QM2017:重クォーク

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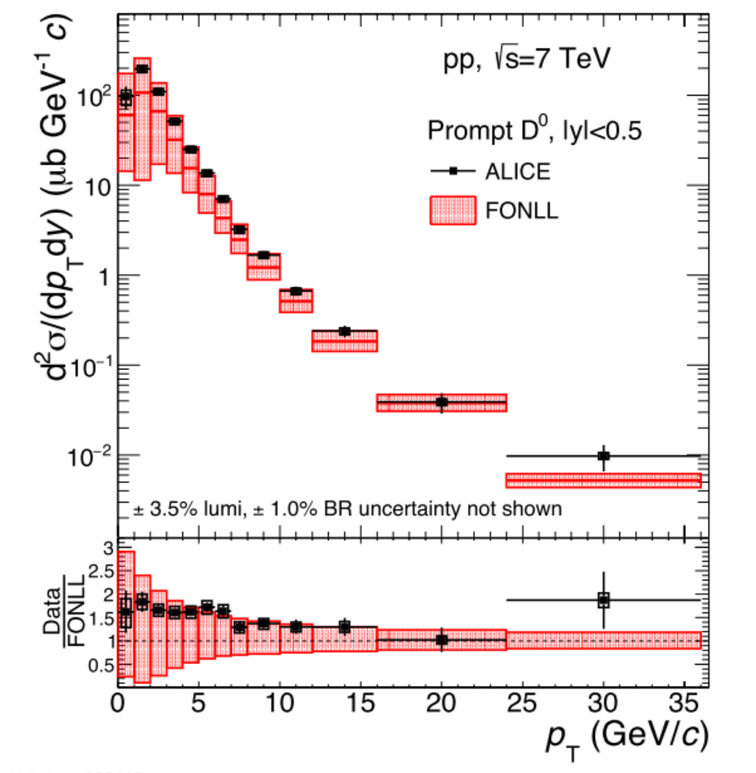
Short summary

- 堅実な結果がいろいろあった
- 一方でΛ_cなどの新しい測定も見られた

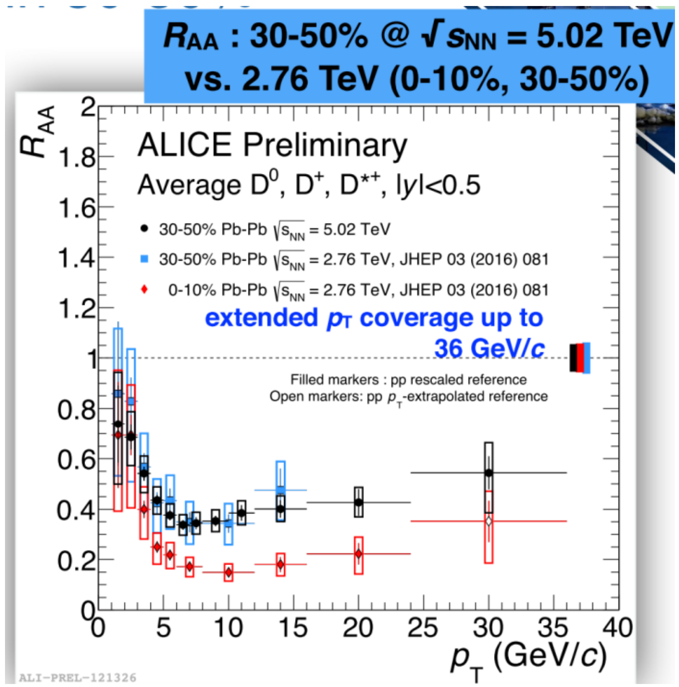
- スライドは全部で20枚あります

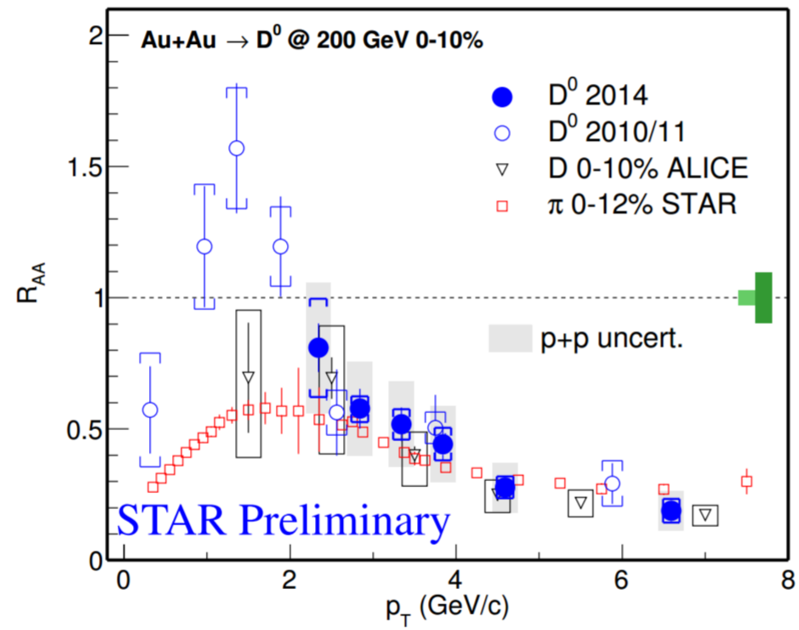
D meson in pp collisions @LHC



- Measured down to zero pT
- Experimental uncertainties are by far smaller than FONLL uncertainties.

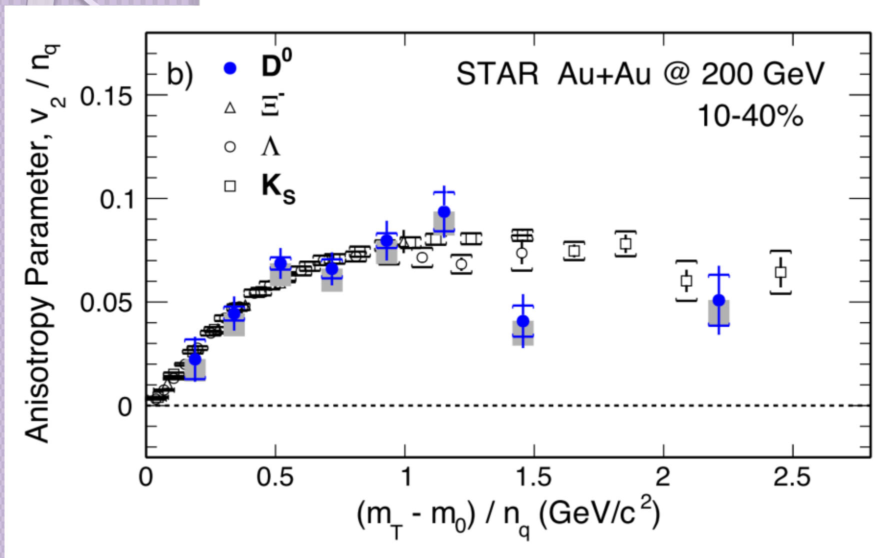
Charmed meson R_{AA}



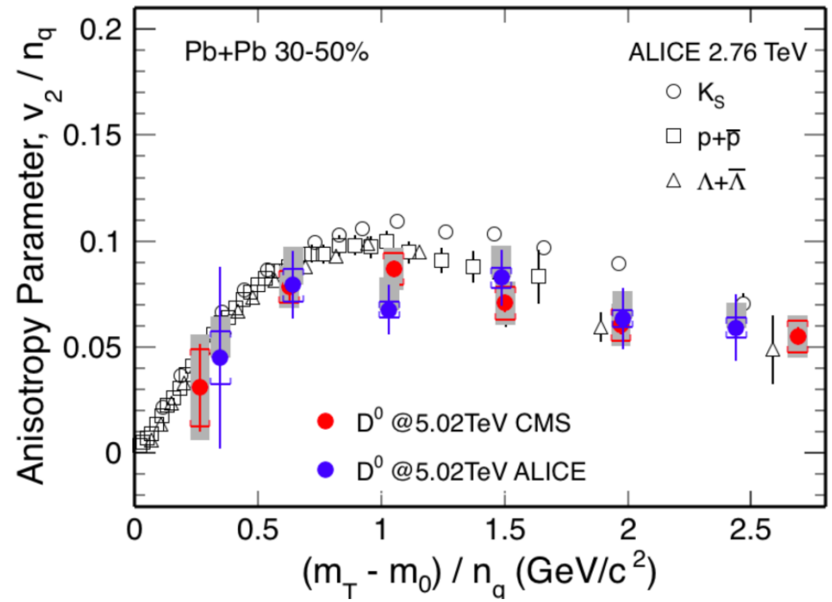


- Clear centrality dependence of the D meson suppression
- Similar suppression for the two collision energies (2.76 TeV and 5.02 TeV)
- Non monotonic structure at low pT at 200 GeV

v_2: NCQ scaling



$*m_T=\sqrt{p_T^2+m_0^2}$

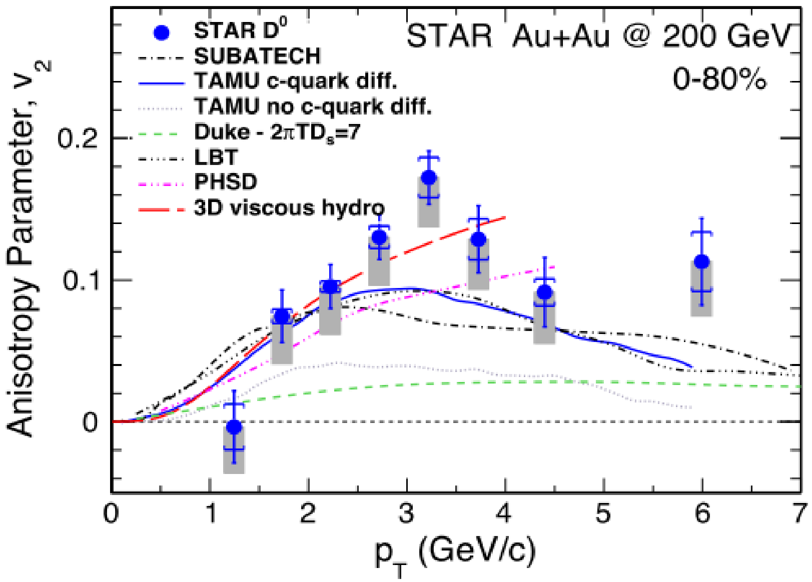


- Mass ordering at $p_T < 2$ GeV/c (hydrodynamic behavior)
- v_2(D) follows the (m_T-m_0) NCQ scaling as light hadrons below 1 GeV/c^2

Evidence of charm quarks flowing the same with the medium

- suggest charm quarks may have achieved thermalization

D^0 v_2 compared to models



Different models:

- **SUBATECH: pQCD + hard thermal loop**
  - *P. B. Gossiaux, J. Aichelin, T. Gousset, and V. Guiho, Strangeness in quark matter*
- **TAMU: T-matrix, non-perturbative model with internal energy potential**
  - *M. He, R. J. Fries, and R. Rapp, PRC86, 014903 (2012)*
- **Duke: free constant D_s, fit to LHC high p_T R_{AA}**
  - *S. Cao, G.-Y. Qin, and S. A. Bass, PRC88, 044907 (2013)*
- **hydro: A 3D viscous hydrodynamic model**
  - *L.-G. Pang, Y. Hatta, X.-N. Wang, and B.-W. Xiao,PRD91, 074027 (2015)*
- **PHSD: Parton-Hadron-String Dynamics, a transport model**
  - *H. Berrehrah et al. PRC90 (2014) 051901*
- **LBT: A Linearized Boltzmann Transport model**
  - *S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, PRC94, 014909 (2016)*

compare with	$2\pi TD_s$	$\chi 2$/n.d.f.	*p*-value
3D viscous hydro	-	3.6 / 6	0.73
LBT	3-6	11.1 / 8	0.73
PHSD	5-12	8.7 / 7	0.28
TAMU c quark diff.	2-12	10.0 / 8	0.26
SUBATECH	2-4	15.2 / 8	0.06
TAMU no c quark diff.	-	29.5 / 8	2 x 10-4
DUKE	7	37.5 / 8	2 x 10-5

Global Bayesian analysis

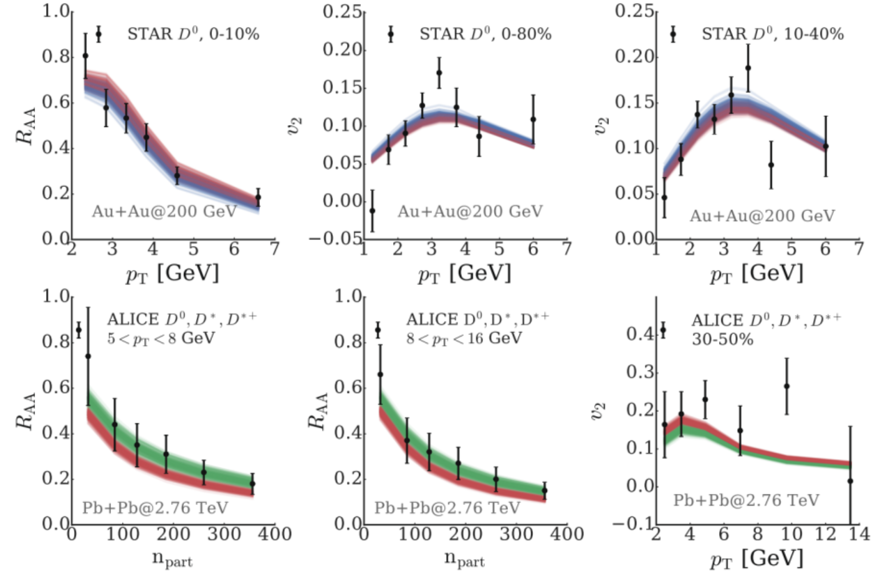
Model Parameter:
eqn. of state
shear viscosity
initial state
pre-equilibrium dynamics
thermalization time
quark/hadron chemistry
particlization/freeze-out

experimental data:
π/K/P spectra
yields vs. centrality & beam
elliptic flow
HBT
charge correlations & BFs
density correlations

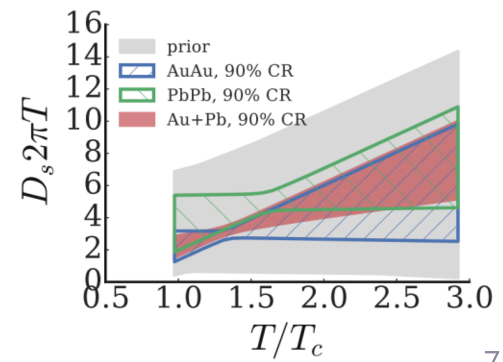
Heavy Quark Diffusion Coefficient

Talk by Yingru Xu (session 8.4)

- calibration on heavy quark v_2 and R_{AA}

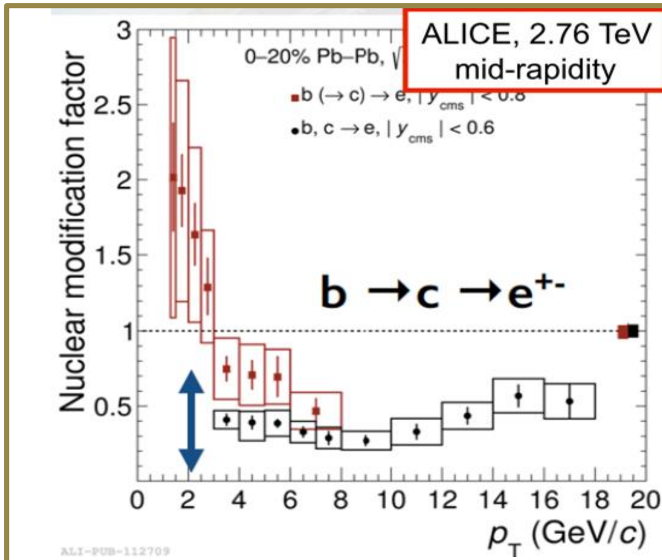


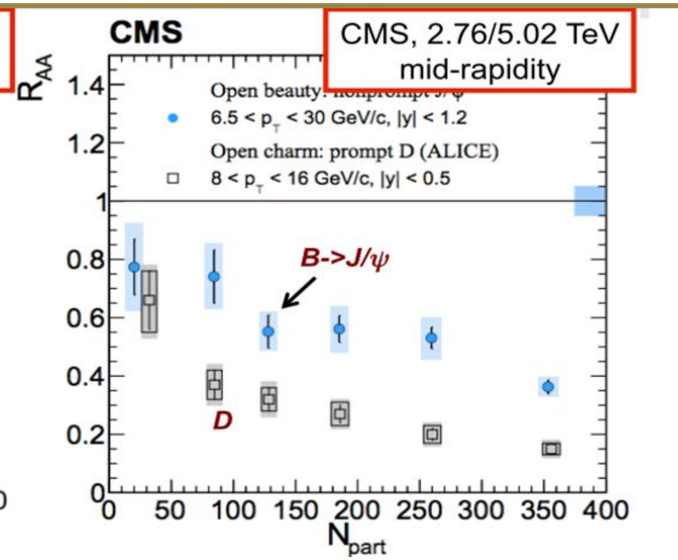
- combining RHIC and LHC data yields significant improvement for the extraction of $D_s(T)$



