Feasibility of jet mass measurements in AA collisions
+
bonus: jet angular structure function

Marta Verweij (Wayne State University)

3rd Heavy Ion Jet Workshop
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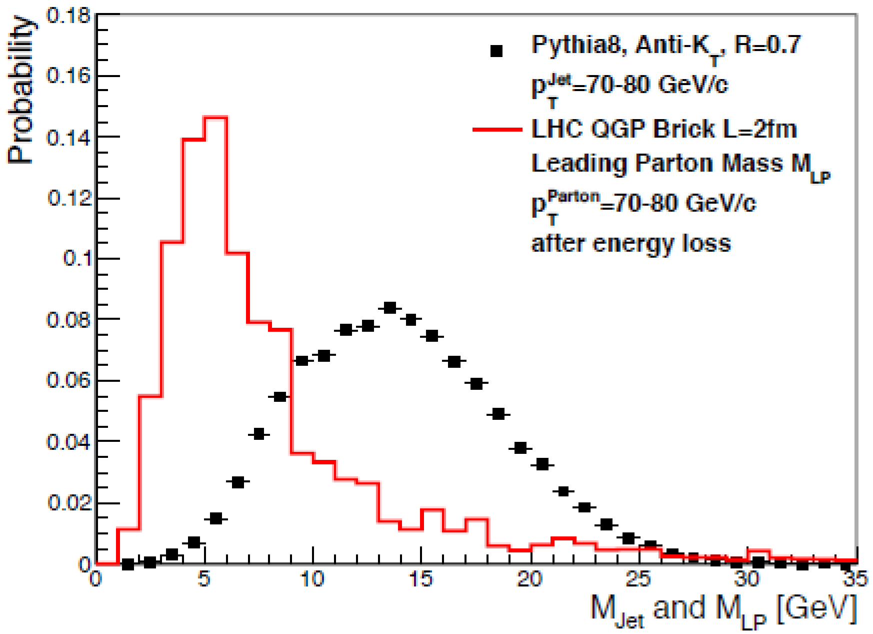
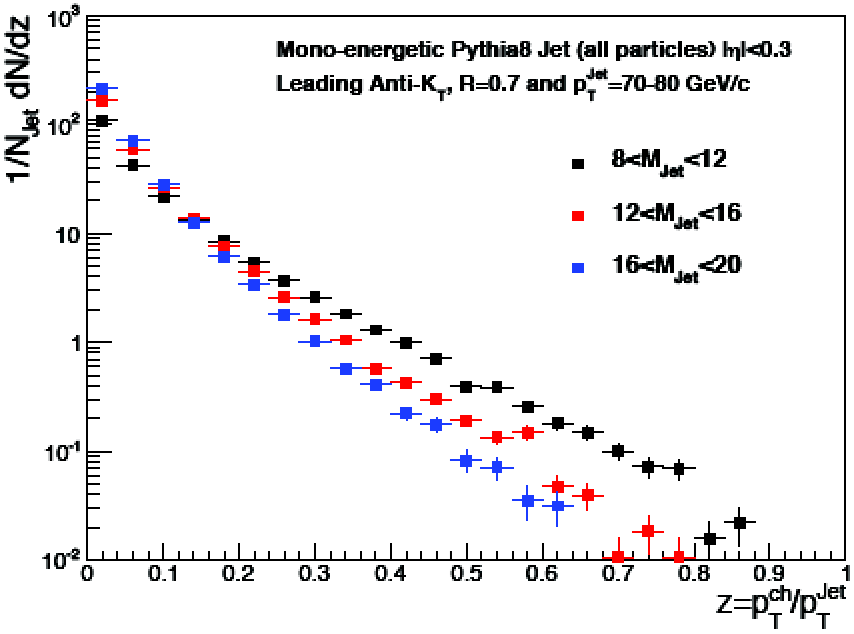
Why measure jet mass in AA?

Abijit Majumder at QM2014

- Reconstructed jet mass has strong correlation to mass of initial parton in PYTHIA → jet mass is measure of virtuality
- In medium: jet looses virtuality faster



Jets loose a lot of mass in the medium

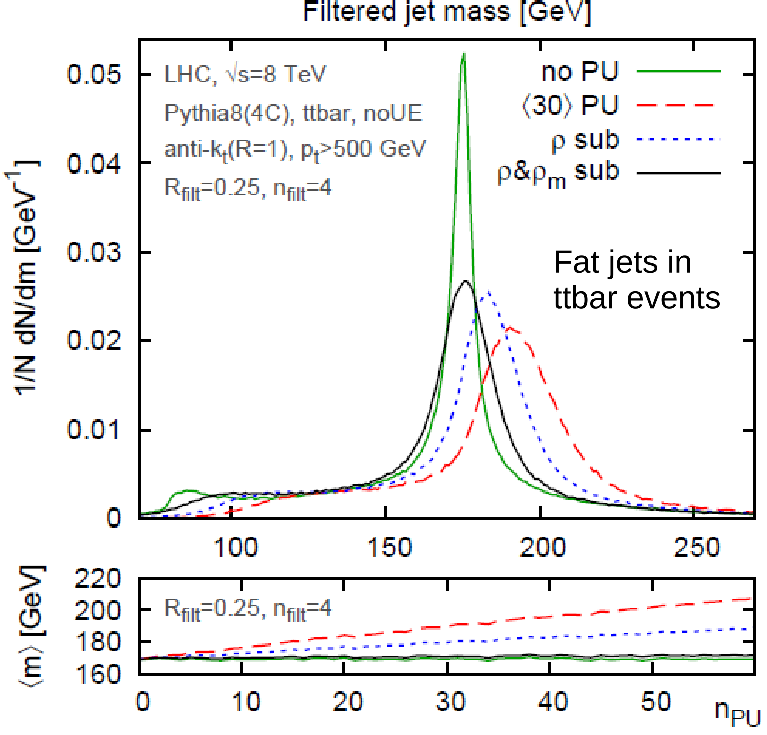


Fragmentation function depends on jet mass

Subtraction methods

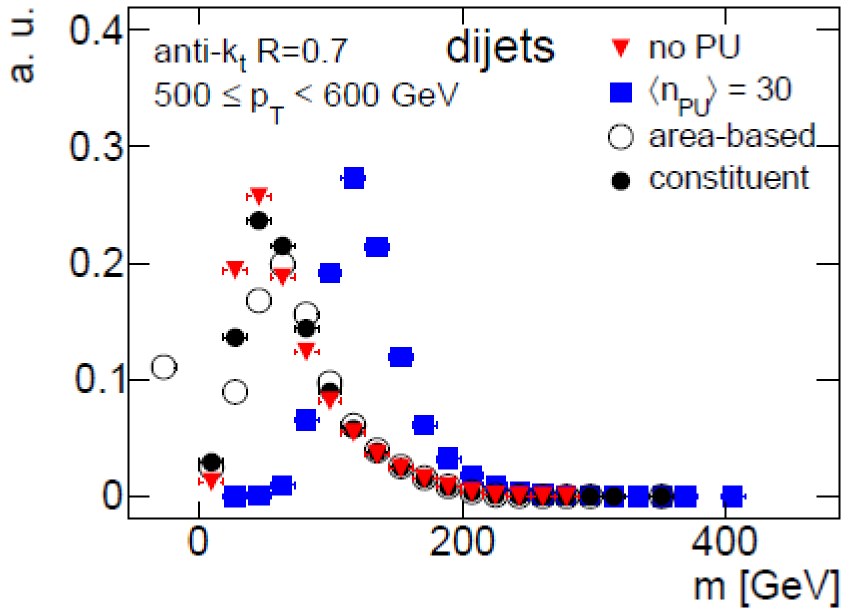
- Explored two subtraction methods. Both available in fastjet contrib package

Jet shape derivative method (area based)



Soyez et al
arXiv:1211:2811

Constituent subtractor



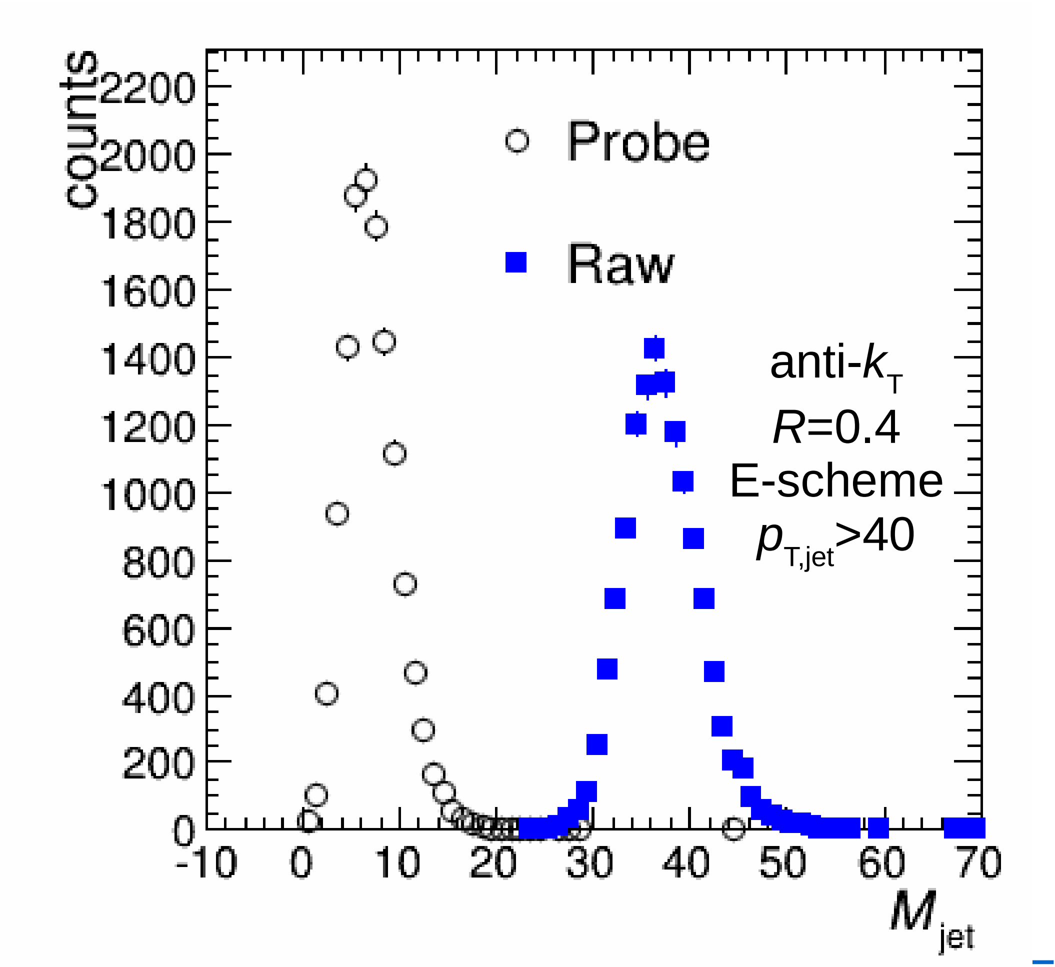
Berta et al
arXiv:1403.3108

- Shown figures for clean jet samples. Influence of fakes in AA?

