The Hybrid Strong/Weak Coupling Model for Jet Quenching

J. Casalderrey-Solana,
D. Gulhan, G. Milhano,
DP, K. Rajagopal,
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Daniel Pablos Alfonso

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Hard Probes

UNIVERSITAT DE BARCELONA

Main (current) Assumptions

- Partonic splittings are not modified by the presence of the medium due to scale separation
- Interaction of the partons with the plasma is strongly coupled and can be modelled via holographic results
- Besides transferring energy and momentum to the plasma, the partons can broaden through random transverse kicks
- The deposited energy and momentum completely thermalizes, remembering only the amount of energy *and momentum* deposited into the fluid, and modifies the hadron spectra produced by hydro

Parton Shower

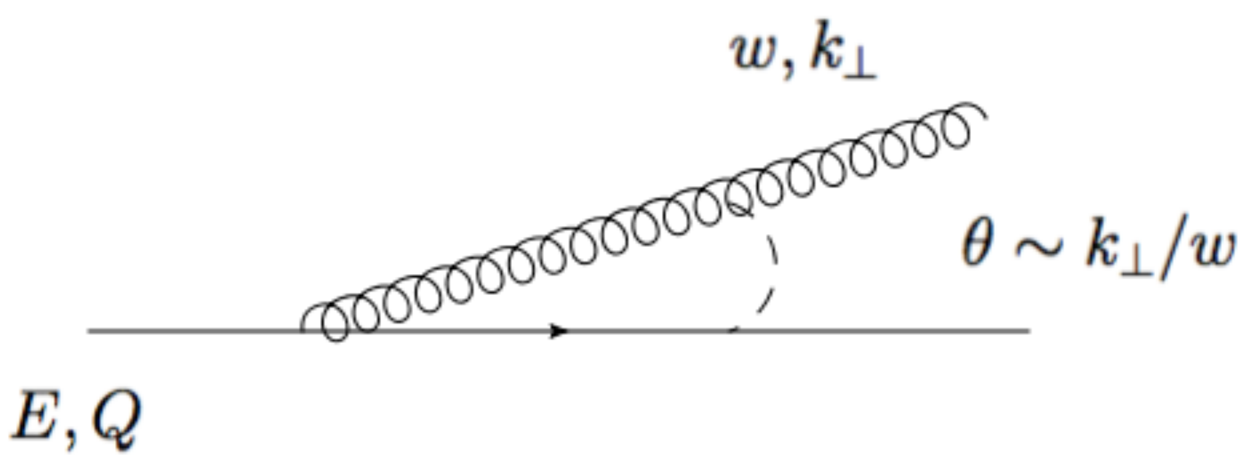
Generate HardQCD pp events with PYTHIA:

version 8.183

- Pt min = 1 GeV (splitting cut-off)
- Initial State Radiation = on
- Multi Partonic Interactions = off
- Stop before hadronization

Where and when do partons effectively split?

Use a *formation time* argument



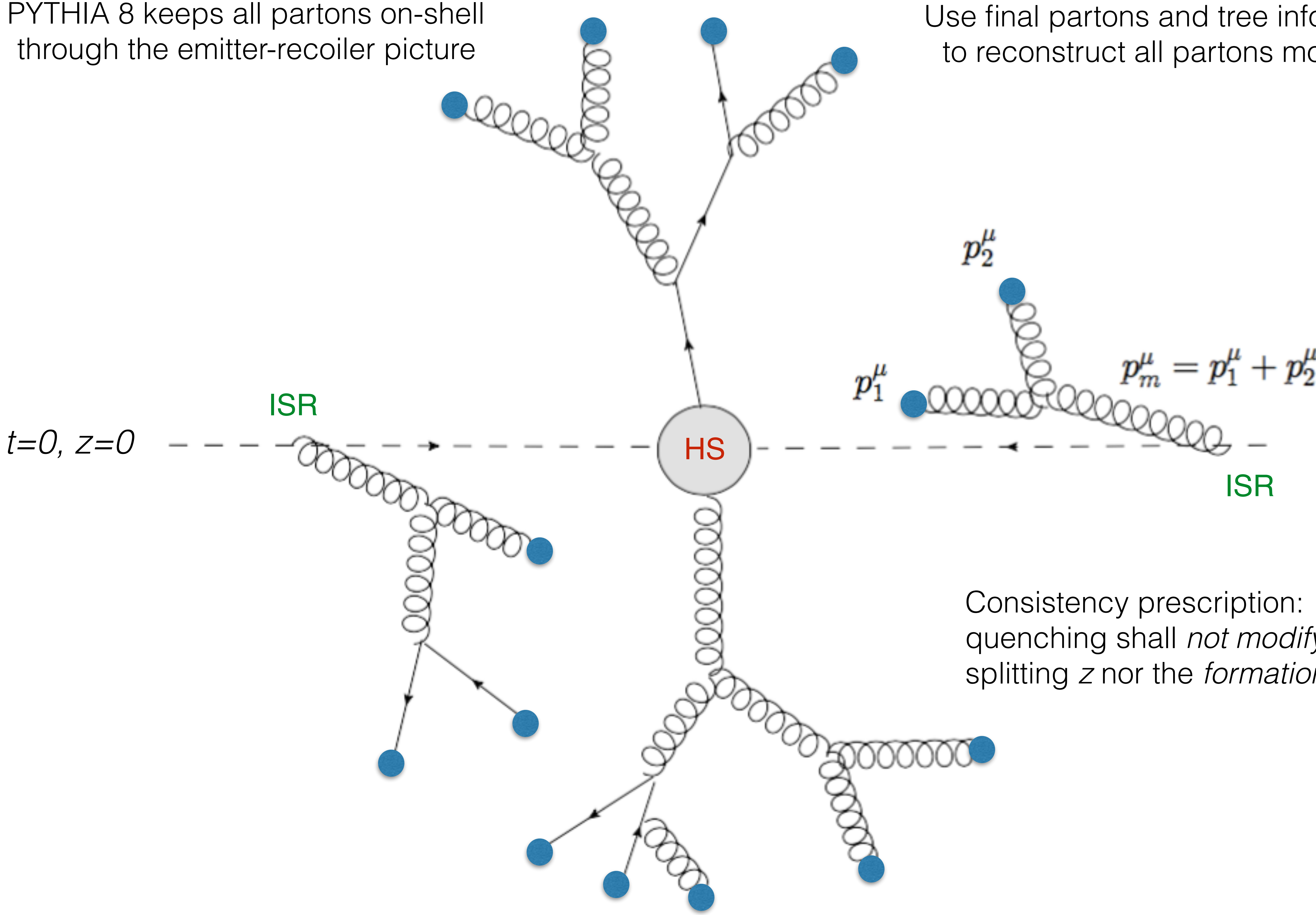
$$\lambda_\perp \sim r \sim \theta \tau_f$$

$$\tau_f \sim w / k_\perp^2 \rightarrow 2E/Q^2$$

Parton Shower

PYTHIA 8 keeps all partons on-shell through the emitter-recoiler picture

Use final partons and tree information to reconstruct all partons momenta



Consistency prescription: quenching shall *not modify* splitting *z* nor the *formation times*

Shower Embedding

- Select position in transverse plane of Hard Scattering according to an optical Glauber Monte Carlo
- Use the appropriate impact parameter range for each centrality class. Select it according to geometry, filter it through Glauber (*i.e.* Ncoll weighted)
- Extract plasma properties (temperature, flow velocity) in the vicinity of the parton of interest by reading an event averaged hydro profile (0-5%, 5-10%, 10-20%, …)
- No quenching before hydro time (for us, proper time 0.6 fm) and no quenching after Tc (use $145 < T_c < 170$ MeV)
- To hadronize the shower simply reintroduce the quenched partons in PYTHIA without colour flow modification. Thermalised partons are put with arbitrarily low energy and momentum

Energy Loss Algorithm

$$\left.\frac{dE}{dx}\right|_{\text{strongly coupled}} = -\frac{4}{\pi} E_{\text{in}} \frac{x^2}{x_{\text{stop}}^2} \frac{1}{\sqrt{x_{\text{stop}}^2 - x^2}}, \qquad x_{\text{stop}} = \frac{1}{2\kappa_{\text{sc}}} \frac{E_{\text{in}}^{1/3}}{T^{4/3}}$$

first parameter κ_{sc}

given that temperature T is meaningful in the local fluid rest frame (LFRF), need to find E. loss in LAB in terms of E. loss in LFRF

$$\frac{dE}{dx} = \mathcal{F}(x, E_{\text{in}}) \xleftarrow{\ ?\ } \frac{dE_F}{dx_F} = \mathcal{F}_F(x_F, E_{\text{in}}^F)$$

simple result: $\mathcal{F}(x, E_{\text{in}}) = \mathcal{F}_F(x_F, E_{\text{in}}^F(E))$

(also assume that quenching does not change parton direction)

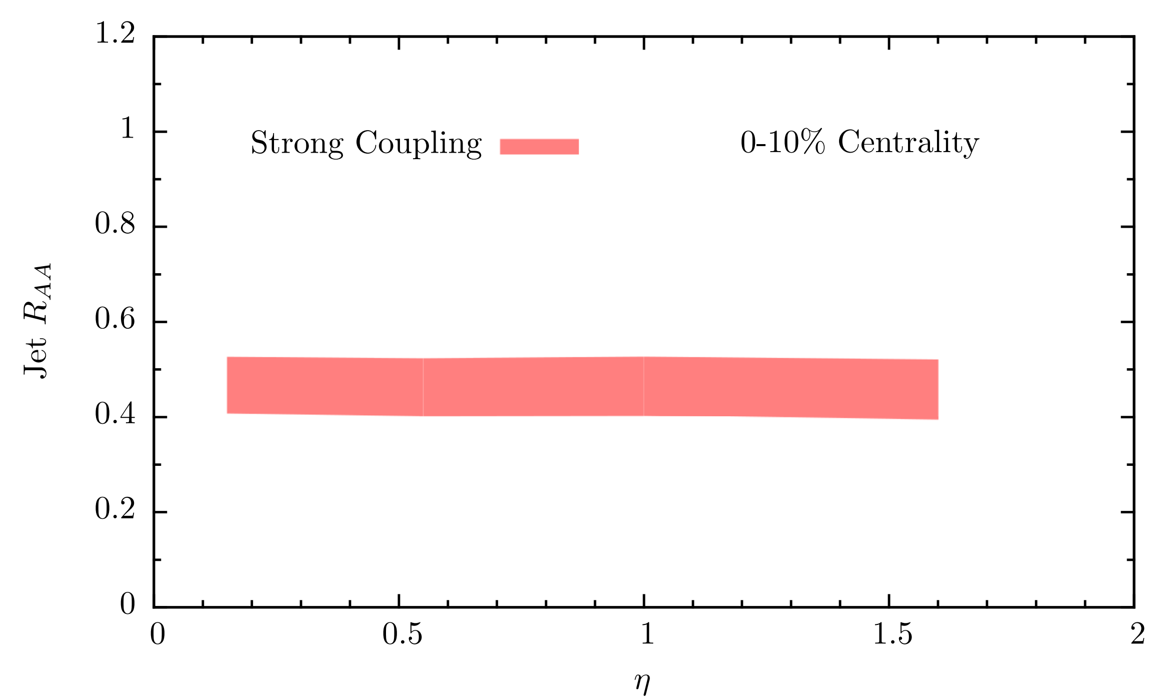
Then need:

$$d\mathbf{x}_F = \mathbf{w}dt + \gamma_F (\mathbf{w}_L - \mathbf{v})\, dt$$

$$x_F(t) = \int_{t_0}^{t} dt \sqrt{[\mathbf{w}^2 + \gamma_F^2 (\mathbf{v}^2 - 2\mathbf{v}\mathbf{w} + (\mathbf{v}\mathbf{w})^2)]}$$

$$E_{\text{in}}^F = E_{\text{in}}\, \gamma_F (1 - \mathbf{w}\mathbf{v})$$

$$dt = 0.01\,\text{fm}$$



Broadening

Transverse kicks in the fluid rest frame

Impose: not change virtuality nor energy (in that frame)

$$P^\mu = E_F(1, \mathbf{w}_F)$$
$$P'^\mu = E_F(1, \mathbf{w}'_F)$$

$$\mathbf{w}'^2_F = \mathbf{w}^2_F \qquad \mathbf{w}'_F = \sqrt{1 - \frac{q^2}{E_F^2 \mathbf{w}_F^2}}\,\mathbf{w}_F + \frac{q}{E_F}\mathbf{e}_\perp$$

Need to express change of momentum in the LAB frame

Use
$$W_T = \frac{1}{W_F^0}\left(W - (W \cdot u)u\right) \qquad W = P/E$$

to build
$$P'^\mu = P^\mu - \beta E_F W_T^\mu + q e_\perp^\mu \ , \qquad \beta \equiv 1 - \sqrt{1 - \frac{q^2}{E_F^2 \mathbf{w}_F^2}}$$

where the transverse vector must satisfy $\quad u \cdot e_\perp = 0\,, \quad W \cdot e_\perp = 0\,, \quad e_\perp^2 = -1$

Then find the basis
$$e_1^\mu = (0, \frac{\mathbf{w} \times \mathbf{v}}{|\mathbf{w} \times \mathbf{v}|})\,, \qquad e_2^\mu = \frac{1}{\sqrt{N}}\left(l_2^\mu + \alpha\, W_\perp^\mu\right)$$

$$l_2^\mu = (0, \frac{\mathbf{w}}{|\mathbf{w}|} \times \frac{\mathbf{w} \times \mathbf{v}}{|\mathbf{w} \times \mathbf{v}|})\,, \qquad W_\perp = W - \frac{W^2}{u \cdot W} u\,,$$
$$\alpha = -\frac{(l_2 \cdot u)\,(u \cdot W)}{(u \cdot W)^2 - W^2}\,, \qquad N = \frac{(u \cdot W)^2 - W^2(1 + (l_2 \cdot u)^2)}{(u \cdot W)^2 - W^2}\,.$$

