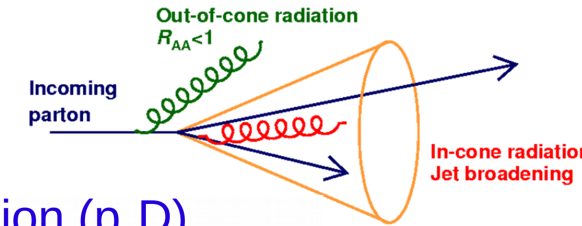
Jet mass measurements in Pb-Pb and p-Pb collisions

Hard Probes 2016

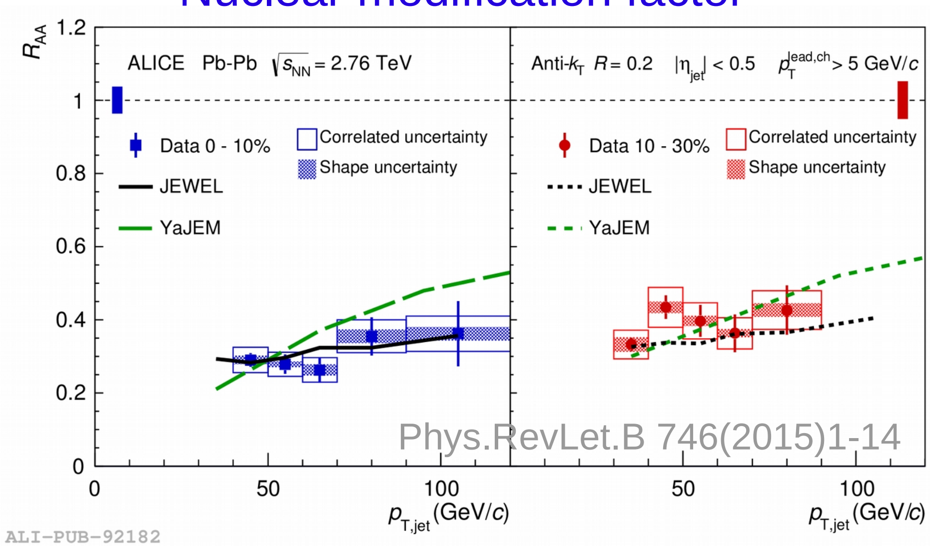
Chiara Bianchin for the ALICE Collaboration

In-medium energy loss

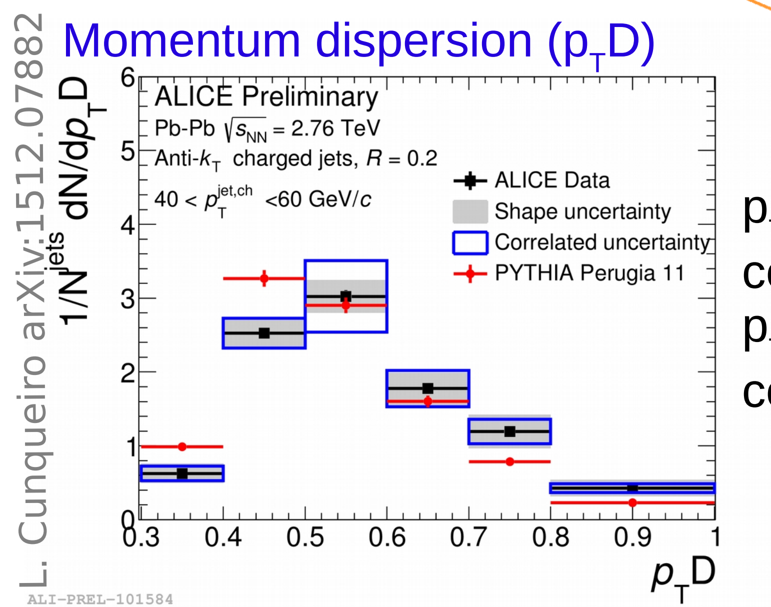
- Hard partons lose energy travelling through the medium
  - Outside → the energy is “lost”, pp-like jets
  - Gluon radiation inside the jet cone → jet broadening



Nuclear modification factor



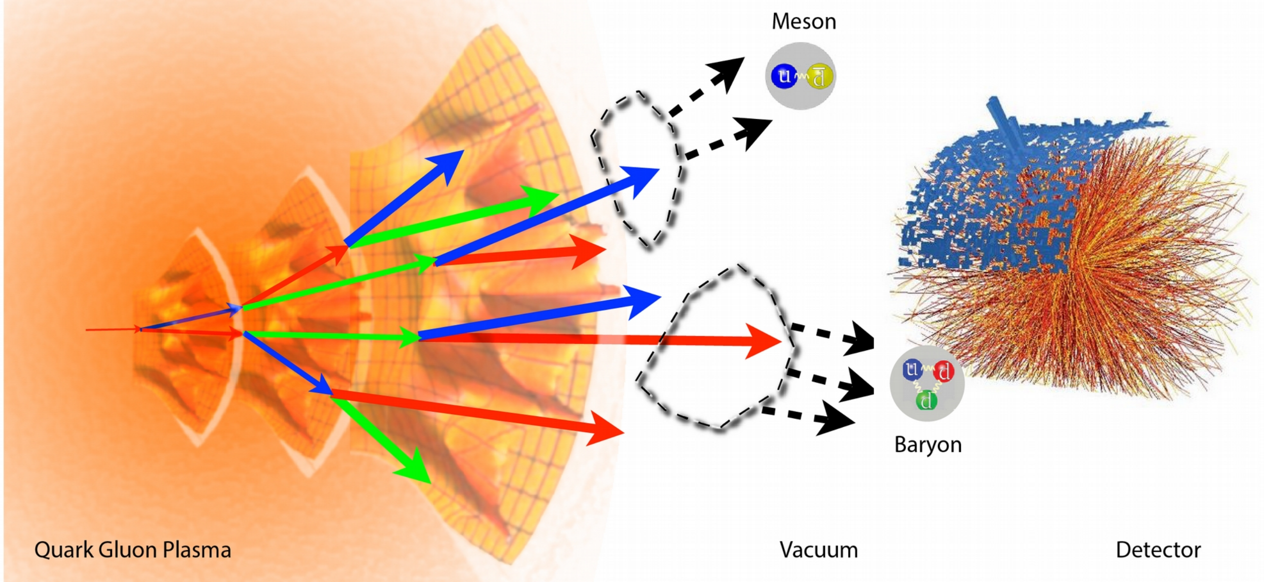
Momentum dispersion (p_TD)



