High p_T Particle Production and Jet Modification in Nuclear Collisions

Ab-initio approaches in many-body QCD confront heavy-ion experiments

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Accessing Hard Probes

Bottom-Up: Particles
> Spectra at high p_T
> Leading particles
> Identified π, K, p, Λ, D
> Particle correlations

Top-Down: Reconstructed jets
> Spectrum
> Angular distribution
> Jet fragmentation

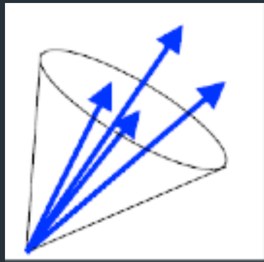
± Underlying Event

single particles

detailed fragmentation

jet like properties

fully reconstructed jets



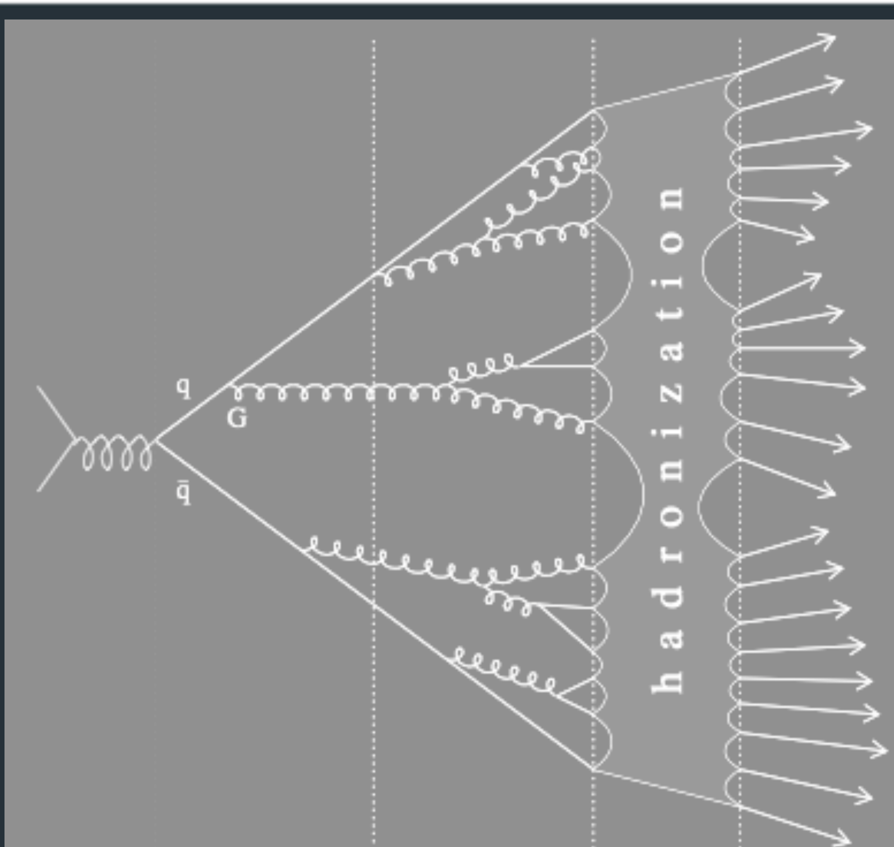
Jet-like properties:
> Spectral shape, back-to-back correlation

Experimentally clearly defined.
Biased: fragmentation, surface…

A+A: large background level, fluctuations
soft ⊗ **hard**

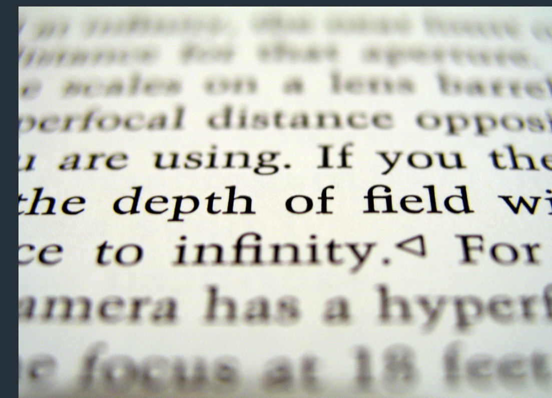
Related to theoretically well defined parton properties.

Picturing Jets/Jet Quenching



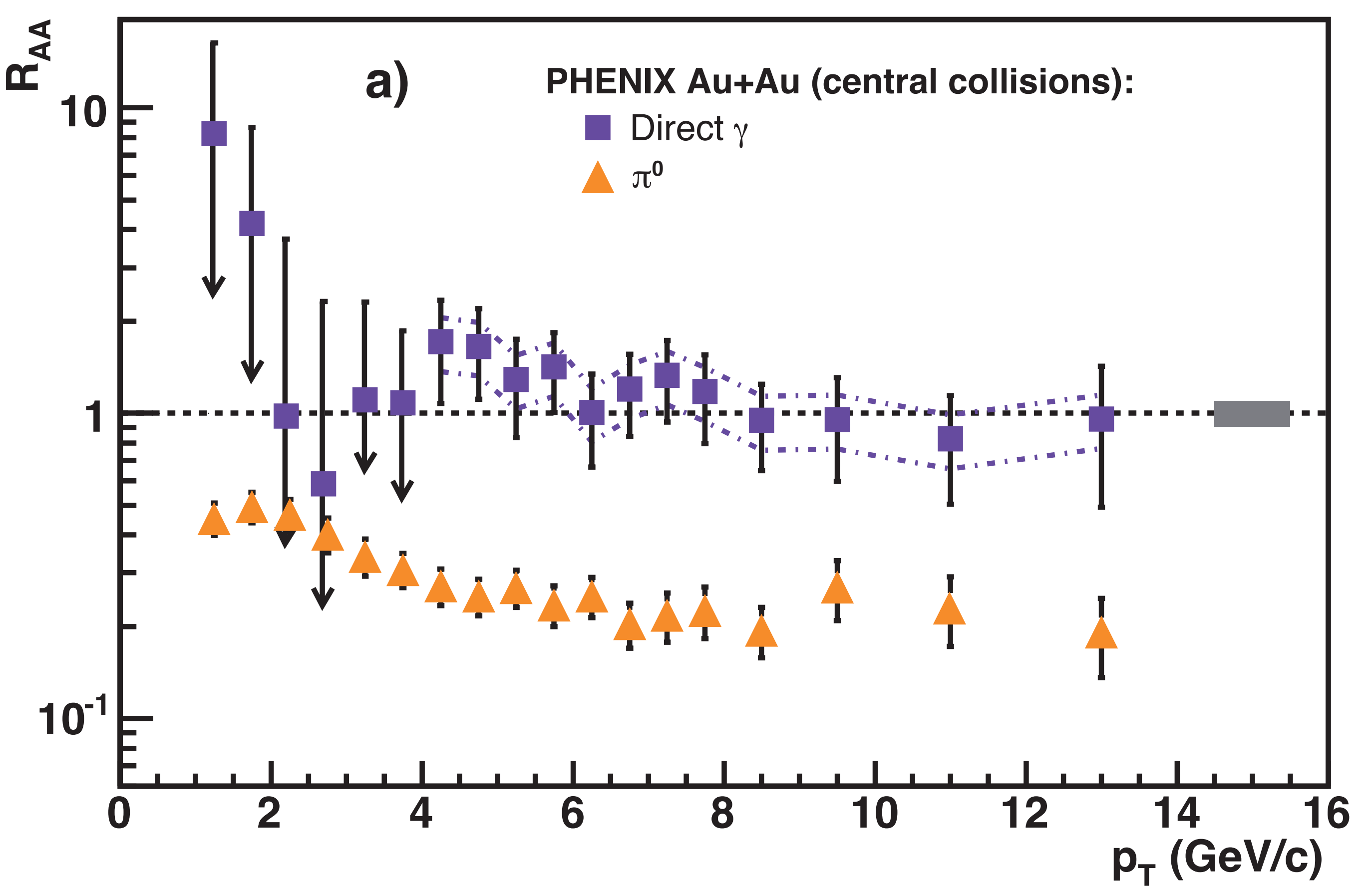
depth of field: jet finding with different R

depth of field



Resolution:
jet fragmentation → single particle (+ PID)

A Close to Perfect Picture



PRL **96** 202301 (2006)

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{T_{AA}\,d^2\sigma_{pp}\,dydp_T}$$

$$T_{AA} = N_{coll}/\sigma_{NN}$$

… the most popular observable for hard probes since 2001

π^0 as proxy for hard scattered partons strongly suppressed
Color neutral probes unaffected → Strong final state effect.

Ab-Initio R_{AA}?

Only above $Q^2 \approx (2\ \text{GeV})^2$ pQCD and factorization is applicable

Transmission: Hard scattering without final state interaction (e.g. from surface)

also over final state particles (jet with certain R)

nuclear PDF

pQCD cross section $\approx p_T^{-n}$

$$R_{AA} = T \cdot \frac{\int \sum_{a,b,c} \mathrm{nPDF}_a(x) \otimes \mathrm{nPDF}_b(x) \otimes \frac{d\sigma^{hard}_{ab\to c+X}}{d^3p} \otimes \mathrm{FF}_{c/h}(z)}{\int \sum_{a,b,c} \mathrm{PDF}_a(x) \otimes \mathrm{PDF}_b(x) \otimes \frac{d\sigma^{hard}_{ab\to c+X}}{d^3p} \otimes \mathrm{FF}_{c/h}(z)}$$

$$+(1-T) \cdot \frac{\int \sum_{a,b,c} \mathrm{nPDF}_a(x) \otimes \mathrm{nPDF}_b(x) \otimes \frac{d\sigma^{hard}_{ab\to c+X}}{d^3p} \otimes \mathrm{FF}^{medium}_{c/h}(z)}{\int \sum_{a,b,c} \mathrm{PDF}_a(x) \otimes \mathrm{PDF}_b(x) \otimes \frac{d\sigma^{hard}_{ab\to c+X}}{d^3p} \otimes \mathrm{FF}_{c/h}(z)}$$

simple: Leading parton $FF^{med} = P(\Delta E)\ FF(z - \Delta E/E)$
realistic: geometry, time evolution, position, energy conservation
medium pick-up?

1) Transmission ($P(\Delta E) = 0$) yields a constant offset to R_{AA} (modulo nPDF)
2) Parton energy loss ($P(\Delta E) > 0$) filtered by steeply falling partonic cross section
3) R_{AA} averages over medium evolution and path-length

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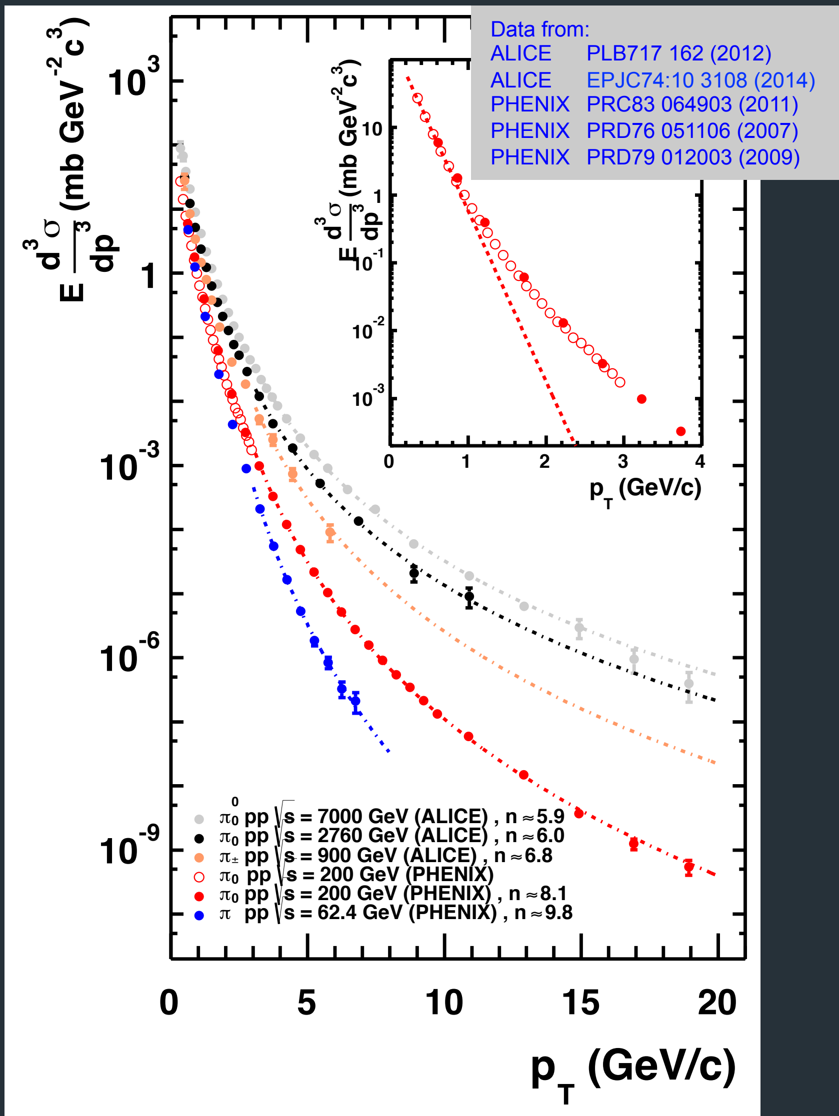
High p_T spectra from RHIC to LHC

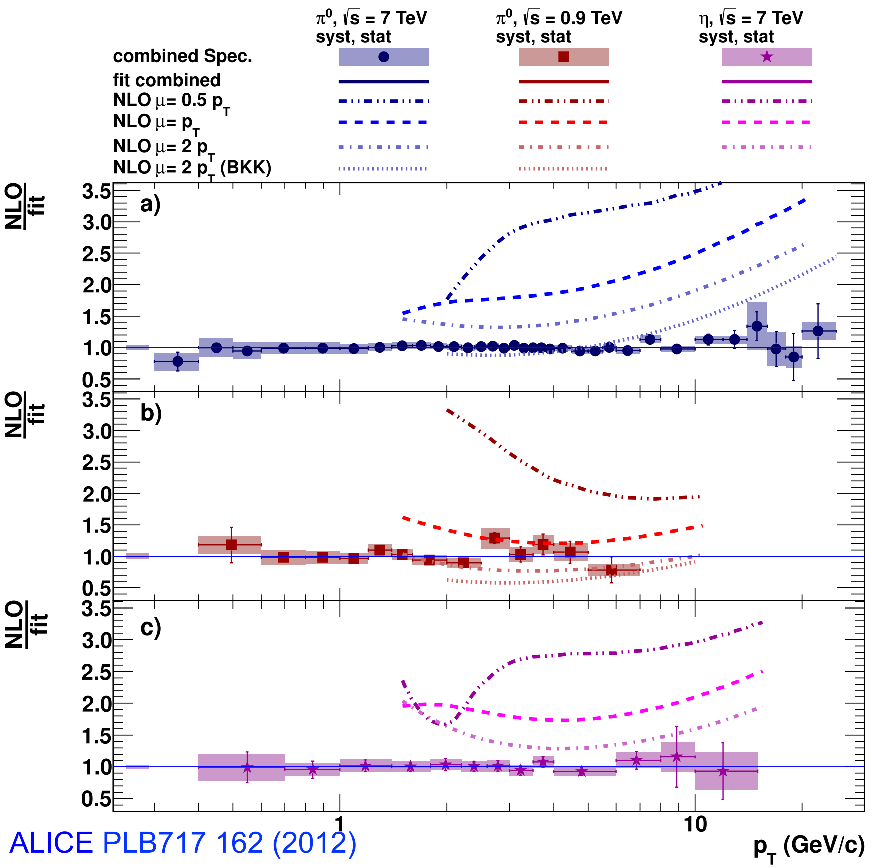


- Power law at high p_T characteristic for QCD hard scattering

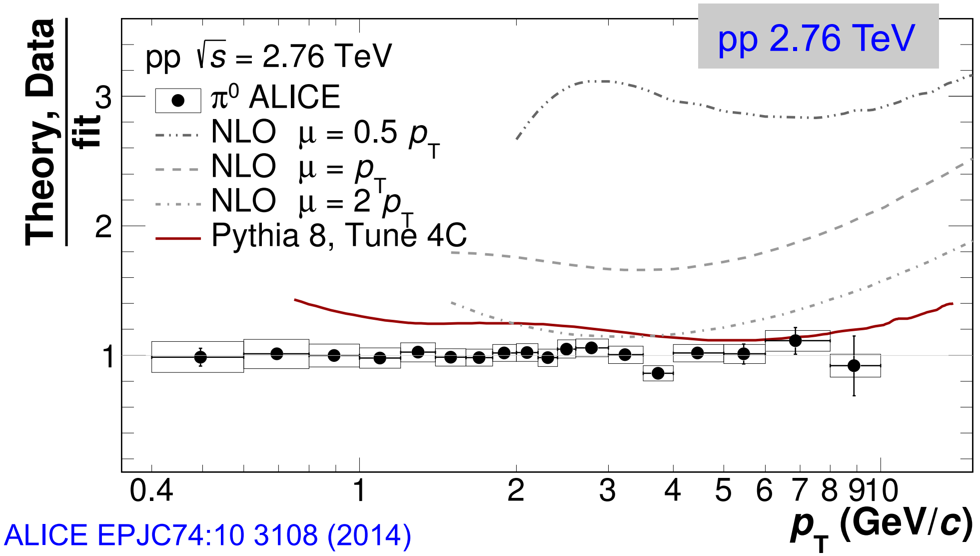
$$E\frac{d^3\sigma}{dp^3} \propto \frac{1}{p_T^n}$$

- To first order *n* reflects slope of parton spectra
- Spectra harden significantly with $\sqrt{s}$
- Leading particle bias reduced at LHC, sub-leading fragments contribute more
- Reduced sensitivity to leading parton energy loss

Confronted with pQCD



ALICE PLB717 162 (2012)



ALICE EPJC74:10 3108 (2014)

For nuetral pions pQCD over predicts the increase with √s and misses the spectral shape for p_T < 20 GeV.
Need to revisit fragmentation functions …

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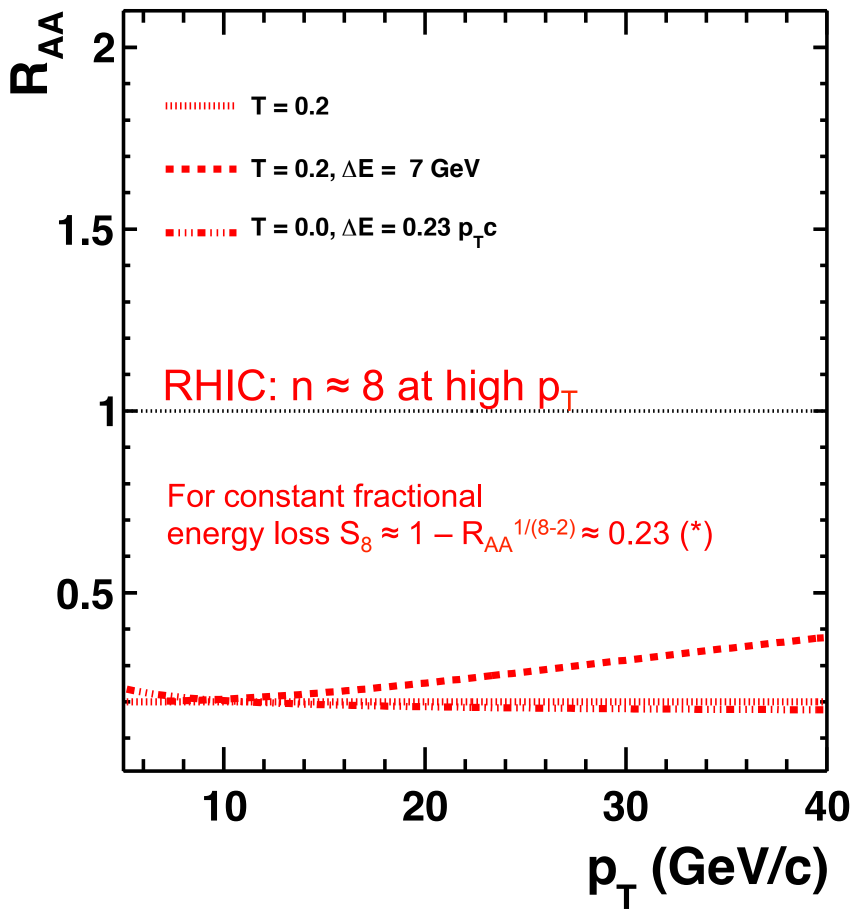
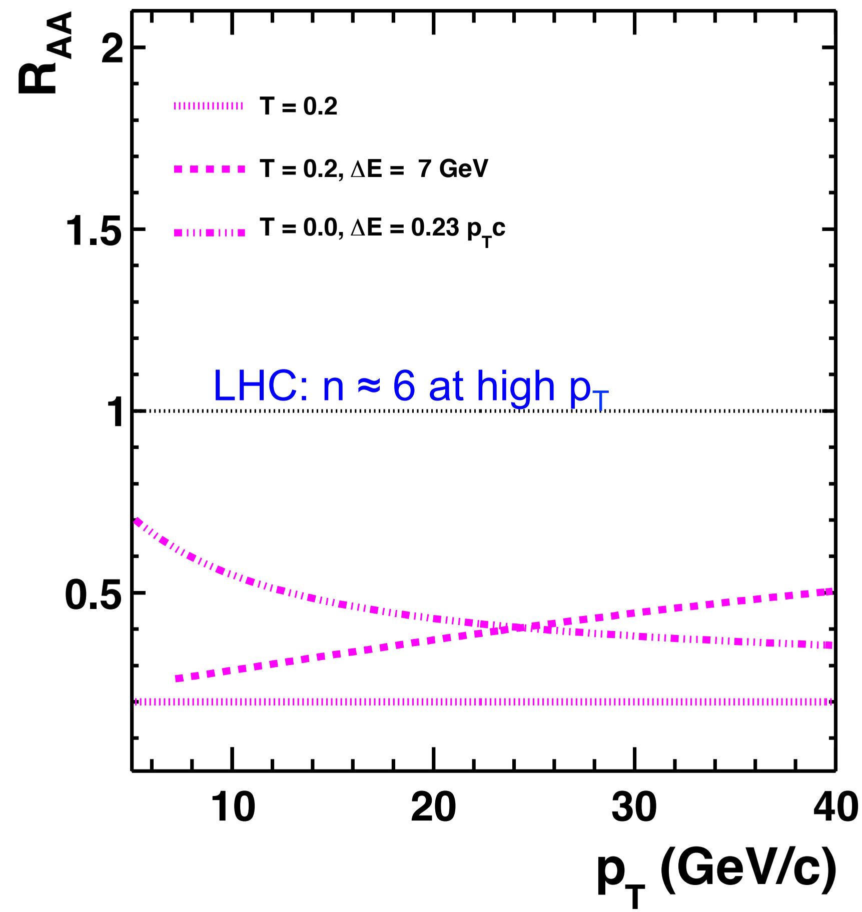
Energy Loss: Over-Simplified

