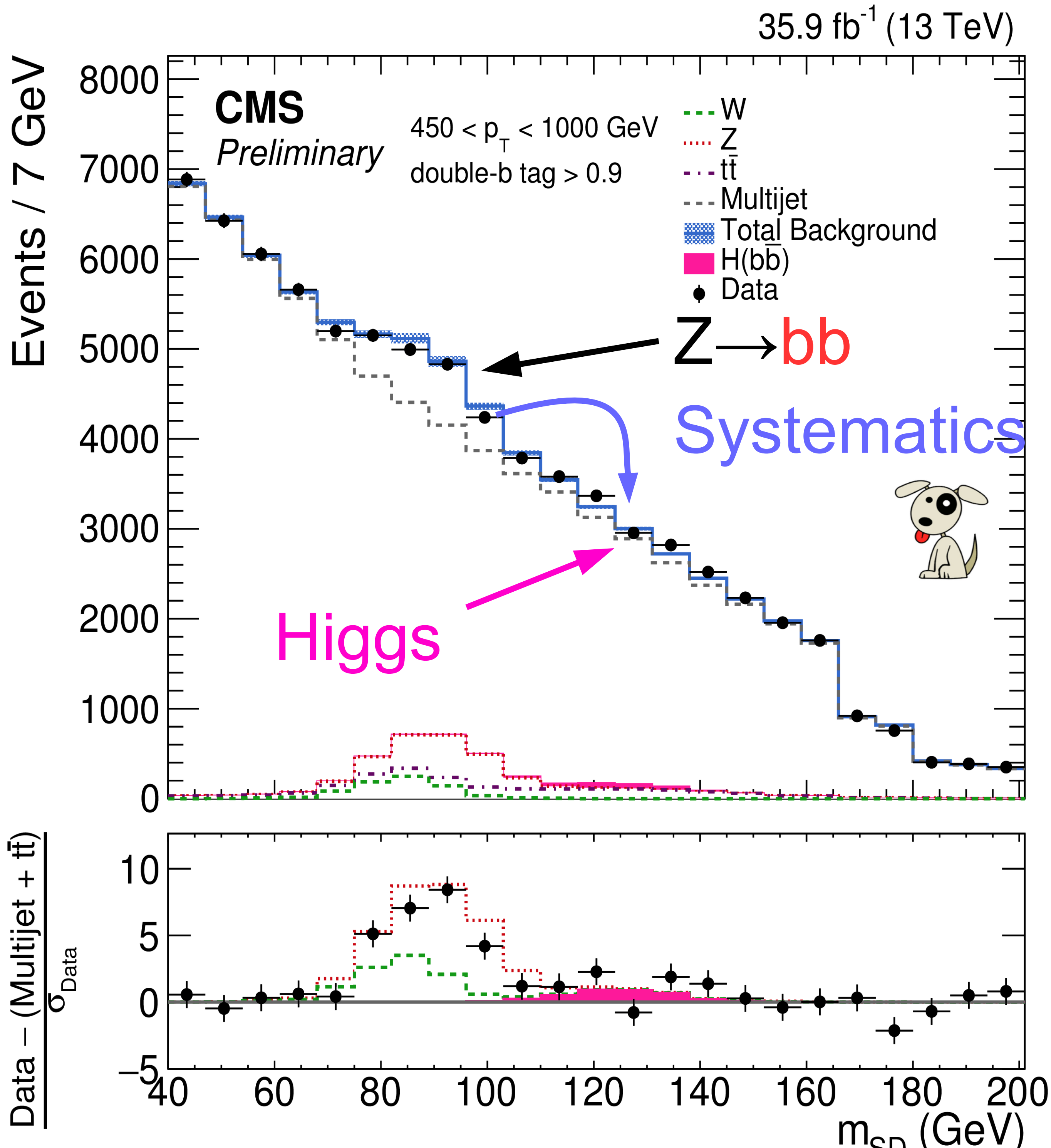



Tag two muons in a jet
Use this to infer signal-like
2 b-quarks in a jet




CMS-BTV-15-002

# Result

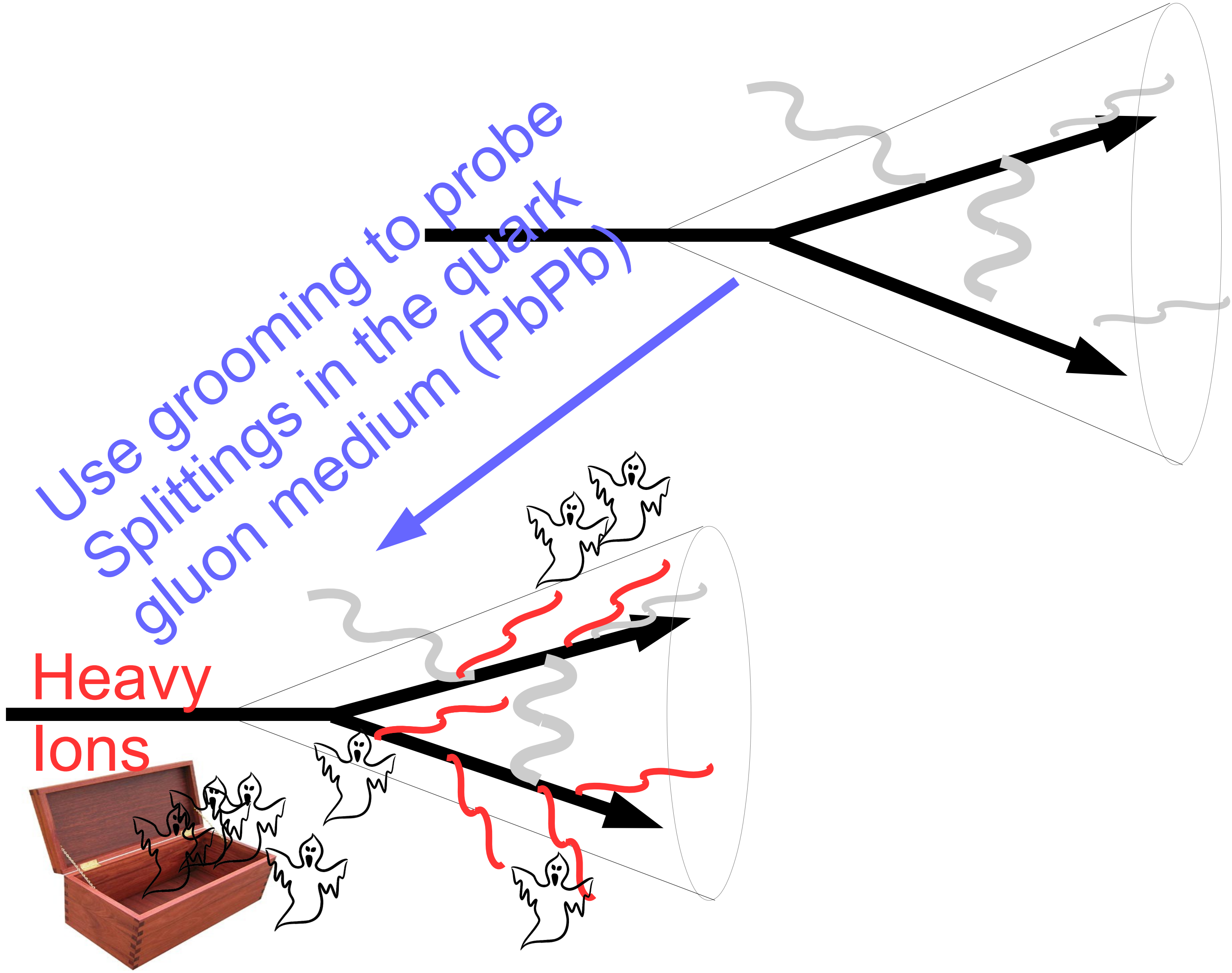



CMS-HIG-17-011

The large Z→bb Allows us to calibrate our signal

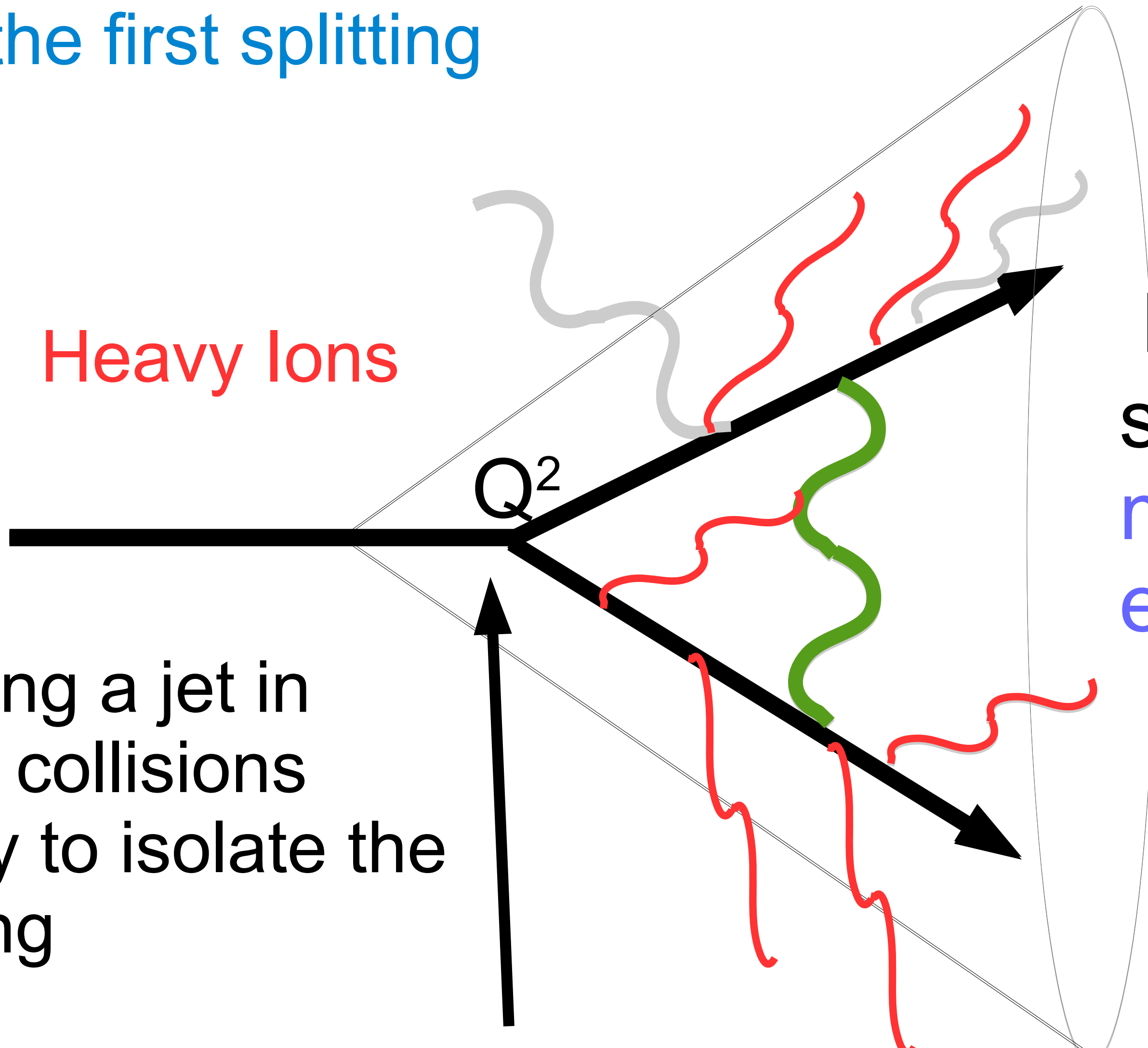
Z peak Allows us to calibrate Higgs

# Where do we go from here?



# Heavy Ion Collisions

Consider the first splitting in jet



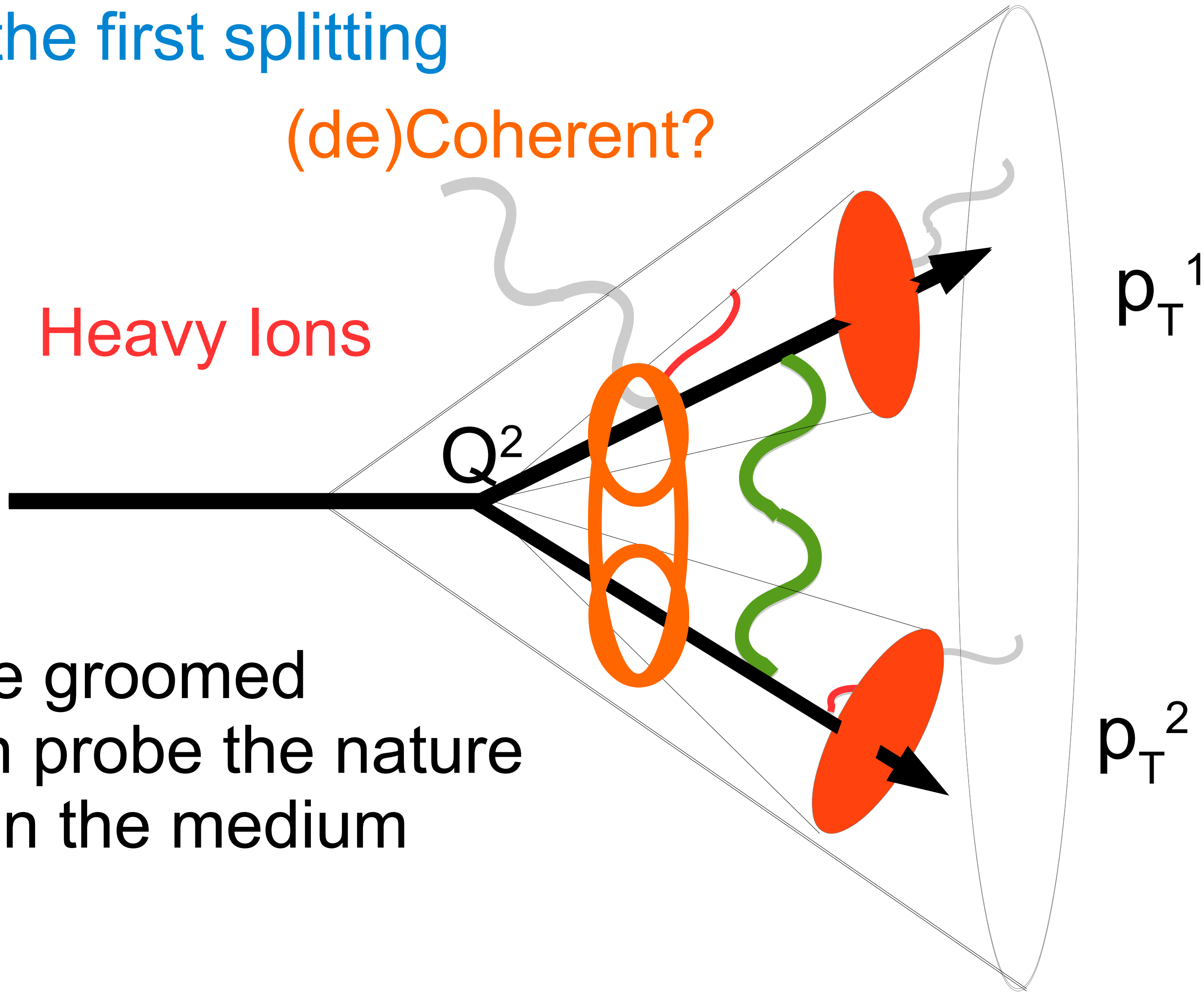

$p_T$ of $1^{st}$ splitting probe modifications early in shower

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



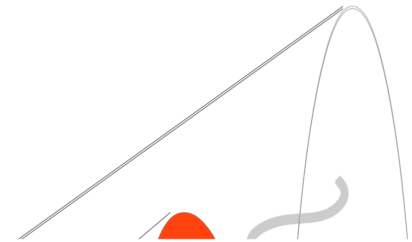

Isolating the groomed Subjets can probe the nature of the loss in the medium

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

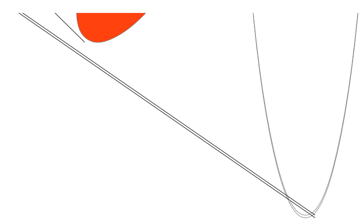
Probes coherence of the energy loss in the medium

# 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



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

$\Delta R_{12}$ 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

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

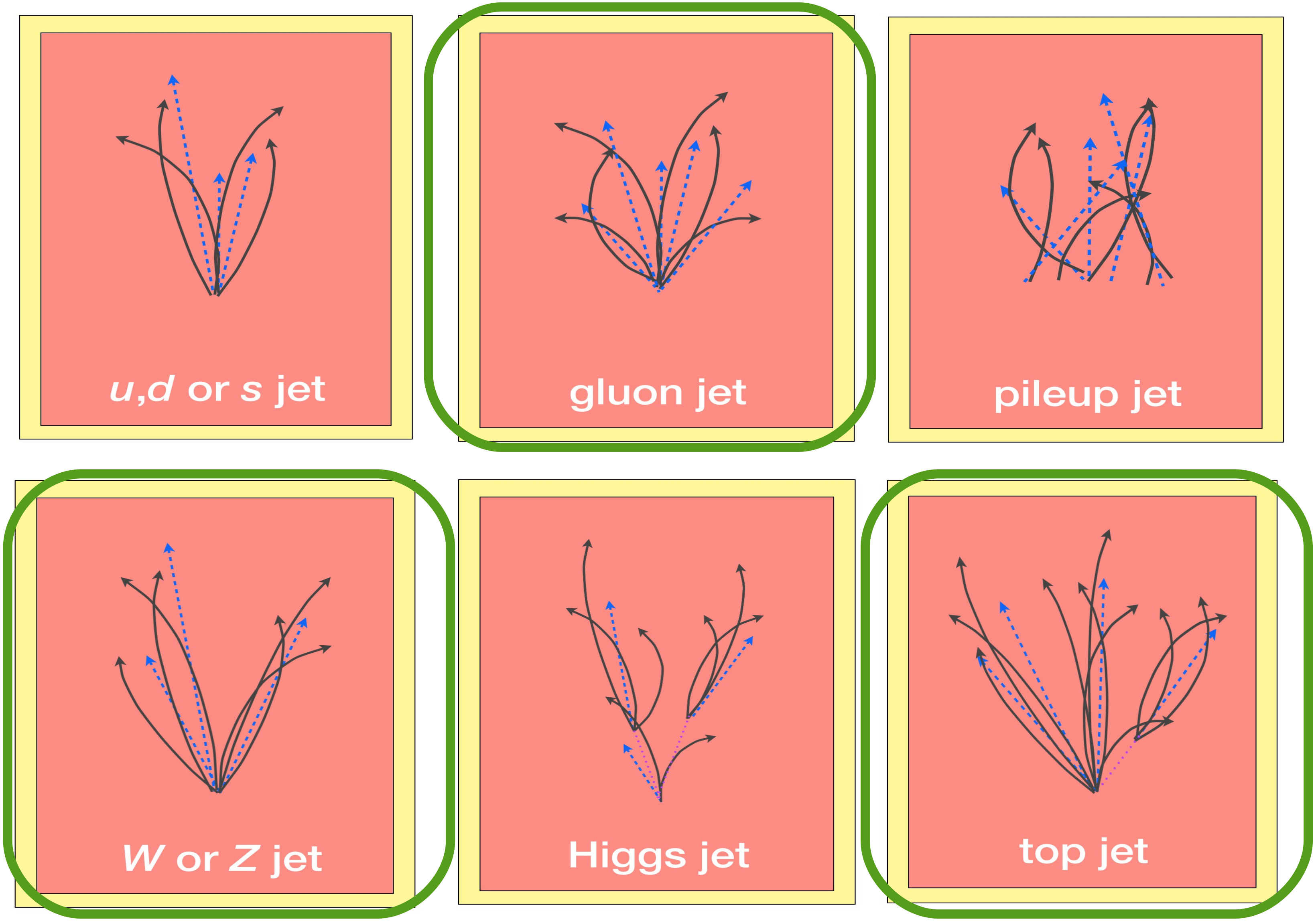
# Thanks!


THE MYSTERY FACE GAME • LE JEU DU PERSONNAGE MYSTERE
EL JUEGO DE LA CARA MISTERIOSA
MB
6+
GUESS
WHO
?
GUESS WHO?

