Latest results on Heavy Ion Physics from ALICE

Marco van Leeuwen, Utrecht University
for the ALICE collaboration

Universiteit Utrecht

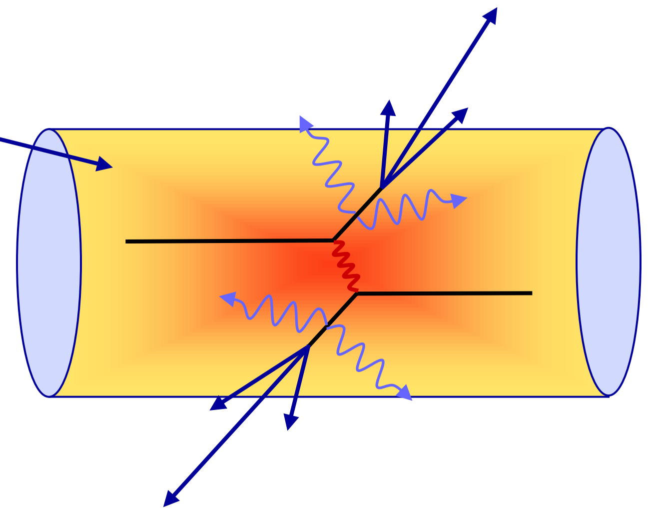
NWO
Netherlands Organisation for Scientific Research

Heavy ion collisions

Heavy-ion collisions produce
soft 'thermal' QCD matter
Dominated by soft partons
p ~ T ~ 100-300 MeV

'Hard probes'
Hard-scatterings produce hard partons
⇒ Probe medium through interactions
$p_T > 5$ GeV

'Bulk observables'
Study hadrons produced by the QGP
Typically $p_T < 1\text{-}2$ GeV



Two basic approaches to learn about the QGP
1) Bulk observables
2) Hard probes

Both measure the same system – expect consistency

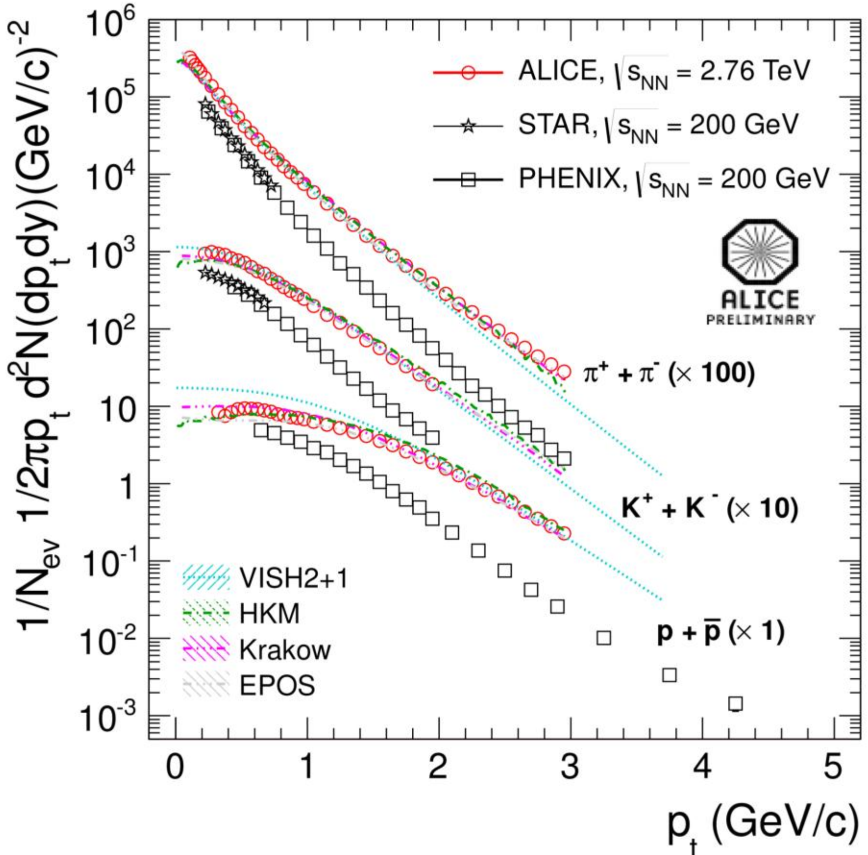
This talk: focus on experimental results
Physics interpretation given for context; fineprint omitted in many cases

Low p_T: thermal production, flow initial geometry

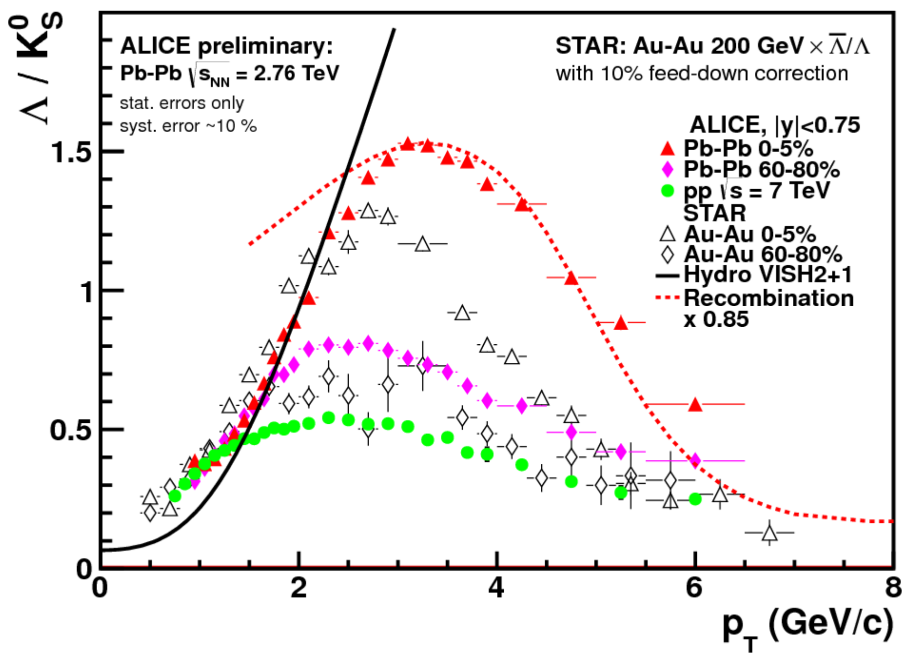
(Not a focus of Hard Probes Conference
Some results shown at ICHEP)

Low and intermediate p_T

F. Bellini@ICHEP



Schukraft. Mueller. Wvslouch. arXiv:1202.3233



Low p_T:
$<p_T>$ increases with mass
(more than in pp)

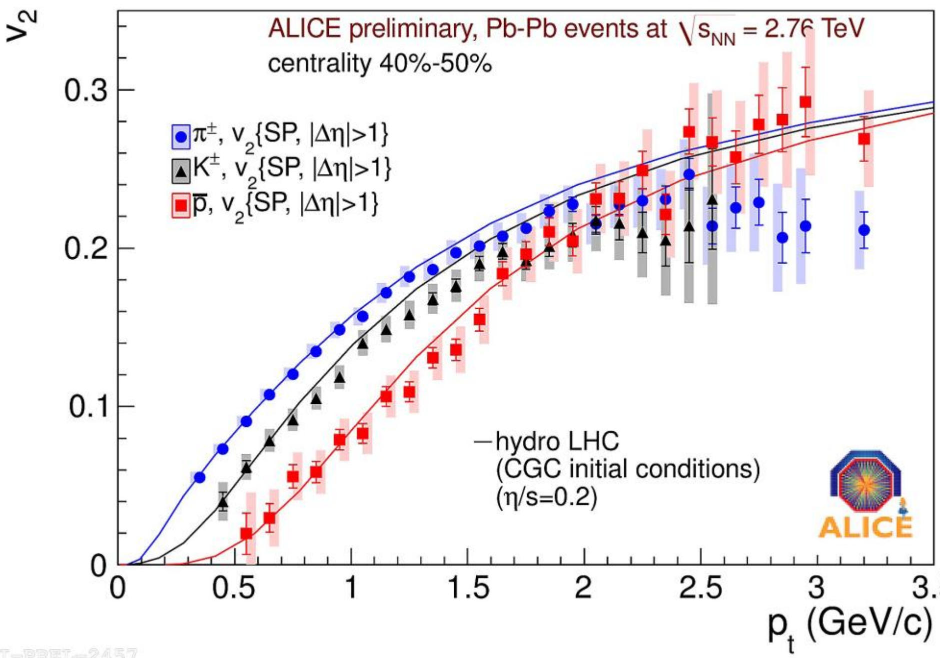
→Flow velocity

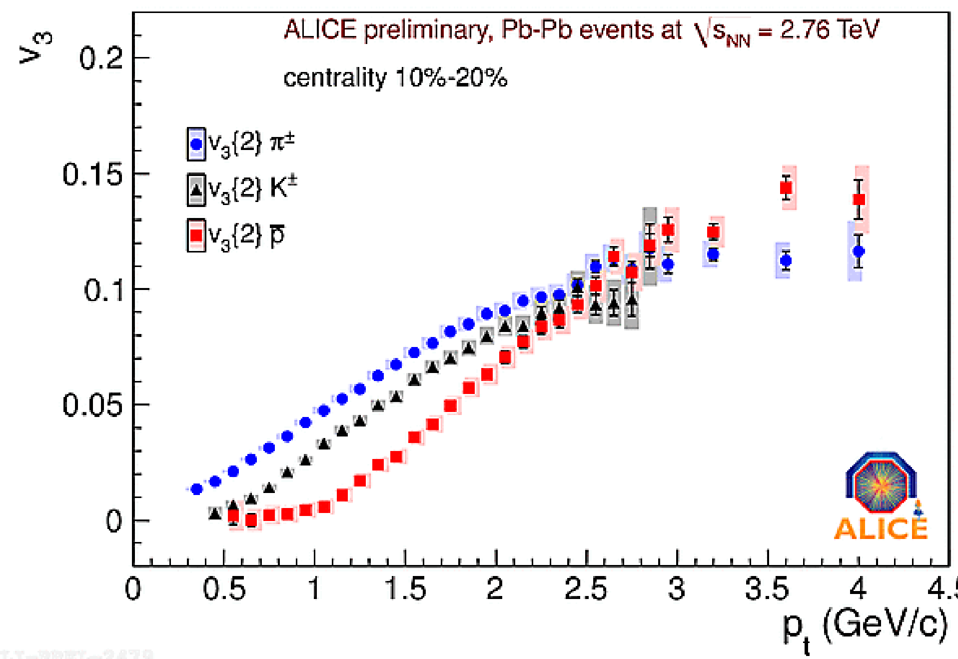
→Hydrodynamical calculations agree with measurements

Intermediate p_T:
large baryon/meson ratio:
- Flow
- Hadronisation via quark coalescence?

More flow: v_2, v_3

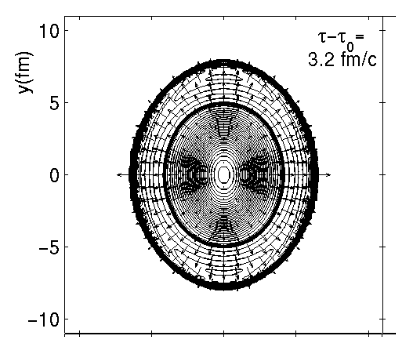
C. Perez Lara@ICHEP

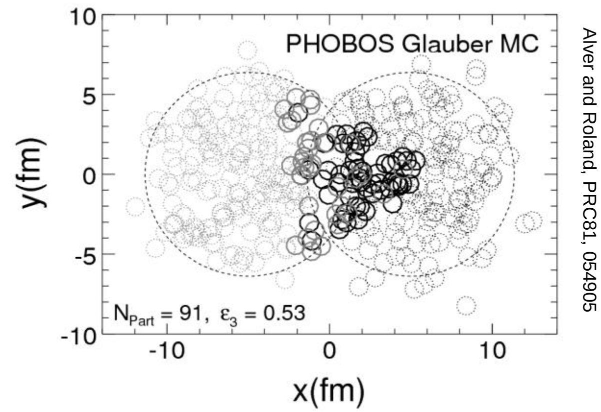




v_2: azimuthal anisotropy

$$\frac{dN}{d\varphi} = N\left(1 + 2v_2 \cos 2\varphi\right)$$



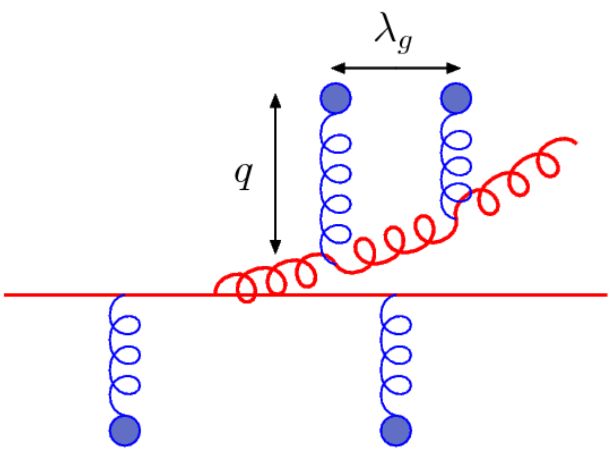


Agreement with hydro: the matter behaves like a fluid

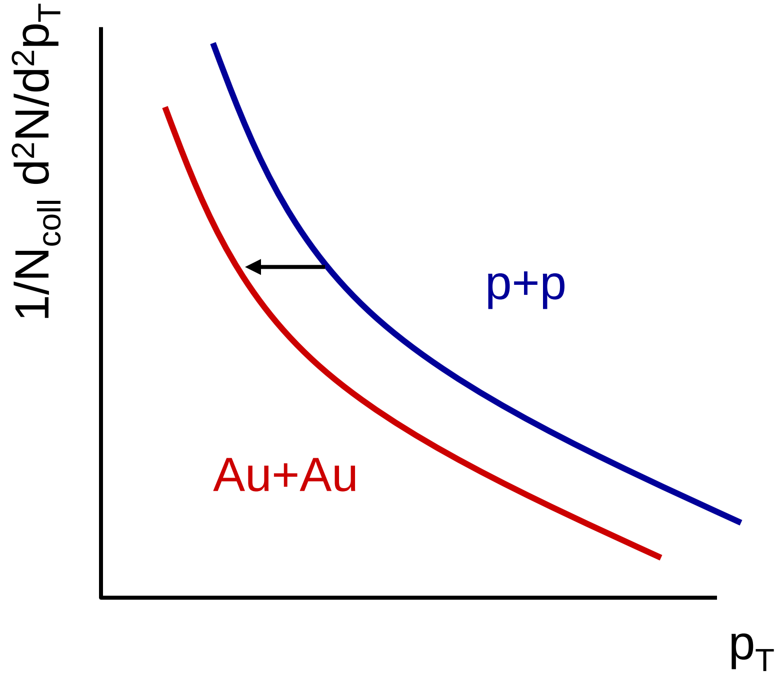
Sensitive to medium density profile
→ Compare with hard probe measurements

v_3: fluctuations in the initial state

High p_T: probes of the medium



High-p_T partons scatter off partons in the medium and radiate gluons

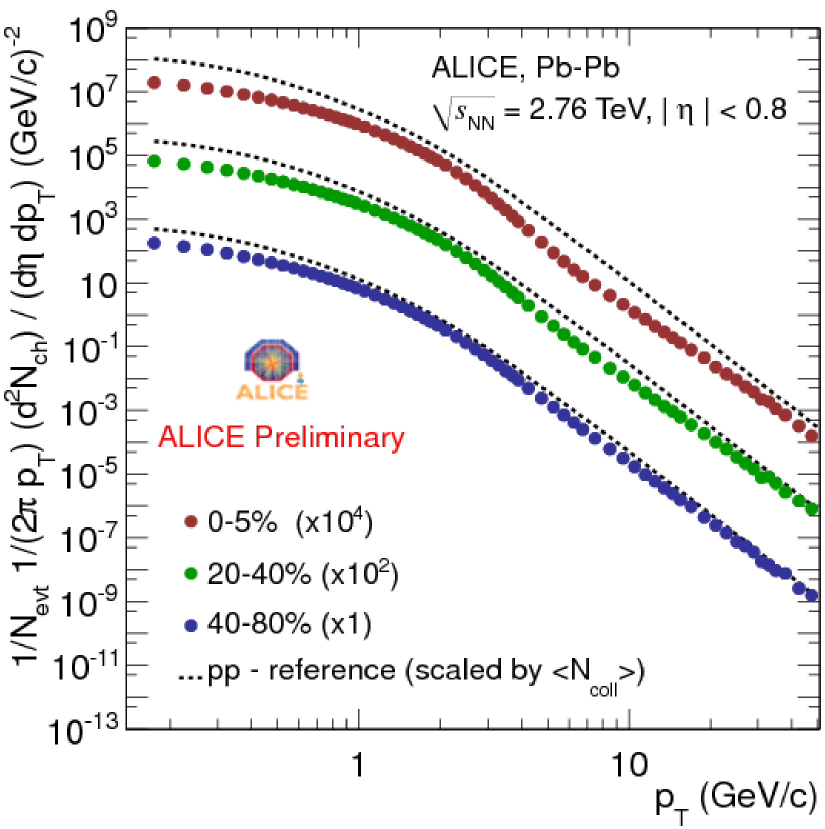


Energy loss: suppression of yield at fixed p_T

Nuclear modification factor $R_{AA} = \dfrac{dN/dp_T\big|_{Pb+Pb}}{N_{coll}\, dN/dp_T\big|_{p+p}}$

