J/ψ elliptic flow
- *Jamais deux sans trois*

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ALICE

QGP France, July 2-4th 2018 • Etretat

Subatech

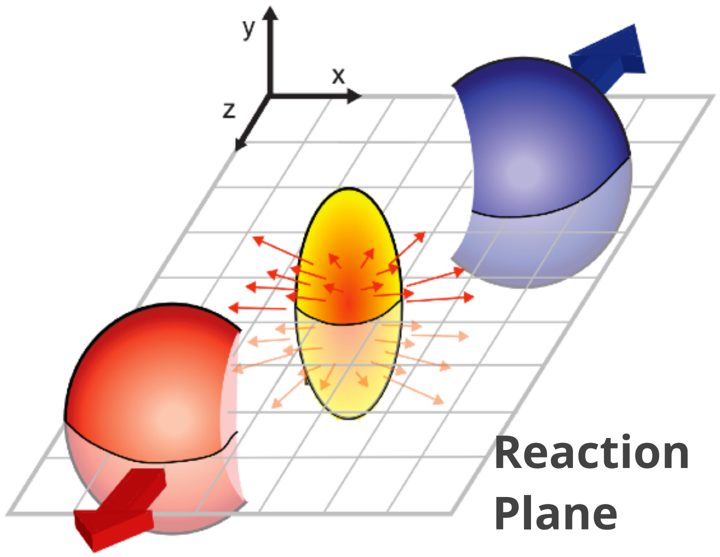
cnrs dépasser les frontières IN2P3 Les deux infinis

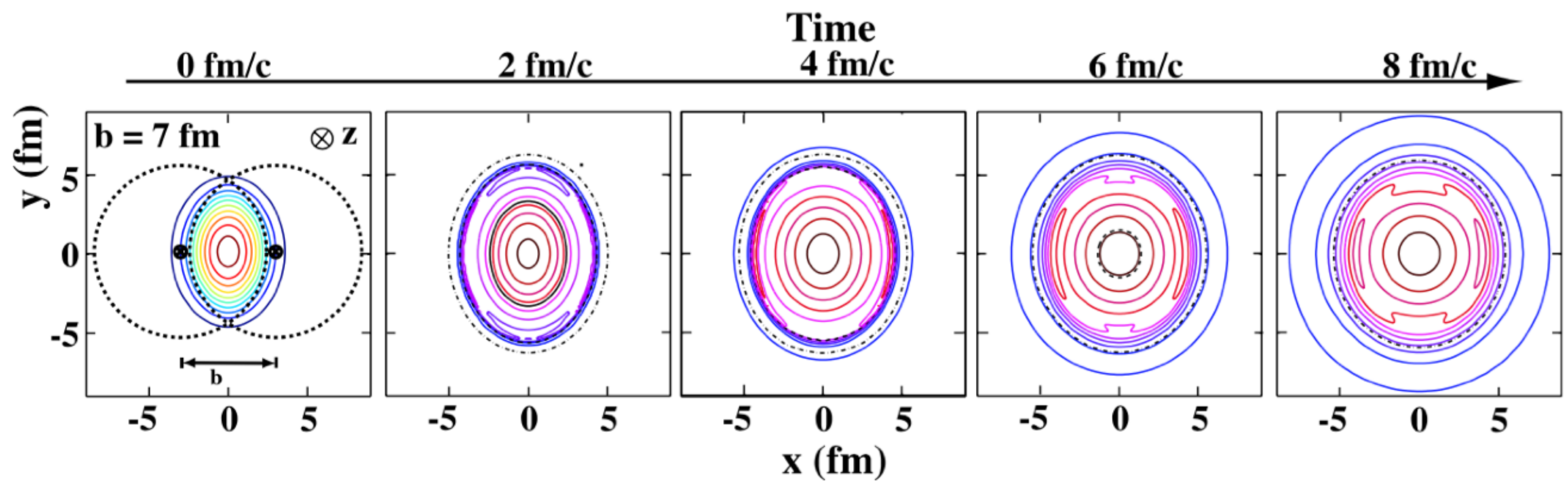
Ecole Doctorale 3MPL Matière, Molécules, Matériaux en Pays de la Loire

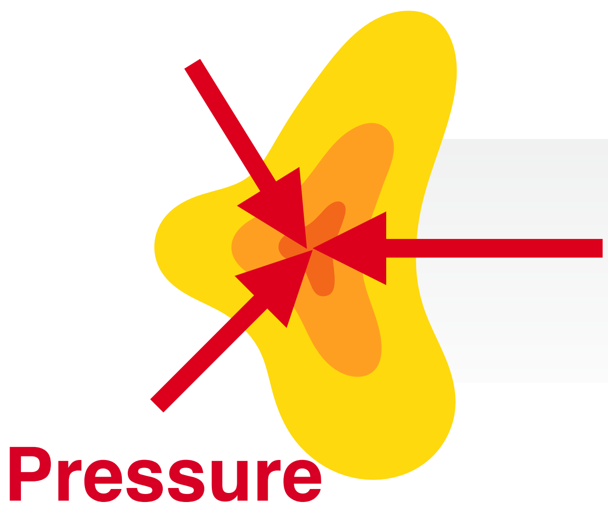
IMT Atlantique Bretagne-Pays de la Loire École Mines-Télécom

Collective flow

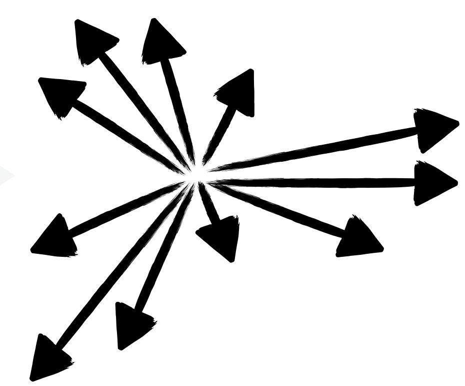
Anistropic matter distribution around the collision…







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

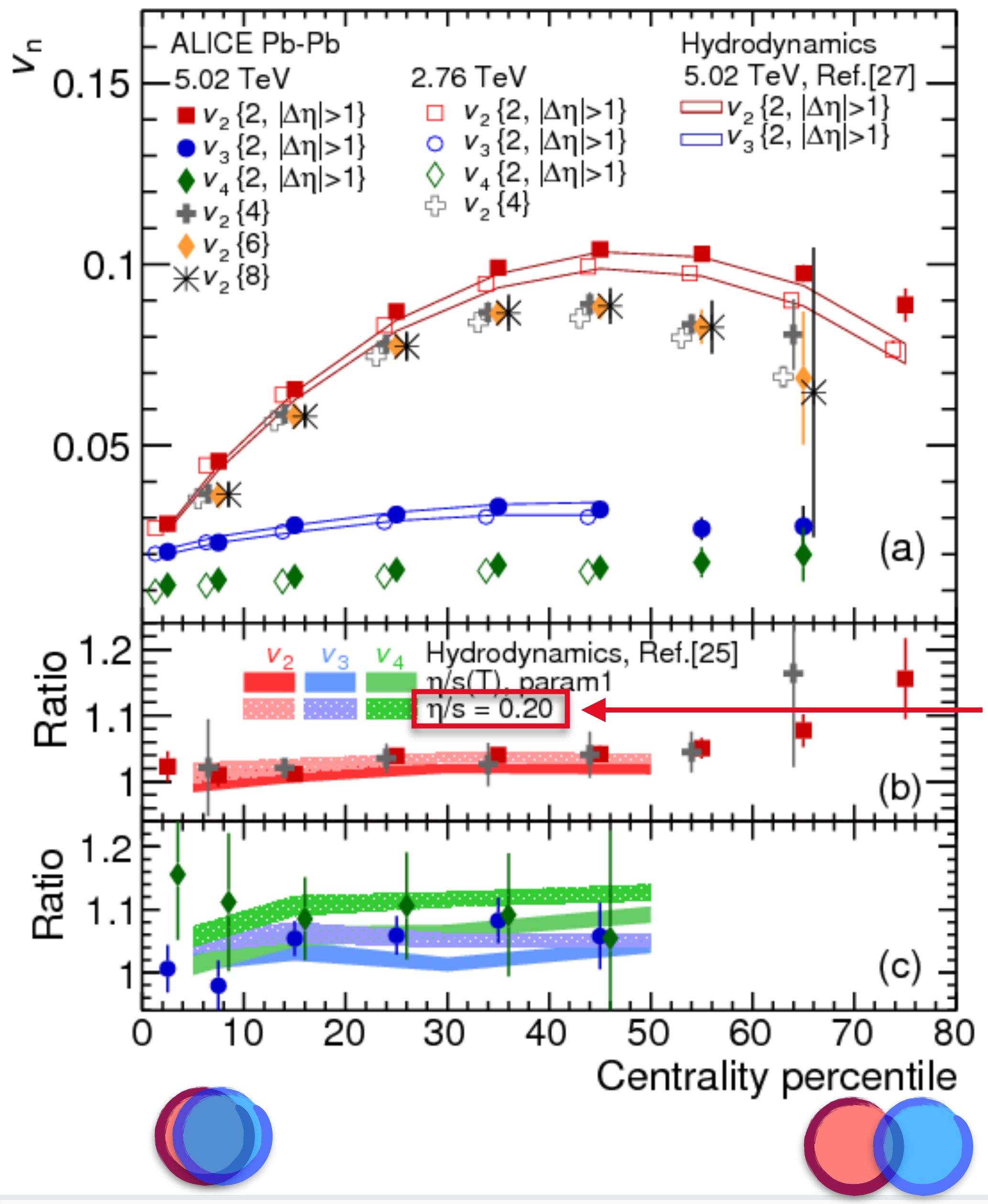


$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\{1+\sum_{n=1}^{\infty} 2 v_n \cos(n(\Phi-\Psi_{RP}))\}$$

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

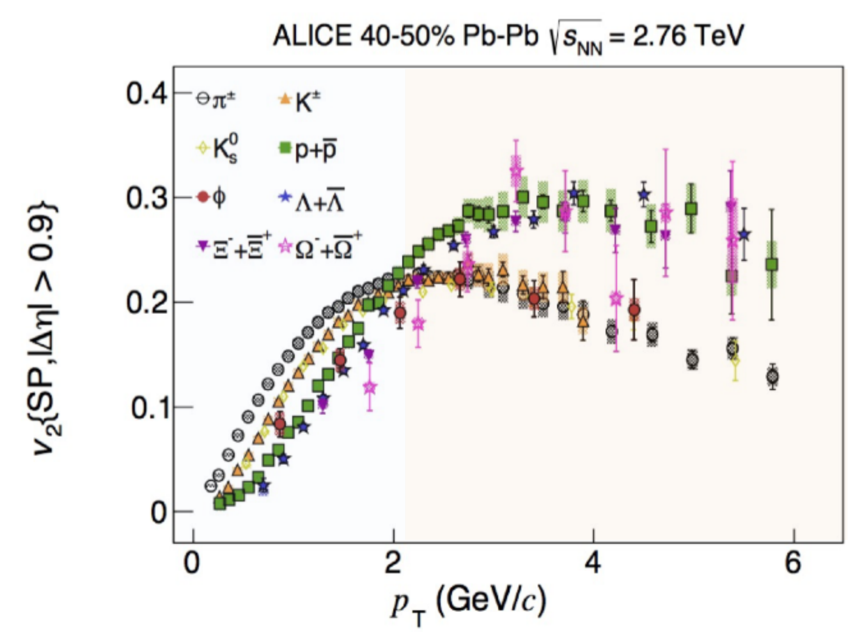
directed flow (v_1), elliptic flow (v_2), triangular flow (v_3), …

Elliptic flow of charged particles



Main features from v_2 observations in A-A:

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



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

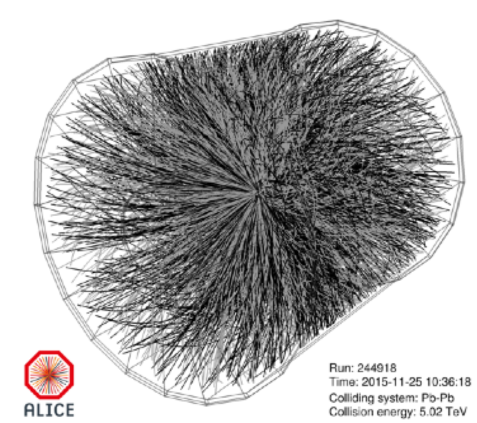
OUTLINE

Why do we measure heavy flavour ?

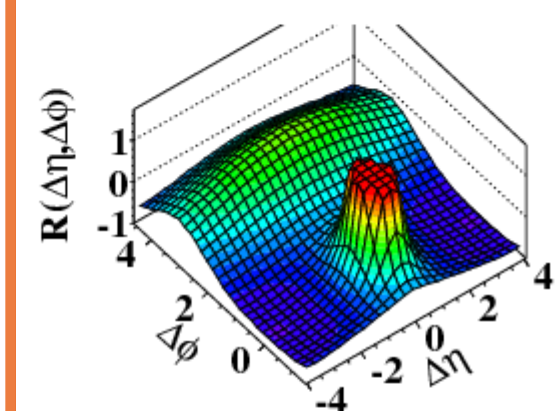
The ALICE detector

ALICE

Results in A-A collisions



Small systems



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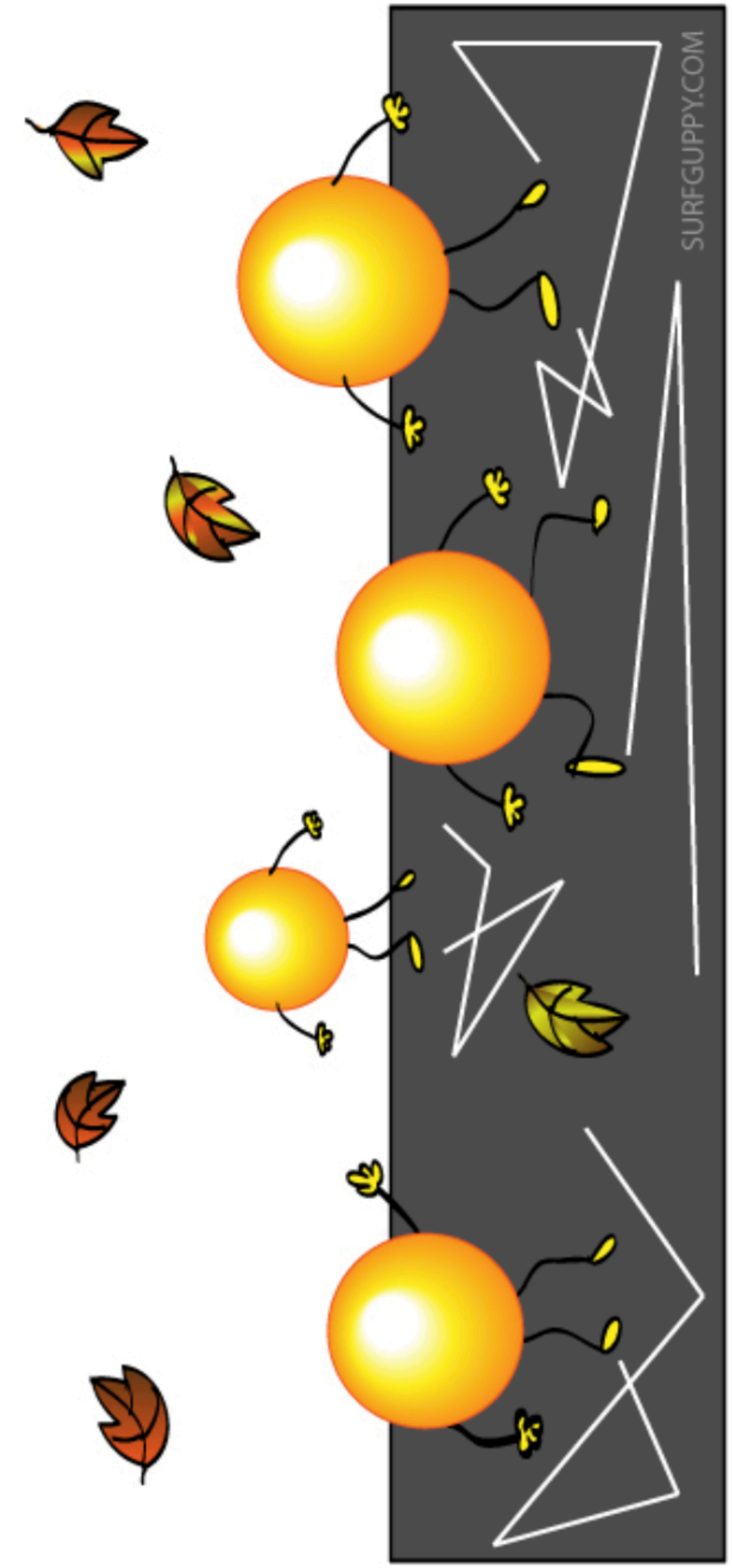
Motivations for HF studies

- 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 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
  - early production (c ~ 0.1 fm/c vs. QGP ~ 0.3 fm/c) → experience the full system evolution
  - interact with the QGP : sensitive to the medium properties



Observables

Nuclear modification factor R_{AA}

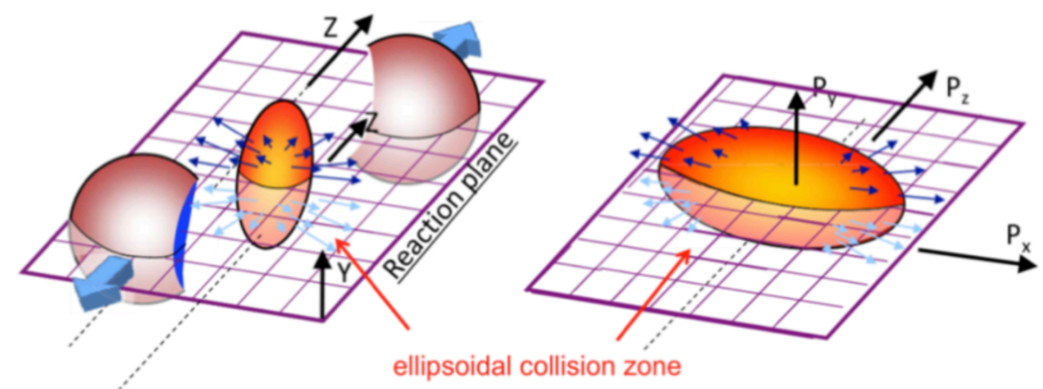
$$R_{AA} = \frac{Y_{AA}}{\langle T_{AA} \rangle \sigma_{PP}}$$

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

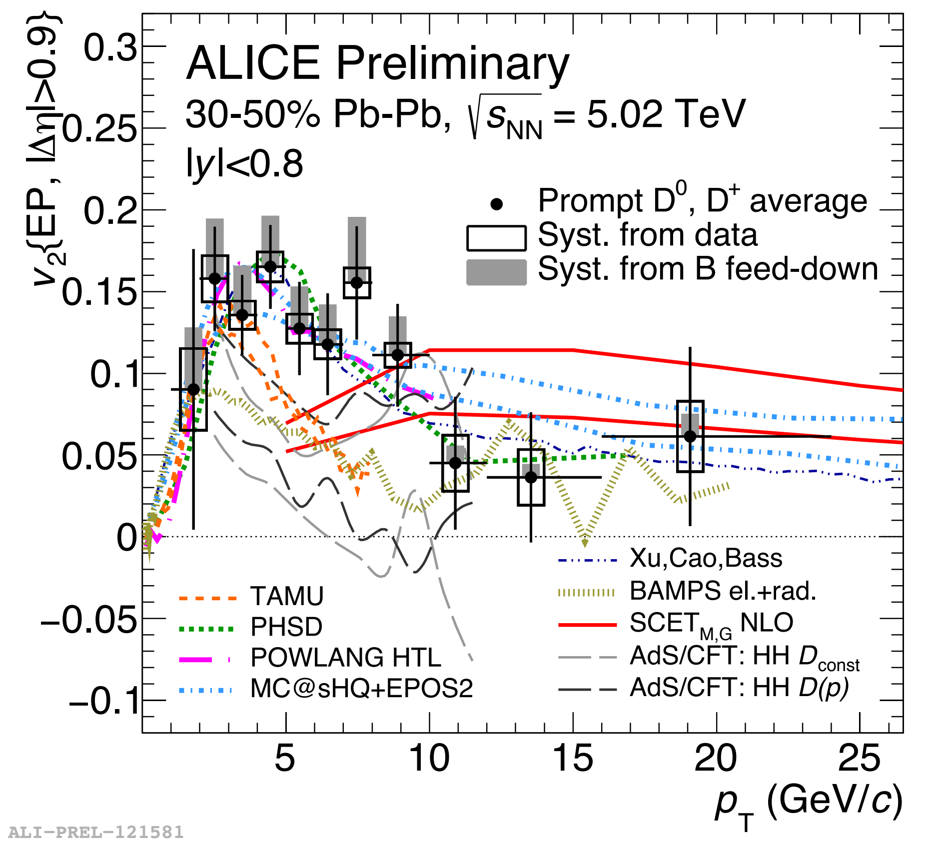
- heavy quarks participate to the collective expansion dynamics

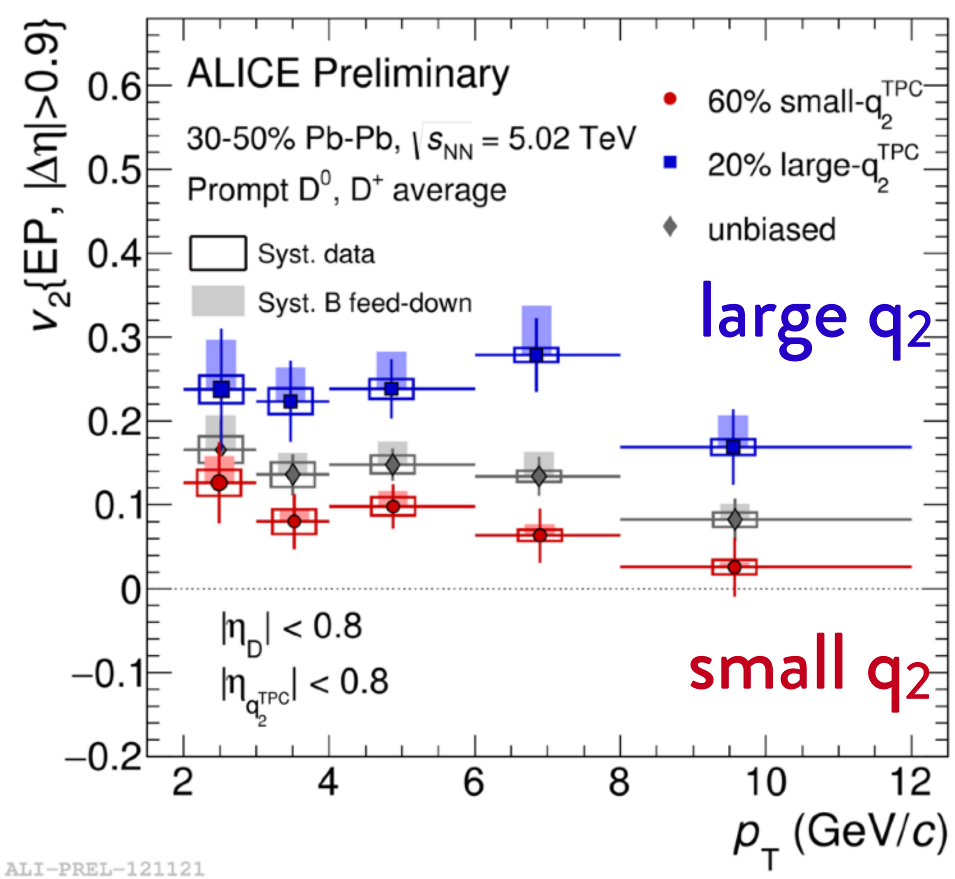


$$v_2 = \langle cos[2(\varphi - \Psi_{2,R})] \rangle$$

- If thermalization, recombined states should inherit their flow
- relevant observable for quarkonium (re)generation study

Observables





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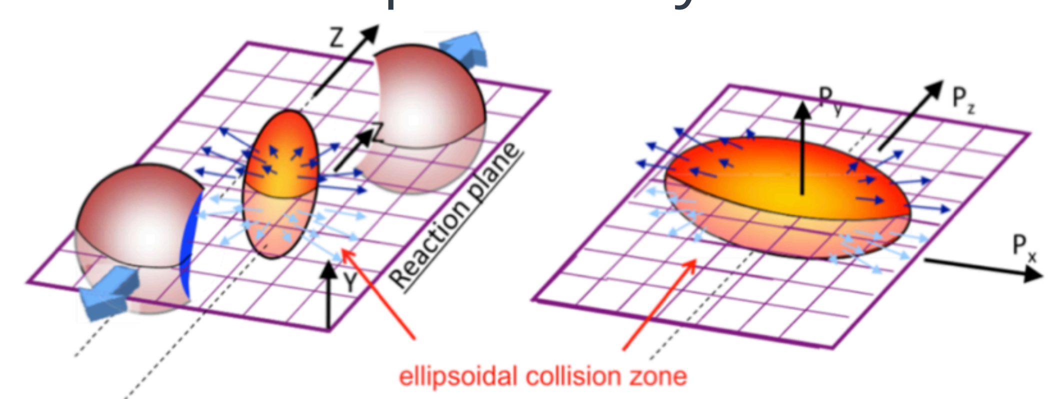

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Results in A-A collisions

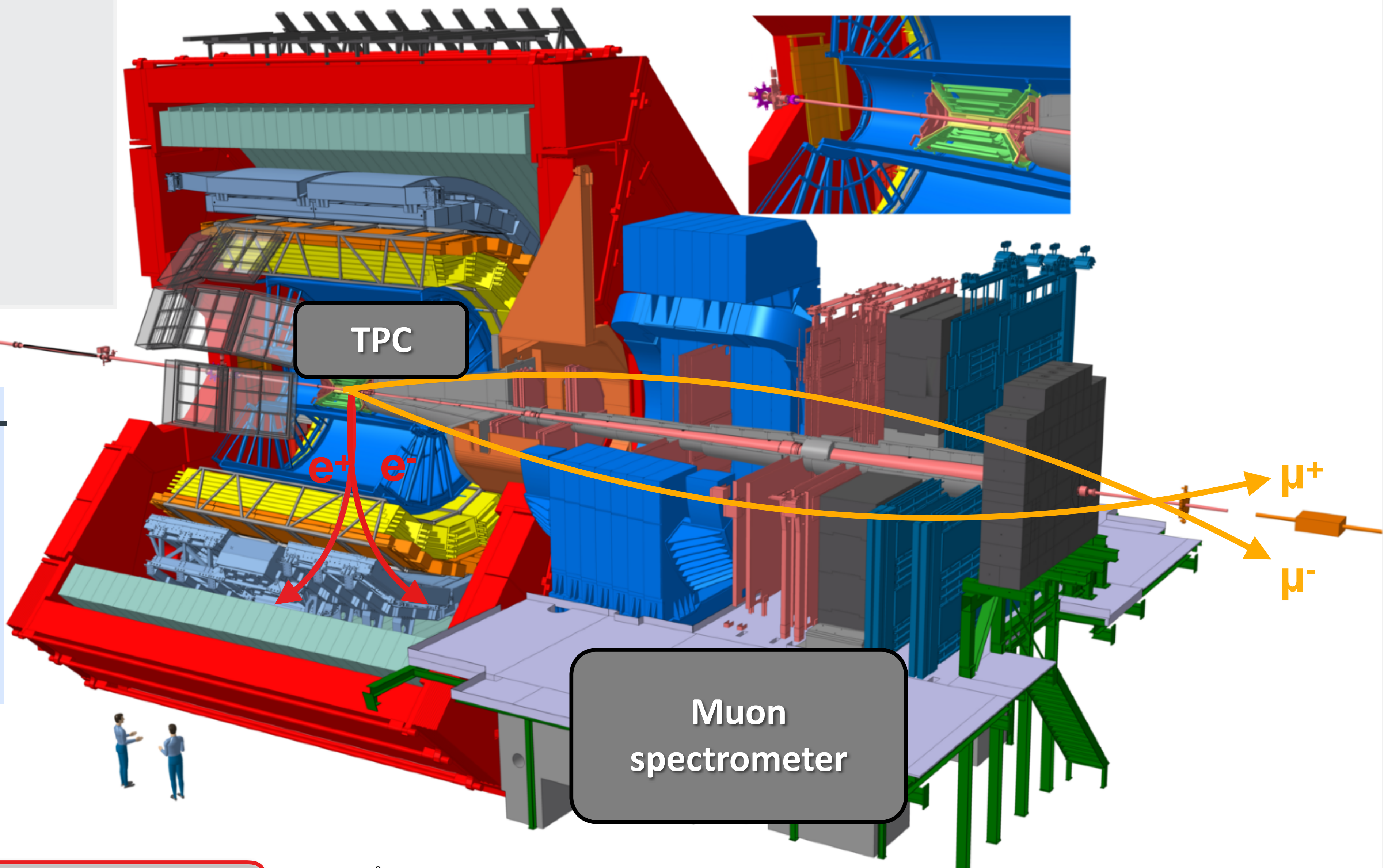
Small systems

Quarkonium with ALICE

Performed both at forward and mid-rapidity

Quarkonium → e^+e^-

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



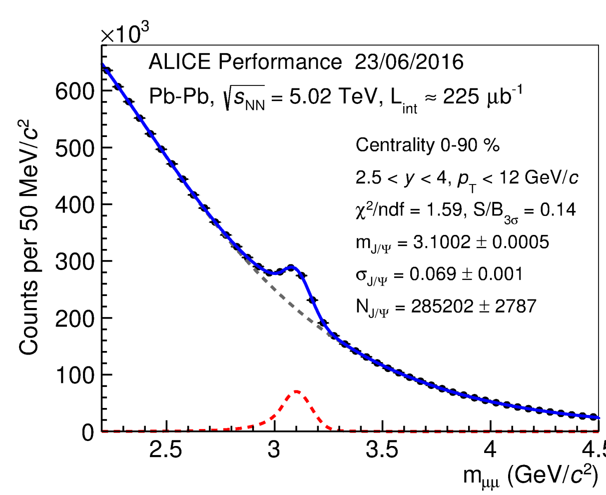
INCLUSIVE

PROMPT

Direct production + Feed-down from excited states

NON-PROMPT

B hadron decays



Quarkonium → $\mu^+\mu^-$

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

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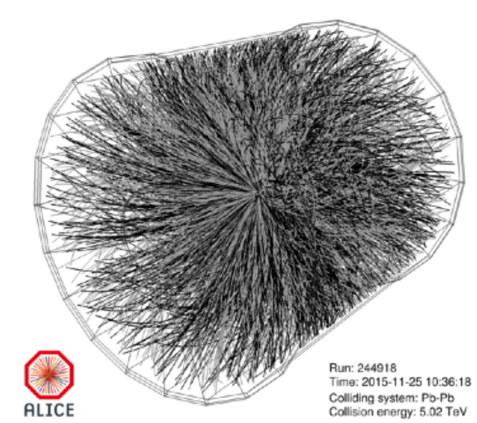
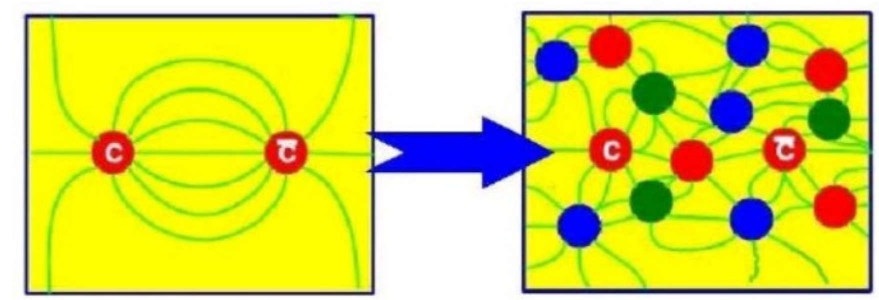