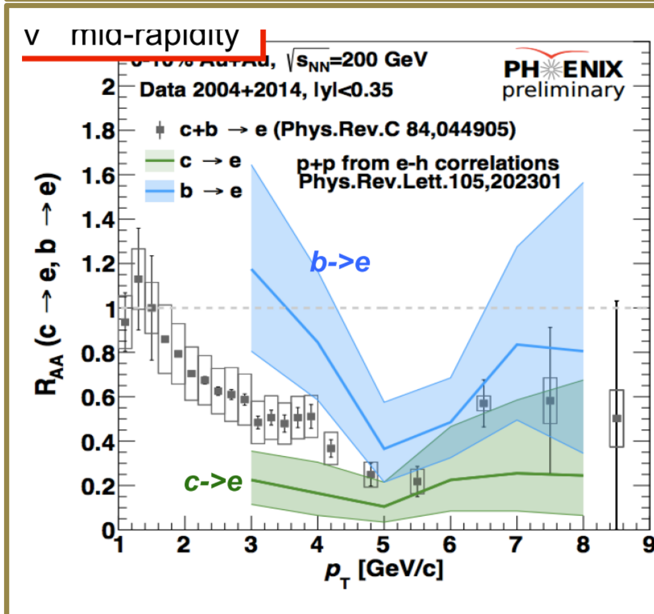
Mass hierarchy of R_{AA}

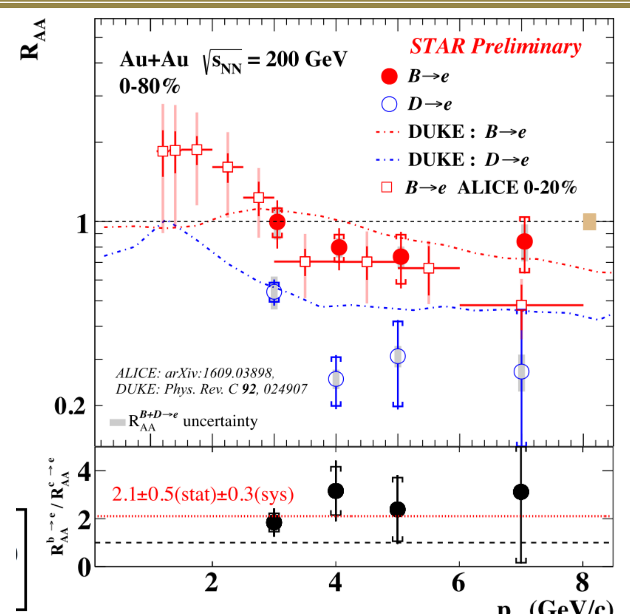
LHC





RHIC



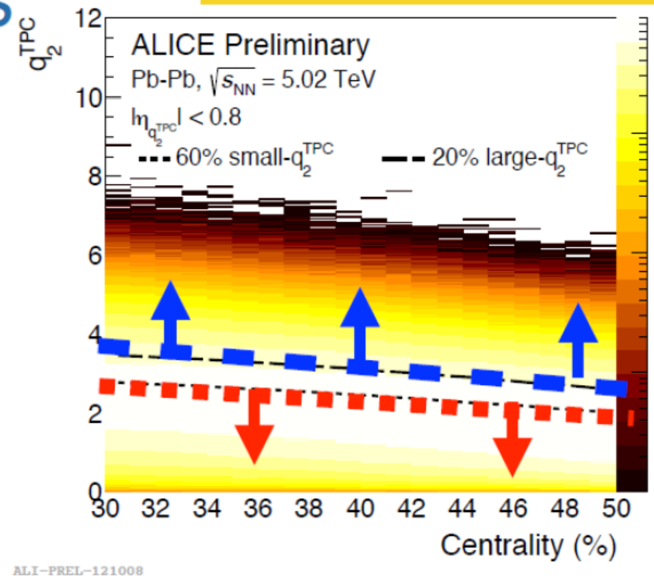


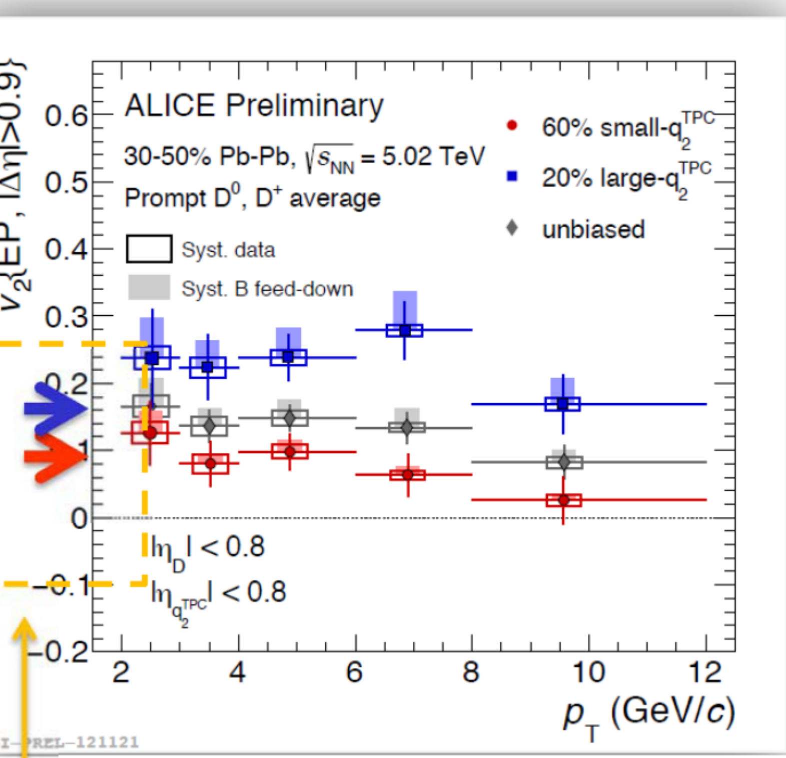
What makes the flow ? Getting closer to experimen

Event-shape engineering analysis

- q_2 measured with TPC tracks:
  - **20%** of the events with **large q_2**
  - **60%** of the events with **small q_2**
- v_2 measured with event plane method (with V0)

q_2 vs centrality



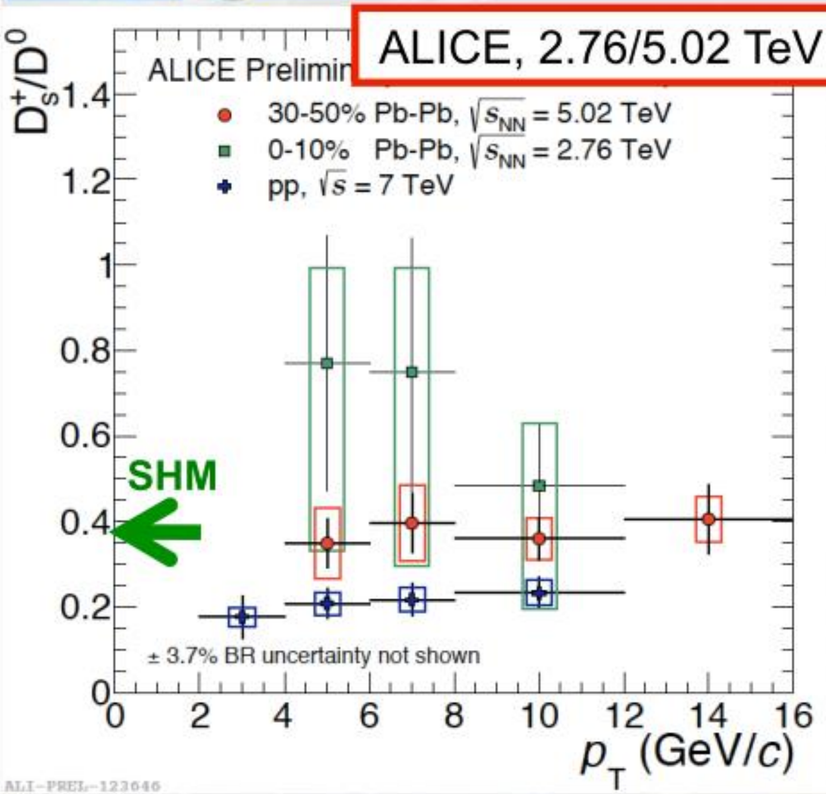


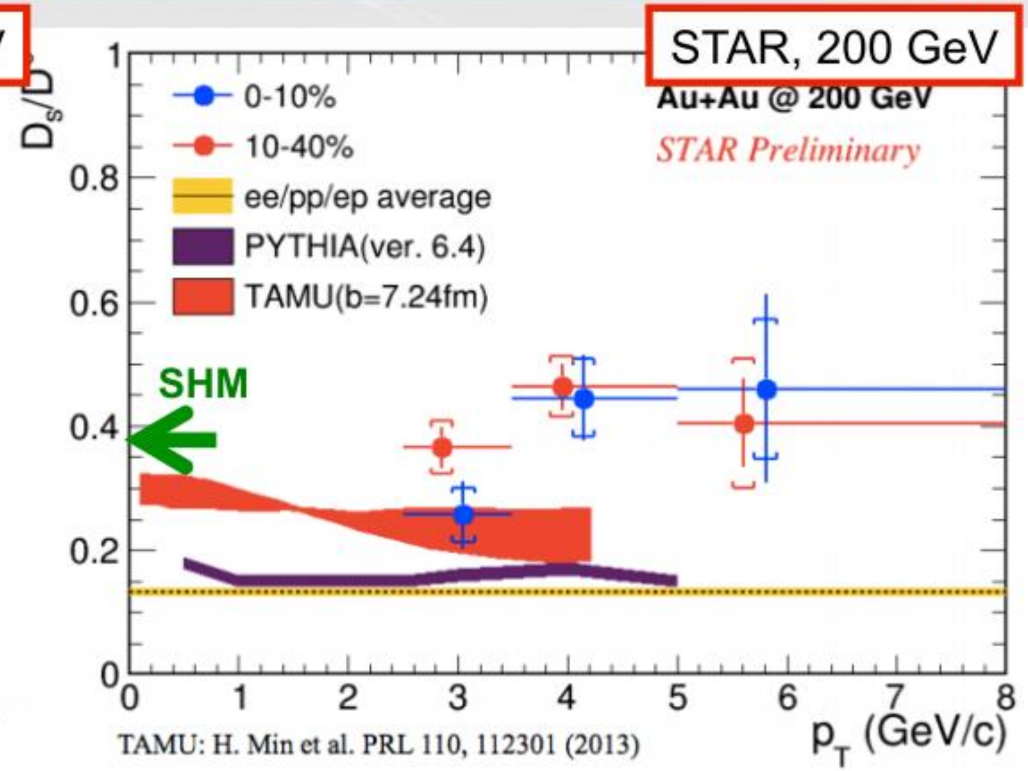
Own predictions (@2.76 TeV)

- **Significant separation** of D-meson v_2 in events with **large and small q_2**
- Autocorrelation and non-flow effects between q_2-determination and D-meson reconstruction are present
- **Charm** quarks **sensitive** to the light-hadron bulk **collectivity** and **event-by-event initial condition fluctuations**

From A. Barbano (//OHF 1, Tuesday)

D_s Enhancement in Heavy Ion Collisions

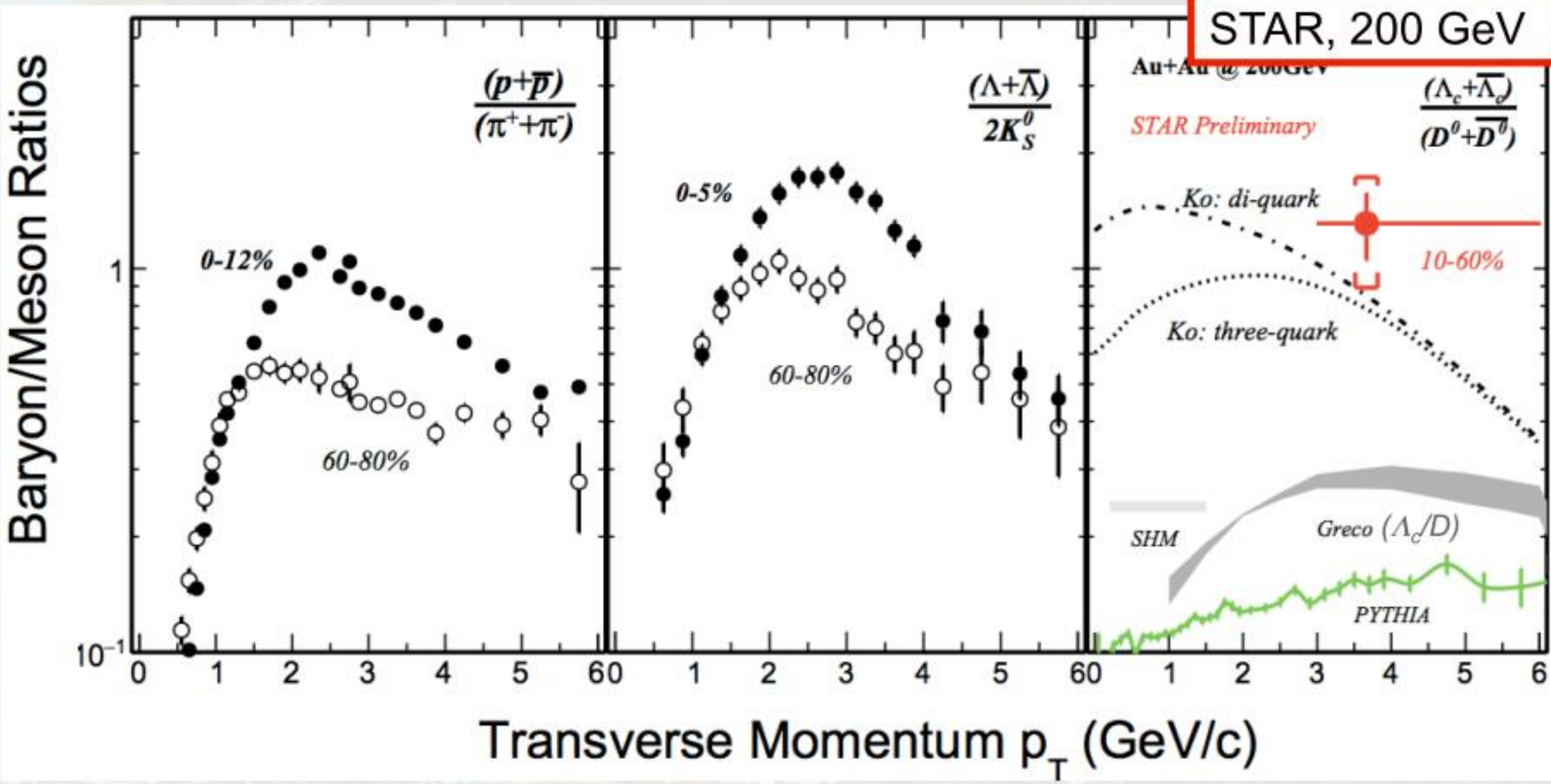




•Significant D_s/D^0 enhancement in mid-central Au+Au and Pb+Pb collisions w.r.t fragmentation baseline or p+p measurement

- Coalescence hadronization
- SHM predicts D_s/D^0 ratio ~ 0.35-0.40 (central) *A. Andronic et al., PLB 571 (2003) 36*
- relation to charm quark thermalization in QGP?

