Pileup and Substructure

Philip Harris (CERN)
CMS collaboration

Bibliography

KEY : Public, Available this week, Available soon

Please consult CMS about our new papers

- JME-12-002 : *MET* performance in CMS
- JME-13-002 : Quark/Gluon Discriination
- JME-13-005 : Pileup Jet Identificaiton
- JME-13-006 : Boosted W Jet tagging
- JME-13-007 : Boosted Top tagging

Supporting documents

HIG-13-004,HIG-13-010,HIG-11-027,QCD-10-011

Spectrum of the Jet Toolbox

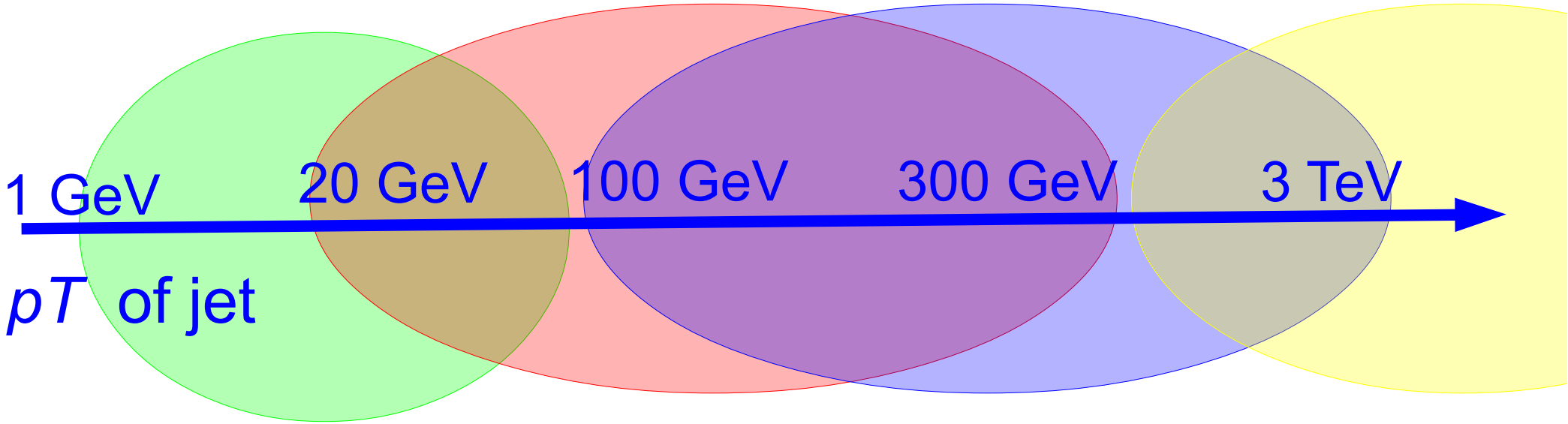
What are the dominant Jet effects vs pT?

Clustered Objects

Quark/Gluon Jets

Merged bosons/tops

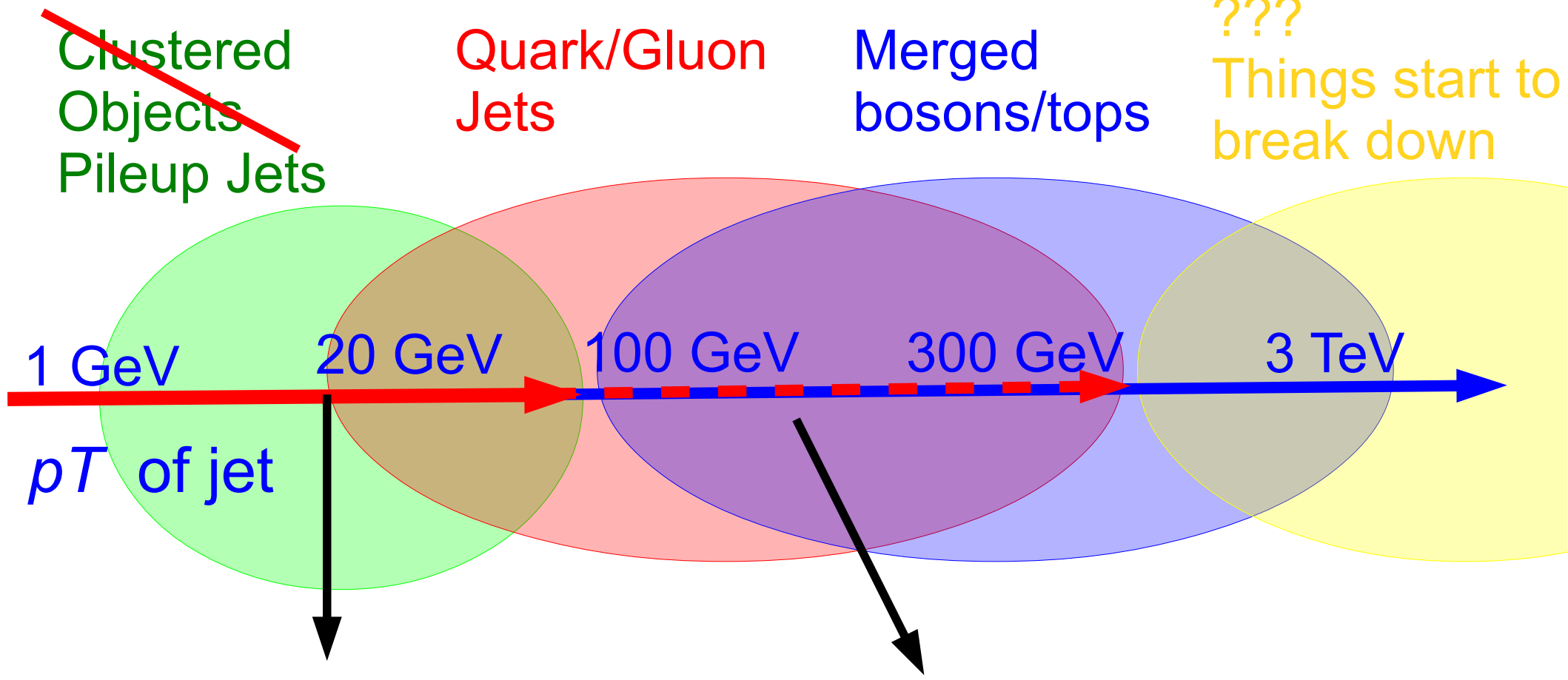
???
Things start to break down



This talk will address each region of Jets

Spectrum of the Jet Toolbox

Where does Pileup play a role?



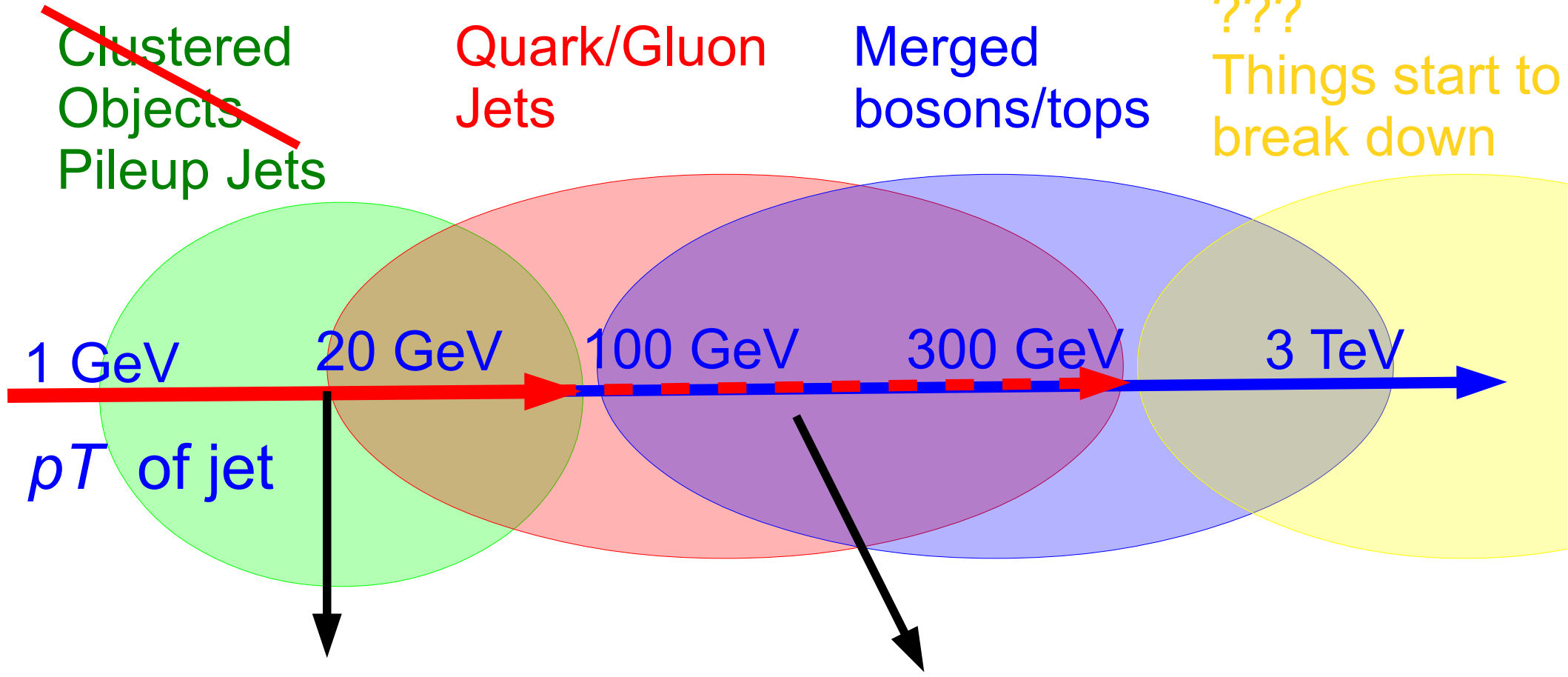
Largest contribution from Pileup Jets

Pileup inside good jet

Pileup Jet : Clustered object not matched real jet (pT > 8 GeV)

Spectrum of the Jet Toolbox

What do we do to address Pileup?



Pileup Jet Id

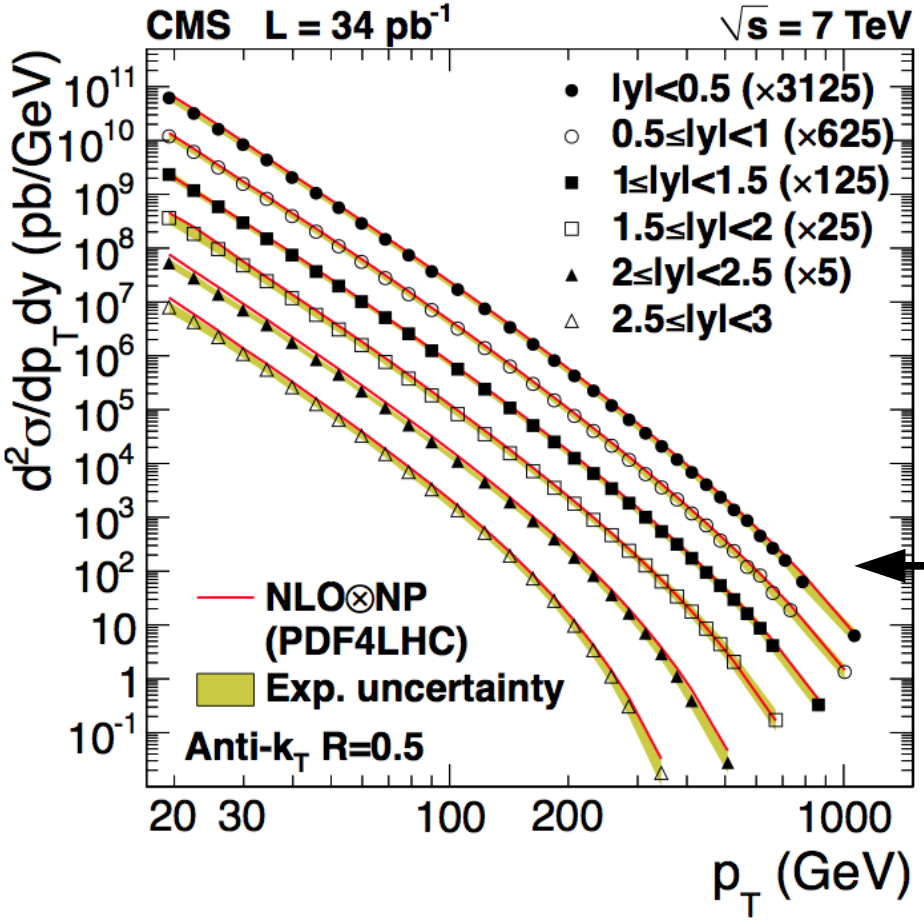
Charge hadron subtraction

Nota bene: We care about in time and out of time pileup but mainly in time pileup

What is Pileup?

- Any object from another collision
  - Some resulting QCD from UE/jet production
  - Consider instance where objects are clustered

What is the rate of overlapping pileup?



Phys.Rev.Lett.107:132001,2011

Two jets w/Sum $pT = pT_1 + pT_2$

Consider a simplified model

$$\mathbf{P(overlap|}pT\mathbf{)} \approx \mathbf{N^2_{pu}\, a^2_{jet} \int A}$$

$$\int A = \int dpT \frac{d\sigma_1}{dpT} \frac{d\sigma_2}{dpT} \delta(pT - pT_1 + pT_2)$$

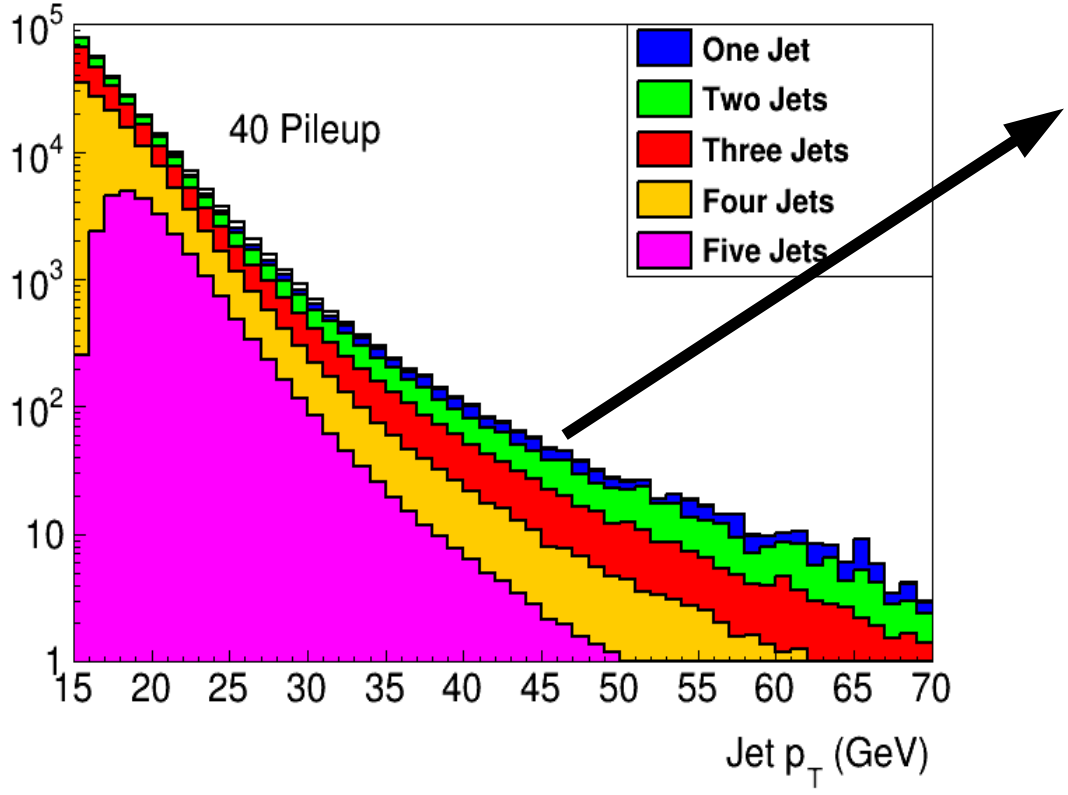
$$\frac{d\sigma}{dpT} = pT^{-5} \text{ (NLO/measurement)}$$

$$\int A = C\ pT^{-6.2} \text{ (C a constant)}$$

What is Pileup?

- Any object from another collision
  - Some resulting QCD from UE/jet production
  - Consider instance where objects are clustered

What is the rate of overlapping pileup?



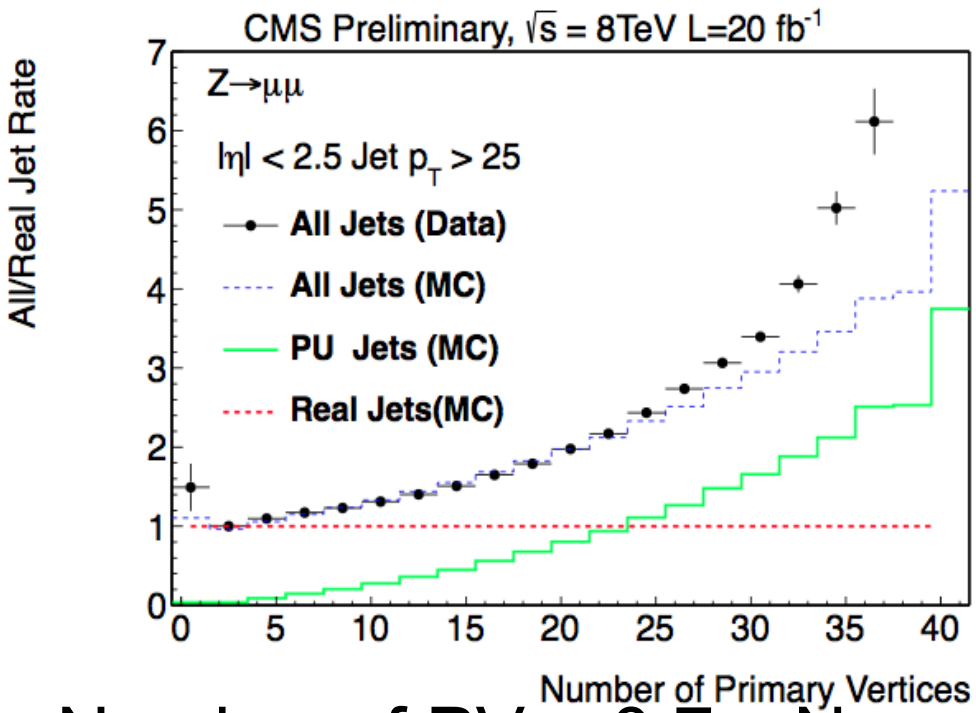
Contribution of overlapping jets To pileup jet spectrum

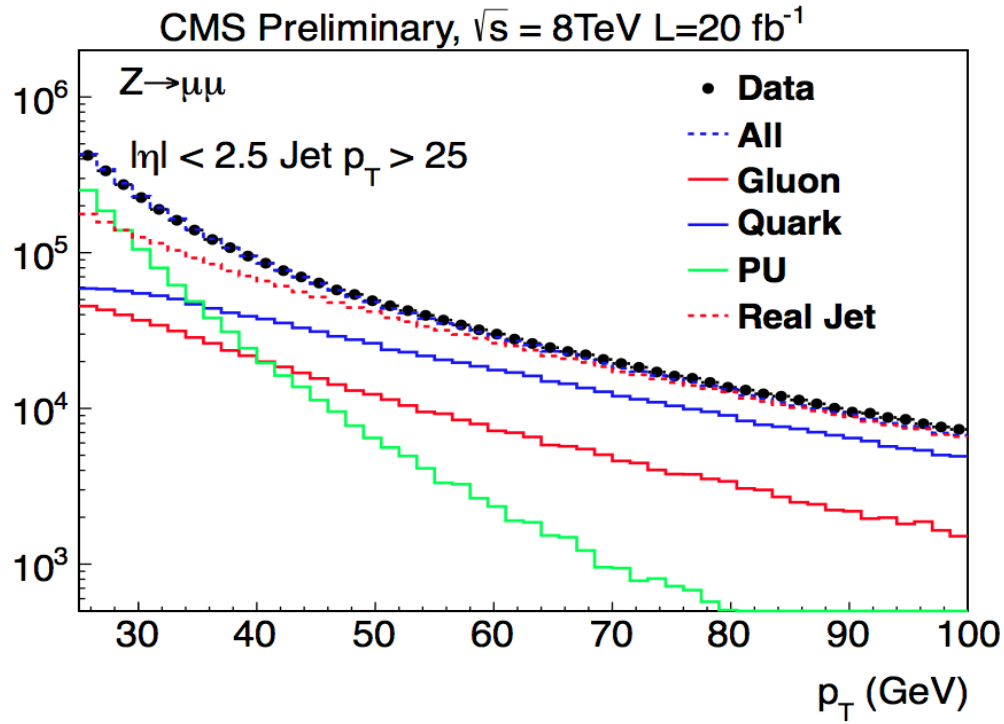
Two jets are dominant contribution

What does it look like in Data?

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

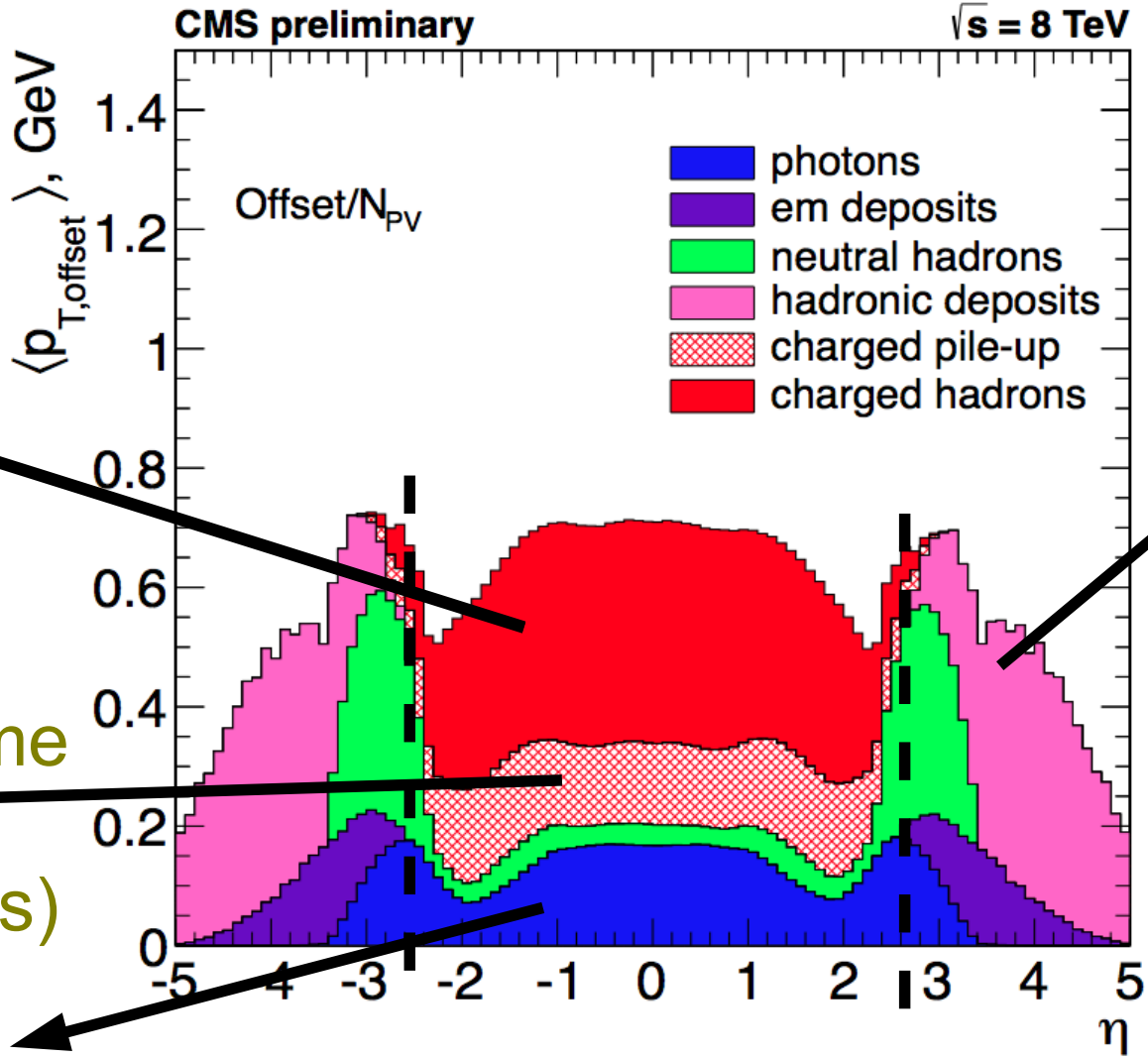
- Expect pileup to grow quadratically
- Expect pileup jets to fall off more rapidly
  - Pileup jets remain a few% level problem up to 70 GeV





Number of PV = 0.7 x N_{pu}

Pileup Composition in CMS



Flag with Vertexing

Flag with some uncertainty (vtx + shapes)

Guilty by Association (rely on clustering)

No tracker
Must rely on shapes to identify

Charge Hadron Subtraction:
Flag from another vertex and remove it

Pileup Removal in CMS

- PF Jet reconstruction
  - Take all particle flow (PF) candidates
  - Cluster
  - Apply ρ correction

- Charged Hadron Subtraction(CHS) Jet reconstruction
  - Remove PF candidates assigned to anoher vertex
  - Cluster
  - Apply modified ρ correction (modified in TK volume)
  - Baseline for substructure and shape variables

Pileup Removal in CMS

- PF Jet reconstruction
  - Take all particle flow (PF) candidates
  - Cluster
  - Apply ρ correction
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  - Cluster
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  - Baseline for substructure and shape variables

