XVI SQM BERKELEY 2016

Summary I: Heavy Flavor Production

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Strangeness in Quark Matter 2016
UC Berkeley, June 17th – July 1st

Why Open Heavy Flavor?

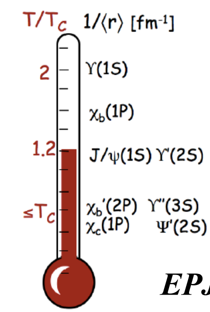
- **HEAVY: $m_{c,b} >> T_{QGP}, \Lambda_{QCD}$**
  - Produced in high-Q^2 scatterings → calculable in pQCD; scales with N_{coll} collisions in AA
  - Produced at early stage → imprint the entire evolution history of QGP
- **Energy loss → QGP kinematics**
  - Radiative energy loss: color charge and quark mass dependence

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

  - Collisional energy loss also plays an important role.
  - R_{AA} is a convolution of both energy loss and spectrum shape
- **Collective motion→ QGP dynamics**
  - Degree of thermalization with the medium
  - v_2 is also affected by path-length dependent energy loss at high p_T

Why Quarkonium?

- **Color-screening**: quark-antiquark potential is screened by surrounding partons, leading to dissociation
  - **J/ψ suppression was thought to be a proof of QGP formation**
- **Thermometer**: different quarkonium states dissociate at different temperatures

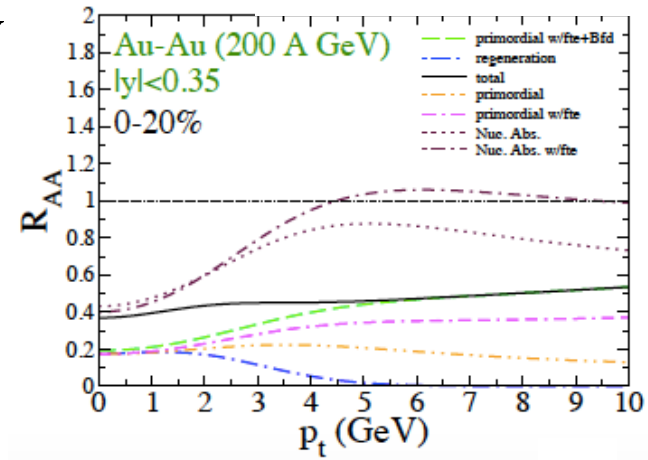


EPJC61 (2009) 705

$$r_{q\bar{q}} \sim 1/E_{binding} > r_D \sim 1/T$$

Phys. Rev. C 82, 064905

- However, other effects come into play
  - **Regeneration** ($\sigma_{c\bar{c}}$ is crucial)
  - Medium-induced energy loss
  - Formation time effects
  - Feed-down



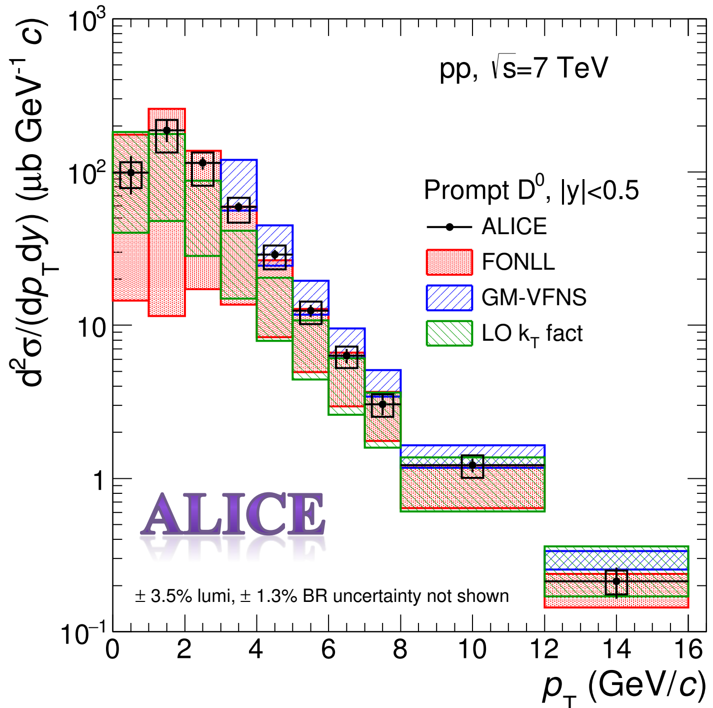
❖ How well are heavy flavor in pp and pA understood?

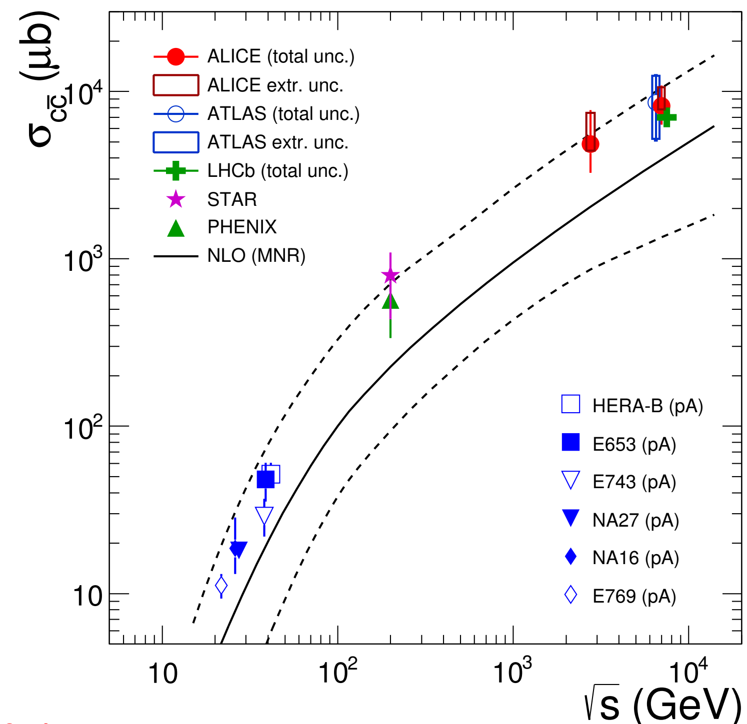
pp Collisions

pA/dA Collisions

AA Collisions

D^0 Measured Down to $p_T = 0$



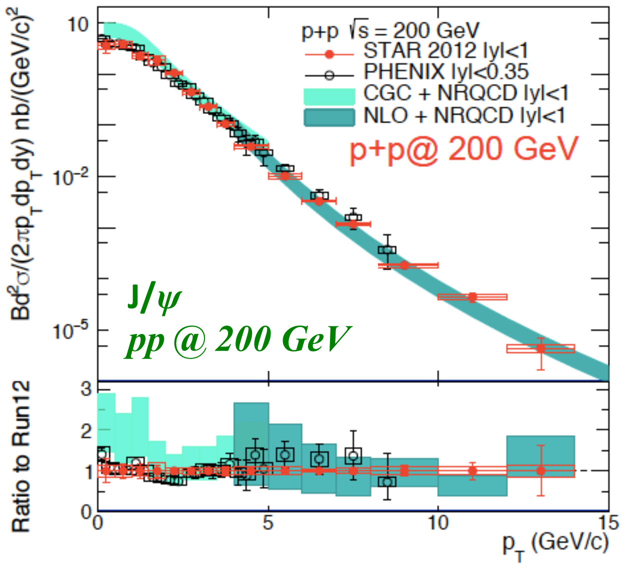


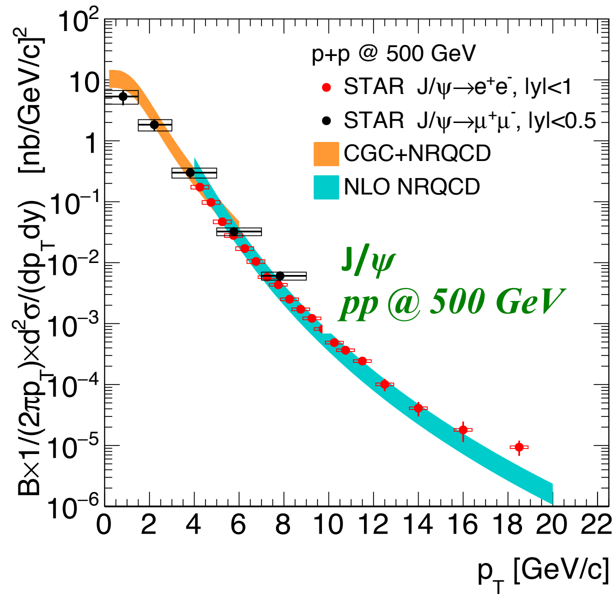
- ***New D^0 measurement down to $p_T = 0$ in pp 7 TeV***
  - No secondary vertexing; subtract ensemble background
- Reduced uncertainty for total charm cross section
  - Crucial input for model calculation of regeneration contribution to quarkonia.
- What about pp at 2.76 TeV?

ALICE:
arXiv: 1605.07569
Theory:
JHEP 0407 (2004) 033
JHEP 1210 (2012) 137
EPJC 72 (2012) 2082
PRD 87 (2013) 094022