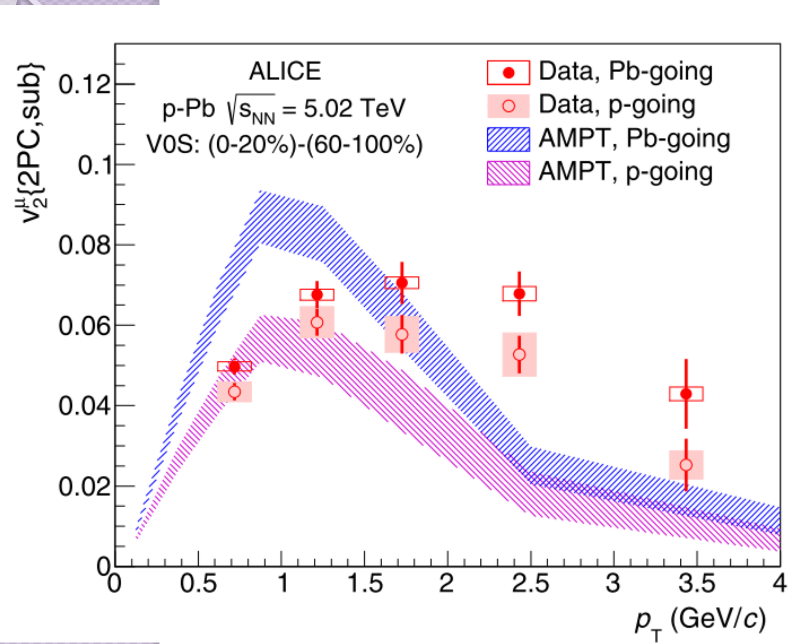
Λ_c Enhancement in Heavy Ion Collisions

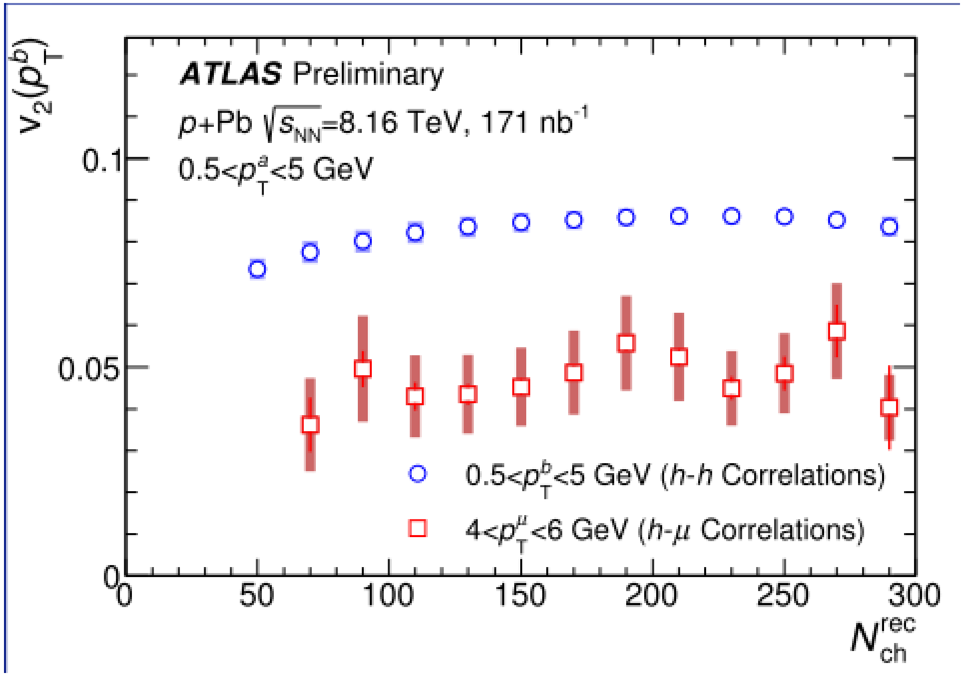


Ko model : Y. Oh, et.al. PRC 79 (2009) 044905; Greco model : S.Ghosh, et. al. PRD 90 (2014) 054018

- Significant enhancement in Λ_c/D compared to PYTHIA/fragmentation baseline
- The Λ_c/D^0 ratio is compatible with light flavor baryon-to-meson ratios
- Consistent with coalescence + thermalized charm quarks

Single-μ v2 in p-Pb collisions





- See significant heavy flavor v_2 for multiplicities > 60

  ⇒ ~ 0.6 x hadron v_2

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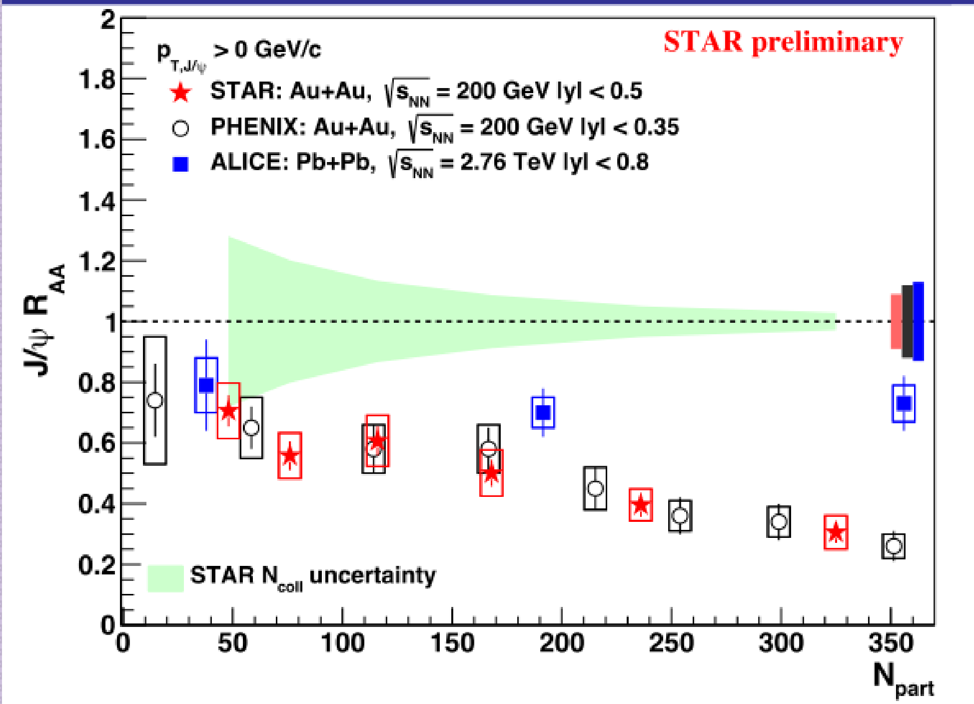
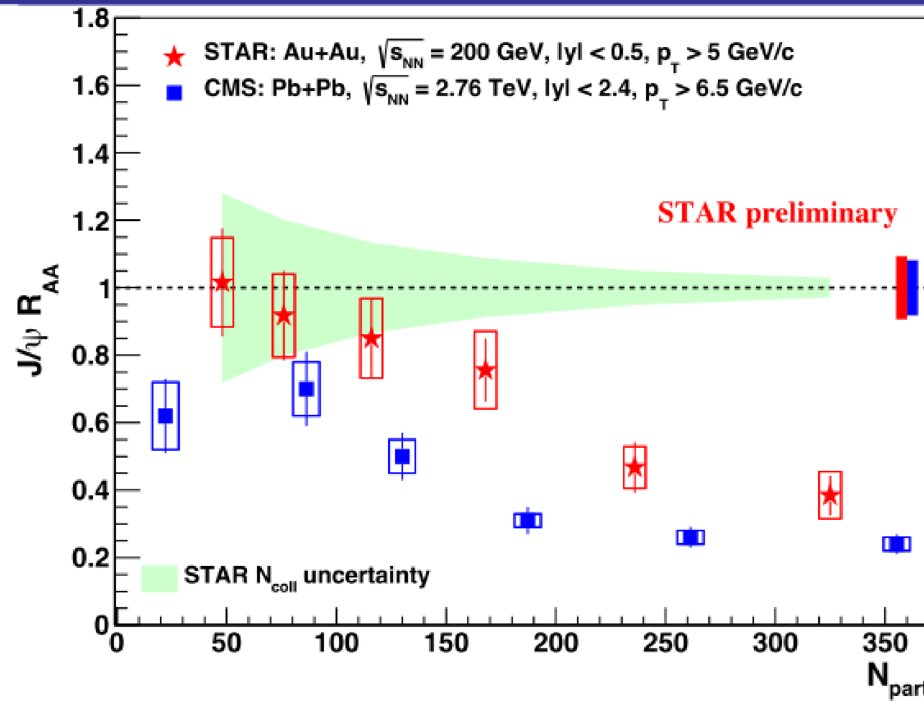
J/ψ - RHIC energy

- Recent highlights by STAR
- **Low vs high p_T J/ψ suppression**



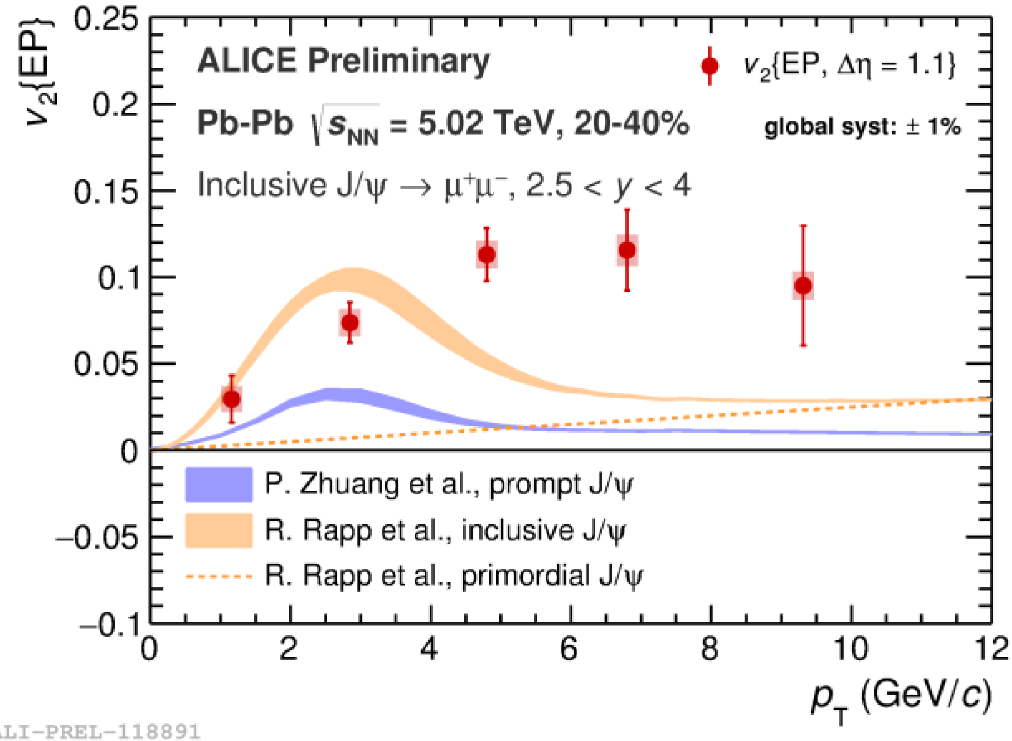


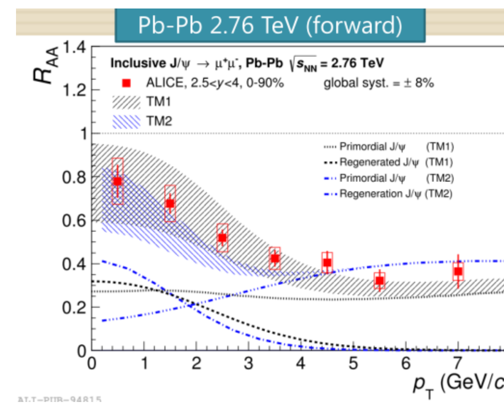
- **Low p_T J/ψ, $R_{AA}^{LHC} > R_{AA}^{RHIC}$** ← strong regeneration
- **High p_T J/ψ, $R_{AA}^{LHC} < R_{AA}^{RHIC}$** ← weak (or no) regeneration

J/ψ elliptic flow (v_2)

[1] Nucl. Phys. A 859 (2011) 114–125
[2] Nucl.Phys.A834:317c-319c,2010

- Charm quarks, if thermalised in the QGP, should exhibit the elliptic flow generated in this phase
  - ➡ Non zero v_2 for re-generated J/Ψ

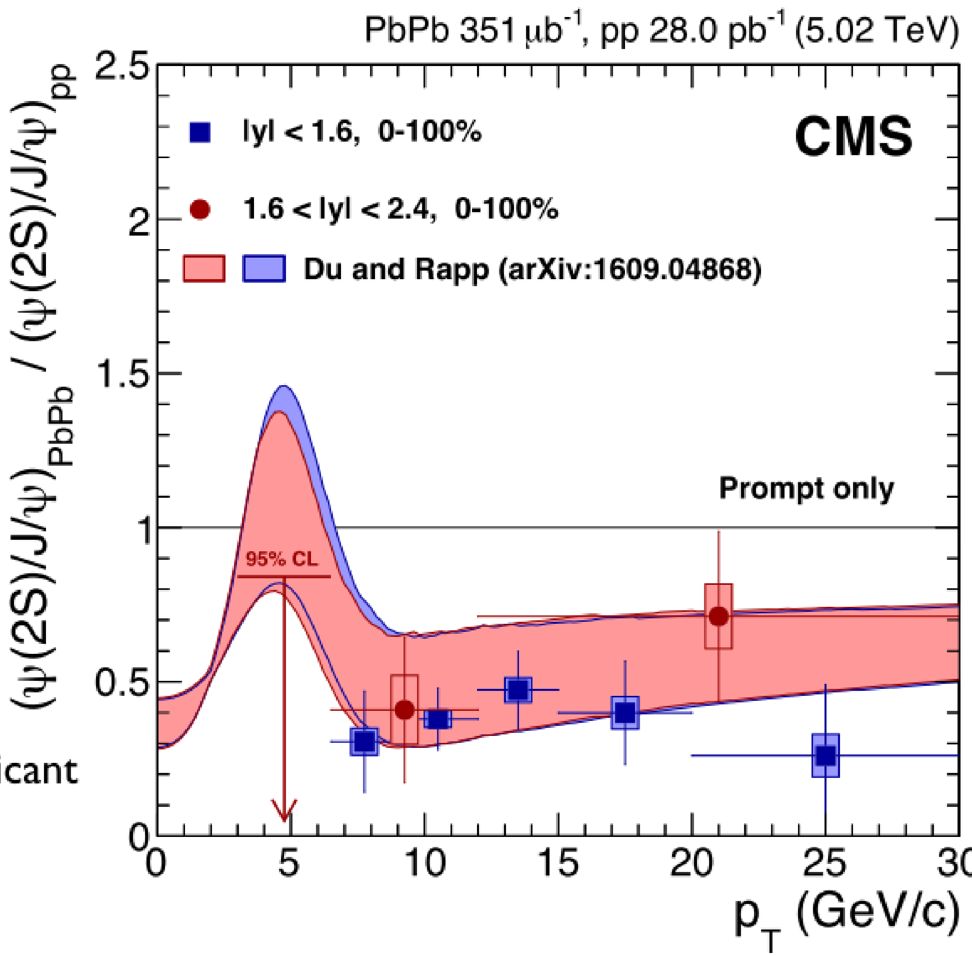


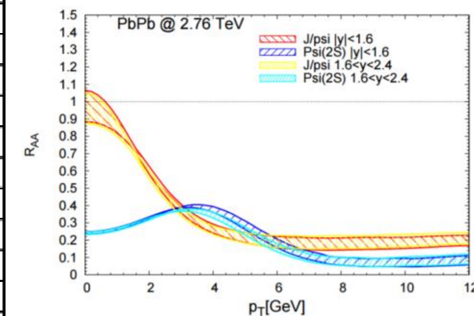


- A non zero J/ψ v_2 seen in semi-central collisions (20-40%) [7.6 σ significance in 4< p_T < 6 GeV/c]
- Precision is significantly increased in run-2 measurement with respect to run-1
- Similar measured v_2 values for hidden and open charm
- Models have difficulties to reproduce the measured J/ψ v_2 in the measured p_T interval

