The interplay between open and closed HF at LHC

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ALICE

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Subatech
CNRS IN2P3 Les deux infinis
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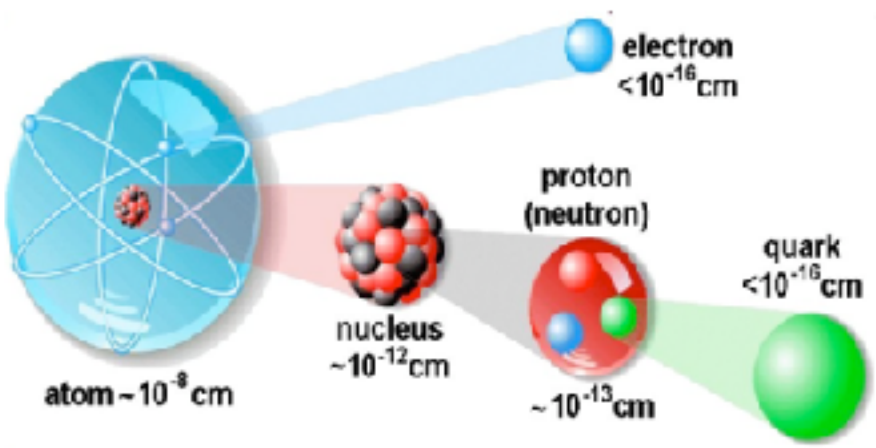
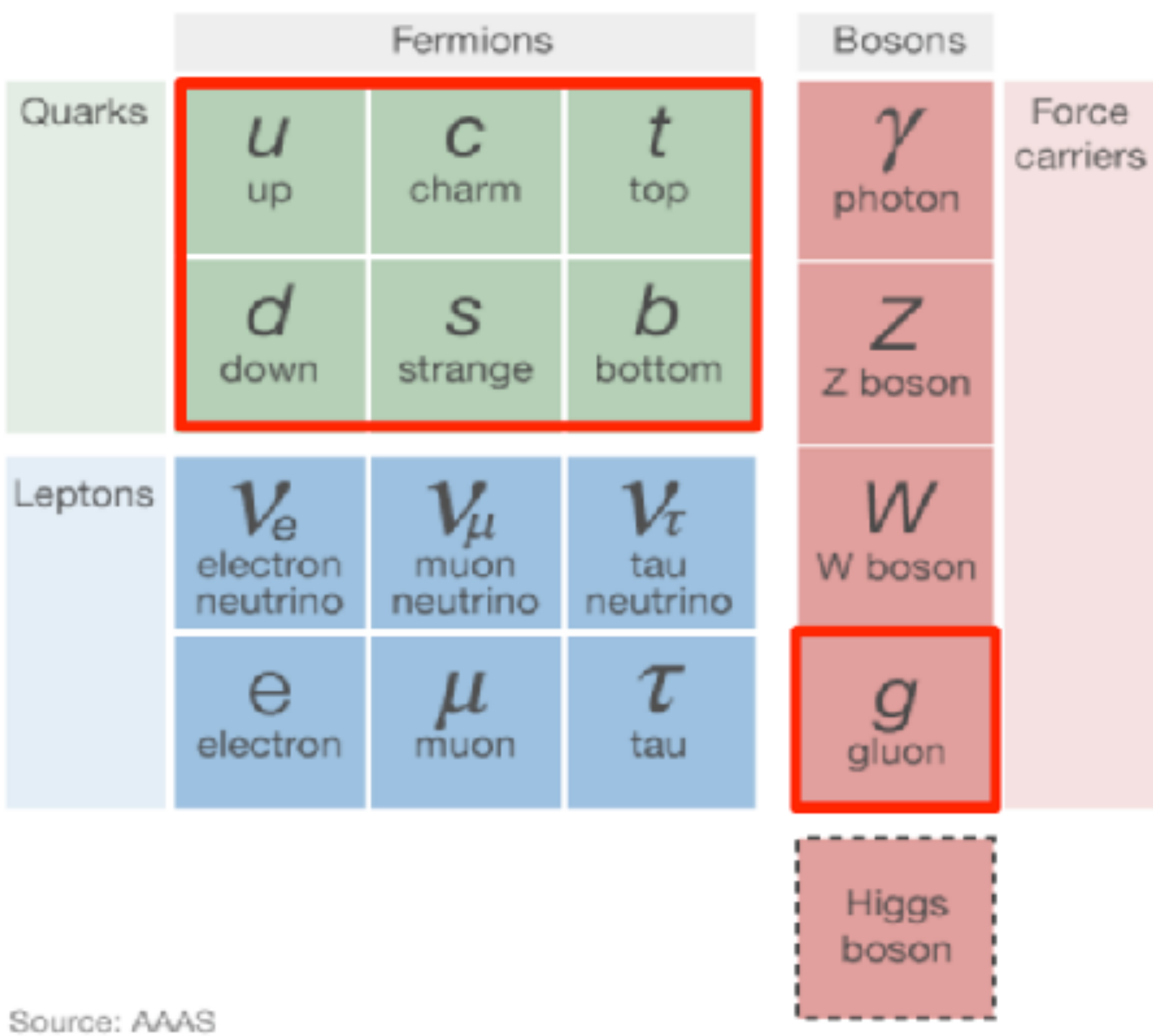
Introduction

Disclaimer: *biased selection of measurements , much more available !*

Quark confinement





Theory of the strong interaction

Quantum Chromodynamics

Quarks carry a color charge

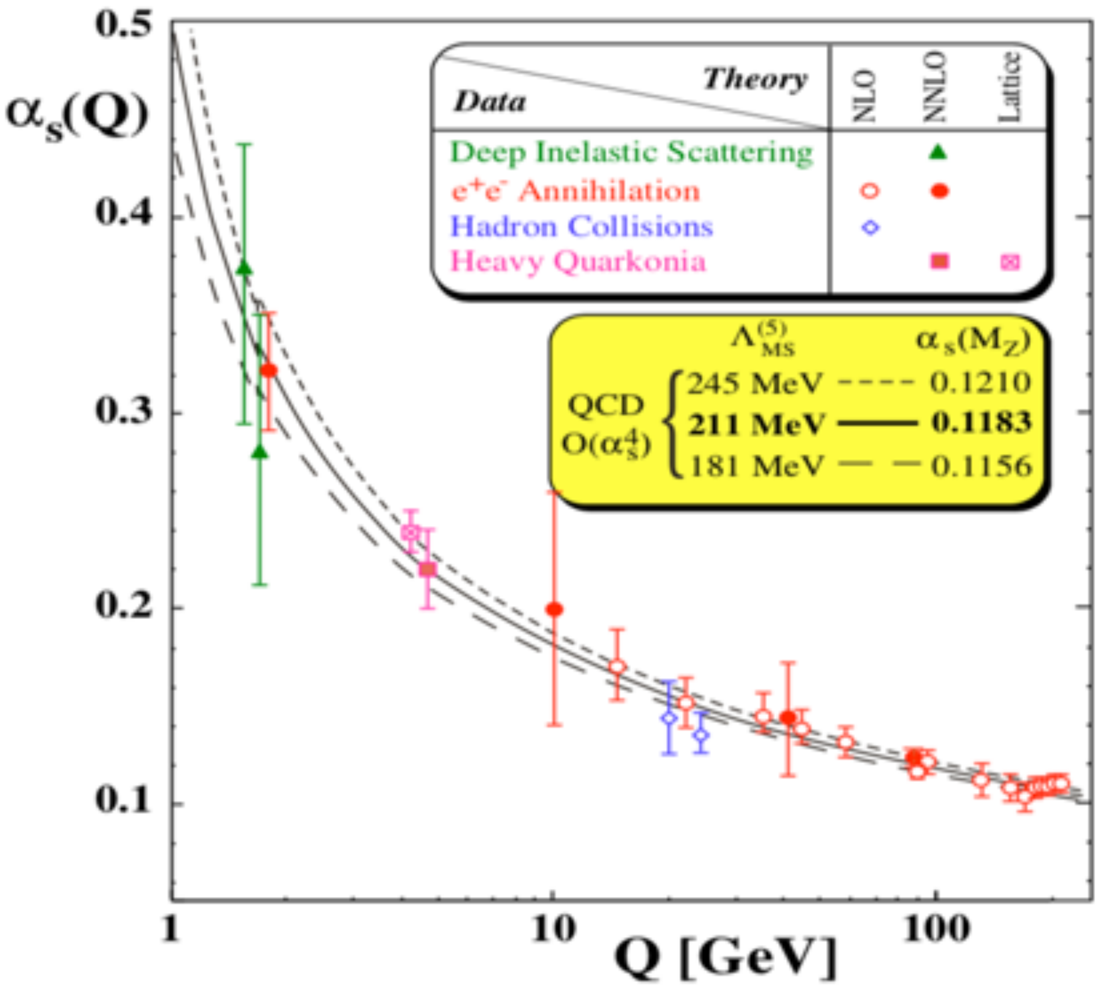
(blue, green, red)

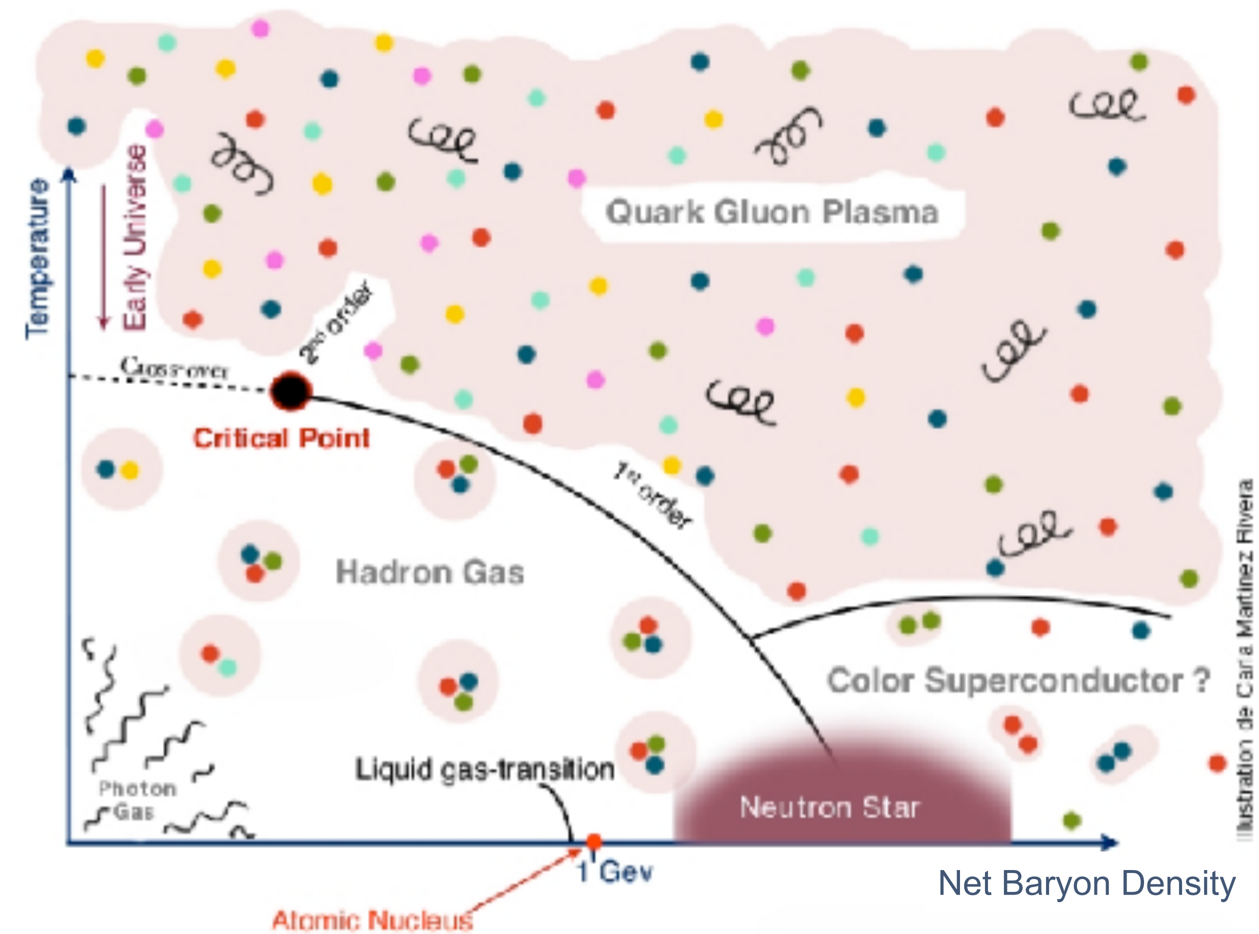
Only colorless object are observed

=

no free quark

Probing the phase diagram of nuclear matter





At low energy:

Confinement regime

At high energy:

Quasi-free particles

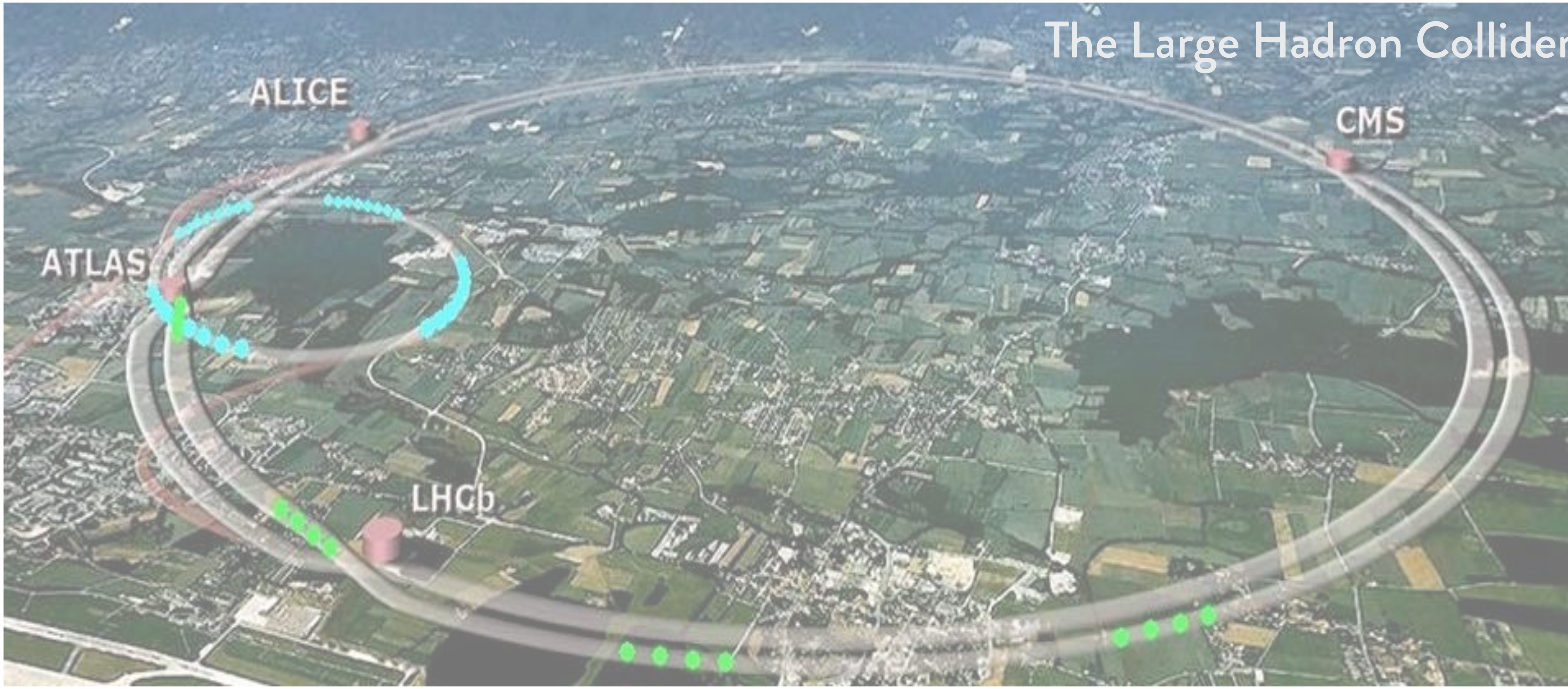
Open questions:

equation of state

transition order

critical point ?

Heavy ion collisions at LHC



p-p collisions •p→←p•

- Reference for p-A and A-A measurements
- Test pQCD calculations (QCD vacuum)

p-A collisions •p→←◎Pb

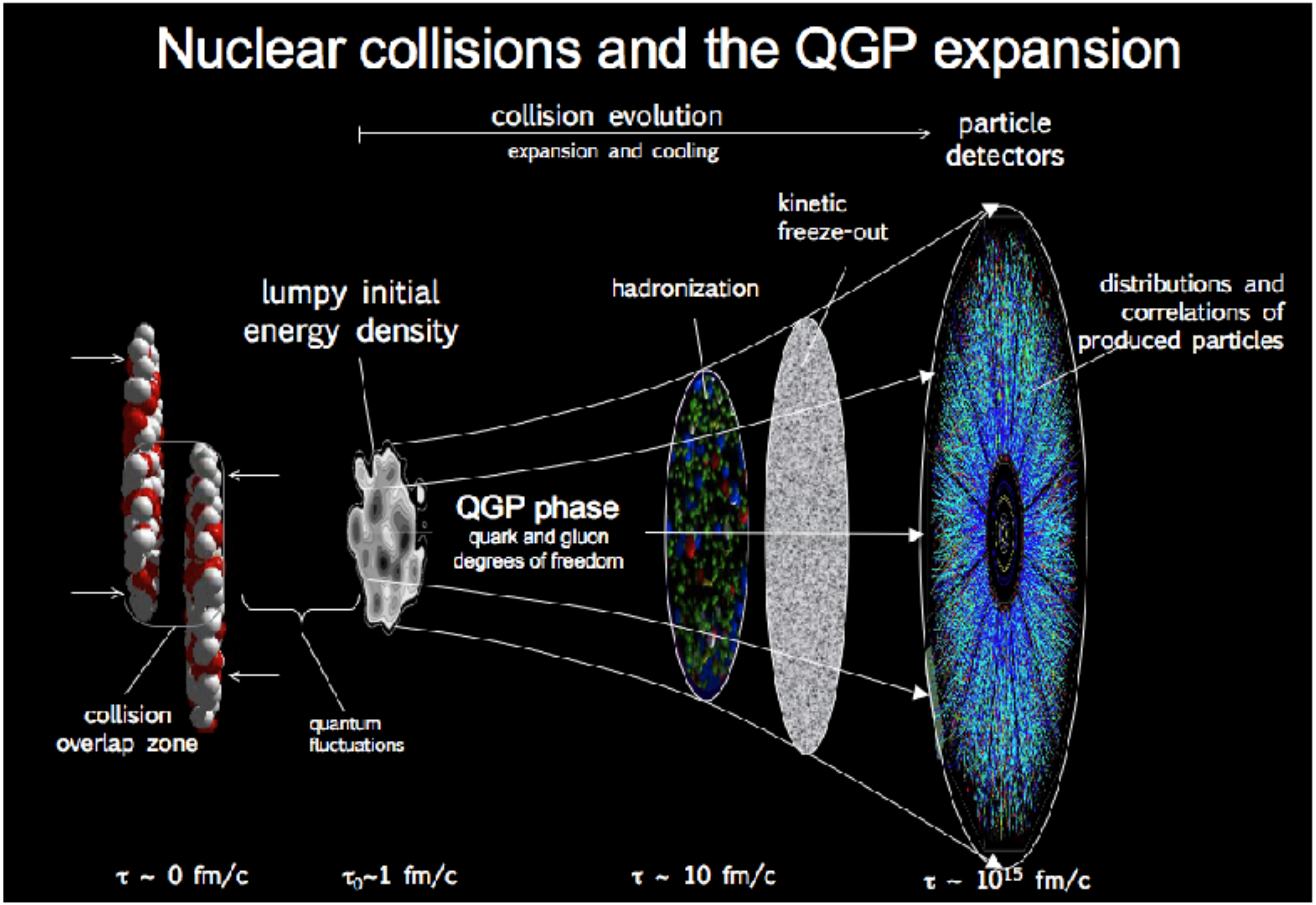
- Study cold nuclear matter (CNM) effects

A-A collisions ◎Pb→←Pb◎

- **Form and study the Quark Gluon Plasma**

Time evolution of a collision

P. Sorensen, arXiv:0905.0174



Observables

- Global
- Light hadrons
- Strange hadrons
- Quarkonia
- Open heavy flavours
- Jet and high p_T hadrons
- Electroweak probes
- Others (Exotic, UPC, …)

x

- Centrality
- Rapidity
- p_T
- Azimuthal angle
- Centre of mass energy
- Reaction plane
- Fluctuations
- Small systems
- Correlations

QCD/Models are crucial in the interpretation of the observables.

Due to complexity, a global and coherent scenario is a must

Collective flow

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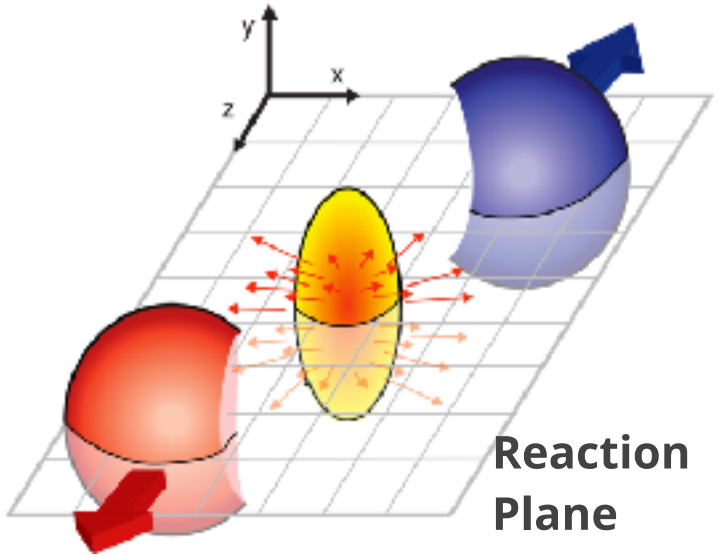
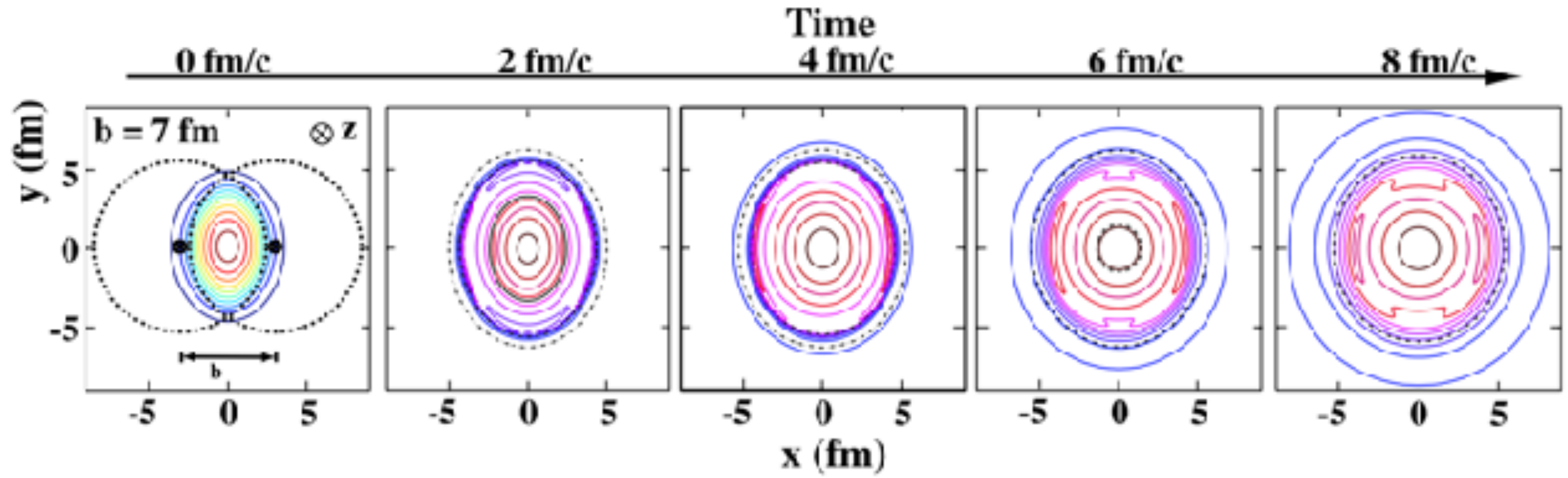
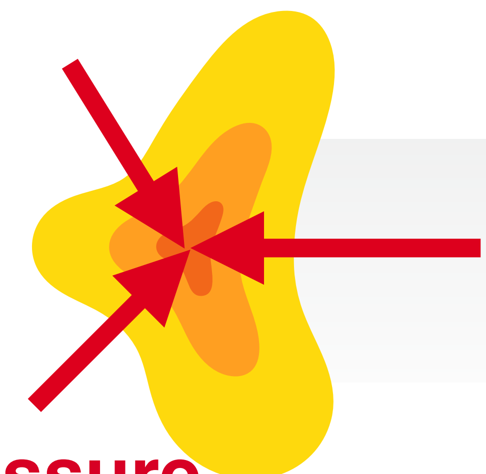
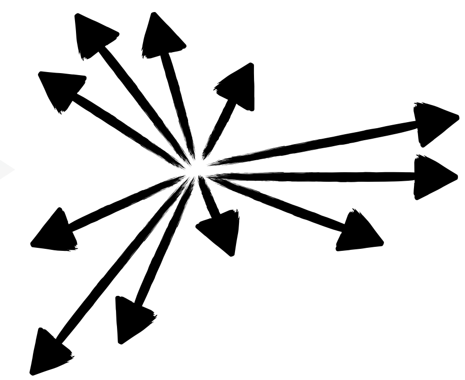
Anistropic matter distribution around the collision…







… if the system is interacting, reflected in the final particle momentum distribution

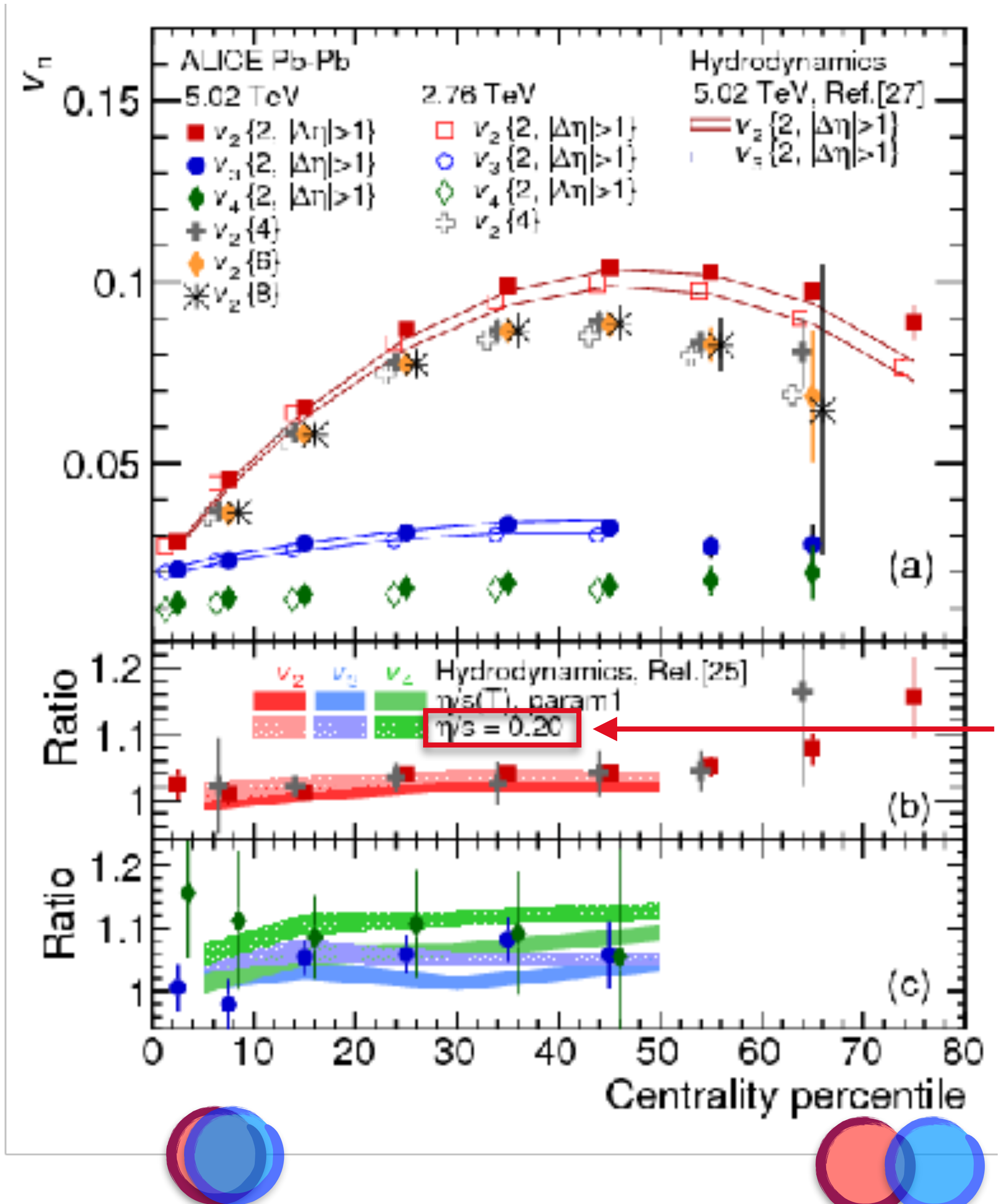


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\{1 + \sum_{n=1}^{\infty} 2 v_n \cos(n(\Phi - \Psi_{RP}))\}$$

Flow coefficients : $v_n = \langle \cos\{n(\Phi_i - \Psi_{RP})\} \rangle$

directed flow (v_1), elliptic flow (v_2), triangular flow (v_3), …

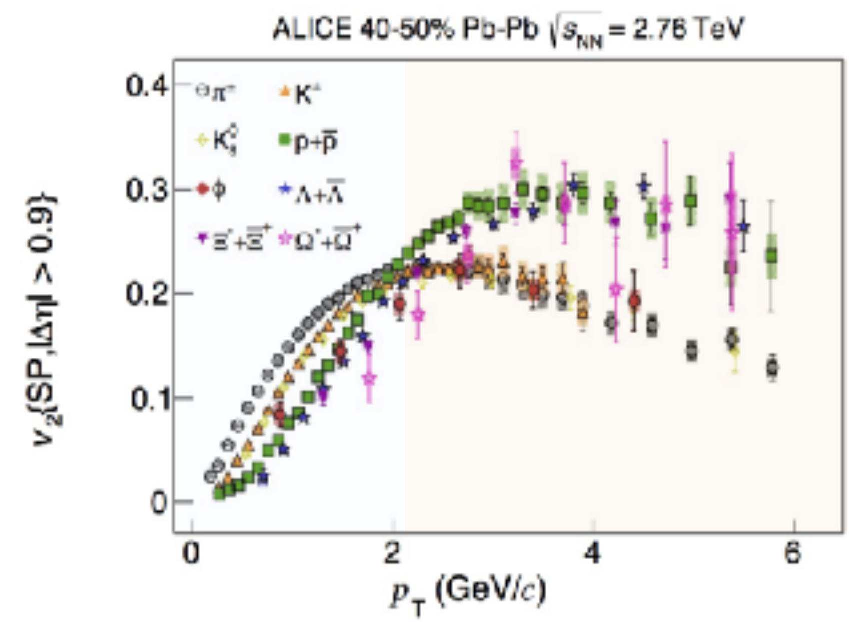
Elliptic flow of charged particles



At low p_T ($p_T < 2$ GeV/c) :
mass ordering

perfect fluid

lowest ratio estimated at $1/4\pi$



For intermediate p_T :
v_2 (Baryons) > v_2 (Mesons)

Comparison to hydro at low p_T :

- v_2 origin: early, partonic stages of the system
- v_2 governed by the QGP evolution

Main observables

Nuclear modification factor R_{AA}

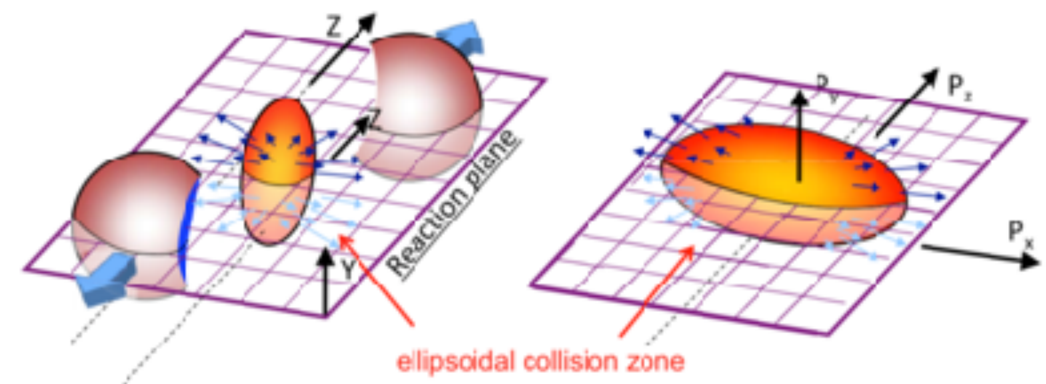
$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{PP}}$$

Quarkonium yield in A-A compared to the pp one, scaled by the overlap factor T_{AA} (from Glauber model)

- No medium effect : $R_{AA} = 1$
- $R_{AA} \neq 1$: cold nuclear matter + hot medium effects

Elliptic flow v_2

$$v_2 = \langle cos[2(\varphi - \Psi_{2,R})] \rangle$$



Almond shape of the overlap region

- v_2 >0: More particles in-plane
- v_2 <0: More particles out-of-plane

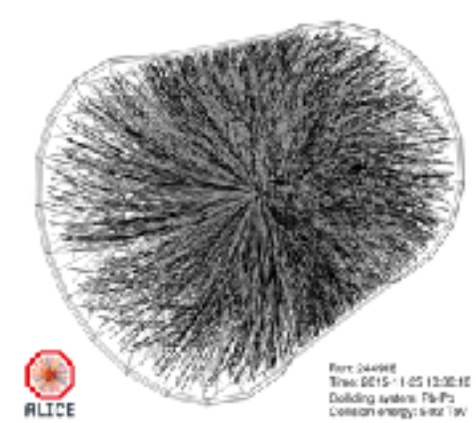
OUTLINE

Why do we measure heavy flavours ?

The ALICE detector

ALICE

Results in A-A and p-A collisions



Upgrade expectations

***Disclaimer:** biased selection of measurements , much more available !*

Why do we measure heavy flavours ?

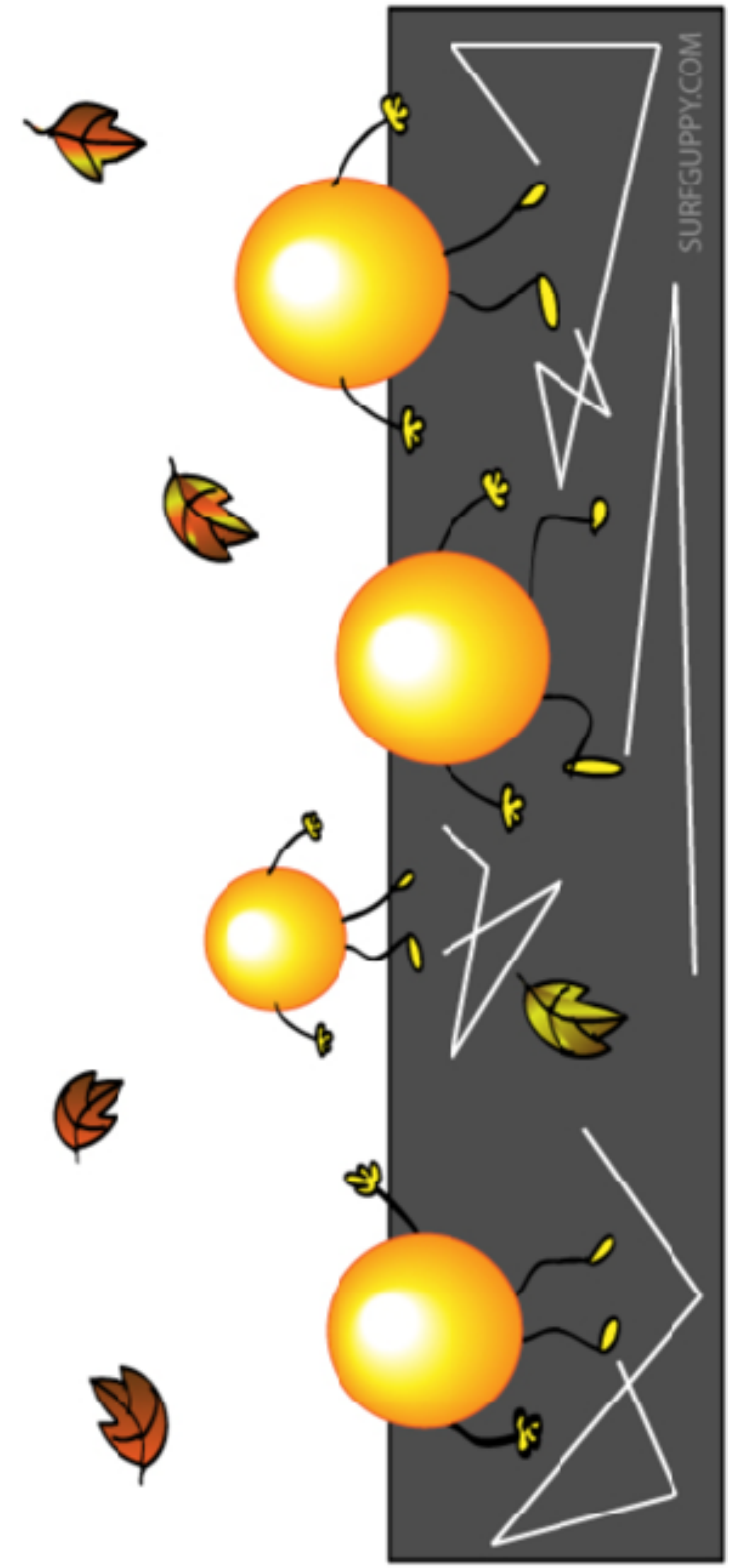
The ALICE detector

Results in A-A and p-A collisions

Upgrade expectations

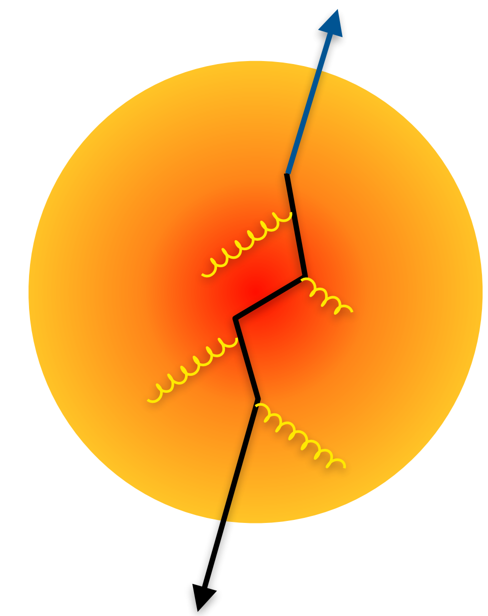
Motivations for HF studies

- In the QGP: local equilibrium is maintained until the phase transition
  - hadrons made of light quarks, carry only information on properties of the plasma close to the phase transition
  - not useful to obtain the desired information on the creation and the early time evolution of the QGP
- **Large mass of heavy quarks**
  - Longer thermal relaxation time
  - Extract transport coefficients in the medium
  - Estimate the thermalisation degree of heavy quarks



Motivations for HF studies

- **Heavy quarks in Pb-Pb collisions at the LHC**
  - early production (c ~ 0.1 fm/*c* vs. QGP ~ 0.3 fm/*c*)
    → experience the full system evolution
    Nucl.Phys. A757 (2005) 184-283
  - interact with the QGP : sensitive to the medium properties
  - No thermal production and negligible annihilation
    → Number conserved throughout partonic and hadronic stages of the collision



- **HF in Pb-Pb collisions: hard probes of the QGP**

Open heavy flavours

D mesons

Λ_c, Ξ_c

HF decay electrons and muons

Closed heavy flavours (Quarkonia)

$c\bar{c}$: charmonium J/ψ, ψ(2S)

$b\bar{b}$: bottomonium ϒ(1S) (2S) (3S)

Why do we measure heavy flavours ?