Jet mass in AA background

- PYTHIA jets embedded into thermal background:
  - Background multiplicity = 2200 and $\langle p_{\mathrm{T,particle}} \rangle$=670 MeV/c
- Jet mass: mass of anti-k_{T} jet 4-vectors using E-scheme

Large shift of jet mass due to underlying background particles



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- Jet mass: mass of anti-k_{T} jet 4-vectors using E-scheme
- Background densities estimated from k_{T} clusters

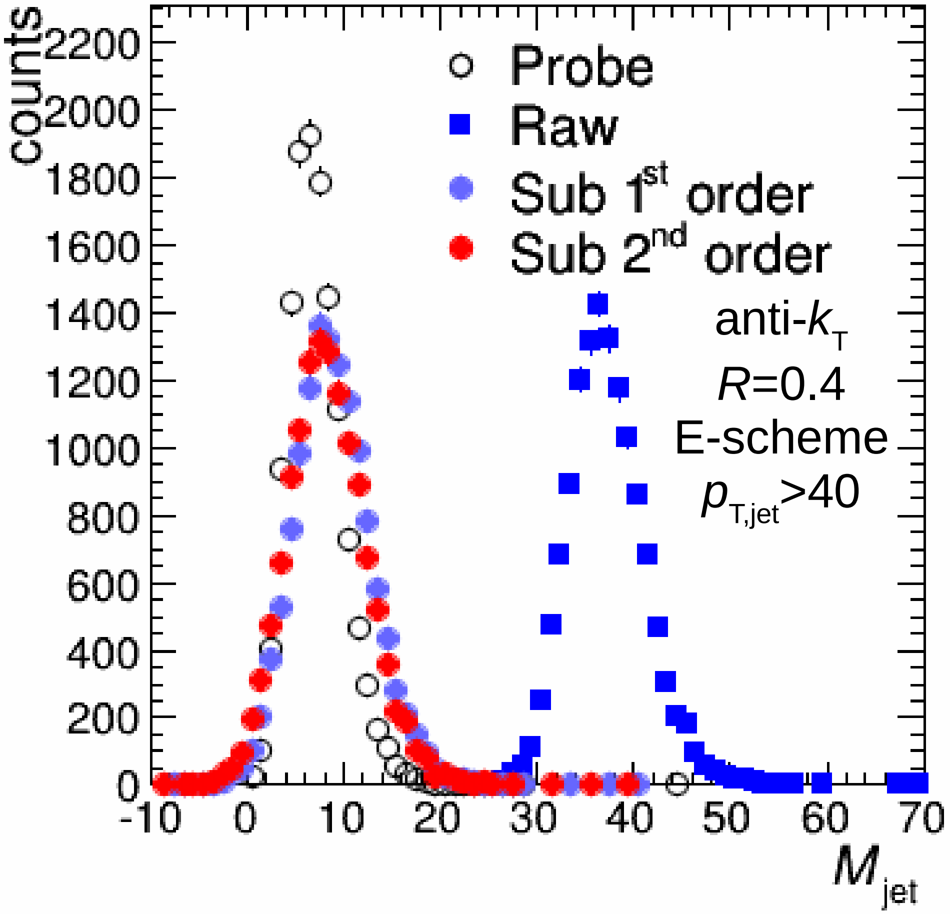
$$\rho = \underset{\mathrm{patches}}{\mathrm{median}} \left\{ \frac{p_{t,\mathrm{patch}}}{A_{\mathrm{patch}}} \right\}$$

~140 GeV

$$\rho_m = \underset{\mathrm{patches}}{\mathrm{median}} \left\{ \frac{m_{\delta,\mathrm{patch}}}{A_{\mathrm{patch}}} \right\}$$

~4.2 GeV

$$m_{\delta\mathrm{patch}} = \sum_{i \in \mathrm{patch}} \left(\sqrt{m_i^2 + p_{\mathrm{T}i}^2} - p_{\mathrm{T}i} \right)$$



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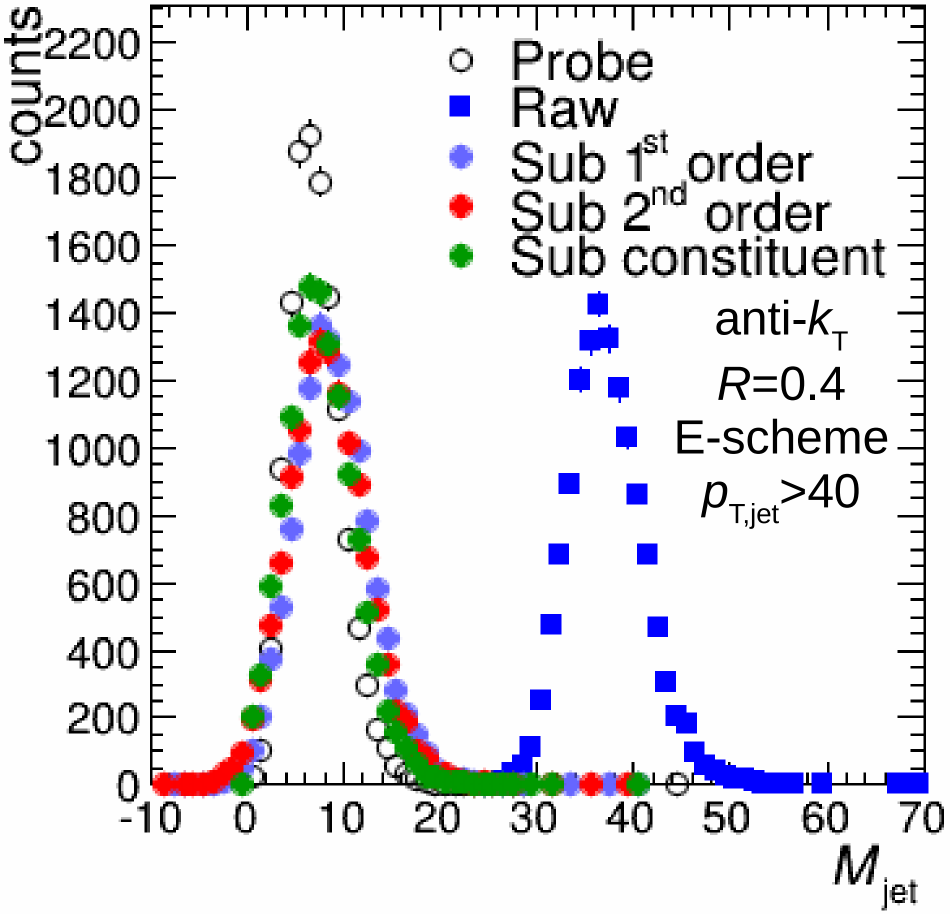
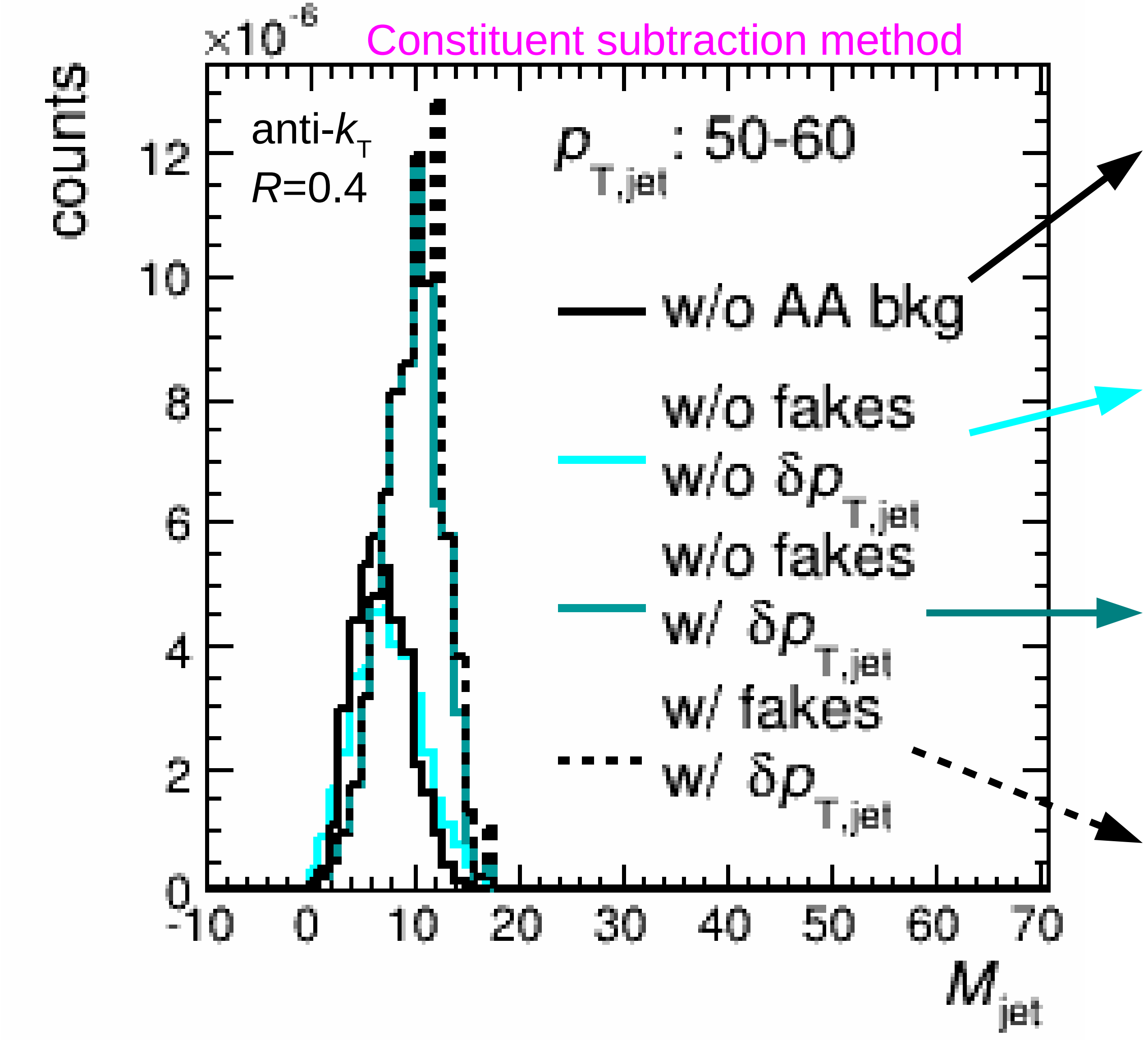


