Heavy Flavor Measurements at RHIC and LHC

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- ❑ **Motivations**
- ❑ **Heavy Quarkonia**
- ❑ **Open Heavy Flavor**
- ❑ **future perspective**

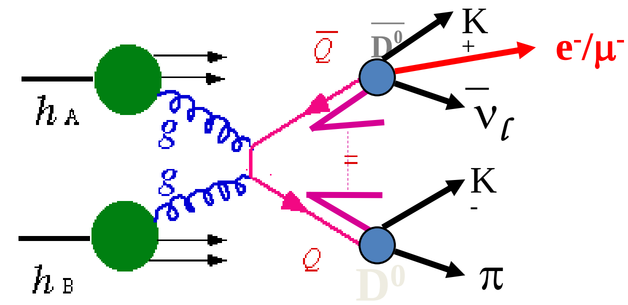
Motivations

- **Sensitive to initial gluon density and gluon distribution at RHIC.**
  - produced mostly from gluon fusion

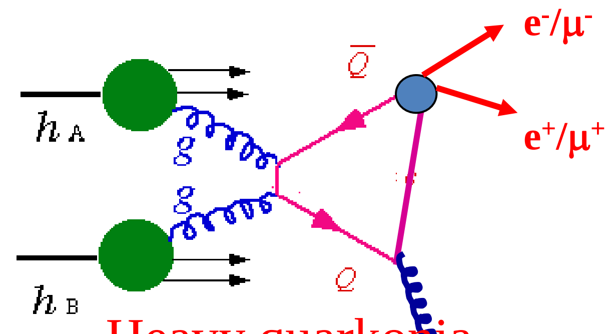
- **Involve different interaction mechanisms from light quarks with the medium**
  - gluon bremsstrahlung radiation
  - collisional energy loss
  - collision dissociation
  - Ads/CFT

- **Heavy quarkonia production reveals critical features of the medium.**
  - suppression from color screening or gluon scattering
  - enhancement from coalescence

- **Cold Nuclear effect.**
  - Gluon shadowing , Color glass condensate, Initial state Energy loss, etc



Open heavy flavor



Heavy quarkonia

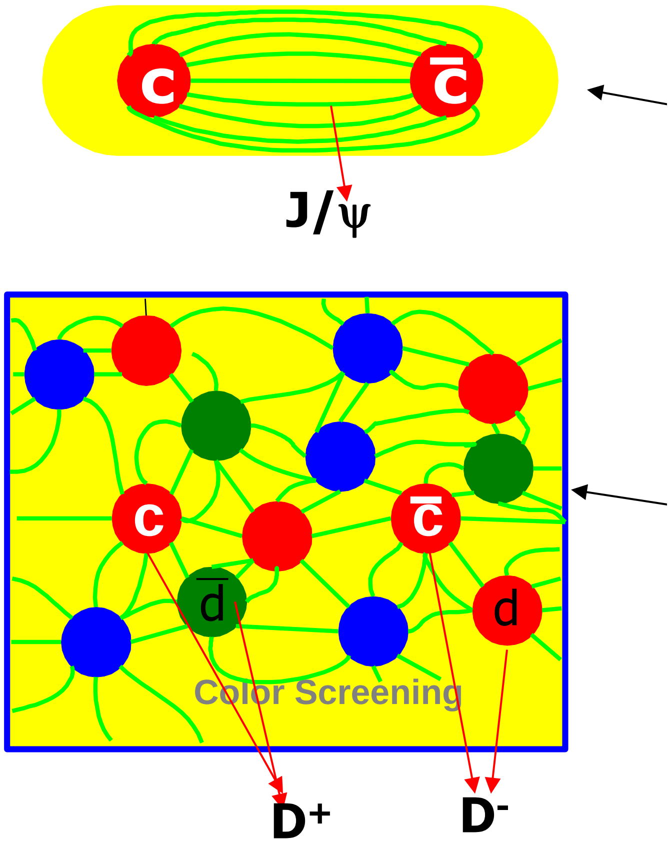
HF Measurements* vs. Energy

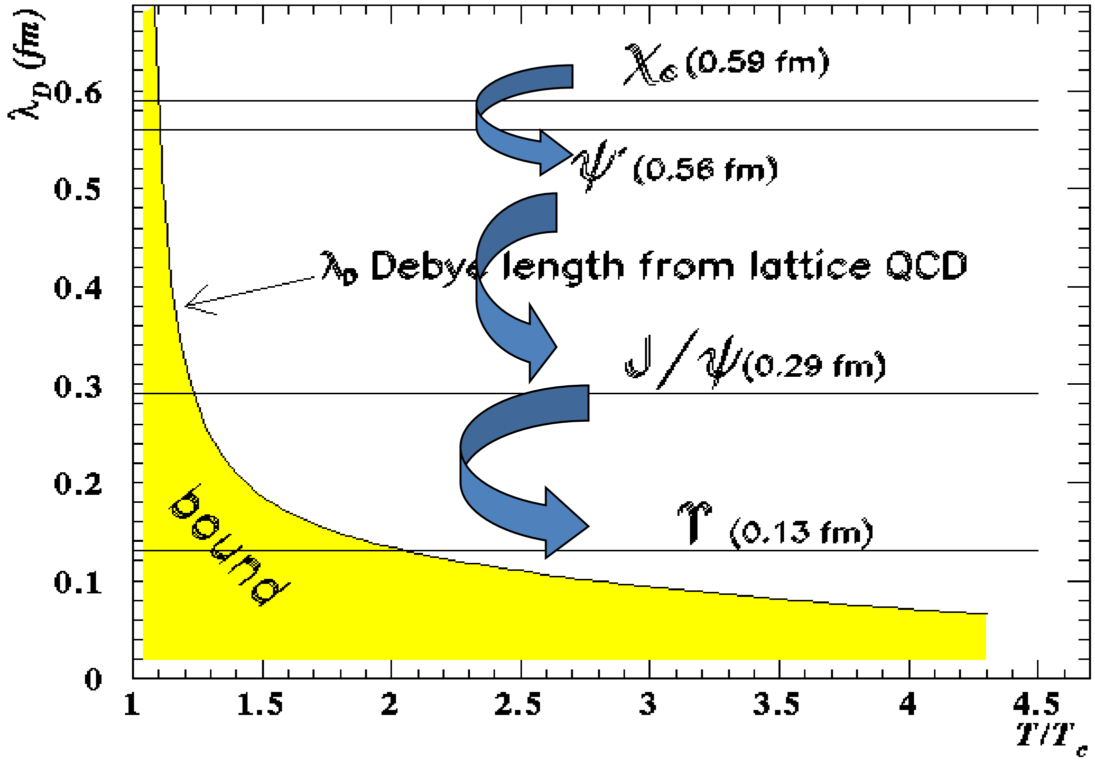
$\sqrt{S_{NN}}$ (GeV) / Coll. Spec.	39	62.4	193	200	2760	5020	7000
p+p				✸	✸		✸
p(d)+A				✸		✸	
A+A	✸	✸	✸	✸	✸		

* note: at RHIC and LHC

- Reference data missing in some energies.
- interpolation based on pQCD.
- Rely on other experiments or model predictions.

Quarkonia Suppression: “Smoking Gun” for QGP





Sequential melting→a QGP thermometer

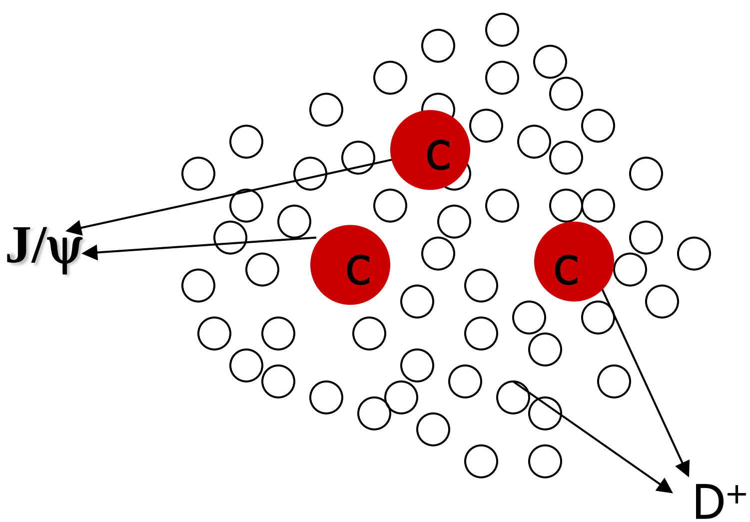
H. Satz, NPA 783 (2007) 249c.

The life of Quarkonia in the Medium can be Complicated

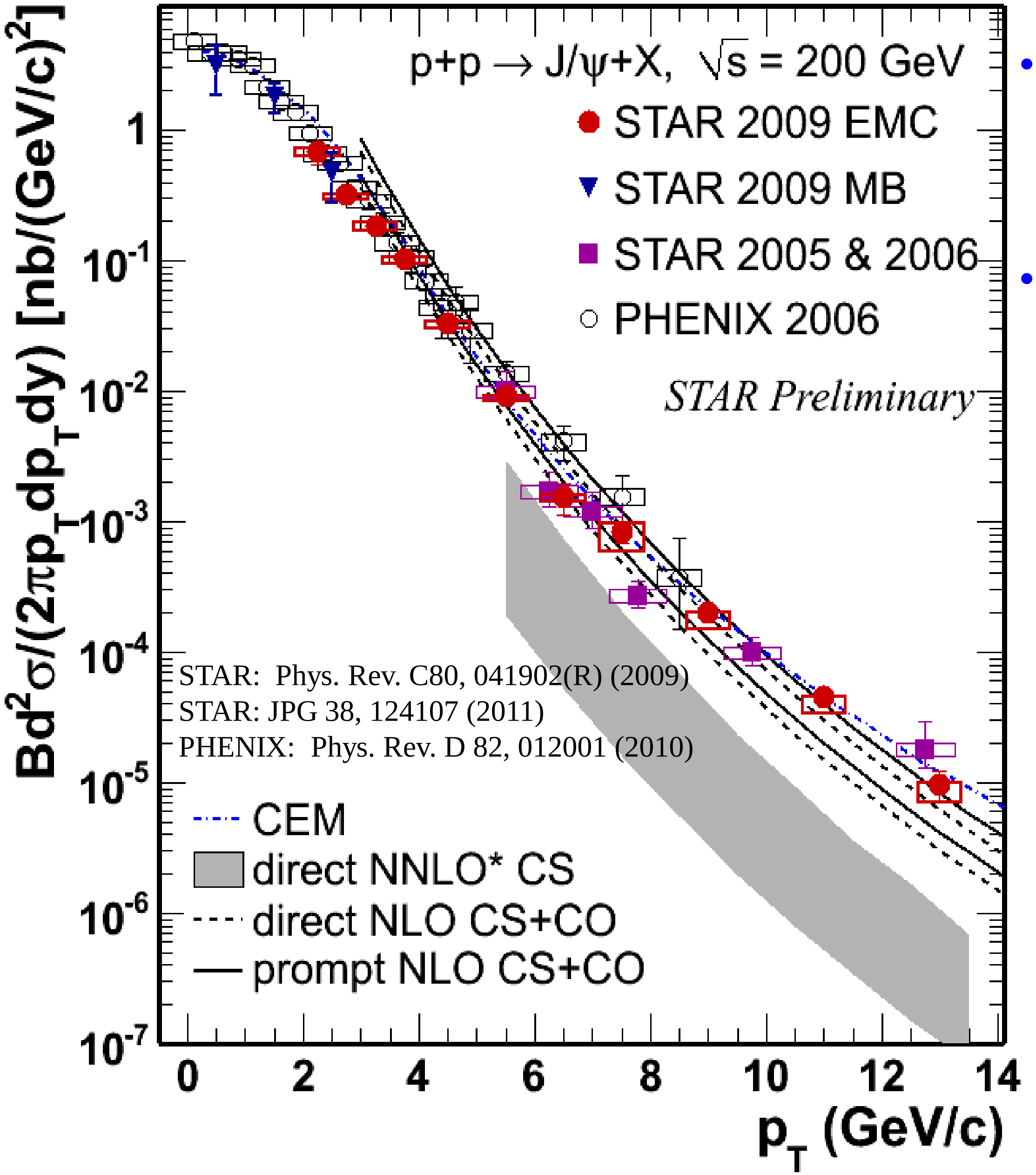
- Observed J/ψ is a mixture of direct production+feeddown (R. Vogt: Phys. Rep. 310, 197 (1999)).
  - All J/ψ ~ 0.6J/ψ(Direct) + ~0.3 χ_c + ~0.1ψ'
  - B meson feed down.
    - Important to disentangle different component

- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation (CGC)
  - Study p+A collisions

- Hot/dense medium effect
  - J/ψ, ϒ dissociation, i.e. suppression
  - Recombination, i.e. enhancement
  - Study different species, e.g. J/psi, ϒ
  - Study at different energy, i.e. RHIC, LHC



Quarkonia Production in p+p Collisions



- **Production mechanisms (J/psi) still need to be clarified.**
- **What's the impact on production in AA collisions?**

Color singlet model (NNLO*CS):

- P. Artoisenet et al., PRL. 101, 152001 (2008), and J.P. Lansberg private communication.

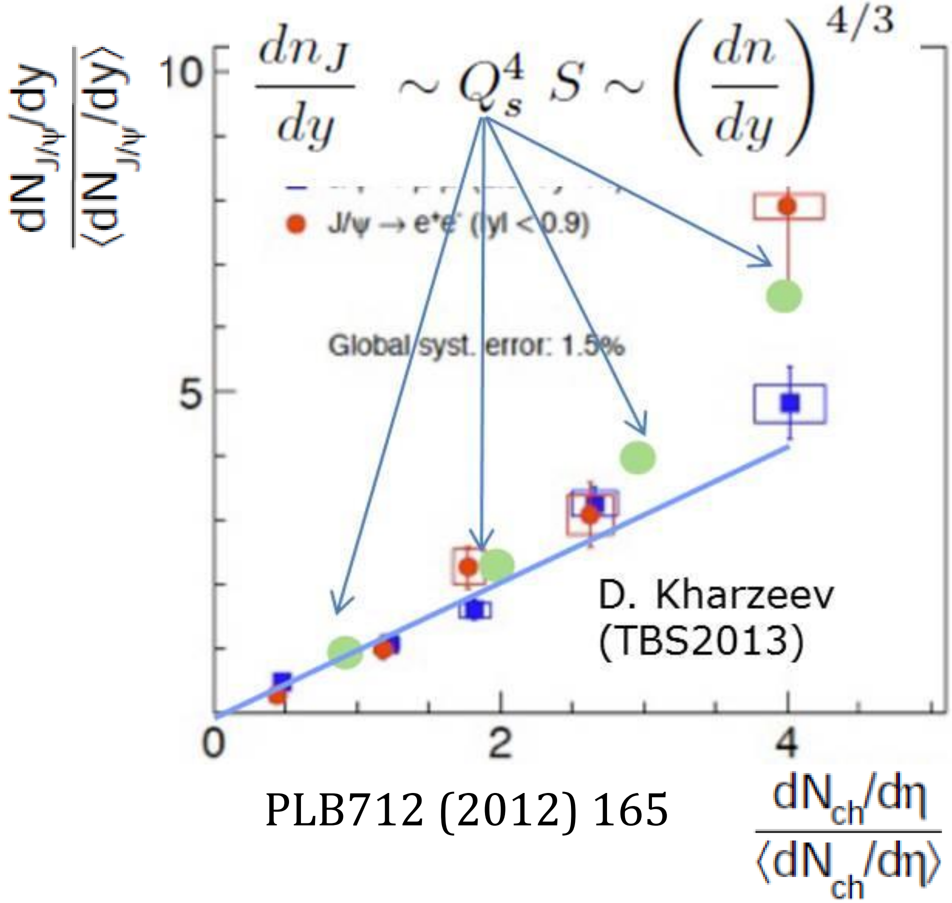
LO CS+ color octet (CO):

- Y.-Q. Ma, et al.,, Phys. Rev. D84, 51 114001 (2011), and private communication

Color Evaporation Model:

- M. Bedjidian et al., hep-ph/0311048; R. Vogt private communication

Quarkonia Production in p+p Collisions



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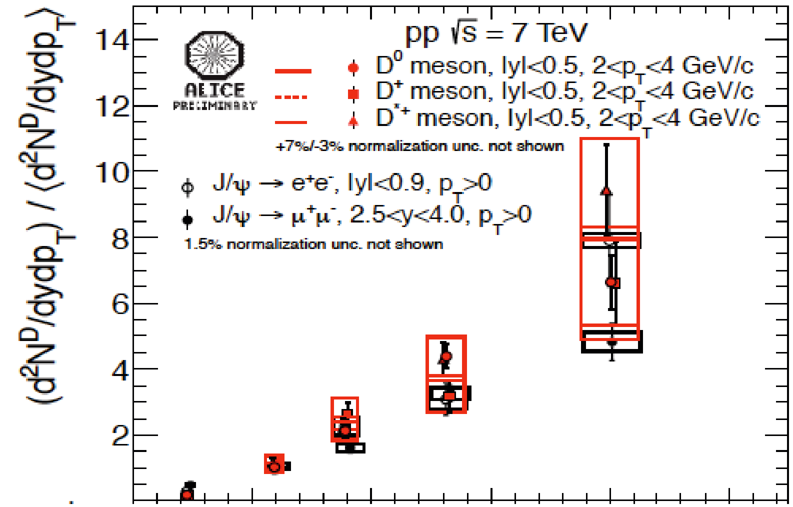
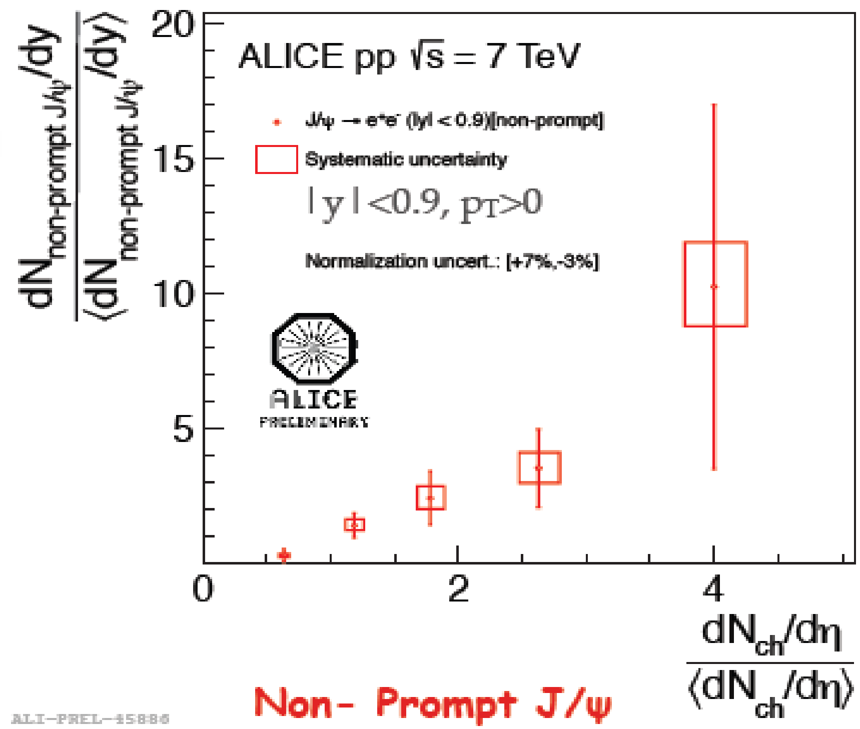
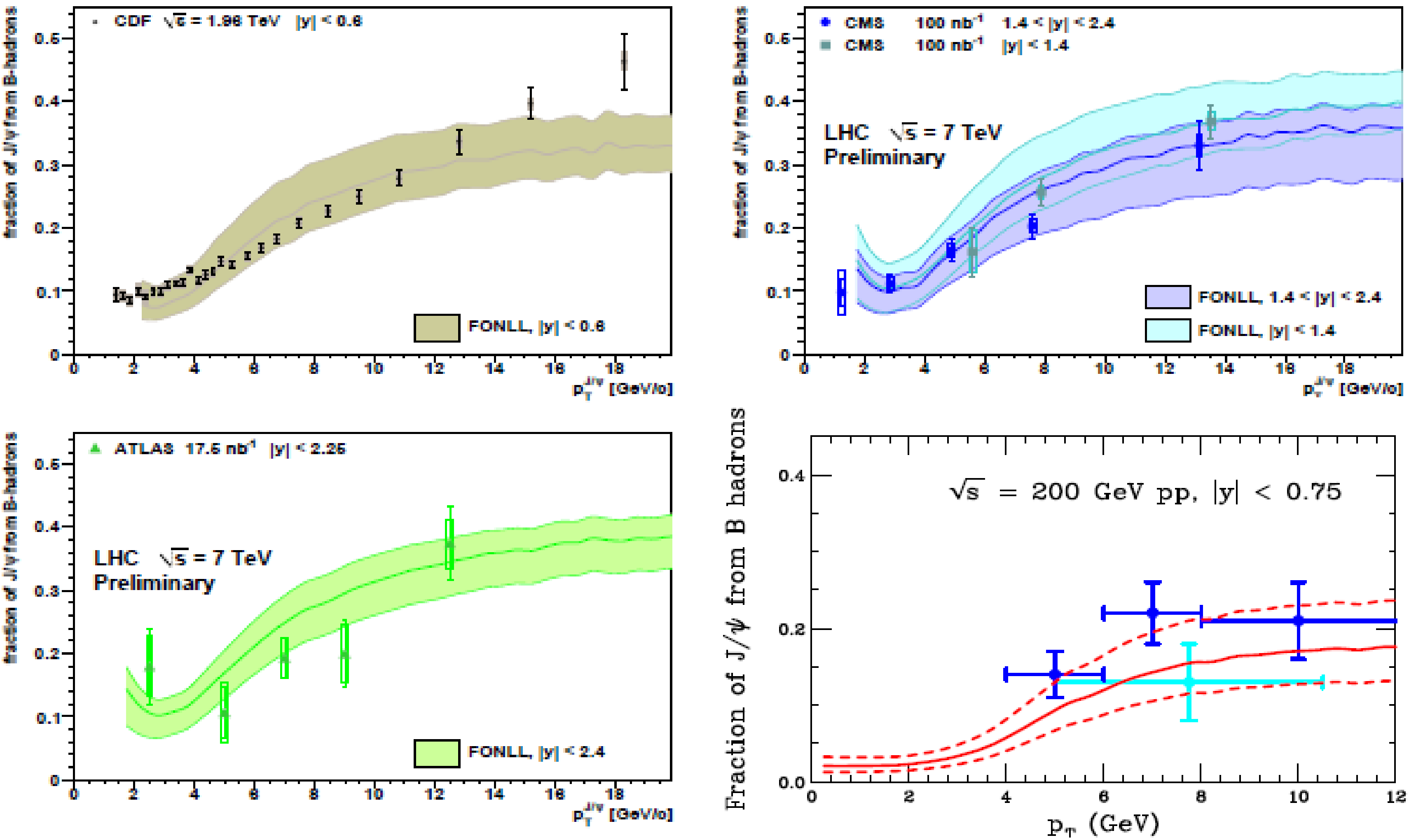




Non- Prompt J/ψ

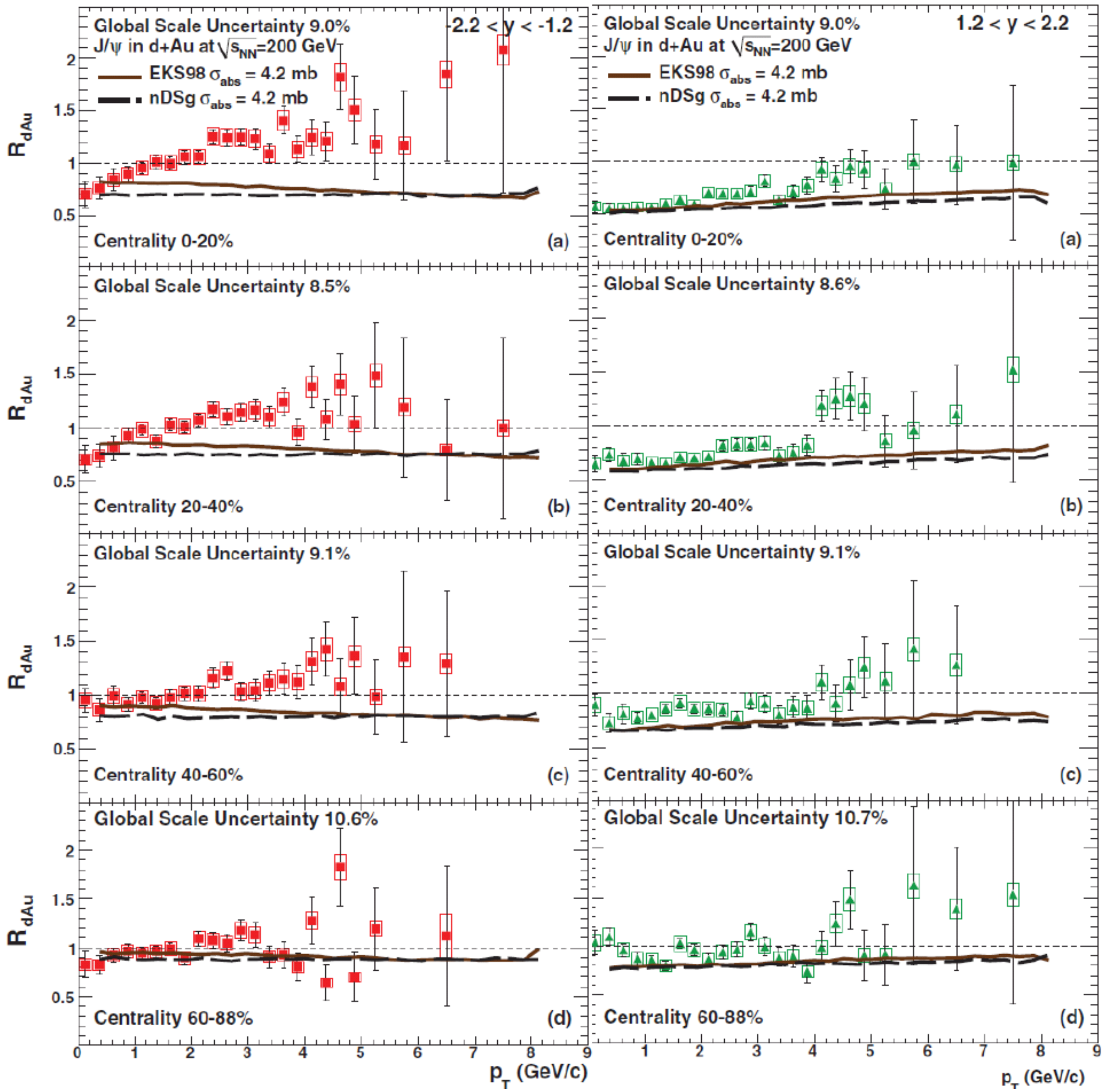
- Multi-parton- interactions?
- CGC describe the data well.