The ALICE detector

Results in A-A and p-A collisions

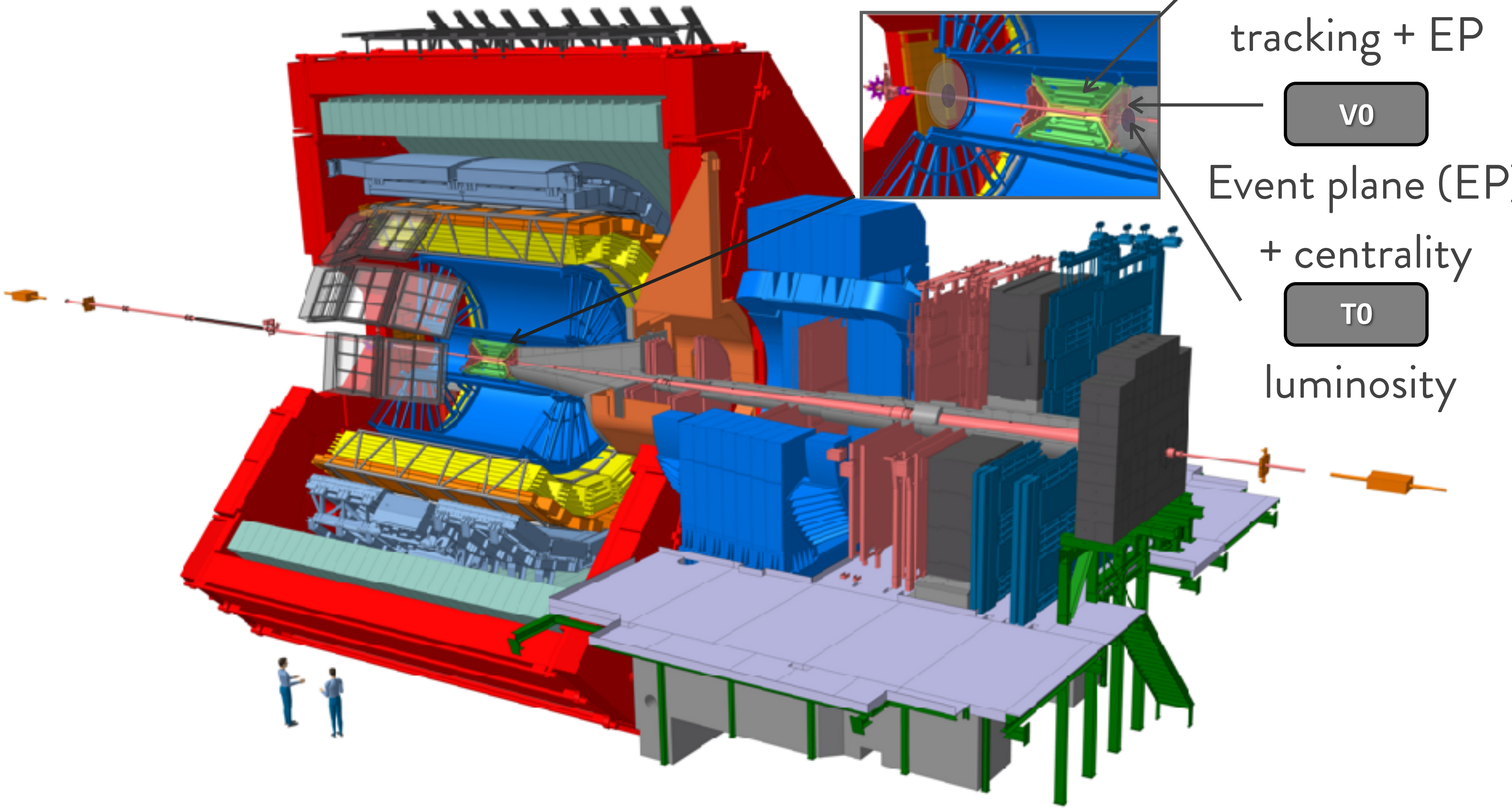
Upgrade expectations

The ALICE detector

Run 2

Pb-Pb at $\sqrt{s_{NN}}$=5.02 TeV

p-Pb (Pb-p) at $\sqrt{s_{NN}}$=5.02 TeV and 8.16 TeV



Open heavy-flavour in ALICE

HF decay electrons

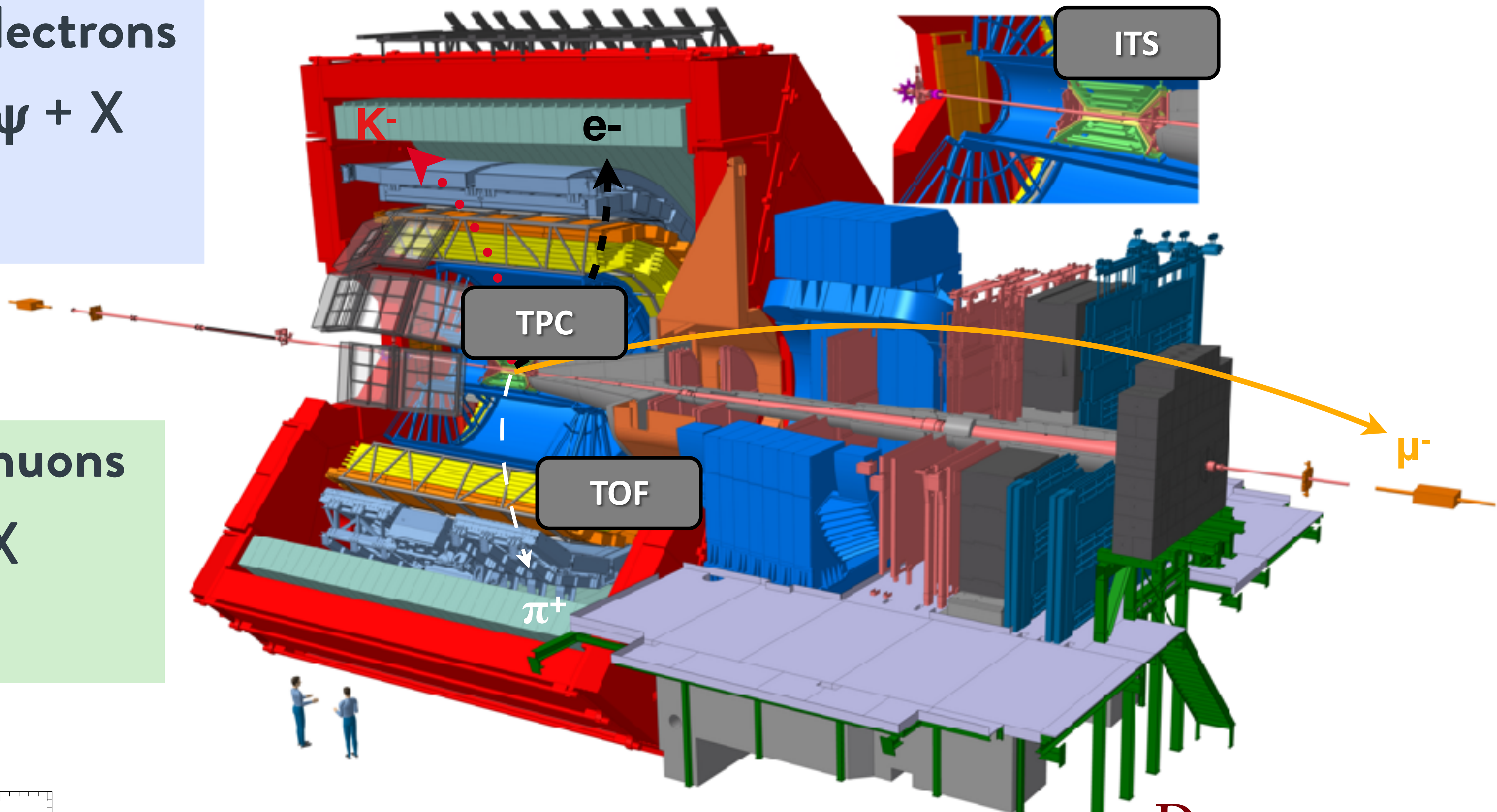
c,b→ $e^{\pm}$, J/ψ + X

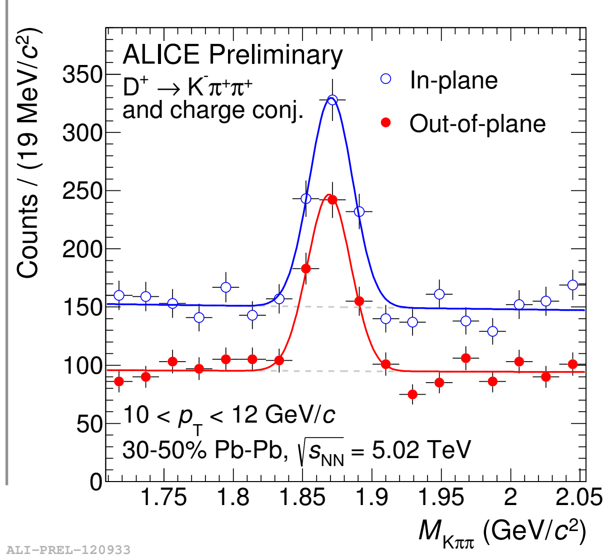
|η|< 0.8

HF decay muons

c,b → $\mu^{\pm}$ +X

-4<η<-2.5

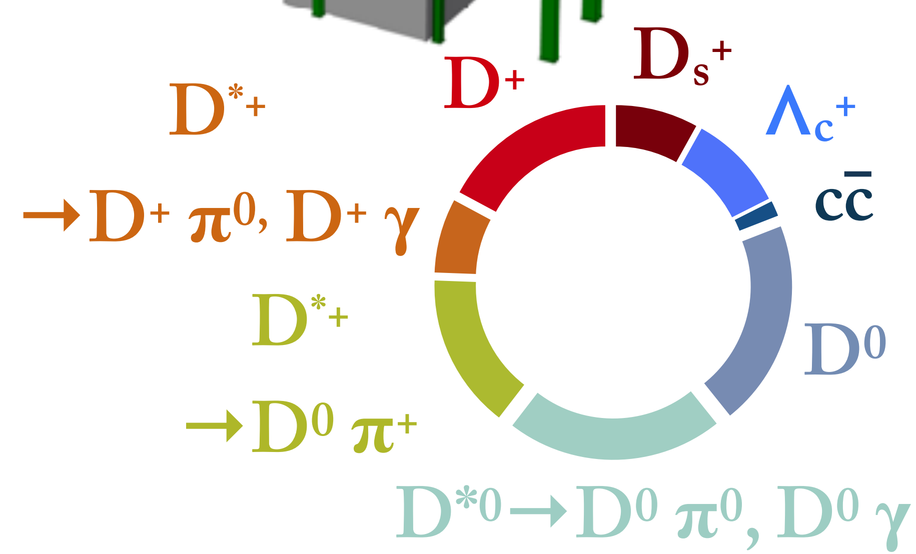




Open charm

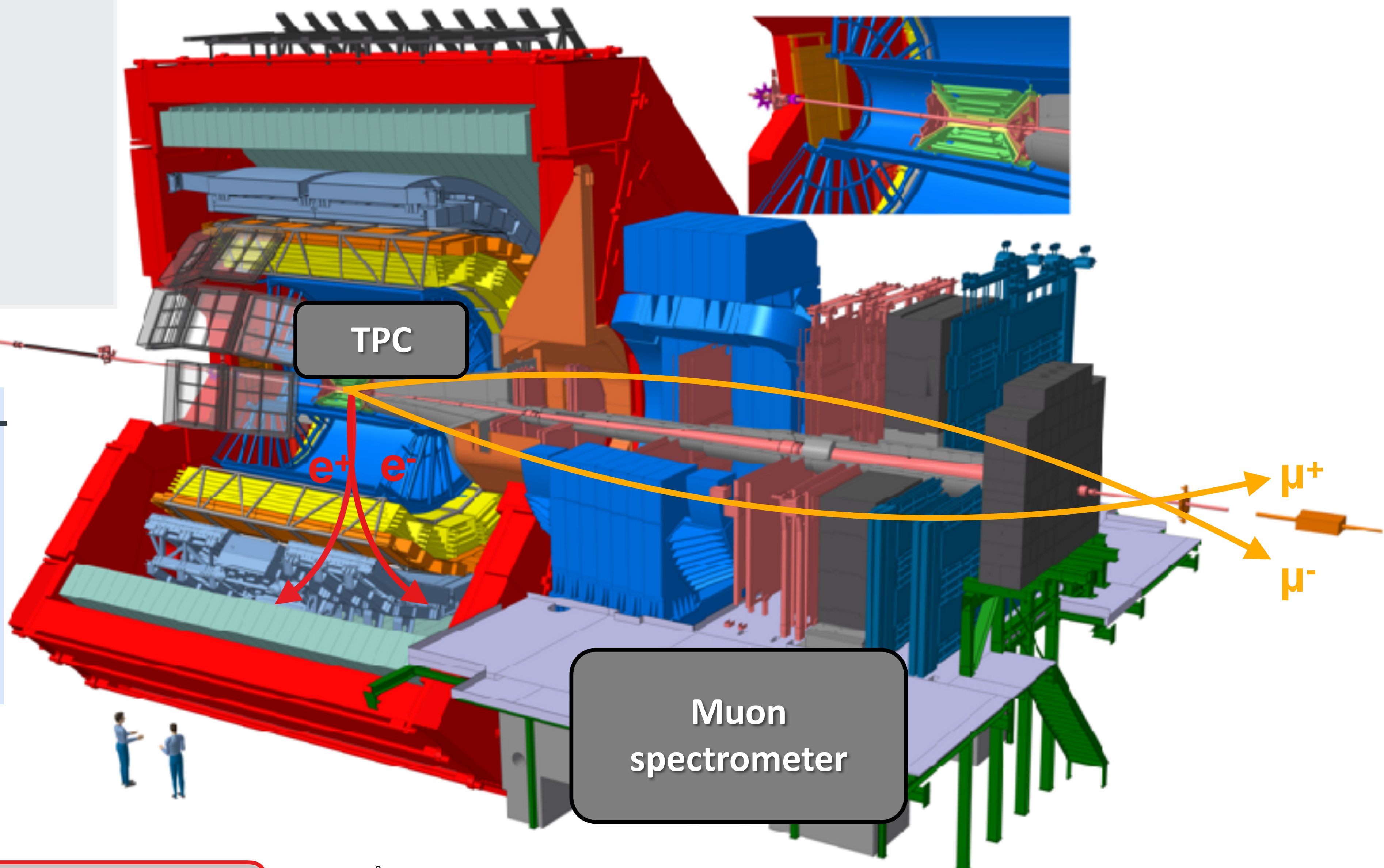
D^0, D^+, D^{*+}, D^+_s→$\pi^{\pm}$,$K^{\pm}$

|η|<0.9



Quarkonium with ALICE

Performed both at forward and mid-rapidity



Quarkonium → e^+e^-

- $|y| < 0.9$
- down to $p_T = 0$
- $\mathcal{L} = 13\mu b^{-1}$

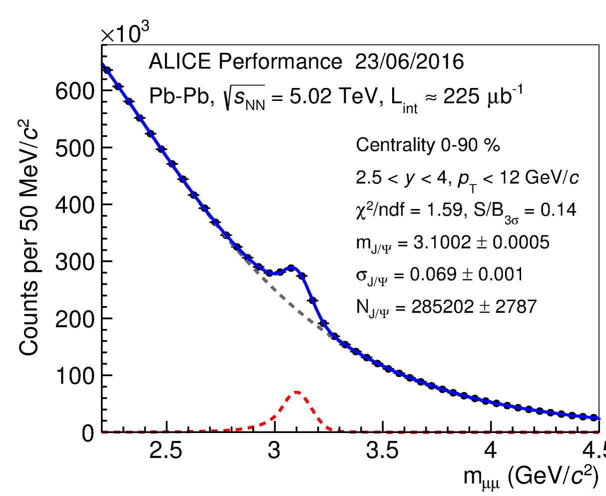
INCLUSIVE

PROMPT

Direct production + Feed-down from excited states

NON-PROMPT

B hadron decays



Quarkonium → $\mu^+\mu^-$

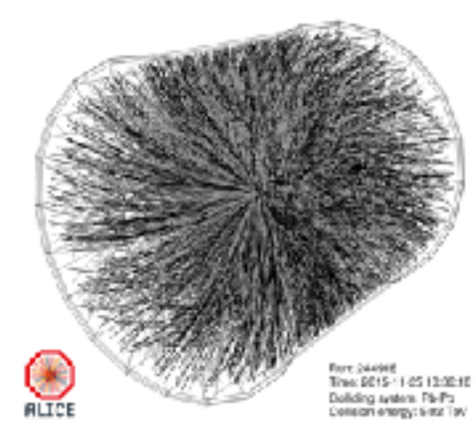
- $2.5 < y < 4$
- down to $p_T = 0$
- $\mathcal{L} = 225\mu b^{-1}$

Why do we measure heavy flavours ?

The ALICE detector

ALICE

Results in A-A and p-A collisions



Upgrade expectations

Open heavy flavours

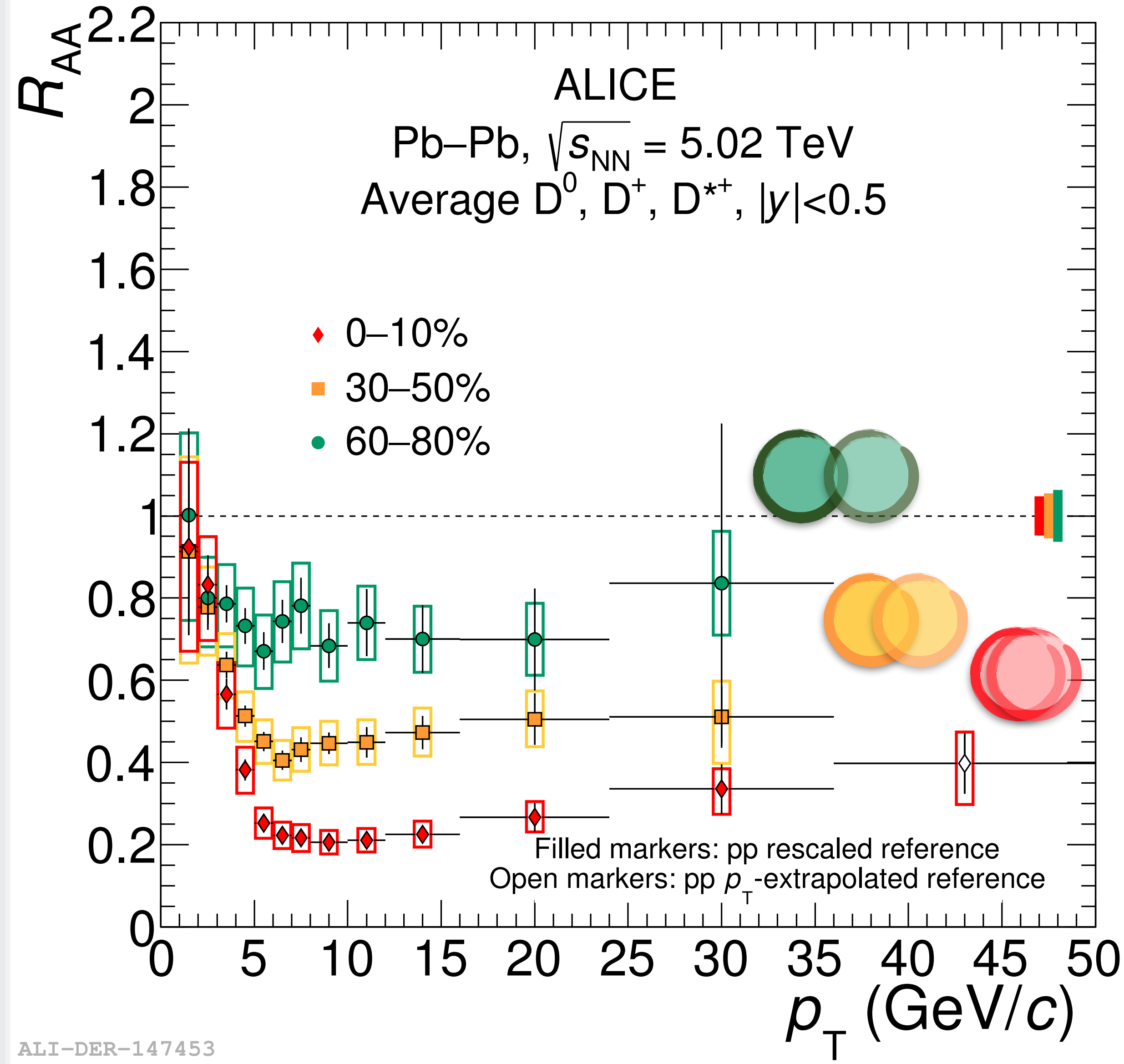
Formation involves both hard and soft processes

Strong suppression in central events
→ affected by energy loss, medium transport properties

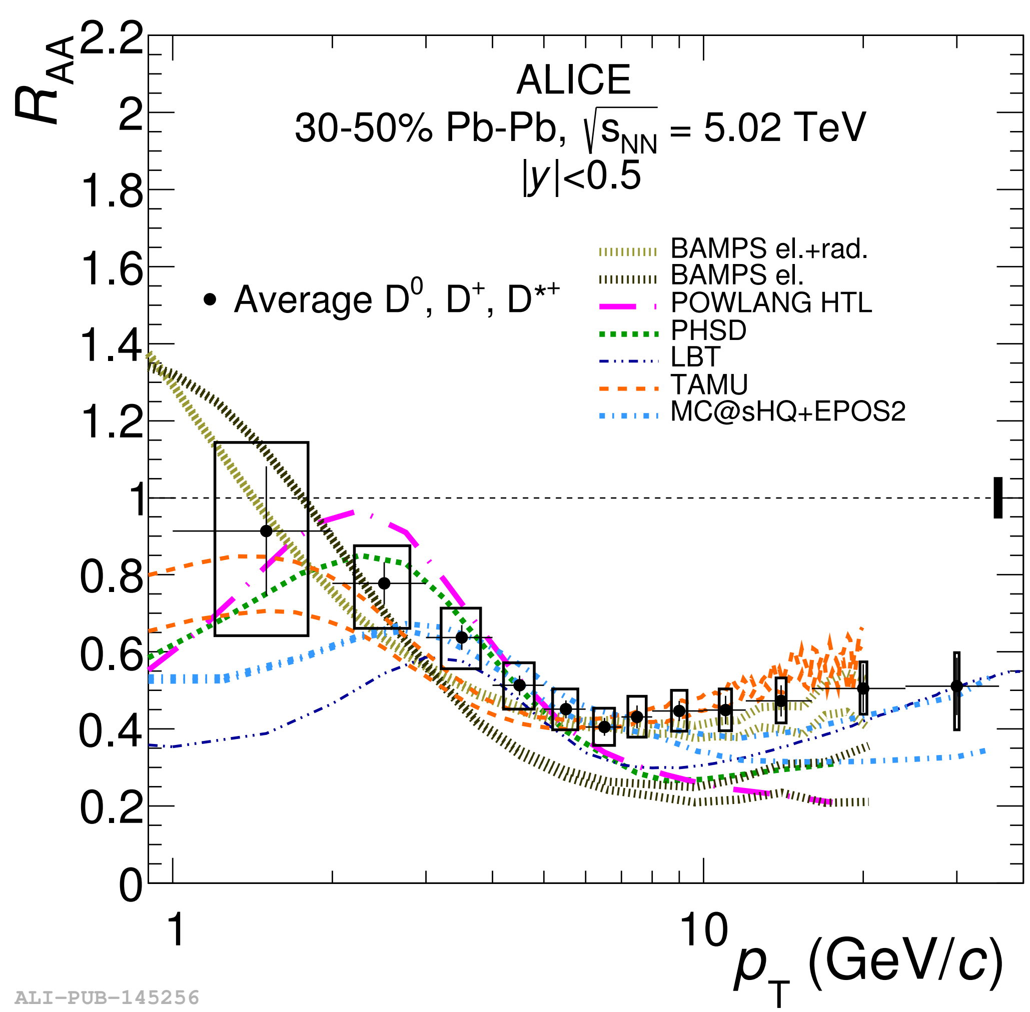
In-medium parton energy loss via collisional and radiative processes:

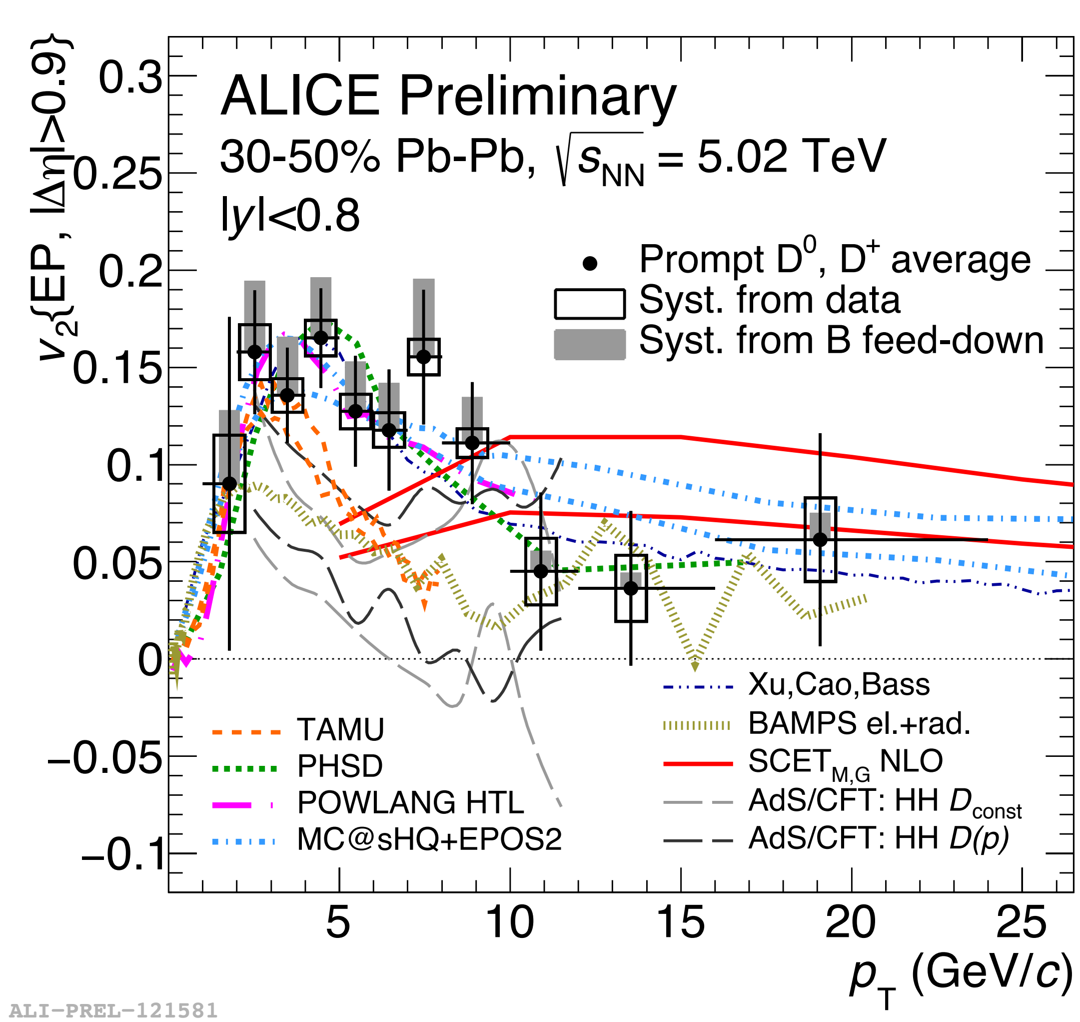
- medium density and path-length dependence
- colour-charge and quark-mass dependence

Modification in the hadronisation mechanism in presence of a medium



The elliptic flow of D mesons at $\sqrt{s_{NN}}$ = 5.02TeV





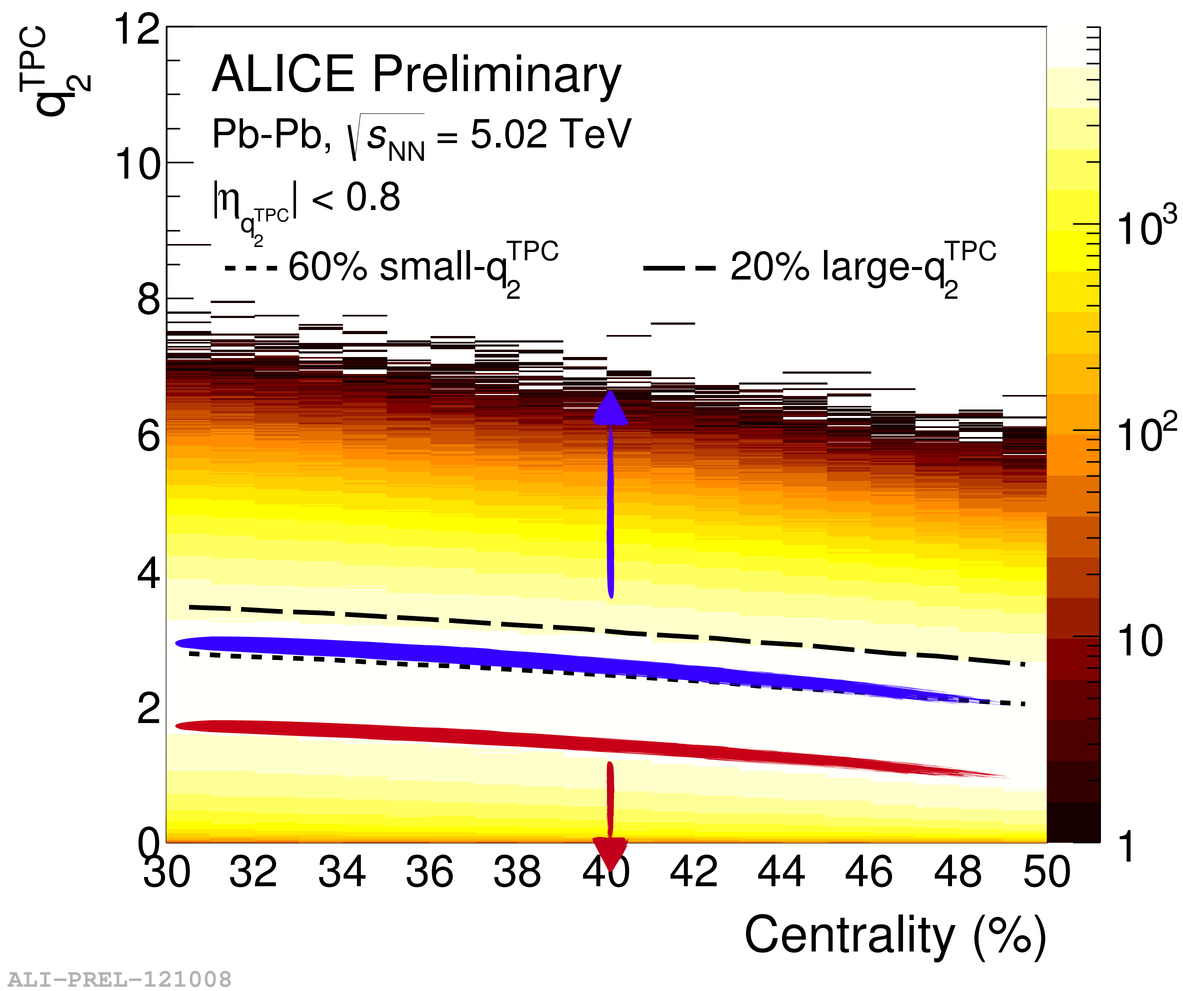
Good theoretical description but challenging when combining both observables

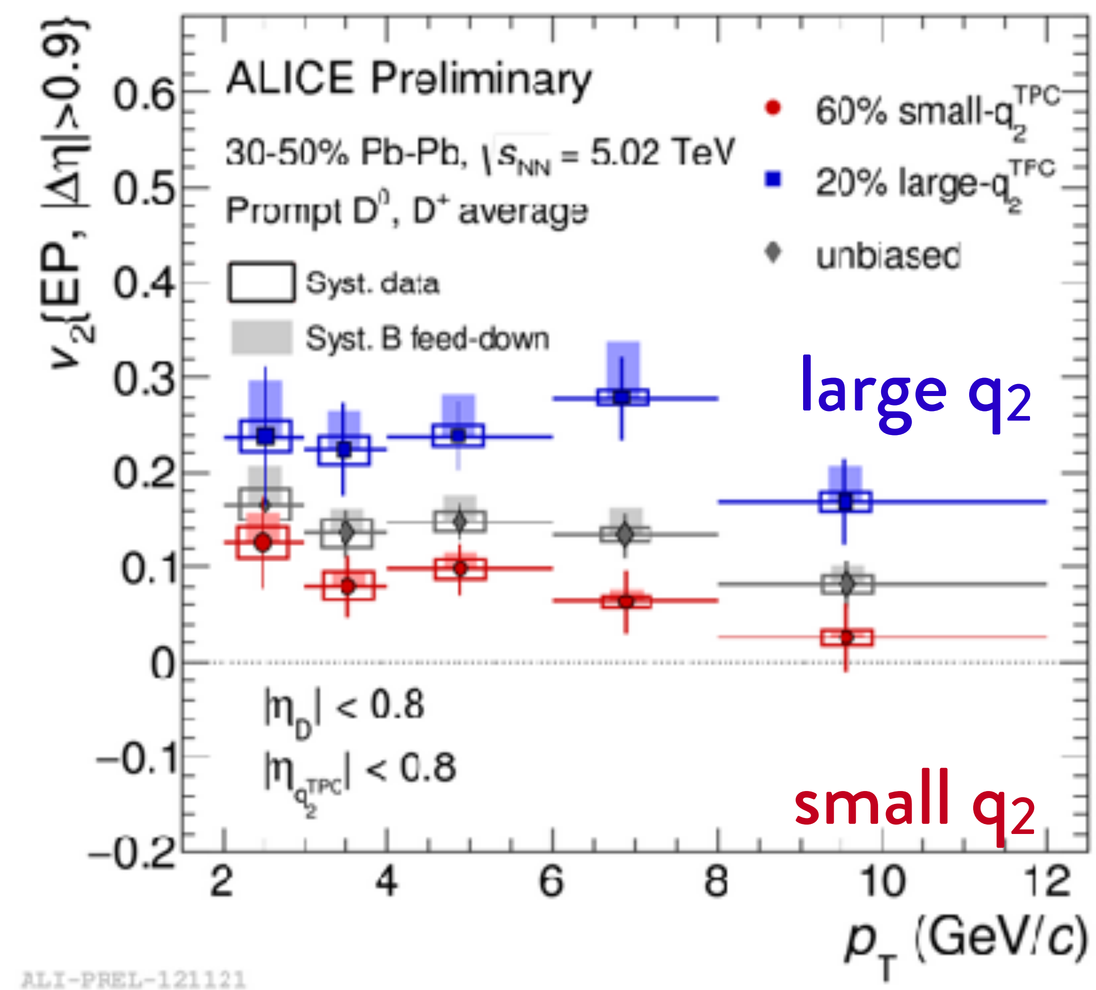
Extract charm transport coefficient

Comparison to other species:

- → **hadronization mechanisms**
- → **Partonic charm v_2, scaling w.r.t. light quarks**

The elliptic flow of D mesons at $\sqrt{s_{NN}}$ = 5.02 TeV





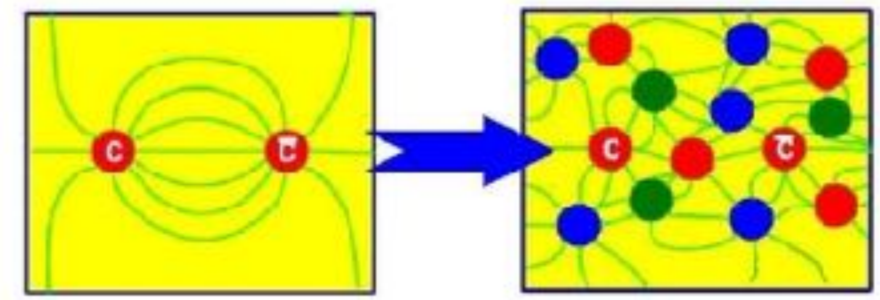
Results with the Event Shape Engineering method:
study the coupling of c quark to the bulk of light quarks

→ Heavy quarks participate to the collective expansion dynamics

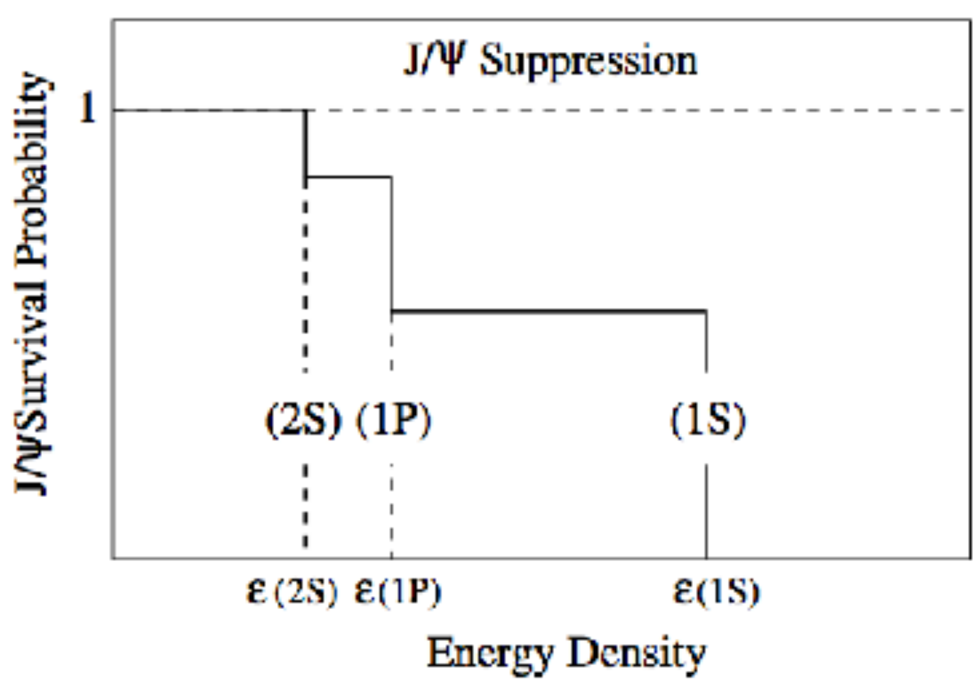
Quarkonium in the QGP

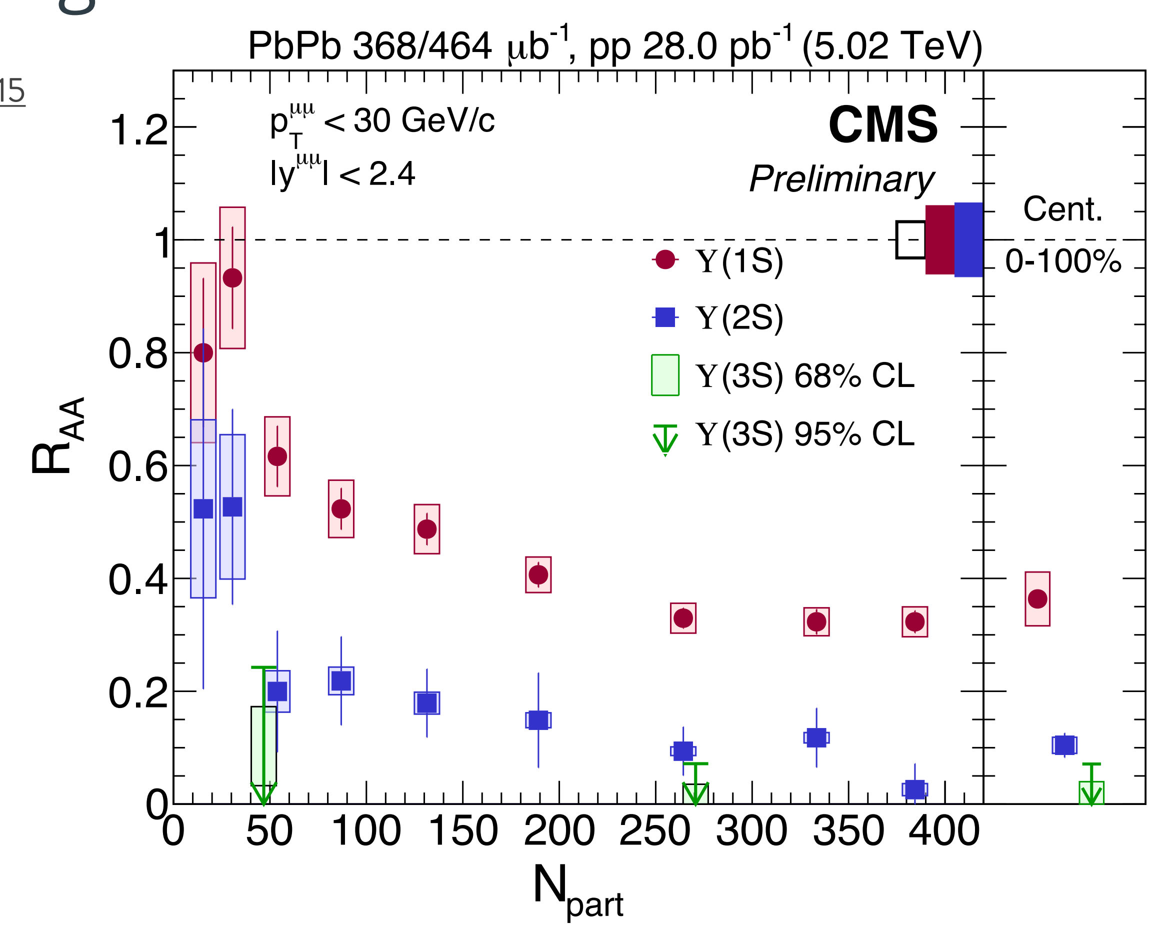
Quarkonium suppression :

- Initially : J/ψ suppression predicted by Matsui and Satz in 1986 by **Debye screening mechanism** Phys.Lett. B178 (1986) 416-422



- Different quarkonium binding energy : **sequential suppression** with increasing medium temperature Phys. Rev. D 64 (2001) 094015





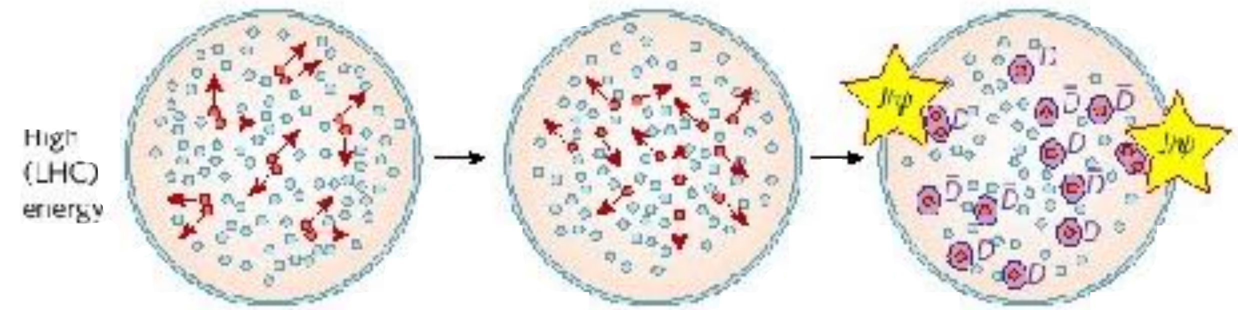
Quarkonium in the QGP

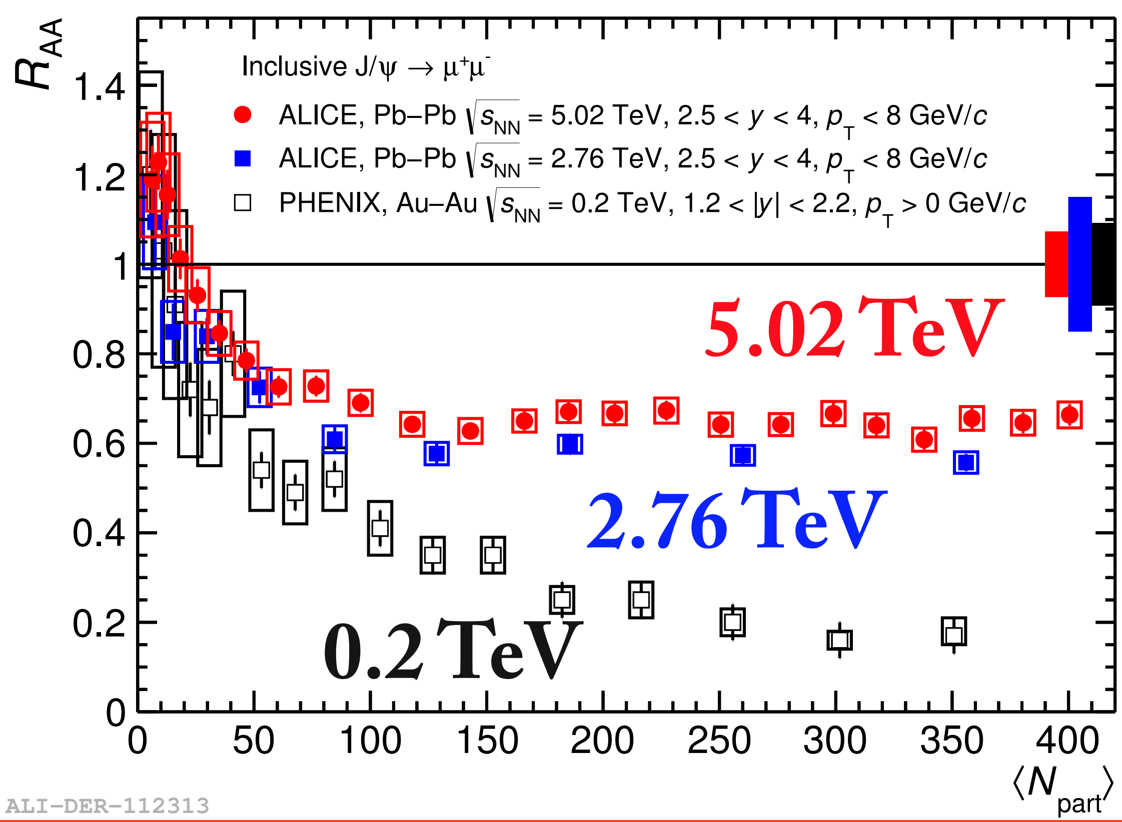
Quarkonium suppression

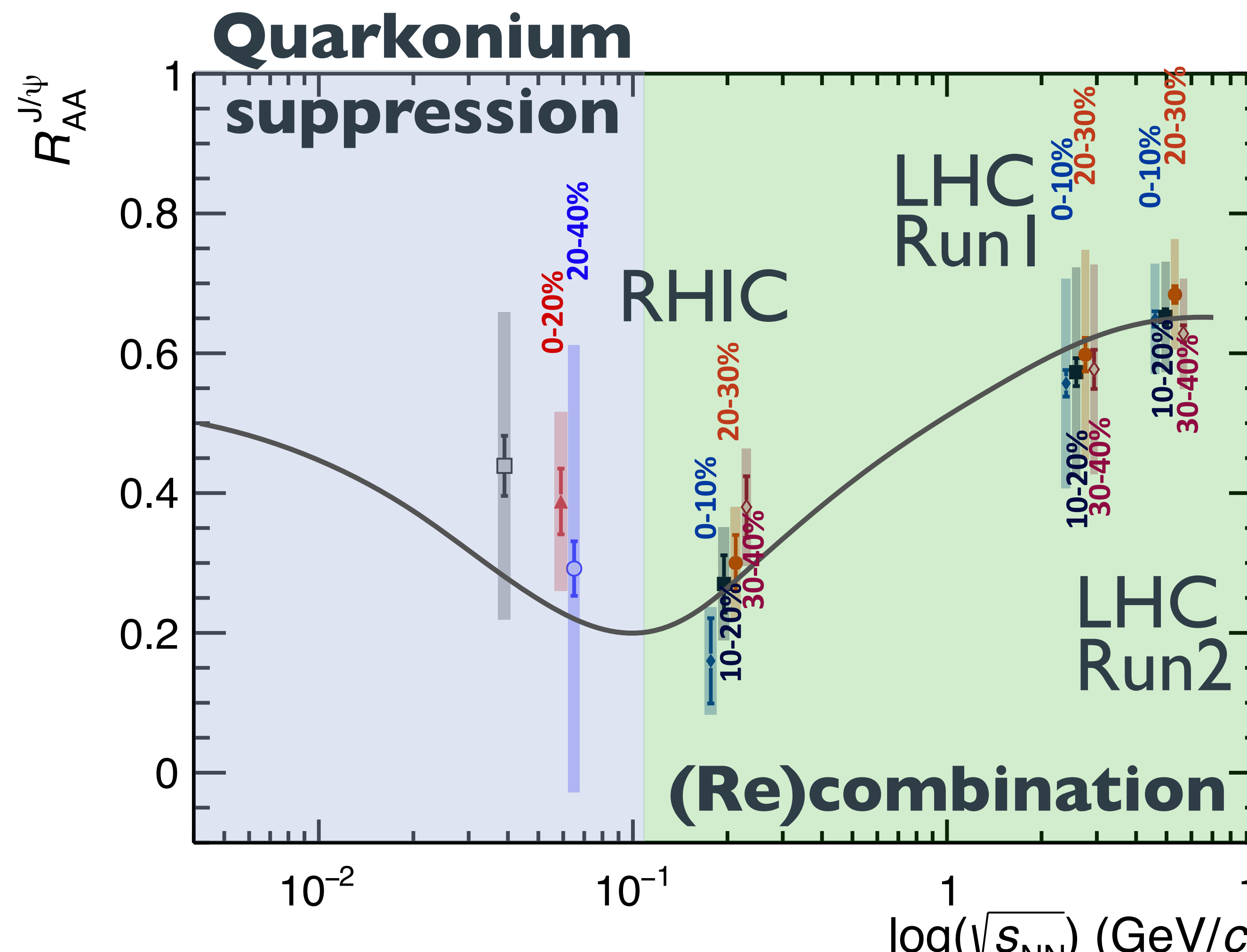
(Re)combination :

