Utrecht University

Netherlands Organisation for Scientific Research

Heavy-flavour and quarkonia Experiment

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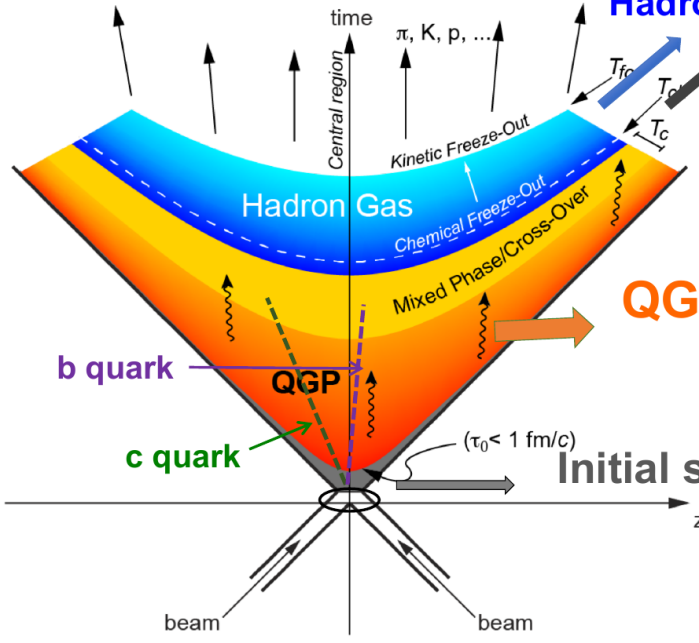
Hard Probes, Student Lecture

30 September 2018

Heavy-flavour in medium

- Heavy c, b quarks produced dominantly at the early hard scattering stage → production cross-section calculable within pQCD; hard fragmentation
- Energy loss of parton due to interactions with the medium → medium transport properties



Hadronic phase

Hadronization

Fragmentation vs recombination

QGP/partonic phase

Microscopic interaction with medium constituents

Initial stages

Produced in initial high-Q^2 processes → calculable with pQCD

Large mass → short formation time → experience medium evolution

Interplay of different mechanisms

↓

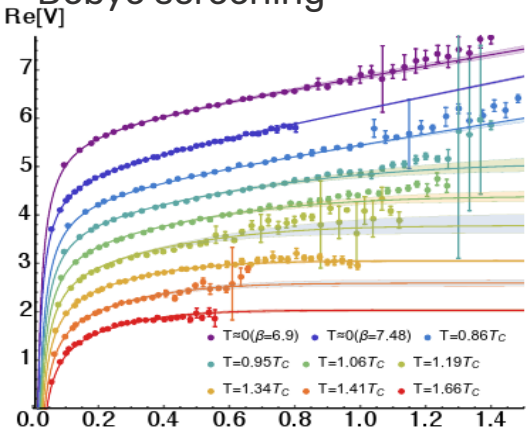
crucial to understand the observed results (R_{AA}, v_2,…)

E. Bruna, QM 2018
HF summary

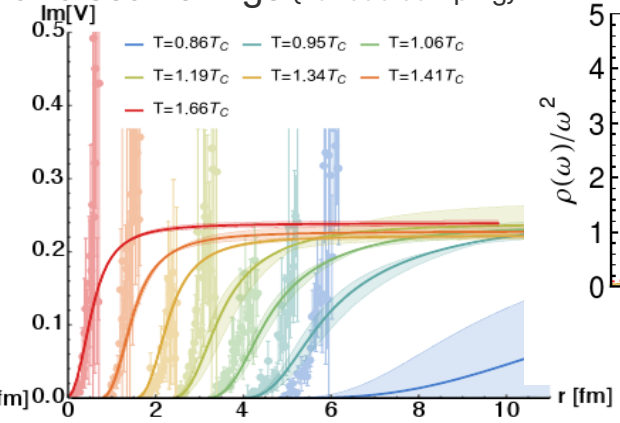
Quarkonia in medium

- Quarkonia: hard probes sensitive to hot and dense medium
  - Debye screening, sequential suppression in the medium expected

Quarkonium gradually weakened by Debye screening and scatterings (Landau damping)



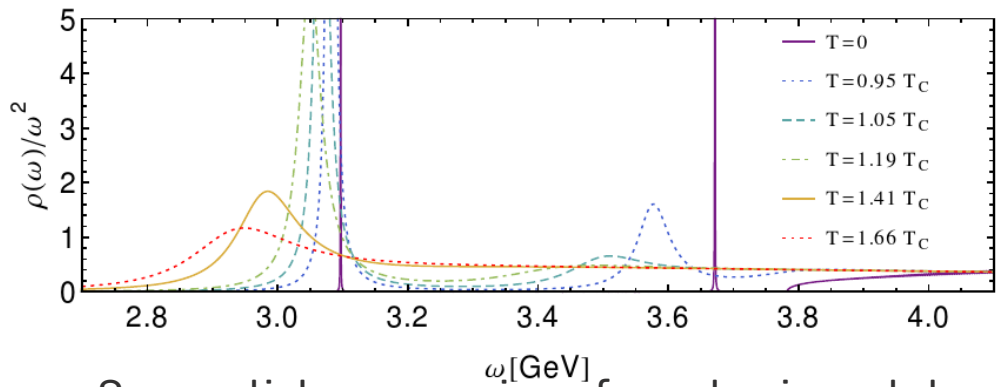
Real part of the in-medium heavy quark potential



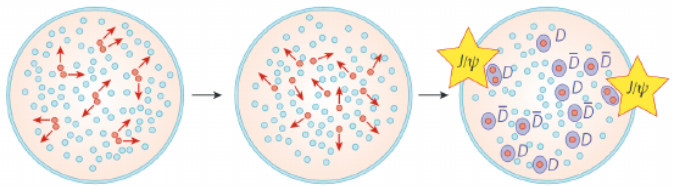
Imaginary part of the in-medium heavy quark potential

[Burnier, Kaczmarek & Rothkopf, JHEP 1512 (2015) 101, JHEP 1610 (2016) 032]

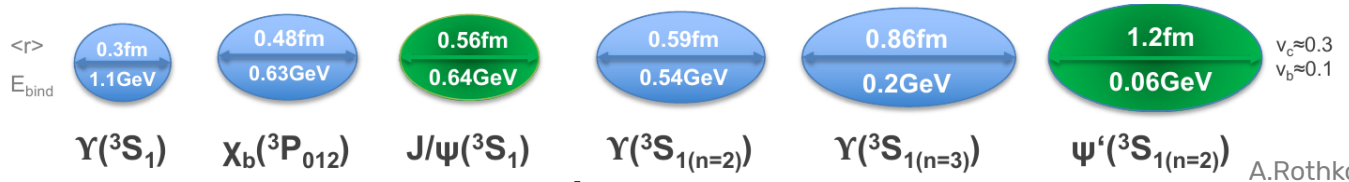
Charmonium (S-wave) in-medium spectral functions



Sequential suppression of quarkonium states + recombination

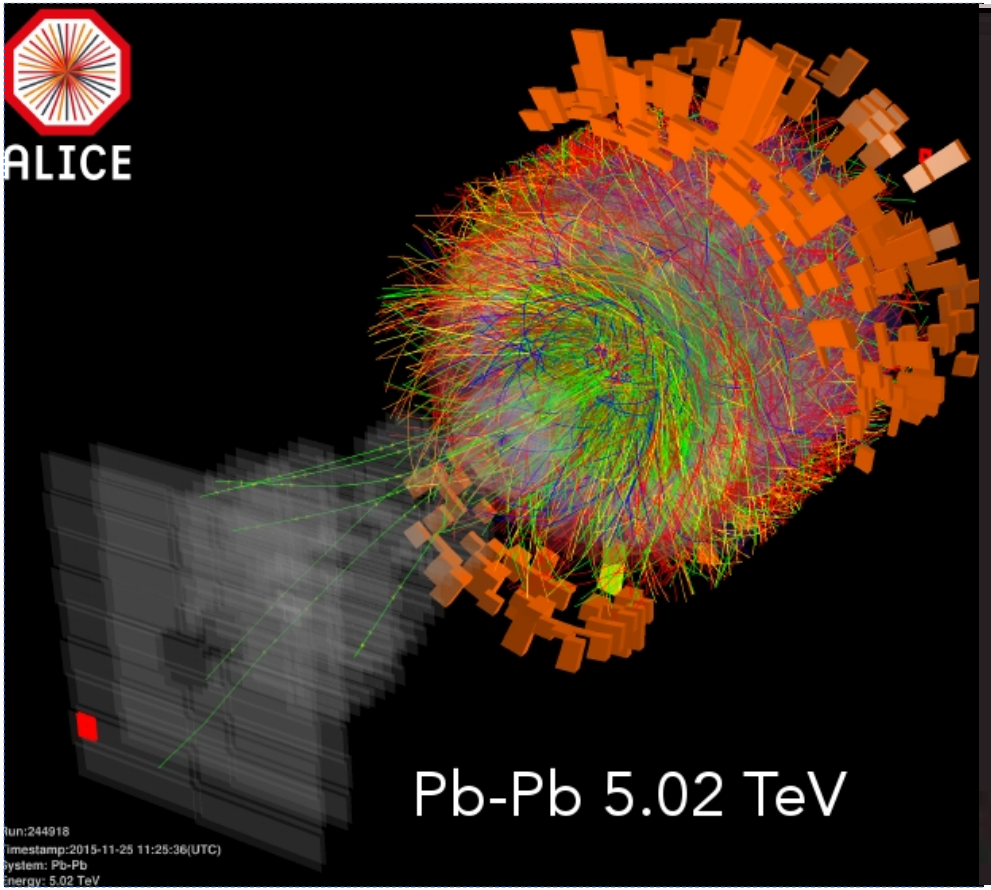


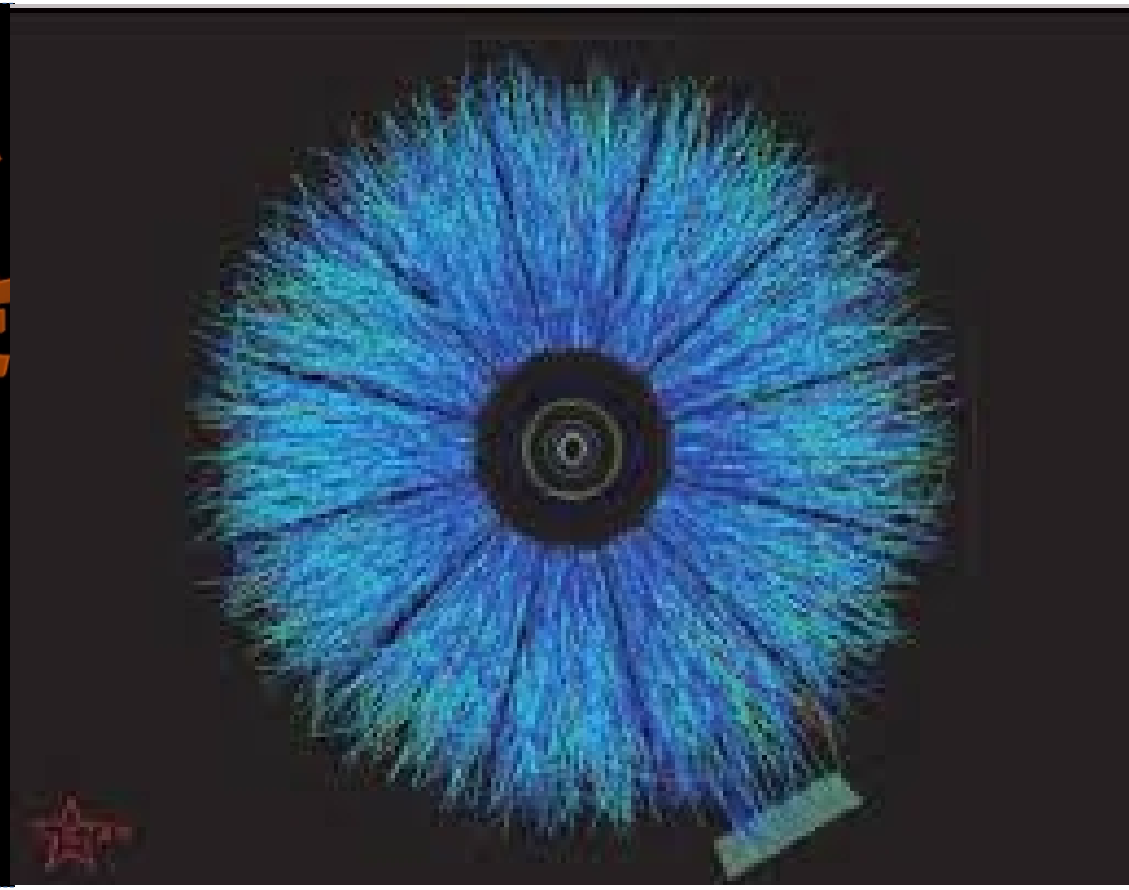
[Braun-Munzinger & Stachel, Nature 448 (2007) 302]



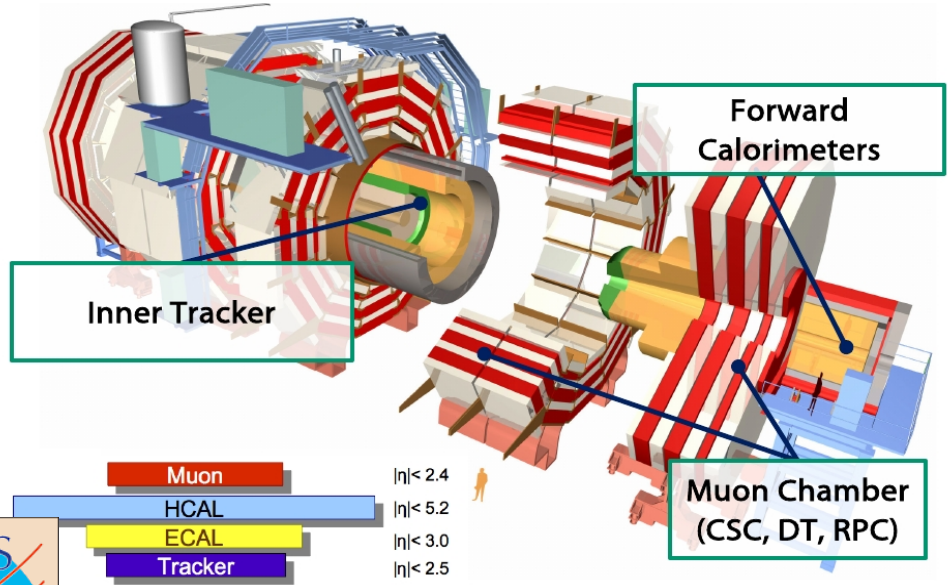
A.Rothkopf, QM18

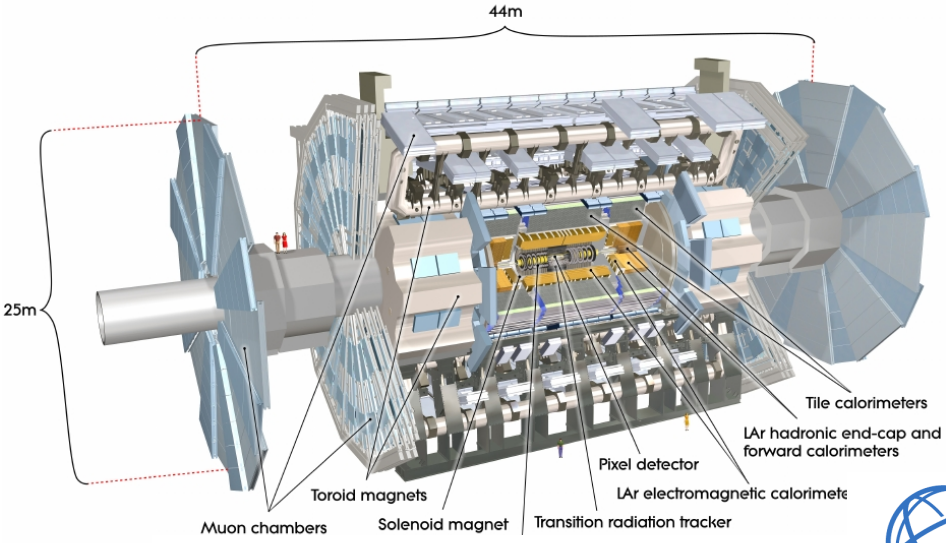
Experimental facilities

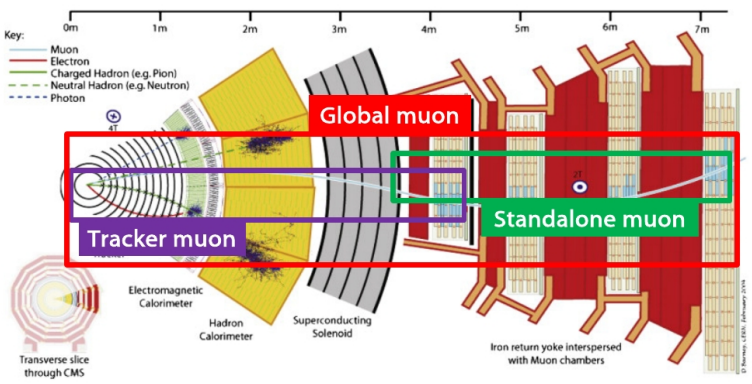


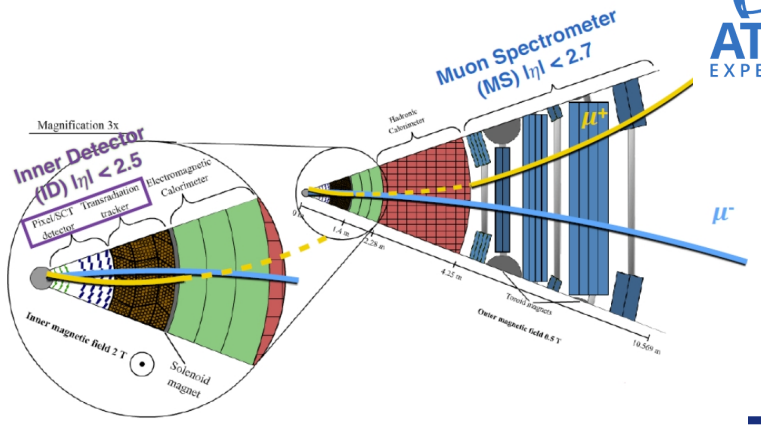


LHC: CMS, ATLAS detectors

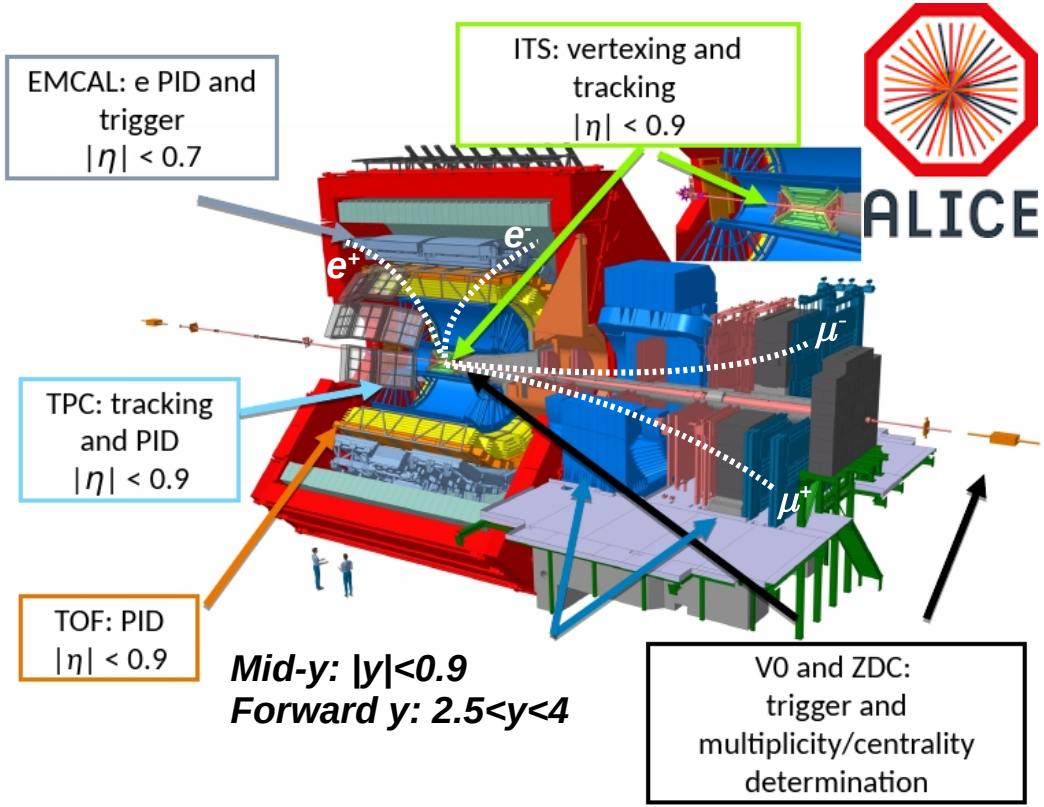




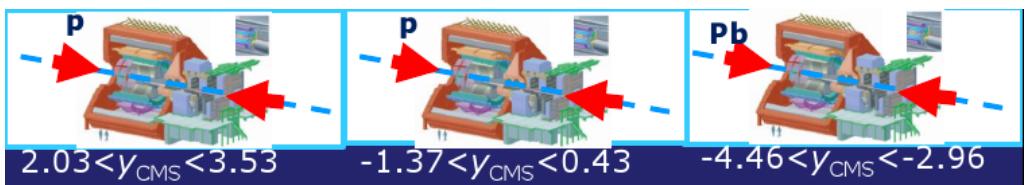




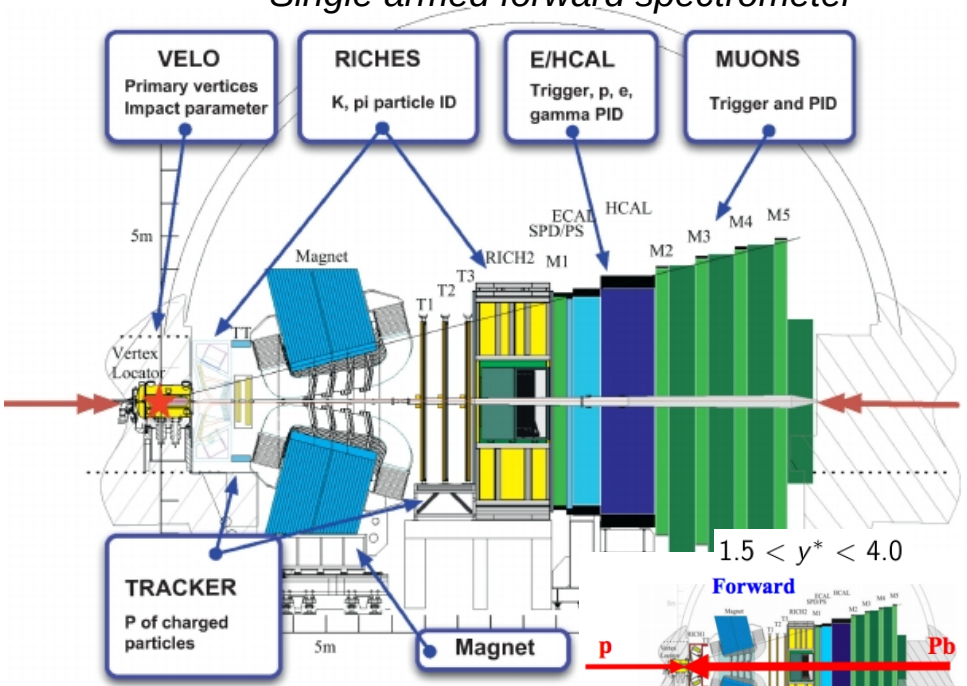
LHC: ALICE, LHCb detectors



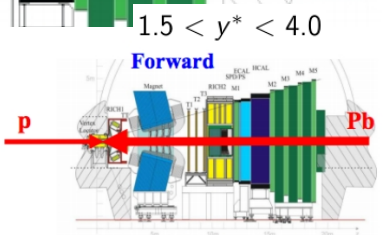
Mid-y: |y|<0.9
Forward y: 2.5<y<4

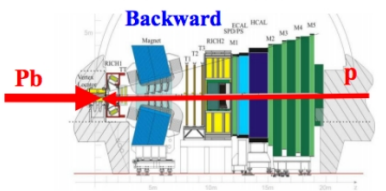


Single armed forward spectrometer



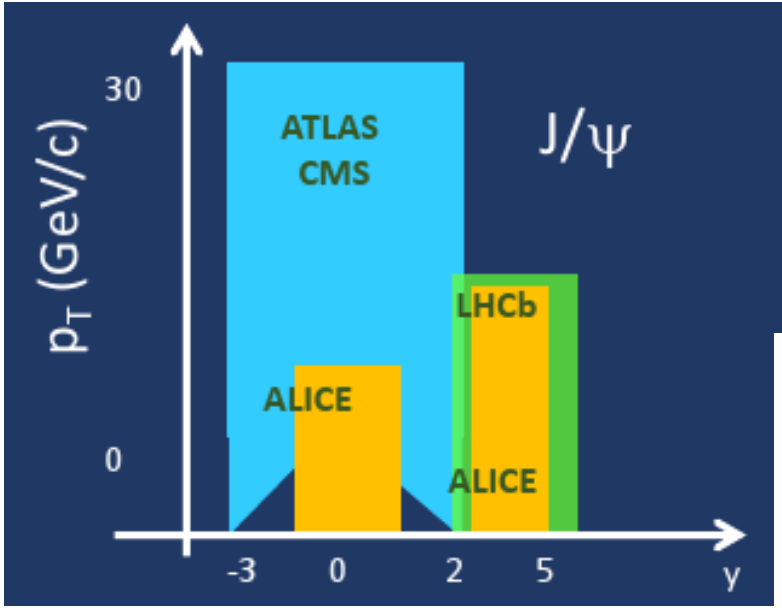
Acceptance: 2 < η < 5





LHC datasets

- Mostly proton and Pb beams, short Xe-Xe run last year
  - Different kinematic coverages of the experiments – complementary information
  - Asymmetric pA collisions → rapidity shift of 0.465 (different energy of the two beams)
    - p-Pb and Pb-p setup
  - LHCb: also a fixed-target mode



Exp.	System	$\sqrt{s_{NN}}$ (TeV)
ALICE ATLAS CMS LHCb	PbPb, XeXe	2.76, 5.02, 5.44
	pPb	5.02, 8.16
	pp	2.76, 5, 7, 8, 13

RHIC: PHENIX and STAR detectors

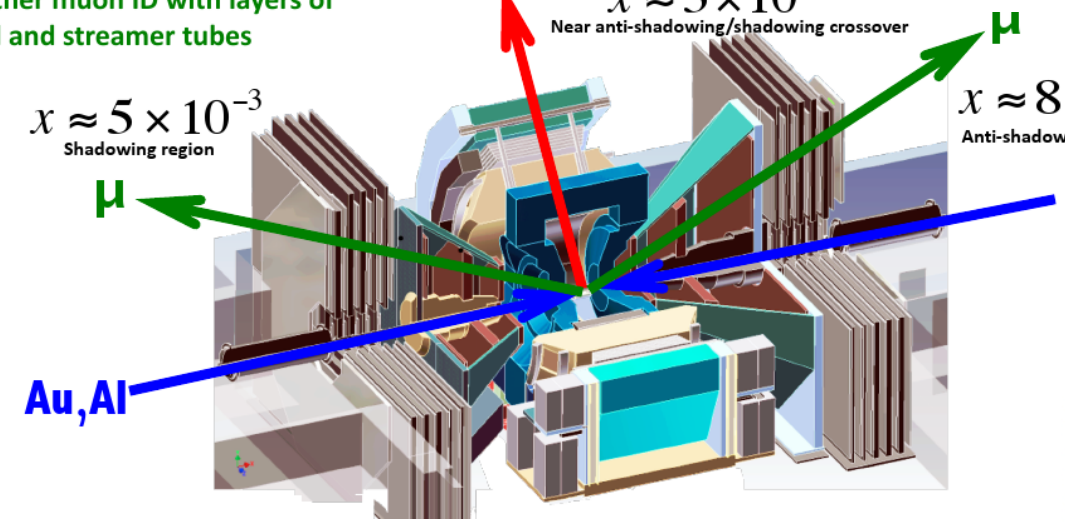
Muons: 1.2 < |y| < 2.2,
-Tracked with silicon,wire chambers
-Further muon ID with layers of steel and streamer tubes

Electrons: |y| <0.35,
-Tracked with DC,PC
-ID with RICH, EmCal

$x \approx 3 \times 10^{-2}$
Near anti-shadowing/shadowing crossover

$x \approx 5 \times 10^{-3}$
Shadowing region

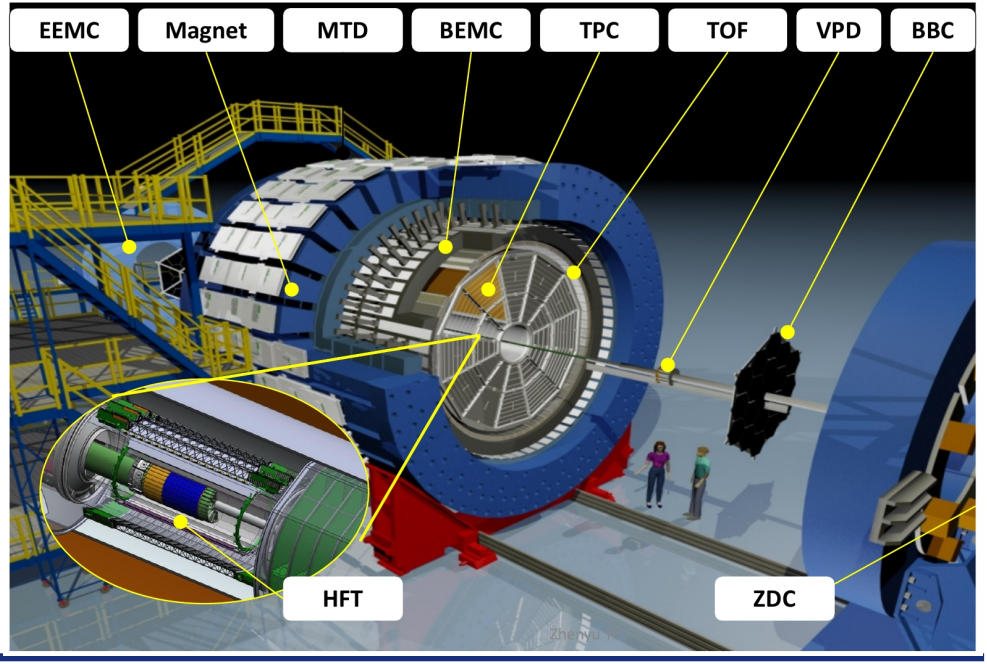
$x \approx 8 \times 10^{-2}$
Anti-shadowing region



