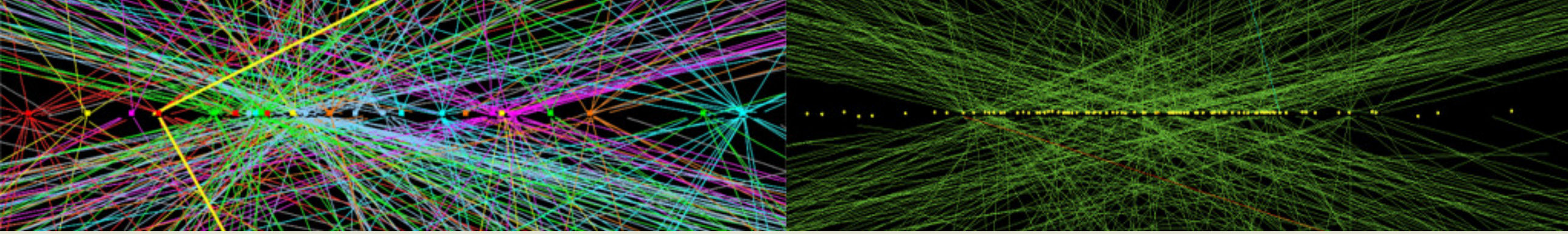
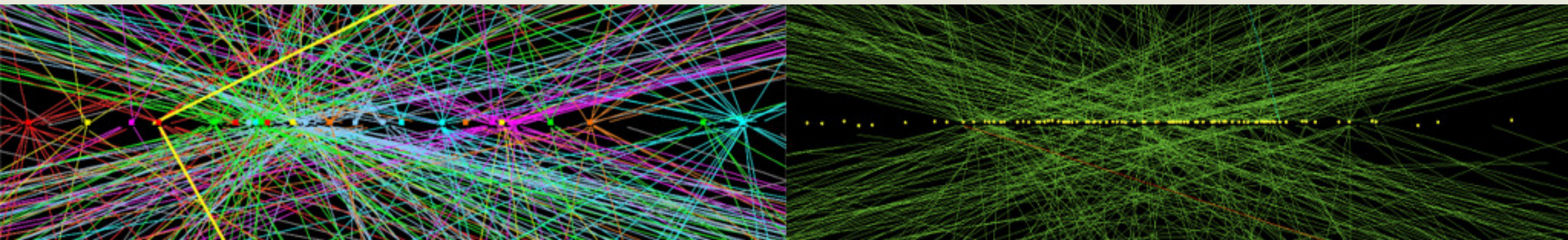
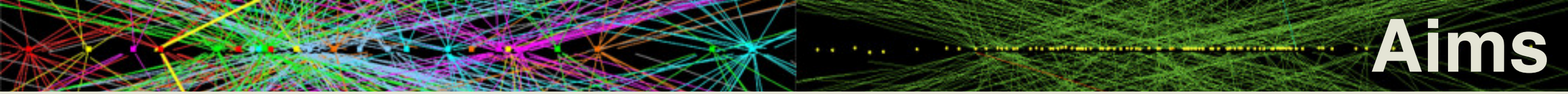


Summary of LPCC Workshop on Mitigation of pileup effects at the LHC

Filip Moorgat (CERN)
Gavin Salam (CERN)
Ariel Schwartzman (SLAC)





Aims

Bring together ATLAS, CMS & theorists to discuss

- Generic jet use: correcting jet transverse momenta and suppression of pileup jets
- Advanced jet use: correcting shapes and masses and groomers/taggers
- questions such as whether to correct whole jet observables (p_T, mass), the particle within a jet, or even attempt event-wide PU correction
- interplay of these questions with different experimental jet reconstruction methods (detector effects, topoclustering and particle flow, etc.)
- pileup in contexts beyond jets, such as lepton & photon isolation and missing transverse energy
- How best to perform comparisons between different experiments and with theorists' studies

Format

hands-on, 3-day weekend workshop for experts
16-18 May 2014, http://indico.cern.ch/event/306155/

Discussion talks, organized in three main themes:

- New pileup removal techniques
- Pileup suppression and experimental issues
- Pileup mitigation techniques for missing ET and heavy ions

- **Hands-on sessions:**
  - Try out and share pileup mitigation code and results using standalone analysis code and event samples
- **Working group reports**

Many thanks to **Matteo Caccari, Pascal Nef**, **Gregory Soyez**, and **Nhan Tran** for their (significant) contribution to preparing the code infrastructure and examples

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  - Try out and share pileup mitigation code and results using standalone analysis code and event samples

- **Working group reports**

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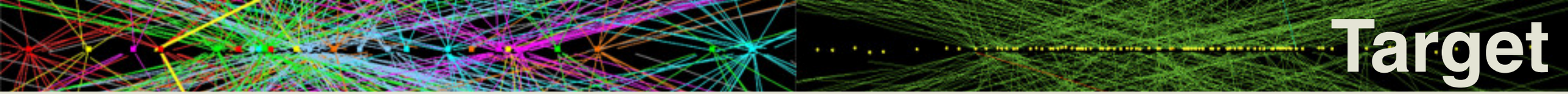
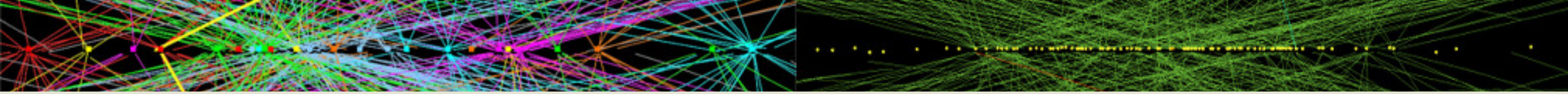


Mainly geared towards LHC
from Run II → high-lumi LHC

But methods developed here may
also be useful for 100 TeV pp collider

To get full benefit of higher energy, i.e. be sensitive to particle masses 100TeV/14TeV ≃ 7 times higher than HL-LHC, FCC-hh would need to collect 150 ab^{-1}

Hardware & “beamware” aspects are important,
but were beyond scope of workshop
(detector timing, forward tracking
beam-spot shaping, etc.)



State of the art

Existing methods

ATLAS

Topoclusters

CMS

Particle flow
with charged-hadron
subtraction (CHS)

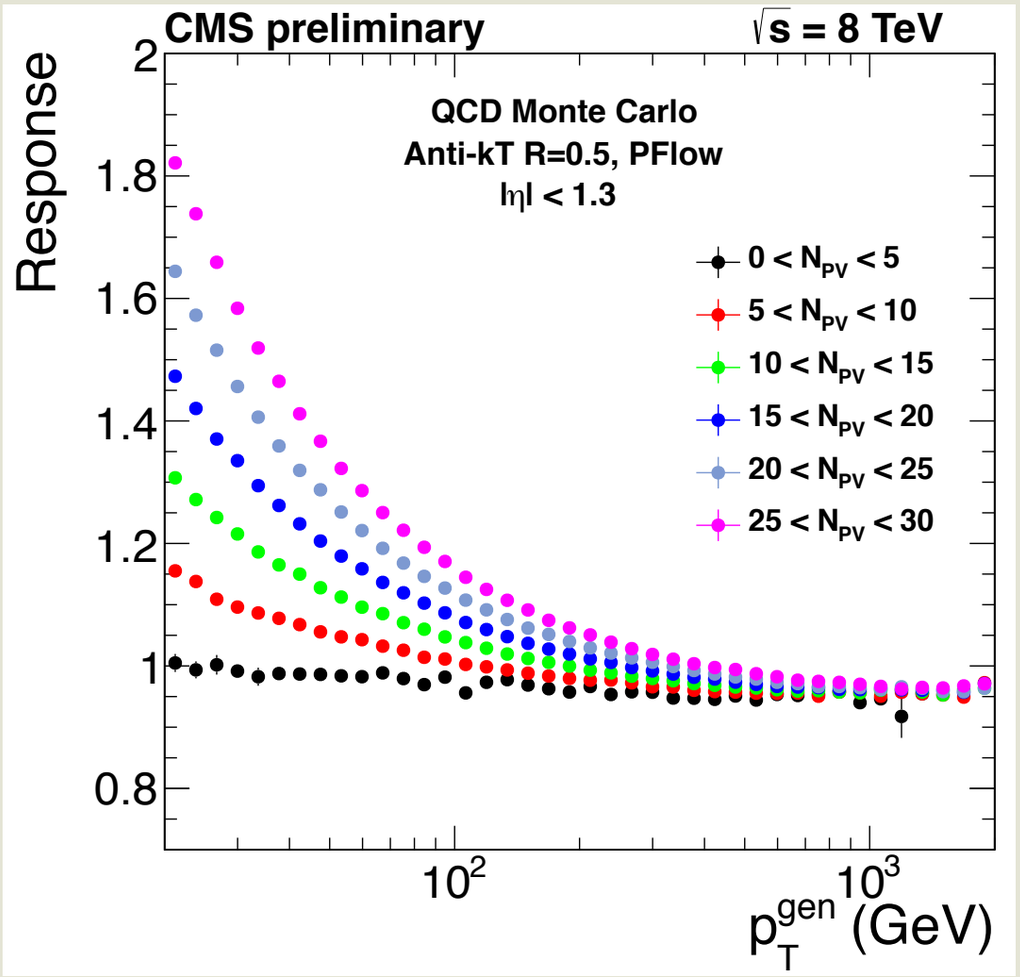
+
area–median subtraction

$p_t \rightarrow p_t - \rho A_{jet}$

ρ from median energy flow
across patches in event

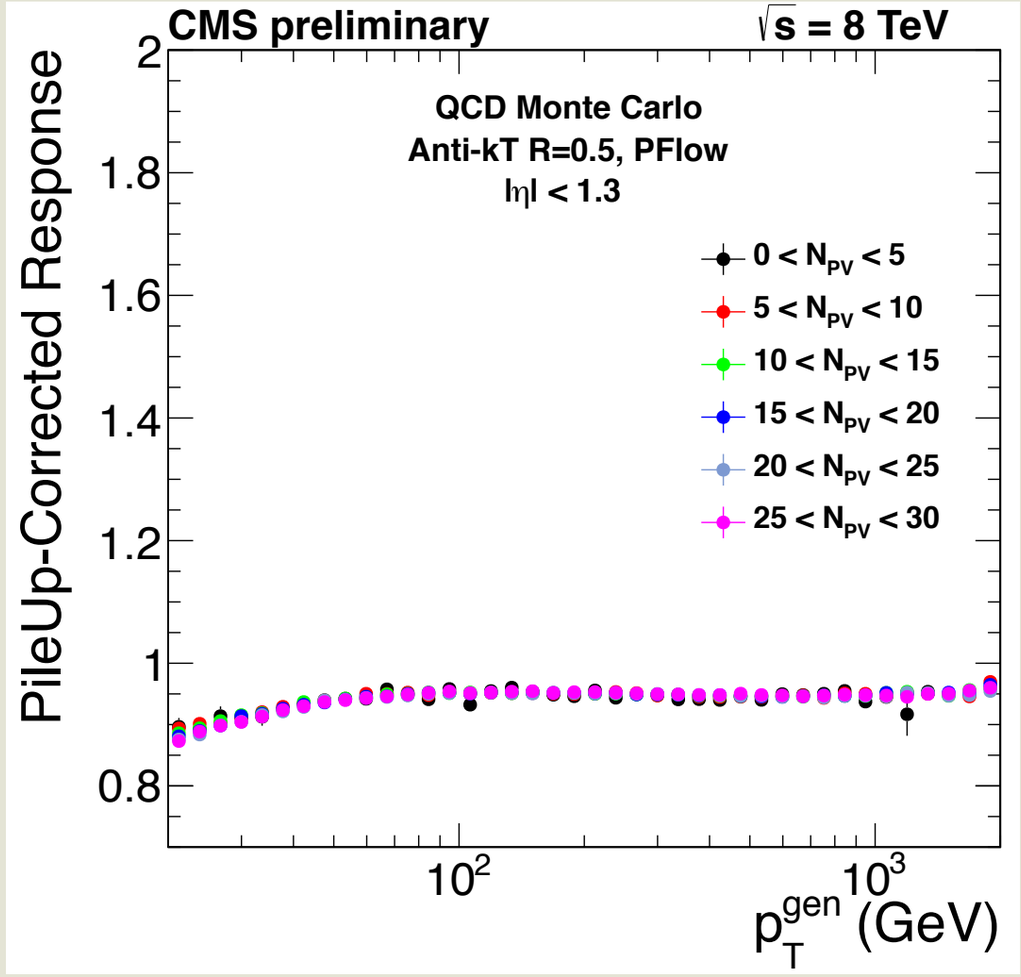
Example from CMS: offset

Before PU correction



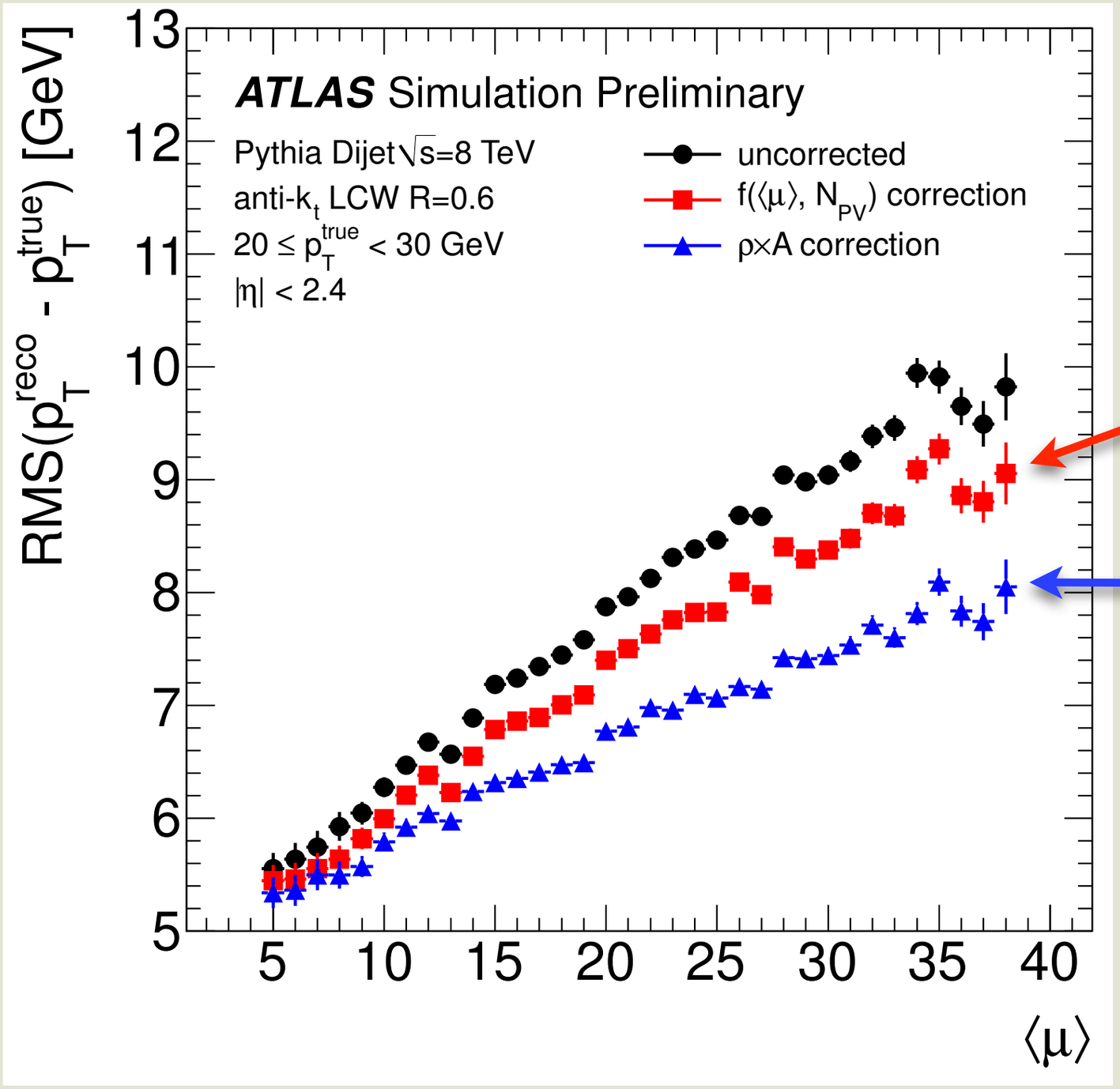
Strong dependence of jet response on N_{PV}

After PU correction



Almost no dependence of jet response on N_{PV}

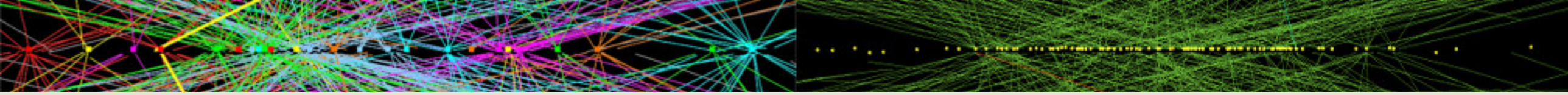
Example from ATLAS: resolution



Offset method (Tevatron style)

Jet area method

10–15% gain in resolution is considered valuable



New methods for correcting jet kinematics and shapes

Warning: if a plot is not labeled ATLAS/CMS, it's often a particle-level study. Detector-level conclusions may differ.

