Recent Results on Heavy Flavour Measurement from ALICE
and
Korean Activities on ALICE Experiment

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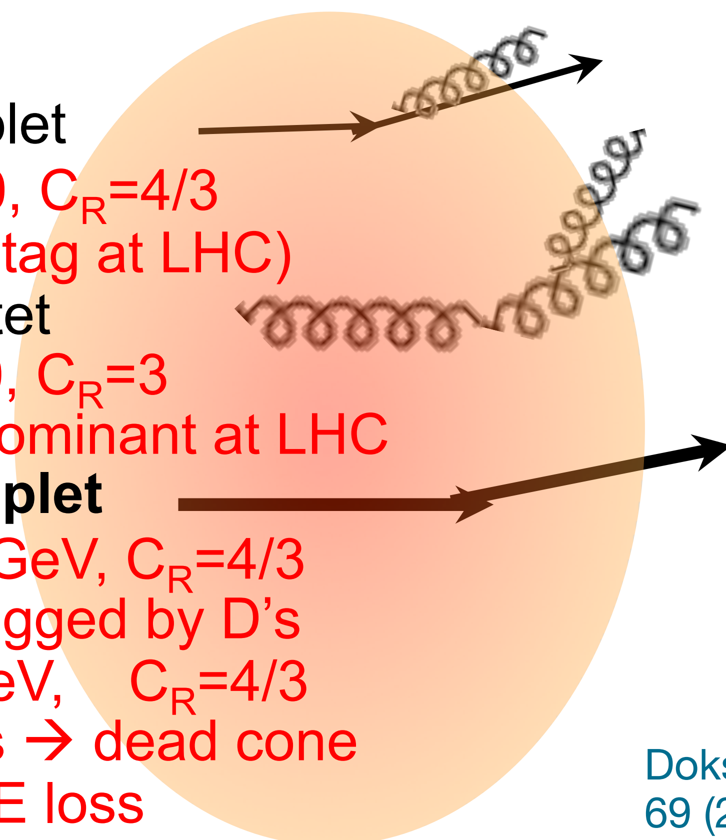
High Energy Strong Interaction: A School for Young Asian Scientists
CCNU, Wuhan, September 23, 2014

Outline of the talk

- Why heavy flavours?
- Heavy flavour physics programs
- Experimental results
- Korean Activities on ALICE experiment at CERN
- Summary

What's special about heavy quarks

- Large mass ($m_q \gg \Lambda_{QCD}$) → produced in the early stages of the HI collision with short formation time(t_{charm} ~ $1/m_c$ ~ 0.1 fm/c << τ_{QGP} ~ O(10 fm/c)), traverse the medium interacting with its constituents
  - ➡ natural probe of the hot medium created in HI interactions
- Interactions with QGP don't change flavour identity
- Uniqueness of heavy quarks: cannot be destroyed/created in the medium
  - ➡ transported through the full system evolution



q: colour triplet
u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)
g: colour octet
g: m=0, C_R=3
> E loss, dominant at LHC
Q: colour triplet
c: m~1.5 GeV, C_R=4/3
small m, tagged by D's
b: m~5 GeV, C_R=4/3
large mass → dead cone
→ < E loss

'Quark Matter'

Parton Energy Loss by
→ medium-induced gluon radiation
→ collisions with medium constituents

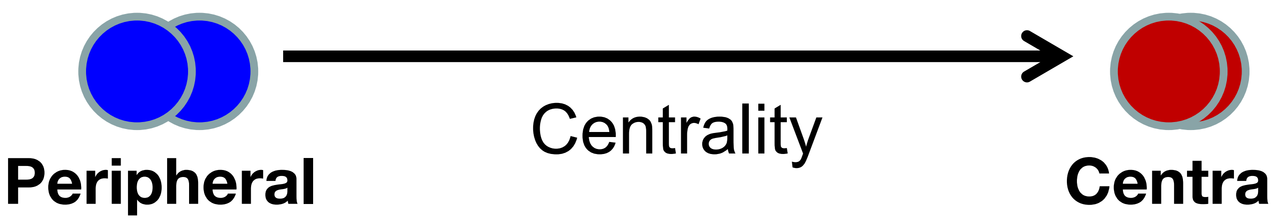
$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

Prediction: $$\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$$

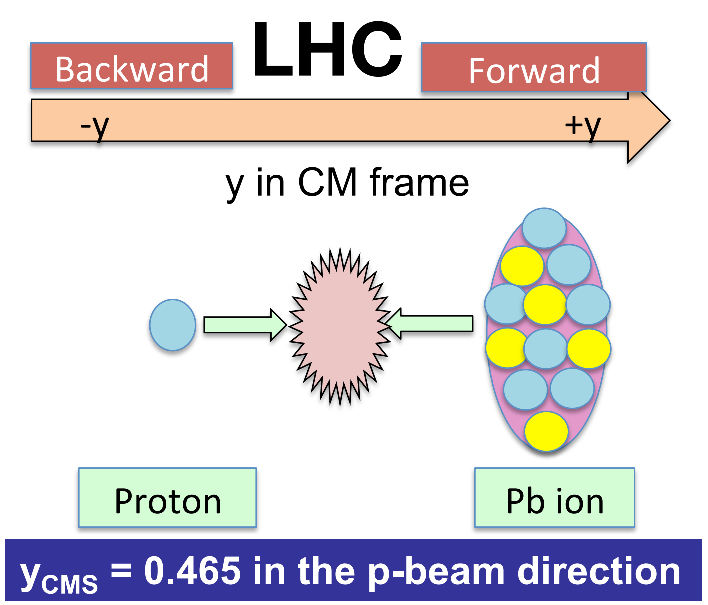
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

Heavy flavour physics programs in pp, p-A, A-A collisions

- Pb-Pb collisions
  - Study the interaction of heavy quarks with the medium
  - Comparison with models in order to extract the transport properties of the medium

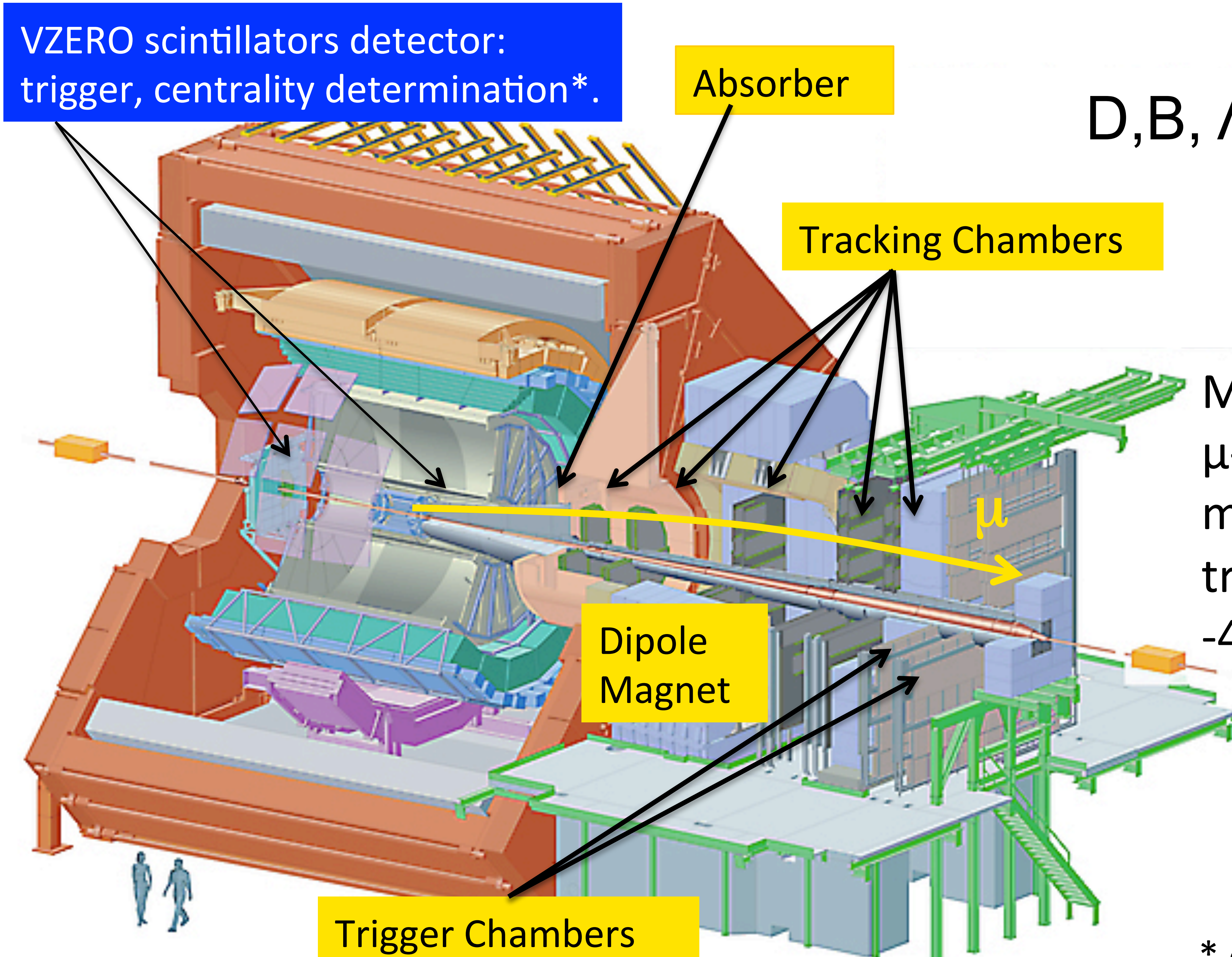


- p-p collisions
  - Reference for p-Pb and Pb-Pb measurements
  - Test of pQCD-based predictions



- p-Pb collisions
  - Control experiment for the Pb-Pb measurement
  - Address cold nuclear matter effects
    - Study of the shadowing influence at LHC energies (Bjorken x ~ 10^{-4})
    - Possible saturation regime

Heavy-flavour decay muons in ALICE



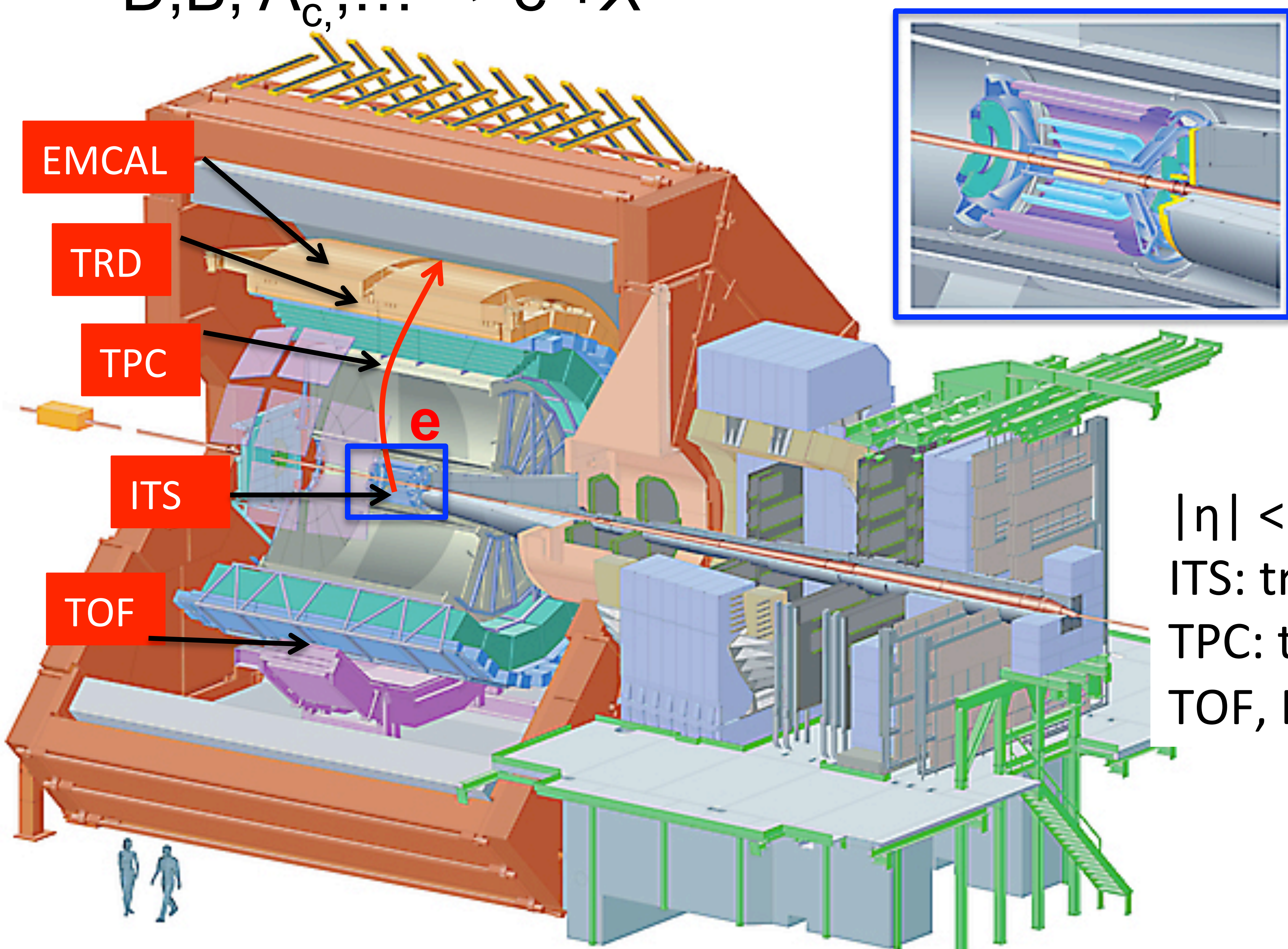
$D, B, \Lambda_{c}, \ldots \rightarrow \mu + X$

Muon spectrometer:
μ-ID via tracks matched with and trigger system
$-4 < \eta < -2.5$

* common for all analyses

Heavy-flavour decay electrons in ALICE

$D, B, \Lambda_c, \ldots \rightarrow e + X$



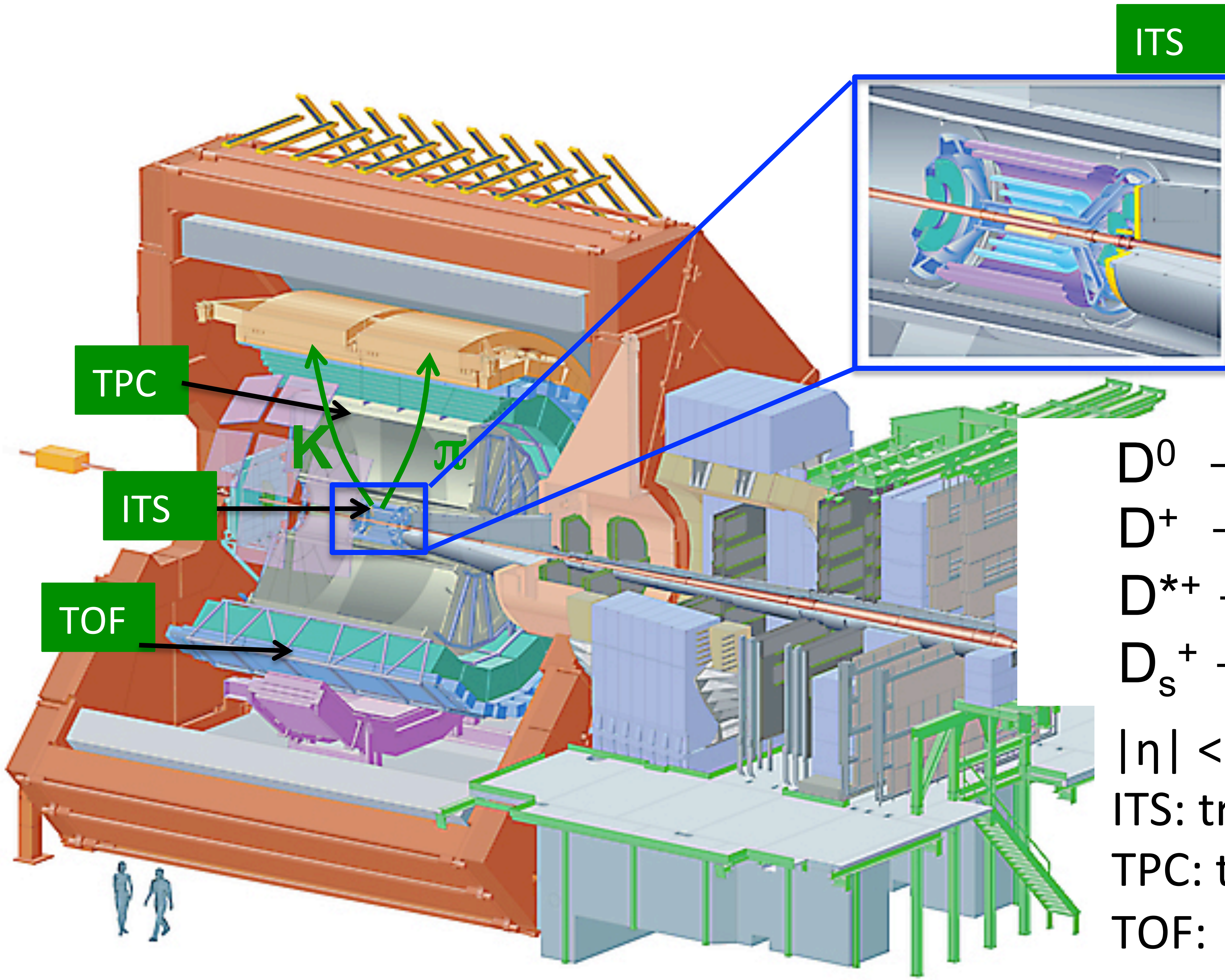
$|\eta| < 0.9$

ITS: tracking, vertexing

TPC: tracking, PID

TOF, EMCAL, TRD: e-ID

D mesons in ALICE



$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^-\pi^+\pi^+$

$D^{*+} \rightarrow D^0\pi^+$

$D_s^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+$

$|\eta| < 0.9$

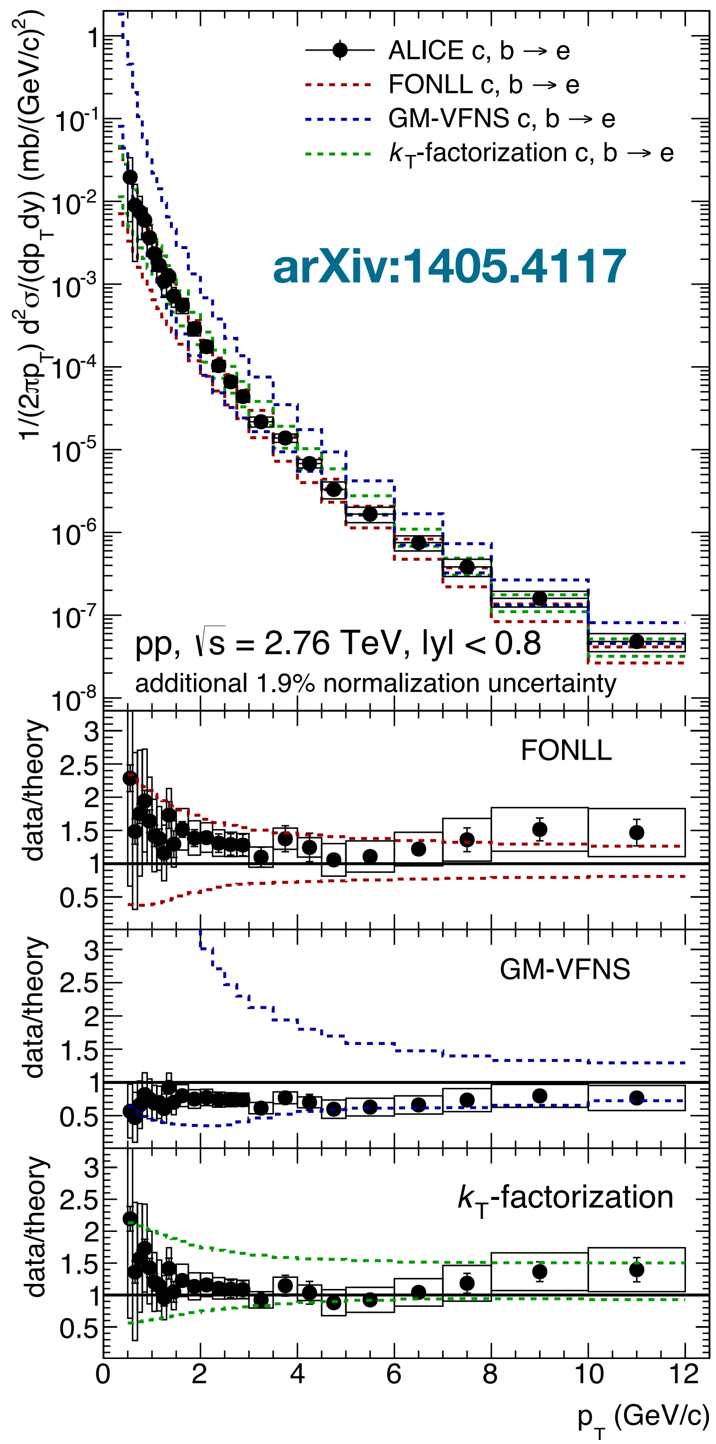
ITS: tracking, vertexing

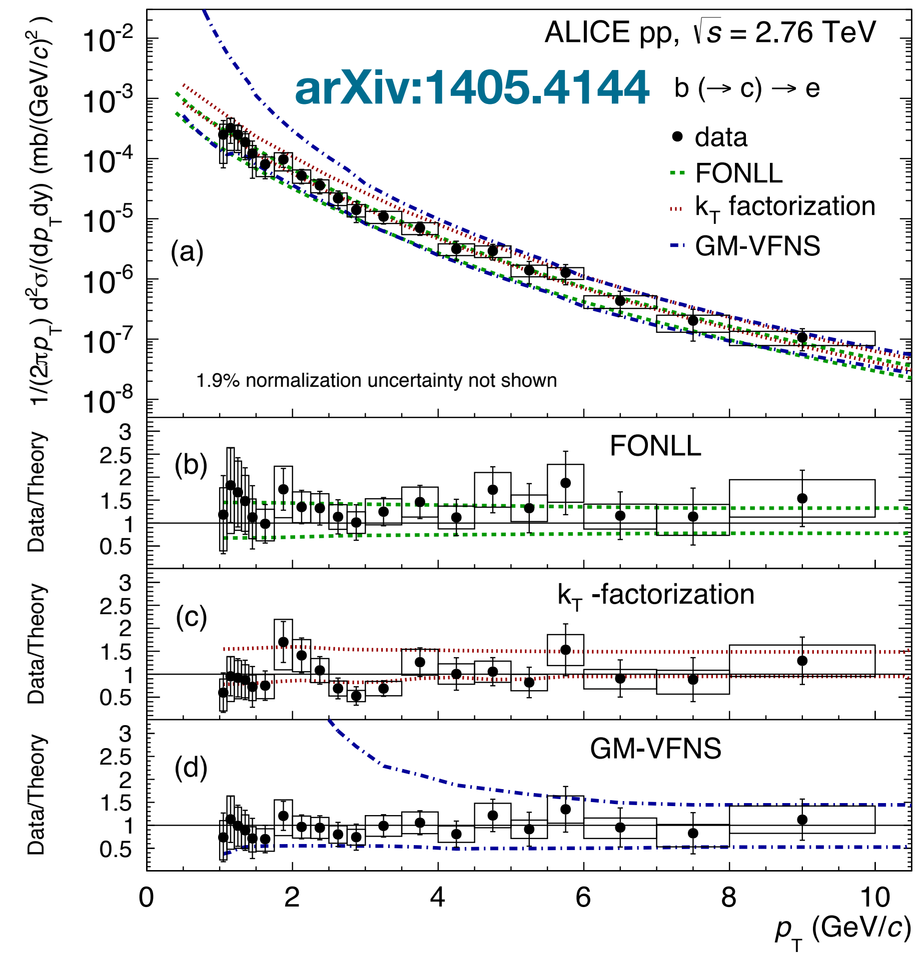
TPC: tracking, PID

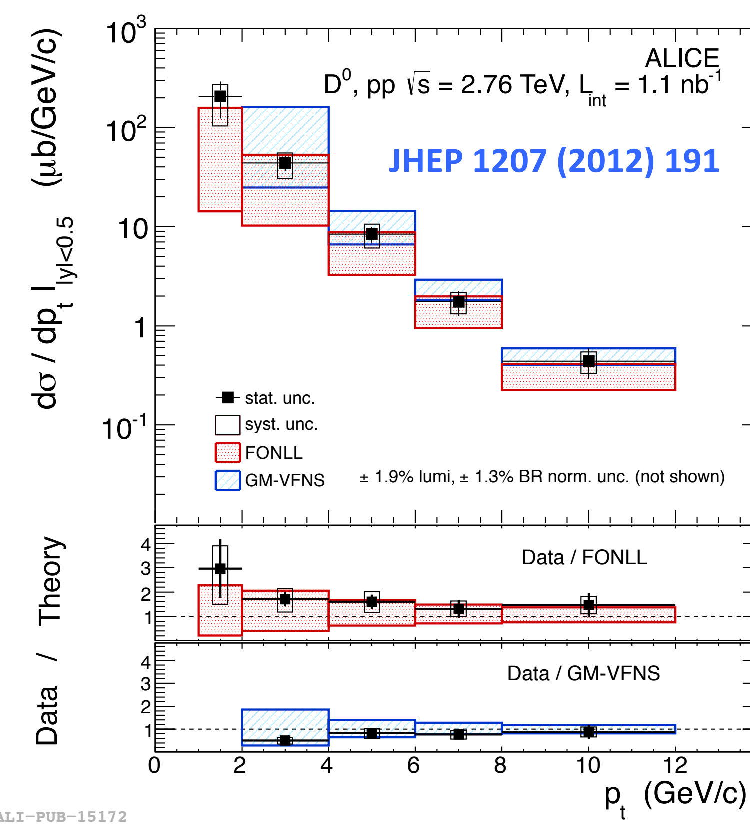
TOF: PID

p_T-differential cross sections in pp collisions

- Heavy flavour cross section measurements: **extended kinetic reaches, several beam energies**
- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data
  - ◉ D^0, D^+, D^{*+} mesons (mid rapidity) at 2.76 & 7 TeV
  - ◉ c,b→e (mid rapidity, down to p_T~0.5 GeV/c) at 2.76 & 7 TeV
  - ◉ c,b→μ (forward rapidity) at 2.76 & 7 TeV
  - ◉ b→e (mid rapidity, down to p_T~1 GeV/c) at 2.76 & 7 TeV

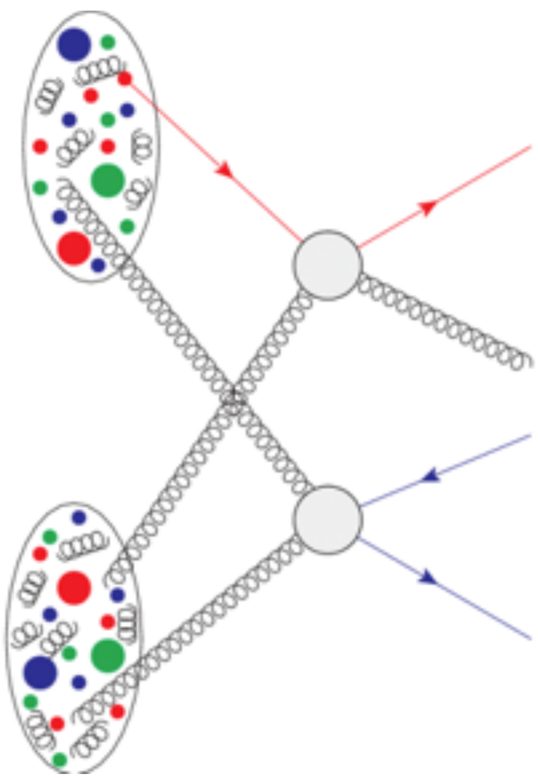






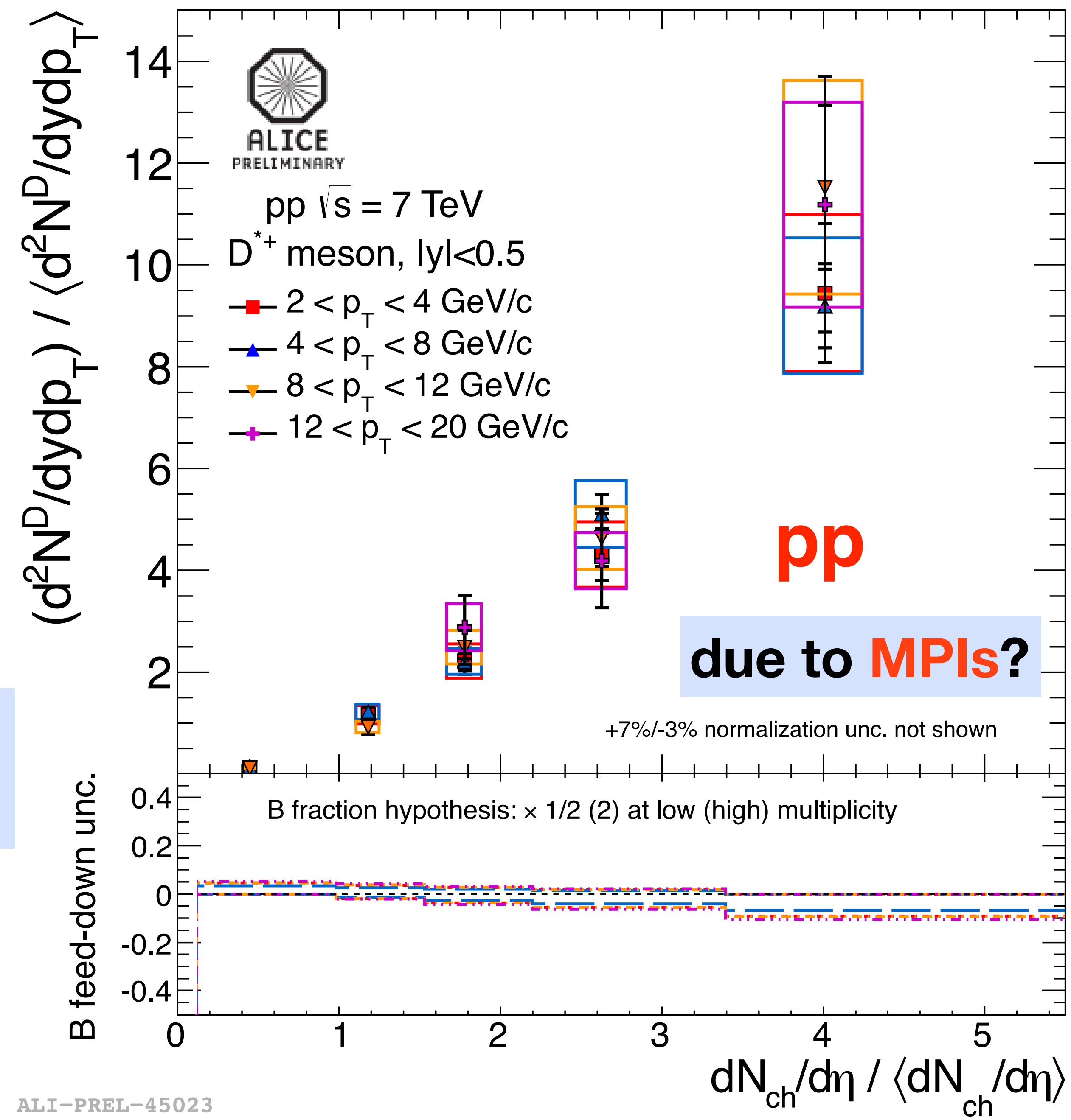
FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082,
k_T factorisation: arXiv:1301.3033

More on production mechanism:
Multiplicity dependences of charm production



Particle production in pp collisions at LHC shows **better agreement with models including MPIs**

Eur. Phys. J. C 73 (2013) 2674



MPIs involving only light quarks and gluons?