- Increased charm quark density
  →enhanced quarkonia production

- **Less relevant for bottomonium than charmonium**

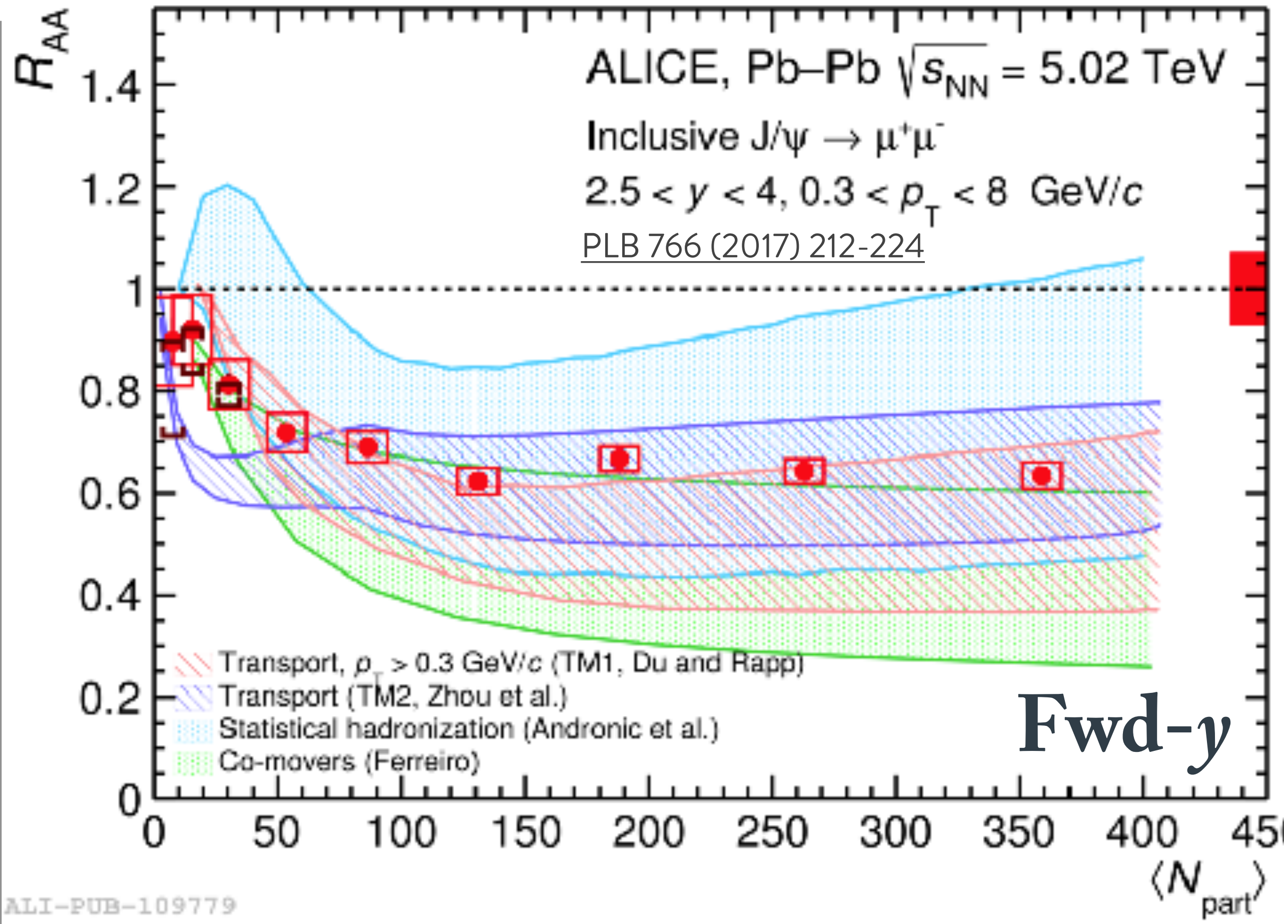


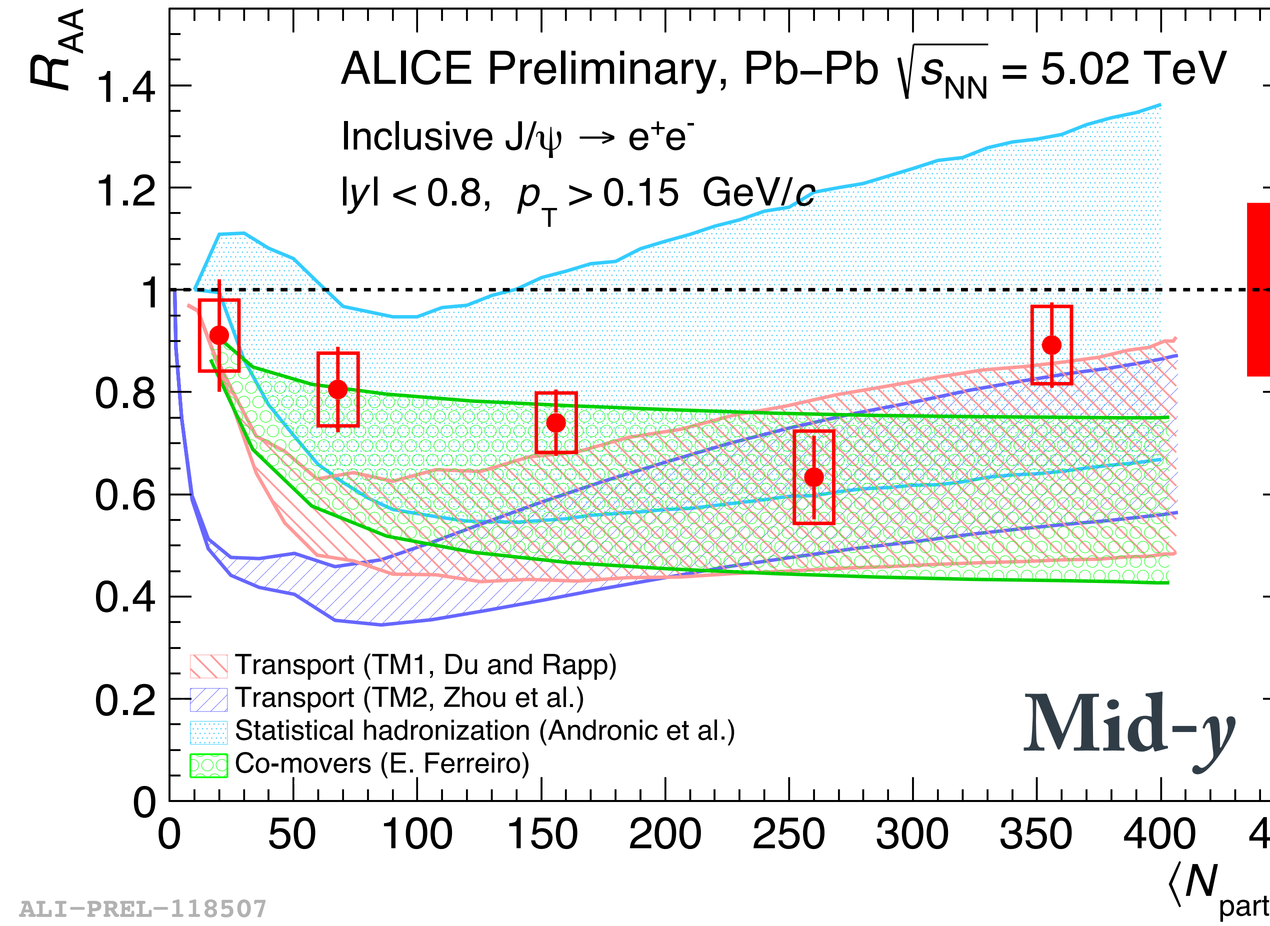




Eur.Phys.J. C39 (2005) 335-345ys. Lett. B 766 (2017) 212-224
Phys.Rev. C84 (2011) 054912 Phys. Rev. C 63 (2001) 054905
Phys.Rev. C86 (2012) 064901 Phys. Lett. B 490 (2000) 196–202
Phys.Rev.Lett. 109 (2012) 072301Phys. Conf. Ser. 509 (2014) 012019

Quarkonium in the QGP





Phys.Lett. B766 (2017) 212-224

Exp. observations interpreted as suppression + (re)combination

All models reproduce data

Main sources of uncertainties

- Precise determination of $c\bar{c}$ cross-section
- CNM effects on quarkonium production

Transport models: TM1 and TM2

Zhao et al., NPA859, 114, Zhou et al., PRC89, 054911

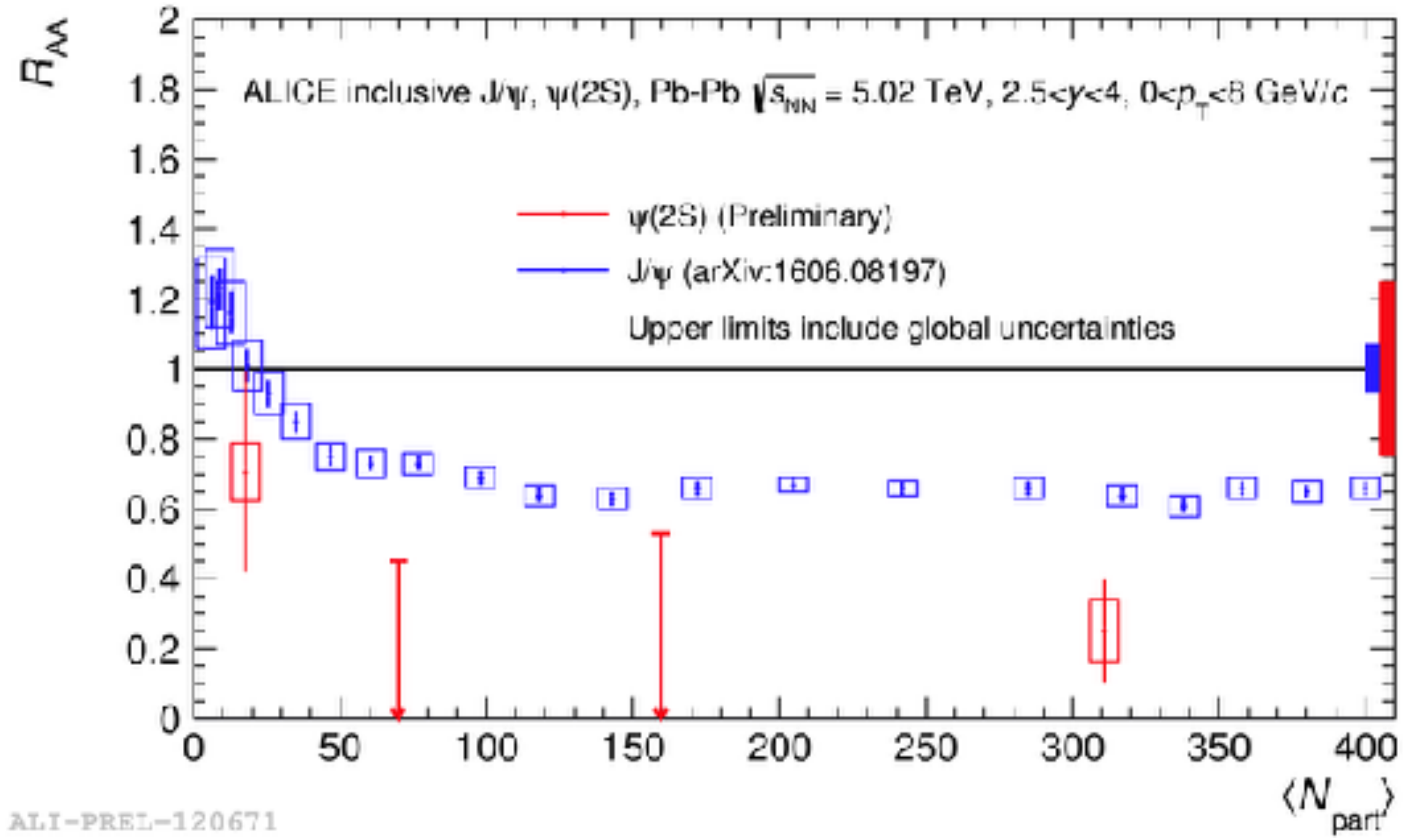
Statistical hadronization

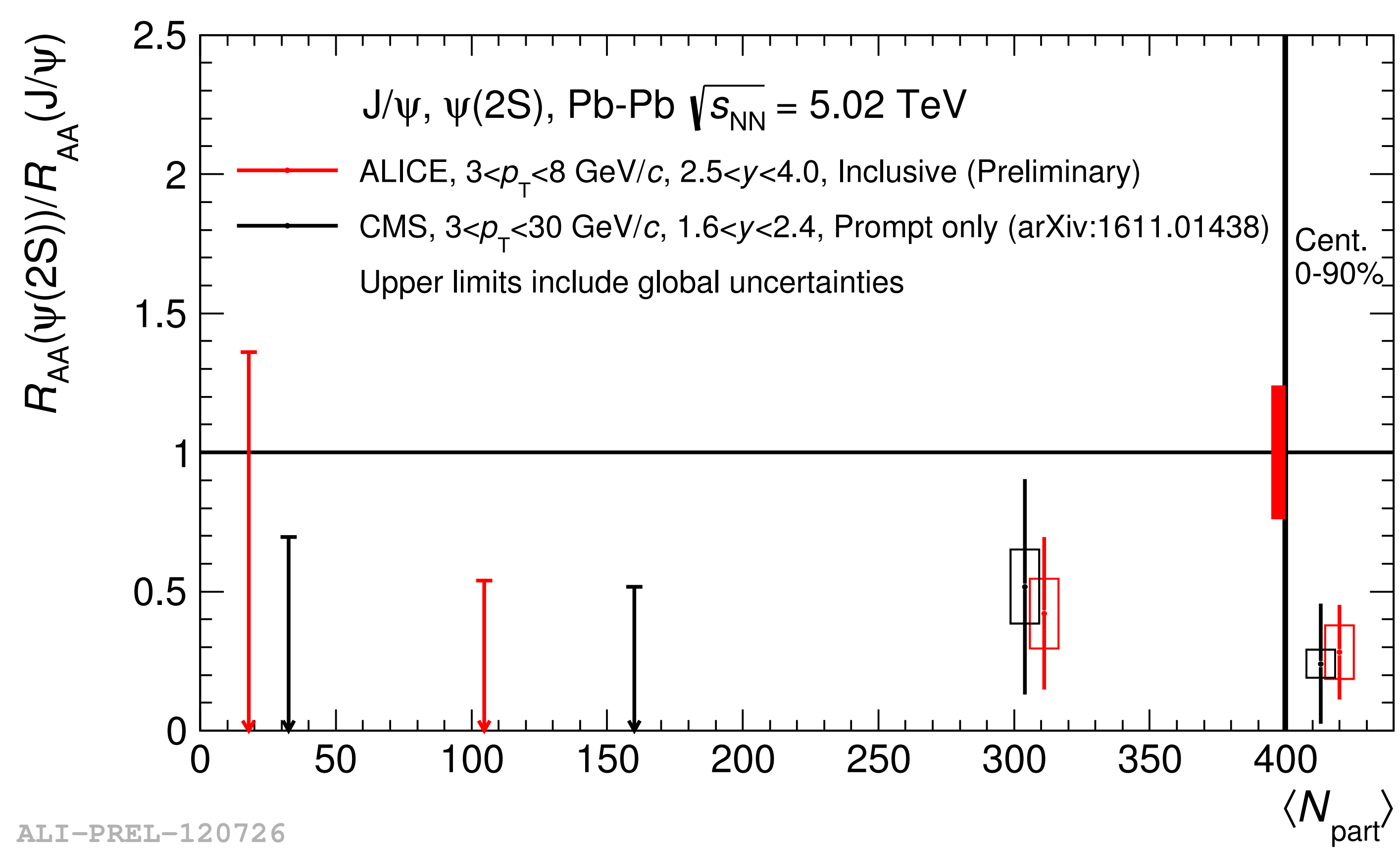
Andronic et al., NPA 904-5, 535c

Co-movers interaction model

Ferreiro et al., PLB731, 57

Charmonium in the QGP





ψ(2S) is expected to be more easily dissociated than J/ψ

ψ(2S)/J/ψ should greatly help model discrimination

Data show a stronger suppression in semi-central and central collisions

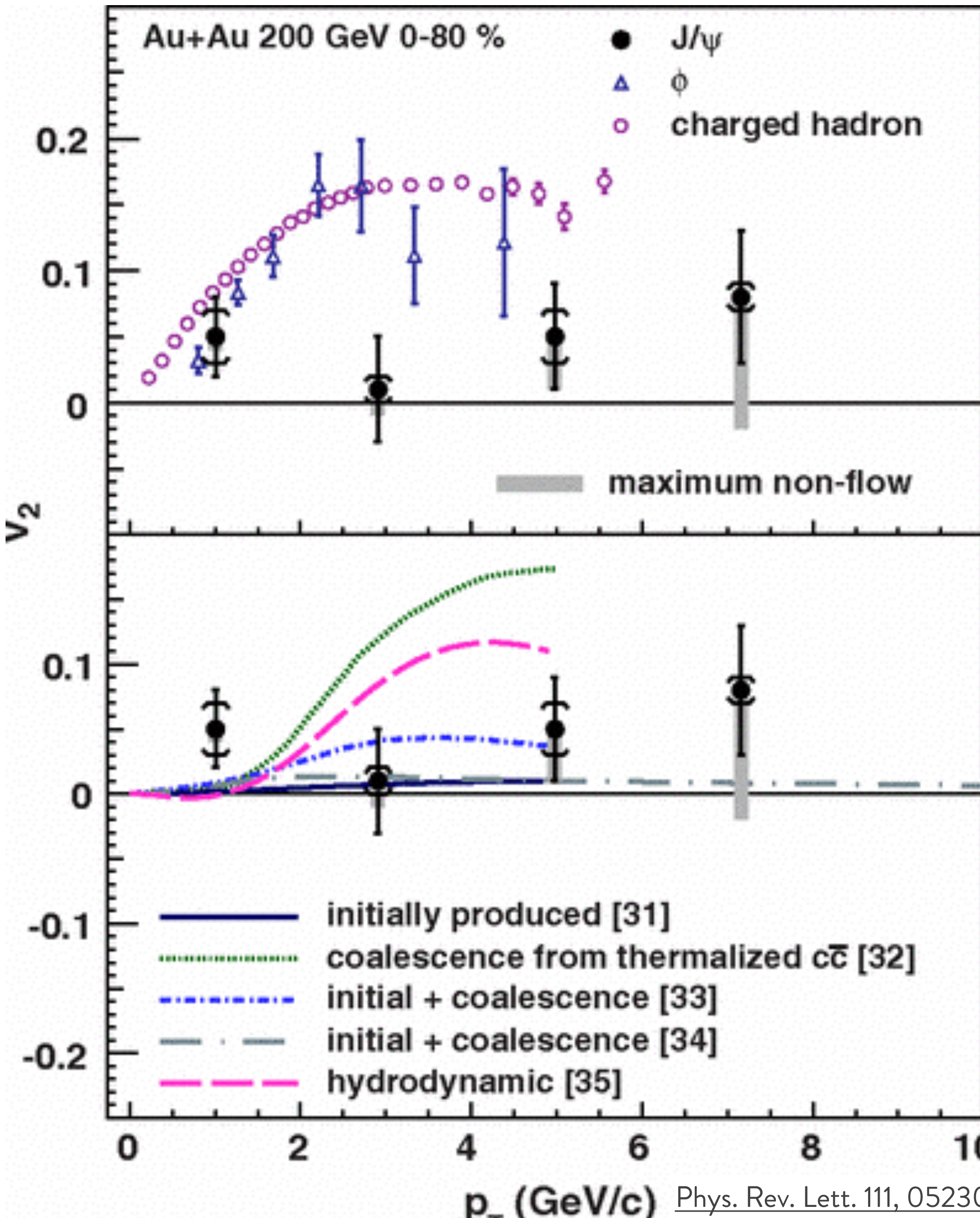
For low significance : upper limit at 95% CL

More statistics are needed
→ upgrades for LHC run 3

J/ψ v_2 at RHIC energies

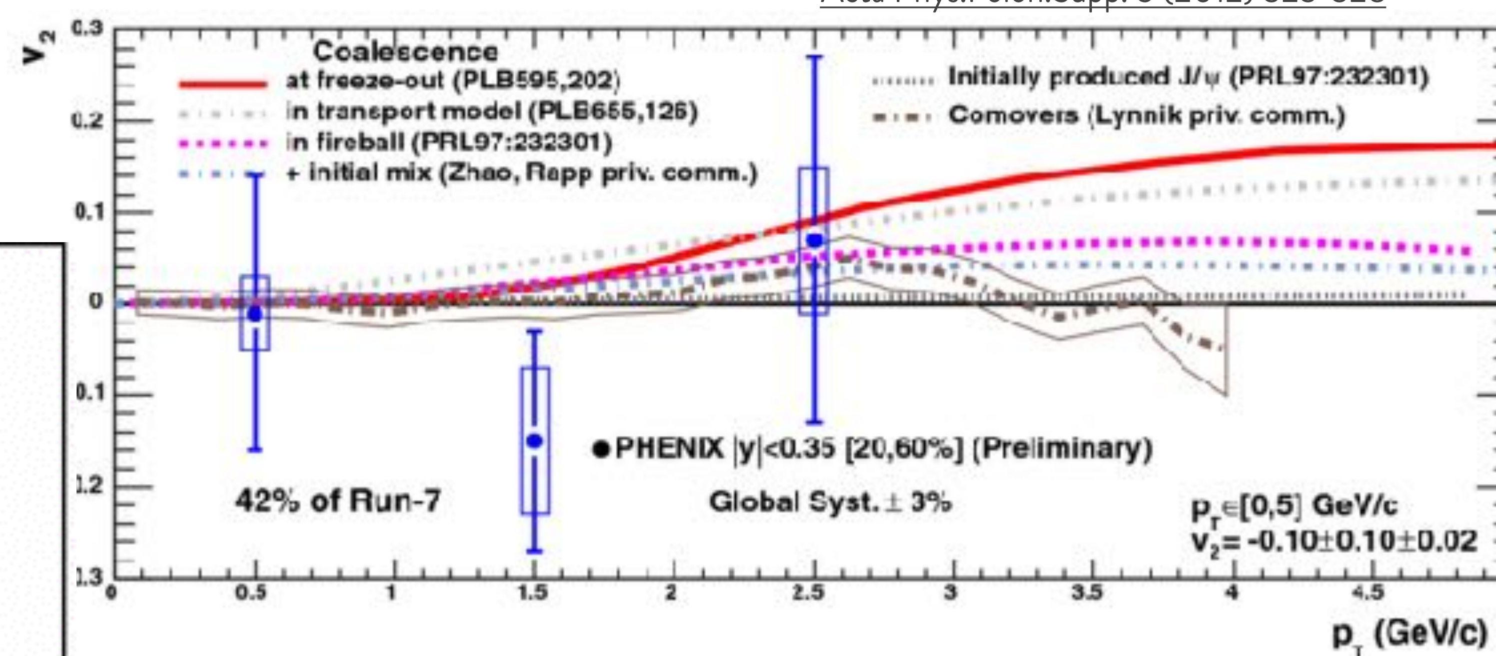
v_2 ~0 at RHIC energies

v_2 <0 at low p_T ?

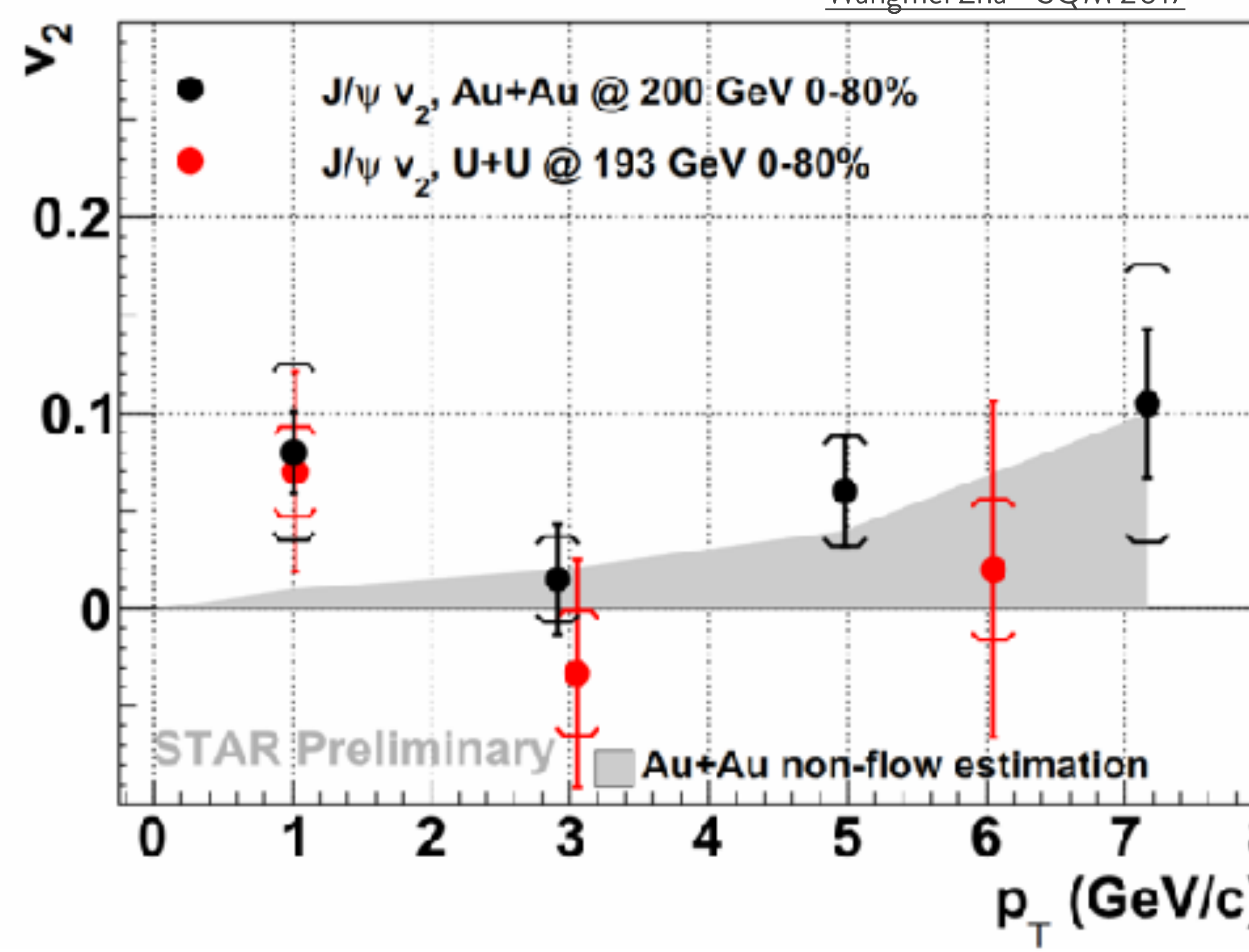


Phys. Rev. Lett. 111, 052301 (2013)

Acta Phys.Polon.Supp. 5 (2012) 323-328



Wangmei Zha - SQM 2017

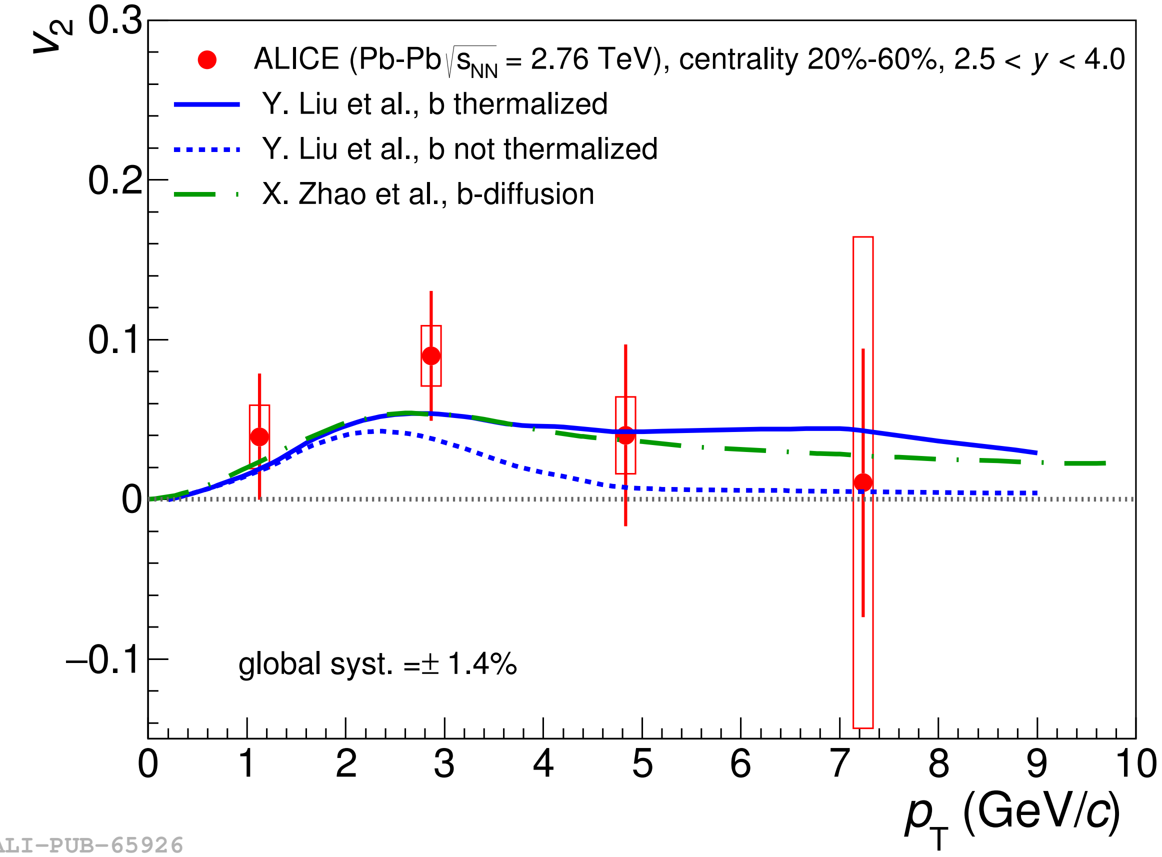


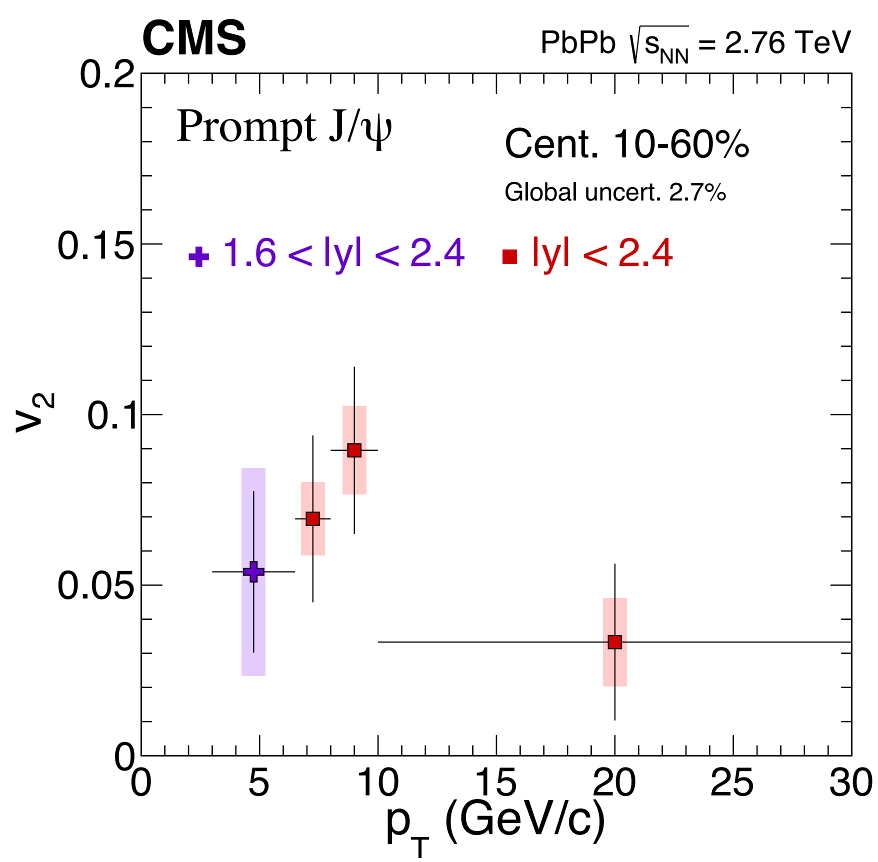
J/ψ v_2 at $\sqrt{s_{NN}}$ = 2.76TeV

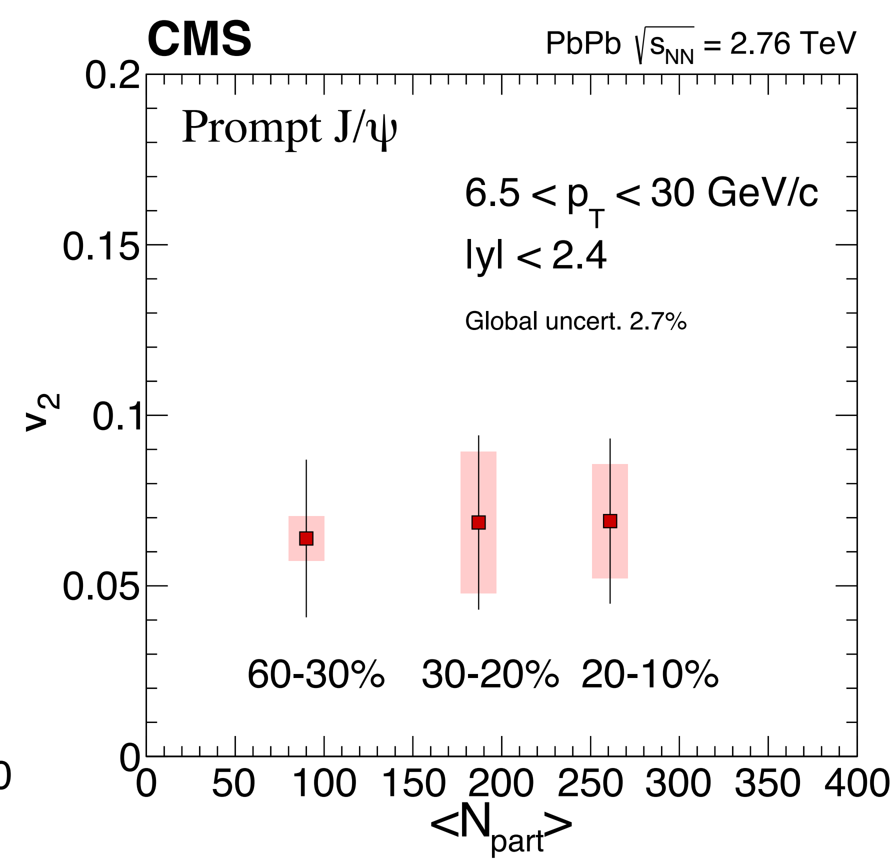
First hint of J/ψ v_2

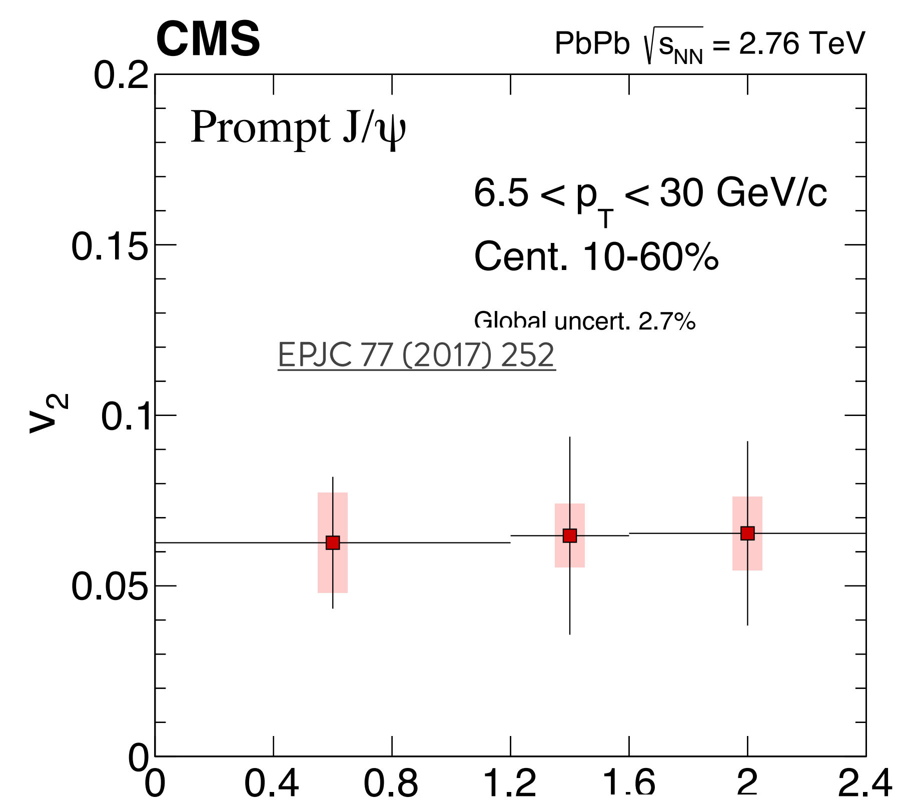
measured by both **CMS and ALICE**

➡ different kinematic regions !







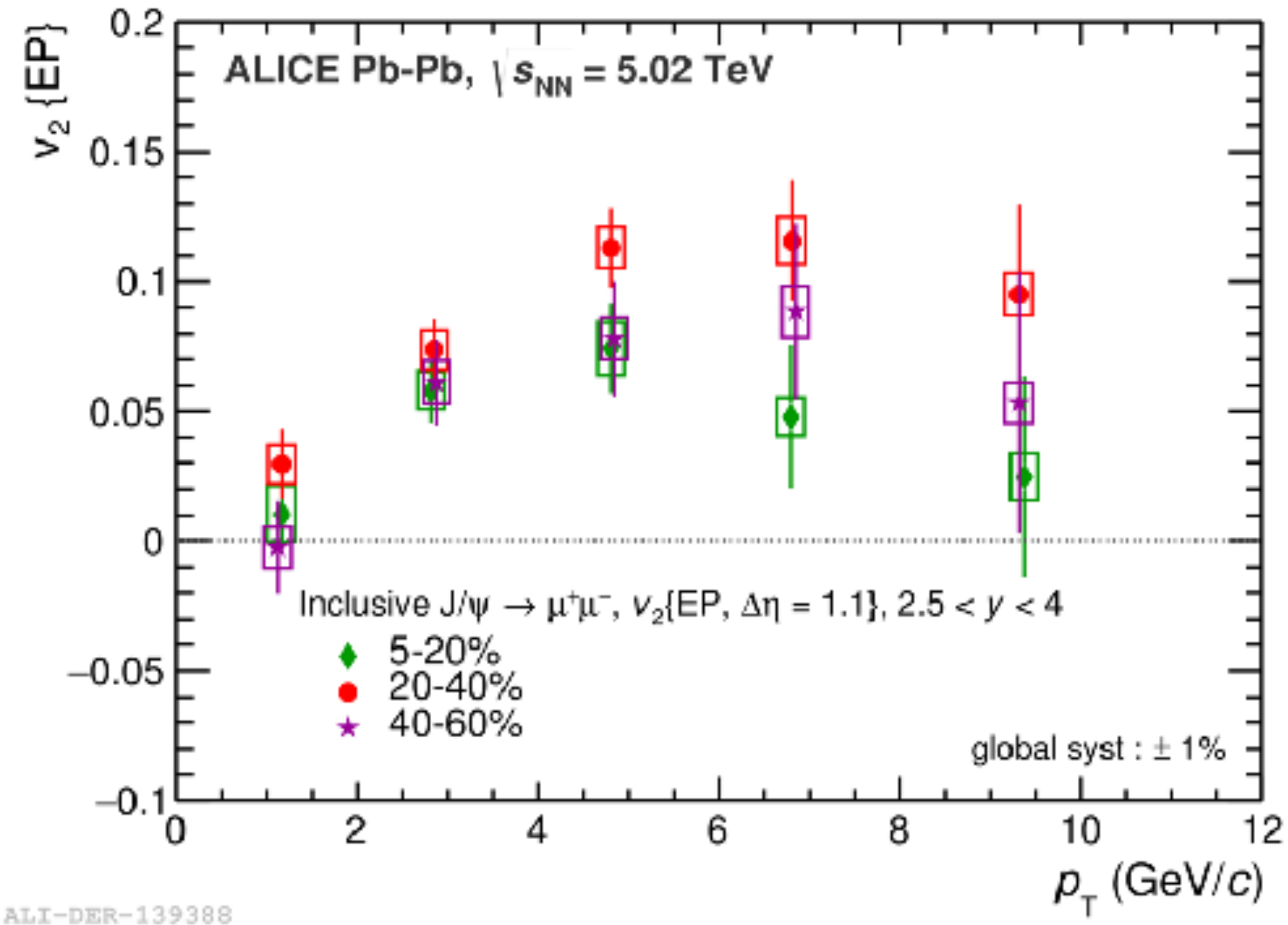


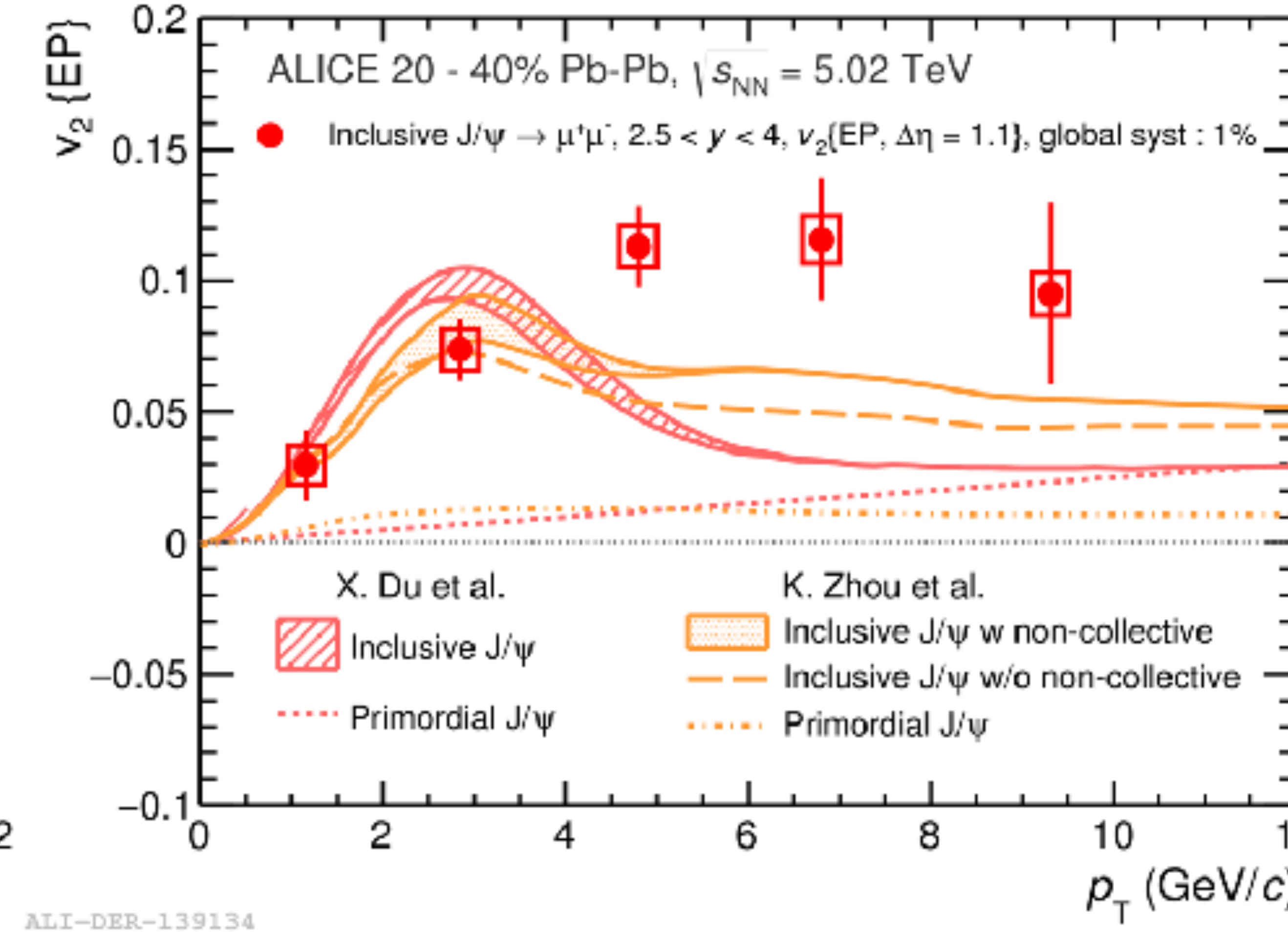
EPJC 77 (2017) 252

EPJC 77 (2017) 252

J/ψ v_2 at $\sqrt{s_{NN}}$ = 5.02TeV

A significant v_2 is observed for various centrality and p_T bins
Compatible between both rapidity

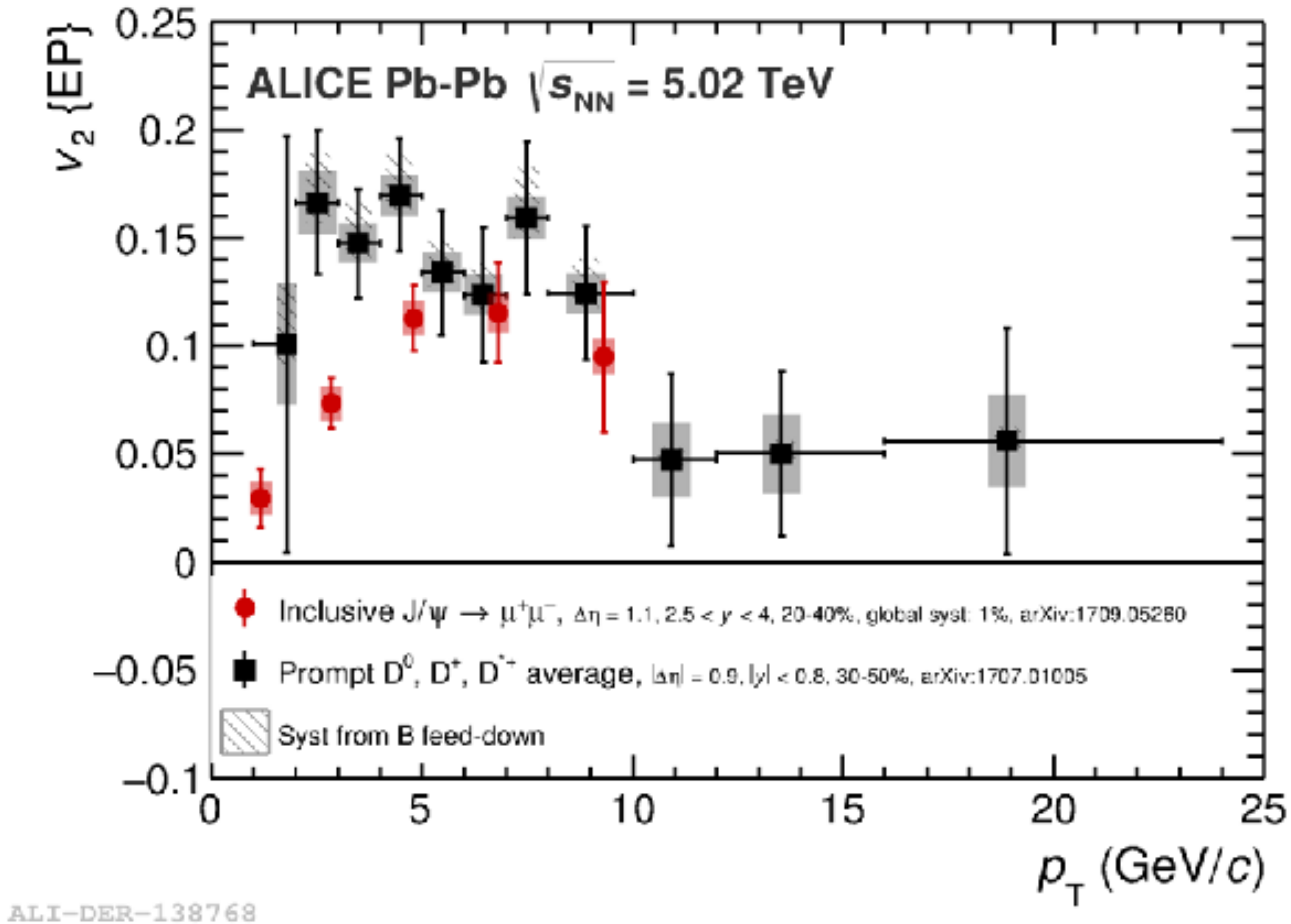




At low p_T: magnitude reproduced by including a strong J/ψ (re)generation component
At high p_T: the v_2 is underestimated

Additionnal component from initial magnetic field could help better describe high p_T anisotropy

J/ψ v_2 comparison with D mesons



Comparison to open charm:

strong hints of

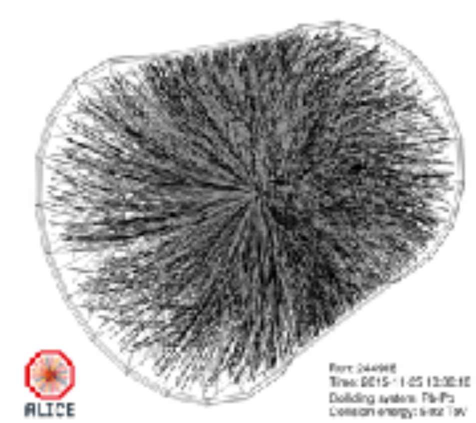
→ charm thermalization

→ charm quark (re)combination

Why do we measure heavy flavours ?

