11th Edition of the Large Hadron Collider Physics Conference

Pile-up and background correction techniques for jets from pp to AA

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PRIMUS

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Outline

1. Pileup and underlying event (background)

2. Background mitigation methods - currently used for physics measurements

3. More background mitigation methods - not used for physics measurements so far

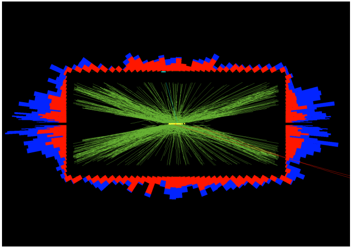
Pileup and underlying event (background)

Background = pileup or underlying event

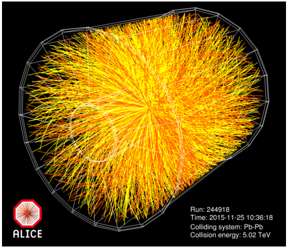
- Pileup in proton-proton (*pp*) collisions
  - simultaneous *pp* collisions in one or in neighboring bunch crossings
- Underlying event in heavy-ion (HI) collisions
  - additional interactions beyond the primary hard scattering
- **Underlying event in HI collisions ≈ Pileup in *pp* collisions**

  ⇒ both adds soft particles approximately uniformly distributed

  ⇒ both negatively affect the reconstruction of jets



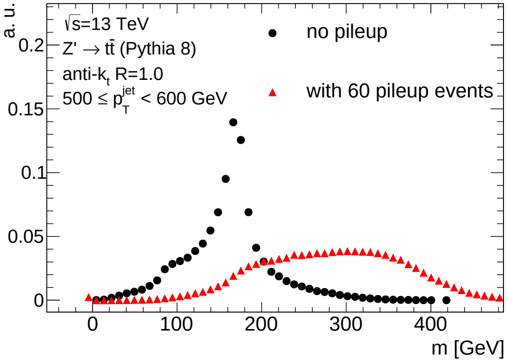
Event with ∼80 pileup collisions in one bunch crossing at the CMS experiment
http://cds.cern.ch/record/1479324



Heavy-ion collision at the ALICE experiment
https://cds.cern.ch/record/2202730

Background effects on jets

- **Jets** - signature from large variety of hard-scattering processes
- Background randomly adds soft particles to jets in hard-scattering processes
  - 100 pileup events add ∼250 GeV additional p_{T} under an anti-k_t R=1.0 jet
  - jet shape variables (mass, width,...) change significantly
- **Necessity to mitigate background effects for jets**



Background effects for jet mass in process $pp \to Z' \to t\bar{t}$

Background mitigation methods - currently used for physics measurements

Background mitigation methods currently used

- Area Subtraction - arXiv:0707.1378, arXiv:0802.1188
  - used in ∼400 measurements
- Jet p_{T} correction based on number of primary vertices and μ
  - used in ATLAS as residual pileup correction - arXiv:2007.02645
- Constituent Subtraction (CS) - arXiv:1403.3108, arXiv:1905.03470
  - used in ∼20 HI measurements in ALICE, ATLAS, CMS, STAR to mitigate underlying event
- SoftKiller (SK) - arXiv:1407.0408
  - used in ATLAS in combination with CS to mitigate pileup - arXiv:2009.04986
- PUPPI - arXiv:1407.6013
  - used in CMS to mitigate pileup
- ATLAS HI background subtraction - arXiv:1208.1967
  - dedicated method developed and used in ATLAS

- Grooming:
  - modification of the jet definition to be less sensitive to background
  - multiple methods: trimming - arXiv:0912.1342, SoftDrop - arXiv:1402.2657,...

Background p_{T} density, ρ

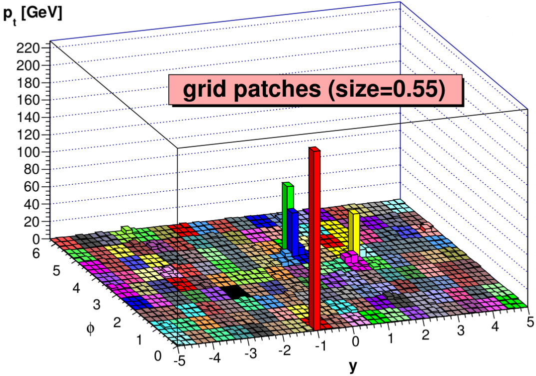
- arXiv:0707.1378
- ρ - amount of p_{T} from background particles per unit area in the $y-\phi$ space
- Main ingredient to Area Subtraction and Constituent Subtraction
- Grid-median approach - one of the possibilities how to estimate ρ:

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

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

2. the estimated pileup p_{T} density:

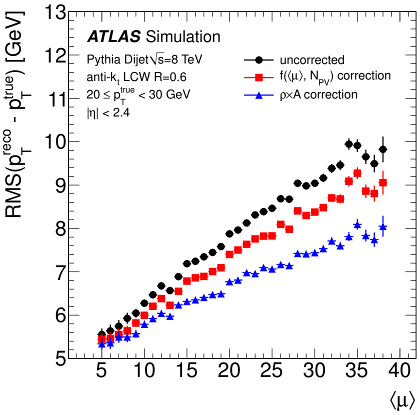
$$\rho = \mathrm{median}_{\mathrm{patches}} \left\{ \frac{p_{\mathrm{Tpatch}}}{A_{\mathrm{patch}}} \right\}$$



Slides from G. Soyez (BOOST2012 conference)

Area Subtraction

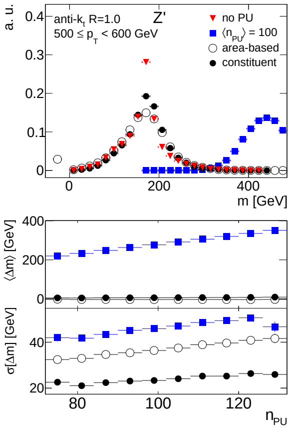
- arXiv:0707.1378, arXiv:0802.1188
- Main idea:
  - pileup particles create approximately uniform background in rapidity - azimuth ($y - \phi$) space
  - $\Rightarrow$ subtract the average expected pileup deposition from jets
- Two ingredients:
  - Background p_{T} density ρ
    - estimated event-by-event
  - Concept of jet area - subtracting amount of ρA_{jet}
- Corrects only the jet 4-momentum (not substructure)