For heavy flavours:

- LHCb: double charm production agrees better with models including double parton scattering

J. High Energy Phys., 06 (2012) 141

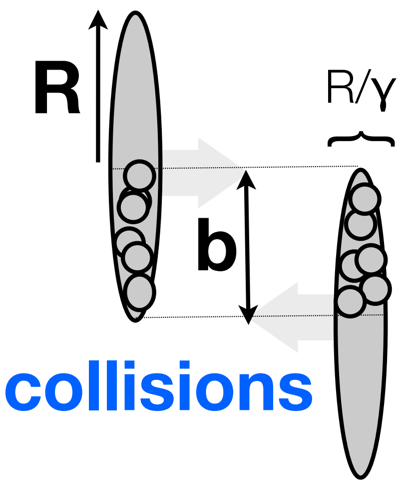
- D-meson yields increase with charged-particle multiplicity

→ presence of MPI and contribution on the a harder scale?

Quantification of medium effects: R_{AA}

- **Nuclear modification factor**: standard method to quantify the effects of the medium on the yield of a hard probe in a AA reaction

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$



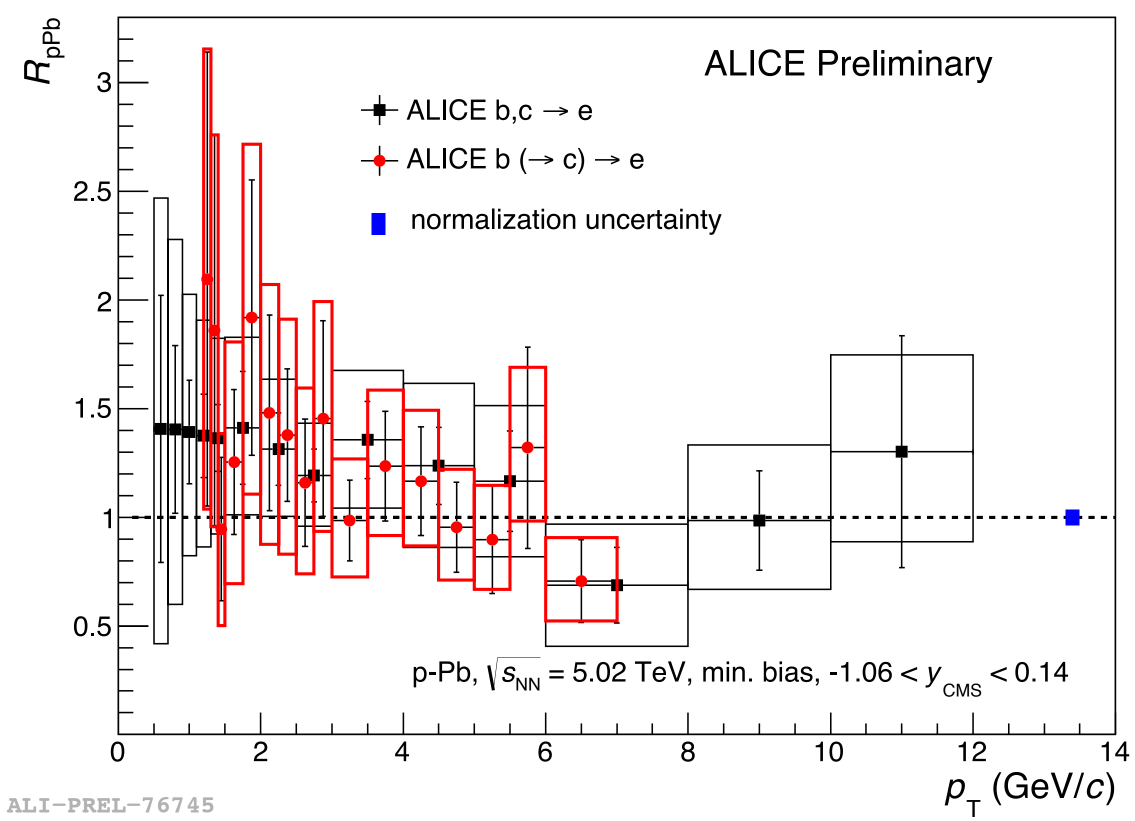
N_{part}, N_{coll},
participants
binary collisions

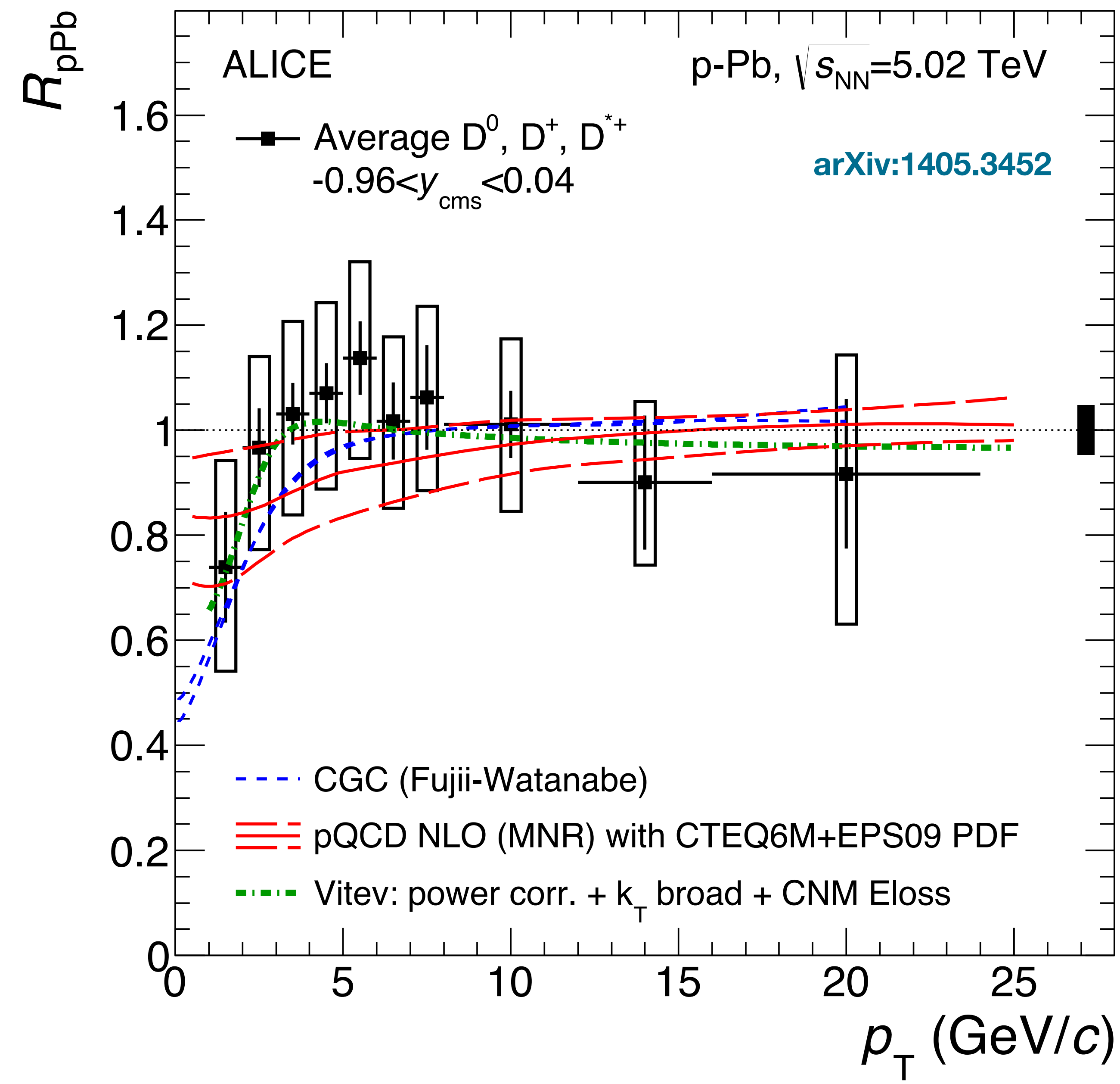
Binary scaling based on the Glauber Model

R_{AA}=1: AA collision ~ incoherent superposition of NN collisions

Heavy flavour in p-Pb at 5.02 TeV

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties
    - D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening
    - c,b→e & b→e (mid rapidity)

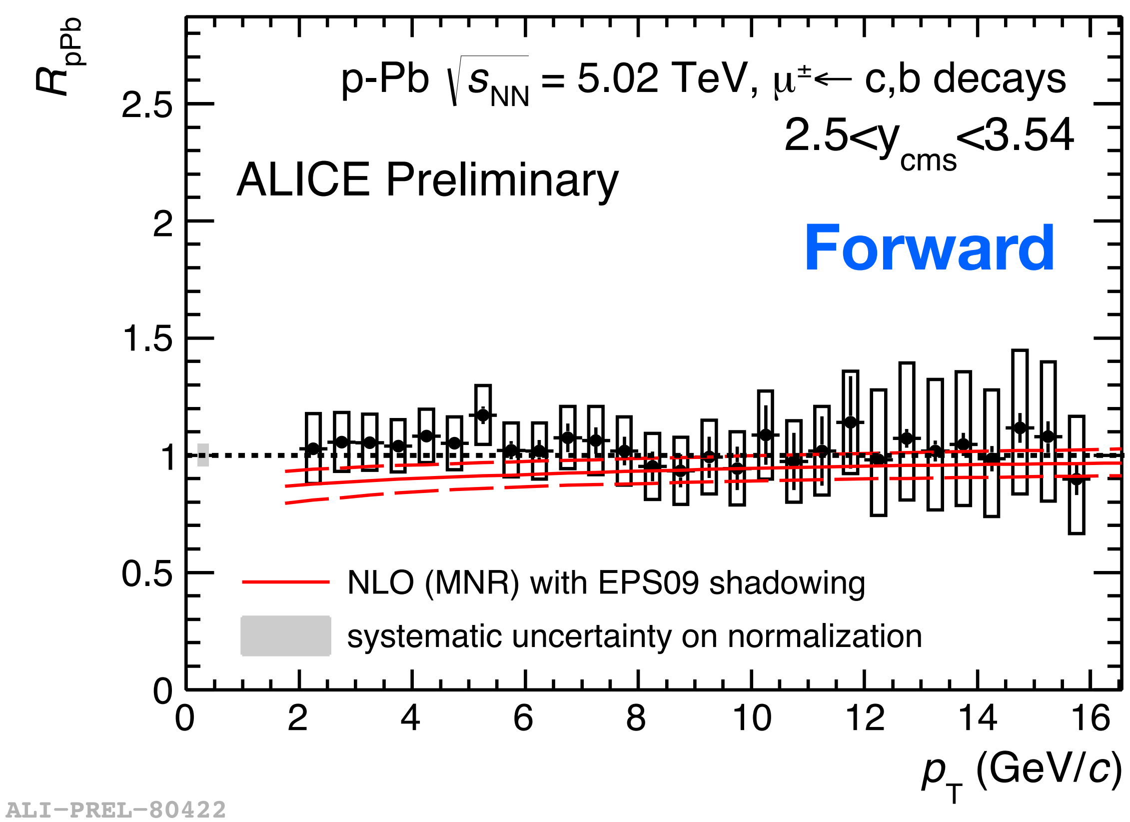


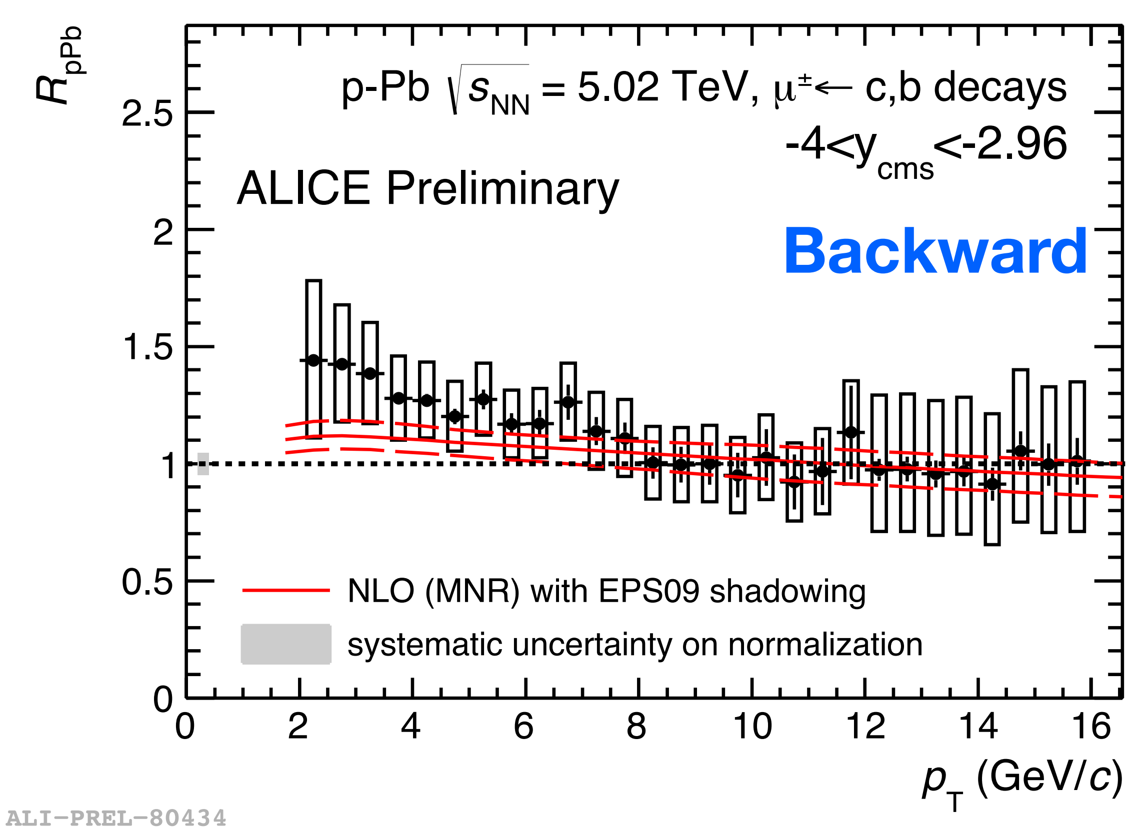


Heavy flavour in p-Pb at 5.02 TeV

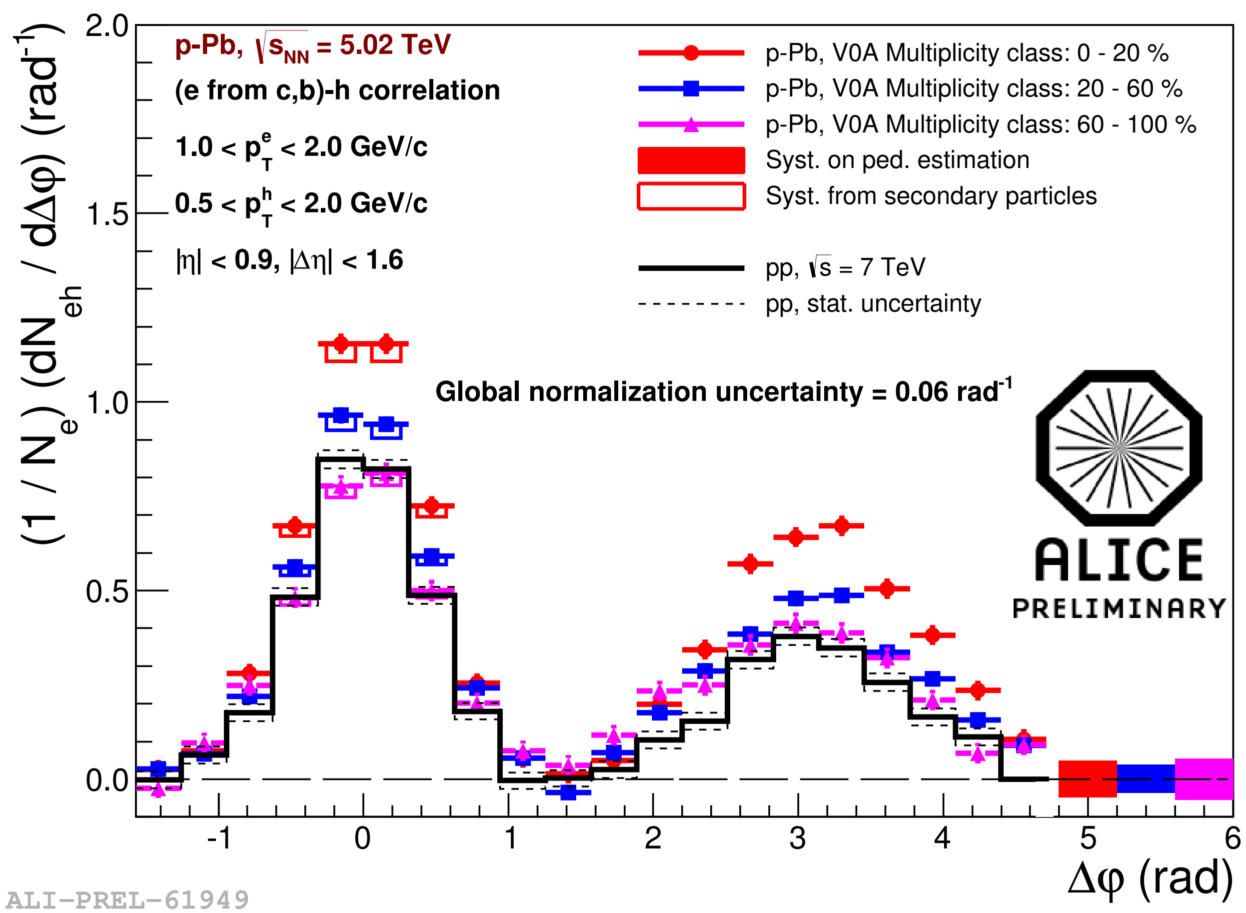
- R_{pPb} measured in various channels
- Slight rapidity dependence
  - ◉ c,b→μ:
    - at forward, consistent with unity within uncertainties
    - at backward, slightly larger than unity in $2<p_T<4$ GeV

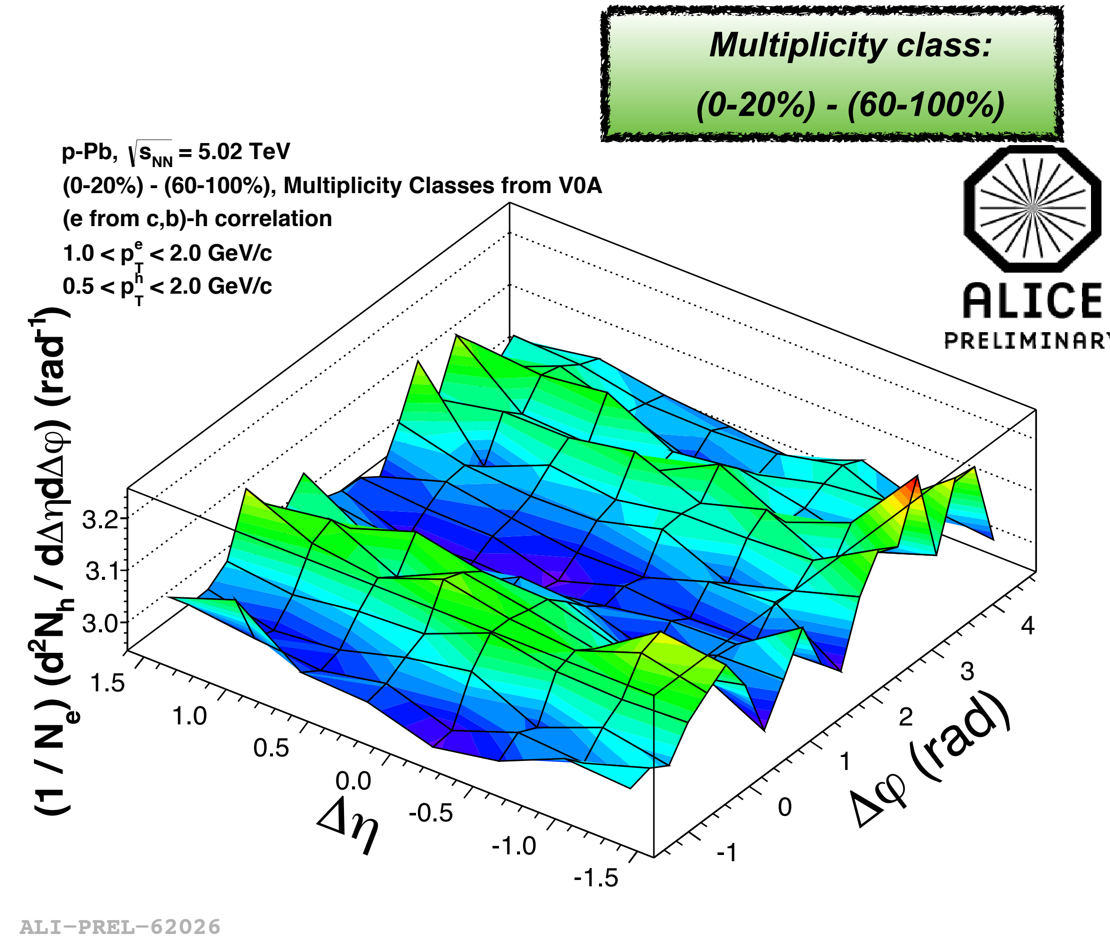
Within uncertainties, data can be described by pQCD calculations with EPS09 parameterization of shadowing





More differential information:
Heavy-flavour electron-hadron correlations





Resembles the structure that in AA is interpreted in terms of collective flow

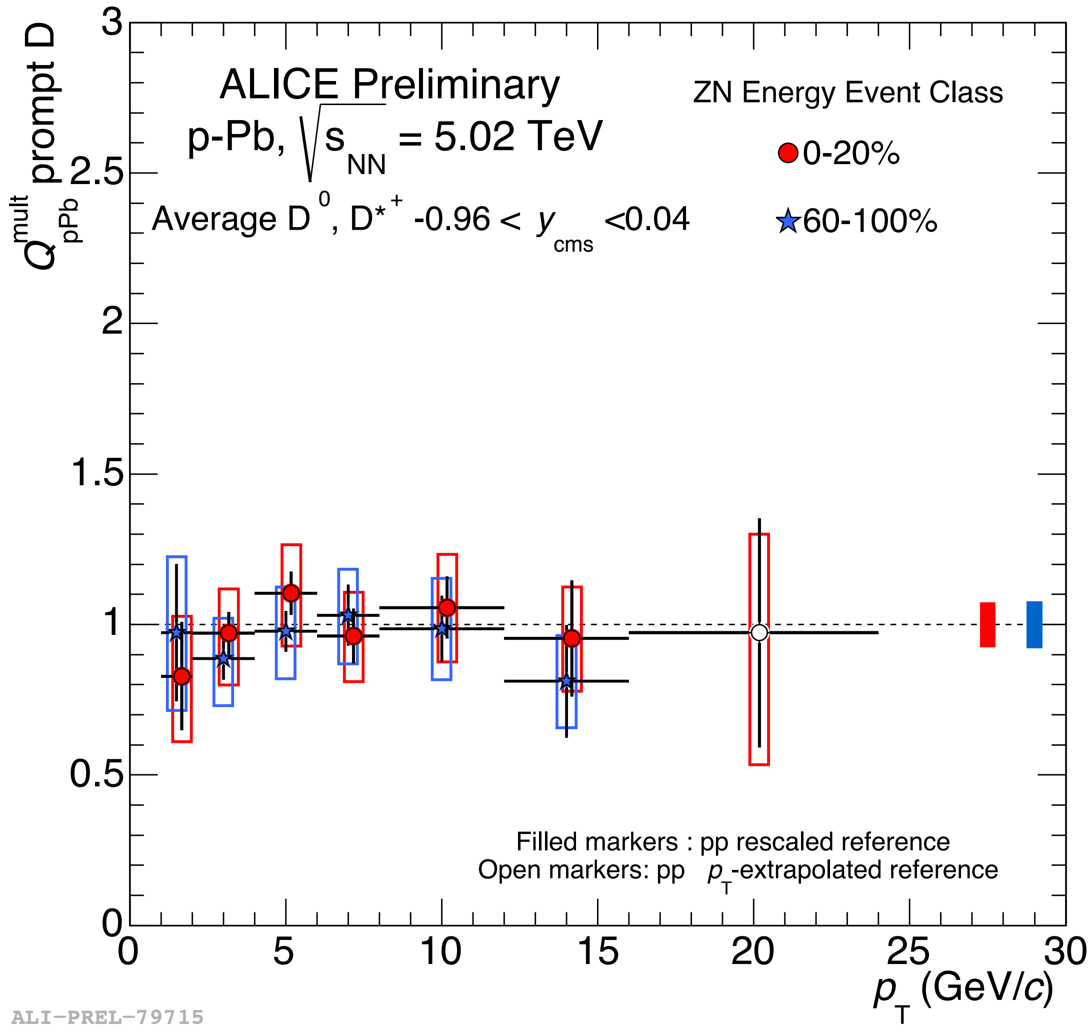
The double ridge also observed in heavy-flavour sector!