Influence of p_T smearing on jet mass



1) Probes = PYTHIA jets w/o AA background

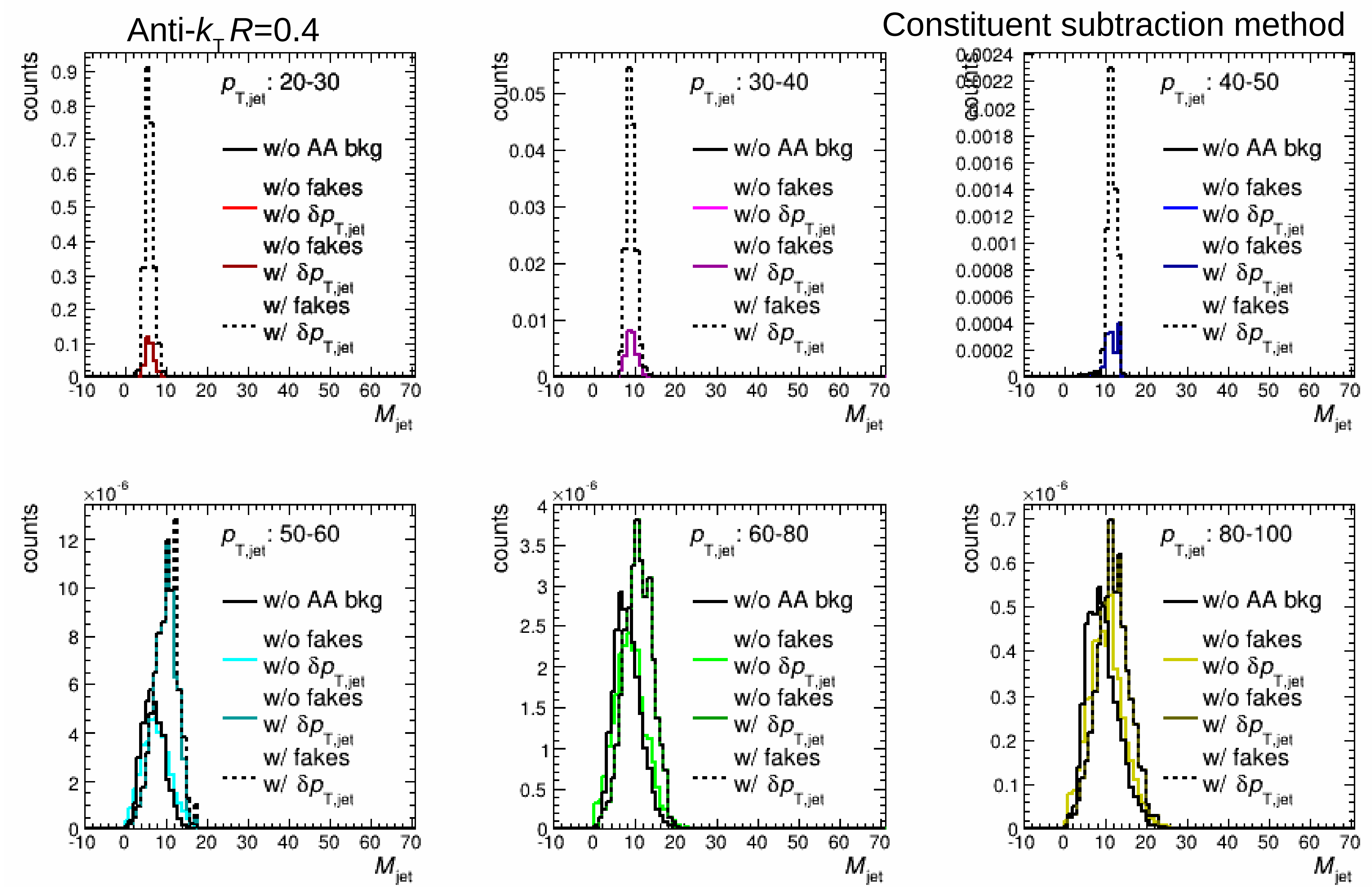
2) Embedded probes. Same jet sample as 1). No feed-in and feed-out due to p_T smearing

3) Embedded probes. Including feed-in and feed-out due to p_T smearing

4) All AA jets including all fakes and fluctuations

For this jet p_T not many fakes but considerable effect from p_T smearing due to background fluctuations

