Semi-inclusive jet mass measurement in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV with STAR

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2025 Hot-Quarks

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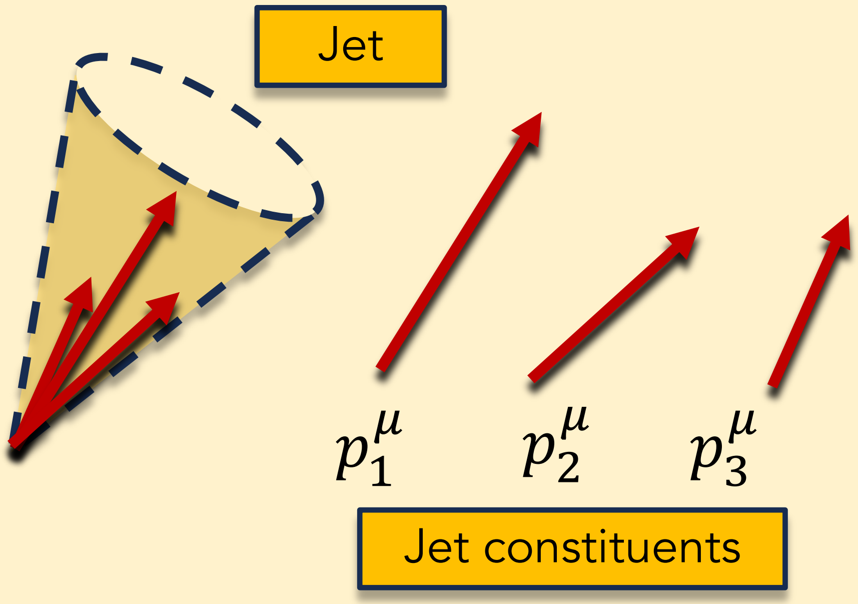
Jet and jet mass (M_{jet})

- Jet
  - Algorithmically clustered final state particles (bunch of stable hadrons)
  - Useful tool to study pQCD in *pp* collisions and properties of QGP in AA collisions
- How to calculate the Jet mass (M_{jet})?
  - $M_{\text{jet}} = |\Sigma_{i\in\text{jet}} p_i| = \sqrt{E^2 - \vec{p}\cdot\vec{p}}$



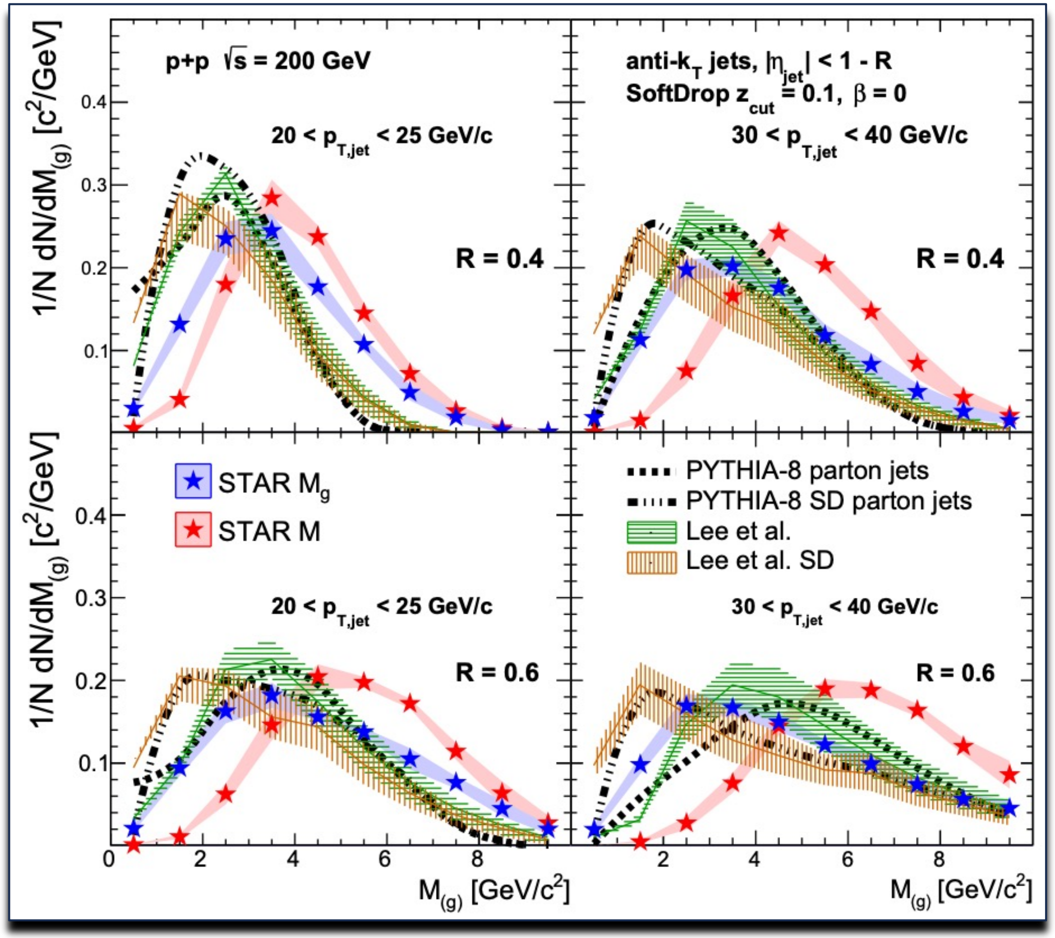
- $\Sigma_{i\in\text{jet}} p_i = p_1^\mu + p_2^\mu + p_3^\mu$
- $M_{\text{jet}} = \sqrt{M_{\text{jet}}^2} = \sqrt{E^2 - \vec{p}\cdot\vec{p}}$

Why do we measure jet mass?

$$\text{• Jet 'invariant mass'} \overset{?}{\longleftrightarrow} \text{➢Substructure}$$

➢Jet mass cross-section

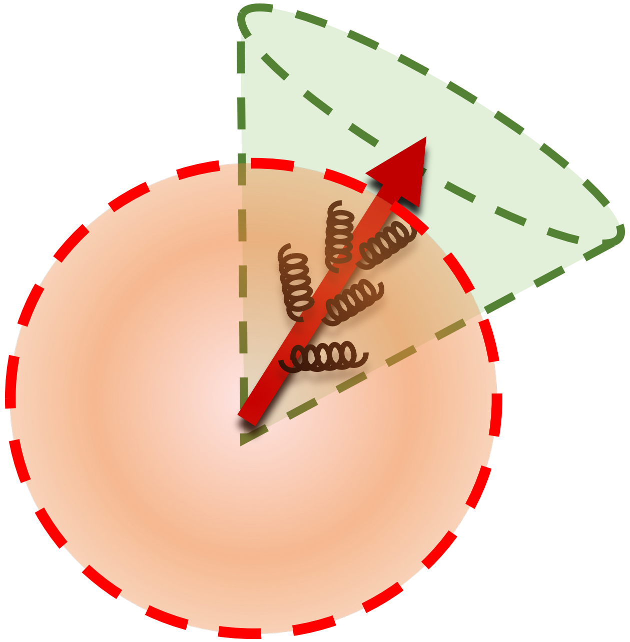
- QCD radiation induces the momentum transfer (~virtuality) to the massless parton
- QCD radiation assigns peak and width to $\sigma(M_{\rm jet})$
- $\sigma(M_{\rm jet})$ contains radiation pattern info in jets



STAR, Phys. Rev. D 104, 052007 (2021)

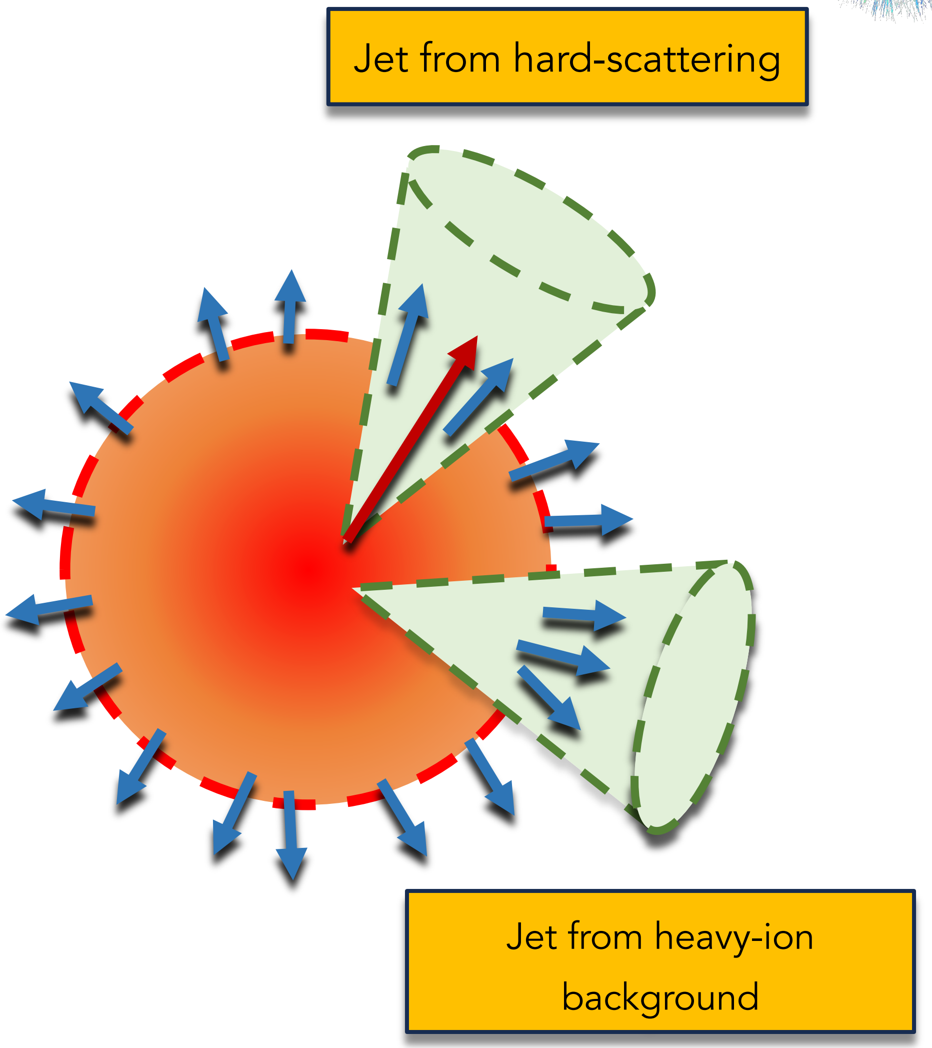
Jet mass in heavy-ion collisions

- The goal of this study
- Measuring M_{jet} in wide $p_{\mathrm{T,jet}}$ range
- Searching modification of final–state radiation pattern in AA
- Searching modification of parton virtuality evolution
  - *pp* : gradually decreased
  - AA : ?



