ICHEP 2020

Pileup and Underlying Event Mitigation with Iterative Constituent Subtraction

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Outline

1. Pileup at the LHC

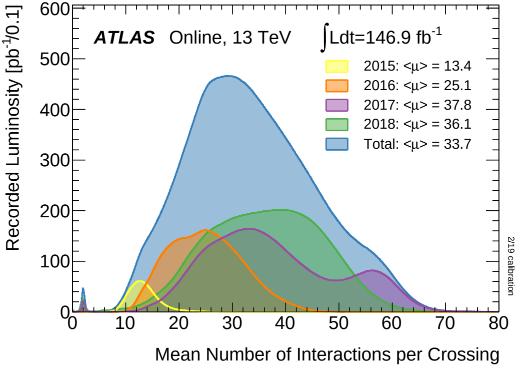
2. Constituent Subtraction

3. Newest developments: Iterative Constituent Subtraction

Pileup at the LHC

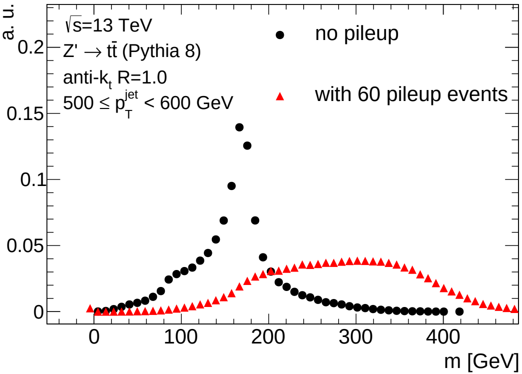
Pileup at the LHC

- Pileup = simultaneous proton-proton collisions in one bunch crossing (or in neighboring bunch crossings)
- Higher instantaneous luminosity $\Longrightarrow$ higher pileup
  - LHC Run2: up to $\sim$70 interactions per bunch crossing,
  - future LHC running: up to 200 interactions per bunch crossing.



Pileup effects for jets

- Pileup randomly adds energy deposits to calorimeter
  - 20 pileup events adds $\sim$50 GeV additional p_{T} under an anti-k_t R=1.0 jet,
  - jet shape variables (mass, width,...) may change significantly.
- Necessity to mitigate pileup effects



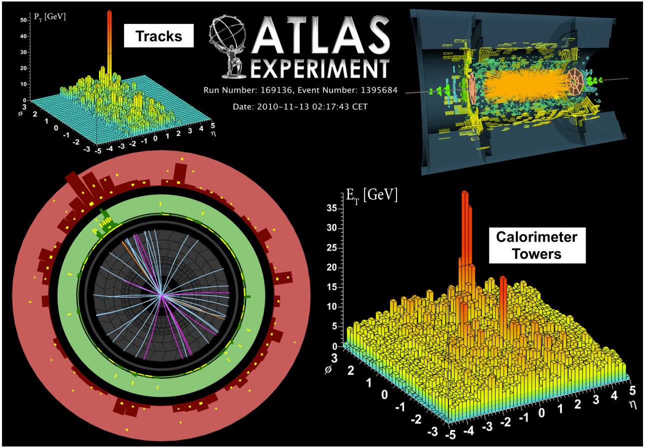
large-R jets containing top quarks

Selection of pileup mitigation methods for jets

- Area Subtraction - arXiv:0707.1378, arXiv:0802.1188
  - used by LHC experiments in ∼600 physics measurements
- **Constituent Subtraction** - arXiv:1403.3108
  - better performance than Area Subtraction
  - already used in 12 physics measurements
- SoftKiller (SK) - arXiv:1407.0408
- PUPPI - arXiv:1407.6013
  - used at the CMS experiment
- **Iterative Constituent Subtraction** - arXiv:1905.03470

Heavy-ion collisions

- Underlying event in heavy-ion collisions ≈ pileup in proton-proton collisions
  ⇒ same methods to correct jets can be used



ATLAS experiment, heavy-ion collision with dijet event
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EventDisplayHeavyIonCollisions

Constituent Subtraction

Constituent Subtraction (CS)