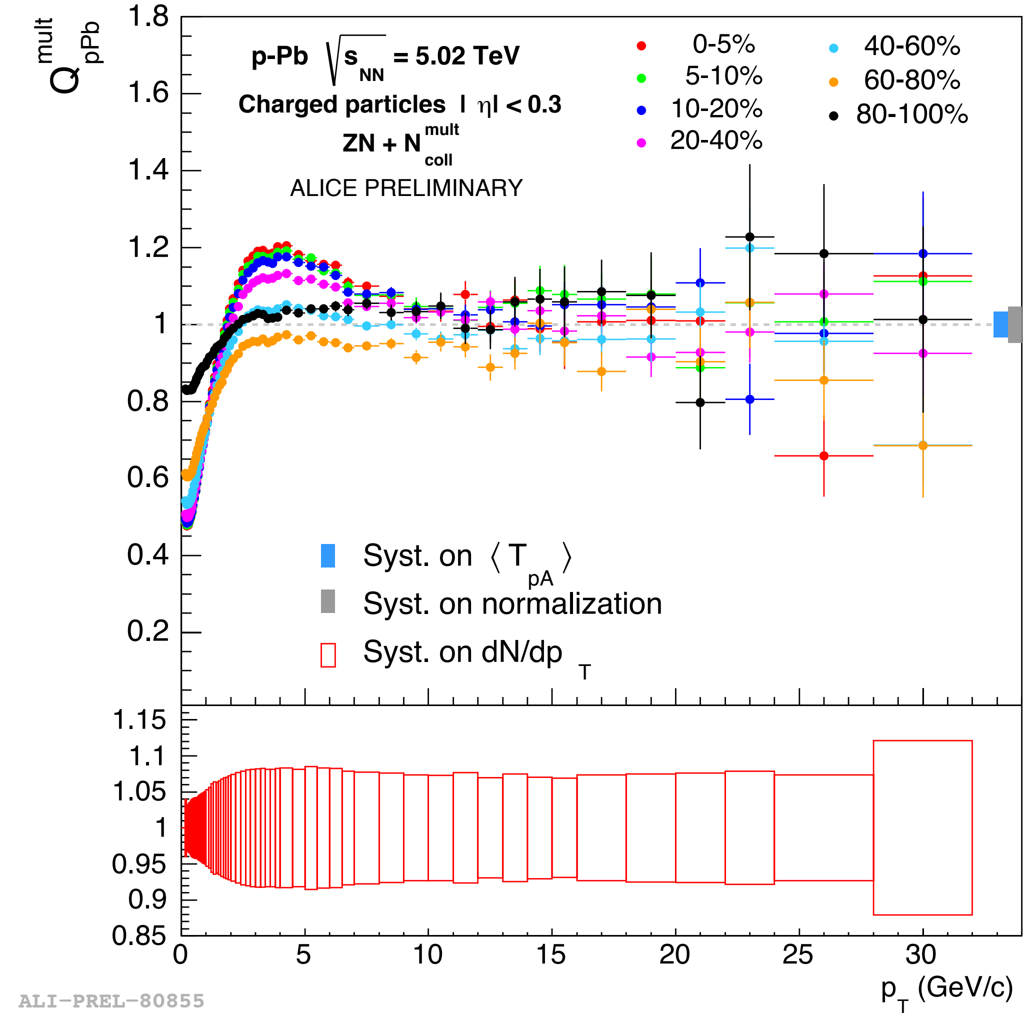
The mechanism (CGC? Hydro?) that generates it affects also HF

More differential information:
Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$Q_{\mathrm{pPb}}^{\mathrm{V0A}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{mult}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}^{\mathrm{Glauber}}\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$





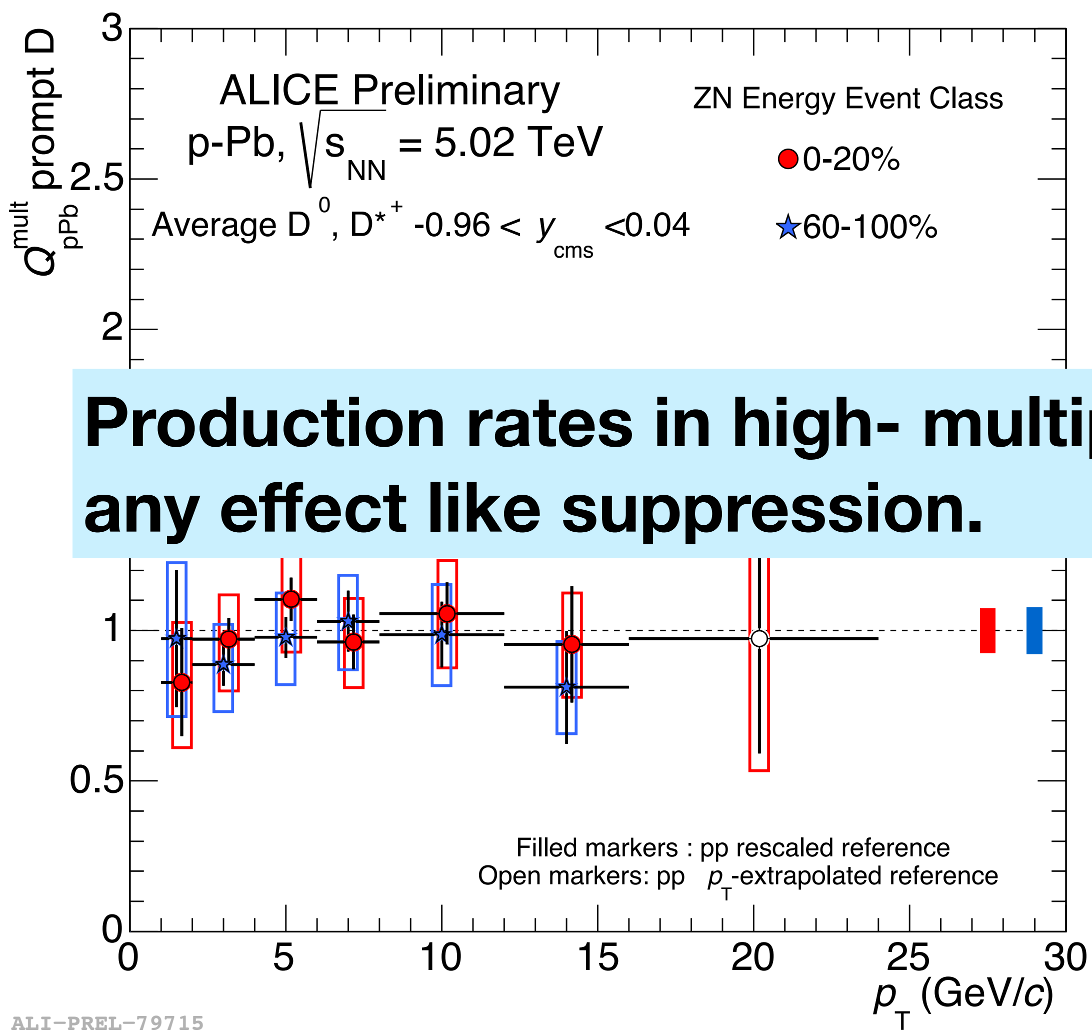
No multiplicity dependent modification of the p_T spectra in p-Pb

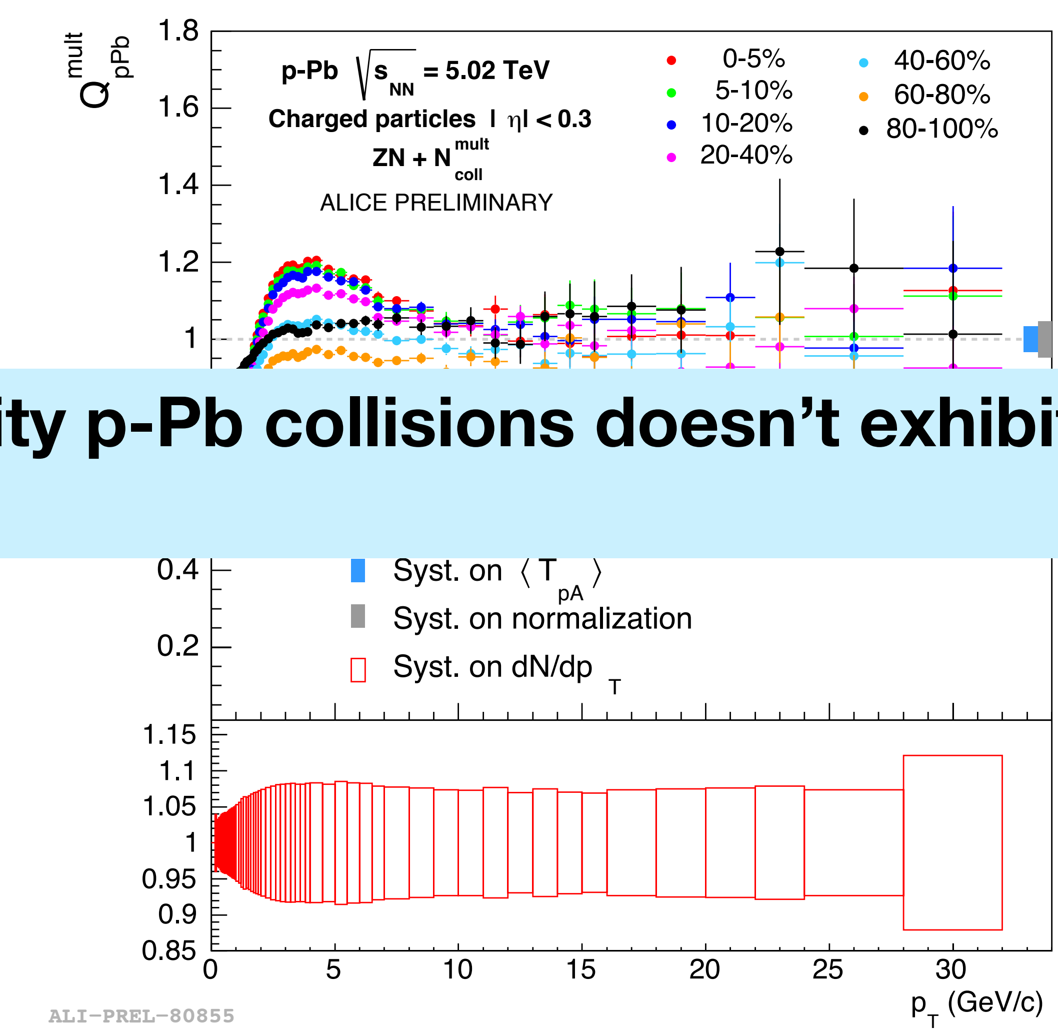
Similar pattern for D mesons and high-p_T charged particles

More differential information:
Multiplicity dependence of modification

Investigate the scaling of charm production in p-Pb collisions w.r.t. pp collisions

$$\boxed{Q^{\mathrm{V0A}}_{\mathrm{pPb}}(p_{\mathrm{T}})} = \frac{\mathrm{d}N^{\mathrm{pPb}}_{\mathrm{mult}}/\mathrm{d}p_{\mathrm{T}}}{N^{\mathrm{Glauber}}_{\mathrm{coll}}\,\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



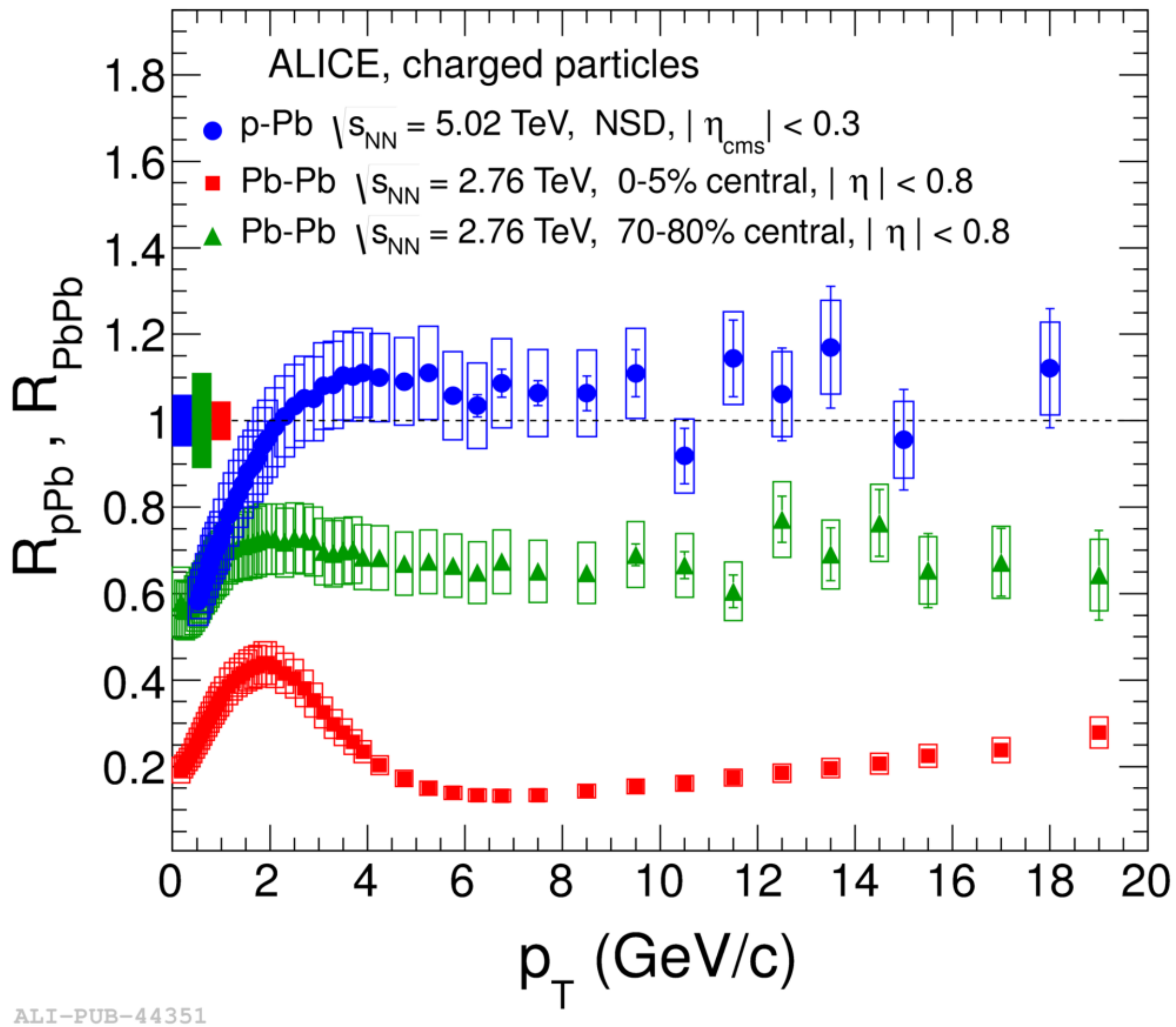


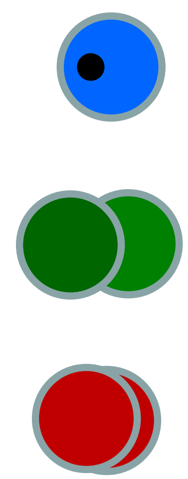
Production rates in high- multiplicity p-Pb collisions doesn't exhibit any effect like suppression.

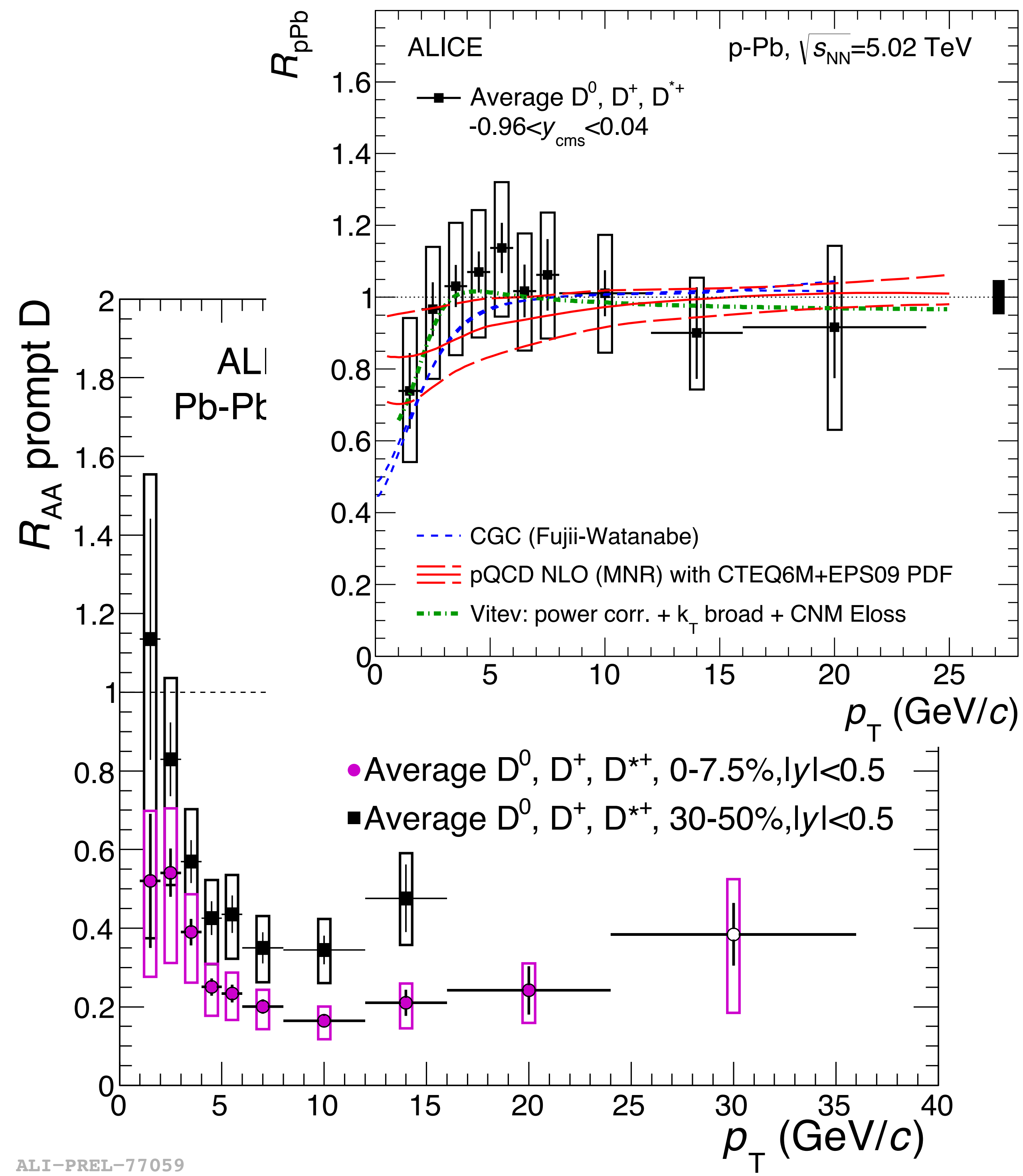
No multiplicity dependent modification of the p_{T} spectra in p-Pb
Similar pattern for D mesons and high-p_{T} charged particles

R_{AA} in p-Pb and Pb-Pb

📖 **ALICE, PRL 110 (2013) 082302**





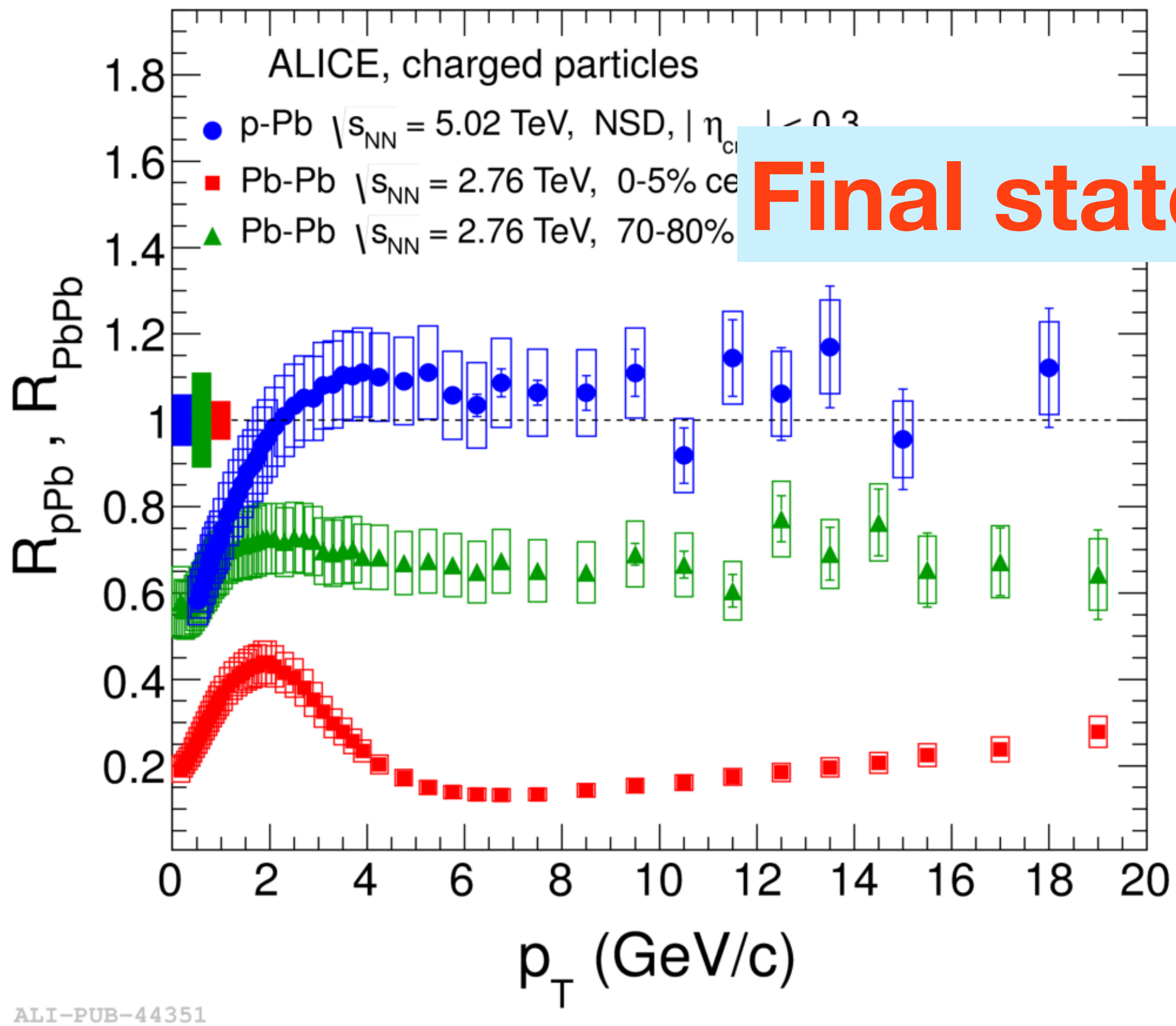


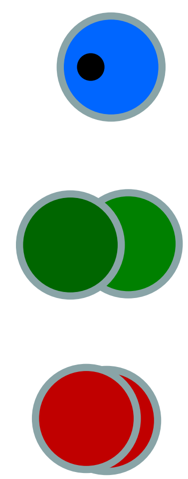
p-Pb results indicate that the suppression observed in Pb-Pb comes from a final state effect

Significant suppression at high p_T for D mesons at mid rapidity

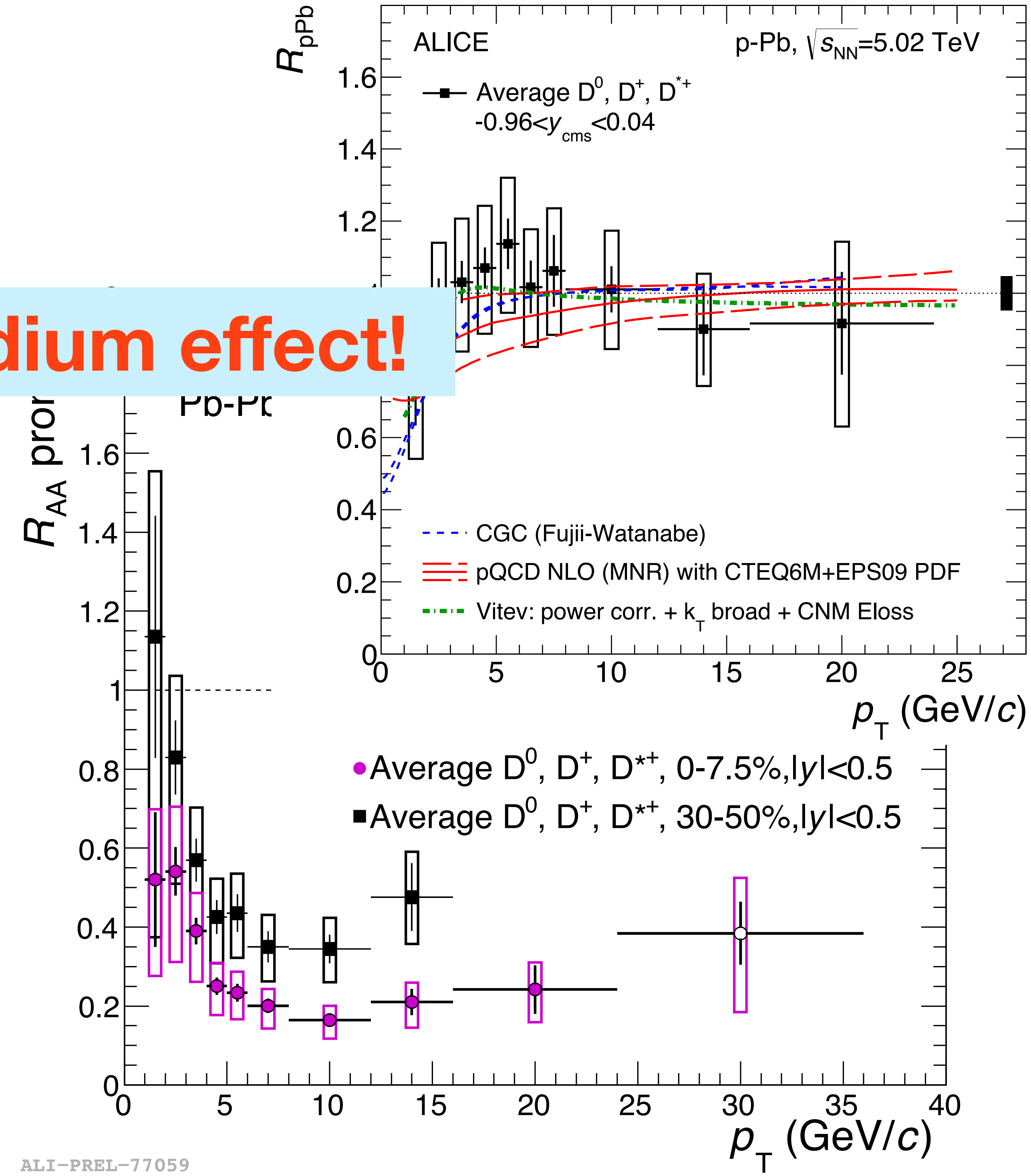
R_{AA} in p-Pb and Pb-Pb

ALICE, PRL 110 (2013) 082302





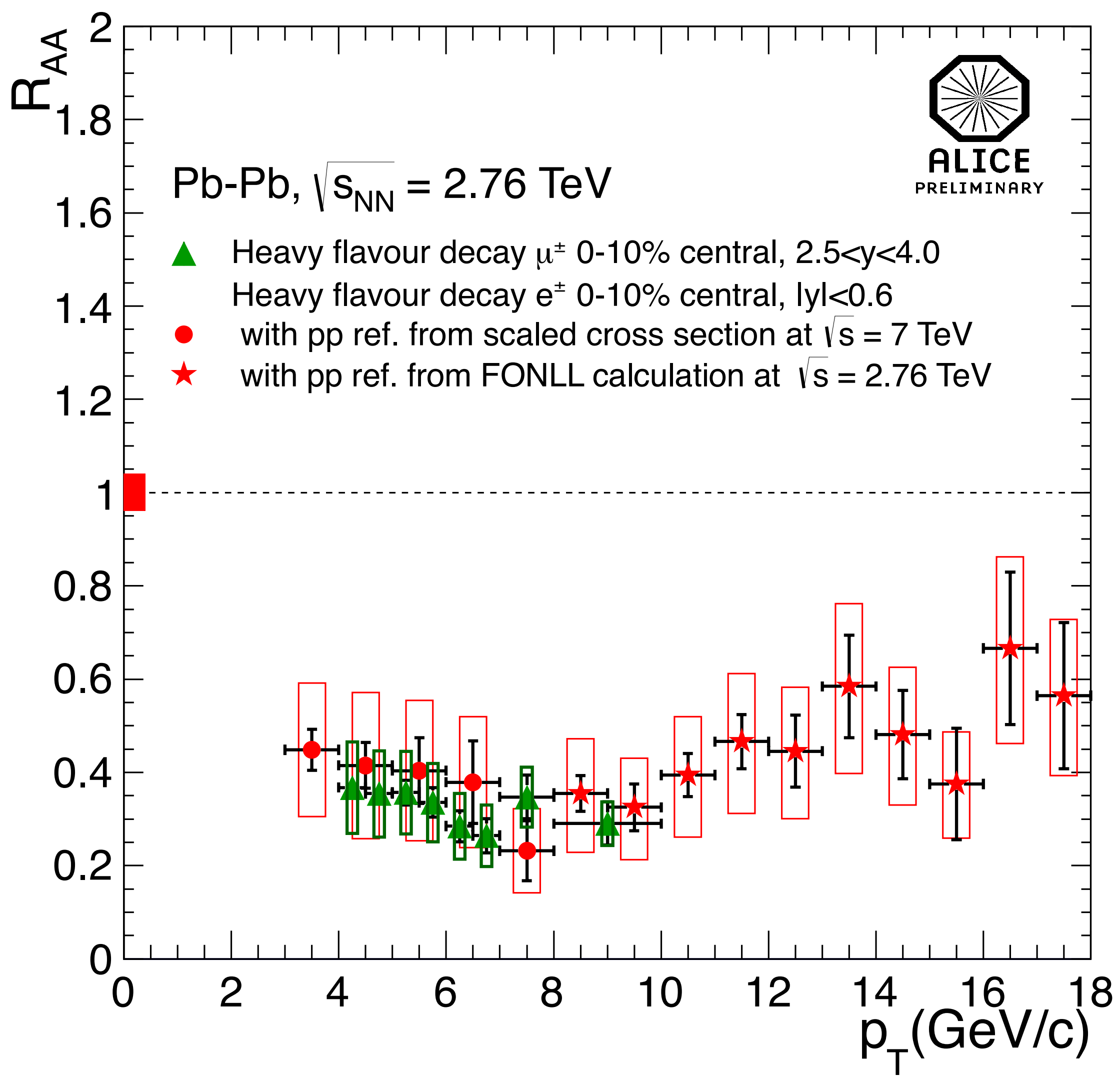
Final state medium effect!