PHENIX

VTX and FVTX improving tracking and vertexing

STAR



MTD: di-muon trigger,
Heavy Flavor Tracker: excellent vertex resolution
TPC, TOF, BEMC: $|\eta| < 1$
HFT (2014-2016): $|\eta| < 1$
MTD (2014+): $|\eta| < 0.5$

- **On-going/future upgrades**
  - iTPC (2019+): $|\eta| < 1.5$
  - eTOF (2019+): $-1.6 < \eta < -1$
  - FCS (2021+): $2.5 < \eta < 4$
  - FTS (2021+): $2.5 < \eta < 4$

RHIC datasets

- Colliding many species in a broad energy range
  - Top: 200 (510) GeV for AA (pp) collisions

√s [GeV]	p+p	p+Al	p+Au	d+Au	^{3}He+Au	Cu+Cu	Cu+Au	Au+Au	U+U
510	✓								
200	✓	✓	✓	✓	✓	✓	✓	✓	✓
130								✓	
62.4	✓			✓		✓		✓	
39				✓				✓	
27								✓	
20				✓		✓		✓	
14.5								✓	
7.7								✓	

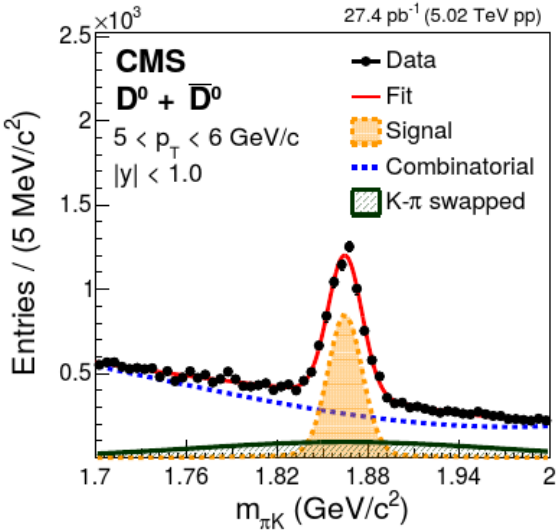
Signal reconstruction

- charm/beuty hadrons:
  - hadronic decays, identification mostly using displaced topology of the decay (+ PID)
  - Semi-leptonic decays
- Quarkonia: di-lepton decay channels, identification based on electron/muon identification

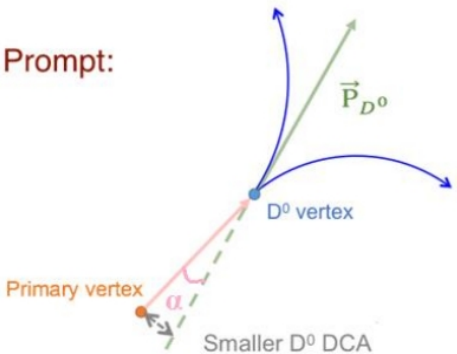
$$J/\psi, \Upsilon \rightarrow \mu^+ \mu^-$$
$$J/\psi, \Upsilon \rightarrow e^+ e^-$$

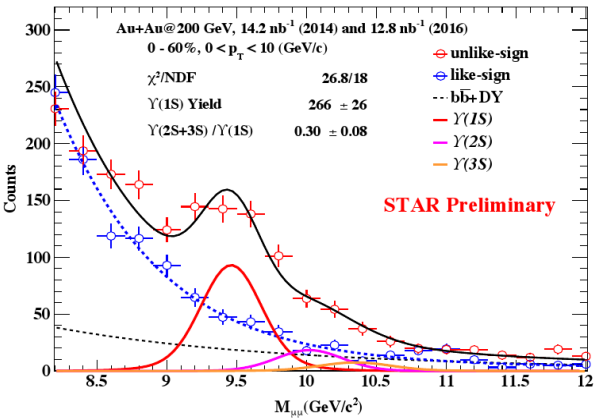
Signal reconstructed using invariant mass technique

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



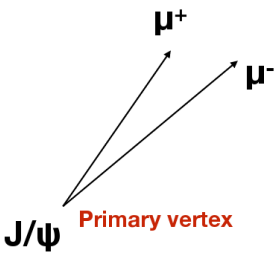
Signal: (double) Gaussian
Bkg: polynomial/exponential



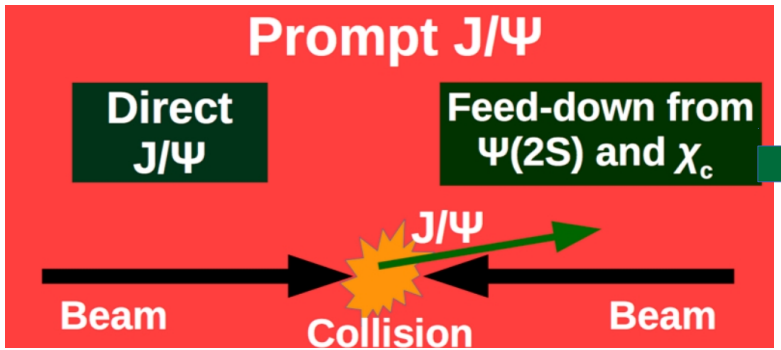


Signal: Crystal Ball
Uncorrelated bkg: like-sign pairs, mixed-event, rotation (*e.g.* fitted with exponential)
Correlated bkg: ccbar, bbbar, Drell-Yan

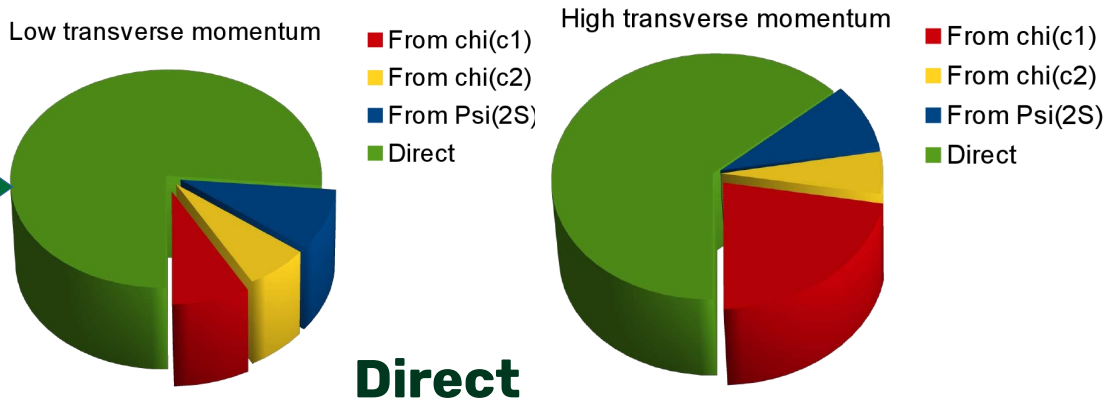
Prompt J/ψ:



Feed-down contributions



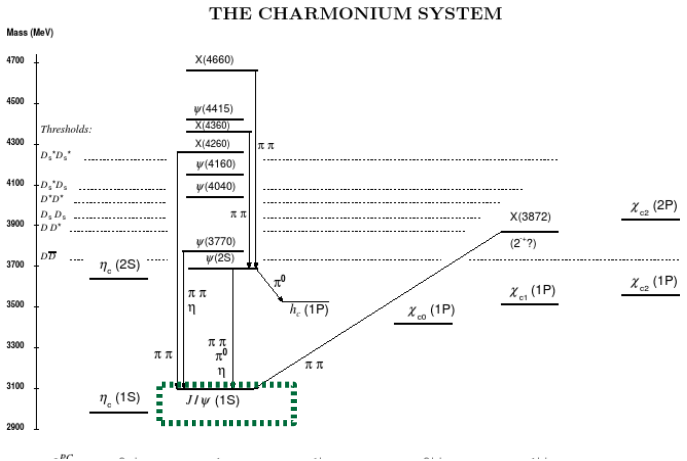
A.Rothkopf, QM18

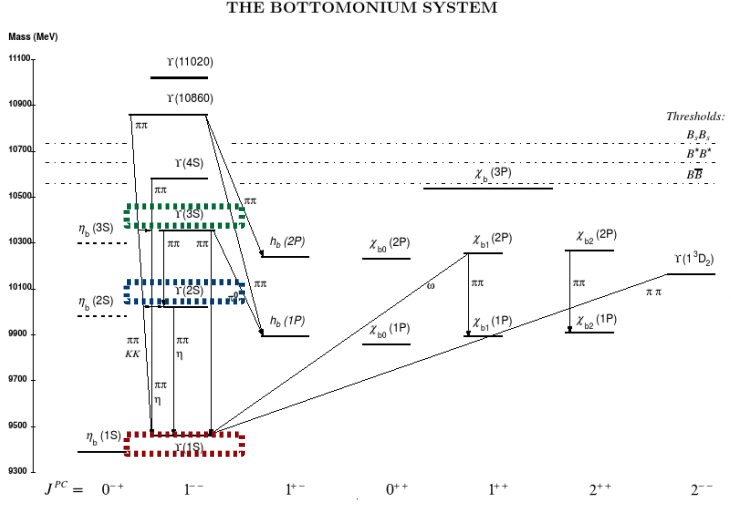


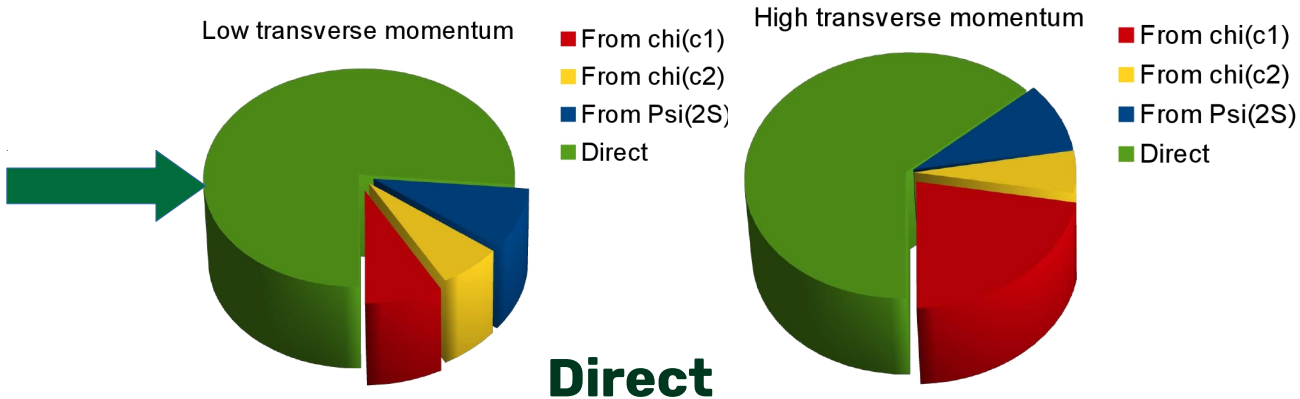
Direct

Eur. Phys. J. C (2016) 76: 107

Feed-down contributions







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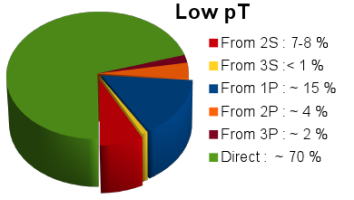
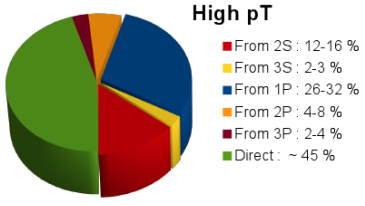
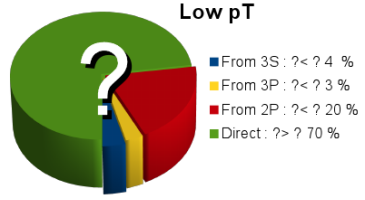
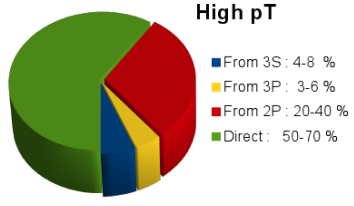


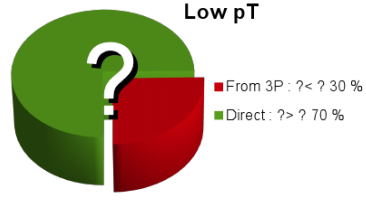


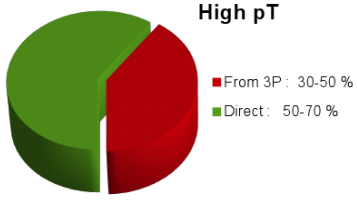
(a) Υ(1S)





(b) Υ(2S)





(c) Υ(3S)

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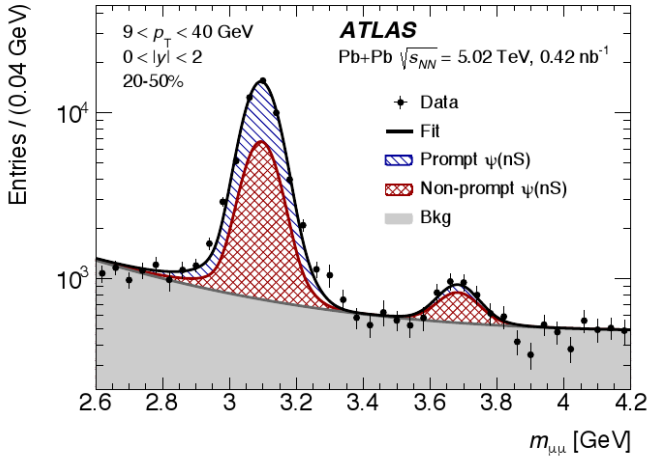
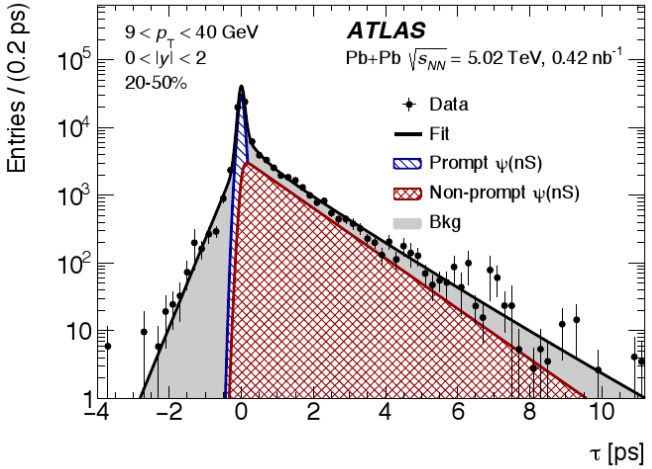
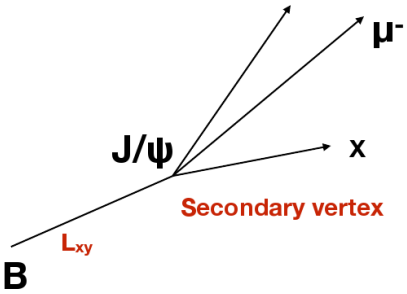
Non-prompt reconstruction

from b-hadron decays



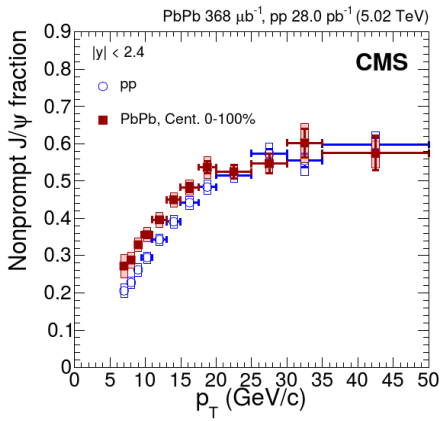


Non-prompt J/ψ: μ^+ μ^-



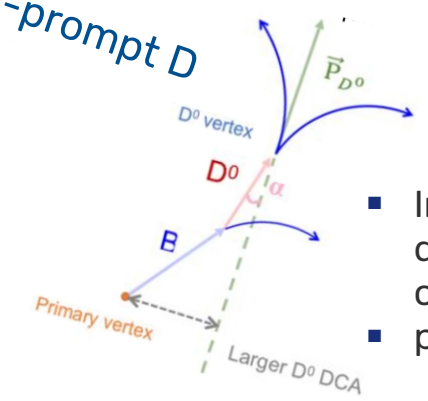
Pseudo-proper decay time

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_T^{\mu\mu}}$$

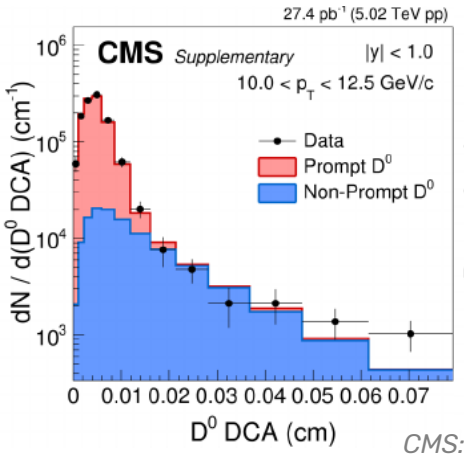


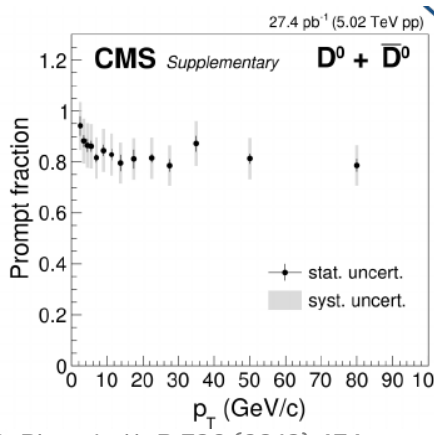
ATLAS: arXiv:1805.04077

Non-prompt D



- Impact parameter distribution
  or
- pQCD calculations



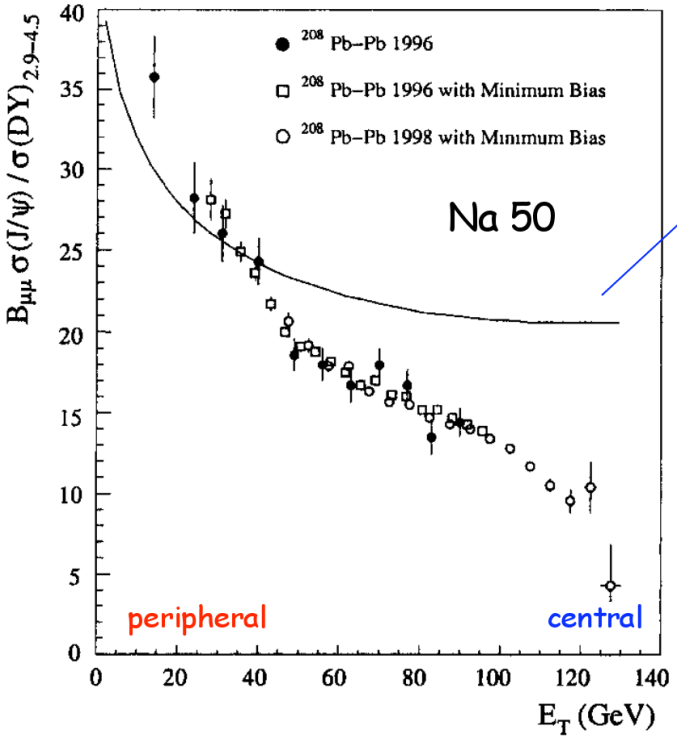


CMS: Phys. Lett. B 782 (2018) 474

“Anomalous” J/ψ suppression at SPS

“Anomalous” suppression of J/psi production yield w.r.t. “normal nuclear absorption” –
“… natural explanation in the framework of a deconfined state of quarks and gluons”

CERN-EP-2000-013



- Quarkonia sensitive to:
  - Debye screening
  - Cold Nuclear Matter effects: nPDFs – (anti-)shadowing, nuclear absorption

Usually suppression quantify using nuclear modification factor:

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

Nuclear overlap function → collision geometry

$$\langle T_{AA}\rangle = \frac{N_{coll}}{\sigma_{inel}}$$

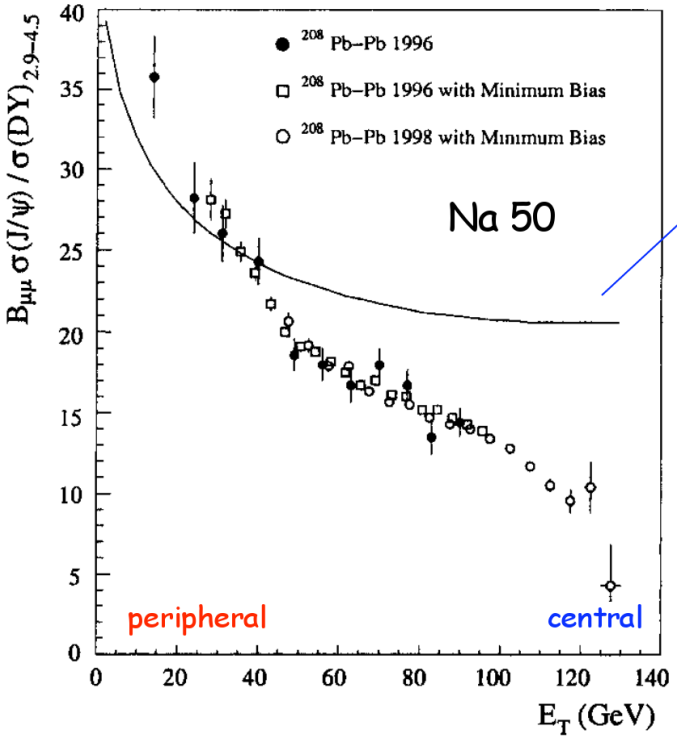
$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll}\rangle}\frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

Number of binary collisions

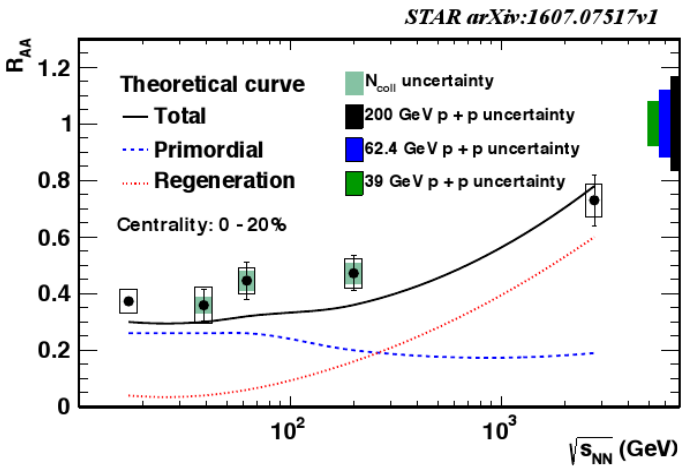
“Anomalous” J/ψ suppression at SPS

“Anomalous” suppression of J/psi production yield w.r.t. “normal nuclear absorption” –
“… natural explanation in the framework of a deconfined state of quarks and gluons”

CERN-EP-2000-013



- Quarkonia sensitive to:
  - Debye screening
  - Cold Nuclear Matter effects: nPDFs – (anti-)shadowing, nuclear absorption, co-movers …
  - Regeneration in the medium
  - Medium induced energy loss
  - + feed-down



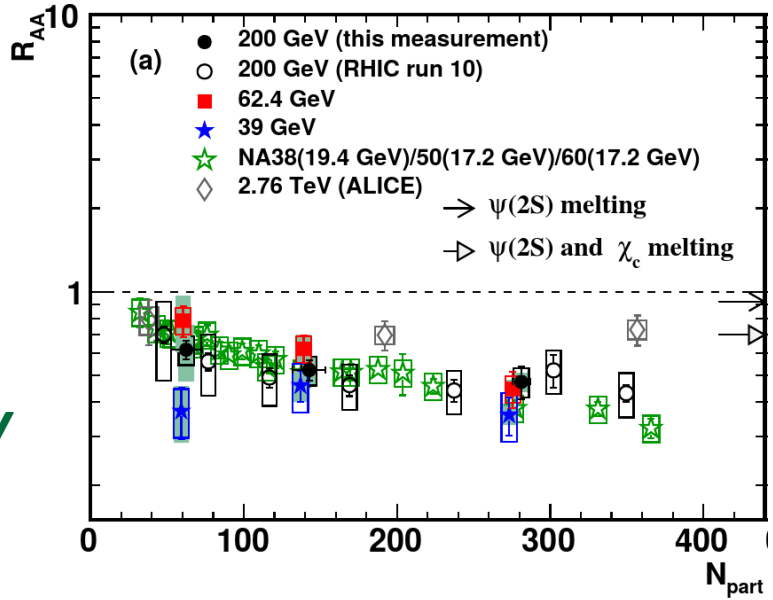
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

$$R_{AA} = \frac{\sigma_{inel}}{\langle N_{coll}\rangle}\frac{d^2N_{AA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

J/ψ in AA – energy scan **low p_T**

Mid-rapidity
Low p_T

2.76 TeV
200 GeV
62.4 GeV
39 GeV
17, 19 GeV



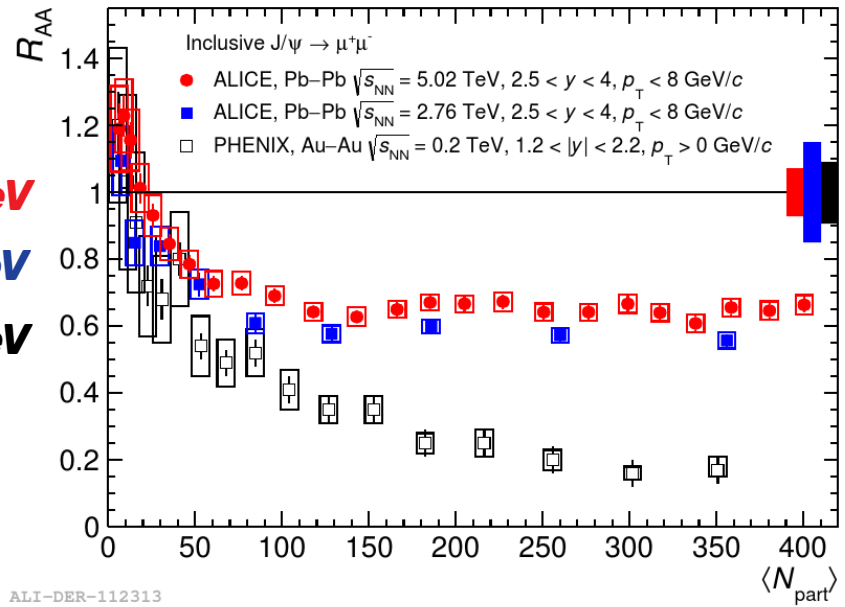
- Similar suppression at RHIC and SPS
- Strong suppression at RHIC energies
  - Increasing with collision centrality
- Less suppression at LHC

ALICE Collaboration PLB 766 (2017) 212
PHENIX Collaboration PRL 98 (2007) 232301

- **Similar suppression at SPS and RHIC energies**

J/ψ in AA – energy scan **low p_T**

Froward (backward) rapidity
Low p_T



5.02 TeV

2.76 TeV

200 GeV

ALICE Collaboration PLB 766 (2017) 212
PHENIX Collaboration PRL 98 (2007) 232301

- Similar suppression at RHIC and SPS
- Strong suppression at RHIC energy, 200 GeV
  - Increasing with collision centrality
- Less suppression at LHC, 2.76 and 5.02 TeV
  - Inconsistent with pure colour screening picture
  - Not strong energy dependence
  - Saturation with collision centrality

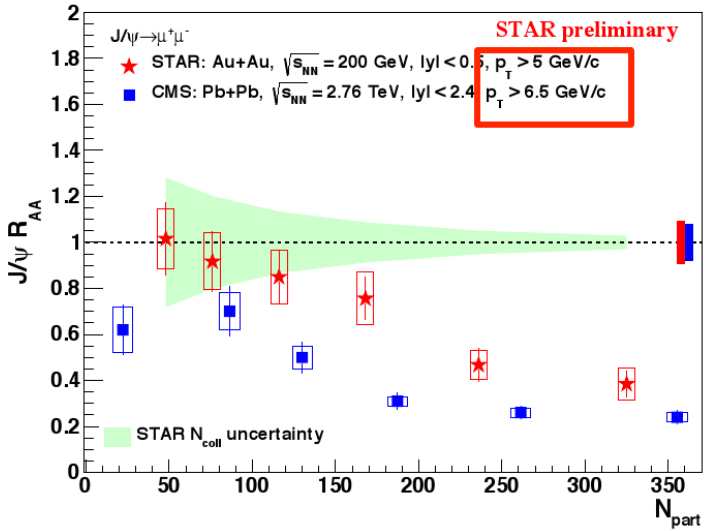
- **Weaker suppression at LHC than at RHIC, low p_T**

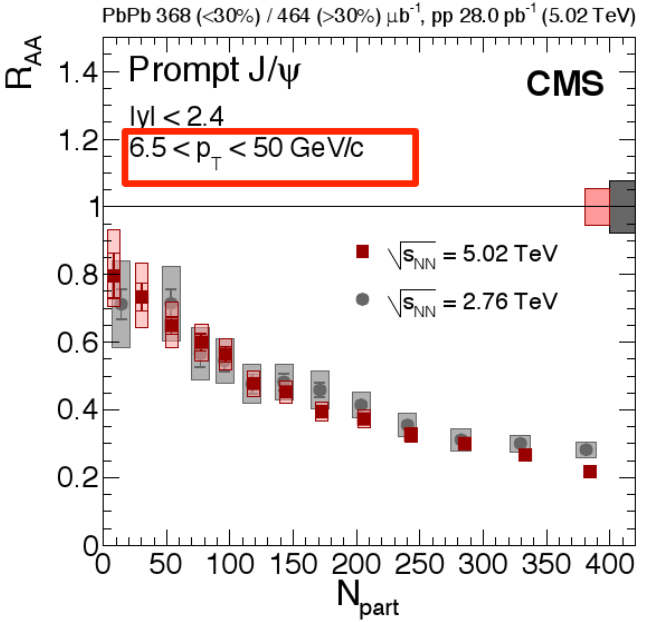
J/ψ in AA – energy scan **high p_T**

Mid-rapidity
High p_T

200 GeV

2.76 TeV





2.76 TeV

5.02 GeV

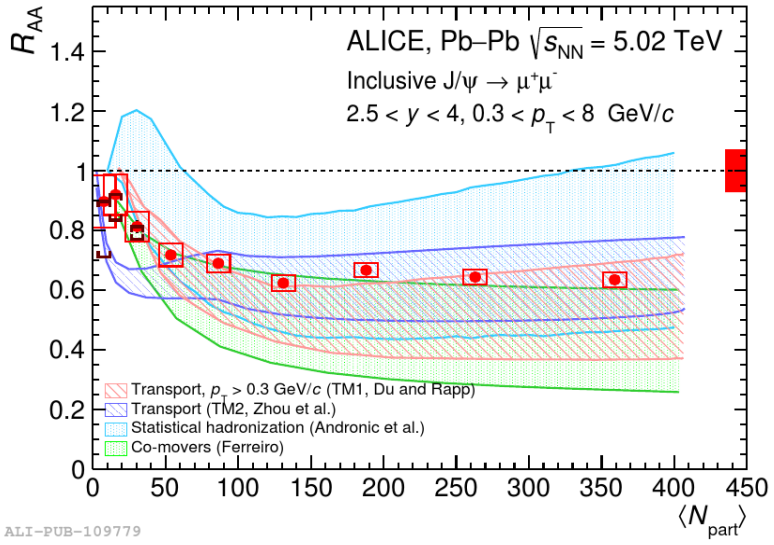
- **Stronger suppression at LHC than at RHIC, high p_T**
- Increasing suppression with centrality
  - Smaller regeneration (and CNM) effects

