

LHCP 2013

(successor to "Hadron Collider Physics" & "Physics at LHC" conferences)

BARCELONA, May 13th - 18th, 2013

Heavy-flavour and quarkonia in Heavy Ion collisions

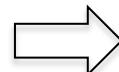
A. Rossi, CERN



Why Heavy Quarks in Heavy Ion?

Early production

- in hard-scattering processes with high Q^2 (large masses)
 - production cross-sections **calculable with pQCD**
 - **prior to Quark Gluon Plasma (QGP) formation**



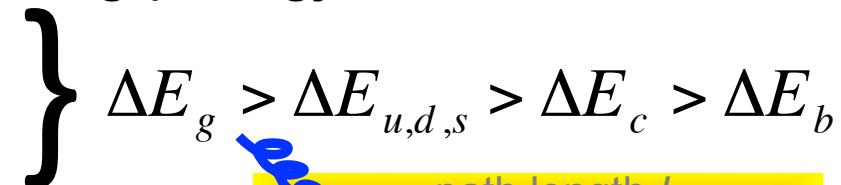
“Calibrated probes” of the medium

Strongly interacting with the medium they **preserve their identity**

→ **sensitivity to medium temperature and density** via

- collisional and radiative (“gluonsstrahlung”) energy loss
 - color charge (Casimir factor)
 - quark mass (← dead cone effect)
 - path length and medium density

Yu. Dokshitzer and D.E. Kharzeev, PLB 519 199–206 (2001).

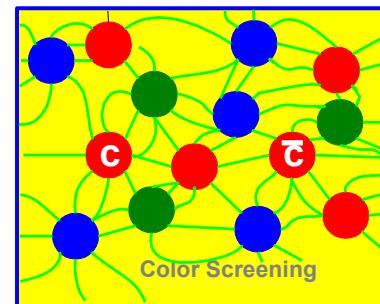


- medium **modification to HF hadron formation**
 - in-medium dissociation [Sharma et al., PRC80 \(2009\) 054902](#)
 - hadronization via quark coalescence

Quarkonia suppression & regeneration

Hot QGP → quarkonia suppression due to Debye-like screening of QCD $Q\bar{Q}$ potential (“melting” of bound $Q\bar{Q}$ states)
→ “historical” signature of deconfinement

(T. Matsui and H. Satz, PLB 178 (1986) 416)



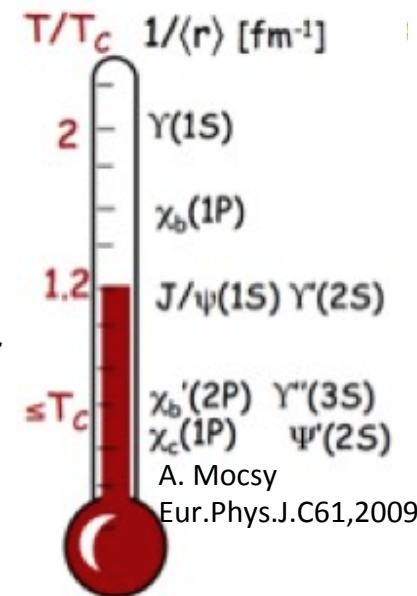
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→ **Sequential suppression of quarkonium states**, stronger for less bounded states (S. Digal, P. Petreczky, H. Satz, PRD 64 (2001) 0940150)



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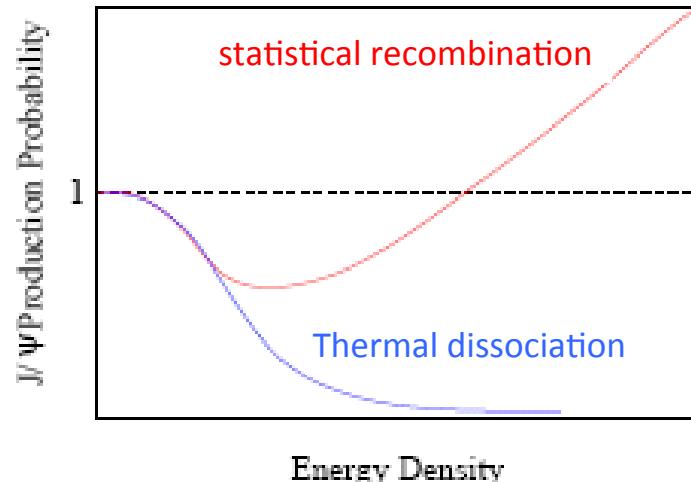
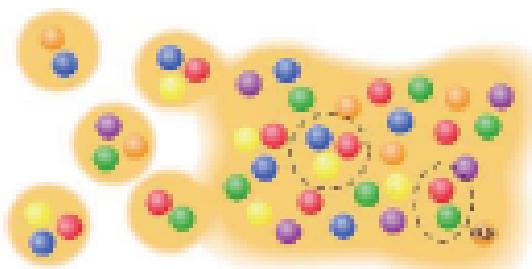
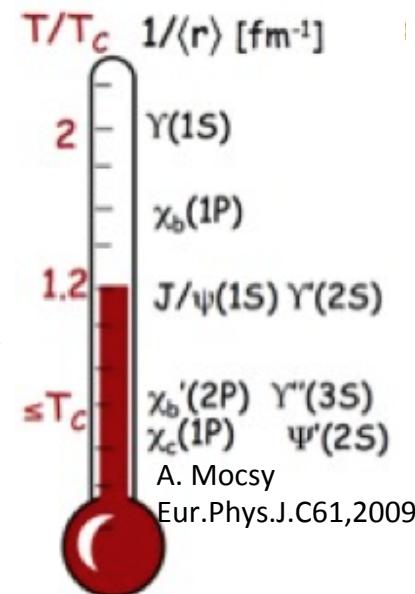
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Surprisingly similar J/ψ suppression at RHIC and SPS energies

→ Could quarkonia states be (re)generated via recombination (coalescence) of deconfined quarks? (P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196)



LHC vs. RHIC

Larger energy density
→ stronger suppression
Higher $c\bar{c}$ multiplicity
→ larger recombination

Heavy Flavour measurements

Quarkonia

Reconstruction of charmonia and bottomonia decays in di-leptonic channels

$J/\psi, \psi(2s), \Upsilon(ns) \rightarrow \mu^+ \mu^-$

$J/\psi \rightarrow e^+ e^-$

**With complementary rapidity
and p_T coverage among ALICE,
ATLAS and CMS**

Open Heavy Flavour

Charm

Full reconstruction of D meson decays in hadronic channels:

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

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

$D^{*+} \rightarrow D^0 \pi^+$

$D_s^+ \rightarrow K^- K^+ \pi^+$

Beauty

Displaced J/ψ from b-hadron decay

b-jets

Charm + beauty

Electrons, muons from semi-leptonic decays of charm and beauty hadrons

How can we measure medium effects?

1) Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a “geometrical” factor (from Glauber model)

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

Nuclear overlap function

PbPb

PP

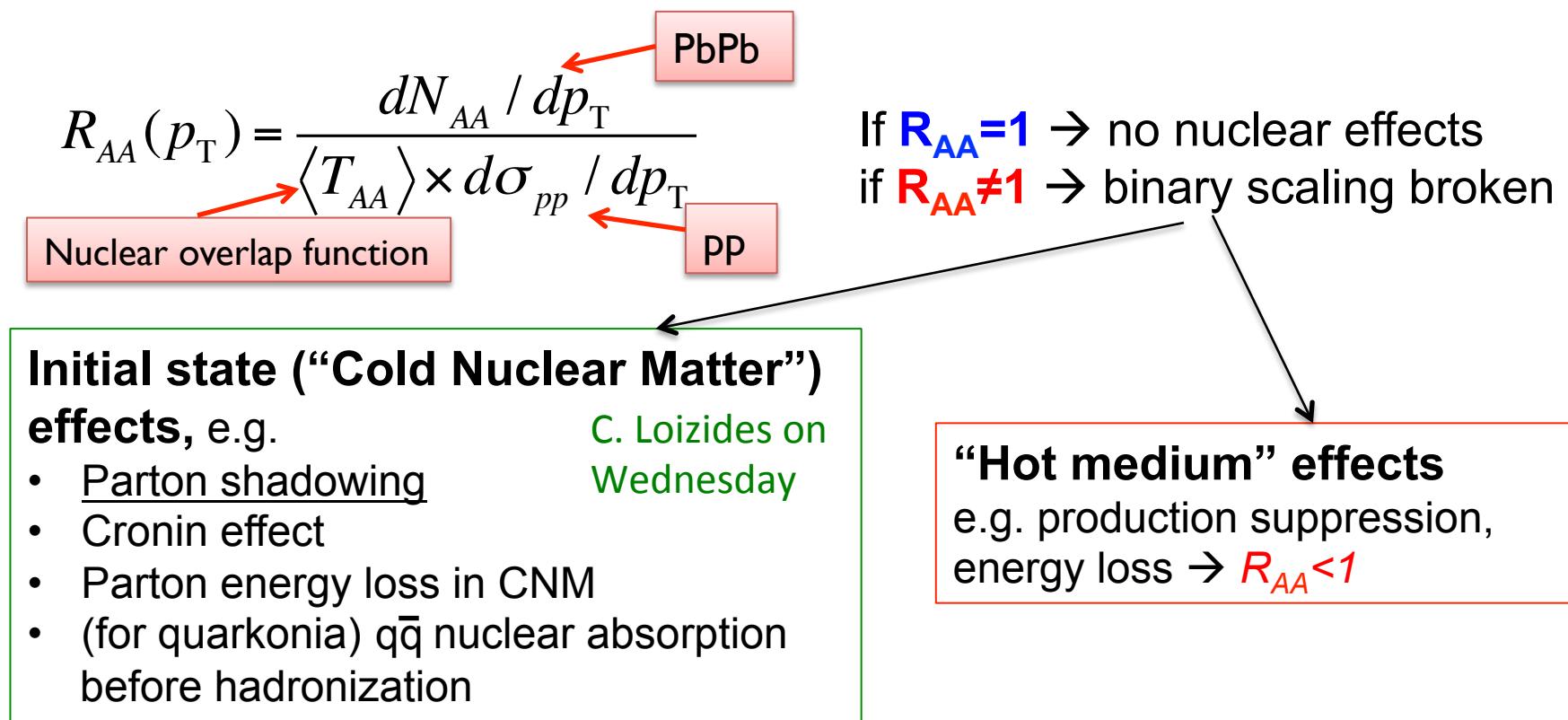
If $R_{AA}=1$ → no nuclear effects
if $R_{AA}\neq 1$ → binary scaling broken

**Understanding of pp reference
fundamental!**

→ HF sessions on Tuesday, Wednesday

How can we measure medium effects?

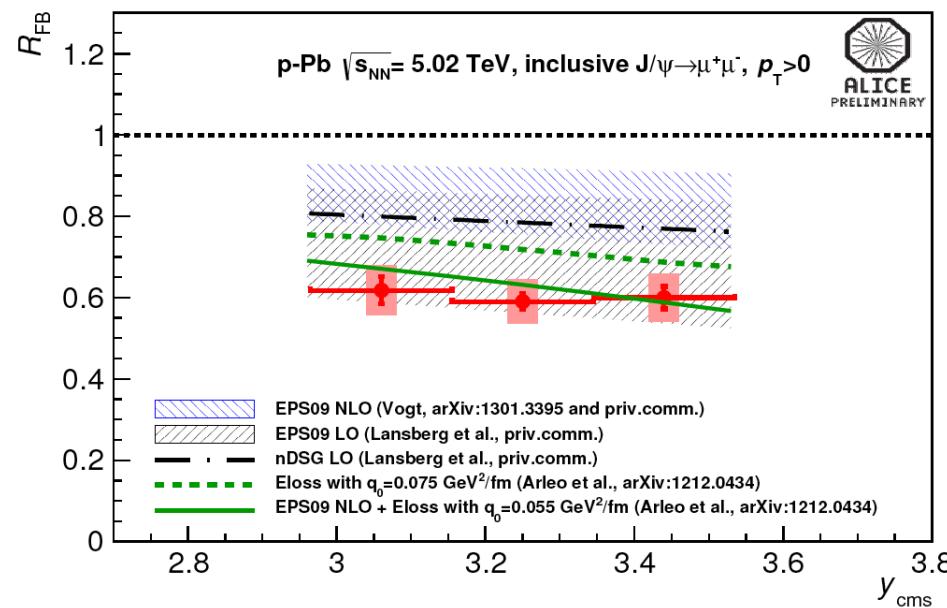
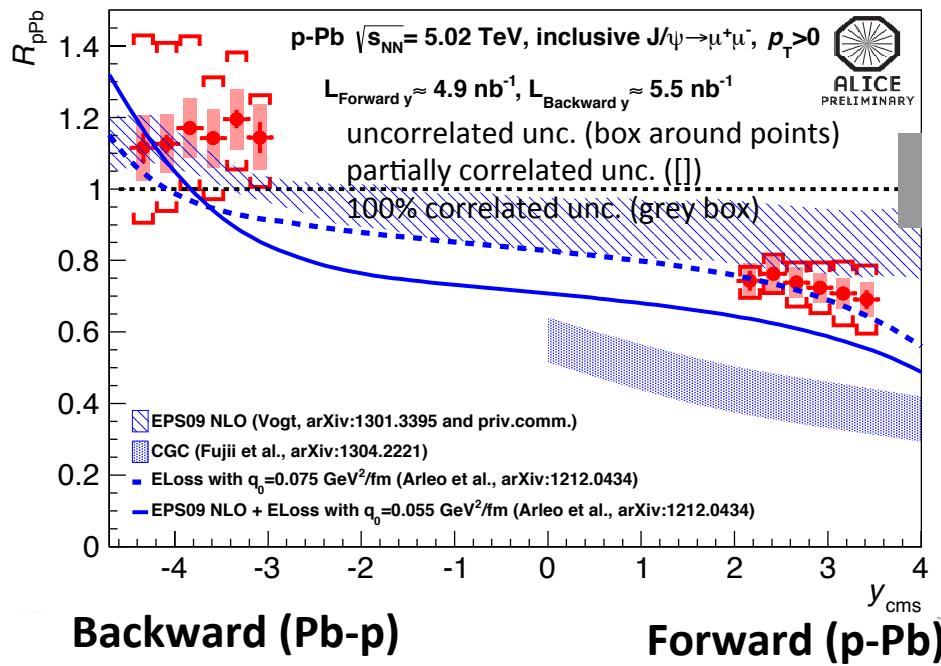
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Ongoing analysis of p-Pb data will be fundamental for interpretation of Pb-Pb results

NEW: J/ ψ in p-Pb

L. Manceau on Monday
C. Loizides on Wednesday



Nuclear modification factor:

- The shadowing EPS09 NLO calculations and models including coherent parton energy loss reproduce the data reasonably (but the latter show a slightly steeper pattern at backward y)
- A Color Glass Condensate (saturation) model seems not to be favoured

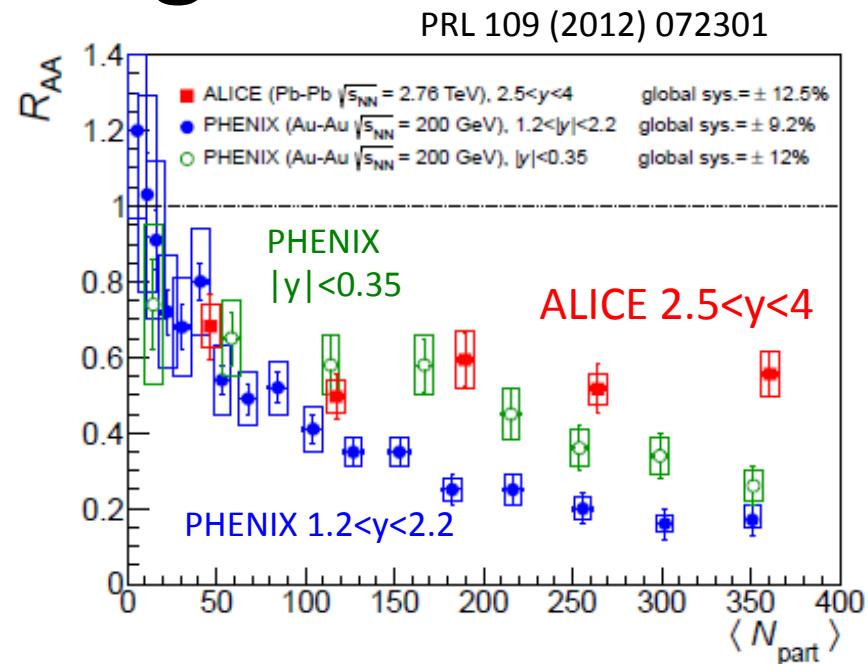
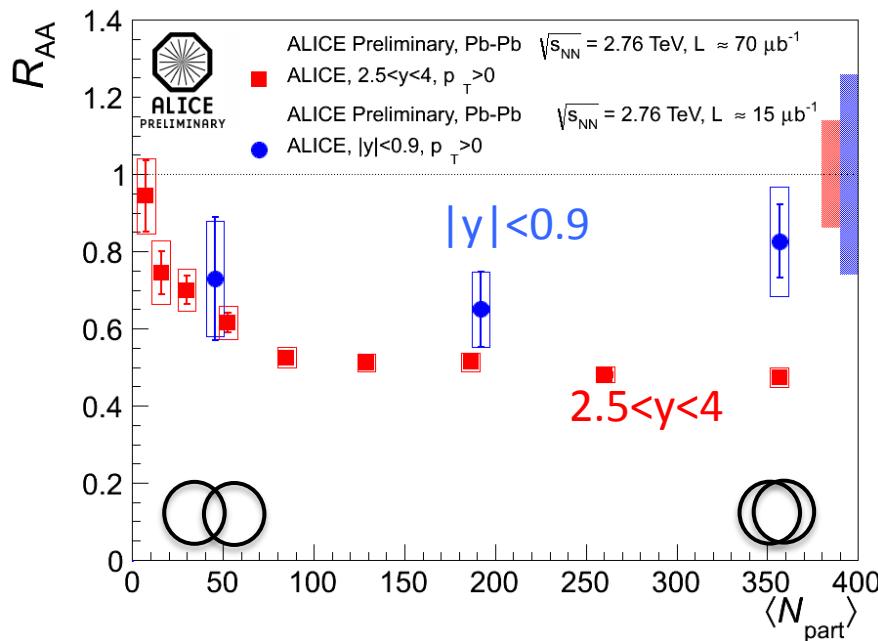
Forward-Backward ratio:

- Shadowing+energy loss model provide a rather good data description
- Shadowing (NLO) or energy loss alone seems to overestimate the R_{FB}

Quarkonia in Pb-Pb

See also
T.T. Fernandez, Tuesday
L. Manceau, Monday

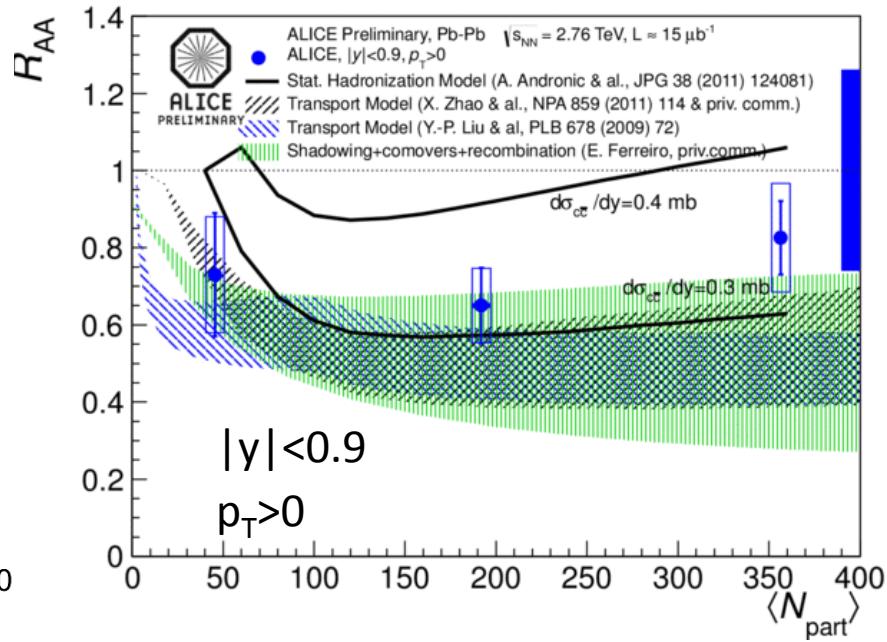
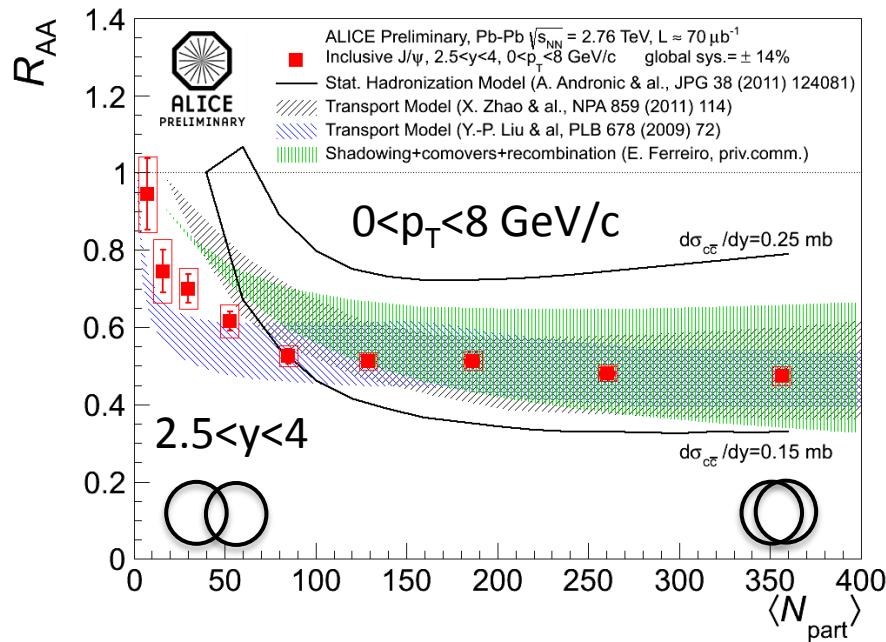
J/ ψ suppression & regeneration?