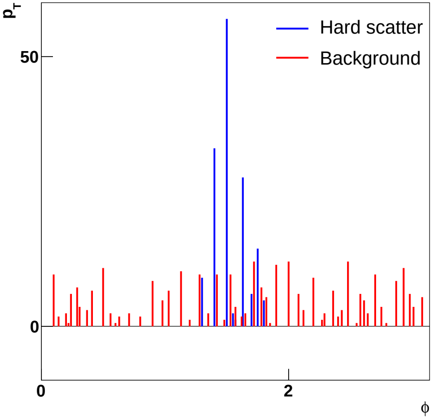
- Pileup subtraction method at the level of inputs
- Generalization of the Area Subtraction
  - exploits the background p_{T} density (ρ)
- $\rho =$ amount of p_{T} from pileup particles per unit area in the rapidity - azimuth ($y - \phi$) space
- Two possibilities of usage:
  - **jet-by-jet** - jet clustering first, then correction of individual jets
  - **event-wide** - correction of the whole event first, then jet clustering
    - jet clustering is less biased

Physics results with Constituent Subtraction

- **ALICE** publications:
  - Measurements of jet fragmentation and jet substructure with ALICE, arXiv:1909.03066
  - Role of Coherence Effects on Jet Quenching in Pb-Pb, arXiv:1705.03383
  - Exploring jet substructure with jet shapes in ALICE, arXiv:1704.05230
  - First measurement of jet mass in Pb-Pb and p-Pb collisions, arXiv:1702.00804
  - Jet shapes in pp and Pb–Pb collisions at ALICE, arXiv:1512.07882
- **ATLAS** publication:
  - Measurement of $Z(\rightarrow b\bar{b})\gamma$ differential cross section, arXiv:1907.07093
- **CMS** publications:
  - Evidence for top quark production in nucleus-nucleus collisions, CMS-PAS-HIN-19-001
  - Measurement of Jet Nuclear Modification Factor in PbPb Collisions, CMS-PAS-HIN-18-014
  - Measurement of the groomed jet mass in PbPb and pp collisions, arXiv:1805.05145
  - Splitting function in pp and PbPb collisions, arXiv:1708.09429
- **STAR** publication:
  - Jet sub-structure and parton shower evolution in p+p and Au+Au collisions at STAR, arXiv:1906.05129

Event-wide CS

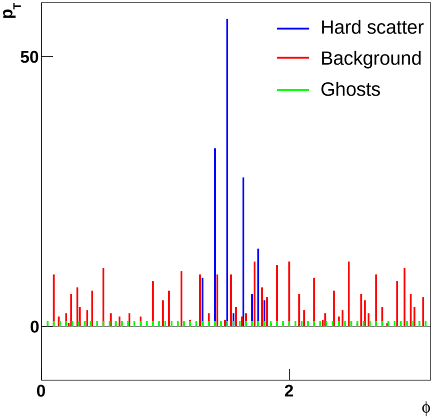
1. **Estimation of ρ**



Whole event

Event-wide CS

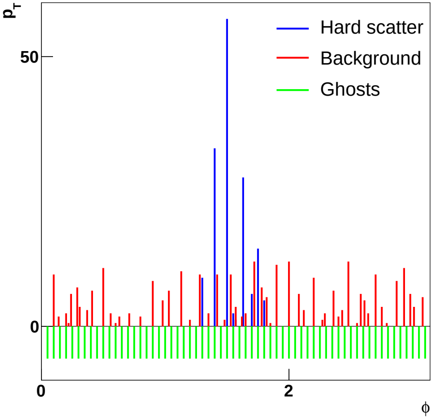
1. Estimation of ρ
2. **Adding ghosts to the whole event**



Whole event

Event-wide CS

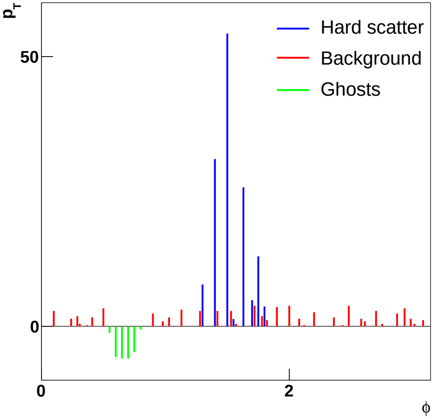
1. Estimation of ρ
2. Adding ghosts to the whole event
3. **Setting ghosts p_T to negative value corresponding to ρ**