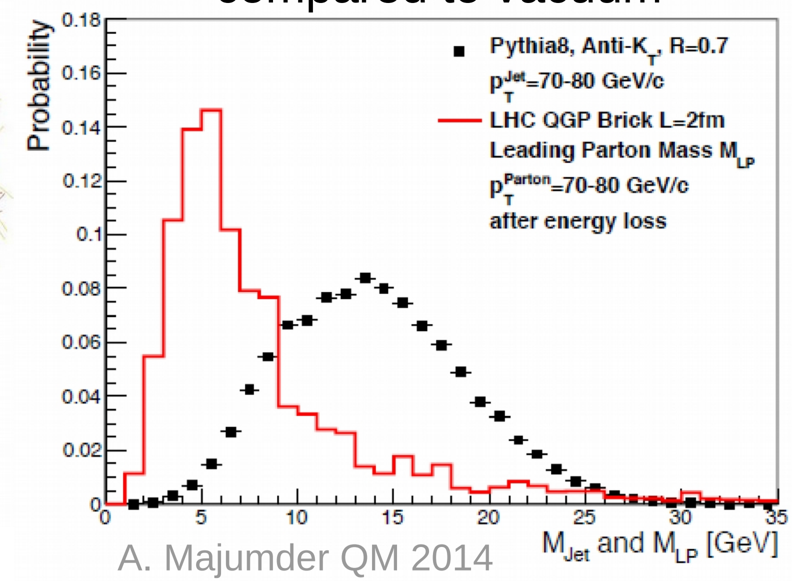
p_TD ~ 1 *few* constituents
p_TD ~ 0 *many* constituents

- Jet yield suppressed (R_{AA} < 1) as much as charged hadrons
  → Large fraction of energy lost out-of-cone
- Jet shapes describe the internal structure of jets
  → e.g. p_TD suggests more collimated jets than PYTHIA

Virtuality evolution



Mass of the LP in a medium in case of radiation at large angle compared to vacuum



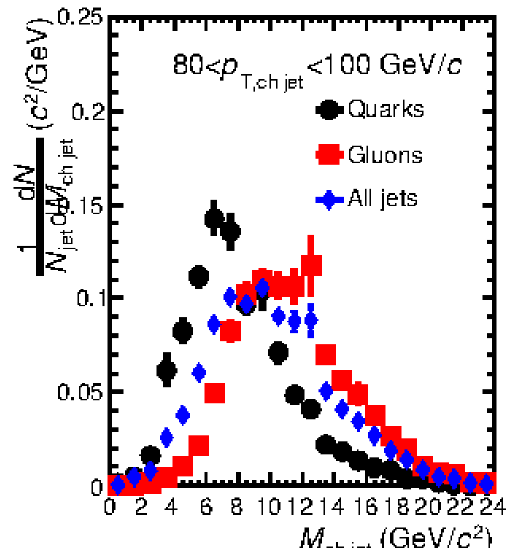
- In hard scattering processes the leading parton (LP) is usually produced off-shell, its off-shellness is the **virtuality ~ jet mass**
  - In vacuum, parton virtuality decreases at each emission
  - In a medium, parton virtuality can rise due to scatterings

Jet mass and virtuality

$$M = \sqrt{p^2 - p_T^2 - p_z^2} \qquad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i \qquad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

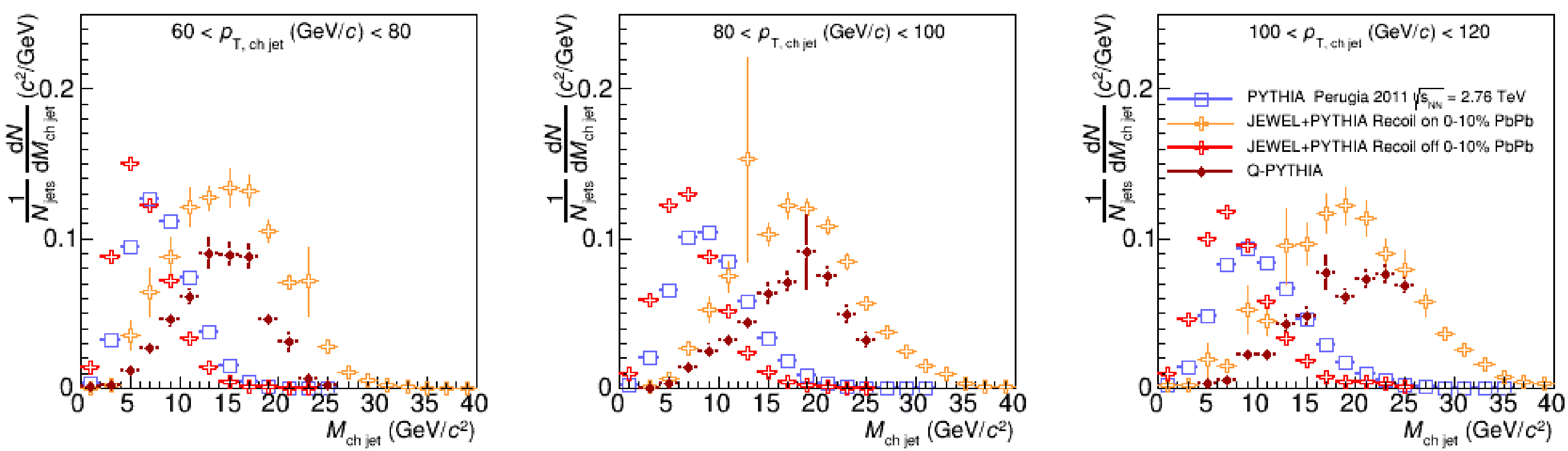
- Jet mass increases with the radial distance of the constituents from the jet axis
  - Soft constituents, away from the jet axis within the cone → larger mass
  - Few hard constituents → smaller mass

→ E.g. gluon vs quark jets jet mass difference



Model expectations

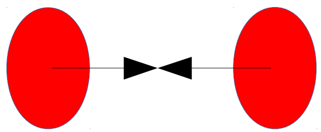
- Quenching models (JEWEL, Q-PYTHIA) show a larger mass than pp-like PYTHIA jets
  - JEWEL: 2→2 pQCD matrix elements with parton shower taking into account radiation
  - Q-PYTHIA: PYTHIA with medium effects in the final state branching through an additive term in the splitting functions computed in the multiple-soft scattering approximation
- JEWEL with "recoil off" (removing recoil centres before hadronization) shows a depletion of the jet mass wrt pp due to less low-p_T fragments wrt recoil on
- Pb-Pb measurement can discriminate among these predictions



JEWEL arXiv:1311.0048, arXiv:1212.1599, private communication Q-PYTHIA Eur.Phys.J.C63:679-690,2009

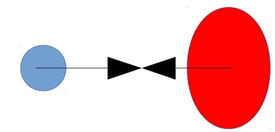
Jet mass analysis strategy in ALICE

Data samples and analysis strategy



- Pb-Pb analysis performed on 2011 ($\sqrt{s_{NN}}$ = 2.76 TeV) min bias sample with centrality trigger, 0-10% central
- Event-by-event background subtracted with derivative and constituent methods

JHEP 0804(2008) 005 Phys. Lett. B659 (2008) 119



- p-Pb analysis performed on 2013 ($\sqrt{s_{NN}}$ = 5.02 TeV) min bias and Emcal jet triggered samples
- Mass sensitive to background even in p-Pb, see later

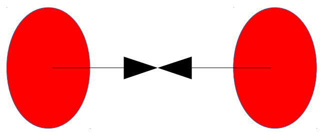
- Charged jets, anti-k_T, E-scheme, R = 0.4, pion mass

M. Cacciari, G. P. Salam and G. Soyez,arXiv:1111.6097

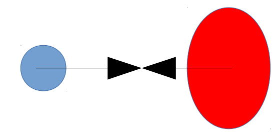
- 2D unfolding technique used to correct to particle level

RooUnfold, CERN–2011–006, pp. 313–318.