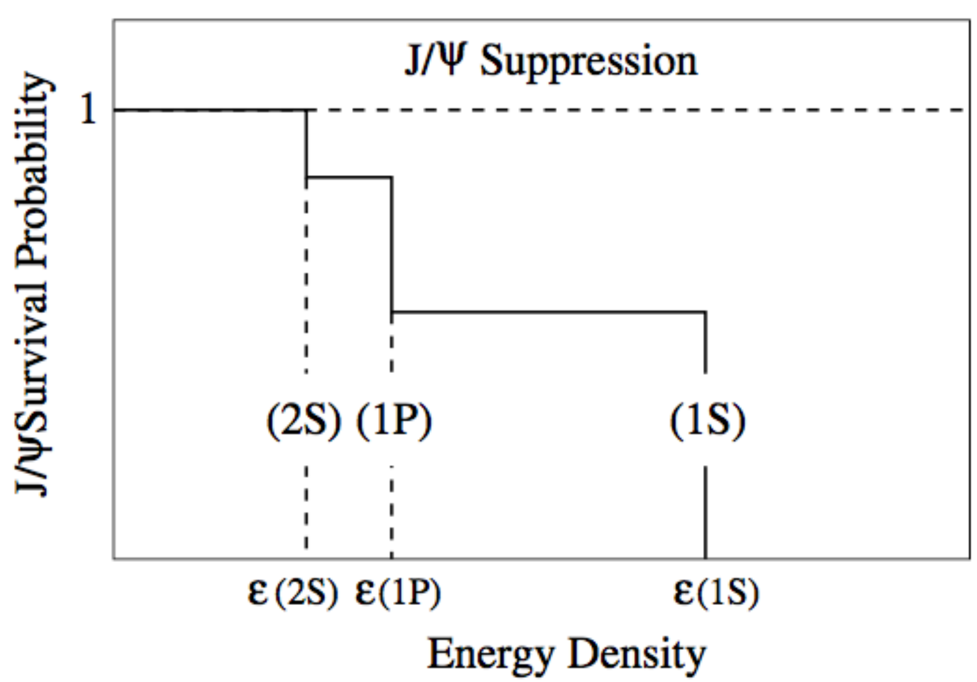
Small systems

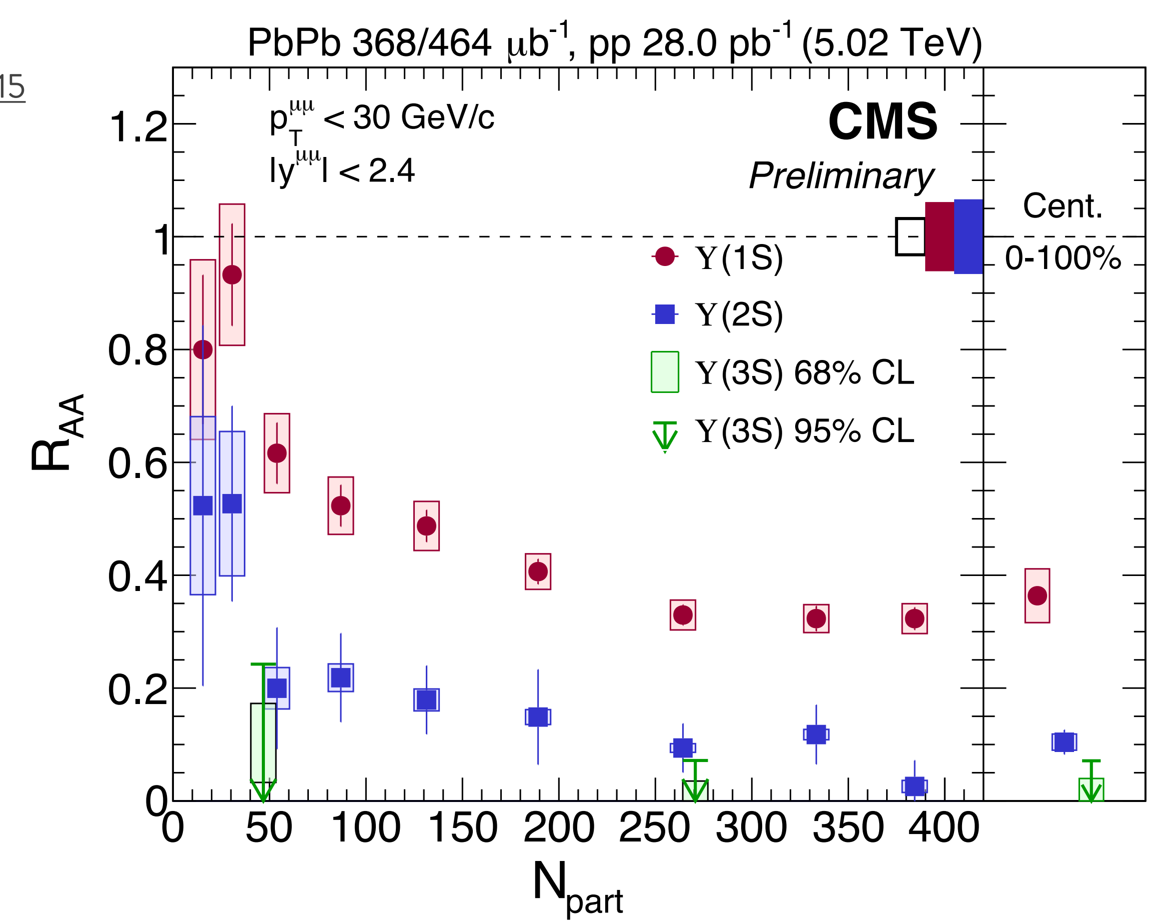
Quarkonium suppression :
(Re)combination



- 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





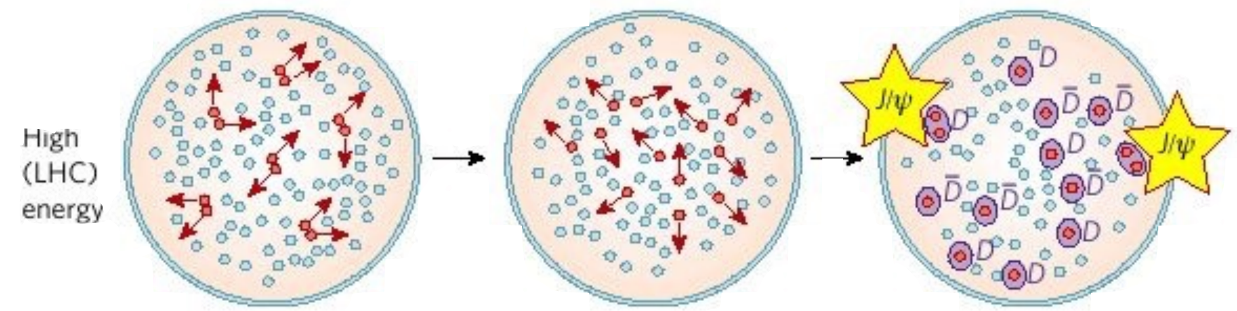
Quarkonium in the QGP

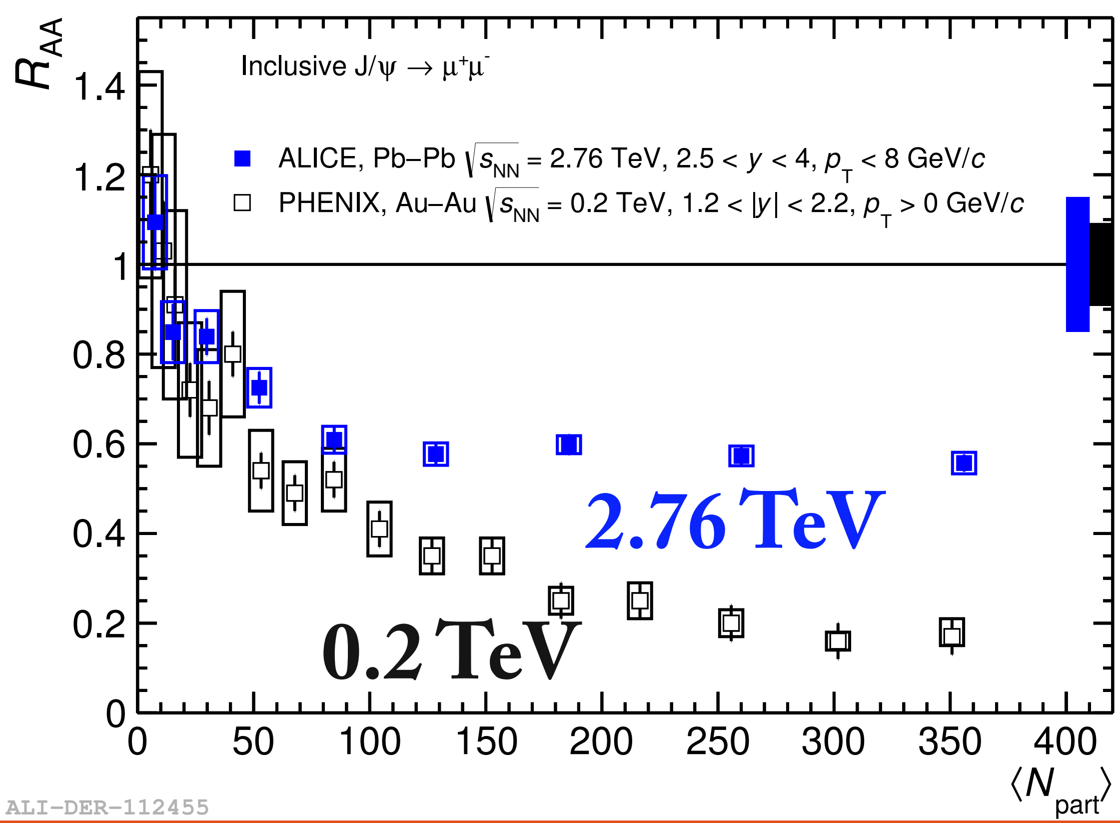
Quarkonium suppression

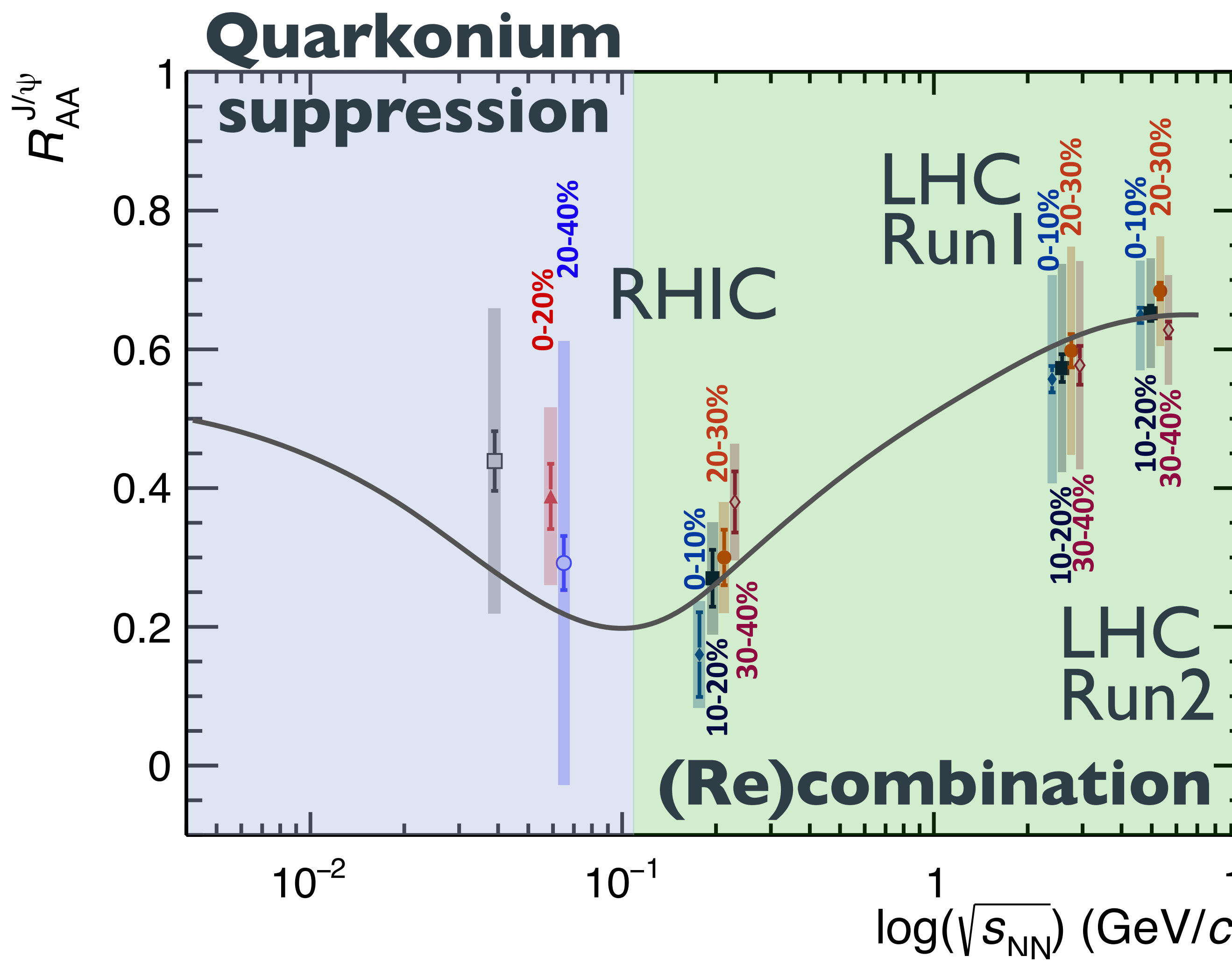
(Re)combination :

- Increased charm quark density
  →enhanced quarkonia production

- **Less relevant for bottomonium than charmonium**







Eur.Phys.J. C39 (2005) 335-345
Phys. Lett. B 766 (2017) 212-224
Phys.Rev. C84 (2011) 054912
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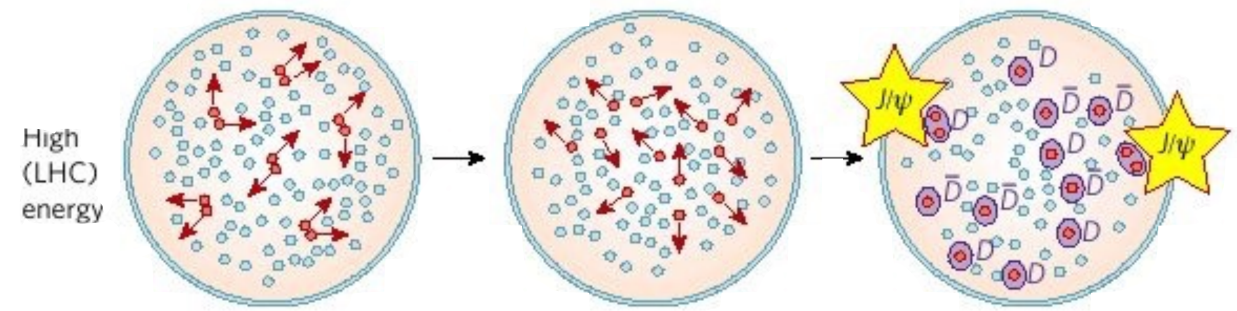

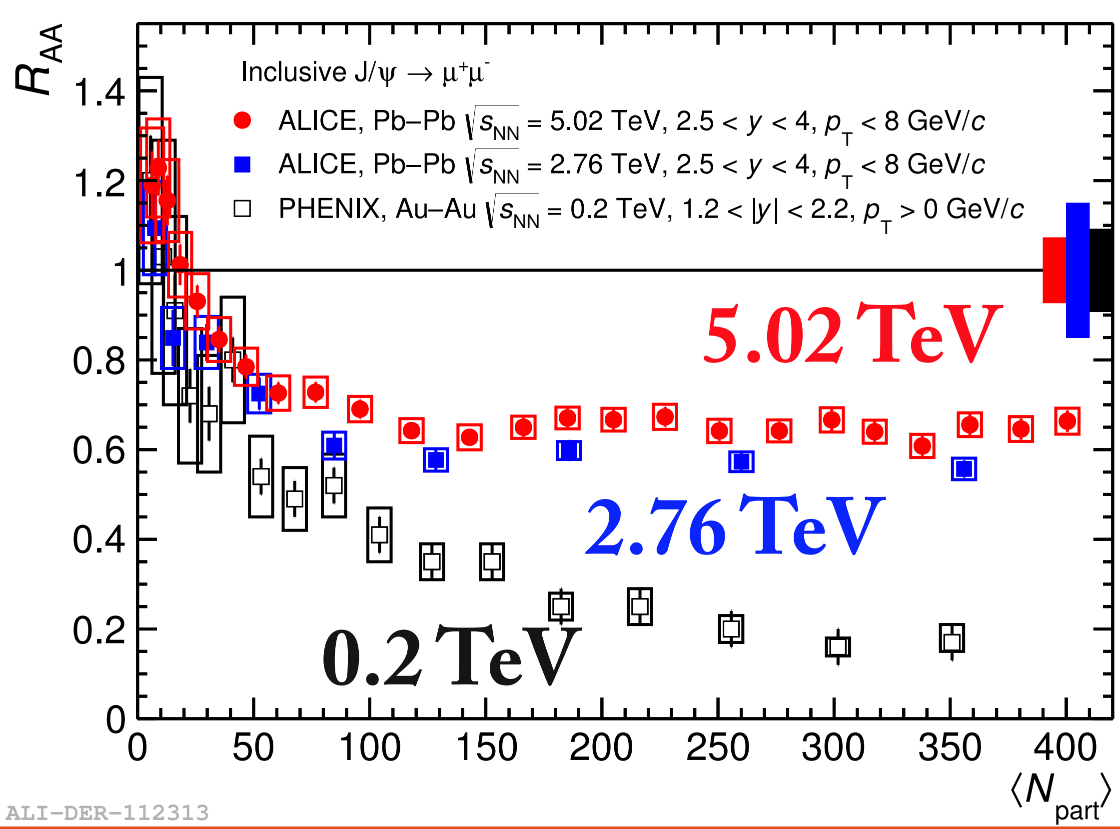

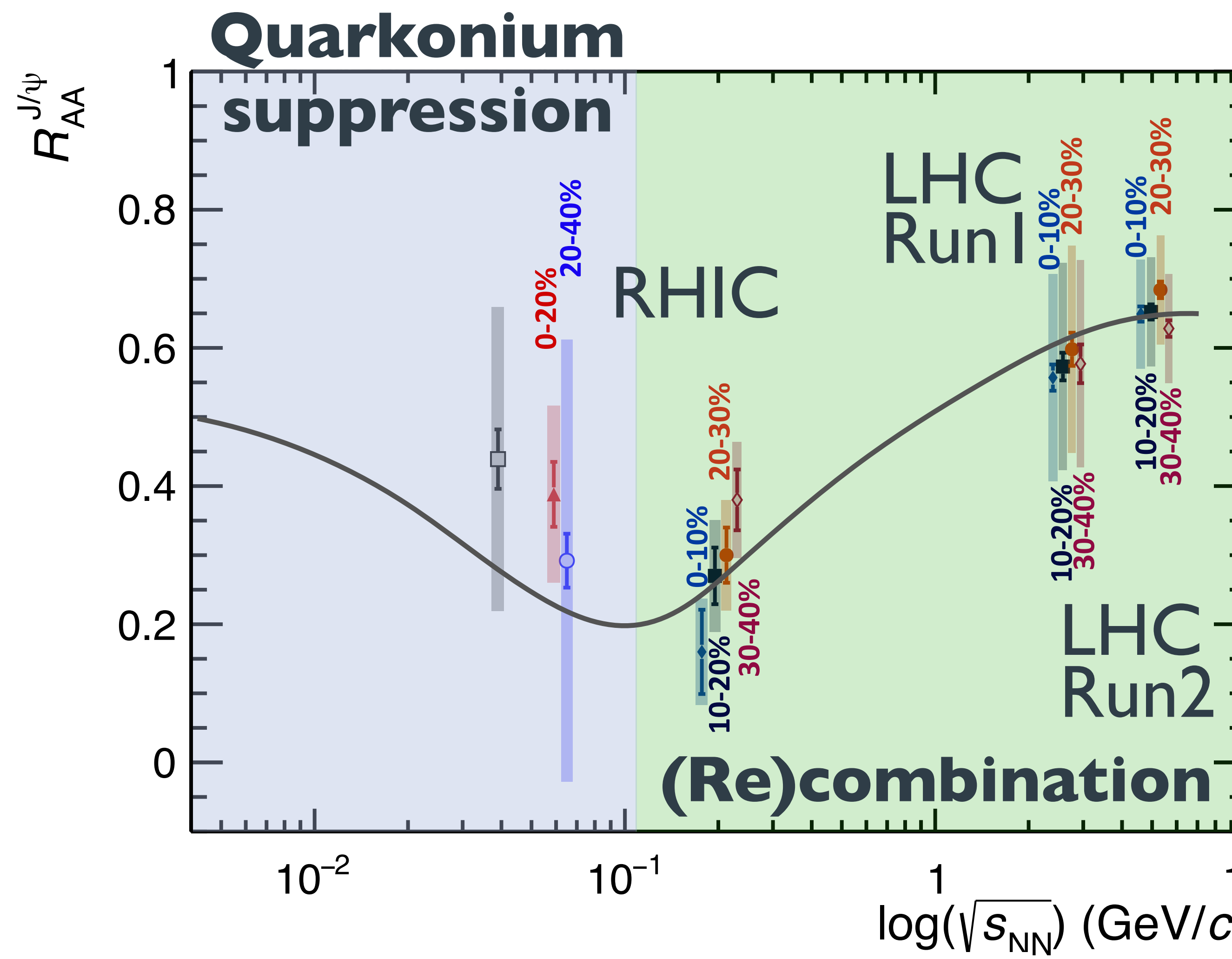

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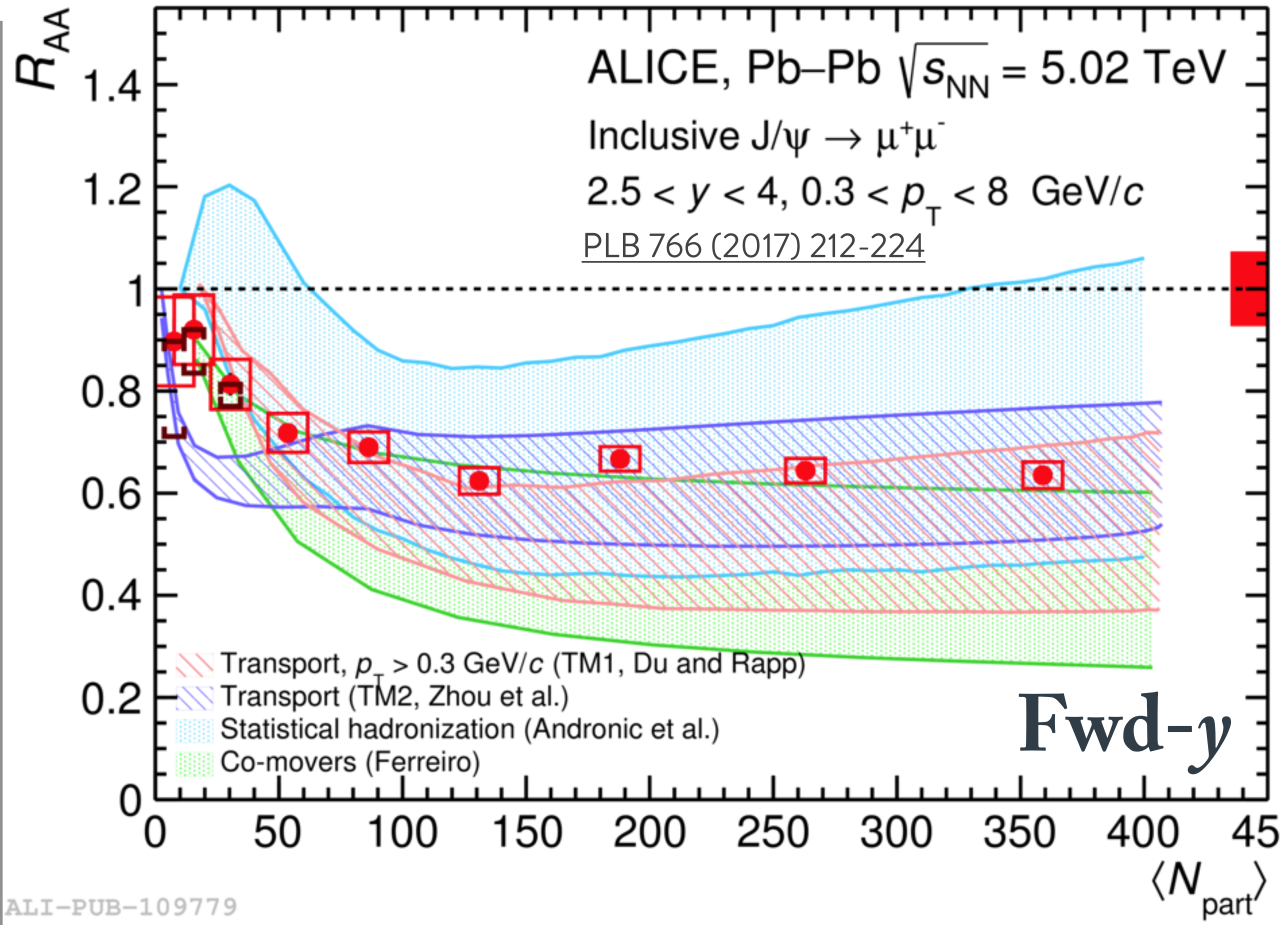
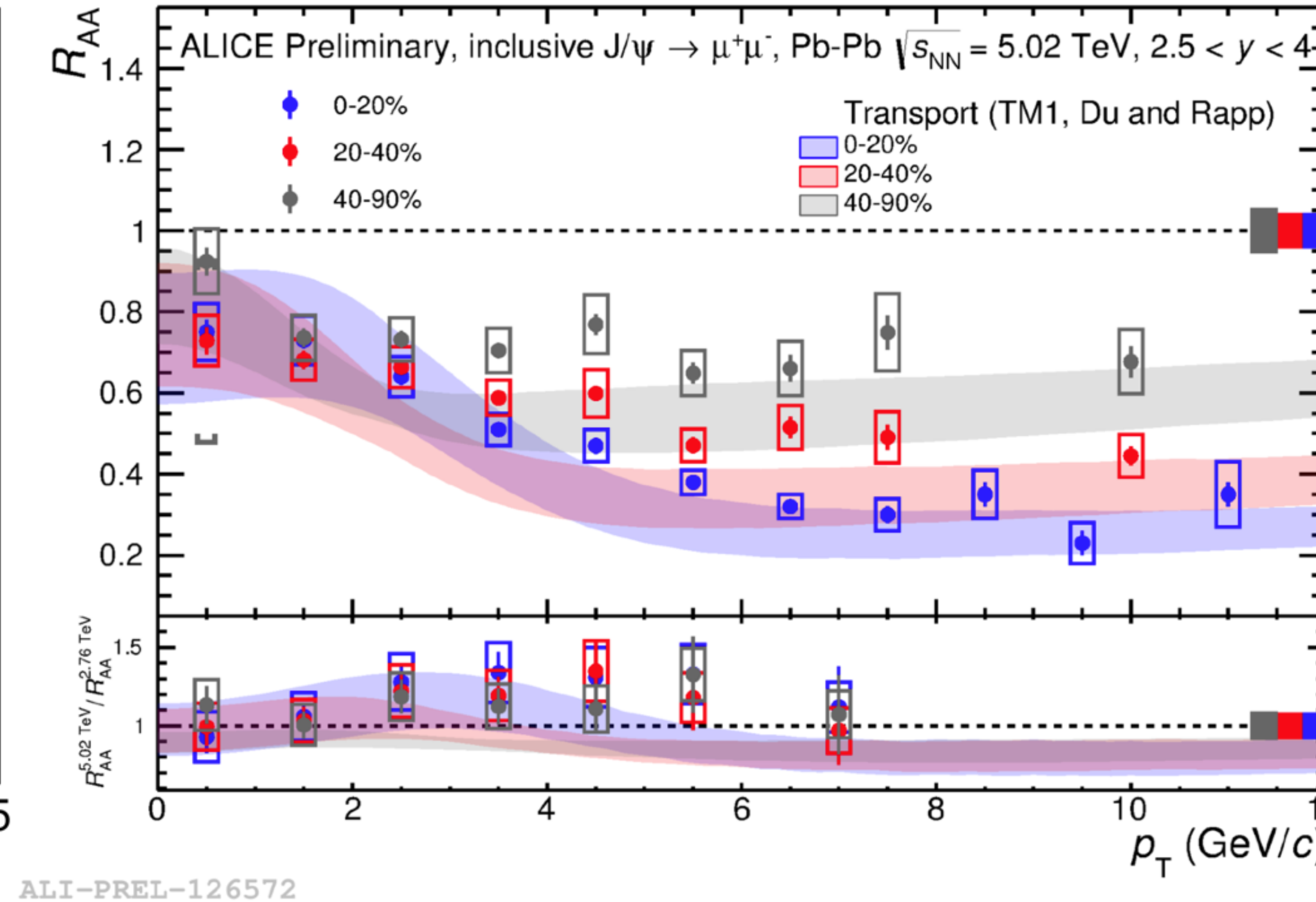




