A NEW LOOK INTO BACKGROUND SUBTRACTION FOR JET PHYSICS IN P+P AND A+A COLLISIONS

Alba Soto-Ontoso

[Yacine Mehtar-Tani, ASO, Marta Verweij arXiv:1904.12815]

[Yacine Mehtar-Tani, ASO, Marta Verweij in preparation]

TH Heavy Ion Coffee

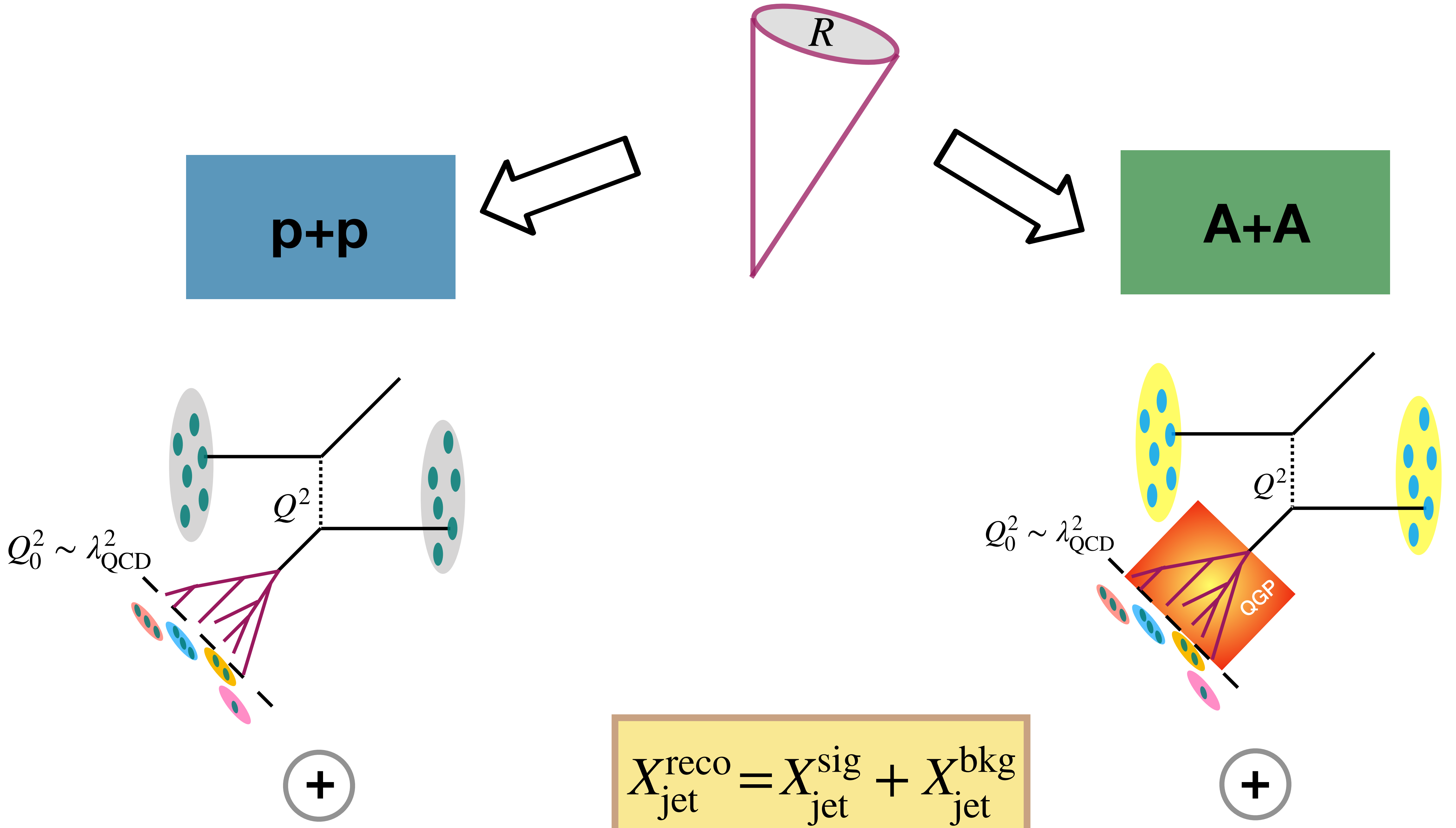
CERN, 18th September, 2019

BROOKHAVEN NATIONAL LABORATORY

Center for Frontiers in Nuclear Science

Jet reconstruction analyses

Cluster all particles in the event with k_T / anti-k_T / Cambridge-Aachen



p+p

A+A

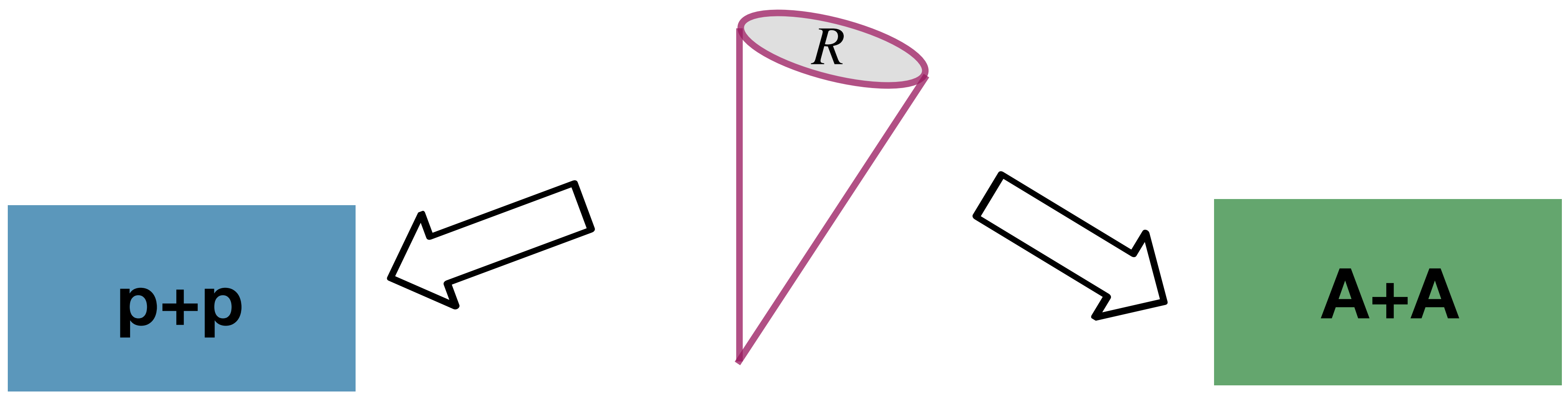
$$X_{\mathrm{jet}}^{\mathrm{reco}} = X_{\mathrm{jet}}^{\mathrm{sig}} + X_{\mathrm{jet}}^{\mathrm{bkg}}$$

pileup interactions

underlying event

Jet reconstruction analyses

Cluster all particles in the event with k_T / anti-k_T / Cambridge-Aachen



p+p

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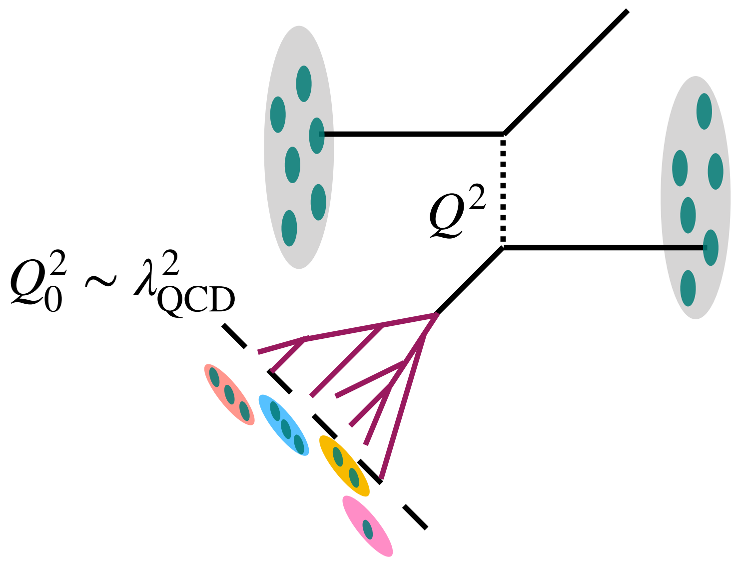
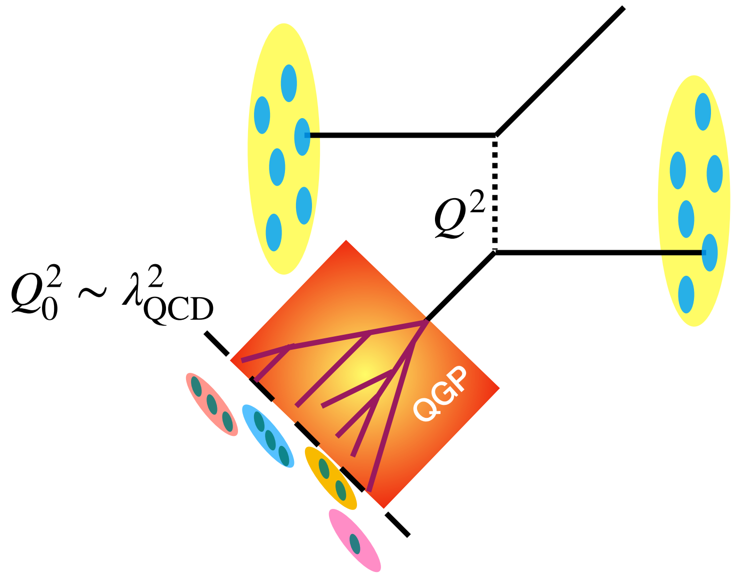


⊕

pileup interactions

$$p_{T,\mathrm{jet}}^{\mathrm{reco}} = p_{T,\mathrm{jet}}^{\mathrm{sig}} + p_{T,\mathrm{jet}}^{\mathrm{bkg}}$$



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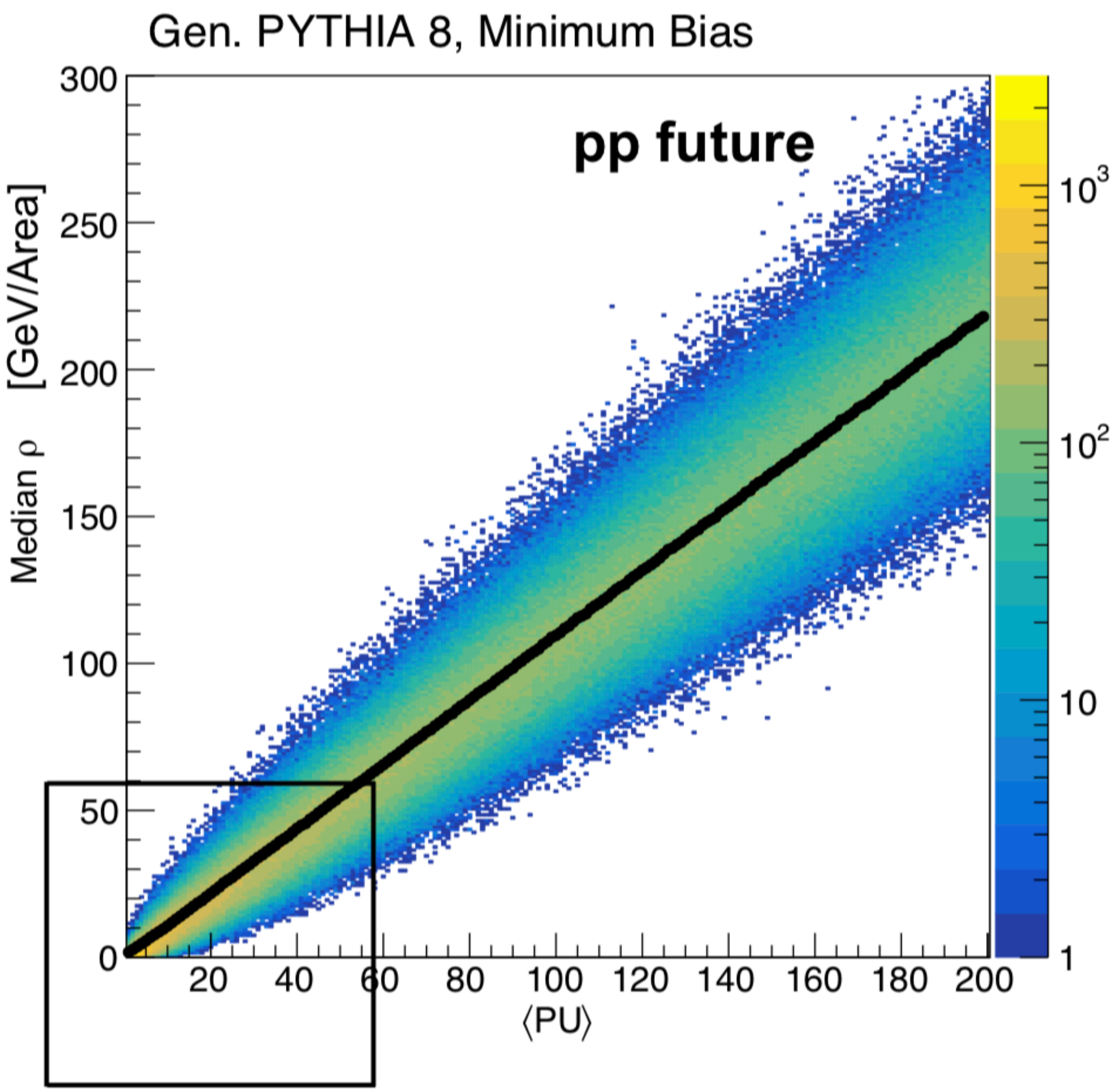
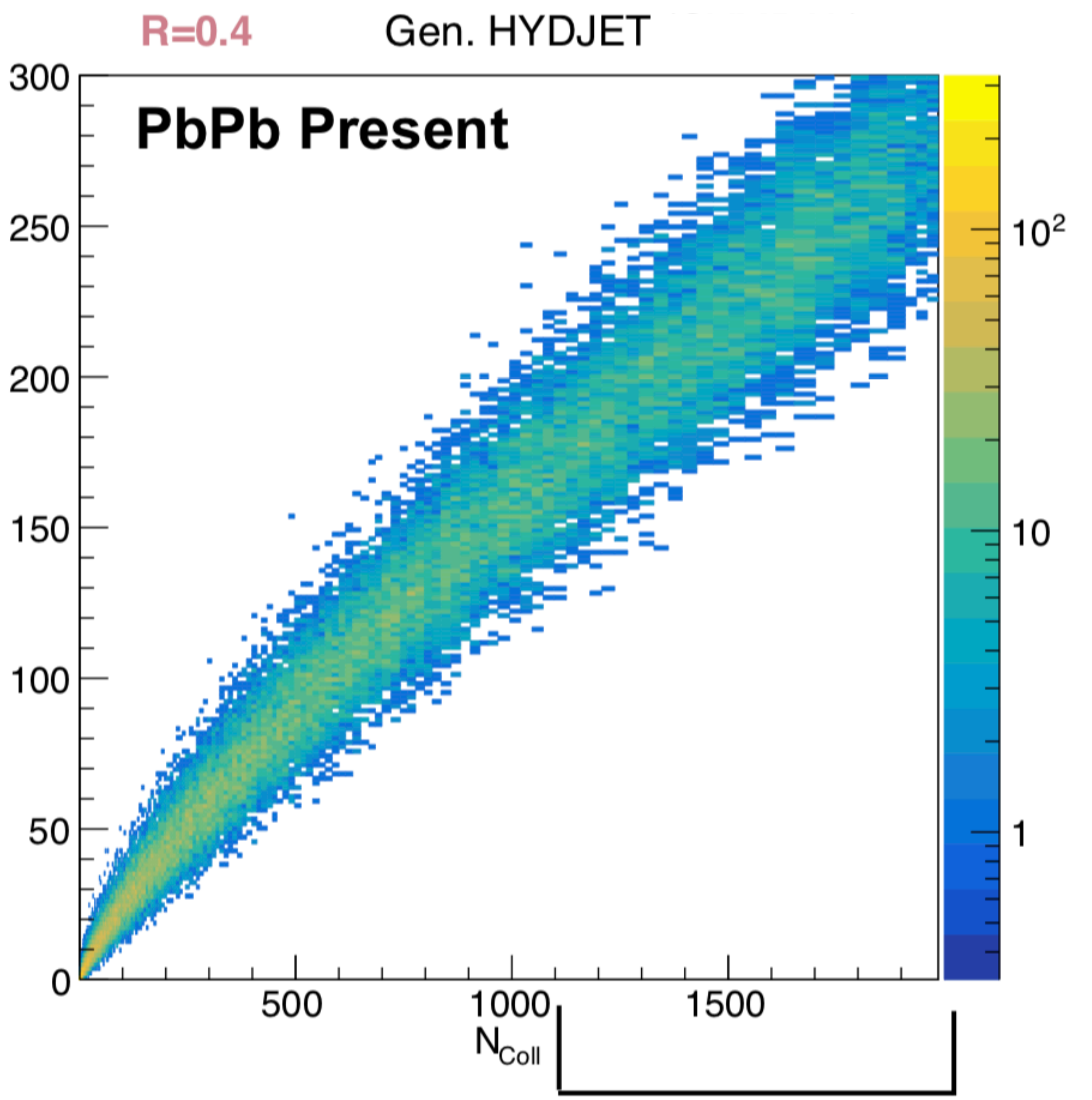
underlying event

HL-LHC and HIC background contamination

Background momentum density per unit area $$\rho = \frac{p_T^{\mathrm{bkg}}}{A}$$