Influence of p_T smearing on jet mass



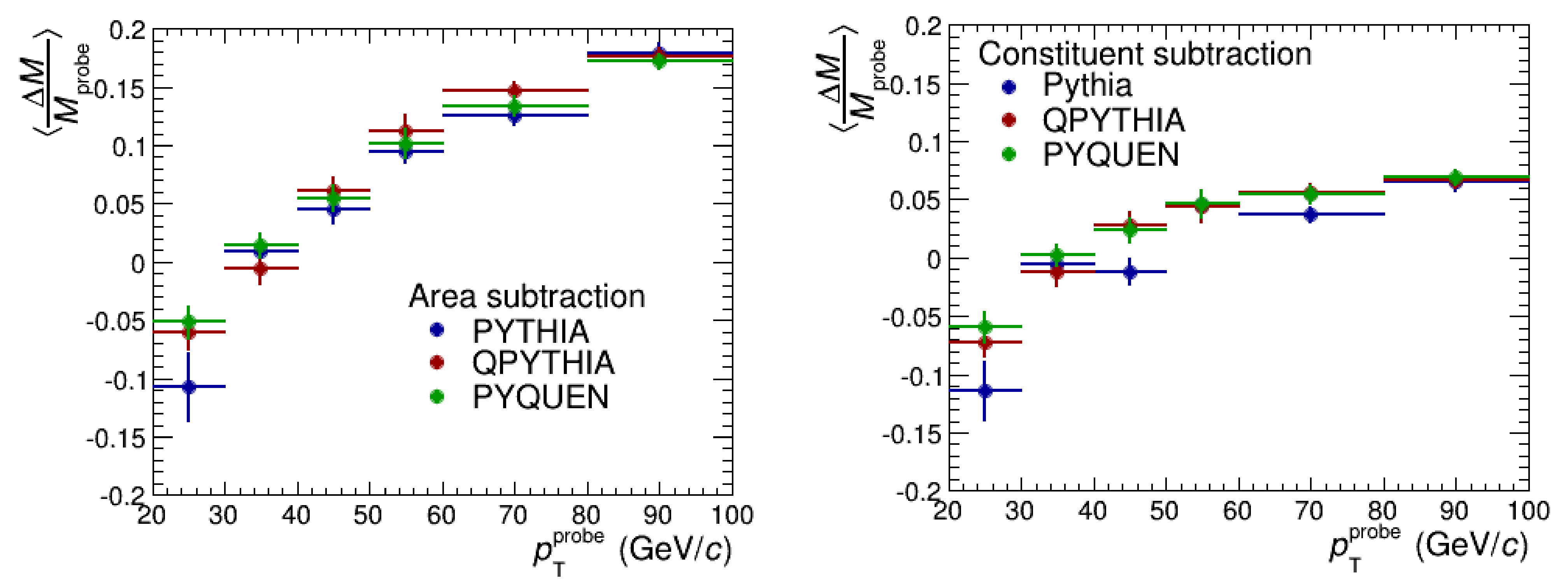
Anti-k_T R=0.4

Constituent subtraction method

At high p_T low number of fakes but shift in jet mass due to fluctuations

Jet Mass Shift

Relative average shift of jet mass with respect to jet mass of embedded probe



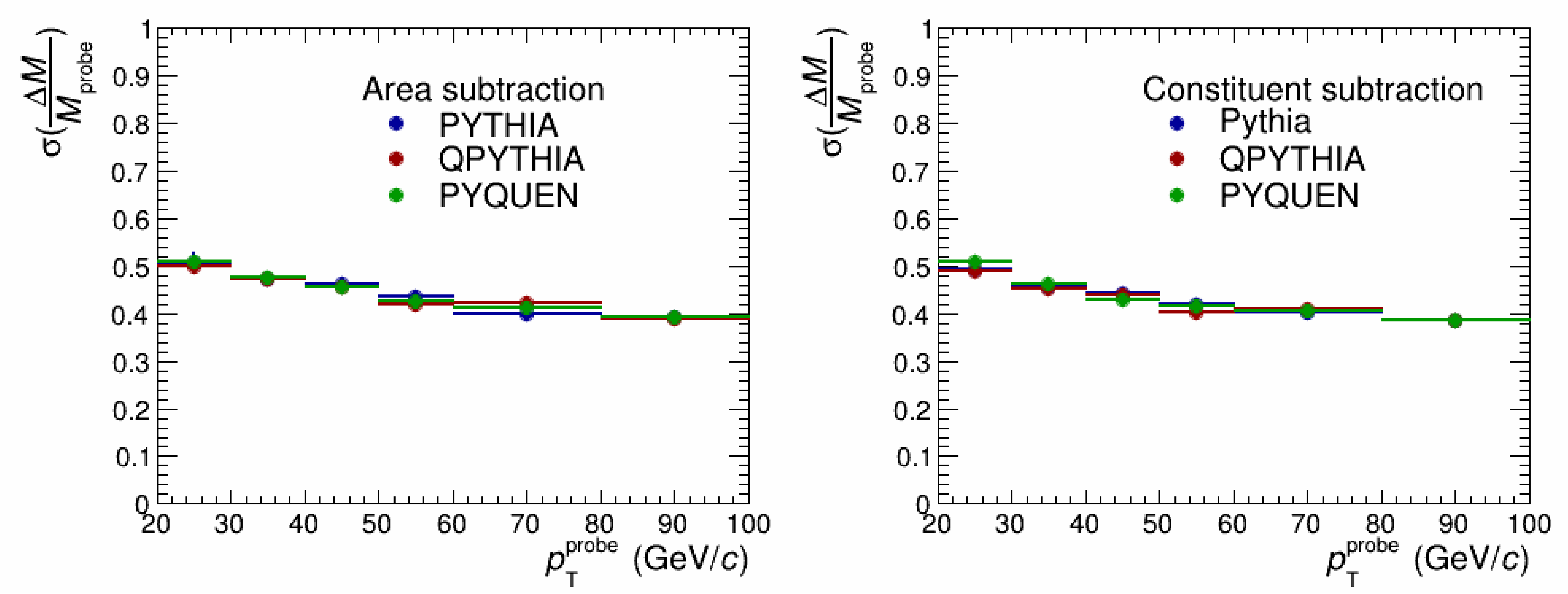
Shift in jet mass depends on jet p_T

Smaller jet shift for constituent method for large jet p_T

QPYTHIA and PYQUEN done with very mild quenching

Jet Mass Resolution

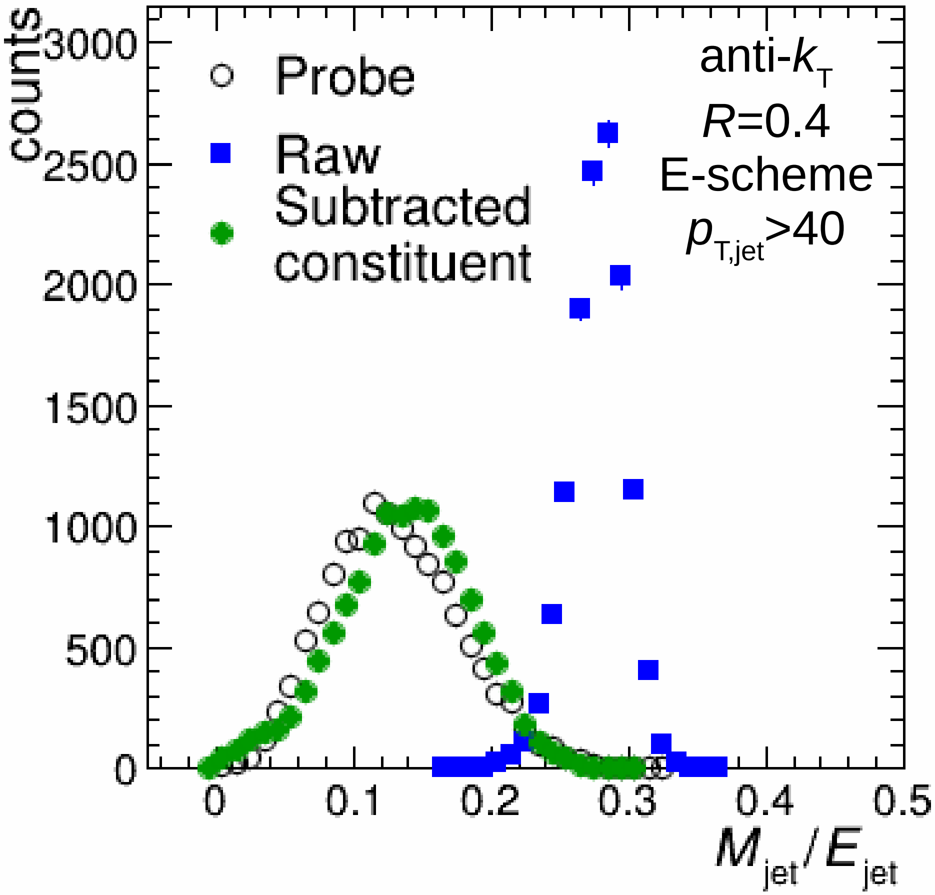
Jet mass resolution as function of jet p_T: 0.5 – 0.4



Similar resolution for both methods
No strong dependence on fragmentation pattern

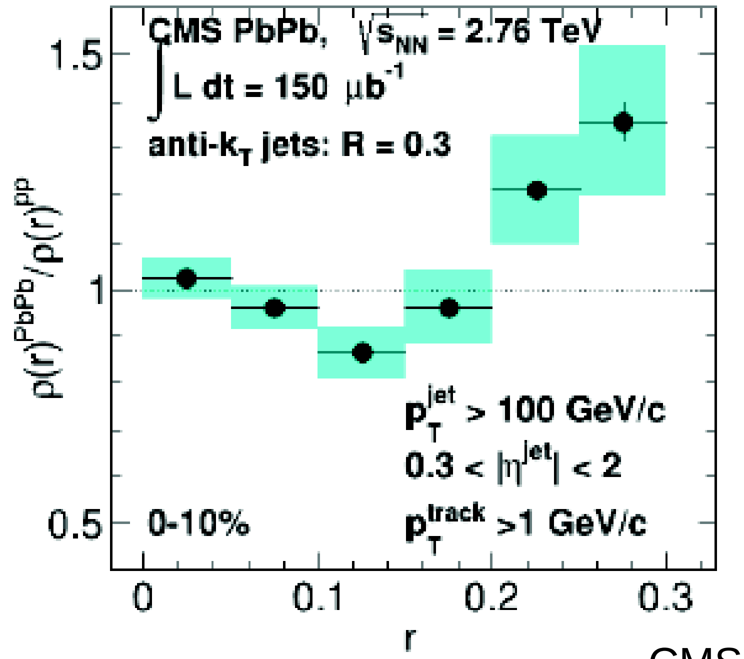
M_{jet} / E_{jet}

- Only available for constituent subtraction method
  - Derivative based method requires rerunning to calculate the derivatives of M_{jet}/E_{jet}
- Background narrows distribution
  - Different background contribution to p and E
- Subtraction method recovers shape of distribution but shifted
- Can we measure this? Looks promising but need to study resolution and understand shift

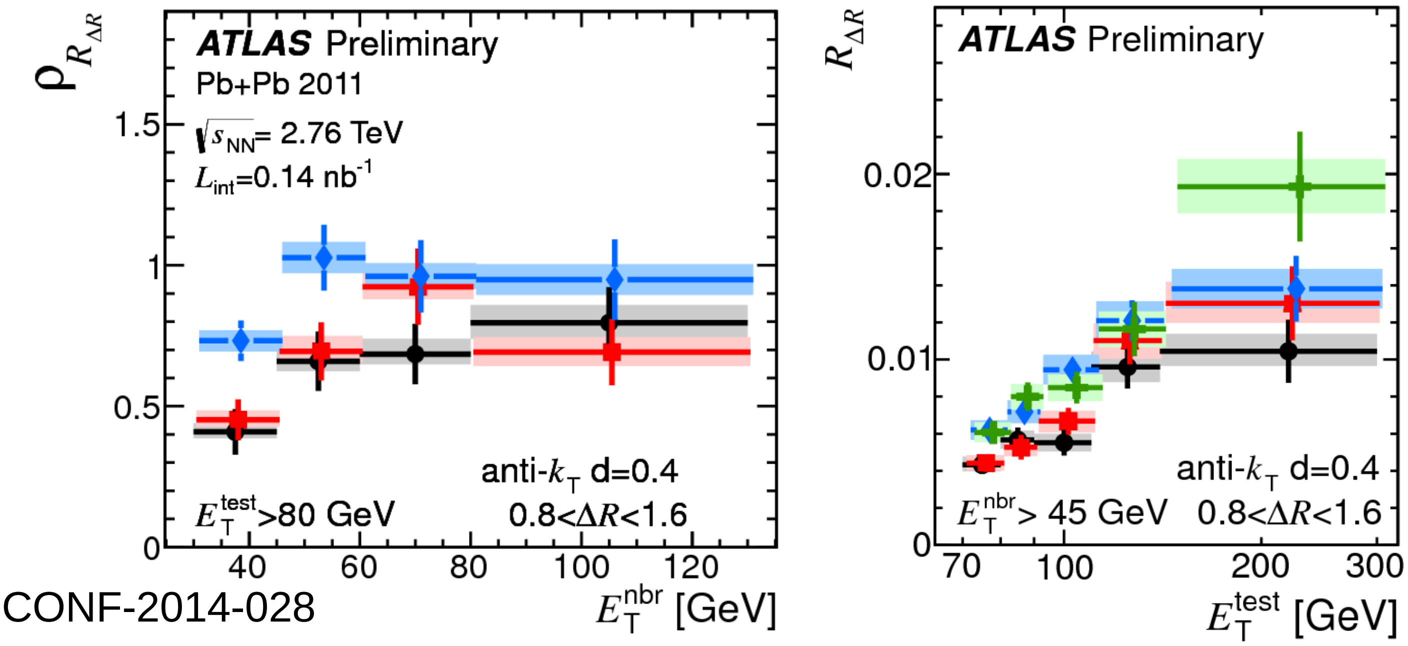


Jet shapes and structures

- Jet shape observables:
  energy distribution within a jet.
  Sensitive to dynamics of parton shower
- Jet structures
  - Subjets
  - Neighbouring jet pairs