Nuclear modification factor

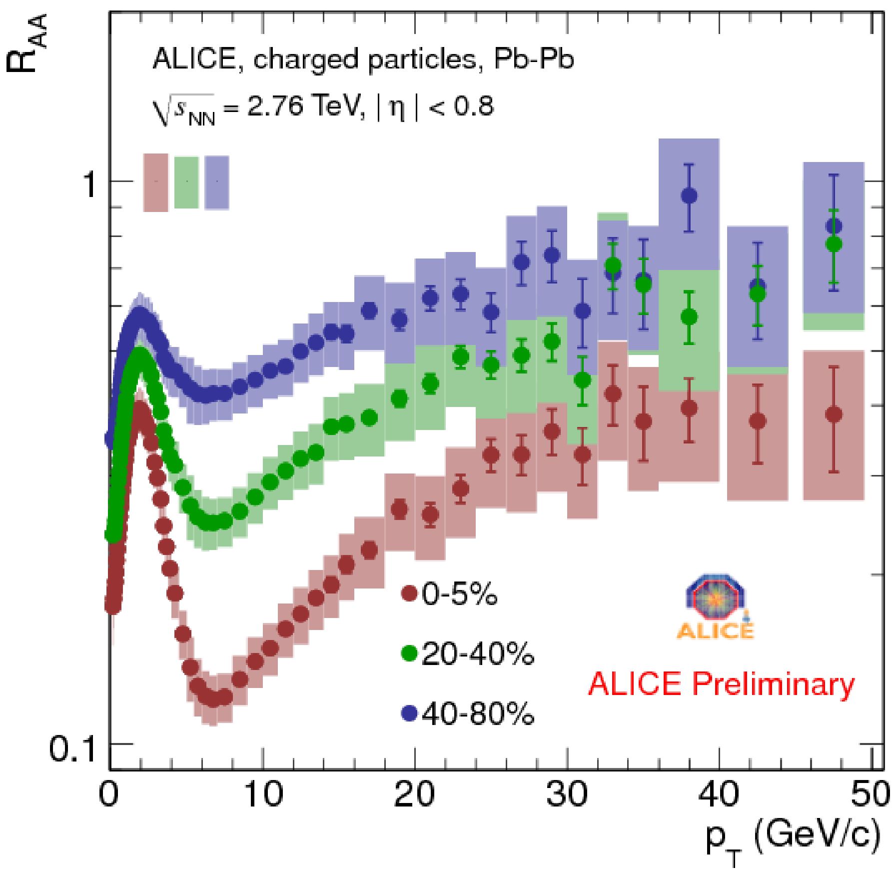
Charged hadron p_T spectra



Shape of spectra in Pb+Pb differ from p+p

Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T|_{Pb+Pb}}{N_{coll}\, dN/dp_T|_{p+p}}$$



Large suppression

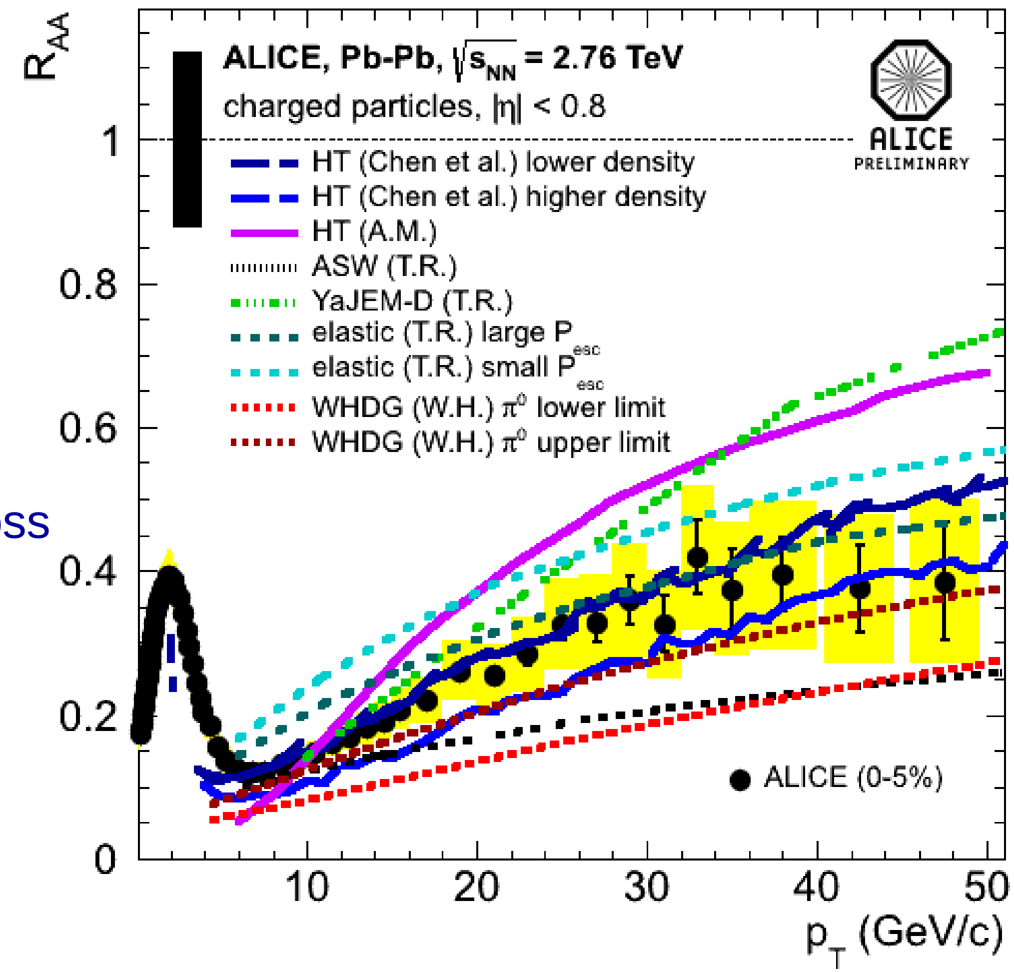
R_{AA} rises with p_T → fractional energy loss ΔE/E decreases

R_{AA} vs theory/models

Rough agreement with extrapolations from lower energy at RHIC

However: large spread of models,
- Improve understanding of energy loss
- Multiple observables needed

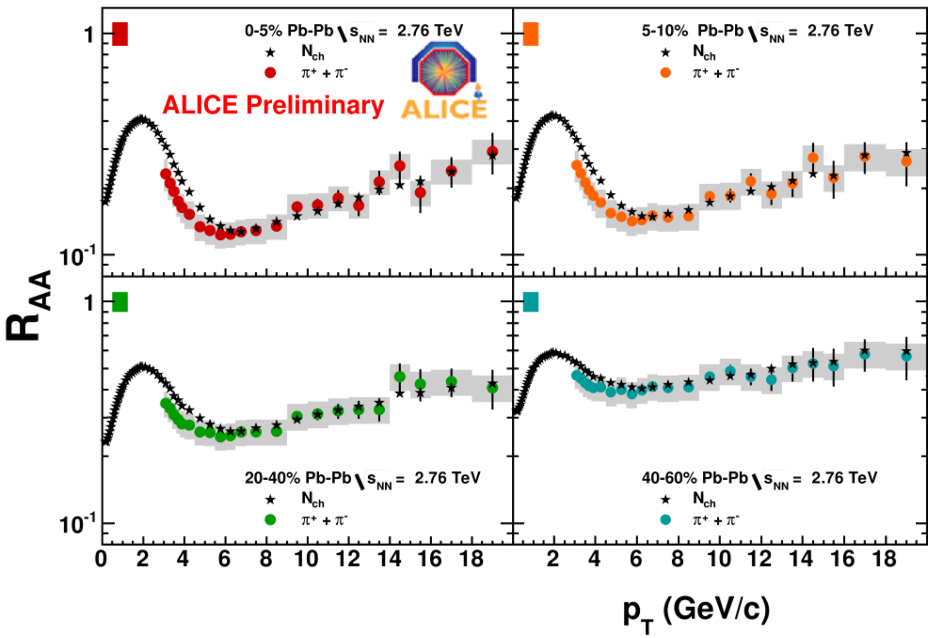
M. Floris, P. Luettig@HP



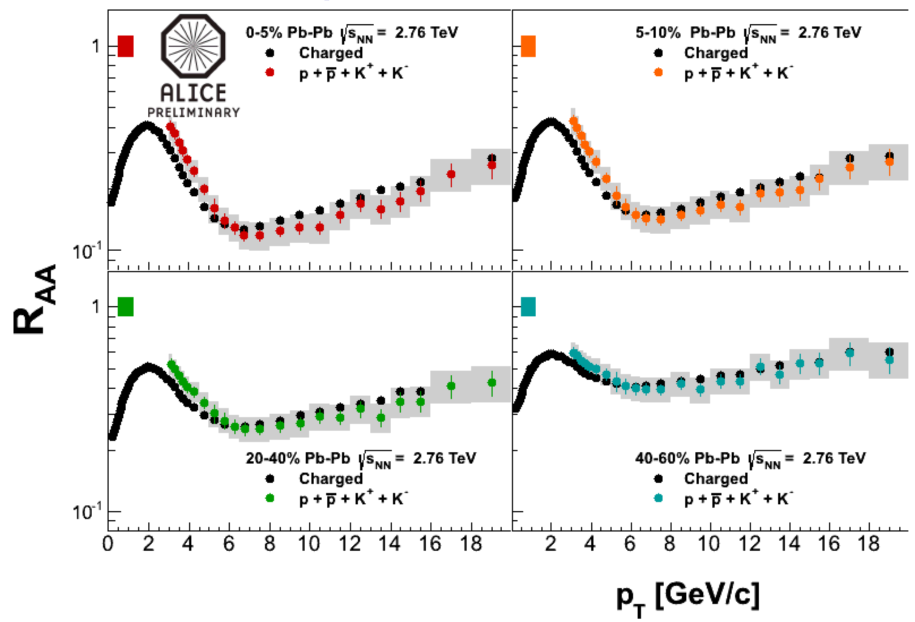
Identified hadrons at high p_T

P. Christiansen@HP

pions



protons+kaons



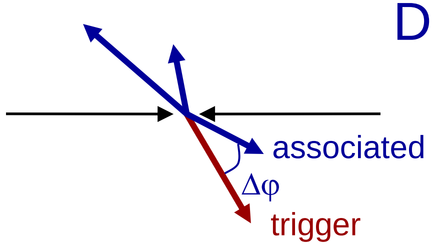
R_{AA} similar for all particles above p_T~6 GeV

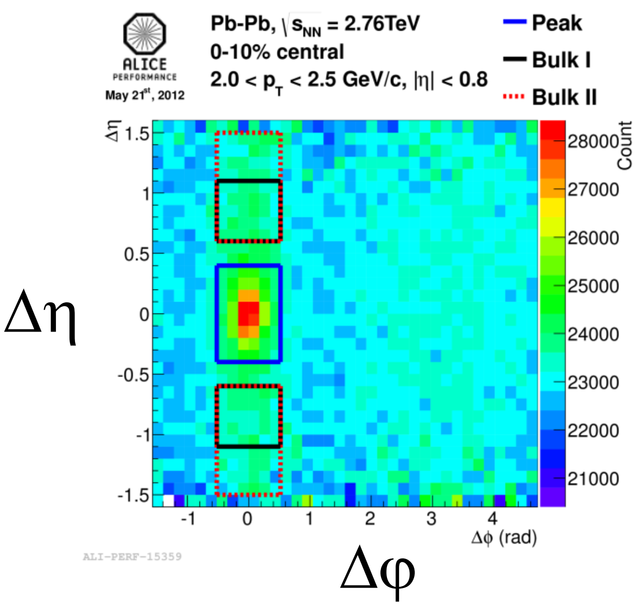
Suggests fragmentation dominant production process
No large modifications of hadronisation (color reconnection, coalescence) above p_T ~ 6 GeV

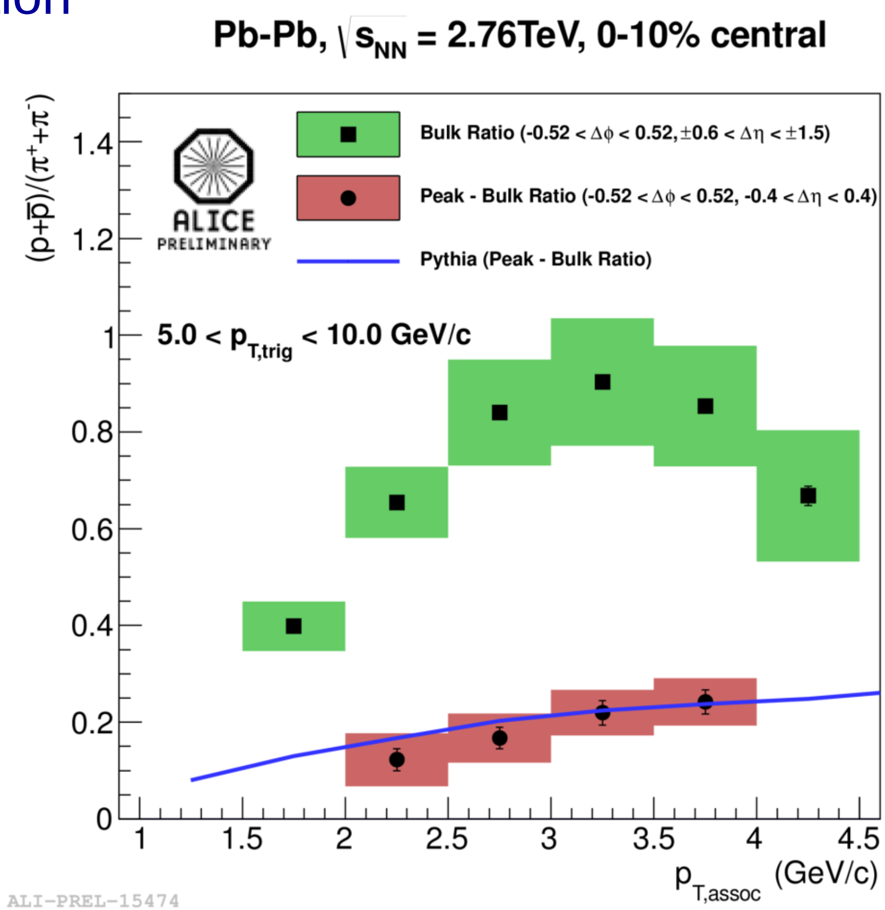
Proton/pion ratio in jets

M. Veldhoen@HP

Di-hadron correlation measurement







Large p/π ratio in Pb+Pb events

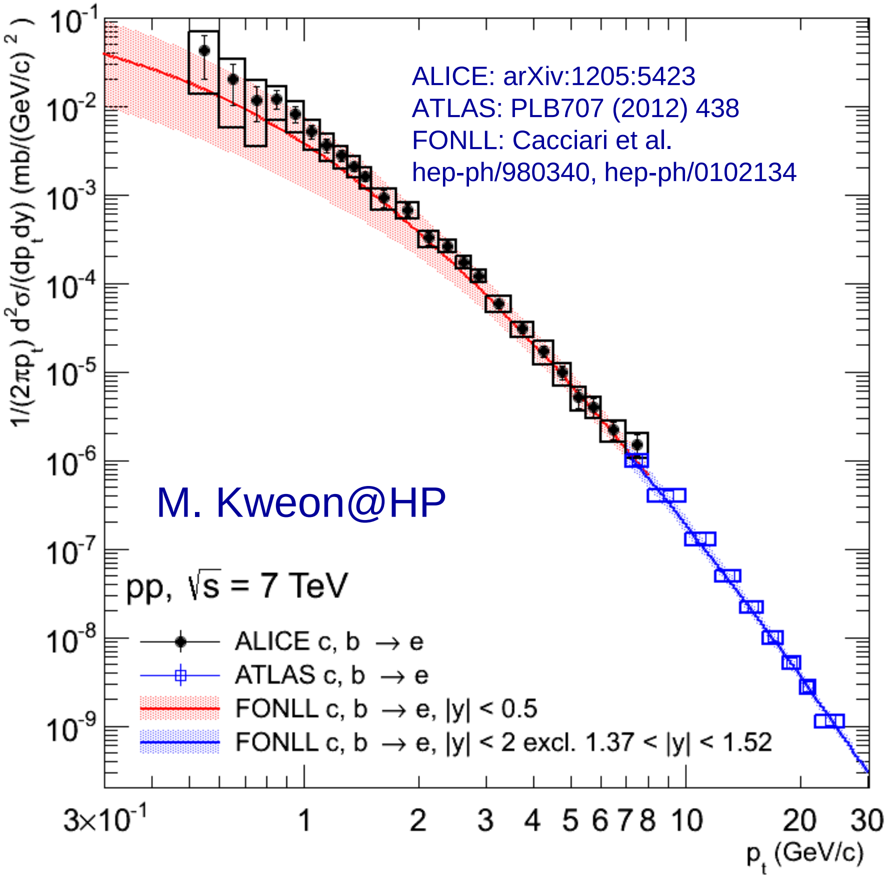
p/π ratio low, similar to pp when associated with high-p_T hadrons