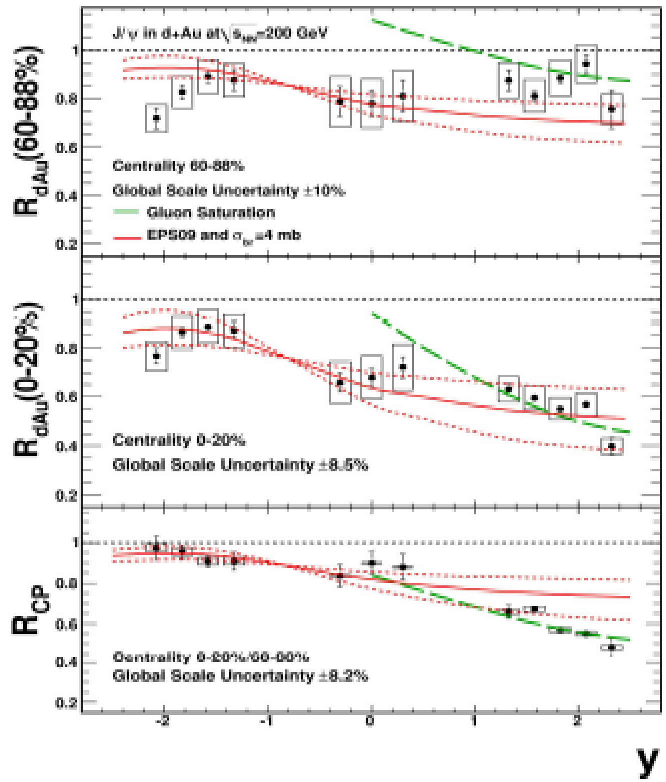
Quarkonia Production in p+p Collisions



- Fraction of non-prompt J/psi ~scale with collisions energy
- Described well by CEM. (R. Vogt 4th IWHF 2011)

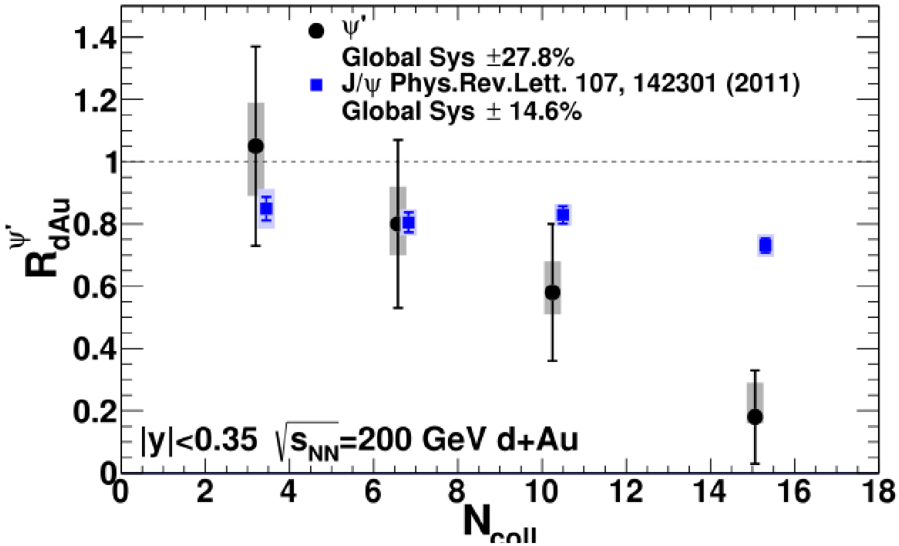
J/ψ Production in d+Au 200 GeV

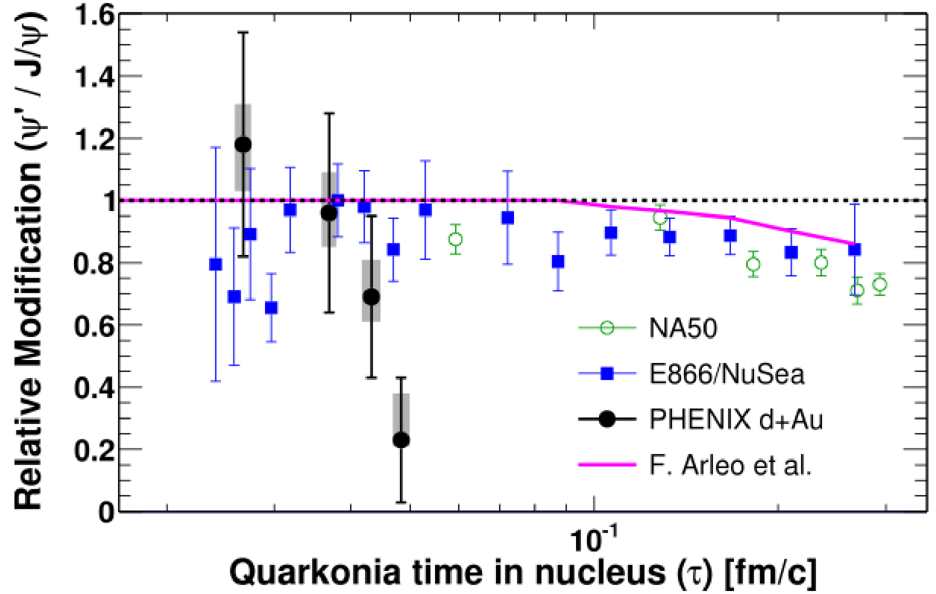


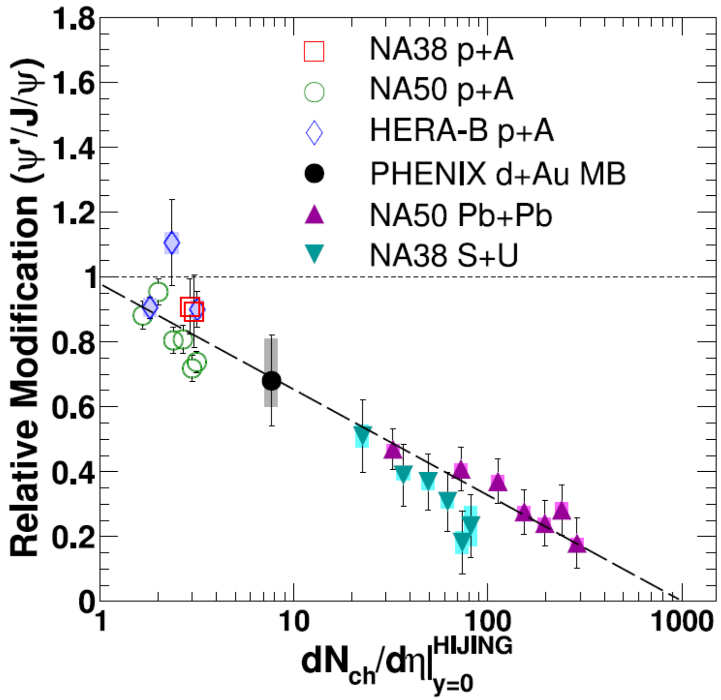


- ❑ Significant suppression in forward region
- ❑ Largely explained by shadowing+abs.
- ❑ Predict different trend in backward region (Au direction)
  - ▪ Cronin?

ψ’ Production in d+Au 200 GeV

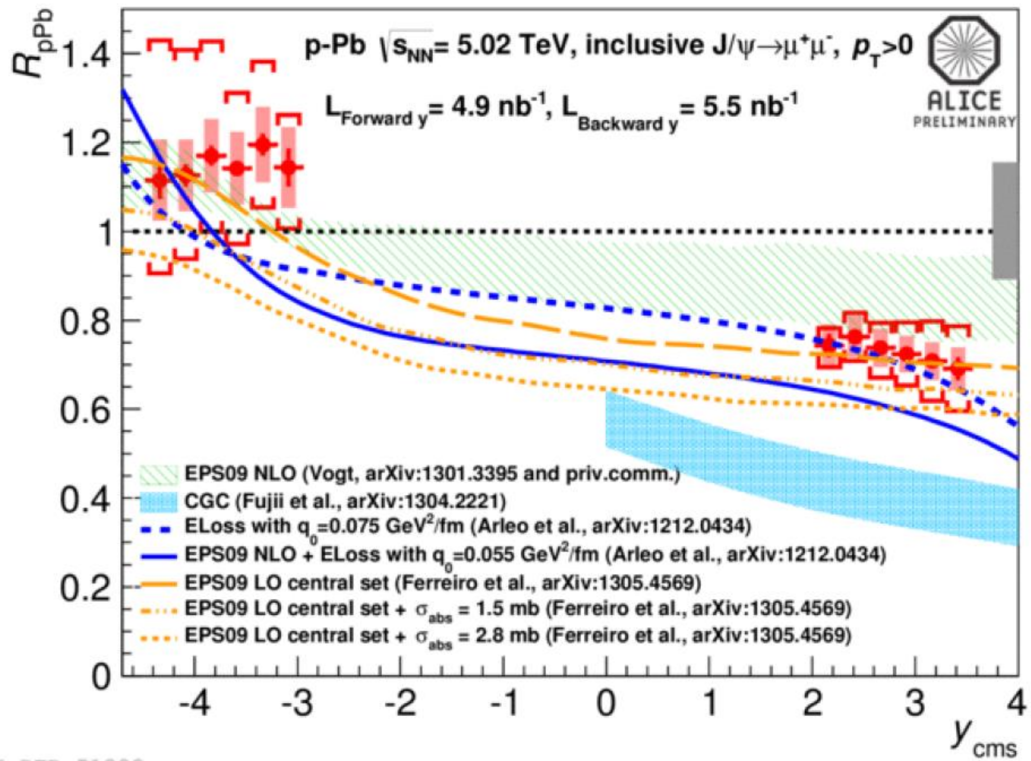


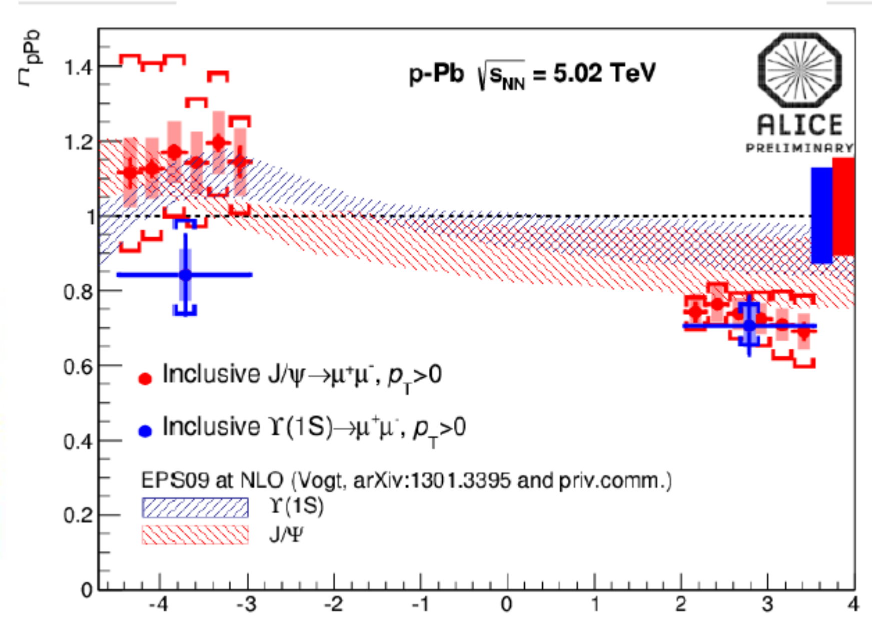




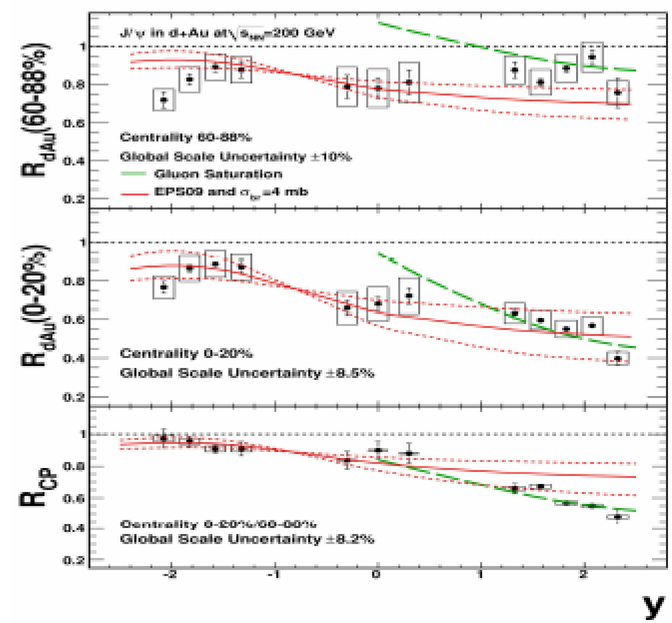
- very different from J/psi on centrality dependence.
- What LHC see?
- Psi’ size ~2x J/psi.
- Psi’ binding E ~0.1 x J/psi.

Quarkonia Production in p+Pb 5.02 TeV

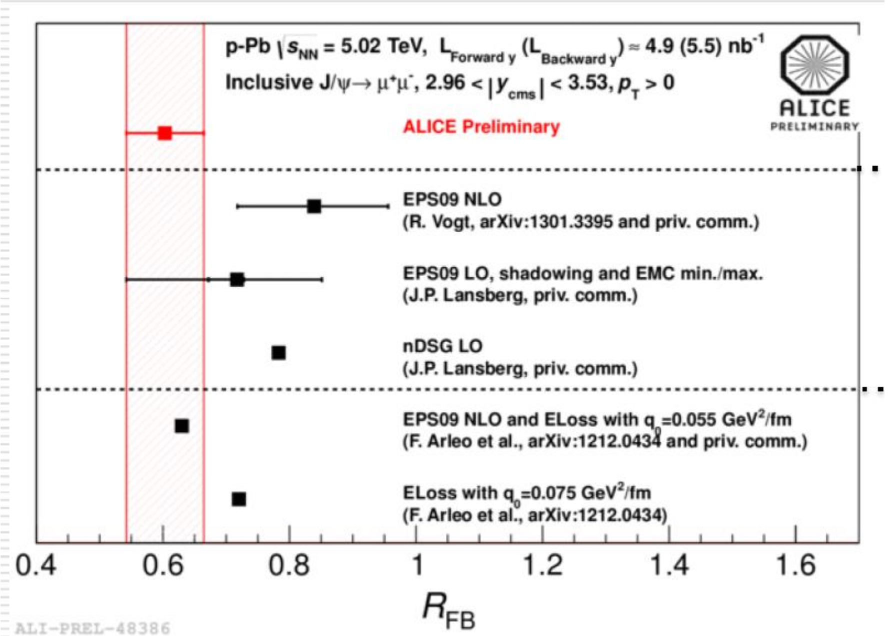


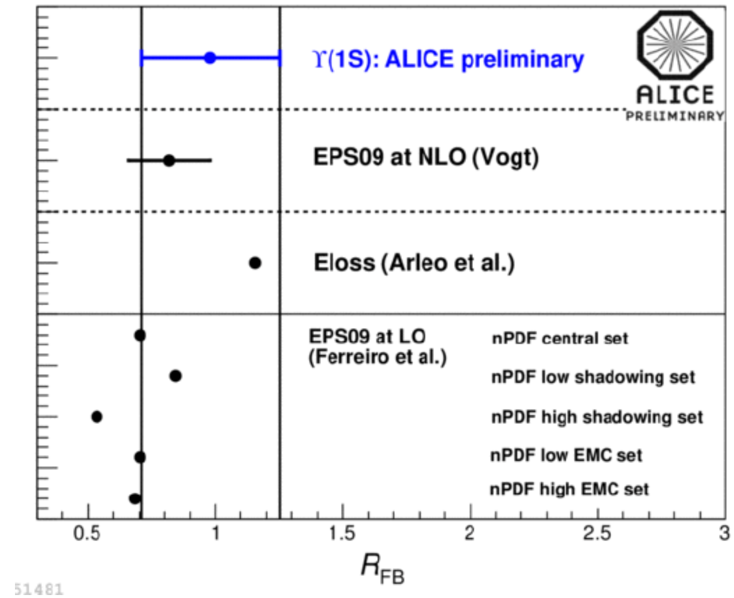


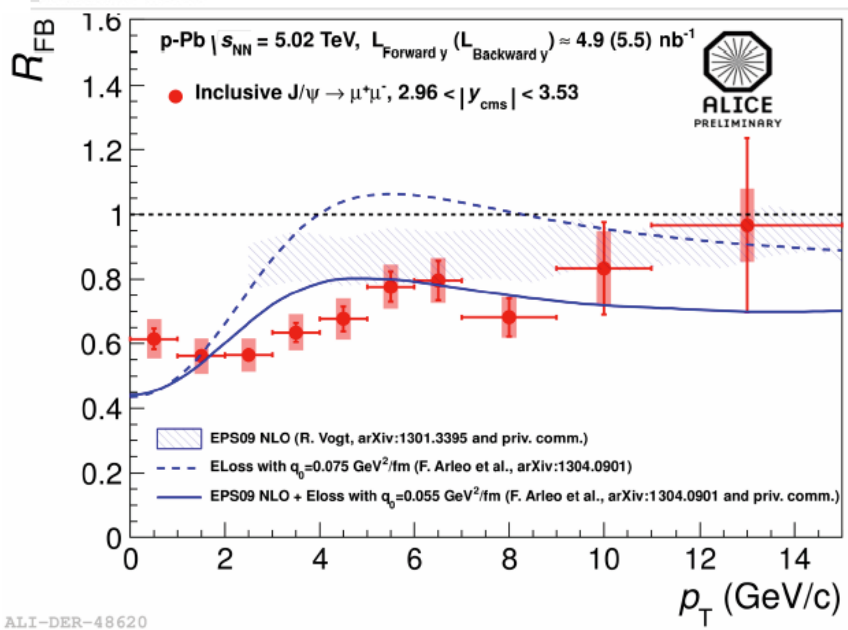
- ❑ CGC disfavored by data
- ❑ sys. Error mostly from p+p reference which is from interpolation
  - ❑ Mostly bin-by-bin correlated.
  - ❑ Hard to say which is better:
    - ❑ shadowing, Eloss, etc
- ❑ Upsilon also suppressed in forward region.
- ❑ Similar to RHIC results.