Whole event before correction

Event-wide CS

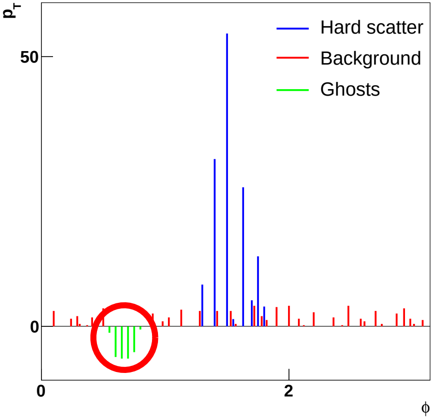
1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. **Matching ghosts to particles**
    - Matching algorithm based on the ΔR distance between particles and ghosts
    - Matching particle-ghost pairs with $\Delta R < \Delta R^{\max}$, where $\Delta R^{\max}$ is a free parameter



Whole event after correction

Event-wide CS

1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. Matching ghosts to particles
   - Matching algorithm based on the ΔR distance between particles and ghosts
   - Matching particle-ghost pairs with $\Delta R < \Delta R^{\max}$, where $\Delta R^{\max}$ is a free parameter
   - **With finite $\Delta R^{\max}$, some ghosts can be unmatched**
     - discussed later



Whole event after correction

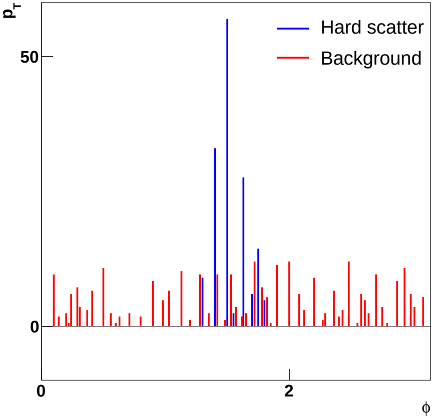
Newest developments: Iterative Constituent Subtraction

Iterative Constituent Subtraction (ICS)

- P. Berta, L. Masetti, D. W. Miller and M. Spousta
  JHEP 08 (2019) 175
- New pileup mitigation method for jets
  - supersedes the original Constituent Subtraction method
- Main idea: application of the Event-wide CS several times
  - After each CS application, the remaining unsubtracted p_{T} in ghosts is redistributed
  - For each iteration, different CS parameters can be used
- Software implementation available in `FastJet Contrib` since v1.041