Heavy flavour

1) Produced in hard scattering, no thermal production in the QGP expected (m < T)
2) Parton energy loss: dead cone effect expect ΔE less than light quarks

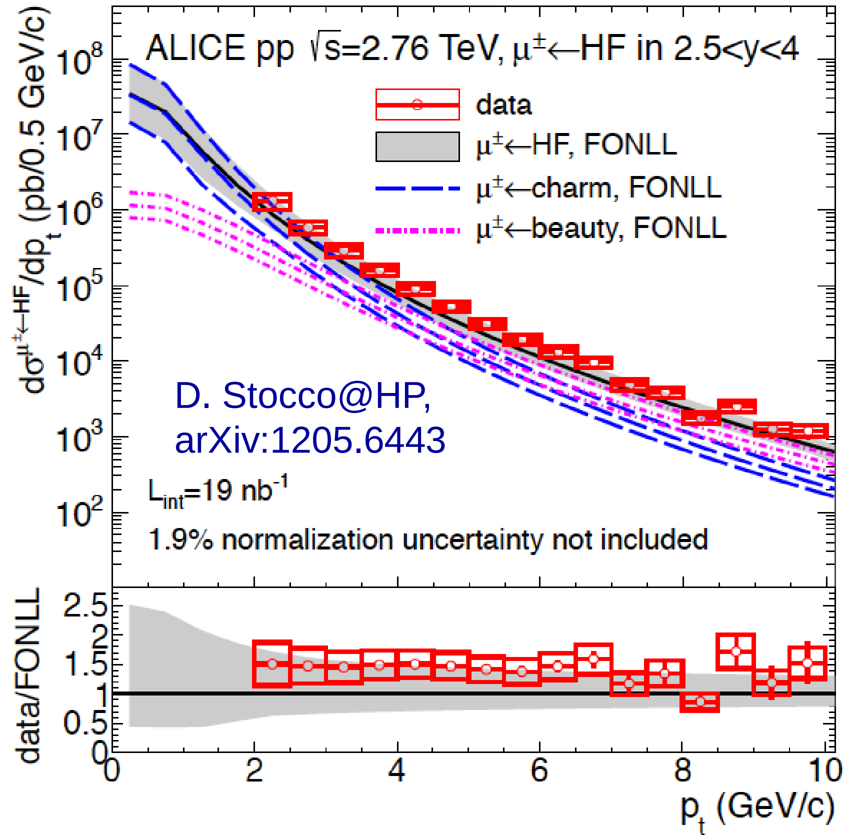
Heavy flavour via leptons in pp

Electrons from heavy flavour



Good agreement with FONLL theory
Nice complementarity with ATLAS
(low-high p_T)

Muons from HF decay (forward)

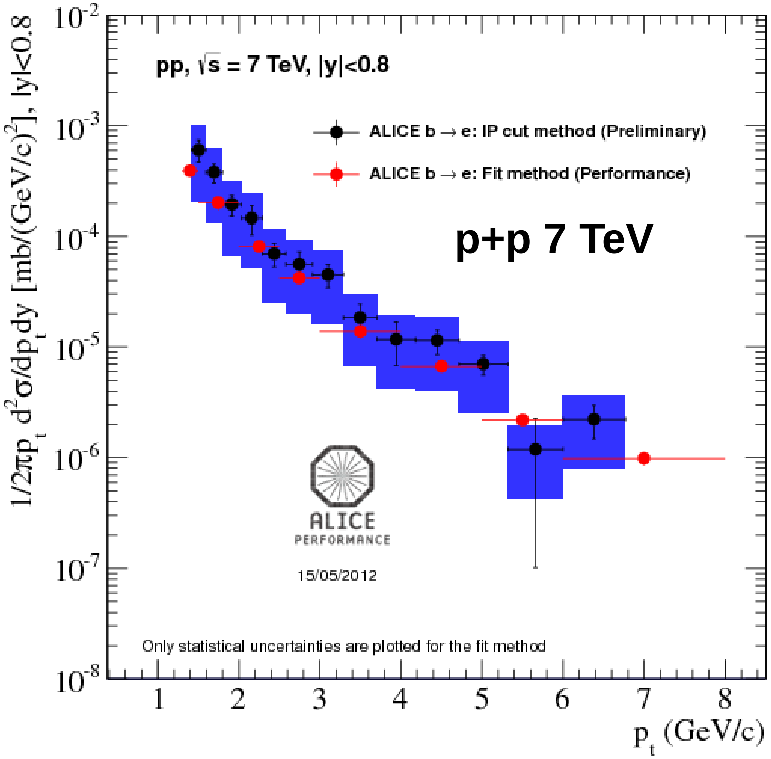


Comparison to theory expectations
Good agreement

Electrons from beauty: 2 methods

M. Kweon, M. Heide, M. Völkl, D. Thomas@HP

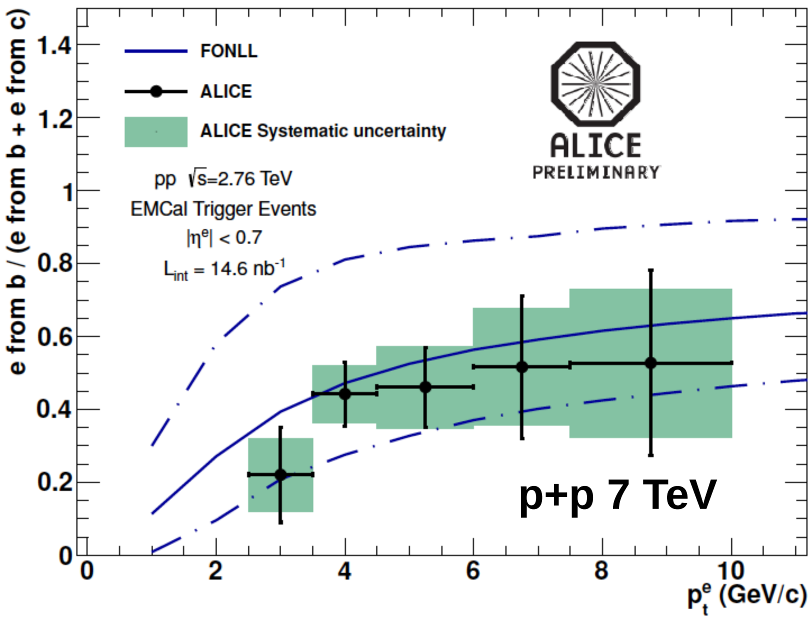
Impact parameter selection



Method being refined

Good agreement with FONLL

B/D separation via decay kinematics



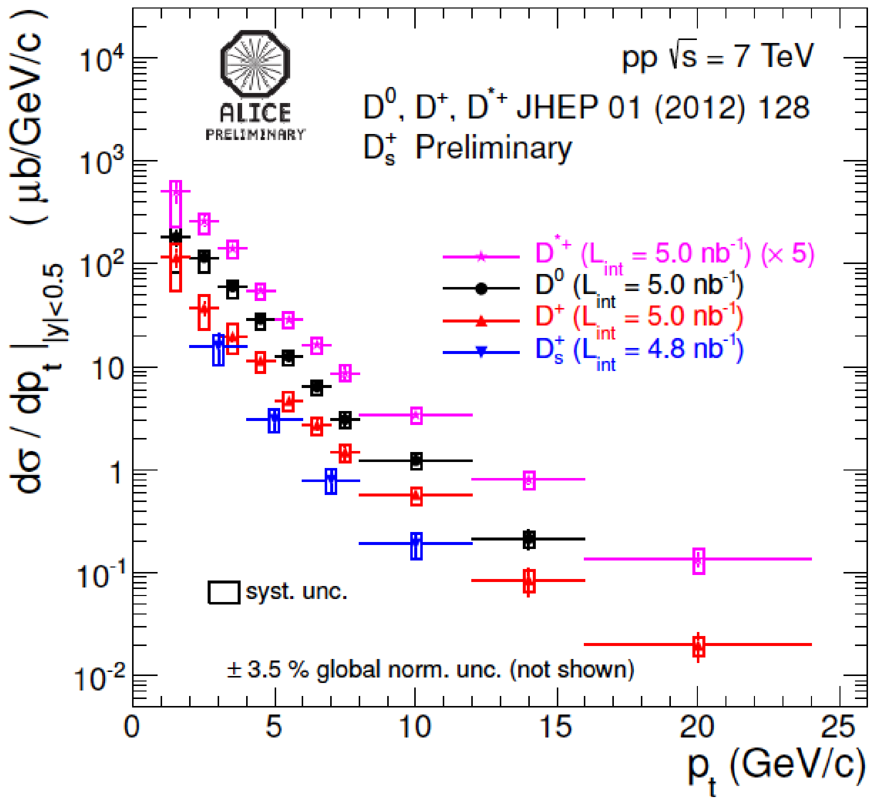
B/D ratio agrees with FONLL

Important baseline for AA, parton energy loss

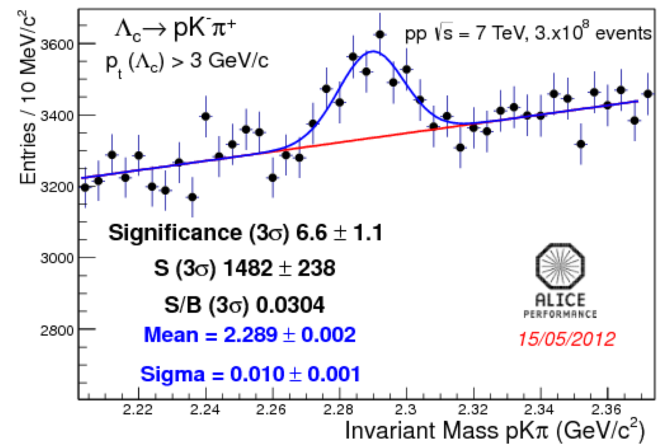
Difficult charm hadrons: D_s and Λ_c

G.M. Innocenti, P. Pagano@HP

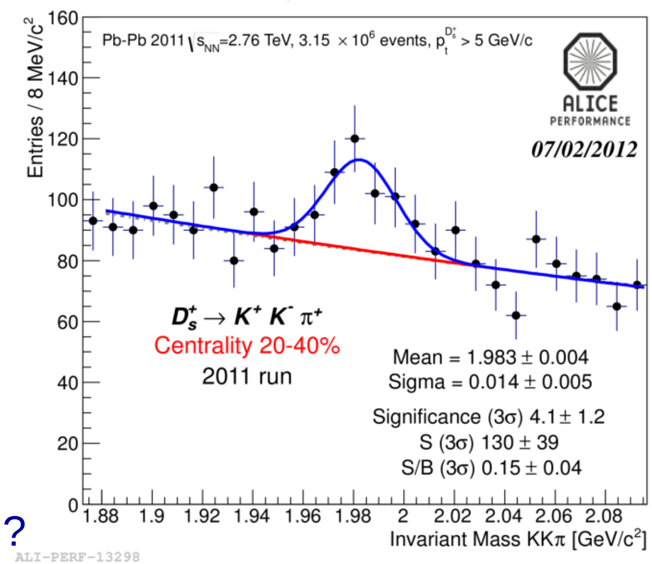
D_s in pp



Λ_c in pp



D_s in PbPb



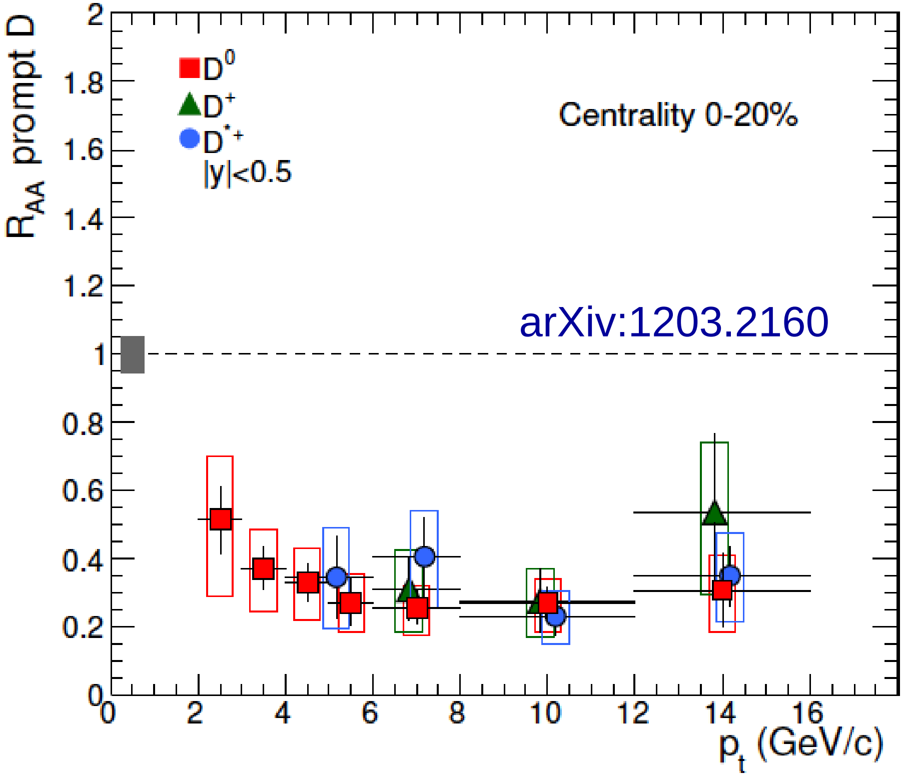
First results on D_s, Λ_c

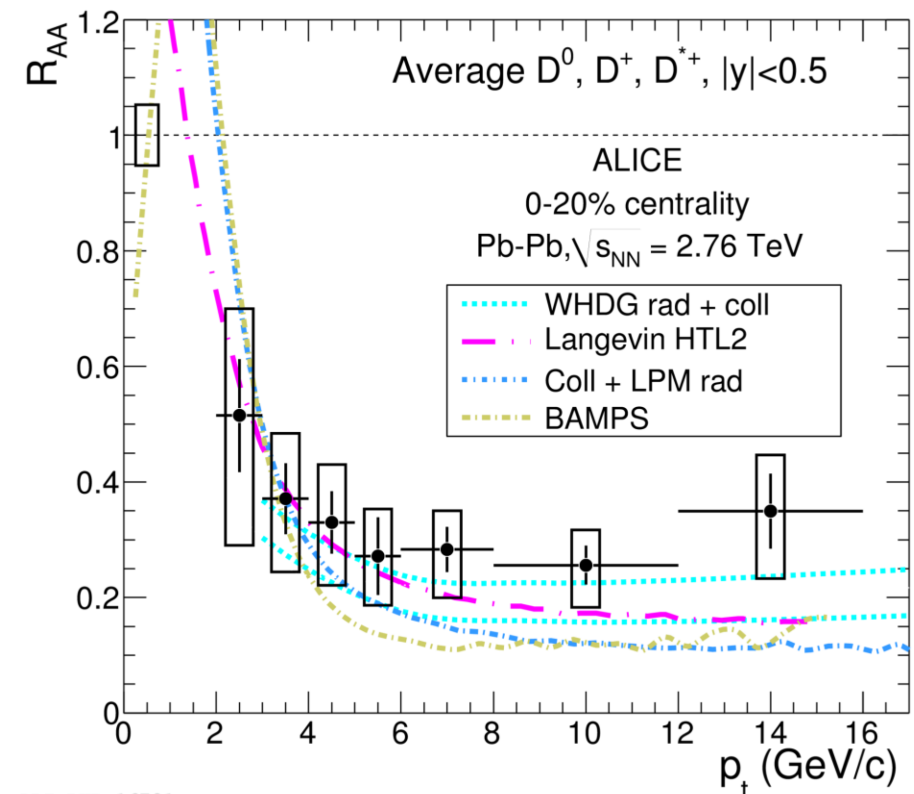
Challenge: 3-prong decays, smaller cross sections

Interest: hadronisation through coalescence/recombination?