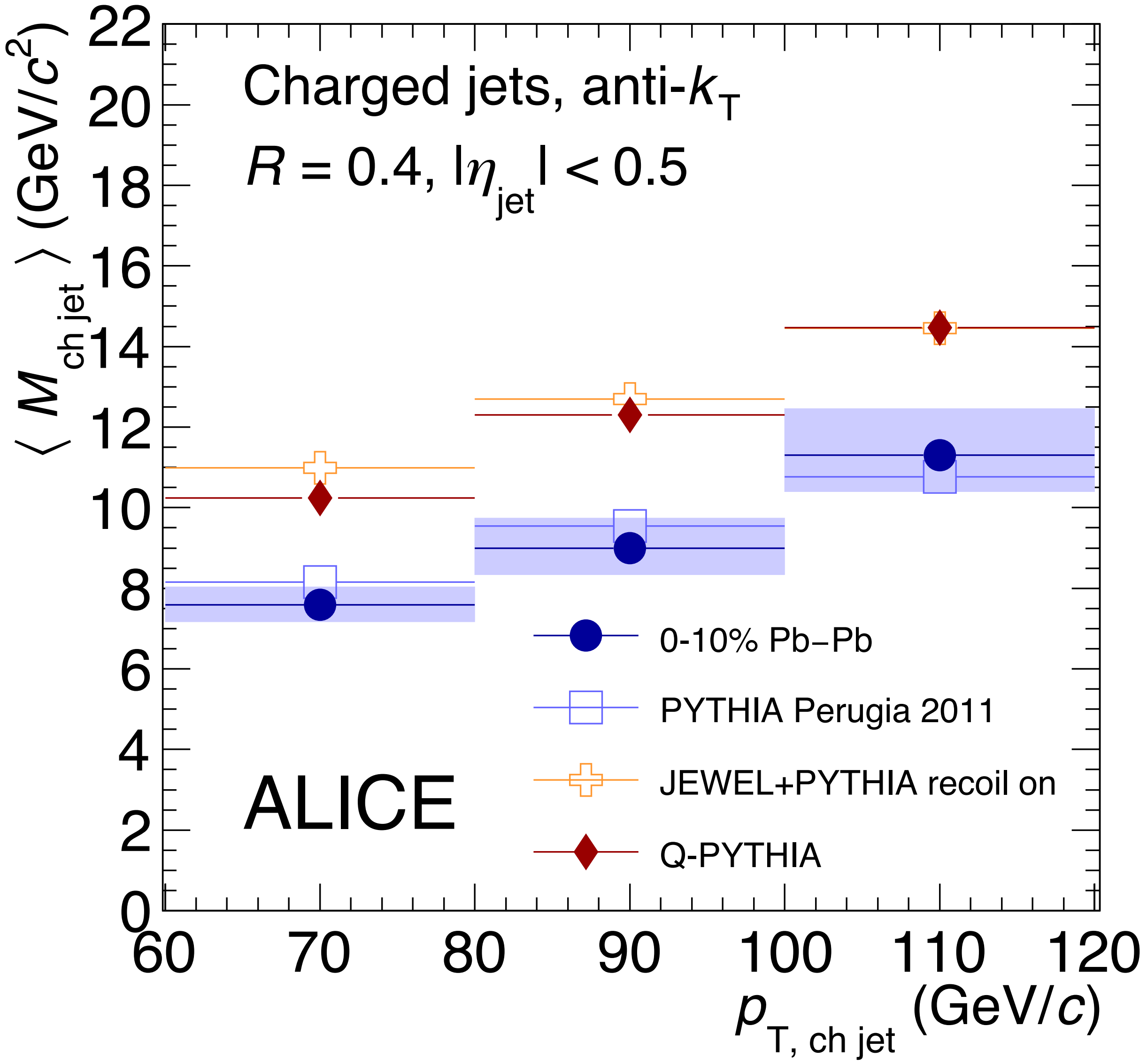
pp present



~0-10% PbPb at 5.02 TeV

[C.McGinn Talk at "The Definition of Jets in Large Background"]

Background as a limiting factor

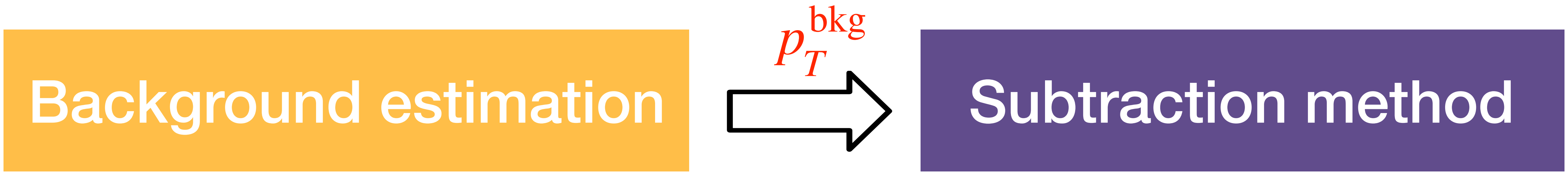


[ALICE Collab Phys. Lett. B776 (2018) 249-264]

Source	Pb–Pb			p–Pb		
$p_{\mathrm{T,ch\,jet}}$ (GeV/c)	60–80	80–100	100–120	60–80	80–100	100–120
Prior	1.0%	3.0%	5.0%	0	0	0
Background	3.0%	3.0%	5.0%	1.0%	0.5%	1.0%
Tracking efficiency	5.0%	5.0%	5.0%	3.0%	3.0%	3.0%
Unfolding (iterations, range)	1.0%	3.0%	4.0%	0.5%	1.0%	4.0%
Total	6.0%	8.0%	9.0%	3.5%	3.5%	4.5%

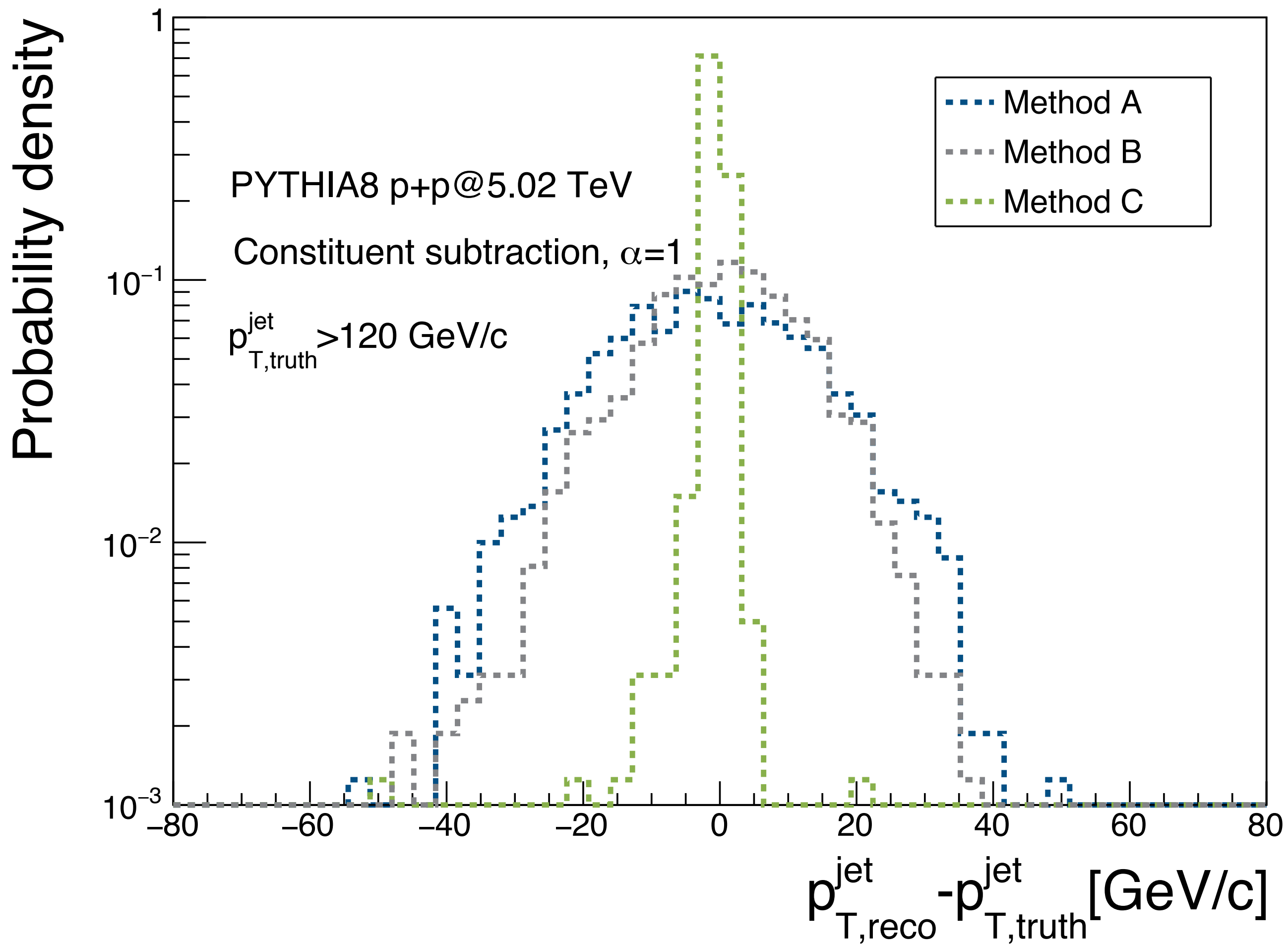
Table 1: Systematic uncertainty in mean jet mass from different sources in the 10% most central Pb–Pb collisions (left) and minimum-bias p–Pb collisions (right).

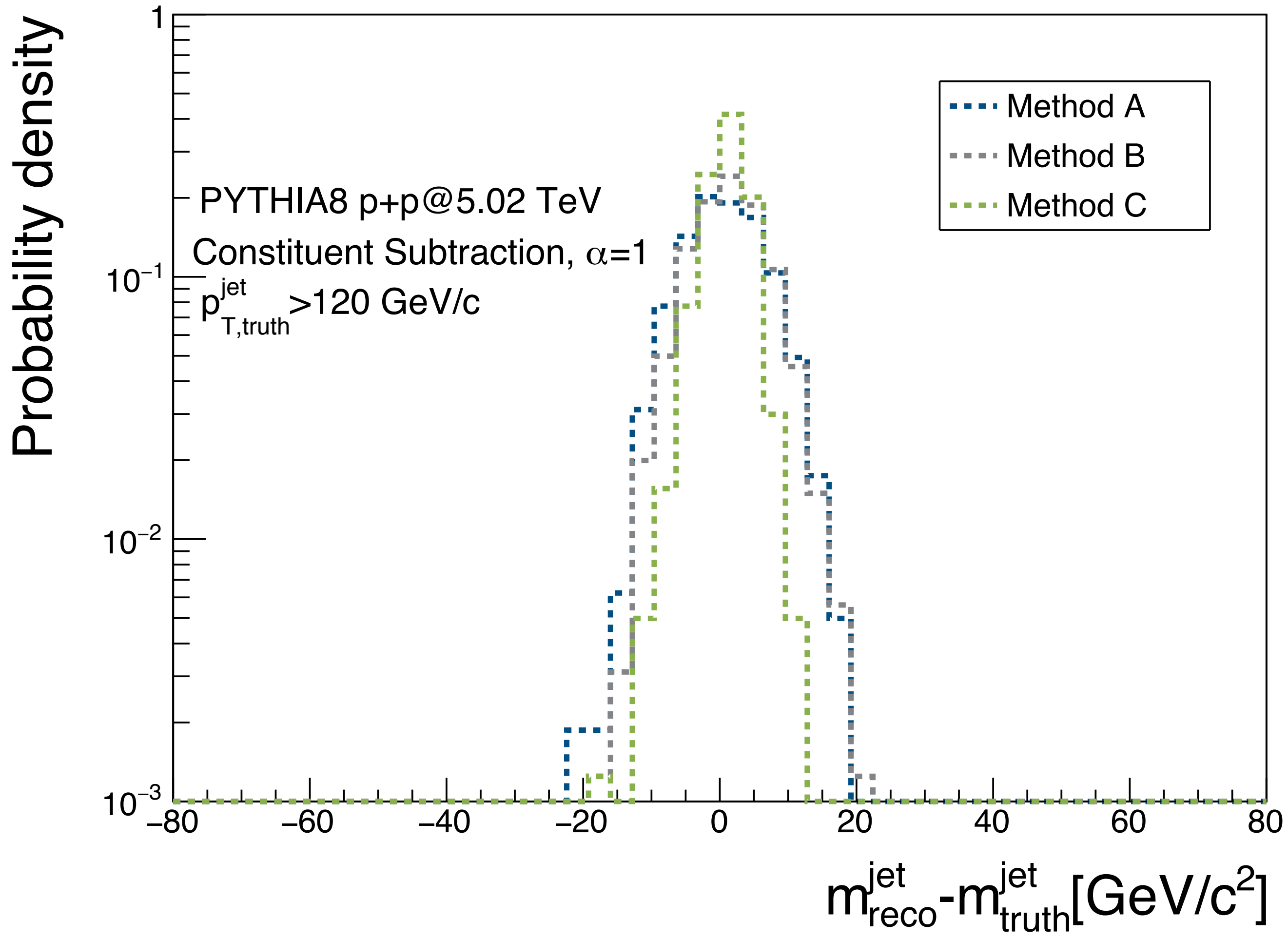
Background subtraction: two-step process



Background estimation

Subtraction method





Method A: Area median

Method B: SoftKiller

Method C: Truth

Simulation setup

[https://github.com/JetQuenchingTools/JetToyHI]

Background

- Randomly distributed in (η, ϕ)
- Thermal distribution with

This talk $\begin{cases} |\eta| < 3, \\ \langle N_{\mathrm{part}} \rangle = 7000{,}12000 \\ \mu \equiv \langle p_{\mathrm{T}} \rangle = 1.2{,}0.7\ \mathrm{GeV/c} \end{cases}$

Signal

- Pythia8 dijet event

This talk: $\langle \hat{p}_{\mathrm{T}} \rangle = 100\ \mathrm{GeV}$

$\sqrt{s} = 5.02\ \mathrm{TeV}$

- JEWEL (back-reaction off)

This talk: $\langle \hat{p}_{\mathrm{T}} \rangle = 150\ \mathrm{GeV}$

$\sqrt{s} = 5.02\ \mathrm{TeV}$

PYTHIA8 + Thermal background == p+p collision @ HL-LHC

JEWEL w/ E-loss + Thermal background == Pb+Pb collision @LHC

BACKGROUND ESTIMATION

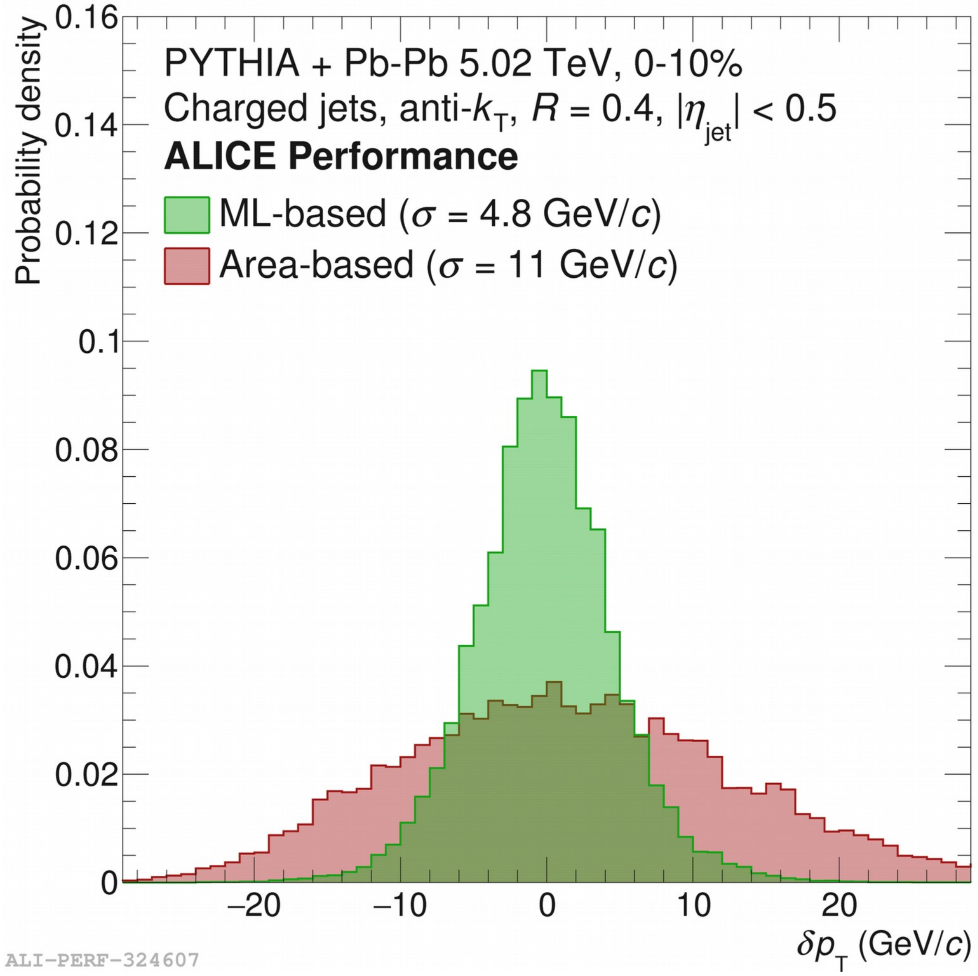
A decade of progress

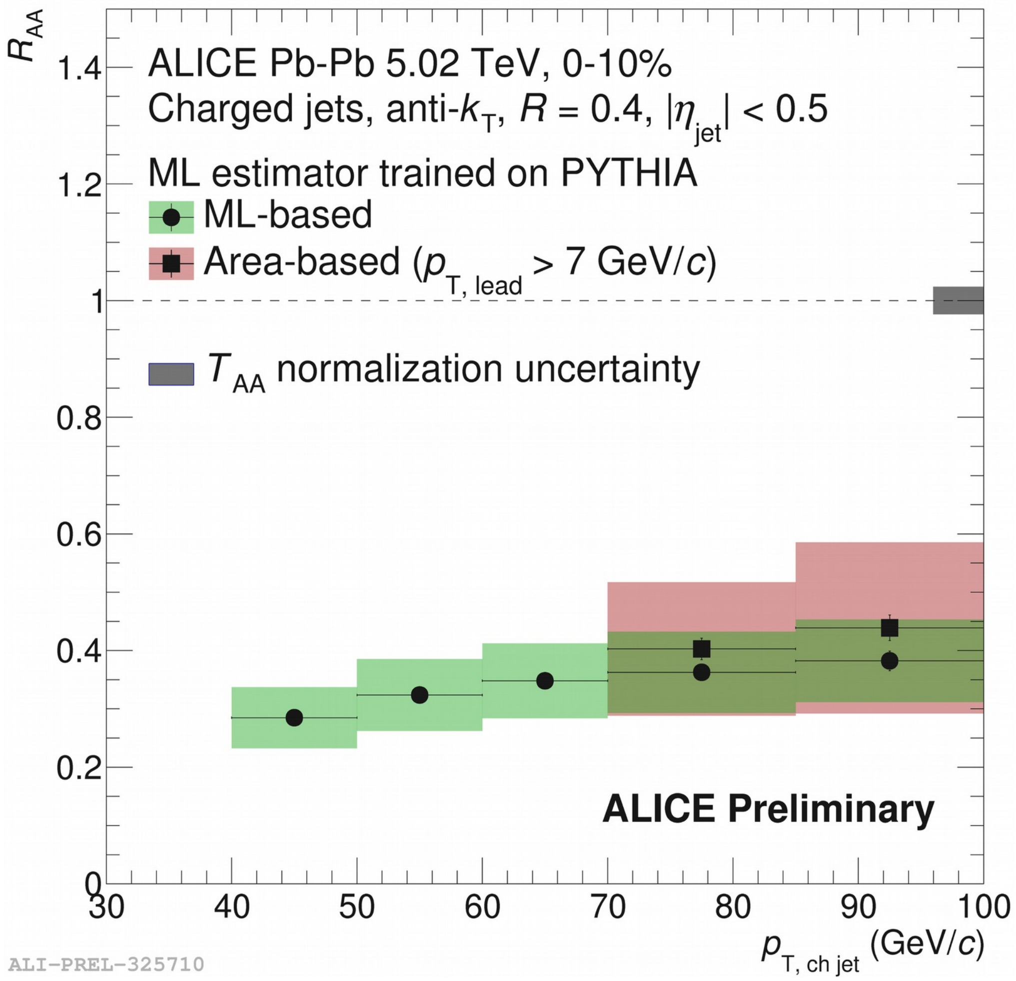
- **Area-median:** an unbiased method [M. Cacciari, G.Salam Phys. Lett. B659 (2008) 119–126]

$$\boxed{p_{\mathrm{T,reco}}^{\mathrm{jet}} = p_{\mathrm{T,raw}}^{\mathrm{jet}} - \mathrm{med}(\rho) A_{\mathrm{raw}}^{\mathrm{jet}}}$$

