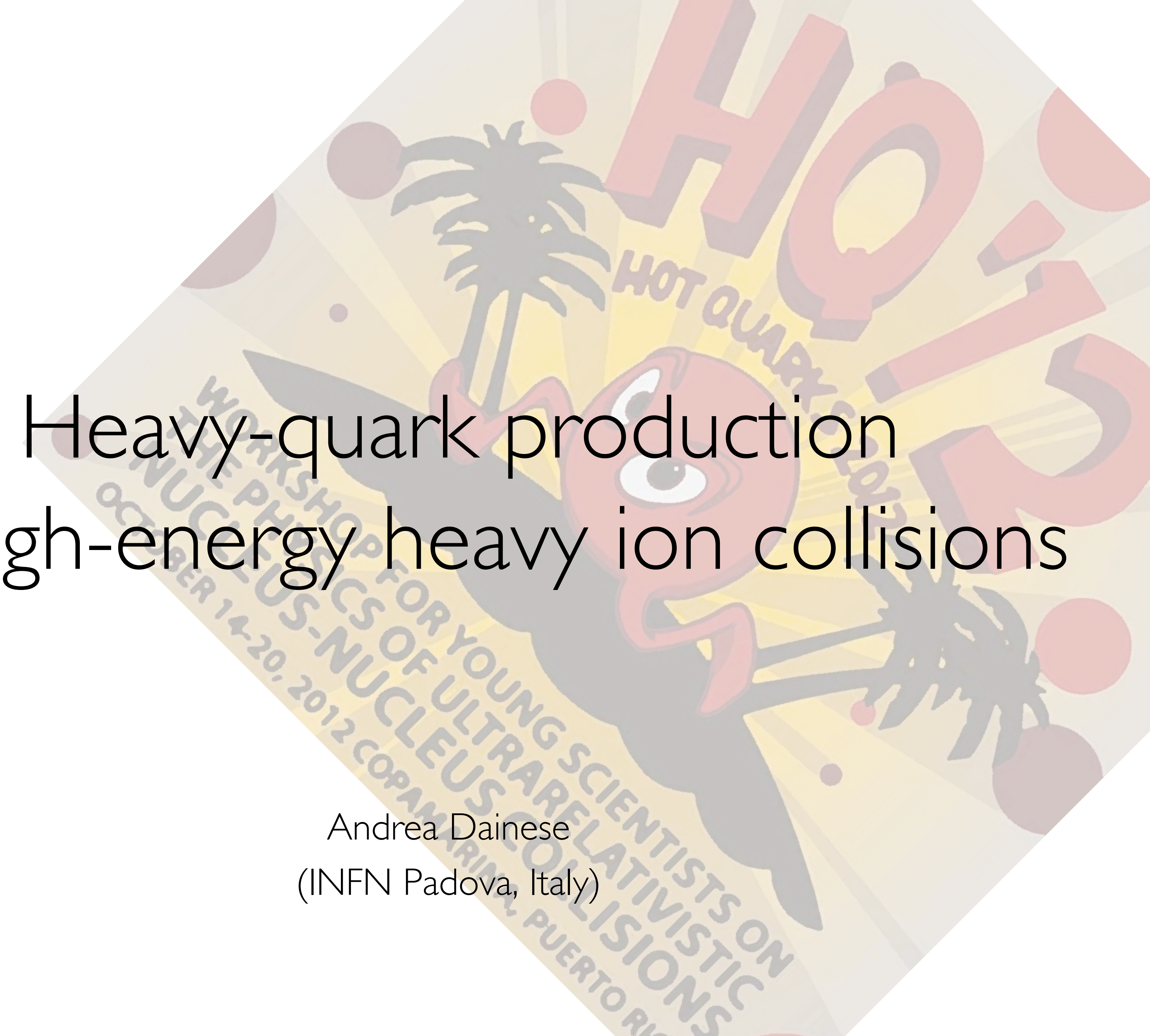
Heavy-quark production in high-energy heavy ion collisions



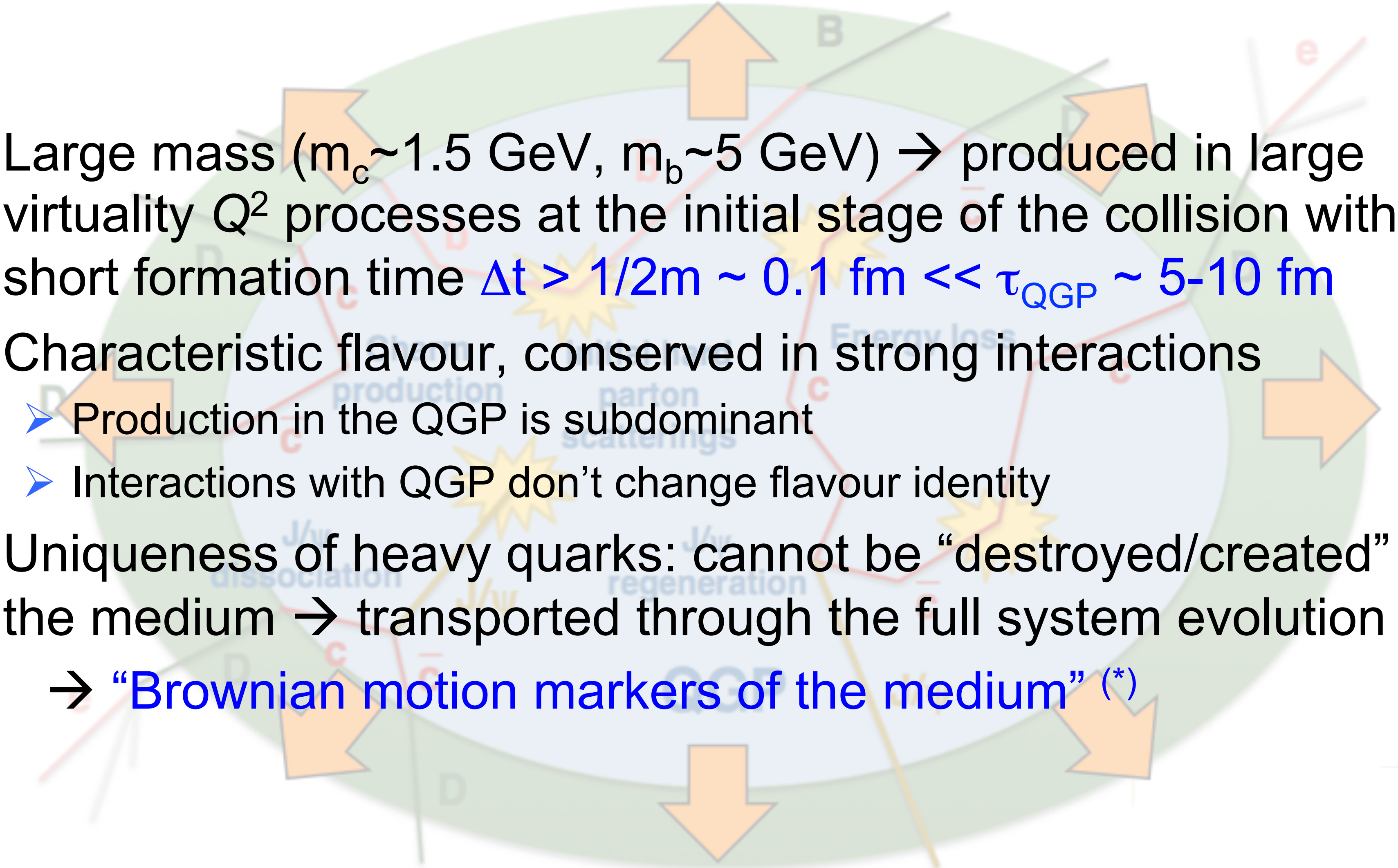
Andrea Dainese
(INFN Padova, Italy)

Outline of the Talk

- Introduction: “what’s special about heavy flavour” and “the two historical pillars”
- Heavy flavour production from pp to AA collisions
  - Production processes
  - Initial state effects and pA
  - Hot medium final state effects
- Summary

} Selected results from RHIC and LHC

What's special about heavy quarks

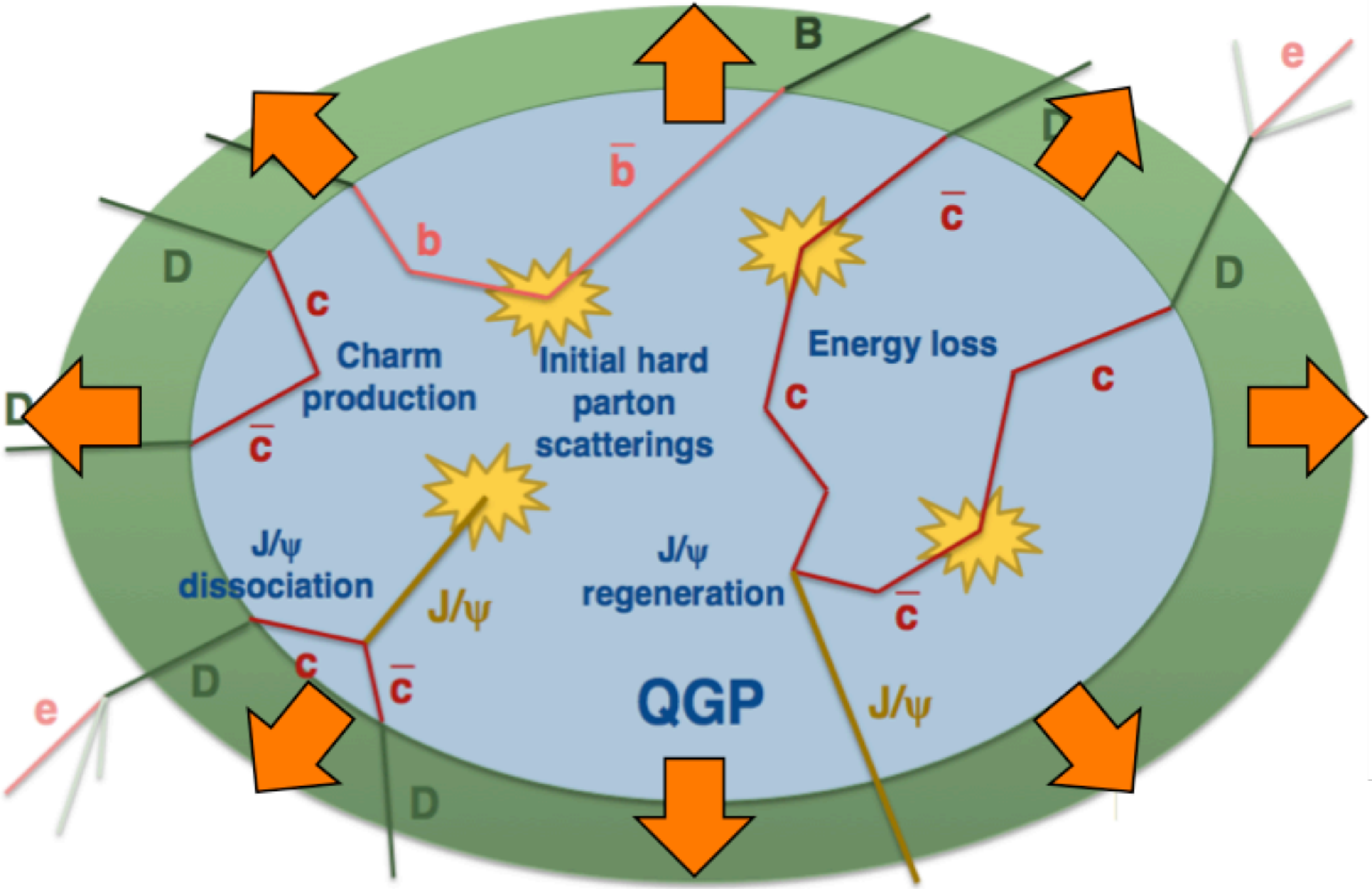


- ◆ Large mass (m_c~1.5 GeV, m_b~5 GeV) → produced in large virtuality Q^2 processes at the initial stage of the collision with short formation time $\Delta t > 1/2m \sim 0.1$ fm $<< \tau_{QGP} \sim$ 5-10 fm
- ◆ Characteristic flavour, conserved in strong interactions
  - ➢ Production in the QGP is subdominant
  - ➢ Interactions with QGP don't change flavour identity
- ◆ Uniqueness of heavy quarks: cannot be "destroyed/created" in the medium → transported through the full system evolution

  → "Brownian motion markers of the medium" (*)

(*) Ralf Rapp

What's special about heavy quarks

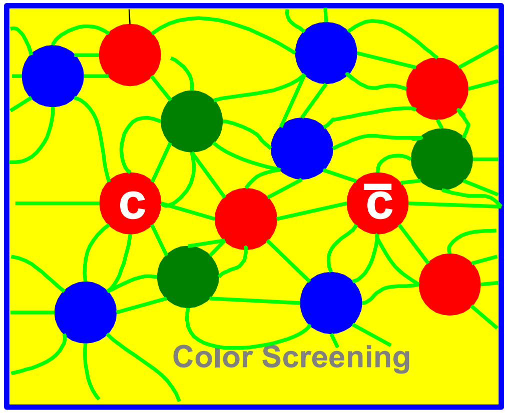


graphics courtesy J. Uphoff

The two “historical” pillars

Dissociation of $Q\overline{Q}$ Via colour-screening

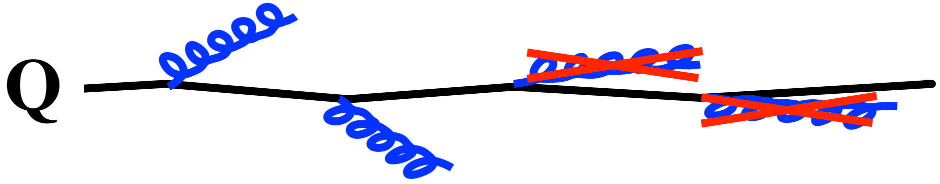
Matsui and Satz, 1986



Direct probe of medium deconfinement and temperature

Mass dependence of parton energy loss (dead cone)

Dokshitzer and Kharzeev, 2001

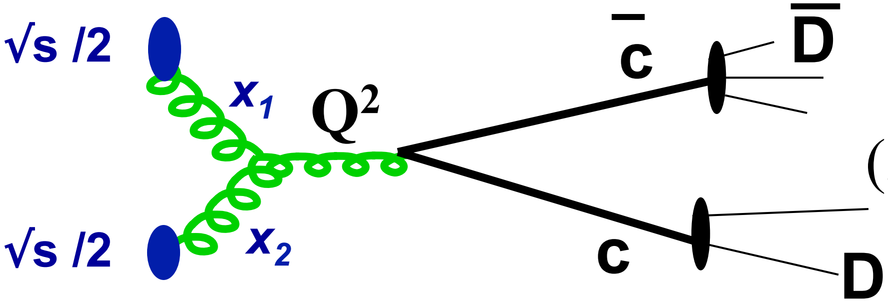


Direct probe of QCD interaction dynamics over extended systems

These make of Heavy Quarks very special probes of the QGP

Open heavy-flavour production: pp

proton-proton collisions: factorised pQCD approach



$$\frac{d\sigma^D}{dp_T^D}(\mu_F,\mu_R) =$$

$$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$$

$$\mu^2_{F,R} \sim Q^2$$

$$= PDFs(x_1,x_2,\mu_F^2)\otimes\frac{d\hat{\sigma}^c}{dp_T^c}(\alpha_S(\mu_R^2))\otimes D_{c\to D}(\mu_F^2,\frac{p_D}{p_c})$$

PDF:

- Q^2 evolution calculated in pQCD
- initial condition from data (HERA)

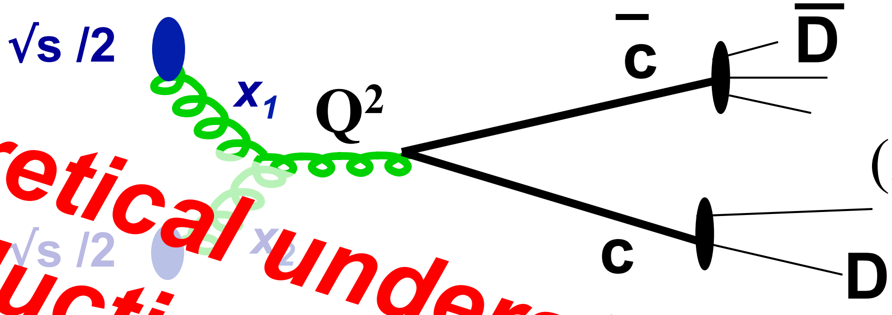
FF:

- non-perturbative
- phenomenolgy
  + fit to data (e^+e^-)

calculable as perturbative series of strong coupling $\alpha_s(\mu_R)$

Open heavy-flavour production: pp

proton-proton collisions: factorised pQCD approach



$(x_1 x_2 s \sim Q^2 \sim M^2_{c\bar{c}})$

Theoretical understanding of pp production is crucial to have a well-calibrated probe in AA

$$\frac{d\sigma^D}{dp_T^D}(\mu_F,\mu_R) = PDFs(x_1,x_2,\mu_F^2) \otimes \frac{d\hat{\sigma}^c}{dp_T^c}(\alpha_s(\mu_R^2)) \otimes D_{c\to D}(\mu_F^2, \frac{p_D}{p_c})$$

$\mu_{F,R} \sim Q^2$

PDF:
- Q^2 evolution calculated in pQCD
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- non-perturbative
- phenomenolgy
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calculable as perturbative series of strong coupling $\alpha_s(\mu_R)$

pp → $Q\bar{Q}$+X: pQCD calculations vs data

- Calculation of partonic cross section $\hat{\sigma}$
  - Fixed Order (NLO) Massive

MNR: Mangano, Nason, Ridolfi, NPB373 (1992) 295

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + \cancel{O(\alpha_s^4)} \qquad B(m) = \beta(m) + \gamma(m)\log(\mu/m)$$

$$\mu \approx p_T$$

  - state-of-the-art: Fixed Order Next-to-Leading Log (FONLL)