Inclusive J/ ψ suppression measurements both in central and forward regions for $p_T > 0$:

- from $N_{\text{part}} > 100$ **suppression independent of centrality**
- in central collisions, **less suppression than at RHIC**

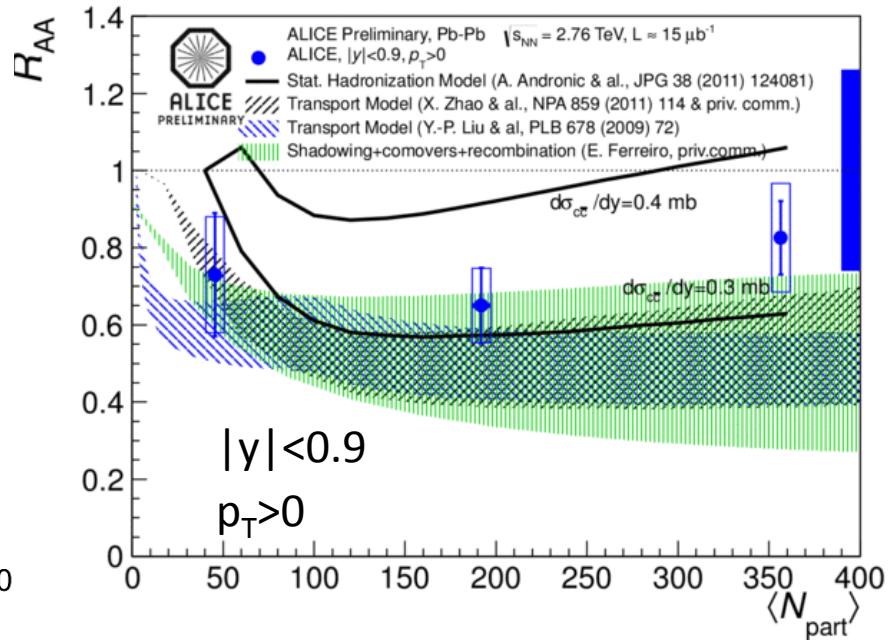
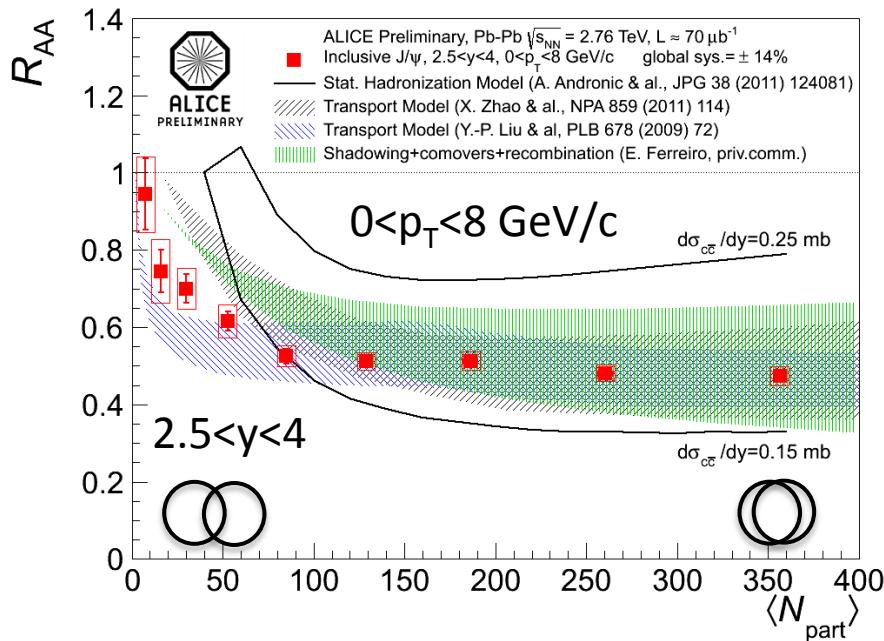
J/ ψ suppression & regeneration?



Models including a **relevant contribution from recombination (>50%)** or models with all J/ ψ produced at hadronization from deconfined quarks can describe data reasonably well

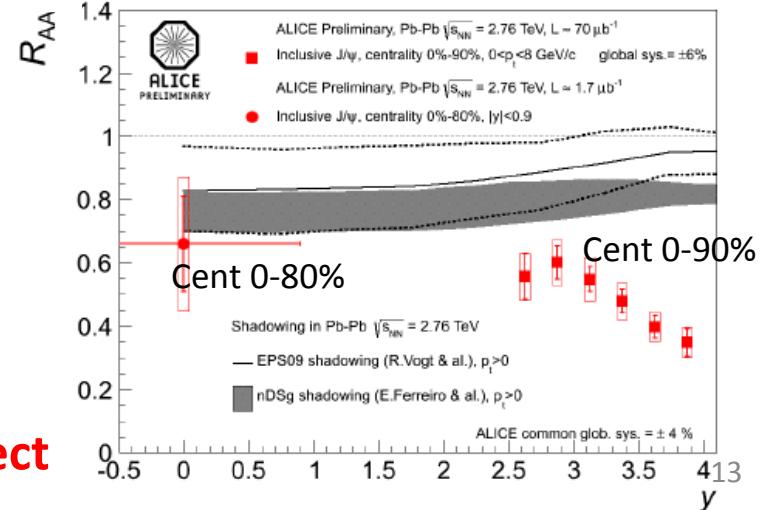
Statistical Hadronization Model [JPG 38 (2011) 124081],
Transport Model I [NPA 859 (2011) 114] and II [PLB 678 (2009) 72] and [Priv. Comm.]

J/ ψ suppression & regeneration?

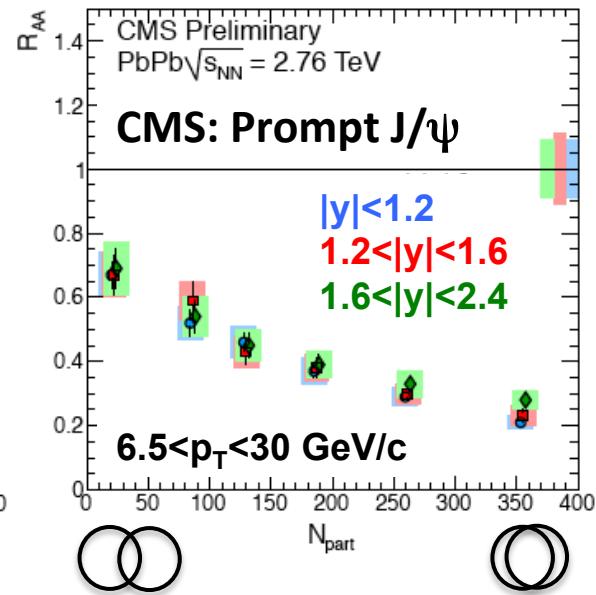
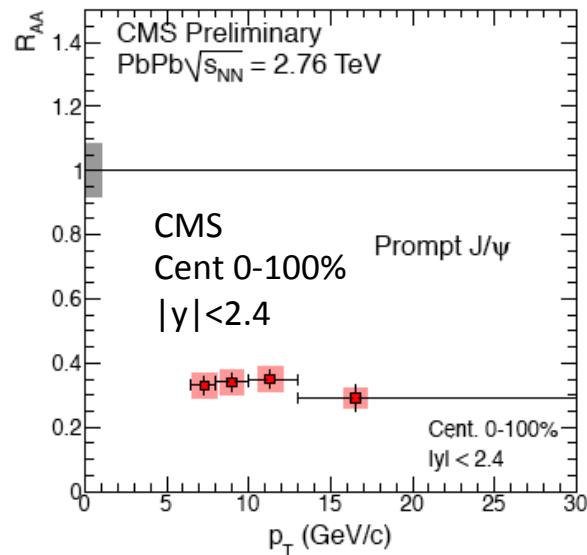
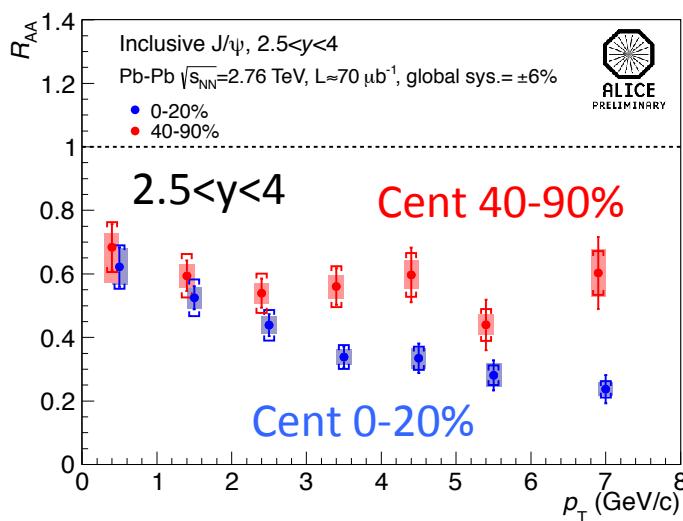


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Shadowing alone cannot explain the observed suppression at forward rapidity \rightarrow **medium effect**



J/ ψ suppression vs. p_T

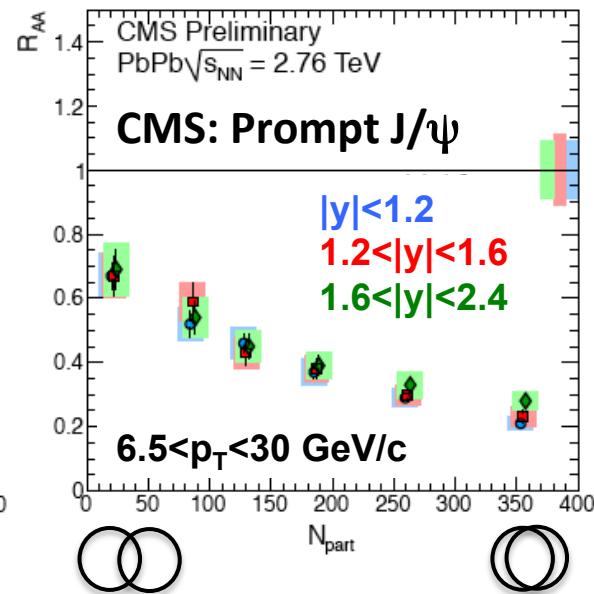
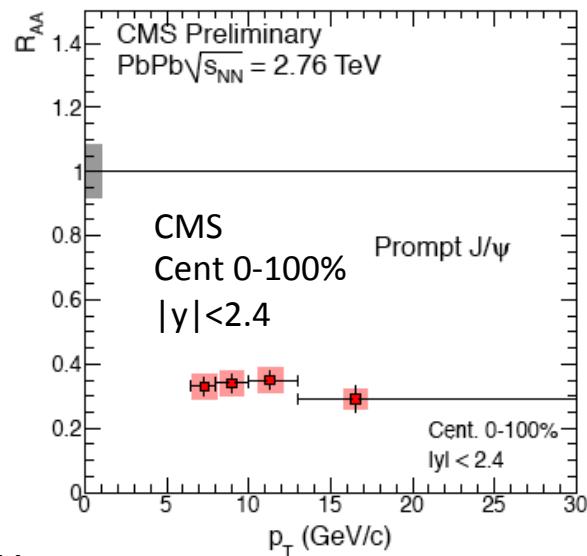
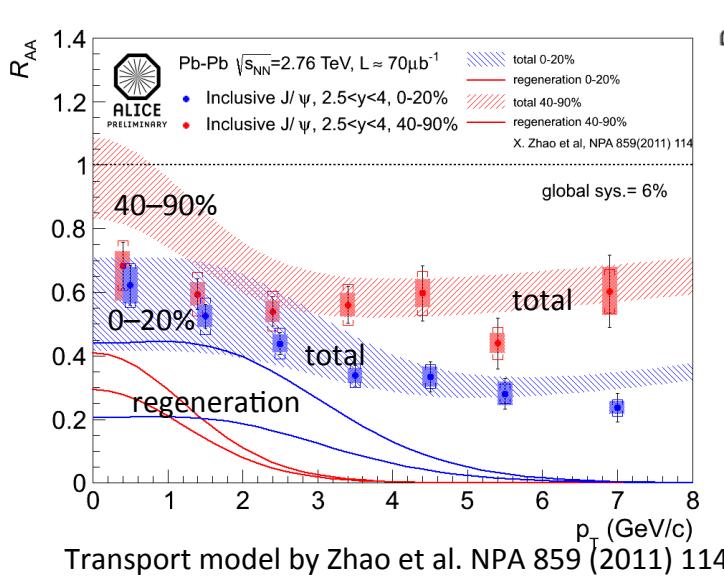


Suppression increasing with p_T

At moderate high p_T : significantly different trends than at low p_T

- Suppression increasing with centrality
- **up to factor 4-5 in central collisions**
- No evidence for dependence on rapidity
- R_{AA} vs. p_T flat for $p_T > 6.5 \text{ GeV}/c$

J/ ψ suppression vs. p_T



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Small/negligible role expected from recombination at high p_T

How can we measure medium effects?

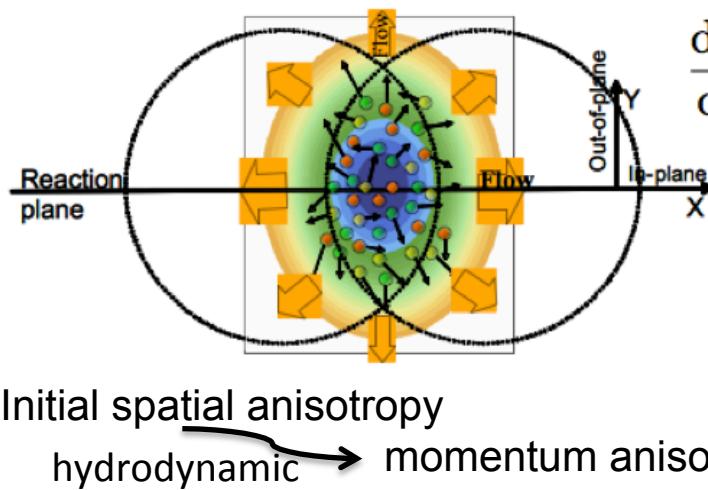
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Nuclei overlap function

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2) Elliptic flow v_2 (azimuthal anisotropy): study azimuthal distribution of produced particle w.r.t. the reaction plane (Ψ)

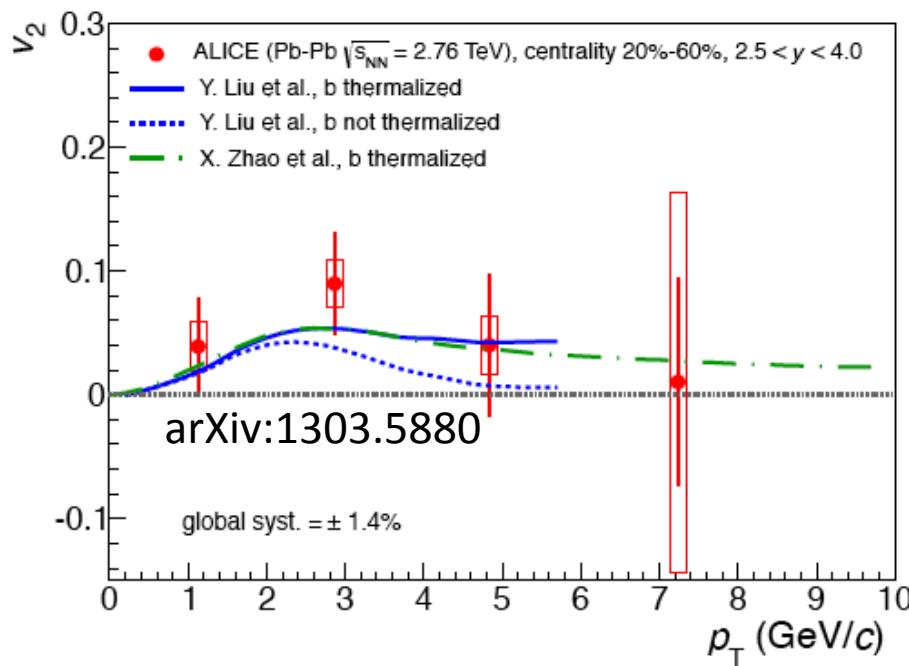


$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos[2(\varphi - \Psi_2)] + \dots)$$

Non-zero v_2

- Thermalization/collective motion (at low p_T)
- Path length dependence of energy loss (at high p_T)

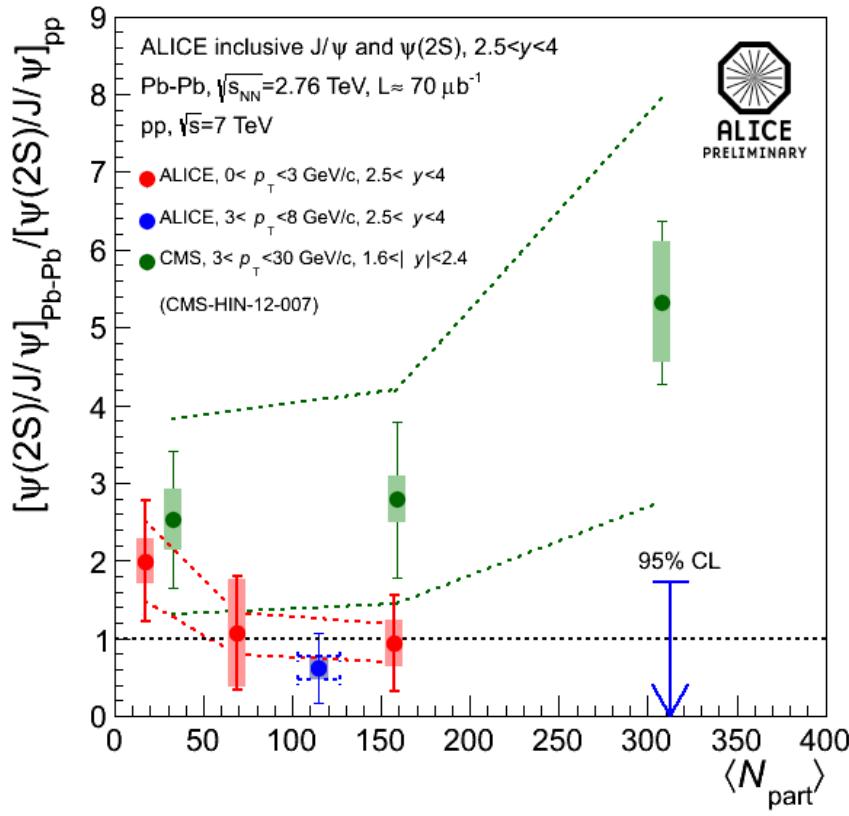
Inclusive J/ ψ v_2



J/ ψ produced via recombination of thermal deconfined c-quarks should show a non zero v_2 :