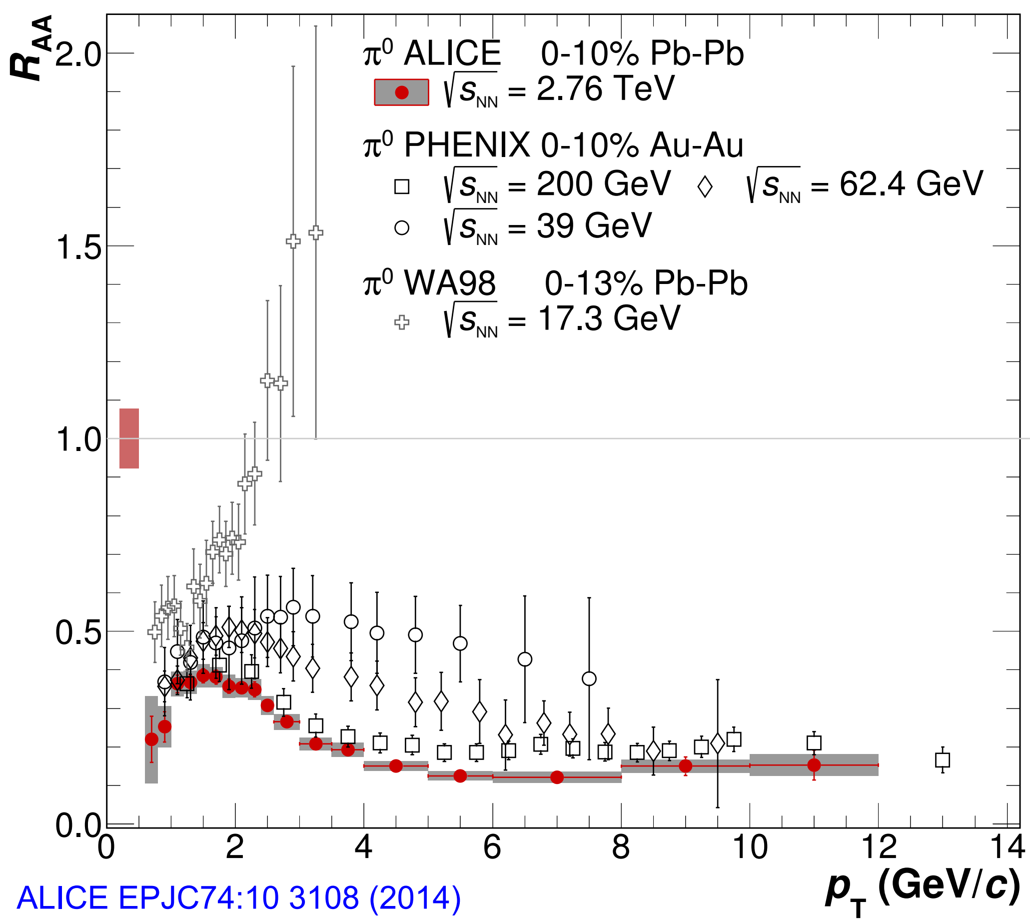


(*) PHENIX PRC 76 034904



Very little discrimination power with central R_{AA} at RHIC.
Same simple picture at LHC → Separation but higher R_{AA} (due to harder parton spectrum)

Nuclear Modification from 17.3 to 2760 GeV



ALICE EPJC74:10 3108 (2014)

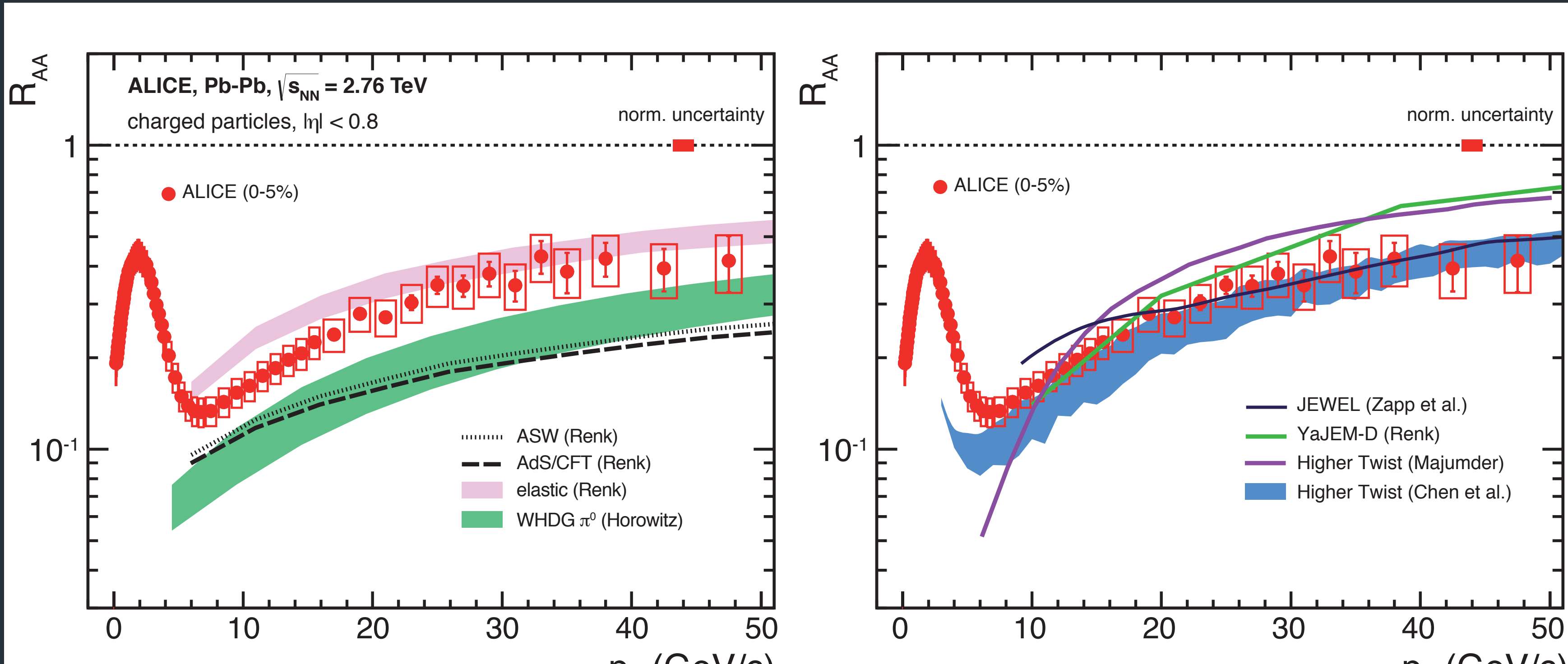
Neutral pion production shows increasing suppression, despite flatter spectrum.

LHC: $S_6(0.10) = 0.43$
RHIC: $S_8(0.18) = 0.25$

Increasing suppression with √s, but pure surface emission (flat R_{AA}) not ruled out here.

Temperature and geometry dependence (centrality/event plane) provide more constraints

The Kinematic Lever Arm
Charged Hadron R_{AA}

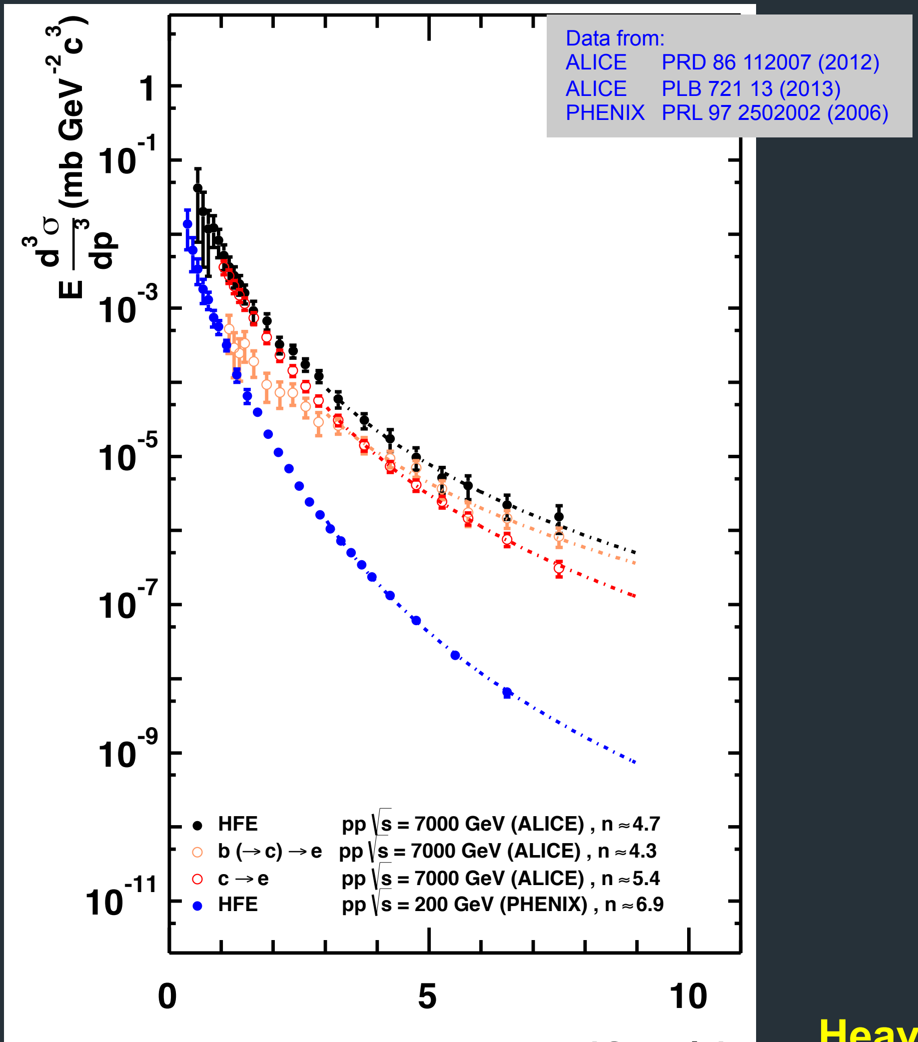


ALICE PLB 720 52-62 (2013)

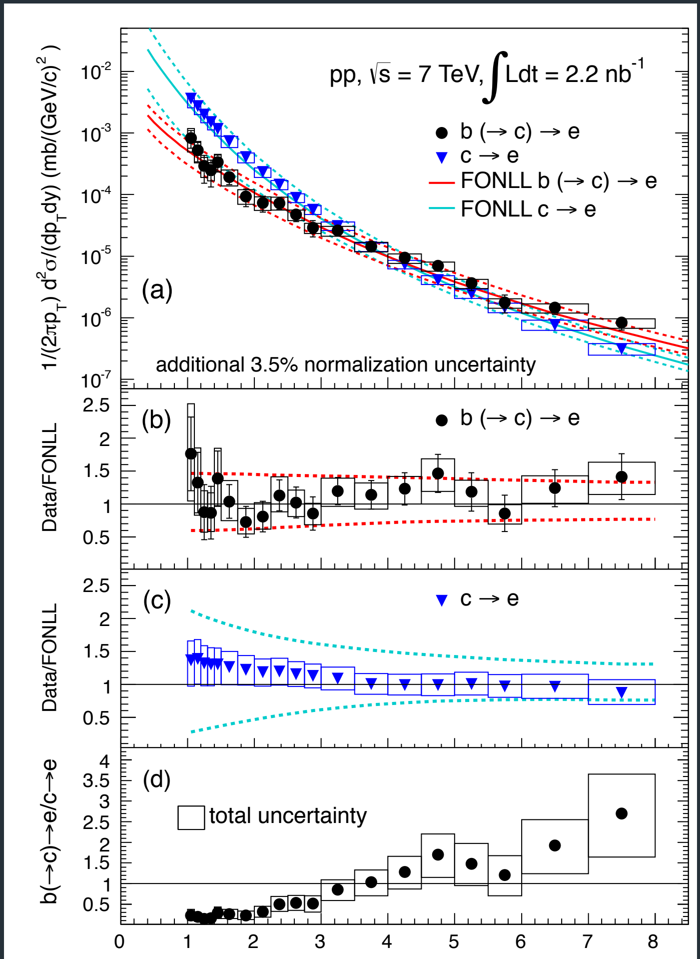
- Suppression of single hadrons, rise and flattening of R_{AA} generic in all energy loss models
- AdS/CFT and pure radiative energy loss over-quench (mixture of mechanisms needed)
- Calculations/simulations beyond leading particle (right) slightly preferred

Include more particles in the observable: Jets
More direct access to the medium modification of colored probes.

Heavy Flavor Spectral Shapes



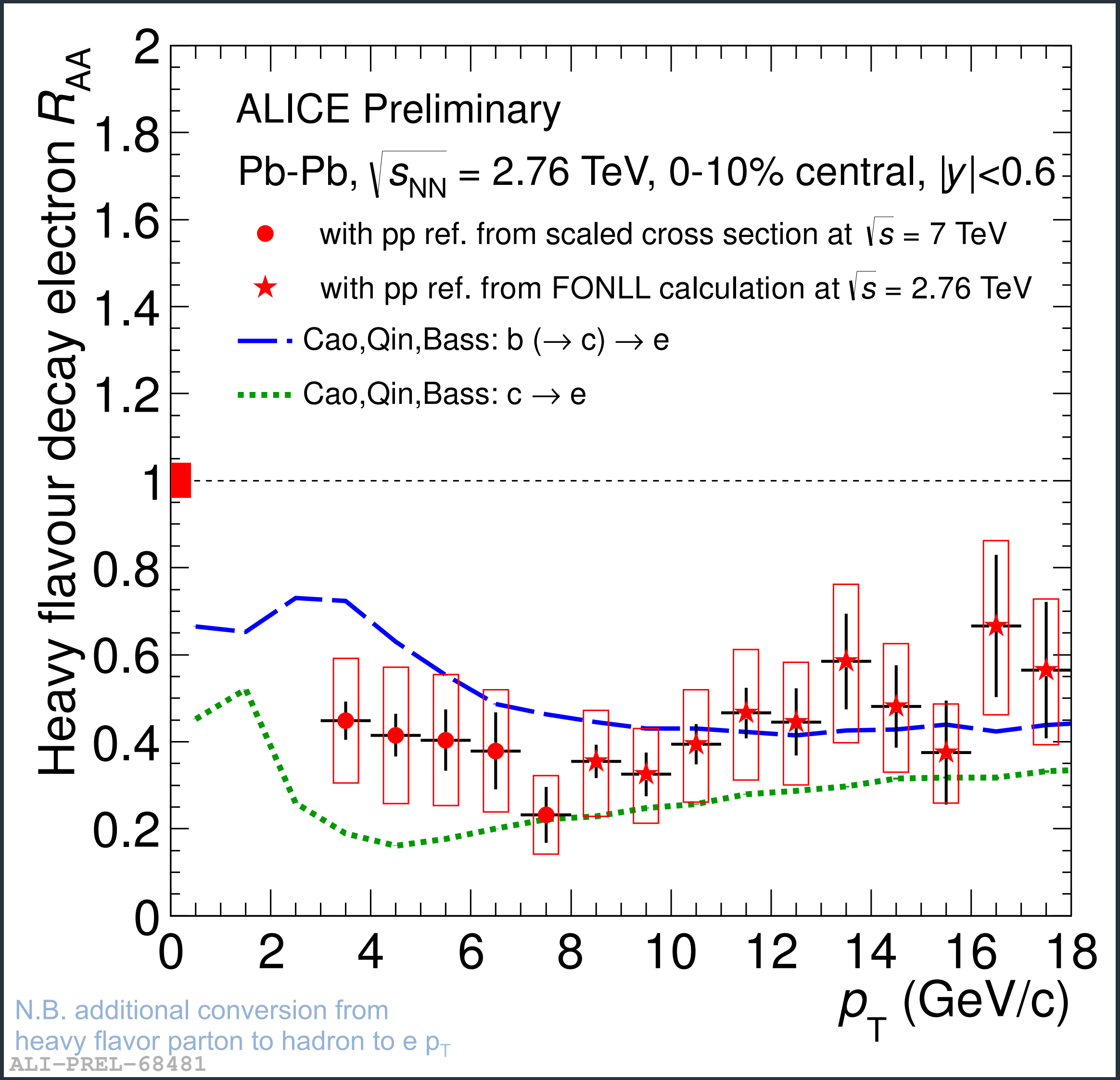
Heavy flavor electrons



ALICE PLB 721 13 (2013)

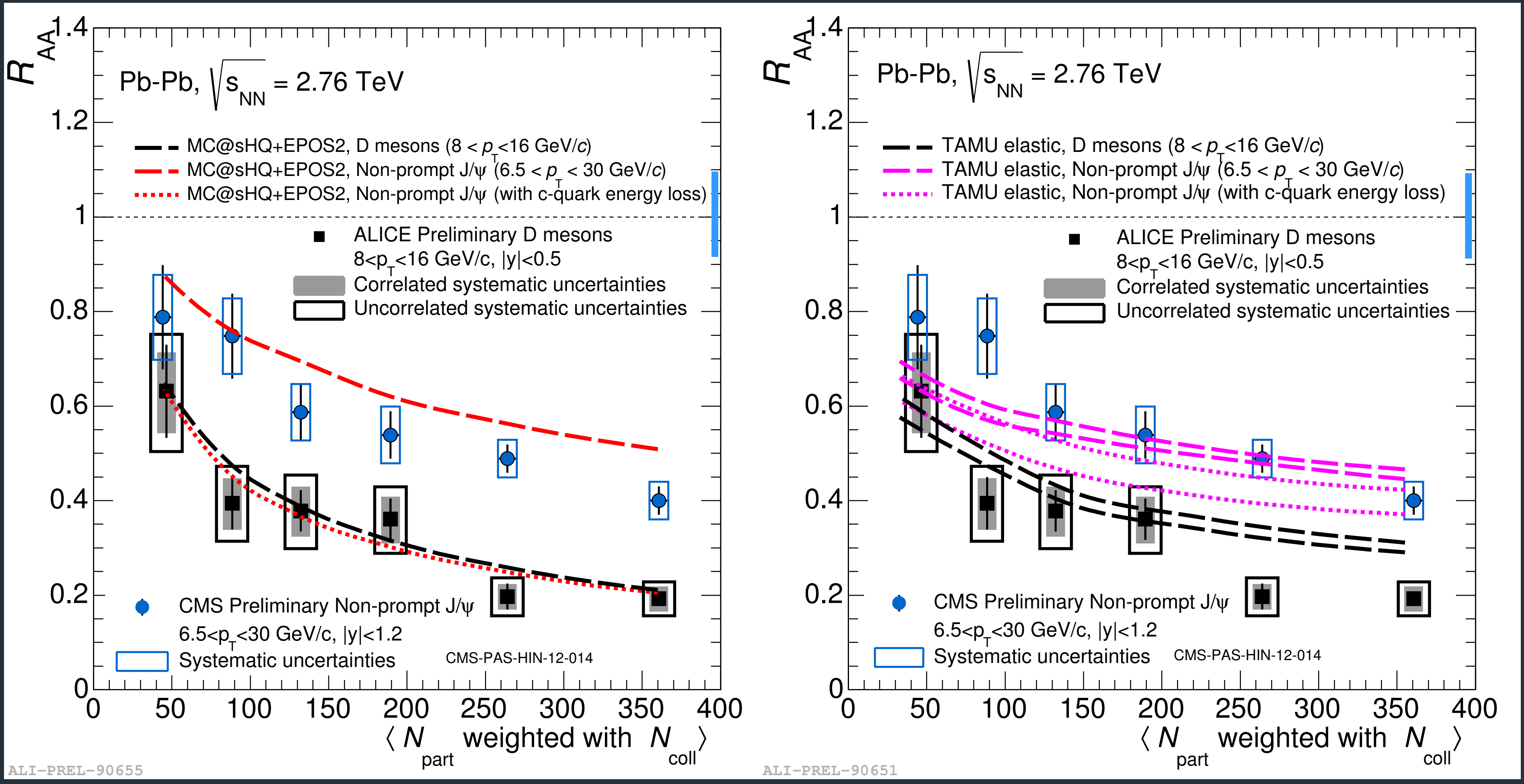
Heavy flavor electron spectra harder than light flavor pions and better described by pQCD.

HFE Electron R_{AA}



Slightly larger than single hadrons, in between charm and beauty expectation.
What is the effect of spectral shape?
Closer to parton pT with Ds…

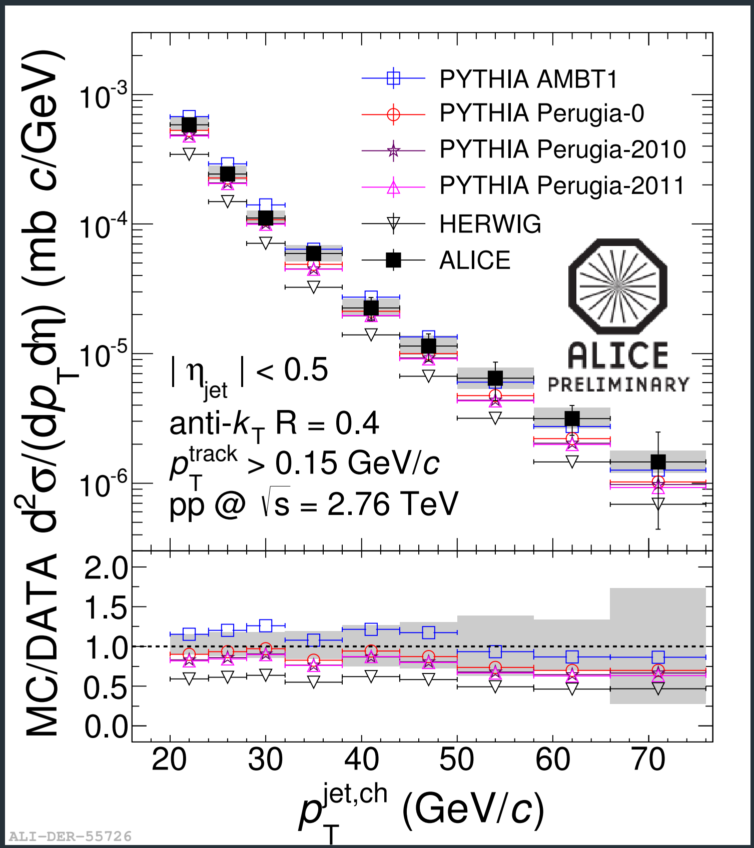
Prompt D vs. Non-Prompt J/ψ



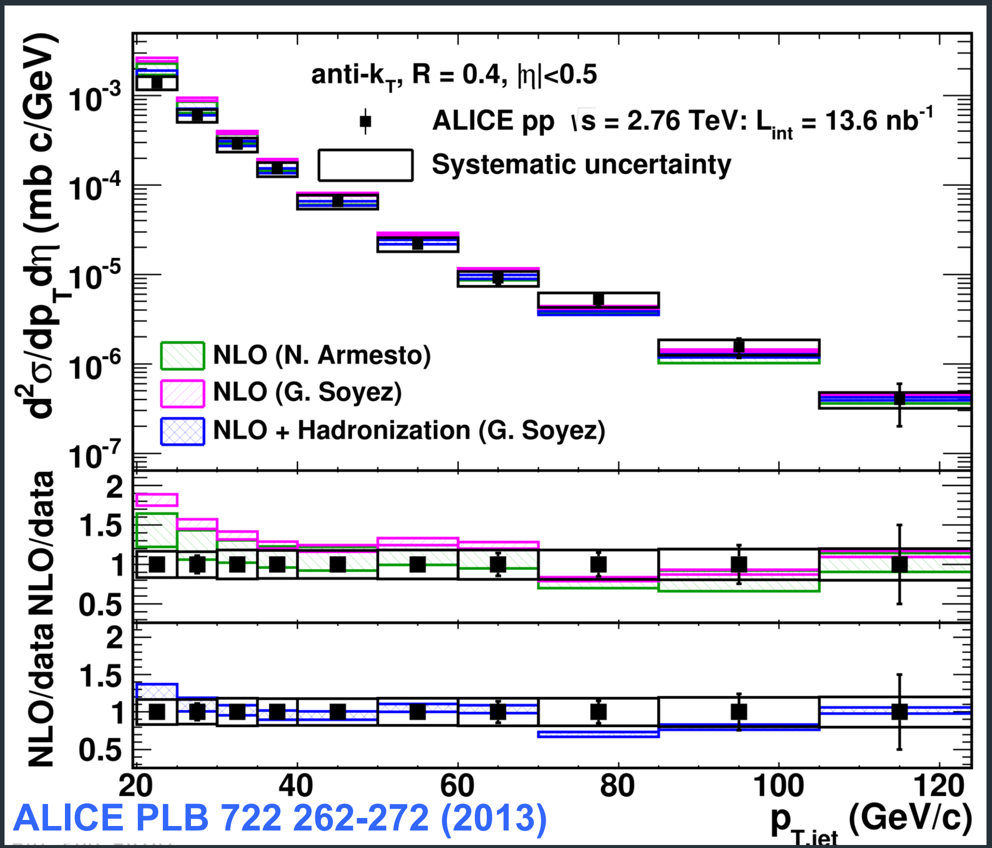
Models reproduce suppression and centrality dependence with different energy loss for charm and beauty.
Magnitude of the effect (modulo spectral shape) shows large deviations.