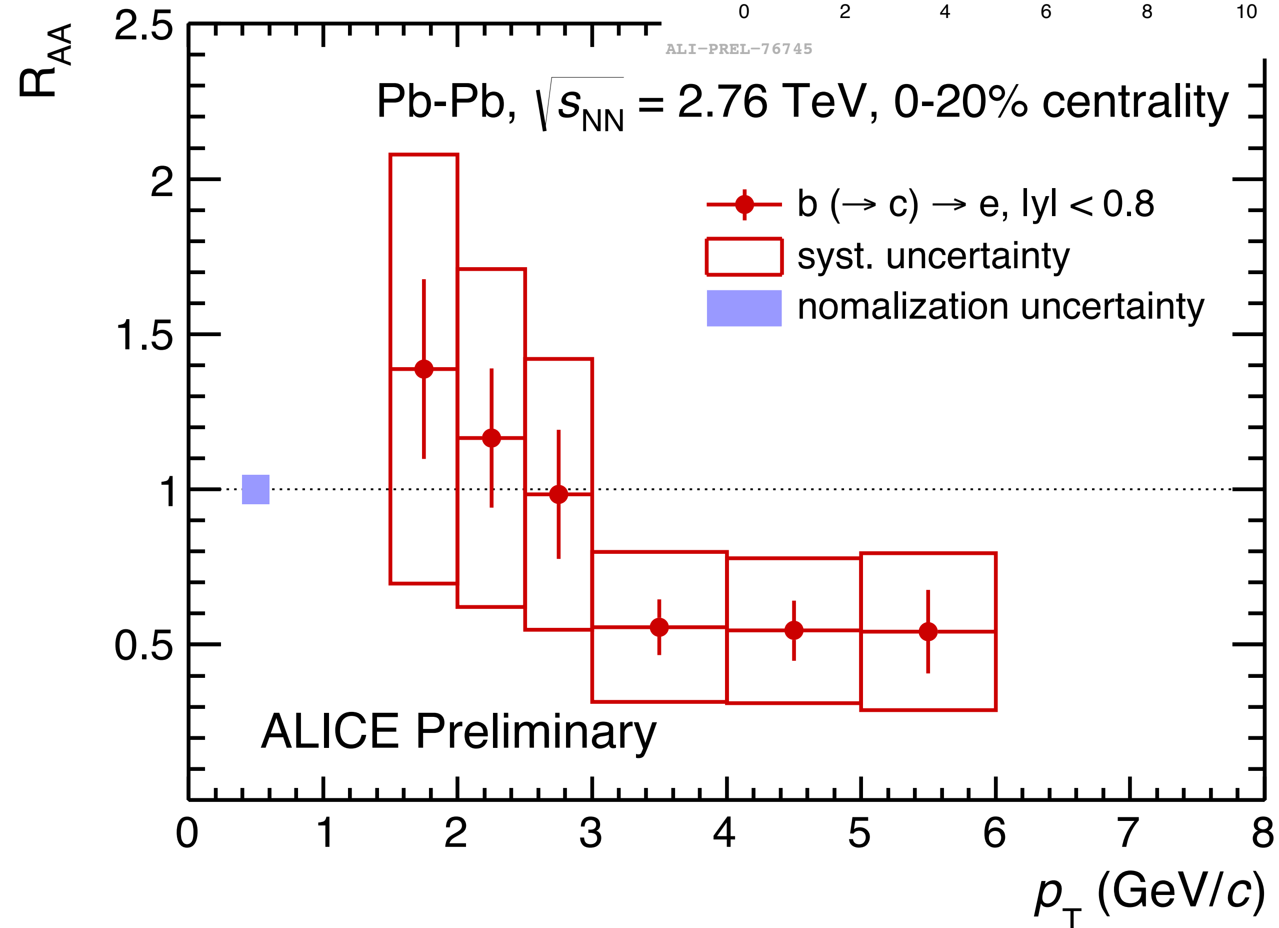
p-Pb results indicate that the suppression observed in Pb-Pb comes from a final state effect

Significant suppression at high p_T for D mesons at mid rapidity

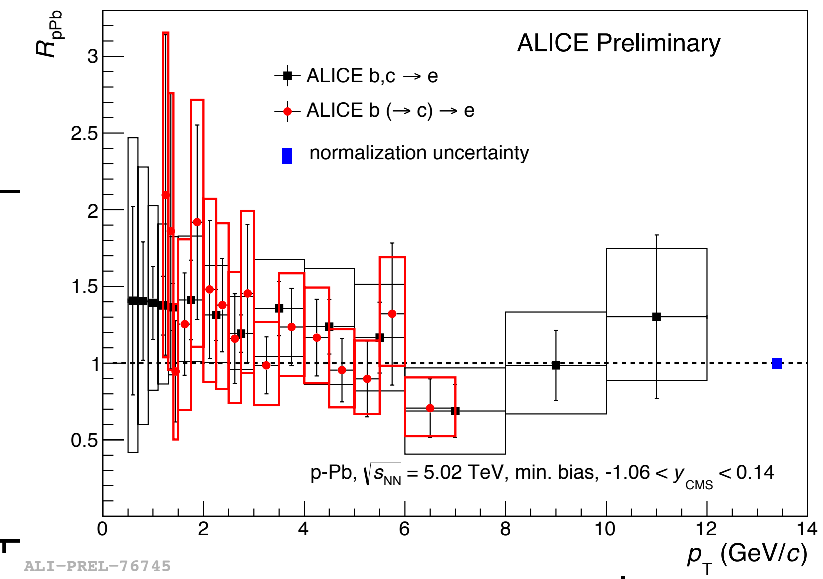
HF-decay lepton R_{AA}



ALI-DER-36791



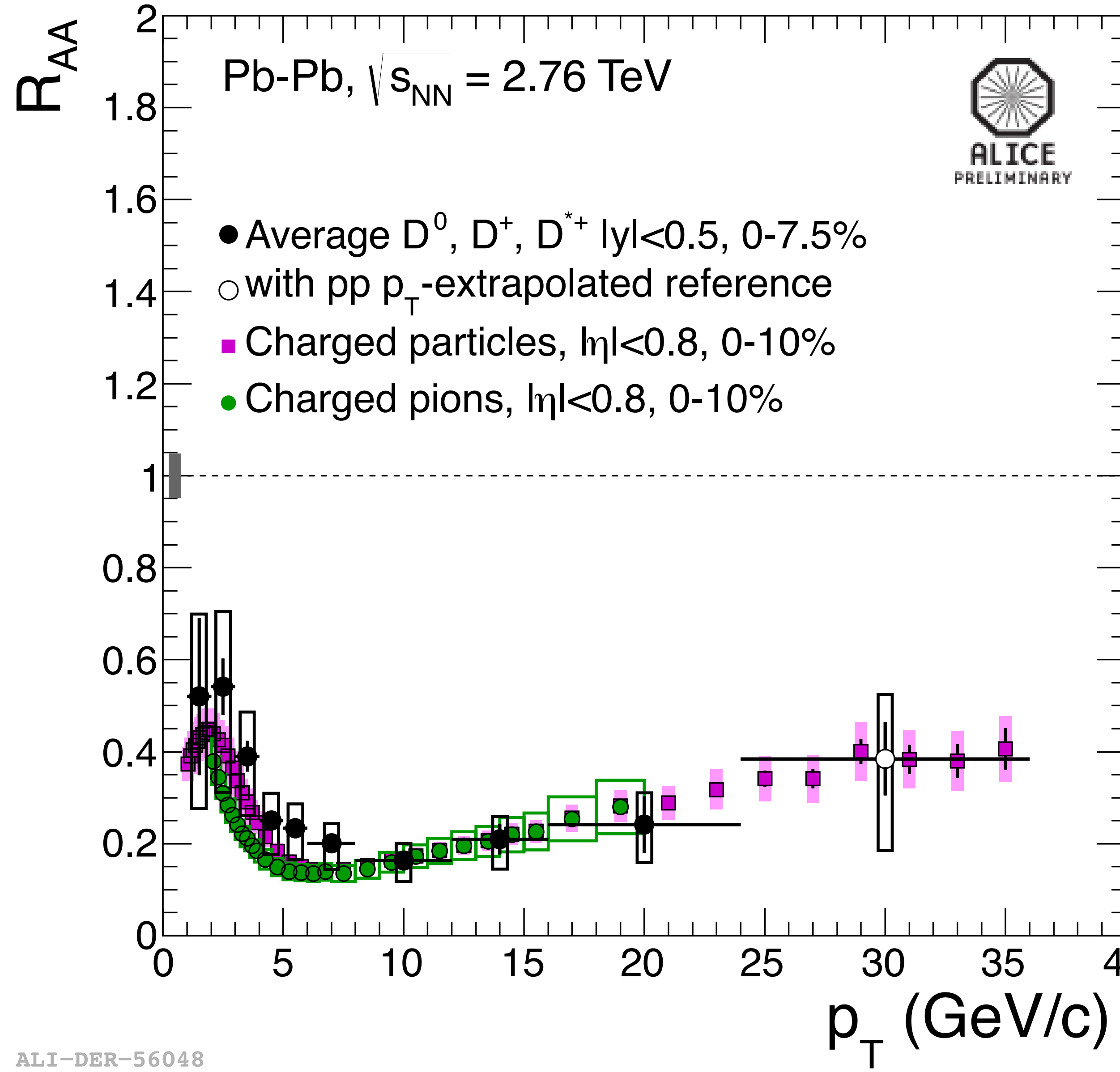
ALI-PREL-74678



ALI-PREL-76745

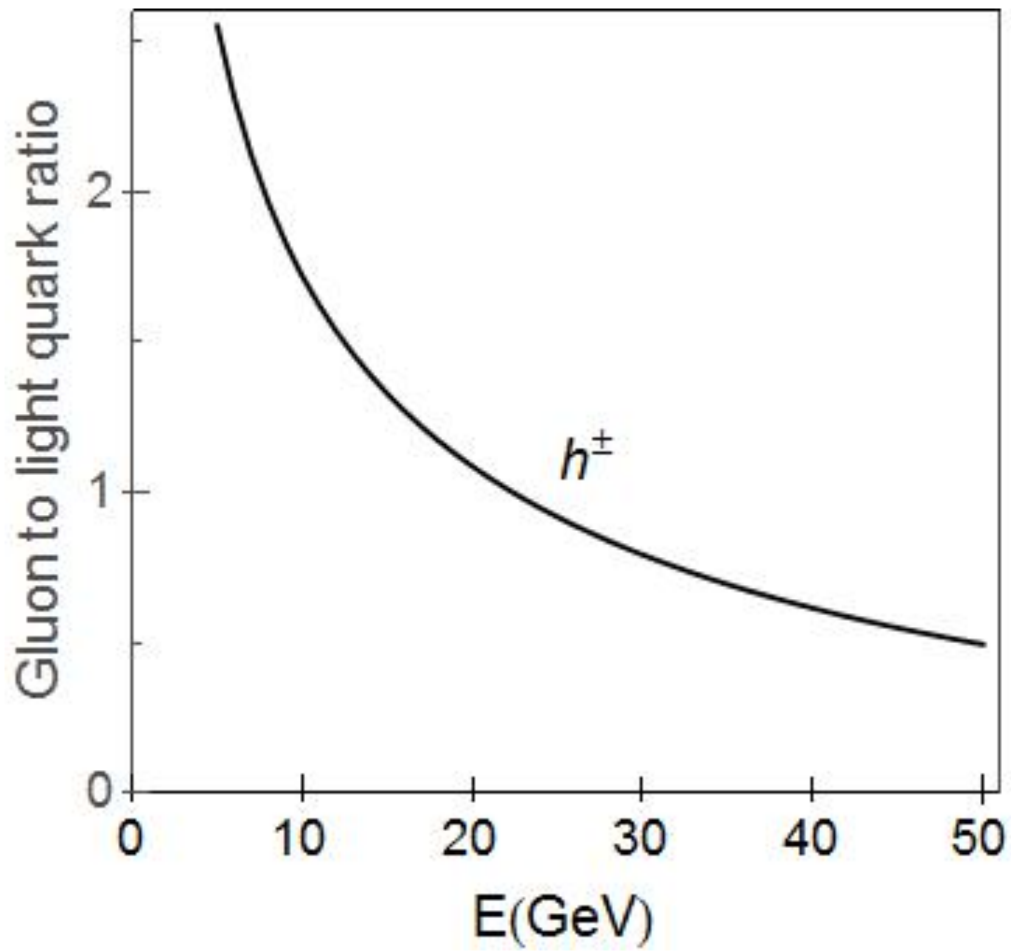
- Significant suppression at high p_T
  - ◉ c,b→e (mid rapidity) & c,b→μ (forward rapidity)
  - ◉ b→e (mid rapidity) **hint of suppression**

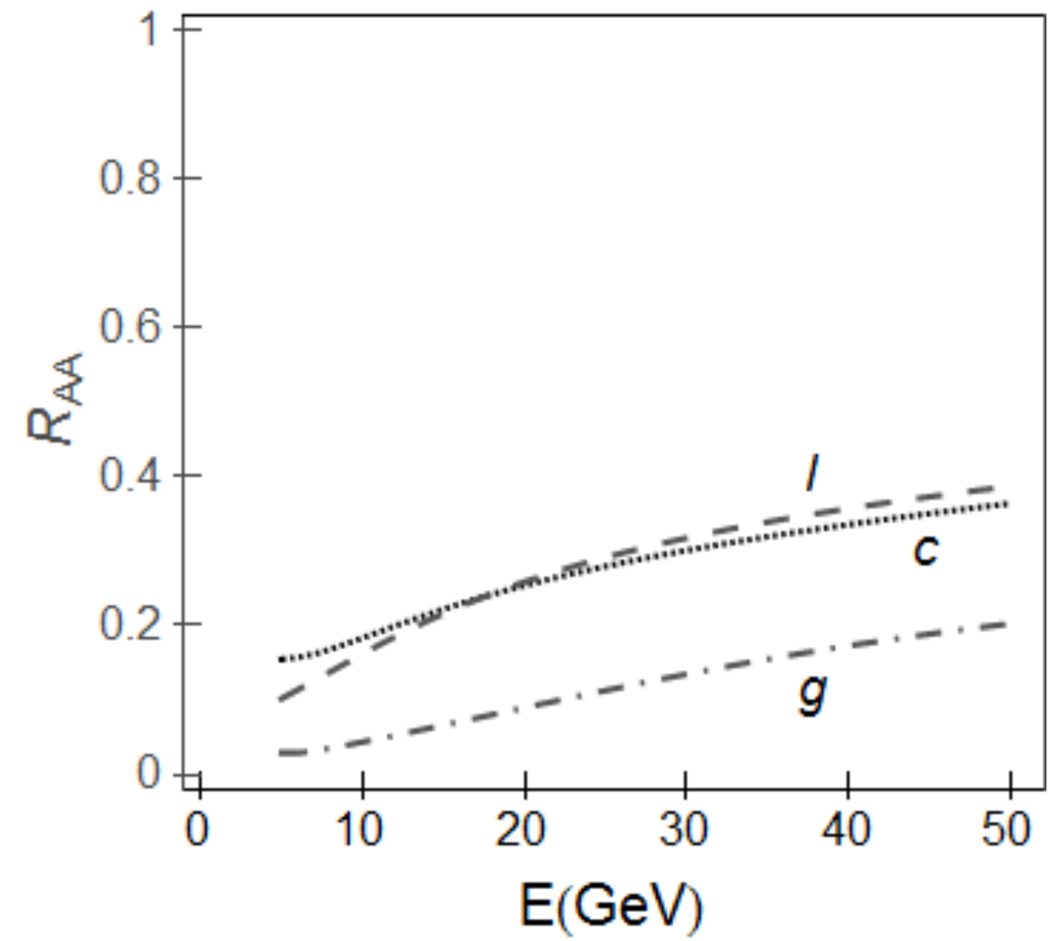
Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



- Comparable results for π and D mesons suppressions within uncertainties
- Is it consistent with the colour charge dependence picture?

Heavy flavour puzzle at LHC



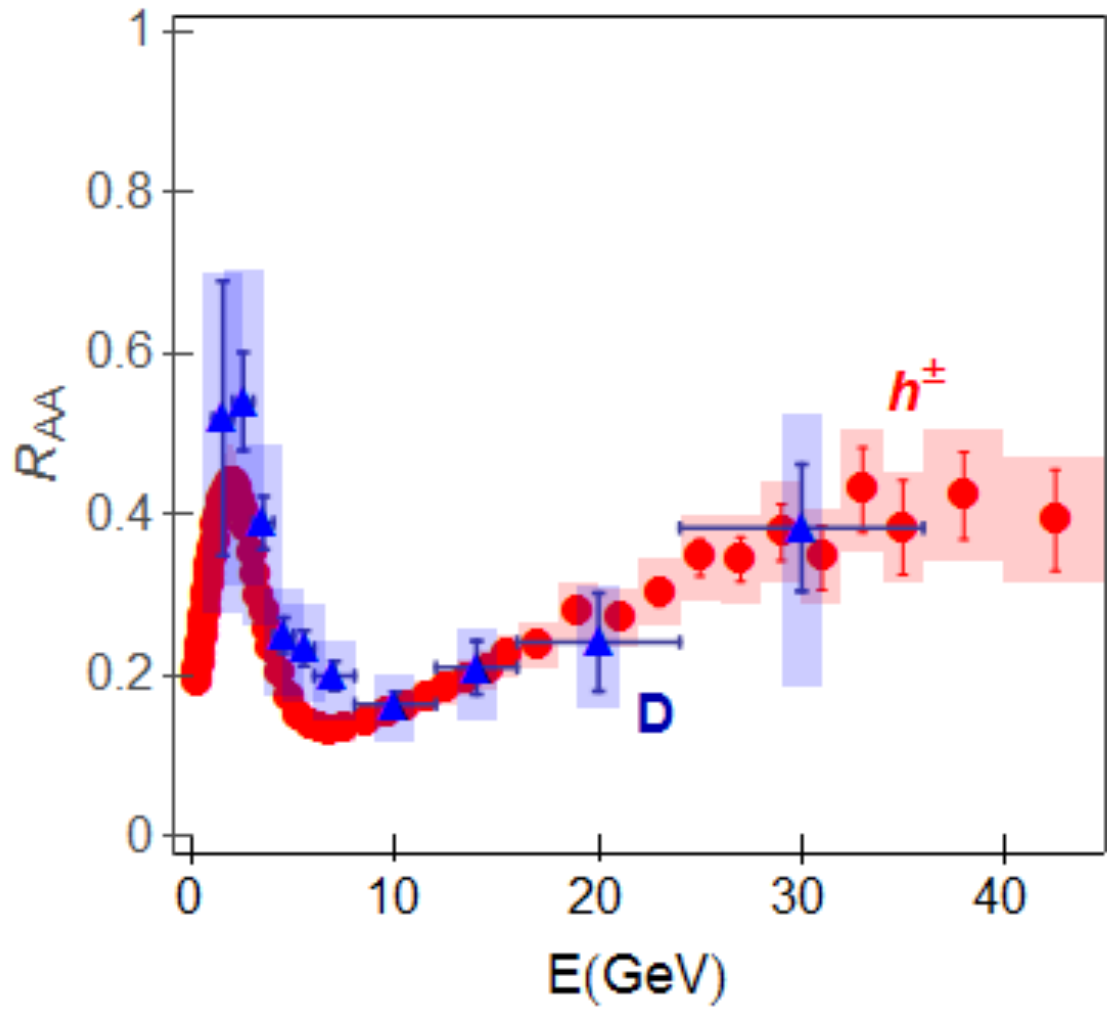


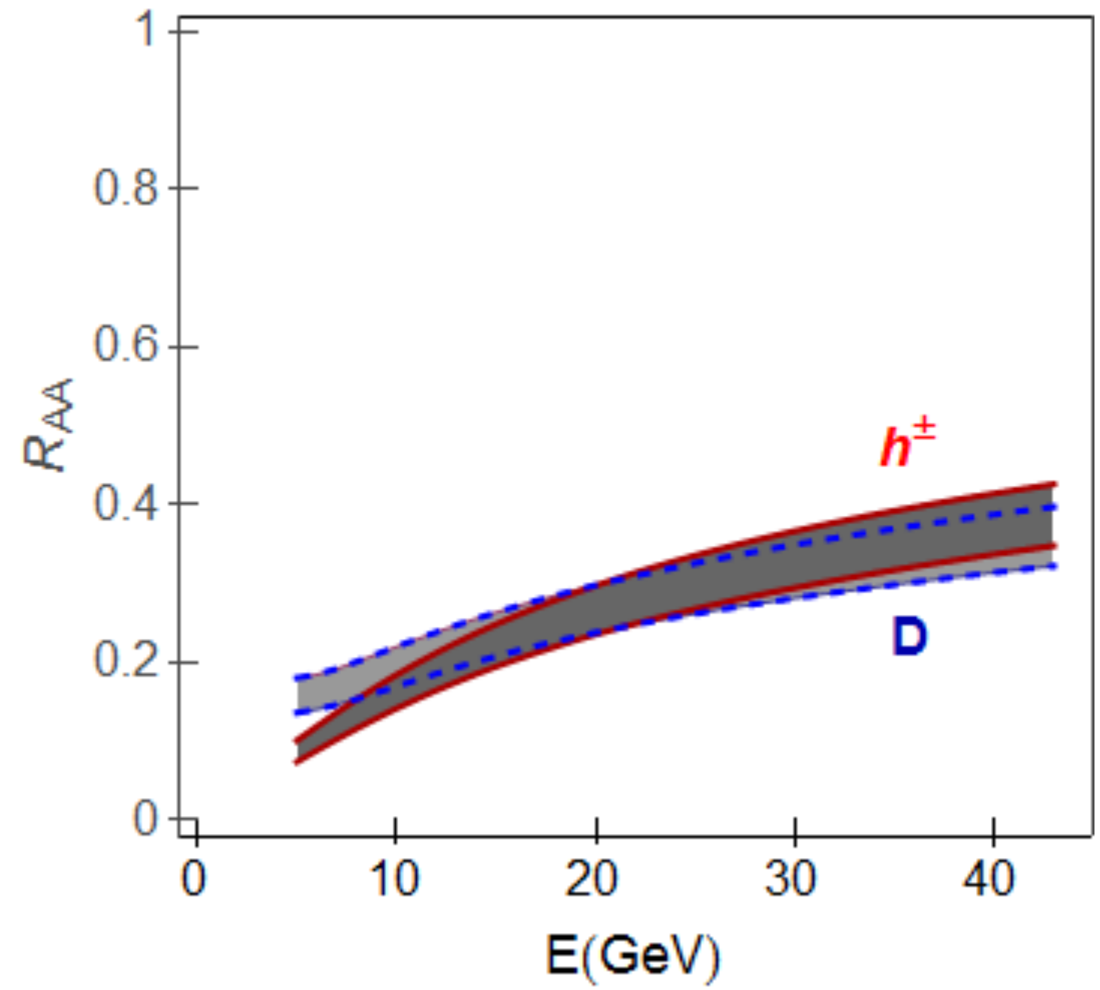
Significant gluon contribution in charged hadrons

Much larger gluon suppression

$$R_{AA}\,(h^{\pm}) < R_{AA}\,(D)$$

Charged hadrons vs D meson R_{AA}



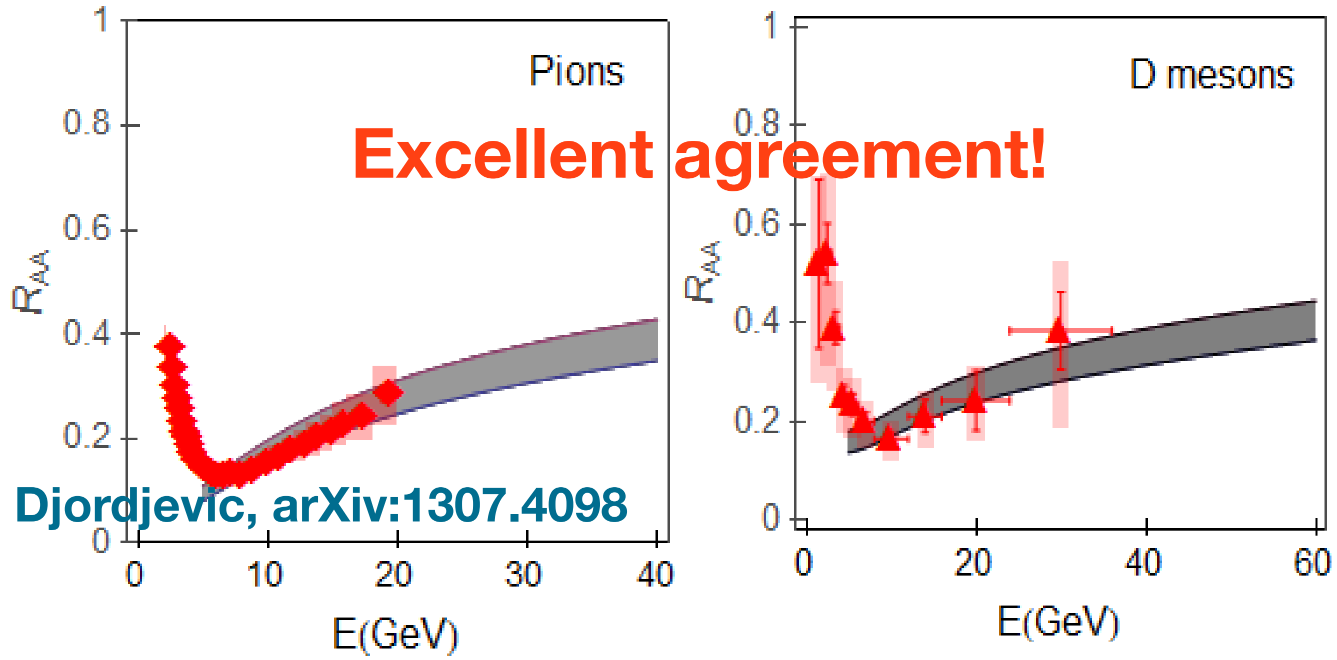


R_{AA} ($h^{\pm}$) = R_{AA} (D)

Excellent agreement with the data!

Disagreement with the qualitative expectations!

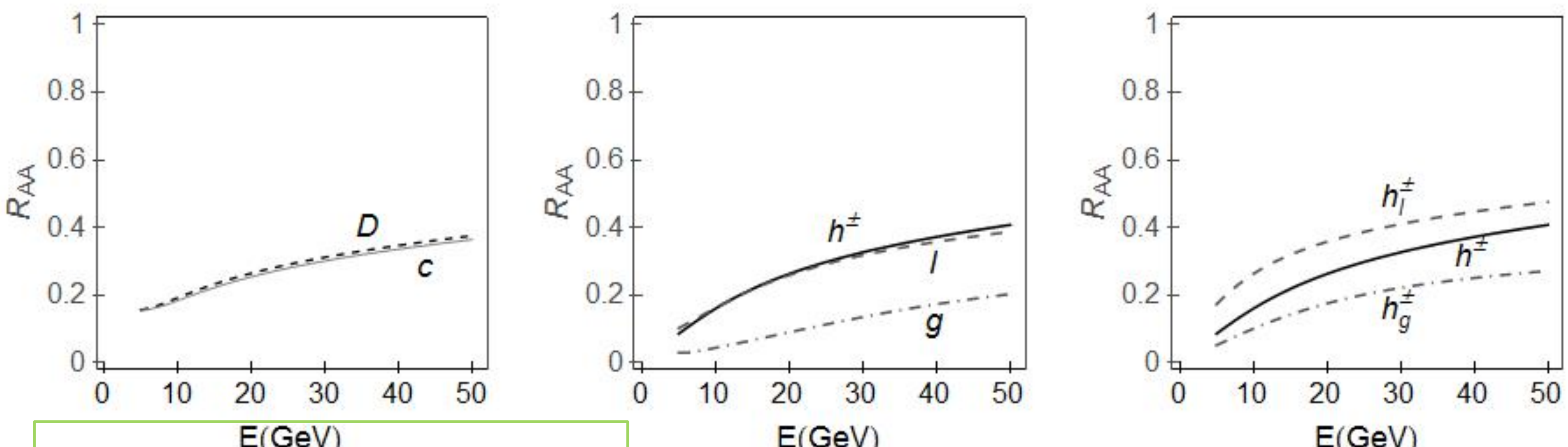
Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



Excellent agreement!

Djordjevic, arXiv:1307.4098

Calculation by M. Djordjevic (rad+coll energy loss) can describe both R_{AA}



Shows strong colour charge effect in partonic R_{AA} (g vs. light and c)

R_{AA} (D) = R_{AA} (charm)

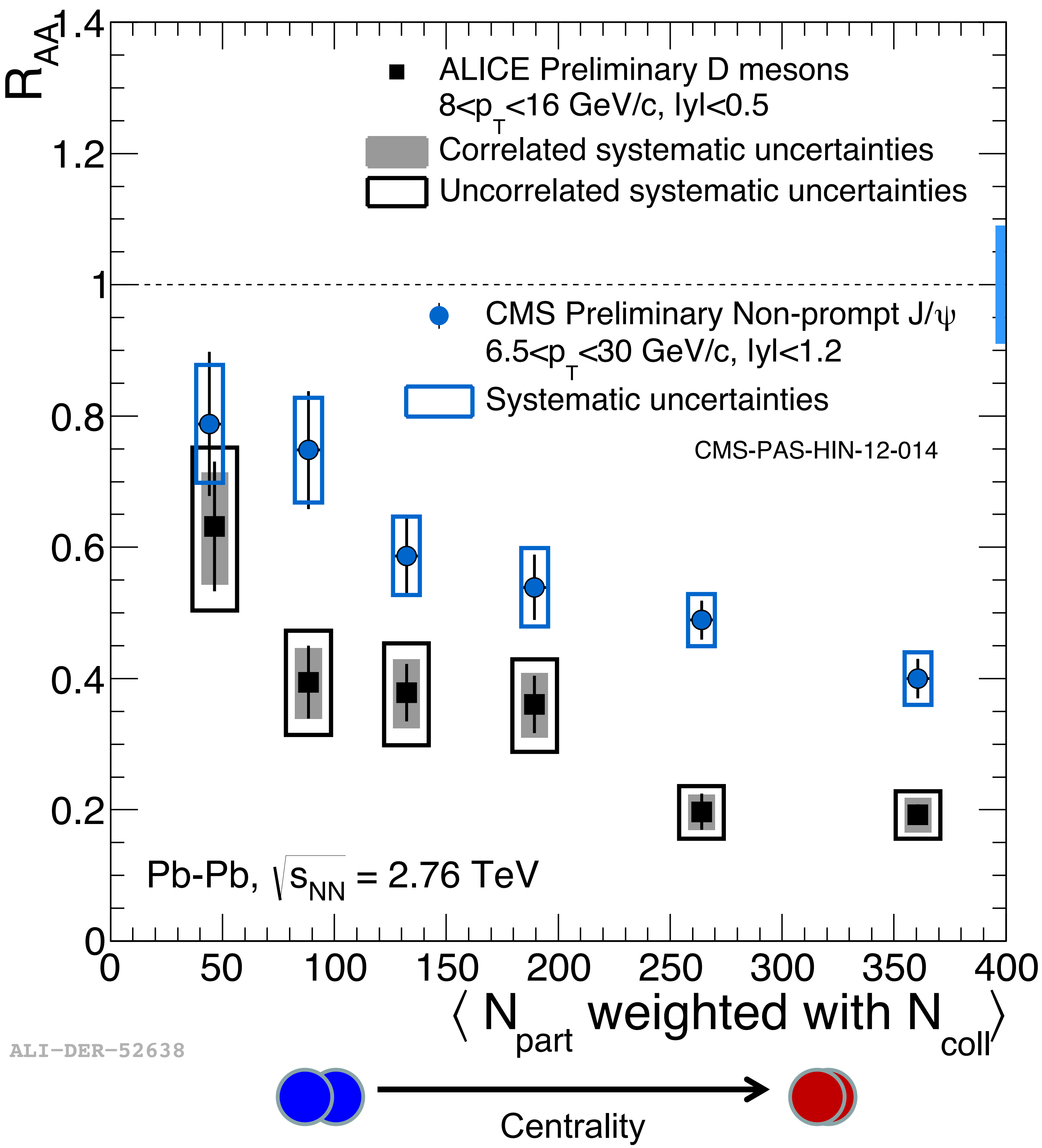
R_{AA} (light quarks) = R_{AA} (charm)

Distortion by fragmentation!