Exp. observations interpreted as suppression + (re)combination

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

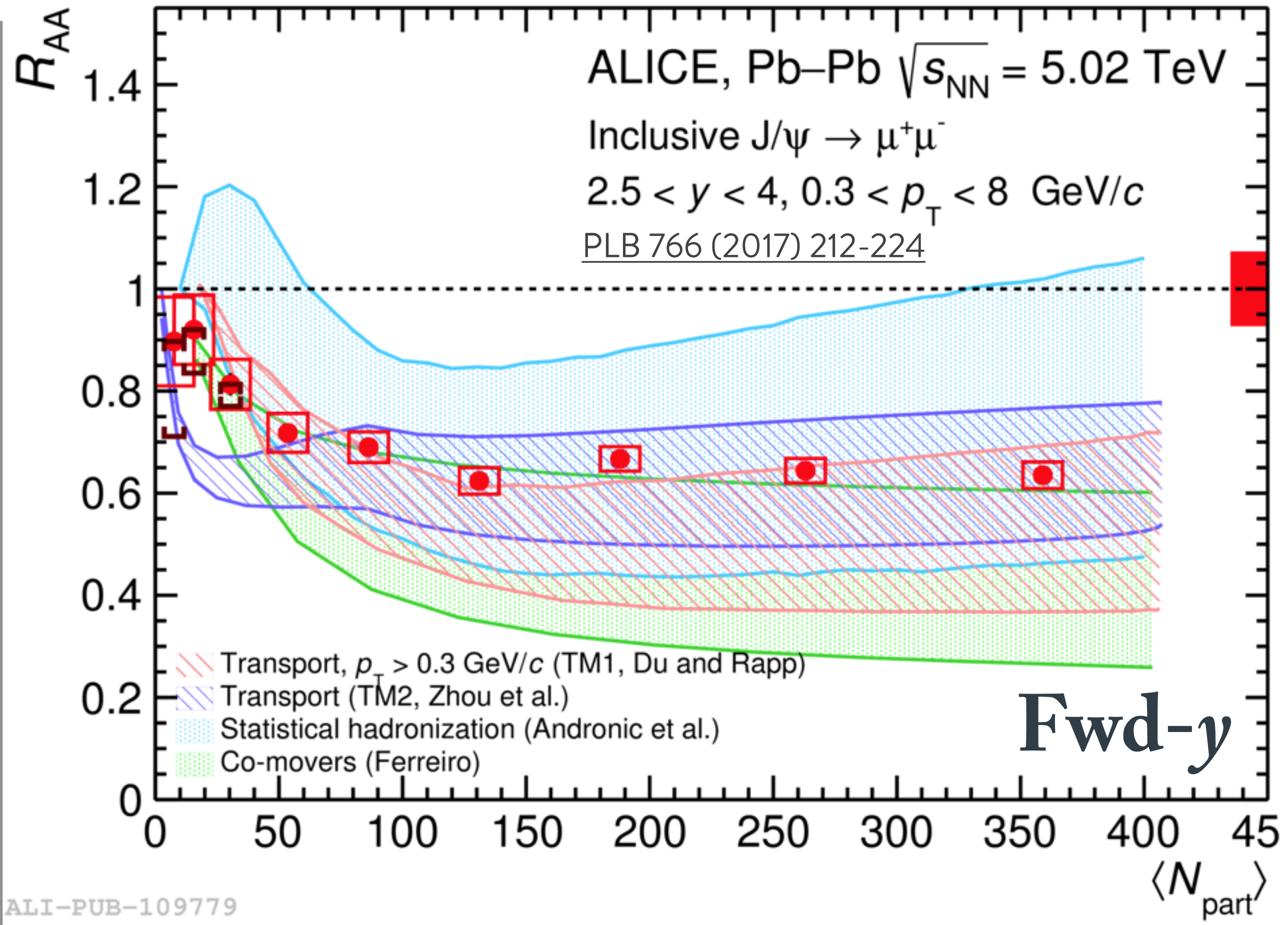
Statistical hadronization

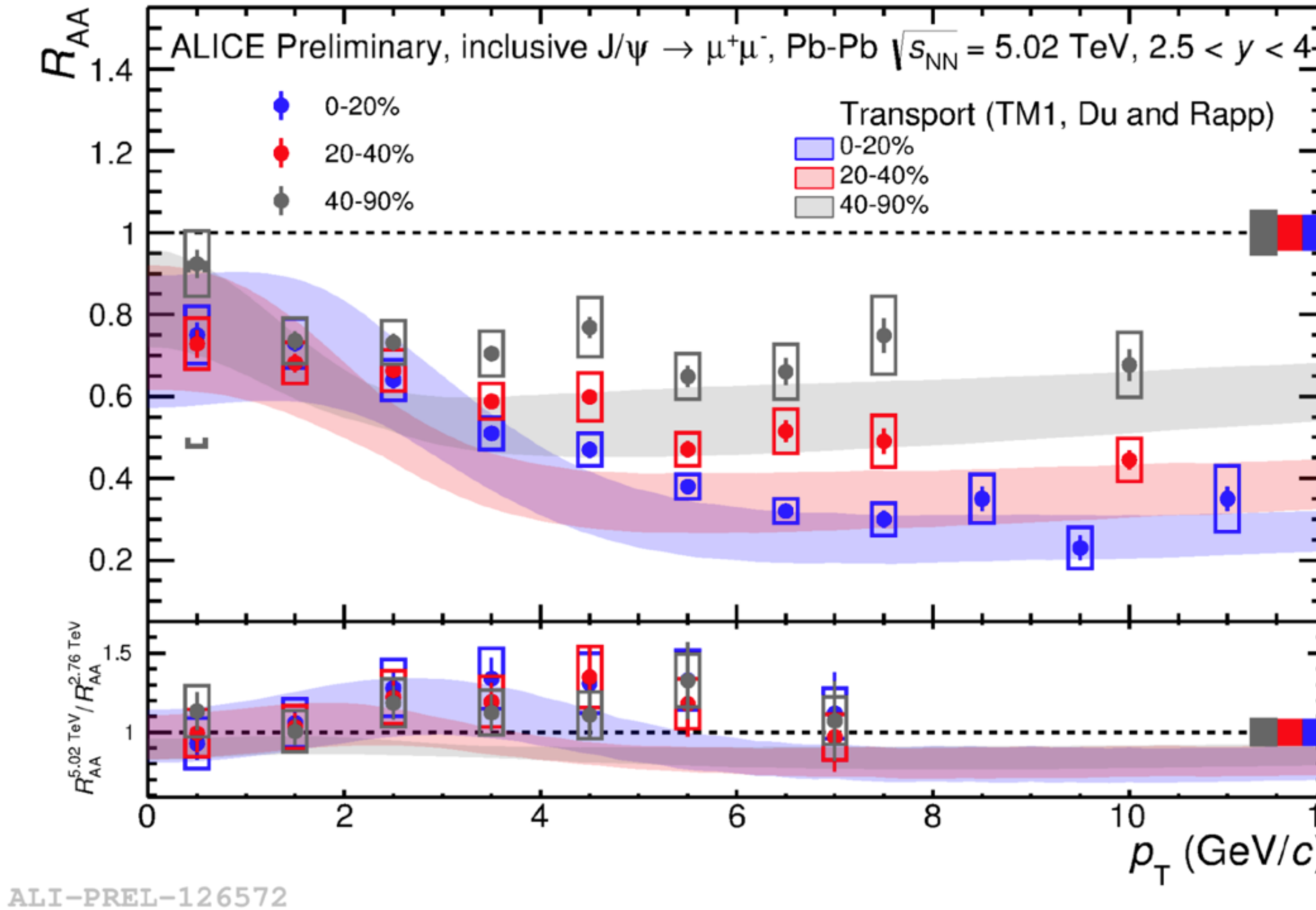
Andronic et al., NPA 904-5, 535c

Co-movers interaction model

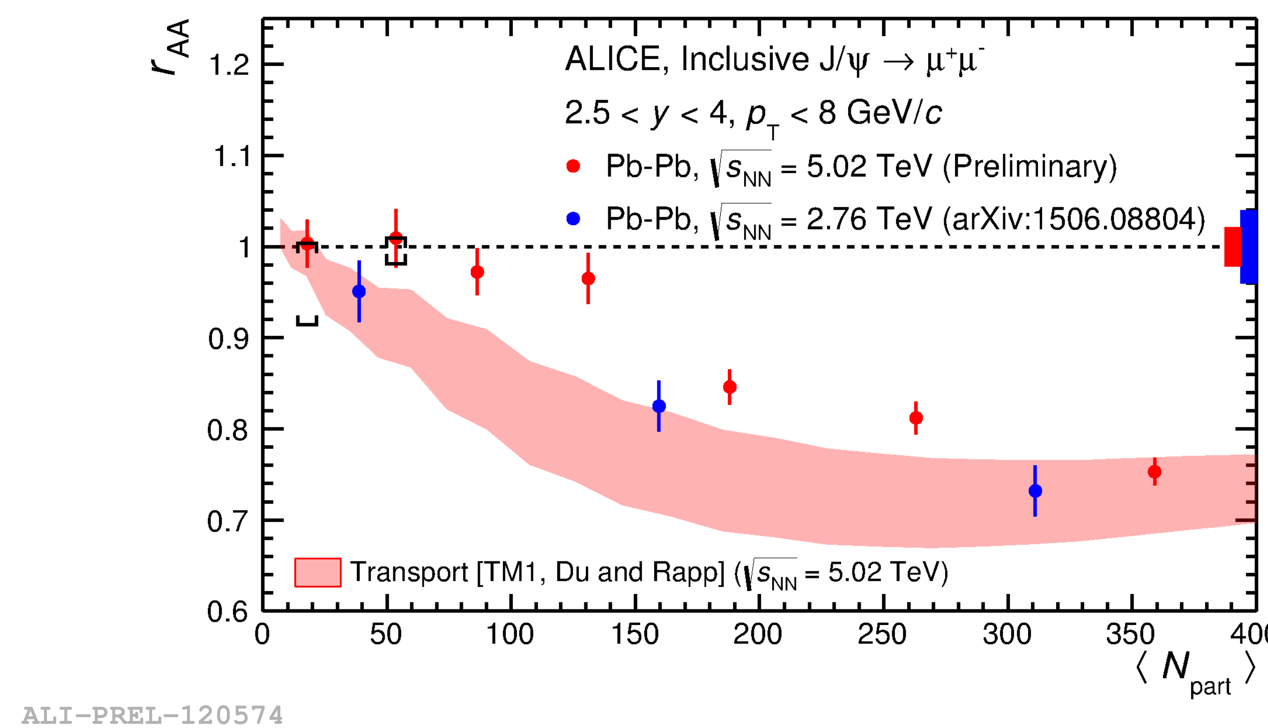
Ferreiro et al., PLB731, 57

Quarkonium in the QGP





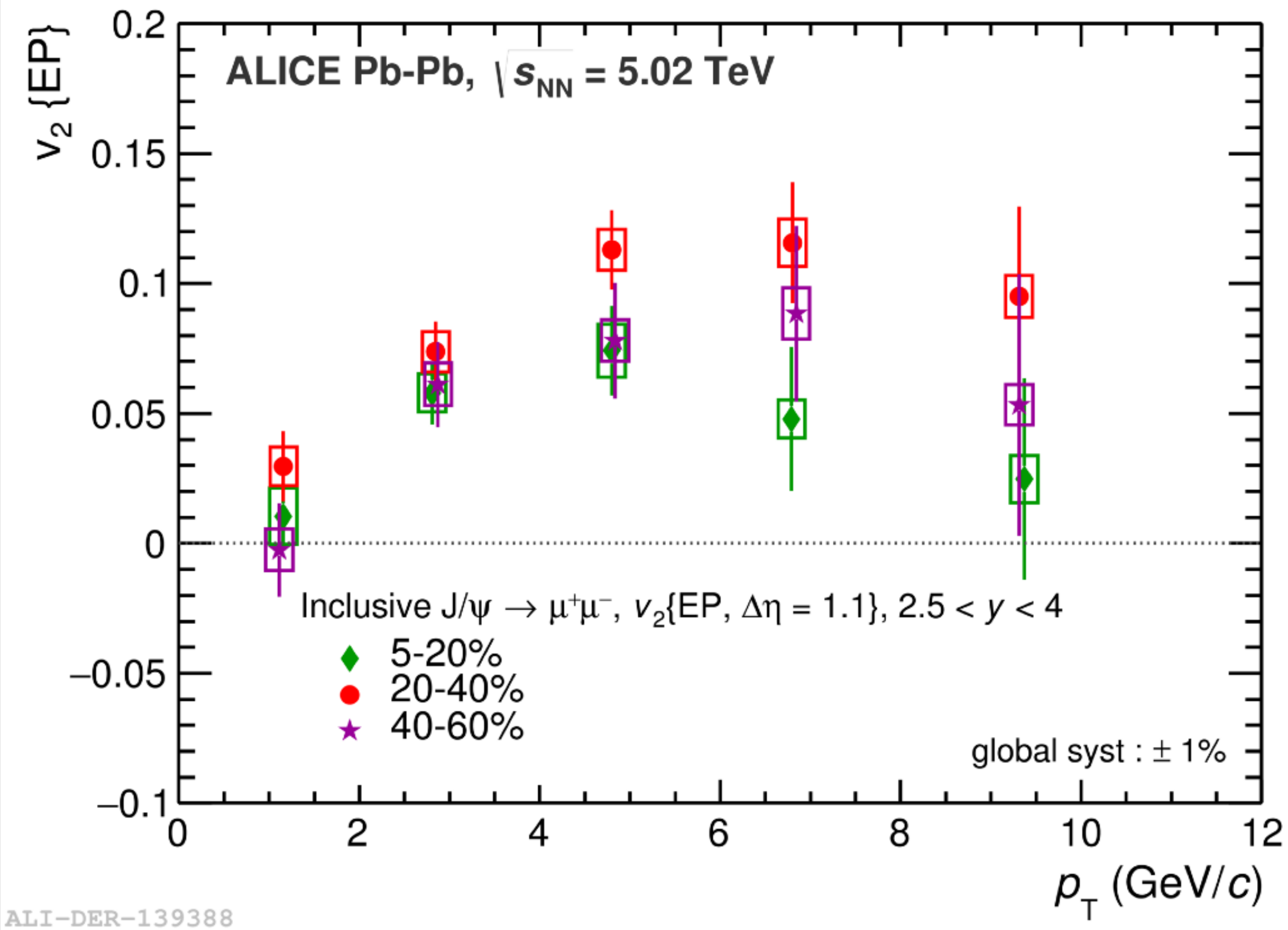
$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$

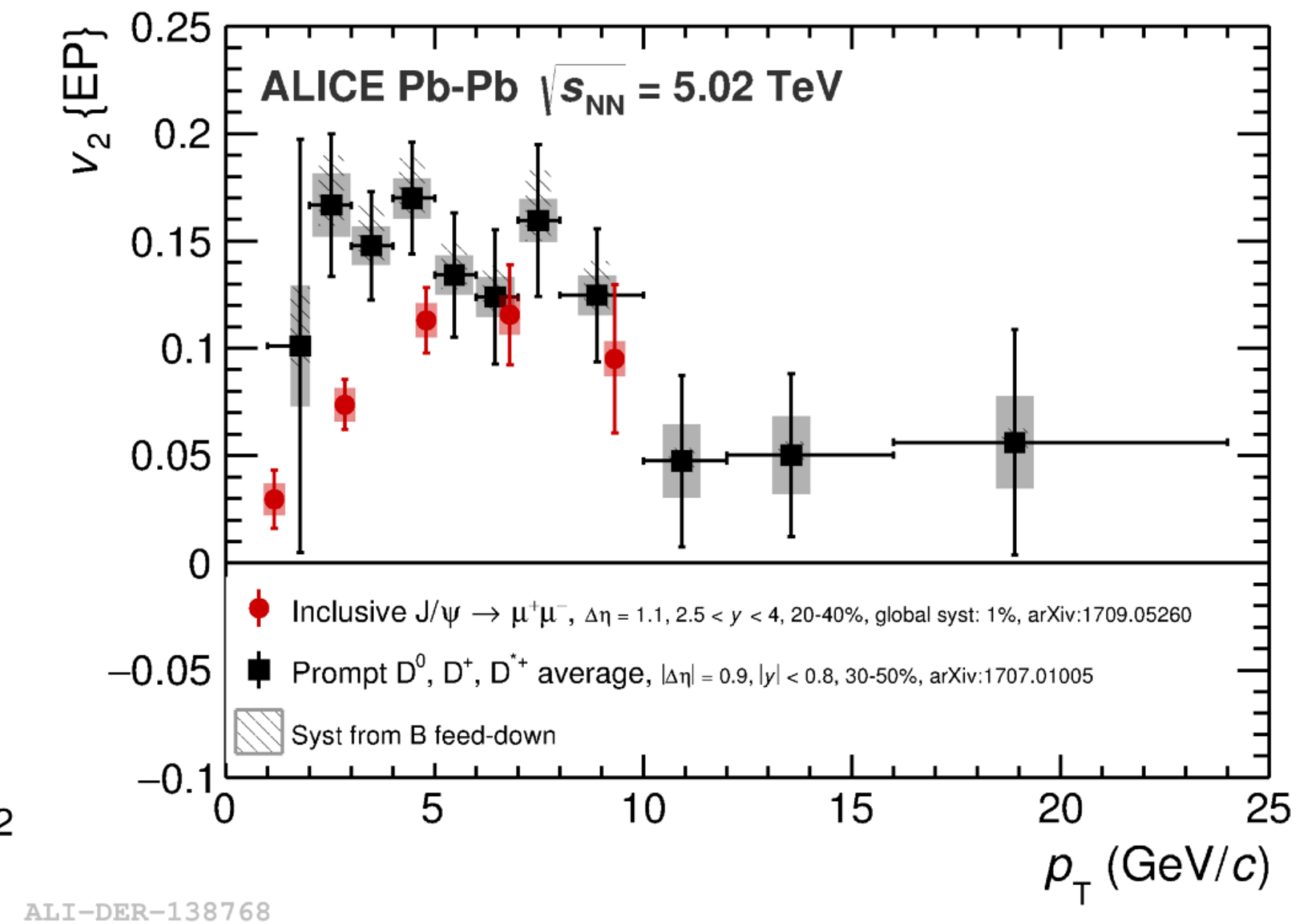


J/ψ v_2 at $\sqrt{s_{NN}}$ = 5.02TeV

Intro HF ALICE **Pb-Pb** p-Pb

A significant v_2 is observed for various centrality and p_T bins





Strong hints of

→ charm thermalization

→ charm quark (re)combination

But difficult comparison because of:

light quark contribution

primordial + (re)combined J/ψ

→ Simplest case: at high p_T ?

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ALICE

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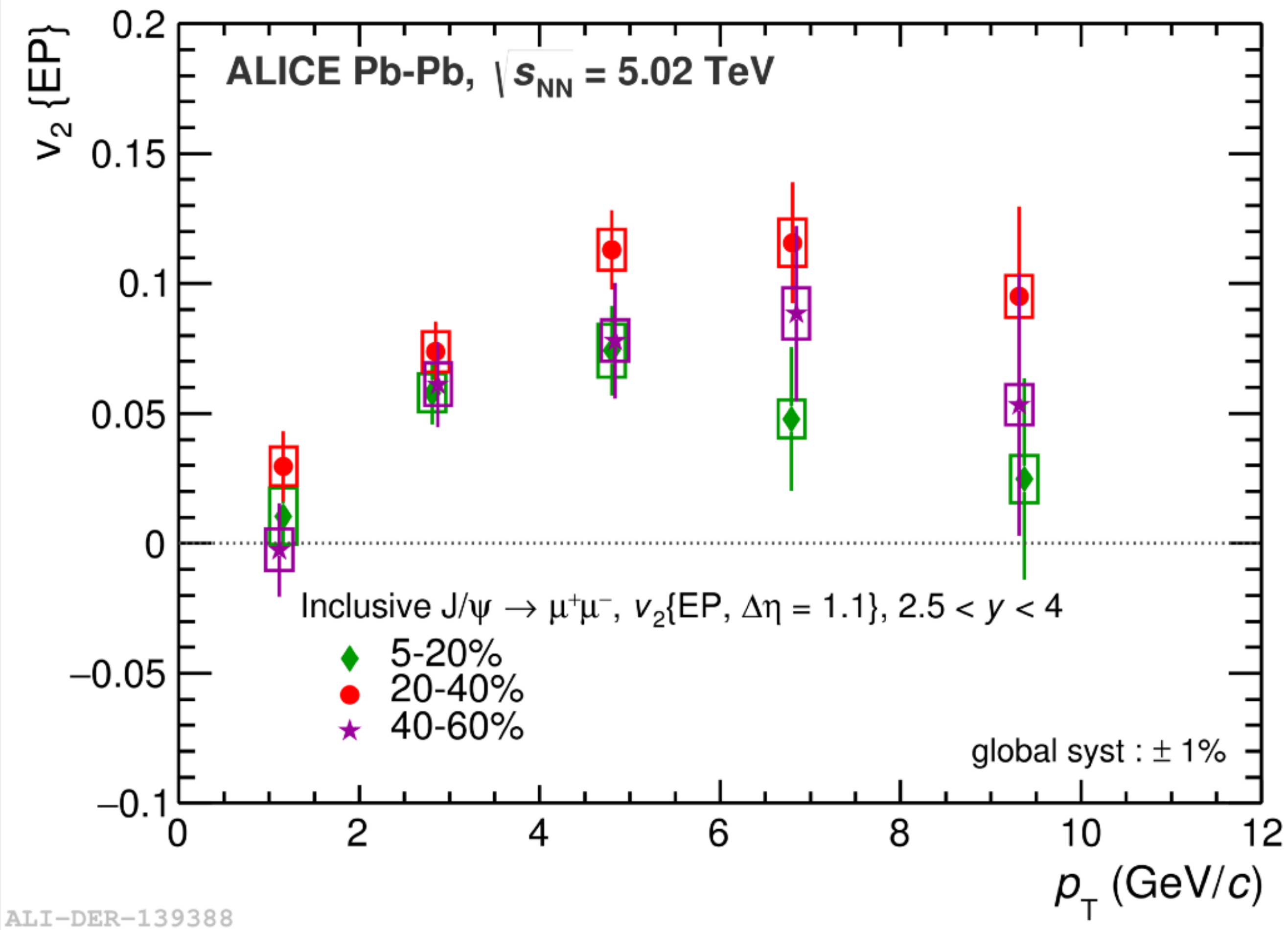

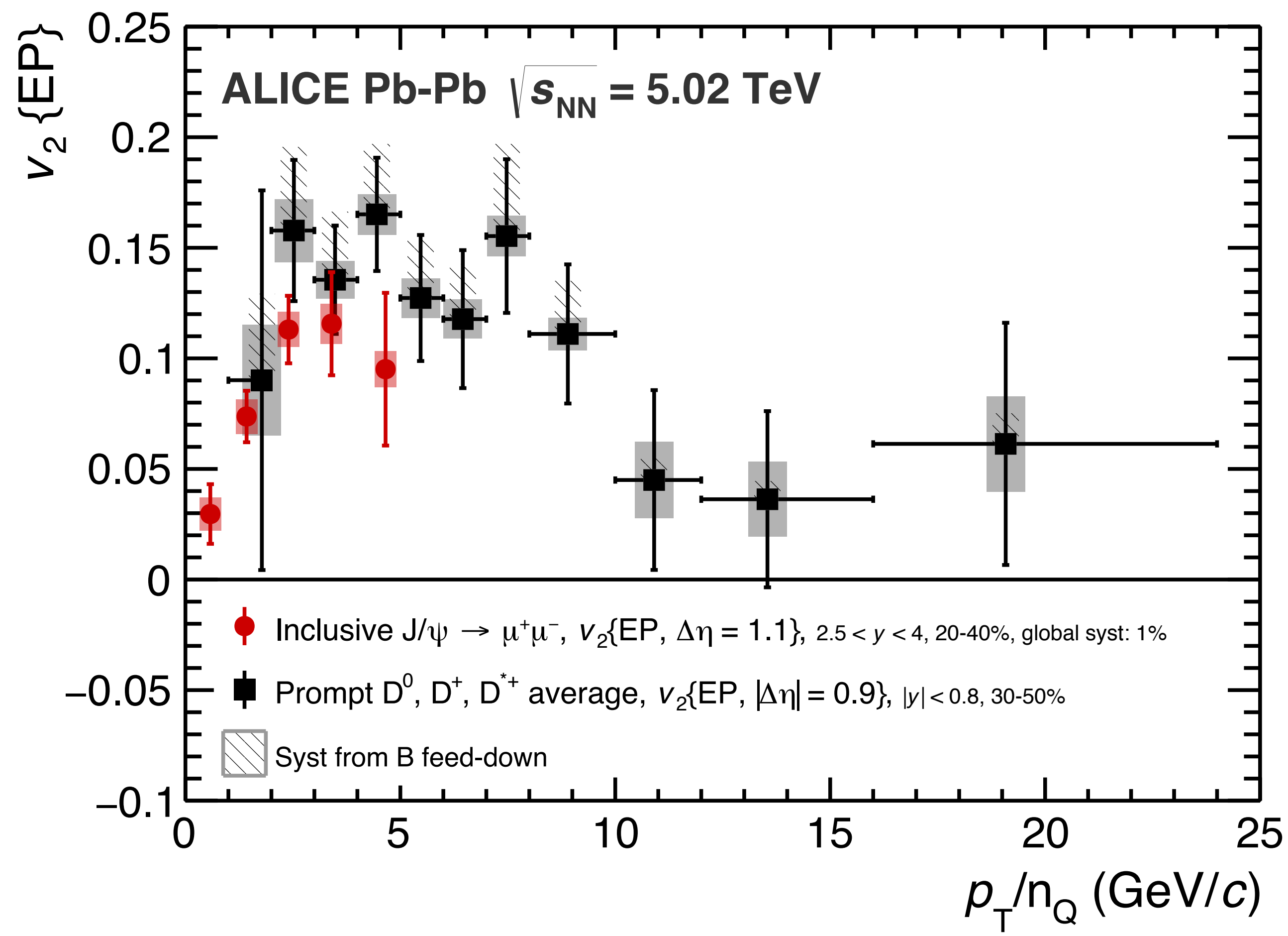

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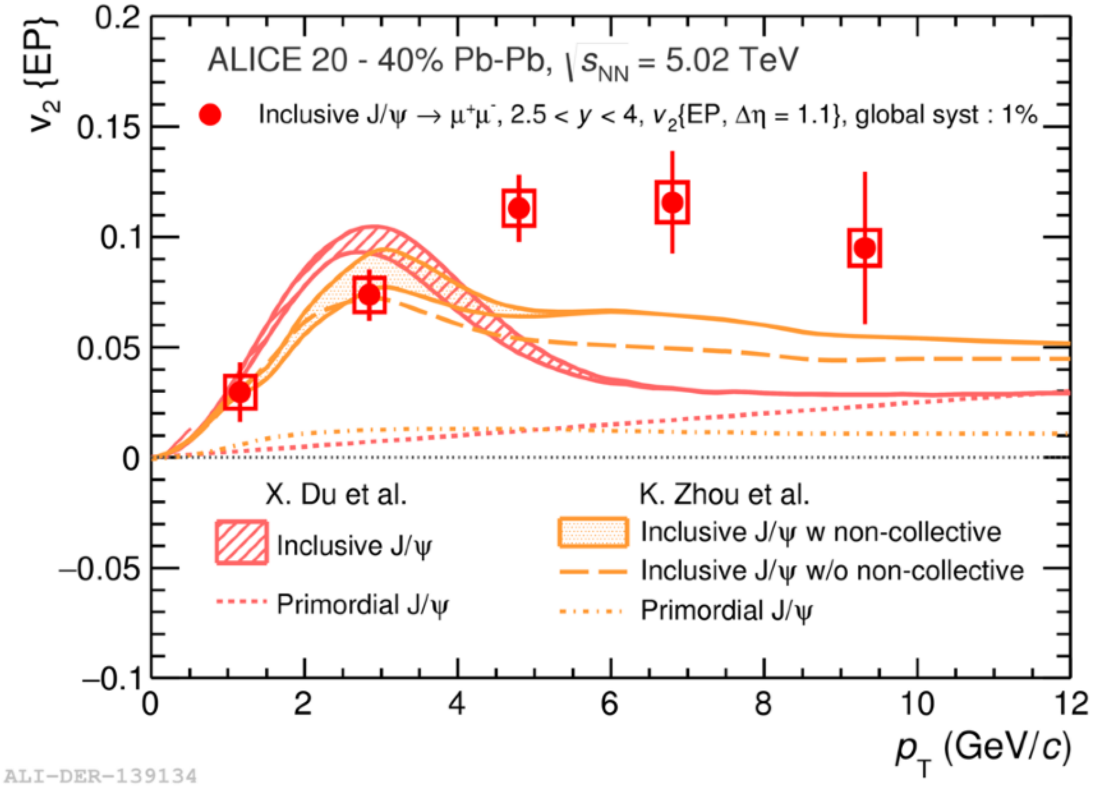
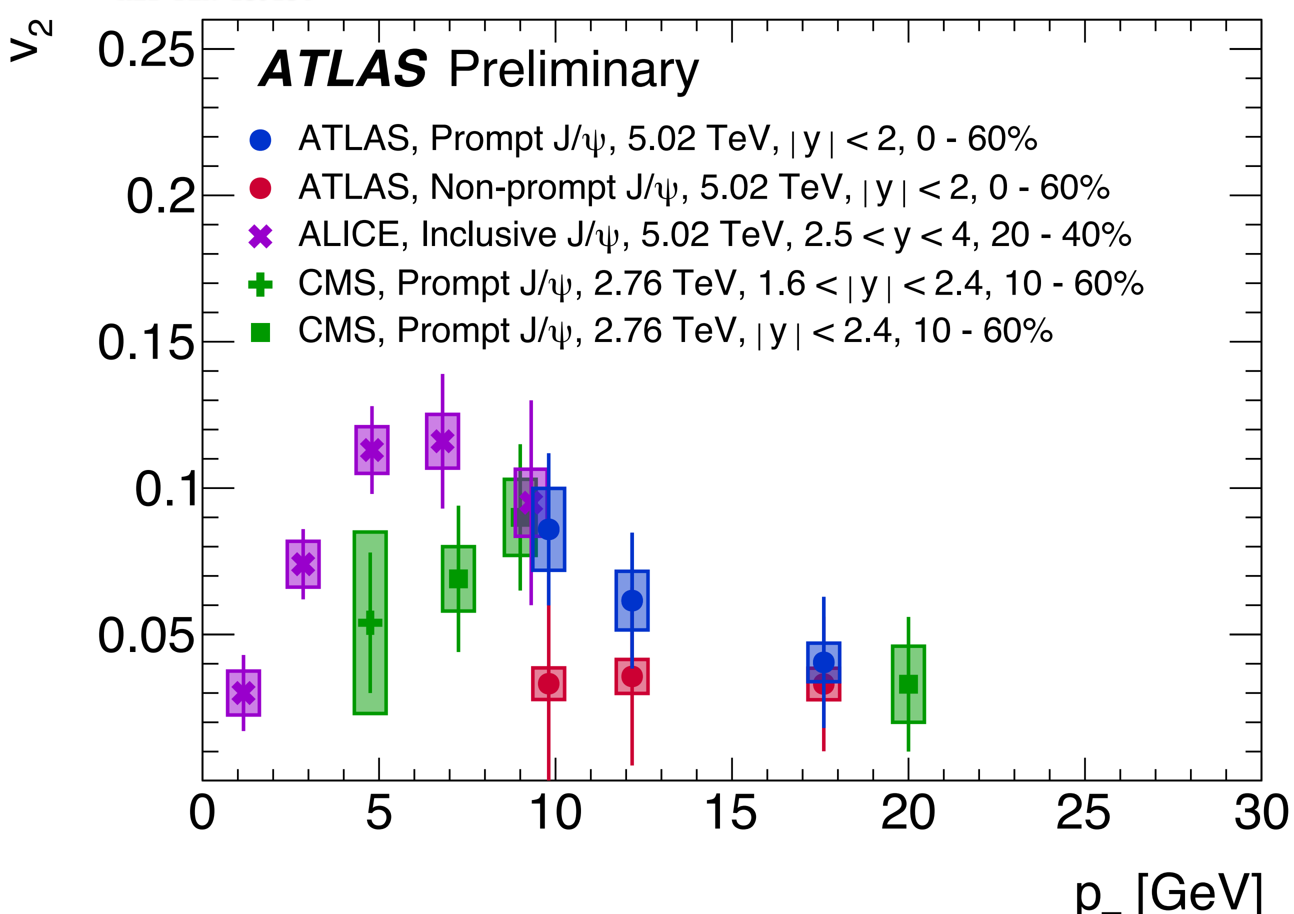
Theoretical models





At low p_T: **strong (re)generation component** is required

At intermediate p_T: tension

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

Transport models reproduce at best *incompletely* exp. data:
→other contrib. (e.g. thermal c/c$\bar{c}$ production ?)[1 2]

Possibilities:

v_2 contribution from primordial J/ψ → v_2 (ϒ)?