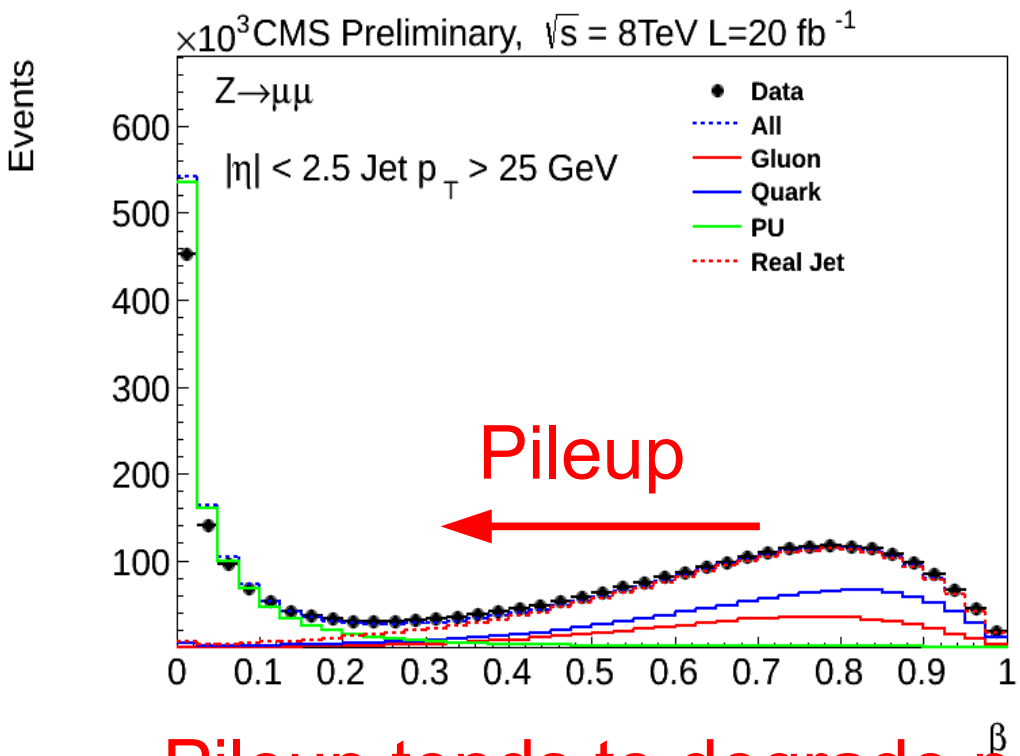
Apply Pileup jet Id on either (separate for each algo)

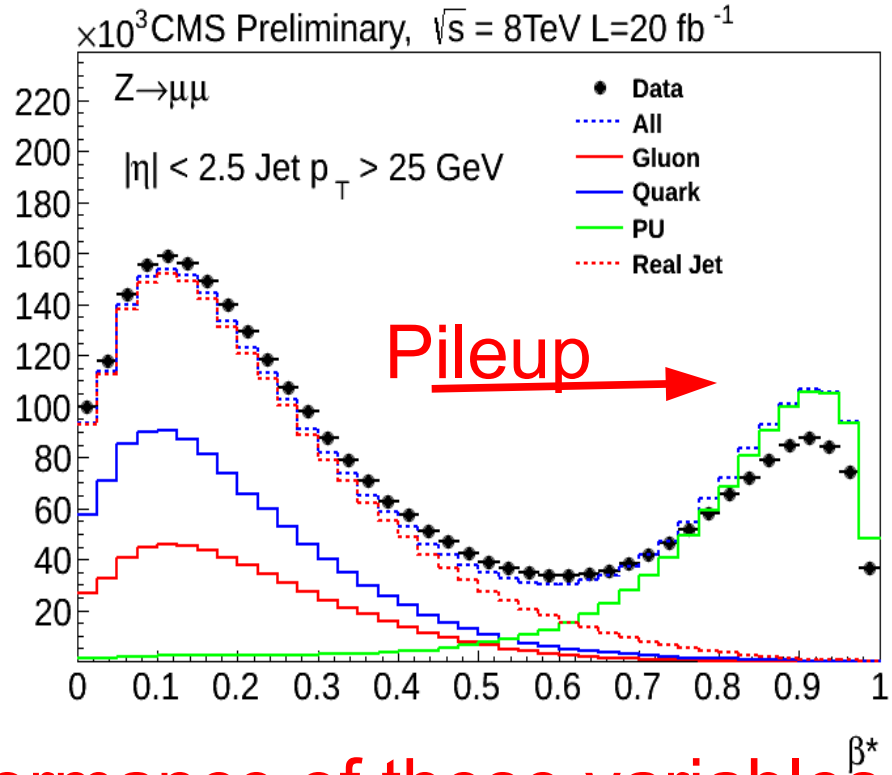
Pileup Jet Id Algorithm:Tracking

- 13 variables for the full discrimination
  - 4 Vertexing related variables (2 most impt shown):

#vertices, dZ of leading track in jet +

$$\beta = \frac{\sum_{i \in PV} p_{Ti}}{\sum_i p_{Ti}} \qquad \beta^* = \frac{\sum_{i \in otherPV} p_{Ti}}{\sum_i p_{Ti}}$$

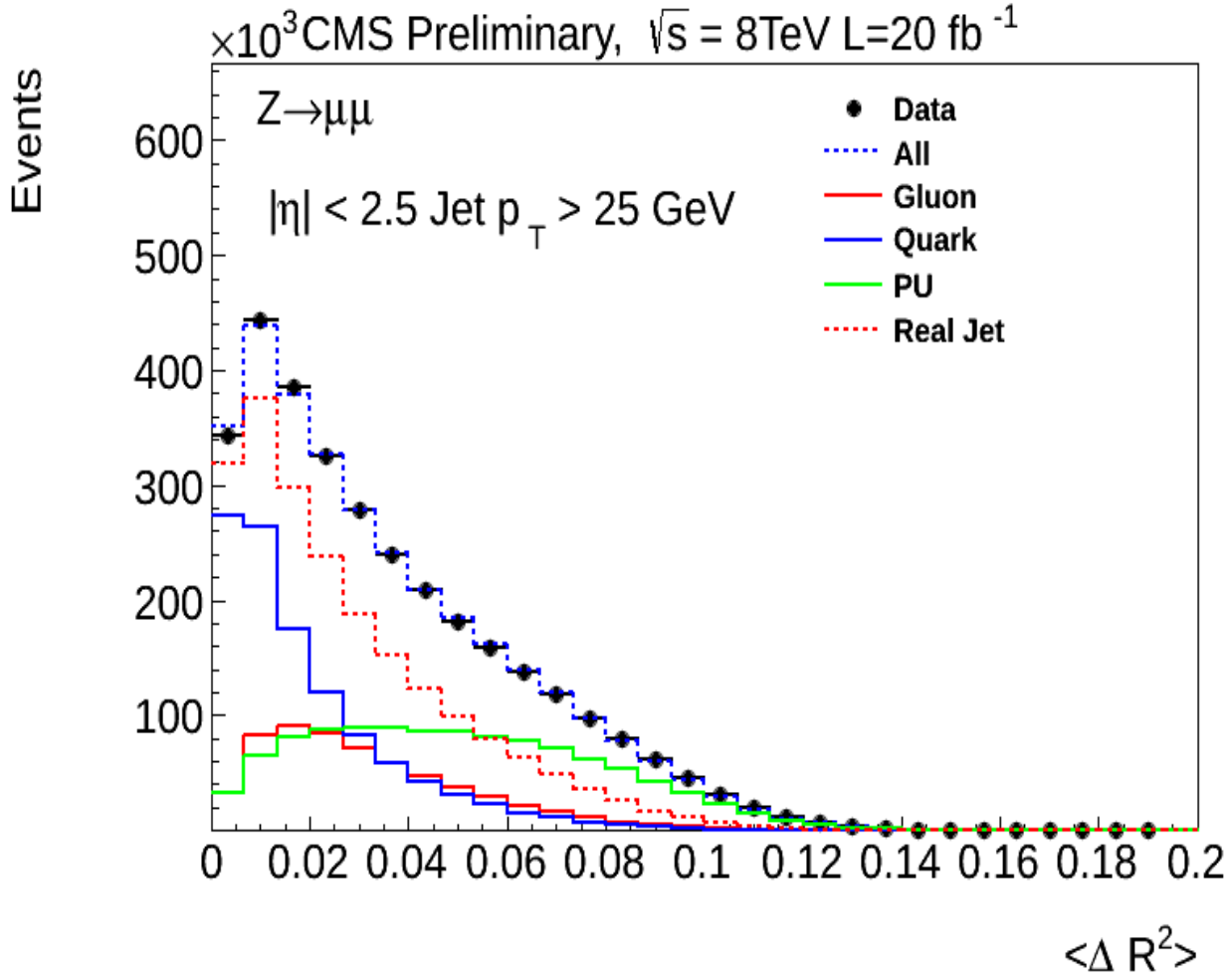




Pileup tends to degrade performance of these variables

Pileup Jet Id Algorithm:Shapes

- 13 variables for the full discrimination
  - QG disc: *pTD*,#Charged particles,#Neutral particles
  - 6 Shape variables

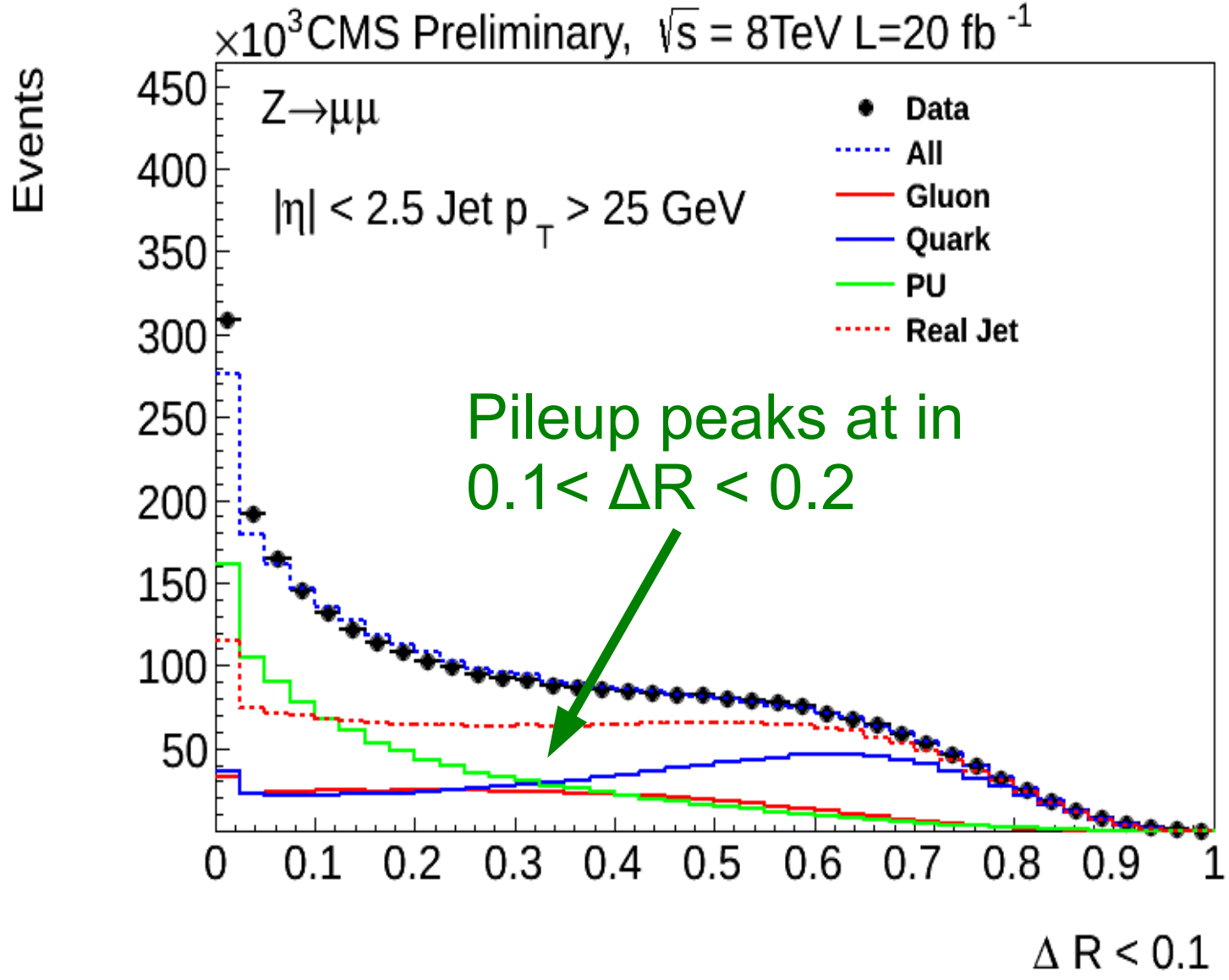


Most Effective
Jet shape variable

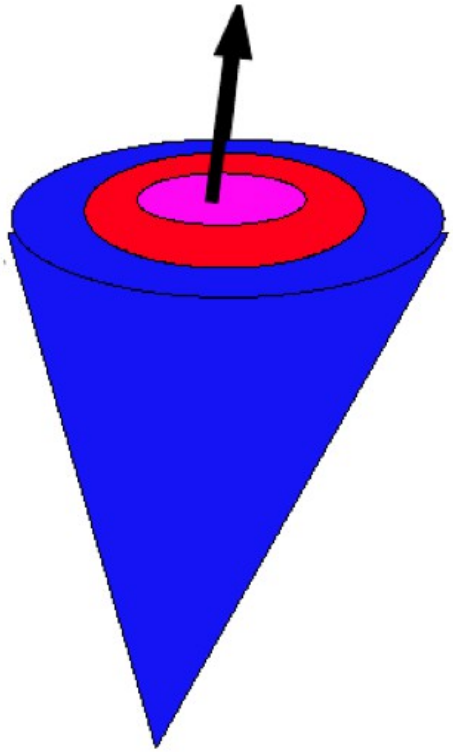
$$\langle \Delta R^2 \rangle = \frac{\sum_i \Delta R_i^2 p_{Ti}^2}{\sum_i p_{Ti}^2}$$

Pileup Jet Id Algorithm:Cones

- Additional shape variables : ΔR annuli



ΔR 0.1=>0.5



Algorithm Construction

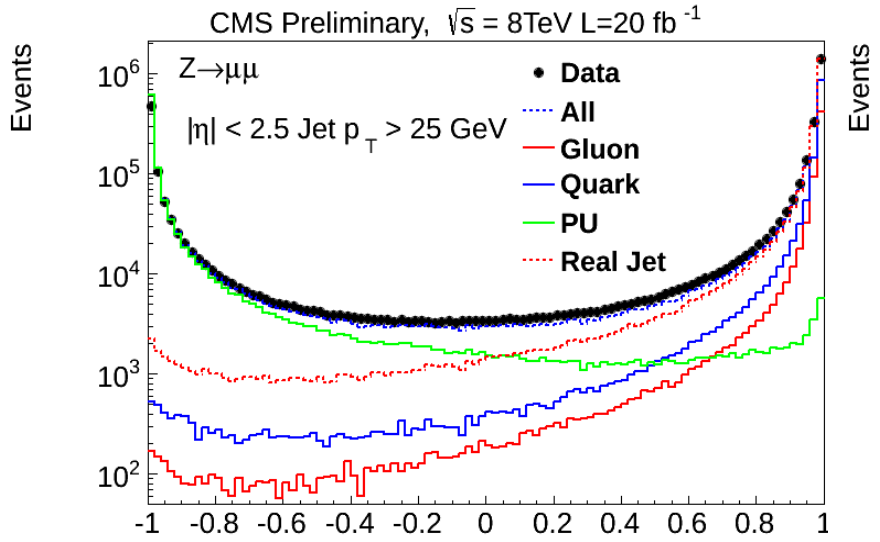
- Construct a Boosted decision tree real vs PU Jets
  - Train in four separate regions of η

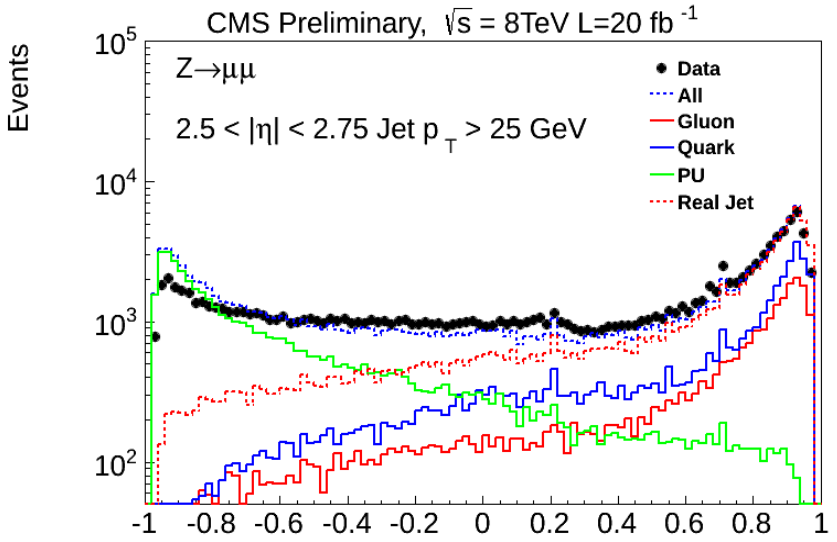
$\|\eta\| < 2.5$ tracking Shape variables	$2.5 < \|\eta\| < 2.75$ Weak tracking (tracking ends at 2.5) Shape variables
$2.75 < \|\eta\| < 3.0$ Shape variables	$3.0 < \|\eta\| < 5.0$ Forward HCAL Shape variables

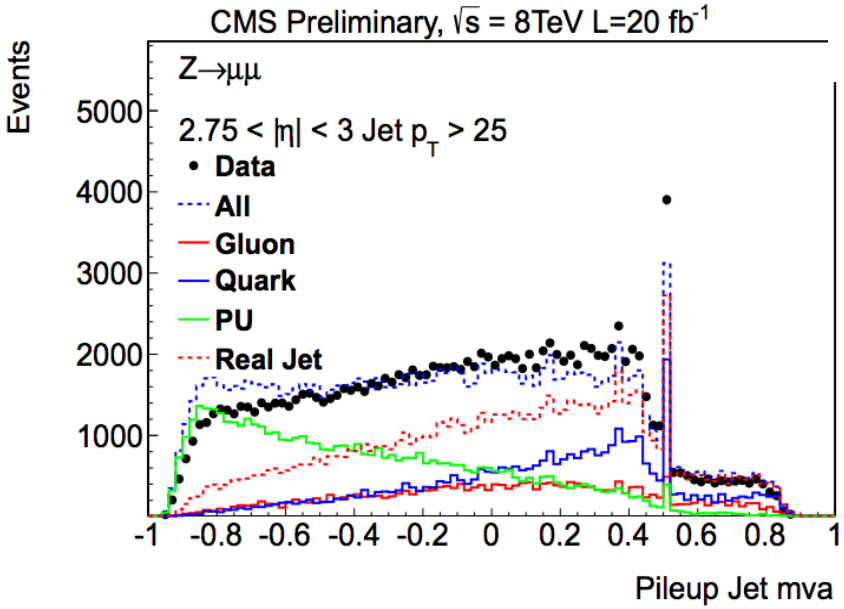
Construct a Boosted decision tree (trained on Z+jets for each)

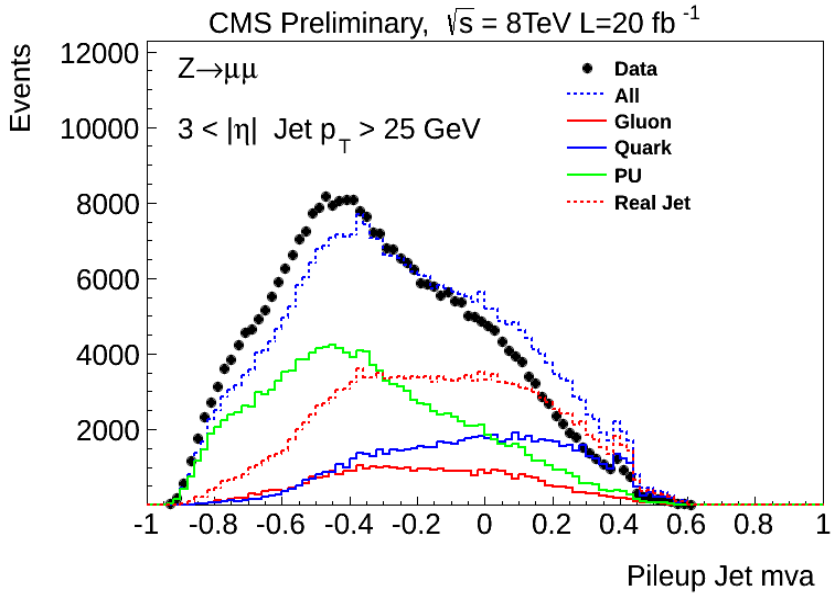
Pileup Jet Id in Data

- Fraction of pileup grows with higher |η|



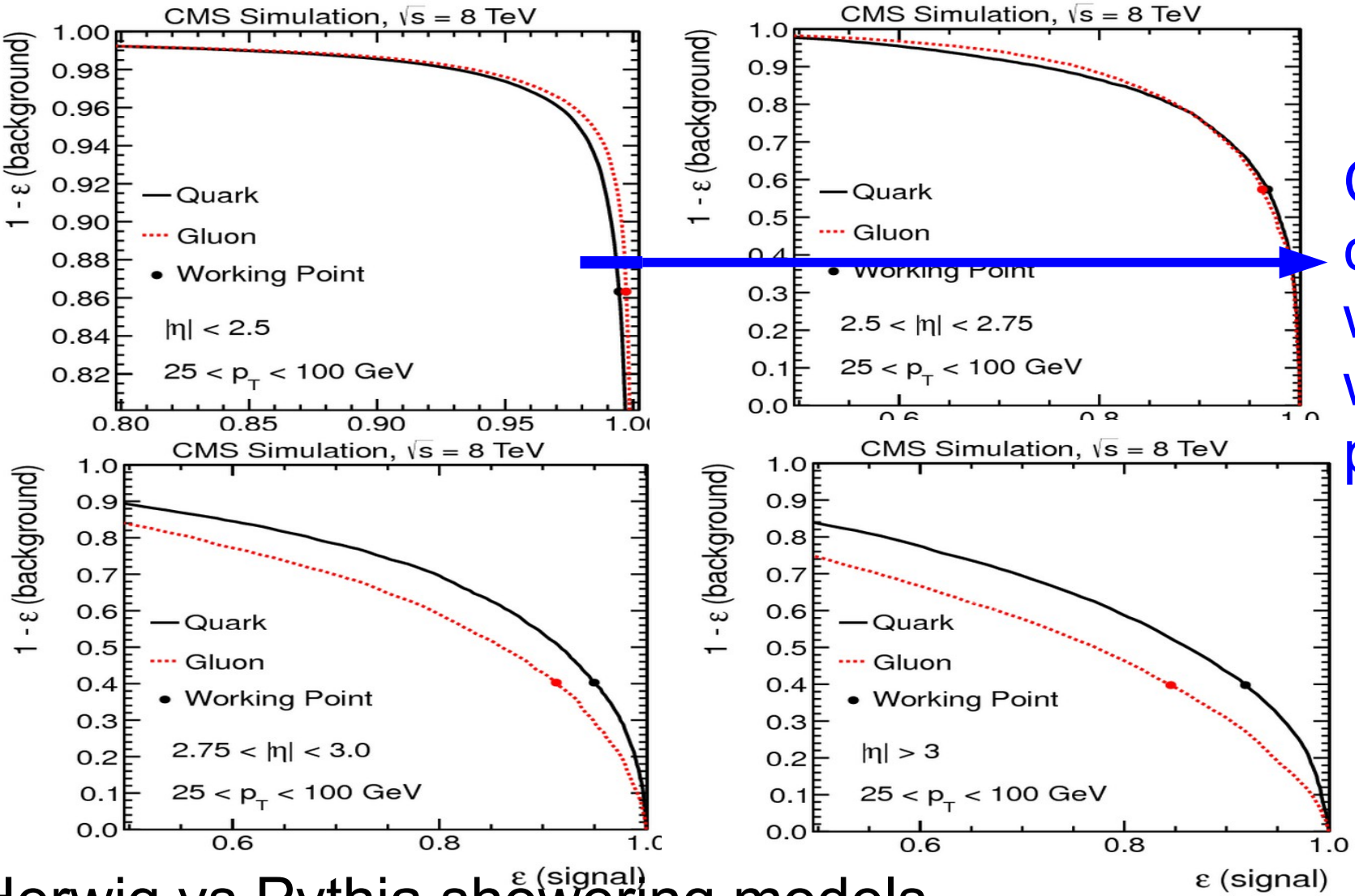






Pileup Jet Id Performance

- Largest systematic : from quark/gluon variation

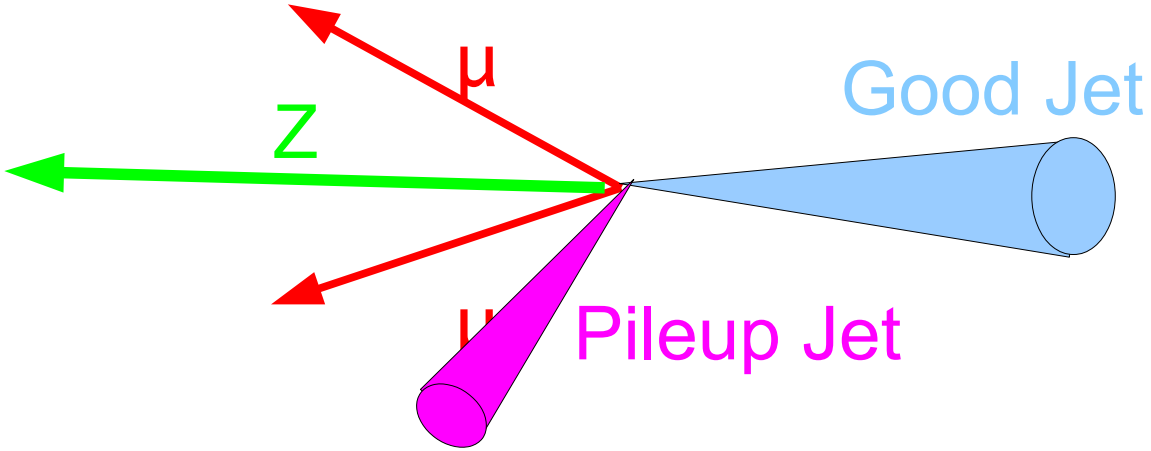


CHS results consistent w/specific working point

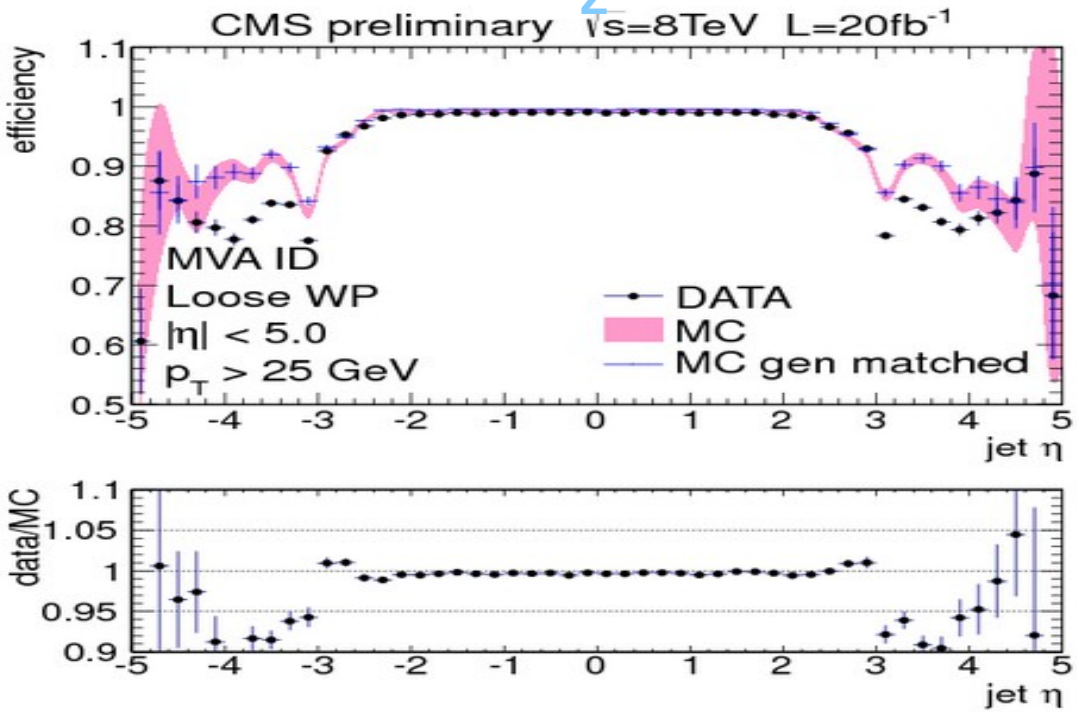
Herwig vs Pythia showering models bounded by quark/gluon variation