R_{AA} ($h^{\pm}$) = R_{AA} (D)

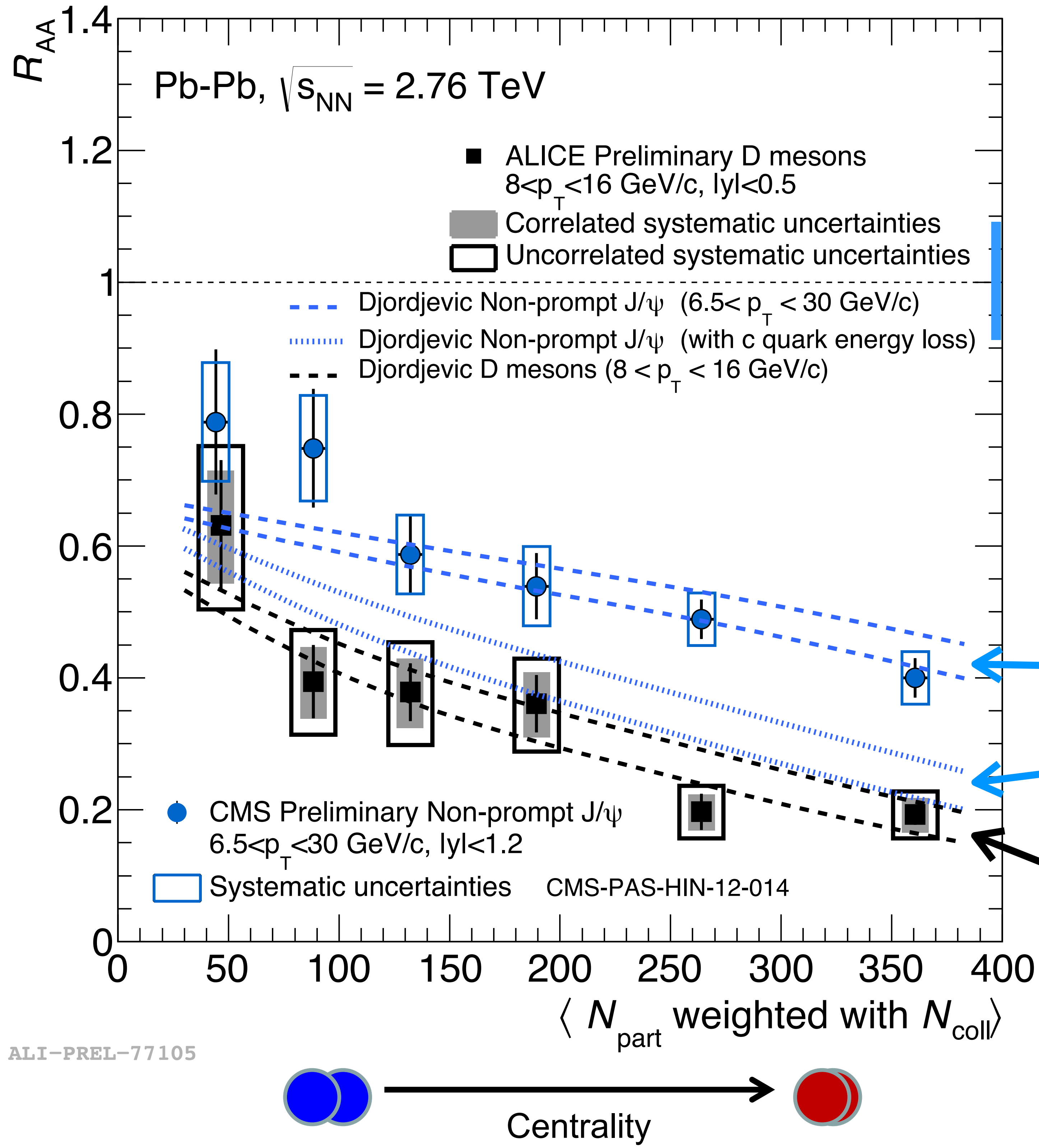
Colour charge effect plays!

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ



- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons $<p_T>$~10 GeV/c
- **Clear indication of a dependence on quark mass : $R_{AA}^B > R_{AA}^D$**

✓ Djordjevic: non-prompt J/ψ R_{AA} considering for energy loss
- b quark mass
- c quarkmass

No trivial relation between ΔE and R_{AA}

✓ Djordjevic: D meson R_{AA}

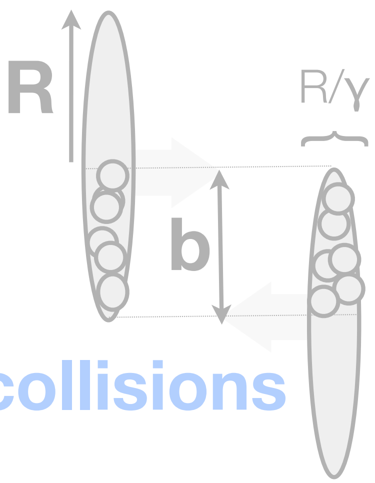
Calculation by M. Djordjevic (including mass-dependent rad+coll energy loss) predict a difference

Similar pattern from other calculations (e.g. BAMPS, WHDG, Vitev et al.).

Quantification of medium effects: R_{AA}, flow

- **Nuclear modification factor**: standard method to quantify the effects of the medium on the yield of a hard probe in a AA reaction

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$



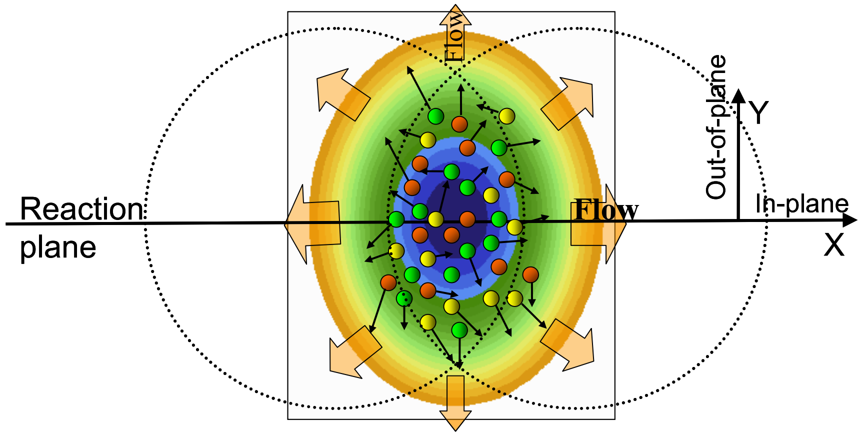
N_{part}, N_{coll},
participants
binary collisions
Binary scaling based on the Glauber Model

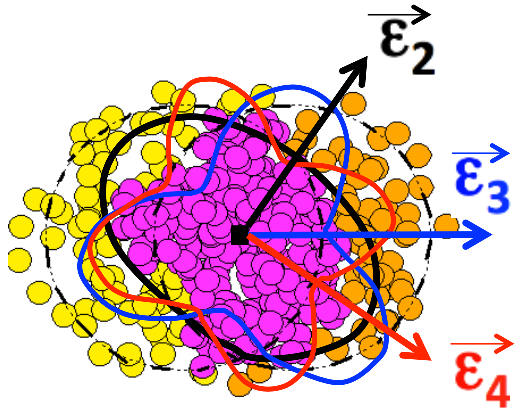
R_{AA}=1: AA collision ~ incoherent superposition of NN collisions

- **Geometry and harmonic flow**

Initial spatial anisotropy —(**via re-scatterings in the medium**)→ momentum anisotropy of particle emission

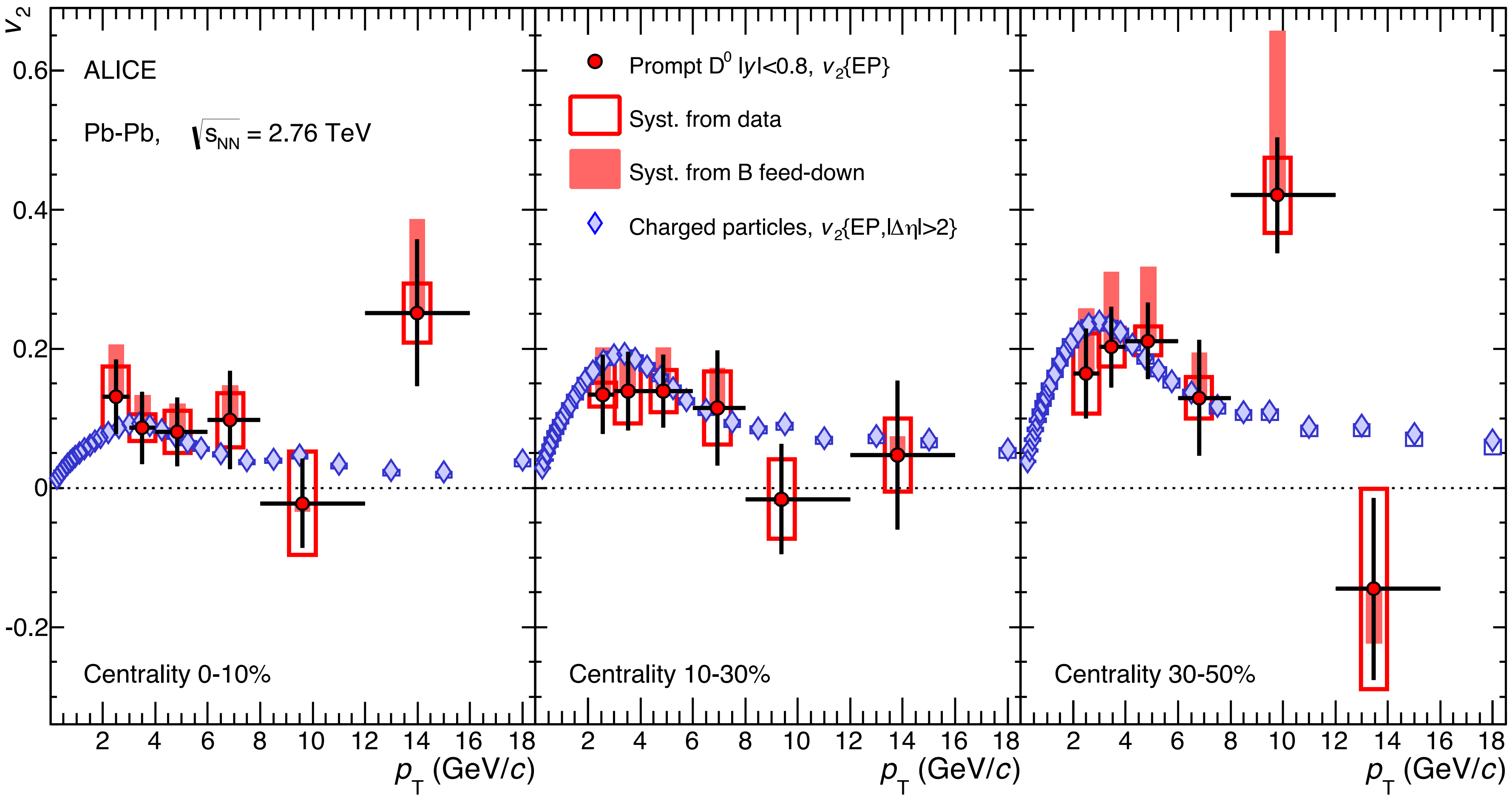
: via a Fourier expansion in azimuthal angle (φ) with respect to the reaction plane (Ψ_{RP})

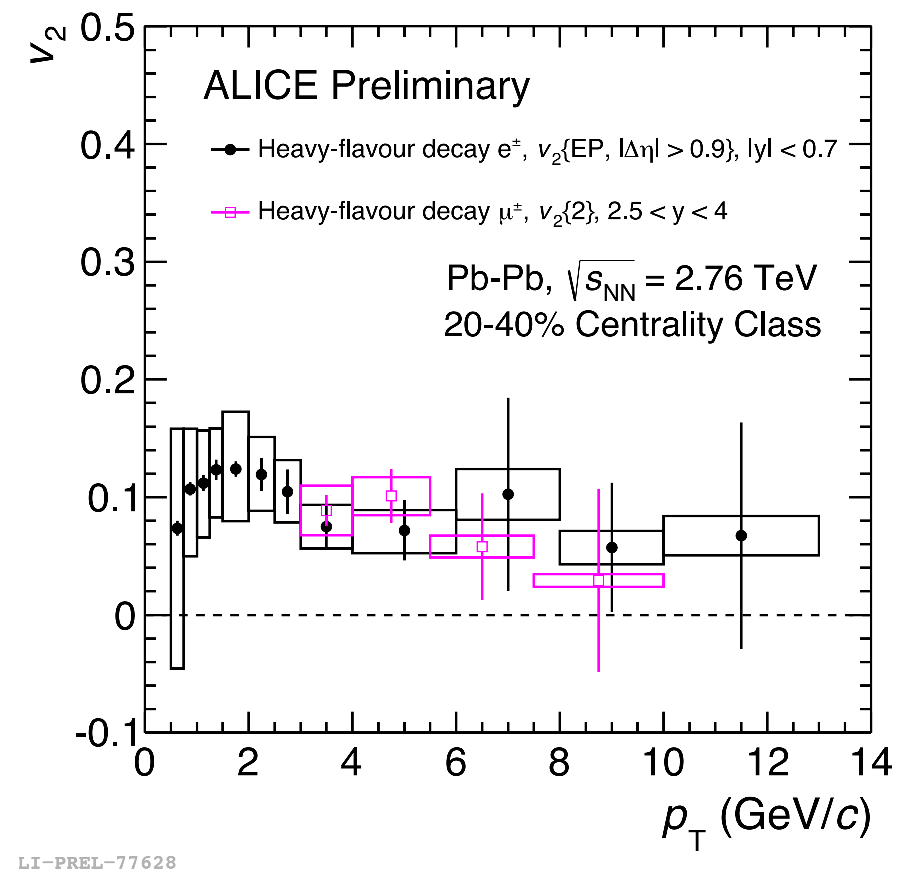




$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_{RP}) + \boxed{2v_2\cos[2(\varphi - \Psi_{RP})]} + \ldots)$$

Heavy flavour v_2





- Charm does flow!
- Confirm significant interaction of charm quarks with the medium
- Suggest **collective motion of low-p_T charm quarks in the expanding fireball**

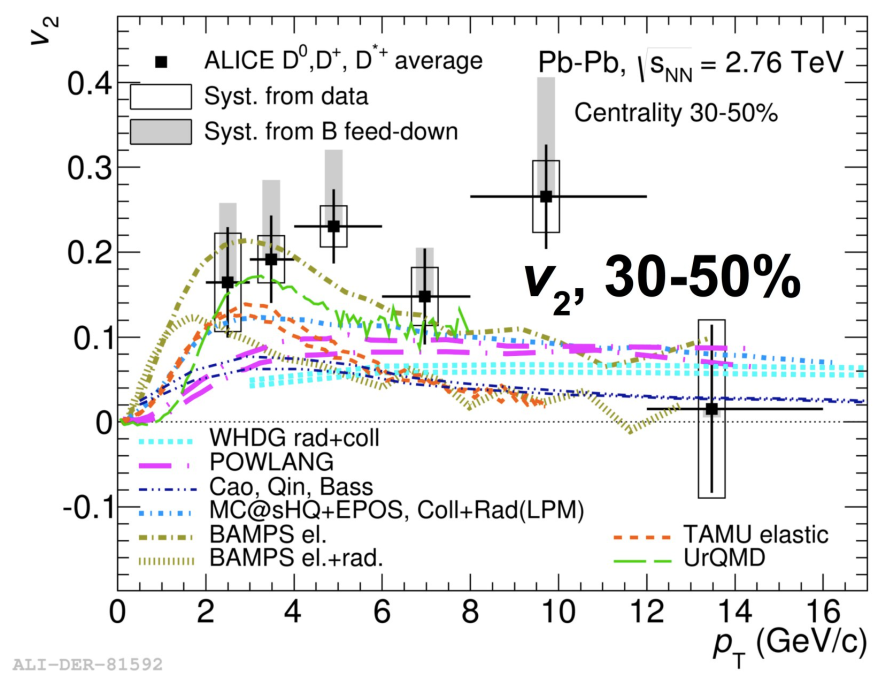
Observables constraining models

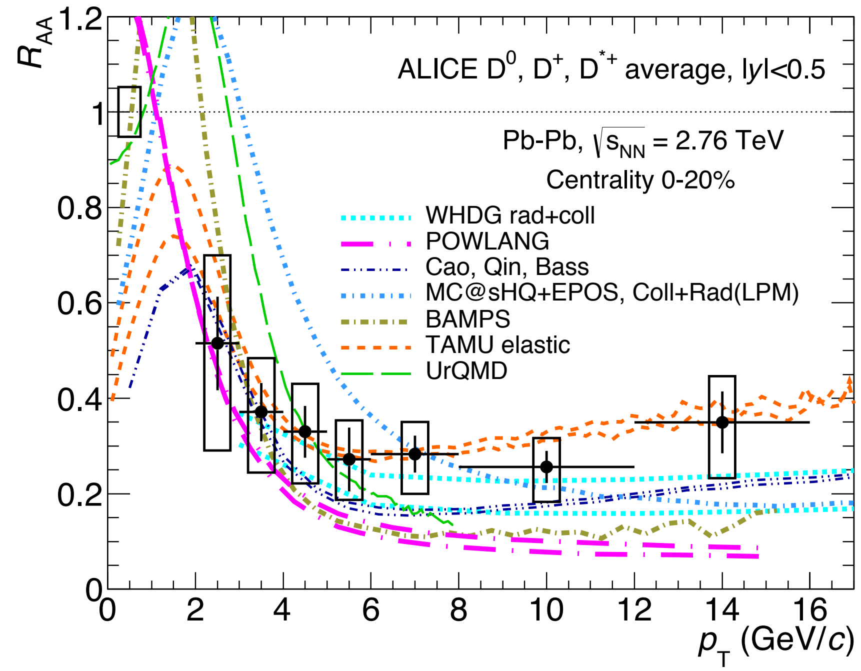
	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss (w/ & w/o radiative)	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation

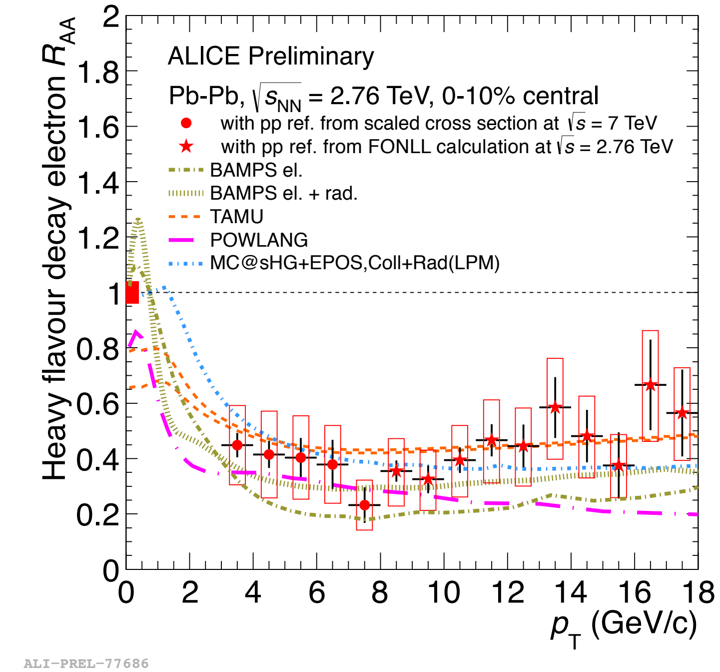
Summarized by Davide Caffarri

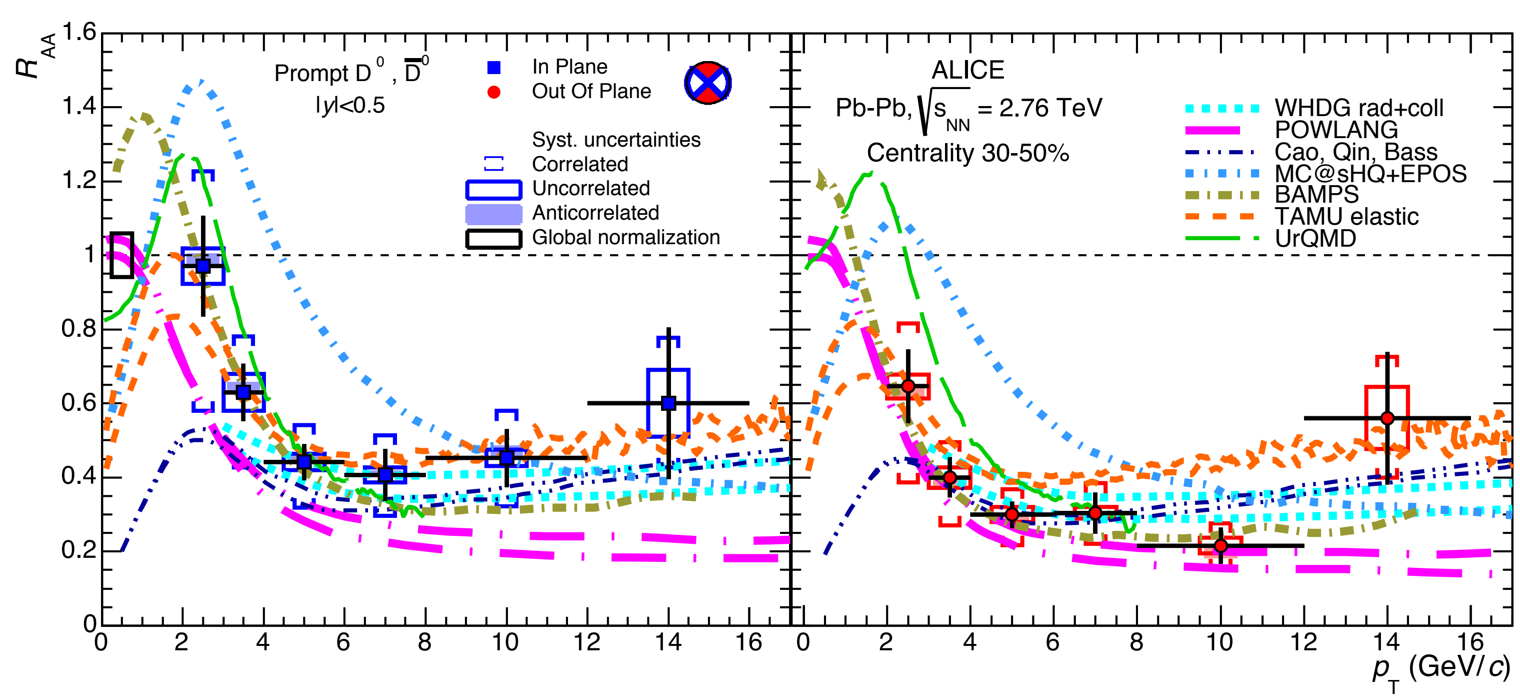
- TAMU elastic: arXiv:1401.3817
- Djordjevic: arXiv:1307.4098
- Cao, Qin, Bass: PRC 88 (2013) 044907
- WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
- MC@sHQ+EPOS: PRC 89 (2014) 014905
- Vitev, rad+dissoc: PRC 80 (2009) 054902
- POWLANG: JPG 38 (2011) 124144
- BAMPS: PLB 717 (2012) 430

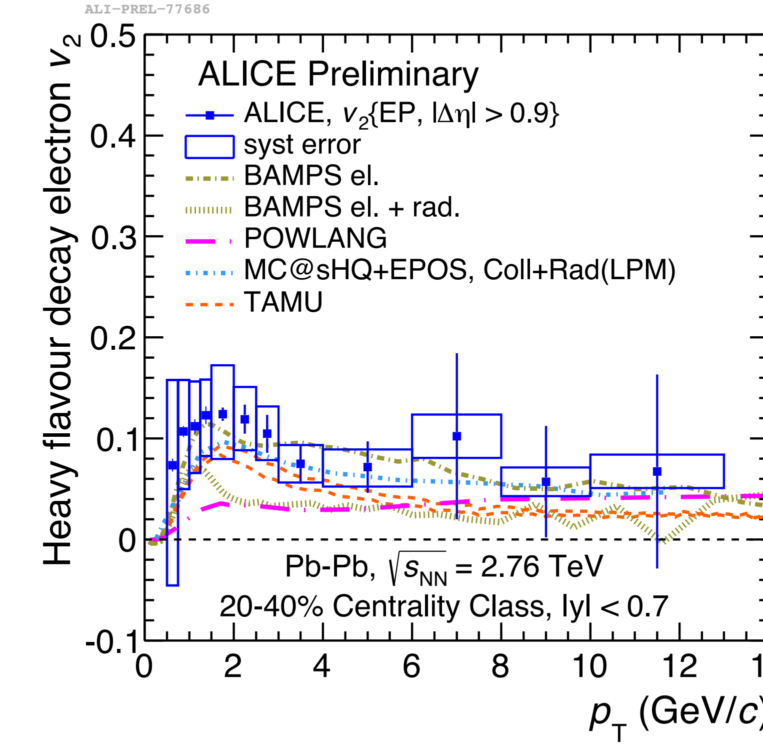
Observables constraining models











- TAMU elastic: arXiv:1401.3817
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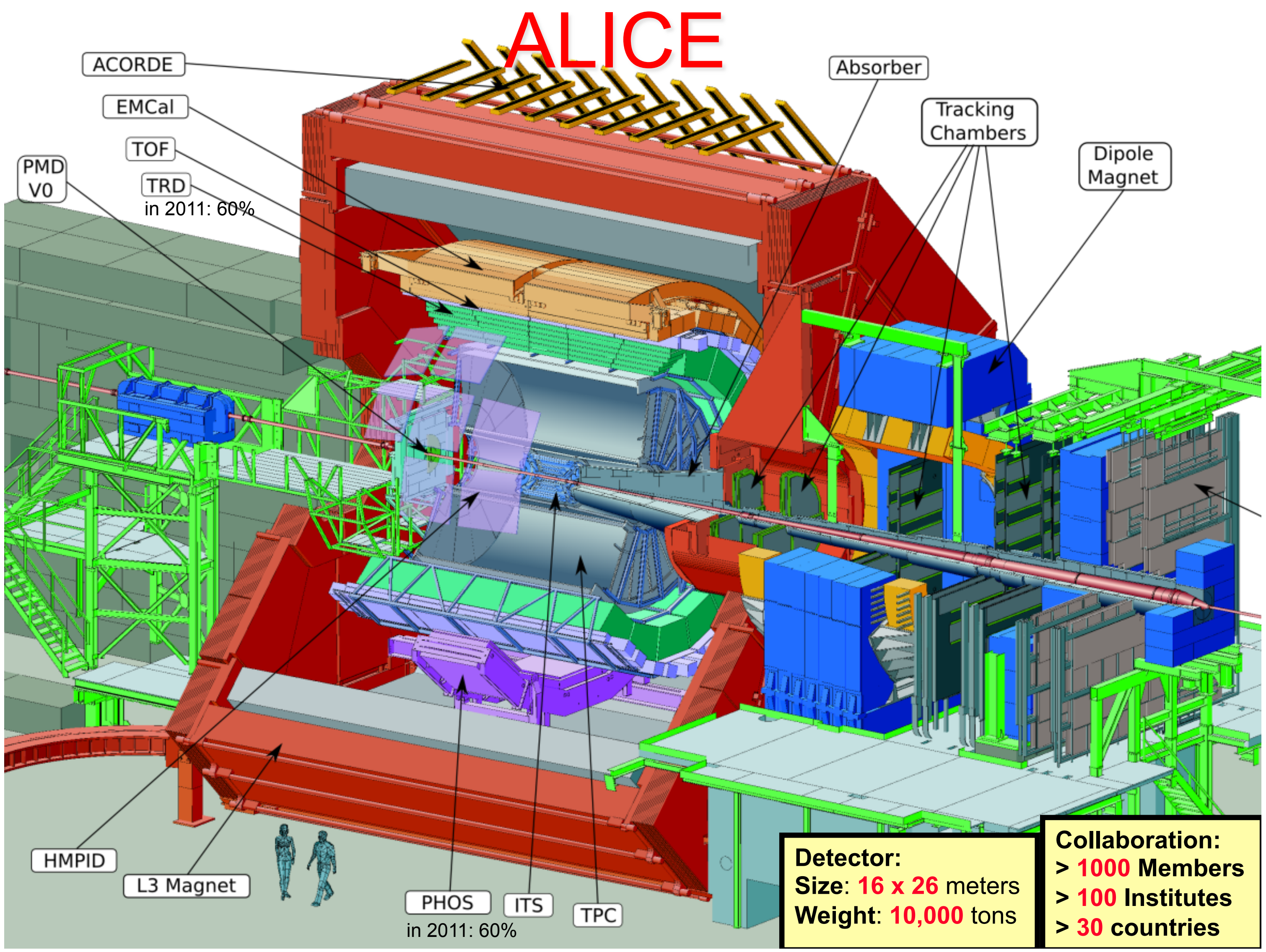
- POWLANG: JPG 38 (2011) 124144
- BAMPS: PLB 717 (2012) 430

Various observables provide constraints for the models

KoALICE Organization & Status (2014-09)



Total 34 researchers are participating from Korea!

Inha Univerisity:	**Prof.1 (1) + MA Stud.3 = 4 (5)**
KW National University:	**(Prof.1 +) PhD.2 + PhD Stud.1 (+ MA Stud.1) = 5 (3)**
Pusan National University:	**Prof.2 (1) + PhD.1 + PhD Stud.2 + MA Stud.1(1) + Sec.1 = 9**
Sejong University:	**Prof.2 = 2**
Yonsei University:	**Prof.2 + PhD Stud.5 + MA Stud.5 = 12**

koALICE activity for ALICE data analysis

Outputs in 2013.05 - 2014.04

- Papers: 25 (Principal 3)
- ALICE analysis notes: 3
- Presentations including PHYSICS working group meeting: 41
- Thesis: 1 MA, 1 PhD
- Regular KoALICE Meetings: every month
- Regular informal weekly coffee-clock meetings on Thursday, 4 PM, restaurant 2.

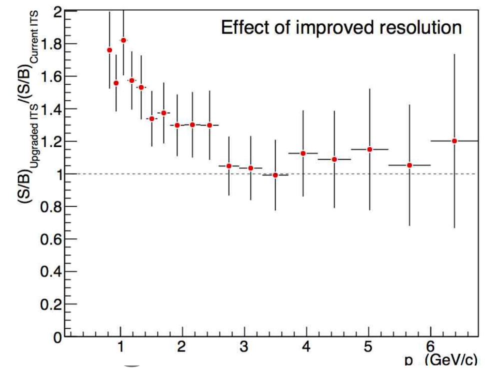
21 researchers long stay

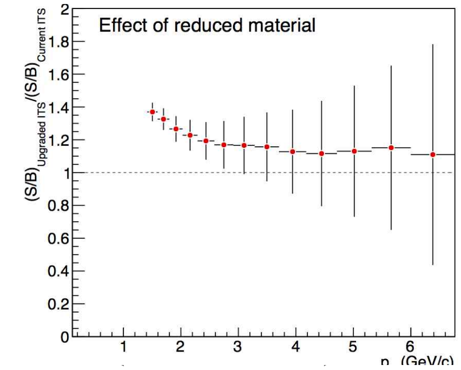
Topics actively working on...