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

$$\frac{d\sigma}{dp_T} = A(m)\,\alpha_s^2 + B(m)\,\alpha_s^3 + G(m,p_T)\left[\alpha_s^2 \sum_{i=2}^{\infty} a_i\,[\alpha_s \log(\mu/m)]^i + \alpha_s^3 \sum_{i=1}^{\infty} b_i\,[\alpha_s \log(\mu/m)]^i\right]$$

→ more accurate at high p_T; coincides with NLO for low p_T (total cross section)

pp → $Q\bar{Q}$+X: pQCD calculations vs data

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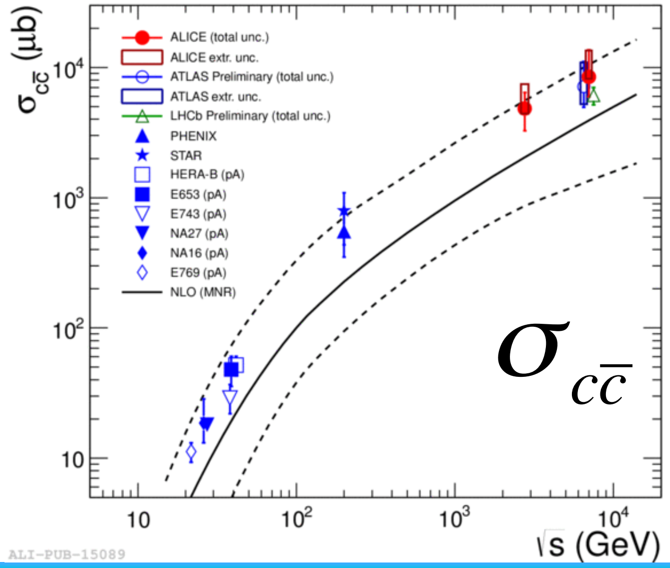
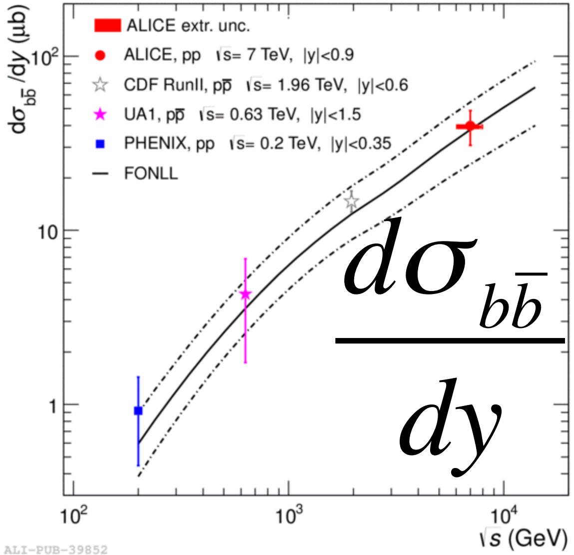


$$\sigma_{c\bar{c}}$$

from JHEP07 (2012) 191



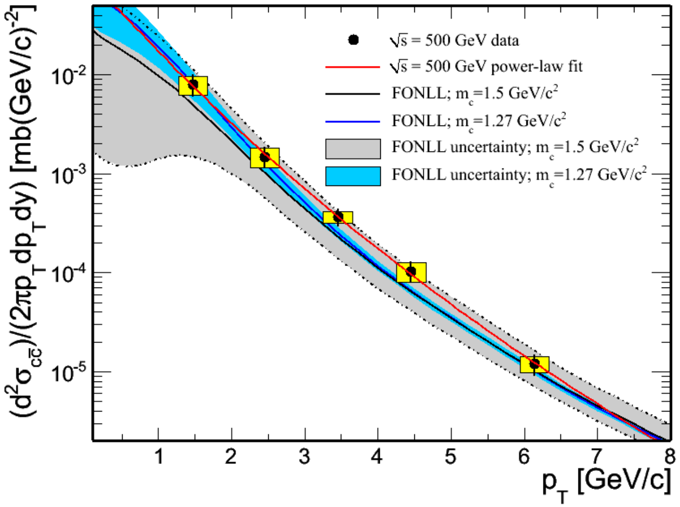
$$\frac{d\sigma_{b\bar{b}}}{dy}$$

from arXiv:1205.5880

pp → $Q\bar{Q}$+X: pQCD calculations vs data

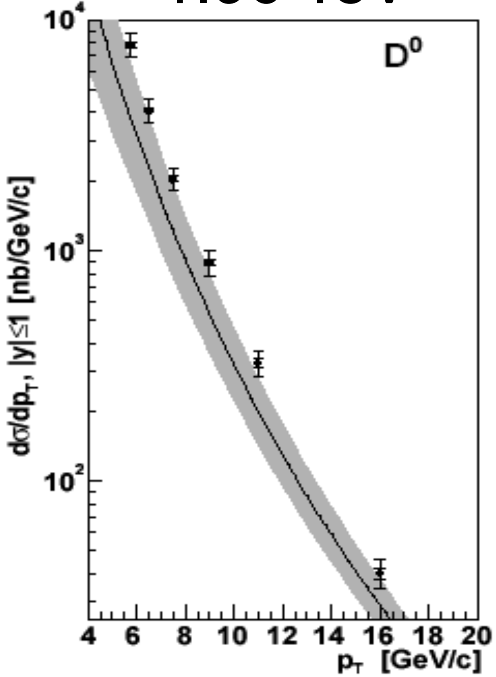
Charm p_T-differential cross section

0.5 TeV



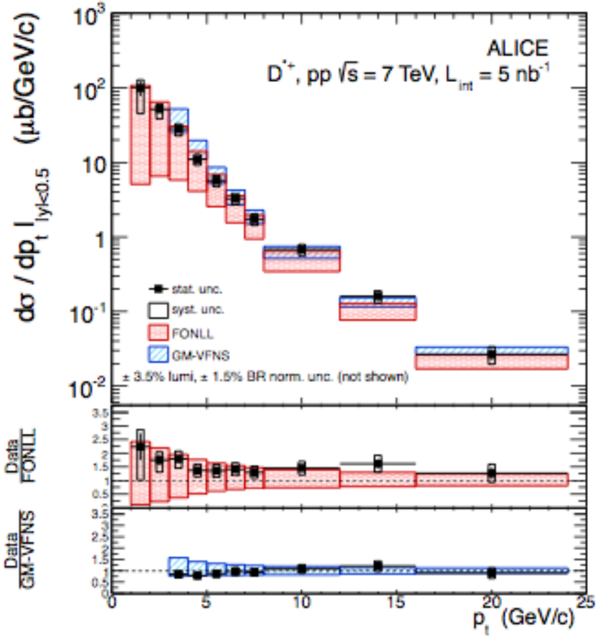
STAR, W.Xie, QM2012

1.96 TeV



CDF, PRL91 (2003) 241804

7 TeV



ALICE, JHEP01 (2012) 128

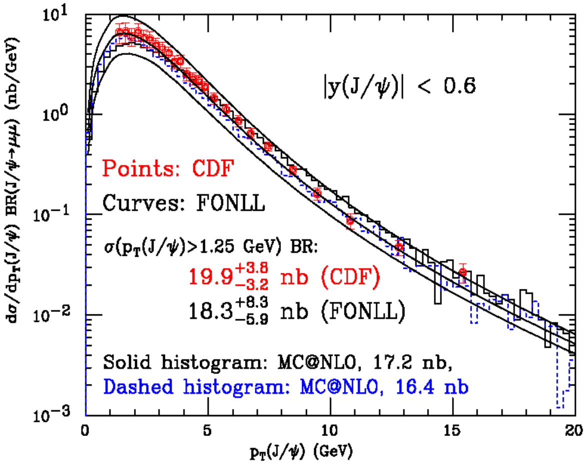
- Charm production described within uncertainties
- Consistently at upper limit of theoretical band from 0.2 to 7 TeV

pp → $Q\bar{Q}$+X: pQCD calculations vs data

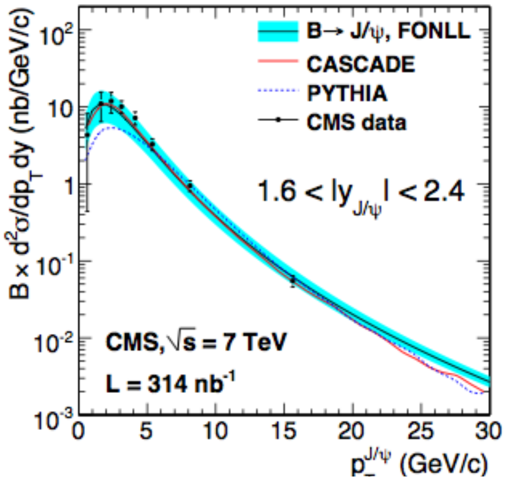
Beauty p_T-differential cross section

1.96 TeV

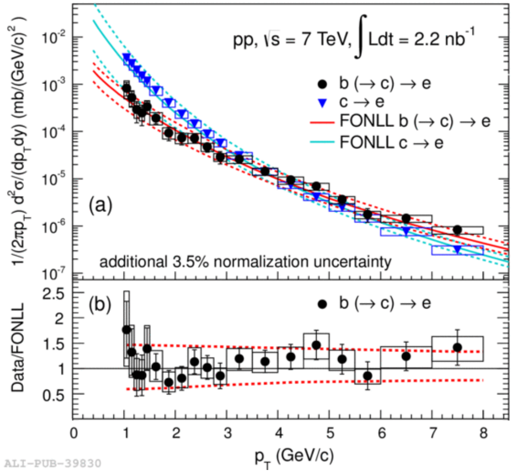
7 TeV



CDF, PRD71 (2005) 032001



CMS, EPJC71 (2011) 1575



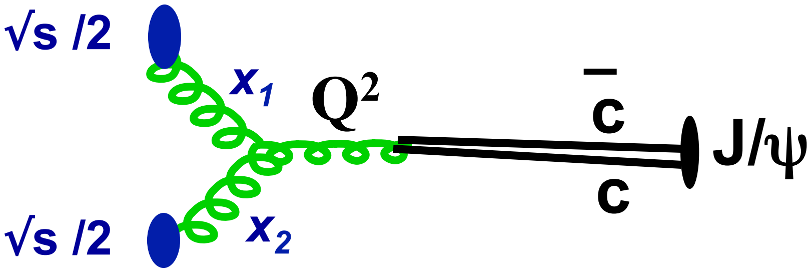
ALICE, arXiv:1208.1902

- Beauty production described very well by central value of calculation

Quarkonia production: pp

proton-proton collisions: factorised pQCD approach

$$\frac{d\sigma^{\psi}}{dp_T^{\psi}}(\mu_F,\mu_R) =$$



$$(x_1 x_2 s \sim Q^2 \sim M_{c\bar{c}}^2)$$

$$= PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^{c\bar{c}}}{dp_T^{c\bar{c}}} \otimes P(c\bar{c} \rightarrow \psi)$$

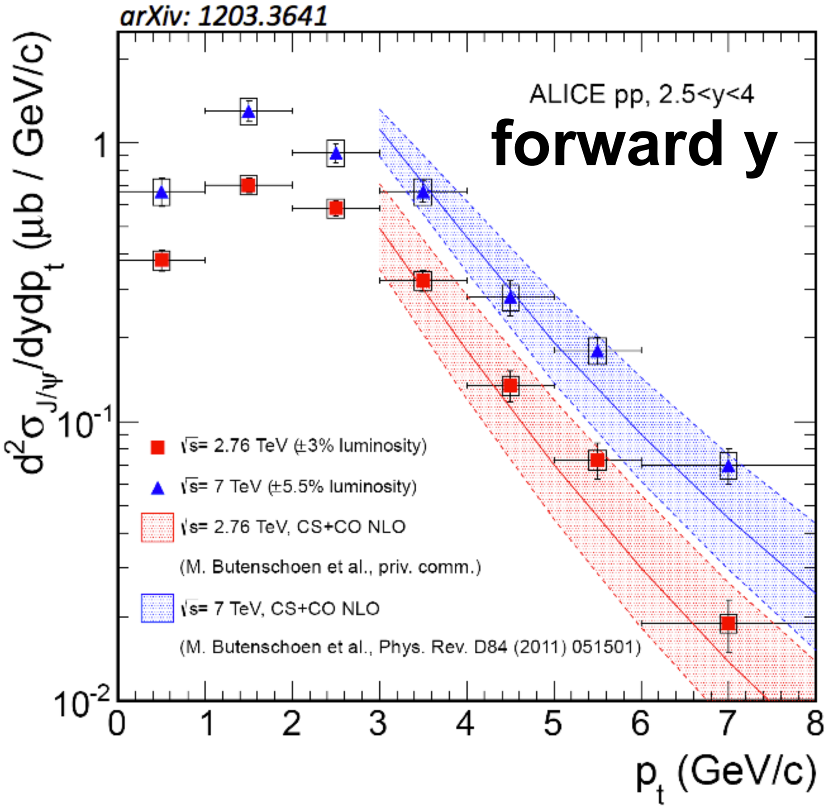
Long-distance matrix elements, embed the non-perturbative part of the calculation

At variance with the case of fragmentation, cannot be "taken" from e^+e^- data (colour neutralization very different in hadronic environment)

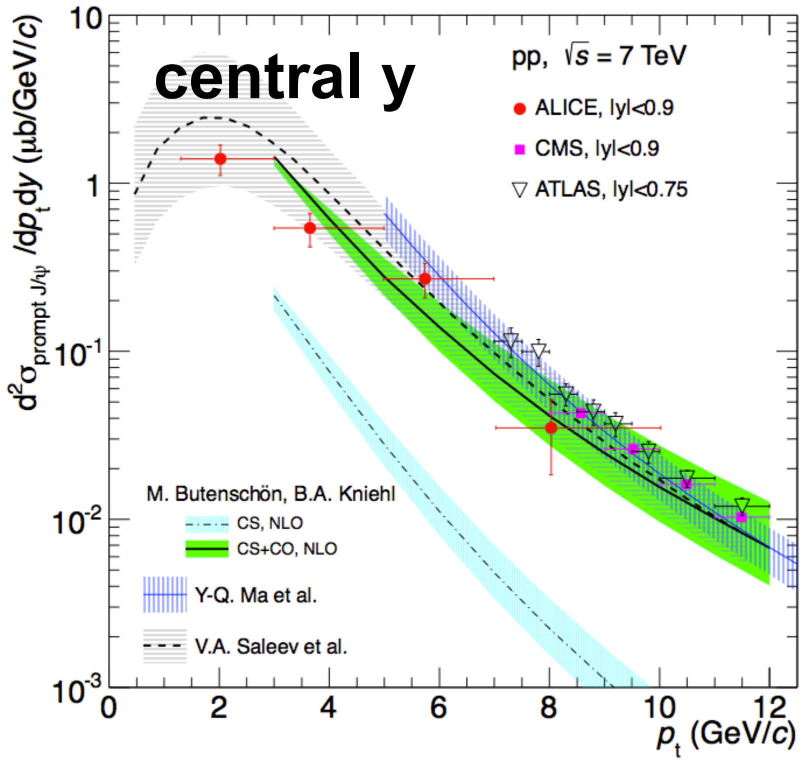
Colour Singlet Model (CSM): the colour of the Q-Qbar neutralizes in the hard process

Nonrelativistic QCD(NRQCD): the colour can be neutralized also in the long-distance part; the hard scattering can create both singlet and octet Q-Qbar states

pp → J/ψ +X: pQCD vs. data (LHC)



ALICE, arXiv:1203.3641

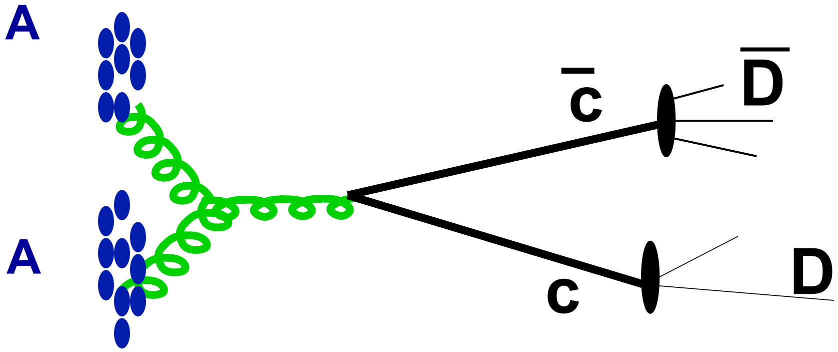


ALICE, arXiv:1205.5880
ATLAS, NPB850 (2011) 387
CMS, JHEP02 (2012) 011

- Cross section described by NRQCD at NLO (CO+CS)
  - Not by CS alone
- Large theoretical uncertainties

HF production: from pp to AA

Binary scaling for hard yields: $\mathrm{d}N_{AA}/\mathrm{d}p_T = \mathrm{d}N_{pp}/\mathrm{d}p_T \times \langle N_{coll} \rangle$



$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}N_{pp}/\mathrm{d}p_T \times \langle N_{coll} \rangle}$$

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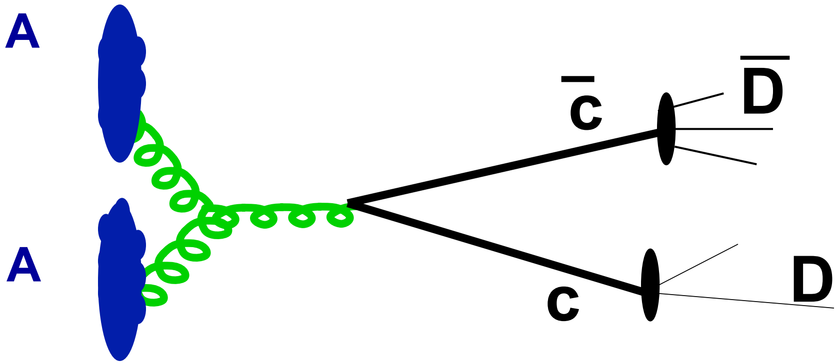