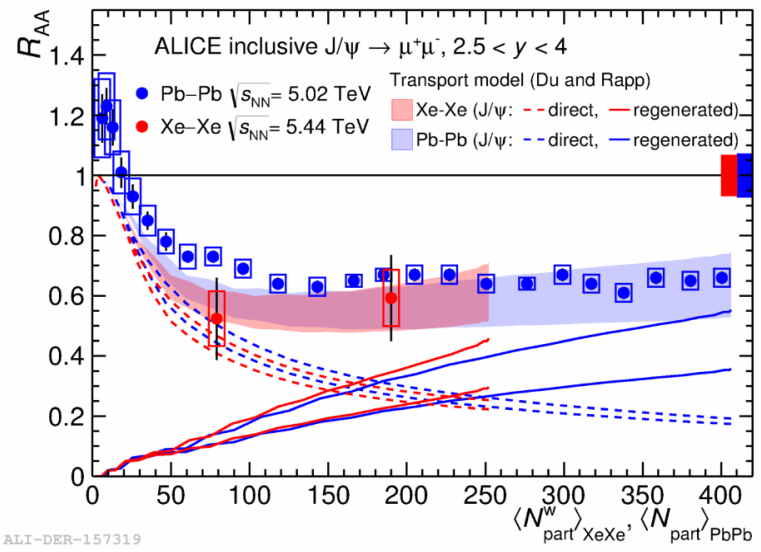
$$R_{AA}^{RHIC} >\sim R_{AA}^{LHC/2.76TeV} >\sim R_{AA}^{LHC/5.02TeV}$$

ATLAS: arXiv:1805.04077

J/ψ in AA – model comparison

Froward rapidity
Low p_T





Pb-Pb 5.02 TeV

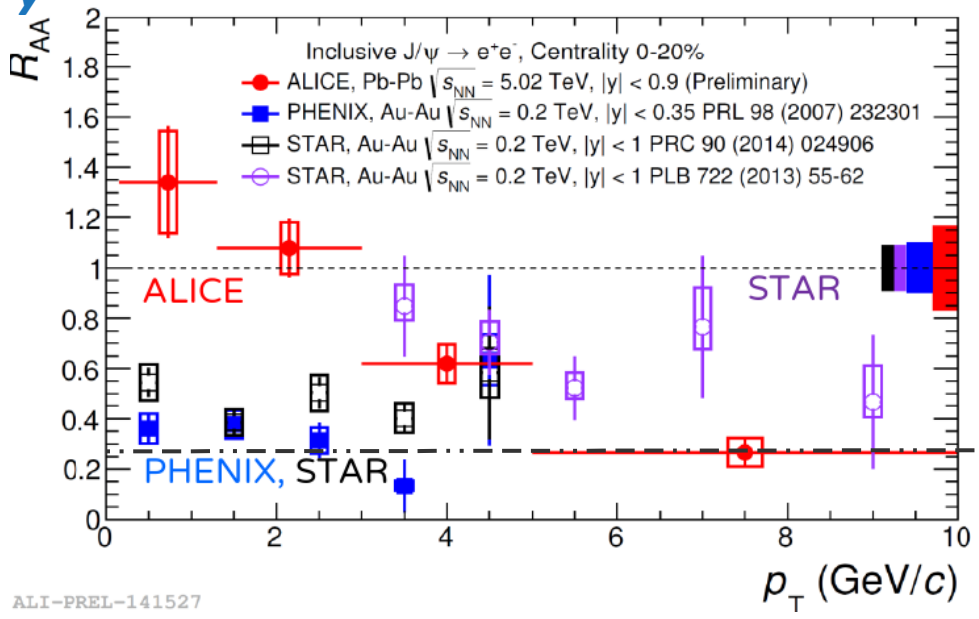
Xe-Xe 5.44 TeV

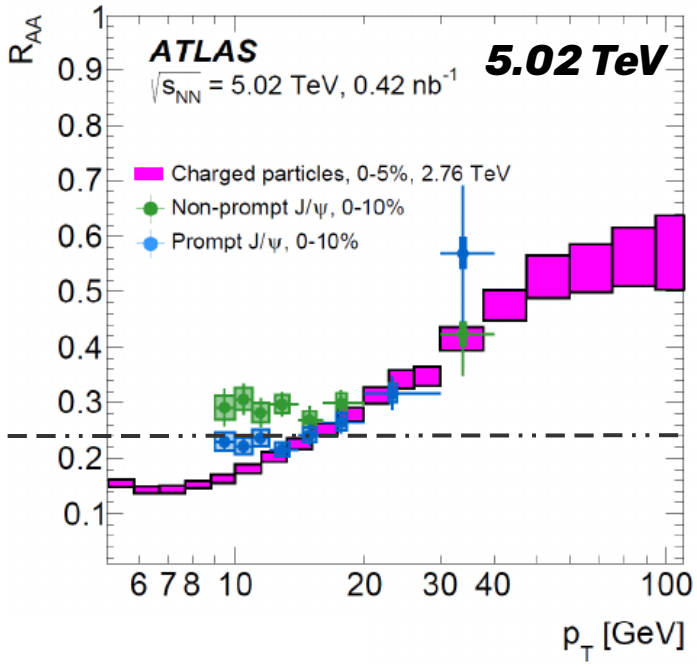
- Similar level of suppression at 2.76 and 5.02 TeV in Pb-Pb and in Xe-Xe at 5.44 TeV
  - Xe-Xe: similar relative contribution of suppression and regeneration
- Consistency with different approaches: transport: dissociation + regeneration, statistical model, co-movers
  - Large uncertainties; hard to discriminate between different models

ALICE: PLB 766 (2017) 212
ALICE: arXiv:1805.04383

J/ψ in AA – p_T dependence

mid-y



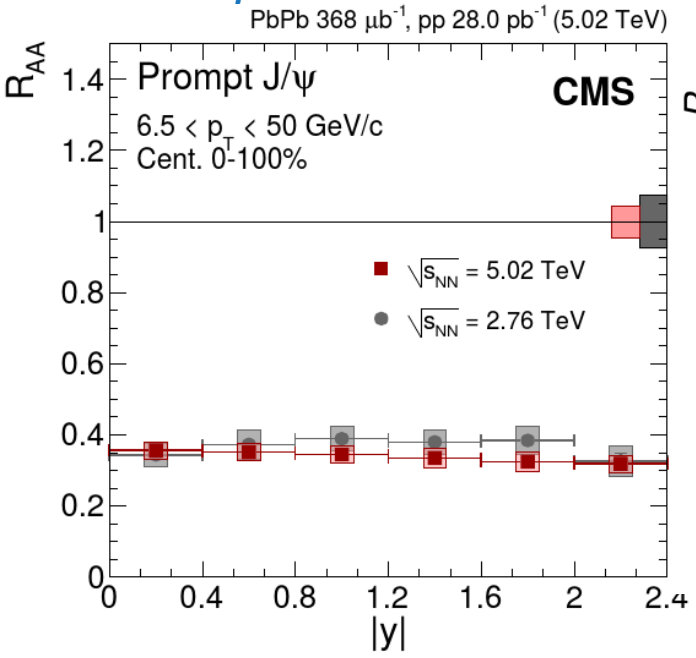


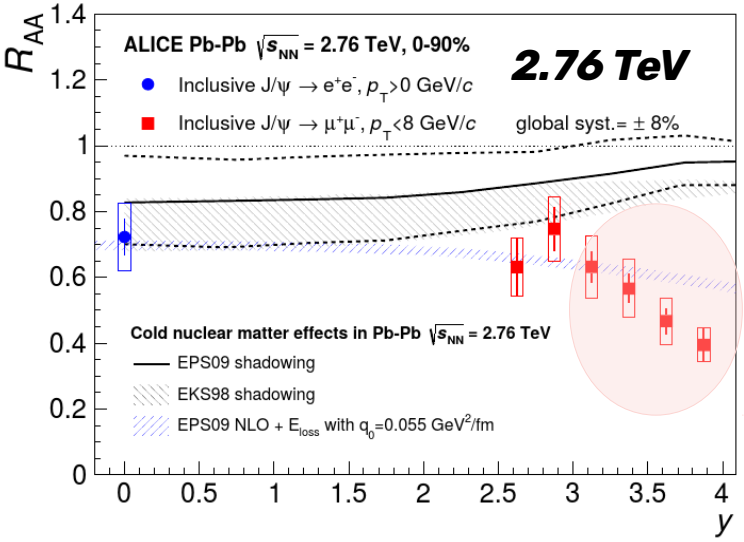
- **Different p_T dependences at RHIC and LHC**
- **LHC: Smaller suppression at low p_T – regeneration in play ?**
- Decreasing suppression with centrality at p_T >~ 12 GeV/c
  - Suppression similar to charged hadrons and open charm at p_T >~ 12 GeV/c. Parton energy loss ?

ATLAS: arxiv: 1805.04077

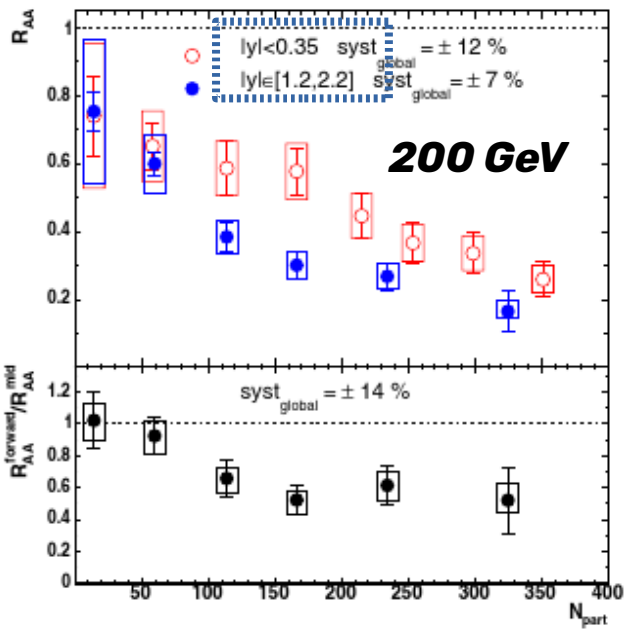
J/ψ in AA – y dependence

High p_T





Low p_T



- Increasing suppression towards forward rapidity, both at RHIC and LHC.
  - Suggests smaller recombination component.

PHENIX:
CMS: Eur. Phys. J. C 78 (2018) 509

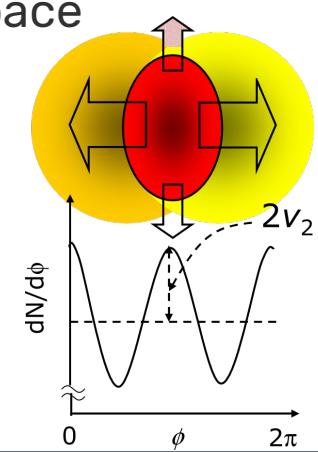
Heavy-flavour v_2 in AA

- Heavy-flavour v_2 probe:
  Low/intermediate p_T – collective motion, degree of thermalization of heavy quarks and hadronization mechanism (recombination)
  High p_T – path-lenght dependence of the energy loss

- Strongly interacting medium – pressure gradients:
  initial spatial anisotropy → final momentum anisotropy
  - $\mathbf{v_2}$ – second component of Fourier decomposition of particle azimuthal distribution in momentum space

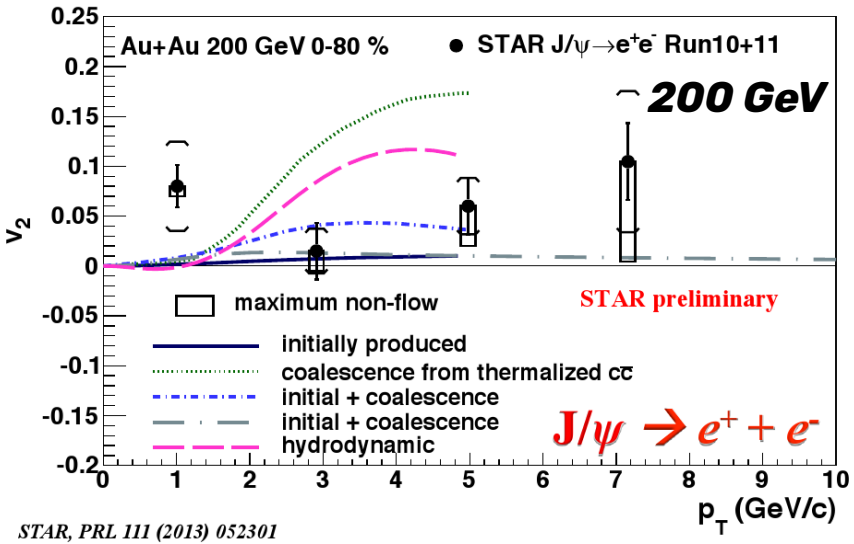
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{i=1}^{\infty} 2v_n \cos(n(\phi - \Phi_n^{RP}))\right)$$

$$v_2 = \langle \cos 2(\phi - \psi) \rangle$$



J/ψ v_2 in AA

- J/ψ inherits v_2 from (thermalized) c quarks ?



STAR, PRL 111 (2013) 052301

- Strongly interacting medium – pressure gradients:
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  - **v_2** – second component of Fourier decomposition of particle azimuthal distribution in momentum space

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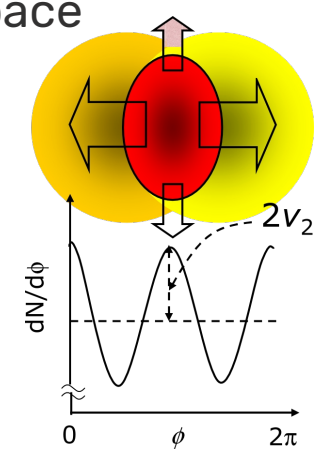
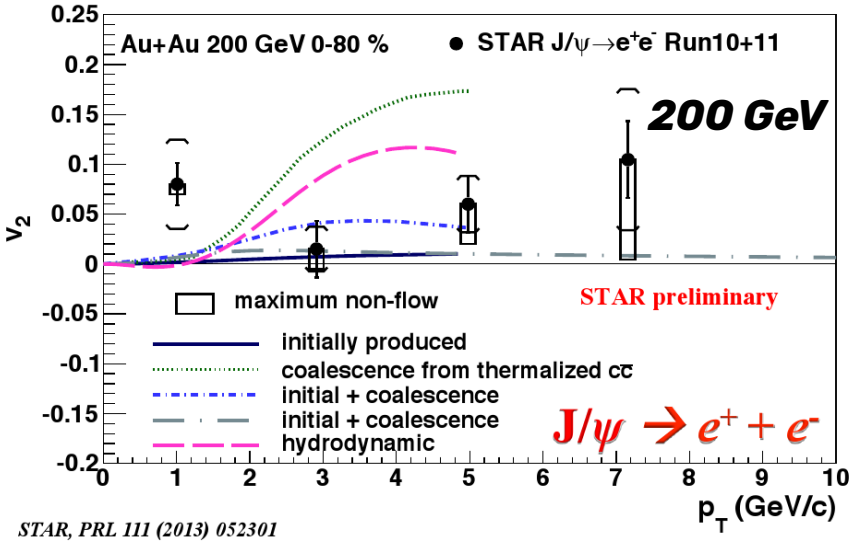


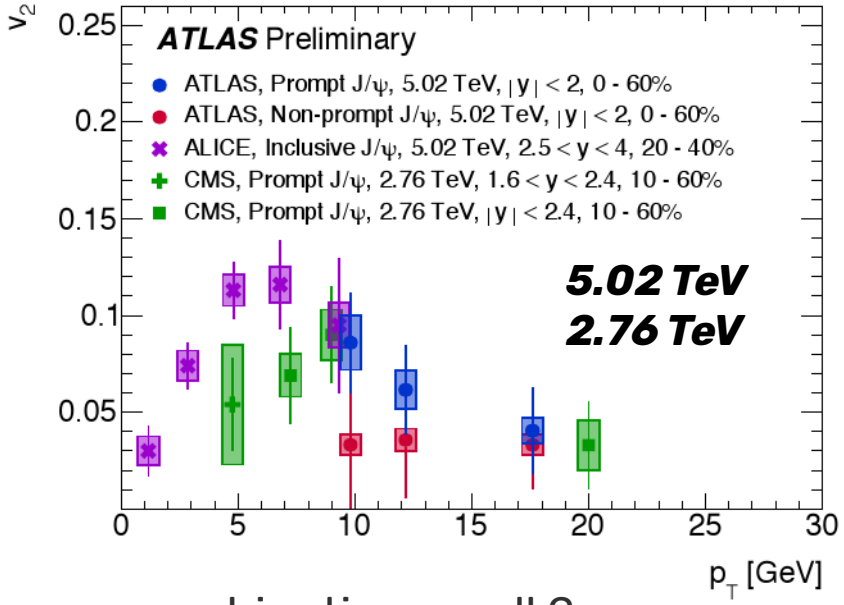
- RHIC: v_2 consistent with 0 – contribution from recombination small ?

J/ψ v_2 in AA

- J/ψ inherits v_2 from (thermalized) c quarks ?



STAR, PRL 111 (2013) 052301



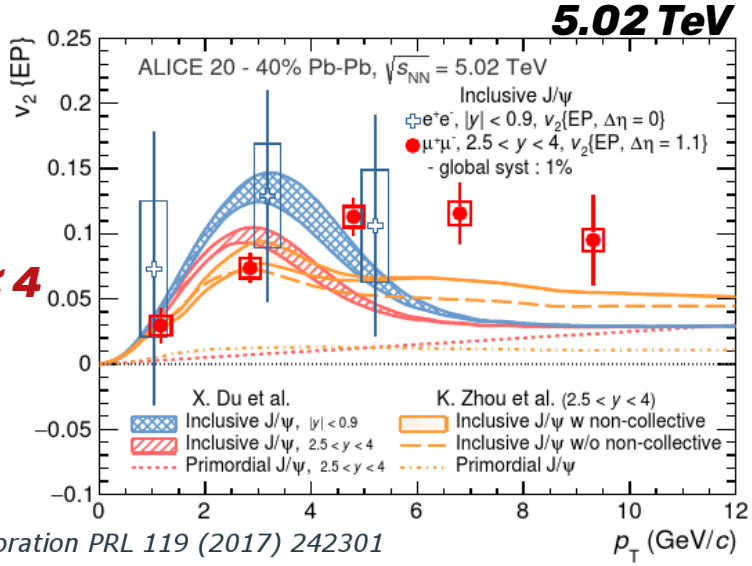
- RHIC: v_2 consistent with 0 – contribution from recombination small ?
- LHC: Positive v_2 up to ~20 GeV/c.

ALICE Collaboration PRL 119 (2017) 242301
ALICE Collaboration PRL 120 (2018) 102301
ATLAS-CONF-2018-013
CMS, EPJC 77 (2017) 252

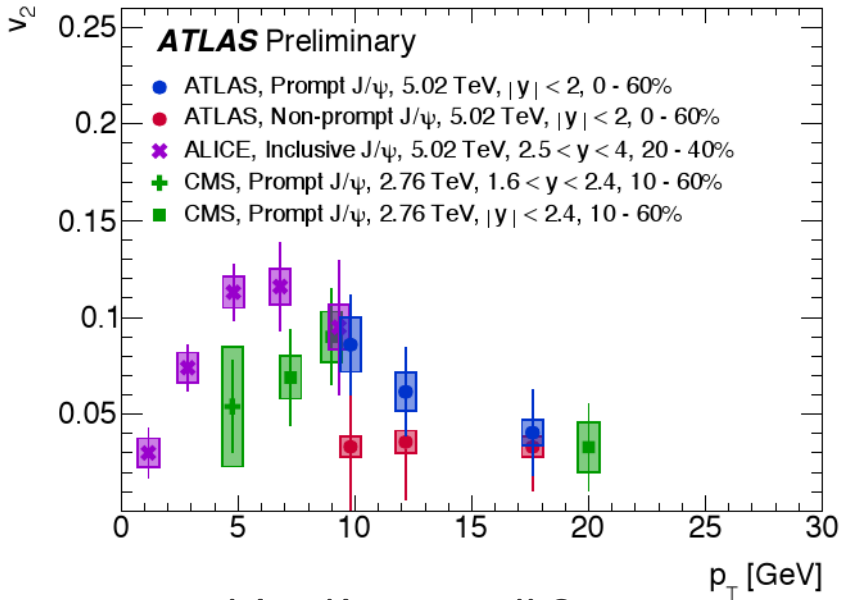
J/ψ v_2 in AA

- J/ψ inherits v_2 from (thermalized) c quarks ?

ATLAS-CONF-2018-013
CMS, EPJC 77 (2017) 252



ALICE Collaboration PRL 119 (2017) 242301
ALICE Collaboration PRL 120 (2018) 102301



- RHIC: v_2 consistent with 0 – contribution from recombination small ?
- LHC: Positive v_2 up to ~20 GeV/c.
- Low p_T: reproduced with strong J/ψ recombination component.
- High p_T: path length dependence of the parton energy loss ? But v_2 still under-predicted.

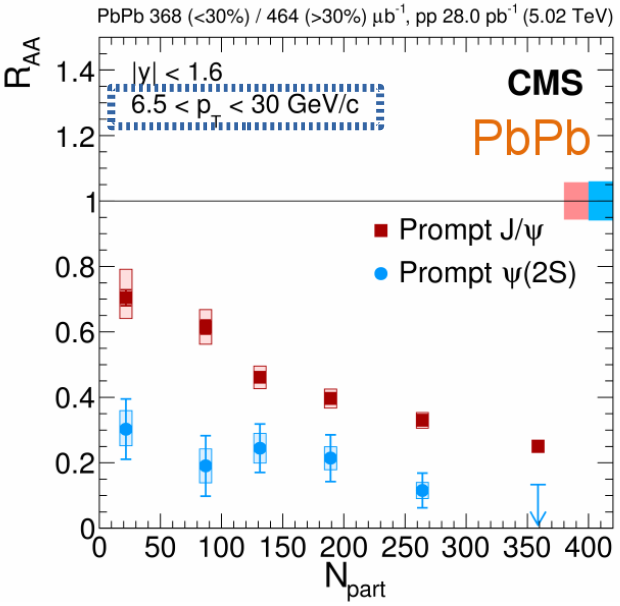
What about ψ(2S) in AA ?

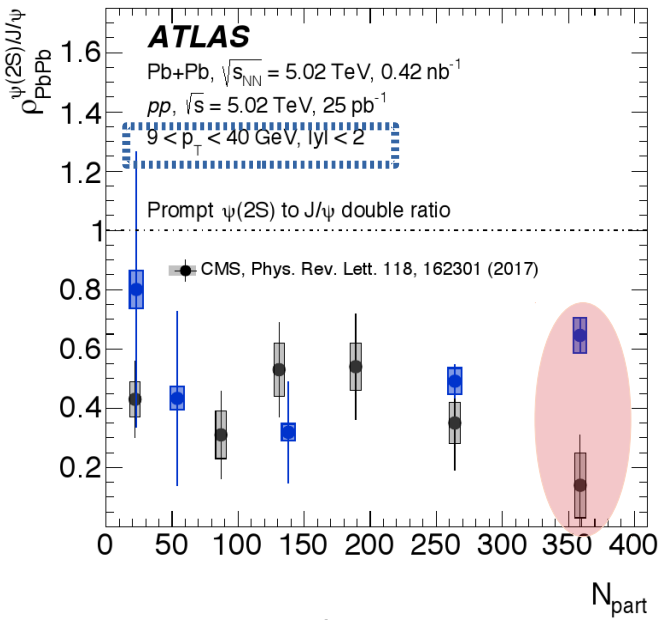
- ψ(2S) larger size and weaker binding compare to J/ψ
  - Different strength of medium effects on the two states production
  - Are the CNM effects the same ?

$$\rho_{\mathrm{PbPb}}^{\psi(2S)/J\psi} = R_{\mathrm{AA}}^{\psi(2S)} / R_{\mathrm{AA}}^{J\psi}$$

5.02 TeV

Mid-y
High p_T





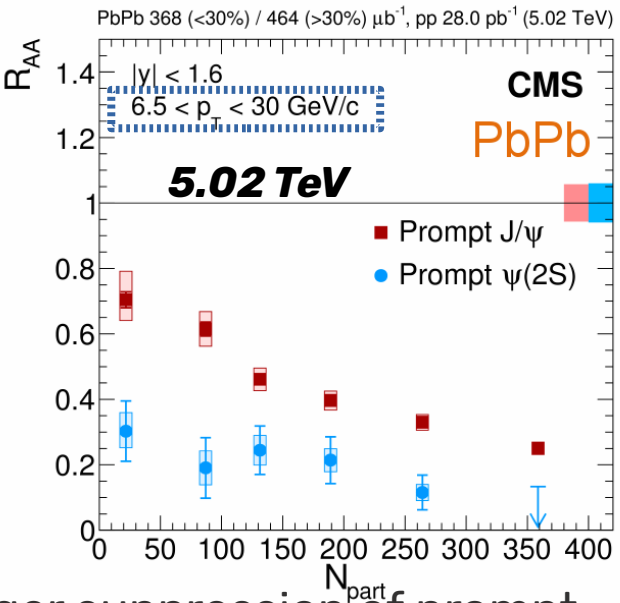
Tension in central collisions

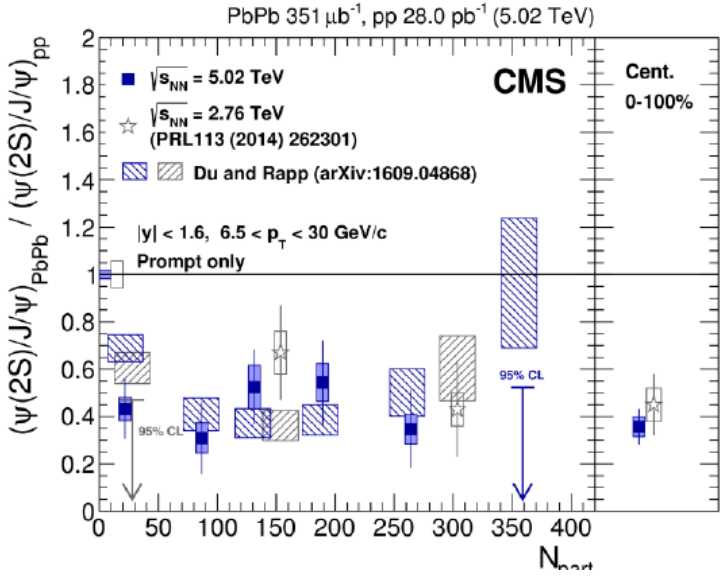
- Larger suppression of prompt ψ(2S) than prompt J/ψ, across p_T bins.

What about ψ(2S) in AA ?

- ψ(2S) larger size and weaker binding compare to J/ψ
  - Different strength of medium effects on the two states production
  - Are the CNM effects the same ?

Mid-y
High p_T



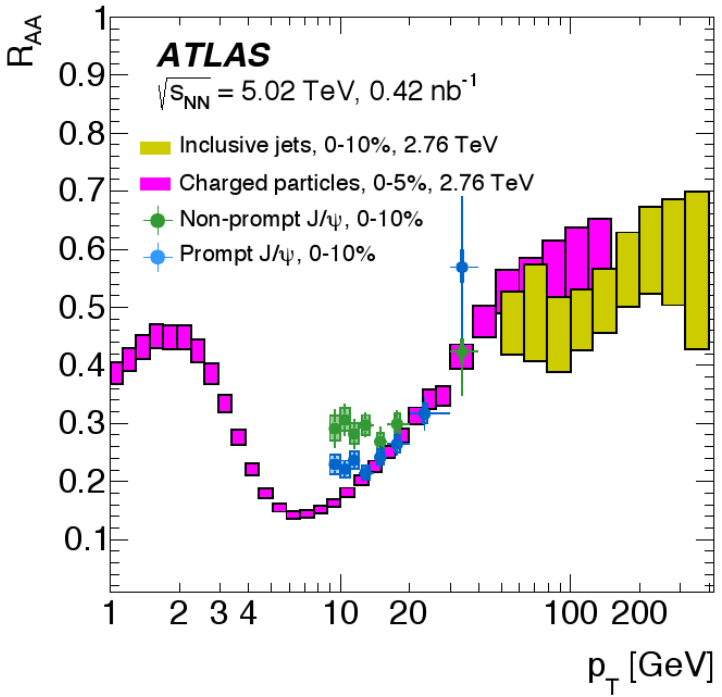


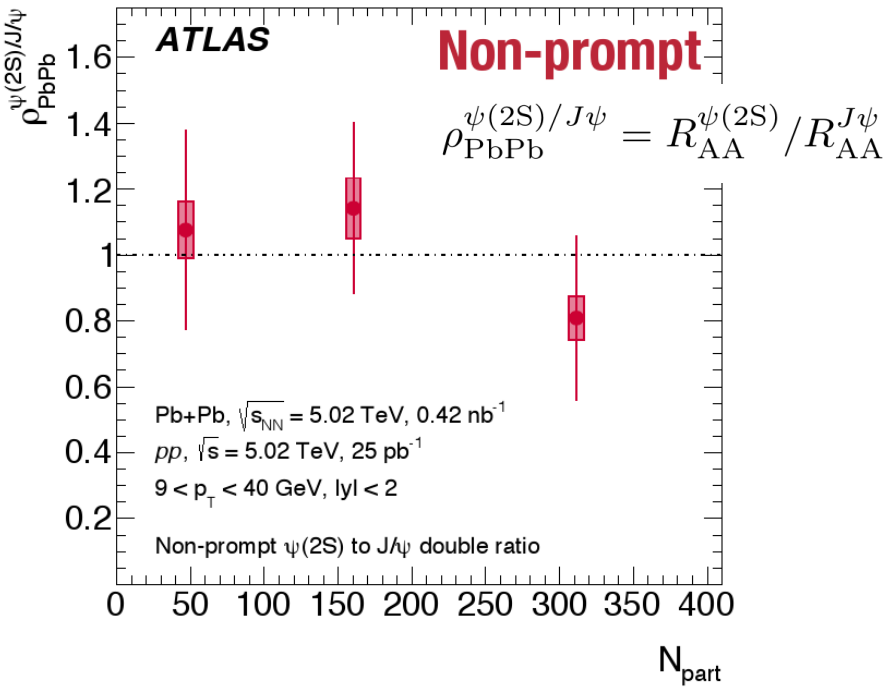
2.76 TeV
5.02 TeV

- Larger suppression of prompt ψ(2S) than prompt J/ψ, across p_T bins.
  - Consistent with transport model: interplay of suppression and regeneration.
  - ψ(2S) more suppressed than J/ψ in pA as well.