Quarkonia Production in p+Pb 5.02 TeV



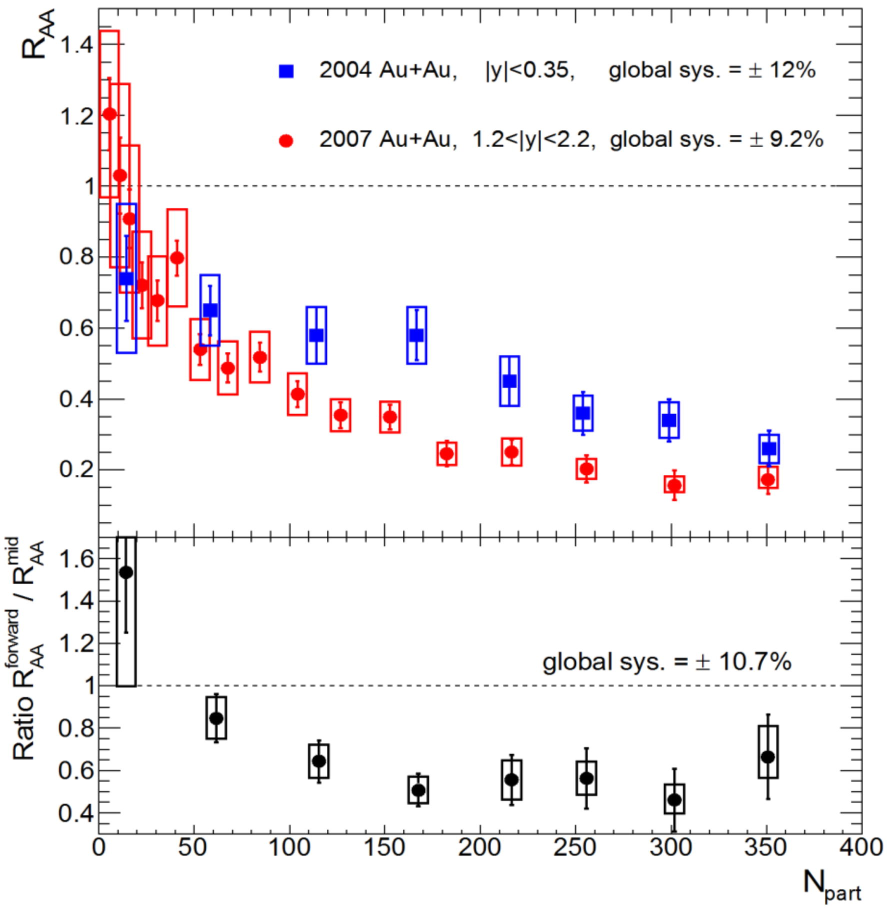


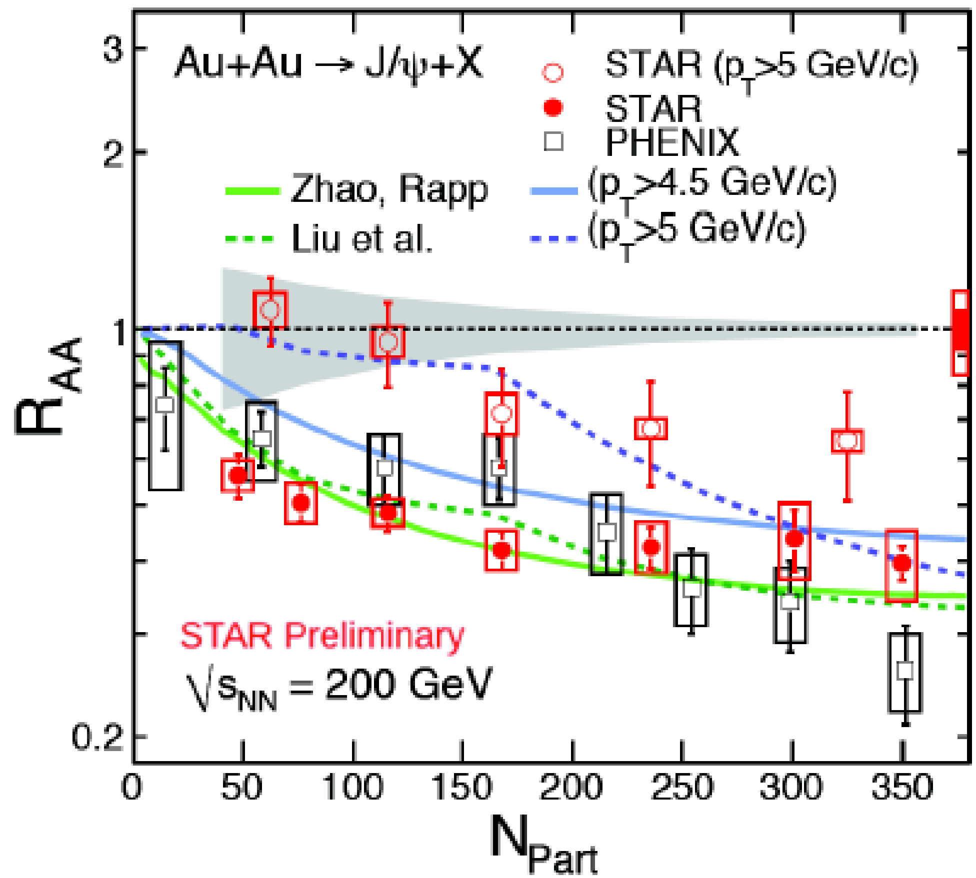


- pp reference not needed for R_{FB}.
- Shadowing + Eloss seems to describe the data better.

$$R_{FB} = \frac{R_{pPb}}{R_{Pbp}} = \frac{Y^{Forward}_{Q\bar{Q}}}{Y^{Backward}_{Q\bar{Q}}}$$

J/ψ Production in Au+Au 200 GeV





- More suppression in forward region
  - Larger CNM effect
  - Re-generation?
- Less suppression for higher pT
  - Longer formation time?
  - Cronin effect?

J/ψ spectra in 200GeV Au+Au

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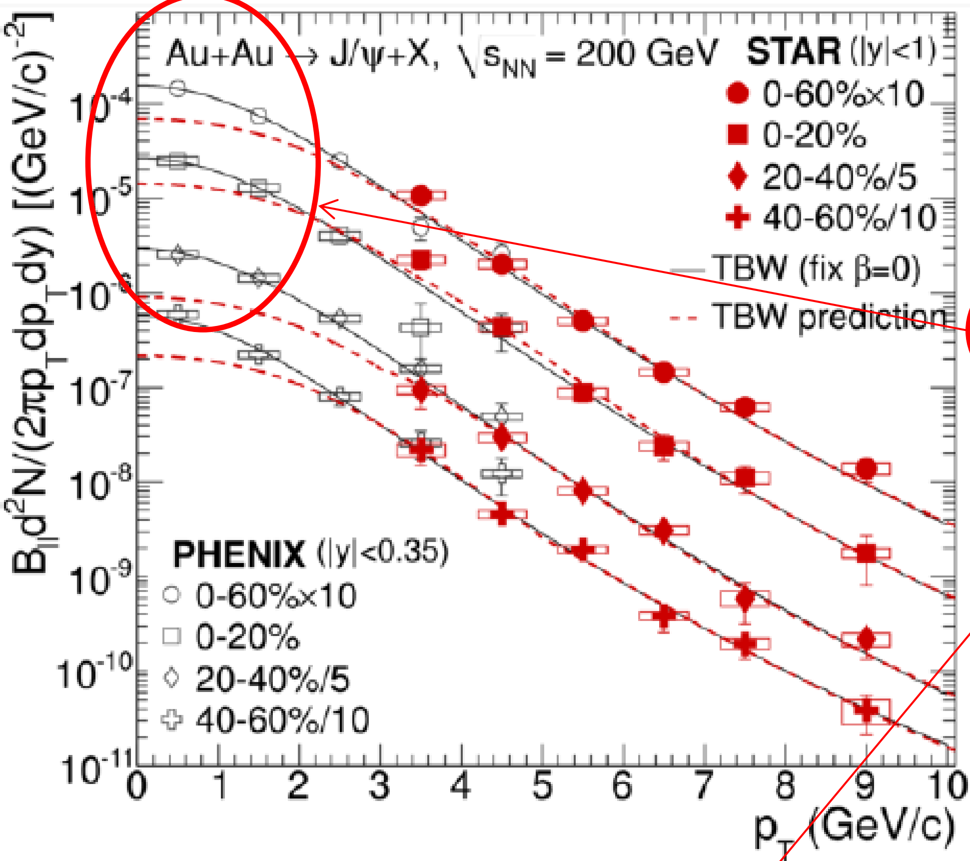

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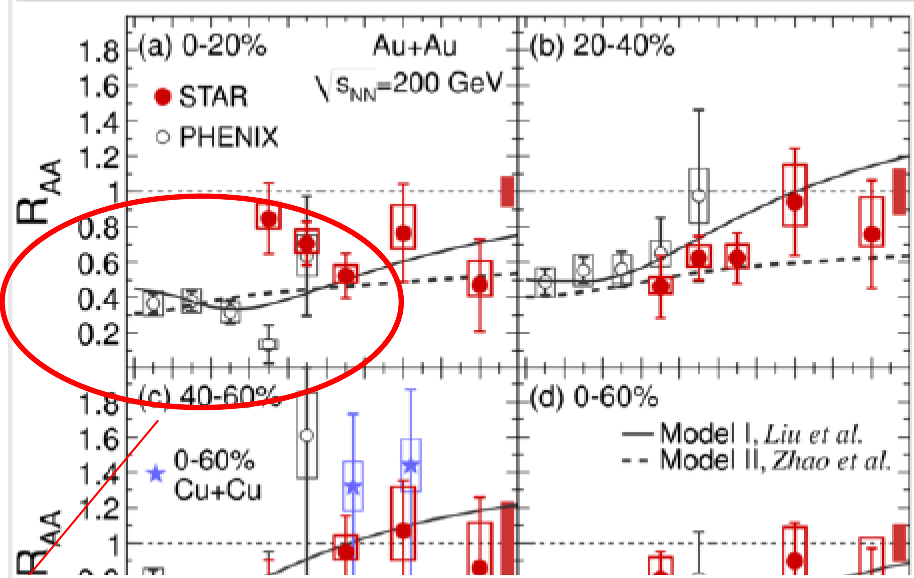
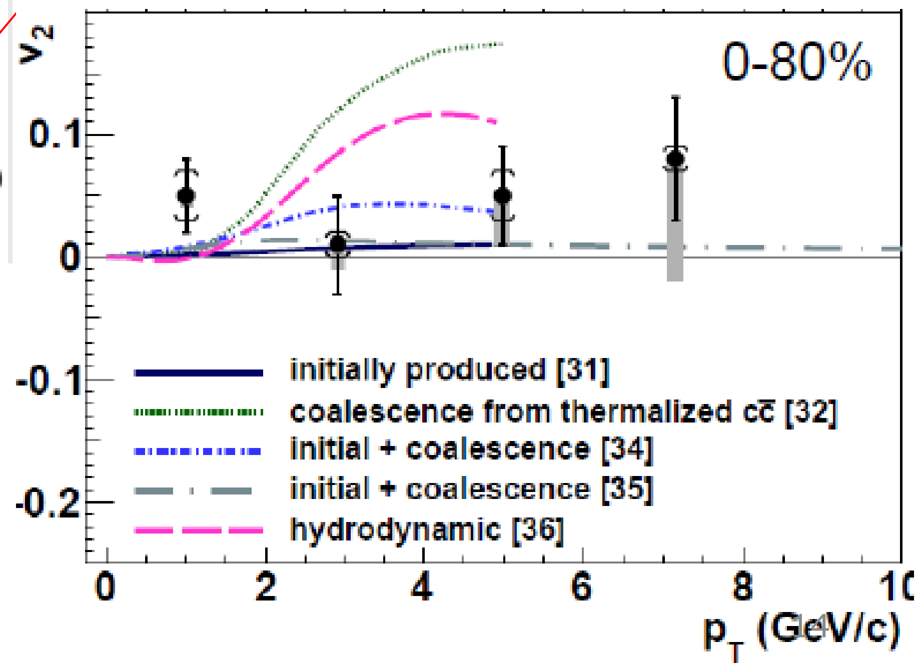
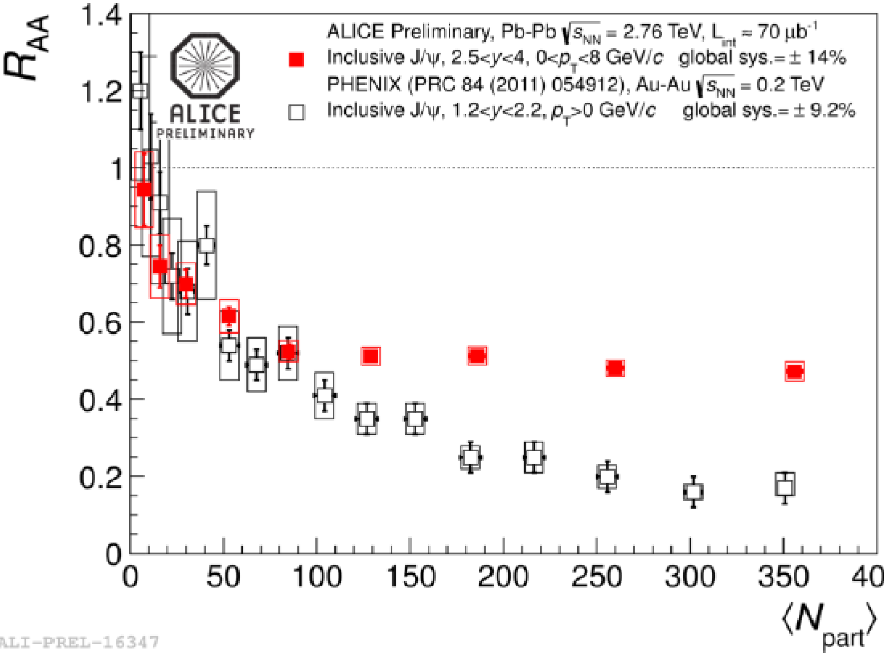
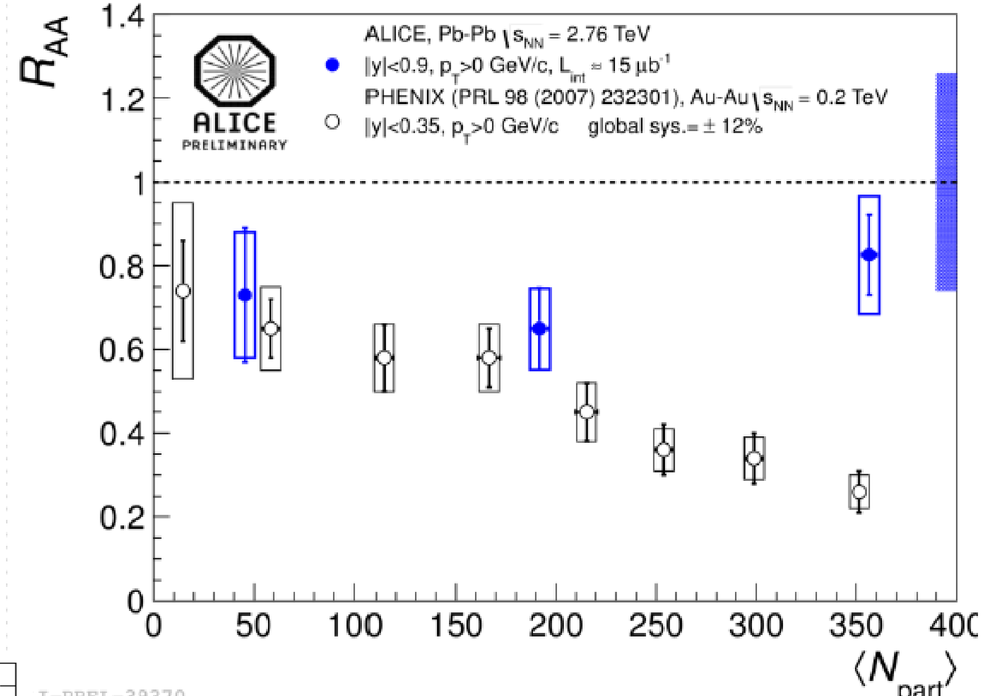


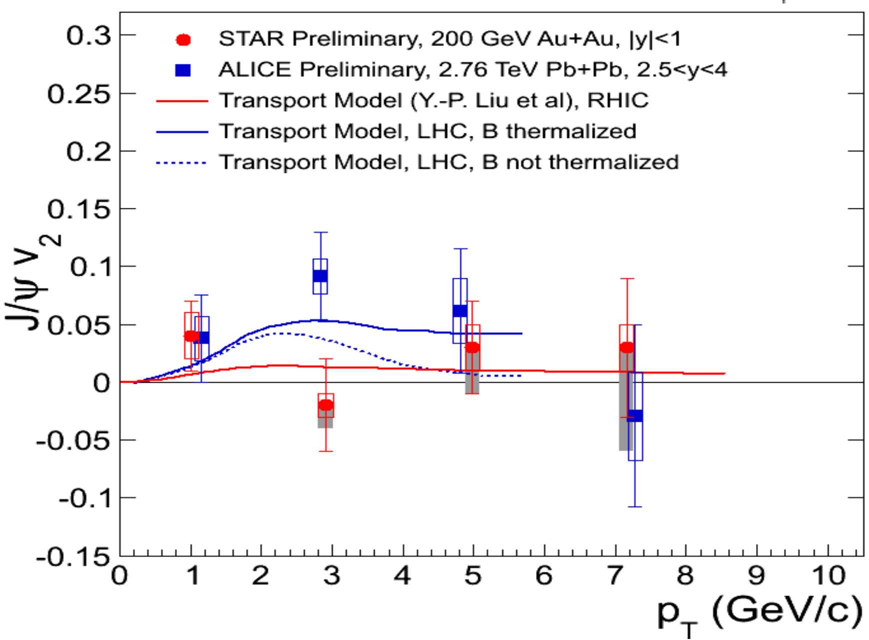


- Much smaller radial flow?
- Regeneration at low p_T?

J/ψ spectra in 2.76 TeV Pb+Pb

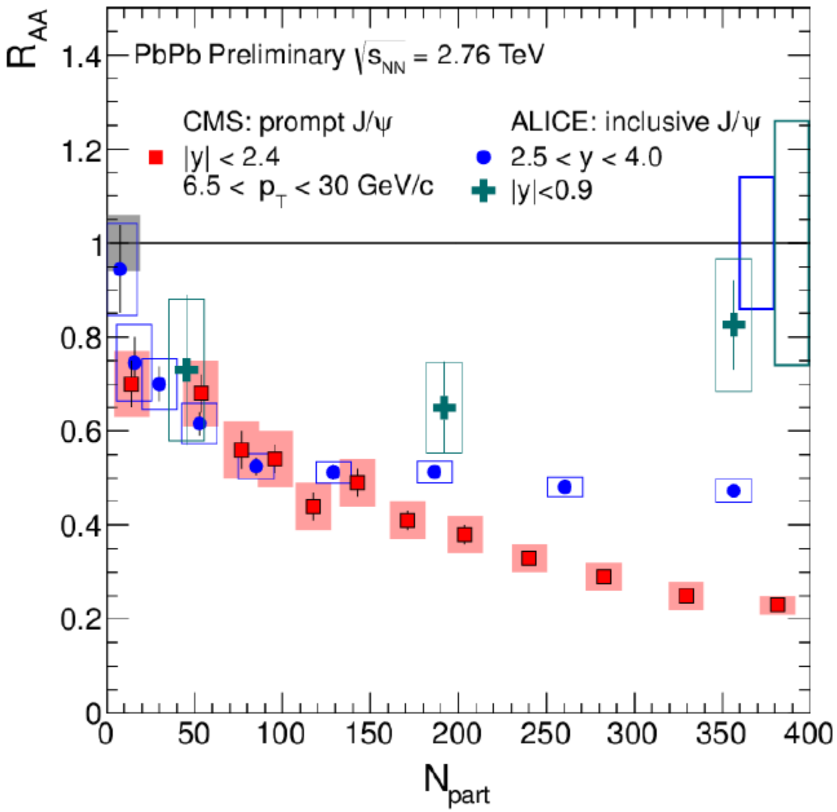


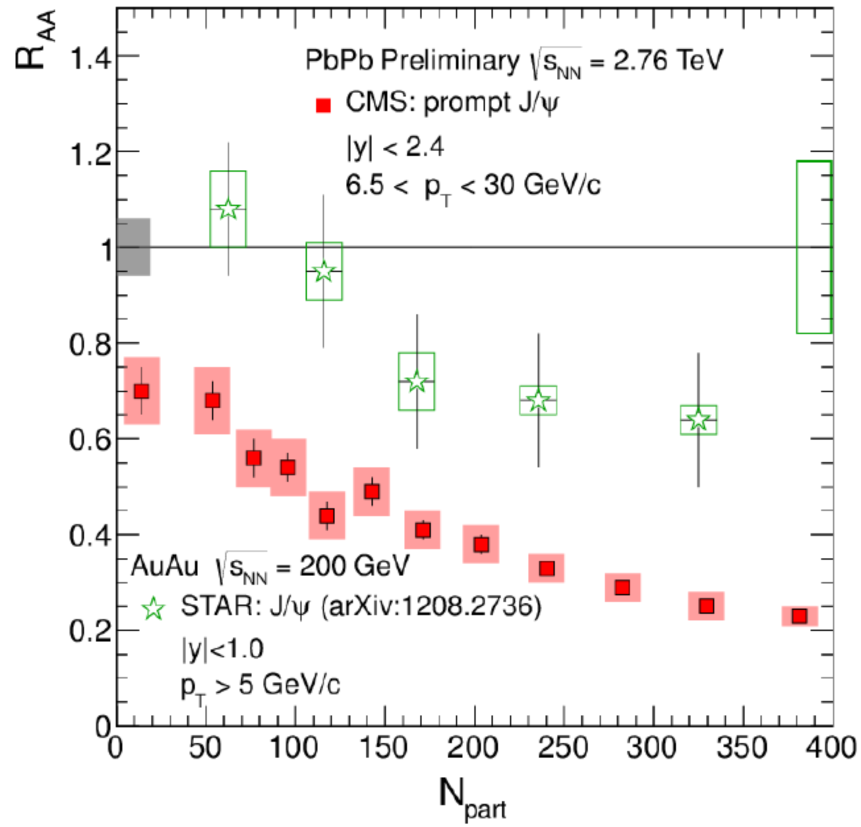




- Significantly less suppression at low pT at LHC.
- N(cc@LHC) ~10x N(cc@RHIC)
- Re-generation at LHC?