ψ(2S) /J/ψ vs p_T

CMS FINAL QM17





arXiv:1611.01438

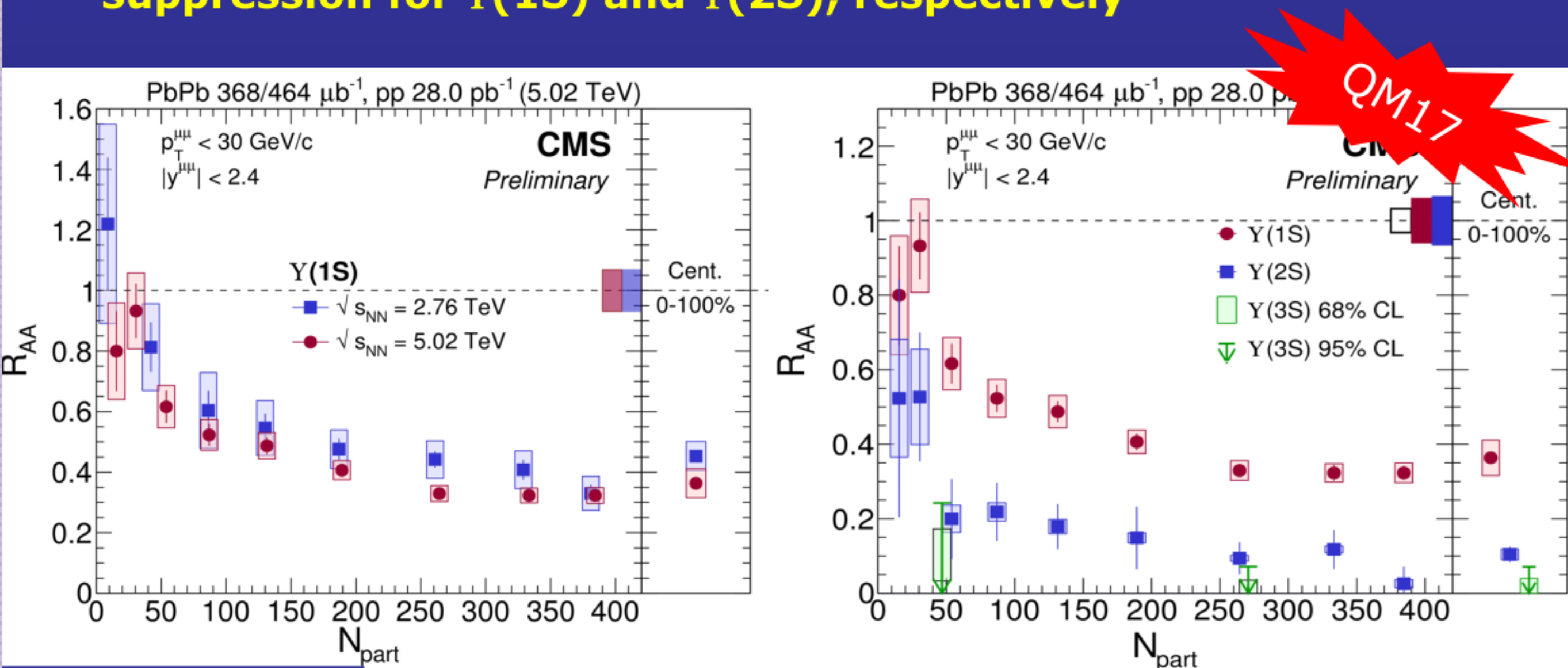
95% CL where no significant ψ(2S) signal in PbPb

- $R_{AA}(\psi(2S))/R_{AA}(J/\psi) < 1$ in all bins → **ψ(2S) is more suppressed than J/ψ**
- No p_T dependence within uncertainties
- X. Du and R. Rapp: transport model with temperature dependent reaction rates

  → ψ(2S) regenerated later than J/ψ in the fireball evolution?

New R_{AA} results

- $\sqrt{s_{NN}}$=2.76 TeV, strong centrality dependence, **up to factor ~2 and ~8 suppression for Υ(1S) and Υ(2S), respectively**



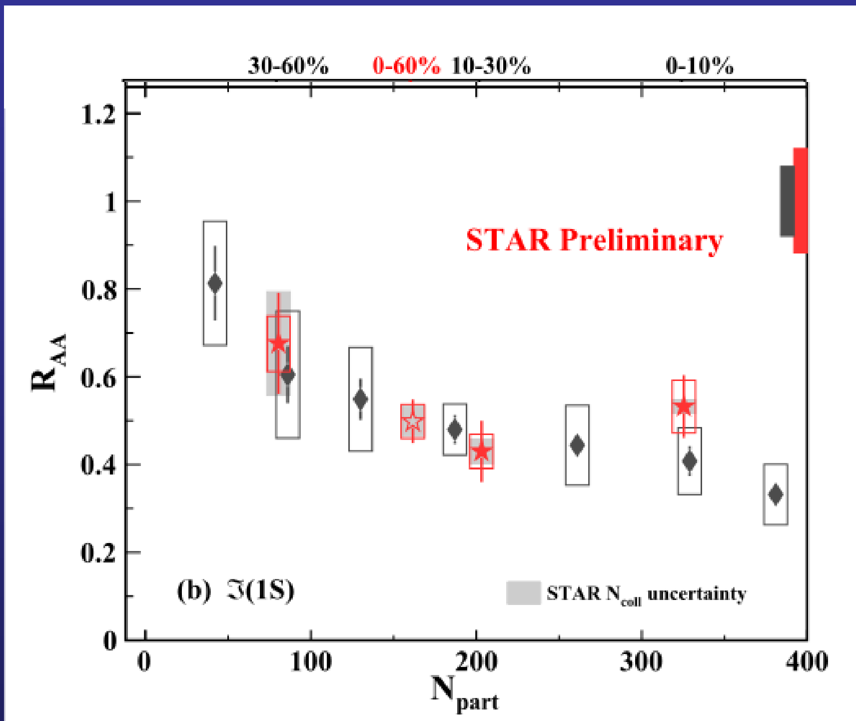
CMS-PAS-HIN16-023

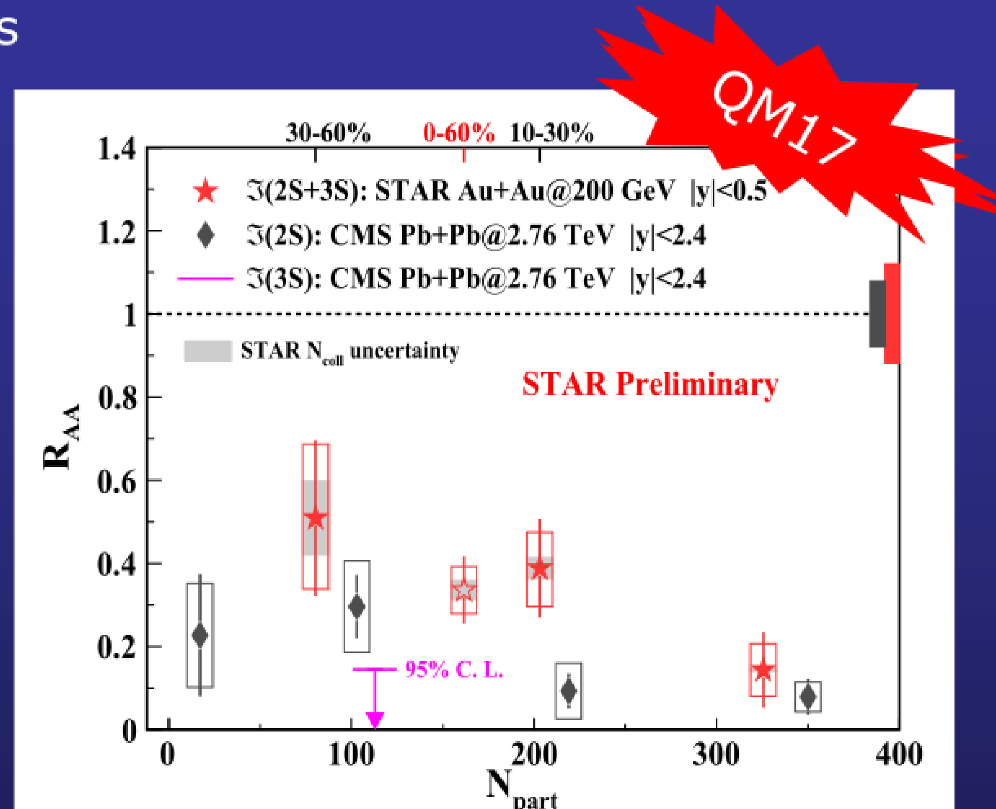
V. Khachatryan et al.,CMS
arXiv:1611.01510

- **New CMS results at $\sqrt{s_{NN}}$=5.02 TeV**
  → Indications for slightly stronger suppression

First precision results from STAR

- New pp reference (run-15) AND combination of $\mu^+\mu^-$ (run 14) and e^+e^- (run 11) Au-Au data samples

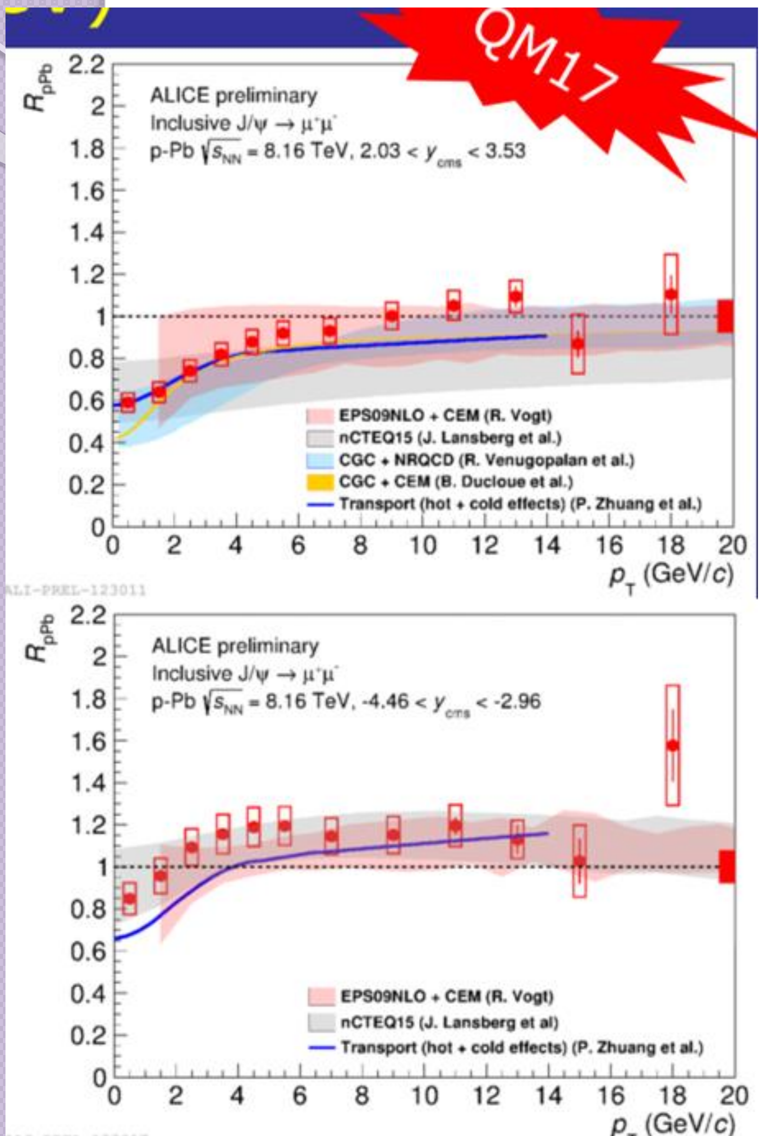


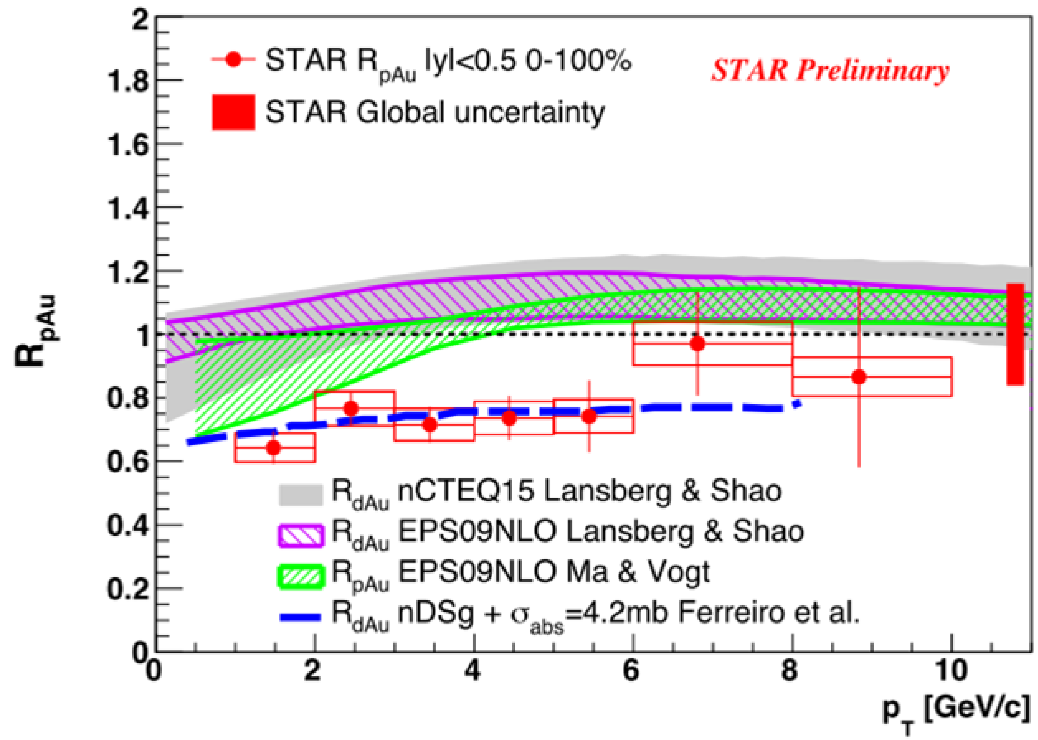


- **Evidence for suppression of the 3 ϒ states** ALSO at RHIC energy

- Hints for ϒ(2S)+ϒ(3S) less suppressed up to semi-central events and then compatible with CMS for central → effect related to energy density ?
- ϒ(1S) identical at RHIC and LHC → dominated by feed-down ?