- **first hint of non-zero v_2** from data
- qualitative agreement with transport models including regeneration

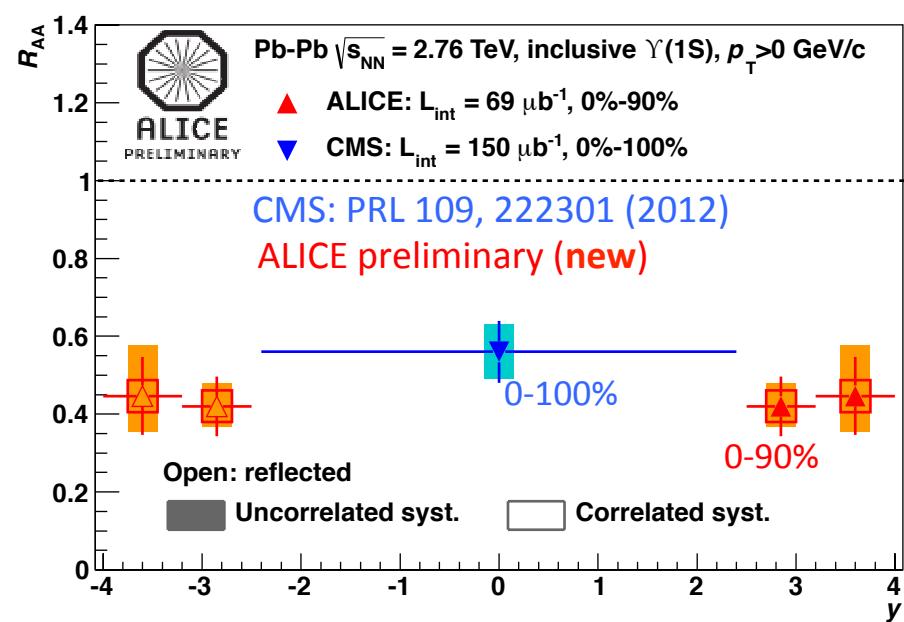
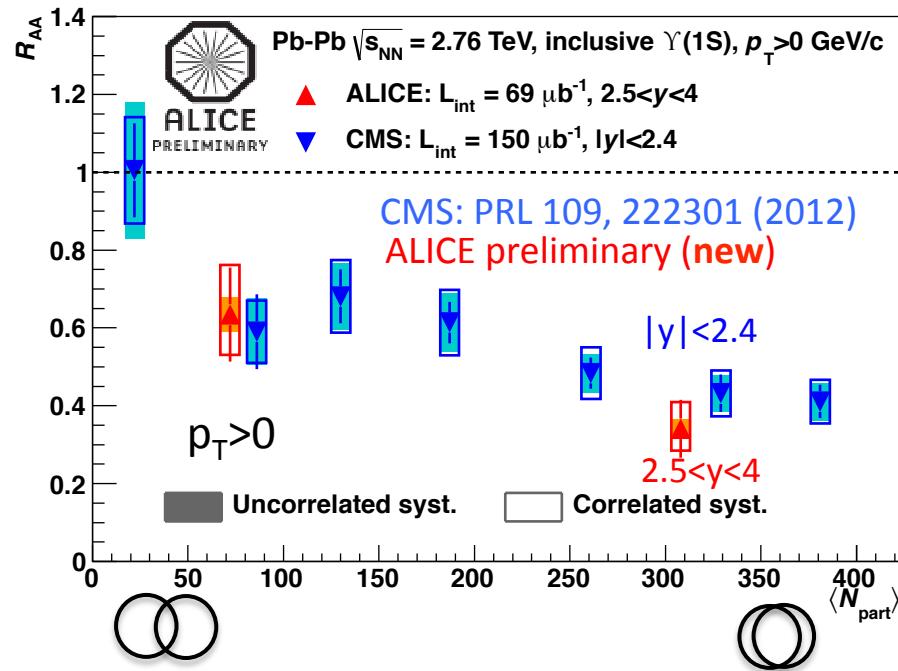
$\psi(2s)$ Vs J/ψ



- Hint of smaller suppression for $\psi(2S)$ than J/ψ from CMS measurement
- Not confirmed by ALICE

Large uncertainty from pp reference (dashed lines) → to be reduced with 2013 pp data

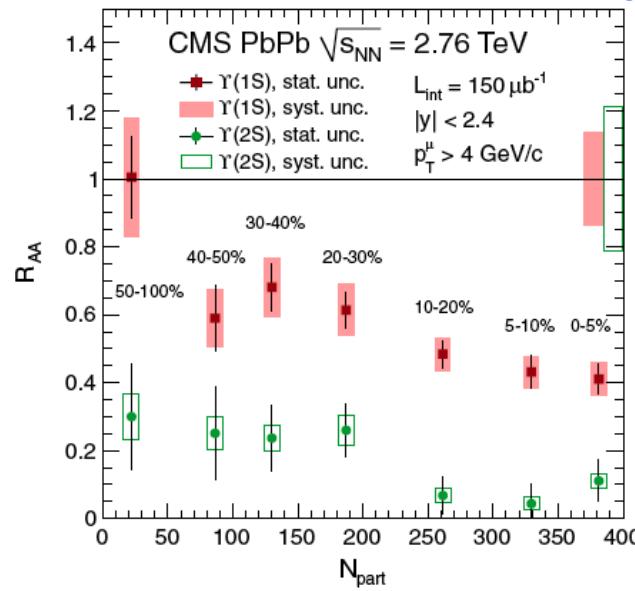
$\Upsilon(1s)$ suppression



- **Relevant suppression**
 - **increasing with centrality (factor 2.5 in central)**
- No significant dependence on rapidity can be appreciated
- ~50% (in pp) of $\Upsilon(1s)$ derives from feed-down from higher states
 - Observed R_{AA} significantly influenced by higher state suppression

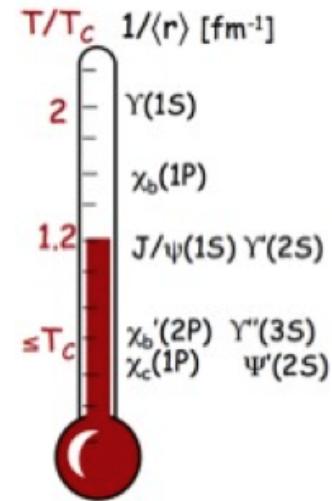
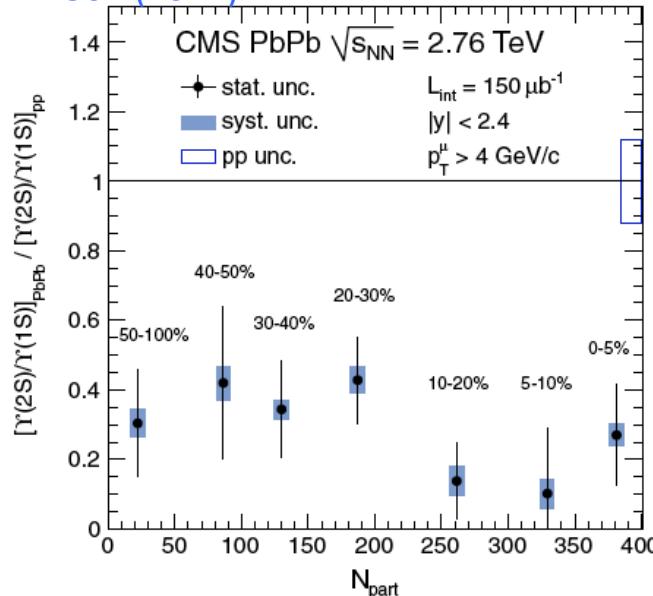
Bottomonia suppression

PRL 109, 222301 (2012)



CMS (0-100% centrality)

$$\begin{aligned}
 R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}), \\
 R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}), \\
 R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}) \\
 &< 0.10(95\%\text{CL}).
 \end{aligned}$$



- **$\Upsilon(2s)$ more suppressed than $\Upsilon(1s)$**
 - As expected from smaller binding energy
- Data suggest that direct $\Upsilon(1s)$ almost unsuppressed

$$R_{AA}^{\text{full}}[\Upsilon(ns)] = \sum_{i \in \text{states}} f_i R_{AA}^i$$

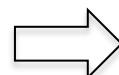
Open heavy flavour in Pb-Pb

See also
C. Bianchin (Monday)

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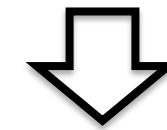
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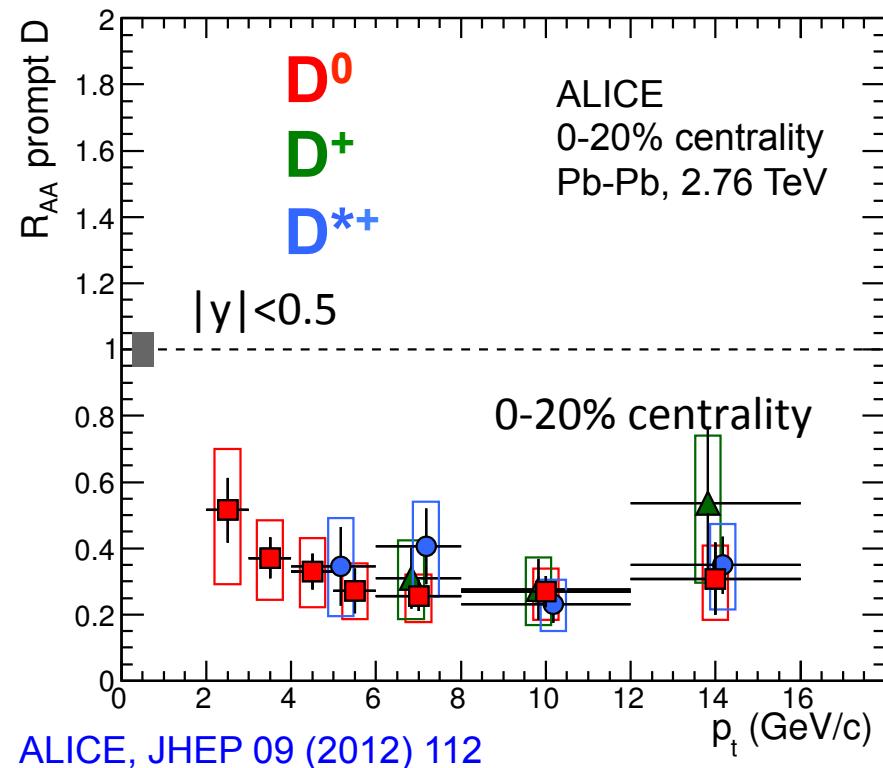
$$\left. \begin{array}{c} \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b \\ \end{array} \right\}$$



$$R_{AA}^\pi < R_{AA}^D < R_{AA}^B$$

- medium **modification to HF hadron formation**
 - in-medium dissociation [Sharma et al., PRC80 \(2009\) 054902](#)
 - hadronization via quark coalescence

Prompt D meson R_{AA}

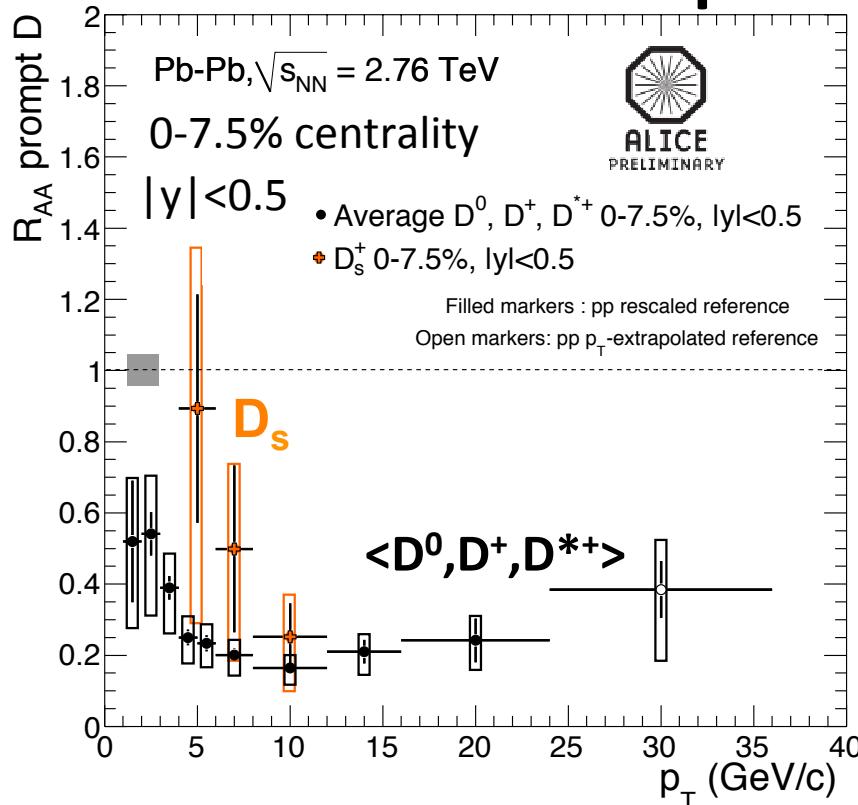


First measurement of D meson R_{AA} in central heavy-ion collisions (2010 Pb-Pb run)

Strong suppression observed (factor 3-5 for $p_T > 5$ GeV/c)

D^0 , D^+ , D^{*+} R_{AA} compatible within errors

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Extended p_T range ($1 < p_T < 36 \text{ GeV}/c$) with 2011 Pb-Pb data

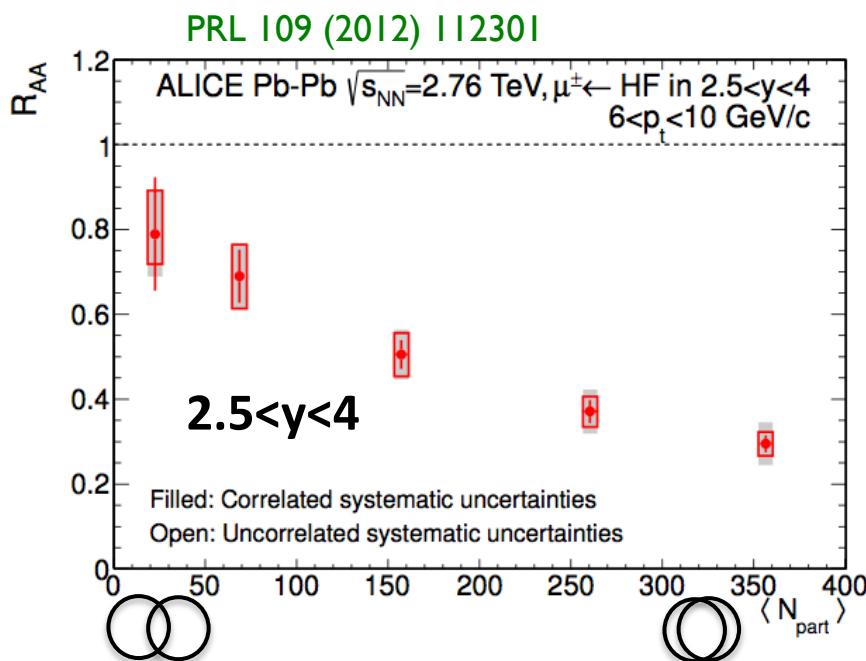
First measurement of D_s in Pb-Pb with 2011 run data

- suppression of 3-5 in 8-12 GeV/c
- $R_{AA}(D_s) > R_{AA}(D^0, D^+, D^{*+})$ at low p_T ? More statistics needed
 - could have quantitative implications for **quark coalescence** models

Kuznetsova & Rafelski, EPJ C51(2007)113;
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488)

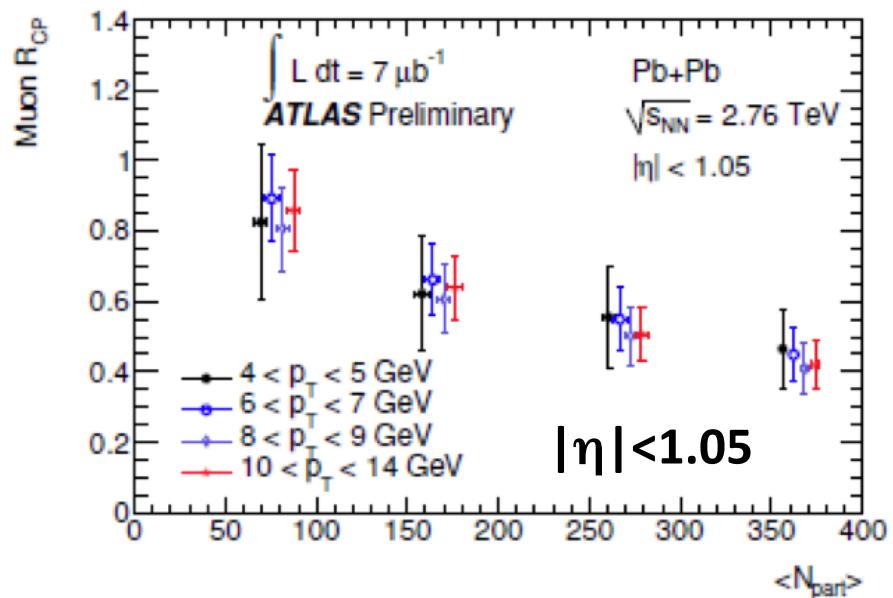
Heavy Flavour decay muons

ALICE forward μ



ATLAS mid-rapidity μ R_{CP}

$$R_{CP}(p_T) = \frac{\langle N_{coll} \rangle_{\text{Per}}}{\langle N_{coll} \rangle_{\text{Cent}}} \frac{dN / dp_T|_{\text{Cent}}}{dN / dp_T|_{\text{Per}}}$$

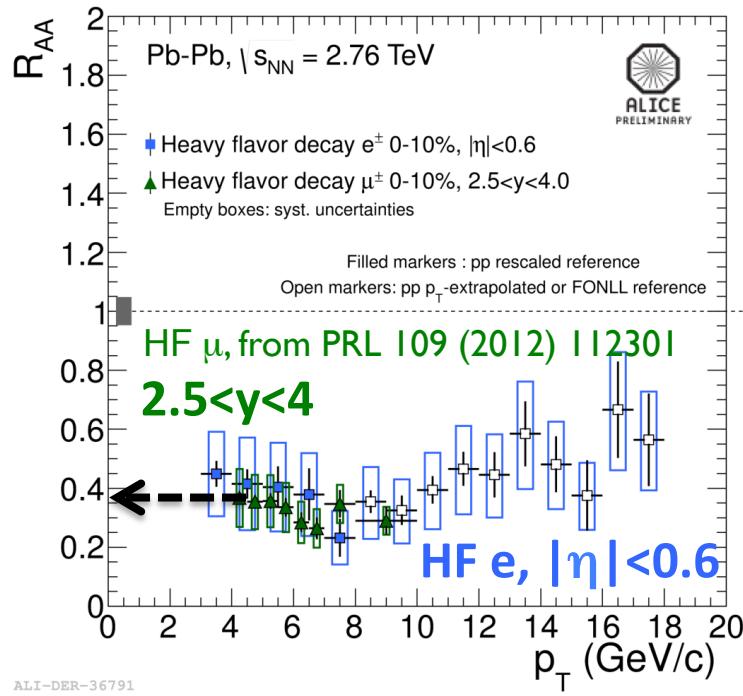


Clear centrality trend

- HF-muon suppression increases with centrality
 - $R_{AA} \sim 0.3$ in most central collisions
- **No evident p_T dependence for R_{AA} in the range $4 < p_T < 14$ GeV/c**