CMS
PLB 730 (2014) 243



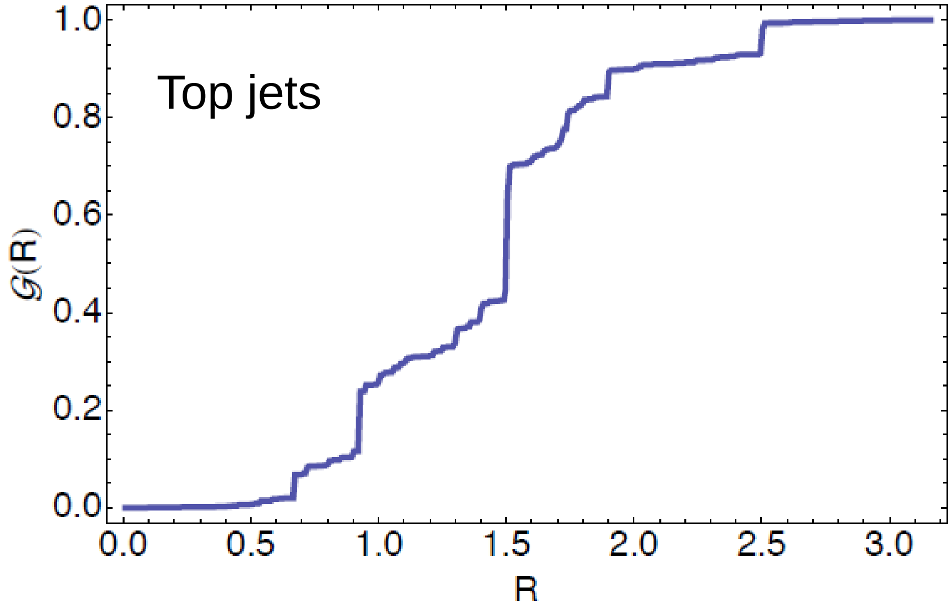
ATLAS-CONF-2014-028

Angular correlation function

- Angular correlation function: characterize jet substructure

$$\mathcal{G}(R) \equiv \frac{\sum_{i \neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2 \Theta(R - \Delta R_{ij})}{\sum_{i \neq j} p_{Ti} p_{Tj} \Delta R_{ij}^2} \approx \frac{\sum_{i \neq j} p_i \cdot p_j \Theta(R - \Delta R_{ij})}{\sum_{i \neq j} p_i \cdot p_j}$$

  IRC safe
- Physical interpretation: mass contribution from constituents separated by an angular distance R or less
- Jet axis doesn't enter
- Substructures cause discontinuities in G(R)



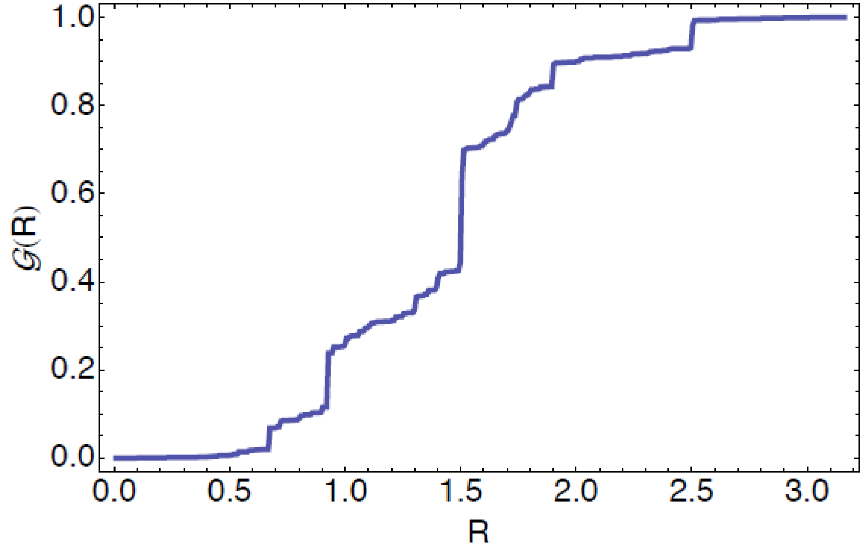
Jankowiak et al
arXiv:1104.1646

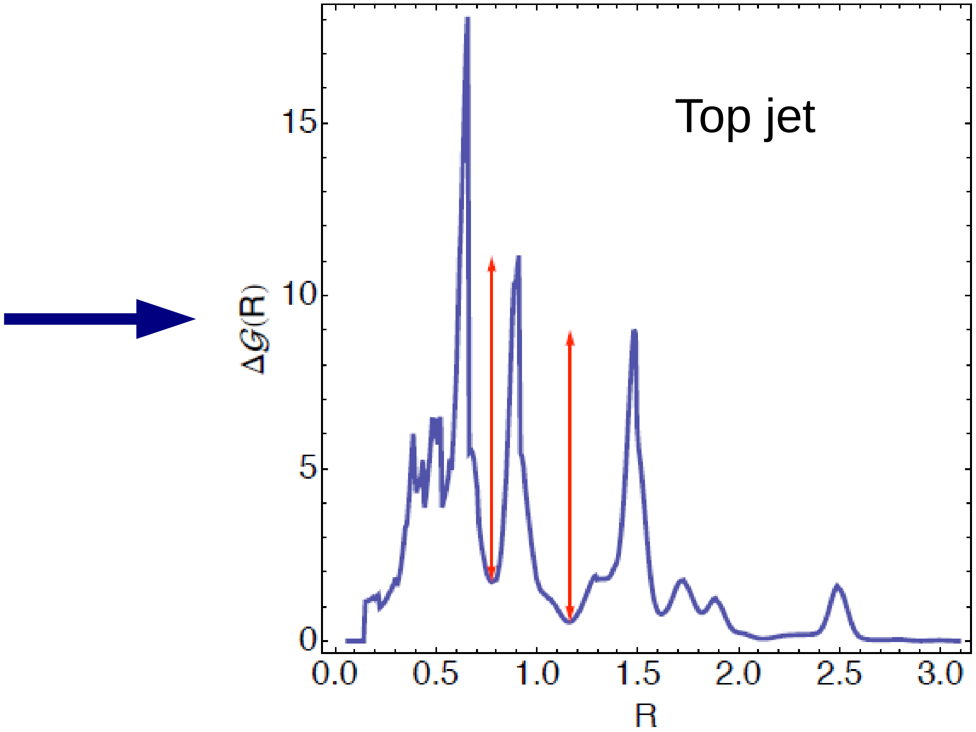
Angular structure function

- Easier to find peaks, take derivative

$$\Delta\mathcal{G}(R) \equiv R\,\frac{\sum_{i\neq j} p_{Ti}p_{Tj}\Delta R_{ij}^2 K(R-\Delta R_{ij})}{\sum_{i\neq j} p_{Ti}p_{Tj}\Delta R_{ij}^2 \Theta(R-\Delta R_{ij})}$$

with K a smooth function





arXiv:1104.1646 → much more details and application in this paper

Average structure function

[1] arXiv:1201.2688

- Proposal by Jankowiak et al [1] to calculate the ensemble average of the structure function

$$\begin{aligned}
\langle \Delta\mathcal{G}(R)\rangle &\equiv \frac{R}{\langle\mathcal{G}(R)\rangle}\frac{d}{dR}\langle\mathcal{G}(R)\rangle \\
&= R\frac{\sum_{k=1}^{N}\mathcal{G}'(R)_k}{\sum_{k=1}^{N}\mathcal{G}(R)_k} \\
&= R\frac{\sum_{k=1}^{N}\sum_{i\neq j} p_{Tk,i}p_{Tk,j}\Delta R_{ij}^2\delta_{\mathrm{dR}}(R-\Delta R_{ij})}{\sum_{k=1}^{N}\sum_{i\neq j} p_{Tk,i}p_{Tk,j}\Delta R_{ij}^2\Theta_{\mathrm{dR}}(R-\Delta R_{ij})}
\end{aligned}$$

δ_{dR} is replaced by a Gaussian and Θ_{dR} by an error function.
k=jet number; i,j=constituent number

- Measure of energy distribution inside jet
- Computationally expensive in AA collisions

LO QCD calculation

arXiv:1201.2688

- Can be calculated analytically
  - At LO: for small R

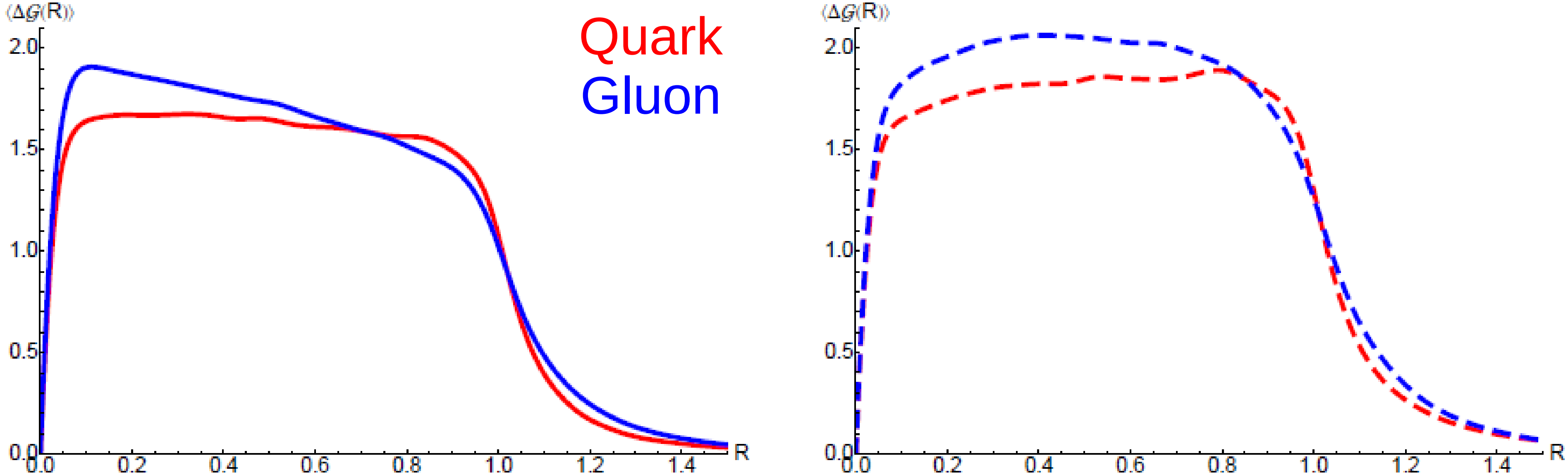
$$\langle \mathcal{G}(R) \rangle = \frac{\alpha_s}{2\pi} p_T^2 R^2 \begin{cases} \frac{3}{4} C_F & \text{quark jets} \\ \frac{7}{10} C_A + \frac{1}{10} n_F T_R & \text{gluon jets} \end{cases}$$