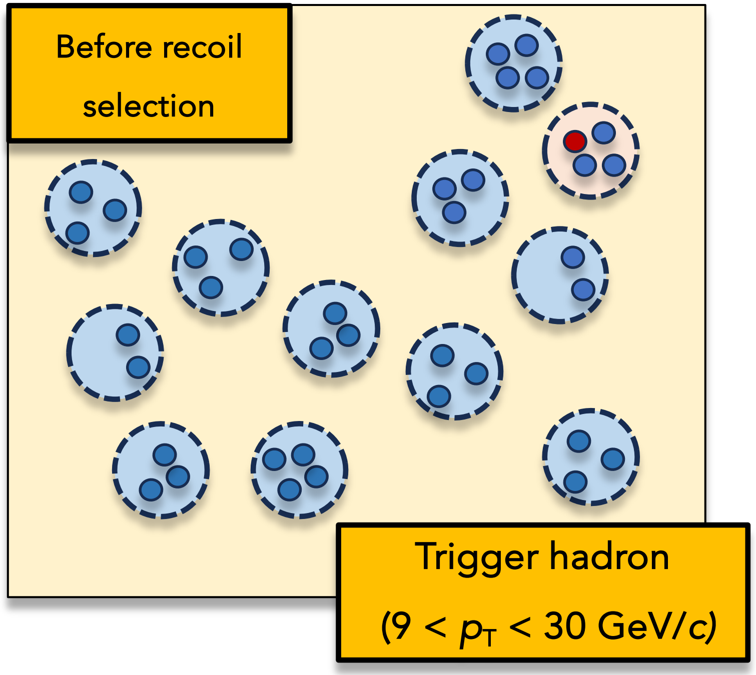
Difficulties of jet measurements in AA

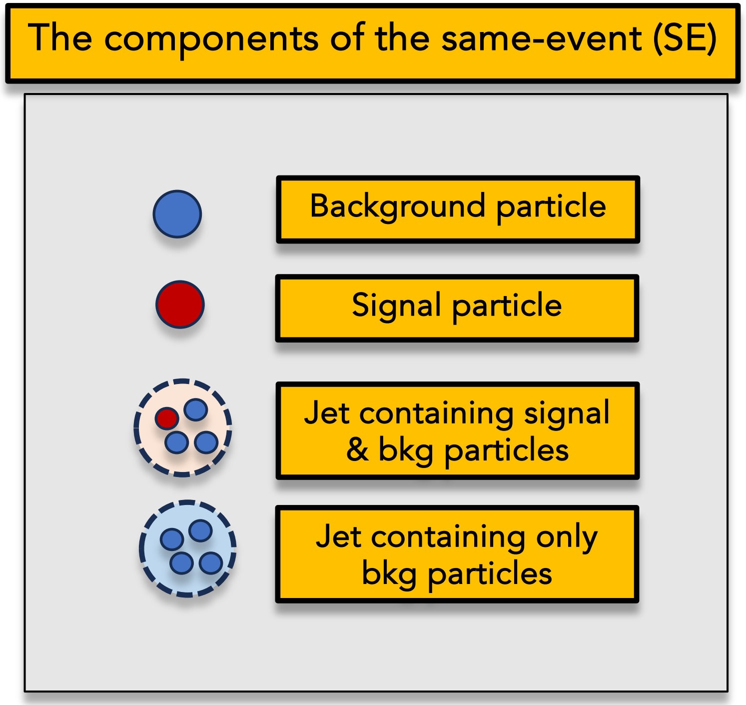
- Combinatorial background
  - Lage background particles uncorrelated with hard scattering are created in AA collisions
  - We cannot clearly distinguish signal jets and background jets on an event-wise basis, especially at low p_T and large R
  - M_{jet} and $p_{T,\mathrm{jet}}$ of signal jets are distorted due to the background particles
- Chellenges
  - **How do we subtract the contribution from background jets?**
  - **How do we correct the distorted signal jets?**



Semi-inclusive recoil jets measurement

➢How do we subtract the contribution from background jets?

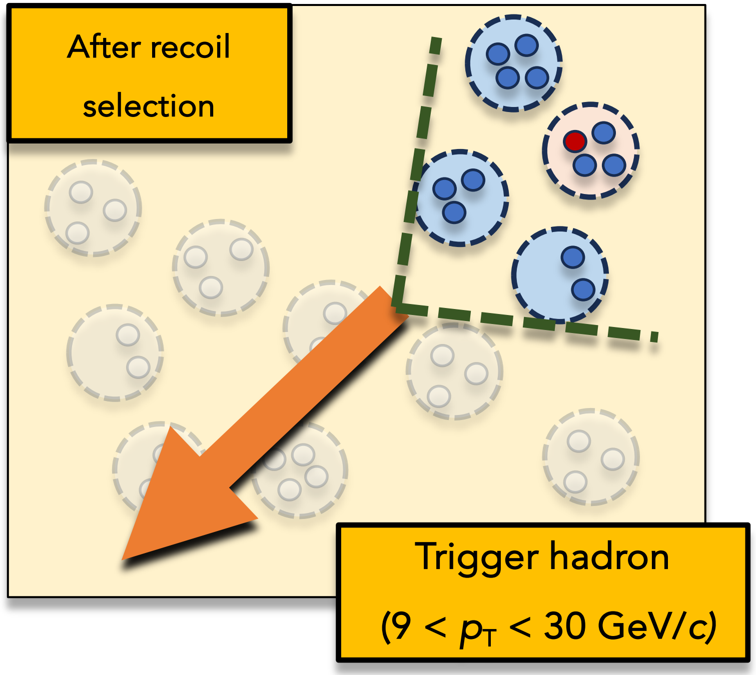


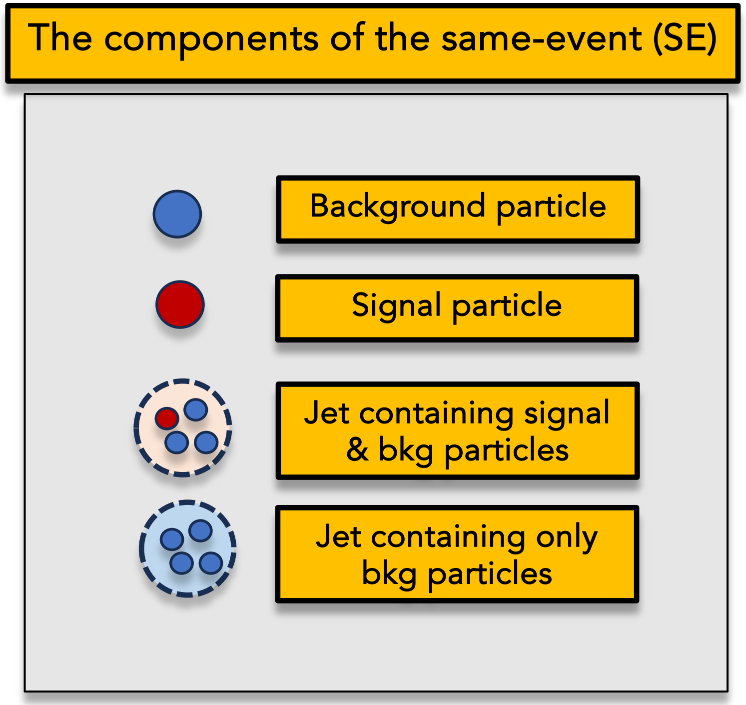


➢ We can't distinguish signal jets and background jets in data

Semi-inclusive recoil jets measurement

➢How do we subtract the contribution from background jets?

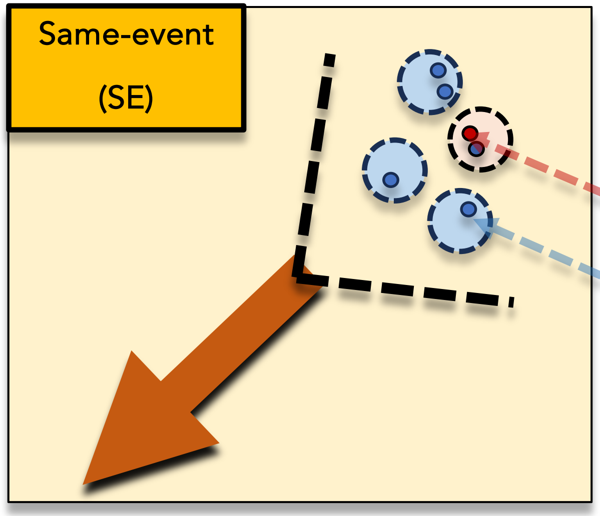




➢ Many of background jets can be easily discarded by selecting recoil-side jets from the hard trigger particle

Mixed-event technique

- Mixed-event technique can further remove the background jets
- **Toy study example :**
  - **Signal : A single high** p_T (15 GeV/c) particle in each event
  - Background : Thermal model
  - **Then,** ($p^{reco}_{T,jet}$) = 15±σ GeV/c



- SE can be decomposed by two parts
  - SE = Smeared signal + bkg
  - We need to subtract bkg in SE

$p^{reco}_{T,jet}$ for example,

- SE = (Smeared signal) + (bkg in SE)
- SE – (bkg in SE) = (Smeared signal)
- But we don't know (bkg in SE)
- Can we make a proxy of (bkg in SE)?
  - Mixed-event (ME) technique

Mixed-event technique

- ➢ Mixed-event technique can further remove the background jets
- ➢ **Toy study example :**
  - **Signal : A single high p_T** (15 GeV/c) particle in each event
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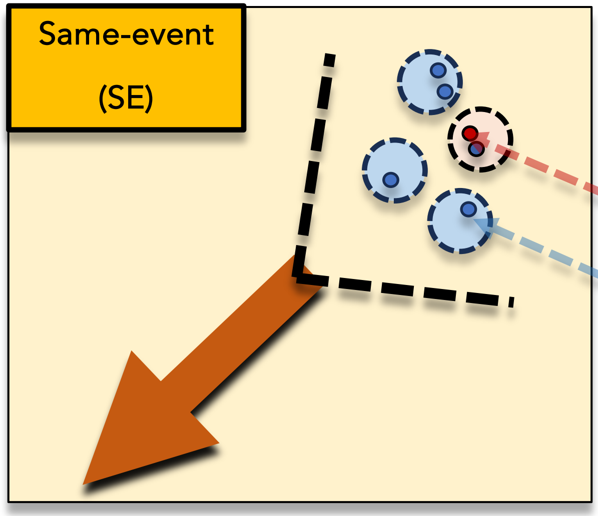

- ➢ SE can be decomposed by two parts
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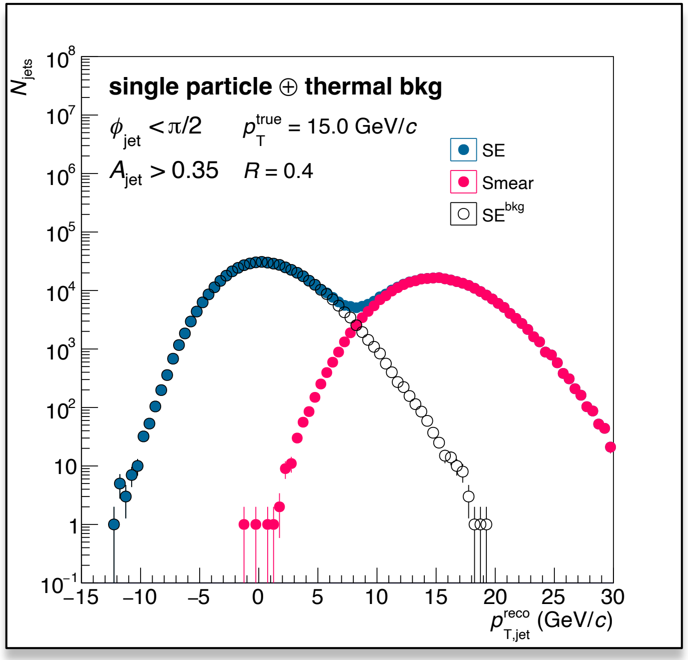
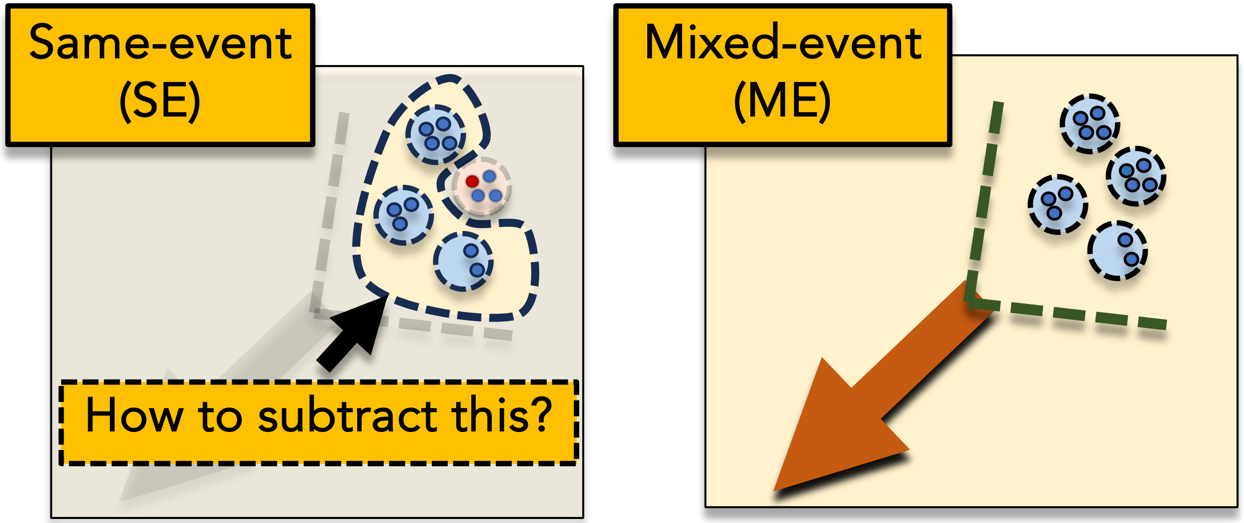
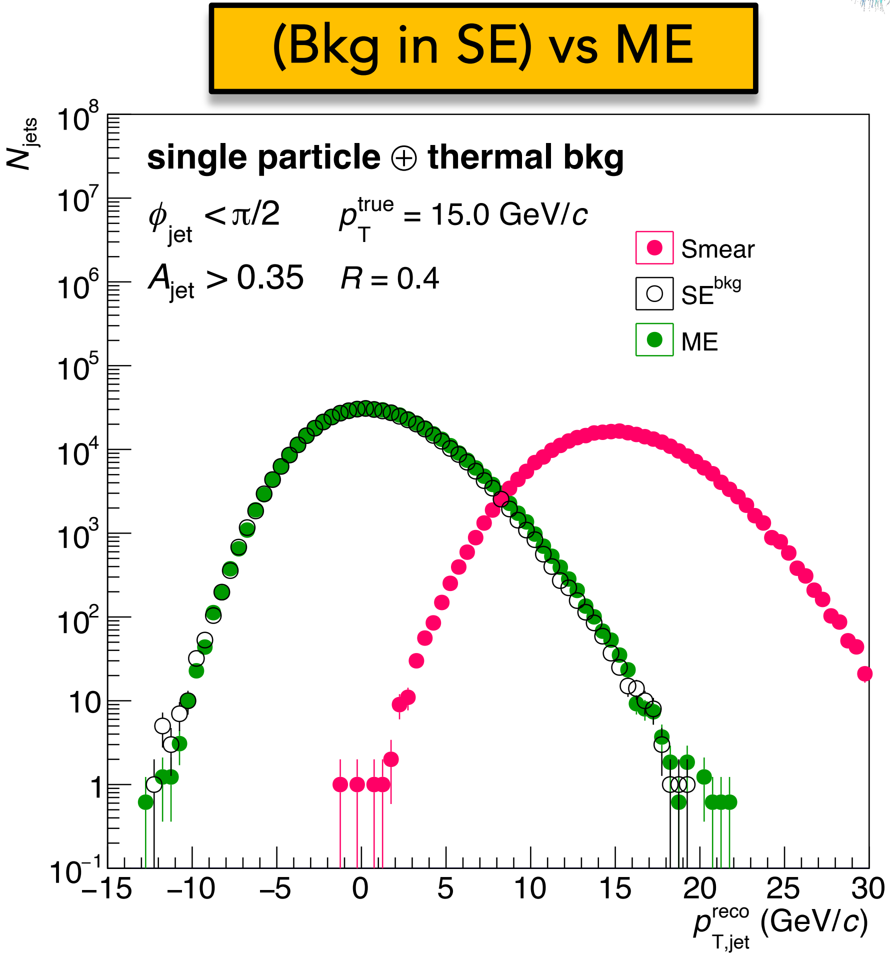
$p^{reco}_{T,jet}$ **for example,**