Response matrix and embedding



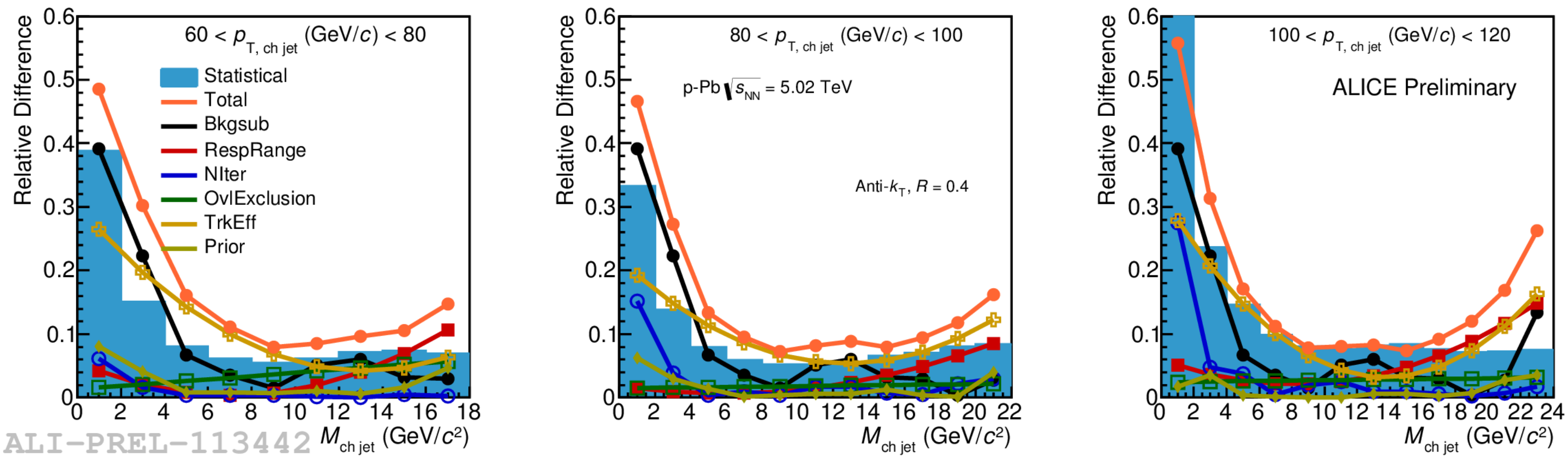
- The response matrix for unfolding is defined embedding PYTHIA events at detector level into data events
- Event-by-event background subtraction with derivative method



- Event multiplicity is small, a PYTHIA event would bias it
  - Embed one track/event
- The response matrix for unfolding is defined embedding 4-vectors corresponding to detector PYTHIA jets into data events
- Background is accounted for in the response (no event-by-event subtraction)

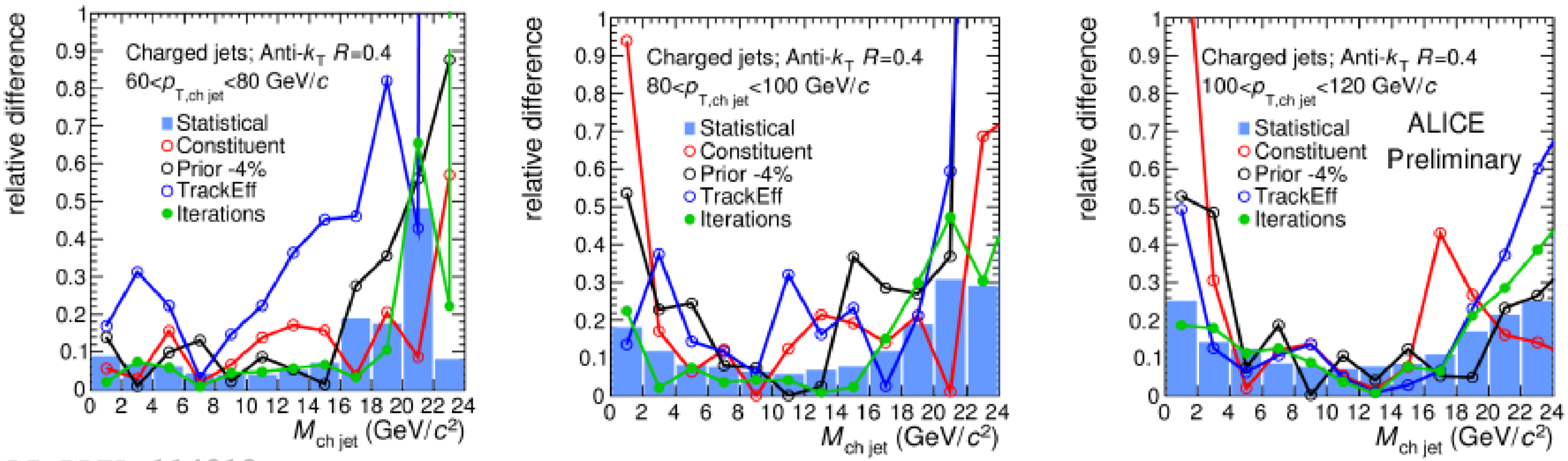
Systematics p-Pb

- Sources
  - Detector effects (tracking efficiency uncertainty)
  - Unfolding (e.g. number of iterations)
  - Background correction (syst variation e-by-e subtraction only)
- Main contributions: background and tracking efficiency uncertainty



Systematics Pb-Pb

- Sources
  - Detector effects (tracking efficiency uncertainty)
  - Unfolding (e.g. number of iterations, priors)
  - Background correction (derivative vs constituent)
- Main contributions: background and tracking efficiency uncertainty, and priors