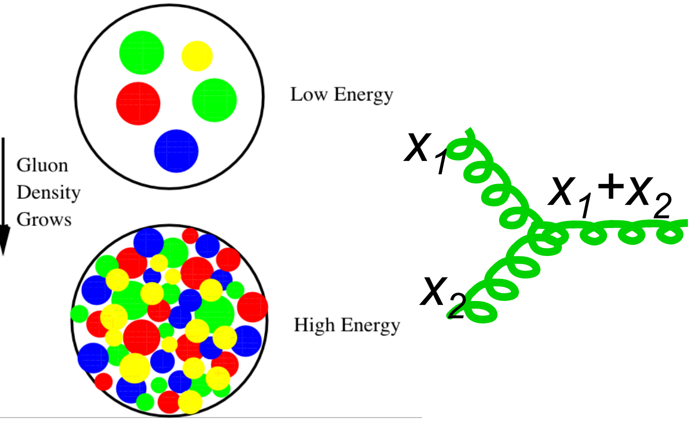
$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{\mathrm{d}N_{pp}/\mathrm{d}p_T \times \langle N_{coll} \rangle}$$

Binary scaling is "broken" by:

- ***initial-state effects:***
  PDF saturation/shadowing → most relevant at high √s
  k_T broadening ("Cronin")
  J/ψ "absorption" in CNM

Small-x gluon saturation & PDF shadowing

- Onset of saturation and non-linear PDF evolution: gluons are numerous enough (low-*x*) & extended enough (low-Q^2) to overlap and merge:



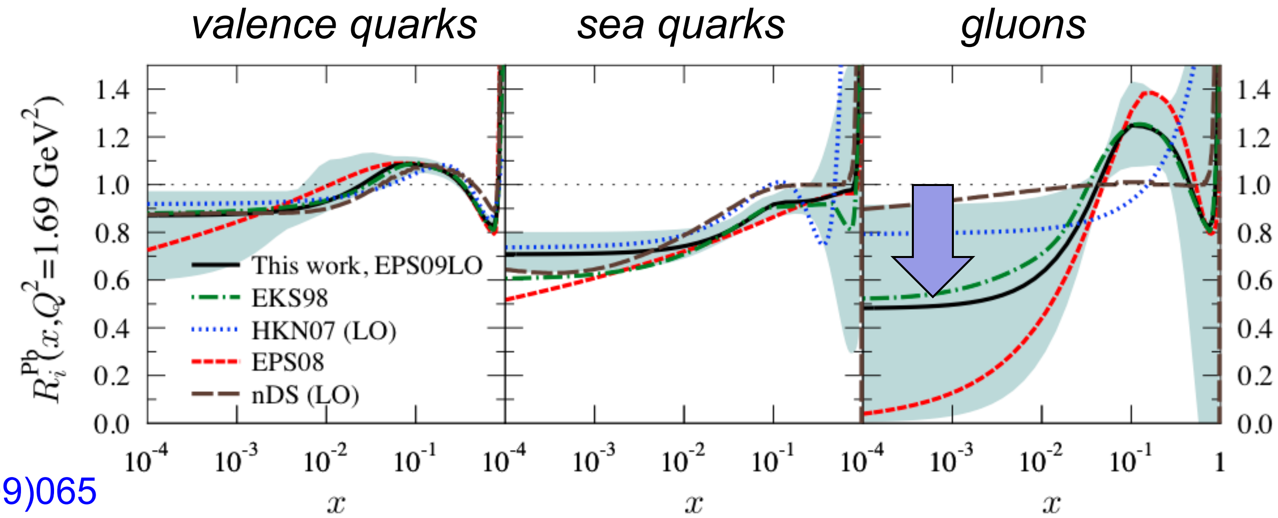
$$Q_s^2 \sim \alpha_s \frac{xG_A(x,Q_s^2)}{\pi R_A^2} \qquad [G_A(x,Q^2)=A\,g(x,Q^2)]$$

$$\sim A^{1/3} x^{-\lambda} \sim A^{1/3} (\sqrt{s})^{\lambda} \sim A^{1/3} e^{\lambda y} \qquad (\lambda \sim 0.3)$$

$Q_s^2 \sim 2$ GeV^2 (at 200 GeV) → x < 10^{-3}-10^{-2}

$Q_s^2 \sim 5$ GeV^2 (at 5 TeV) → x < 10^{-4}-10^{-3}

Effective reduction of the parton flux (shadowing) → also described with nuclear-modified PDFs



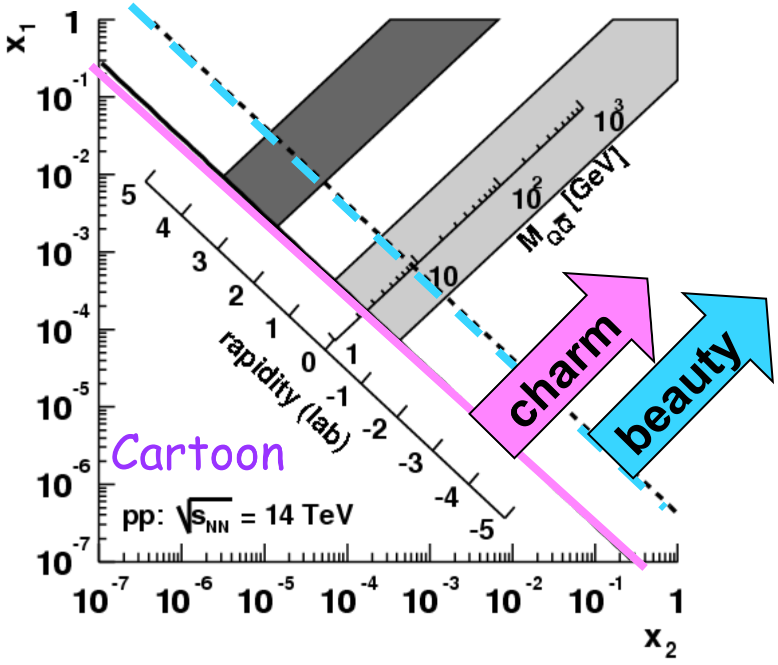
see e.g. Eskola et al. JHEP0904(2009)065

Heavy flavour at LHC: a probe sensitive to small-x gluon dynamics

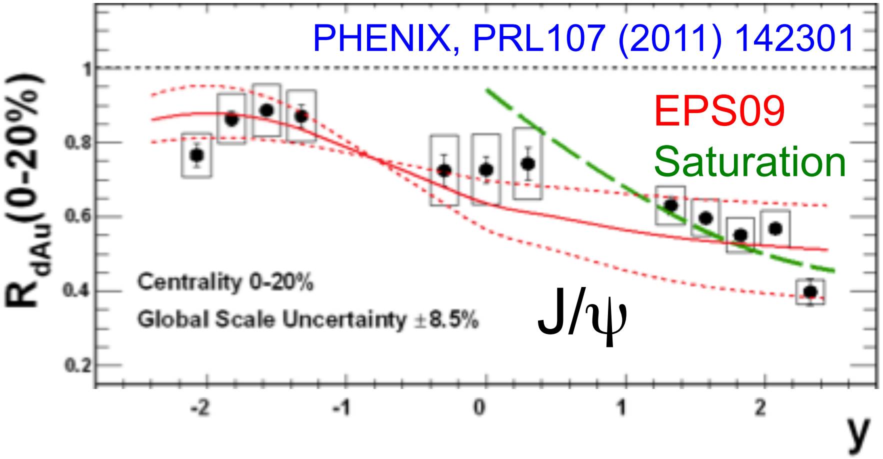
- Charm production at low p_T: **Q^2 ($4m_c^2 \sim$ 5-10 GeV^2) ~ Q_s^2**
- Down to $x \sim 10^{-4}$ with charm at $y=0$, $x \sim 10^{-6}$ at $y=4$

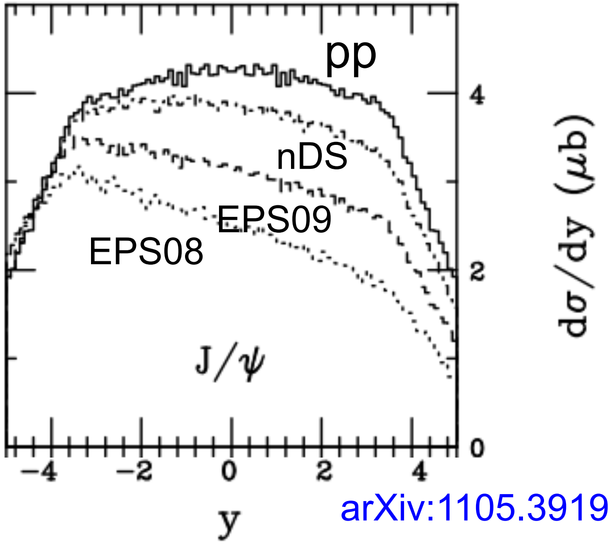
→ interpretation of HF (charm) measurements in AA requires pA reference

→ charm in pA: access to small-x gluons with perturbative probes



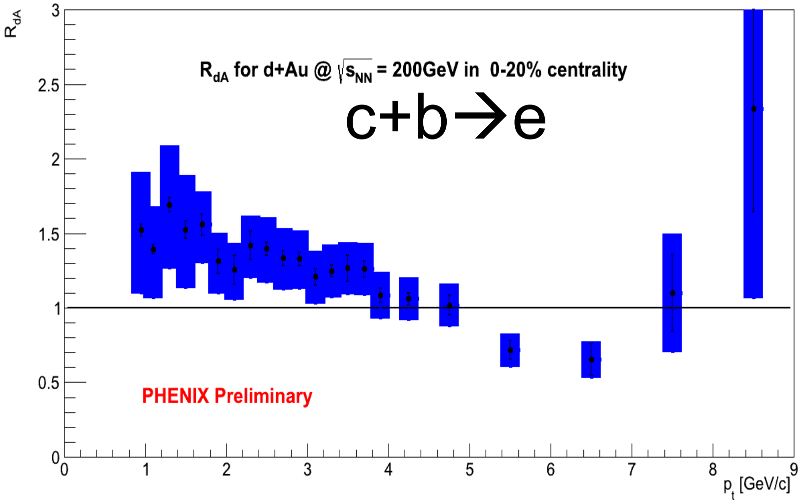
Charm in pA:
RHIC results and predictions for LHC

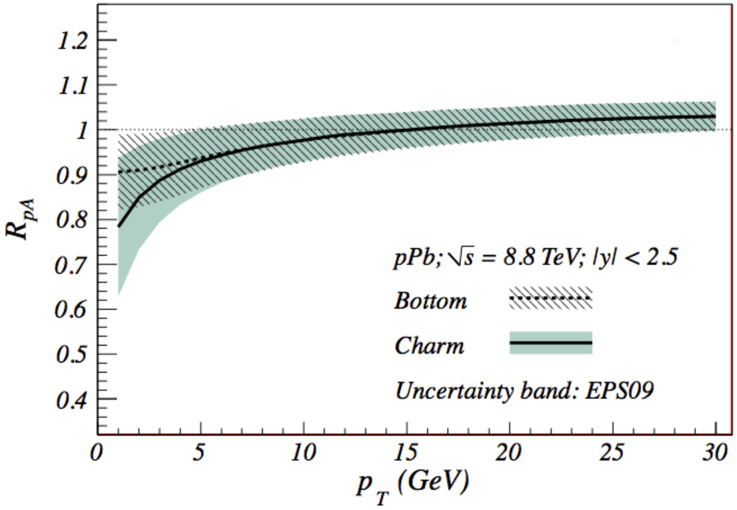




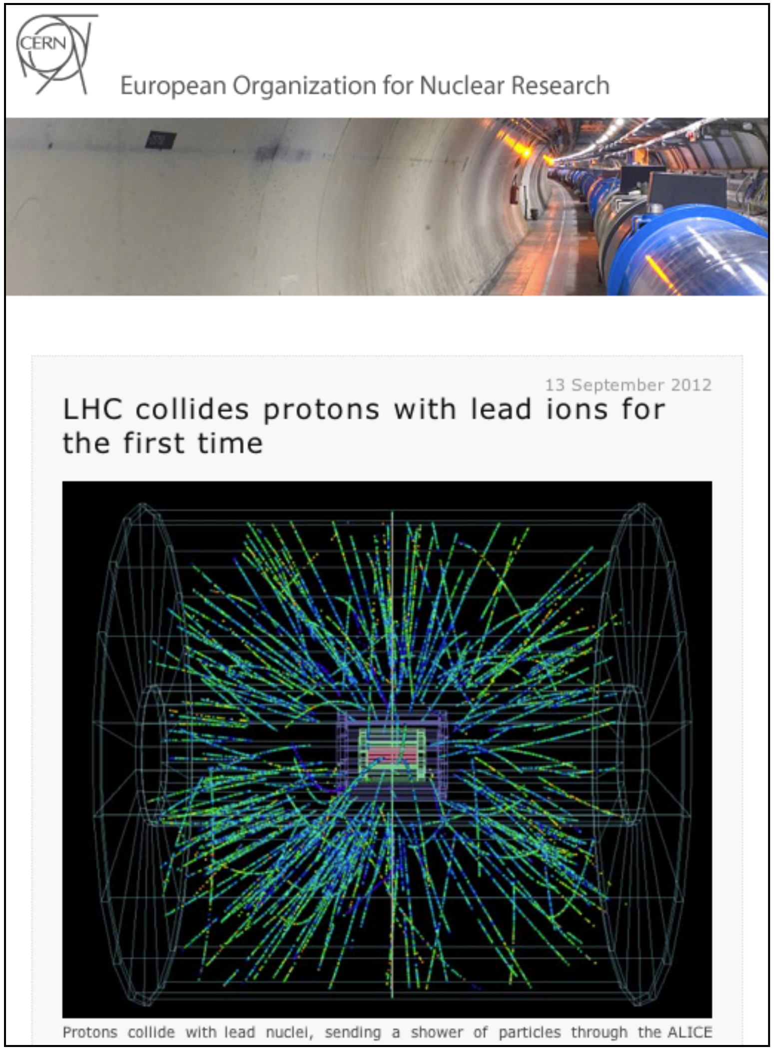
arXiv:1105.3919

- J/ψ well described by shadowing
- Low-p_T electrons surprisingly enhanced





p-Pb at LHC is behind the corner …
… meanwhile, a good appetizer



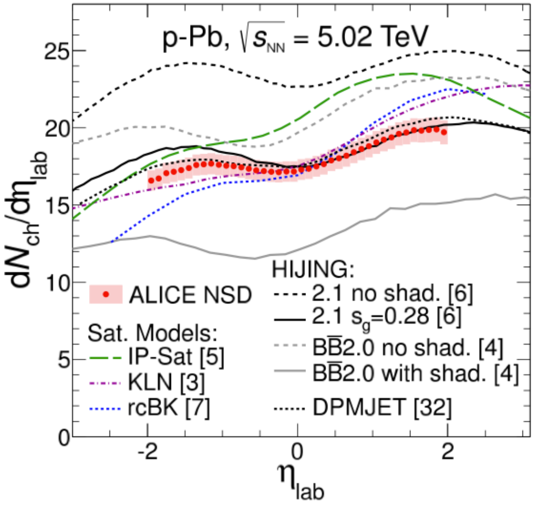
European Organization for Nuclear Research

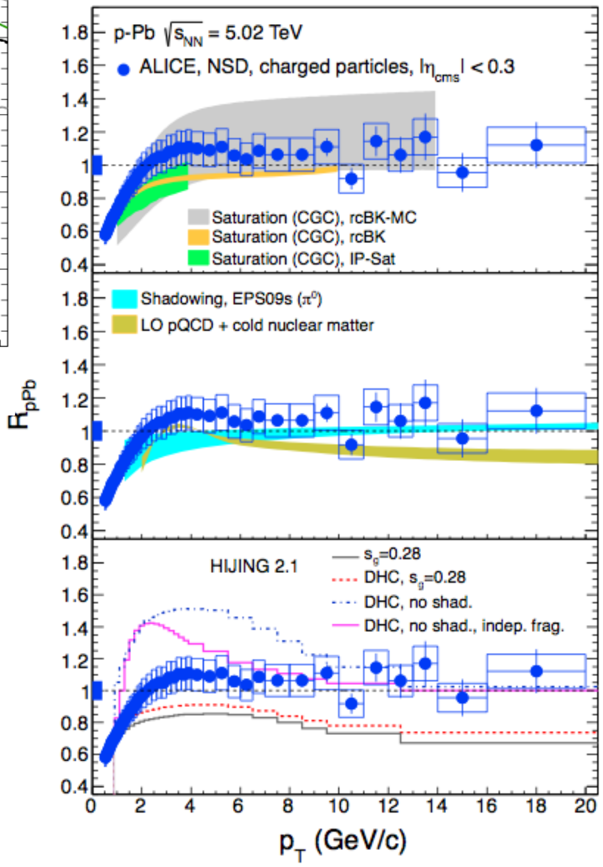
13 September 2012

LHC collides protons with lead ions for the first time

Protons collide with lead nuclei, sending a shower of particles through the ALICE