Jet Production in pp @ 2.76 TeV

Charged Jets

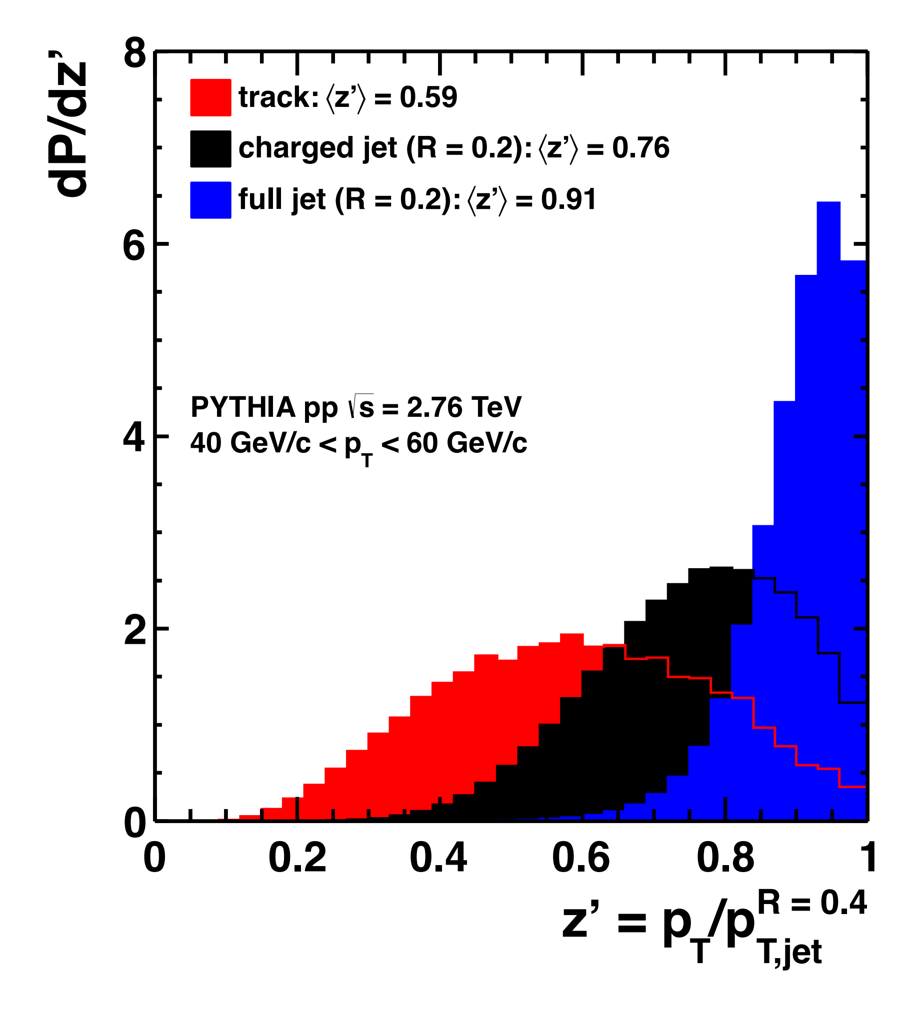


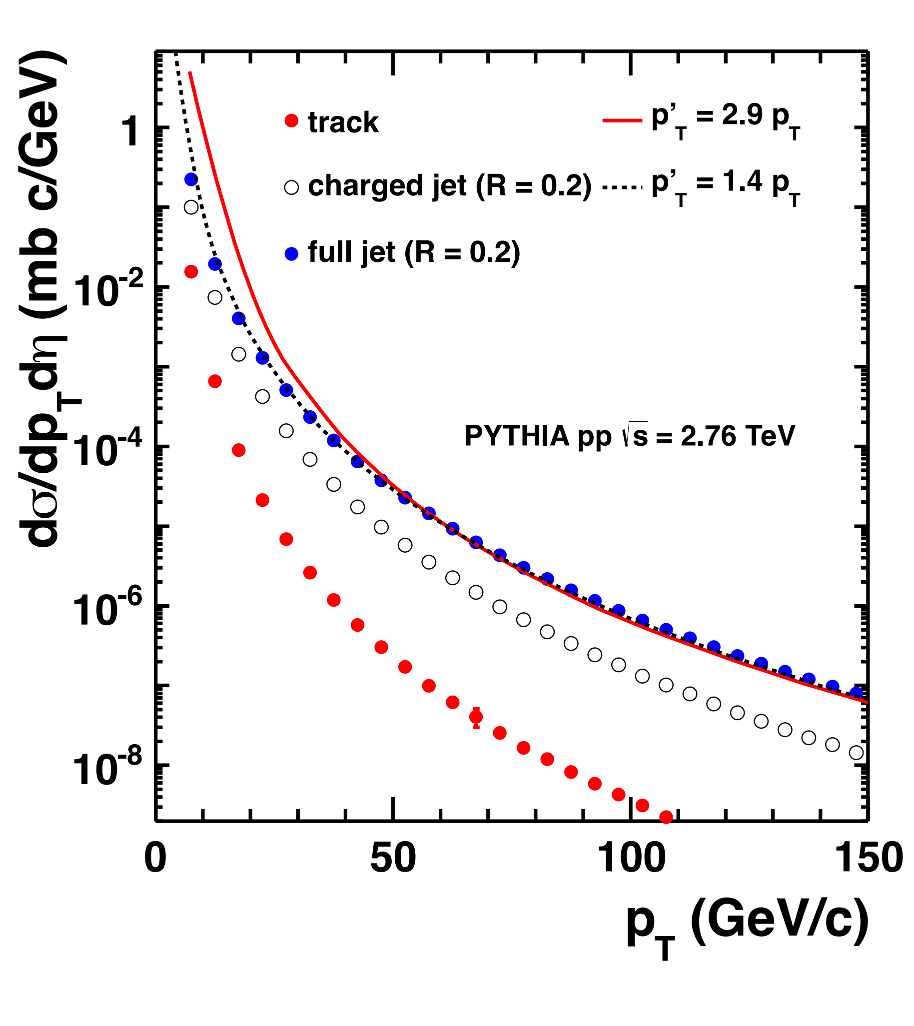
Full Jets



NLO pQCD with hadronization reproduces full jet data well, some variance in overall normalization of different MC/tunes.

Comparing Single Particles and Jets

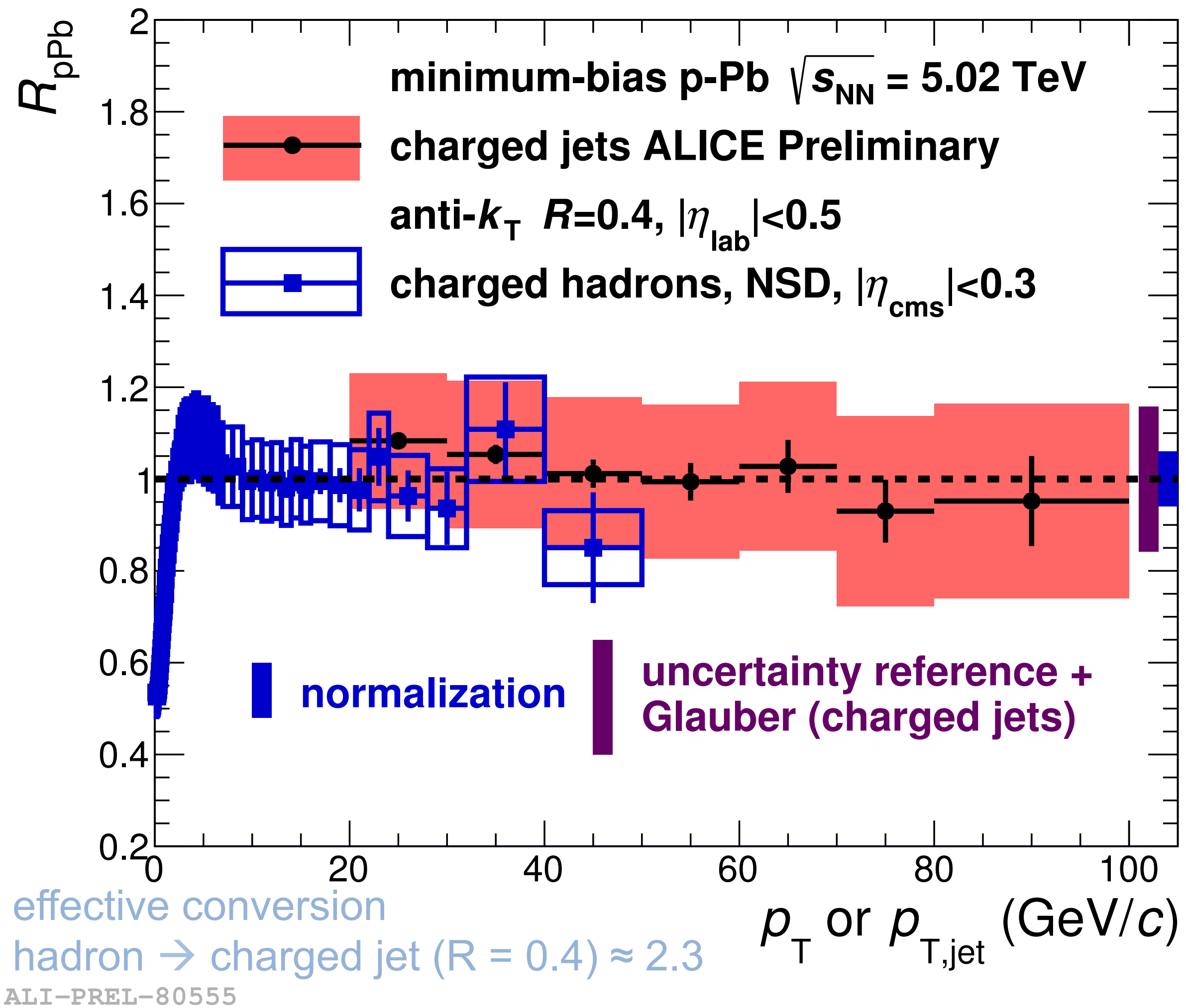




Different parton p_T at same reconstructed p_T.

Effective conversion possible, depends on fragmentation pattern + slope

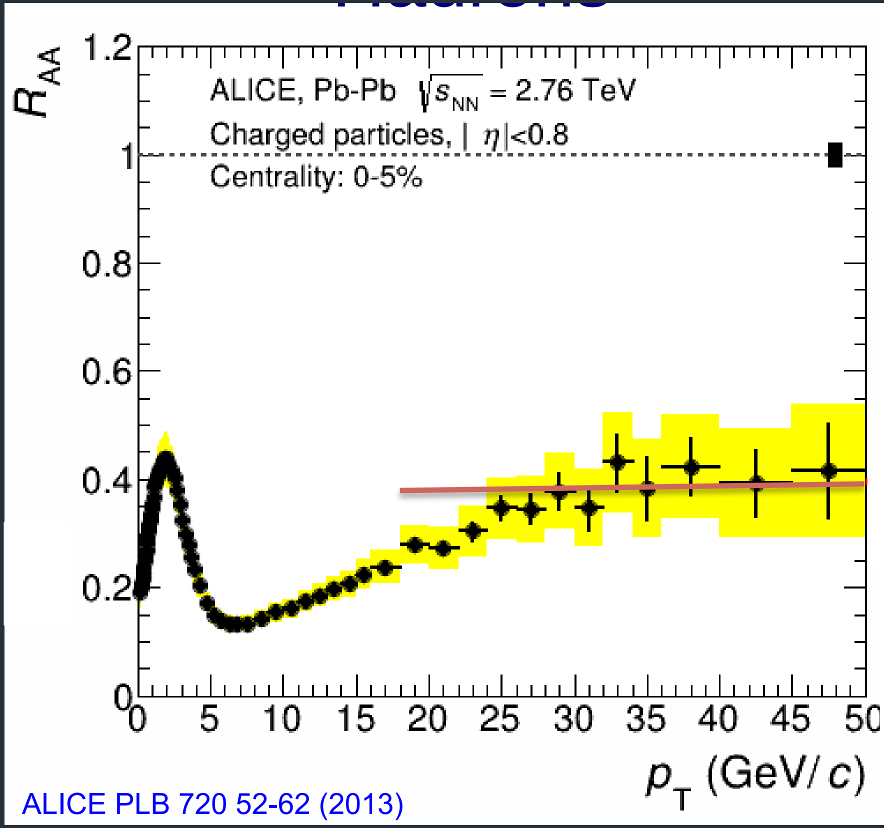
R_{pA} Charged Jets and Hadrons

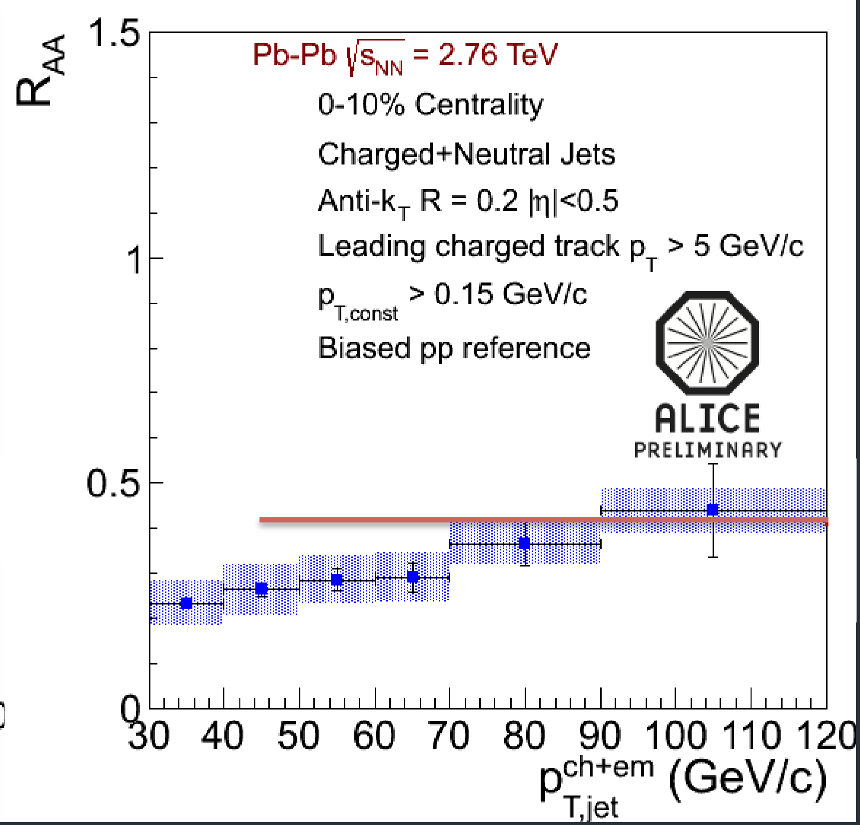


effective conversion
hadron → charged jet (R = 0.4) ≈ 2.3

Similar limiting value $R_{pA} \approx 1$ for hadrons and jets.

R_{AA} Full Jets and Hadrons





effective conversion hadron → full jets ≈ 3

Similar limiting value R_{AA} ≈ 0.45 for hadrons and jets.
Same underlying parton p_T seen with different depth of focus
→ fragmentation not strongly modified compared to pp

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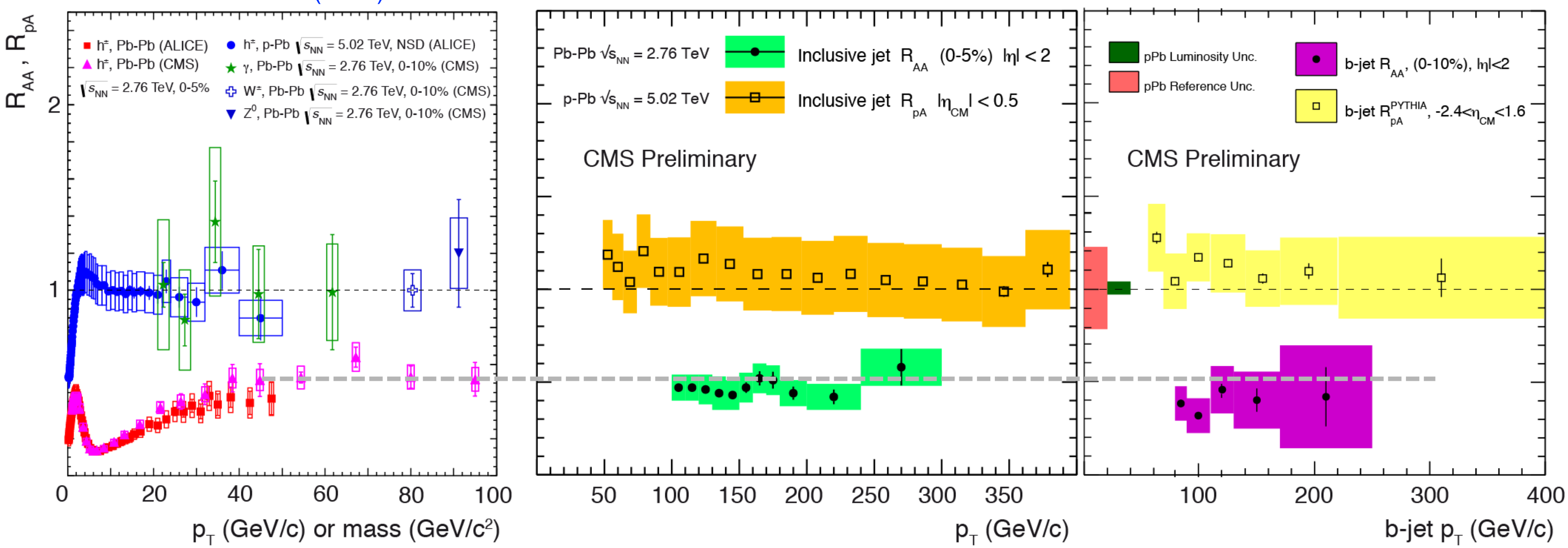
Hadrons, Jets and b-Jets

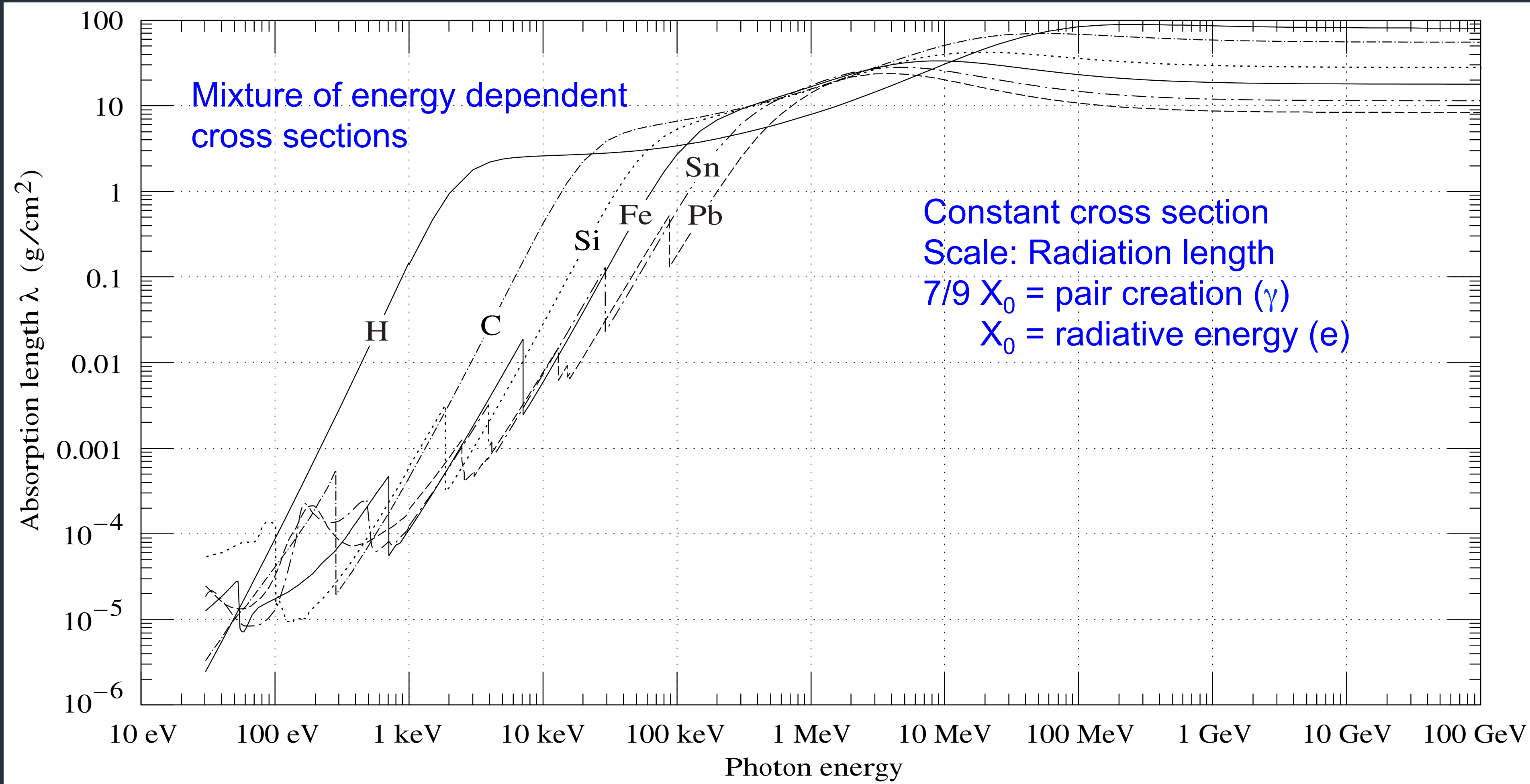
ALICE EPJ C74 3054 (2014)

CMS QM 2014 arxiv:1410.2576



Soft:	Dominated by non-perturbative production, flow, coalescence
Semi-Hard:	Minimum R_{AA} (set by surface emission?) and slow increase
Hard:	p_T > 8 GeV, rising R_{AA}, no obvious difference between species, only from b increased sensitivity to (mixed) mechanisms
Hardest:	p_T > 35 (100) GeV for hadrons (jets), identical flat R_{AA}, pure power law parton spectrum mass differences no longer important? Complete Absorption of jets? dominance of radiative energy loss? , ideal ground for isolating effect on fragmentation, L dependence: $R_{AA} \rightarrow e^{-L/\lambda}$

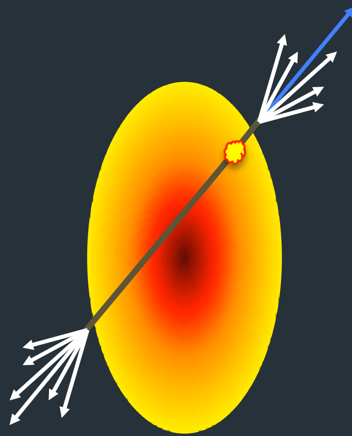
Can we extract this for the QGP?