- ➢ SE = (Smeared signal) + (bkg in SE)
- ➢ SE – (bkg in SE) = (Smeared signal)
- ➢ But we don't know (bkg in SE)
- ➢ Can we make a proxy of (bkg in SE)?
  - **Mixed-event (ME) technique**

Mixed-event technique

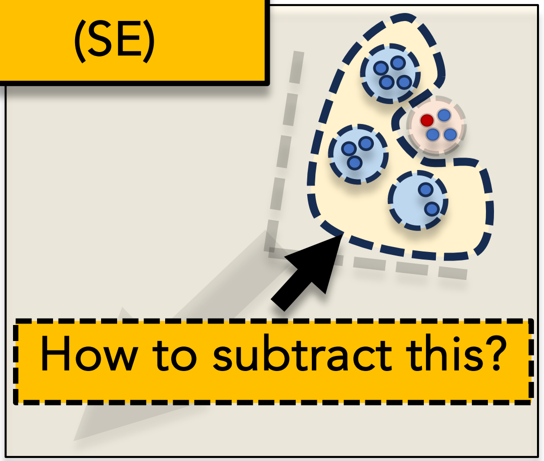




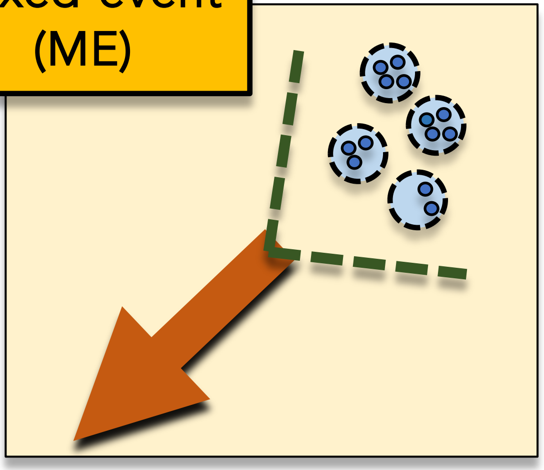
- Mixed-event
  - Synthesizing uncorrelated events from real data events within the same class
  - ME ~ bkg in SE
- Yield corrected spectra (SE-ME)
  - Subtract ME instead of (bkg in SE) in ensembel level
  - SE-ME = (Smeared true) + (bkg in SE) – ME ~ (Smeared true)

Mixed-event technique

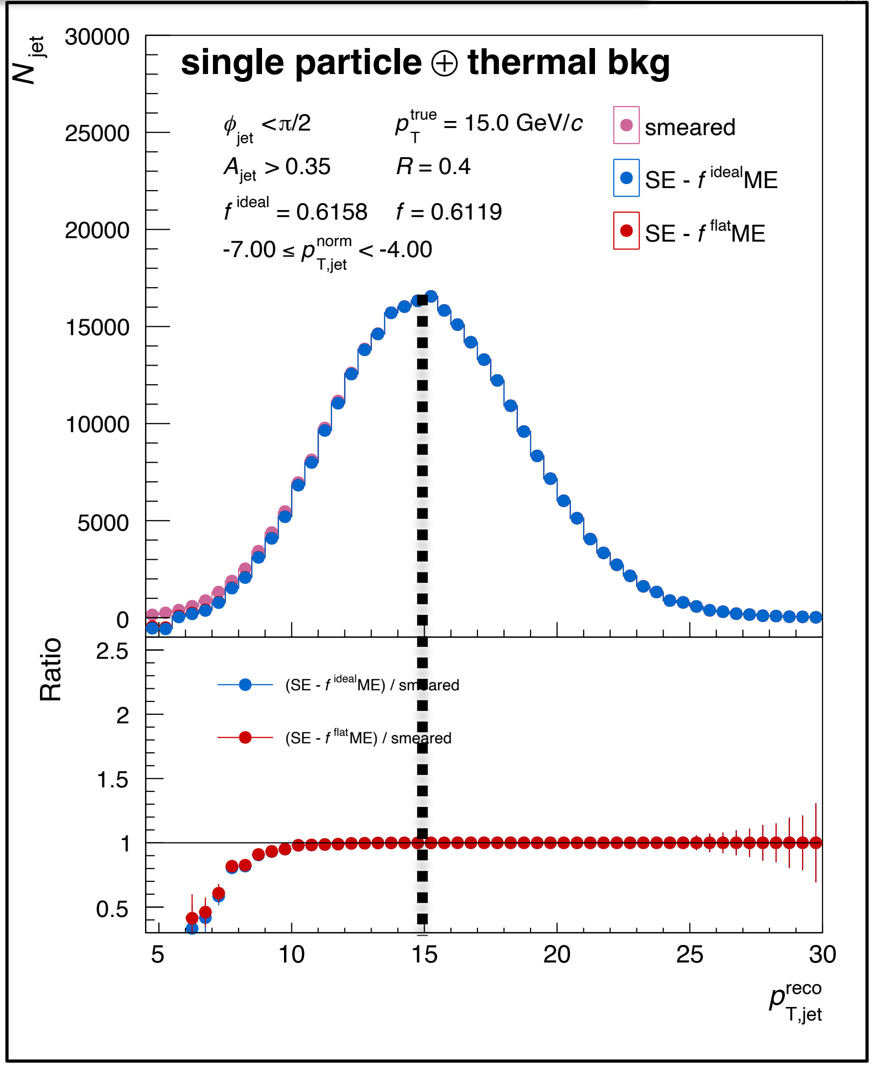
Same-event (SE)



Mixed-event (ME)



(SE-ME) vs Smeared true



- Mixed-event
  - Synthesizing uncorrelated events from real data events within the same class
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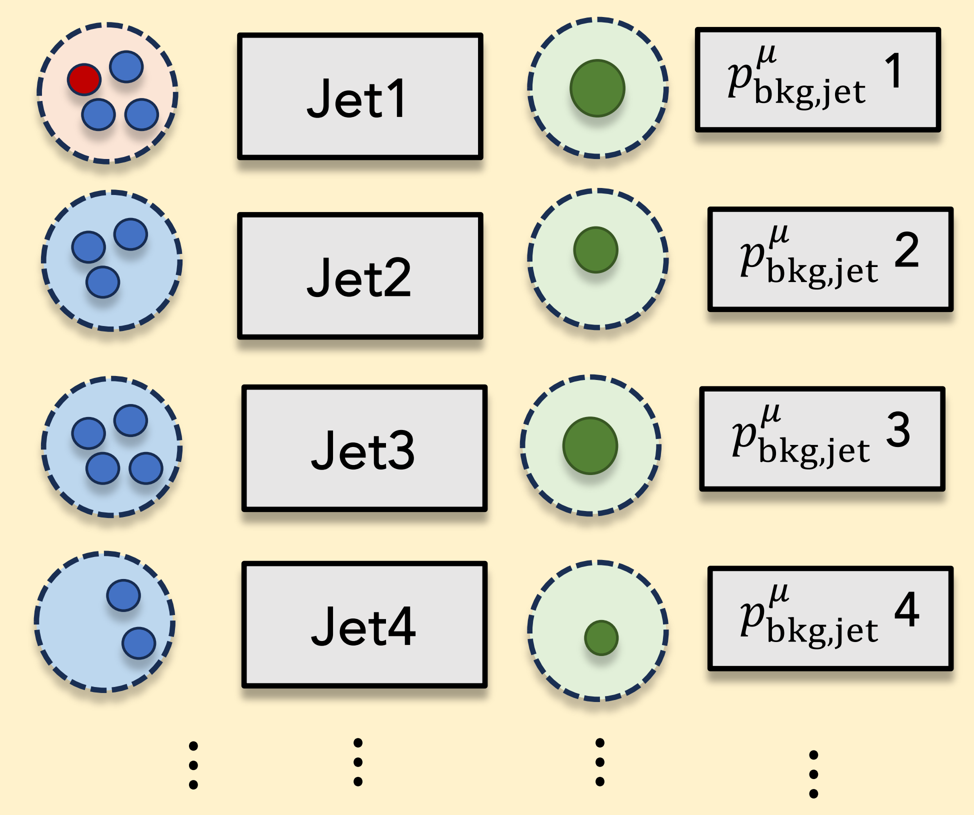
Uncorrelated background effect

➢ How do we correct the distorted signal jets?

Each jet has it's own background jet 4-vector



- Jet reconstruction has been applied in event-by-event
- Proxy of background jet four-vector ($p^{\mu}_{\text{bkg,jet}}$)
  - Calculated by $p_{\text{T,jet}}$ and $m_{\text{T,jet}}$ density (ρ, ρ_m) based on median value estimation
- Reconstructed $p_{\text{T,jet}}$ and M_{jet} ($p^{\text{reco}}_{\text{T,jet}}, M^{\text{reco}}_{\text{jet}}$)
  - $p^{\text{reco}}_{\text{T,jet}} = p^{\text{raw}}_{\text{T,jet}}$ - ($p_{\text{T,jet}}$ of $p^{\mu}_{\text{bkg,jet}}$) = $p^{\text{raw}}_{\text{T,jet}} - \rho A_{\text{jet}}$
  - $M^{\text{reco}}_{\text{jet}} = M^{\text{raw}}_{\text{jet}}$ - (M_{jet} of $p^{\mu}_{\text{bkg,jet}}$) = $M^{\text{raw}}_{\text{jet}} - M_{\text{c}}$ (?)
- Smearing effect (uncorrelated background effect)
  - $M^{\text{reco}}_{\text{jet}} = M^{\text{signal}}_{\text{jet}} \pm \sigma_{M_{\text{jet}}}$
  - $p^{\text{reco}}_{\text{T,jet}} = p^{\text{signal}}_{\text{T,jet}} \pm \sigma_{p_{\text{T}}}$

Uncorrelated background effect

➢ How do we correct the distorted signal jets?

