Precision in a high pileup environment at the LHC

Nhan Tran
Fermilab

Precision theory for precise measurements
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Quy Nhon, Vietnam

introduction/outline

Pileup is the greatest experimental challenge for the LHC going forward

it affects everything:

detector design, object performance and physics sensitivity

will focus on techniques and methods with examples from both CMS and ATLAS

[outline]

what is pileup? (and its relationship to the Higgs)

how do we get rid of it?

performance of pileup mitigation techniques

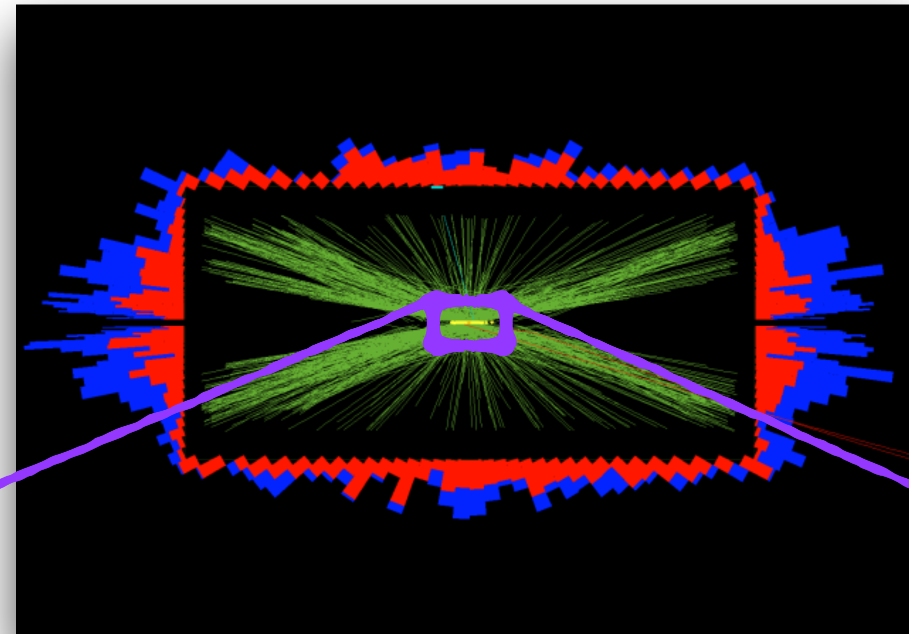
newer ideas and outlook

see talks by A. Perieanu and O. Boeriu for more on future performance and Higgs

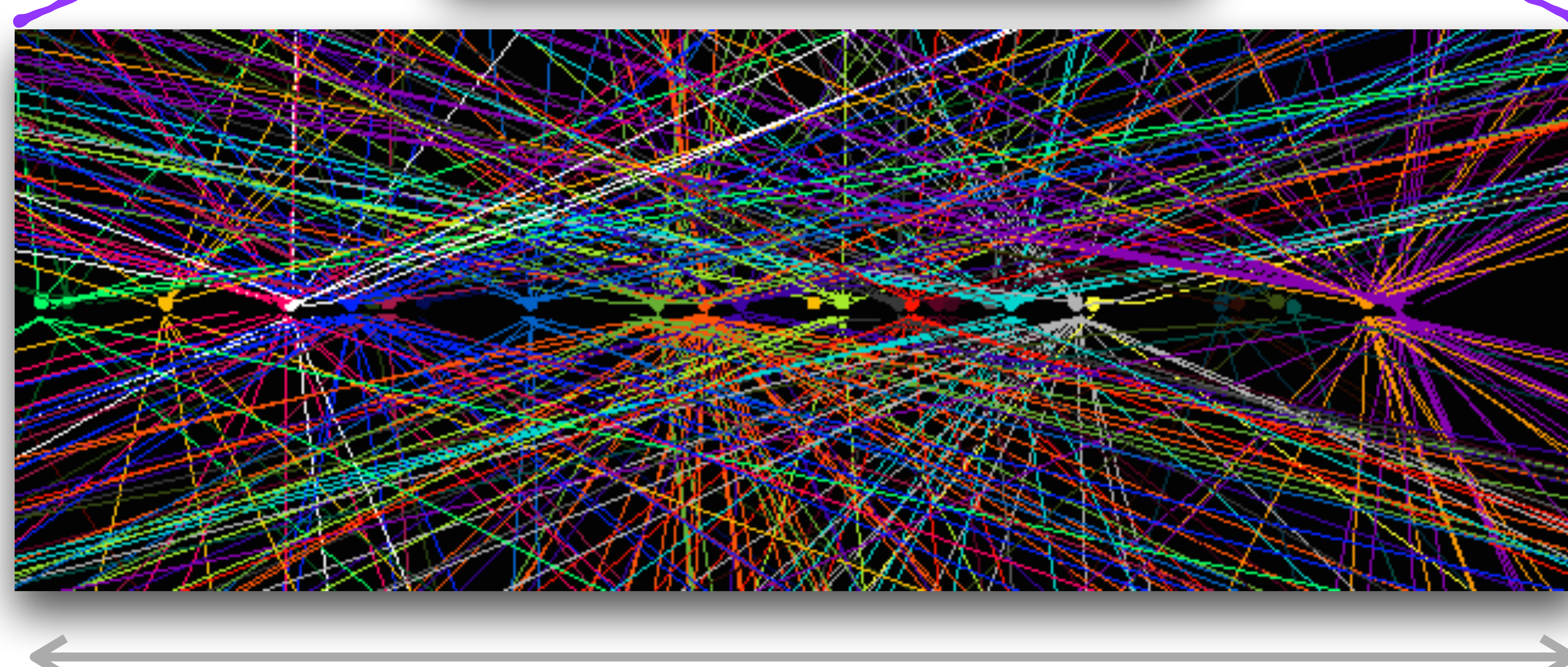
what is pileup?

2012: <PU> ~ 20
2016: <PU> ~ 20-40
2017: <PU> ~ 50
Run 3: > 50
HL-LHC: 140-200

Multiple pp collisions in the same beam crossing
(mostly minimum bias events)



to give a sense of scale:
1 PU vertex ~ 0.7 GeV of energy per unit area

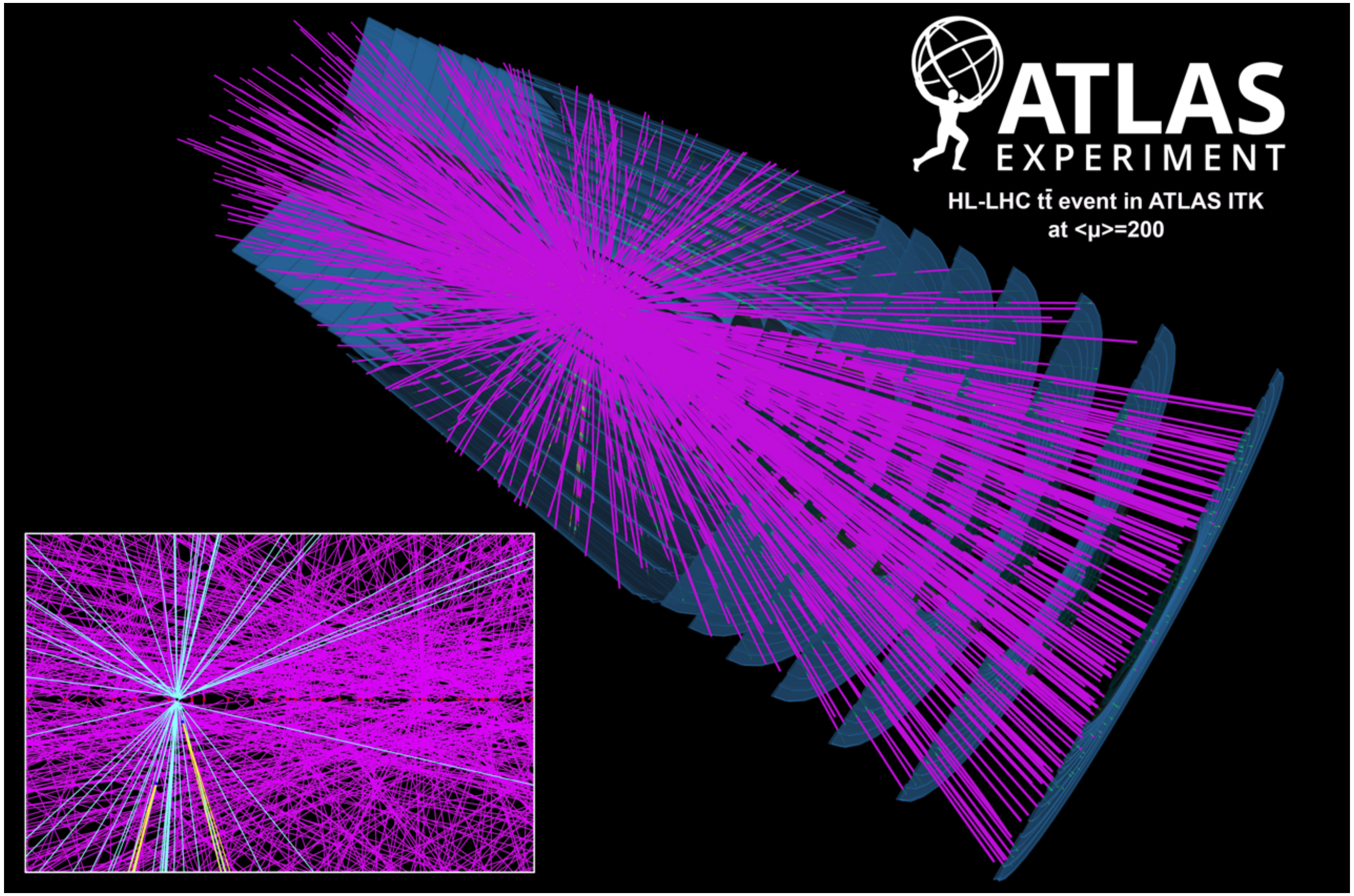


~10 cm

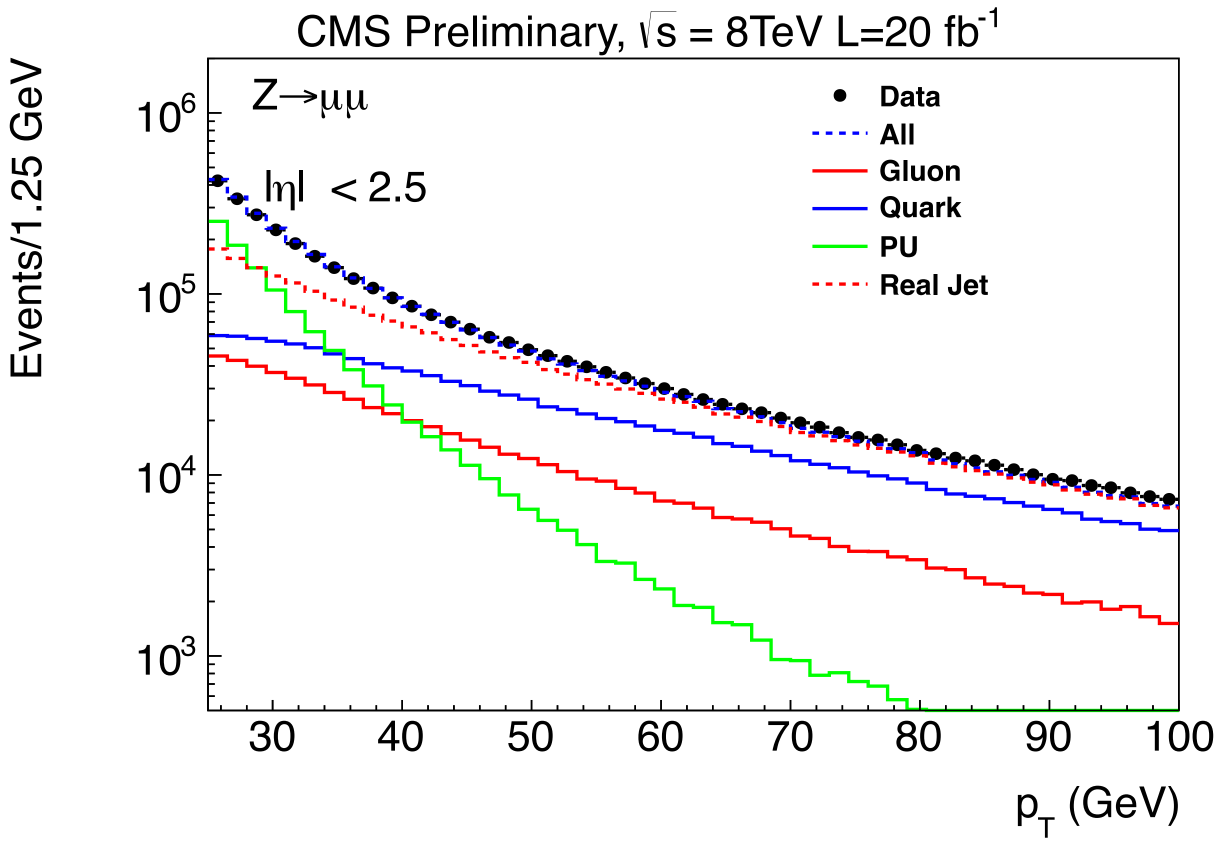
what is pileup?