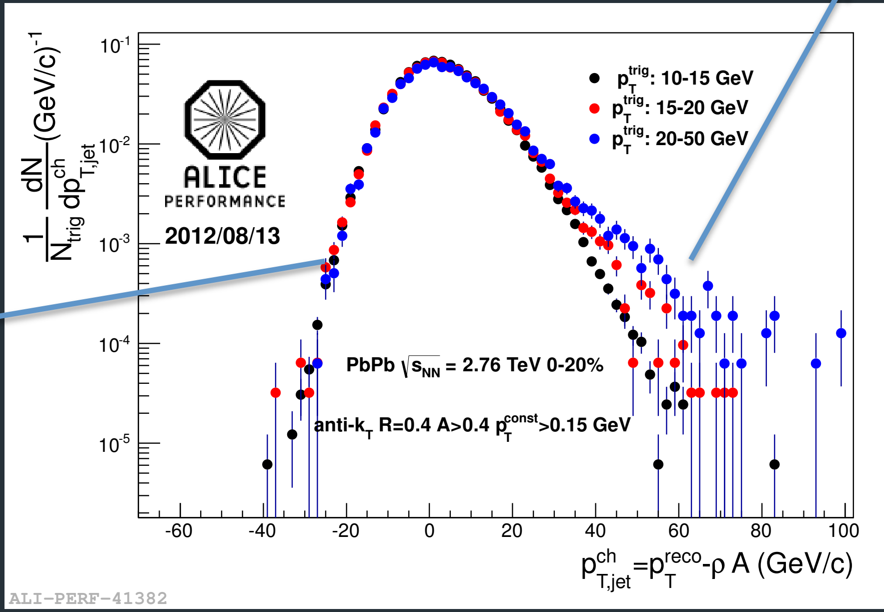


A constant cross section at high p_T and power law spectrum would lead to constant R_{AA}
Is this a coincidence (ignoring path length fluctuations, evolution)? Or first step …

A new approach: Recoil Jets

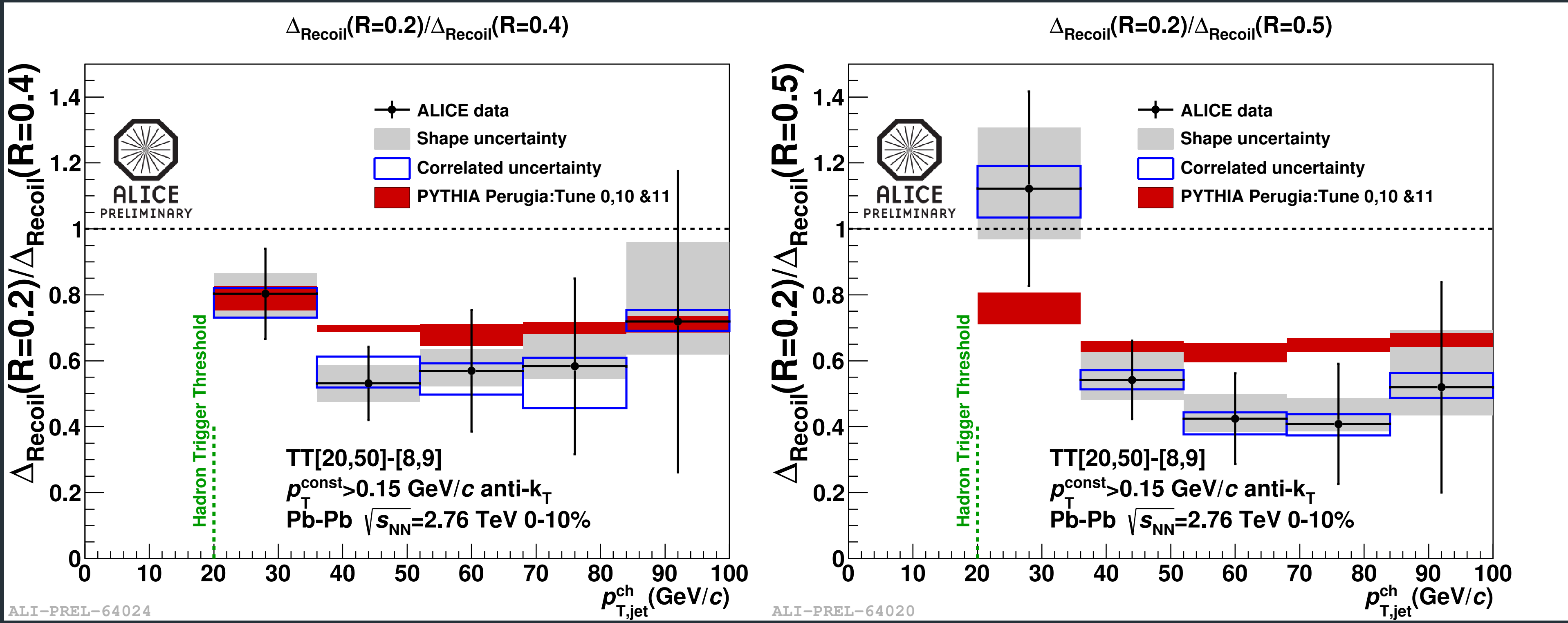
- Hadron triggered semi-inclusive jet distribution
  Δ_{recoil} = RecoilYield[20-50] - RecoilYield[10-15]
- Data driven background removal
  - arxiv:1208.1518
- No fake jets in Δ_{recoil}
- Same unfolding techniques as for inclusive spectrum
- Validation in pp
  - Comparison to PYTHIA and pQCD
- (Deliberate) biases
  - Minimum Q^2
    → harder spectrum
  - Surface bias





Goal: Access parton fragmentation at lower jet p_T and larger R.

"Structure Ratio"



No significant modification of jet structure for up to R ≈ 0.5.
→ Naturally extension with PID/Q/γ tagging in the next run.

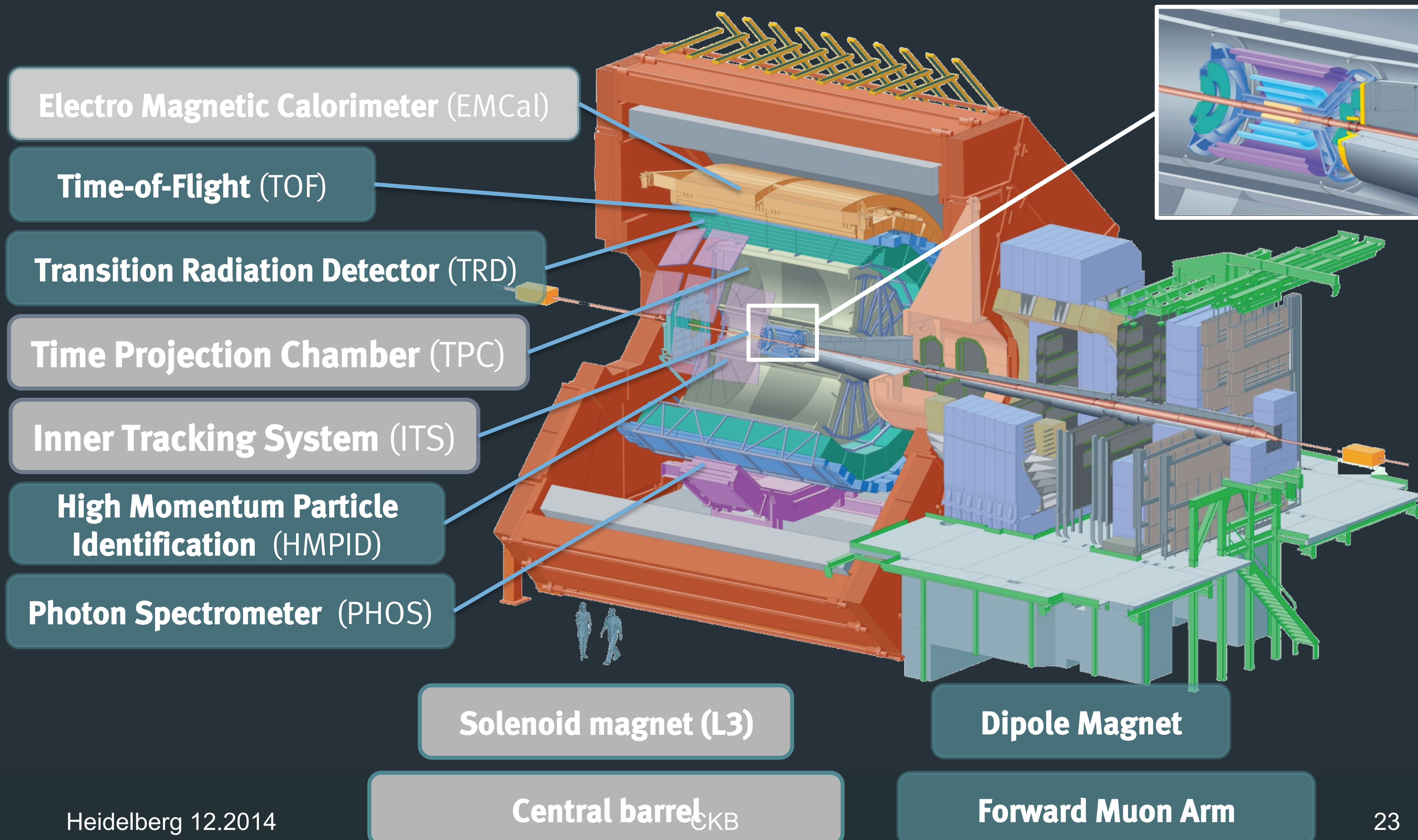
Summary

- Increasingly differential picture of parton energy loss
  - Collisional and radiative energy loss, energy re-distributed to large angles
  - R_{AA} observable alone cannot reflect this complexitiy but still highly popular
    Wish for simple, clear pictures

- Availability of parton energy loss has become MCs essential
  - Development of new observables
  - Comparison to all existing observables, with evaluation of (event-by-event) biases and separation of effects averaged/washed out in R_{AA}

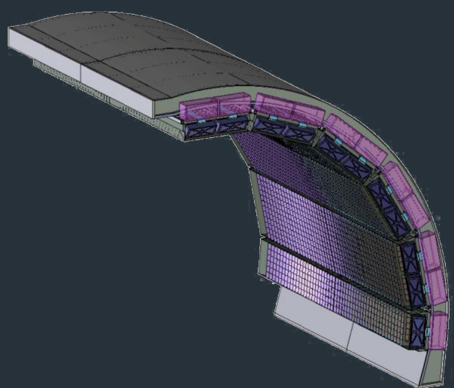
- Two qualitatively different regimes at LHC
  - Parton p_T larger $\approx$ 100 GeV: isolation of radiative energy loss
  - Below: mixture of processes and separation of flavor/mass dependence
  - + Energy (T) dependence with RHIC

ALICE @ LHC


Electro Magnetic Calorimeter (EMCal)
Time-of-Flight (TOF)
Transition Radiation Detector (TRD)
Time Projection Chamber (TPC)
Inner Tracking System (ITS)
High Momentum Particle Identification (HMPID)
Photon Spectrometer (PHOS)
Solenoid magnet (L3)
Dipole Magnet
Central barrel
Forward Muon Arm

Reconstructed Jets in ALICE

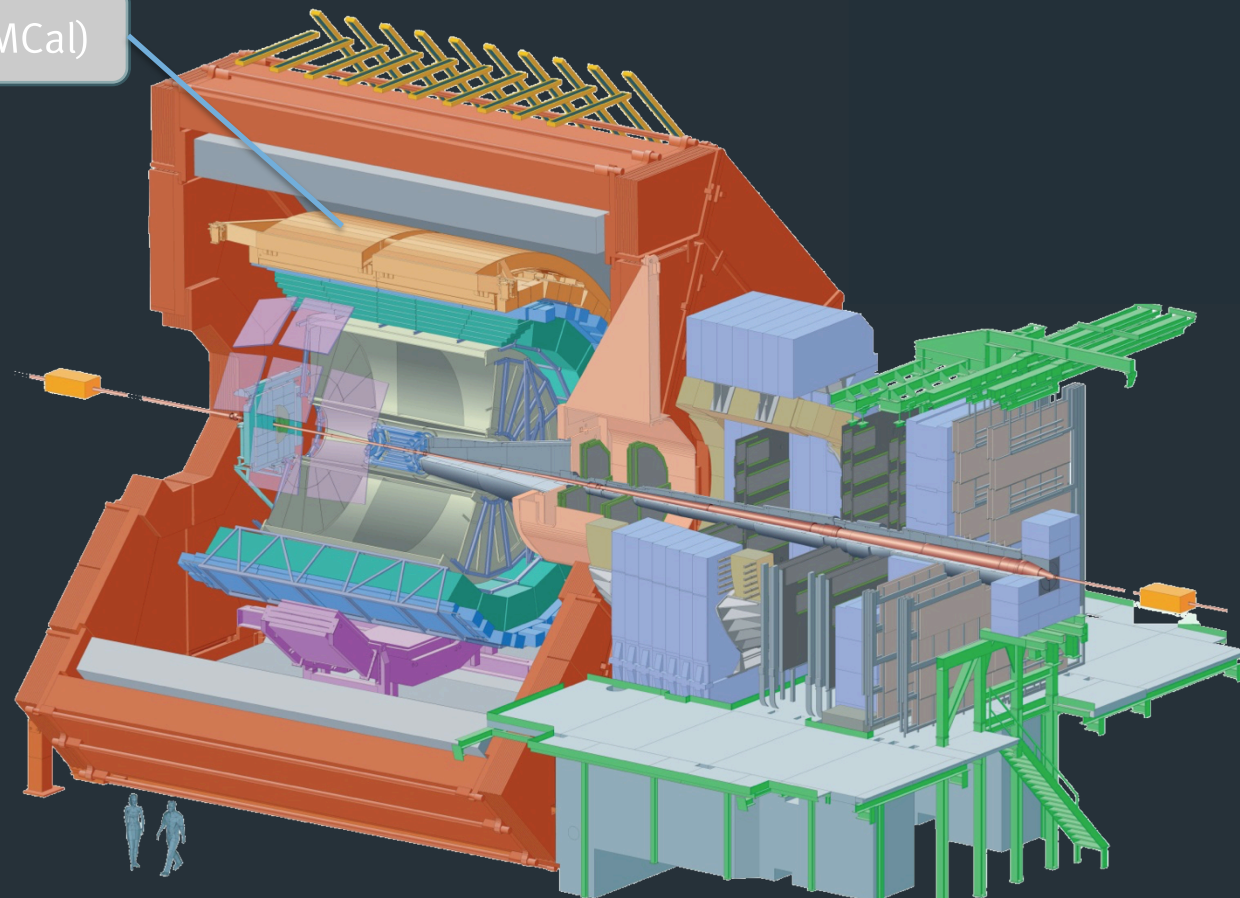
Electro Magnetic Calorimeter (EMCal)



Pb-Scintillator sampling:

- $|\eta| < 0.7$, $1.4 < \varphi < \pi$
- Track matching to account for double counted energy

Neutral constituents



Full jet

Charged constituents
(**Charged jet**)

Central barrel tracking

Combined TPC+ITS:

- $|\eta| < 0.9$, $0 < \varphi < 2\pi$

V0 topology

Converted photon

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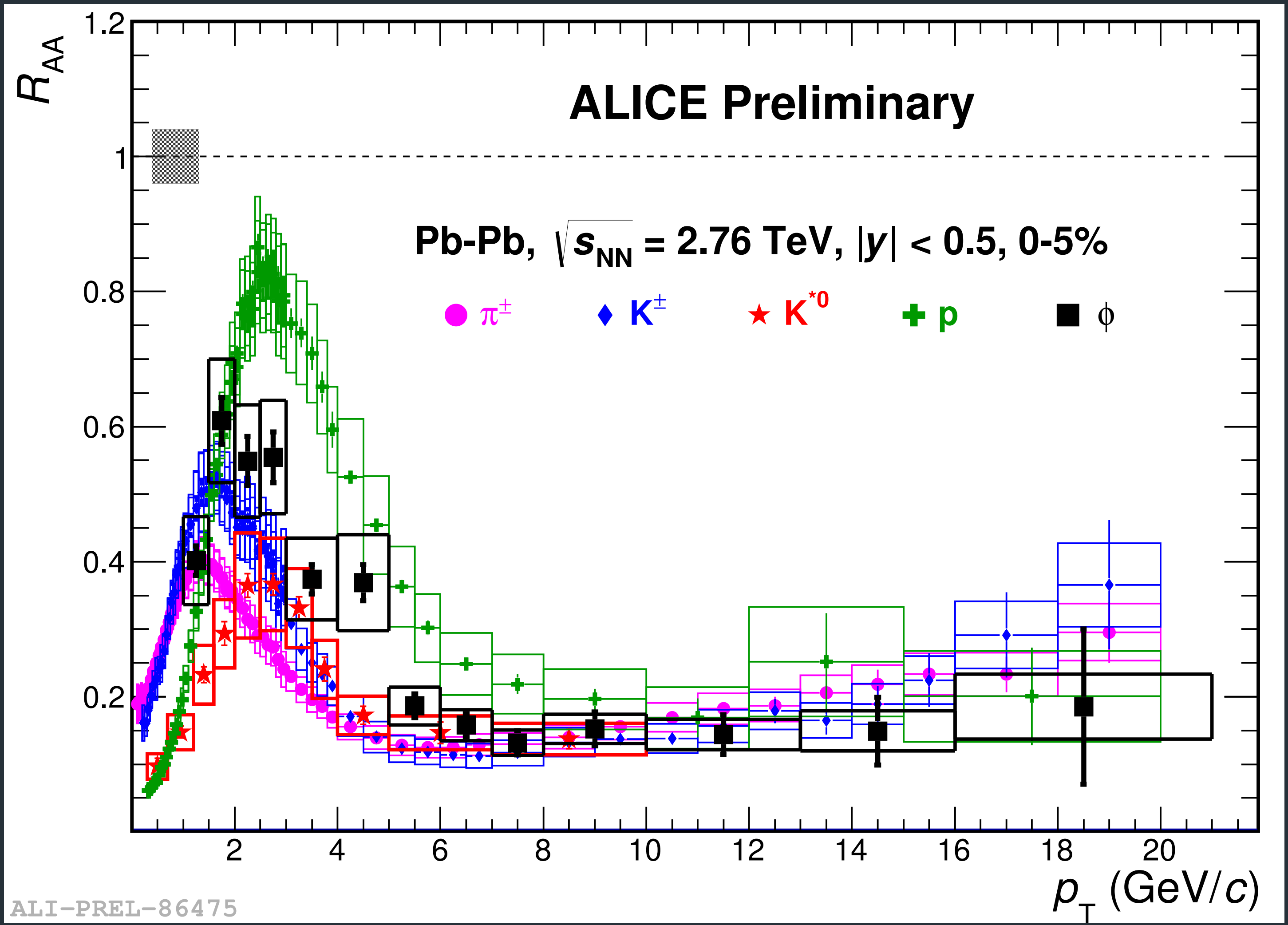
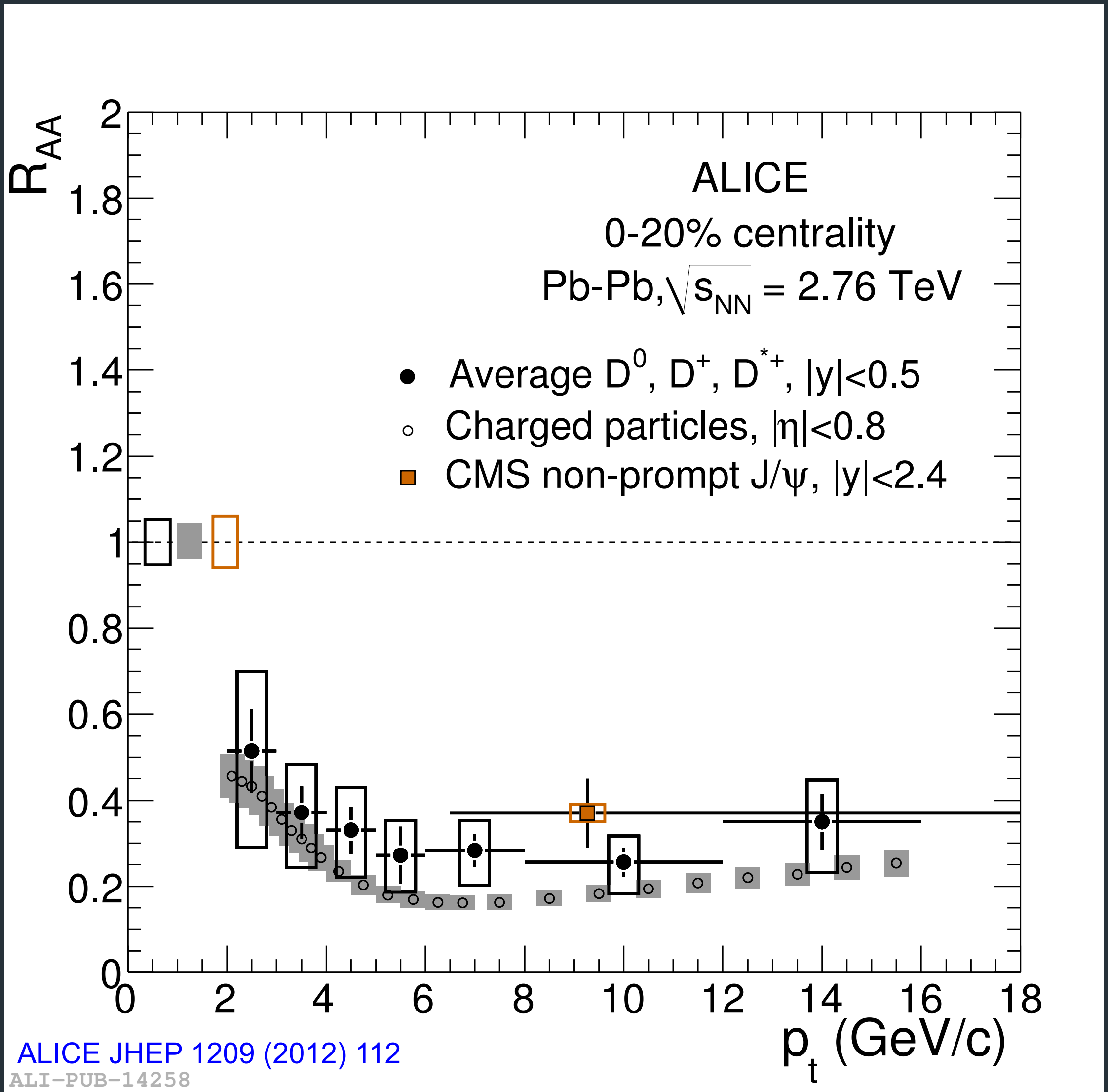
Resolving Hadron Species



Low p_T: Flow and possible quark-recombination (baryon-anomaly).

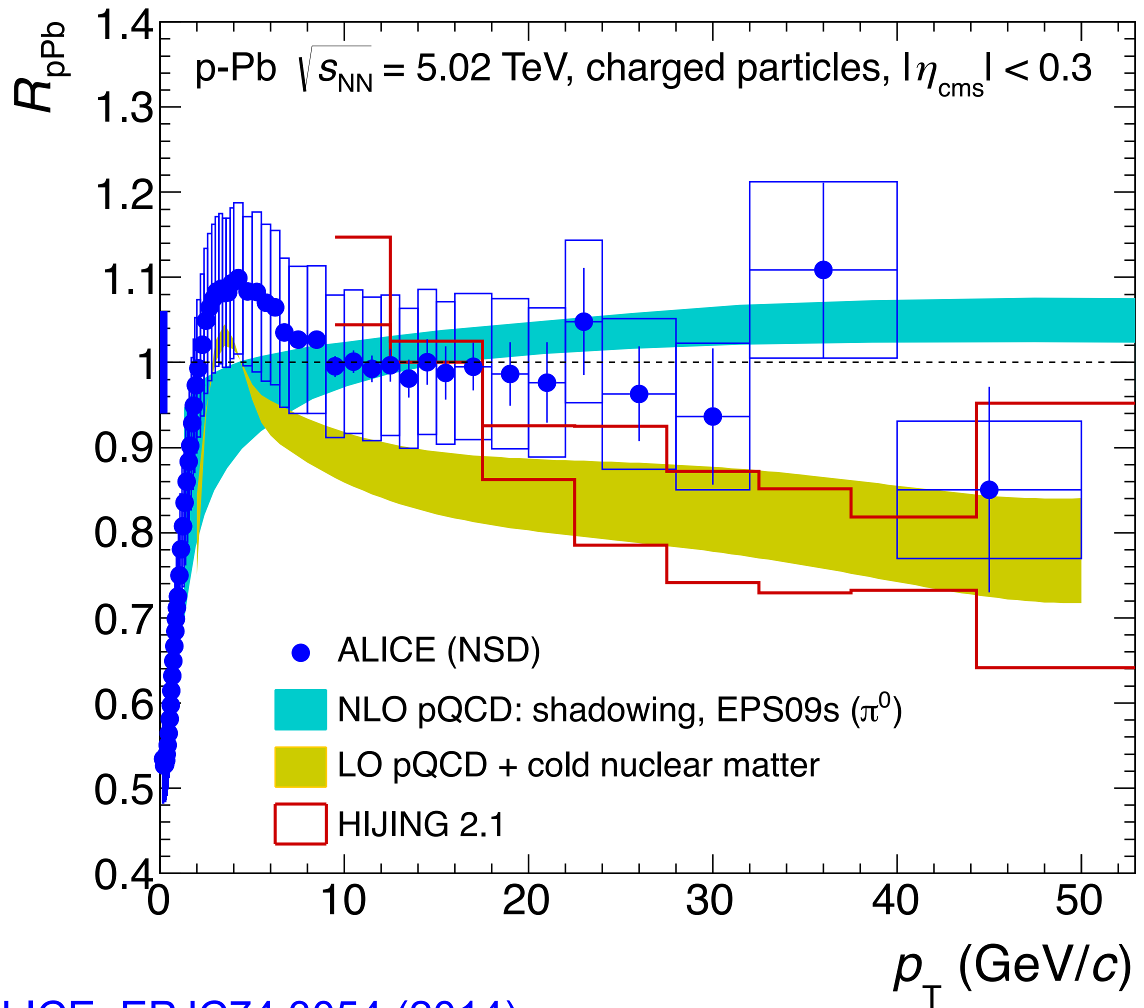
p_T > 8 GeV: Common suppression pattern, parton energy loss dominant.