Broadening

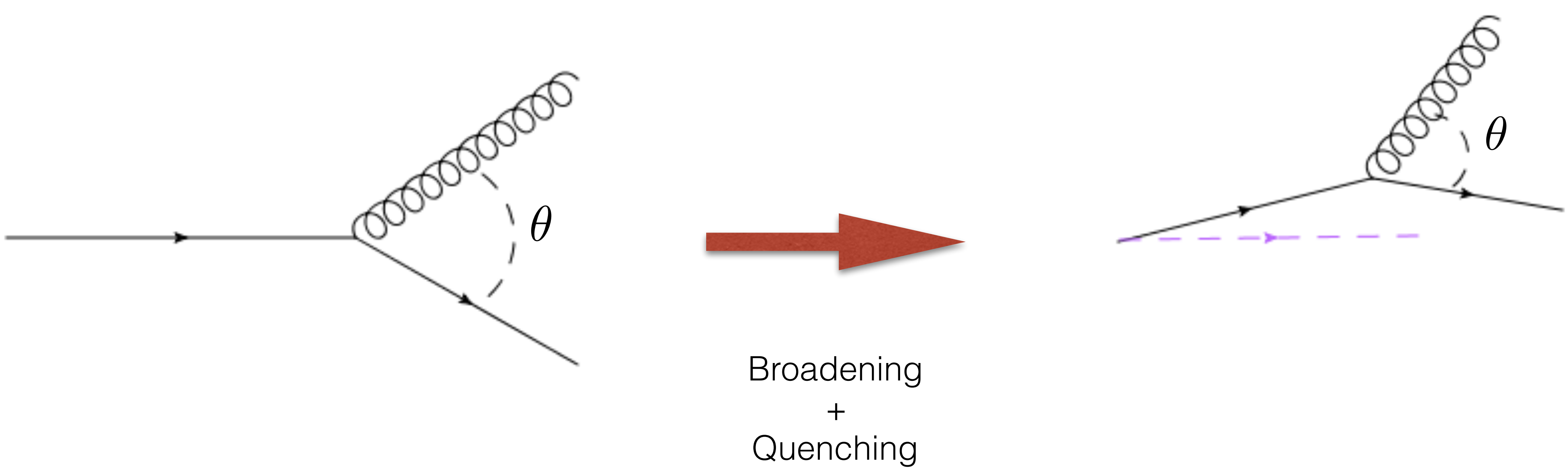
- Choose random kick *q* according to a gaussian with width $\Delta Q_\perp^2 = \hat{q}\, dt_F$ $\hat{q} = KT^3$

$dt_F = dt\, \gamma_F\, (1 - \mathbf{wv})$.

second parameter *K*

- Choose random direction in the transverse plane

- Propagate medium modification to the daughters respecting energy fraction and splitting angle



An Estimate of Backreaction

Perturbations on top of a Bjorken flow

$$\Delta P^i_\perp = w\tau \int d\eta\, d^2x_\perp\, \delta u^i_\perp$$

$$\Delta P^\eta = 0$$

$$\Delta S = \tau c_s^{-2} s \int d\eta\, d^2x_\perp\, \frac{\delta T}{T}$$

$$c_s^2 = \frac{s}{T}\frac{dT}{ds}$$

Cooper-Frye $$E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int d\sigma^\mu p_\mu f(u^\mu p_\mu)$$

expand to linear order

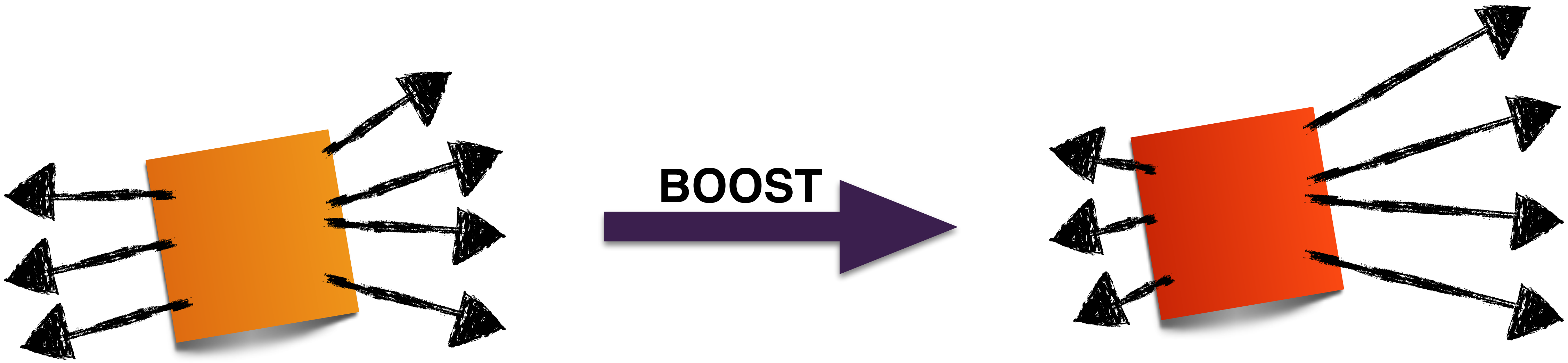
One body distribution (OBD)

$$E\frac{dN}{d^3p} = \frac{1}{32\pi}\frac{m_T}{T^5}\cosh(y-y_j)e^{-\frac{m_T}{T}\cosh(y-y_j)}$$

$$\left[p_T\Delta P_T\cos(\phi-\phi_j) + \frac{1}{3}m_T\Delta M_T\cosh(y-y_j)\right]$$

An Estimate of Backreaction

One body distribution has negative contributions at large azimuthal separation



Background diminished w.r.t unperturbed hydro for that region in space

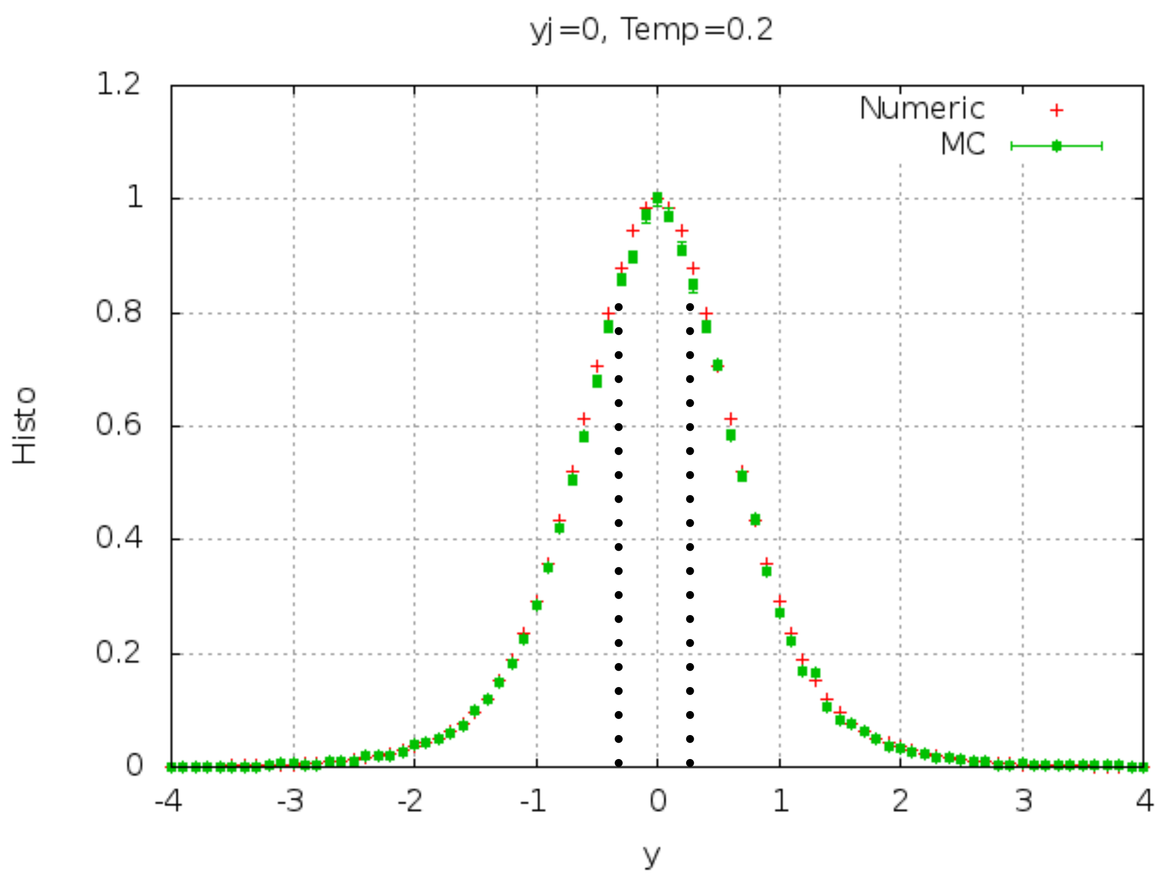
Need to emulate experimental background subtraction

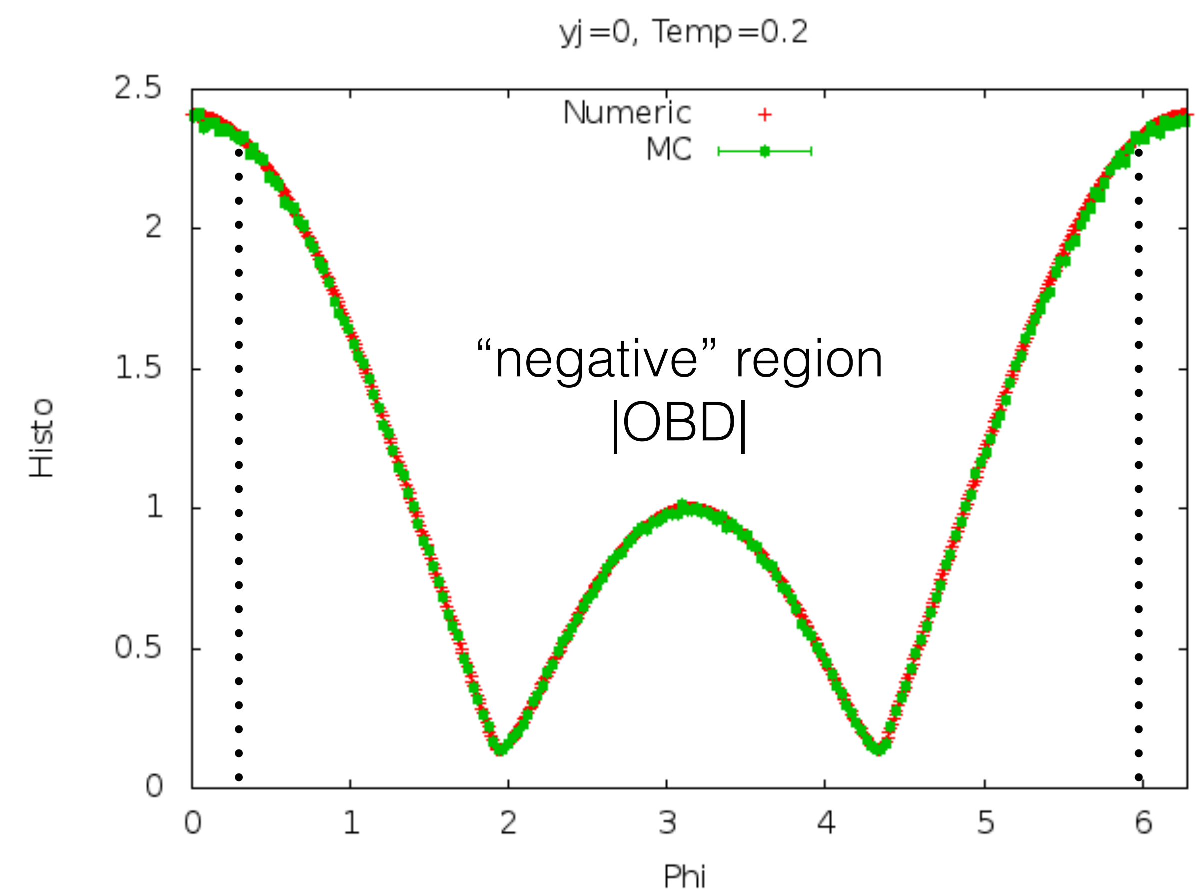
Add background,
embed jets,
subtract background