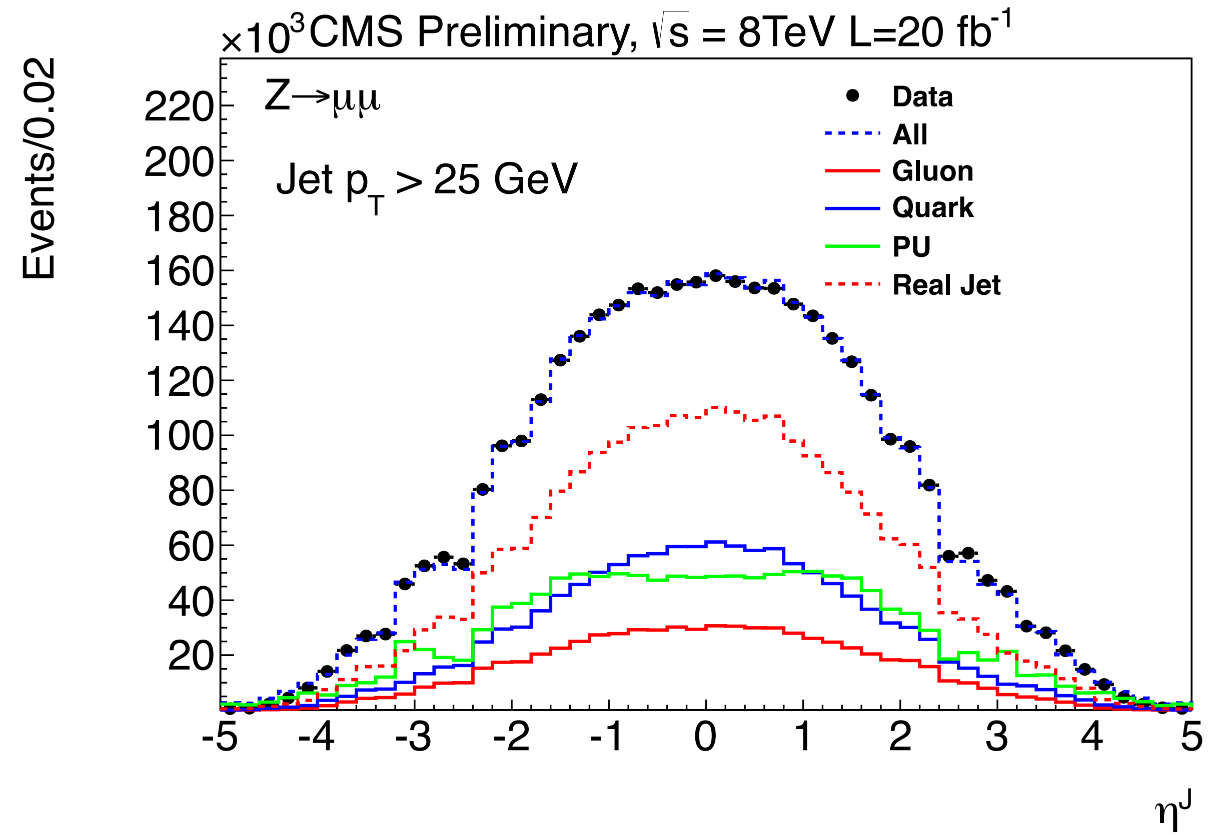
yesterday, peak pileup of 43!

Fill	CreateTime	Duration Stable	BField	PeakInstLumi $\times 10^{30} cm^{-2} s^{-1}$ pp $\times 10^{24} cm^{-2} s^{-1}$ PbPb	Peak Pileup <n>	PeakSpecLumi $\times 10^{27} cm^{-2} sec^{-1} (10^{11} p)^{-2}$	DeliveredLumi pb^{-1} pp μb^{-1} PbPb	RecordedLumi pb^{-1} pp μb^{-1} PbPb	EffByLumi %	EffByTime %
	LHC Fill Declared	*HH:MM*	Tesla							
5345	2016.09.28 09:37:55	12:39	3.800	13384.146	43.141	5.458	398.854	384.126	96.307	100.000

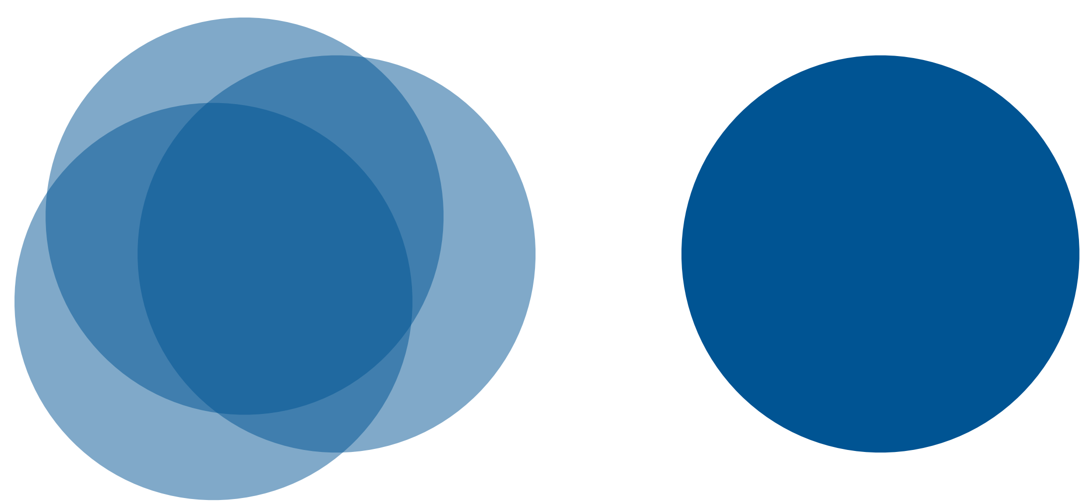


what is pileup?

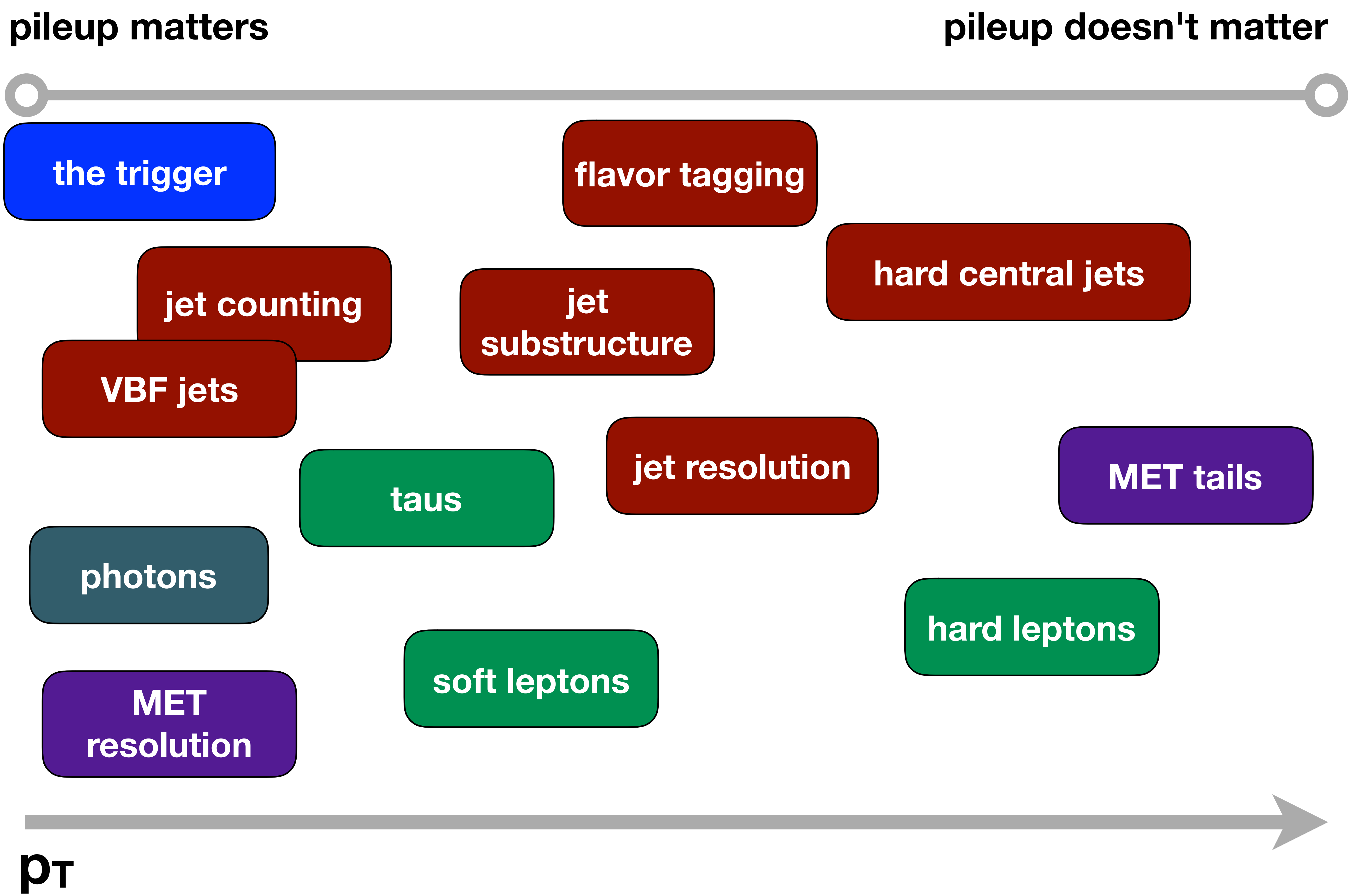


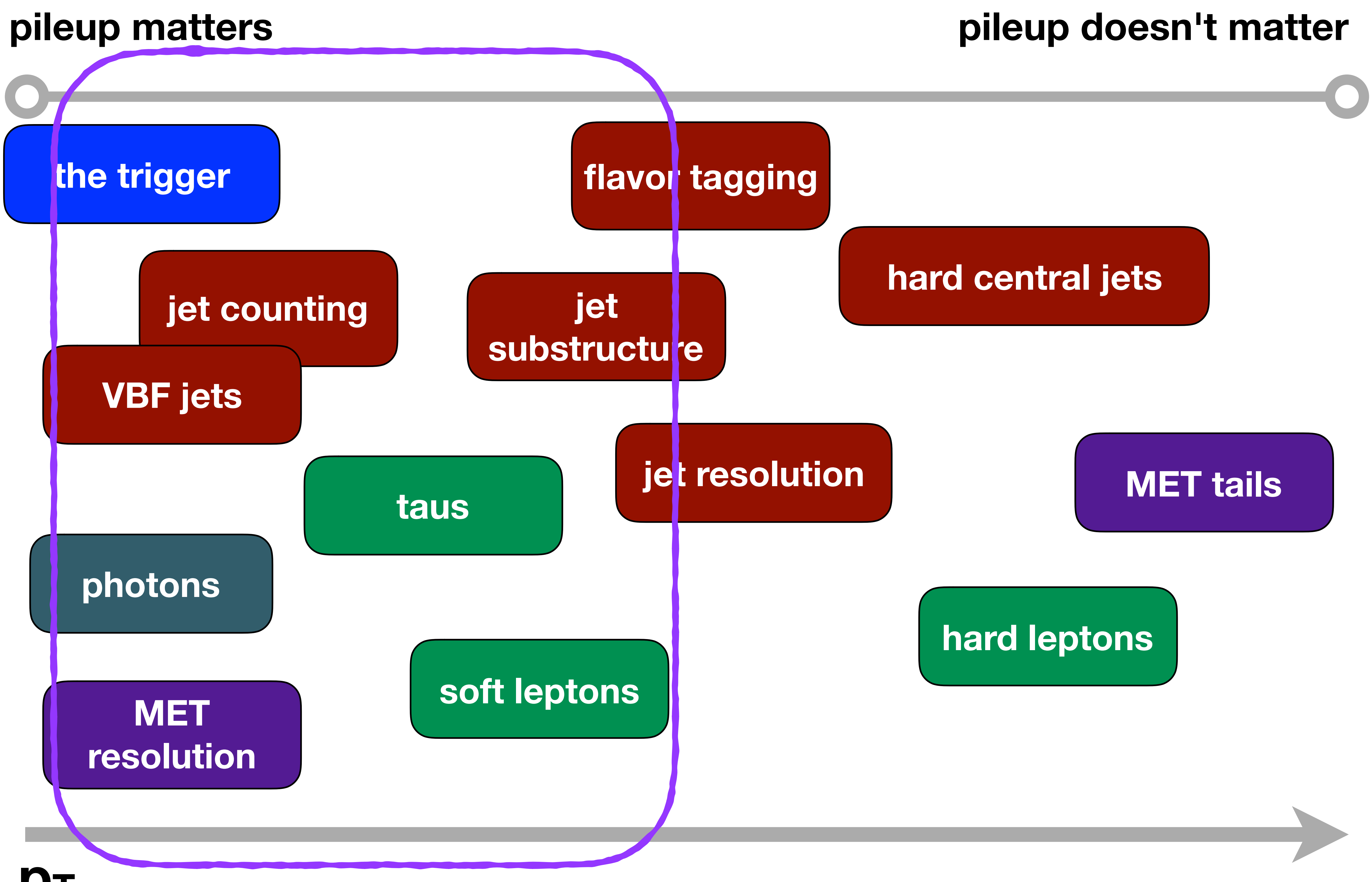


“stochastic” vs. “hard” pileup jets



both contribute to pileup, it’s not necessarily either/or


pileup matters
pileup doesn't matter
the trigger
flavor tagging
hard central jets
jet counting
jet substructure
VBF jets
jet resolution
MET tails
taus
photons
hard leptons
soft leptons
MET resolution
p_T



All important for Higgs!

PU mitigation translates directly into background rejection and physics sensitivity!

handles on pileup

properties

- asymptotic behavior
- local shape
- tracking/vertexing
- precision timing
- depth segmentation

techniques

(apologies, not a complete list!)

- ρ correction/subtraction
  (area, 4-vector, shape, particle)
- grooming
- topoclustering
- charged hadron subtraction
- jet cleansing
- pileup jet ID
- …

asymptotic behavior

local shape

tracking/vertexing

precision timing

depth segmentation

(apologies, not a complete list!)

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handles on pileup

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charged hadron subtraction

jet cleansing

pileup jet ID

...

a lot of methods out there!