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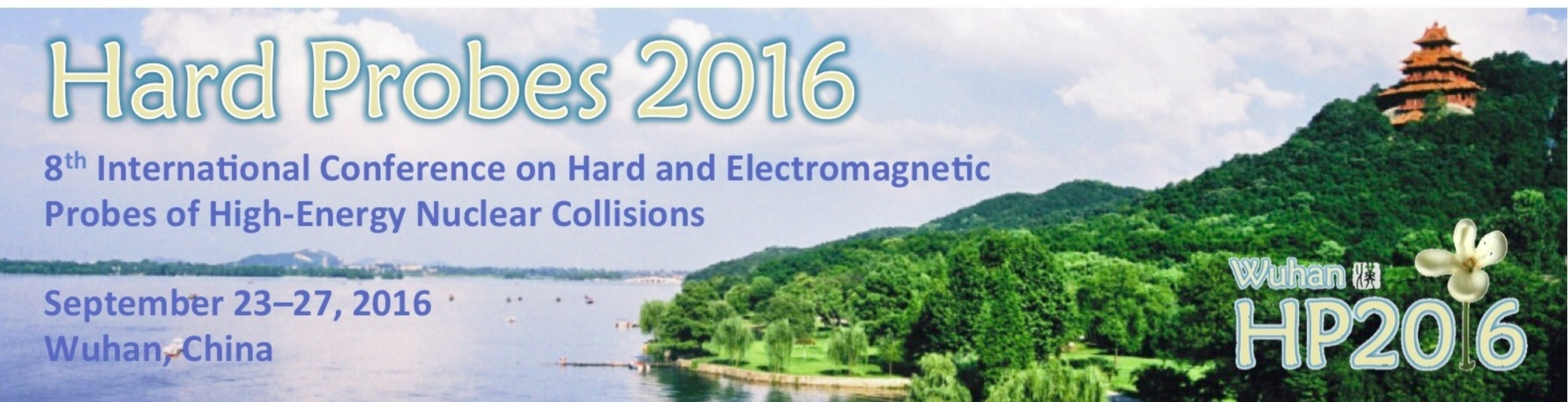
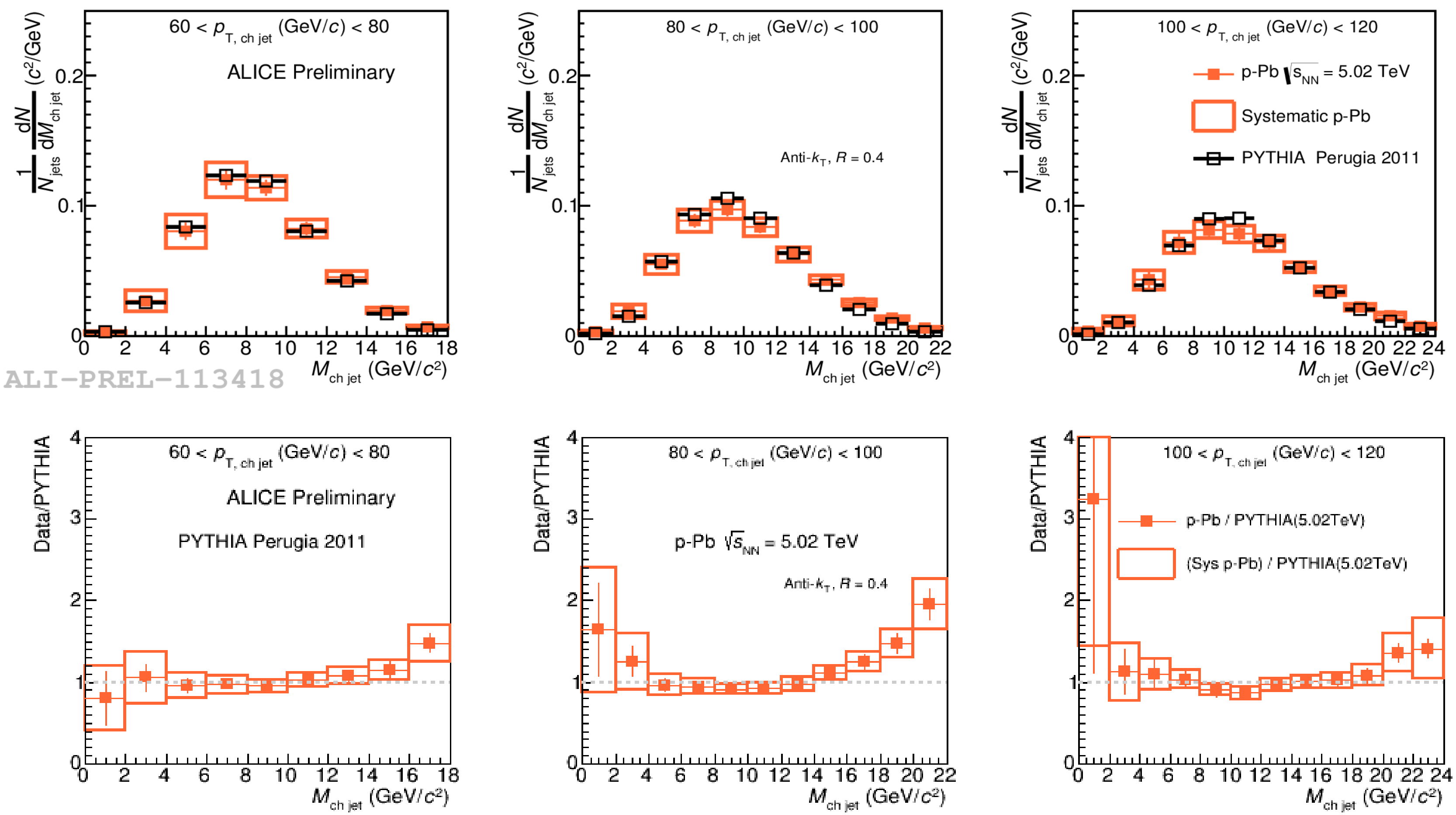
Results and comparison with models