- **Supervised learning approach** [R. Haake, C.Loizides, PRC 99, 064904 (2019)]

$$\boxed{p_{\mathrm{T,reco}}^{\mathrm{jet}} = p_{\mathrm{T,raw}}^{\mathrm{jet}} - p_{\mathrm{T,ML}}^{\mathrm{bkg}}}$$

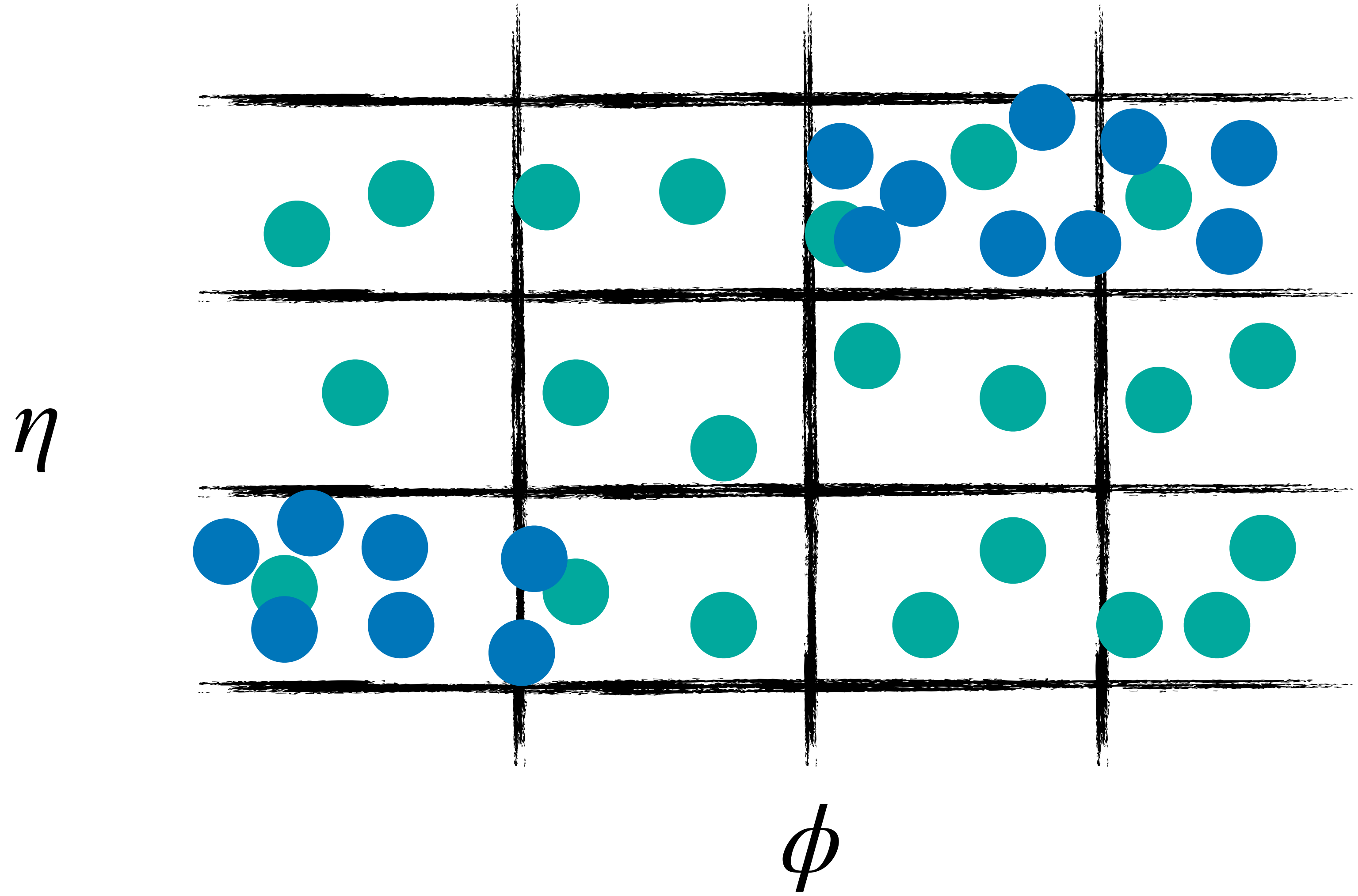




Area-median: an unbiased method

[M. Cacciari, G.Salam Phys. Lett. B659 (2008) 119–126]

Cluster all particles (sig+bkg) in the event with **k_T algorithm**



Area-median: an unbiased method

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Cluster all particles (sig+bkg) in the event with **k_T algorithm**

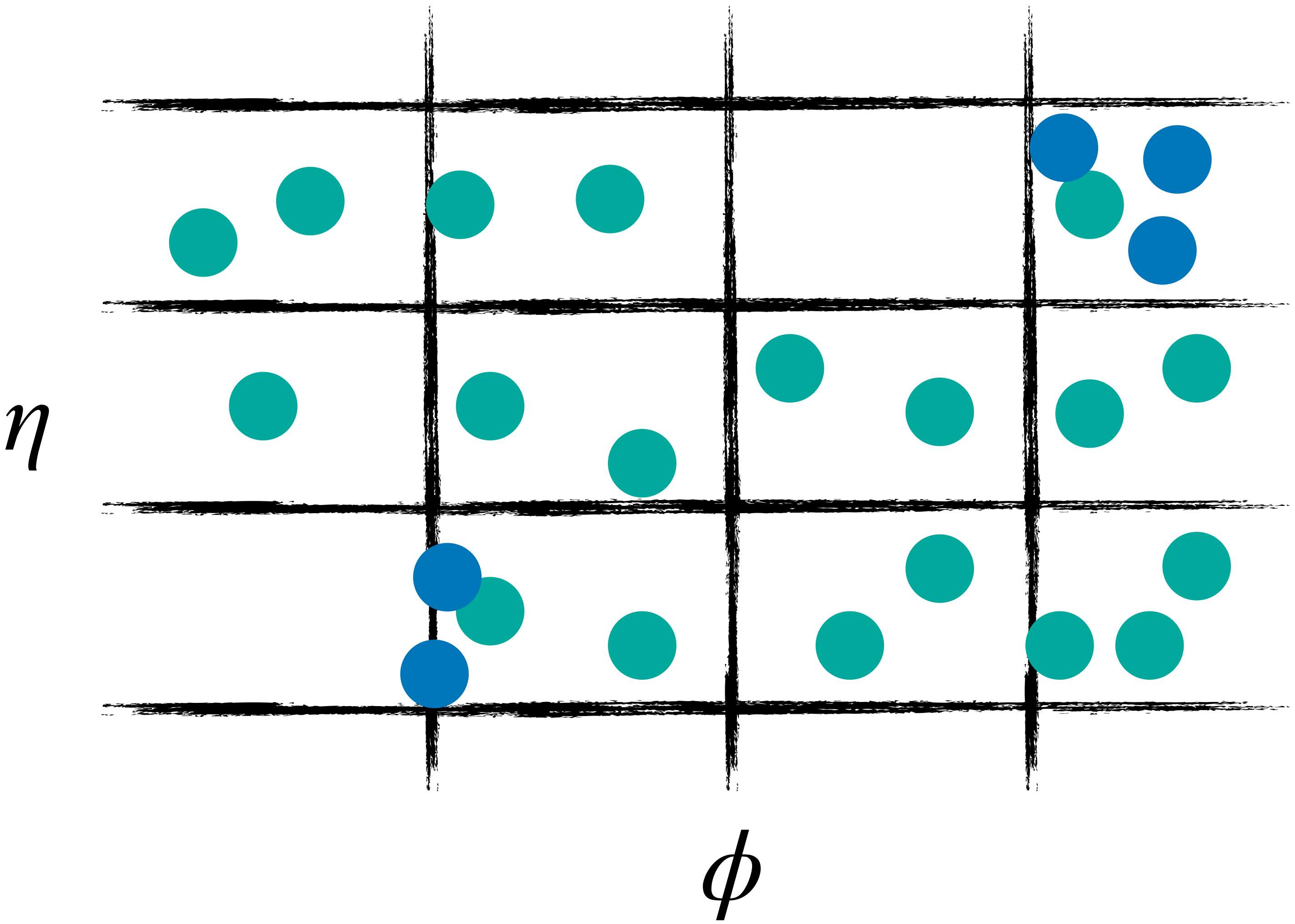
→

Remove the **2 hardest** jets from the sample

↓

For every patch, i, compute

$$\rho_i = \frac{p_{\mathrm{T},i}}{A_i}$$



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Cluster all particles (sig+bkg) in the event with **k$_T$ algorithm**

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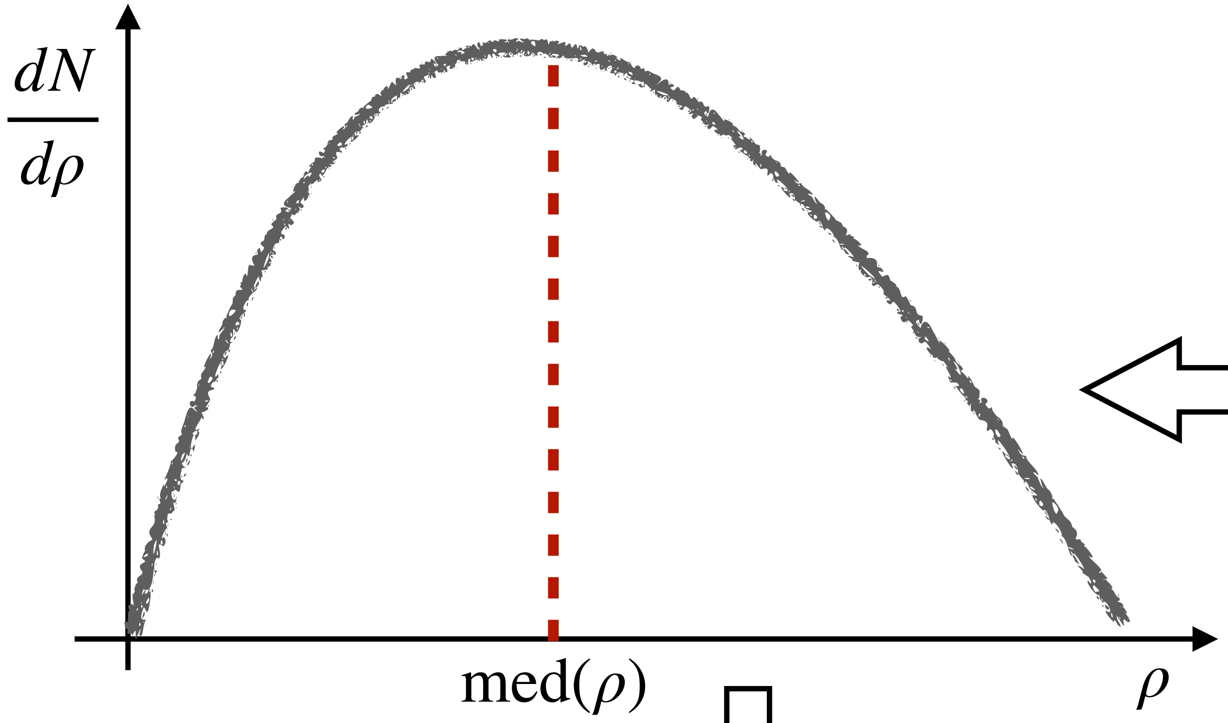


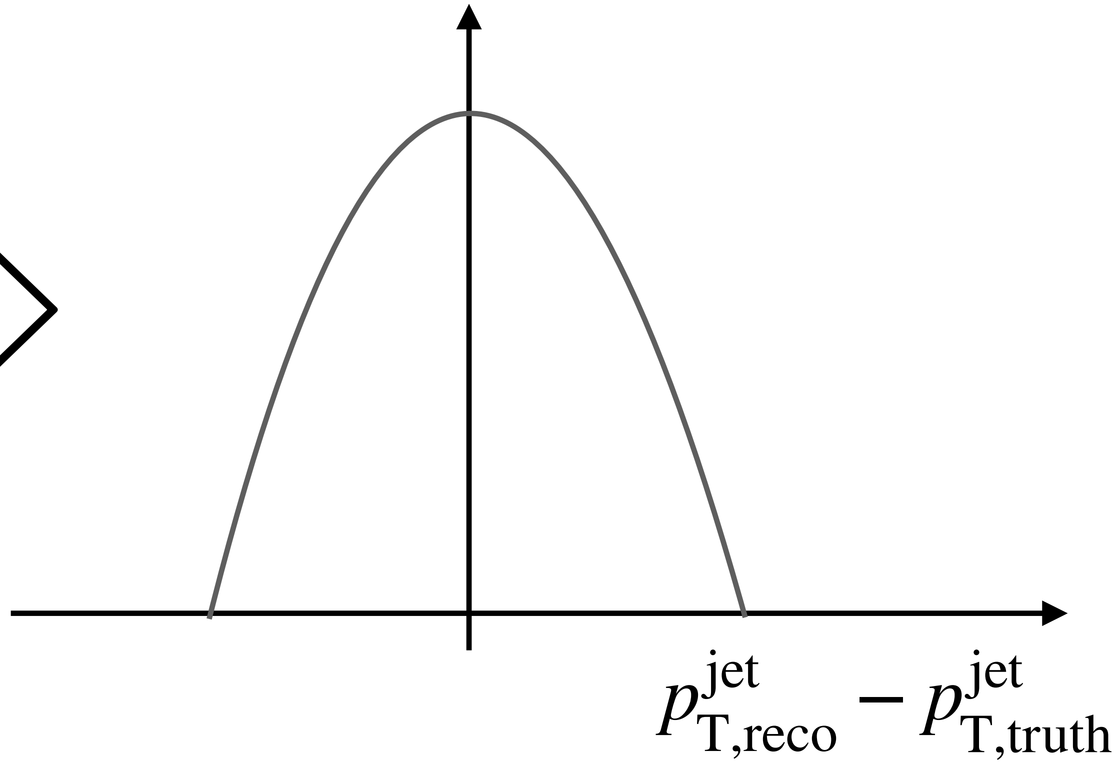
Cluster all particles (sig+bkg) in the event with **anti-k$_T$ algorithm**

$$\boxed{p^{\text{jet}}_{\text{T,reco}} = p^{\text{jet}}_{\text{T,raw}} - \text{med}(\rho) A^{\text{jet}}_{\text{raw}}}$$

Area-median: an unbiased method

[M. Cacciari, G.Salam Phys. Lett. B659 (2008) 119–126]

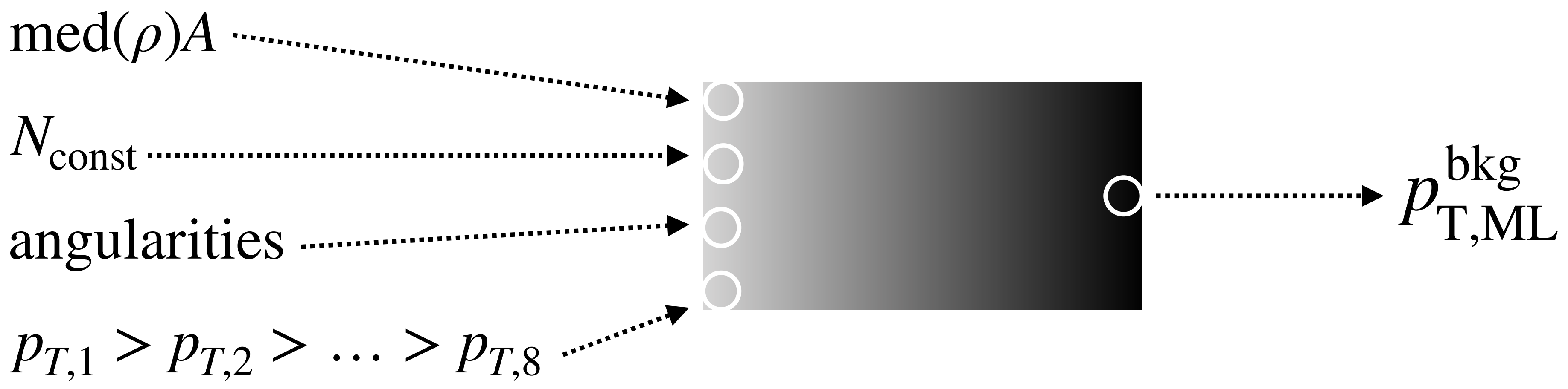
$$\boxed{p^{\mathrm{jet}}_{\mathrm{T,reco}} = p^{\mathrm{jet}}_{\mathrm{T,raw}} - \mathrm{med}(\rho)A^{\mathrm{jet}}_{\mathrm{raw}}}$$



- Data-driven, unbiased, correct $\langle p^{\mathrm{jet}}_{\mathrm{T,reco}} - p^{\mathrm{jet}}_{\mathrm{T,truth}} \rangle$
- No control over background fluctuations (needs unfolding)

Supervised learning approach

[R. Haake, C.Loizides, PRC 99, 064904 (2019)]