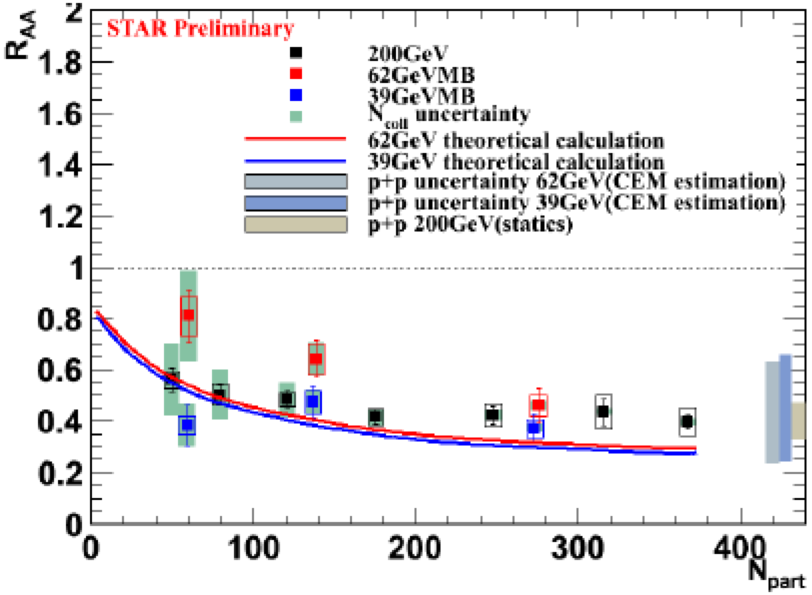
J/ψ spectra in 2.76 TeV Pb+Pb

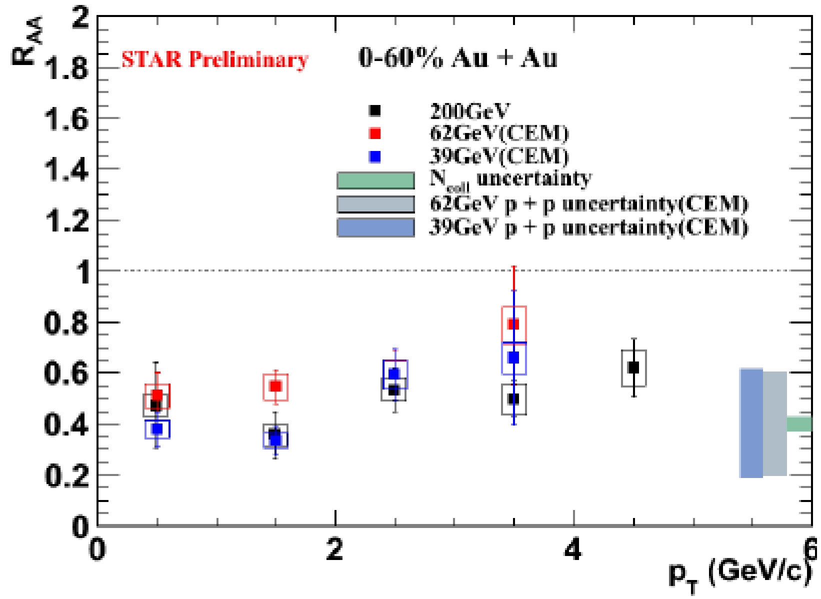


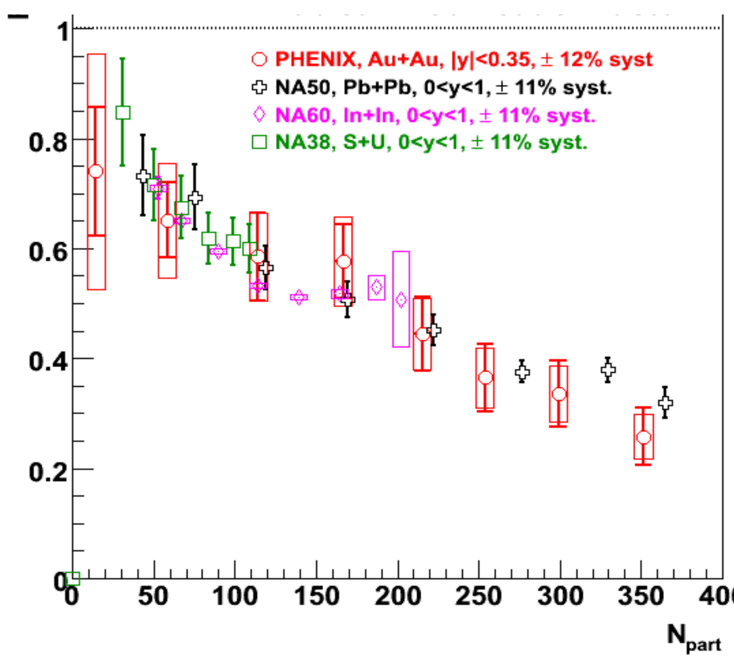


- More suppression at high pT than at low pT
  - Consistent with the re-generation picture.
- High pT J/psi suppression
  - LHC > RHIC

Comparing with the Lower Energy Results

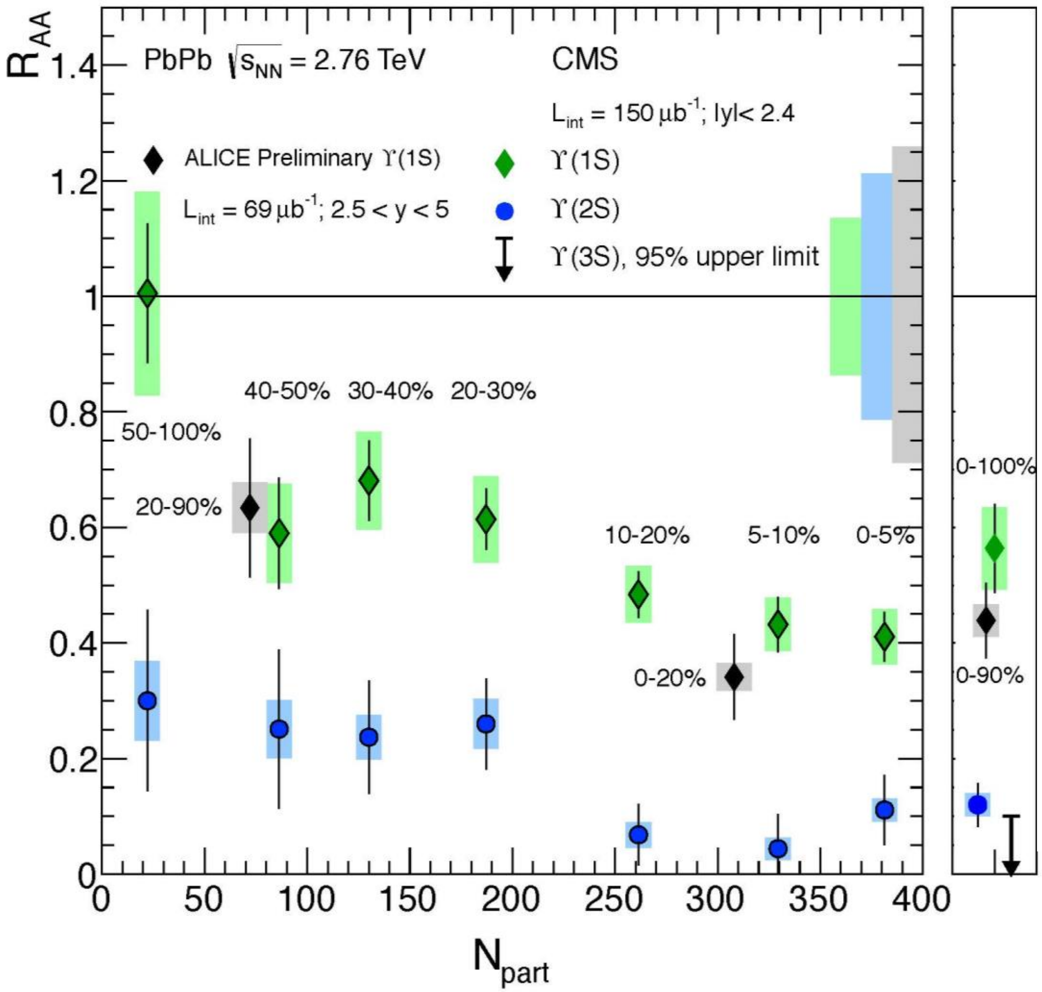


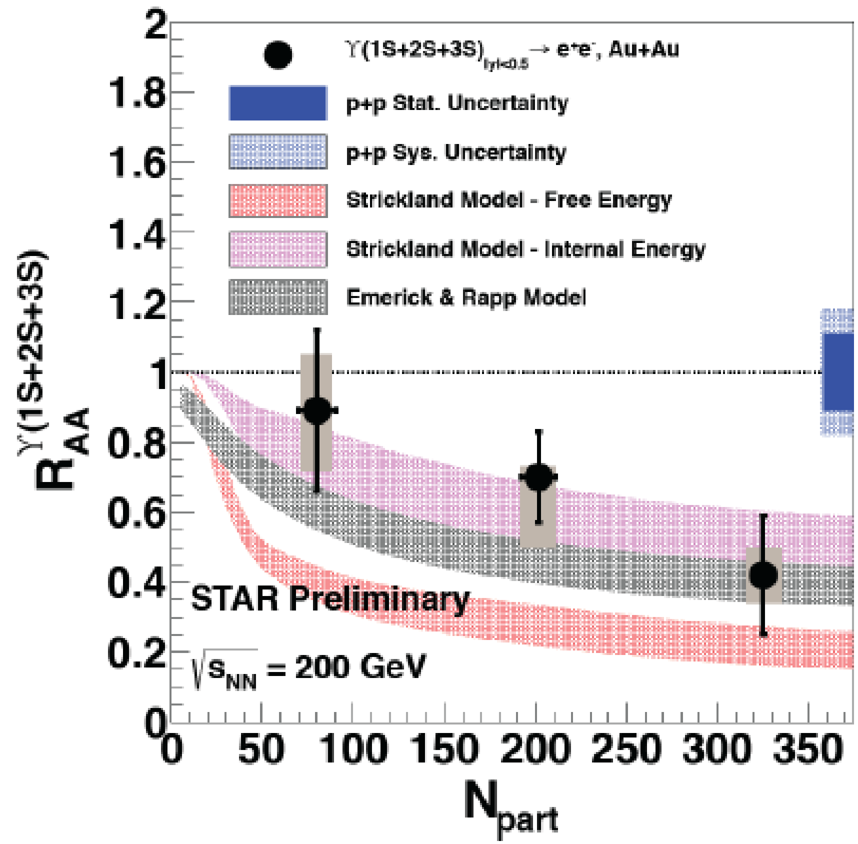


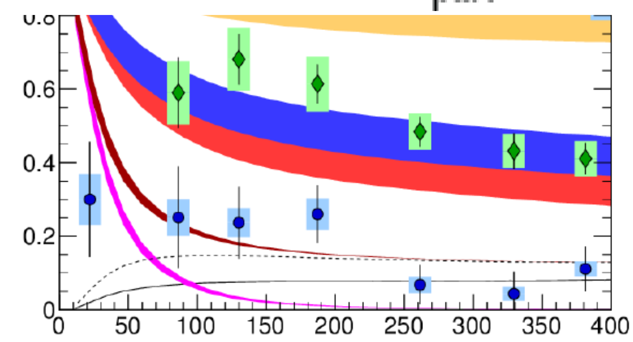


- Similar level of suppression from 20 – 200 GeV at all centrality and at all pT
- Sequential melting?

Upsilon Production in A+A Collisions





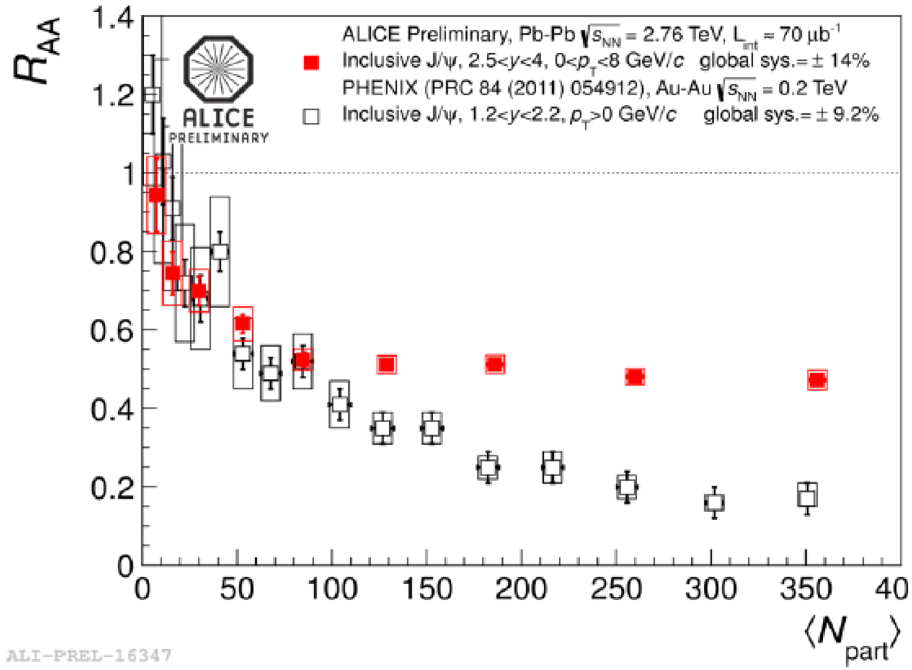


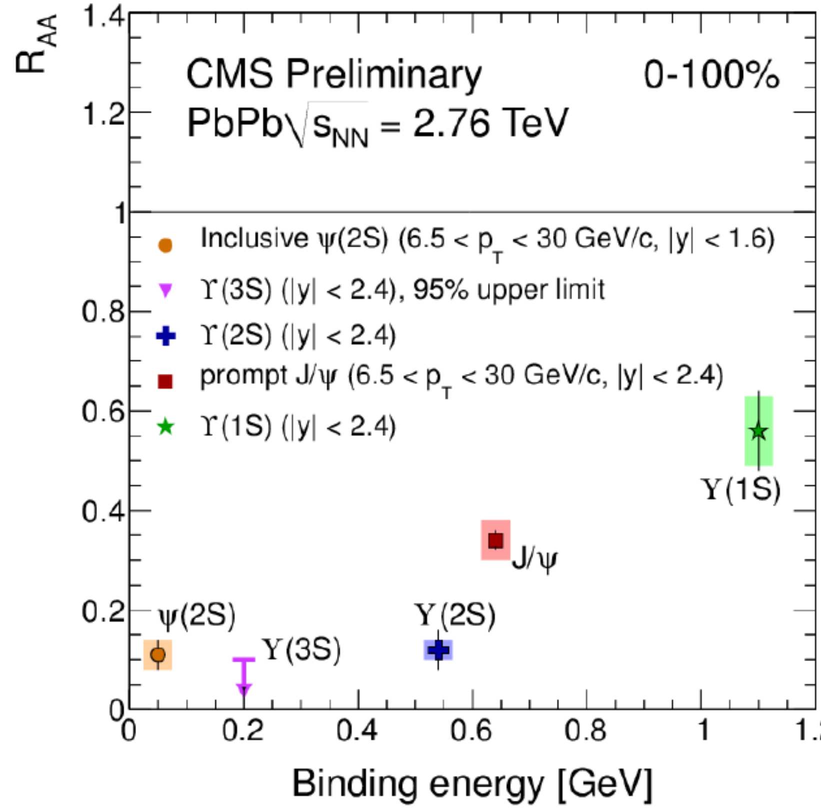
$$R_{AA}(Y(1S)) = 0.56 \pm 0.08(stat.) \pm 0.07(syst.)$$

$$R_{AA}(Y(2S)) = 0.12 \pm 0.04(stat.) \pm 0.02(syst.)$$

$$R_{AA}(Y(3S)) < 0.1 \quad (95\% \, C.L.)$$

Look at All Quarkonia Together





- ❑ Low pT J/psi results seems to indicate contributions from re-generation.
- ❑ High pT J/psi/psi' and upsilon results seems to indicate a sequential melting picture.
- ❑ Does the J/psi melt?

Important to Study Open Heavy Flavor Production

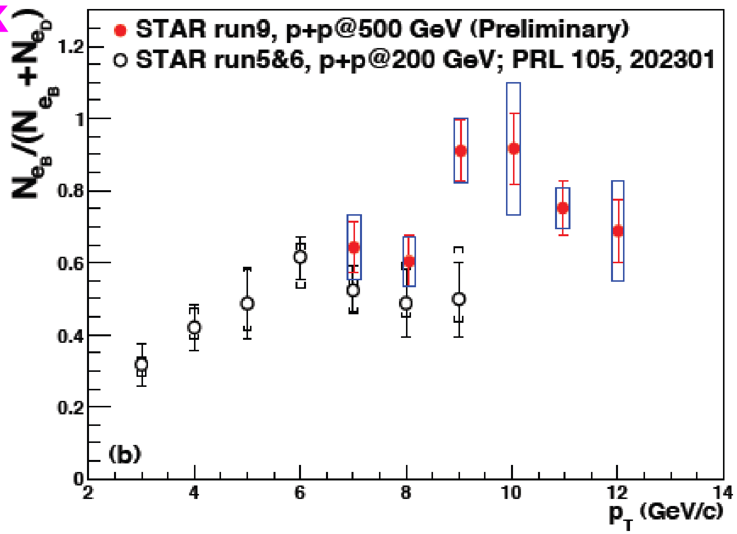
- A good reference to quarkonia production
  - Similar initial state effect.
    - CGC, Shadowing, initial state energy loss, etc.
  - Large cross section (compared to J/ψ).
    - Accurate reference measurements.

- One of the most important probes for sQGP
  - Interactions between heavy quark and medium are quite different from the ones for light quarks
    - gluon radiation, collisional energy loss, collisional disassociation, etc
  - allow further understanding of the medium properties.
  - A “Gold Mine” to be fully explored soon.

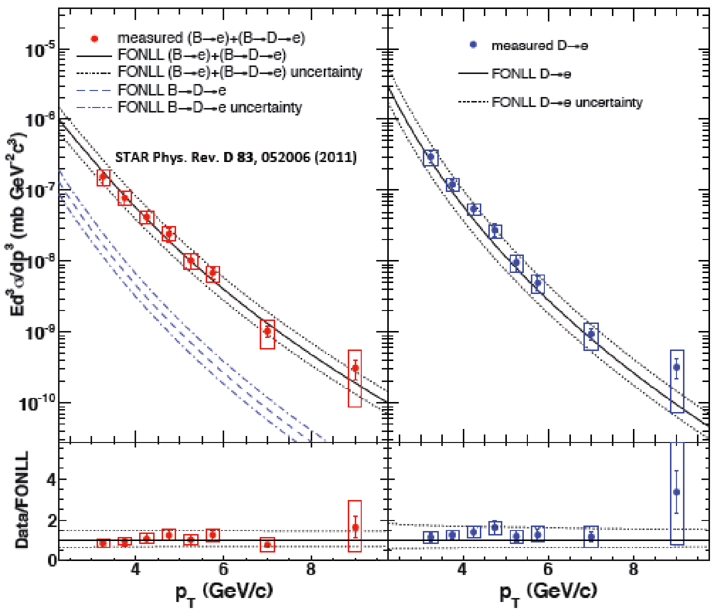
The Pros and Cons of Different Methods

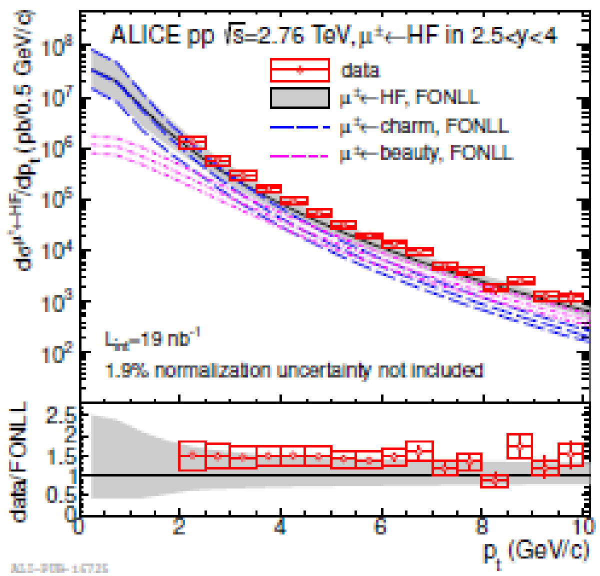
- **Direct reconstruction**
  - **allow direct access to the heavy quark kinematics,**
  - **hard to trigger.**
    - ✓ *Limit the pT reach of the measurements*
  - **small(er) Branching Ratio:**
    - ✓ $B^+ \to K^+ + J/\psi \to ee$: $BR: \sim 6 \times 10^{-5}$
    - ✓ $B^0 \to K\pi$: $BR: \sim 5 \times 10^{-6}$
    - ✓ $D^0 \to K\pi$: $BR: \sim 4\%$
    - ✓ $D^+ \to K\pi\pi$: $BR: \sim 9.4\%$ (lower acceptance)

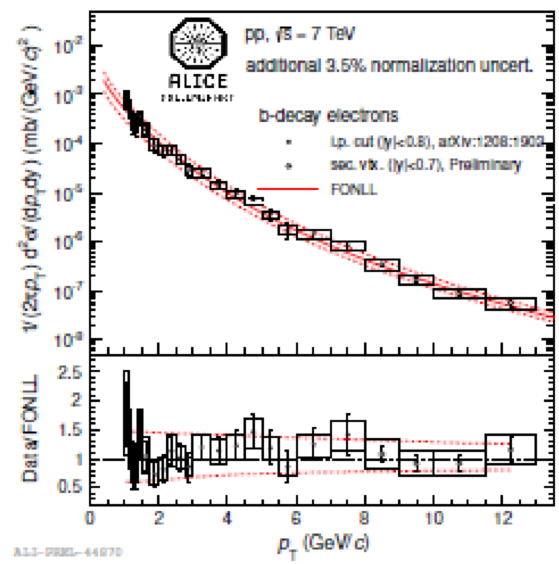
- **Indirect measurement through decays**
  - **Indirect access to the heavy quark kinematics**
  - **Mixture of B and D contribution.**
  - **can be triggered easily.**
    - ✓ *Ideal for high pT measurements*
  - **High(er) branching ratio**
    - ✓ $B^0/B^+ \to e^+ + X$: $BR: \sim 10\%$
    - ✓ $B \to J/\psi + X$: $BR: \sim 1\%$
    - ✓ $D^0 \to e^+ + X$: $BR: \sim 7\%$
    - ✓ $D^+ \to e^+ + X$: $BR: \sim 17\%$

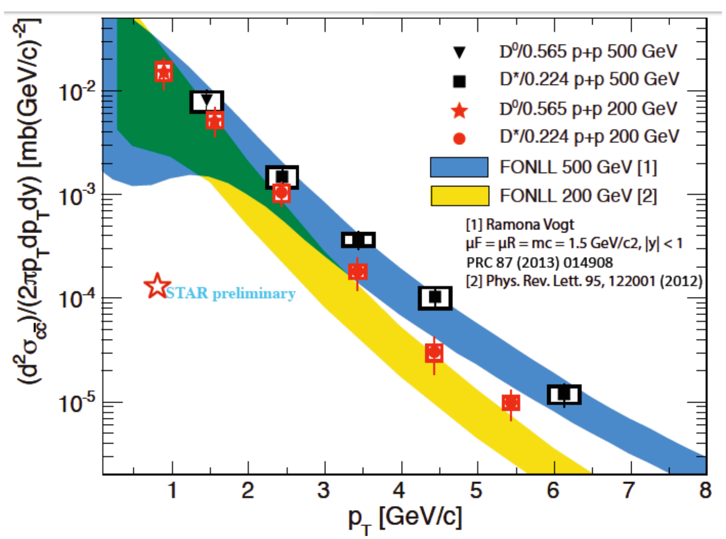


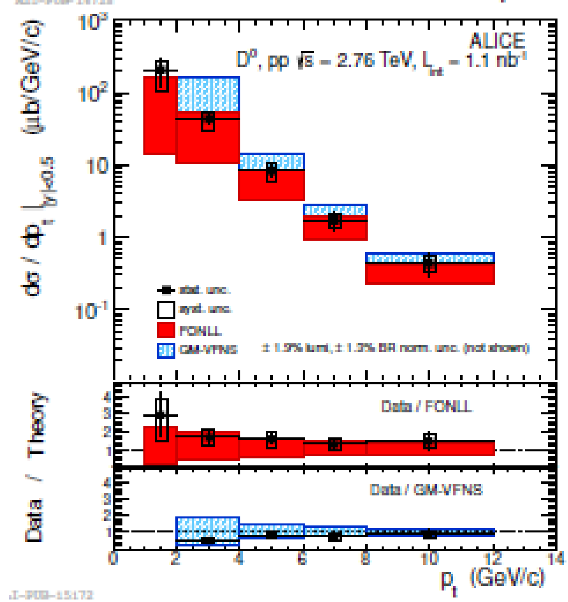
FONLL provide a good platform to describe Open HF in pp Collisions at RHIC and LHC