Each jet has it's own background jet 4-vector

- $\rho = \mathrm{median}\left\{\frac{p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\right\}$
- $\rho_m = \mathrm{median}\{\frac{m_{\mathrm{T,jet}} - p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\}$
- $p^{\mu}_{\mathrm{bkg,jet}} = \left((\rho_m + \rho)A_E\,, -\rho A_x\,, -\rho A_y\,, -(\rho + \rho_m)A_z\right)$

➢ Jet reconstruction has been applied in event-by-event

d jet four-vector ($p^{\mu}_{\mathrm{bkg,jet}}$)

$p_{\mathrm{T,jet}}$ and $m_{\mathrm{T,jet}}$ density (ρ, ρ_m) based on stimation

and M_{jet} ($p^{\mathrm{reco}}_{\mathrm{T,jet}}, M^{\mathrm{reco}}_{\mathrm{jet}}$)

$p_{\mathrm{T,jet}}$ of $p^{\mu}_{\mathrm{bkg,jet}}$) = $p^{\mathrm{raw}}_{\mathrm{T,jet}} - \rho A_{\mathrm{jet}}$

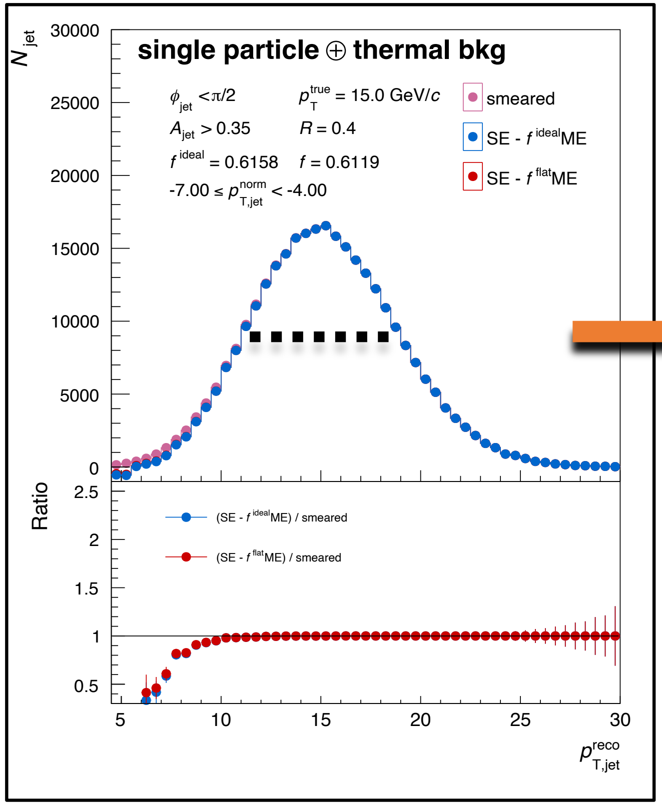
M_{jet} of $p^{\mu}_{\mathrm{bkg,jet}}$) = $M^{\mathrm{raw}}_{\mathrm{jet}} - M_{\mathrm{c}}$ (?)

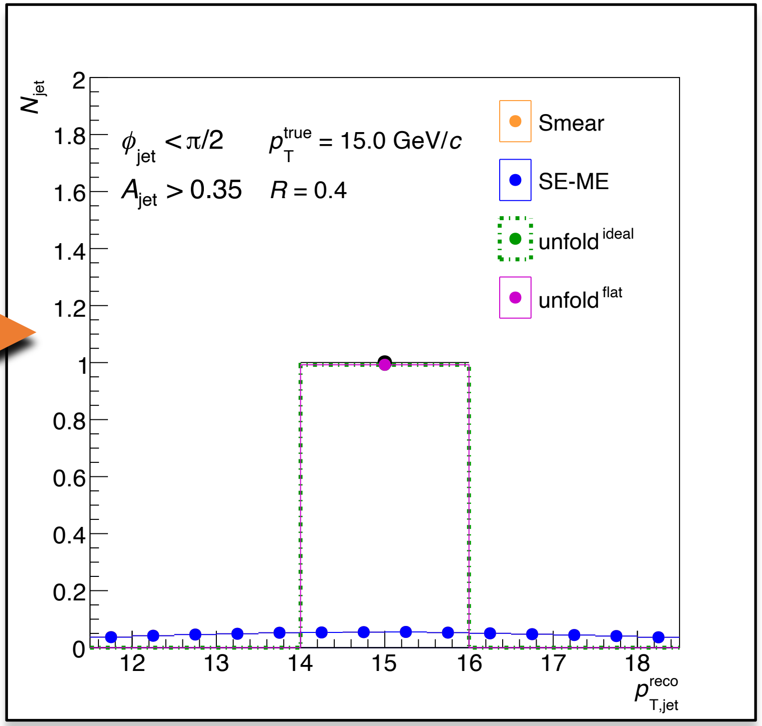
➢ Smearing effect (uncorrelated background effect)

- $M^{\mathrm{reco}}_{\mathrm{jet}} = M^{\mathrm{signal}}_{\mathrm{jet}} \pm \sigma_{M_{\mathrm{jet}}}$
- $p^{\mathrm{reco}}_{\mathrm{T,jet}} = p^{\mathrm{signal}}_{\mathrm{T,jet}} \pm \sigma_{p_{\mathrm{T}}}$

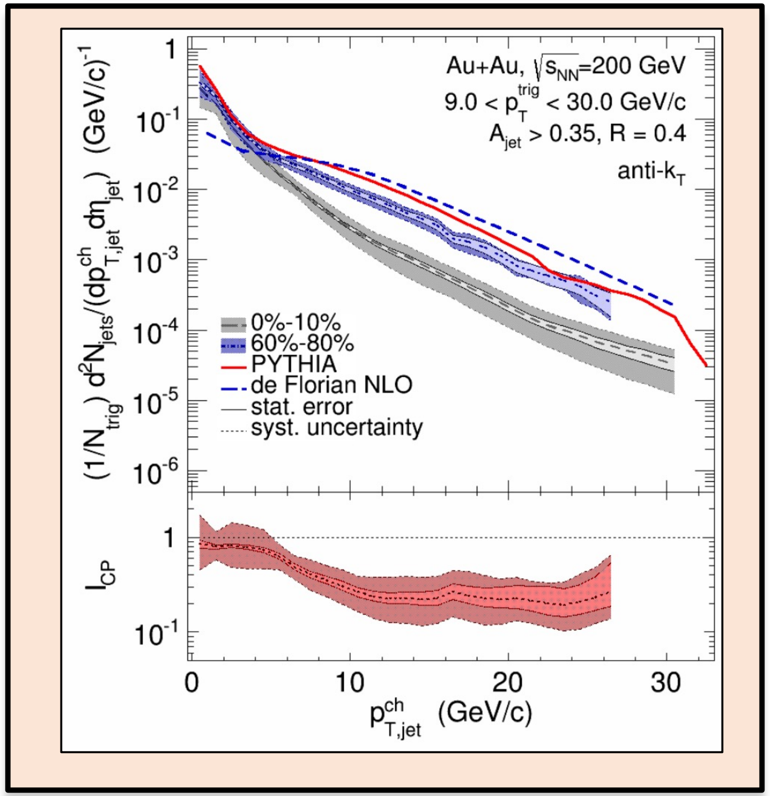
Unfolding

➢How do we correct the distorted signal jets?





Previous $p_{T,jet}$ measurement with this analysis chain



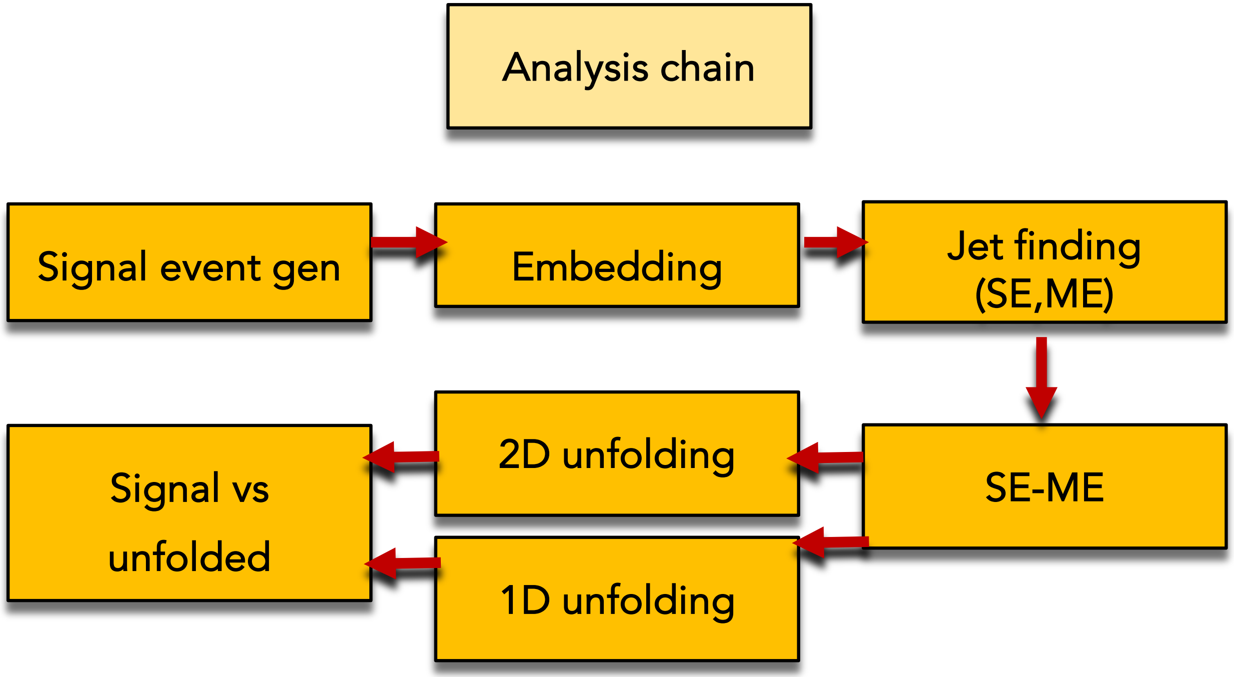
➢ STAR, Phys. Rev. C 96, 024905 (2017)

➢ Correction of uncorrelated background effect using RooUnfold package

➢ Response matrix $R^{\rm bkg}(p_{\rm T,jet}^{\rm reco}, p_{\rm T,jet}^{\rm signal}) = R^{\rm bkg}(p_{\rm T,jet}^{\rm reco}, 15\ {\rm GeV}/c)$