Inputs to cleansing

Let us assume we can measure

$p_\mu^{\rm tot}$ = total momentum in a subjet (charge+neutral)

$p_T^{\rm C,LV}$ = total charged energy in subjet coming from leading vertex

$p_T^{\rm C,PU}$ = total charged energy in subjet coming from PU vertices

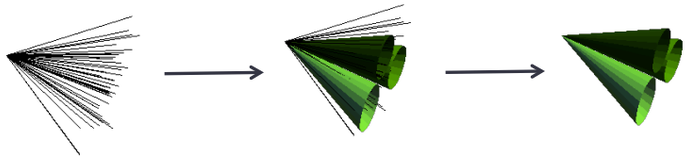
Goal: combine these to get

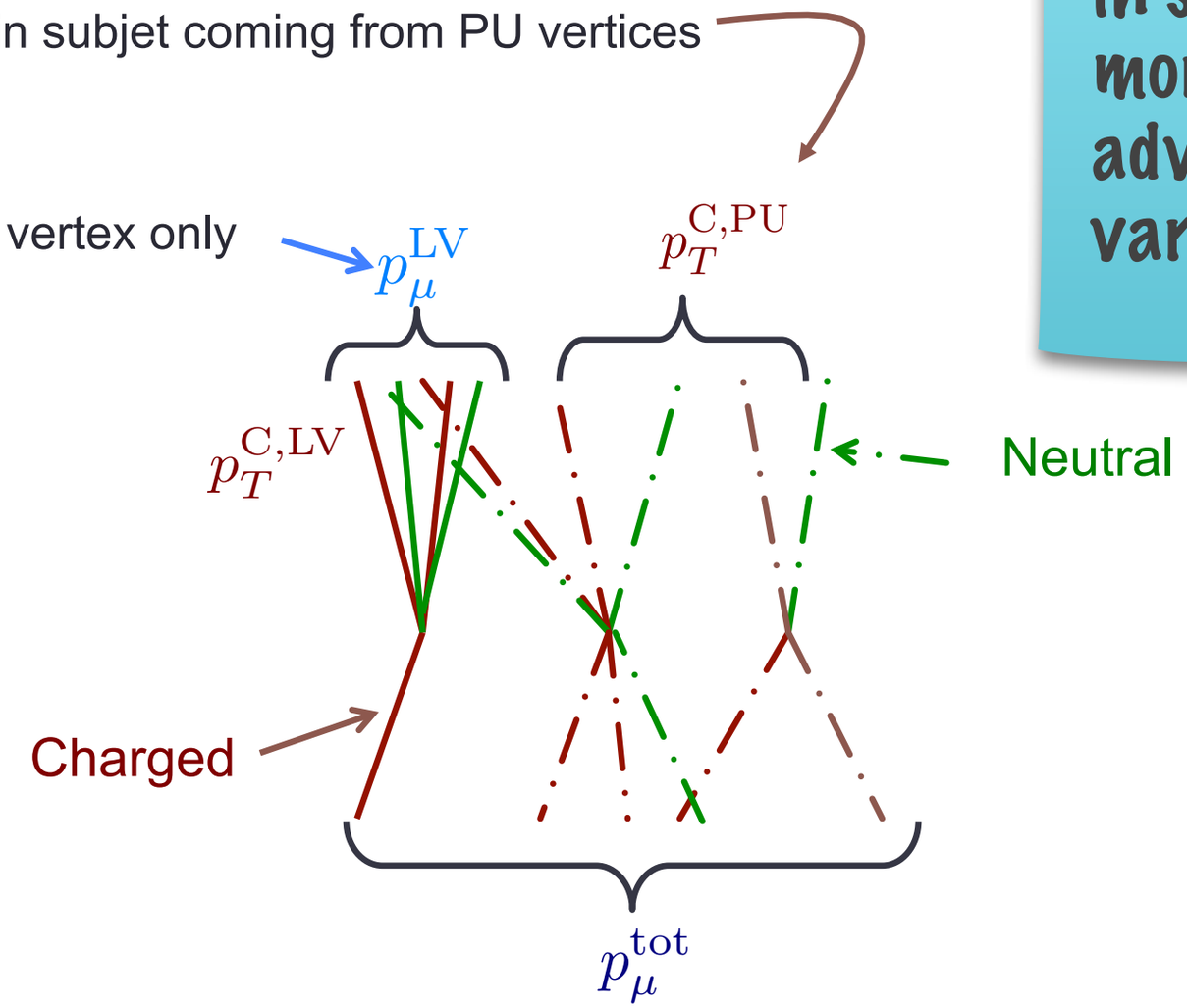
$p_\mu^{\rm LV}$ = 4-momentum of subjet, leading vertex only

Breaks jet into subjets, corrects each one in proportion to charged pileup in subjet (+ more advanced variants)

Use subjets

- Natural infrared safe constituents are subjets
  - Find jets, then recluster at smaller R.
  - Can drop some soft subjets (e.g. filtering, trimming, pruning)

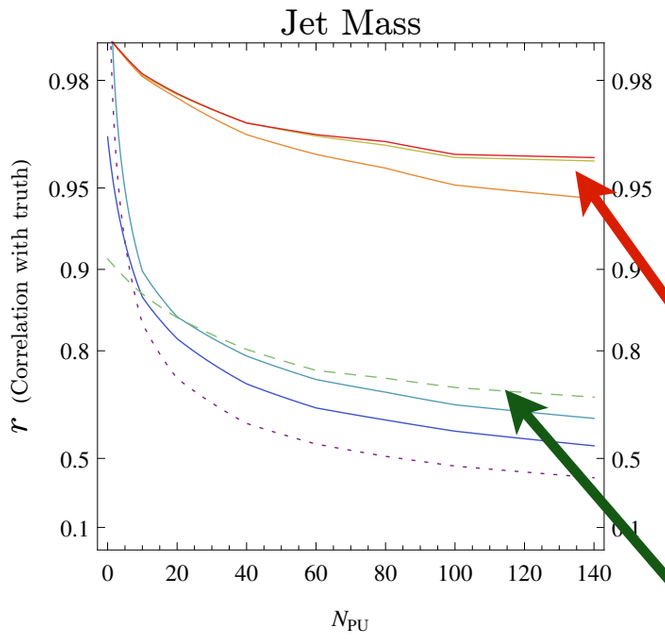




Cleansing

Our original results (KLSW)

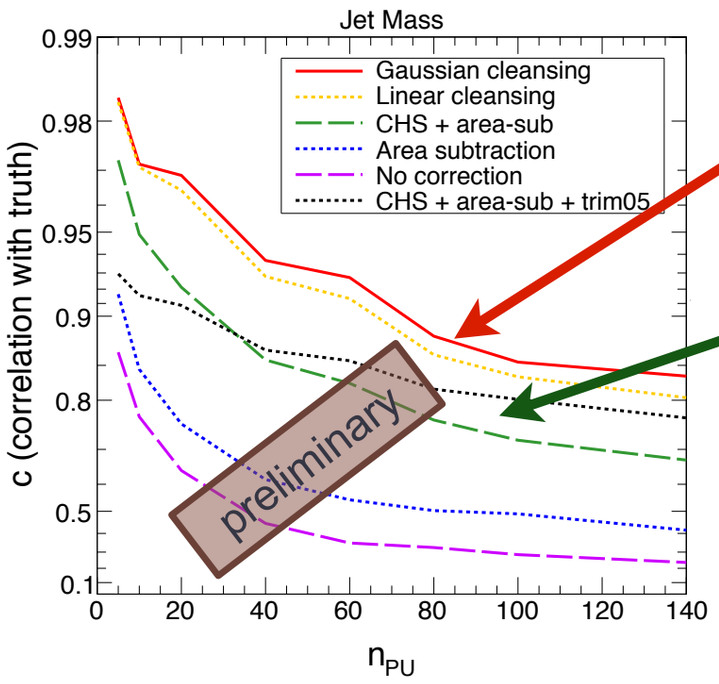
- Cleansing
  R_{sub}=0.3
- KLSW truth definition
- Fastjet area subtraction

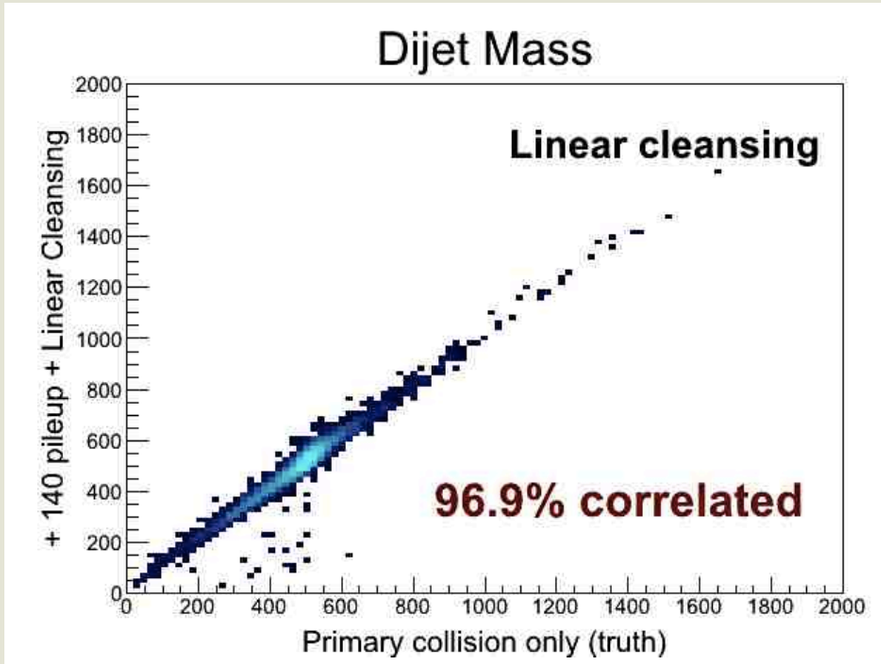


Better

Our results (new)

- Cleansing
  R_{sub}=0.3
- CSS truth definition
- Safe area subtraction





NEW: cleansing, better than

OLD: area subtraction

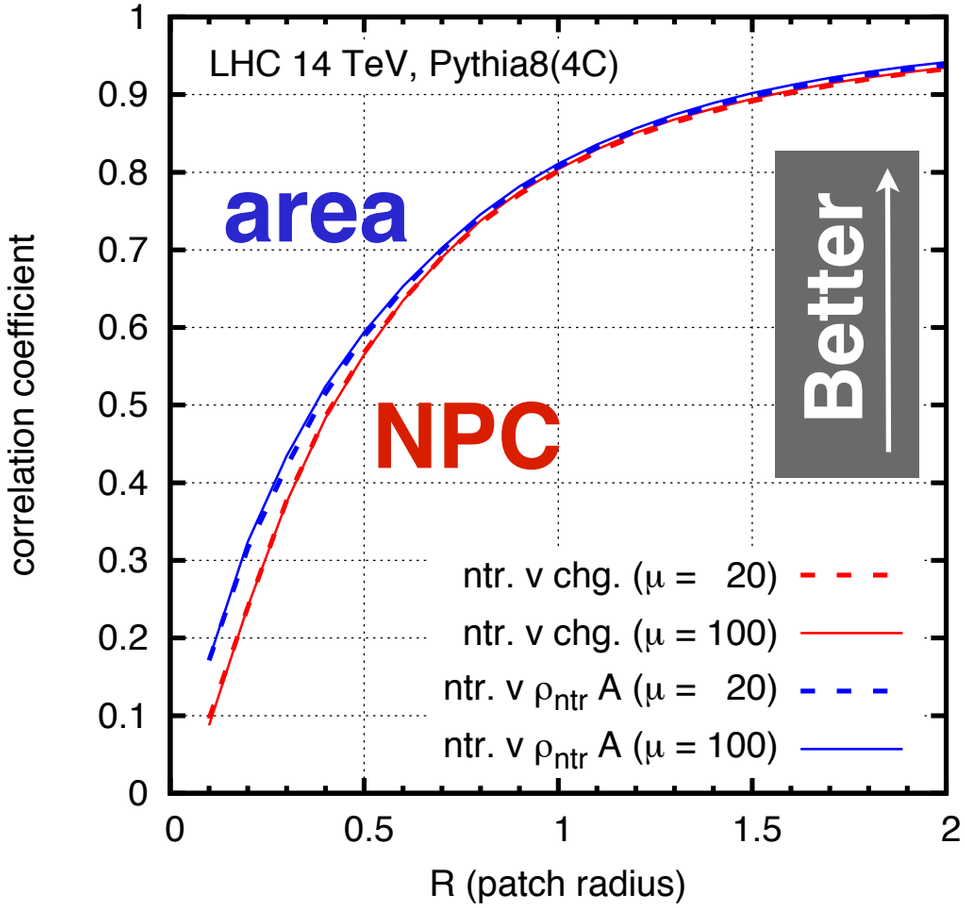
higher correlation-coefs are better

Neutral Proportional to Charge (NPC)

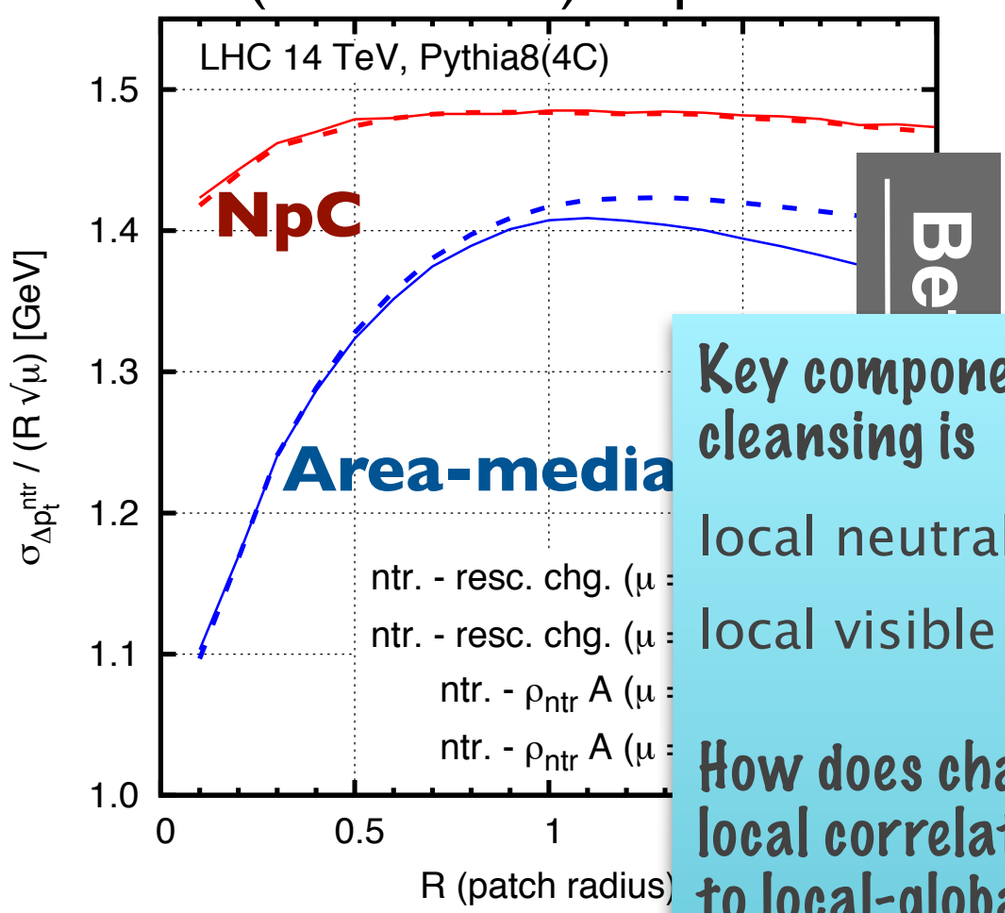
Matteo Cacciari

area-median v. NpC

Correlation coefficient



(normalized) dispersion



Key component of cleansing is

local neutral PU ∝

local visible charged PU.

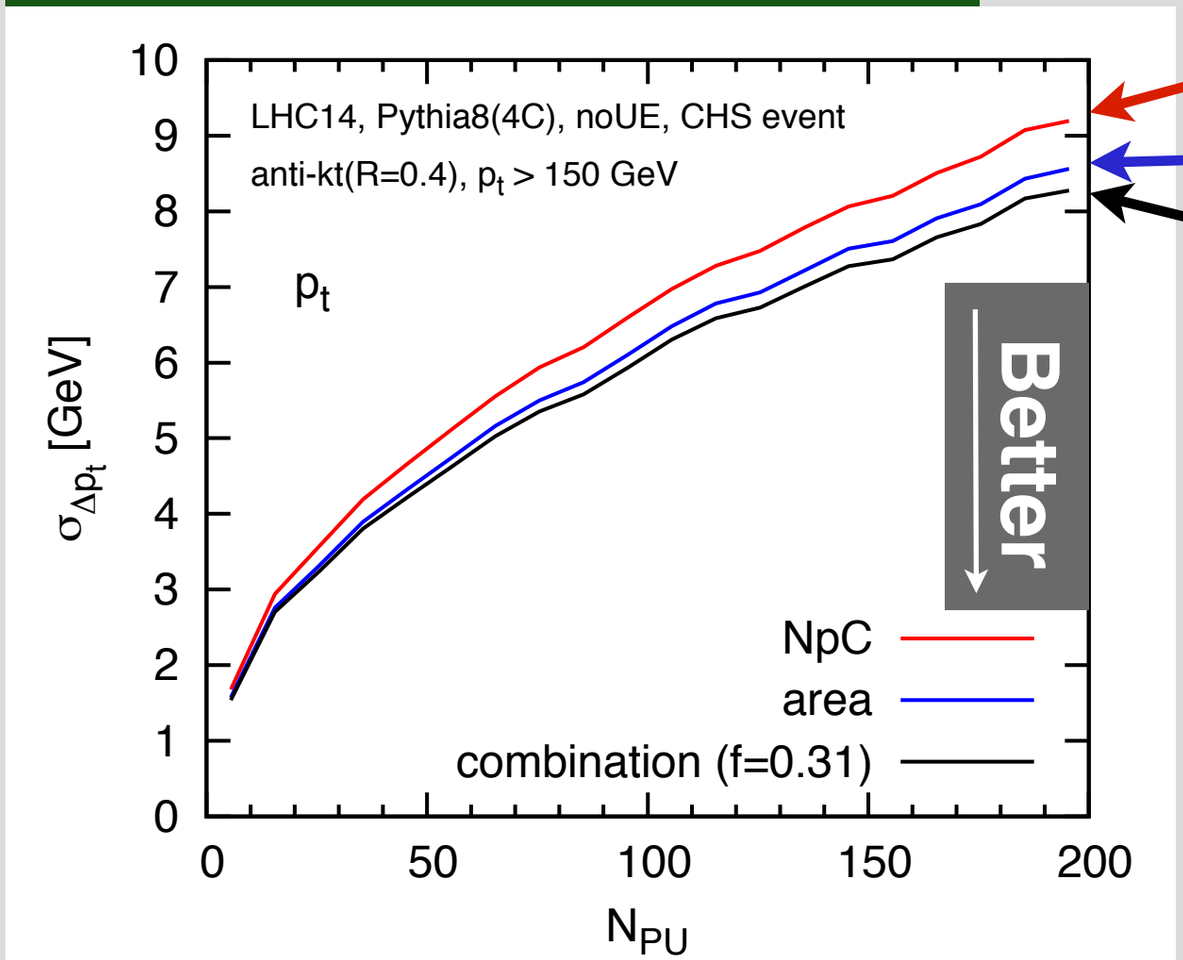
How does charge-neutral local correlation compare to local-global correlation used in area-median subtraction?

NpC is no better than area-median at estimating the neutral component of pileup p_t^{ntr} in a patch

In fact, area-median is slightly better at all values of R, and especially at small R (< 0.5)

Neutral Proportional to Charge (NPC)

Performance on jet p_t

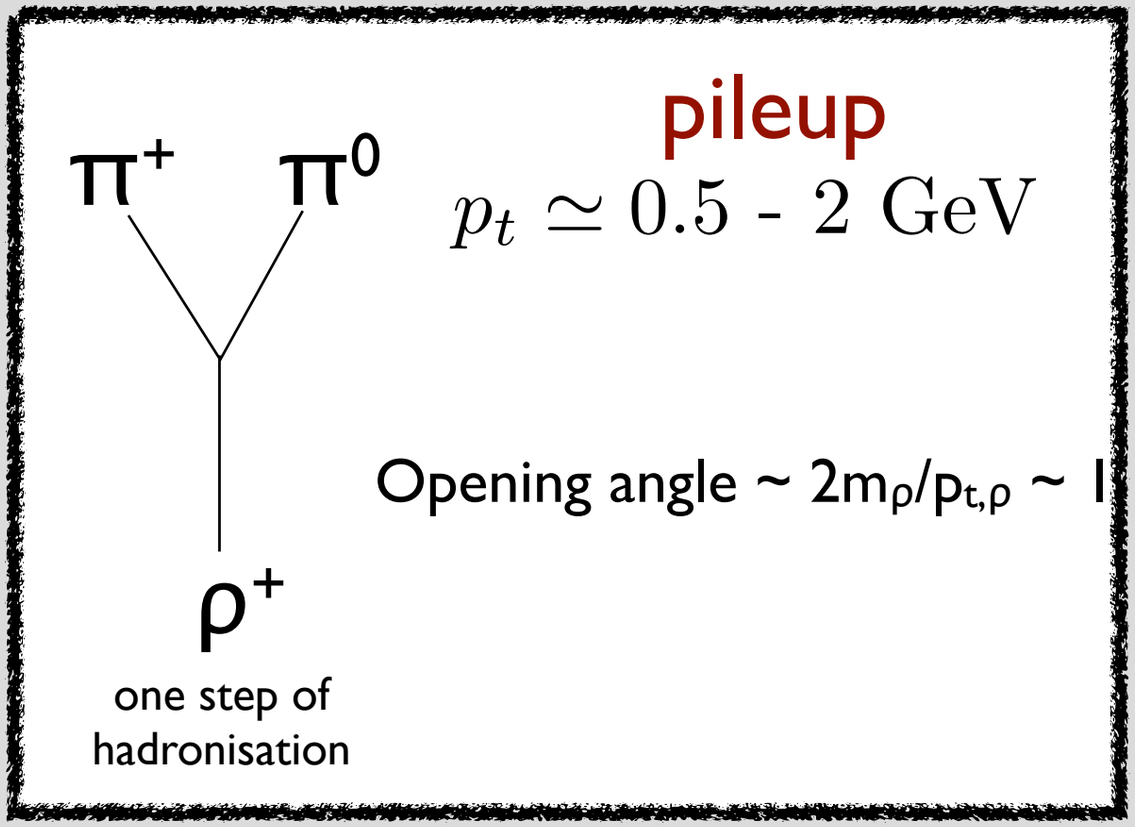


NpC

Area

Both, linearly combined

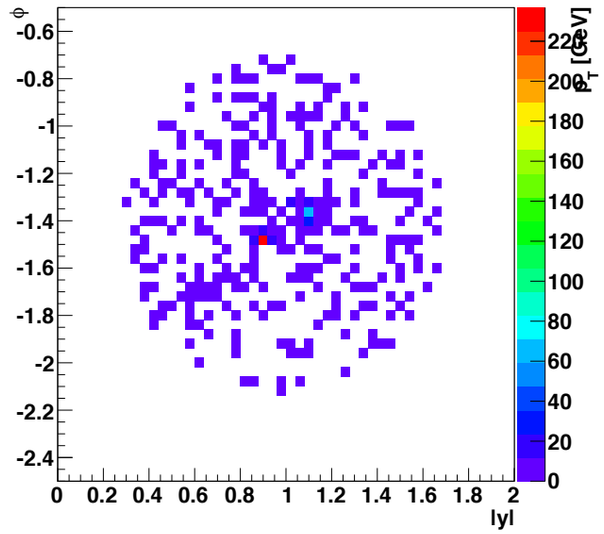
So why does cleansing paper appear to see such good performance...?