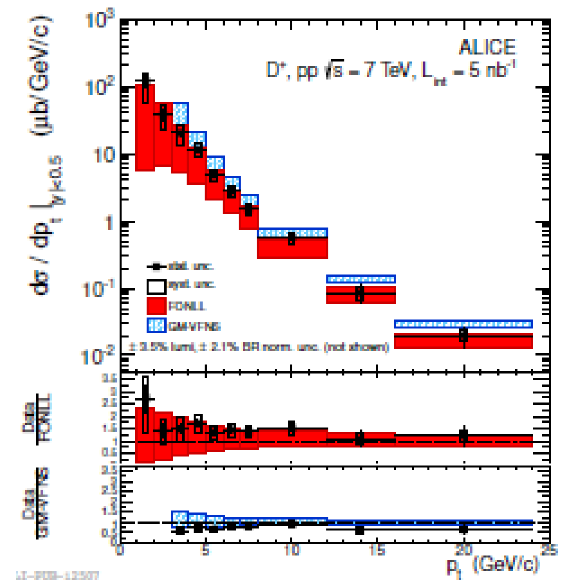




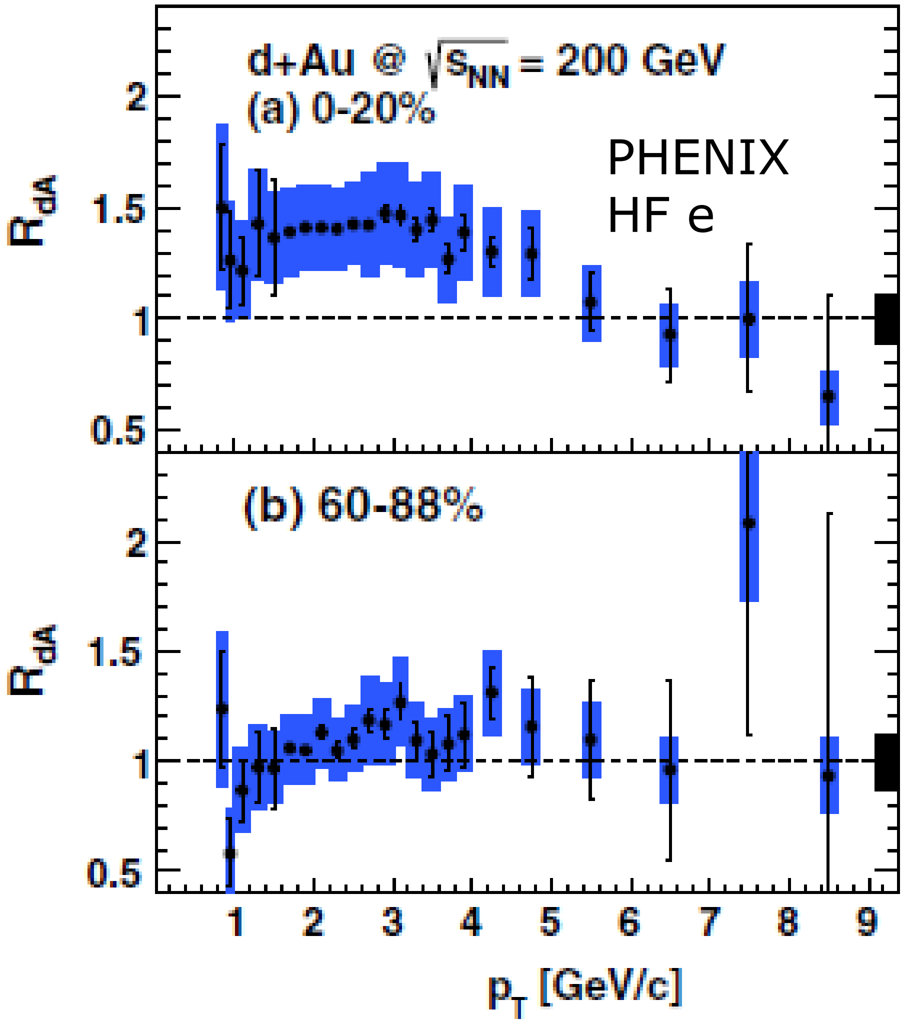


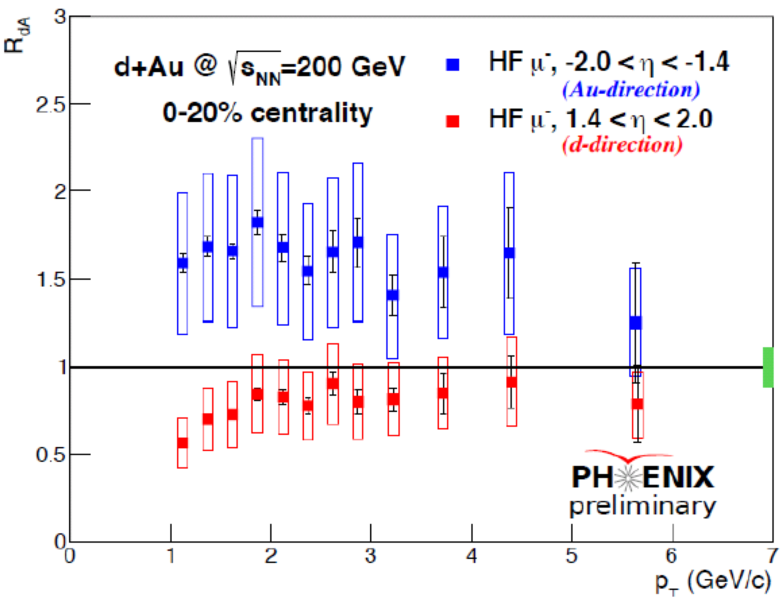






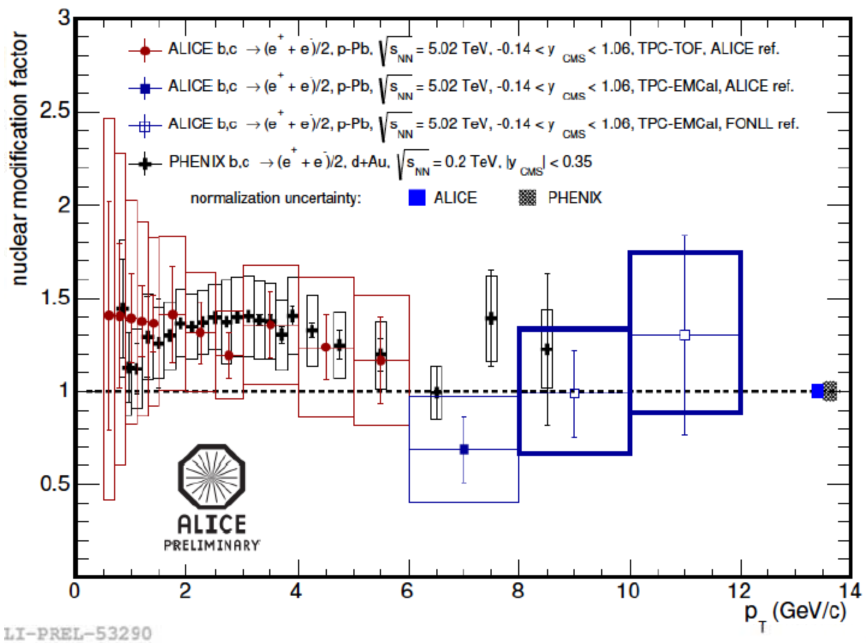
Large CNM Effect Observed at RHIC

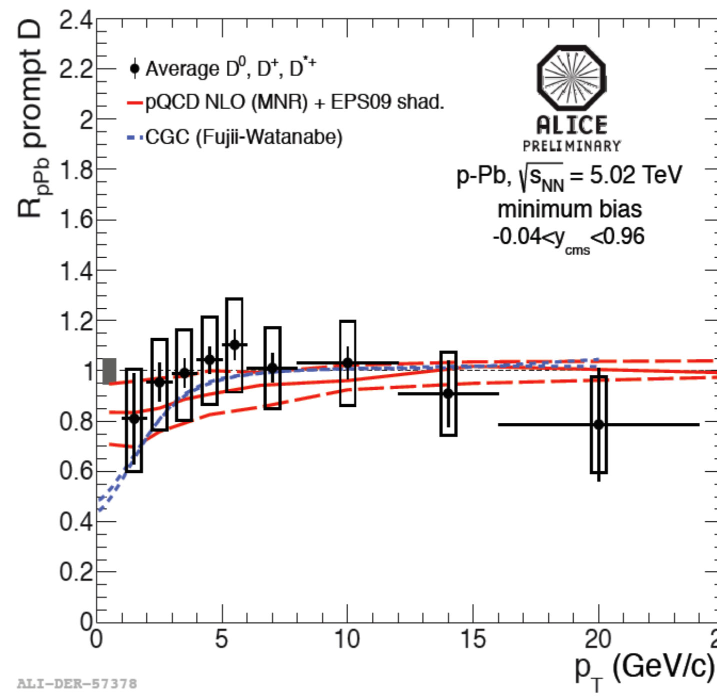




- Large enhancement in d+Au collision at mid and backward rapidity.
- small suppression at low pT at forward rapidity.

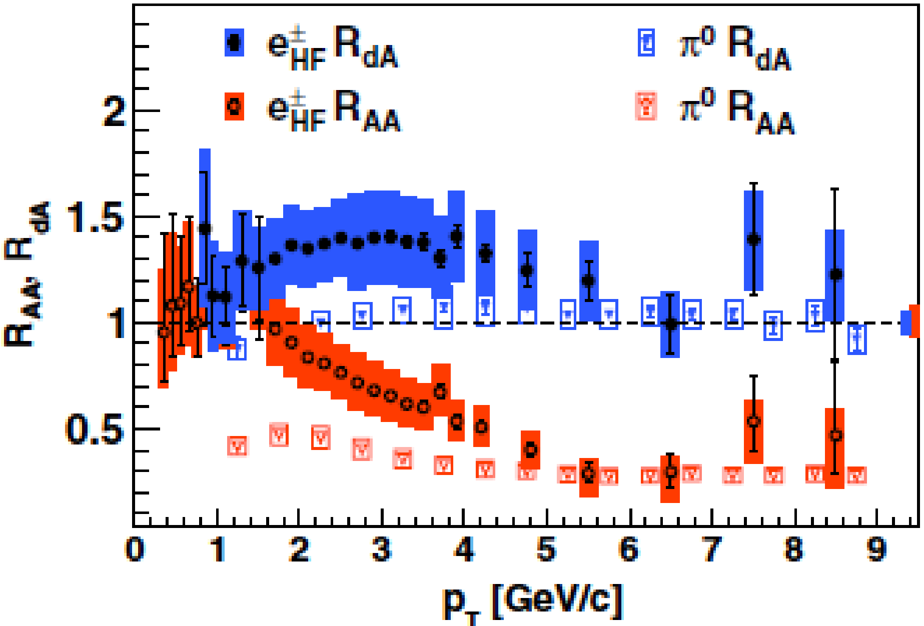
CNM Effects Observed at LHC

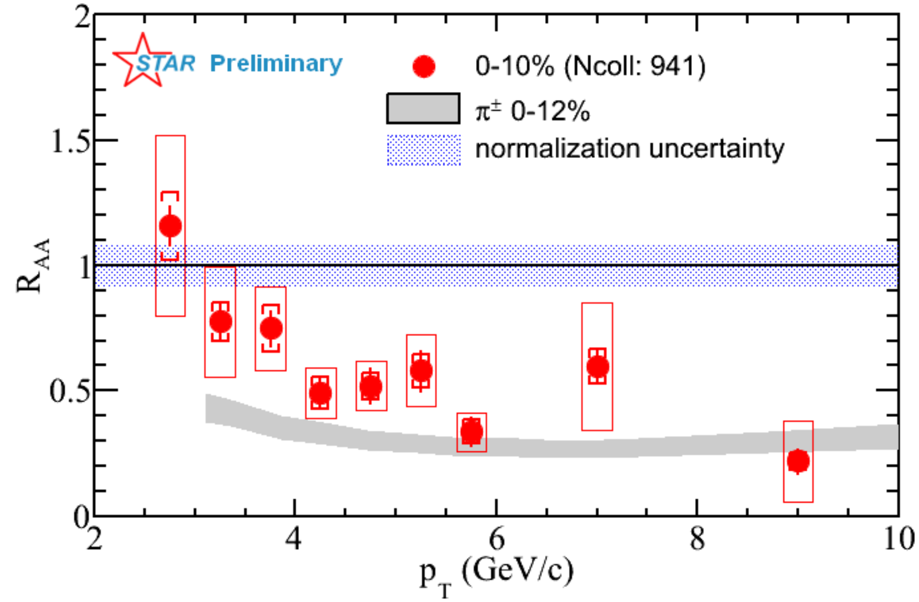


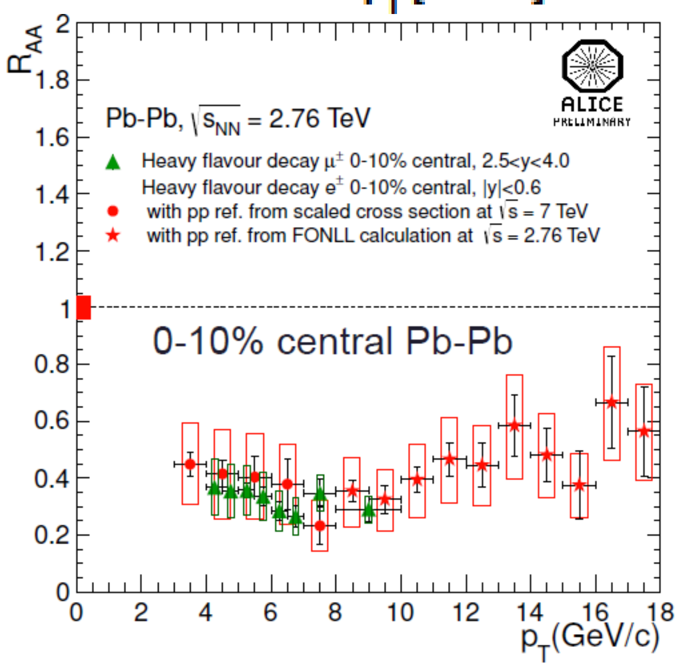


- ❑ R_{pPb}(NPE) systematically above 1.0, consistent with PHENIX
- ❑ while R_{pPb}(D) ~1.0.
- ❑ Coincidence due to systematics or B→e?
- ❑ Consistent with the shadowing and CGC.

Non-photonic Electron Production A+A Collisions

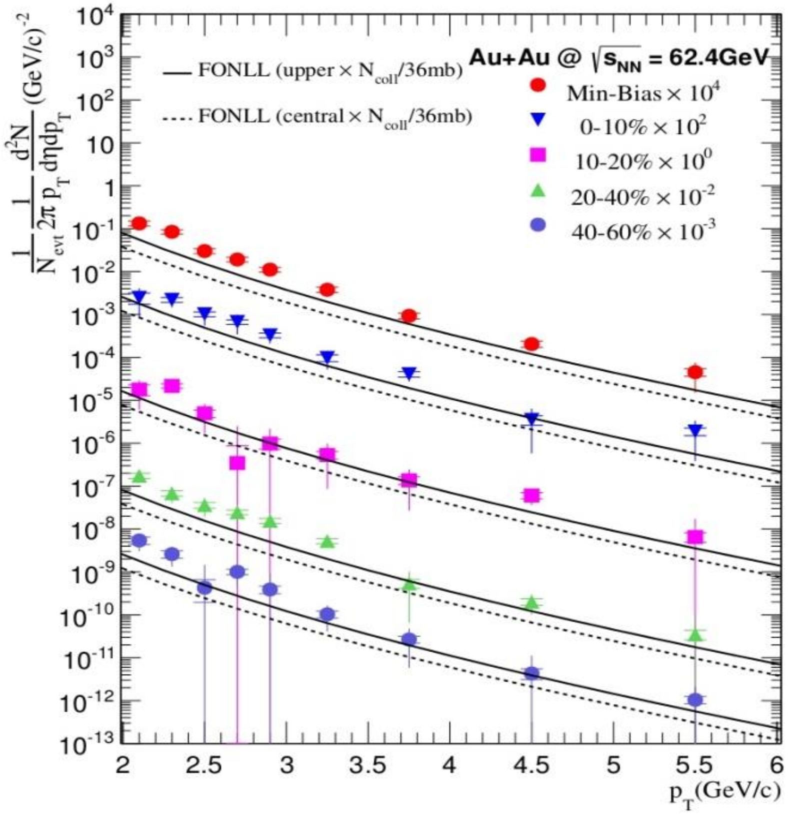


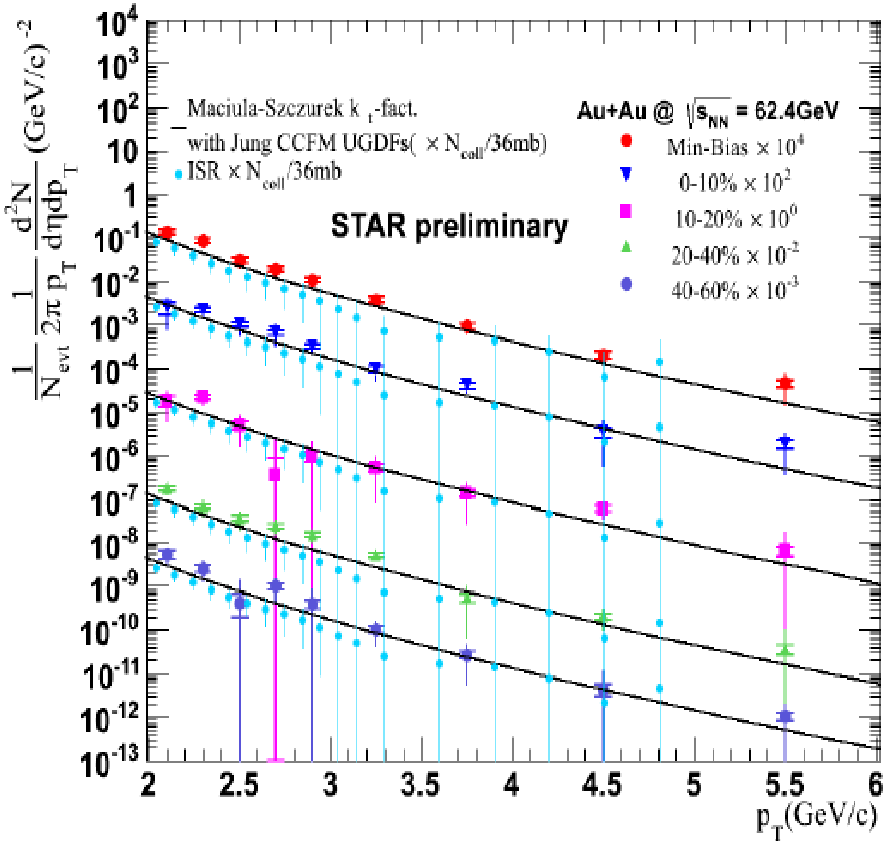




- large suppression of high pT NPE suppress.
- Similar suppression level at RHIC and LHC.
- CNM seems to be responsible for the ramp at pT< 5 GeV at RHIC
- R_{AA} from QGP medium seems to be the same for HF and light quark

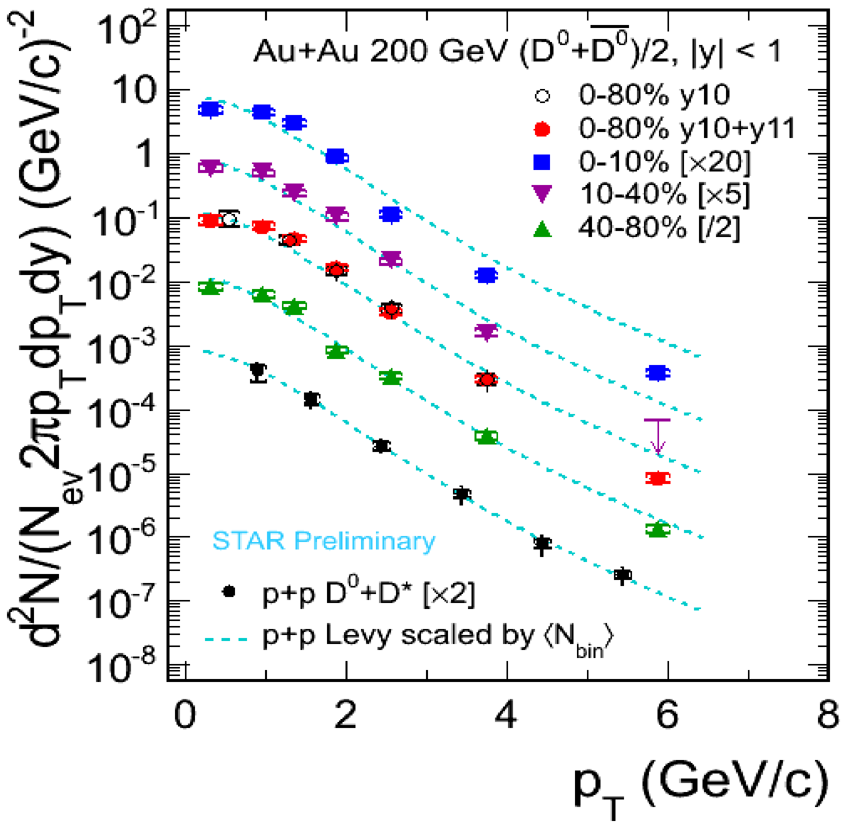
Non-photonic Electron Production at Low Energy

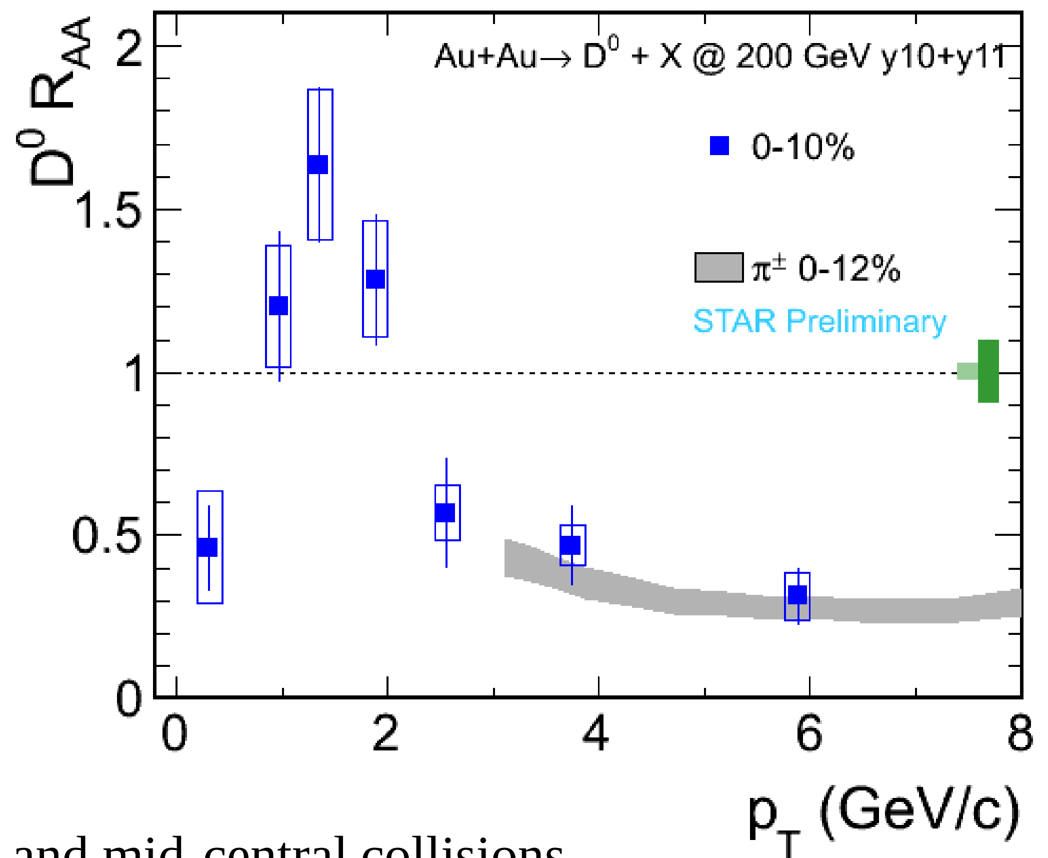




- ❑ Note: J/psi not subtracted.
- ❑ seems to indicate no suppression at 62.4 GeV.
  - Cold nuclear effect?