- Multiplicity (dN/dη) in pp
- Lambda anisotropy
- Pomeron reactions in pp→4π
- Lattice calculation for Υ in T
- Heavy flavor (NPE) production and R_{AA}: c, b→e+X, b→e+X
- R_{AA} vs. path-length
- Flow analysis using two-particle correlations
- Hyperon (Σ, Ξ) search from pp to AA

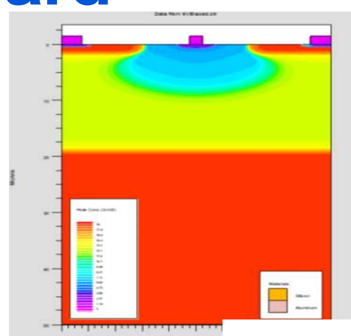
koALICE activity for ALICE ITS upgrade R&D

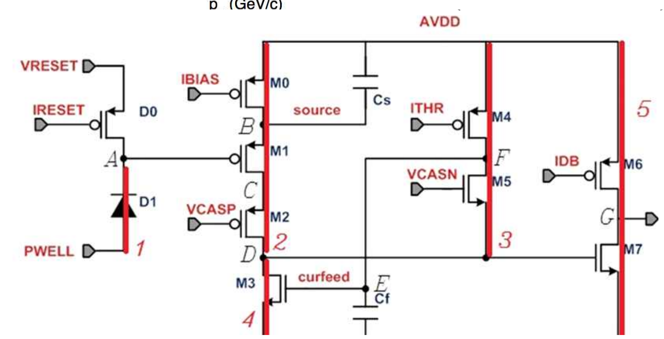
Physics performance study (Inha)

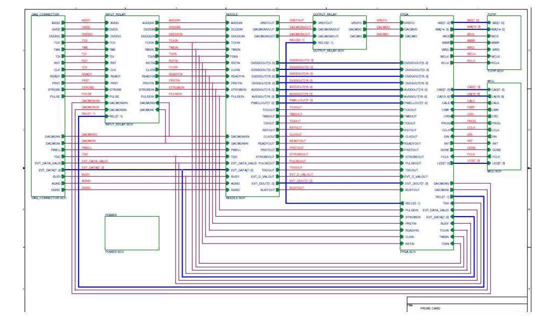




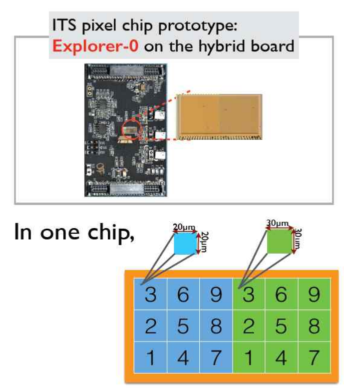
Chip-design & Probe card development (Yonsei)

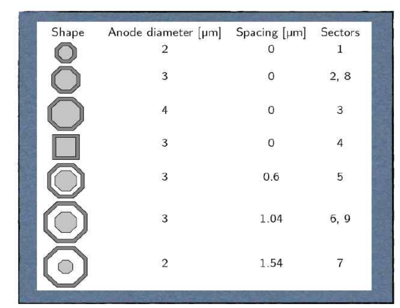


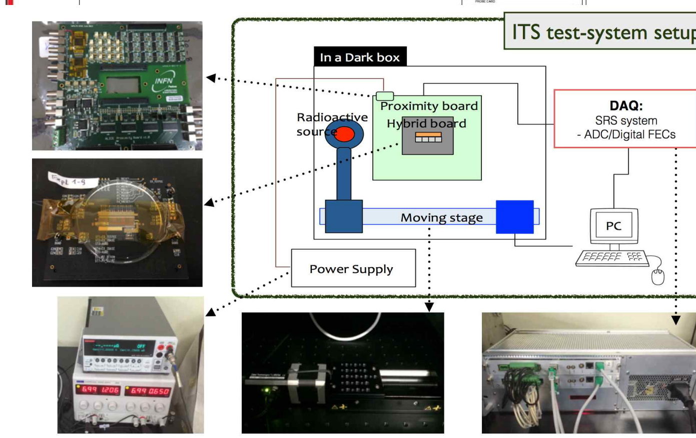




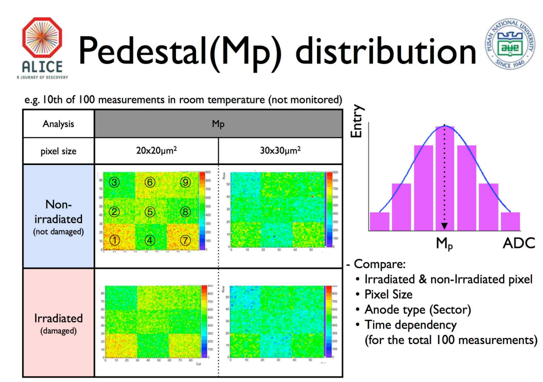
Chip characterization test bench (Pusan, Inha)

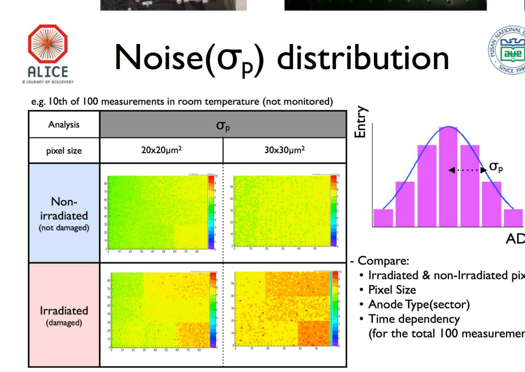






Mass chip test and Module assembly system setup (Pusan)





ALICE ITS Upgrade Asian Workshop since 2013 Spring (twice per year): Inha University(2013.4), CCNU Wuhan(2013.12), Thailand(2014.6), Pusan University(2014.12 scheduled)

Research theme and activities reported recently

Hyeonjoong Kim

- Very recently joined ALICE, so still in very explorative stage.
- Dete
- To c proc

Beomkyu Kim

1st koALICE national workshop

- $dN_{ch}/d\eta$ measurement in p+p collisions
- Paper draft is ready to distribute to the collaboration to edit

ave A

Taesoo Kim

- Partial Wave Analysis for 2 pions of central production in p+p collisions at 7 TeV
- Th
- Se

formula

- ABorissov (CERN)
  - GA/LF, Σ Resonance
  - Research/Education Assistance at CERN for KoALICE

- SUChung (CERN)
  - Glueball/Exotics/ Diffractive Physics/ PW

- KEChoi (PNU/CERN)
  - Cherenkov Det. → ATLAS@IUB.US → PNU
  - Performance study → ITS Coordinator
  - Characterization System @ P
  - Series Test + Module Assembly Station @ PNU

- JYKim
  - Chip Characterization

Minwoo Kim

- Various PID methods have be
- Using two-particle correlation and Flow Coefficients are out

- JHSong (PNU/CERN)
  - EPICS Expert (CBM@GSI)

- Collision data analysis (Soyeon Cho, Minjung Kim)
  - Measurement of electron spectra from beauty hadron decays in pp, p-Pb and Pb-Pb collisions
- ITS Upgrade
  - Pixel chip test (Jonghan Park)
    - Build a 2nd version of the chip test system in Inha after the 1st version built in Pusan
  - Physics performance study (MinJung Kweon)
    - Improvement of the b→e measurement by the ITS upgrade in Pb-Pb collisions
- Theory (Kayoung Park)
  - Modeling medium energy loss of jet via Bremsstrahlung

Myunggeun Song

- The measurement of R_{AA} as a functi en made by using flow method
- Convert $\Delta\varphi$ to Path-Length using Glauber simulation
- Then, draw R_{AA} vs Path-Length and compare it with RHIC resul

JinSook Kim

Lambda anisotropy

- BHLim
  - Series Test + Module Assembly System

Summary and Outlook

data are described by perturbative QCD ⇒ Heavy-flavours are a calibrated probe

-Pb data:

Hints of a stronger suppression for charm than for beauty at intermediate/high p_T.

No strong conclusions from the comparison of D mesons and pions R_{AA}, given the arge uncertainties

Pb data:

Results consistent with pQCD + shadowing: the observed suppression in Pb-Pb collisions is a final state effect

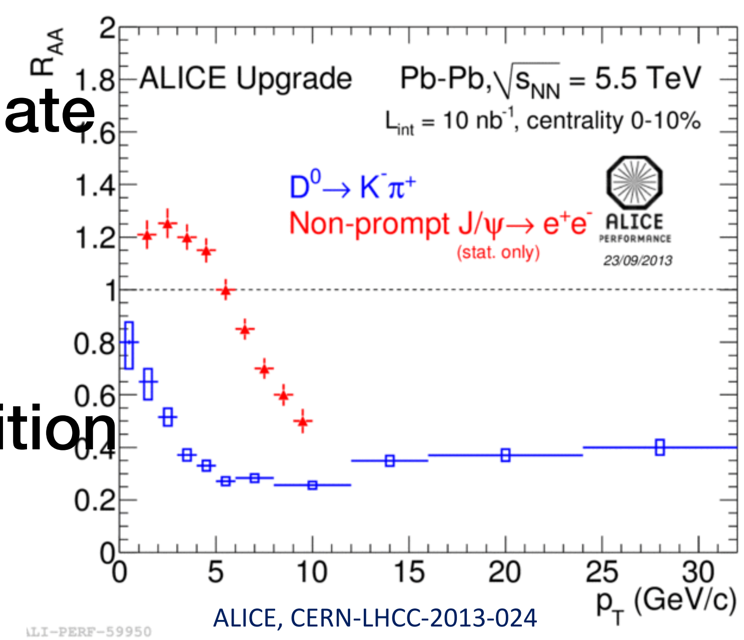
ecision measurements would greatly benefit from larger statistics scheduled ahead rom ongoing detector upgrades

LHC upgrades

Toward precision measurements!

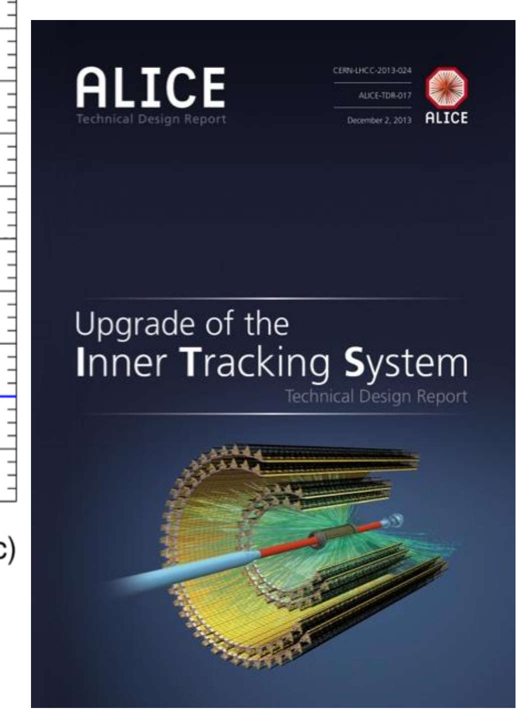
- Why:
  - Physics: the best is yet to come
  - Detectors: replace aging components, update technologies
- How:
  - Upgrades of the LHC (incl. injection chain)
  - Upgrades of detectors, trigger, data acquisition
  - Goal: upgrade performance in increasingly challenging environment
- When:
  - Three phases: 2013 – 2018 – 2022

Upgrade



ALICE, CERN-LHCC-2013-024

Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ

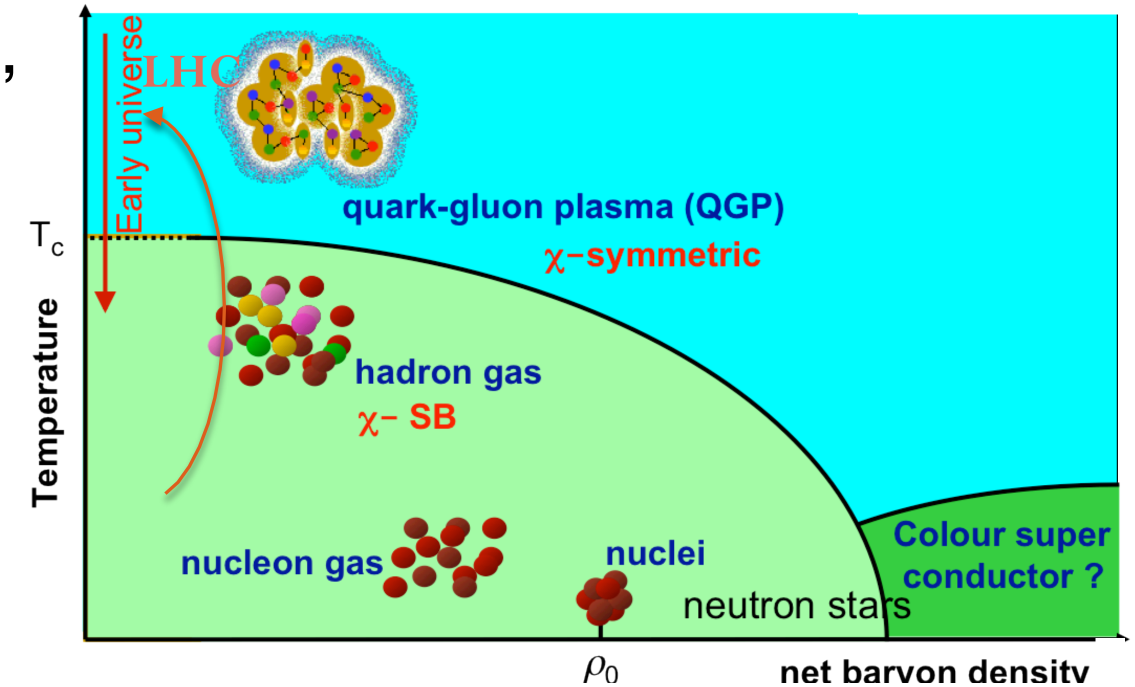


Thank you for your attention!

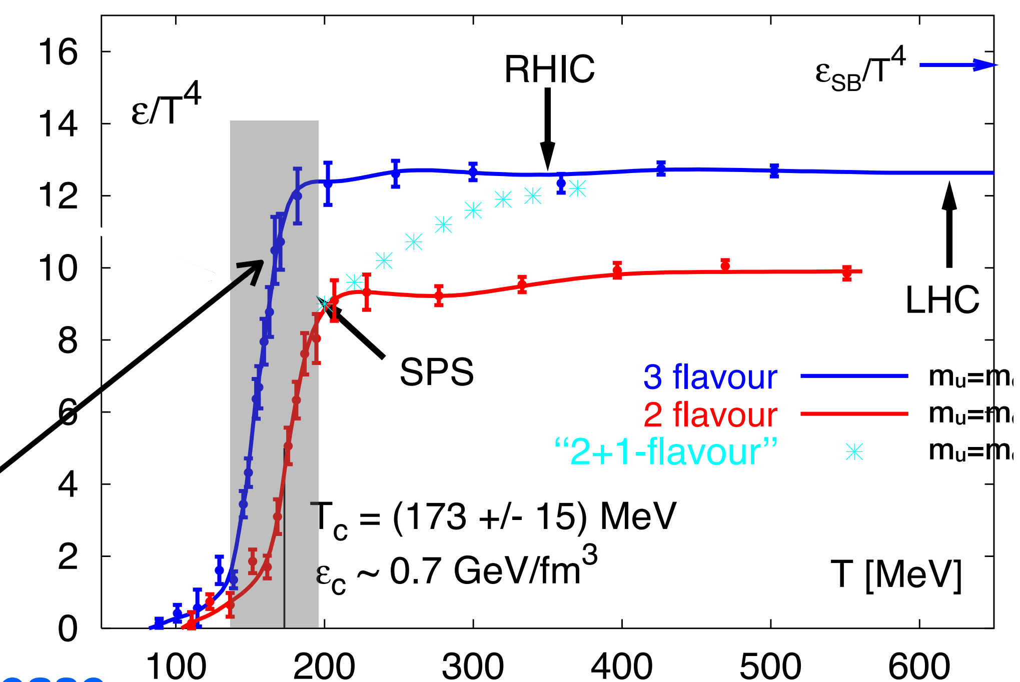
Additional slides

Heavy-ion physics

First phase diagram for nuclear matter: Cabibbo, Parisi PL B59 (1975): “We suggest ... a different phase of the vacuum in which quarks are not confined”



- T.D. Lee (1975) suggested to distribute a high amount of energy over a relatively large volume
- Collisions of nuclei at very high energy
  - Temperature of the produced “fireball” $O(10^{12}$ K)
    - $10^5 \times$ T of the centre of the Sun
    - ≈T of the Universe 10^{-5}s after Big Bang
- Study nuclear matter at extreme conditions of temperature and density
  - Collect evidence for a state where quarks and gluons are deconfined (Quark Gluon Plasma) and study its properties
  - Phase transition predicted by Lattice QCD calculations
    - $T_C \approx 170$ MeV → $\varepsilon_C \approx 0.6$ GeV/fm^3



sharp increase

Heavy Quark Energy Loss in Medium

Radiative energy loss via gluon radiation

Color charge dependence of energy loss

gluon radiation spectrum by the parton propagation in the medium:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$\text{where} \quad C_R = 3 \ \text{for } g, \ \frac{4}{3} \ \text{for } q$$

Dead Cone Effect

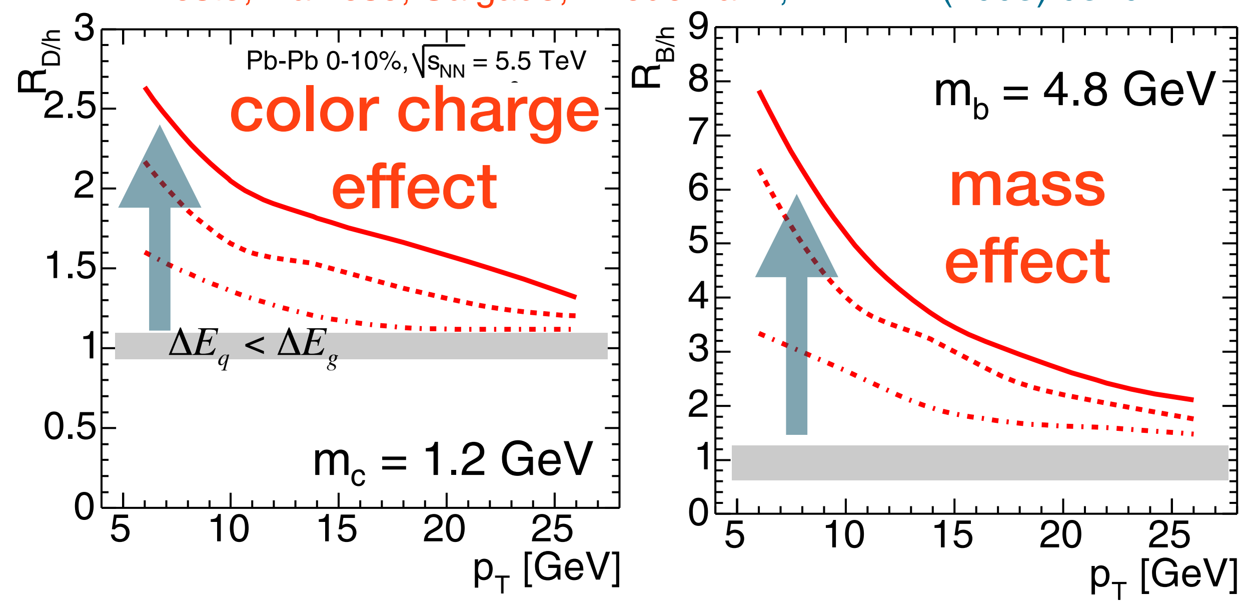
- In vacuum, gluon radiation is suppressed at angles smaller than M_Q/E_Q (ratio of the quark mass to its energy)
- In medium, dead cone implies lower energy loss for massive partons

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \qquad R_{AA}(p_T) = \frac{1}{<T_{AA}>} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

$R_{D/h}$: R^D_{AA}/R^h_{AA}

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.



Elastic energy loss is not negligible?

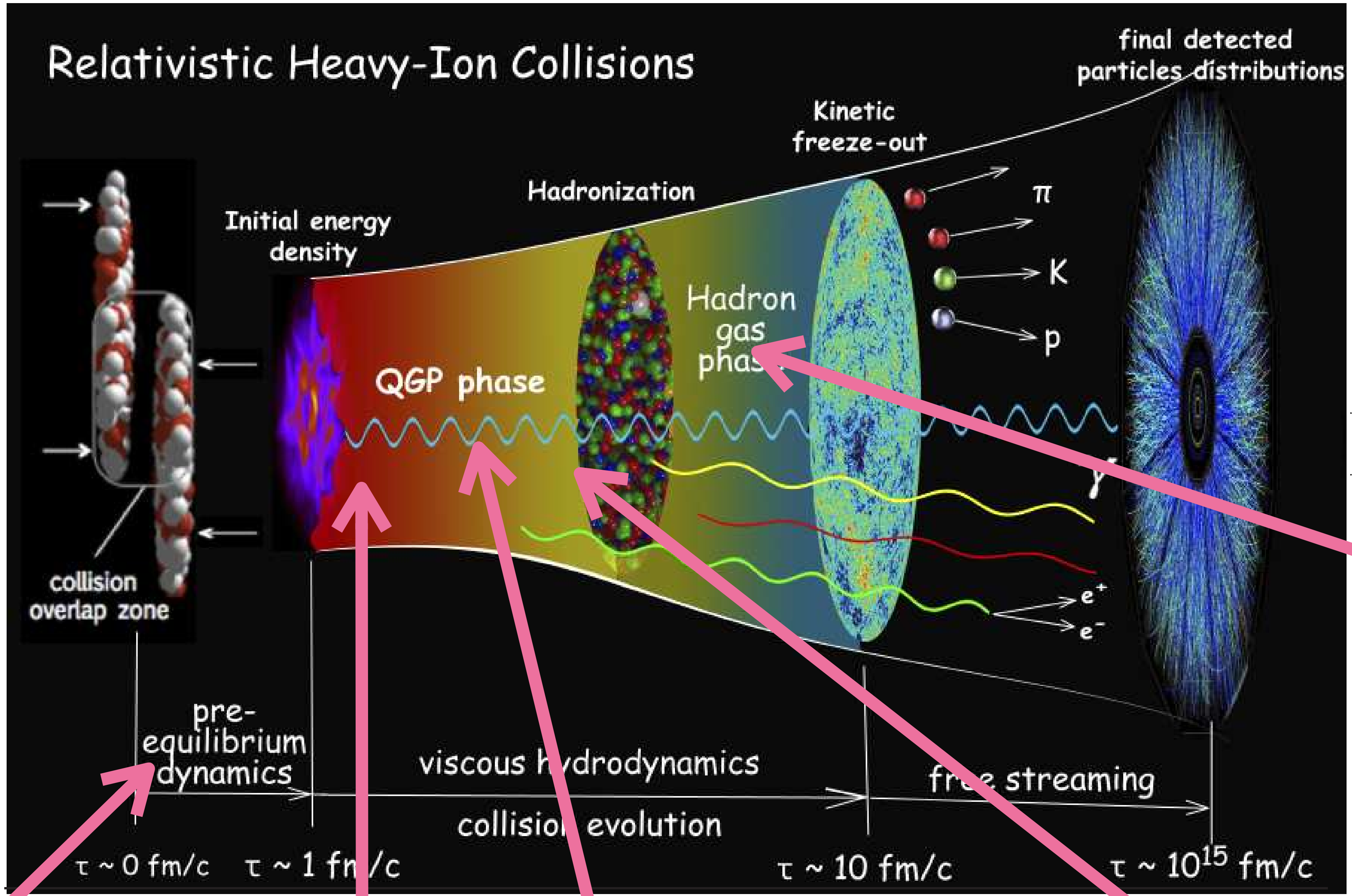
Simon Wicks, William Horowitz, Magdalena Djordjevic, Miklos Gyulassy, Nucl.Phys.A784:426-442,2007

Collisional dissociation probability of heavy mesons in the QGP?

I Vitev, A Adil and H van Hees, J. Phys. G: Nucl. Part. Phys. 34 (2007) S769–S773

Proton-proton collisions: provide important test of pQCD in a new energy domain and heavy ion reference

Nucleus-nucleus collision processes



Hard processes:
- Charm, Beauty, Jets
- Probe the whole evolution of the collision

Photons (QGP radiation):
- No interaction with the QGP constituents
- Insensitive to the hadronization phase

Transition to hadron gas

Freeze-out:
- Chemical: particle composition is fixed (no more inel. collisions)
- Thermal: momentum spectra are fixed (no more elastic collisions)

QGP phase
- Sharp increase of energy density at T_C (≈170MeV)
- Thermalization time (RHIC): $\tau_{th} \approx 0.6$ fm/c

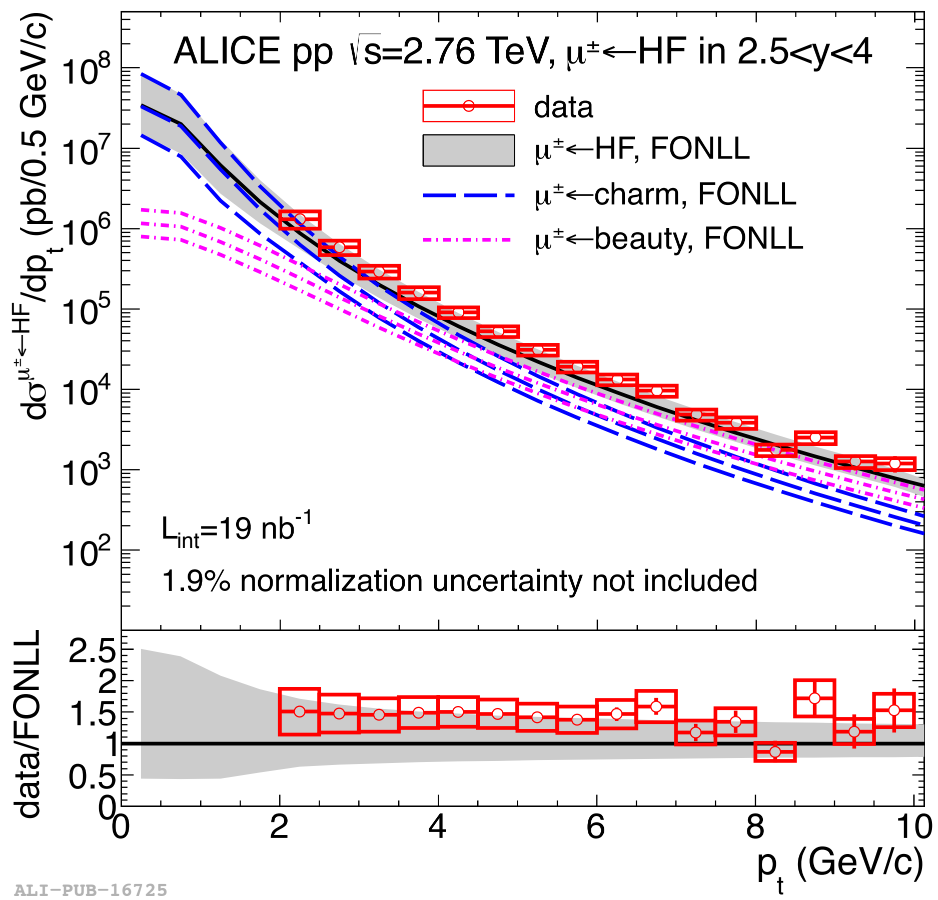
Data samples

LHC Run	Data Samples	D mesons	Heavy Flavour muons	Heavy Flavour electrons
2010	pp, 7 TeV	**5 nb^{-1} (MB trigger)** JHEP 01 (2012) 128	**16.5 nb^{-1} (μ trigger)** PLB 708 (2012) 265	**2.6 nb^{-1} (MB trigger)** PRD 87 052016 (2013)
2010	Pb-Pb, 2.76 TeV	**2.12 μb^{-1} (0-80%)** JHEP 09 (2012) 112	**2.7 μb^{-1} (μ trigger)** PRL 109 112301 (2012)	**2.0 μb^{-1} (0-80%)**
2011	pp, 2.76 TeV	**1.1 nb^{-1} (MB trigger)** JHEP 07 (2012) 191	**19 μb^{-1} (μ trigger)** PRL 109 112301 (2012)	**0.5 (11.9) nb^{-1}** MB (EMCAL) triggers
2011	Pb-Pb, 2.76 TeV	**23 μb^{-1} (0-10%)** **6.2 μb^{-1} (10-50%)** PRL 111 102301 (2013)	**11.3 μb^{-1} (0-10%)** **3.5 μb^{-1} (10-40%)**	**22 (37) μb^{-1} in 0-10%** **6 (34) μb^{-1} in 20-40%** MB (EMCAL) trig.
2013	p-Pb 5.02 TeV	**48.6 μb (MB trigger)**	work in progress	**48.6 μb (MB trigger)**