Pileup Jet Id: Efficiency in Data

- Use Z+Jet balance to measure efficiency in data



Good jet eff: $|\Delta\varphi - \varphi_z| > 3.0$ (subtract scaled PU)



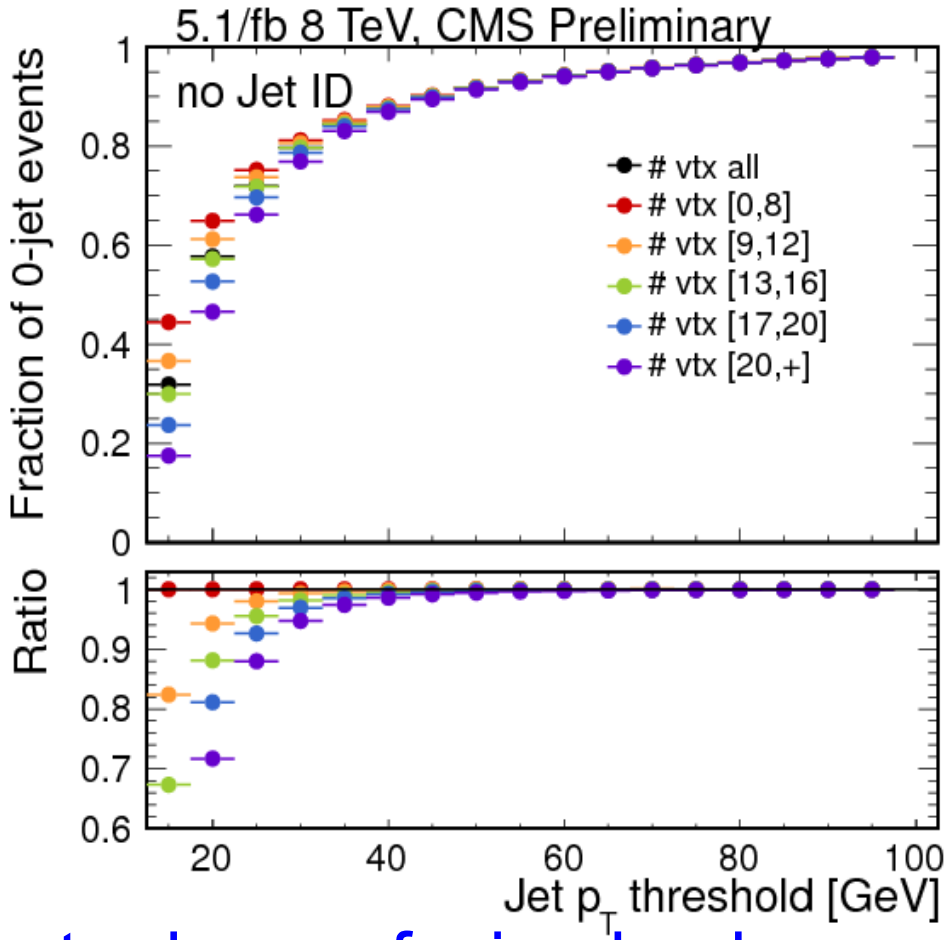
Example VBF:

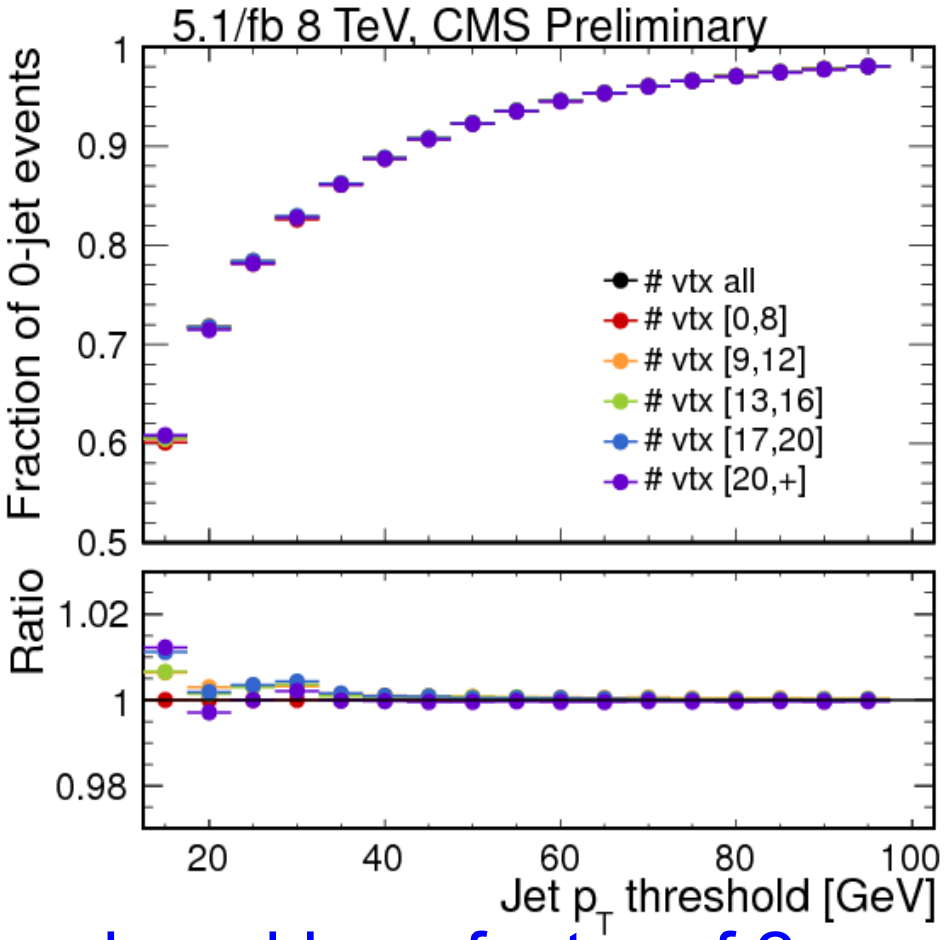
VBF Eff: 90%

VBF Fake rate 15%

Usage Examples: Jet Vetos

- Pileup jet id allows extension of jet vetos to low *pT*
  - Critical for b-tag veto (requires jets with *pT* > 10 GeV)

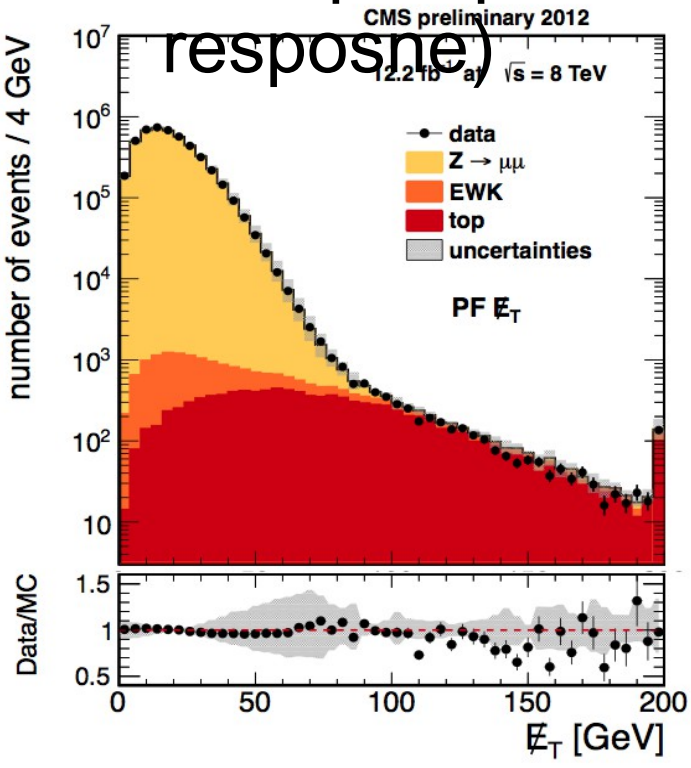


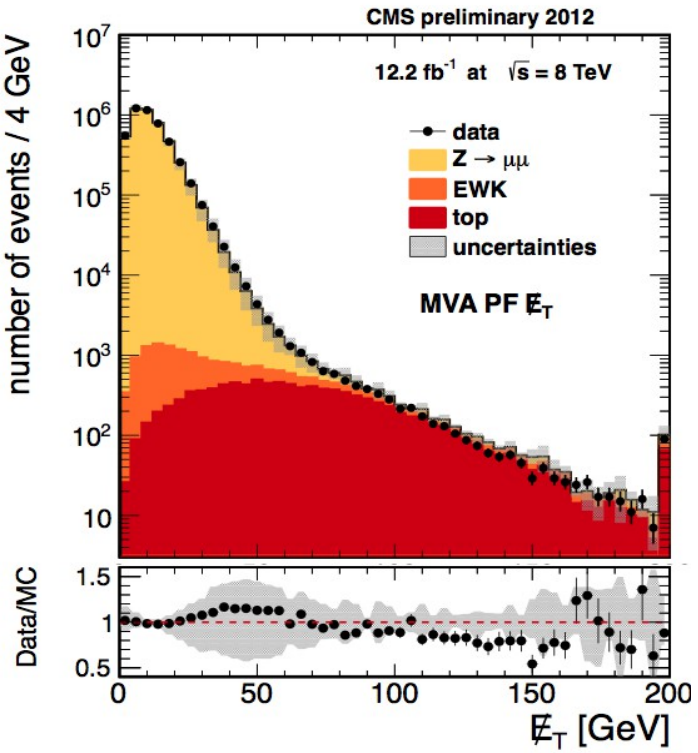


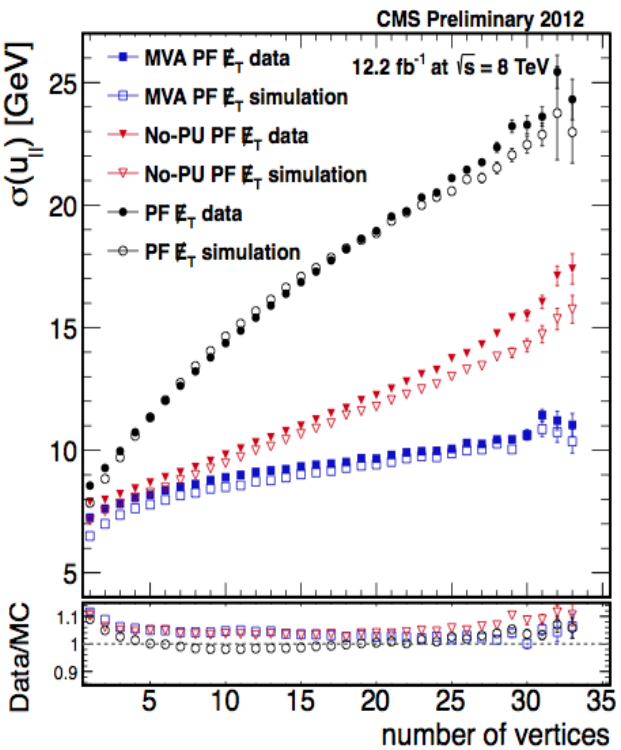
Vector boson fusion background reduced by a factor of 2 (90% good jet eff)

MVA *MET* Performance

- Consider separating out hadronic portion of event
  - Use the pileup jet id to classify neutrals (in jets pT > 5 GeV
  - Use vertex information to classify charged hadrons
- Recombine sub-components through BDT/Algo
  - Pileup dependence reduced by factor of 4 (~same response)







Quark/Gluon Discrimination

- Available for all regions in jet η + pT > 30 GeV
- Construction of id
  - Require tracks to point from PV + neutrals > 1 GeV
  - Construct likelihood built on 3 variables
    - Binned in both ρ and *pT*

$$p_T D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

$$W_{ij} = \frac{1}{\sum_i p_T^2} \sum_i \begin{pmatrix} (\Delta\phi_i)^2 p_T^2 & (\Delta\eta_i \Delta\phi_i) p_T^2 \\ (\Delta\phi_i \Delta\eta) p_T^2 & (\Delta\eta_i)^2 p_T^2 \end{pmatrix}$$

Take the minor axis from diagonalized W_{ij}

Number of total constituents

Quark/Gluon Discrimination

- Available for all regions in jet η + pT > 30 GeV
- Construction of id
  - Require tracks to point from PV + neutrals > 1 GeV
  - Construct likelihood built on 3 variables + binned in ρ
    - Binned in both ρ and *pT*

Best variable in the Central region ~|η| < 3

$$p_T D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

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Take the minor axis from diagonalized W_{ij}

Number of total constituents

Quark/Gluon Discrimination

- Available for all regions in jet η + pT > 30 GeV
- Construction of id
  - Require tracks to point from PV + neutrals > 1 GeV
  - Construct likelihood built on 3 variables + binned in ρ
    - Binned in both ρ and *pT*

Best variable in the forward region ~|η| > 3

$$p_T D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$$

$$W_{ij} = \frac{1}{\sum_i p_T^2} \sum_i \begin{pmatrix} (\Delta\phi_i)^2 p_T^2 & (\Delta\eta_i \Delta\phi_i) p_T^2 \\ (\Delta\phi_i \Delta\eta) p_T^2 & (\Delta\eta_i)^2 p_T^2 \end{pmatrix}$$

Take the minor axis from diagonalized W_{ij}

Number of total constituents

Quark/Gluon Discrimination

- Available for all regions in jet η + pT > 30 GeV
- Construction of id
  - Require tracks to point from PV + neutrals > 1 GeV
  - Construct likelihood built on 3 variables + binned in ρ
    - Binned in both ρ and *pT*

Best variable at high *pT*

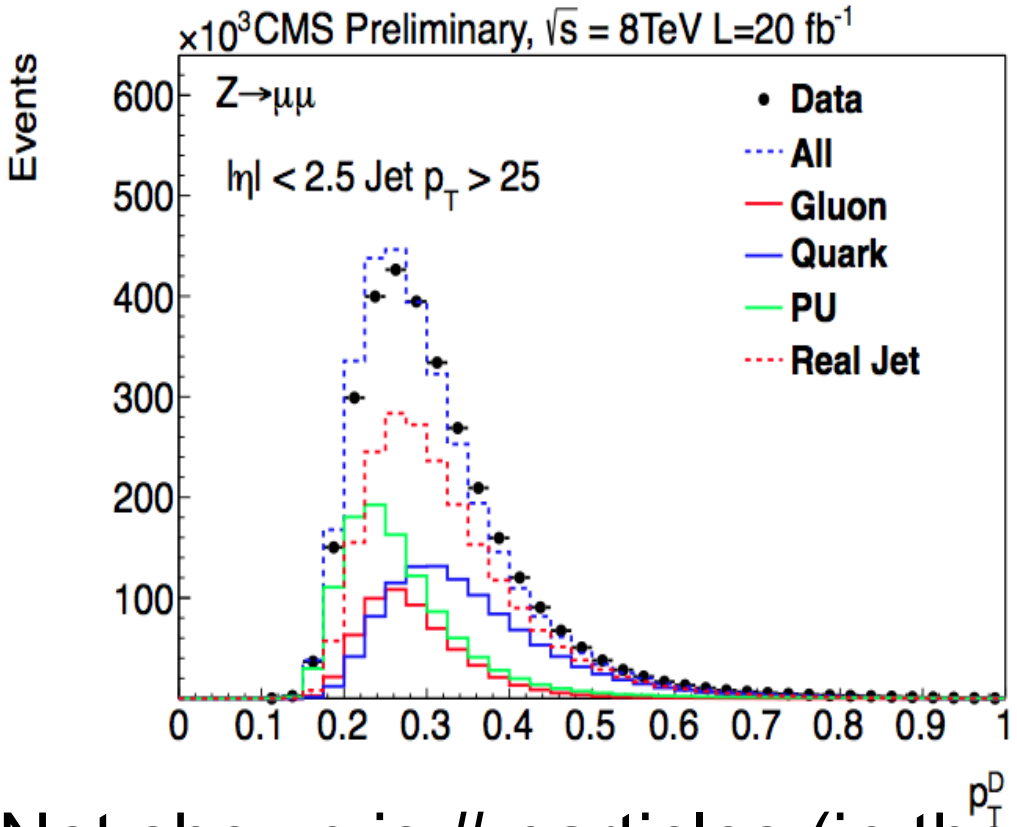
$$p_T D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}} \qquad W_{ij} = \frac{1}{\sum_i p_T^2} \sum_i \begin{pmatrix} (\Delta\phi_i)^2 p_T^2 & (\Delta\eta_i \Delta\phi_i) p_T^2 \\ (\Delta\phi_i \Delta\eta) p_T^2 & (\Delta\eta_i)^2 p_T^2 \end{pmatrix}$$

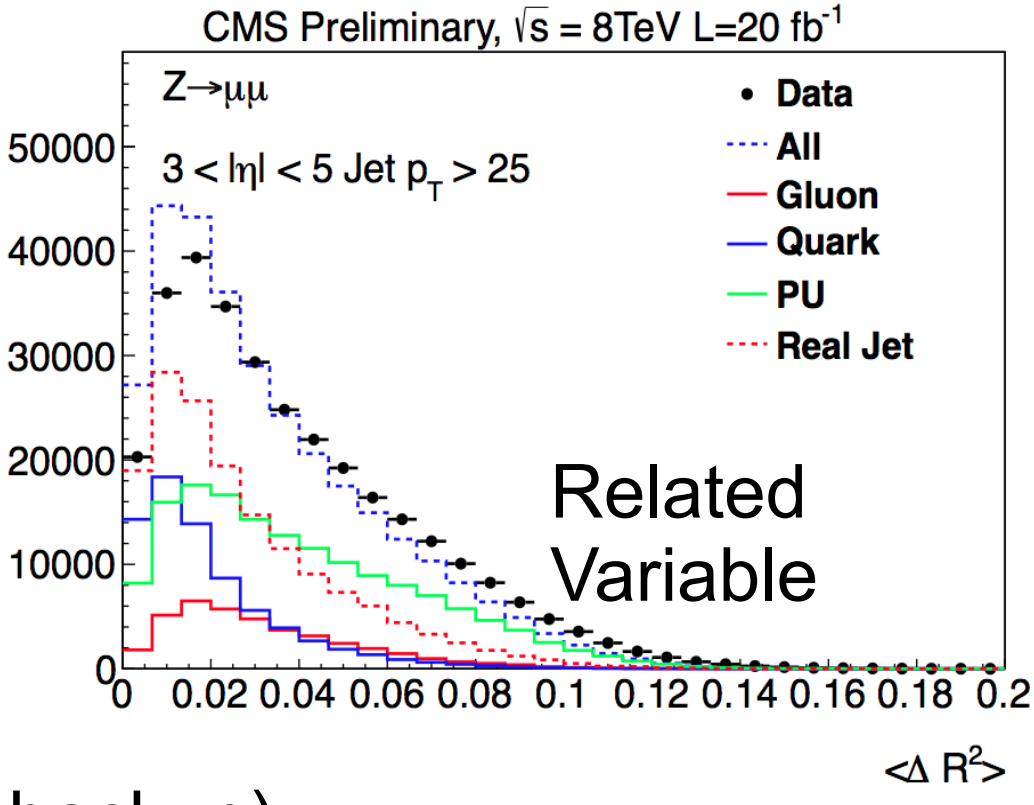
Take the minor axis from diagonalized W_{ij}

Number of total consituents

Quark/Gluon Disc. Concept

- Similar concept to the pileup jet id
  - Must rely on the shower shape to discriminate
- Concept
  - Several of these variables overlap with PU Jet id



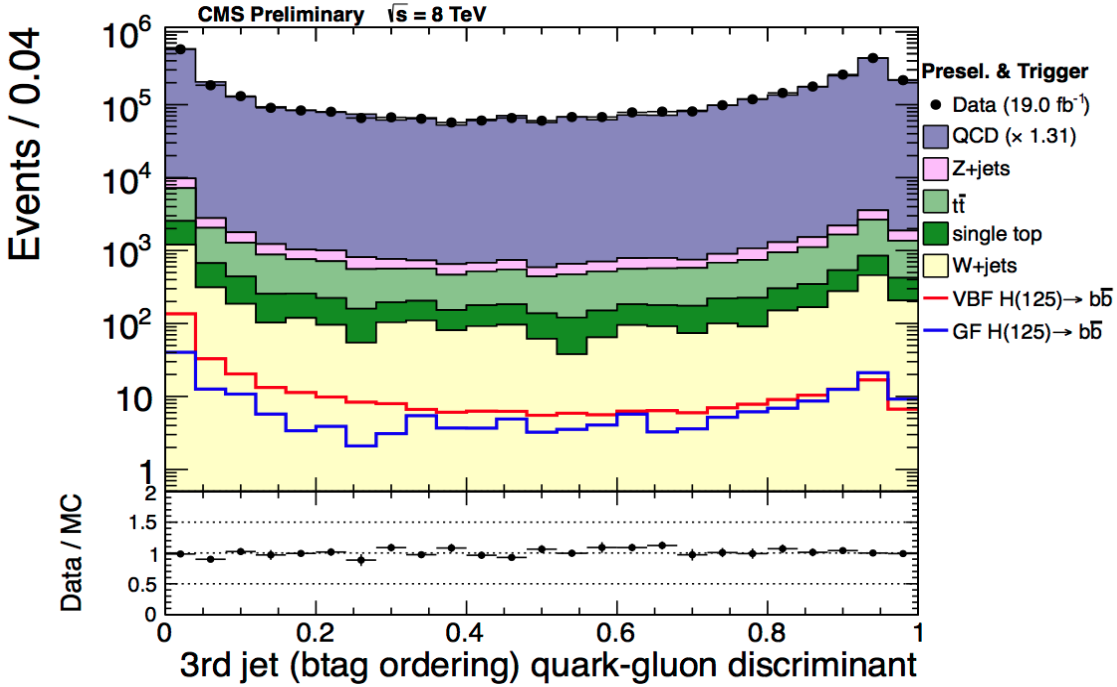


Not shown is # particles (in the backup)

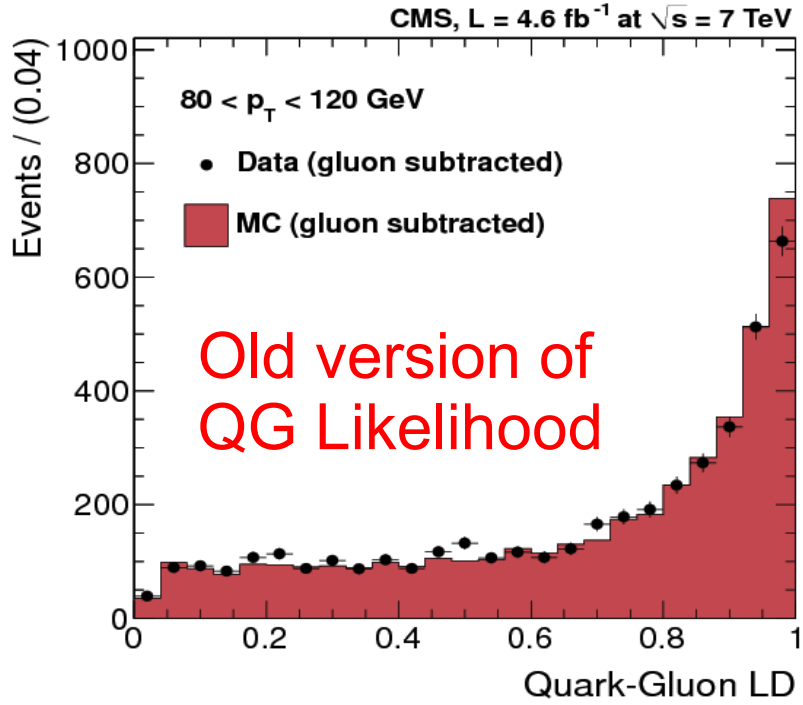
QG Performance + Usage

- QG discrimination used in VBF selection
  - Reduces the QCD/Pileup bkgs for forward jets
- QG discrimination used in Z boson tagging
- Reduction of 60% gluon for 80% quark eff