# Guess the Jet by asking questions?*

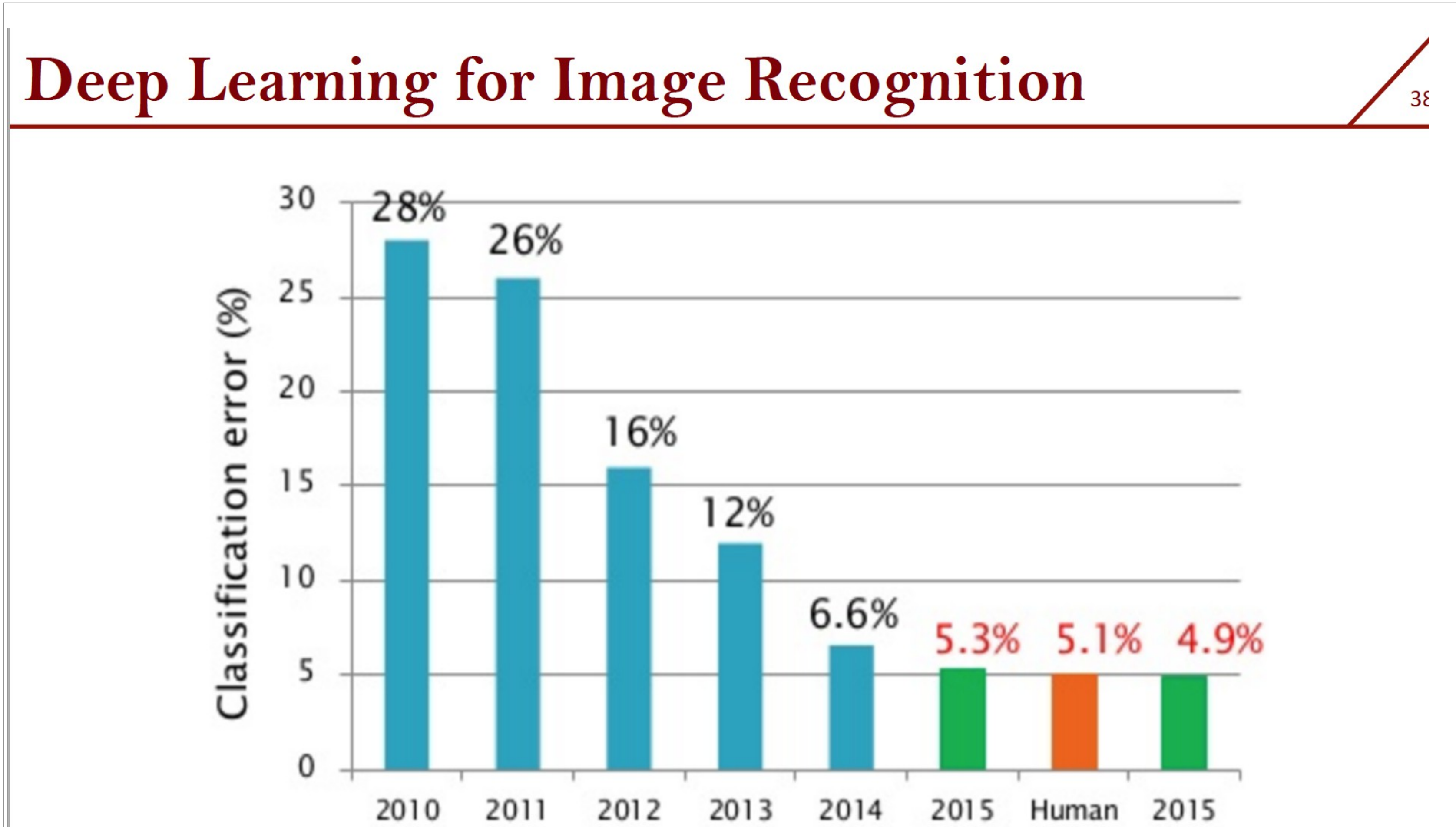

*Concept by N. Tran

# What are you options?




*Concept by N. Tran

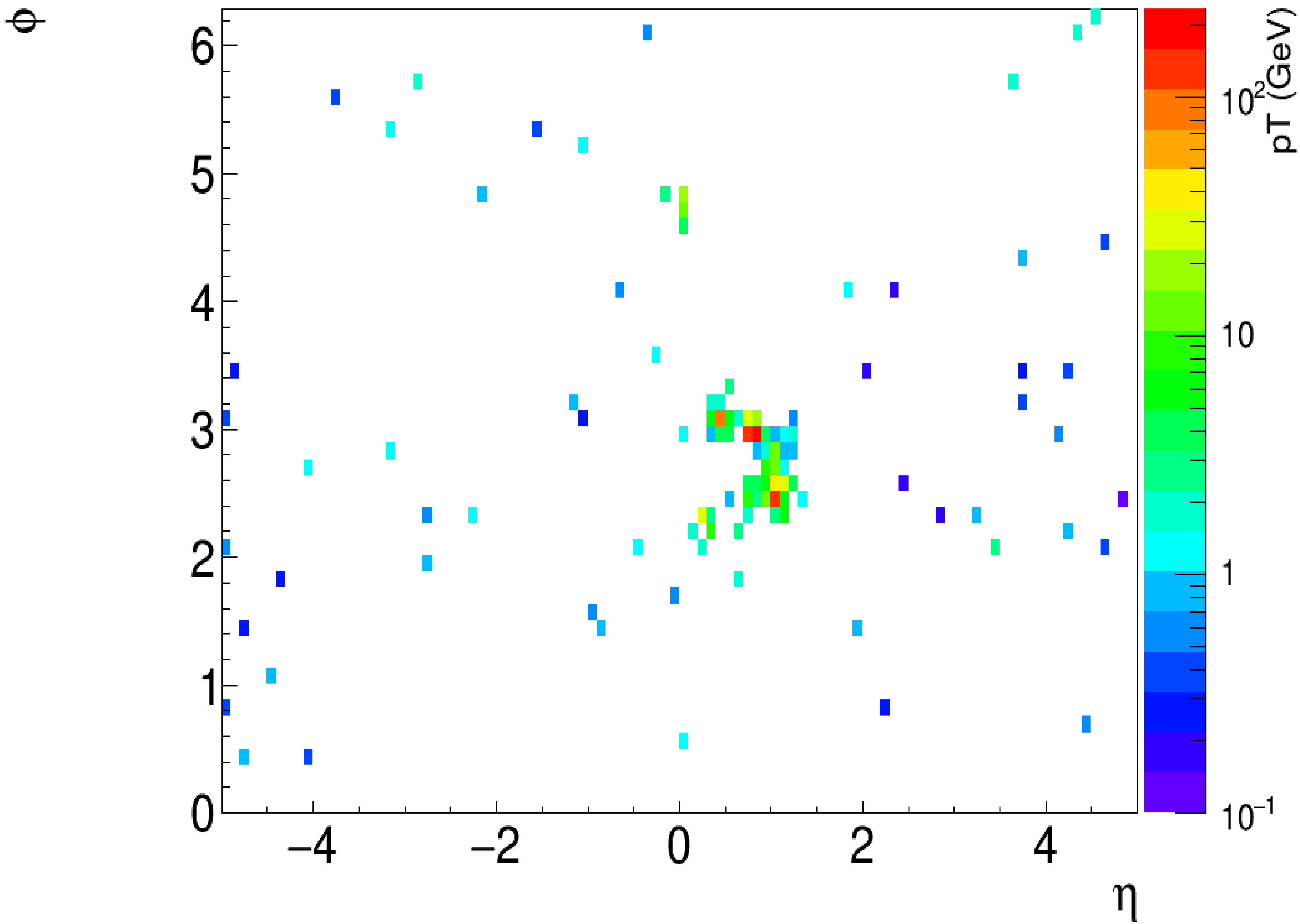
We will just use the 3 in green

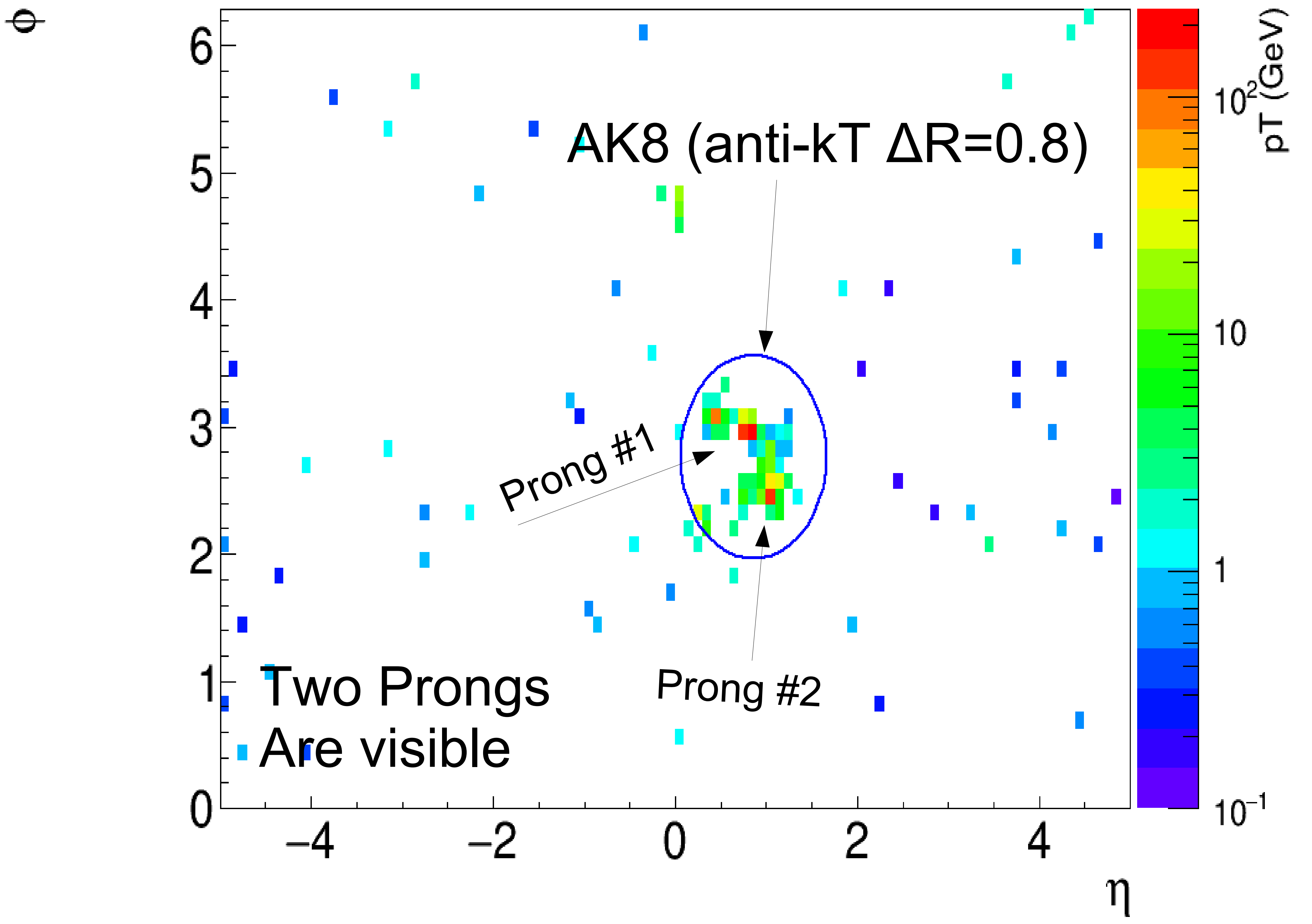



*Michael Kagan's slides (Yesterday)

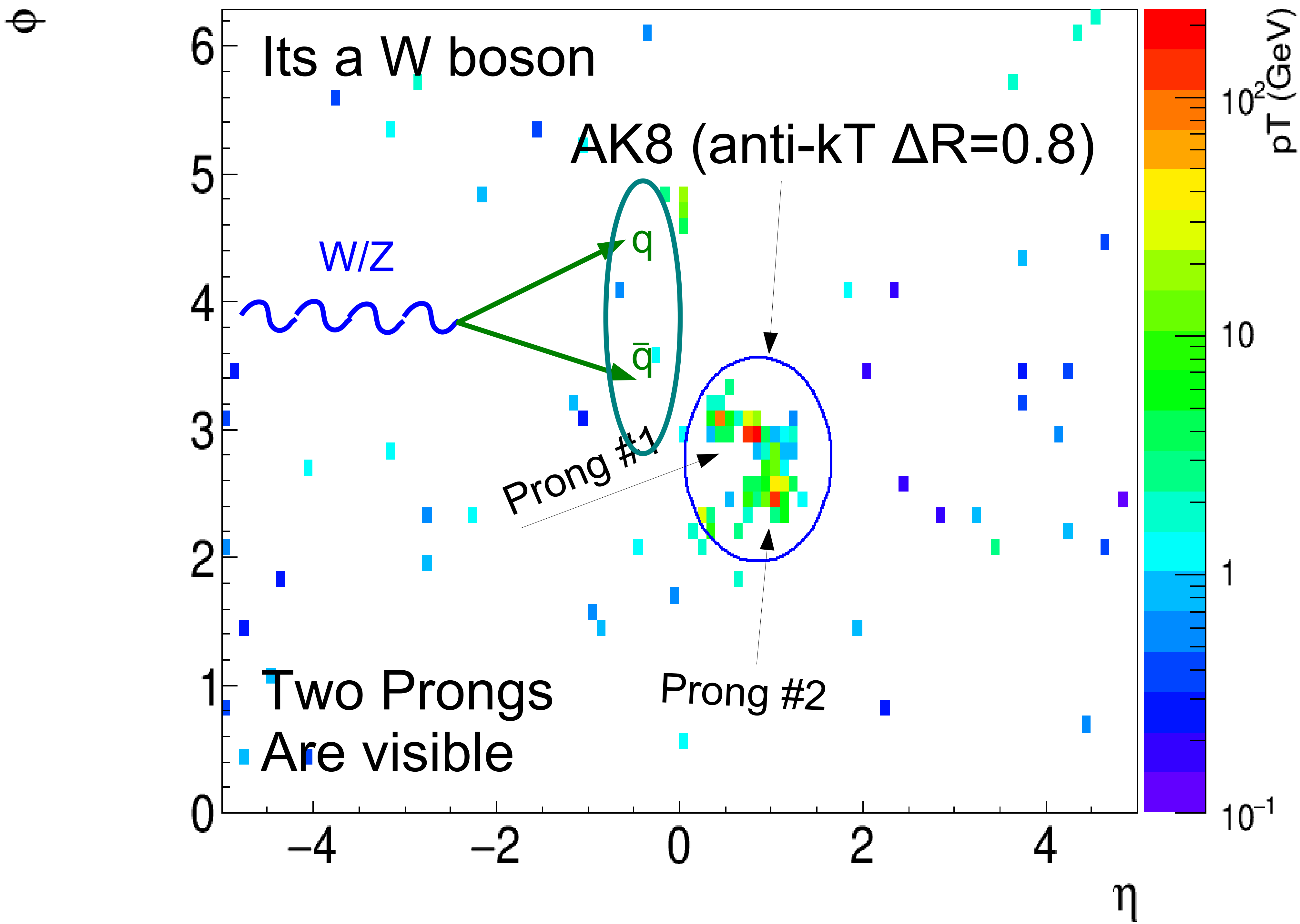
# Start @ 0 PU

# What is it?

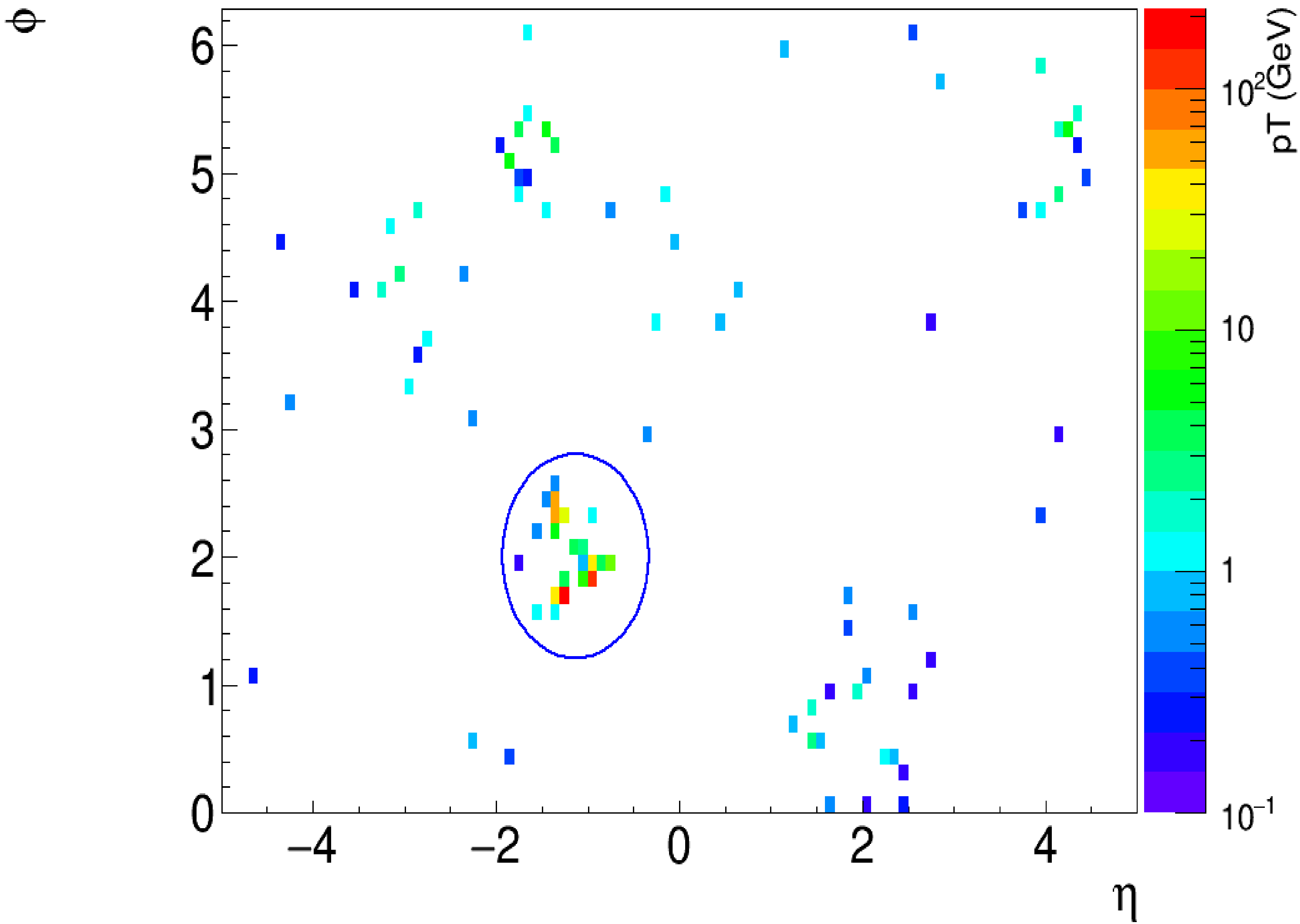



φ
η
pT (GeV)
AK8 (anti-kT ΔR=0.8)
Prong #1
Prong #2
Two Prongs
Are visible

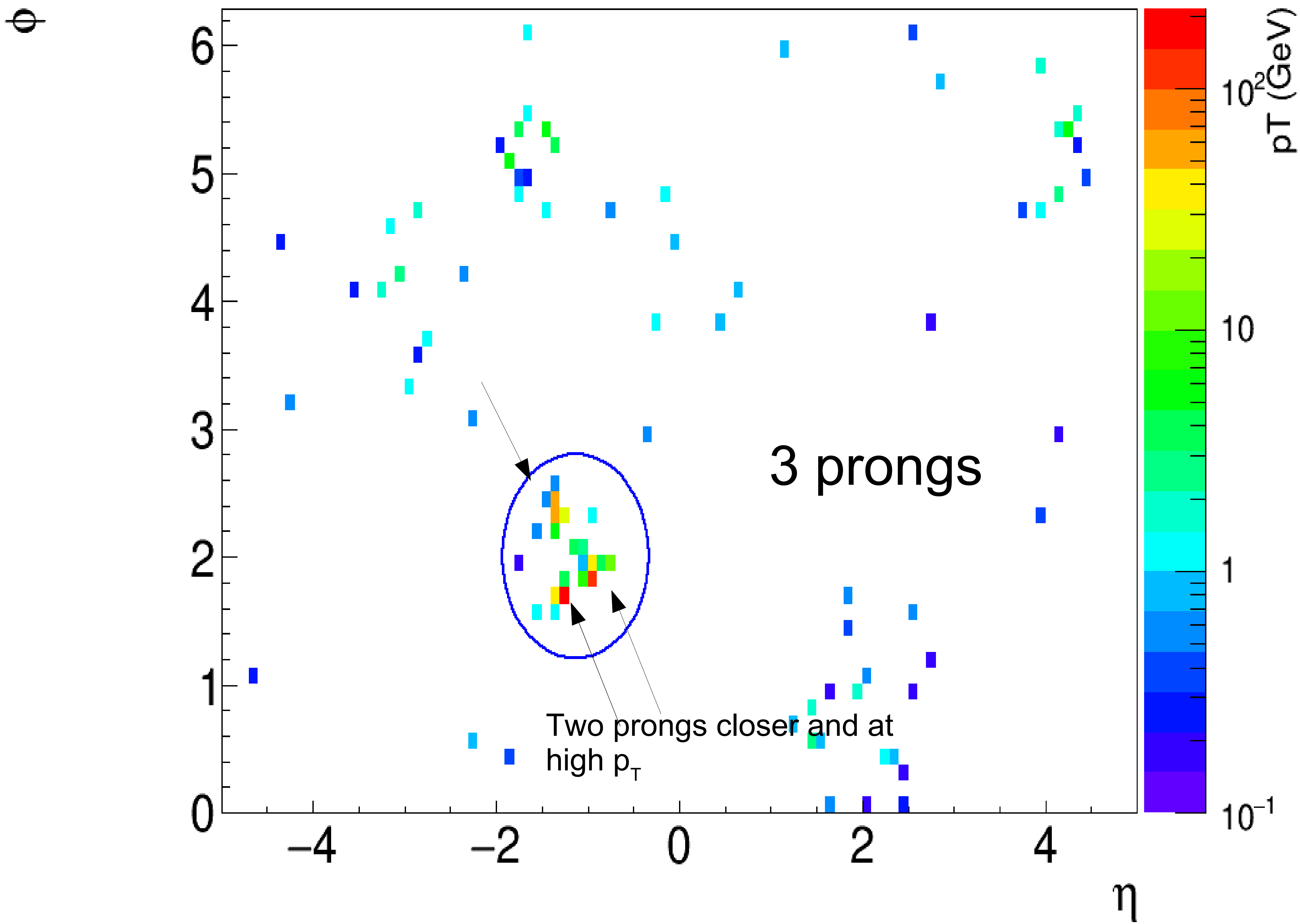
# What is it?


