Pileup mitigation at the LHC

A theorist's view

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What is pileup and why is it there?
Why is it bad?

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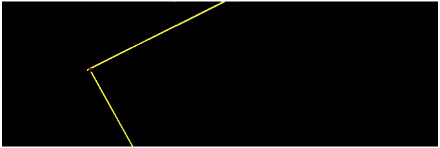
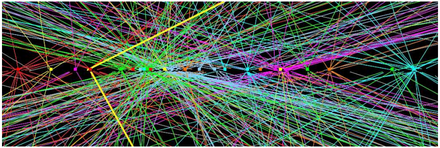
No pileup



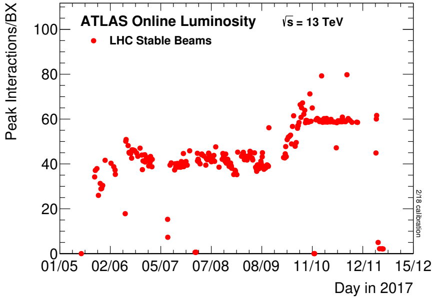
Clear picture

With pileup [ATLAS event]

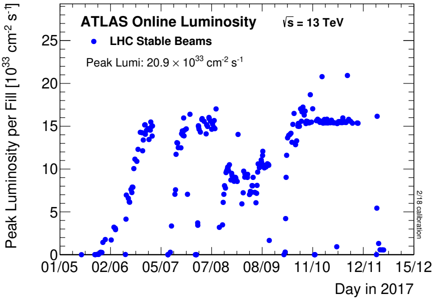


Not so clear!

Soft (low-energy) background blurring your resolution ⇒ to be mitigated (peak) Pileup multiplicity



(peak) collision rate (luminosity)



- $\mu = \langle N_{PU} \rangle$: increased from ~ 20 (Run I) to ~ 40 (early Run II) and now ~ 60 (late 2017)
- Will keep increasing in the future with $140 - 200$ planned for HL-LHC
- Collisions rate (luminosity) increases in parallel

Idea/Plan for the talk

- Useful simple characterisation of pileup
- Review of the area–median pileup subtraction technique (currently in use at the LHC)
- Comparison with other basic approaches
- Go over ideas for new pileup mitigation techniques
  Introduce the SoftKiller approach
- If time: highlight some level of (analytic) understanding

Early clarifications/disclaimers

A few (purposeful) over-simplifications

- no detector response/simulation
- purely "in-time" pileup
- often neglect UE for simplicity
- will concentrate on jet quantities (MET and lepton/photon isolation have extra dependence (tuning) on detector details)
- will mostly focus on the jet p_t

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But...

- detector and out-of-time PU: minor impact expected (at least qualitatively and for the physics message)
- I'll briefly discuss other quantities than the jet p_t when relevant
- I can come back to these points if necessary (ask at the end)

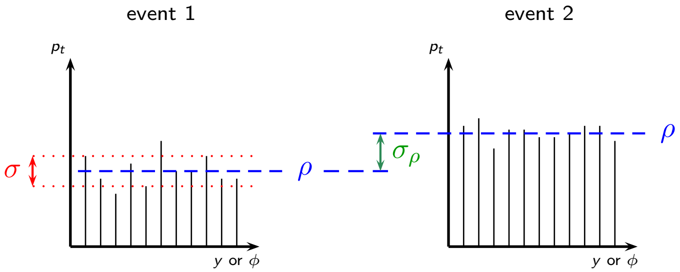
Simple characterisation of pileup

Simple (and very helpful!) characterisation

Pileup is roughly uniform (in $y - \phi$)

Pileup mostly characterised by 3 numbers

- ρ: the average activity in an event (per unit area)
- σ: the intra-event fluctuations (per unit area)
- σ_ρ: the event-to-event fluctuations of ρ



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Jet of momentum p_t and area A (more below):

$$\text{one event:}\ \ p_t \xrightarrow{+\text{pileup}} p_t + \rho A \pm \sigma\sqrt{A}$$

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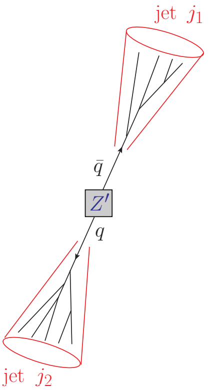
p_t shift

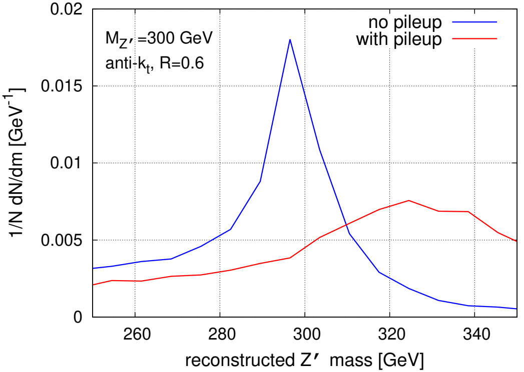
p_t smearing

resolution degradation

Example: (fictitious new) Z' boson with $M_{Z'} = 300$ GeV

$Z' \to q\bar{q} \to jj$





"$Z' \approx j_1 + j_2$"

Pileup mitigation

1. generic strategy

Pileup subtraction

$$p_t^{(\text{truth})} \xrightarrow{+\text{pileup}} p_t^{(\text{full})} \xrightarrow{\text{subtract}} p_t^{(\text{sub})}$$

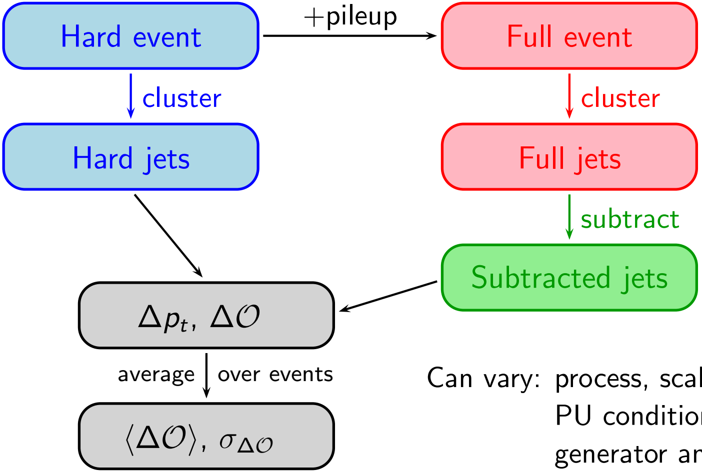
Goal: $p_t^{(\text{sub})} \approx p_t^{(\text{truth})}$, i.e. $\Delta p_t = p_t^{(\text{sub})} - p_t^{(\text{truth})} \approx 0$.

More precisely, the subtraction should be:

1. Unbiased: $\langle \Delta p_t \rangle_{\text{events}} \approx 0$
2. Sharp (good resolution): $\sigma_{\Delta p_t}$ as small as possible
   Alternative width measurements possible (but avoid correaltion coefficients)
3. Robust: independent of the jet p_t, rapidity, N_{PU}, the process, ...

Testing framework

Tests based on Monte-Carlo event generators:



Can vary: process, scales,
PU conditions
generator and tune

Pileup mitigation

2. the area–median technique

Defining jet area

[M.Cacciari, G.P. Salam, GS, 2008]

Remember:

$$p_t \xrightarrow{+\text{pileup}} p_t + \rho A \pm \sigma\sqrt{A}$$

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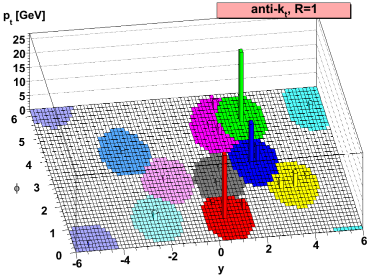
Introduce an "Active" area definition:

- Add "ghosts" to the event:
  - particles with infinitesimal p_t
  - on a grid (+fluct.) of cell area a_0
- Include the ghosts in the clustering
- If a jet contains N_g ghosts, its area is $N_g a_0$



Area–median pileup subtraction method

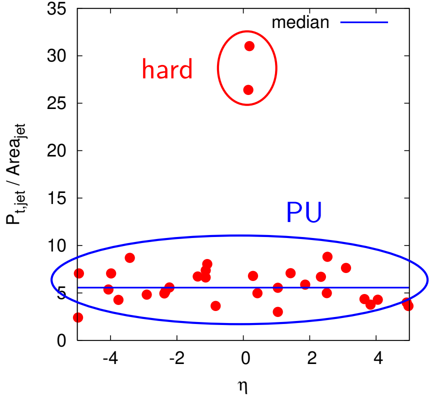
[M.Cacciari, G.P. Salam, 08]