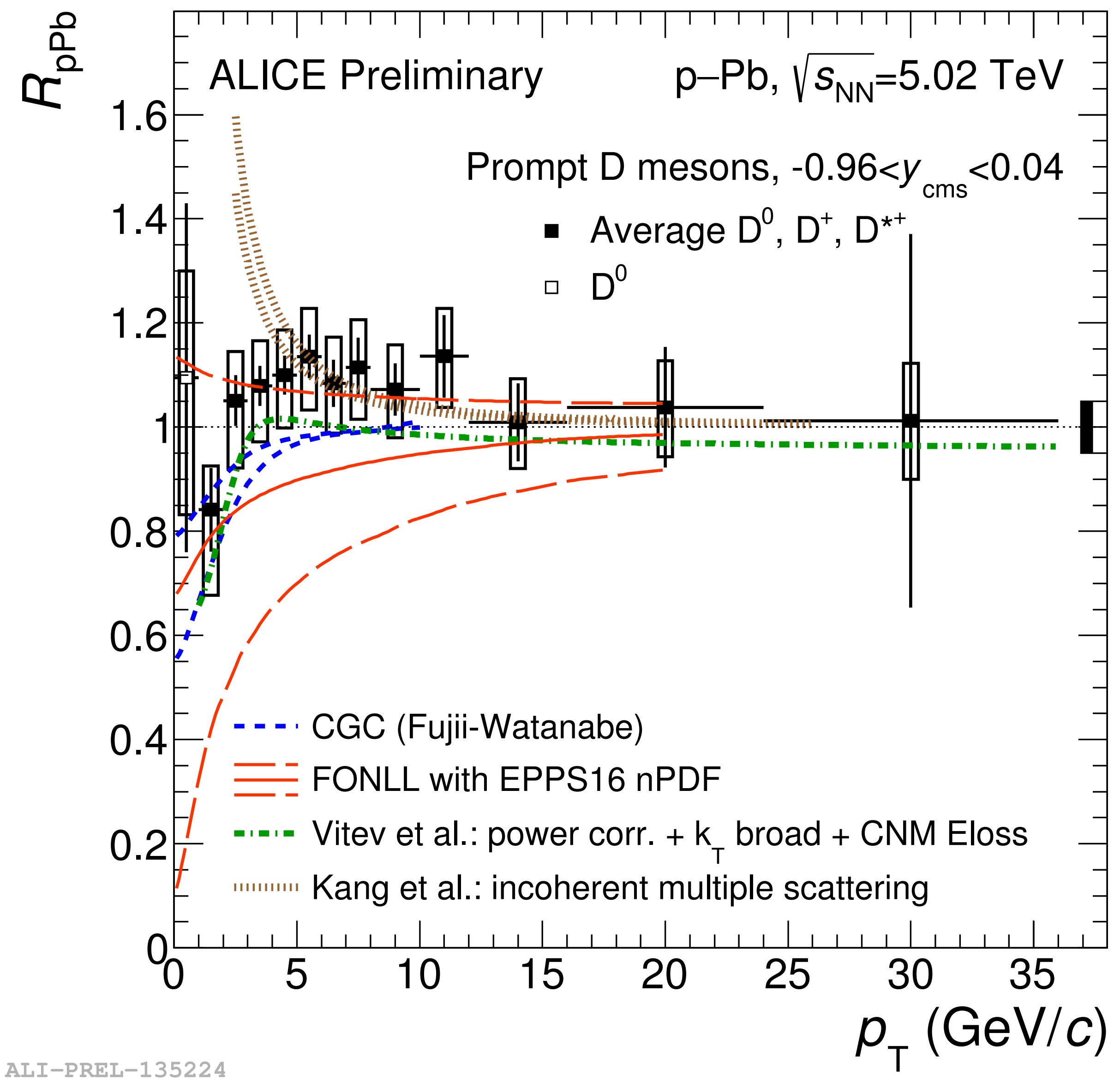
The ALICE detector

Results in A-A and p-A collisions



Upgrade expectations

D meson production in p-Pb collisions



Small/negligible Cold Nuclear Mater (CNM) effects at high p_T

Transport models assuming QGP formation are disfavoured

Models assuming CNM effects (nPDF, kT broadening, E_{loss}, ...) reproduce the measurements

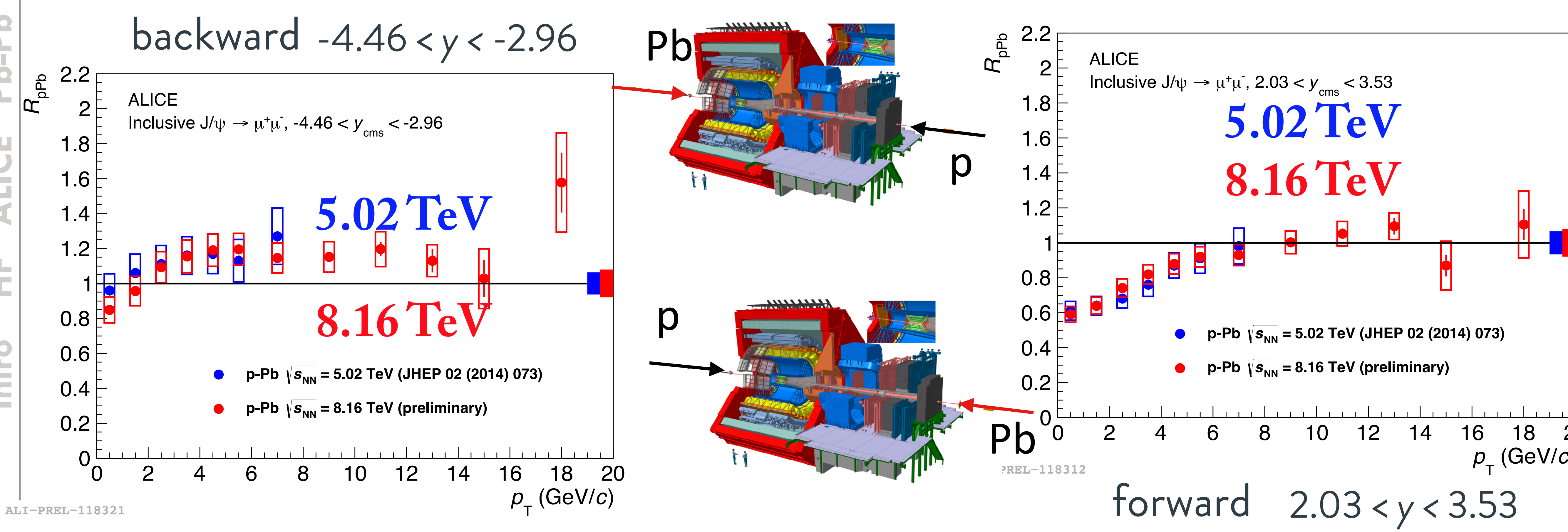
Improved precision of the measurement is required for a more conclusive statement

Cold nuclear matter effects on charmonium

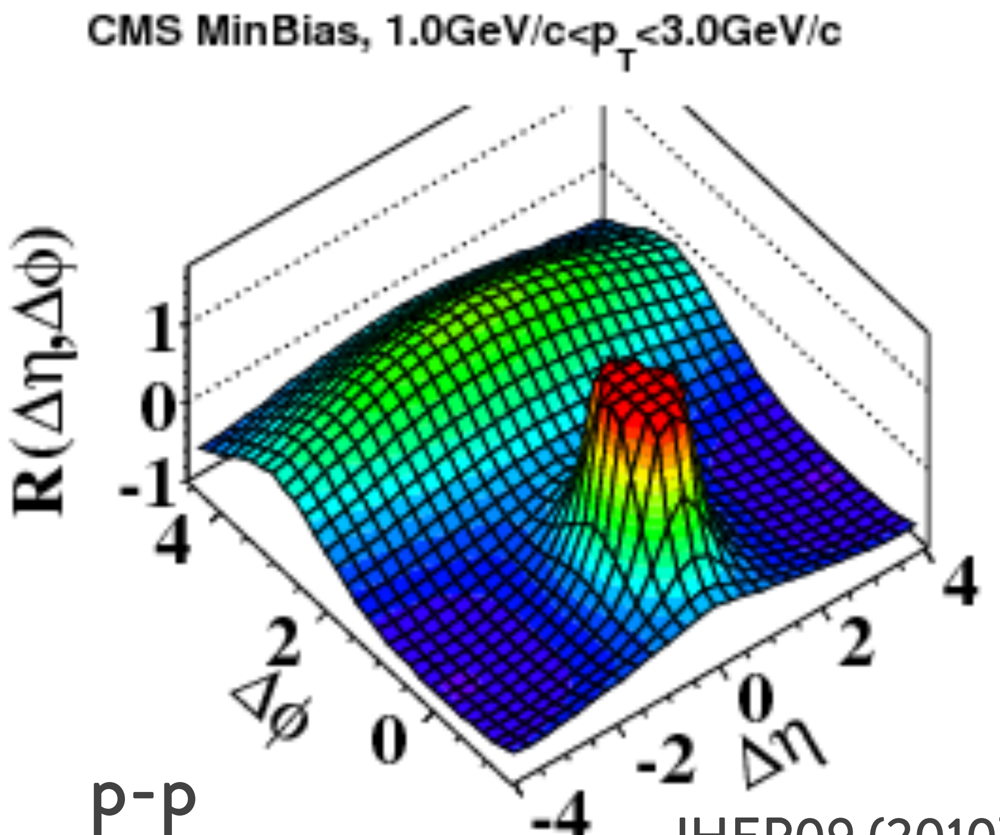
Outside hot matter mechanisms, other effects might affect quarkonium production

- Energy loss
- Initial state: nuclear parton shadowing/CG condensate
- Final state: nuclear absorption

CNM investigated in p-A collisions

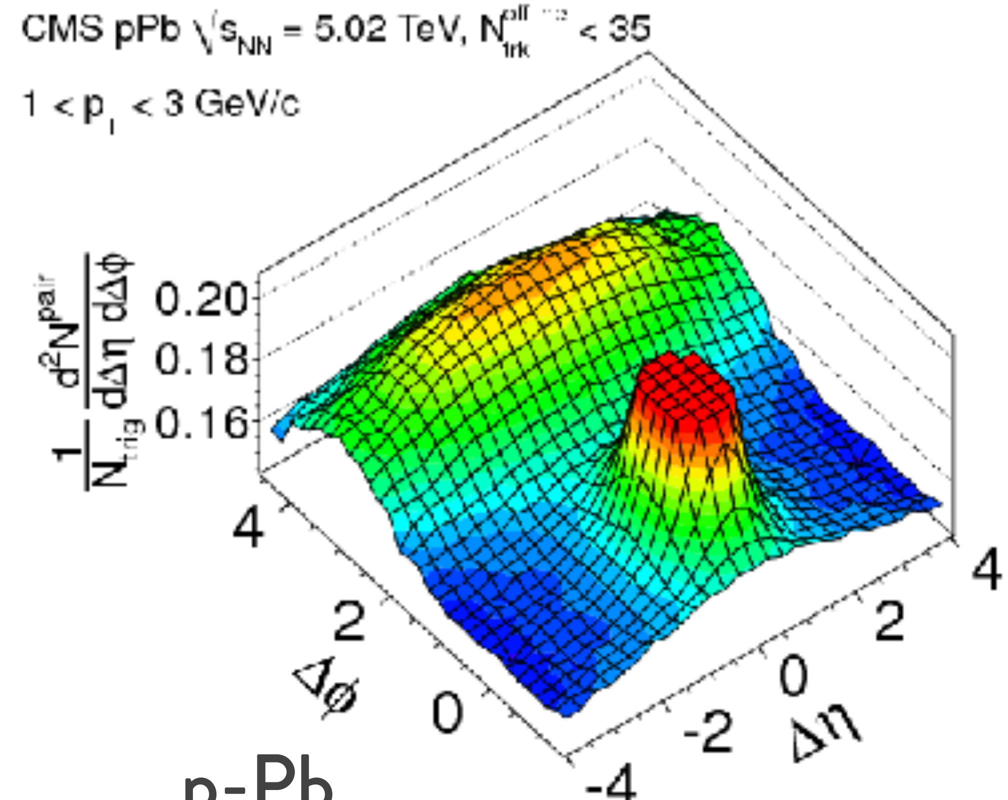


Collectivity in small systems



p-p

JHEP09 (2010) 091



p-Pb

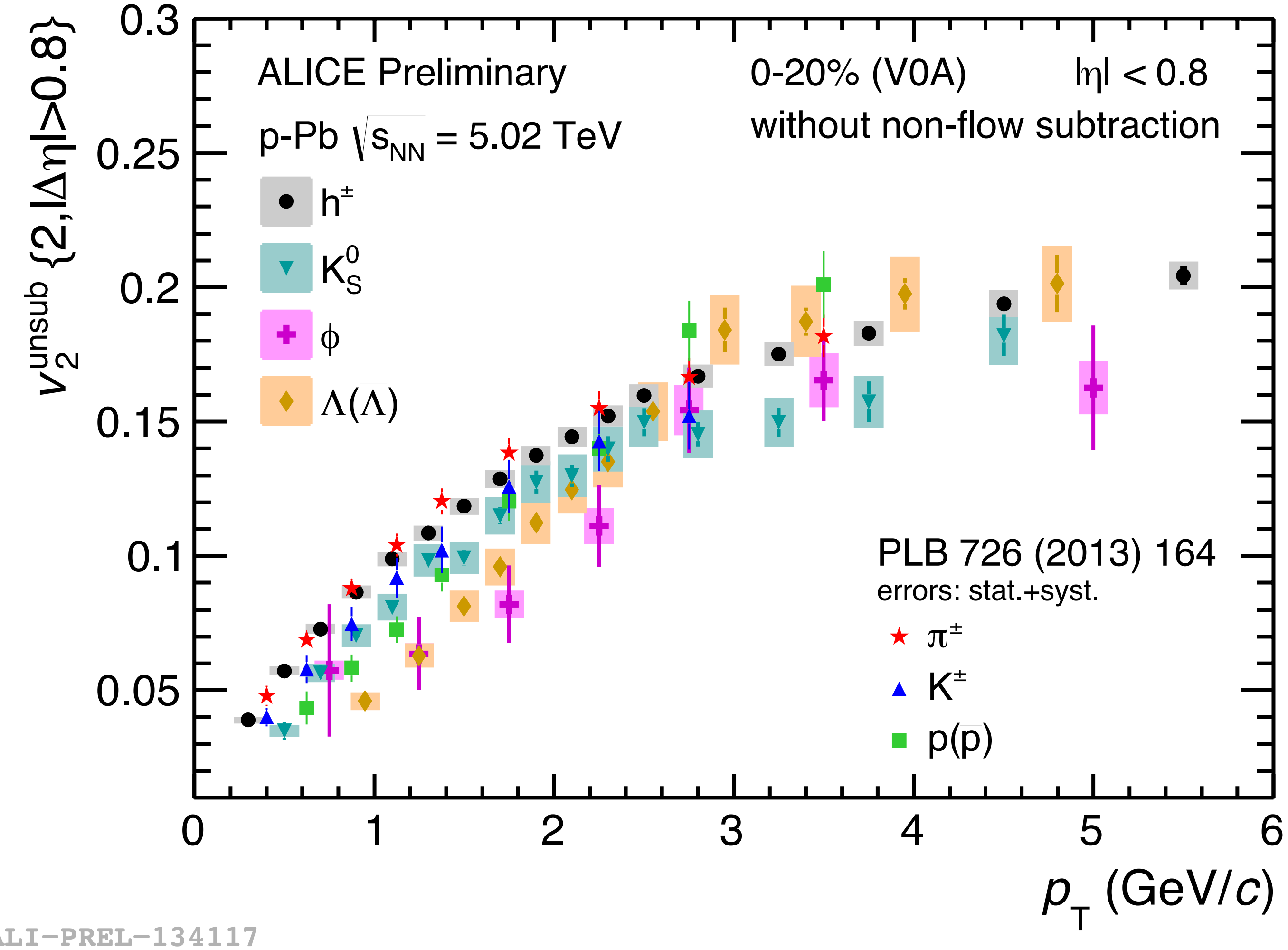
PLB718 (2013) 795-814

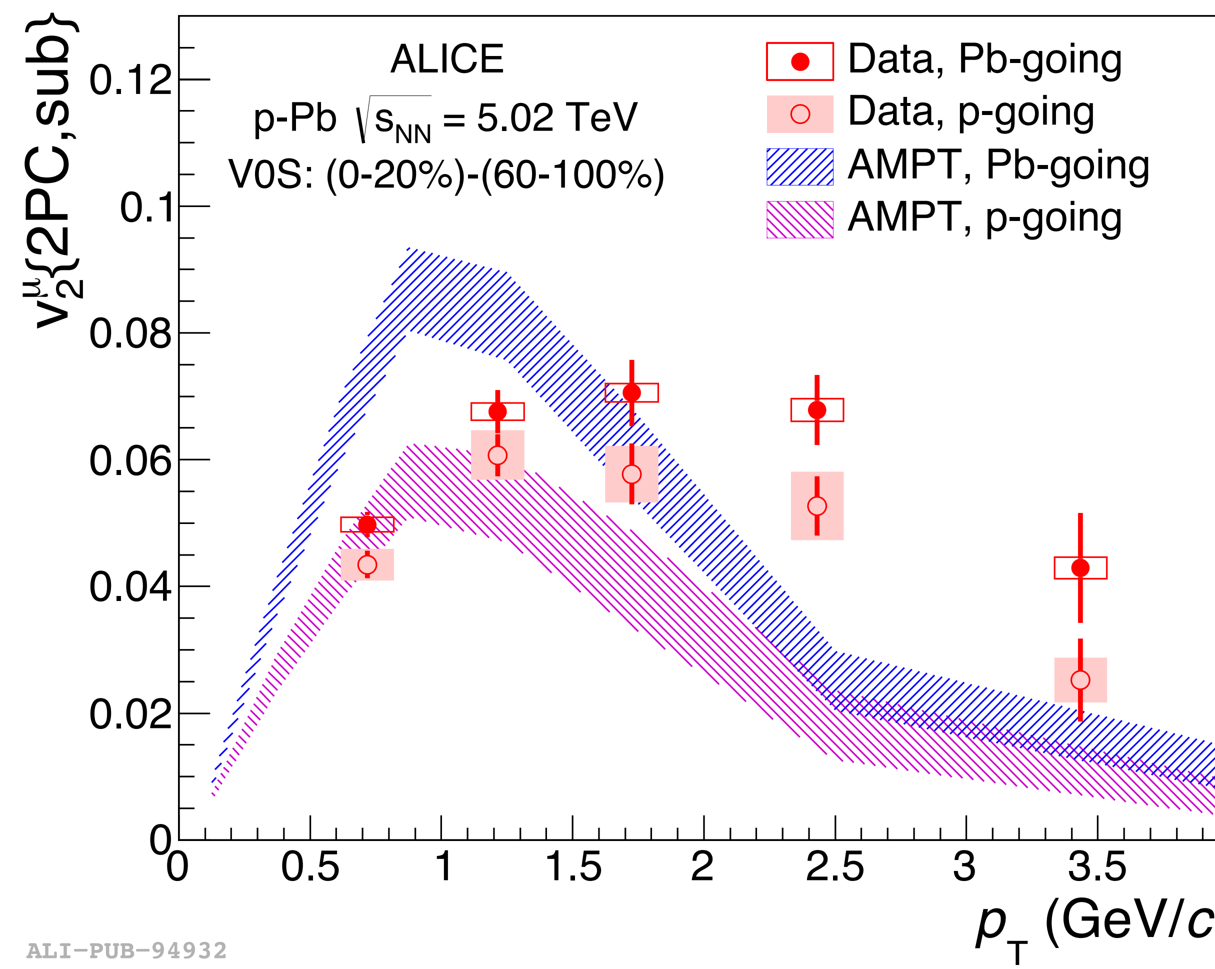
Double ridge structure in high multiplicity pp event di-hadron correlations

Similar structure observed in p-Pb

Are these QGP-like collective effects present in the charm sector ?

Indirect hints



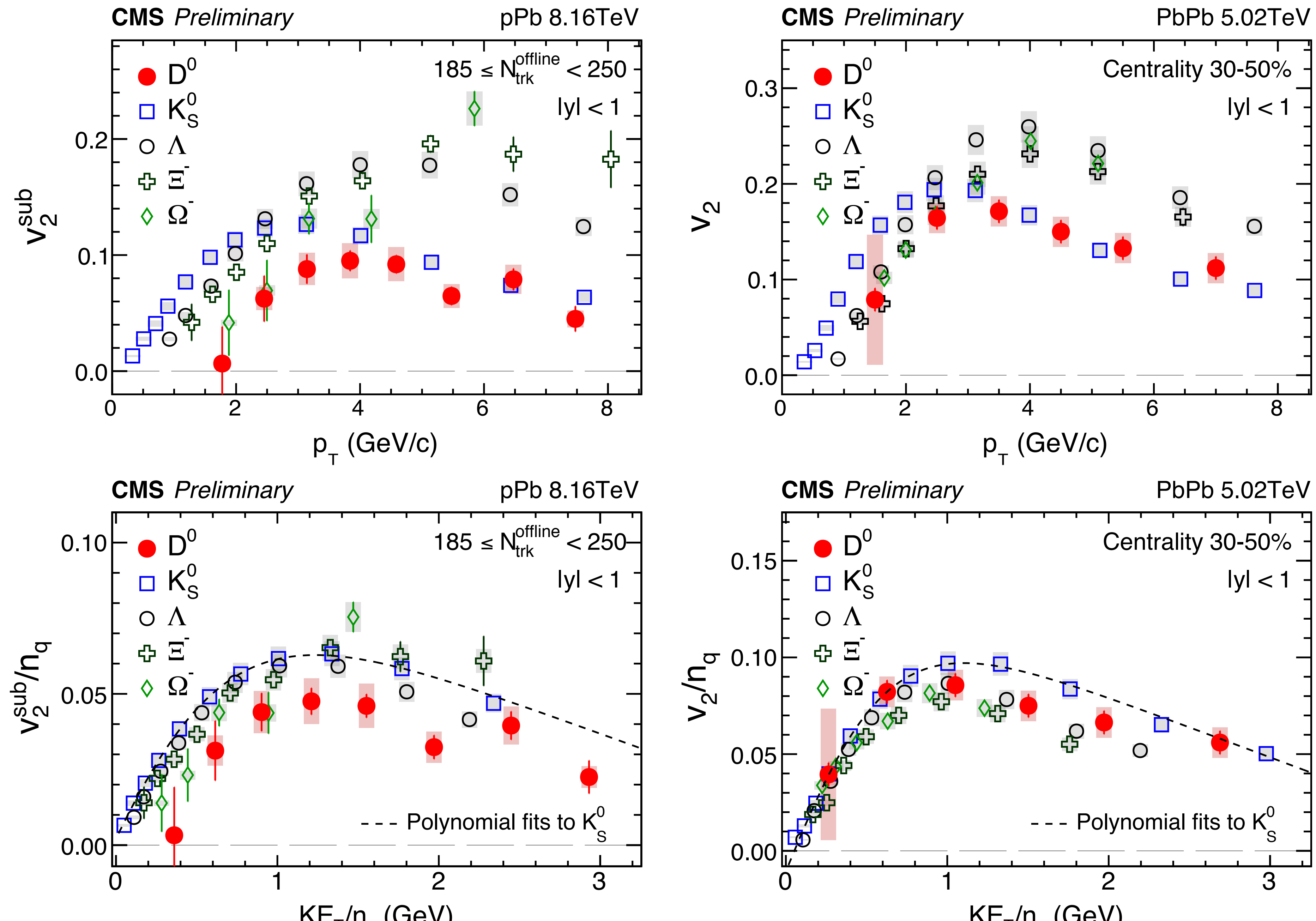


Positive v_2 observation for charged particles

Mass ordering for $p_T < 2.5$GeV/c

At high p_T muons are dominated by HF decays

Collectivity in p-Pb collisions

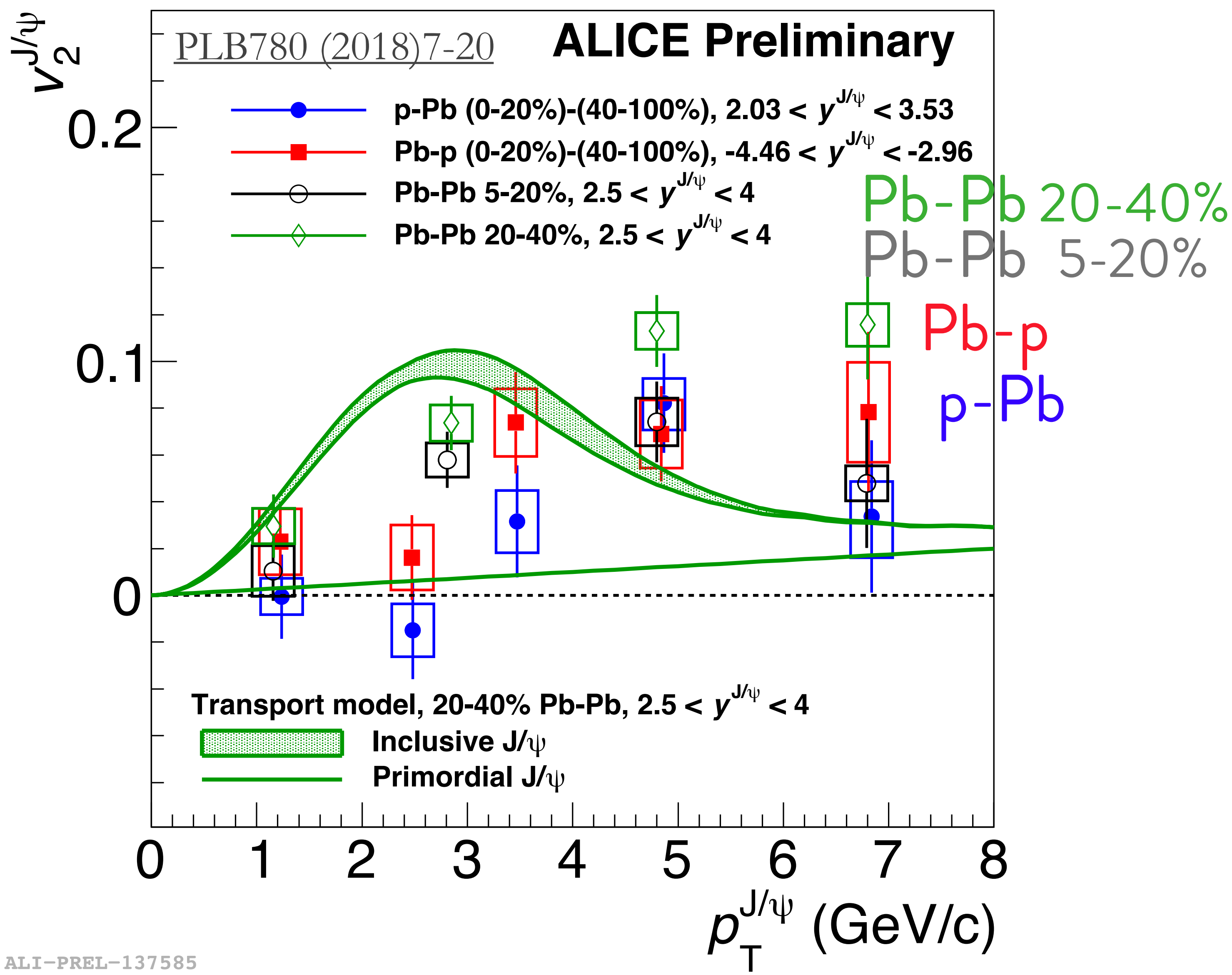


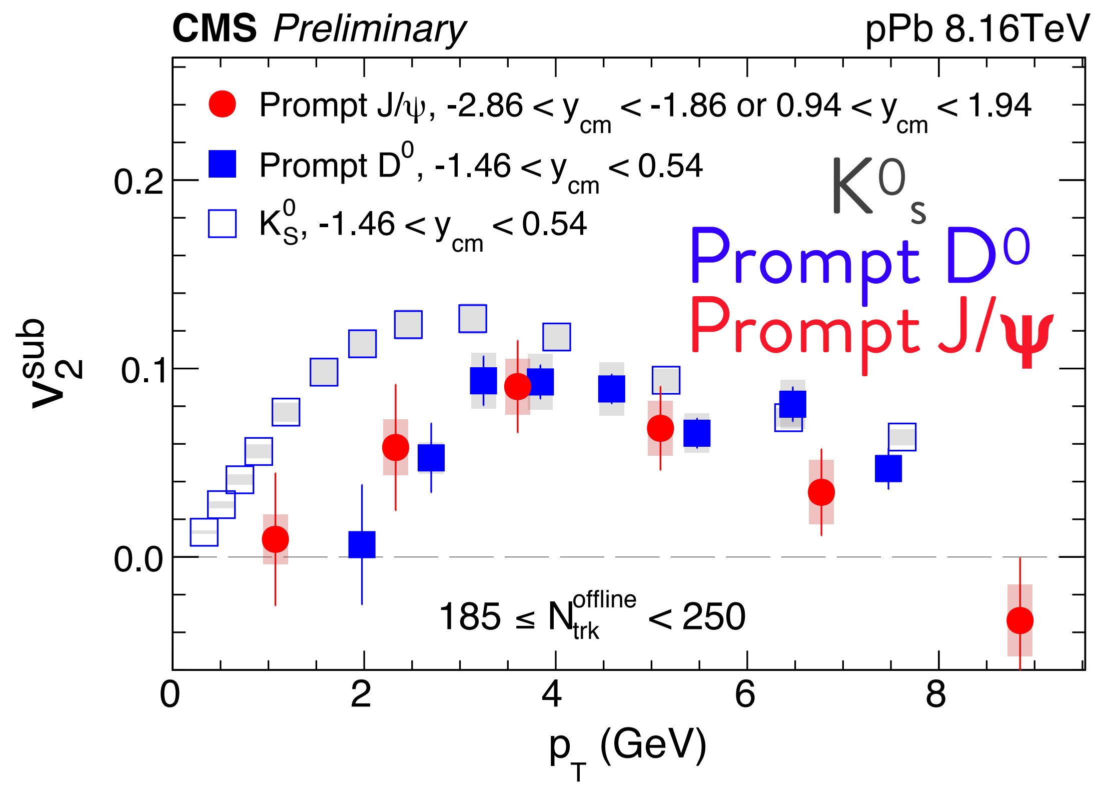
CMS-HIN-17-003

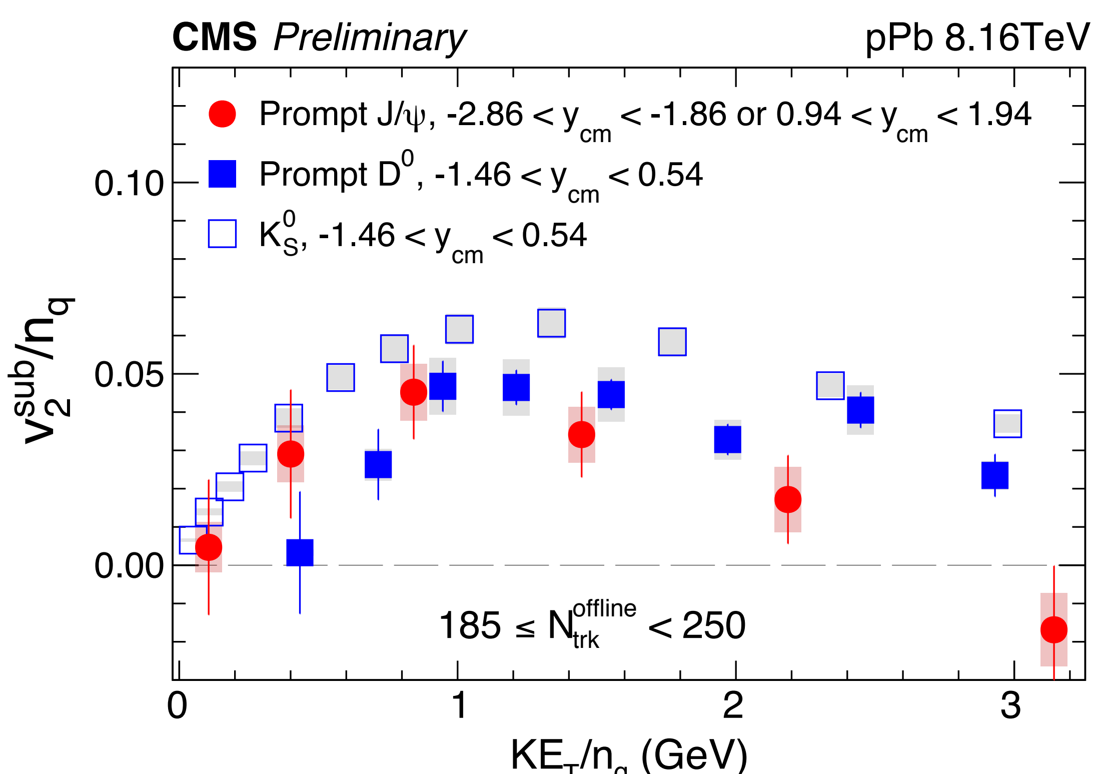
Smaller v_2 observed for D^0 compared to strange-hadrons in p-Pb

Weaker charm interaction with the medium w.r.t. light quarks ?

Collective effect for J/ψ in p-Pb ?







CMS-PAS-HIN-18-010

Sizeable v_2 (compatible with Pb-Pb in 5-20%)

No significant (re)generation contribution is expected and lesser path-length effect w.r.t Pb-Pb

$v_2(c) < v_2(s)$: sign of weaker charm interaction ?

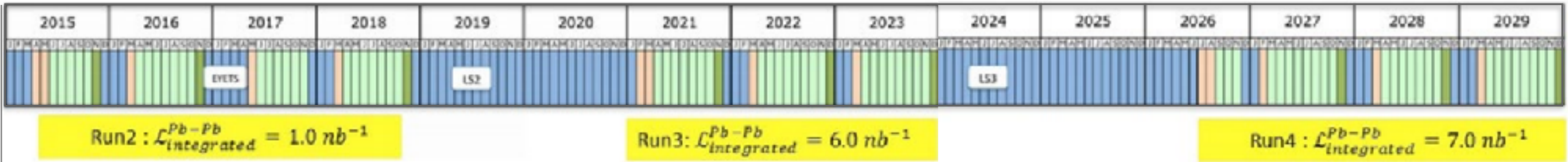
Why do we measure heavy flavours ?

The ALICE detector

Results in A-A and p-A collisions

Upgrade expectations

Upgrade programme



Higher precision, low signal/background observables, low p_T heavy quarks, rarest probes

- Global observables……………
- Light hadrons……………………
- Strange hadrons………………
- Quarkonia…………………………
- Open heavy flavours…………
- Electromagnetic probes…..
- Jets and high p_T hadrons….
- Hypernuclei………………………

→ Better significance

→ New observables

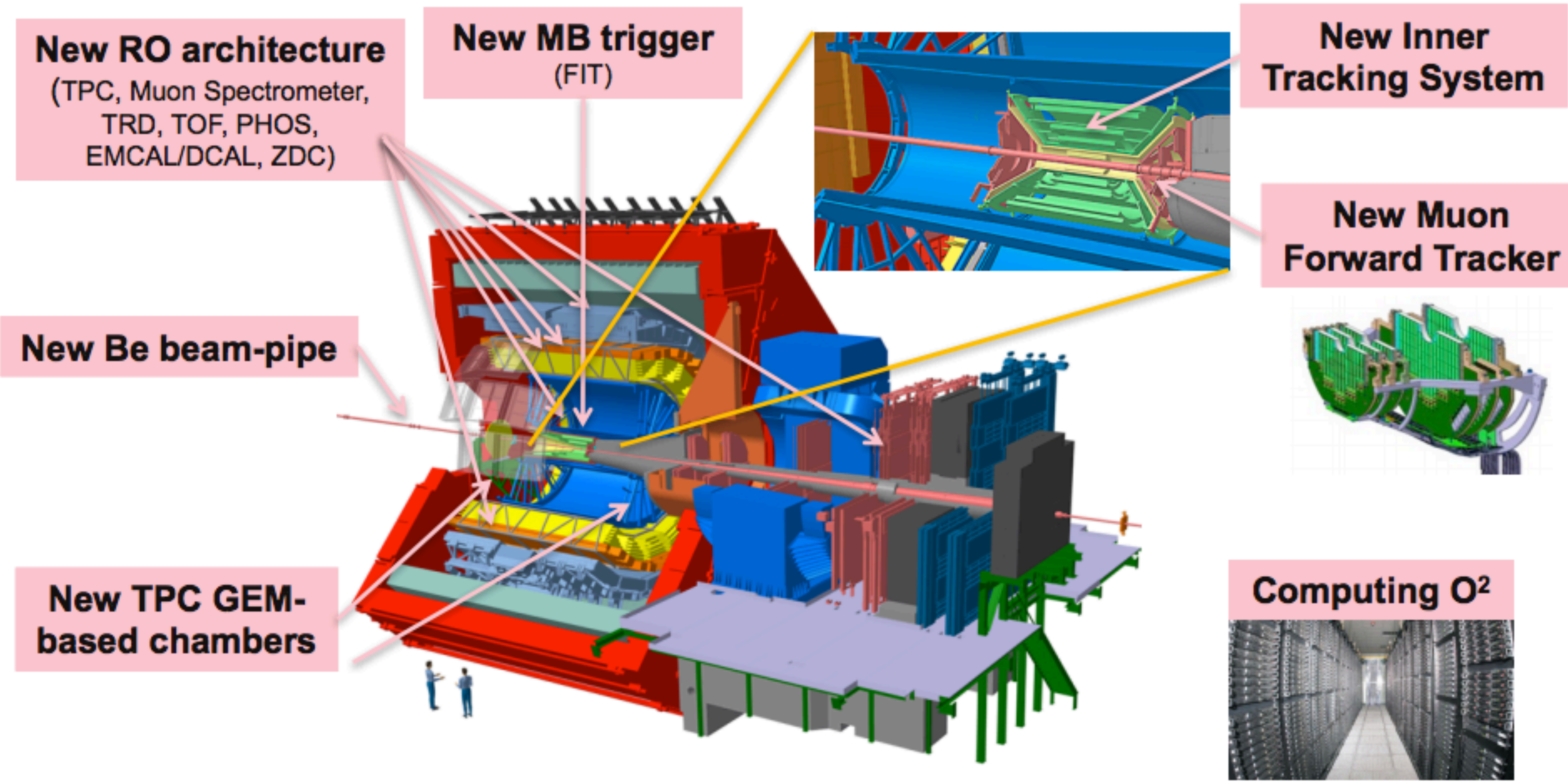
- PbPb 50kHz
- New rea-out electronics
- New TPC GEM chambers
- New computing system
- Inner tracker (ITS) upgrade
- New forward tracker (MFT)
- New forward calo (2024)?

100-fold larger integrated luminosity than run 1 and run 2

Low signal over background: hardware trigger filtering nearly impossible at low p_T

The detector upgrade

Increase of luminosity (50kHz IR) and improve vertexing and tracking at low p_T



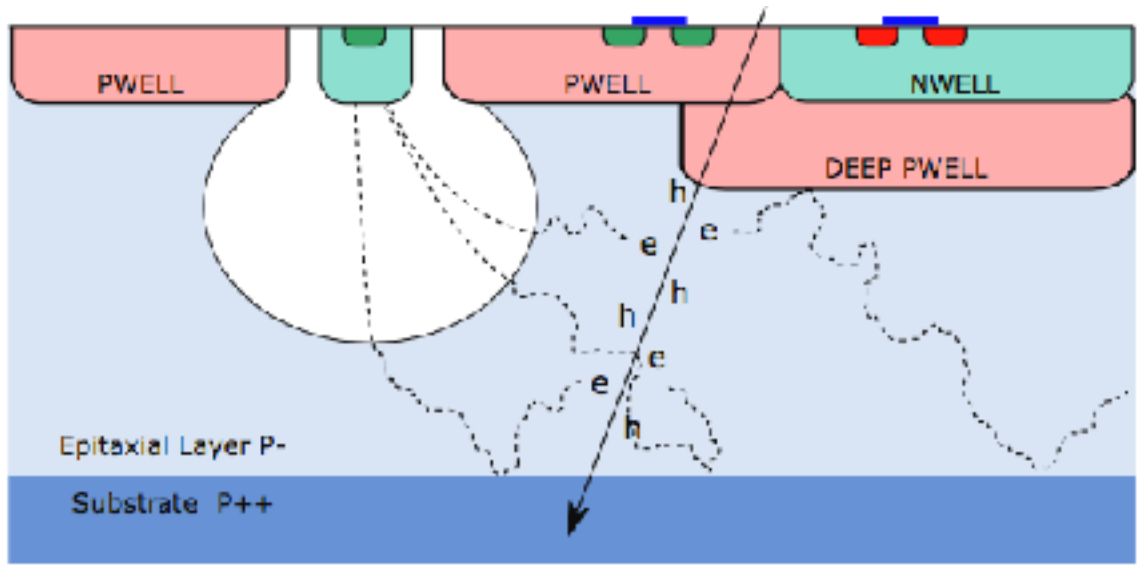
Increase statistics to 10 nb^{-1}

Interaction rate: 8 -> 50 kHz (LHC)

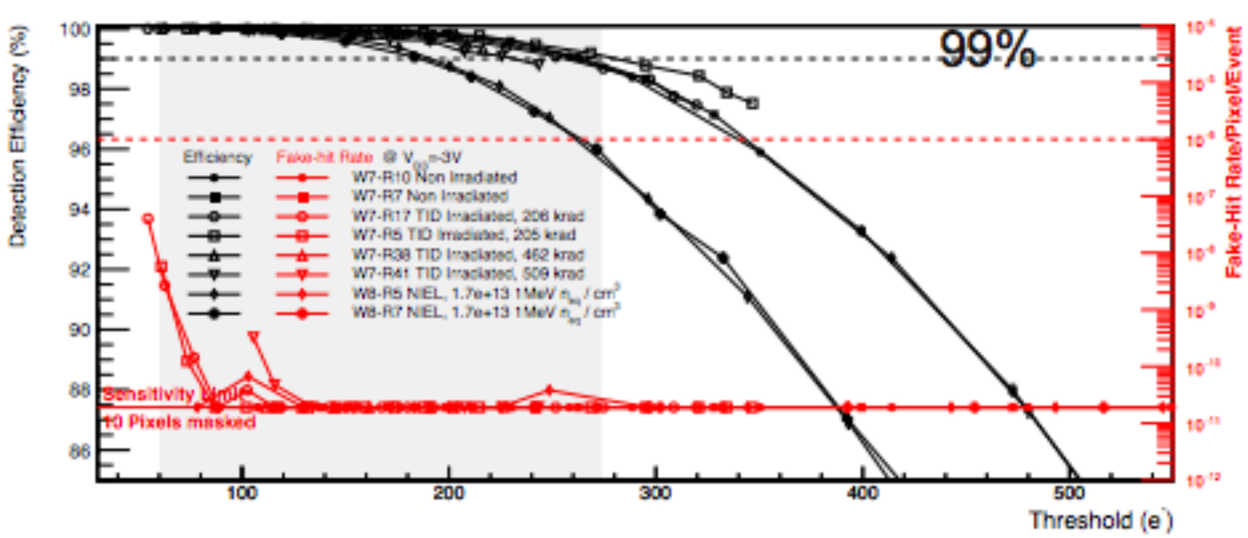
Trigger rate: 1 kHz -> 50 kHz (ALICE O^2)

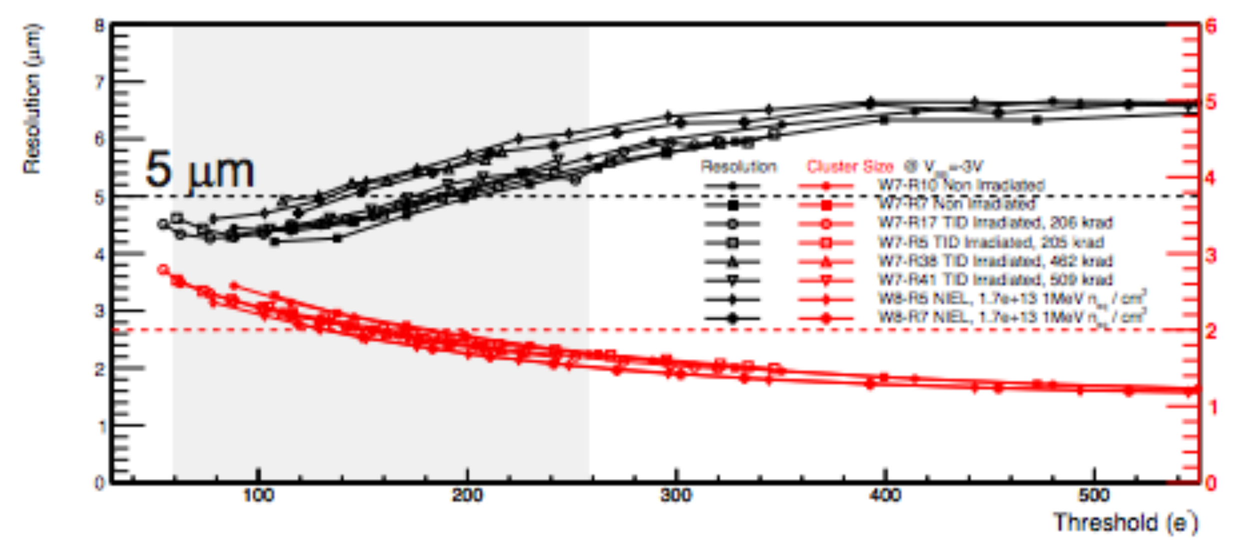
New silicon sensor

- CMOS Monolithic Active Sensors (MAPS), TowerJazz 0.18 µm technology
- Sensor size: 15mm x 30mm
- Pixel size: 29 µm x 27 µm
- high resistivity (>1kΩ cm) epitaxial layer
- deep p-well (shields n-well of PMOS transistors)



- ➡ high granularity
- ➡ Event time resolution < 4us
- ➡ low material budget
- ➡ low power consumption
- ➡ binary output (in-pixel discri)
- ➡ fast readout time
- ➡ medium radiation hardness