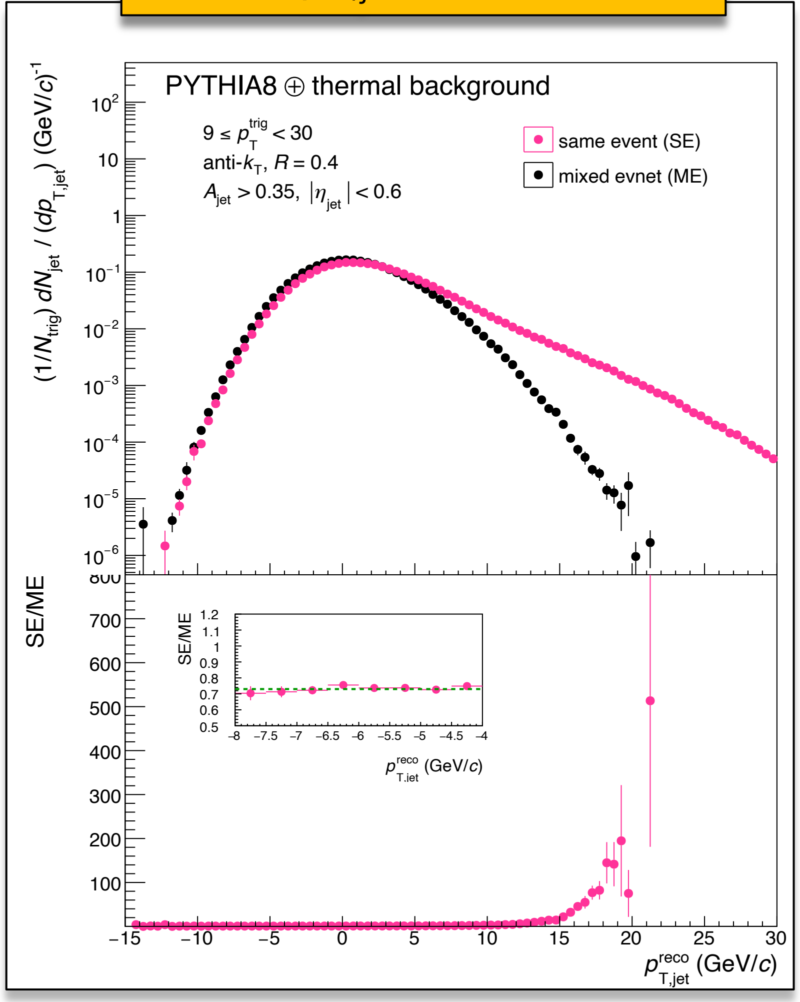
Closure test for ($p_{T,jet}$, M_{jet}) measurement

- Semi-inclusive jet mass measurement with ME technique
  - Extension of previous $p_{T,jet}$ measurement
  - $p_{T,jet}$ to ($p_{T,jet}$, M_{jet}) measurement
- MC closure test
  - PYTHIA events are embedded to thermal background model and tested

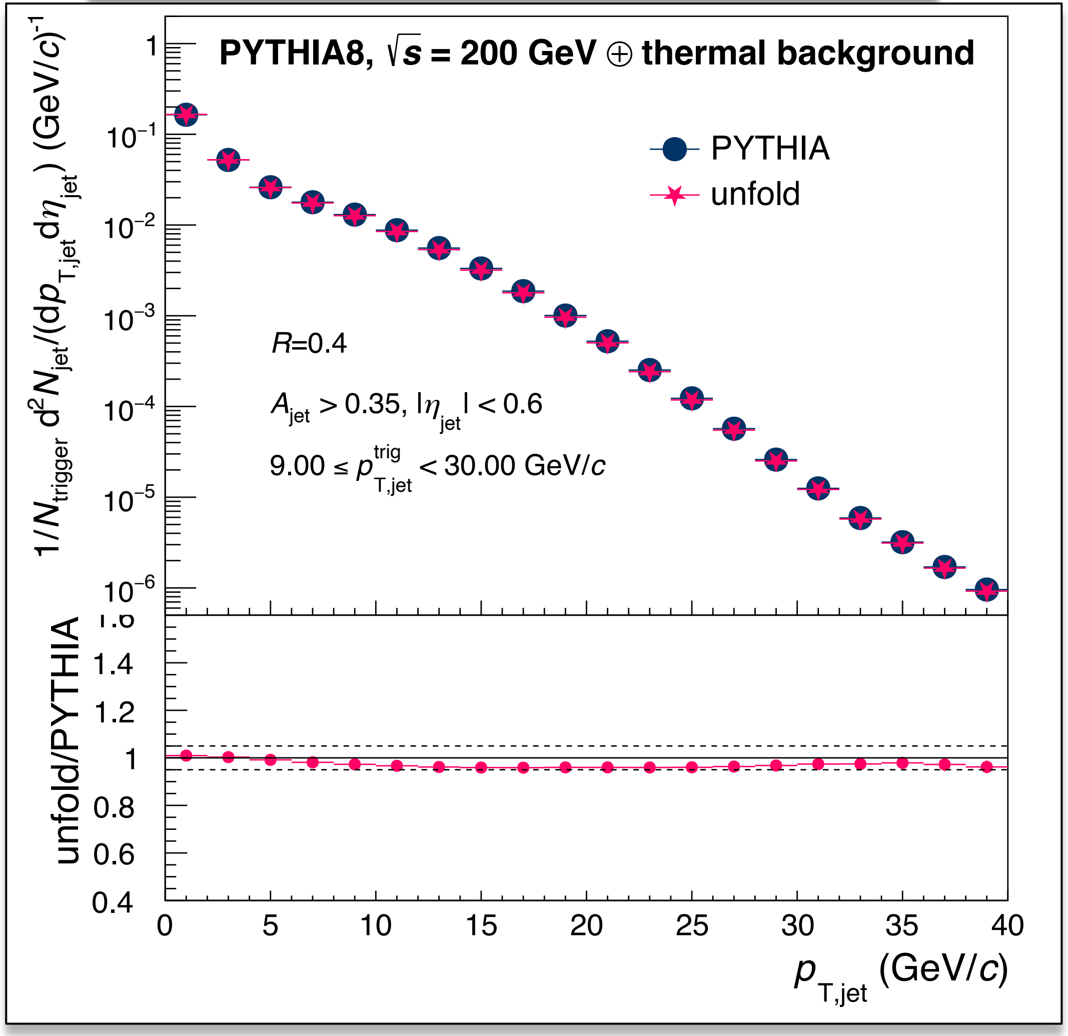


$p_{\mathrm{T,jet}}$ closure test result

➢ Raw $p_{\mathrm{T,jet}}$ distribution



➢ Fully corrected $p_{\mathrm{T,jet}}$ distribution



$p_{\mathrm{T,jet}}$ closure test result

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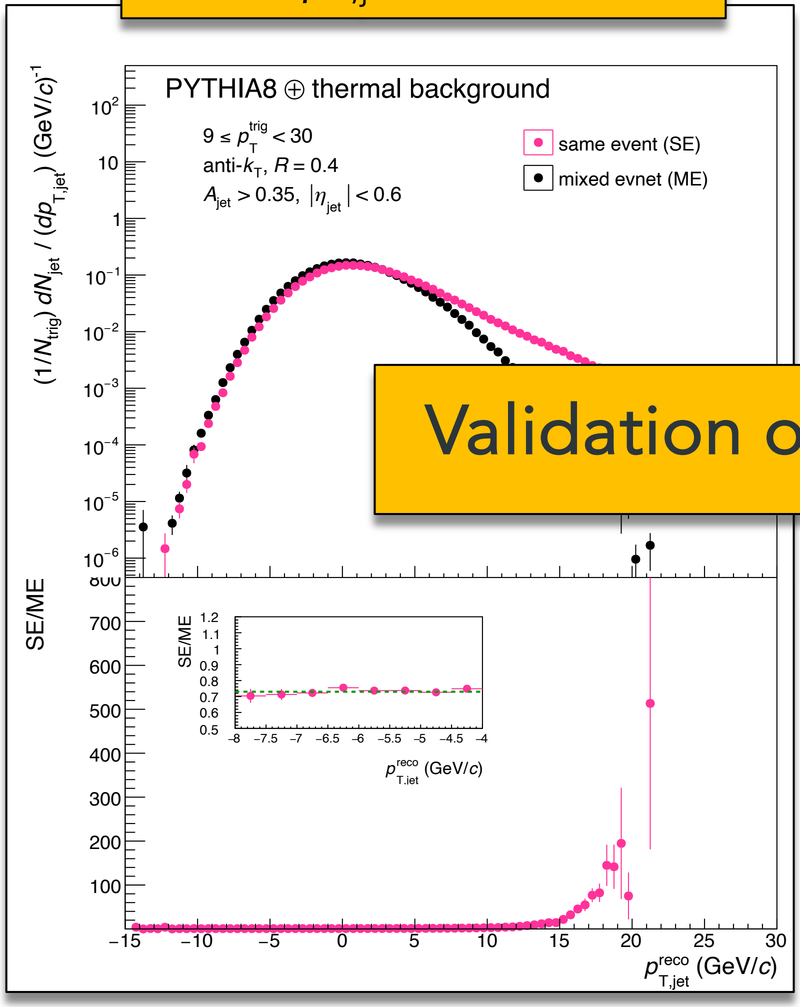

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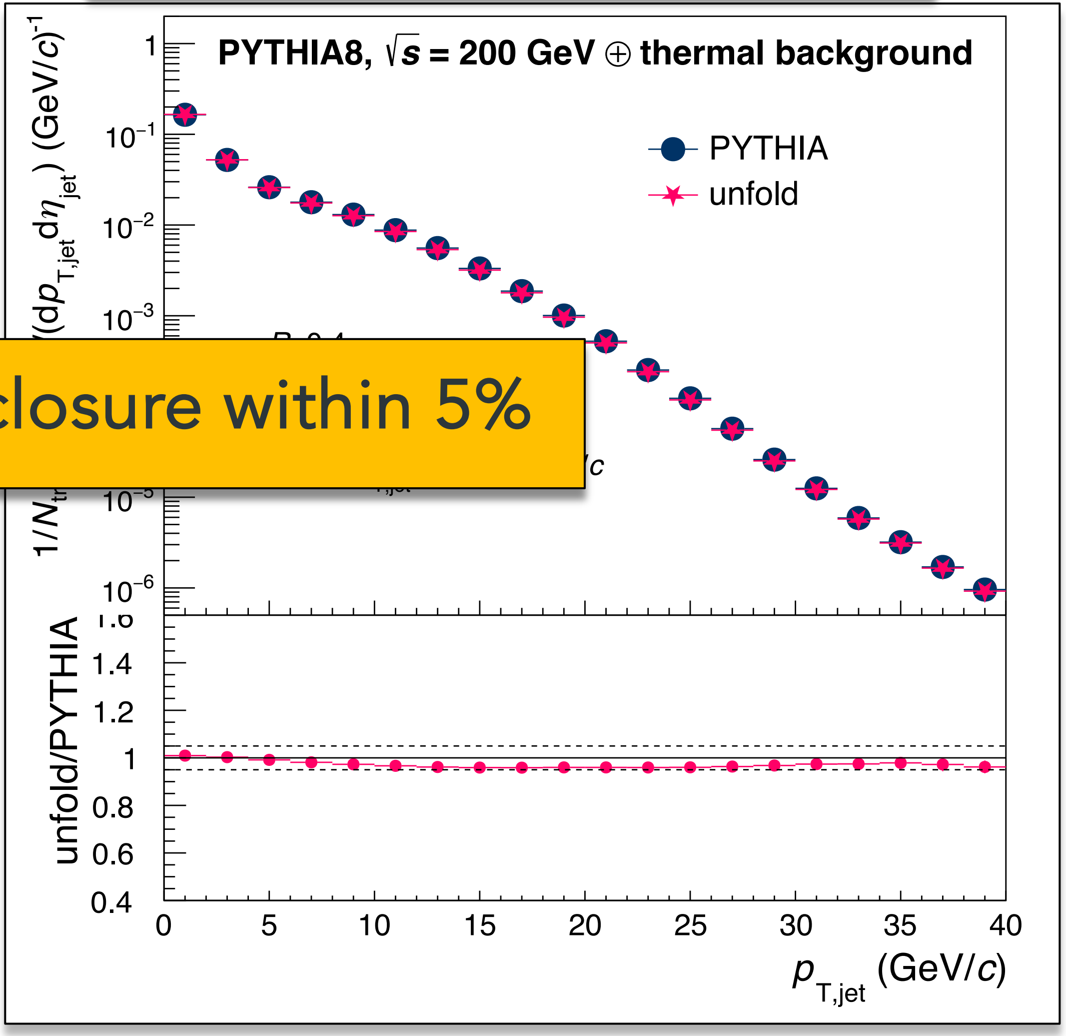
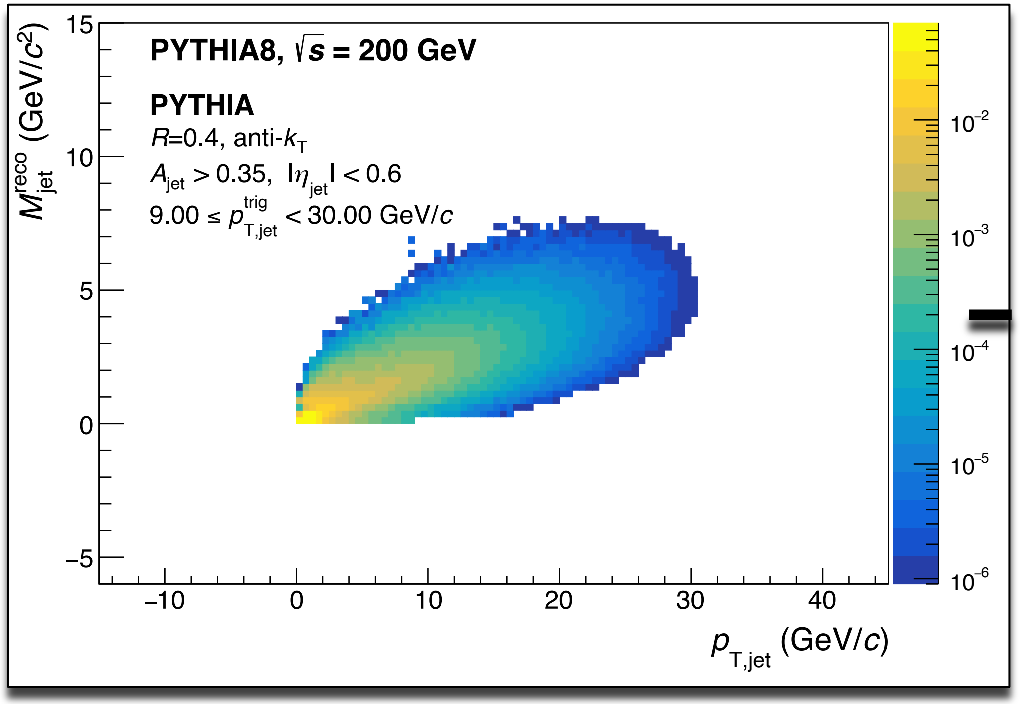