J/ψ from b-hadron decay

- The modification of prompt J/ψ production is not expected to be similar to the modification of non-prompt J/ψ



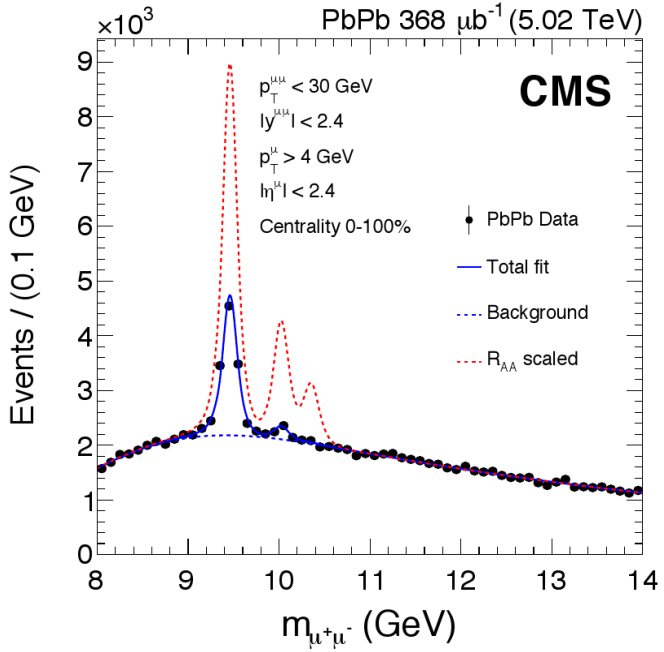


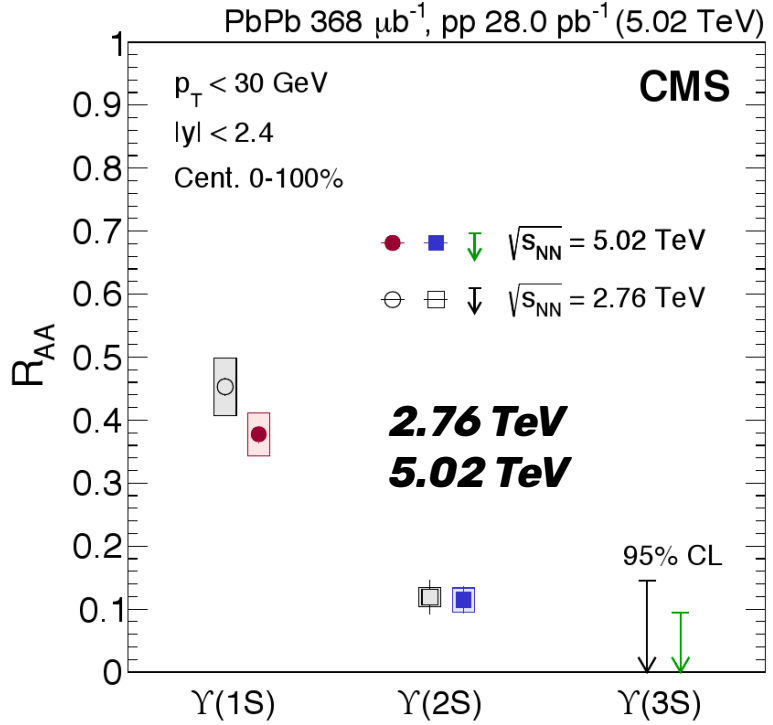
- High p_T → similar suppression of different probes
- Similar ψ(2S) and J/ψ similar suppression → B hadron decay outside of the medium

ATLAS: arXiv:1805.04077

Υ states in AA

- Different sensitivity to the medium w.r.t charmonia
  - Much smaller recombination expected
  - But larger feed-down from excited states
  - And small production cross-section
- Higher excited states more suppressed ?

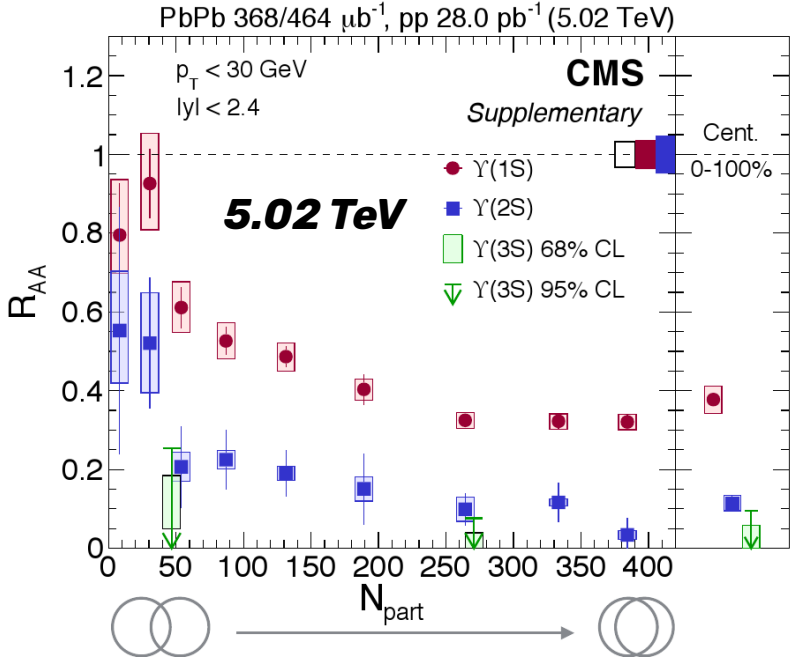


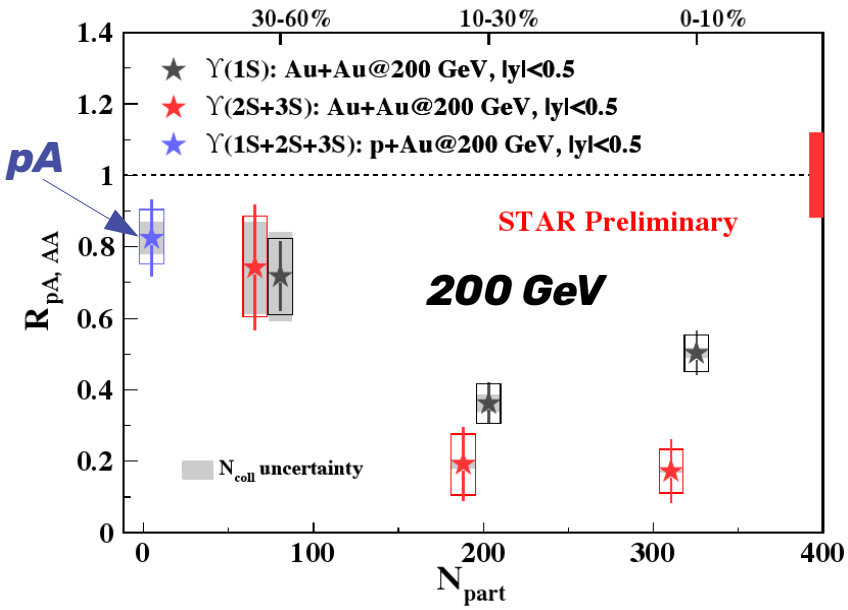


CMS: 1805.09215 , CMS-HIN-16-023

ϒ states in AA – different energies

mid-y



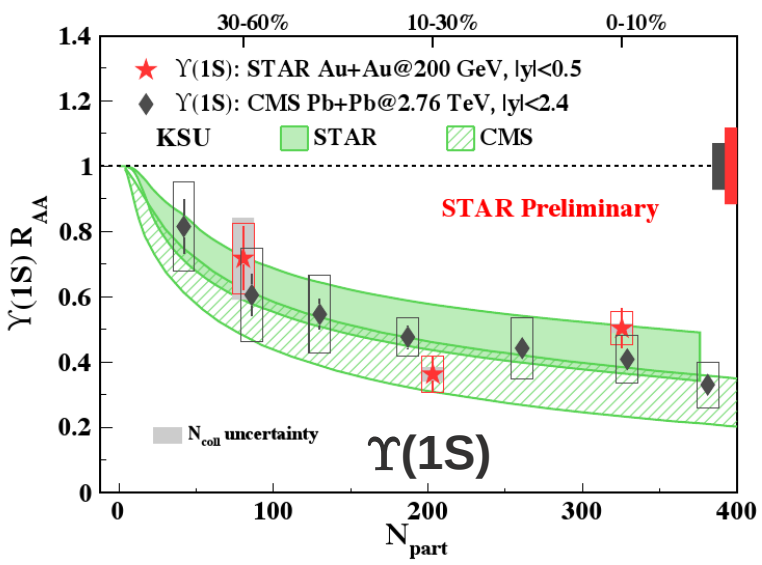


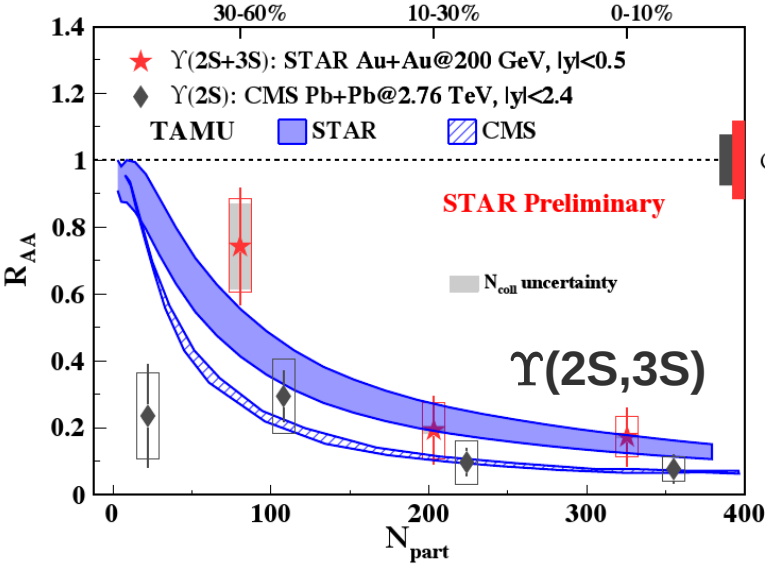
- Stronger suppression of ϒ(2S+3S)
  - No significant p_T dependence observed

CMS: 1805.09215 , CMS-HIN-16-023

ϒ states in AA – model comparison

200 GeV
2.76 TeV



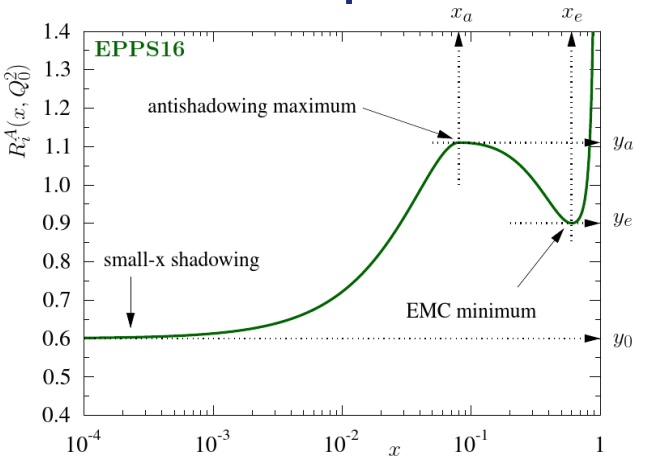


- Similar suppression of ϒ(1S) at RHIC and LHC
- Indication of stronger suppression of ϒ(2S+3S) at LHC than at RHIC
- Agreement with models
  - Different T_0 in the models, especially for RHIC – KSU: 440 MeV, TAMU: 310 MeV, LHC – KSU: 546 MeV, TAMU: 555 MeV
  - KSU more suppression compared to TAMU

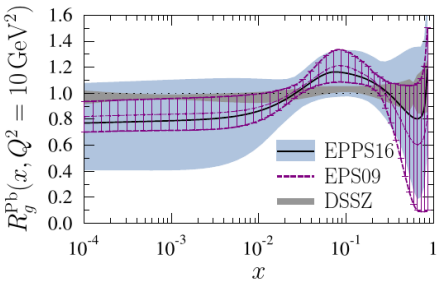
CMS: 1805.09215 , CMS-HIN-16-023

p-A collisions

- *Initial-state effects* – modification of the gluon flux
  - Gluon saturation at low x (CGC)
  - Modification of PDFs in nuclei ((anti-)shadowing)
- *Final-state effects*
  - Break up in the nuclear matter (nuclear absorption)
  - Break up by the comoving particles
- *Initial-/final-state effects* – parton propagation in medium (coherent energy loss)
  - Different rapidity ranges → access to different x
  - Depends on energy, p_T, probe
    - Forward: small x → shadowing
    - Backward: higher x → anti-shadowing



A typical form of a PDF modifications in a nucleus



arXiv:1802.05927

p-A collisions

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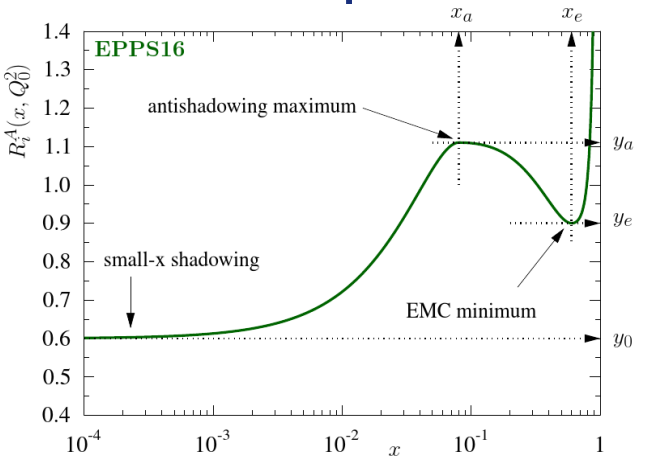
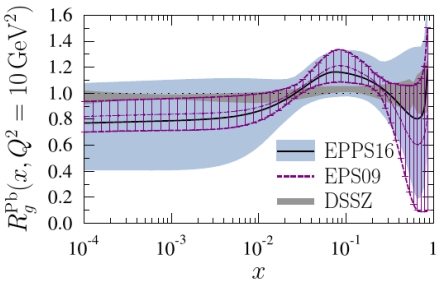


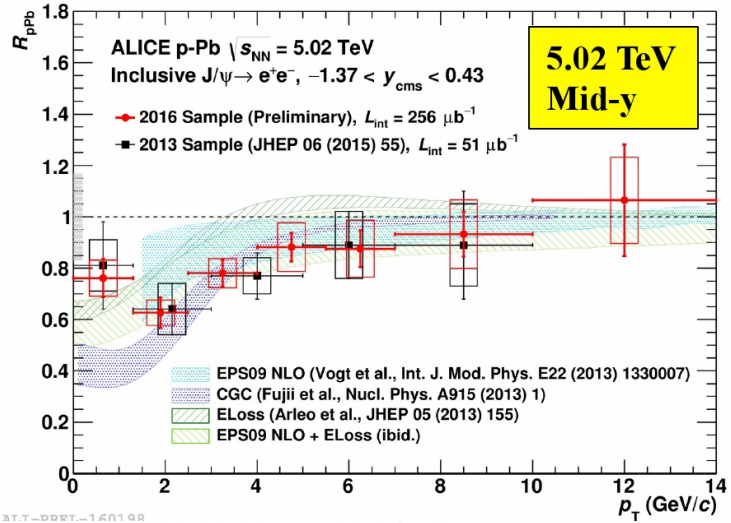
A typical form of a PDF modifications in a nucleus

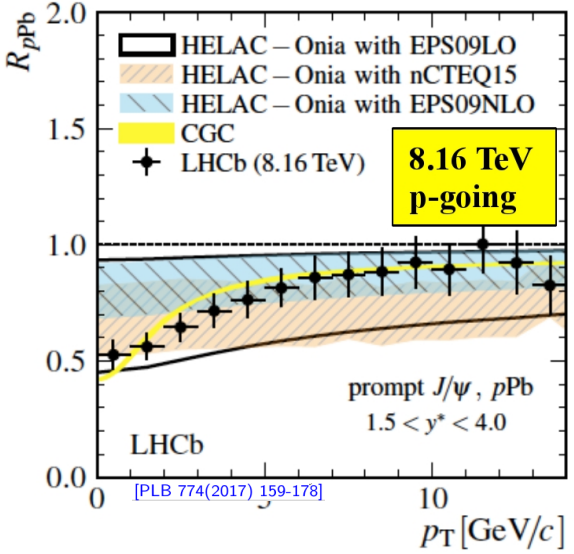


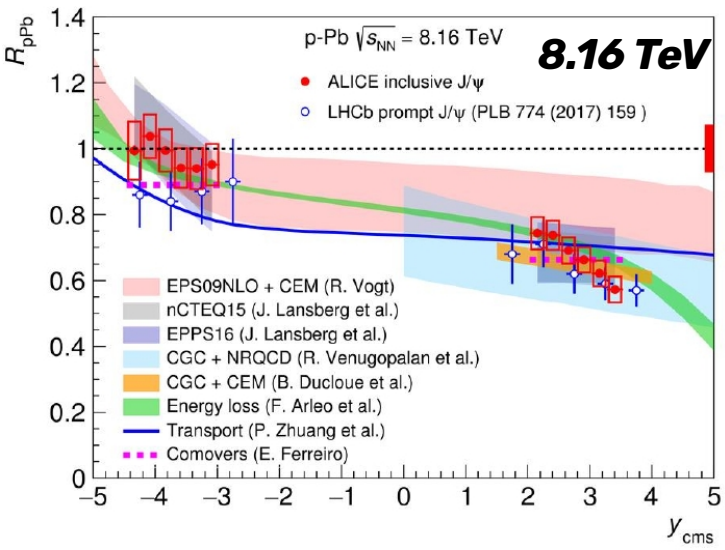
arXiv:1802.05927

- What presented here is only a very small selection of all the p(d)A results
- But pA no less interesting, and mandatory to understand if we want to interpret the AA case
  - *Caveats:*
    - *Production in pp not fully understood*
    - *How to extrapolate initial and final state effects from pA to AA*

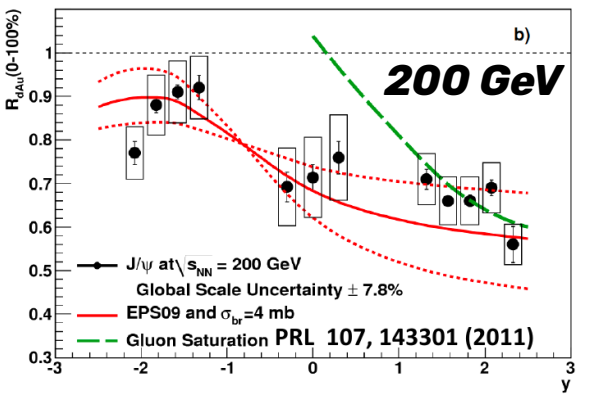
J/ψ in pA







$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{1}{\mathrm{A}} \frac{\mathrm{d}\sigma_{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



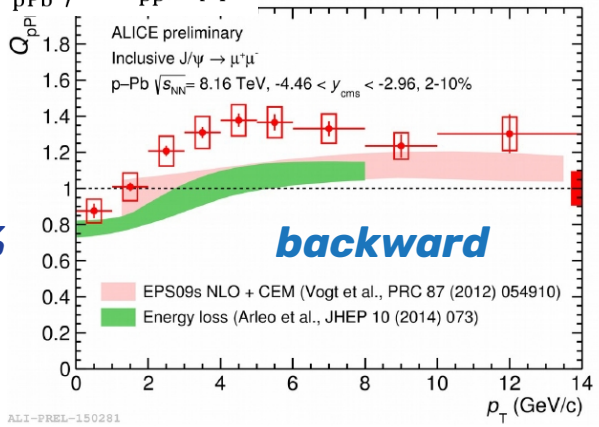
- Strong CNM effects at forward rapidity and low p_T
  - Agreement with models with initial-state effects: nPDF, CGC and/or coherent energy loss, final state effects: comover interaction
  - Constraints on models from the data side

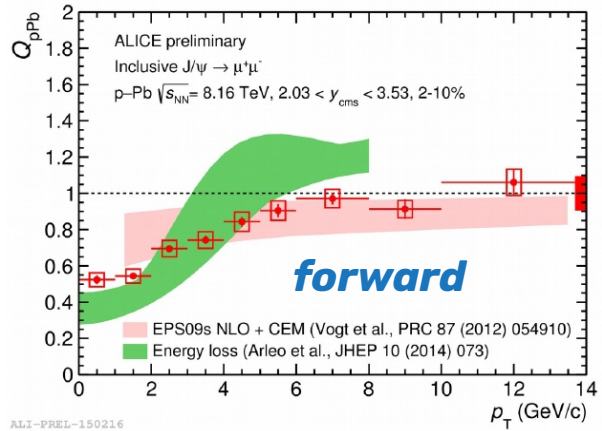
J/ψ in pA in multiplicity bins

$$Q_{\mathrm{pPb}}^{\mathrm{cent}} = \frac{1}{\langle T_{\mathrm{pPb}}^{\mathrm{cent}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{pPb}}^{\mathrm{cent}} / \mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}} / \mathrm{d}p_{\mathrm{T}}}$$

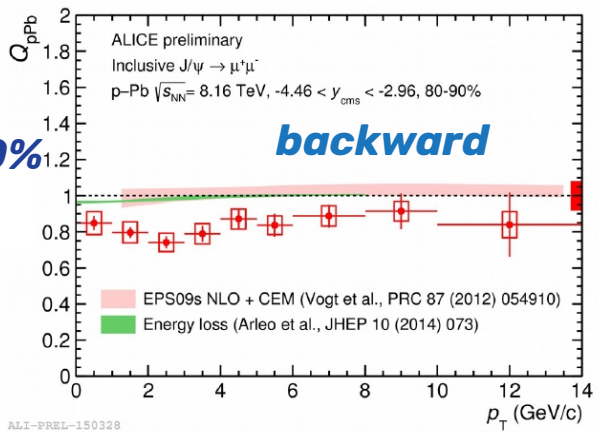
8.16 TeV

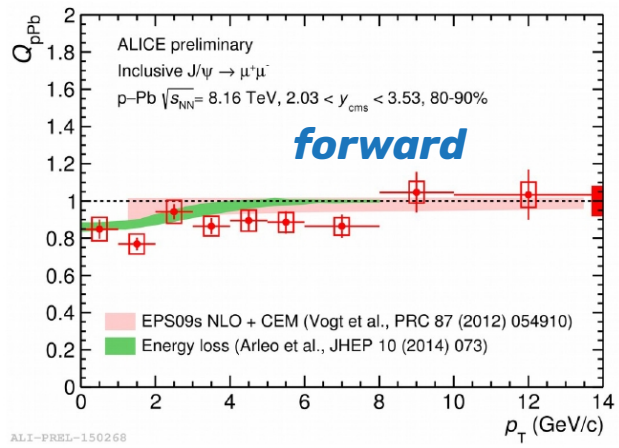
2-10%





80-90%





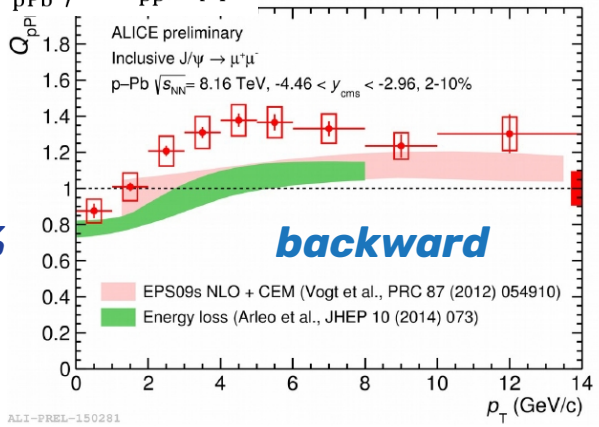
- But less agreement with models in multiplicity classes.

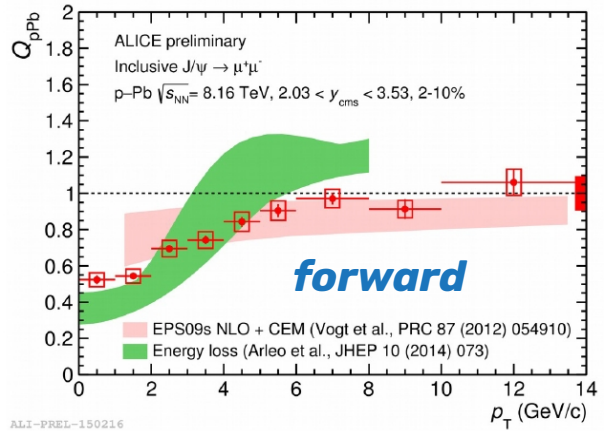
J/ψ in pA in multiplicity bins

$$Q_{\mathrm{pPb}}^{\mathrm{cent}} = \frac{1}{\langle T_{\mathrm{pPb}}^{\mathrm{cent}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{pPb}}^{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

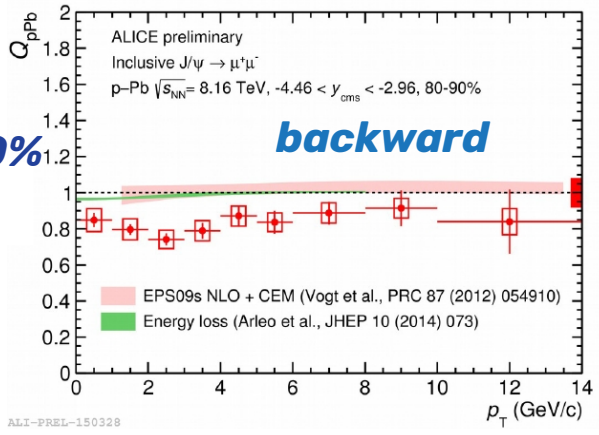
8.16 TeV

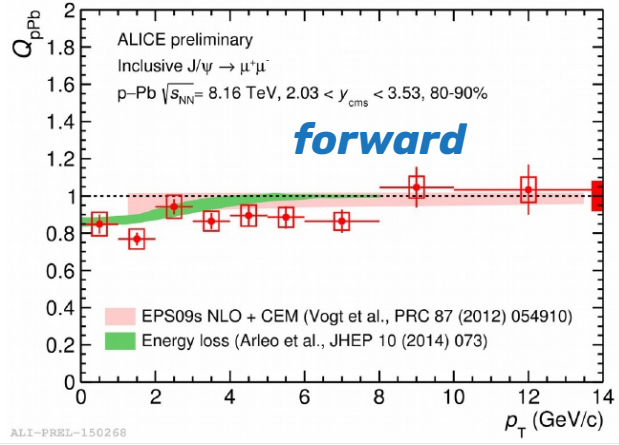
2-10%



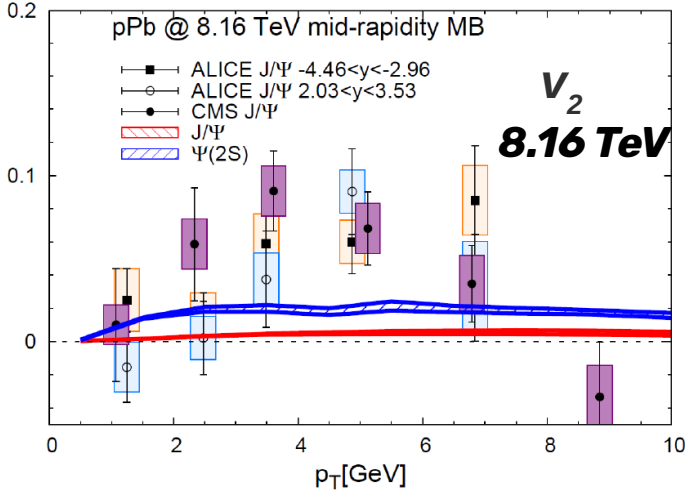


80-90%

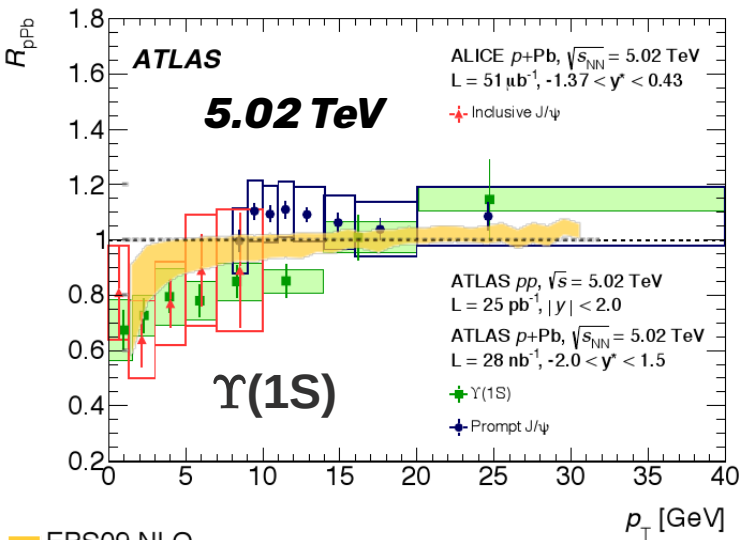


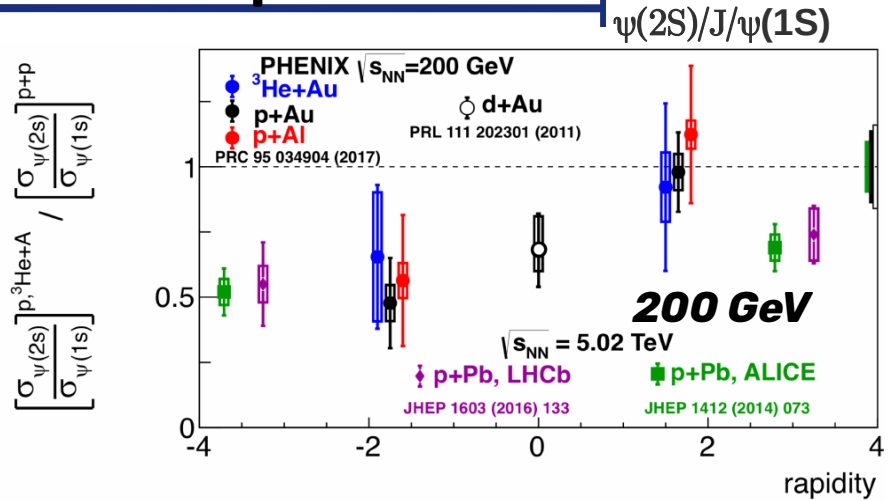


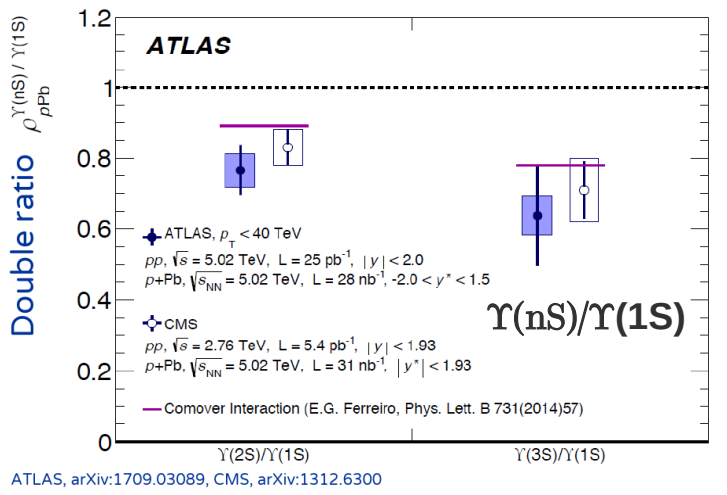
- But less agreement with models in multiplicity classes.
- Elliptic flow in high-multiplicity pA !
  - Models underestimate the data.