VBF H→bb Search

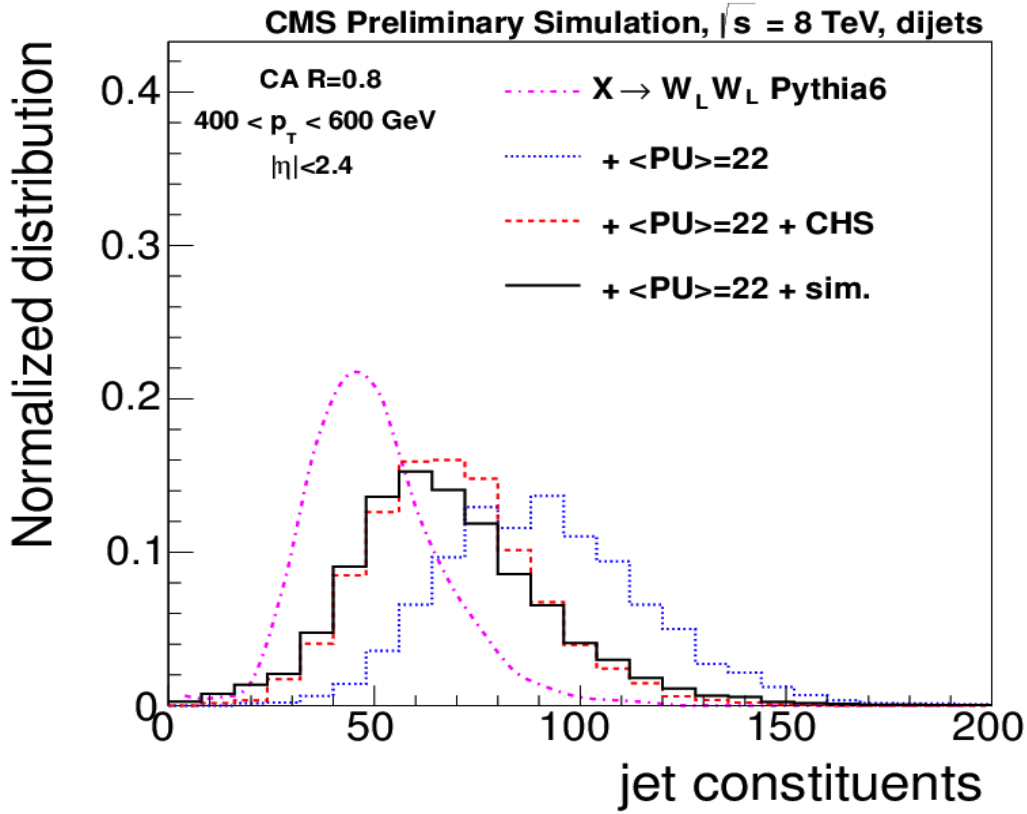


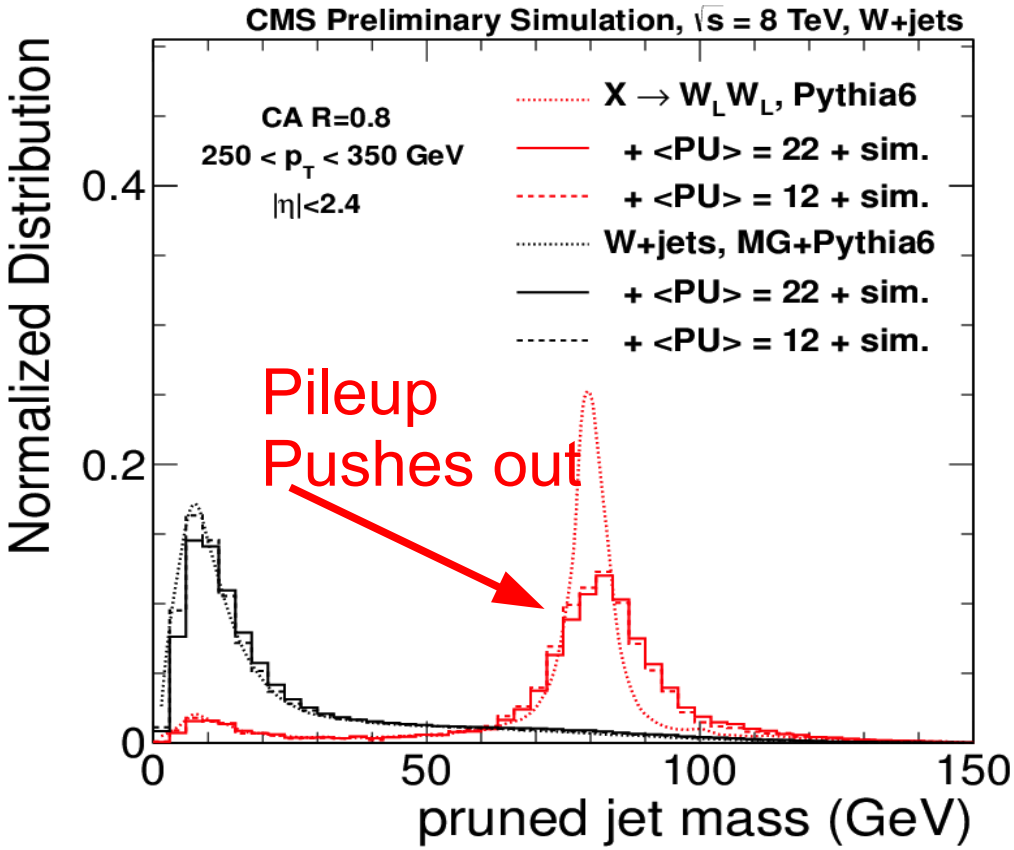
H→ZZ→2l2q Search



Adding Substructure

- Substructure starts with CHS
  - Build variables on top of CHS
- Cluster jets CA8 + apply ρ correction
- Targeting W reconstruction for now



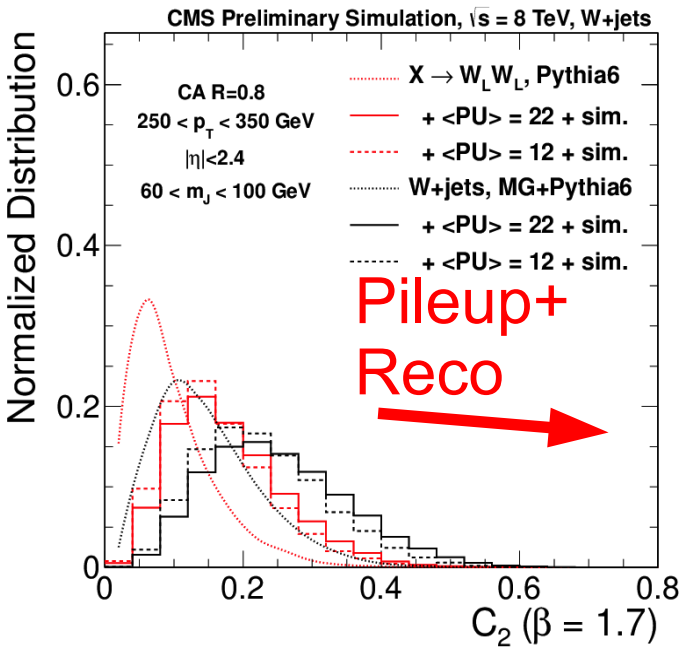


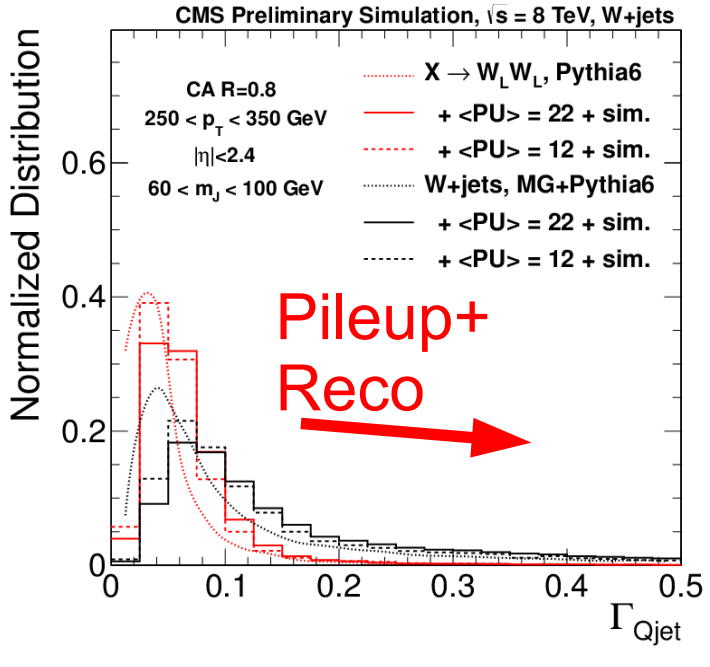
W Substructure tagging vs PU

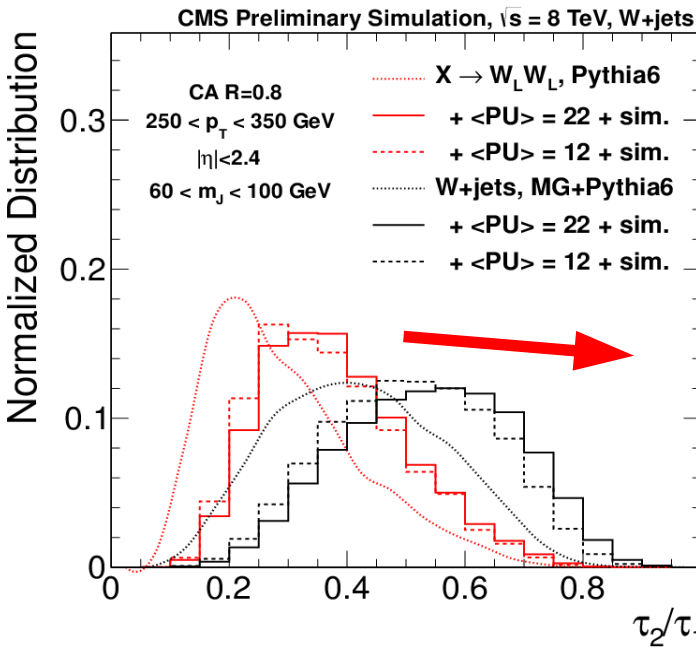
- Scan performed over a number of observables
  - All proposed taggers start with a cut on pruned mass
  - General tendency to focus on τ_2/τ_1
  - See Emanuele/Nhan/Petar's talk for more info

Performance of 3 most effective variables vs pileup

Trend vs Pileup similar in all => gradual degradation in perf.

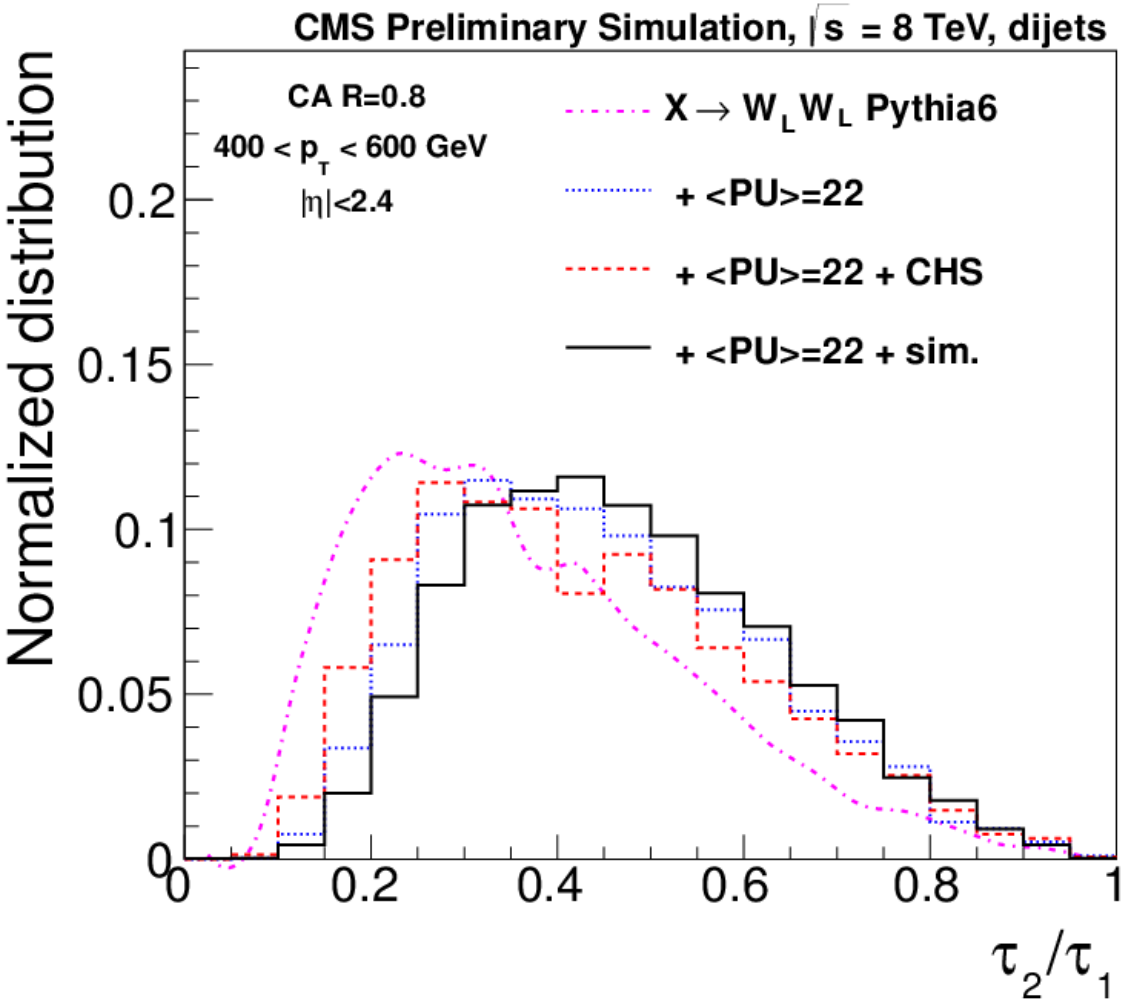






W Substructure : CHS

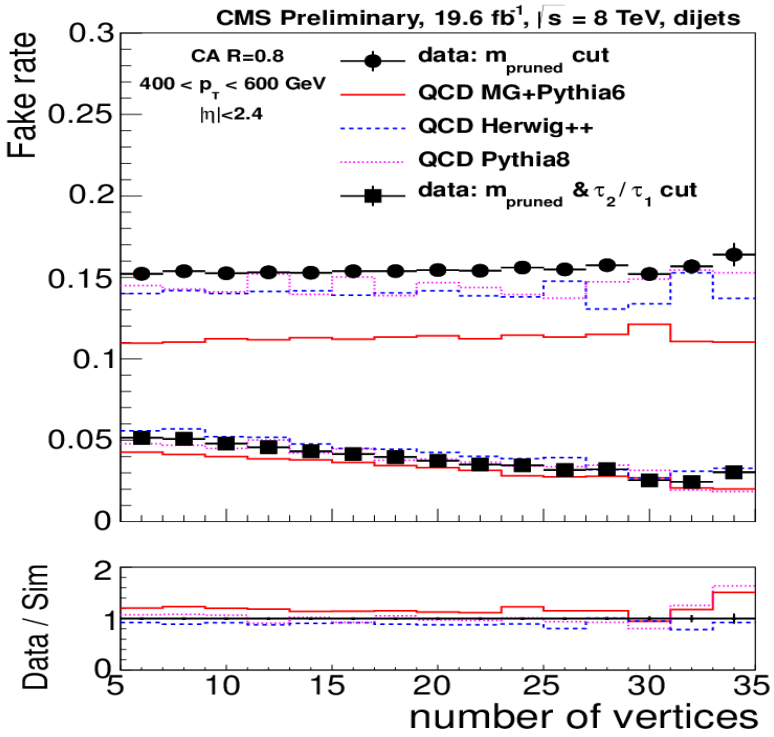
- Charge hadron subtraction clustering default
  - Jet shape effects minizmied with the CHS

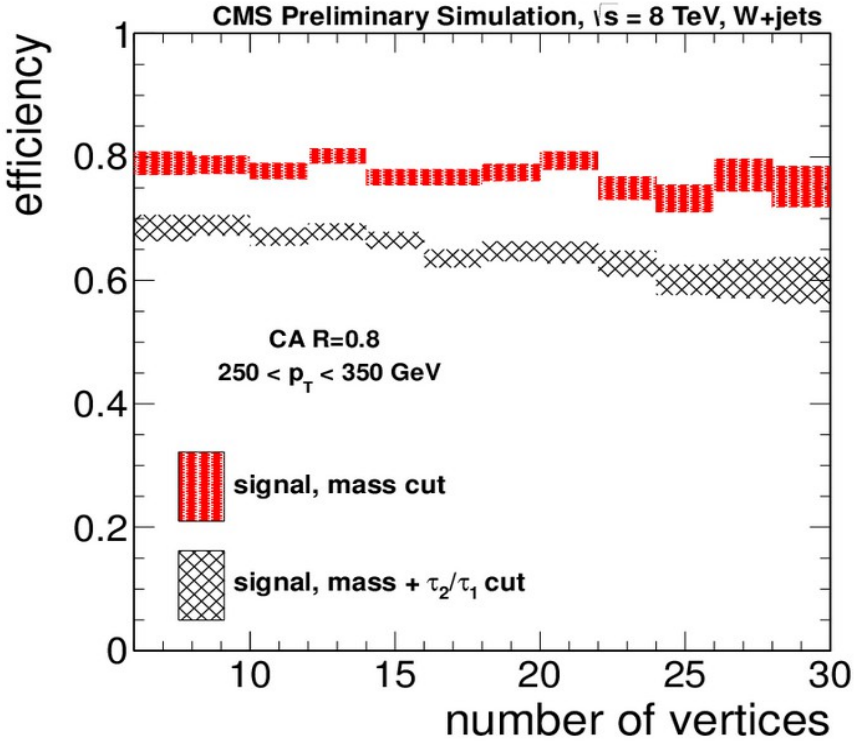


Charged hadron subtraction reduces the Pileup effect by 2

Substructure tagging in Data

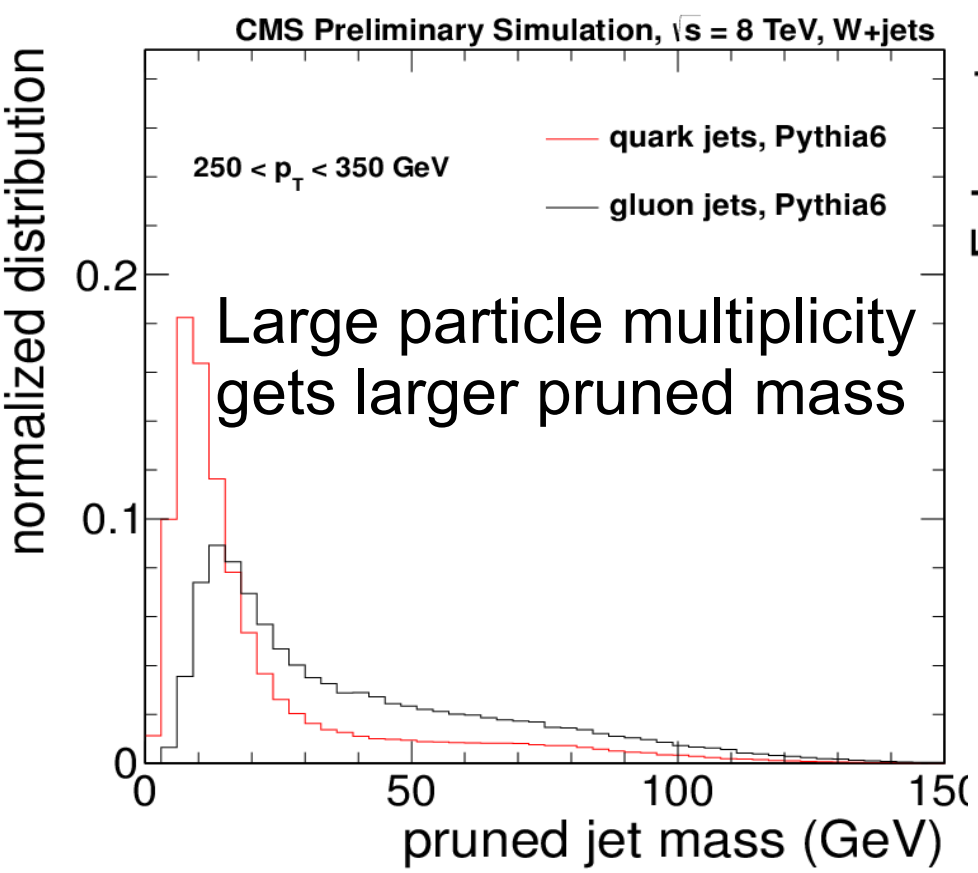
- Fakes :
  - Mass cut does has pileup dependence (bkg is flat)
  - N-subjettiness bkg reduced with pileup
- Signal :
  - Drop in eff for both mass cut and n-subjettiness

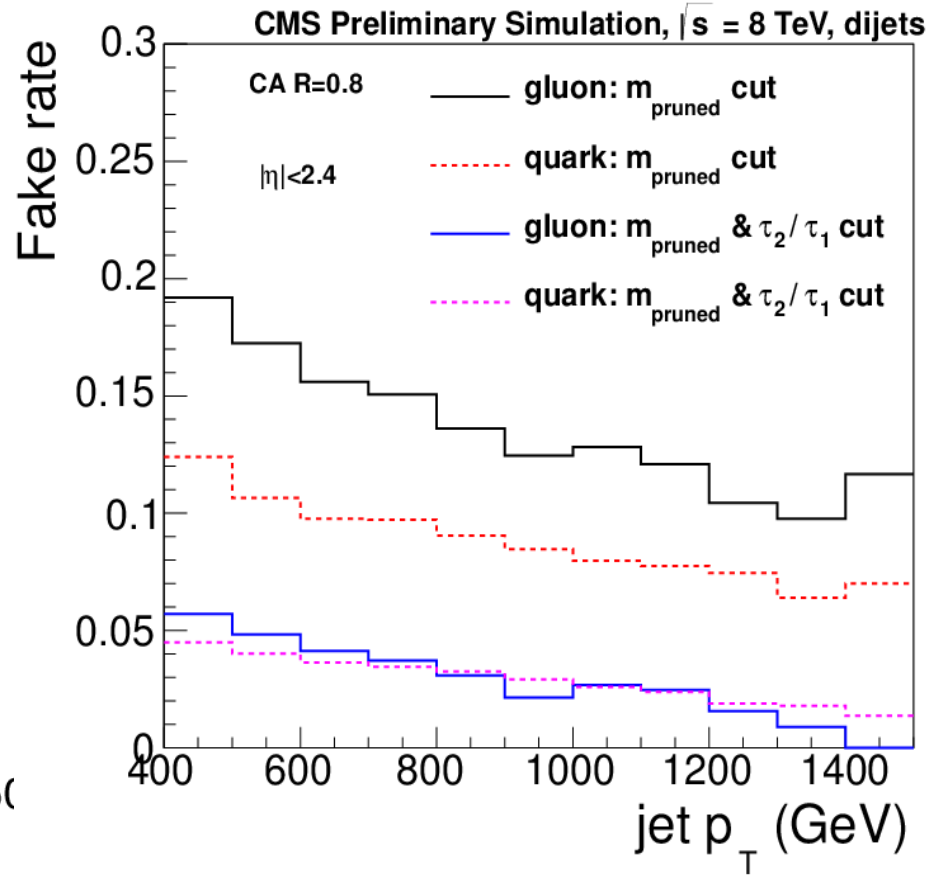




Quark and Gluons w/Substructure

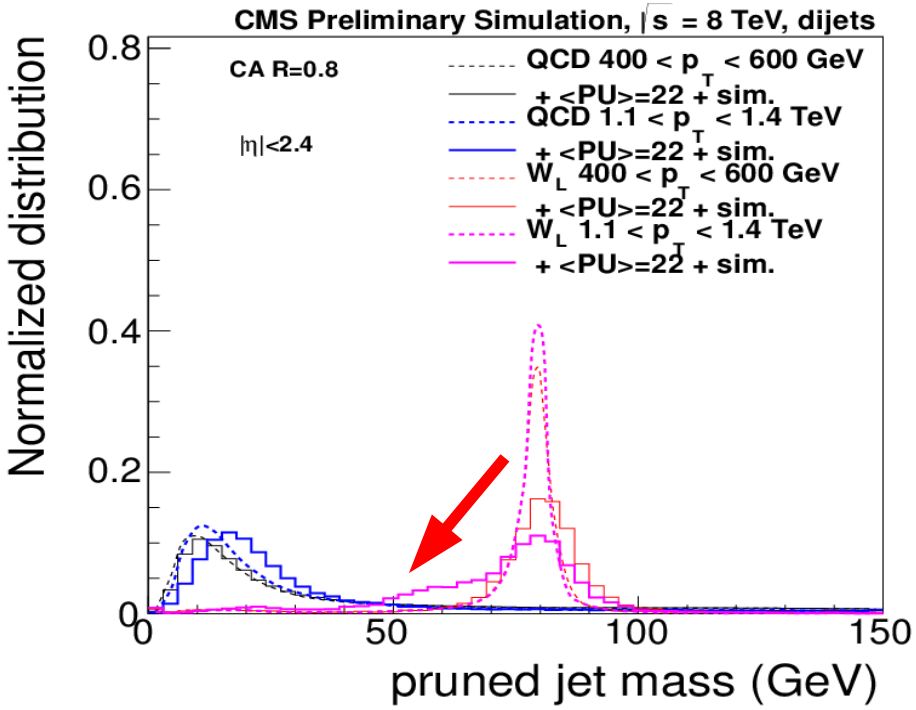
- Quark/gluon separation vs W same after cuts
  - Mass cut more effective on quark separation
  - N-subjettiness more effective on gluon separation
    - Once mass the cut is applied