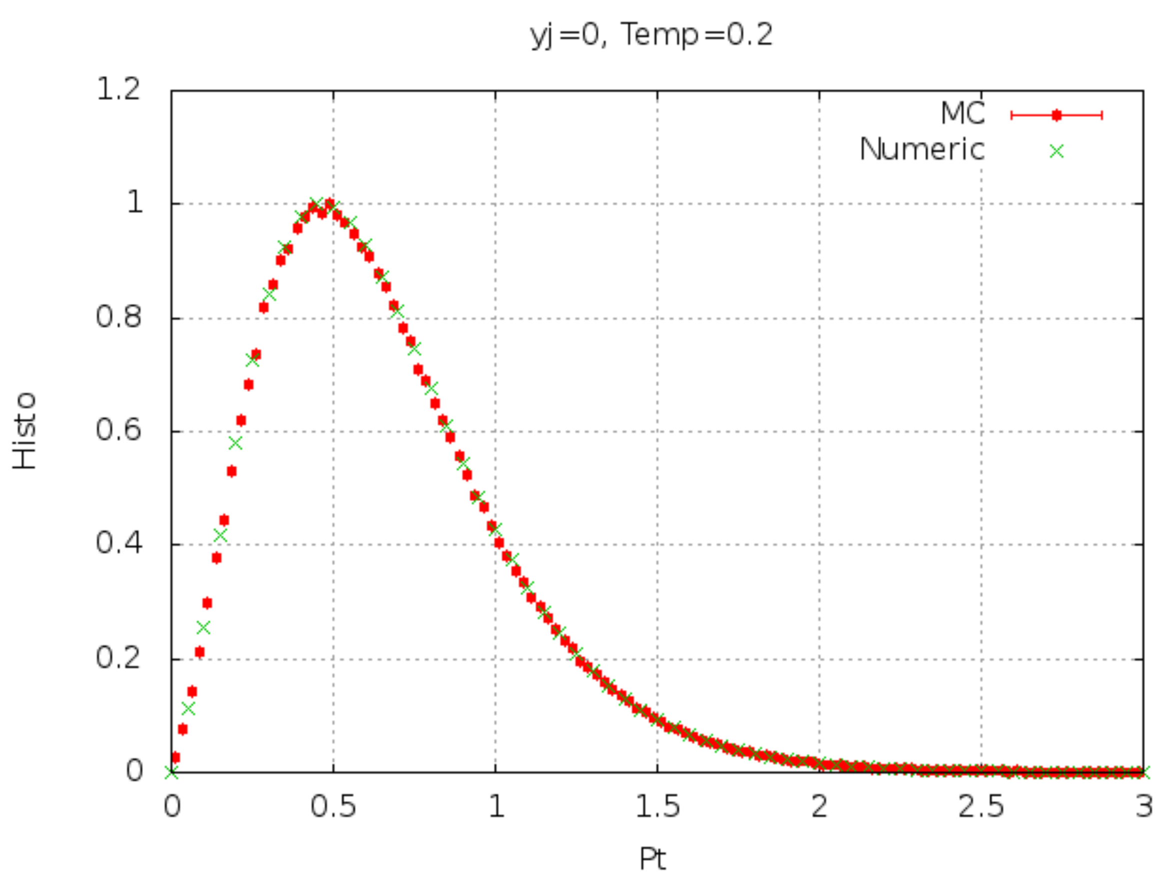
Event by event, determine the extra particles distribution enforcing energy/momentum conservation

$y_j = 0,\ \phi_j = 0,\ T = 0.2\,\mathrm{GeV}$

Example of the one body distribution







.... $r < 0.3$

- Wide in azimuthal angle
- Wide in rapidity
- Peaked at very low transverse momentum

$y_j = 0,\ \phi_j = 0,\ T = 0.2\,\mathrm{GeV}$

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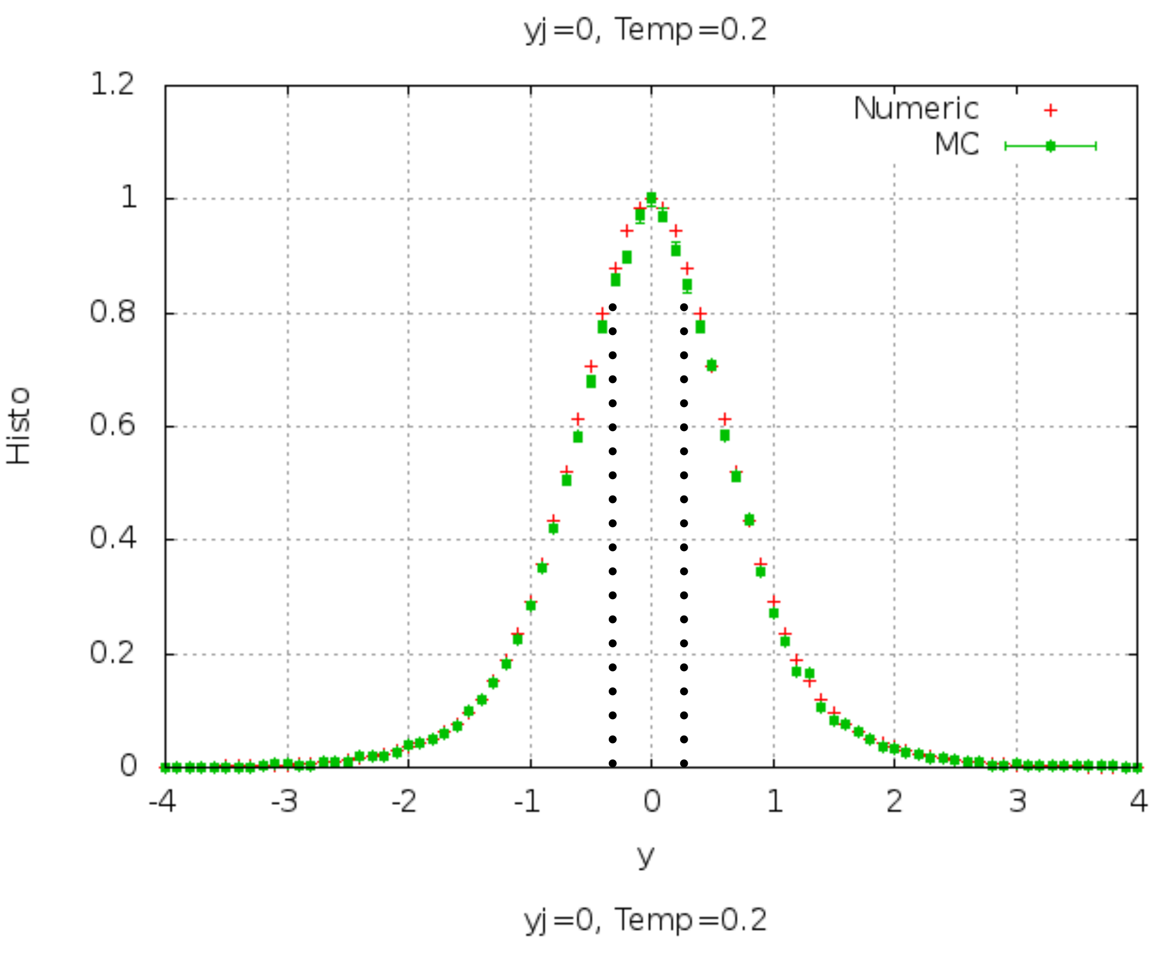

