Selected
Open Heavy Flavor Results

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QGP France - Etretat - September 2014

Outline

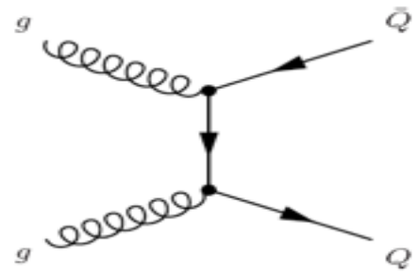
- Brief introduction
- Highlights of pp measurements
- Measurements of pA data (R_{pA})
- Suppression (R_{AB}) and azimuthal anisotropy (v_2) in AB collisions
- Summary

Related talks in this meeting:
Lizardo Valencia Palomo
Shuang Li
Mihee Jo
Matthew Nguyen

Why measuring Heavy Flavor ?

Why charm and beauty ?

- Production in hard partonic collisions ⇨ ⇨ pp data
  - Production time $\tau_p \sim 1/m_Q \sim 0.05 - 0.15$ fm/c
    ⇨ **Tool to test pQCD calculations**



- Nuclear environment influence: p-A collisions ⇨ ⇨ p-Pb or d-Au data
  - Shadowing (PDF modifications in nuclei) and Gluon saturation
    ⇨ **Tool to study high density small-x gluons**

- Effects in a QGP: A-B collisions ⇨ ⇨ Pb-Pb or Au-Au data
  - Thermalisation in the QGP (low p_T)
    - Medium transport properties ⇨ dN/dp_T, R_{AA}, v_2
  - Energy loss in the QGP (high p_T)
    - Medium density and size ⇨ dN/dp_T, R_{AA}, v_2
    - Color charge (Casimir factor) : $\Delta E_{u,d,s} < \Delta E_g$ ⇨ compare to light hadrons
    - Parton mass (dead cone effect) : $\Delta E_b < \Delta E_c <...$ ⇨ compare c and b production

    ⇨ **Probe of the QCD medium**

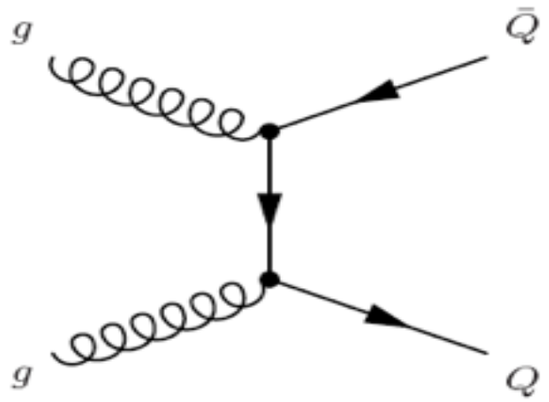
[Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003. Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493...]

Proton-proton Results

Production in hard partonic collisions

- Production time $\tau_p \sim 1/m_Q \sim 0.05 - 0.15$ fm/c

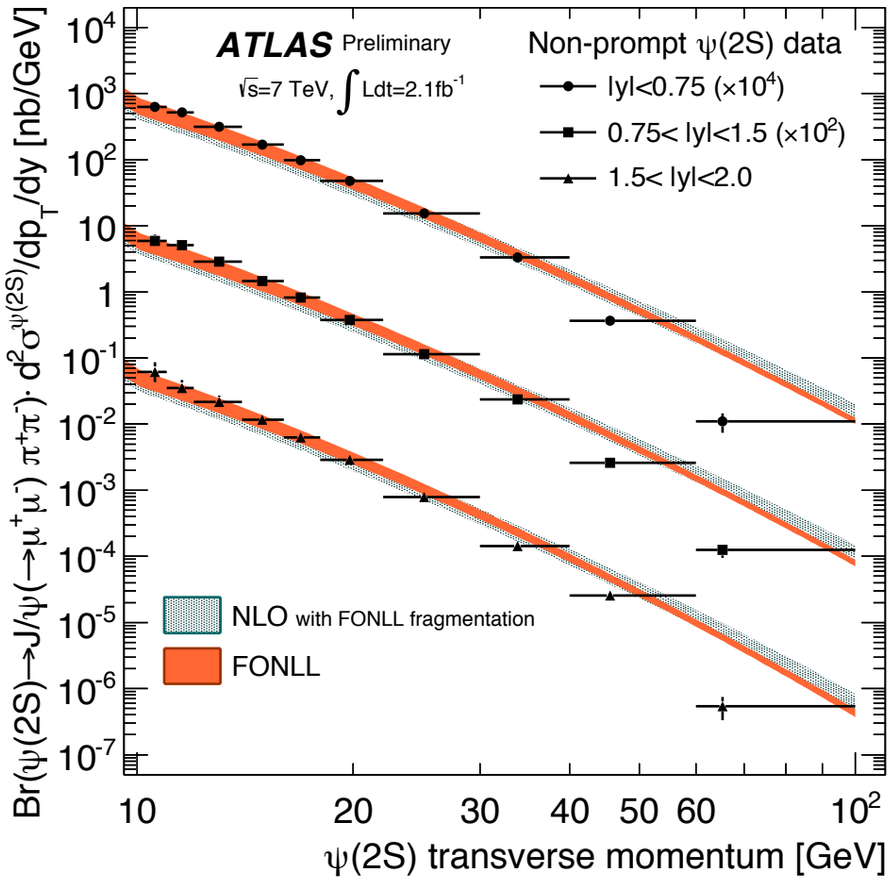
  ⇨ **Tool to test pQCD calculations**



Charm & Beauty Cross Sections

pp at 7 TeV

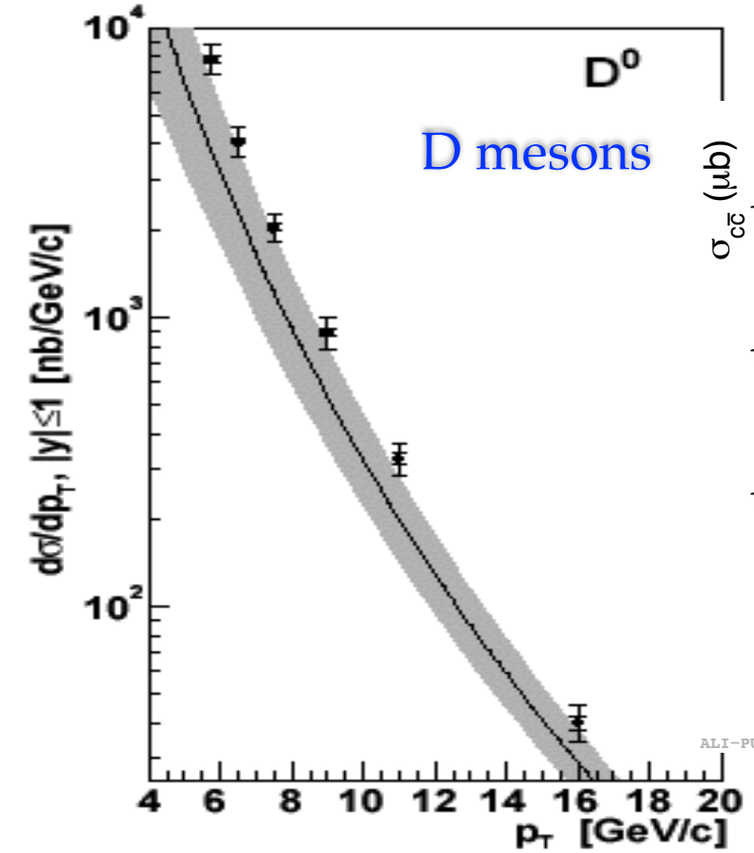
$B \rightarrow \psi(2S) \rightarrow \mu\mu$



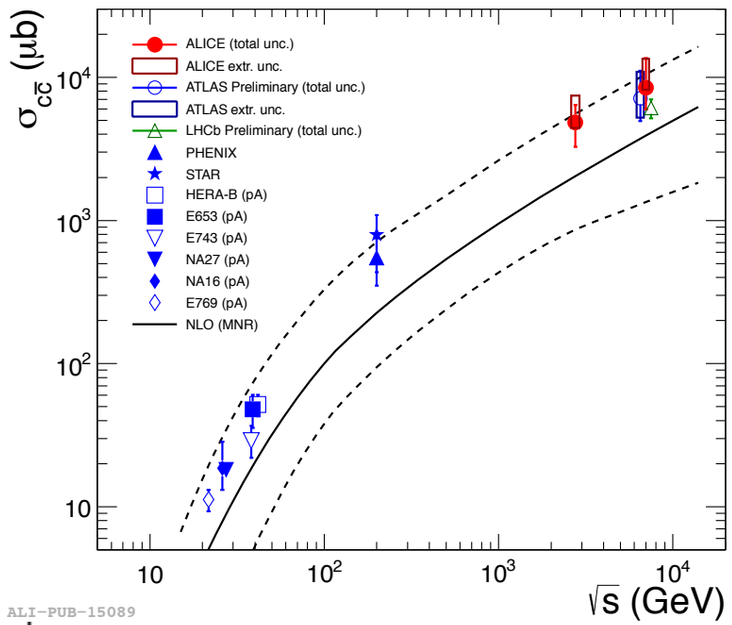
[B+→J/ψ K→μμ K, ATLAS Coll. ATLAS, JHEP 10 (2013) 042]
[B+→ψ(2S)→μμ, ATLAS Coll. ATLAS, ATLAS-CONF-2013-094]

pp at 1.96 TeV

[CDF, PRL 91 (2013) 241804]



[ALICE Coll. JHEP 07 (2012) 191]



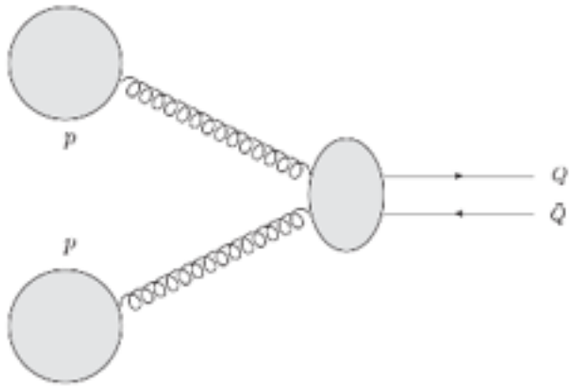
➡ Beauty production seems globally well described by pQCD

There might be some caveats at very large p_T: insufficient "LL" corrections ? B decay/fragmentation?

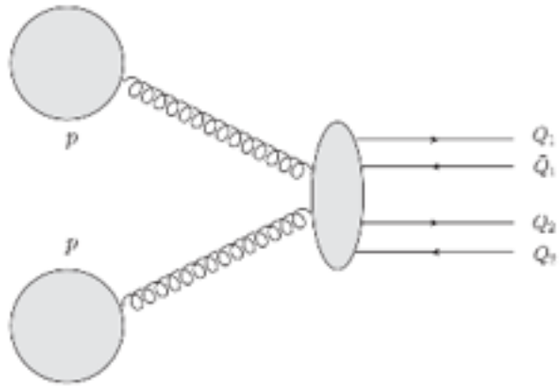
➡ Charm production seems globally well described by pQCD

Caveats: central values of FONLL/GM-VFNS seem to sit systematically below/ above the measurements

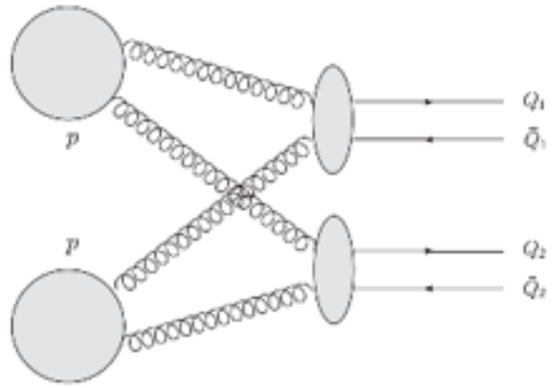
Charm and Multi-Parton Interations



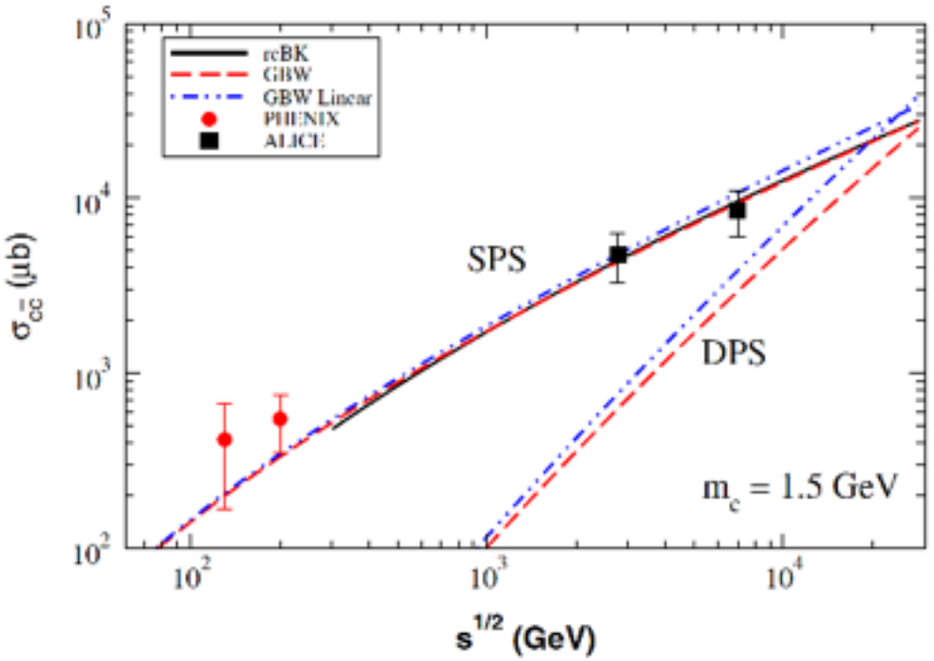
Single production

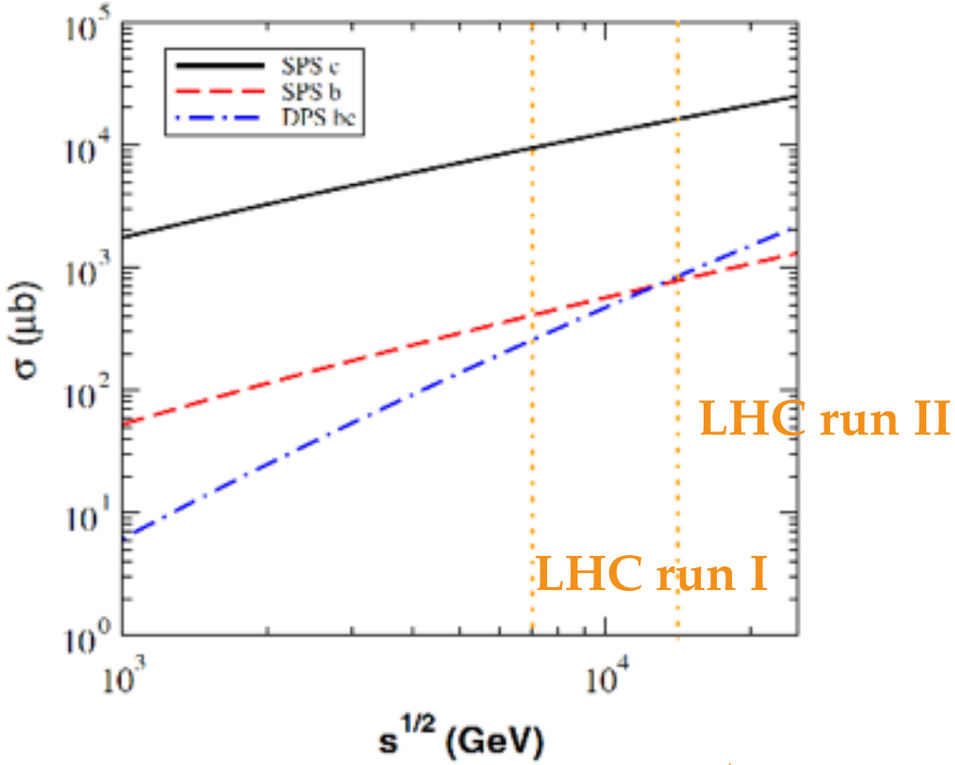


Double production by SPS



Double production by DPS



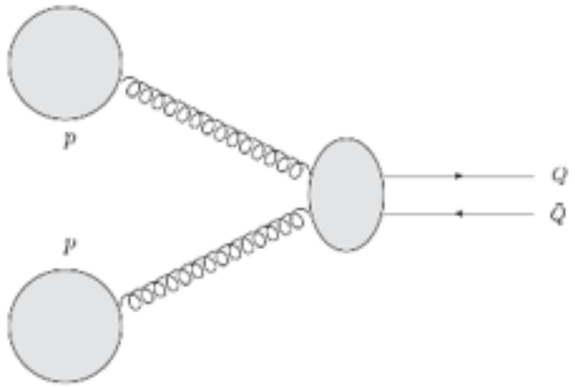


❖ **Contribution from Double Parton Scattering increasing with √s expected to be comparable to Single Parton Scattering for the LHC run II**