Prompt Ds



Prompt D mesons compatible with charged hadrons and below non-prompt J/ψ.

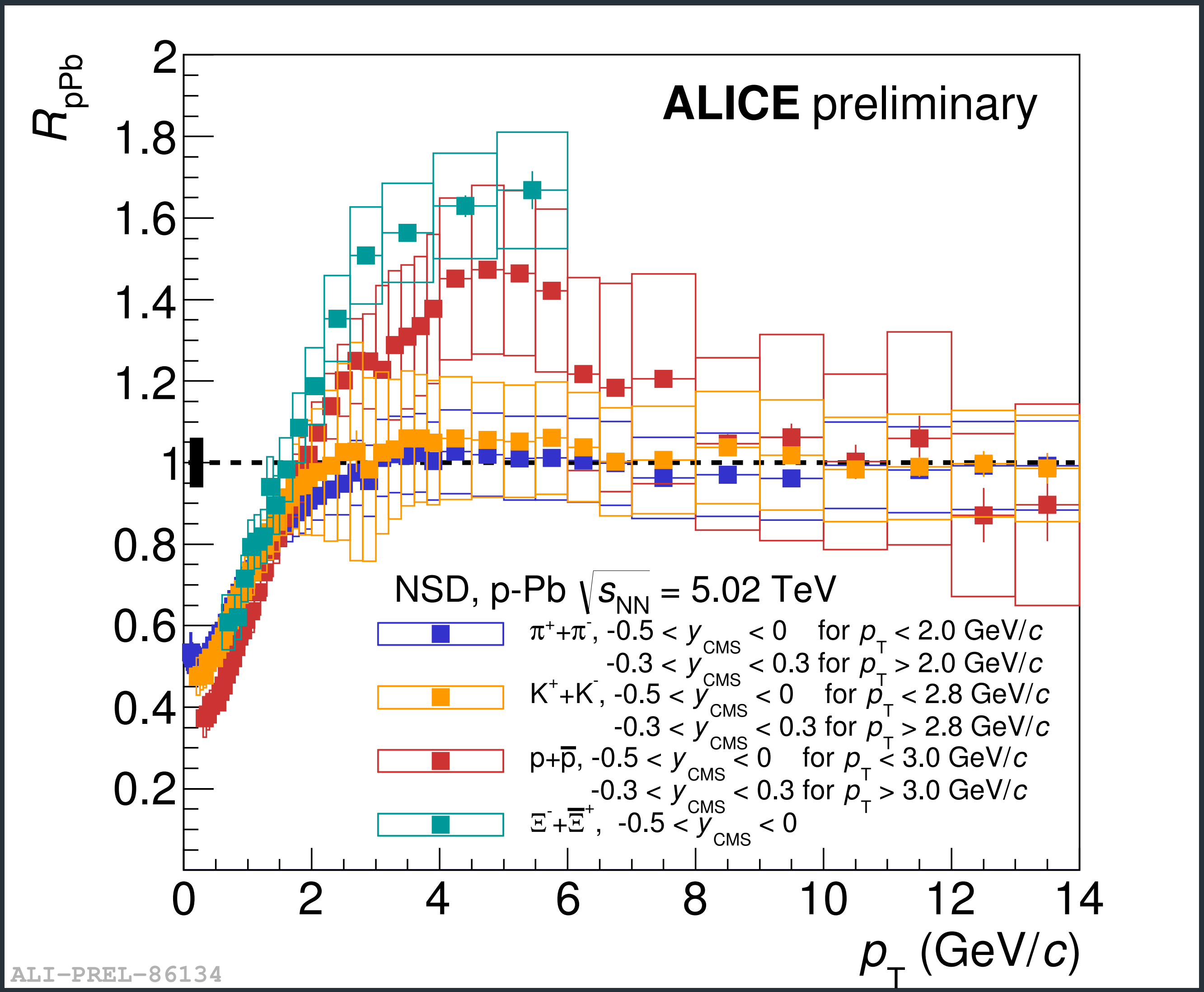
Charged Hadron R_{pA}



ALICE: EPJC74 3054 (2014)

No strong nuclear modification at high p_T.
Hint for peak below 10 GeV.
Confirmed with PID:
Mass ordering, baryons enhanced

Resolving Hadron Species

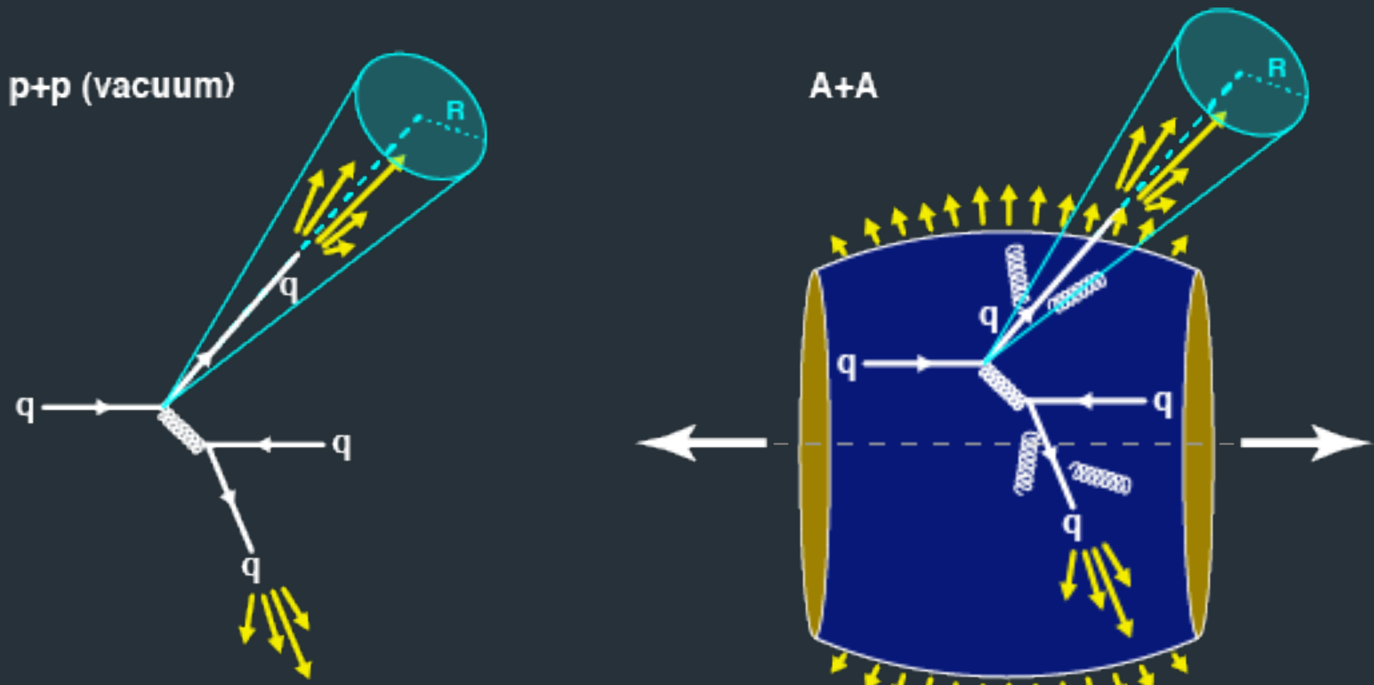


See talk by Alexander Kalweit

Seperation of Baryons and Mesons.
“Classical”-Explanation cannot account for this.
Flow and recombination in pPb?

Jet Modification

Interactions of the hard parton with the medium modify the jet relative to pp, but a jet is not uniquely defined (algorithm, radius, p_T cuts, …)



Out-of-cone radiation:

- Energy loss, $R_{AA} < 1$

$$R_{AA}(p_T) = \frac{d^2N_{AA}/dydp_T}{T_{AA}\, d^2\sigma_{pp}\, dydp_T}$$

$$T_{AA} = N_{coll}/\sigma_{NN}$$

In-cone radiation:

- R_{AA} unchanged
- Jet broadening

Experimental challenge in A+A: Separate jet signal/constituents from large soft background

Reconstructed Jets in ALICE

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- Input to jet reconstruction
  - Charged tracks (ITS+TPC): p_T > 150 MeV/c
  - Neutral energy clusters (EMCal): E_T > 300 MeV
    - Correction for matched tracks avoids energy double counting
  - High precision at single particle level down to very low p_T
- Jet reconstruction via FastJet*
  - Anti-k_T for signal
  - k_T for background density
  - Boost invariant p_T recombination scheme
- Correction for detector effects via unfolding
  - Momentum resolution
  - Energy resolution
  - Track matching

Charged jets

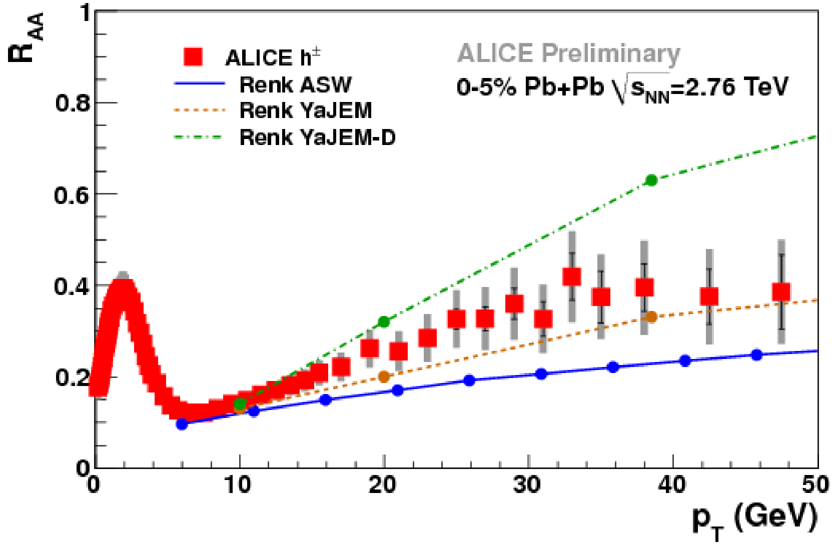
Full jets

N.B.: Different parton p_T scale at same jet p_T for charged and neutral jets.

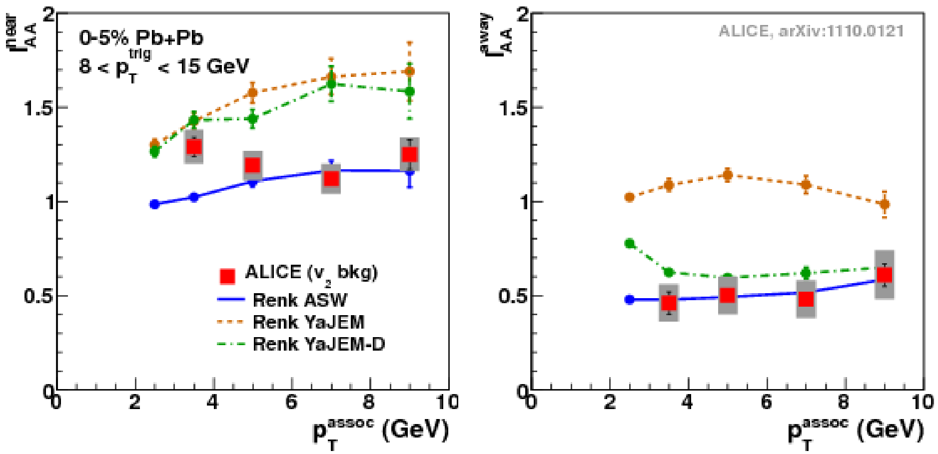
*Cacciari et al. EPJ C72:1896 (2012)

Theory Comparison R_{AA} and I_{AA}

Need simultaneous comparison to several measurements to constrain geometry and E-loss



Here: R_{AA} and I_{AA}



Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)

The Kinematic Lever Arm

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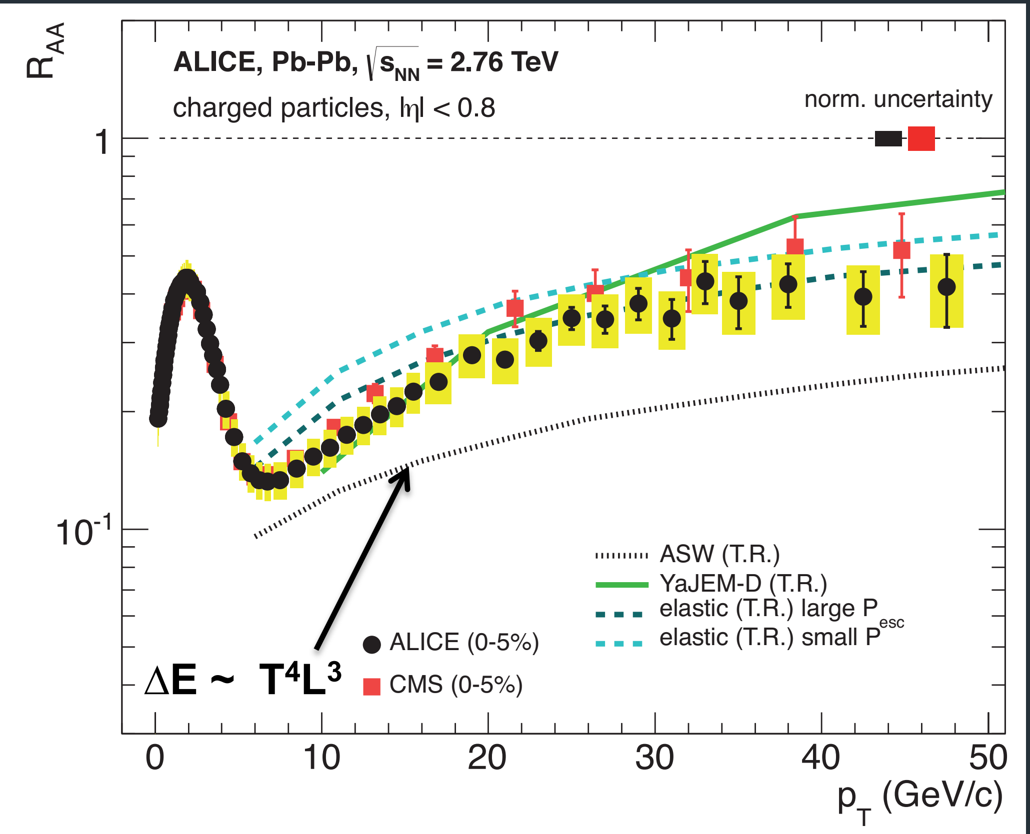
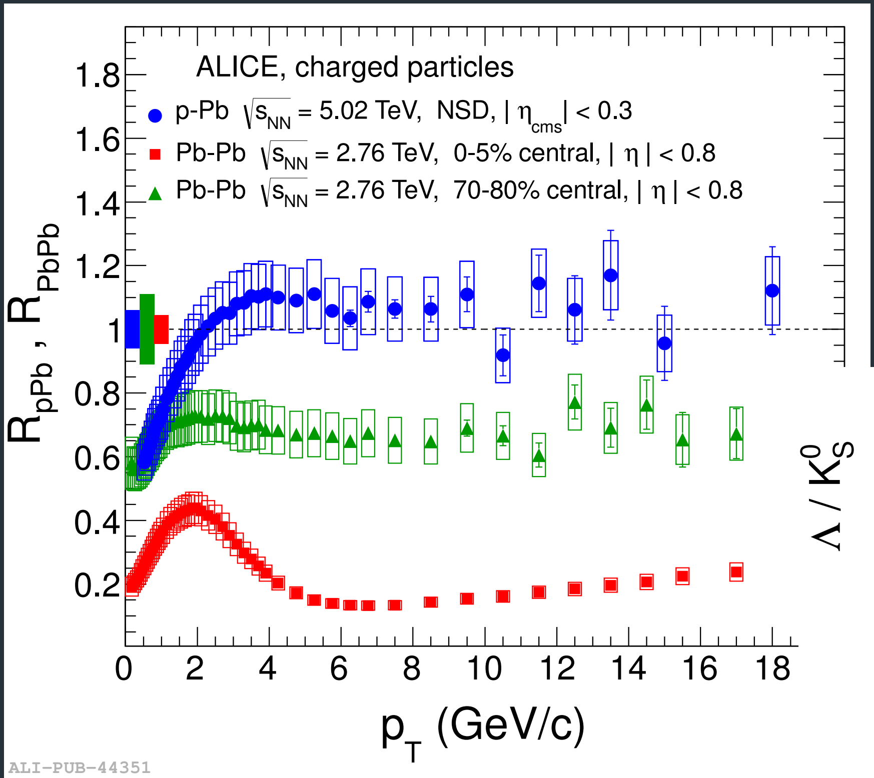
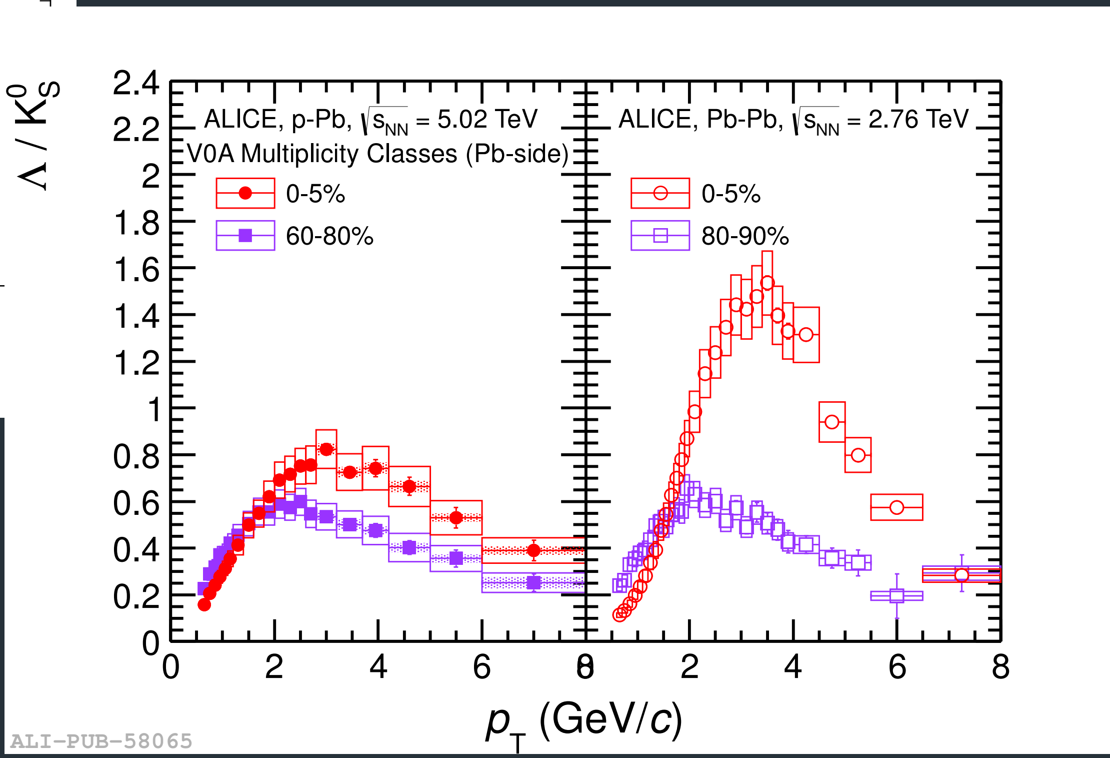
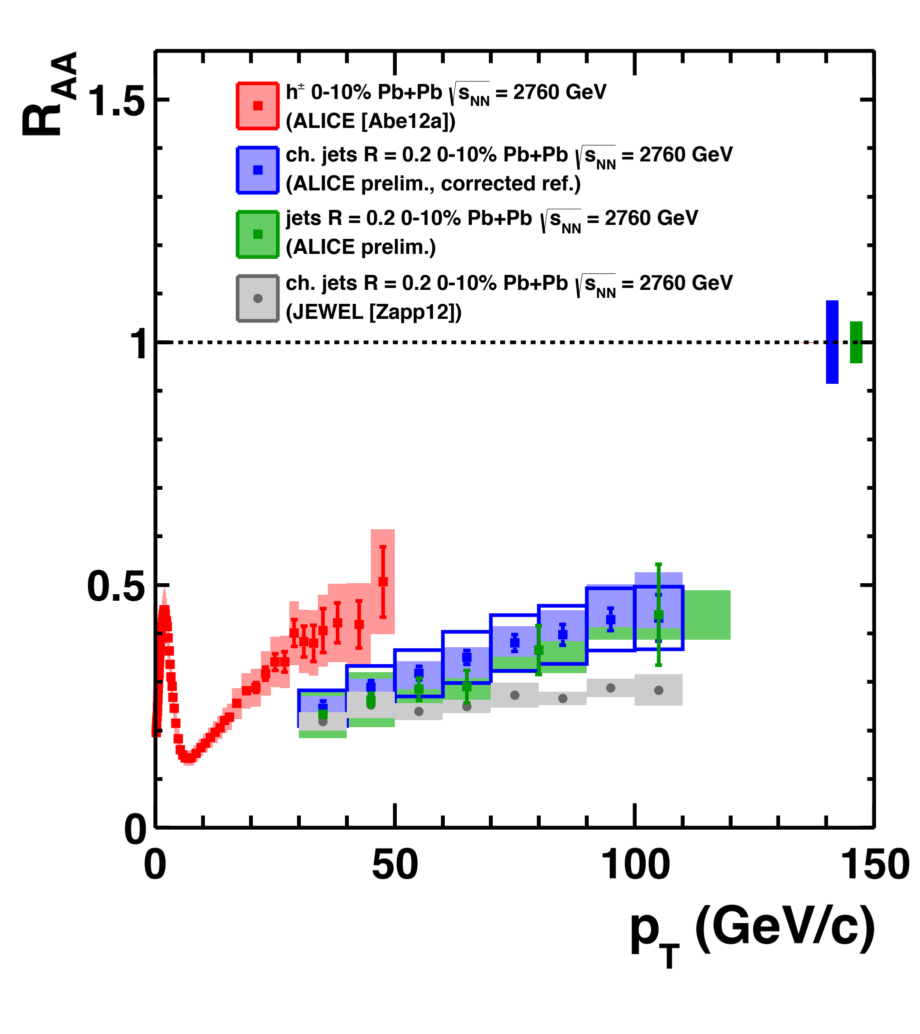


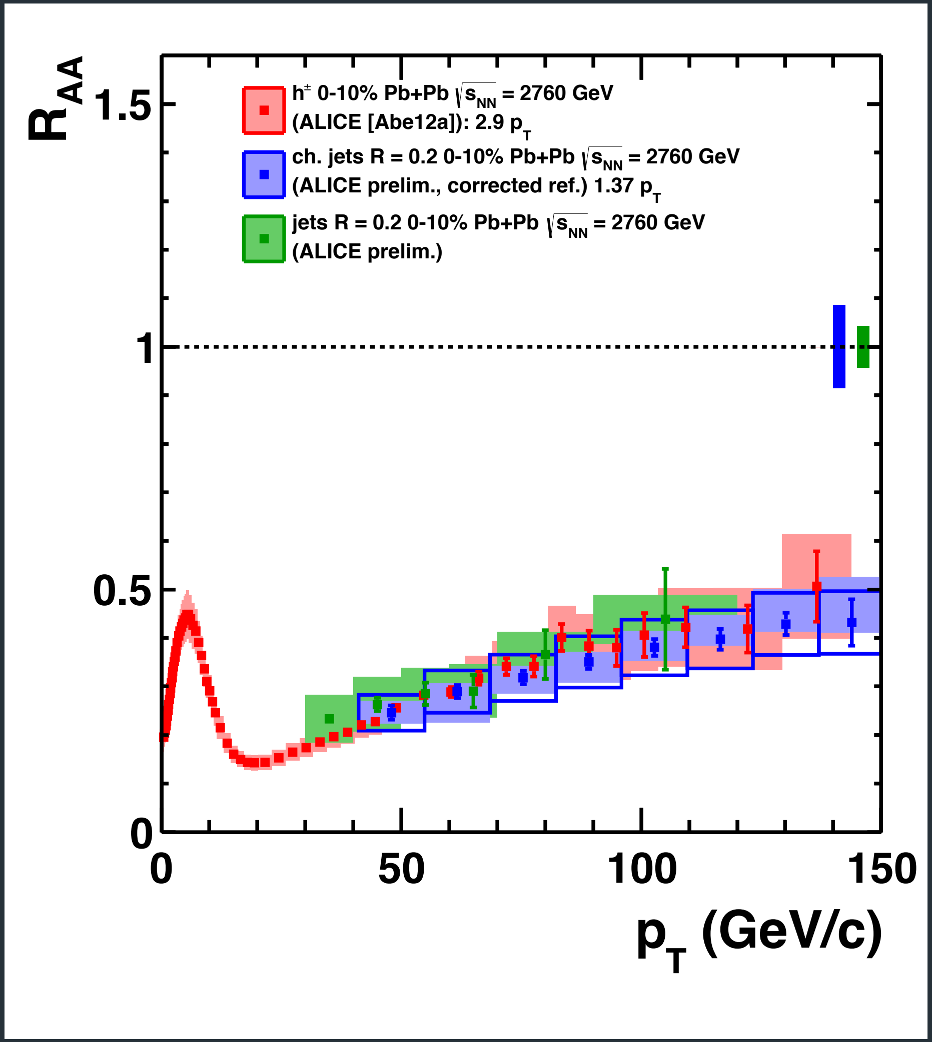
- Models tuned to RHIC data
  - Identical expansion model Renk PRC85 044903 (2012)
  - LHC-extrapolation: Test of T-dependence
- Flattening of R_{AA}
  - Generic property of all models
- LHC data favor
  - $\Delta E \sim T^3 L^n$ ($n \leq 2$)

Further constraint of energy loss scenarios.