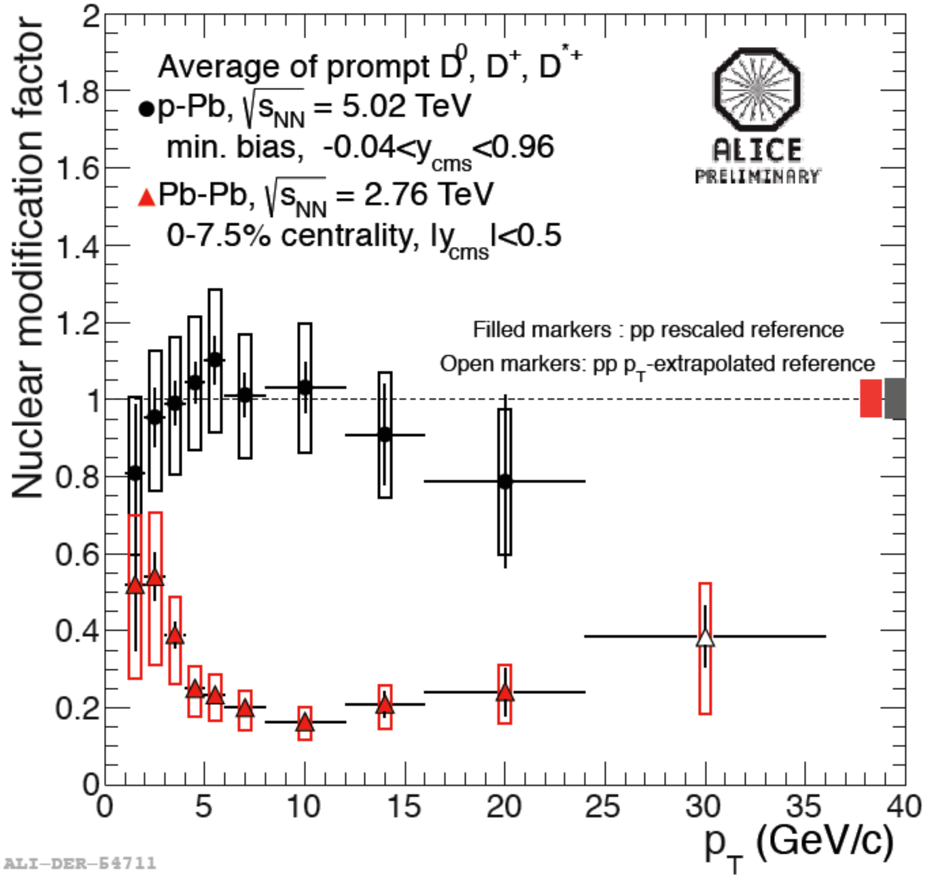
D^0 Production in Au+Au 200 GeV

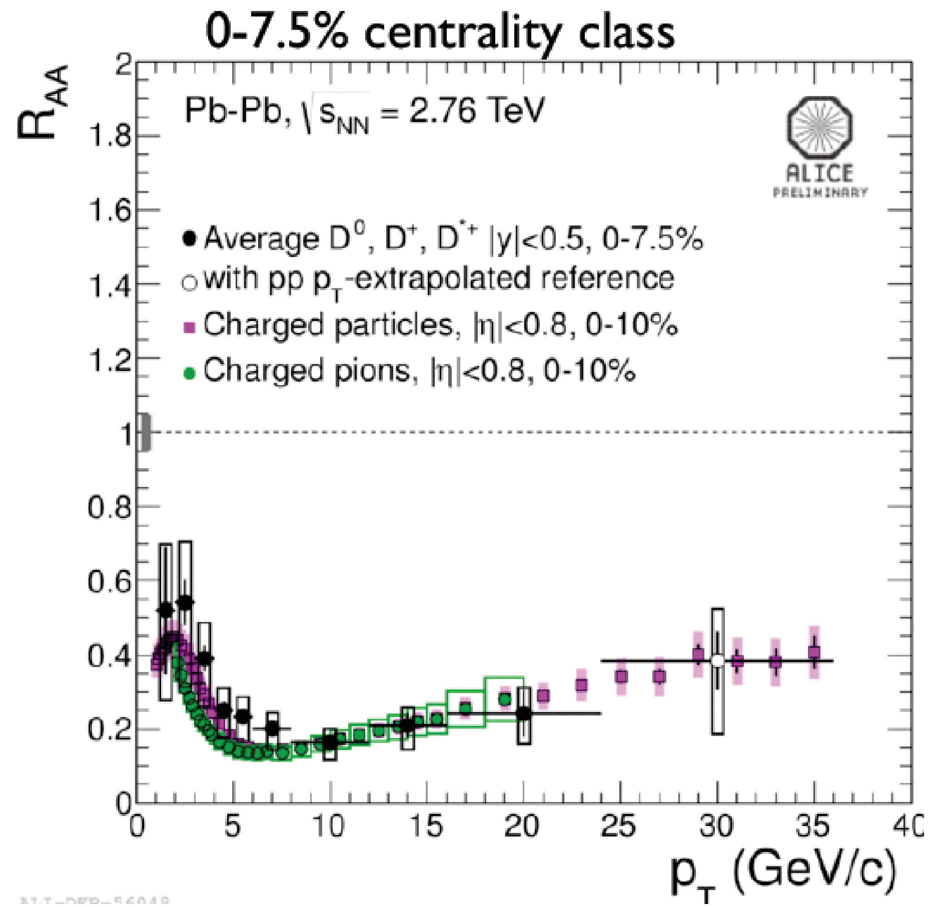




- Suppression at high p_T in central and mid-central collisions
- Seems to be the same as pion suppression pattern at pT > 3 GeV/c.
  - As observed in NPE results.
- Enhancement at intermediate p_T.
  - Radial flow due to coalescence OR
  - CNM effect as part of NPE enhancement?

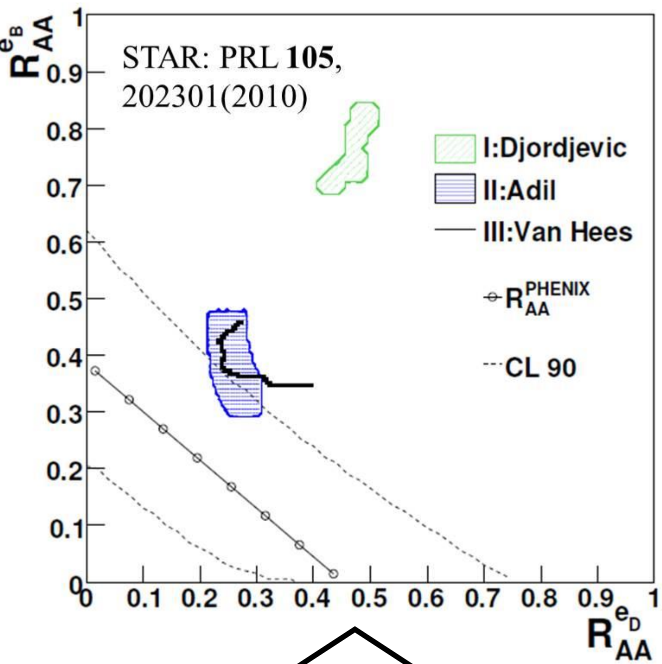
D Meson Production in p+Pb 2.76 TeV



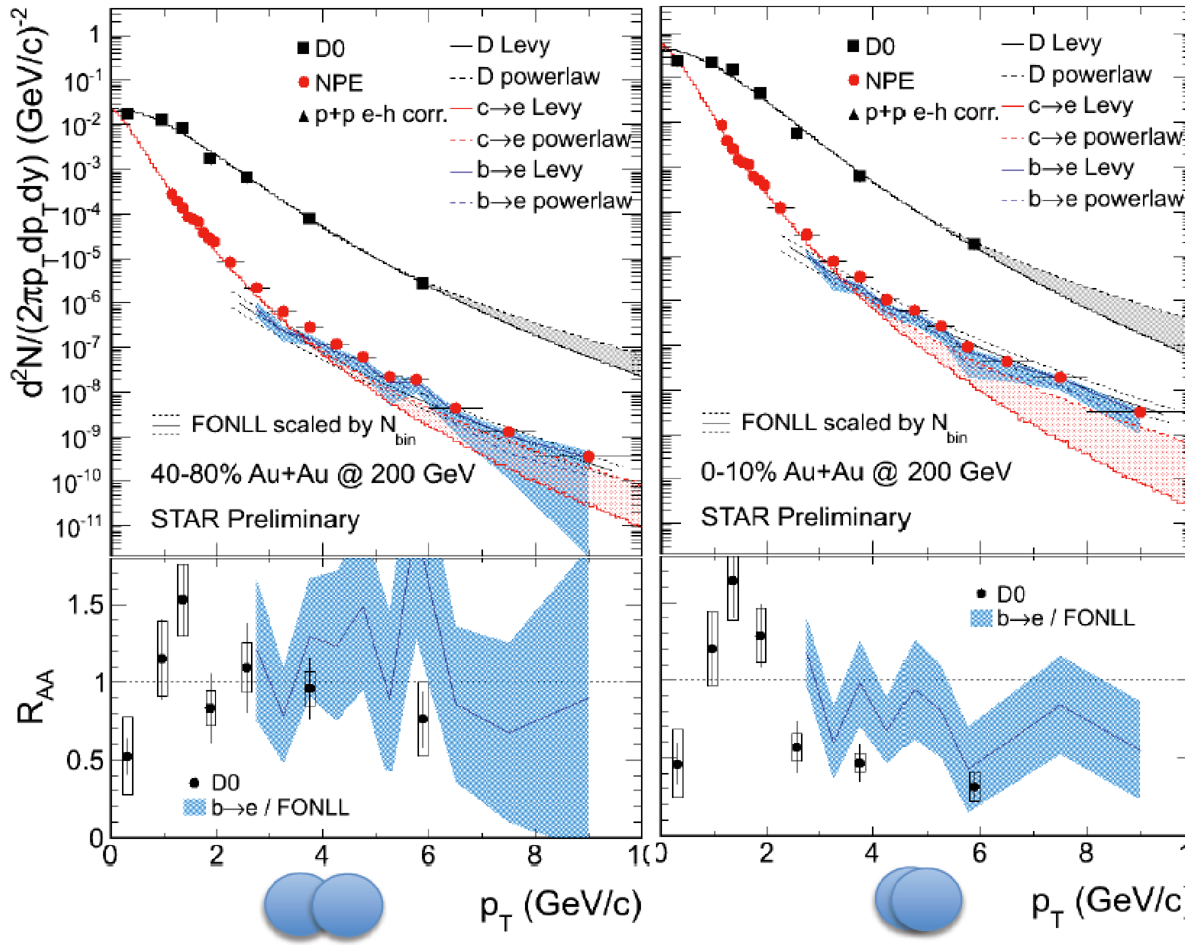


- ❑ Similar level of suppression as RHIC for 2 < pT <6 GeV/c
- ❑ Within errors, follow light hadron suppression pattern
  - as indicated at RHIC.
- ❑ need more precision.

B suppression in Au+Au 200 GeV

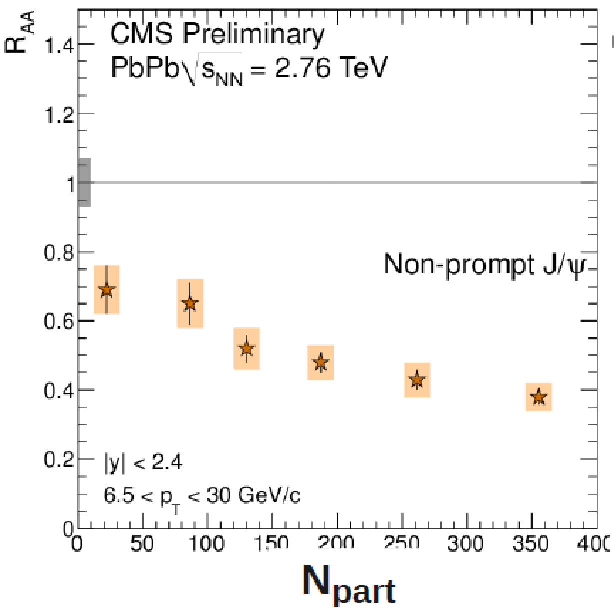


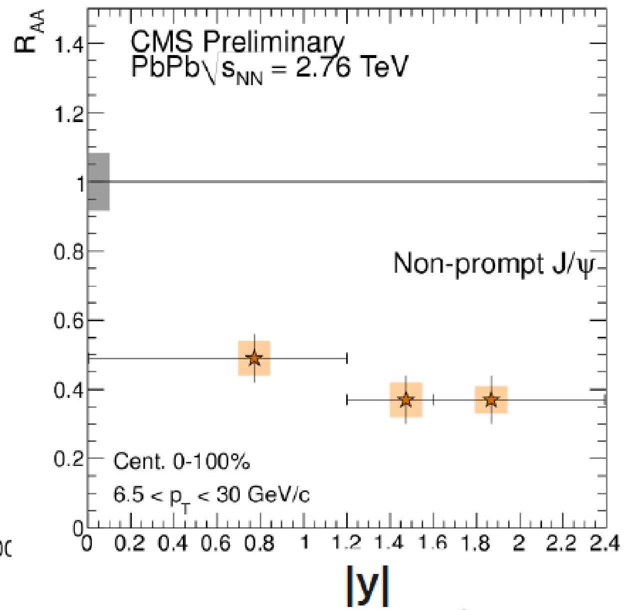
- Based on NPE R_{AA} at pT > 5 GeV/c and B fraction measurement.
- B significantly suppressed

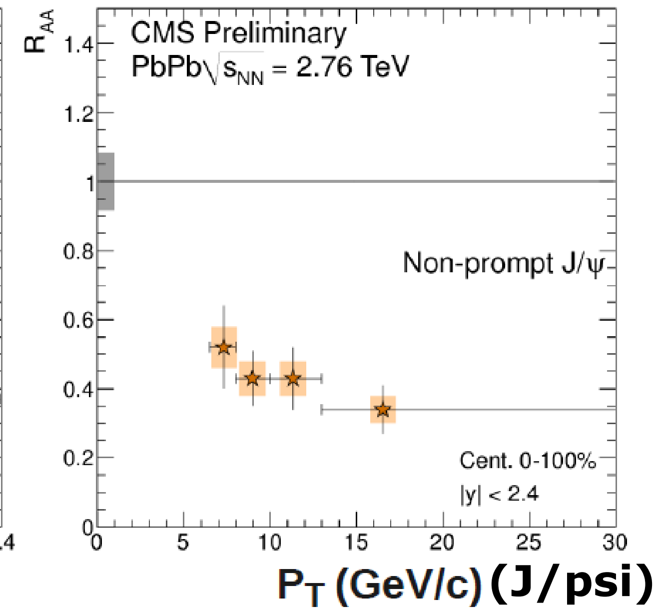


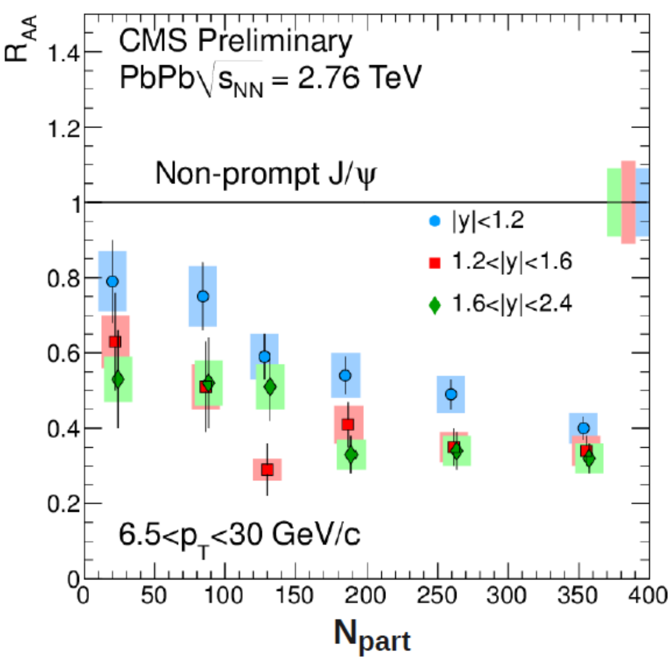
- Based on NPE and D0 measurements
- Indicate suppression of B
  - Large uncertainty.

B suppression in Pb+Pb 2.76 TeV



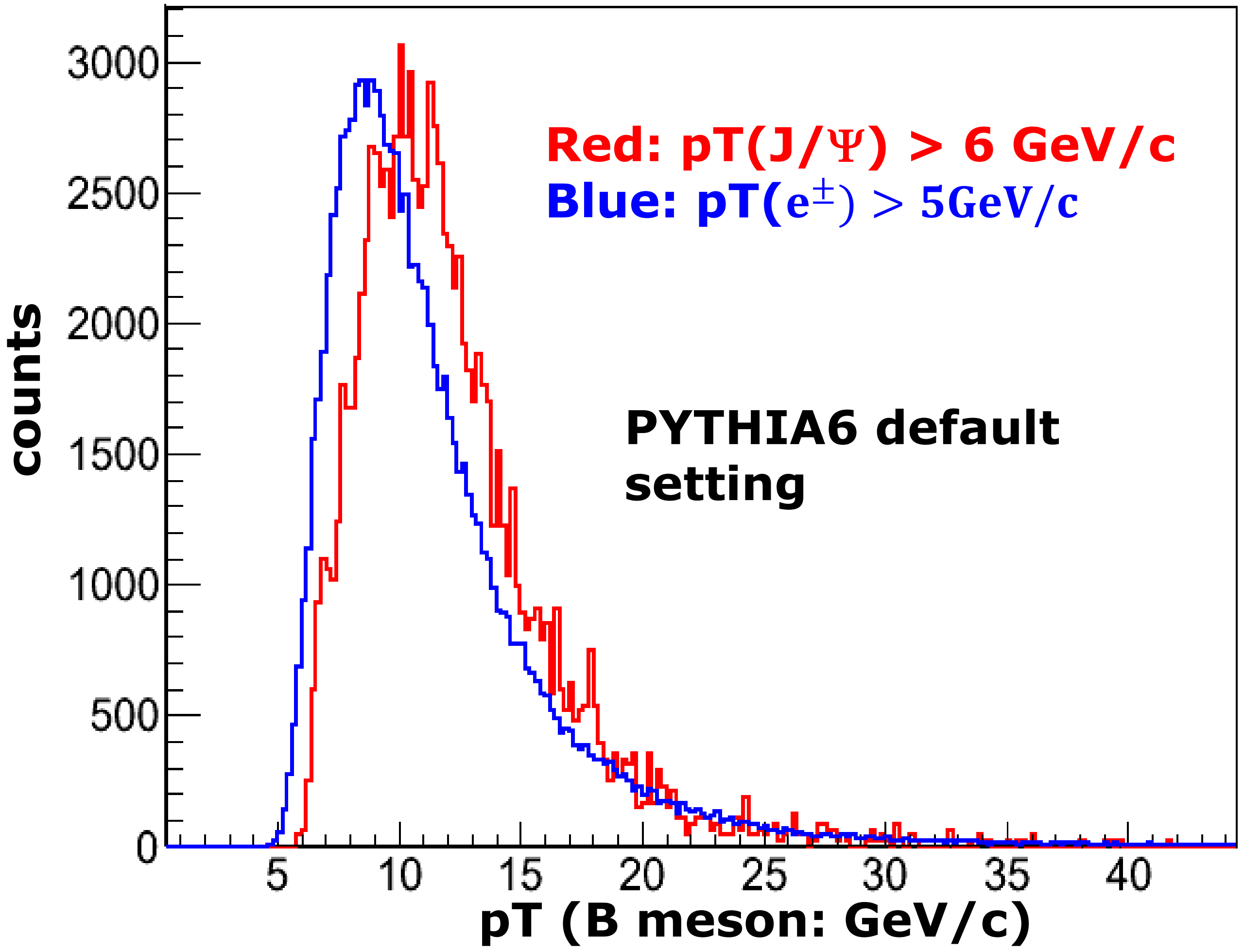






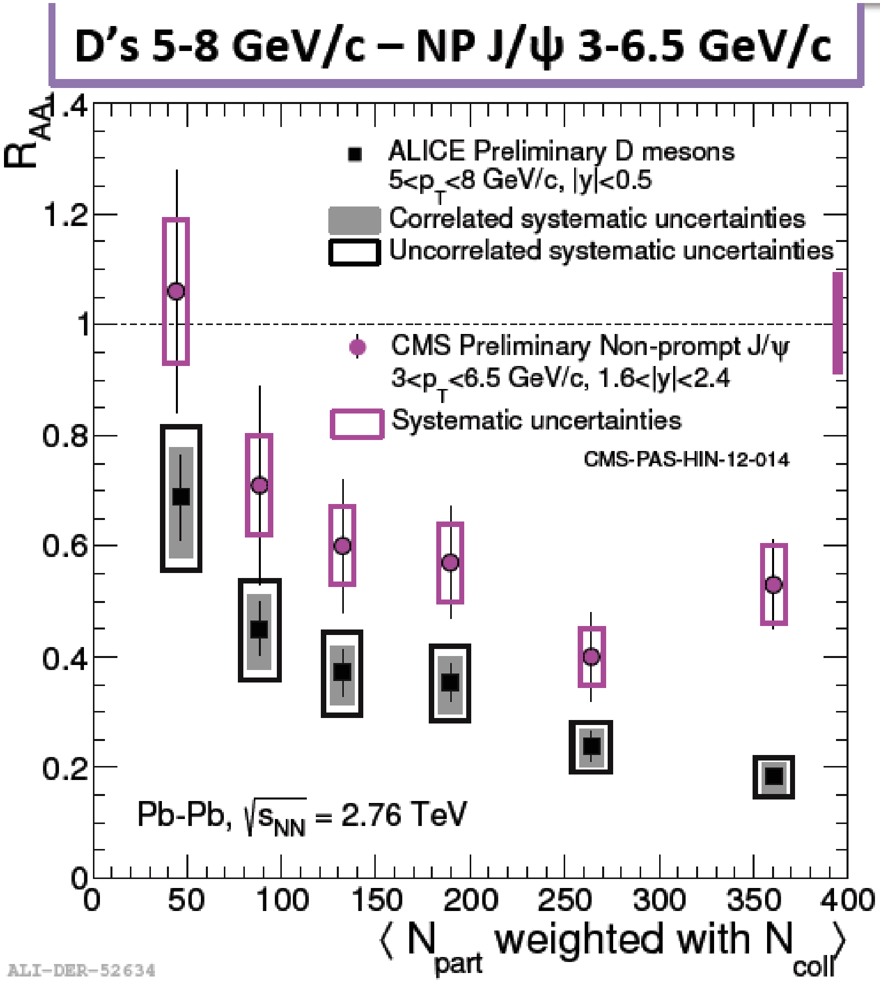
- From non-prompt J/psi measurements.
- Significant B suppression observed.
- Even at most peripheral bin
  - shadowing?
- Suppression seems larger at forward rapidity region.

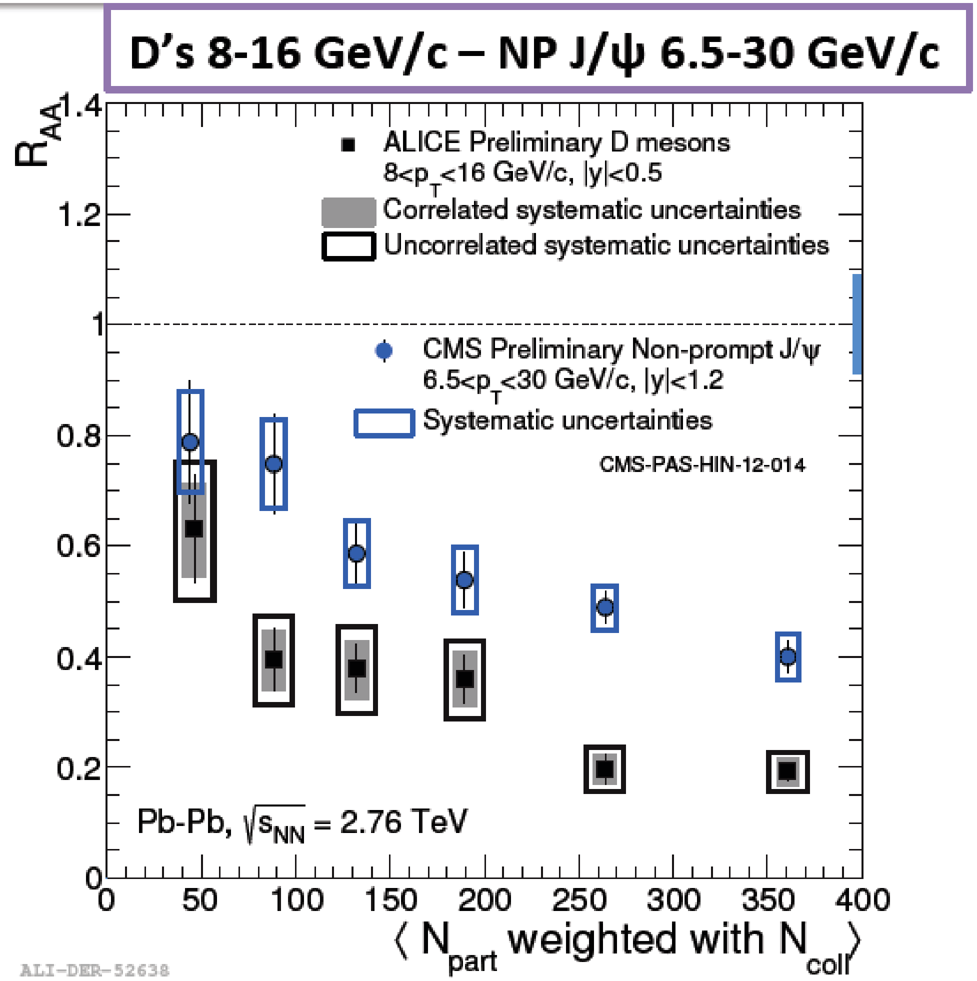
What are the corresponding pT (B meson)



❑ B meson significantly suppressed at 5-20 GeV/c at RHIC and LHC.