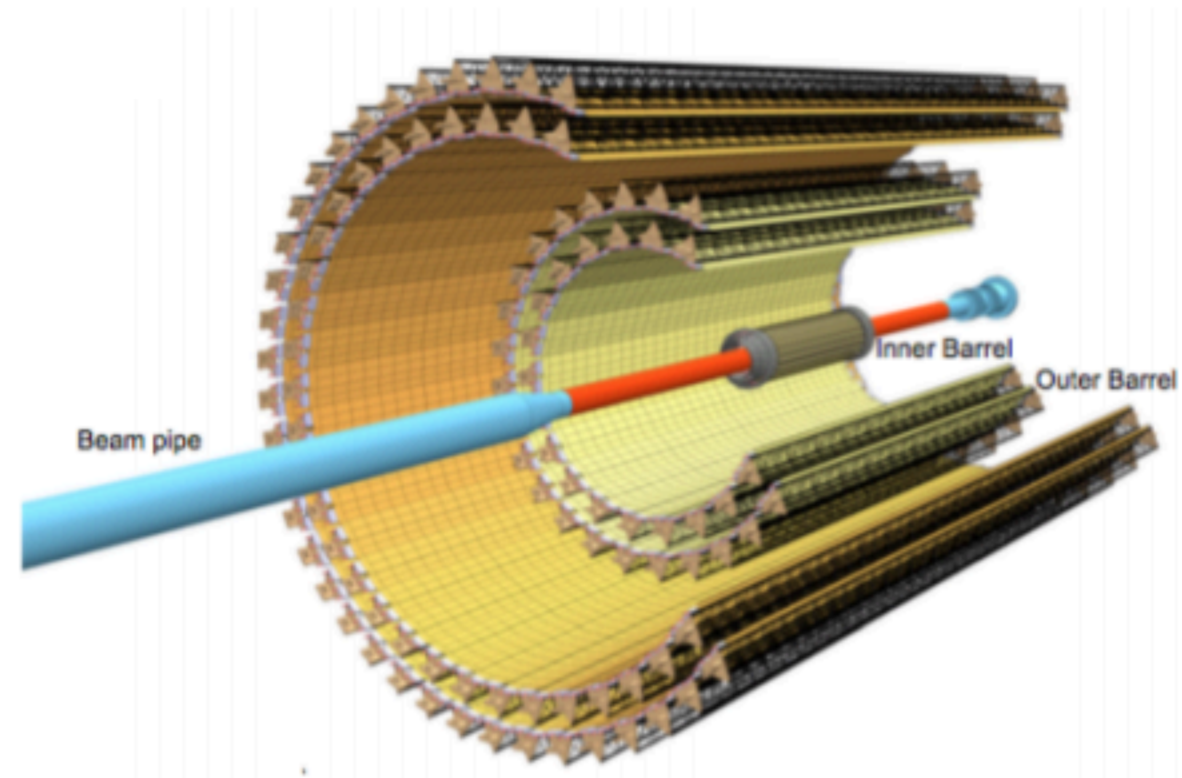


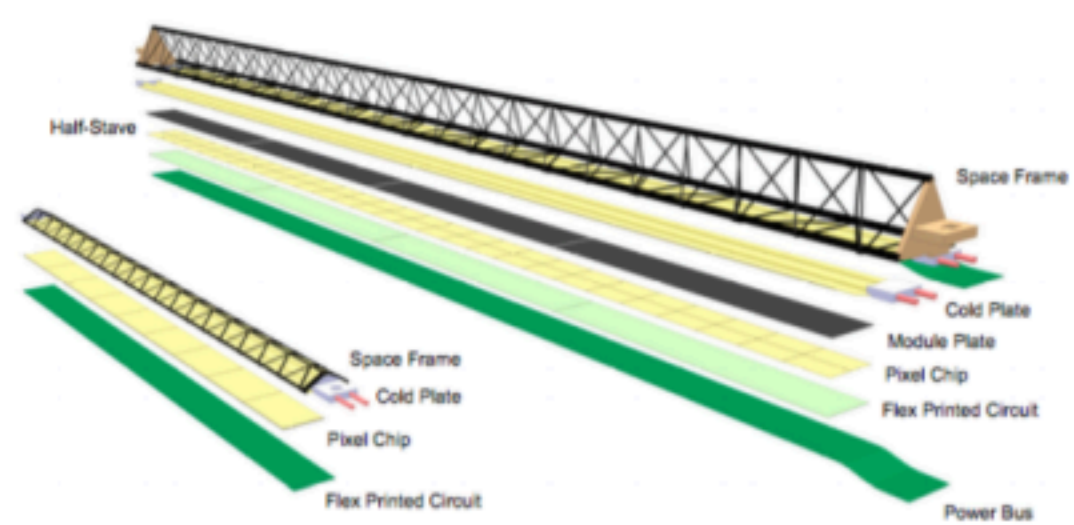


The ITS upgrade

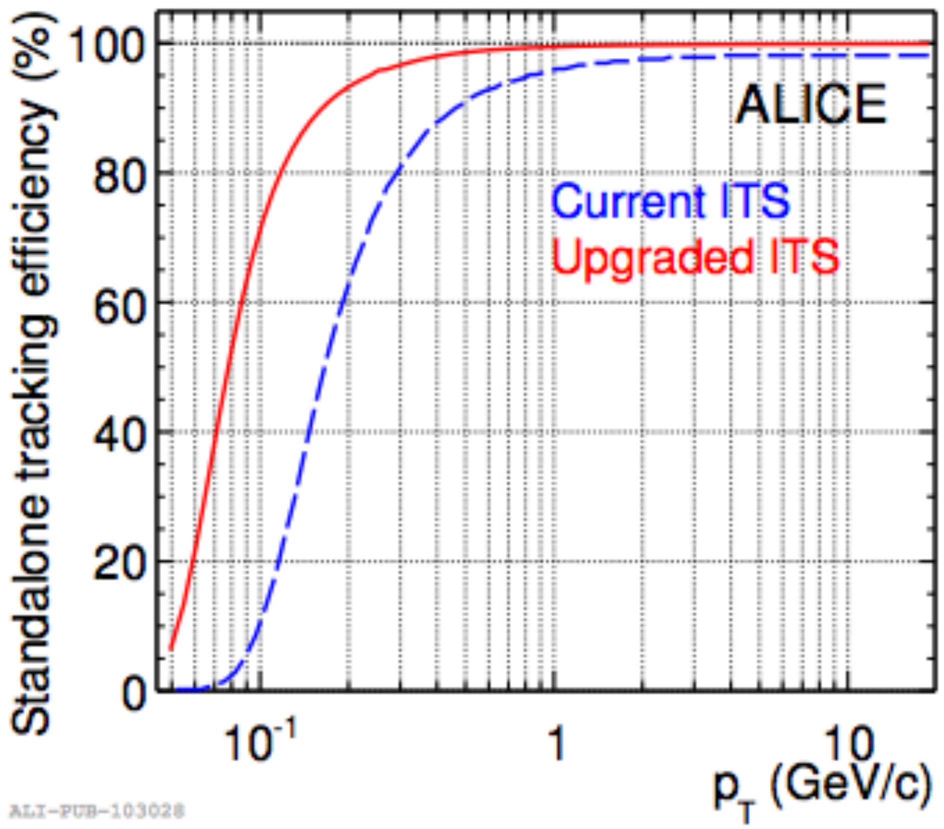
Improving tracking performances at low p_T

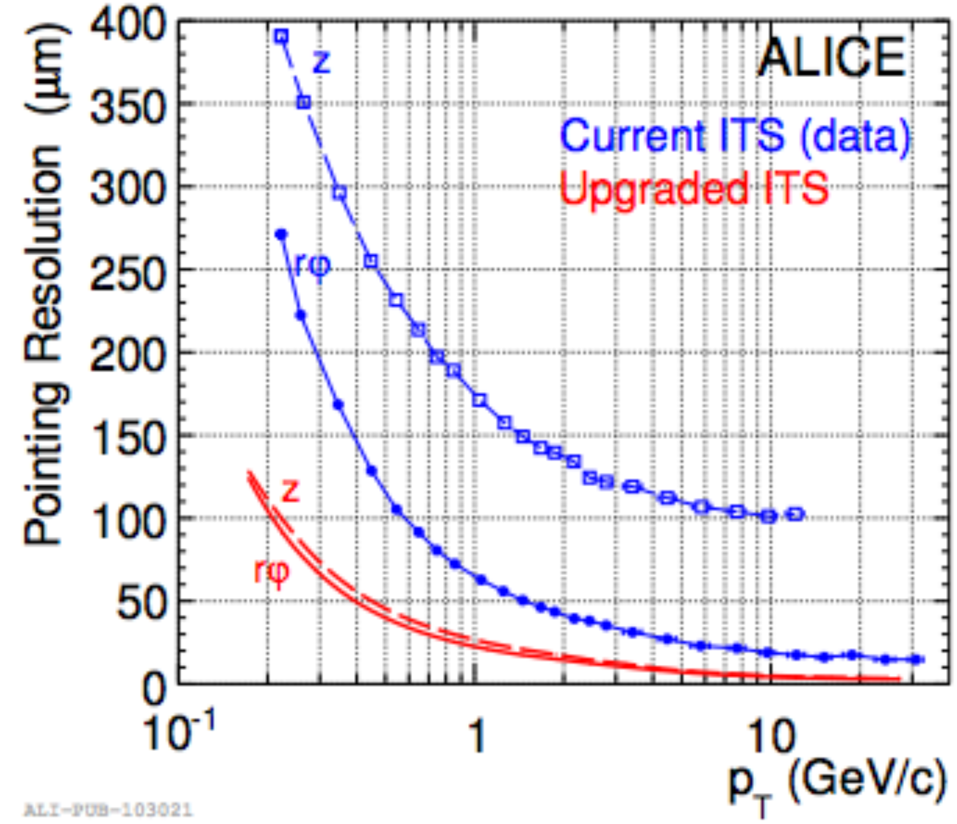
- Large area (10 m^2) tracker made of monolithic active silicon pixel sensors
- 7 layers from R=22mm to R=400mm Inner Barrel, Outer Barrel (Middle layers & Outer layers)
- Spatial resolution 0(5 μm)
- First layer closer to IP (smaller beam pipe radius)
- 0.3%X_0 per layer in the inner most 3 layers (light mechanical structure)



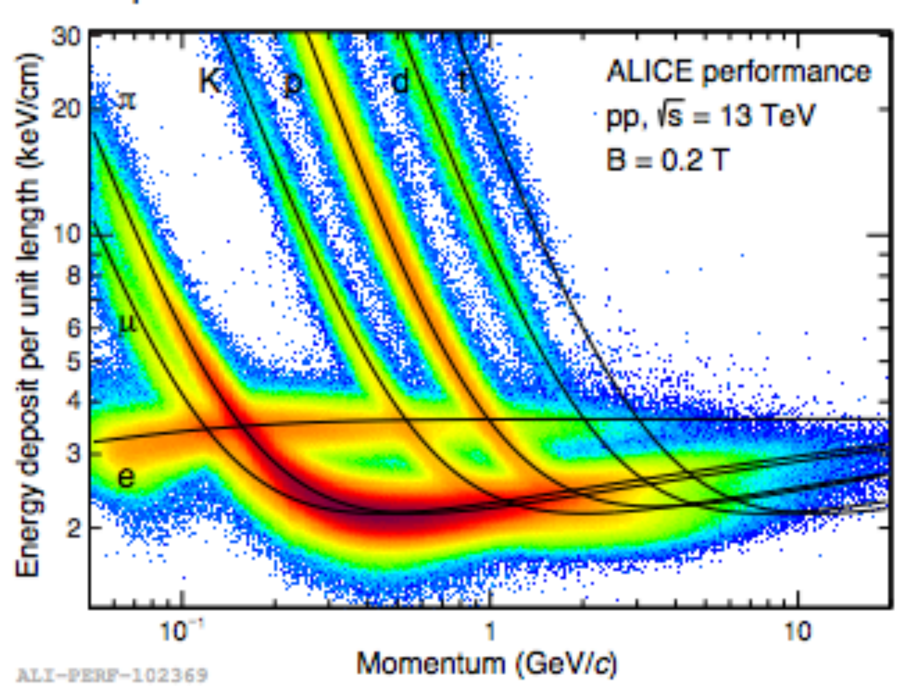


ITS upgraded performance





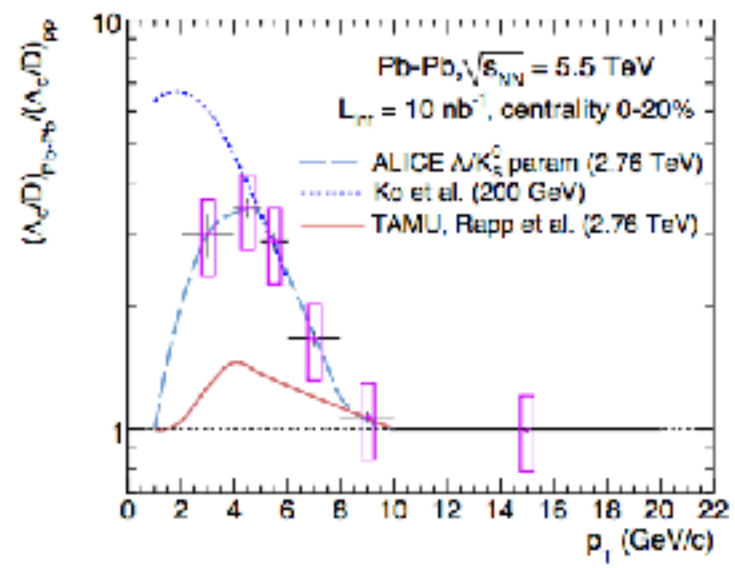
Improved efficiency and resolution (mostly at low p_T)

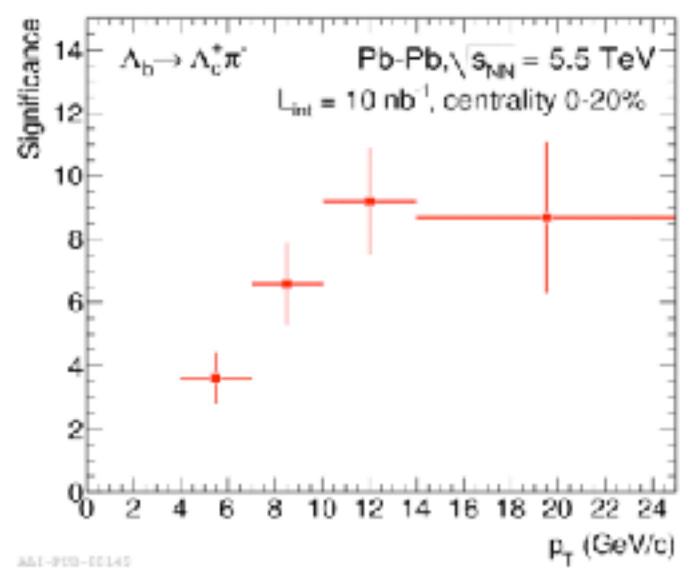


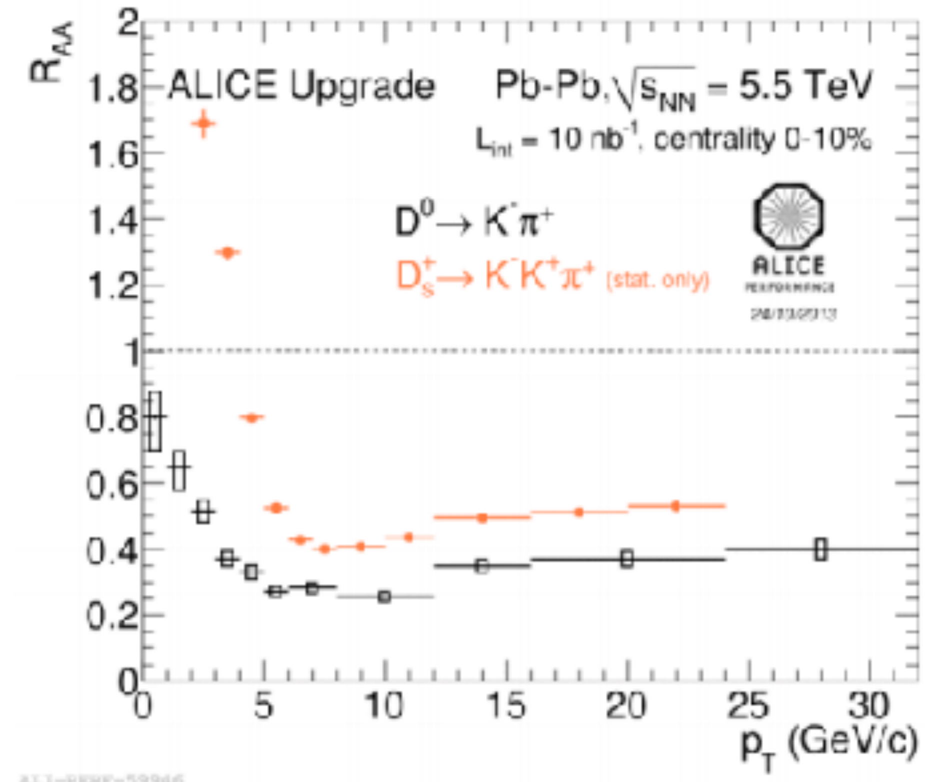
Keep particle identification performances

Upgrade expectations for open

Charmed and Beauty baryons |η|<0.9

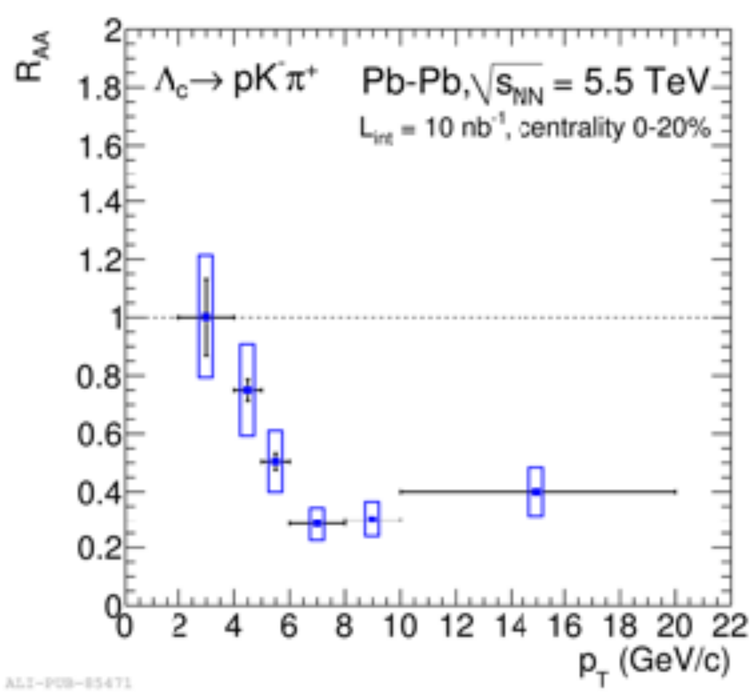


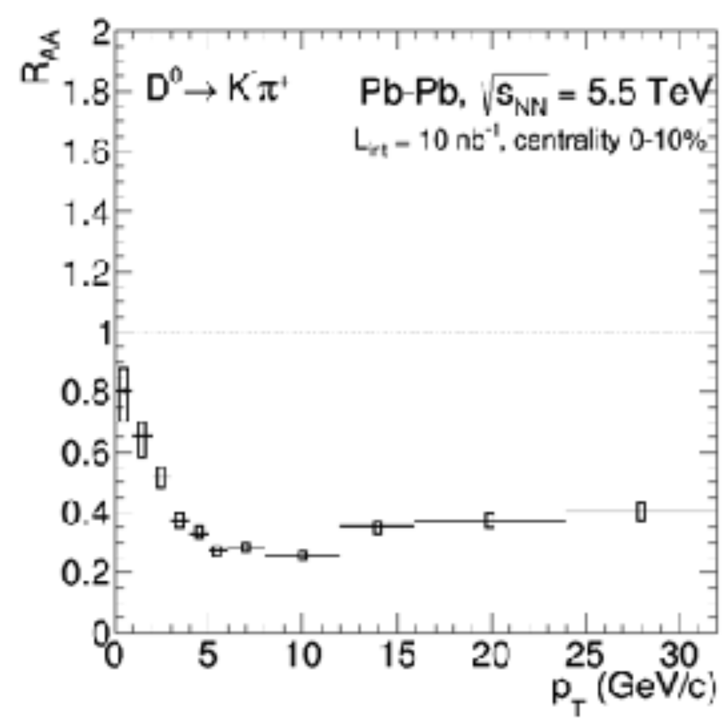


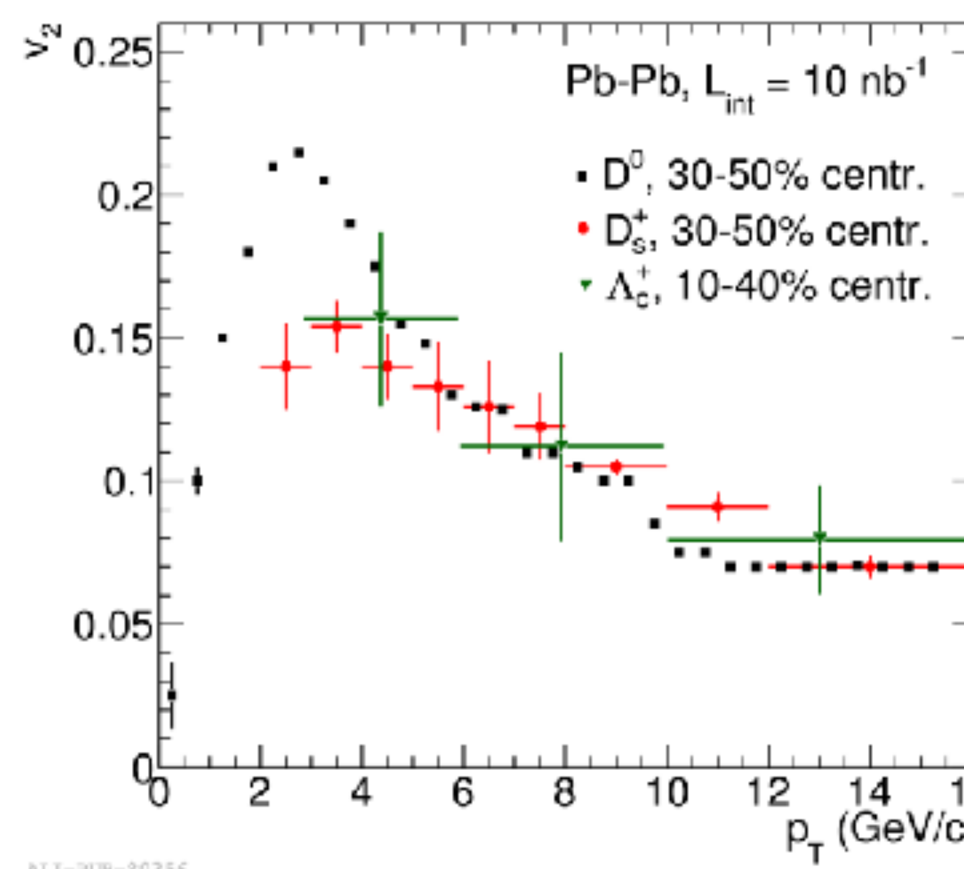


New observables in Pb-Pb: baryon production in the charm and beauty sector!

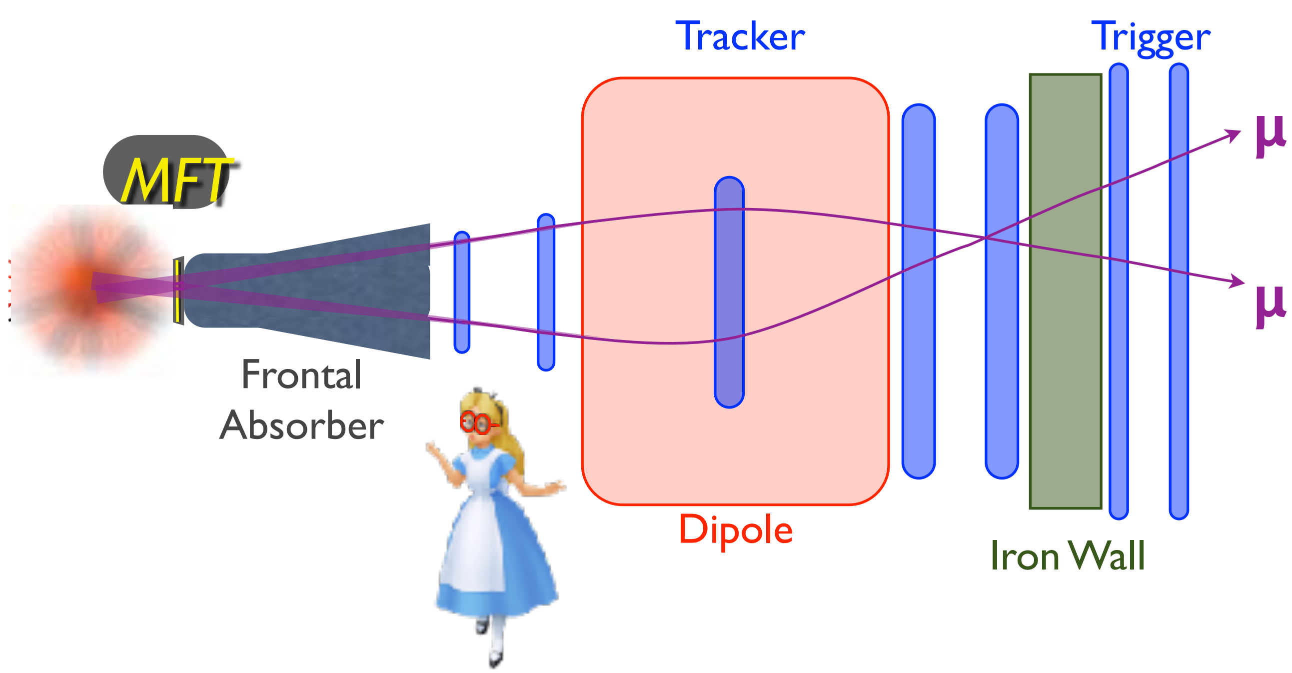
For the moment, only observed in pp and p-Pb collisions: [*https://arxiv.org/abs/1712.09581*](https://arxiv.org/abs/1712.09581)

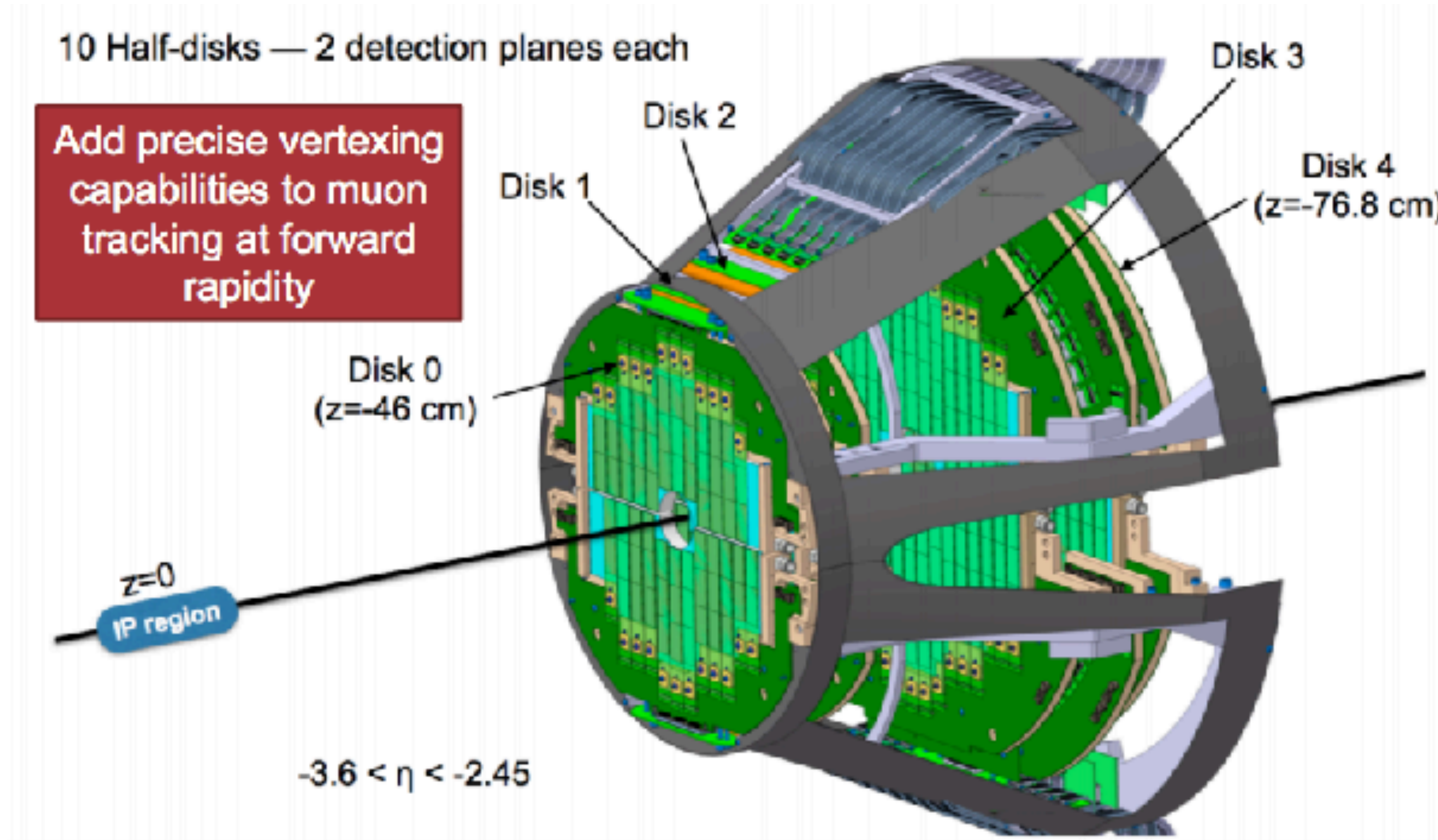






MFT upgrade





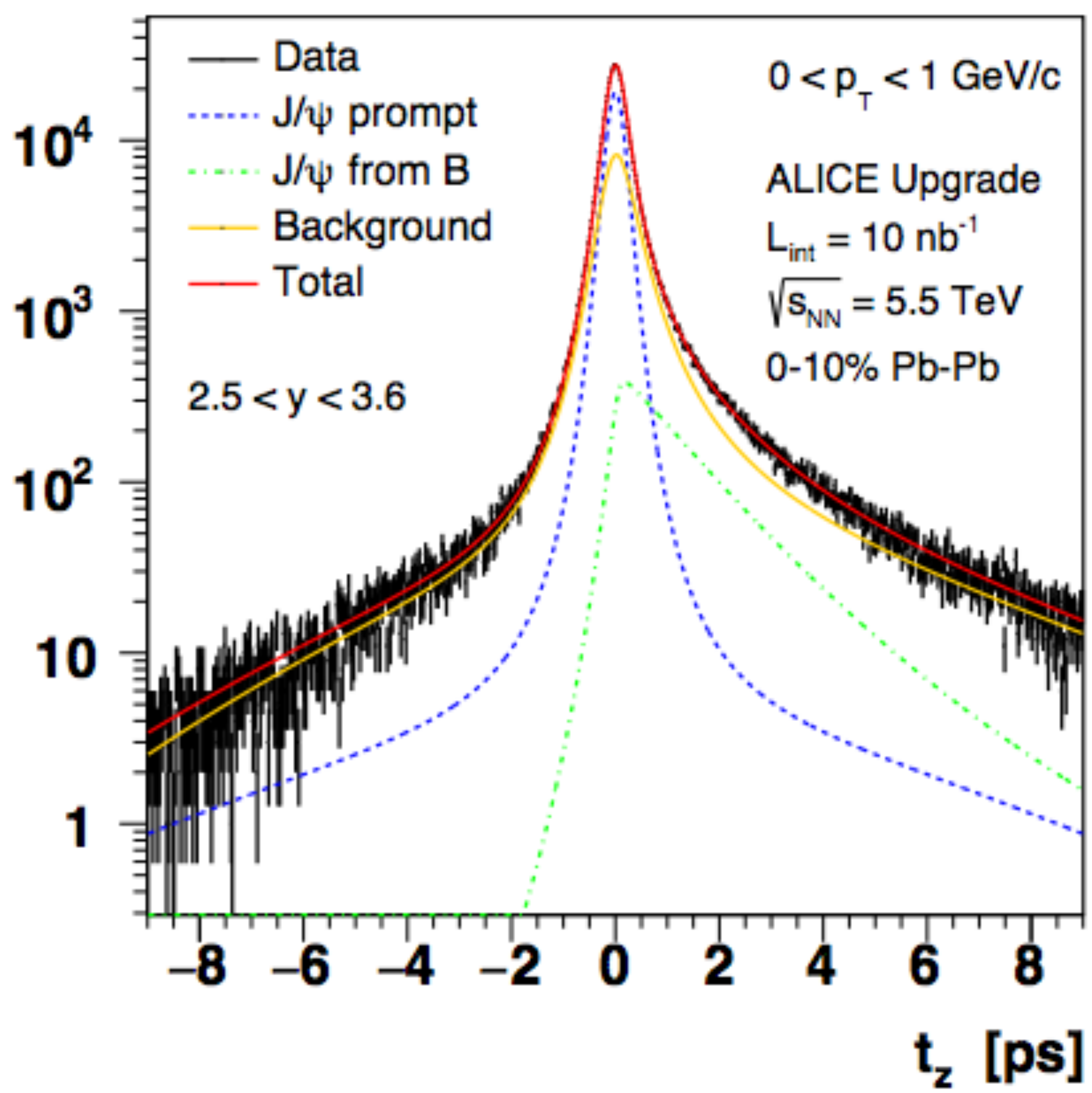
920 silicon pixel sensors ($0.4 m^2$) on 280 ladders of 2 to 5 sensors each

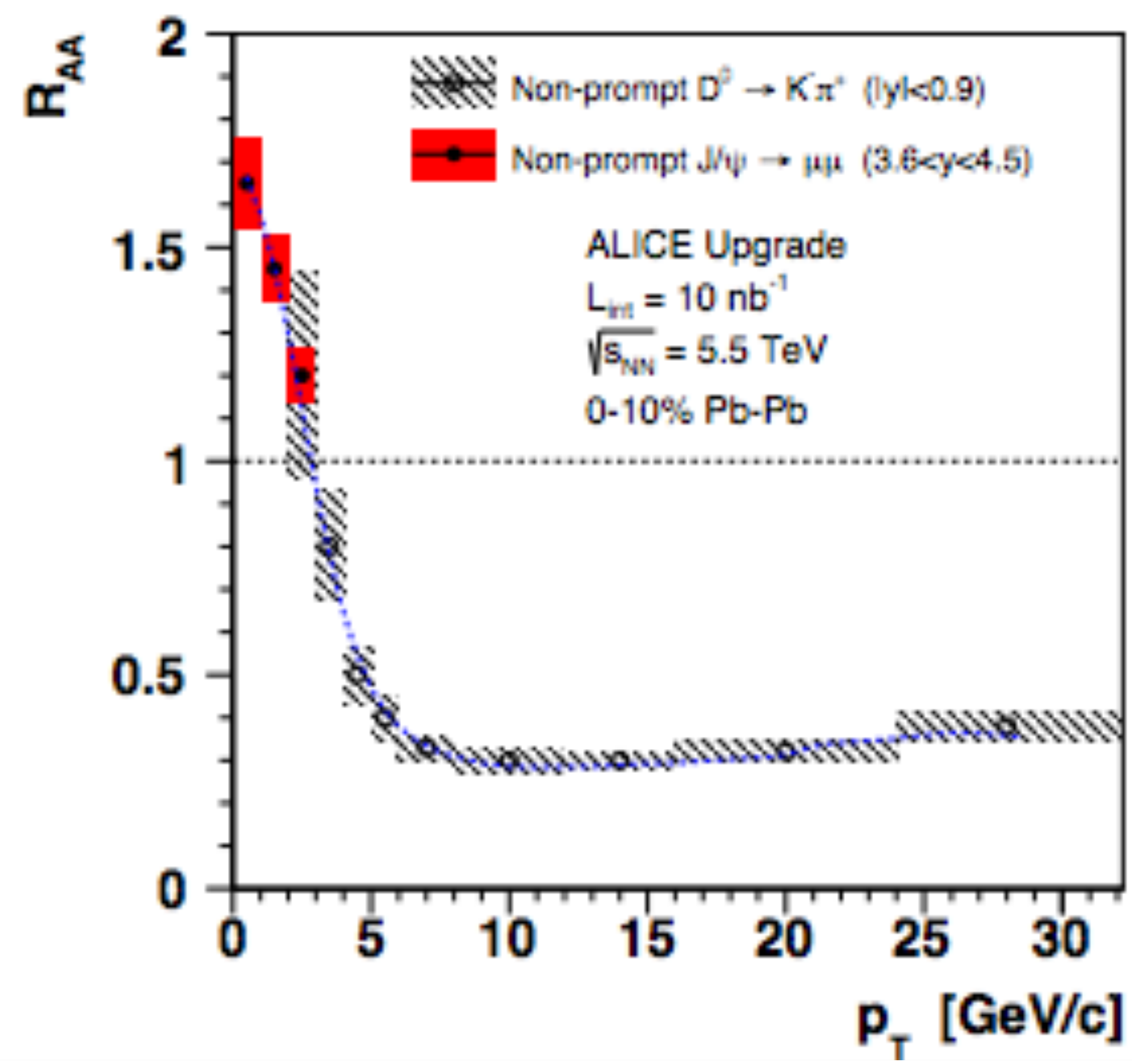
Upgrade expectations for quarko

Prompt charmonium

Beauty measurement via displaced J/psi

More precise bottomonium and ψ(2S) measurements, v_2 ?





SUMMARY

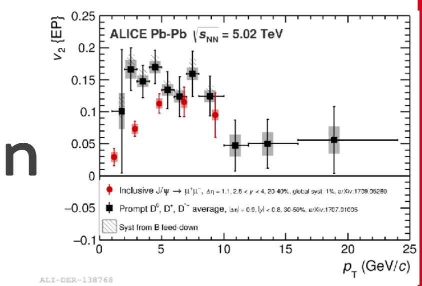
Open HF Hard probes of HI collisions

Pb-Pb

Positive v_2 is observed for D mesons and J/ψ

Strong case for charm thermalisation and (re)combination

Transport models underestimate J/ψ v_2 at high p_T

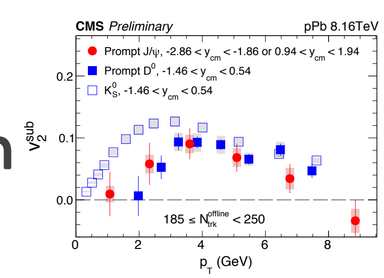


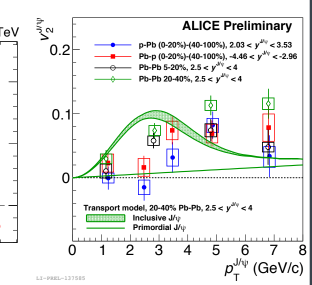
p-Pb

(Unexpected) v_2 for D mesons and J/ψ

Signs of weaker charm interaction in the medium

J/ψ v_2 in p-Pb is not yet understood





Upgrade expectations

improved precision +
D mesons down to p_T=0 + Λ_c ratio and v_2

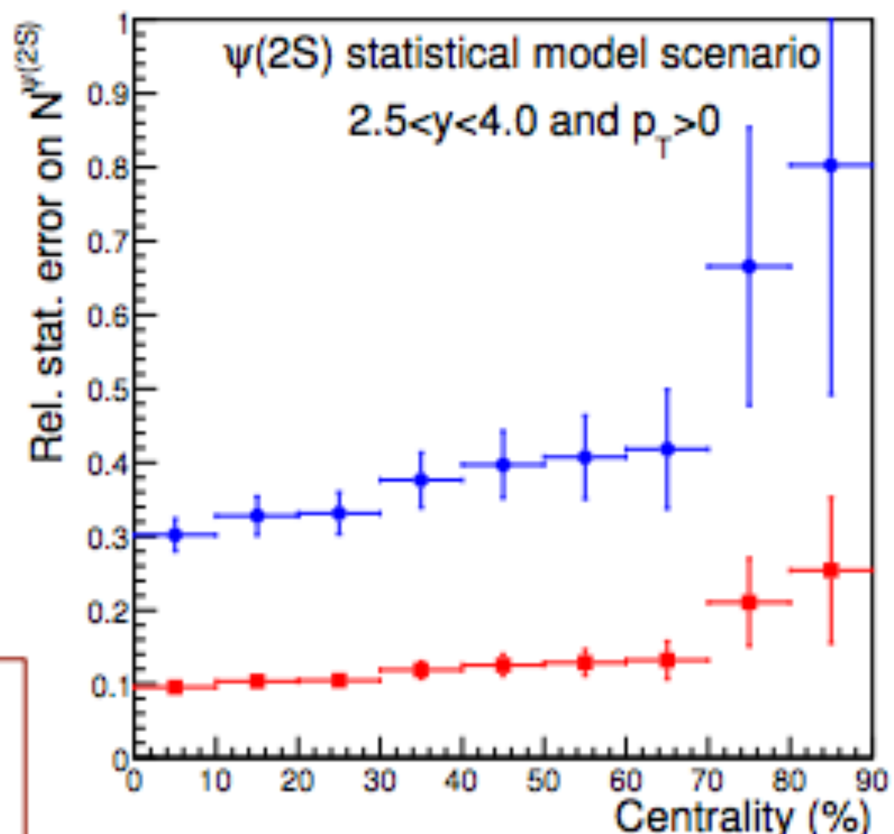
New observables: beauty

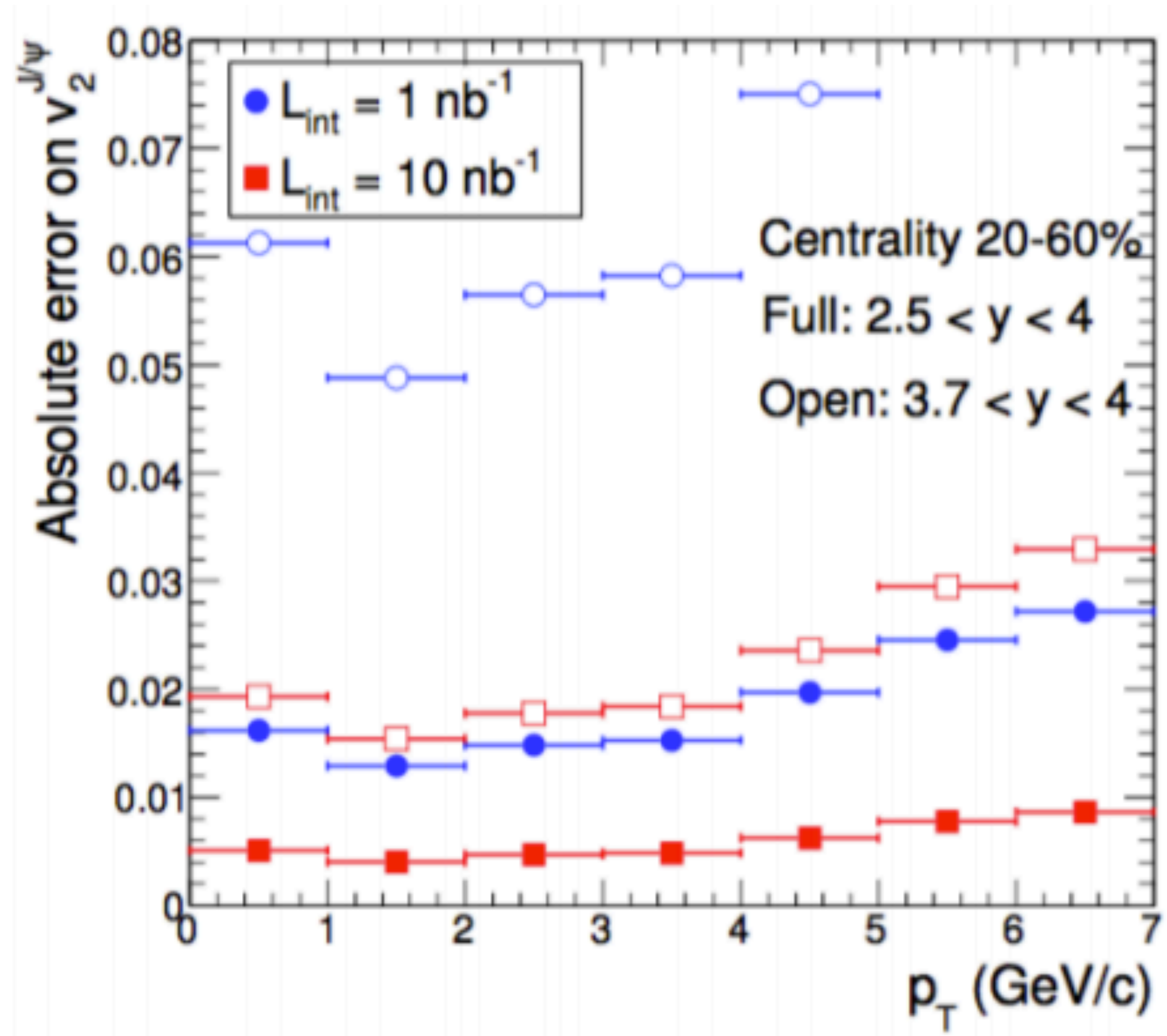
Quarkonium: prompt/non prompt separation, ψ(2S), ϒ

Thank you for your attention!