CERN PU mitigation workshop,
an early exploration of methods
https://indico.cern.ch/event/306155/

handles on pileup

asymptotic behavior

local shape

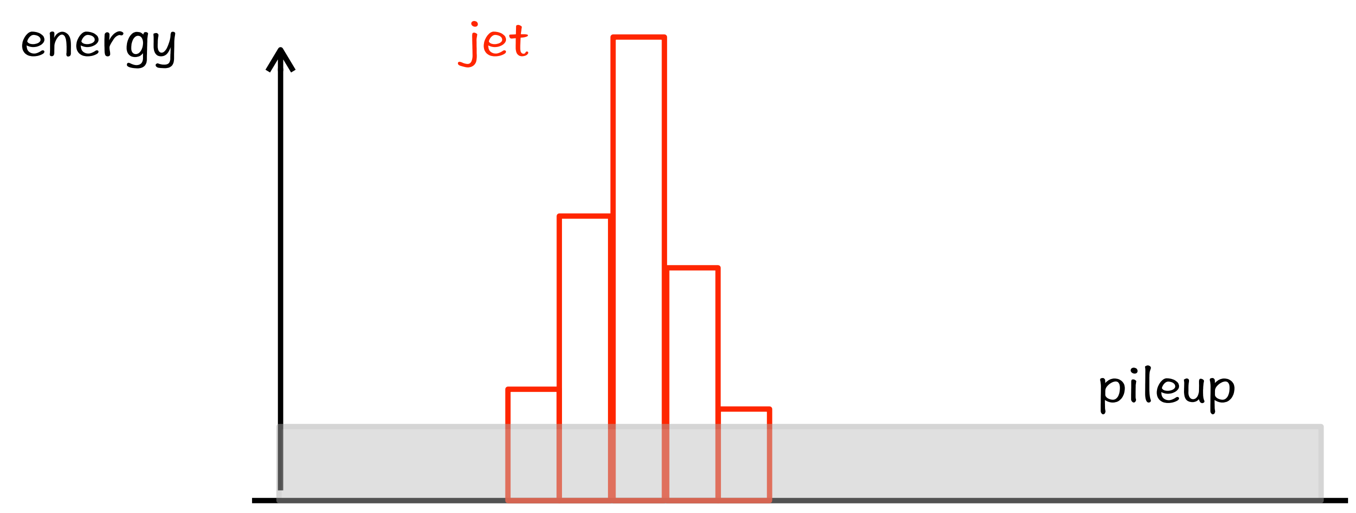
tracking/vertexing

precision timing

depth segmentation

“ρ subtraction”

jet pt correction =
median energy density x area



many variations of this method, including for jet shapes

Modification of the lepton isolation variable in PU

$$I^{\mu}_{\Delta\beta} = \frac{\sum p_T^{\text{CH-PV}} + \max\left(0\,,\, \sum p_T^{\text{NH}} + \sum p_T^{\gamma} - \frac{1}{2}\sum p_T^{\text{CH-PU}}\right)}{p_T^{\mu}}$$

Using the charged-to-neutral ratio (2/3 vs. 1/3) and vertexing information

handles on pileup

jet grooming, cleans up soft and wide-angle radiation

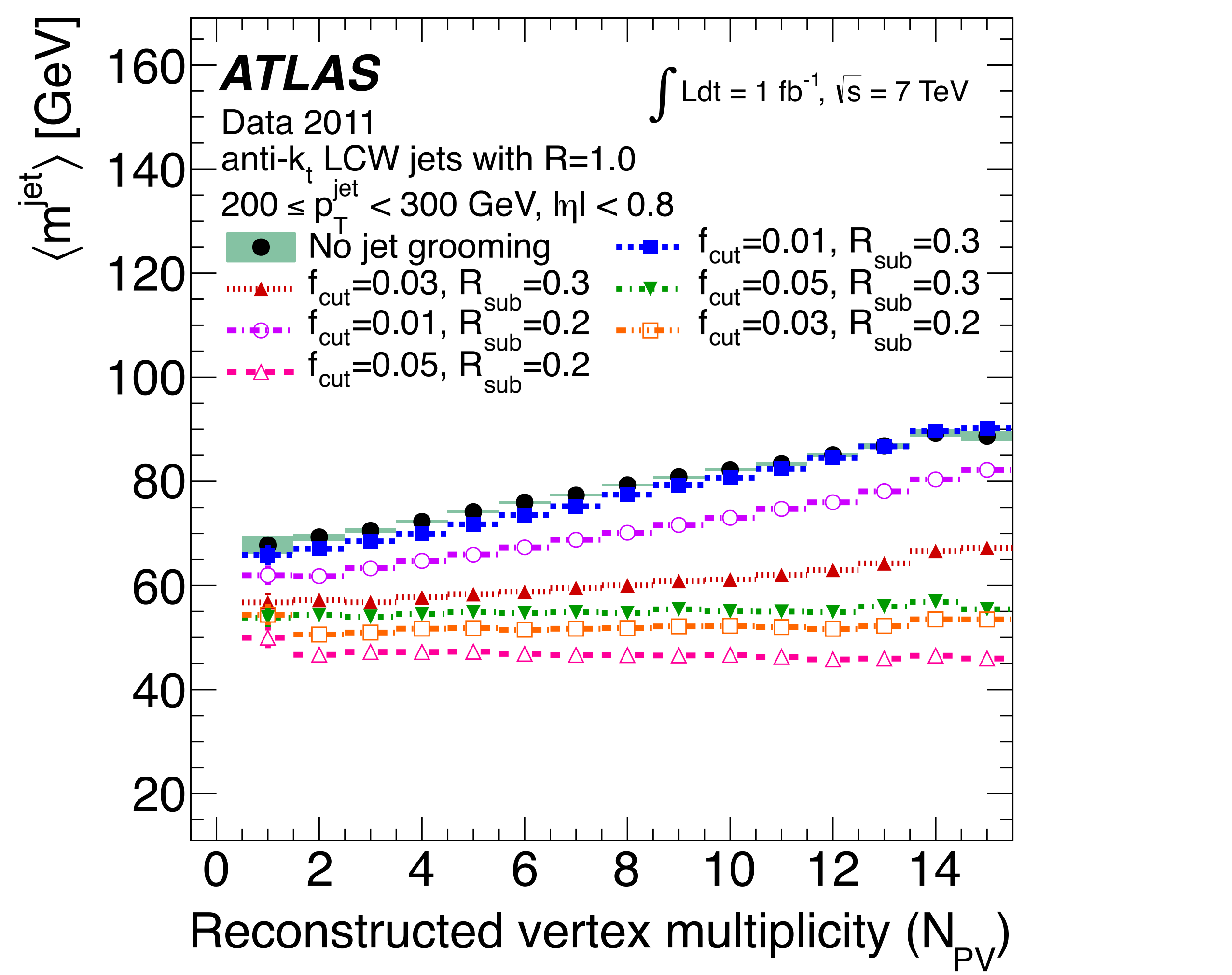
asymptotic behavior

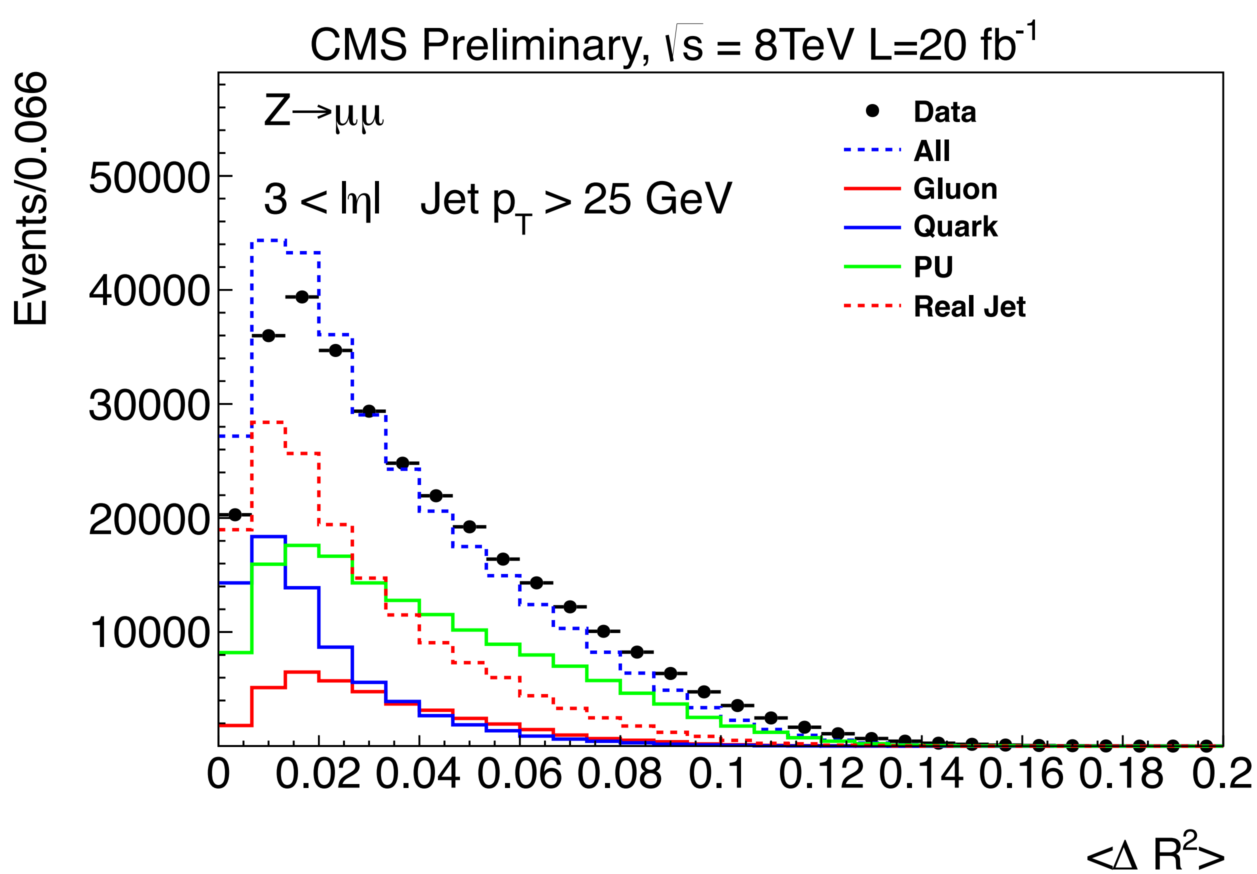
local shape

tracking/vertexing

precision timing

depth segmentation





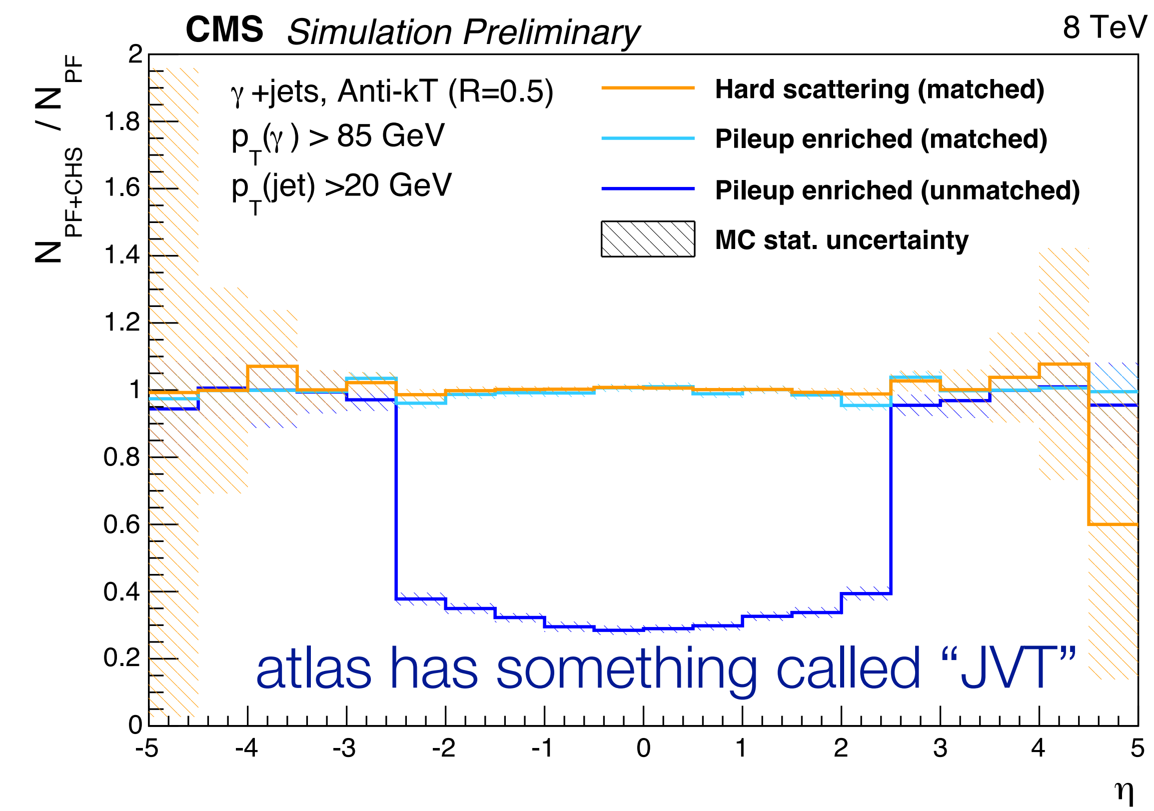
"jet RMS" of forward pileup jets

handles on pileup

- asymptotic behavior
- local shape
- **tracking/vertexing**
- precision timing
- depth segmentation

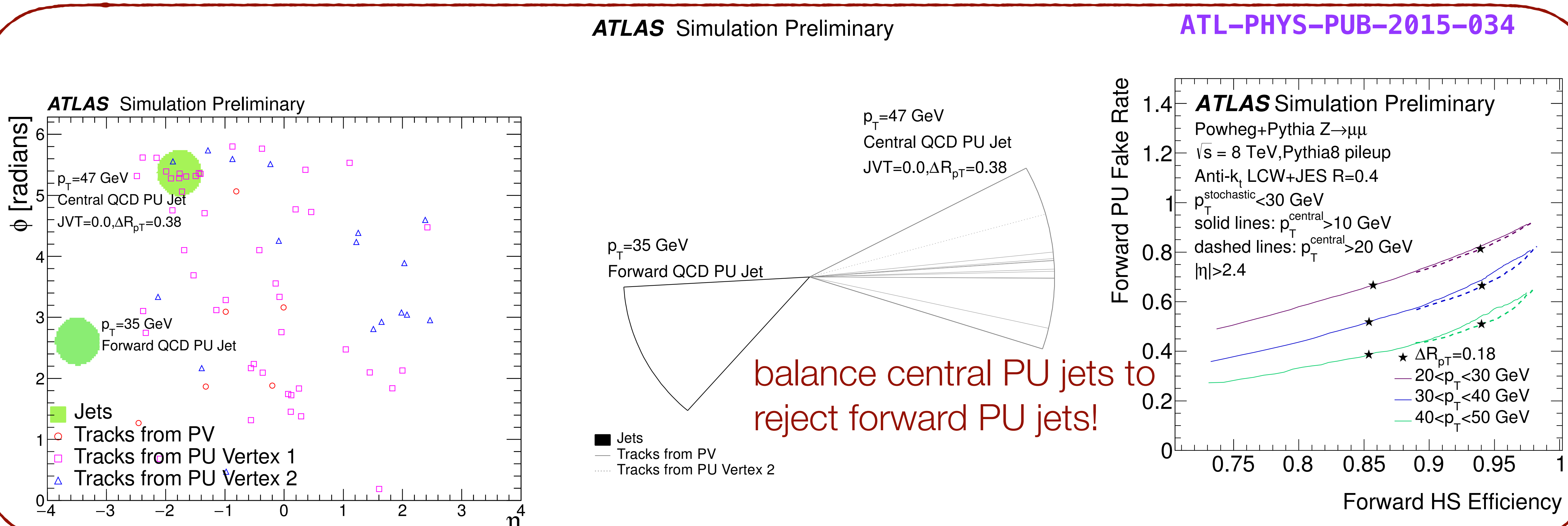
CMS-PAS-JME-14-001

PF vs. PFCHS jets



atlas has something called “JVT”

ATL-PHYS-PUB-2015-034



balance central PU jets to reject forward PU jets!