J/ψ in pA



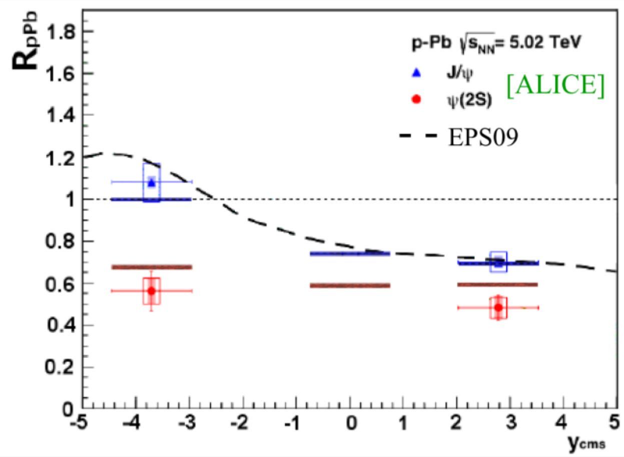


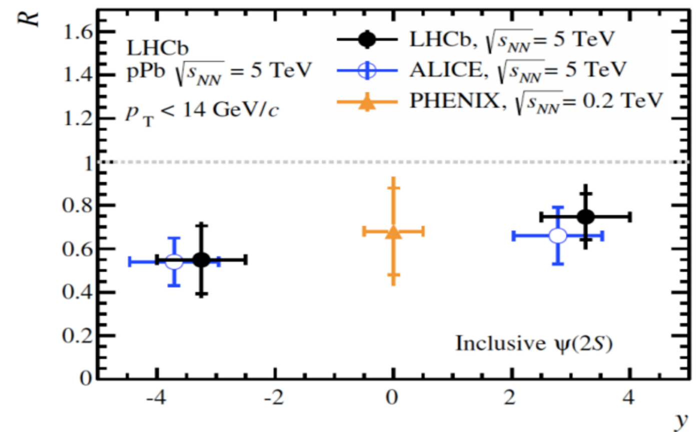
LHC: Shadowing, CGC, energy loss describe the data

RHIC: Additional nuclear absorption is preferred by data

ψ(2S) in pA

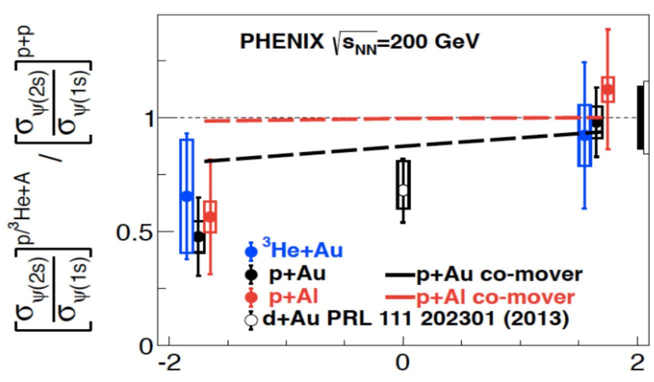
p-Pb (5.02TeV)





• noticeable ψ′ and little J/ψ suppression, consistent with "comovers"

[Ferreiro '15]



Similar relative suppression of ψ(2S) at backward rapidity, but larger relative suppression of ψ(2S) at forward rapidity at LHC

まとめ

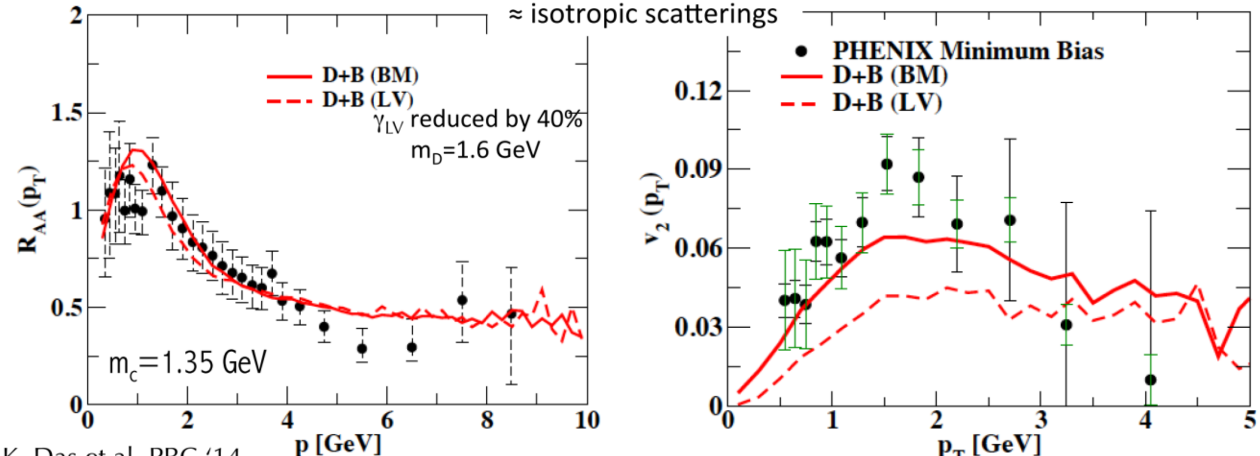
- 重クォーク
  - R_{AA}, Elliptic flow, (triangular flow)から物理量へ
  - Energy lossのMass hierarchyが見えた
  - ESE, D_s, Λ_cといった新しい測定も始まった
- クォーコニア
  - R_{AA}でsequential suppressionが見えている
  - v_2はtransport modelで再現できない
  - ψ(2S)のpAでのsuppressionはcomover?

backup

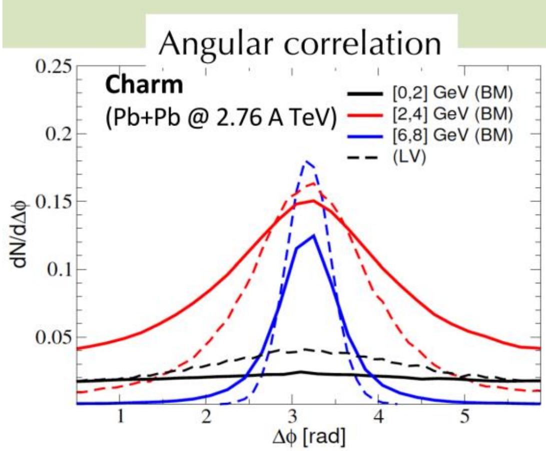
Model comparison

- **BAMPS:** Boltzman equation with collisional energy loss in expanding QGP *[Phys. Rev. C **84** (2011) 024908; J. Phys. G **38** (2011)124152; Phys. Lett. B **717** (2012) 430]*
- **TAMU:** HQ transport with coll. e.loss only, resonant scattering and coalescence+hydro *[Phys.Lett. B735 (2014) 445-450]*
- **POWLANG HTL:** HQ transport with Langevin equation with collisional energy loss and, recombination, viscous hydrodynamic expansion. Transport coeff. dependence on quark momentum *[Eur. Phys. J. C **71** (2011) 1666; J. Phys. G **38** (2011) 124144]*
- **Djordjevic:** energy loss due to both radiative and collisional, processes in a finite size dynamical QCD medium *[Phys. Rev. C 92 (2015) 024918]*
- **Ads/CFT:** energy loss fluctuations included in a realistic strong coupling energy loss model from AdS/CFT *[arXiv:1610.02043, arXiv:1605.09285]*
- **SCET$_{M,G}$ NLO:** in-medium formation and dissociation of D and B, ideal fluid with Bjorken expansion *[arXiv: 1610.02043]*
- **Xu, Cao, Bass:** Langevin with coll. and rad. term and recombination+hydro *[Phys. Rev. C **88** (2013) 044907]*
- **PHSD:** Parton-Hadron-String Dynamics transport approach, coalescence *[Phys.Rev. C92 (2015) no.1, 014910, Phys.Rev. C93 (2016) no.3, 034906]*
- **MC@sHQ+EPOS:** coll. and rad. e.loss in expanding medium based on EPOS model, recombination *[Phys. Rev. C **89** (2014) 014905]*

Langevin vs Boltzmann

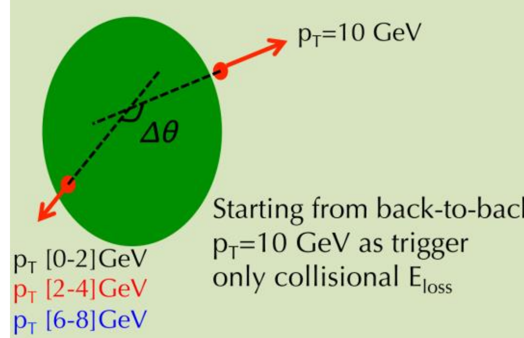


S.K. Das et al.,PRC '14

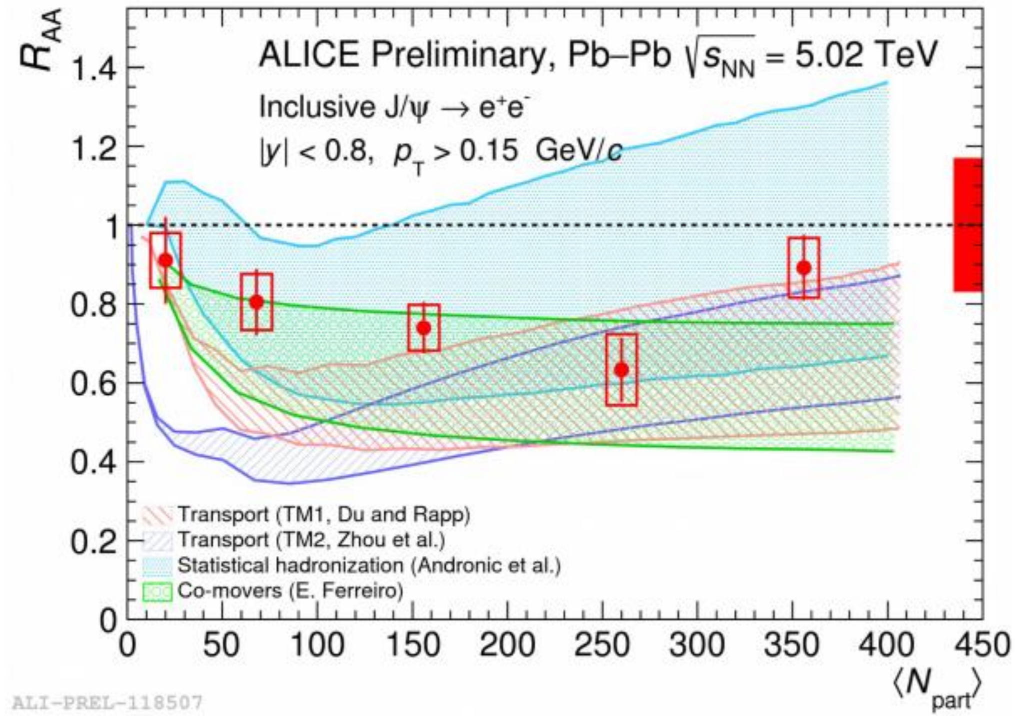


In $dN/d\Delta\phi_{12}$ sizeable differences between BM& LV also for **Bottom**

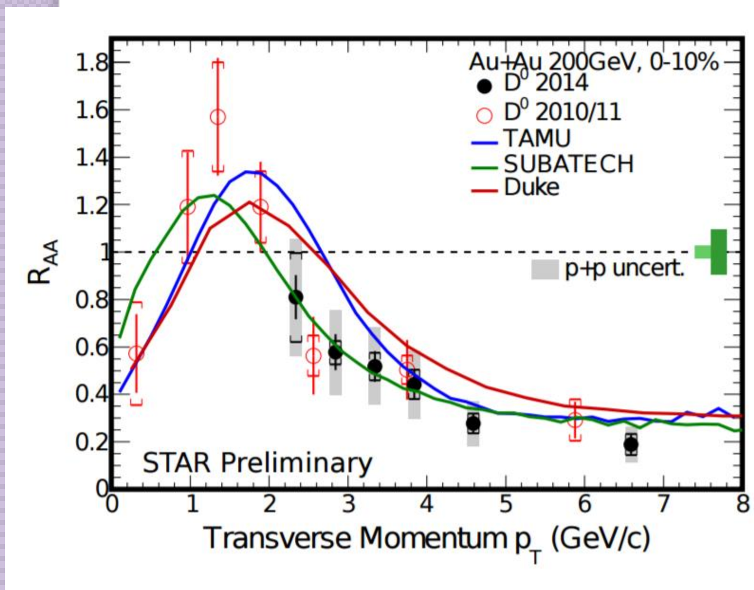
BM vs LV would make a difference for up coming [D-h] + [D-D̲] triggered angular correlations

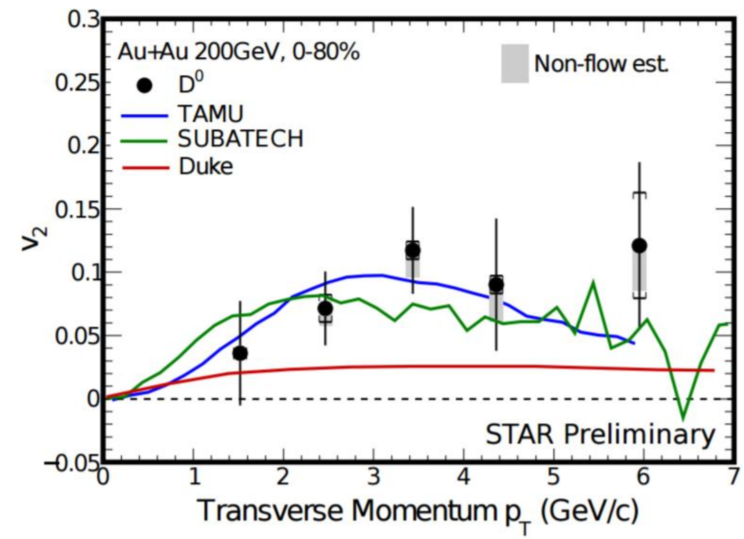


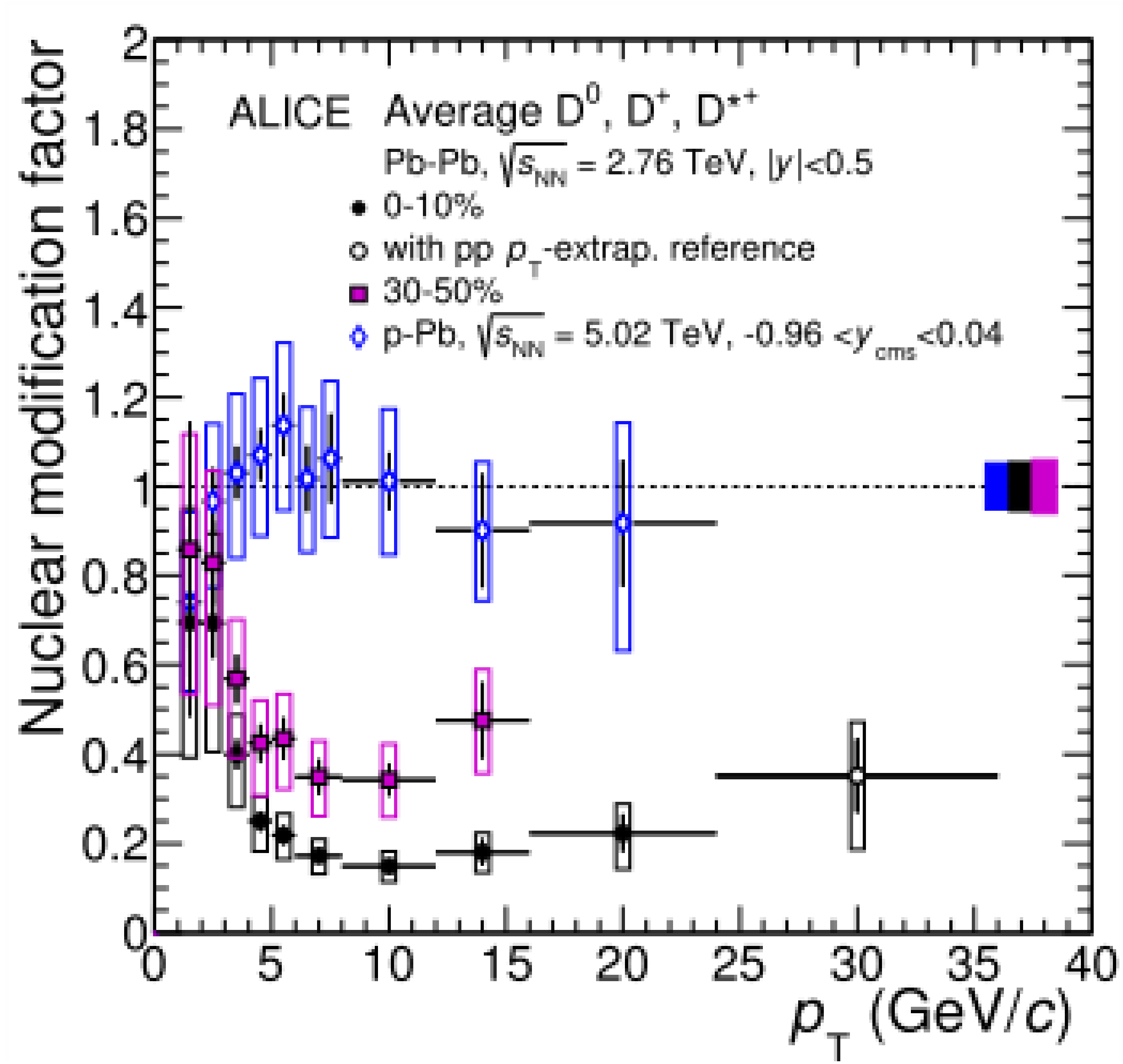
Models $c\bar{c}$ cross sections



Model	$\sigma_{c\bar{c}}$(mb)	Shadowing
TM1	0.72 +-0.13	EPS09 NLO
TM2	0.86+-0.085	EPS09 NLO
SHM	0.448 ± 0.169	EPS09 NLO
Co-movers	0.555±0.105	Glauber-Gribov theory