Charmonium cross-section in pp

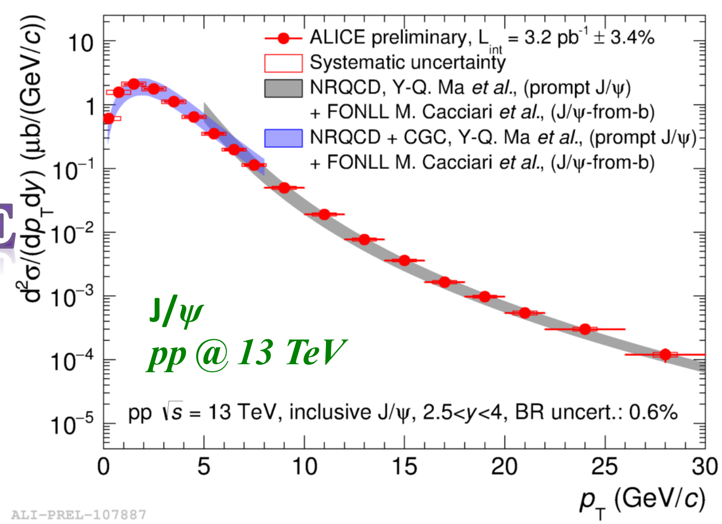
STAR

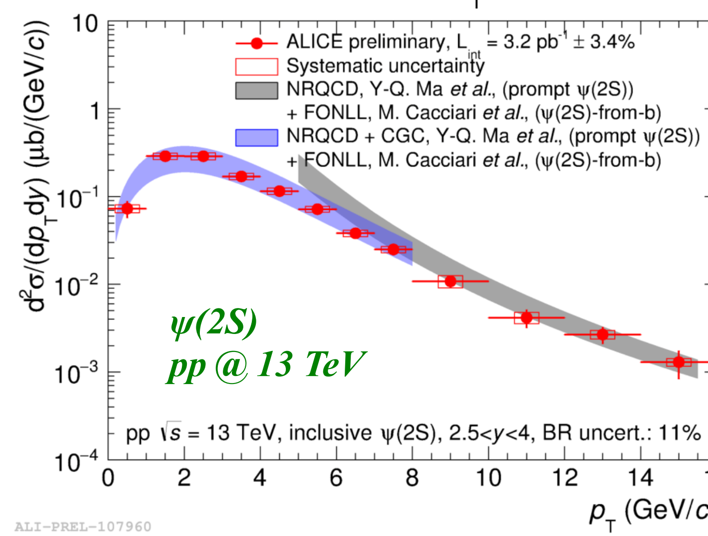




Theory:
PRL 106 (2011) 042002
PRL 113 (2014) 192301
JHEP 1210 (2012) 137

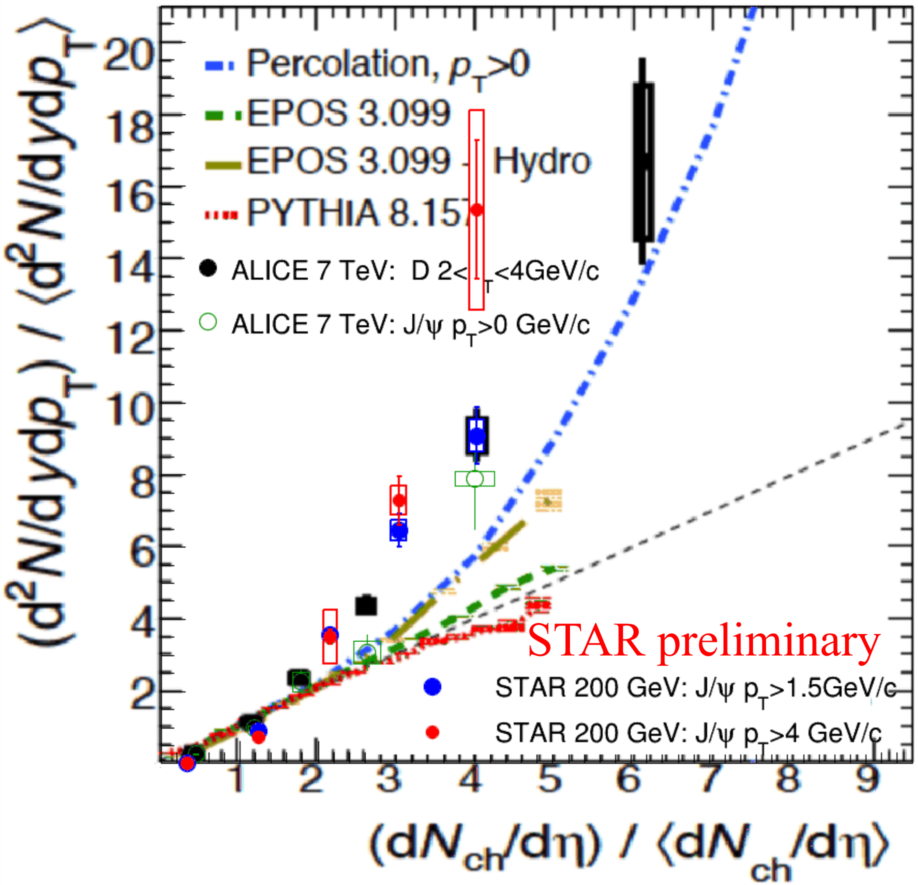
ALICE





- **Good understanding of charmonium cross section for √s = 0.2 – 13 TeV**

Heavy Flavor Yield vs. Multiplicity



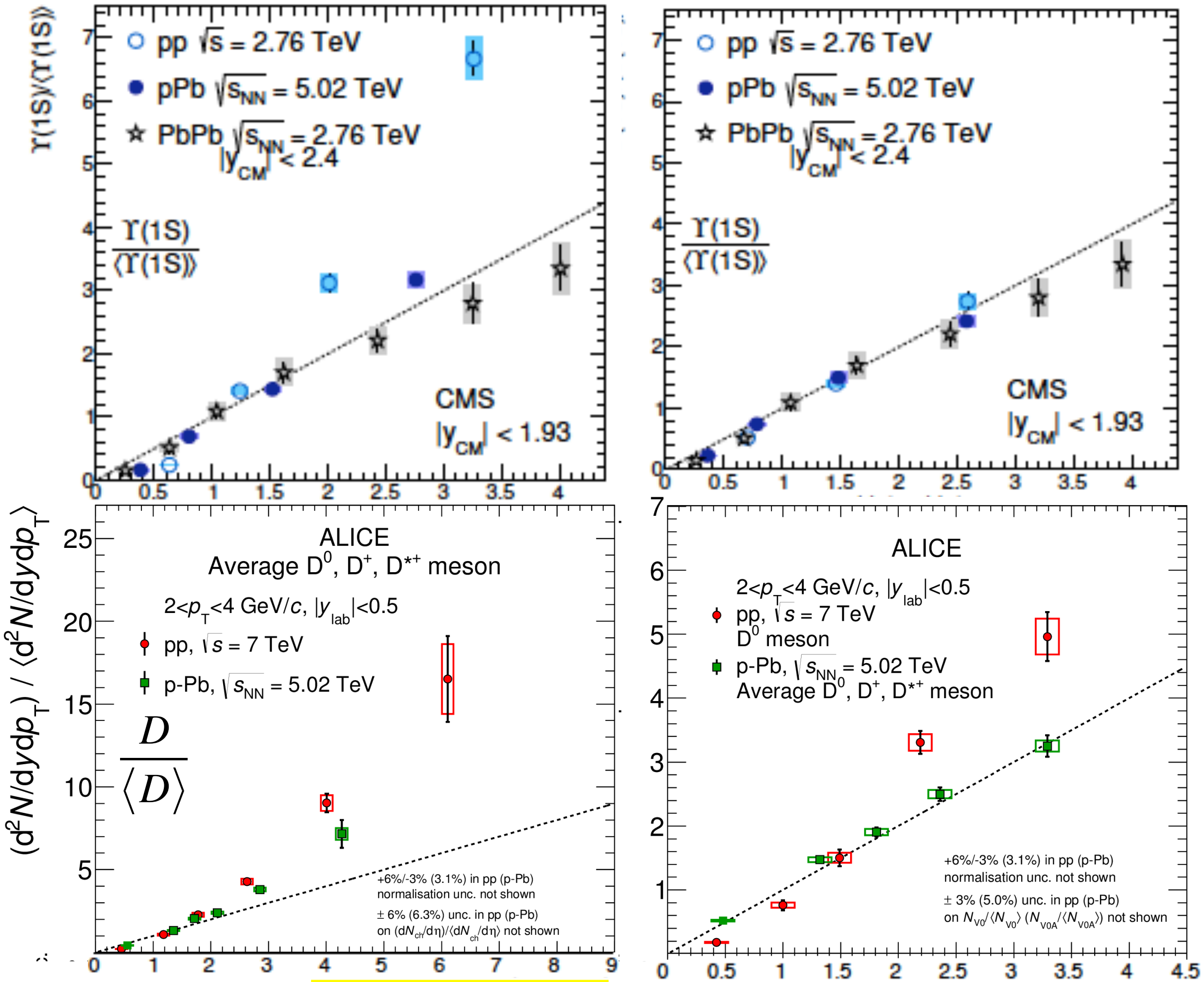
ALICE:
PLB 712 (2012) 165
JEHP 09 (2015) 148
Model:
PRC 86 (2012) 034903

- Self-normalized heavy-flavor yield increases stronger-than-linearly than event multiplicity
  - Interplay between soft and hard processes
- Similar trend is observed at RHIC and LHC
  - Fundamental underlying mechanism. MPI?
- Models on the markets
  - Percolation: high energy density suppresses soft more than hard processes
  - EPOS3+hydro: is it applicable at RHIC?
  - PYTHIA8: strong dependence on tunes

Does it Matter Where Event Activity is Measured?

CMS

ALICE



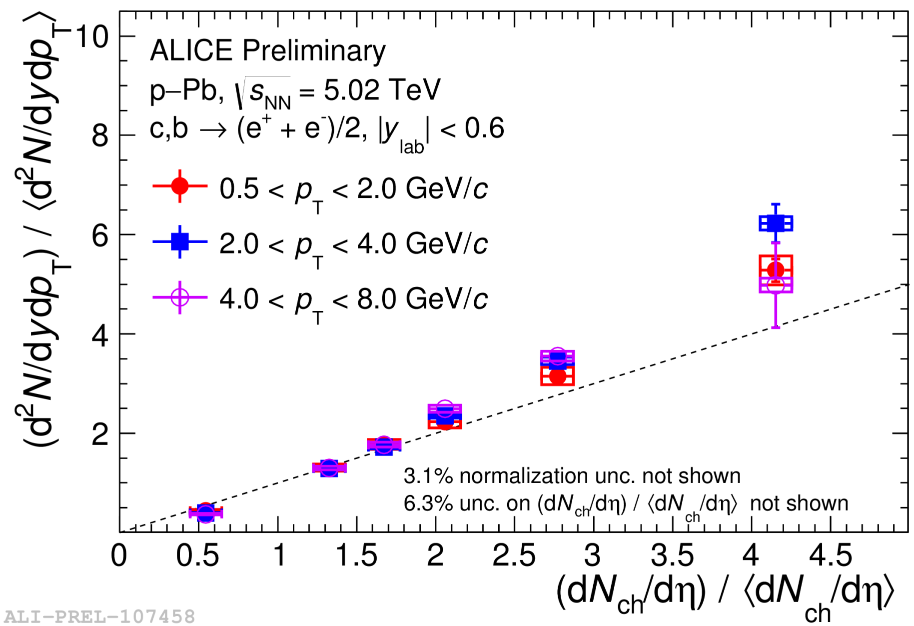
Mid-rapidity **Forward-rapidity**

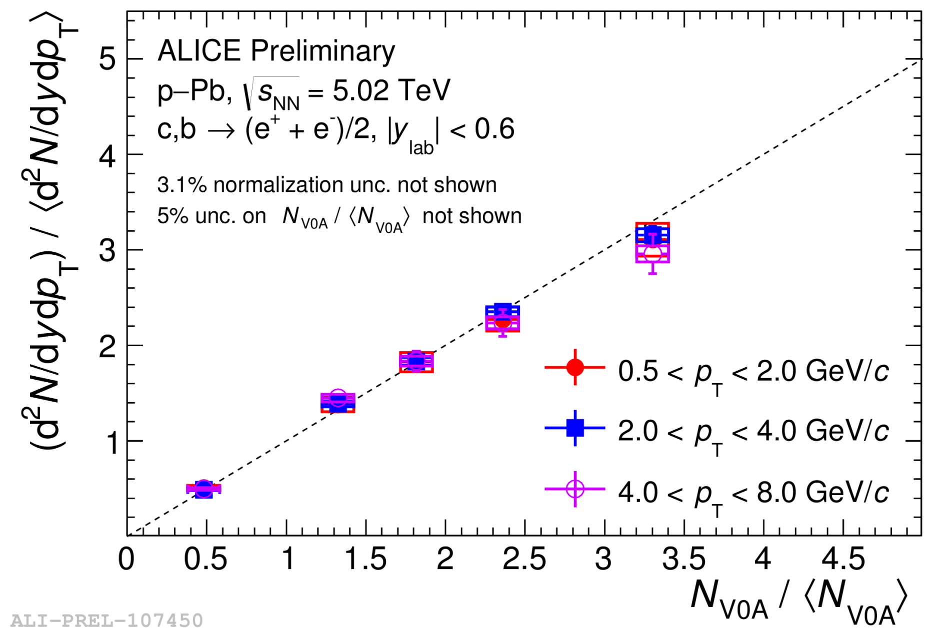
ALICE:
arXiv: 1602.07240
CMS:
JHEP 04 (2014) 103

- Different behavior vs. forward-rapidity multiplicity. Physics or tension?

HF Electron vs. Multiplicity

ALICE





- New measurements for production of HF decayed electron
  - Mid-rapidity multiplicity: stronger-than-linear
  - Backward multiplicity: linear
- Different from pp collision → role of CNM, N_{coll}
- No significant change for p_T > 4 GeV/c (>50% b->e contribution)