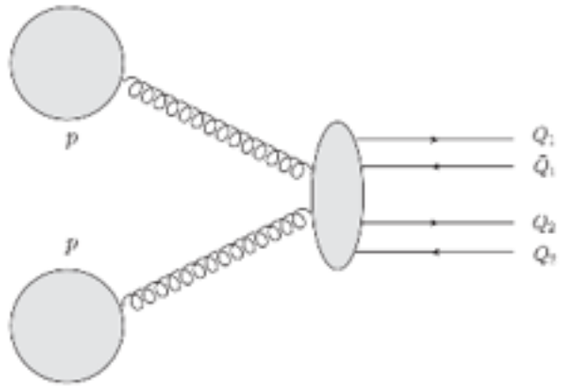
E.R. Cazaroto et al, Phys. Rev. D 88 (2013) 034005

M. Maciula, A. Szczurek, Phys. Rev. D 87 094022 (2013); A. Hameren, M. Maciula, A. Szczurek, arXiv:1402.6972 (2014)

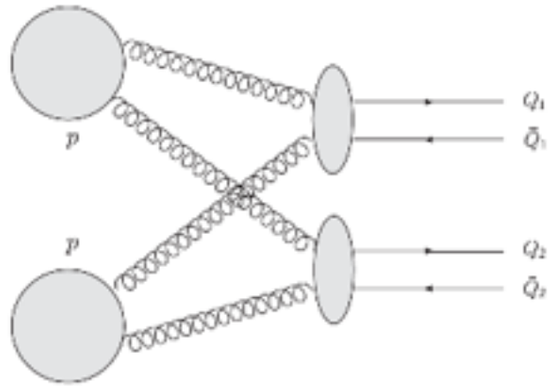
Charm and Multi-Parton Interations



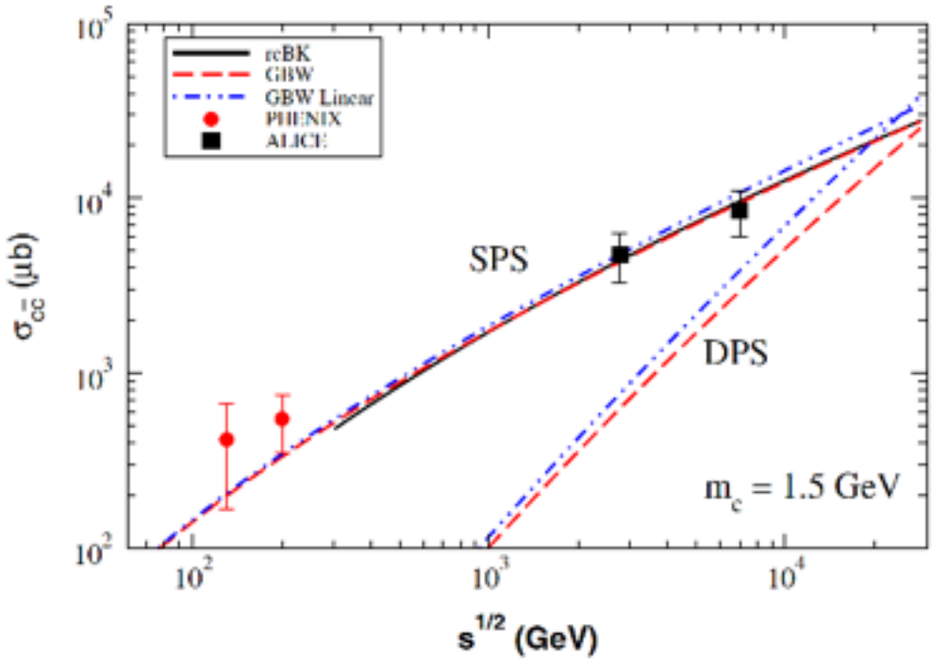
Single production

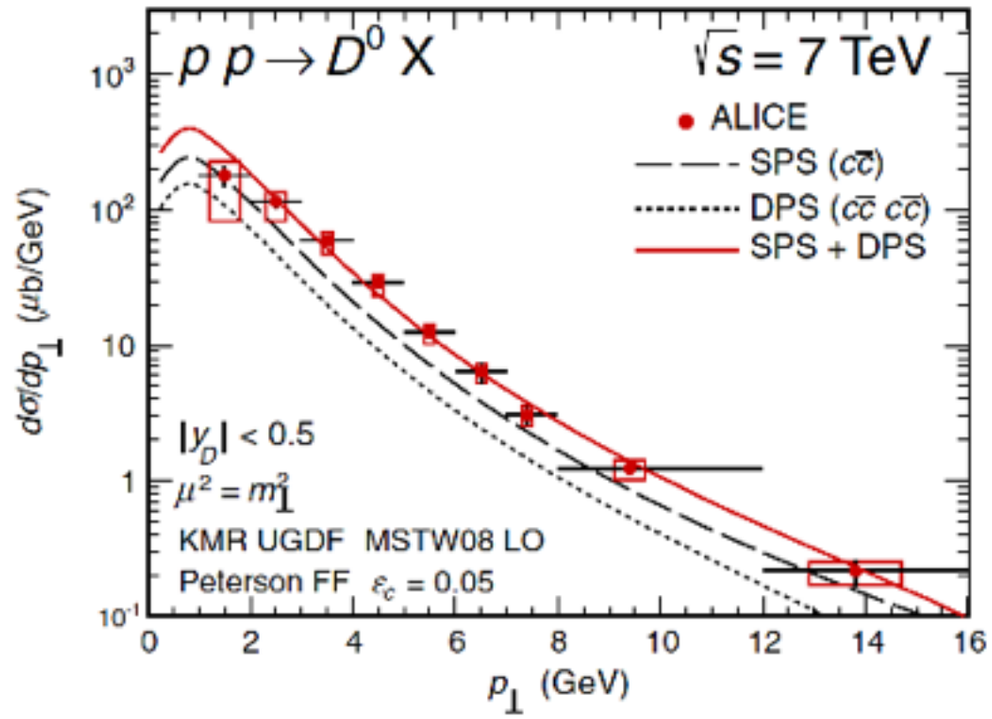


Double production by SPS



Double production by DPS



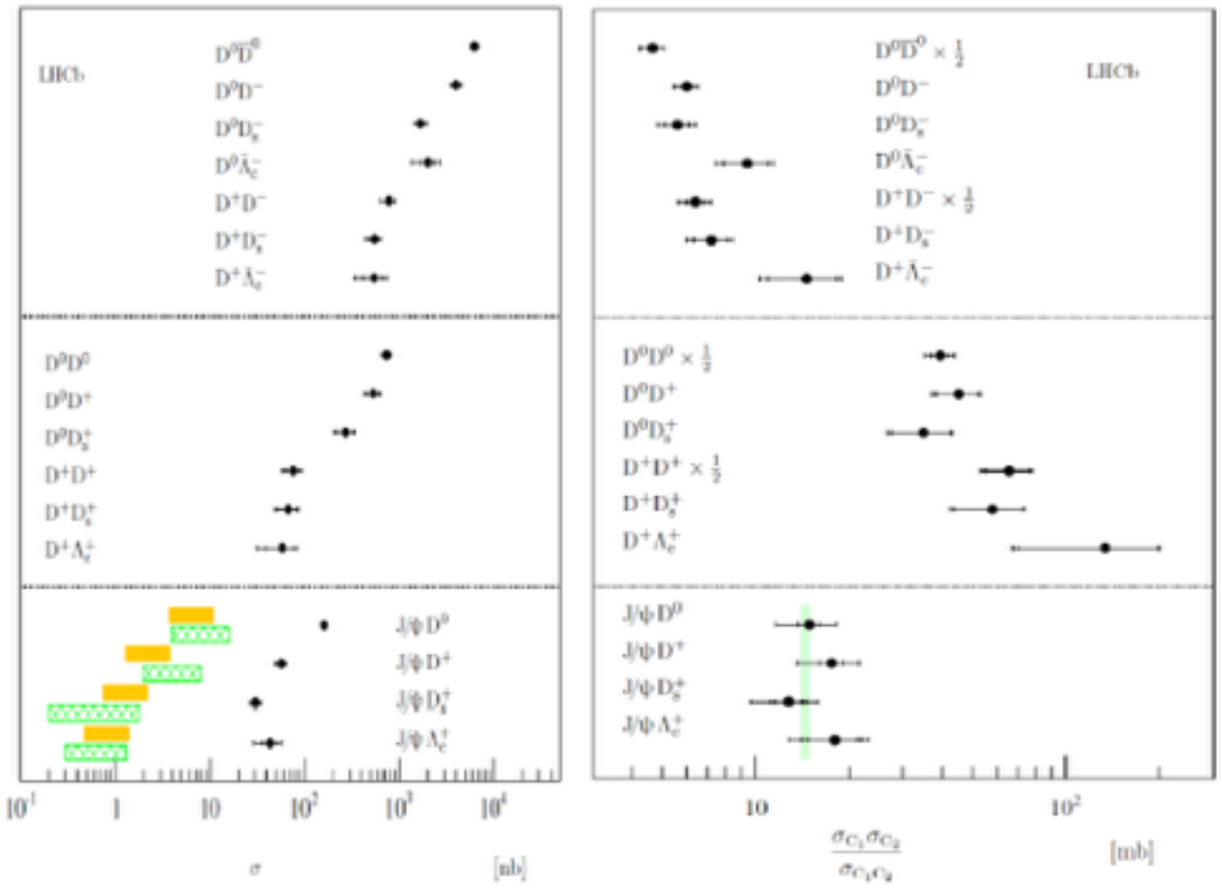


- **Contribution from Double Parton Scattering increasing with √s expected to be comparable to Single Parton Scattering for the LHC run II**
- **Improved description of charm results with calculations of SPS+DPS**

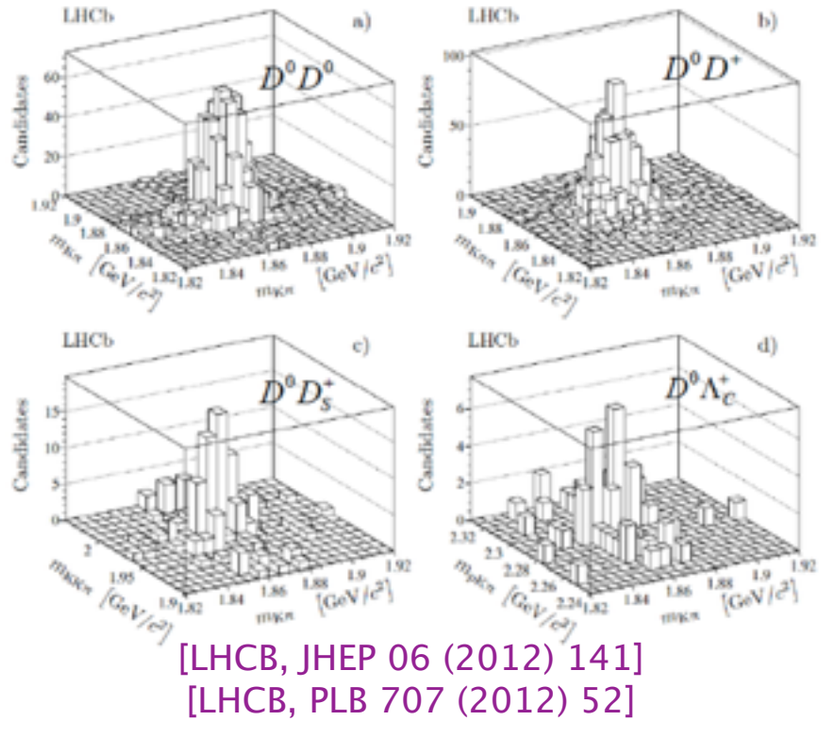
E.R. Cazaroto et al, Phys. Rev. D 88 (2013) 034005