Constituent Subtraction

Example jet clustered with anti-k_t with R=0.7

Peter Berta



jet with pileup

jet without pileup

ghosts clustered into the jet

jet after correction

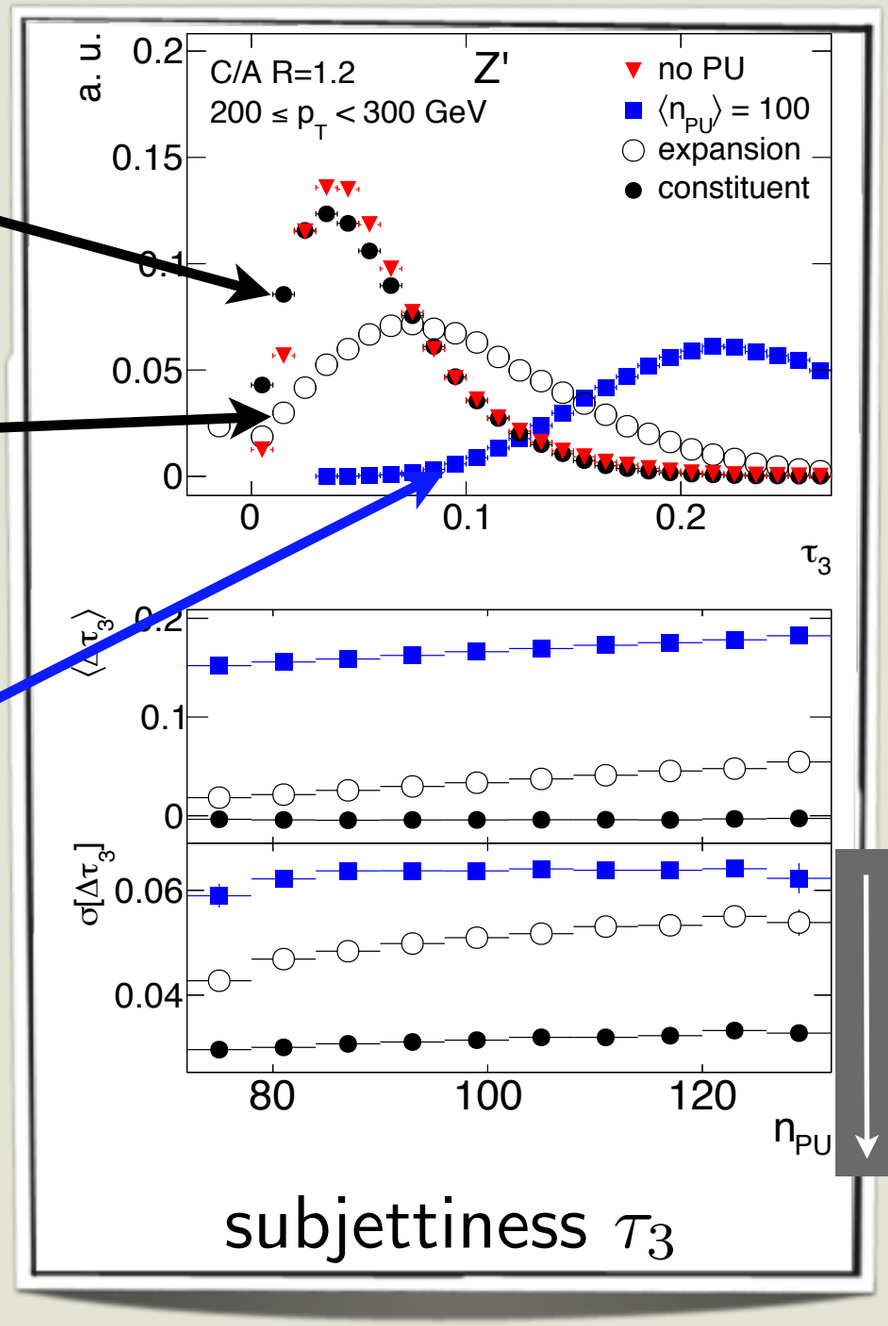
A recipe, locally within a jet, to cancel "negative" ghosts against "positive" pileup

Constituent Subtraction

NEW: constituent subtraction

OLD: shape subtraction

no correction



Peter Berta

One Solution: Jet Reclustering

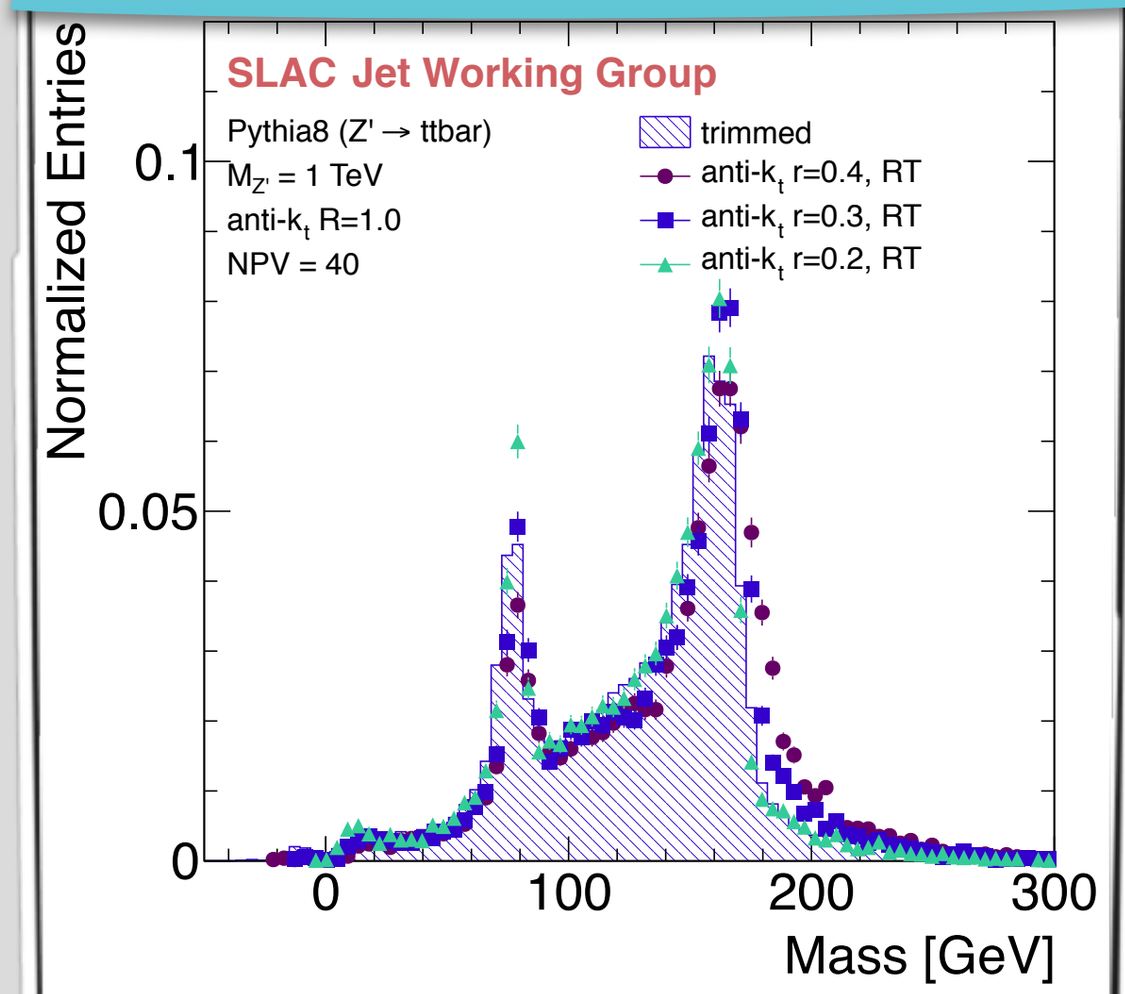
- ATLAS (and now CMS!) have one existing, exquisitely understood jet collection: $r = 0.4$
- Can use small-r jets as input to large-R algorithm
  - Already used by ATLAS in several analyses, mostly for technical reasons (lack of information in datasets)
- Immediate benefit: substructure becomes **accessible** and **flexible**
  - In this talk we perform a systematic study and optimization of this approach to gain a deeper understanding
  - What do we lose (or gain?) when using small jets as inputs?

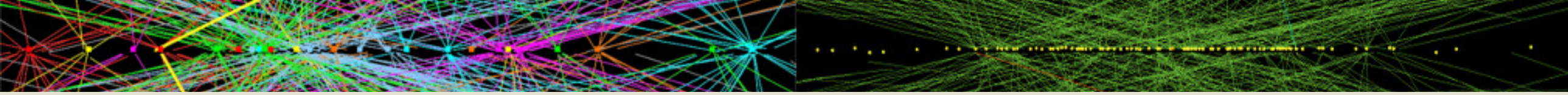
Max Swiatlowski

Jet Reclustering

Don't try to directly handle large-R jets

Instead construct them from R=0.4 jets (experimentally very well understood)