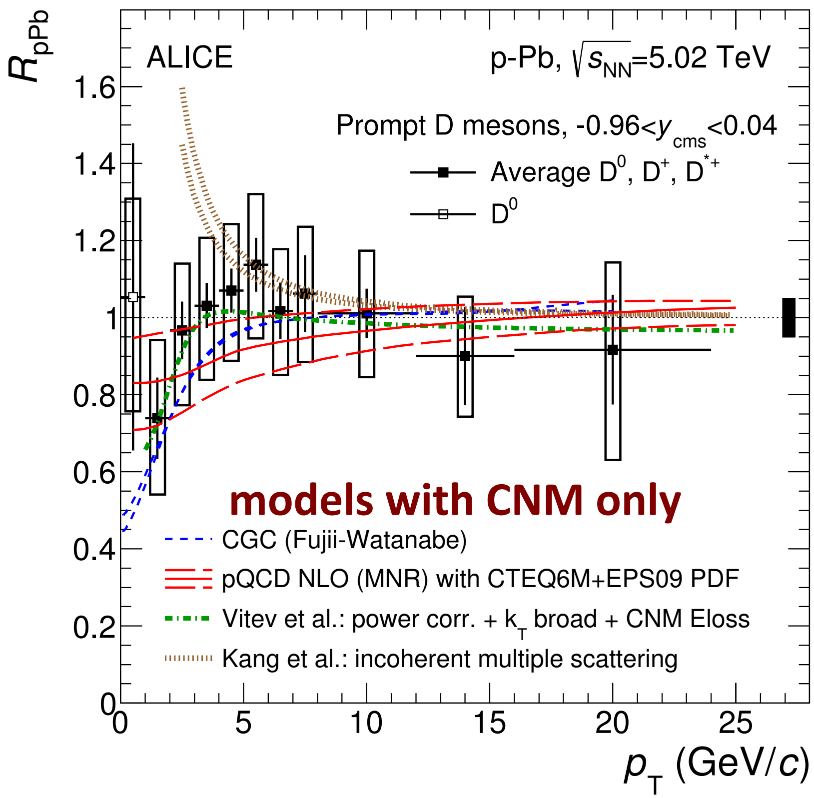
pp Collisions

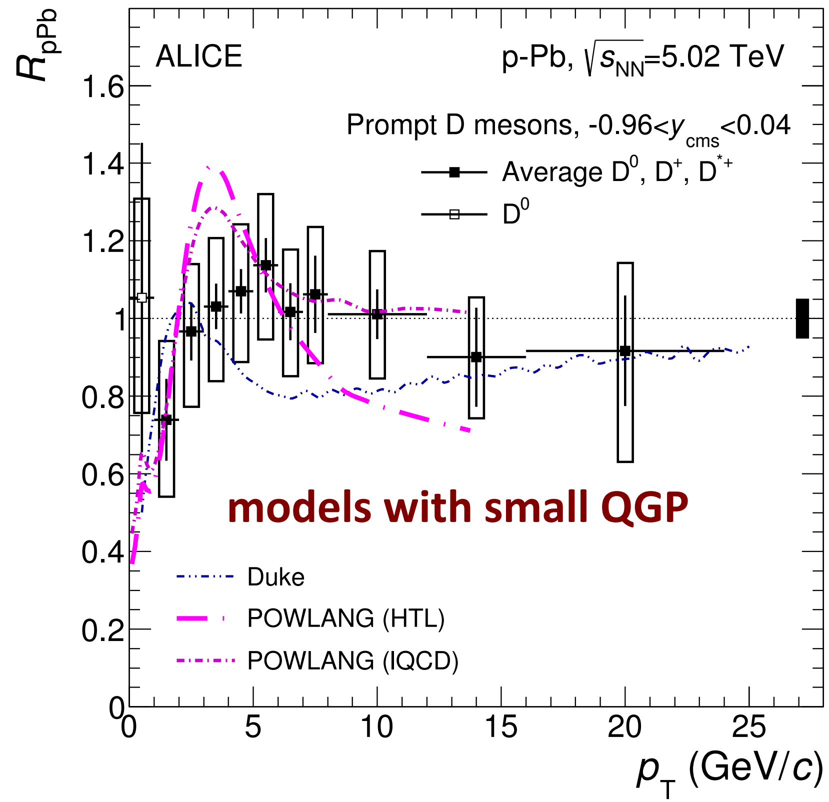
pA/dA Collisions

AA Collisions

Inclusive D Production

ALICE

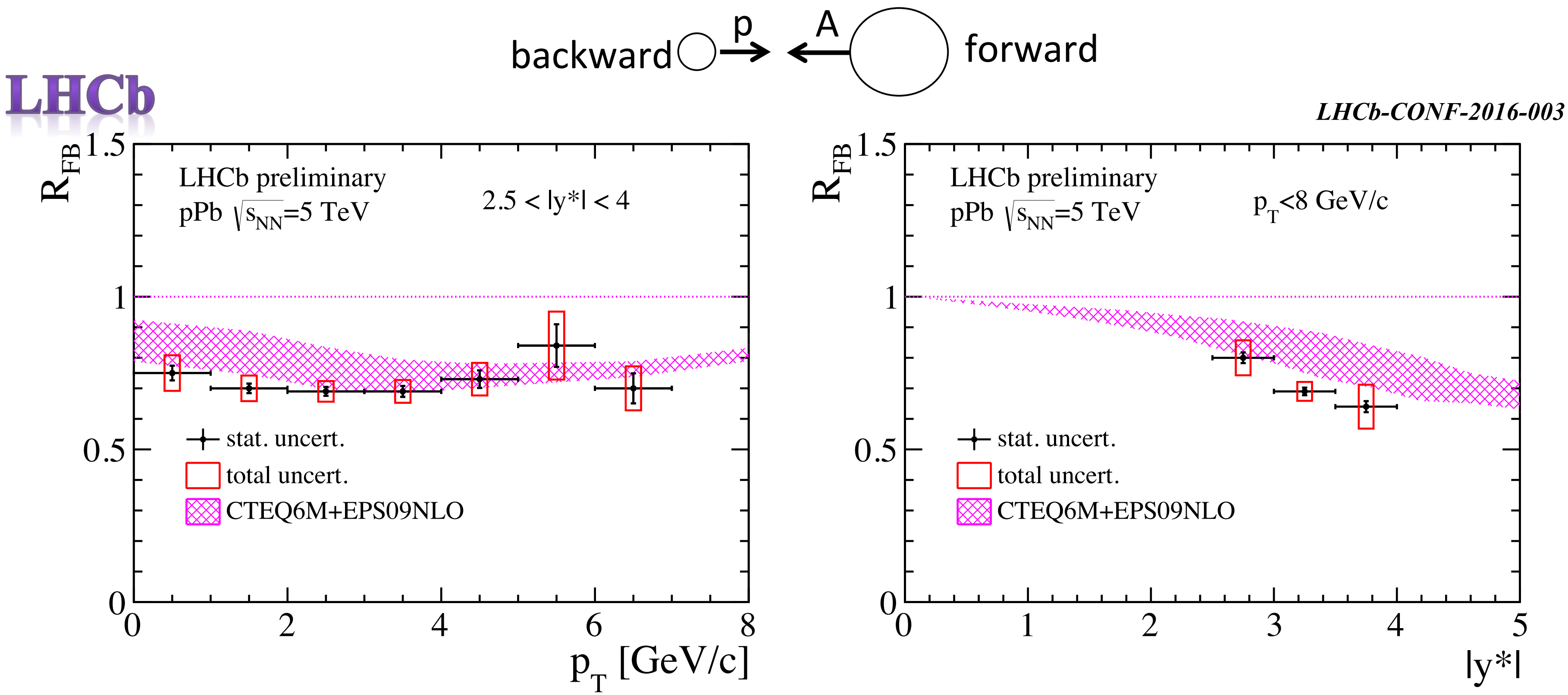




ALICE:
arXiv: 1605.07569
PRL 113 (2014) 232301

- **R_{pPb} is consistent with unity**
  - Low p_T: hint of showering?
  - High p_T: not much room for >20% suppression
- Models with initial- or final- state effects are consistent with data

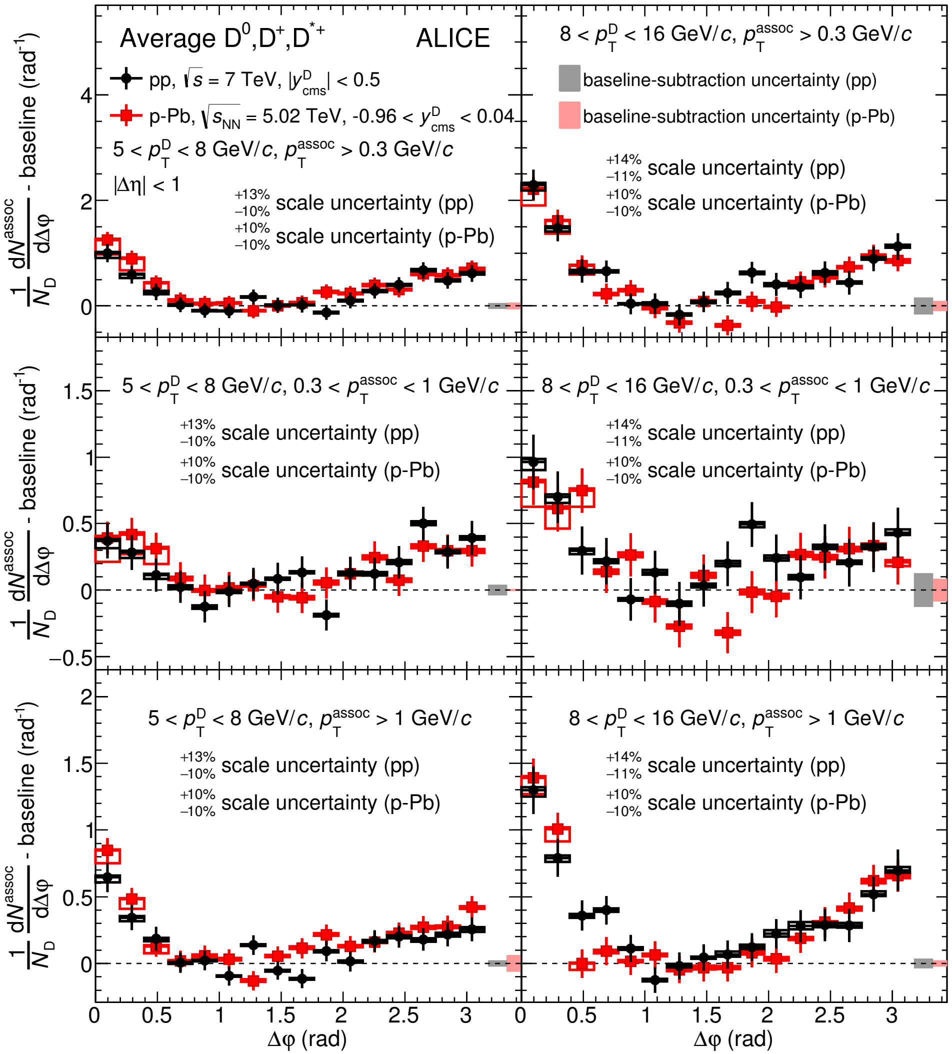
Inclusive D Production



- Models with CNM can qualitatively describe R_{FB}

D Fragmentation

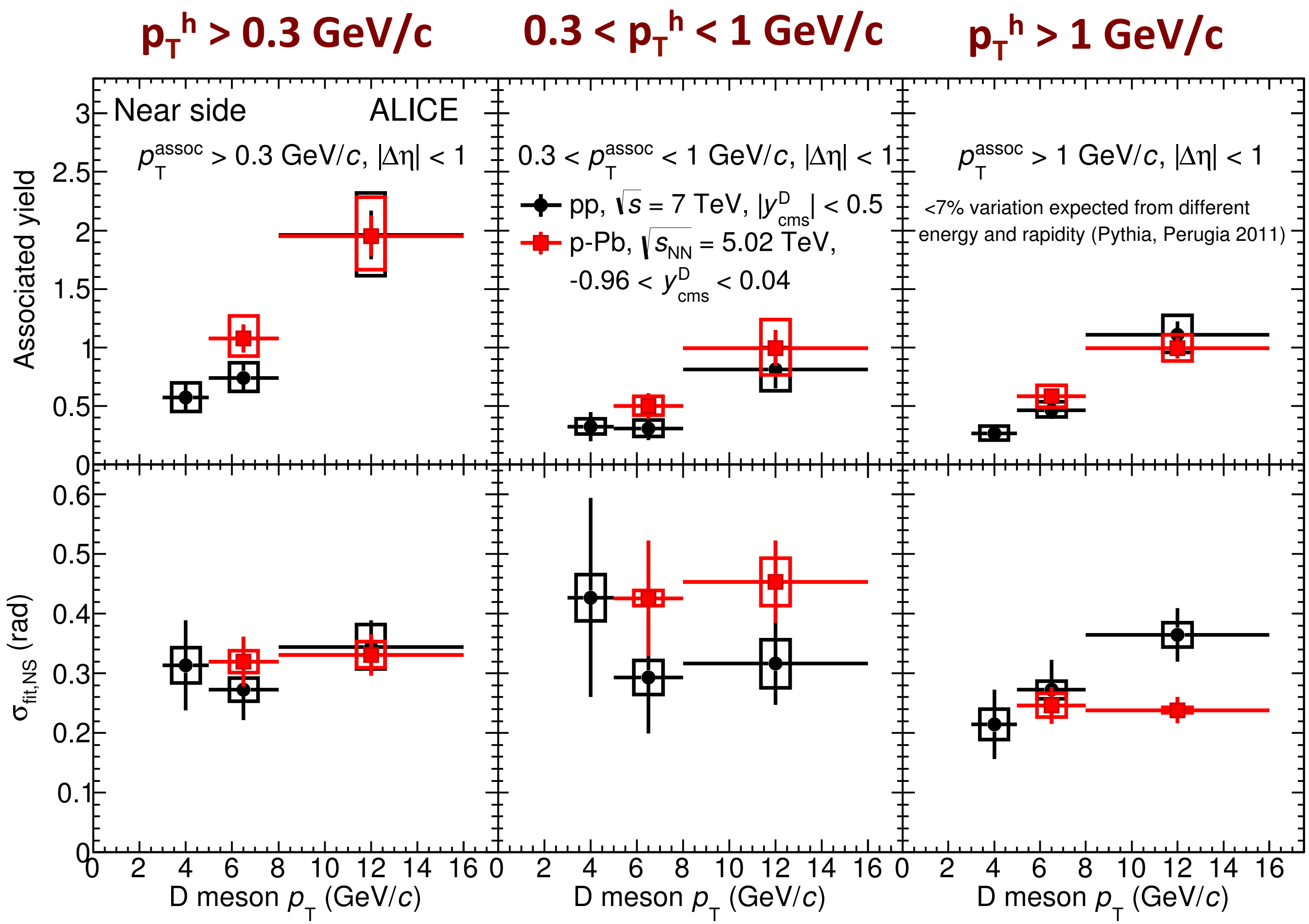
$5 < p_T^D < 8$ GeV/c $8 < p_T^D < 16$ GeV/c



- New measurements of D-h correlation
- Azimuthal correlations are fitted with double-Gaussian + constant baseline
- Baseline-subtracted correlations are compatible between pp and pPb

arXiv: 1605.06963

D Fragmentation

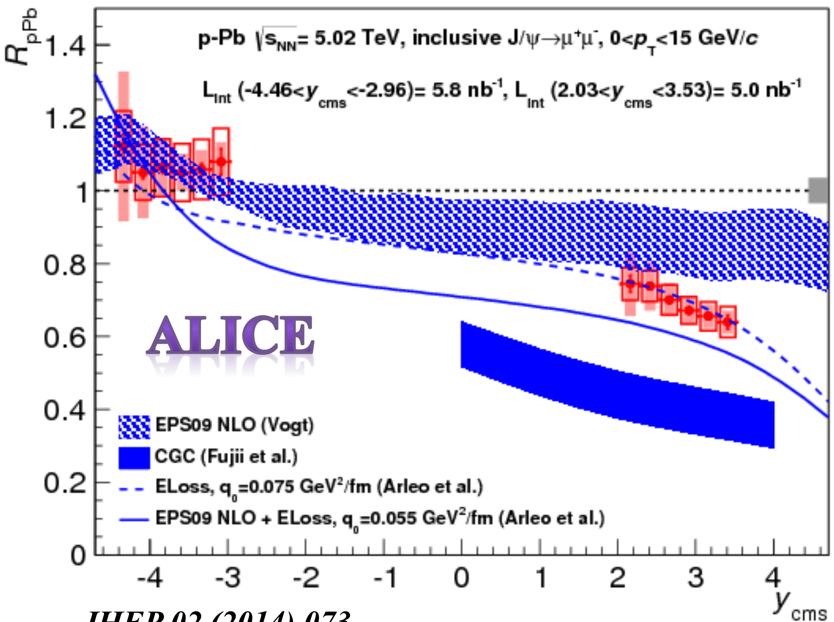


arXiv: 1605.06963

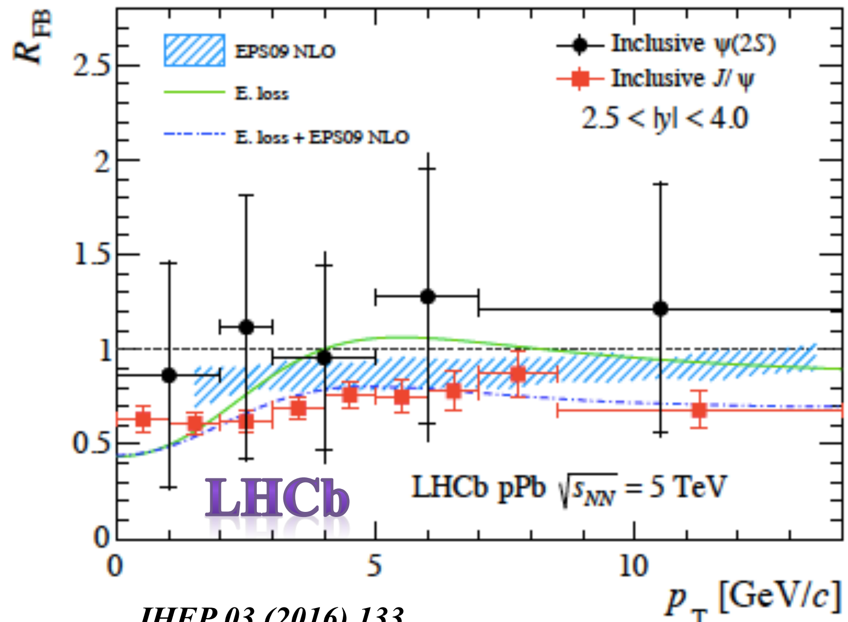
- Near-side peak is compatible between pp and pPb
- Fragmentation to D meson seems largely unaltered in pPb