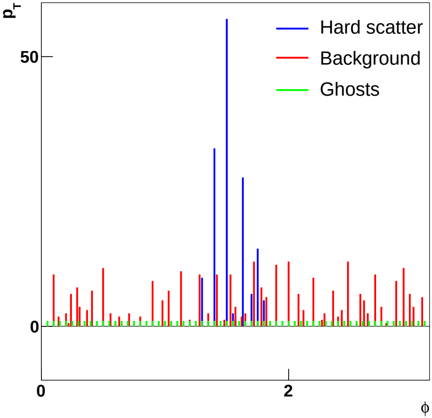
ICS - example with two iterations

1. **Estimation of ρ**



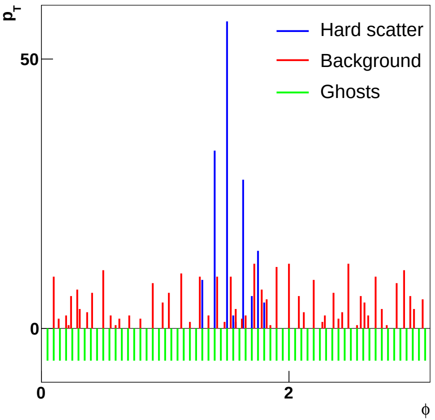
ICS - example with two iterations

1. Estimation of ρ
2. **Adding ghosts to the whole event**



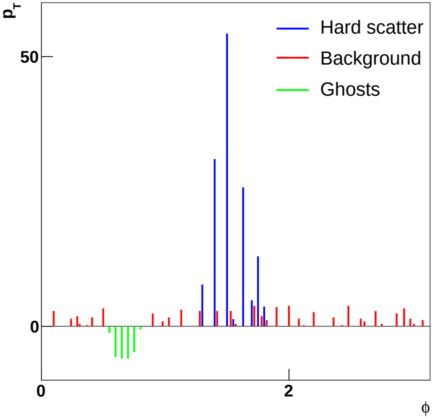
ICS - example with two iterations

1. Estimation of ρ
2. Adding ghosts to the whole event
3. **Setting ghosts p_{T} to negative value corresponding to ρ**



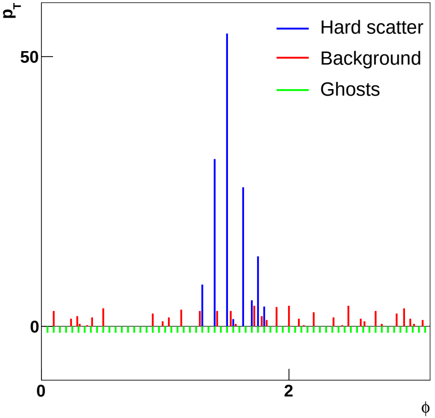
ICS - example with two iterations

1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. **1. iteration: matching of ghosts to particles**



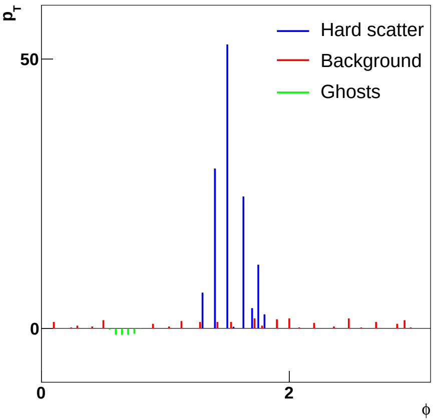
ICS - example with two iterations

1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. 1. iteration: matching of ghosts to particles
5. **Redistribution of remaining p_{T}**

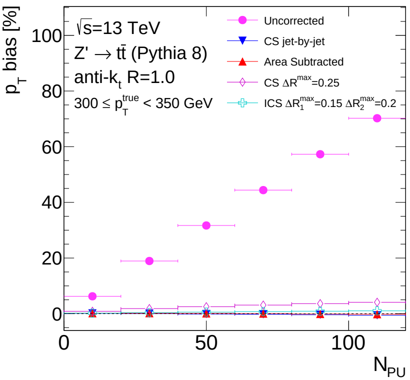


ICS - example with two iterations

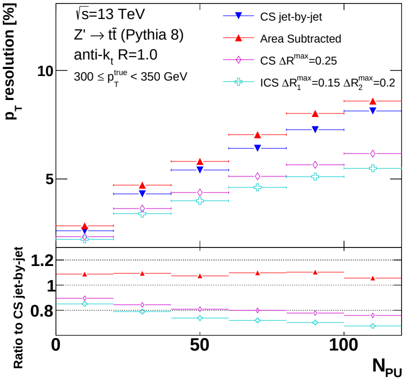
1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. 1. iteration: matching of ghosts to particles
5. Redistribution of remaining p_{T}
6. **2. iteration: matching of ghosts to particles**



Iterative CS - performance for jet p_T



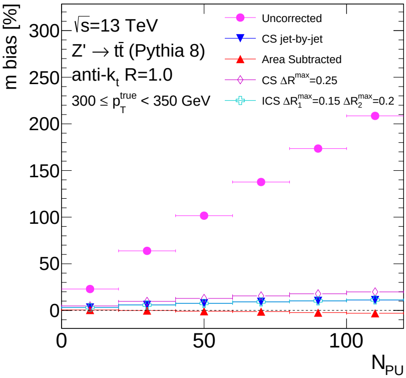
Bias



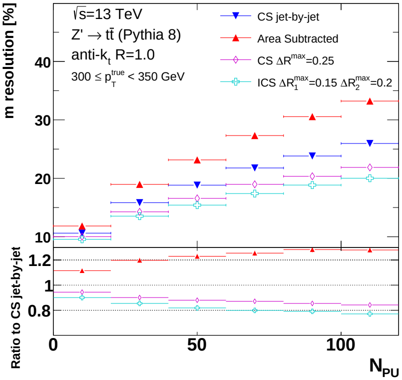
Resolution

- ICS improves the jet p_T resolution

Iterative CS - performance for jet mass



Bias



Resolution

- ICS improves the jet mass resolution

Summary

- Constituent Subtraction
  - competitive pileup mitigation method
- Iterative Constituent Subtraction
  - new method
  - large improvement in resolution keeping the bias well controlled
  - experiments are encouraged to test it