Excited quarkonia states in pA

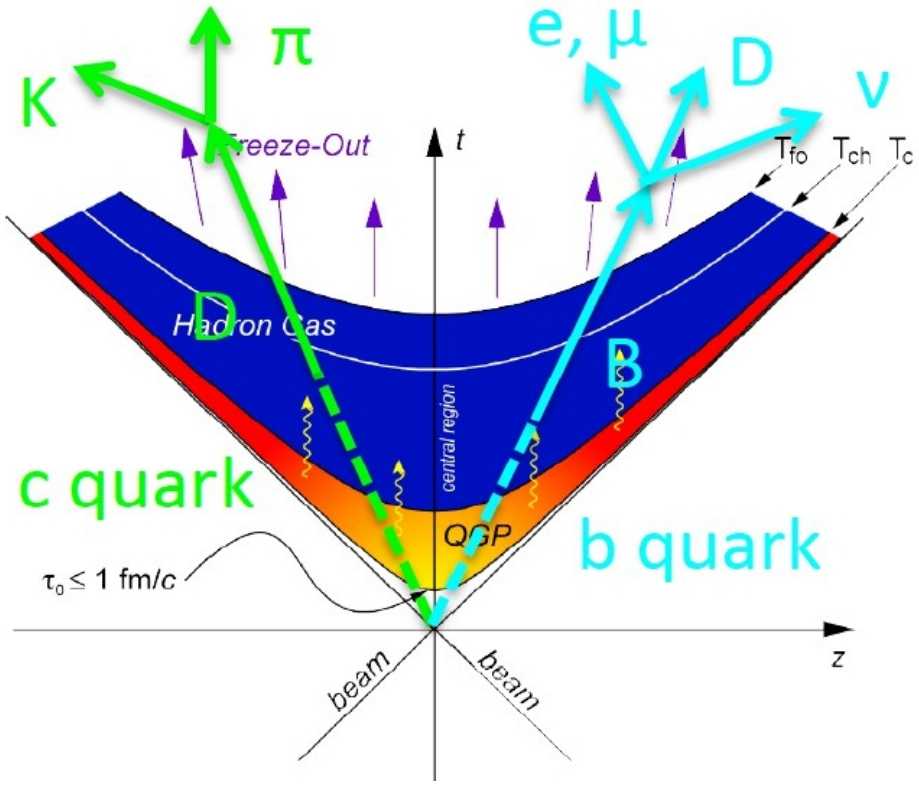






- ϒ(1S) suppression at low p_T – 30-40%.
  - Consistent with nPDFs
- Suppression of ϒ(2S) and ϒ(3S) w.r.t. ϒ(1S).
- ψ(2S) more suppressed ! Similar suppression at forward/backward rapidity.
- Final-state effects affect excited states differently.

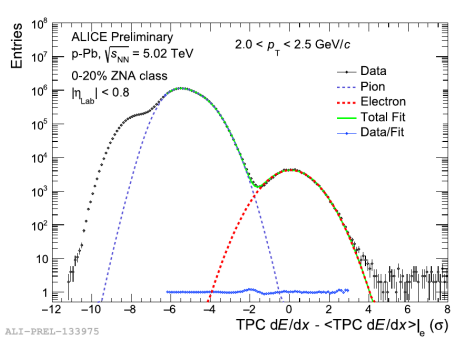
Open Heavy-Flavour

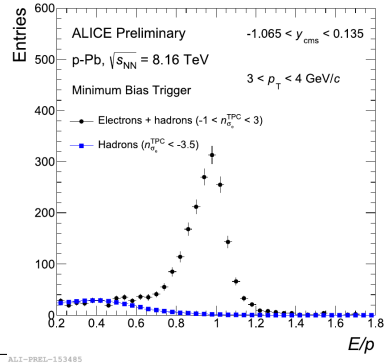


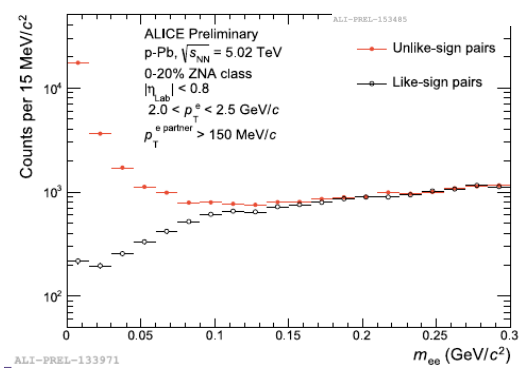
- Hadronic decays
- Semi-leptonic decays

$$b, c \rightarrow e^{\pm} X (\mathrm{BR} \approx 10\%)$$

$$b, c \rightarrow \mu^{\pm} X (\mathrm{BR} \approx 10\%)$$

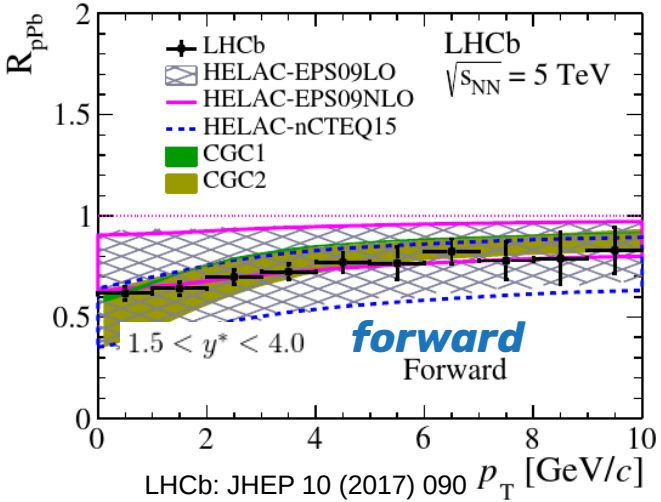




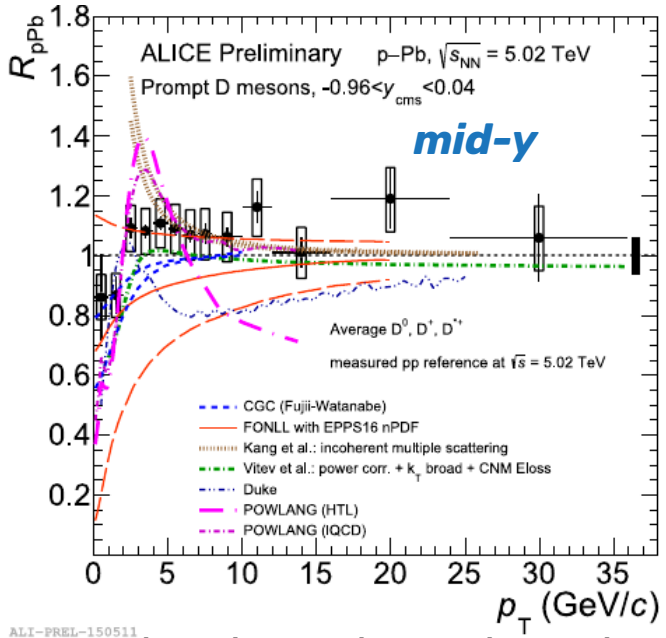


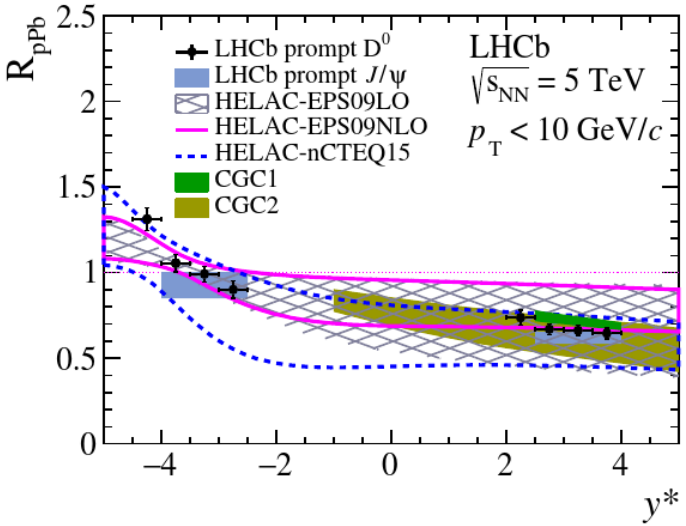
Open Heavy-Flavour in pA

- Impact of the CNM effects



LHCb: JHEP 10 (2017) 090

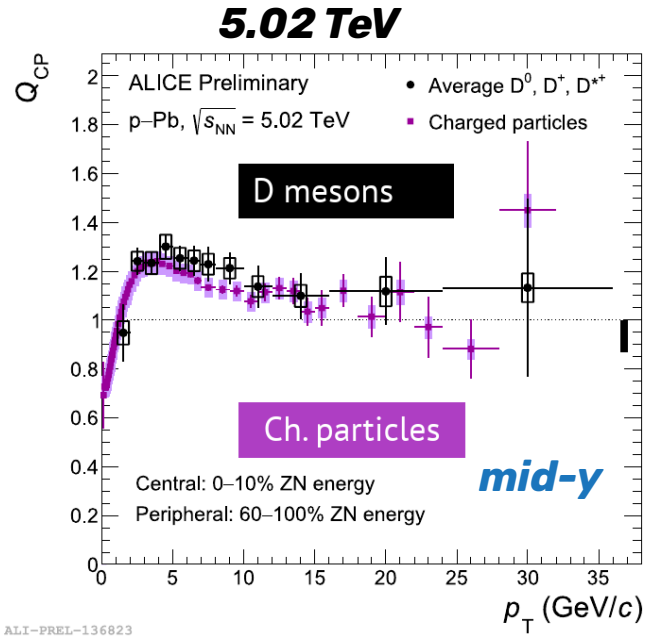




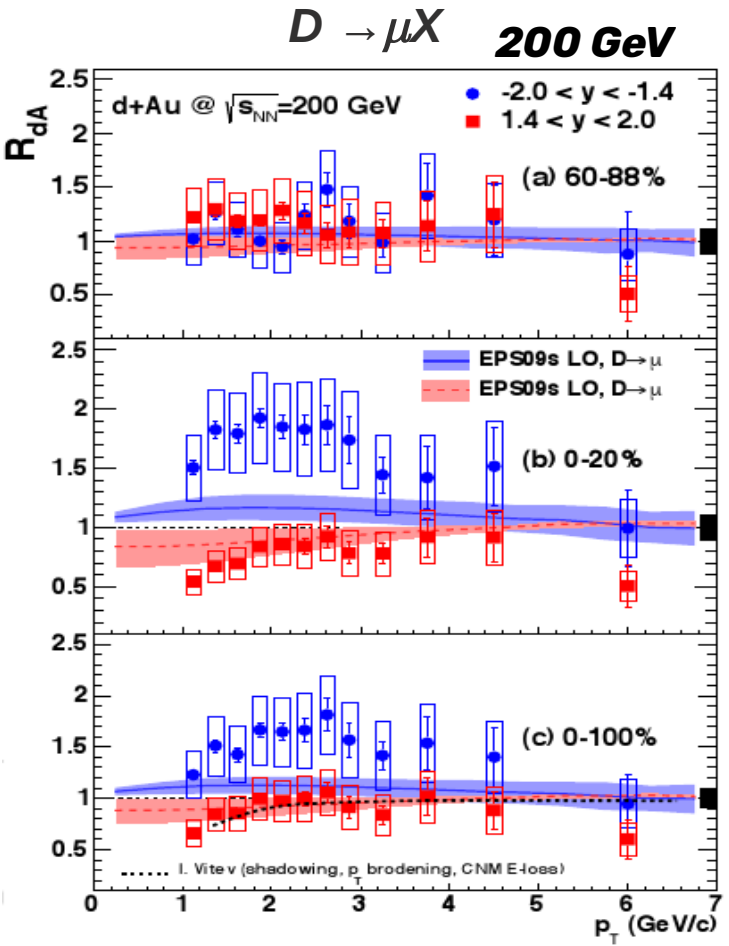
- Forward: $R_{pA} < 1$, Mid-y: $R_{pA} \approx 1$ (<at low p_T), Backward: $R_{pA} \approx 1$ (>at low p_T)
- p_T and rapidity dependence of the CNM effects, measurements down to 0 p_T
- Powerful constrain for gluon nPDF down to x ~ 5×10^{-6}
- Consistent also with CGC picture, parton energy loss in CNM
- Data disfavours models with QGP formation

- **CGC**: arXiv:1706.06728
- **FONLL** (JHEP 1210 (2012) 137, arXiv:1205.6344) **with EPPS16 nPDFs** (Eur. Phys.J. C77 no. 3, (2017) 163, arXiv:1612.05741).
- **Vitev et al**: Phys.Rev. C80 (2009) 054902, arXiv:0904.0032.
- **Kang et al.**: Phys. Lett. B740 (2015) 23–29, arXiv:1409.2494.
- **Duke**: Nucl. xPart. Phys. Proc. 276-278 (2016) 225–228, arXiv:1510.07520.
- **POWLANG**: JHEP 03 (2016) 123, arXiv:1512.05186.

Open HF in pA in multiplicity bins



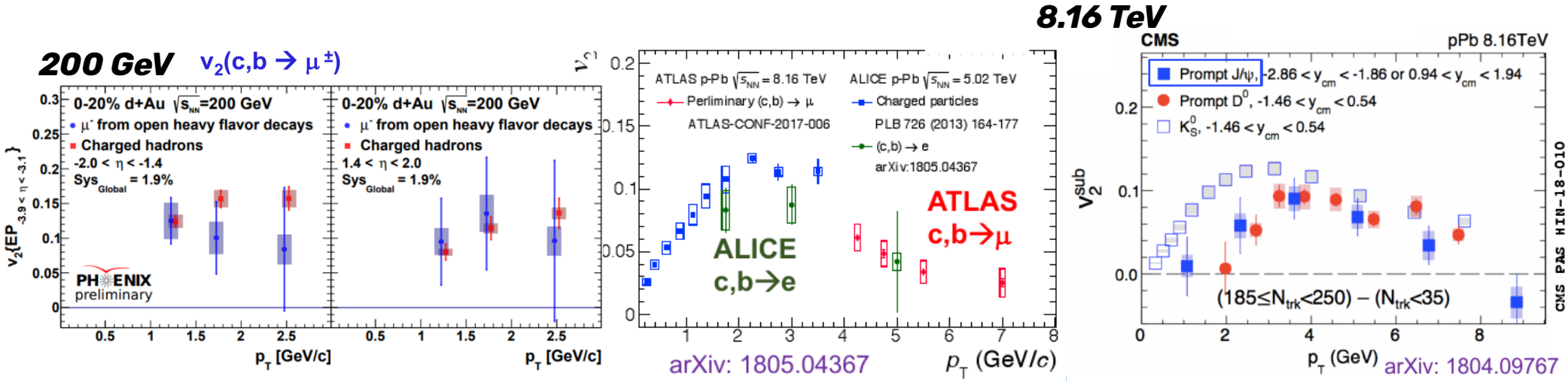
$$Q_{cp} = \frac{\mathrm{d}^2N_{\mathrm{pPb}}^{\mathrm{central}}/\mathrm{d}p_T}{\langle T_{\mathrm{pPb}}^{\mathrm{central}}\rangle} \Big/ \frac{\mathrm{d}^2N_{\mathrm{pPb}}^{\mathrm{peri}}/\mathrm{d}p_T}{\langle T_{\mathrm{pPb}}^{\mathrm{peri}}\rangle}$$



- RHIC: enhancement/suppression at backward/forward rapidity in central collisions at low p_T
- LHC mid-y: enhancement in central collisions in $3 < p_T < 8$ GeV/c, 1.5σ significance, similar to charge particles

Open HF v_2 in pA

- Collectivity in pA: HF elliptic flow in pA, mass ordering, initial/final state effects ?

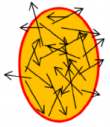


- **D meson v_2 in high multiplicity p(d)A, at RHIC and LHC**
- Hint of mass dependence
- Initial/final state effects ? QGP in high multiplicity pA ?

E. Bruna, QM18

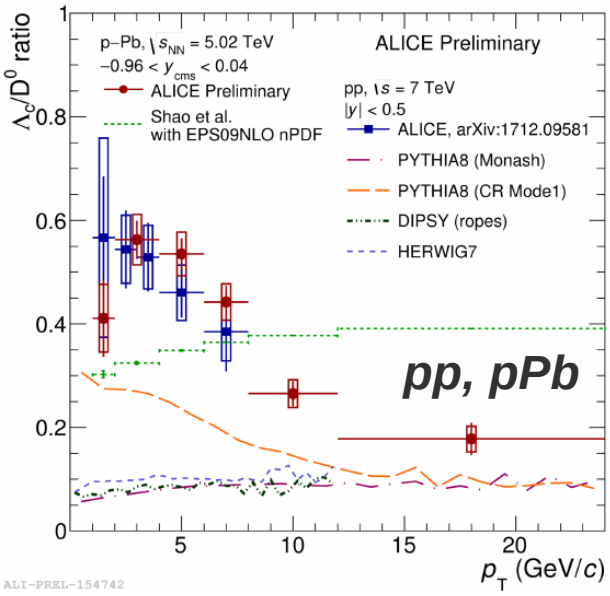
Mechanisms at play in small systems:

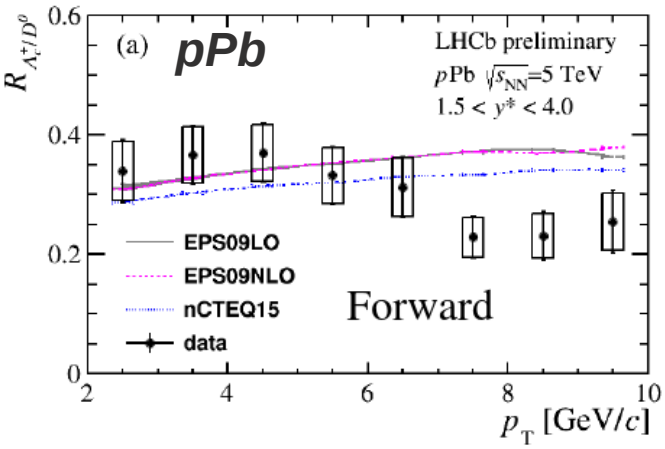
- Hydrodynamics
  P. Bozek, PRC 85 (2012) 014911, A. Bzdak et al., PRC 87 (2013) 064906
  K. Werner et al, P.R.L. 106 (2011) 122004
- Color glass condensate
  K. Dusling et al., Phys.Rev. D87 (2013) no.9, 094034
- "escape mechanism" (AMPT)
  L. He et al., PLB 753 (2016) 506,
  H. Li et al., PRC 96 (2017) 014901, arXiv: 1804.02681
- no-interaction QCD interference effects?
  B. Blok et al., JHEP 1712 (2017) 074

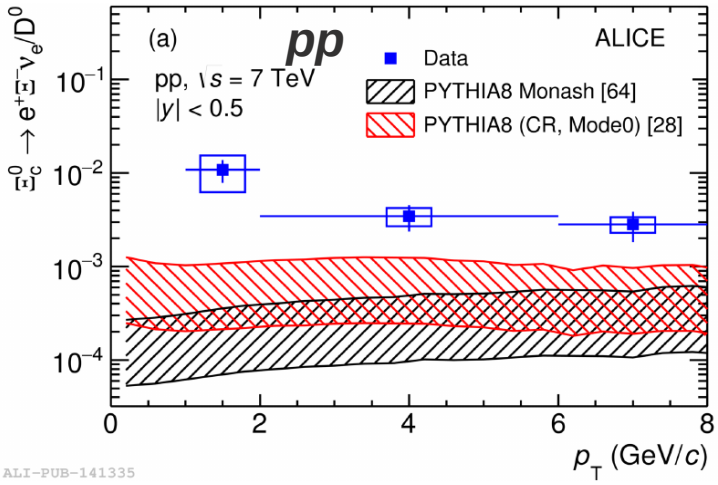


HF baryons, Λ_c,Ξ_c / D^0 ratio

- Understanding hadronisation





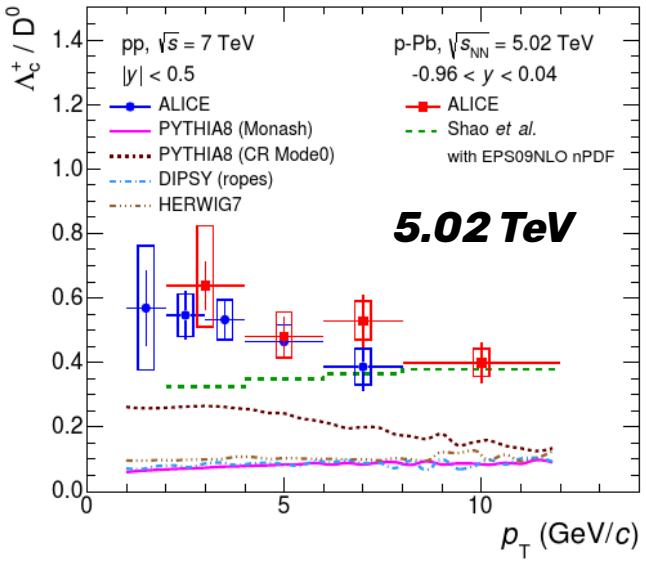


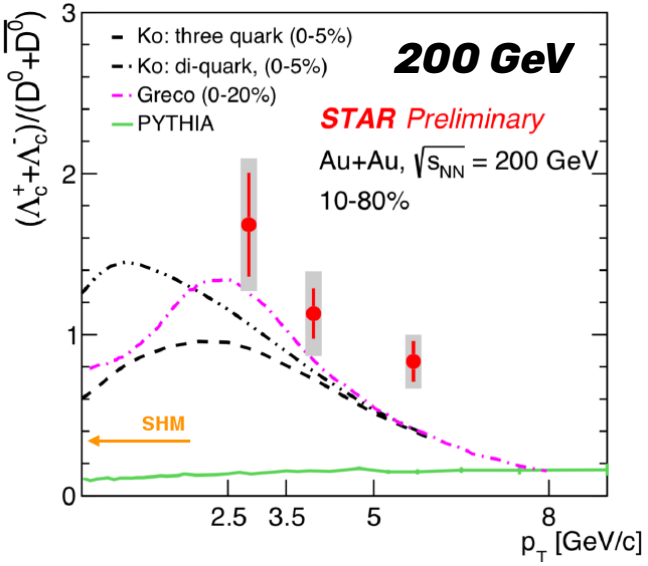
- Λ_c/D^0 and Ξ/D^0 enhancement relative to Pythia (tuned based on e^+e^- data) in pp and pA
- Trend similar to baryon-to-meson ration in the light-flavour sector
- pPb: consistent with nPDFs predictions

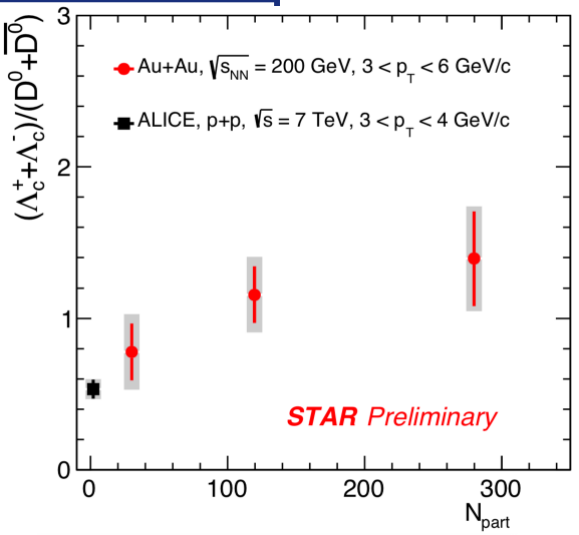
ALICE: arXiv:1712.09581

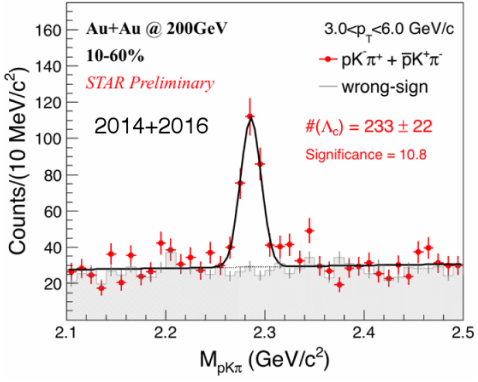
Λ_c / D^0 ratio in AA

- **Hadronisation in medium**: fragmentation vs recombination









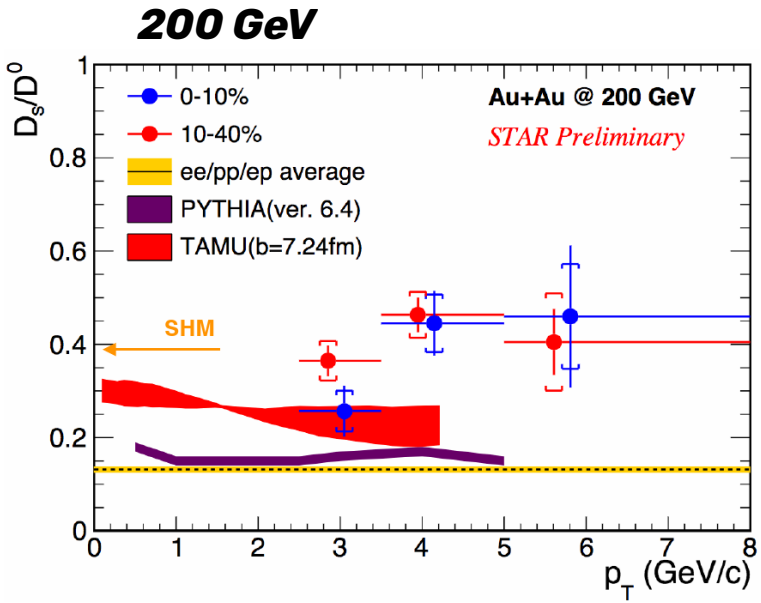
- Enhancement relative to Pythia in pp and pA
- **Strong enhancement in AA**
  - Coalescence (+fragmentation) models closer to the data
  - Not described by the Statistical Hadronisation Model
  - Big contribution to the total charm cross-section

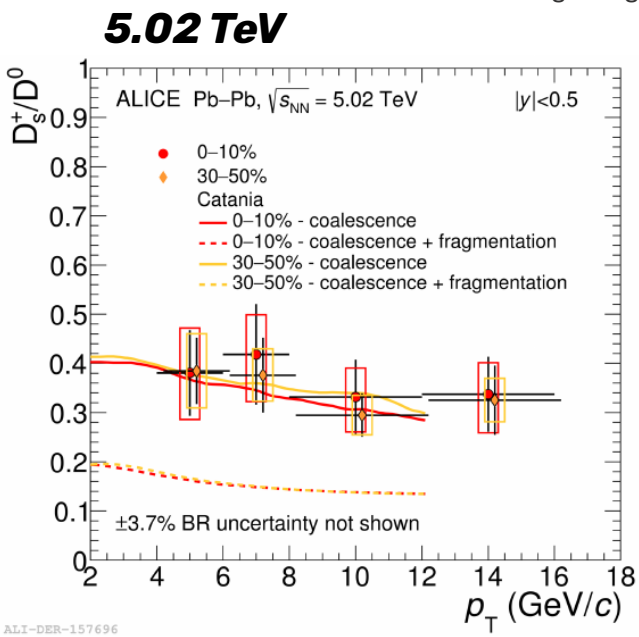
Ko: Phys.Rev.C 79 (2009) 044905
Greco: Eur.Phys.J.C (2018) 78:348
SHM: Phys.Rev.C 79 (2009) 044905