Performance of the Area Subtraction ($\rho \times A$ correction), arXiv:1510.03823

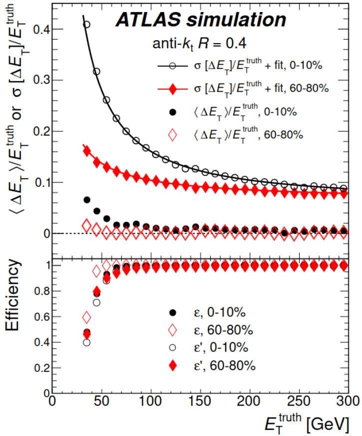
Constituent Subtraction (CS)

- arXiv:1403.3108, arXiv:1905.03470
- Generalization of the Area Subtraction
  - recombination of real particles with the expected background deposition expressed by ghosts
  - corrects jet constituents
    - any jet substructure observable can be obtained from the corrected jet
- 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
- Constituent Subtraction performs better than the Area Subtraction
- Used in JEWEL arXiv:2207.14814
- The heavy-ion community extensively uses CS for physics results



ATLAS HI background subtraction

- arXiv:1208.1967
- Dedicated method to correct calorimeter cells
- Input: average transverse energy density, $\rho(\eta, \phi)$
  - calorimeter-layer dependent
  - pseudo-rapidity and azimuth dependent
    - parametrizing flow harmonics up to the 4th order
  - excluding areas around hard-scatter jets
- Corrected calorimeter cell: $E_T^{corr} = E_T - A_{cell}\,\rho(\eta, \phi)$
- Iterative procedure in two steps



ε - efficiency after background subtraction

ε' - efficiency before background subtraction

More background mitigation methods - not used for physics measurements so far

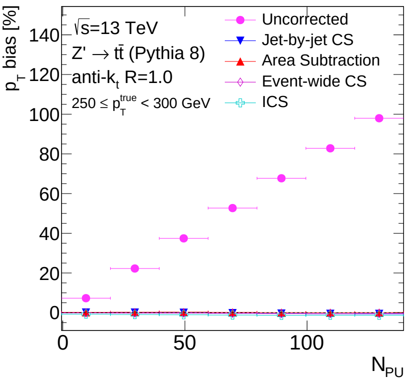
More background mitigation methods (not full list)

- Iterative Constituent Subtraction (ICS) arXiv:1905.03470
- A background estimator for jet studies arXiv:1904.12815
- Improved background density estimation arXiv:2304.08383
- Pileup and Infrared Radiation Annihilation (PIRANHA) - arXiv:2305.00989
- Pileup Mitigation with Machine Learning (PUMML) - arXiv:1707.08600
- Pileup mitigation using attention (PUMA) - arXiv:2107.02779
- Pileup mitigation with Graph Neural Networks (PUPPIML) - arXiv:1810.07988
- Jet Grooming through Reinforcement Learning - arXiv:1903.09644
- Semi-supervised graph neural networks for pileup noise removal arXiv:2203.15823

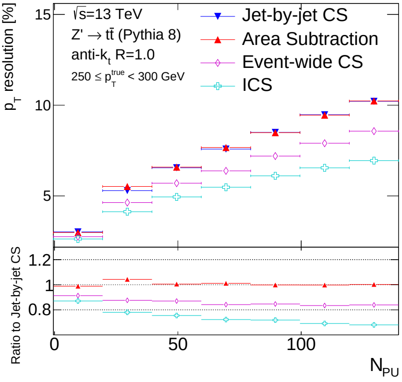
Iterative Constituent Subtraction (ICS)

- arXiv:1905.03470
- Supersedes the Event-wide 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

Comparison of CS-based methods - jet p_{T}



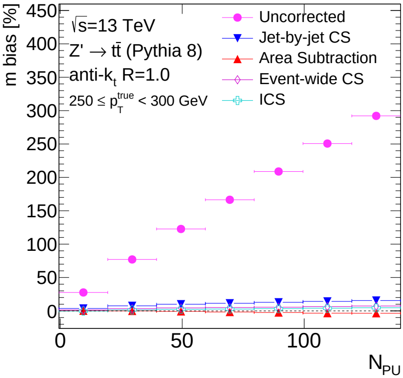
Bias



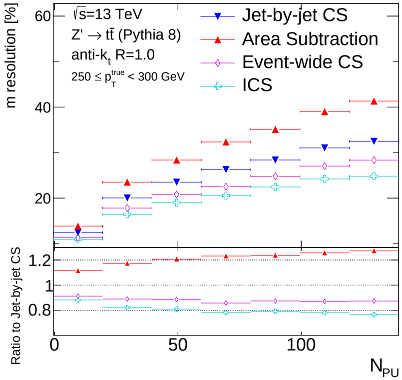
Resolution

- ICS improves the jet p_{T} resolution without introducing any significant bias

Comparison of CS-based methods - jet mass



Bias

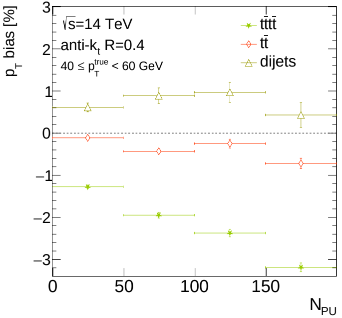


Resolution

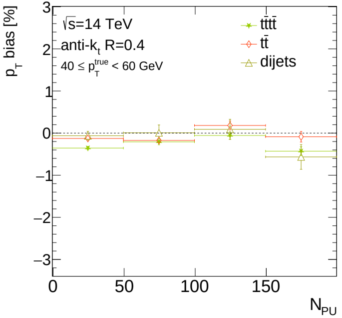
- ICS improves the jet mass resolution without introducing any significant bias