M. Maciula, A. Szczurek, Phys. Rev. D 87 094022 (2013); A. Hameren, M. Maciula, A. Szczurek, arXiv:1402.6972 (2014)

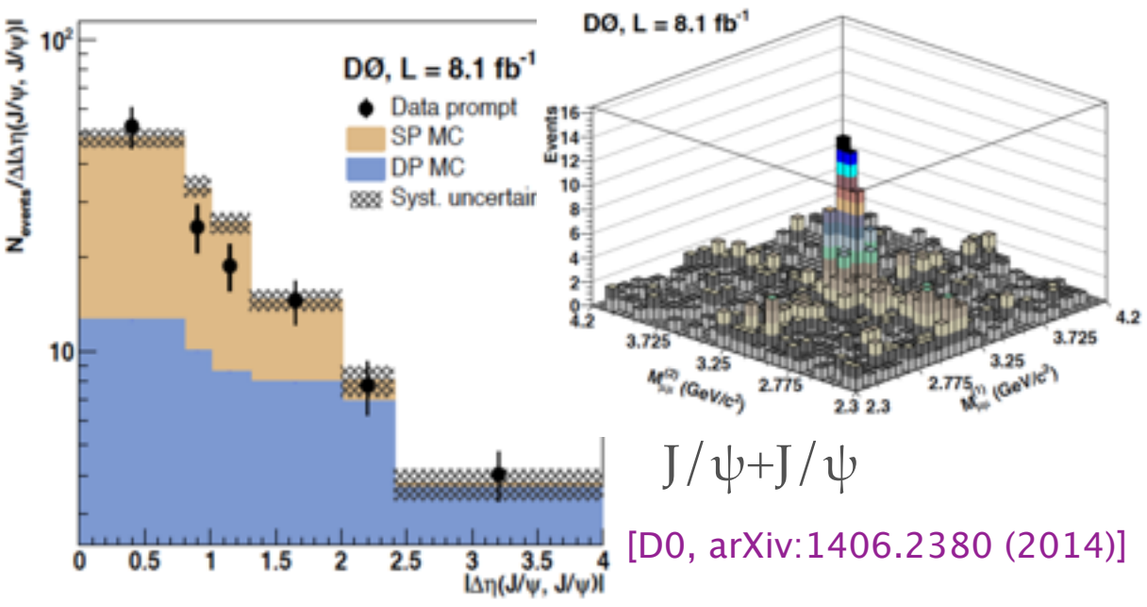
Double Charm Production



$$\sigma^{\mathrm{DPS}}(C_1C_2) = k \times \frac{\sigma(C_1)\sigma(C_2)}{\sigma_{\mathrm{eff}}^{\mathrm{DPS}}}, \qquad k = \frac{1}{2}\,(1) \text{ for } C_1 = (\neq)C_2$$



[LHCB, JHEP 06 (2012) 141]
[LHCB, PLB 707 (2012) 52]



J/ψ+J/ψ

[D0, arXiv:1406.2380 (2014)]

➡ **Theoretical predictions from gg fusion underestimate LHCb J/ψ C cross section, whereas DPS estimates (from CDF multi-jets) agree with LHCb J/ψ C cross section**

➡**D0 J/ψ+J/ψ DPS contribution is consistent with the CDF 4-jet low-pt results, but lower than the W(γ)+jet results → smaller distance between gluons than q-q or q-g ?**

Kom et al PRL 107 (2011) 082002; Baranov et al, PLB 705 (2011) 116; Novoselov, arXiv:1106.2184; Luszczak et al, arXiv:1111.3255

Production process
τ_p~0.05-0.15fm/c

DPS (double parton scattering)
& MPI (multiple parton interaction)

D+D or J/ψ+ J/ψ or J/ψ+D production rates and kine properties in DPS no angular correlation

B and D hadron production rates, ratios, and kinematic properties

+

+

+

B and D hadron
$d^2\sigma/dp_Tdy$
vs $dN/d\eta$
+ azimuthal
(baryon/meson)

D+D & J/ψ+ J/ψ
& J/ψ+D
$d^2\sigma/dp_Tdy$

Decay kinematics
(fetch hadron and parton p_T)

d-Au, Cu-Cu & p-Pb Results

$\sqrt{s_{NN}} = 0.2, 5.0$ TeV

Nuclear environment influence: p-*A* collisions

- Shadowing (PDF modifications in nuclei) and Gluon saturation

  ⇨ **Tool to study high density small-x gluons**

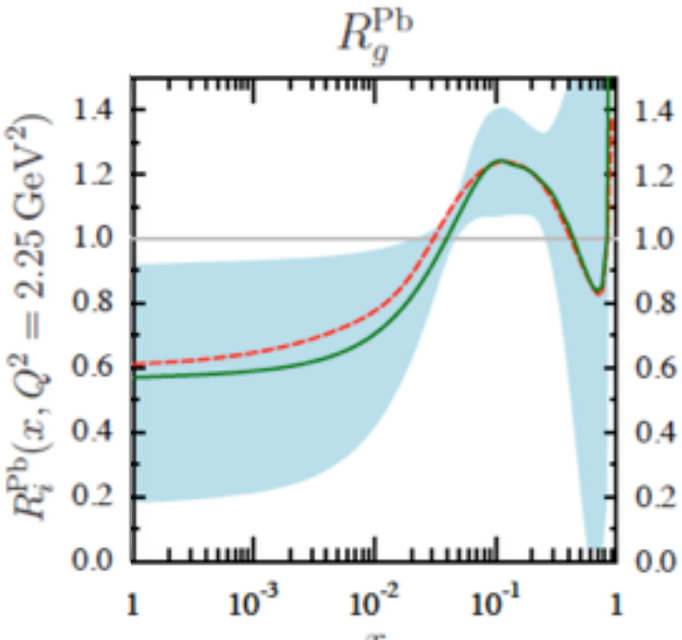
The Control Reaction ?

RHIC, $\sqrt{s_{NN}}$ = 200 GeV: deuteron → ← Gold

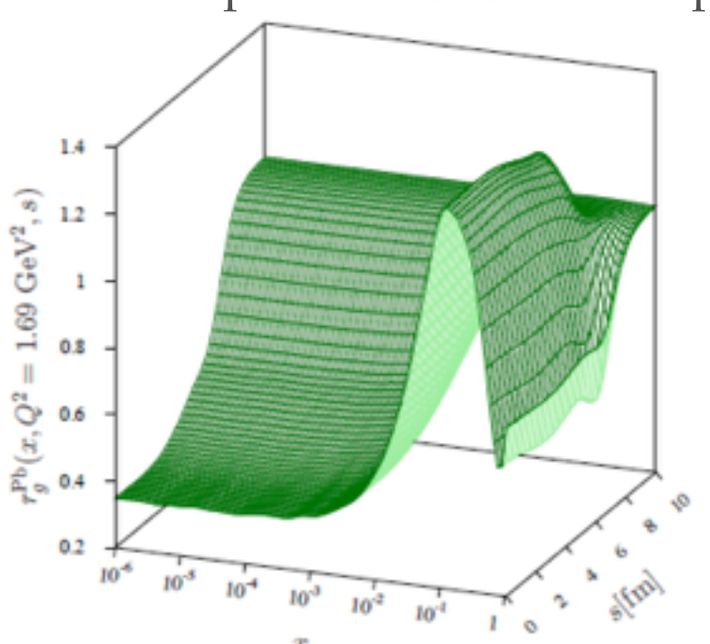
LHC, $\sqrt{s_{NN}}$ = 5 TeV: proton → ← Lead

Rapidity	System	√s		x-range p	~x for HFm	Probing
y=0	d-Au	200		10	10	shad
y=0	p-Pb	5023		5×10		shad
1.4<y<2.0	d-Au	200	d-going	(1.7-3)×10	5×10	shad
2.5<y<4.0	p-Pb	5023	p-going	(1-4)×10		shad
-2.0<y<-1.4	d-Au	200	Au-going	(5-9)×10	8×10	anti-shad
-4.0<y<-2.5	p-Pb	5023	Pb-going	(0.6-3)×10		anti?-shad

Example values for charm production at p_T~0



K.J Eskola et al,JHEP04 (2009) 065.

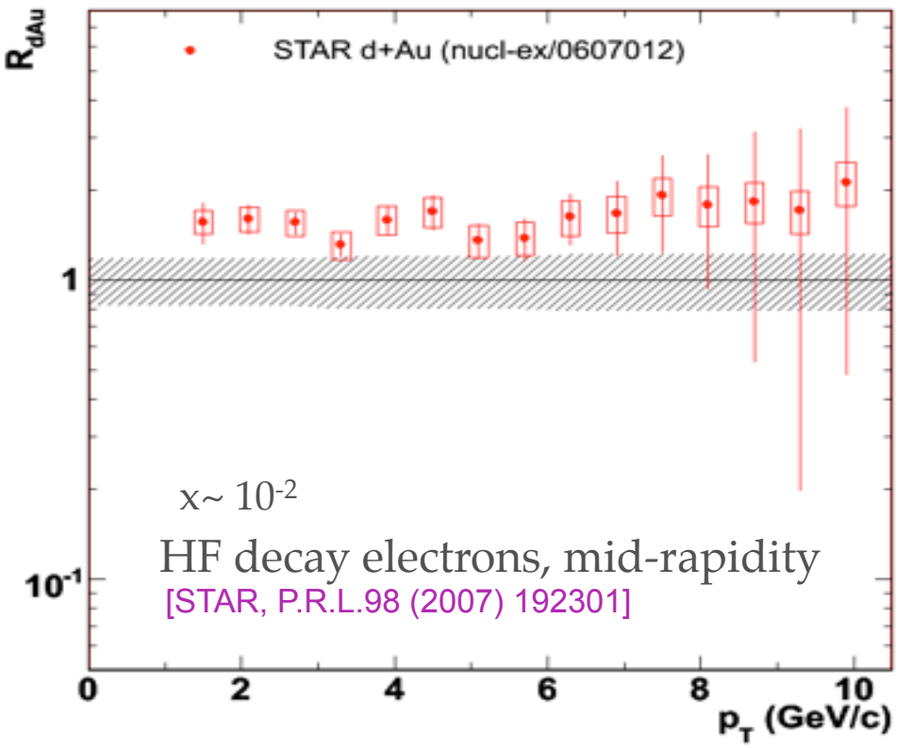


I.Helenius et al, arXiv:1205.5359 [hep-ph]

➡ To keep in mind when comparing RHIC & LHC pA data !

HF Decay Leptons at RHIC

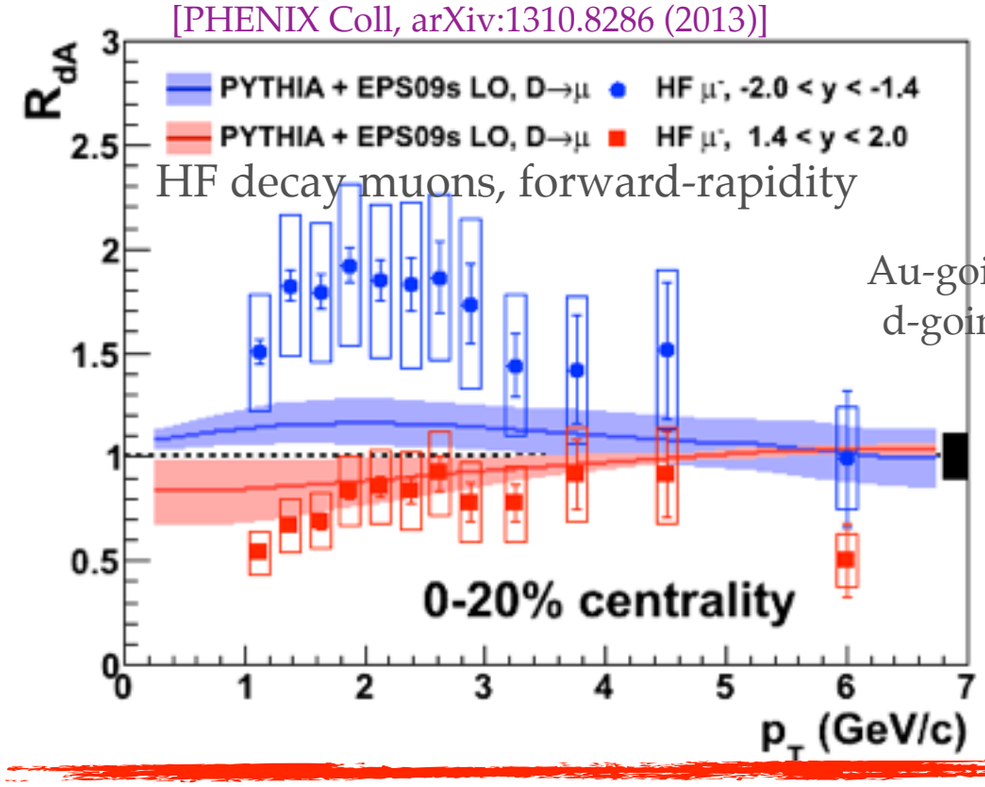
d-Au at 200 GeV



[STAR, P.R.L.98 (2007) 192301]

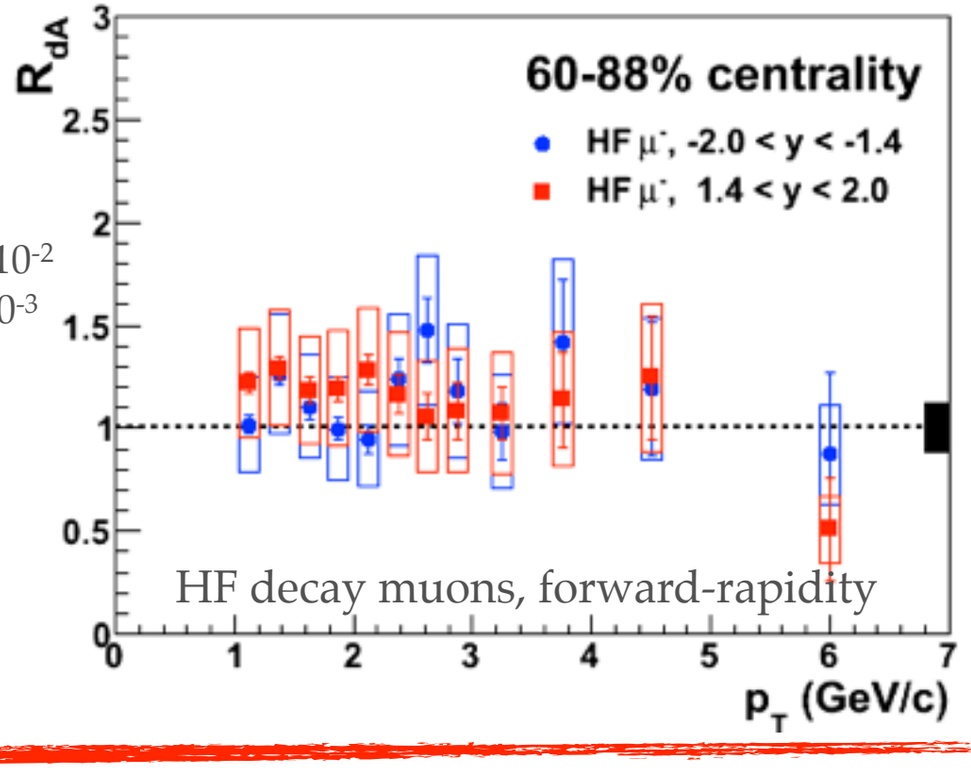
[PHENIX Coll, arXiv:1310.1005 (2013)]

[PHENIX Coll, arXiv:1310.8286 (2013)]