Estimation: $\rho_{\text{est}} = \underset{j\in\text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\}$

Subtraction: $p_{t,\text{jet}}^{(\text{sub})} = p_{t,\text{jet}} - \rho_{\text{est}} A_{\text{jet}}$

per event (typically)

per jet



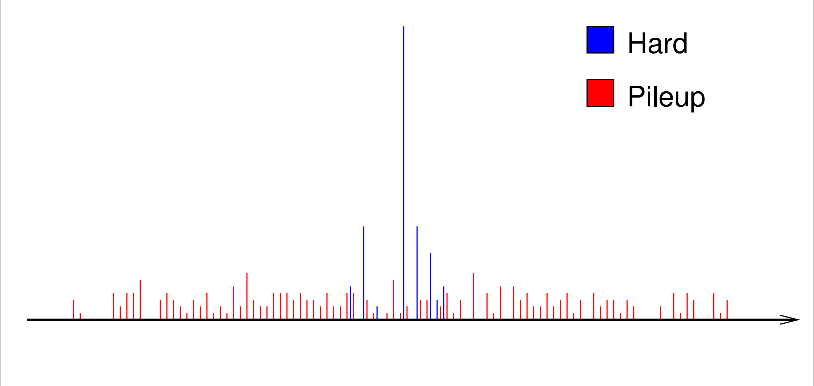
break the event in patches of similar size

e.g. cluster with k_t

or break into grid cells

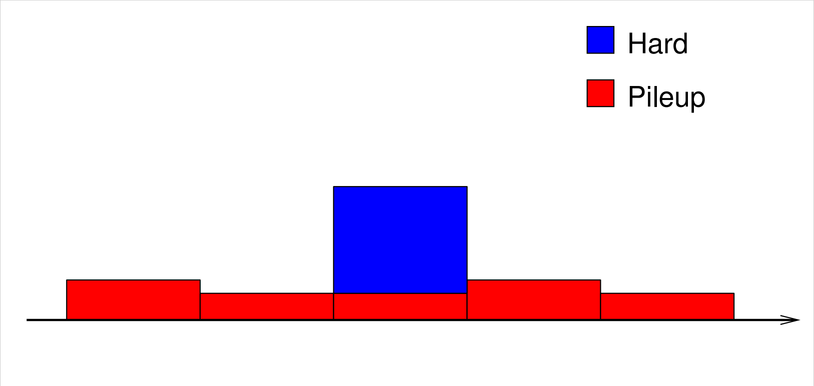
Simple discussion of pileup subtraction (take 1)

To illustrate the physics, use a simple (1-D) event with 1 jet + PU



Simple discussion of pileup subtraction (take 1)

Subtract pileup from the hard jets



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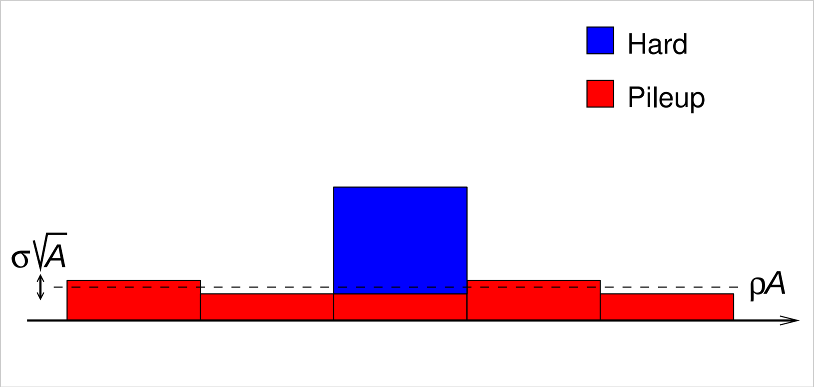
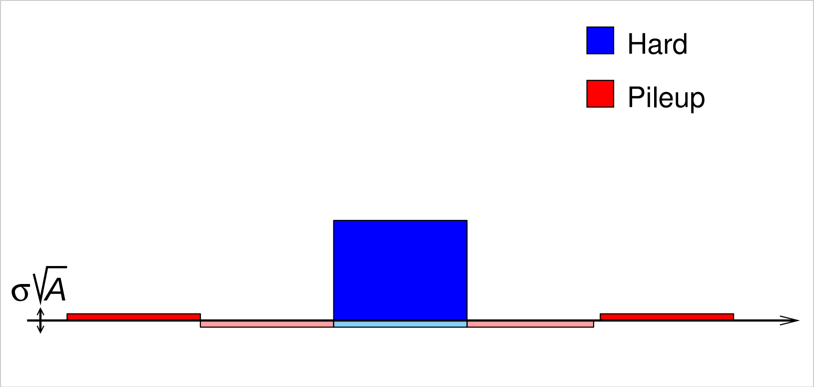


Area-median subtraction would subtract ρA

Simple discussion of pileup subtraction (take 1)

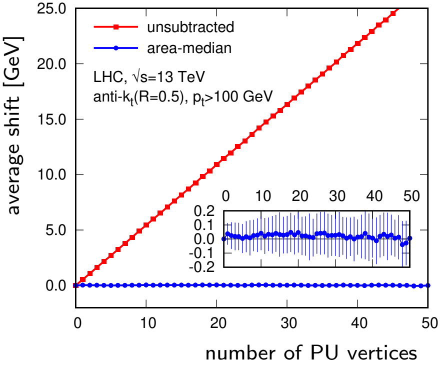
Subtract pileup from the hard jets



For the hard jets: unbiased (average ≈ 0) and robust smearing $\approx \sigma\sqrt{A}$ (smaller than $\pm\sigma_\rho A \pm \sigma\sqrt{A}$)

[revamped Les-Houches 2011 study]

average p_t shift



No subtraction

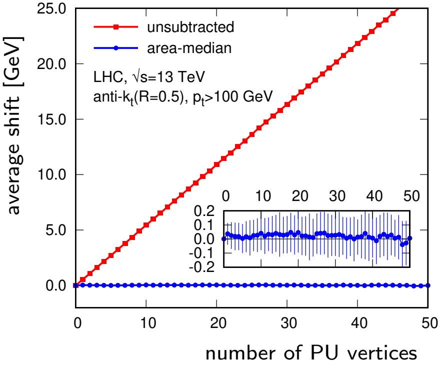
area-median subtraction

corrected for shift

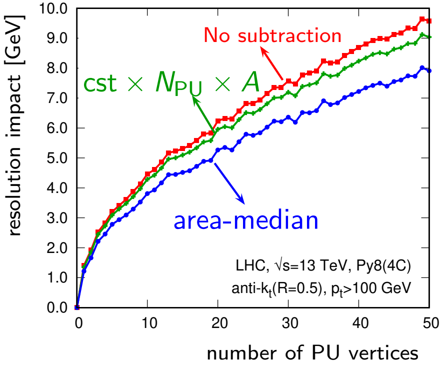
Subtraction benchmarks

[revamped Les-Houches 2011 study]

average p_t shift



impact on resolution



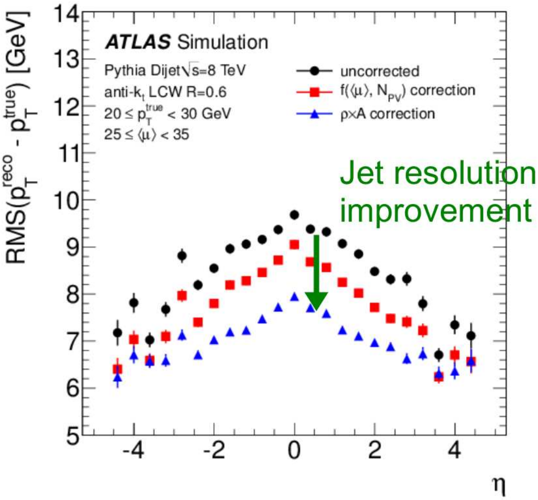
corrected for shift

resolution improved

event-by-event ρ is key

PU subtraction as seen in ATLAS

[B. Petersen, ATLAS Status report for the LHCC, 2013]