J/ψ Production in pPb

- *J/ψ* in forward and backward rapidity



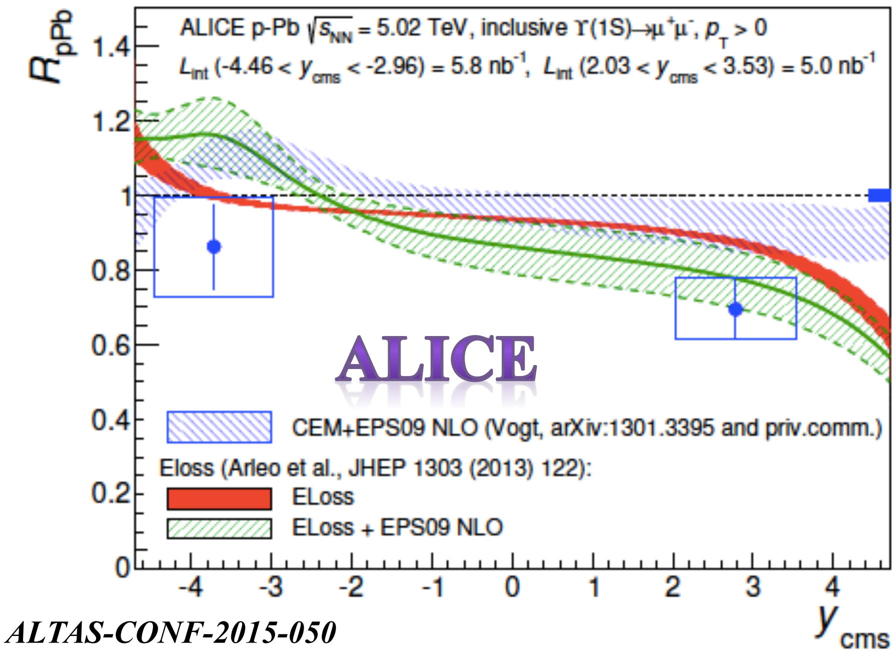
JHEP 02 (2014) 073

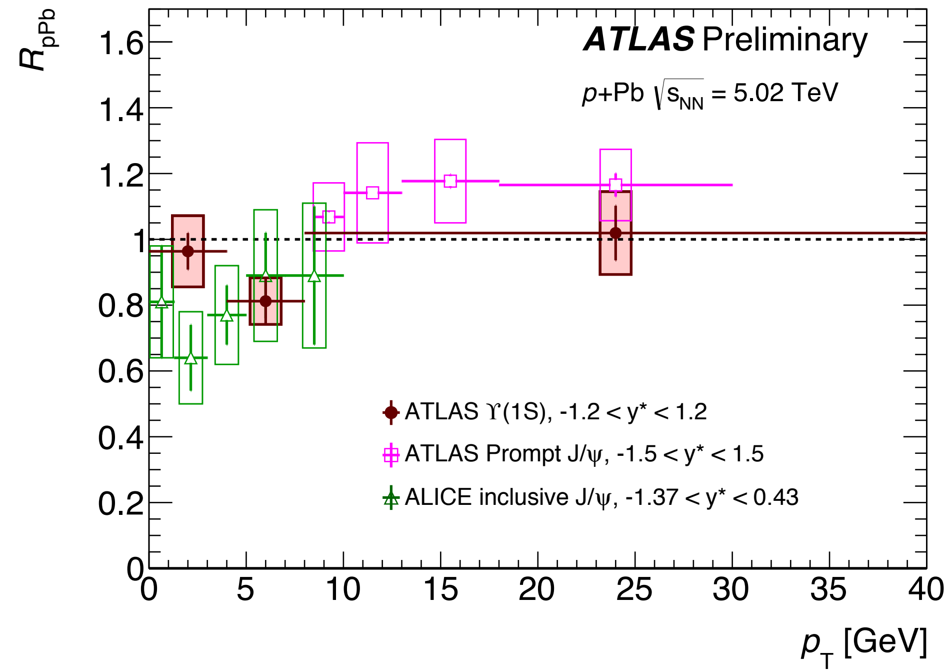


JHEP 03 (2016) 133

- Strong suppression at forward rapidity. Backward rapidity is consistent with unity.
- Consistent with shadowing only, but also room for energy loss

What about Upsilon?

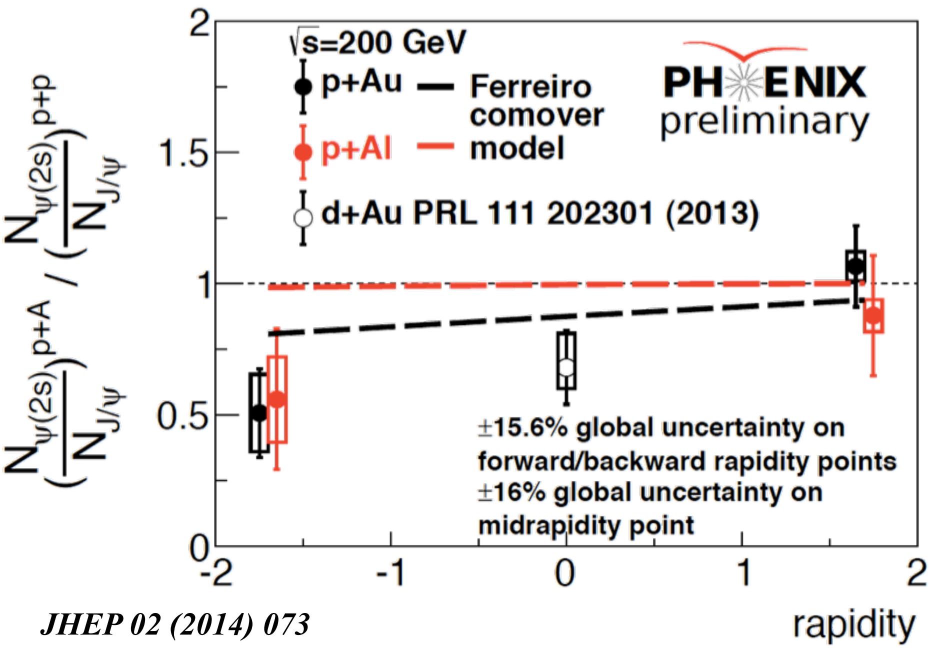


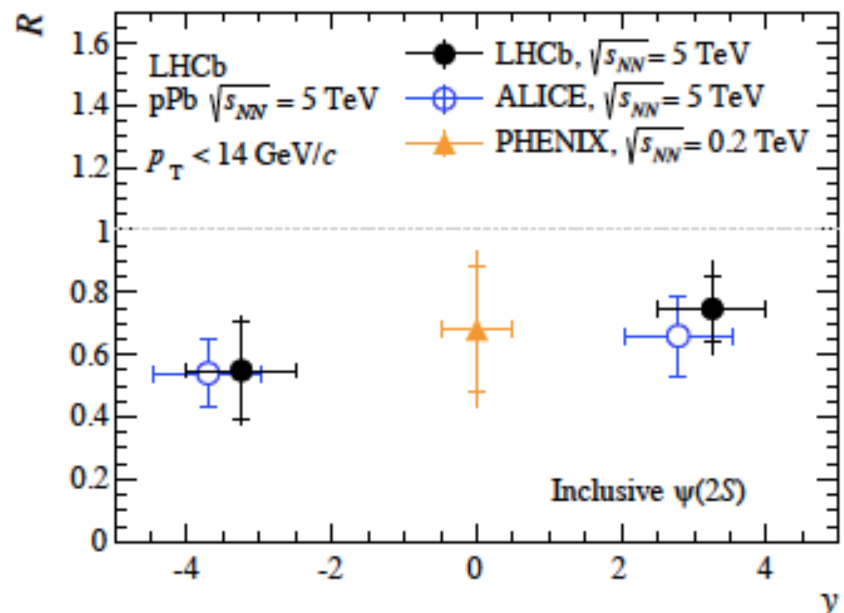


ALTAS-CONF-2015-050
PLB 740 (20115) 105
JHEP 07 (2014) 094

- ϒ(1S) suppression is consistent with shadowing. Also room for energy loss.
- Mild p_T dependence. Uncertainties are still large.

ψ(2S) is More Suppressed





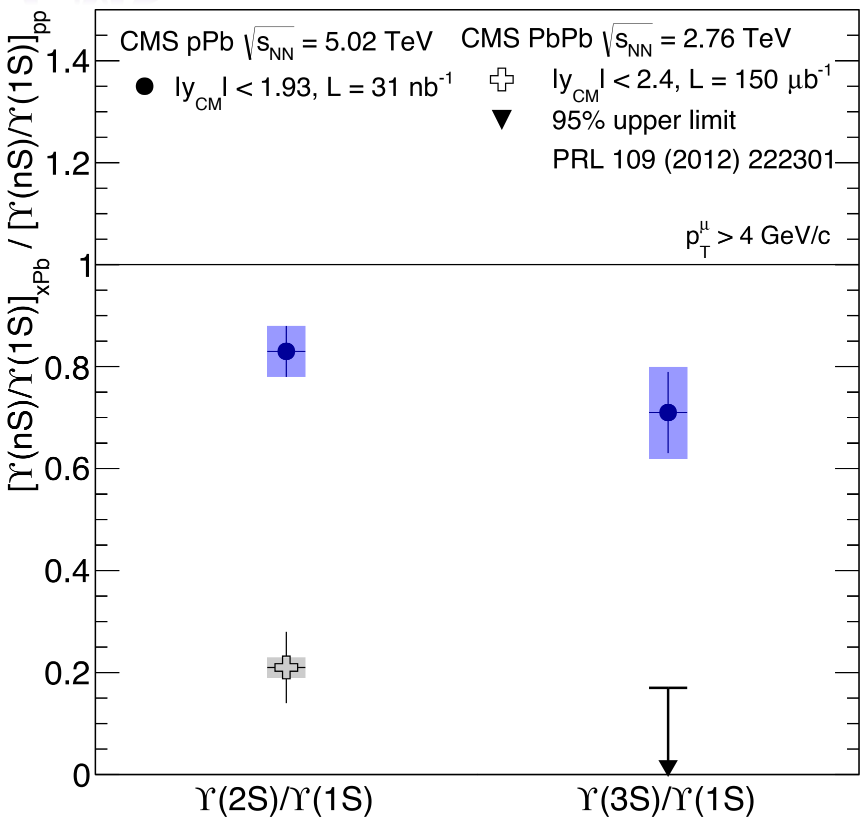
JHEP 02 (2014) 073
JHEP 03 (2016) 133
PRL 111 (2013) 202301

- ψ(2S) is more suppressed than J/ψ in both forward (LHC only) and backward direction
- Ordering reflects co-mover multiplicity?

$$R_{LHC}^{\eta\sim-3.5} \sim R_{RHIC}^{\eta\sim-1.7} < R_{LHC}^{\eta\sim3.5} < R_{RHIC}^{\eta\sim1.7}$$

Also True for ϒ(2S+3S)?

CMS *JHEP 04 (2014) 103*



Suppression of excited states in pPb collisions at mid-rapidity

- Larger co-mover absorption due to smaller binding energy?

New ALICE results at large rapidity:

- $[\Upsilon(2S)/\Upsilon(1S)]_{bwd} = 25.8 \pm 9.1 \pm 3.9\%$
- $[\Upsilon(2S)/\Upsilon(1S)]_{fwd} = 27.3 \pm 8.1 \pm 4.0\%$
- Consistent with pp within larger uncertainties

- Additional final-states in PbPb leading to further suppression
  - Extrapolation of pPb results to PbPb is model-dependent