  - $\langle \Delta G(R) \rangle = 2$ for any jet algorithm in LO QCD at small R
  - For jets without any structure $\langle G(R) \rangle \sim R^4 \rightarrow \langle \Delta G(R) \rangle = 4$
- Caveats:
  - Including running coupling reduces $\langle \Delta G(R) \rangle$ by ~0.15
  - Higher order corrections

Quark vs Gluon jets

- MC anti-k_T jets with p_T>200 GeV/c and R=1

arXiv:1201.2688

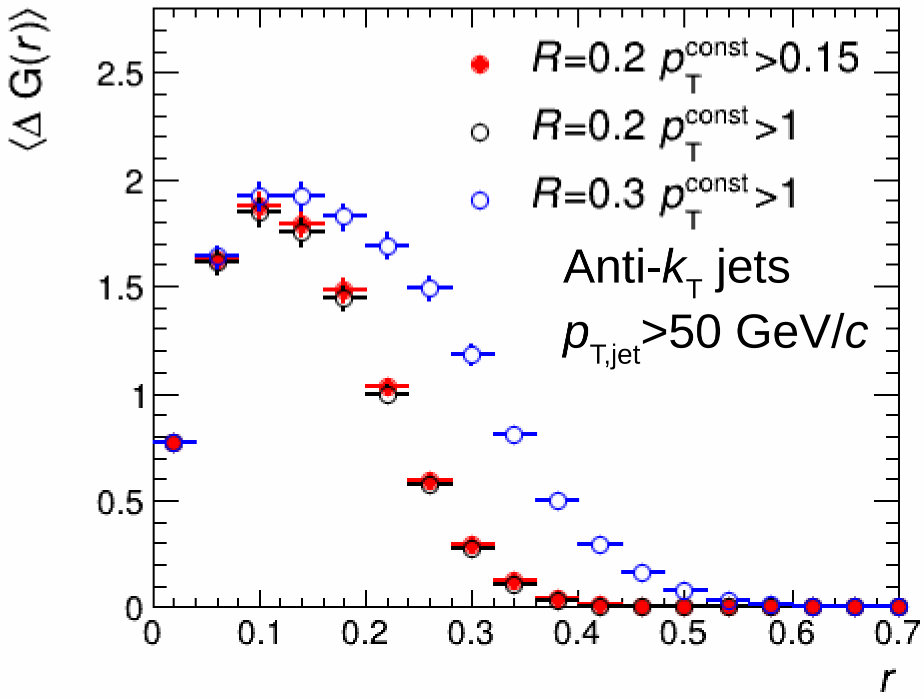


(a) Pythia8

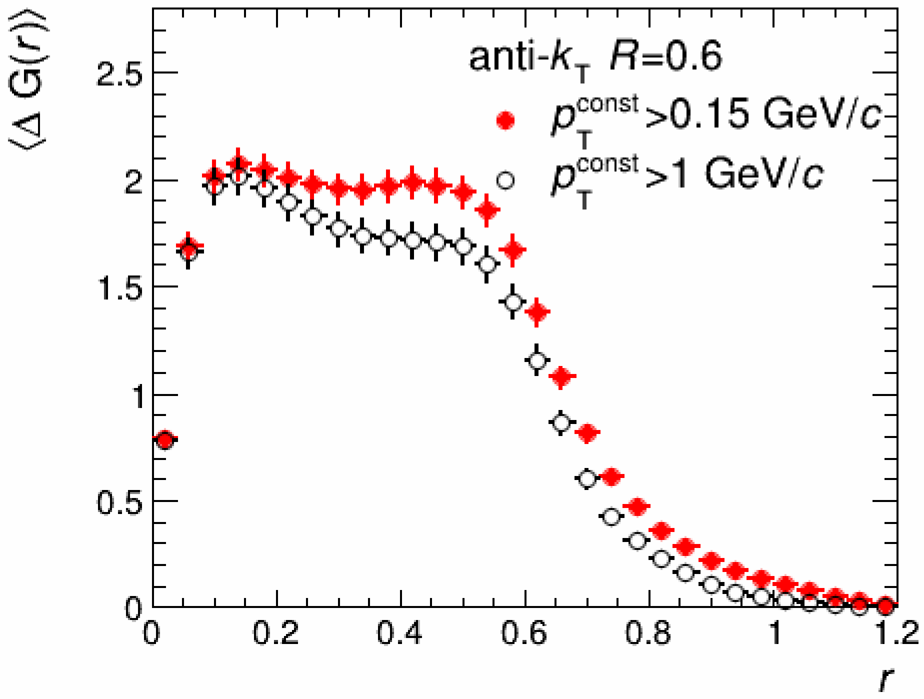
(b) Herwig++

⟨ΔG(r)⟩ for small resolution parameter

Will write ⟨ΔG(R)⟩ as ⟨ΔG(r)⟩ to avoid confusion with jet resolution parameter
r still is a resolution parameter
In AA: small resolution parameters for jet finding → ⟨ΔG(r)⟩ drops at smaller r



PYTHIA for some typical jet finder configurations used in AA



PYTHIA jets for larger resolution parameter

Sensitivity in small jets limited

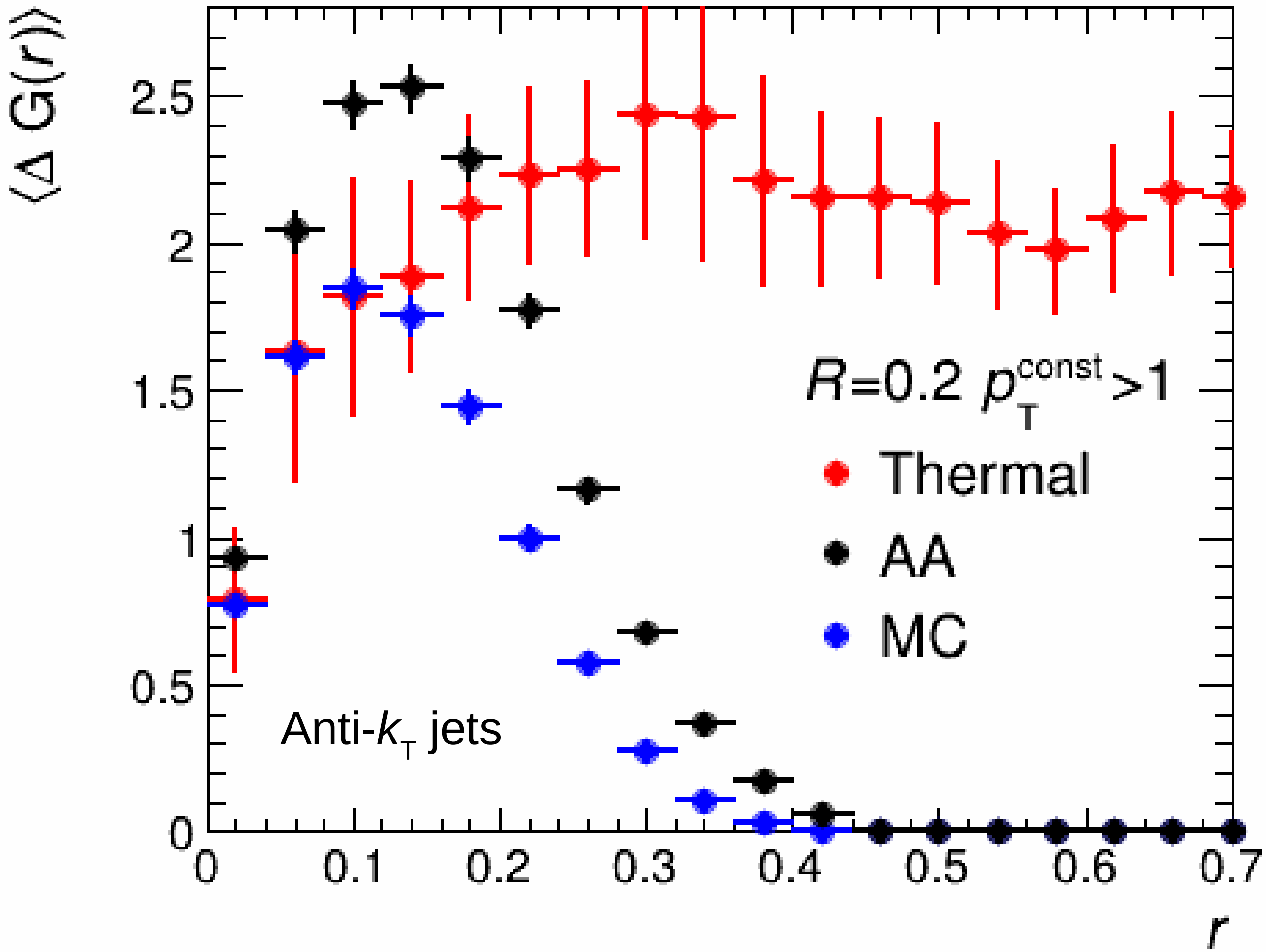
⟨ΔG(r)⟩ in AA

$$G_{AA}(r) \sim c_{jet} \times c_{jet} + c_{jet} \times c_{UE} + c_{UE} \times c_{UE}$$

Thermal:
jets from background particles only (multiplicity=3300)