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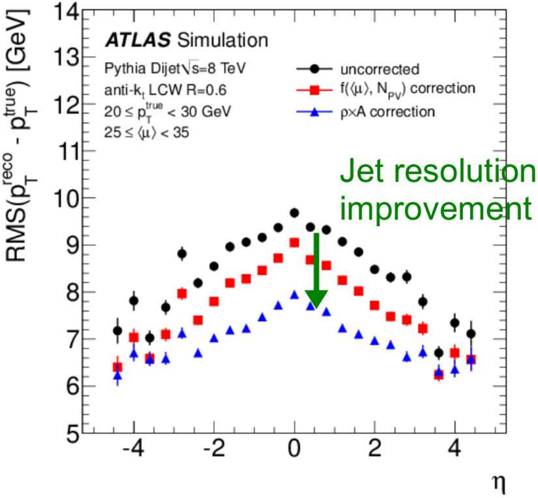


Gain compared to a $f(\mu, N_{PV})$ correction:

even-by-event determination of ρ captures the fluctuations better than an (averaged) fixed function

(one partial exception where $f(\mu, N_{PV})$ info helps the area–median is for the rapidity profile in the forward calorimater; ask details later)

Further developments

Improvements/extensions of the basic method

- Methods to handle positional dependence of ρ
  Directly relevant for the LHC (*e.g.* rapidity dependence)
  [M.Cacciari,G.Salam,GS,2010-2011]

- Subtraction for jet mass and jet shapes (not discussed here)
  Important for jet tagging ("q v. g jet", b jet, top jet, $H \to b\bar{b}$)
  [GS,G.Salam,J.Kim,S.Dutta,M.Cacciari,2013]
  [P.Berta,M.Spousta,D.Miller,R.Leitner,2014]

- Applications to CHS events
  [M.Cacciari,G.Salam,GS,2013]

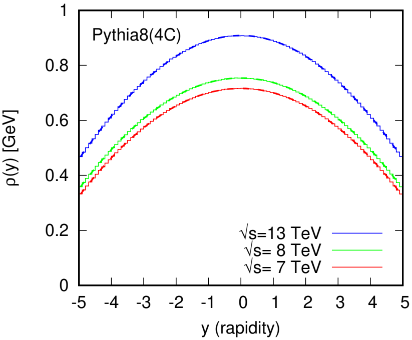
- Applications to heavy-ion collisions (not discussed here)
  [M.Cacciari,J.Rojo,G.Salam,GS,2011]

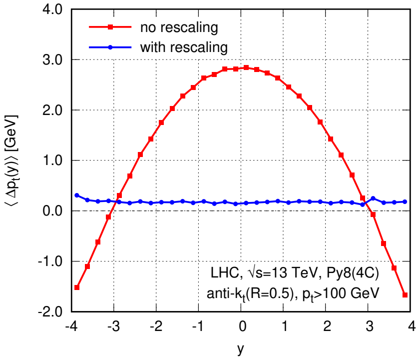
- Subtraction of fragmentation function (moments) (not discussed here)
  Useful for quenching in *PbPb* collisions
  [M.Cacciari,P.Quiroga,G.Salam,GS,2012]

Rapidity dependence

$$\rho = \underset{j\in\text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j} \right\} \quad \longrightarrow \quad \rho(y) = f(y) \underset{j\in\text{patches}}{\text{median}} \left\{ \frac{p_{t,j}}{A_j f(y_j)} \right\}$$

$f(y)$ from minbias





Application to CHS events

- Assume idealised CHS (perfect separation between charged and neutral, perfect charged pileup identification)

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- Subtleties
  - PU charged tracks can be kept as ghosts (with ∞^{al} momentum)
  - additional $+$ivity constraints
  - A "neutral-proportional-to-charged" (NpC) approach like

$$p_{t,\text{neutral}}^{(\text{sub})} = p_{t,\text{neutral}}^{(\text{full})} - \gamma p_{t,\text{charged}}^{(\text{PU})}$$

  does a slightly worse job than the area–median
  (mostly because soft physics looses the collinear correlation between charged and neutrals; both can be combined w gain $\sim 5\%$)

Area–median: final recommendations

Issue: information scattered over several papers

$\Rightarrow$ Goal/Idea: summarise recommendations for the area–median method

Recommendations

- Basic setup:
  - use active areas with ghosts up to the particle rapidity acceptance
    (+ use n_repeat=1 + try lowering a_0 + keep random seeds)
  - estimate ρ using a grid of size 0.55 (0.5-0.7)
  - use rapidity rescaling for the positional dependence
- Generic usage:
  - use explicit ghosts
  - include the extra ρ_m term for observables sensitive to particle masses
  - use "safe mass" subtraction (avoids negative m^2)
- Specific usage:
  - CHS events: ρ from neutral or CHS (PU tracks as ghosts)
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Everything implemented in FastJet

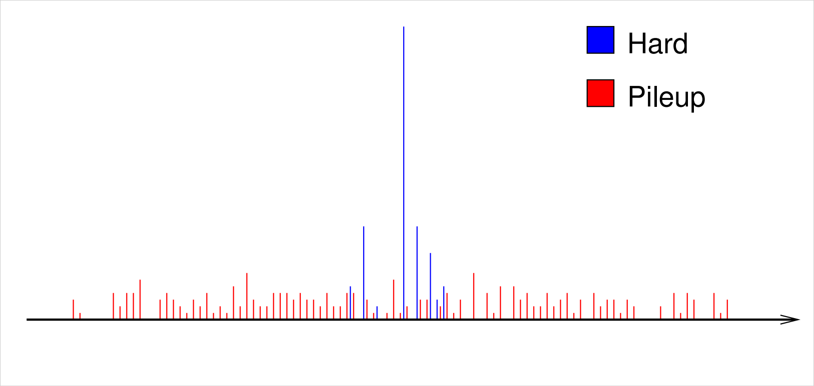
Pileup mitigation

3. towards new strategies

Goal/Challenges

Goal: get a better resolution i.e. reduce effects of σ

Come back to our simple (1-D) event with 1 jet + PU



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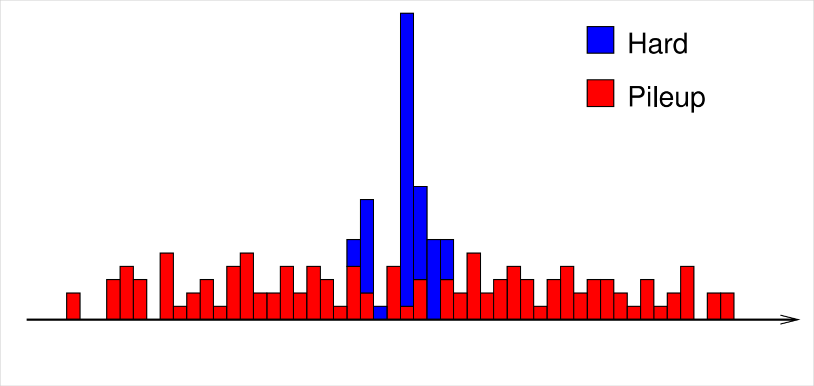
Now, we look at a smaller scale, *e.g.* subjets (or particles)



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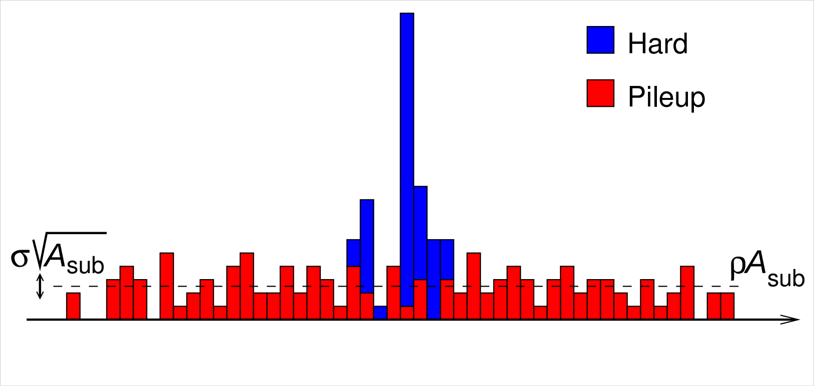

Similar to before: $\sum \rho A_{\text{sub}} = \rho A_{\text{jet}}$ and $\sum \sigma^2 A_{\text{sub}} = \sigma^2 A_{\text{jet}}$