Its a W boson
AK8 (anti-kT ΔR=0.8)
W/Z
q
q̄
Prong #1
Prong #2
Two Prongs
Are visible
φ
η
pT (GeV)
0
1
2
3
4
5
6
−4
−2
0
2
4
10^−1
1
10
10^2

# What is it?

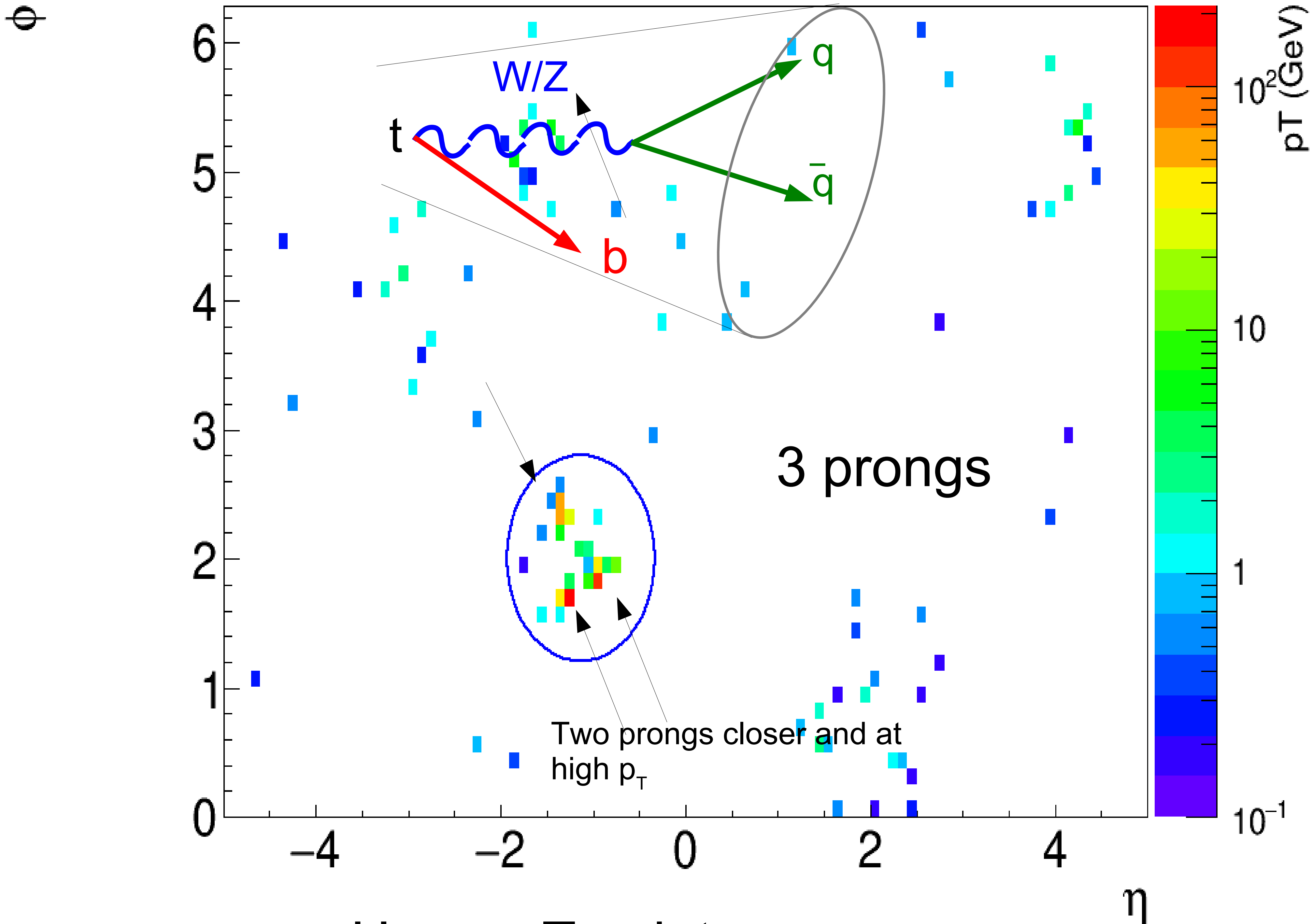


# What is it?

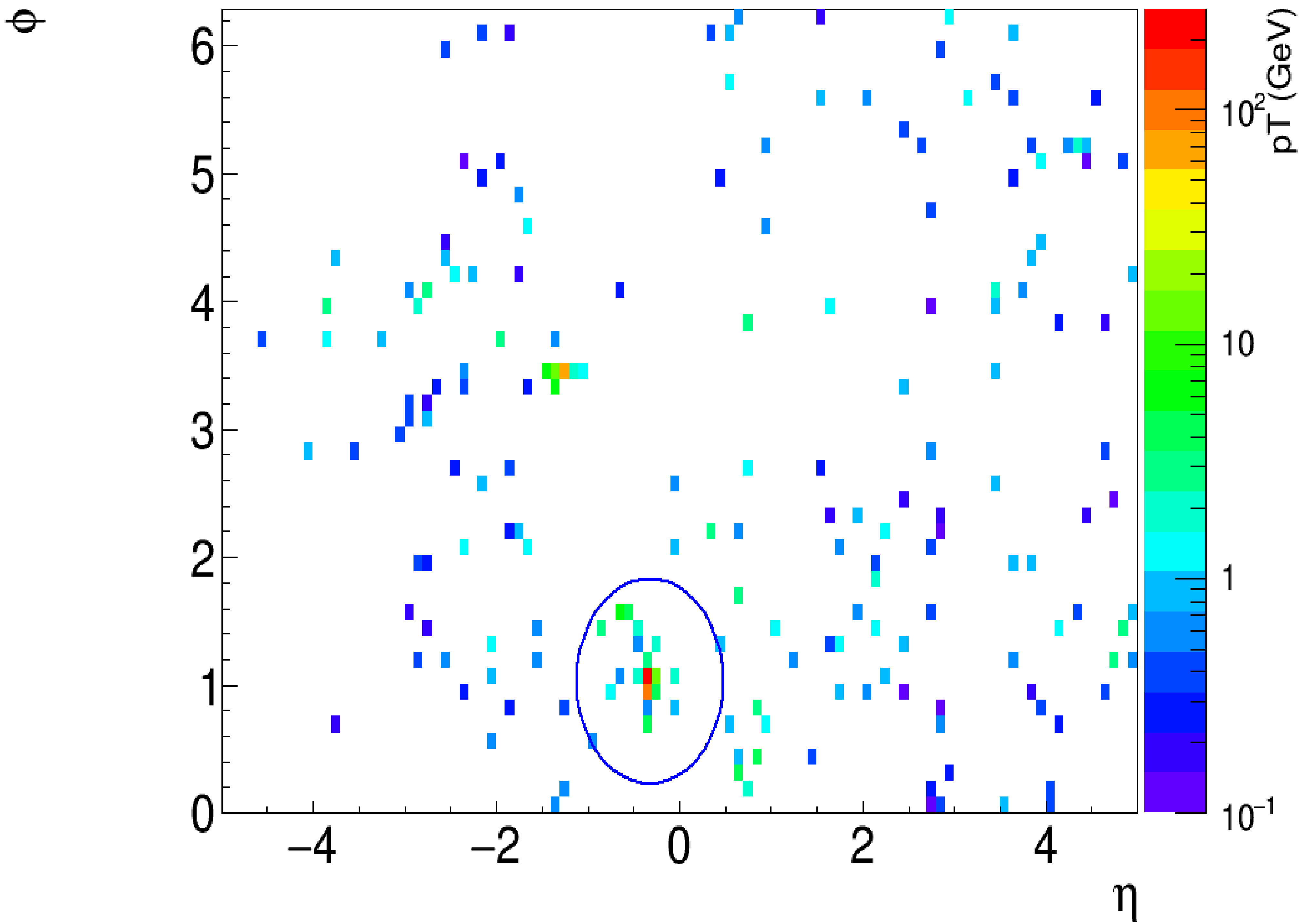


φ
6
5
4
3
2
1
0
−4
−2
0
2
4
η
pT (GeV)
$10^2$
10
1
$10^{-1}$
3 prongs
Two prongs closer and at high $p_T$

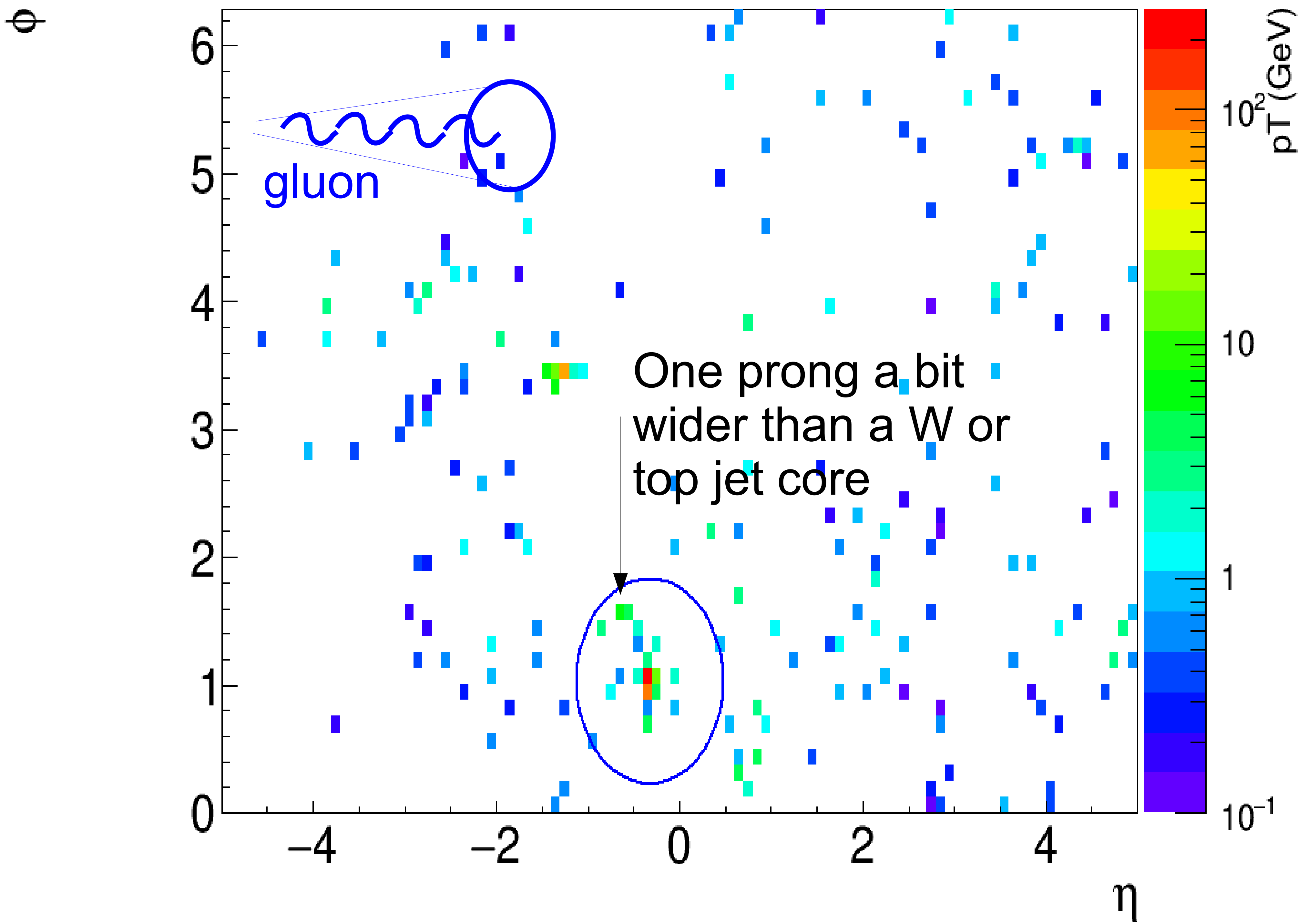
# What is it?