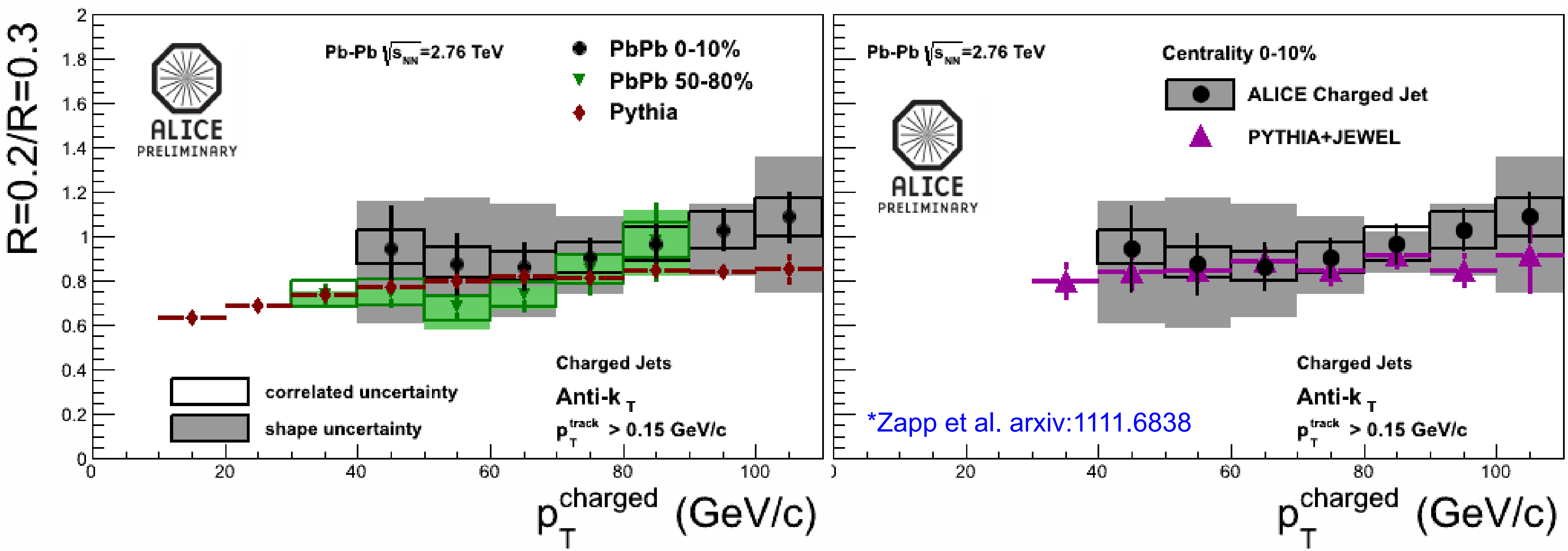

ALICE, charged particles
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV, NSD, | η_{cms}| < 0.3
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV, 0-5% central, | η | < 0.8
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV, 70-80% central, | η | < 0.8
R_{pPb} , R_{PbPb}
p_T (GeV/c)
ALI-PUB-44351


Λ / K^0_S
ALICE, p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
V0A Multiplicity Classes (Pb-side)
0-5%
60-80%
ALICE, Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
0-5%
80-90%
p_T (GeV/c)
ALI-PUB-58065

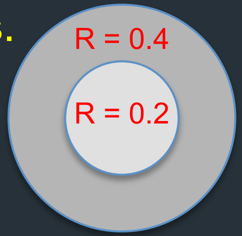

R_{AA}
1.5
1
0.5
0
0
50
100
150
p_T (GeV/c)
h± 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE [Abe12a])
ch. jets R = 0.2 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE prelim., corrected ref.)
jets R = 0.2 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE prelim.)
ch. jets R = 0.2 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(JEWEL [Zapp12])


R_{AA}
1.5
1
0.5
0
0
50
100
150
p_T (GeV/c)
h± 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE [Abe12a]): 2.9 p_T
ch. jets R = 0.2 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE prelim., corrected ref.) 1.37 p_T
jets R = 0.2 0-10% Pb+Pb $\sqrt{s_{NN}}$ = 2760 GeV
(ALICE prelim.)

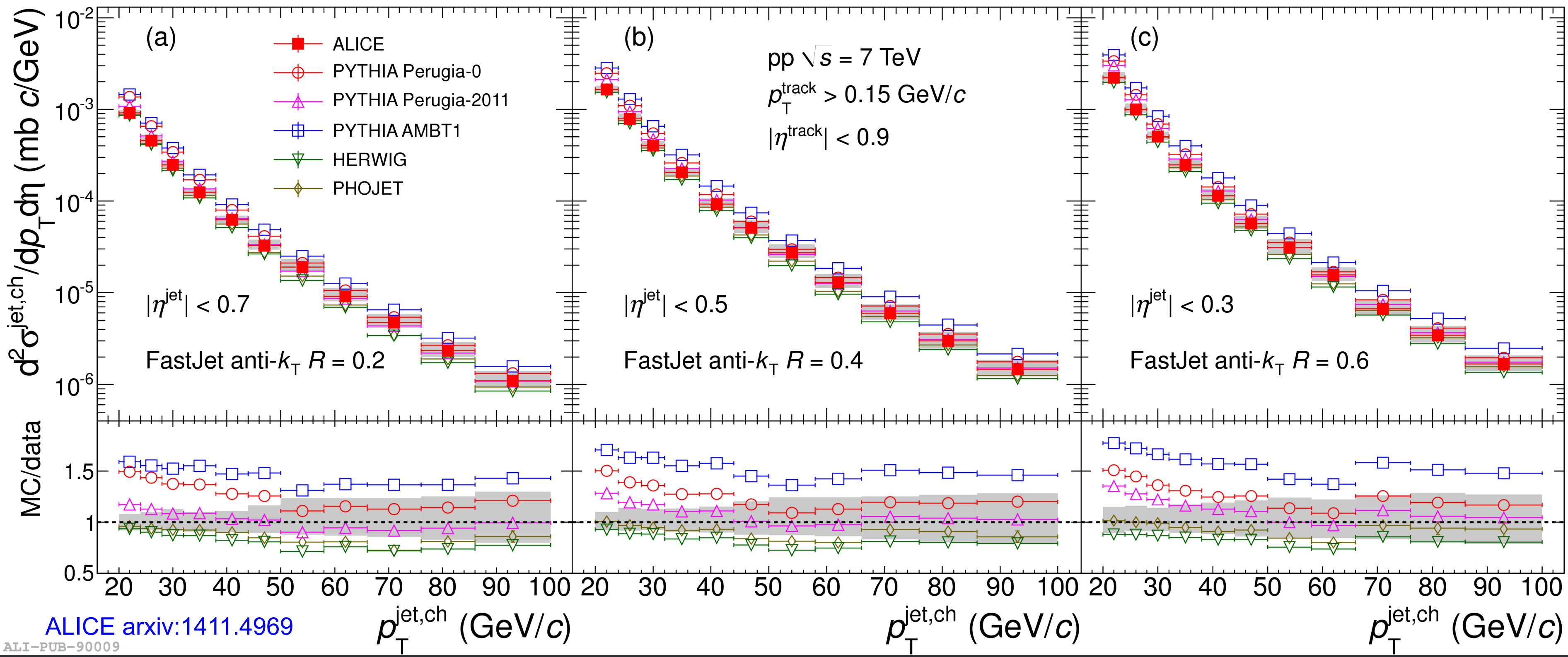
Jet Structure Cross Section Ratio



Ratio consistent with vacuum jets for peripheral and central collisions.
No significant jet broadening.
Consistent with expectation from JEWEL* energy loss MC.



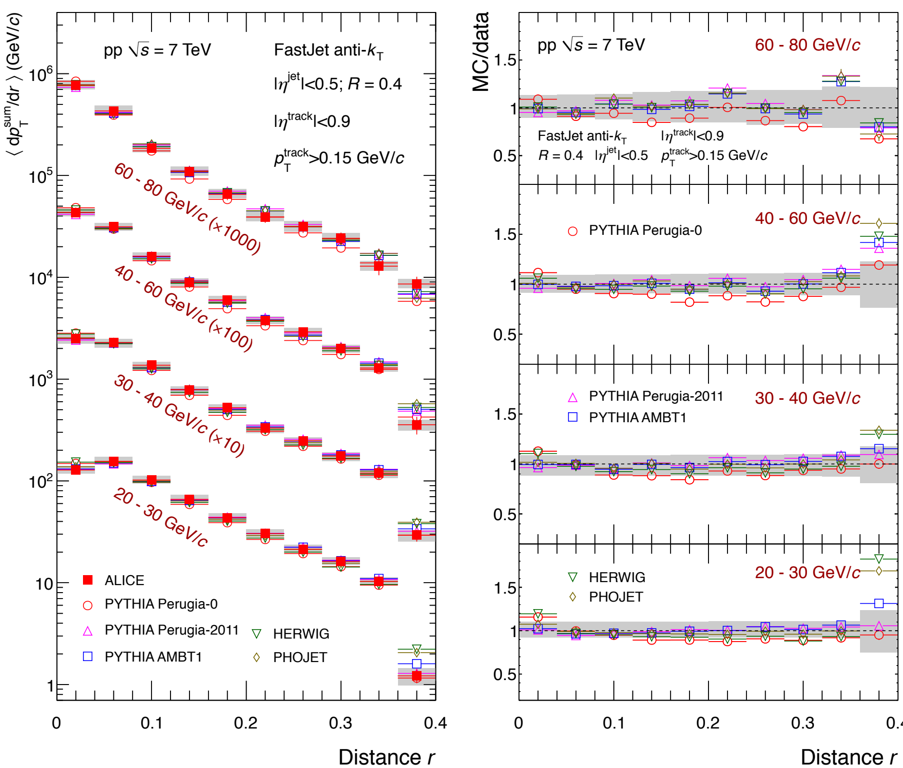
(Charged) Jet Production pp @ 7 TeV



Larger variance of MC/tunes at higher √s (important for increased LHC energy)

A Closer Look
Jet Structure in pp II

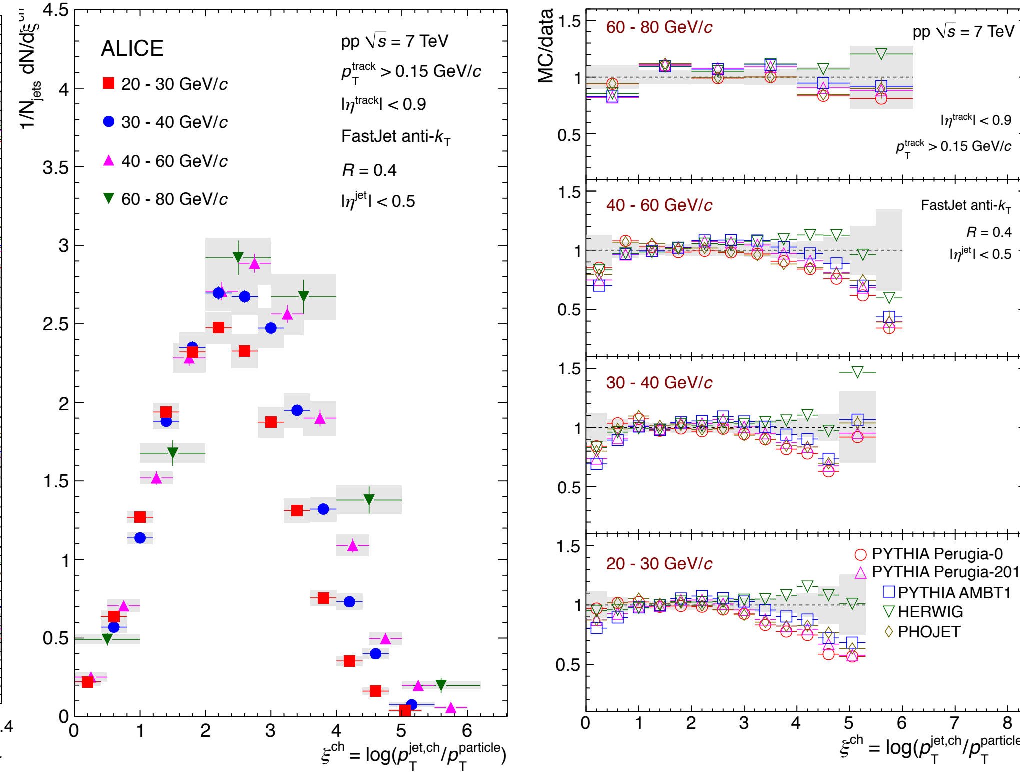
Radial structure



Radial structure well reproduced by MC.

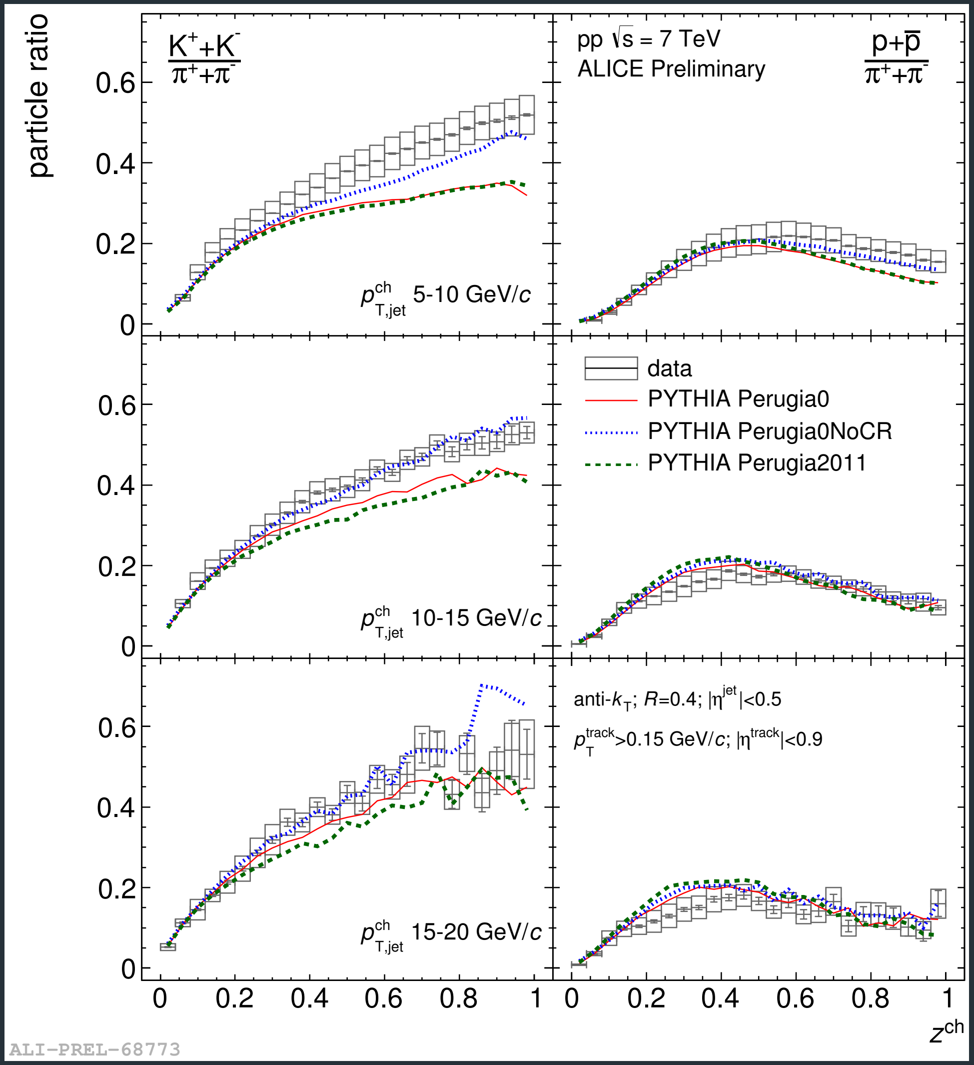
Longitudinal structure

Scaled transverse momentum: $\xi = -\ln \frac{p^{ch}_{T,jet}}{p_{T,track}}$

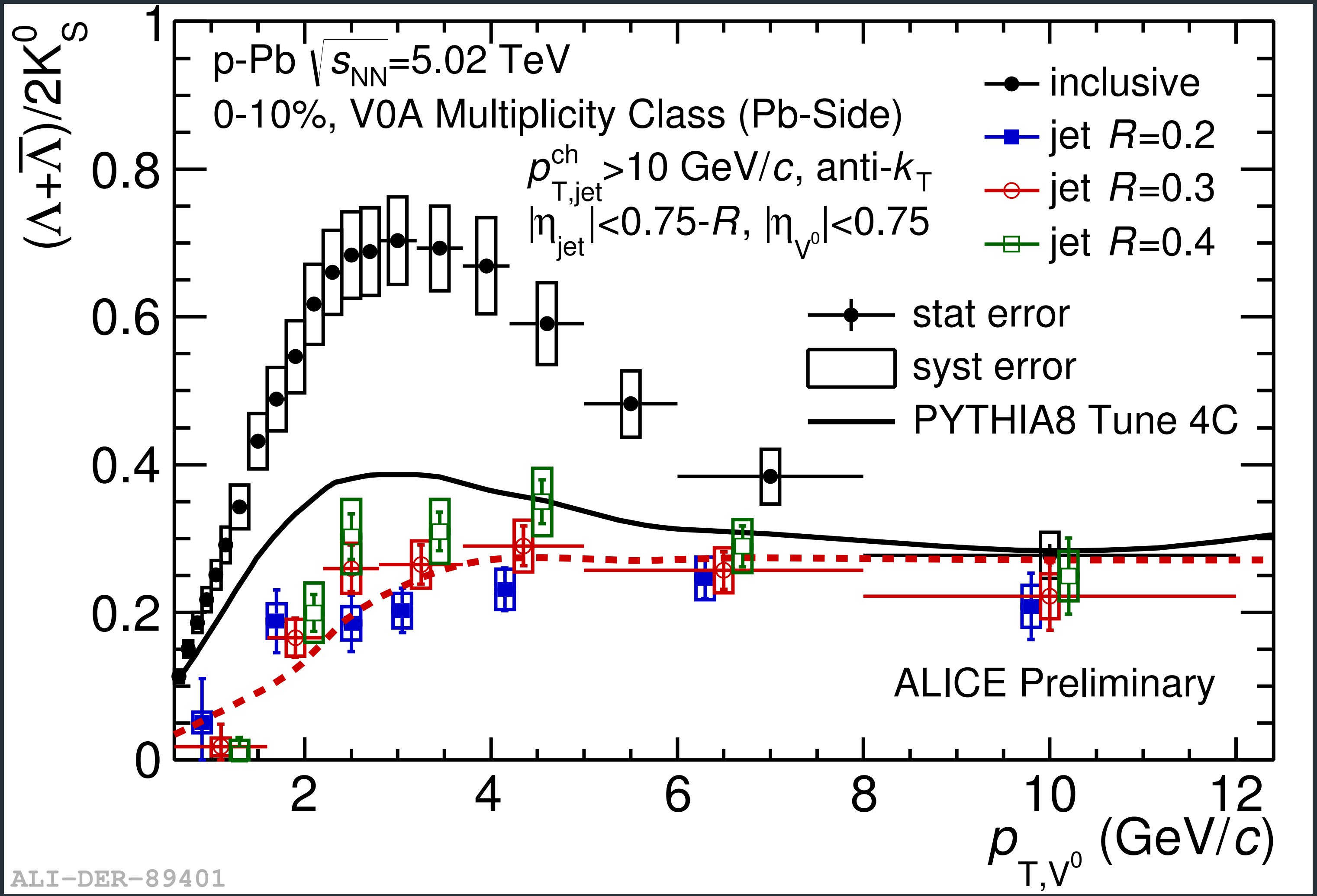


Hump-backed plateau, well reproduced by MC.

A Closer Look III
Identified Fragmentation



More discriminating between different MC tunes.