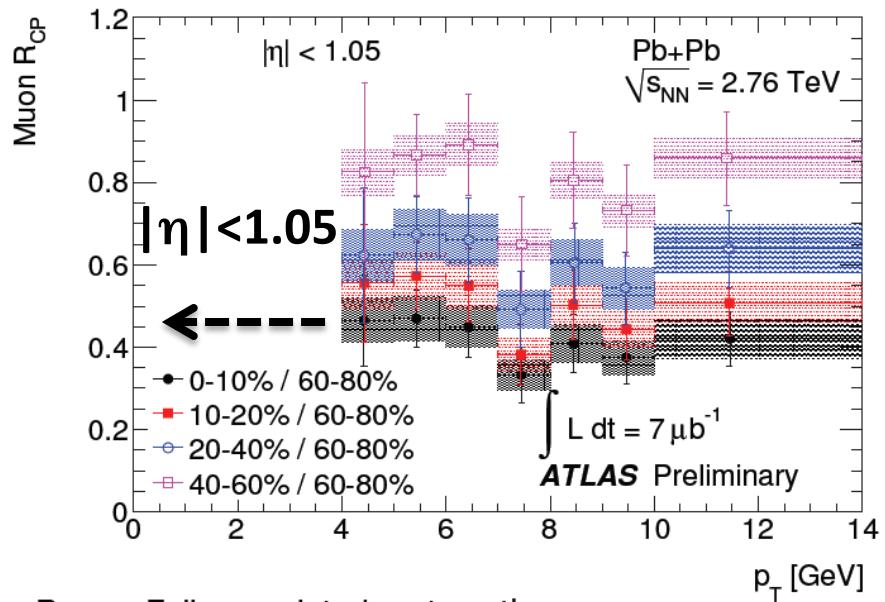
Heavy Flavour decay muons & electrons

ALICE forward μ and mid-rapidity electron



ATLAS mid-rapidity μ R_{CP}

$$R_{CP}(p_T) = \frac{\langle N_{coll} \rangle_{\text{Per}}}{\langle N_{coll} \rangle_{\text{Cent}}} \frac{dN / dp_T|_{\text{Cent}}}{dN / dp_T|_{\text{Per}}}$$

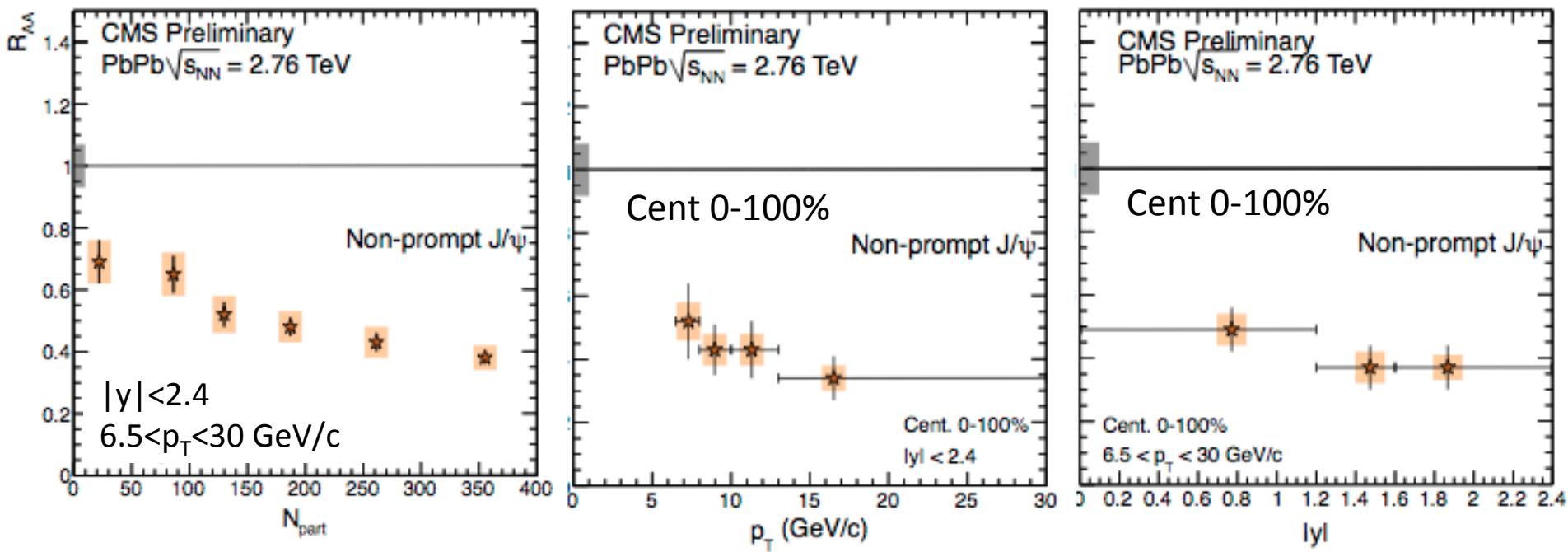


Similar suppression in 0-10%

Factor 2 up to 18 GeV/c (mainly from beauty)

Similar suppression for electrons in $|\eta|<0.6$ and muons in $|\eta|<1.05$ in 0-10%
(though a quantitative comparison not straightforward)

J/ ψ from b-hadron decays

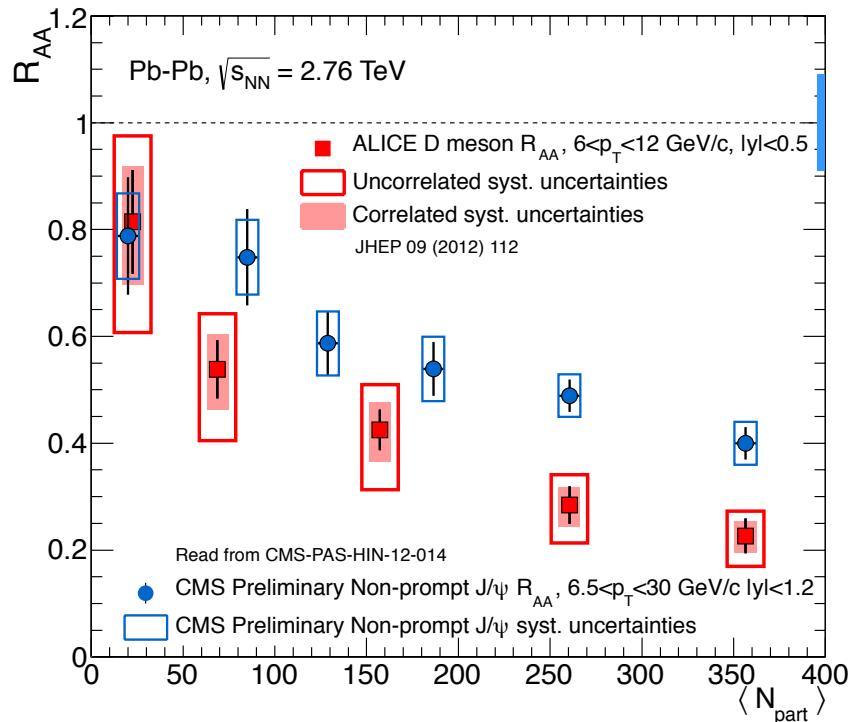


First measurement of beauty R_{AA} by CMS

Suppression increasing with centrality

- factor 2.5 in central collisions (0-10%)

ALICE D vs CMS J/ ψ from b-hadrons



J/ψ : from B, $6.5 < p_T < 30$ GeV/c

D: $6 < p_T < 12$ GeV/c

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

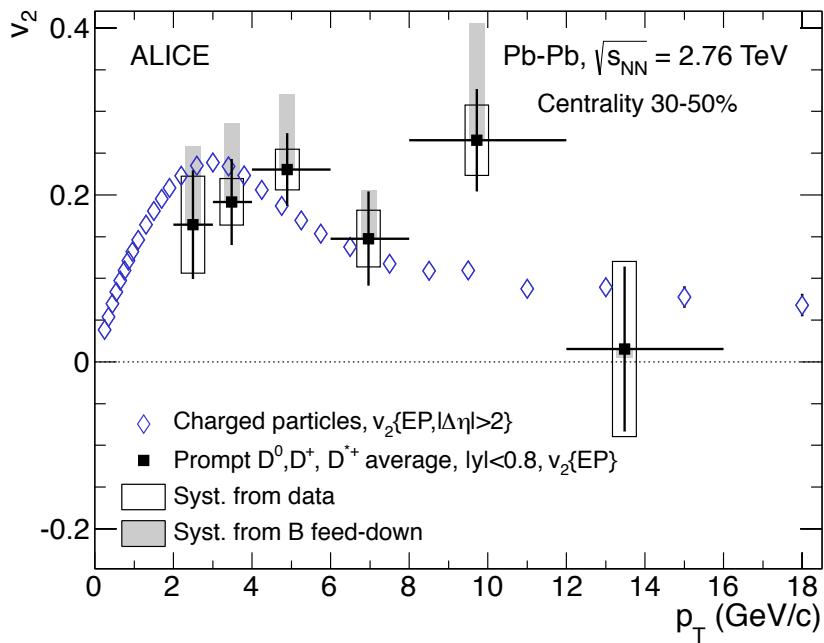
$$\Rightarrow R_{AA}^\pi < R_{AA}^D < R_{AA}^B$$

Indication of mass dependence
of energy loss

But kinematic ranges (w.r.t. to parent quarks)
are not exactly the same

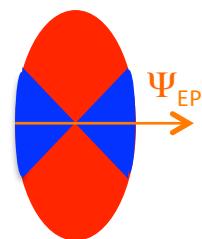
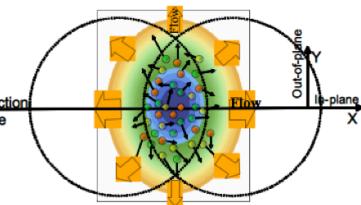
D meson azimuthal anisotropy

Today on arXiv: 1305.2707



$$v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N^{\text{In-Plane}} - N^{\text{Out-Of-Plane}}}{N^{\text{In-Plane}} + N^{\text{Out-Of-Plane}}}$$

R_2 : event plane resolution



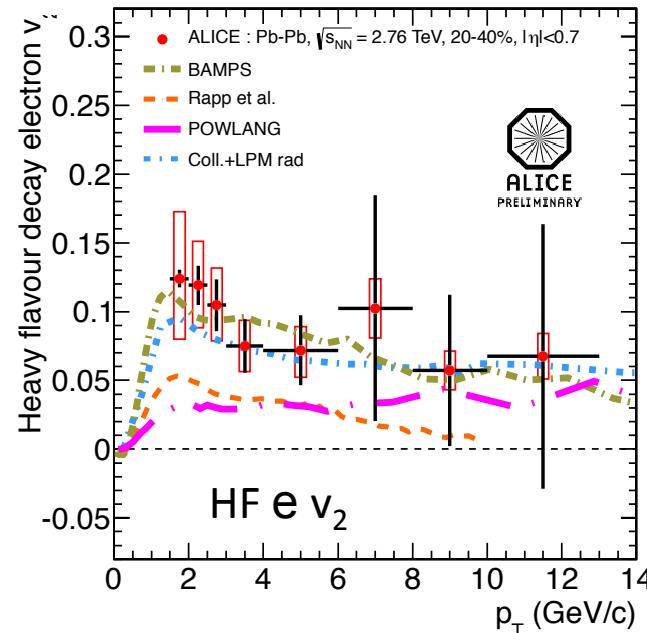
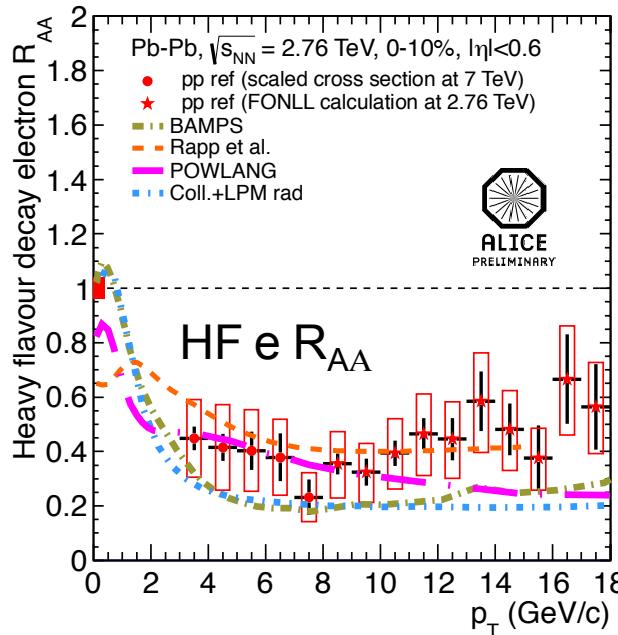
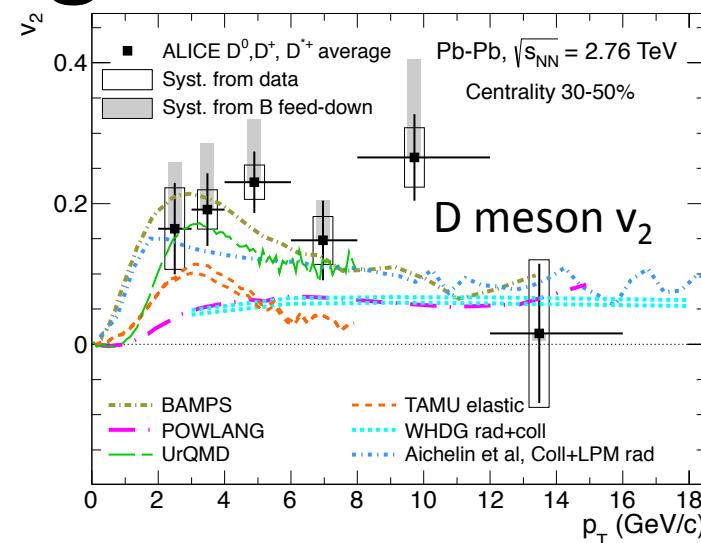
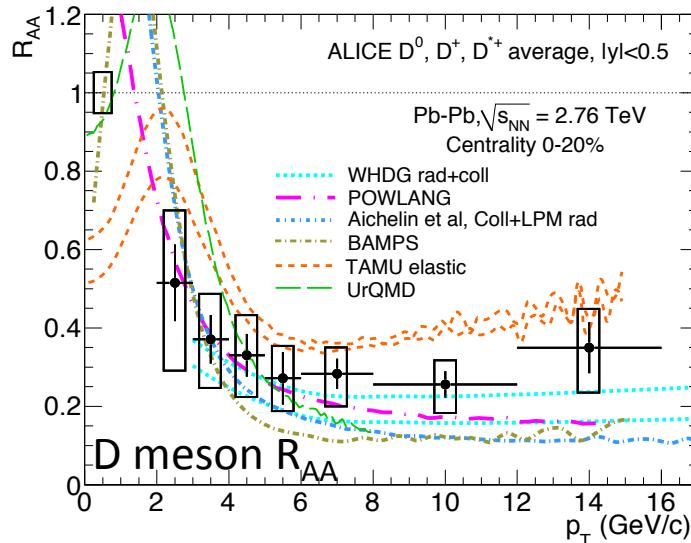
First measurement of D meson v_2 !

- D meson $v_2 > 0$ in 30-50% class
- Comparable to v_2 of charged hadrons

Suggests

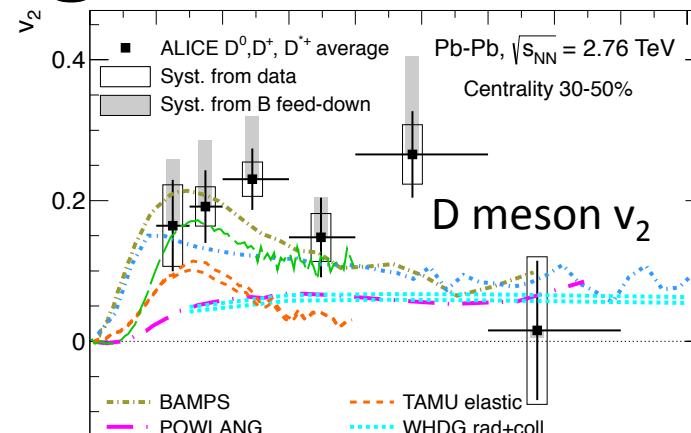
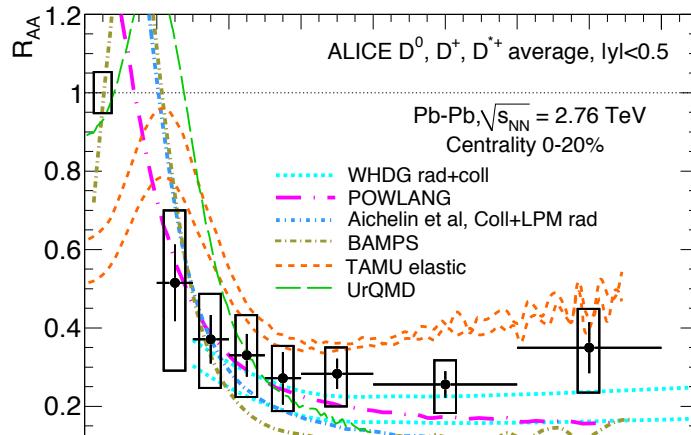
- at low p_T : **charm quarks taking part in the collective expansion of the system?**
- at intermediate-high p_T : path-length dependence of energy loss

Stimulating for models

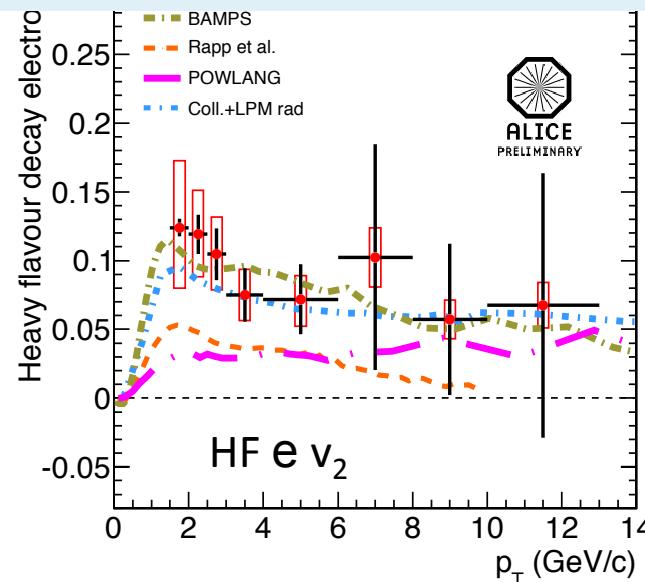
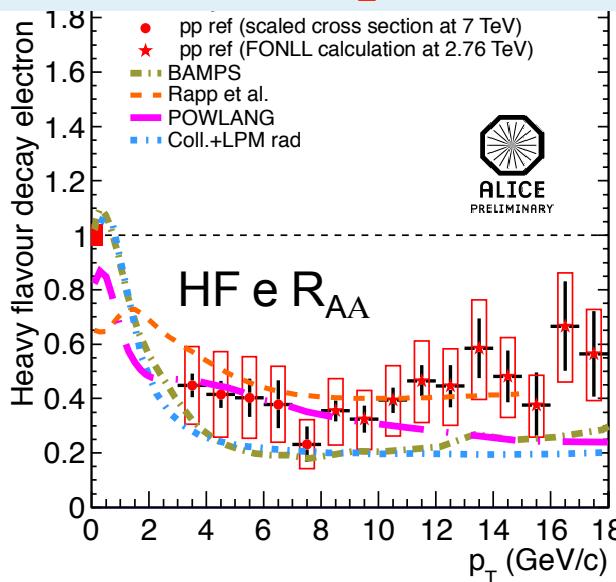


Model references
in backup slides

Stimulating for models



Successful models are required to predict both R_{AA} and v_2 - measurements stimulate theory



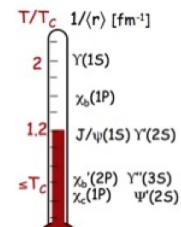
Model references
in backup slides

Conclusions: what we are learning on QGP

Debye-like screening of $q\bar{q}$ color potential

- high- p_T J/ψ suppression
- Upsilon states suppression pattern

→ Constrain QGP temperature



Coalescence of charm in QGP

- J/ψ relatively small suppression at low p_T
- Hint of non-zero $J/\psi v_2$
- Intriguing result from comparisons of $D_s R_{AA}$ to $D^0, D^+, D^{*+} R_{AA}$

QGP is opaque even to heavy quarks

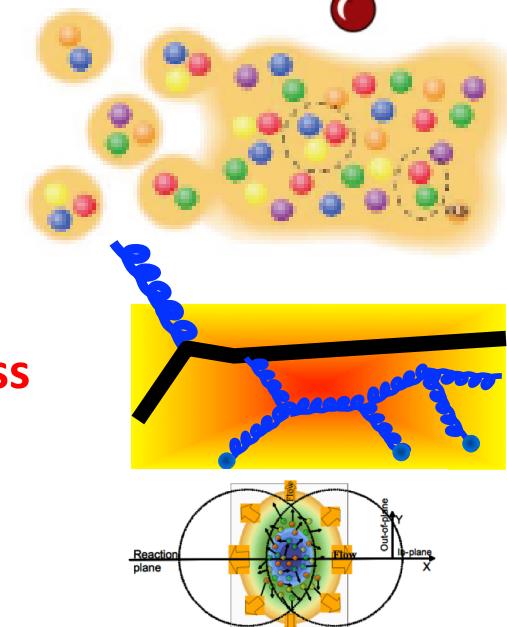
- D meson suppressed by a factor 3-5 at $p_T > 5 \text{ GeV}/c$

Experimental hints of mass dependence for parton energy loss

- Indication that beauty is less quenched than charm
- $R_{AA}(J/\psi \leftarrow B) > R_{AA}(D)$ for similar p_T

Bulk of hot QGP flows: charm as well? → is charm thermalized?