Back-up

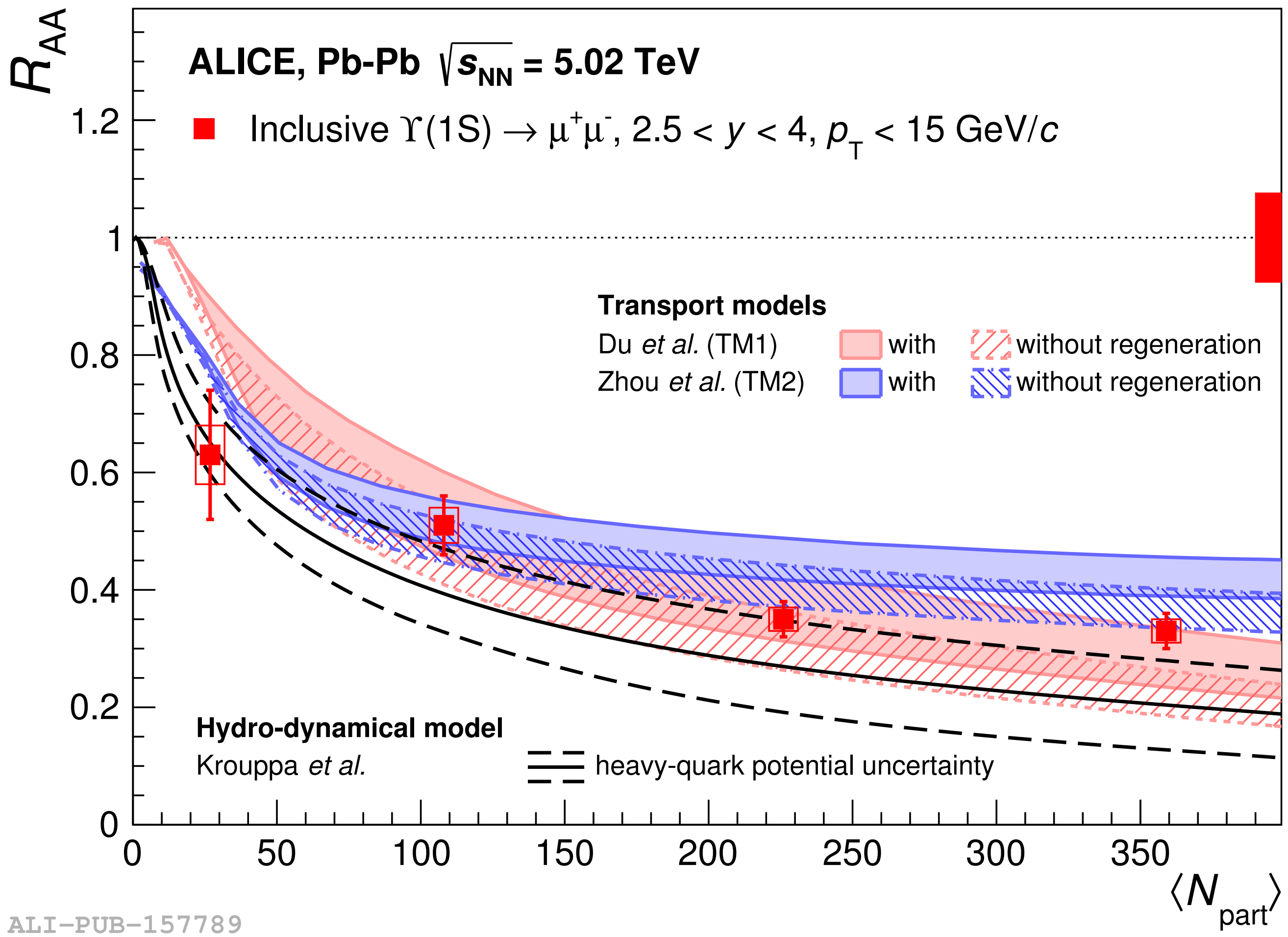
Expected performances for quarkonia

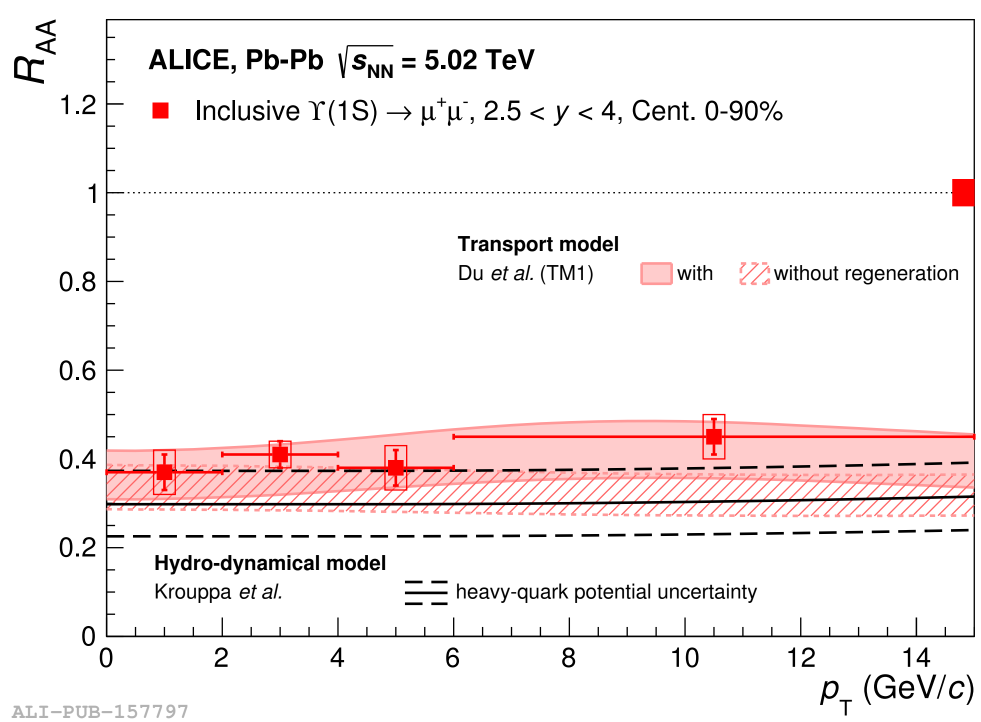




Future precision

Bottomonium in the QGP





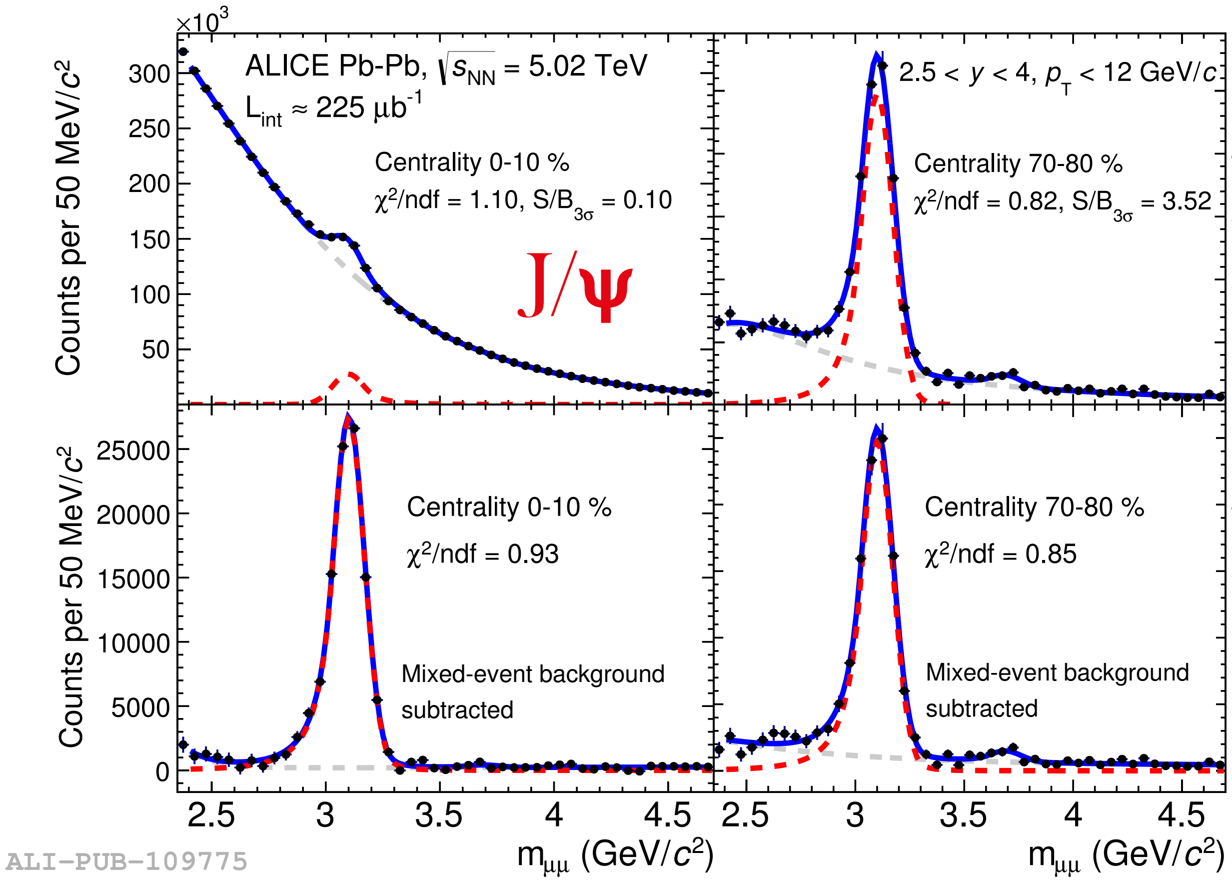
Strong ϒ(1S) suppression

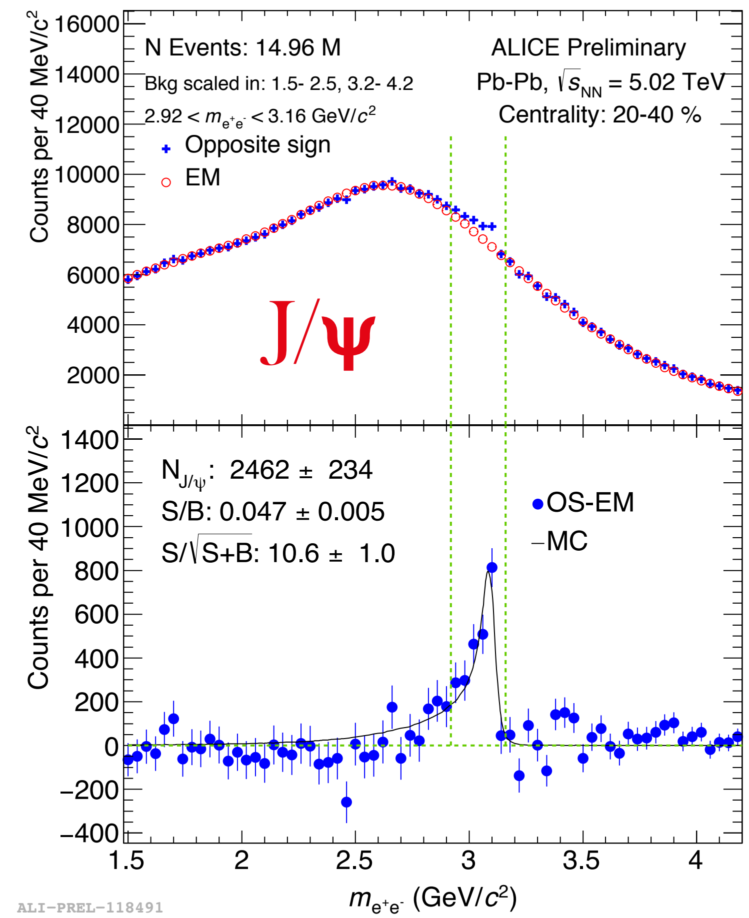
➡ Direct ϒ(2S) and ϒ(3S) production suppressed ?

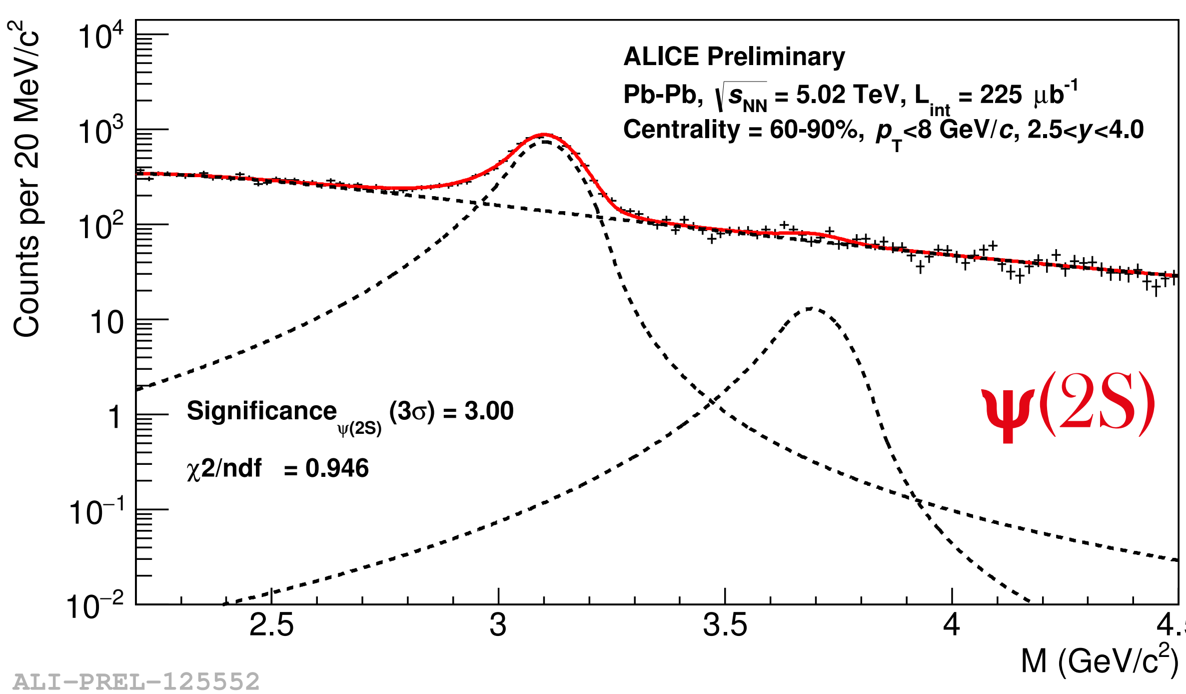
But rather different than for $c\bar{c}$

- No plateau is observed
- ~ no p_T dependence
- Compatible with transport models w/wo (re)generation

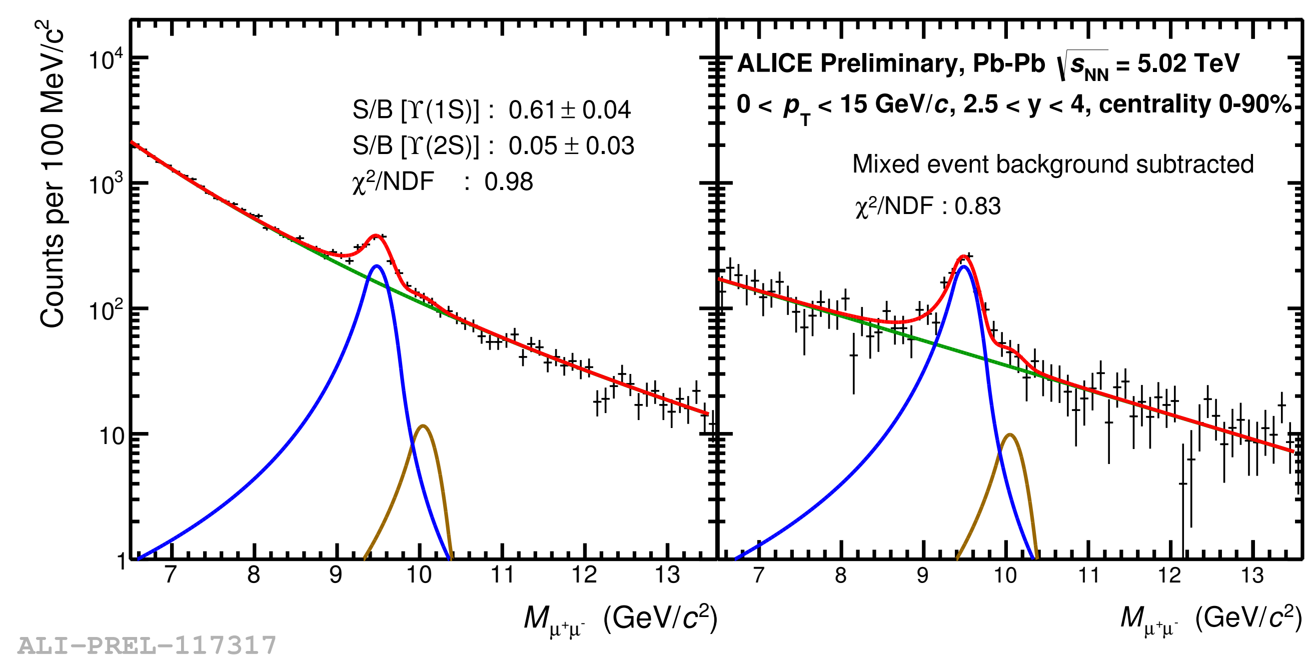
Charmonium reconstruction







ϒ(1S), ϒ(2S)

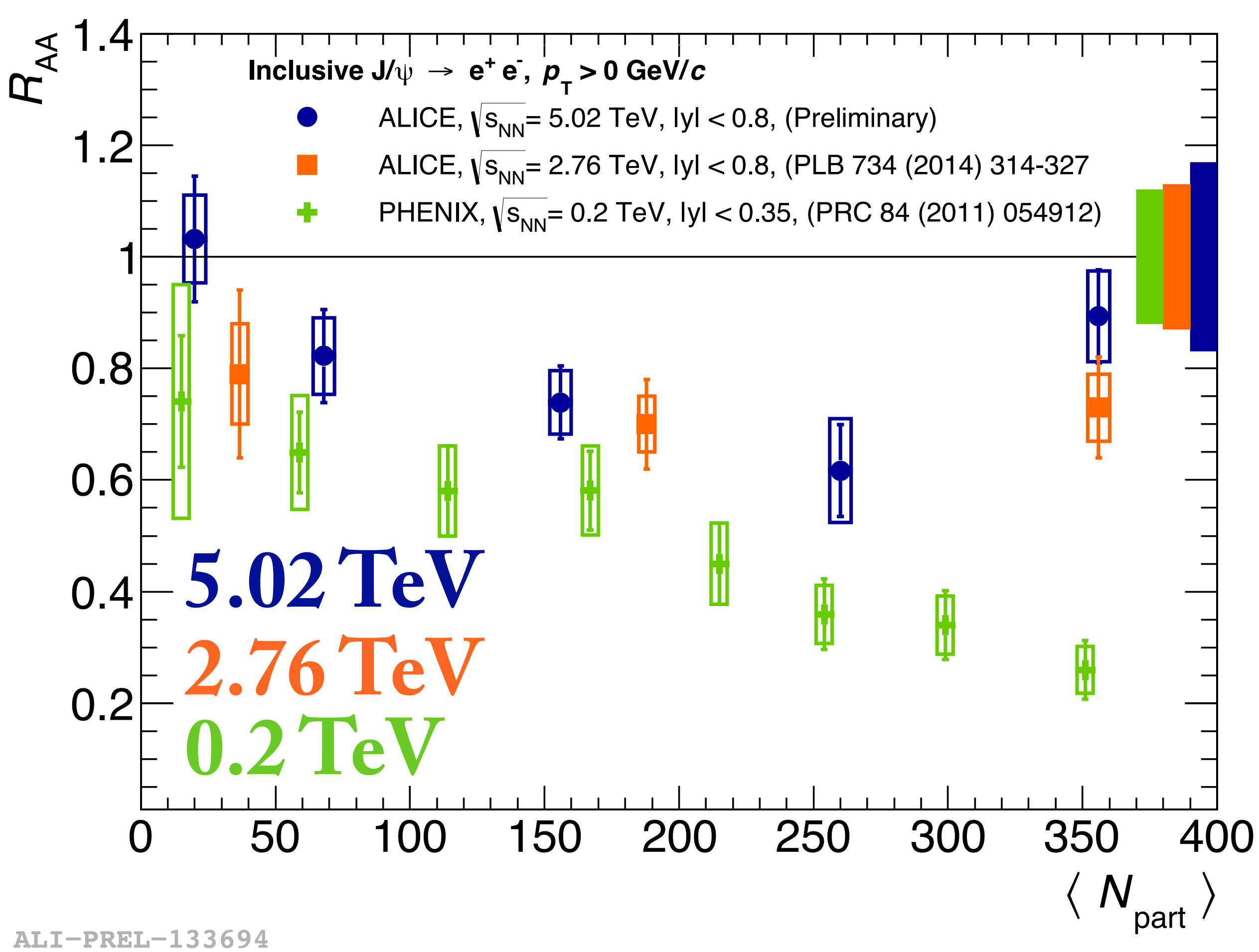


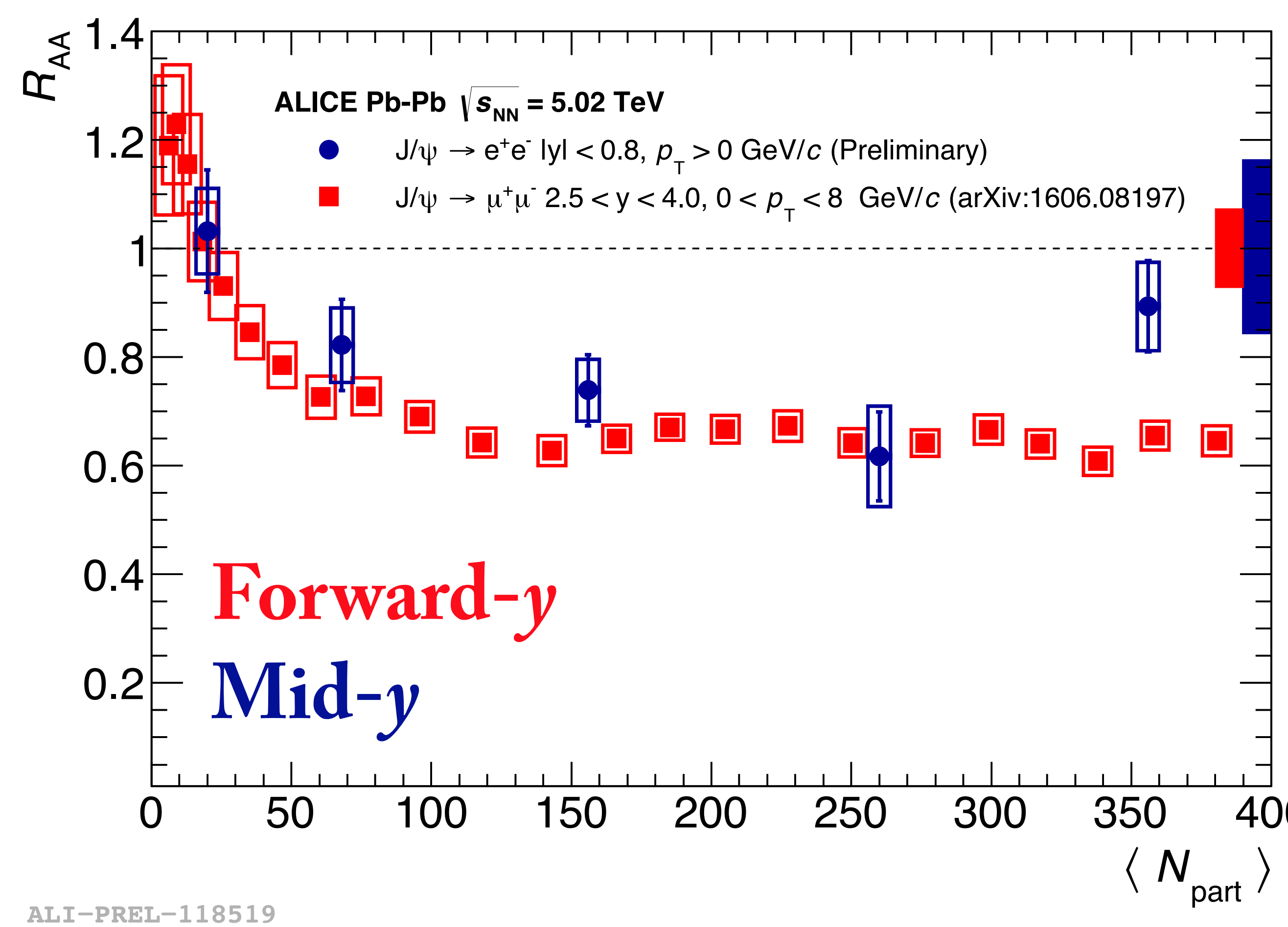
Yield extraction : Fit of the dimuon invariant mass distribution with several signal + background shapes

Mid-rapidity results

Good agreement between both rapidity measurements

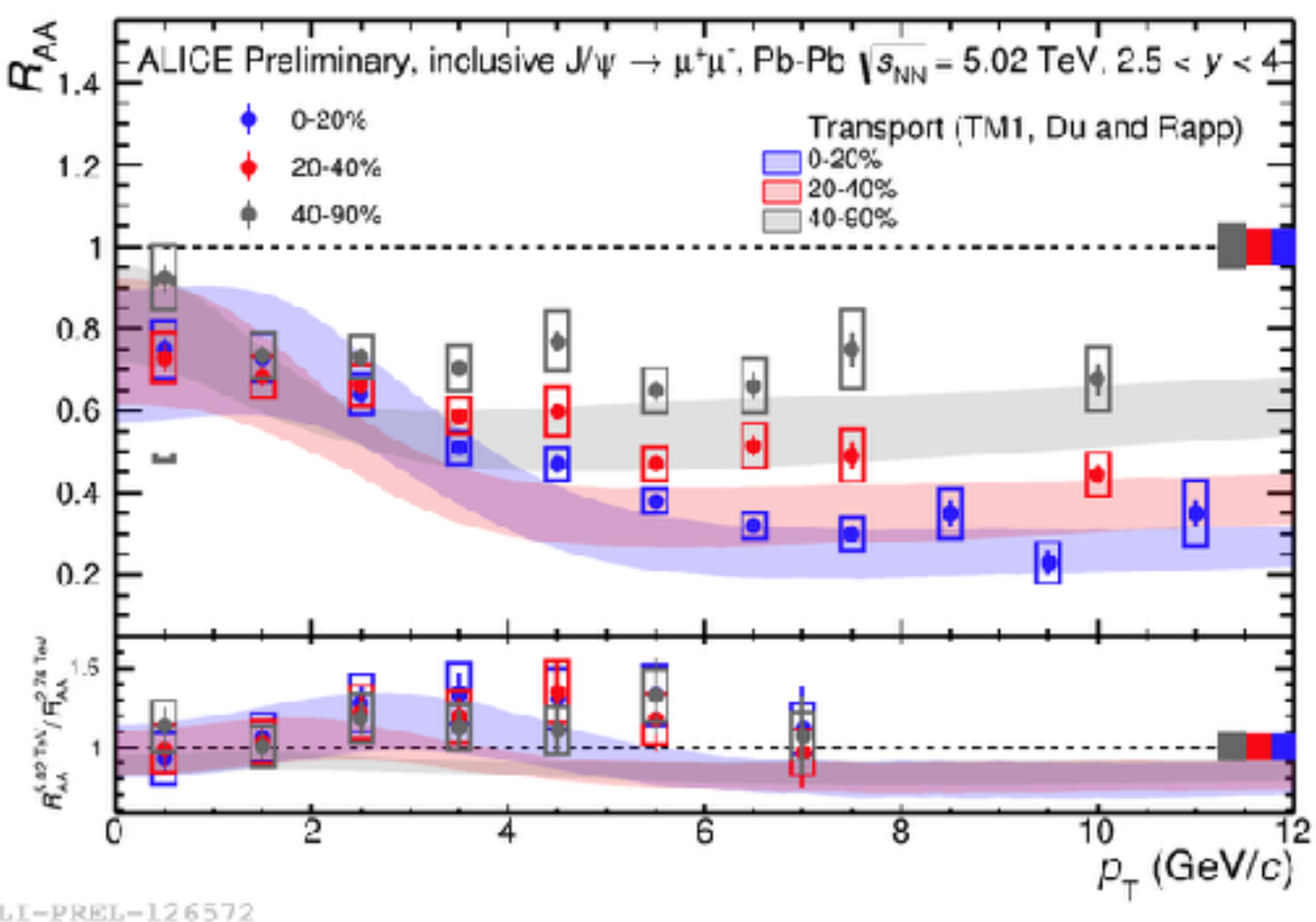
Hint of a production increase for the most central collisions at mid-y

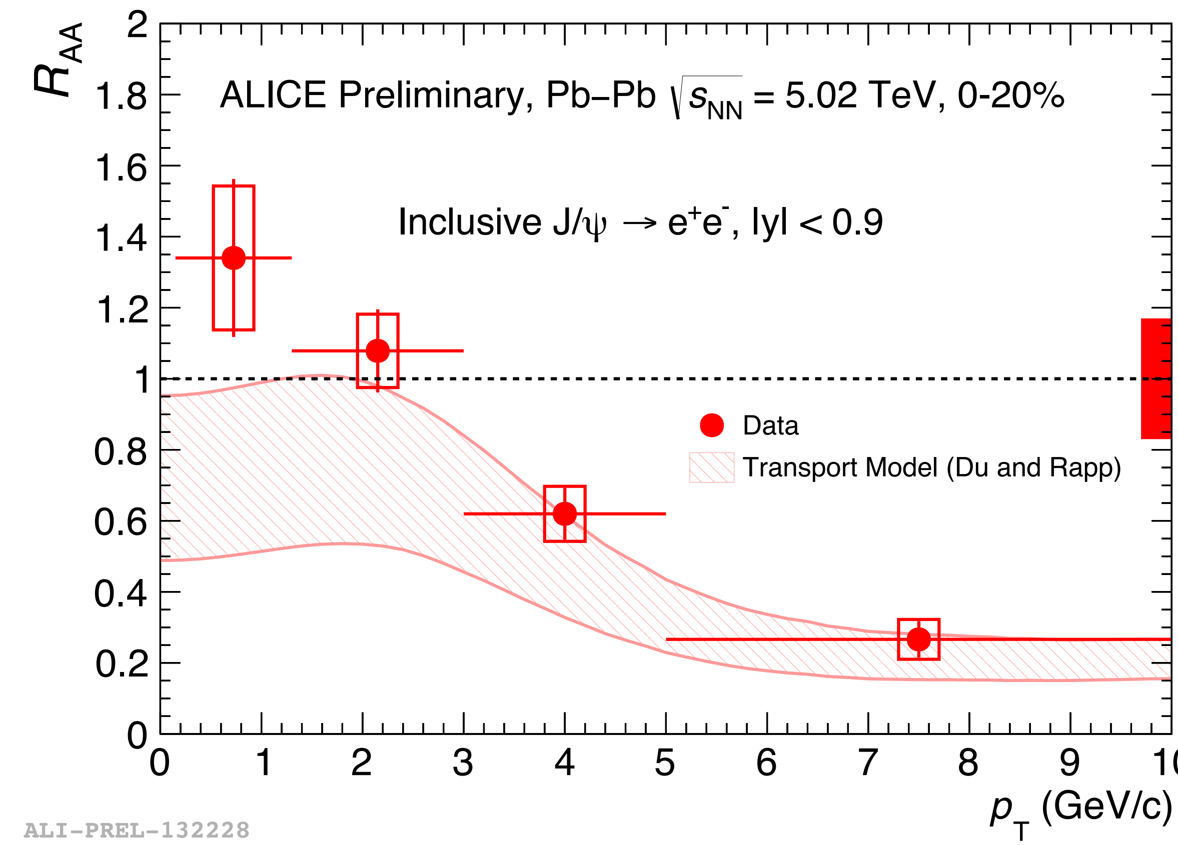


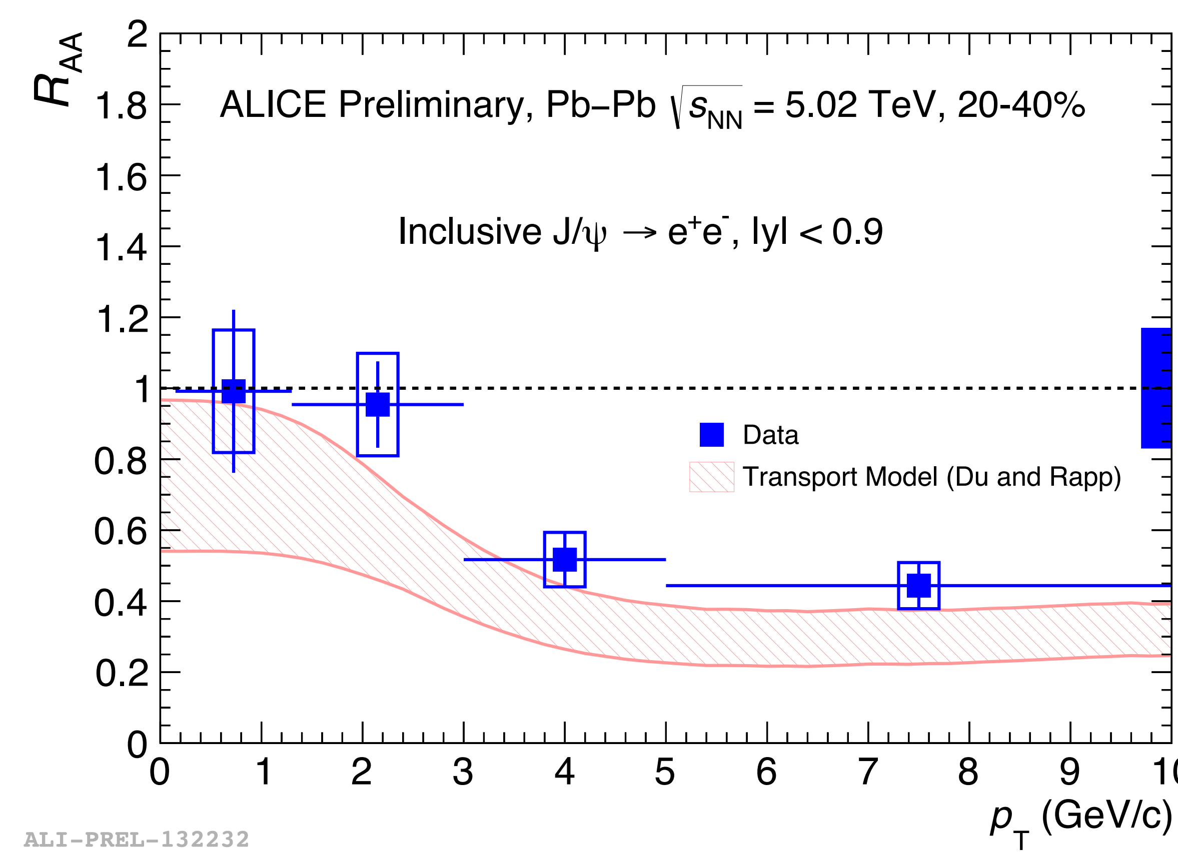


Charmonium production vs p_T

Intro | HF | ALICE | Pb-Pb | p-Pb | Upgrade



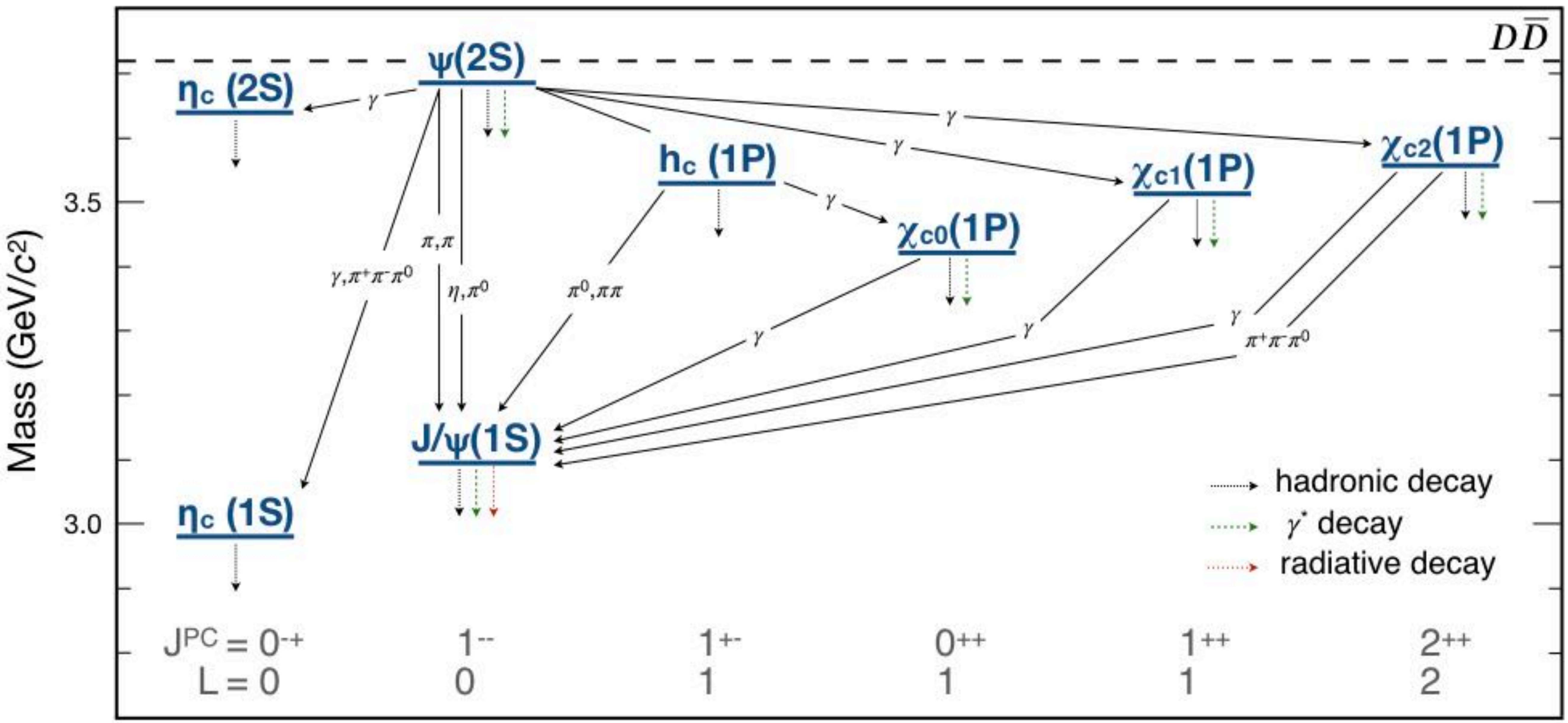




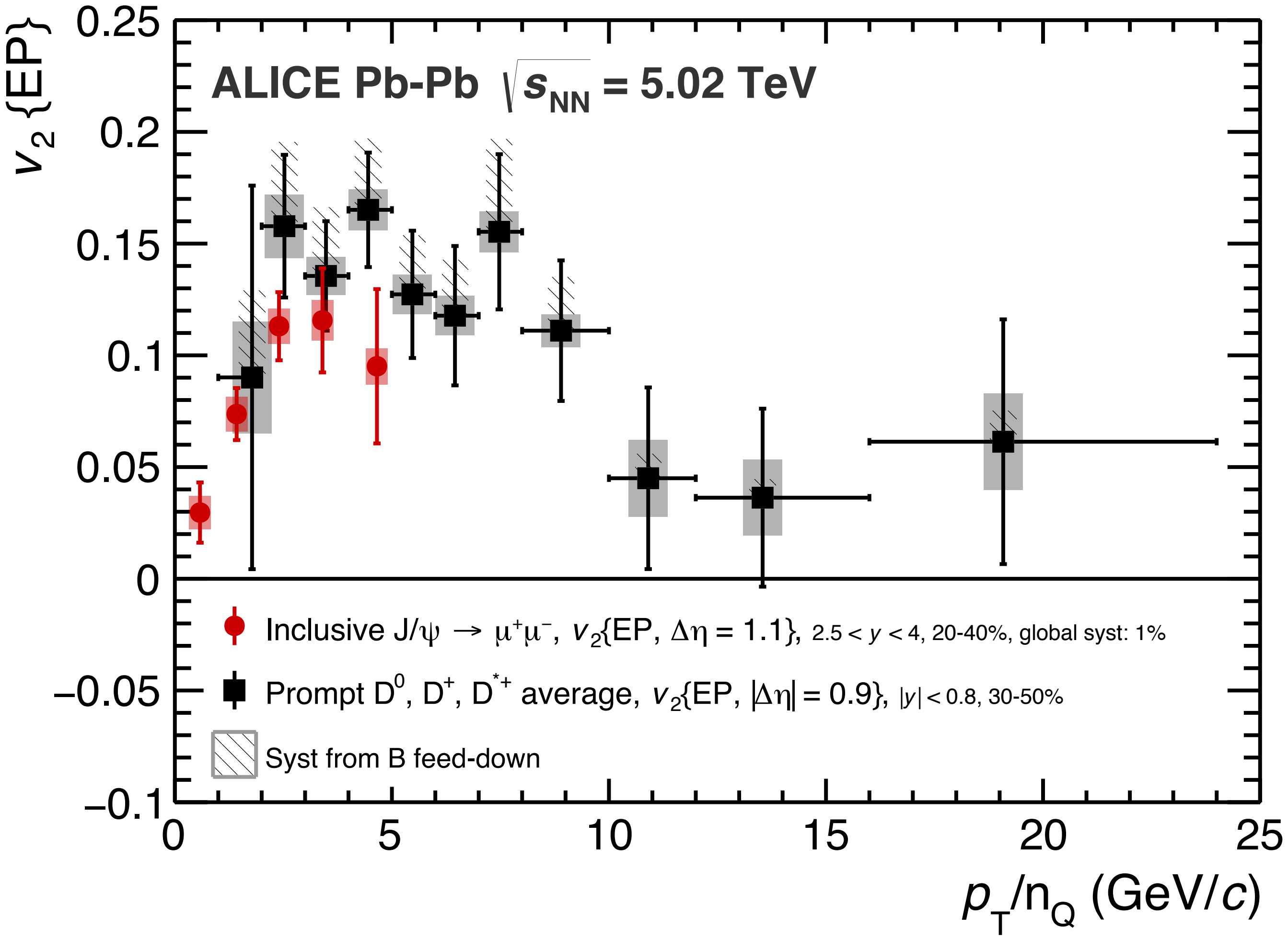
Stronger p_T dependence for the most central collisions