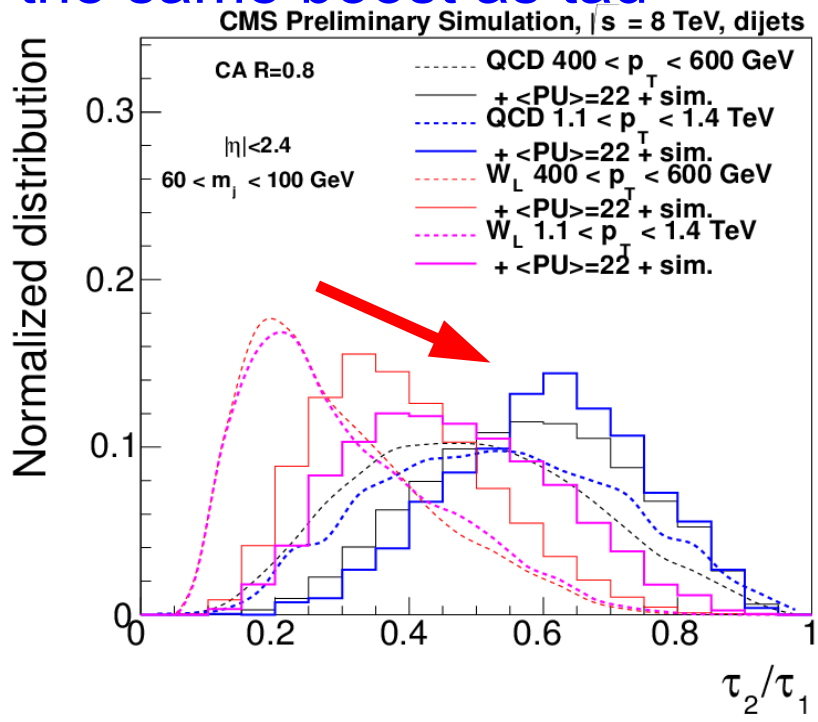




Jet Substructure at high *pT*

- At high *pT* (1.2 TeV) substructure starts to break
  - Things merge into one another
    - Detector cannot resolve the subjets (even w/tracking)
  - Shape variables are difficult to separate
  - Such high *pT* may call for alternative approaches
    - At this scale a W jet has the same boost as tau





Jet Substructure at high *pT*

- At high *pT* (1.2 TeV) substructure starts to break
  - Things merge into one another
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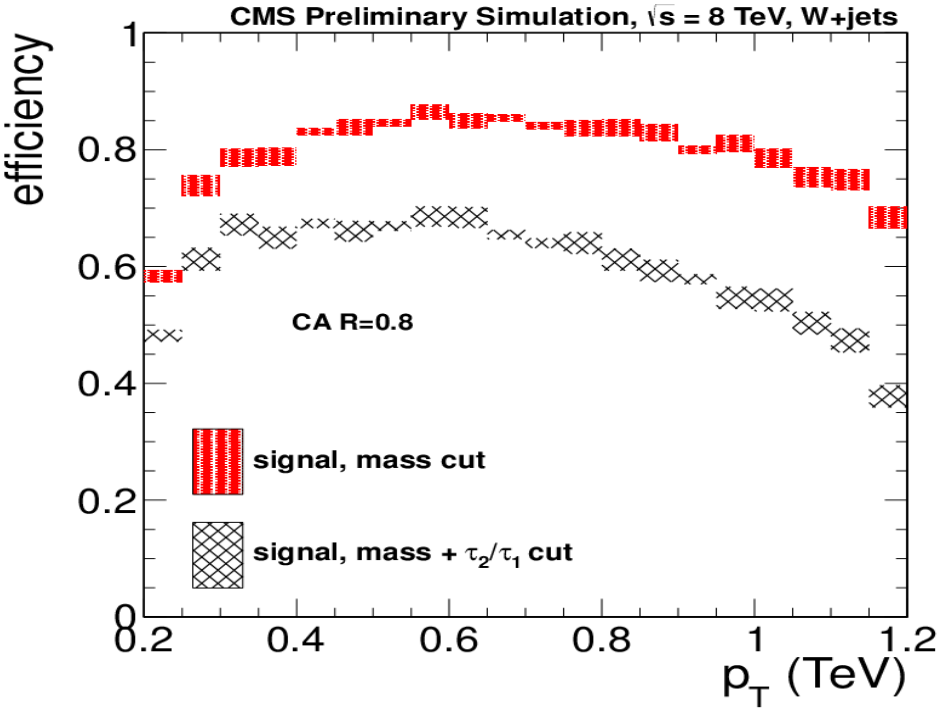
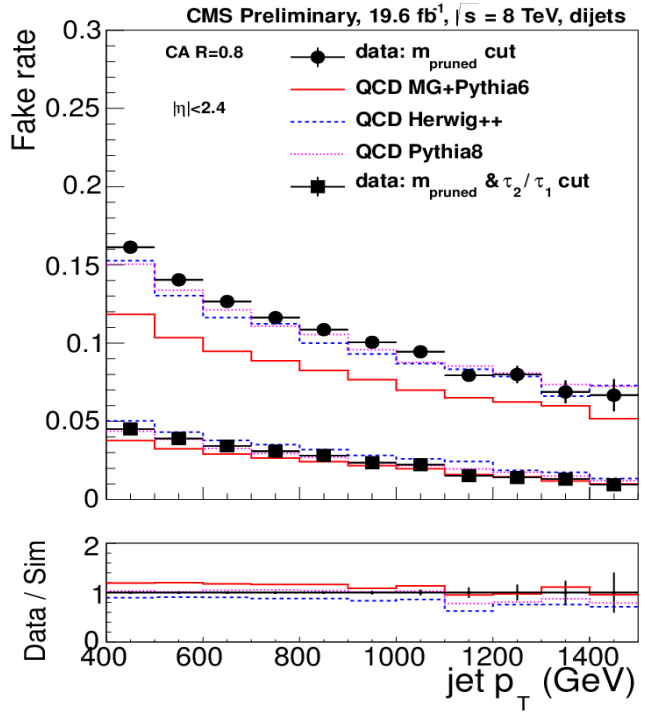
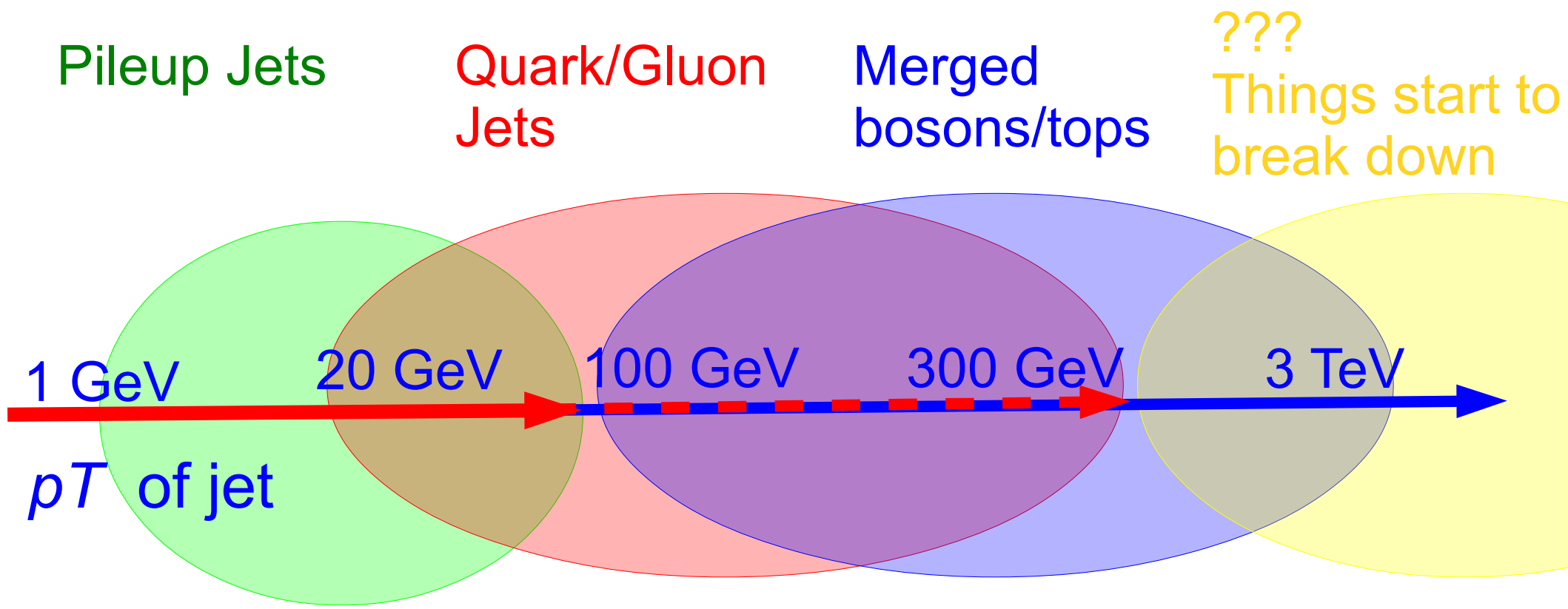




Review of What we have Studied



Pileup treated with Pileup Jet Id at low *pT*

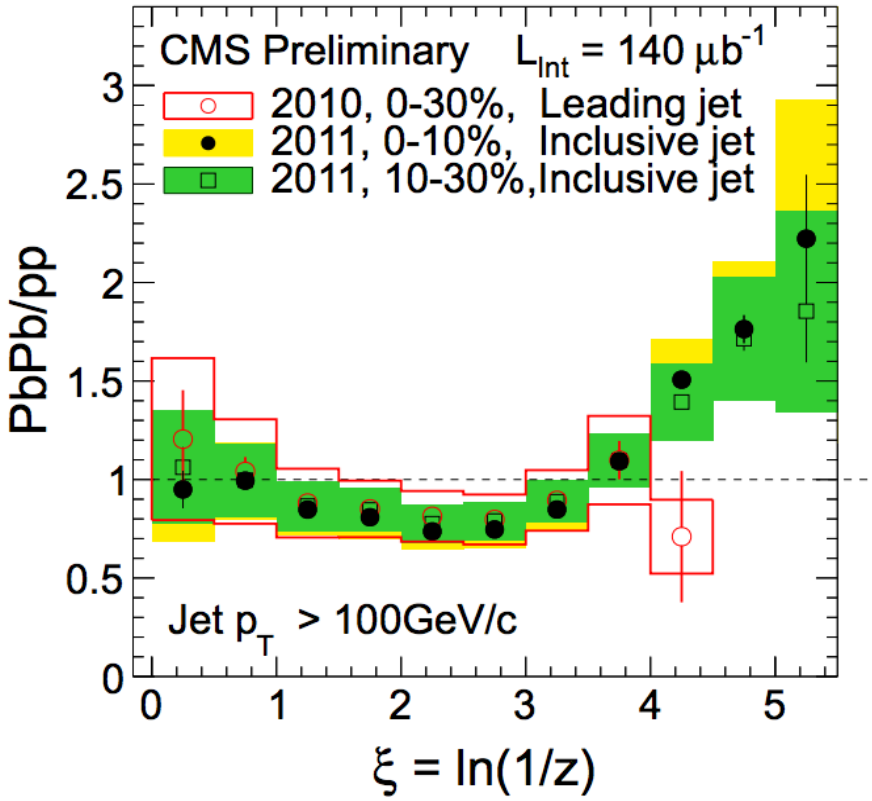
At high *pT* use Charge Hadron Subtraction

At 1 TeV Reconstruction effects limit substructure

Outlook

- Substructure is a good approach against PU
  - There is still a lot more we can do
  - Effective for Jets, but also *MET*
- CHS: to enhance substructure against pileup
  - Charge assignment and/or pT threshold on neutrals
  - Techniques effective for quark/gluon/W/Top/??
- Both of the above approach can be extended

- At high *pT* substructure start to break down
  - This is really a detector effect
  - More work needs to be done to approach problem


CMS Preliminary L_{Int} = 140 μb^{-1}
2010, 0-30%, Leading jet
2011, 0-10%, Inclusive jet
2011, 10-30%,Inclusive jet
Jet p_T > 100GeV/c
PbPb/pp
ξ = ln(1/z)
0
0.5
1
1.5
2
2.5
3
0
1
2
3
4
5

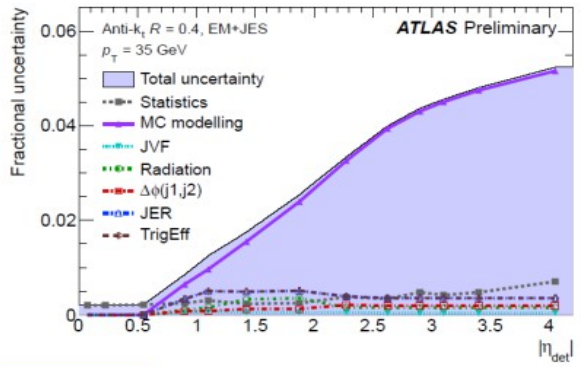
BACKUP

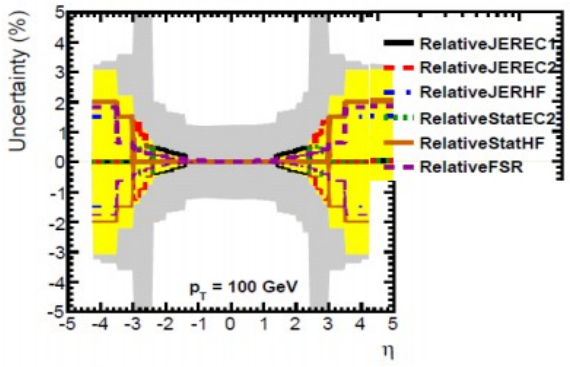
A Call for Consolidation

- Its time to think about consolidation btwn CMS/ATLAS
  - Not necessarily synchronization of Jet cone or Algos
  - Organization between CMS/ATLAS to make results robust
- CMS/ATLAS has had recent success organizing
  - http://indico.cern.ch/getFile.py/access?contribId=7&sessionId=1&resId=0&materialId=slides&confId=245769

12

Relative calibration uncertainties





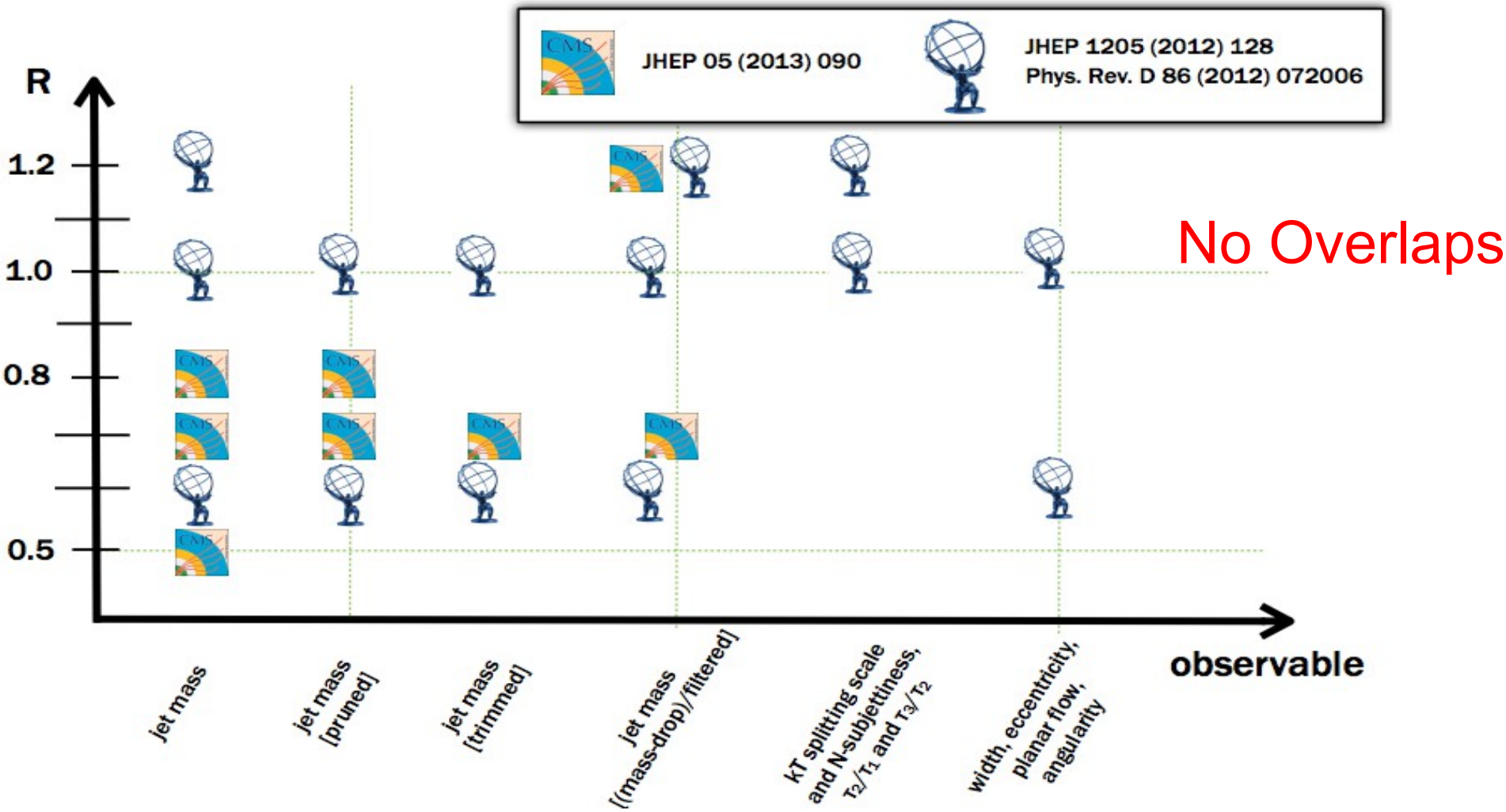
ATLAS

- Dominated by modelling
  - Herwig/Pythia difference, no extrapolation to zero radiation
- Small JER and statistics contribution

CMS

- Dominated by statistical component/JER at high eta
- Modelling/FSR uncertainty reduced due to extrapolation to zero rad.

A Call for Consolidation

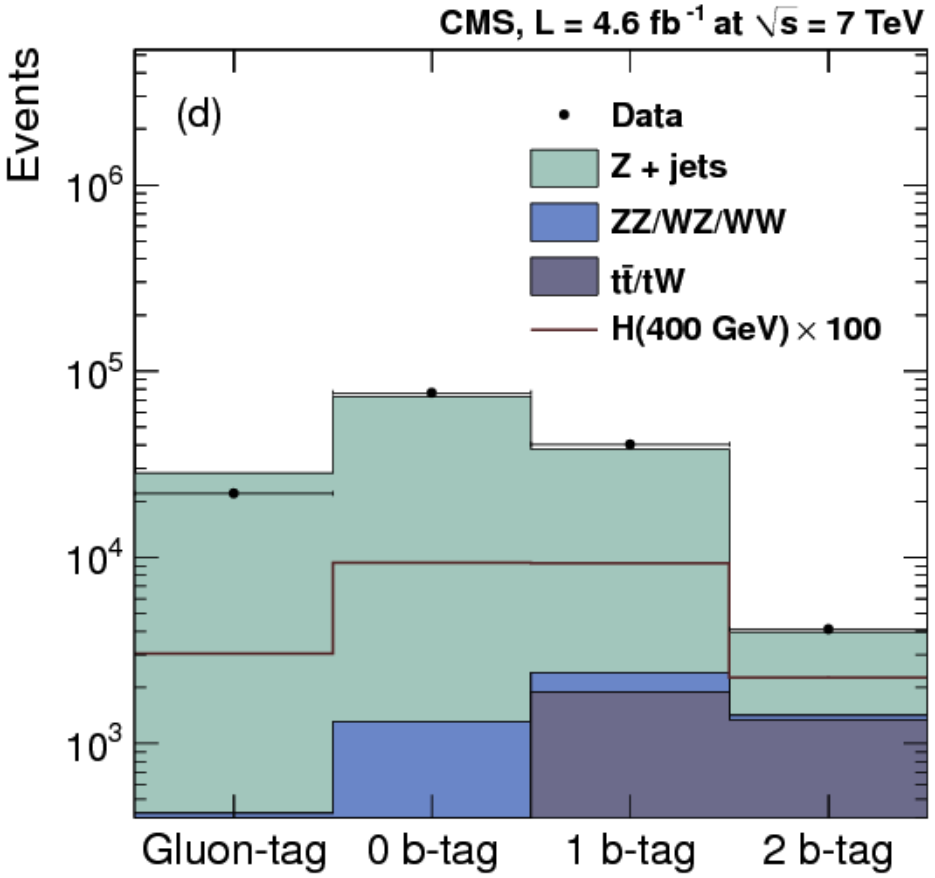


No Overlaps

- Large coverage of the phase space
- Is there appropriate set Cones/Algos to synchronize?

QG Peformance (Limited view)

- QG performance in the old tagger

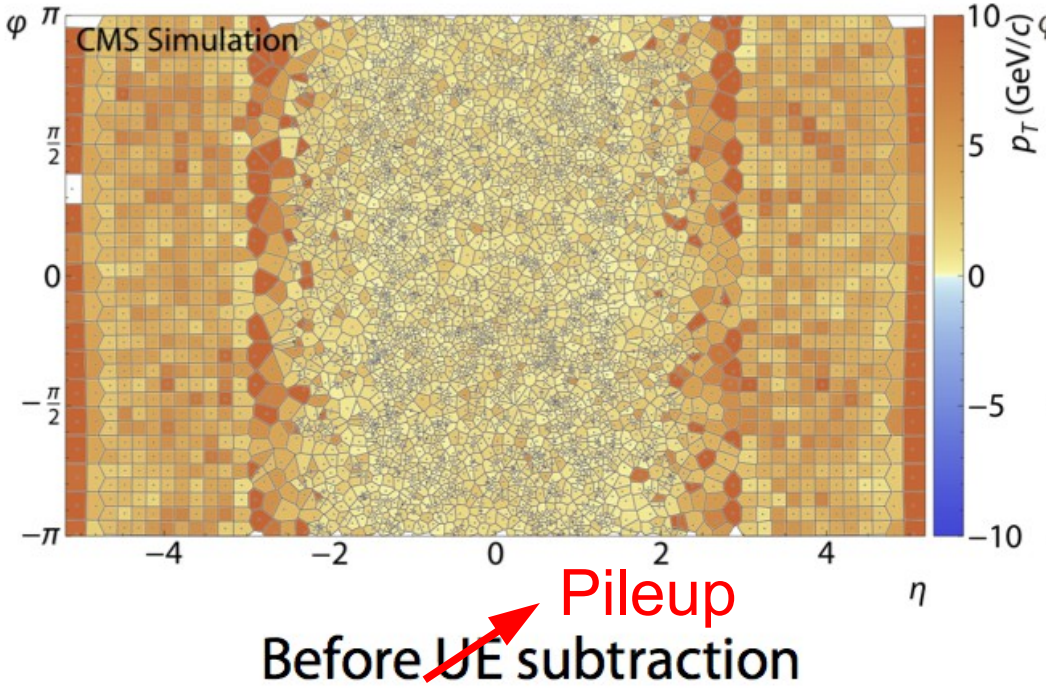


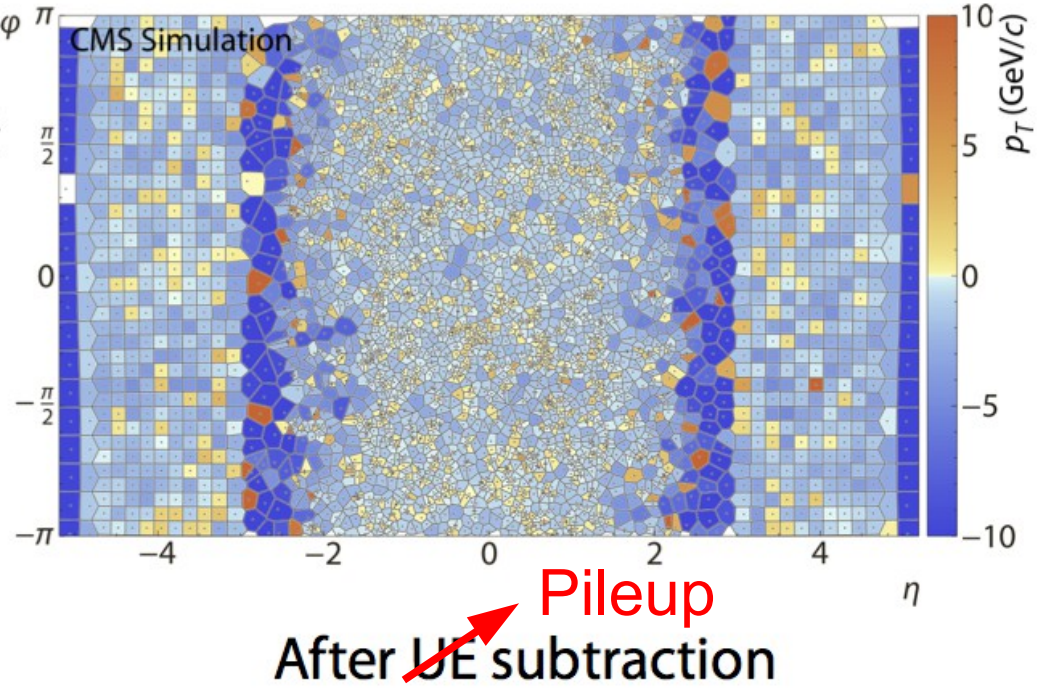
Recap of Talk

- 4+ kinds of jets : All are very much related
  - Pileup Jets,Quark Jets,Gluon Jets,W-tag jets,...
- For the low *pT* region pileup starts to form jets
  - Pileup Jets can be resolved from real jets
    - Using both shape and vertex information
  - Can be used effectively (*MET*,jet veto,VBF)
- Quark/Gluon discrimination being used in CMS
  - CHS effecitive medium for to minimize pileup
- W-tagging effectively used in CMS
  - CHS reduces W-tagging pileup dependence by 50%
  - W-tagging reconstruction starts breaks down at high *pT*