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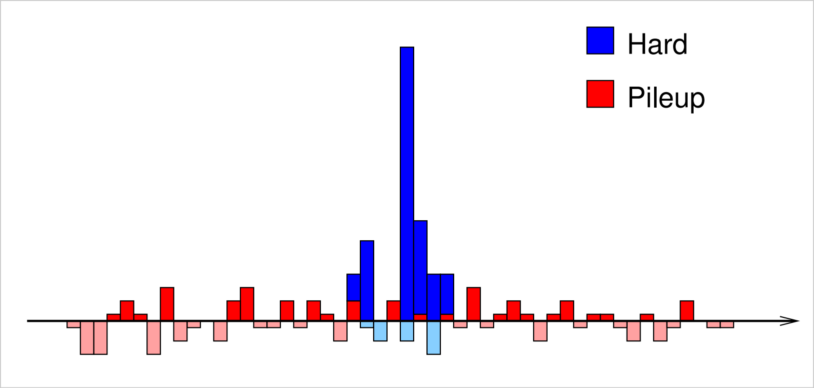

subtract ρA_{sub} in each subjet

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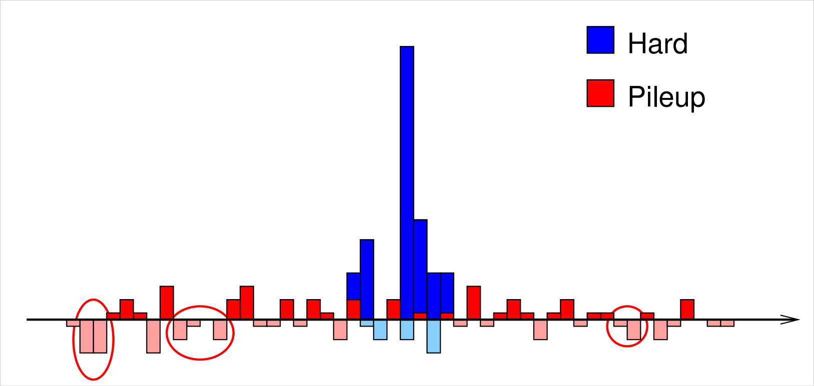

But one gets (unphysical) negative subjets!!

Goal/Challenges

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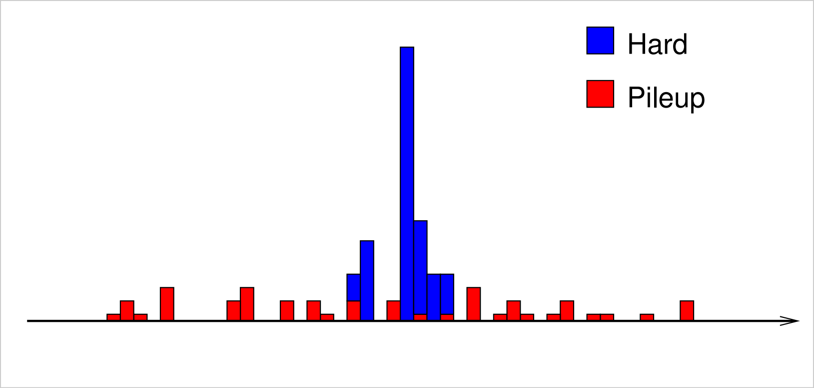

With a simple cut: reduced energy smearing, but biased (undersubtraction)

Goal/Challenges

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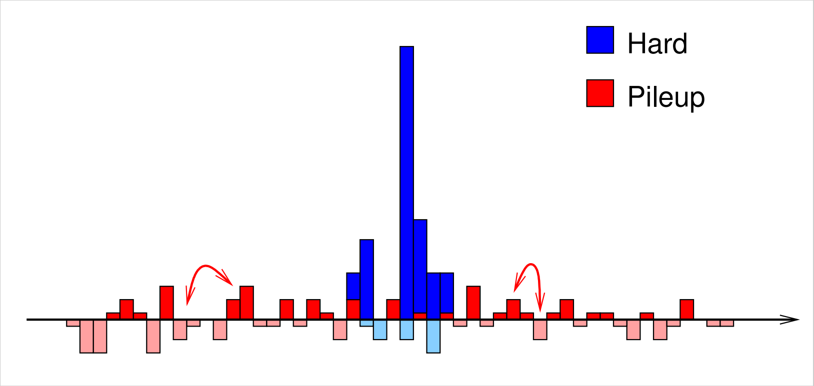


For an unbiased method, we need to balance negative and positive subjets

Goal/Challenges

Goal: get a better resolution i.e. reduce effects of σ

Now, we look at a smaller scale, *e.g.* subjets (or particles)

Generic idea

Say we have a method that keeps/thrown away particles (or subjets)

- PU particles kept: positive bias
- "hard" particles thrown out: negative bias

The two biases need to balance generically (all p_t, $N_{\rm PU}$,...)

Challenge: fine-tuning to get small biases + robustness at stakes

Preliminary ideas to explore (0/2)

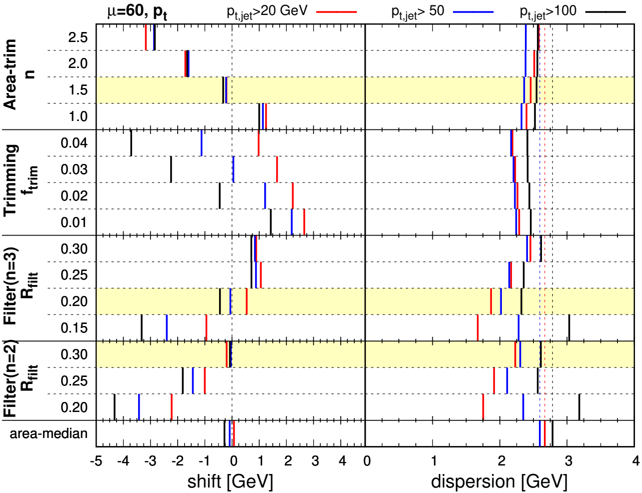
We have explored many options mostly in 2 directions:

- Subjet-based (grooming) techniques
  - Idea: use a grooming technique
  - Cluster the jet into smaller subjets, subtract the subjets, keep only some of the hard subjets
  - Example: keep subjets with $p_t \geq n\sigma\sqrt{A_{\text{subjet}}}$ ("above noise")
- event-wide particle-level subtraction (before jet clustering)
  - Idea: cut or subtract soft particles in the whole event
  - Useful quantities to consider: particle p_t, Voronoi particle area, ...
  - various "stopping conditions" considered (examples later)

Preliminary ideas to explore (1/2)

[GS, unpublished, started in Les-Houches 2013]

Category 1: use subjets (grooming: Filtering, trimming, area-trimming)



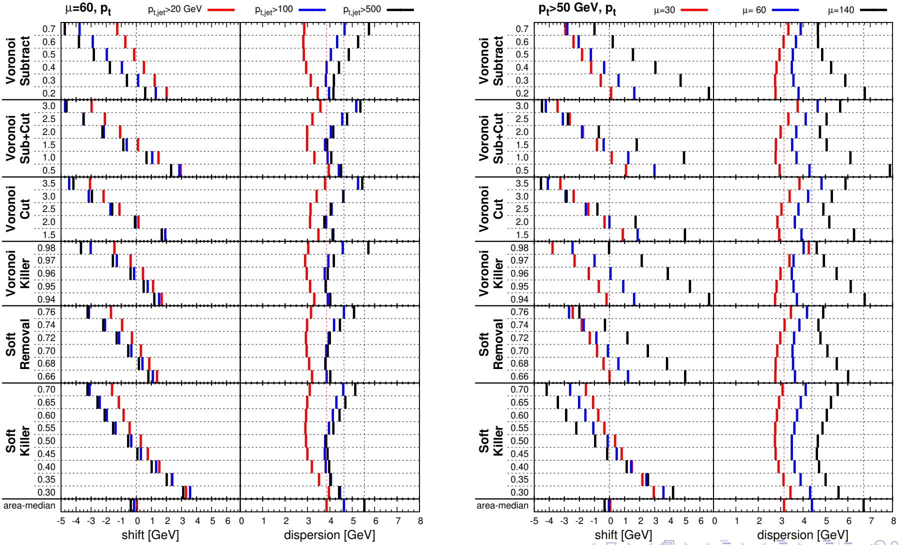
Observations:

- fine-tuning
- not so robust
- sharper

Preliminary ideas to explore (2/2)

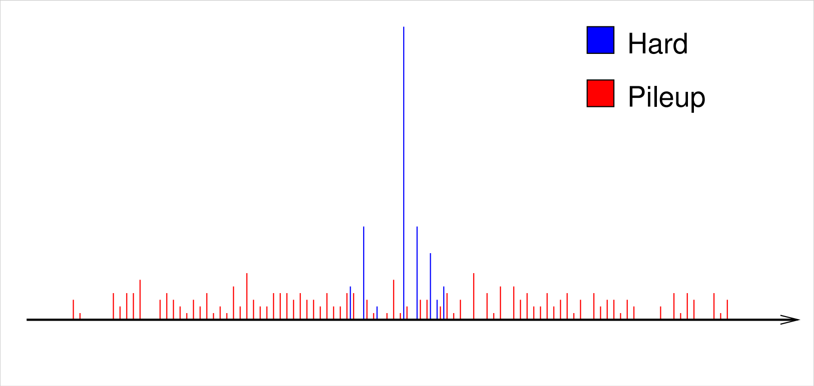
[M.Cacciari,G.Salam,GS, unpublished]

Category 2: particle-level subtraction



[M.Cacciari,G.Salam,GS,2014]

Come back to our toy event...