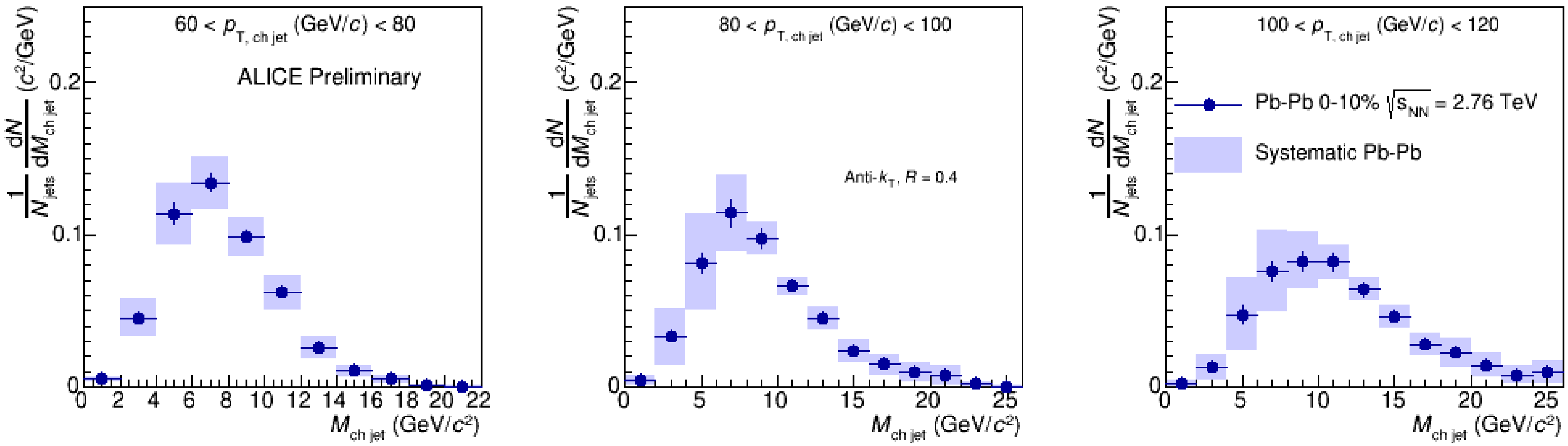


p-Pb results

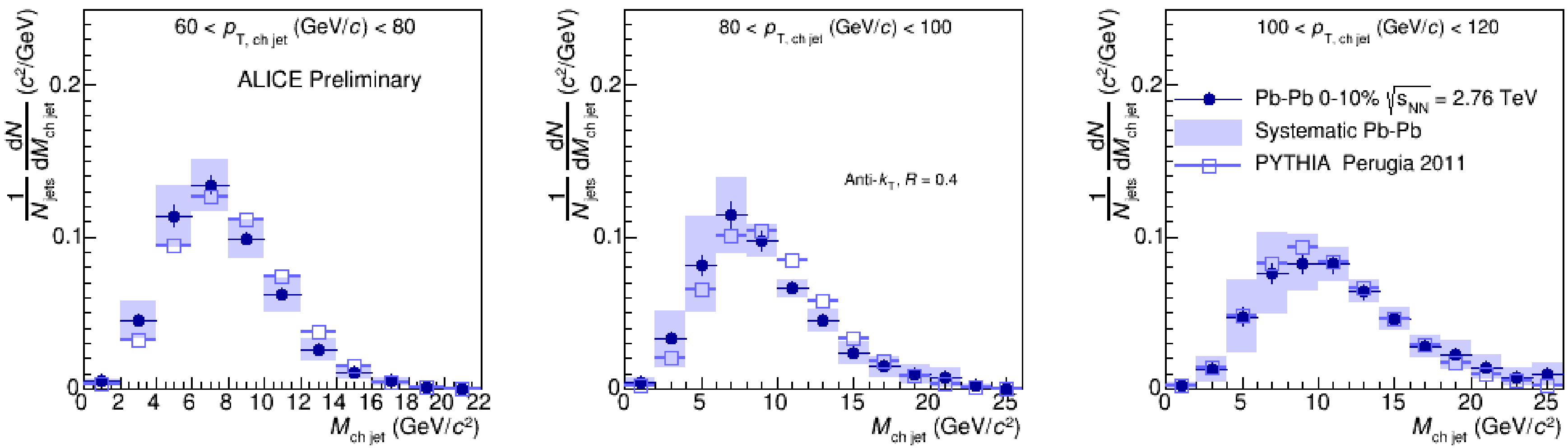


- p-Pb jet mass overall well described by PYTHIA with some tension in the tails

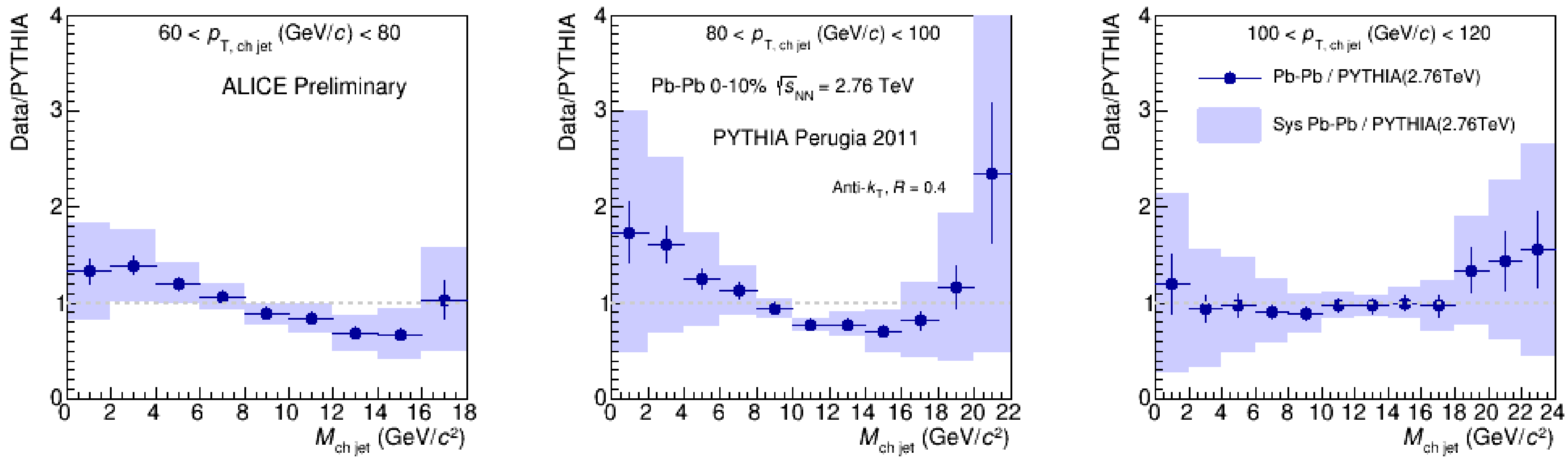
Pb-Pb results



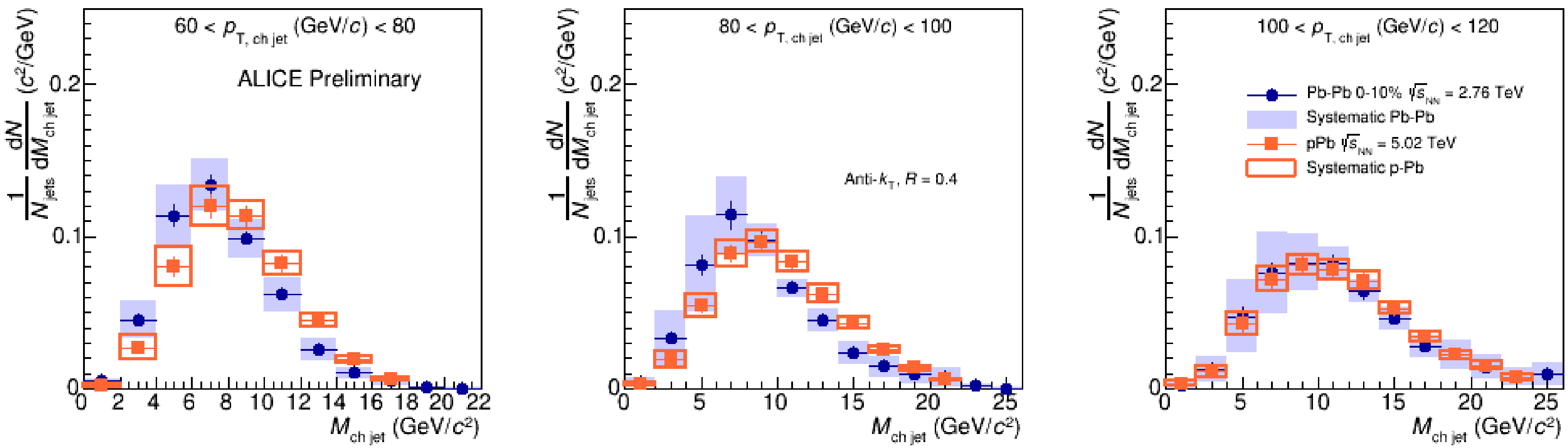
Pb-Pb results



- Jet mass in Pb-Pb collisions compared to PYTHIA



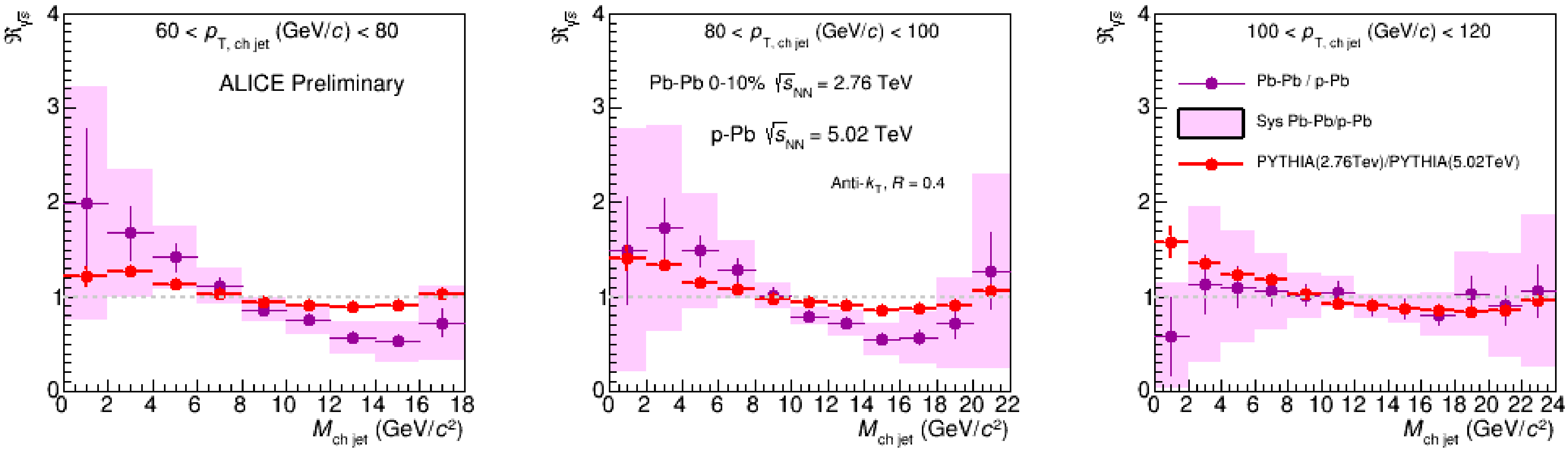
Comparison Pb-Pb and p-Pb results



- Jet mass in Pb-Pb collisions compared to p-Pb
- In order to directly compare Pb-Pb and p-Pb we have to consider the "trivial" √s dependence of quark/gluon jets in a given p_T bin
  - We compare the ratio of data with the ratio of PYTHIA at the two energies