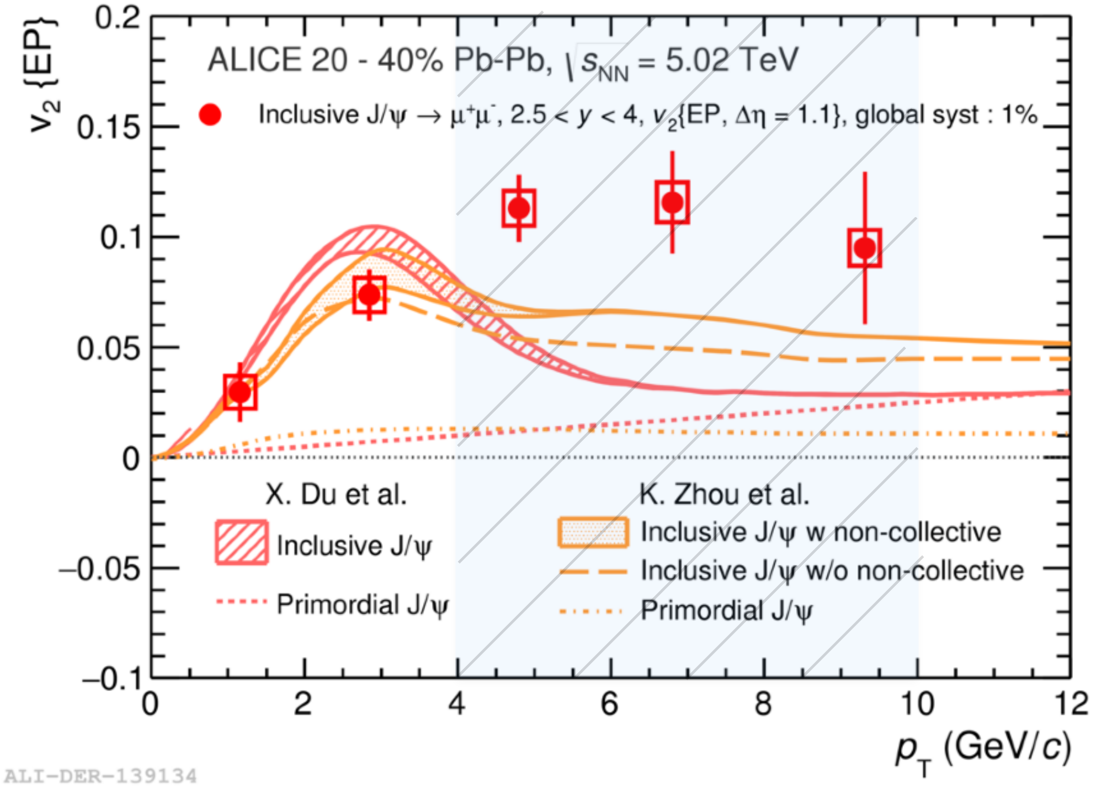
higher (re)combination at large p_T → v_2 (ψ′)?

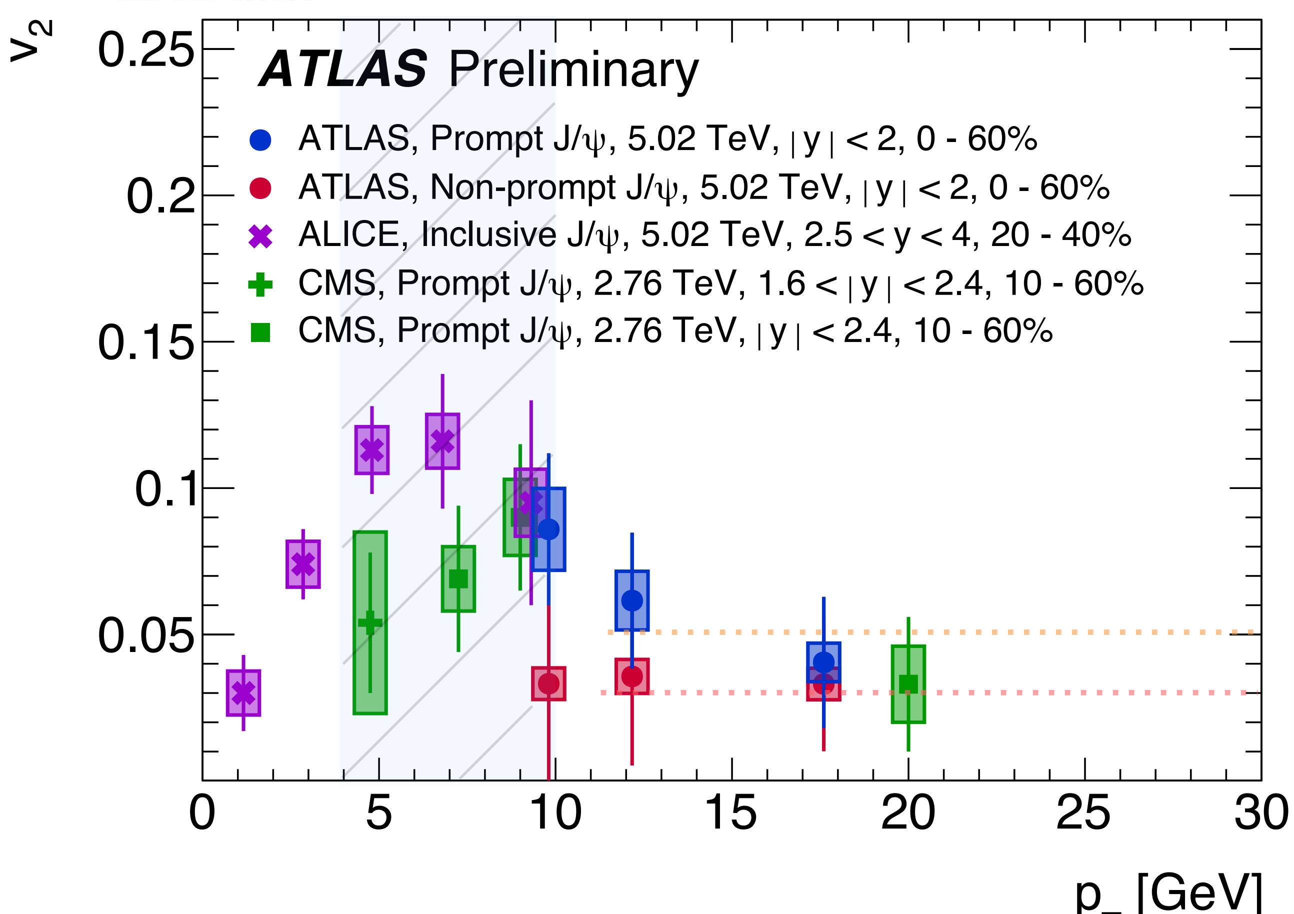
neglected magnetic field effect/intensity
→*direct flow*

Unknown mechanism

→new studies and correlations ?

Theoretical models





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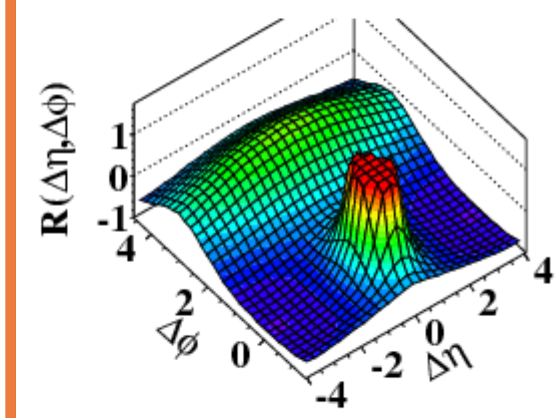
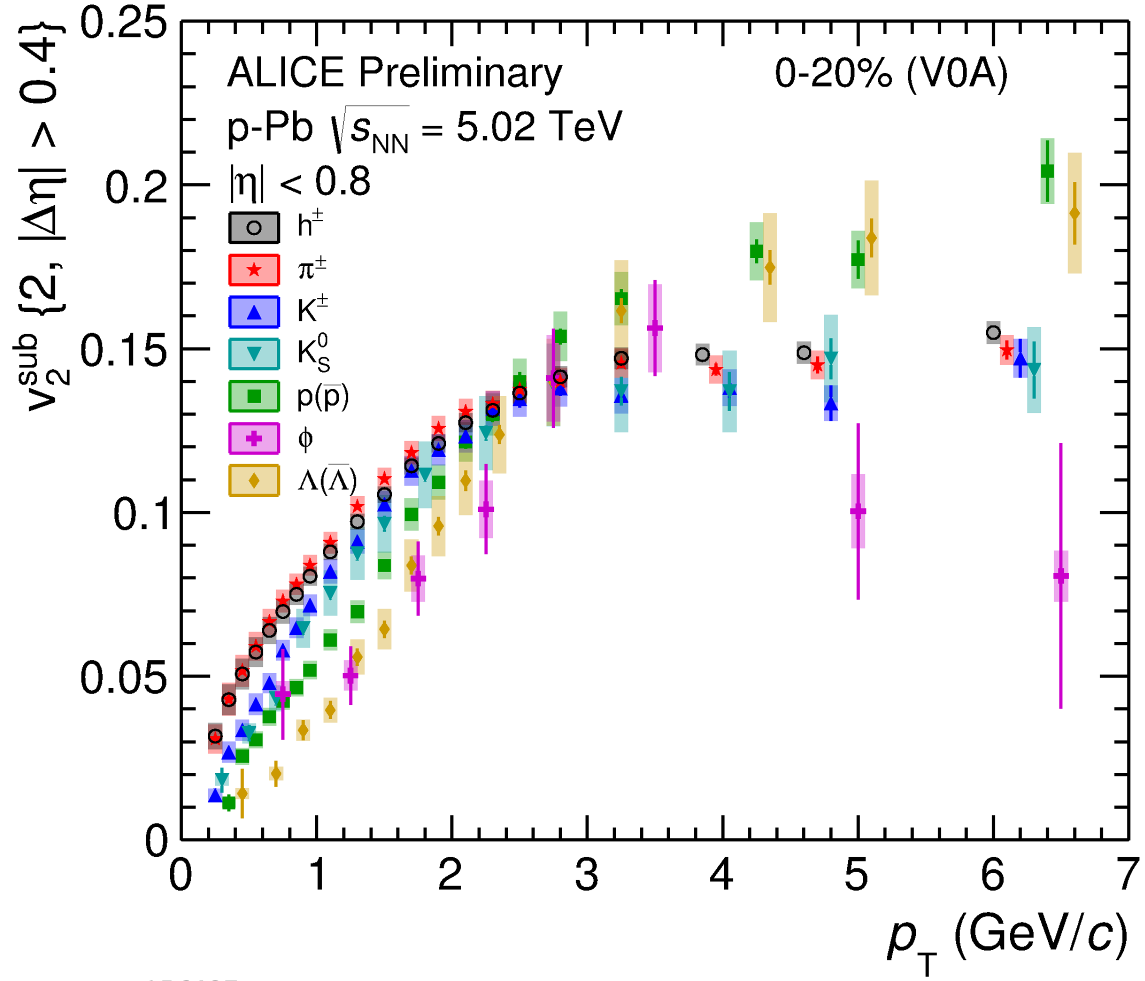
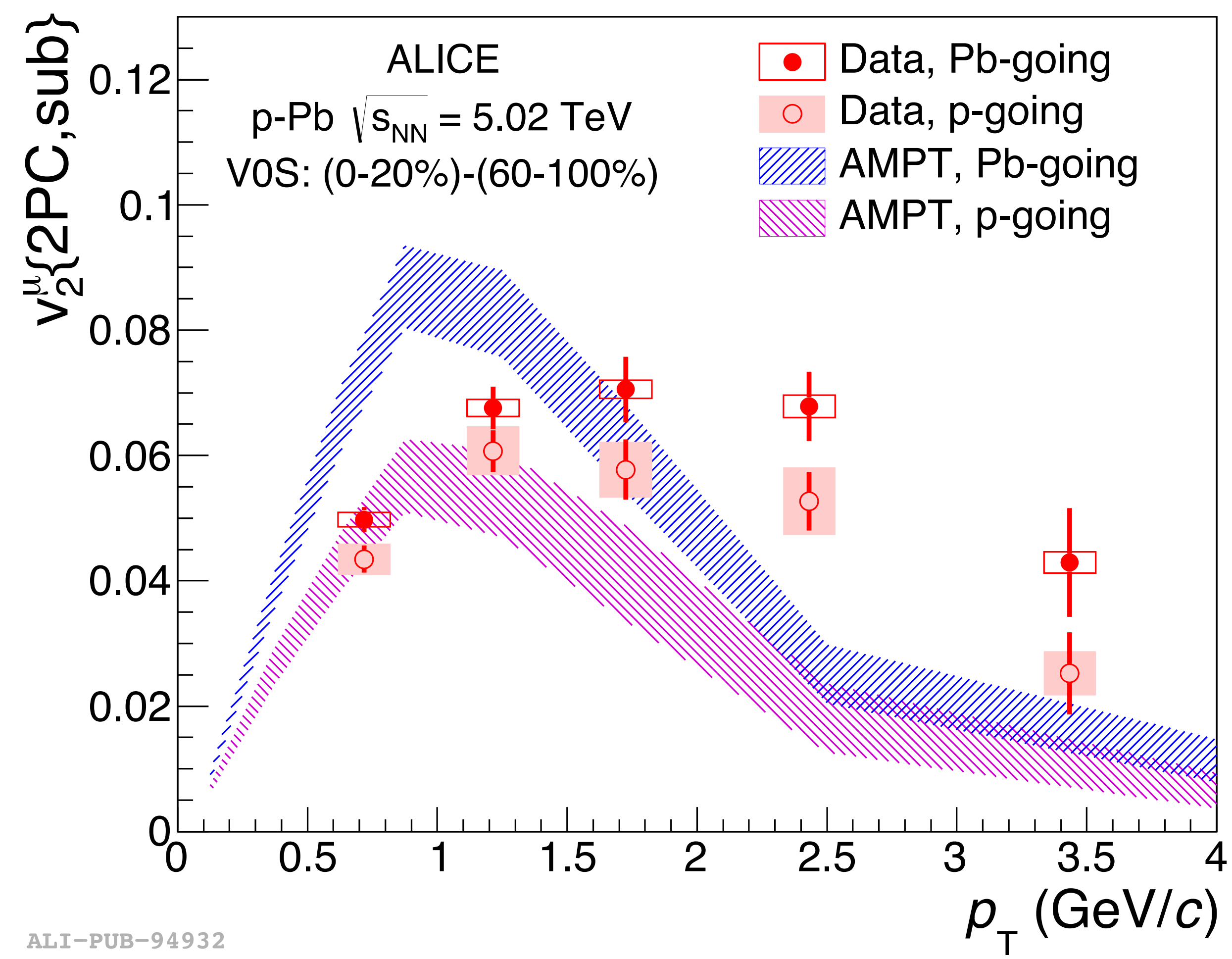


Indirect hints





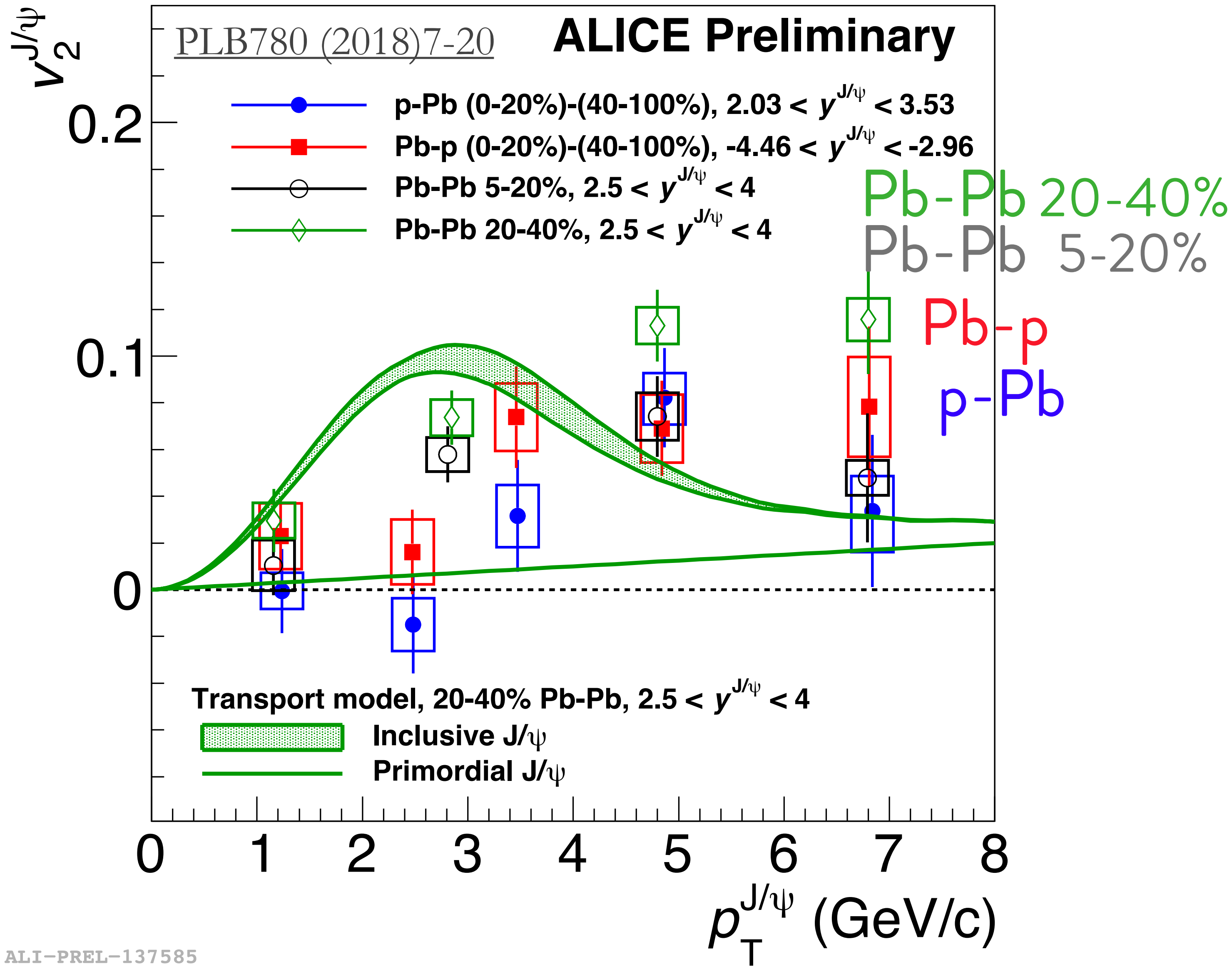
Positive v_2 observation for charged particles

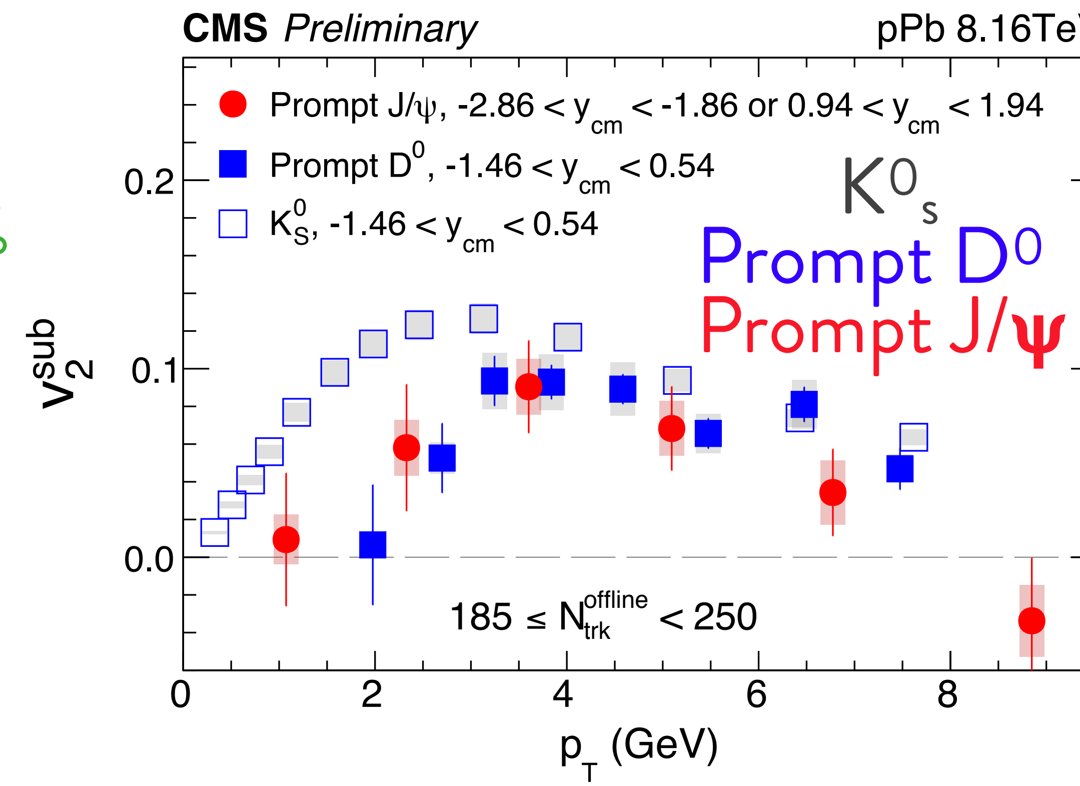
Flow features from A-A are observed:

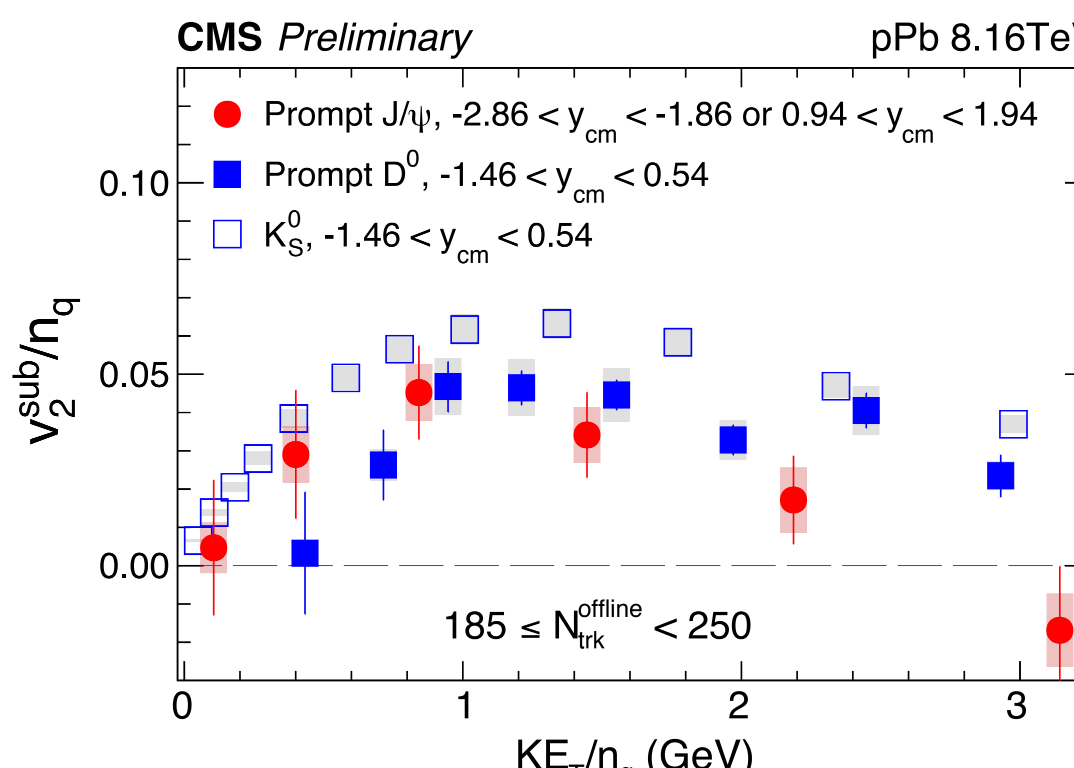
- Mass ordering for $p_T < 2.5$GeV/c
- B/M splitting

At high p_T muons are dominated by HF decays

Collective effect for J/ψ in p-Pb ?







CMS-PAS-HIN-18-010

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

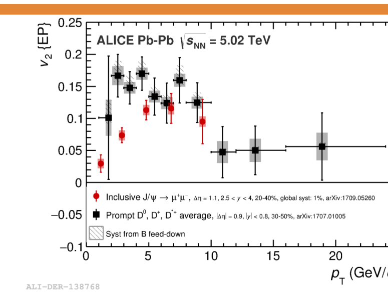
No significant (re)generation contribution is expected and lesser path-length effect w.r.t Pb-Pb

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

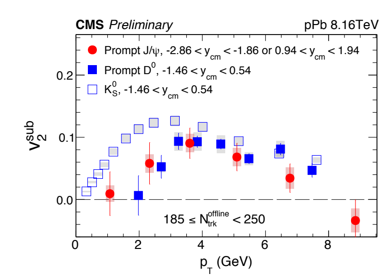
SUMMARY

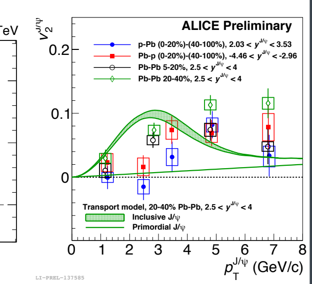
HF Hard probes of HI collisions

Pb-Pb	Positive v_2 is observed for D mesons and J/ψ Case for charm thermalisation and (re)combination Transport models underestimate J/ψ v_2 at intermediate p_T Same transport model for D and J/ψ ?



p-Pb	(Unexpected) v_2 for D mesons and J/ψ J/ψ v_2 in p-Pb is not yet understood Signs of weaker charm interaction in the medium





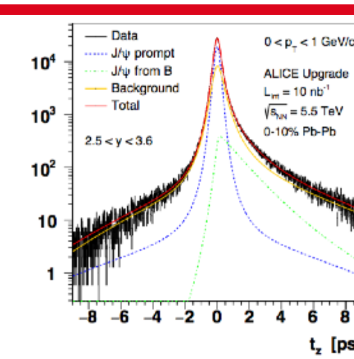
Upgrade

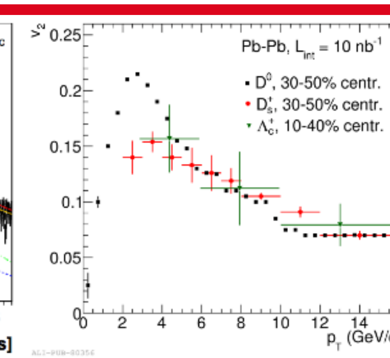
improved precision +

D mesons down to p_T=0 + Λ_c v_2

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

New observables: beauty

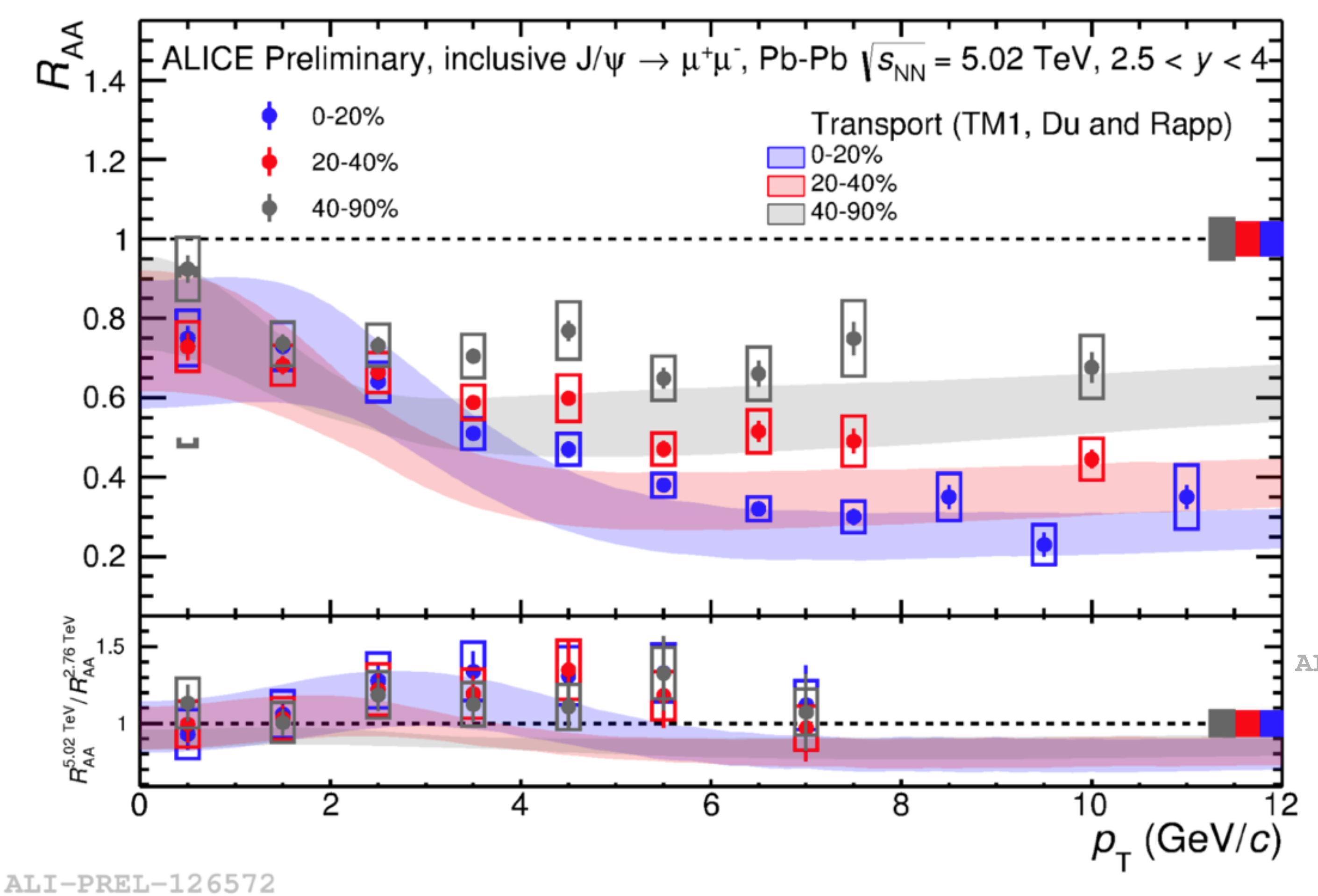


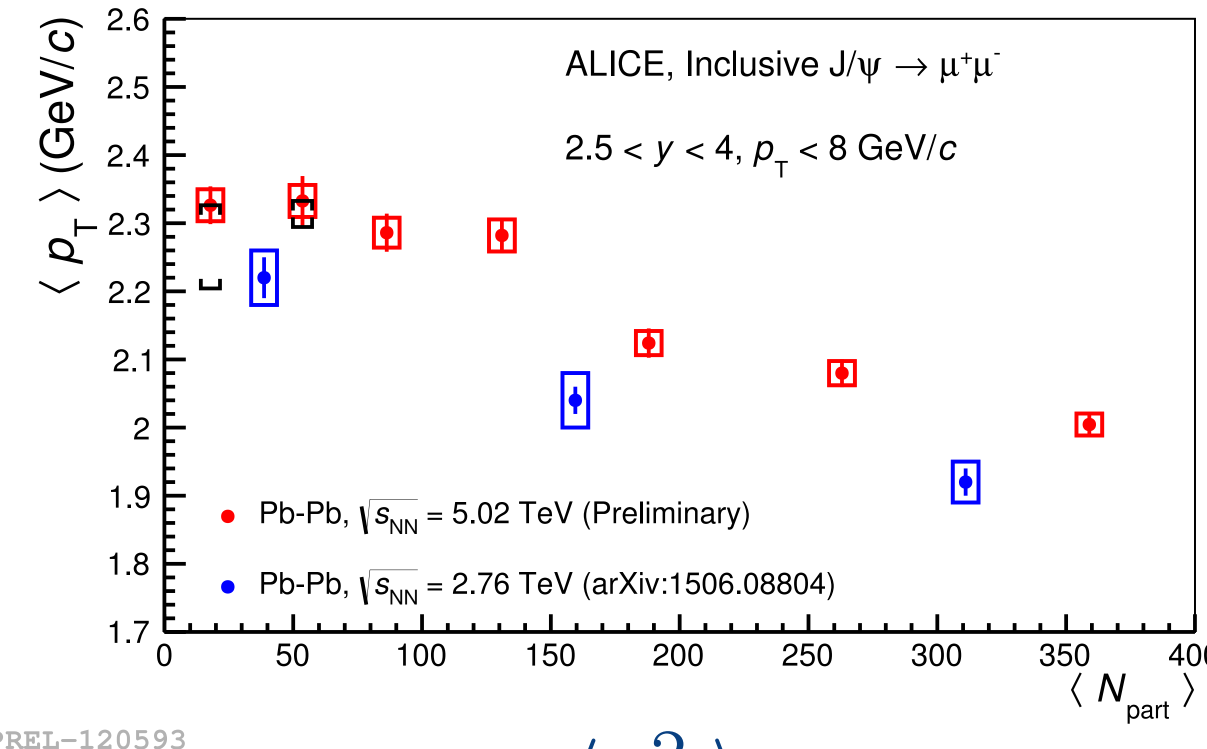


Thank you for your attention!