The SoftKiller approach to event-wide subtraction

[M.Cacciari,G.Salam,GS,2014]

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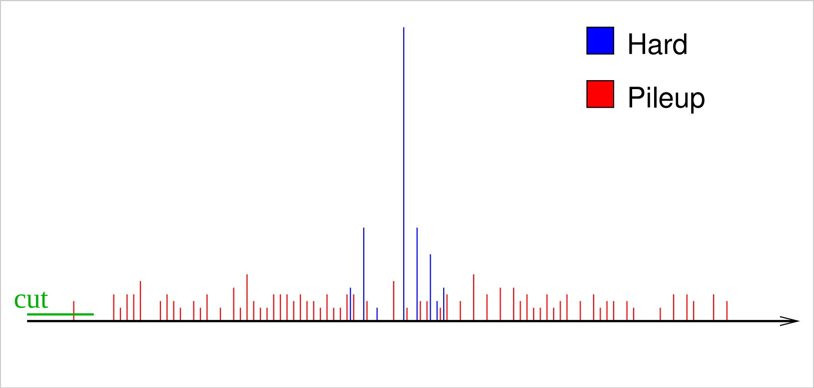

start to remove the softest particles

[M.Cacciari,G.Salam,GS,2014]

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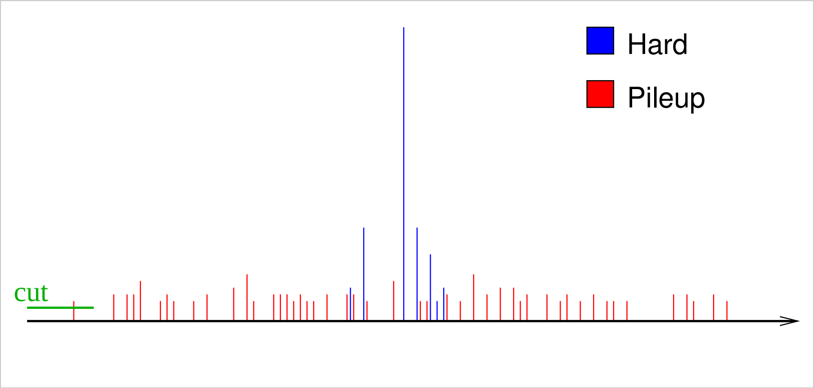

progressively increase the cut on soft particles

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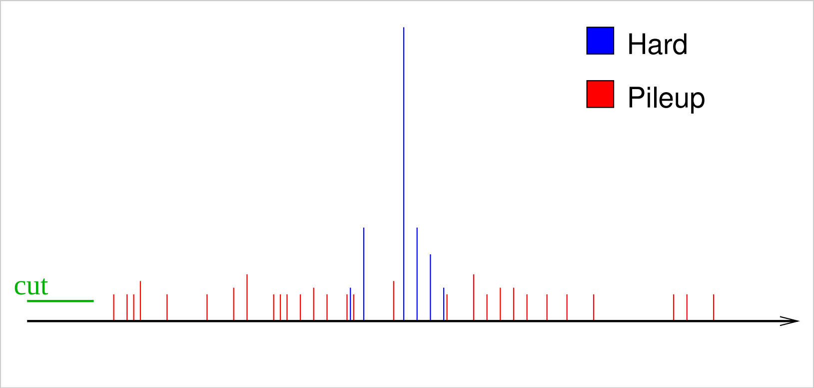

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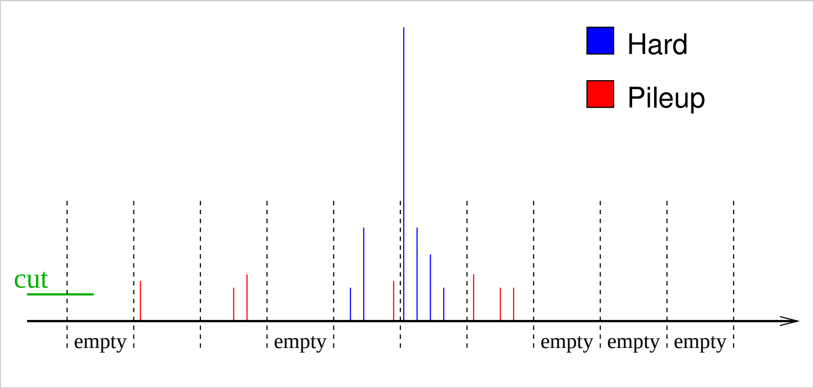
[M.Cacciari,G.Salam,GS,2014]

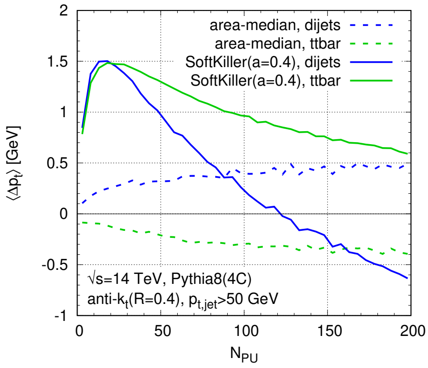
Come back to our toy event...

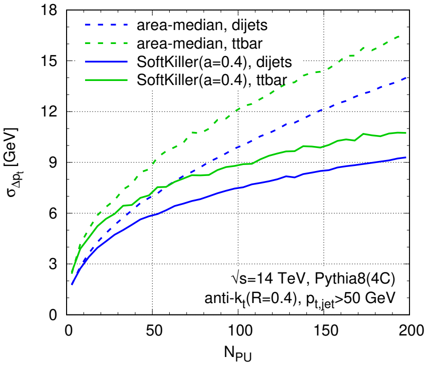


until the estimated ρ is 0 (*i.e.* half the patches are empty)

SoftKiller: basic performance

[M.Cacciari,G.Salam,GS,2014]





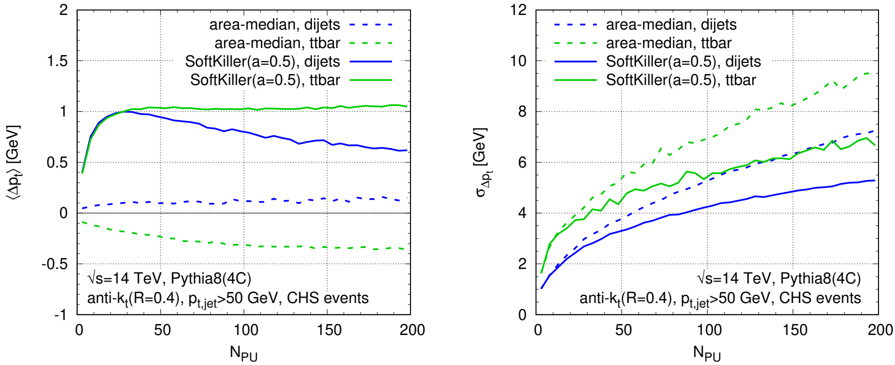
Reasonable bias

smaller dispersion

SoftKiller: performance w CHS events

[M.Cacciari,G.Salam,GS,2014]

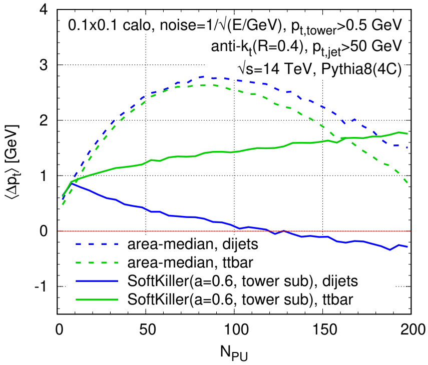
Same observations with CHS events

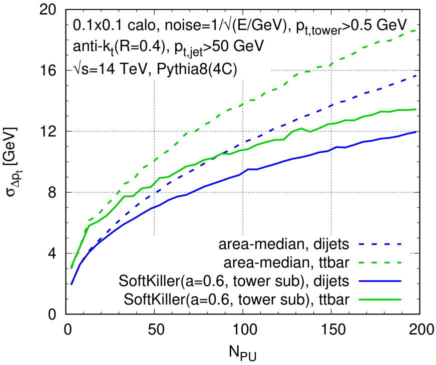


Note: slightly larger *a* (expected so)