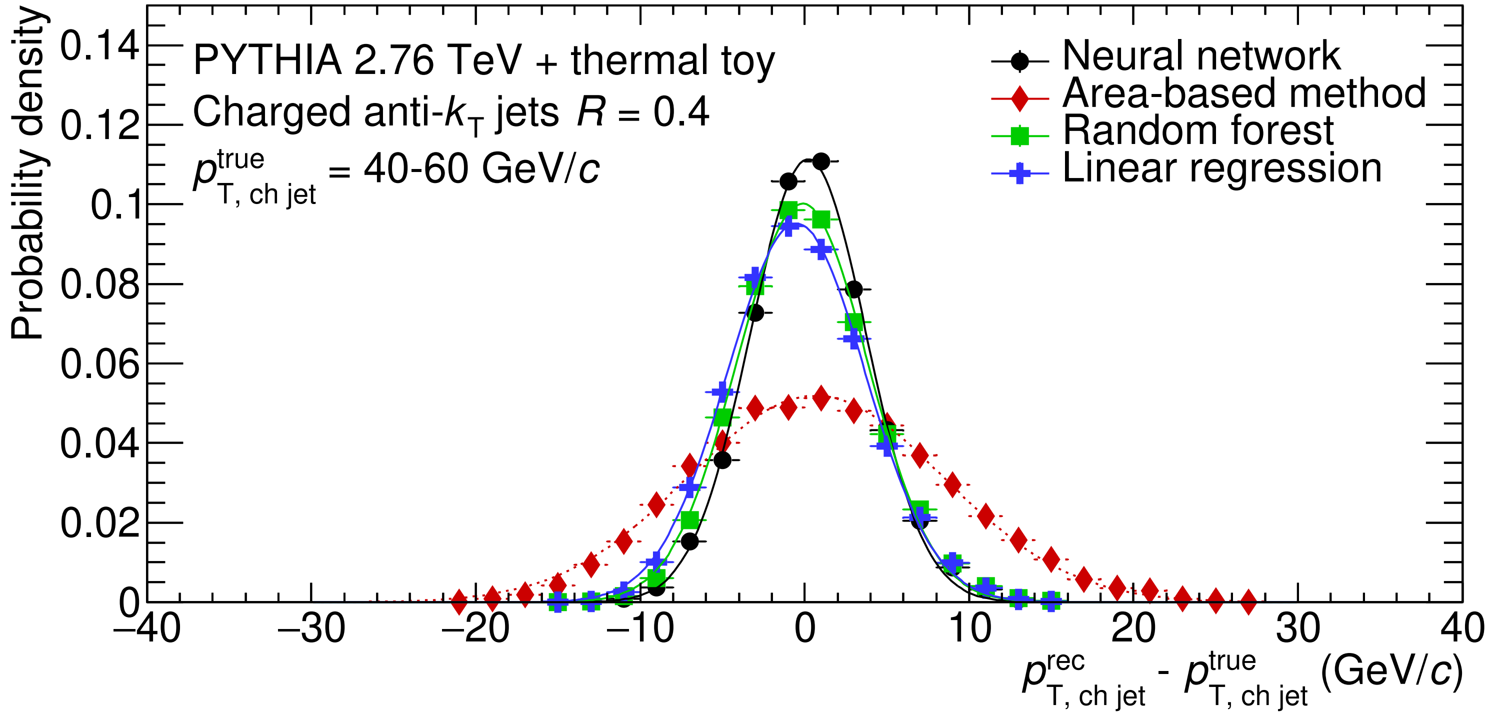
$\mathrm{med}(\rho)A$

N_{const}

angularities

$p_{T,1} > p_{T,2} > \ldots > p_{T,8}$

$p_{\mathrm{T,ML}}^{\mathrm{bkg}}$

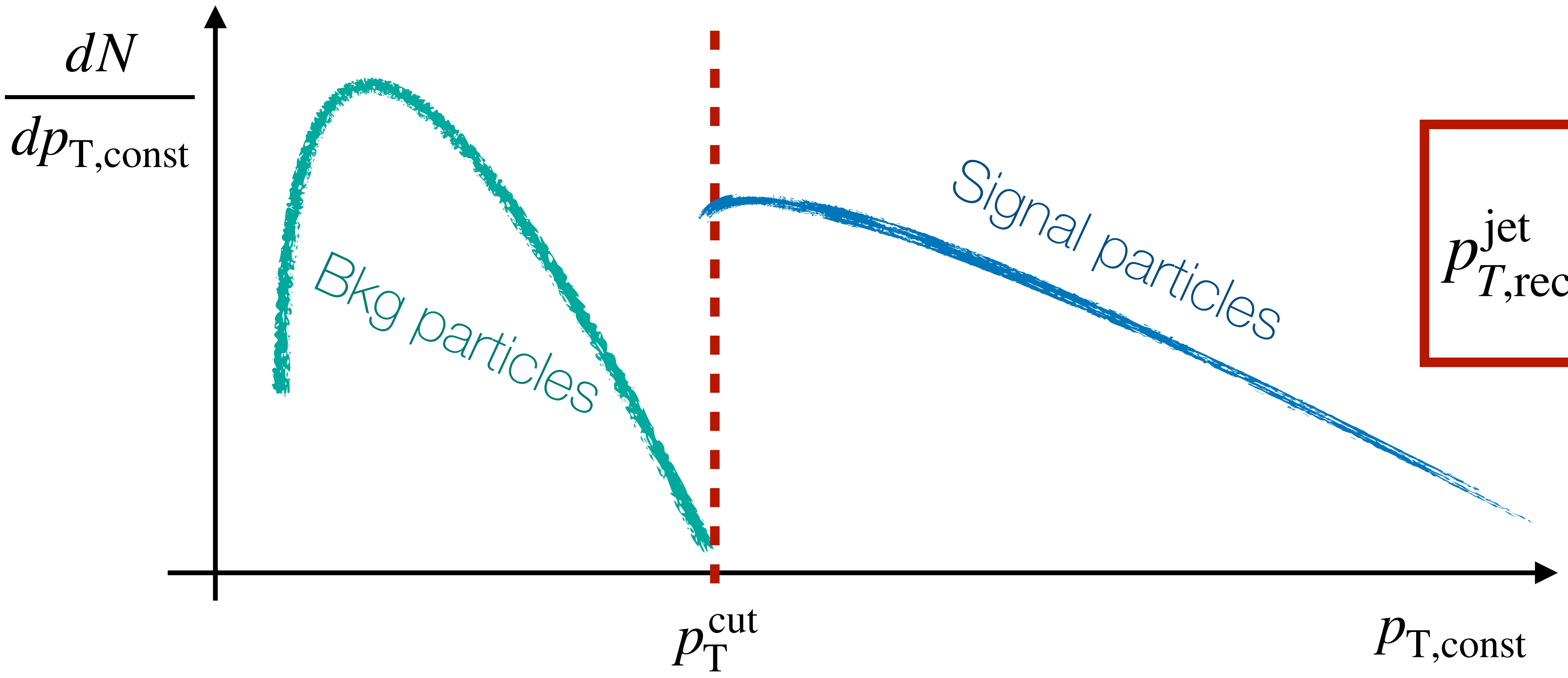


Estimator	Inclusive jets		Quark jets		Gluon jets	
Fit param. (GeV/c)	Mean	σ	Mean	σ	Mean	σ
Area-based method	0.7	7.8	0.8	7.3	0.9	7.7
Neural network	0.2	3.5	1.0	3.1	-0.5	3.6
Random Forest	-0.1	4.0	0.7	3.6	-0.8	3.9
Linear regression	-0.5	4.2	0.8	3.8	-1.4	4.1

TABLE I. Properties of the residual distributions for the considered estimators for $40 \leq p_{\mathrm{T,\,ch\,jet}}^{\mathrm{true}} < 60$ GeV/c. Mean and σ represent mean and standard deviation of the Gaussian fits, respectively.

SoftKiller: introducing a soft p$_T$-cut

[M. Cacciari, G. Salam and G. Soyez Eur.Phys.J. C75 (2015) no.2, 59]



$$p_{T,\mathrm{reco}}^{\mathrm{jet}} = p_{T,\mathrm{raw}}^{\mathrm{jet}} - \sum_{i}^{p_{T,i}<p_T^{\mathrm{cut}}} p_{T,i}$$

If there is no signal below the p$_T$-cut, exact handle on background fluctuations

$$\langle p_{\mathrm{T,reco}}^{\mathrm{jet}} - p_{\mathrm{T,truth}}^{\mathrm{jet}} \rangle = 0$$

$$\sigma(p_{\mathrm{T,reco}}^{\mathrm{jet}} - p_{\mathrm{T,truth}}^{\mathrm{jet}}) = 0$$

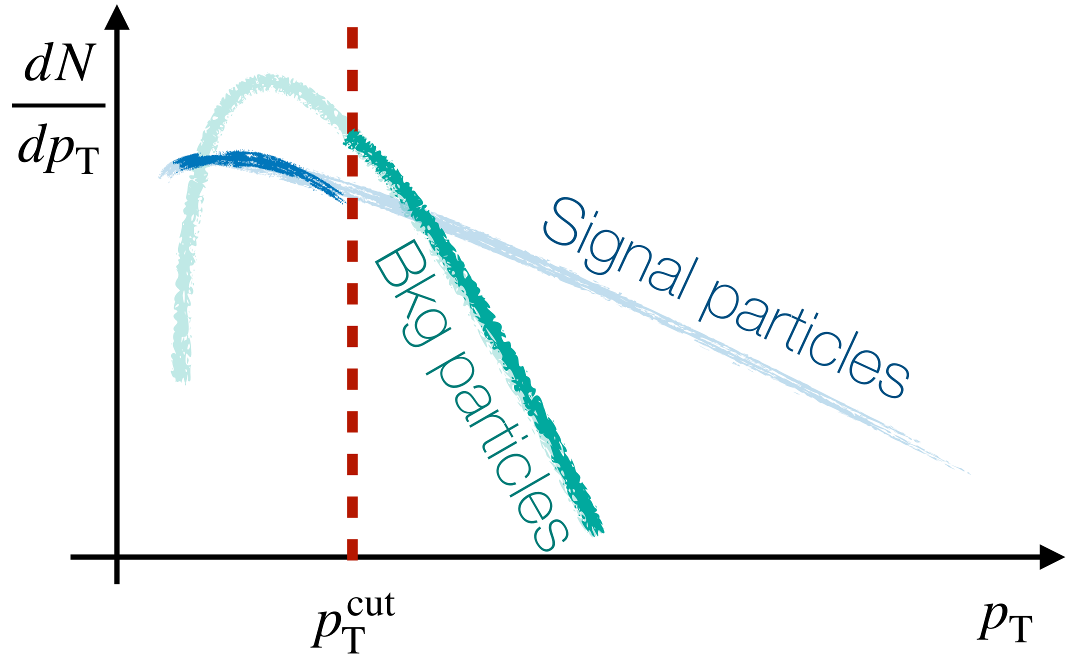
SoftKiller: introducing a soft p_T-cut

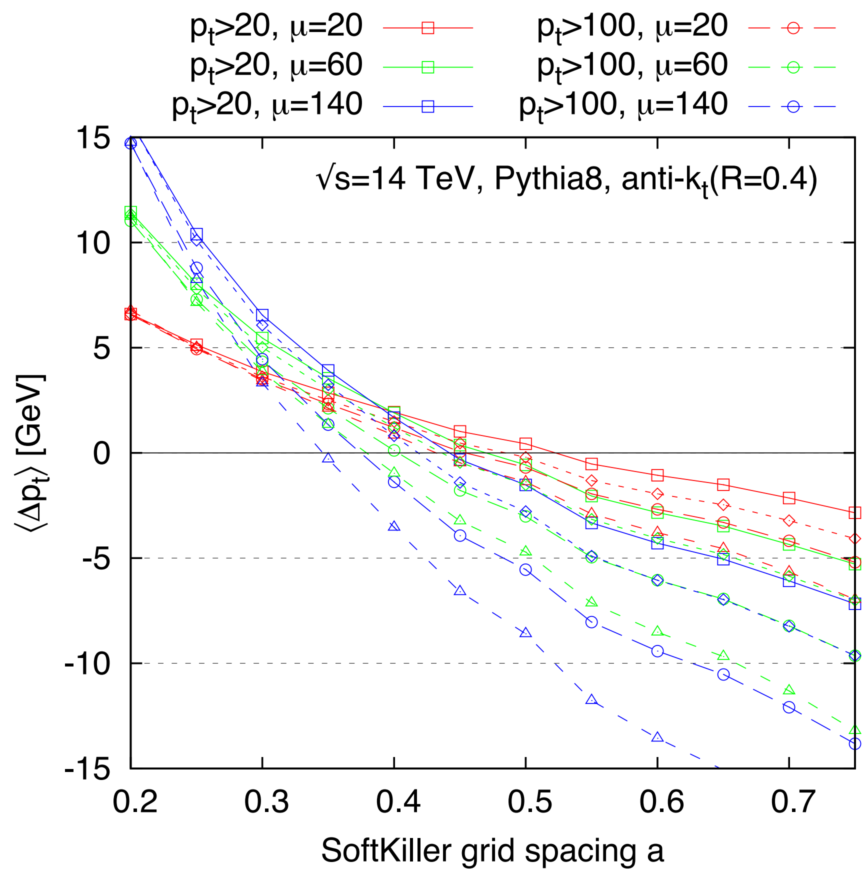
[M. Cacciari, G. Salam and G. Soyez Eur.Phys.J. C75 (2015) no.2, 59]

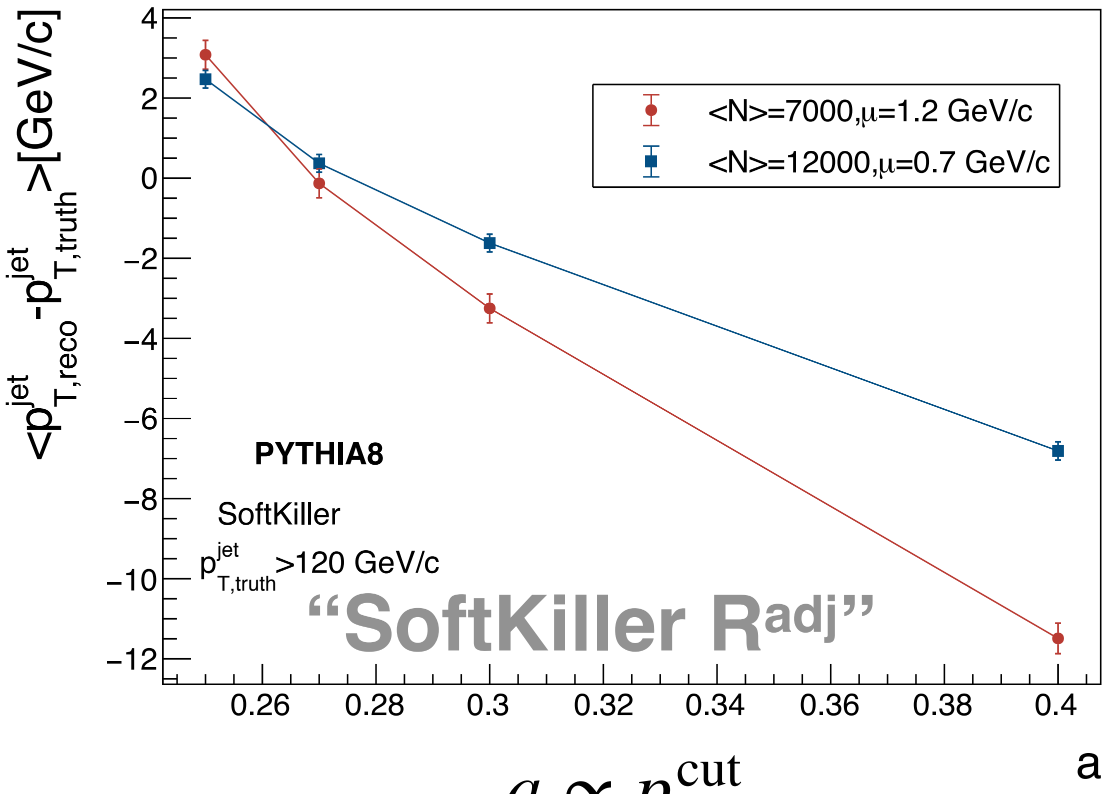
- Choose p_T-cut such that $p_{T,<}^{\mathrm{sig}}$ and $p_{T,>}^{\mathrm{bkg}}$ balance each other

$$\langle p_{T,\mathrm{reco}}^{\mathrm{jet}} - p_{T,\mathrm{truth}}^{\mathrm{jet}} \rangle \sim 0$$

- But…this actually requires a large degree of fine tuning





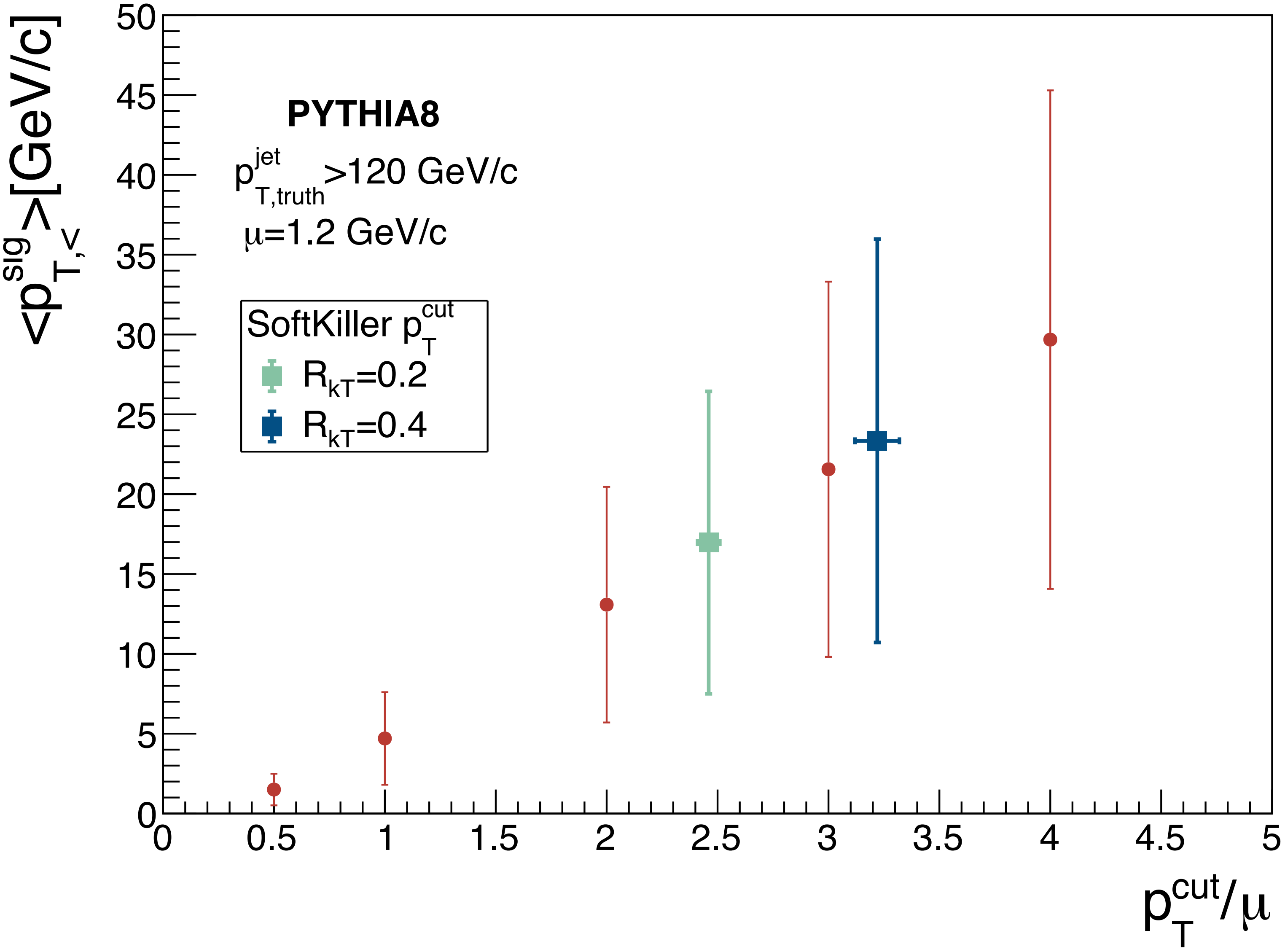


$a \propto p_T^{\mathrm{cut}}$

Impact of signal contamination

Any background estimator that relies on a soft pT-cut is sensitive to QCD radiation below this threshold