Improved ρ estimation method

- ρ estimate depends on the hard-scatter jet multiplicity for the baseline methods
- New approach to estimate ρ - arXiv:2304.08383
  - cover areas in rapidity-azimuth space which contain hard-scatter jets
  - less dependent on the hard-scatter jet multiplicity



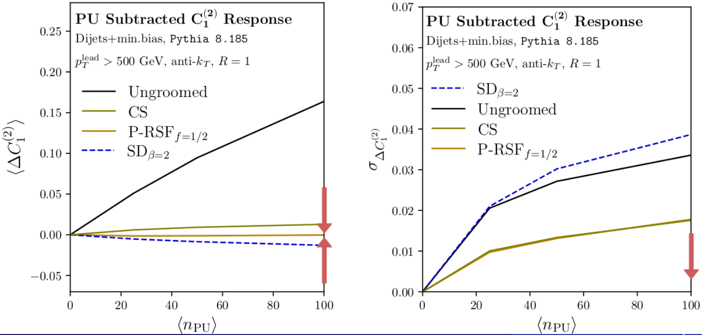
CS using grid-median, size 0.55



CS using the new ρ estimation method

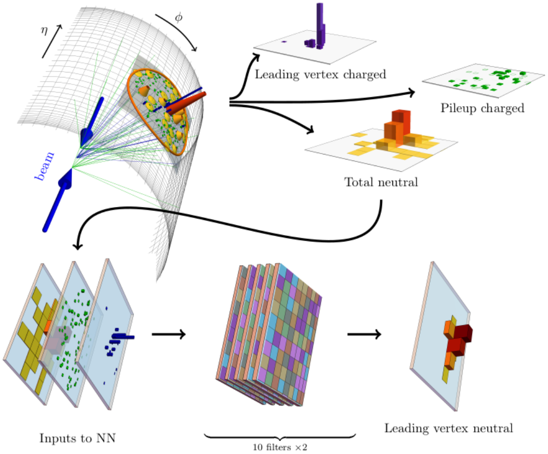
Pileup and Infrared Radiation Annihilation (PIRANHA)

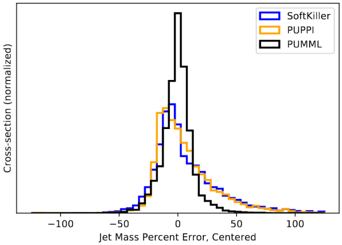
- arXiv:2305.00989
- P-RSF$_f$ - Recursive Subtraction (P-RS) with a Fraction (f)
- Similar strategy as Jet-by-jet CS
  - Jet declustered using C/A algorithm
  - Subtracting background in amount ρA_{jet}
    - Redistributed among the jet constituents based on the branching history
- Similar performance as Jet-by-jet CS
  - P-RSF$_f$ is faster
  - not clear whether it is possible to extend to the whole event



PUMML

- arXiv:1707.08600
- Convolutional neural networks
- Based on color-image recognition technology





Summary

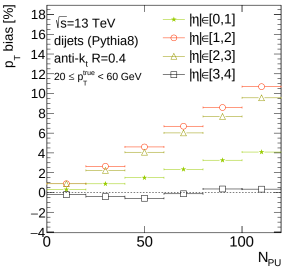
- Multiple background mitigation methods for jets on the market
- Constituent Subtraction
  - extensively used among the heavy-ion community for physics results
  - Jet-by-jet version - corrects jet constituents
  - Event-wide version - corrects the whole event
    - can obtain event-wide observables, such as missing transverse energy
- Many other novel advanced techniques to be tested at experiments
  - Iterative Constituent Subtraction
  - Improved ρ estimation
  - PIRANHA-RSF$_f$
  - wealth of machine learning techniques

BACKUP

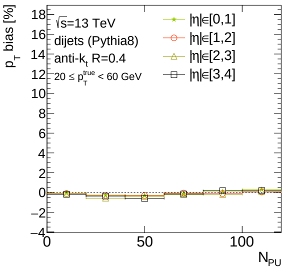
ρ estimation - rapitidy-azimuth dependence

- Recommended to use rescaling classes to estimate ρ:
  - rapidity in 1D histogram and azimuth parametrized with elliptic flow parameters,. . .

For usage, see example:
https://phab.hepforge.org/source/fastjetsvn/browse/contrib/contribs/ConstituentSubtractor/tags/1.4.6/example_background_rescaling.cc



no rapidity rescaling (constant ρ)



with rapidity rescaling

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:

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

  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:

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

The CS correction procedure - detailed

- 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:

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

     α - free parameter

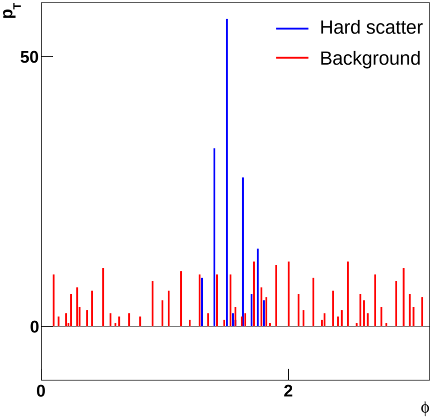
  5. iteratively change transverse momenta by applying the following procedure for each ghost-particle pair until no more pairs remain or $\Delta R_{i,k} > \Delta R^{\max}$:

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

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

Jet-by-jet CS

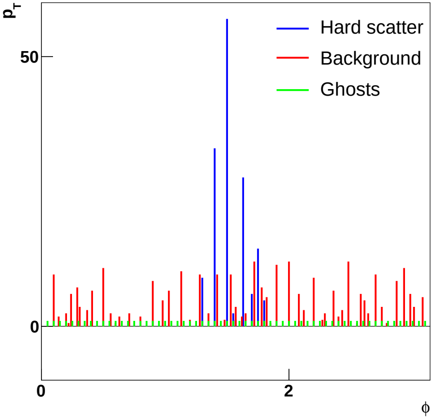
1. **Estimation of ρ**



Whole event

Jet-by-jet CS

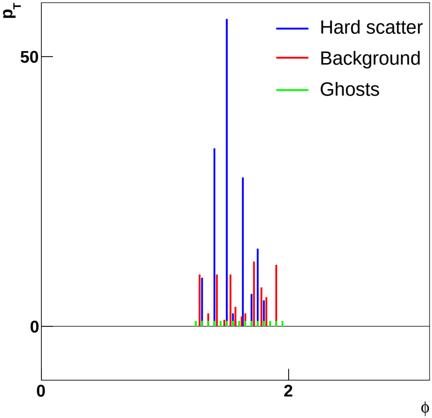
1. Estimation of ρ
2. **Adding ghosts to the whole event**



Whole event

Jet-by-jet CS

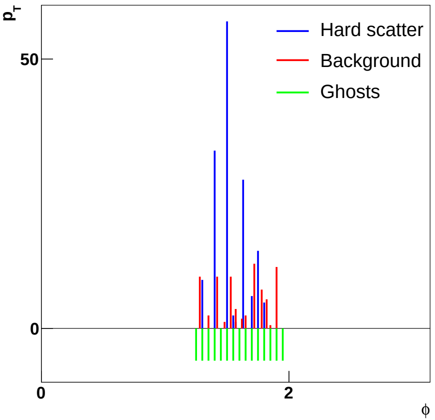
1. Estimation of ρ
2. Adding ghosts to the whole event
3. **Jet clustering**



Leading jet before correction

Jet-by-jet CS

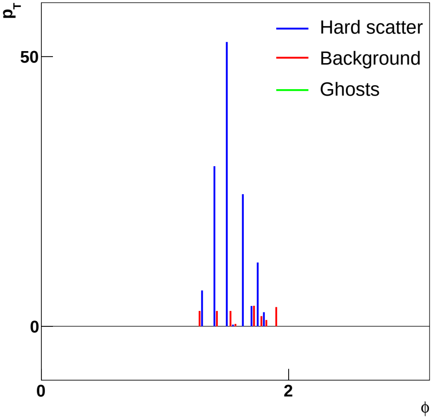
1. Estimation of ρ
2. Adding ghosts to the whole event
3. Jet clustering
4. **Setting ghosts p_{T} to negative value corresponding to ρ**



Leading jet before correction

Jet-by-jet CS

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



Leading jet after correction

Jet-by-jet CS

1. Estimation of ρ
2. Adding ghosts to the whole event
3. Jet clustering
4. Setting ghosts p_{T} to negative value corresponding to ρ
5. **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 $\Delta R_{i,k}$:

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

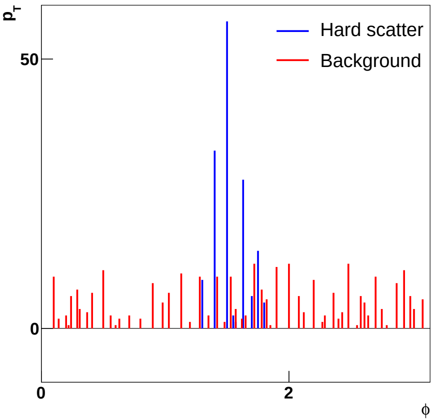
   - Procedure stops for $\Delta R_{i,k} > \Delta R^{\max}$

Jet-by-jet CS

1. Estimation of ρ
2. Adding ghosts to the whole event
3. Jet clustering
4. Setting ghosts p_{T} to negative value corresponding to ρ
5. **Matching of ghosts to particles**
   - Free parameters: α and $\Delta R^{\max}$

Event-wide CS

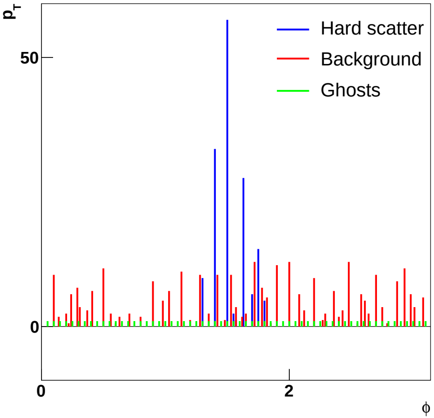
1. **Estimation of ρ**



Whole event

Event-wide CS

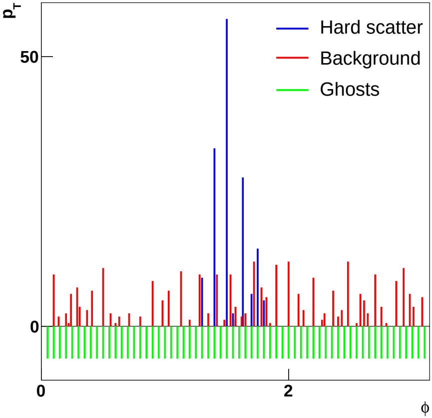
1. Estimation of ρ
2. **Adding ghosts to the whole event**



Whole event

Event-wide CS

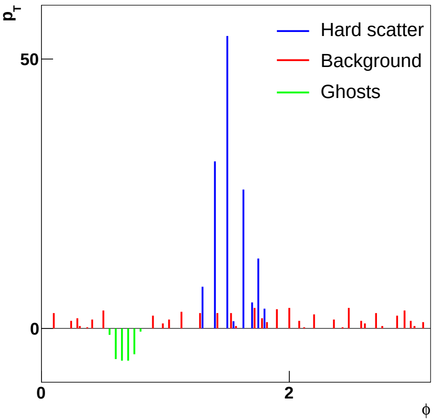
1. Estimation of ρ
2. Adding ghosts to the whole event
3. **Setting ghosts p_{T} to negative value corresponding to ρ**