D meson R_{AA}

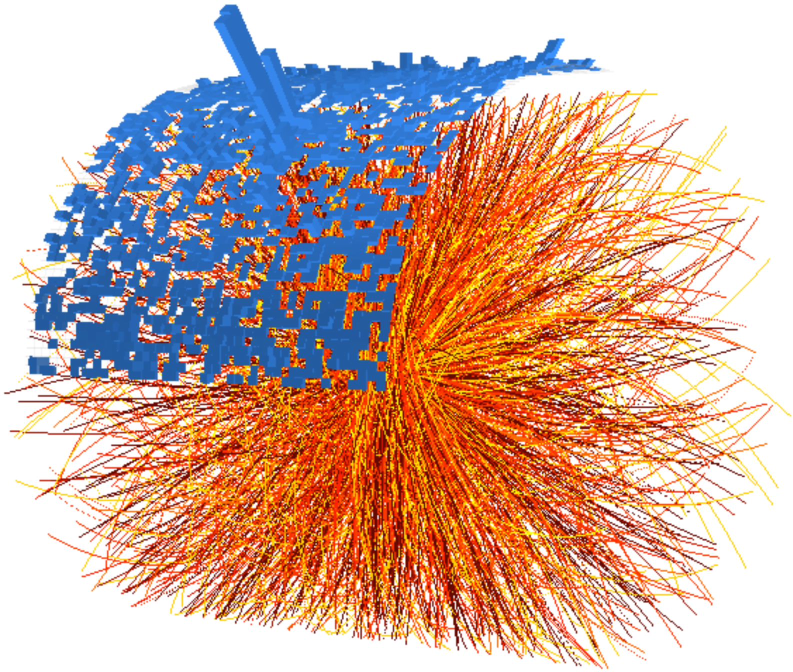
Z. Conesa del Valle@HP



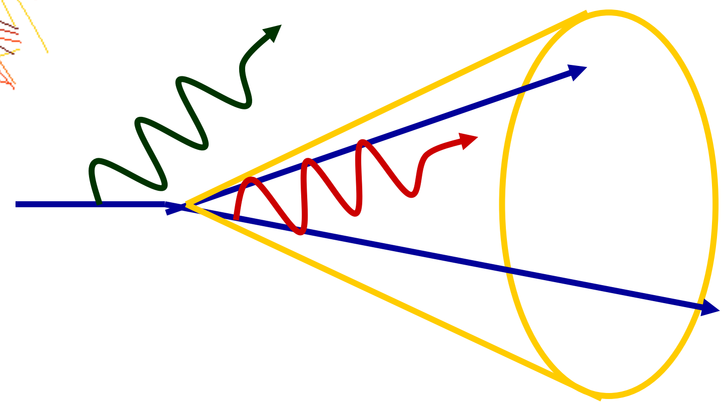


R_{AA} < 1: charm also loses energy
Agrees with model calculations

Jets in pp and Pb+Pb



Out-of-cone radiation:
suppression of jet yield: $R_{AA}^{jets} < 1$



In-cone radiation: softening and/or broadening of jet structure

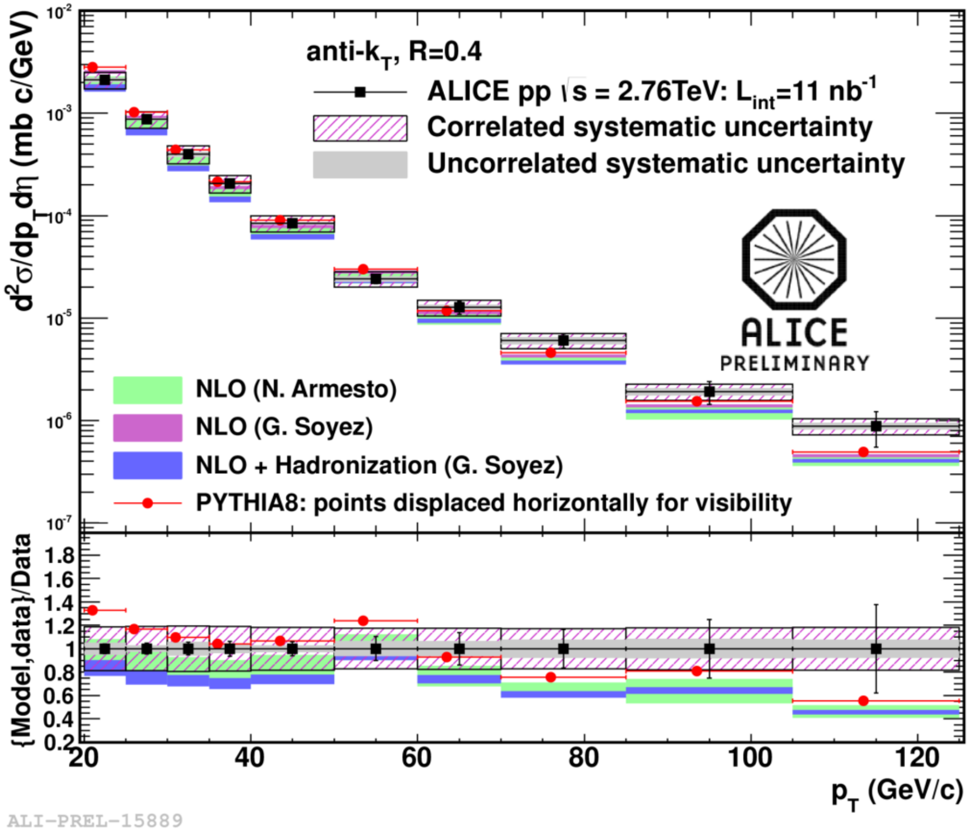
ALICE: use charged tracks p_T > 150 MeV to 'catch' soft gluon fragments

Jets in pp at √s=2.76 TeV

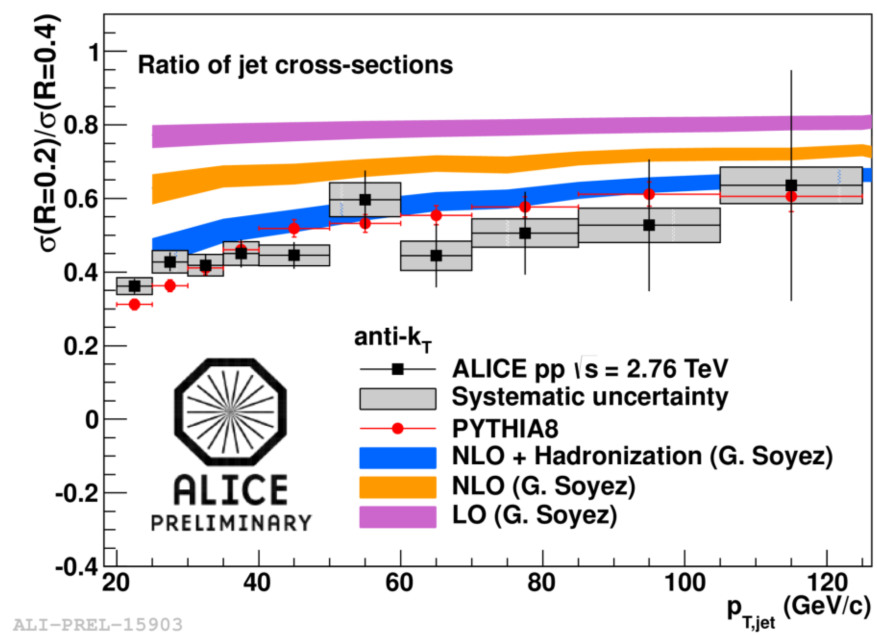
EMCAL installed in Dec 2010: |η|<0.8, φ ~π/3

R. Ma@HP

Charged tracks+EMCAL, R=0.4



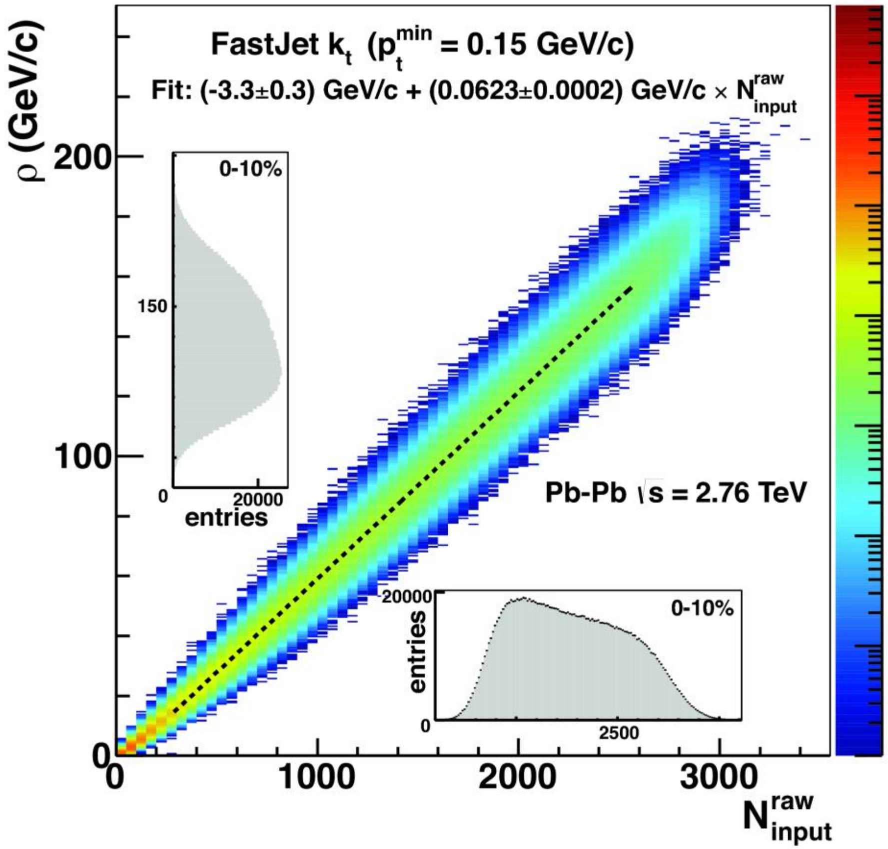
R=0.2/R=0.4

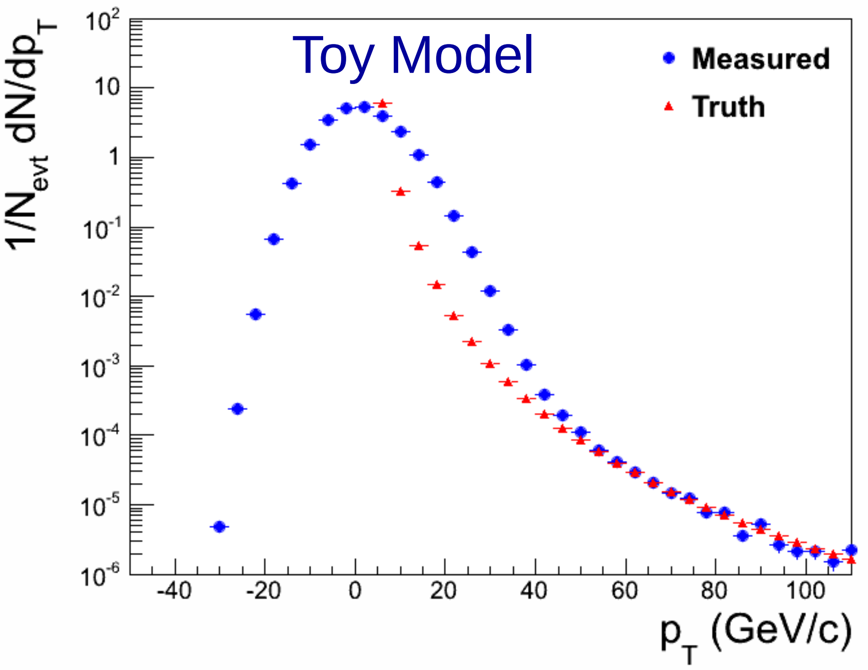


Reasonable agreement with NLO calculations

Need to include hadronisation for jet shapes

PbPb jet background





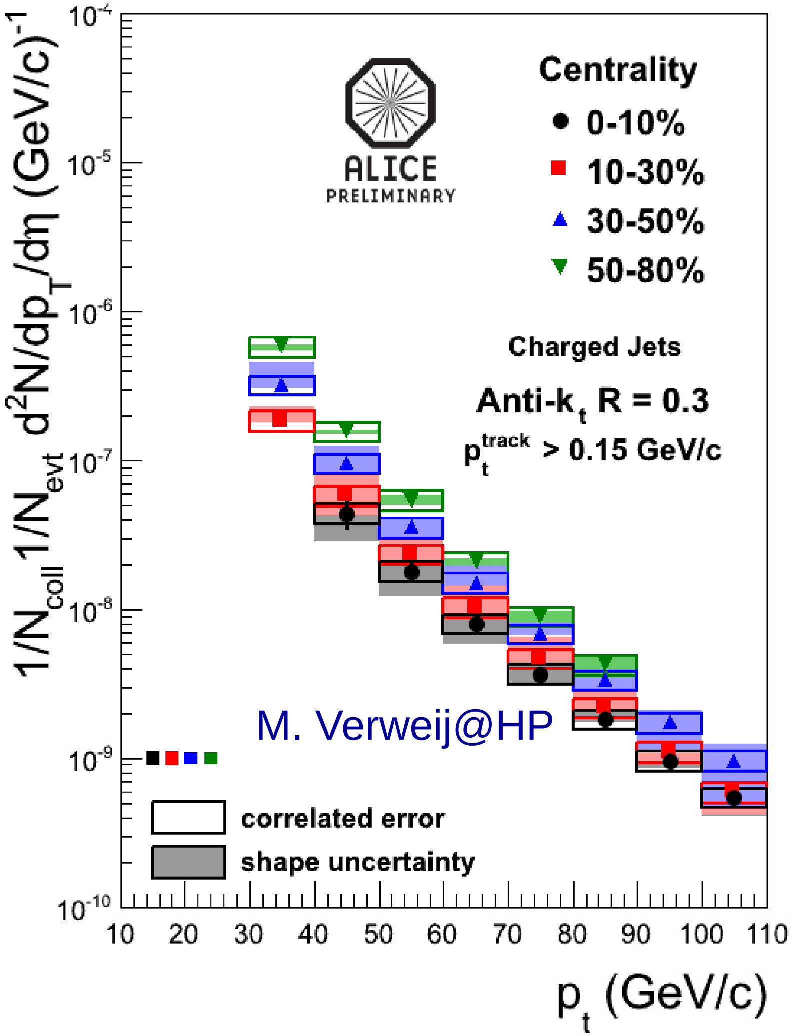
Main challenge: large fluctuations of uncorrelated background energy

(Size of fluctuations depends on p_T cut)