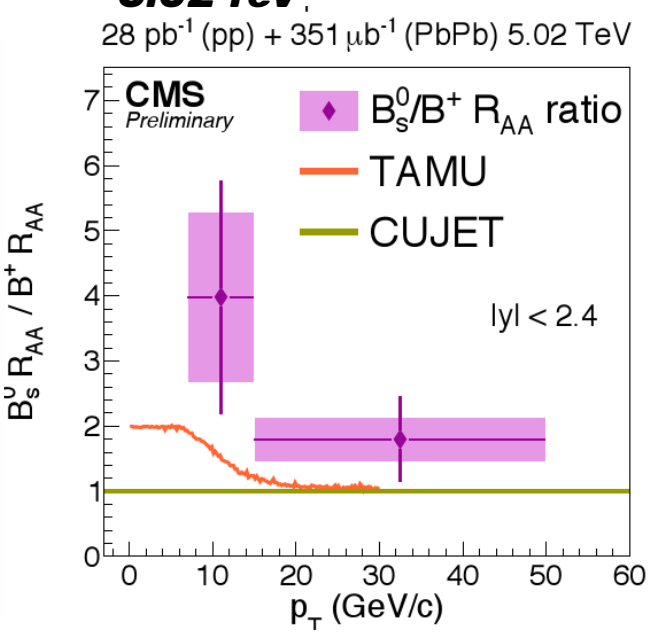
ALICE: arXiv:1712.09581

D_s/D^0

- Strangeness enhancement in HI collisions – what about D_s, B_s







- D_S/D^0 enhanced in AA, indication of B_s enhancement
- Expected from AA models, RHIC: ratio closer to SHM
- Suggests coalescence and strangeness enhancement

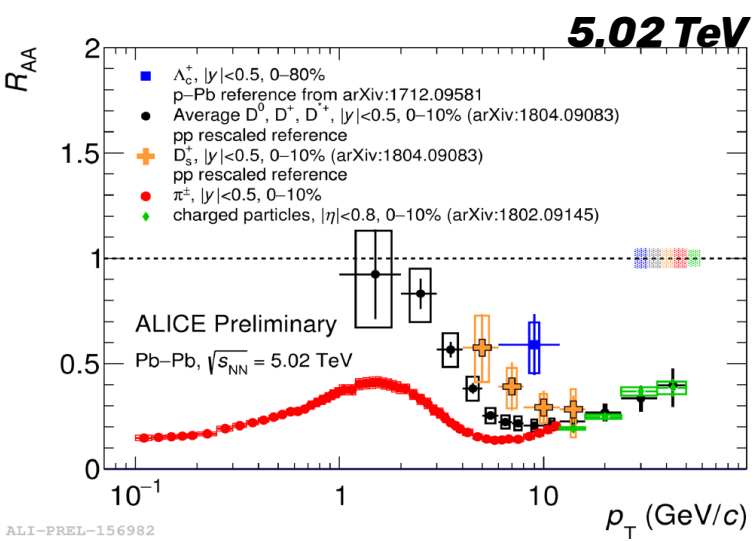
ALICE: arXiv:1804.09083

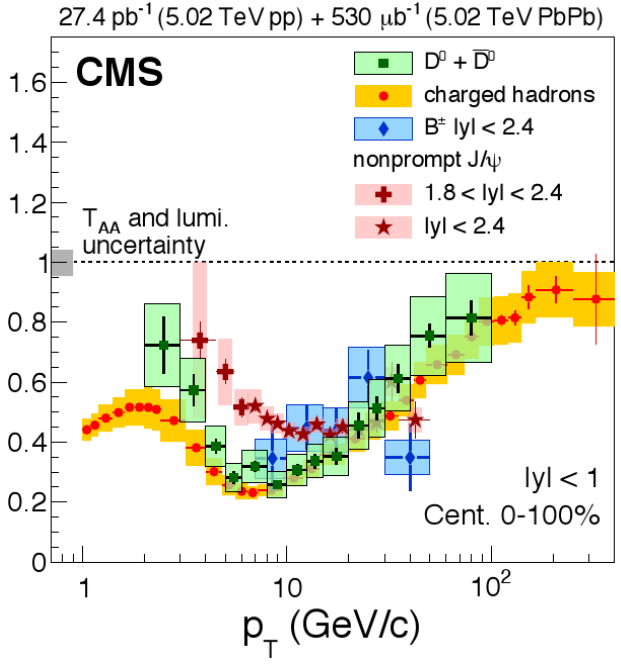
Open HF in AA

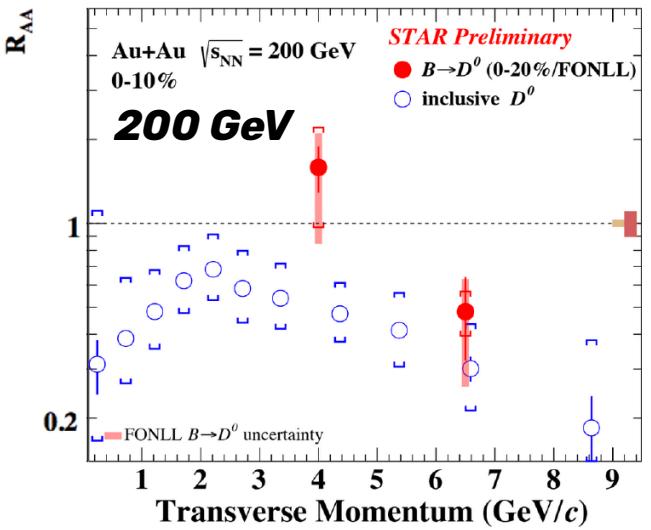
- Study in-medium energy loss, towards more precise measurements
  - Radiative and collisional energy loss
  - Flavour and mass dependence

$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Many years of efforts to get these results



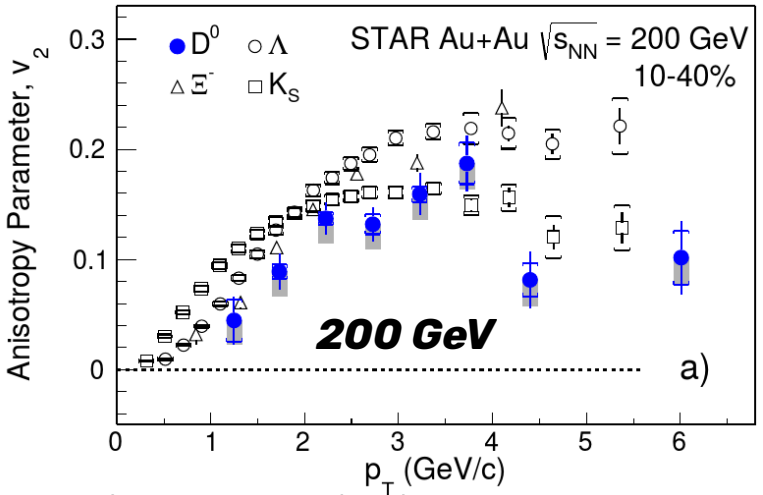




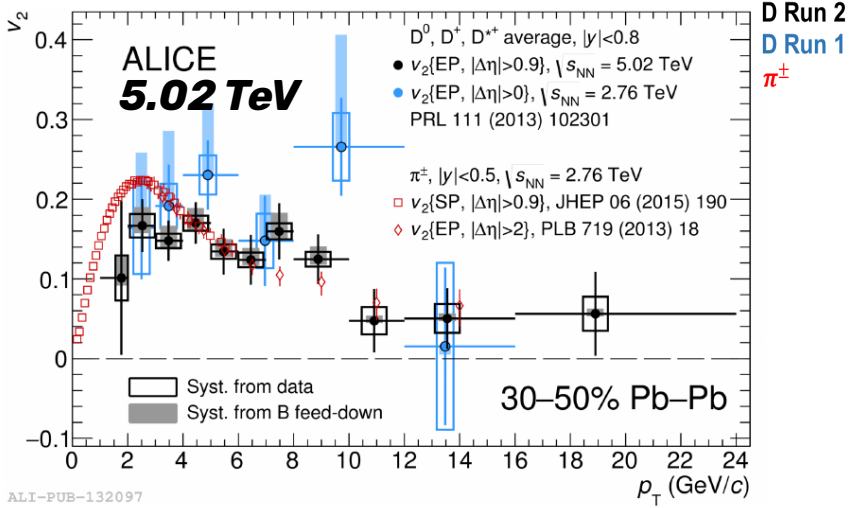
Note: rapidity ranges B → J/psi, D kinematics

- **High p_T: similar D, B and charge particle suppression**
- **Indication of smaller D suppression at lower p_T and less suppressed B**

HF v_2 in AA



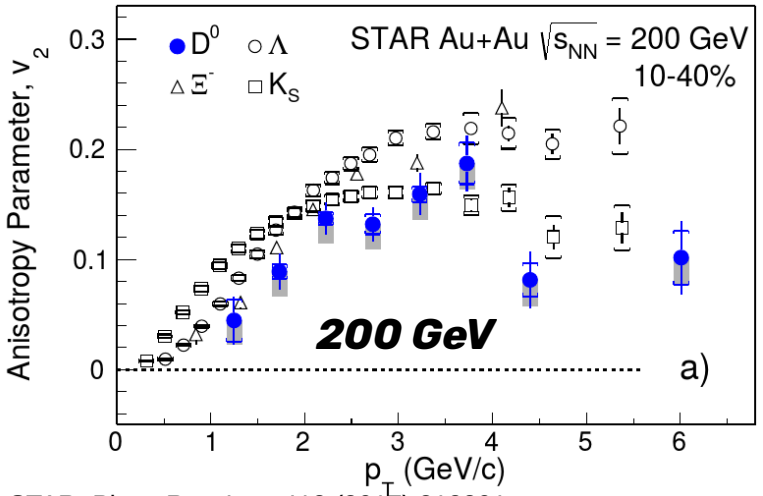
STAR: Phys. Rev. Lett. 118 (2017) 212301



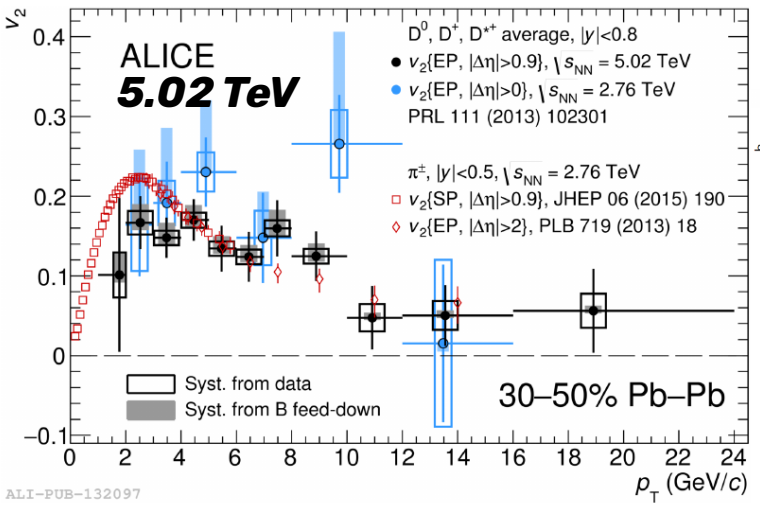
ALICE: Phys. Rev. Lett. 120 (2018) 102301

- Strong charm v_2 both at RHIC and LHC
  - Decreases with centrality
  - Charm quark sensitive to medium collective motion
- Low p_T: D v_2 smaller than charged particles
- High p_T: D v_2 comparable to charged particles

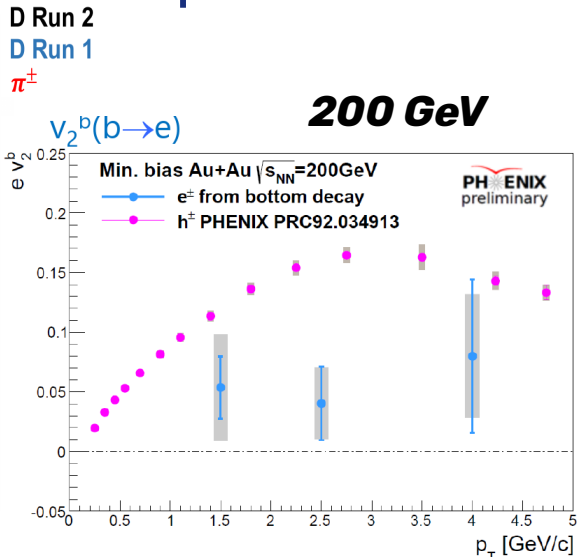
HF v_2 in AA

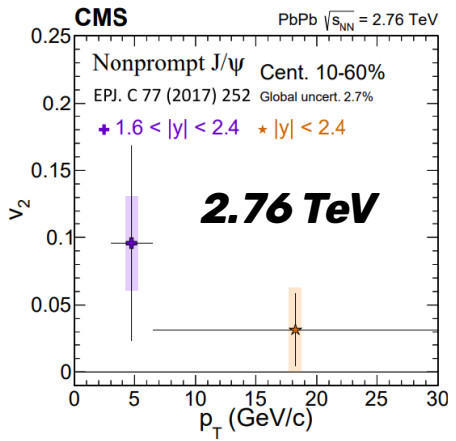


STAR: Phys. Rev. Lett. 118 (2017) 212301



ALICE: Phys. Rev. Lett. 120 (2018) 102301

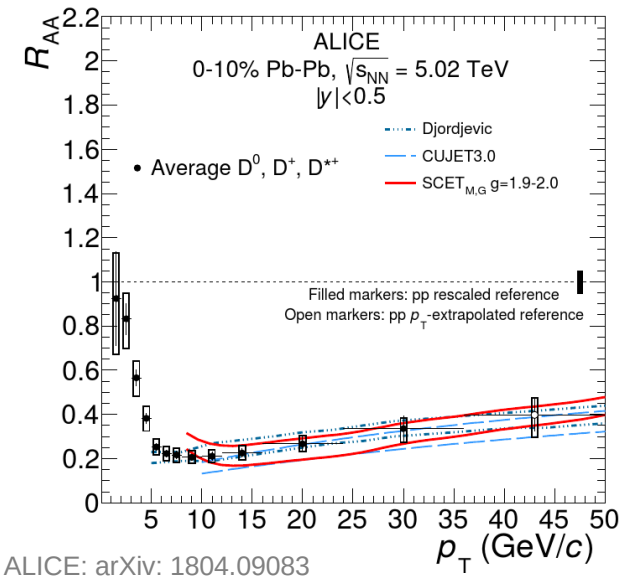


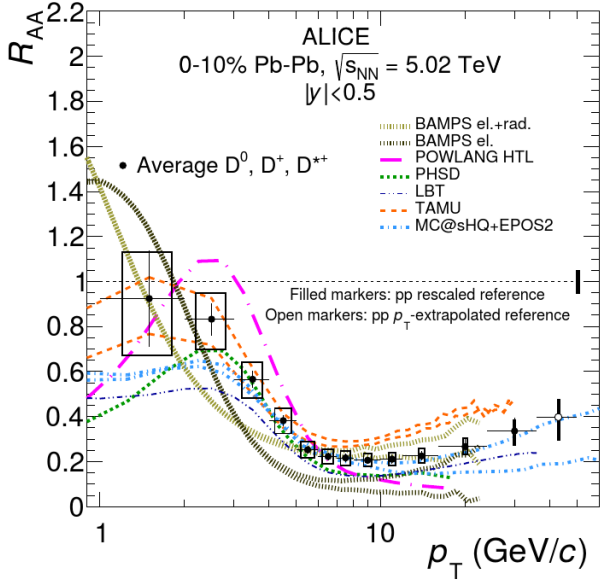


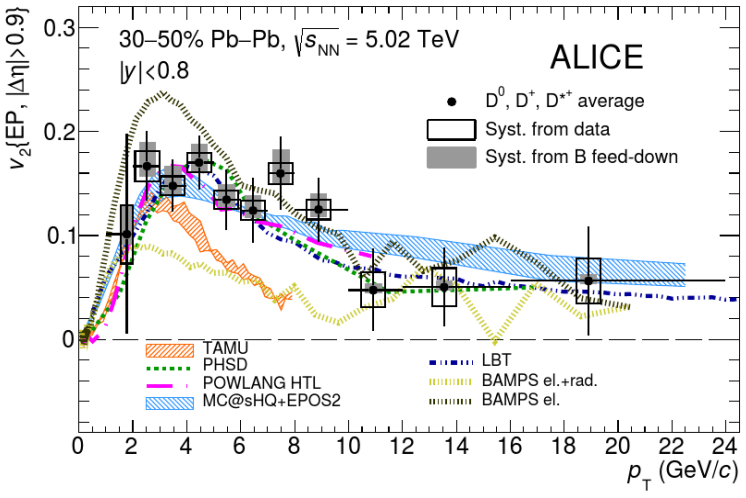
- Strong charm v_2 both at RHIC and LHC
  - Decreases with centrality
  - Charm quark sensitive to medium collective motion
- Low p_T: D v_2 smaller than charged particles
- High p_T: D v_2 comparable to charged particles
- Hint of smaller (≈0) B v_2 (also at LHC)

Open HF – comparison to models

- Can models describe consistently the data ?







ALICE: arXiv: 1804.09083

- Still no full description of data by models: across p_T, centralities, v_2
  - R_{AA}: radiative energy loss in high p_T needed to describe the data
  - v_2: Models with charm quark flow due to recombination or elastic collisions in expanding medium describe the data better
- Simultaneous description of R_{AA} and v_2 starts to constrain model parameters

EMMI RRTF : arXiv:1803.03824

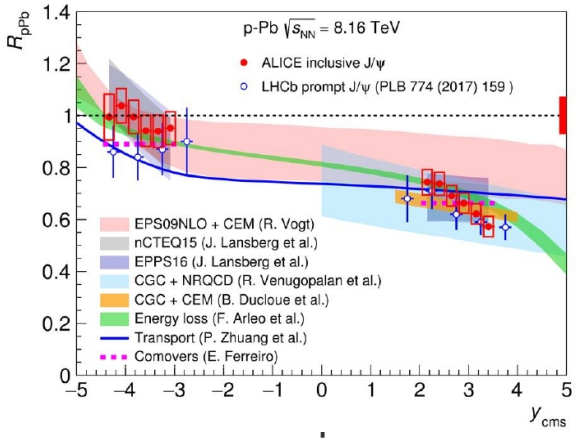
Summary

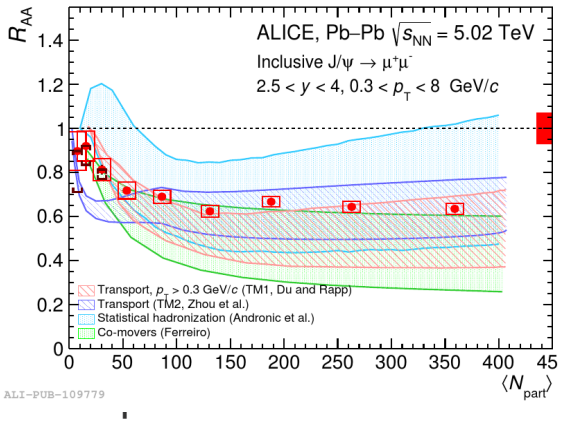
- Improved experimental results over the last year
  - Good agreement between the experiments, complementary measurements
- Mostly R_{AA}s, v_2 shown, but there is much more

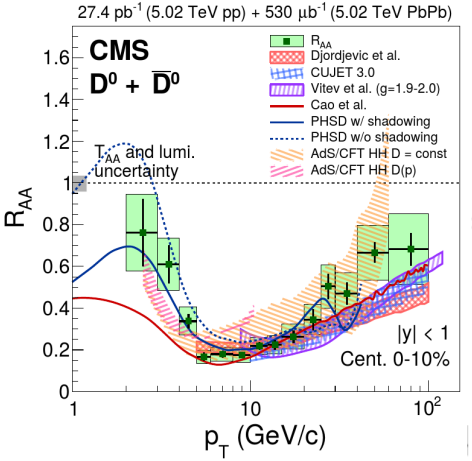
Summary

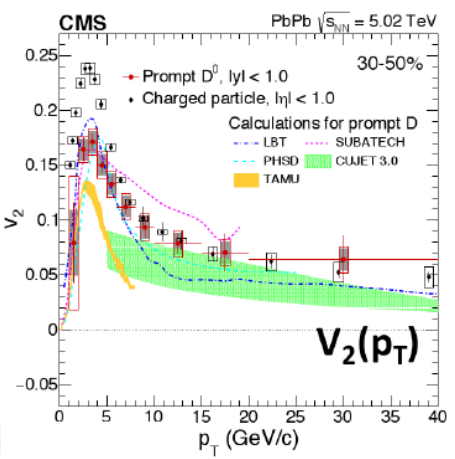
- Improved experimental results over the last year
  - Good agreement between the experiments, complementary measurements
- Mostly R_{AA}s, v_2 shown, but there is much more
- A lot of progress in developing experimental techniques, and detector upgrades
  - More precise measurements
  - More differential measurements, new observables (correlations, HF jets, event shape engineering, ...)
  - … More questions on the interpretation of what we observe

Summary







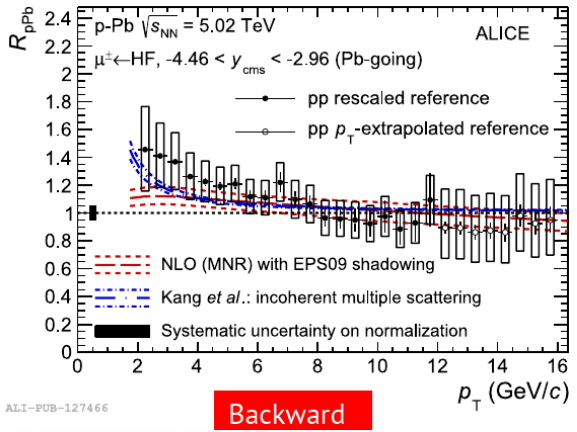


- Comparison to the theoretical predictions still not conclusive
  - But modelling is very complex: initial production, propagation in the medium, medium dynamics, CNM effects, hadronisation ….
- Upcoming detector upgrades / new experiments
  - sPHENIX – jets and quarkonia
  - LS2 – upgrade of detectors at LHC
    - New vertex detectors for improved open HF measurements

Backup

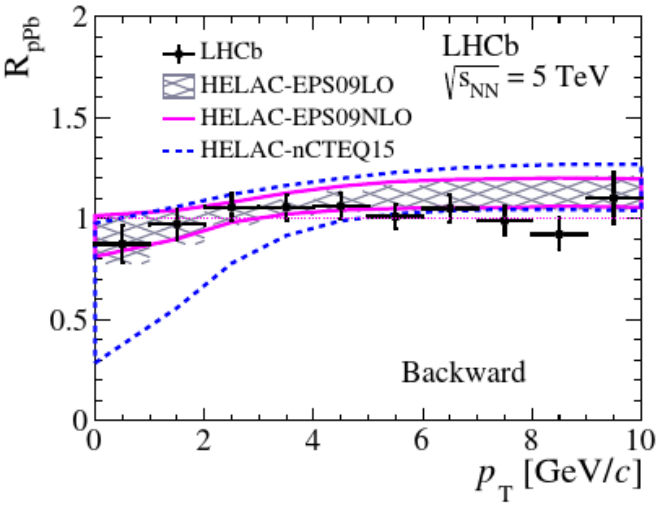
Open Heavy-Flavour in pA

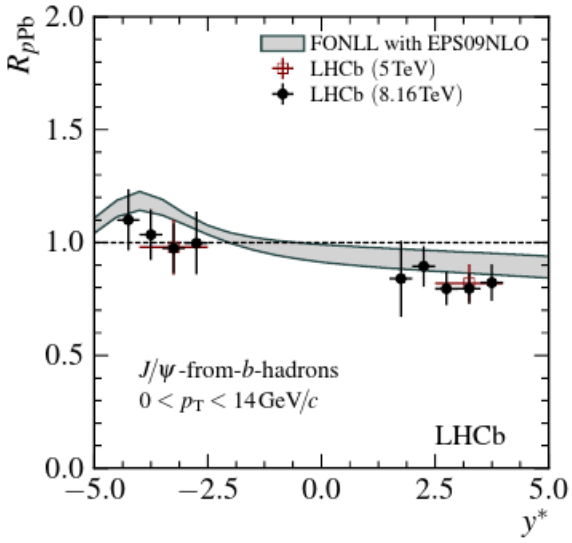
HF muons



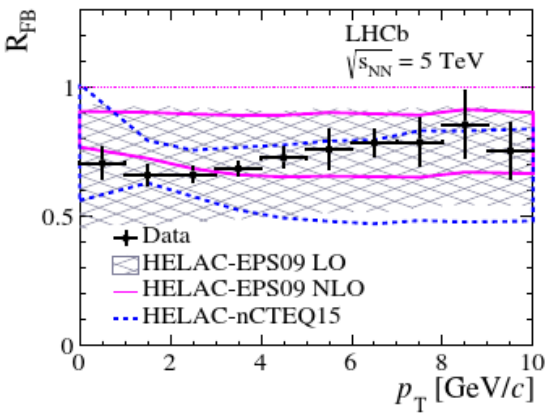
Backward

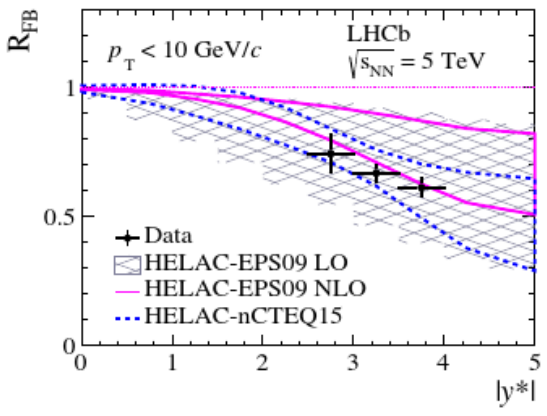
NLO with EPS09 (Nucl. Phys. B, 373 (1992)
Vitev: Phys. Rev. C, 80 (2009), Article 054902, arXiv:0904.0032
Kang et al: Phys. Lett. B, 740 (2015), pp. 23-29, arXiv:1409.2494

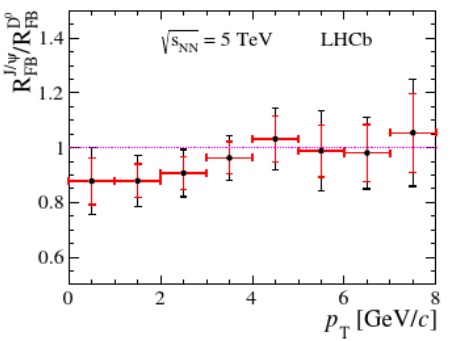


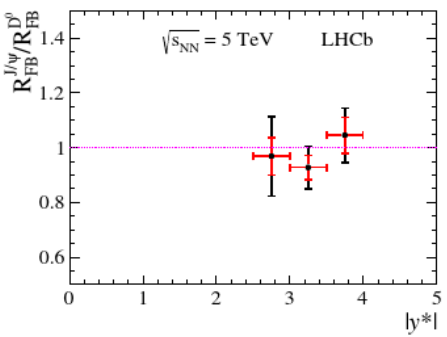


[PLB 774(2017) 159-178]



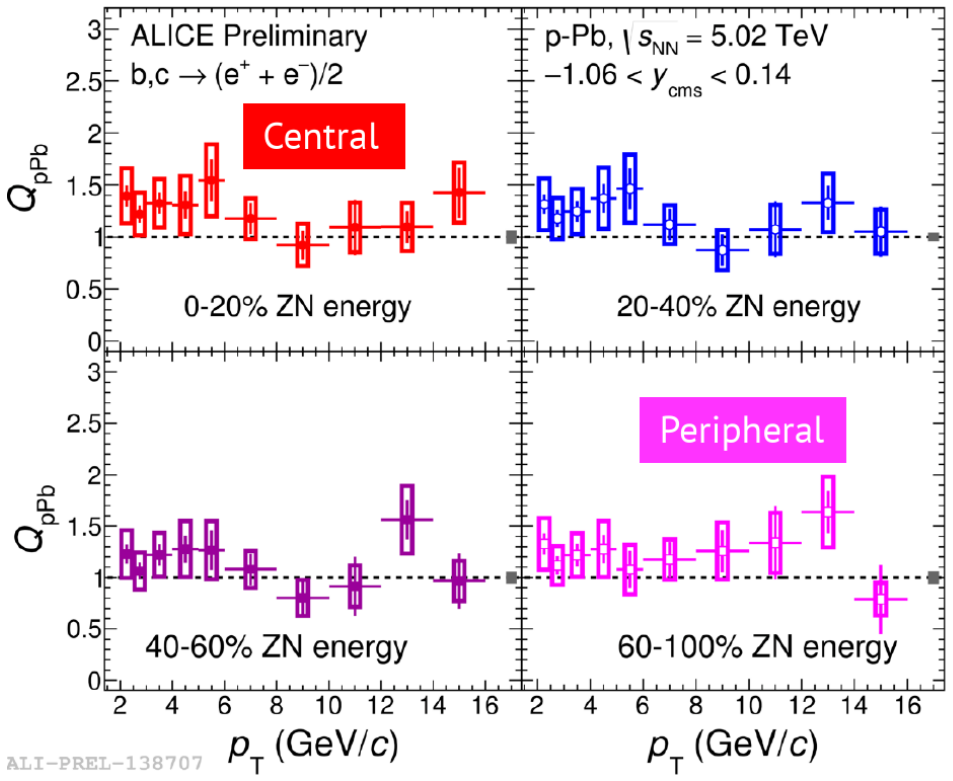


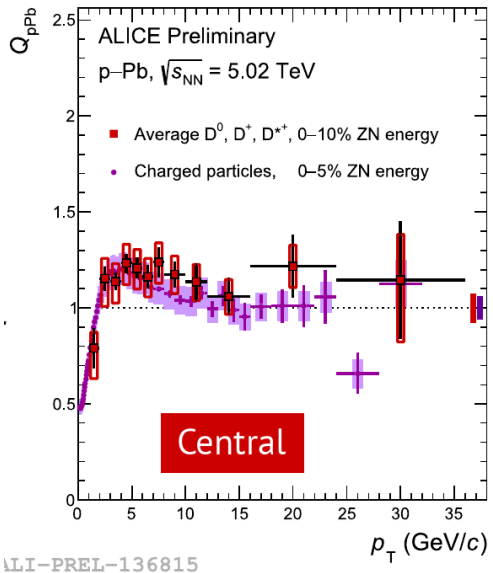


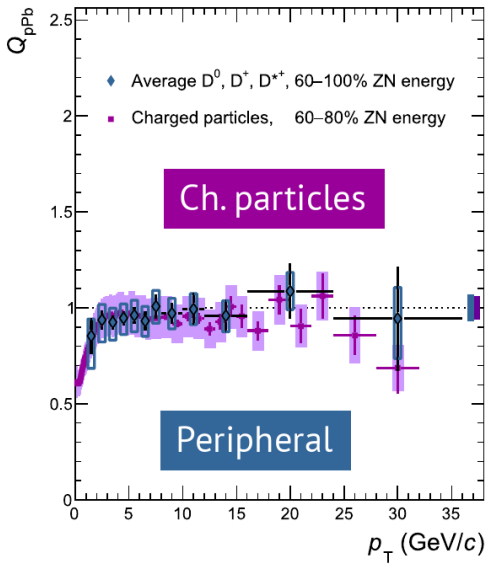


Open Heavy-Flavour in pA

$$Q_{\mathrm{pPb}}^{\mathrm{cent}} = \frac{1}{\langle T_{\mathrm{pPb}}^{\mathrm{cent}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{pPb}}^{\mathrm{cent}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