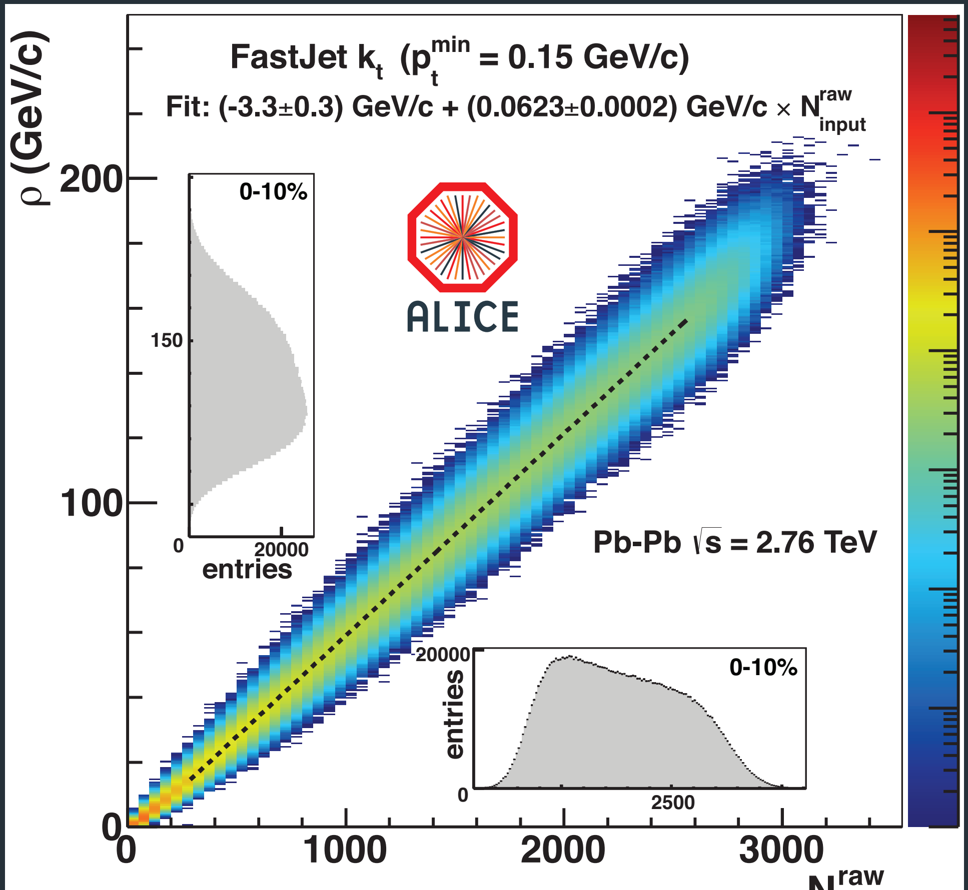


p-Pb √s_NN=5.02 TeV
0-10%, V0A Multiplicity Class (Pb-Side)
p^ch_T,jet>10 GeV/c, anti-k_T
|η_jet|<0.75-R, |η_V0|<0.75
inclusive
jet R=0.2
jet R=0.3
jet R=0.4
stat error
syst error
PYTHIA8 Tune 4C
ALICE Preliminary
(Λ+Λ̄)/2K0S
p_T,V0 (GeV/c)
ALI-DER-89401

Event Background

$$p_{T,jet} = p_{T,jet}^{rec} - \rho \times A_{jet}$$

- ρ: Median of p_T/area, determined event by event via k_T clustering
  - Here k_T clusters |η| < 0.5, excluding two leading clusters
  - Advantage: robust statistical measure
- Natural connection of ρ to event properties/characteristics of p_T spectrum
  - $\rho \approx N \langle p_T \rangle$
- Typical value for R = 0.4, $A \approx 0.5$
  - 50 – 100 GeV/c background for 0-10%



ALICE JHEP03 (2012) 053, arxiv:1201.2423

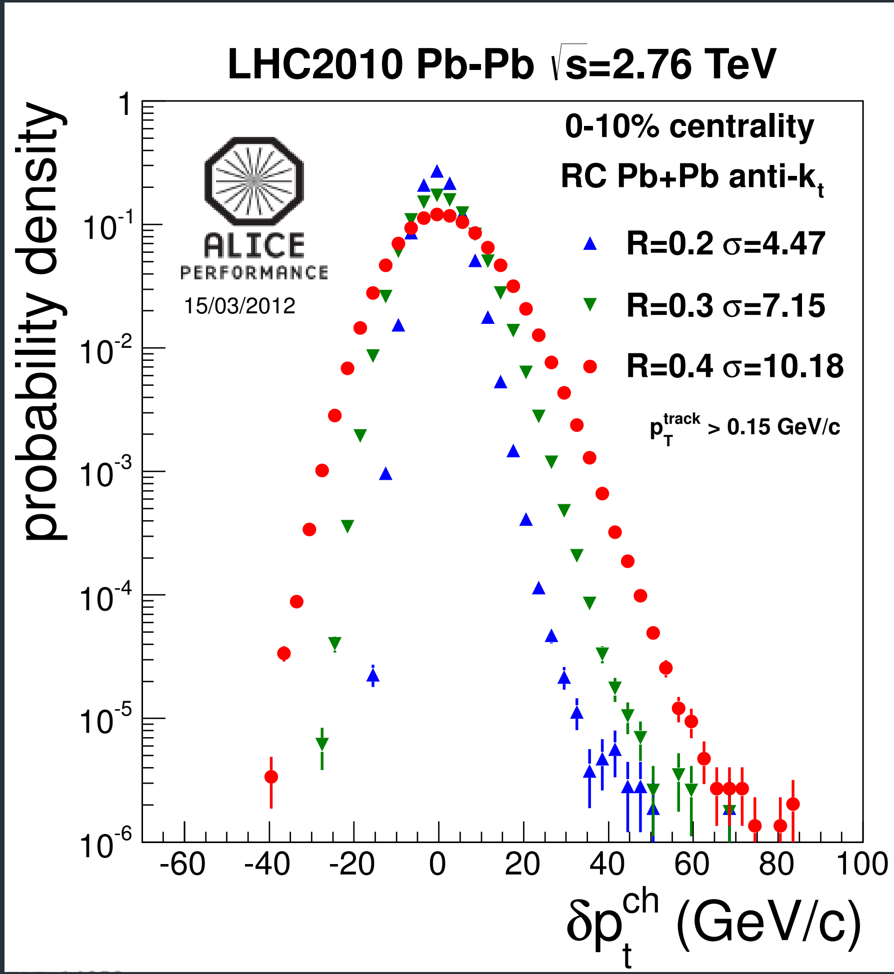
Background increases linearly with input raw multiplicity. Depends on p_T cuts and R.

Background Fluctuations

- Region-to-region deviations from median
  - Statistical fluctuations (**~$\sqrt{N}$**)
  - Collective effects (**~ v_2 N**)
  - Mini-jets
  - Non-uniform detection
- Data driven determination
  - Random cone, probe embedding in Pb-Pb events

$$\delta p_T = p_{T,rec} - A \cdot \rho - p_{T,probe}$$

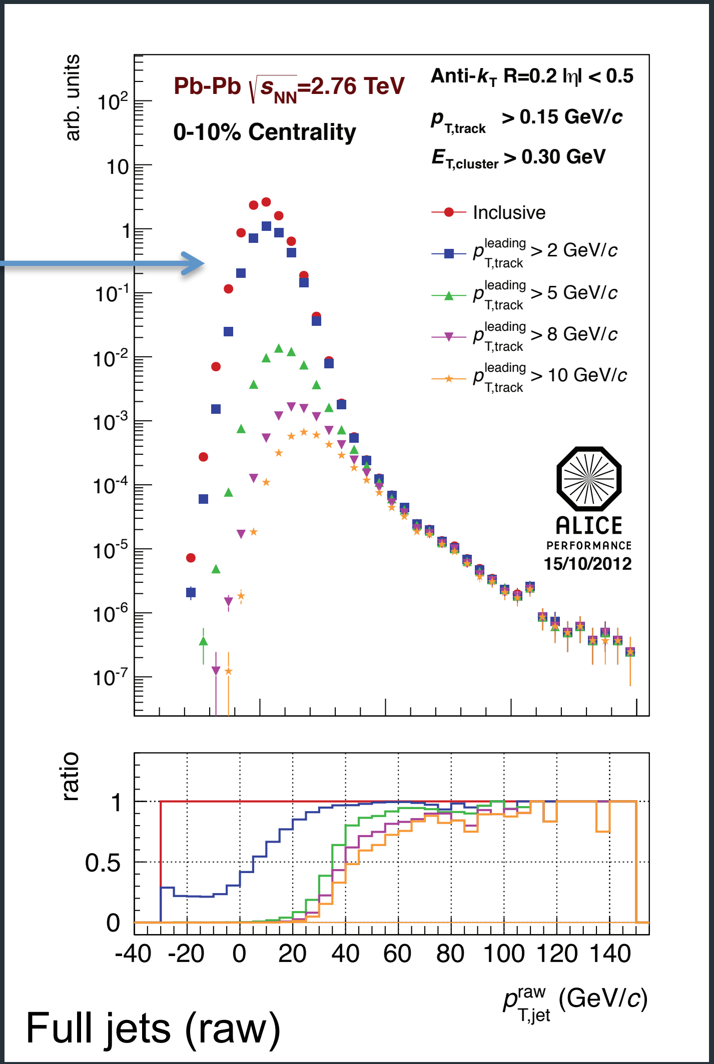
  - Width of distribution dependent on R and p_T cuts
    - These change multiplicity within cone



ALICE tracking capabilities essential to characterize background properties.

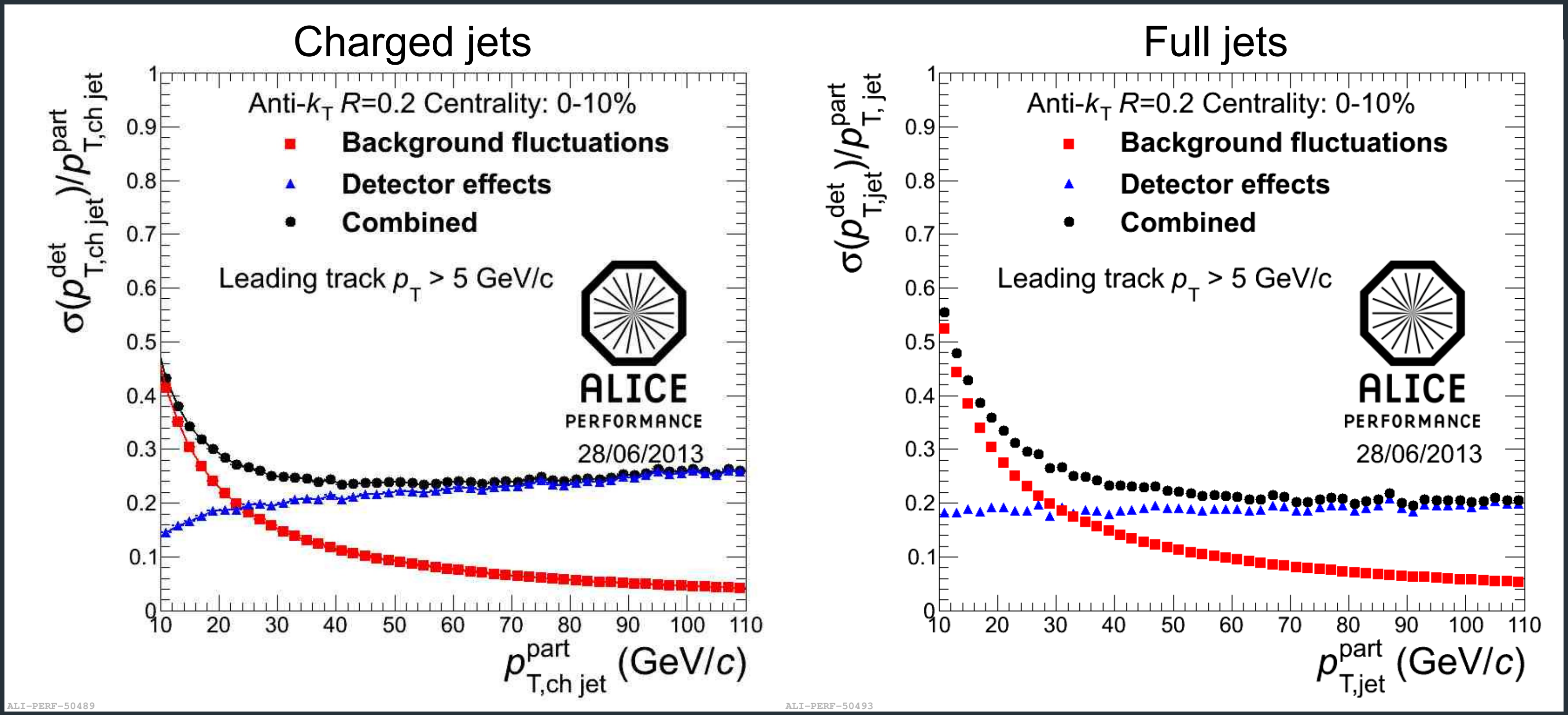
Combinatorial Jets

- Reconstructed jet clusters which do not originate from hard process
  - Determined by fluctuations of particle number and p_T
  - Bump around zero after background subtraction similar to δp_T
- No clear separation possible
  - Impact reduced for smaller jets
- Leading track bias to tag a hard process
  - p_T > 5, 8, 10 GeV/c **after** jet reconstruction
  - No reconstruction bias, only fragmentation
- Hard jets dominate beyond $p_T \approx 60$ GeV/c



Jet p_T resolution

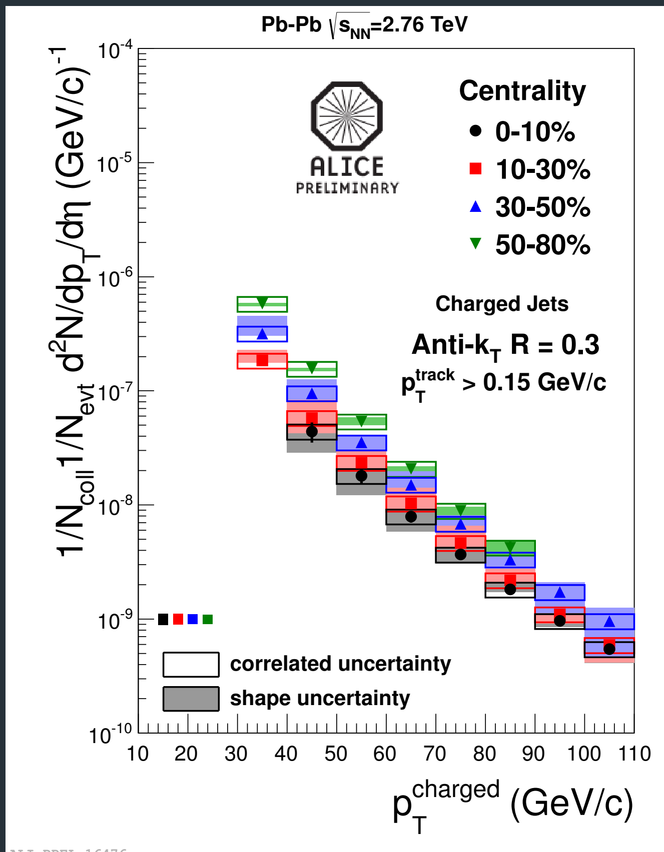
- Background fluctuations and detector effects partially compensate
  - Low jet p_T: background fluctuations dominate
  - High jet p_T: detector effects dominate



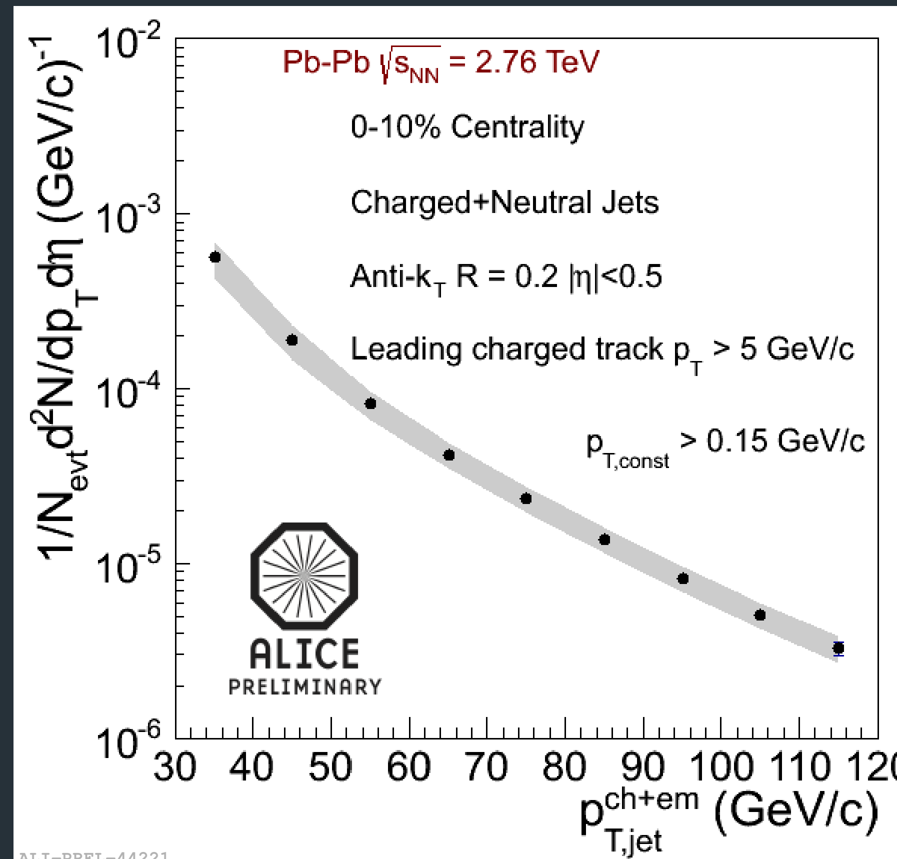
Resolution main effect on jet spectra: Corrected via unfolding (χ^2, SVD, Bayesian)

Jet Production in Pb-Pb

Charged jets, R = 0.3
4 centralities, no leading track bias

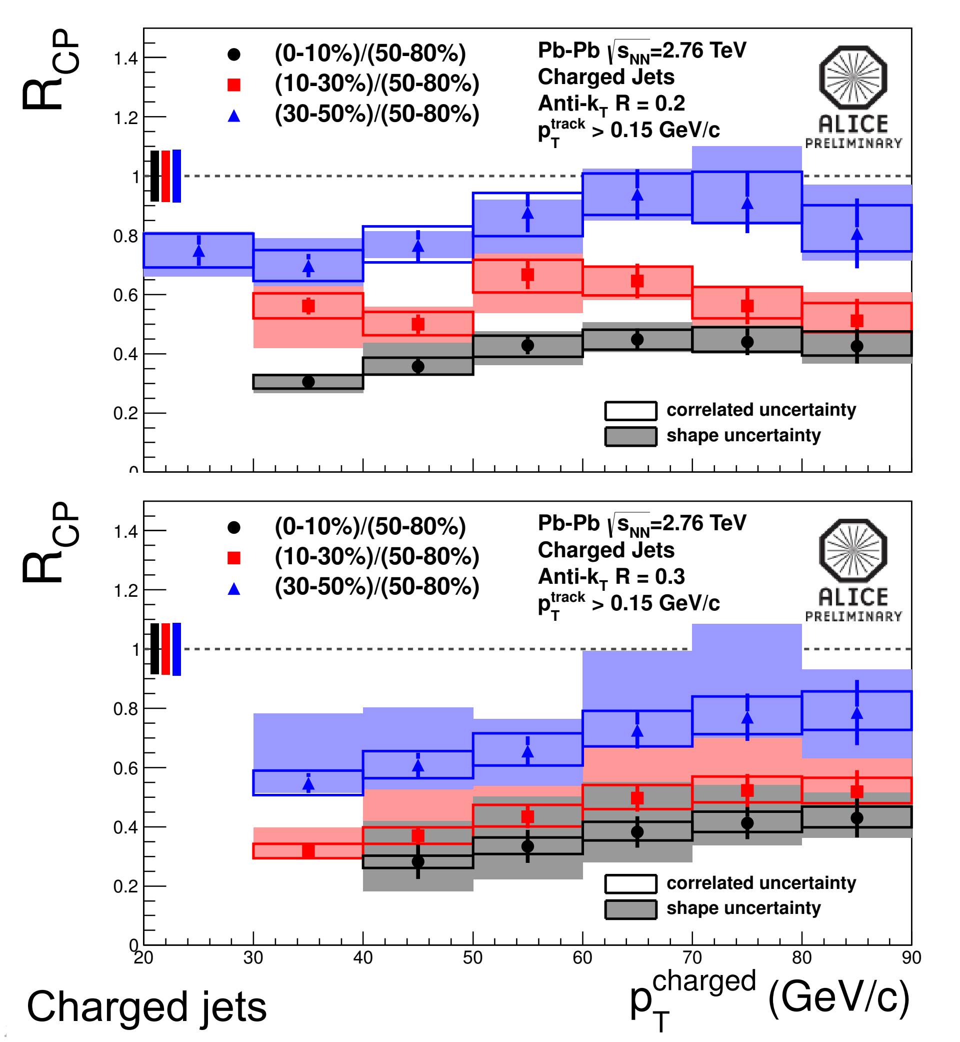


Full jets, R = 0.2
central events



R_{CP} Charged Jets

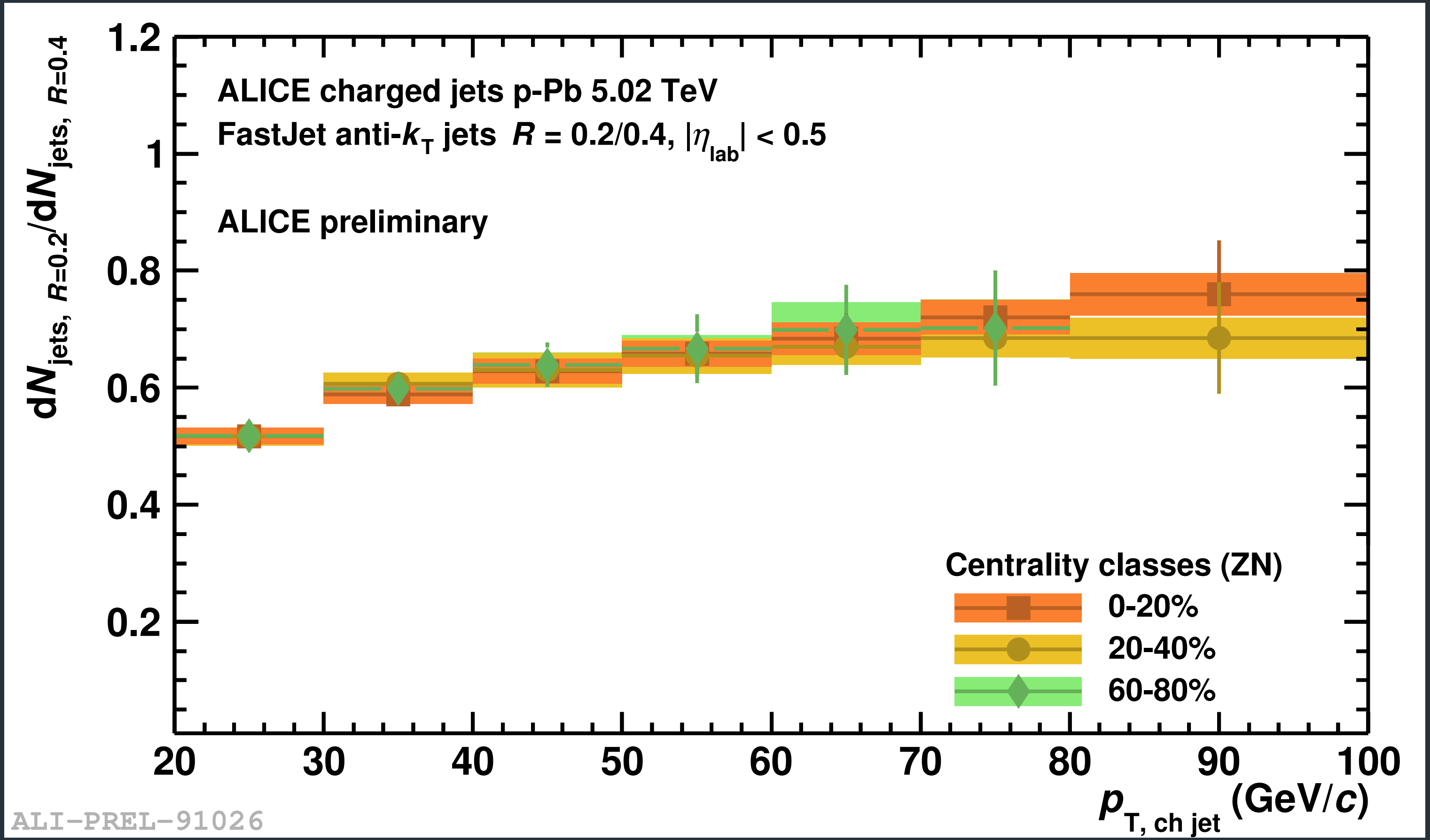
$$R_{CP} = \frac{N_{coll}^{peri} \cdot d^2N/dydp_T|_{cent}}{N_{coll}^{cent} \cdot d^2N/dydp_T|_{peri}}$$



Jets clearly suppressed in central collisions.
Centrality ordered suppression pattern.