handles on pileup

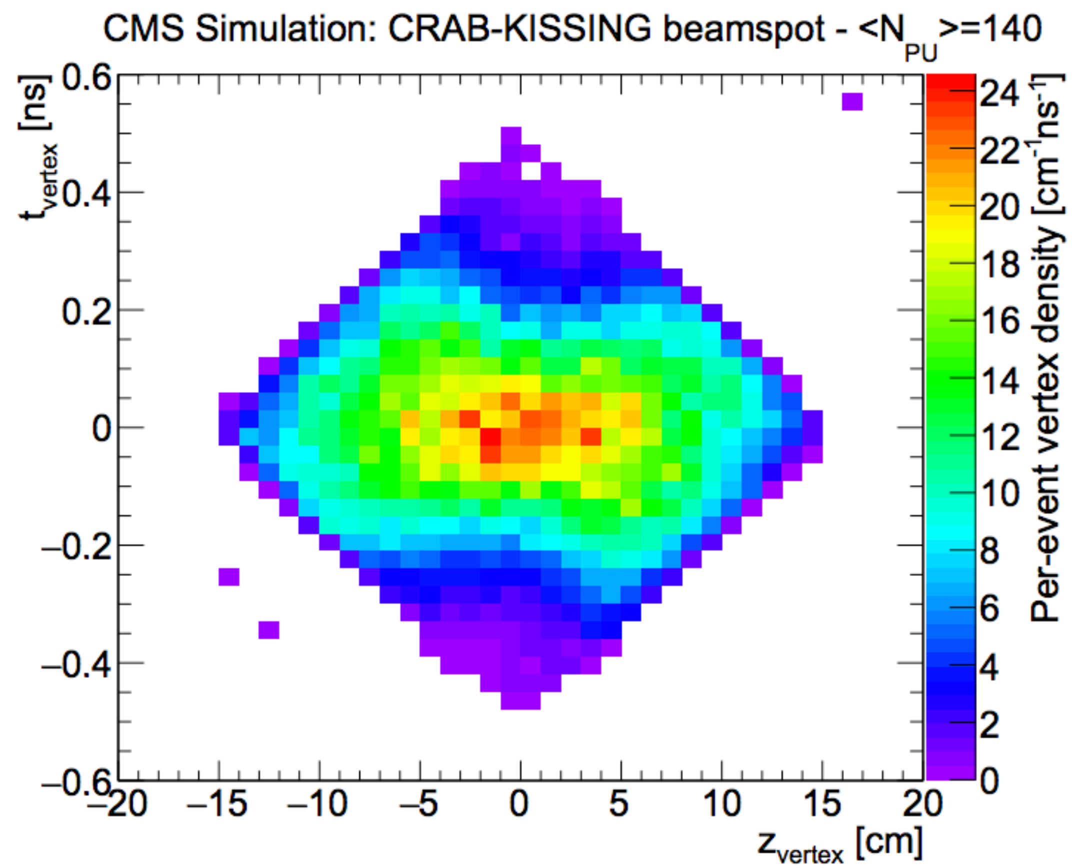
asymptotic behavior

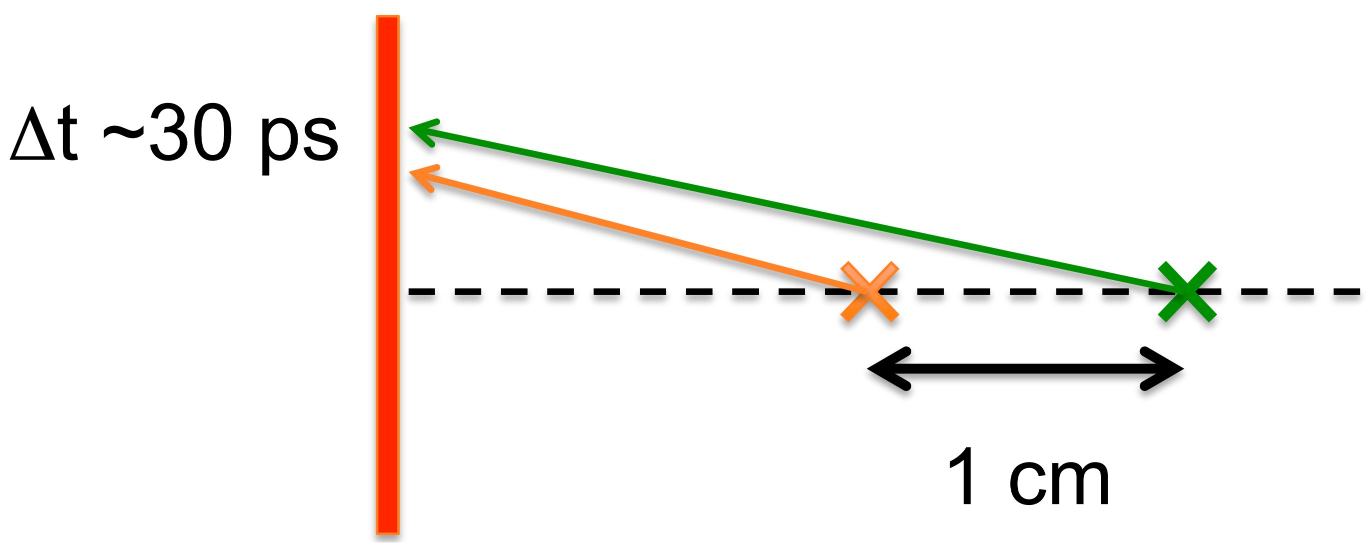
local shape

tracking/vertexing

precision timing

depth segmentation





σ_t ~ 30 ps buys a factor of ~10 reduction in effective pileup

but open questions…
e.g. can we achieve that time resolution for ~few GeV photons?

handles on pileup

asymptotic behavior

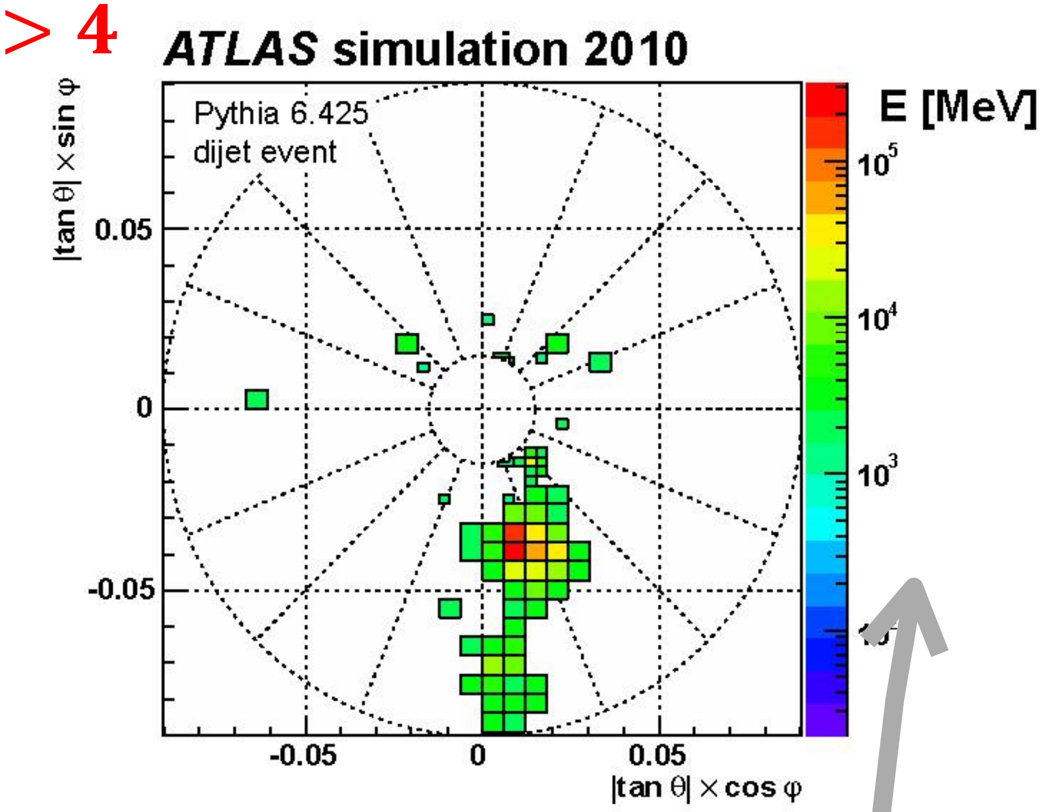
local shape

tracking/vertexing

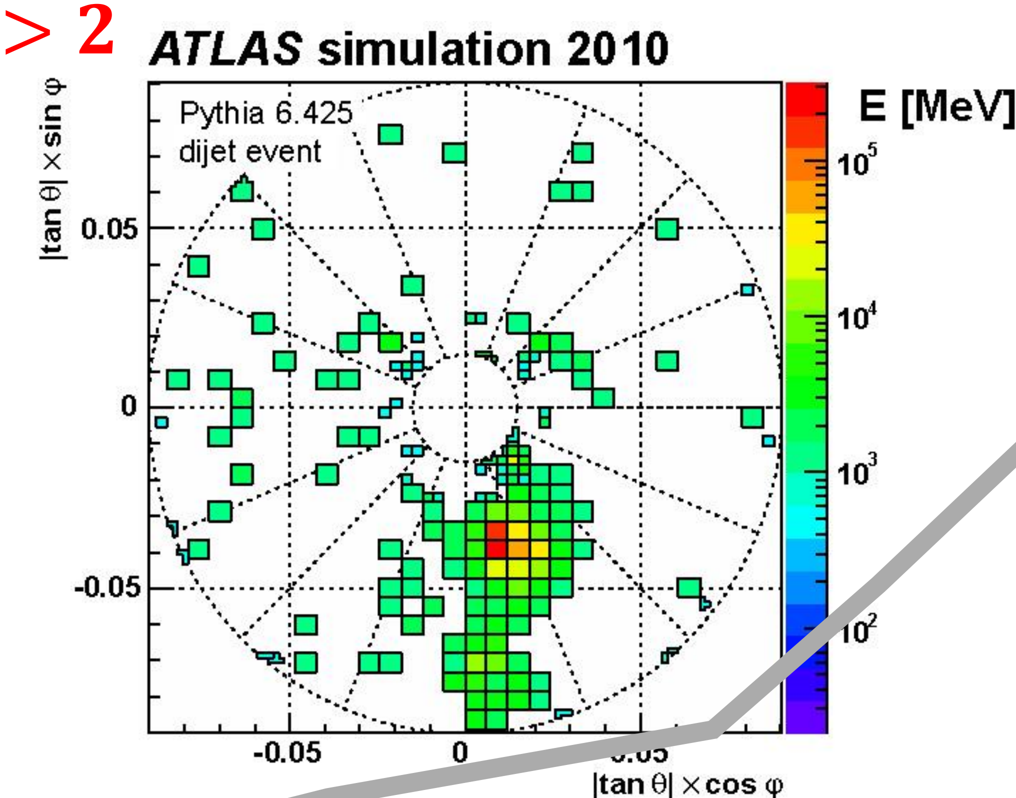
precision timing

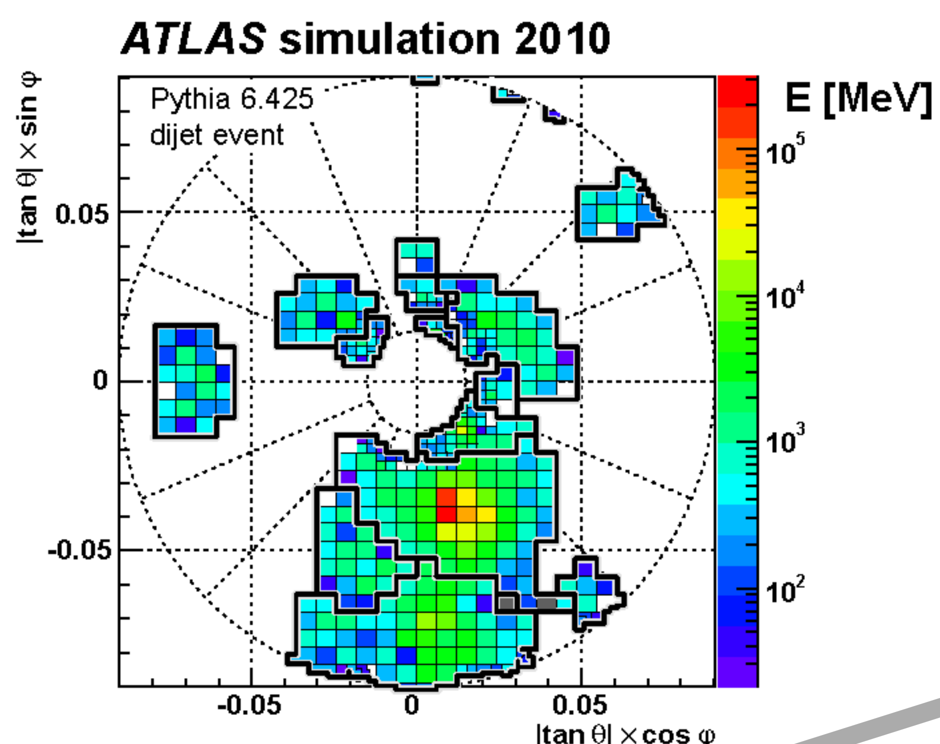
depth segmentation

$\left|\frac{E}{\sigma}\right| > 4$



$\left|\frac{E}{\sigma}\right| > 2$





clustering uses neighbors in depth too!
no longer 2D clustering

holistic views on pileup

Notice that each method that we've described works on a given **physics object**…

each method presented so far also has its downfalls

What if we act on the event building blocks? constituents/particles

constituent subtraction, softkiller, PUPPI

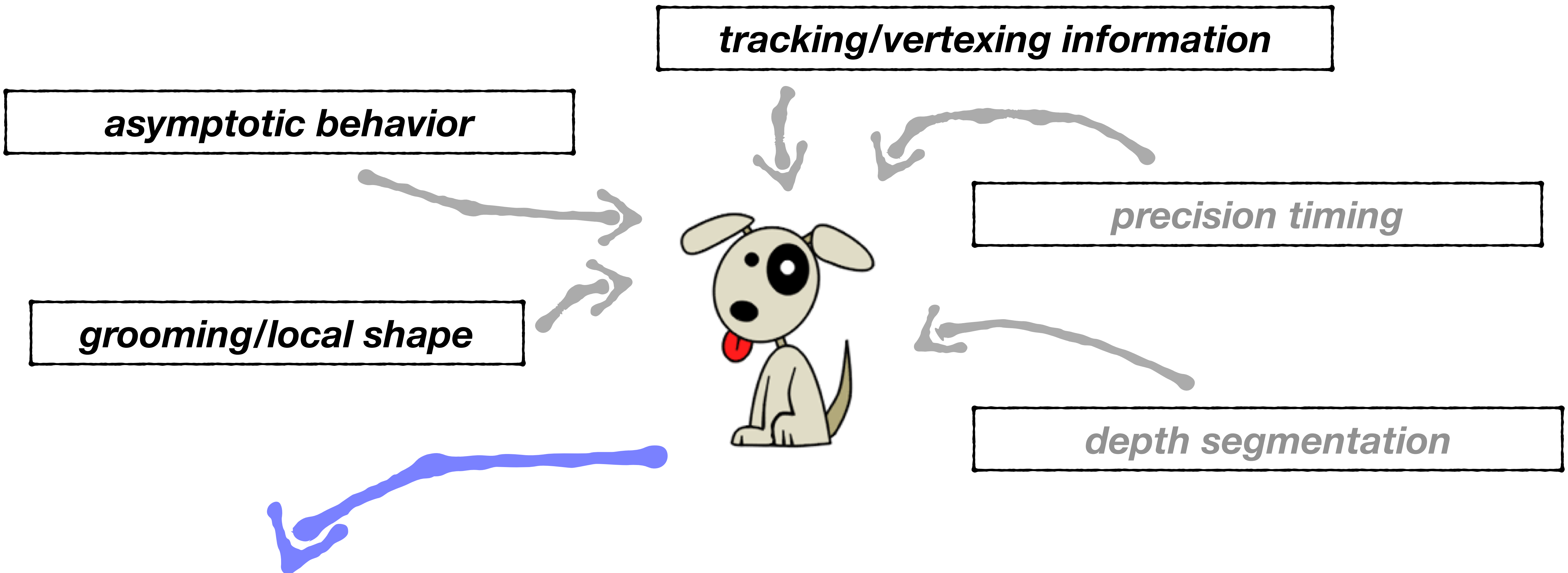
hep-ph:1403.3108
hep-ph:1407.0408
hep-ph:1407.6013