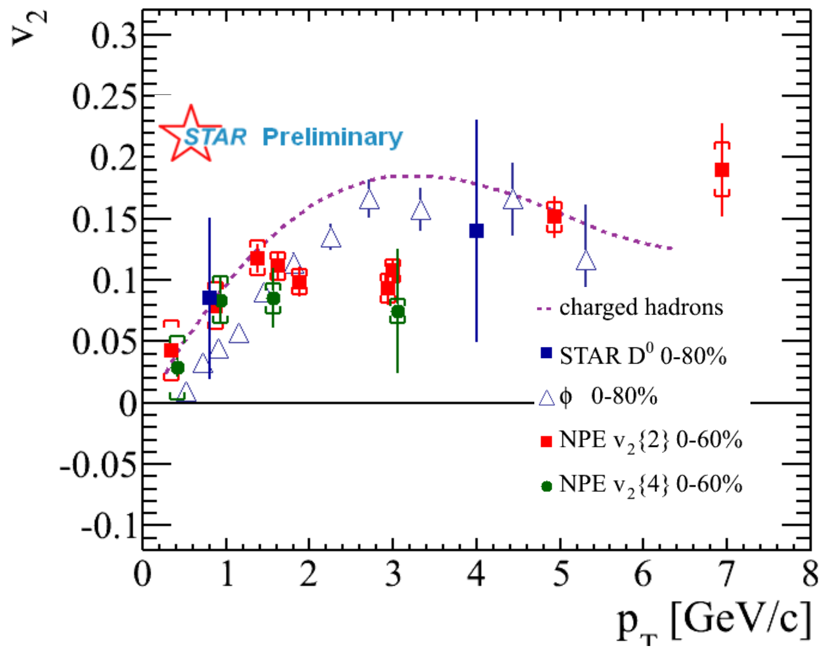
Charm Suppressed More than Bottom

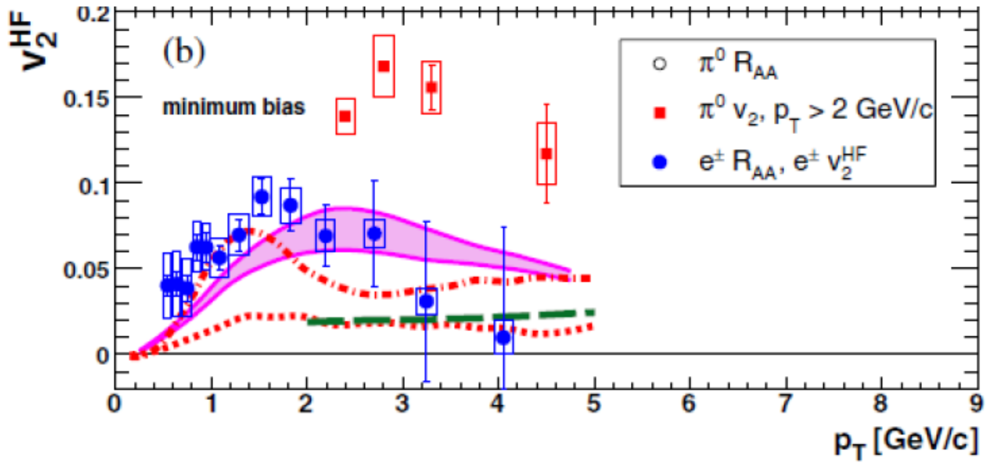


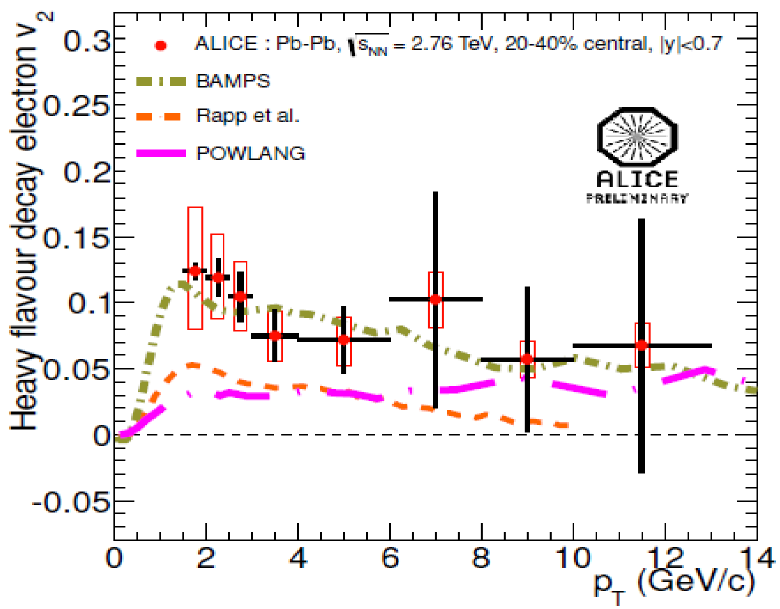


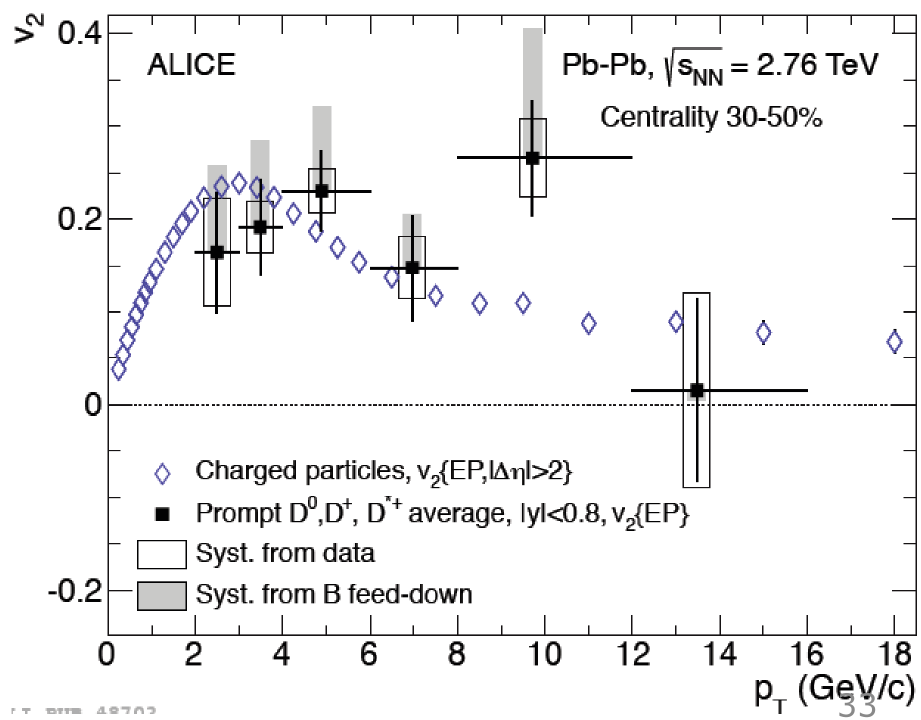
- Comparison in similar pT region of B and D mesons.

Large Heavy Flavor Elliptic Flow Observed

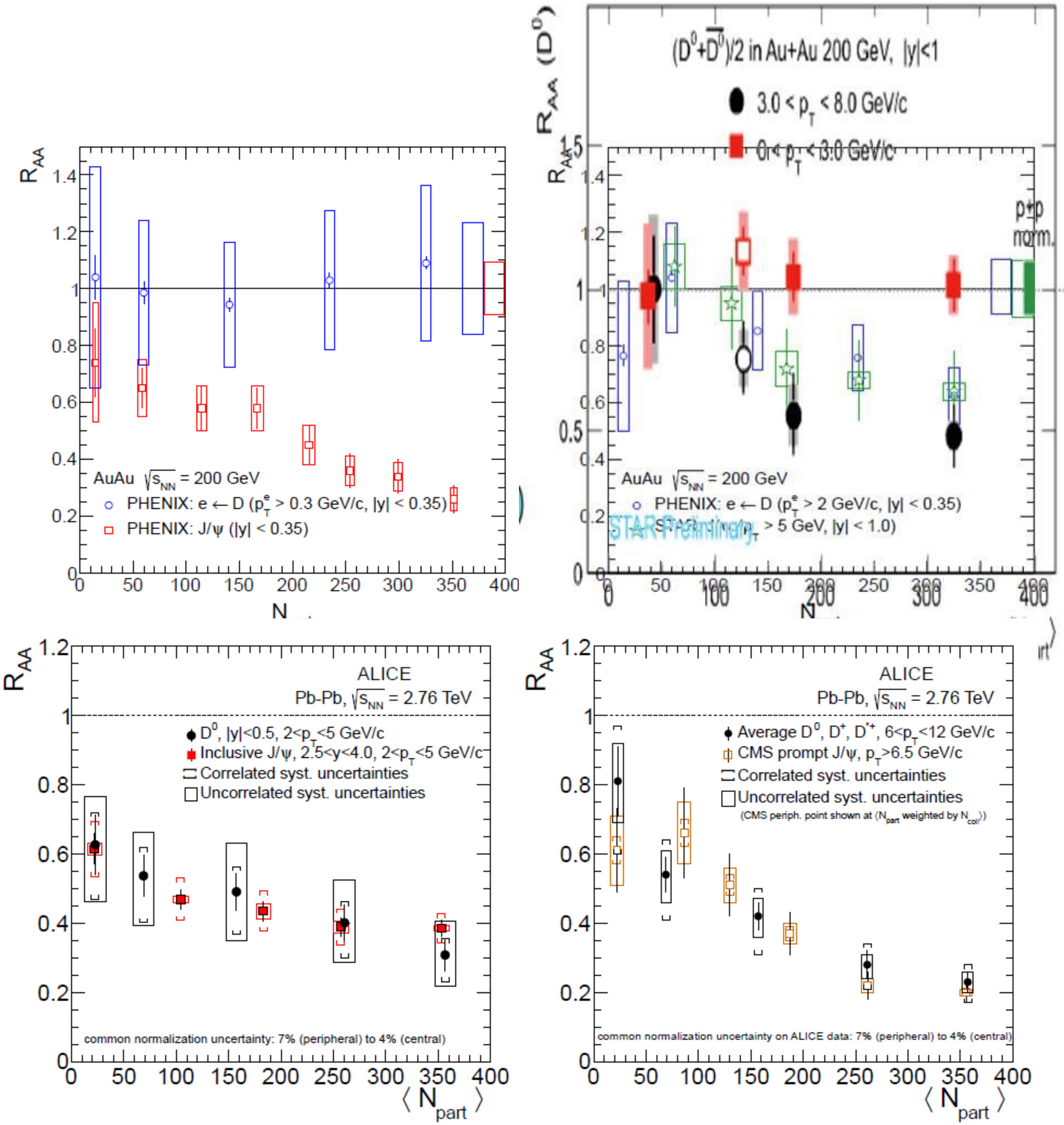








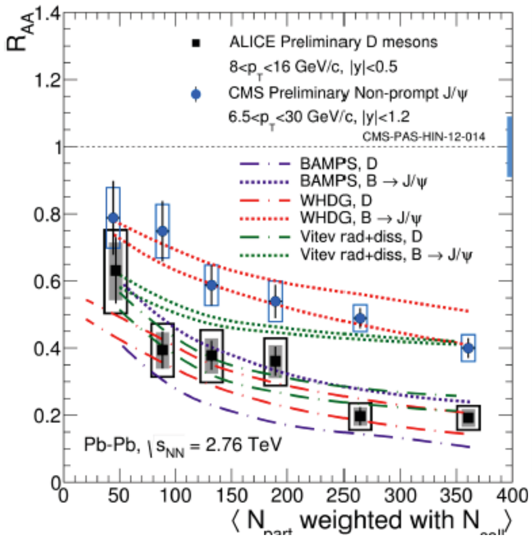
Look at Open and Hidden Charm Together

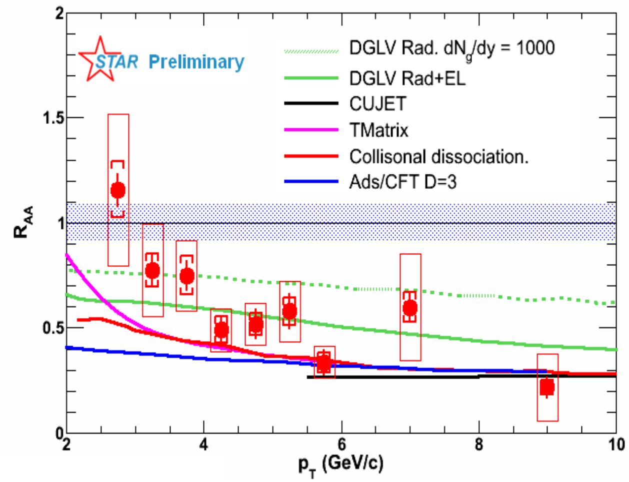


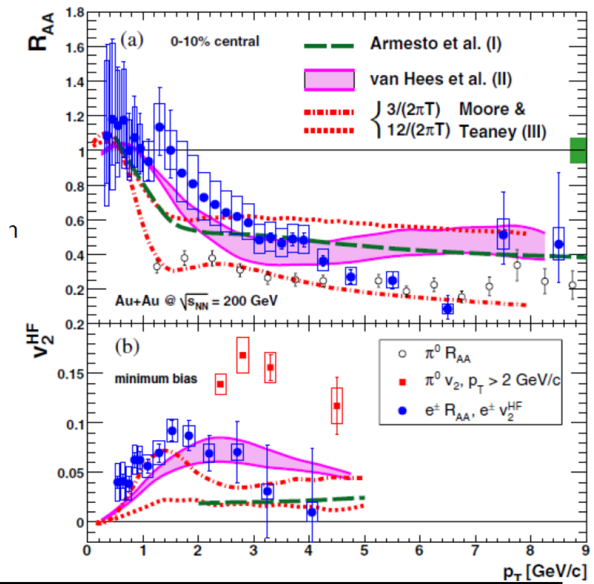
- At RHIC, low pT J/psi is suppressed rel. to open charm
- High pT J/psi seems to follow the same suppression pattern as open charm
- High pT J/psi NOT suppressed relative to open charm ?

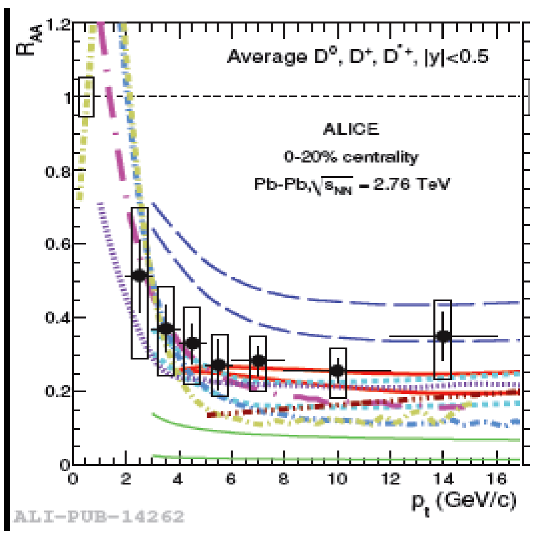
  H. Satz, arXic:1303.3493v2
- Is it a fair to compare the two in same pT region?

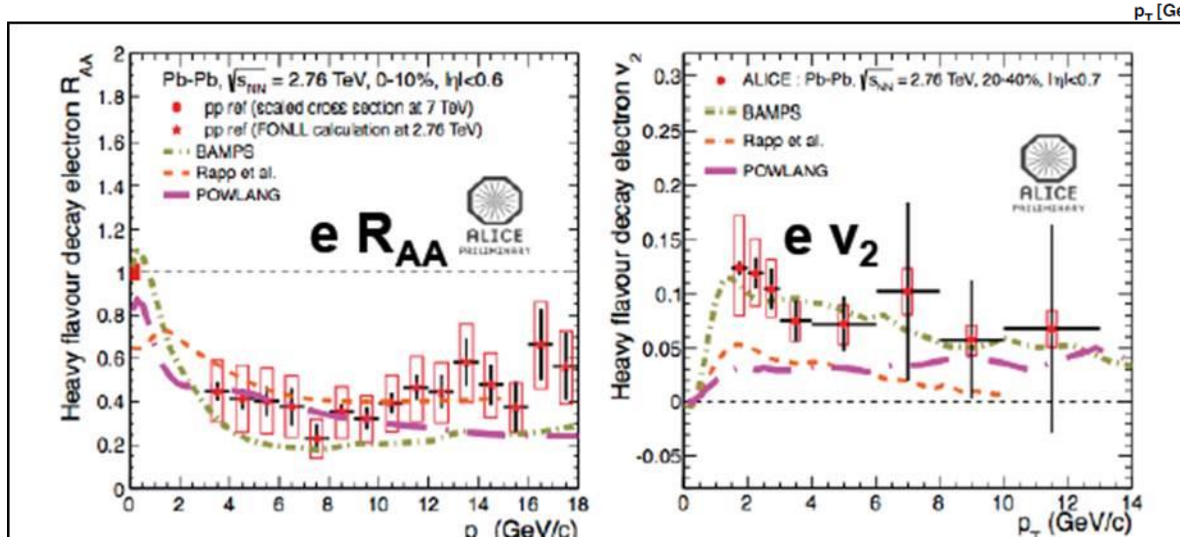
Comparison with Models





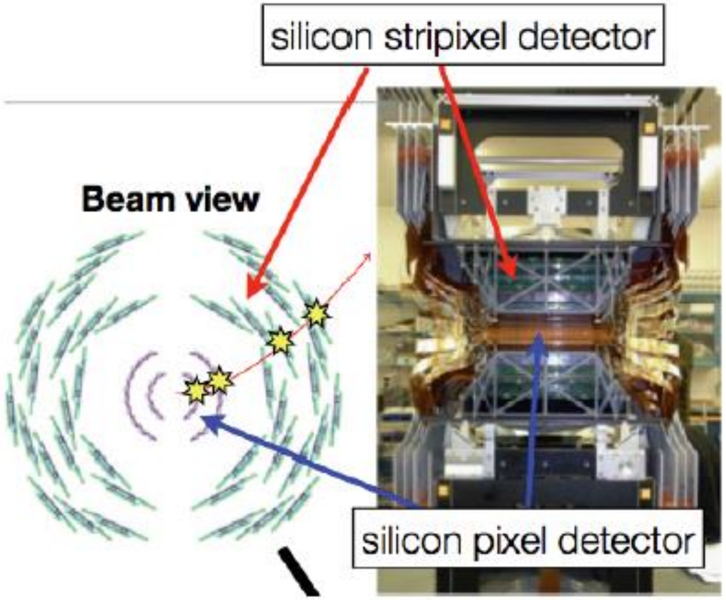


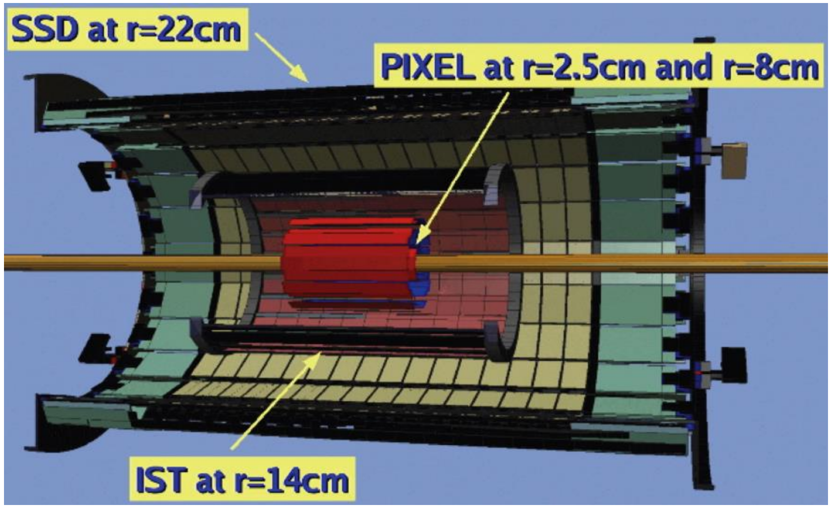


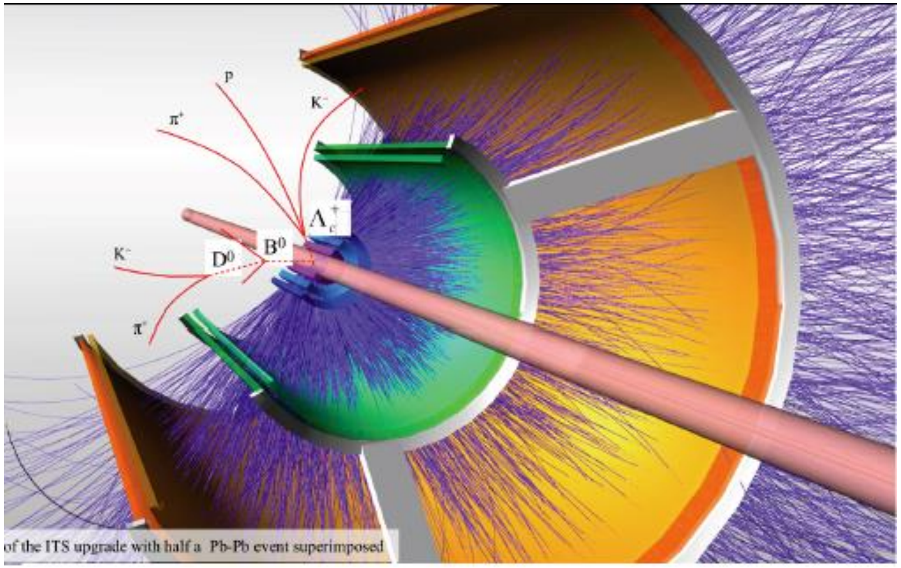


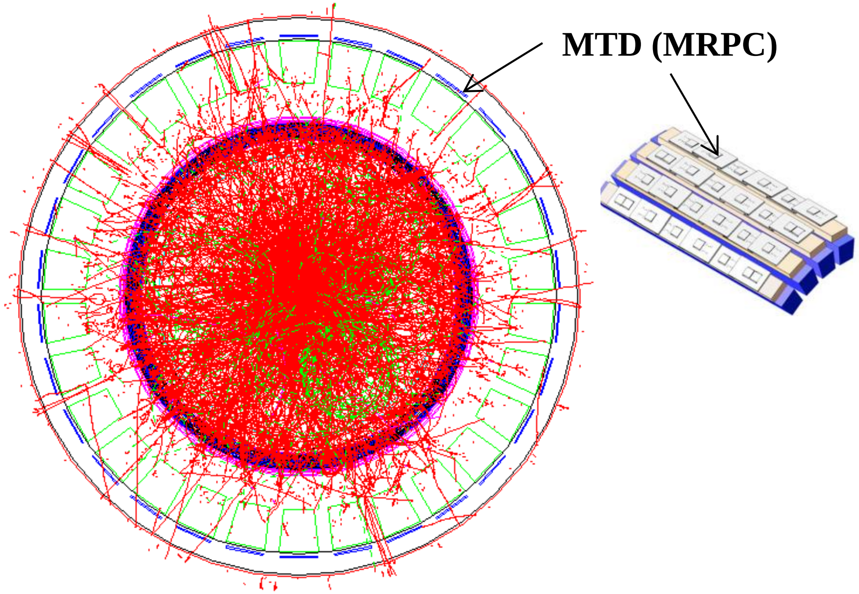
- ❑ Current data placed some constraints on models
- ❑ Need **PRECISION**