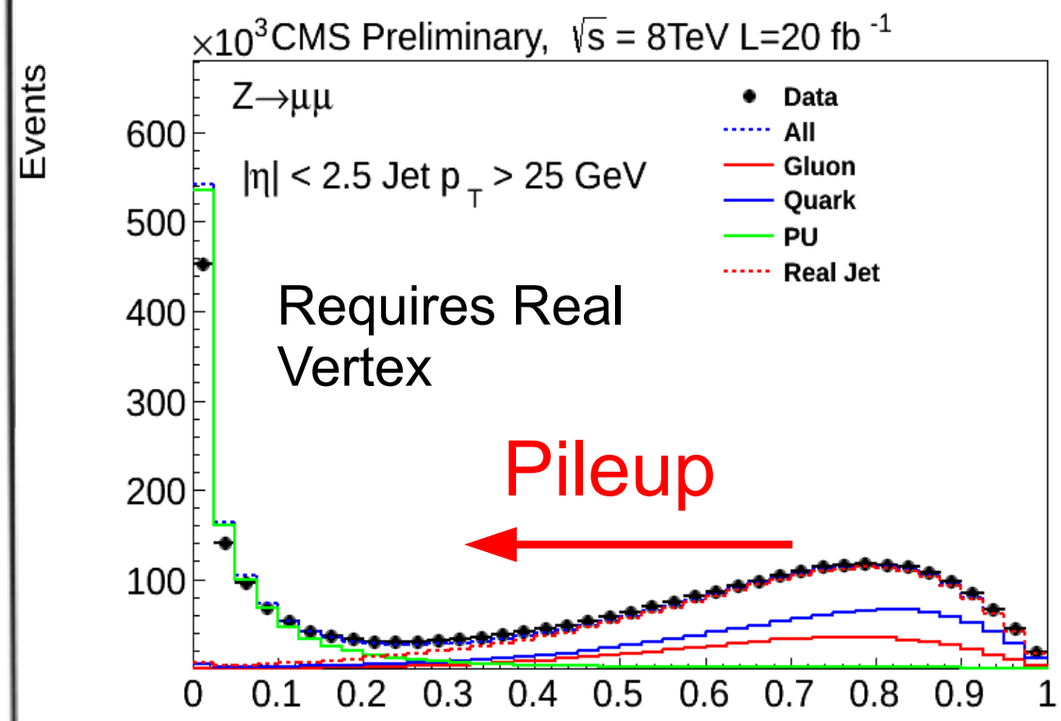
Rejecting jets that are from pileup

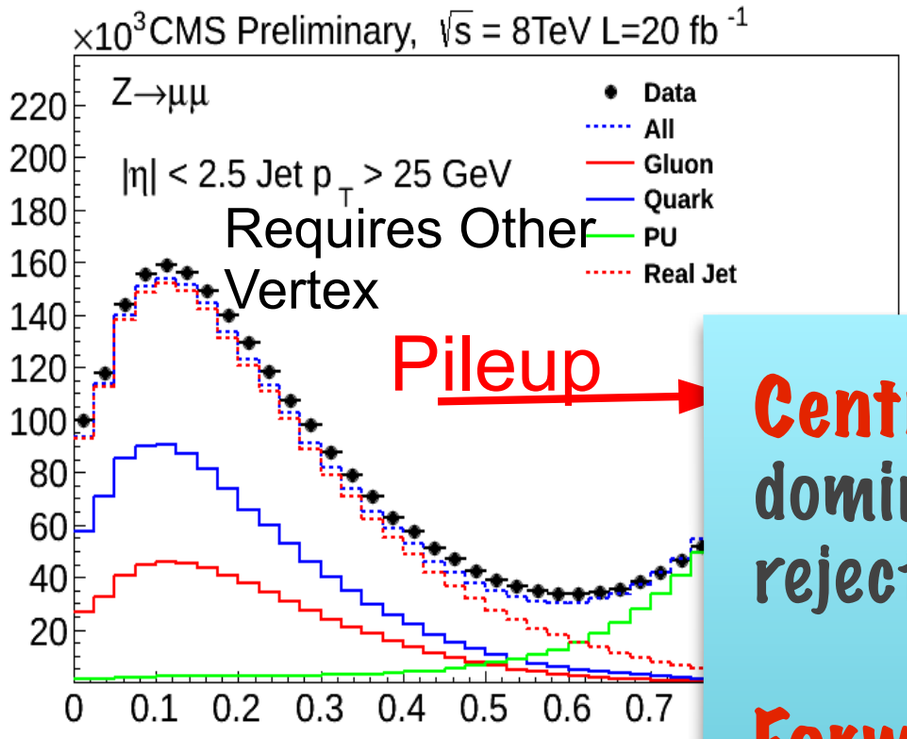
Pileup Jet Id Algorithm:Tracking

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

#vertices, dZ of leading track in jet +

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

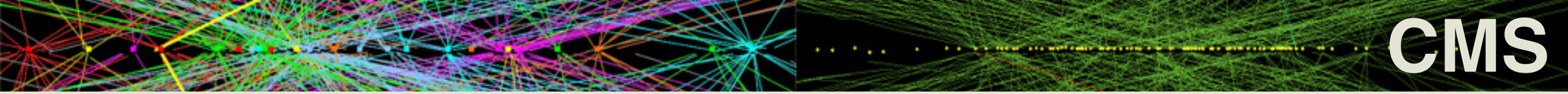




Pileup tends to degrade performance of these var

Central: tracking dominates PU jet rejection

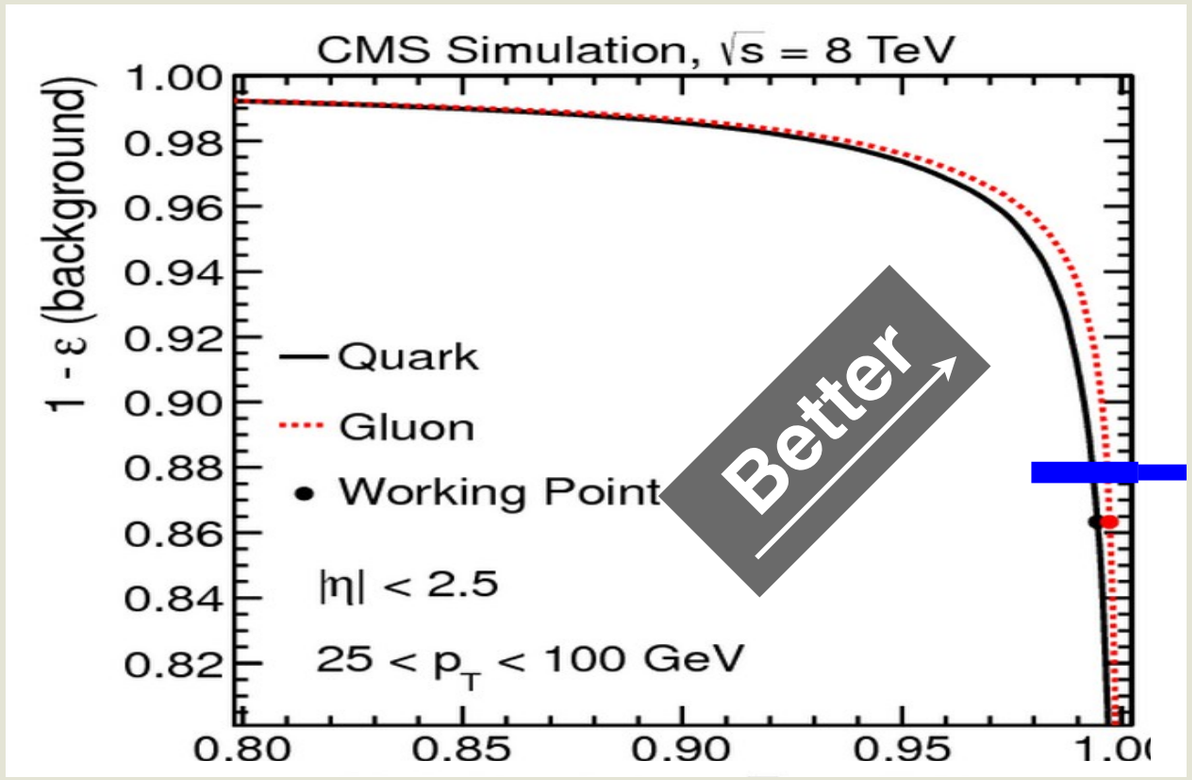
Forward: jet shapes

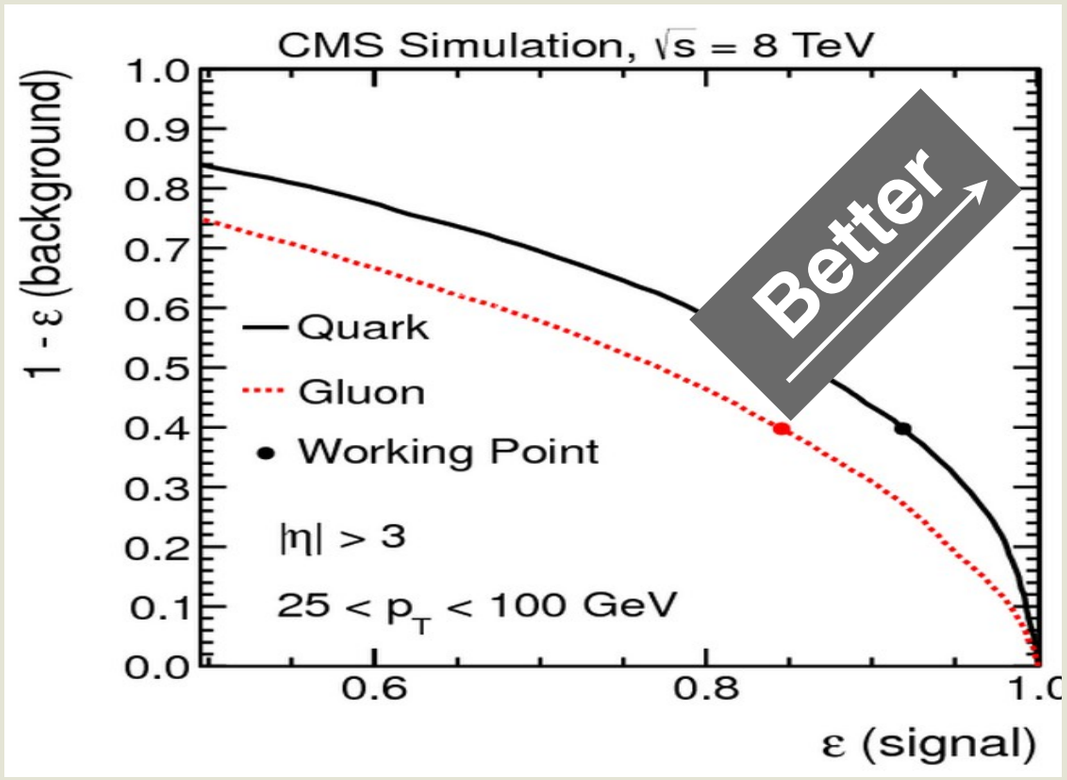


Central

Forward

Bkgd rejection





Signal efficiency

Central: tracking dominates PU jet rejection

Forward: jet shapes

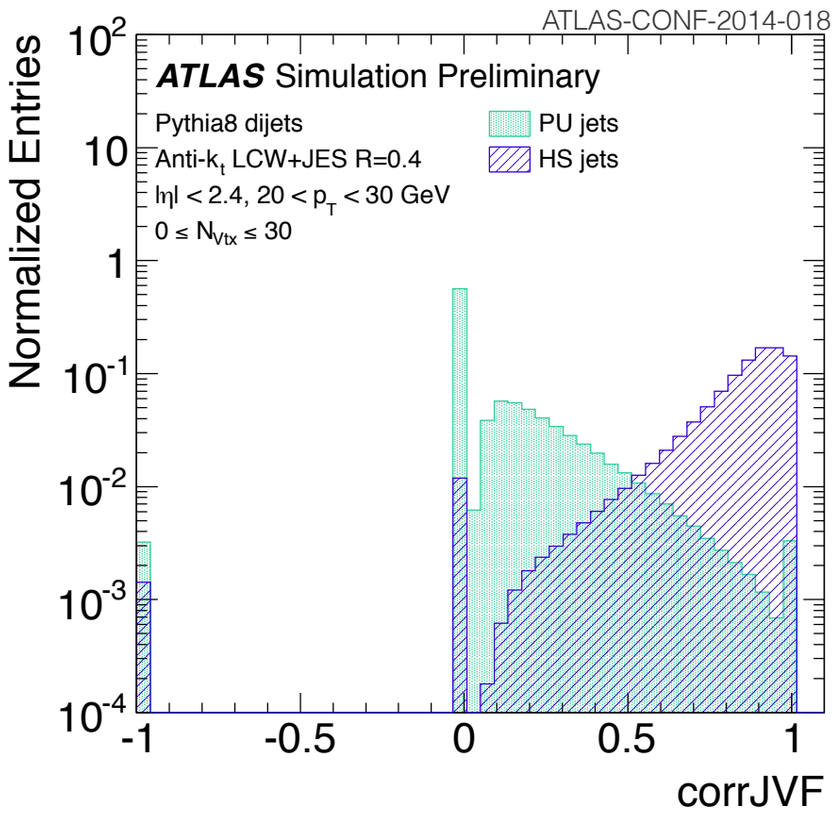
from JVF to corrJVF

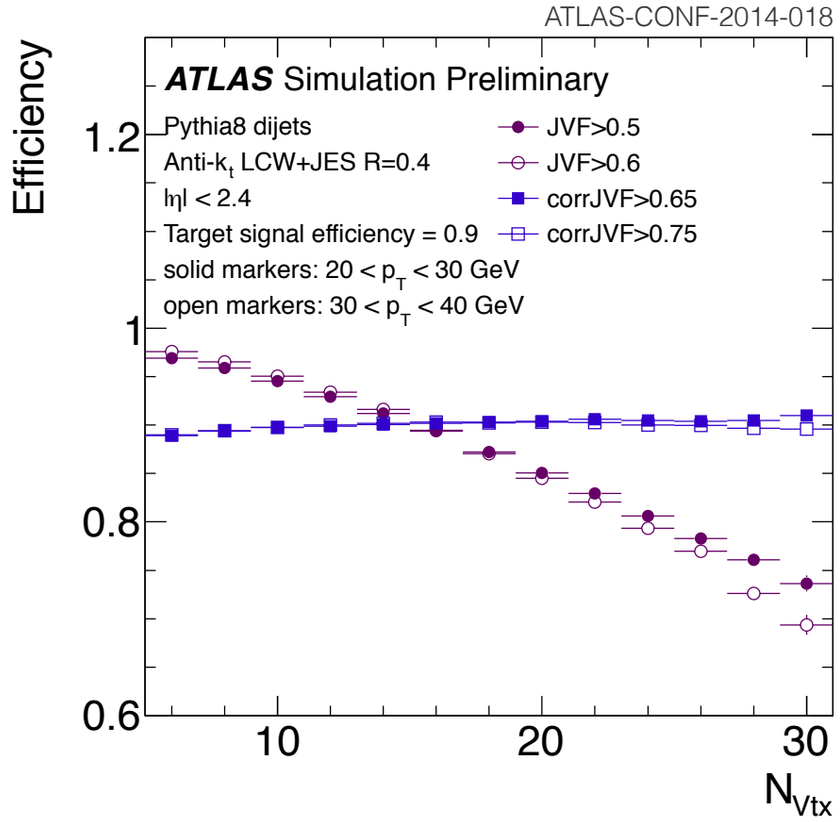
- Correcting JVF (in average) for its pileup dependence:

$$\mathrm{corrJVF} = \frac{\sum_k p_{\mathrm{T}}^{\mathrm{trk}_k}(\mathrm{PV}_0)}{\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_0) + \frac{\sum_{n\geq 1}\sum_l p_{\mathrm{T}}^{\mathrm{trk}_l}(\mathrm{PV}_n)}{(k\cdot n_{\mathrm{trk}}^{\mathrm{PU}})}}$$

- mean p_T from pileup tracks associated with jets increas
  linearly with the **total number of pileup tracks in the event** (n_{trk}^{PU})
  - n_{trk}^{PU} is a proxy for the event pileup activity:
  - tried different variables: μ, N_{Vtx}, p_T density ρ

Emphasis on finding variables naturally stable across different levels of pileup

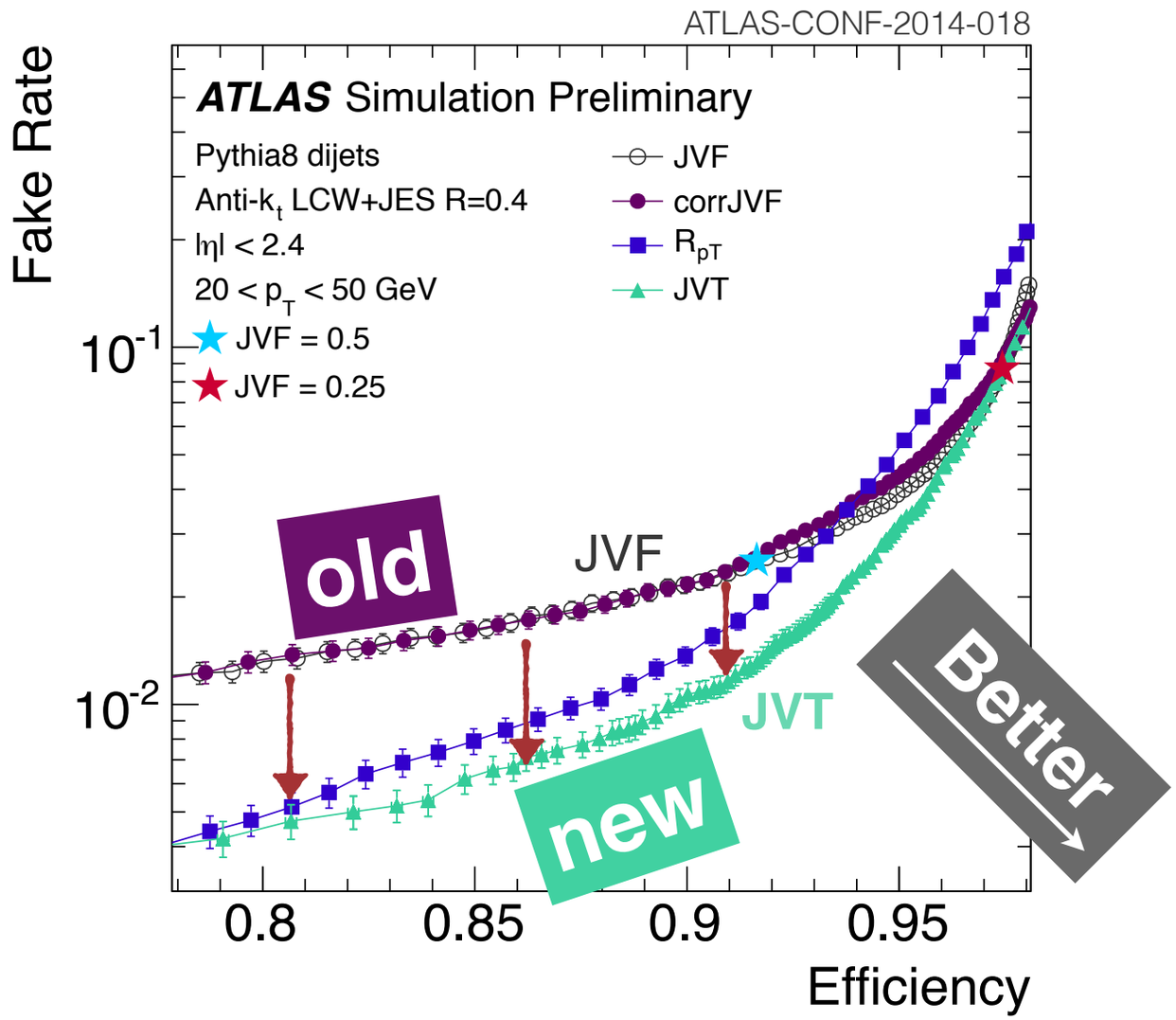




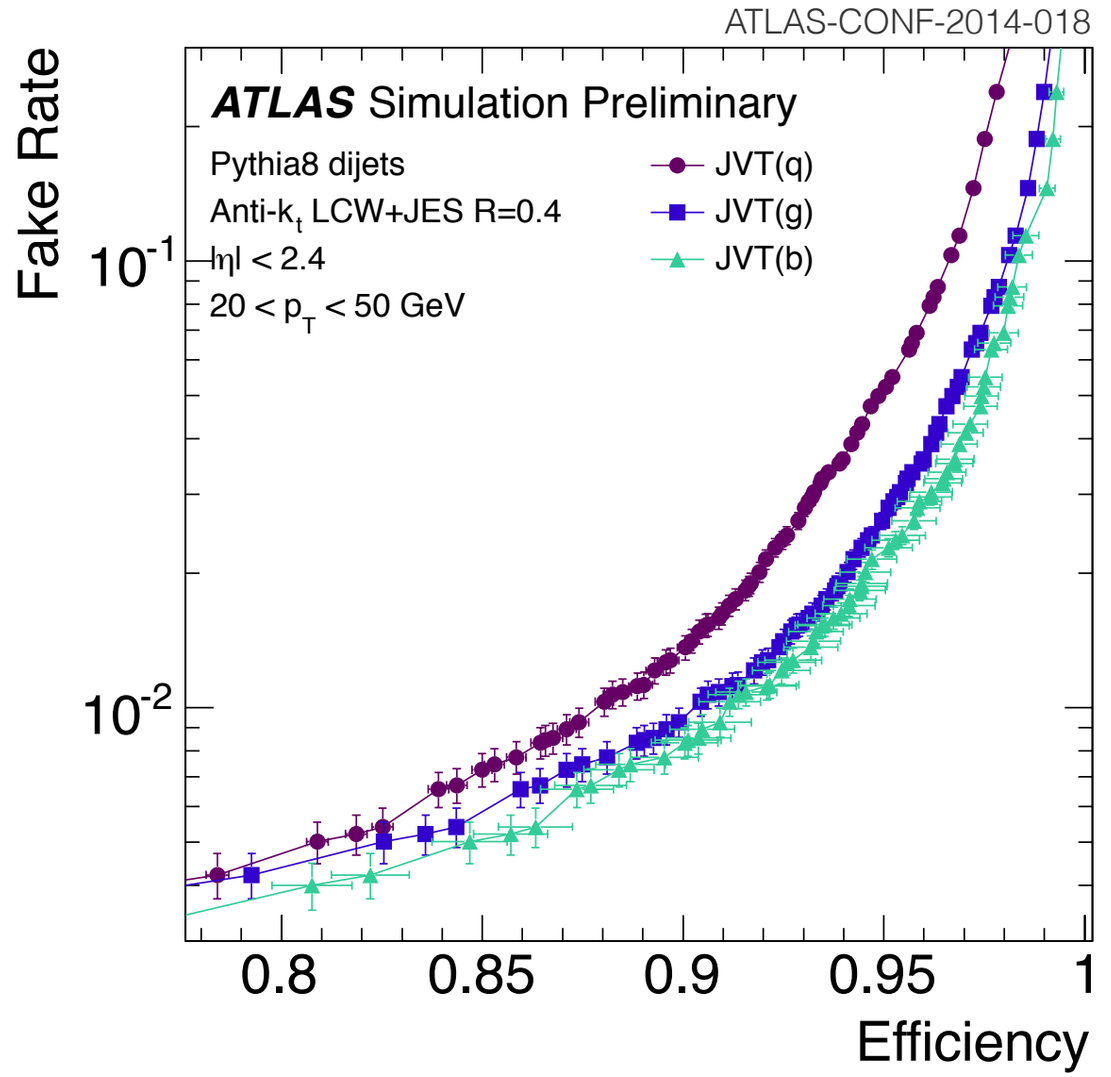
ACCELERATOR LABORATORY

ATLAS PU jet rejection

old v. new

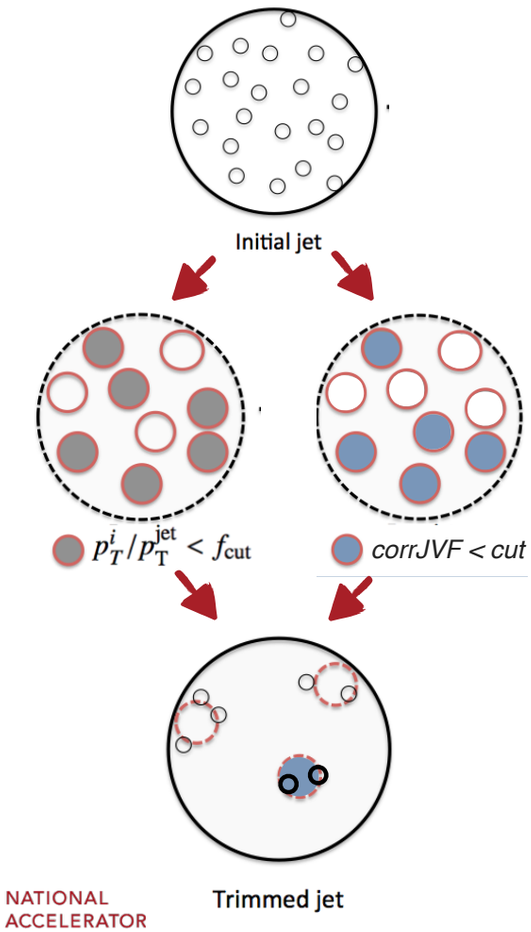


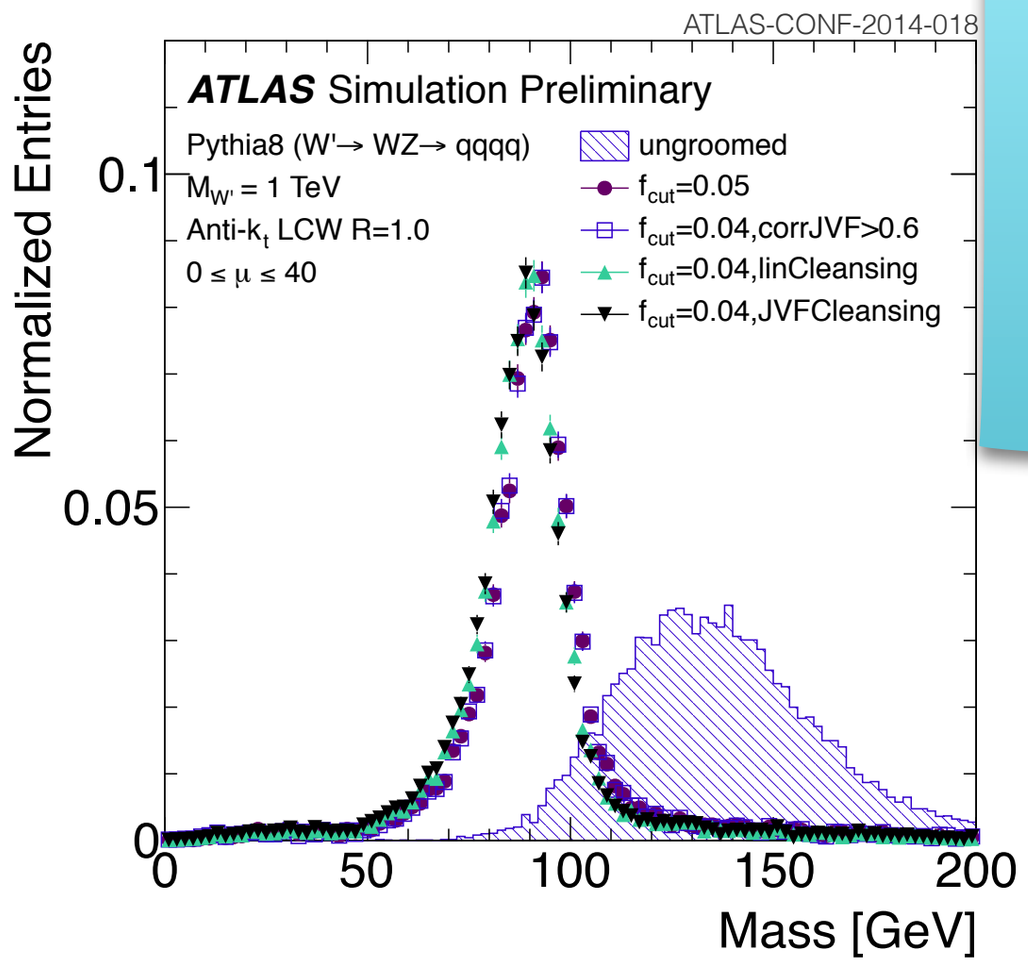
flavour dependence



corrJVF-based grooming

- corrJVF-based grooming
  - use subjet corrJVF in combination with trimming to groom large-R jets
- this is different **not** a '**neutral-proportional-to-charge**' approach!