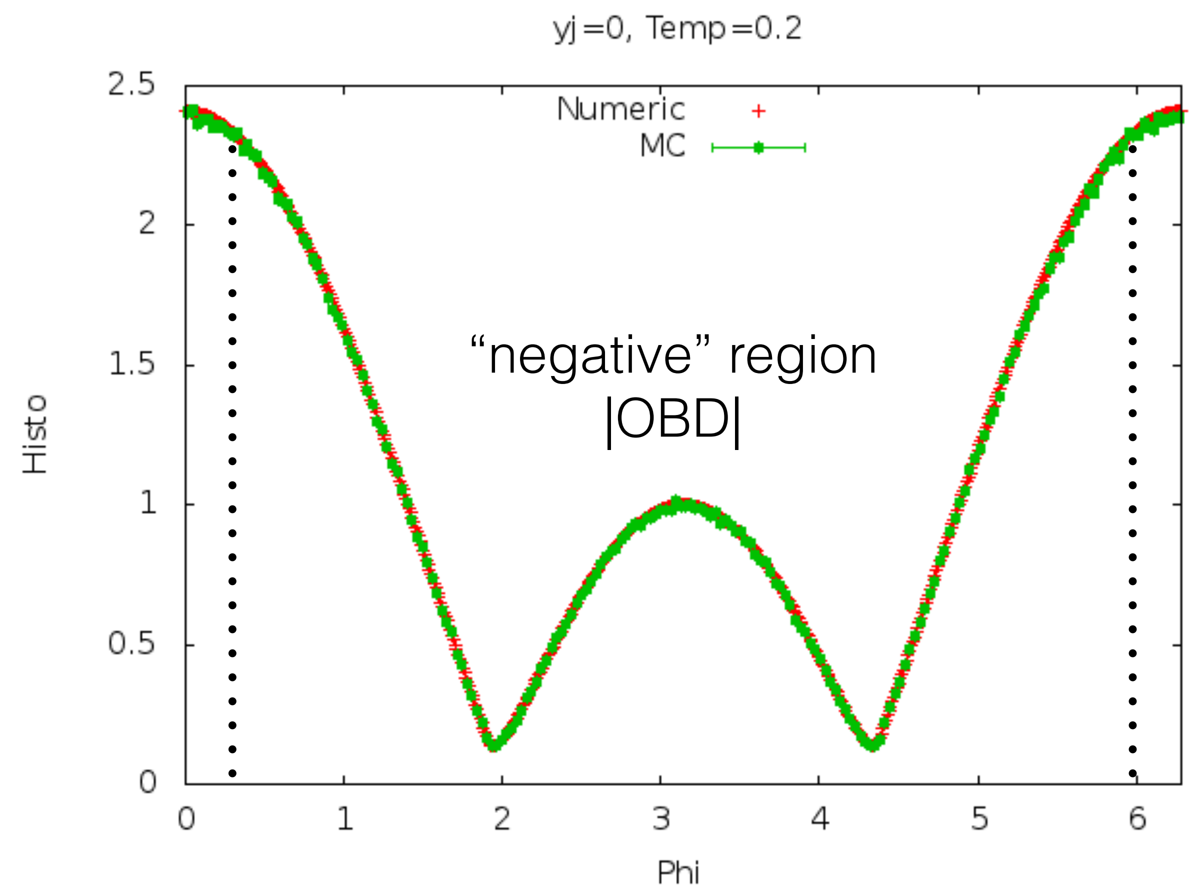

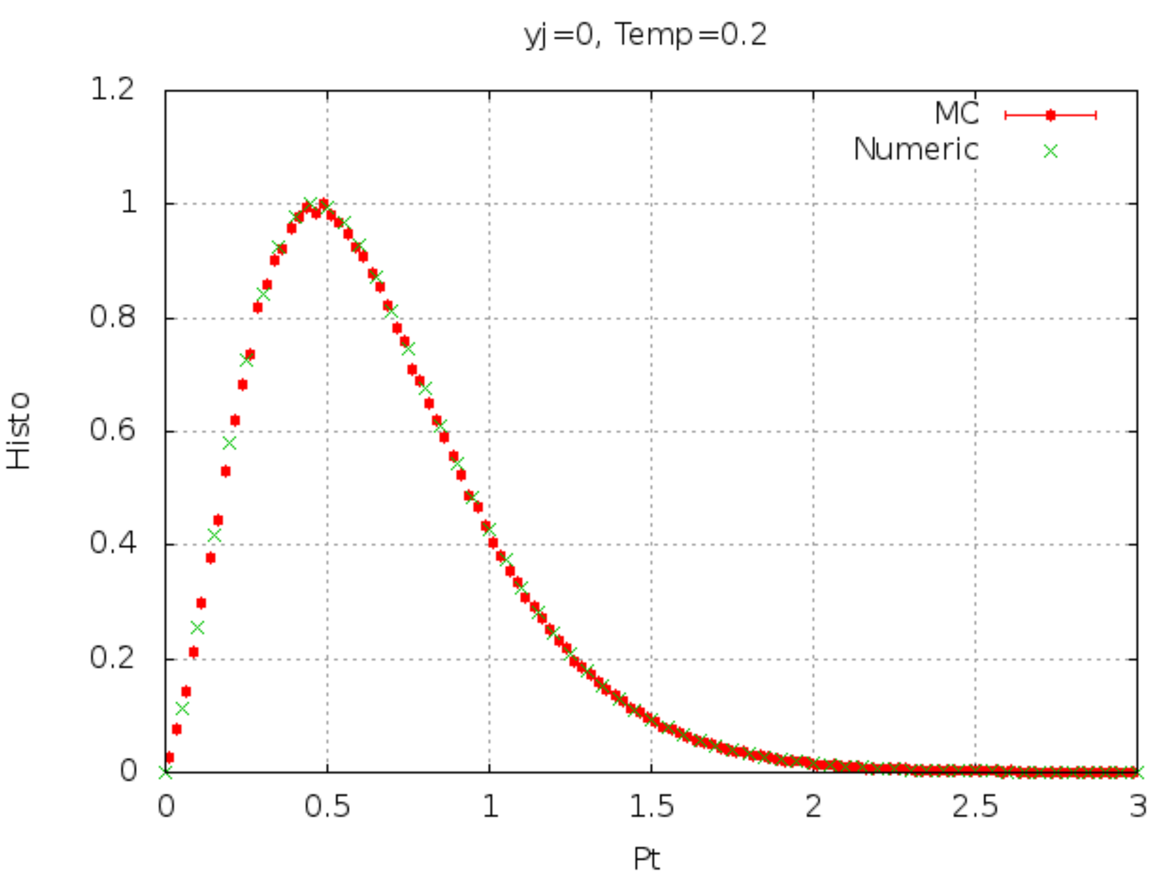

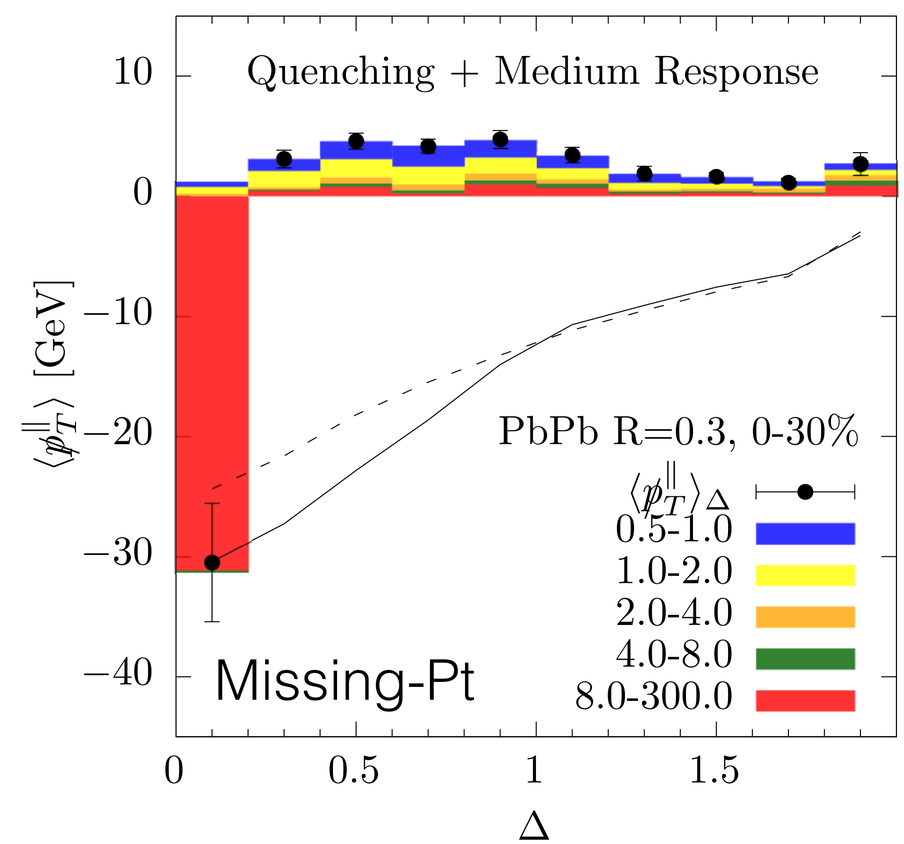

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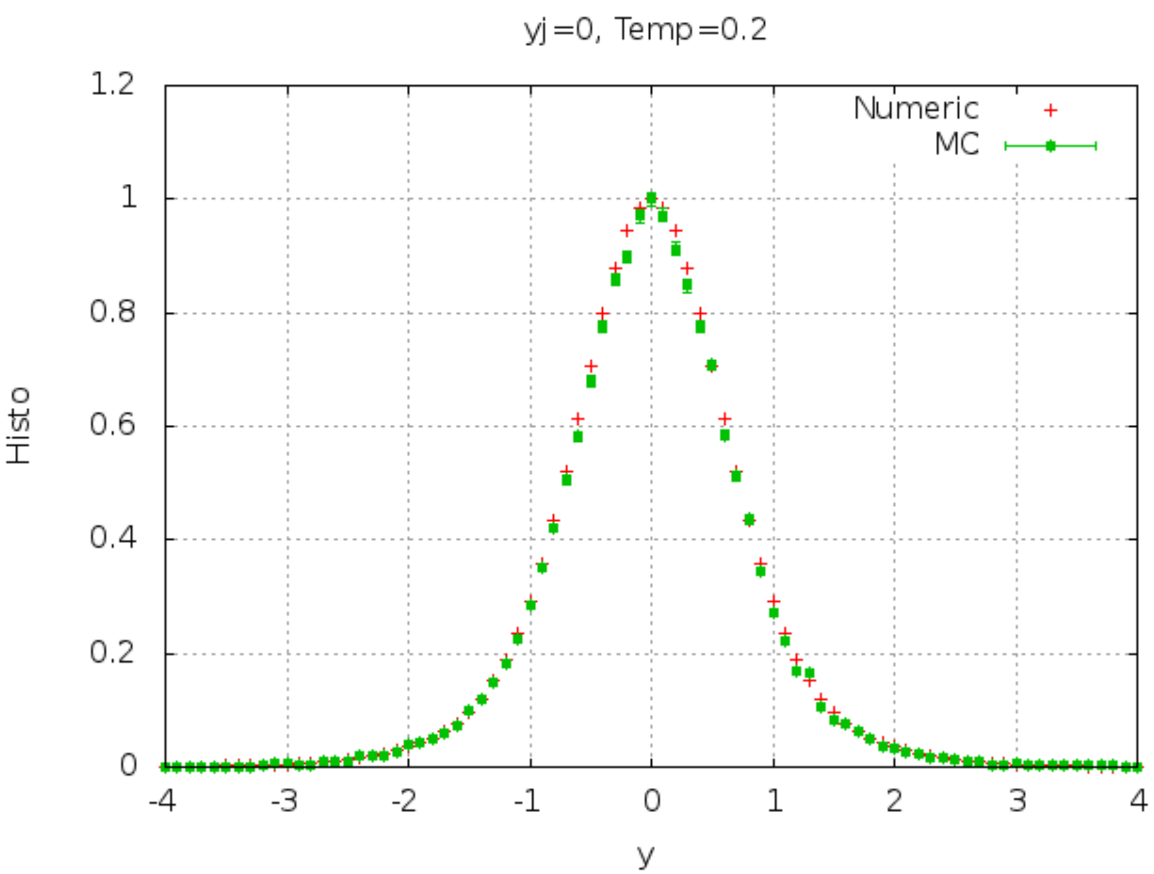
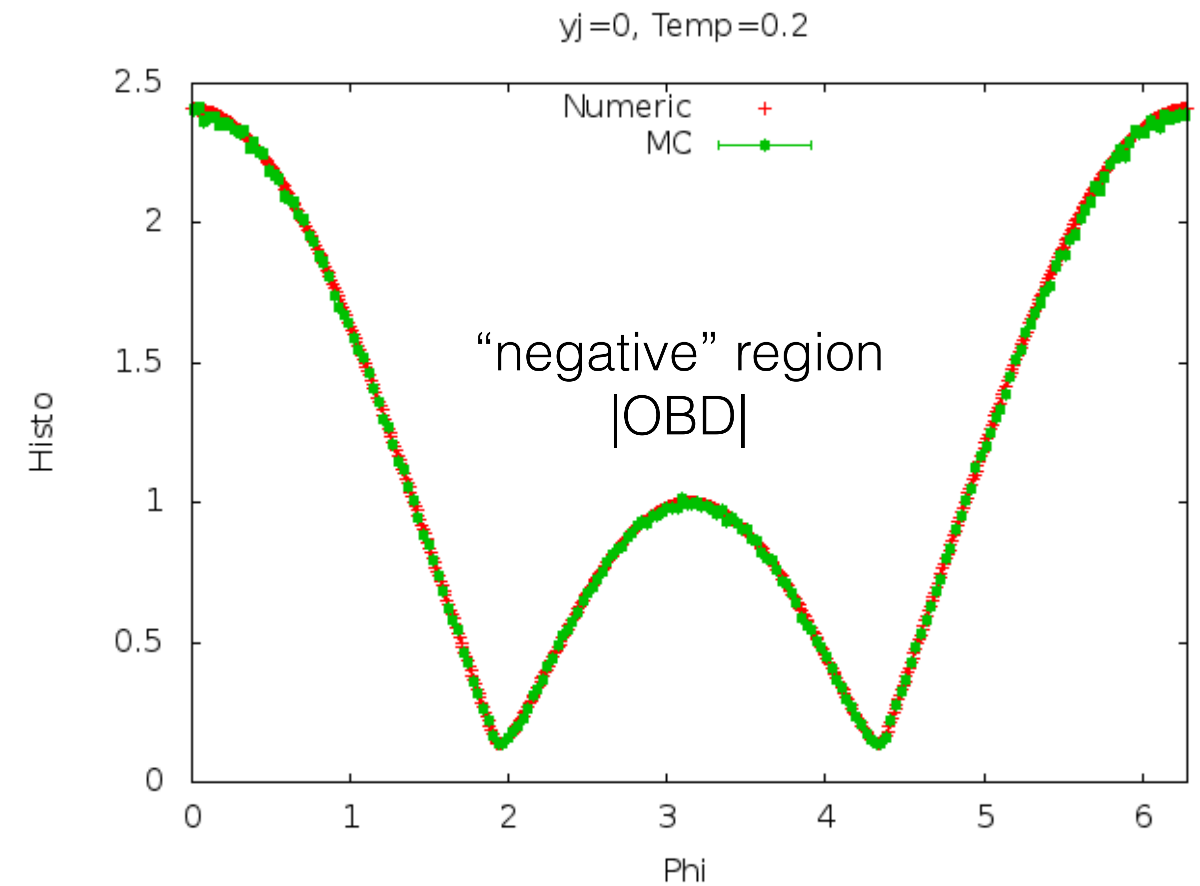
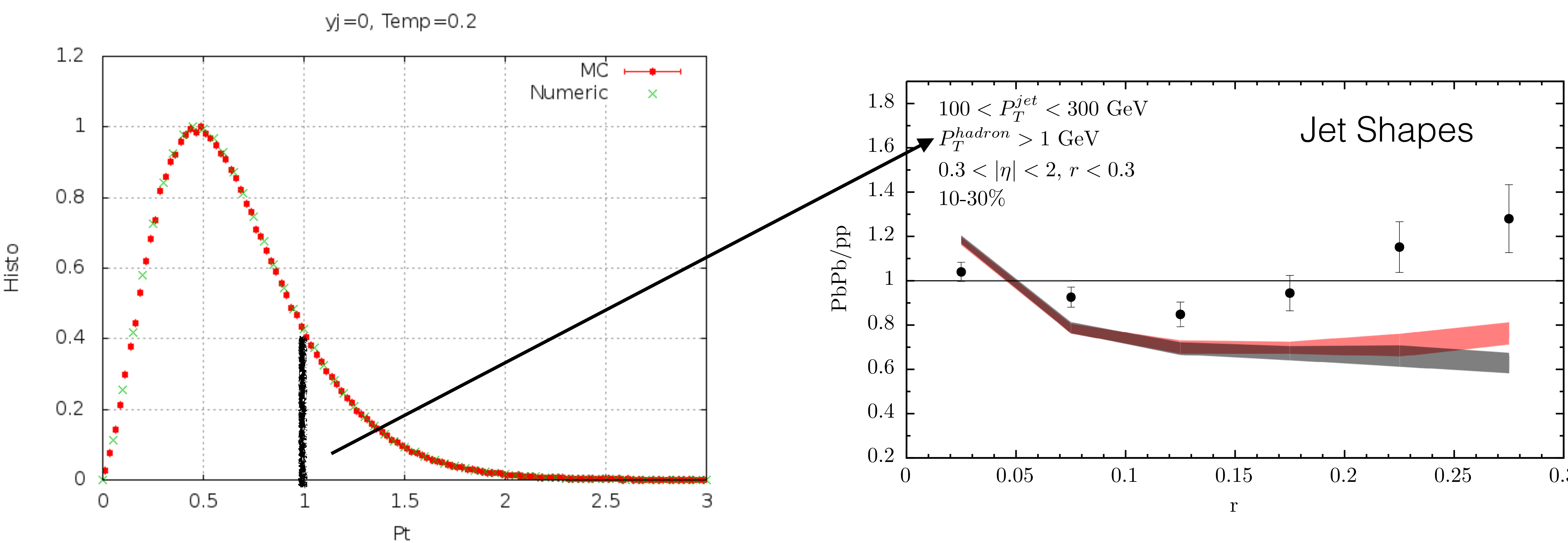






EbE energy-momentum conservation

1. Generate a list of particles according to OBD until the sum of their energies reaches ΔE. “Positive” adds, “negative” subtracts (same for momentum)

2. Select a random particle and regenerate its momentum with OBD (don’t allow “positive” or “negative” status change)

3. If the change increases “pass” function, accept it. Else, accept it with a probability

$$W(p^{\mu}_{\text{new ensemble}}) = \frac{e^{-\left(p^{\mu}_{\text{new ensemble}} - \Delta P^{\mu}\right)^2}}{e^{-\left(p^{\mu}_{\text{ensemble}} - \Delta P^{\mu}\right)^2}}$$

4. Iterate until all components of momentum imbalance are within chosen tolerance

$$p^{\mu}_{\text{ensemble}} - \Delta P^{\mu} \, < \, 0.4\,\text{GeV}$$

More on Backreaction

Effective “temperatures” for 0-10%

Consider just pions and protons for simplicity

$$T_\pi(p_T) = \begin{cases} 0.19\ \mathrm{GeV} & \text{if } p_T < 0.7\ \mathrm{GeV} \\ 0.21\ \left(\frac{p_T}{\mathrm{GeV}}\right)^{0.28}\ \mathrm{GeV} & \text{if } p_T > 0.7\ \mathrm{GeV} \end{cases}$$

Use these “temperatures” both for the background and the backreaction spectra

$$T_p(p_T) = \begin{cases} 0.15\ \mathrm{GeV} & \text{if } p_T < 0.07\ \mathrm{GeV} \\ 0.33\ \left(\frac{p_T}{\mathrm{GeV}}\right)^{0.3}\ \mathrm{GeV} & \text{if } 0.07\ \mathrm{GeV} < p_T < 1.9\ \mathrm{GeV} \\ 0.4\ \mathrm{GeV} & \text{if } p_T > 1.9\ \mathrm{GeV} \end{cases}$$

Fits ALICE spectra in arXiv:1303.0737

…………………

Use background particles to neutralise “negative” tracks
with an algorithm that maximises energy and angular position coincidence