Whole event before correction

Event-wide CS

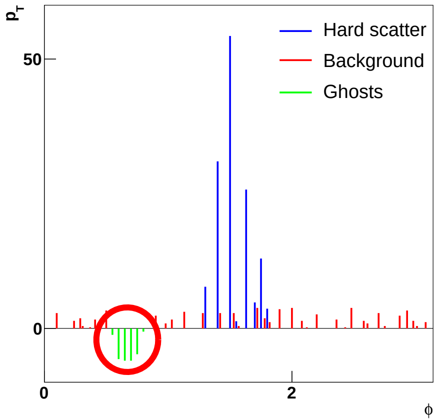
1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_{T} to negative value corresponding to ρ
4. **Matching ghosts to particles**
   - Same matching algorithm as for Jet-by-jet CS
   - Matching stops when particle-ghost distance larger than $\Delta R^{\max}$



Whole event after correction

Event-wide CS

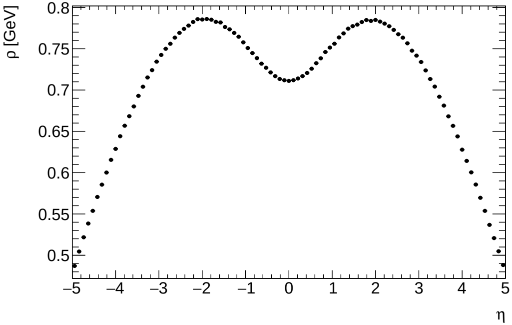
1. Estimation of ρ
2. Adding ghosts to the whole event
3. Setting ghosts p_T to negative value corresponding to ρ
4. Matching ghosts to particles
    - Same matching algorithm as for Jet-by-jet CS
    - Matching stops when particle-ghost distance larger than $\Delta R^{\max}$
    - **With finite $\Delta R^{\max}$, some ghosts can be unmatched**
        - discussed later



Whole event after correction

ρ rescaling

- The estimated ρ is by default constant in $y - \phi$ space
- But ρ can depend on y and ϕ:

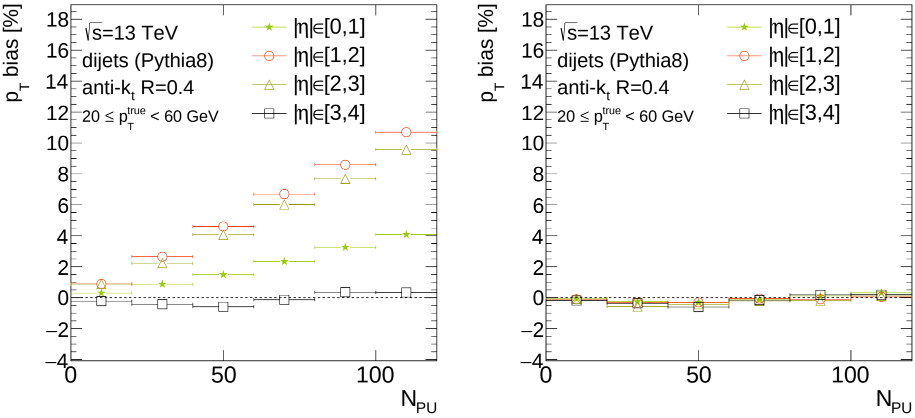


Rapidity dependence from Pythia (massless inputs)

ρ rescaling

- Important for CS:
  - more precise estimation of ρ
  - the ghosts p_{T} are scaled according to the $y - \phi$ dependence
- Done by fastjet's background estimation classes
- Limited number of rescaling classes:
  - rapidity parametrized as polynom
- New rescaling classes within CS:
  - rapidity in 1D histogram
  - rapidity in 1D histogram and azimuth parametrized with elliptic flow parameters,. . .
- For usage, see example:
  https://phab.hepforge.org/source/fastjetsvn/browse/contrib/contribs/ConstituentSubtractor/tags/1.4.6/example_background_rescaling.cc

ρ rescaling - demonstration



no rescaling (constant ρ) | with rescaling

- ρ rescaling using rapidity in 1D histogram (CS with $\Delta R^{\max} = 0.25$)
- Dependence on jets η is removed

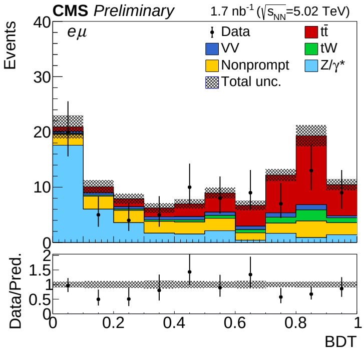
Physics results with Jet-by-jet CS (not full list)

- **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
- **CMS** publications:
  - 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
  - Fragmentation of jets containing a prompt J/Ψ meson in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$, arXiv:2106.13235
  - Evidence for top quark production in nucleus-nucleus collisions, arXiv:2006.11110
- **STAR** publications:
  - Jet sub-structure and parton shower evolution in p+p and Au+Au collisions at STAR, arXiv:1906.05129
  - Differential measurements of jet substructure and partonic energy loss in Au+Au collisions at $\sqrt{s_{NN}} = 200\ \mathrm{GeV}$, arXiv:2109.09793

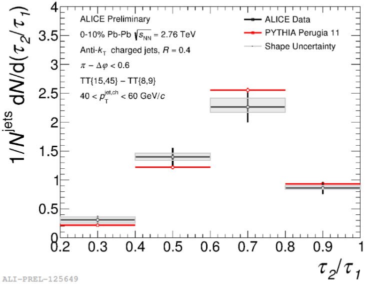
Physics results with Event-wide CS (not full list)

- **ALICE** publications:
  - Measurement of the angle between jet axes in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$, arXiv:2303.13347
  - Measurement of inclusive and leading subjet fragmentation in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$, arXiv:2204.10270
  - Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$, arXiv:2107.12984
- **ATLAS** publication:
  - Measurement of $Z(\to b\bar{b})\gamma$ differential cross section, arXiv:1907.07093