ALICE, arXiv:1210.3615, arXiv:1210.4520



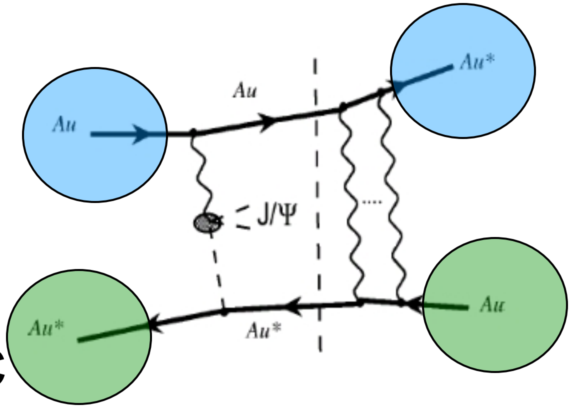


\+

near-side ridge

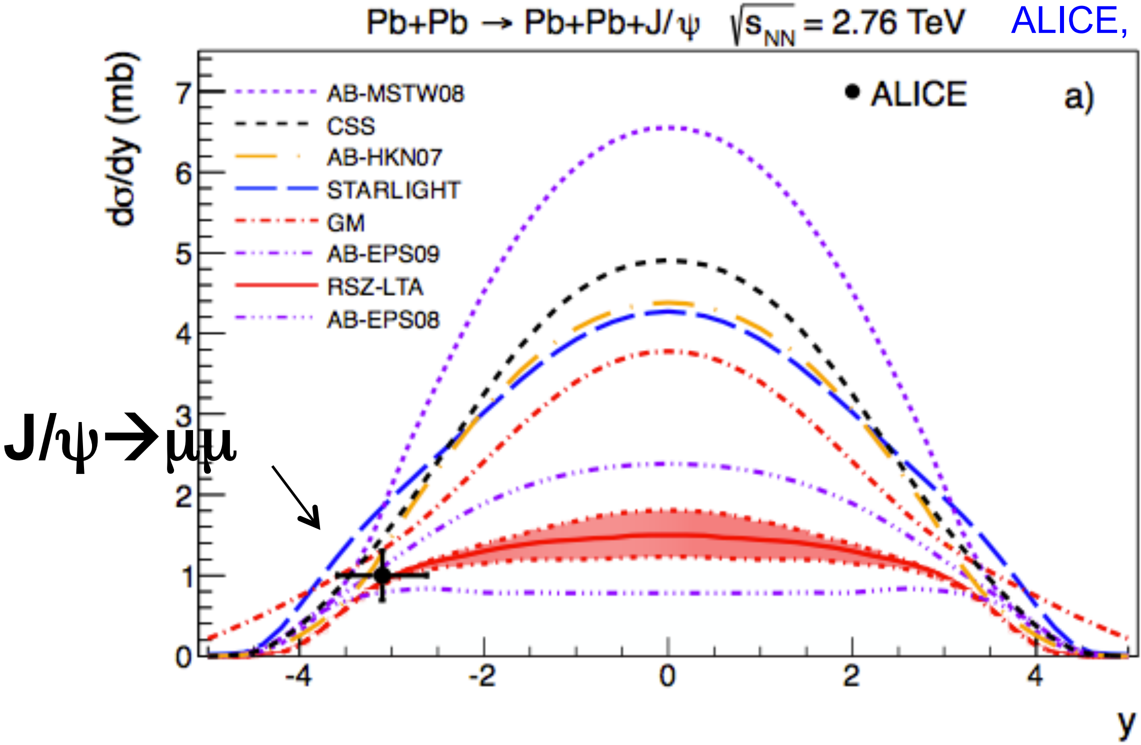
→ D. Velicanu

Low-x gluons via J/ψ in UPC



J/ψ photoproduction in Ultra-Peripheral Collisions:
Pb+γ→Pb+J/ψ
Probes nuclear gluon density, down to x~10^{-5} at LHC

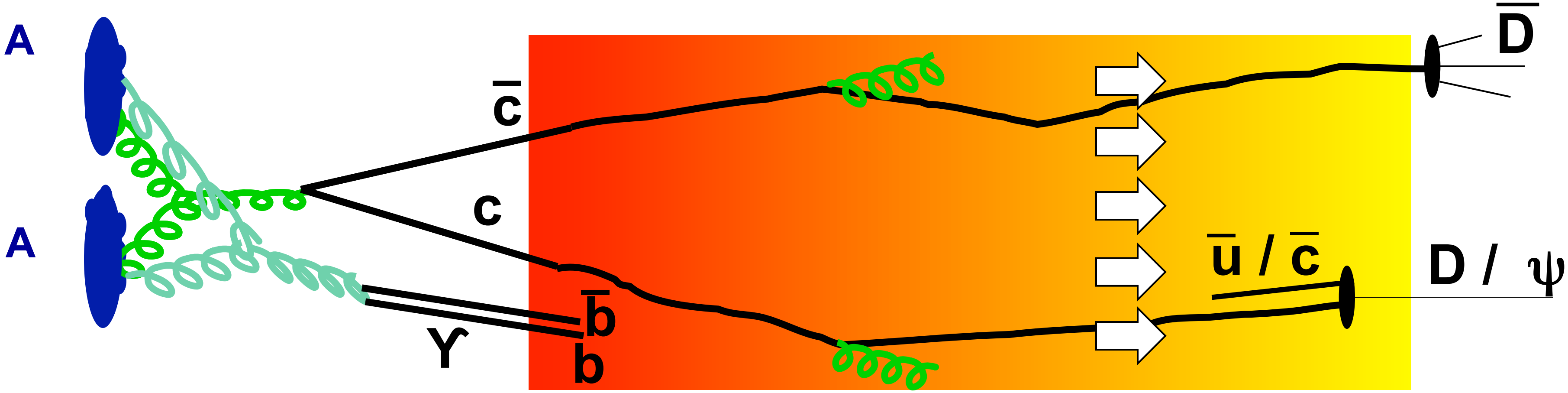
ALICE, arXiv:1209.3715



Best agreement with models that include nuclear gluon shadowing; consistent with EPS09 parameterization

HF production: from pp to AA

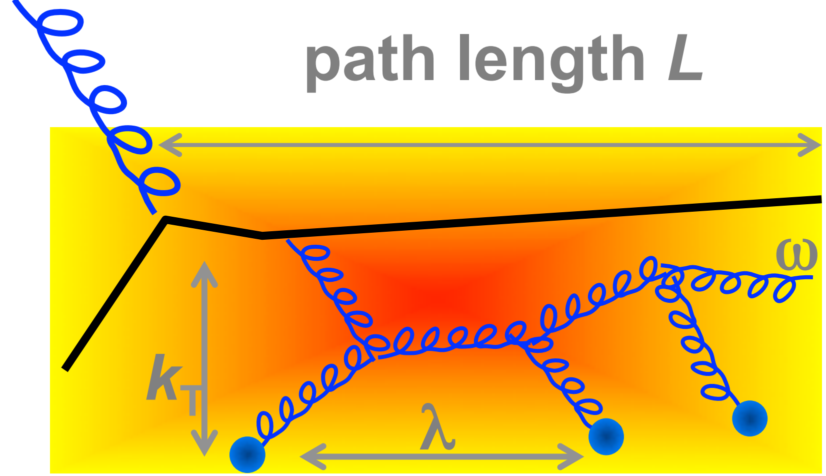
Binary scaling for hard yields:



Binary scaling is "broken" by:

- ***initial-state effects:***
  PDF shadowing
  k_T broadening ('Cronin')
- ***final-state effects***
  mass-dependent energy loss?
  in-medium formation?
  colour-screening?
  collective flow?

Parton energy loss basics



BDMPS-Z formalism

$$\hat{q} = \frac{\langle k_T^2 \rangle}{\lambda}$$ transport coefficient

Radiated-gluon energy distrib.:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R \sqrt{\frac{\hat{q}L^2}{\omega}}$$

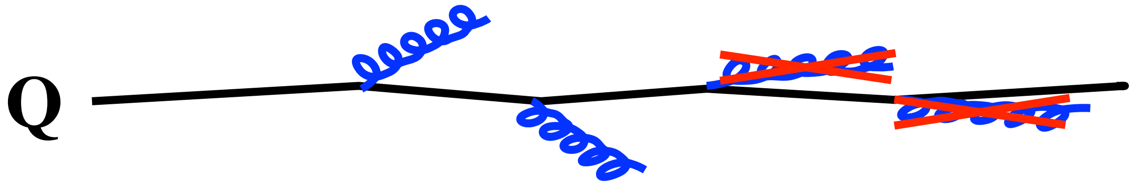
C_R = Casimir coupling factor: 4/3 for q, 3 for g

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291.
Zakharov, JTEPL 63 (1996) 952.
Salgado, Wiedemann, PRD 68(2003) 014008.

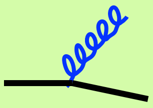
Less gluon radiation for heavy quarks ?

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

  → “dead cone” effect



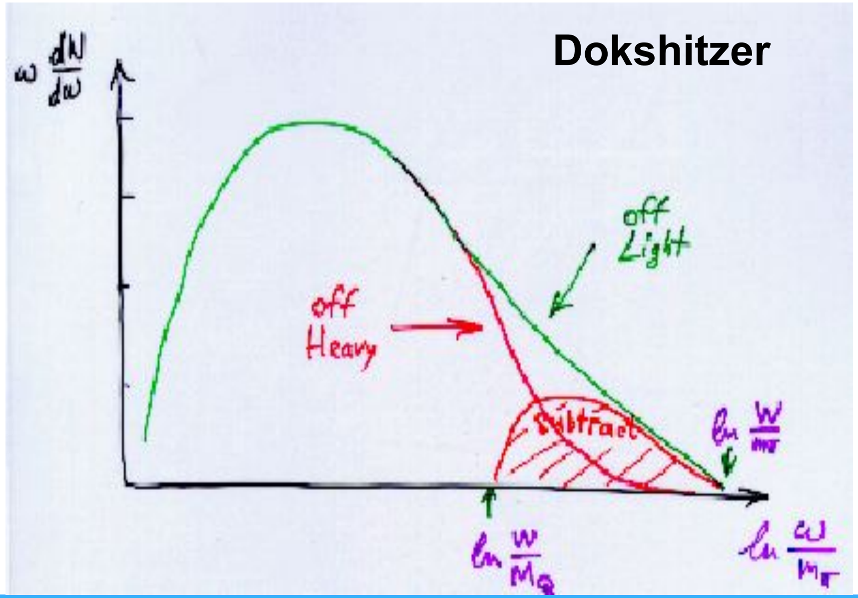
Gluonsstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

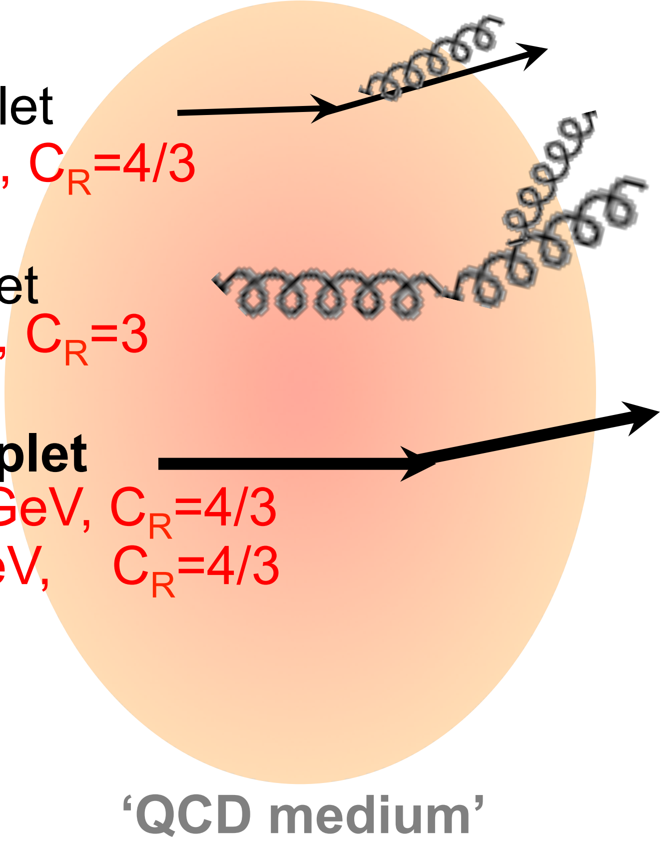
- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001):
  - energy distribution $\omega dI/d\omega$ of radiated gluons suppressed by angle-dependent factor
  - suppresses high-ω tail

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{HEAVY} = \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{LIGHT} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$



Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

The parton palette
and the properties of QCD energy loss



q: colour triplet
u,d,s: m~0, C_R=4/3

g: colour octet
g: m=0, C_R=3

Q: colour triplet
c: m~1.5 GeV, C_R=4/3
b: m~5 GeV, C_R=4/3

Parton Energy Loss by
- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\varepsilon_{medium};C_R,m,L)$$

pred: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

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

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

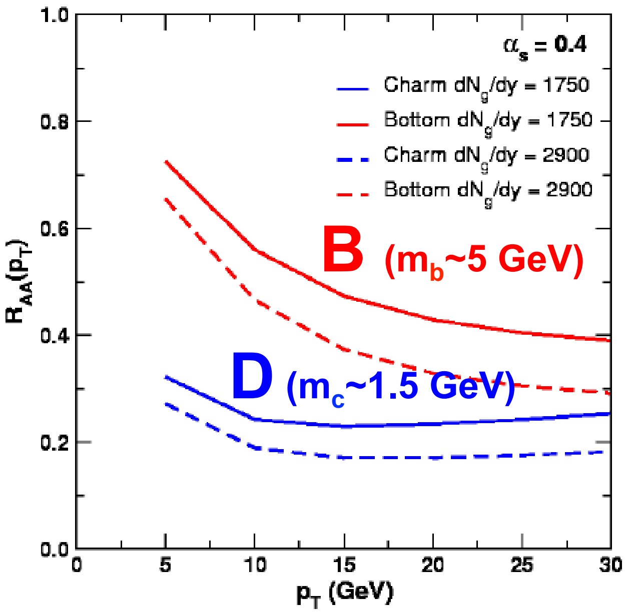
See e.g.:
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

HQs E loss: some expectations …

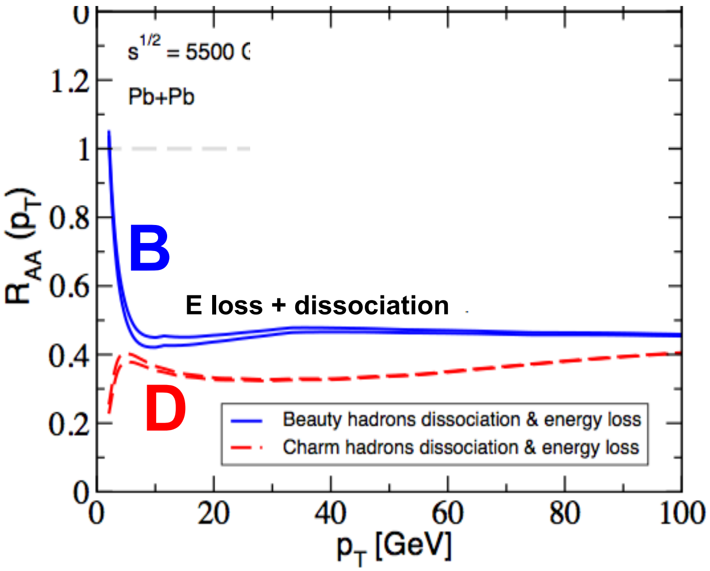
- Energy loss based predictions: factor 3-5 suppression for D mesons
- Significantly smaller suppression for B

$$R^D_{AA}(p_T) \text{ and } R^B_{AA}(p_T)$$

Radiative E loss



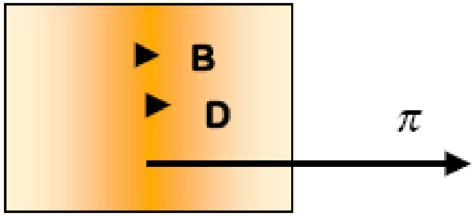
Radiative E loss + dissociation



- Shorter formation time of heavy hadrons → additional R_{AA} suppression due to in-medium dissociation?

$$\tau_{\text{form}}(p_T = 10\ GeV)$$

π	D	B
25 fm	1.6 fm	0.4 fm

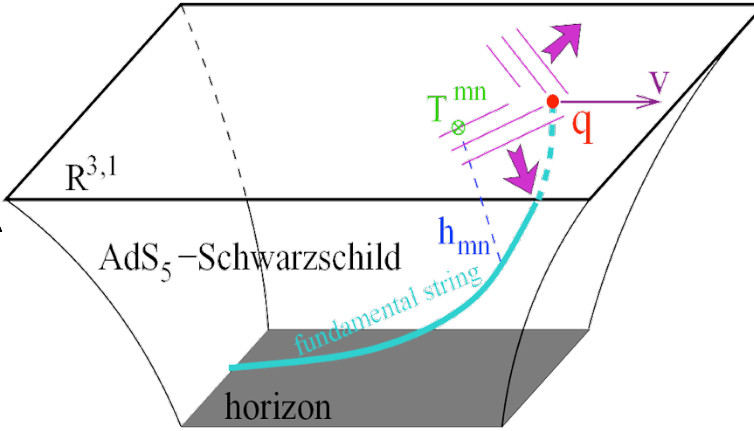


Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

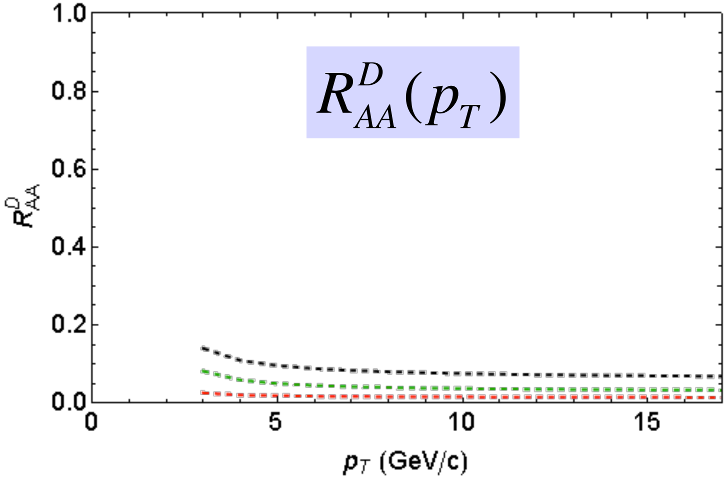
Vitev, et al, PRC80 (2009)

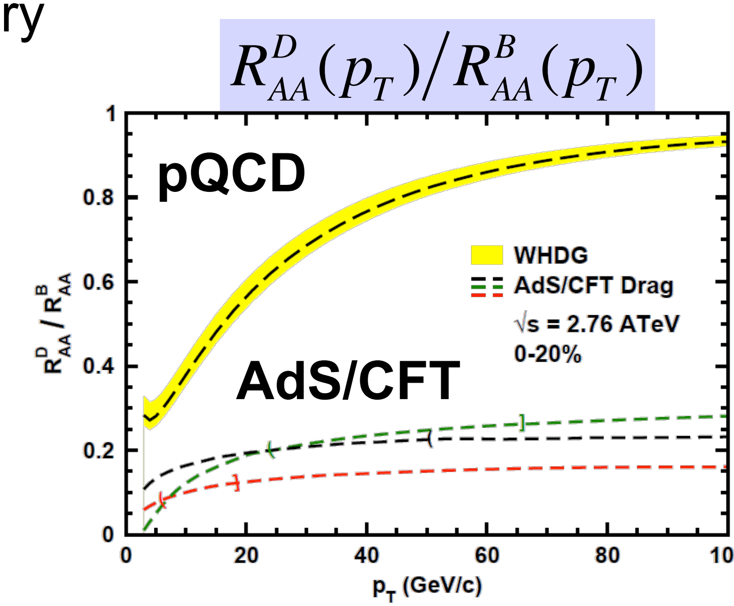
HQs E loss: the AdS/CFT way…?