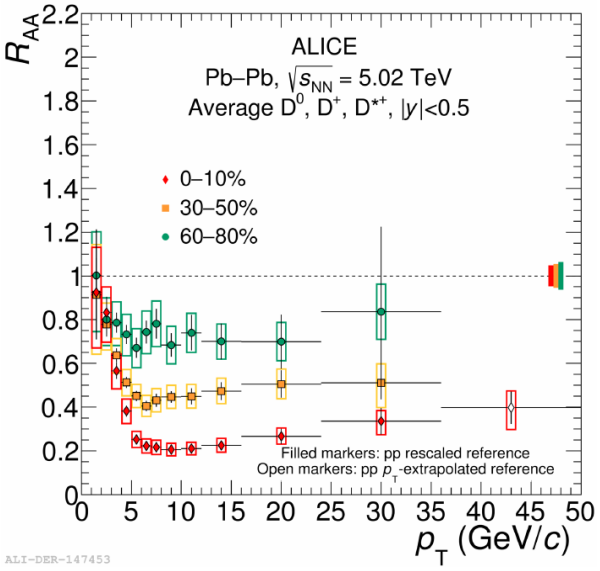






Open Heavy-Flavour in AA

PHSD: Phys. Rev. C93 no. 3, (2016) 034906
TAMU: Phys.Lett. B735 (2014) 445–450
Catania: Eur.Phys.J.C (2018) 78:348



60-80%
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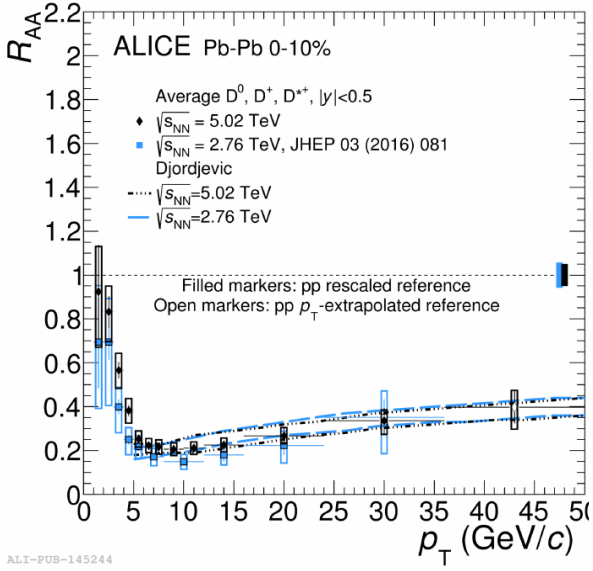
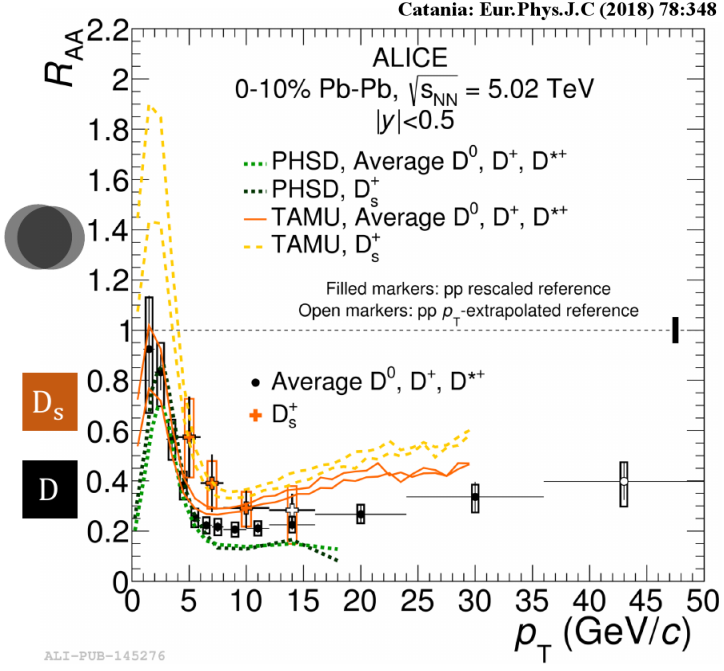


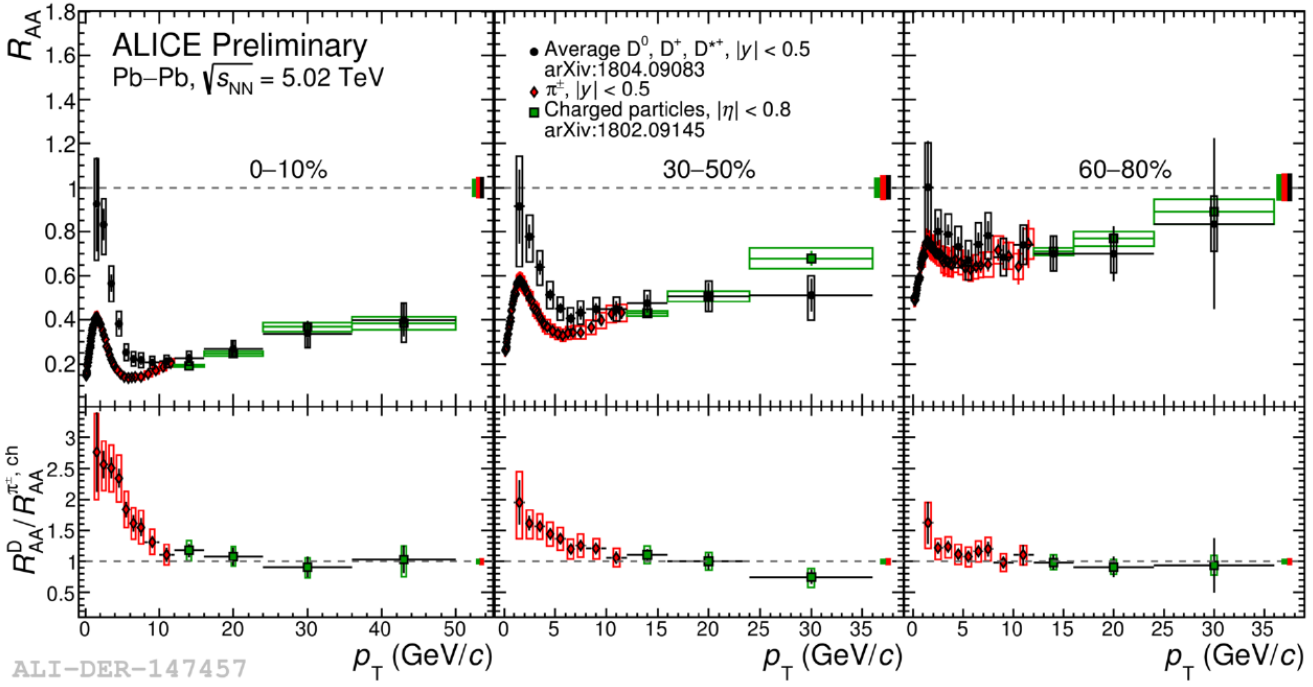


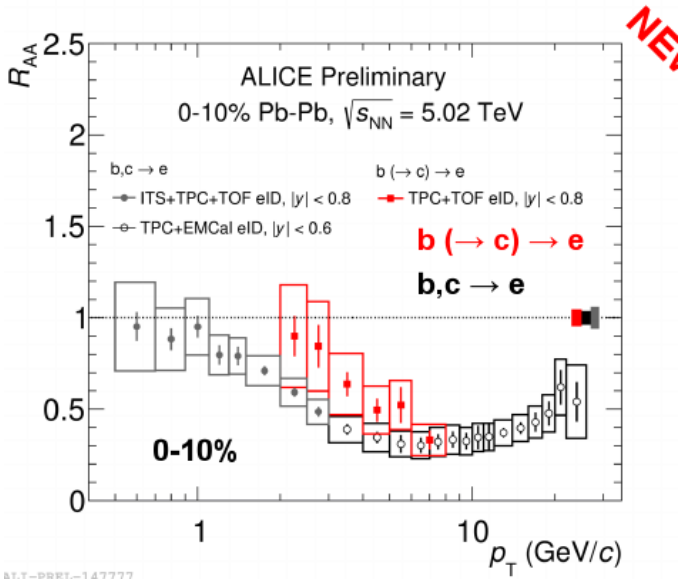
arXiv:1804.09083

- **R_{AA} < 1 in central collisions**

- Hint of **enhanced** D_s production in comparison to non-strange D mesons in Pb-Pb collisions. Expected from models
  - ➢ **Effect of coalescence + strangeness enhancement?**
- D_s/D^0: no evidence for centrality dependence within uncertainties
  - ➢ Negligible centrality-dependence expected by pure-coalescence scenario

Open Heavy-Flavour in AA





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arXiv:1804.09083

Open HF – comparison to models

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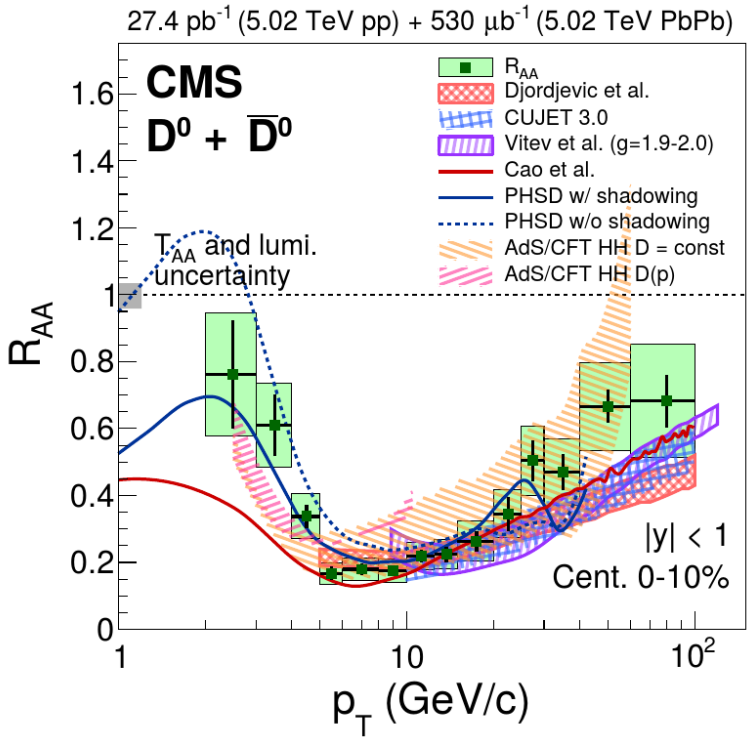

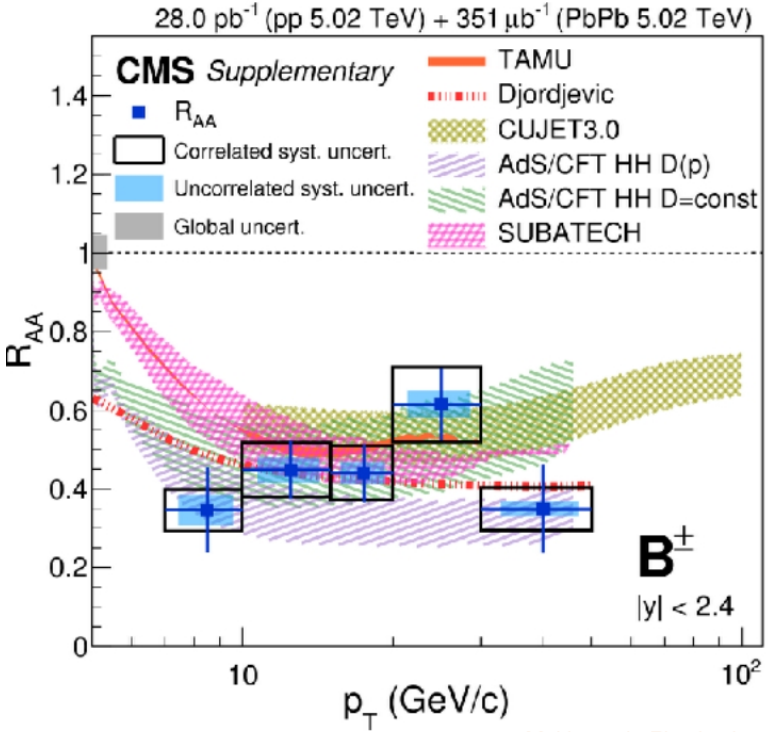

M. He et al., Physics Letters B **735** (2014) 445 – 450
M. Djordjevic, *Phys. Rev. C* **94** (Oct, 2016) 044908
X. Jiechen et al., Journal of High Energy Physics **2** (2016)
W. A. Horowitz, Phys. Rev. D 91 (2015) 085019
P. B. Gossiaux et al, Nucl. Phys., A931 (2014) 581

Open HF – comparison to models

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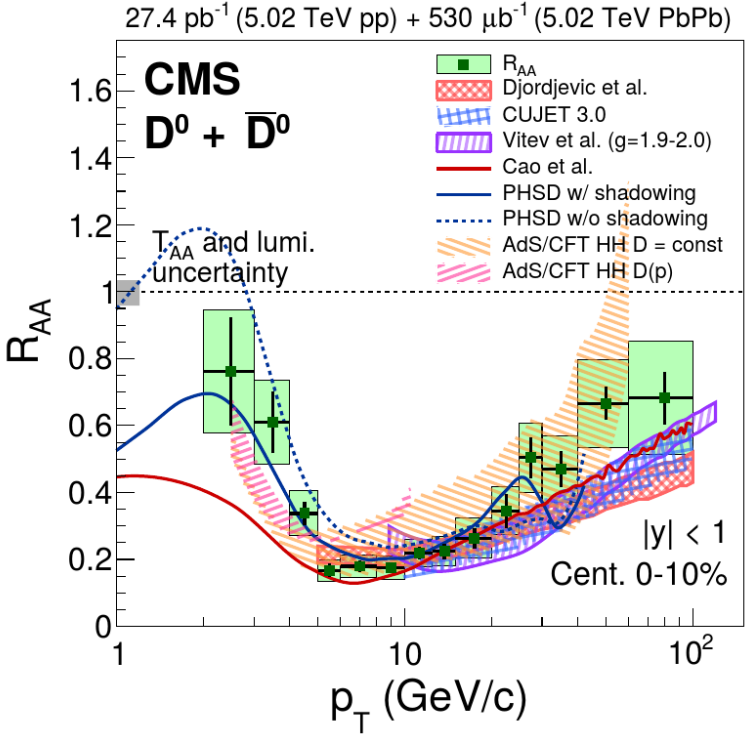
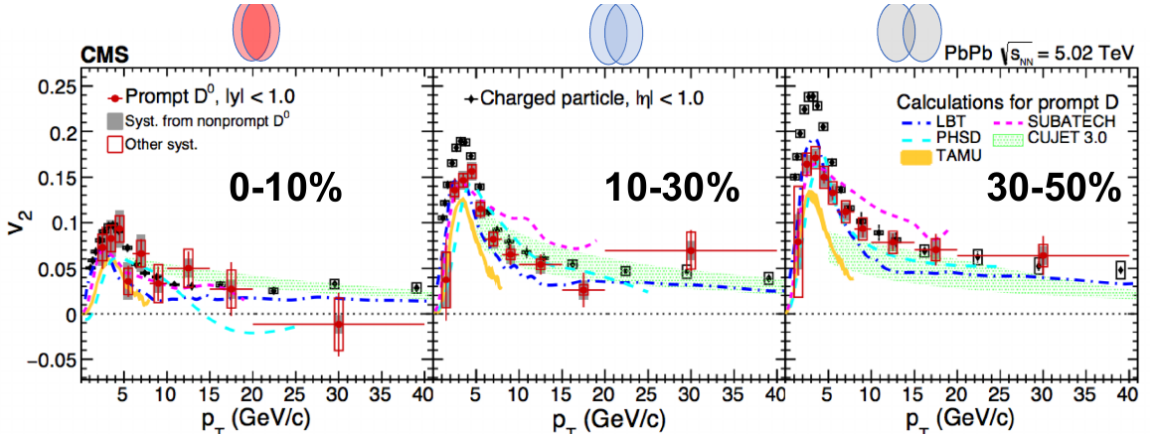
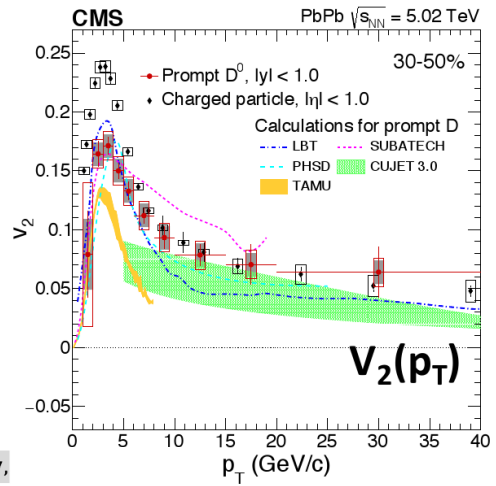
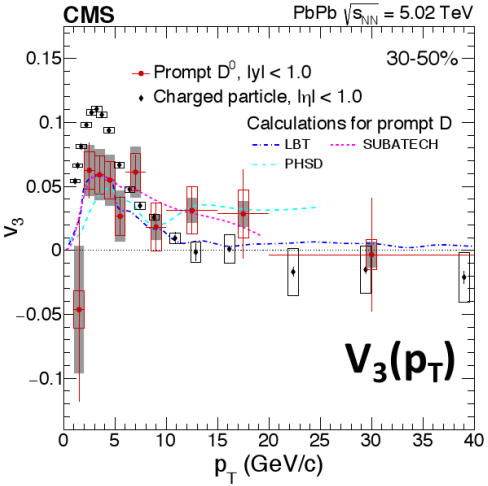




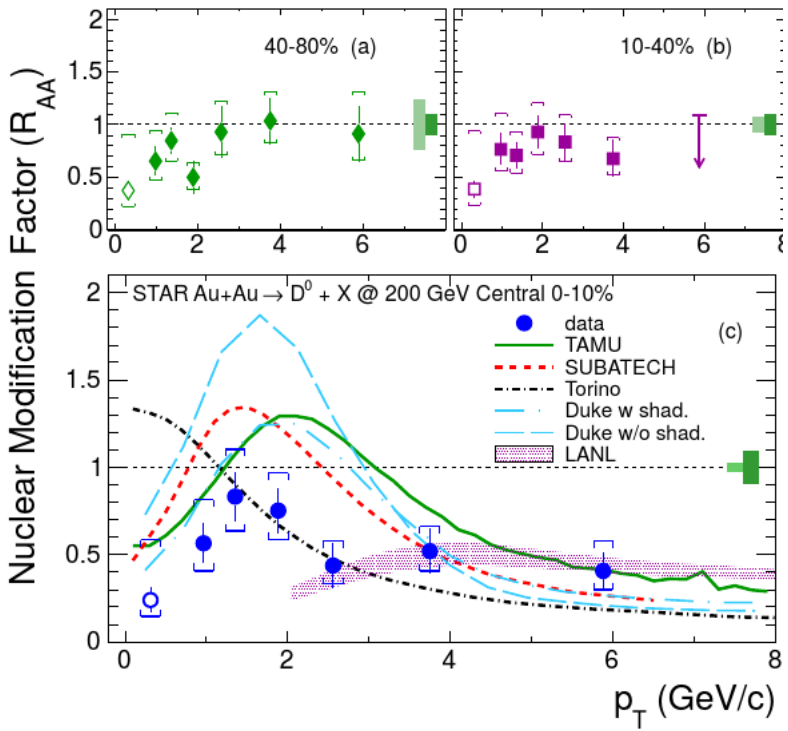




arXiv: 1708.03497,

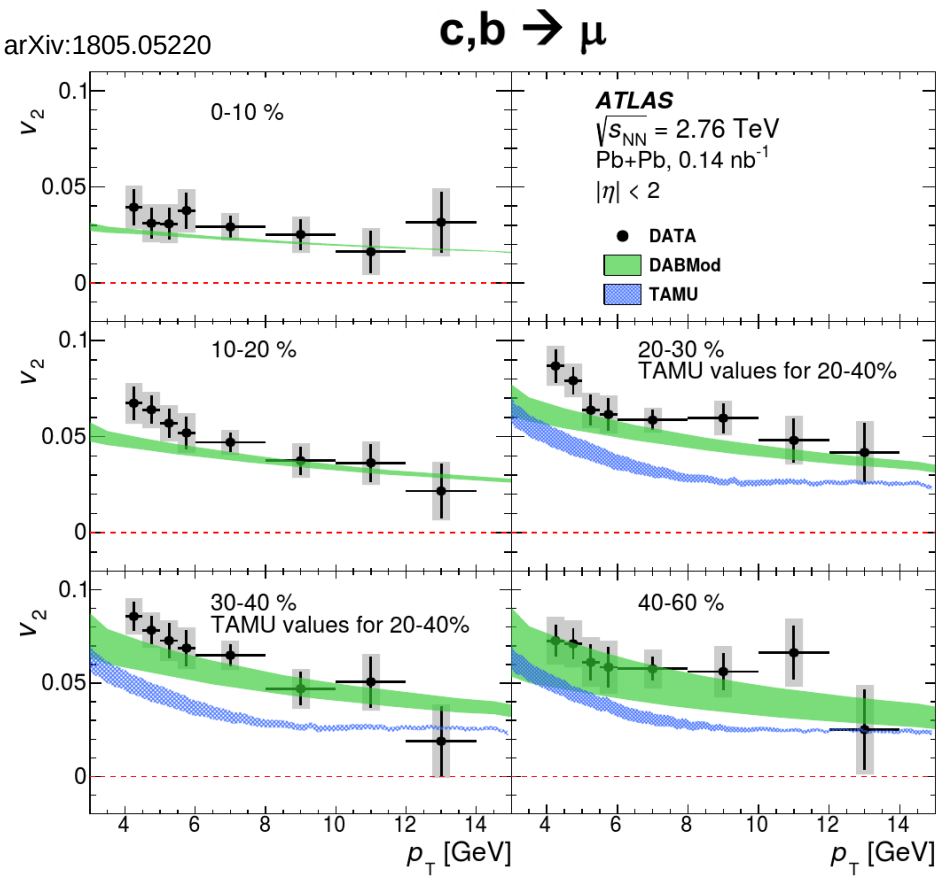
Open HF in AA – comparison to models

- RHIC

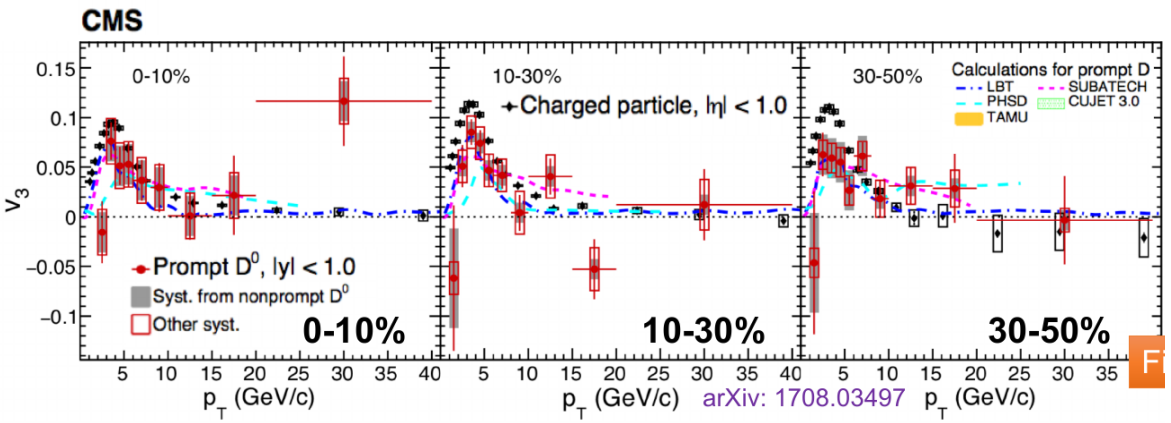


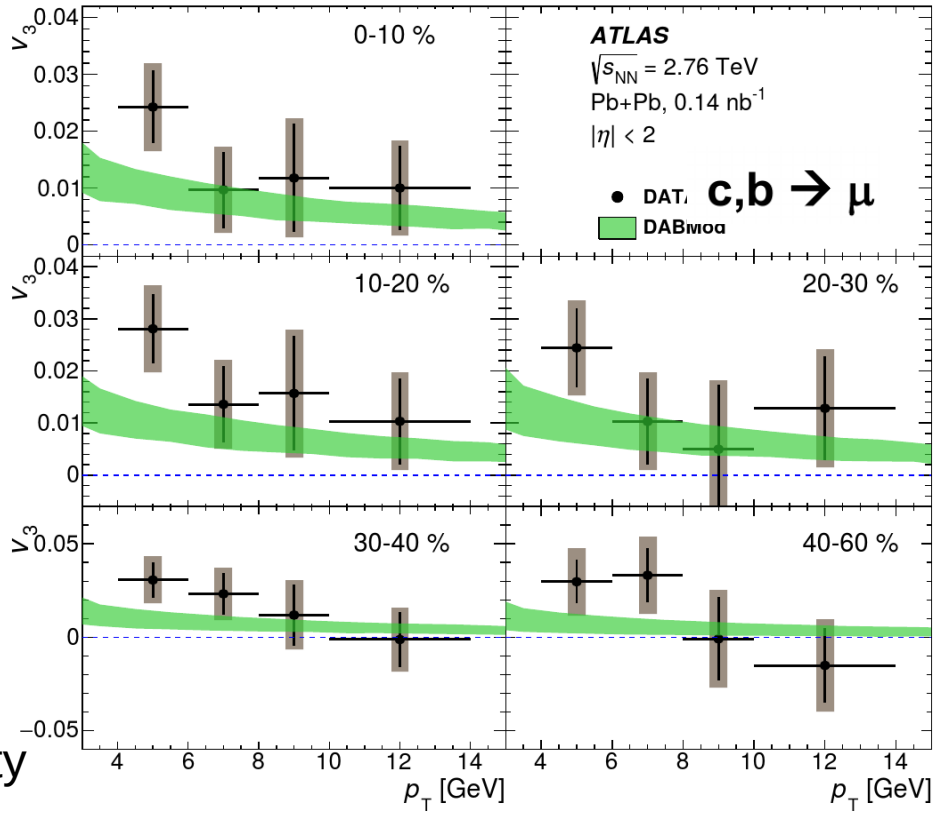
HF v_2 in AA

arXiv:1805.05220



HF v_3 in AA





Positive v_3 for HF !