Au-going: x~ 8×10^{-2}

d-going: x~ 5×10^{-3}

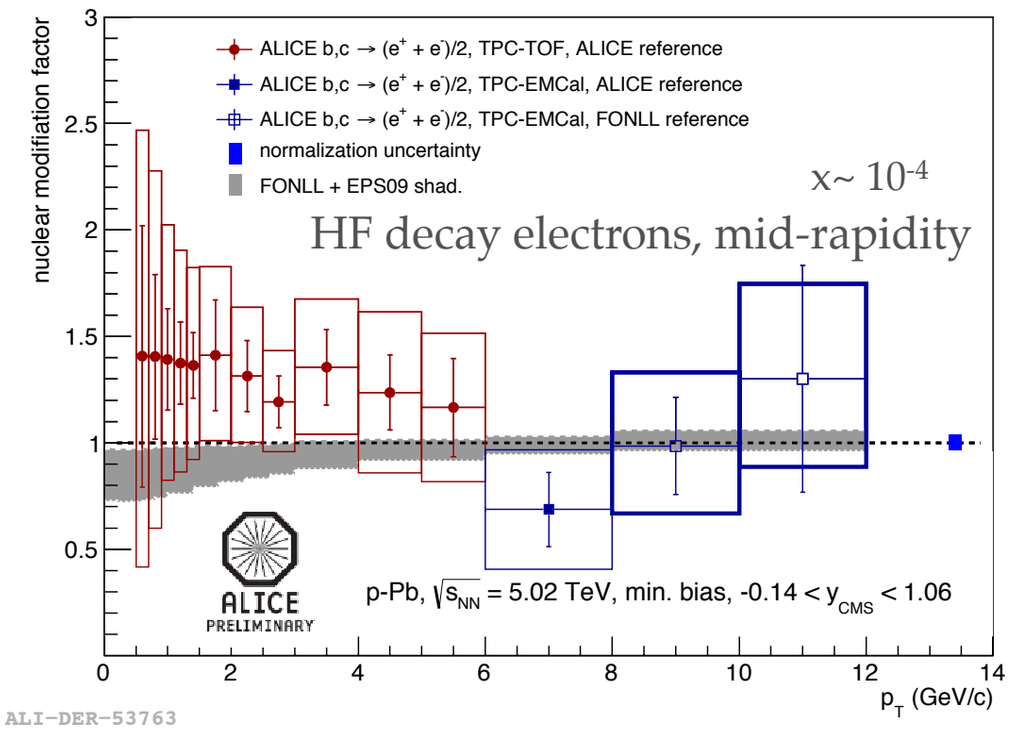


➡ **No suppression observed for heavy flavor decay electrons at mid-rapidity within uncertainties (flat-like shape)**

➡ **Different behavior vs rapidity and centrality. Mild (strong) rapidity dependence in peripheral (central) collisions**

➡ **nPDFs do not reproduce backward rapidity results. Might impact parameter nPDFs help?**

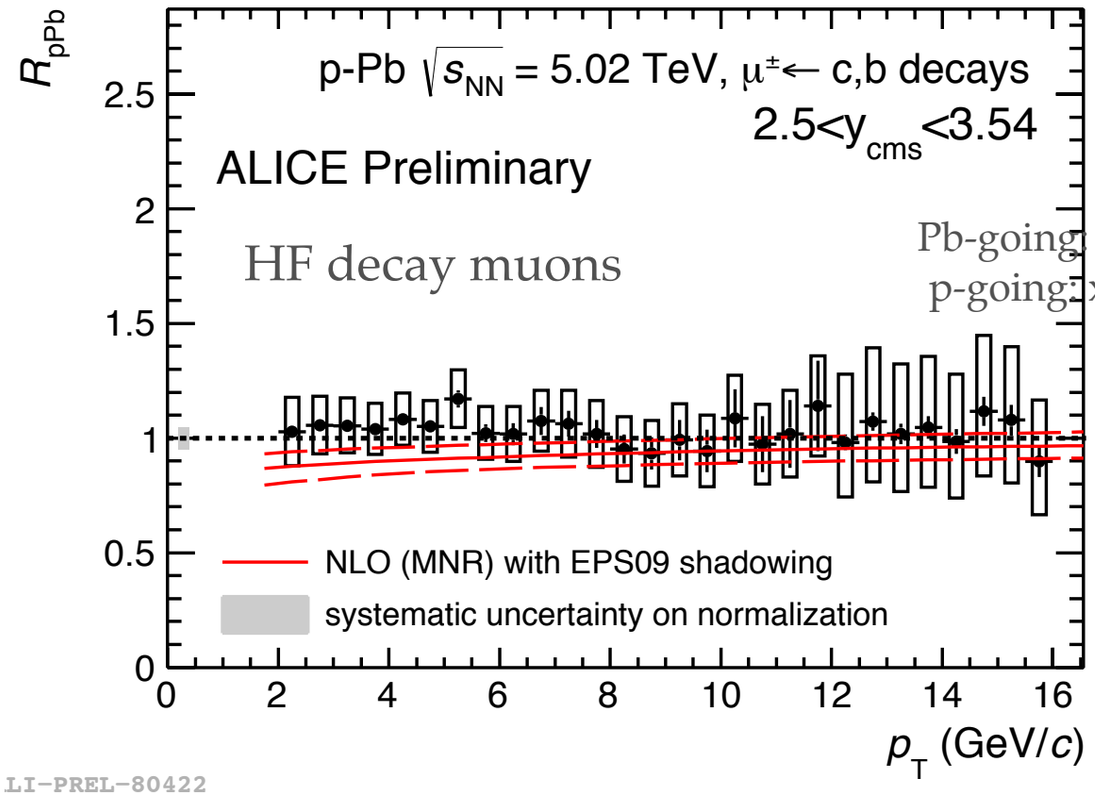
HF Decay Leptons at LHC



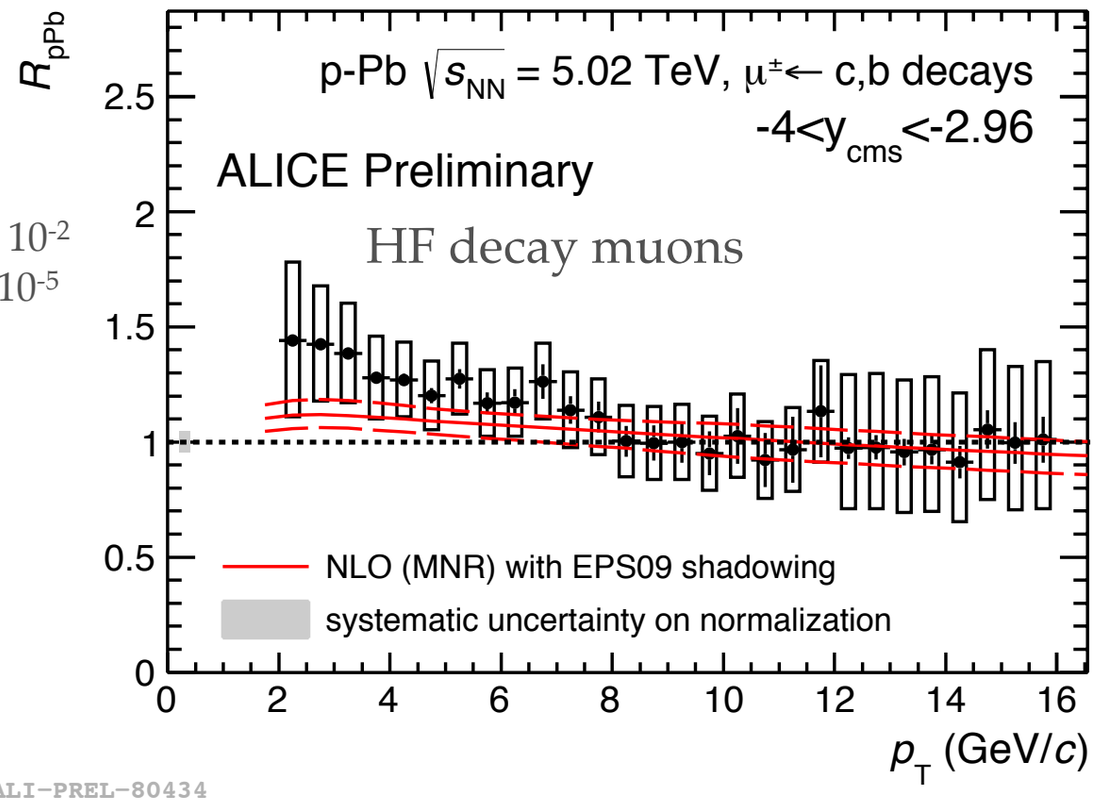
ALI-DER-53763

p-Pb at 5.023 TeV

- ➡ Different behavior vs rapidity.
- ➡ R_{pPb} is close to unity at high p_T
- ➡ Fair agreement with MNR calculations with EPS09 shadowing



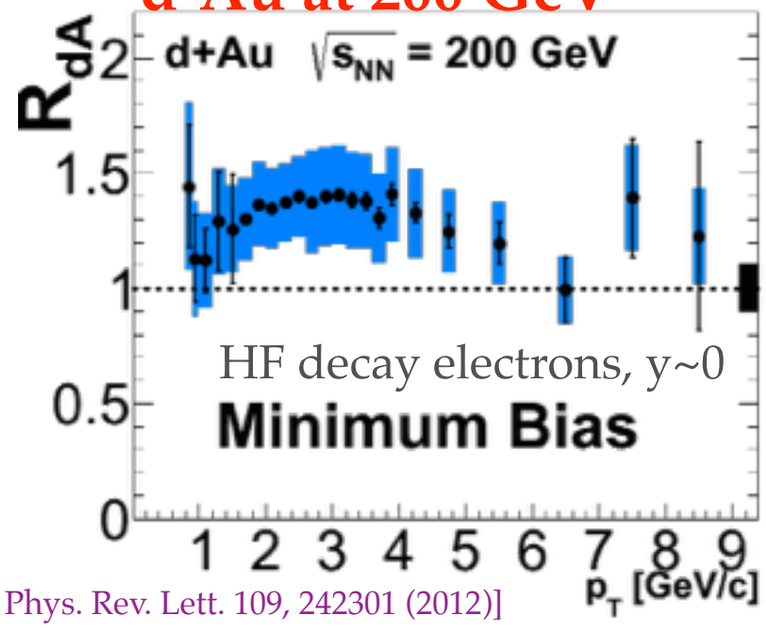
LI-PREL-80422



ALI-PREL-80434

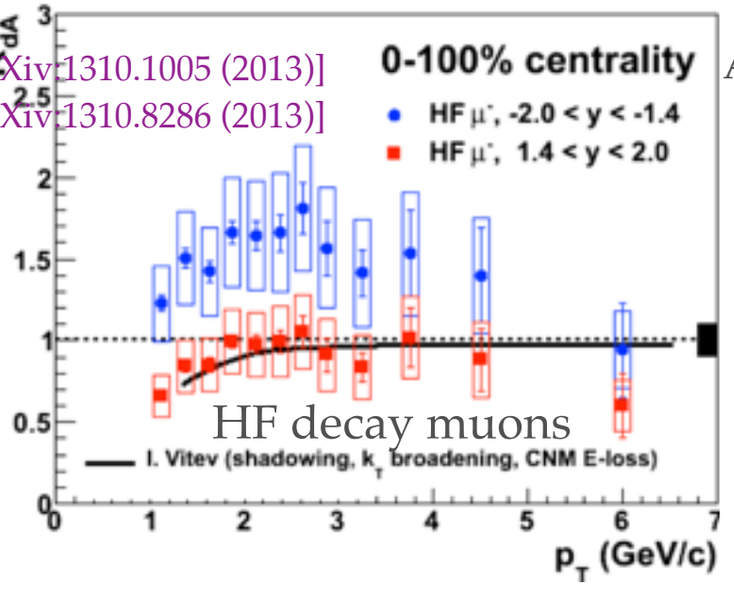
HF vs Energy

d-Au at 200 GeV



x~10^{-2}

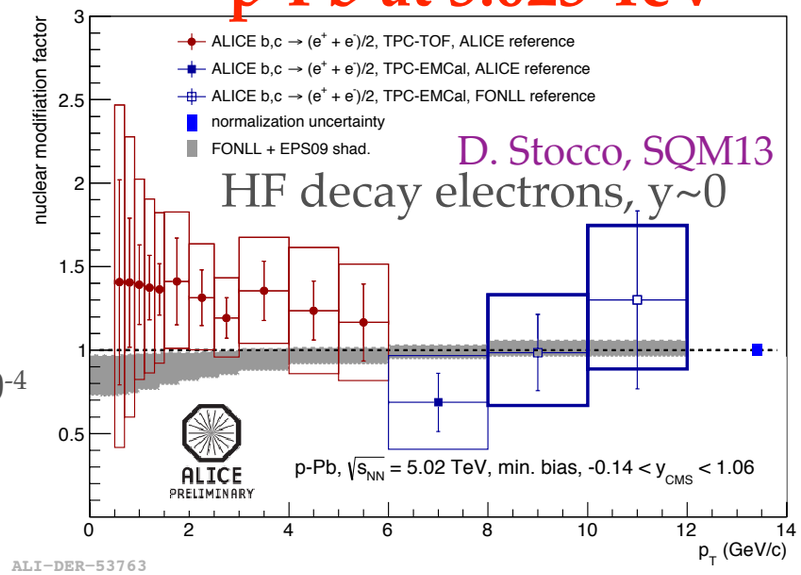
[PHENIX Coll, Phys. Rev. Lett. 109, 242301 (2012)]



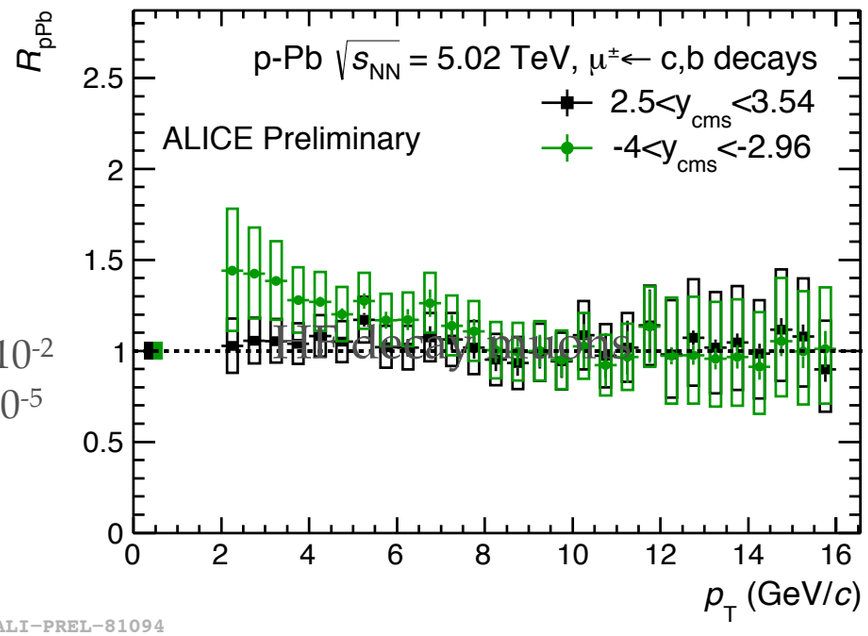
[PHENIX Coll, arXiv:1310.1005 (2013)]
[PHENIX Coll, arXiv:1310.8286 (2013)]