What if we exploit all information possible simultaneously?

asymptotic, local shape, tracking, etc…

What if, you could identify each particle in the event and give the likelihood that it's pileup?

the PUPPI approach:
Pile**U**p **P**er **P**article **I**dentification



Define on a ***per particle*** basis, ***before jet clustering***, a weight for ***how likely*** a particle (or jet constituent) is to be from pileup or the leading vertex, then rescale each particle four momentum by that weight

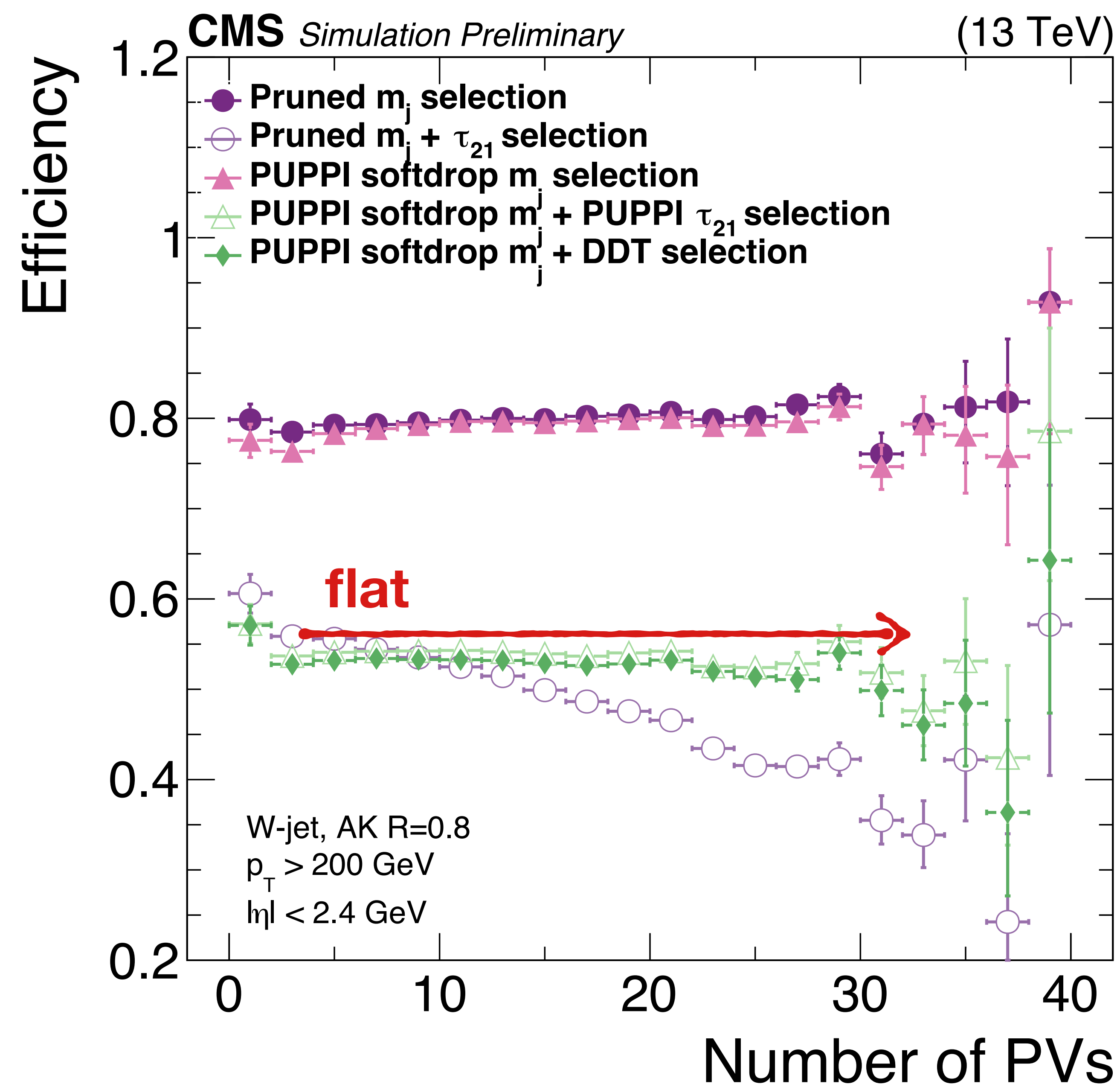
$$\alpha_i^C = \log\left[\sum_{j\in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij})\right]$$

define an α_i per particle; sample the PU α distribution per event; ask how likely particle i is to be pileup

PUPPI performance

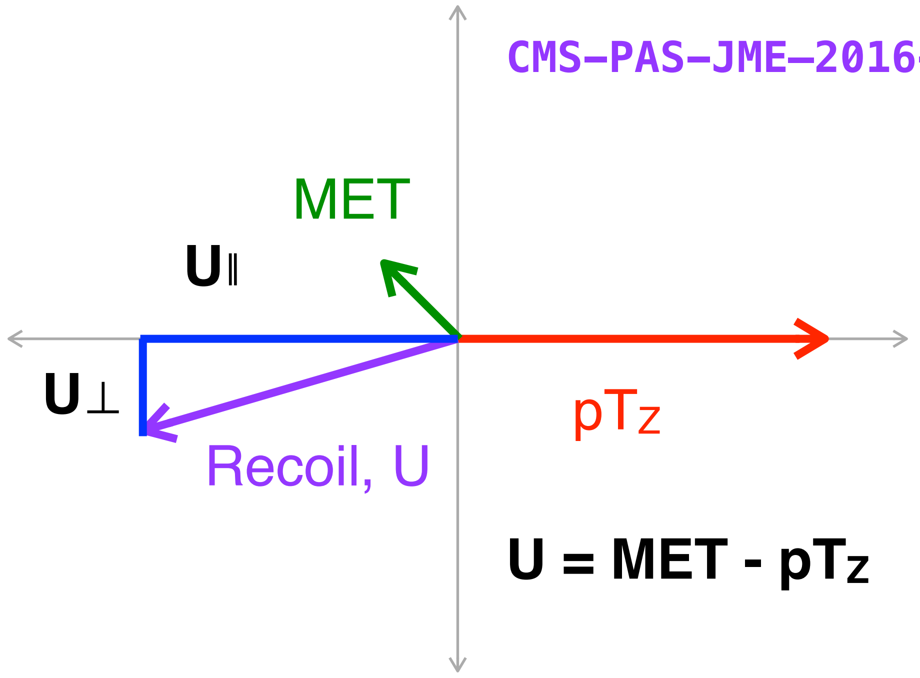
"Classic" use-case for per particle pileup mitigation, it works for all jet shapes

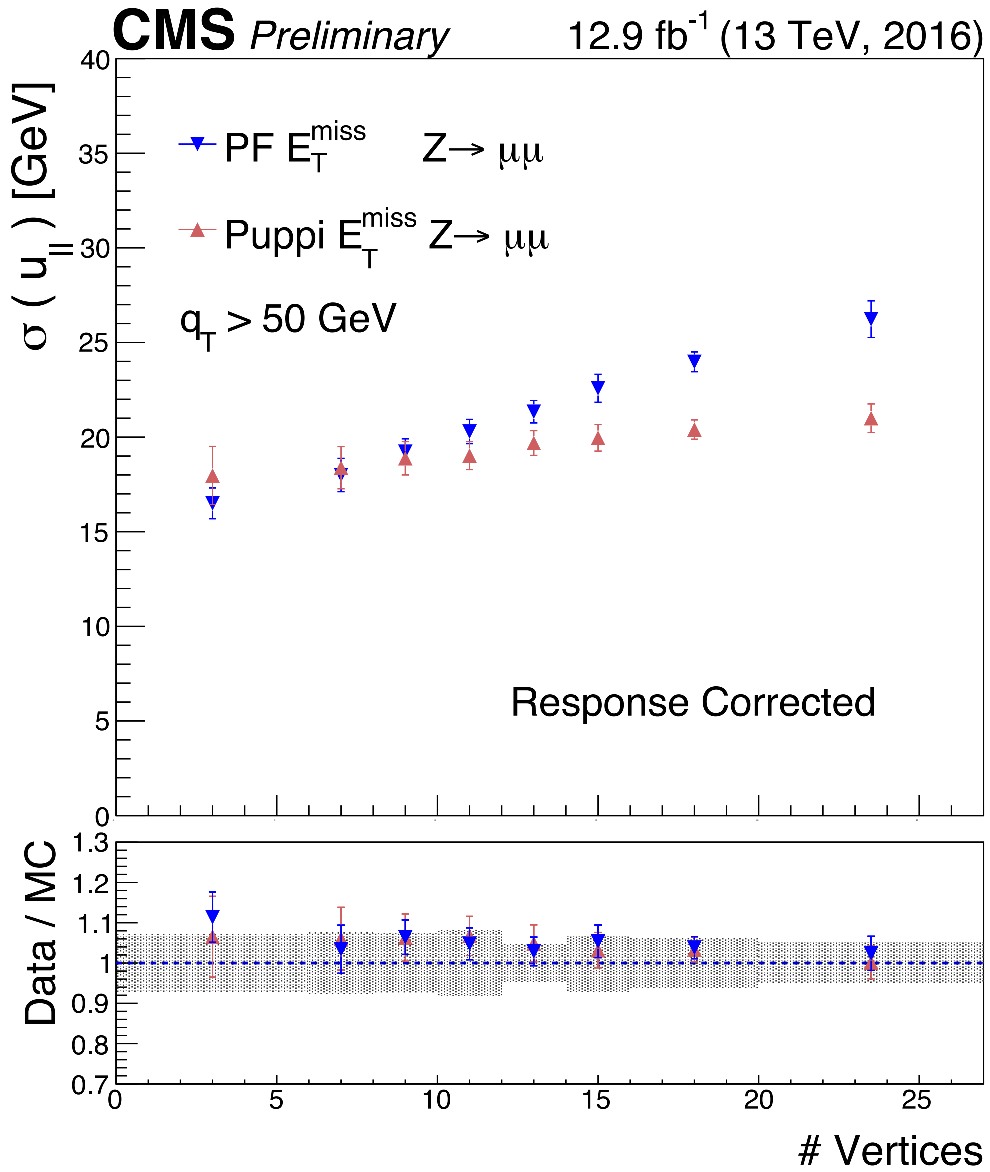
Here, this is the effect of PUPPI on W-tagging shown for PFCHS inputs vs. PUPPI inputs