Have a Top jet

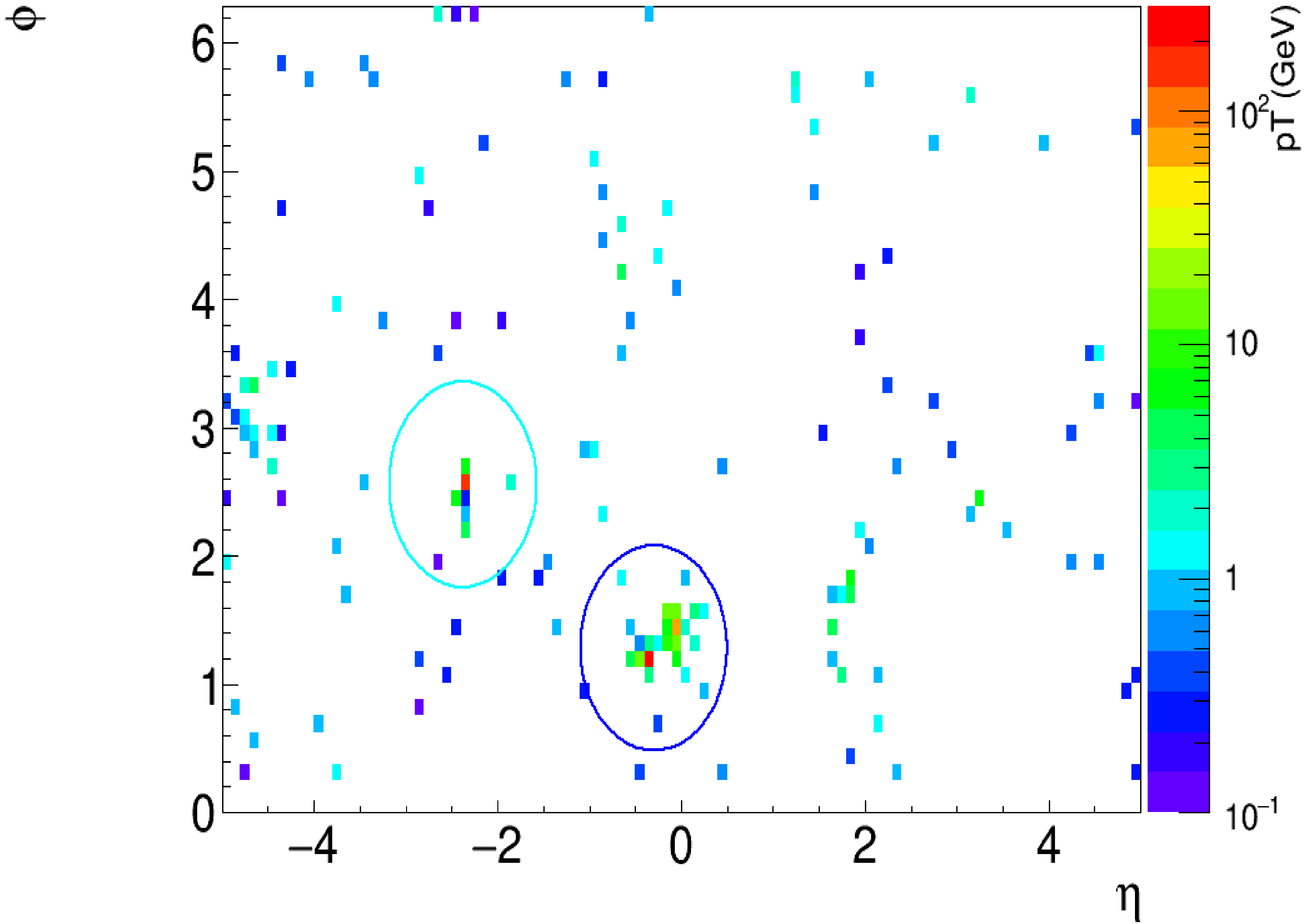


φ
6
5
4
3
2
1
0
−4
−2
0
2
4
η
pT (GeV)
$10^2$
10
1
$10^{-1}$

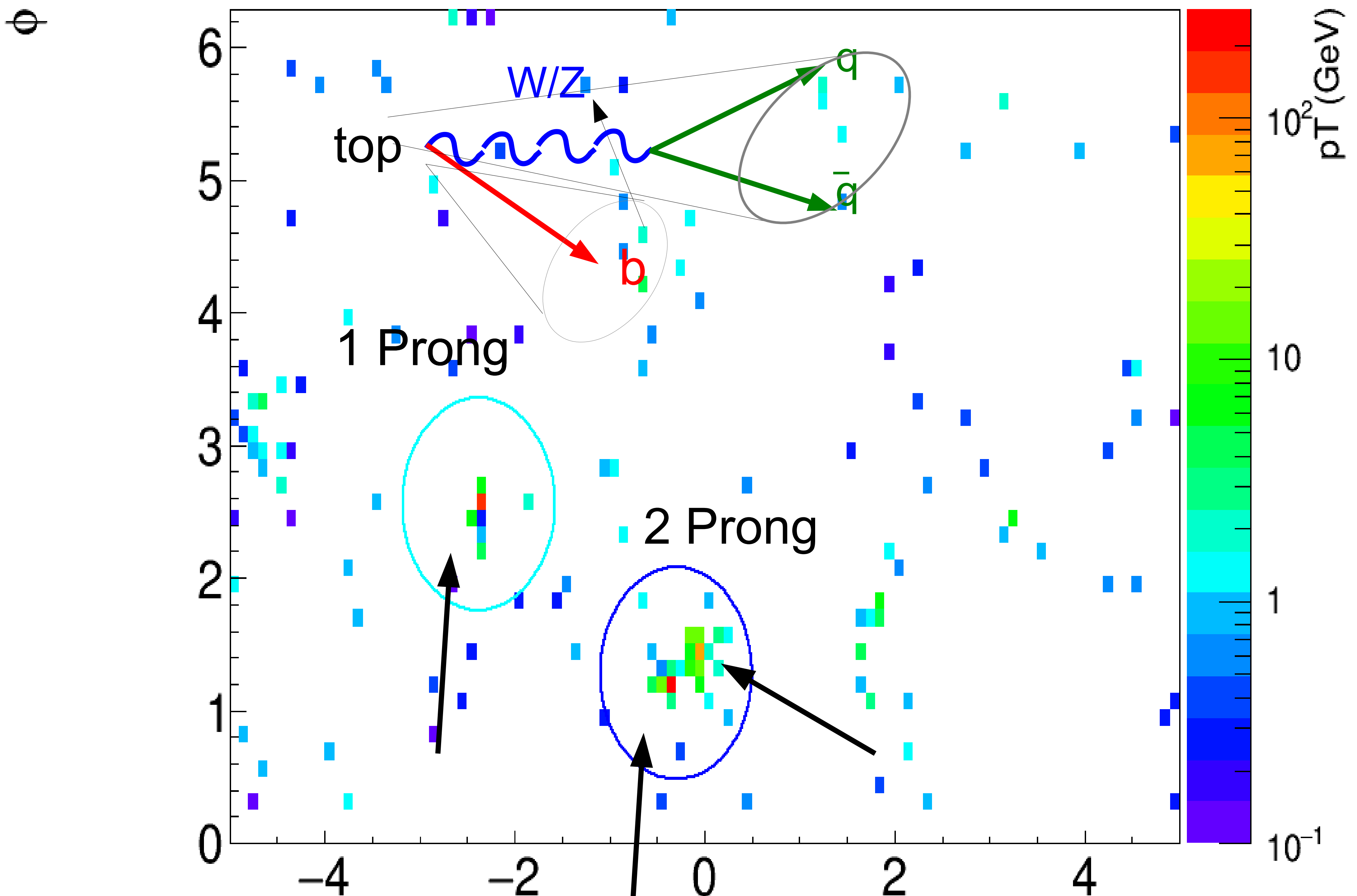


φ
η
pT (GeV)
gluon
One prong a bit wider than a W or top jet core

# What is it?

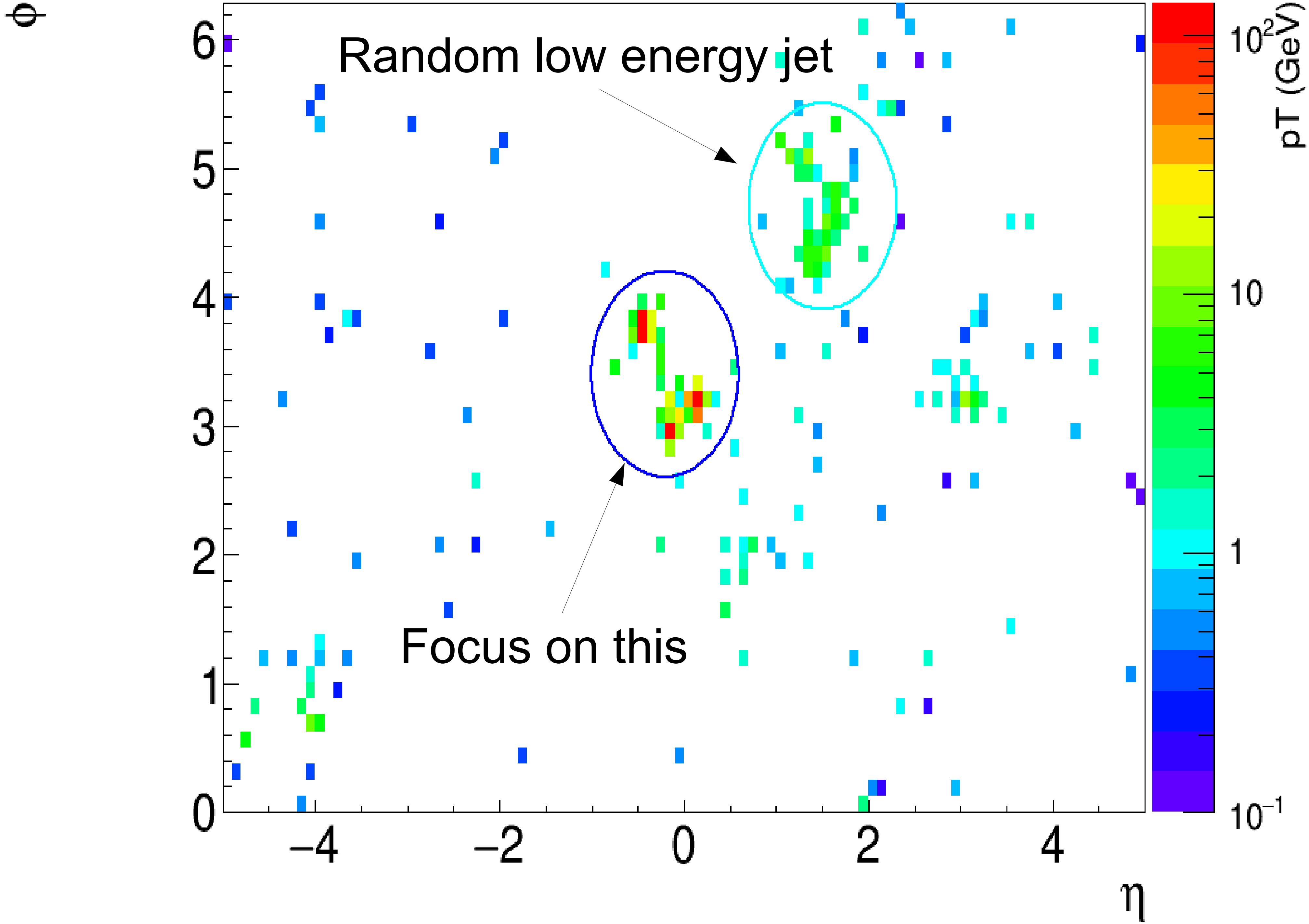


# What is it?



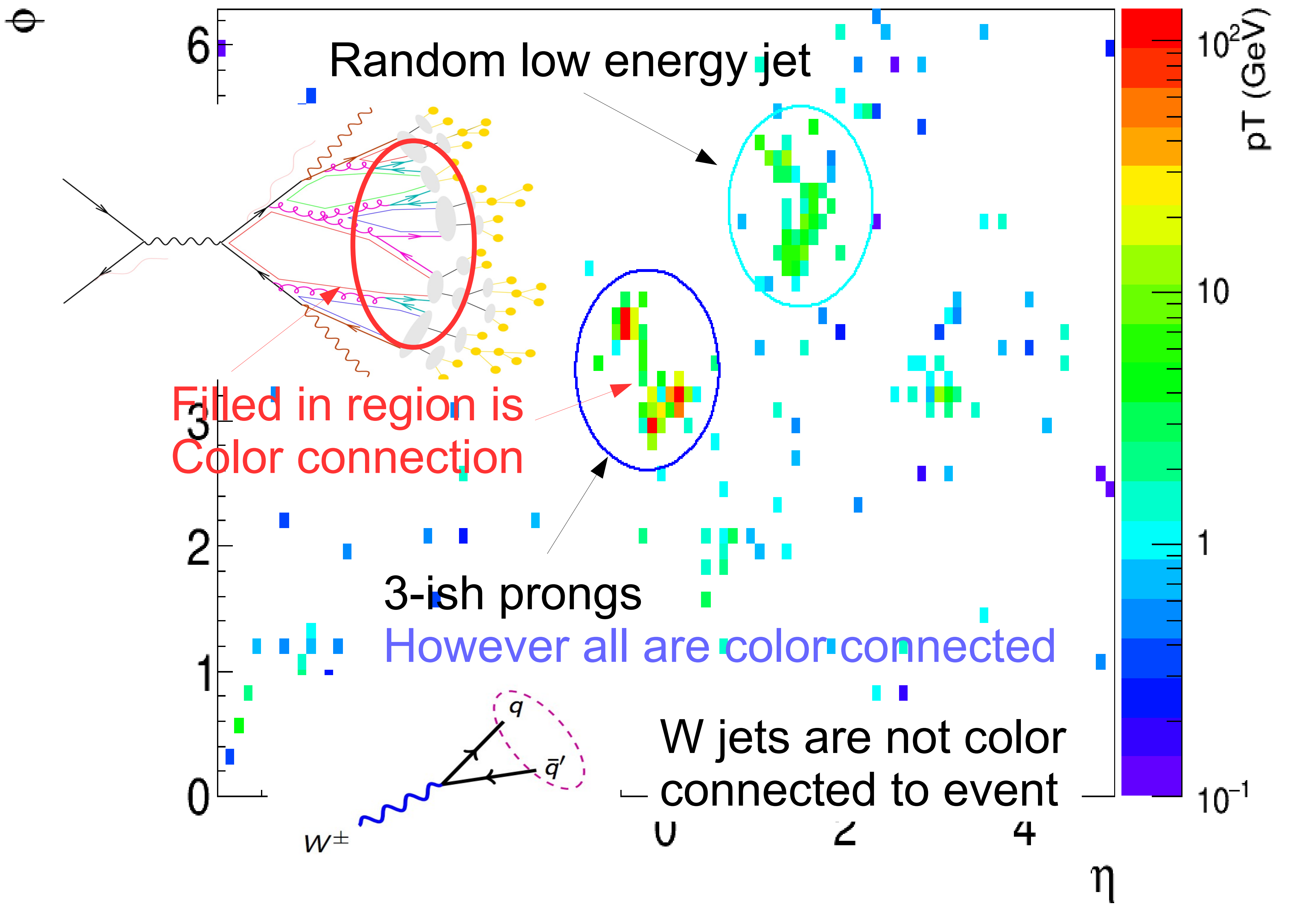

A top quark decaying to 2 jets

# What is it?



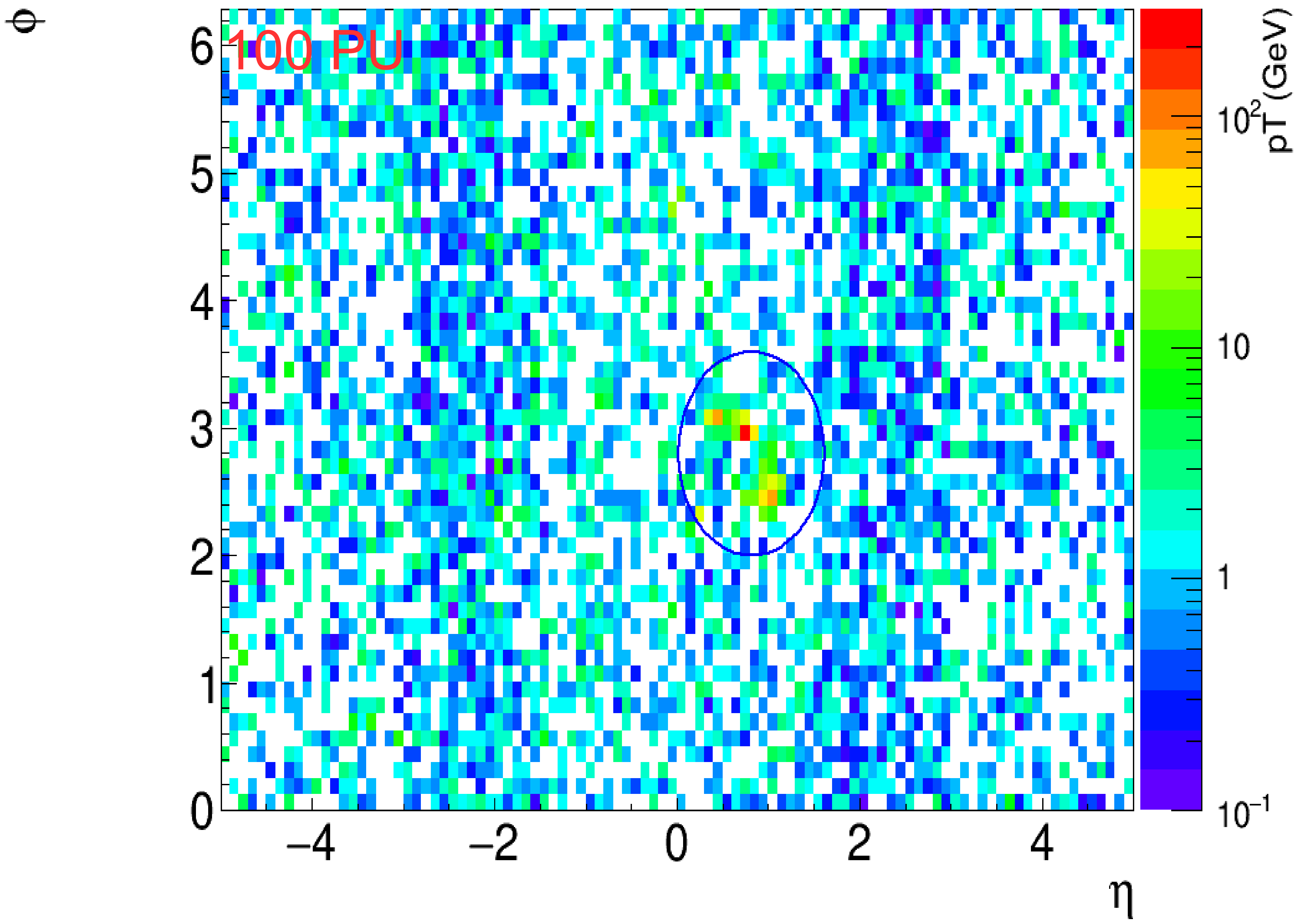
φ
6
5
4
3
2
1
0
−4
−2
0
2
4
η
Random low energy jet
Focus on this
$10^2$
10
1
$10^{-1}$
pT (GeV)

# What is it?

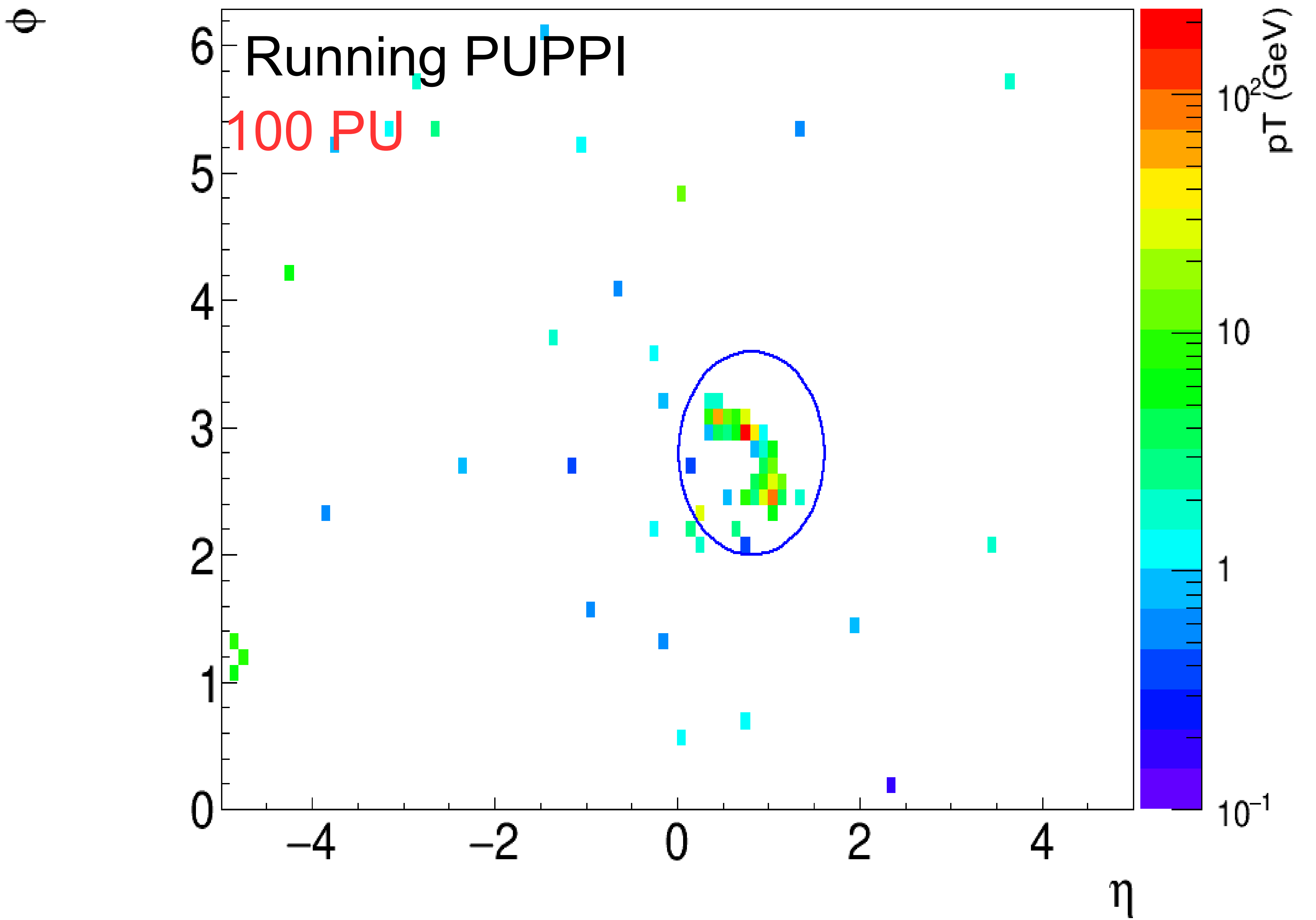


φ
6
3
2
1
0
0
2
4
η
pT (GeV)
$10^2$
10
1
$10^{-1}$
Random low energy jet
Filled in region is
Color connection
3-ish prongs
However all are color connected
q
$\bar{q}'$
$W^\pm$
W jets are not color
connected to event

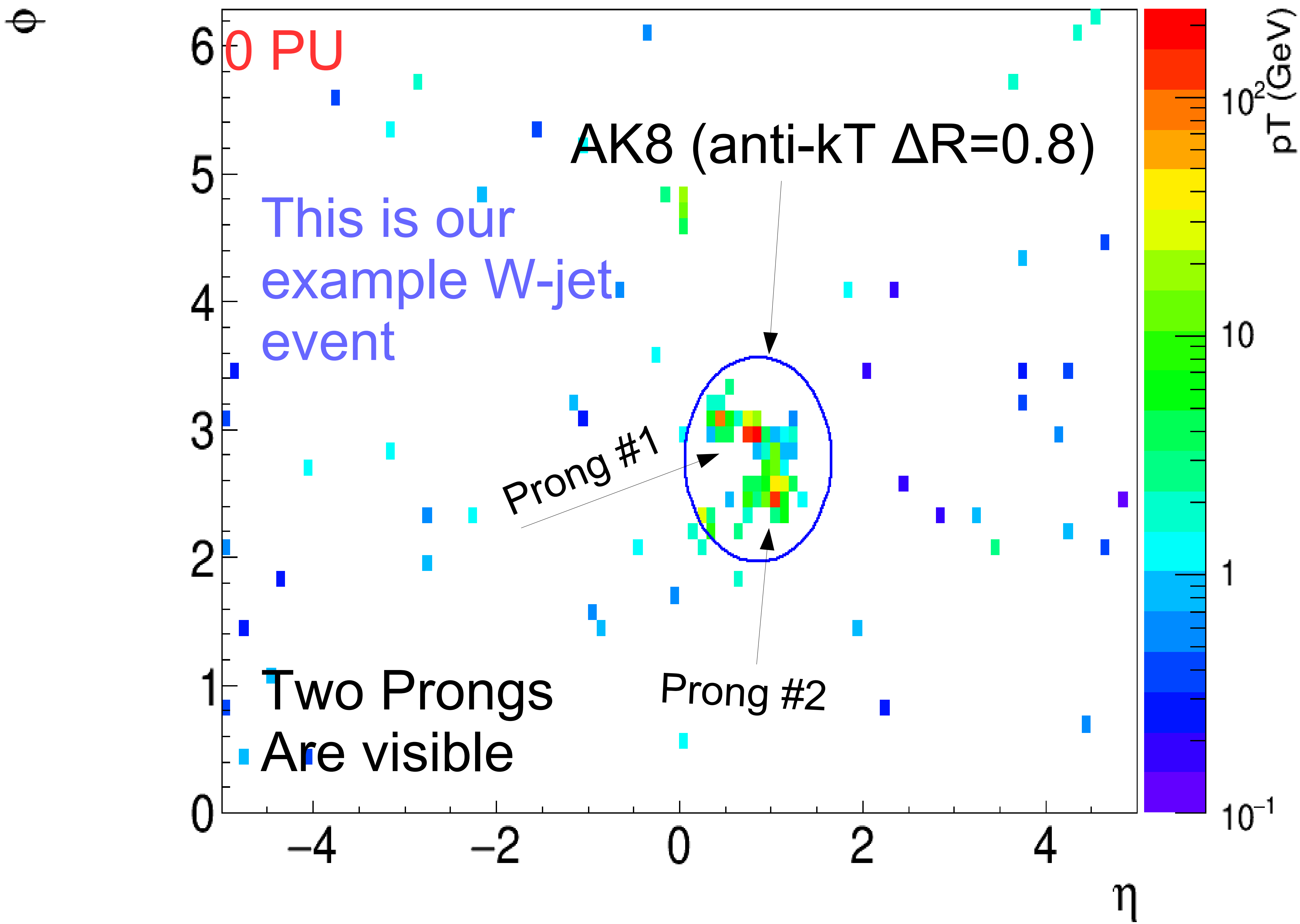
# Now @ 100 PU (Next year)



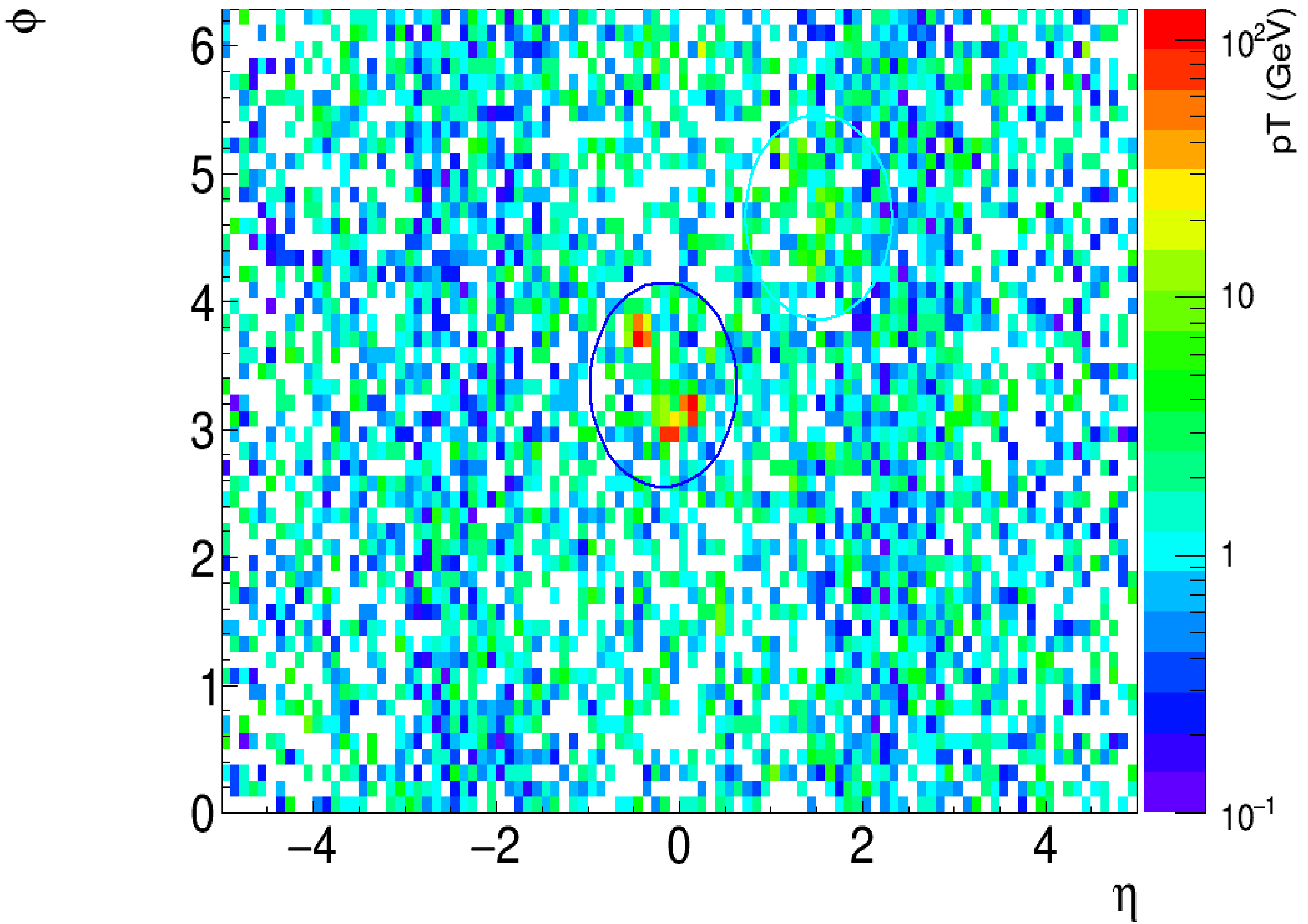
φ
100 PU
6
5
4
3
2
1
0
−4
−2
0
2
4
η
pT (GeV)
$10^2$
10
1
$10^{-1}$