Back-up

J/ψ Nuclear Modification factor vs p_T, $<p_T>$, r_{AA}





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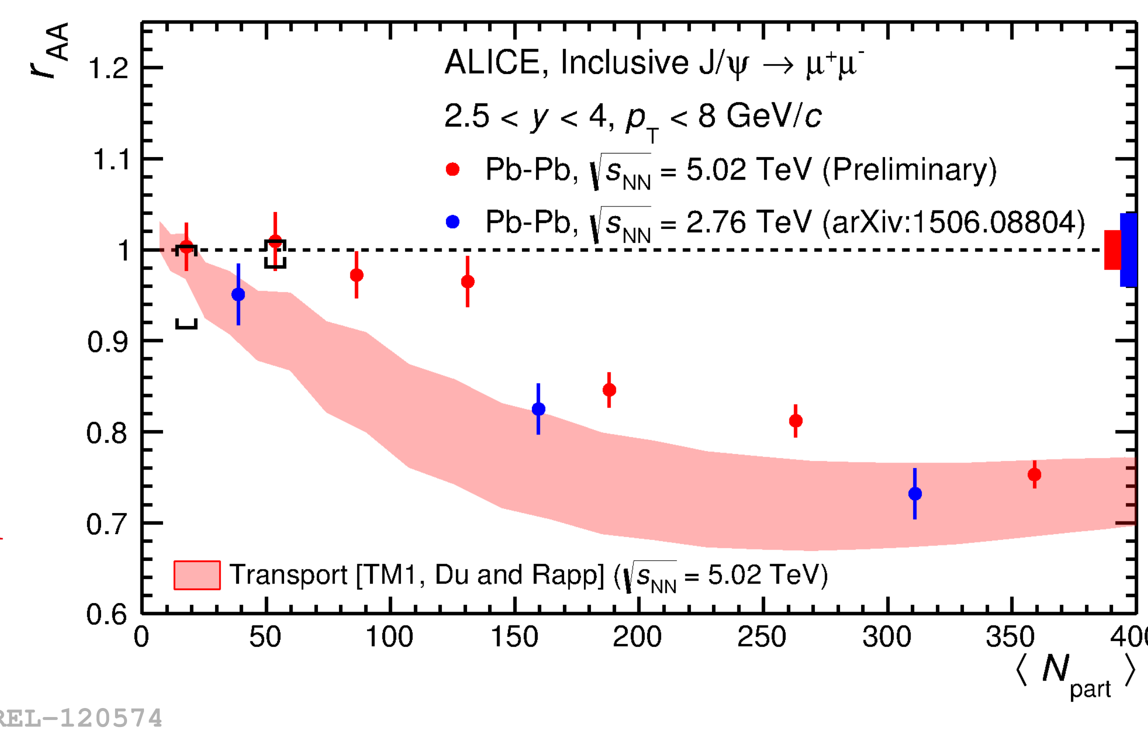
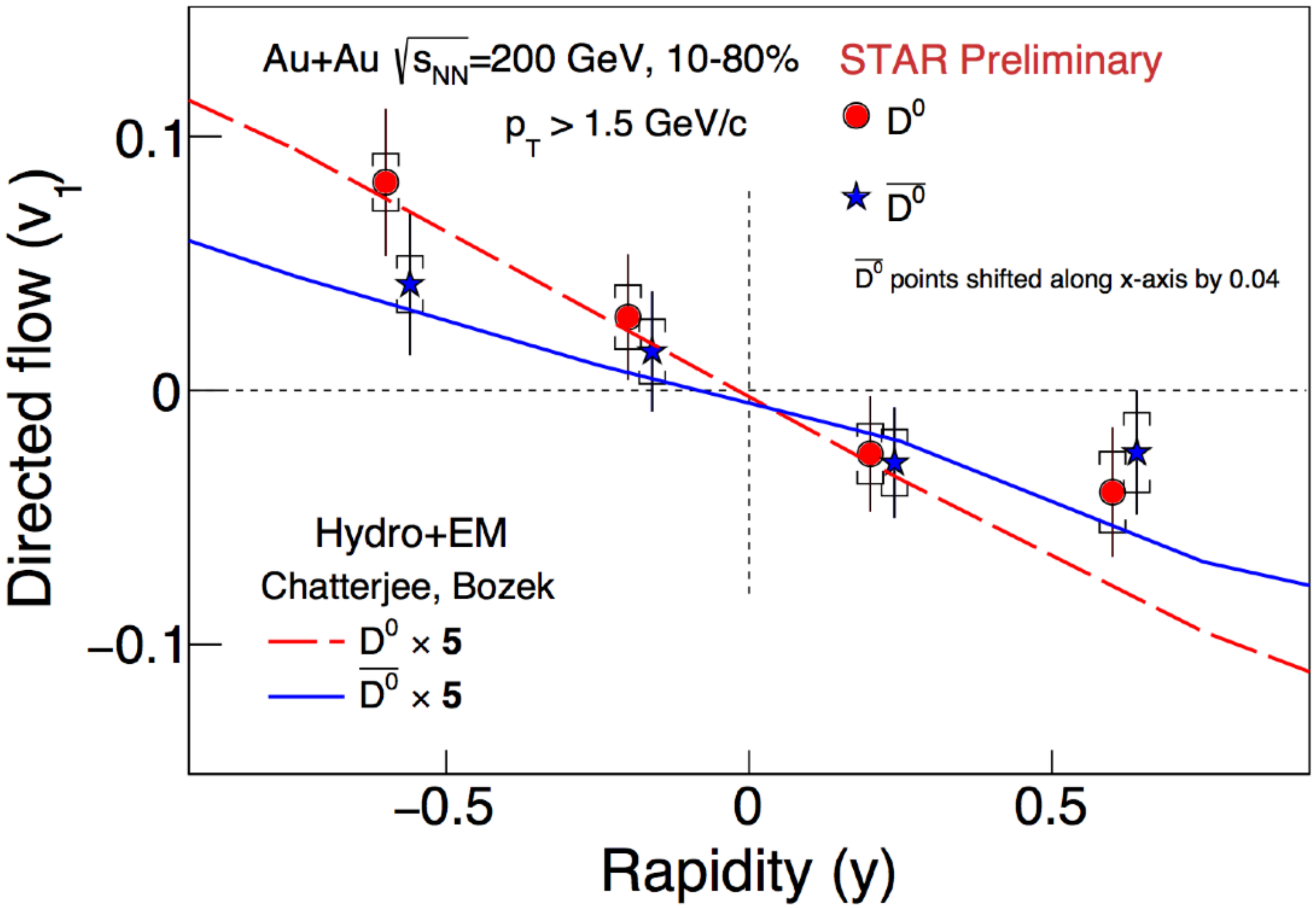
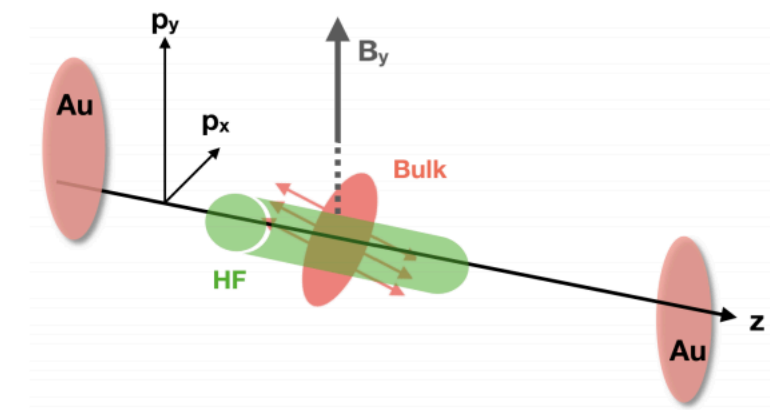


- J/ψ suppression is stronger at high p_T and in central collisions
- Transport model predicts similar trend
- Brackets give limits for possible contamination from J/ψ photo-production

D0 v1 from STAR (QM2018)

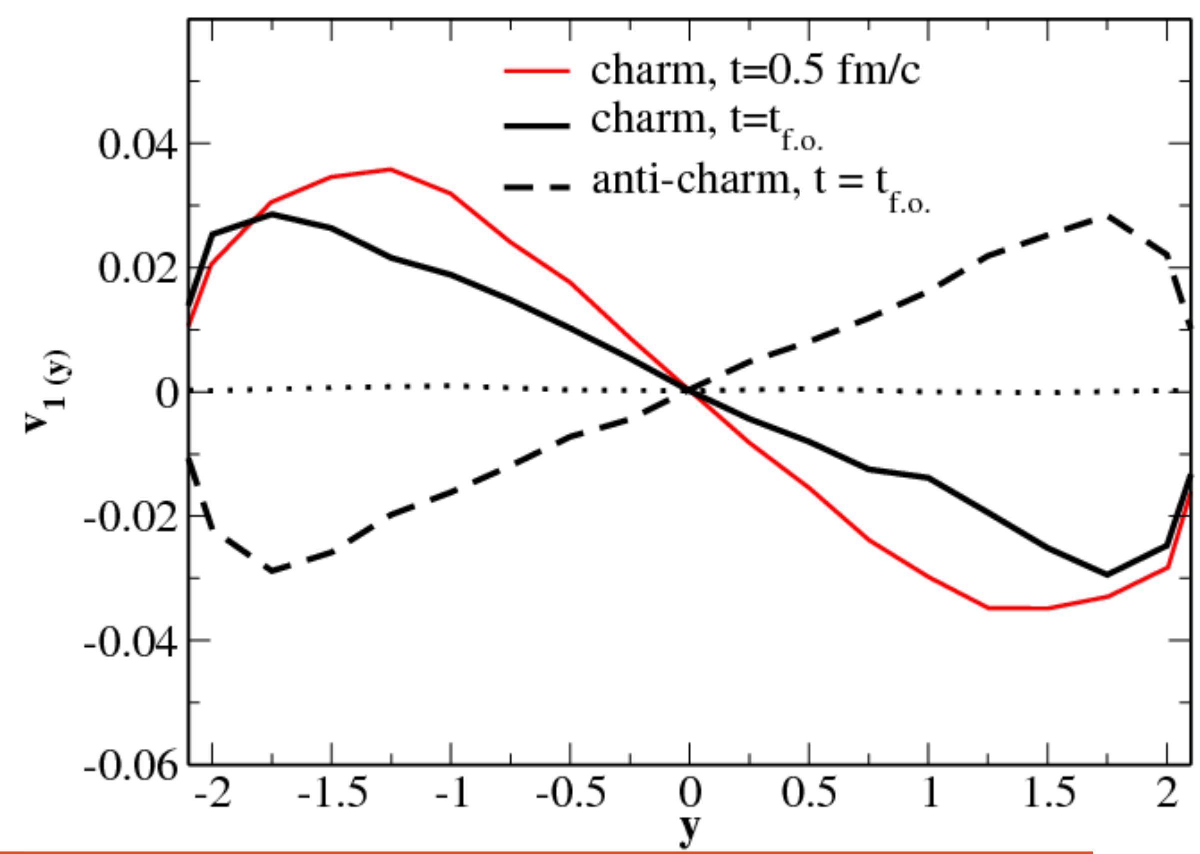




Expected v_1 from Hydro+EM field

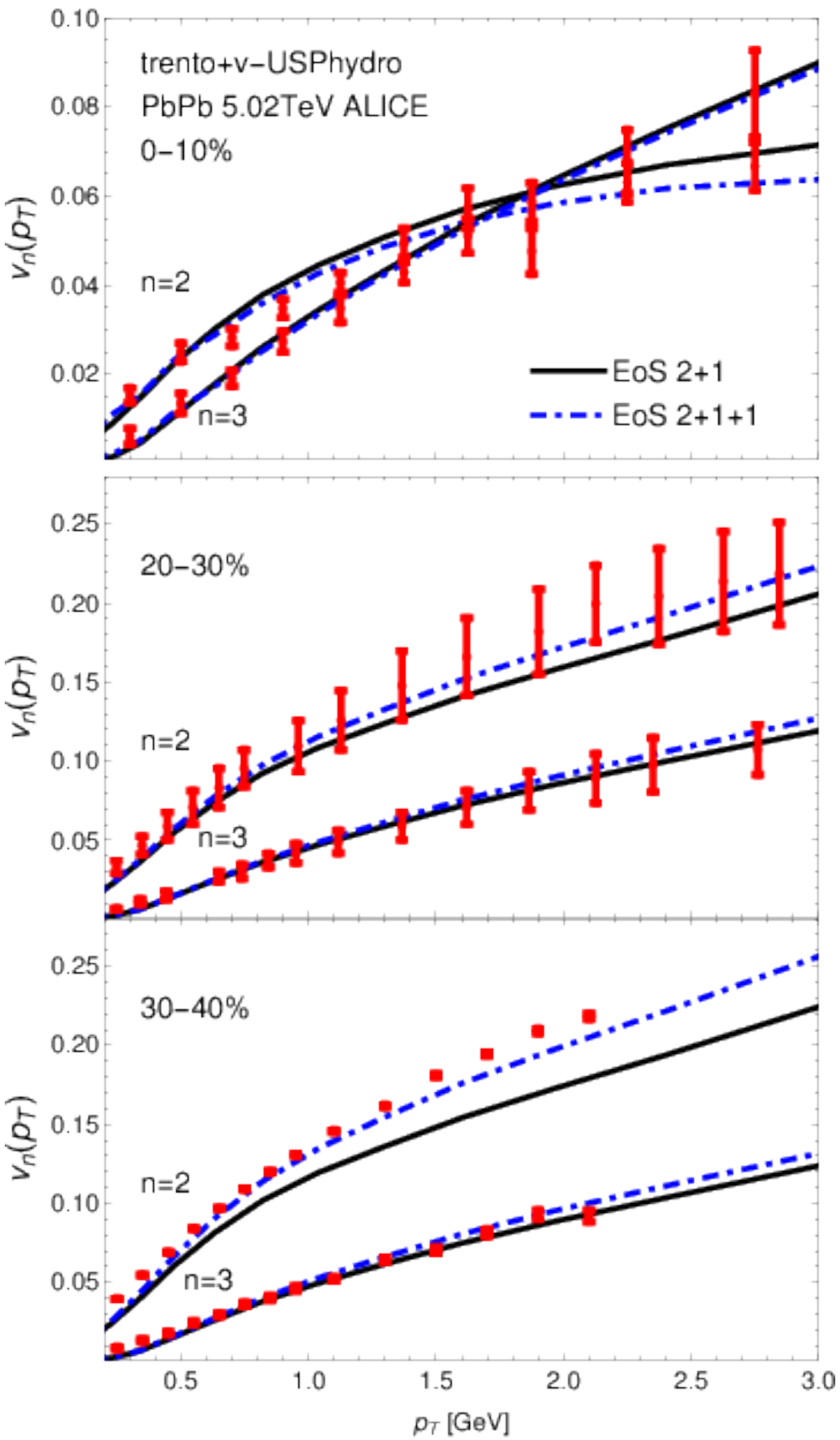
correct slope but wrong magnitude

https://arxiv.org/abs/1608.02231



Number of flavours in the EoS

ALICE



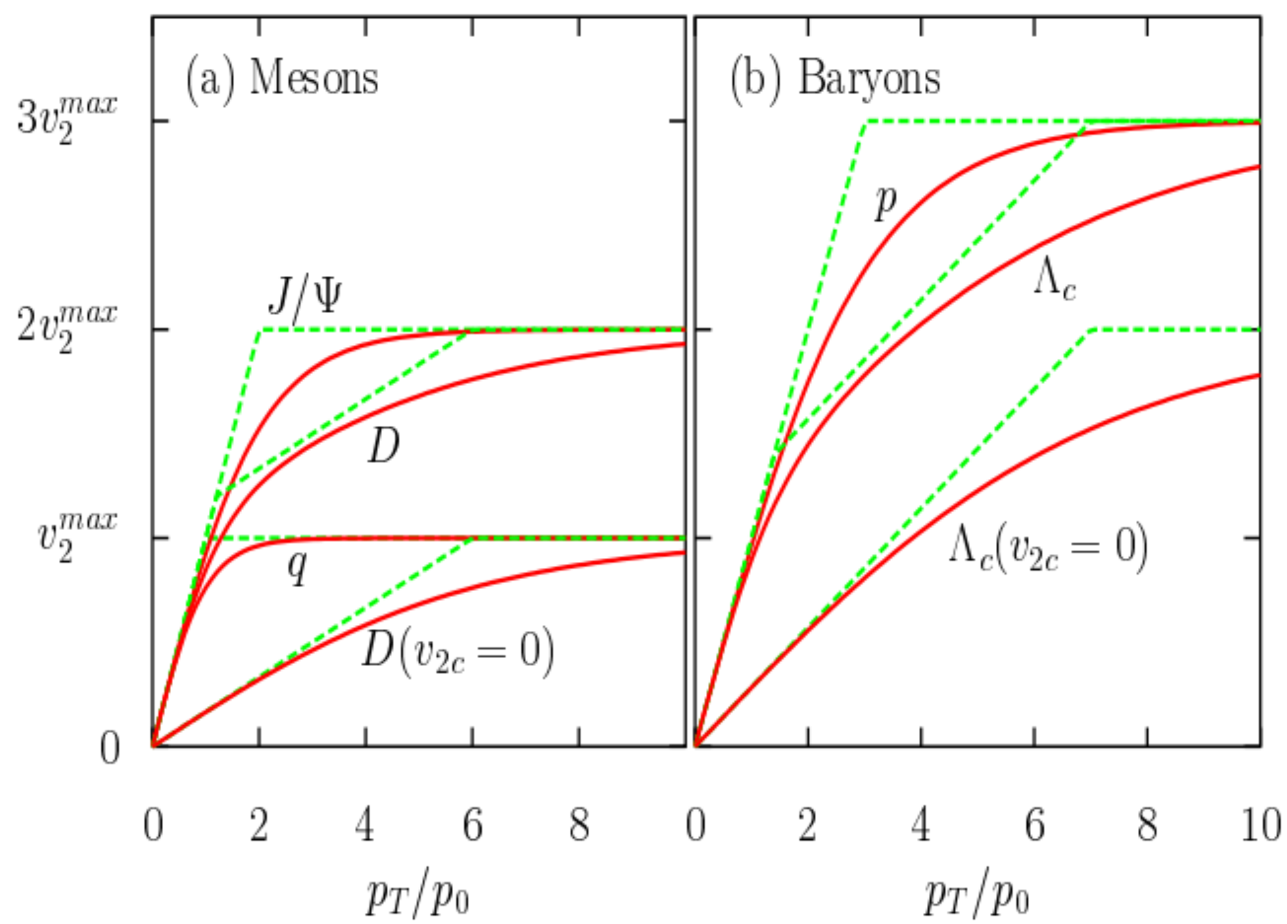
New and different approach on charm thermalization:

Impact of the number of flavours in the final equation of state of the system: comparison to ALICE results for charged particles

https://arxiv.org/pdf/1804.10661.pdf

In a coalescence picture

(not including independent fragmentation of partons)



v_2(c) can be unfolded from M/B measurements

$$v_2^M(p_\perp) = \frac{\overline{v_{2,\alpha}} + \overline{v_{2,\beta}}}{1 + 2\,\overline{v_{2,\alpha}}\,\overline{v_{2,\beta}}} \simeq \overline{v_{2,\alpha}} + \overline{v_{2,\beta}},$$

$$v_2^B(p_\perp) = \frac{\overline{v_{2,\alpha}} + \overline{v_{2,\beta}} + \overline{v_{2,\gamma}} + 3\,\overline{v_{2,\alpha}}\,\overline{v_{2,\beta}}\,\overline{v_{2,\gamma}}}{1 + 2\,(\overline{v_{2,\alpha}}\,\overline{v_{2,\beta}} + \overline{v_{2,\alpha}}\,\overline{v_{2,\gamma}} + \overline{v_{2,\beta}}\,\overline{v_{2,\gamma}})} \simeq \overline{v_{2,\alpha}} + \overline{v_{2,\beta}} + \overline{v_{2,\gamma}},$$

ex: Λ_c and D mesons

$$v_2^q(p_\perp) = v_2^{\Lambda_c}((2+r)p_\perp) - v_2^D((1+r)p_\perp),$$

$$v_2^c(p_\perp) = 2v_2^D\left(\frac{1+r}{r}p_\perp\right) - v_2^{\Lambda_c}\left(\frac{2+r}{r}p_\perp\right)$$

$$r \equiv m_c/m_q$$

Magnetic field effect on charmonium formation

ALICE

Motivations: $t_B \sim 0.1$ fm/c vs tf ~ 0.5 fm/c from cc to final charmonium state
→profound effects from **B on Charmonium yields and distributions**

From Schrödinger eq including a magnetic potential A

$$i\frac{\partial}{\partial t}\Phi = \hat{H}\Phi \qquad \hat{H} = \frac{(\hat{\mathbf{p}}_c - q\mathbf{A}_c)^2}{2m_c} + \frac{(\hat{\mathbf{p}}_{\bar{c}} + q\mathbf{A}_{\bar{c}})^2}{2m_c} + V,$$

Hamiltonian divided as

vacuum ↑

$$\hat{H} = \hat{H}_0 + \hat{H}_B$$

↓ magn. field dep.

Lorentz force

$$\hat{H}_B = -\boldsymbol{\mu}\cdot\mathbf{B} + \frac{q}{2m_c}(\hat{\mathbf{P}}_p \times \mathbf{B})\cdot\mathbf{r} + \frac{q^2}{4m_c}(\mathbf{B}\times\mathbf{r})^2$$

spin-field int.

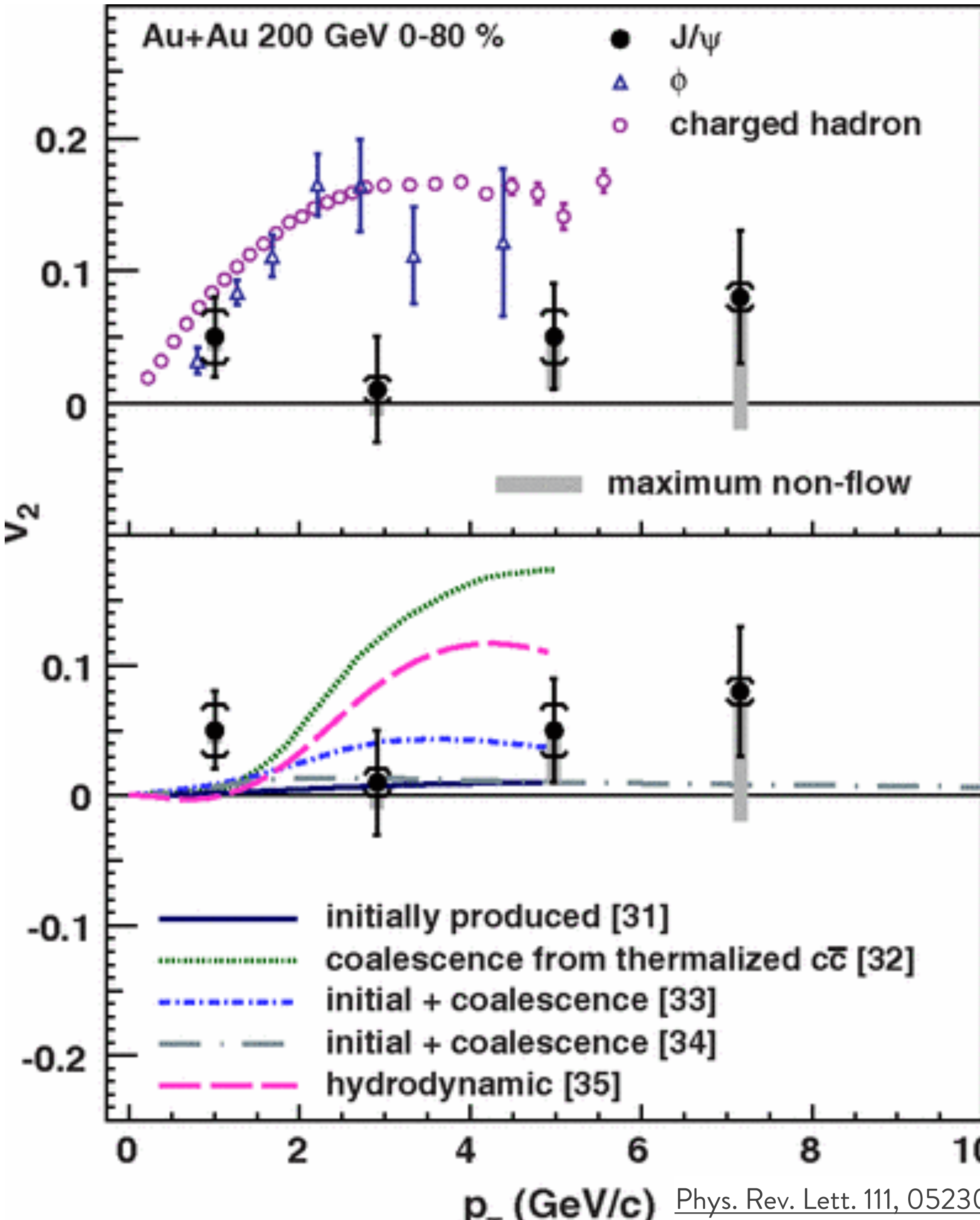
harmonic pot. (negligible)

! conserved momentum: $\mathbf{P}_p = \mathbf{P} + q(\mathbf{A}_c - \mathbf{A}_{\bar{c}})$

J/ψ v_2 at RHIC energies

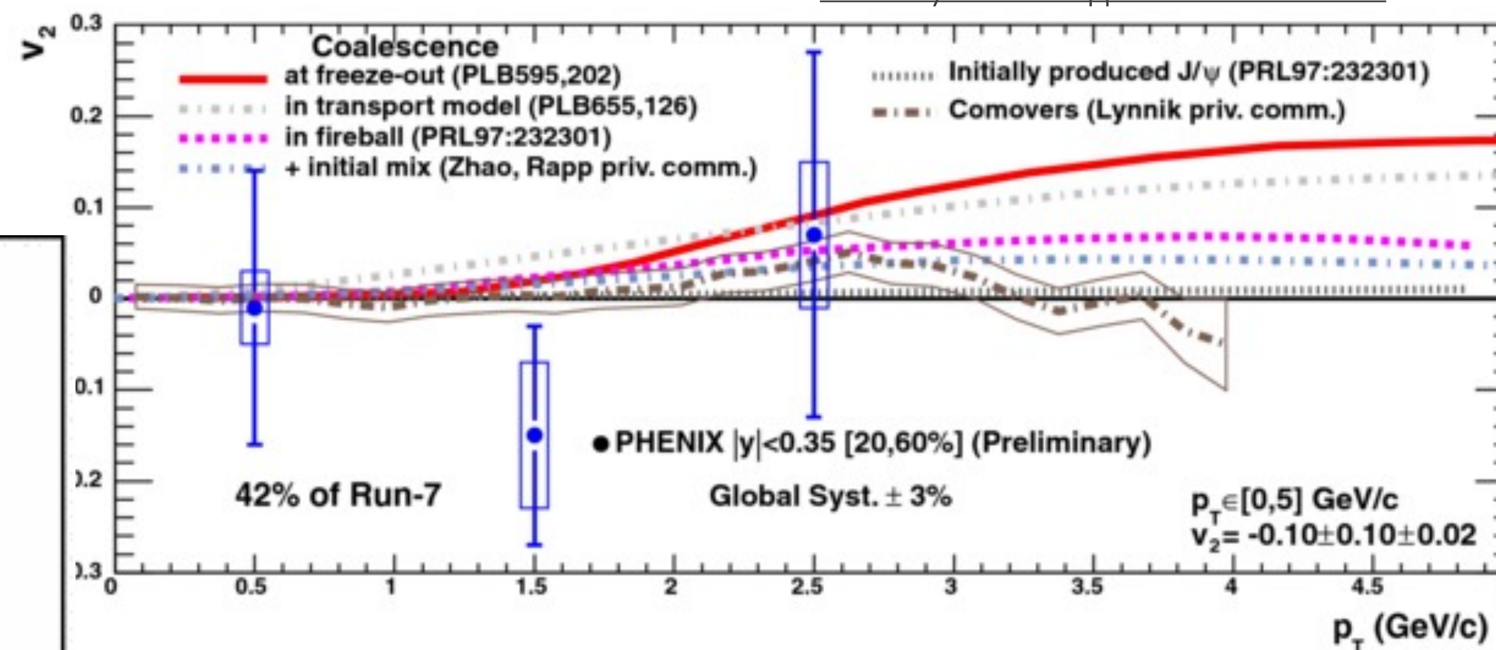
v_2 ~0 at RHIC energies

v_2 <0 at low p_T ?