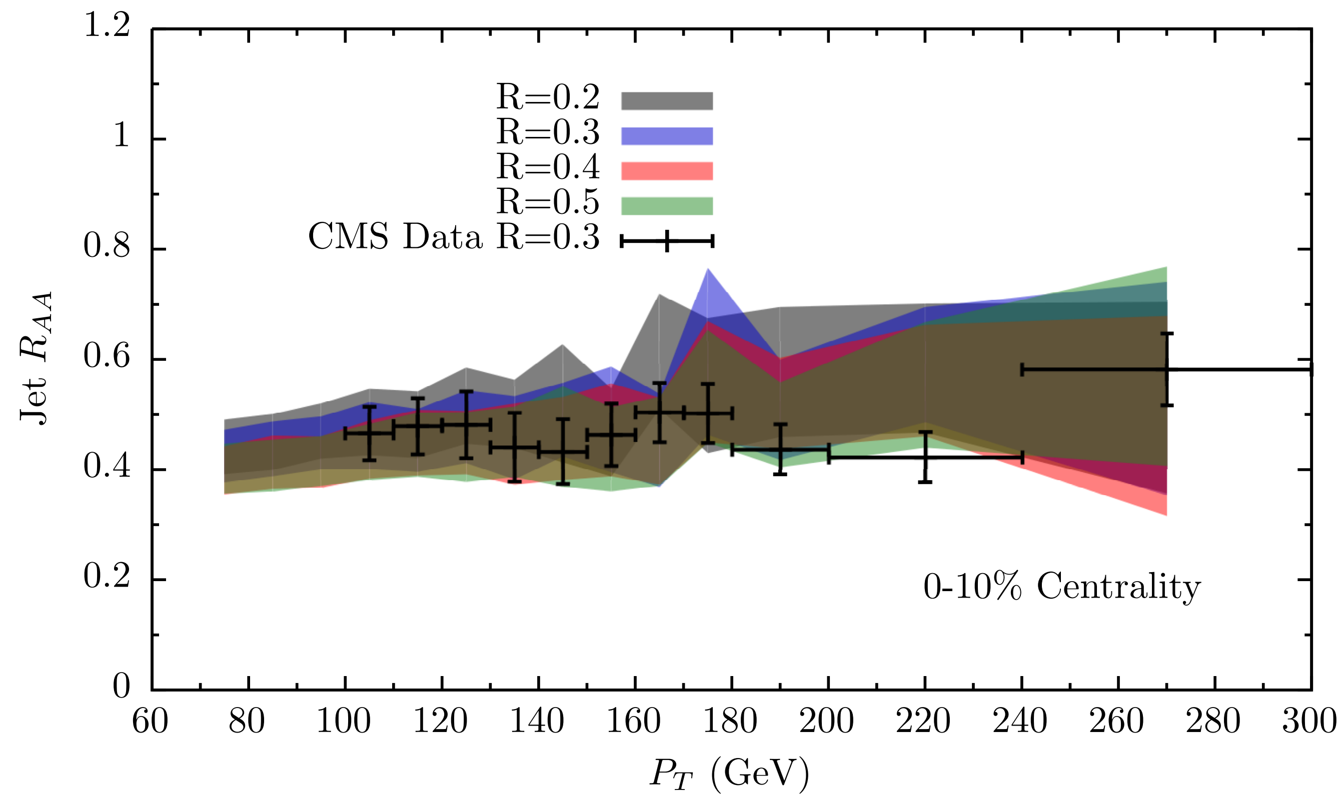
…………………

Emulate to a “reasonable” degree of accuracy
experimental background subtraction (noise/pedestal iteration)
and jet corrections:

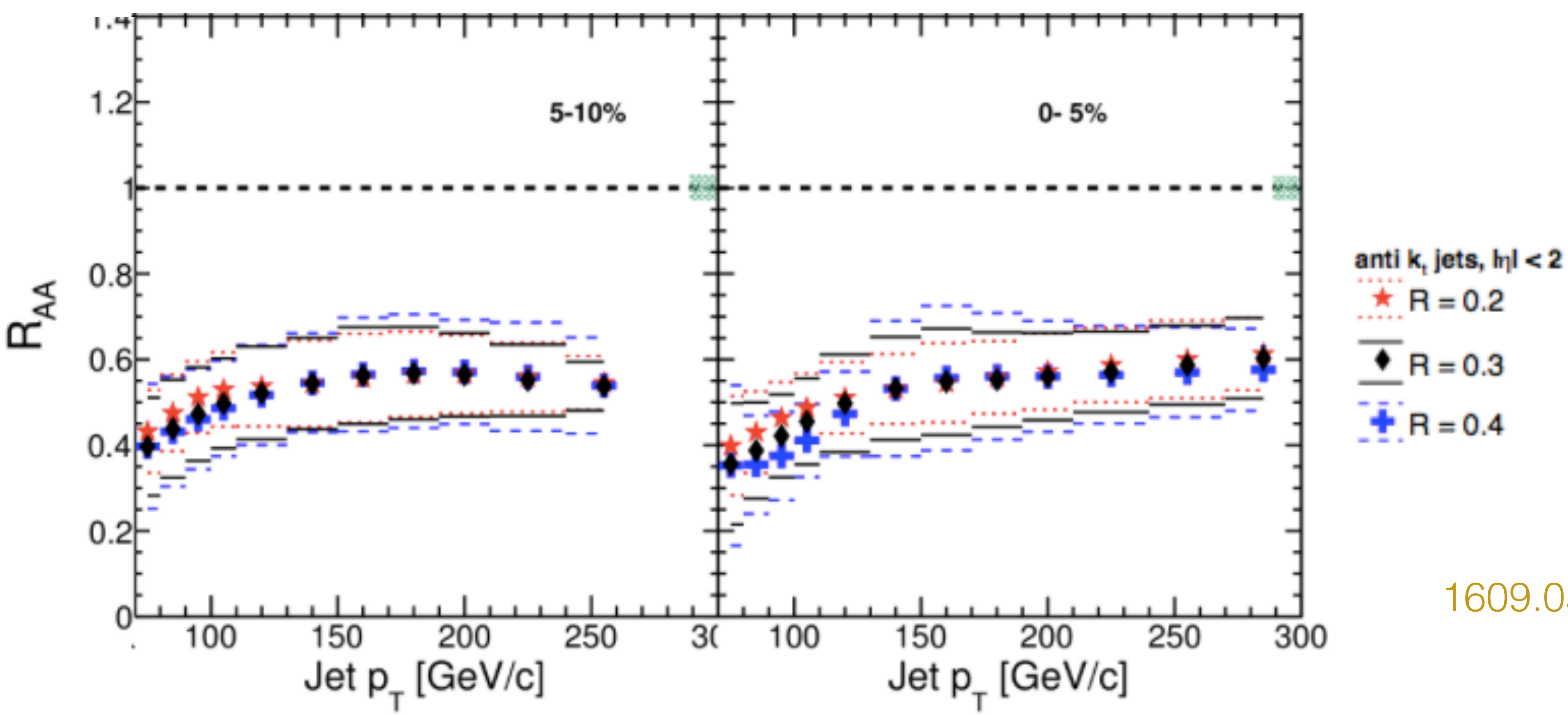
JES, JER, spectra “unfolding”, eta-reflection, etc

Data Comparison

R_{AA} vs R



Consistent with the trend hinted in experiments (?)



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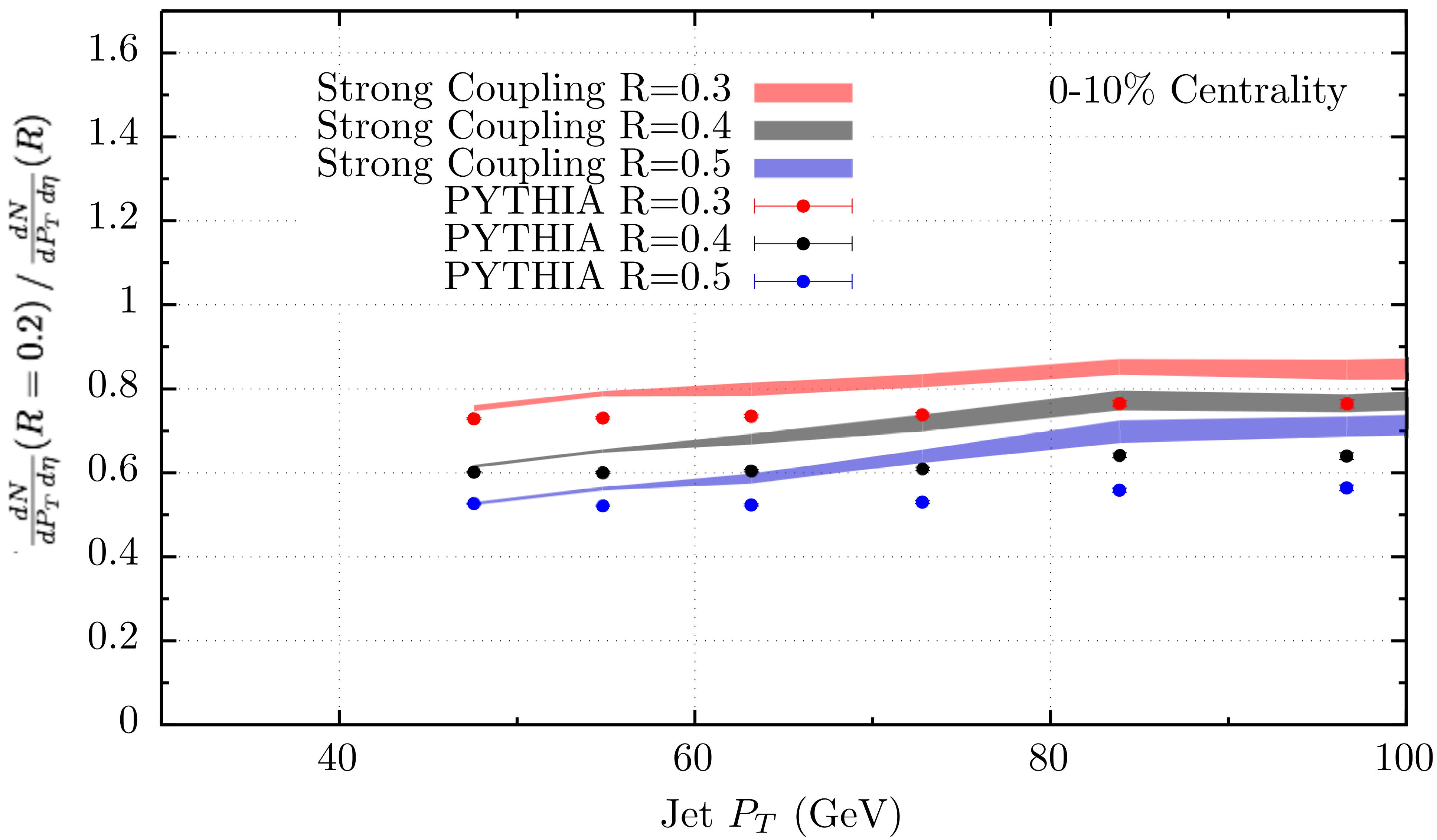
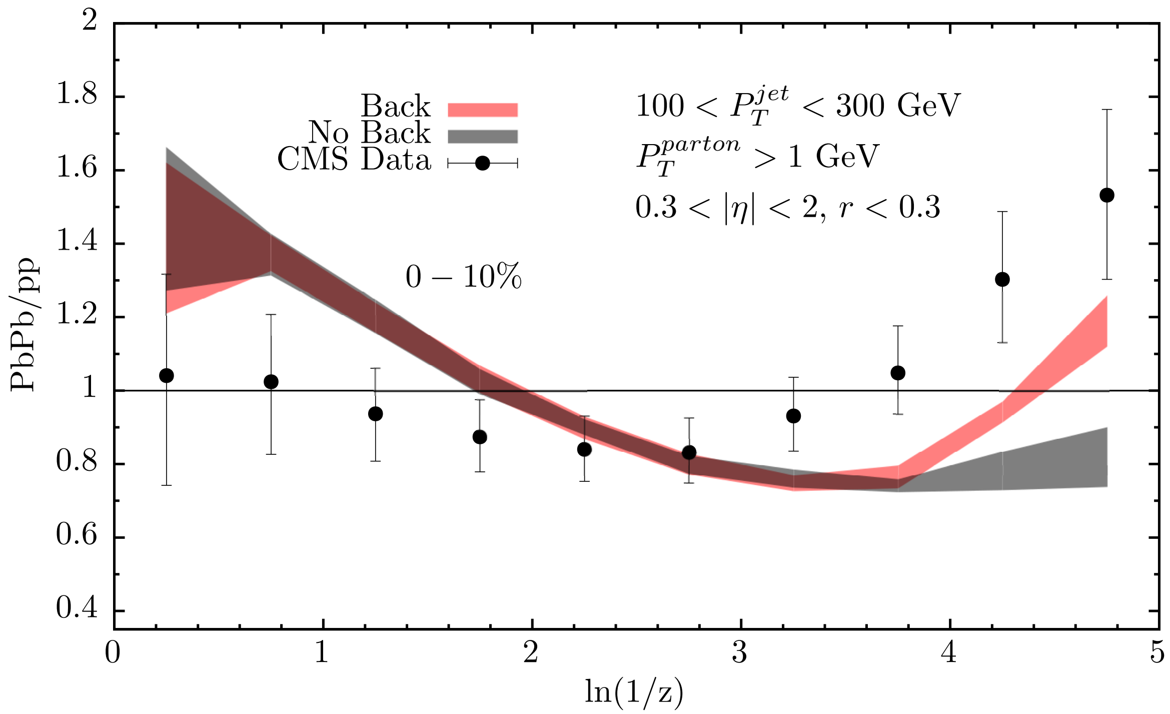
Jet Spectra Ratios