Au+Au 200GeV, 0-10%
D0 2014
D0 2010/11
TAMU
SUBATECH
Duke
p+p uncert.
STAR Preliminary
RAA
Transverse Momentum pT (GeV/c)


Au+Au 200GeV, 0-80%
D0
TAMU
SUBATECH
Duke
Non-flow est.
STAR Preliminary
v2
Transverse Momentum pT (GeV/c)

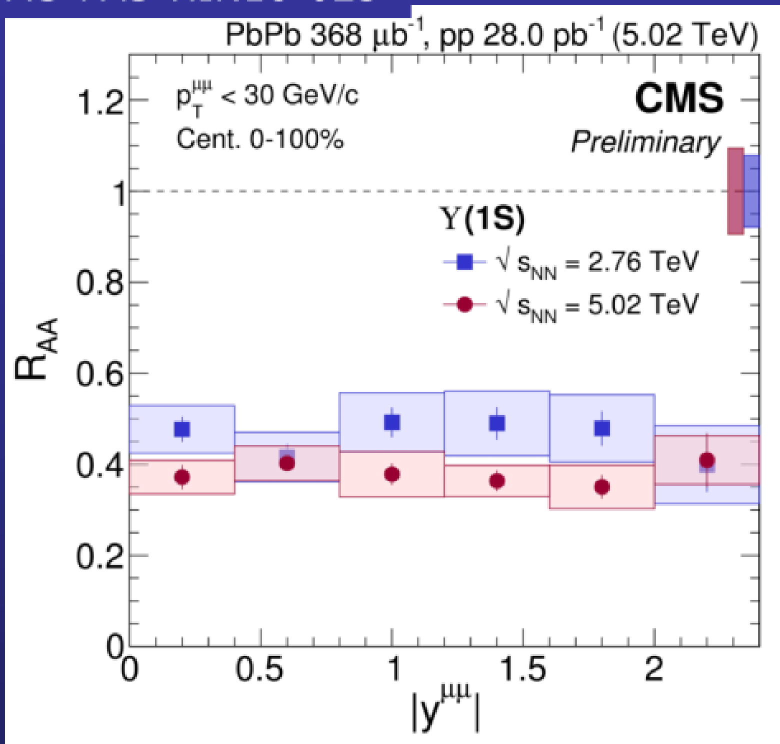


ALICE Average D^0, D^+, D^{*+}
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, |y|<0.5
0-10%
with pp p_T-extrap. reference
30-50%
p-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV, -0.96 <y_{cms}<0.04
Nuclear modification factor
p_T (GeV/c)

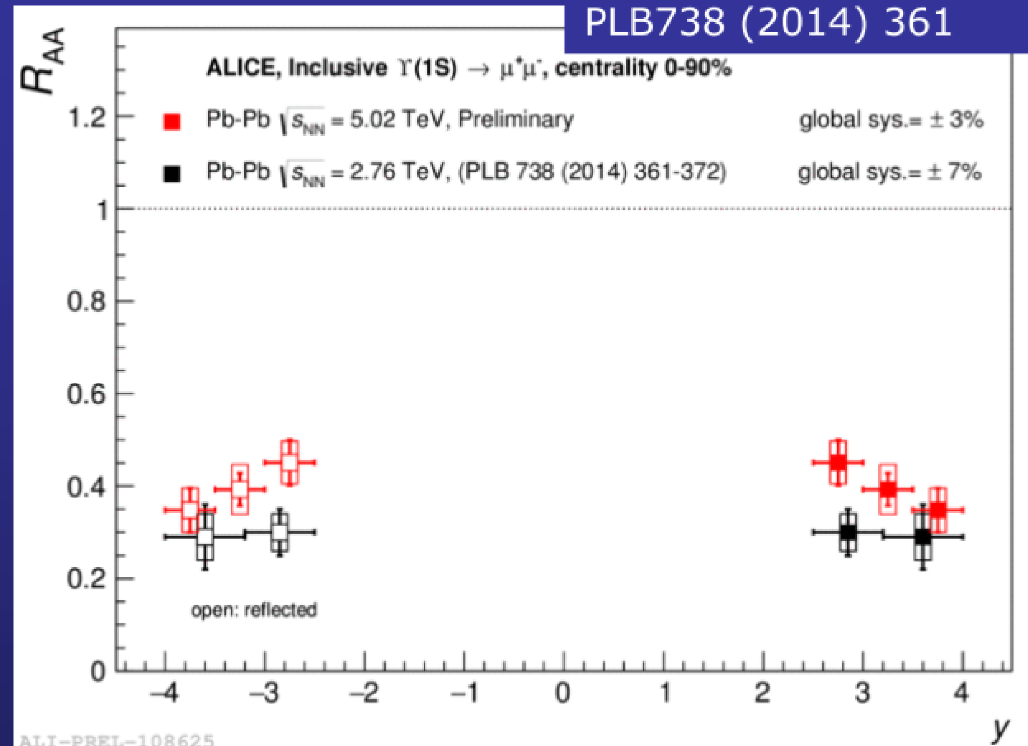
V. Khachatryan et al., CMS arXiv:1611.01510

R_{AA} vs y: ALICE and CMS Υ(1S)

CMS-PAS-HIN16-023



B. Abelev et al., (ALICE) PLB738 (2014) 361



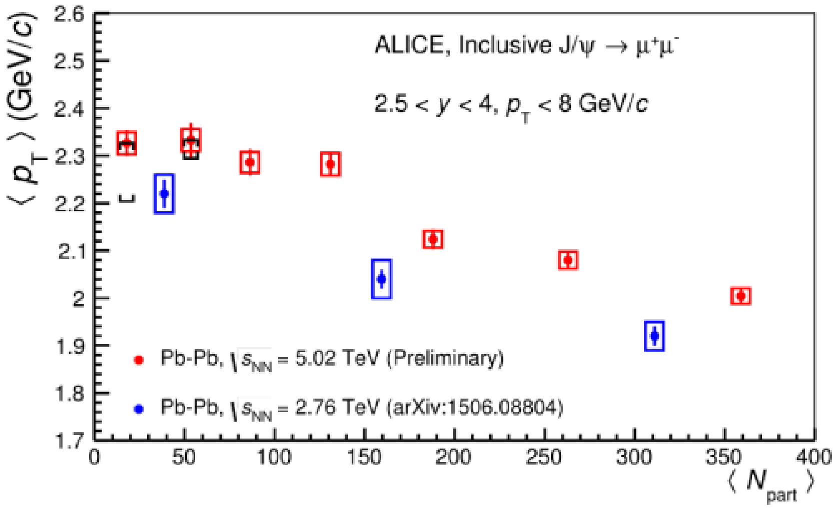
- ❑ ALICE → hints for **less suppression** at $\sqrt{s_{NN}}$= 5.02 TeV
- ❑ CMS → hints for **more suppression** at $\sqrt{s_{NN}}$= 5.02 TeV

- ❑ Compare R_{AA} vs y for the two experiments in a single plot

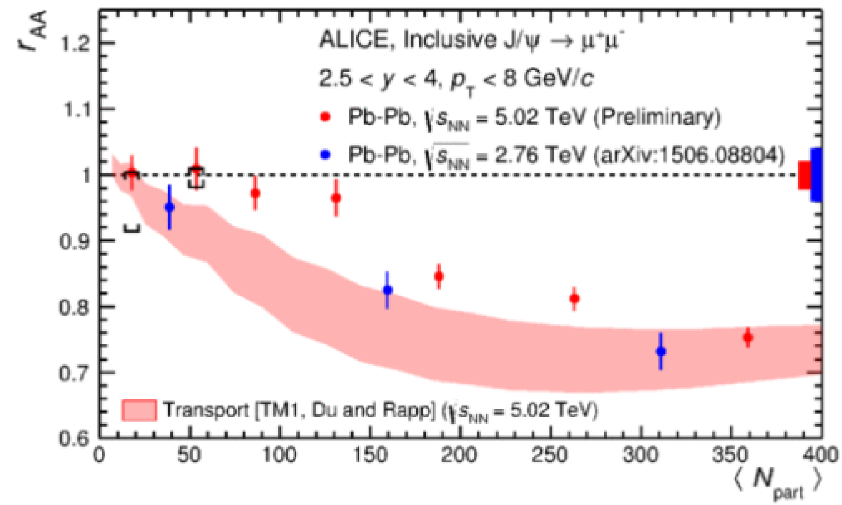
New J/ψ average p_T ($<p_T>$)

[1] JHEP 05 (2016) 179
[2] Nucl. Phys. A 859 (2011) 114–125

- The J/ψ $<p_T>$ and the r_{AA} are complementary observables to the R_{AA} and the v_2



ALI-PREL-120593

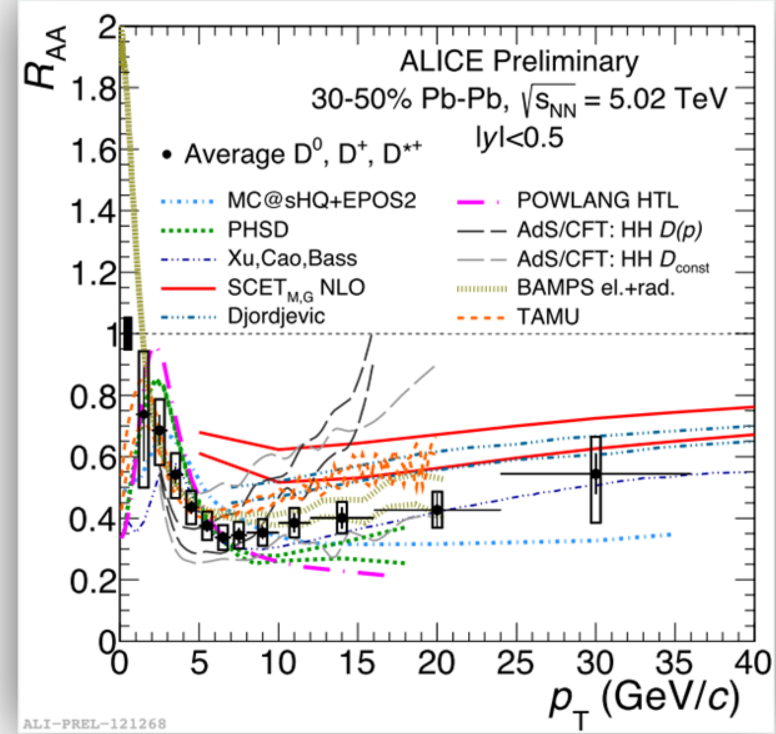


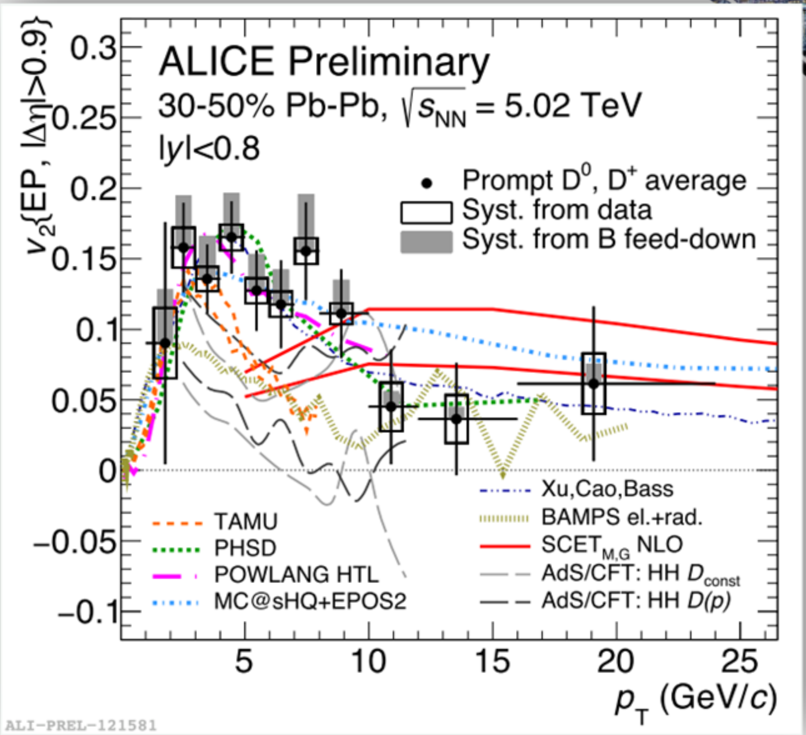
ALI-PREL-120574

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

- The J/ψ $<p_T>$ is smaller in central events than in peripheral ones→ (re)generation
- The results of r_{AA} at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s_{NN}} = 2.76$ TeV [1] are compatible within uncertainties
- Discrepancies are seen in some centralities (e.g > 3 σ for 30-40 %) between the measurements and calculations based on TM1[2] model

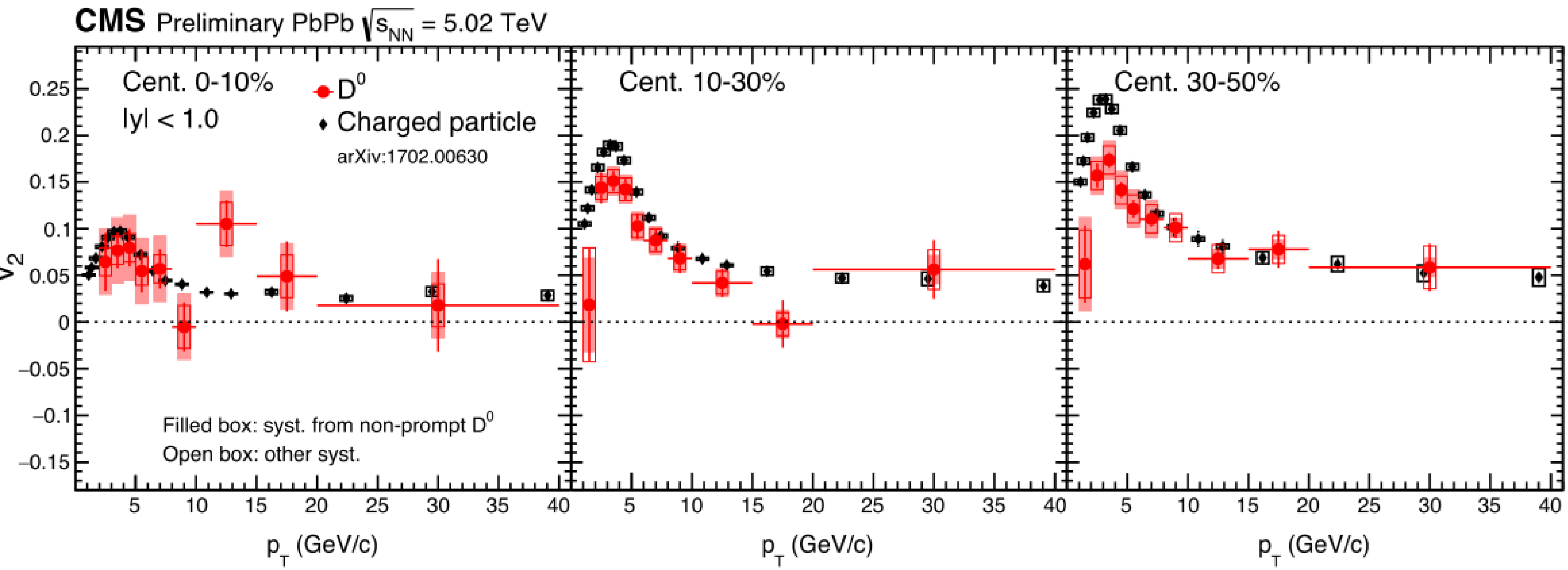
D-meson R_{AA} and v_2: model comparison





- Experimental results with improved precision → potential to constrain models giving a simultaneous description of quenching and collectivity