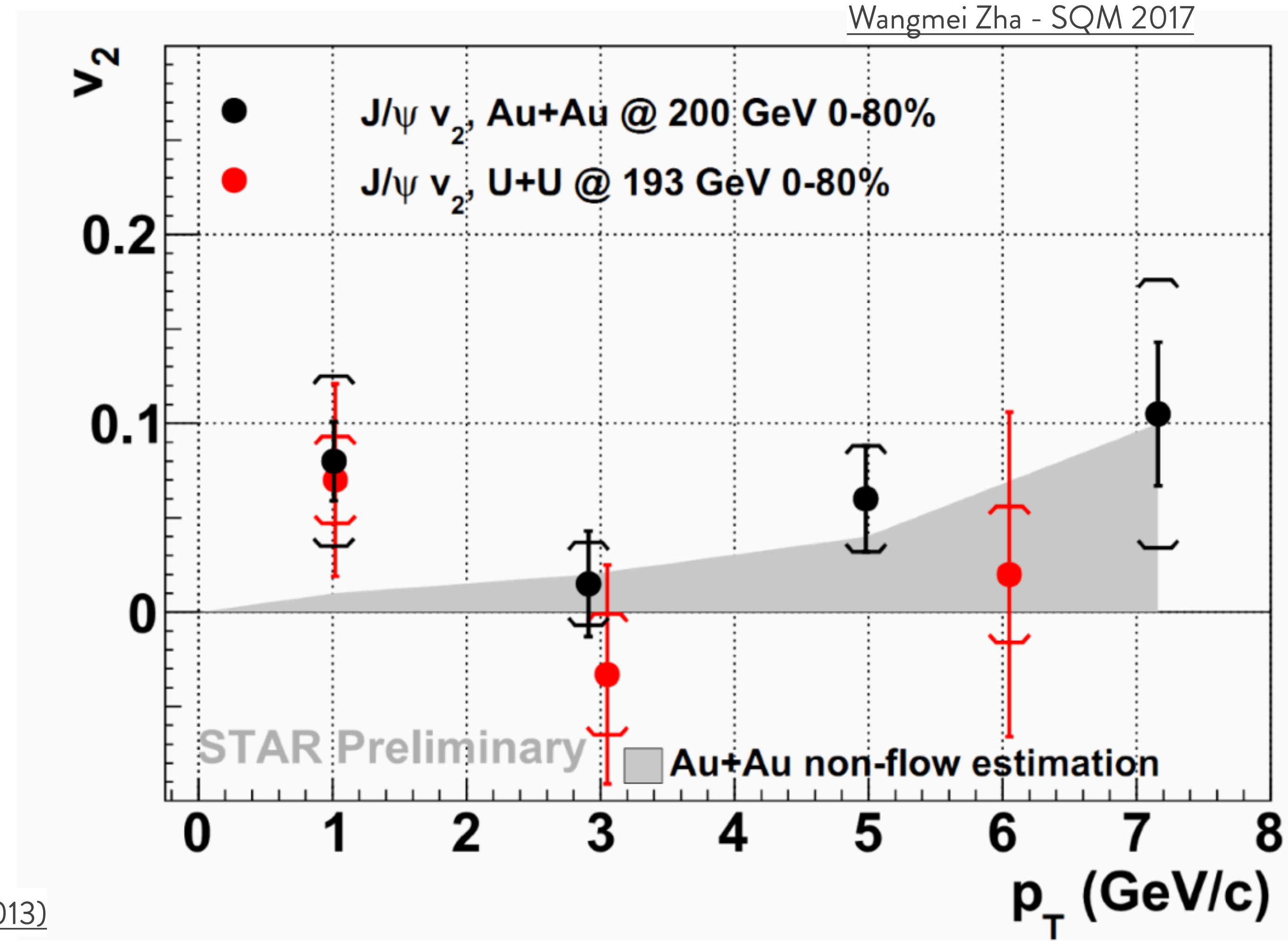


Phys. Rev. Lett. 111, 052301 (2013)

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



Wangmei Zha - SQM 2017



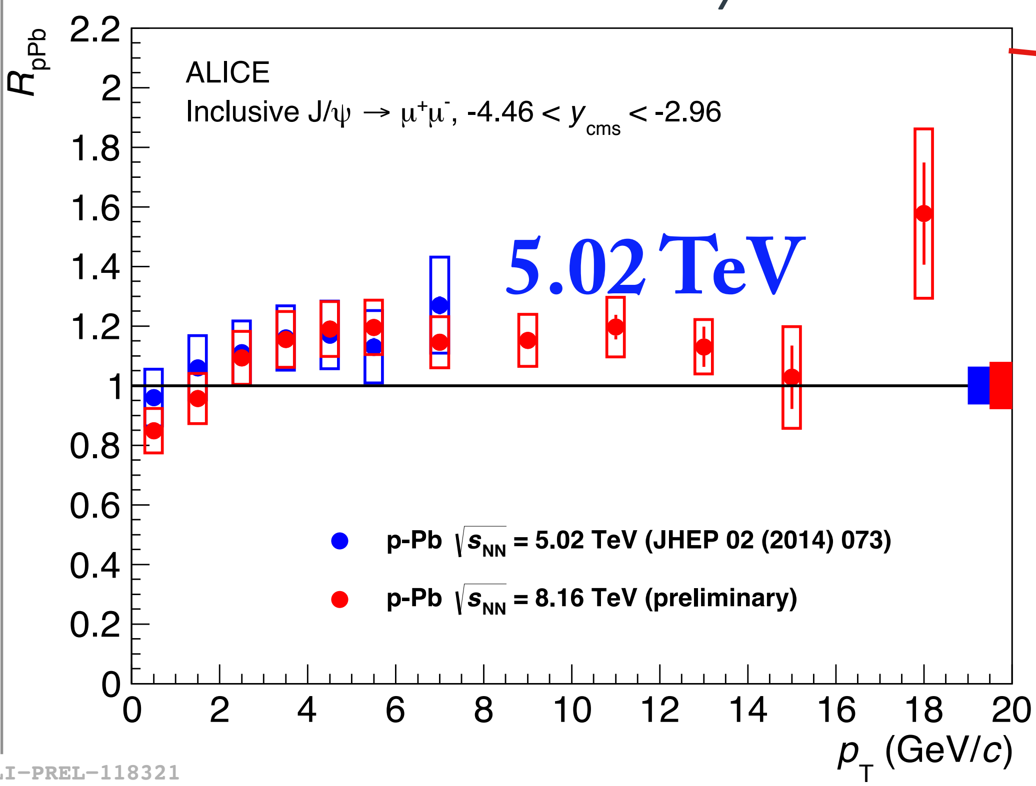
Cold nuclear matter effects on charmonium

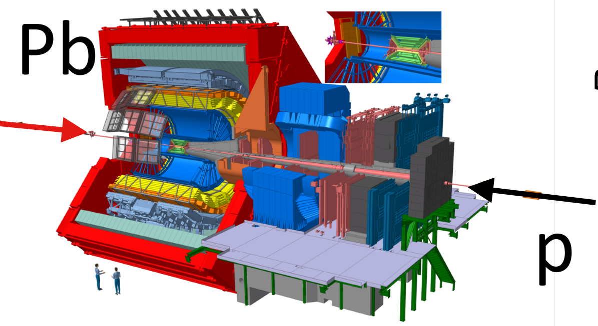
Outside hot matter mechanisms, other effects might affect quarkonium production

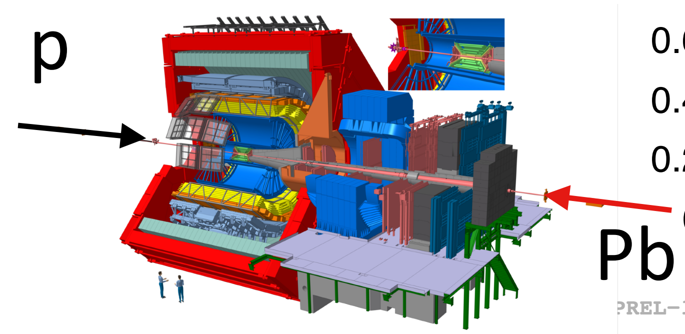
- Energy loss
- Initial state: nuclear parton shadowing/CG condensate
- Final state: nuclear absorption

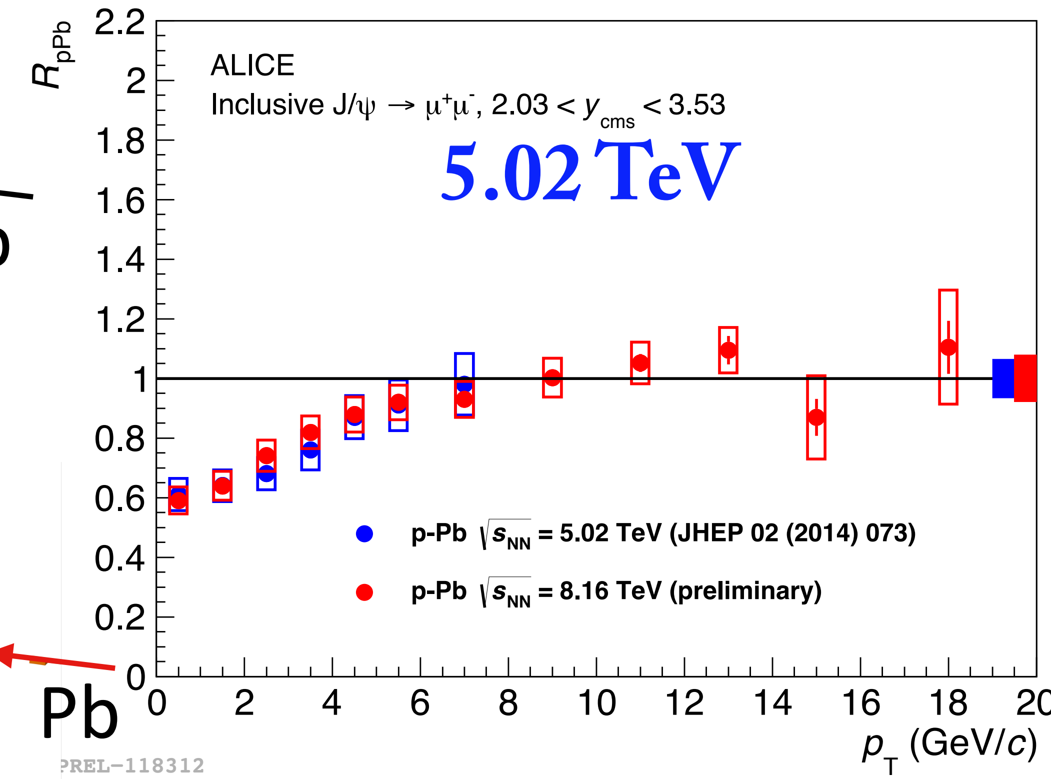
CNM investigated in p-A collisions

backward $-4.46 < y < -2.96$









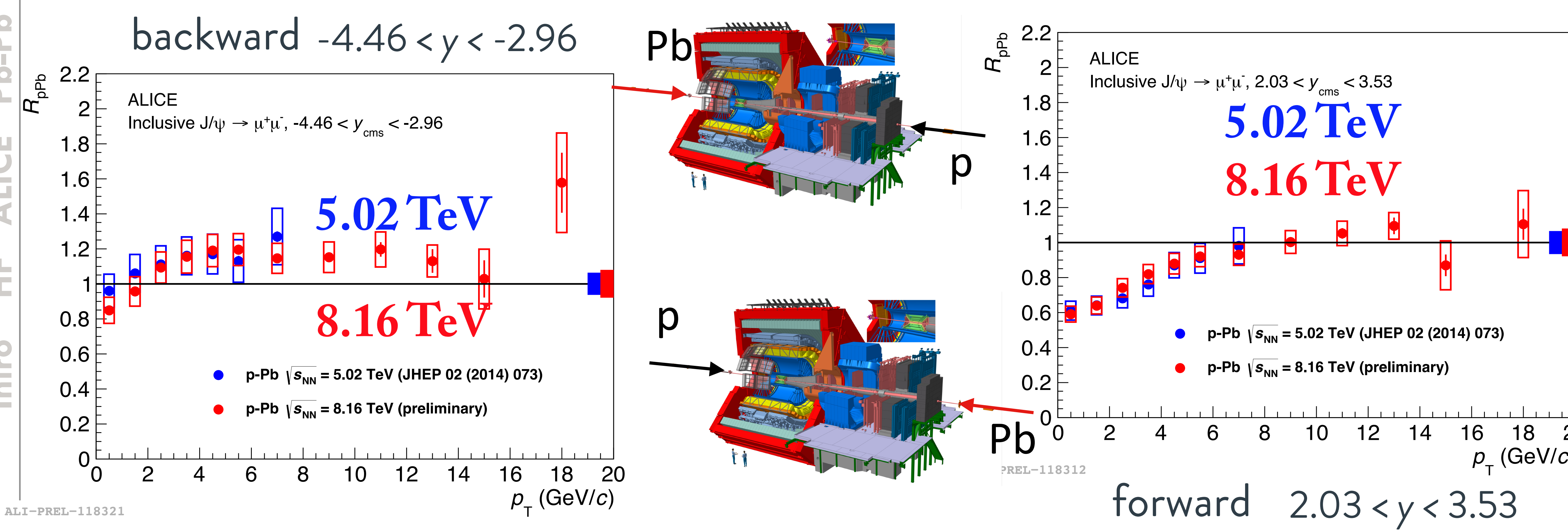
forward $2.03 < y < 3.53$

Cold nuclear matter effects on charmonium

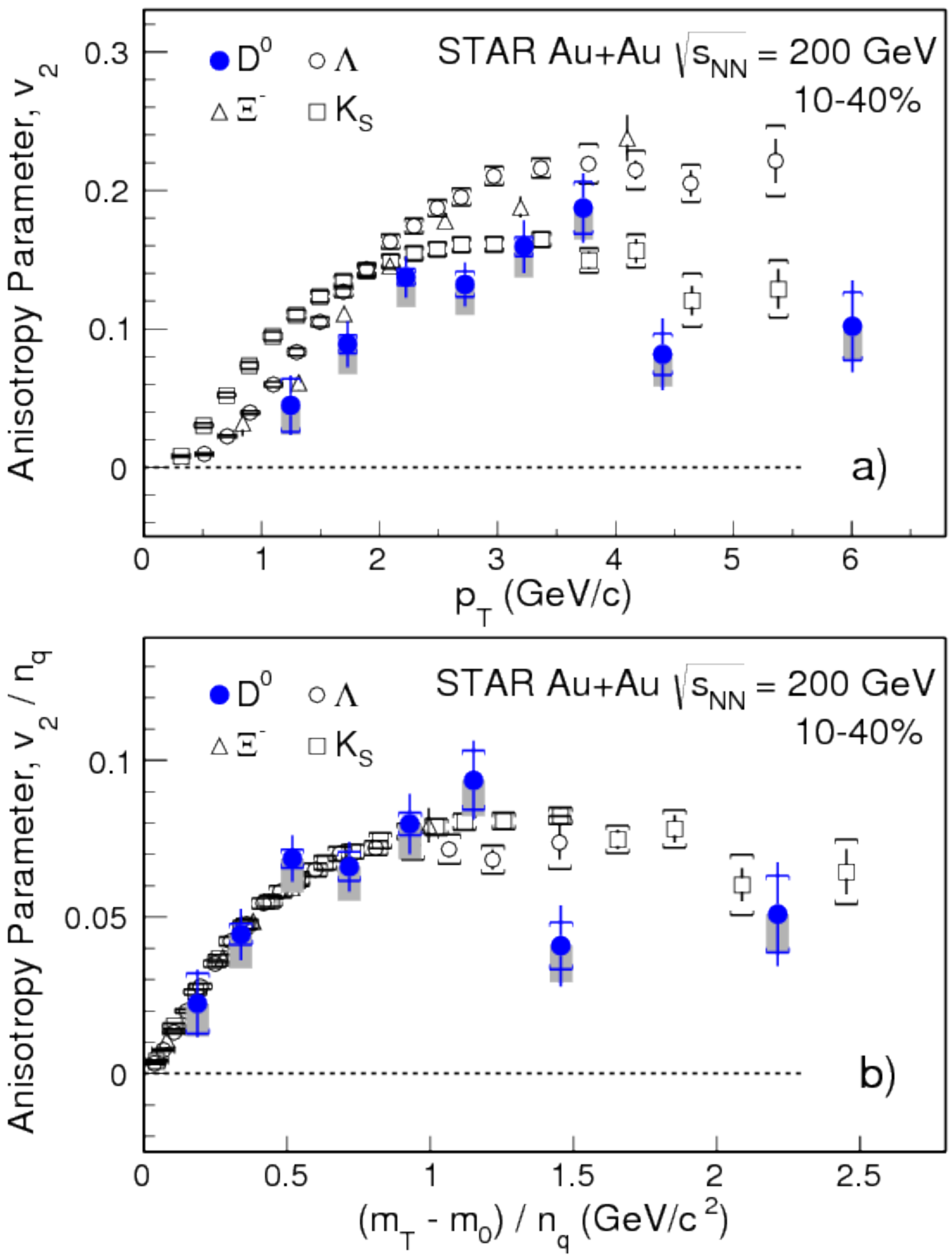
Outside hot matter mechanisms, other effects might affect quarkonium production

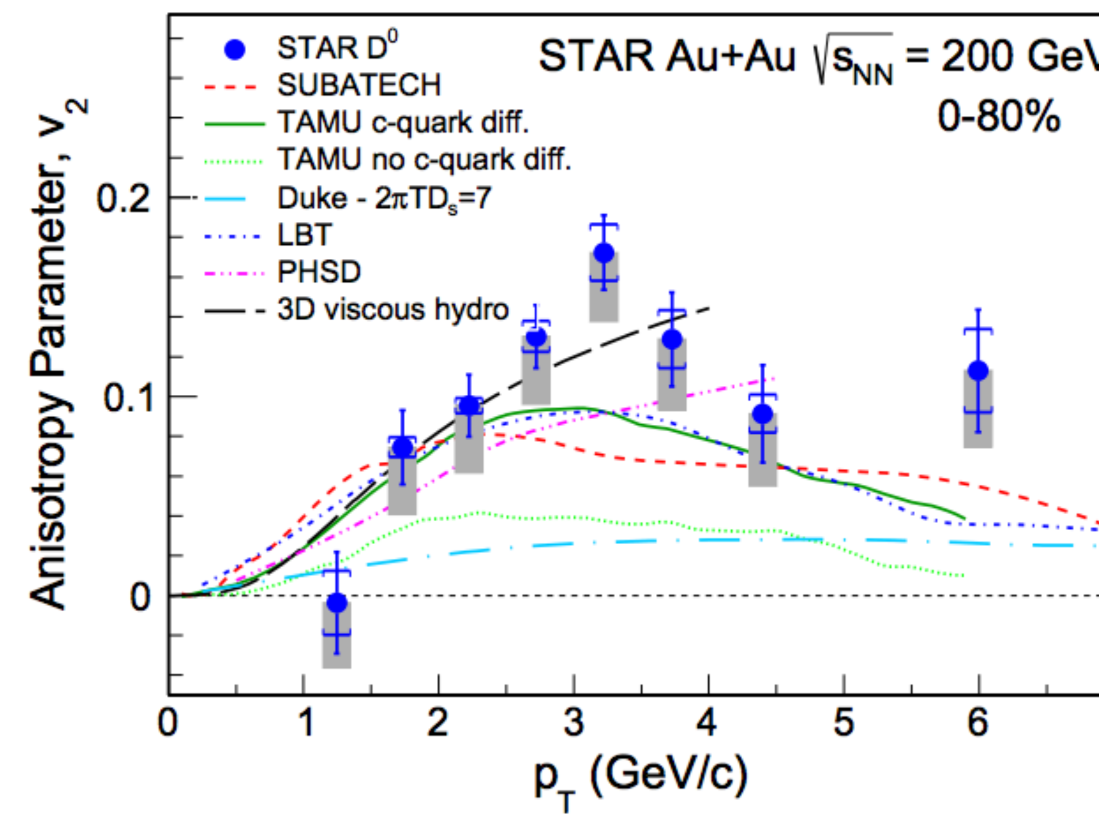
- Energy loss
- Initial state: nuclear parton shadowing/CG condensate
- Final state: nuclear absorption

CNM investigated in p-A collisions



D meson flow at RHIC



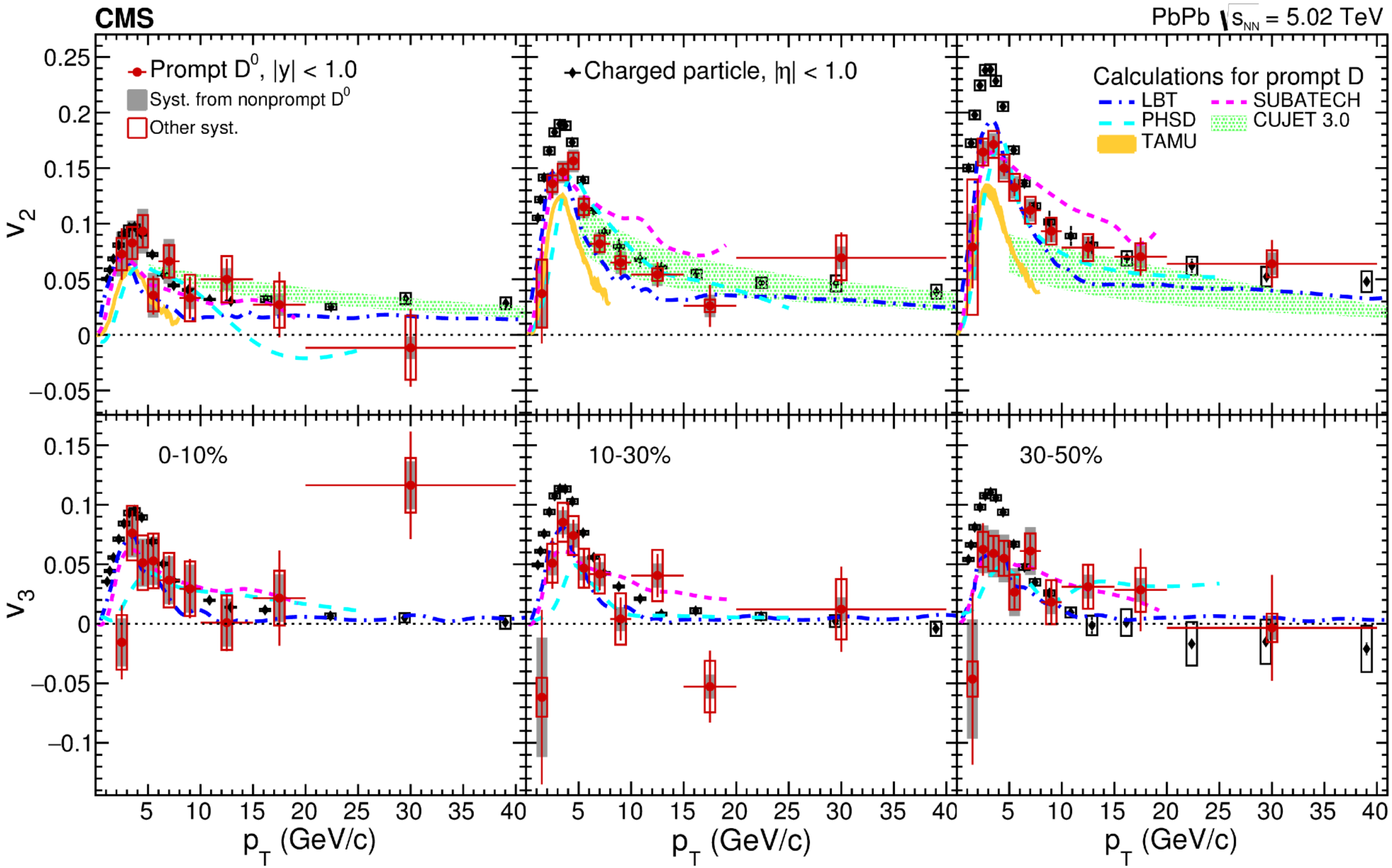


Clear mass ordering below 2 Gev/c

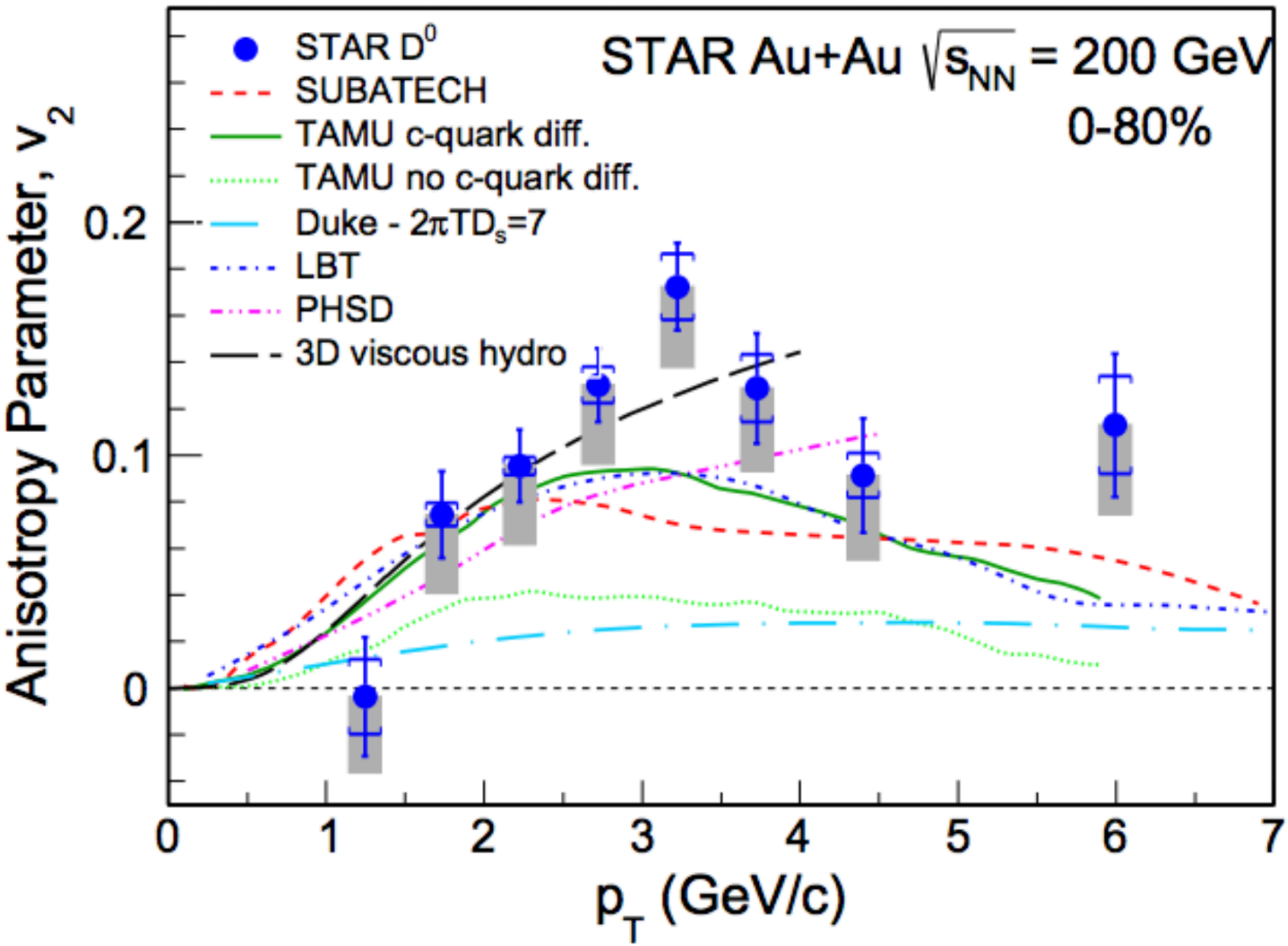
Scales with NCQ, following same trend as light hadrons