- Non zero elliptic flow (v_2) for D mesons



Coming soon: results from p-Pb data, crucial to isolate cold nuclear matter effects

Run 2 (2014): data from future runs will help to improve the precision of the measurements

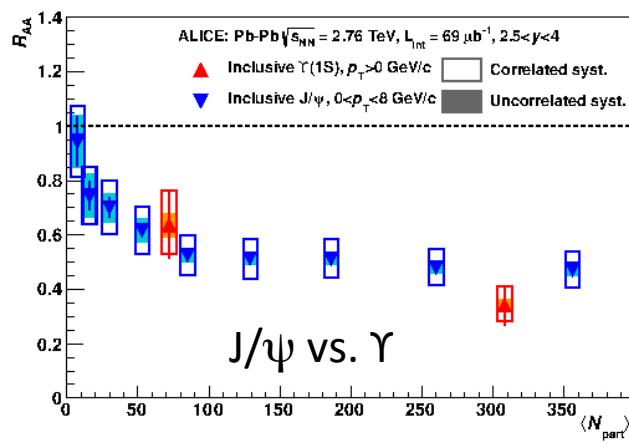
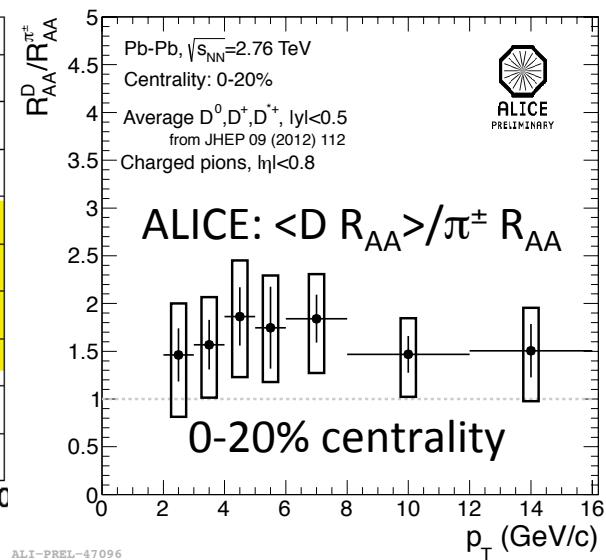
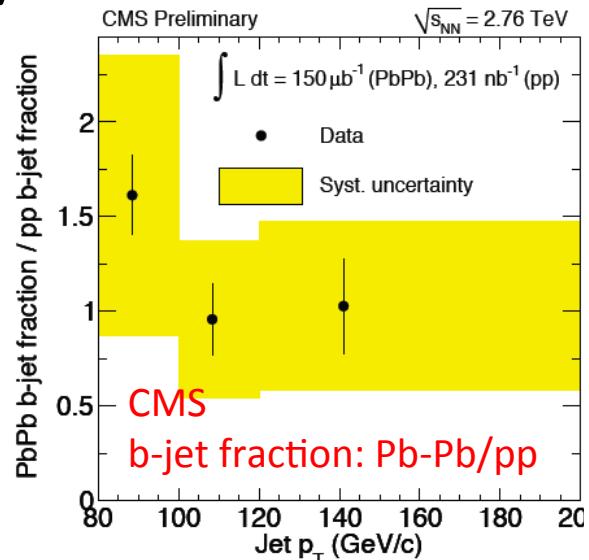
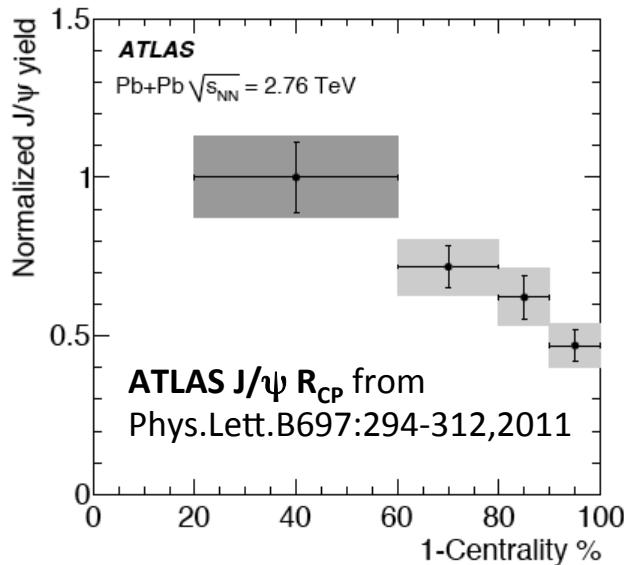
LS2 (2018): detector upgrade → revolution for charm and beauty in HI

Upgrade session,
Saturday

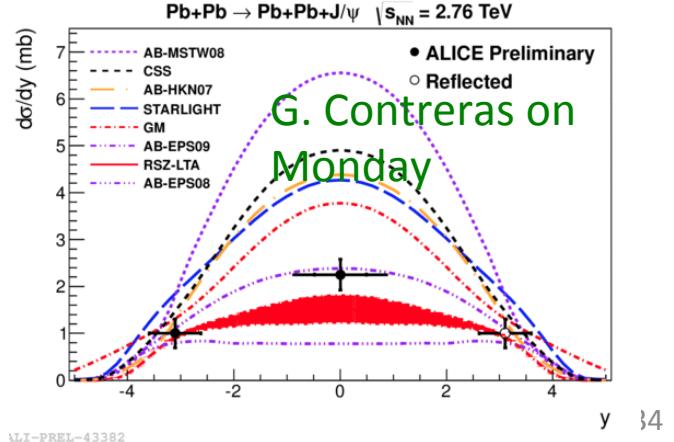
Entering the charm and beauty era of QGP

Thanks!

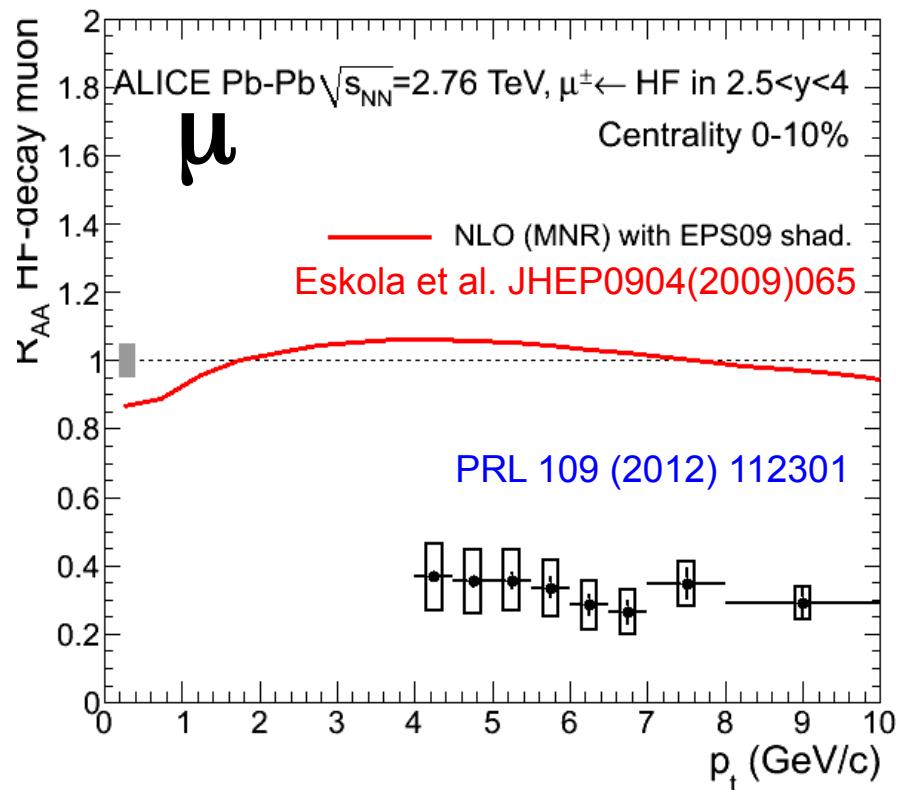
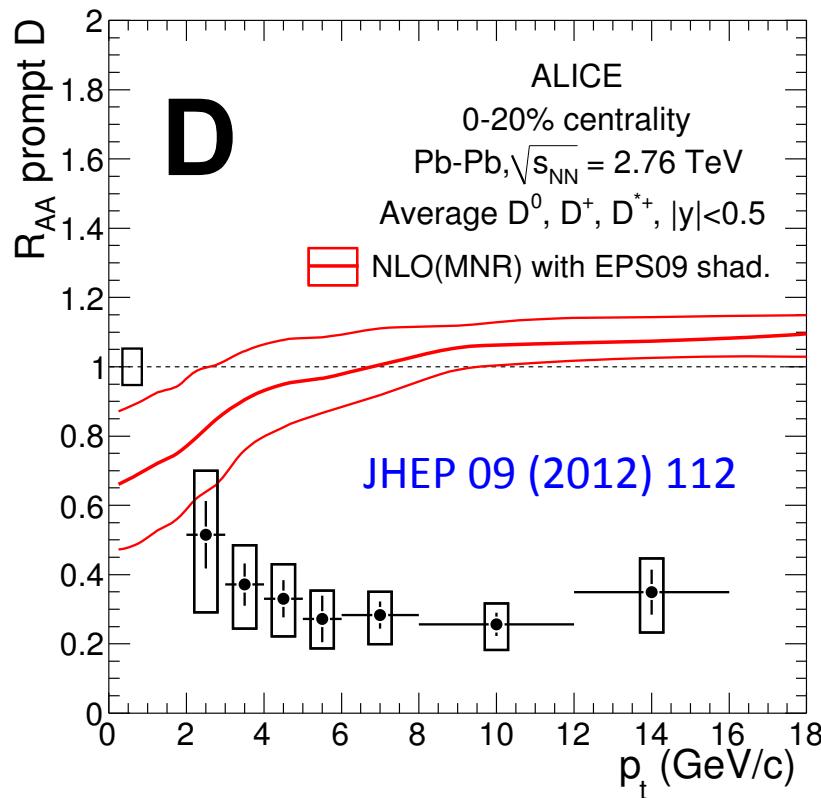
Sorry for not showing



J/ψ photoproduction in Pb-Pb and p-Pb



Comparison to shadowing

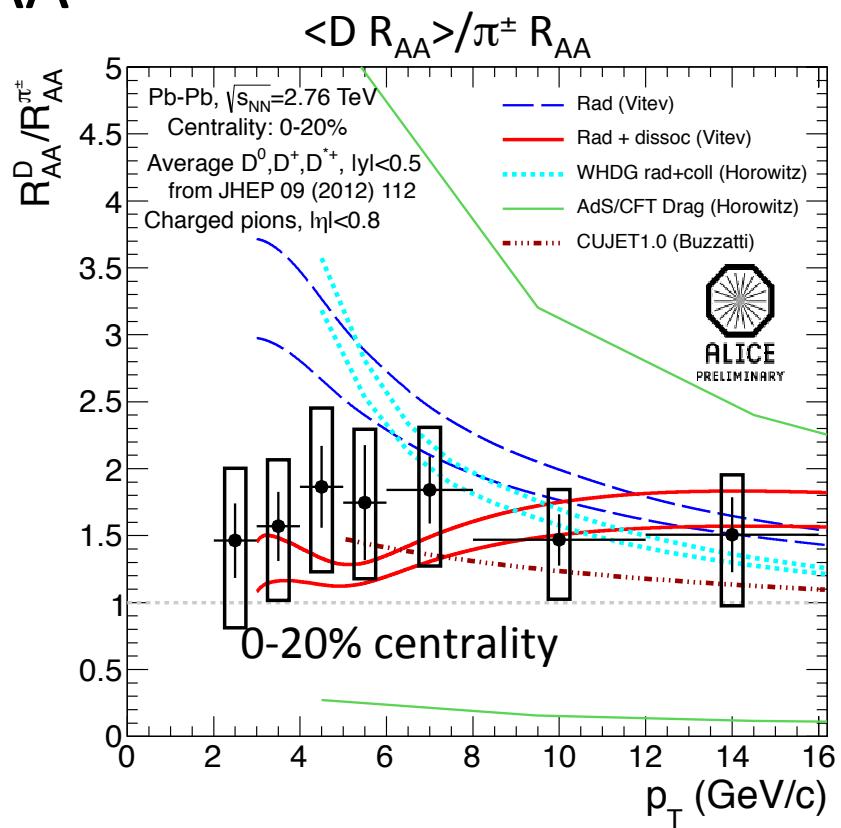
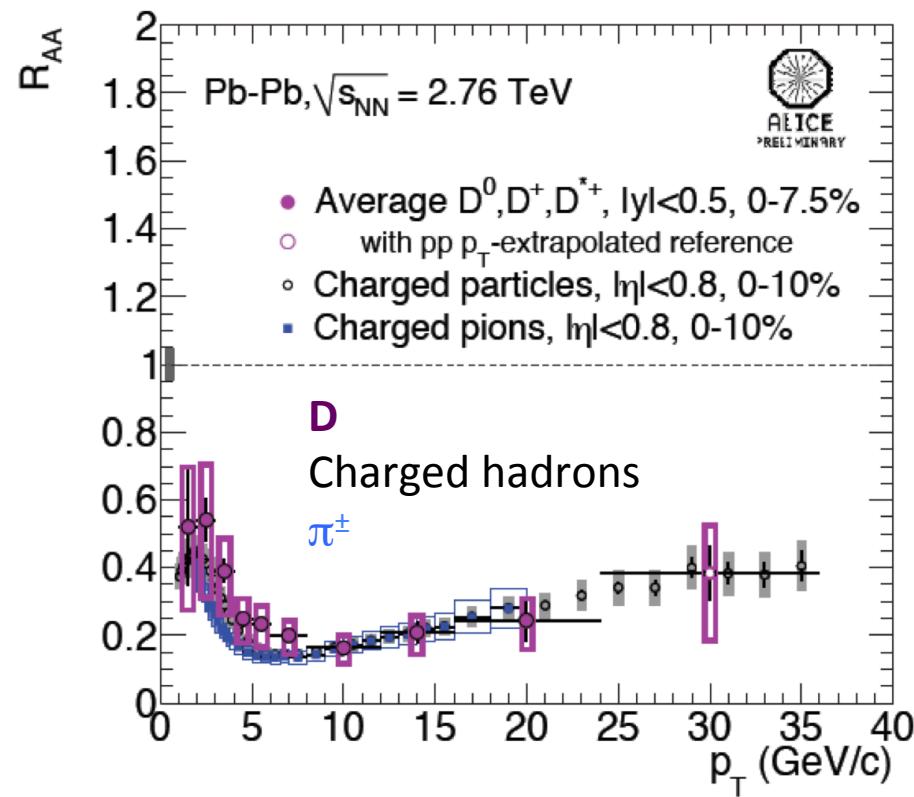


Small negligible effect expected from shadowing for $p_T > 5$ GeV/c

-> Observed suppression is a hot medium effect for $p_T > 5$ GeV/c

...but crucial to quantify initial state effects (analysis of p-Pb data ongoing)

Prompt D meson R_{AA} vs. charged pions

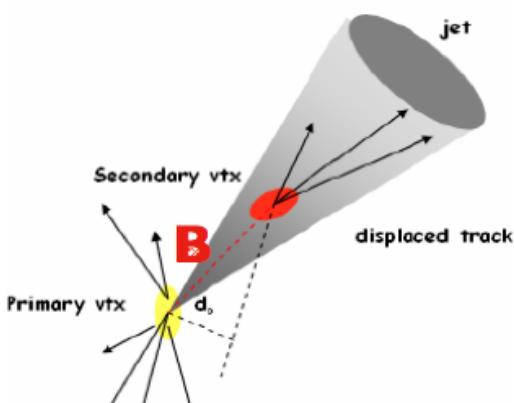
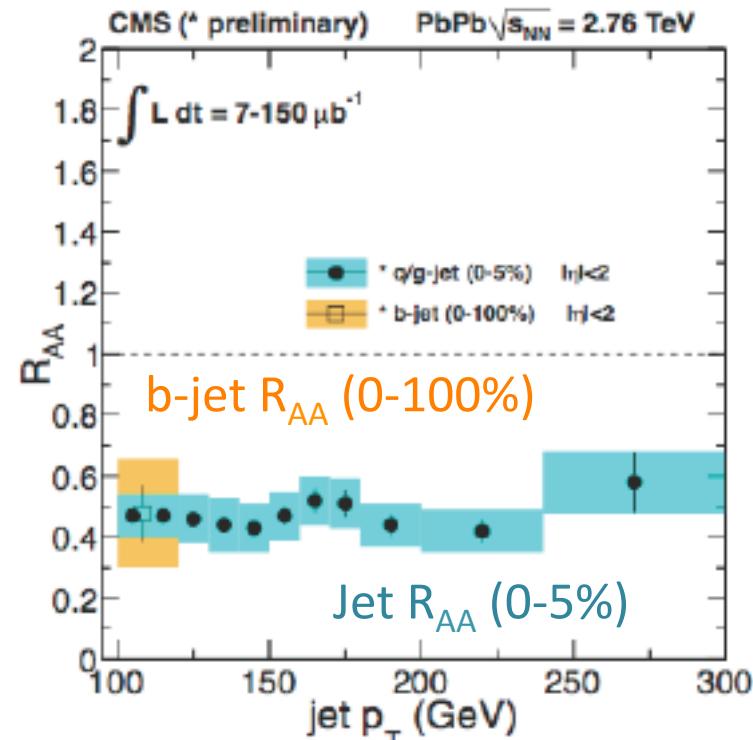
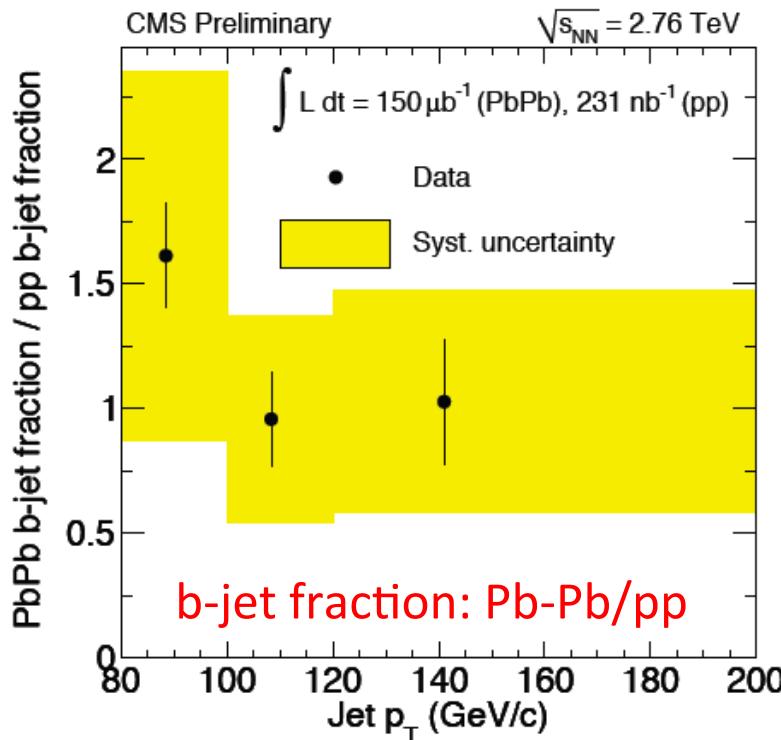