The Next Step: PRECISION









backup

Heavy ion program timeline

2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025

LS1 — ~0.3-1.5 nb^{-1} PbPb — LS2 — ~2-4 nb^{-1} PbPb — LS3 — ~10 nb^{-1} PbPb

CMS request

Also corresponding pp reference

PbPb 5.1TeV | PbPb 5.1TeV | pPb? 8.2TeV

Also corresponding pp reference

ArAr pPb PbPb 5-8 TeV

PbPb pp (?) 5.5 TeV

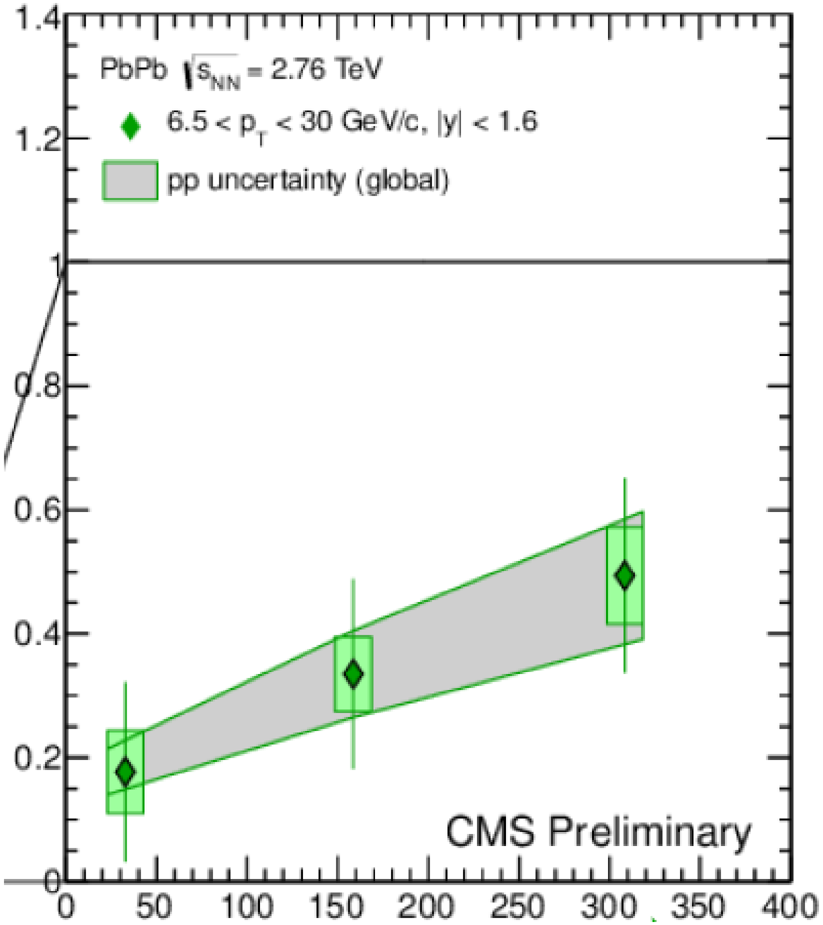
L1 trigger upgrade

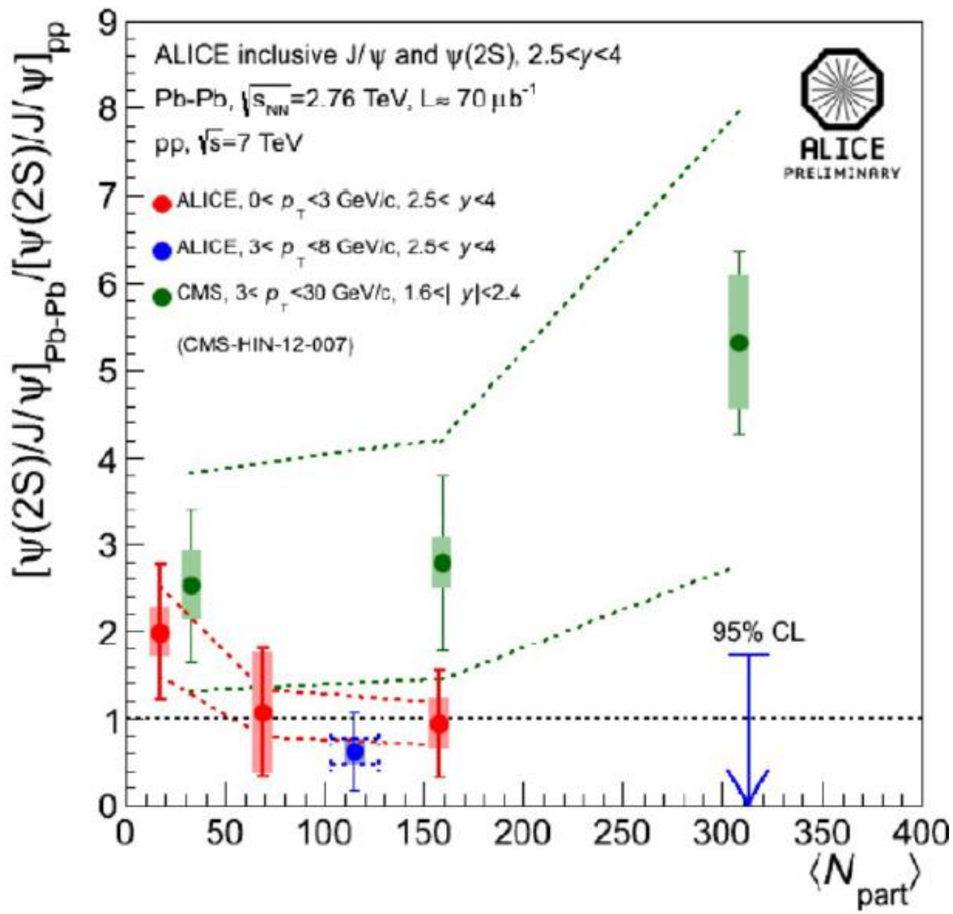
Pixel detector upgrade

3 layers → 4 layers

Extended tracker coverage $|\eta|<4$ (?)

- PbPb statistics: 1.5nb^{-1} and 10nb^{-1} PbPb
- What is the expected pp statistics we should use?





Psi(2s) more suppressed at pT>6.5 GeV/c in |y|<1.6

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

Eur. Phys. J. C (2010) 68: 345–354

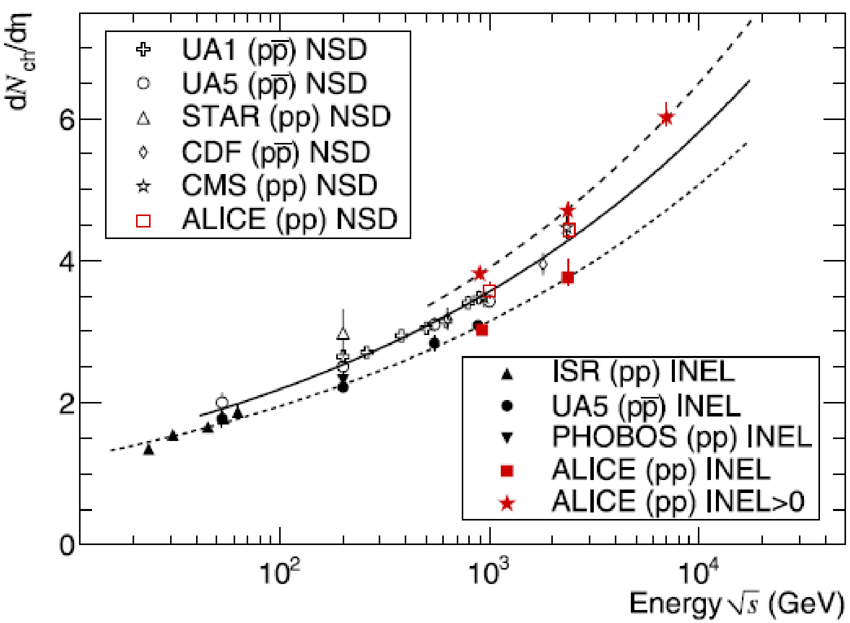


Fig. 2 Charged-particle pseudorapidity density in the central pseudorapidity region $|\eta| < 0.5$ for inelastic and non-single-diffractive collisions [4, 16–25], and in $|\eta| < 1$ for inelastic collisions with at least one charged particle in that region ($\mathrm{INEL} > 0_{|\eta|<1}$), as a function of the centre-of-mass energy. The *lines* indicate the fit using a power-law dependence on energy. Note that data points at the same energy have been slightly shifted horizontally for visibility

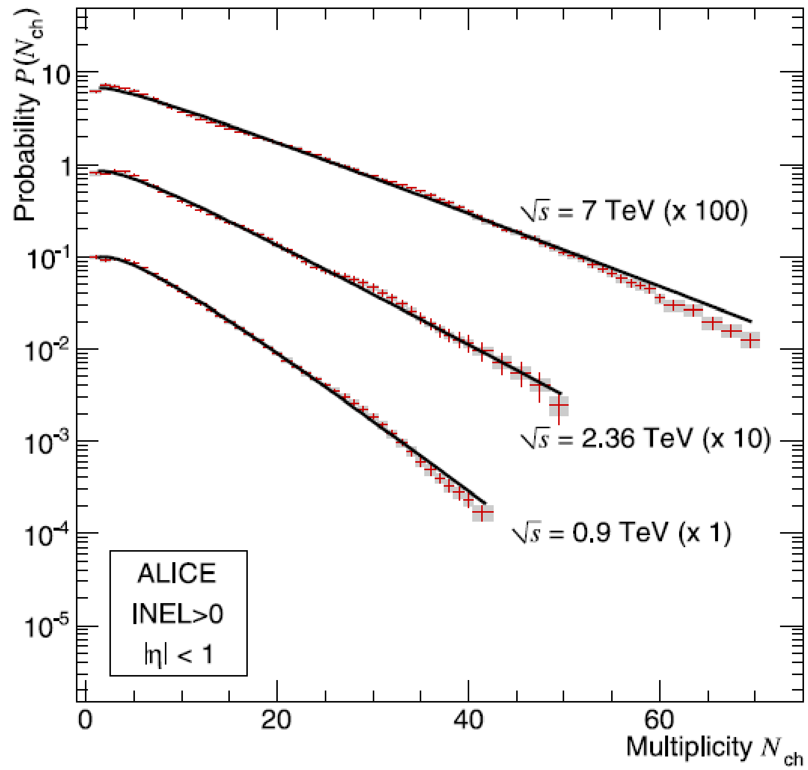
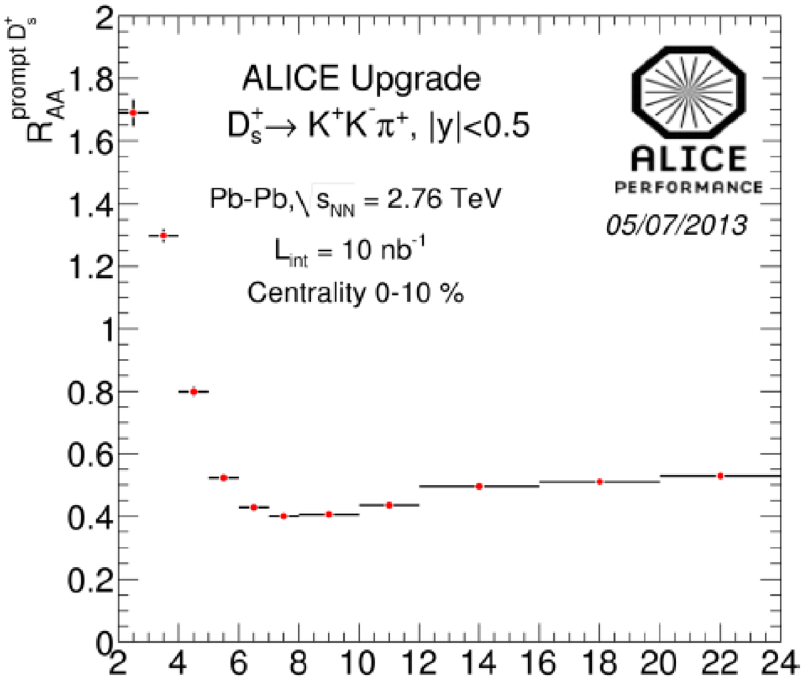
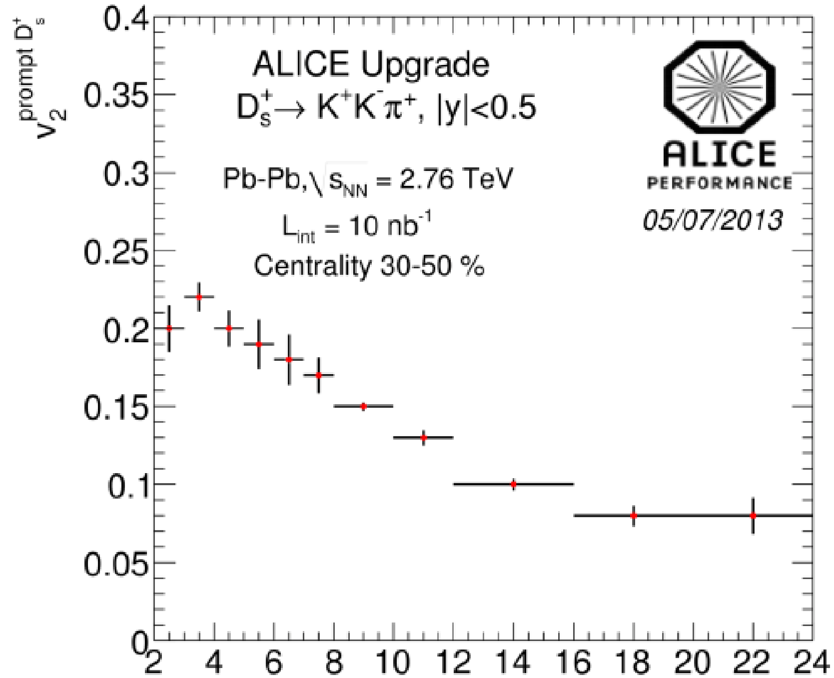
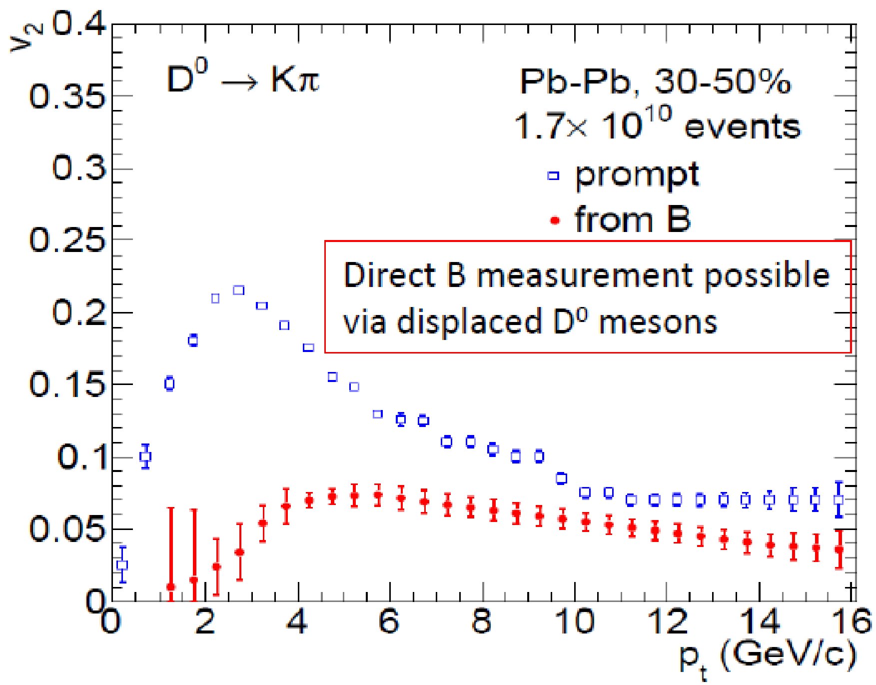
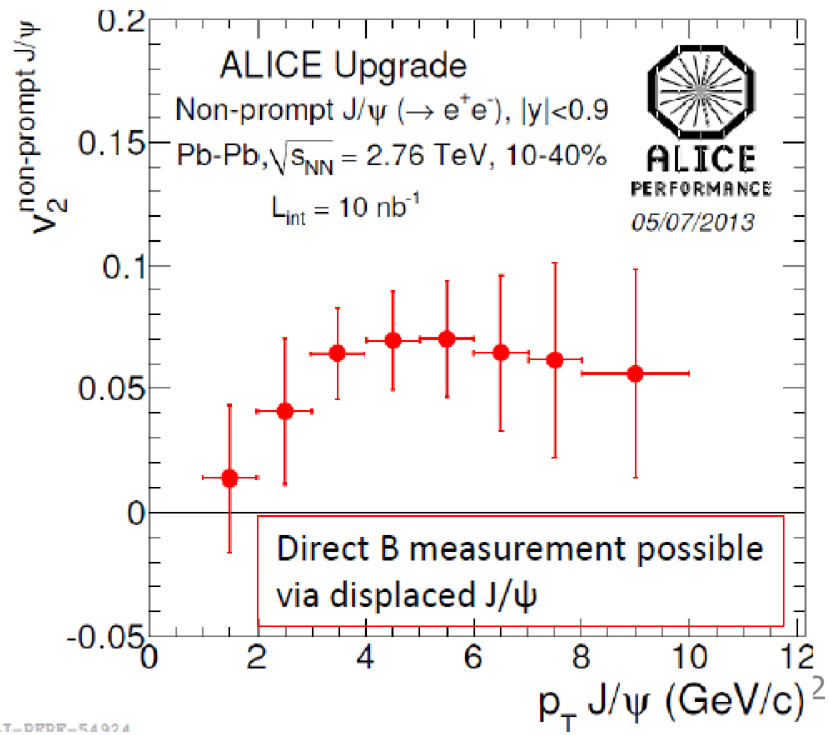


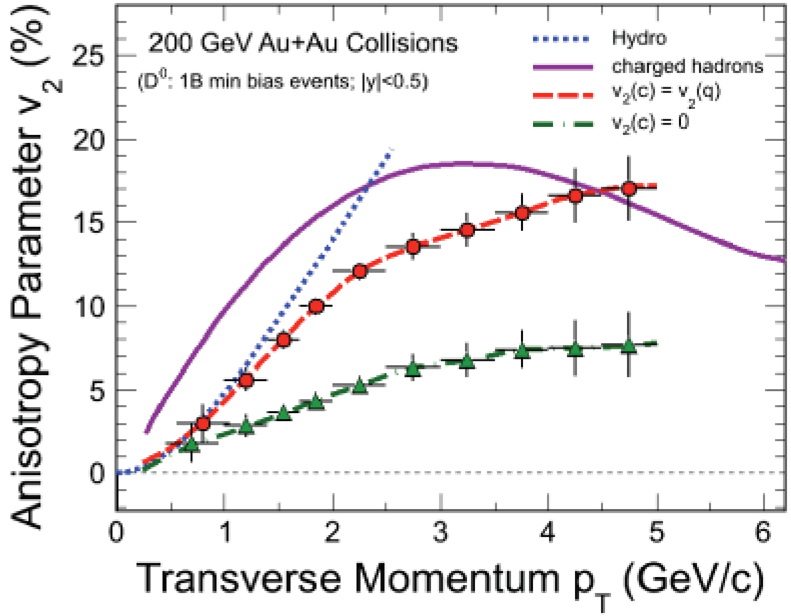
Fig. 3 Measured multiplicity distributions in $|\eta| < 1$ for the $\mathrm{INEL} > 0_{|\eta|<1}$ event class. The error bars for data points represent statistical uncertainties, the shaded areas represent systematic uncertainties. *Left*: The data at the three energies are shown with the NBD fits (*lines*). Note that for the 2.36 and 7 TeV data the distributions have been scaled for clarity by the factors indicated. *Right*: The data at 7 TeV

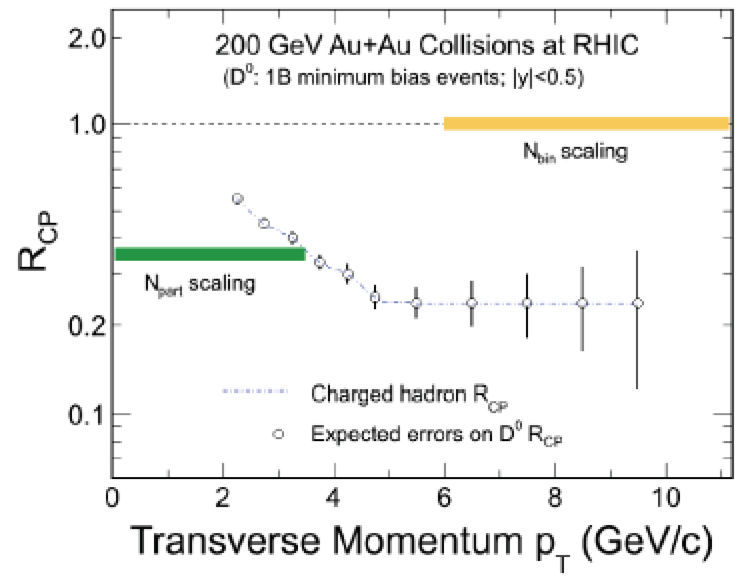

ALICE Upgrade
$D_s^+ \to K^+K^-\pi^+$, |y|<0.5
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} = 10 nb^{-1}
Centrality 0-10 %
ALICE PERFORMANCE
05/07/2013
$R_{AA}^{prompt\ D_s^+}$


ALICE Upgrade
$D_s^+ \to K^+K^-\pi^+$, |y|<0.5
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int} = 10 nb^{-1}
Centrality 30-50 %
ALICE PERFORMANCE
05/07/2013
$v_2^{prompt\ D_s^+}$


$D^0 \to K\pi$
Pb-Pb, 30-50%
1.7×10^{10} events
prompt
from B
Direct B measurement possible via displaced D^0 mesons
v_2
p_t (GeV/c)

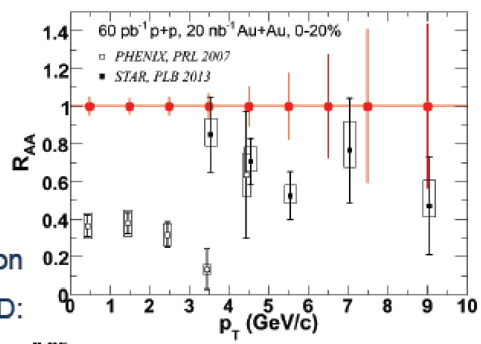

ALICE Upgrade
Non-prompt J/ψ (→ e^+e^-), |y|<0.9
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV, 10-40%
L_{int} = 10 nb^{-1}
ALICE PERFORMANCE
05/07/2013
Direct B measurement possible via displaced J/ψ
$v_2^{non-prompt\ J/\psi}$
p_T J/ψ $(GeV/c)^2$

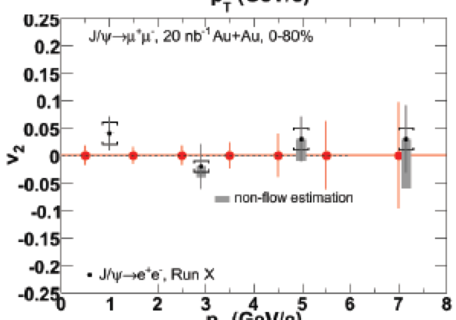




STAR projection with HFT

simulation with MTD:





4

m & charm flow