[M.Cacciari,G.Salam,GS,2014]

- First subtract each tower with area–median:
$$p_{t,\text{tower}}^{\text{pre-sub}} = p_{t,\text{tower}} - \rho A_{\text{tower}}$$
- then apply the SoftKiller on the result (note again larger a)

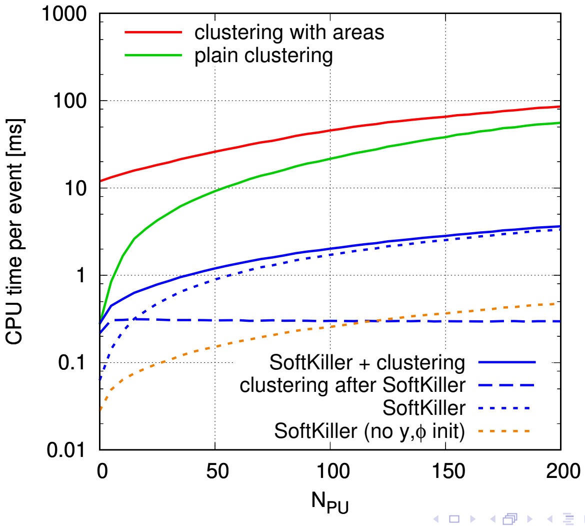




SoftKiller timings

[M.Cacciari,G.Salam,GS,2014]

Remarkable timings (great e.g. for trigger)



SoftKiller improvement: (protected) zeroing

[preliminary]

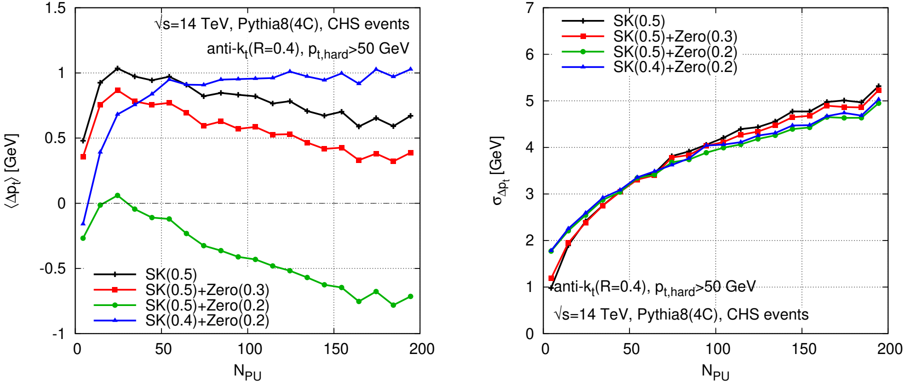
<u>Idea</u>:

- work with CHS events
- apply SoftKiller(a)
- for each neutral particle $p_{neutral}$, draw a circle of radius R_0 around it. Keep the particle if
  - there is a leading-vertex charge track in the circle
  - OR, $p_{t,\text{neutral}} > p_{t,\text{min}}$ (used $p_{t,\text{min}} = 10$ GeV) ("protection")

Note: now a 2-parameter method, a and R_0

SoftKiller: performance w CHS events

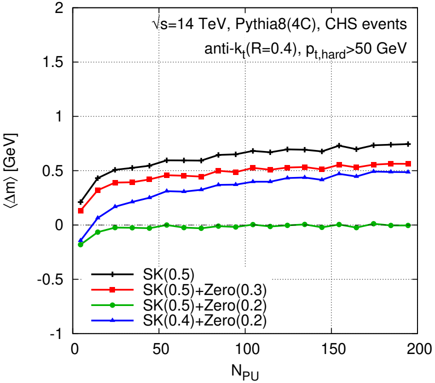
[preliminary]

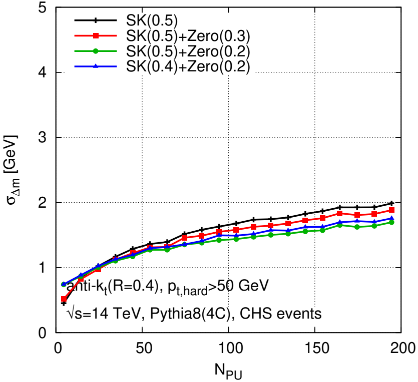


- bias in the same ballpark, small resolution gains at large μ

SoftKiller: performance w CHS events

[preliminary]





- bias in the same ballpark, small resolution gains at large μ
- SK($a = 0.5$)+Zeroing($R_0 = 0.2$) shows great stability for the jet mass

Analytic properties

- Many effects understood e.g. from a Gaussian approximation
- Here: also discussing more specific examples

Simple example PU+steeply-falling spectrum

Gaussian pileup: $(\sigma \ll \rho \ll p_{t,\text{jet}})$

$$\frac{dP}{d\delta p_{t,\text{PU}}} = \frac{1}{\sqrt{2\pi A}\sigma} \exp\left(-\frac{(p_{t,\text{PU}} - \rho A)^2}{2\sigma^2 A}\right),$$

"hard" spectrum can be approximated by:

$$\frac{d\sigma_{\text{truth}}}{dp_t} = \frac{\sigma_0}{\mu} e^{-p_t/\mu}$$

We find the expected shift and smearing effects:

$$\frac{d\sigma_{\text{reco}}}{dp_t} = \frac{d\sigma_{\text{truth}}}{dp_t} \exp\left(\frac{\rho A}{\mu} + \frac{\sigma^2 A}{2\mu^2}\right)$$

and

$$p_{t,\text{truth}}^{\text{most likely}} = p_{t,\text{reco}} - \rho A - \frac{\sigma^2 A}{\mu}$$

Analytic properties of jet areas

[M.Cacciari, G.Salam, GS, 08]

Jet areas are (almost by definition) infrared unsafe.
But we can say many (analytic) things about them

Passive area (for simplicity)

Add one "ghost" ($\infty^{\text{al}} p_t$): $a_{\text{jet}} = \int dy\, d\phi\, \Theta(\text{ghost at } (y, \phi) \in \text{jet})$

Perturbative calculations of area

1 particle:

$$a = \pi R^2$$

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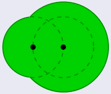
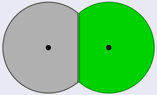
1 particle + 1 soft particle:

$$a = a(\Delta) \neq \pi R^2$$



R/2 < Δ_{12} < R



R < Δ_{12} < 2R

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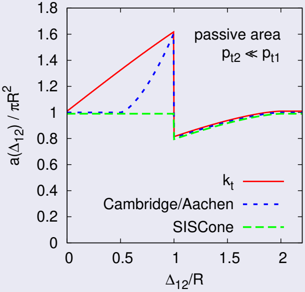

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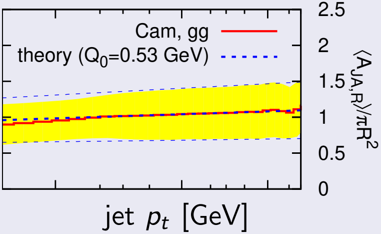
$$\langle a \rangle = \frac{\alpha_s}{2\pi} \int \frac{dz}{z} \frac{d\Delta}{\Delta} [a(\Delta) - a(0)]$$
$$= \frac{\alpha_s}{2\pi} \log \frac{p_t}{Q_0}\, \mathbf{d}$$



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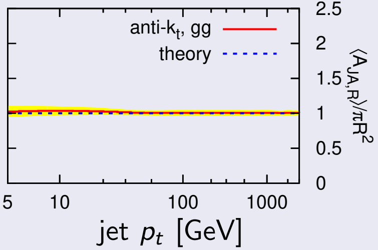
Perturbative calculations of area

One noticeable exception:

anti-k_t jets are insensitive to soft particles



Analytic properties of the ρ estimation

[Adapted from [M.Cacciari, G.Salam, S.Sapeta, 10]

How good is our estimation of ρ? What drives differences?