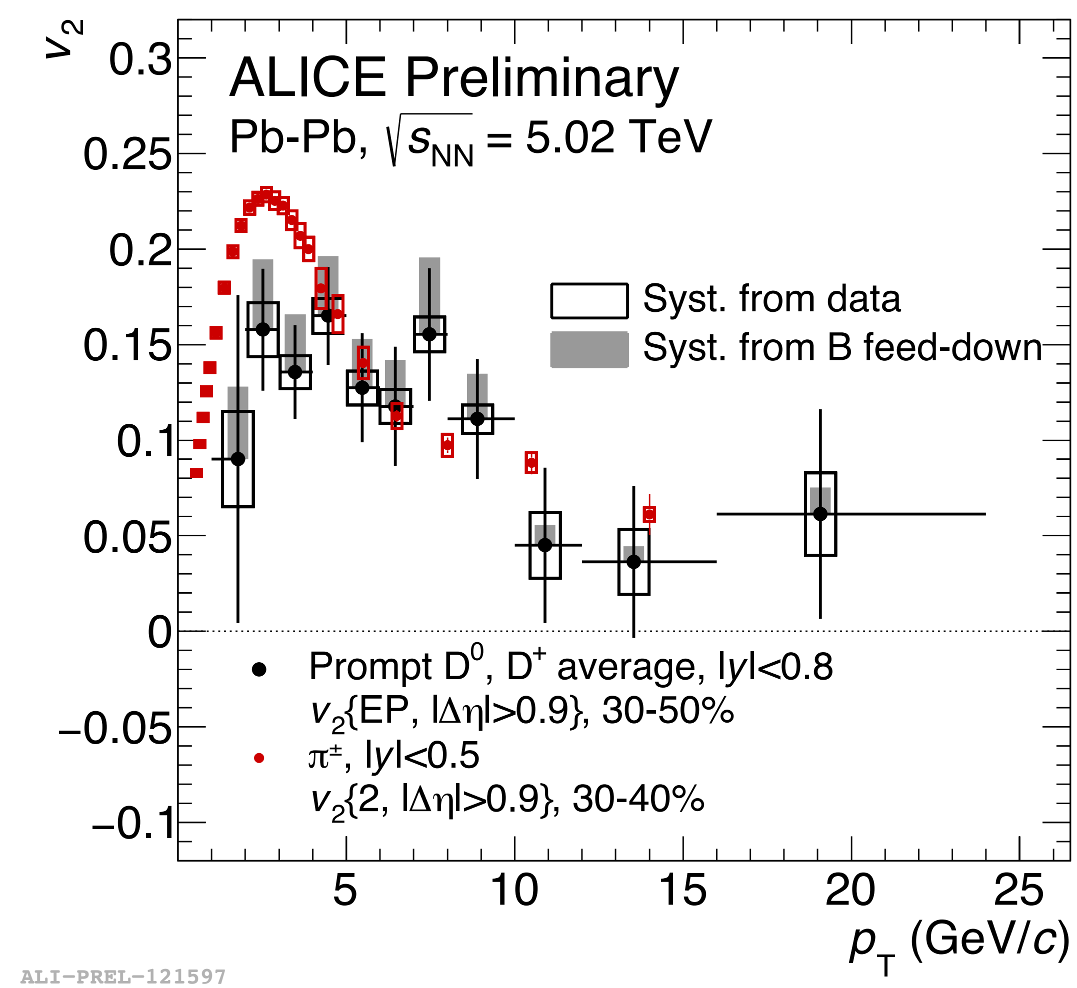
Transport model predicts similar trend

Charmonium spectroscopy

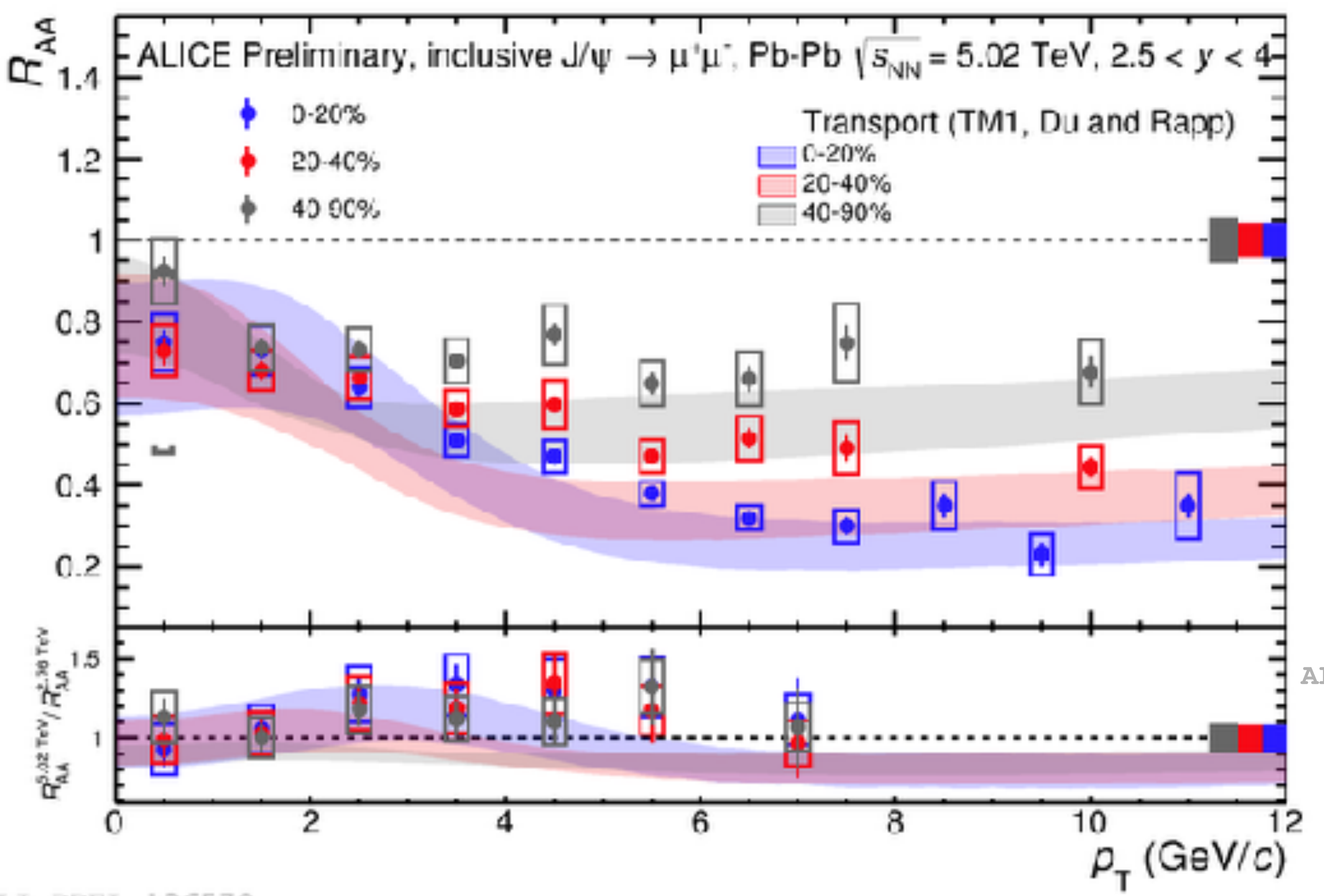


v_2 results comparison

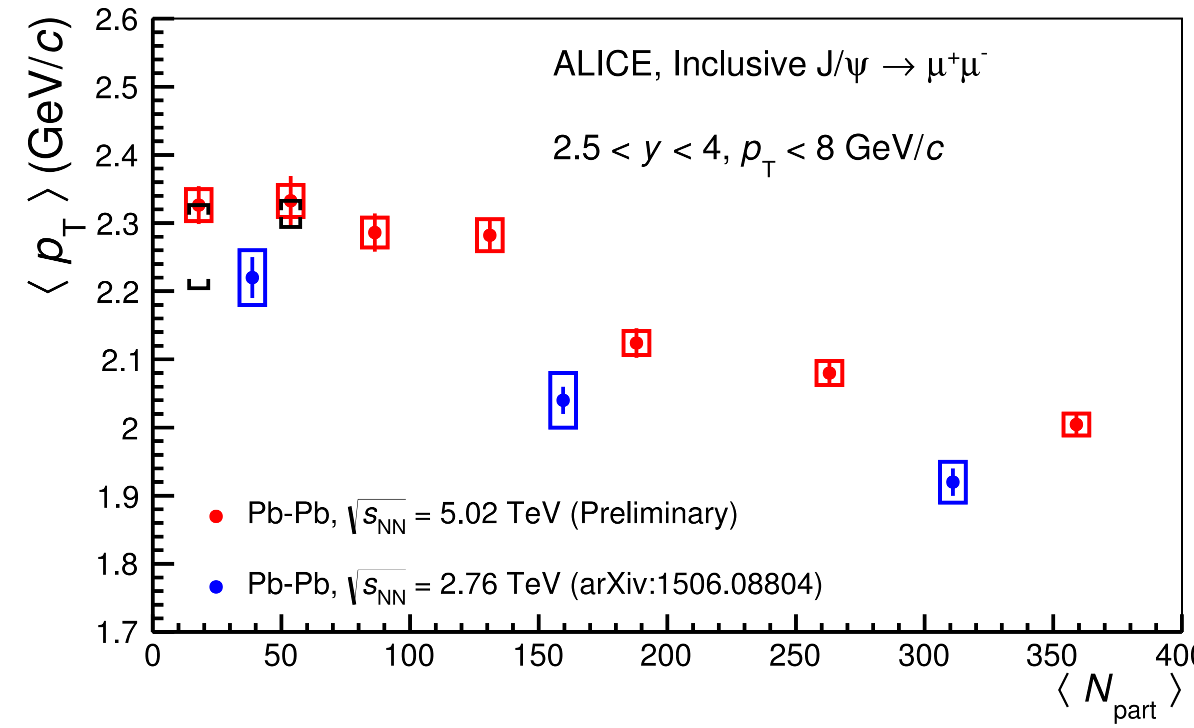




J/ψ Nuclear Modification factor vs p_T, $\langle p_T \rangle$, r_{AA}

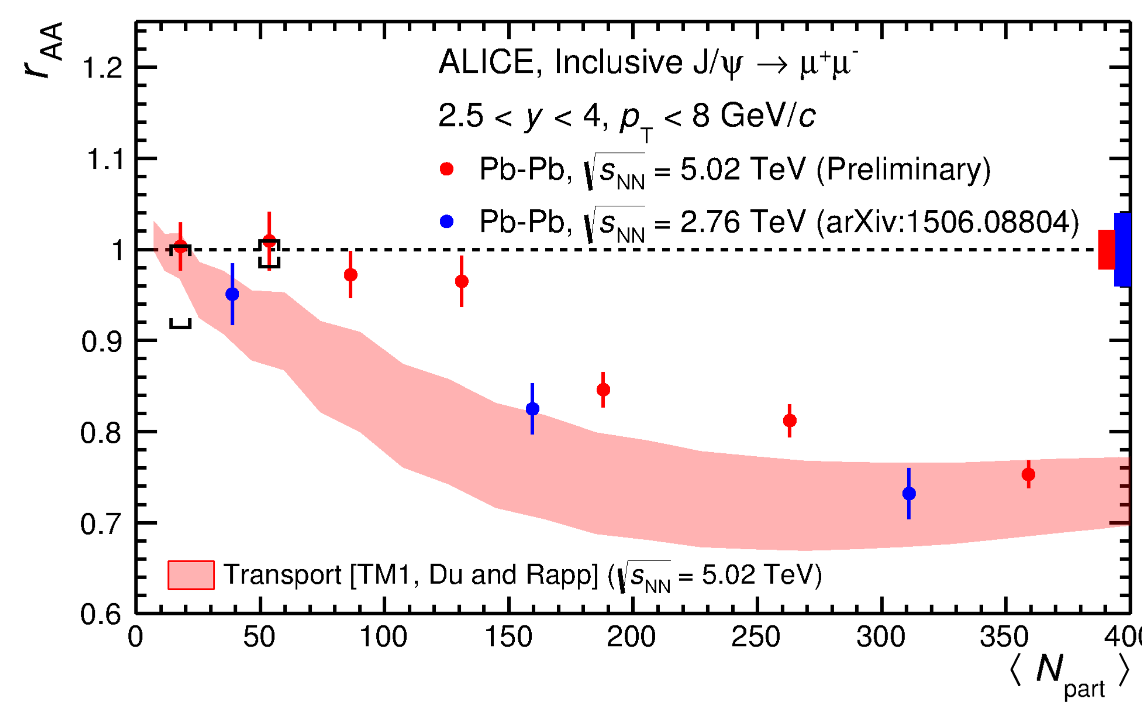


ALI-PREL-126572



ALI-PREL-120593

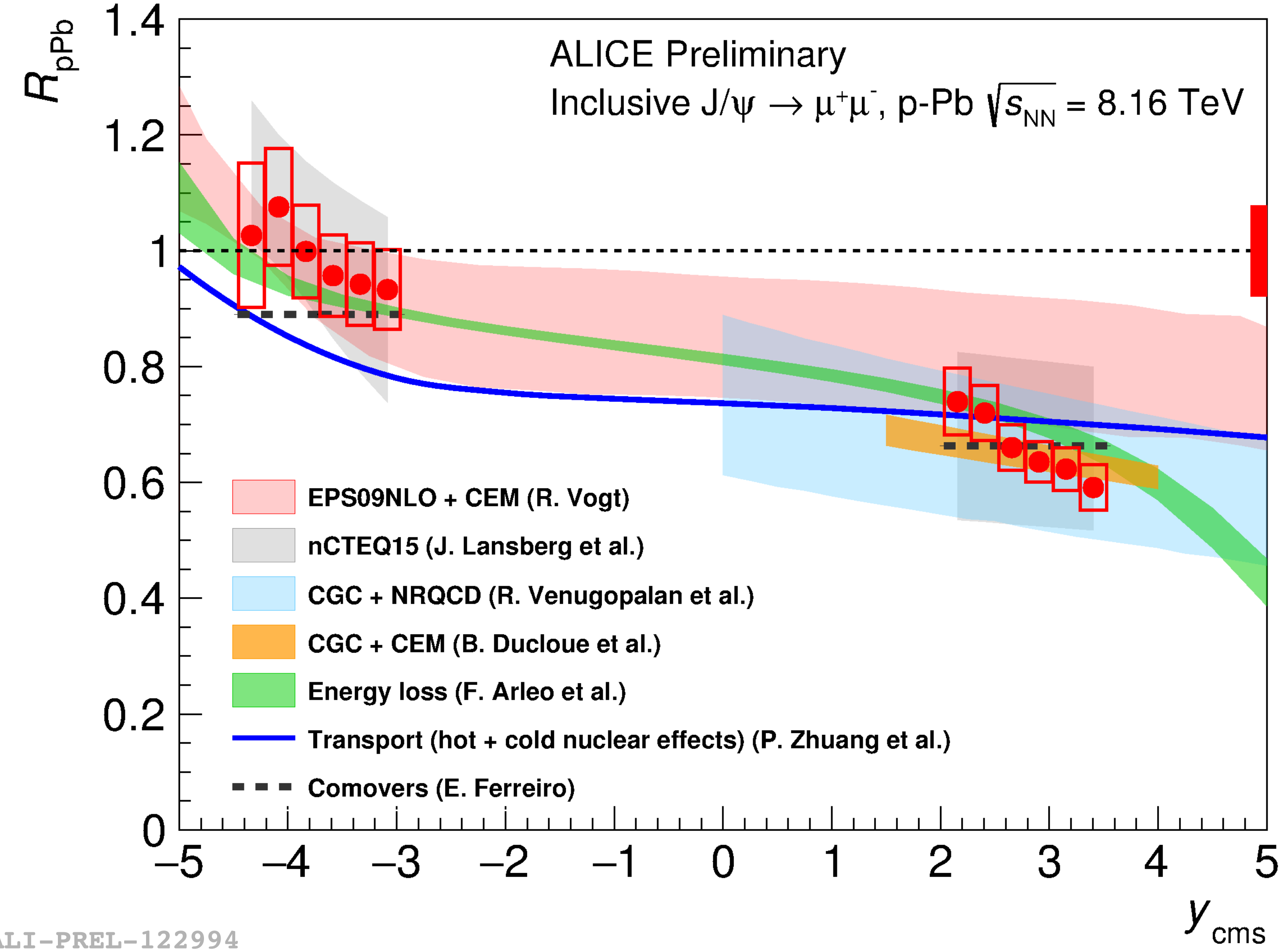
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

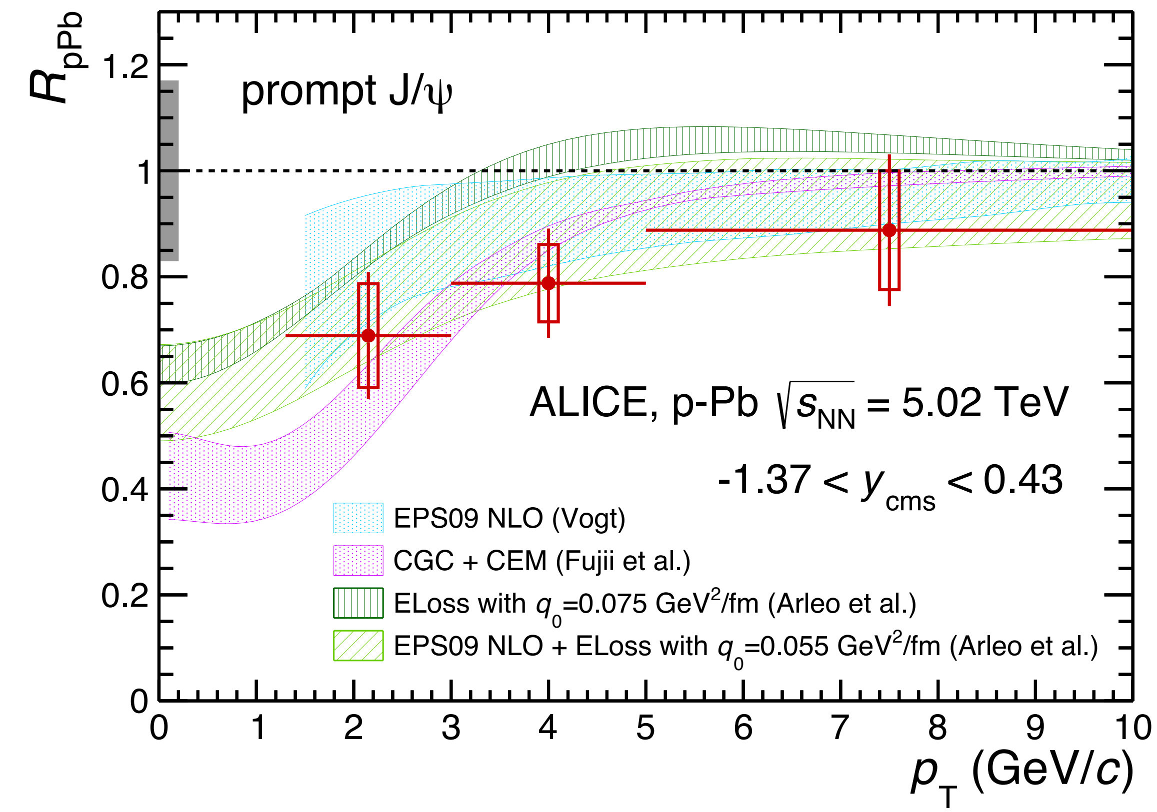


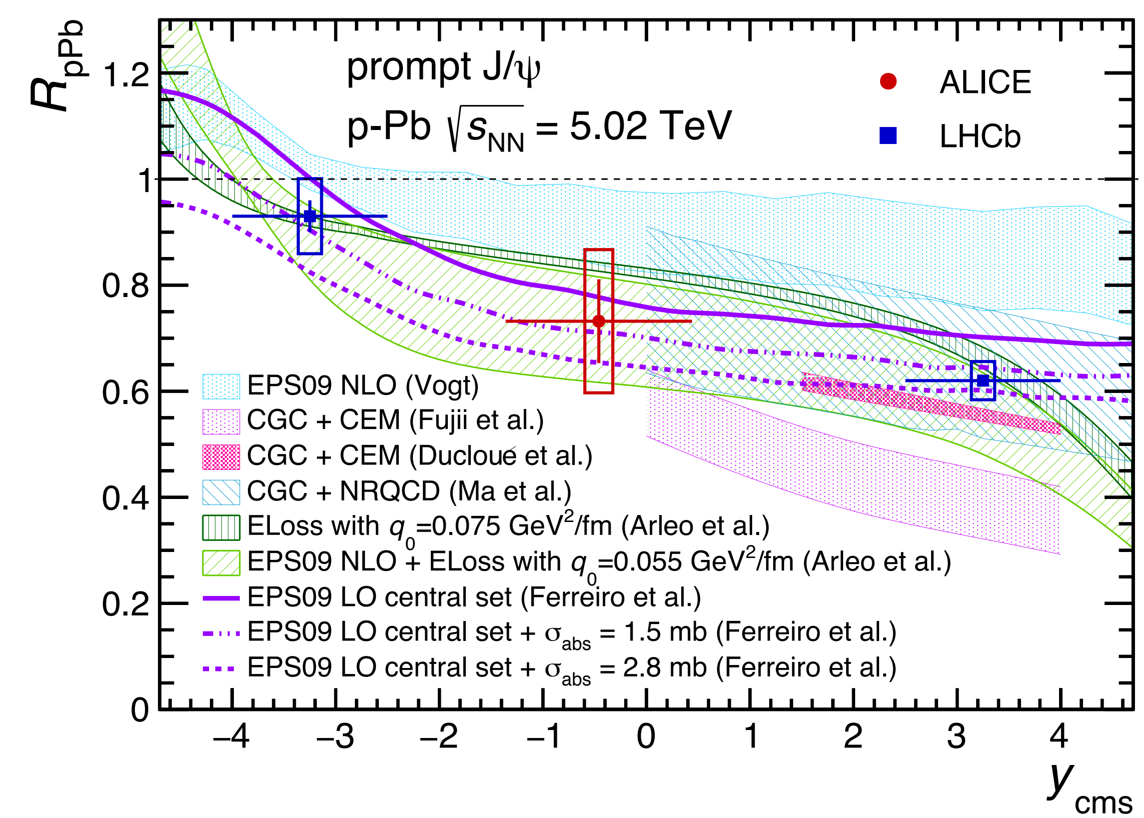
ALI-PREL-120574

- J/ψ suppression is stronger at high p_T and in central collisions
- Transport model predicts similar trend
- Brackets give limits for possible contamination from J/ψ photo-production

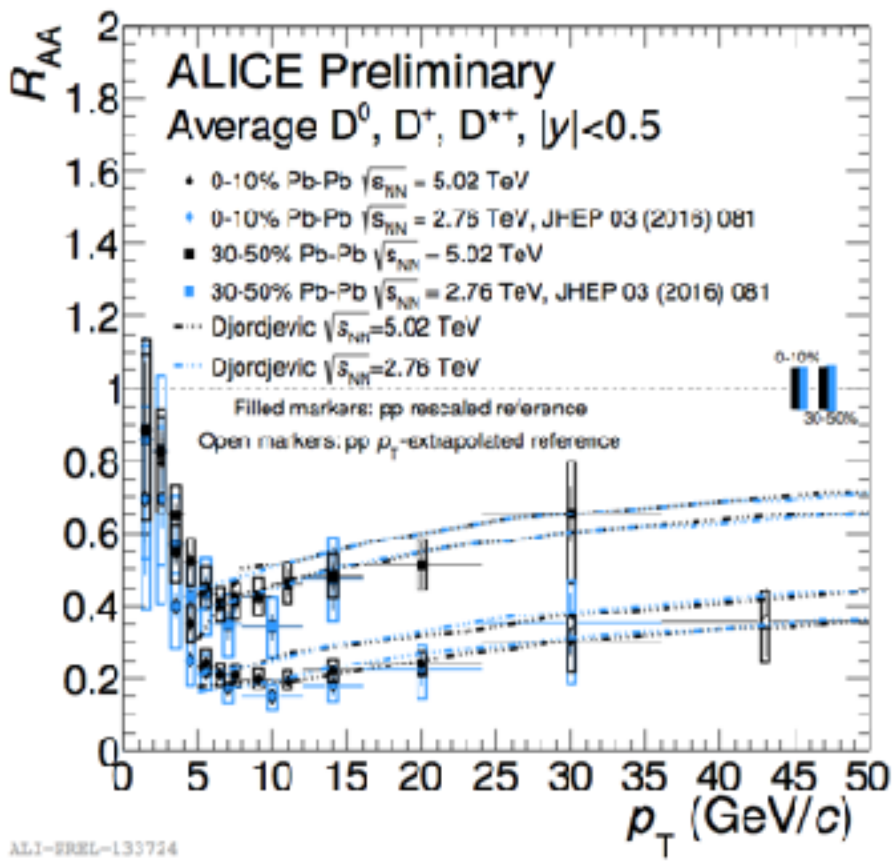
Charmonium production in p-Pb

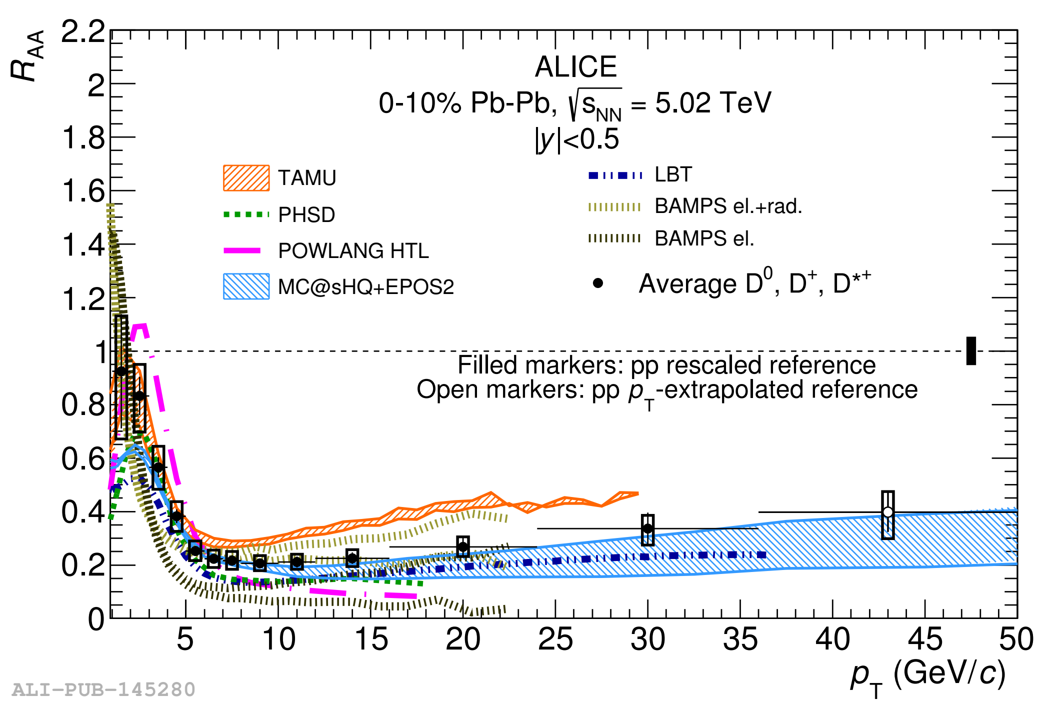






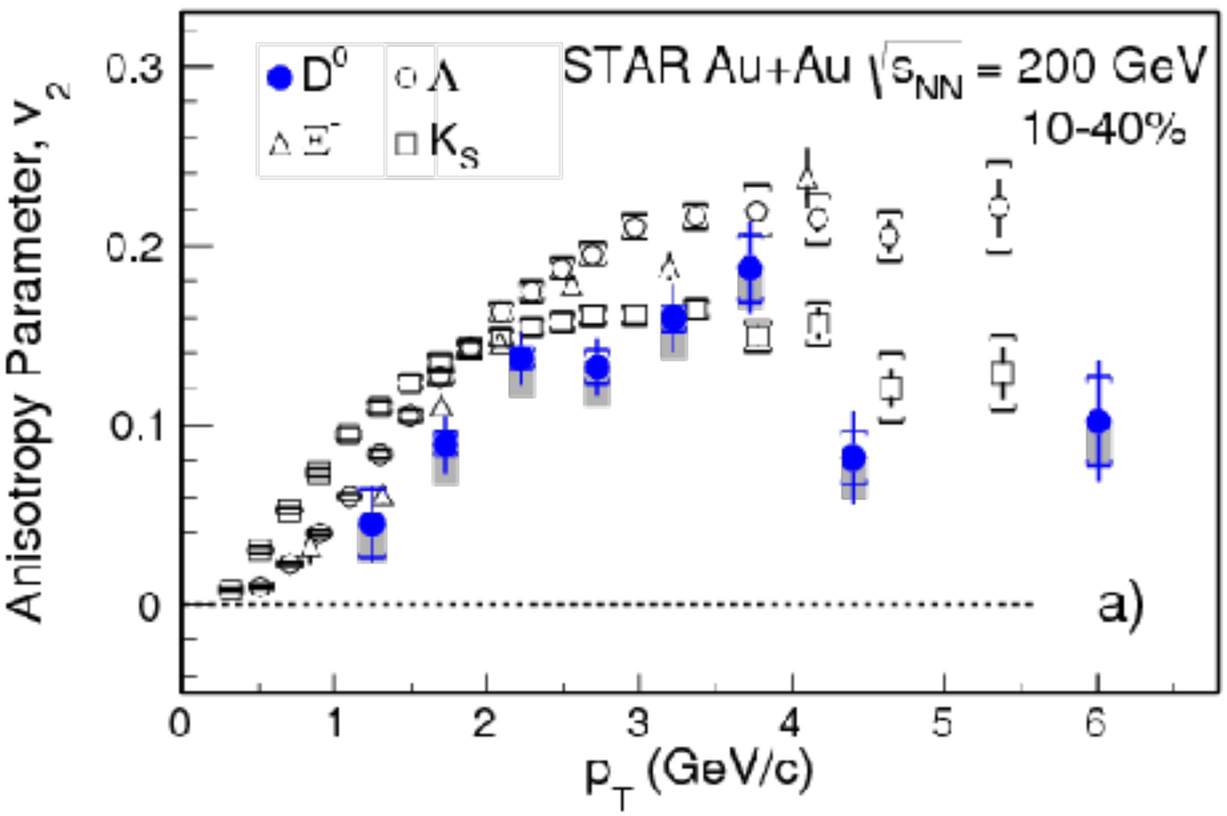
Open heavy flavours

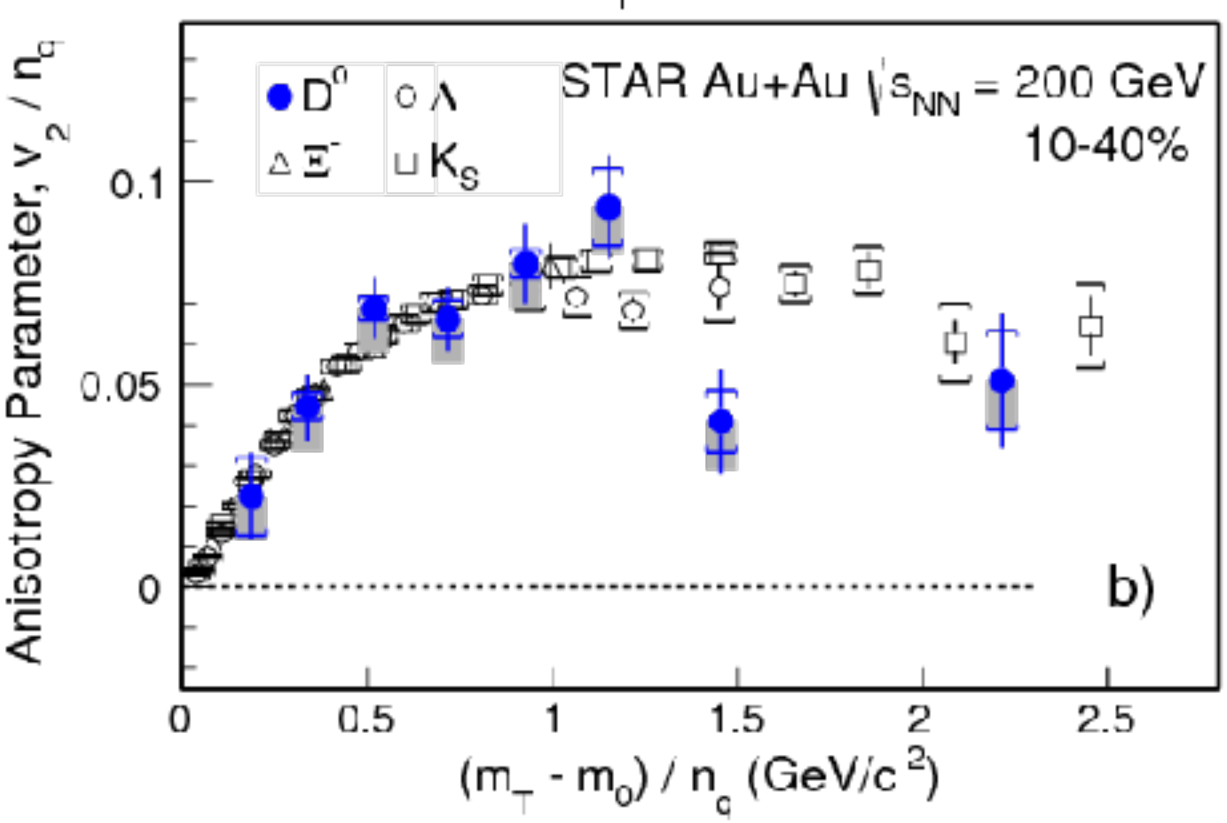


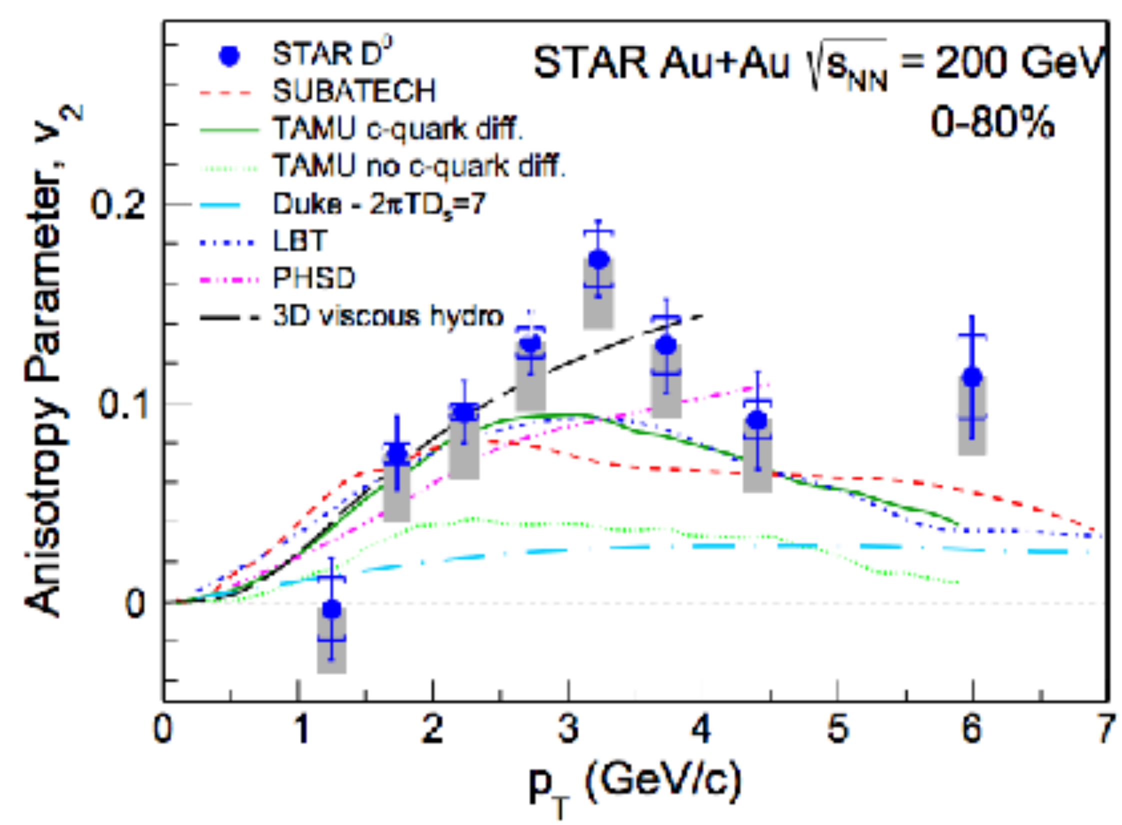


- Strong suppression in the medium
- Well reproduced by theory

D meson flow at RHIC



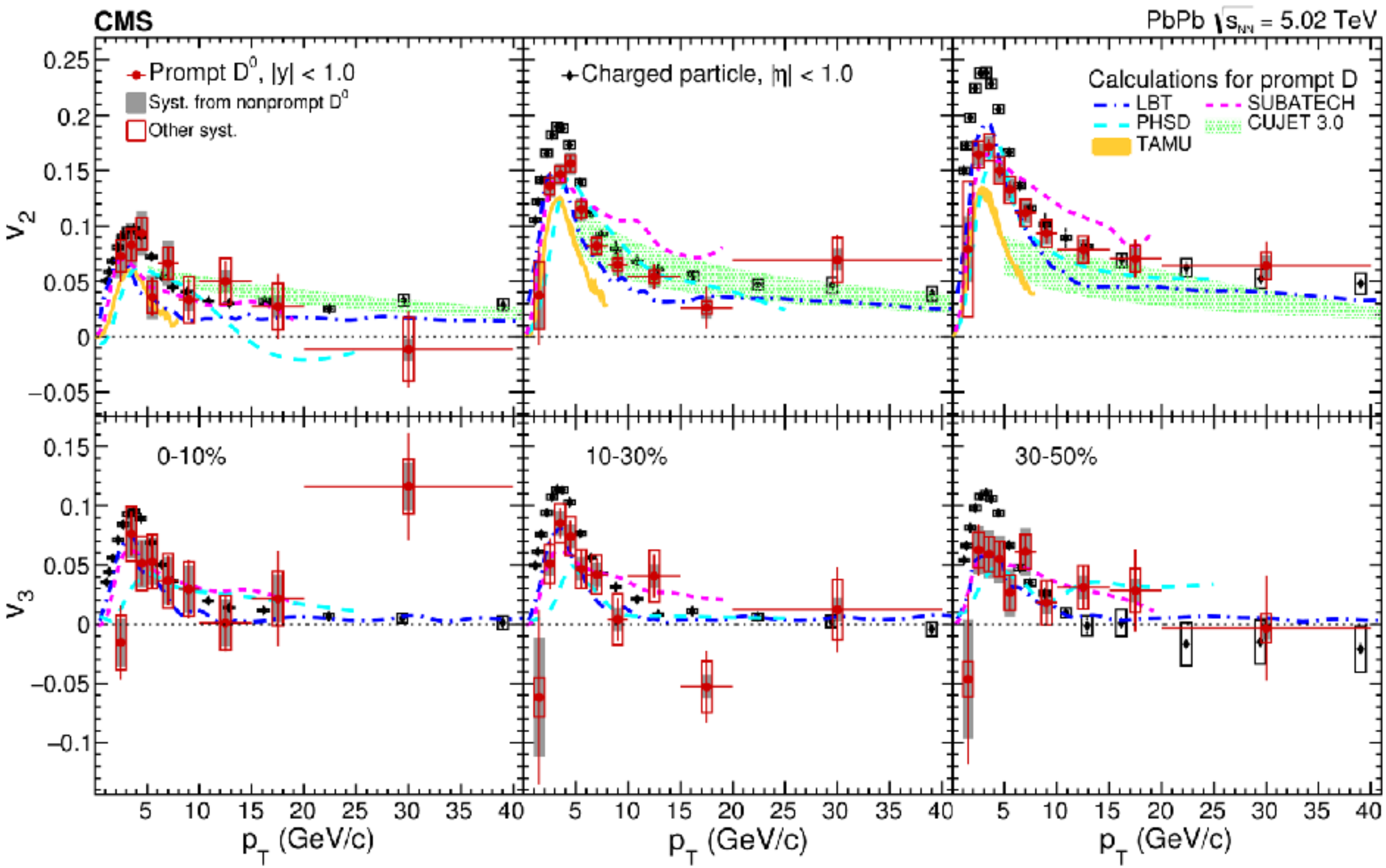




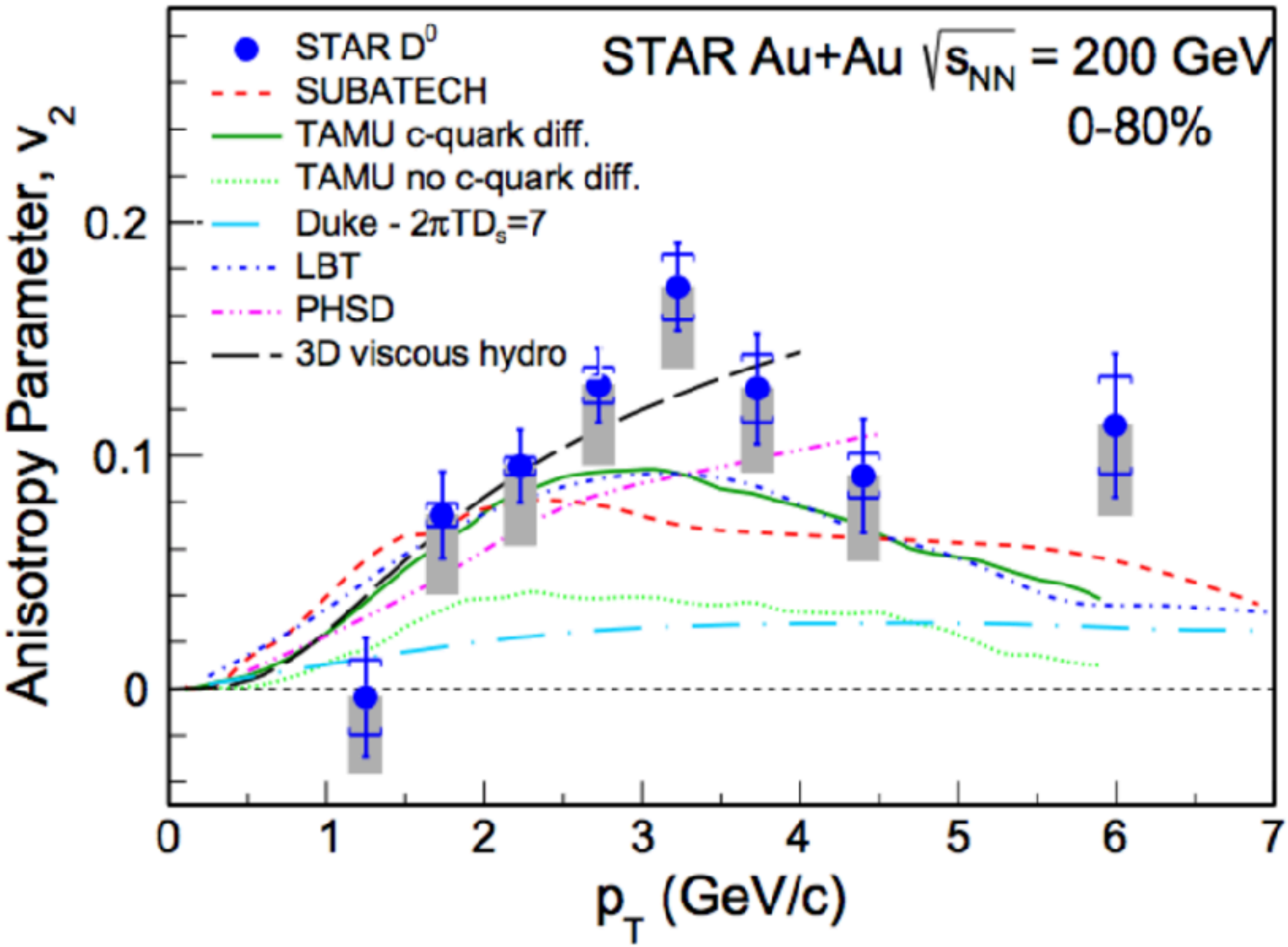
Clear mass ordering below 2 Gev/c

Scales with NCQ, following same trend as light hadrons

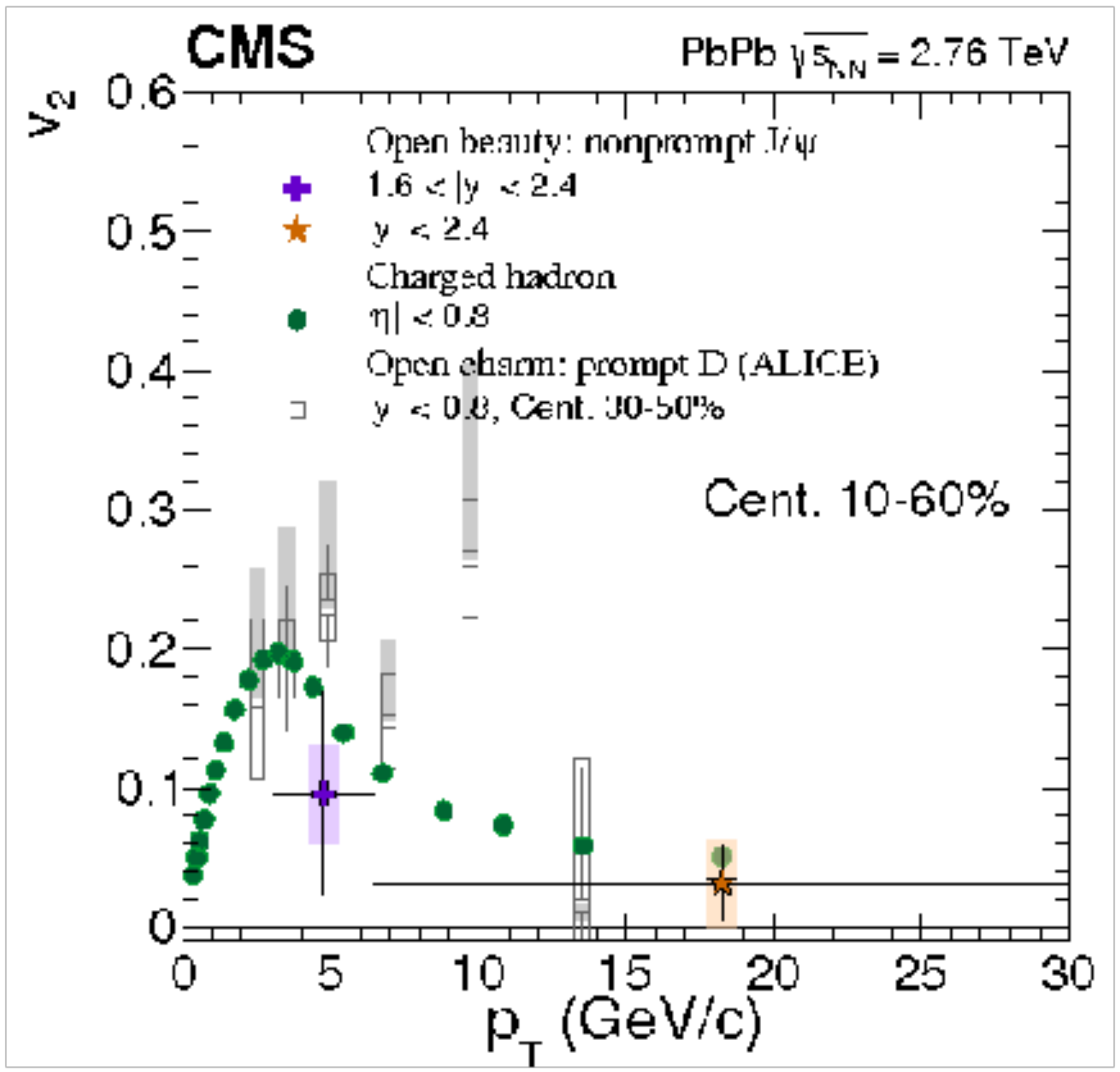
CMS measurement of prompt D^0 v_2 at 5.02 TeV