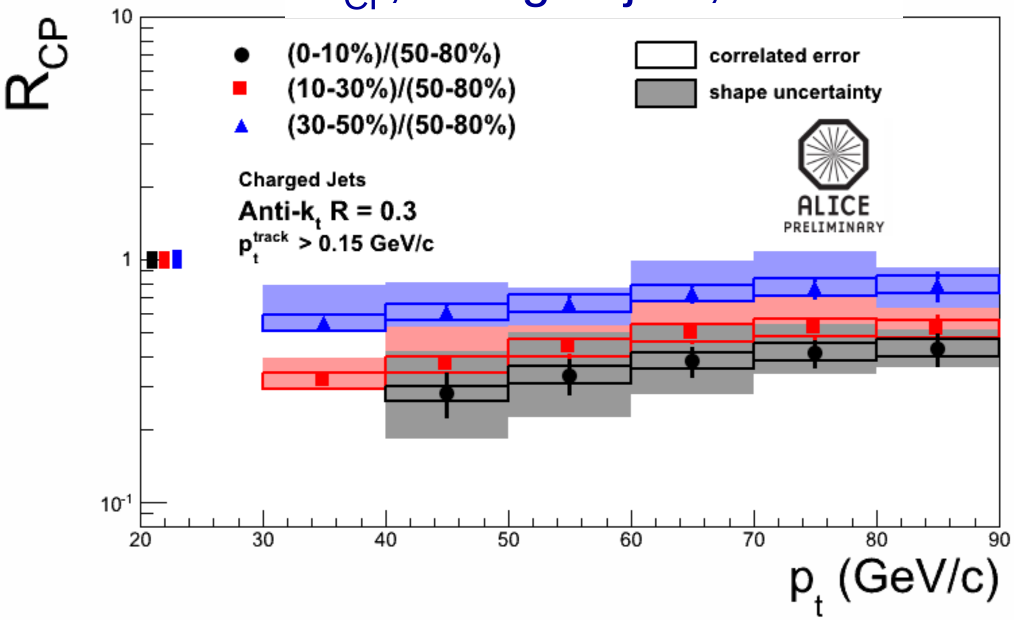
PbPb jet spectra

M. Verweij@HP

Charged jets, R=0.3



R_{CP}, charged jets, R=0.3



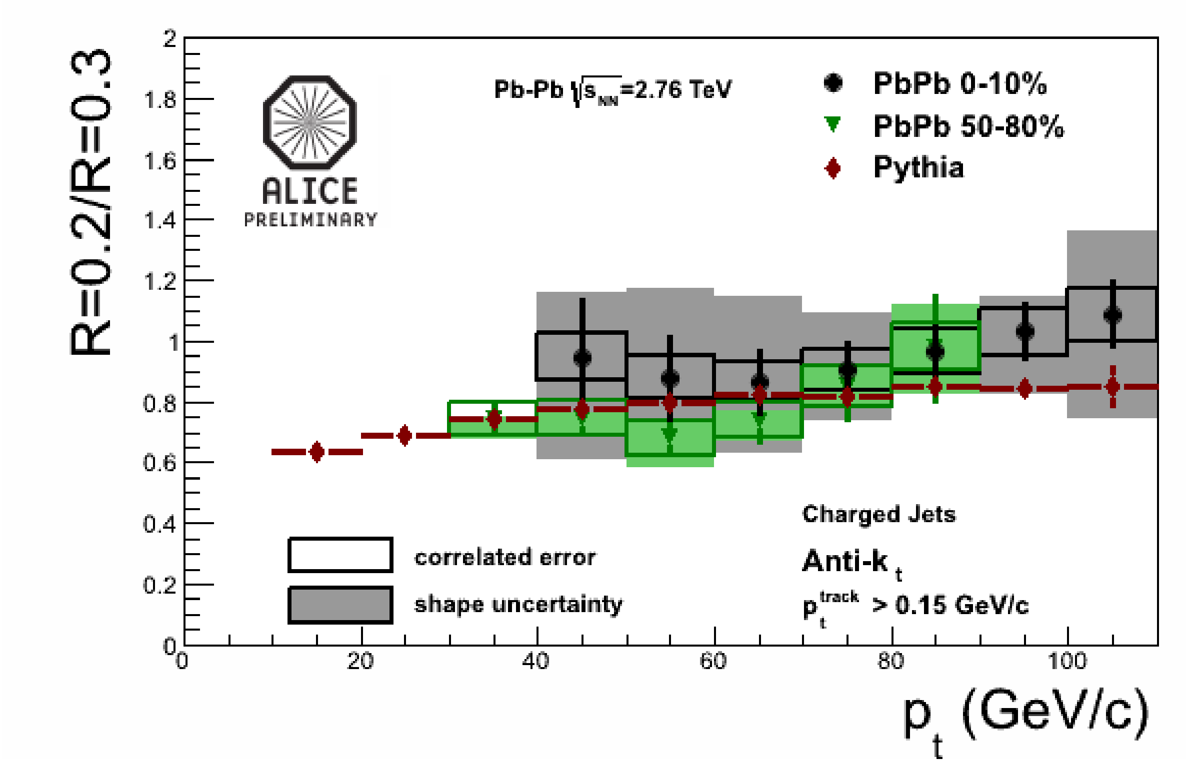
Suppression of jet production:
out-of-cone radiation

Jet spectrum in Pb+Pb: charged particle jets
Two cone radii, 4 centralities

Jet broadening: R=0.2/R=0.3

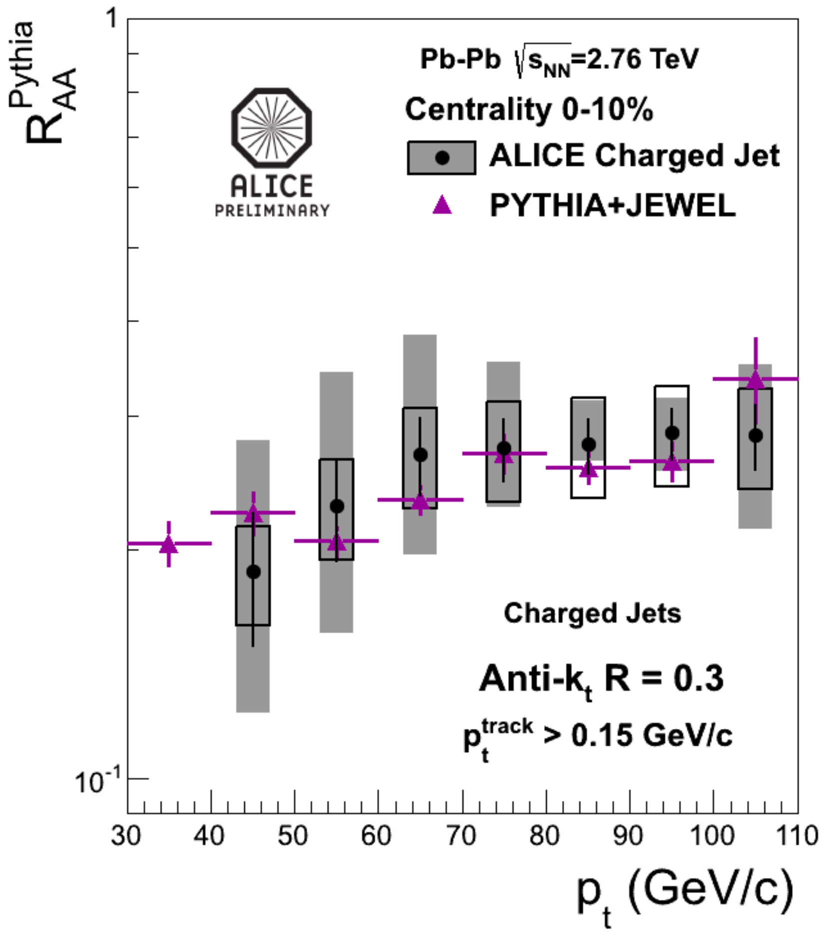
Ratio R=0.2/R=0.3

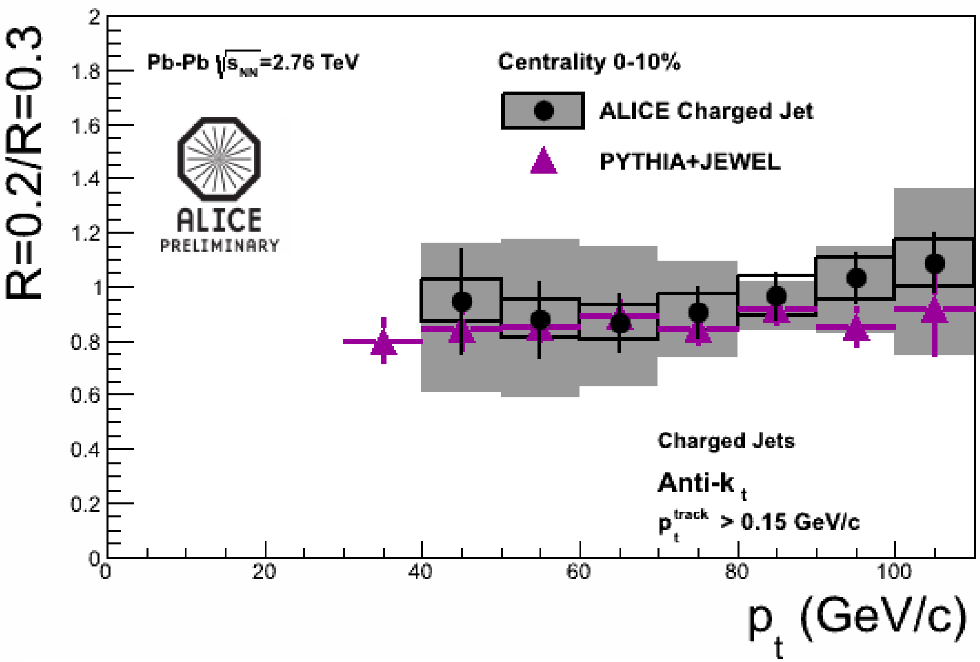
Similar in PbPb, pp, Pythia



No significant broadening observed

Comparison to JEWEL





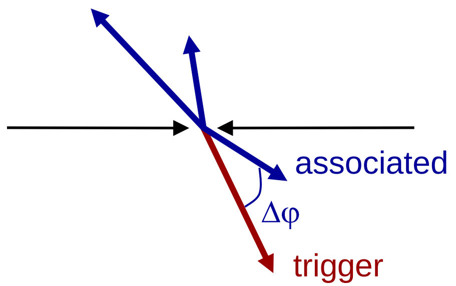
Good agreement with JEWEL energy loss MC

(tuned to charged particle R_{AA})

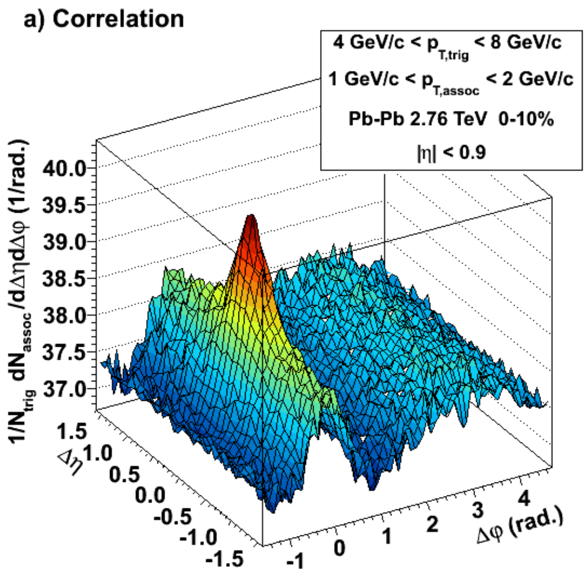
⇒ Towards understanding energy loss mechanism with MC-data comparisons

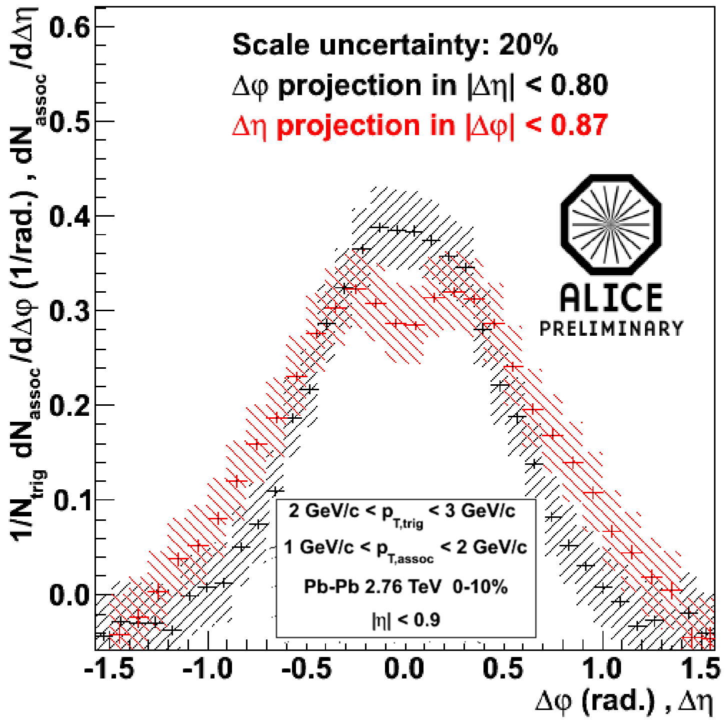
Di-hadron correlations

J-F Grosse-Oetringhaus, A. Morsch@HP



0-10%
$2 < p_{T,t} < 3$ GeV/c
$1 < p_{T,a} < 2$ GeV/c





Δφ , Δη

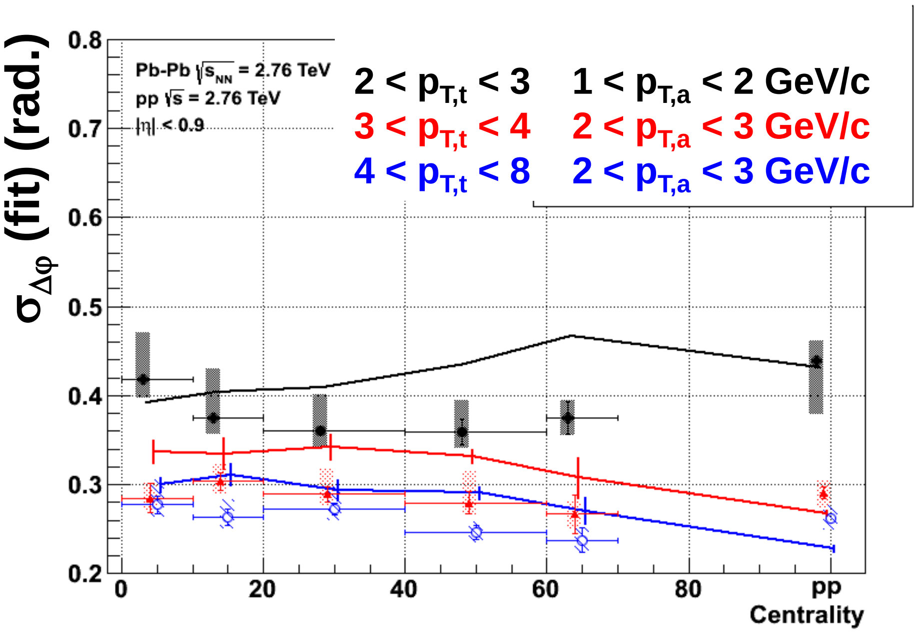
Width larger in η than φ
Not expected for jet fragmentation
Longitudinal flow?

Di-hadron correlations

J-F Grosse-Oetringhaus, A. Morsch@HP

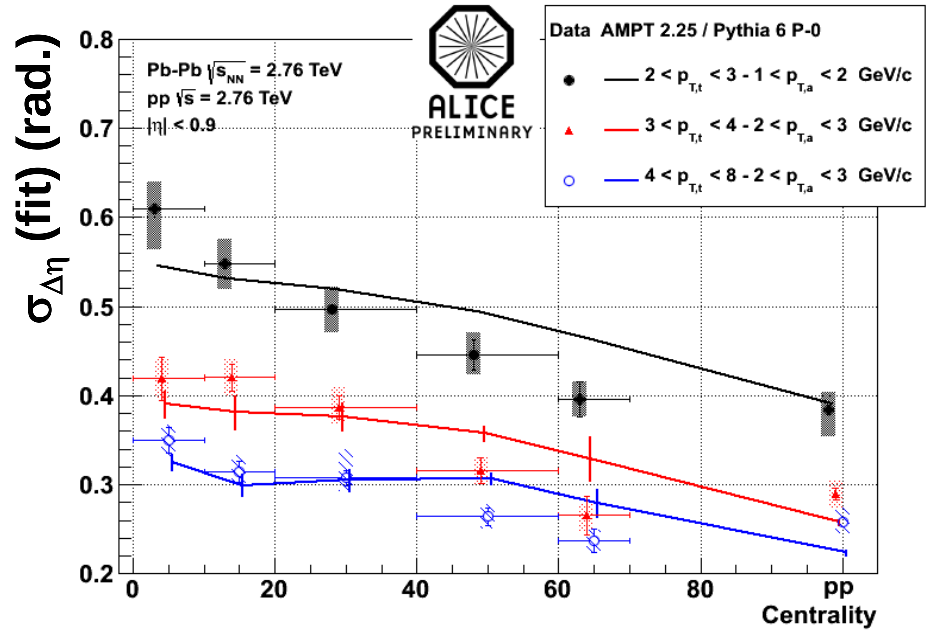
0-10%
$2 < p_{T,t} < 3$ GeV/c
$1 < p_{T,a} < 2$ GeV/c

$\Delta\varphi$ width



Lines: AMPT 2.25
and Pythia P-0 (for pp)

$\Delta\eta$ width



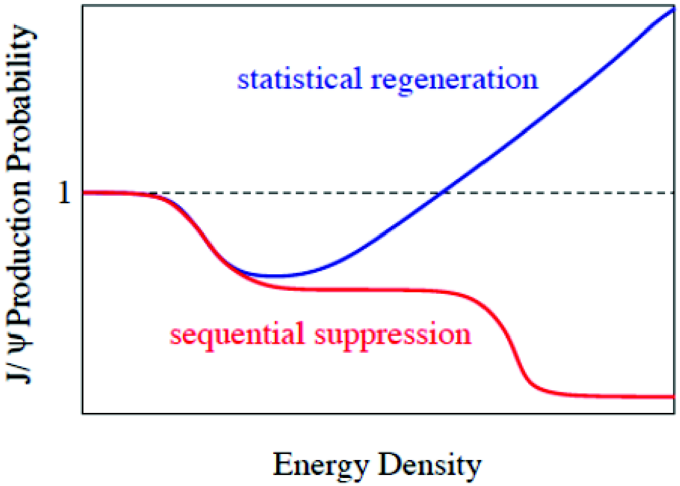
Width larger in η than φ
Not expected for jet fragmentation
Longitudinal flow?