- Maldacena conjecture: correspondence between super-gravity (Super Yang Mills) and QCD
- → calculate strongly-coupled QCD in SUGRA
- Model energy loss by embedding a string in AdS space → A. Ficnar
- One distinctive prediction:
  - Very strong suppression for charm
  - Small suppression for beauty up to very large p_T



Friess, Phys Rev D75 (2007)

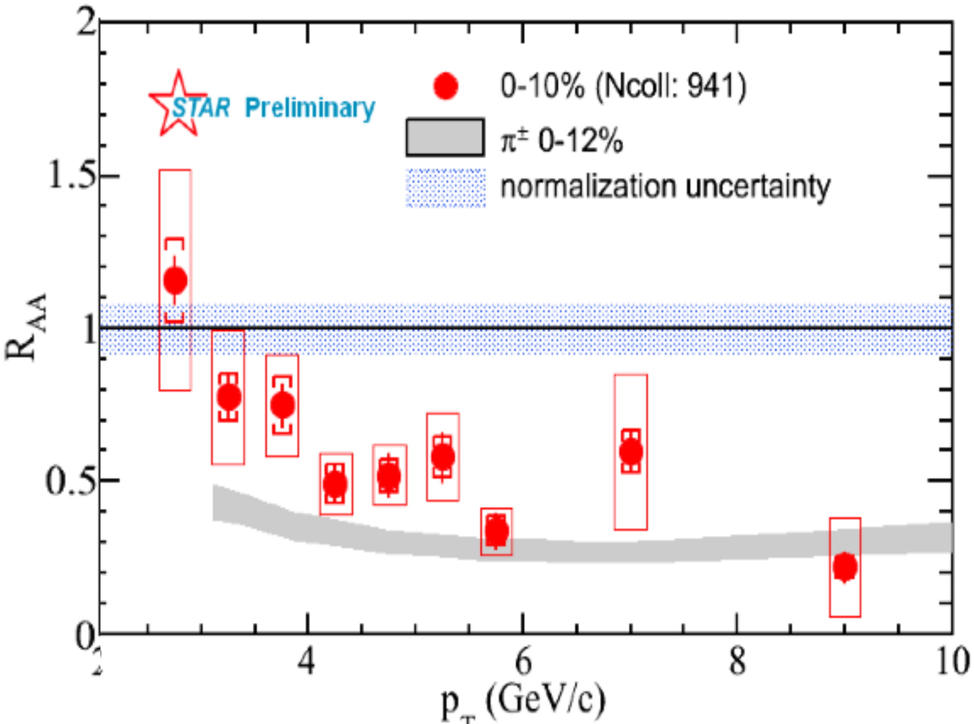




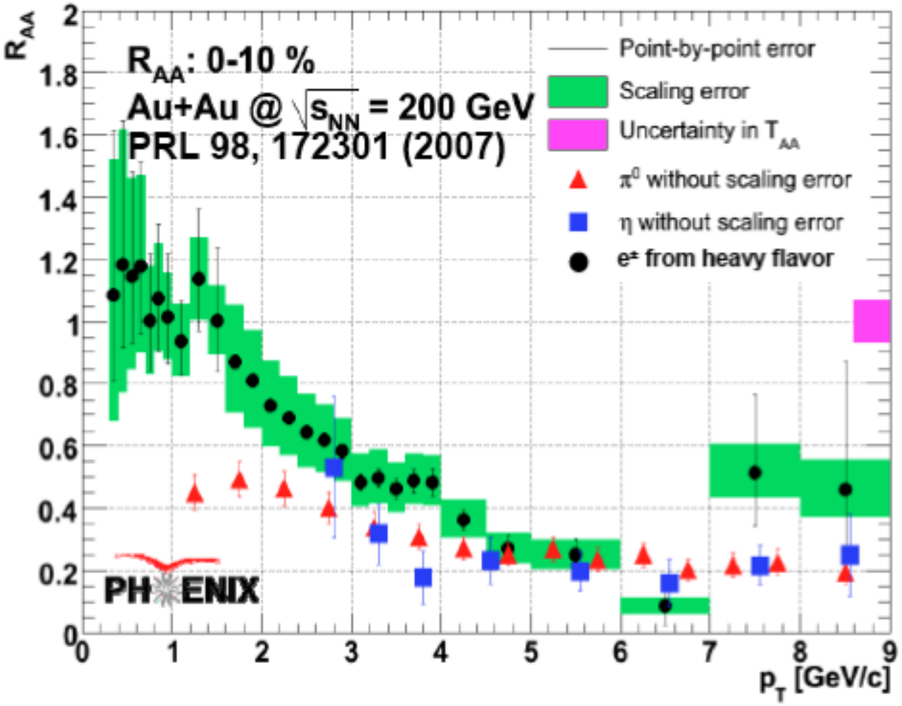
Horowitz, Gyulassy, PLB666 (2008), Horowitz, arXiv:1108.5876

HF suppression at RHIC: electrons

- Inclusive measurement (c+b) using non-photonic electrons



see also Phys. Rev. Lett. 98, 192301 (2007)

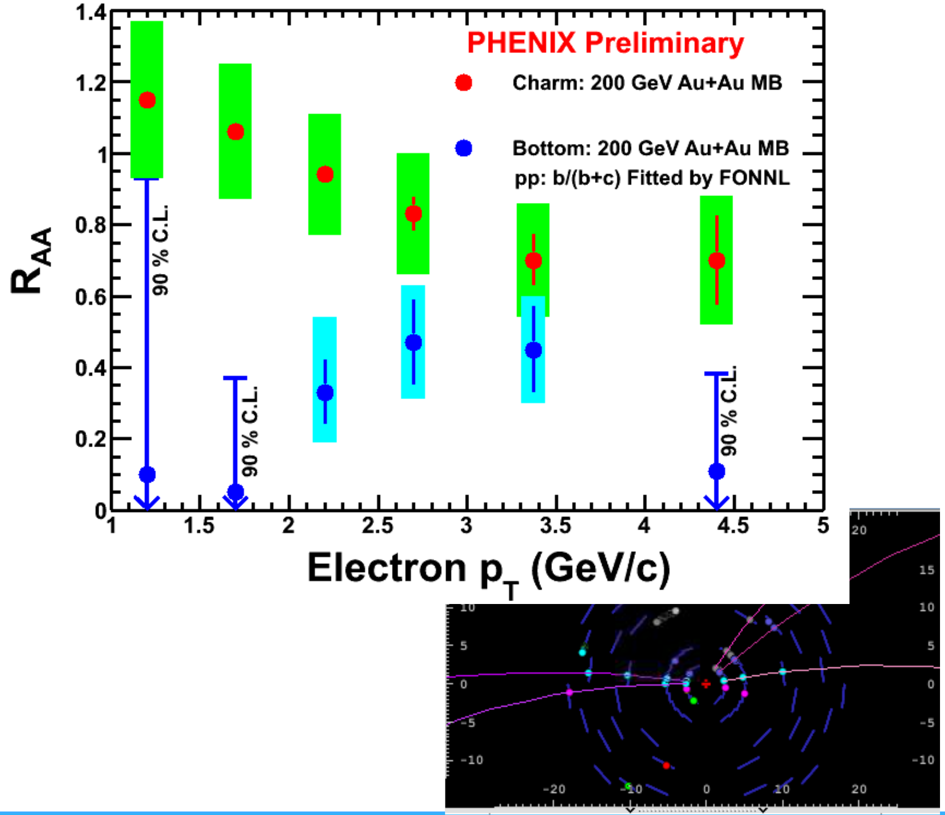


Phys. Rev. Lett. 98, 172301 (2007)

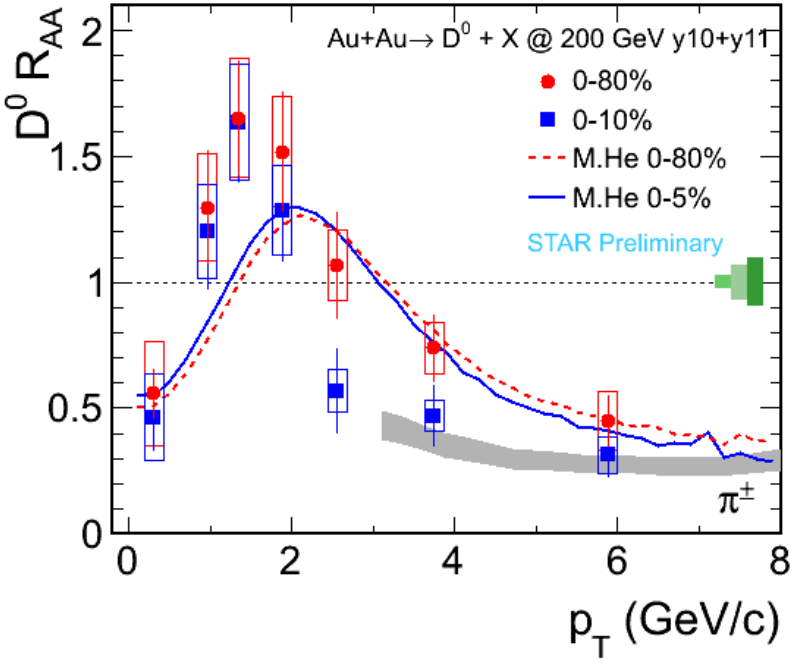
- Same suppression as for light-flavour hadrons above 6 GeV/*c*
- ... and the dead cone?

HF suppression at RHIC: news from QM

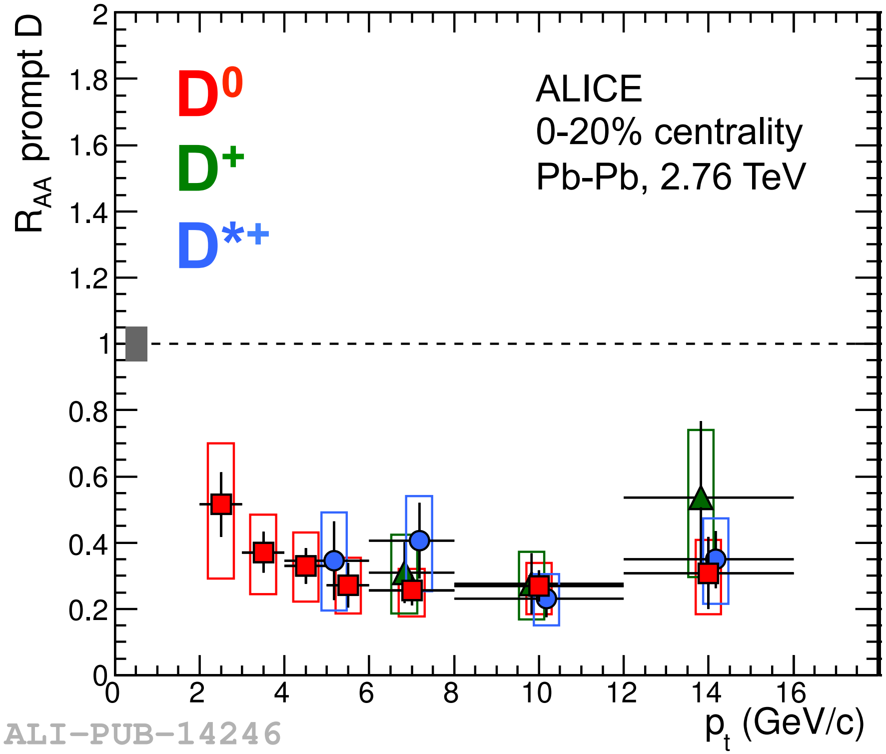
- PHENIX: first separation of c and b at RHIC with new VTX
    - b more suppressed than c at low p_T!

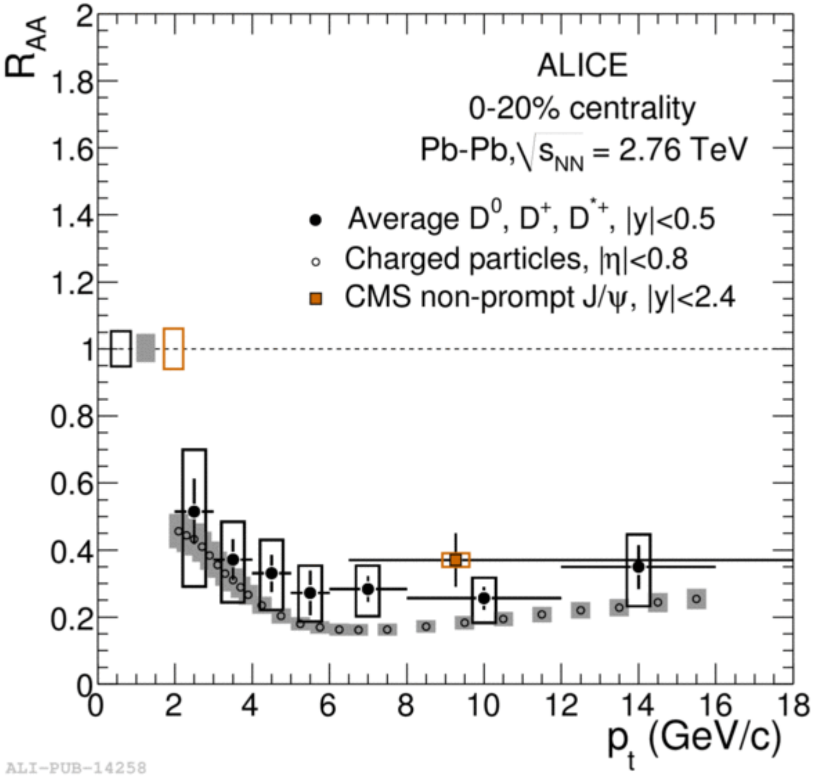


- STAR: first D R_{AA} in central Au-Au at RHIC
    - Suppressed as much as pions at high p_T
    - Large enhancement at low p_T



HF suppression at LHC (run 2010)

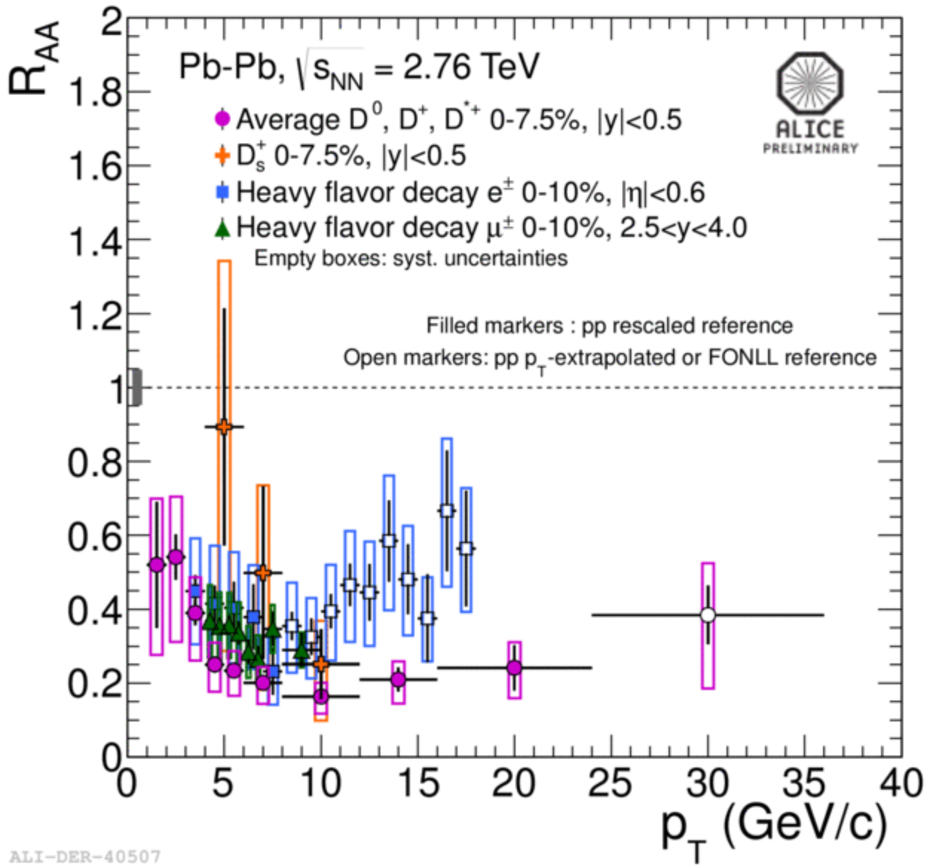




ALICE, JHEP 09 (2012) 112
CMS, JHEP 05 (2012) 063

- First charm and beauty results presented at QM2011:
  - Charm in ALICE: D mesons
  - Beauty in CMS: J/ψ from B decays
- Strong suppression
  - Comparison D to charged not yet conclusive for $R_{AA}^{D} > R_{AA}^{\pi}$
  - Comparison D to B not yet conclusive for $R_{AA}^{B} > R_{AA}^{D}$

HF suppression at LHC: news from QM (ALICE)