Au-going: x~ 8×10^{-2}
d-going: x~ 5×10^{-3}

p-Pb at 5.023 TeV



x~5×10^{-4}

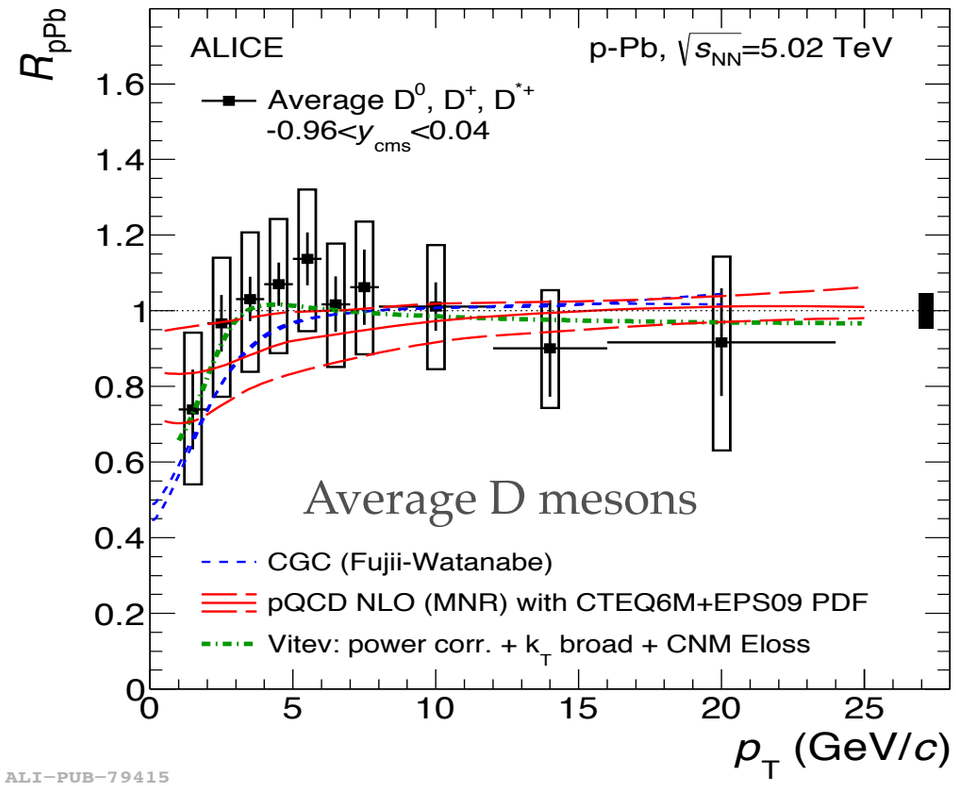


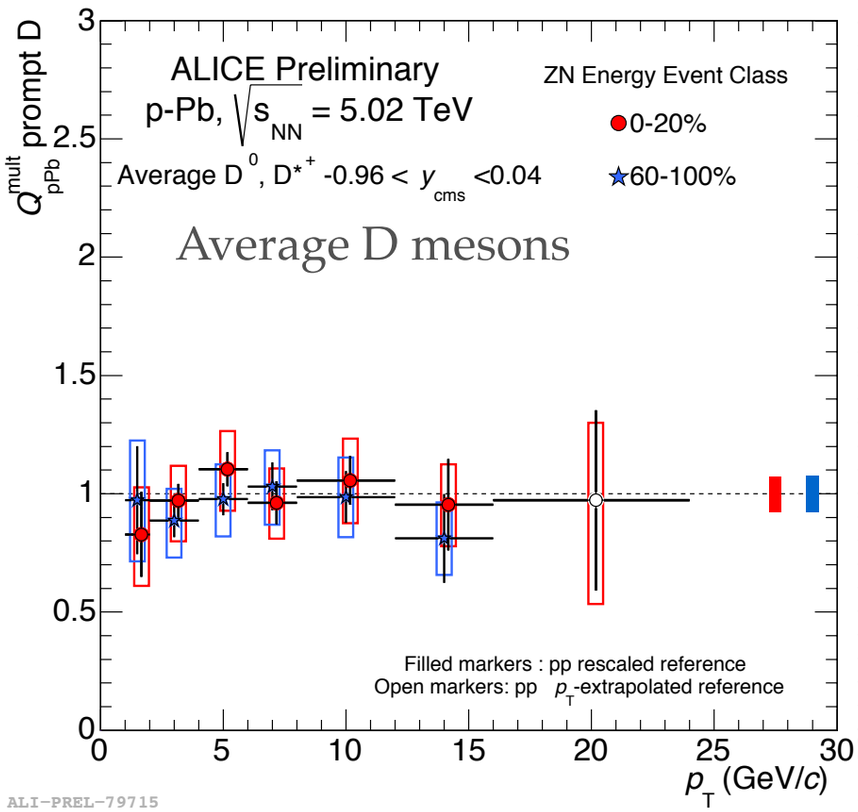
Pb-going: x~ 10^{-2}
p-going: x~ 10^{-5}

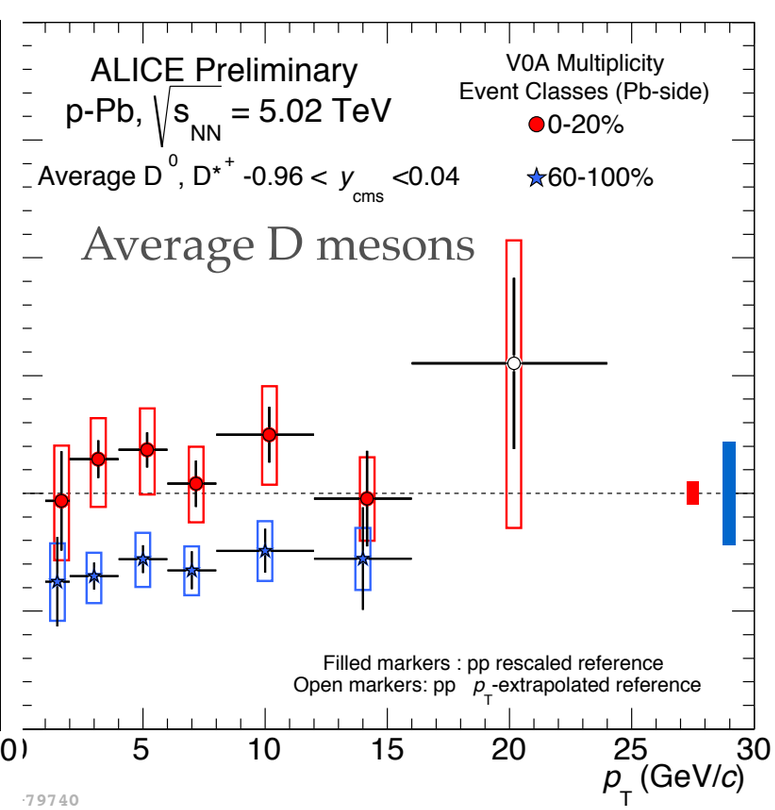
➡ **Similar behaviour even if the x-range covered is different, but uncertainties are sizable. May be shadowing is not the dominant mechanism at play ?**

❖ **Additional effects: k_T broadening, Eloss, comovers, coalescense, hydro may be at play ?**

Charm production at LHC





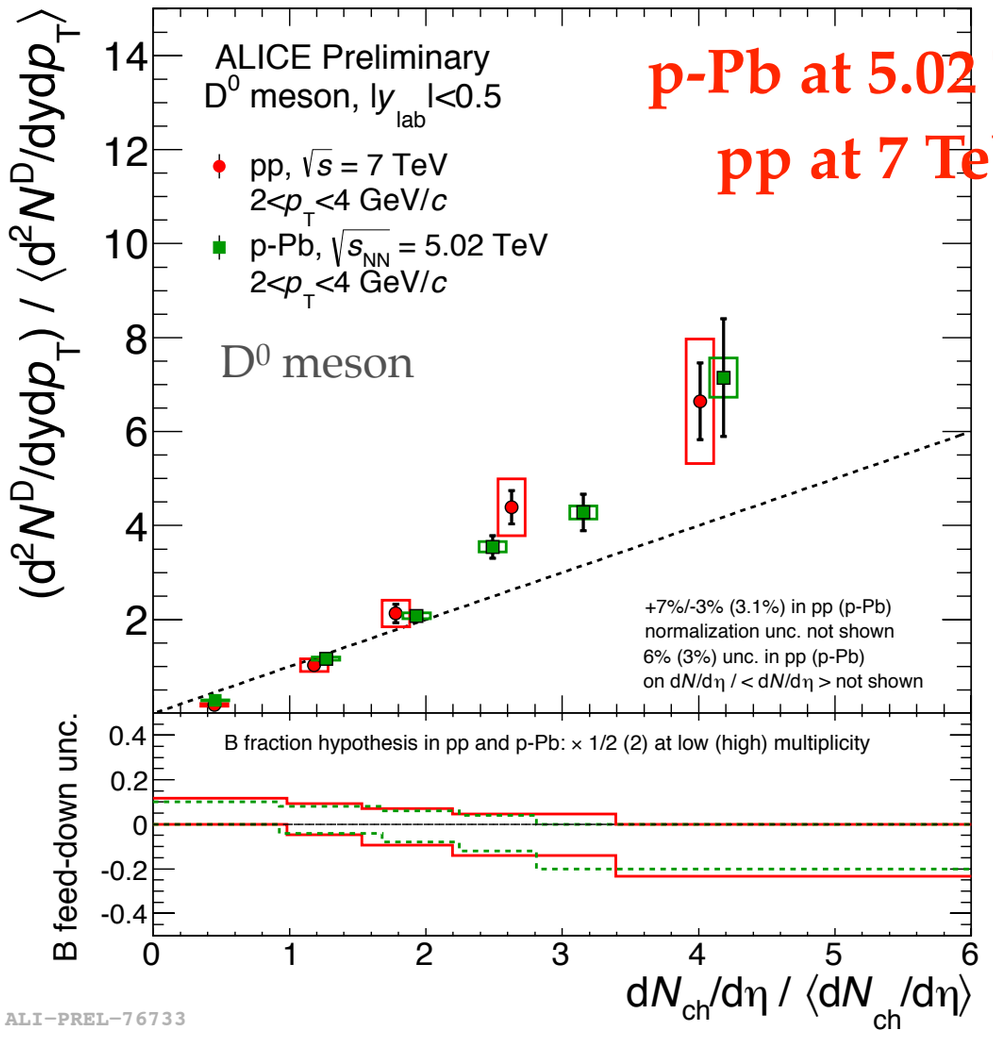


- ➡ R_{pPb} is close to unity at high p_T
- ➡ Good agreement with calculations:
  - ➡ MNR with EPS09 shadowing
  - ➡ CGC [Fuji-Watanabe]
  - ➡ Eloss+k_T-broadening+shadowing [Vitev]
- ➡ Not obvious centrality dependence, bias depending on the centrality estimator ?

❖ **Nuclear effects expected to be small at high p_T in Pb-Pb collisions**

[M. Mangano, P. Nason and G. Ridolfi, Nucl. Phys. B 373 (1992) 295;
K. Eskola, H. Paukkunen and C. Salgado, JHEP 04467 (2009) 065.;
H. Fujii and K. Watanabe, arXiv:1308.1258.
R. Sharma, I. Vitev and B. -W. Zhang, Phys. Rev. C 80461 (2009) 054902.]

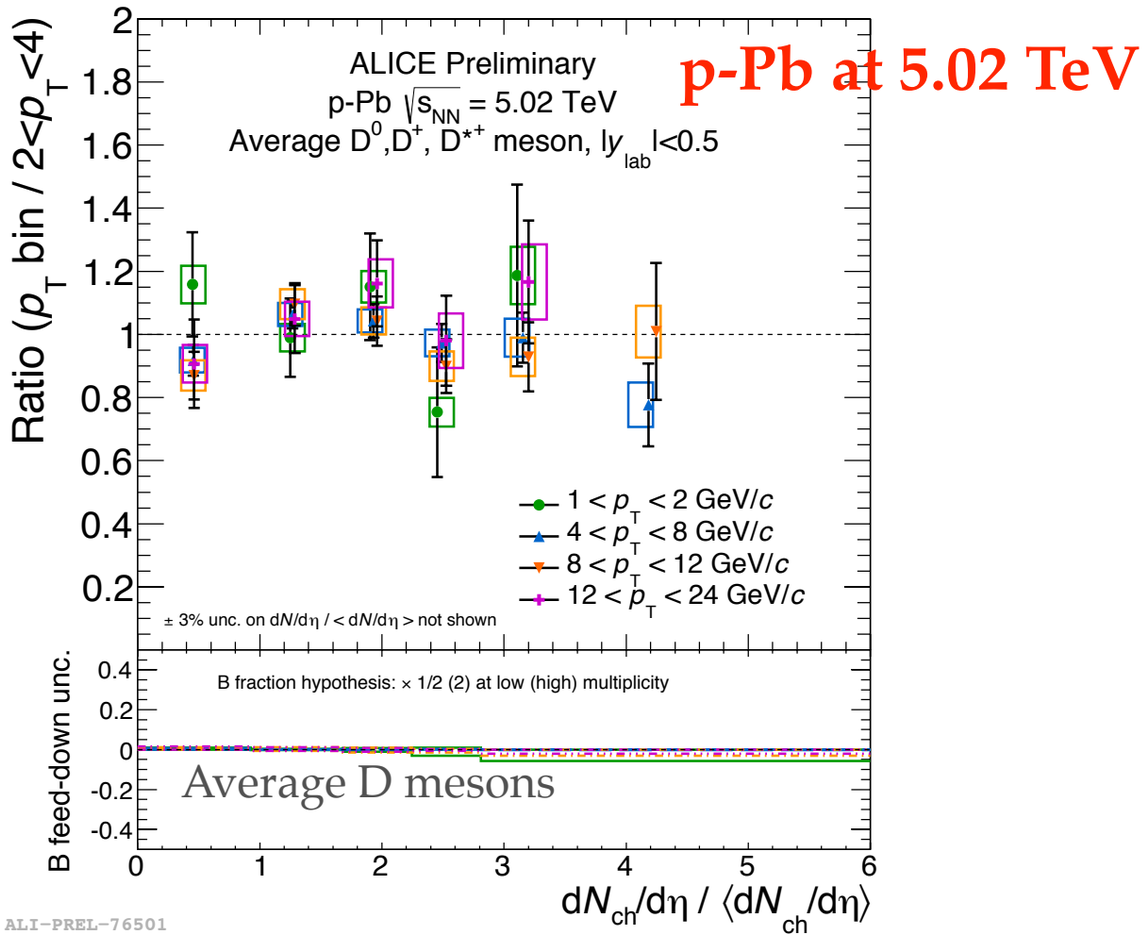
Charm yields vs dN/dη



p-Pb at 5.02 TeV

pp at 7 TeV

$$Y^{\mathrm{corr}} = \frac{Y^{\mathrm{mult}} / (\epsilon^{\mathrm{mult}} \times N_{\mathrm{event}}^{\mathrm{mult}})}{Y^{\mathrm{tot}} / (\epsilon^{\mathrm{tot}} \times N_{\mathrm{event}}^{\mathrm{tot}} / \epsilon^{\mathrm{trigger}})}$$