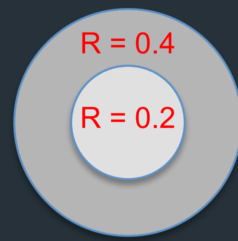
No strong p_T dependence

Jet Structure
Cross Section Ratio

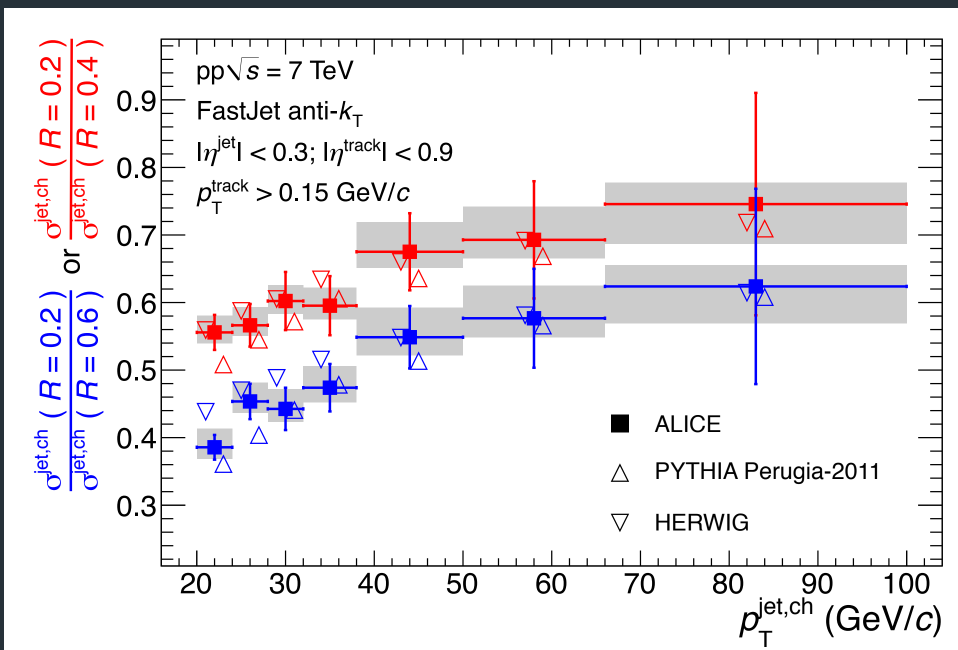


Jet Structure
Cross Section Ratio

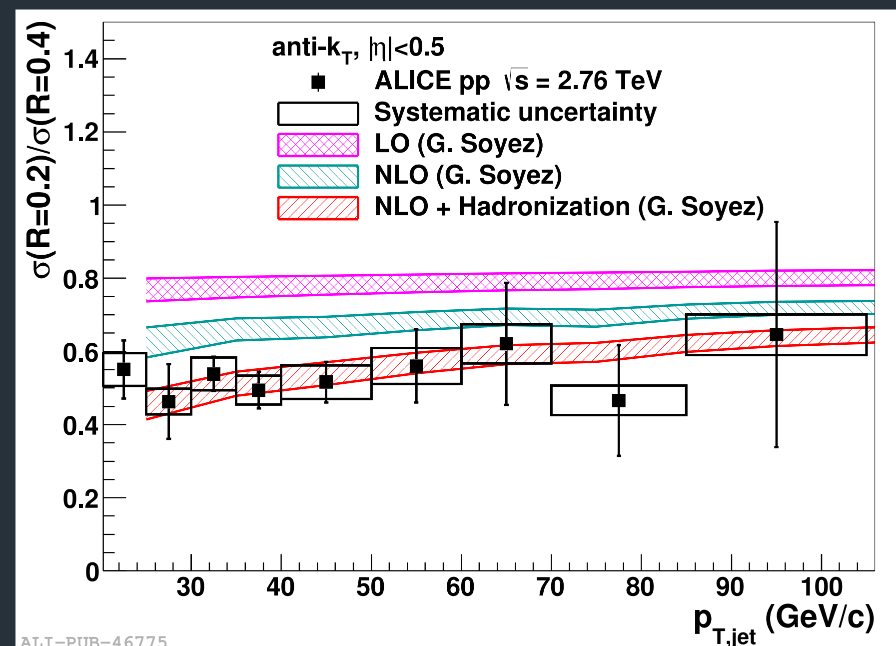
Cross section ratio tests jet collimation



Charged jets

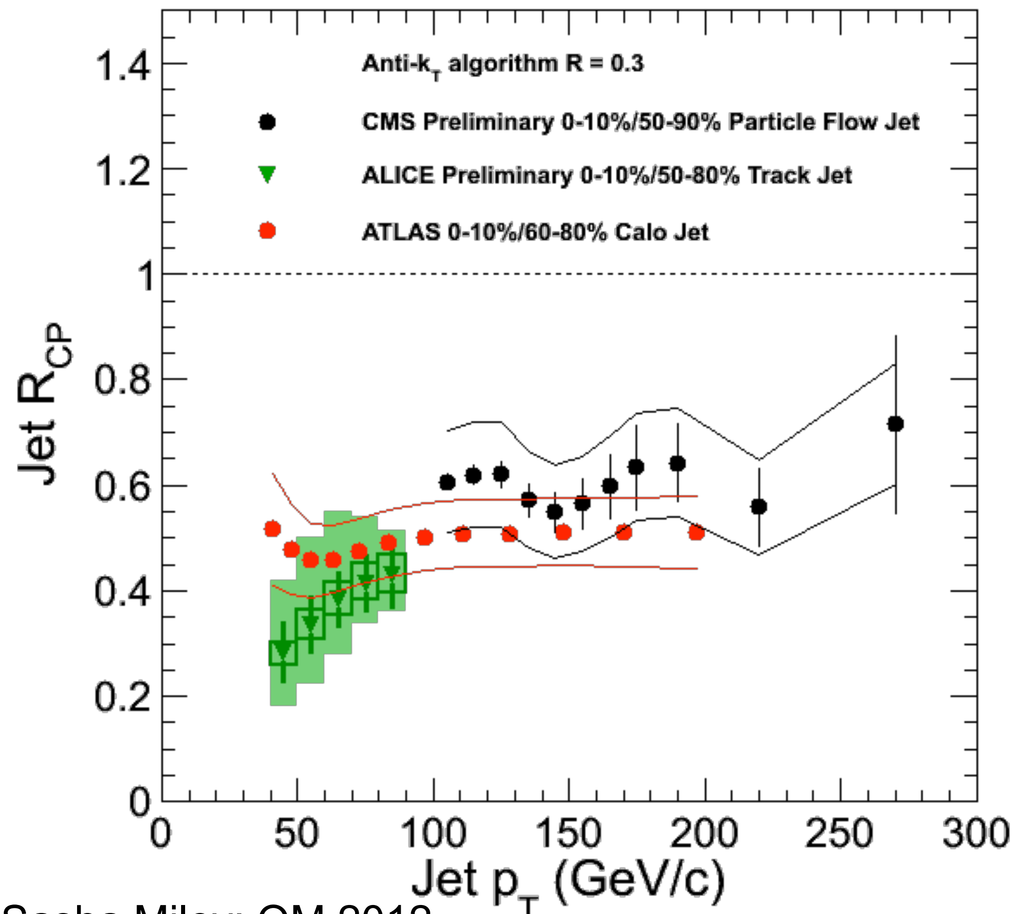


Full jets



Consistent with PYTHIA, pQCD+hadronization.
Larger collimation at high jet p_T.
Spectra approach similar slope.

R_{CP} LHC-Comparison

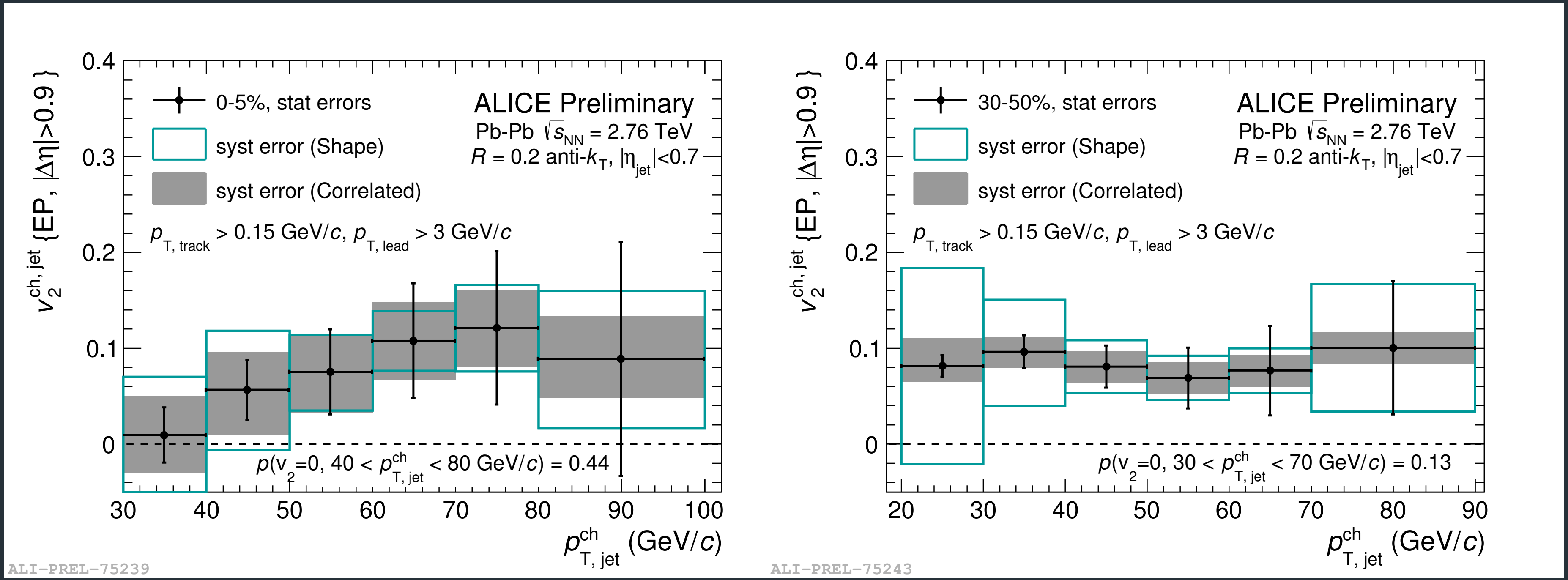


Sasha Milov: QM 2012

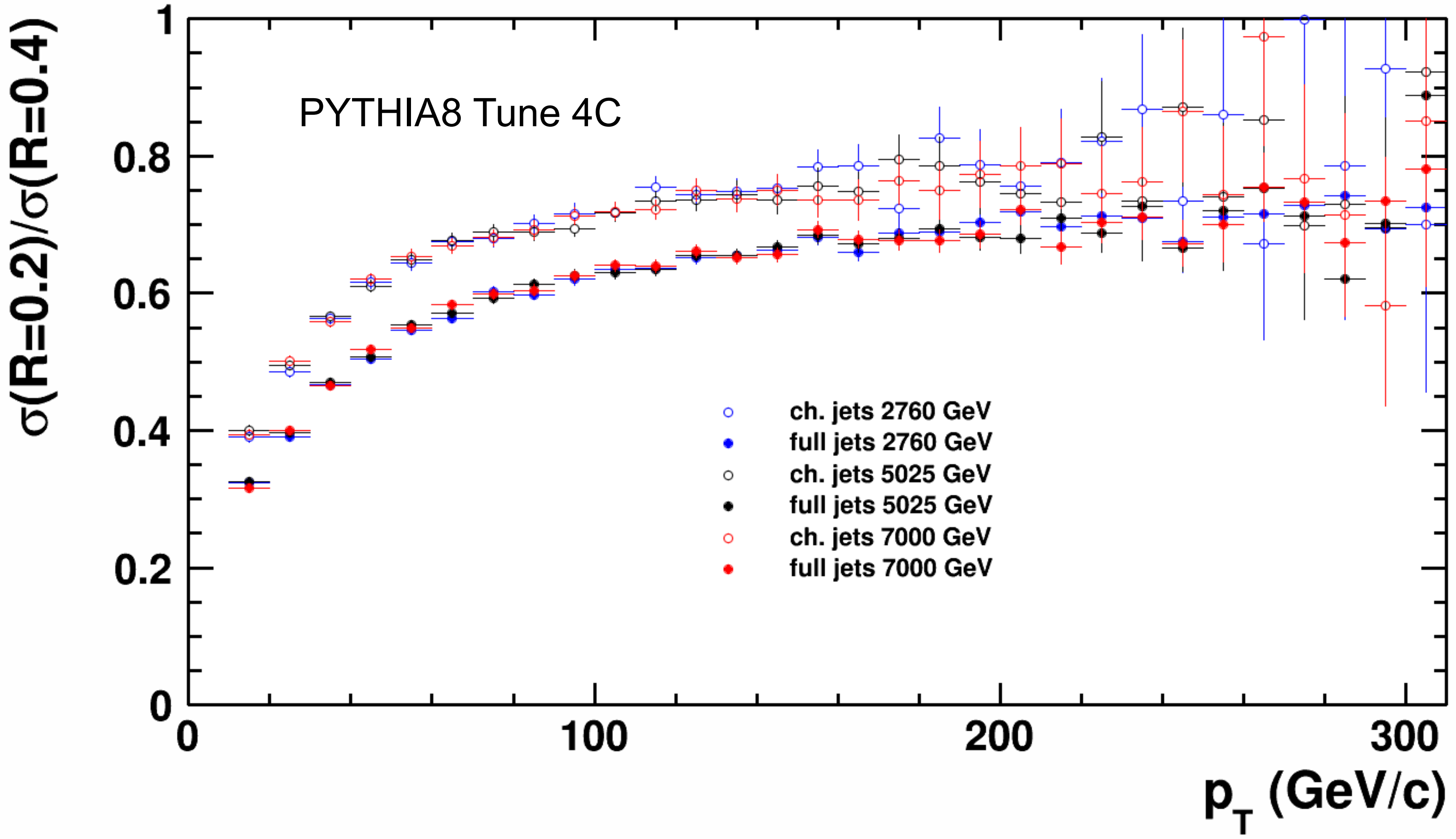
- N.B.: Different
  - Jet constituent objects
  - Momentum cut-offs
  - Treatment/suppression of UE background fluctuations

Similar message from all LHC experiments: Jets are strongly suppressed over a broad p_T range.
Low p_T region (rise?), most difficult/interesting.
Other methods to explore reconstructed jets?

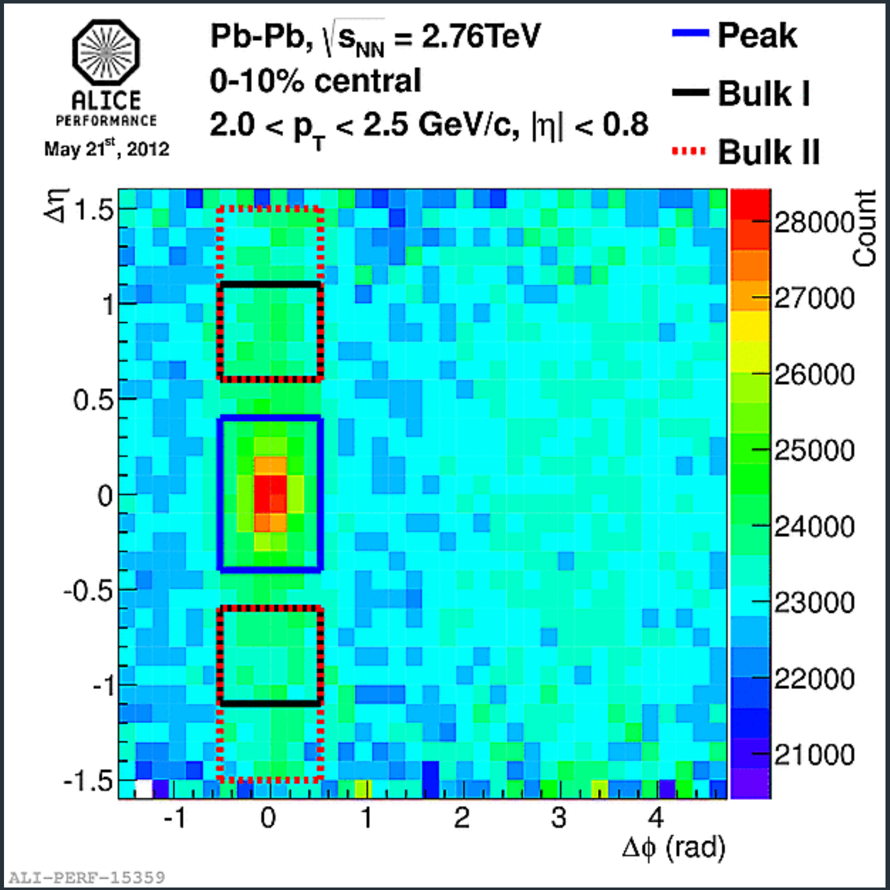
Other Knobs …

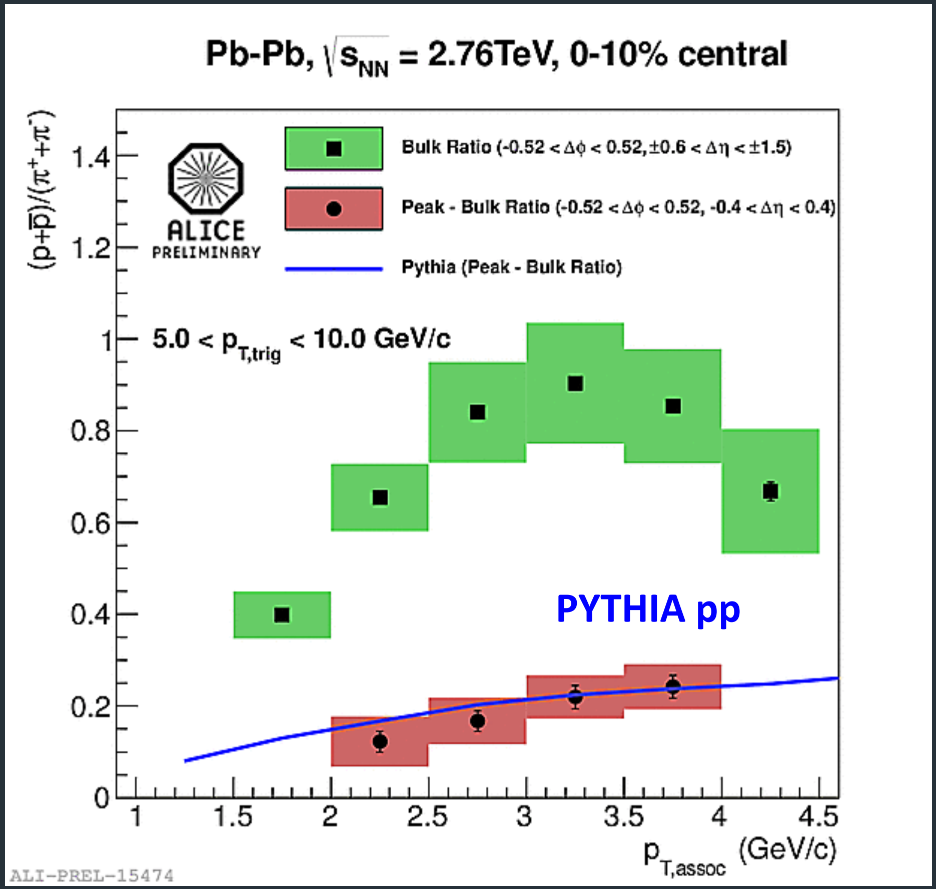

ALICE Preliminary
Pb-Pb √sNN = 2.76 TeV
R = 0.2 anti-kT, |ηjet|<0.7
0-5%, stat errors
syst error (Shape)
syst error (Correlated)
pT, track > 0.15 GeV/c, pT, lead > 3 GeV/c
p(v2=0, 40 < pchT, jet < 80 GeV/c) = 0.44
v2ch, jet{EP, |Δη|>0.9}
pchT, jet (GeV/c)
ALI-PREL-75239
ALICE Preliminary
Pb-Pb √sNN = 2.76 TeV
R = 0.2 anti-kT, |ηjet|<0.7
30-50%, stat errors
syst error (Shape)
syst error (Correlated)
pT, track > 0.15 GeV/c, pT, lead > 3 GeV/c
p(v2=0, 30 < pchT, jet < 70 GeV/c) = 0.13
v2ch, jet{EP, |Δη|>0.9}
pchT, jet (GeV/c)
ALI-PREL-75243

Cross Section Ratio Charged vs. full Jets



PID in Jets

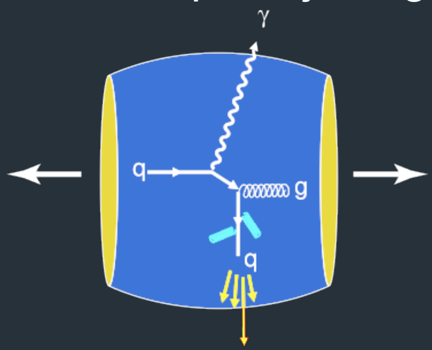




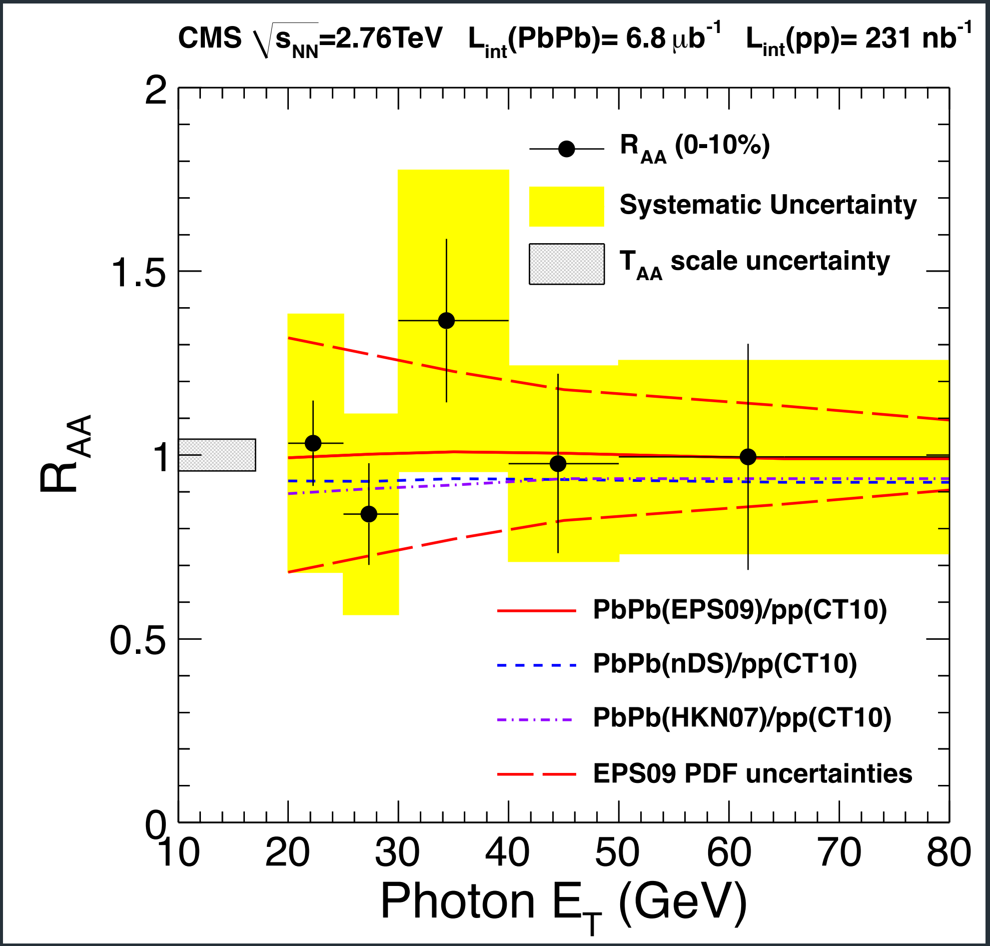
Near-side peak (after bulk subtraction): p/π ratio compatible with that of pp (PYTHIA)
Bulk region: p/π ratio strongly enhanced – compatible with overall baryon enhancement
Jet particle ratios not modified in medium? Could this still be surface bias?

Color Neutral Probes

- Also hard production
  - t ~1/*Q* « 1 fm/*c*
  - Not affected by medium
  - Effective quark-jet tag



  - p_T < 20 GeV/*c*: fragmentation photons start to dominate
- Other sources
  - Production from thermalized partons and hadrons
  - Jet-medium interaction



CMS PRL 106 212301 (2011)

Direct photons are produced and escape throughout the full evolution of the system!

Hard (Colored) Probes in Heavy-Ion Collisions

- Probe the created medium
  - Parton scattering prior to QGP formation (t ≈ 1/Q « 1 fm/c)

- History imprinted into jet structure
  - High p_T partons interact strongly with QCD medium prior to fragmentation **("jet tomography")**

- Experimental access
  - Single particles at high p_T
  - Two-particle correlations
  - Reconstructed jets
  - Jet fragmentation pattern

↓ **increasing influence of underlying event background on observable**

Direct effect on high p_T/jet observables compared to p+p.