Clusters and New Technology

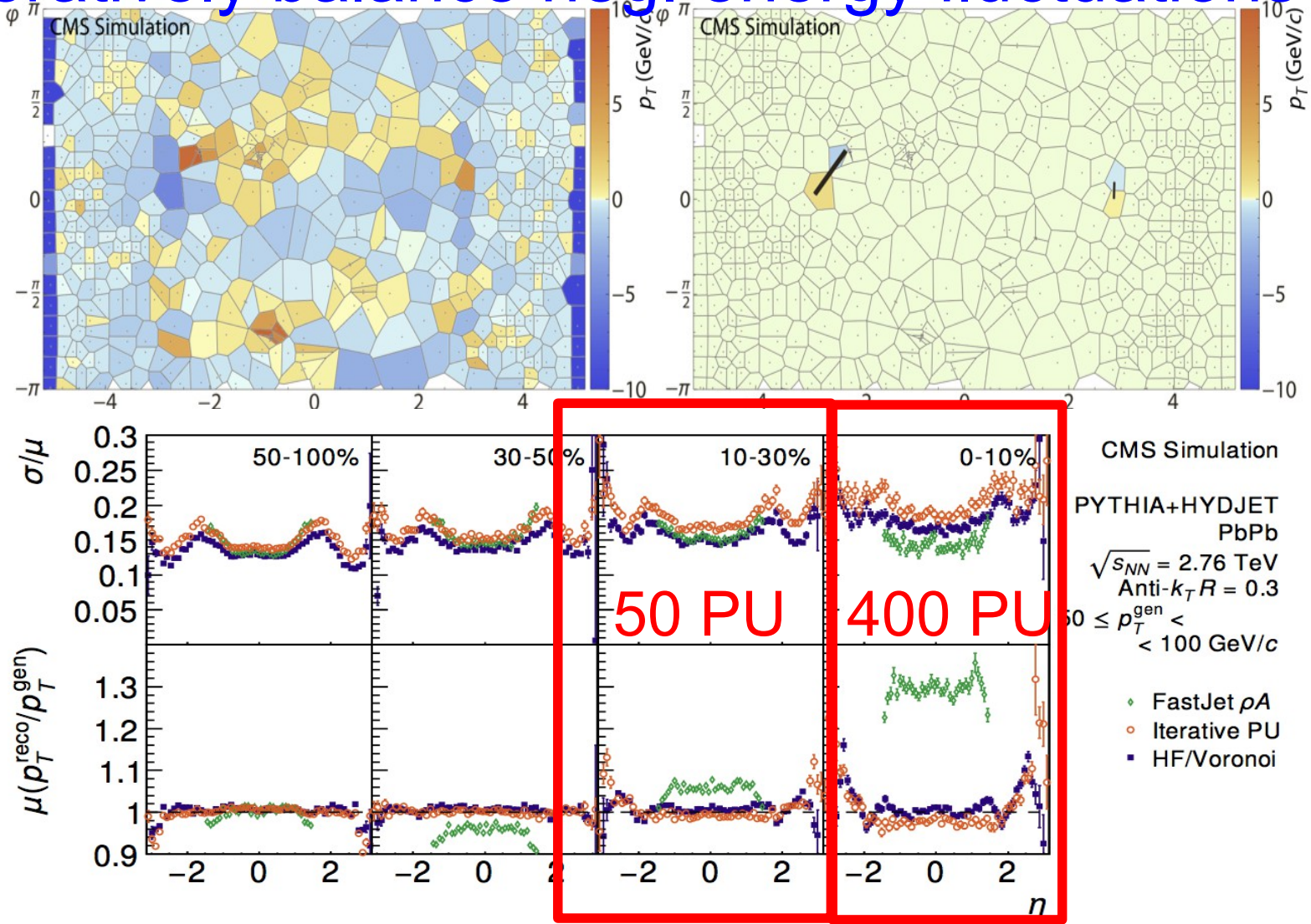
- Where can we go in cluster calibration?
  - We are looking at a MVA regression to calibrate
    - Not yet successful => we are just starting
    - May benefit from new techniques see discussion later on
- Can we incorporate pileup into this calibration?
  - Looks like it => Learning from Heavy Ion group





Removing PU Cand by Cand

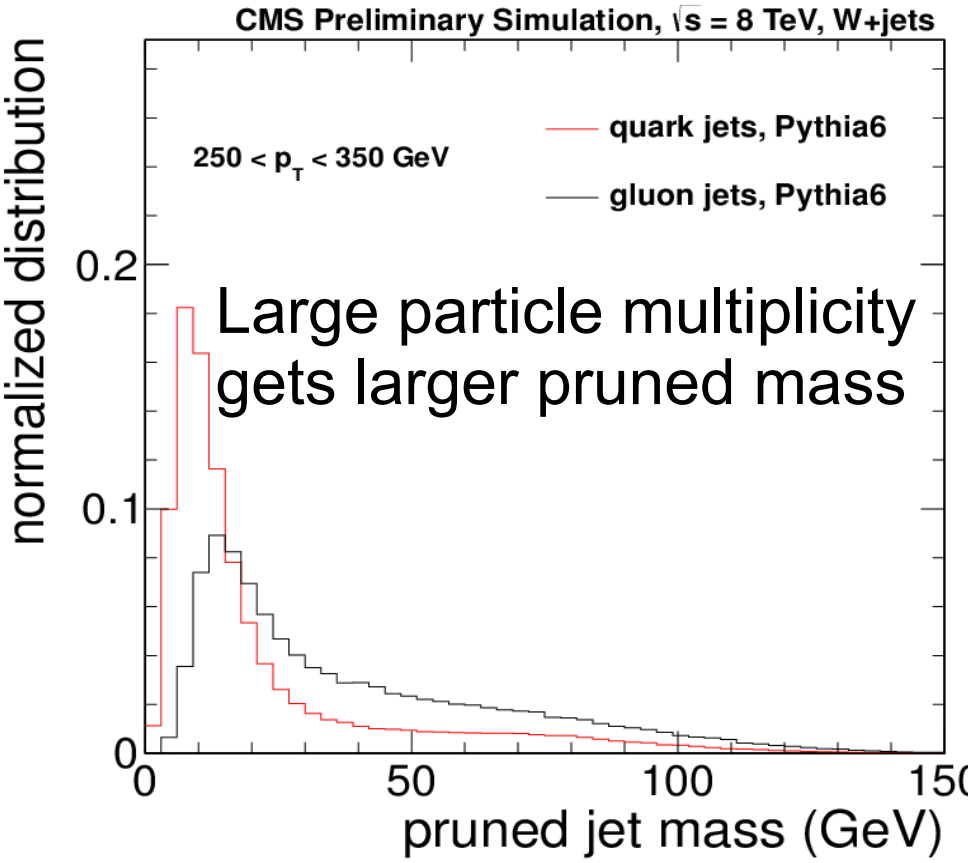
- Divide the volume into candidate cells
  - Use the vorinoi tesselation algorithm
- Iteratively balance neg. energy fluctuations w/pos.

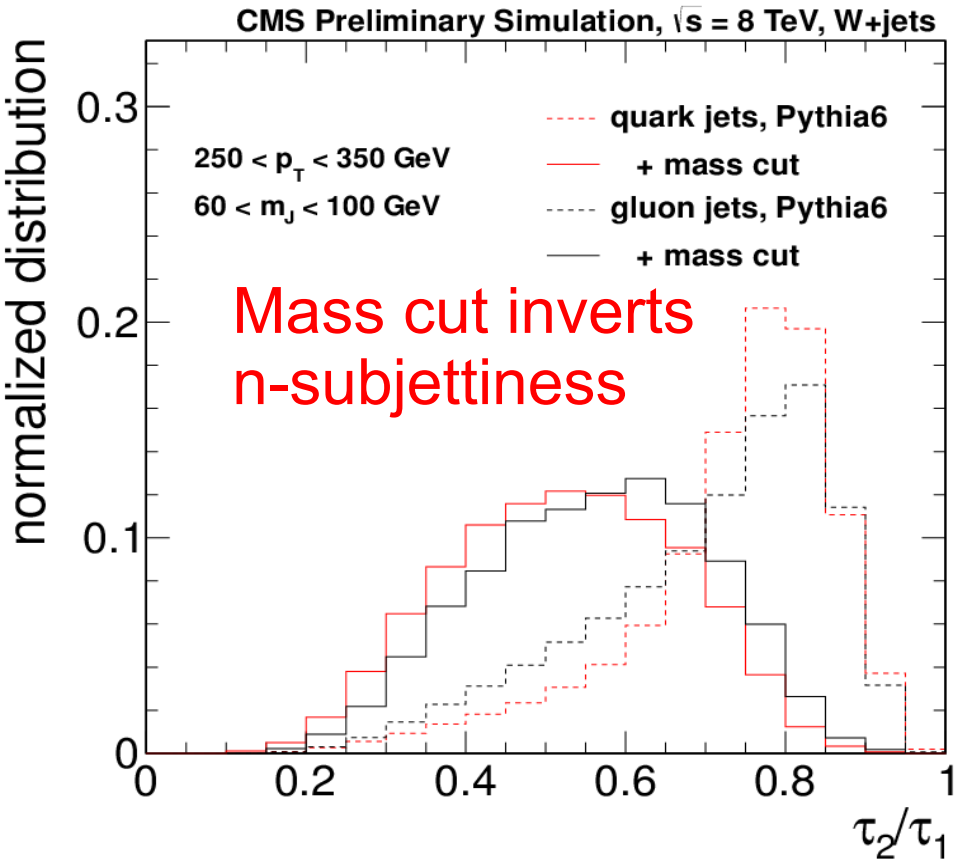


Impact on jet resolution

Quark and Gluons w/Substructure

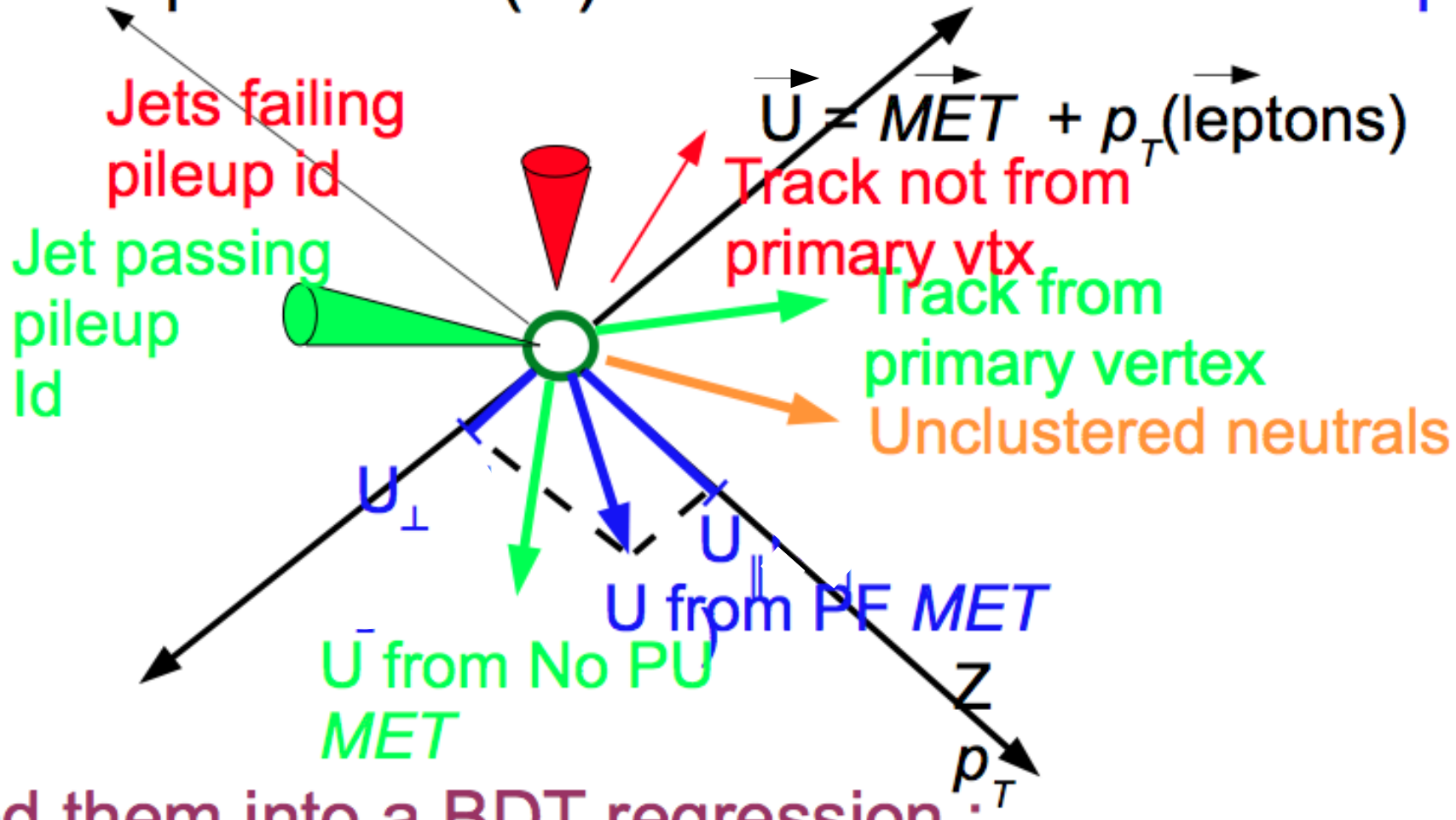
- Quark/gluon separation vs W same after cuts
  - Mass cut more effective on quark separation
  - N-subjettiness more effective on gluon separation
    - Once mass the cut is applied





Combining Jets: *MET*

- Concept:
  - Compute recoil(U) of all of the different components

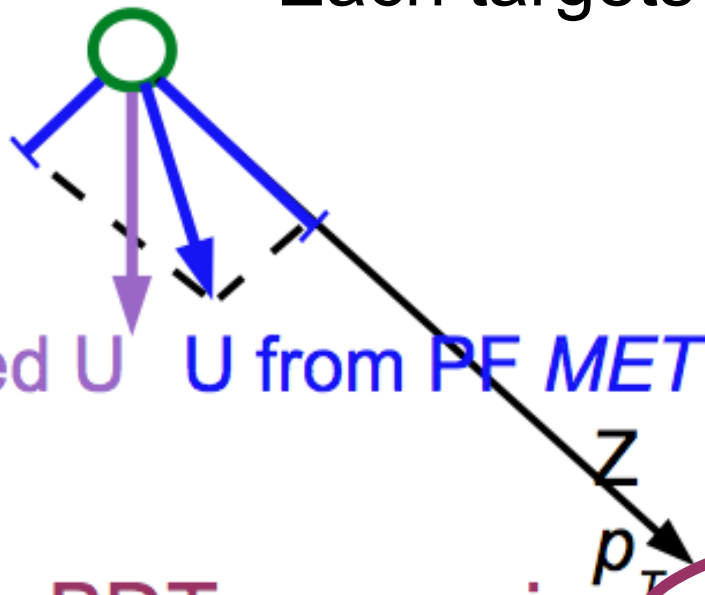


Feed them into a BDT regression :

MVA *MET*

- Concept:
  - Recoil here ➡ defined as *MET* – leptons

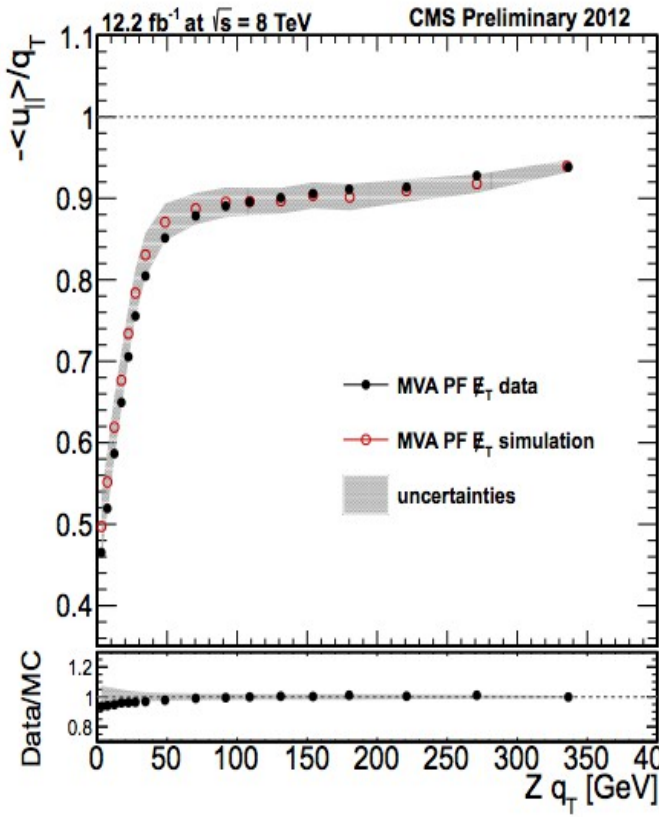
5 Separate recoils calculated
Each targets different component

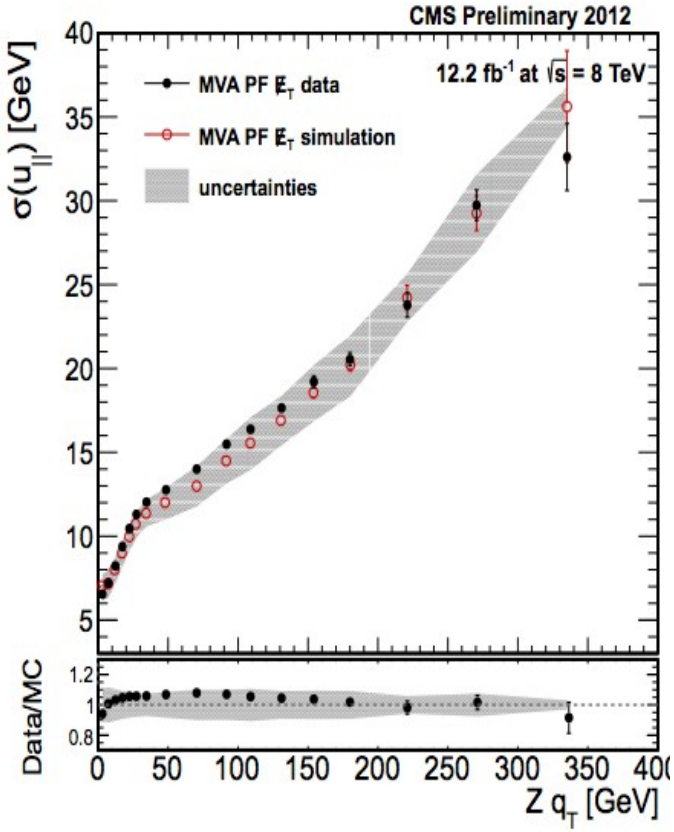


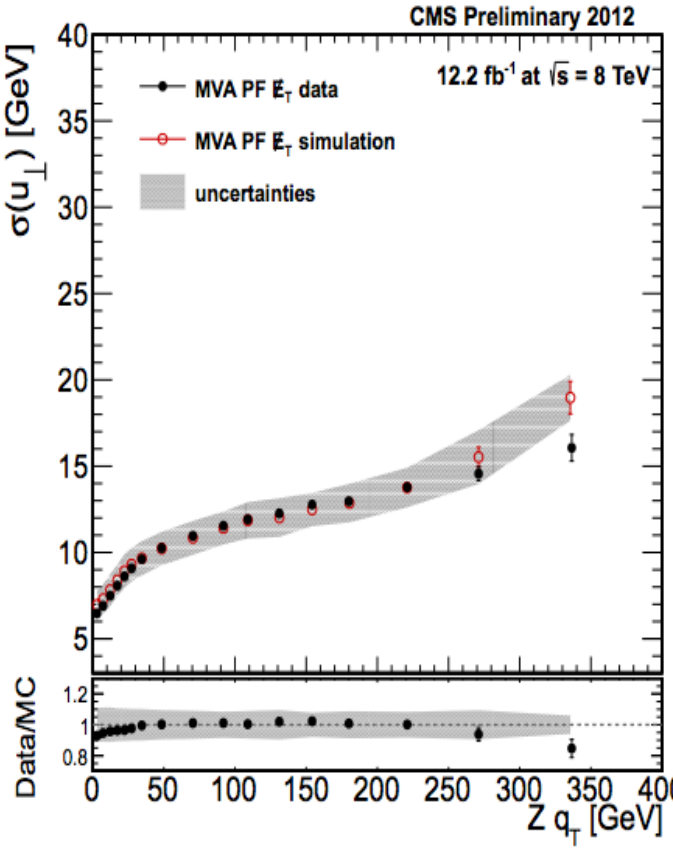
Feed them into a BDT regression: Correct Recoil

MET Performance

- Response plateaus at 0.92
  - Feature of the training (unity response also available)
  - Performance is comparable

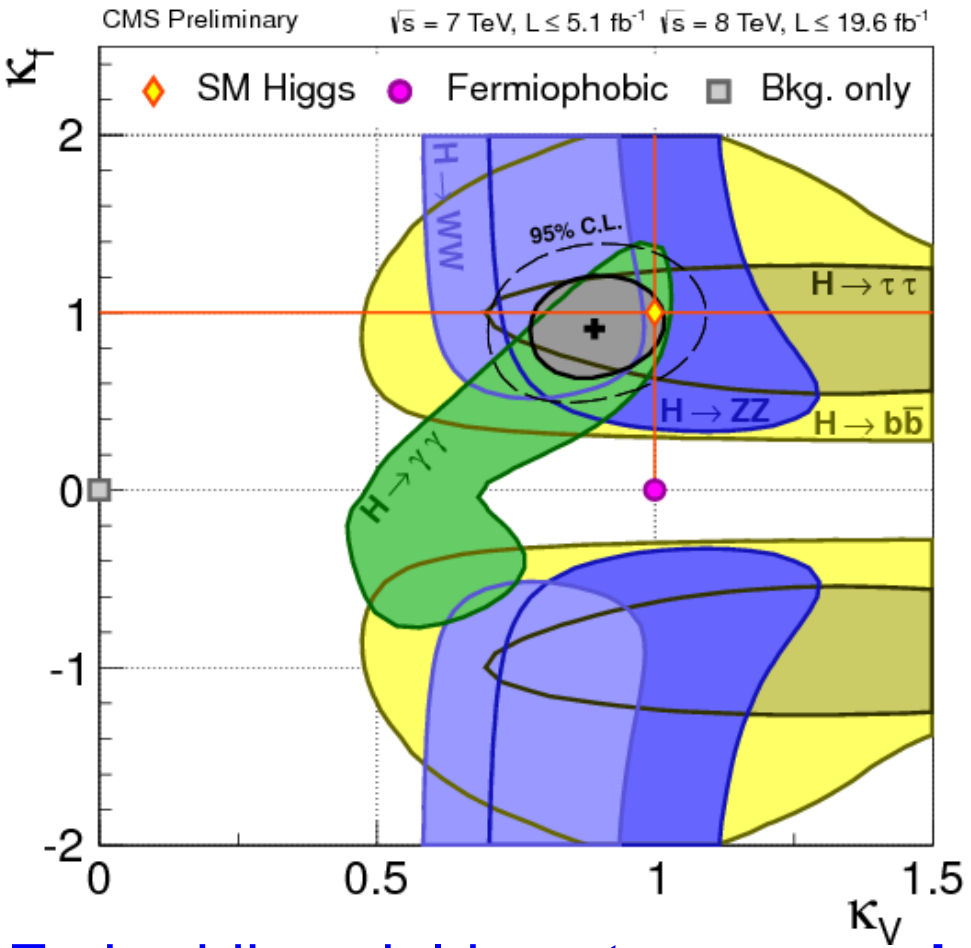


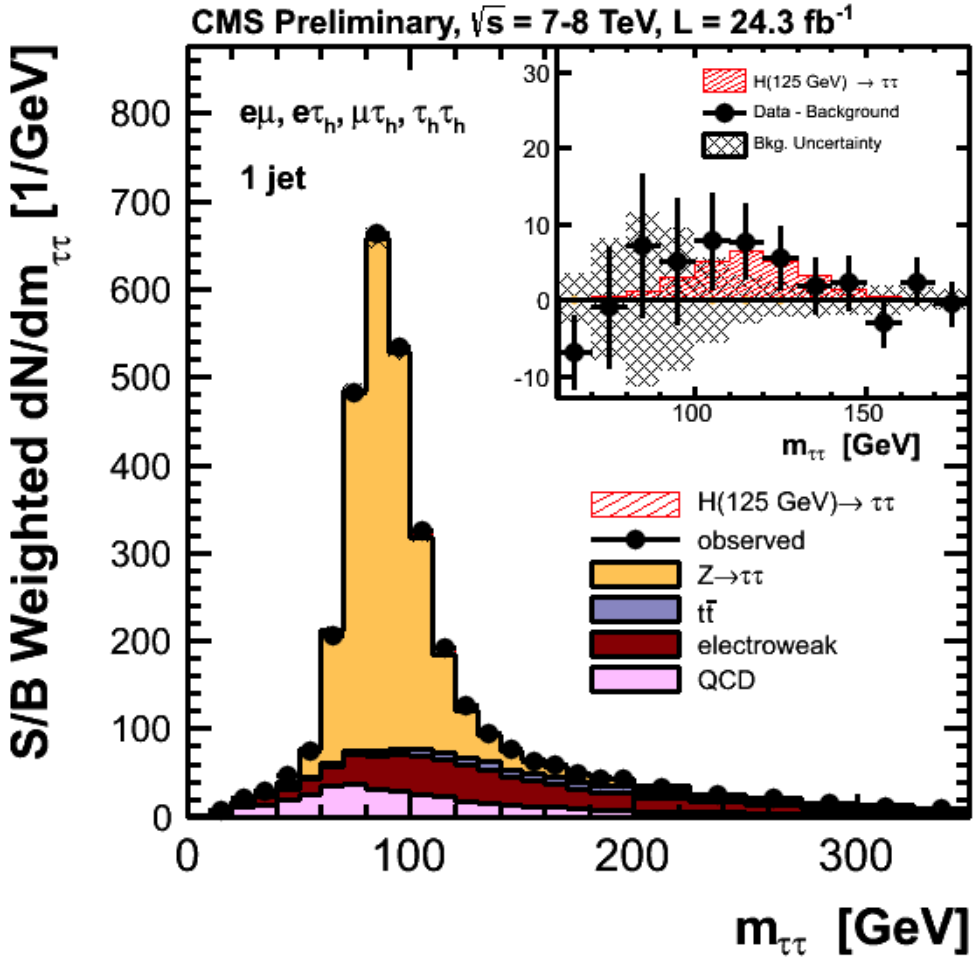




MET Performance

- Reduced *MET* resolution critical for H→ττ
  - Most important in the ggH→ττ (cF^2)