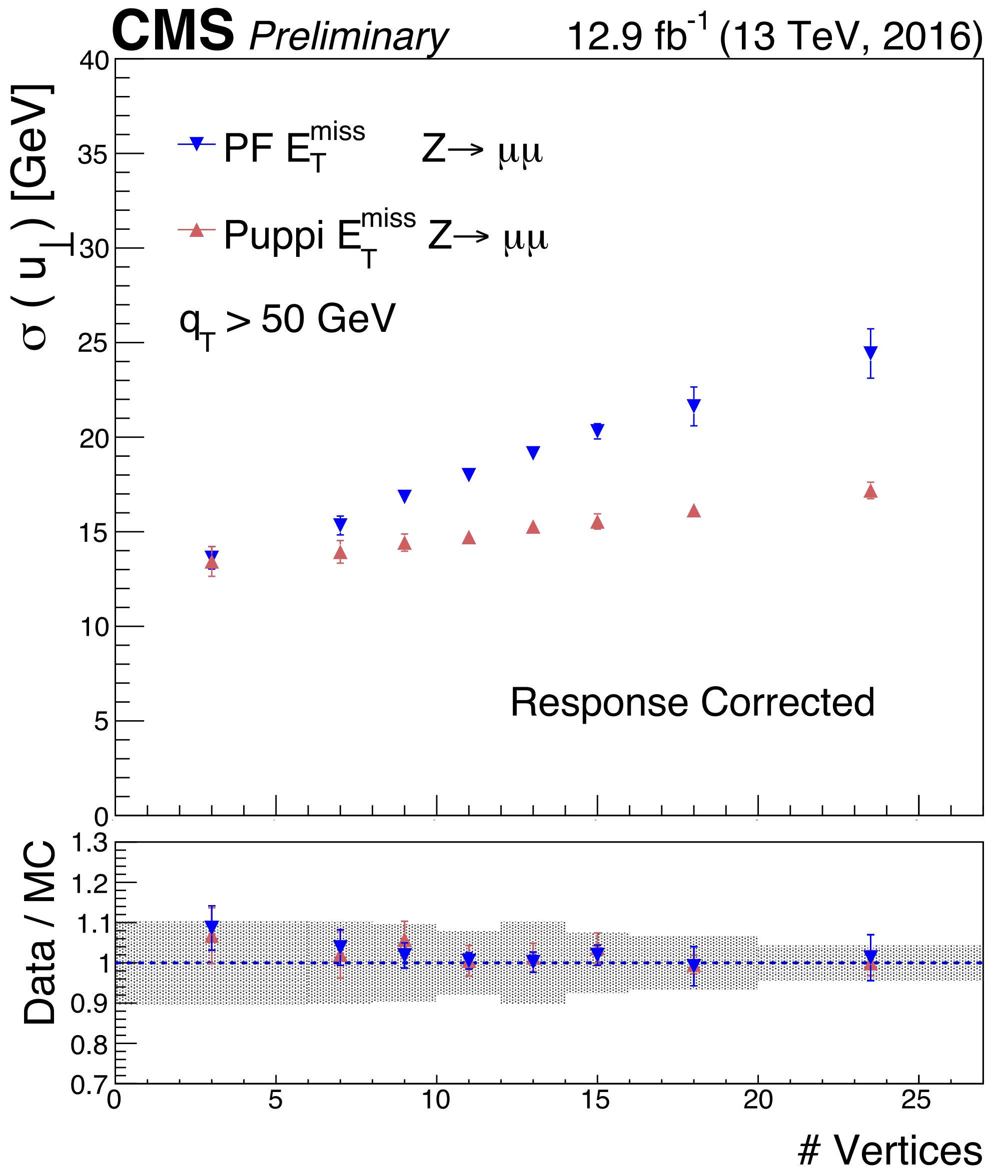


PUPPI performance

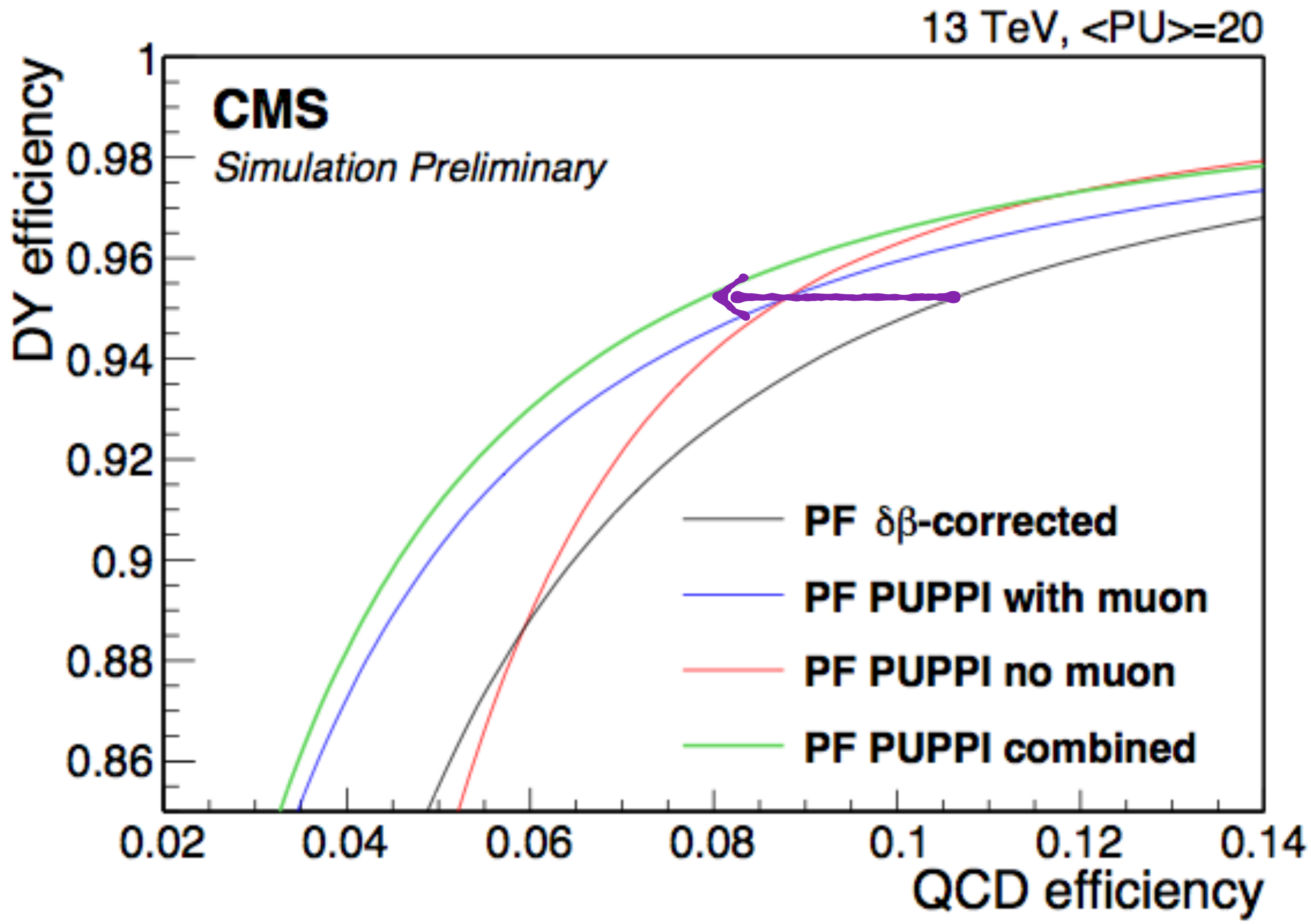
20-30% resolution improvement in the MET resolution @ N_{PV} ~20 over traditional "PU" corrected MET







PUPPI performance



25% decrease in backgrounds using per particle uncertainties at 20 PU!

"combined" curve uses both muon hypotheses

Vs. traditional methods

Full performance @ HL-LHC is still under evaluation at the experiments.

- Detector improvements: track triggering @ L1, extended tracker, precision timing, high granularity calorimeters, etc.
- Likewise, reconstruction methods will have to be optimized for new detector configurations

Not yet ready for a final word on ultimate HL-LHC performance though initial studies are promising

- ECFA studies show, for example, effect of forward tracking on MET resolution (see backup for more details)

other ideas: embracing pileup

"Leveraging pileup as a zero bias trigger"

Pileup is not noise — it's physics to exploit!

Trigger selects a given event, but then you have 140-200 other uncorrelated "events" that are "zero bias". Do physics with those interactions.

$$\mathcal{L}(\text{ZBT}) = \frac{w}{40\ \text{MHz}} \times \int \mathcal{L} dt.$$

LHC Run	Total Lumi. [1/fb]	$\langle\mu\rangle$	L1 Rate	HLT Rate	ZBT [1/fb]	ZBT @ HLT [1/fb]
1	20	20	100 kHz	100 Hz	$5 \cdot 10^{-5}$	0.05
2+3	300	80	100 kHz	1 kHz	$7.5 \cdot 10^{-3}$	0.75
4+5 (ATLAS)	3000	200	400 kHz	10 kHz	0.75	30
4+5 (CMS)	3000	200	750 kHz	7.5 kHz	0.56	56.3

study was in the context of BSM searches, but are there some other applications?

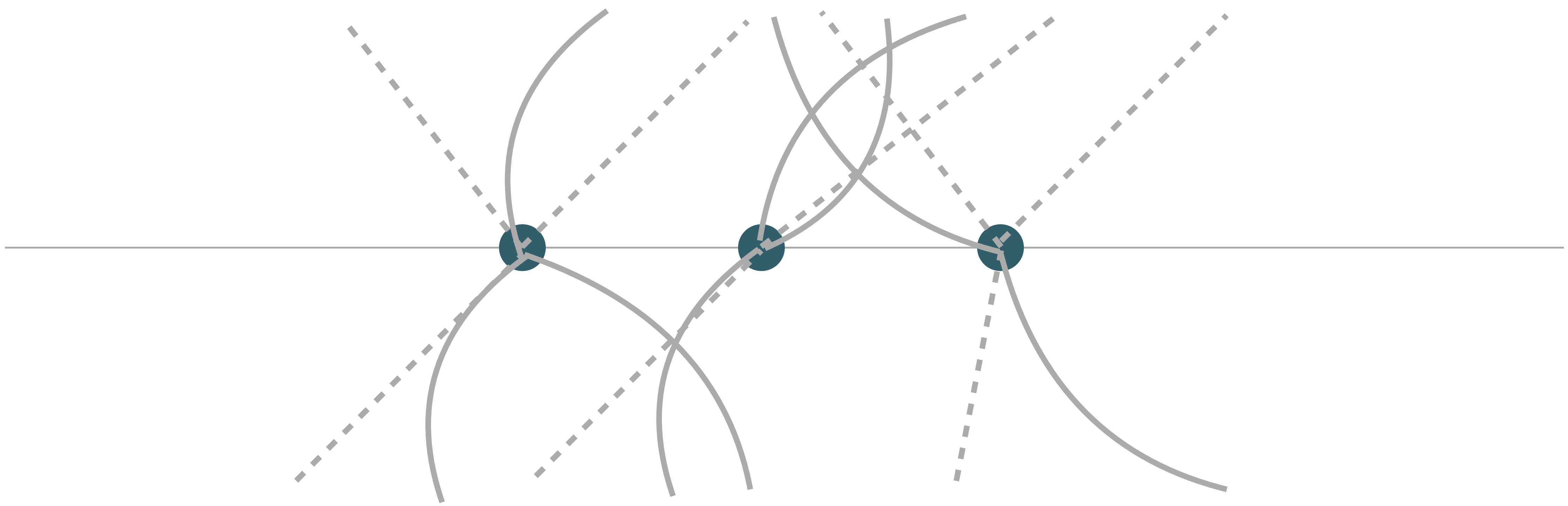
what could you do with a 100 fb^{-1} of zero-bias LHC data? HLT trigger level analysis information?

a really holistic approach

What if, you could identify each particle in the event and give the likelihood that it's pileup?

What if, you could identify each particle in the event and give the likelihood that it belongs to a given vertex i?

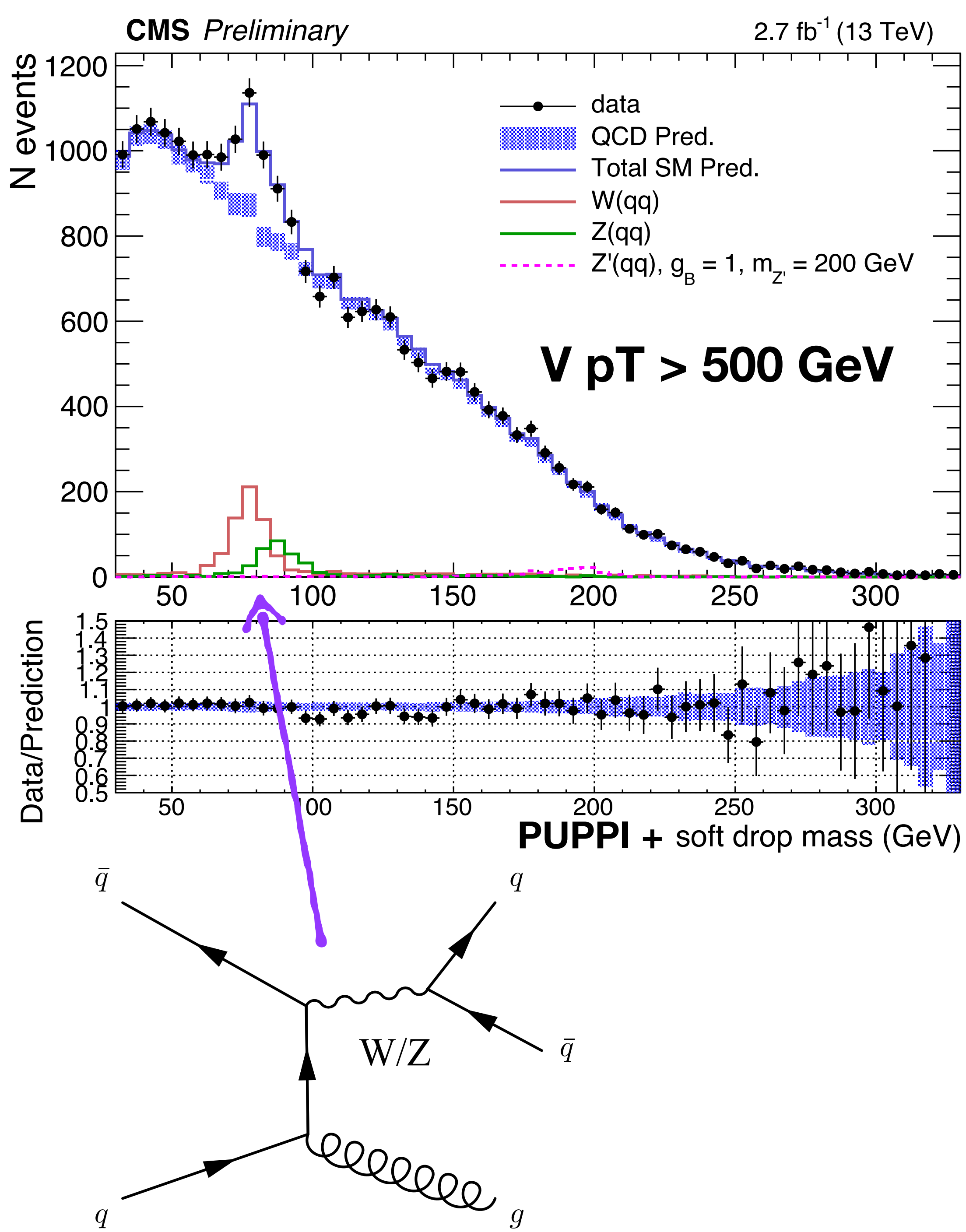
a combination of the PUPPI approach and the ATLAS forward vertex jet tagging ideas…