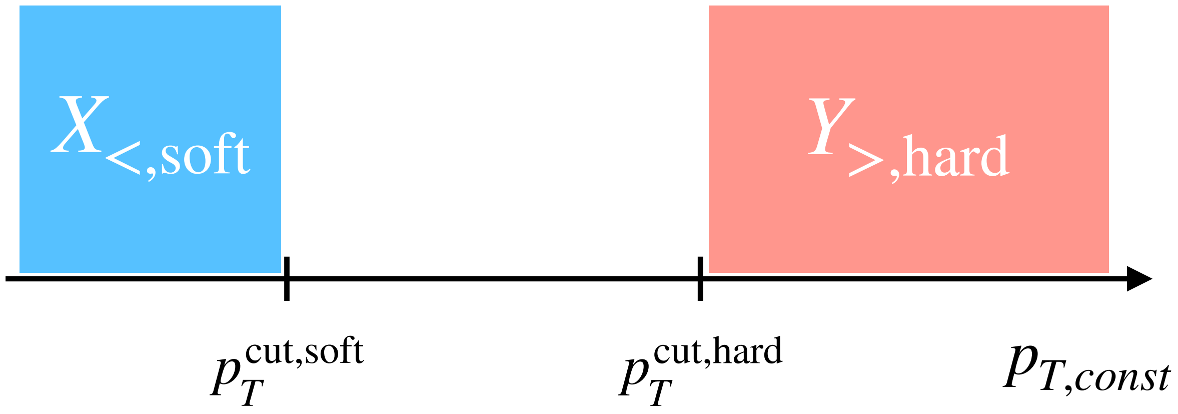
[Mehtar-Tani, ASO, Verweij arXiv:1904.12815]

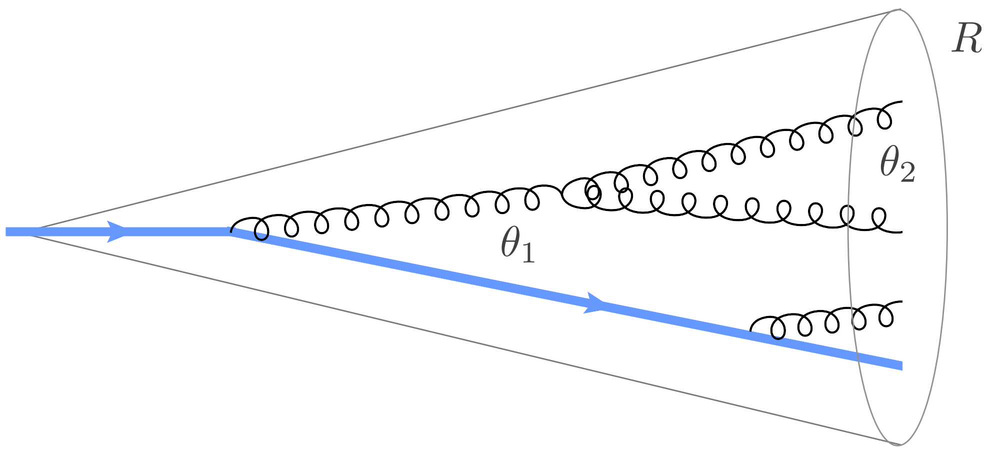


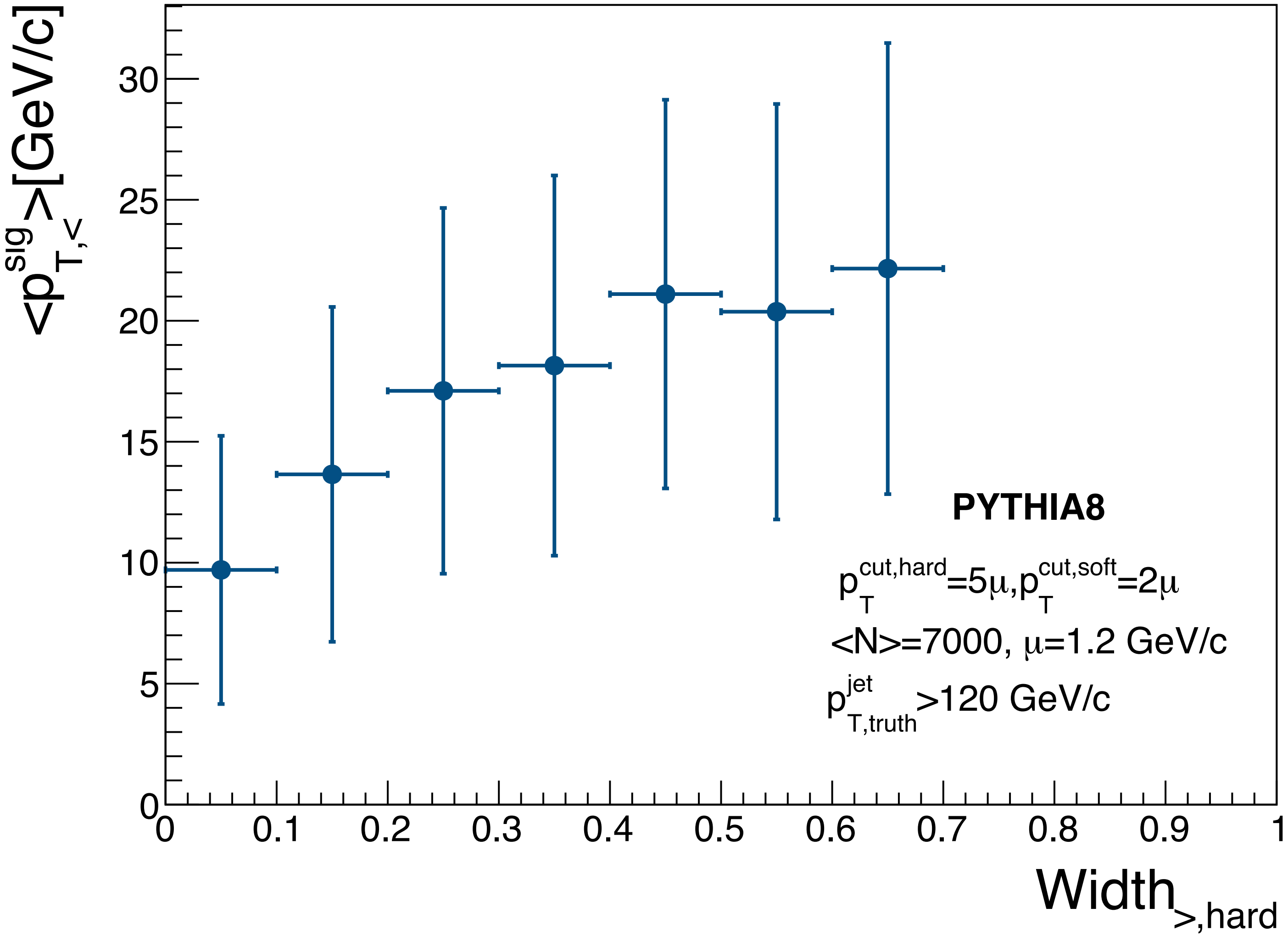
$$p_{T,<}^{\mathrm{sig}} = \sum_{i\in \mathrm{sig}}^{p_{T,i}<p_{\mathrm{T}}^{\mathrm{cut}}} p_{T,i}$$

$$\langle p_{T,\mathrm{reco}}^{\mathrm{jet}} - p_{T,\mathrm{truth}}^{\mathrm{jet}} \rangle \propto -\langle p_{T,<}^{\mathrm{sig}} \rangle + \ldots \qquad \sigma(p_{\mathrm{T,reco}}^{\mathrm{jet}} - p_{\mathrm{T,truth}}^{\mathrm{jet}}) \propto \sigma(p_{T,<}^{\mathrm{sig}})$$

Hard-soft correlations within a QCD jet



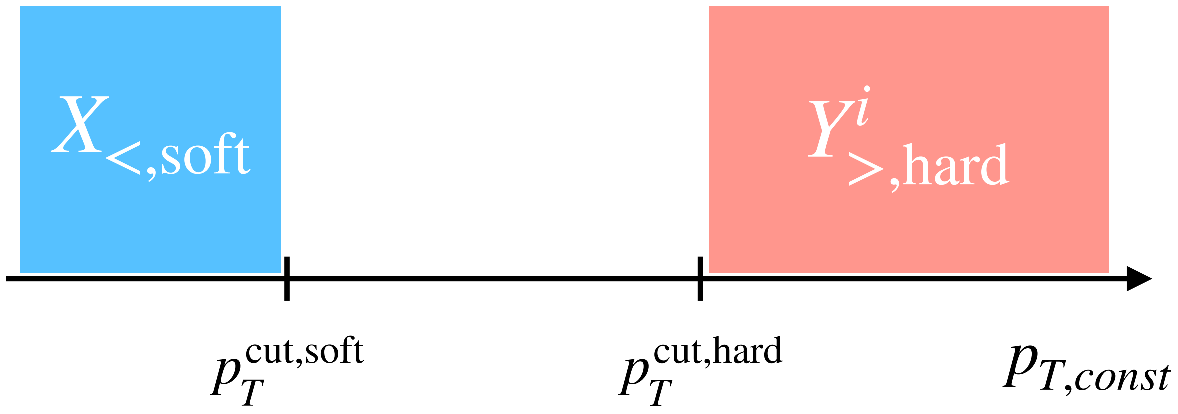


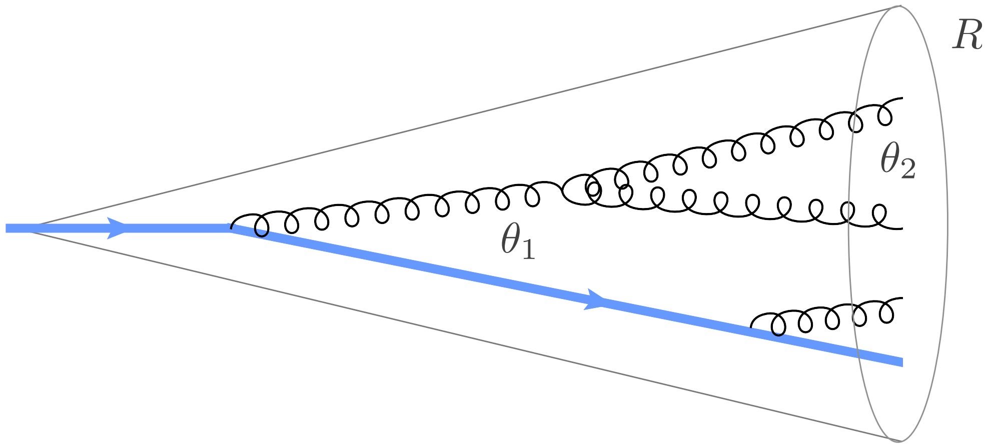


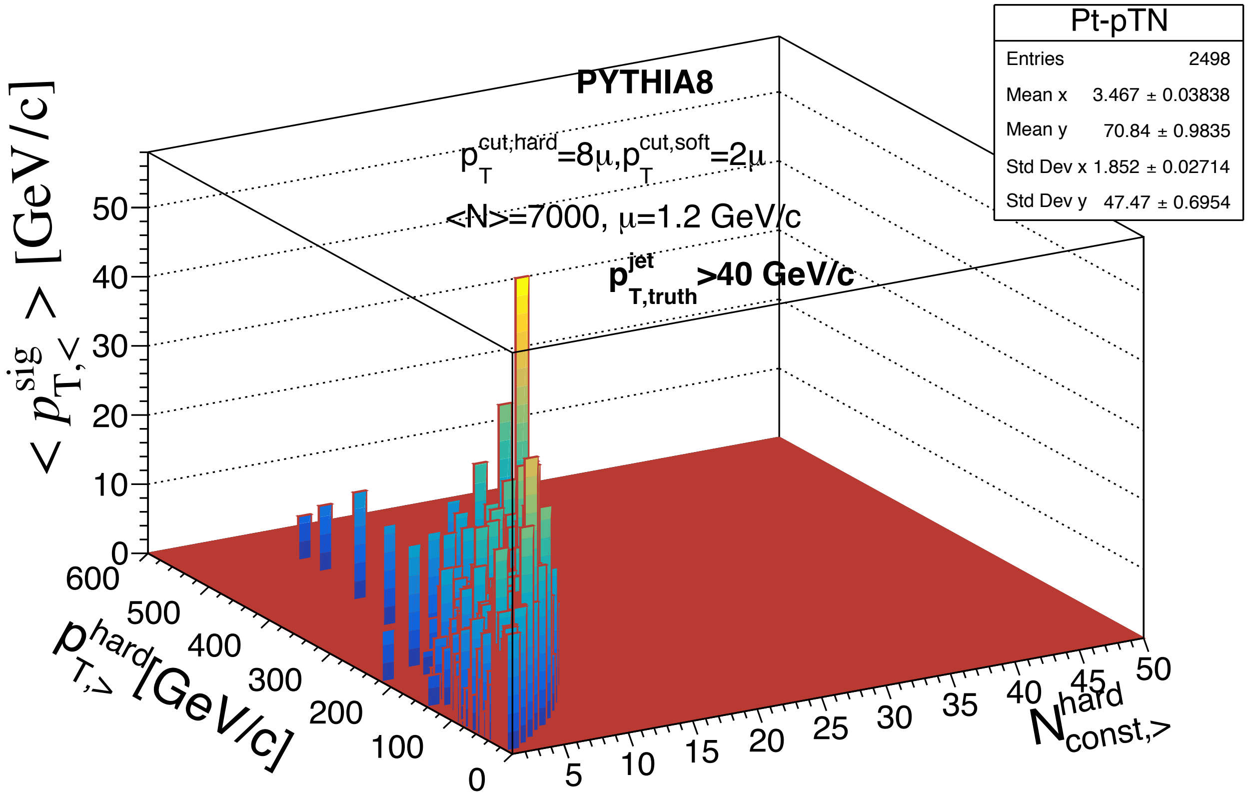
$\langle p_{T,<}^{\mathrm{sig}}\rangle$ and $\sigma(p_{T,<}^{\mathrm{sig}})$ can be mitigated by knowing/measuring jet properties in the hard sector i.e. a bkg free environment

$$\mathrm{width}_{>,\mathrm{hard}} = \sum_{i}^{p_{T,i}>p_{\mathrm{T}}^{\mathrm{cut,hard}}} \frac{p_{T,i}}{p_{T,>}} \frac{\theta_i}{R}$$