$$\Re_{\sqrt{s}} = \frac{\frac{1}{N_{\text{jets}}}\frac{dN}{dM_{\text{chjet}}}\Big|_{\sqrt{s_{\text{NN}}}=2.76\ \text{TeV}}}{\frac{1}{N_{\text{jets}}}\frac{dN}{dM_{\text{chjet}}}\Big|_{\sqrt{s_{\text{NN}}}=5.02\ \text{TeV}}}$$

Ratio Pb-Pb/p-Pb

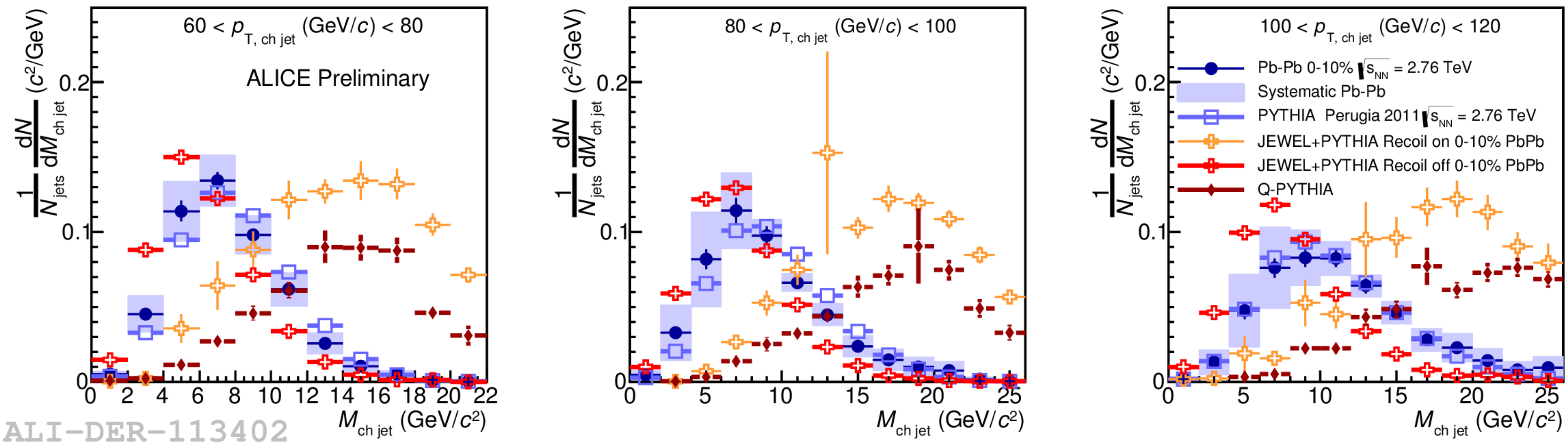


$$\Re_{\sqrt{s}} = \frac{\frac{1}{N_{\mathrm{jets}}}\frac{dN}{dM_{\mathrm{chjet}}}\Big|_{\sqrt{s_{\mathrm{NN}}}=2.76\ \mathrm{TeV}}}{\frac{1}{N_{\mathrm{jets}}}\frac{dN}{dM_{\mathrm{chjet}}}\Big|_{\sqrt{s_{\mathrm{NN}}}=5.02\ \mathrm{TeV}}}$$

Slope of ratio indicates that Pb-Pb distribution is shifted towards smaller masses wrt p-Pb

- Large uncertainties, propagated as uncorrelated → need further studies to determine possible correlations between the two data sets