D and charged pion R_{AA} very similar

Hint of smaller D suppression

Data from future runs should provide a more precise comparison with models

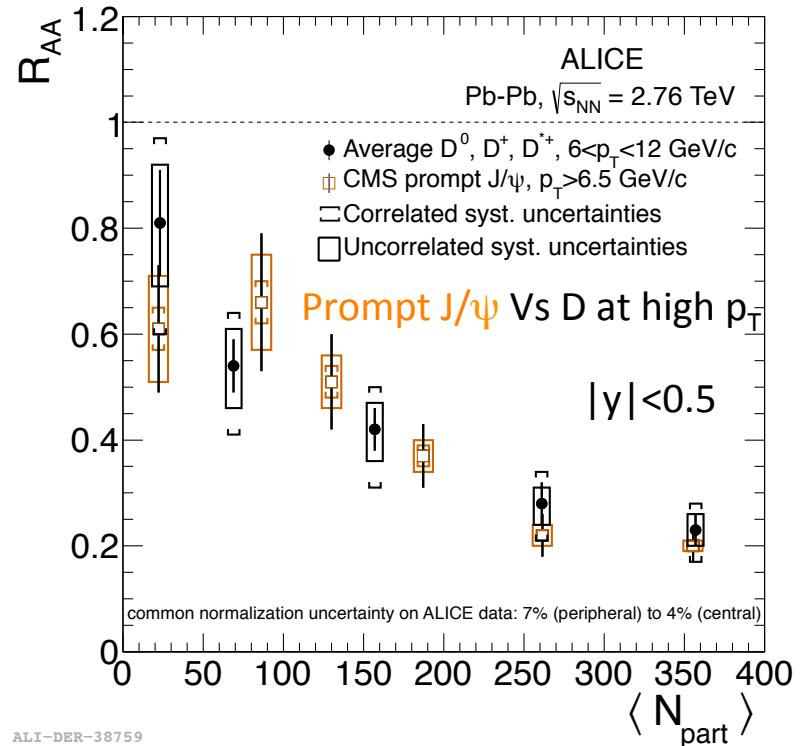
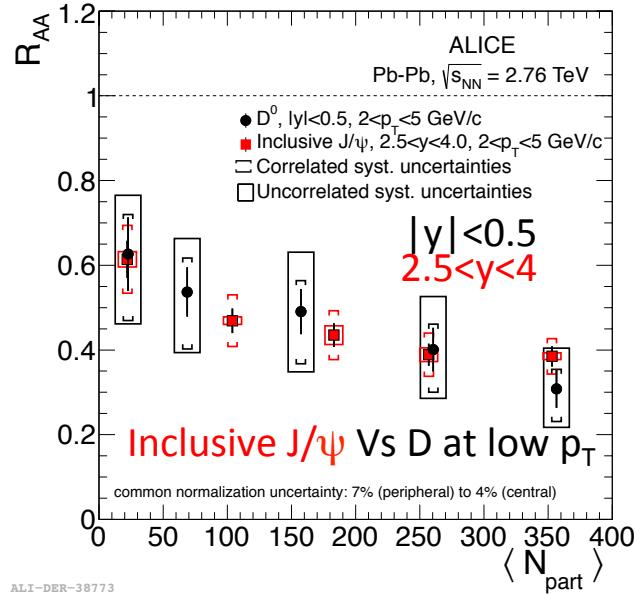
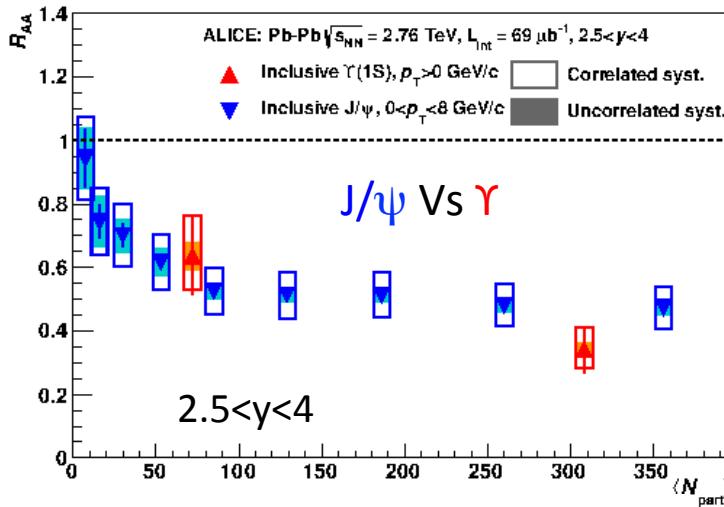
Beauty at high p_T with b-jets



Same R_{AA} for b-jets and jets from lighter quarks/gluon (expected at this p_T)

Ongoing analysis for pushing to lower p_T , muon-jets, double b-tagged dijets

Just a soup of results?



Many caveats!

Quarkonia suppression & regeneration

Hot QGP → quarkonia suppression due to Debye-like screening of QCD $Q\bar{Q}$ potential (“melting” of bound $Q\bar{Q}$ states)

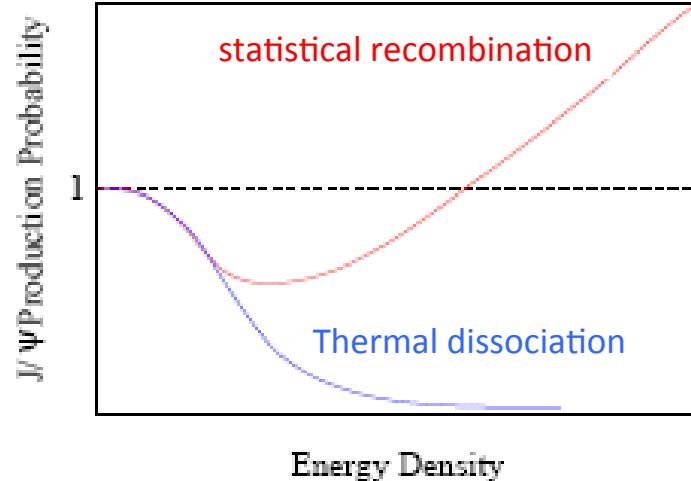
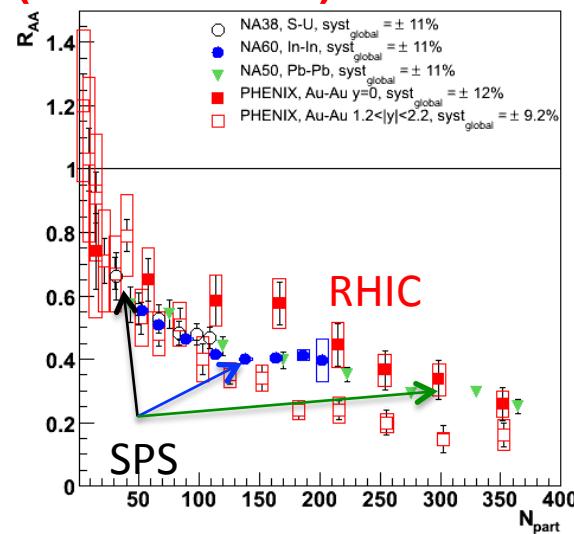
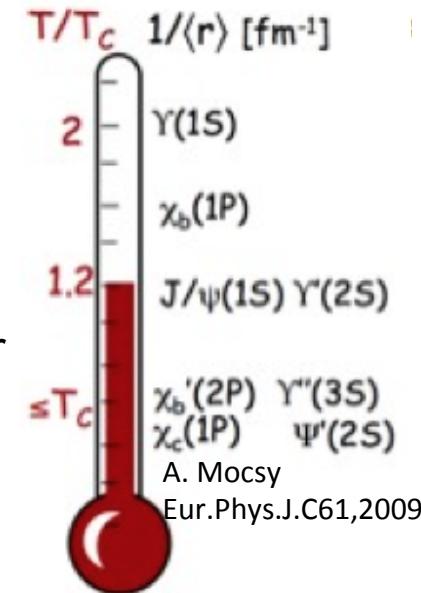
→ “historical” signature of deconfinement

(T. Matsui and H. Satz, PLB 178 (1986) 416)

→ Sequential suppression of quarkonium states, stronger for less bounded states (S. Digal, P. Petreczky, H. Satz, PRD 64 (2001) 0940150)

Surprisingly similar J/ψ suppression at RHIC and SPS energies

→ Could quarkonia states be (re)generated via recombination (coalescence) of deconfined quarks? (P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196)

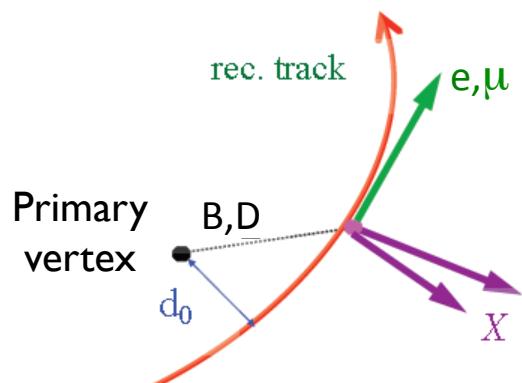


LHC vs. RHIC

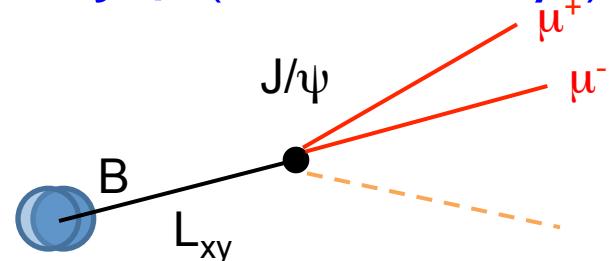
Larger energy density
→ stronger suppression
Higher $c\bar{c}$ multiplicity
→ larger recombination

Open heavy flavor measurements

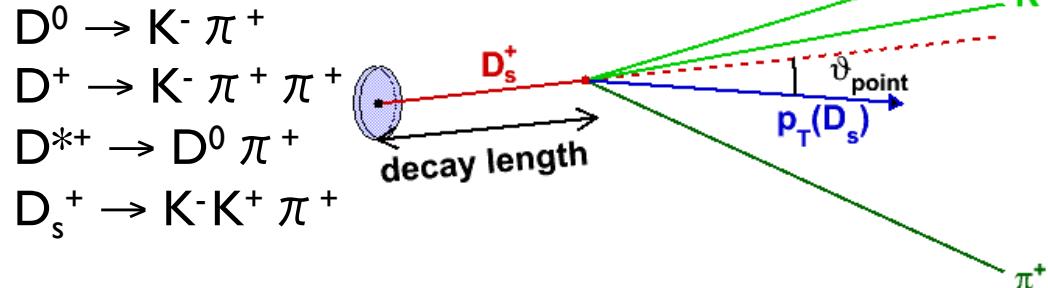
Semi-leptonic decays (c,b)



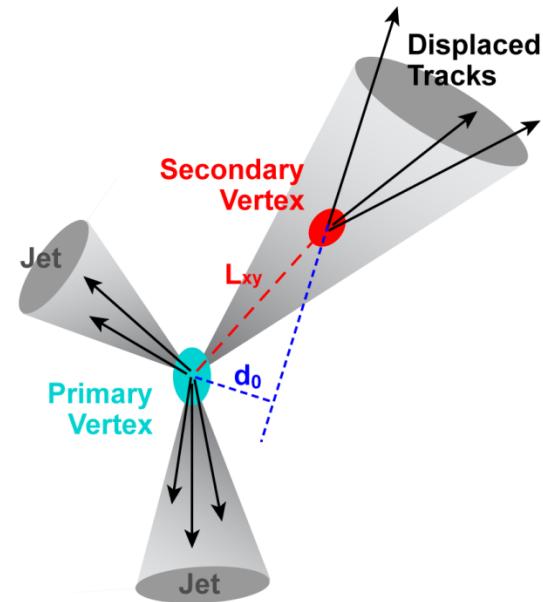
Displaced J/ ψ (from B decays)



Full reconstruction of D meson hadronic decays

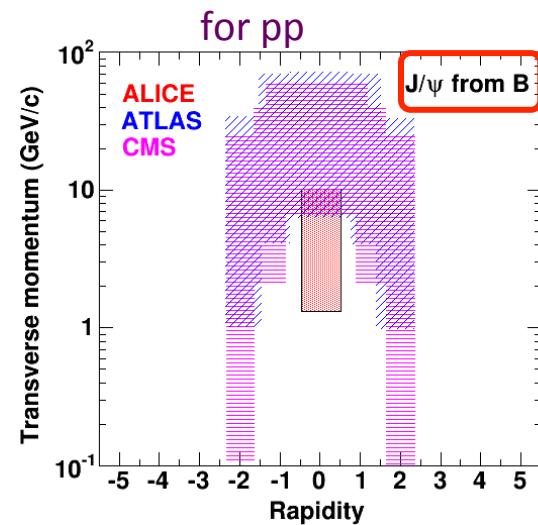
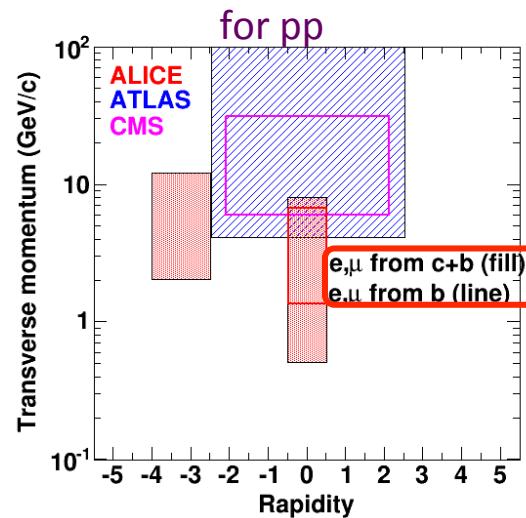
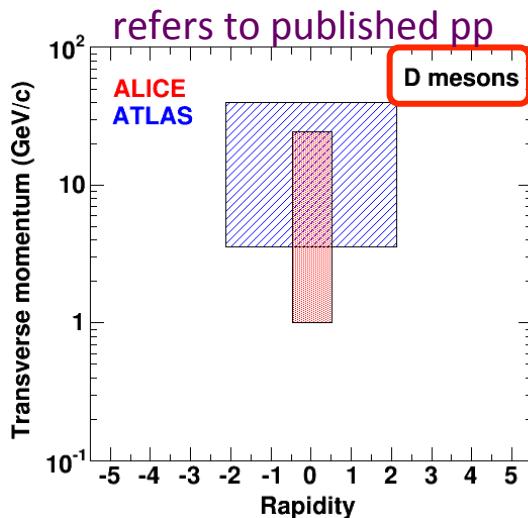


Jet b-tagging



ALICE, ATLAS, CMS kinematic coverage

- Open heavy flavour-



Complementary rapidity and p_T coverage:

ALICE: unique low- p_T reach (thanks to tracking and PID)

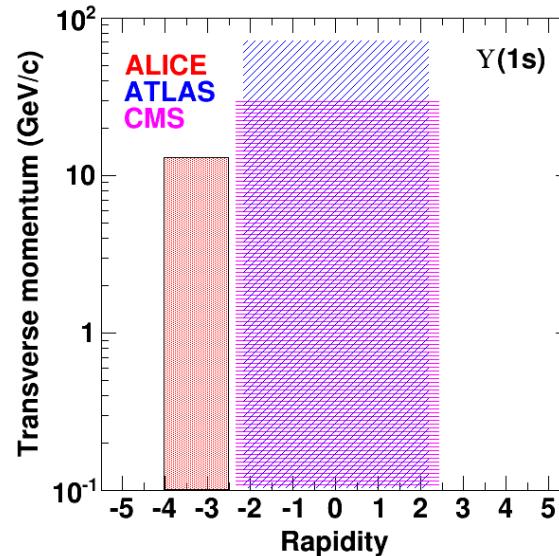
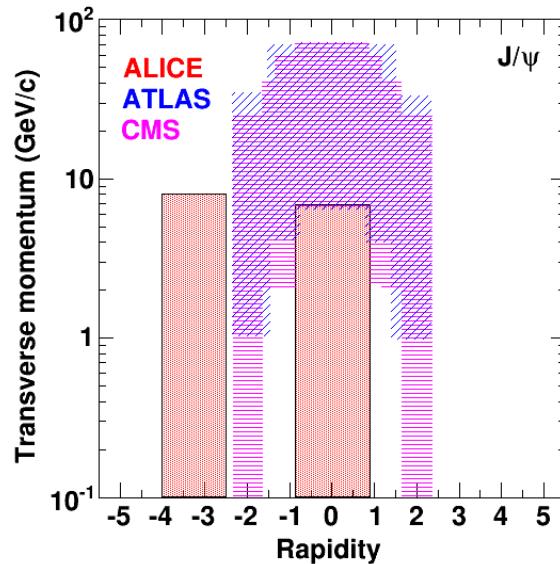
ATLAS/CMS: large rapidity coverage. High momentum space explored. Low momentum reachable with secondary J/ψ but not at mid-rapidity (CMS).

Quarkonia measurements and kinematic coverage

ALICE (forward), ATLAS, CMS: $J/\psi, \psi(2s), Y(ns) \rightarrow \mu^+\mu^-$

ALICE (mid rapidity): $J/\psi \rightarrow e^+e^-$

refers to published pp

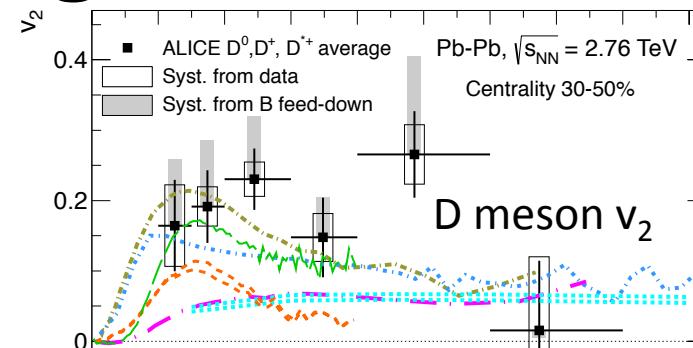
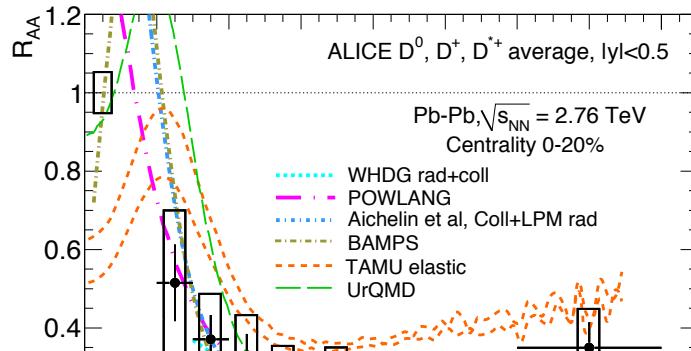


Complementary rapidity and p_T coverage:

ALICE: unique low- p_T reach for charmonia especially at central rapidity, unique for bottomonia at forward rapidity

ATLAS/CMS: large rapidity coverage. Similar coverage, down to $p_T=0$ for bottomonia

Stimulating for models



Successful models are required to predict both R_{AA} and v_2 - measurements stimulate theory

BAMPS, O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. **G38** (2011) 124152.