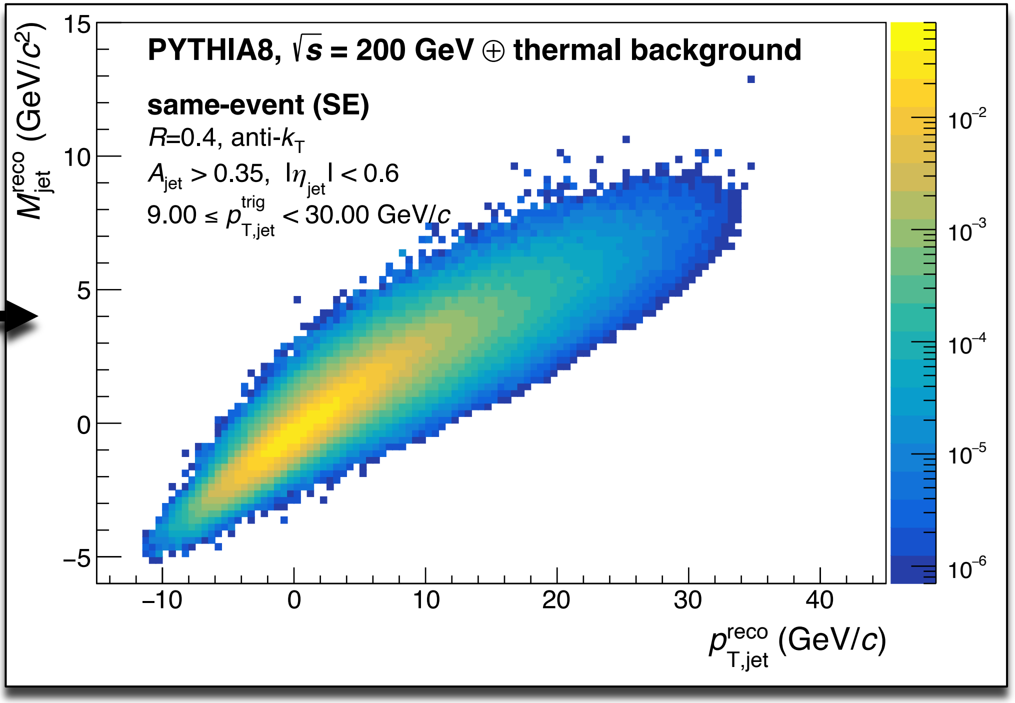
Validation of closure within 5%

M_{jet} Closure test result (PYTHIA and SE)

Signal (PYTHIA)



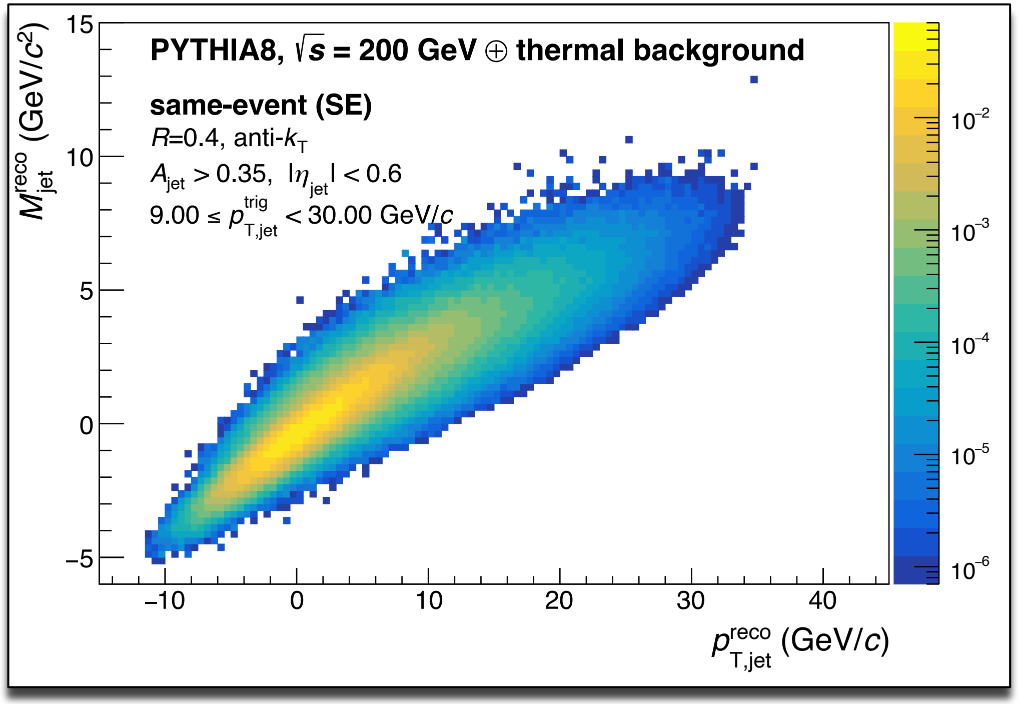
Smeared signal + bkg



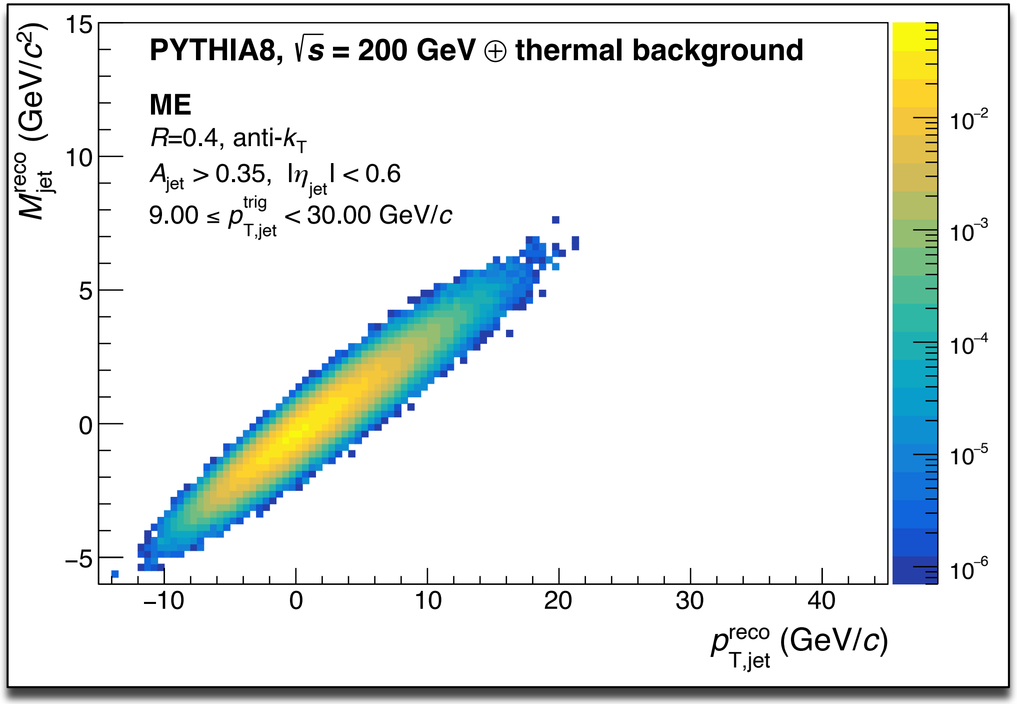
1. Signal distribution (PYTHIA) was distorted by bkg
2. Distorted PYTHIA was hidden in SE
3. SE-ME (subtract bkg in SE)
4. (SE-ME) -> Unfolding -> PYTHIA

M_{jet} Closure test result (SE and ME)

Same-event (Smeared signal + bkg)



Mixed-event (bkg)



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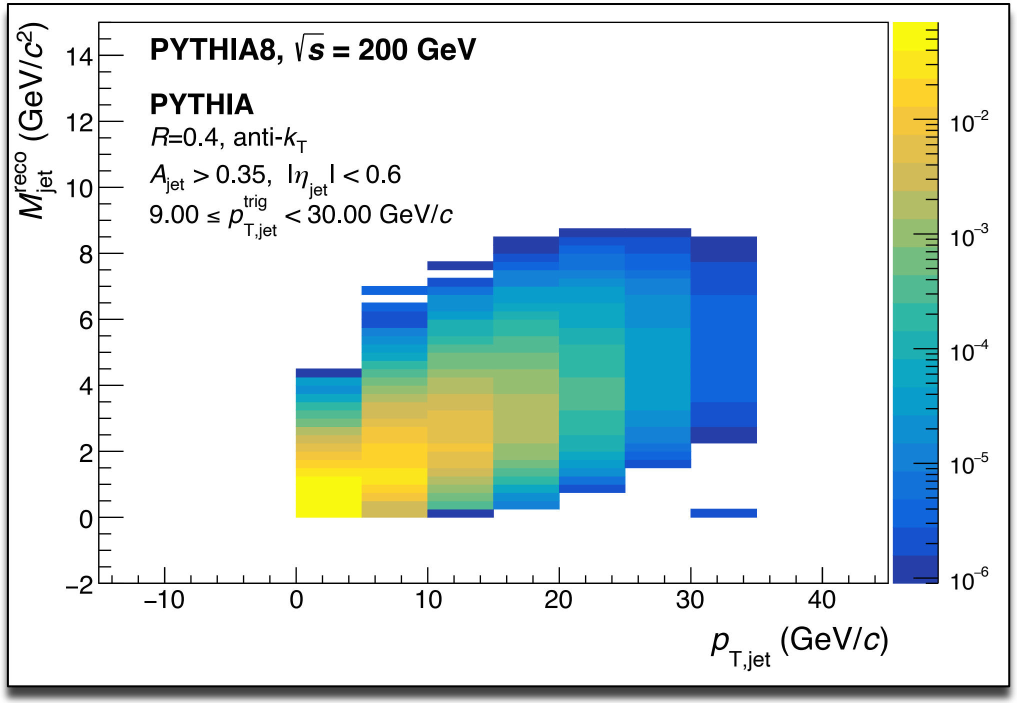
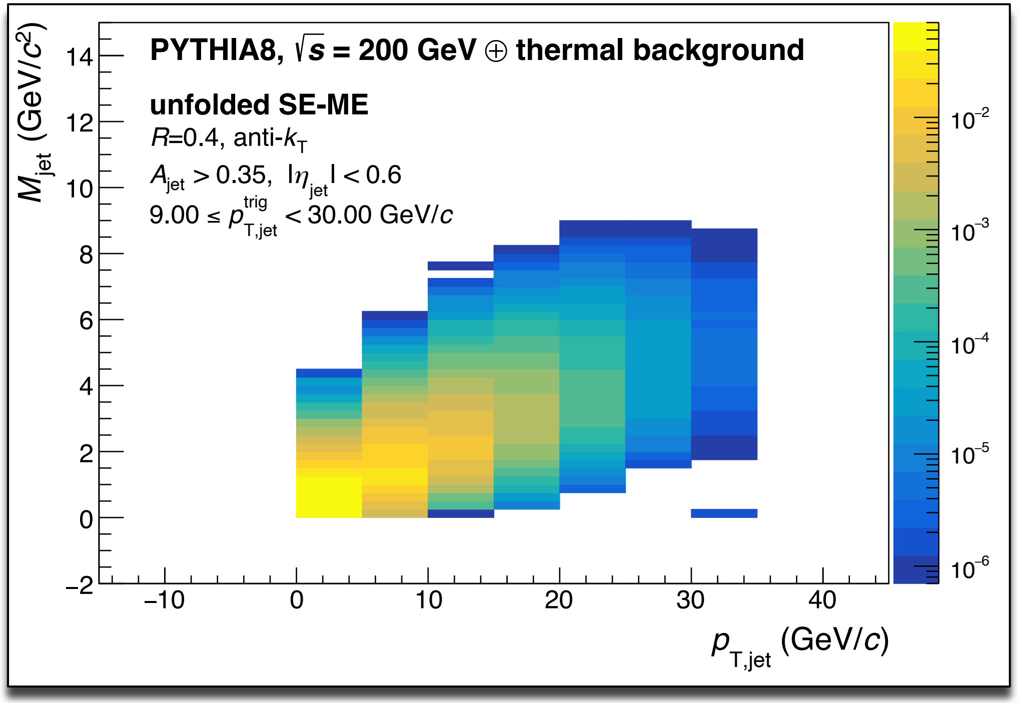
M_{jet} Closure test result (SE-ME and unfolded)