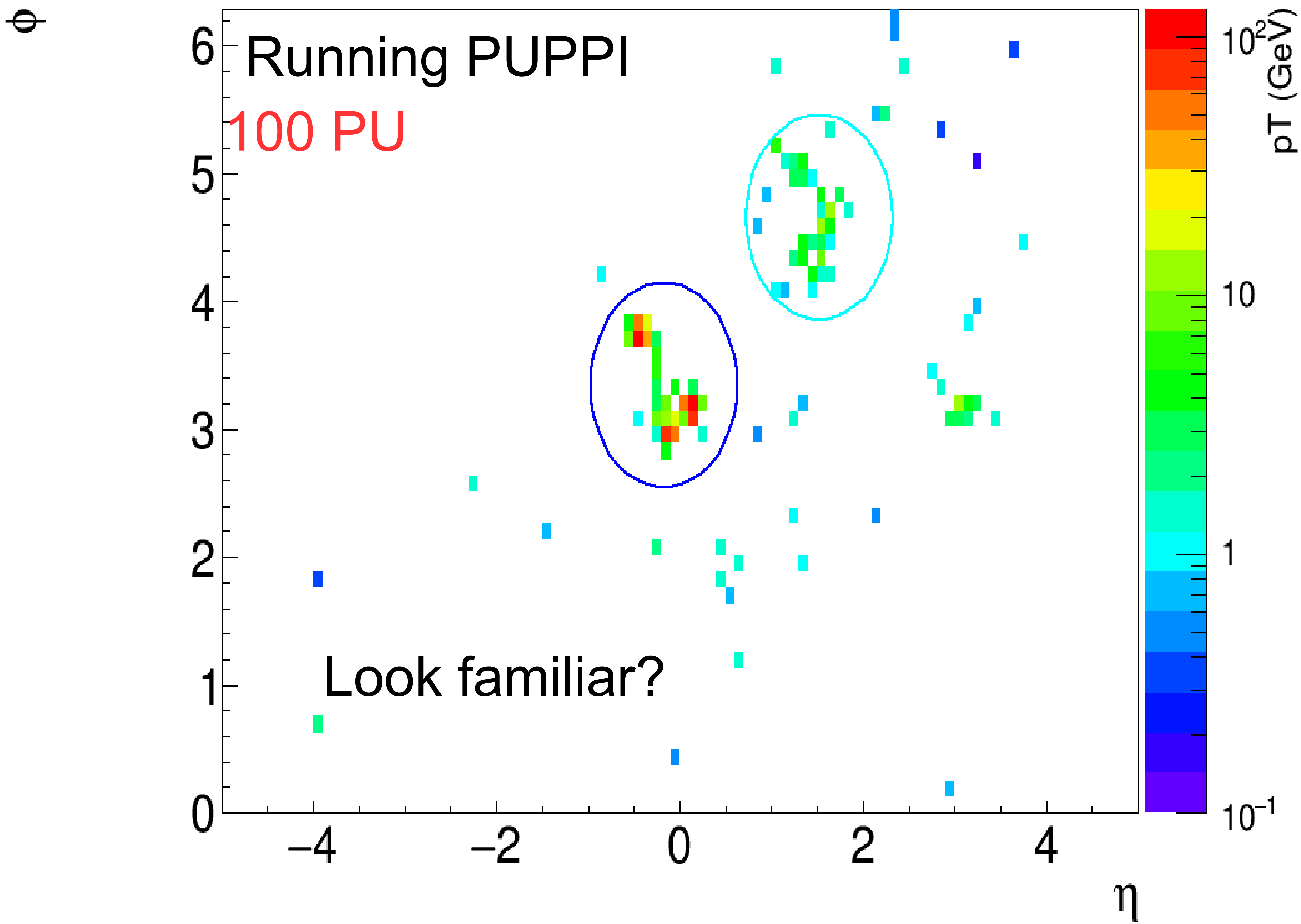
Running PUPPI
100 PU
φ
η
pT (GeV)
0
1
2
3
4
5
6
−4
−2
0
2
4
$10^{-1}$
1
10
$10^2$



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)

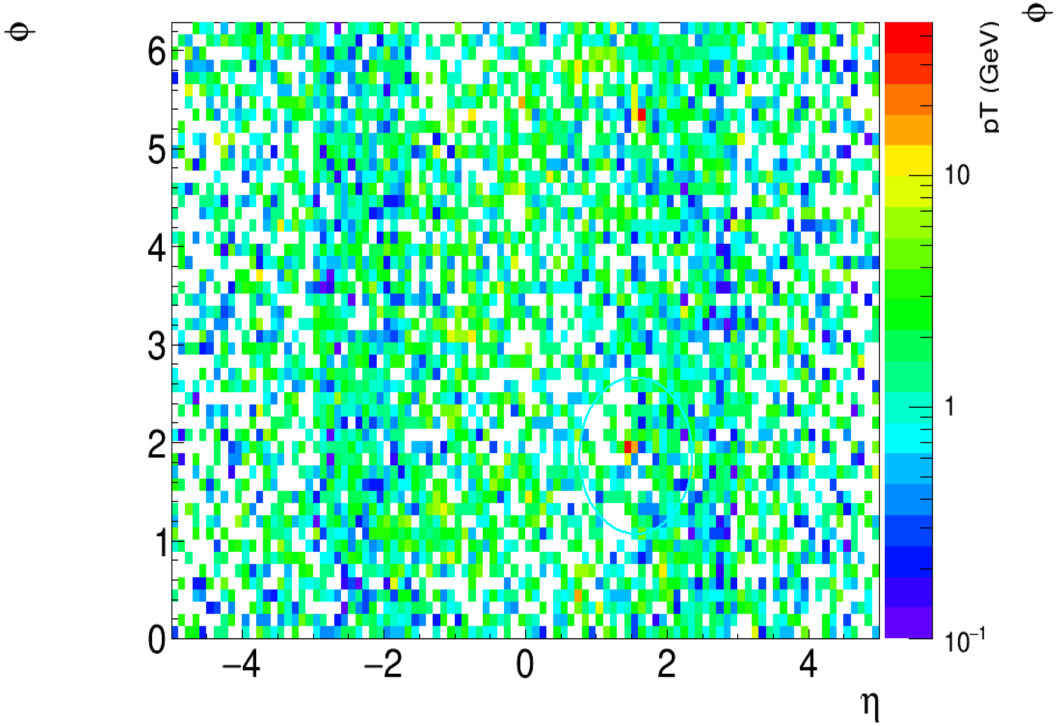


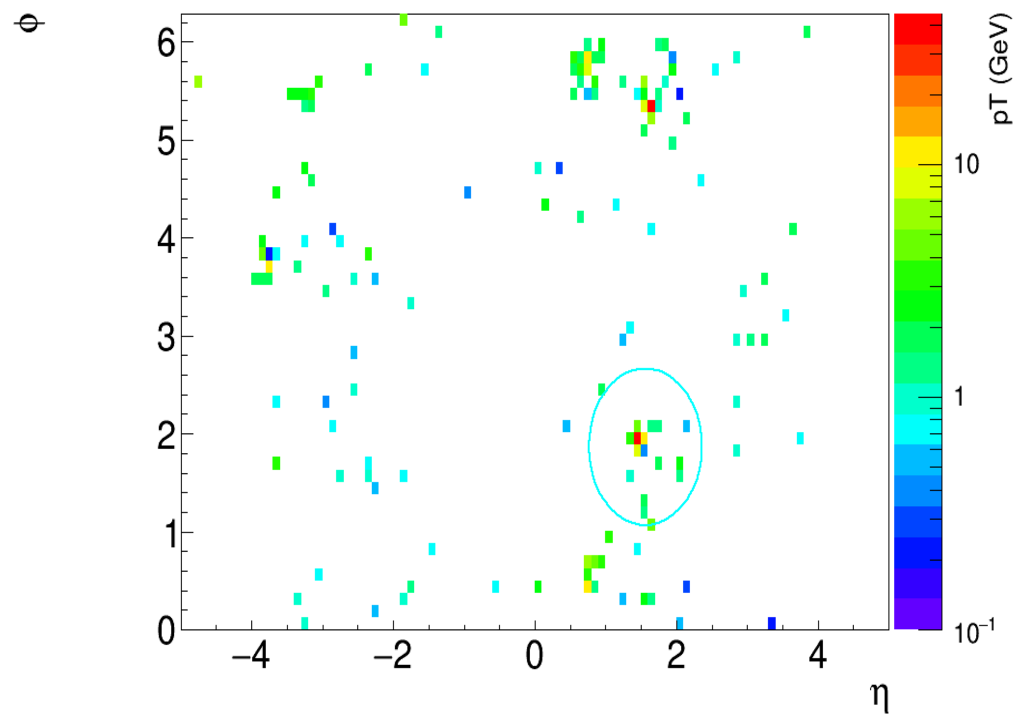
φ
6
5
4
3
2
1
0
−4
−2
0
2
4
η
$10^2$
10
1
$10^{-1}$
pT (GeV)



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?

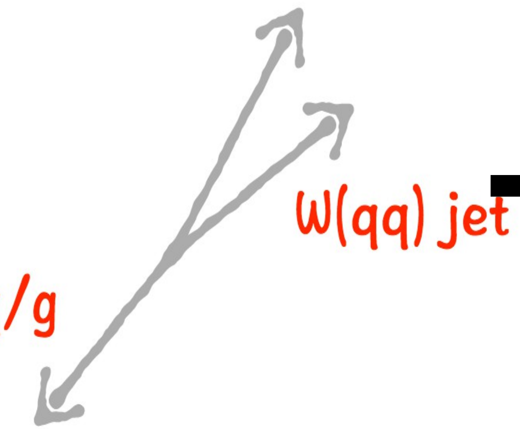


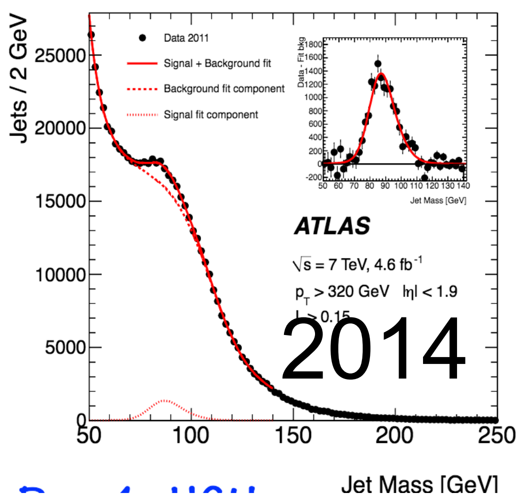

See backup

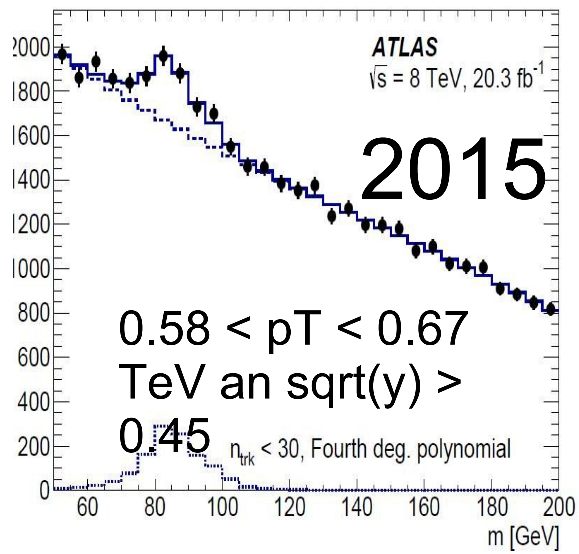
# Recap

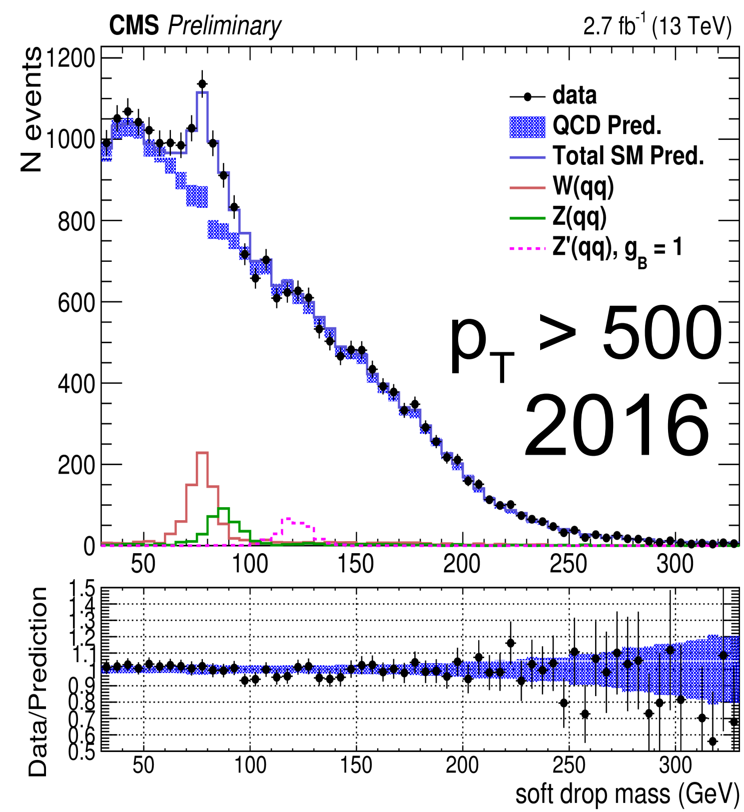
- Actual analyses are on objects combining deposits
- Particle flow combines the deposits to particles
  - Takes into account many features (Brem/Nuclear Int)
- Hadronic τ decays are composite "particle" objects
  - Find the decays and rely heavily on isolation
- Jets have rich & interesting identification 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!



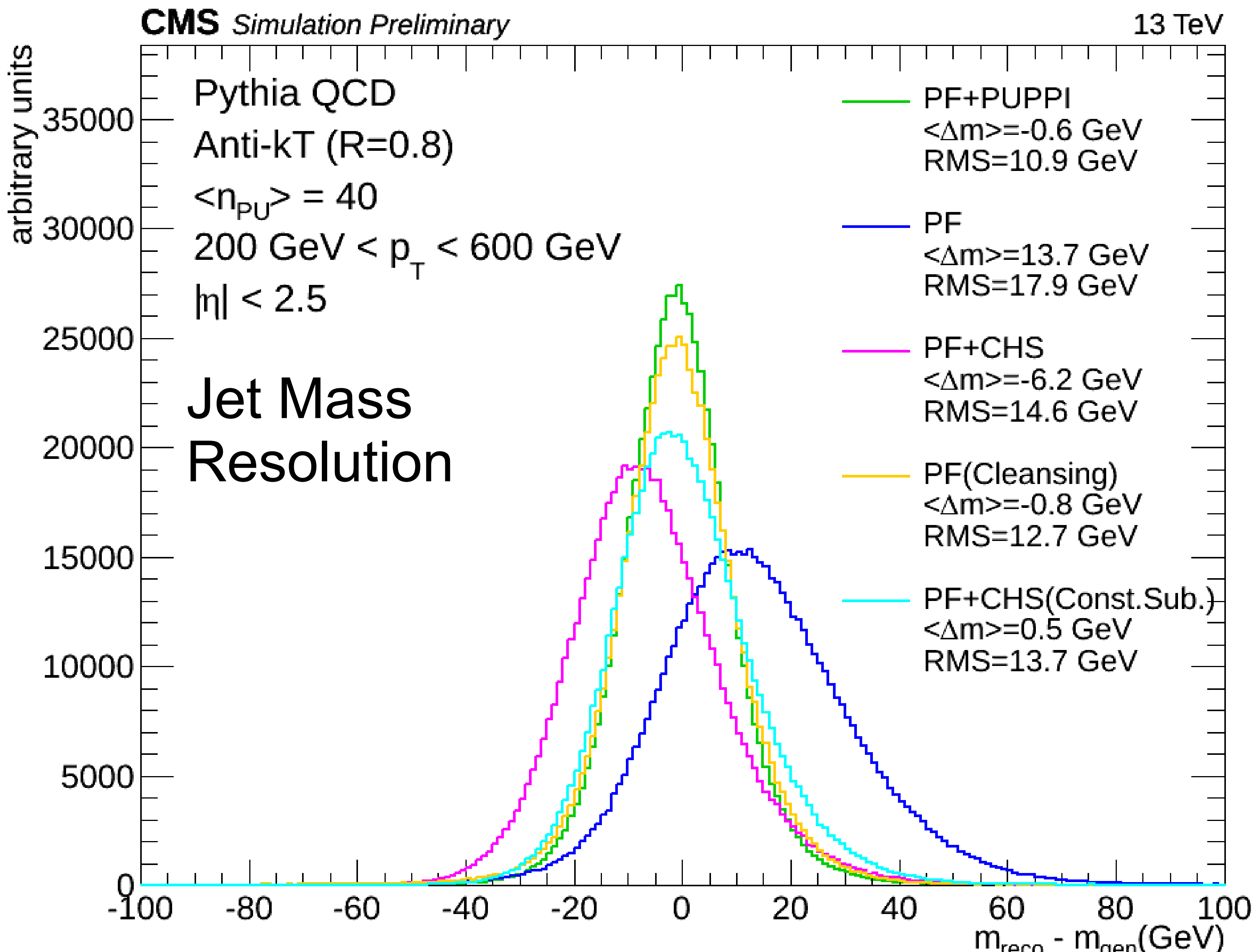




This peak has only been observed over past 2 year

# Thanks to the Organizers! Have a good trip back

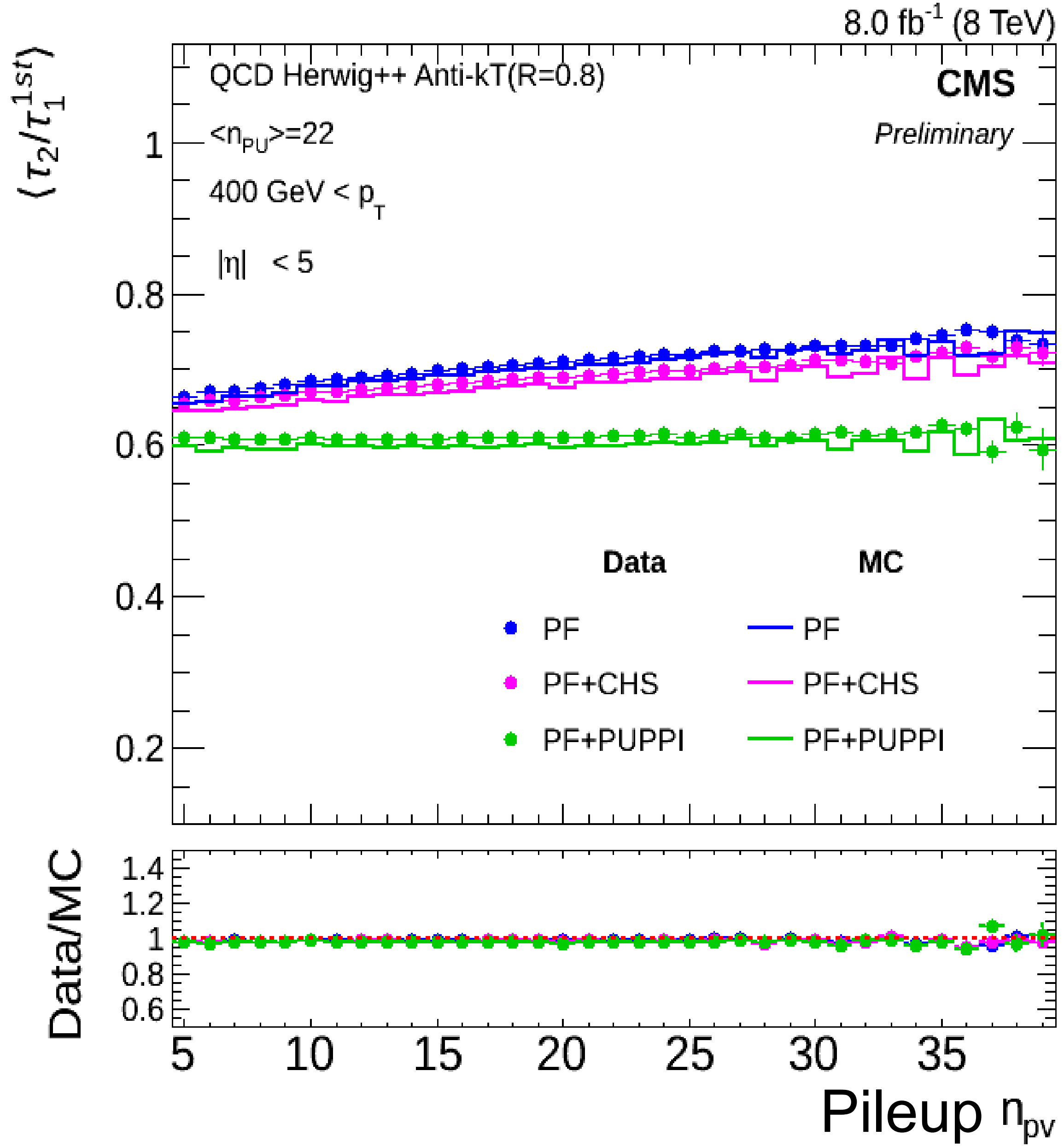
# Jets in CMS




Mass resolution shows clear improvement (40 PU )