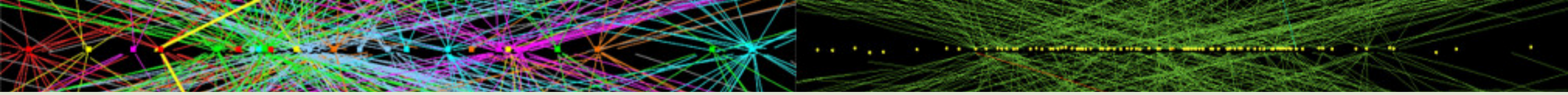


- for 2012 pileup conditions, no improvement observed w.r.t. calorimeter-only based trimming
  - similar conclusion for jet cleansing [1309.4777] (updated due to bug)

Breaks jet into subjets, discards those identified as dominantly from pileup

SLAC NATIONAL ACCELERATOR LABORATORY

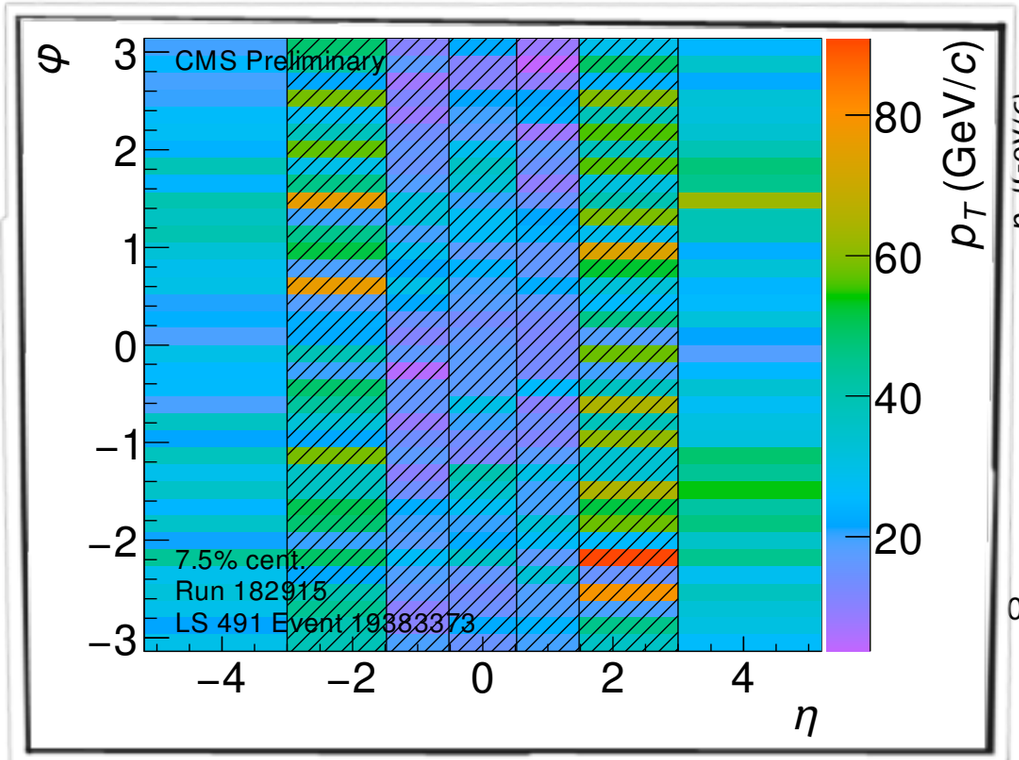
Pascal Nef (ATLAS)

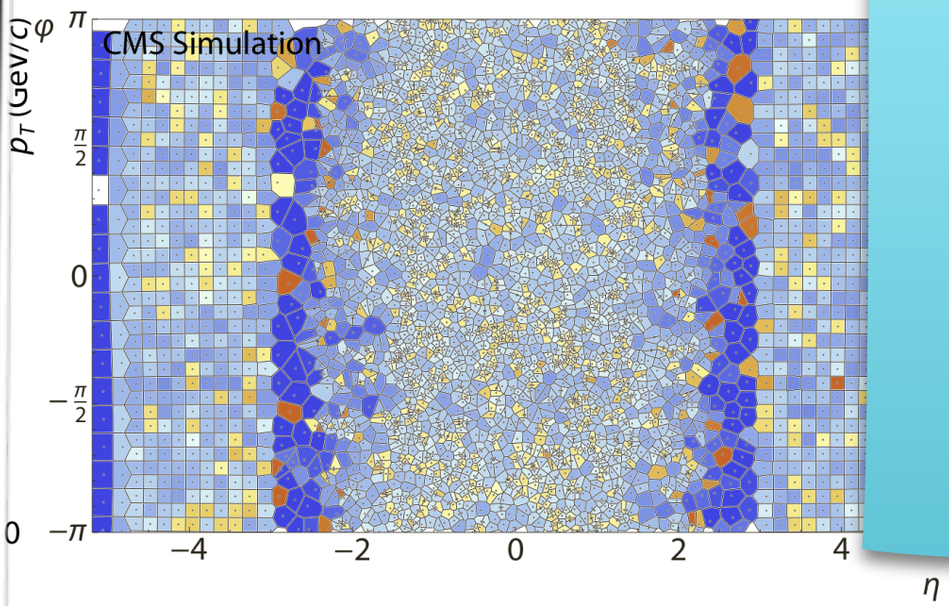


Correcting the whole event for pileup

new CMS Heavy-Ion Method

Step 2: Subtraction by Voronoi Diagram





After UE subtraction

- Subtraction algorithm matches the particle position with the area where the nearest neighbor of a given point is that particle-flow candidate
- Note the 2nd Fourier component with $\Psi^{EP} \approx 0$ that is subtracted away

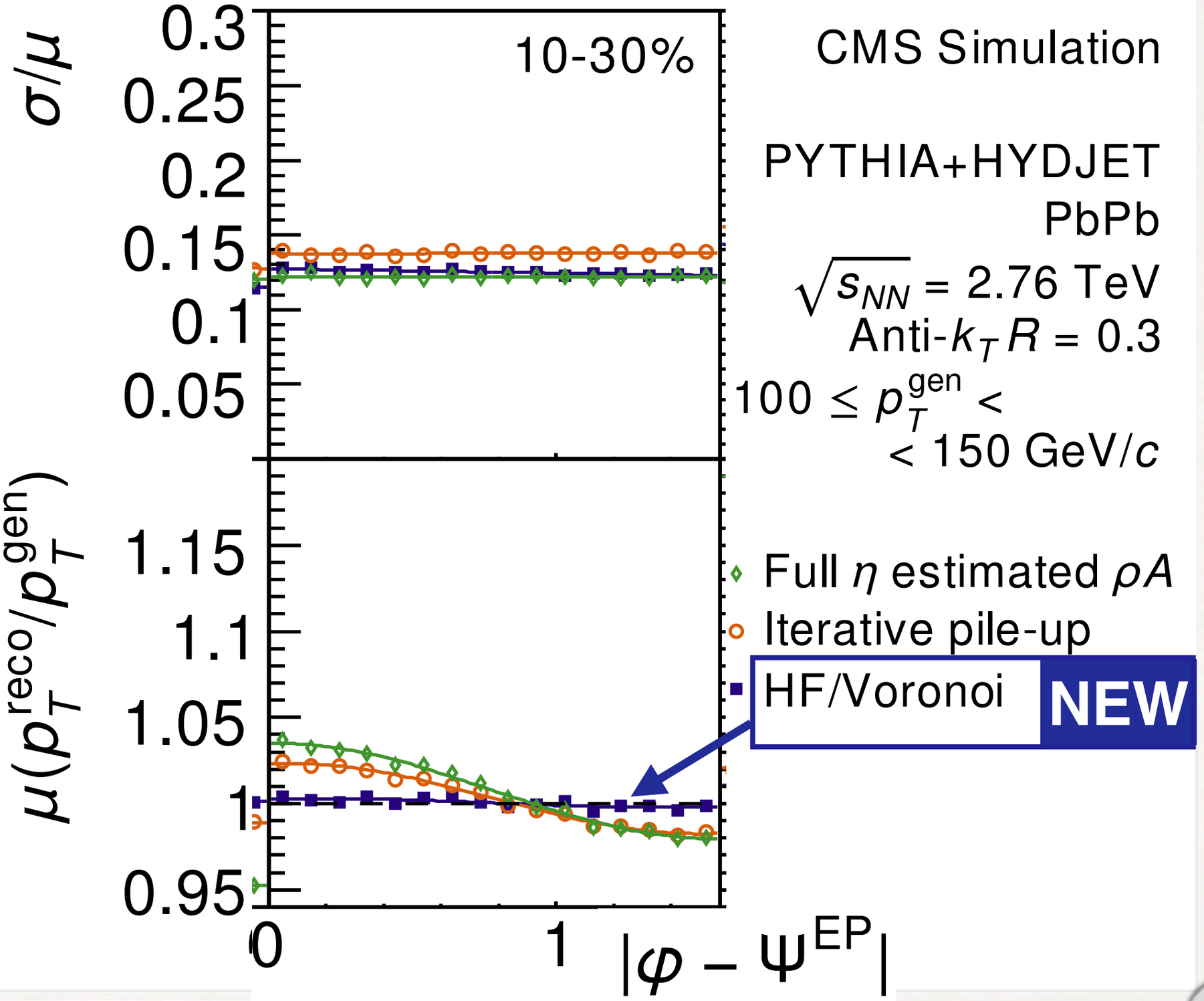
CMS DP-2013/018

Use forward E-flow to predict central "pileup"

Assign correction to particles with help of Voronoi tesselation

Yue Shi Lai (CMS)

new CMS Heavy-Ion Method



One critical aspect for HI collisions is absence of **azimuthally dependent bias**

Yue Shi Lai (CMS)

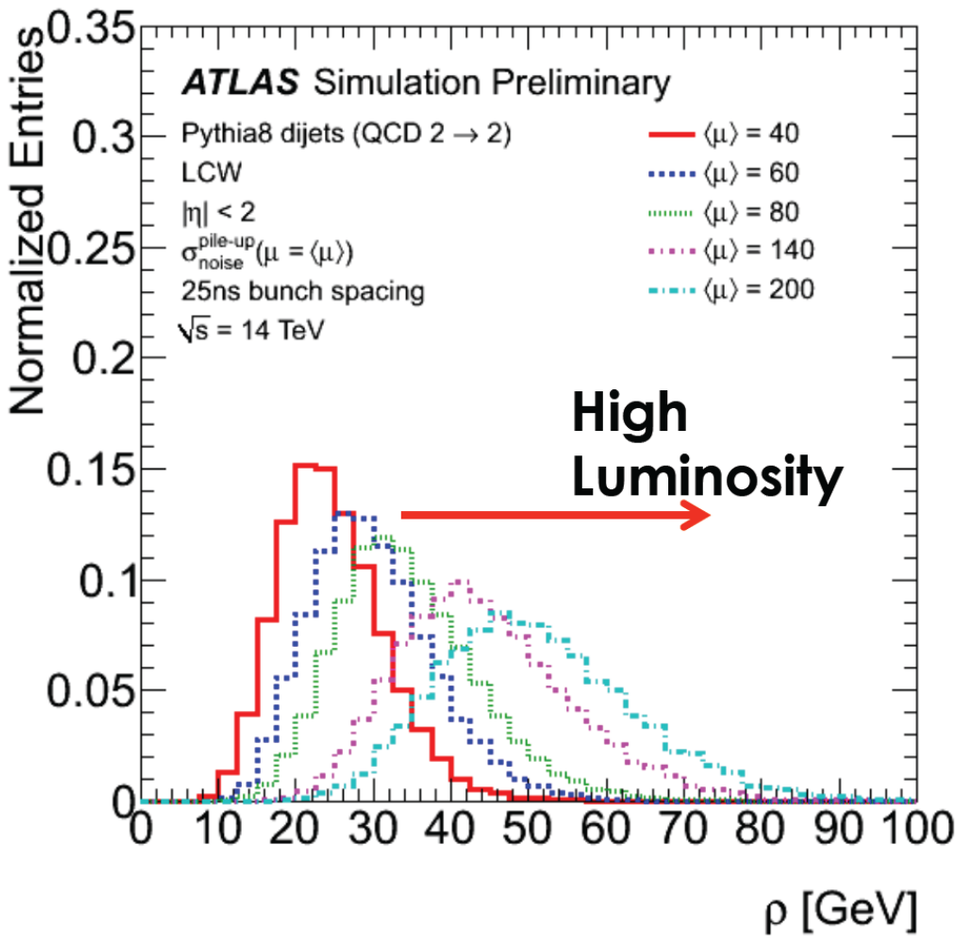
PU reduction in topoclustering

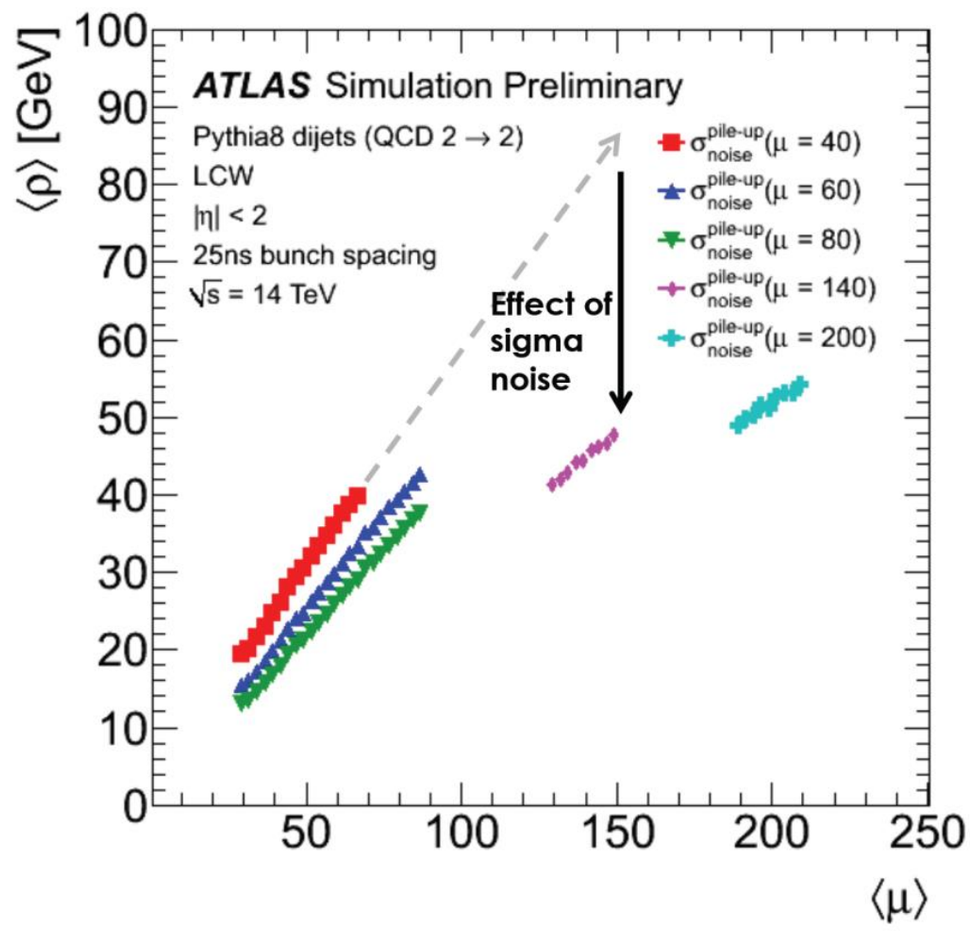
11

THE UNIVERSITY OF ARIZONA.

Pile-up Suppression at High Intensity

P. Loch
U of Arizona
May 17, 2014



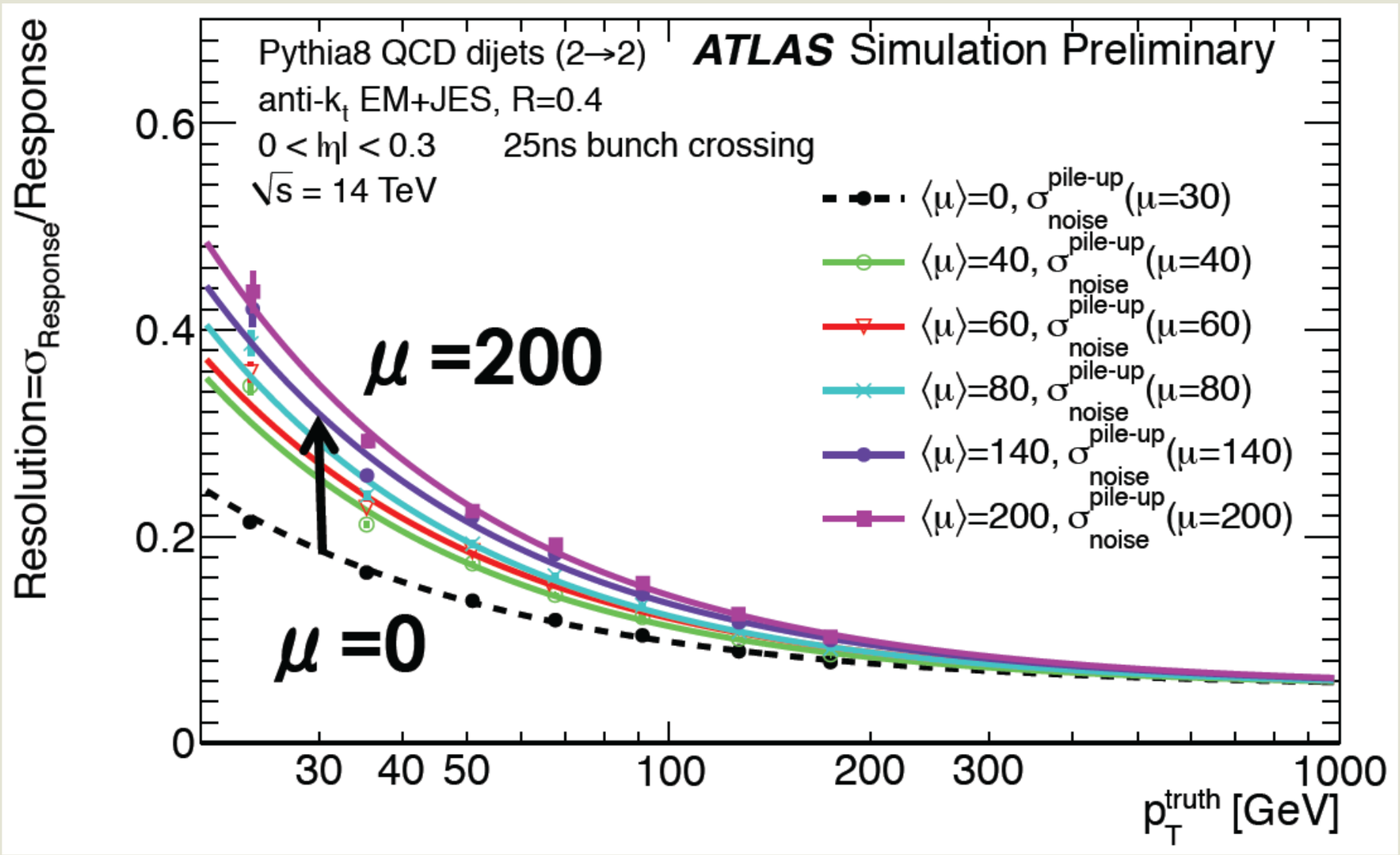


Jet-area based pile-up correction

- ρ-based mitigation technique (like for 2012 data)
  - Reconstructed from TopoClusters in $|\eta| \leq 2$
- $\sqrt{s} = 14$ TeV, 25 ns bunch spacing
  - "Correct" adjustment of σ_{noise} suppresses pile-up

Adjust noise thresholds in topoclustering as a function of the level of pileup

PU reduction in topoclustering



How much do higher noise thresholds improve resolution?