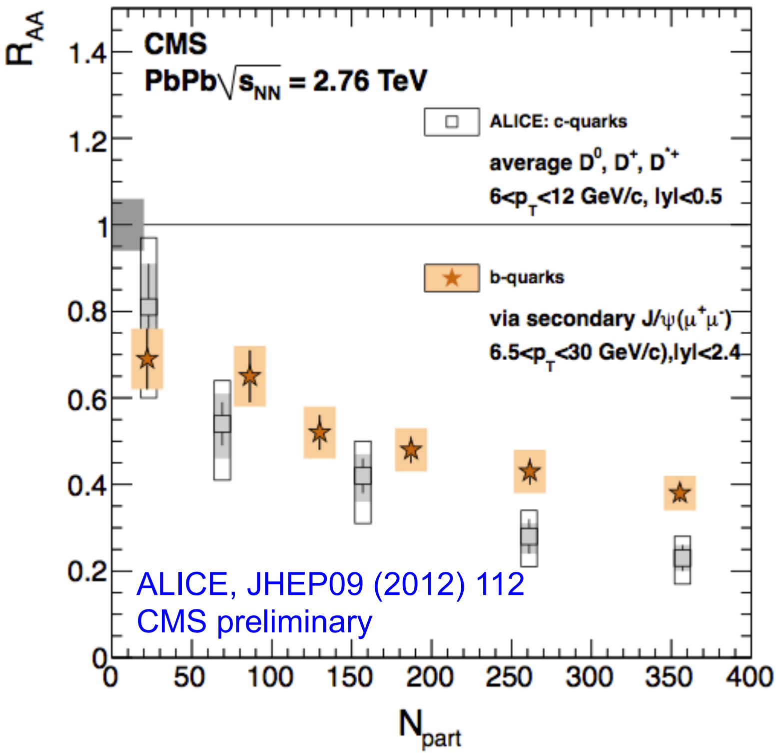


μ: PRL 109 (2012) 112301

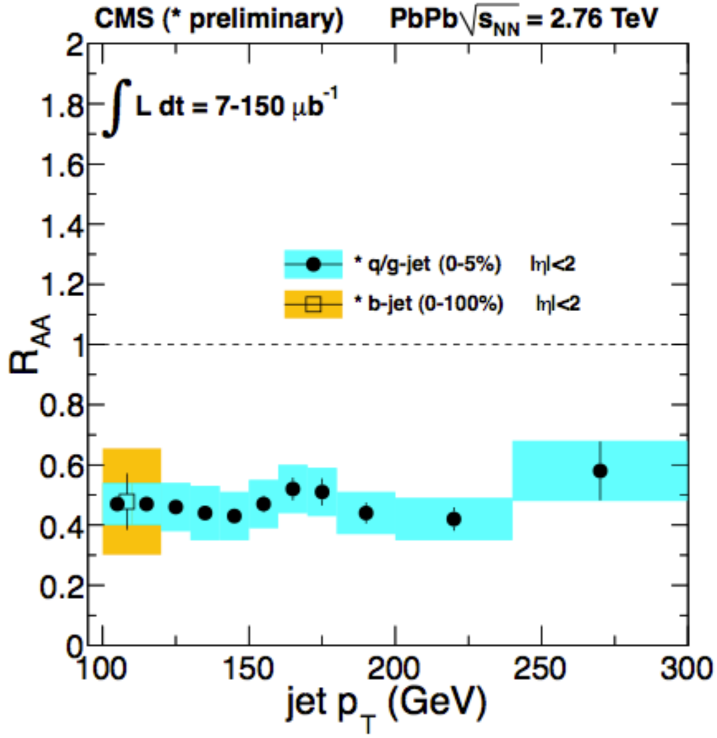
- D mesons (D^0,D^+,D^*) extended at low and high p_T
  - Charm suppression up factor 5!
  - Strong suppression even at 30 GeV/*c*
- First D_s measurement
  - Same suppression at high p_T
  - Low p_T: suggestive of strangeness enhancement?
- HF-decay electrons up to 18 GeV/*c*
  - Consistent with D mesons (considering that $p_T^e \sim 1/2\ p_T^B$)
  - Doesn't imply a difference D vs B
- HF-decay muons at forward rapidity
  - Similar suppression as at central y

→ M. Fasel, G.M. Innocenti

HF suppression at LHC: news from QM (CMS)

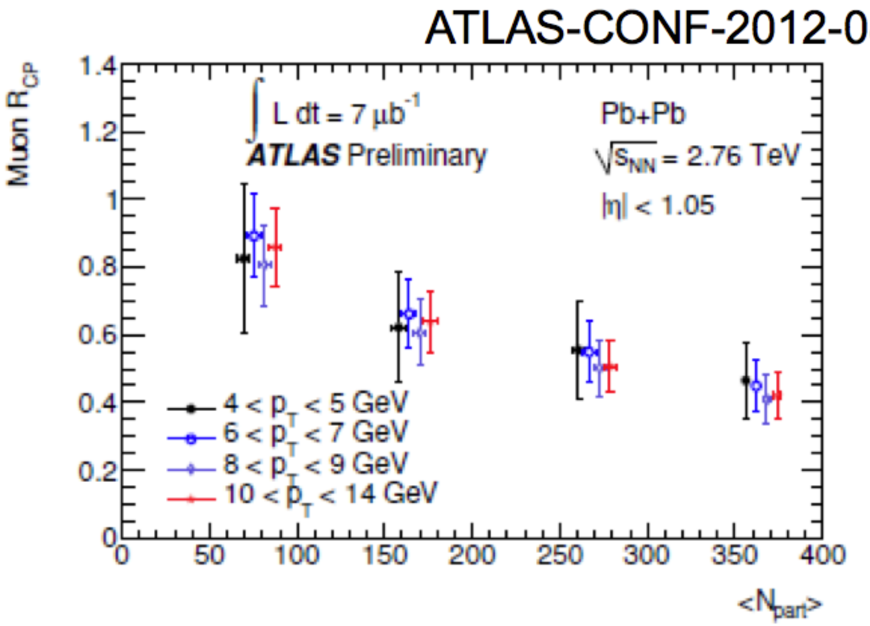


ALICE, JHEP09 (2012) 112
CMS preliminary

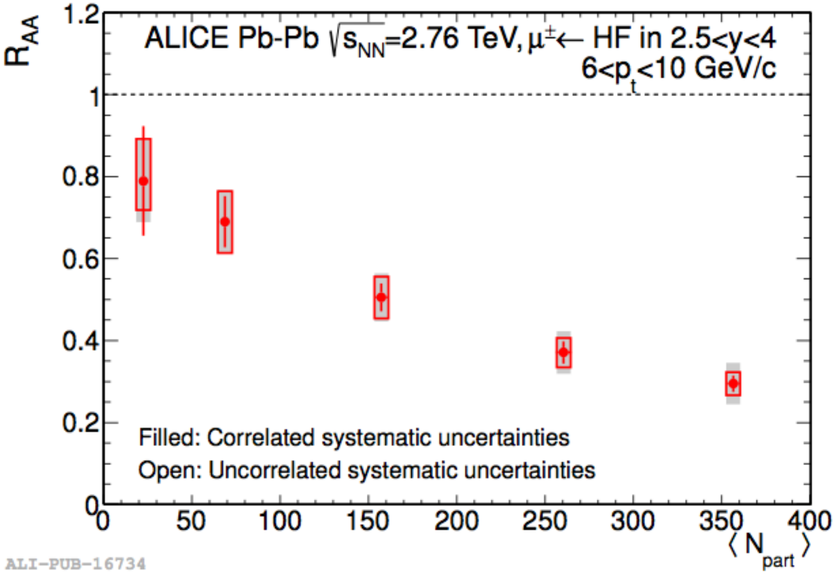


- Better 2011 statistics shows a first indication of $R_{AA}^{B}>R_{AA}^{D}$ in cmp with ALICE data
  - Warning: p_T range not the same!
  - Only in central collisions?
- First measurement of b-tagged jets in AA!
- Shows the same R_{AA} as for light jets, as expected at this p_T (not from AdS/CFT?)

HF suppression at LHC: news from QM (ATLAS)



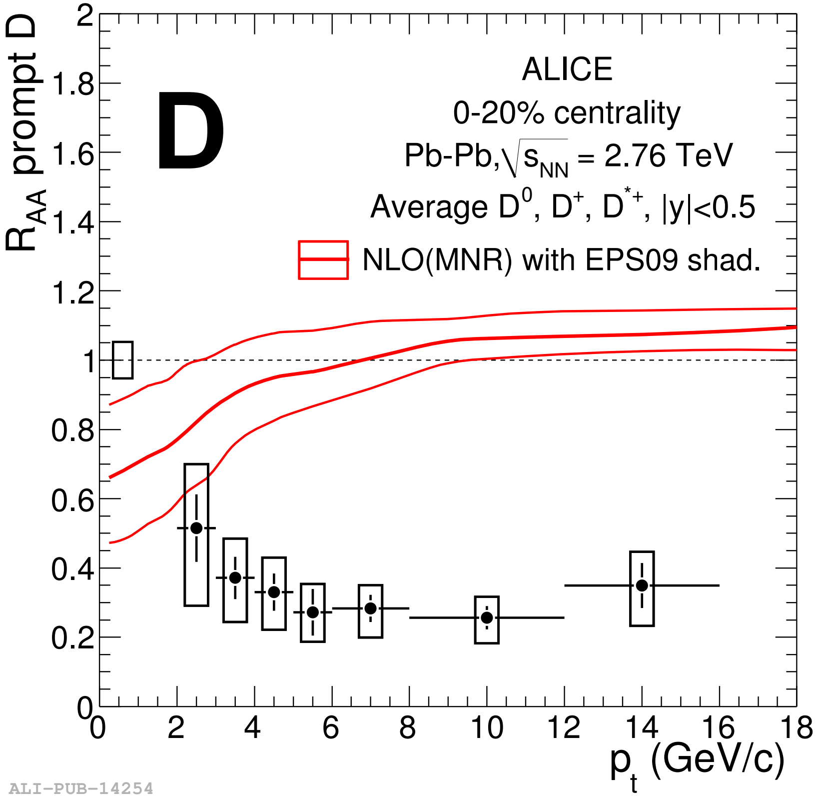
ATLAS-CONF-2012-081

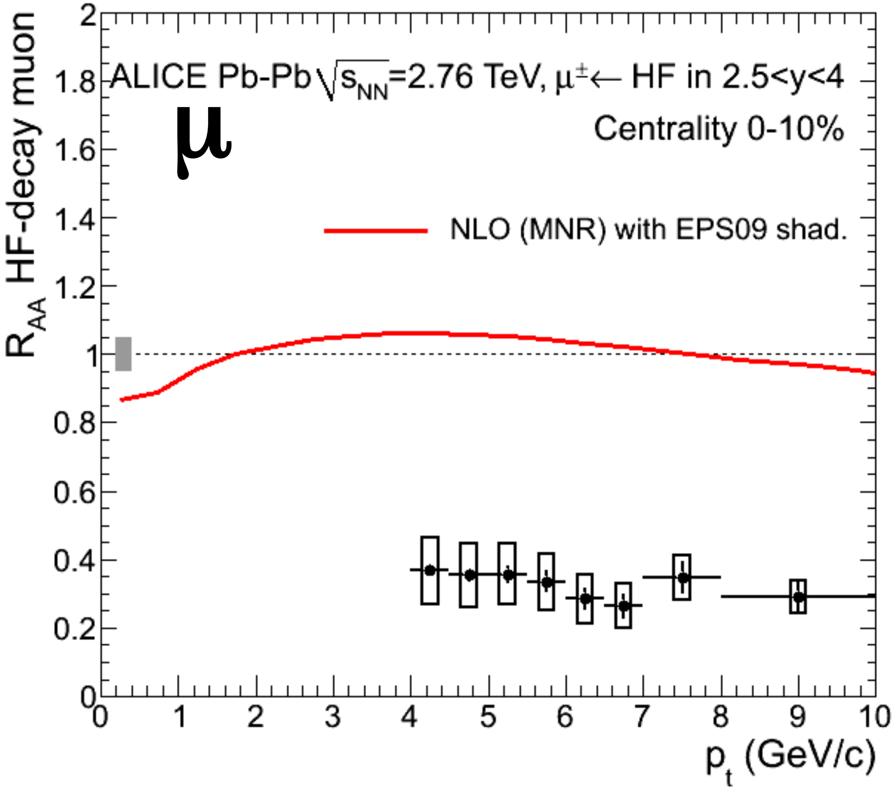


PRL 109 (2012) 112301

- R_{CP} of muons from HF decay
  - Clear centrality dependence
  - No sign of p_T dependence
- Consistent with ALICE published R_{AA} (at forward rapidity)

Is it a QCD medium effect?





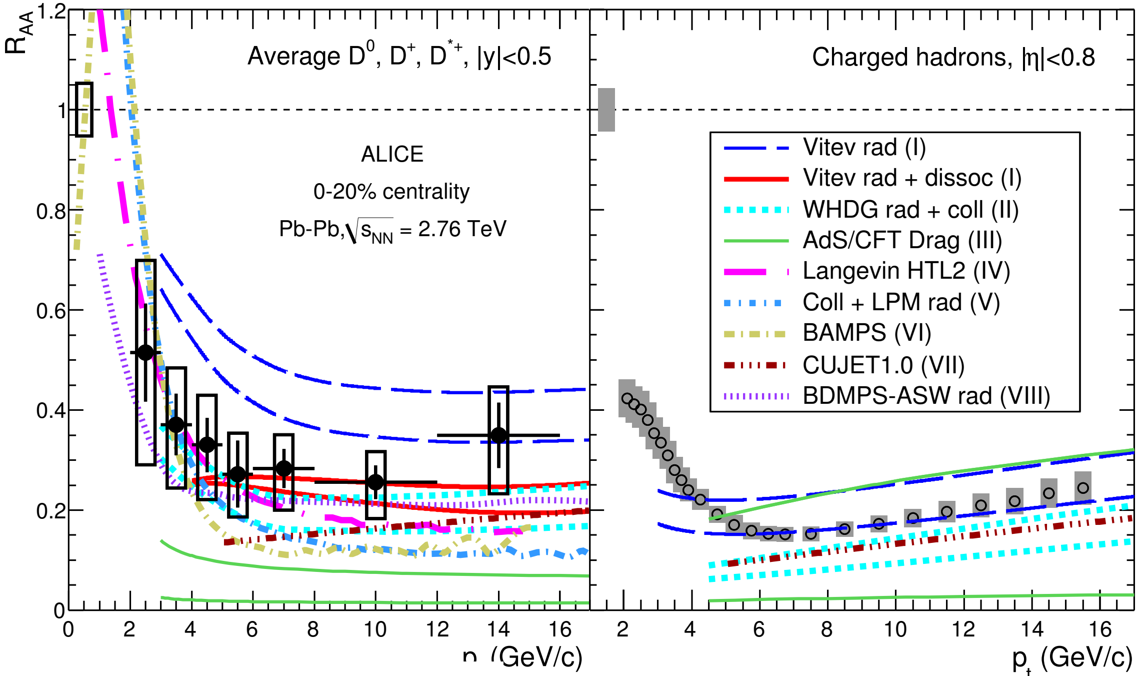
JHEP 09 (2012) 112
PRL 109 (2012) 112301

- Small effect expected from PDFs shadowing above 5 GeV/c
- Suggests that this is a hot medium effect
- p-Pb run in Jan 2013 crucial to measure initial-state effects

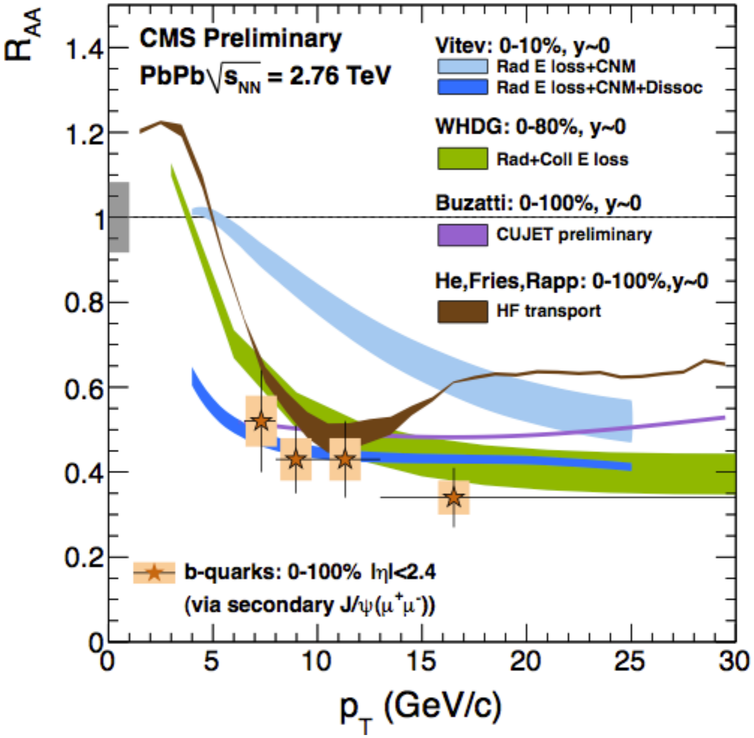
EPS09: Eskola et al. JHEP0904(2009)065

HF R_{AA}: comparison with E-loss models

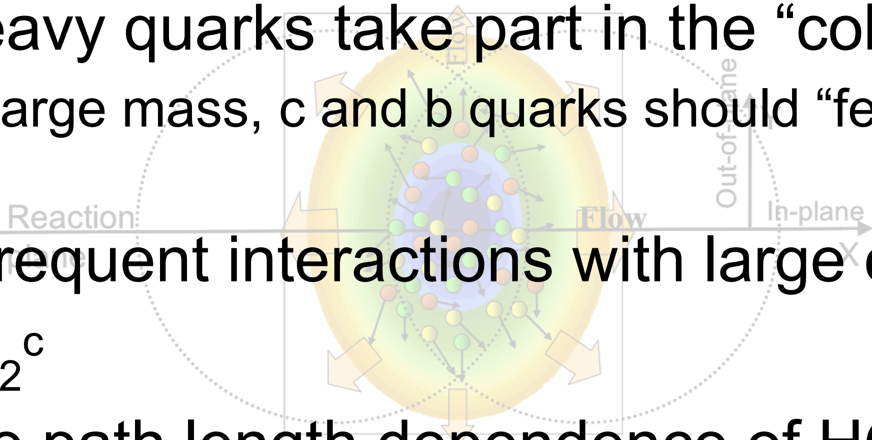
- Several models based on E-loss and heavy-quark transport describe qualitatively the measured light, charm, and beauty R_{AA}