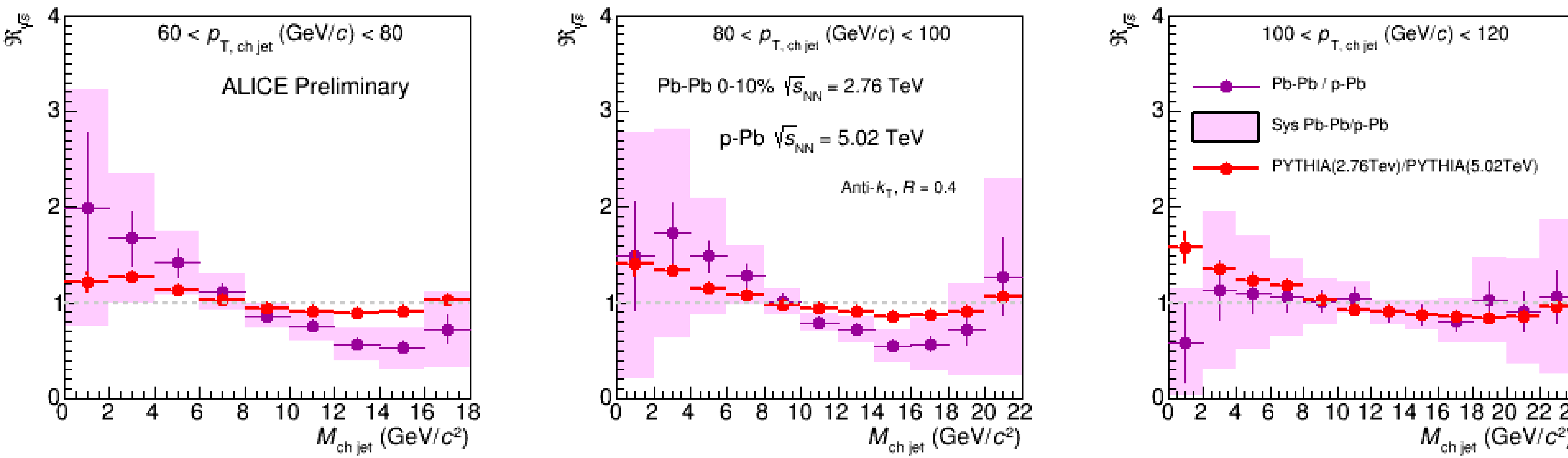
Comparison with models



- Data lay in between PYTHIA and JEWEL “recoil off”
- Models with quenching produce too large mass

Conclusions

- First jet mass measurement in heavy-ion collisions → first attempt to access the virtuality evolution of parton shower
  - Mass distribution in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- p-Pb data are well reproduced by PYTHIA and used as reference for Pb-Pb
- Pb-Pb/p-Pb jet mass ratio indicates a shift towards smaller masses of Pb-Pb wrt p-Pb
- Models implementing quenching are not able to reproduce the data, which show in-between no effect and little depletion
  - Measurement access energy and virtuality loss in models and can constrain models
  - Effort ongoing to reduce the uncertainties on the ratio

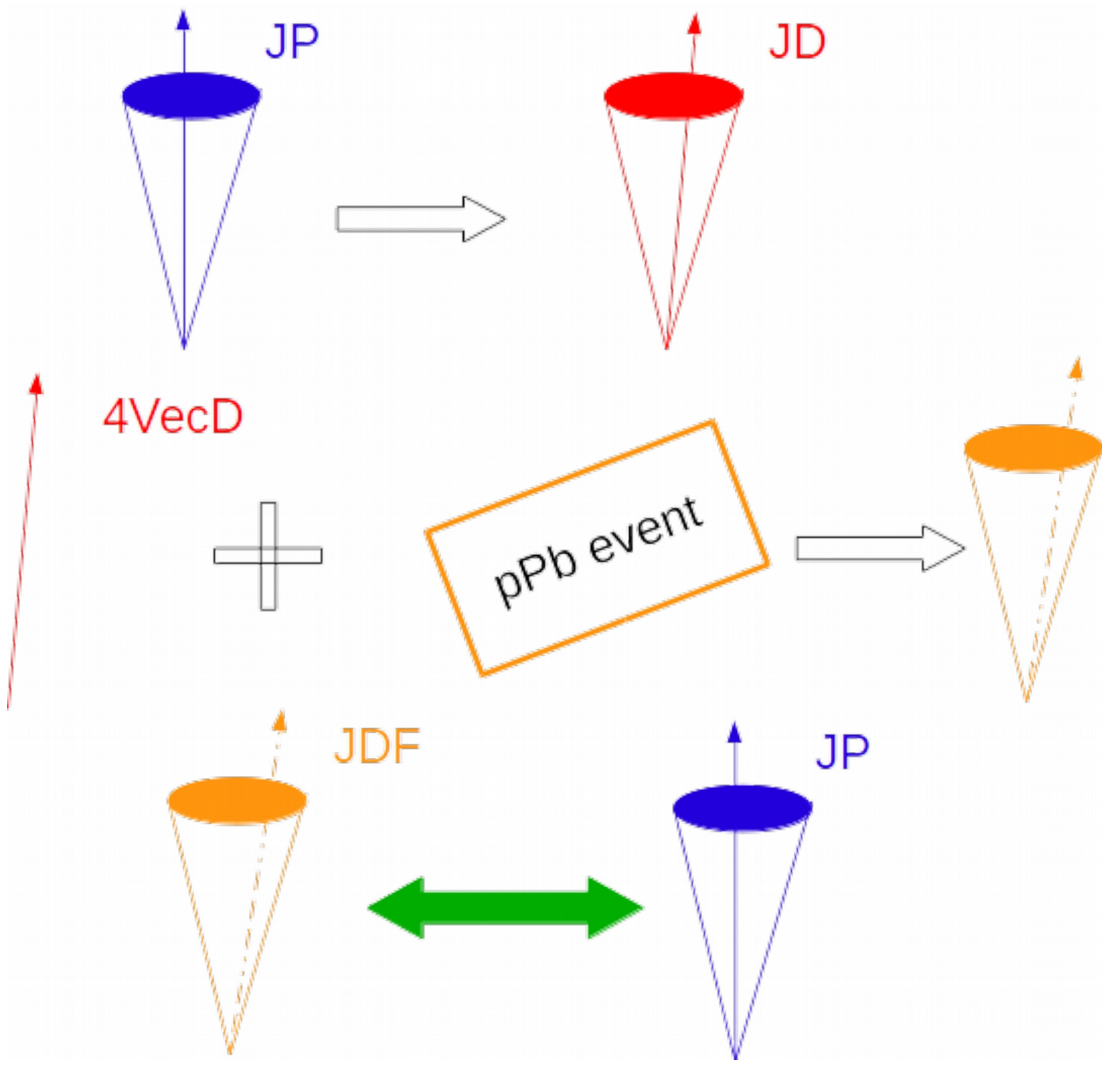


$\mathfrak{R}_{\sqrt{s}}$
$60 < p_{T,\,ch\,jet}$ (GeV/c) < 80
ALICE Preliminary
$M_{ch\,jet}$ (GeV/c^2)
$80 < p_{T,\,ch\,jet}$ (GeV/c) < 100
Pb-Pb 0-10% $\sqrt{s_{NN}}$ = 2.76 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Anti-k_T, R = 0.4
$100 < p_{T,\,ch\,jet}$ (GeV/c) < 120
Pb-Pb / p-Pb
Sys Pb-Pb/p-Pb
PYTHIA(2.76Tev)/PYTHIA(5.02TeV)

Hard Probes 2016
8th International Conference on Hard and Electromagnetic
Probes of High-Energy Nuclear Collisions
September 23–27, 2016
Wuhan, China
Wuhan
HP2016