(Official ATLAS plots not yet available; but there is a hint on this plot that it beats √μ scaling…)

PileUp Per Particle Id (PUPPI)

PUPPI overview

May 16,

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

Let's assume something similar to
Flow inputs (*not a requiremen*
neutral hadrons
charged hadrons from LV
charged hadrons from PU

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

[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

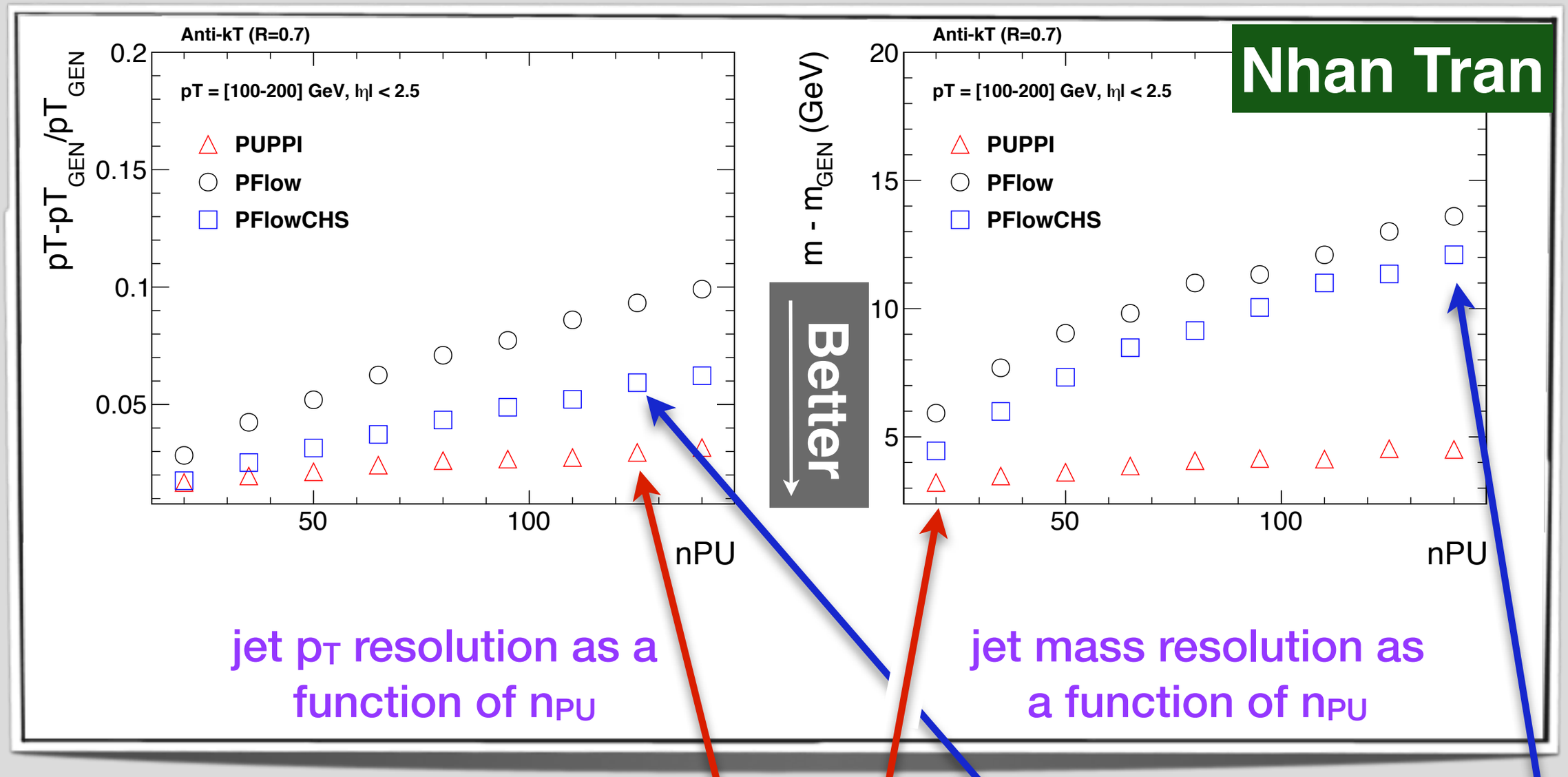
[4] reweight the four-vector of the particle by this weight, then proceed to cluster the

Assign a weight for each particle (based on its neighbourhood) for it to be from hard scatter v. pileup.

(α → weight) + cuts

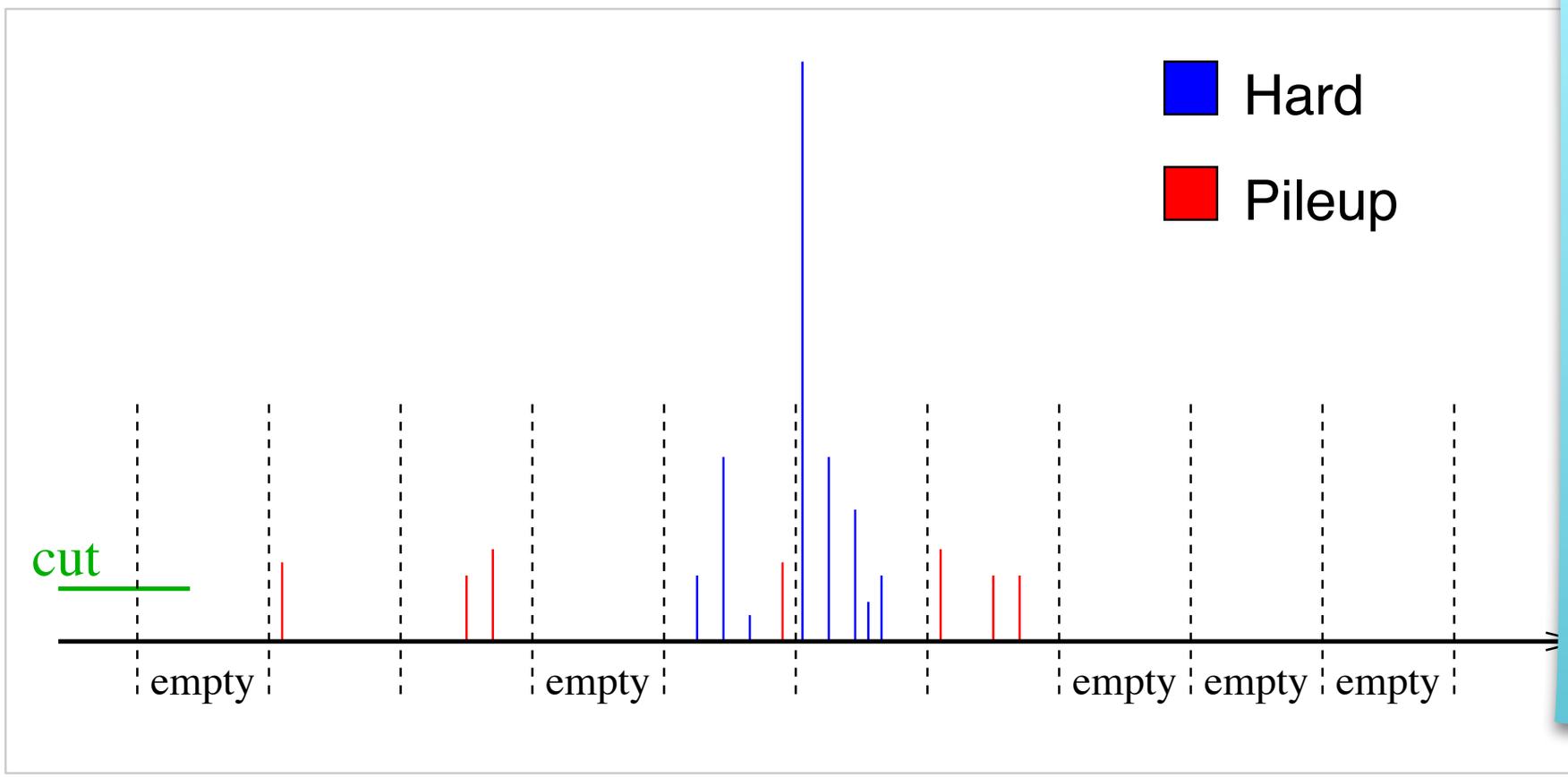
Bertolini, Harris, Low & Tran, in progress

PileUp Per Particle Id (PUPPI)



The SoftKiller approach to event-wide subtraction

Come back to our toy event...

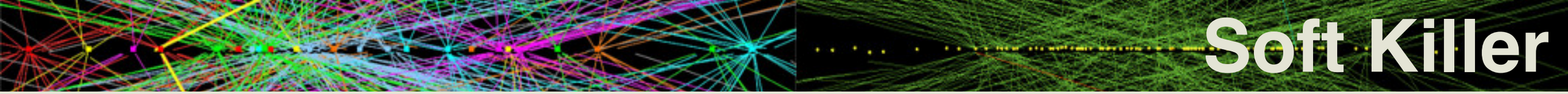


Cut out all particles below some $p_{t,min}$, chosen such that with remaining particles, half the event is empty,

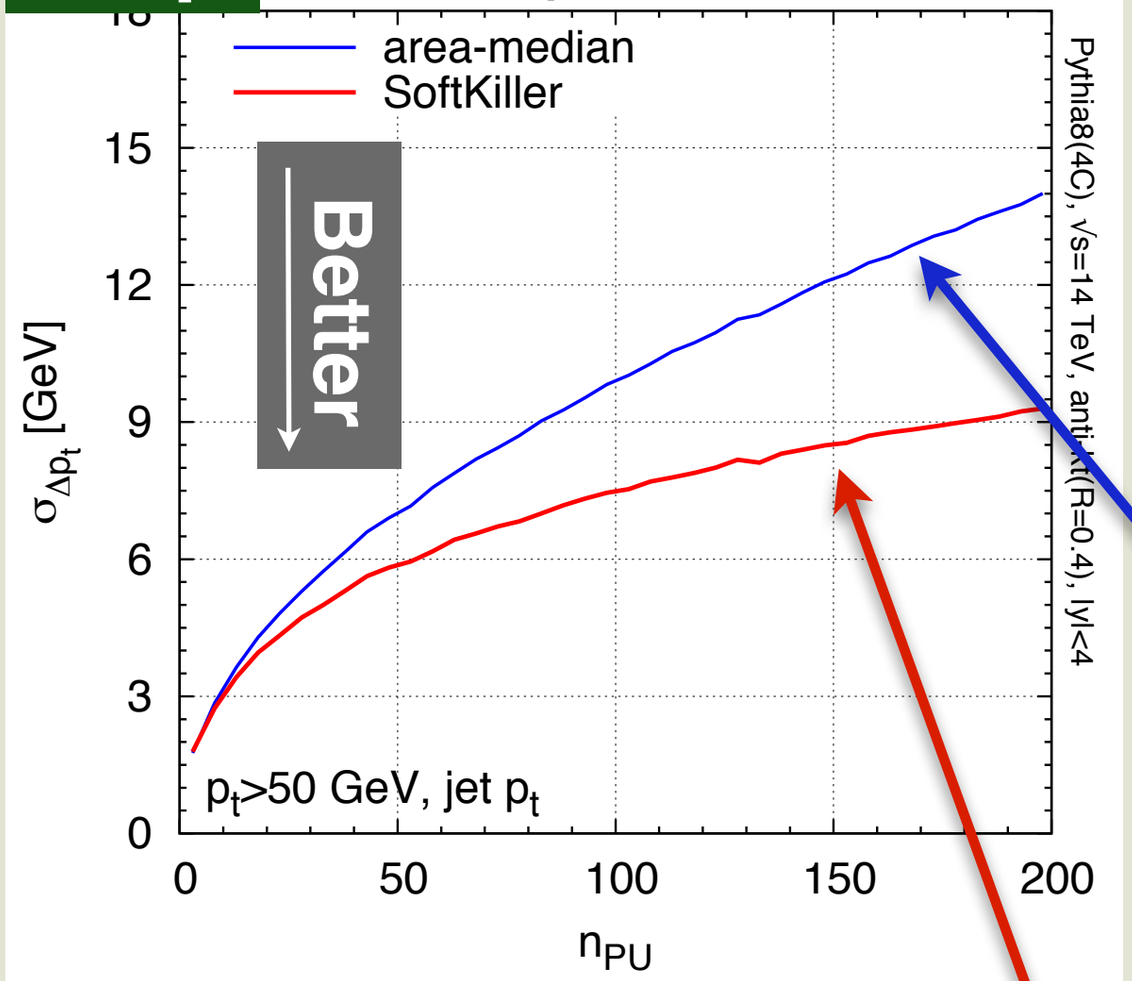
$\rho = 0$

until the estimated ρ is 0 (*i.e.* half the event is empty)

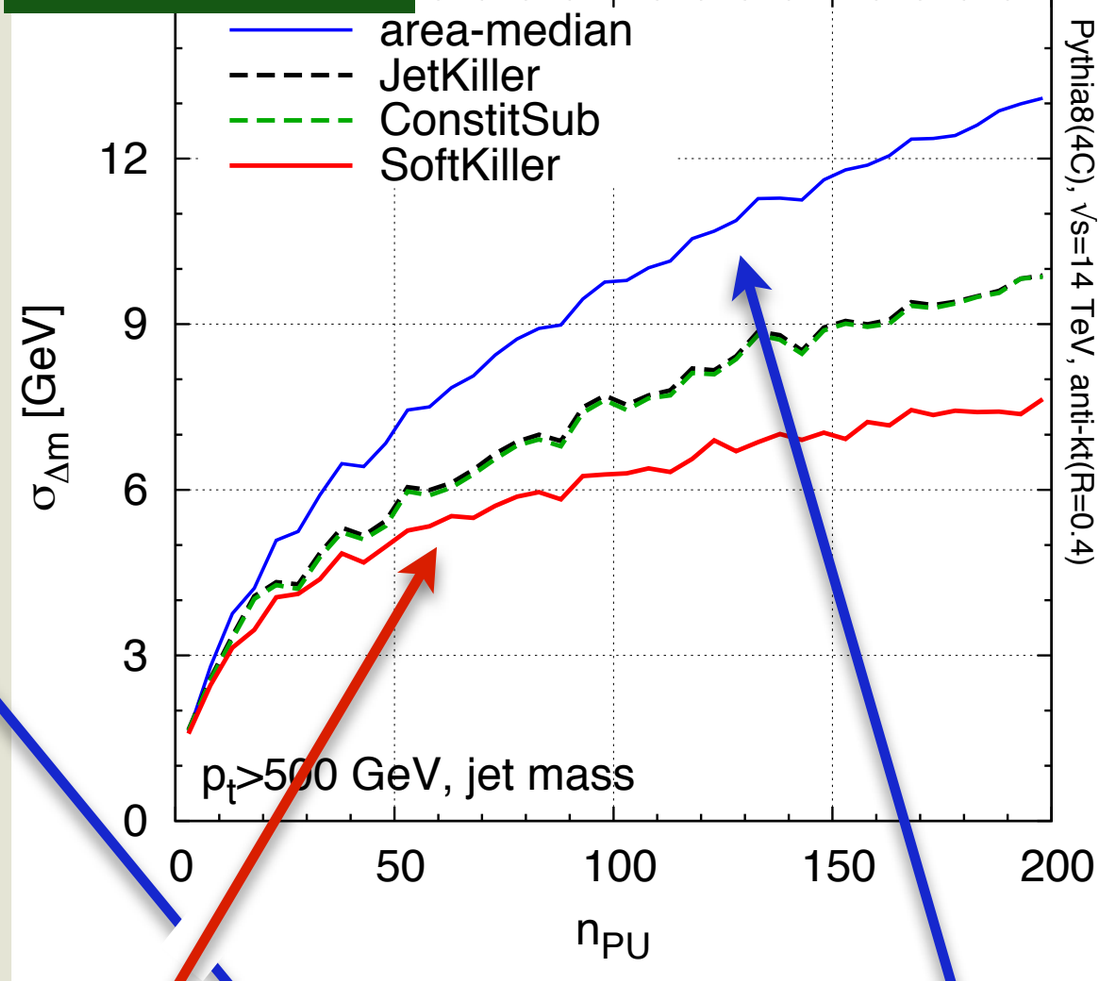
Cacciari, GPS, Soyez, in progress



Jet p_t dispersion

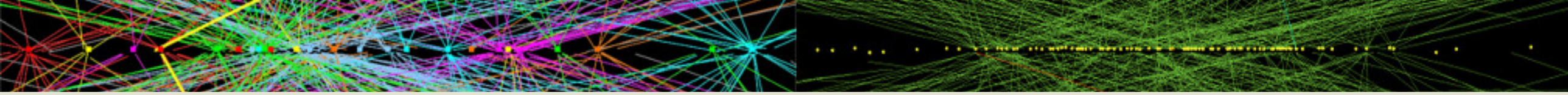


Jet mass dispersion



OLD: area subtraction

NEW: results from Soft Killer



Missing Transverse Energy

Pileup has (almost) no intrinsic MET

MET degradation entirely due to pileup-detector interaction

→ MET pileup mitigation is difficult

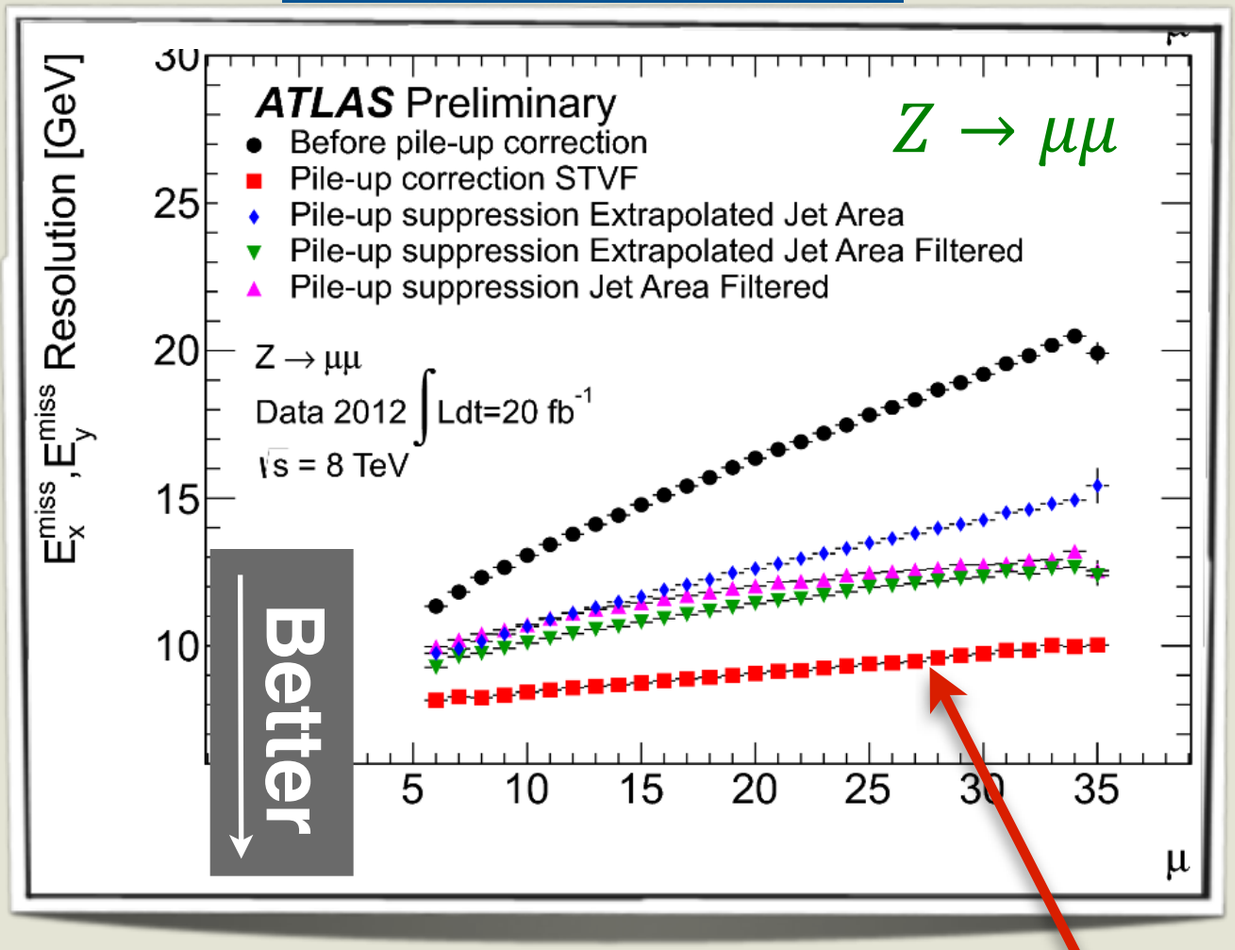
First attempt for MET SoftTerm pile-up suppression