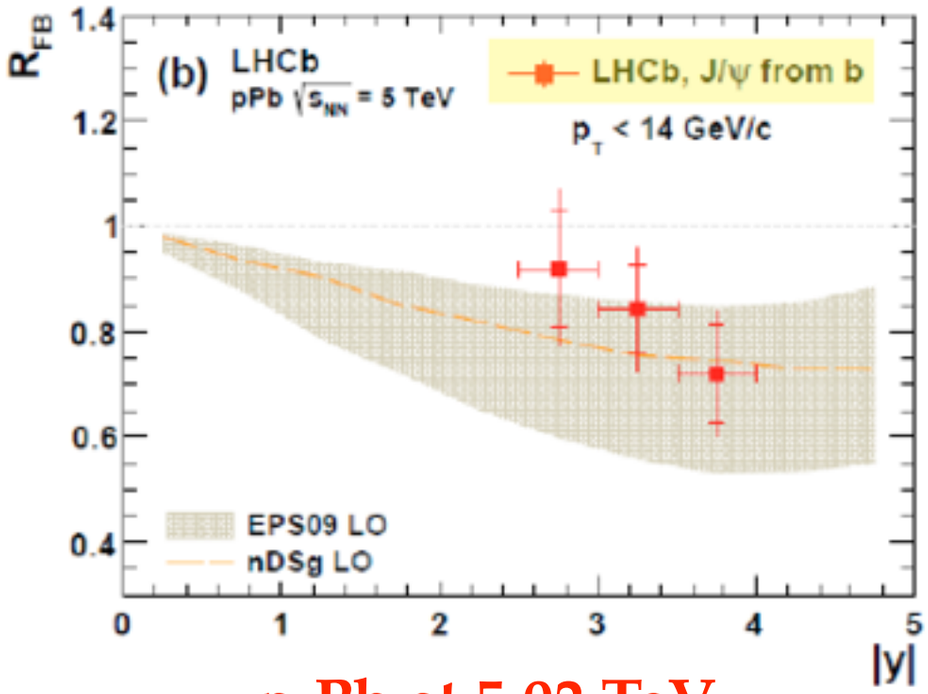
p-Pb at 5.02 TeV

- ➡ **The relative D-meson average yields (|y|<0.5) increase with the relative charged-particle multiplicity at mid-rapidity (|η|<1)**
  - ➡ **no p_T dependence observed (within uncertainties)**
  - ➡ **with a similar trend in pp collisions and p-Pb collisions**

- ❖ **High-multiplicity pp collisions are mainly from MPIs, while high-multiplicity p-Pb collisions are also due to a larger number of binary collisions.**

Beauty production at LHC

Non-Prompt J/ψ R_{pPb}

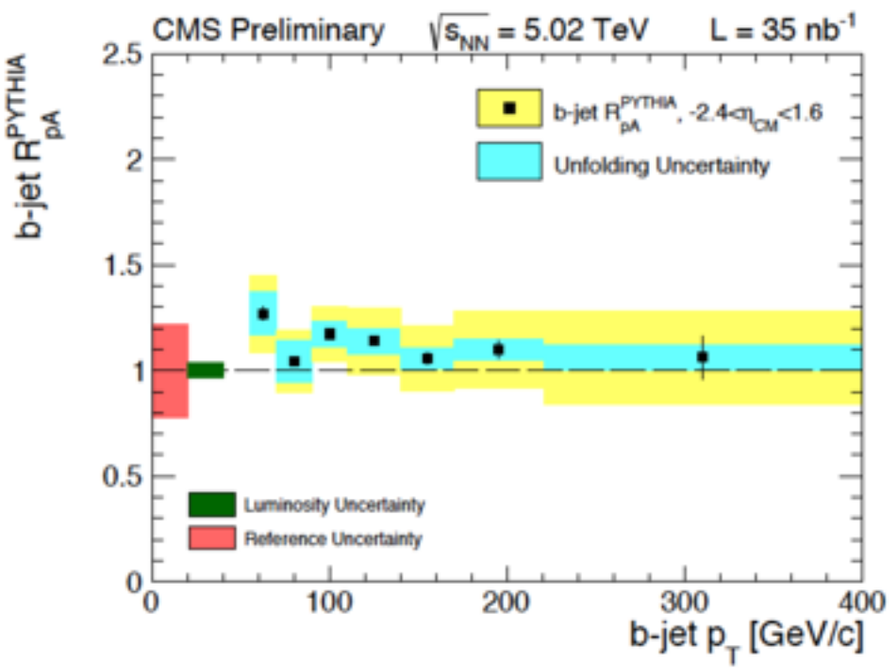


p-Pb at 5.02 TeV

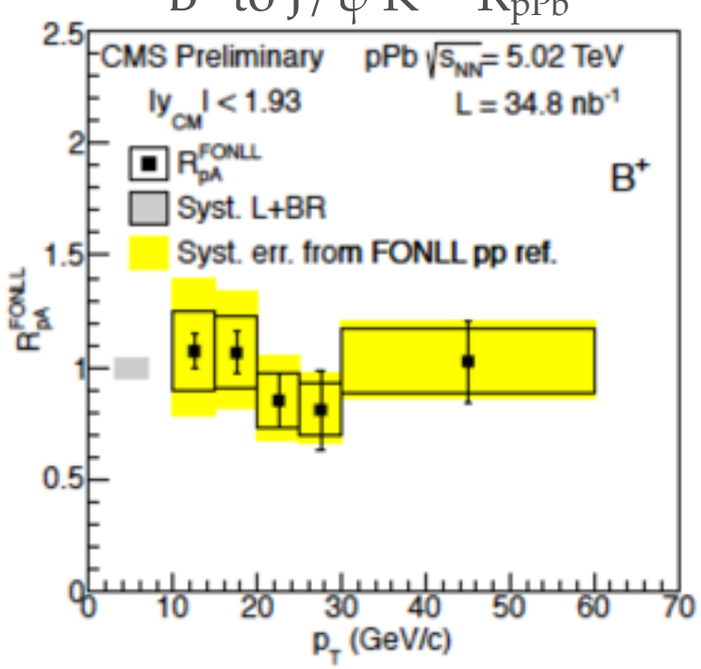
- **LHCb did the first measurement of beauty production down to p_T~0 in heavy ion collisions !**
  - **R_{FB} suggests a possible rapidity dependence**
  - **Reasonable agreement with LO calculations with EPS09 shadowing**
- **CMS examines the high p_T range via B-jets and B hadrons (B^0, B^+, B_s) of p_T> 10GeV/c**
  - **R_{pPb} is close to unity at high p_T**

❖ **Nuclear effects expected to be small at high p_T in Pb-Pb collisions but not negligible and low p_T**

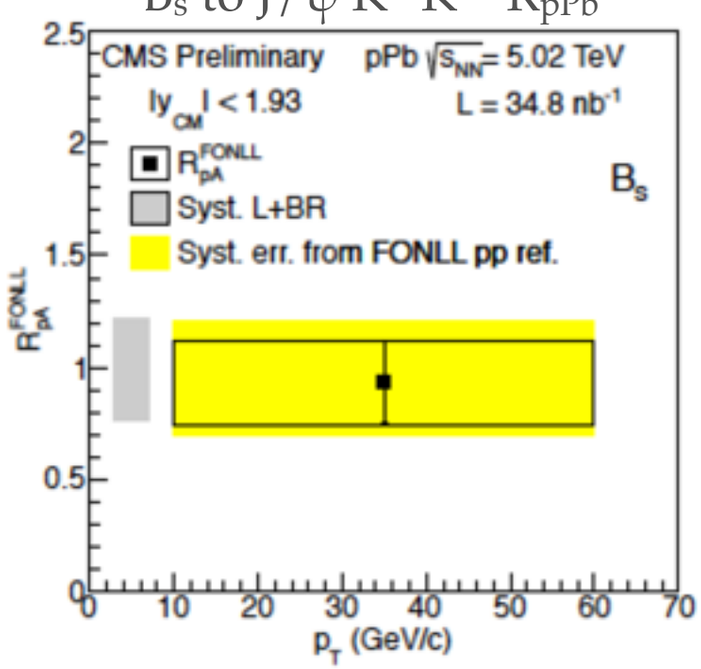
B-Jet R_{pPb}



B^+ to J/ψ K^+ R_{pPb}



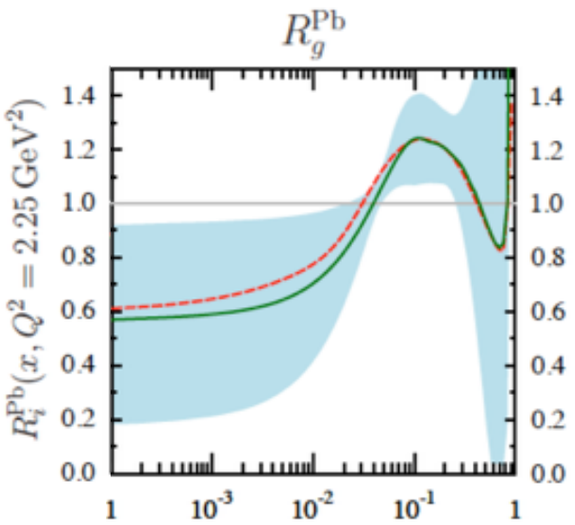
B_s to J/ψ K^+ K^- R_{pPb}

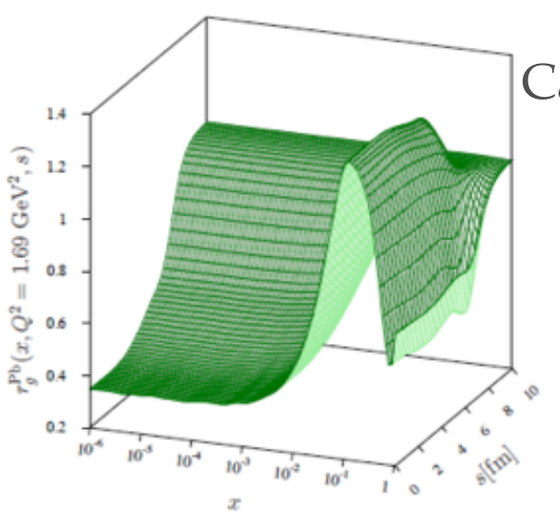


The Control Reaction ?

Rapidity	System	√s		x-range p	~x for HFm	Probing
y=0	d-Au	200		10	10	shad
y=0	Au-Au	200		10		shad
y=0	p-Pb	5023		5×10		shad
y=0	Pb-Pb	2760		9×10		shad
1.4<y<2.0	d-Au	200	d-going	(1.7-3)×10	5×10	shad
1.4<y<2.0	Au-Au	200		(1.7-3)×10		shad
2.5<y<4.0	p-Pb	5023	p-going	(1-4)×10		shad
2.5<y<4.0	Pb-Pb	2760		(1-7)×10		shad
-2.0<y<-1.4	d-Au	200	Au-going	(5-9)×10	8×10	anti-shad
-2.0<y<-1.4	Au-Au	200		(5-9)×10		anti-shad
-4.0<y<-2.5	p-Pb	5023	Pb-going	(0.6-3)×10		anti?-shad
-4.0<y<-2.5	Pb-Pb	2760		(1-5)×10		anti?-shad

Example values for charm production at p_T~0
Caveat, rapidity shift of Δy ~0.5 at LHC pPb not considered





➡ **Be careful when comparing p-Pb and Pb-Pb data at different energies !**
⇨ **Need models that reproduce them**

K.J Eskola et al,JHEP04 (2009) 065. I.Helenius et al, arXiv:1205.5359 [hep-ph]

Production process
τ_p~0.05-0.15fm/c

DPS (double parton scattering)
& MPI (multiple parton interaction)

D+D or J/ψ+ J/ψ or J/ψ+D production rates
and kine properties in DPS no angular correlation

B and D hadron production rates, ratios, and kinematic properties

+

Nuclear PDFs
gluon shadowing

Saturation
gluon saturation

Eloss by scattering

Multiplicity dependence

k_T broadening

B and D hadron production rates, ratios, and kinematic properties

+

hydro?

comovers

+

Baryon / meson contribution
(might vary the p_T trend)

Decay kinematics
(fetch hadron and parton p_T)

B and D hadron
$d^2\sigma/dp_Tdy$
vs dN/dη
+ azimuthal
(baryon/meson)

D+D & J/ψ+ J/ψ
& J/ψ+D
$d^2\sigma/dp_Tdy$

Pb-Pb & Au-Au Results

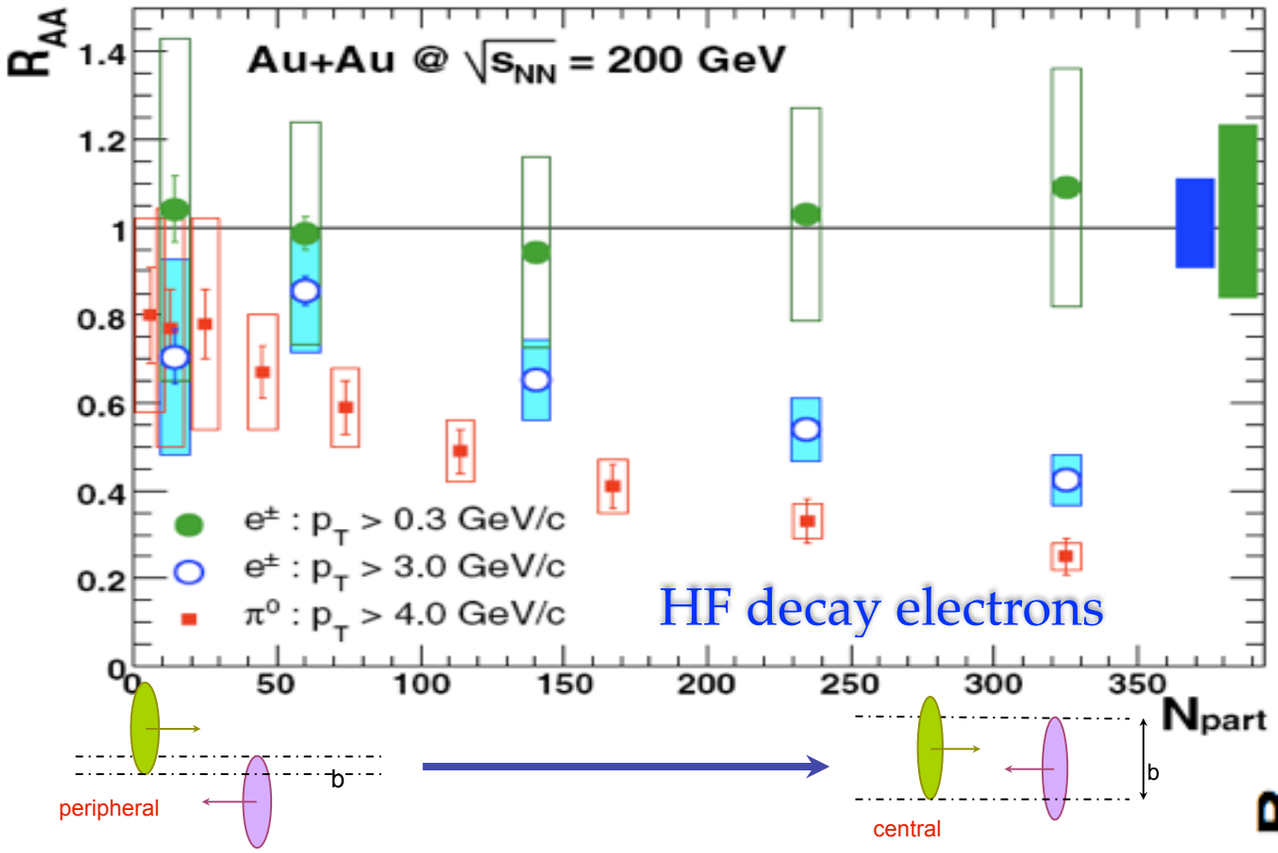
$\sqrt{s_{NN}} = 0.2$ and 2.76 TeV

Effects in a QGP: A-B collisions ⇨ ⇨ Au-Au, Pb-Pb

- Thermalisation in the QGP (low p_T)
  - Medium transport properties ⇨ dN/dp_T, R_{AA}, v_2
- Energy loss in the QGP (high p_T)
  - Medium density and size ⇨ dN/dp_T, R_{AA}, v_2
  - Color charge (Casimir factor) : $\Delta E_{u,d,s} < \Delta E_g$ ⇨ compare to light hadrons
  - Parton mass (dead cone effect) : $\Delta E_b < \Delta E_c <...$ ⇨ compare c and b production