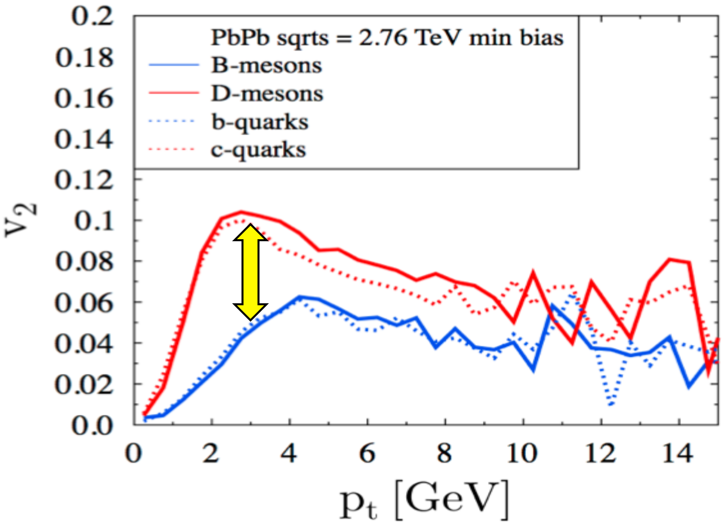
ALICE, JHEP 09 (2012) 112



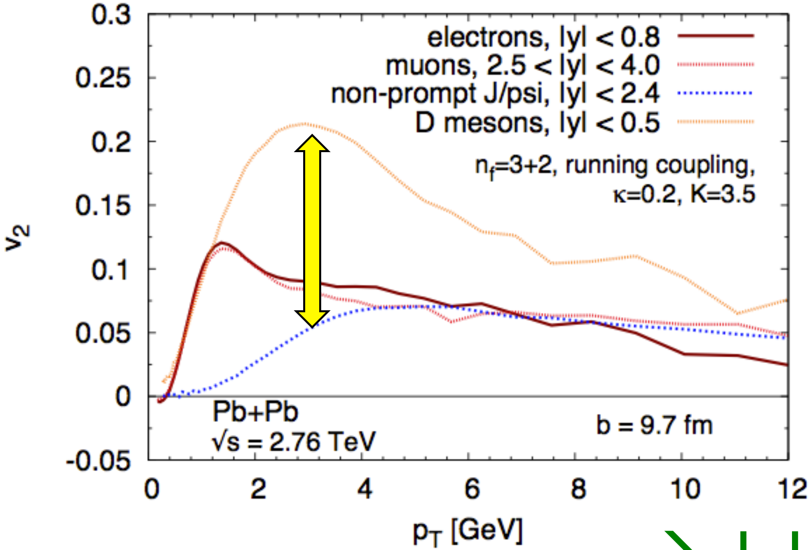
Heavy flavour v_2: a two-fold observable



- Low p_T: do heavy quarks take part in the “collectivity”?
  - Due to their large mass, c and b quarks should “feel” less the collective expansion
    - → need frequent interactions with large coupling to build v_2
    - → $v_2^b < v_2^c$
- High p_T: probe path length dependence of HQ energy loss



J. Aichelin et al. in arXiv:1201.4192



J. Uphoff et al. in arXiv:1205.4945

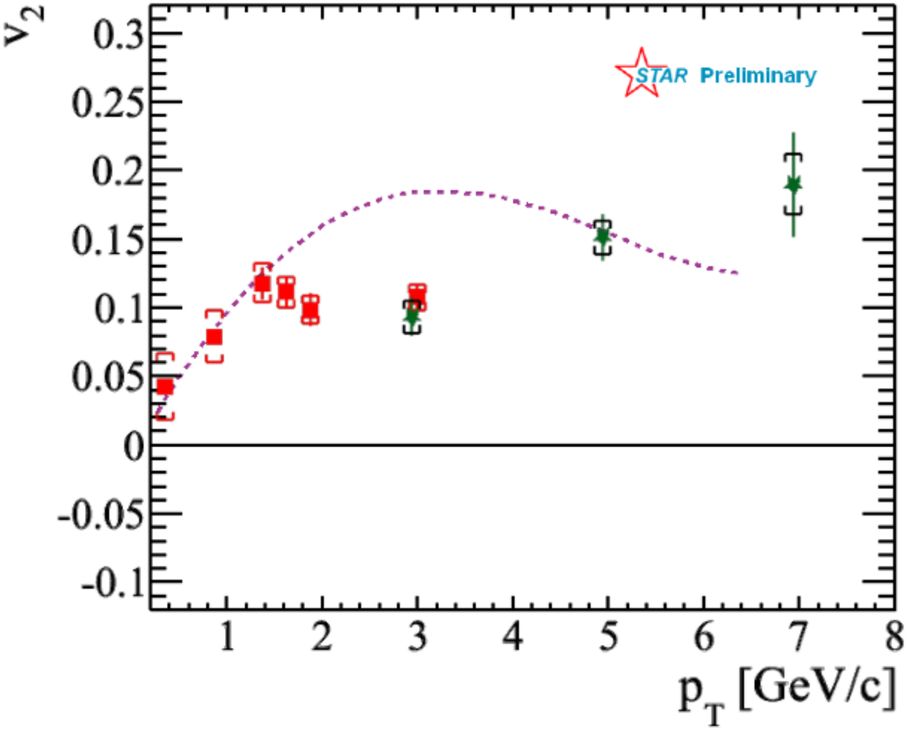
→ J. Uphoff

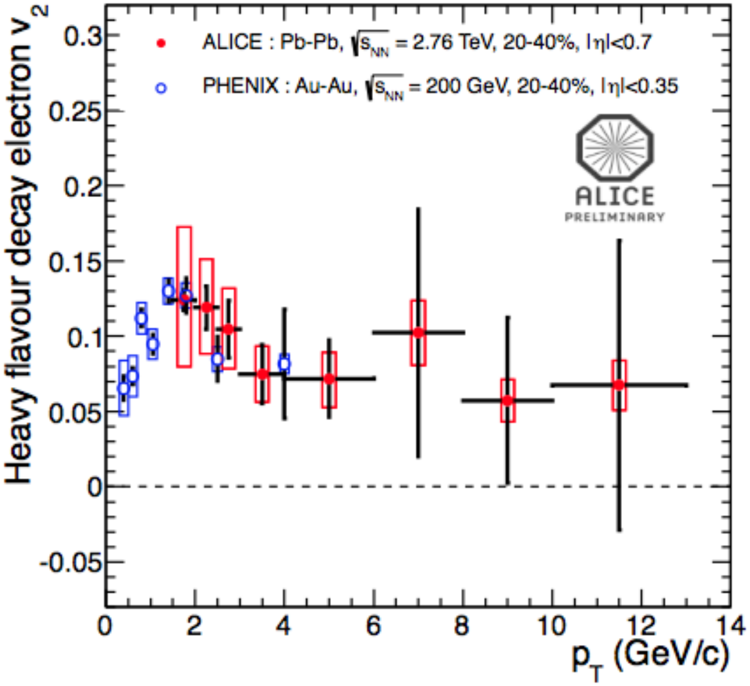
Heavy-flavour azimuthal anisotropy, from RHIC to LHC

- Electrons from HF show a v_2 of up to 0.15 at RHIC (PHENIX, STAR)
  - Charm does flow!

→ L. Ding, M. Fasel

  - v_2 significantly smaller than for pions above 2 GeV/c (might be decay kinematics, rather than a difference heavy vs. light)
- First measurements at the LHC (ALICE): electron v_2 comparable to RHIC





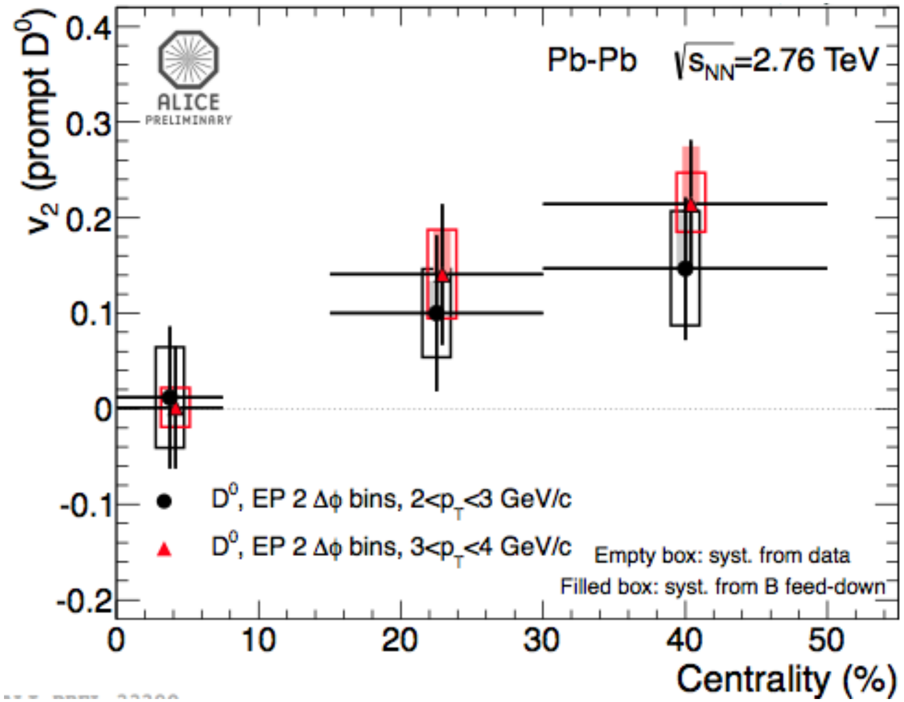
PHENIX, PRC84 (2011) 044905

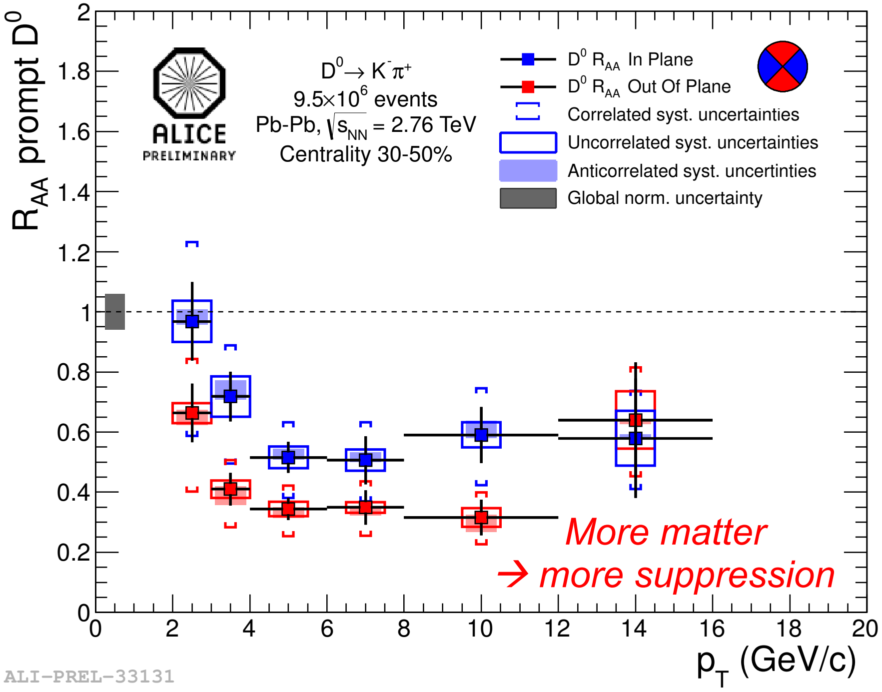
Heavy-flavour azimuthal anisotropy, from RHIC to LHC

- First D measurements at the LHC (ALICE): D meson $v_2>0$, D^0 R_{AA} in and out of plane
  - Suggests flow at low p_T and path-length dependent suppression at high p_T

→ G. Luparello

- First D v_2 measurement at RHIC presented at QM by STAR (limited statistics)

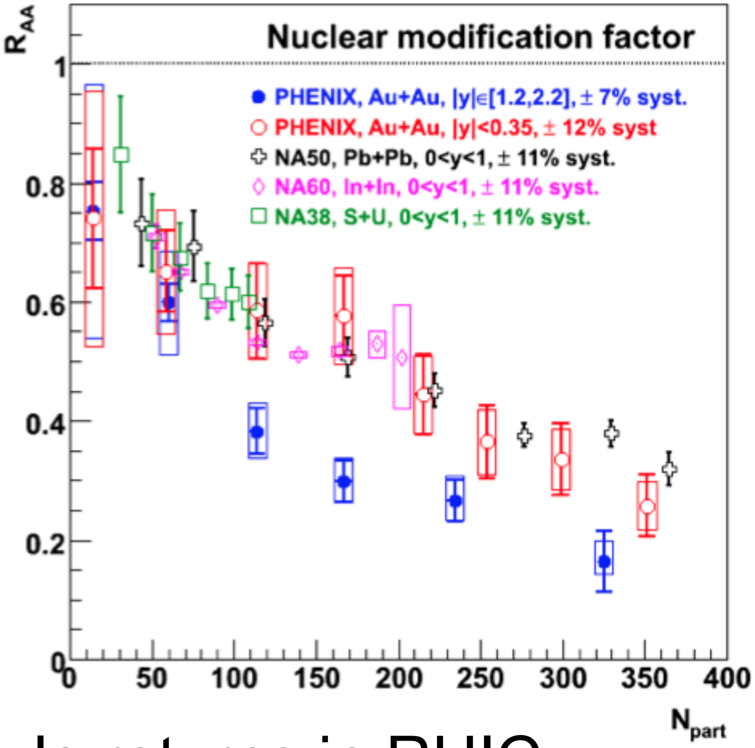


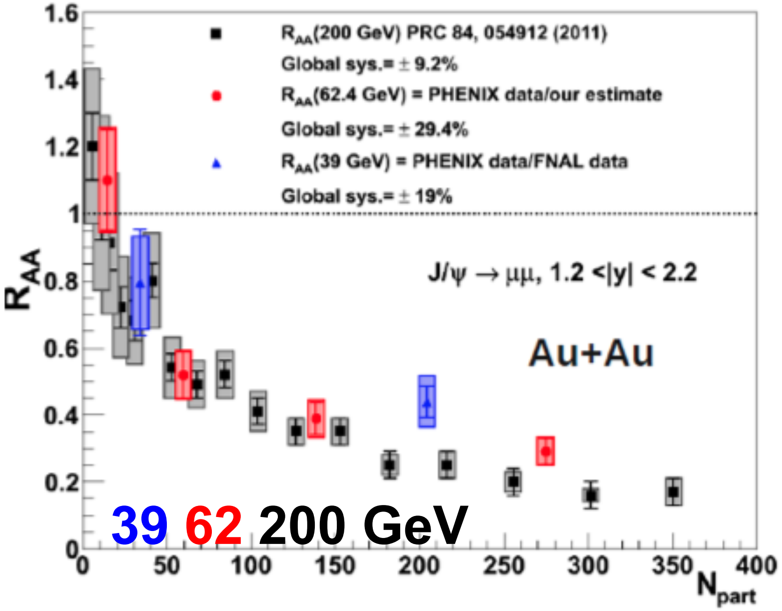


More matter → more suppression

Quarkonia: the J/ψ puzzle at SPS and RHIC

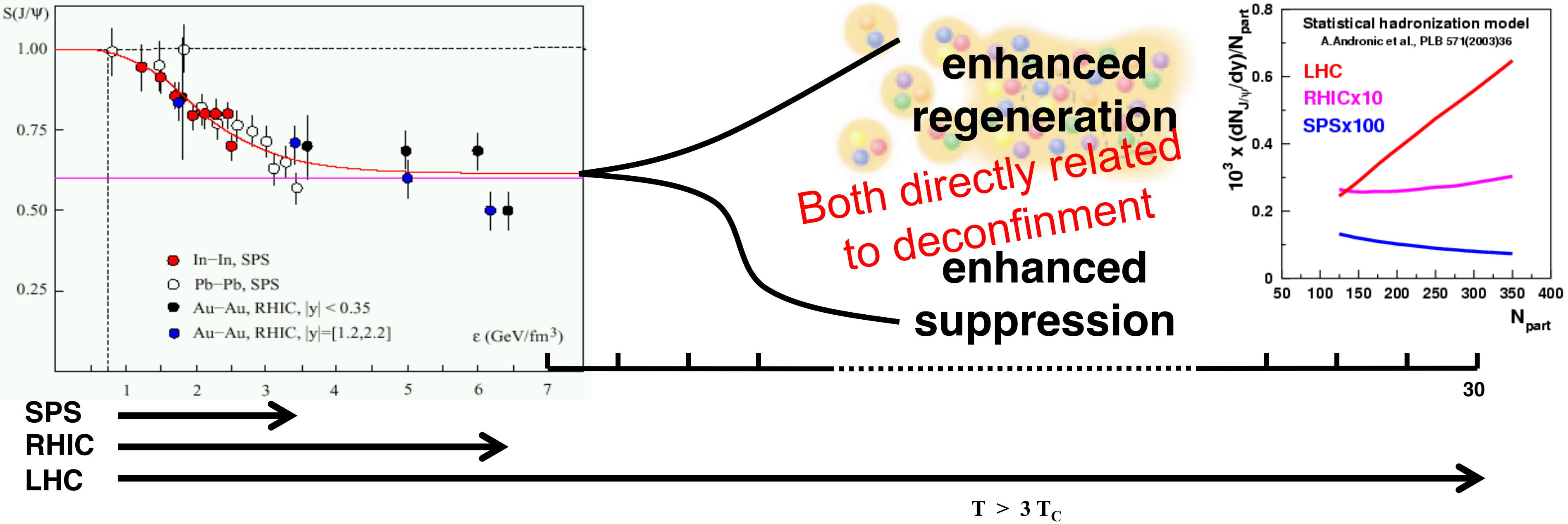
- Significant suppression observed, beyond "cold nuclear matter effects"
- Why is it not larger at RHIC than at SPS?
- Why is it not larger at mid-y?