Heavy-flavour cross section in pp at √s = 2.76 TeV

Heavy flavour decay muons

Phys. Rev. Lett. 109 (2012) 112301



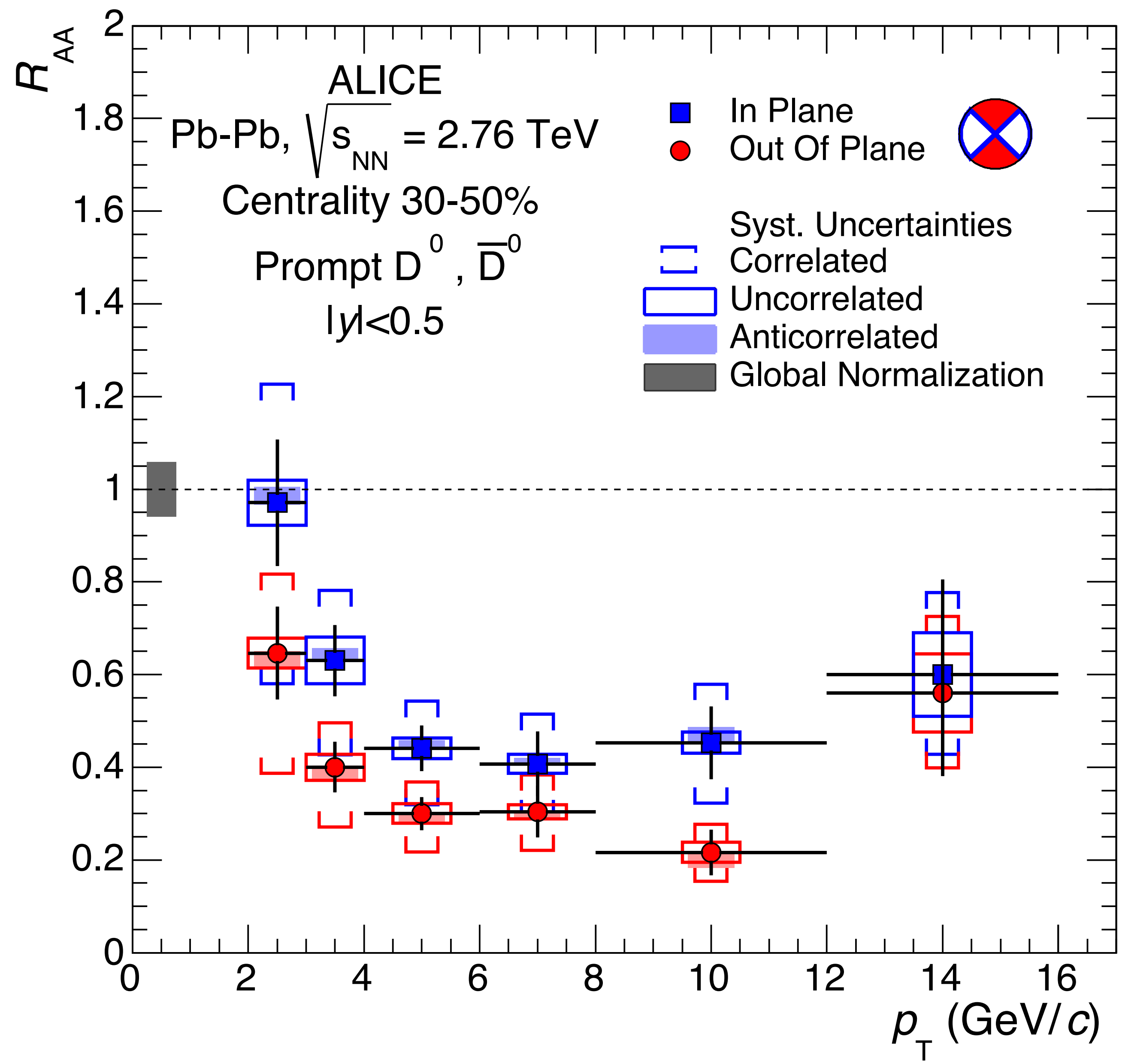
R.Averbeck et al., arXiv:1107.3243

Heavy flavour muon data is used as reference for Pb-Pb at the same energy, for the other channels a √s extrapolation based on pQCD calculation is used

pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

Path length dependence of R_{AA}

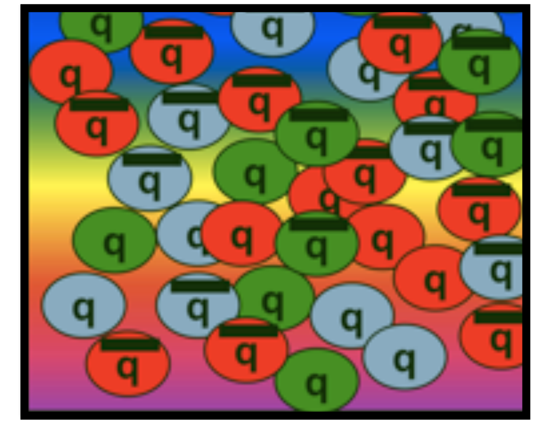


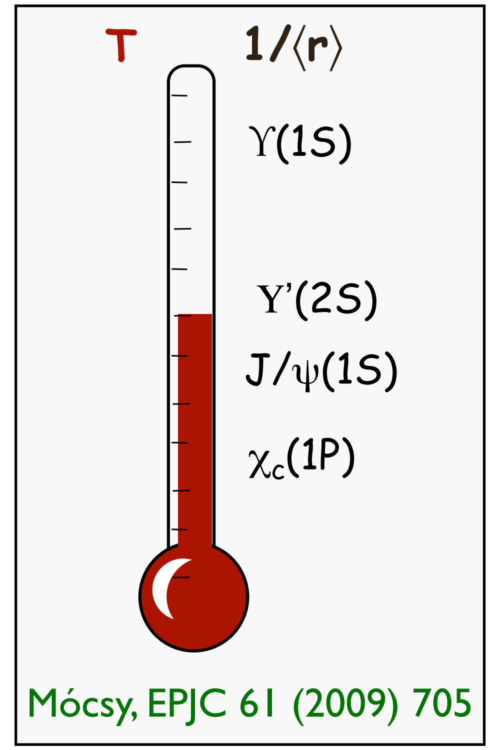
R_{AA} measured in-plane and out-of-plane, sensitive to

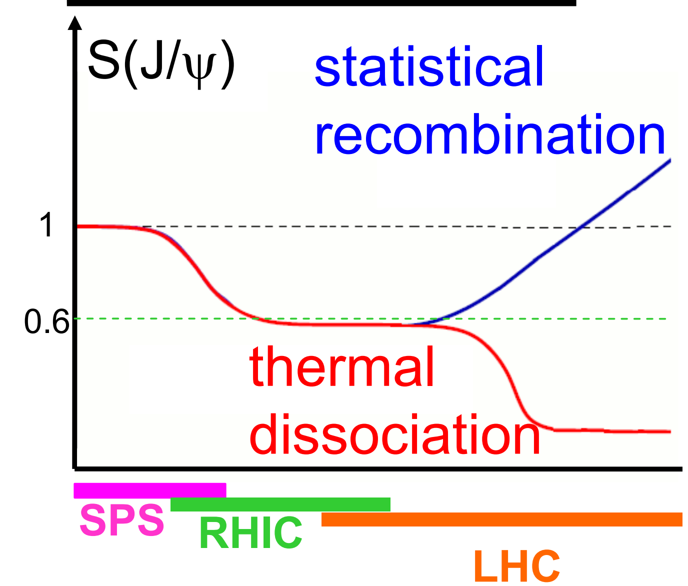
- high p_T: path length dependence of parton energy loss
- low p_T: collectivity

What's special about Quarkonia

What happens in QGP to the Quarkonia?
→ Suppression by color screening (disappearance of specific quarkonium states signals)
→ Regeneration by statistical recombination?

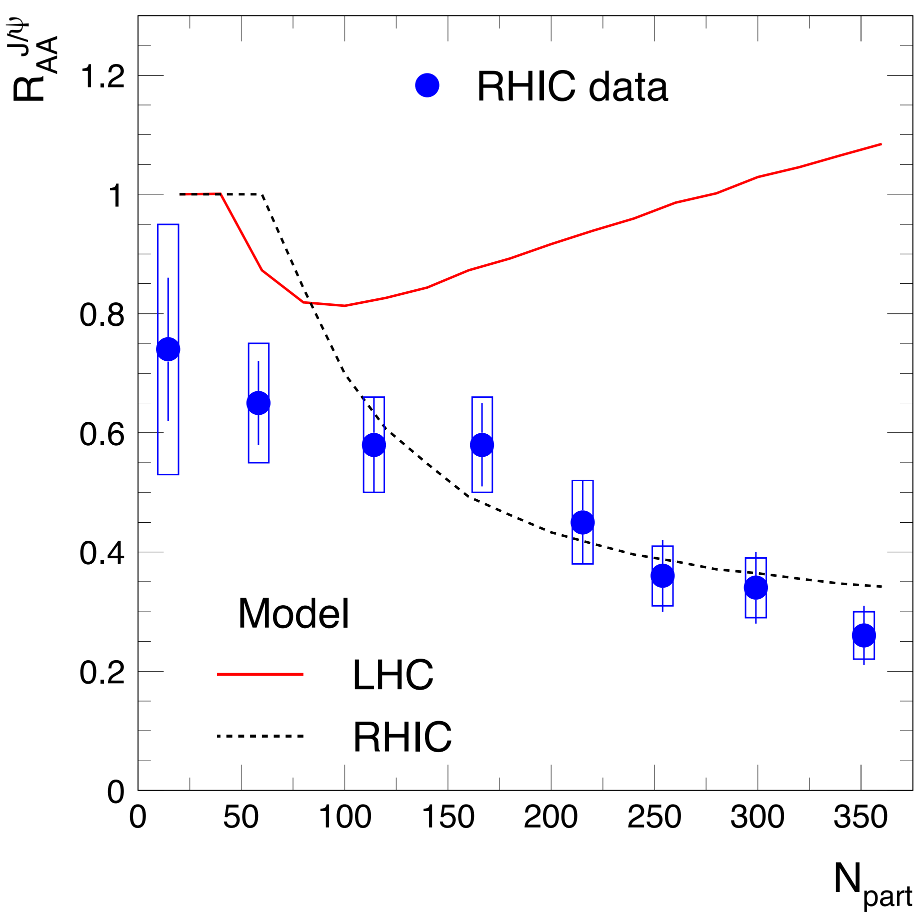






Matsui, Satz, PLB178 (1986) 416
Digal et al., PRD64 (2001) 094015
Braun-Munzinger, Stachel, PLB 490 (2000) 196

40



AA et al., PLB 652 (2007) 259

What is so different at LHC?

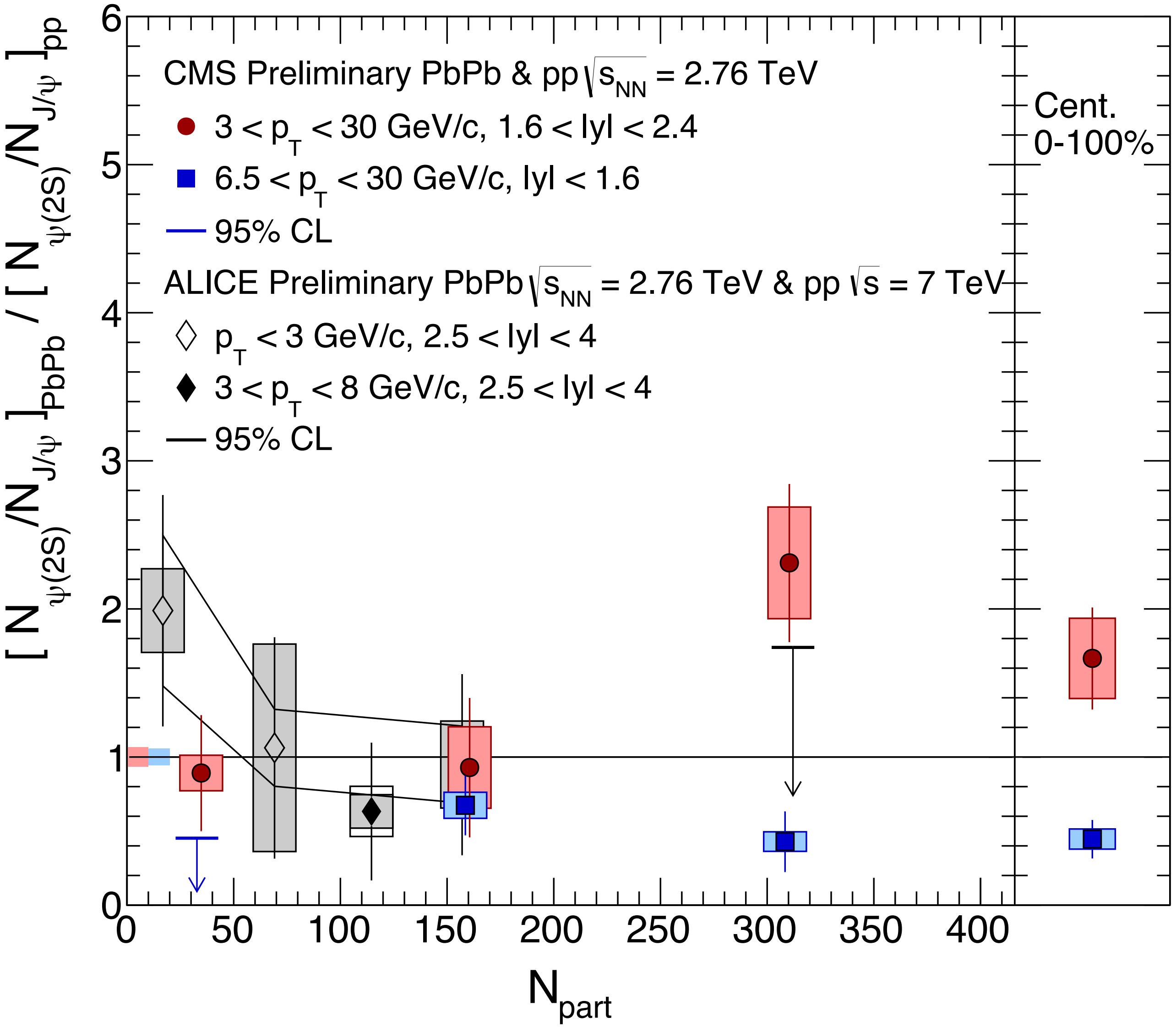
(compared to RHIC)

$\sigma_{c\bar{c}}$: ~10x, Volume: 2.2-3x

$\psi(2S)$ production at the LHC

A.Andronic@GSI.de

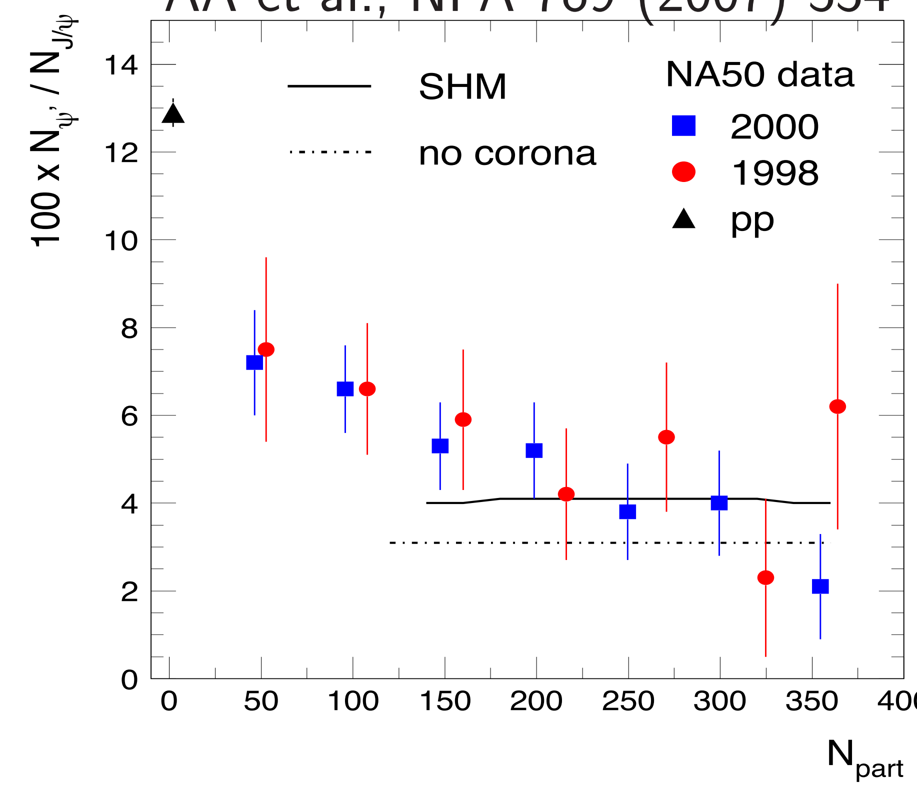
$$R = \frac{N^{\psi(2S)}_{\mathrm{Pb-Pb}}/N^{J/\psi}_{\mathrm{Pb-Pb}}}{N^{\psi(2S)}_{\mathrm{pp}}/N^{J/\psi}_{\mathrm{pp}}} = \frac{R^{\psi(2S)}_{\mathrm{AA}}}{R^{J/\psi}_{\mathrm{AA}}}$$



(light) "discrepancy" ALICE / CMS ?

mind diff. p_T, y ranges (thanks, Raphaël:)

AA et al., NPA 789 (2007) 334



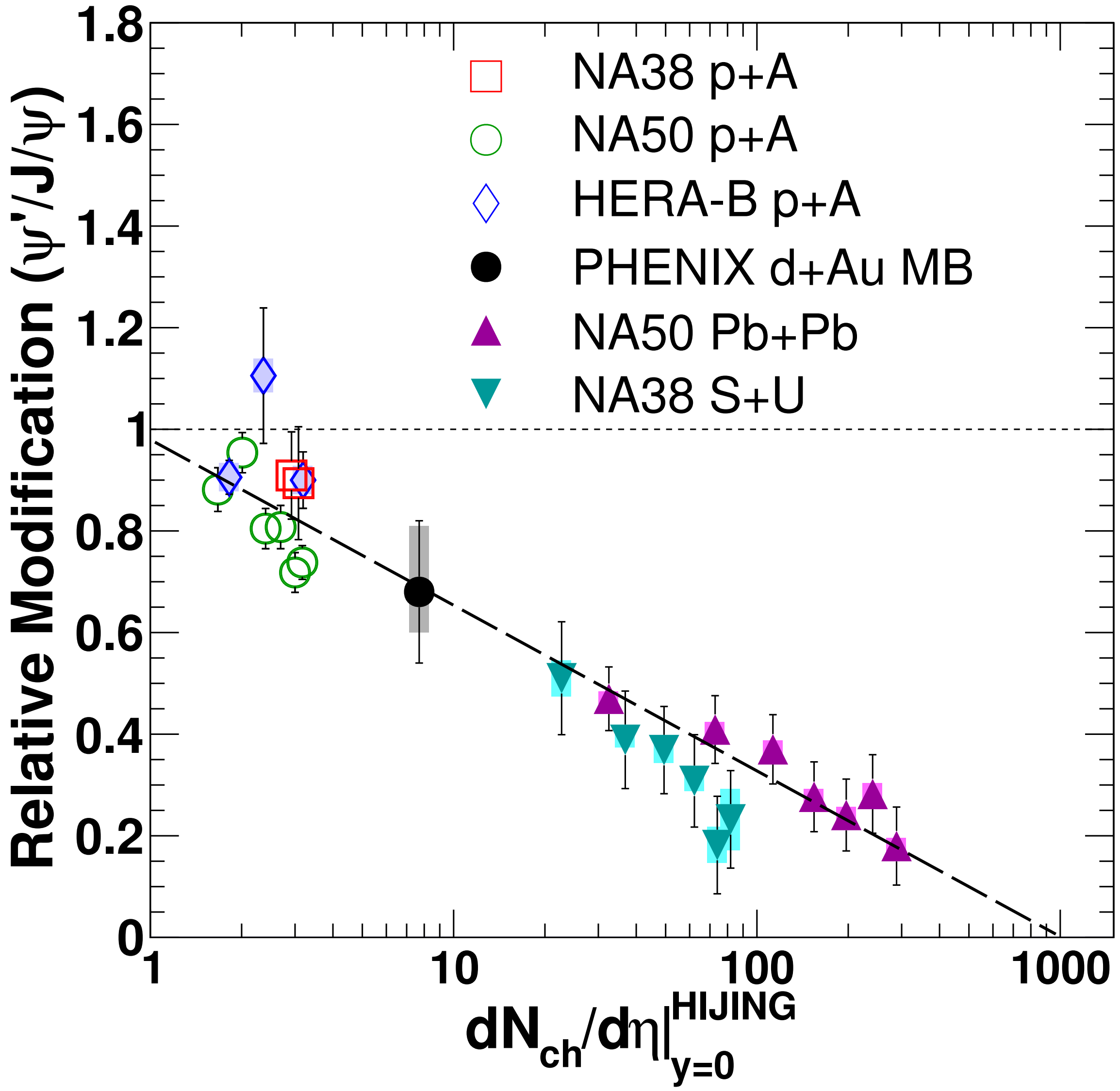
at SPS: $R \simeq 0.24$ (p_T-integrated)

...evidence against sequential dissociation

Charmonium in p(d)-A collisions

A.Andronic@GSI.de

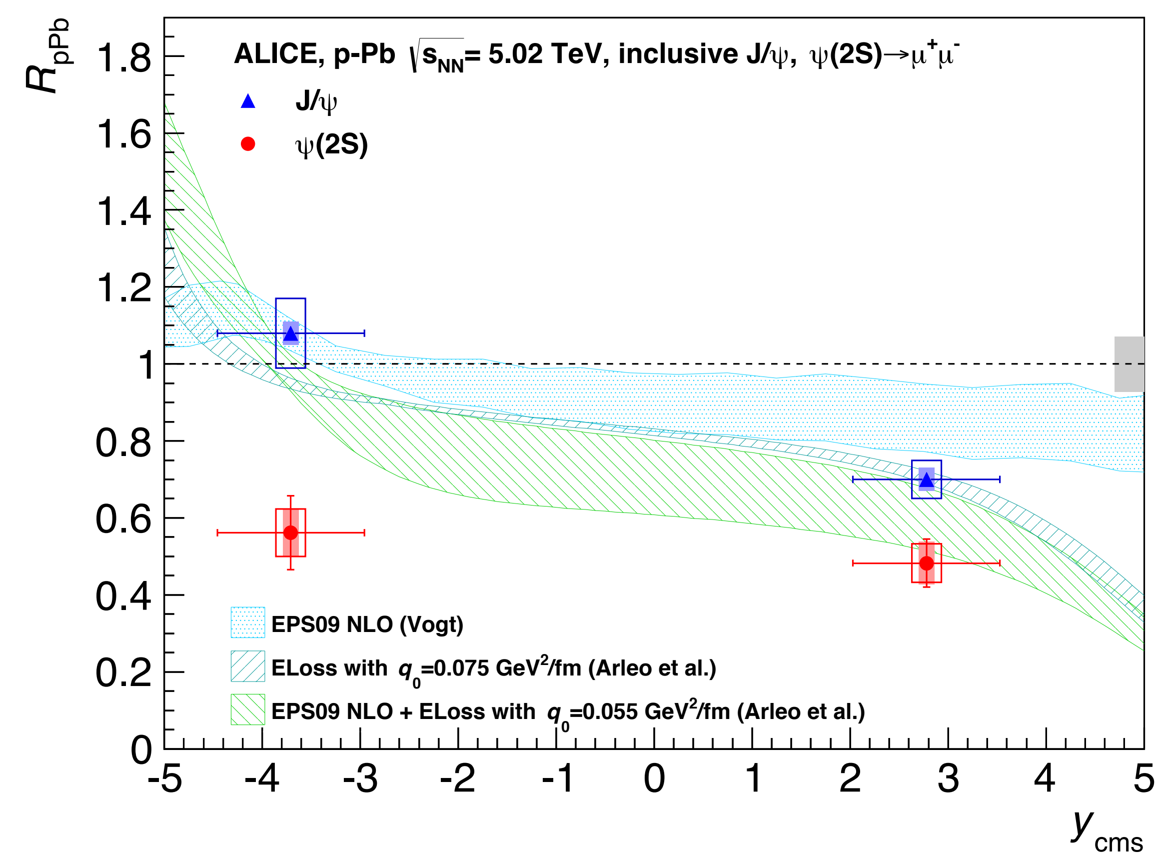
PHENIX, arXiv:1305.5516 (Durham, HF 5)



abs. cross sect. depends on time spent in the nucleus

(McGlinchey et al., PRC 87 (2013) 054910)

ALICE, arXiv:1405.3796 (Arnaldi, HF 5)



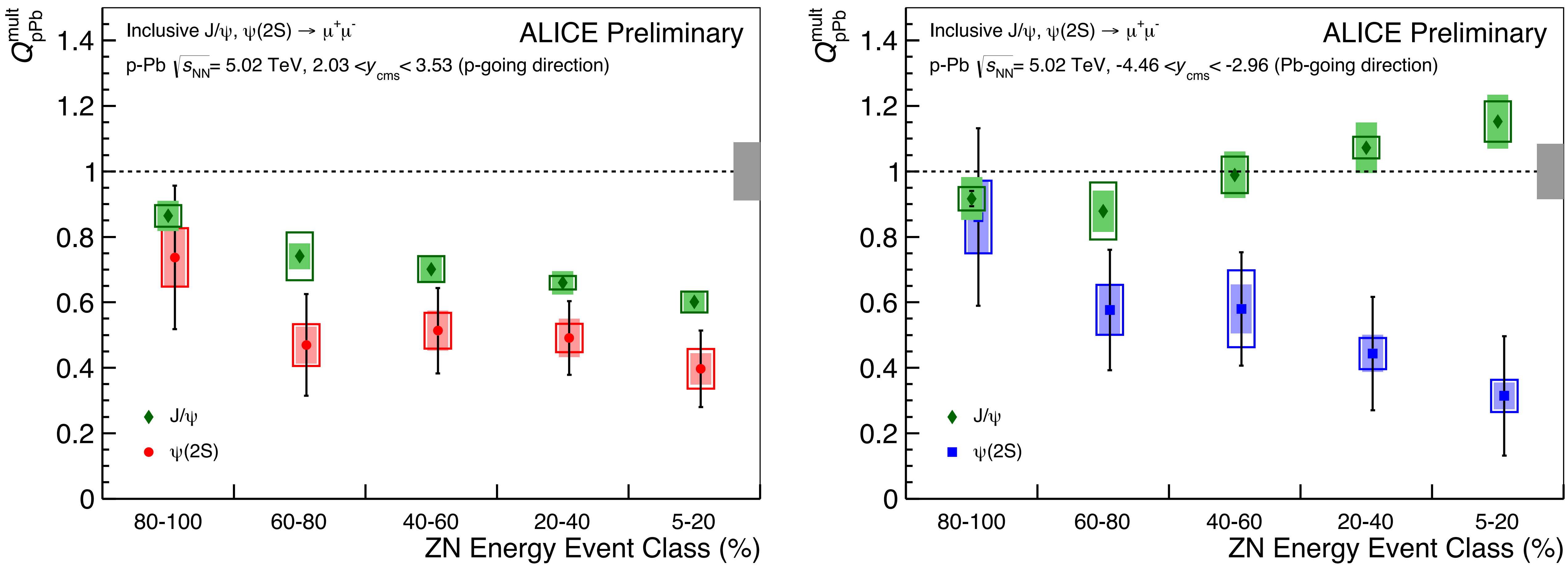
at the LHC, the strong $\psi(2S)$ suppression in Pb-side remains puzzling

indication for final-state effects?