# Pileup performance in data

Likelihood of two prongs




- No more trends in pileup with Puppi

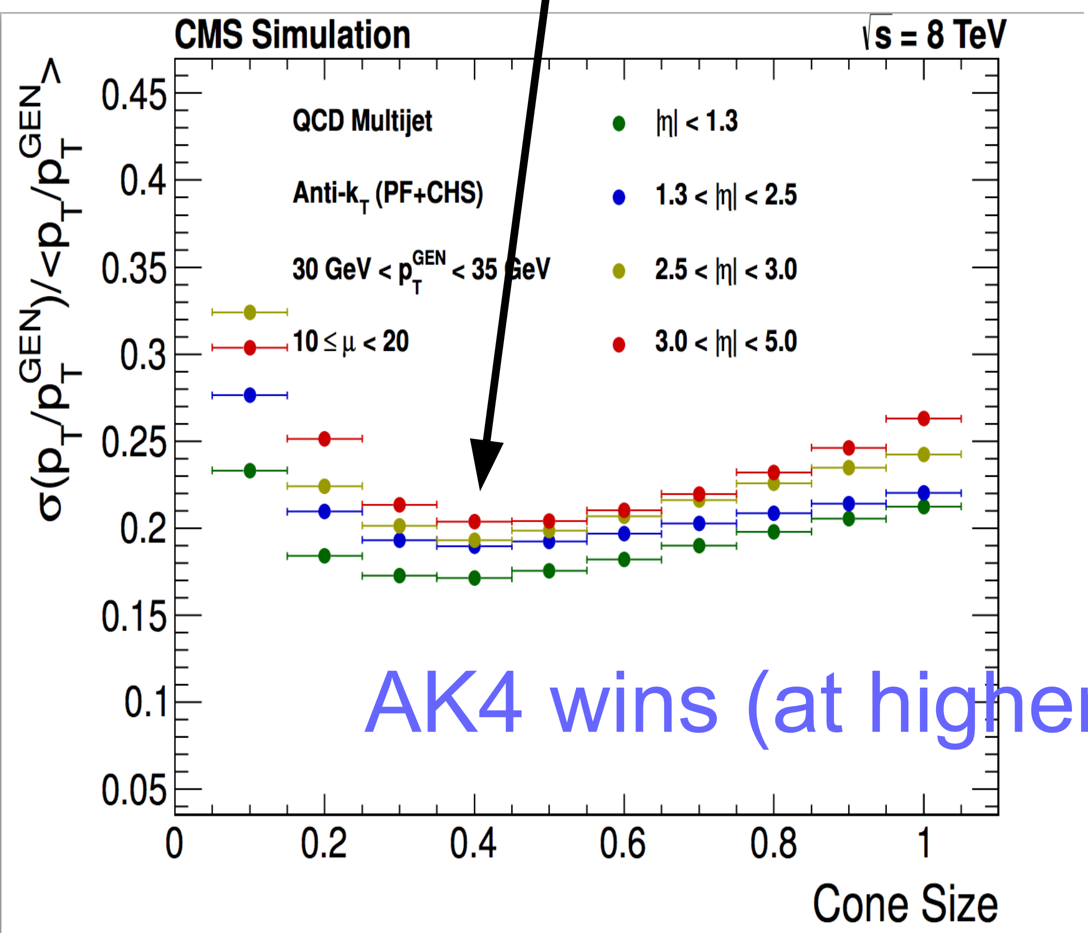
# Jet Energy Correction

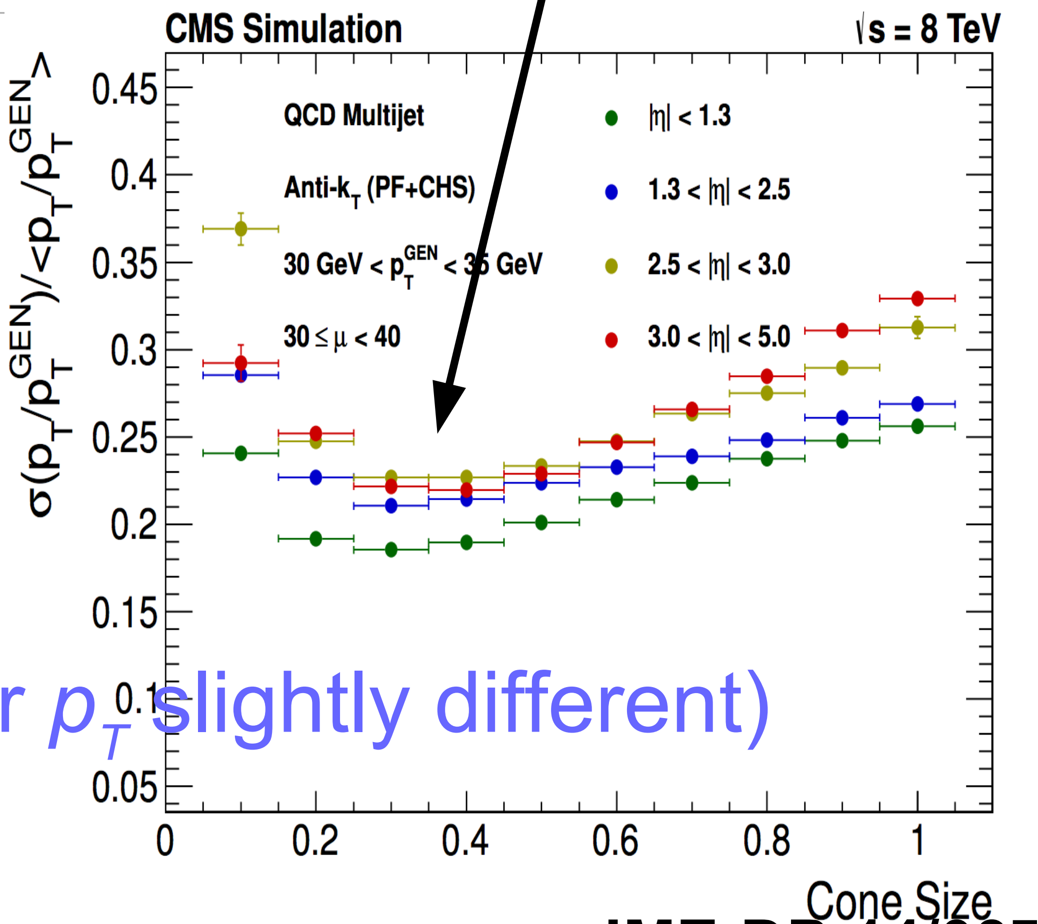
- Executive Summary :

We switch to AK4

Run I PU

Run II PU




AK4 wins (at higher $p_T$ slightly different)

JME-DP-14/037

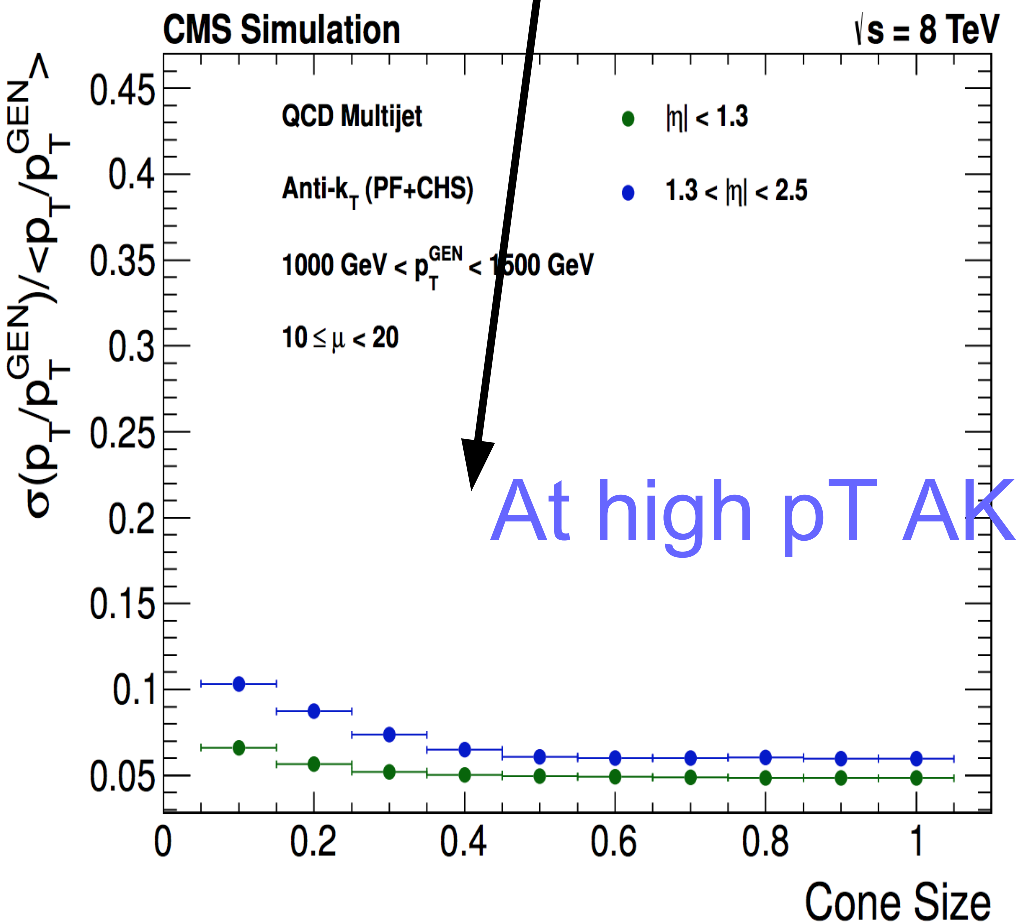
# Jet Energy Correction

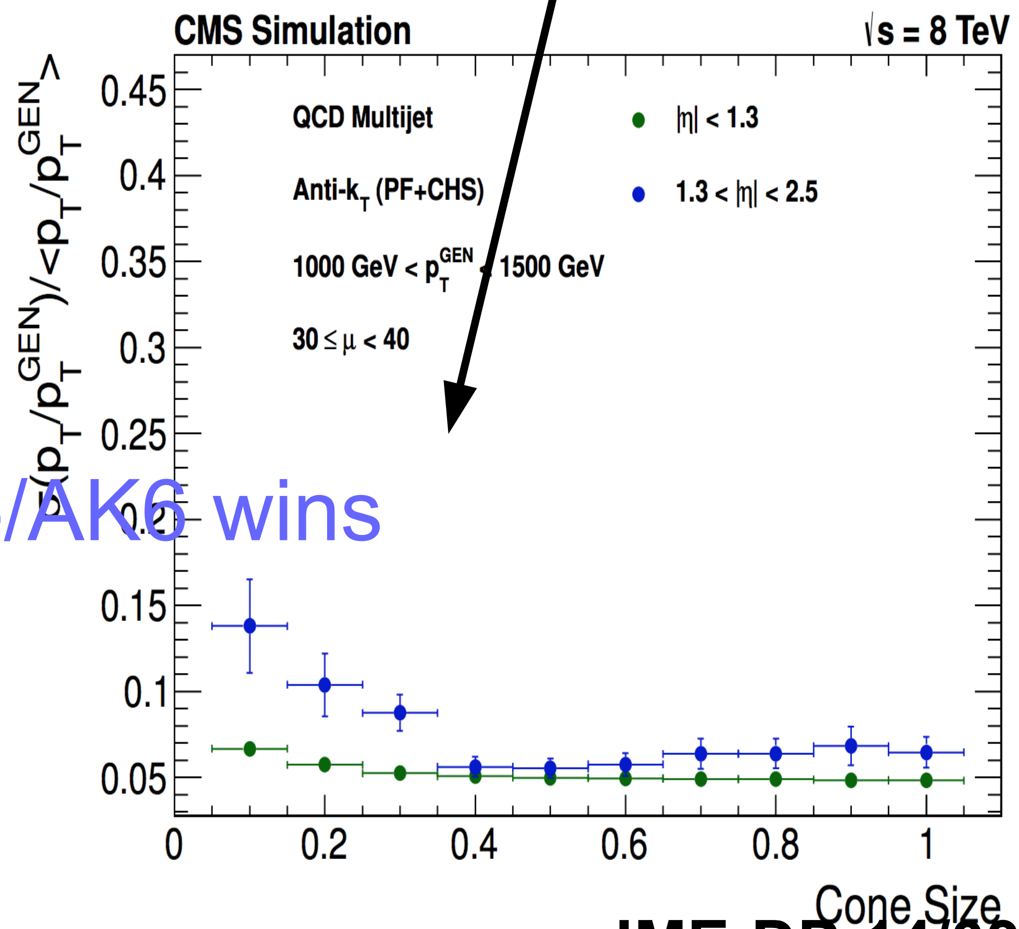
- Executive Summary :

We switch to AK4

Run I PU

Run II PU



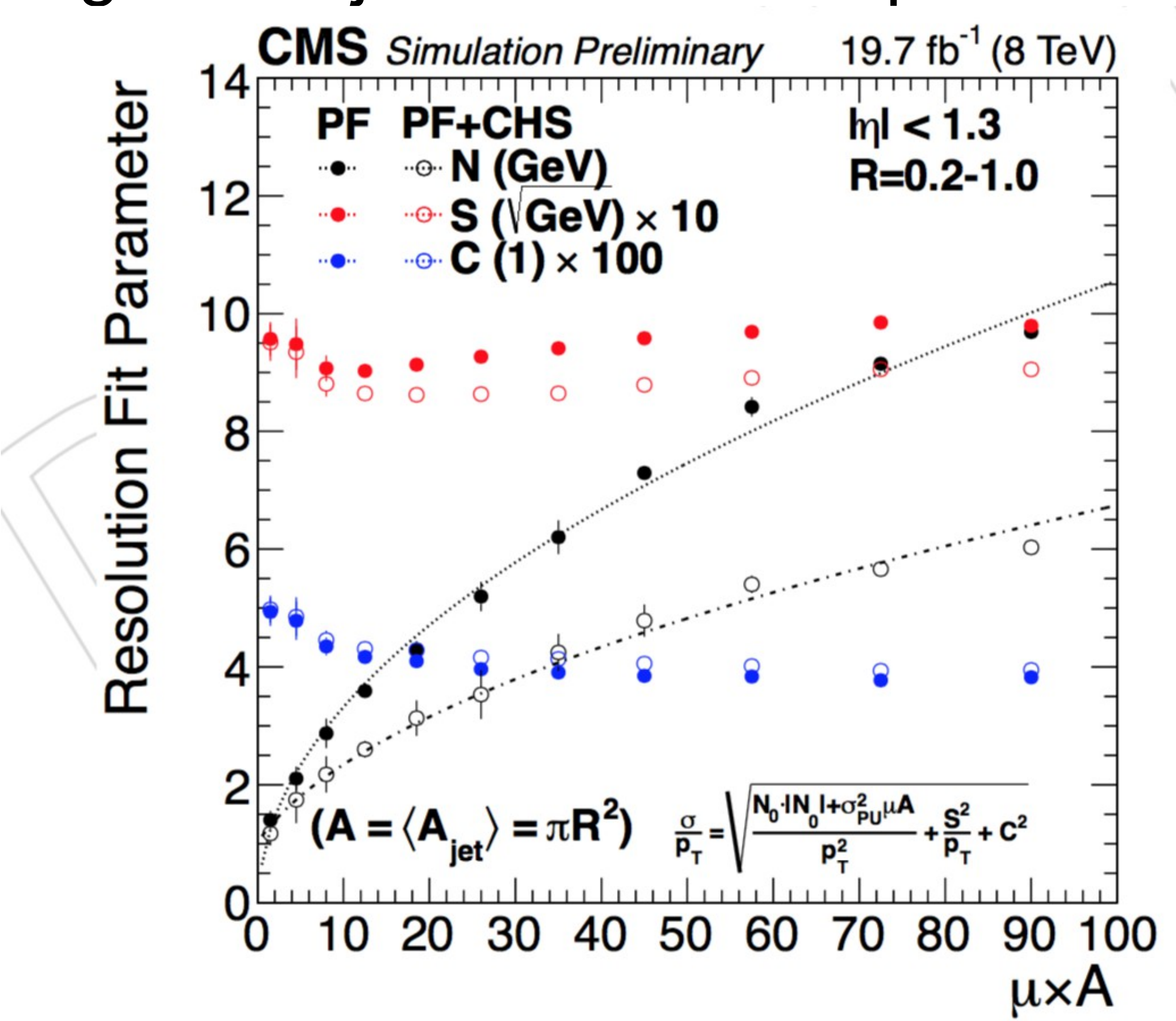




At high pT AK5/AK6 wins

**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?

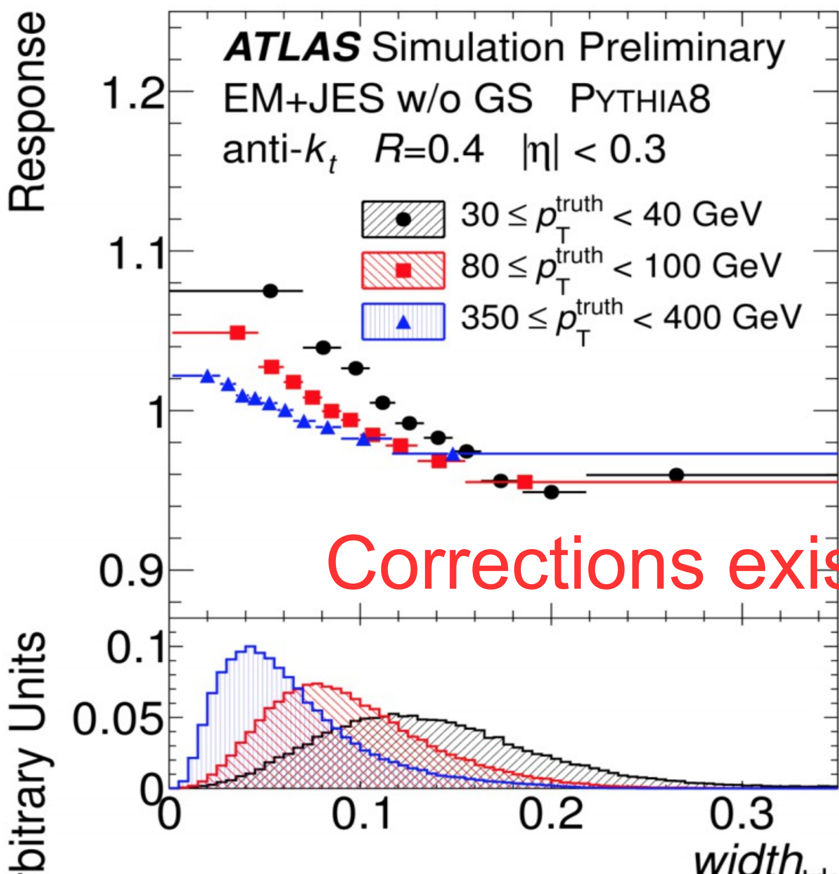
- Need to reconstruct a jet and correct it

| | | | |
|---|---|---|---|
| ***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) |