motivated by ALICE analysis arXiv:1506.03984

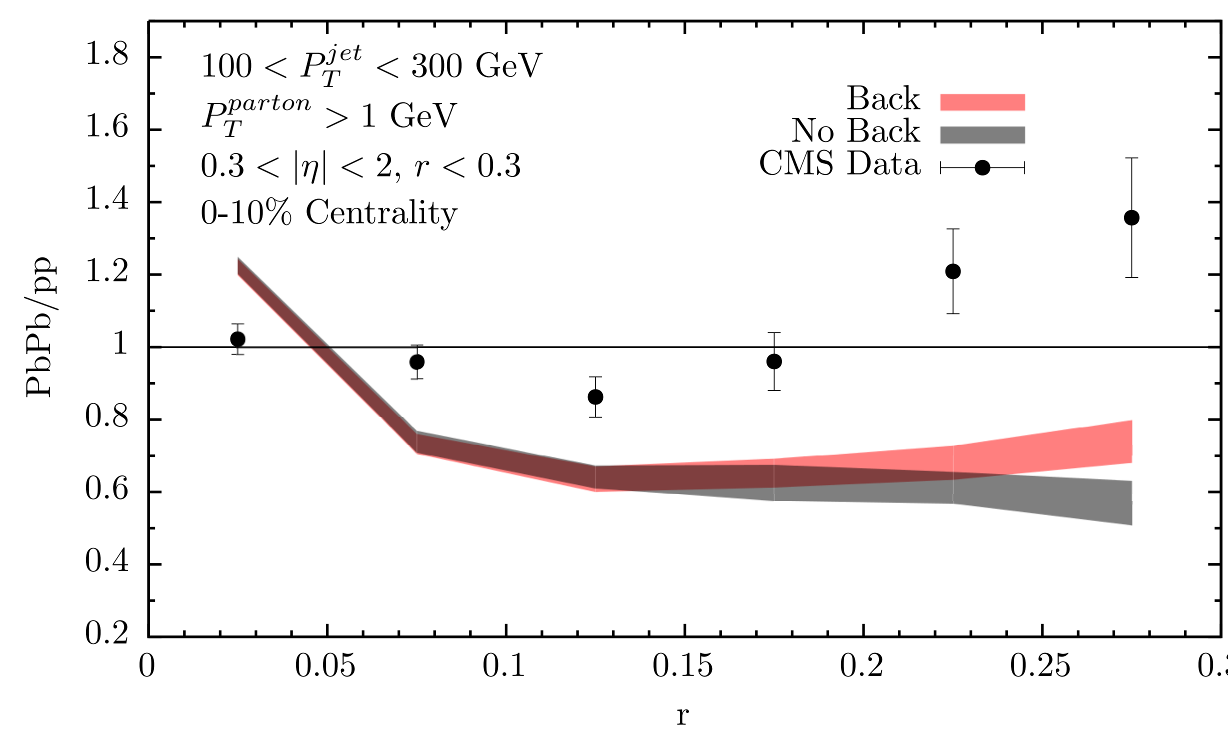


- Higher Pt jets tend to be narrower — increase of ratios with Pt
- Wider jets more suppressed — PbPb ratios always above pp ones
- <#Tracks> increases with Pt — PbPb vs pp separation increases with Pt

Backreaction on Intra-Jet Observables



Fragmentation Functions

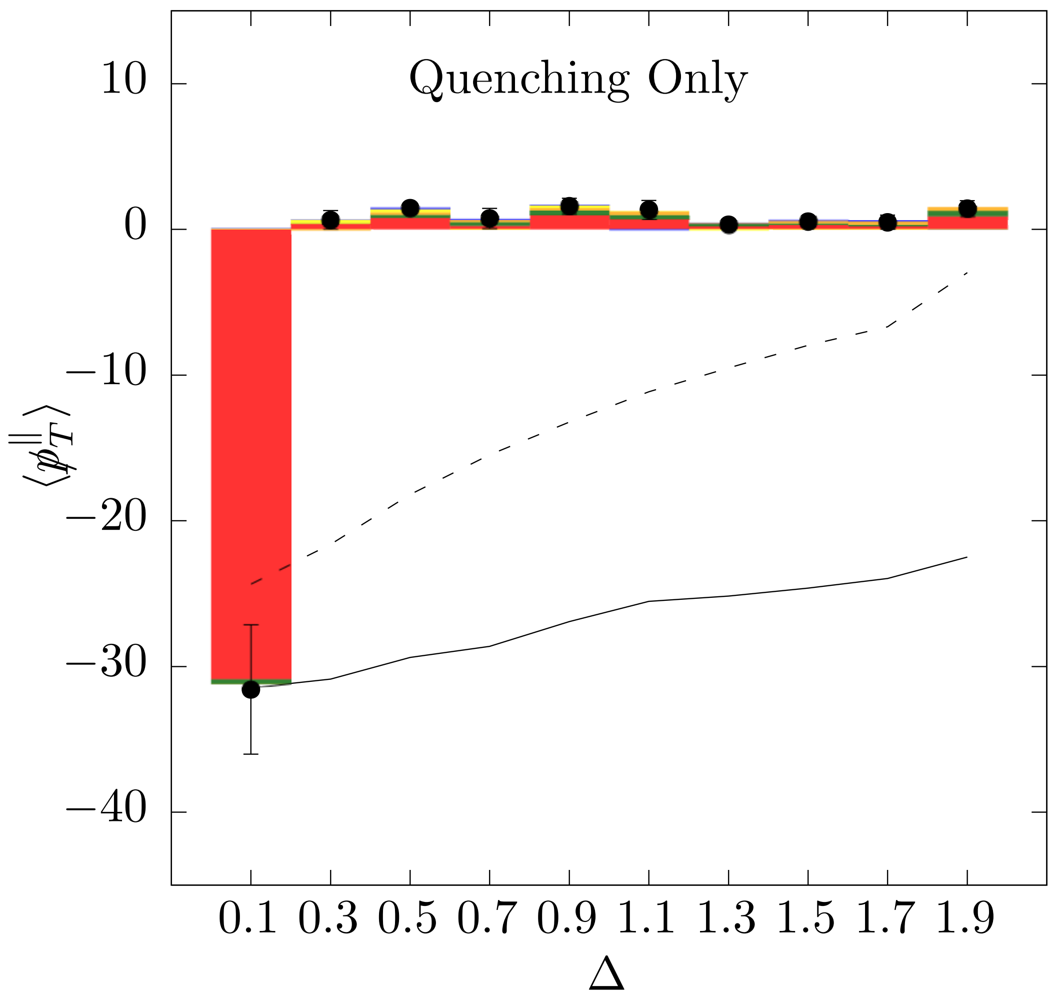


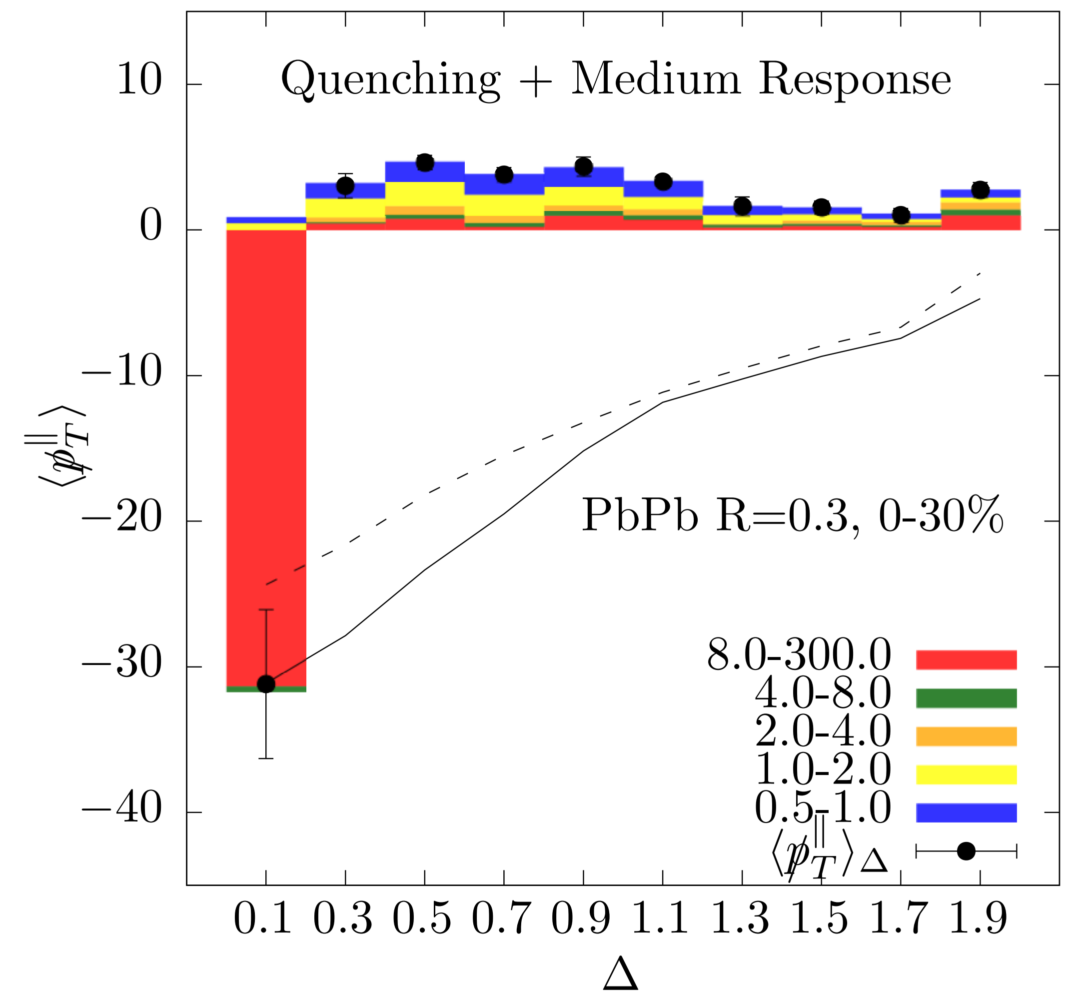
Jet Shapes

- The effect goes in the right direction
- Clearly not enough to explain angular structure

- Oversimplified backreaction?
- Hadronization uncertainties? (medium *and* vacuum)
- Finite resolution effects?

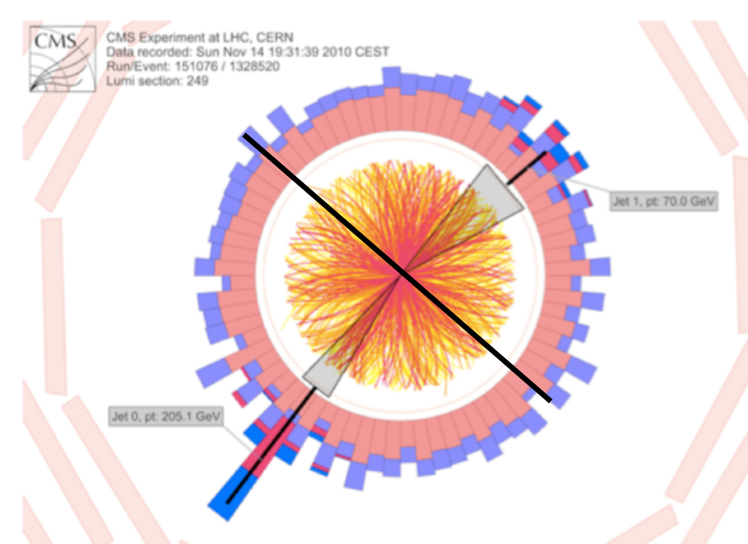
Recovering Lost Energy: Missing Pt





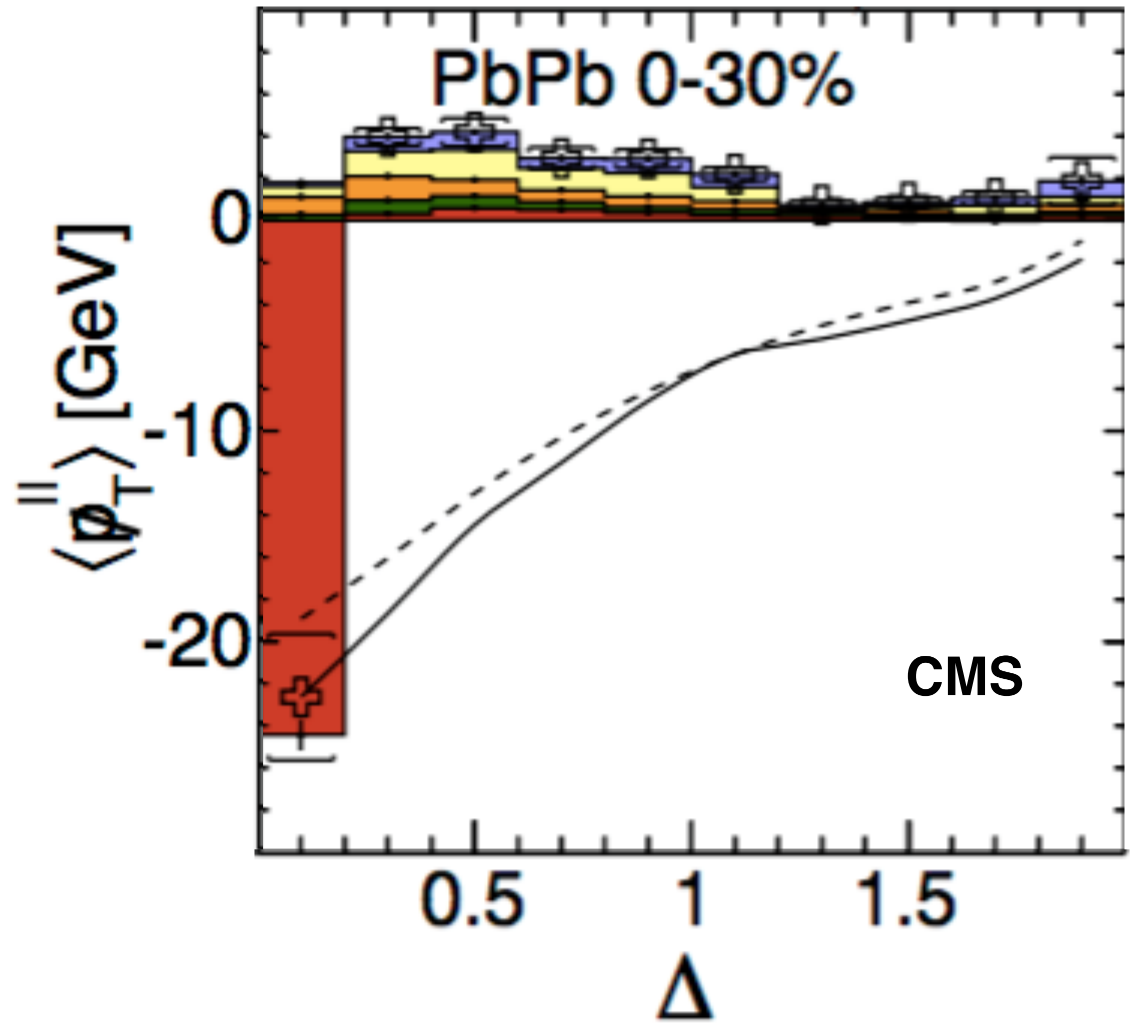
- Energy is recovered at large angles in the form of soft particles