- Puzzle returns in RHIC energy scan results
- *Interplay of shadowing and regeneration?*

Quarkonia at LHC: high expectations …



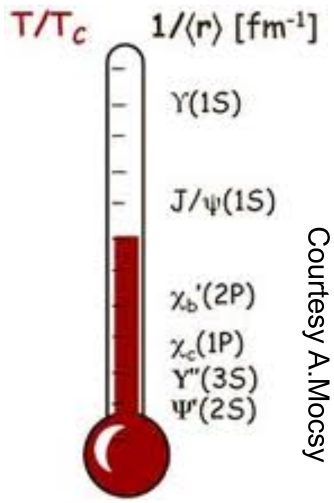
enhanced regeneration

Both directly related to deconfinement

enhanced suppression

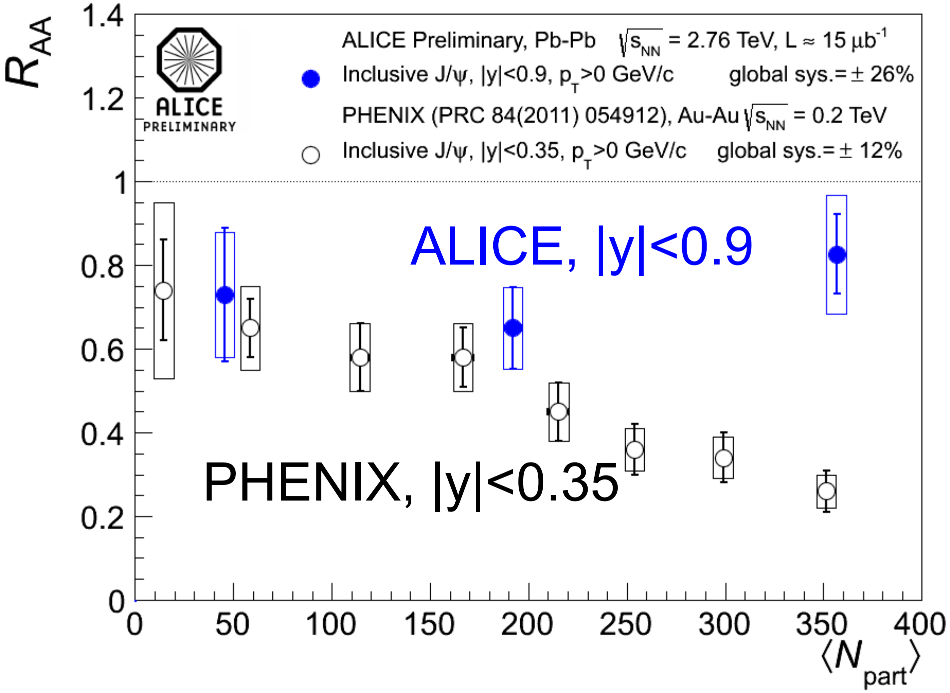
In addition: the quakonium thermometer

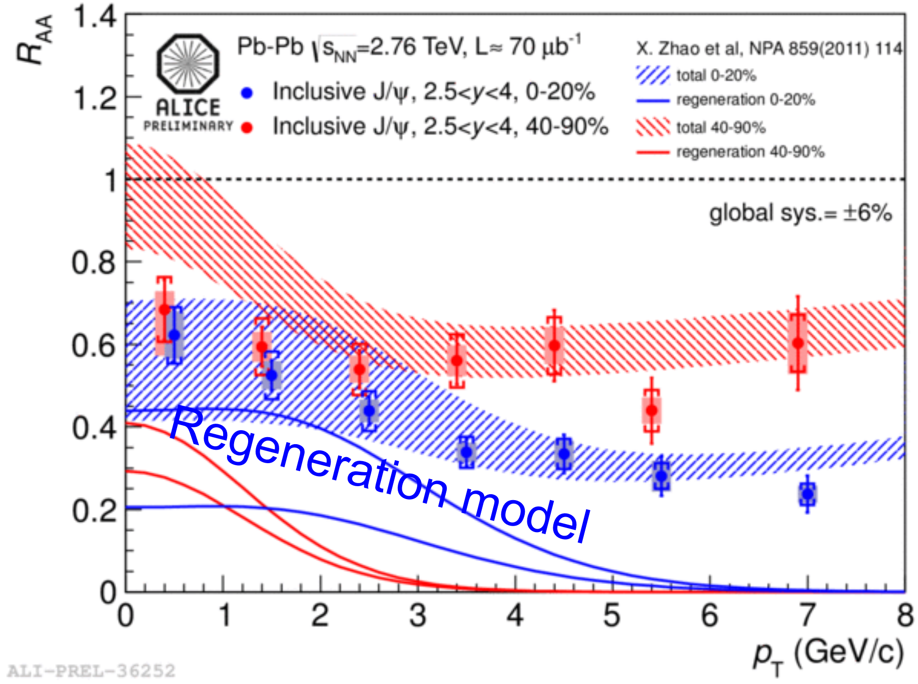
- Comparison of different quarkonia states → **T/T_c**
- ϒ would melt only at LHC
- Small ϒ regeneration
  → help to pin down the J/ψ suppression VS regeneration



Courtesy A.Mocsy

LHC: J/ψ suppression and regeneration ?



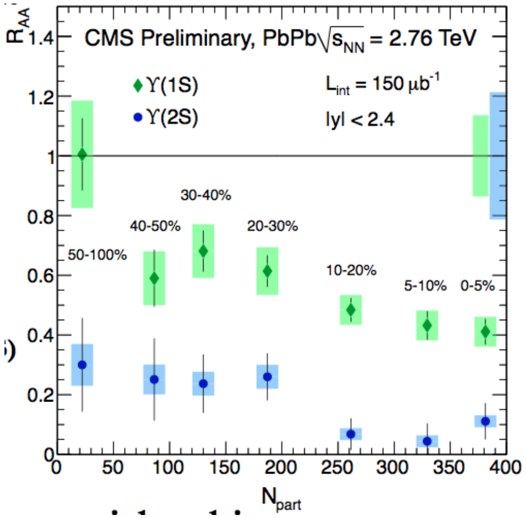


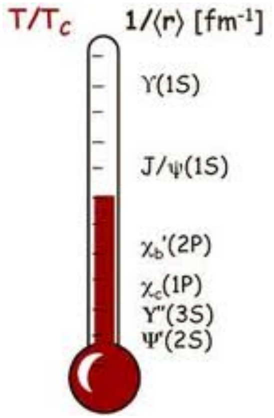
- Suppression of the J/ψ yield (R_{AA}<1) measured by ALICE, ATLAS, CMS
- At low p_T ALICE measures smaller suppression than at RHIC, at both central and forward y
- The suppression is reduced towards p_T=0
- This pattern can be explained by models with J/ψ regeneration from the large number of freely roaming charm quarks in the QGP

→ A. Lardeux

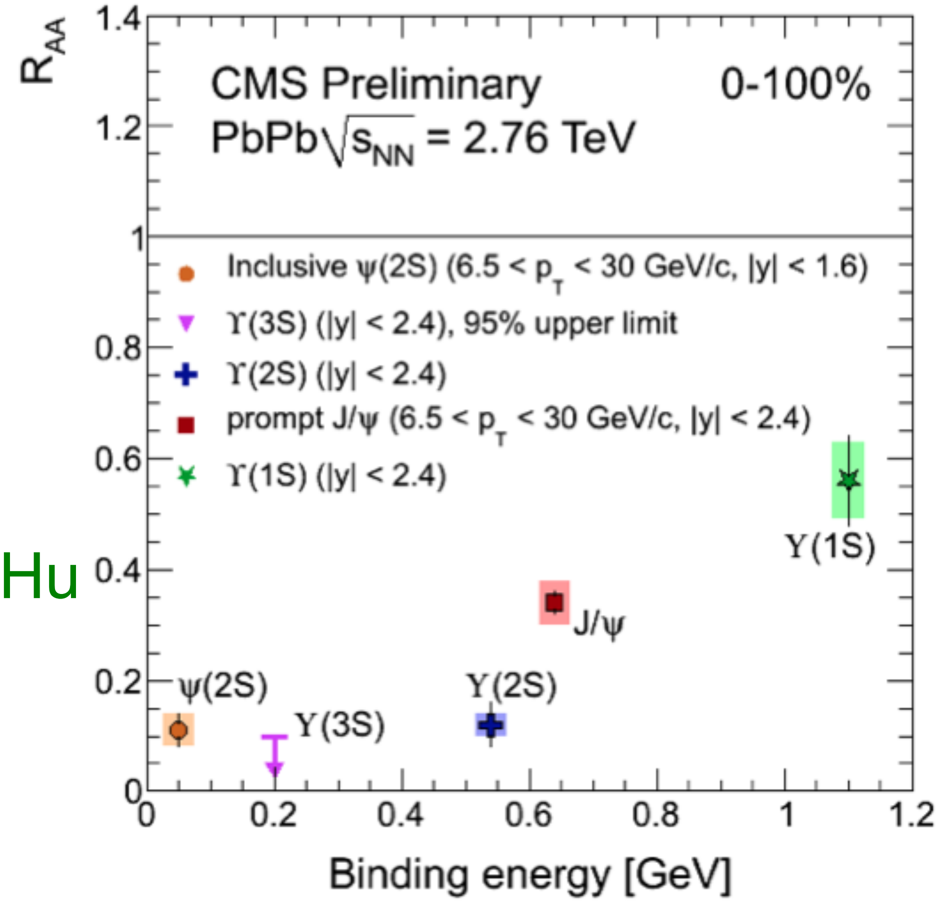
LHC: the quarkonium thermometer ?

Upsilon suppression (CMS):

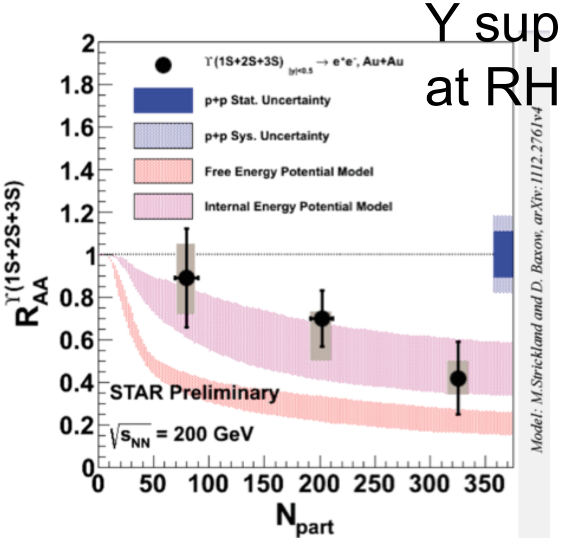




→ Z. Hu

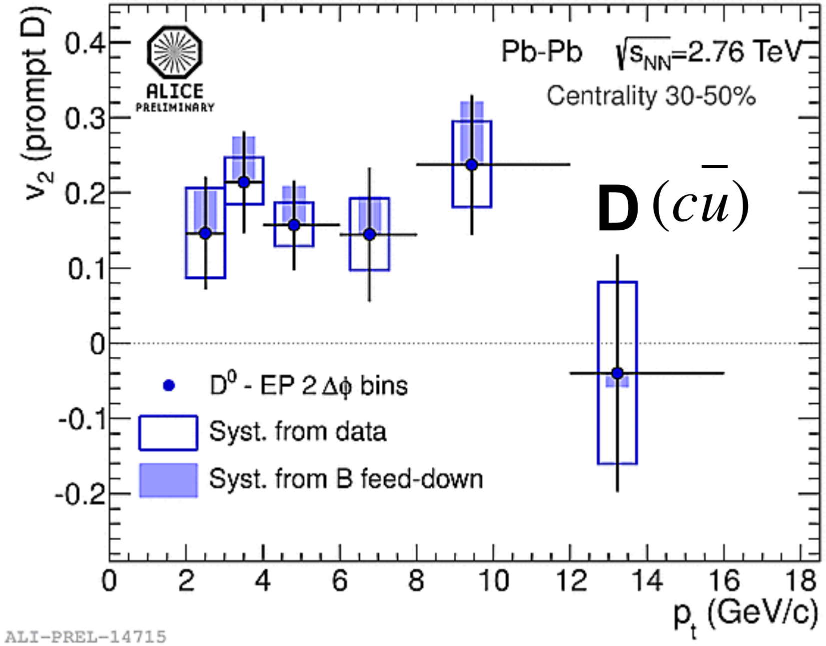


Υ suppression at RHIC (STAR)

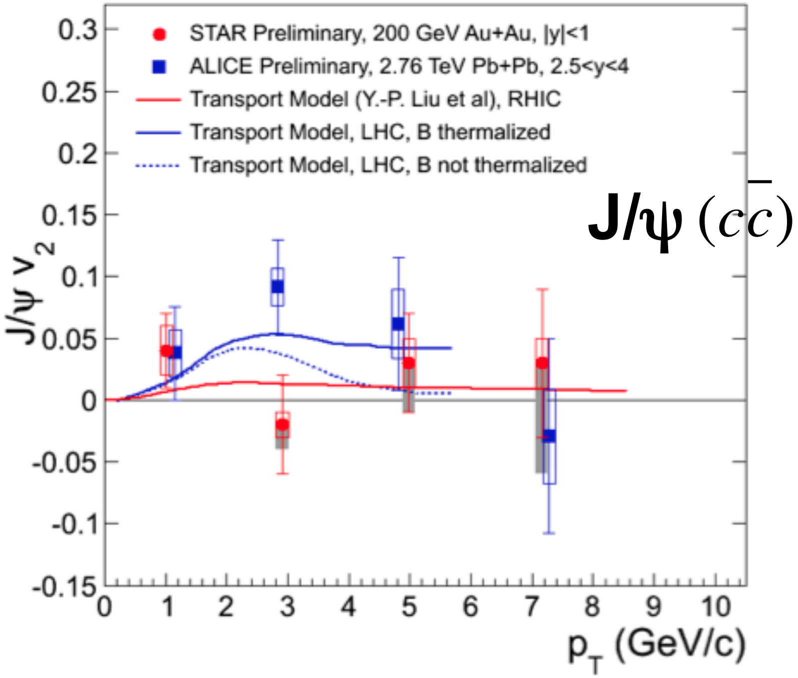


- A pattern starts to emerge
  - Caveats: p_T ranges, centrality, regeneration, initial state

Charm flowing with the QGP?



D $(c\bar{u})$



J/ψ $(c\bar{c})$

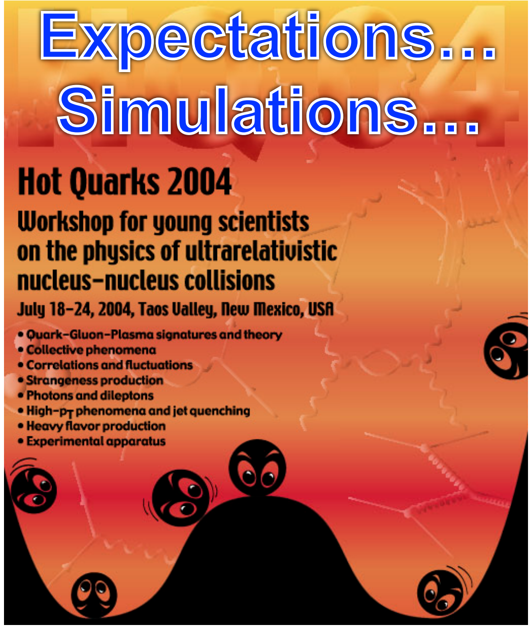
Open charm hadrons exhibit a significant elliptic flow
→ they may take part in collective expansion of the QGP

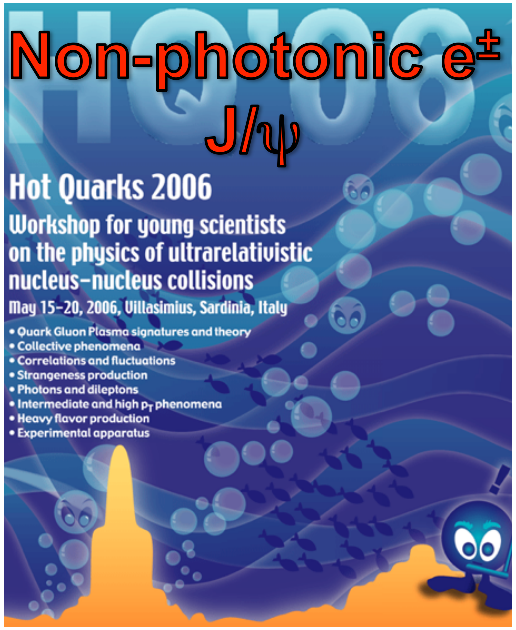
Hint / NoHint for a finite J/ψ v_2 observed at LHC / RHIC
→ consistent with re-generation scenario ?

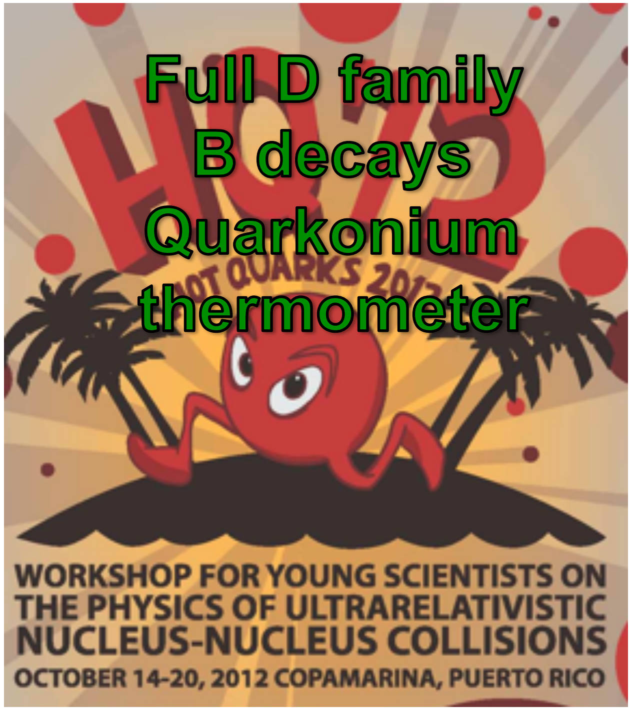
→ G. Luparello, A. Lardeux

Final Words

- From the experimental point of view, we have just entered the “golden age” for heavy-flavour observables in HI collisions:
  - Thanks to the LHC detectors and RHIC upgrades
    - And much more to come!


Expectations… Simulations…


Non-photonic $e^{\pm}$
J/ψ


Full D family
B decays
Quarkonium
thermometer

A hot topic for many Hot Quarks to come!

… and now, enjoy the following talks of this session!