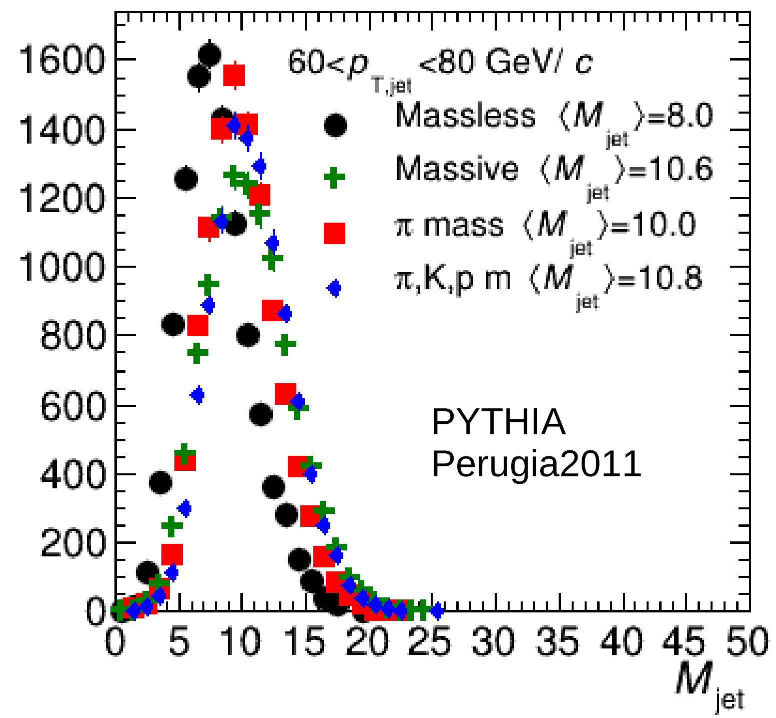
Extra slides

Embedding p-Pb



Jet mass dependence on constituent mass

- Relatively small dependence on the constituent mass
  - Assumed pion mass for all constituents



Background subtraction for jet-shape observables

- Background density determined using k_T clusters

$$\rho = \text{median}\left\{\frac{p_{T,i}}{A_i}\right\}$$

$$\rho_m = \text{median}\left\{\frac{m_{\delta,i}}{A_i}\right\} \qquad m_{\delta,k_T^{\text{cluster}}} = \sum_j \left(\sqrt{m_j^2 + p_{T,j}^2} - p_{T,j}\right)$$

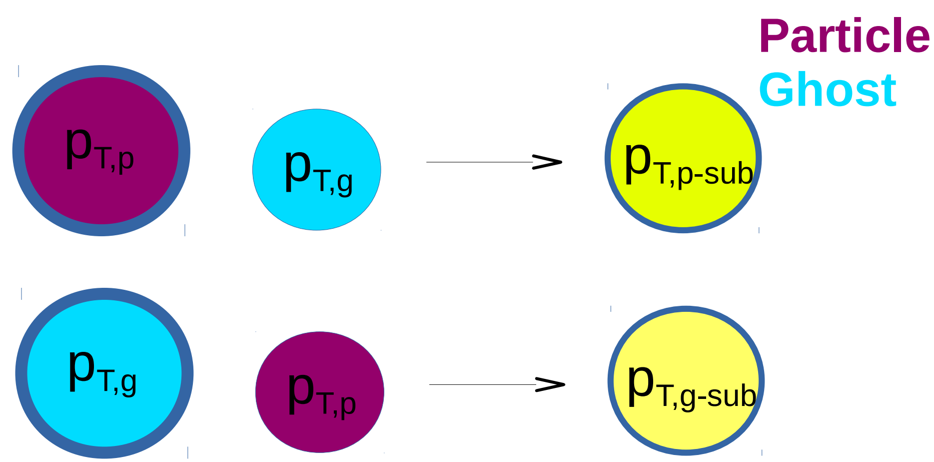
- ρ and ρ_m have only a small dependence on y and φ
- "Ghosts" (very low-momentum particles) are added uniformly in y-φ

Derivative subtraction

- Function describing the jet shape $V(\{p_{jet}\})$
- Calculate its derivative at $\rho = 0$ and $\rho_m = 0$

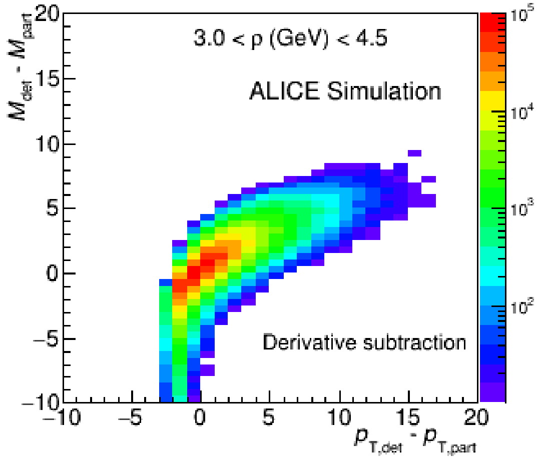
G. Soyez et al. Phys.Rev.Lett. 110 no. 16, (2013) 162001

Constituent subtraction

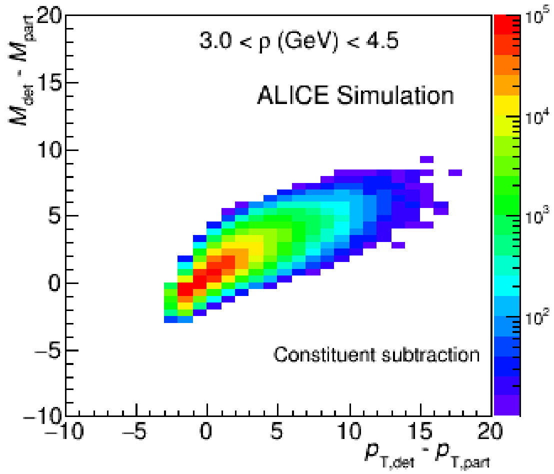


Background subtraction in p-Pb

Derivative subtraction



Constituent subtraction



- Two effects: Event-by-event background estimate + remaining fluctuations
- Derivative method over subtracts the background event by event

- Issues in sparse events:
  - Possible anti correlation between average background and fluctuations
  - The effect might not be captured by embedding

- We do not subtract the background event-by-event and treat both effects as fluctuations included in the response

Background subtraction for jet-shape observables

- Background density determined using k_T clusters

$$\rho = \text{median}\left\{\frac{p_{T,i}}{A_i}\right\}$$

$$\rho_m = \text{median}\left\{\frac{m_{\delta,i}}{A_i}\right\} \quad m_{\delta,k_T^{cluster}} = \sum_j \left(\sqrt{m_j^2 + p_{T,j}^2} - p_{T,j}\right)$$

- ρ and ρ_m have only a small dependence on y and φ
- "Ghosts" (very low-momentum particles) are added uniformly in y-φ

Area based/derivative method:

- Define the jet shape's sensitivity $V(\{p_{jet}\})$
- Take the derivative and calculate it at zero background

G. Soyez et al. Phys.Rev.Lett. 110 no. 16, (2013) 162001

Constituent subtraction:

- Particle level subtraction
- Pairs of particle-ghost are considered
- p_T and m are adjusted for the largest between $p_{T,g} = A_g\rho$ and $p_{T,p}$
- Do the same with mass and recluster