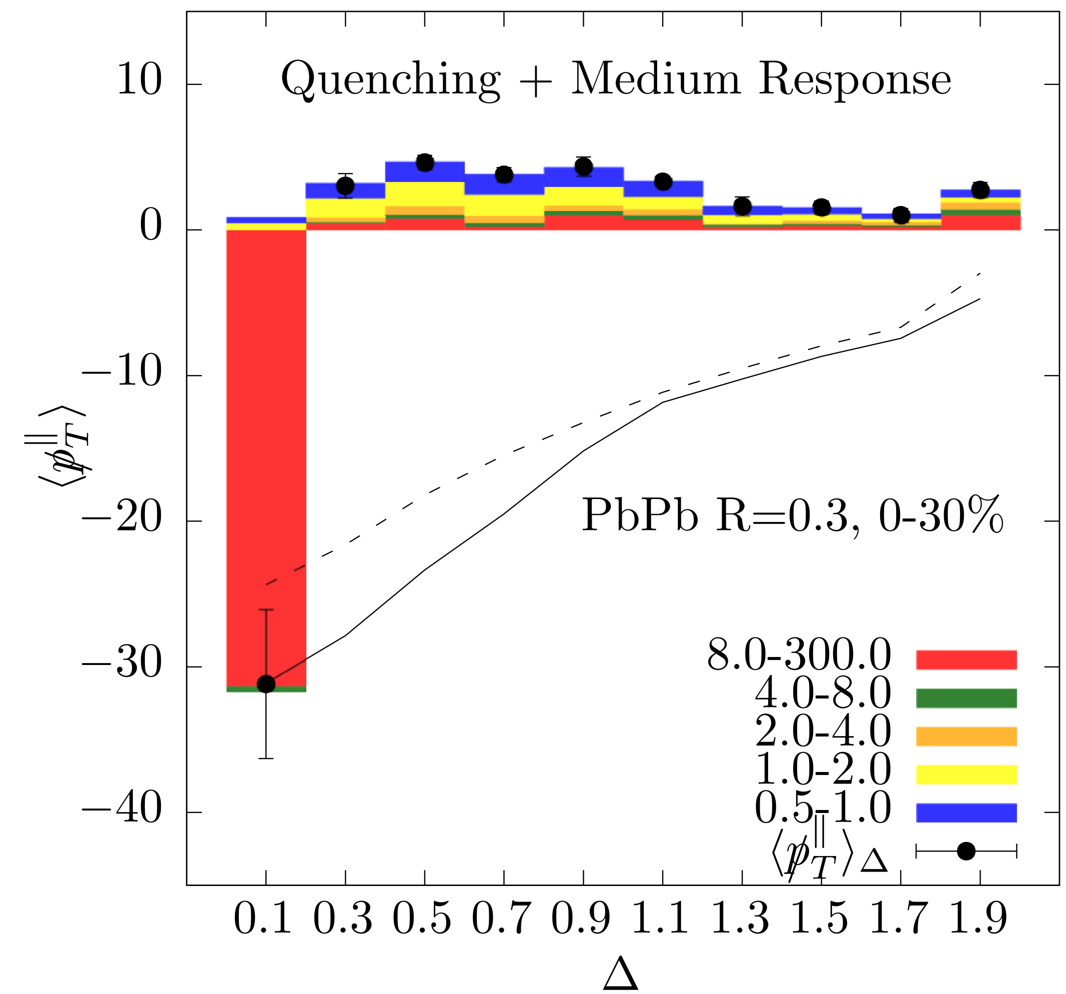
- Adding medium response is essential for a full understanding of jet quenching



Recovering Lost Energy: Missing Pt

CMS-HIN-14-010





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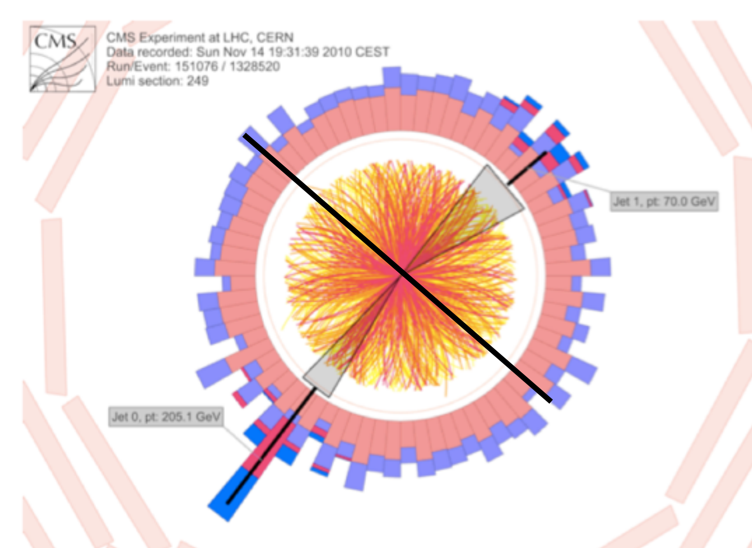

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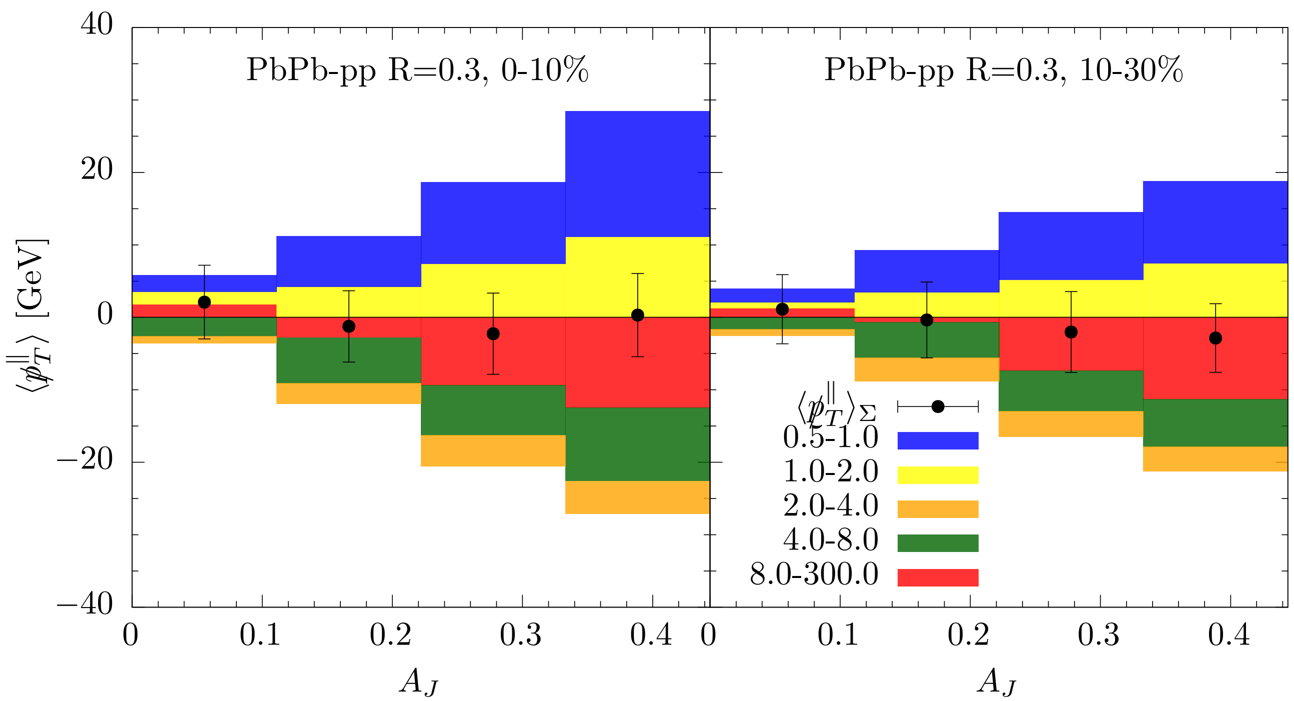
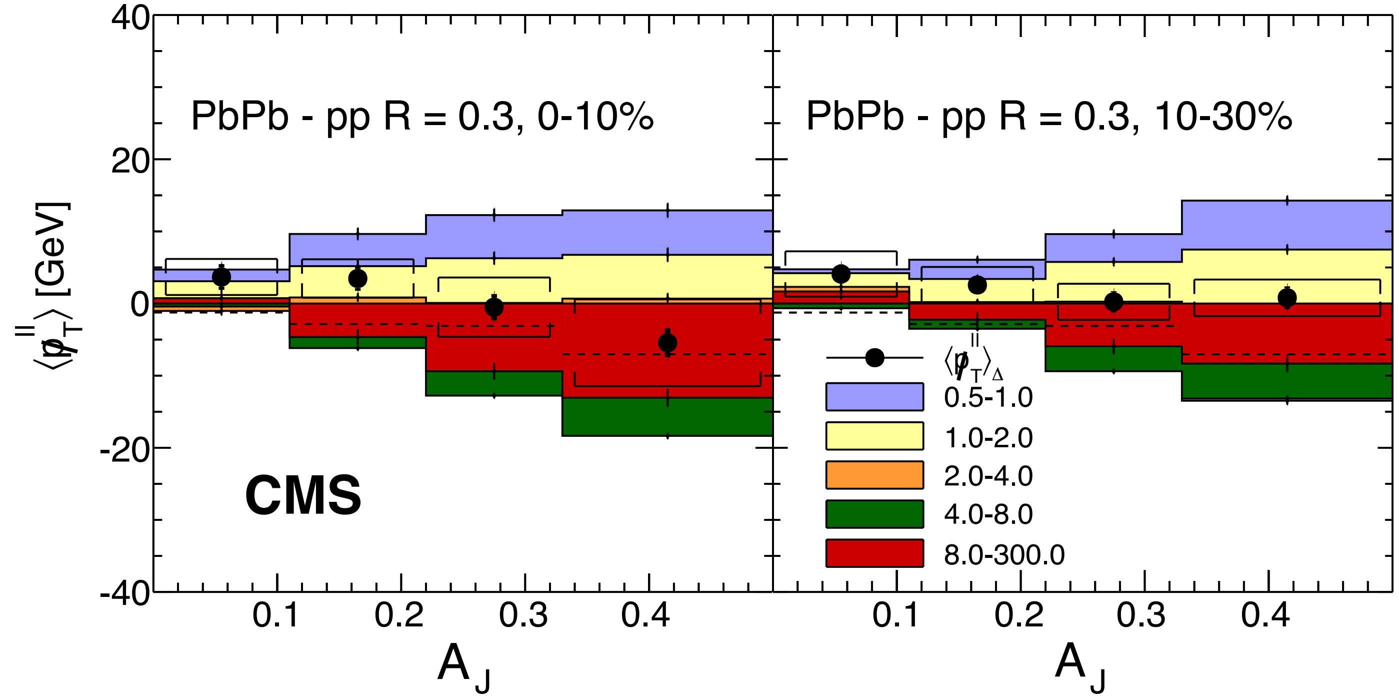
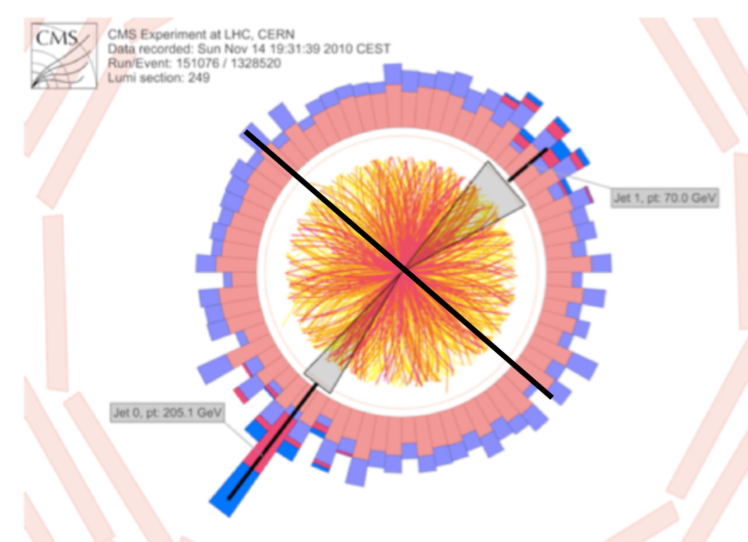