Hard-soft correlations within a QCD jet







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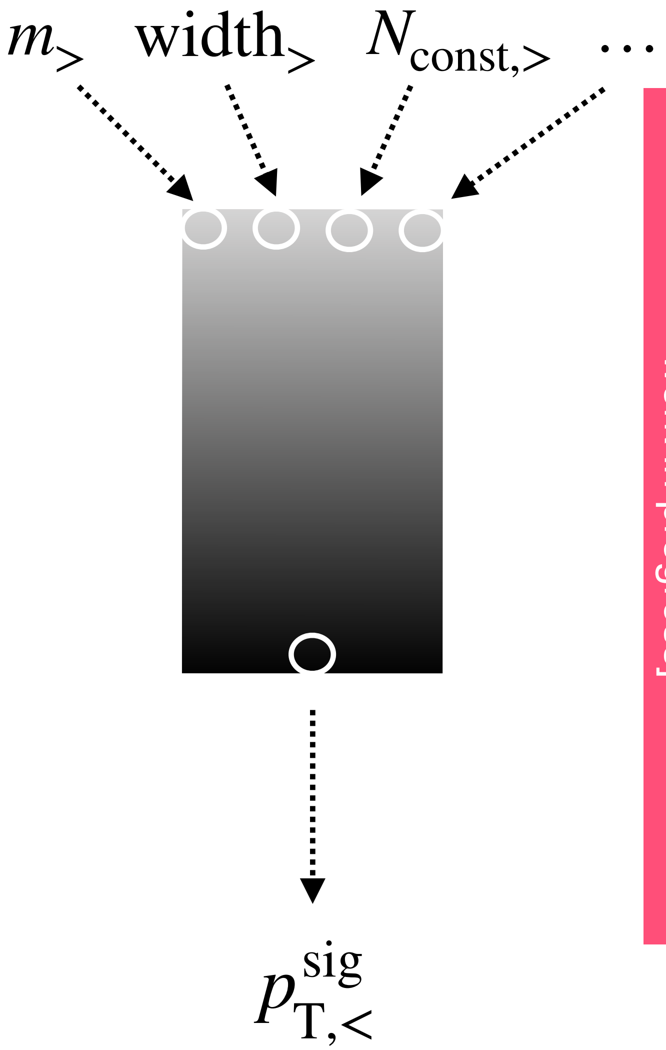
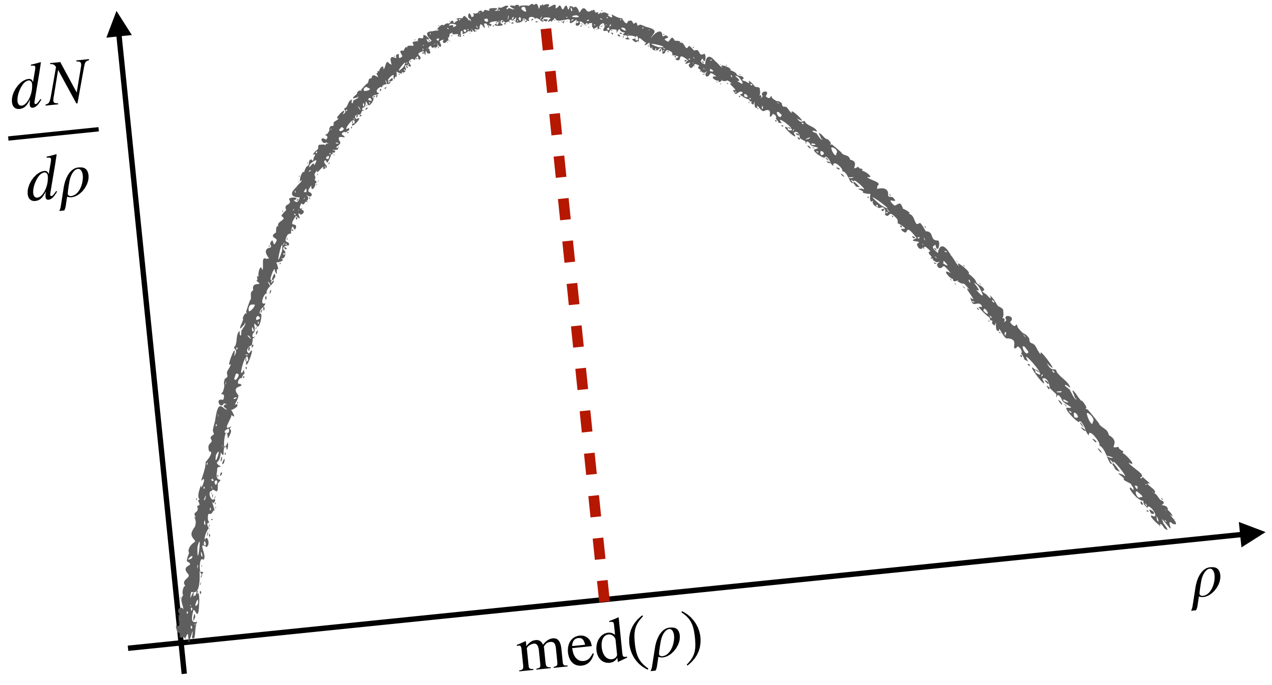
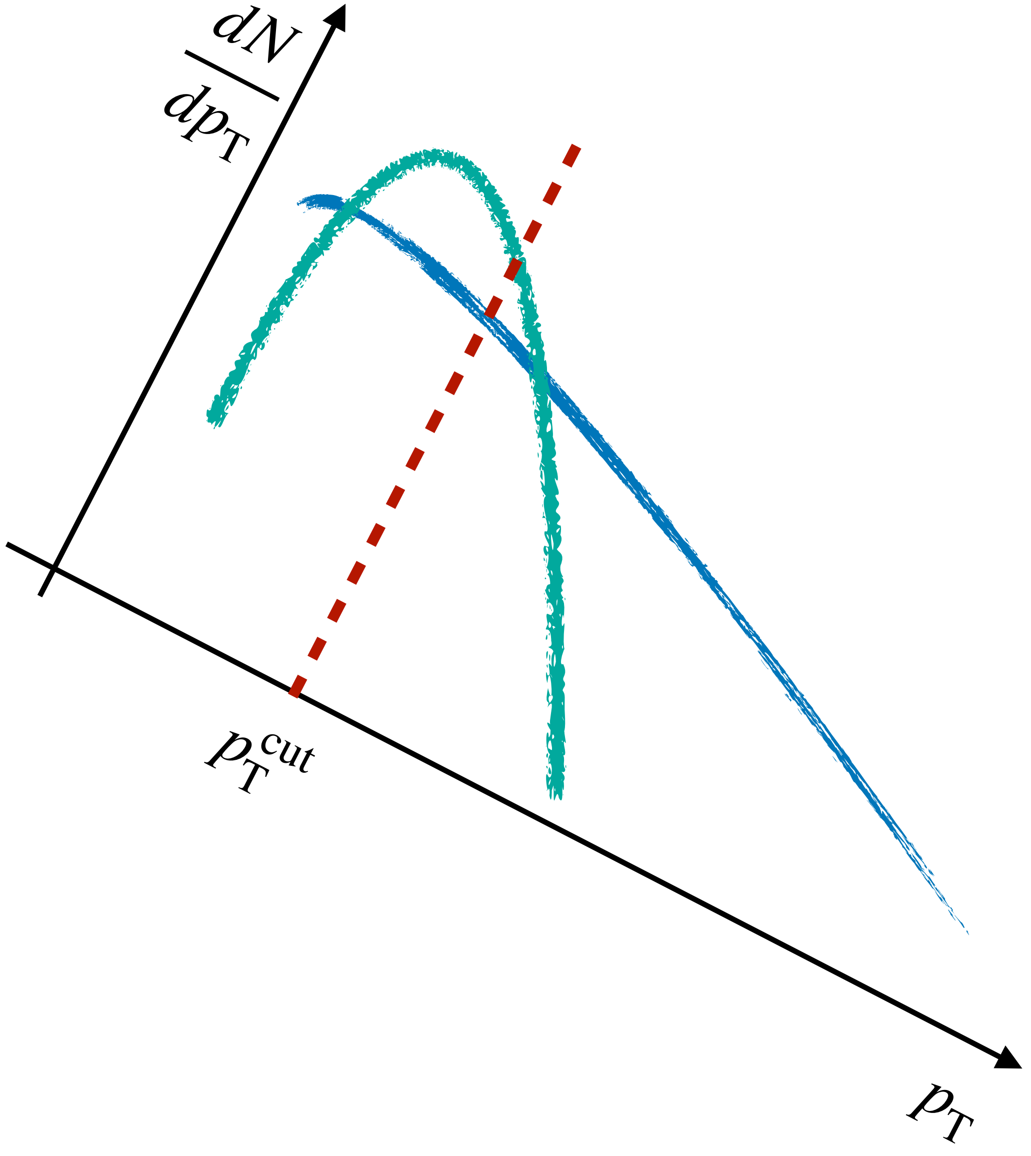


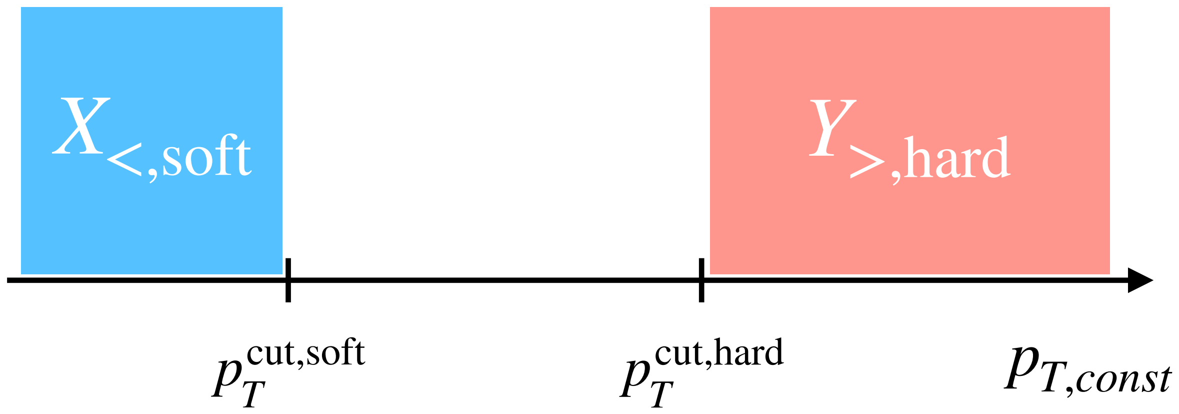
[Haake, Loizides,Mehtar-Tani, ASO, Verweij work in progress]

The ρ-correction approach

[Mehtar-Tani, ASO, Verweij arXiv:1904.12815]







The ρ-correction approach

[Mehtar-Tani, ASO, Verweij arXiv:1904.12815]

1

Cluster all particles (sig+bkg) in the event with **k_T algorithm, R=0.4**

⇨

Remove the **2 hardest** patches from the sample

For each patch, $\rho_> = \frac{1}{A} \sum_i^{p_T > p_T^{\mathrm{cut,soft}}} p_{T,i}$ ⇨ $\mathrm{med}(\rho_>)$

2

Re-cluster the whole event (sig+bkg) in the event with **anti-k_T algorithm, R=0.4**

For each jet, $p_{T,<} = \sum_i^{p_T < p_T^{\mathrm{cut,soft}}} p_{T,i}$

3

For a given $p_T^{\mathrm{cut,soft}}$ measure $\langle p_{T,<}^{\mathrm{sig}} \rangle$ in low pileup proton-proton collisions

The ρ-correction approach

[Mehtar-Tani, ASO, Verweij arXiv:1904.12815]

$$\boxed{p_{\mathrm{T,reco}}^{\mathrm{jet}} = p_{\mathrm{T,raw}}^{\mathrm{jet}} - \mathrm{med}(\rho_>)A_{\mathrm{raw}}^{\mathrm{jet}} - p_{T,<} + \langle p_{T,<}^{\mathrm{sig}} \rangle}$$

- Neglecting $\langle p_{T,<}^{\mathrm{sig}} \rangle$-term, $\begin{cases} p_{\mathrm{T}}^{\mathrm{cut,soft}} = 0 : \text{Area-median} \\ p_{\mathrm{T}}^{\mathrm{cut,soft}} = p_{\mathrm{T}}^{\mathrm{cut,SK}} : \text{SoftKiller } \mathrm{R_{kT}} \end{cases}$
- Role of $\langle p_{T,<}^{\mathrm{sig}} \rangle$: correct for the signal contamination below $p_{\mathrm{T}}^{\mathrm{cut,soft}}$
  - If measured inclusively, ρ-correction
  - If measured as a function of $\mathrm{width}_{>,\mathrm{hard}}$, ρ-correction $\mathrm{HS_{corr}}$

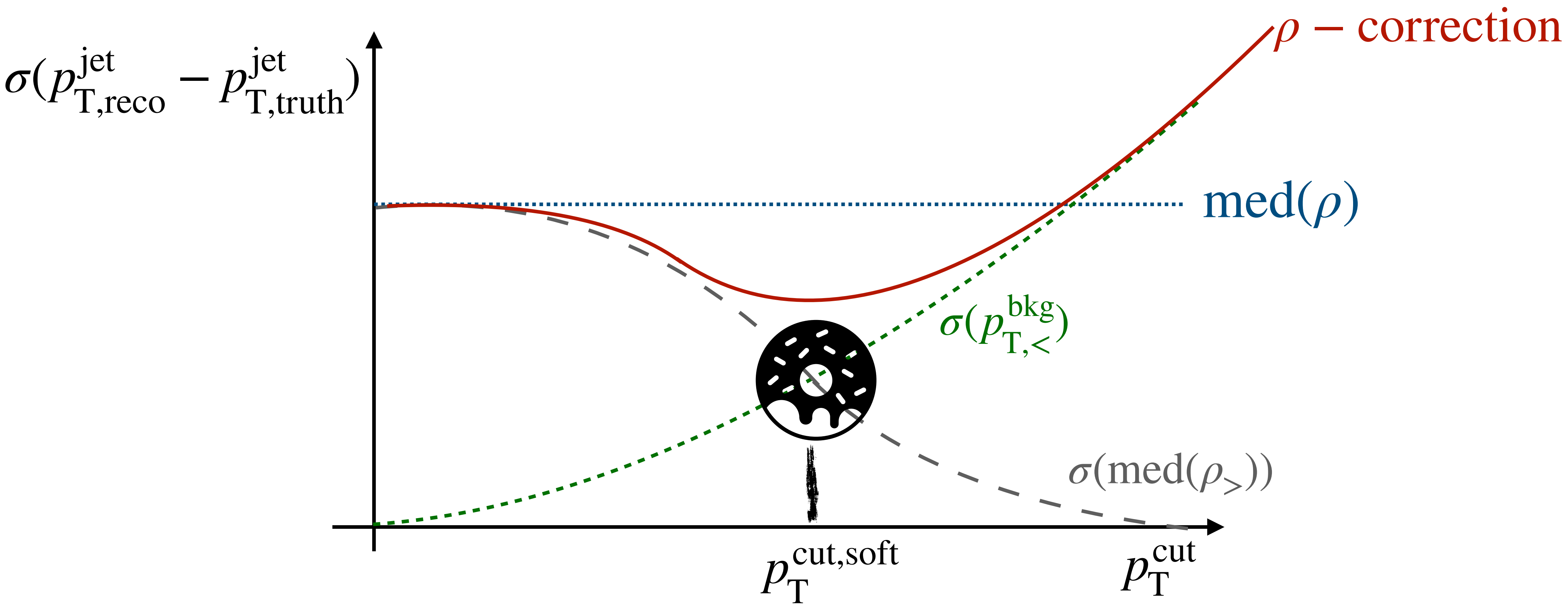
Value of $p_T^{\mathrm{cut,hard}}$? Large enough to be in the background-free region

$$p_T^{\mathrm{cut,hard}} = 5\mu$$ (μ : average momentum of bkg constituents)

The ρ-correction approach

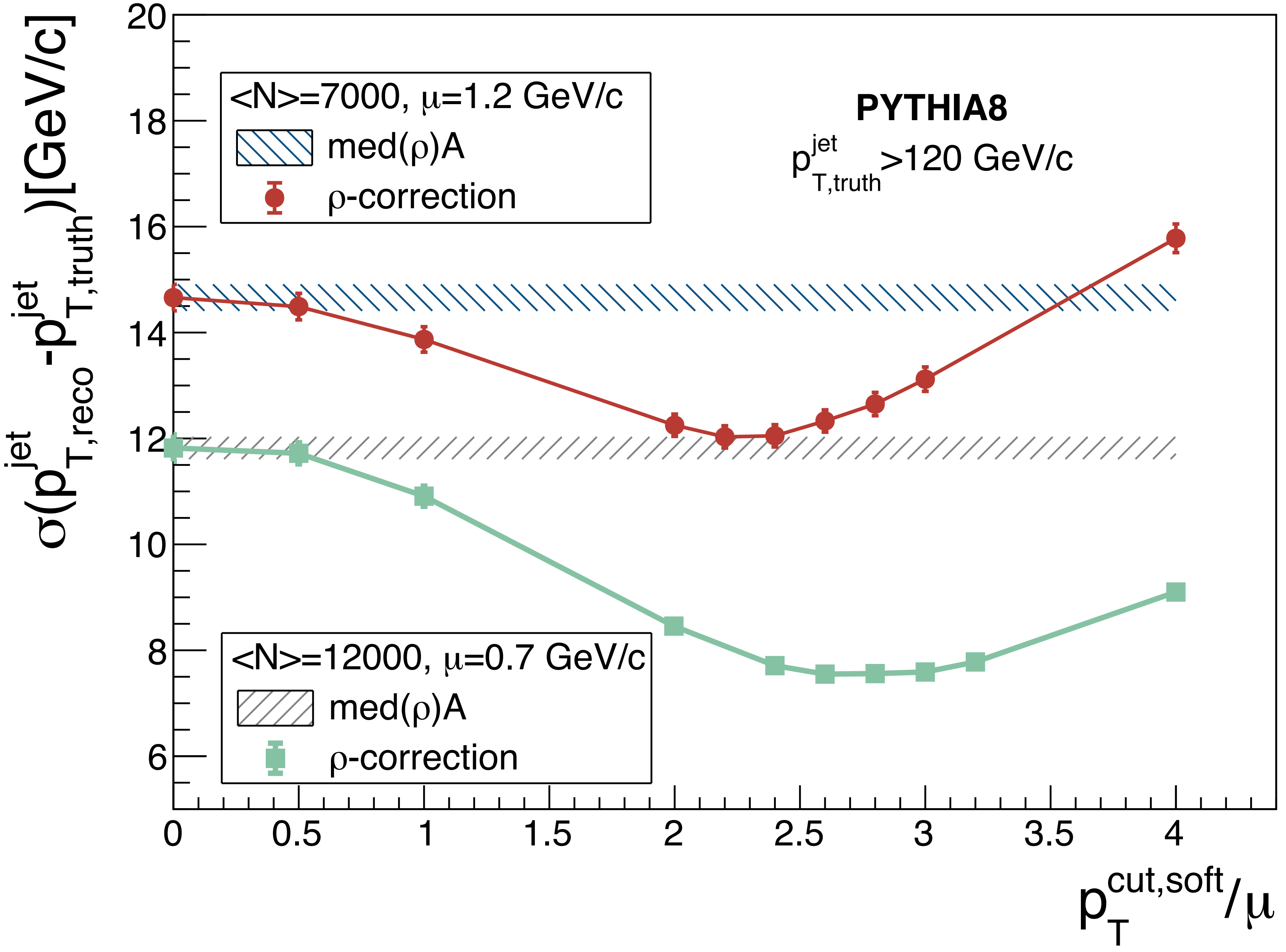
[Mehtar-Tani, ASO, Verweij arXiv:1904.12815]

- Prescription to choose $p_T^{\mathrm{cut,soft}}$: minimize $\sigma(p^{\mathrm{jet}}_{\mathrm{T,reco}} - p^{\mathrm{jet}}_{\mathrm{T,truth}})$



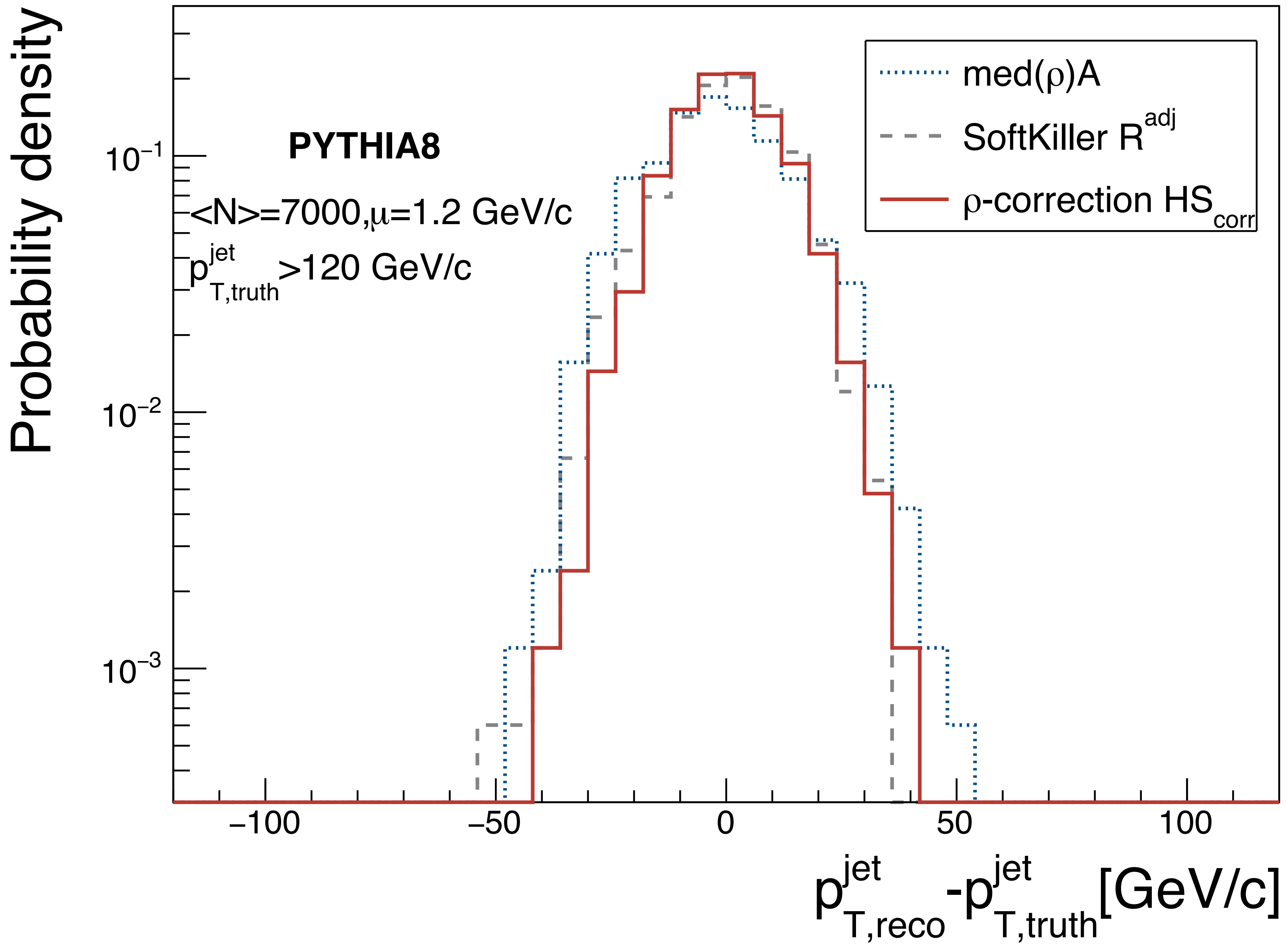
$$\boxed{p^{\mathrm{jet}}_{\mathrm{T,reco}} = p^{\mathrm{jet}}_{\mathrm{T,raw}} - \mathrm{med}(\rho_>)A^{\mathrm{jet}}_{\mathrm{raw}} - p_{T,<} + \langle p^{\mathrm{sig}}_{T,<}\rangle}$$