PYTHIA



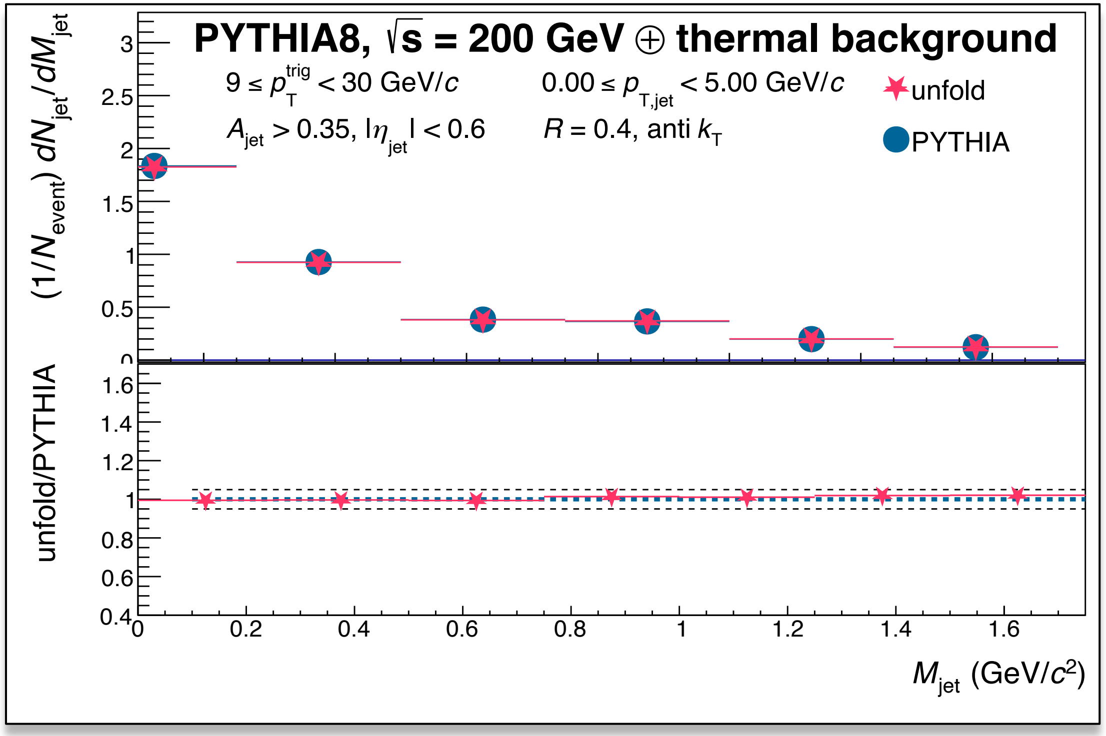
Unfolded



1. Signal distribution (PYTHIA) was distorted by bkg
2. Distorted PYTHIA was hidden in SE
3. SE-ME ~ Smeared PYTHIA
4. (SE-ME) -> Unfolding -> PYTHIA

M_{jet} closure test result (PYTHIA vs unfold)

➢ Fully corrected M_{jet} spectra



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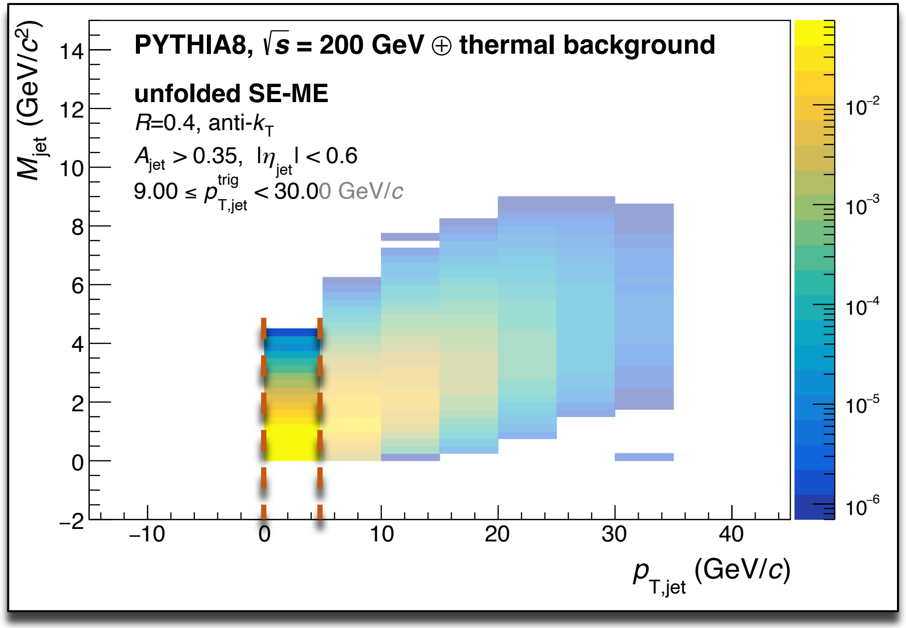
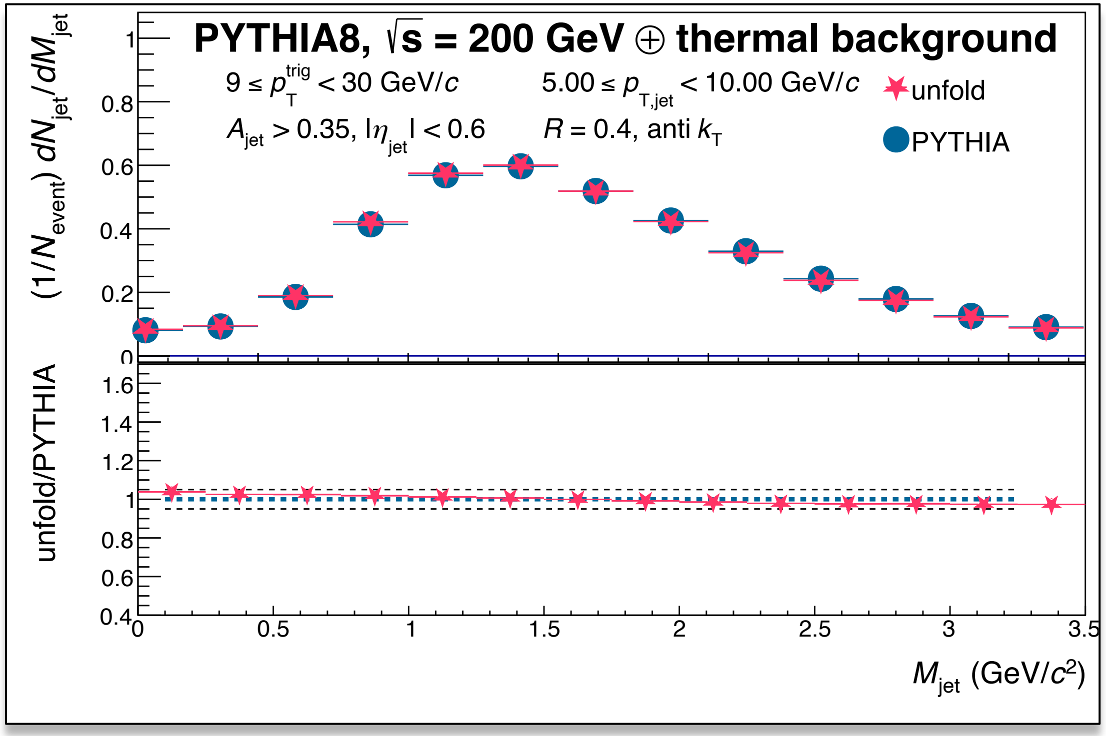


➢ Projection into M_{jet} integrate several $p_{T,jet}$ bin

- [0,5] GeV/c (PYTHIA ~ unfold)
- [5,10] GeV/c (PYTHIA ~ unfold)
- [10,30] GeVc (PYTHIA ~ unfold)

M_{jet} closure test result (PYTHIA vs unfold)

➢ Fully corrected M_{jet} spectra



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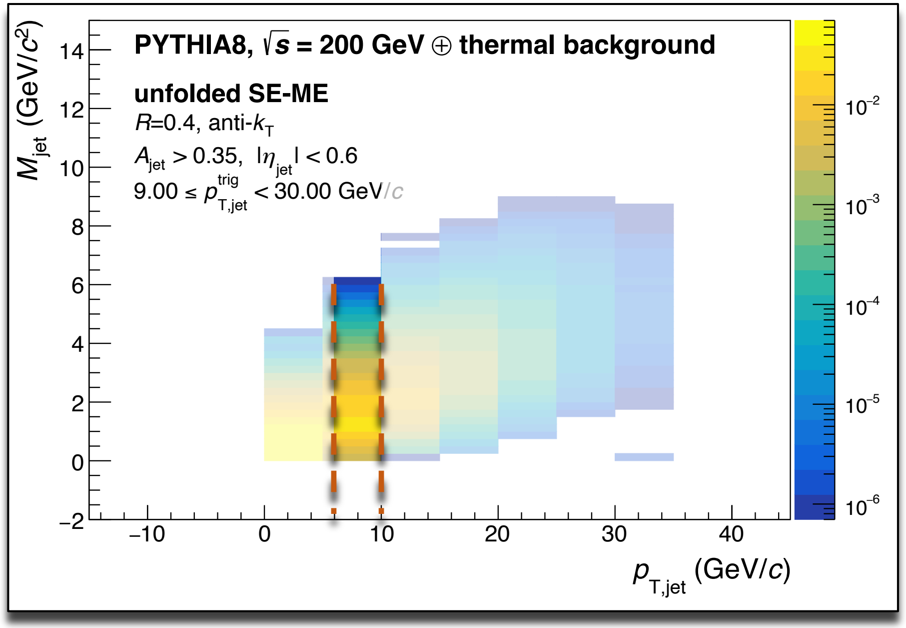

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M_{jet} closure test result (PYTHIA vs unfold)