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Setup

- Toy-model for pileup (indep particles with exp spectrum)
- soft emissions from the hard event (initial-initial state)
- Gives at least parametric estimates (p_t, ρ, σ, R,range)

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Median $\neq$ average:

$$\frac{\rho_{\text{est}} - \rho}{\rho} \propto -\frac{\sigma^2}{\rho^2 a_{\text{grid}}^2}$$

Hard contaminates median:

$$\frac{\rho_{\text{est}} - \rho}{\rho} \propto +\frac{a_{\text{grid}}\sigma}{\rho}$$

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Many applications (in the thesis and beyond)

sizeable a_{grid} range, range size estimates, jet R optimisation

Usefulness of analytic control

Analytic control of 3 types:

- simple Gaussian description of PU effects
- understanding of how a jet reacts to soft particles (area understanding)
- understanding of biases of the area–median

have greatly helped the understanding of jet algs and PU subtraction

- Cone v. k_t v. anti-k_t around 2008
- understanding of areas–median biases (e.g. number of jets in the median estimate)
- understanding of grooming selection biases
- ...

Future perspectives

Ideas for future work

Several directions of varying interest and impact

Towards better PU mitigation techniques

Can we get analytic control from $(\mathrm{pQCD})_{\mathrm{hard}} + (\mathrm{toy\text{-}model/data})_{\mathrm{PU}}$?

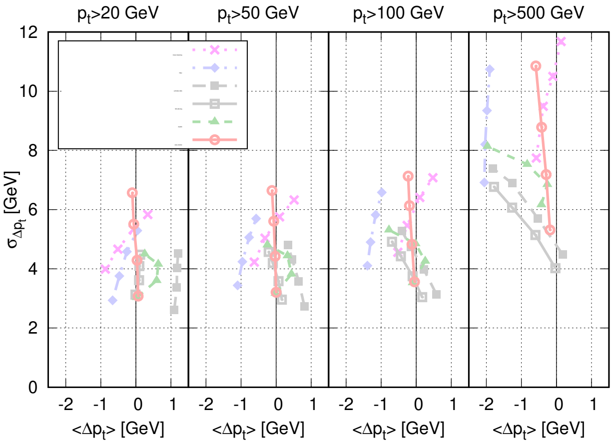
- Analytic control over SoftKiller parameter (N_{PU}, p_t, R dependence)
- Better analytic understanding of grooming techniques
- Deeper exploration of other noise-reduction techniques

Ultimate goal: use that knowledge to design efficient new techniques

Other curiosities/open questions

- Areas to tune Monte-Carlo?
- Better analytic understanding of actve areas (e.g. pure-ghost jets)
- What is the maximal reach of anti-k_t jets?

Conclusions



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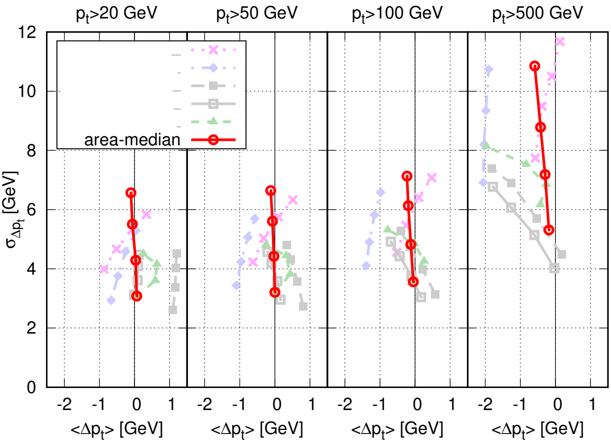

- Area–median
  - unbiased
  - robust

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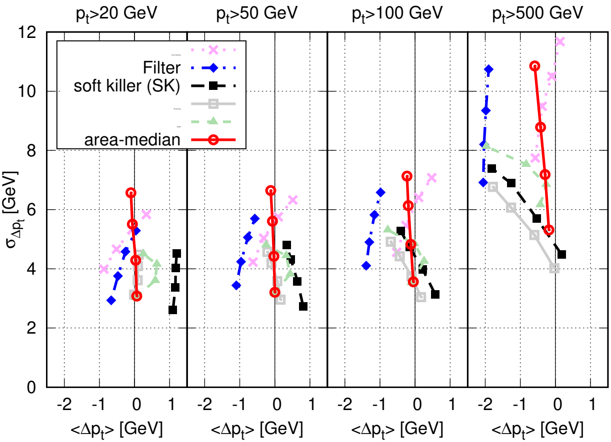

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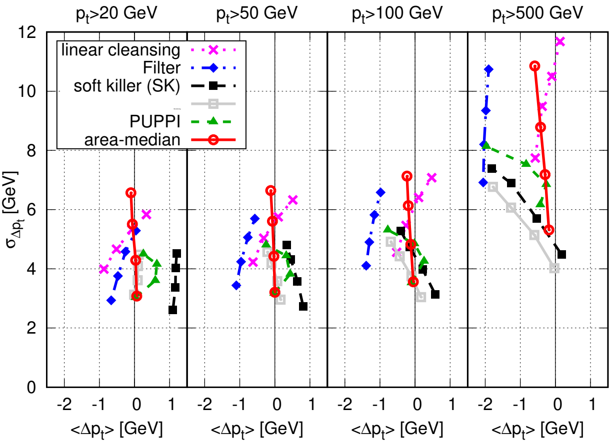
- New candidates:
  - better resolution
  - fine-tuning



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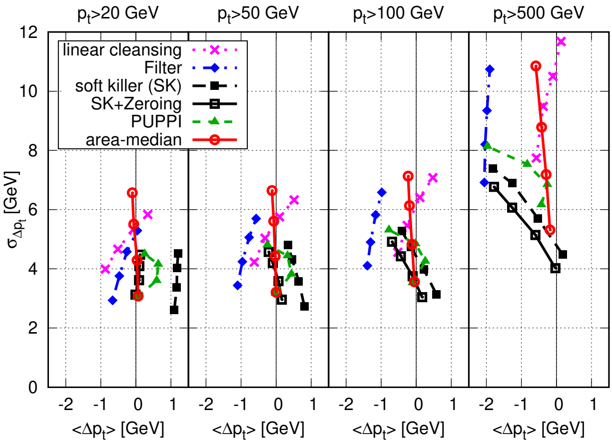

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- "external" not reviewed here
- Stay tuned

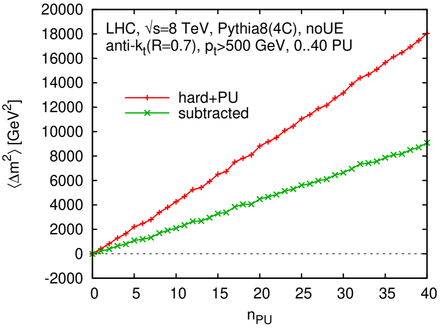
BACKUP

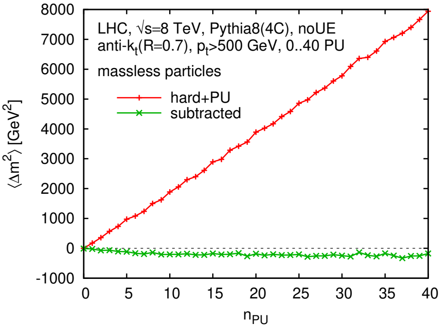
4-vector and jet mass subtraction

$$p_{\rm jet}^{\mu,({\rm sub})} = p_{\rm jet}^{\mu} - \rho_{\rm est} A_{\rm jet}^{\mu}$$

$$p_{\rm jet}^{\mu,({\rm sub})} = p_{\rm jet}^{\mu} - \rho_{\rm est} A_{\rm jet}^{\mu}$$

How do we do for the jet mass?





$$\Delta m^2 = (m_{\rm full}^{({\rm sub})})^2 - m_{\rm hard}^2$$

poor subtraction

OK for massless particles

4-vector and jet mass subtraction

Generic 4-vector: $(m_t = \sqrt{p_t^2 + m^2})$

$$p^\mu \equiv (p_t \cos(\phi), p_t \sin(\phi), m_t \sinh(\phi), m_t \cosh(\phi))$$

Background uniform in y and ϕ
$\Rightarrow$ 2 degrees of freedom: p_t and m_t

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Background uniform in y and ϕ
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For pile-up contamination in a jet:

$$\begin{aligned}\sum_i p_i^\mu &= \sum_i (p_{t,i} \cos(\phi_i), p_{t,i} \sin(\phi_i), m_{t,i} \sinh(\phi_i), m_{t,i} \cosh(\phi_i)) \\ &= \sum_i p_{t,i}(\cos(\phi_i), \sin(\phi_i), \sinh(\phi_i), \cosh(\phi_i)) \\ &\quad + (m_{t,i} - p_{t,i})(0, 0, \sinh(\phi_i), \cosh(\phi_i))\end{aligned}$$