BACKUP

Background density ρ

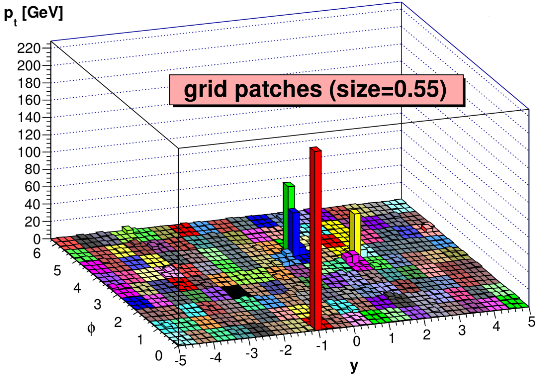
- ρ - amount of p_{T} from pileup particles per unit area in the rapidity - azimuth $(y - \phi)$ space
- many possibilities how to estimate ρ. One of them:

1. event divided into rectangular patches in the $(y - \phi)$ space; p_{T} of each patch:

$$p_{\mathrm{T}\text{patch}} = \sum_{i \in \text{patch}} p_{\mathrm{T}i}$$

2. the estimated pileup p_{T} density:

$$\rho = \text{median}_{\text{patches}} \left\{ \frac{p_{\mathrm{T}\text{patch}}}{A_{\text{patch}}} \right\}$$



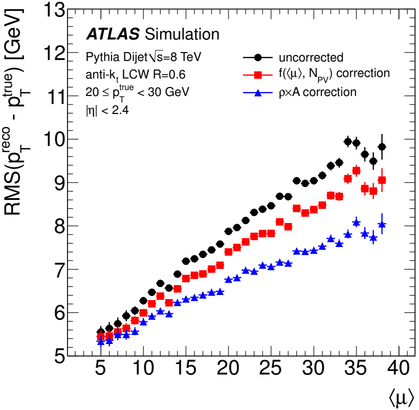
Slides from G. Soyez (BOOST2012 conference)

Pileup mitigation for jets - other methods

- SoftKiller - arXiv:1407.0408
  - removes particles up to certain p_T threshold
    - the p_T threshold estimated based on the pileup activity in the event
- PUPPI - arXiv:1407.6013
  - used in CMS
- Grooming:
  - removal of particles within large-R jets
  - makes the signal-to-background separation better (e.g. top quarks vs QCD jets)
  - several methods:
    - trimming - arXiv:0912.1342
    - SoftDrop - arXiv:1402.2657
    - pruning - arXiv:0903.5081
    - ...

Jet Area Subtraction

- Current pileup mitigation method for 8 TeV and 13 TeV data in ATLAS
- Correction of jet 4-momentum
- Basic ingredients:
  - pileup p_{T} density (ρ)
  - concept of jet area



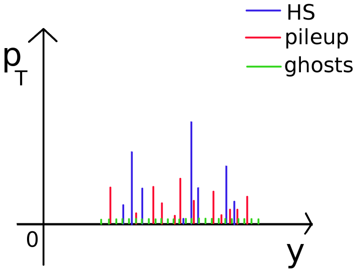
Jet p_{T} resolution for the Area Subtraction method ($\rho \times A$ correction), arXiv:1510.03823

Ghosts

- ghosts - important ingredient to the "pileup p_{T} density" methods
- ghosts - infinitesimally soft massless particles uniformly distributed in the $y - \phi$ space. The 4-momentum of ghost k is:

$$g_{\mu,k} = p_{\mathrm{T}}^{g} \cdot [\cos\phi_k^g, \sin\phi_k^g, \sinh y_k^g, \cosh y_k^g], \quad (1)$$

  p_{T}^{g} - ghost transverse momentum
- each ghost occupies an area A_g in the $y - \phi$ space,
- the ghosts may be clustered into the jet with arbitrary jet algorithm,
- **ghosts mimick pileup $\Longrightarrow$ they can be used to subtract pileup.**



Area Subtraction for 4-momentum

- 4-momentum of jet with pileup:

$$[p^x, p^y, p^z, E]. \tag{2}$$

- corrected jet 4-momentum:

$$p^{\mu}_{\mathrm{corr}} = [p^x - \rho A^x, p^y - \rho A^y, p^z - \rho A^y, E - \rho A^E]. \tag{3}$$

where area 4-vector A^{μ} is defined:

$$A^{\mu} = \frac{A_g}{p_{\mathrm{T}}^g} \sum_{k \in \mathrm{ghosts}} g_{\mu,k} \tag{4}$$