AA:
jets in thermal+PYTHIA events with $p_{T,jet}$>50 GeV/c

MC:
embedded PYTHIA jets

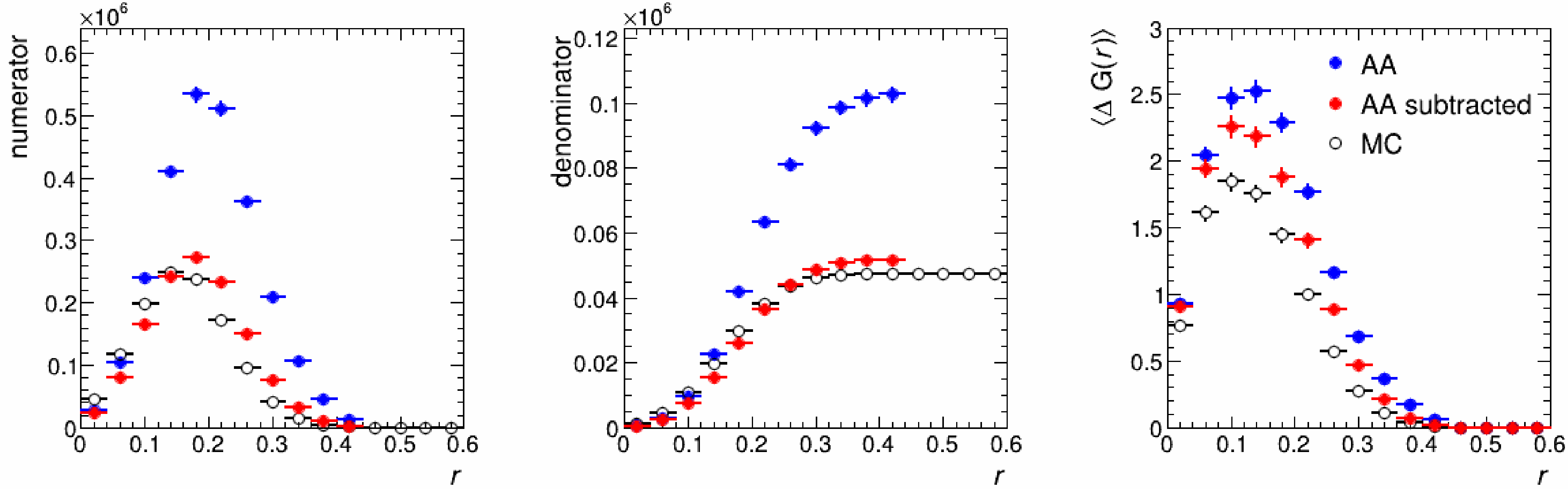


Clear difference between real and pure background jets

⟨ΔG(r)⟩ subtraction

$$\langle \Delta \mathcal{G}(R) \rangle = R \frac{\sum_{k=1}^{N} \sum_{i \neq j} p_{Tk,i} p_{Tk,j} \Delta R_{ij}^2 \delta_{\mathrm{dR}}(R - \Delta R_{ij})}{\sum_{k=1}^{N} \sum_{i \neq j} p_{Tk,i} p_{Tk,j} \Delta R_{ij}^2 \Theta_{\mathrm{dR}}(R - \Delta R_{ij})}$$

- Subtraction using jet derivatives: area based
- Subtraction done separately for nominator and denominator



Numerator of ⟨ΔG(r)⟩

Denominator of ⟨ΔG(r)⟩

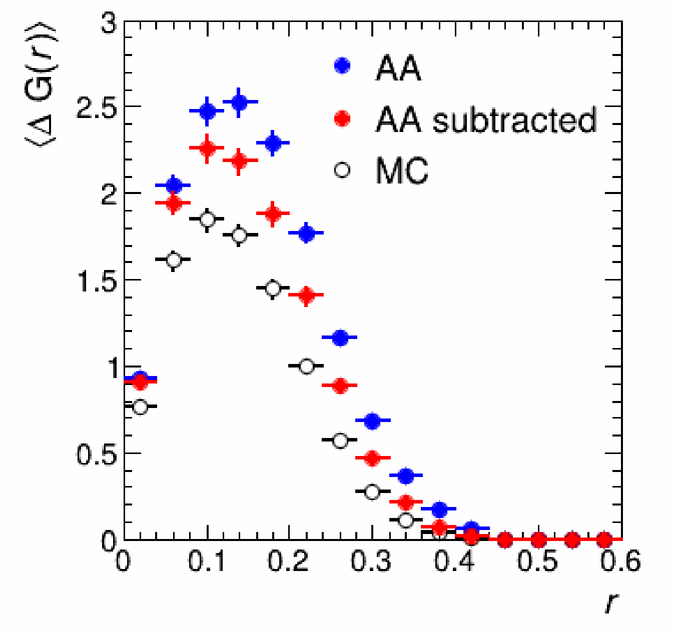
⟨ΔG(r)⟩

Anti-k_T R=0.2 $p_{T,\mathrm{const}}$>1 GeV/c

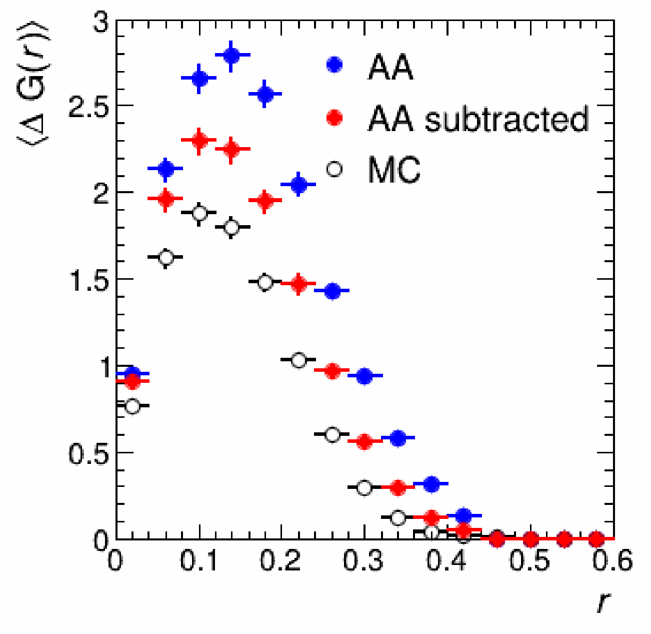
⟨ΔG(r)⟩ subtraction

- Lower constituent p_T threshold in jet finding
  - Does not add a significant amount of jet fragments for jets with R=0.2. But it does add a large amount of background
- Larger jet resolution parameter
  - Adds jet fragments and background