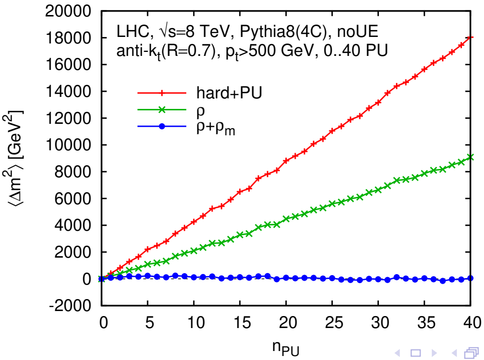
1st line is $\propto \rho \times$ ghost coverage; 2nd line is a new correction

4-vector and jet mass subtraction

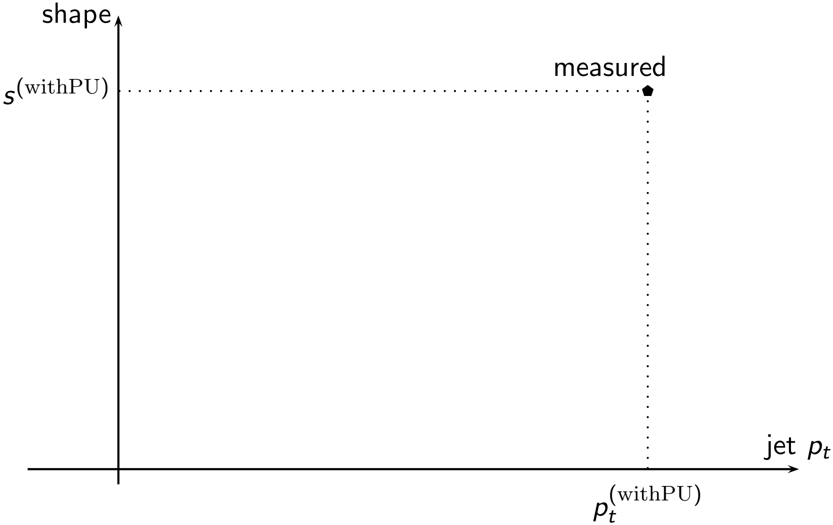
$$p^\mu_{\rm sub} = p^\mu - \rho A^\mu - \rho_m A^\mu_m$$

with

$$\rho_m = \underset{j\in\text{patches}}{\text{median}} \left\{ \frac{\sum_{i\in j} m_{t,i} - p_{t,i}}{A} \right\} \quad \text{and} \quad A^\mu_m \equiv (0, 0, A_z, A_E)$$



Jet shapes: extrapolation to 0 pileup



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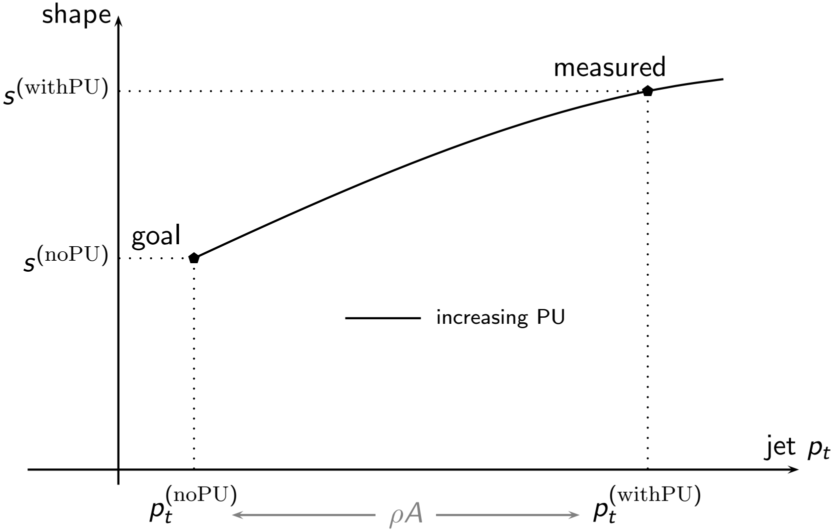
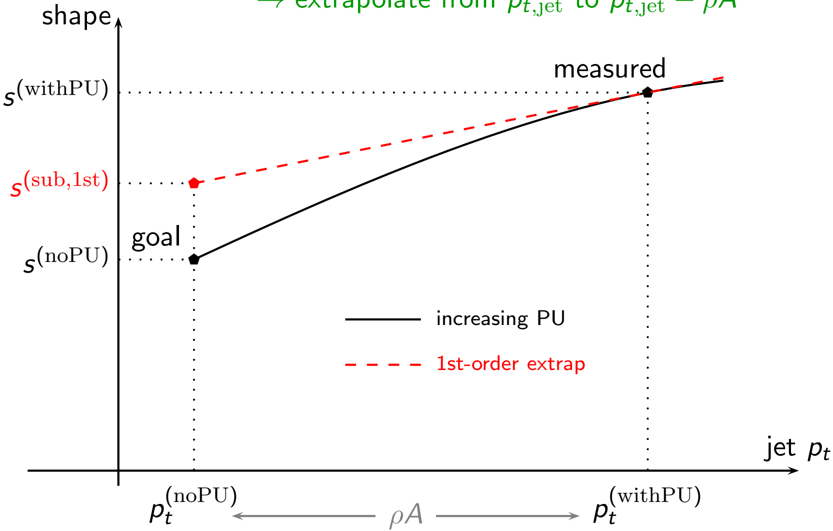


Jet shapes: extrapolation to 0 pileup

knowledge of the derivatives wrt uniform shift of PU

$\rightarrow$ extrapolate from $p_{t,\mathrm{jet}}$ to $p_{t,\mathrm{jet}} - \rho A$



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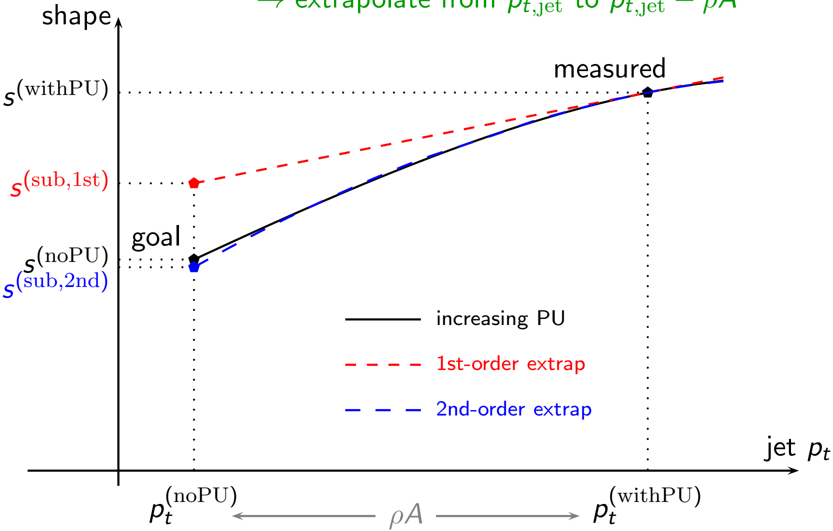
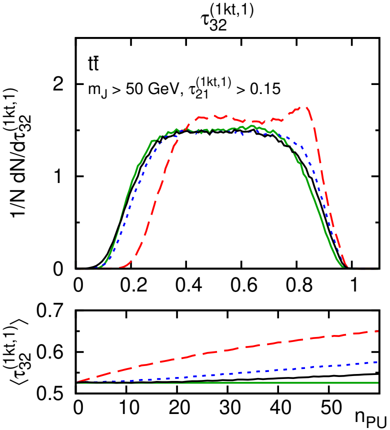
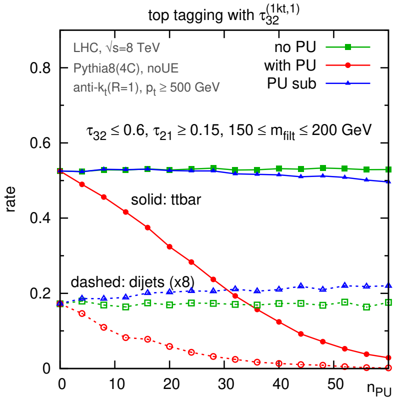


Example: *N*-subjettiness for boosted top tagging





Green: truth

Red: truth+PU (unsub)

Blue: 1st order sub

Black: 2nd order sub

good performance and stability