Physics results with Constituent Subtraction



Evidence for top quark production in heavy-ion collisions, arXiv:2006.11110



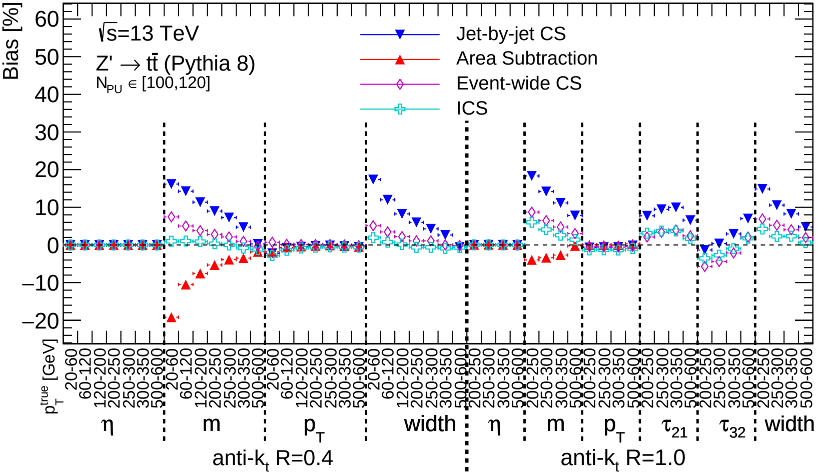
Measurement of jet substructure variable τ_{21} in heavy-ion collisions , arXiv:1705.03383

- Heavy-ion community extensively uses CS for physics results

Setup for performance studies

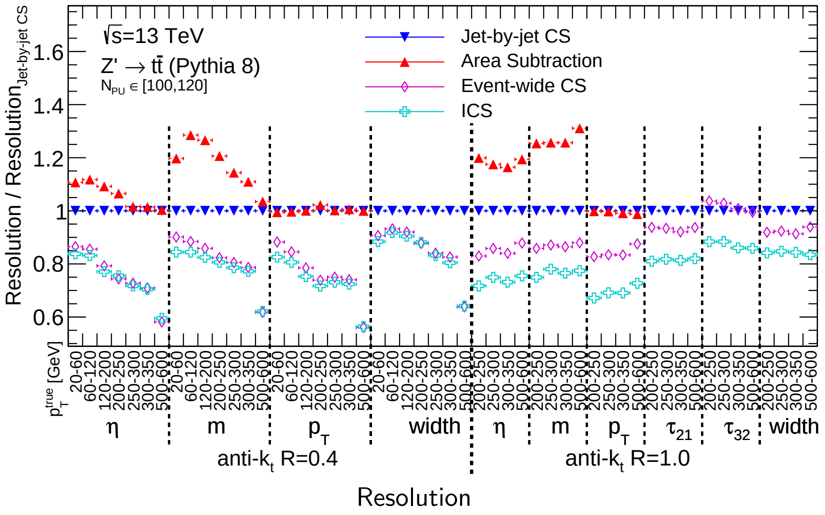
- Pythia8 simulation of signal and pileup events
- Number of pileup events, N_{PU}, is uniformly distributed in range [0,120] (LHC Run 3)
- Particles grouped into massless towers of size 0.1×0.1 in $y - \phi$ space
- CS correction of whole event up to $|\eta| < 5$
- Using CS parameter $\alpha = 0$
- 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**