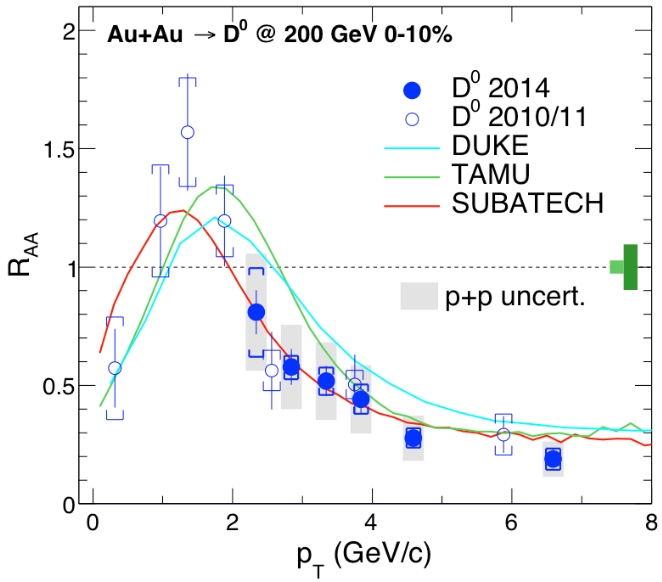
pp Collisions

pA/dA Collisions

AA Collisions

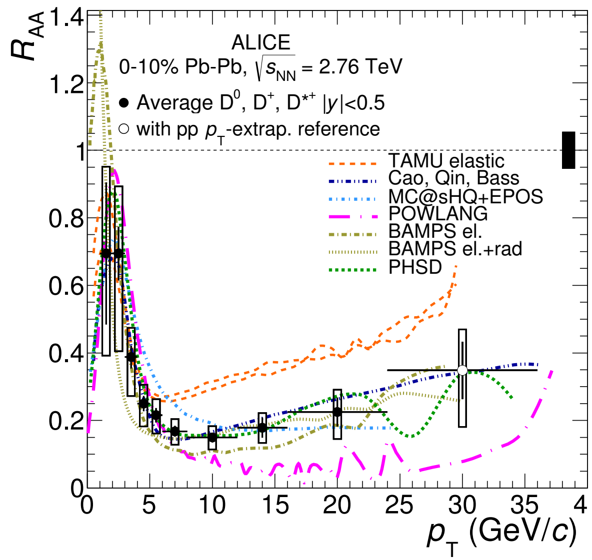
D Meson Suppression in AA

STAR @ 0.2 TeV



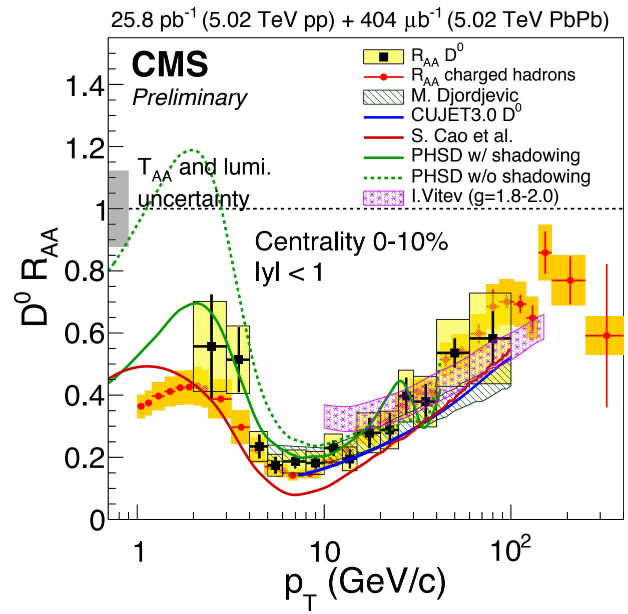
PRL 113 (2014) 142301

ALICE @ 2.76 TeV



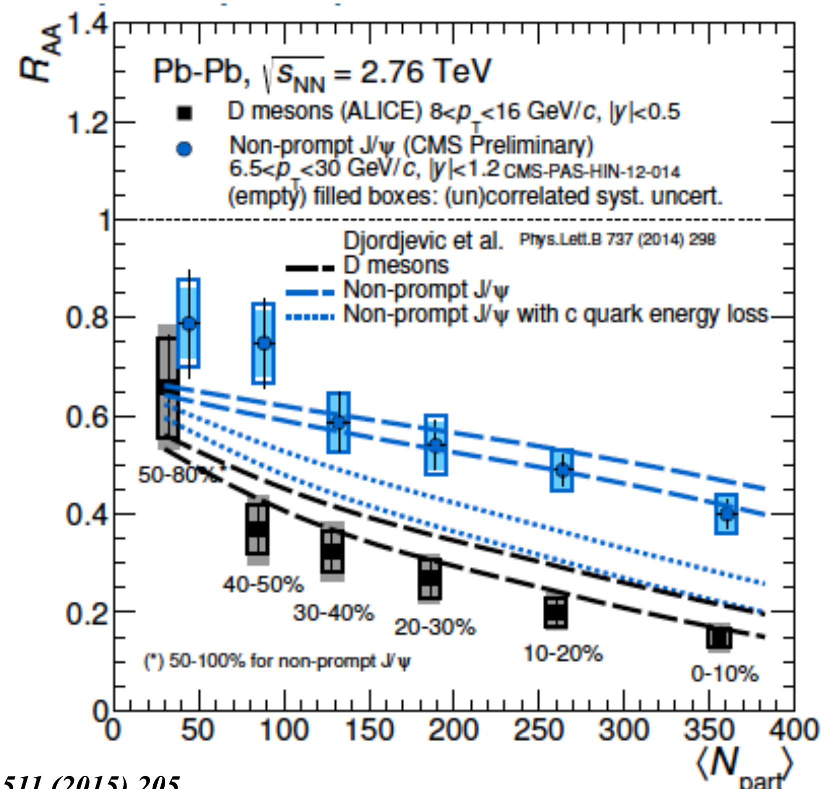
JHEP 03 (2016) 081

CMS @ 5.02 TeV

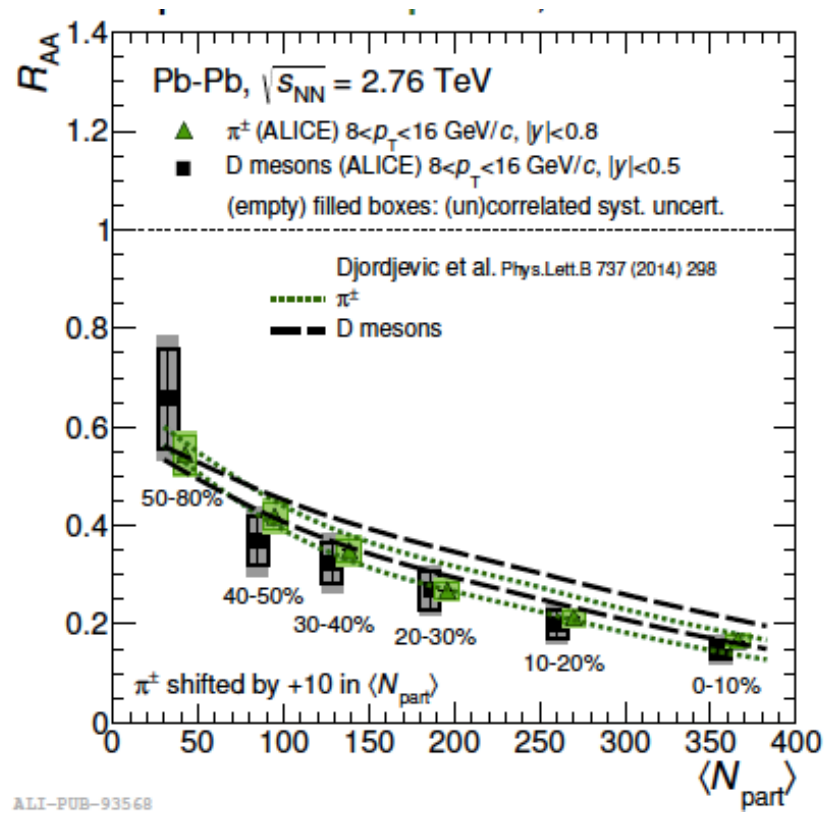


- High p_T: suppressed by a factor ~5 in central AA collisions → Strong charm-medium interaction
- Low p_T: R_{AA} ~ 1.5 at RHIC while R_{AA} ~ 0.6 at LHC → Shadowing?
- Different models can qualitatively describe the data. Need better precision and more measurements.

Mass Hierarchy at LHC

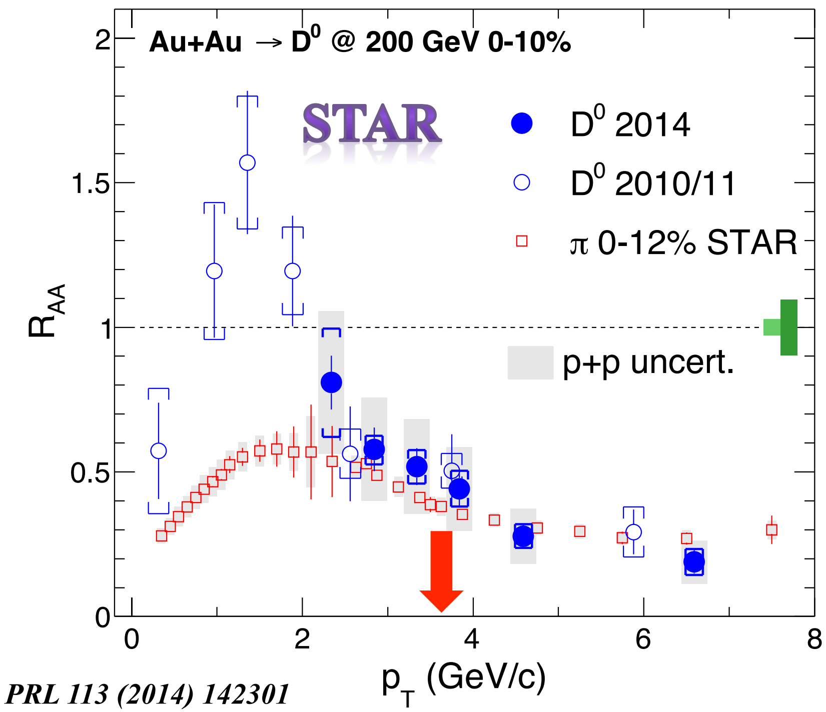


JHEP 1511 (2015) 205

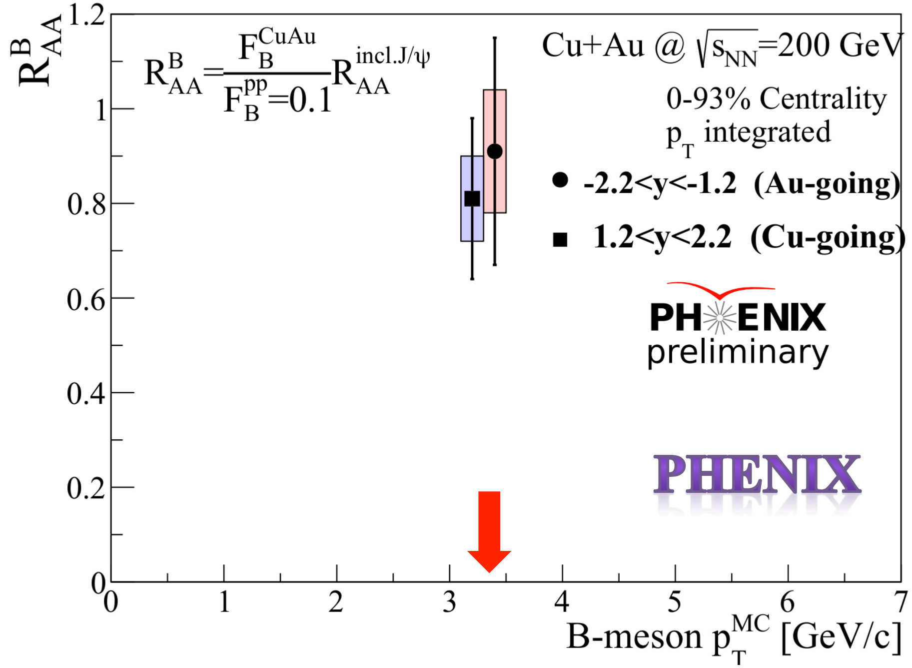


- $R_{AA}(B\text{->}J/\psi) > R_{AA}(D) \sim R_{AA}(\pi)$
  - Shapes of parton spectra and fragmentation function need to be taken in account
  - Mass ordering of energy loss seems hold

What about at RHIC?



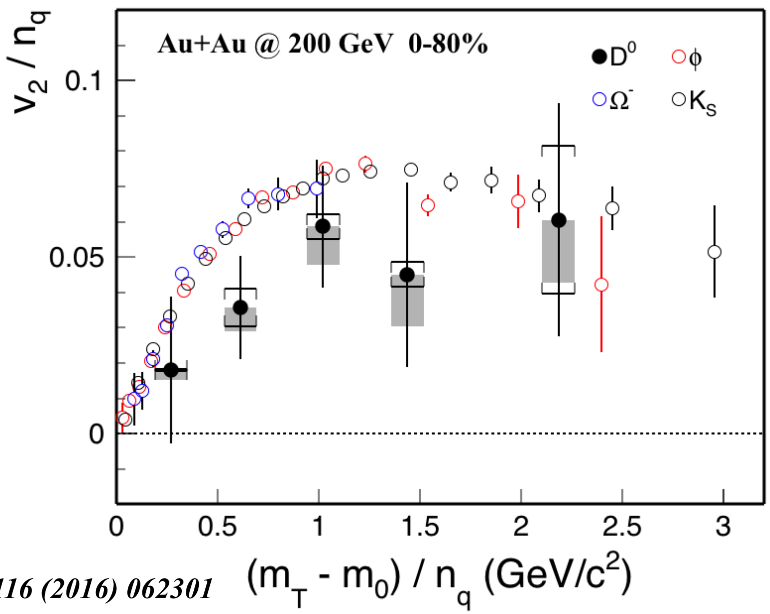
PRL 113 (2014) 142301



- $R_{AA}(B) >\sim R_{AA}(D) \sim R_{AA}(\pi)$
- Mass ordering of radiative energy loss still holds
- Need B & D measurements in Au+Au collisions with better precision.

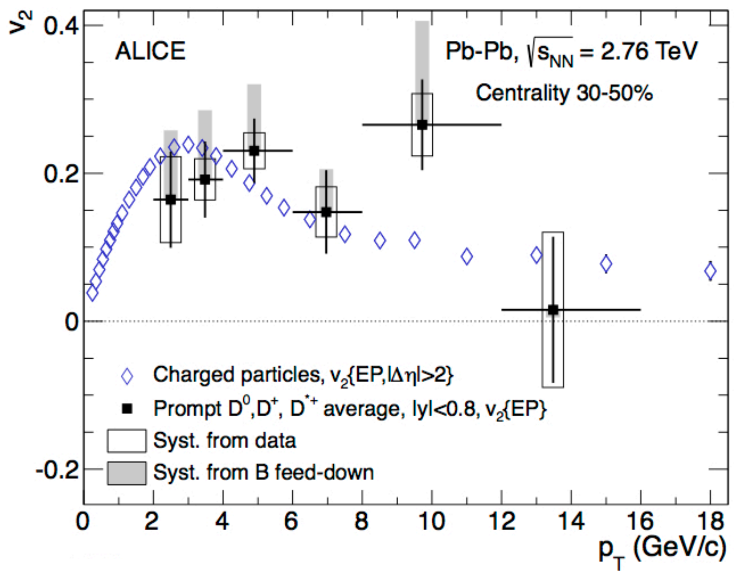
D Meson Flow in AA

STAR @ 0.2 TeV



PRL 116 (2016) 062301

ALICE @ 2.76 TeV



PRC 90 (2014) 034904

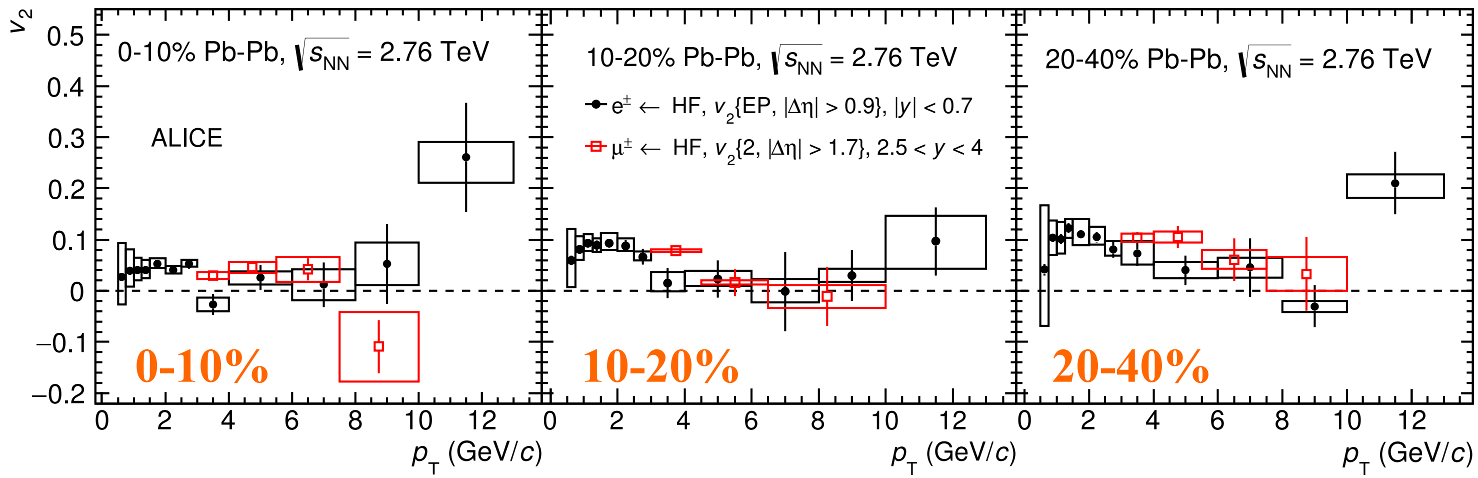
- Finite v_2 above 2 GeV/c both at RHIC and LHC → Charm flows in the medium
- D v_2 is compatible with light hadron at LHC, but seems to be lower at RHIC → Different degrees of thermalization?
- Need a theory to coherently describe both R_{AA} and v_2 for heavy and light hadrons at both RHIC and LHC. Some work in progress.