WHDG, W. A. Horowitz and M. Gyulassy, J. Phys. **G38** (2011) 124114.

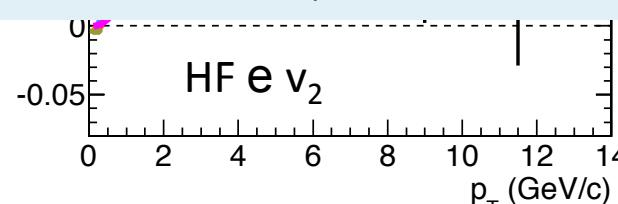
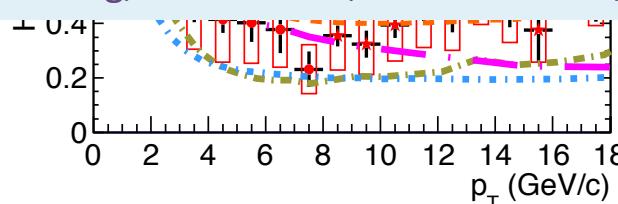
POWLNG, W. M. Alberico, *et al.*, Eur. Phys. J. **C71** (2011) 1666; J. Phys. **G38** (2011) 124144.

Coll+LPM P. B. Gossiaux, R. Bierkandt and J. Aichelin, Phys. Rev. **C79** (2009) 044906;
P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. **G37** (2010) 094019.

TAMU: M. He, R. J. Fries and R. Rapp, Phys. Rev. **C86** (2012) 014903.

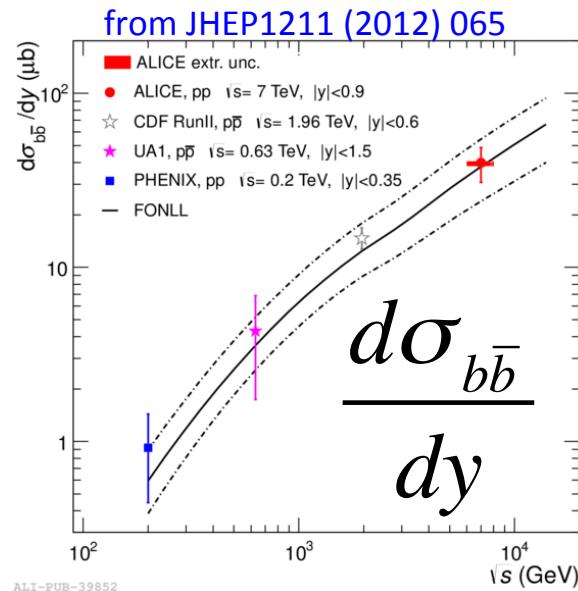
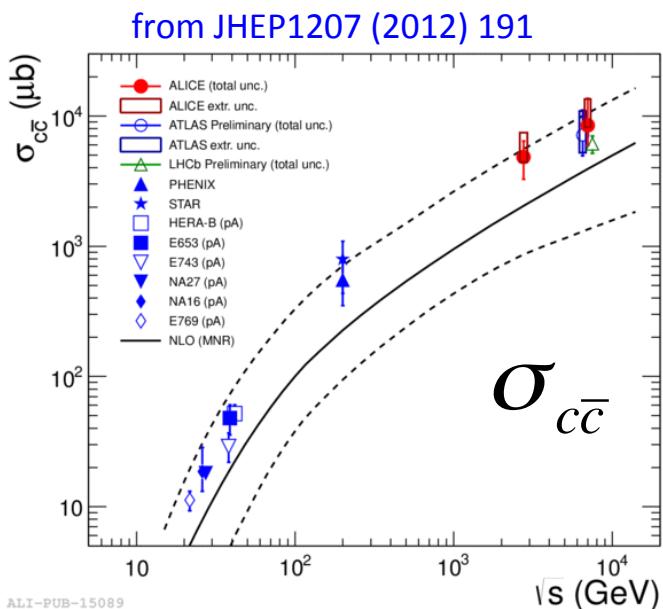
UrQMD: T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1211.6912;
T. Lang, H. van Hees, J. Steinheimer, Y. -P. Yan and M. Bleicher, arXiv:1212.0696.

el references
ckup slides



The reference: HF in pp

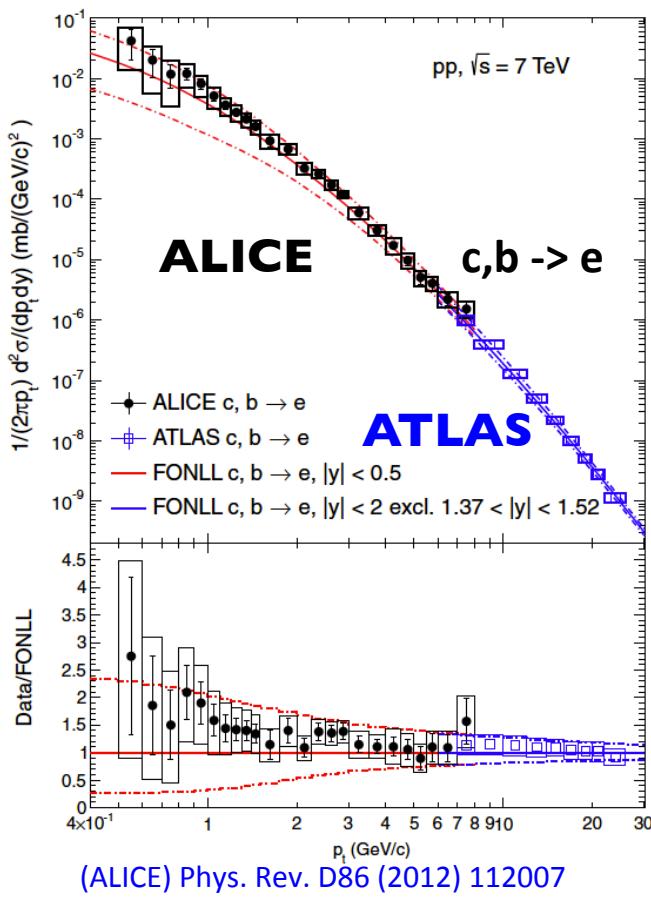
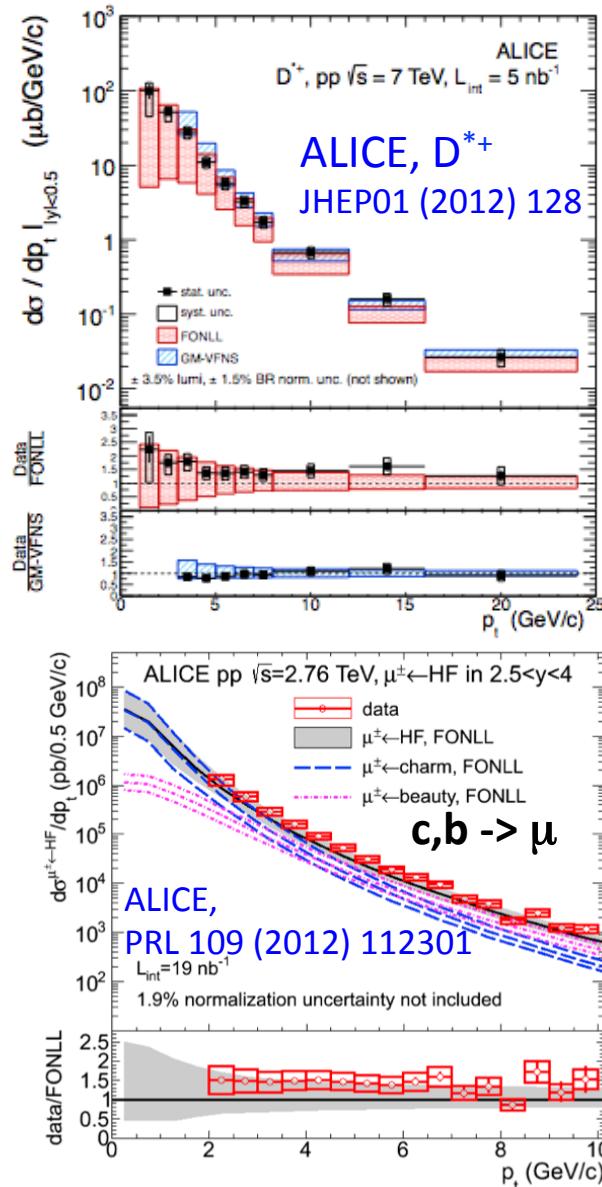
HF sessions
on Tuesday,
Wednesday



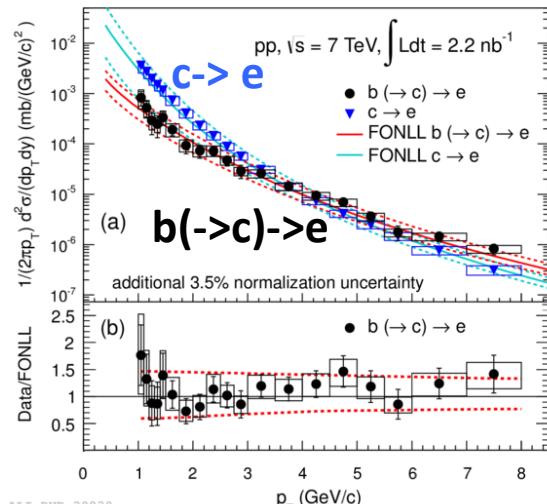
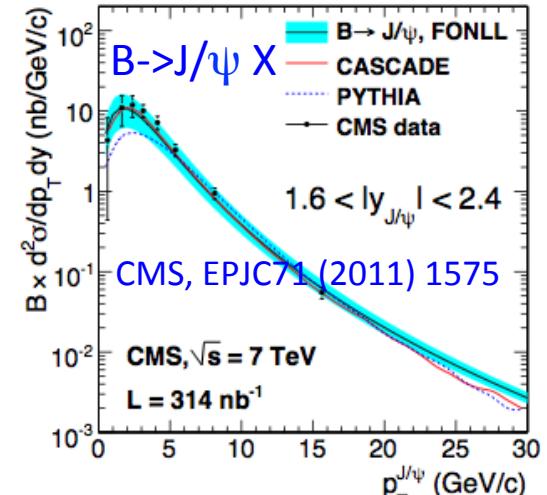
- Consistent results among LHC experiments
- Charm (beauty) x10 (100) from 0.2 (RHIC energy) to 2.76 TeV
- Energy dependence of total charm [beauty] cross-section well reproduced by pQCD calculations over 4[3] order of magnitude

The reference: HF in pp

HF sessions
on Tuesday,
Wednesday



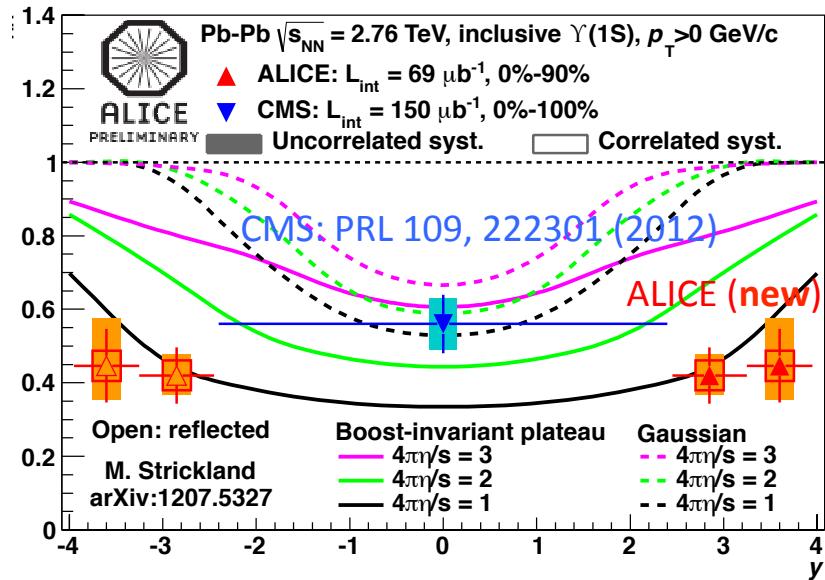
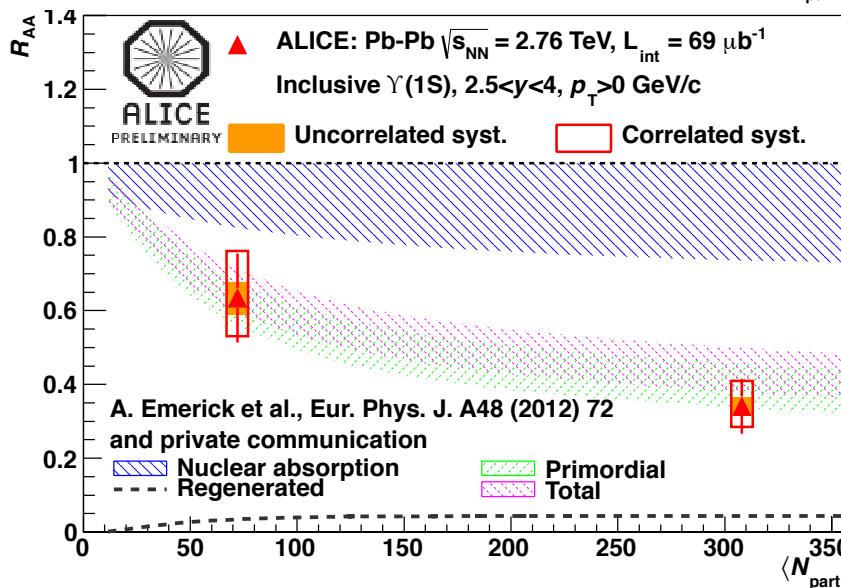
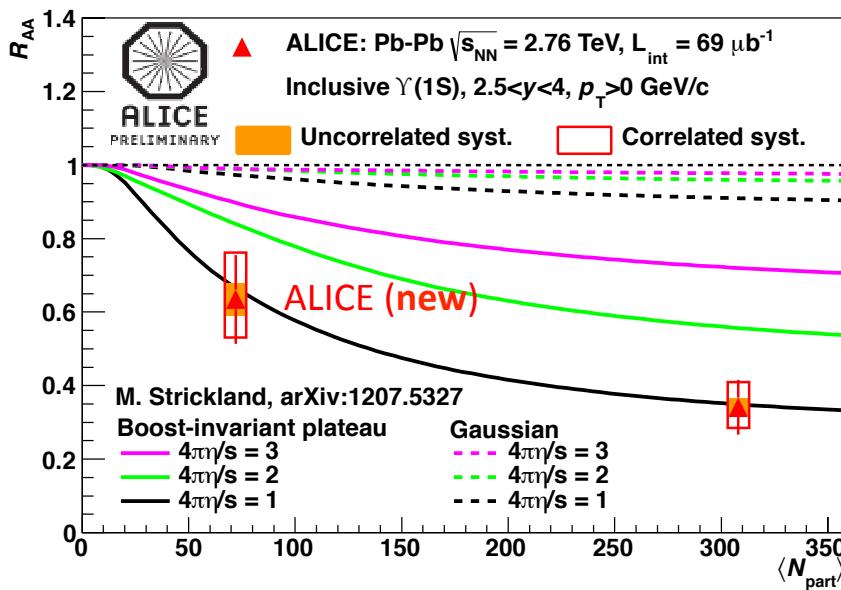
FONLL: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033



... and p_T differential cross-section as well

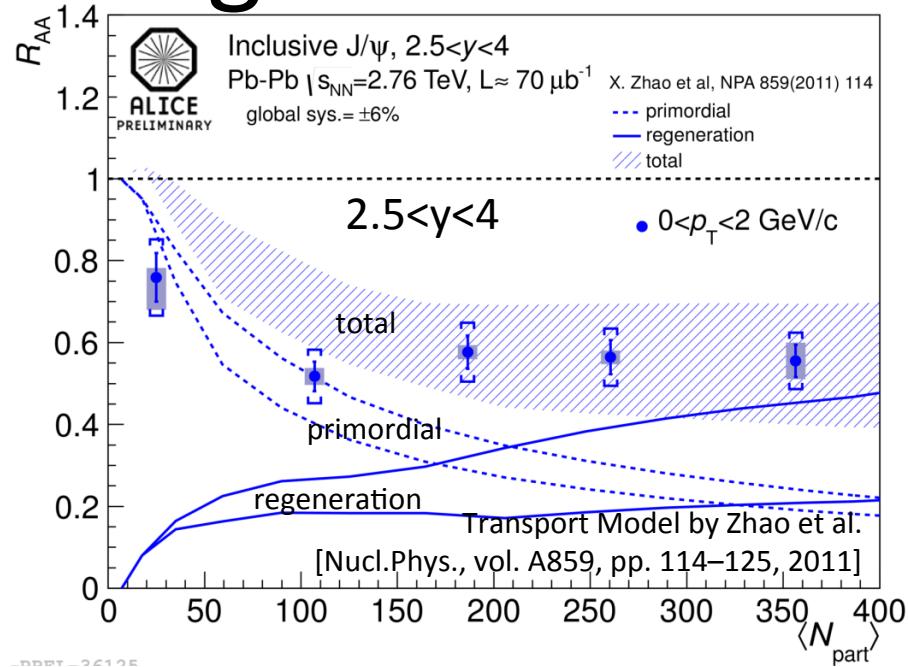
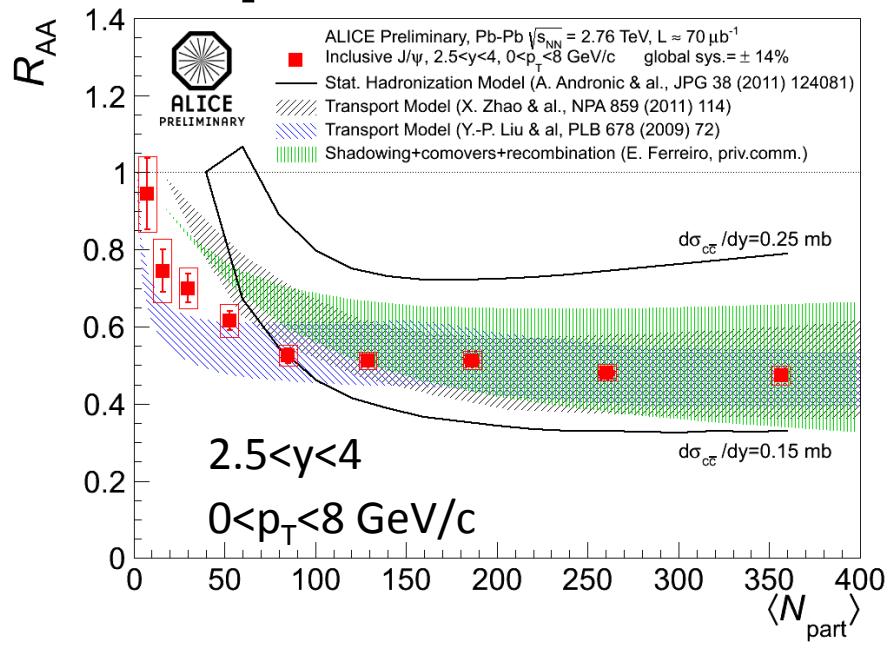
Leptons: “ $b > c$ ” for $p_T > 5$ GeV/c (FONLL)

$\Upsilon(1s)$ suppression



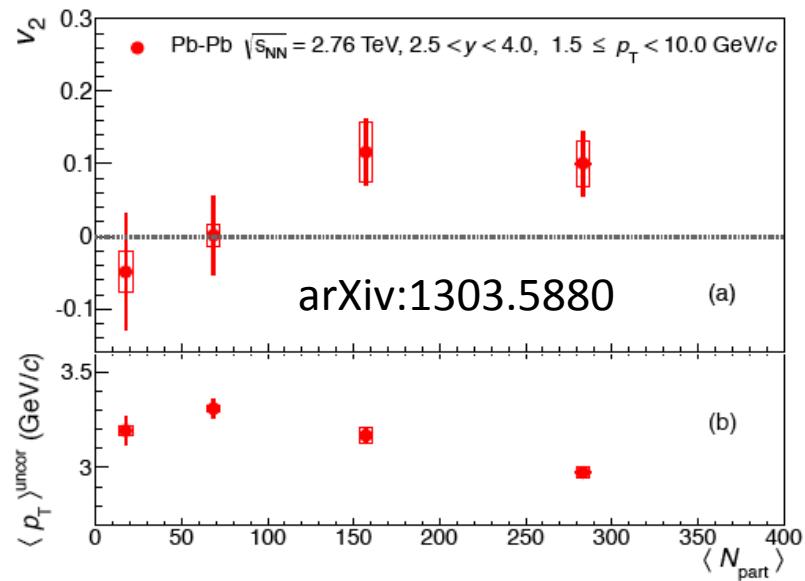
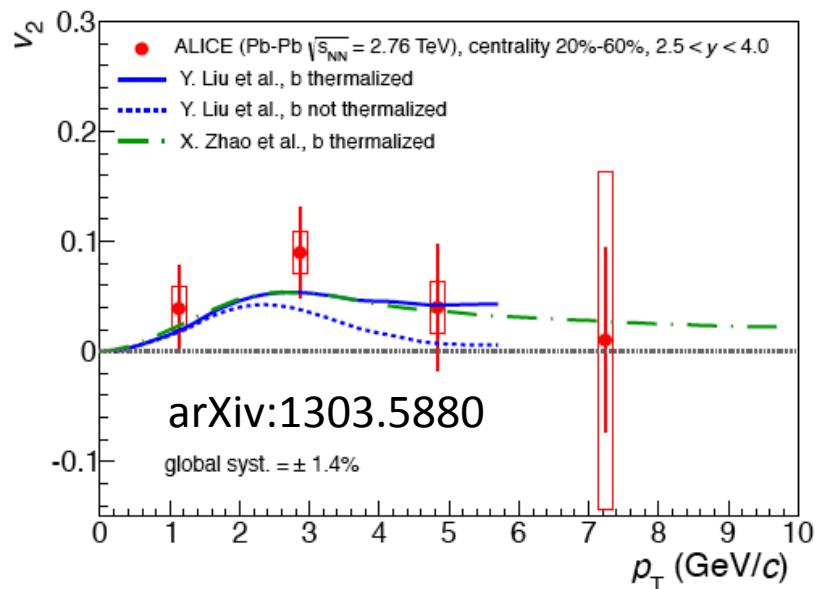
- Models based on anisotropic hydrodynamics formalism with a boost-invariant wide plateau temperature profile in the spatial rapidity direction can reproduce the results (CNM effects not included)
- A kinetic model including suppression & (small) regeneration can reproduce data as well

J/ ψ suppression & regeneration?