Comparison of CS-based methods - bias

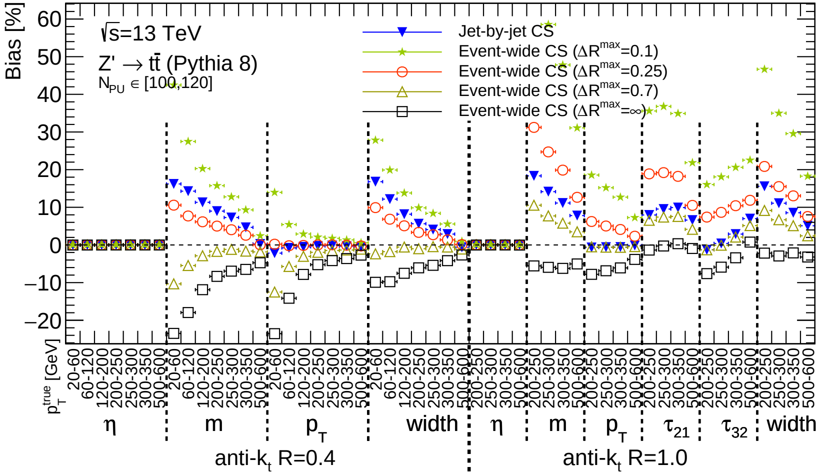


Bias

Comparison of CS-based methods - resolution

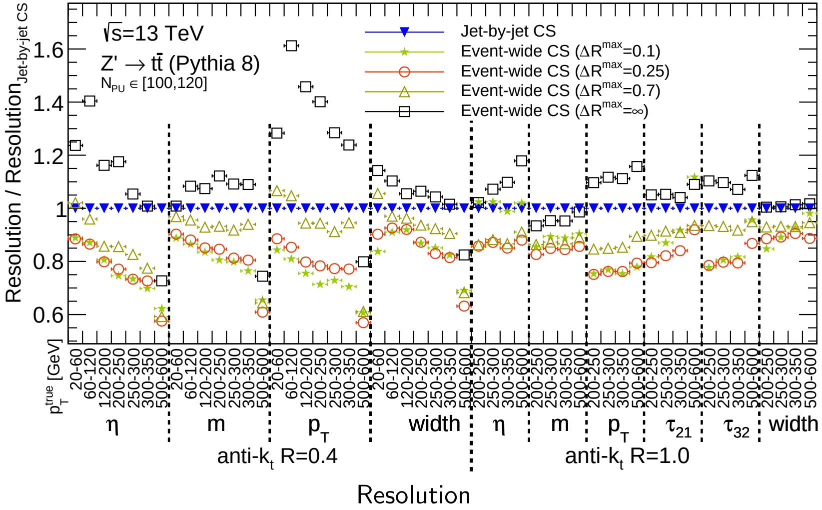


Event-wide CS, $\Delta R^{\max}$- bias

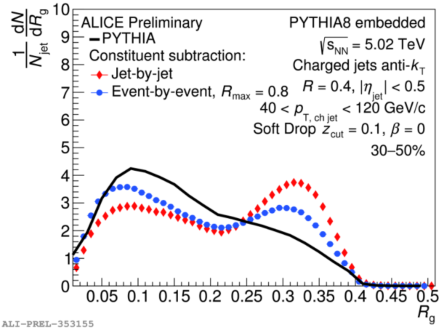


Bias

Event-wide CS, $\Delta R^{\max}$- resolution



Jet-by-jet CS vs Event-wide CS

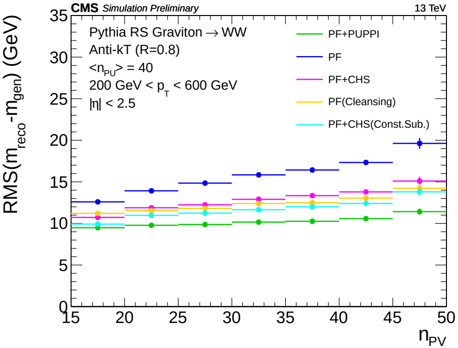


ALI-PREL-353155

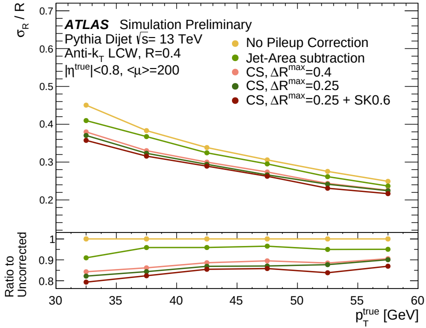
- Event-wide CS performs better than Jet-by-jet CS

Constituent Subtraction performance in *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 arXiv:2009.04986
- Jet constituent multiplicity ATL-PHYS-PUB-2018-011
- Improved performance compared to the Area Subtraction