S. Cao Mon 14:30

Flow of HF-lepton

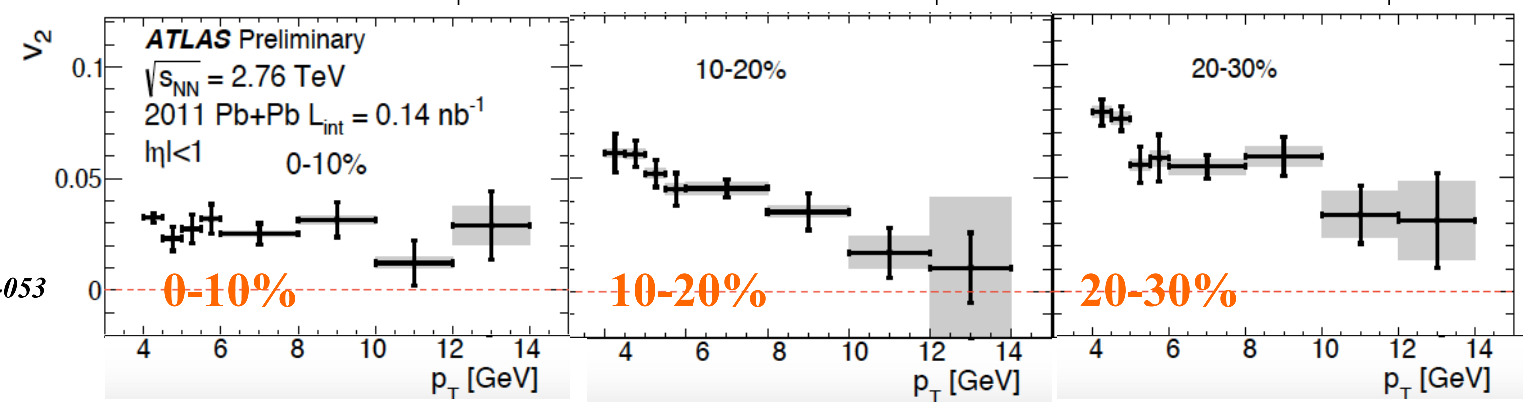
ALICE

arXiv:1606.00321



ATLAS

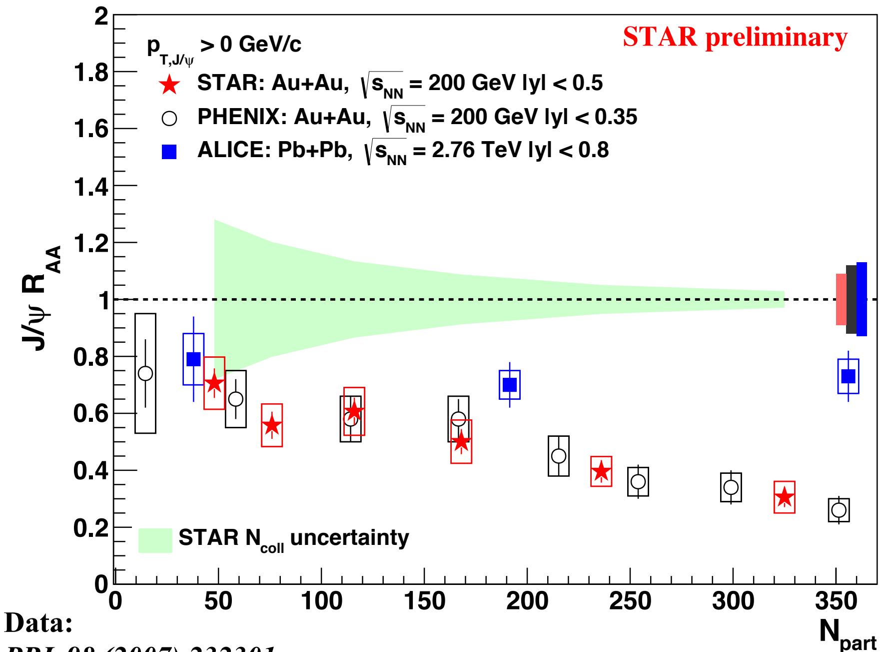
ATLAS-CONF-2015-053



- Sizable lepton v_2 → heavy quarks flow with the medium
  - How large is non-flow?
- Tension at $p_T > 6$ GeV/c for 10-20% between ALICE and ATLAS?

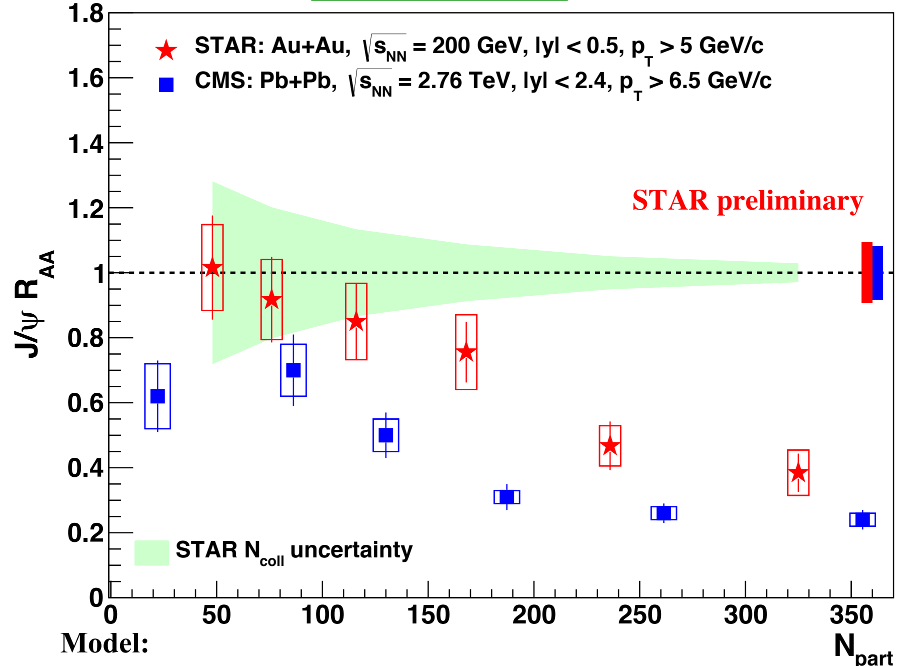
J/ψ Suppression in AA

$p_T > 0$ GeV/c



Data:
PRL 98 (2007) 232301
PLB 734 (2014) 314

High p_T

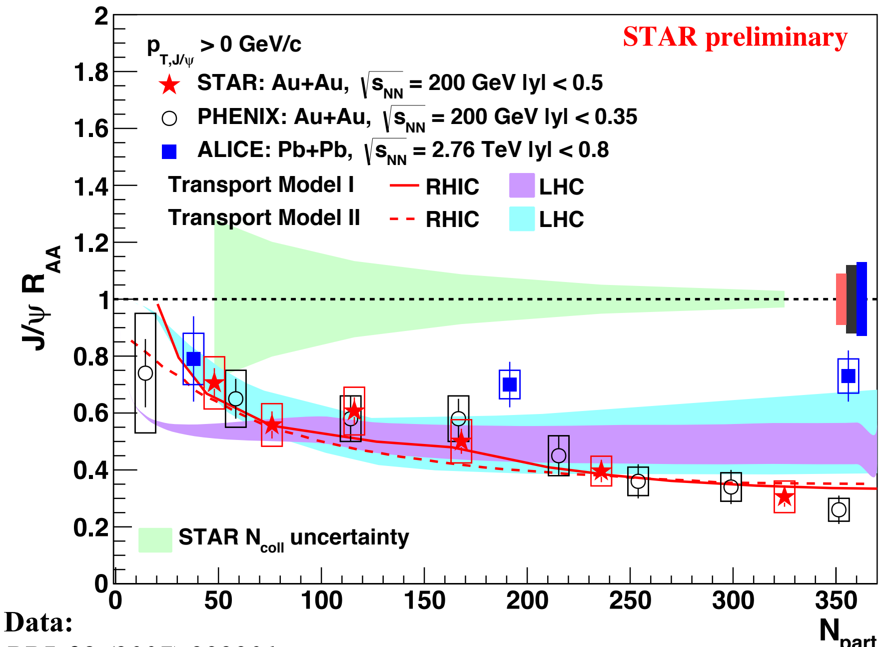


Model:
PLB 678 (2009) 72, PRC 89 (2014) 054911
PRC 82 (2010) 064905, NPA 859 (2011) 114

- Low p_T: less suppression at LHC → more regeneration due to more charm
- High p_T: more suppression at LHC → larger dissociation due to higher temperature

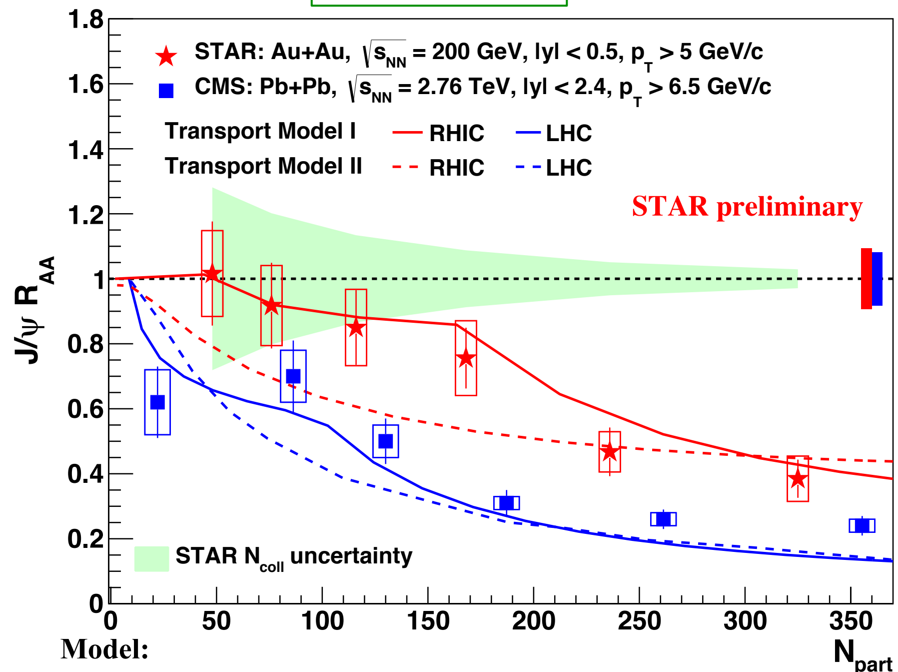
J/ψ Suppression in AA

$p_T > 0$ GeV/c



Data:
PRL 98 (2007) 232301
PLB 734 (2014) 314

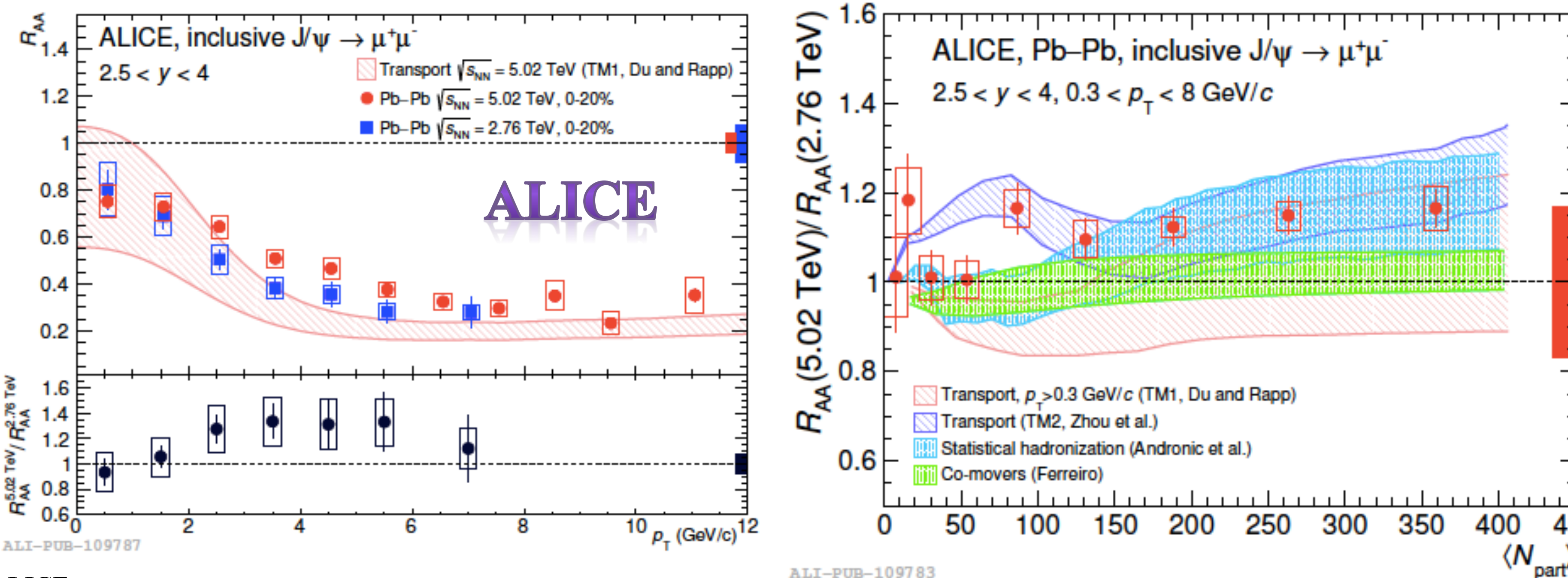
High p_T



Model:
PLB 678 (2009) 72, PRC 89 (2014) 054911
PRC 82 (2010) 064905, NPA 859 (2011) 114