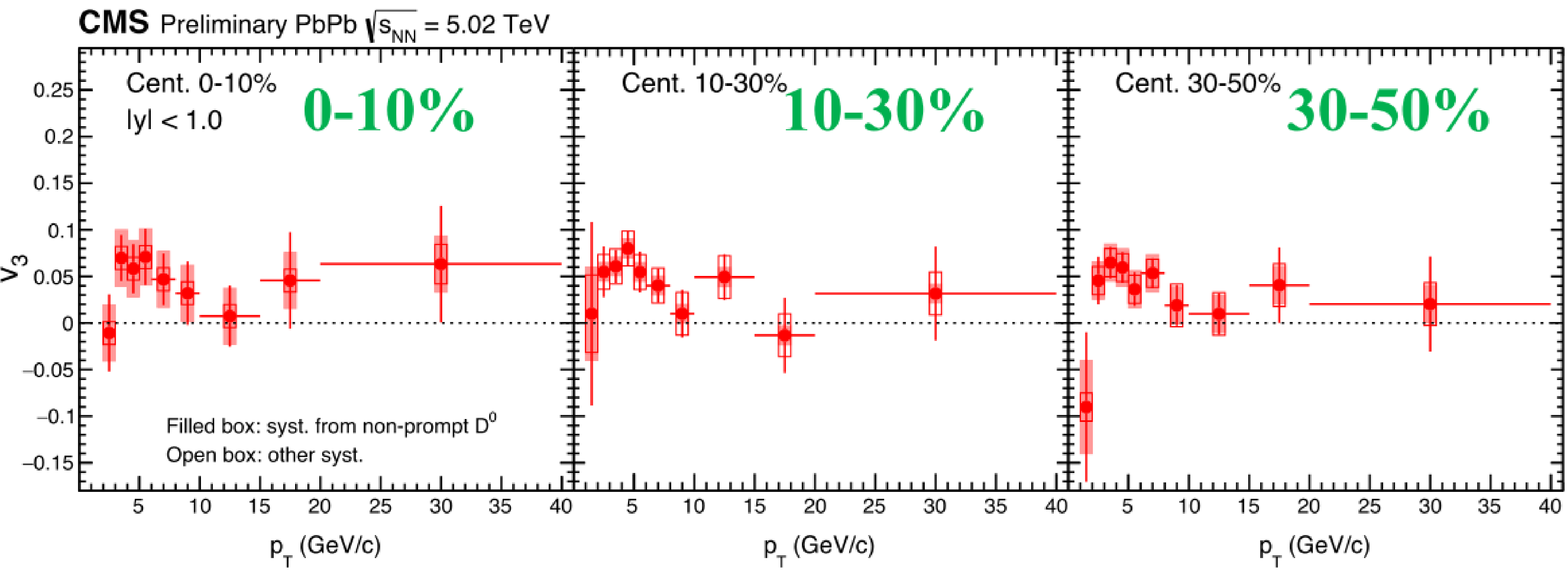
Prompt D^0 v_2 compared with v_2 of charged particle



- ❑ **Low p_T: v_2 (prompt D^0) < v_2 (charged particle)**
- ❑ **High p_T: v_2 (prompt D^0) ≈ v_2 (charged particle)**
  - ➢ ΔE (charm) ≈ ΔE (light quark) at high p_T from R_{AA} and v_2
- ❑ **Similar p_T dependence**
- ❑ **At low p_T, weaker centrality dependence than charged particle**

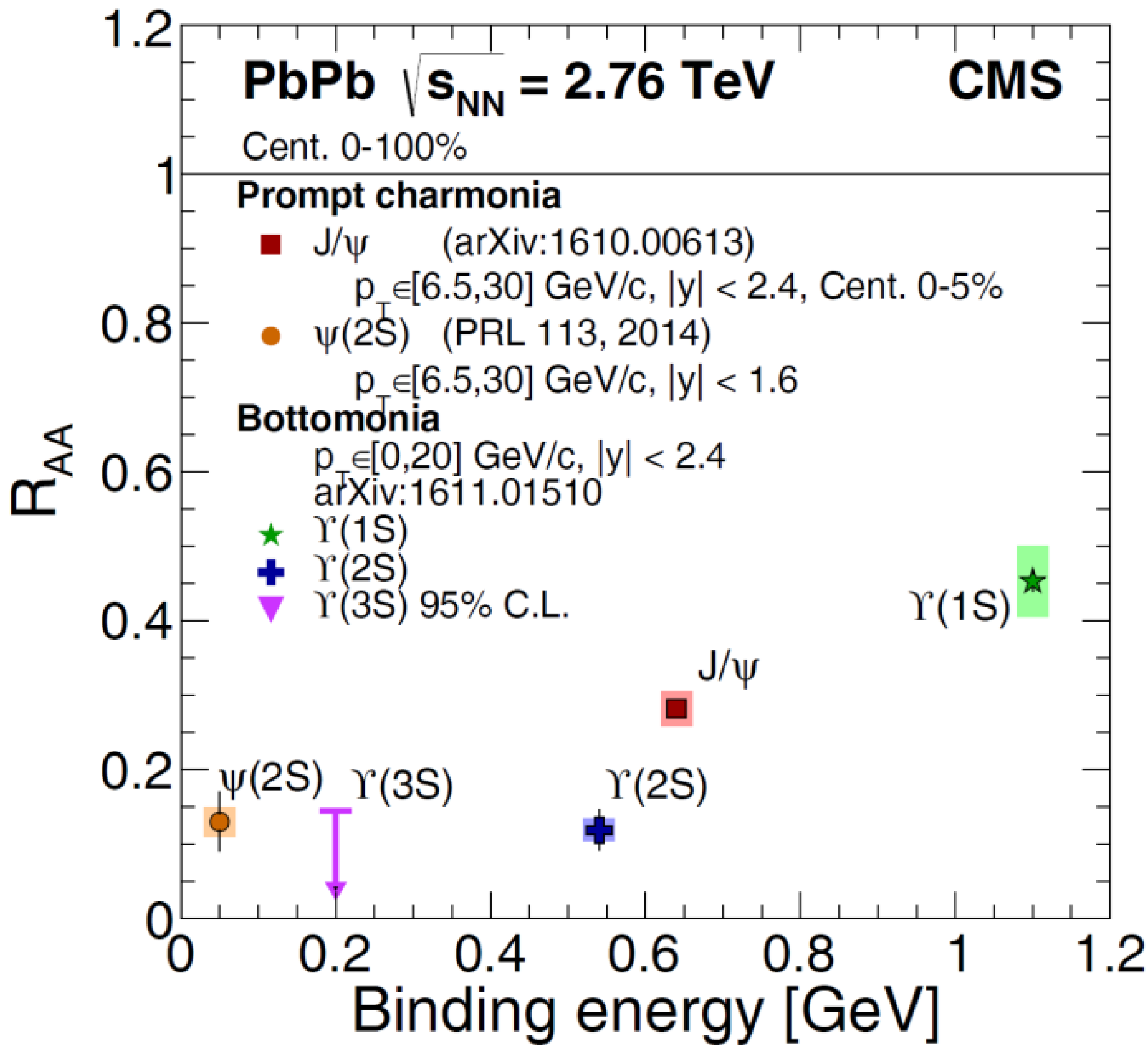
V3の結果もあった（バックアップ）

Prompt D^0 v_3 results



- First measurement of D^0 v_3
- Low p_T: v_3 (prompt D^0) > 0;   High p_T: v_3 (prompt D^0) ≈ 0
- Peaks around 3 GeV, then decrease vs p_T
- Little centrality dependence

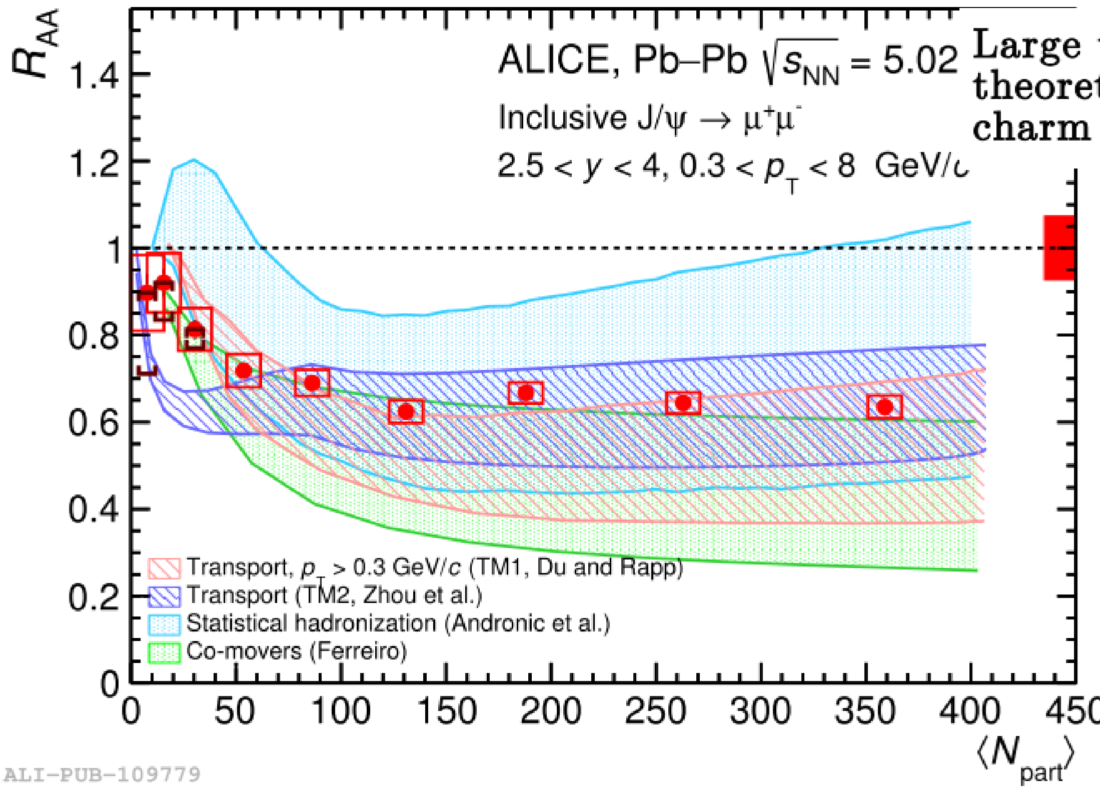
Sequential Suppression of Quarkonia



At 5 TeV: What will be the results from a **hotter** and **denser** QGP?

J/ψ R_{AA} vs centrality (comparison with models)

[1] Nucl. Phys. A 859 (2011) 114–125
[2] Phys. Rev. C 89 no. 5, 459 (2014) 054911
[3] Nucl. Phys. A 904-905 (2013) 535c
[4] Phys. LeX. B 731 (2014) 57–63
[5] ALICE Coll. PRL116 (2016) 222301

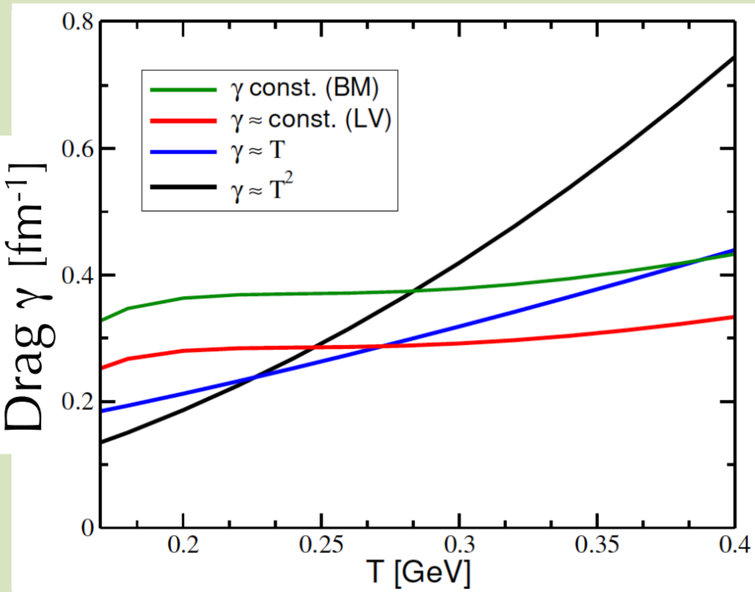


Large uncertainties on the theoretical calculations due to the charm cross section and shadowing

- p_T > 0.3 GeV/c to remove possible J/ψ photo-production contribution [5]
- Brackets represent maximum remaining contribution

- Results are compared with calculations based on different models:
  - Two transport models (**TM1 [1]** and **TM2 [2]**): continuous interplay between dissociation and (re)generation
  - **Statistical hadronisation model [3]:** all J/ψ are dissociated in the plasma. (Re)generation occurs at the phase boundary
  - **Comover model (CIM) [4]:** J/ψ are suppressed via interaction with a parton co-moving medium. (Re)generation added as a gain term
- **Measurement is precise enough to constrain the models**

Impact of T dep. interaction on $R_{AA} - v_2$

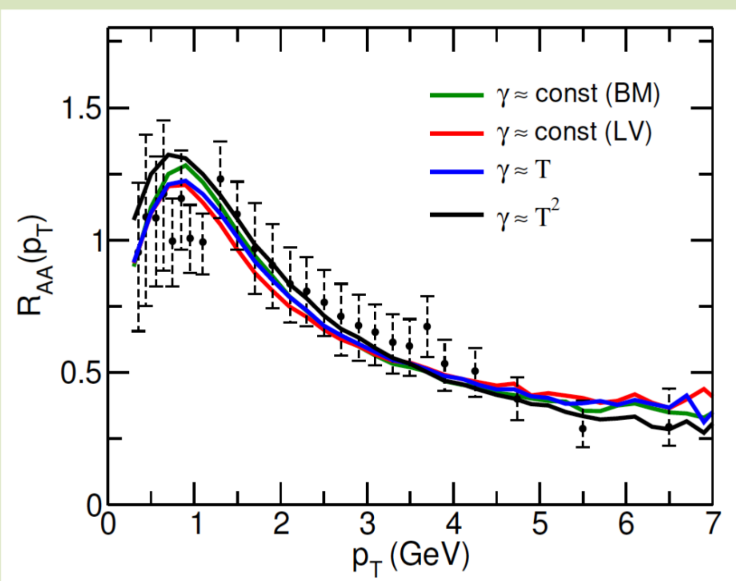


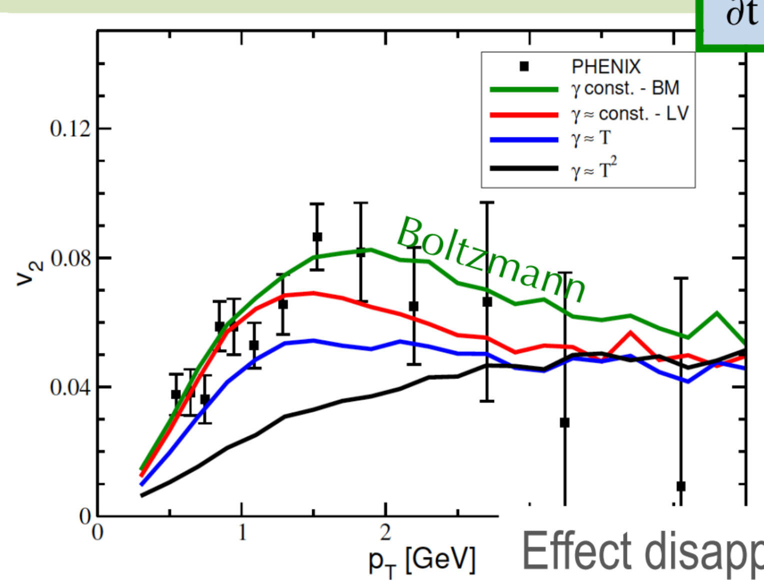
Looking at it beyond the specific modelings

- **$\gamma \approx T^2$** [Ads/CFT, pQCD α_s=const, *Duke*]
- **$\gamma \approx T$** [pQCD strong α_s running] [MC@HQ] [LBT]
- **$\gamma \approx$ const.** [QPM, PHSD,..] [T-matrix]

γ rescaled to fit $R_{AA}(p_T)$, D from FDT

$$\frac{\partial f_Q}{\partial t} = \gamma \frac{\partial (p f_Q)}{\partial p} + D \frac{\partial^2 f_Q}{\partial p^2}$$