CMS measurement of prompt D^0 v_2 at 5.02 TeV

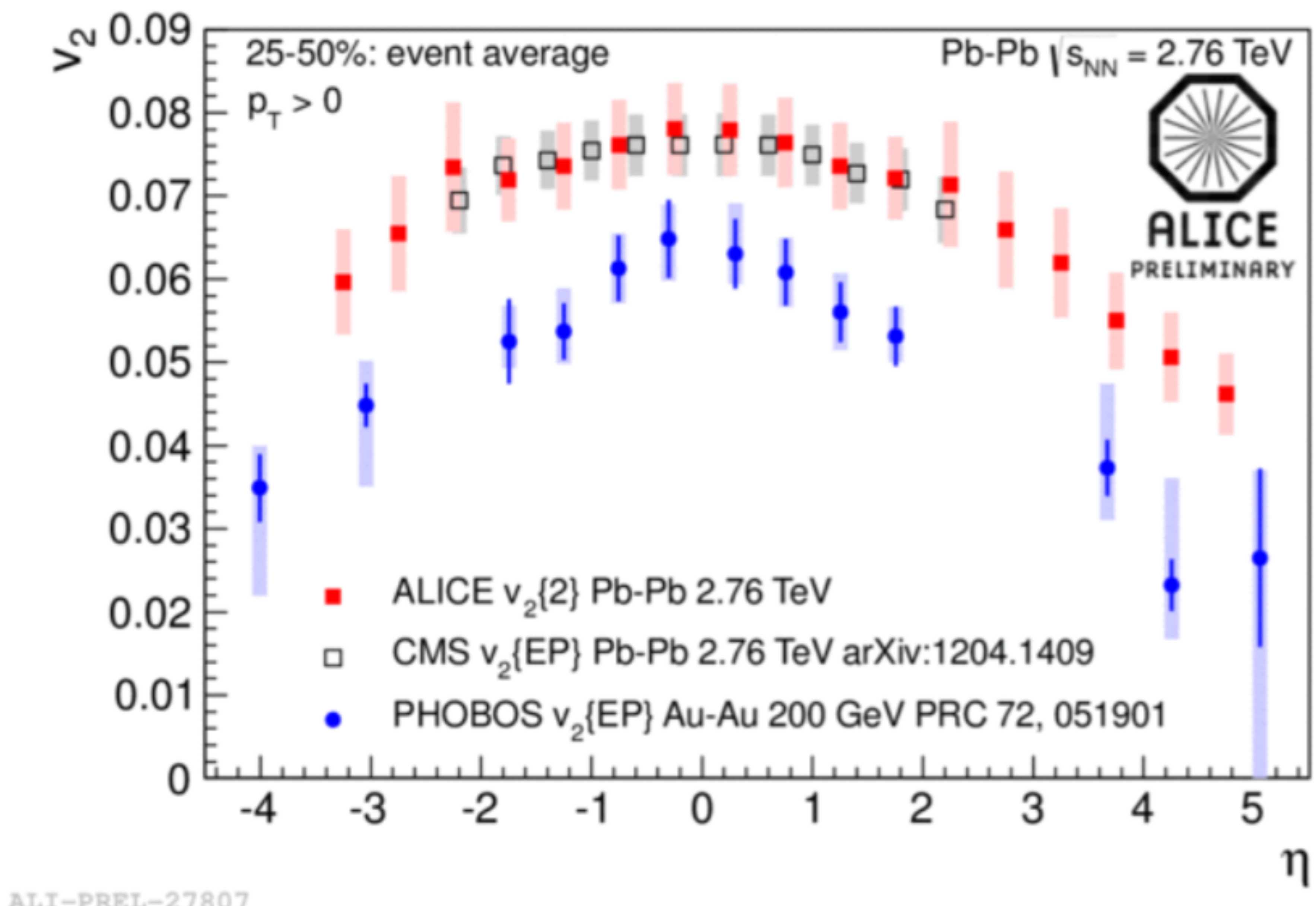
ALICE



STAR measurement of prompt D^0 v_2 at 200 GeV



Pseudo-rapidity dependency



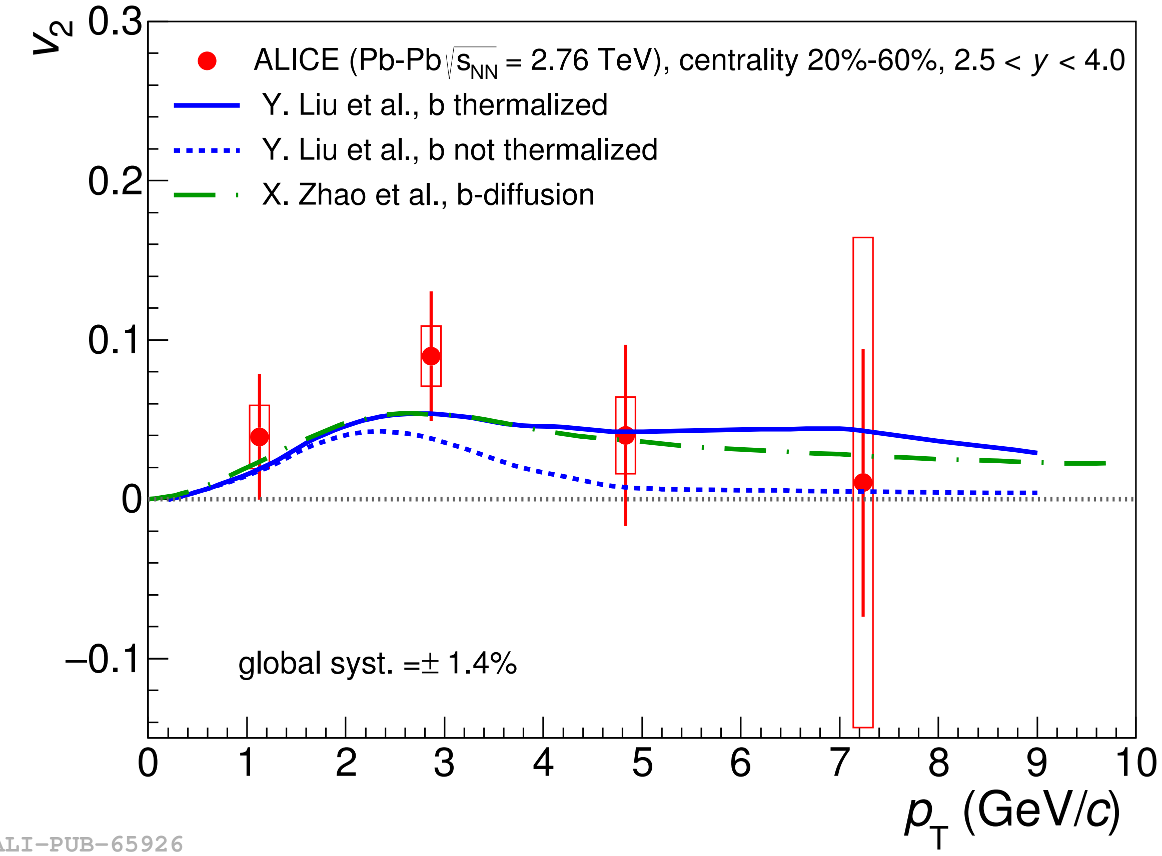
- depends on particle multiplicity

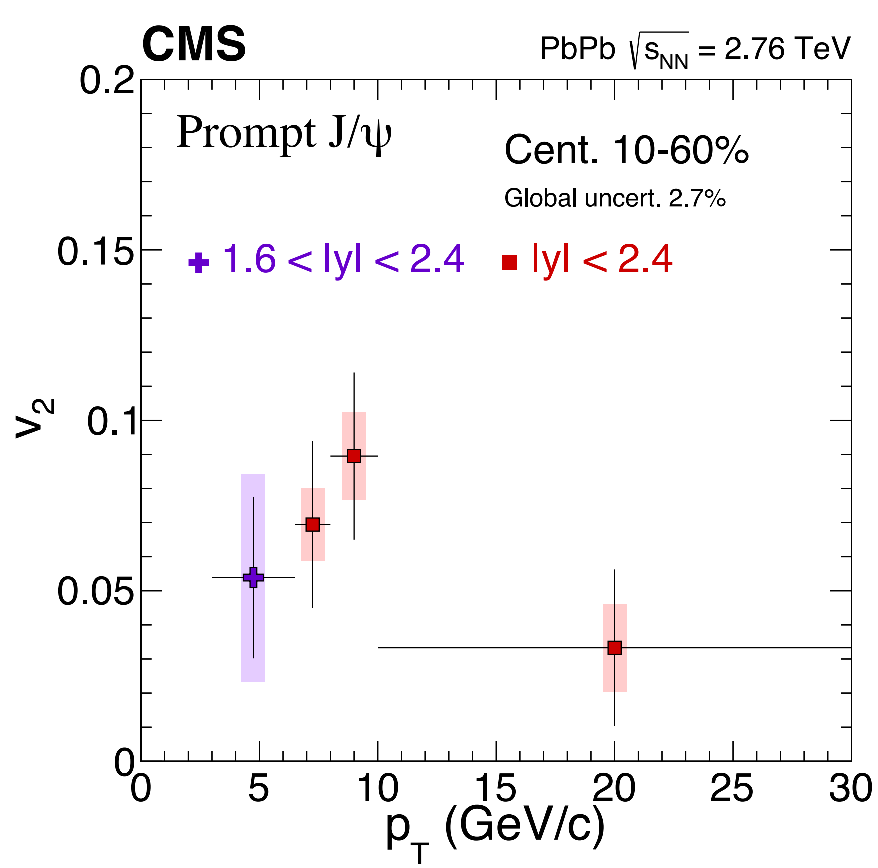
J/ψ v_2 at $\sqrt{s_{NN}}$ = 2.76TeV

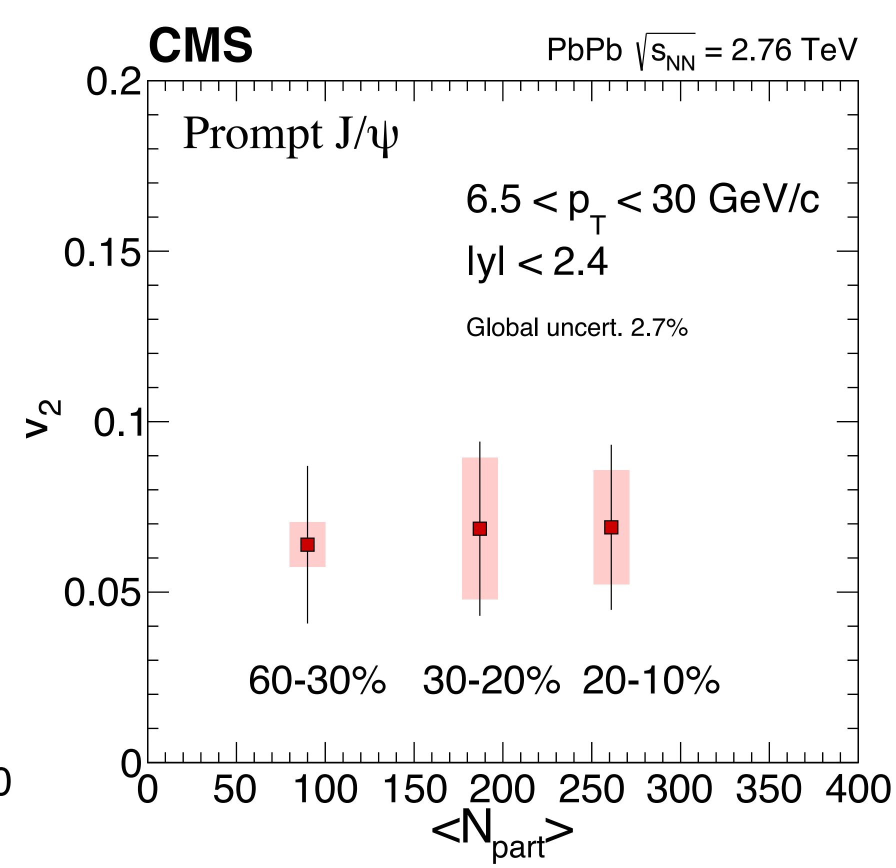
First hint of J/ψ v_2

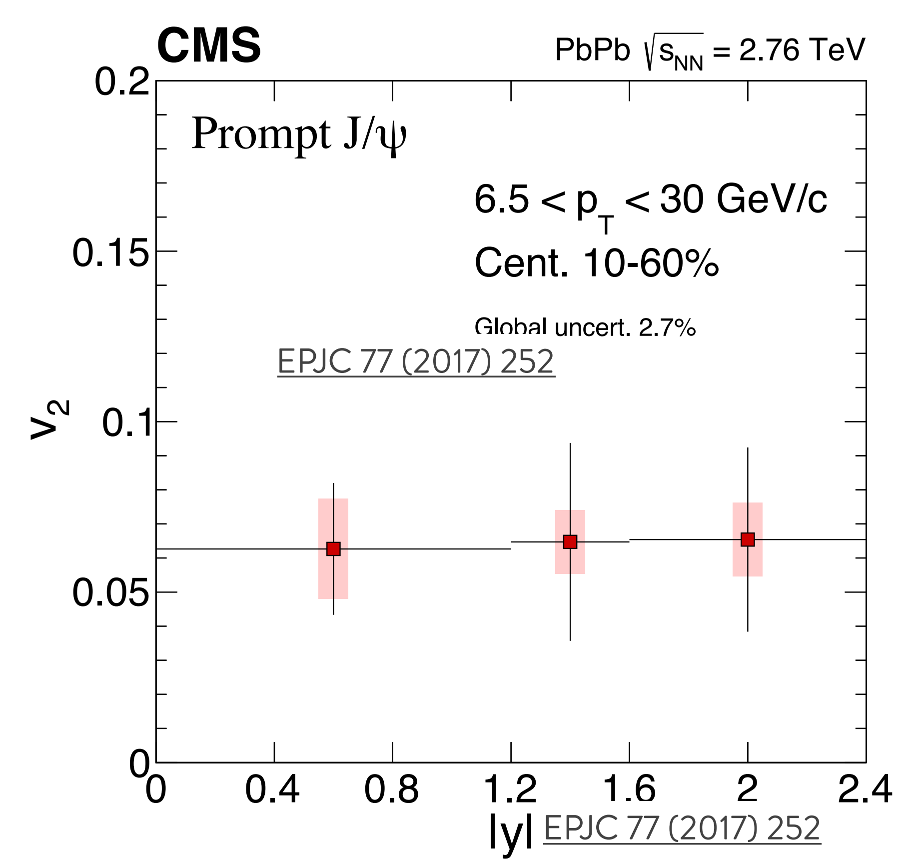
measured by both **CMS and ALICE**

➡ different kinematic regions !

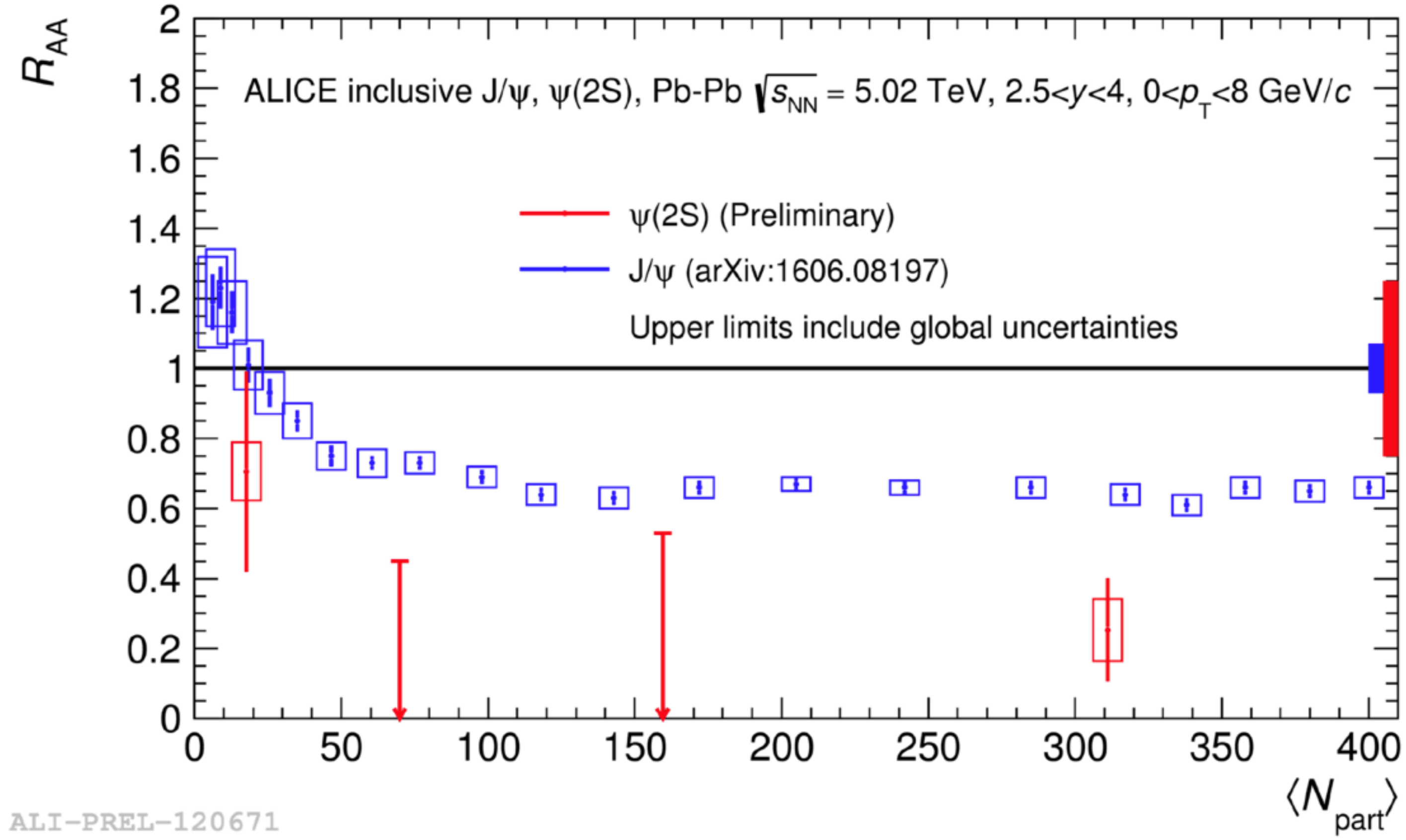


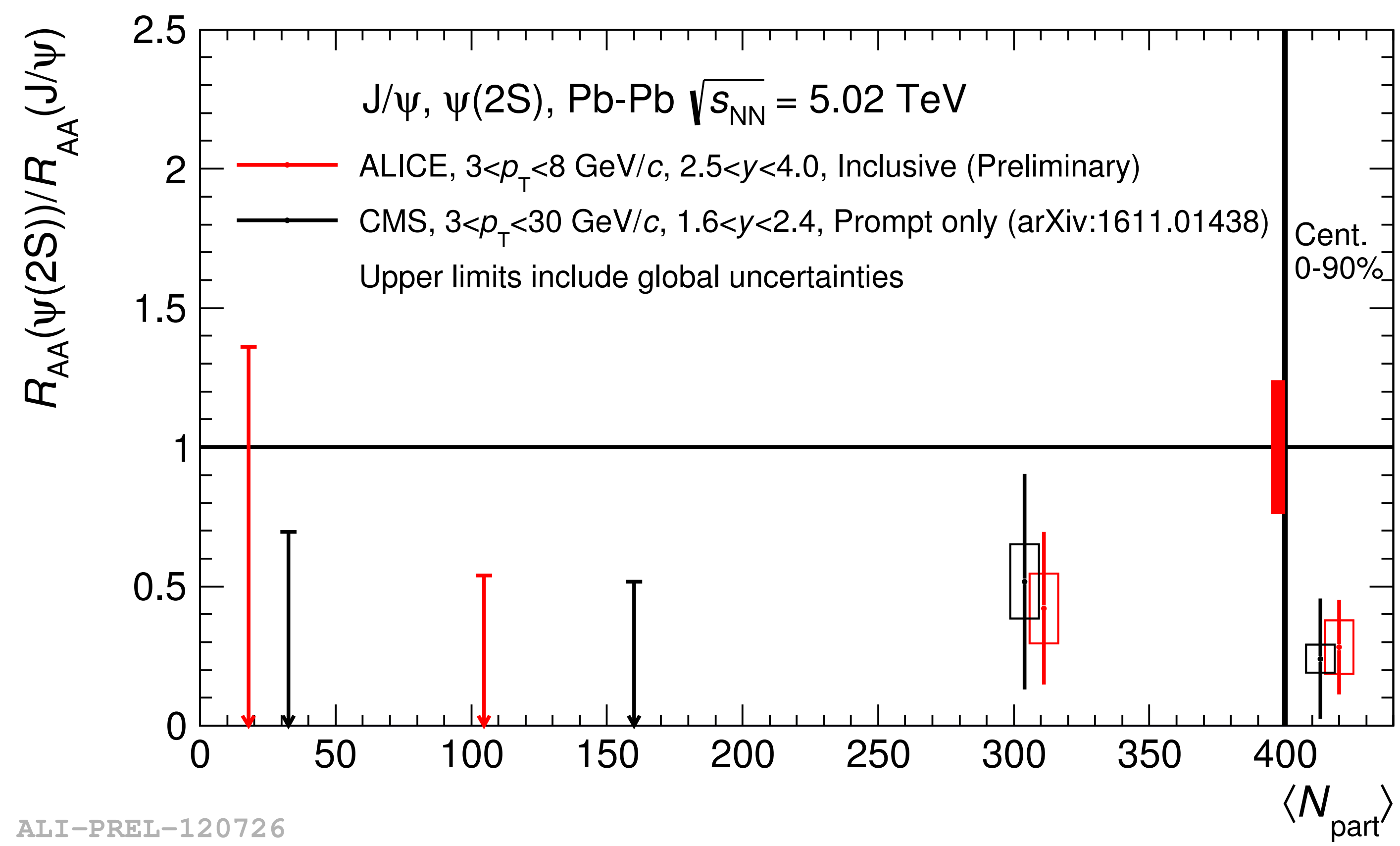






Charmonium in the QGP





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

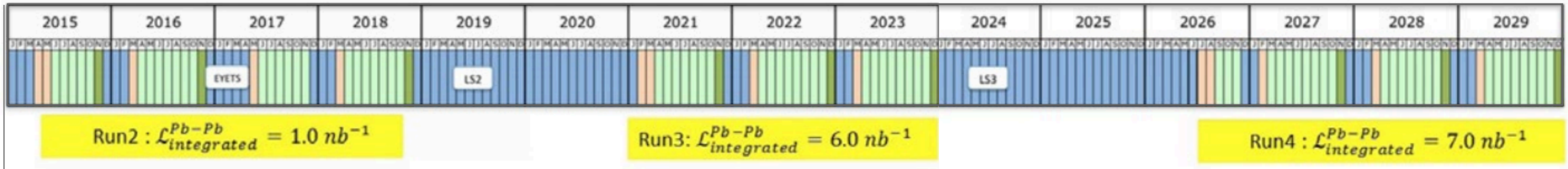
ψ(2S)/J/ψ should greatly help model discrimination

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

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

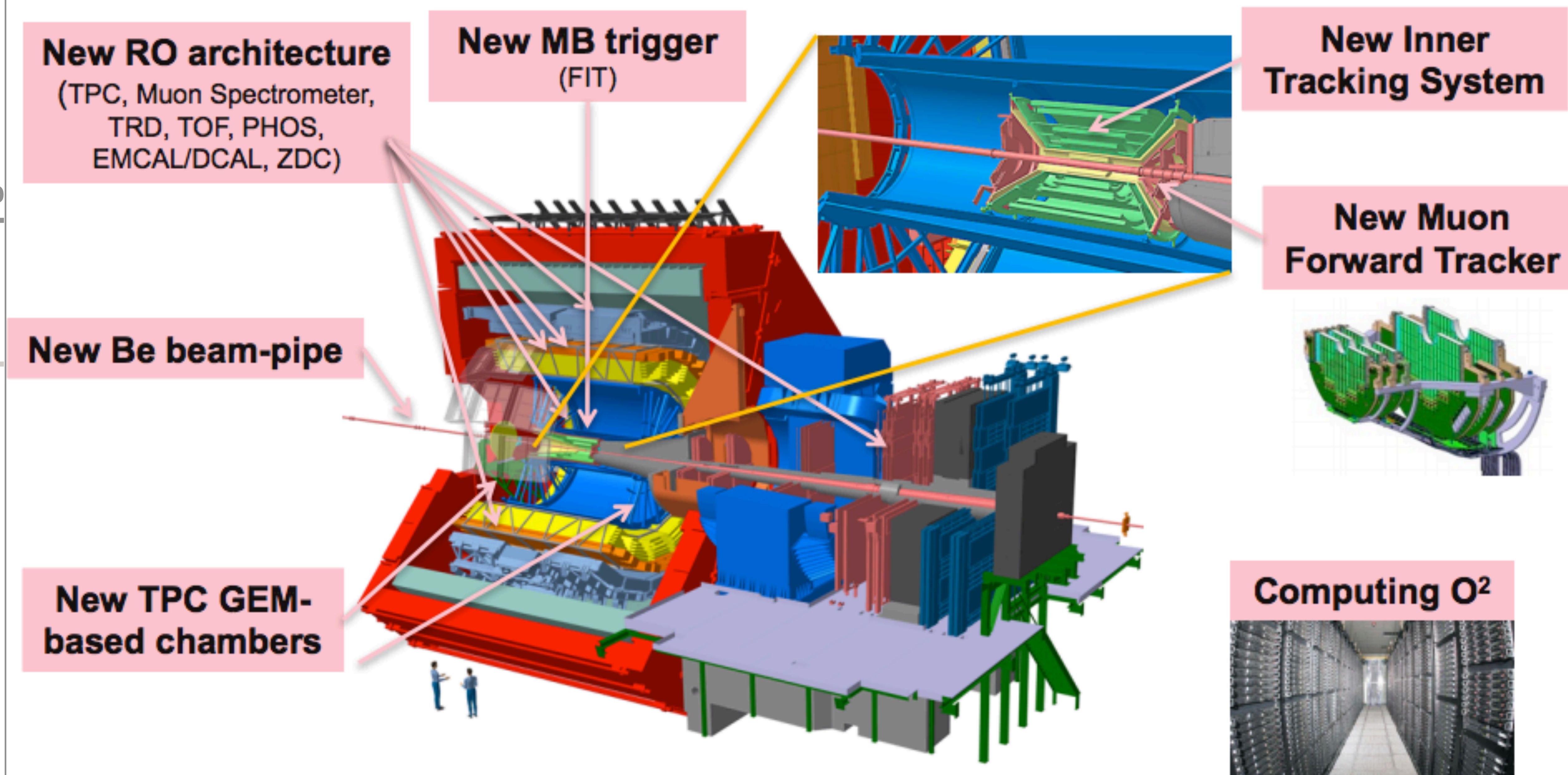
- PbPb 50kHz
- New read-out electronics
- New TPC GEM chambers
- New computing system
- Inner tracker (ITS) upgrade
- New forward tracker (MFT)
- New forward calo (2024)?

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

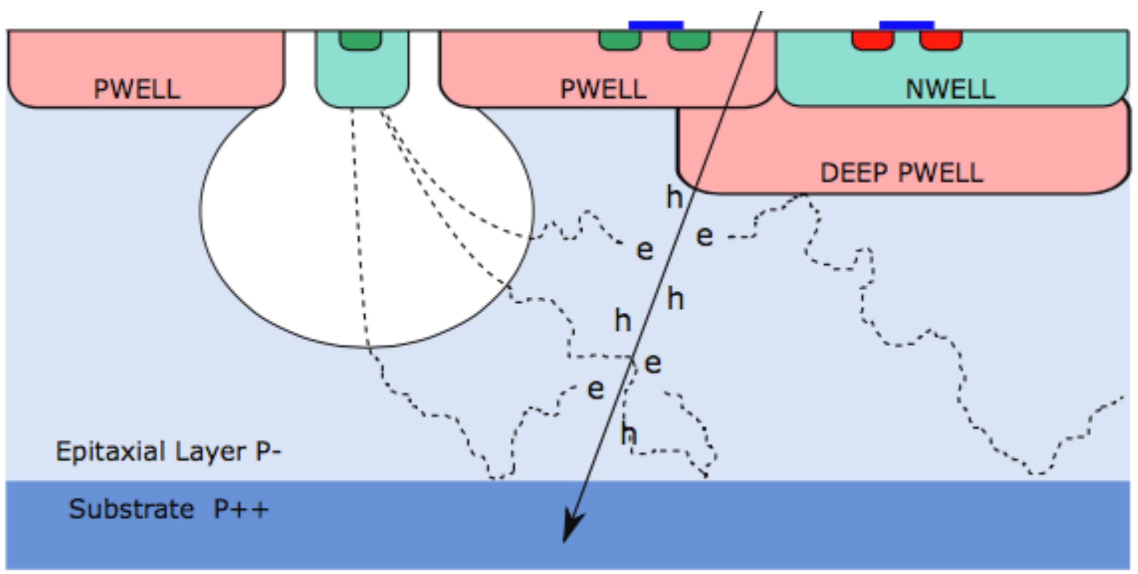
CMOS Monolithic Active Sensors (MAPS), TowerJazz 0.18 μm technology

Sensor size: 15mm x 30mm

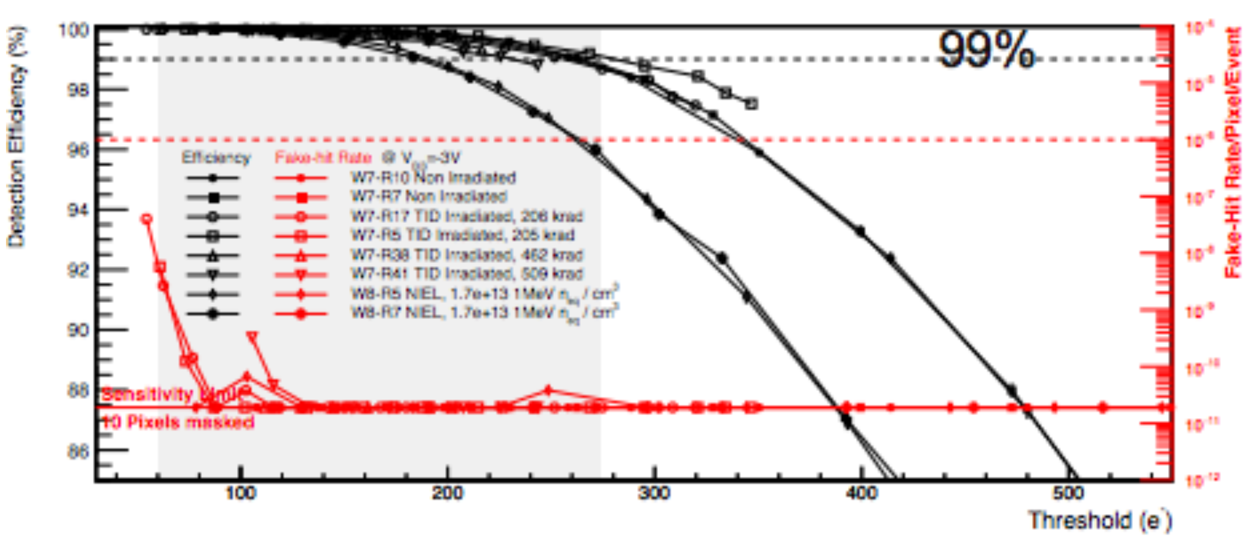
Pixel size: 29 μm x 27 μm

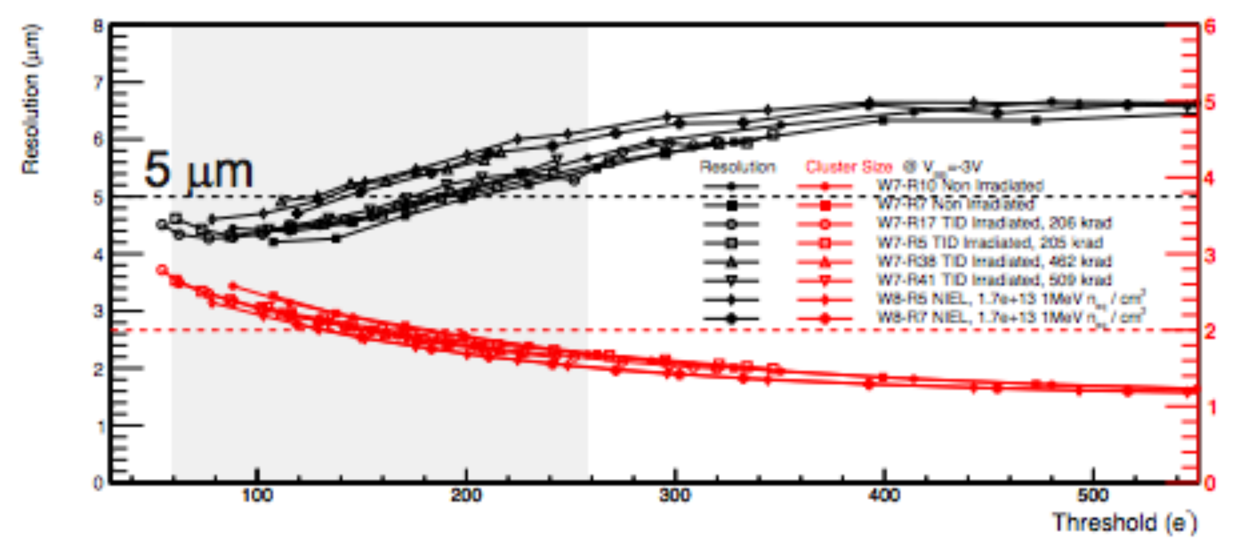
high resistivity (>1kΩ cm) epitaxial layer

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

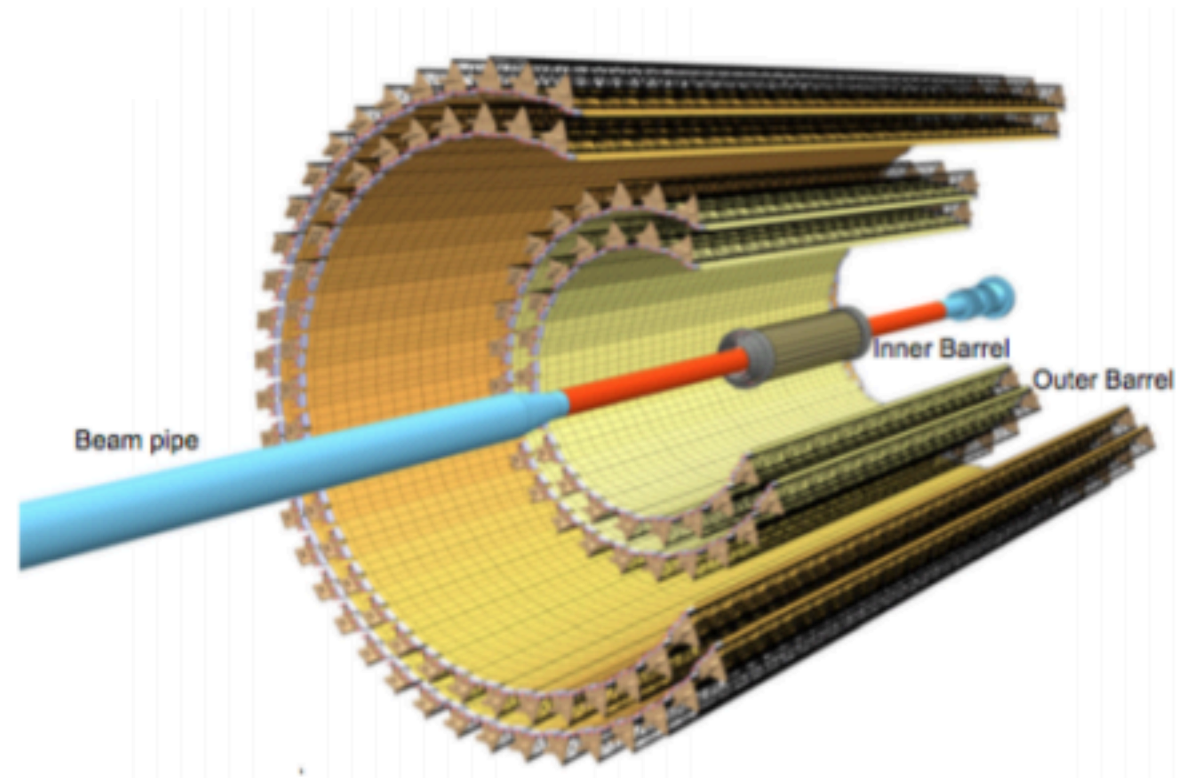
- Large area (10 m^2) tracker made of monolithic active silicon pixel sensors

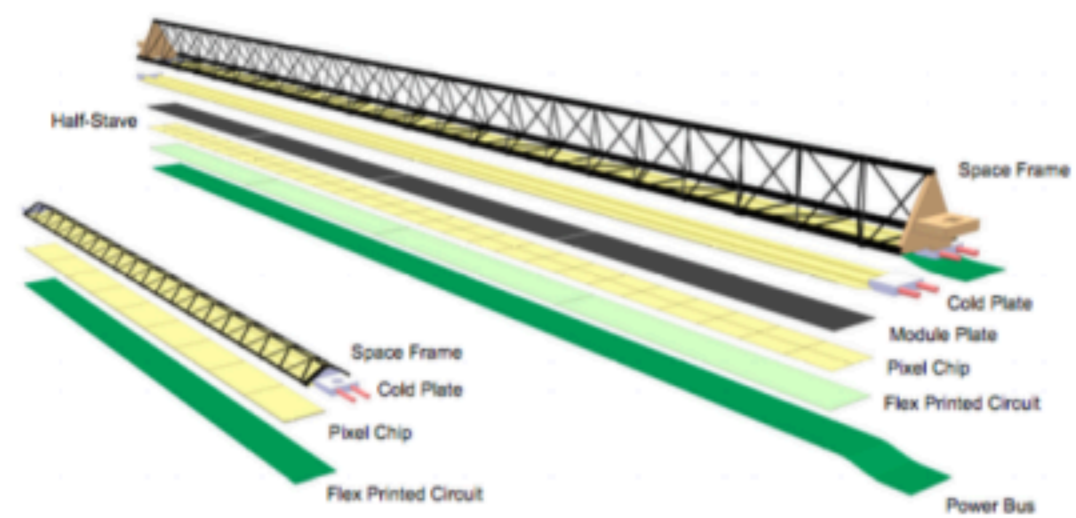
- 7 layers from R=22mm to R=400mm Inner Barrel, Outer Barrel (Middle layers & Outer layers)