- Purely track-based (STVF), jet-area based (EJA) and combinations (EJAF, JAF)
  - Calorimetric jet-area based EJA alone does not perform that well – purely stochastic subtraction cannot reinstate performance w/o pile-up
  - Additional use of JVF improves performance (EJAF/JAF)
  - STVF performs best for MET resolution but suppresses MET scale – and suffers from the same problems as JVF at high pile-up (Pascal Nef's talk)
  - Calorimeter based methods do very well for SumET pile-up mitigation – important for analyses using MET significance
- Particular choice is final state dependent
  - No universal recommendation – mostly hangs on importance of soft term and topology of energy flow
  - Jet-area based methods clearly an alternative for final states with track-starved hard-scatter vertex and genuine MET

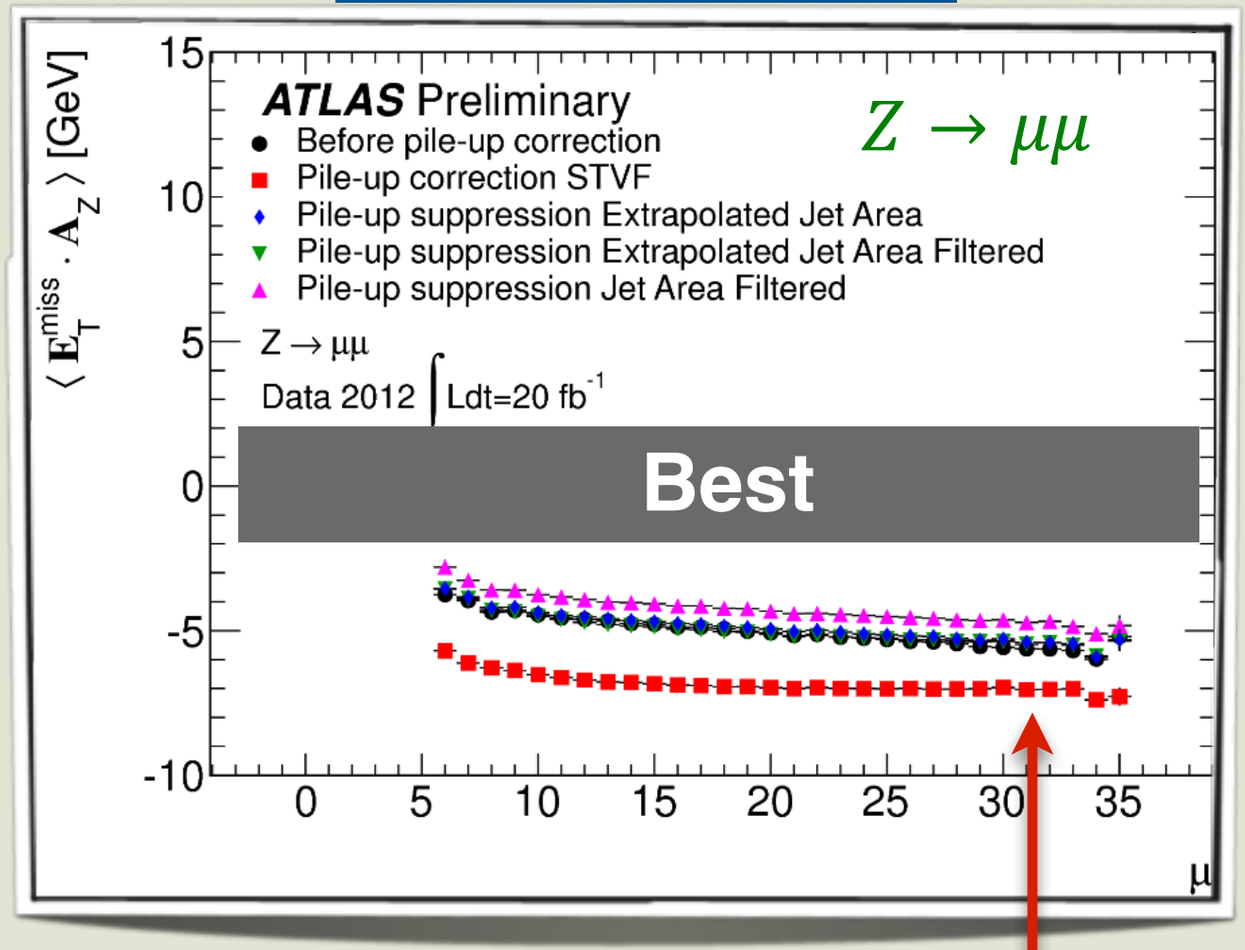
Peter Loch (ATLAS)

No single technique is optimal for MET — a tough problem

Resolution



Biases



Best option for resolution (track-based rescaling) does worst for bias

Scaling down the contribution of particles in an event is just removing energy

If only pileup is removed everything is fine, but this is never the case

→ impact on the MET energy scale

The MVA PF MET algorithm

Defined with a MVA regression : trained on Z events → targeted MET is zero

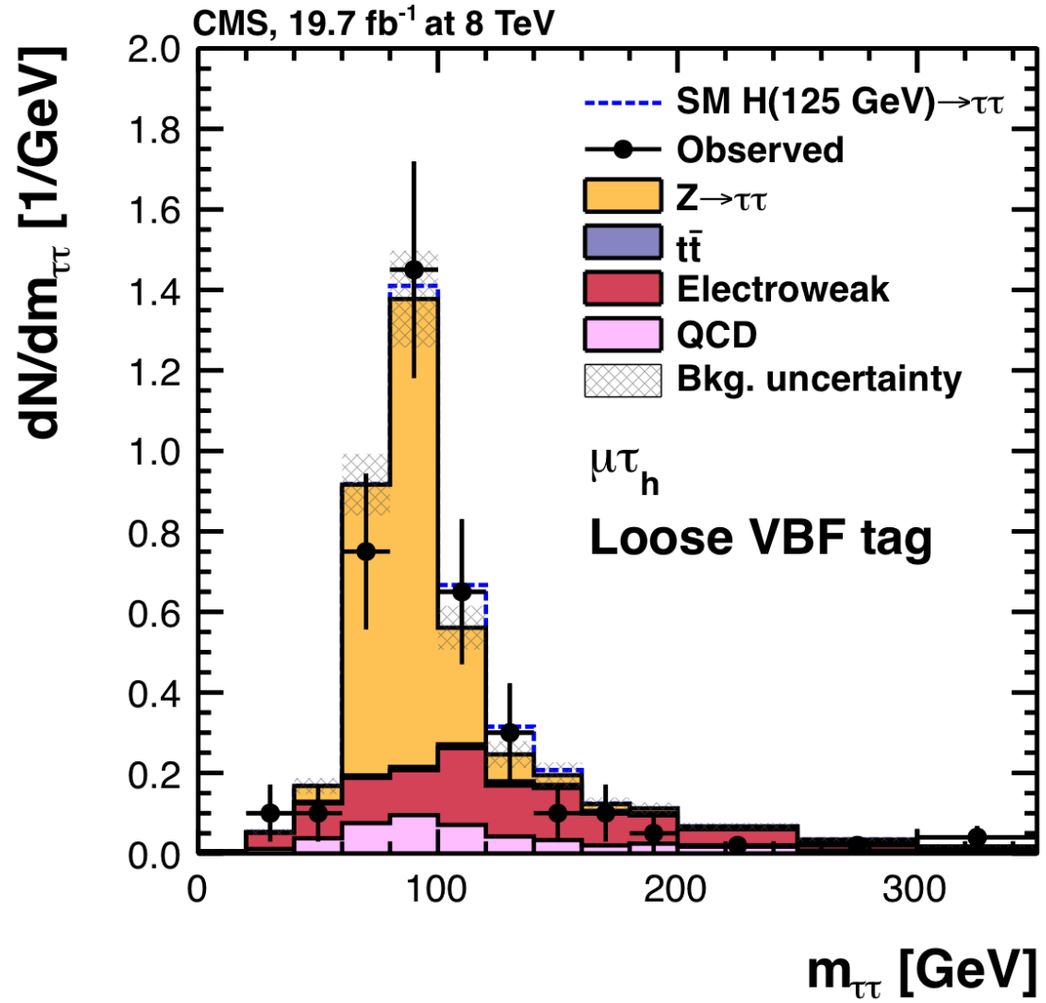
Use of 5 different "MET-like" variables constructed with :

- all particles reconstructed in the event (PF MET)
- HS charged particles
- HS charged particles + neutral particles within HS jets
- PU charged particles + neutral particles within PU jets
- HS charged particles + neutral particles within HS jets + isolated neutral particles

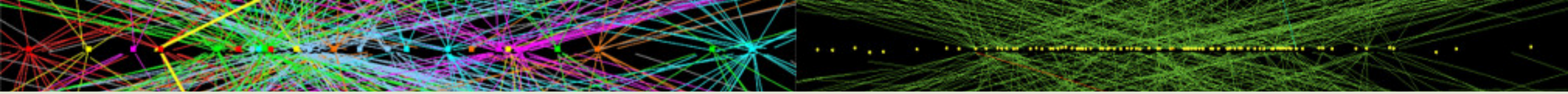
Matthieu Marionneau (CMS)

Precision measurements :

- W mass measurement
- H → ττ, MVA MET used by CMS, gain of ~30% on the resolution with no loss of response



Matthieu Marionneau (CMS)



ATLAS – CMS comparisons

Proposal for ATLAS-CMS comparison

DRAFT formulated jointly by the 4 ATLAS & CMS Jet/MET conveners

Jet matching:
- AK4
- pTgen>10 GeV
- deltaR < R/2, R (not anti-kT: A_overlap < 75%, 50%)
- matching criterion and parameters
- propose to use R=0.4 with matching deltaR<Rcone/2=0.2 (loosest unambiguous match)
- require pTgen>10 GeV, pTreco>20 GeV

Resolution
- 2 sigma fit, sigma/mu , mu (mu calibrated to 1.00)

Pile-up jet
- pile-up: Not matched within deltaR<R
- signal: Matched within deltaR<R/2
- gray: Matched within R/2<deltaR<R (important to know this fraction)

PU comparison
- use mu (MC truth Poisson mean) and PV,corr (=N_PU)
- show <PV,corr> vs mu is linear at x=y (correct for any non-linearity for PV,corr)

Plots to show
- vs eta with natural segmentation
- dpT/dmu, dpT/dPV,corr, sigma_PU from JER,
- JER: sigma_pT/pT = sqrt(sigma_PU^2/pT^2 + N0^2/pT^2 + S^2/pT + C^2)

Samples to use
- QCD Dijet Pythia, some tune

MET
- Zmumu events
- mean(u_parallel/pT)
- width(u_parallel/pT)
- width(u_perpendicular/pT)
- width from Voigtian (or any fit with 1 sigma)
- plot vs PU (mu), fit with sigma = sqrt(Npu*sigma_PU^2 + C^2)

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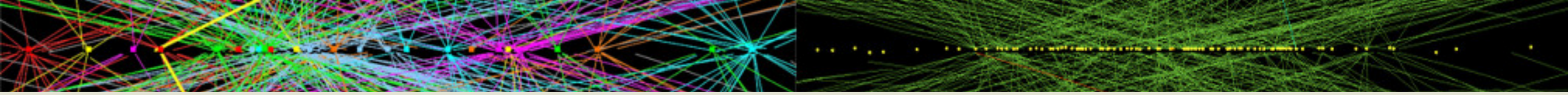
A starting point — non-trivial to have reached this point

Some aspects may be improved (e.g. matching). Current version has advantage of simplicity.



Common Software Exercise

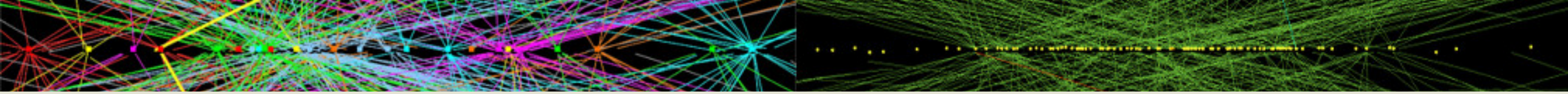
https://github.com/PileupWorkshop/2014PileupWorkshop

Direct comparisons are impossible because groups are using different samples, cuts, matching, quality criteria, etc.

Proposal

set up a framework with common event samples
and analysis code to solve this problem

participants were generous in exchanging preliminary "proprietary" code, and put a lot of effort in getting results in 3 x ½ half days



Common Software Exercise

https://github.com/PileupWorkshop/2014Pil rkshop

Direct comparisons are im roups are using different sample riteria, etc.

BEWARE

Particle-level studies

Conclusions may not carry over to detector level

set samples

this problem

participants generous in exchanging preliminary "proprietary" code, and put a lot of effort in getting results in 3 x ½ half days

Workshop comparisons

Work program for comparing various subtraction methods in identical setups

Ideally, each method should be studied by at least two people/groups

Code and results should be uploaded to a subdirectory of the directory "Comparisons/" on github

Signal samples

- dijets (pt > 20, pt > 100, pt > 500), with UE off and massless particles
- both full and CHS

The samples are in the usual location (/afs/cern.ch/user/p/puws2014/public/events or http://cern.ch/puws2014/events/).

```
lhc14-pythia8-4C-dijetsel20-noUE-nevsel1e5.pu14.gz
lhc14-pythia8-4C-dijetsel100-noUE-nevsel1e5.pu14.gz
lhc14-pythia8-4C-dijetsel500-noUE-nevsel1e5.pu14.gz
```

Each event in those files has at least one jet with |y|<2.5 and above the pt [GeV] indicated after the "dijetsel" tag. They are intended to be used respectively for the analyses with 20, 50 and 100 GeV pt cuts.

The files have been produced with a generation cut at 80% of jet pt selection cut. For validation purposes, there are files (on afs) labelled .res that indicate the average number of jets with pt>20 GeV, |y|<2.5 in each sample.

Observables

- pt
- mass
- angularity/width/girth with alpha = 1

Pileup levels: 30, 60, 100, 140

Particles and jet selection

particles: |y| < 4 jet definition: antikt R=0.4

jets: take the two hardest jets, then apply a selection of |y| 20 (or 100, or 500), and study the impact of pileup on any jets that pass that selection. Pileup jets are matched to the hard jets with a deltaR = 0.3 criterion.

A separate study counts the jets above 20 GeV with |y| < 2.5. That count is only in events that have at one jet from the selection described in the preceding paragraph.

Note that in example03.cc prior to revision 107 (git rev-list --count HEAD) or hash d1b6590c2f2758d765c3... the number of jets was counted for all events.

How to compare (quality measures)

- offset v. dispersion (use trimmed jet as ref when using trimming). There' a template offset-v-dispersion.gp gnuplot macro in the example/ directory for quick plotting
- number of jets above 20 GeV as a function of npu

File format for results

Use the following file format for each subtractor/observable/sample (write out the "+-" to output):

```
 # comments
 # npu    jet_ptmin  <DeltaO>     sigma_DeltaO
corr.coeff.     #_of_jets>20_GeV   matching_efficiency
<O_hard>           obs & method names
   xxx    xxx         xxx +- yyy   xxx +- yyy      xxx
xxx +- yyy          xxx +- yyy             xxx +- yyy
#  e.g. pt_areasub
```

Template code

Look at example/example03.cc to see code that has the selection, matching and output as illustrated above. Run it for example with

```
./example03 -hard ../sample-events/lhc14-pythia8-4C-
dijet50-nev20.pu14.gz \
            -pileup ../sample-events/lhc14-pythia8-4C-
minbias-nev100.pu14.gz \
            -massless -npu 5 -nev 20 -jet-ptmin 20 >
output.dat
```

Adapt the -jet-ptmin option depending on what you plan to study. There's also a -chs option for running with CHS type events.