- Low p_T: less suppression at LHC → more regeneration due to more charm
- High p_T: more suppression at LHC → larger dissociation due to higher temperature
- *Transport models with dissociation & regeneration can qualitatively describe data*

J/ψ Suppression at 5.02 TeV

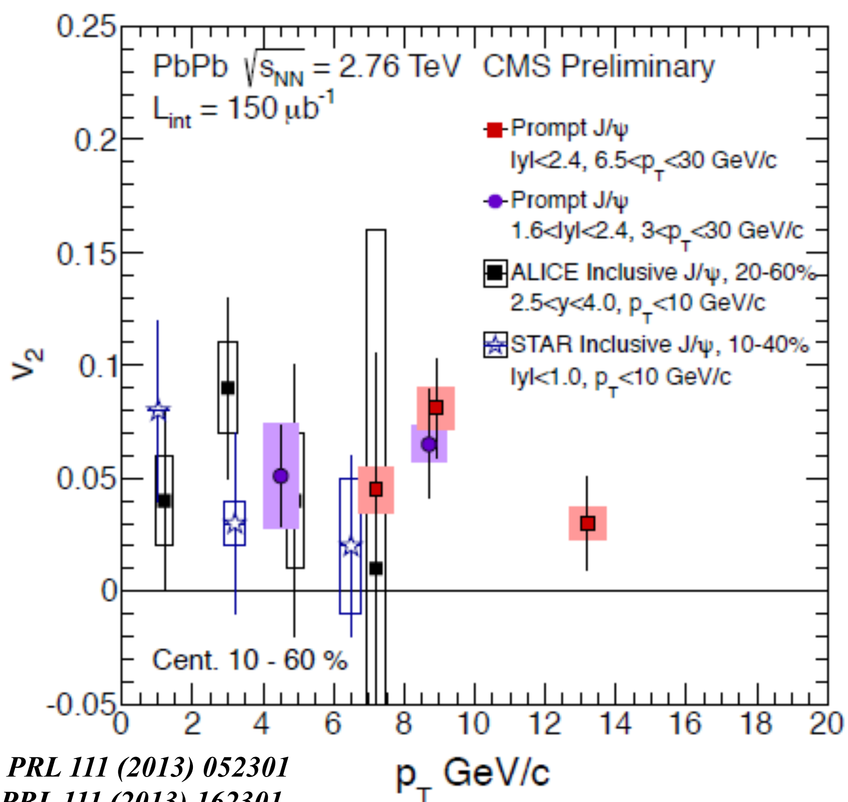


ALICE:
CENR-EP-2016-062

- New measurements at 5.02 TeV reveals ~10% increase in R_{AA} from 2.76 TeV above 2 GeV/c for N_{part} > 80
  - *Consistent with regeneration picture*
  - *Explained by transport models, SHM*

J/ψ Flow in AA

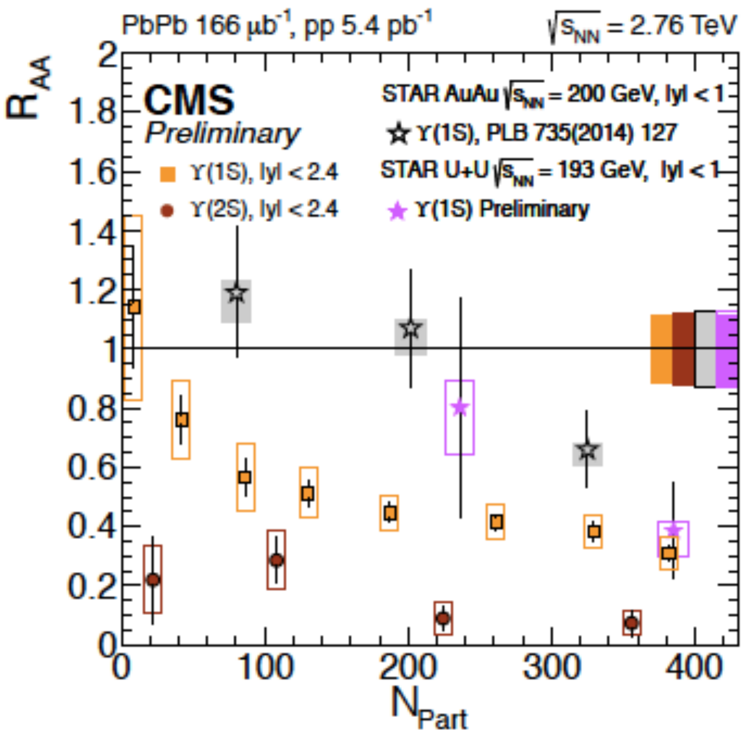
- J/ψ v_2: another constraint on regeneration
  - Primordial: little or zero v_2
  - Regenerated: inherit v_2 of the constituent charm quarks

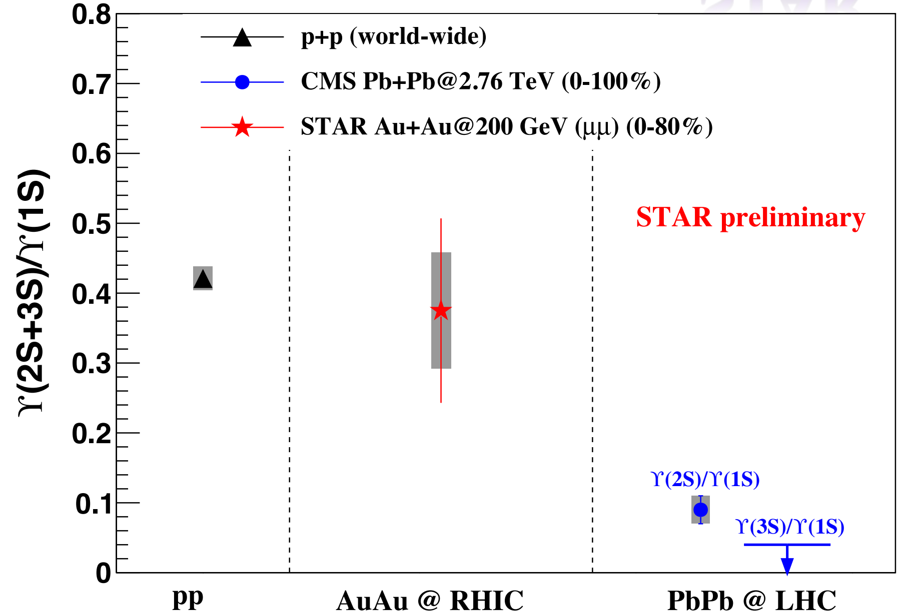


PRL 111 (2013) 052301
PRL 111 (2013) 162301

- Finite *J/ψ* v_2 at the LHC → sizable regeneration contribution
- *J/ψ* v_2 ~ 0 at RHIC above 2 GeV/c → regeneration contribution is small
- *Need to reduce uncertainties on the measurements*

Upsilon: Still A Thermometer?

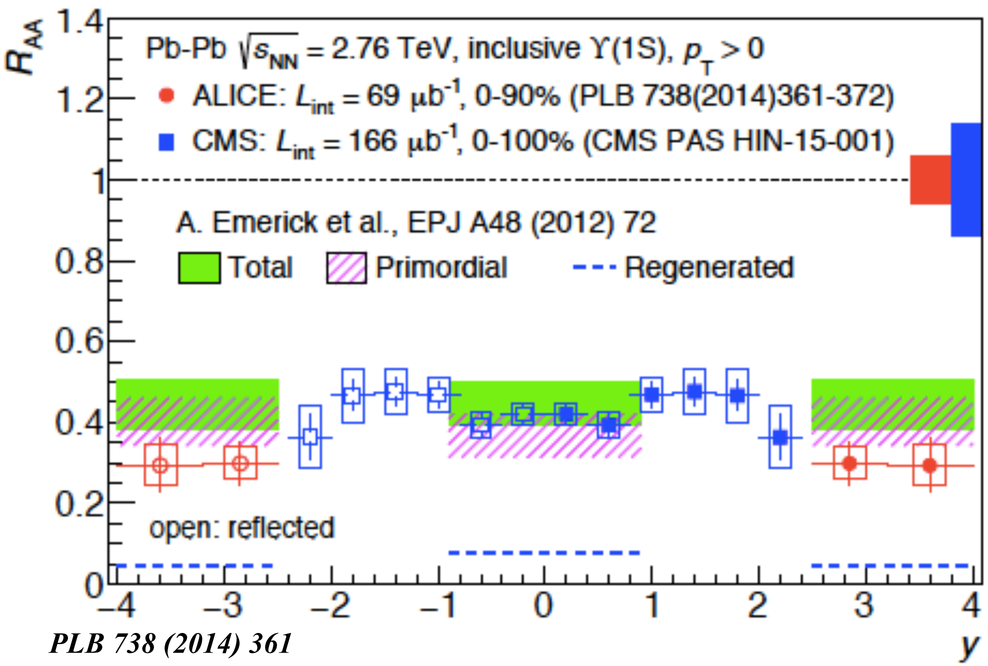




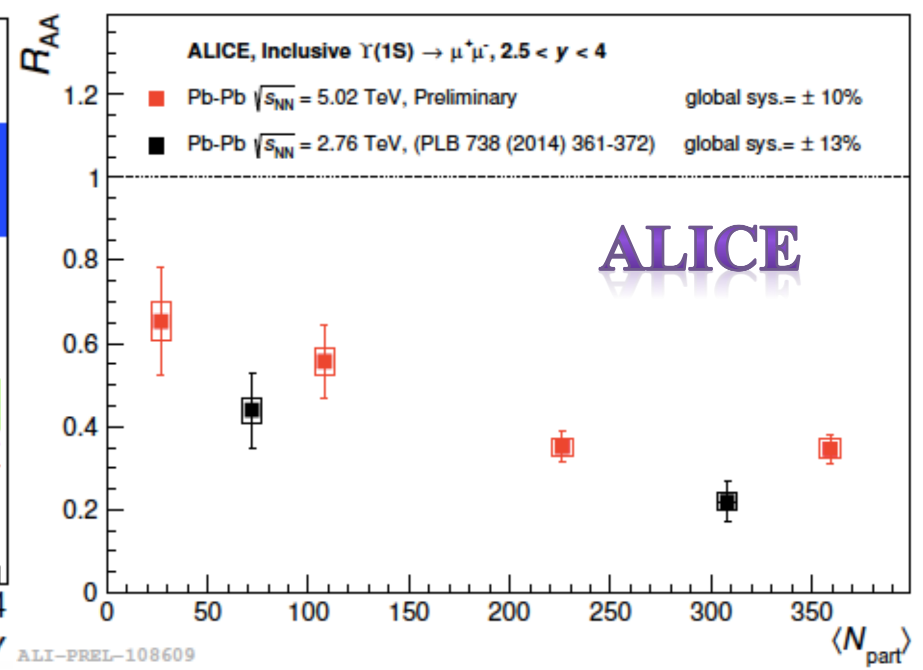
PRC 88(2013) 067901
PRL 109(2012) 222301
JHEP 04 (2014) 103

- *Seems consistent with thermometer picture*
  - LHC: $R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$; peripheral $R_{AA}(1S)$ > central $R_{AA}(1S)$
  - RHIC: all three Υ states seems less suppressed
- **Really need to measure feed-down contribution**

Upsilon: the New J/ψ?

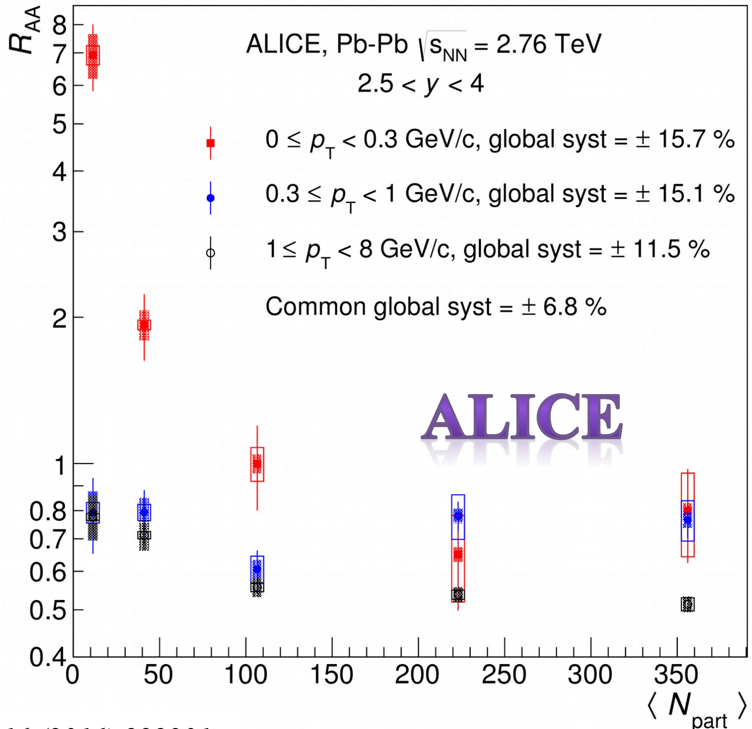


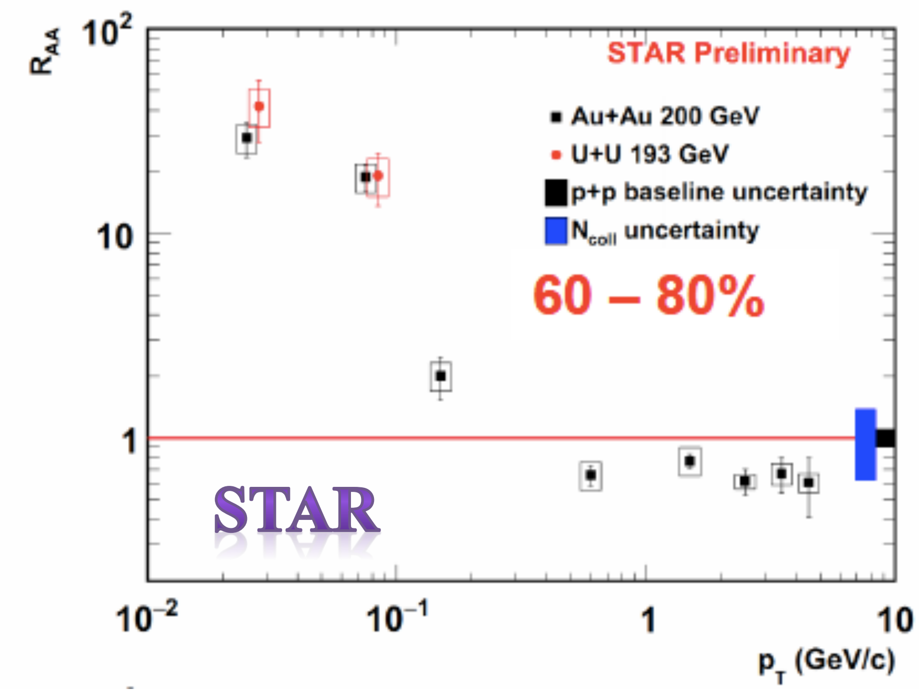
PLB 738 (2014) 361



- More suppression at forward rapidity
  - Uncertainty is still large
- Less suppression at higher collision energy
- *Regeneration of bottom quarks is stepping up a gear?*
  - *Feed-down, CNM …*