Event-wide CS

1. Adding ghosts to the whole event
2. Setting ghosts p_{T} to negative value corresponding to ρ
3. **Matching of ghosts to particles**

- Evaluate distances between each particle-ghost pair.
  - Distance between particle i and ghost k:

$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{(y_i - y_k^g)^2 + (\phi_i - \phi_k^g)^2}$$

- Combine each ghost-particle pair starting from lowest $\Delta R_{i,k}$:

If $p_{\mathrm{T}i} \geq p_{\mathrm{T}k}^g$: $\quad p_{\mathrm{T}i} \to p_{\mathrm{T}i} - p_{\mathrm{T}k}^g$, $\quad p_{\mathrm{T}k}^g \to 0$

otherwise: $\quad p_{\mathrm{T}i} \to 0$, $\quad p_{\mathrm{T}k}^g \to p_{\mathrm{T}k}^g - p_{\mathrm{T}i}$

- Procedure stops for $\Delta R_{i,k} > \Delta R^{\max}$

Jet-by-jet CS - detailed description

- for each event
  1. estimate the pileup p_{T} density, ρ, in the event,
  2. add ghosts (infinitesimally small p_{T}^{g}) among particles in the event and apply jet clustering algorithm to all particles and ghosts $\Rightarrow$ the jets are composited from particles and ghosts,
- for each jet in the event
  3. set for each ghost $p_{\mathrm{T}}^{g} = \rho A_g$
  4. evaluate distance $\Delta R_{i,k}$ between particle i and ghost k for each possible particle-ghost pair and sort them in ascending order:

$$\Delta R_{i,k} = p_{\mathrm{T}i}^{\alpha} \cdot \sqrt{(y_i - y_k^g)^2 + (\phi_i - \phi_k^g)^2}. \qquad (5)$$

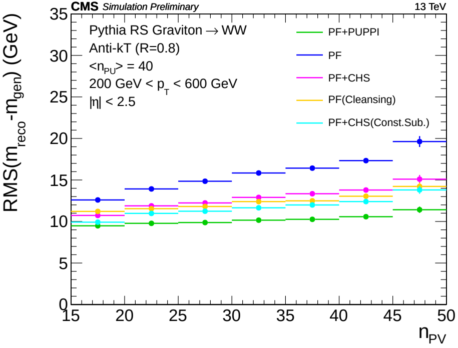
     α - free parameter
  5. iteratively change transverse momenta by applying the following procedure for each ghost-particle pair until no more pairs remain or $\Delta R_{i,k} > \Delta R^{\max}$:

$$\text{If } p_{\mathrm{T}i} \geq p_{\mathrm{T}k}^{g}: \quad p_{\mathrm{T}i} \to p_{\mathrm{T}i} - p_{\mathrm{T}k}^{g}, \; p_{\mathrm{T}k}^{g} \to 0; \qquad \text{otherwise:} \quad p_{\mathrm{T}i} \to 0, \; p_{\mathrm{T}k}^{g} \to p_{\mathrm{T}k}^{g} - p_{\mathrm{T}i}. \qquad (6)$$

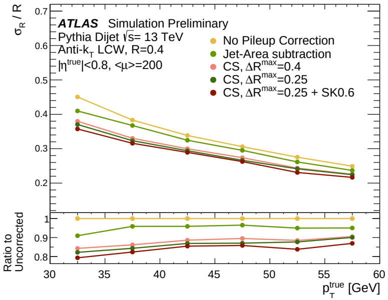
  6. after the iterative process, discard all particles with zero transverse momentum.

CS performance in ATLAS and CMS (pp collisions)

- CMS performance CMS-PAS-JME-14-001
- ATLAS low p_{T} performance in ATLAS-CONF-2017-065
- ATLAS large-R jets performance in ATL-PHYS-PUB-2017-020
- Improved performance compared to the Area Subtraction



CMS-PAS-JME-14-001

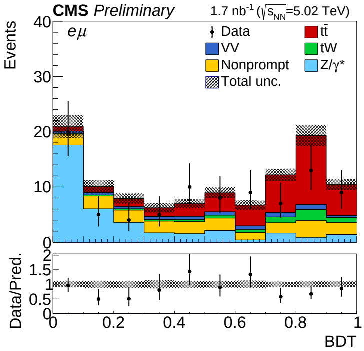


ATLAS-CONF-2017-065

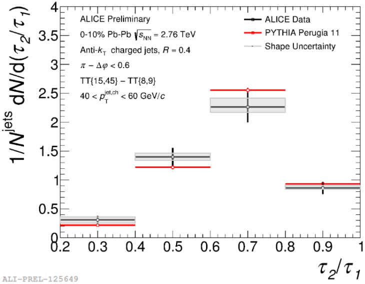
New developments - setup for performance studies