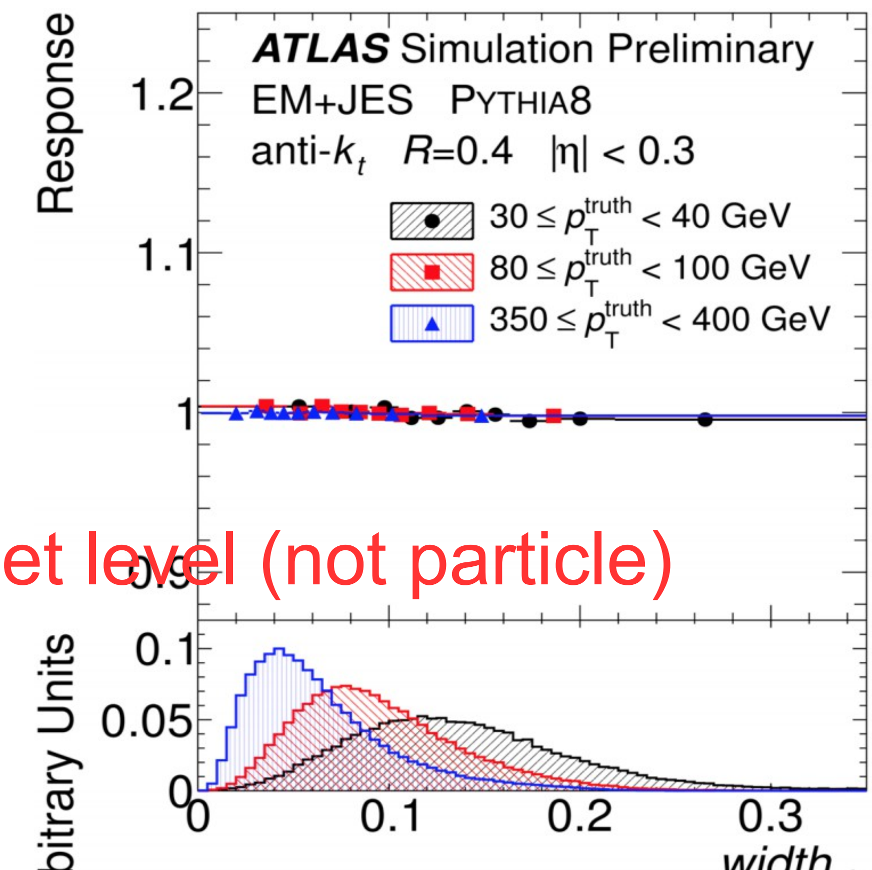
# Jet-Level in ATLAS

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

Before GSC



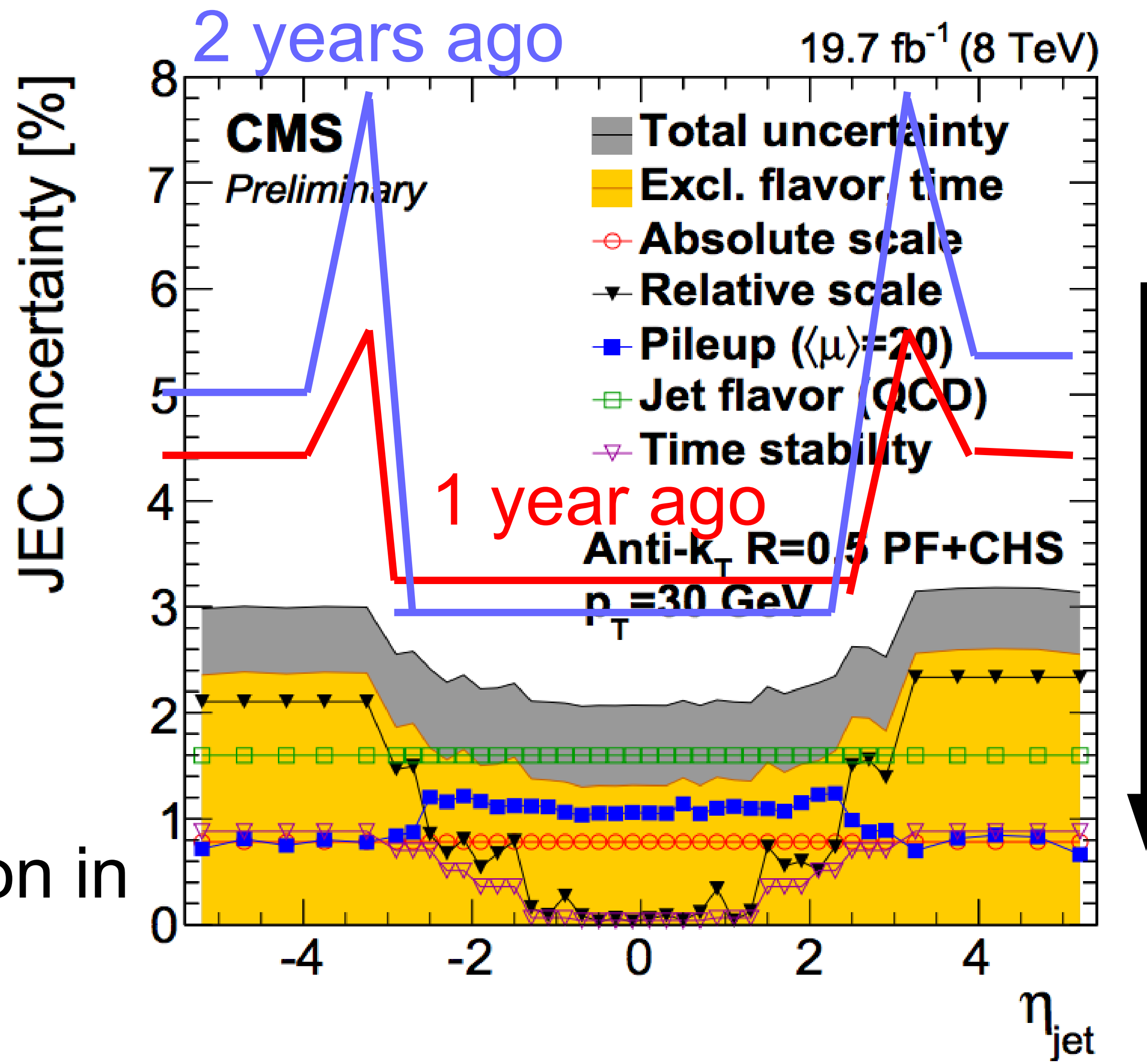

After GSC




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

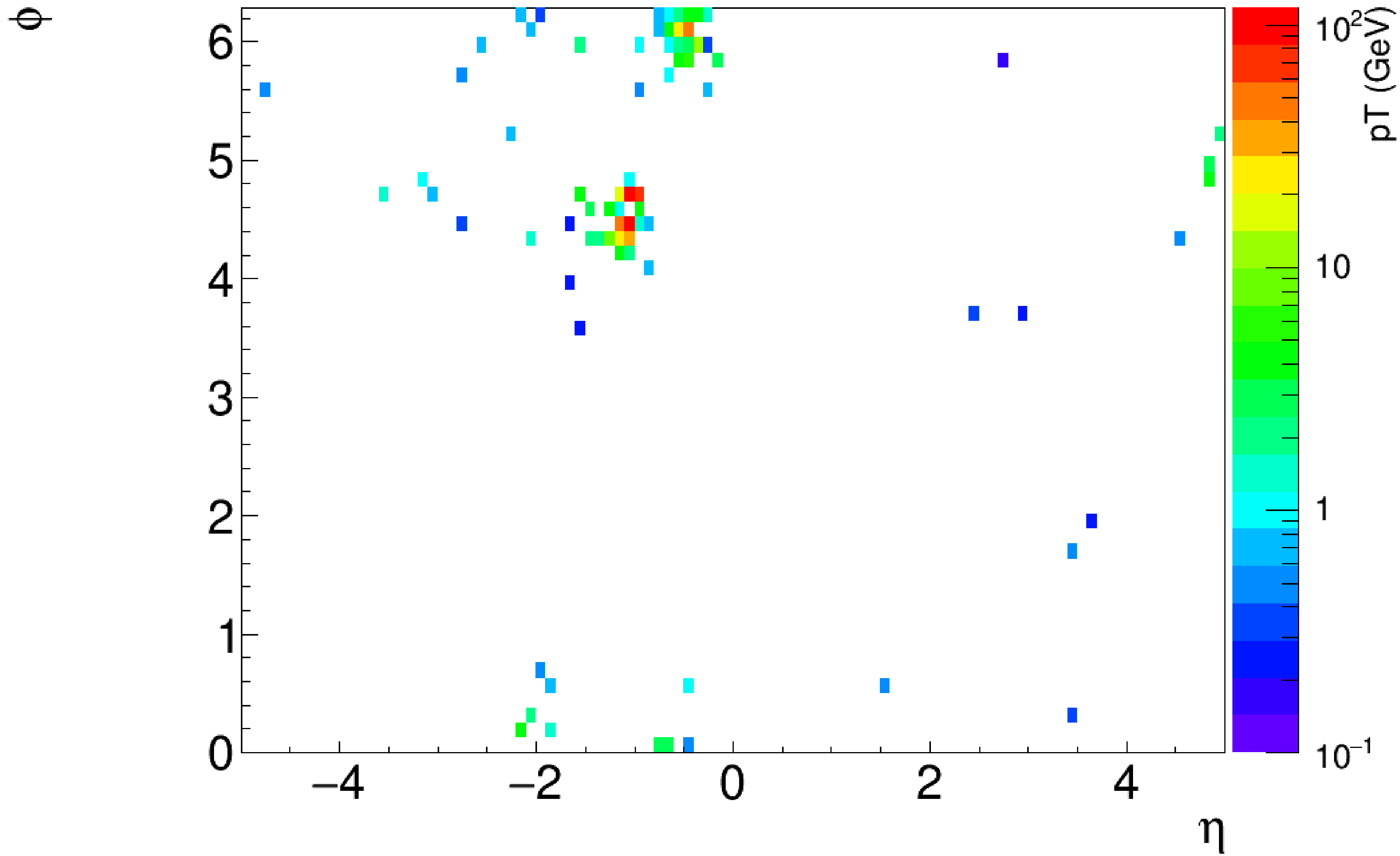
As we dealt with detector effects

Similar progression in ATLAS

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

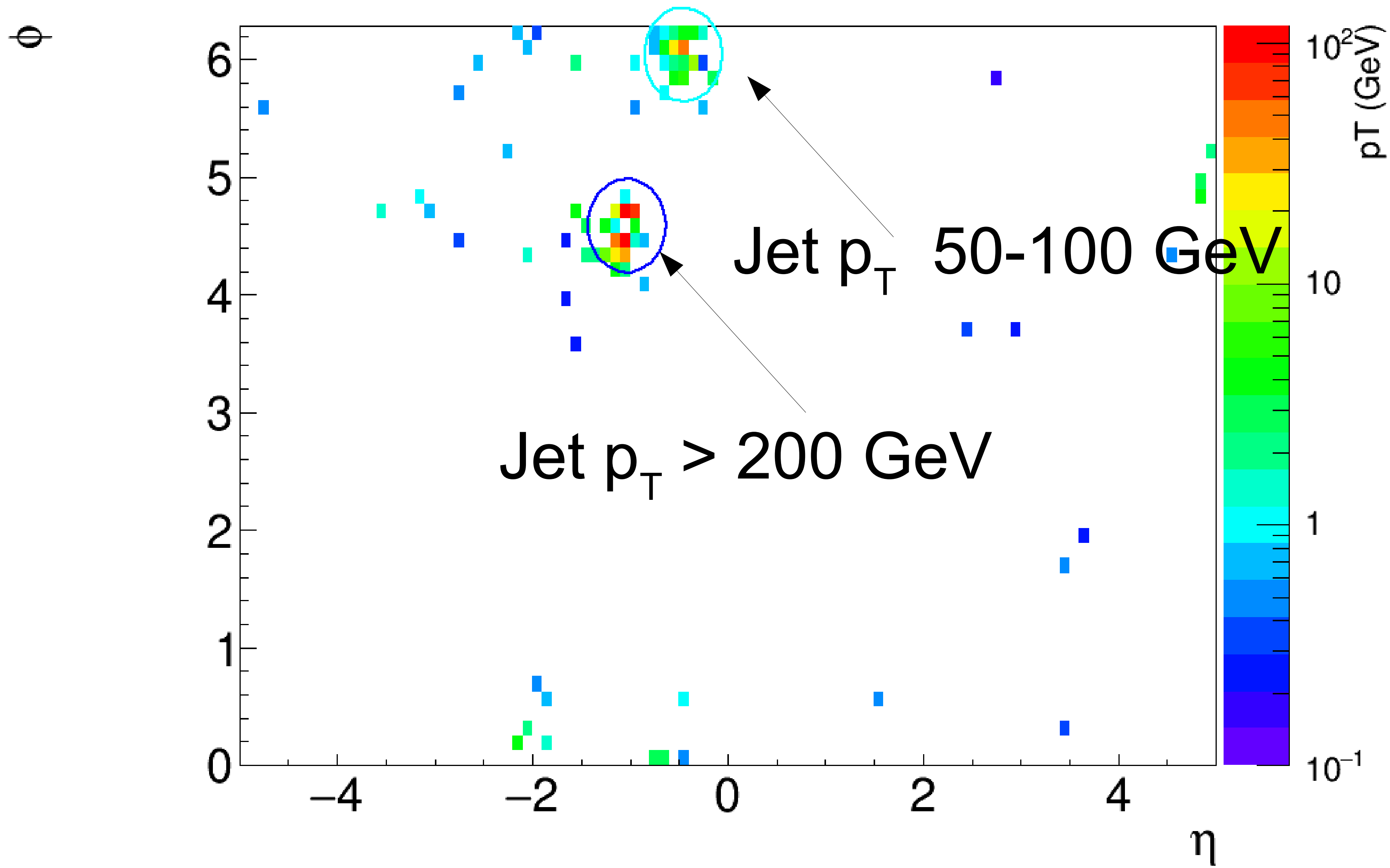
**JME-13-004**

# What is it?

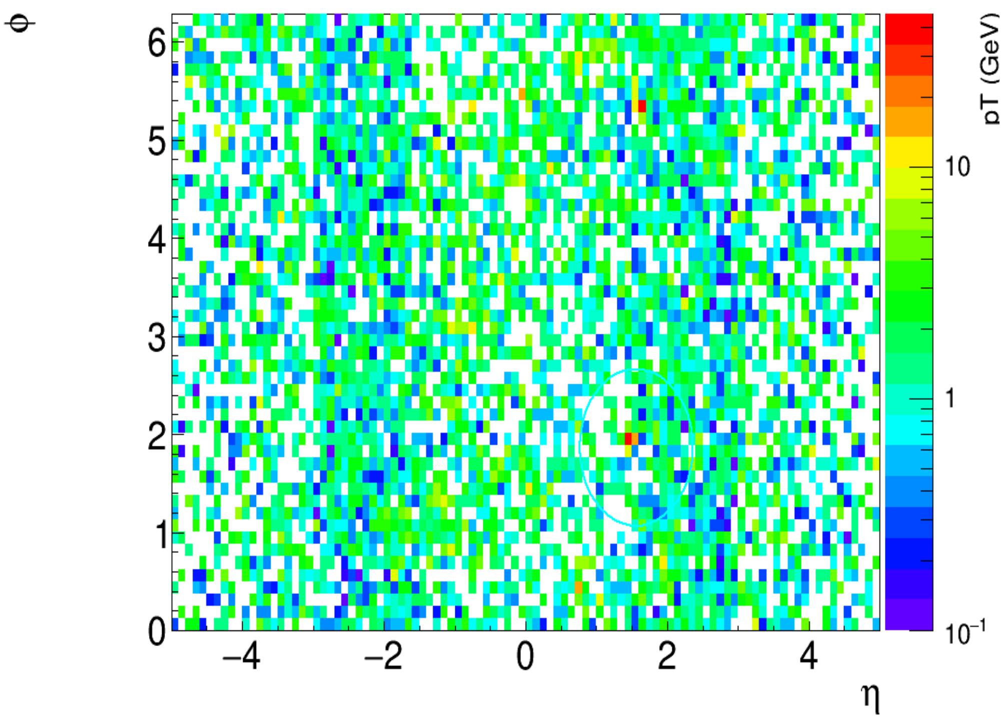


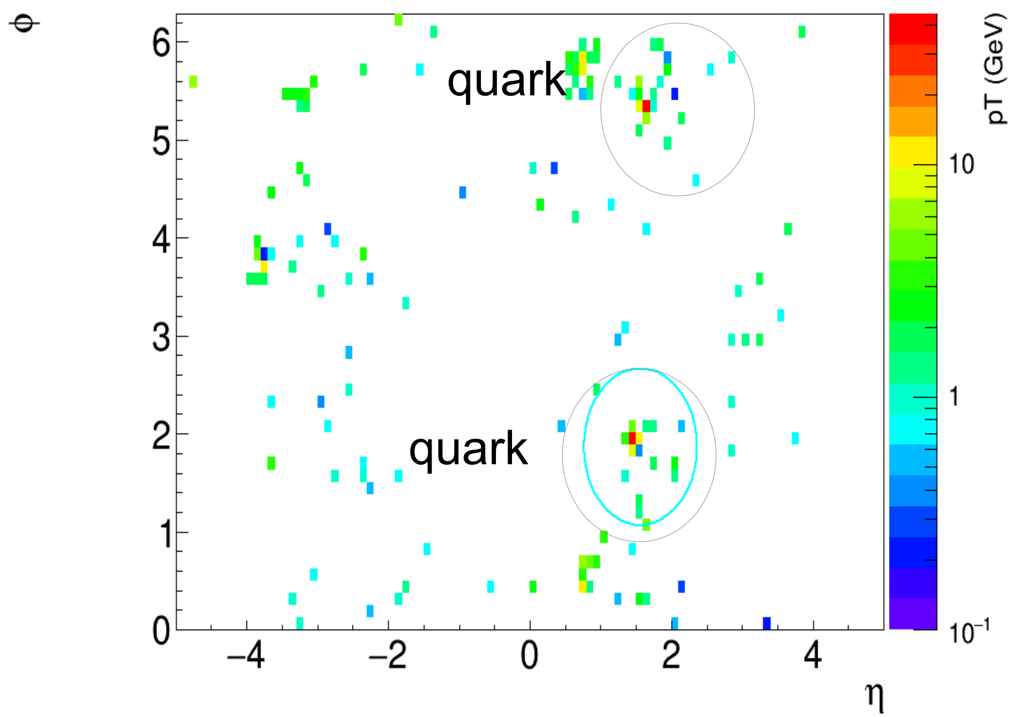
# What is it?

Run Jet reco

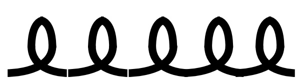


# Any guesses?



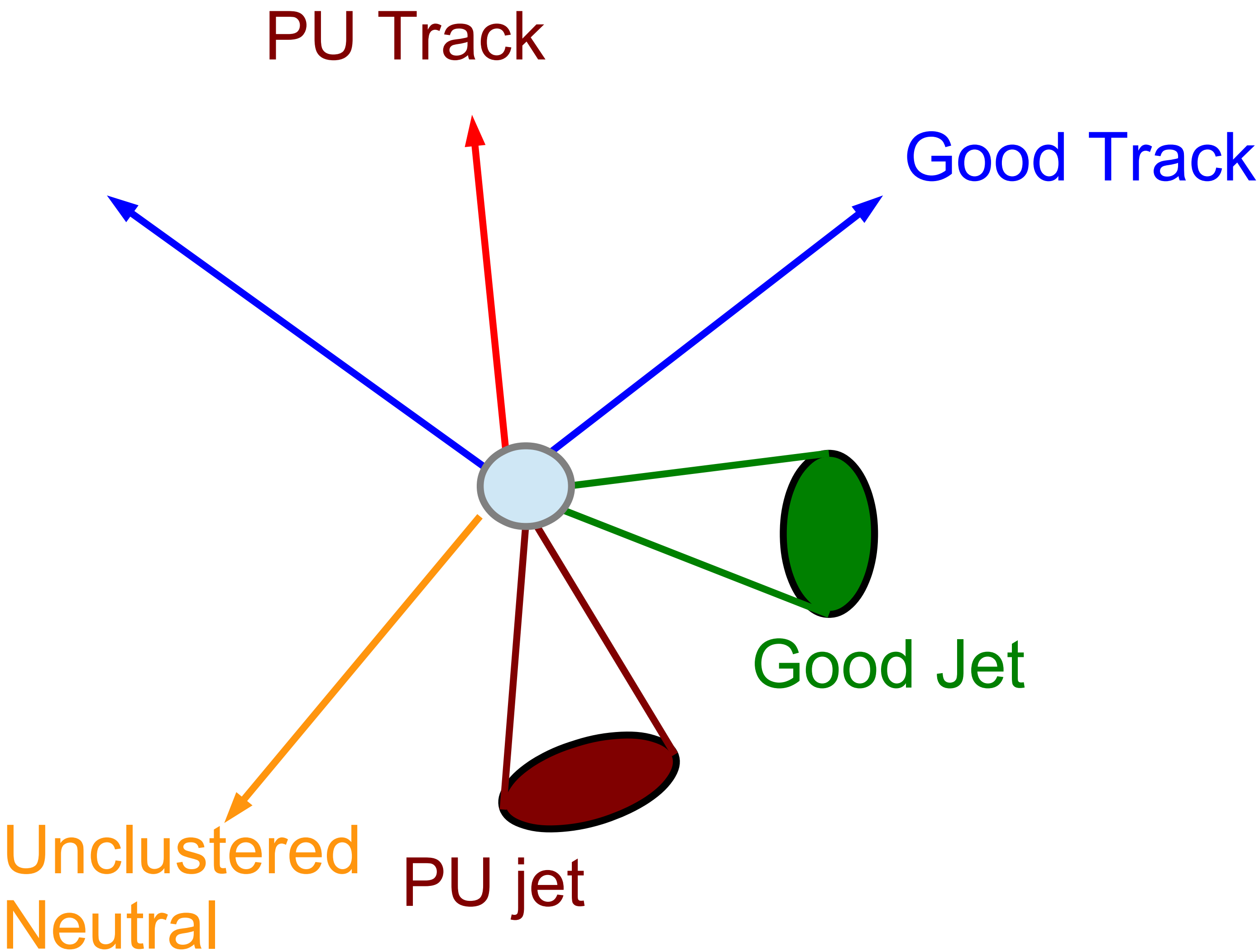

Its a low pT W boson



# Pileup outside of jets

Lets look at objects outside of the jet!