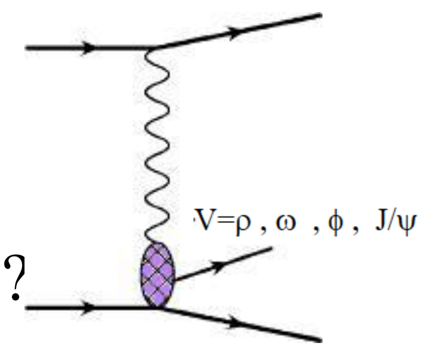
Excess of Low-p_T J/ψ





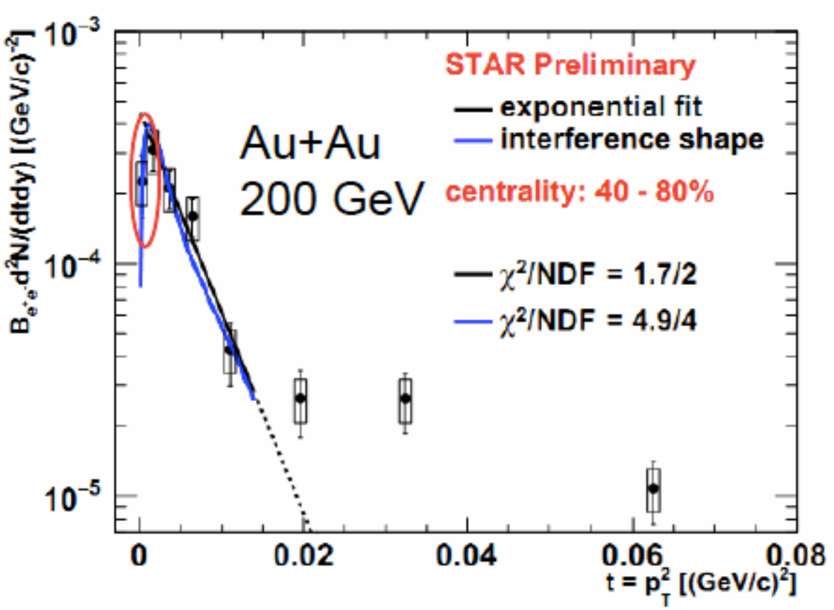
PRL 116 (2016) 222301

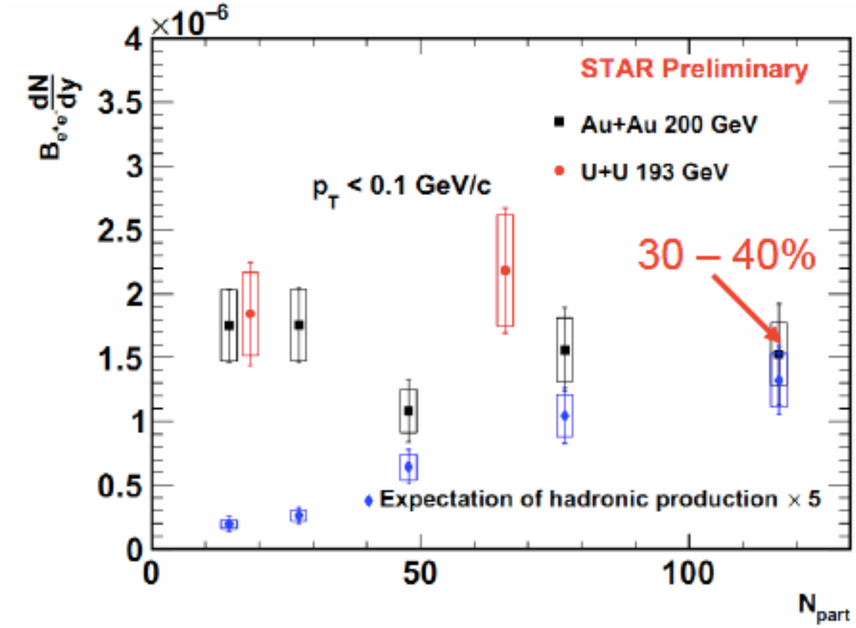
- Access of *J/ψ* with 0 < p_T < 0.2-0.3 GeV/c beyond hadronic expectation in peripheral collisions
  - R_{AA} ~ 7 at LHC; ~ 20 at RHIC
- Are they from coherent photon-nucleus interactions?



Properties of Low-p_T J/ψ Excess

STAR





- **Suggestive feature of coherent photon-nucleus interactions**
  - Interference at $0 < p_T < 0.03$ GeV/c
  - Exponential slope is consistent with size of Au nucleus
- Excess yield is independent of centrality → interplay of nuclei distance and photon flux cancellation?
- *A new opportunity to probe QGP? Need theoretical input!*

Summary: Open Heavy Flavor

What have we learned?

- pp: charm cross section agrees with pQCD
  - *Invariant yield increases with event multiplicity*
- pA: D meson production is consistent with CNM effects
  - *Inclusive production; fragmentation*
- AA: parton flavor ordering of radiative energy loss is respected.
  - $R_{AA}(B) > R_{AA}(D) \sim R_{AA}(\pi)$

What is needed?

- How to relate hadronic observables to parton kinematics?
  - *Heavy-flavor tagged jets. How about gluon contribution?*

Summary: Quarkonium

What have we learned?

- pp: cross section can be described by CGC, NRQCD, FONLL
- pA: production of ground state is consistent with CNM effects
  - *Larger co-mover absorption is needed for excited states*
- AA: all suppression patterns so far are consistent with dissociation + regeneration picture
  - *Alternatives: co-mover …*

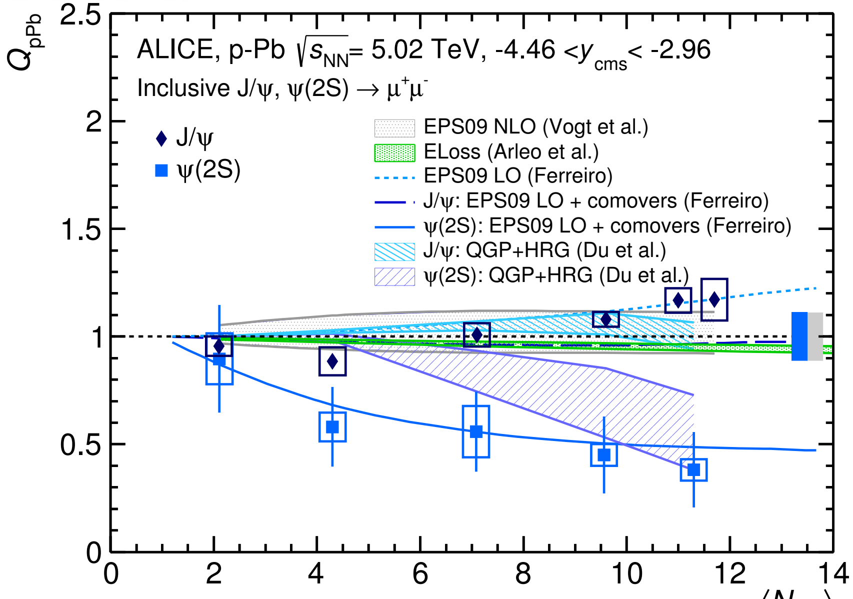
What is needed?

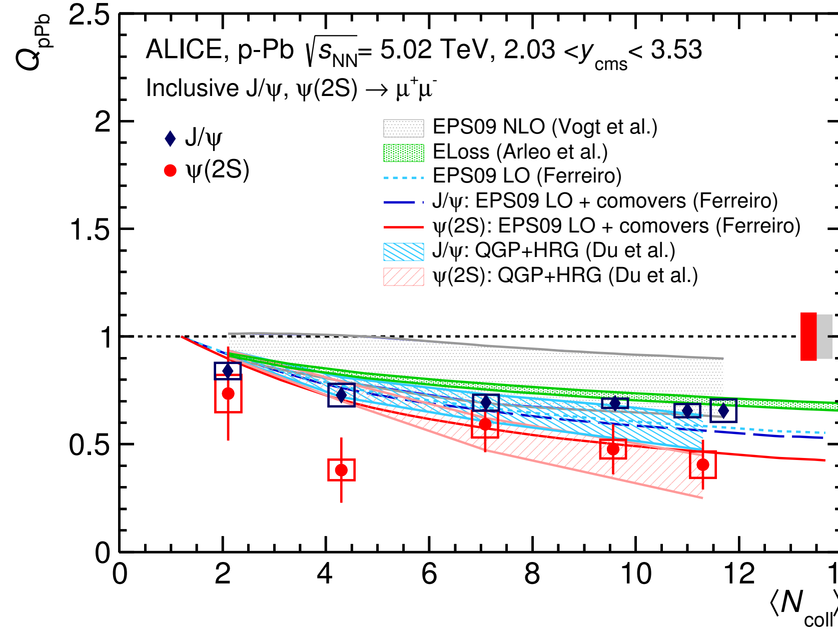
- What about J/ψ polarization in pp? What about very low-p_T J/ψ in peripheral AA?
- How large is feed-down contribution to ground states?
- Total charm cross-section for theory.

Backup

ψ(2S) is More Suppressed

ALICE





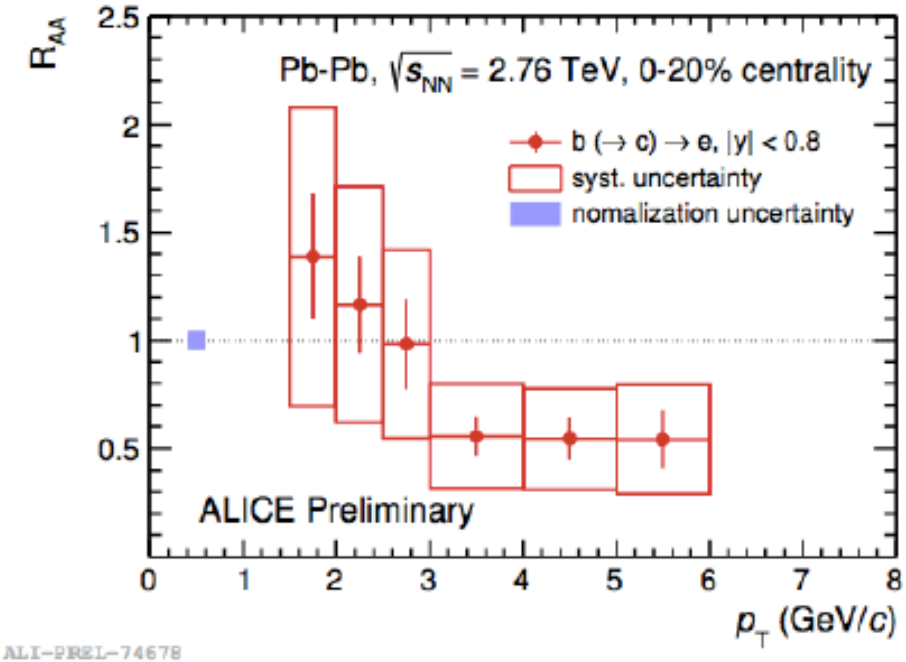
arXiv: 1603.02816

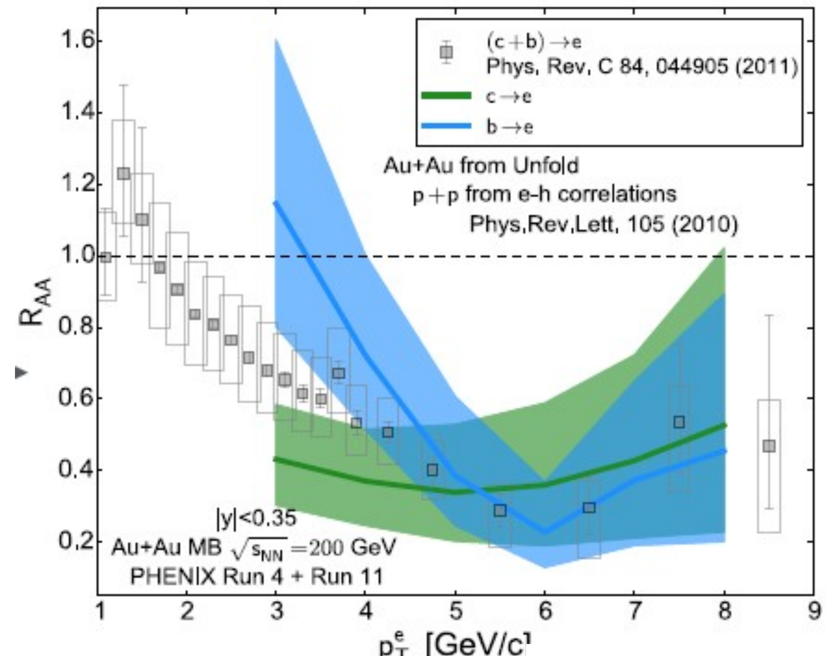
- **Backward: strong suppression for ψ(2S), but none for J/ψ**
  - Hint of anti-showing in central collisions
- Forward: ψ(2S) consistently more suppressed than J/ψ
- *Models including larger co-mover absorption for ψ(2S) can describe both J/ψ and ψ(2S)*

Also Show Mass Hierarchy?

ALICE @ LHC

PHENIX @ RHIC





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- R_{AA}(b->e) >~ R_{AA}(c->e) at low p_T
  - Mass ordering of energy loss seems hold
- Need to improve uncertainties for firm conclusions.