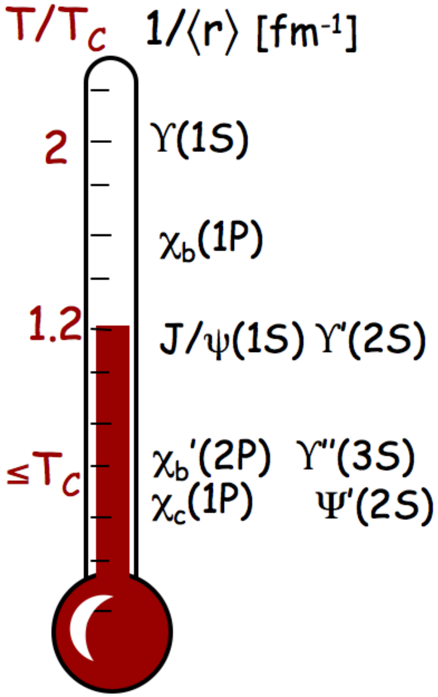
AMPT model has similar behaviour
Mechanism not clear yet...

J/ψ production and suppression

Motivation:
J/ψ and quarkonia melt
in Quark Gluon Plasma

Debeye screening



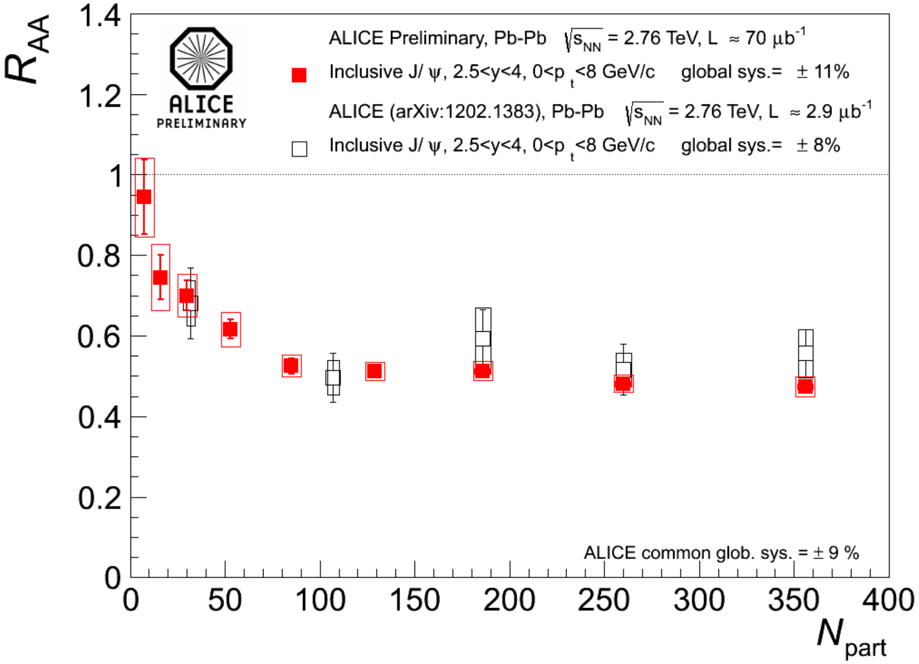


Thermometer:
Suppression depends on
local temperature

J/ψ R_{AA}

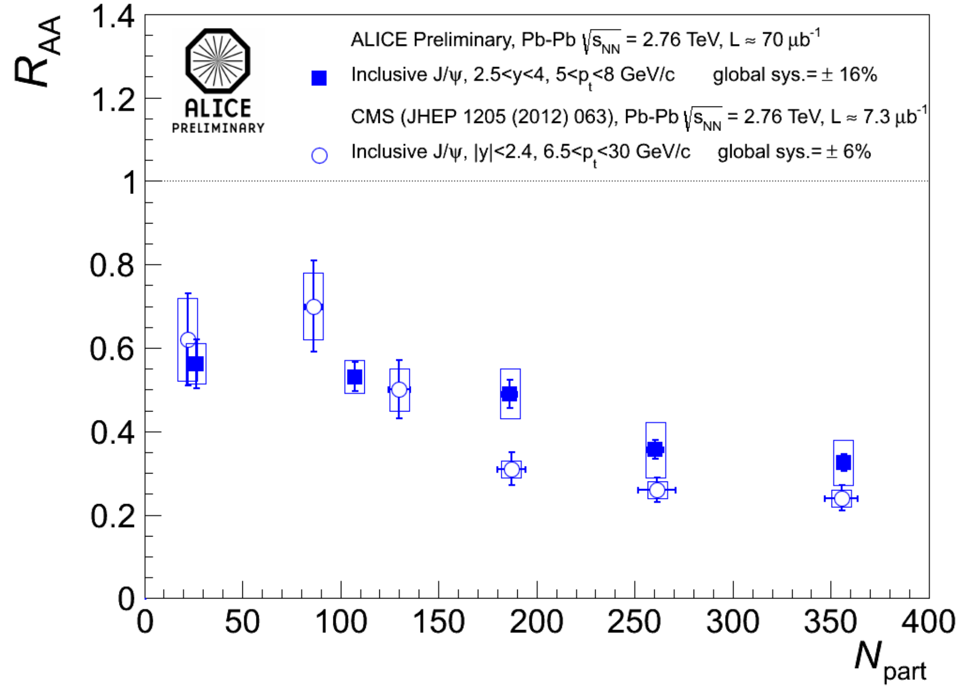
J. Wiechula, C. Suire, L. Massacrier@HP

Forward rapidity, low p_T



2011 data: clear improvement in statistical uncertainties

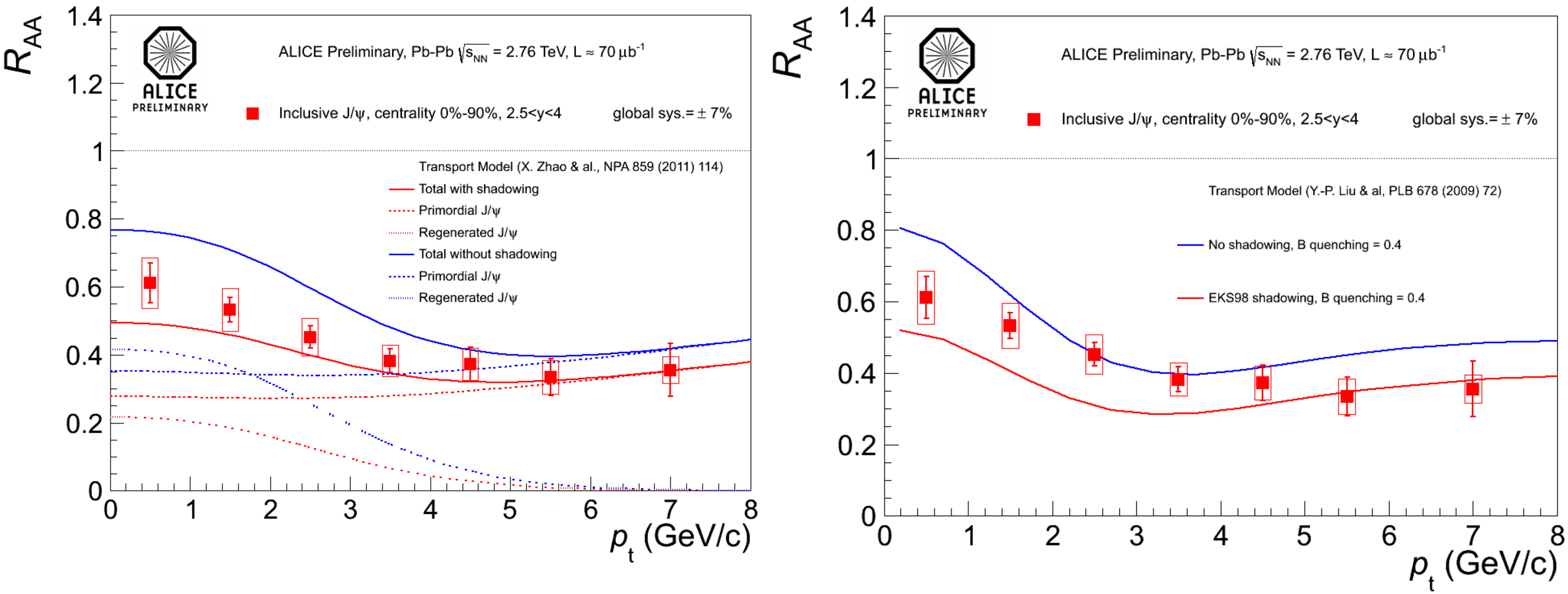
Forward rapidity, high p_T



Suppression observed: melting, but also other mechanisms? Compare SPS, RHIC

High-p_T results agree with CMS measurements

J/ψ R_{AA} vs p_T: regeneration/coalescence?

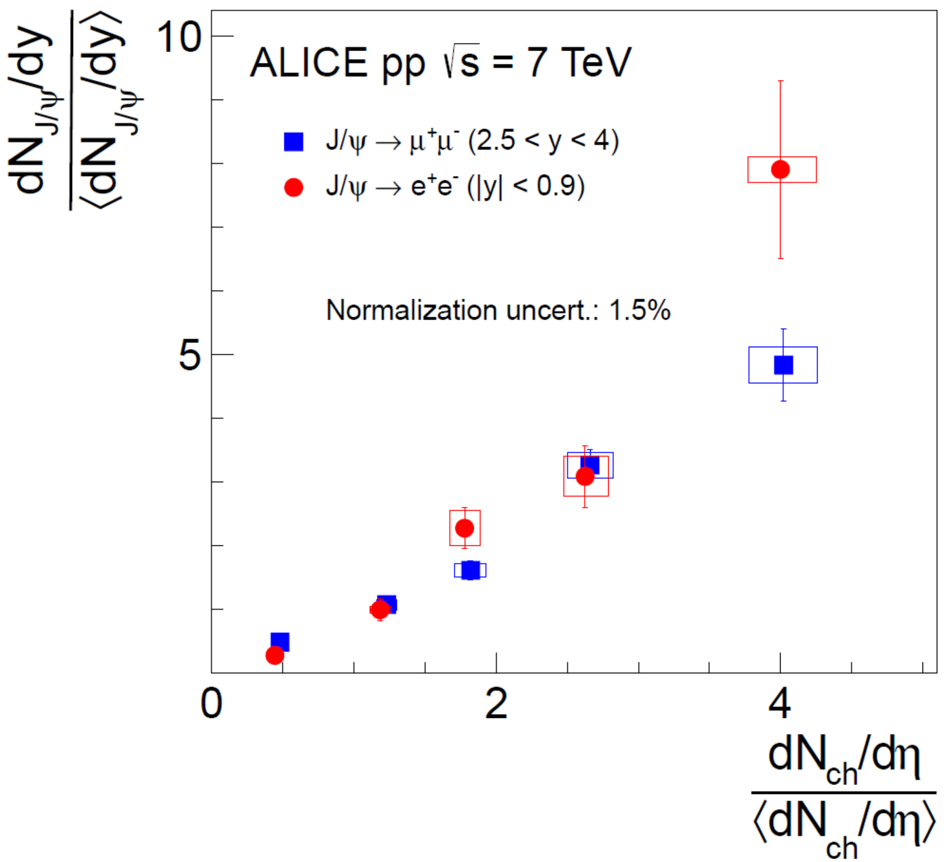


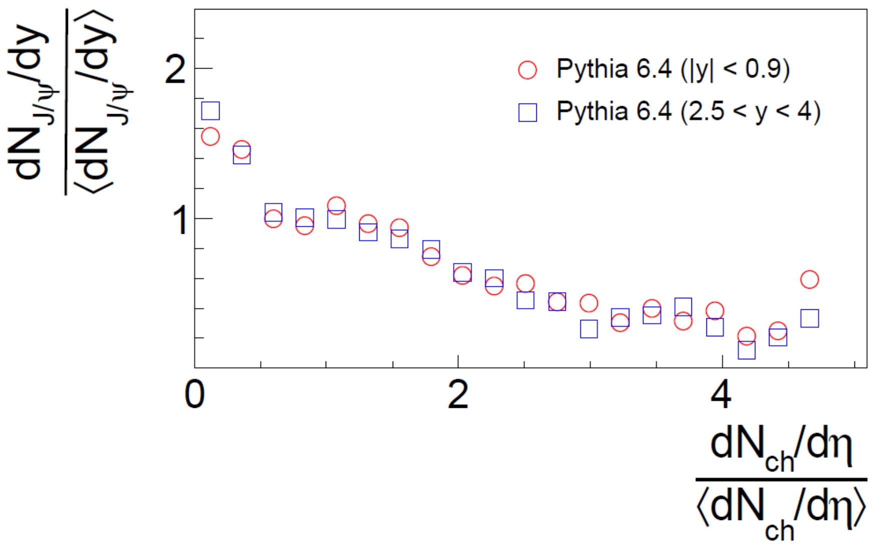
Low p_T R_{AA} > High p_T R_{AA}

J/ψ formed by recombination of c-cbar pairs at low p_T ?

Multiplicity dependence in pp

arXiv:1202.2816, PLB





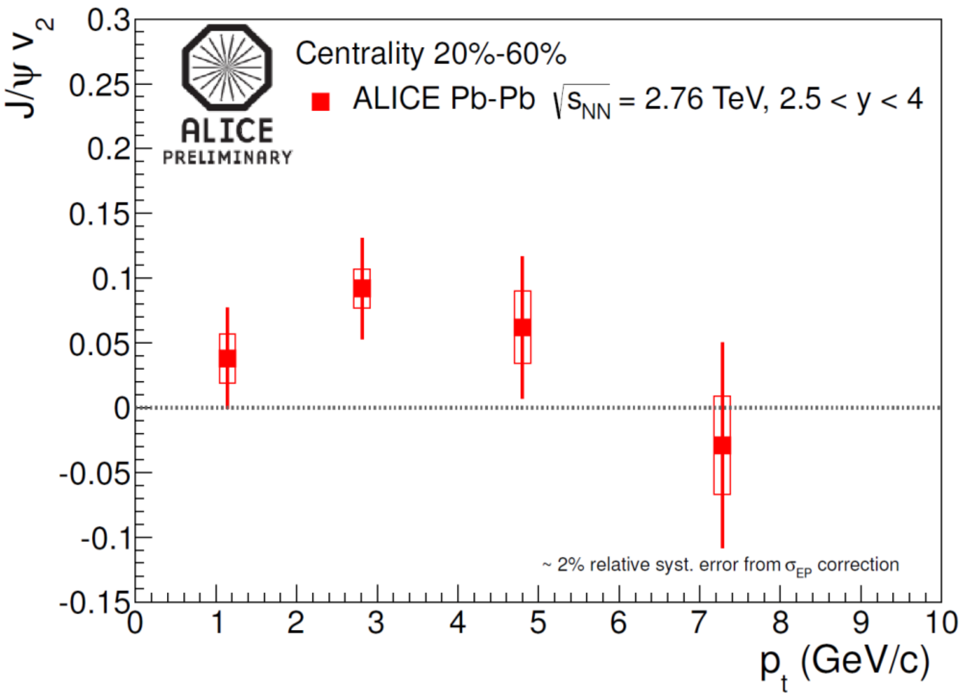
Not understood:
e.g. Pythia expects opposite

J/ψ yield in pp increases with event multiplicity

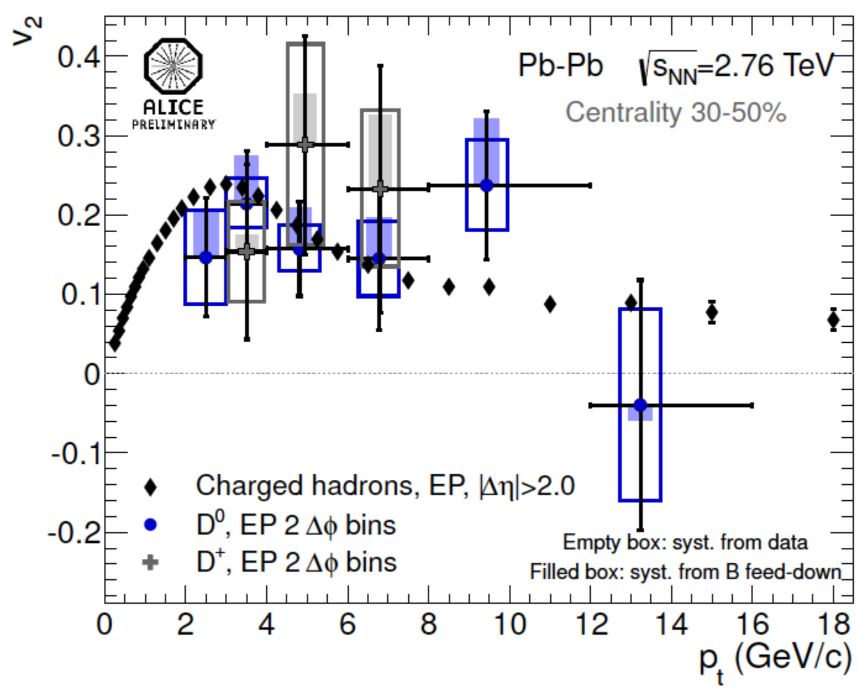
Do we understand J/ψ production?