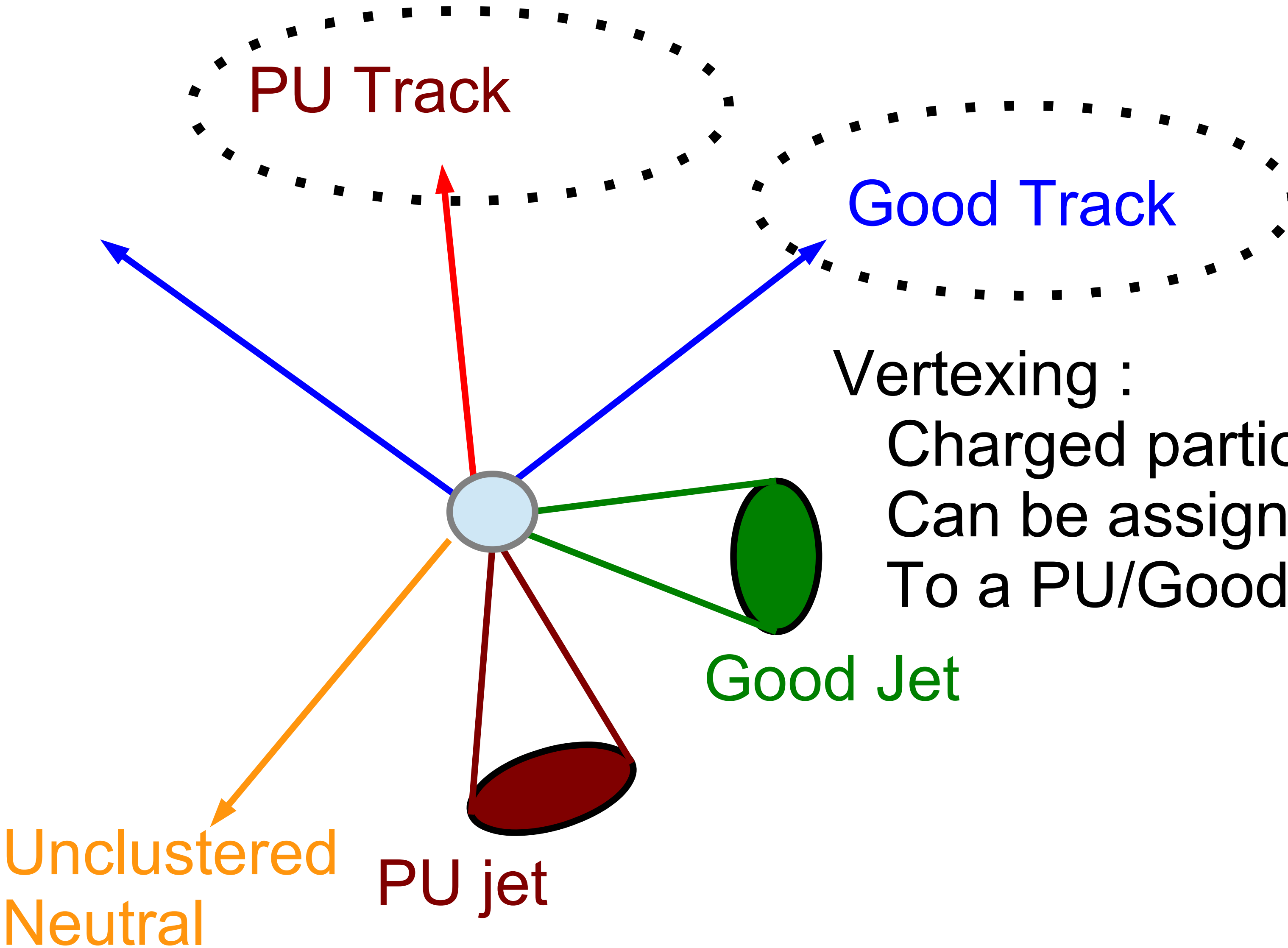
# Pileup in the Event




Simplified event can be decomposed into 5 different objects

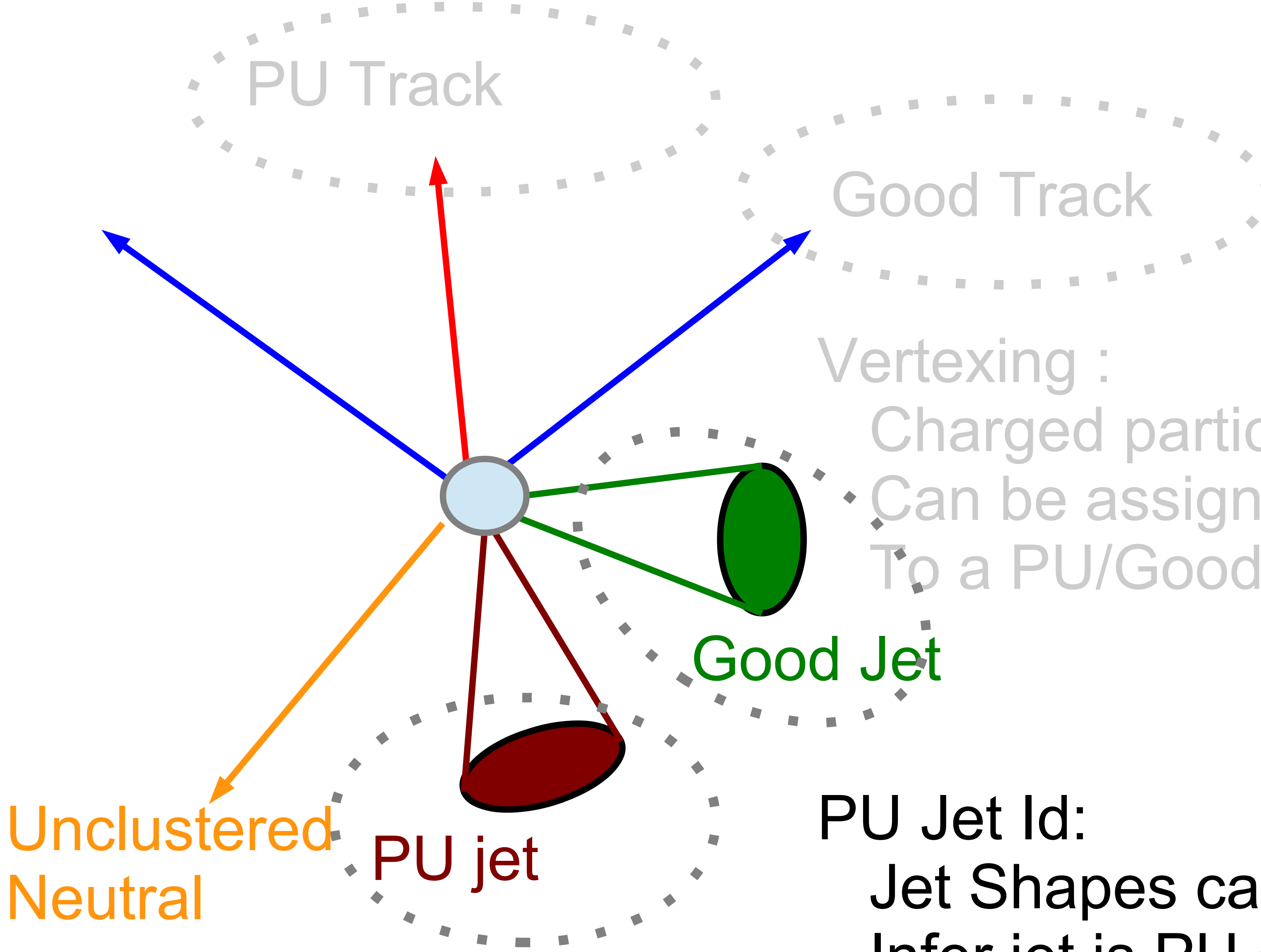
We have tools to go after all

# Pileup in the Event




Vertexing :
Charged particles
Can be assigned
To a PU/Good vertex

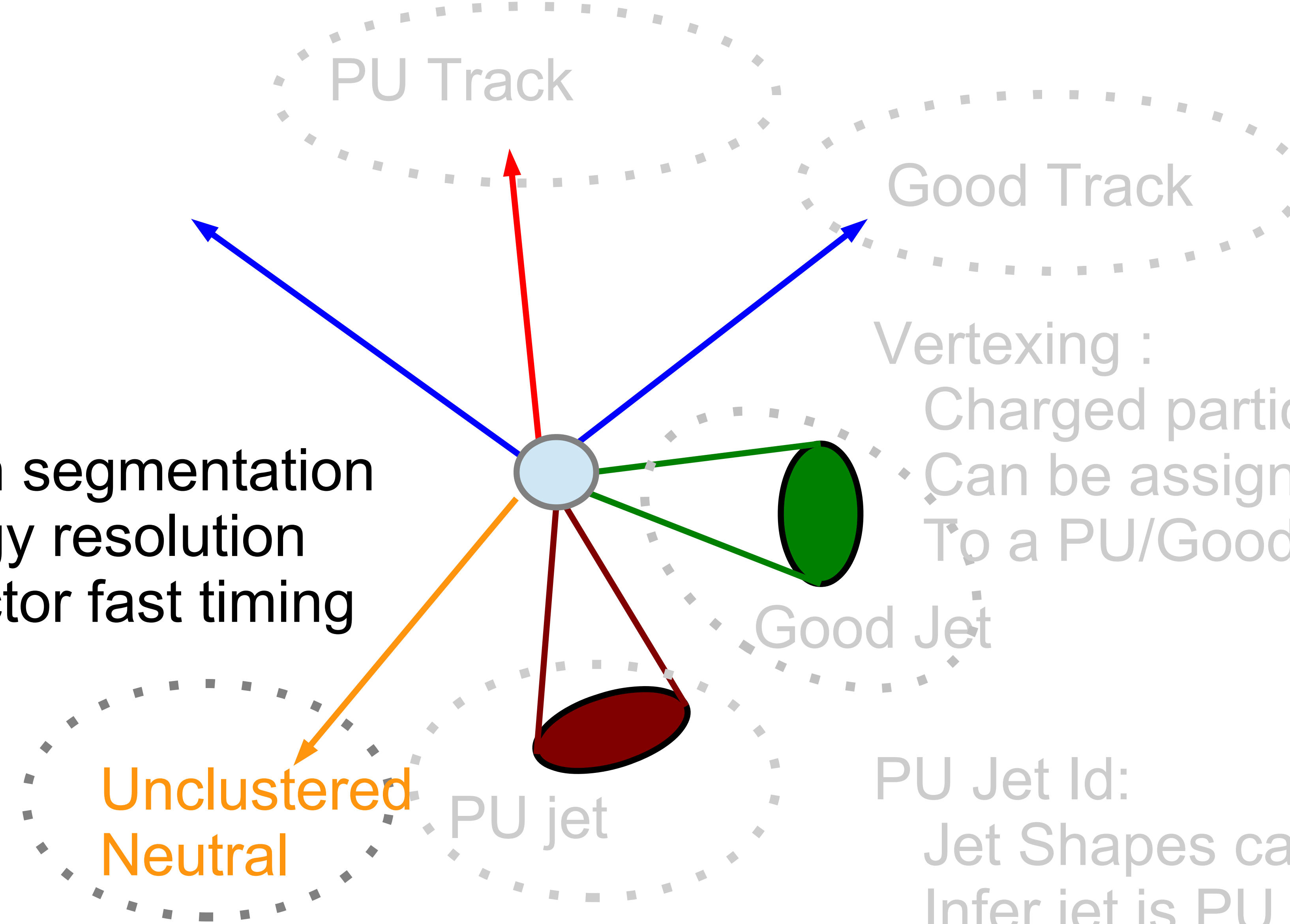
# Pileup in the Event




Vertexing :
Charged particles
Can be assigned
To a PU/Good vertex

PU Jet Id:
Jet Shapes can
Infer jet is PU or not

# Pileup In the Event



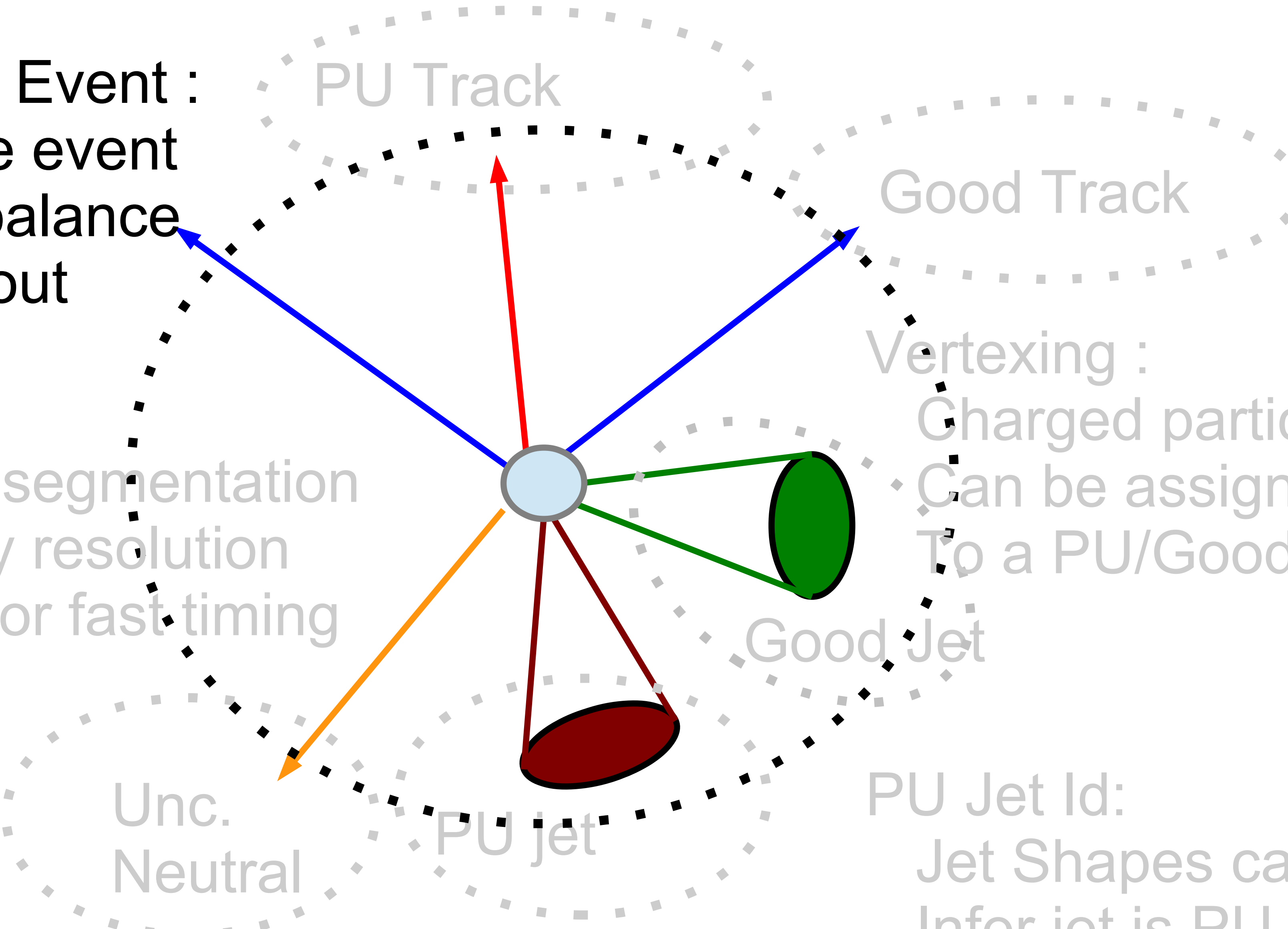

Vertexing :
Charged particles
Can be assigned
To a PU/Good vertex

Depth segmentation
Energy resolution
Detector fast timing

PU Jet Id:
Jet Shapes can
Infer jet is PU or not

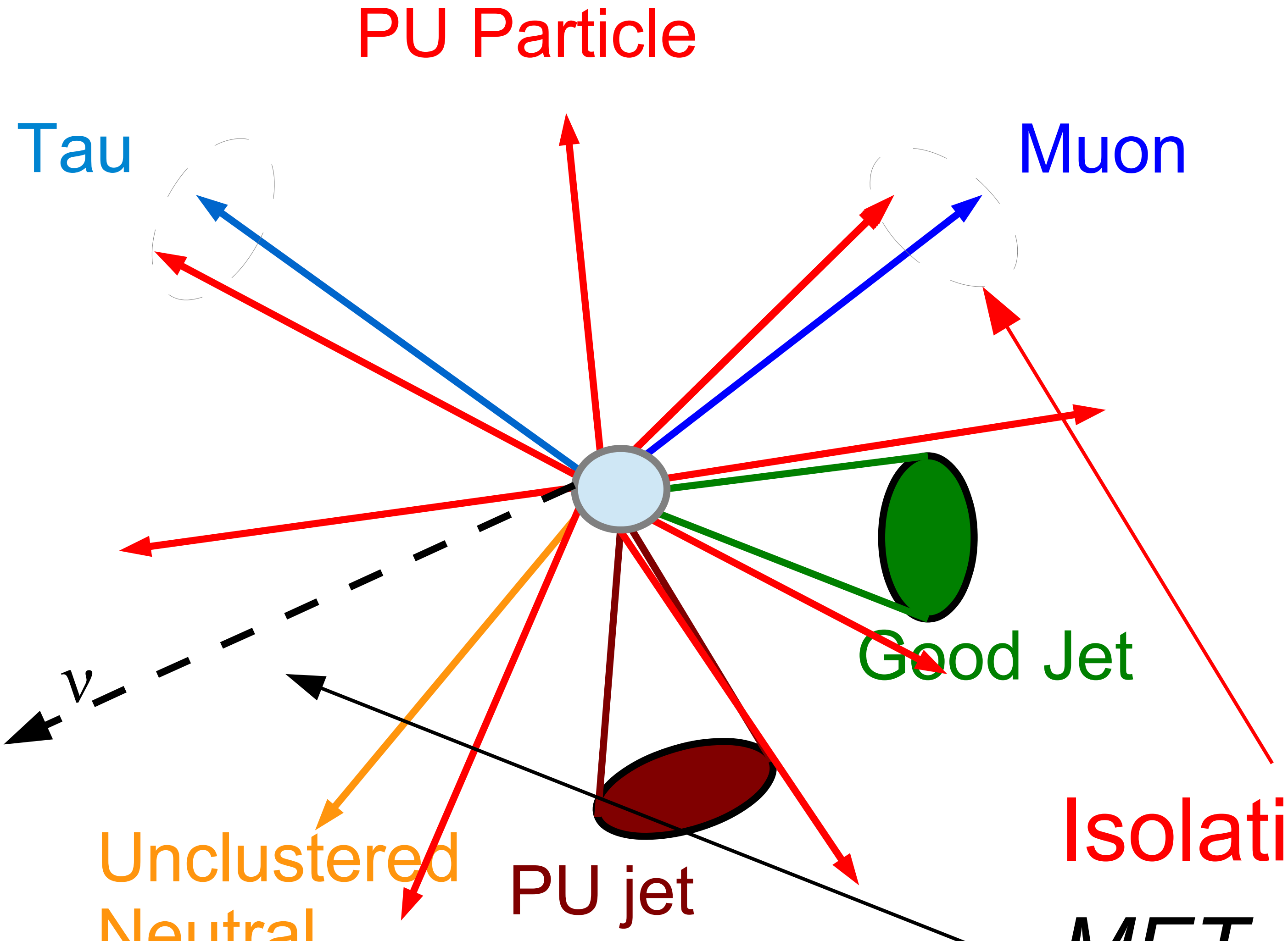
# Pileup In the Event

Whole Event :
Whole event
Can balance
itself out



# Puppi affects everything

- It does not just work on jets!



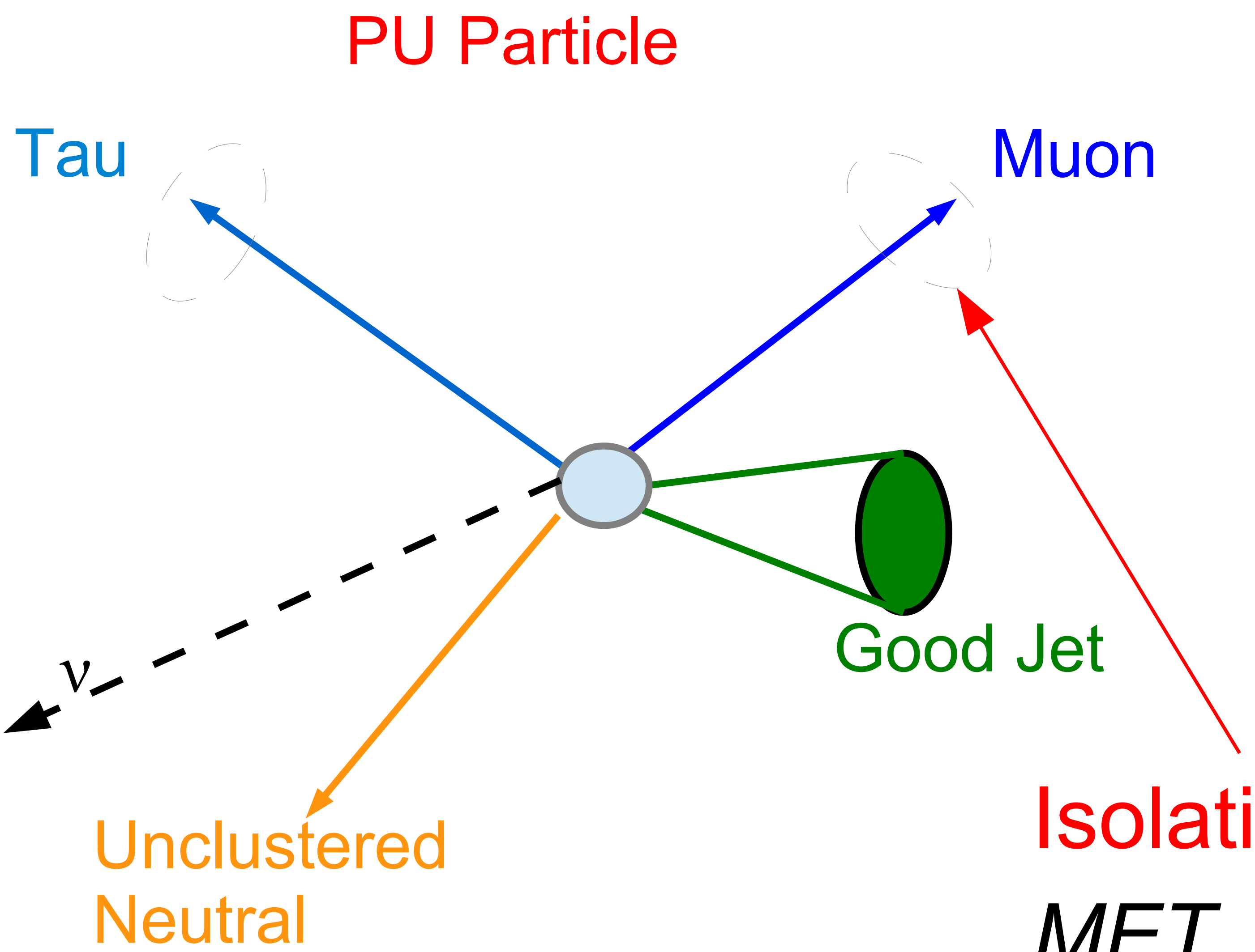

Isolation = $\Sigma_{\Delta R} p_T$

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

*SUMET* = $\Sigma p_T$

# Puppi affects everything

- It does not just work on jets!




Apply the Puppi Weights $w$

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

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

$SUMET = \Sigma p_T w$