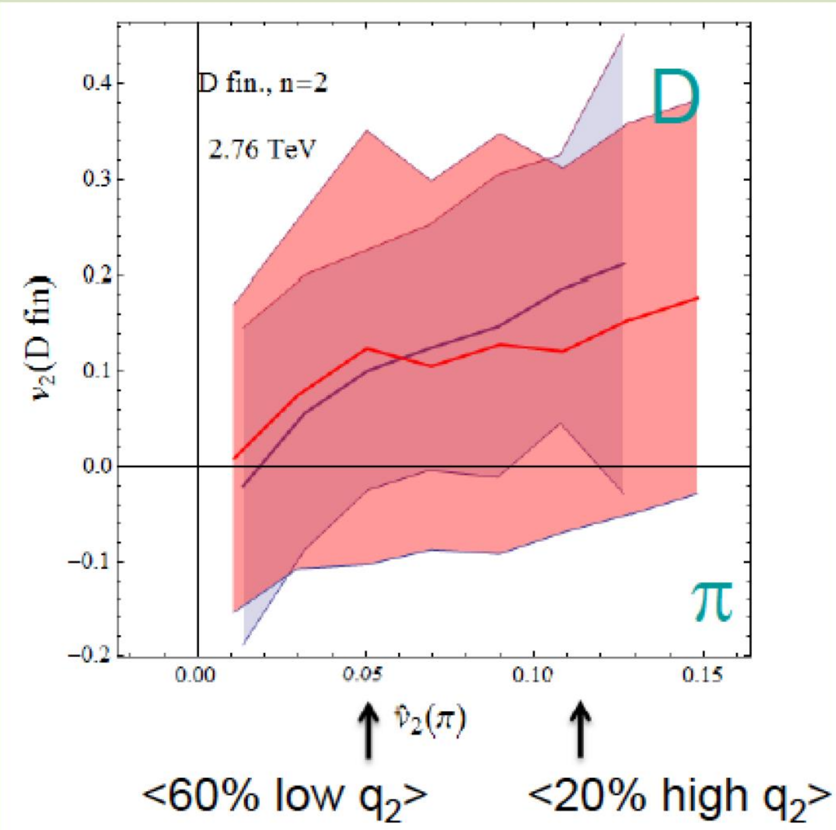


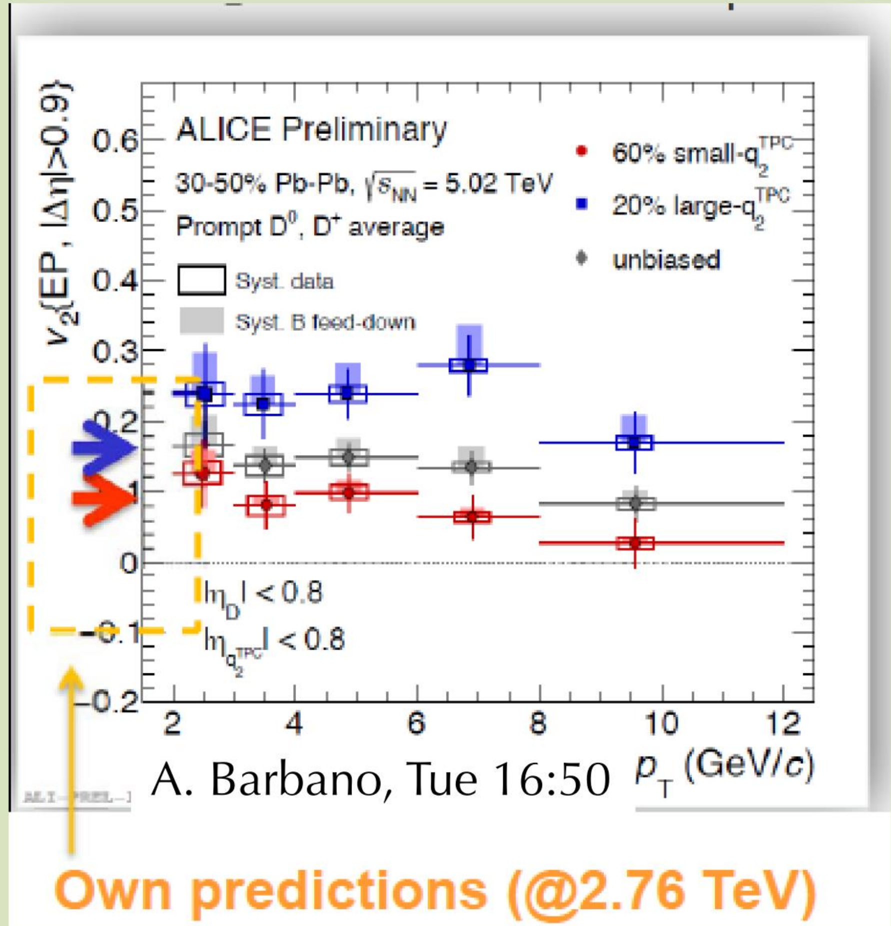
Effect disappears at p_T> 3 GeV
extends for v_3 Caio's talk

S. Das et al., PLB747 (2015) 260

How v_2 of D is build-up?

SUBATECH-Nantes [MC@sNLO + EPOS]





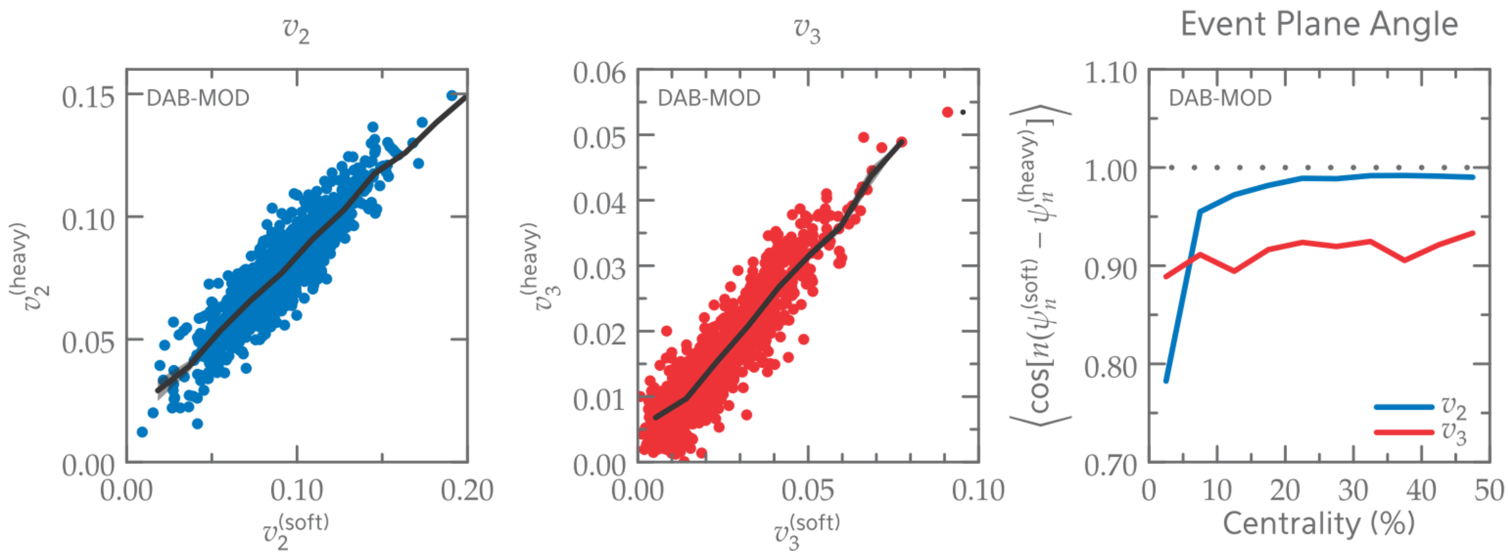
This is just the beginning of a new step forward, how we will learn from it … next QM2018

Gossiaux over night calculation

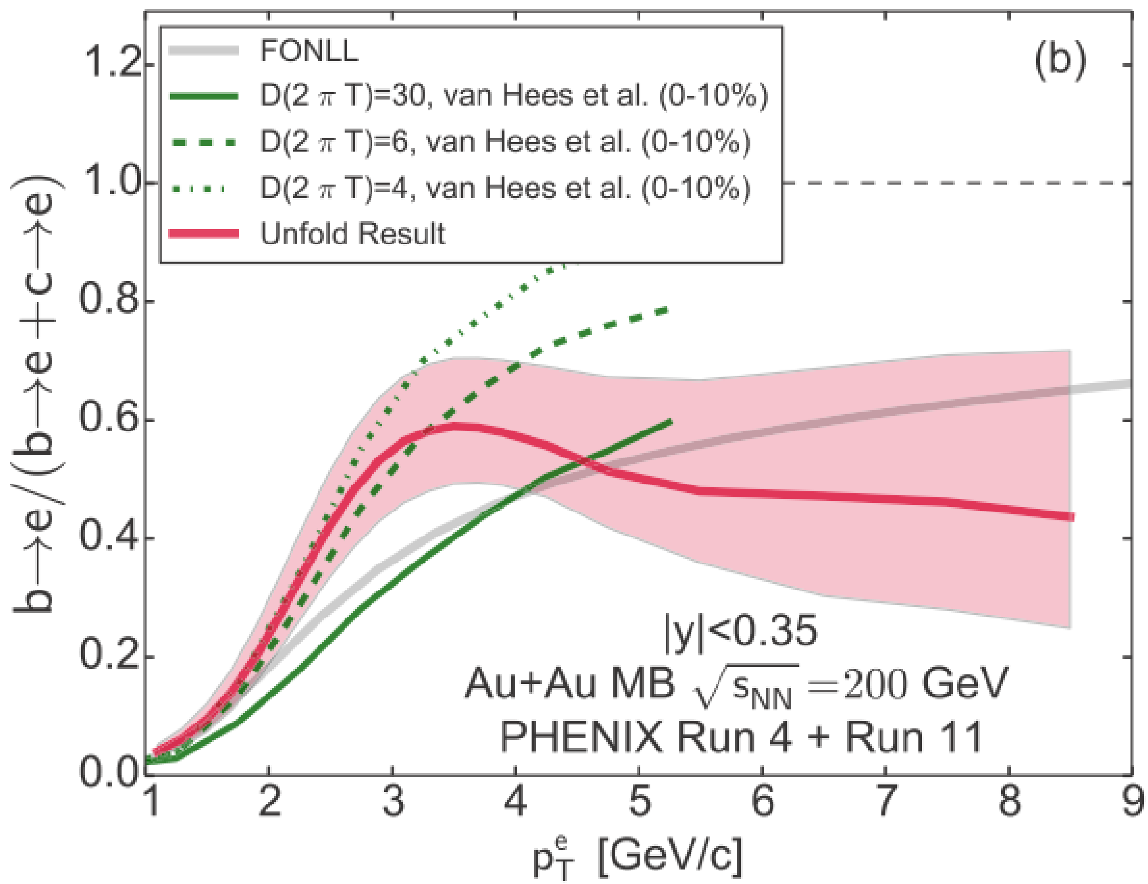
Flow Harmonics

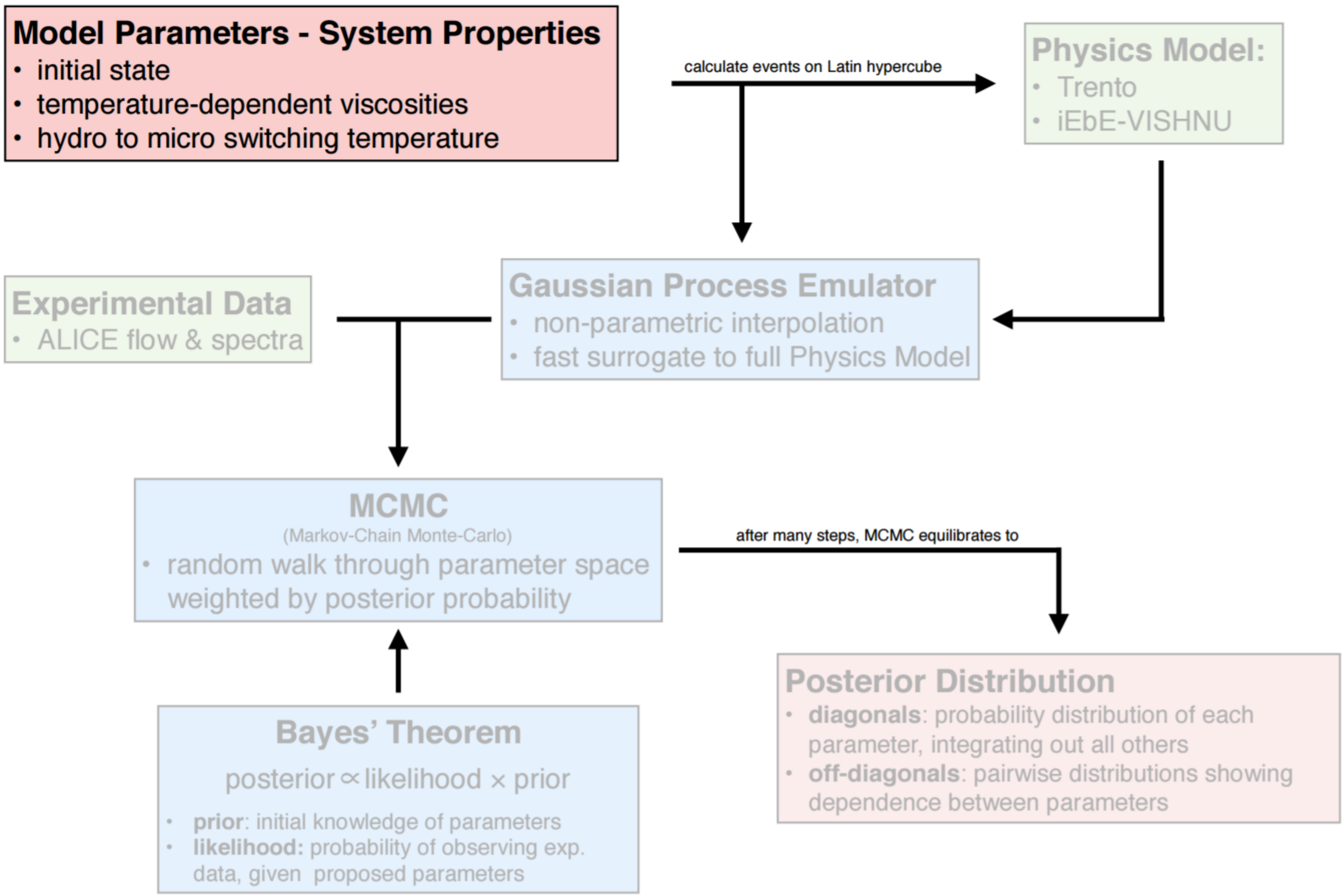
- 2-particle correlation: $v_n\{2\}(p_T) = \frac{\left\langle v_n^{(\text{heavy})}(p_T) v_n^{(\text{soft})} \cos\left[n\left(\psi_n^{(\text{heavy})}(p_T) - \psi_n^{(\text{soft})}\right)\right]\right\rangle}{\sqrt{\left\langle \left(v_n^{(\text{soft})}\right)^2 \right\rangle}}.$
  - This formula maximizes v_n.
  - Heavy and soft sectors have the medium as the same underlying cause for flow;

D meson; 30–40% Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV



Noronha-Hostler *et al*, PRL **116**, 252301 (2016) Nahrgang *et al*, PRC **91**, 014904 (2015)


FONLL
D(2 π T)=30, van Hees et al. (0-10%)
D(2 π T)=6, van Hees et al. (0-10%)
D(2 π T)=4, van Hees et al. (0-10%)
Unfold Result
(b)
|y|<0.35
Au+Au MB √sNN =200 GeV
PHENIX Run 4 + Run 11
b→e/(b→e+c→e)
pTe [GeV/c]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1
2
3
4
5
6
7
8
9


Model Parameters - System Properties
• initial state
• temperature-dependent viscosities
• hydro to micro switching temperature
calculate events on Latin hypercube
Physics Model:
• Trento
• iEbE-VISHNU
Experimental Data
• ALICE flow & spectra
Gaussian Process Emulator
• non-parametric interpolation
• fast surrogate to full Physics Model
MCMC
(Markov-Chain Monte-Carlo)
• random walk through parameter space weighted by posterior probability
after many steps, MCMC equilibrates to
Bayes' Theorem
posterior ∝ likelihood × prior
• prior: initial knowledge of parameters
• likelihood: probability of observing exp. data, given proposed parameters
Posterior Distribution
• diagonals: probability distribution of each parameter, integrating out all others
• off-diagonals: pairwise distributions showing dependence between parameters