First glimpse of Charm flow

J/ψ

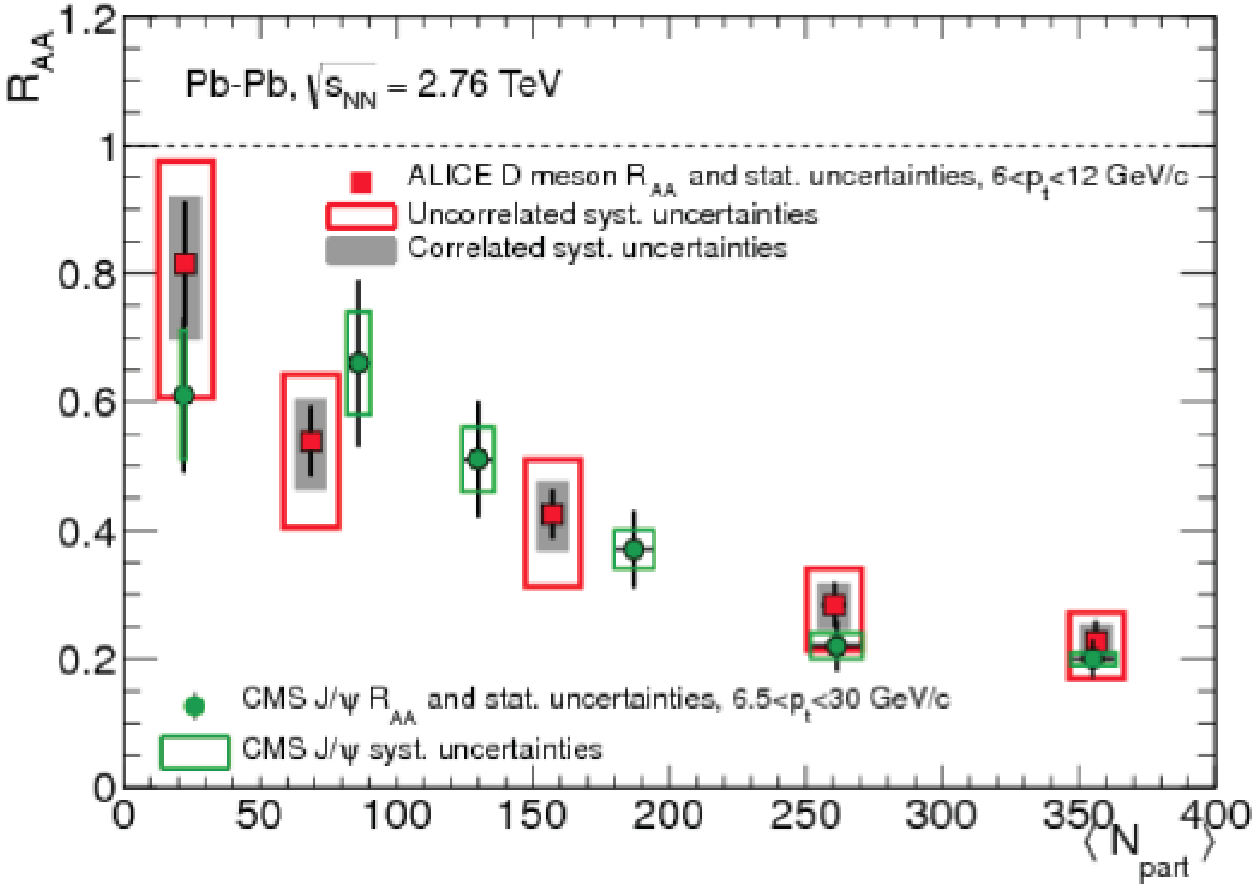


D mesons



Hint of non-zero v_2 for charm: interactions with medium

Comparing open charm and J/ψ



Open charm: parton energy loss and fragmentation
J/ψ: production and dissociation (+regeneration?)

A priori, do not expect similar values for R_{AA}

J. Schukraft: Apples&Broccoli

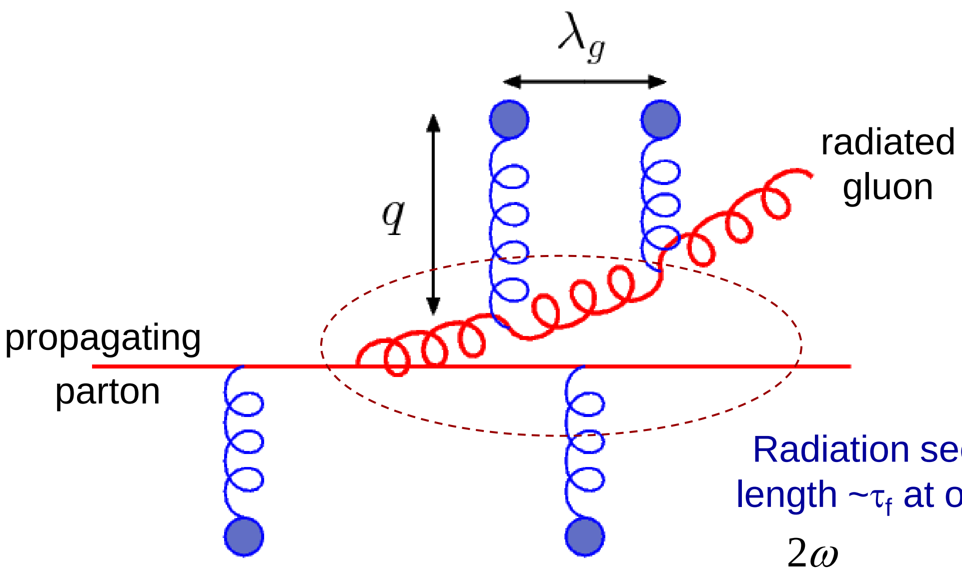
Summary/outlook

- Many new results:
  - Identified hadrons
  - Open heavy flavour
  - Jets
  - J/ψ
- Comparisons to theory/models ongoing
  - Should lead to consistent understanding of medium density (evolution), parton energy loss and charmonium melting
- Future:
  - Increase data sample of Pb+Pb (2011 data and future runs)
    - B, D_s, Λ_c, di-jets, jet structure, photons ...
  - Early 2013: p+Pb run for cold nuclear effects
  - Higher energy: 5.5 TeV systematically constrain models/interpretation

Extra slides

Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important



Radiation sees length ~τ_f at once

$$\tau_f = \frac{2\omega}{k_T^2}$$

Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

and nature of scattering centers
(scattering cross section)

Transport coefficient $\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$

Energy loss

$$\Delta E_{med} \sim \alpha_S \, C_R \, \hat{q} \, L^n F(m, E)$$

C_R: color factor (q, g)
$\hat{q}$: medium density
L: path length
m: parton mass (dead cone eff)
E: parton energy

Path-length dependence L^n
$n=1$: elastic
$n=2$: radiative (LPM regime)
$n=3$: AdS/CFT (strongly coupled)

Two extreme scenarios

(or how P(ΔE) says it all)

Scenario I

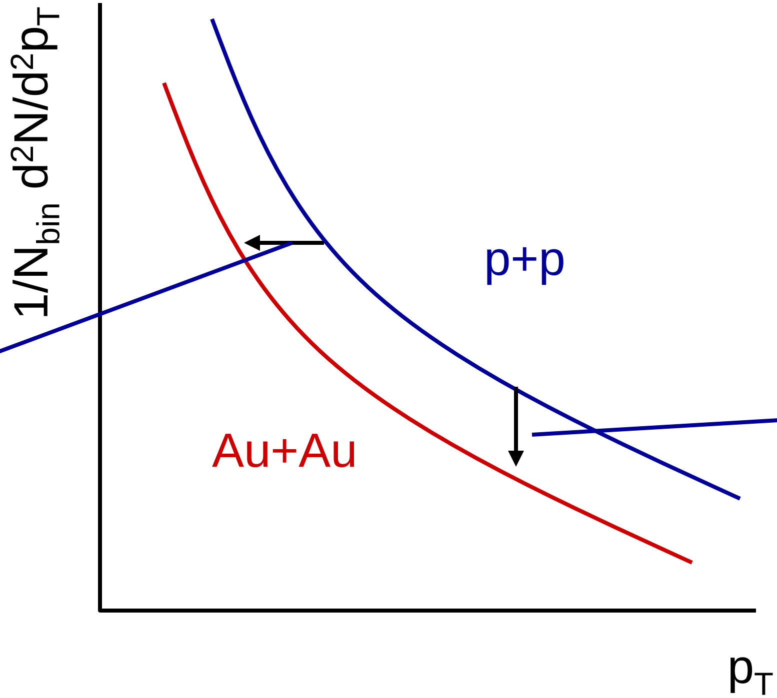
$P(\Delta E) = \delta(\Delta E_0)$

'Energy loss'

Scenario II

$P(\Delta E) = a\,\delta(0) + b\,\delta(E)$

'Absorption'



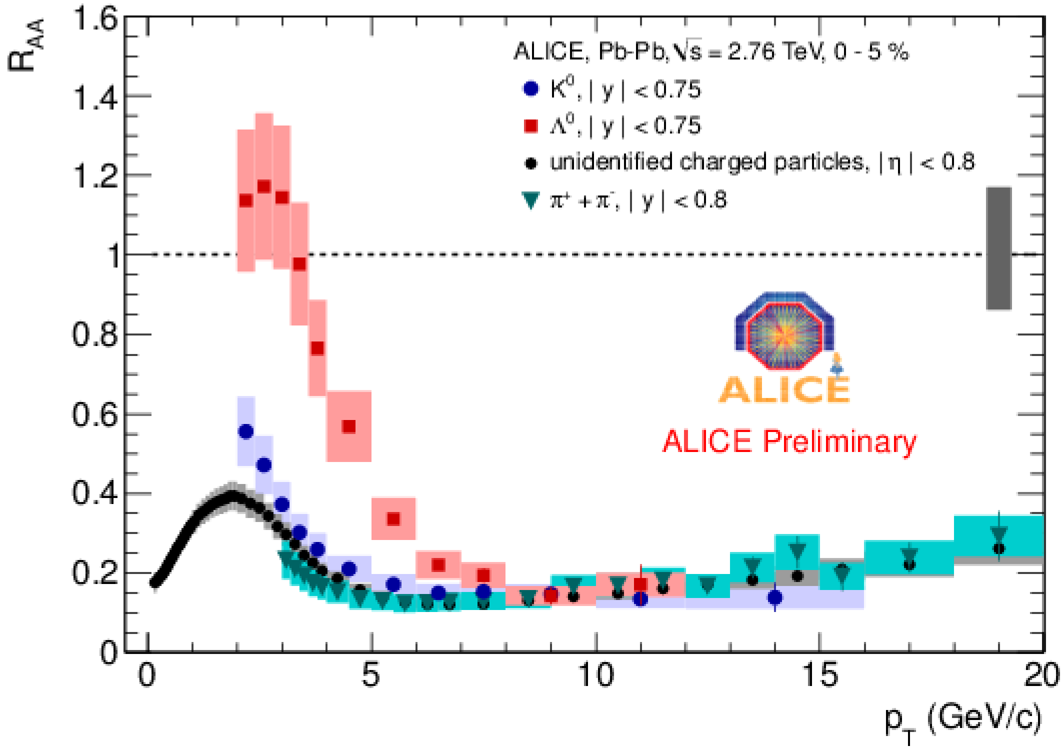
Shifts spectrum to left

Downward shift

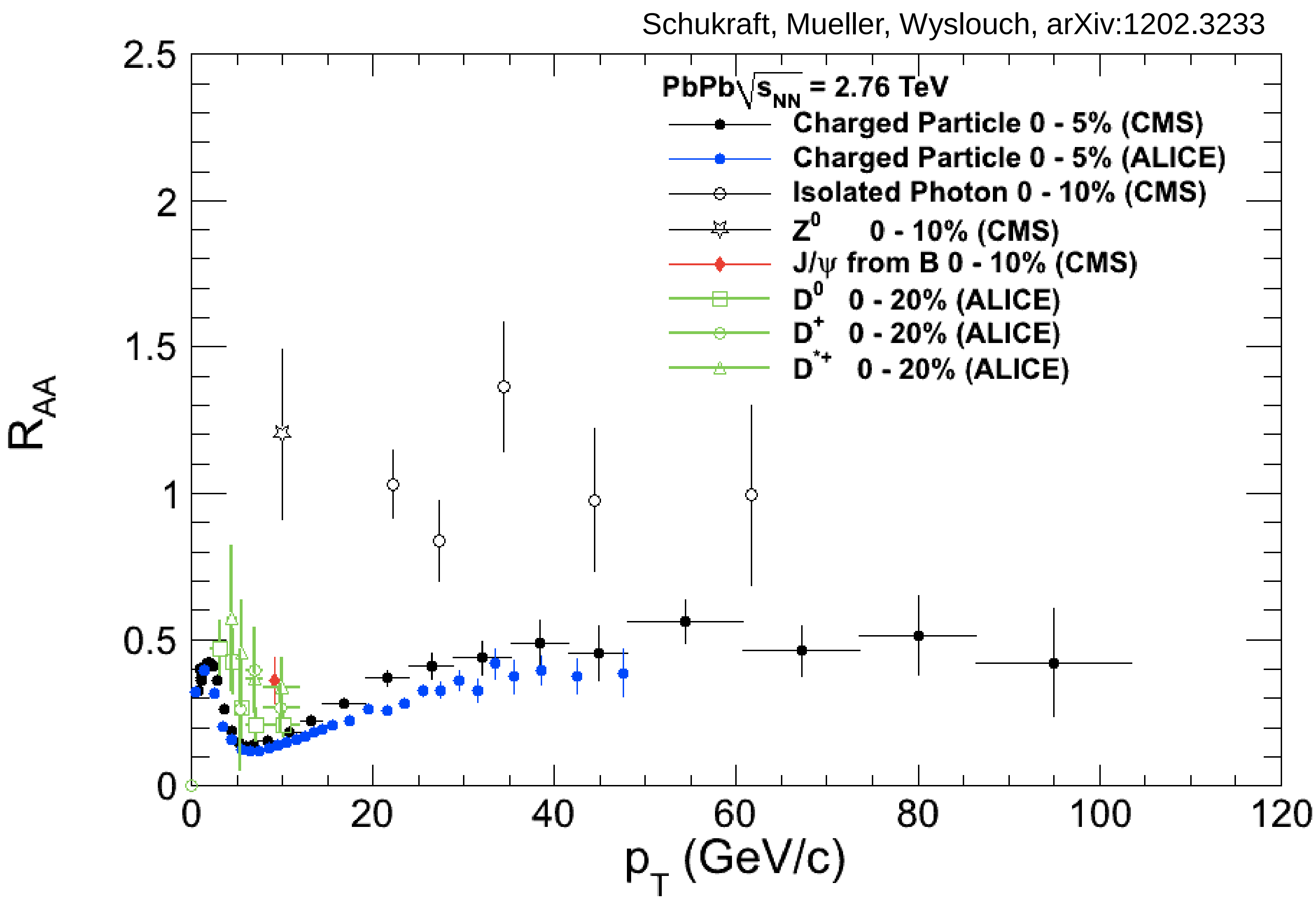
P(ΔE) encodes the full energy loss process