PYTHIA8 + Thermal background



Plateau-like region around the optimal $p_T^{\text{cut,soft}}$.
No need to fine-tune

PYTHIA8 + Thermal background



ρ-correction HS_{corr}

- 23% improvement w.r.t area-median
- 6% improvement w.r.t SoftKiller R^{adj}

[GeV/c]	Mean	Standard deviation
med(ρ)A	-1.51±0.36	14.66±0.25
SoftKiller R^{adj}	0.29±0.29	12.10±0.21
ρ-correction	0.37±0.31	12.03 ± 0.21
ρ-correction $\mathrm{HS_{corr}}$	0.49±0.28	11.39 ±0.21

JEWEL w/ E-loss + Thermal background

Hard to know $p_{\mathrm{T,truth}}^{\mathrm{jet}}$ due to energy loss + cannot switch off the background

⇨ $p_{\mathrm{T}}^{\mathrm{cut,soft}}$ minimizes $\sigma(p_{\mathrm{T,reco}}^{\mathrm{jet}} - p_{\mathrm{T,truth}}^{\mathrm{jet}})$ in JEWEL w/o E-loss

⇨ Apply $\langle p_{T,<}^{\mathrm{sig}} \rangle$ as measured in low pileup p+p

[GeV/c]	Mean	Standard deviation	Δ_{truth}
med(ρ)A	-0.61±0.17	14.73±0.12	10.1
SoftKiller R^{adj}	2.90±0.12	10.91± 0.09	7.55
ρ-correction	2.96±0.12	10.92± 0.09	7.6
ρ-correction HS$_{\mathrm{corr}}$	2.04±0.12	10.34± 0.08	6.9

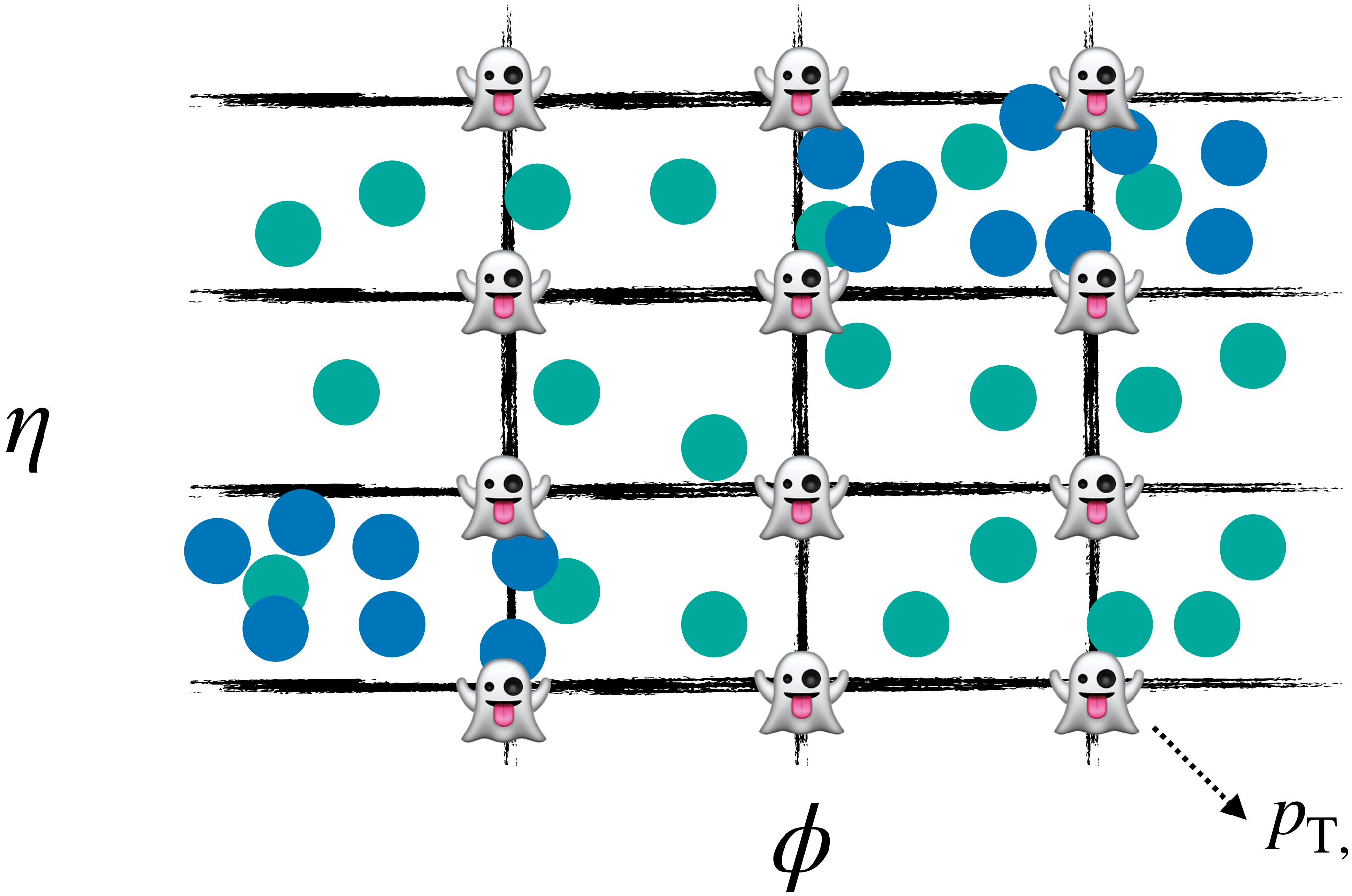
$[-\Delta_{\mathrm{truth}}, \Delta_{\mathrm{truth}}]$: interval in $p_{\mathrm{T,reco}}^{\mathrm{jet}} - p_{\mathrm{T,truth}}^{\mathrm{jet}}$ centered around 0 and containing 1/2 jets

Better resolution but not straightforward to control the bias due to in-medium modifications

SUBTRACTION METHOD

Constituent subtraction

[P. Berta, M. Spousta, D. Miller and R. Leitner JHEP 1406 (2014) 092]



$p_{\mathrm{T,g}} = \rho^{\mathrm{bkg}}_{\mathrm{est}} A_g = \mathrm{med}(\rho) A_g$

1) For each jet, compute all the ghost-to-particle distances

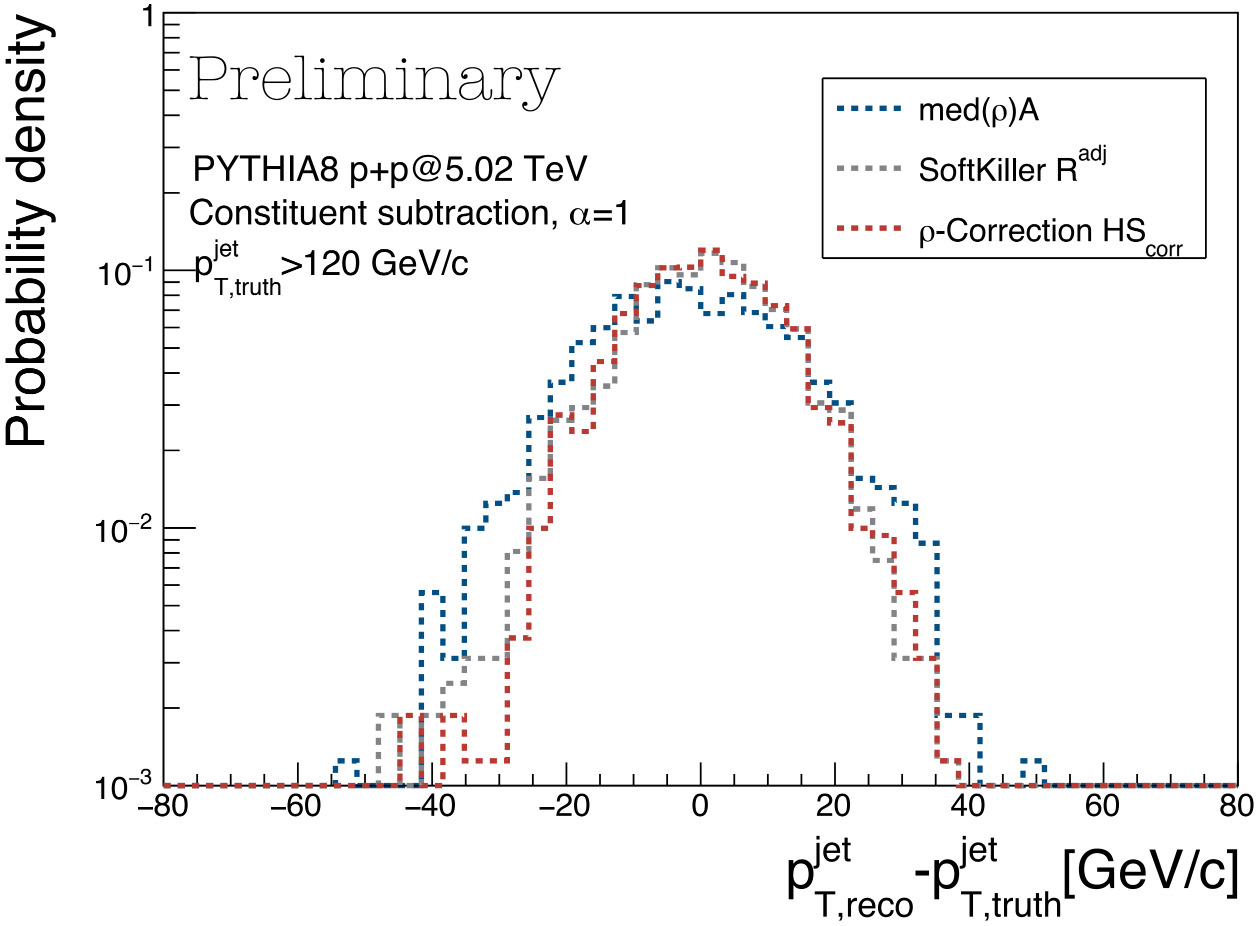
$\Delta R_{i,k} = p^{\alpha}_{\mathrm{T},i}\sqrt{(y_i - y^g_k)^2 + (\phi_i - \phi^g_k)^2}$ and sort them from smallest to largest.

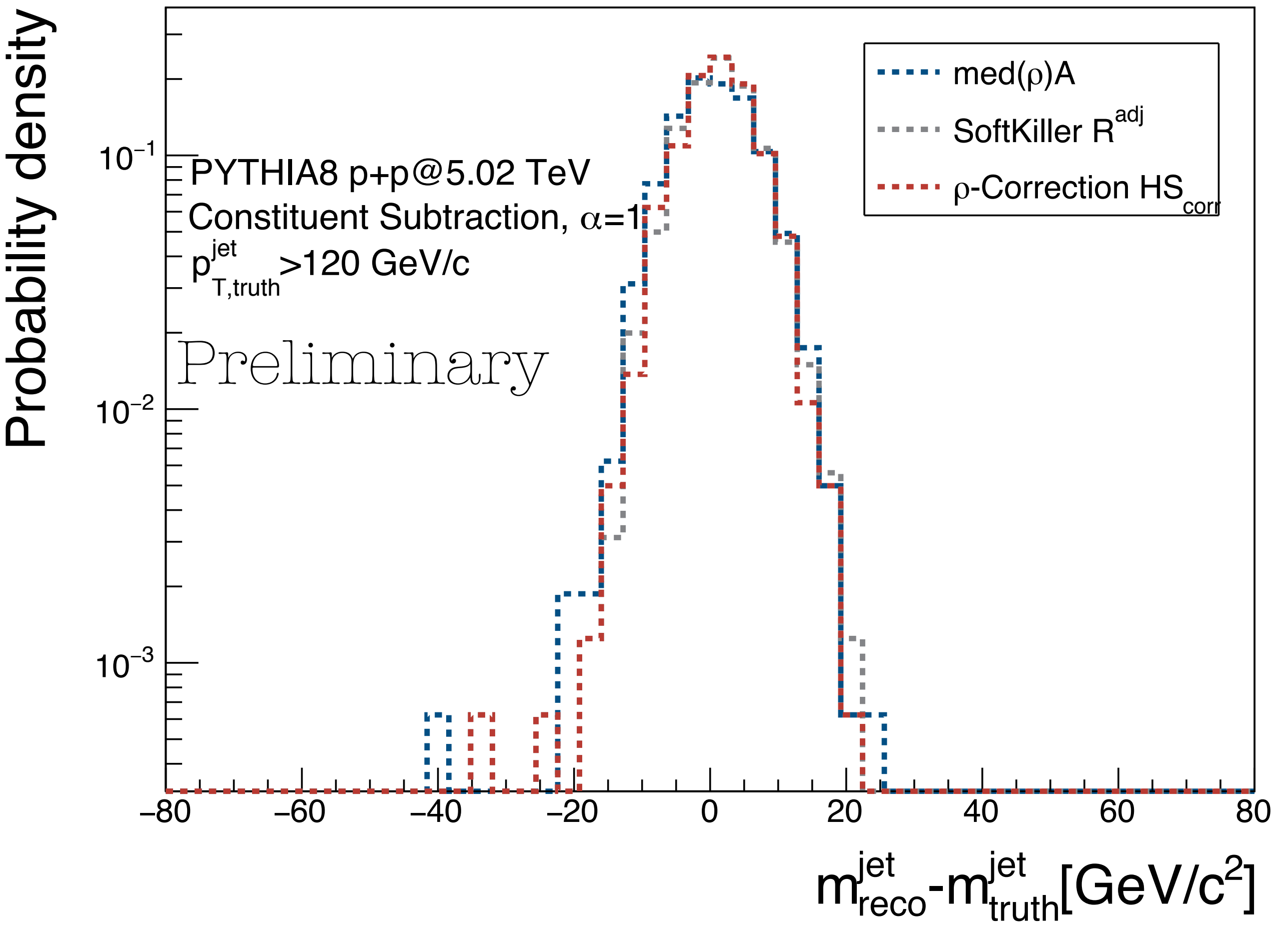
2) For each pair,

- If $p_{\mathrm{T},i} > p^g_{\mathrm{T},k}$: $p_{\mathrm{T},i} -= p^g_{\mathrm{T},k}$ && $p^g_{\mathrm{T},k} = 0$
- If $p_{\mathrm{T},i} < p^g_{\mathrm{T},k}$: $p_{\mathrm{T},i} = 0$ && $p^g_{\mathrm{T},k} -= p_{\mathrm{T},i}$

3) Remove every particle/ghost with $p_{\mathrm{T}} = 0$

Constituent subtraction beyond area-median

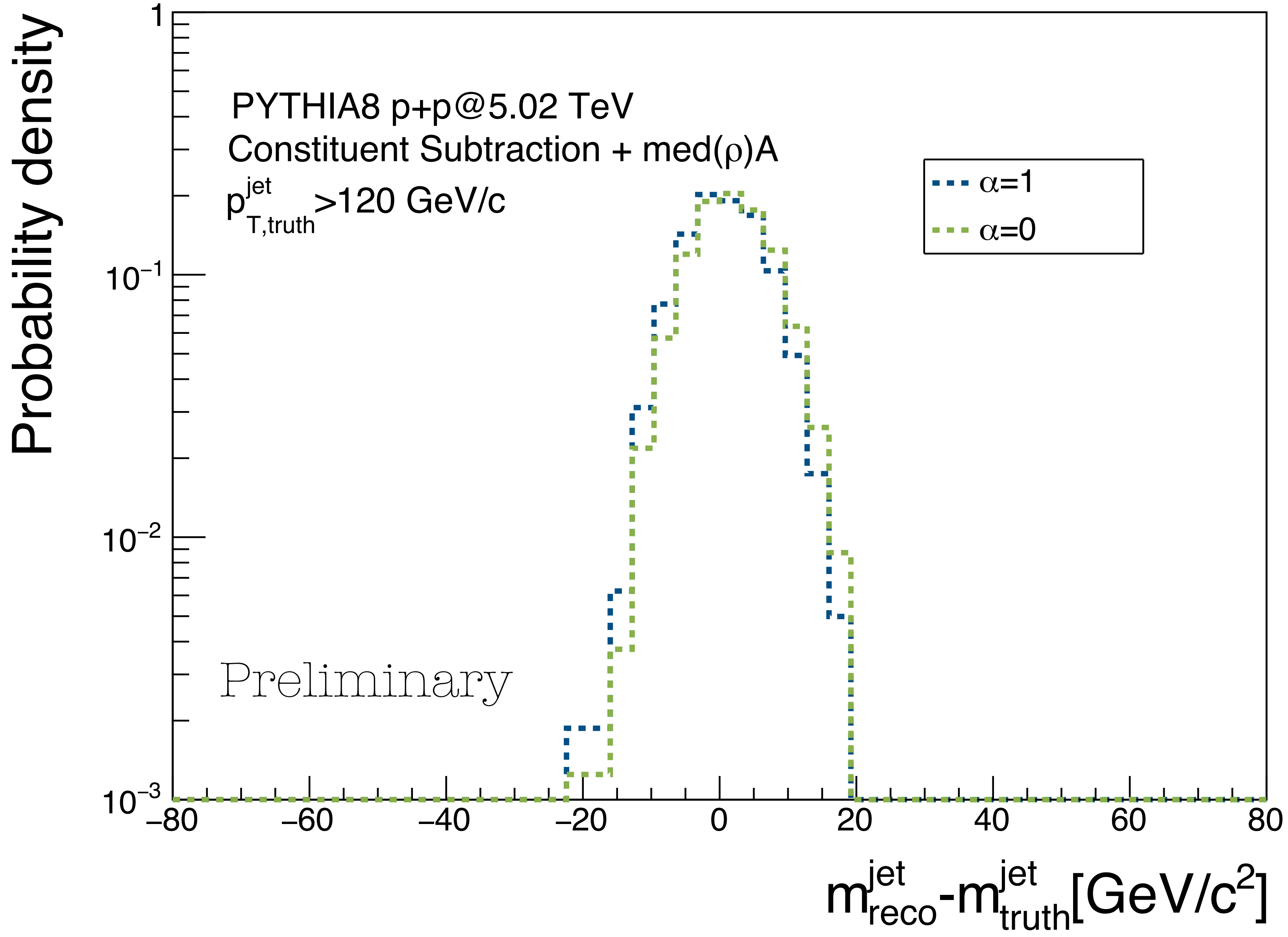




Improved mass and pT resolutions just by having a more precise estimate for p_T^{bkg}