- Spatial resolution 0(5 μm)

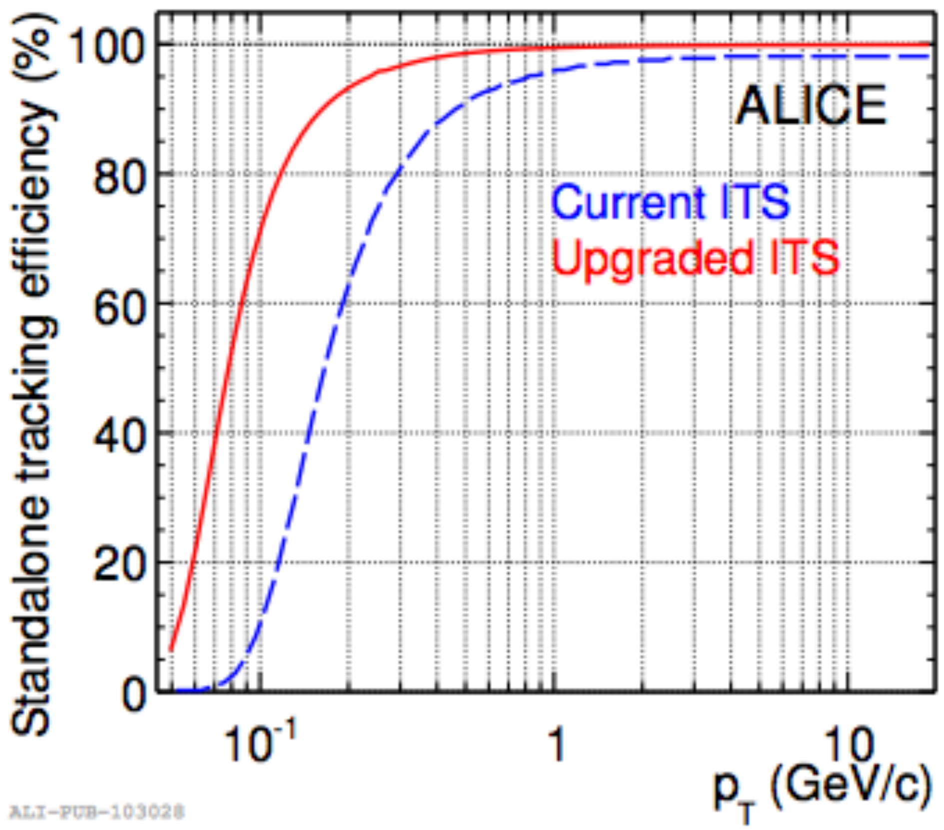
- First layer closer to IP (smaller beam pipe radius)

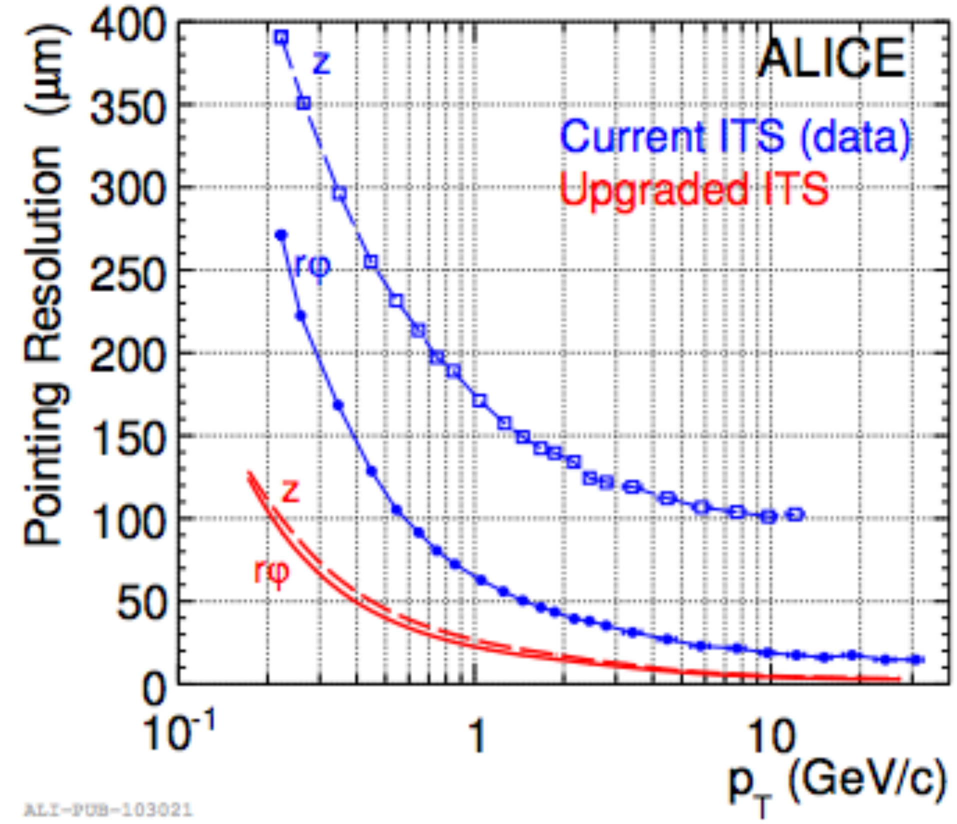
- 0.3%X_0 per layer in the inner most 3 layers (light mechanical structure)



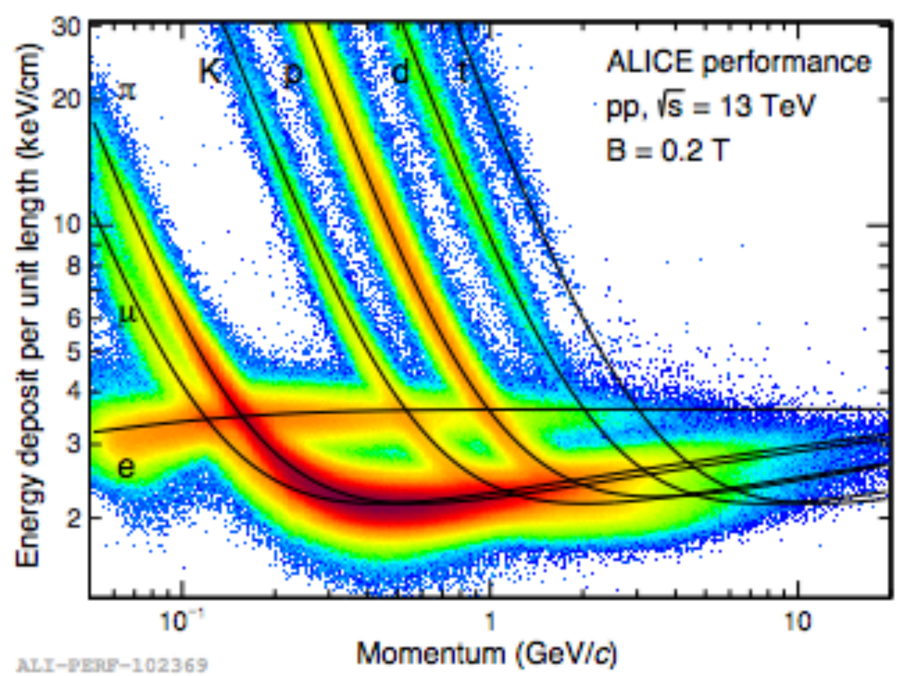


ITS upgraded performance





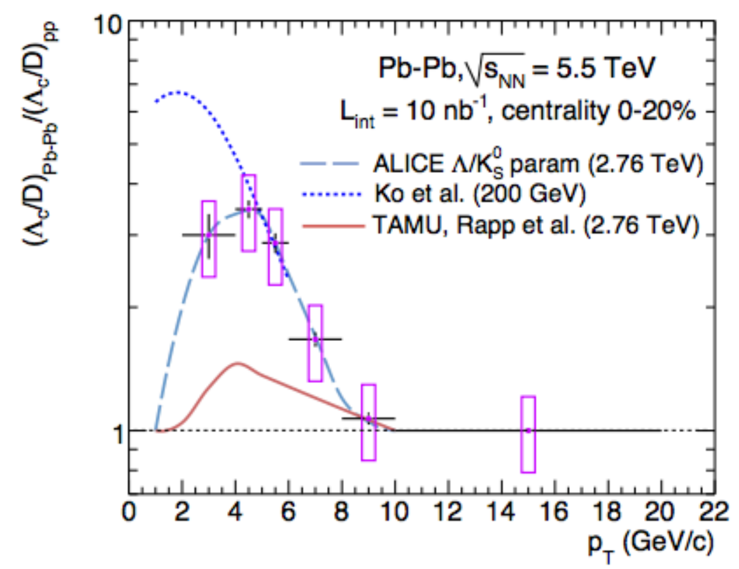
Improved efficiency and resolution (mostly at low p_T)

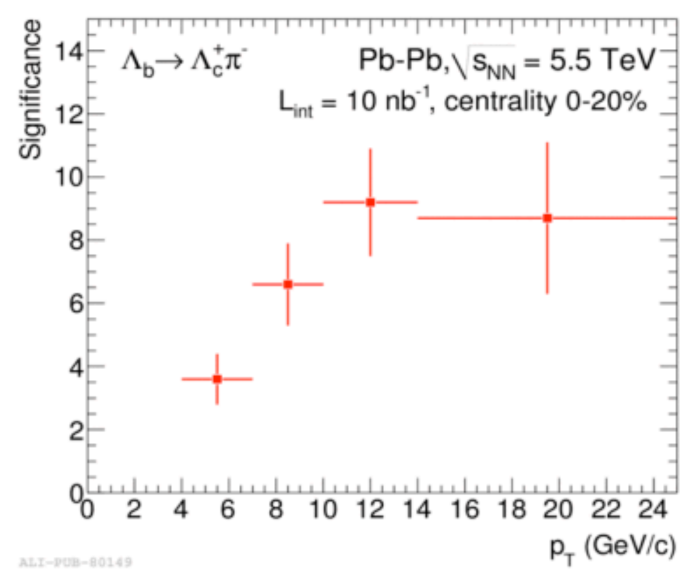


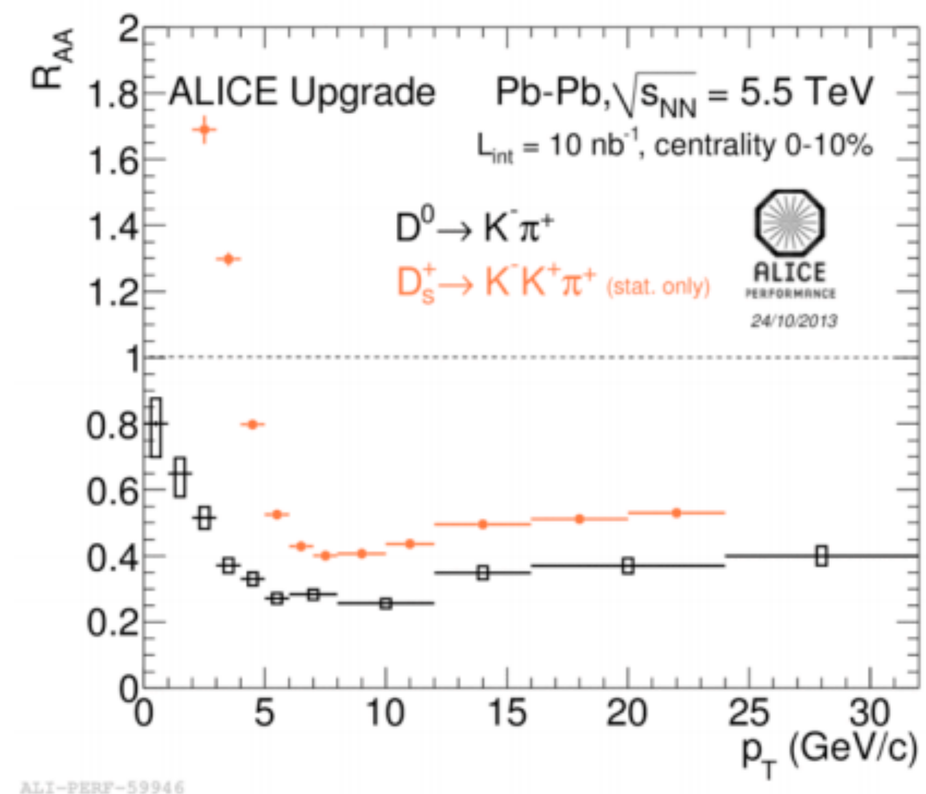
Keep particle identification performances

Upgrade expectations for open HF

Charmed and Beauty baryons $|\eta|<0.9$

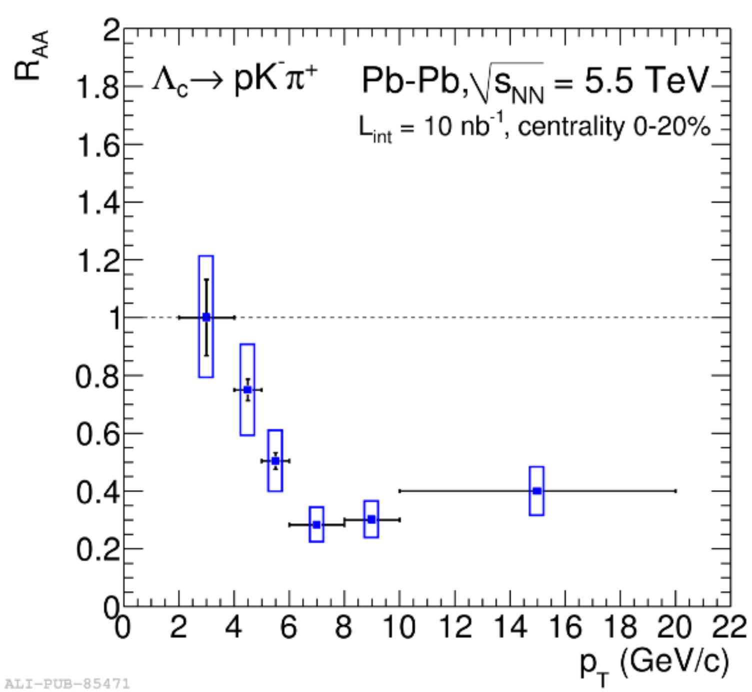


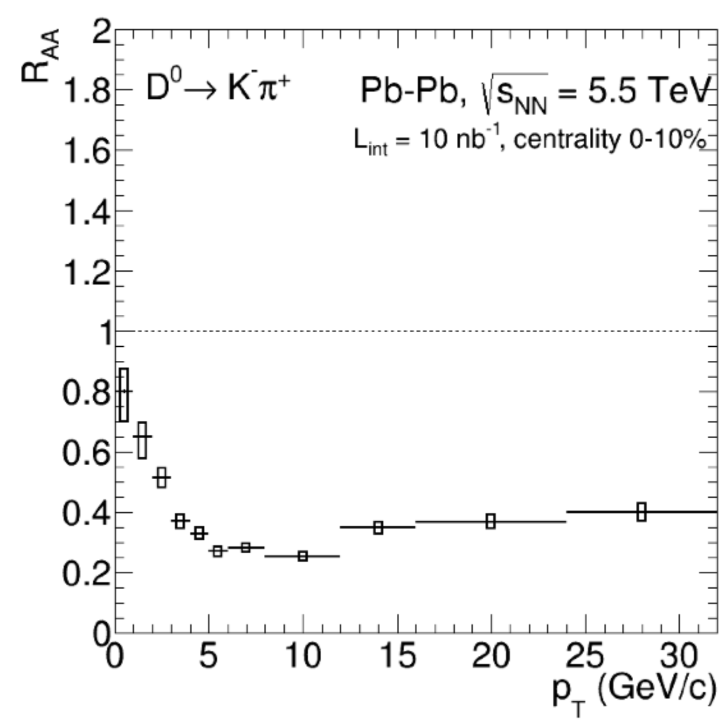


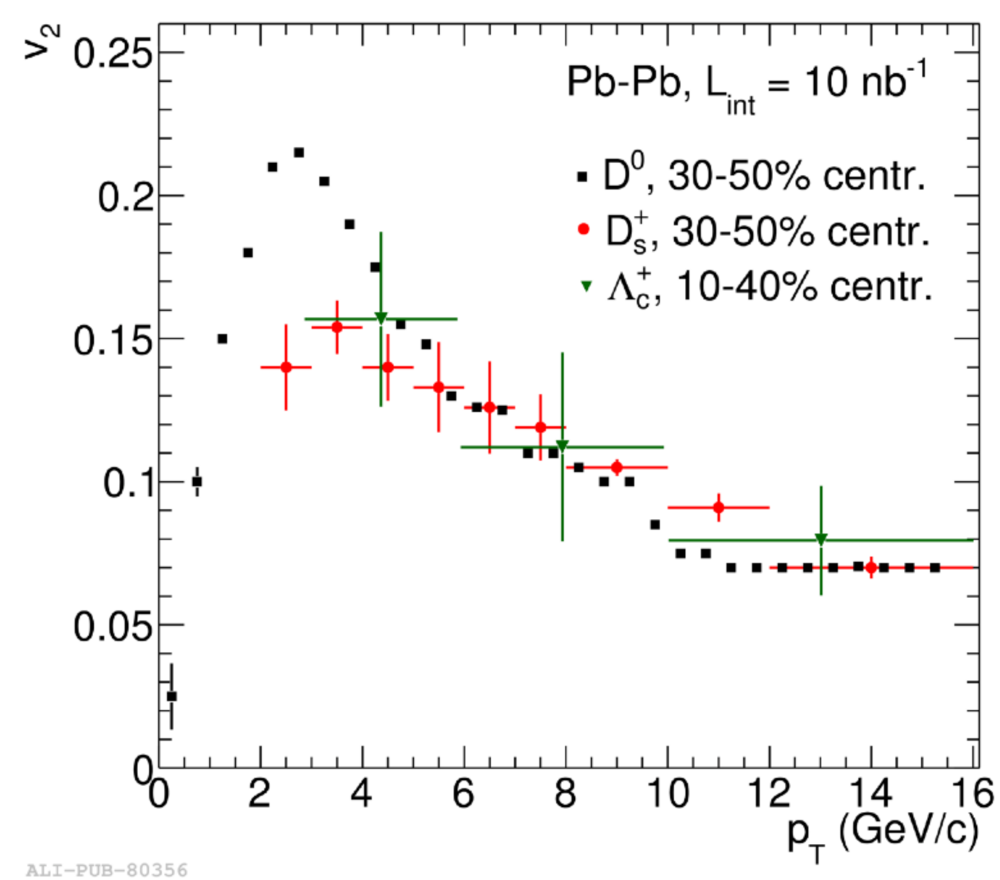


New observables in Pb-Pb: baryon production in the charm and beauty sector!

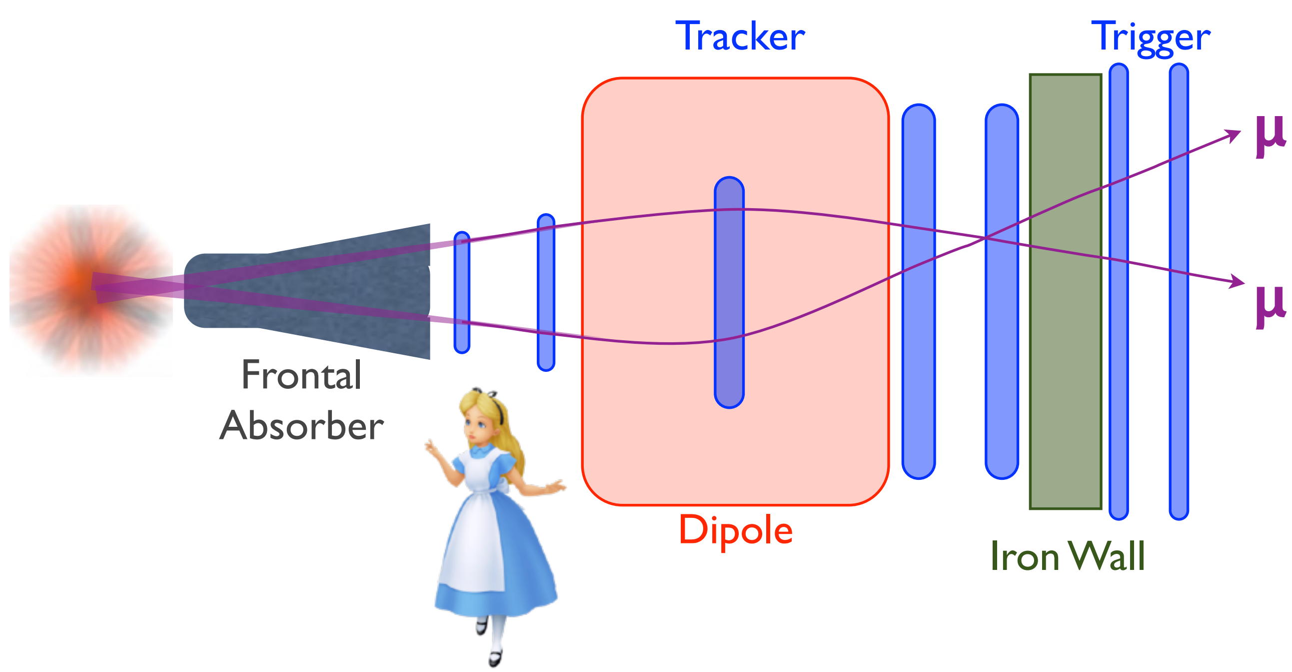
For the moment, only observed in pp and p-Pb collisions: https://arxiv.org/abs/1712.09581



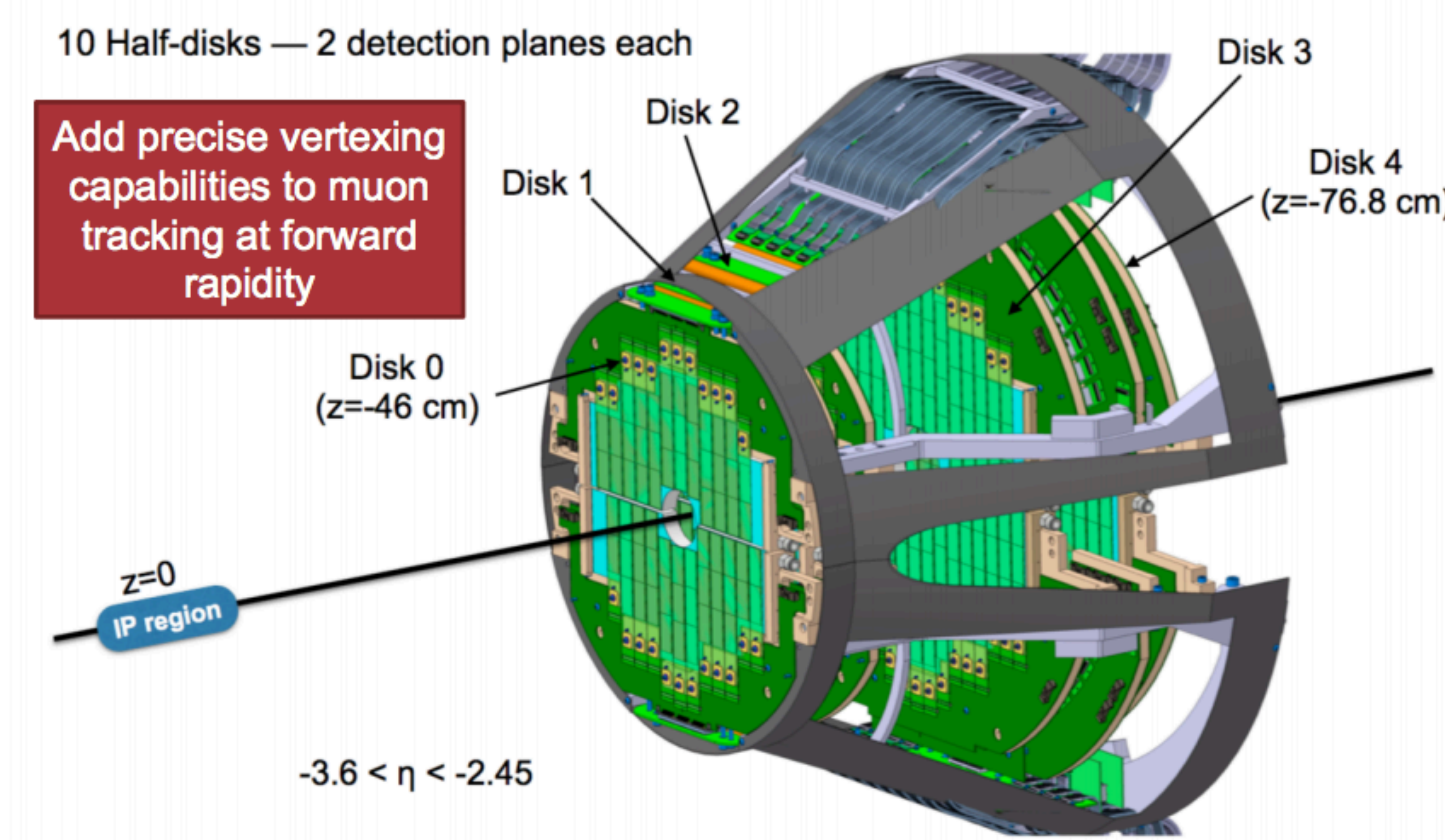




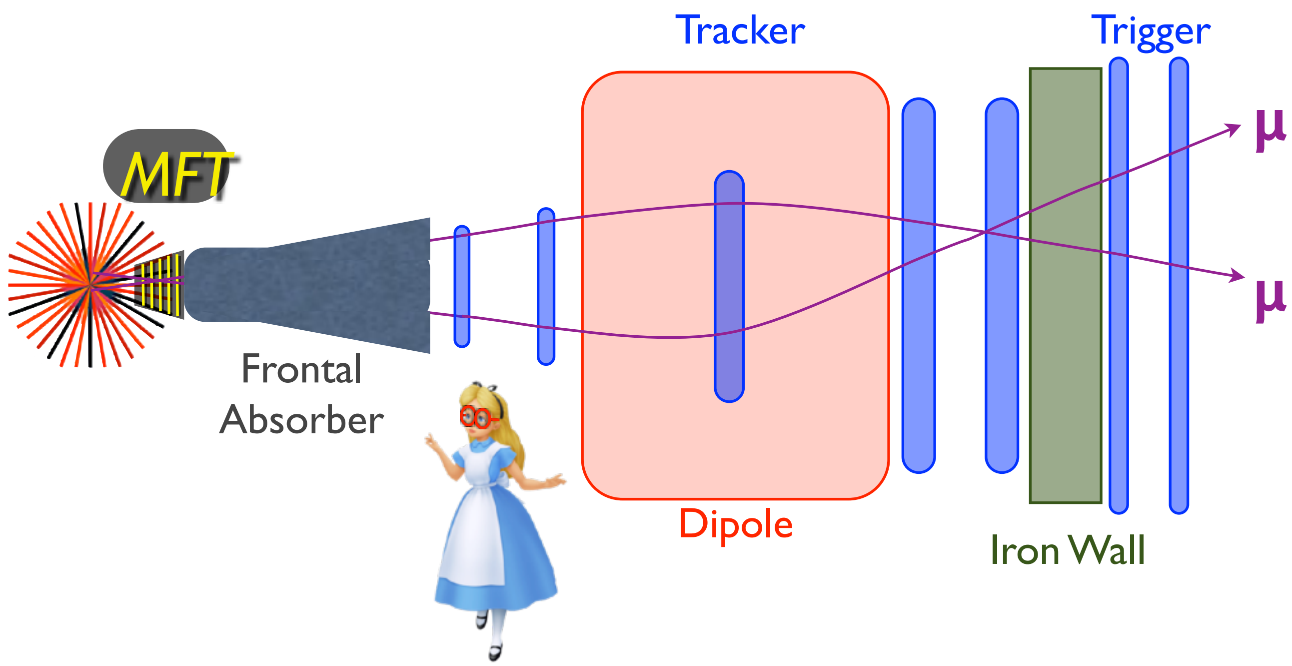
The MFT upgrade



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



The MFT upgrade



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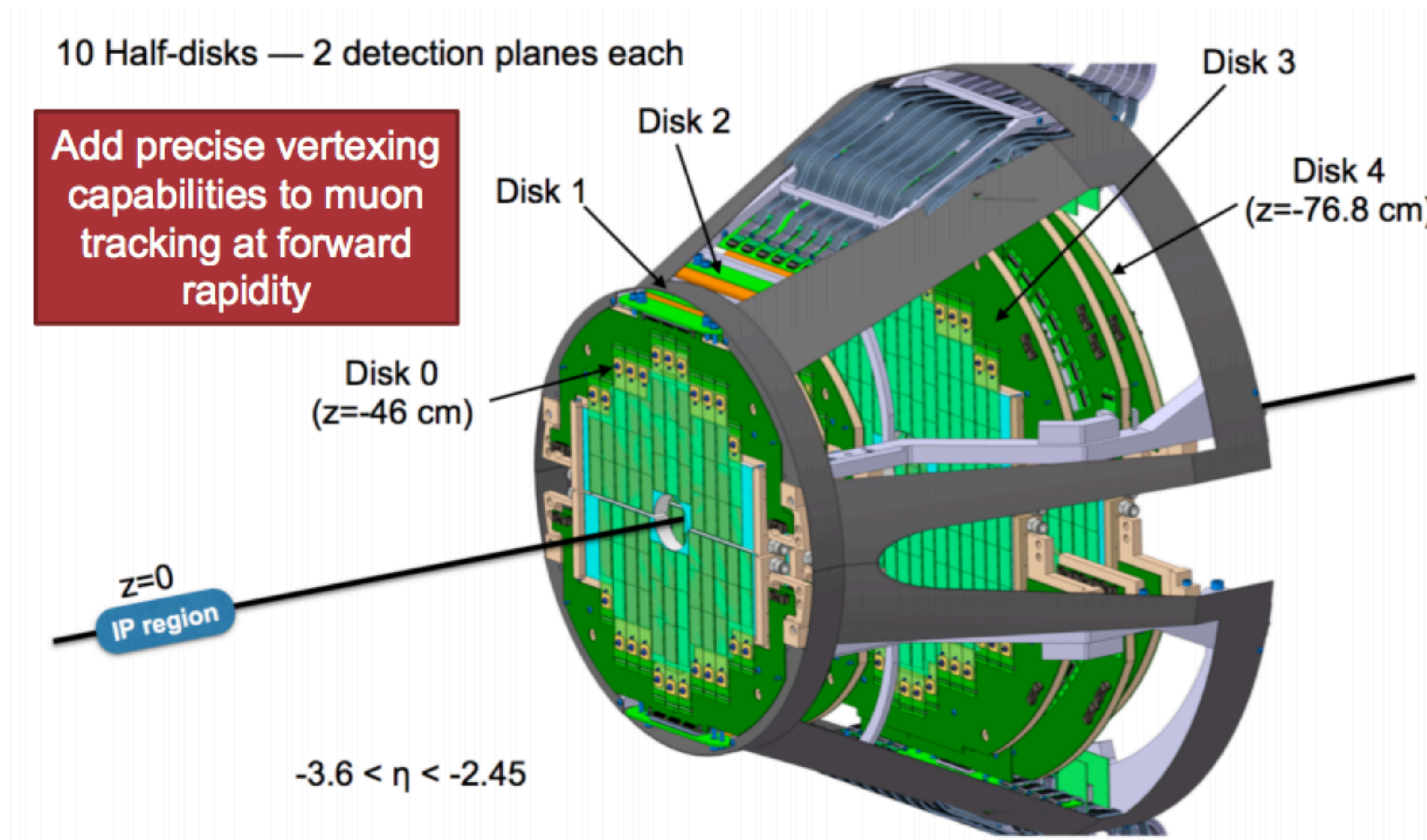

Upgrade expectations for quarkonium

Prompt charmonium

Beauty measurement via displaced J/ψ

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