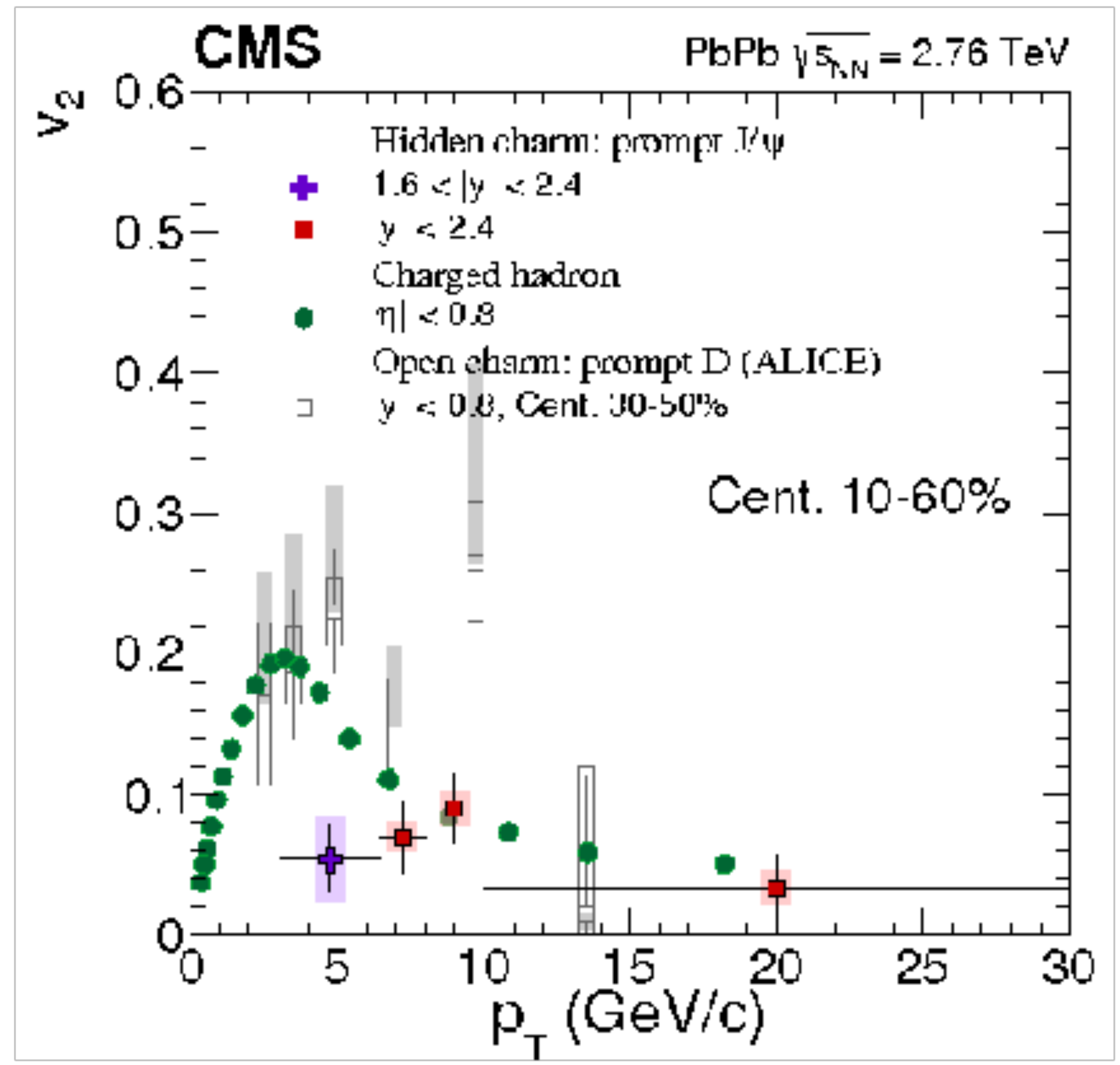


STAR measurement of prompt D^0 v_2 at 200 GeV

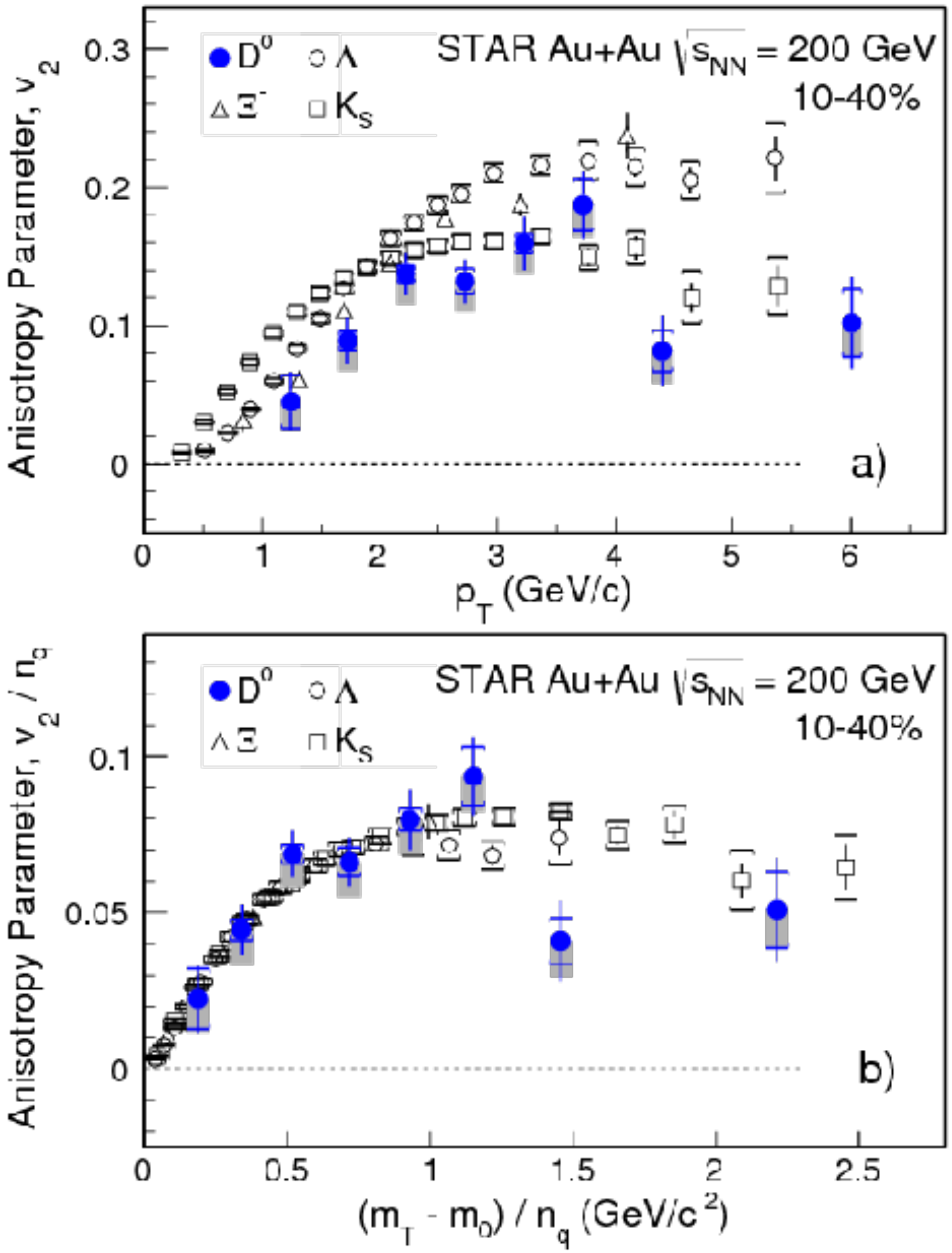


Non-prompt J/ψ v_2 with CMS





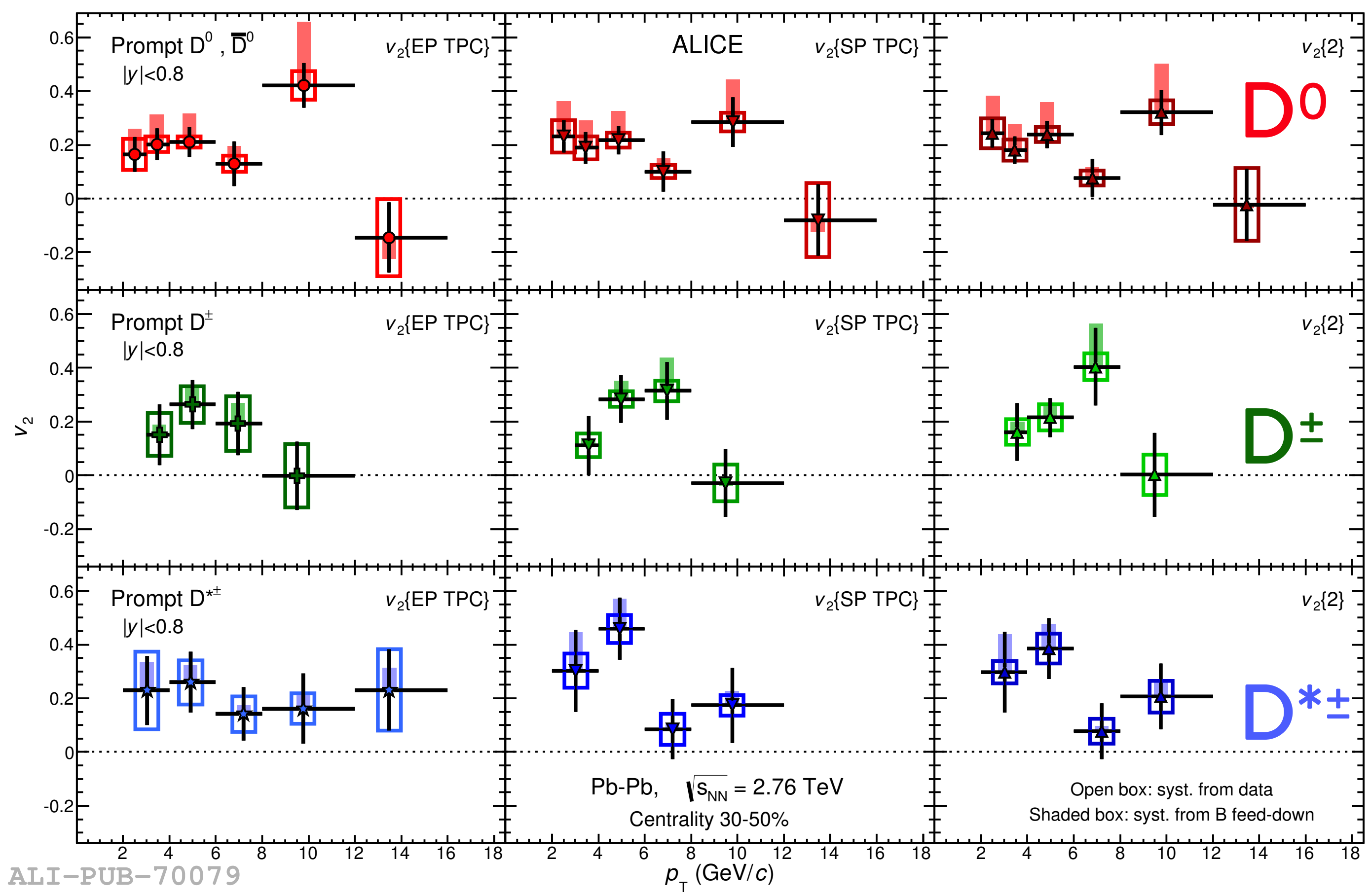
D^0 meson v_2 with STAR at 200GeV/c

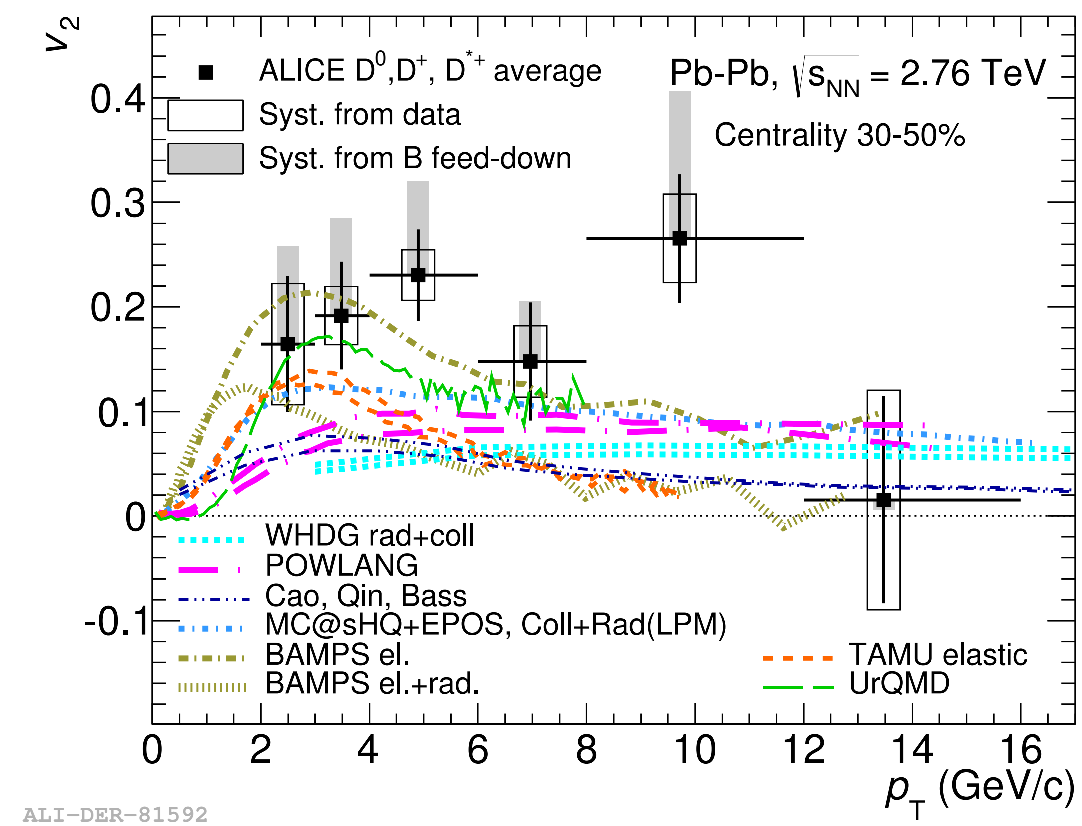


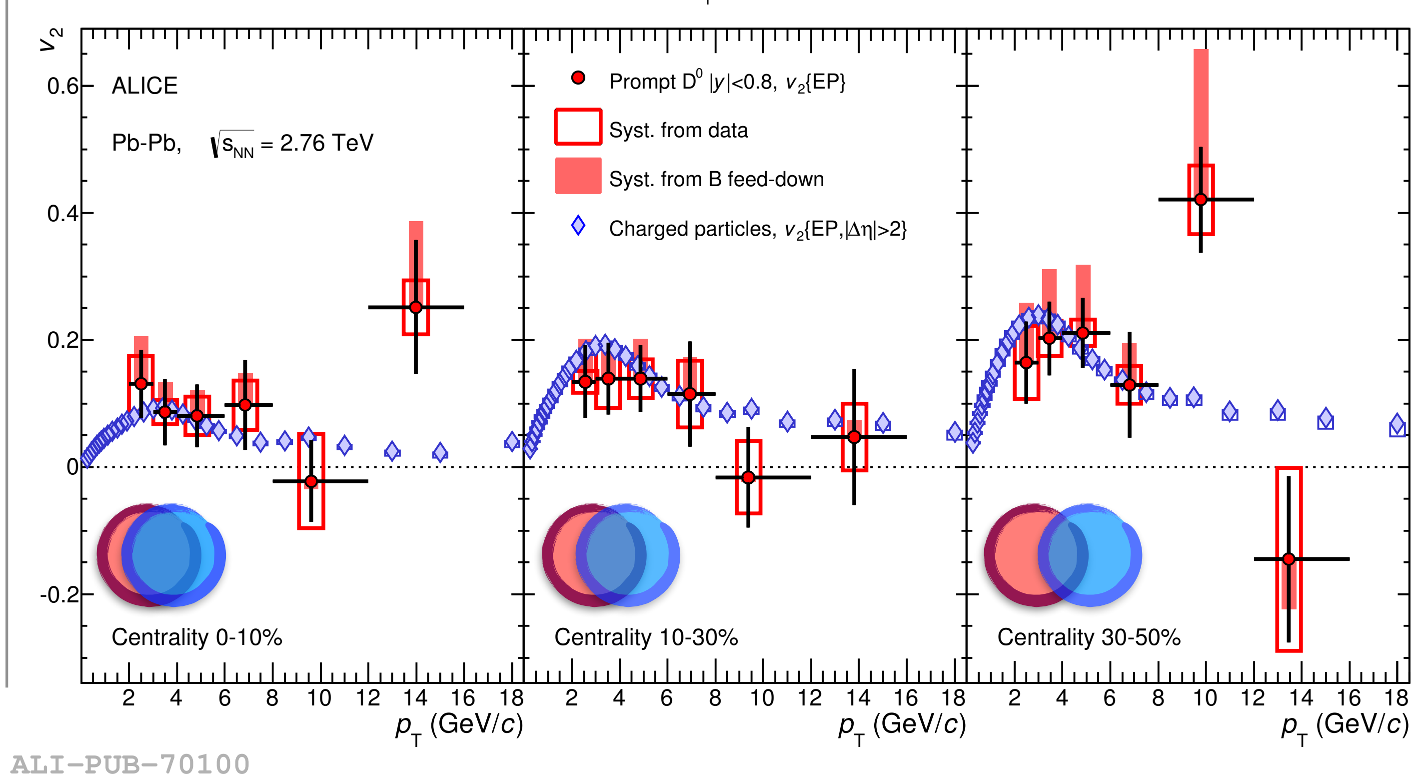
v_2 consistent with light mesons

suggestion of local thermal equilibrium for charm quarks

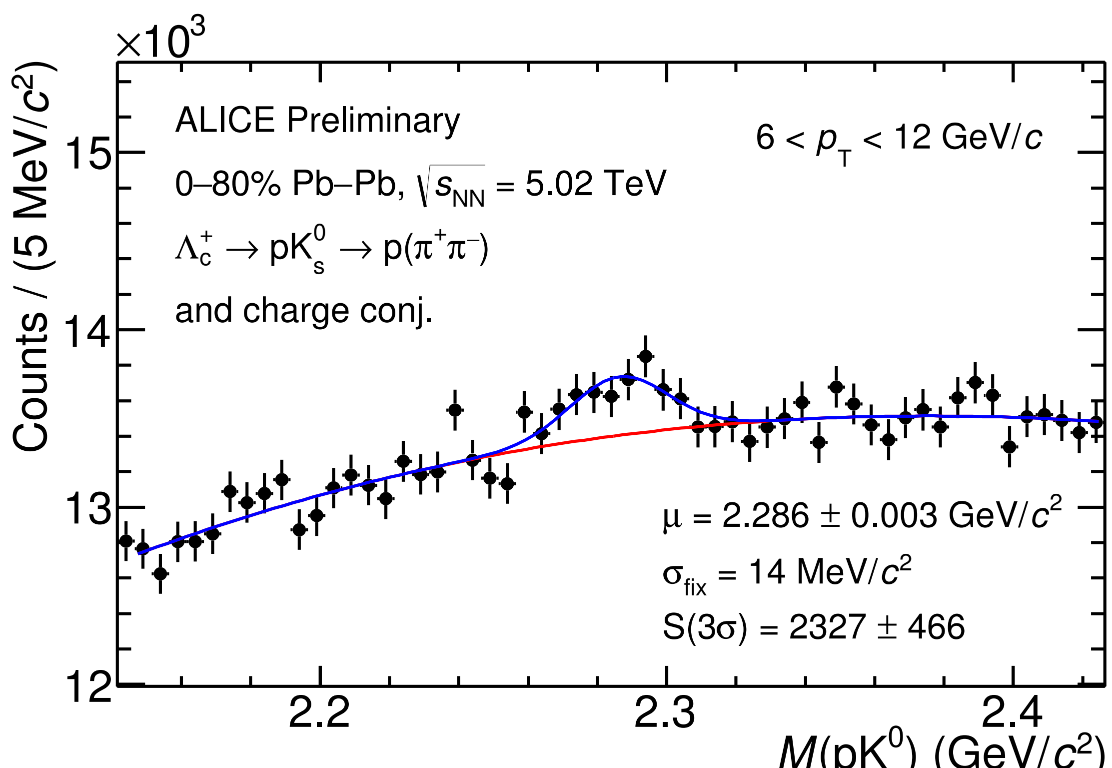
D meson flow at $\sqrt{s_{NN}}$ = 2.76TeV

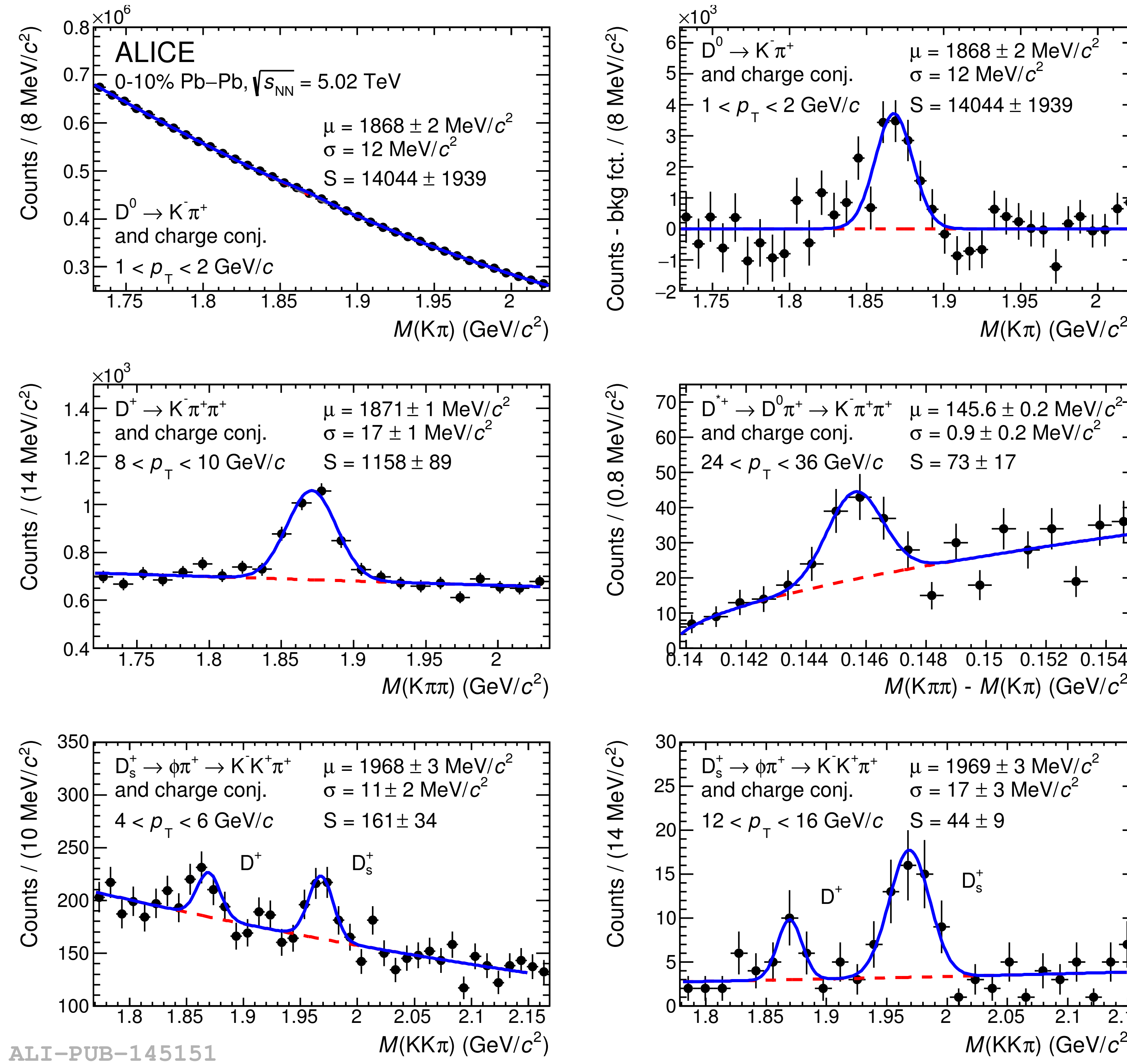




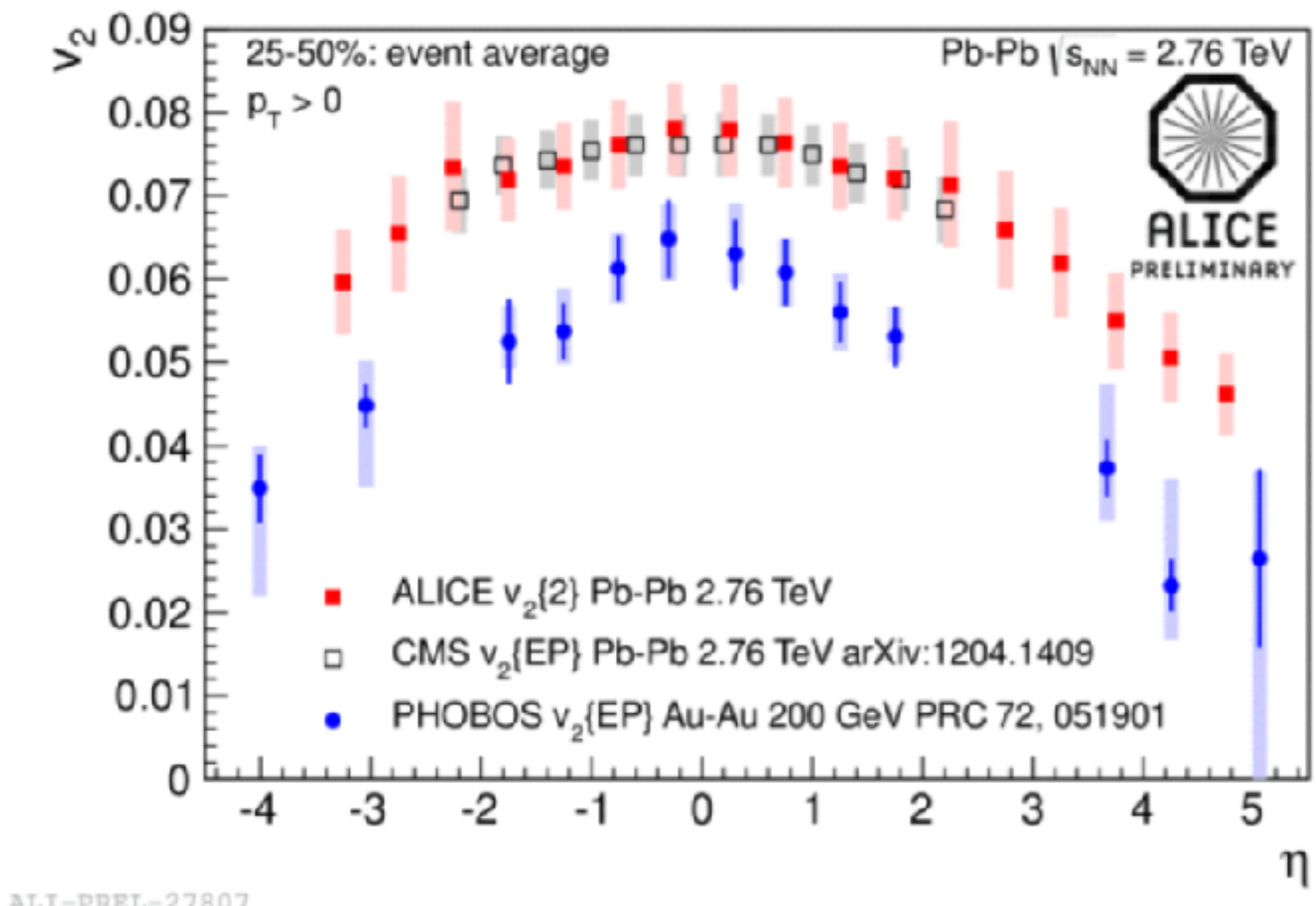


Open HF reconstruction



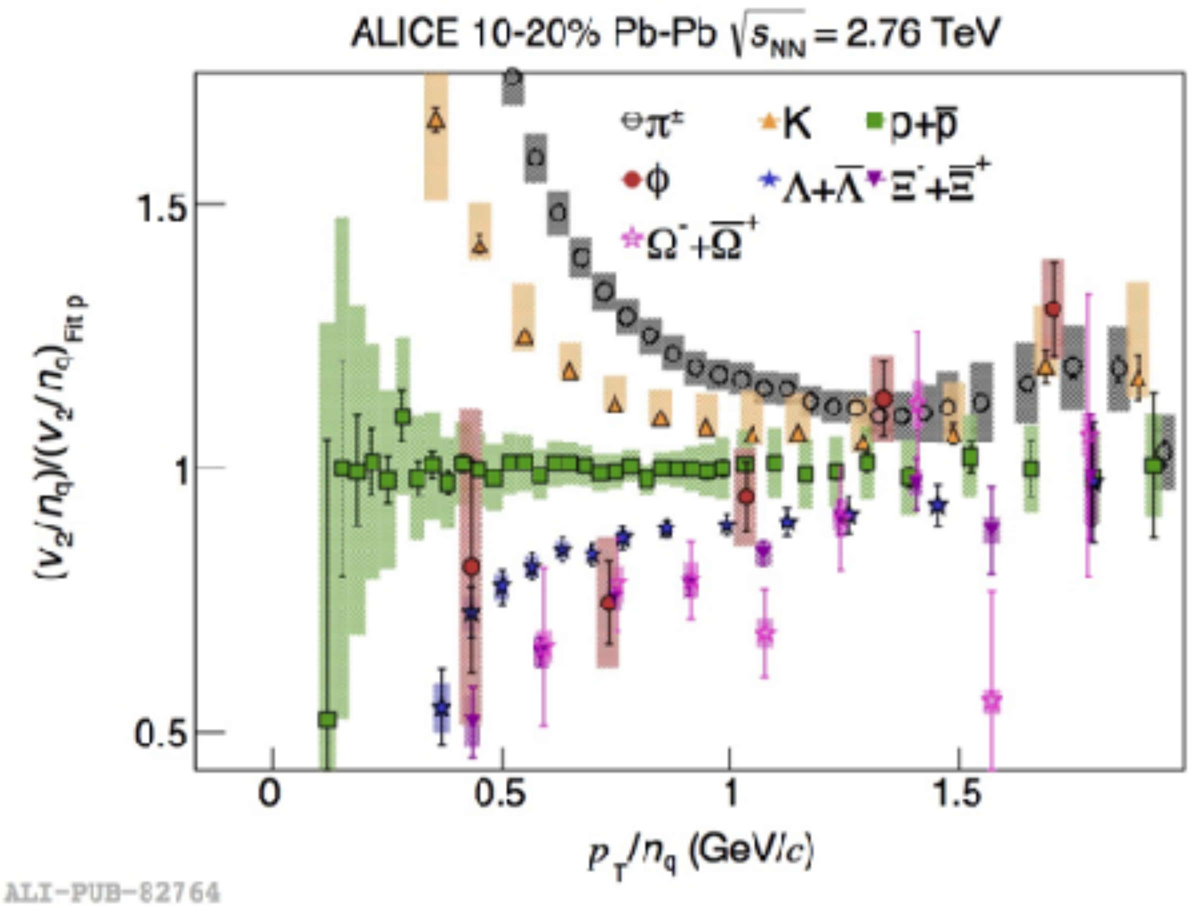


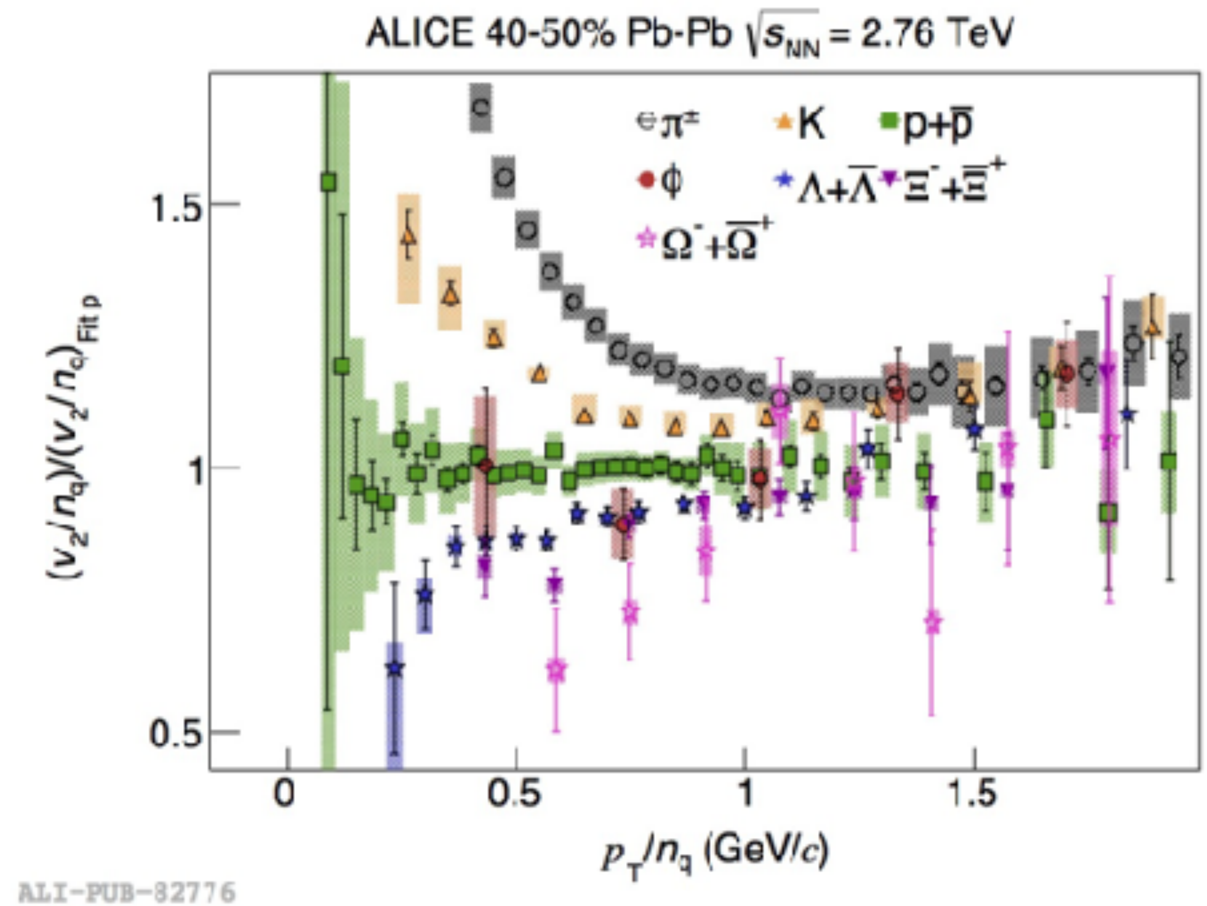
Pseudo-rapidity dependency



- depends on particle multiplicity

p_T/n_q scaling ?

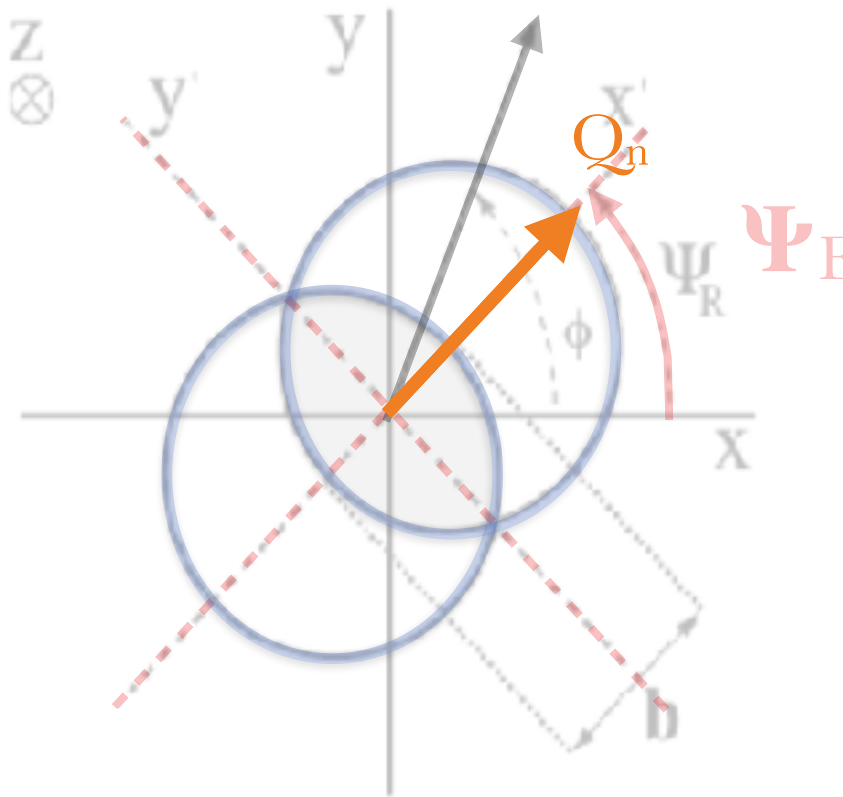




- below 1 GeV/c : ok
- then : 20% variations in both centralities

Detector equalization and resolution

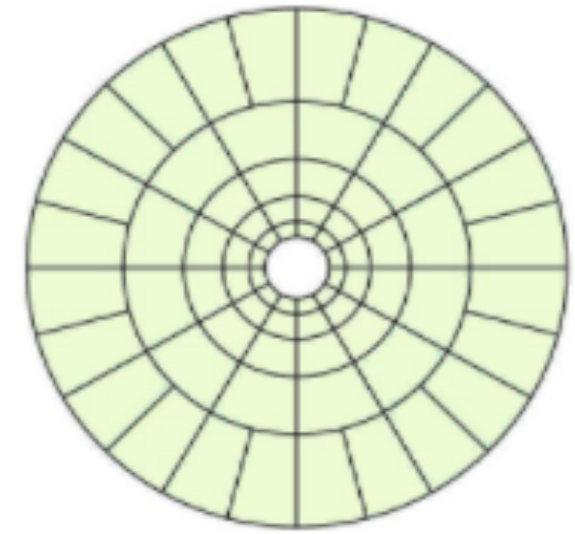
- Focus on methods based on event plane determination
  - From detector multiplicities :



$$Q_n = \sum_{i=0}^{\infty} e^{in\Phi_i} = Q_{n,x} + i\,Q_{n,y}$$

$$Q_{n,x} = \frac{\sum^{scint.} s_i \cos(n\Phi_i)}{\sum^{scint.} s_i} = |Q_n| \cos(n\Psi_n)$$

$$Q_{n,y} = \frac{\sum^{scint.} s_i \sin(n\Phi_i)}{\sum^{scint.} s_i} = |Q_n| \sin(n\Psi_n)$$



$$\Psi_n = \frac{1}{n} \arctan(Q_{n,x}, Q_{n,y})$$

- Correct for detector resolution : using 3 sub-event method

$$< \cos\{n(\Psi_2^a - \Psi_R)\} > = \sqrt{\frac{<\cos\{n(\Psi_2^a - \Psi_2^b)\}><\cos\{n(\Psi_2^a - \Psi_2^c)\}>}{<\cos\{n(\Psi_2^b - \Psi_2^c)\}>}}$$

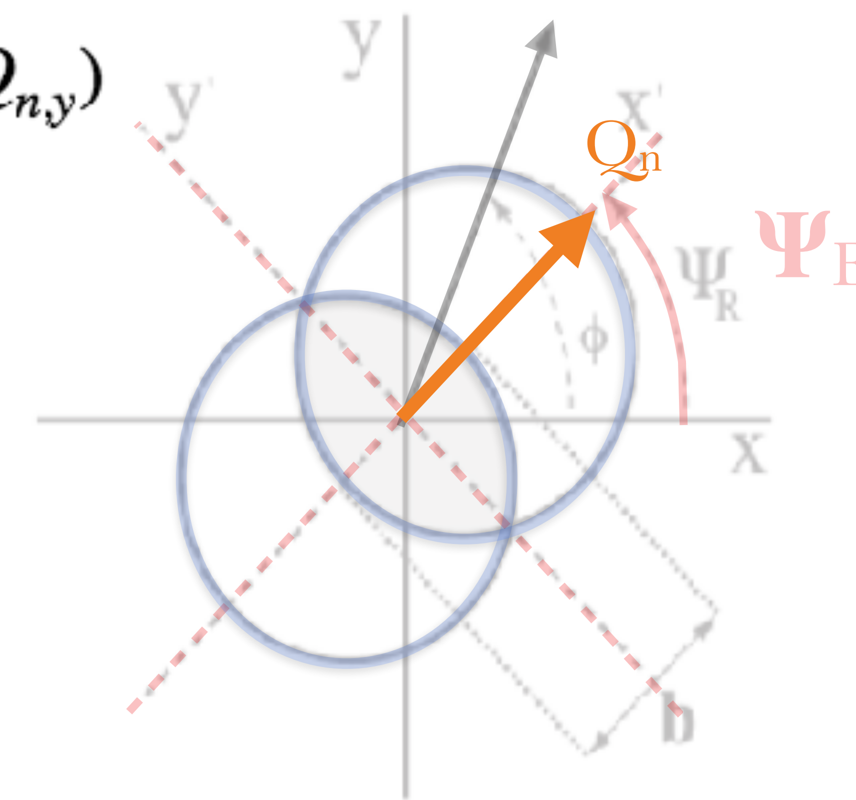
A. M. Poskanzer and S. A. Voloshin, Phys Rev. C58, 1671

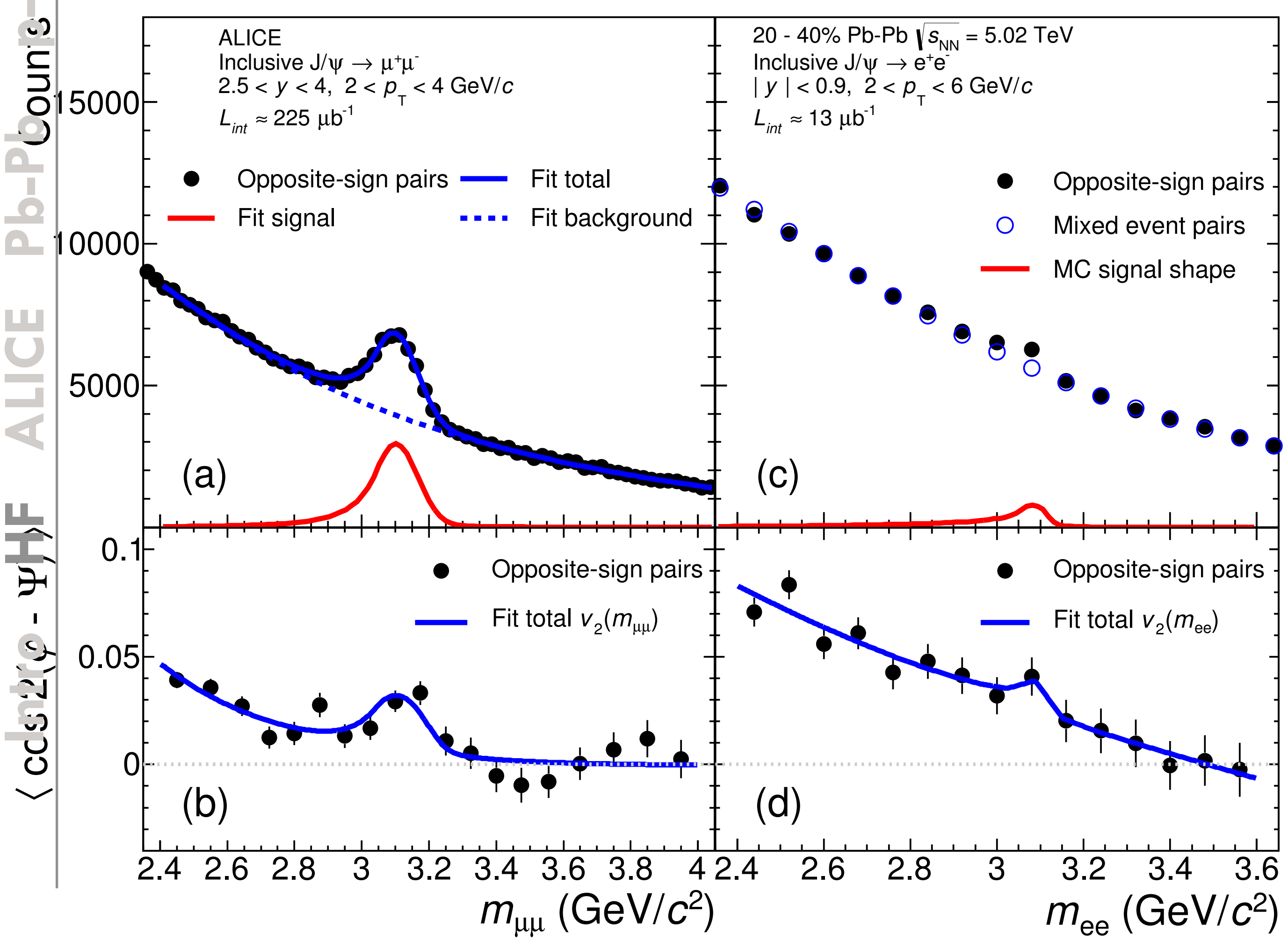
- Detector equalization to deal with non-uniform acceptance

J/ψ elliptic flow: how to measure it ?

- Methods based on event plane determination
  From detector multiplicities : $\Psi_n = \frac{1}{n} arctan(Q_{n,x}, Q_{n,y})$

- Fit of ⟨cos(2 Δφ)⟩ distribution vs inv. mass
  with $\Delta\varphi = \varphi_{\mu\mu} - \Psi_{2,EP}$





Model total flow as

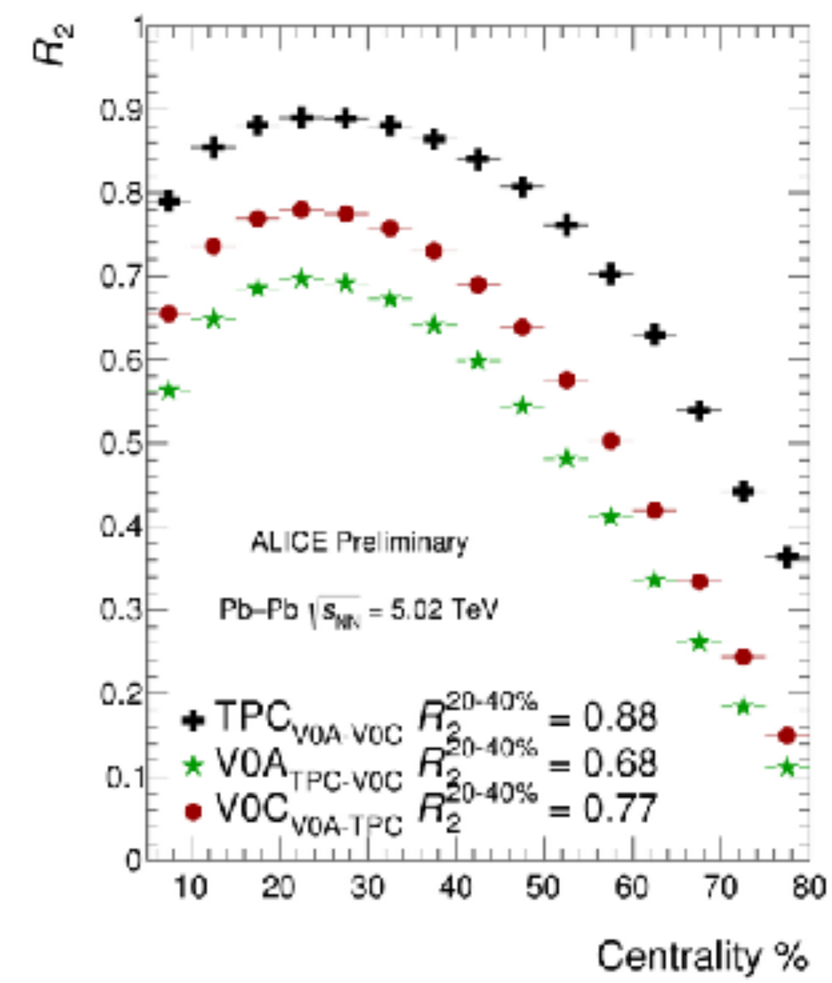
$$v_2(m_{\mu\mu}) = v_2^{sig}\alpha(m_{\mu\mu}) + v_2^{bck}(1-\alpha(m_{\mu\mu}))$$

signal shape extracted from M_{inv} fit

background : e.g. polynomial function

Detector equalization and resolution

- Maximum residual oscillations after equalisation :
  SPD (20-30%): $v_2 \simeq 0.0012$; $v_4 \simeq 0.015$; $v_6 \simeq$ 2e-6
- ratio of cross-terms to same-terms as an estimation of the uncertainty on the EP determination : 1% systematic uncertainty correlated with centrality
- Resolution calculated using the 3 sub-events method with V0A, V0C and SPD
- Centrality bins used for J/ψ v_2 analysis are large
- Non uniform distribution of the number of J/ψ



	5-20%	20-40%	40-60%	60-90%
SPD	0.87297±0.00019	0.91031±0.00014	0.83192±0.00022	0.55432±0.00333

Equalization steps

1. Gain equalization of individual detector channels

$$M'_c = M_c / \langle M_c \rangle$$

2. Recentering

$$\boldsymbol{q}'_n = \boldsymbol{q}_n - \langle \boldsymbol{q}_n \rangle$$

3. Width equalization

$$\boldsymbol{q}''_n = \boldsymbol{q}'_n / \sigma_{\boldsymbol{q}_n}$$

4. Alignment

$$\boldsymbol{q}'''_n = \boldsymbol{q}''_n + \boldsymbol{q}''_{n,\phi}$$

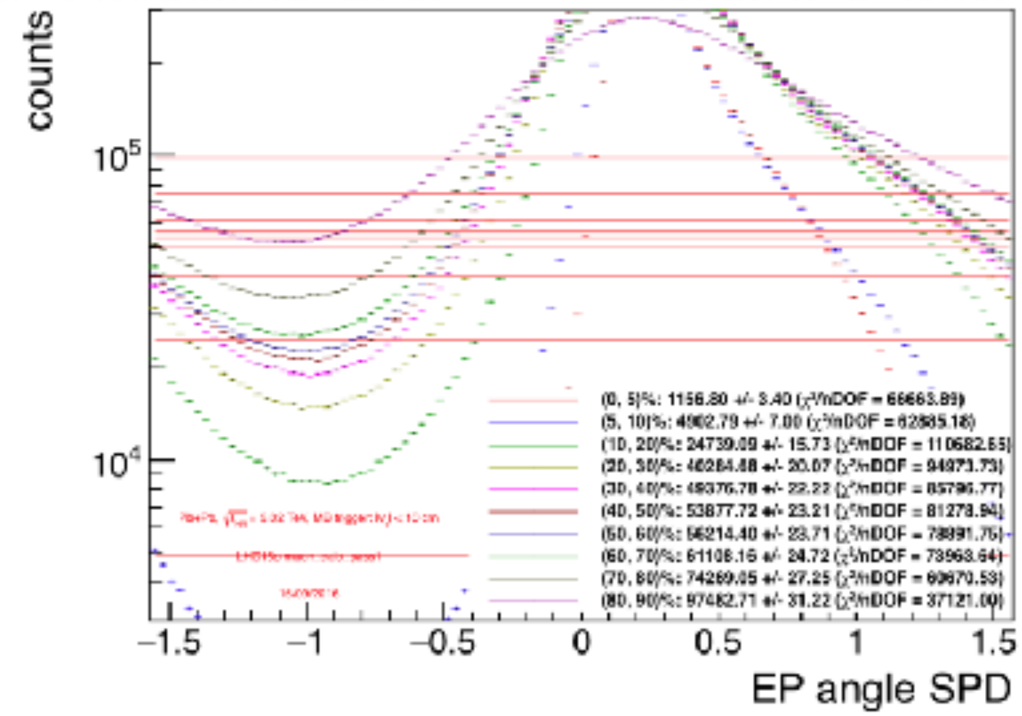
5. Twist

$$q''''_{n,(x,y)} = (q'''_{n,(x,y)} - \Lambda^{s(+,-)}_{2n} q'''_{n,(y,x)}) / (1 - \Lambda^{s-}_{2n} \Lambda^{s+}_{2n})$$

6. Rescaling

$$q'''''_{n,(x,y)} = q''''_{n,(x,y)} / A^{(+,-)}_{2n}$$

Before correction



After correction