Constituent subtraction: the role of α

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

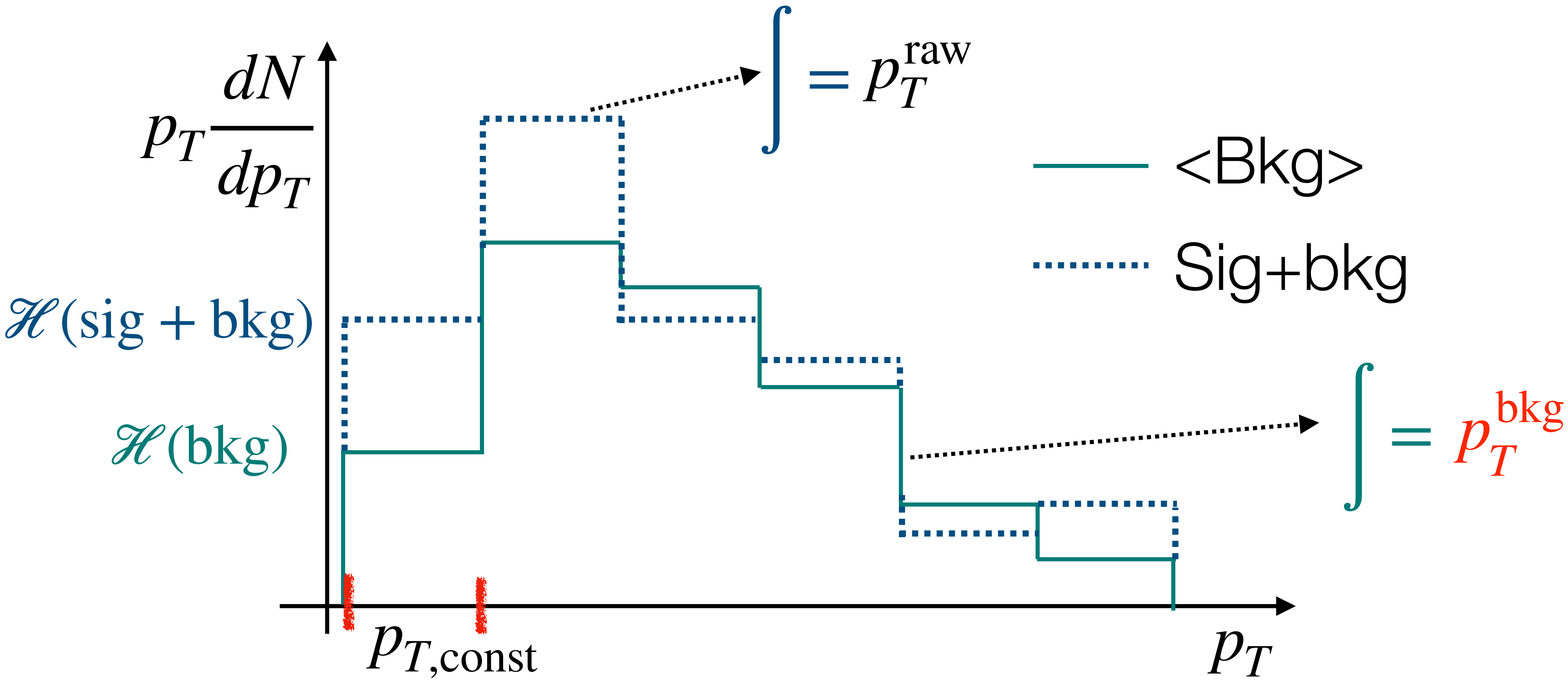


$\Delta m_{\alpha=0\rightarrow\alpha=1} \sim 1\ \mathrm{GeV}/c^2$ **as due to the lack of pT information**

pTSampler Subtractor

[Mehtar-Tani, ASO, Verweij, In preparation]

Exploit that background and signal particles have distinct angular and momentum distributions

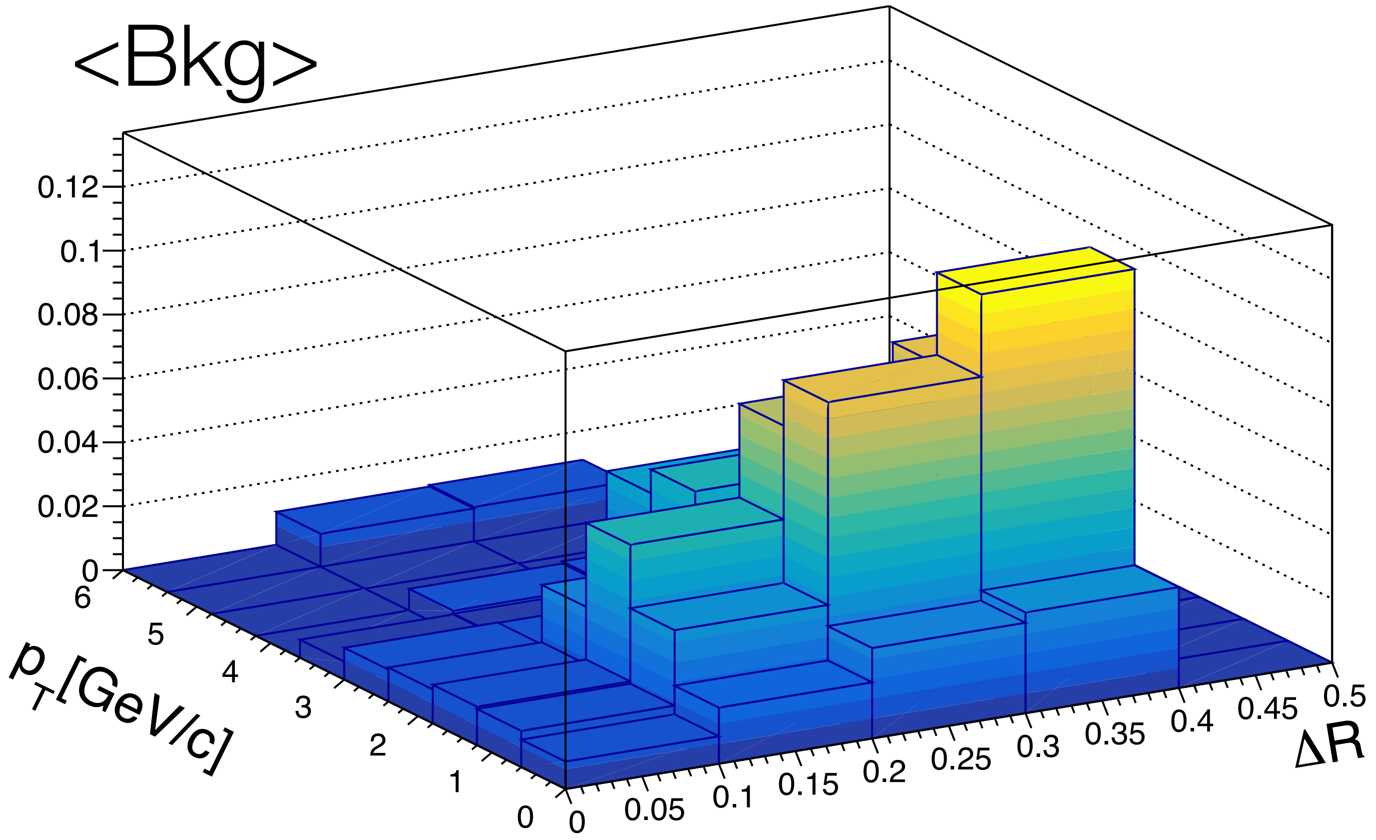


$$\mathscr{P}(p_i \in \mathrm{bkg}) = \frac{\mathscr{H}_{\mathrm{part}}(\mathrm{bkg})}{\mathscr{R}}$$ with $\mathscr{R} \in \left(0, \mathscr{H}(\mathrm{sig}+\mathrm{bkg})\right)$

pTSampler Subtractor

[Mehtar-Tani, ASO, Verweij, In preparation]

Exploit that background and signal particles have distinct angular and momentum distributions

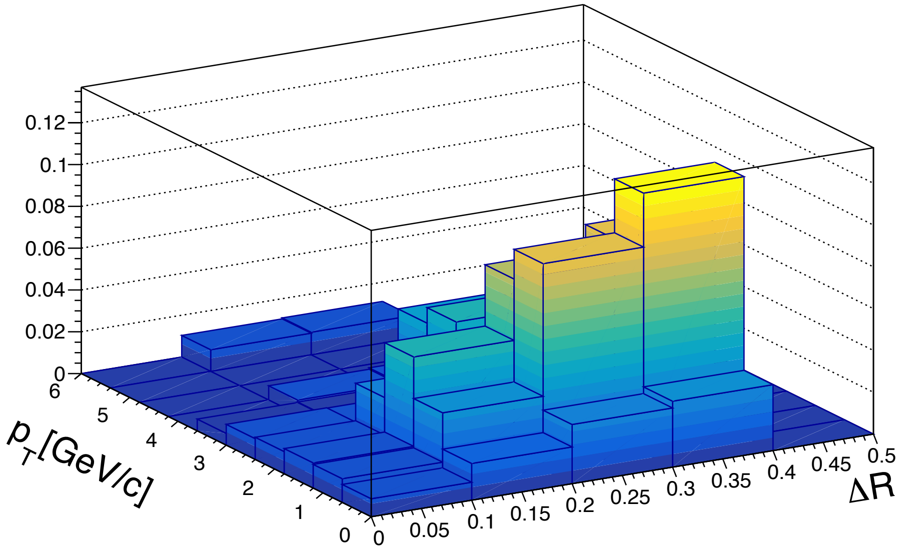


$$\mathscr{P}(p_i \in \mathrm{bkg}) = \frac{\mathscr{H}_{\mathrm{part}}(\mathrm{bkg})}{\mathscr{R}} \quad \text{with} \quad \mathscr{R} \in \left(0, \mathscr{H}(\mathrm{sig}+\mathrm{bkg})\right)$$

pTSampler Subtractor

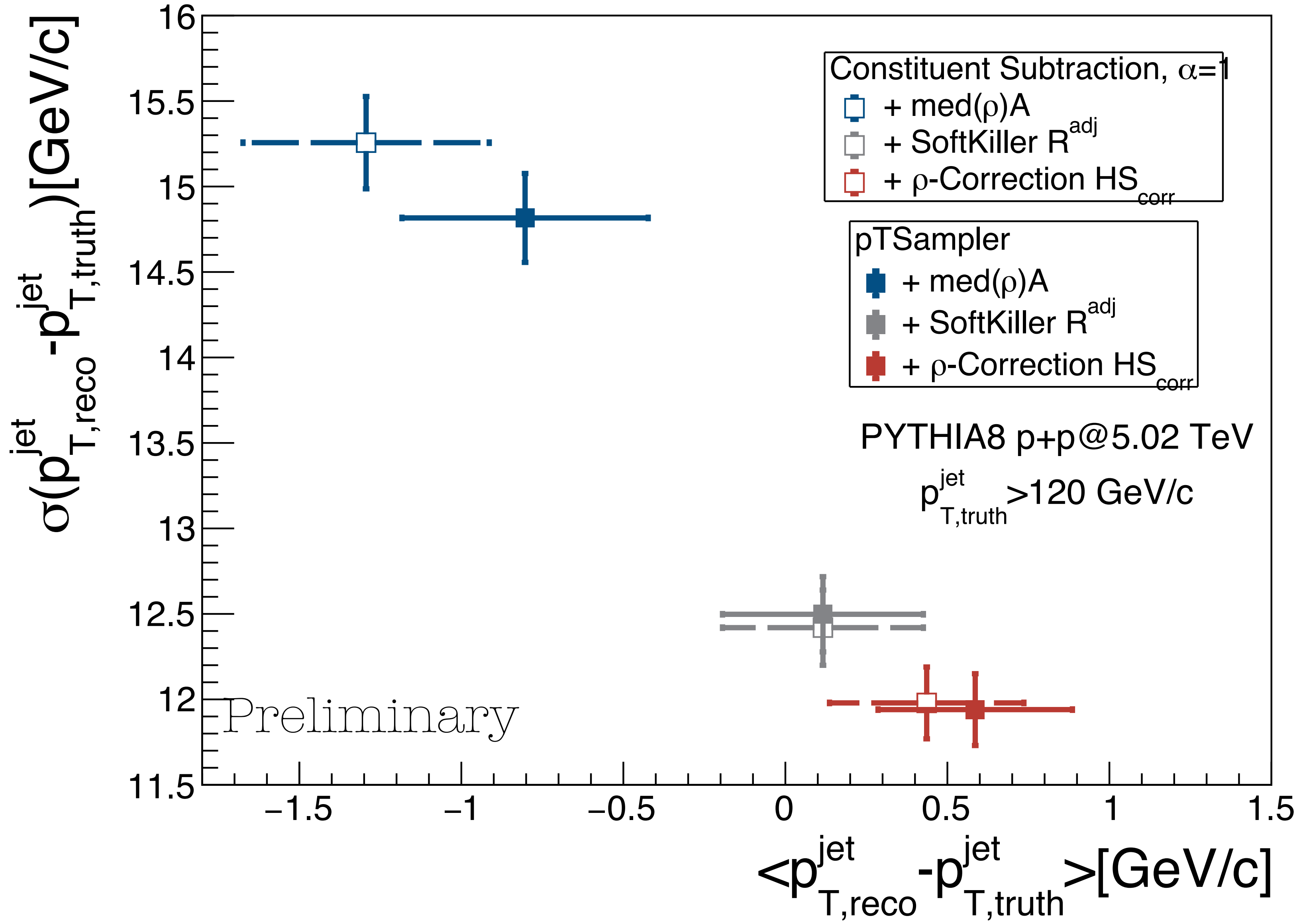
[Mehtar-Tani, ASO, Verweij, In preparation]

1. Cluster all particles (sig+bkg) in the event with anti-k$_T$ R=0.4
2. For each jet, generate 5 cones with $\eta = -\eta_{\text{jet}}, R = 0.4, \phi \in (0,2\pi)$



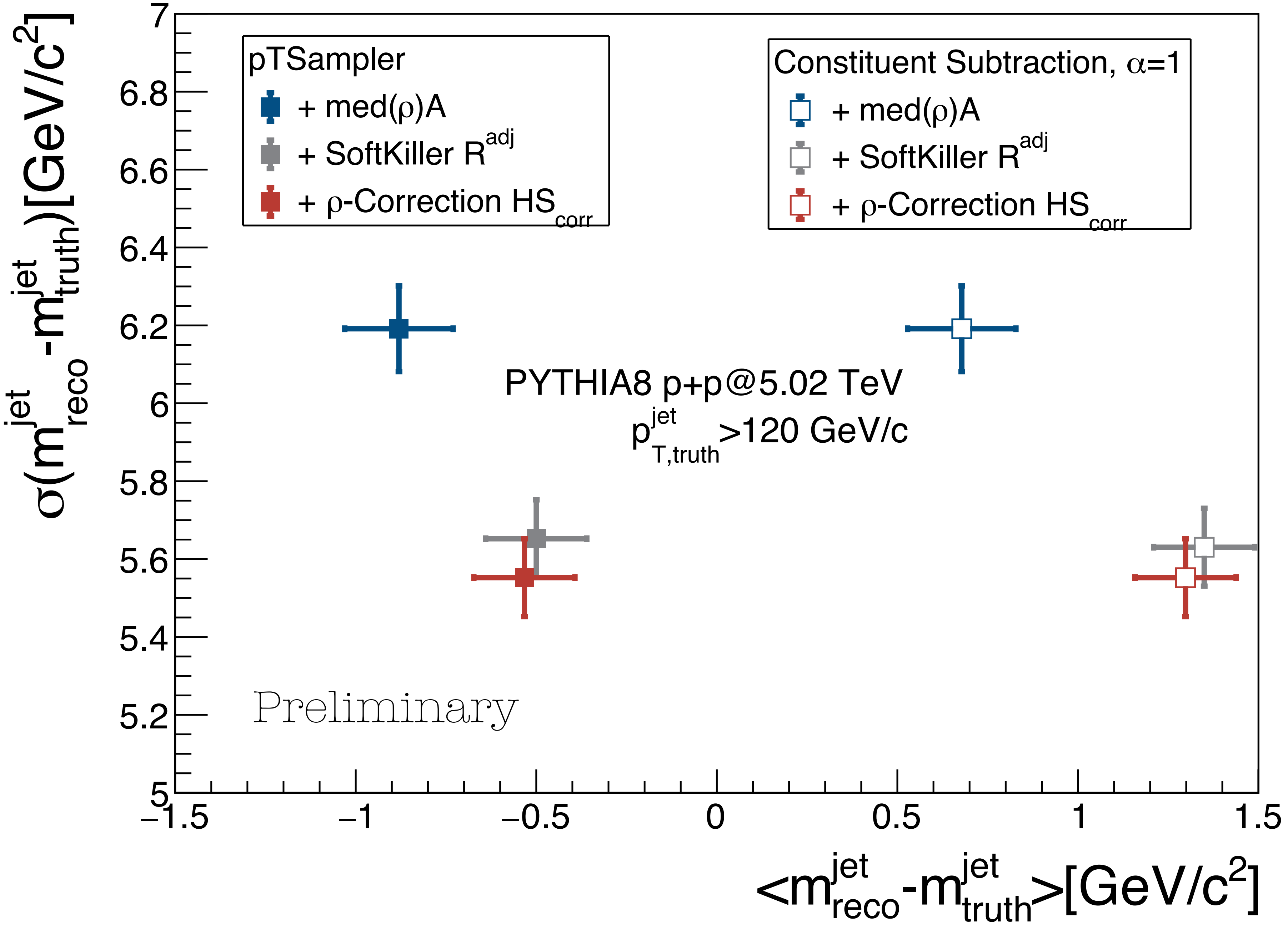
3. For each particle in the jet obtain its $\mathscr{P}(p_i \in \text{bkg})$
4. Sort the list of particles from largest to smallest probability
5. Add particles to the background list until $p_T^{\text{bkg}} > p_{T,\text{est}}^{\text{bkg}}$

pT reconstruction



CS/pTSampler + rhoCorrection results into a 20% improvement on the pT resolution

Mass reconstruction



pTSampler leads to an improvement of ~1GeV on the jet mass response wrt to CS when using rhoCorrection

Wrap-up

- Jets are instrumental both for BSM searches and to bolster our knowledge about in-medium modifications and QGP
- Overwhelming and fluctuation background is a showstopper for precision physics
- Very sophisticated background subtraction methods on the market
- Our goal: obtain similar performance in a simpler fashion thanks to QCD

ρ-correction+pTSampler

Keep tuned and find more on: https://github.com/aontoso/JetToyHI

Soon in FastJet/contrib