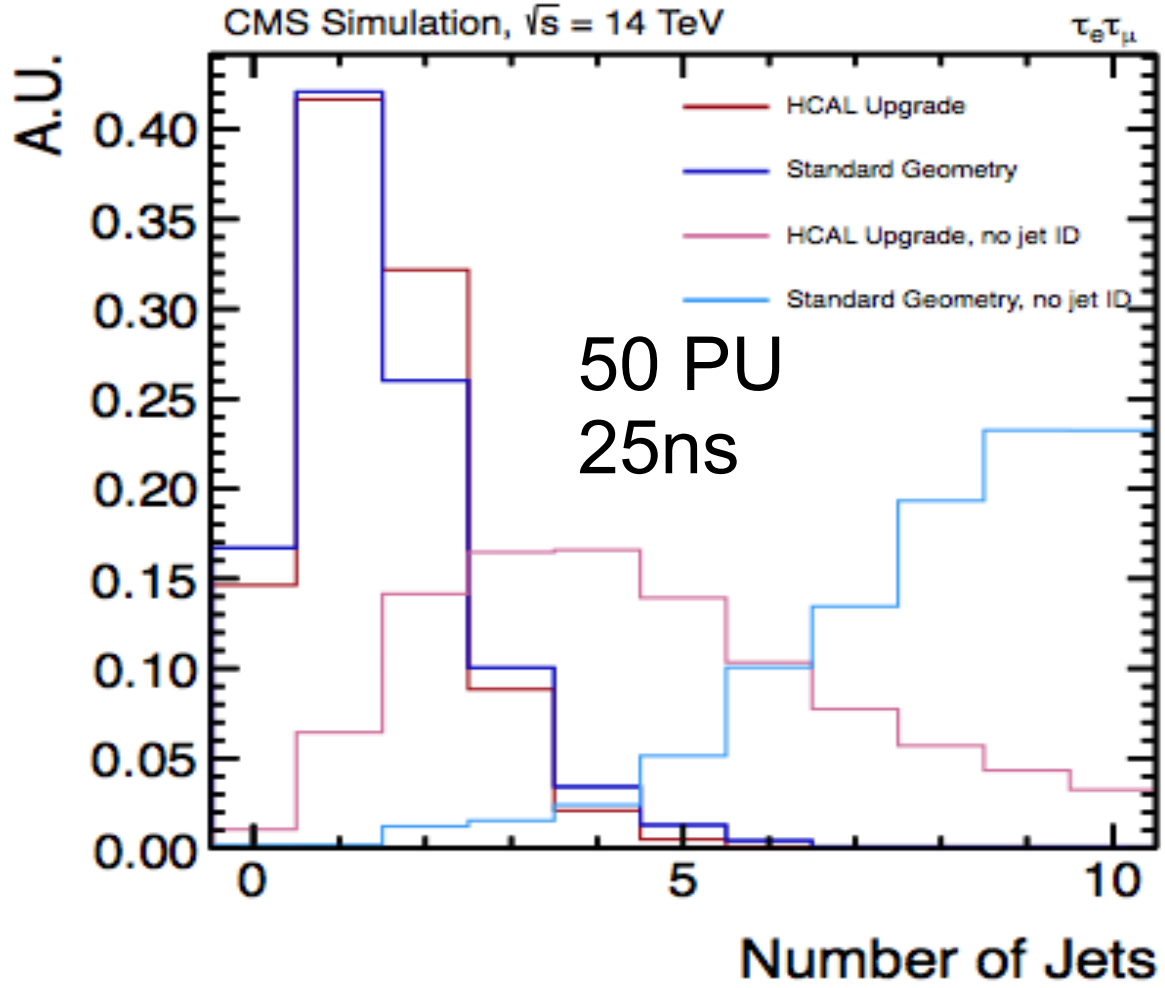




Embedding yields **extreme precision** in *MET* model of Drell-Yan

What about Out of Time PU

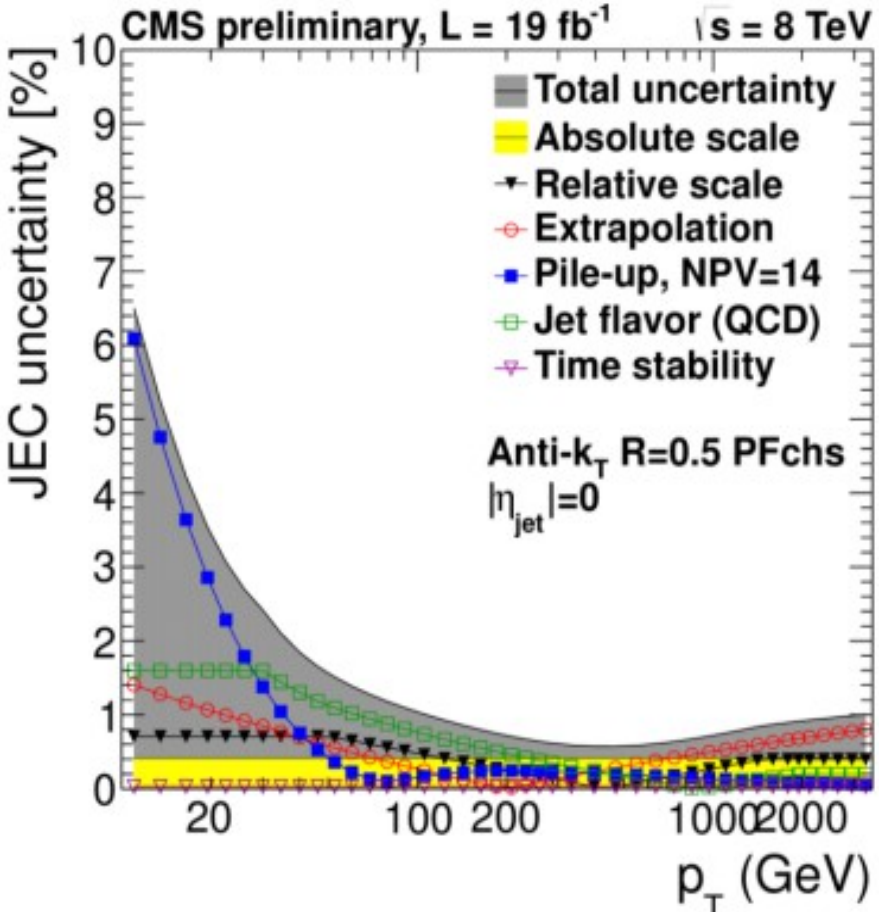
- Turns out the Pileup Jet Id resolves this effect

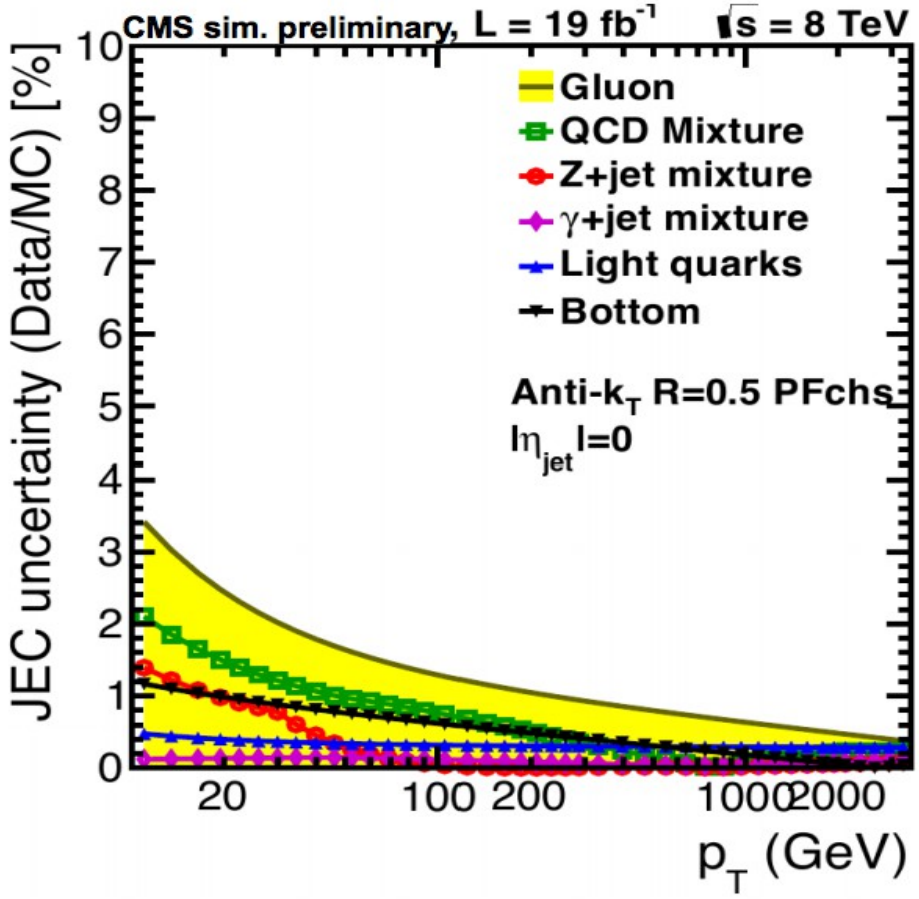


VBF selection (expect 1-2 jets)

Quarks/Gluons and JEC (JES)

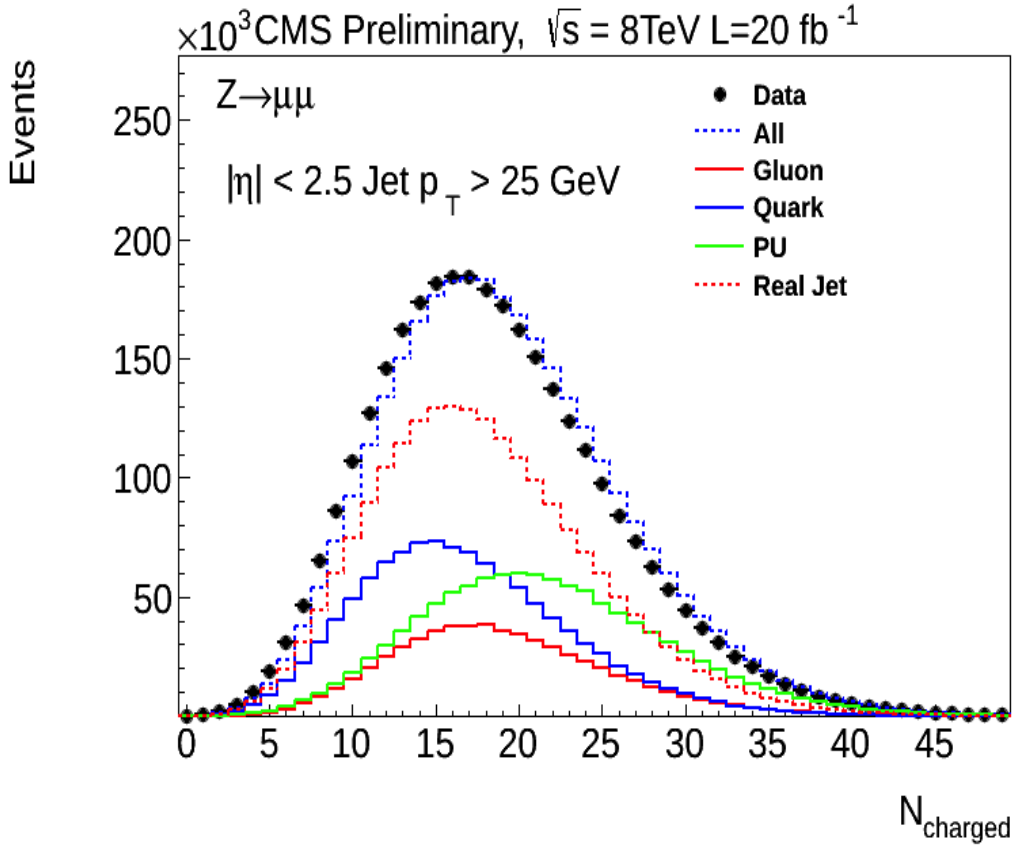
- Jet energy corrections (scale) change w/flavor
- New approach in CMS : propagate flav ratio
  - Assume di-jet flavor ratio propagate herwig-pythia difference to JEC

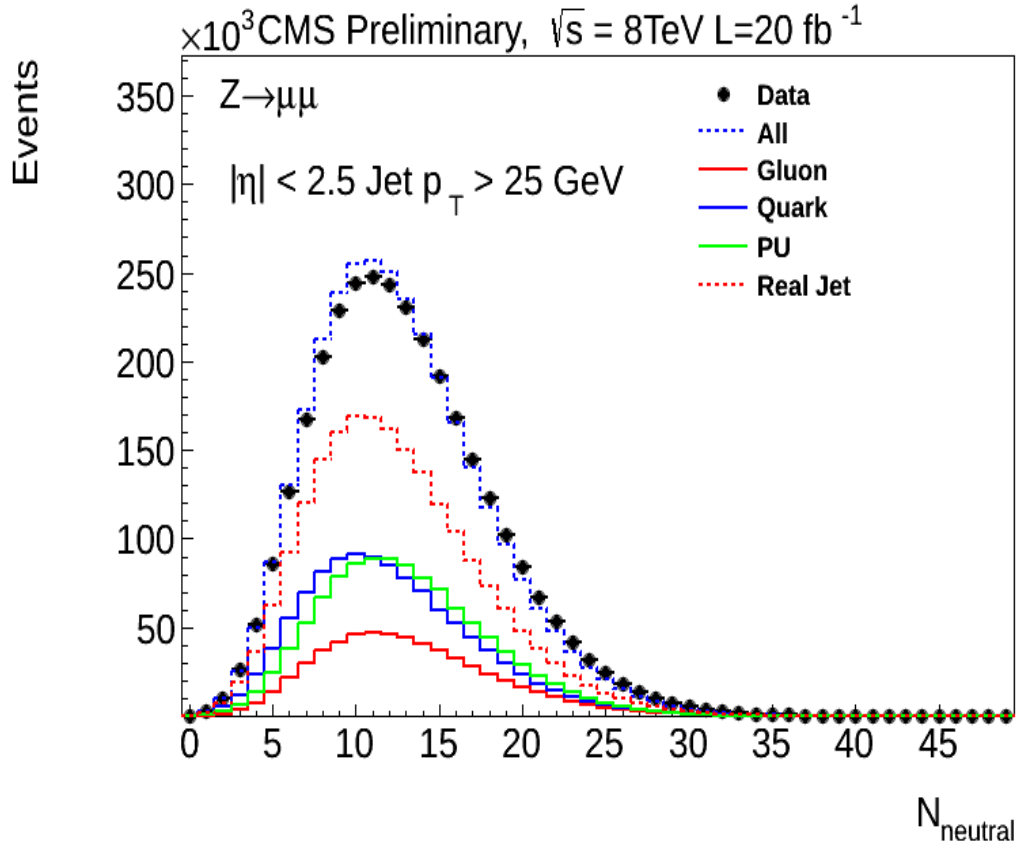




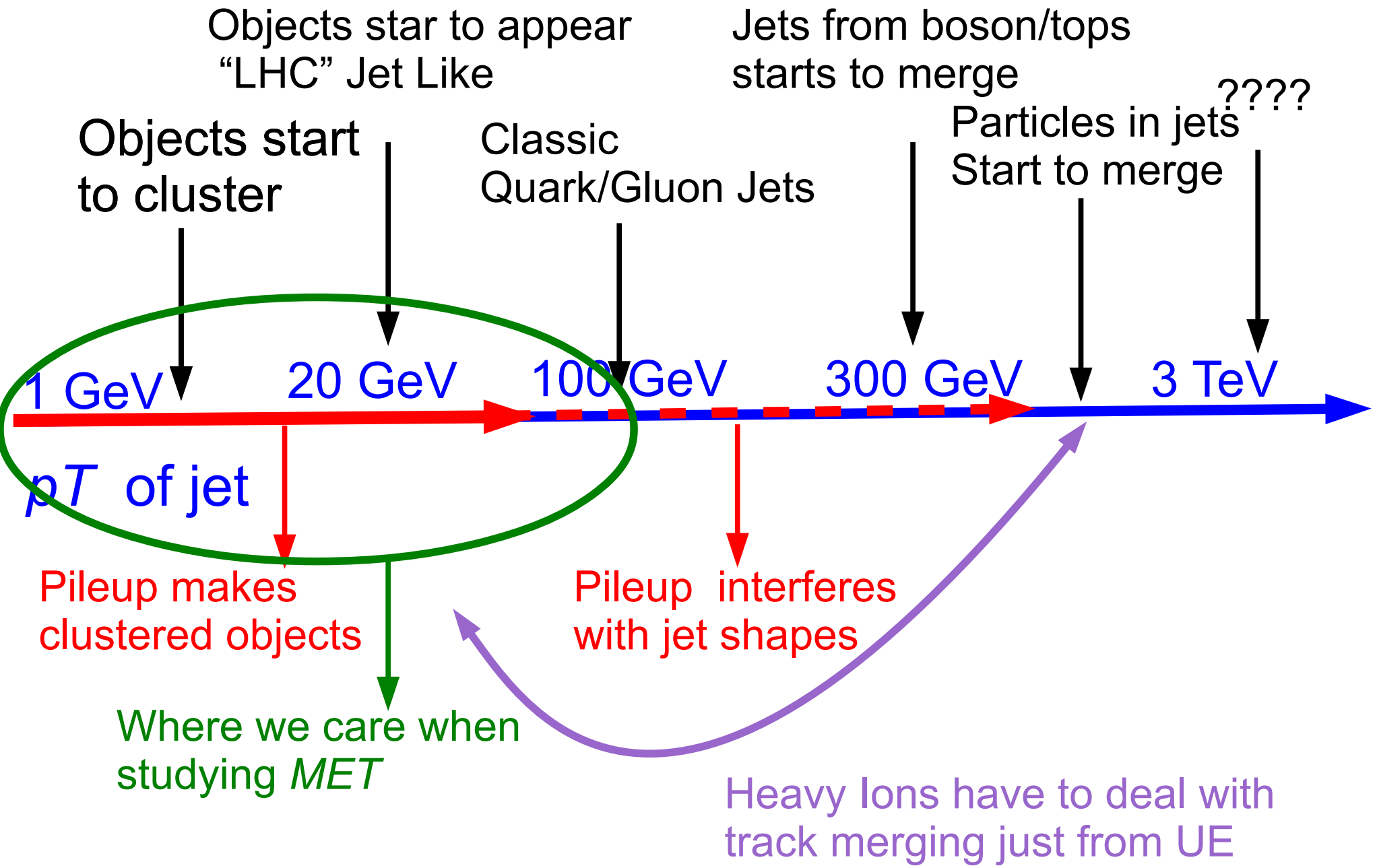
Particle Multiplicities

- Particle multiplicities (Charged+Neutrals)
  - Allow for Quark gluon separation
    - $N_{gluon}/N_{Quark} = 9/4$
  - Effective in pileup separation as well