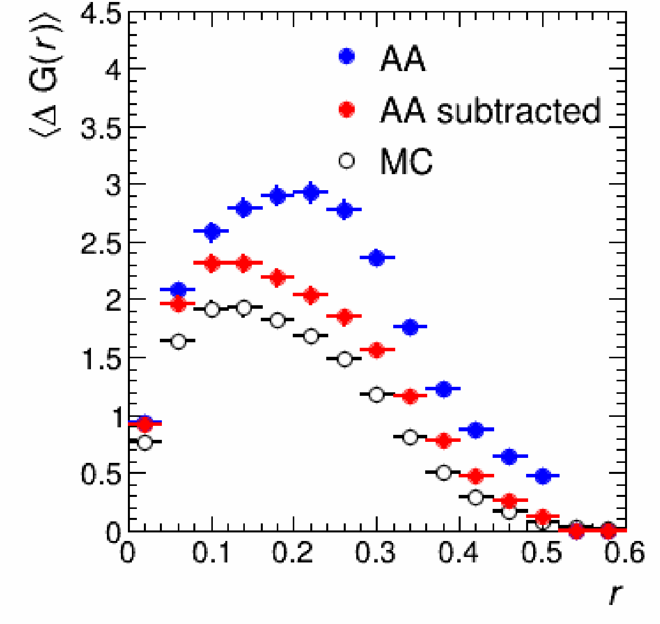
Anti-k_T R=0.2
$p_{T,const}$>1 GeV/c



Anti-k_T R=0.2
$p_{T,const}$>0.15 GeV/c



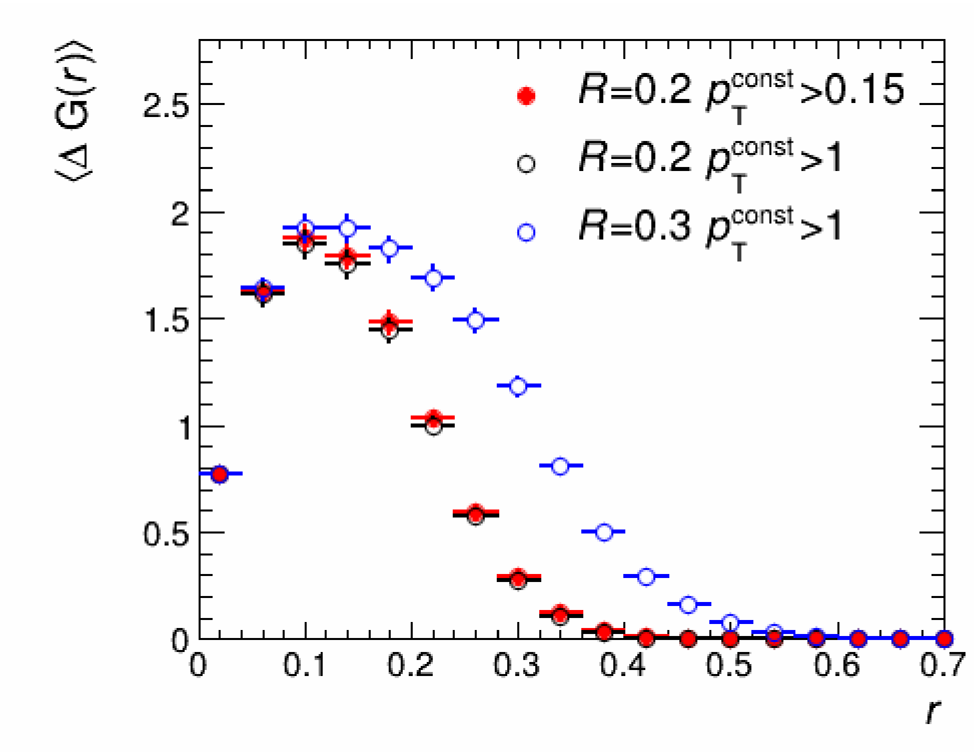
Anti-k_T R=0.3
$p_{T,const}$>1 GeV/c



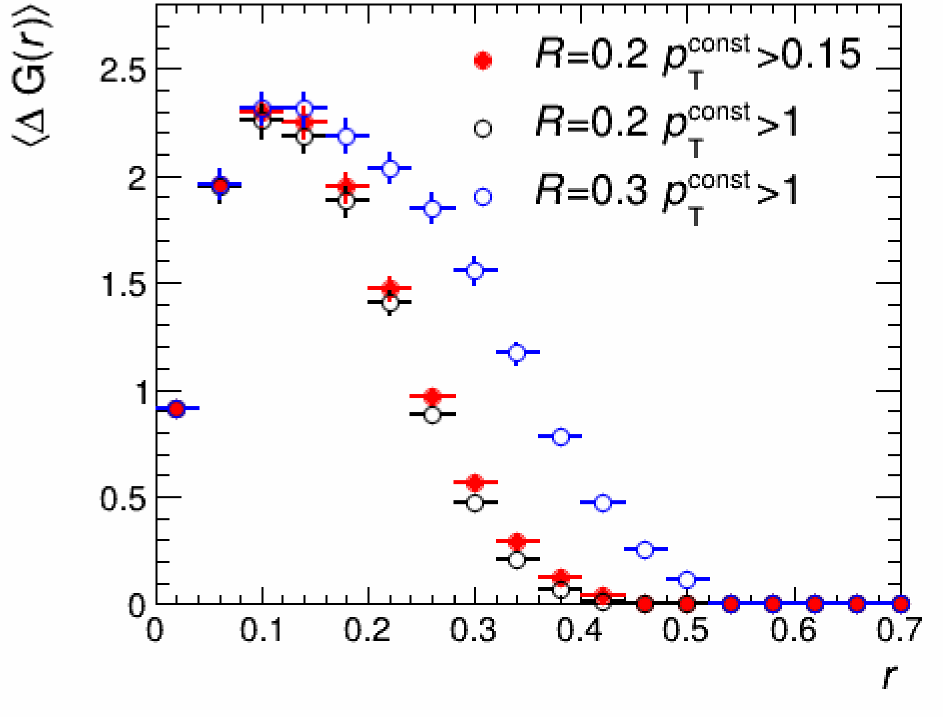
- Performance of background subtraction similar

$\langle \Delta G(r) \rangle$ in AA

PYTHIA



PYTHIA embedded in thermal background



Without precise UE subtraction dangerous → background induces same effect as an increase in soft particle production due to jet quenching

Summary

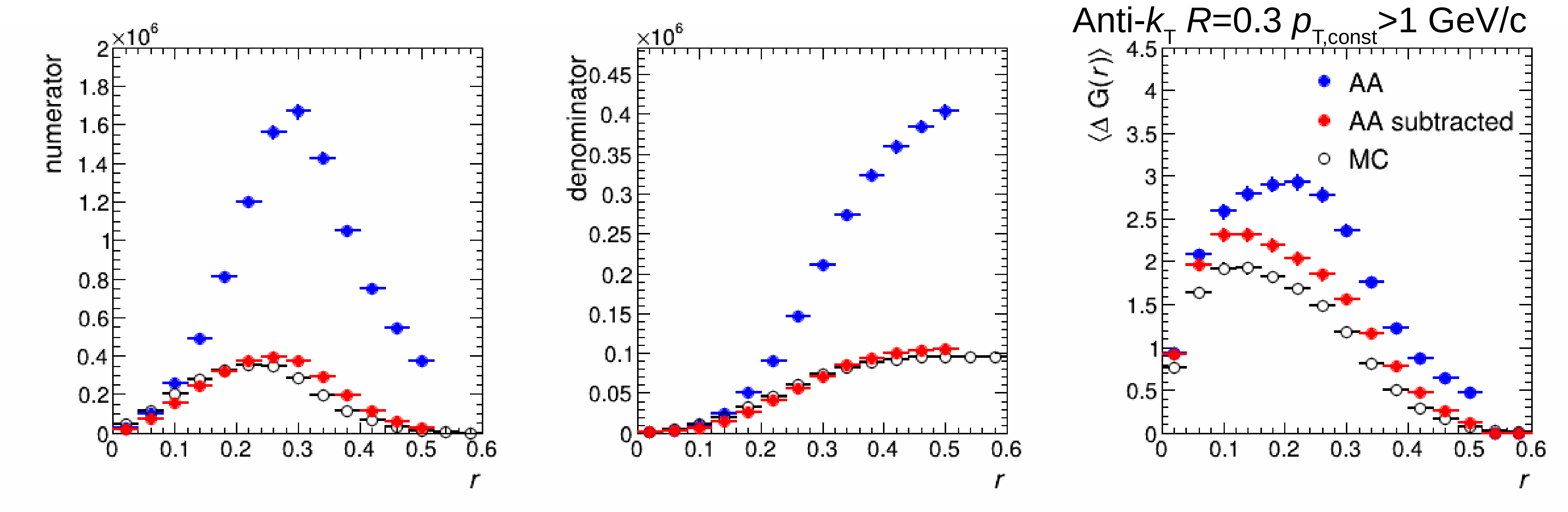
- Mean jet mass measurement in AA is feasible
- For full mass distribution improvement of resolution desirable

- Angular structure function
    - Based on correlation between jet fragments
    - Promising observable. Especially for larger R
    - Explored subtraction method do not correct for the entire background effect

backup

⟨ΔG(r)⟩ subtraction

- Increase resolution parameter to *R*=0.3
  - Background contamination larger



- Subtraction closer to truth (MC) but the full background effect is not cancelled

Derivatives

Derivatives of jet shape V with respect to ghost $p_{T,g}$ and $m_{d,g}$

$$V_{\text{jet}}^{(n,m)} \equiv A_g^{n+m}\, \partial_{p_{t,g}}^n\, \partial_{m_{\delta,g}}^m\, V(\{p_i\}_{\text{jet}})$$

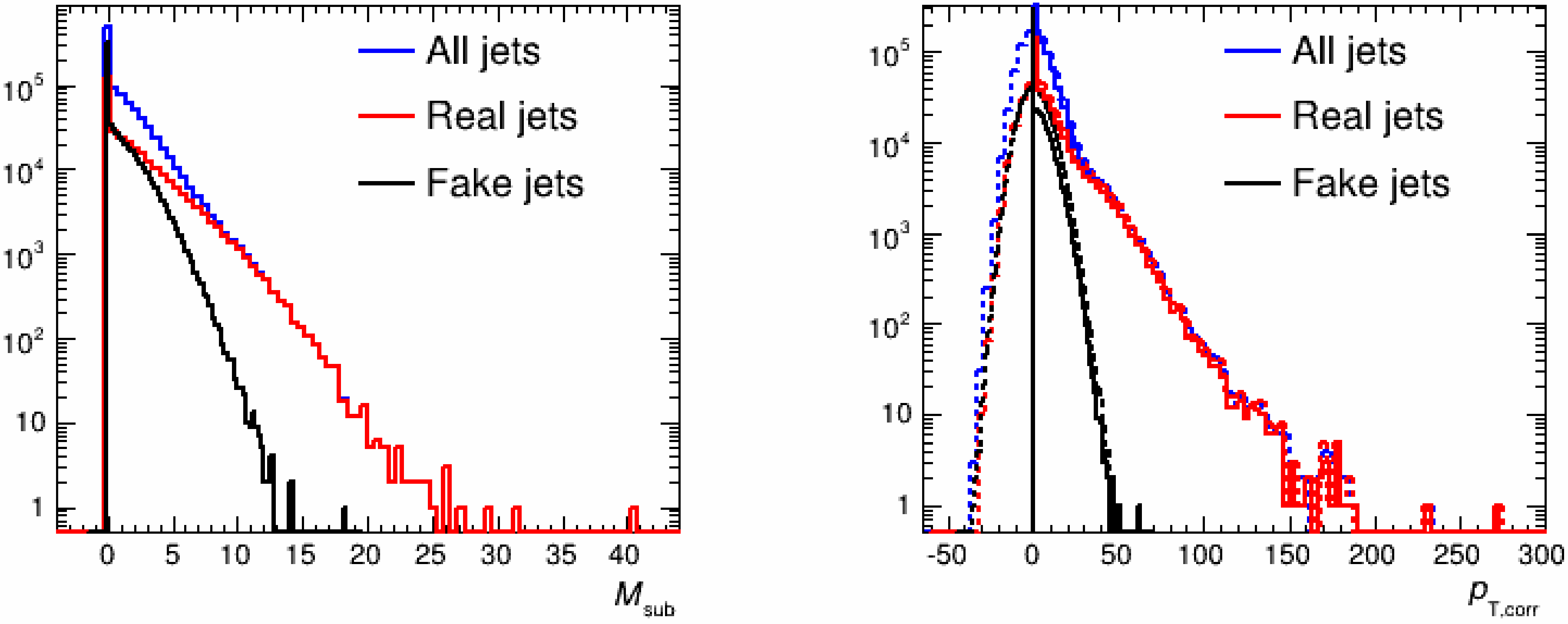
Jet shape is extrapolated back to zero underlying event

$$V_{\text{jet,sub}} = V_{\text{jet}} - \rho V_{\text{jet}}^{(1,0)} - \rho_m V_{\text{jet}}^{(0,1)} + \frac{1}{2}\rho^2 V_{\text{jet}}^{(2,0)} + \frac{1}{2}\rho_m^2 V_{\text{jet}}^{(0,2)} + \rho\rho_m V_{\text{jet}}^{(1,1)} + \cdots$$

Soyez et al
arXiv:1211:2811

Fakes
constituent subtraction

- Comparison of fakes as function of subtracted M and pT



Dotted: scalar method

Note: a real jet can also be a Pythia jet with p_T=0 GeV/c