⇨ **Probe of the QCD medium**

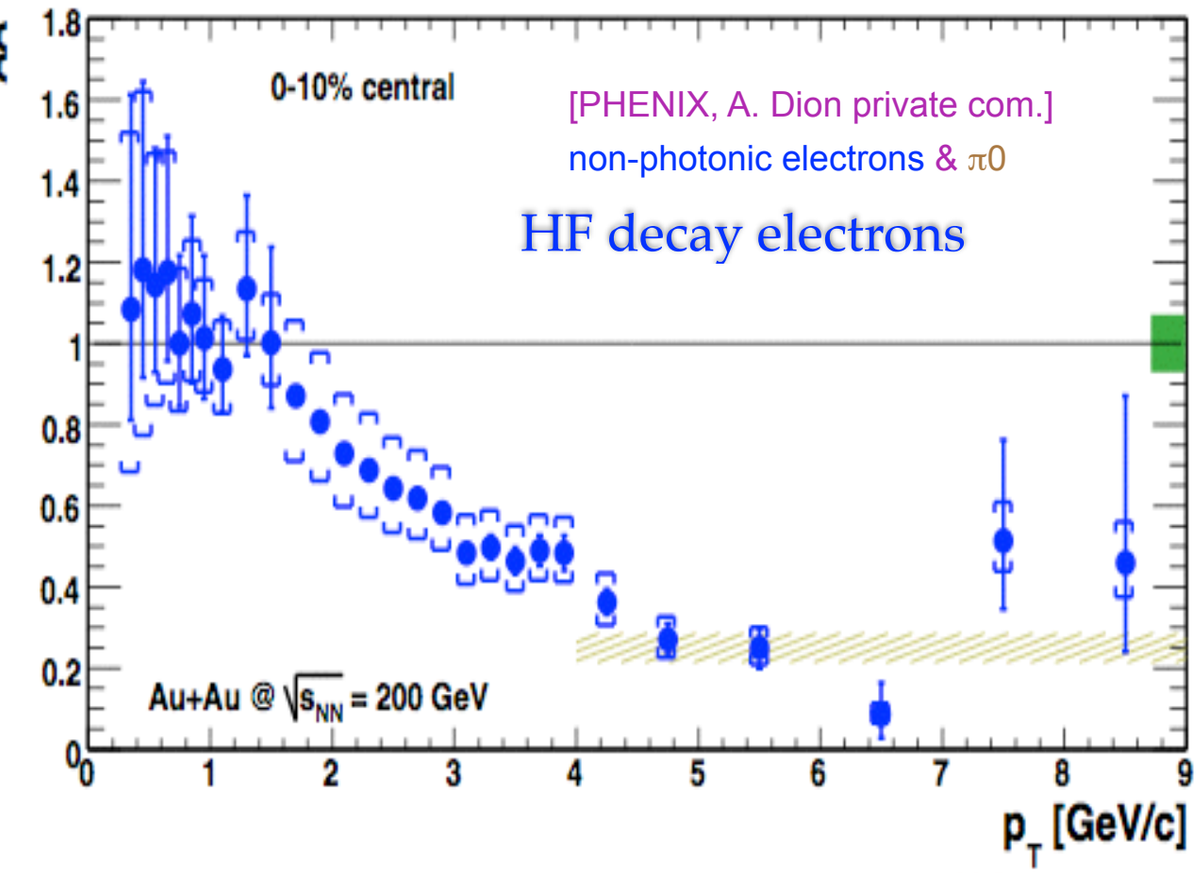
RHIC, Heavy Flavor Suppression



[STAR, P.R.L.98 (2007) 192301]
[PHENIX, P.R.L.98 (2007) 172301]

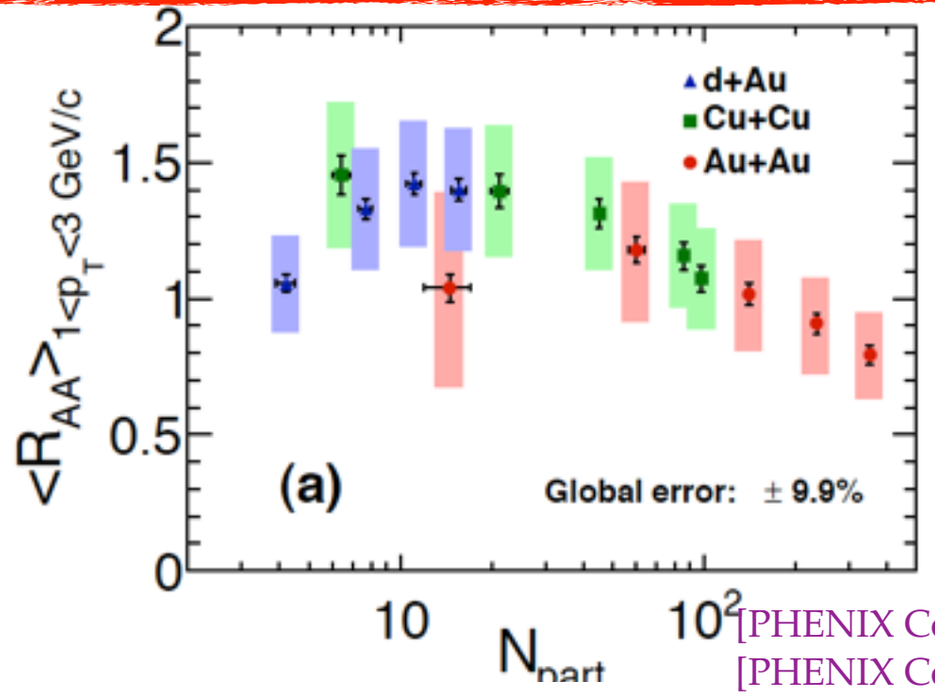
➡ **Binary scaling of the total HQ-yields, R_{AuAu}(all p_T)~1**

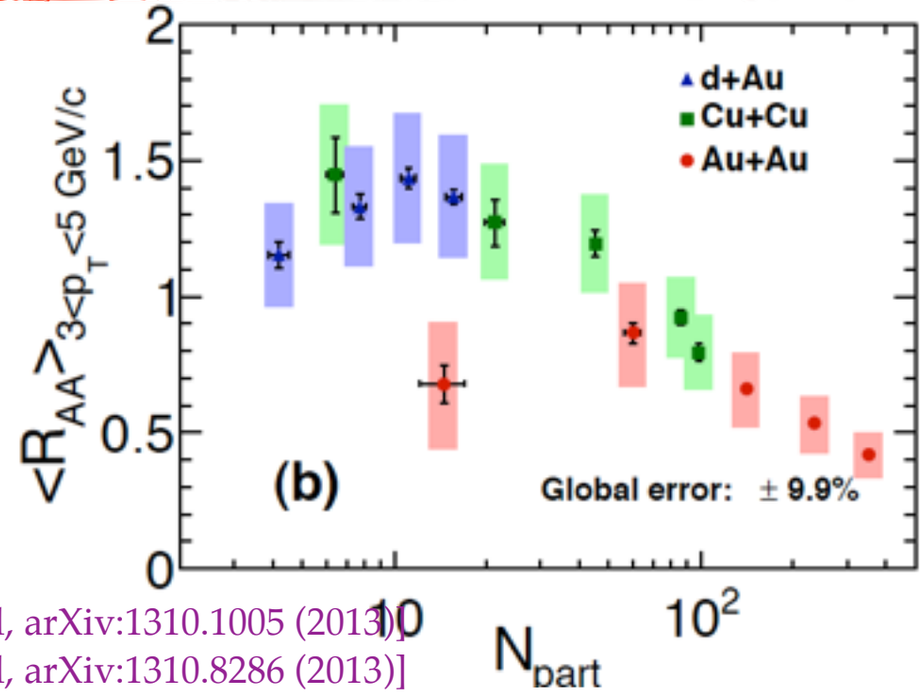
Au-Au at 200 GeV



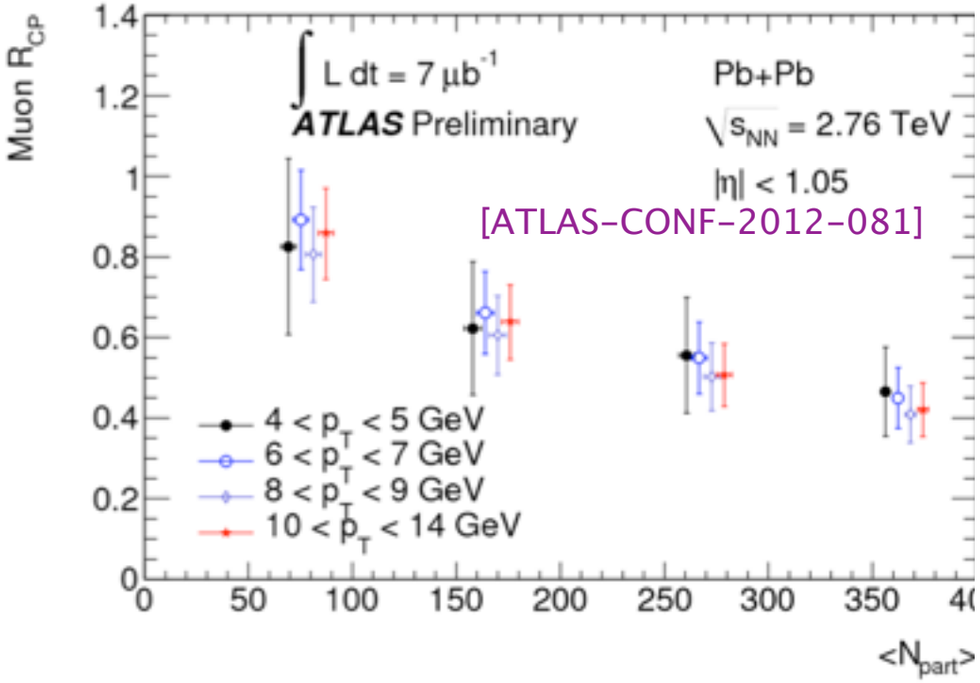
➡ **Heavy quarks suffer from energy loss. At large p_T, HF and π^0 present a similar suppression.**

HF production vs System Size

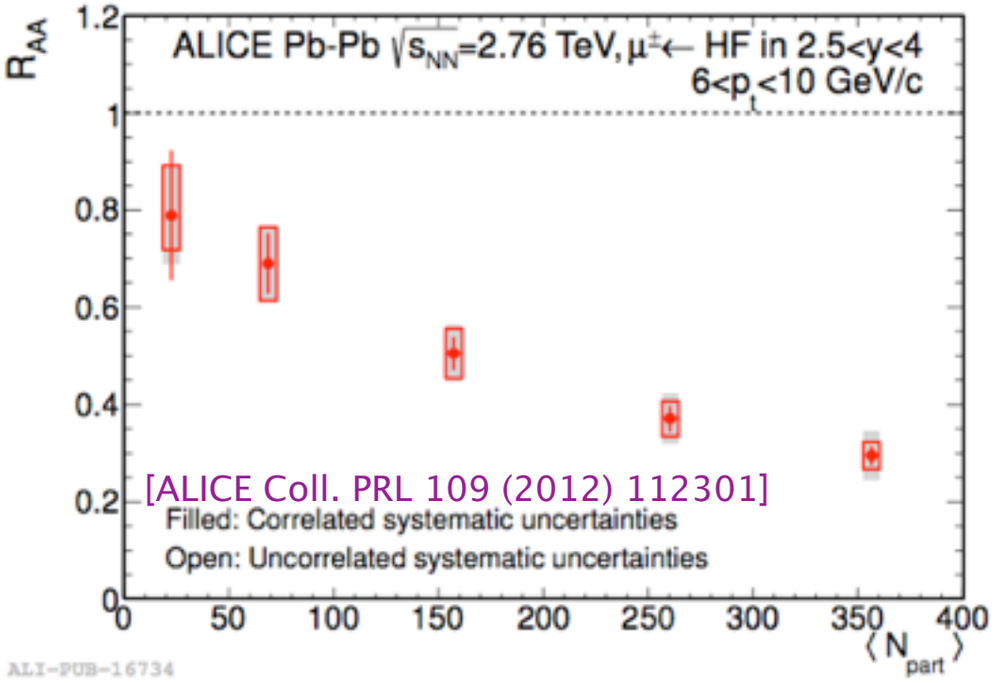




[PHENIX Coll, arXiv:1310.1005 (2013)]
[PHENIX Coll, arXiv:1310.8286 (2013)]



[ATLAS-CONF-2012-081]