- Pythia8 simulation of signal and pileup events
- Number of pileup events, N_{PU}, is uniformly distributed in range [0,120] (LHC Run 3)
- Particles grouped into massless towers of size 0.1×0.1 in $y - \phi$ space
- CS correction of whole event up to $|\eta| < 5$
- Using CS parameter $\alpha = 0$
- Using ρ rescaling (rapidity dependence)
- Figures of merit:
  - $\mathrm{Bias} = \frac{\langle x - x^{\mathrm{true}} \rangle}{\langle x^{\mathrm{true}} \rangle}$ **- the closer to zero, the better**
  - $\mathrm{Resolution} = \frac{\mathrm{RMS}(x - x^{\mathrm{true}})}{\langle x^{\mathrm{true}} \rangle}$ **- the smaller, the better**

Physics results with Constituent Subtraction



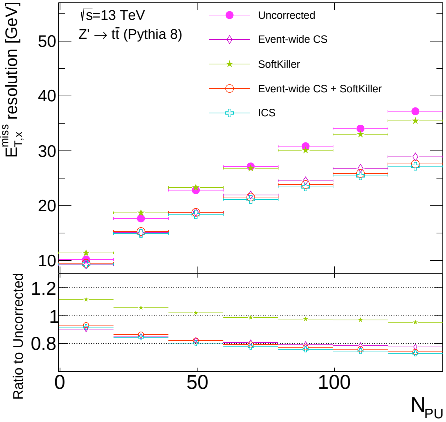
Evidence for top quark production in heavy-ion collisions, CMS-PAS-HIN-19-001



Measurement of jet substructure variable τ_{21} in heavy-ion collisions , arXiv:1705.03383

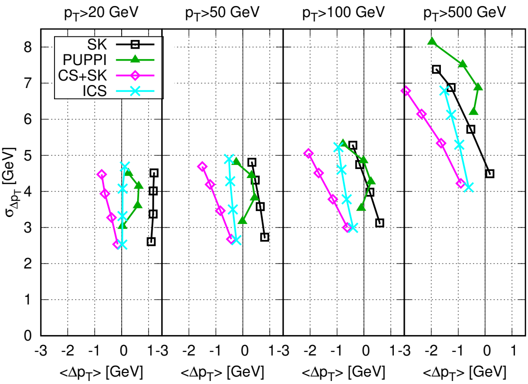
- Heavy-ion community extensively uses Constituent Subtraction for physics results

ICS - missing transverse energy



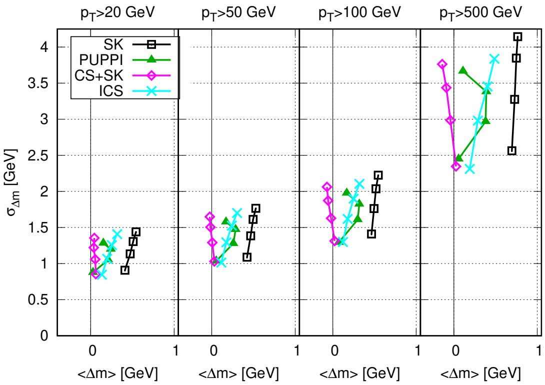
- ICS improves MET resolution

ICS - Comparison with other methods



- Using framework from Pileup workshop in 2014
- Jet p_{T} resolution vs jet p_{T} bias
- Each panel corresponds to dijet sample with certain jet p_{T} threshold
- The 4 points on each curve correspond to N_{PU} =30, 60, 100 and 140 from bottom to top
- ICS brings improved resolution while keeping the bias low

ICS - Comparison with other methods



- Using framework from Pileup workshop in 2014
- Jet mass resolution vs jet mass bias
- Each panel corresponds to dijet sample with certain jet p_{T} threshold
- The 4 points on each curve correspond to N_{PU} =30, 60, 100 and 140 from bottom to top
- ICS brings improved resolution while keeping the bias low