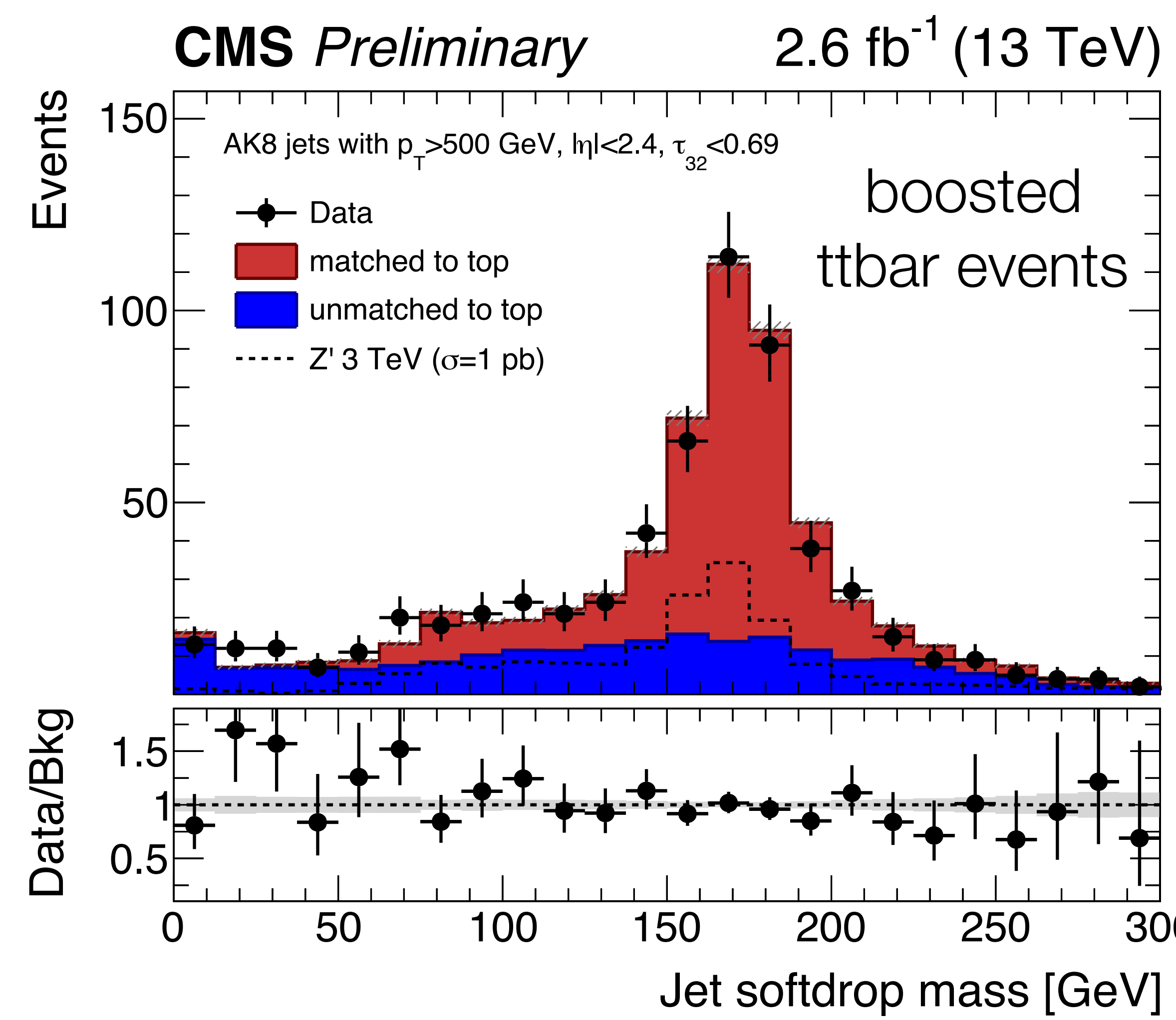


other ideas: boost away from pileup

Finally, connecting this with some other discussions beyond Higgs session

instead of mitigating pileup, go to more striking high pT topologies to boost away from the difficult effects of pileup





See talk by M. Beneke, A. Hoang for more discussion

we will have ~1M boosted tops at the end of next year (m_{tt} > 1 TeV)!

summary and outlook

Give some basic principles on how pileup is mitigated at the LHC and how much improvement can be gained

Newer ideas for global treatment of pileup and further gains on collective “particle-level” observables

Work is on-going to define methods for HL-LHC, integration of reconstruction algorithms and detector upgrades

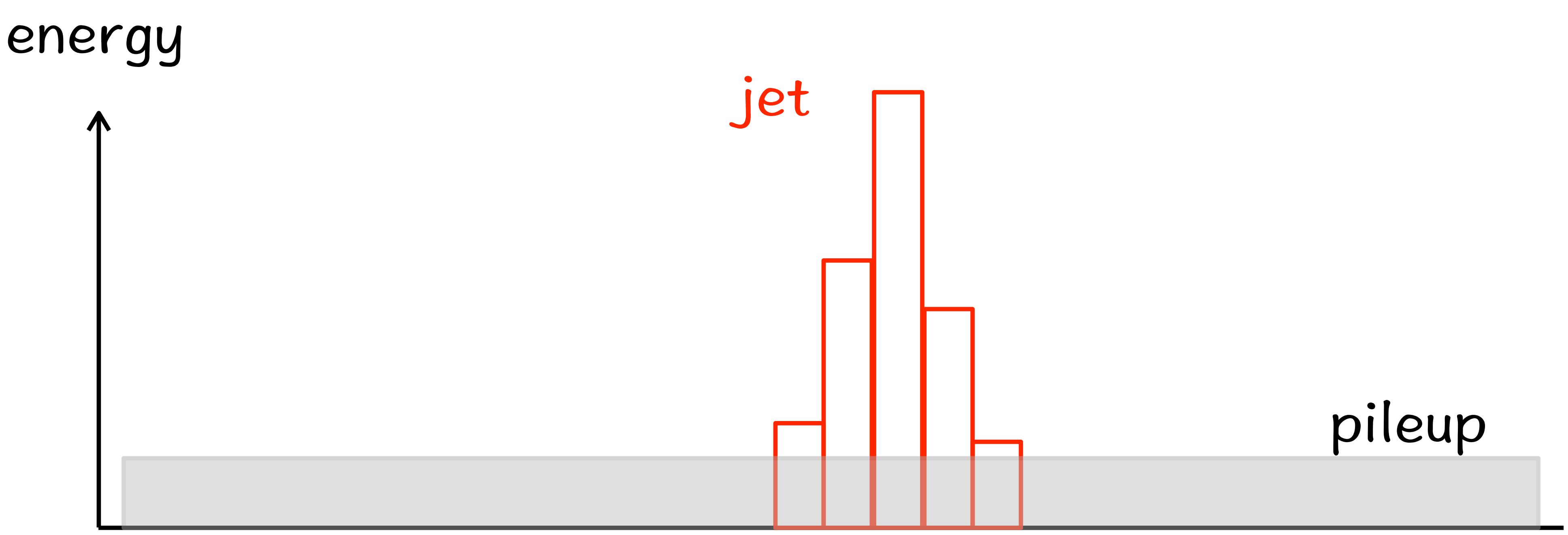
Other ways to confront pileup: physics in pileup, boosting away from pileup

Backup

Run I ways to get rid of pileup

use the asymptotic behavior of pileup

uniform, charged-to-neutral fraction

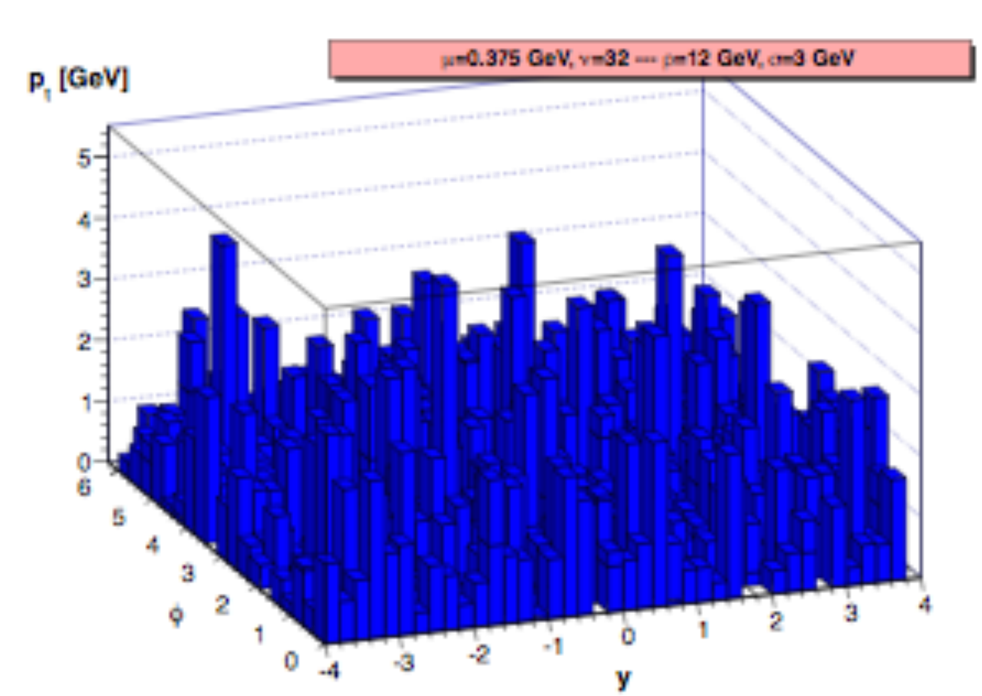


Run I ways to get rid of pileup

use the asymptotic behavior of pileup

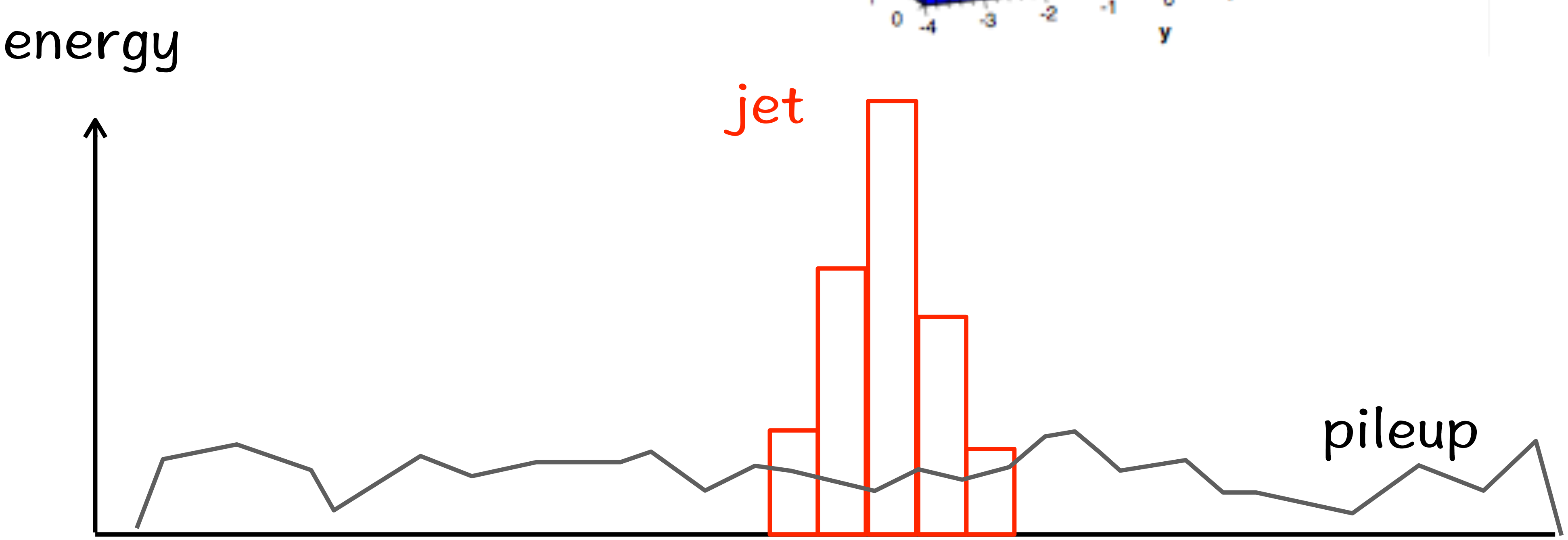
uniform, charged-to-neutral fraction

pileup is lumpy



$\rho = 12$ GeV, $\sigma = 3$ GeV

typical for LHC (20 PU)



Run I ways to get rid of pileup

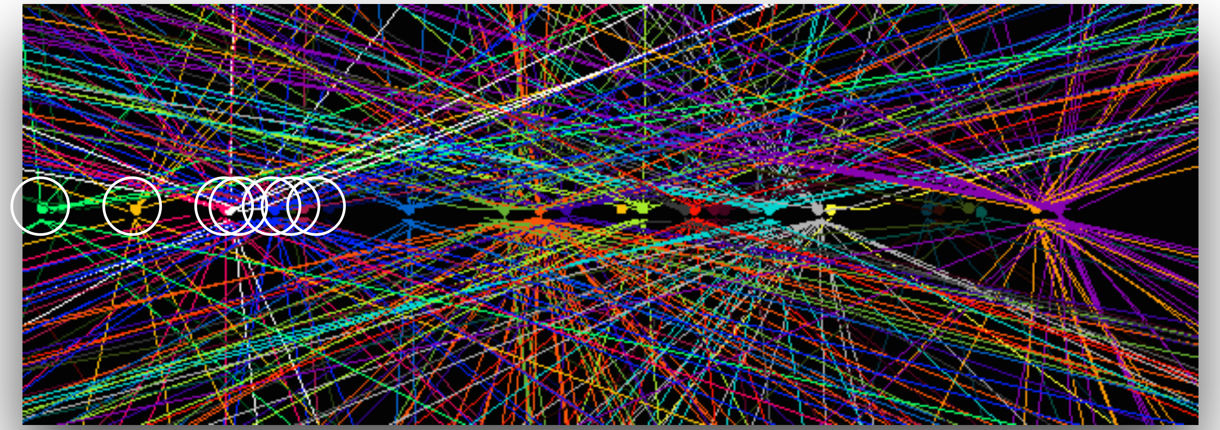
use the asymptotic behavior of pileup

uniform, charged-to-neutral fraction

pileup is lumpy

use tracking to remove charged particles

says nothing about neutrals



Run I ways to get rid of pileup

use the asymptotic behavior of pileup

uniform, charged-to-neutral fraction

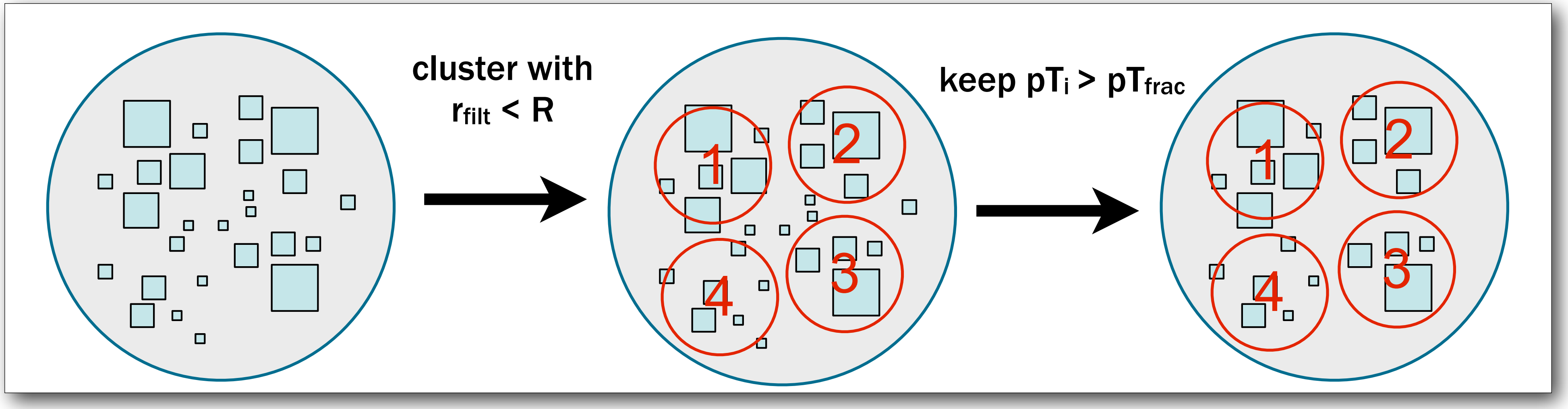
pileup is lumpy

use tracking to remove charged particles

says nothing about neutrals

grooming/topoclustering

only topological info, removes real radiation



PUPPI

for a particle *i* with nearby particles *j*

[1] define a local metric, α, that differs between pileup (PU) and leading vertex (LV)

example: 2-body system, for a particle **i**, what does particle **j** tell us?