Full draft: https://github.com/PileupWorkshop/2014PileupWorkshop/blob/master/WORK.md

Results

Working group reports

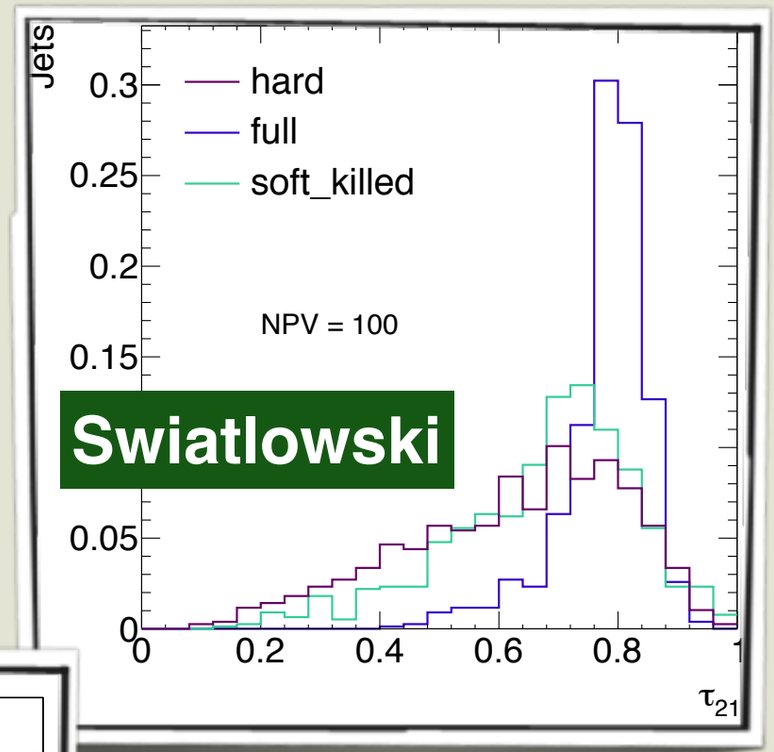
16:00 **report** *20'*
Speakers: Matteo Cacciari (LPTHE Paris), Gavin Salam (CERN), Gregory Soyez (CEA/IRFU,Centre d'etude de Saclay Gif-sur-Yvette (FR))
Material: **Slides**

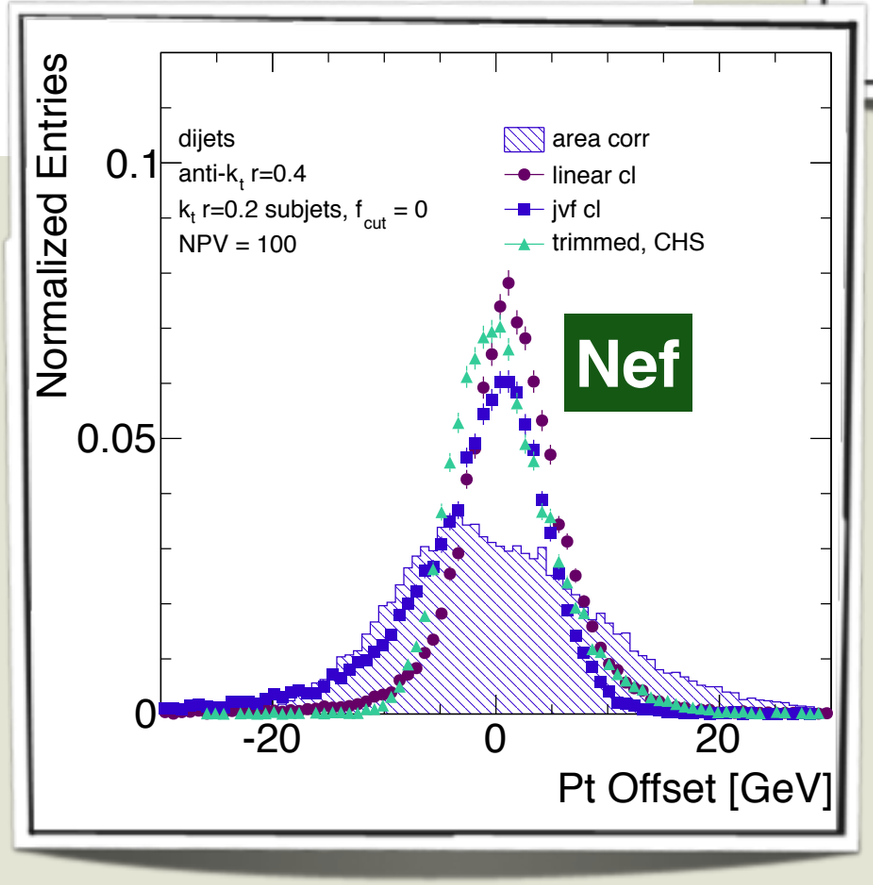
16:20 **report** *20'*
Speaker: Maximilian J Swiatlowski (SLAC National Accelerator Laboratory (US))
Material: **Slides**

16:40 **report** *20'*
Speakers: Nhan Viet Tran (Fermi National Accelerator Lab. (US)), Philip Coleman Harris (CERN), Matthew Low (University of Chicago (US))
Material: **Slides**

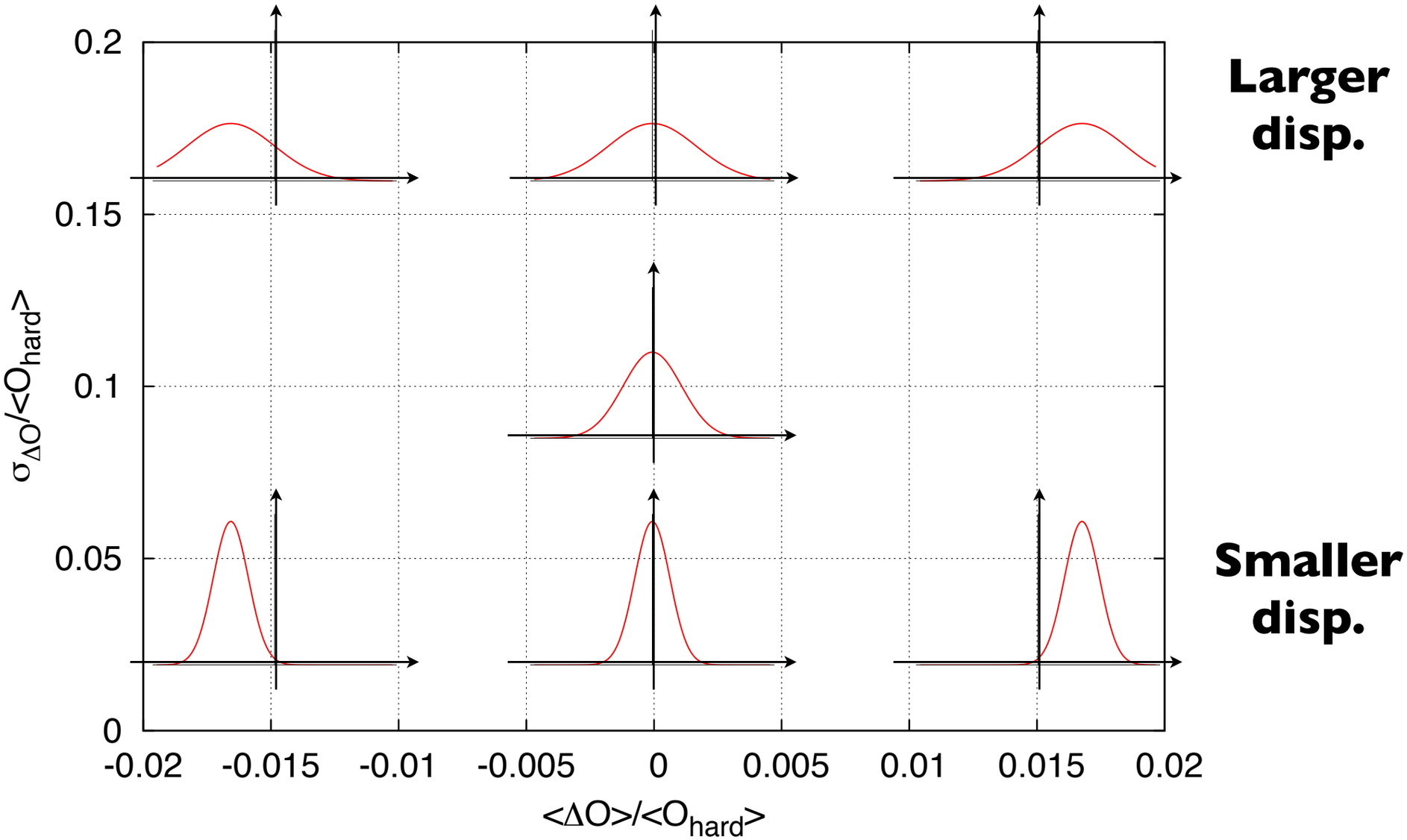
17:00 **report** *20'*
Speaker: Pascal Nef (SLAC National Accelerator Laboratory (US))
Material: **Slides**

17:20 **report** *20'*
Speaker: Peter Berta (Charles University (CZ))

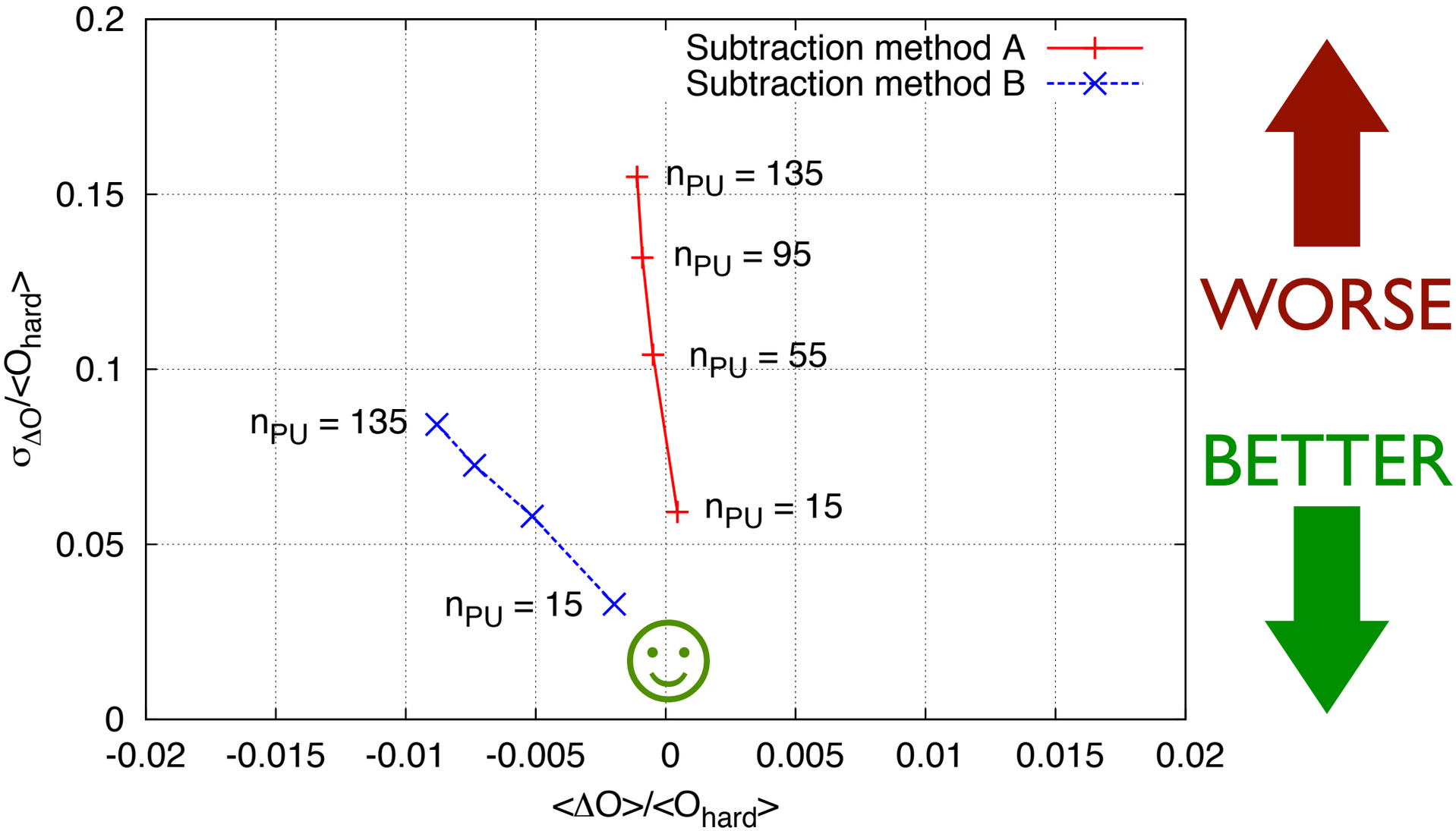




Representation of quality measures

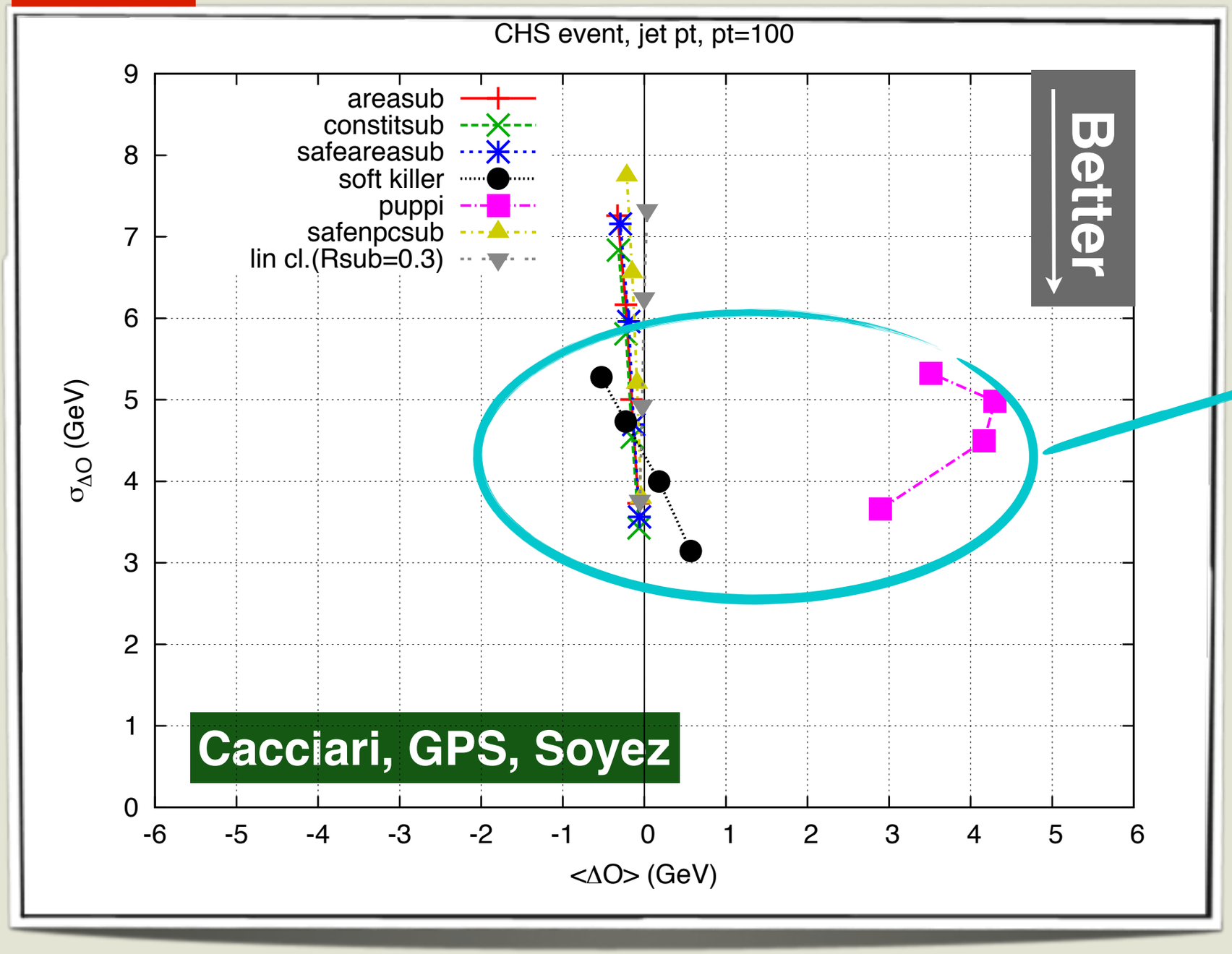


Representation of quality measures



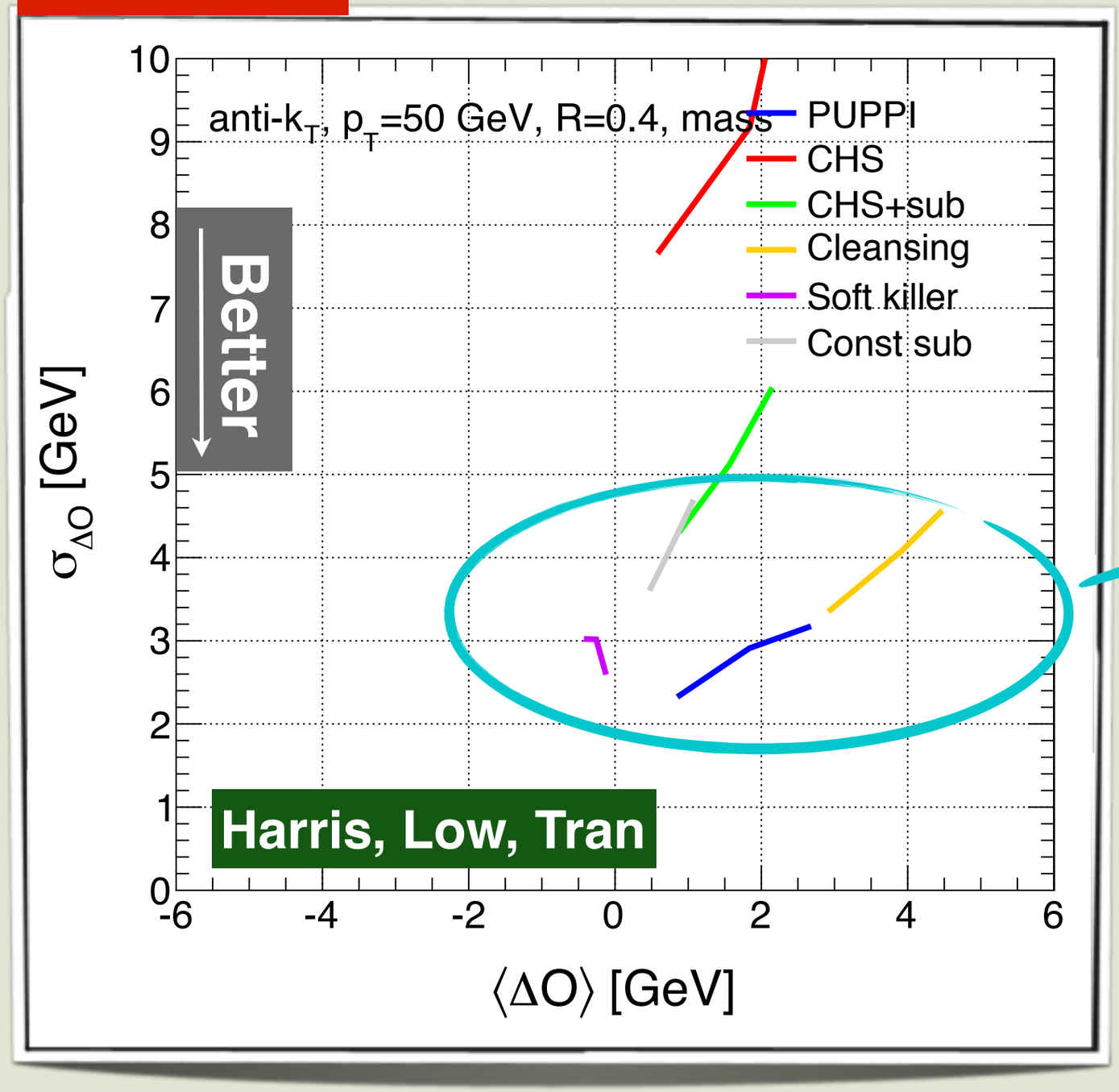
Results

Jet p_t



New methods bring real improvement

Jet mass



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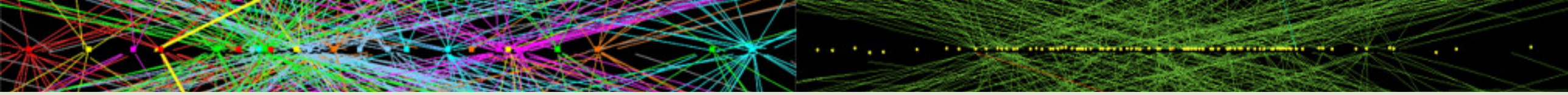

Conclusions

Prospect of near and far-future high lumi running has spurred development of new PU mitigation methods

Many new ideas, which genuinely bring improved performance, with greatest potential at the highest lumis (but some potential maybe even post LS1)

Non-trivial steps towards direct comparisons between ATLAS & CMS and among particle-level methods

Next steps

Some methods still preliminary, some still need study with detector sim; more news, more comparisons in coming months, possibly also follow-up workshop