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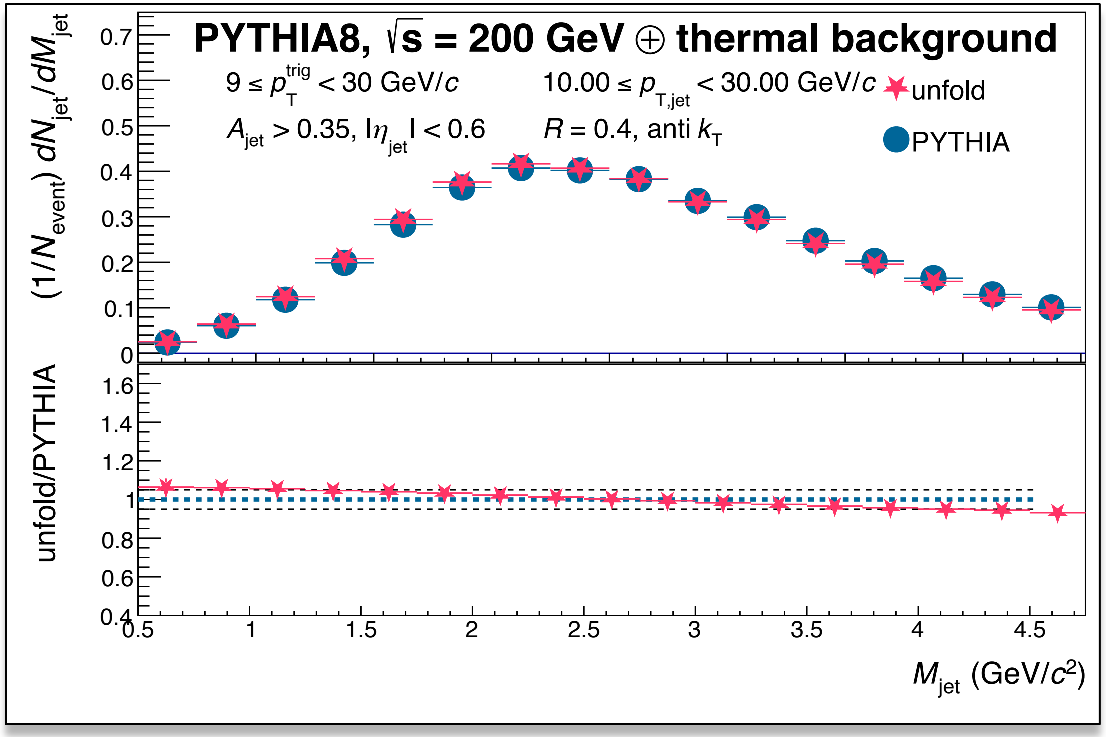

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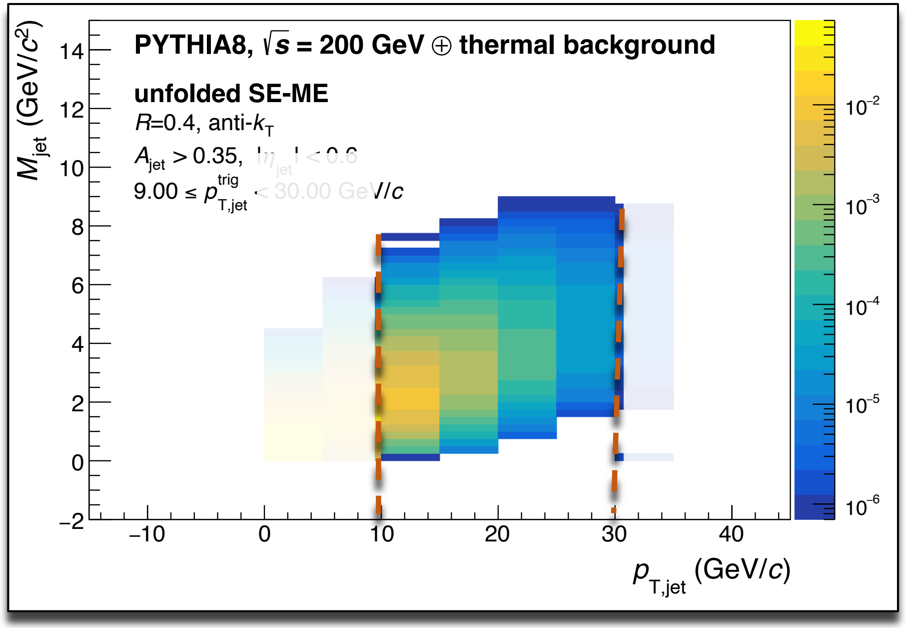

➢ Projection into M_{jet} integrate several $p_{\text{T,jet}}$ bin

- [0,5] GeV/c (PYTHIA ~ unfold)
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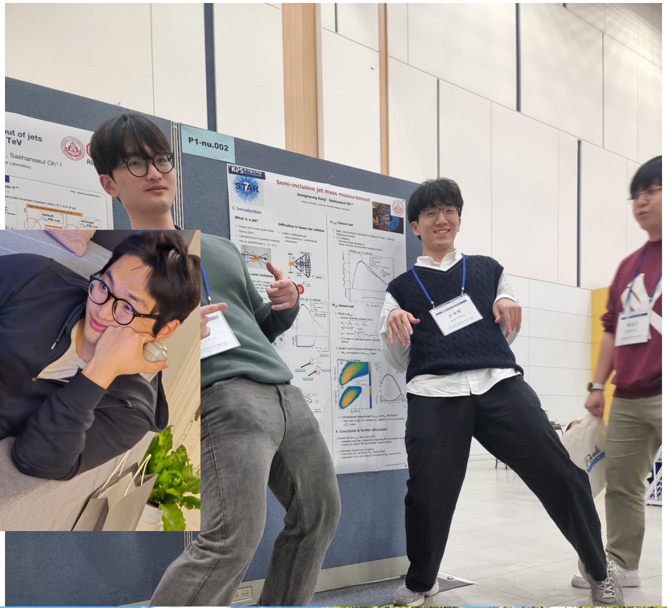
Summary

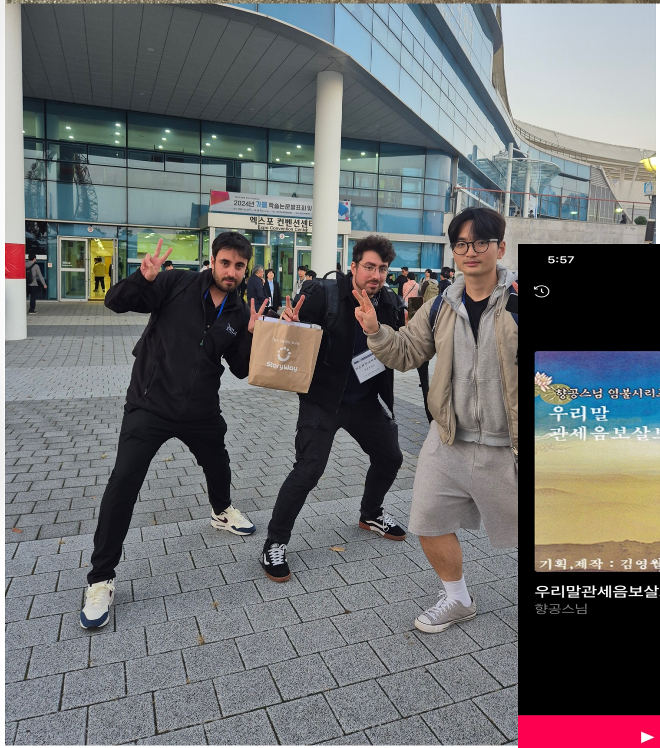
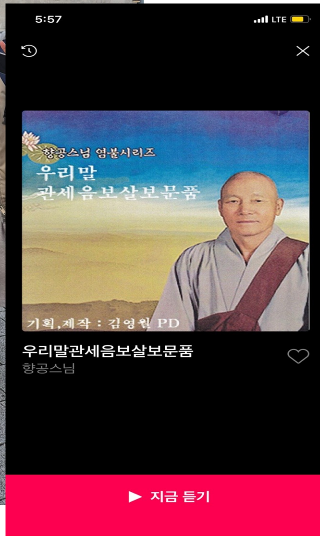
- Jet is a useful tool to study QGP and we can access to the parton virtuality evolution in AA by measuring precise jet mass in heavy-ion collisions
- As a correction of combinatorial background for jet mass measurement, framewrok of semi-inclusive measurement as a function of ($p_{T,jet}$, M_{jet}) is developed and tested via PYTHIA embedding
- Both $p_{T,jet}$, M_{jet} closure tests are showing reasonable closure result
- Next step
  - Apply to the data (200 GeV Au+Au collisions with STAR collaboration)

감사 합니다

thank you





BACK UP

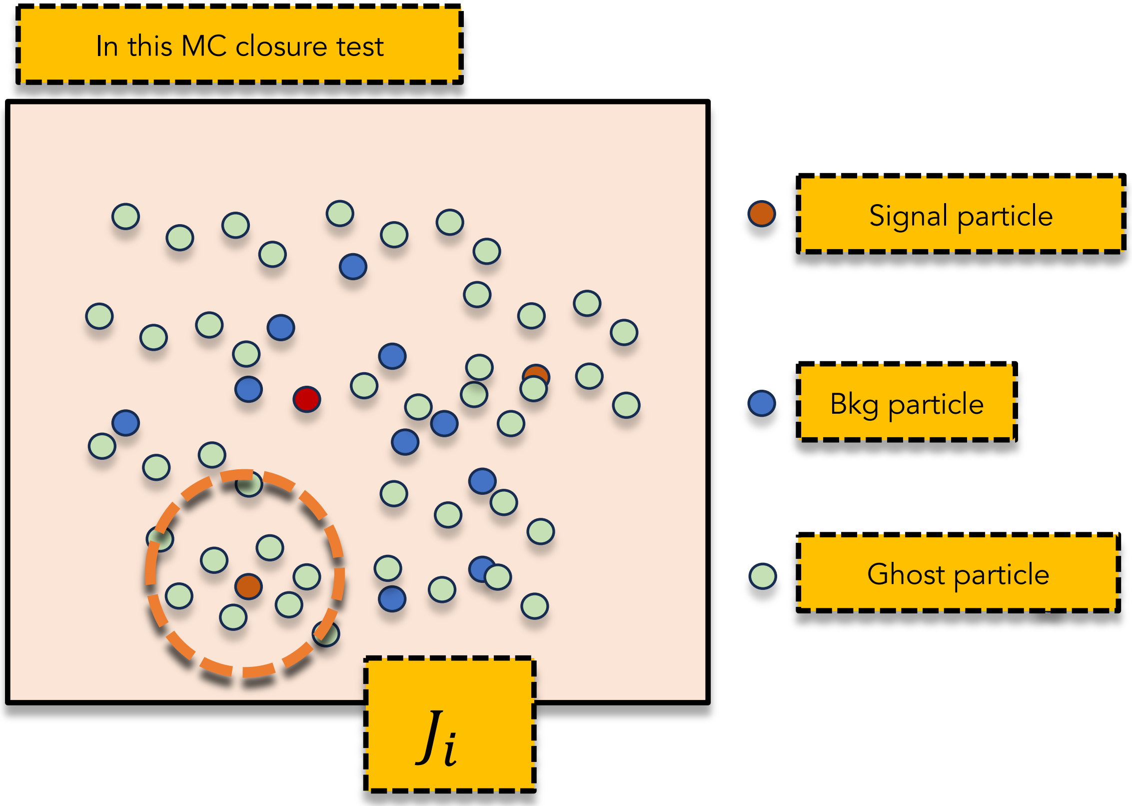
Median density estimation

- Proxy of background jet four-vector $(p^{\mu}_{\mathrm{bkg,jet}})$
  - Calculated by $p_{\mathrm{T,jet}}$ and $m_{\mathrm{T,jet}}$ density (ρ, ρ_m) based on median value estimation
  - $p^{\mu}_{\mathrm{bkg,jet}} = \left((\rho_m + \rho)A_E\, , -\rho A_x\, , -\rho A_y\, , -(\rho + \rho_m)A_z\right)$
  - $\rho = \mathrm{median}\left\{\frac{p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\right\}$
  - $\rho_m = \mathrm{median}\{\frac{m_{\mathrm{T,jet}} - p_{\mathrm{T,jet}}}{A_{\mathrm{jet}}}\}$
  - Jets for density estimation were reconstructed by k_{T} algorithm
  - 3-hardest jets were excluded in same-event (SE)

Jet area

➢ Jet Area

- Let g^{μ} is a 4-vector of infinitesimal soft particle (ghost particle)
- Then the jet area a^{μ} can be defined by
- $a^{\mu}(J) = \int dy d\phi f^{\mu}(g(y,\phi),J)$ (J is a set of constituents in particular jet)
- Where $f^{\mu}(g,J) = \begin{cases} \frac{g^{\mu}}{g_{\mathrm{T}}} & g \in J \\ 0 & g \notin J \end{cases}$
- (where g_{T} is a transverse momentum of ghost particle g)



Jet mass in *pp* collisions

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