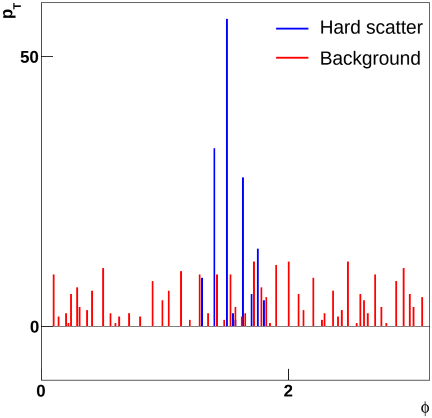
CMS-PAS-JME-14-001



ATLAS-CONF-2017-065

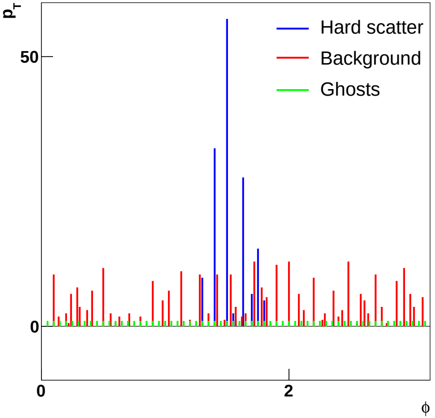
ICS - example with two iterations

1. **Estimation of ρ**



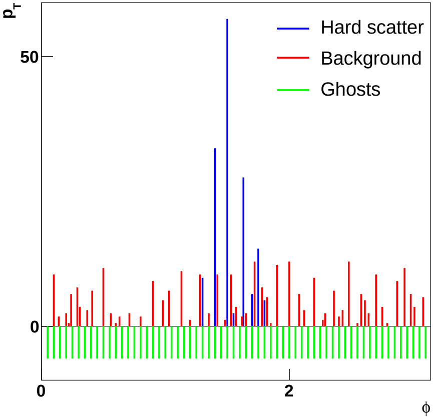
ICS - example with two iterations

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



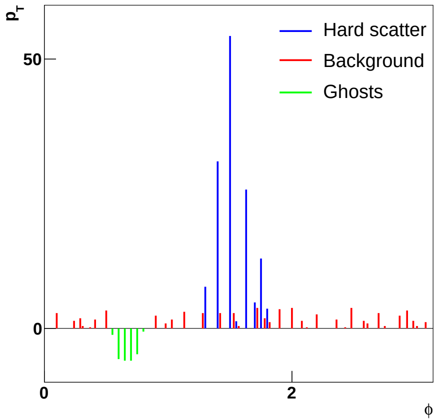
ICS - example with two iterations

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



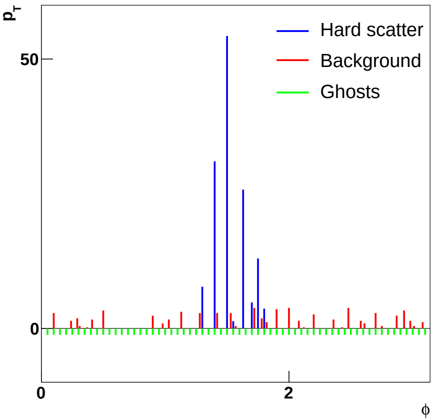
ICS - example with two iterations

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**



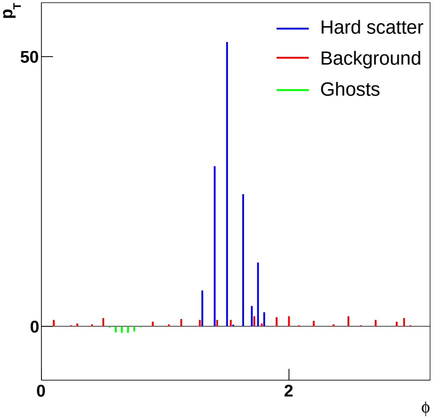
ICS - example with two iterations

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}**

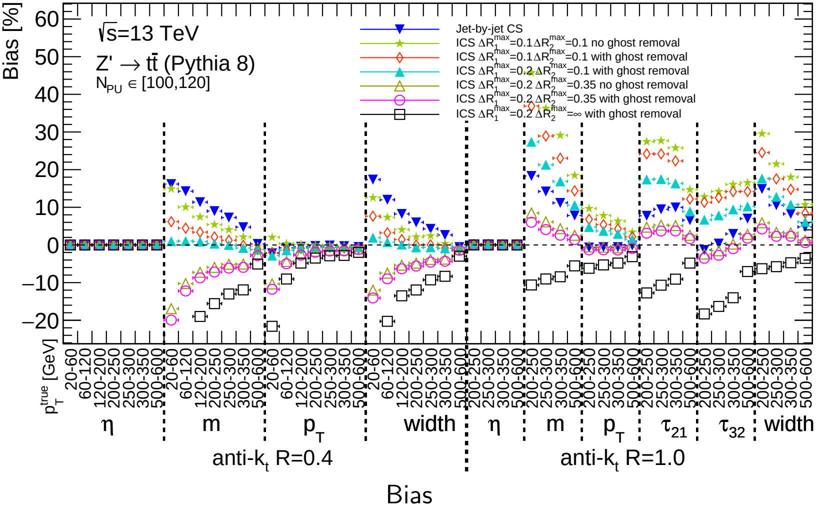


ICS - example with two iterations

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**

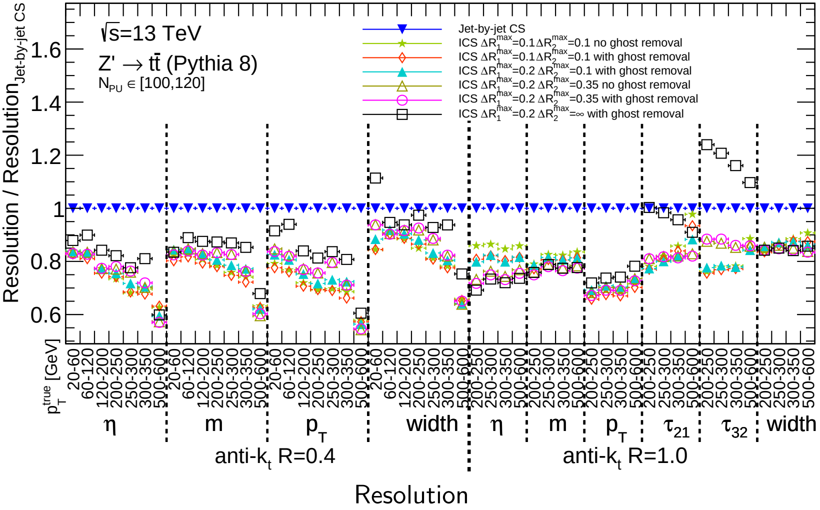


ICS - bias

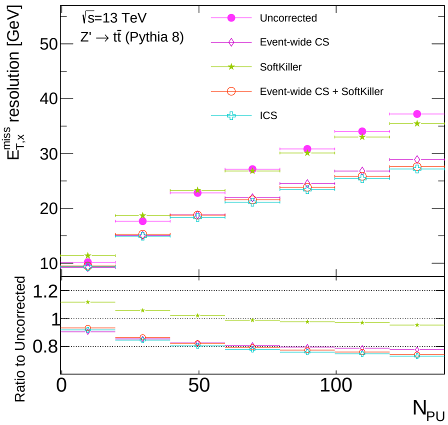


Bias [%]
√s=13 TeV
Z' → tt̄ (Pythia 8)
N_PU ∈ [100,120]
Jet-by-jet CS
ICS ΔR1max=0.1ΔR2max=0.1 no ghost removal
ICS ΔR1max=0.1ΔR2max=0.1 with ghost removal
ICS ΔR1max=0.2ΔR2max=0.1 with ghost removal
ICS ΔR1max=0.2 ΔR2max=0.35 no ghost removal
ICS ΔR1max=0.2 ΔR2max=0.35 with ghost removal
ICS ΔR1max=0.2 ΔR2max=∞ with ghost removal
pTtrue [GeV]
η
m
pT
width
τ21
τ32
anti-kt R=0.4
anti-kt R=1.0
Bias

ICS - resolution

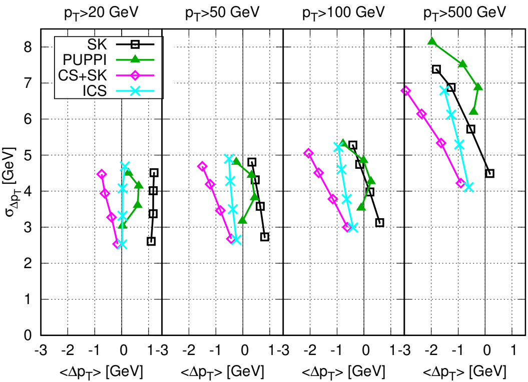


ICS - missing transverse energy



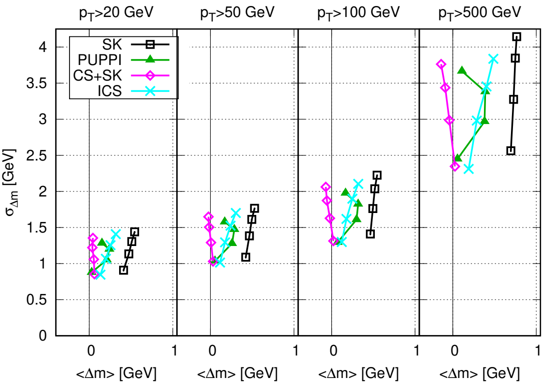
- ICS improves MET resolution

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