Charmonium prod. vs. event activity in p-Pb collisions

A.Andronic@GSI.de

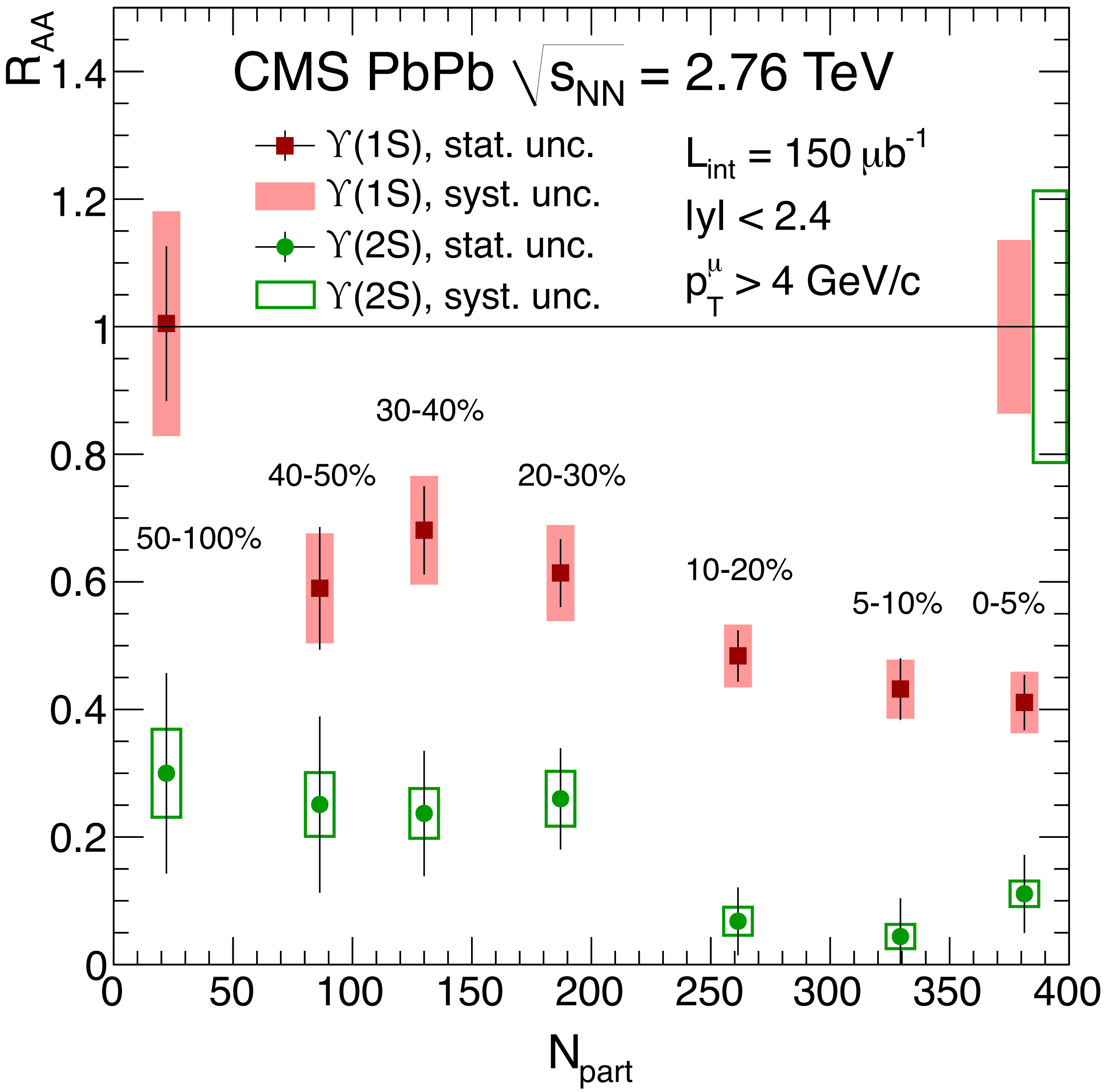
ALICE (Arnaldi, HF 5, Lakomov, F-26)



different suppression pattern on Pb-side

Bottomonium at the LHC

A.Andronic@GSI.de



CMS, PRL 109 (2012) 222301

interpreted as effect of (almost:) full dissoc. of $\Upsilon(2S)$, $\Upsilon(3S)$, χ_b

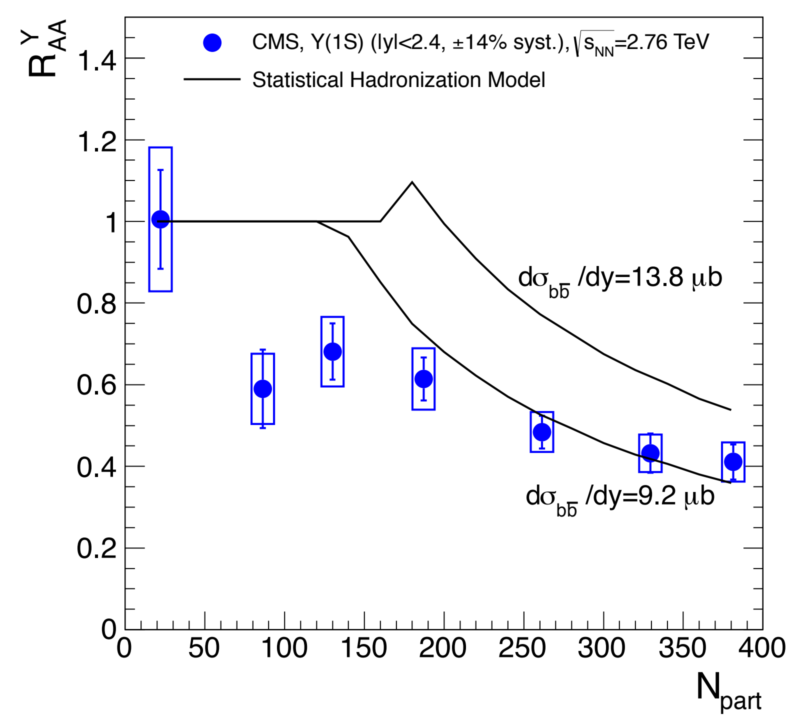
Transport models:

Emerick et al./TAMU, EPJA 48 (2012) 72

Zhuang, HF 6

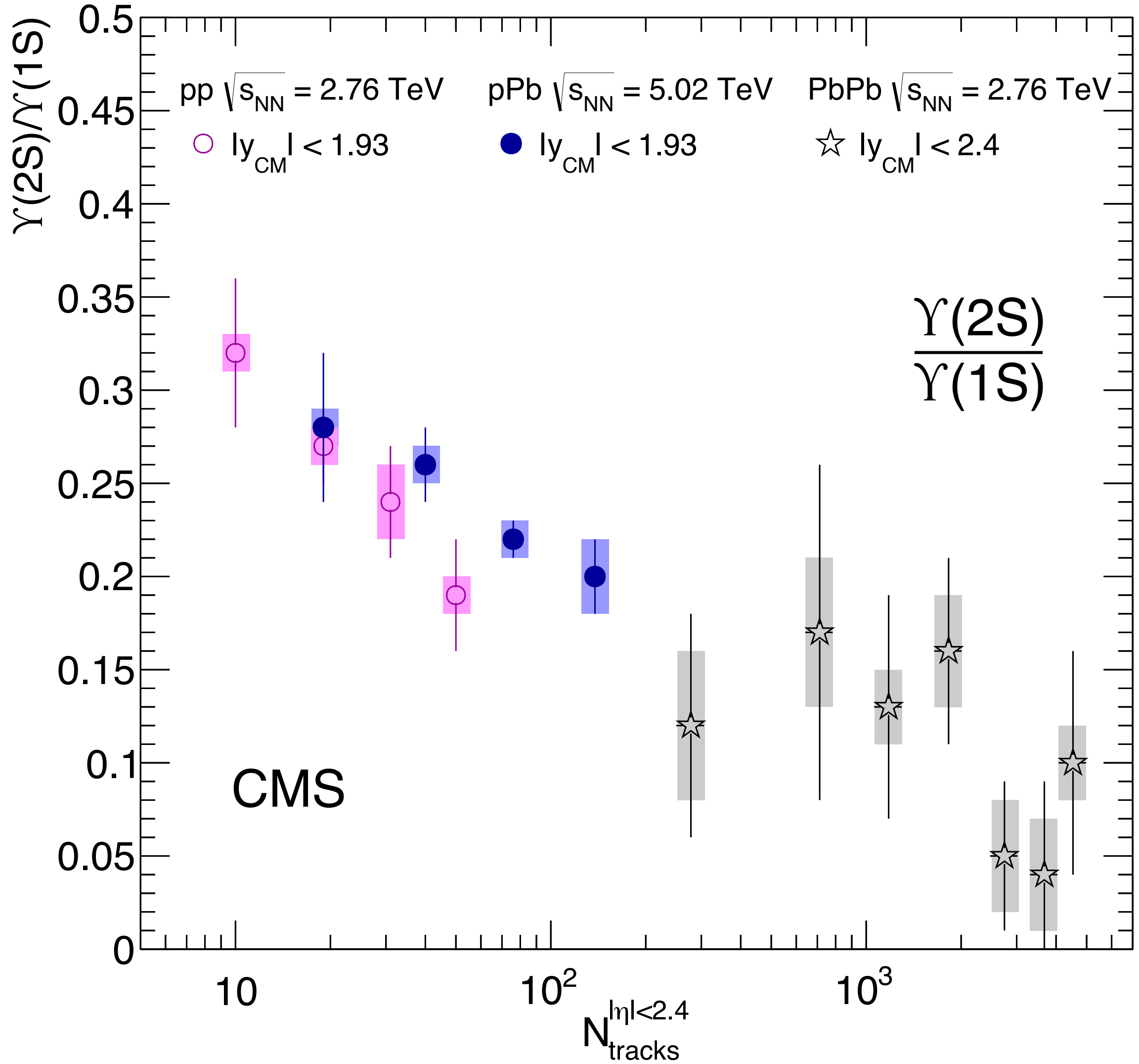
(re)gen. component small ($\lesssim$10%),

Stat. Hadr. model



Bottomonium ratios in p-Pb collisions

A.Andronic@GSI.de



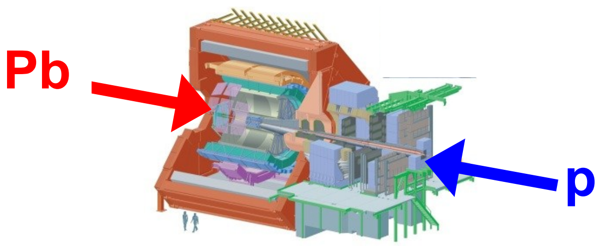
approximate scaling with multiplicity

thermal model:
$\Upsilon(2S)/\Upsilon(1S)$=0.033
(and again against sequential dissoc.)

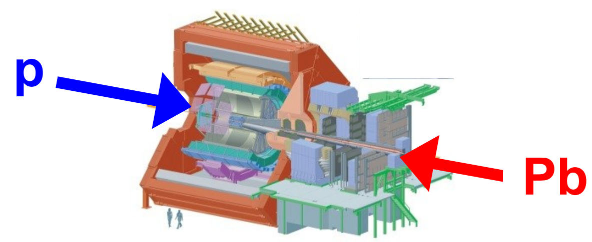
CMS, arXiv:1312.6300 (Valiyavalappil Kizhakkepura, HF 6)

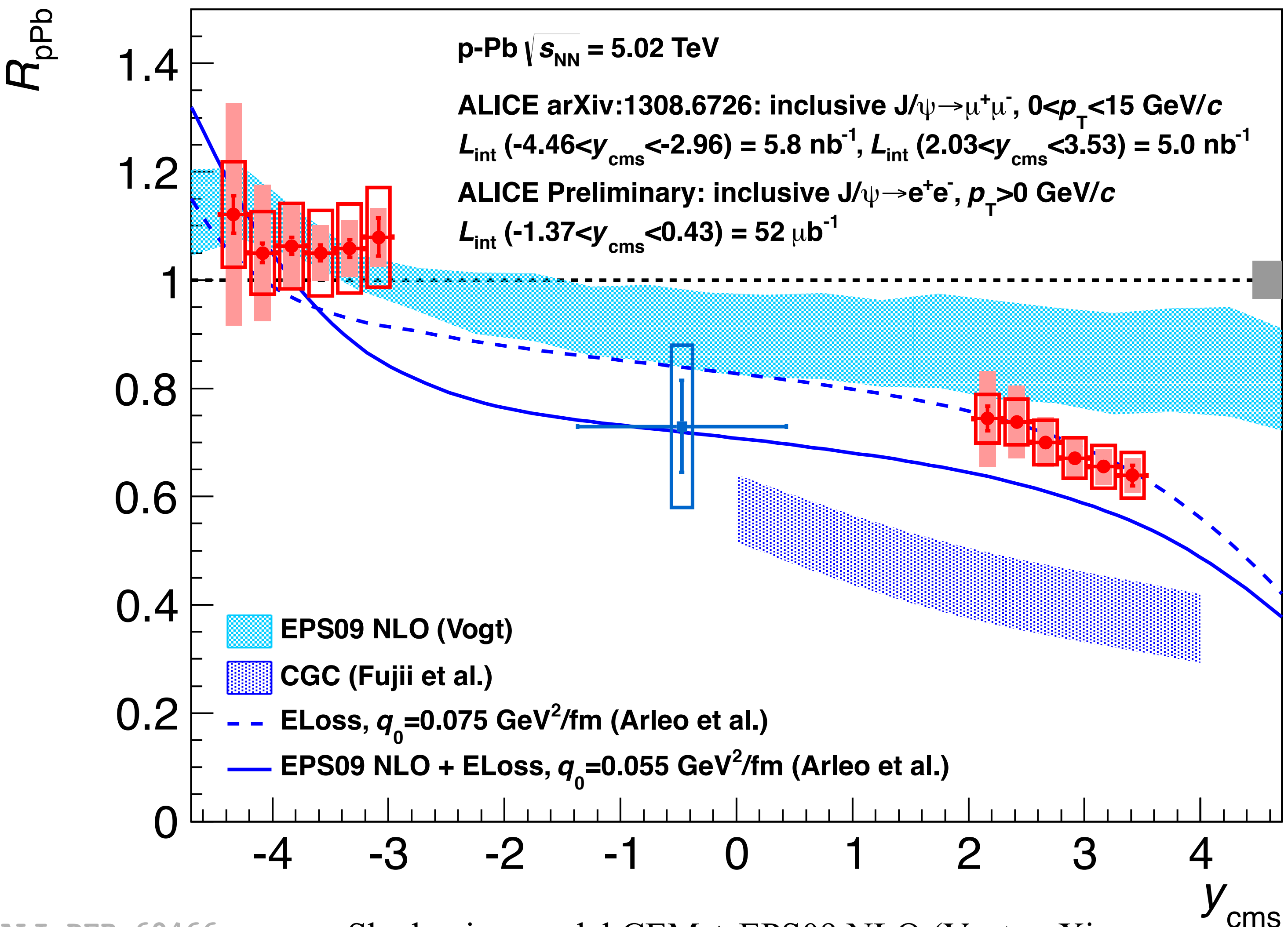
J/ψ R_{pPb} vs rapidity

Backward rapidity



Forward rapidity





- Shadowing model CEM + EPS09 NLO (Vogt, arXiv: 1301.3395)
- Coherent energy loss (Arleo et al., arXiv:1212.0434) with pp data parametrization
- Gluon saturation (Fuji et al., arXiv: 13042221): Color Glass Condensate framework with CEM LO with saturation scale $Q^2_{s,A}(x = 0.01)$= 0.7-1.2 GeV/c^2

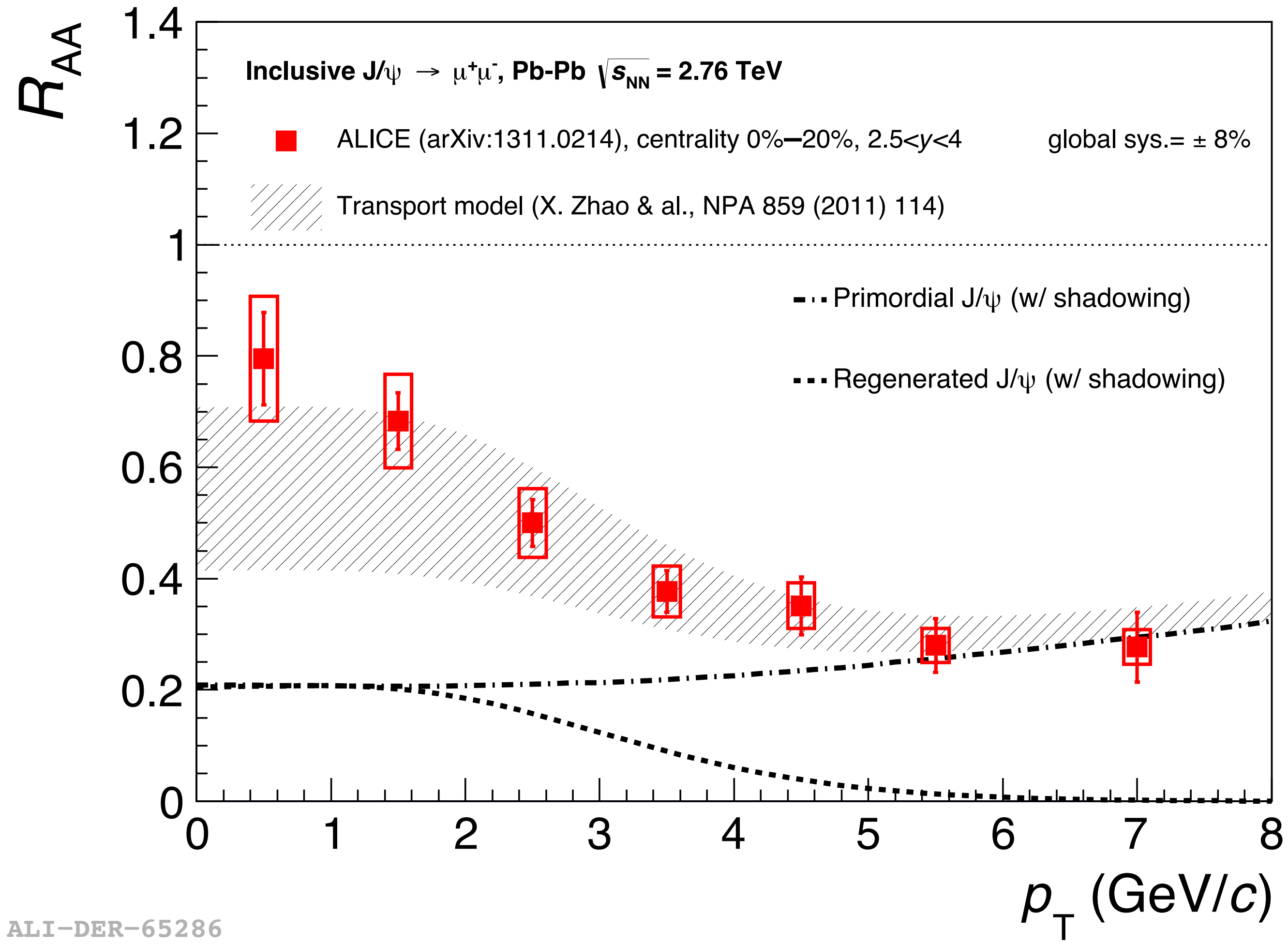
Models of cold nuclear matter effects

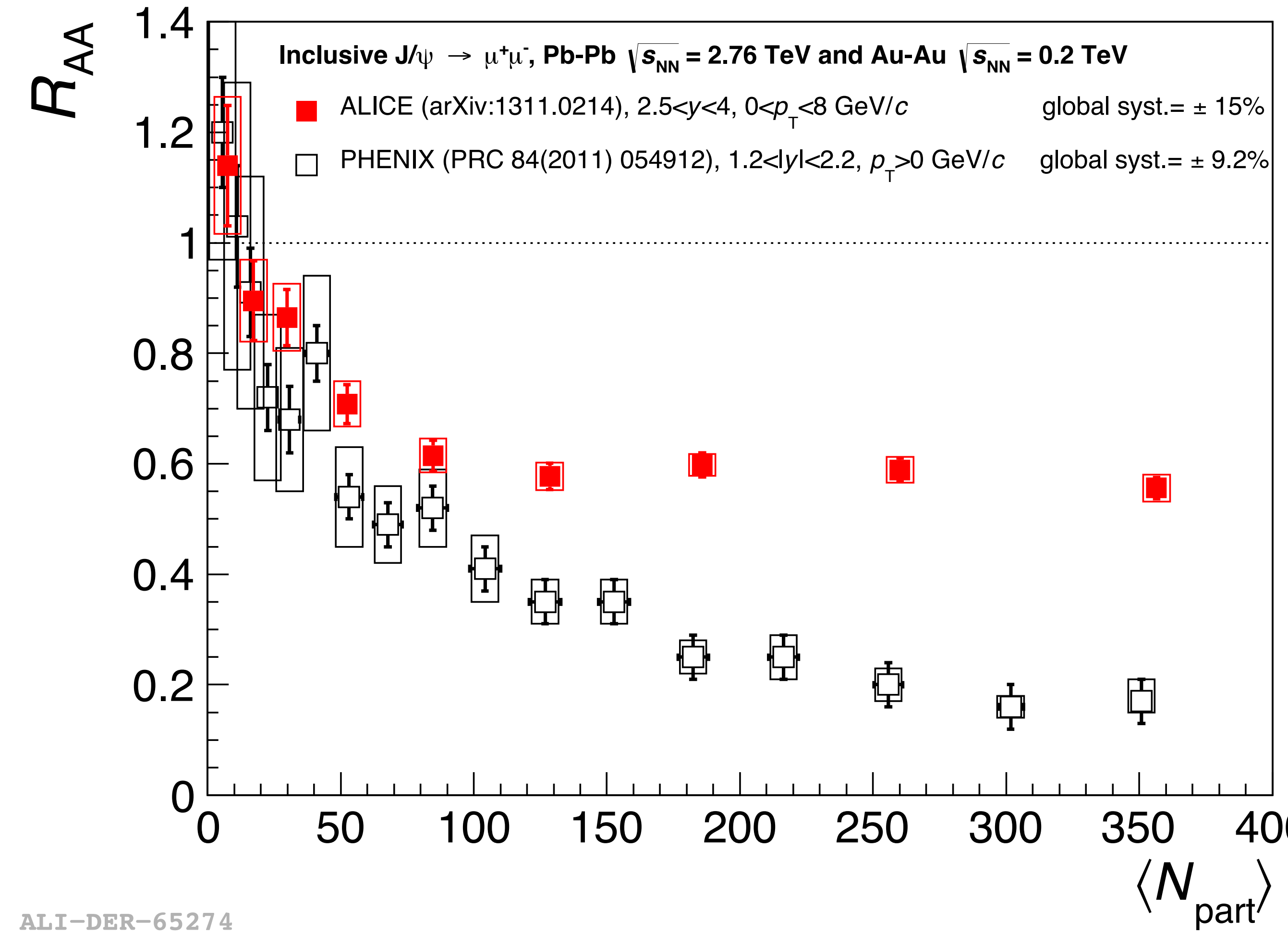
EPS09 nuclear PDFs: backward rapidity data well reproduced, strong shadowing favoured at forward rapidity

Coherent energy loss: y-dependence well reproduced, better agreement with pure energy loss

CGC calculations underestimate the data

J/ψ R_{AA} in Pb-Pb





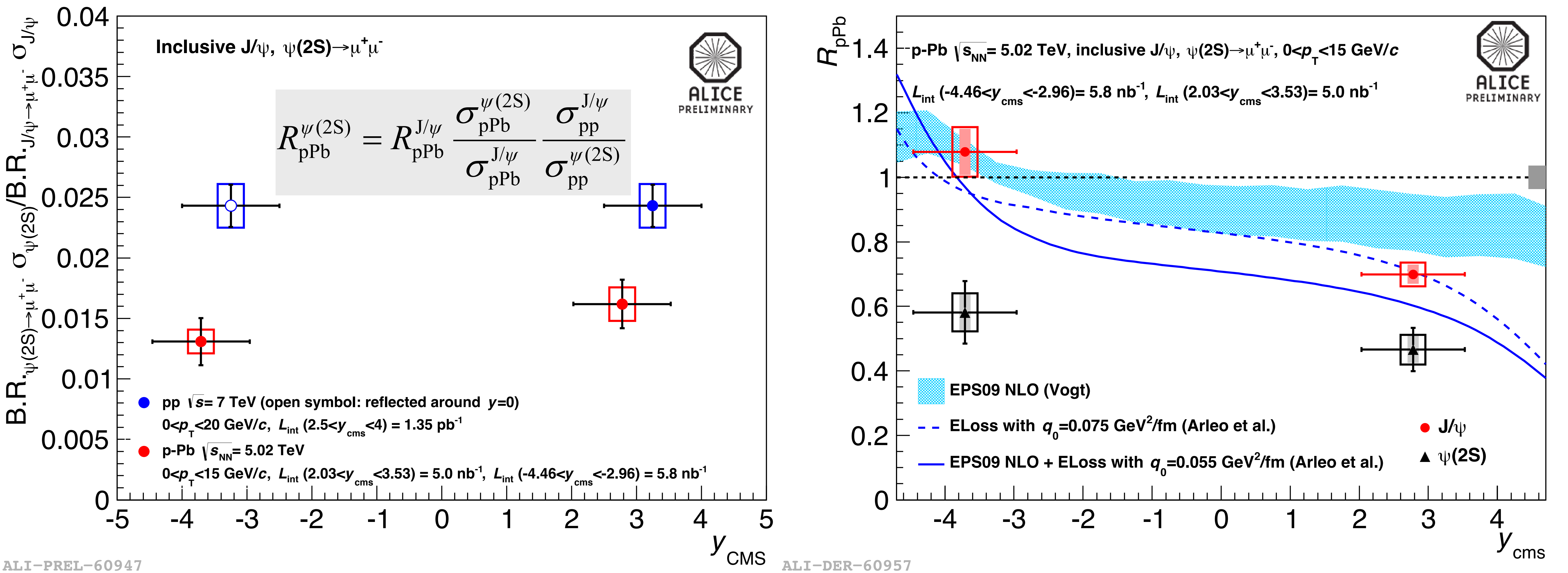
J/ψ is less suppressed at low p_T than at high p_T

Less suppression at LHC than at RHIC at mid-central and central collisions

⇒ Hint of the $c\bar{c}$ recombination? (as expected in regeneration models: regeneration contribution important at low p_T)

Liu, Qiu, Xu and Zhuang, PLB678(2009) 72
Zhao, Rapp, NPA859(2011) 114
Andronic et al., arXiv:1210.7724

ψ(2S) production in p-Pb



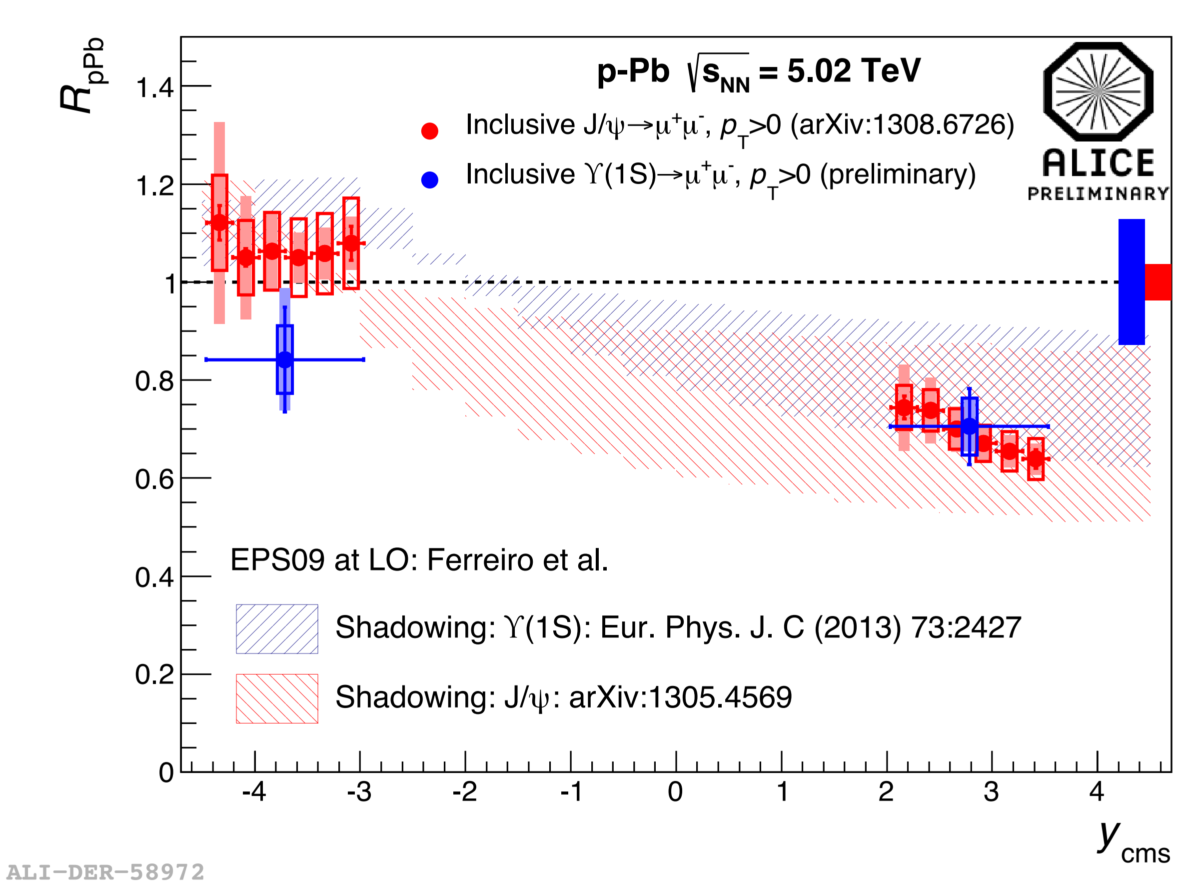
$$R_{\rm pPb}^{\psi(2S)} = R_{\rm pPb}^{J/\psi} \frac{\sigma_{\rm pPb}^{\psi(2S)}}{\sigma_{\rm pPb}^{J/\psi}} \frac{\sigma_{\rm pp}^{J/\psi}}{\sigma_{\rm pp}^{\psi(2S)}}$$

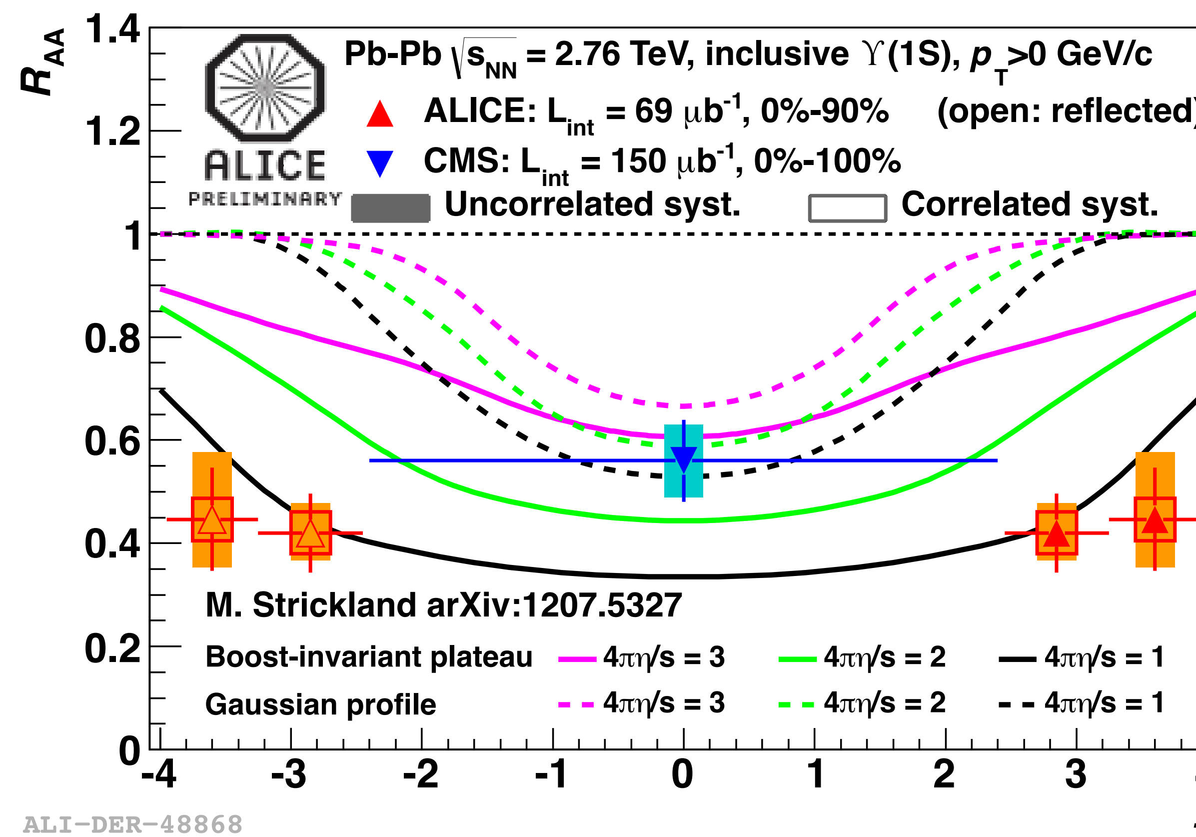
Stronger suppression of ψ(2S) in p-Pb relative to J/ψ

⇒ **Not described by initial state CNM effect and coherent energy loss**

⇒ **Final state effects? Other mechanisms?**

ϒ(1S) production in p-Pb and Pb-Pb





Similar R_{pPb} of J/ψ and ϒ(1S)

⇒ EPS09 shadowing in fair agreement with both J/ψ and ϒ(1S) within uncertainties

- ϒ(1S) yield suppressed relative to binary-scaled pp
- Small rapidity dependence as compared with CMS
- Hydro model reproduces well ALICE data but not both ALICE and CMS data

Summary for Quarkonium

- **Quarkonium:**
  - J/ψ production studied vs. p_T and rapidity. The observed v_2 and R_{AA} vs centrality indicate that the J/ψ production occurs also through recombination, especially at low p_T
  - ϒ : Suppression has been observed also for the bottomonium. The suppression is stronger for central events.
  - p-Pb: J/ψ R_{AA} is in fair agreement with models including shadowing and a coherent energy loss of the partons in cold nuclear matter