$$\alpha_i^C = \log \left[\sum_{j \in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \right]$$

PUPPI

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[1] define a local metric, α, that differs between pileup (PU) and leading vertex (LV)

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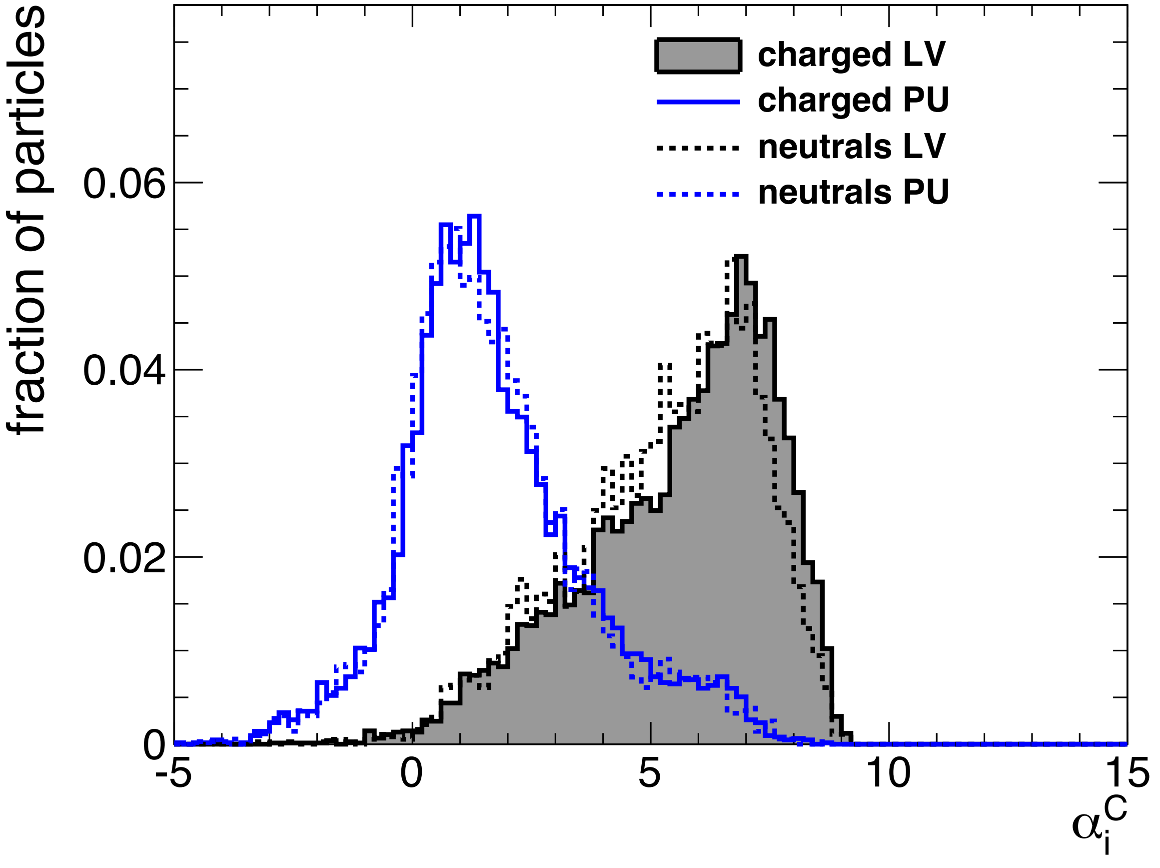


PUPPI

for a particle *i* with nearby particles *j*

[1] define a local metric, α, that differs between pileup (PU) and leading vertex (LV)

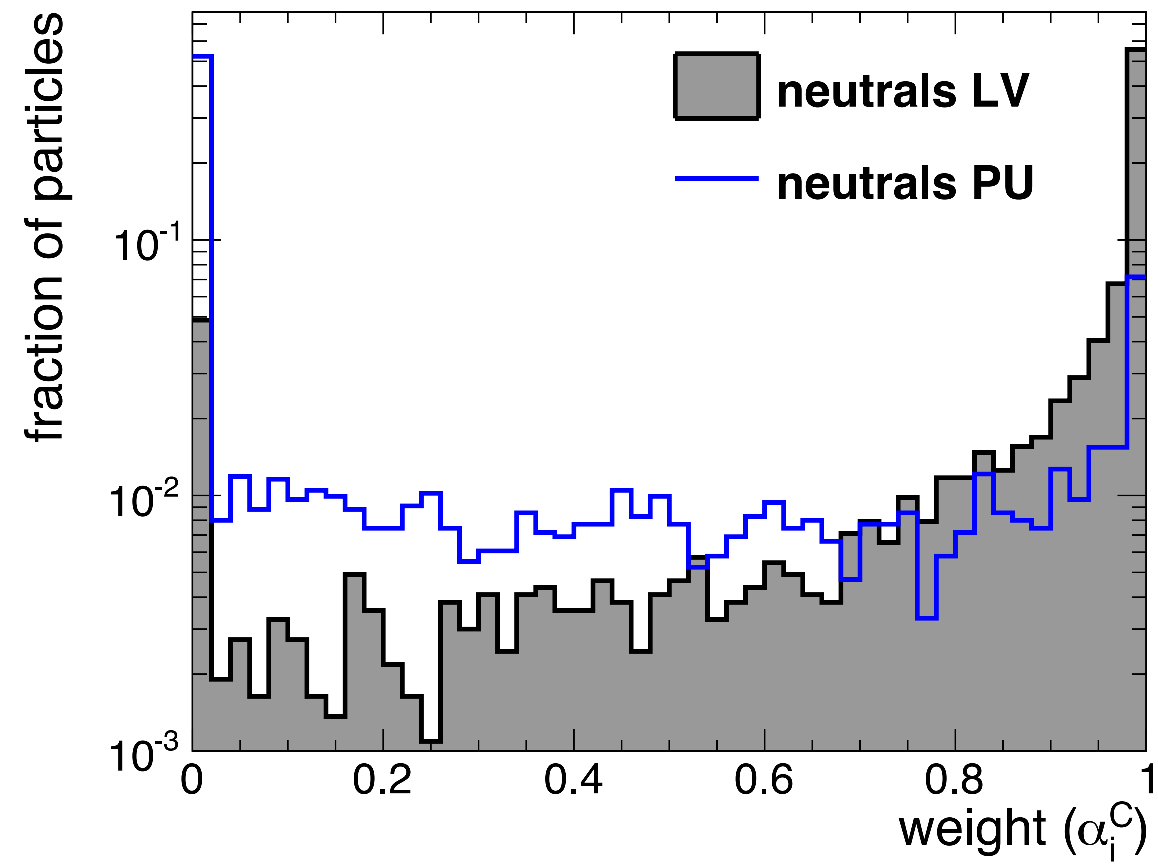
[2] using tracking information (e.g. charged particles) "sample" the event, define unique distributions of α for PU and LV

[3] for the neutrals, ask "how PU-like is α for this particle?", compute a weight for how un-PU-like (or LV-like) it is

[4] reweight the four-vector of the particle by this weight, then proceed to cluster the event as usual

example: 2-body system, for a particle **i**, what does particle **j** tell us?

$$\alpha_i^C = \log \left[\sum_{j \in \mathrm{Ch,LV}} \frac{p_{T,j}}{\Delta R_{ij}} \Theta(R_0 - \Delta R_{ij}) \right]$$



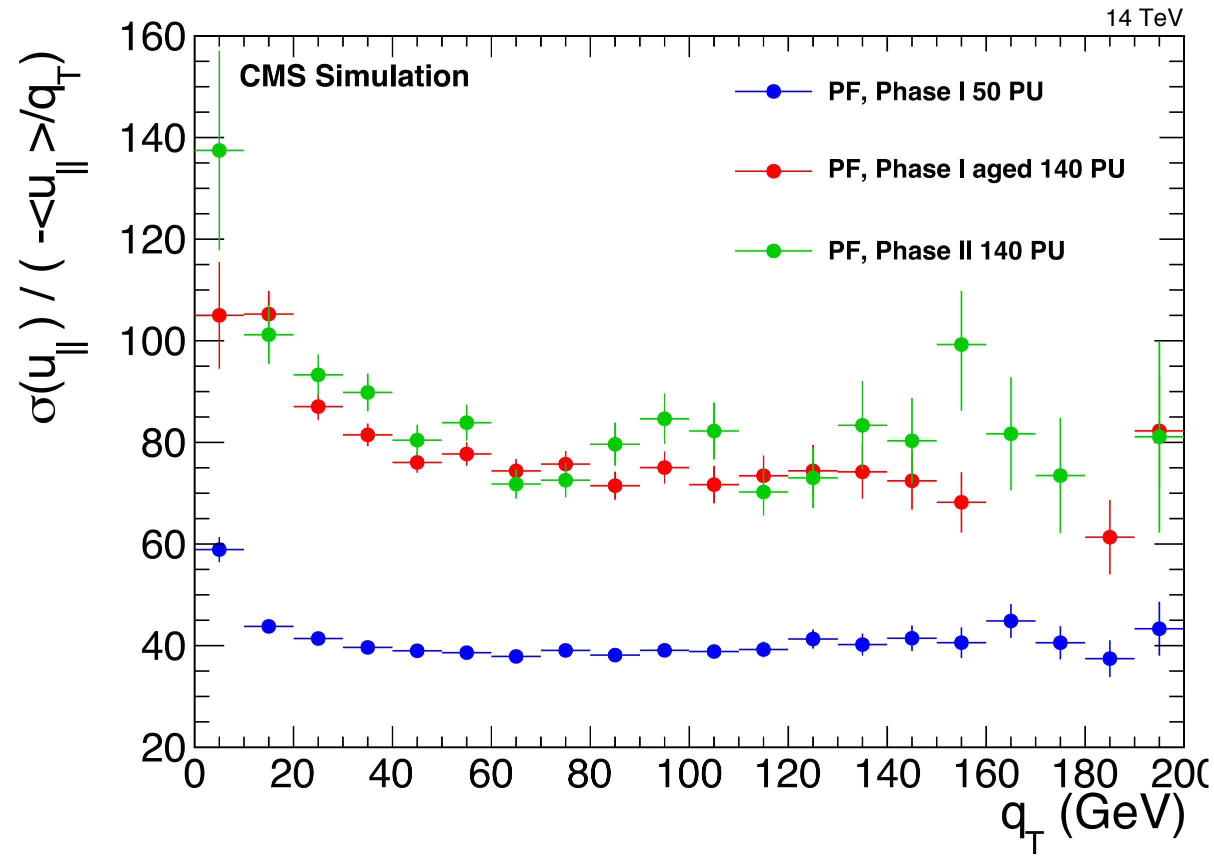
Technical proposal studies

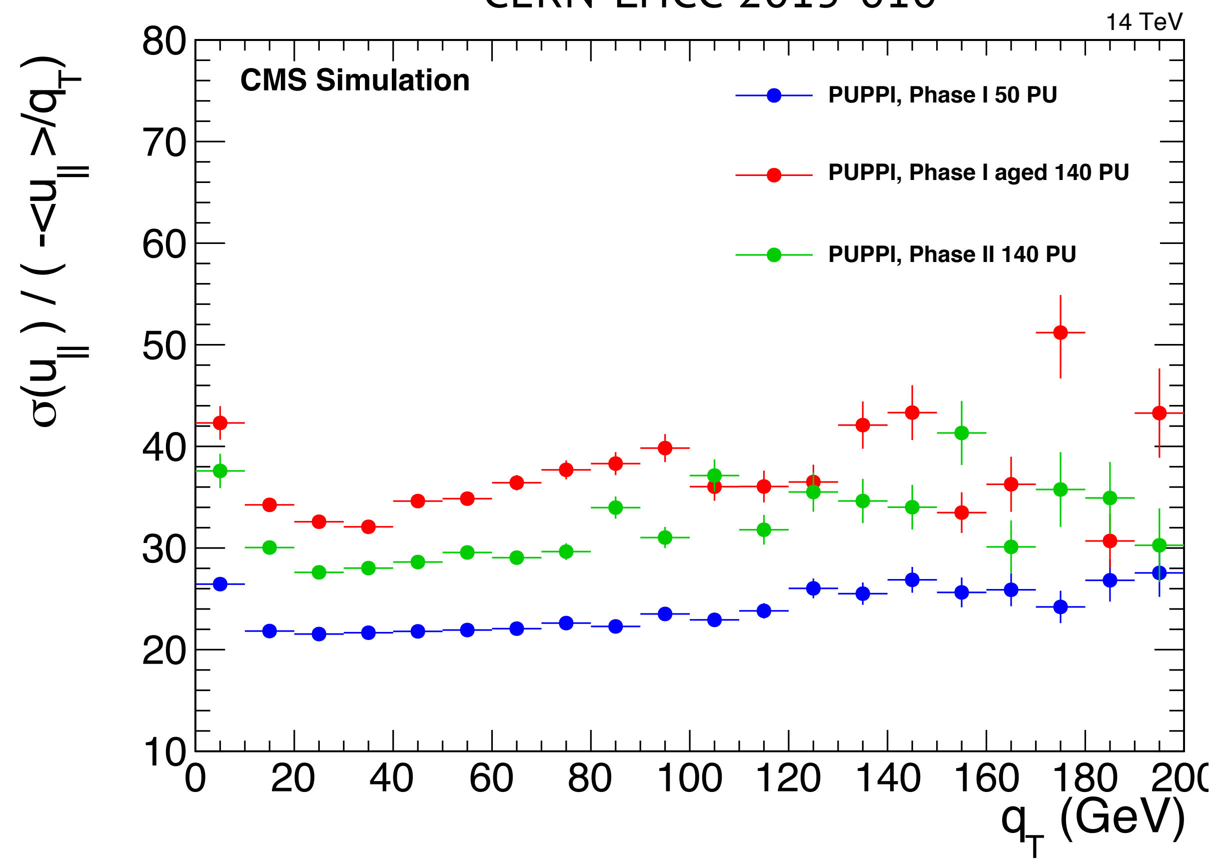
Focused primarily on jet p_T resolution and MET resolutions

- PUPPI implemented into DELPHES, tunes to be updated

MET shows strong gains from forward tracking and advanced methods; more detailed studied are needed

CERN-LHCC-2015-010





recoil resolution vs. W/Z qT

n.b. the different scales!