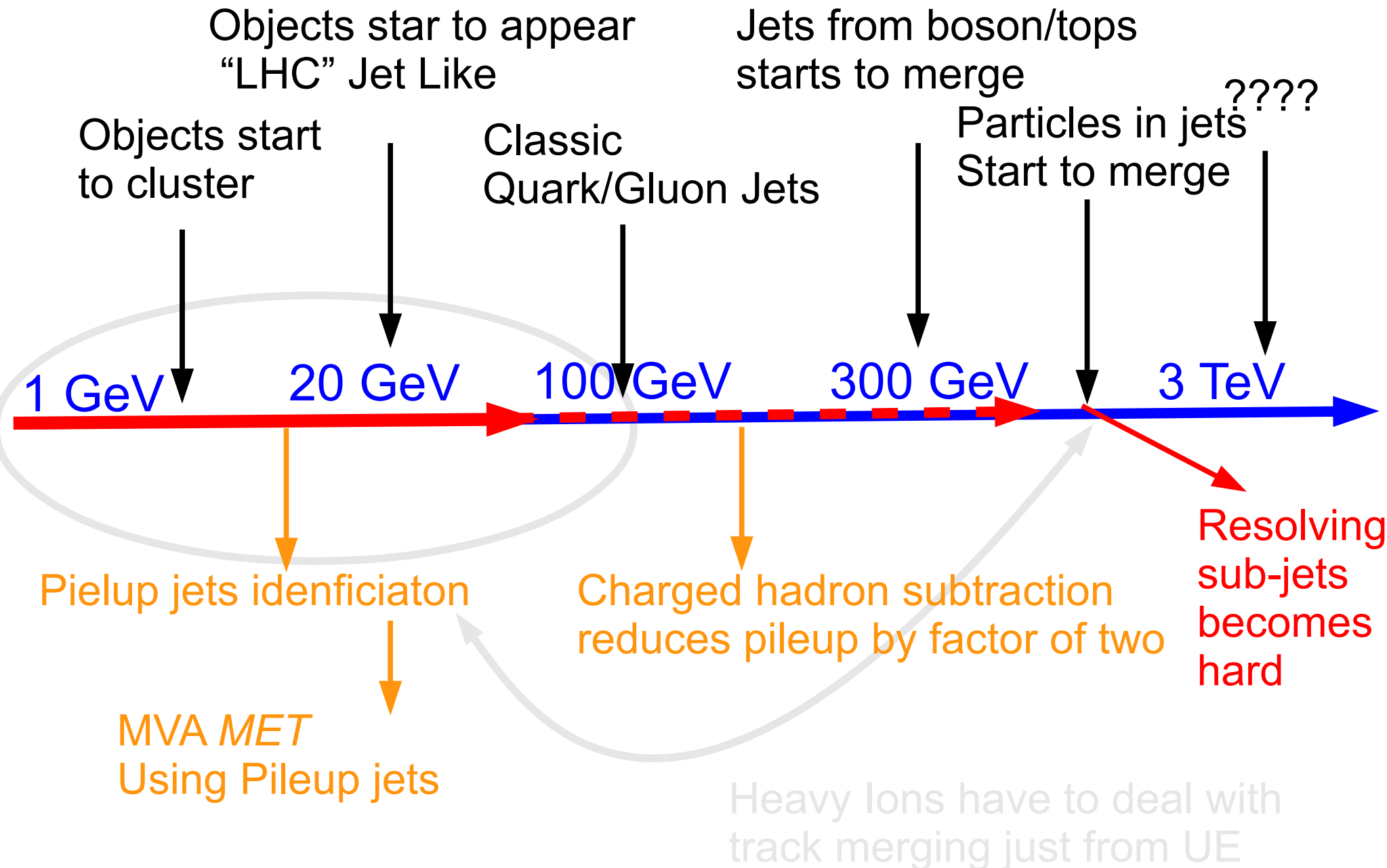




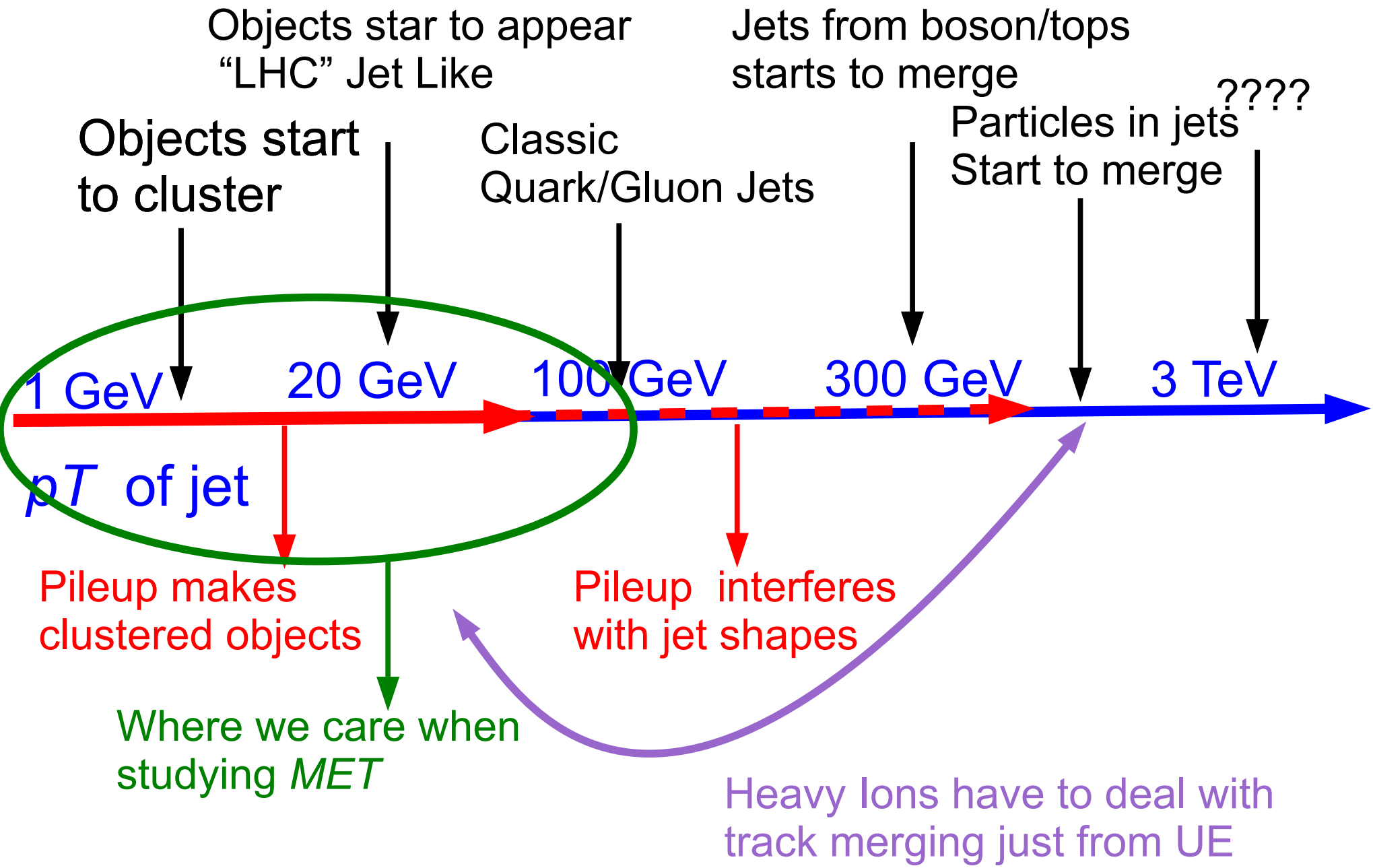
Spectrum of the Jet Toolbox



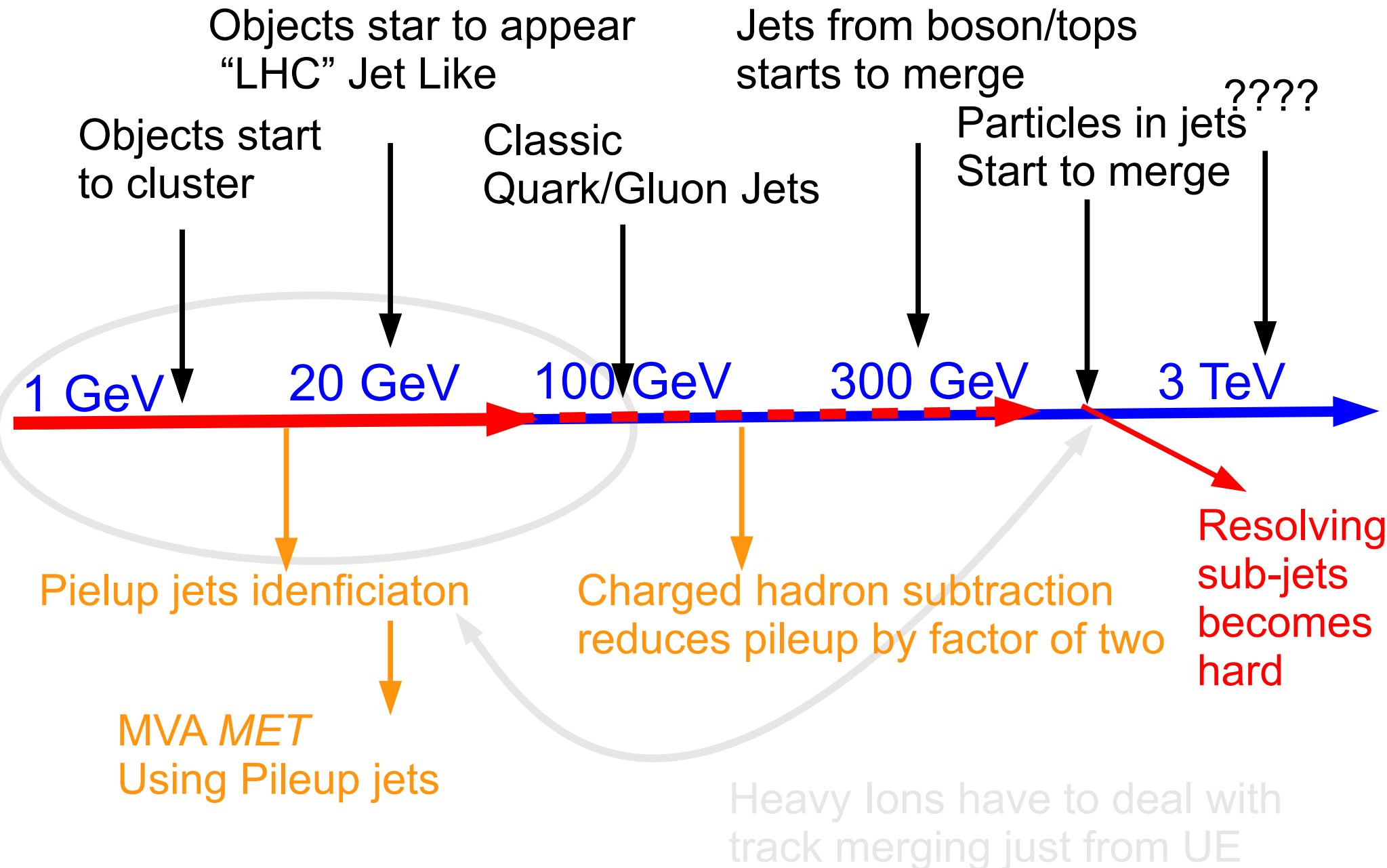
Status of Pileup Mitigation



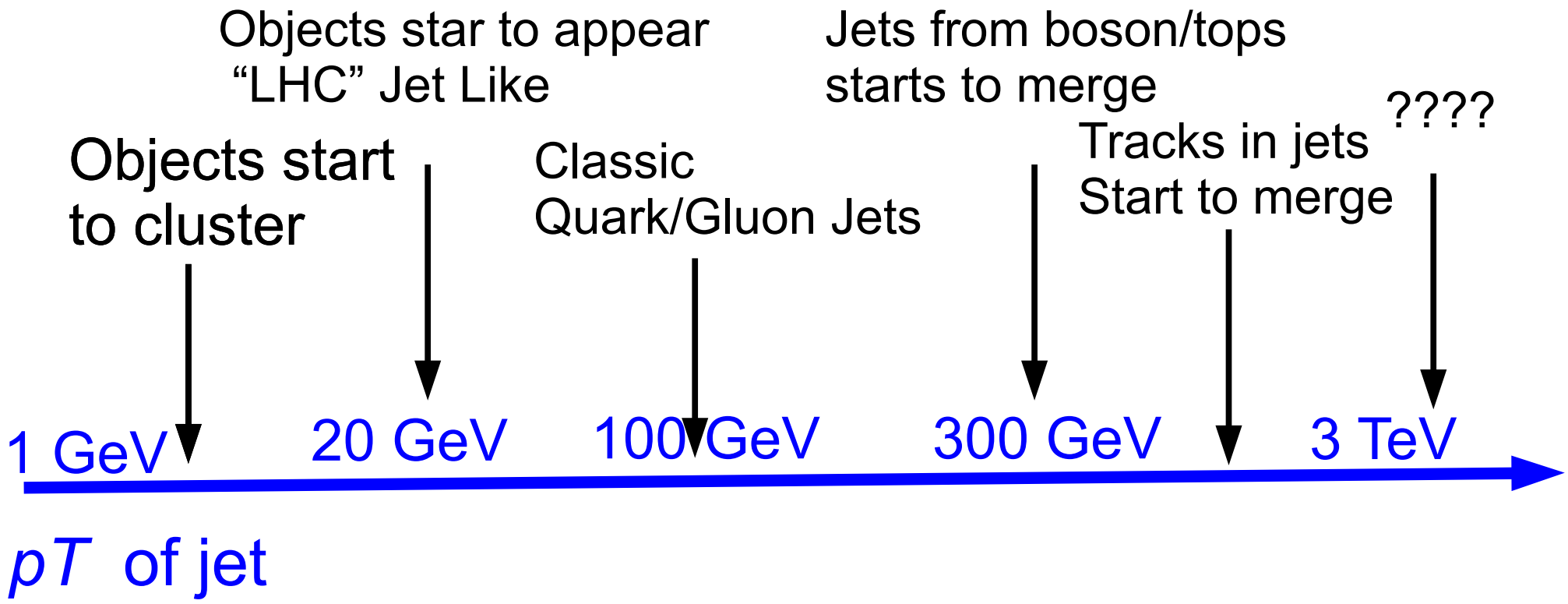
Spectrum of the Jet Toolbox



Status of Pileup Mitigation

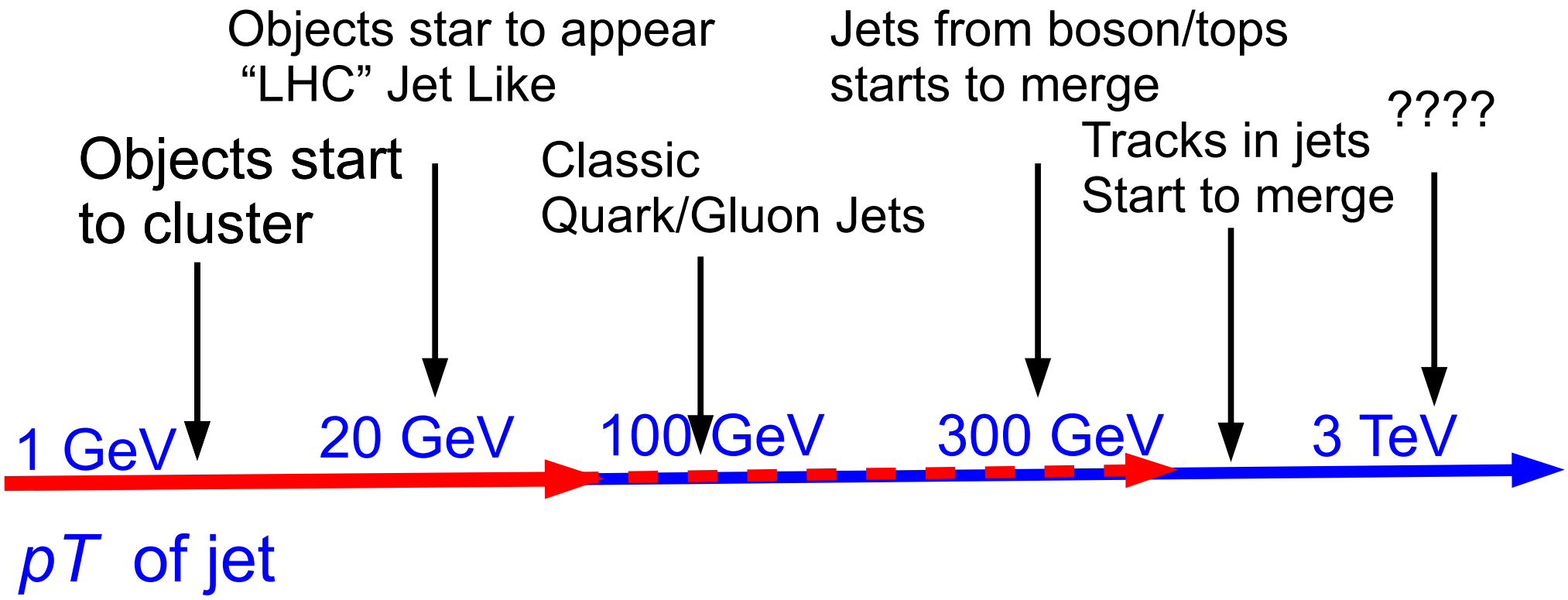


Spectrum of the Jet Toolbox

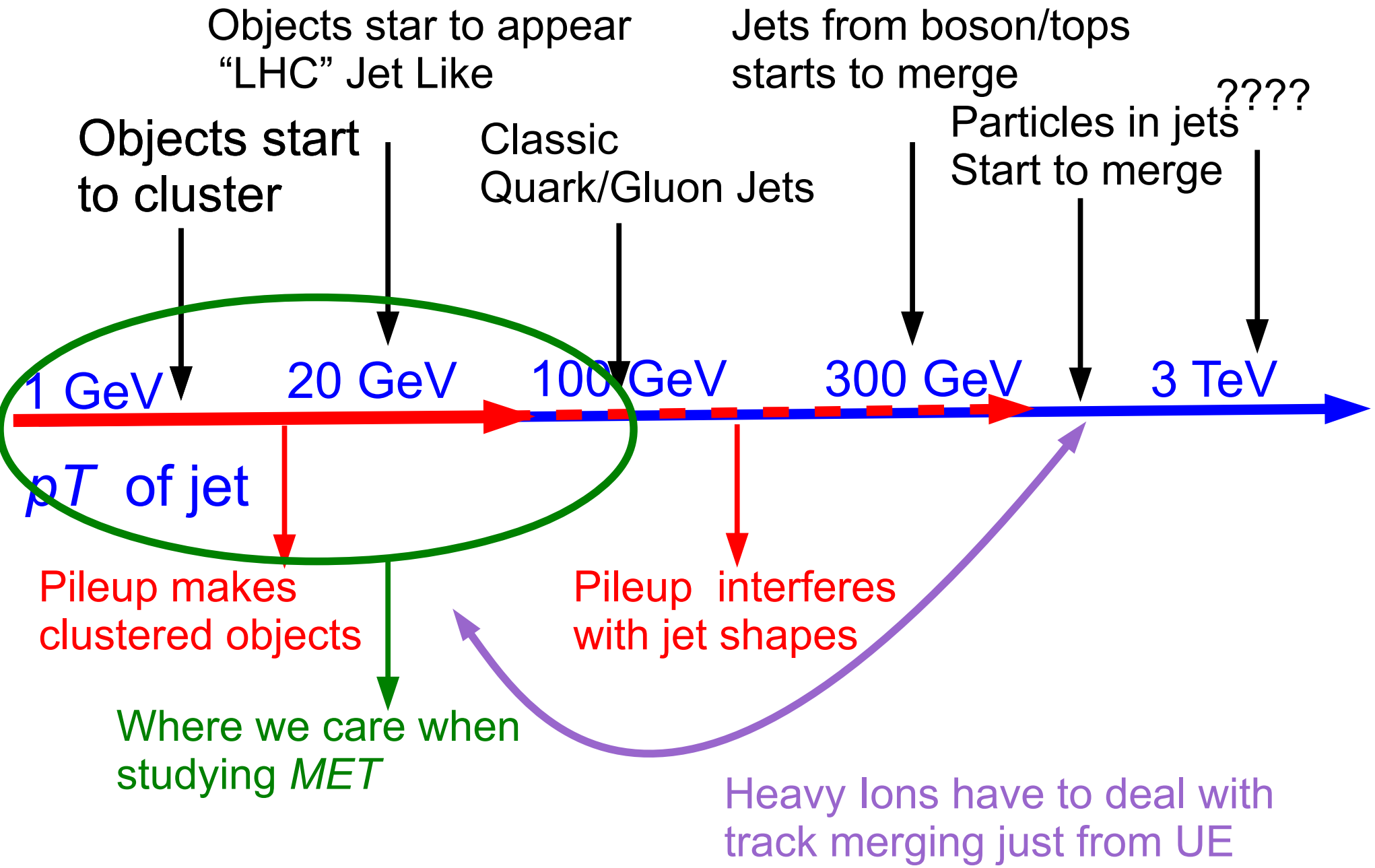


- Different regions cover different issues
  - At low *pT* deal with clustered nebulous objects
  - At high *pT* deal with highly columnated objects

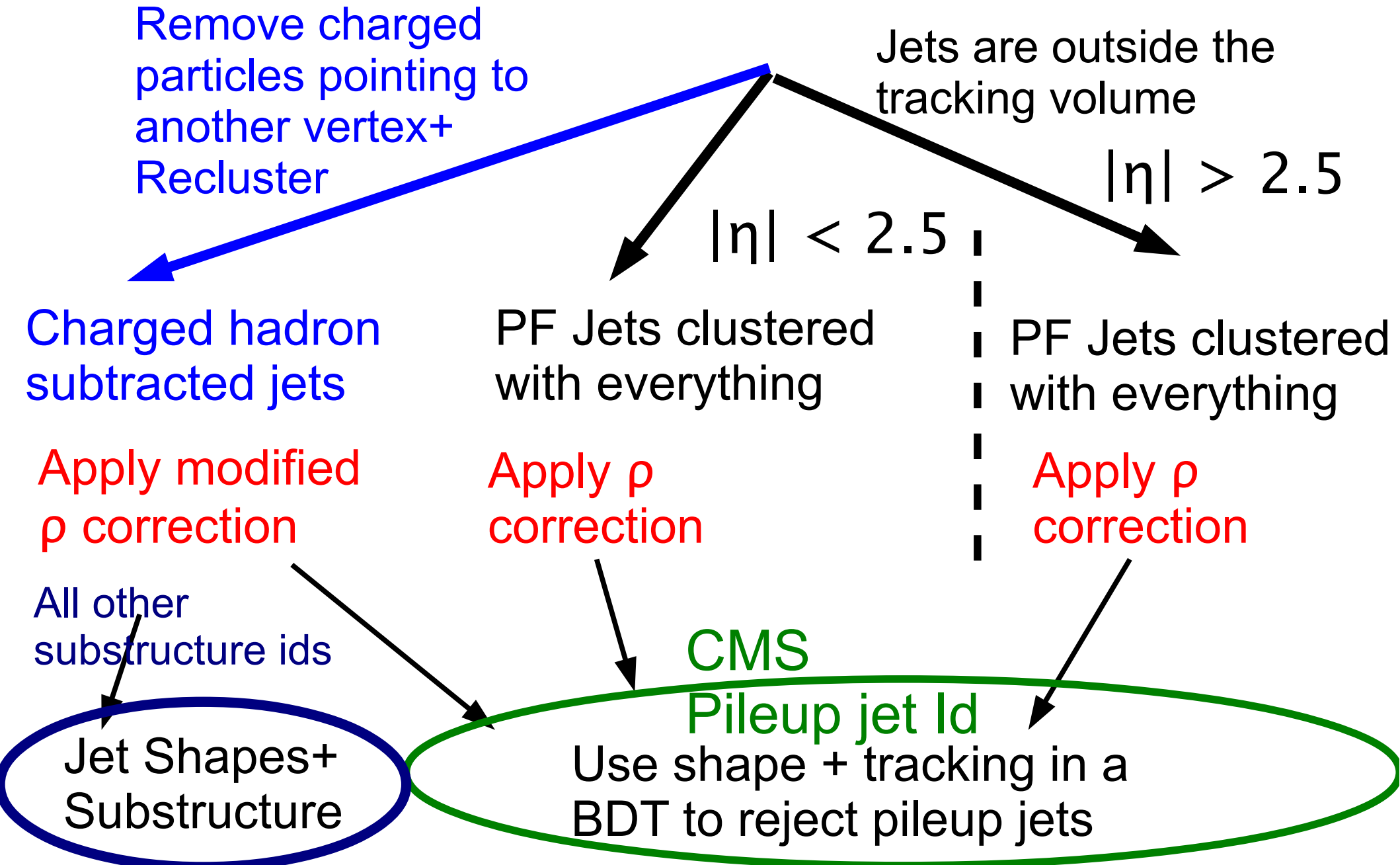
Spectrum of the Jet Toolbox



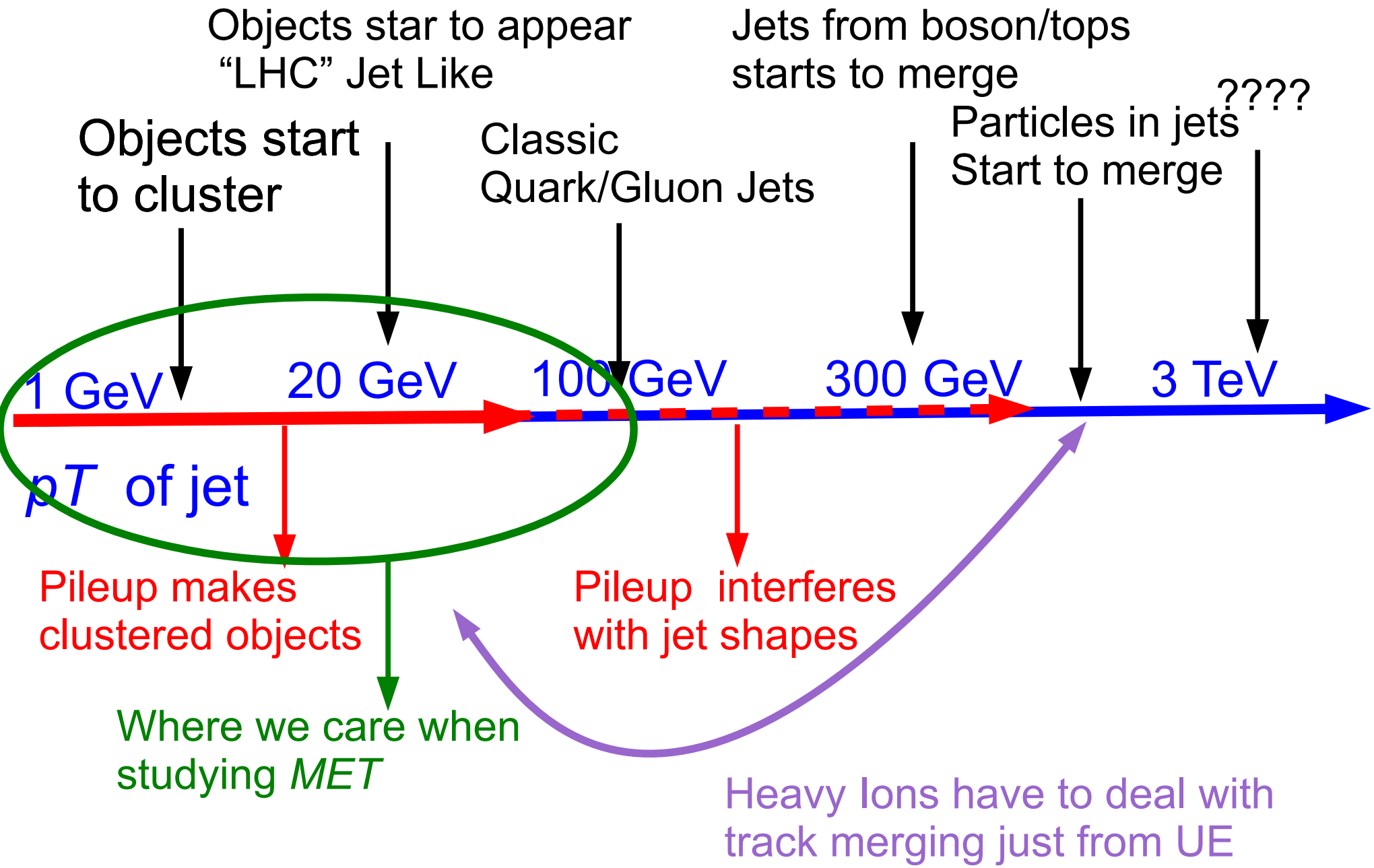
Spectrum of the Jet Toolbox



Pileup Removal in CMS



Spectrum of the Jet Toolbox



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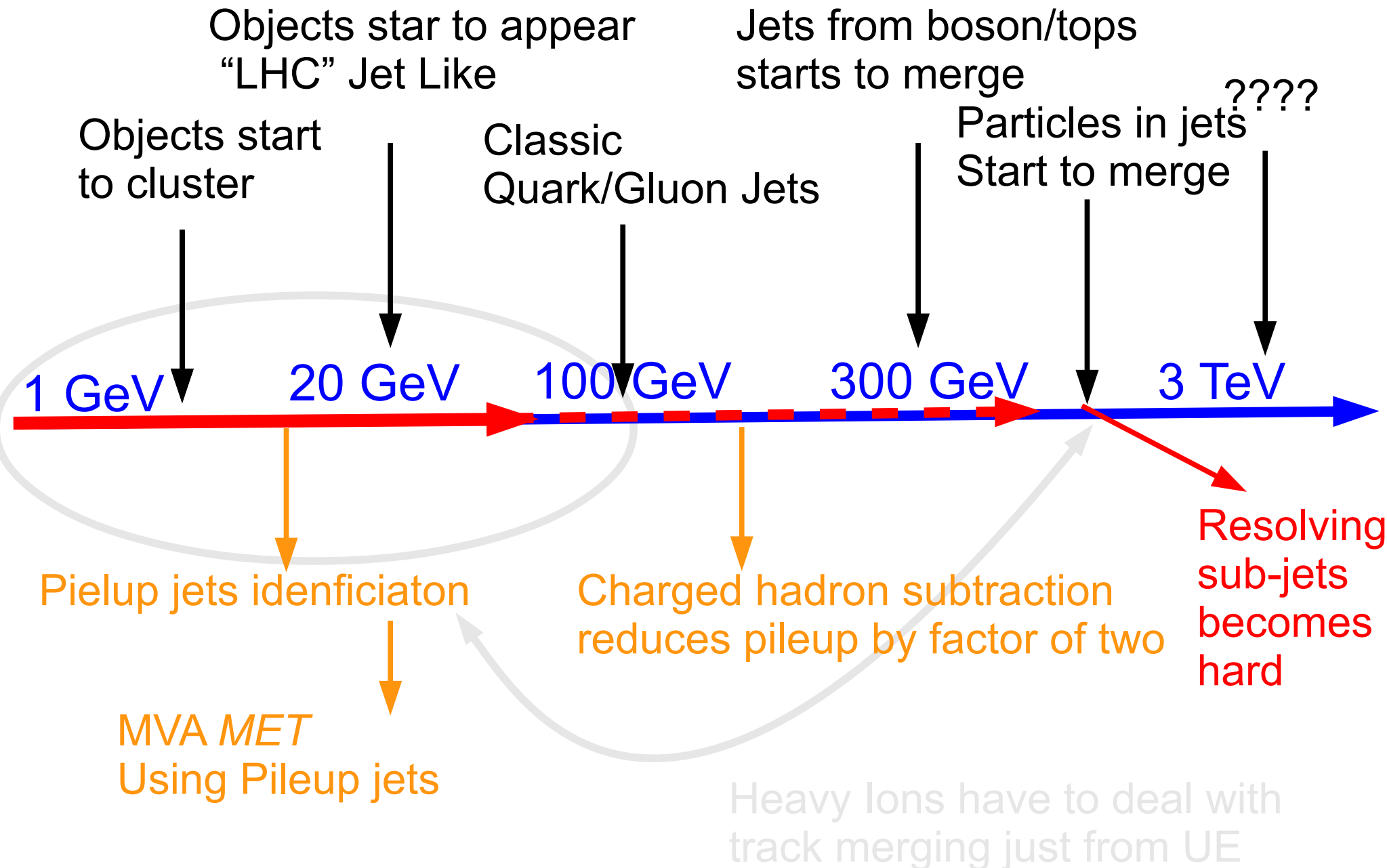

Status of Pileup Mitigation