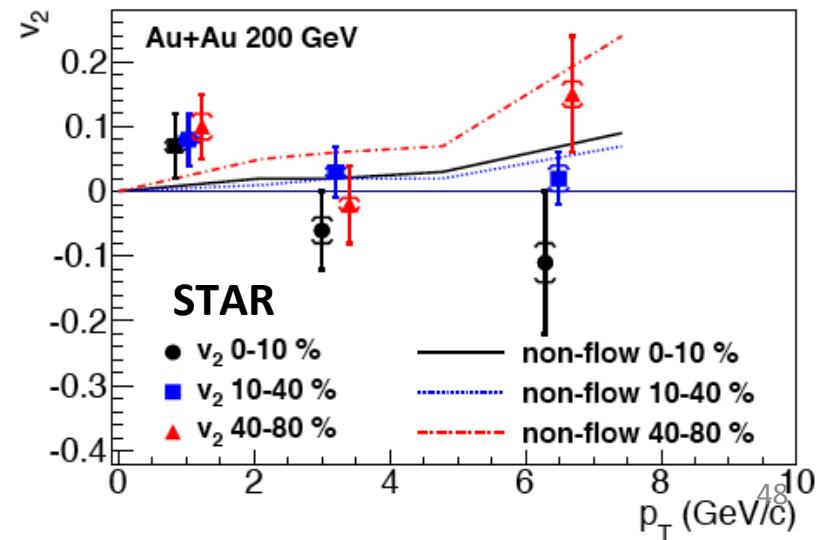
Models including a **relevant contribution from recombination (>50%)** or models with all J/ ψ produced at hadronization from deconfined quarks can describe data reasonably well

Inclusive J/ ψ v_2



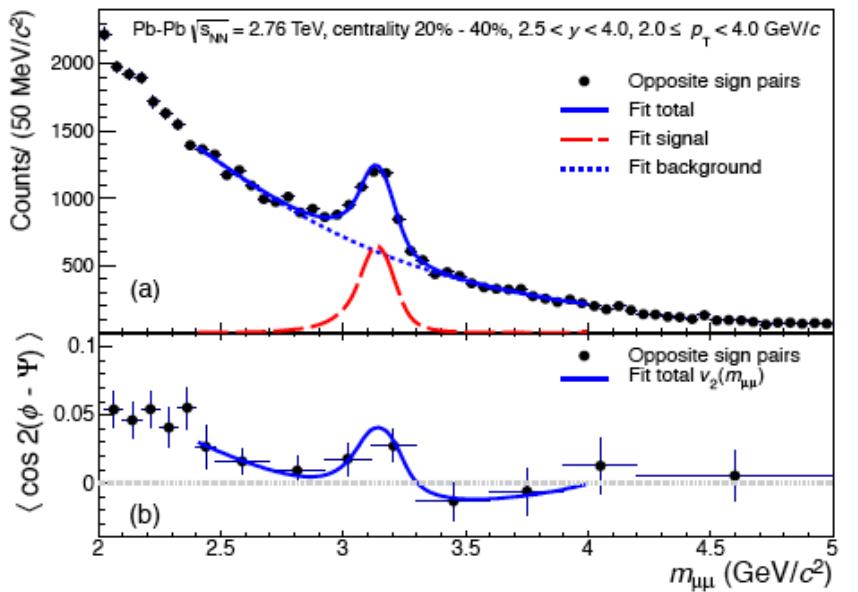
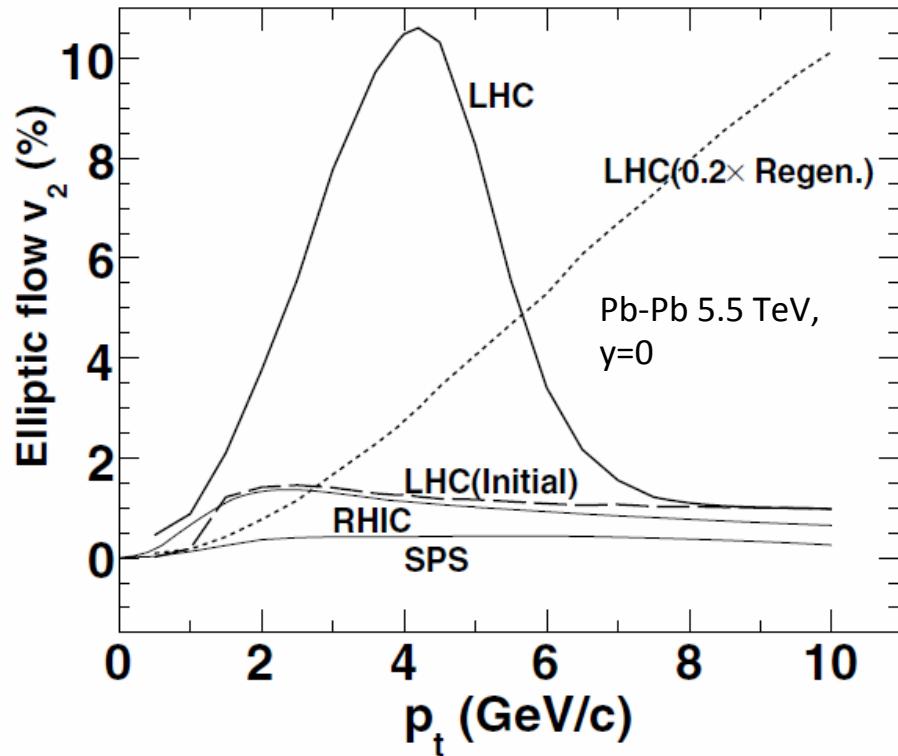
J/ ψ produced via recombination of thermal deconfined c-quarks should show a non zero v_2 :

- hint of non-zero v_2 from data
- qualitative agreement with transport models including thermalization
- not large variation of $\langle p_T \rangle$ with centrality-> genuine trend
- STAR at RHIC: J/ ψ v_2 compatible with 0



J/ ψ elliptic flow

Liu, Xu and Zhuang NPA834(2010) 317c

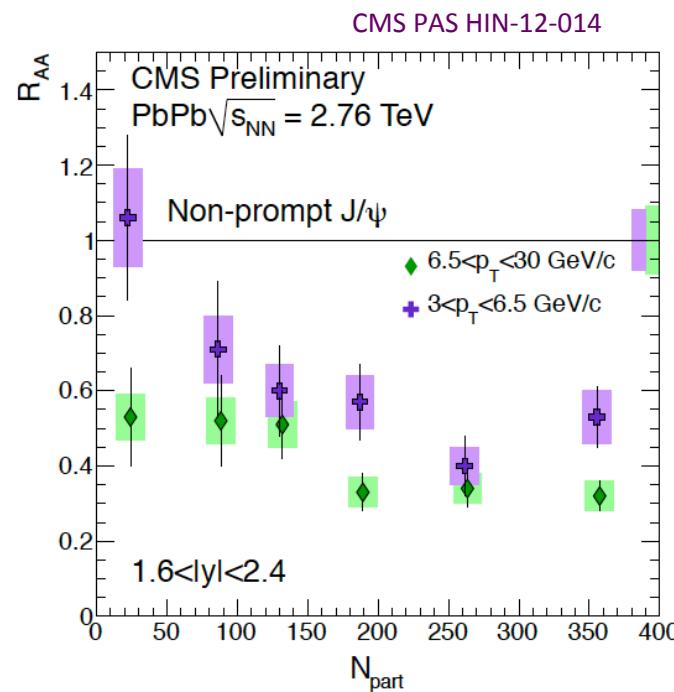
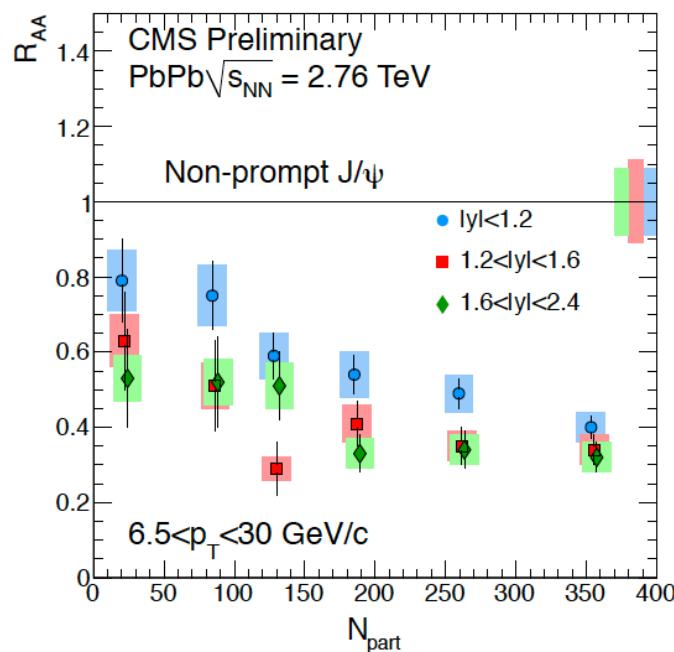


$$v_2^{obs}(m_{\mu\mu}) = v_2^{obs,sig} \alpha(m_{\mu\mu}) + v_2^{obs,back} (1 - \alpha(m_{\mu\mu}))$$

$$\alpha(m_{\mu\mu}) = \frac{S}{S+B}(m_{\mu\mu})$$

- Analysis performed with the EP approach (using EP from VZERO-A)
- Correct v_2^{obs} by the event plane resolution, $v_2 = v_2^{obs}/\sigma_{EP}$ (σ_{EP} measured by 3 sub-events method)
- Checks with alternative methods performed

J/ ψ from b-hadron decay

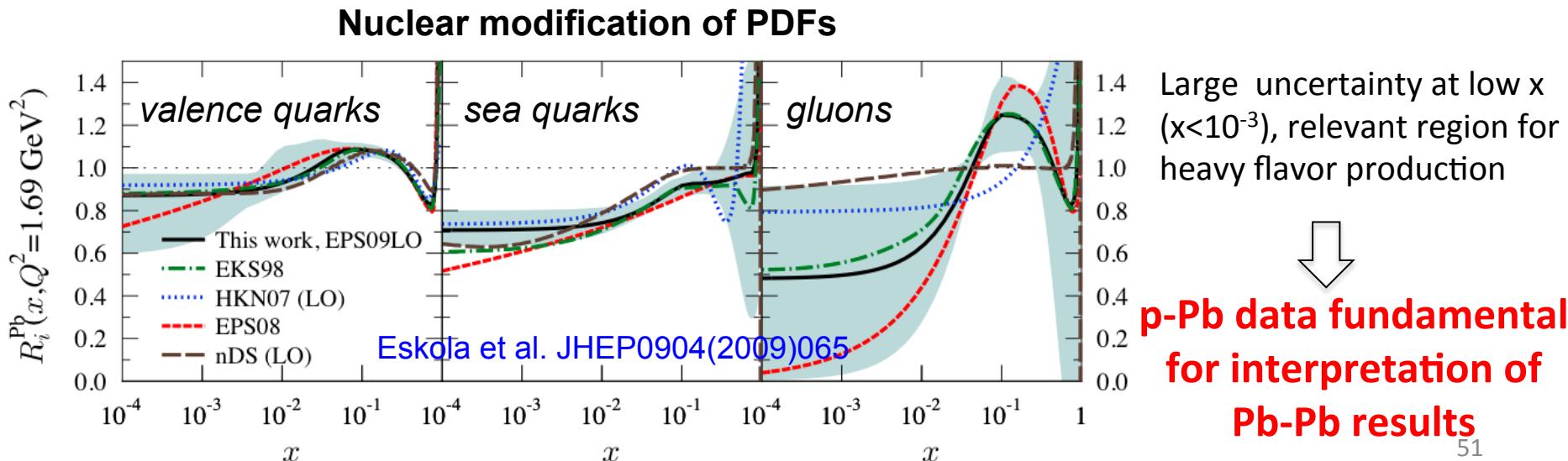


Cold nuclear matter effects

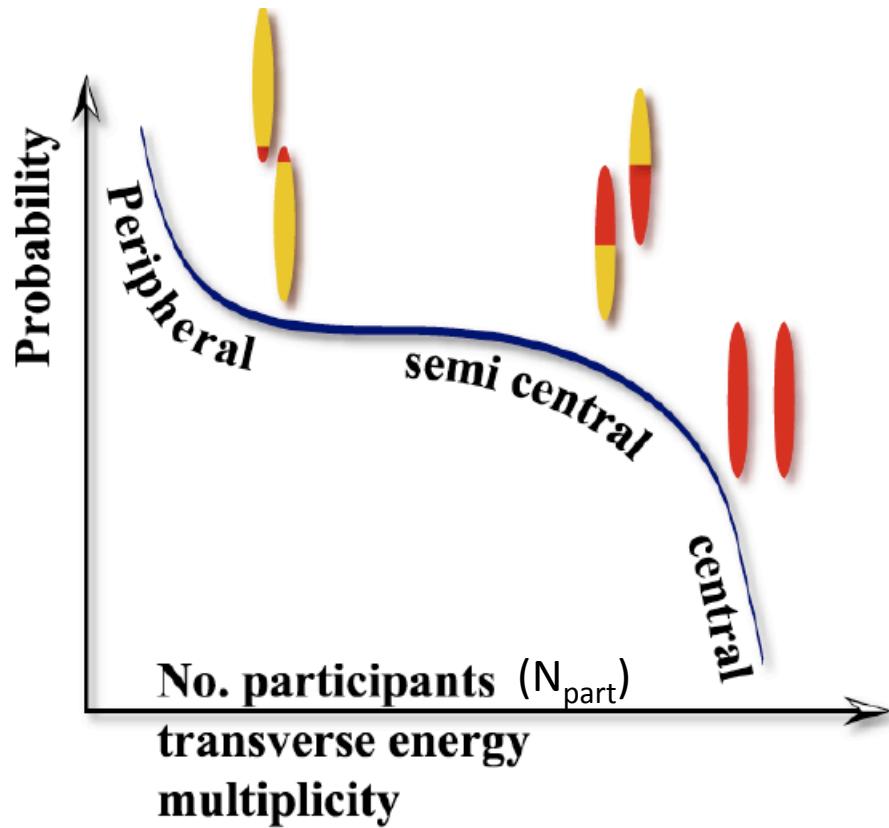
Even in the absence of effects from “hot deconfined medium” R_{AA} can be different from 1 due to cold nuclear matter effects (CNM). Many effects, main ones:

L. Manceau on Monday
C. Loizides on Wednesday

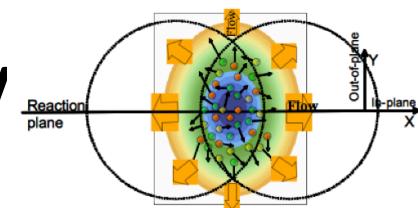
- **Parton shadowing**: modification of nuclear PDFs with respect to proton ones (suppression at low x value).
- **Cronin effect** (enhancement of intermediate- p_T hadron spectra in p-A collisions), due to transverse momentum (k_T) broadening of both initial and final-state partons
- **Parton energy loss** in cold nuclear matter
- (for quarkonia) **Nuclear absorption** of the $q\bar{q}$ pair before hadronization



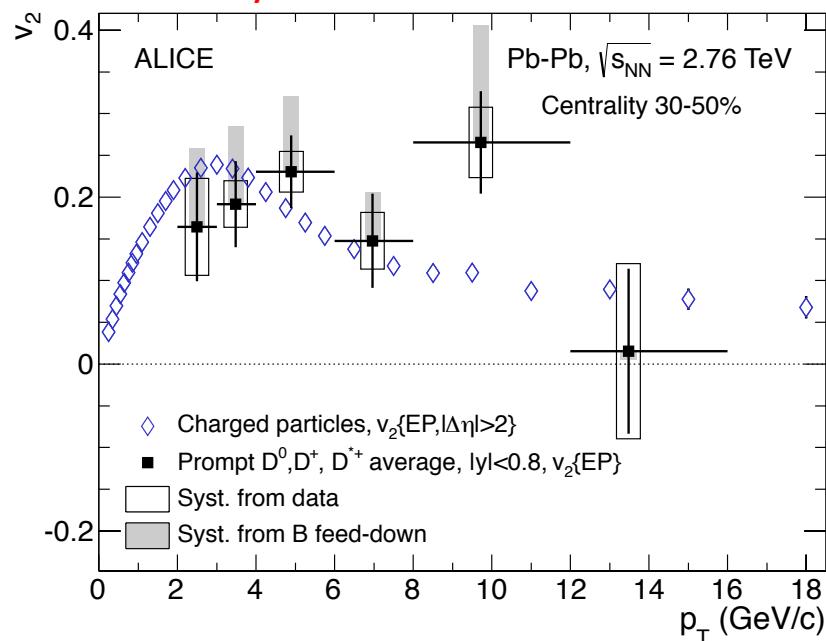
Geometry of AA collisions



D meson azimuthal anisotropy



Today on arXiv: 1305.2707

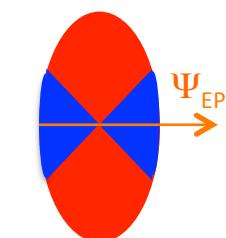


- at intermediate-high p_T : path-length dependence of energy loss

R_{AA} “in-plane” (shorter path in the medium)
vs. R_{AA} “out-of-plane” (longer path)

$$v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N^{\text{In-Plane}} - N^{\text{Out-Of-Plane}}}{N^{\text{In-Plane}} + N^{\text{Out-Of-Plane}}}$$

R_2 : event plane resolution



First measurement of D meson v_2 !

- D meson $v_2 > 0$ in 30-50% class
- Comparable to v_2 of charged hadrons