CMS-HIN-14-010

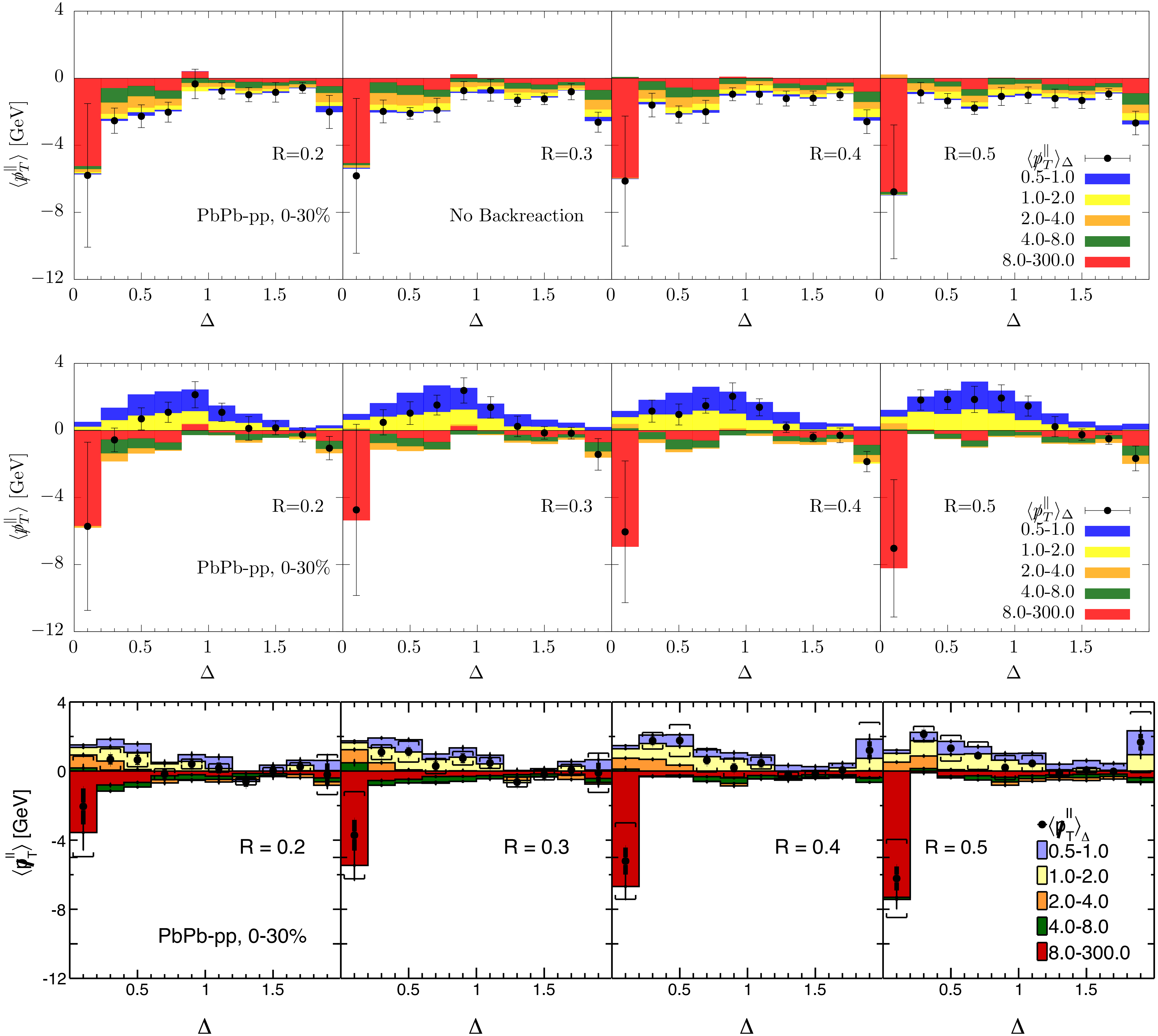


- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side

- Discrepancies w.r.t. data in the semi-hard regime motivate improvements to our model



Jet radius dependence of Missing Pt

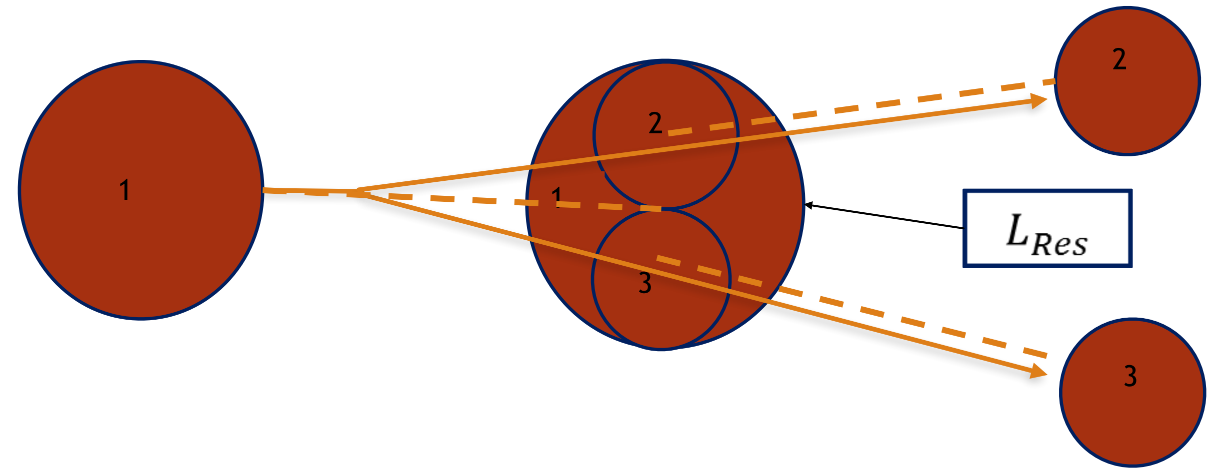


CMS-HIN-14-010

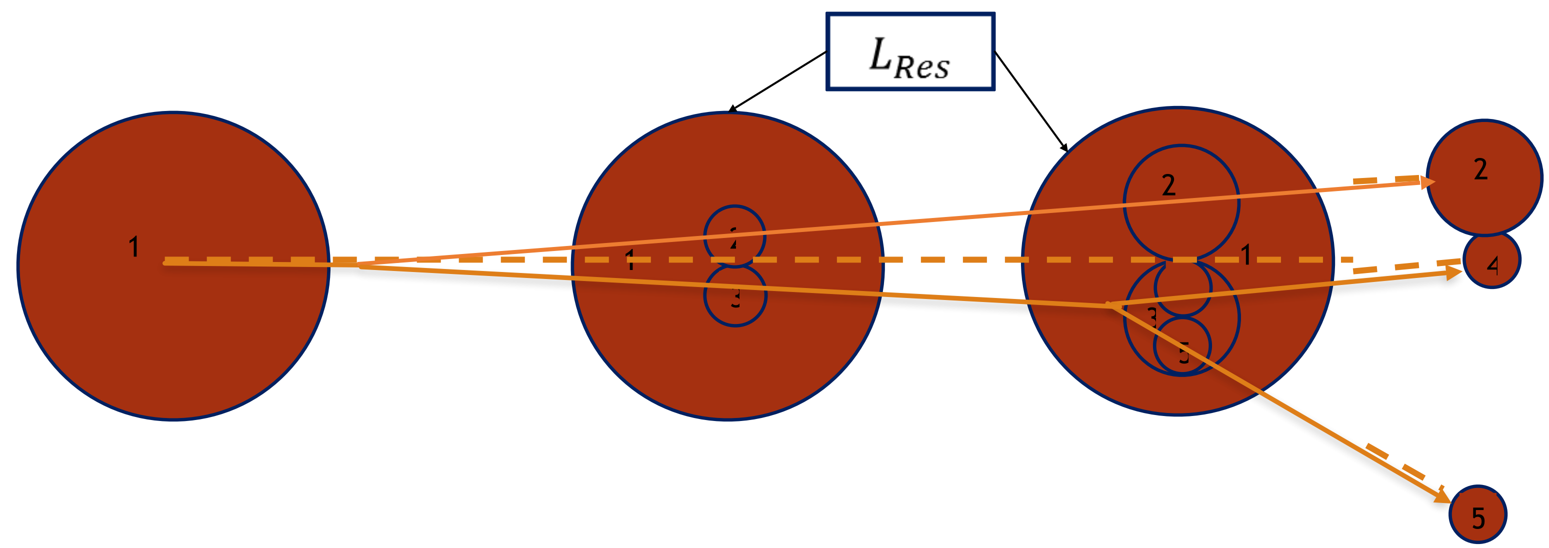
Z. Hulcher, DP,
K. Rajagopal, in progress

Finite Resolution Effects

The QGP cannot resolve sister partons until they are separated a certain distance L_{Res}



If a member of the offspring of a certain parton resolves, then color correlations break and such parton resolves as well



Expect L_{Res} to be comparable to the plasma screening length λ_D

Both weak and strong coupling give approximately $\lambda_D \simeq \dfrac{1}{\pi T}$

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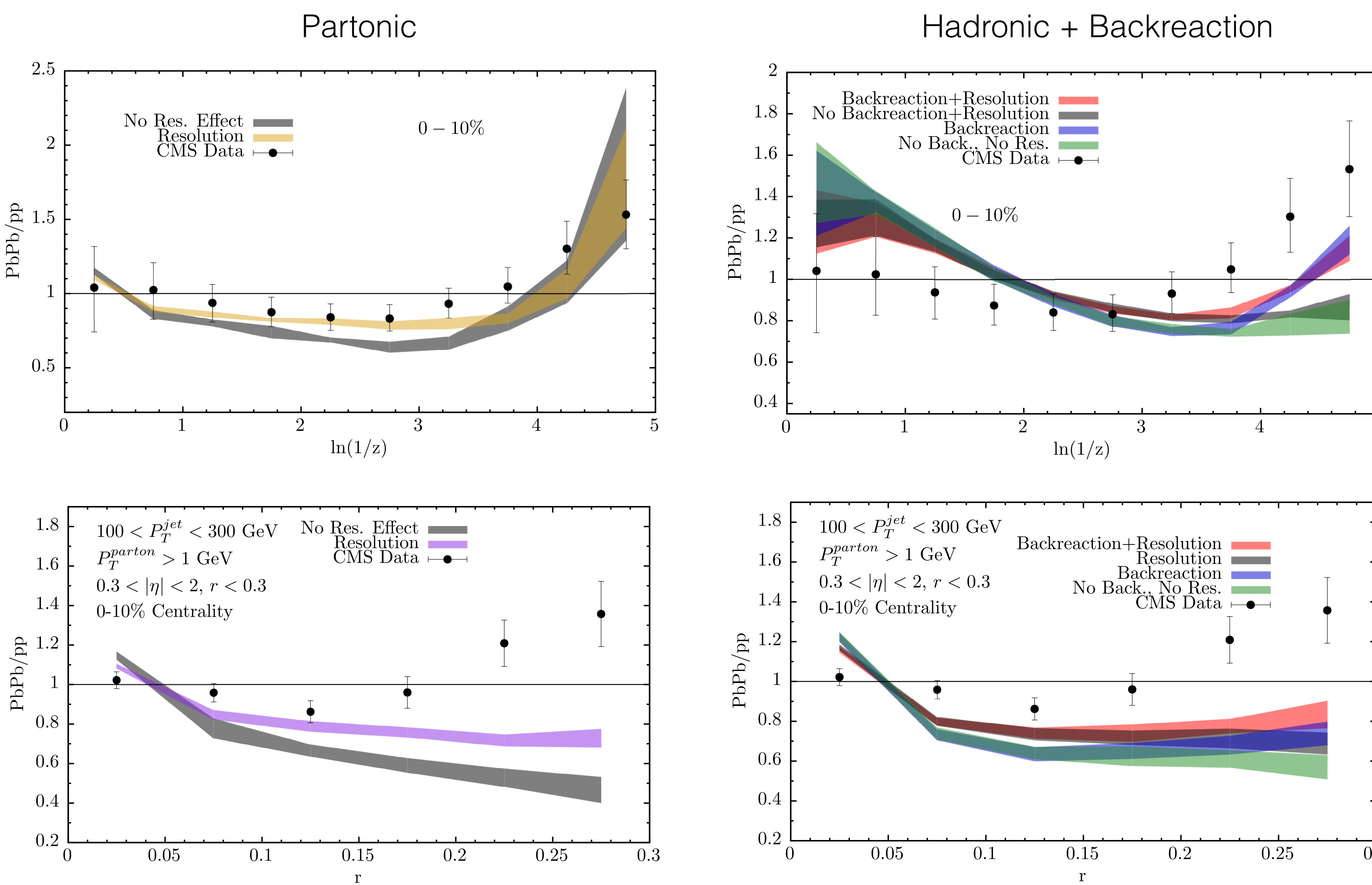
Finite Resolution Effects

PRELIMINARY



$$L_{\text{Res}} = \frac{1}{\pi T}$$

(had to refit κ_{sc} to the10% level)