R_{AA} not sensitive to energy loss distribution, details of mechanism

Identified hadron R_{AA}

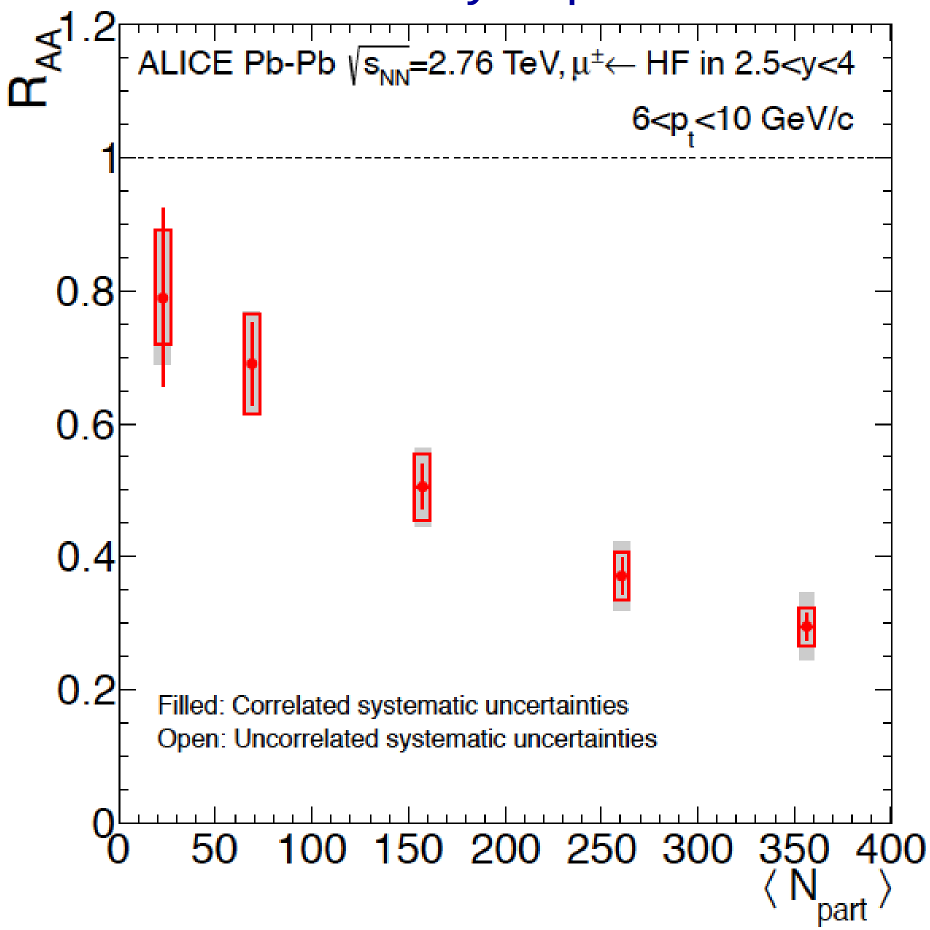


R_{AA} comparison



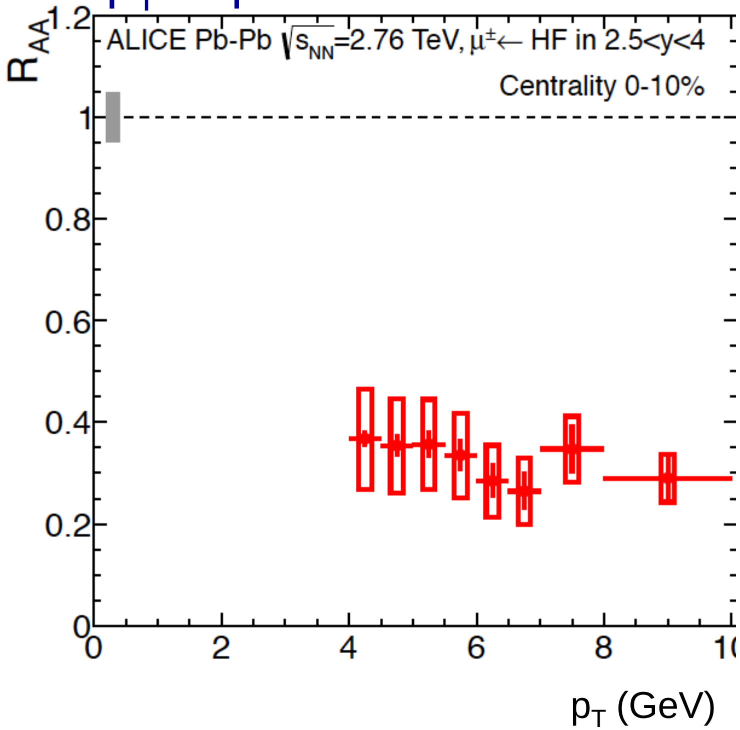
Single muon R_{AA}

Centrality dependence



D. Stocco@HP

p_T dependence central bin



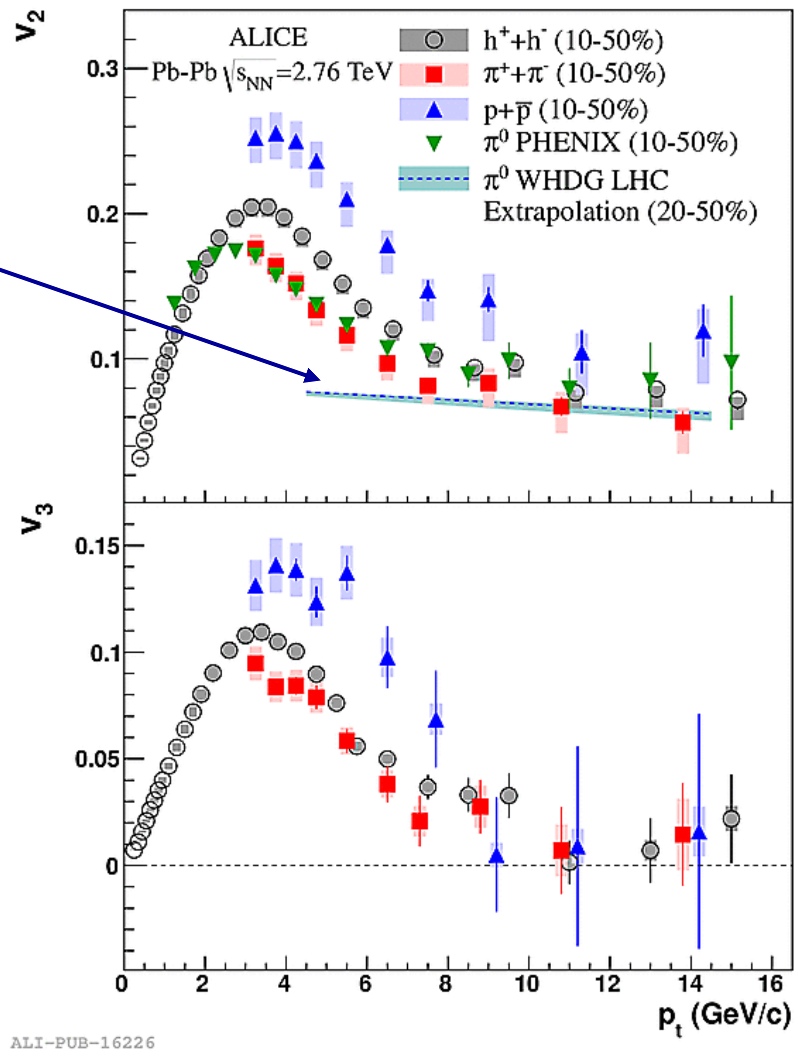
Hard Probes conference

- Parton energy loss
  - Jets, high-pt hadrons, heavy flavours
- Color screening
  - J/psi, Y
- Thermal production/radiation
  - Photons, di-leptons

v_2 at high p_T: path length dependent energy loss

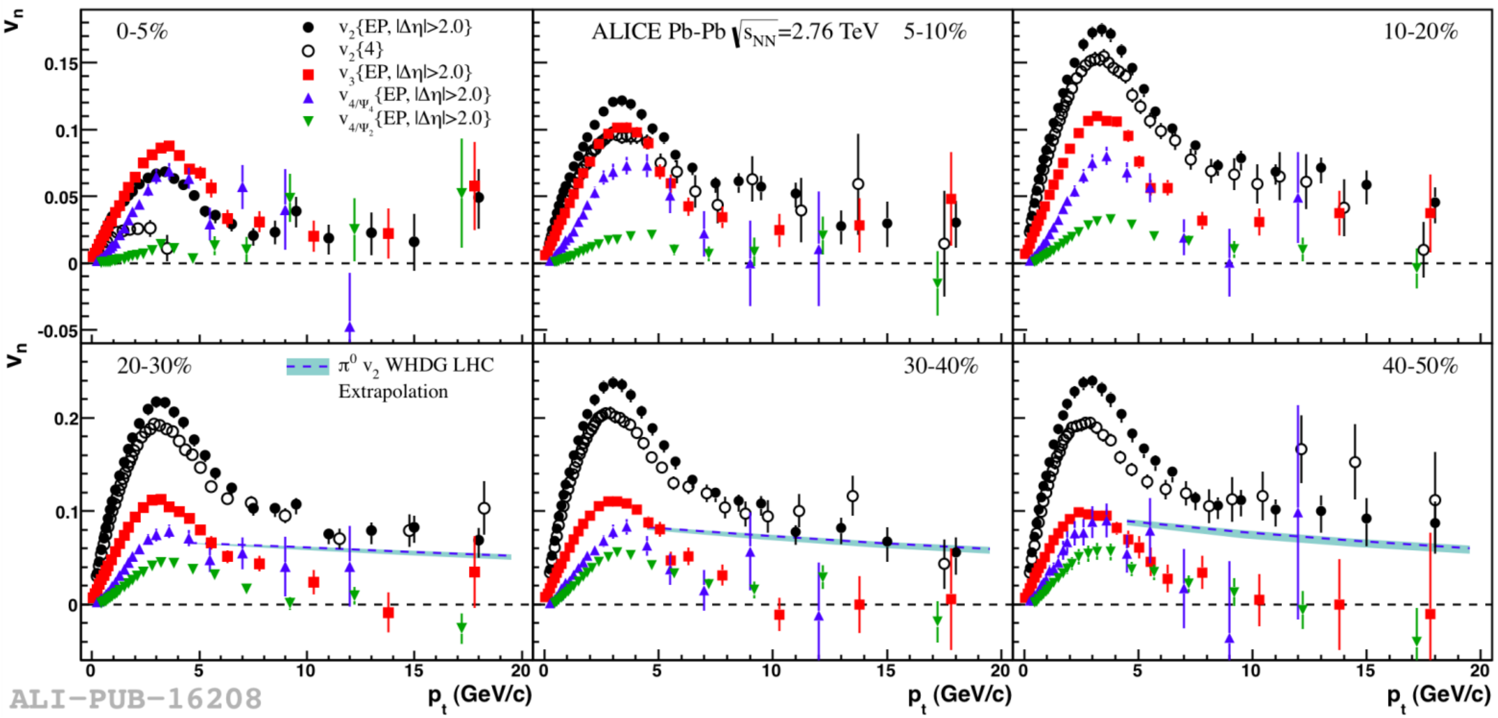
ALICE, arXiv:1205.6761

Agrees with energy loss models at high p_T



Suggests:
Medium density profiles from bulk models consistent with high-p_T observations

High-p_T v_2

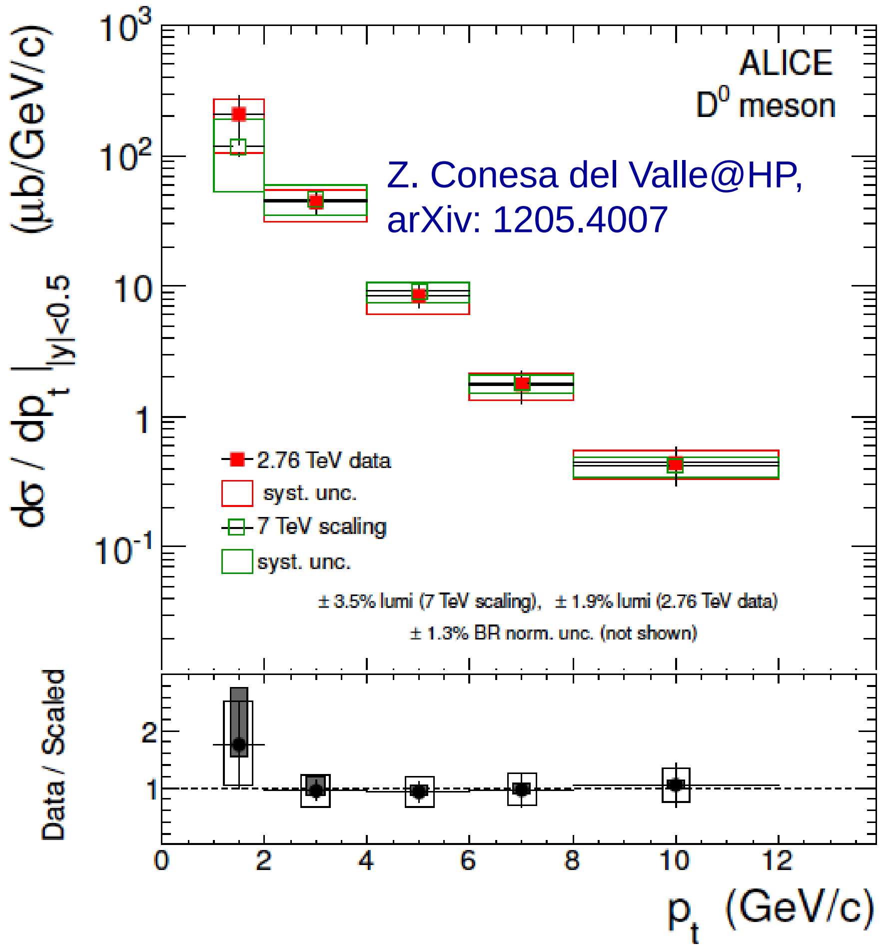


0-5%
$v_2\{EP, |\Delta\eta|>2.0\}$
$v_2\{4\}$
$v_3\{EP, |\Delta\eta|>2.0\}$
$v_{4/\Psi_4}\{EP, |\Delta\eta|>2.0\}$
$v_{4/\Psi_2}\{EP, |\Delta\eta|>2.0\}$
ALICE Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
5-10%
10-20%
20-30%
π^0 v_2 WHDG LHC Extrapolation
30-40%
40-50%
v_n
p_t (GeV/c)
ALI-PUB-16208

Heavy flavour in pp 2.76 TeV

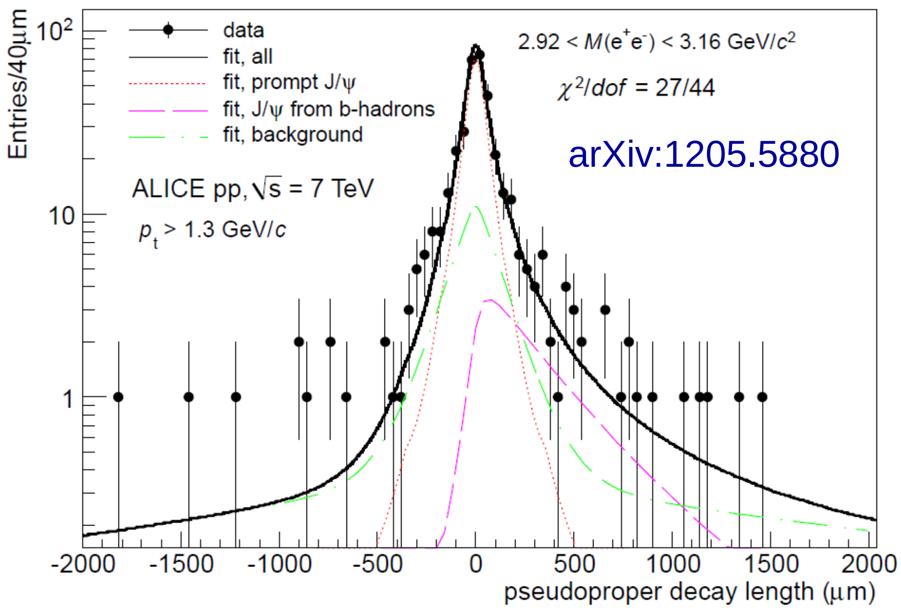
D mesons

Comparison to scaled 7 TeV data:
(pp reference for RAA)
Good agreement

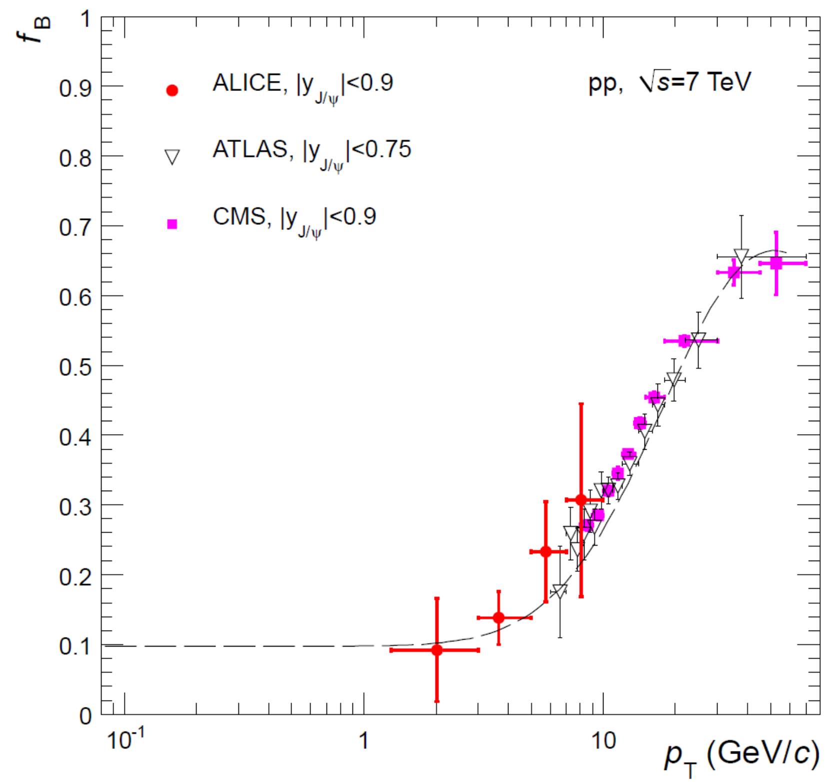


J/y from B in pp

Use impact parameter distribution



Fraction of J/y from B



Clear increase from pT~5 GeV

Good agreement between experiments – different p_T ranges

J/ψ η, p_T dependence