Both v_2 and v_3 smaller for charm wrt light quarks:
different degree of thermalization,
Recombination?
Very little centrality dependence: constant triangularity from geometrical fluctuations

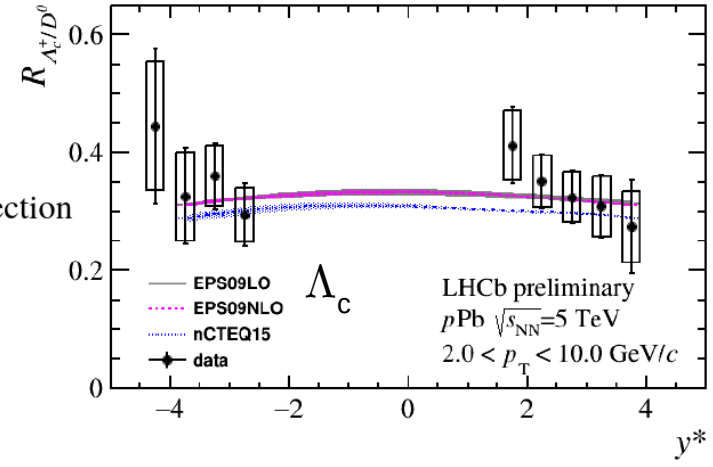
Models (including charm re-scattering) qualitatively describe v_2 and v_3 data

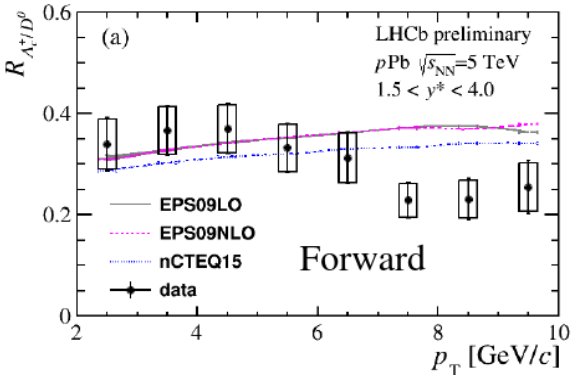
→ **confirm that charm takes part in collective motion**

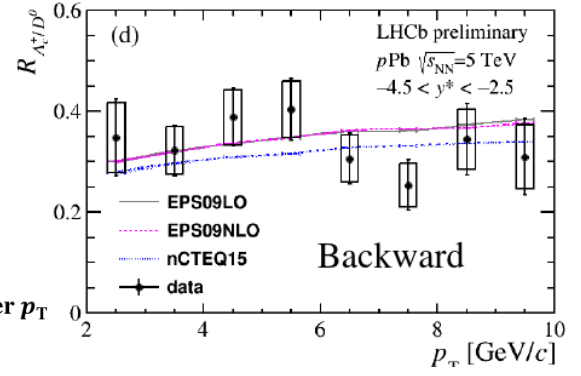
HF baryons, Λ_c / D^0 ratio

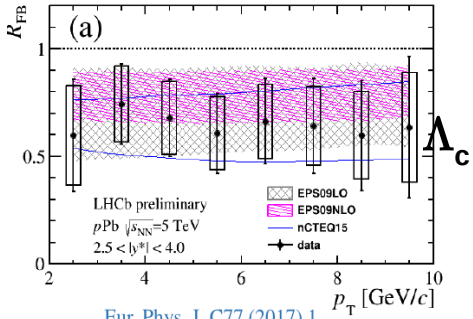
$$R_{\Lambda_c^+/D^0} = \frac{\sigma_{\Lambda_c^+}(y^*, p_T)}{\sigma_{D^0}(y^*, p_T)}$$

- Sensitive to charm hadronisation mechanisms
- Model based on measured *pp* cross-section
- nPDF effects mostly cancel
  - EPS09LO & EPS09NLO similar
  - nCTEQ15 slightly lower
- Flat across y^*
- **Consistent with theories for all y^***

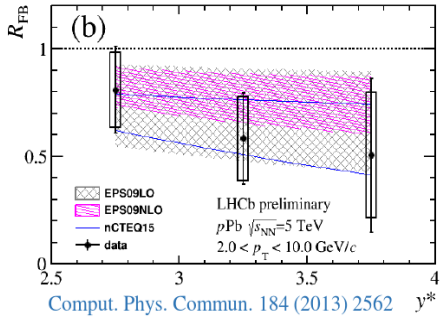








Eur. Phys. J. C77 (2017) 1
LHCb-PAPER-2018-021 in preparation



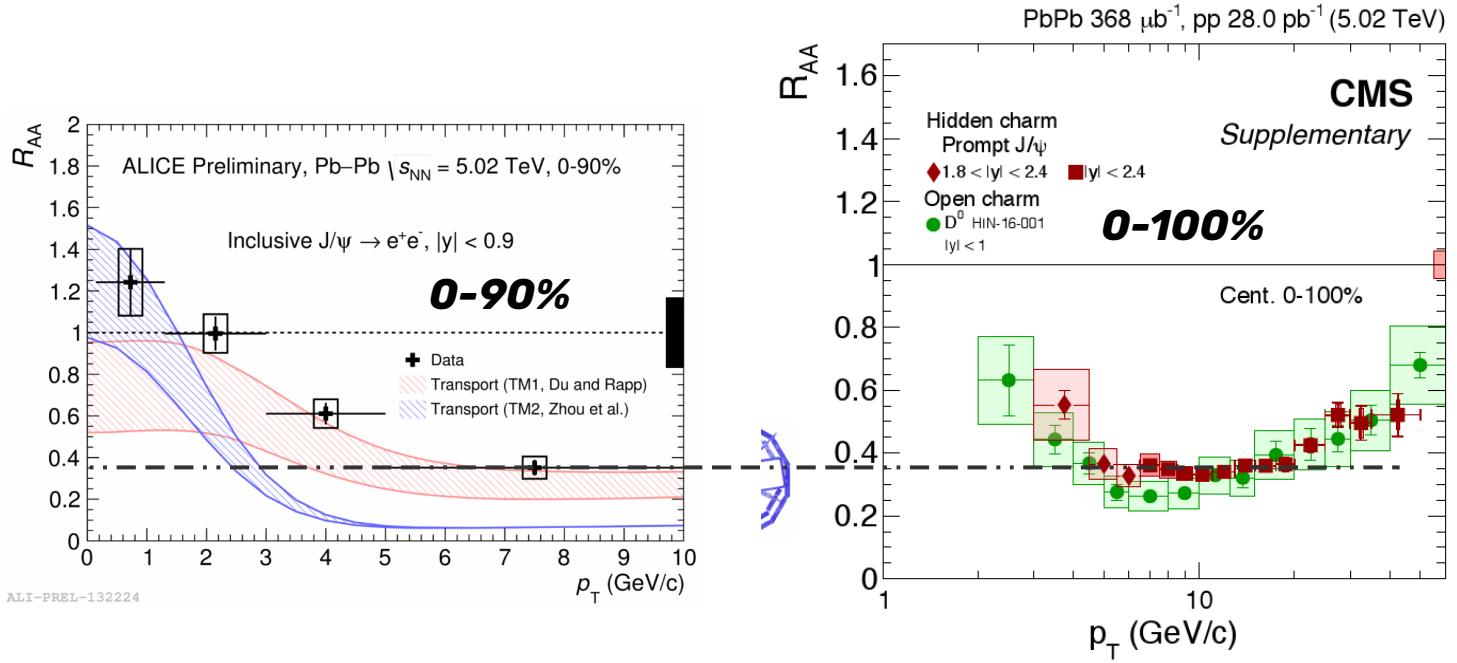
Eur. Phys. J. C77 (2017) 1
Comput. Phys. Commun. 184 (2013) 2562
Comput. Phys. Commun. 198 (2016) 238
LHCb-PAPER-2018-021 in preparation

- Consistent with nPDF predictions within uncertainty
- **Data uncertainties comparable to nPDF calculations**

- **Forward:**
  - **Consistent at lower p_T**
  - **Below theories at higher p_T**
- **Backward:**
  - **Consistent for all p_T**

LHCb QM18

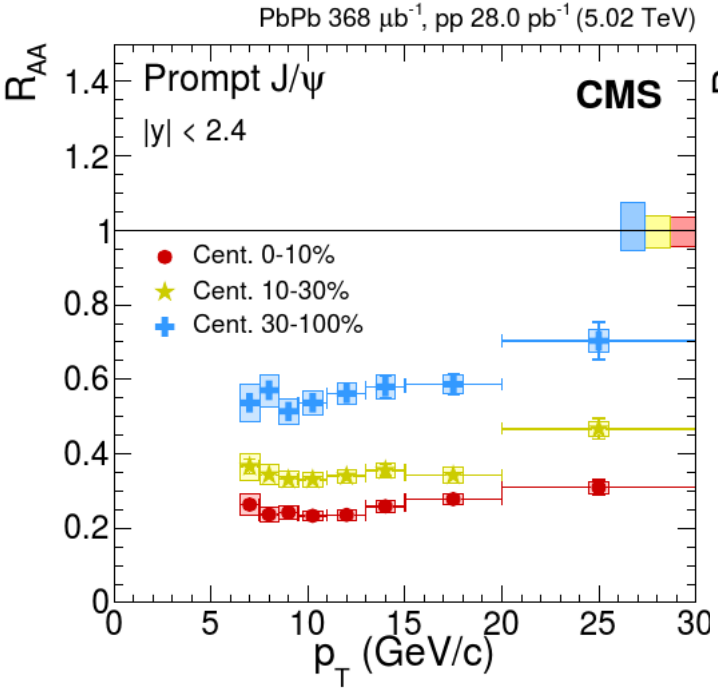
J/ψ in AA – p_T dependence

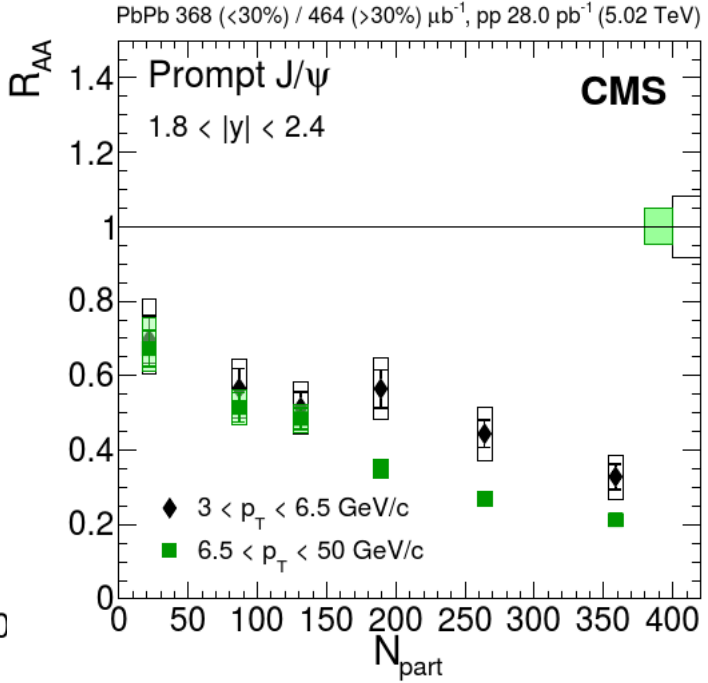


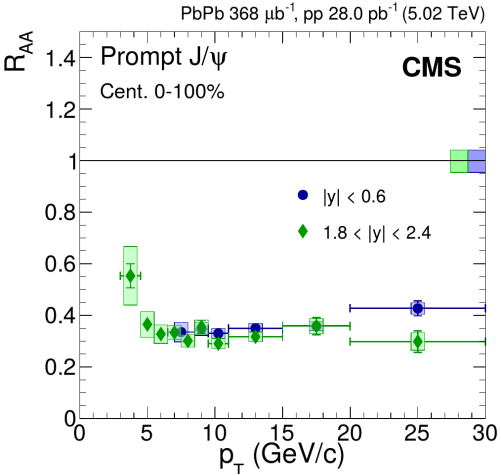
- **LHC: Smaller suppression at low p_T – regeneration in play ?**
- Decreasing suppression with centrality at p_T >~ 12 GeV/c
  - Suppression similar to charged hadrons and open charm at p_T >~ 12 GeV/. Parton energy loss ?

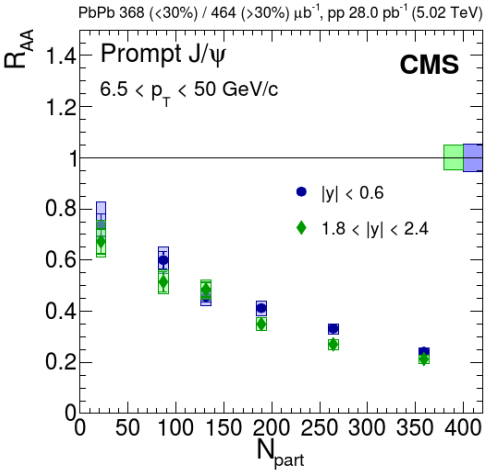
CMS: Eur. Phys. J. C 78 (2018) 509

J/ψ in AA – CMS





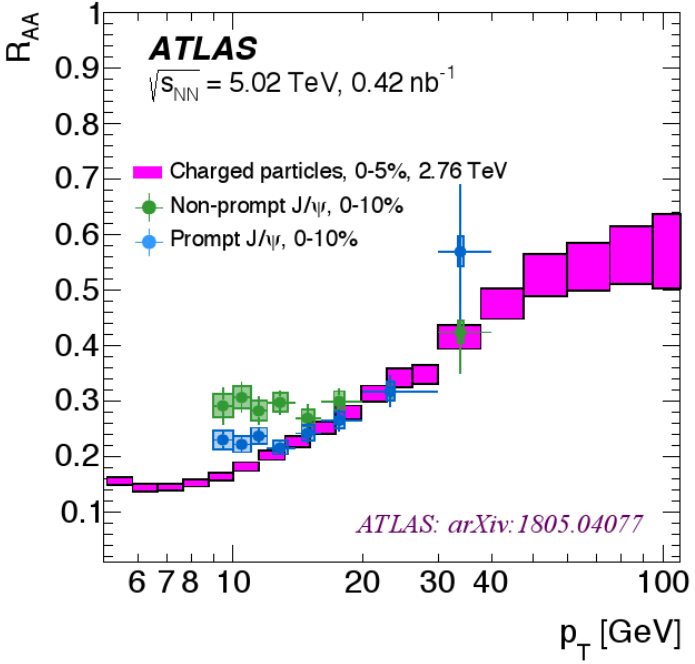


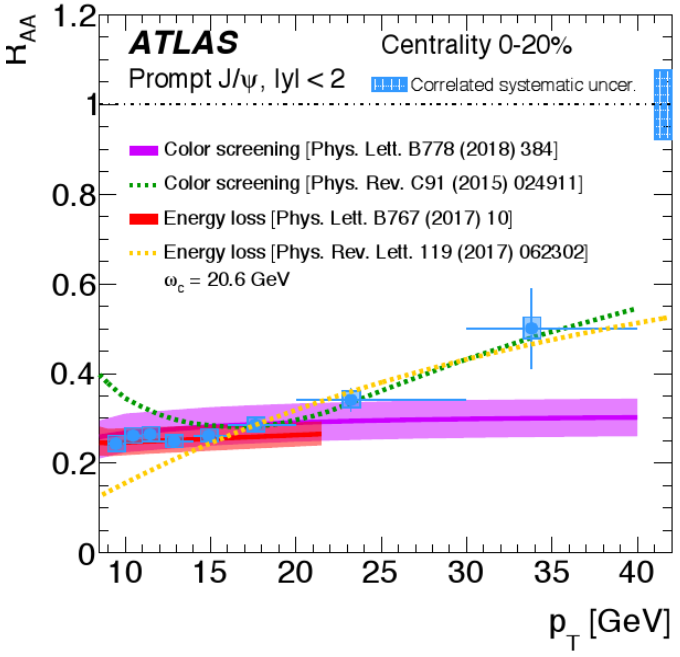


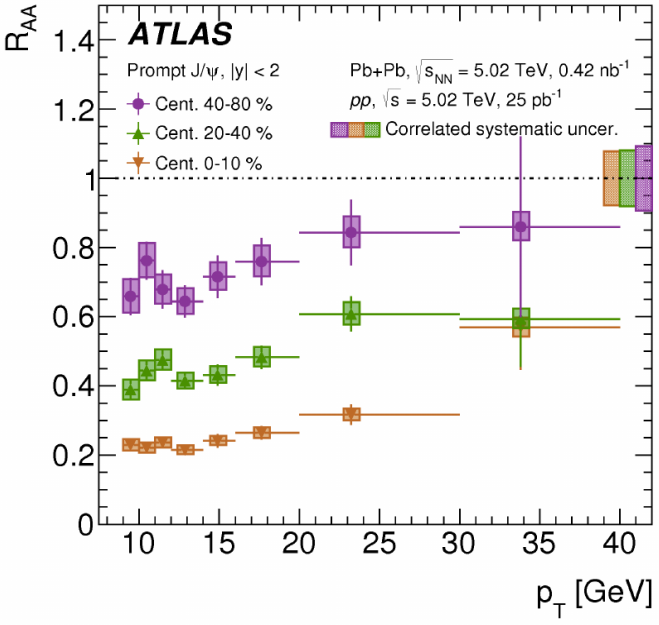
CMS: Eur. Phys. J. C 78 (2018) 509

J/ψ in AA – p_T dependence

Backup





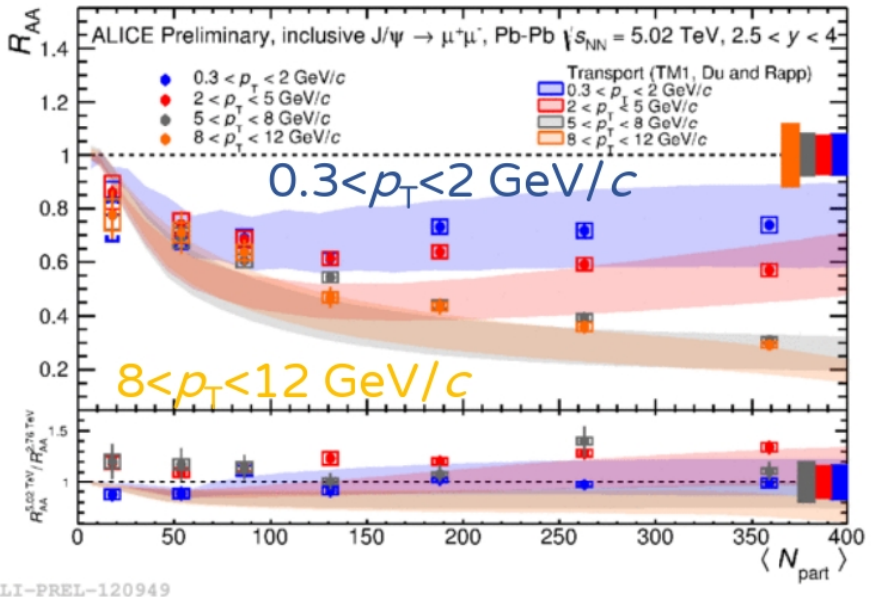


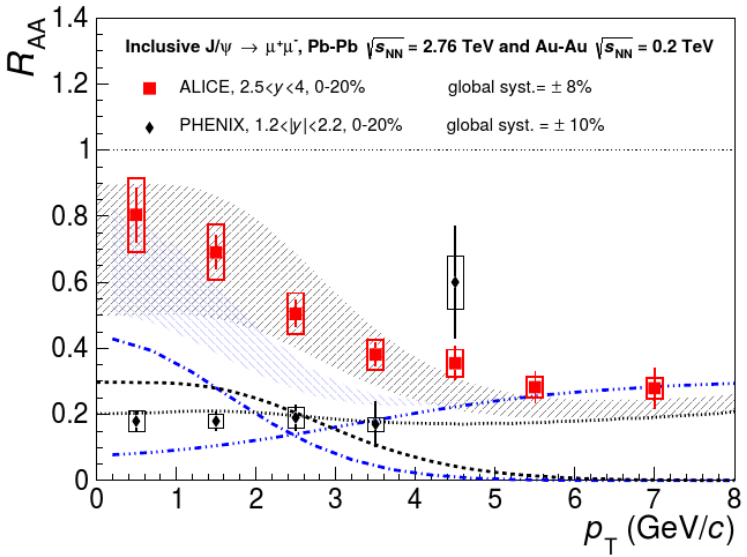
- Decreasing suppression with increasing p_T – similar to charged hadrons at p_T >~ 12 GeV/c
- Consistent with colour screening and parton energy-loss predictions

ATLAS: arXiv:1805.04077

J/ψ in AA

Backup

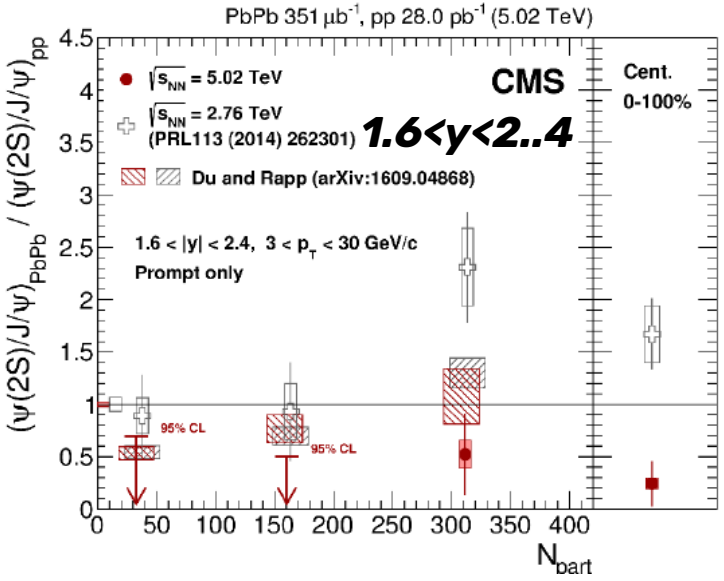


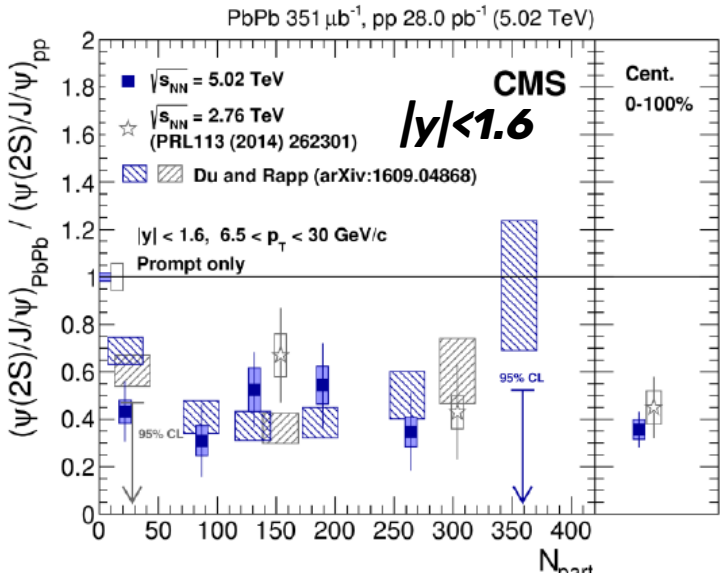


ALICE, PRL 119 (2017) 242301
ATLAS-CONF-2018-013
CMS, EPJC 77 (2017) 252

What about ψ(2S) in AA ?

2.76 TeV
5.02 TeV

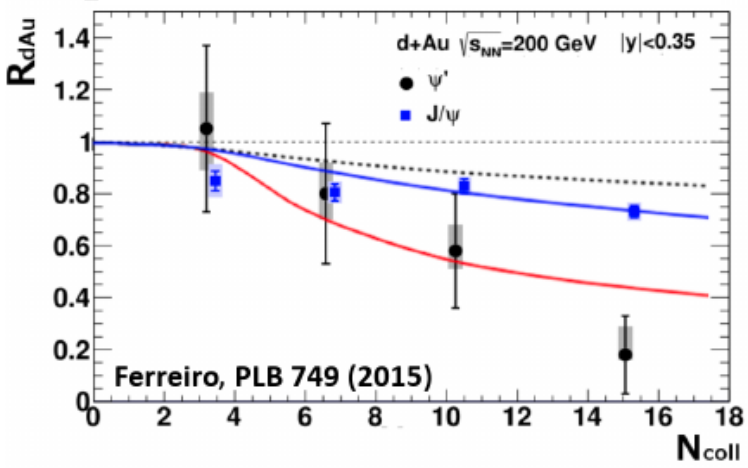


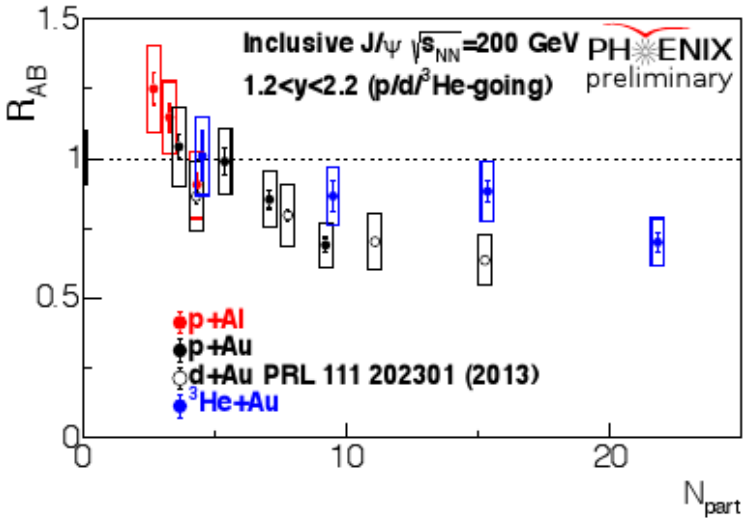


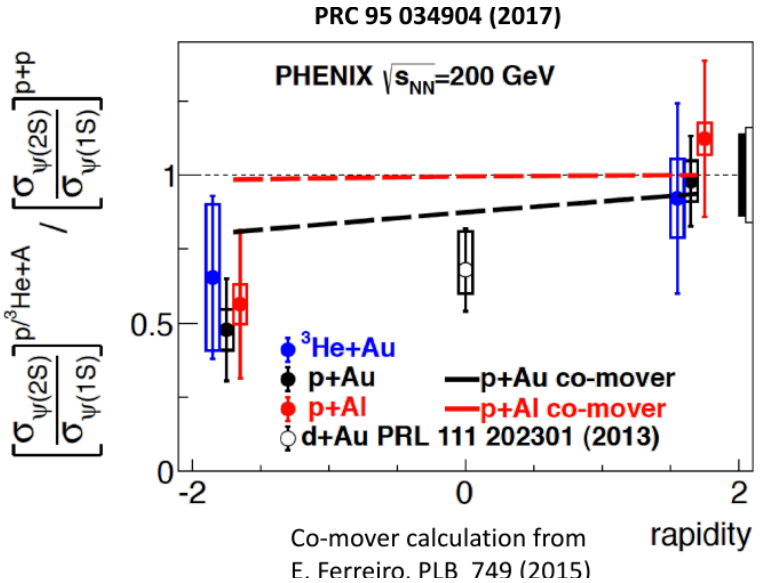
2.76 TeV
5.02 TeV

- More suppression of prompt ψ(2S) than prompt J/ψ, across p_T bins.
  - Consistent with transport model: interplay of suppression and regeneration.
  - ψ(2S) more suppressed than J/ψ in pA as well.

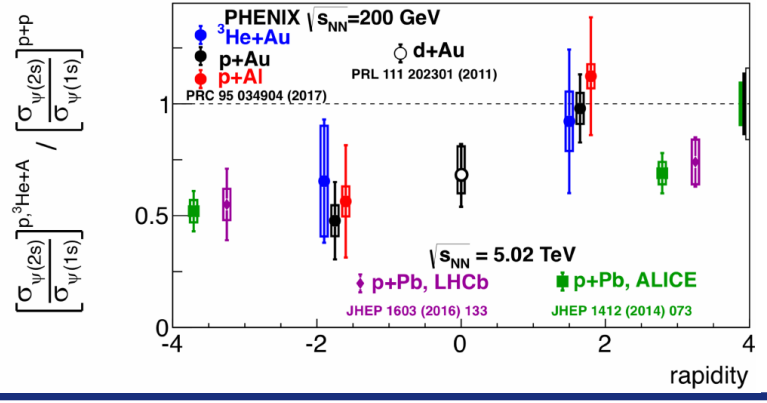
ψ in pA



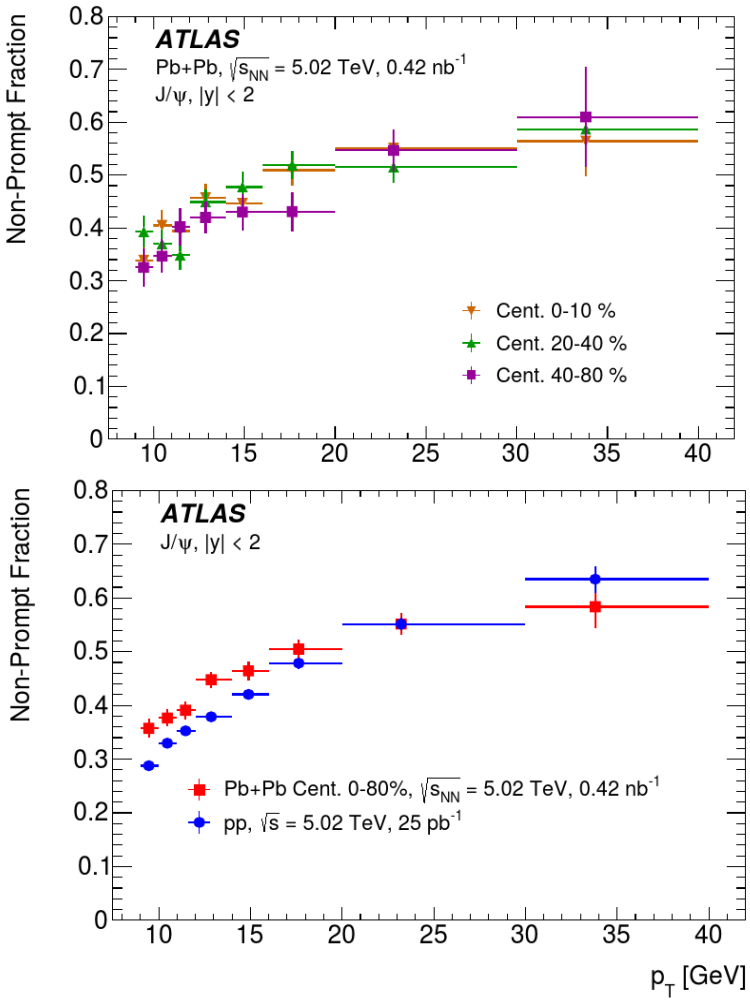


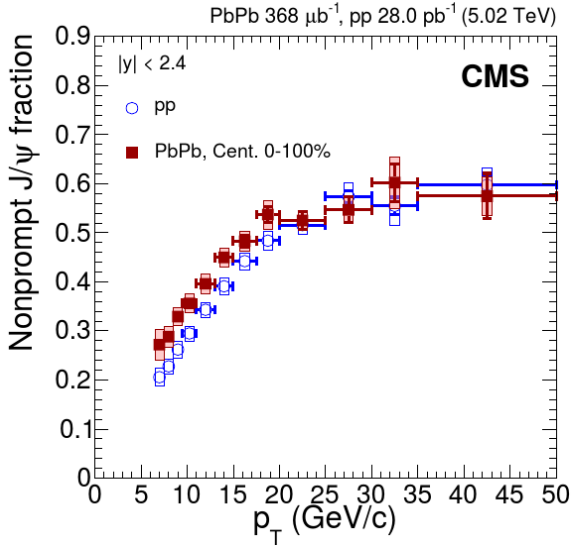


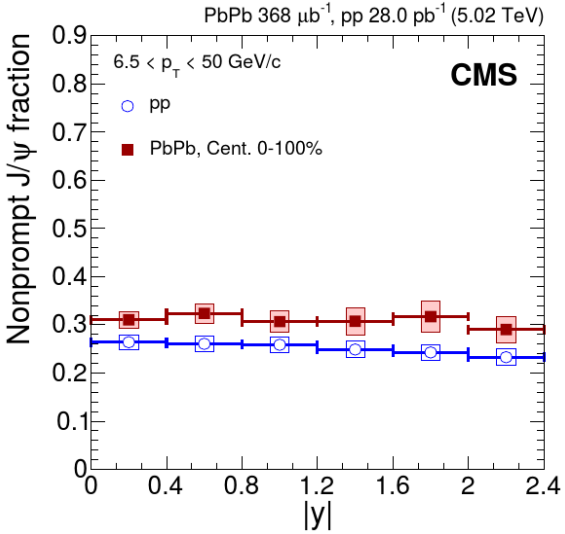
Co-mover calculation from E. Ferreiro, PLB 749 (2015)



Non-prompt J/psi







Open Heavy-Flavour

	Mass (GeV/c^2)	$c\tau$ (μm)	Decay	BR (%)
D^0	1.865	123	$K^- \pi^+$	3.93
D^+	1.870	312	$K^- \pi^+ \pi^+$	9.46
D^{*+}	2.010	-	$D^0 (K^- \pi^+) \pi^+$	67.7 x 3.93
D_s^+	1.968	150	$\Phi(K^- K^+) \pi^+$	2.27

$\Lambda_c^+ \to e^+ \Lambda \nu_e$	**BR ~ 3.6%**
$\Xi_c^0 \to e^+ \Xi^- \nu_e$	**BR unknown**

$D^0 \to K^- \pi^+$	BR ~ 3.93%	$c\tau \sim 123\ \mu m$
$D^+ \to K^- \pi^+ \pi^+$	BR ~ 9.46%	$c\tau \sim 312\ \mu m$
$D^{*+} \to D^0(K^- \pi^+)\pi^+$	BR ~ 2.66%	-
$D_s^+ \to \phi(K^- K^+)\pi^+$	BR ~ 2.27%	$c\tau \sim 150\ \mu m$
$\Lambda_c^+ \to pK^- \pi^+$	BR ~ 6.35%	$c\tau \sim 60\ \mu m$
$\Lambda_c^+ \to pK_s^0$	BR ~ 1.58%	"

$$b, c \to e^{\pm} X (BR \approx 10\%)$$

$$b, c \to \mu^{\pm} X (BR \approx 10\%)$$