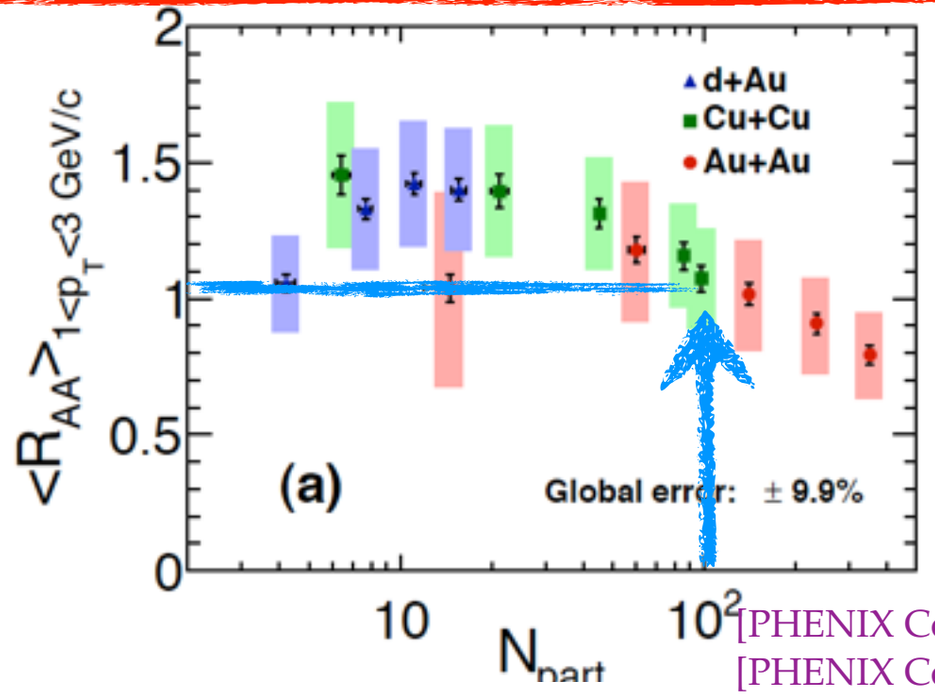


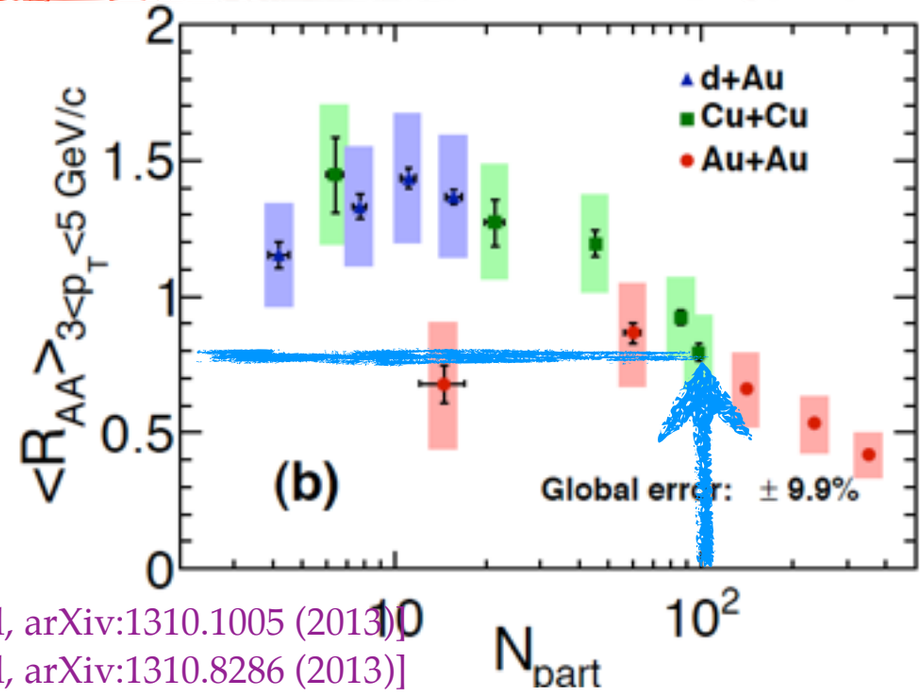
[ALICE Coll. PRL 109 (2012) 112301]

➡ **Production evolves with the increase of the size of the colliding system and the produced medium**

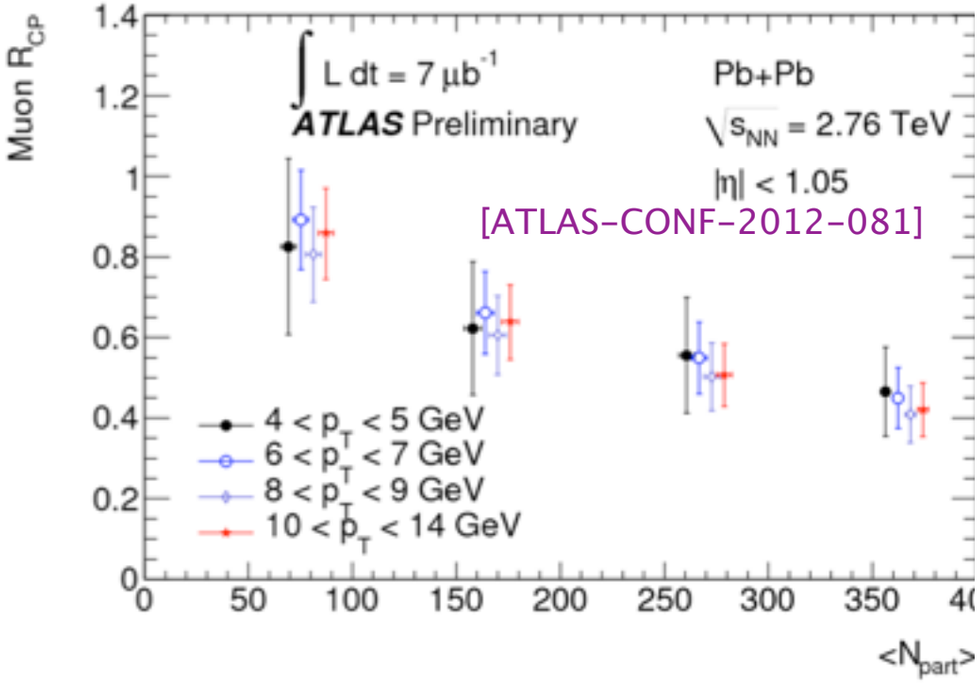
❖ **Open heavy-flavor production is affected by partonic energy loss in the most central collisions**

HF production vs System Size

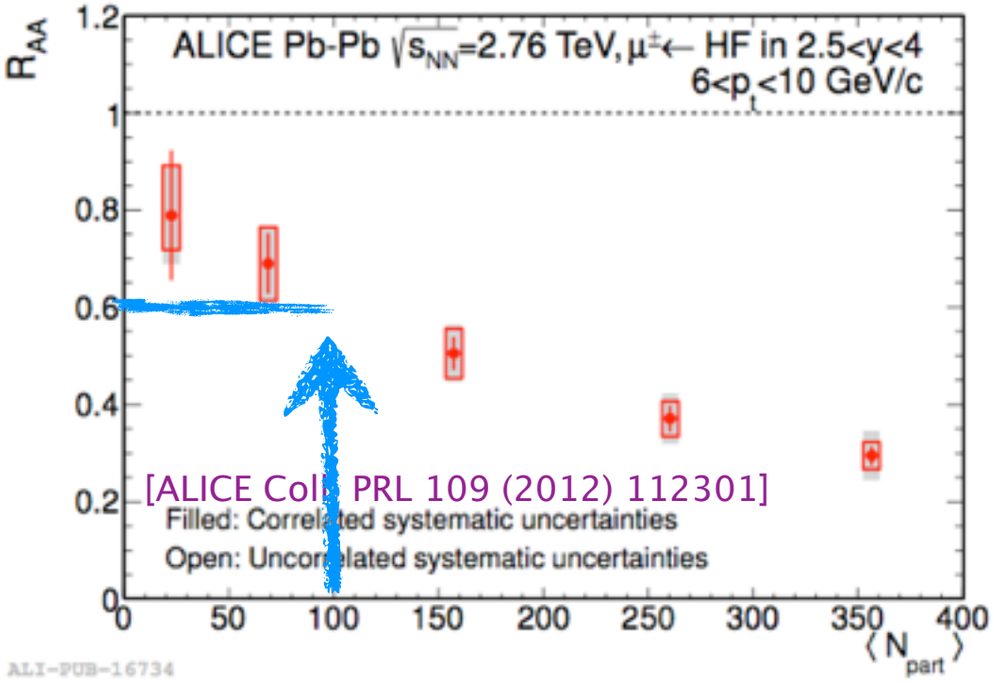




[PHENIX Coll, arXiv:1310.1005 (2013)]
[PHENIX Coll, arXiv:1310.8286 (2013)]



[ATLAS-CONF-2012-081]



[ALICE Coll, PRL 109 (2012) 112301]

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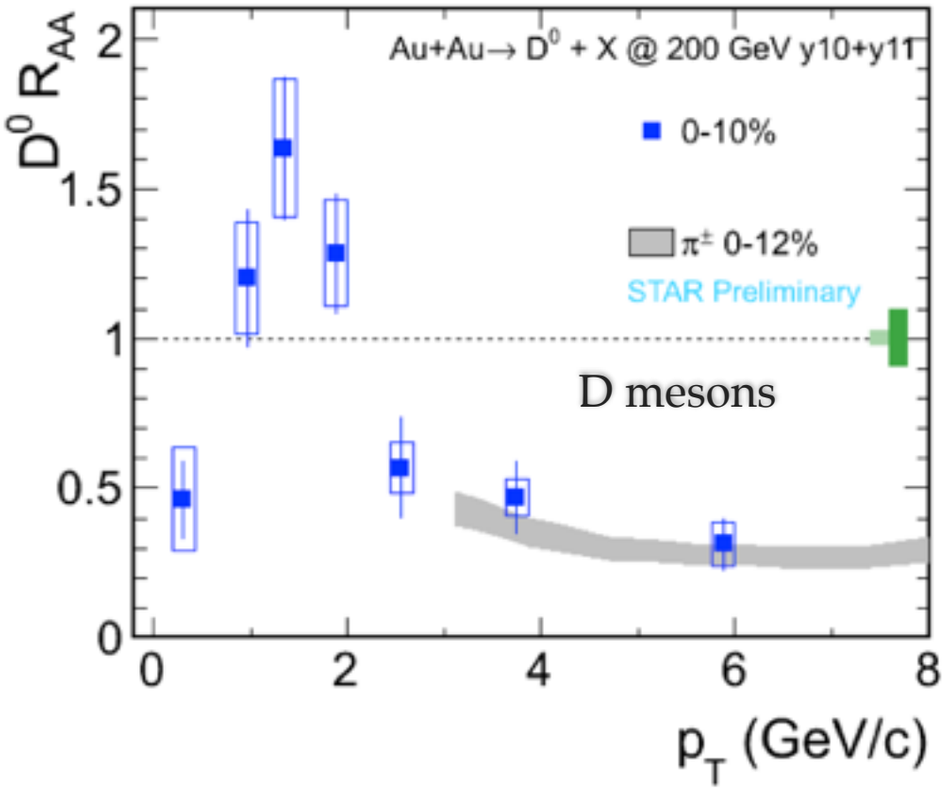
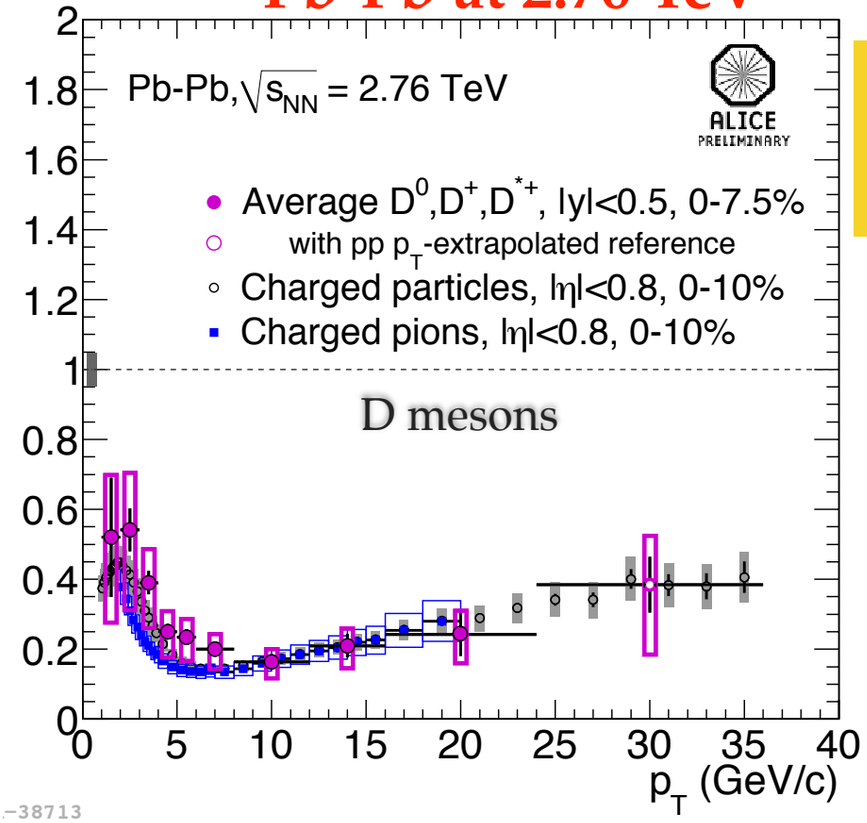
Charm & Pion R_{AA} vs p_T

Au-Au at 200 GeV



Pb-Pb at 2.76 TeV



Energy loss color charge dependence, $\Delta E_{u,d,s} < \Delta E_g$?

- ➡ **Similar D R_{AA} at high p_T at RHIC and LHC, while at low p_T is different: shadowing + radial flow + coalescence ?**
- ➡ **D R_{AA} versus charged particles and $\pi^{\pm}$**
  - **Similar trend for p_T>5, due to fragmentation ?**
  - **Hint of D>π for 2<p_T<5 ??**
  - **For p_T<2, no direct comparison, Ncoll-scale does not hold for low p_T pions**
- ❖ **Consistent with color charge dependence of Eloss**

Charm & Pion R_{AA} vs p_T

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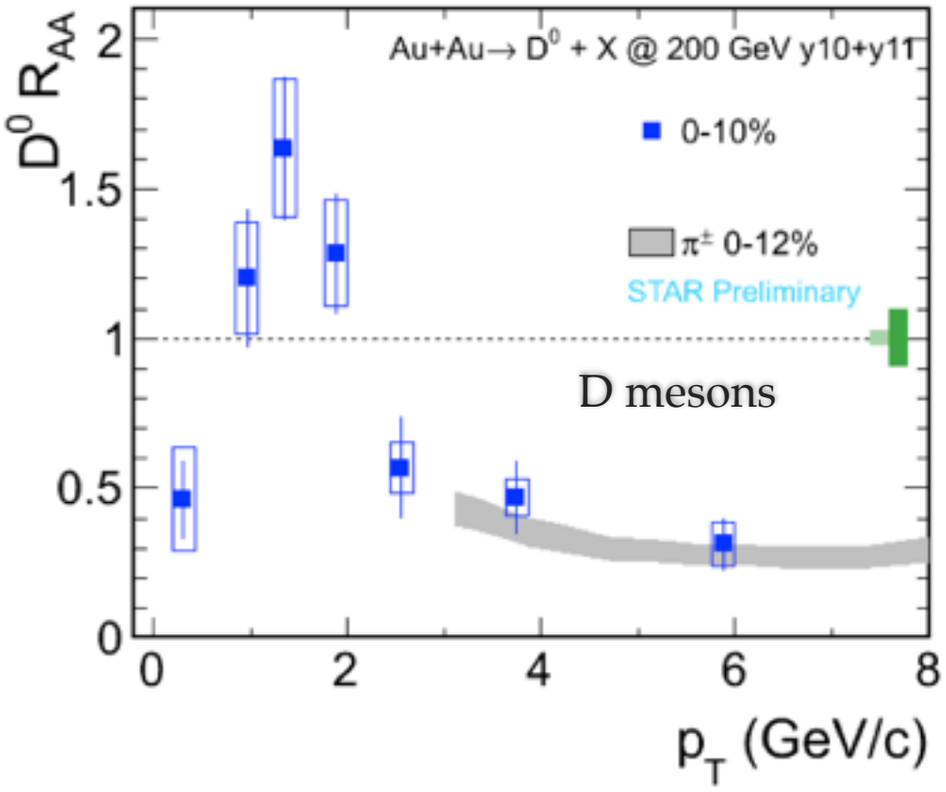

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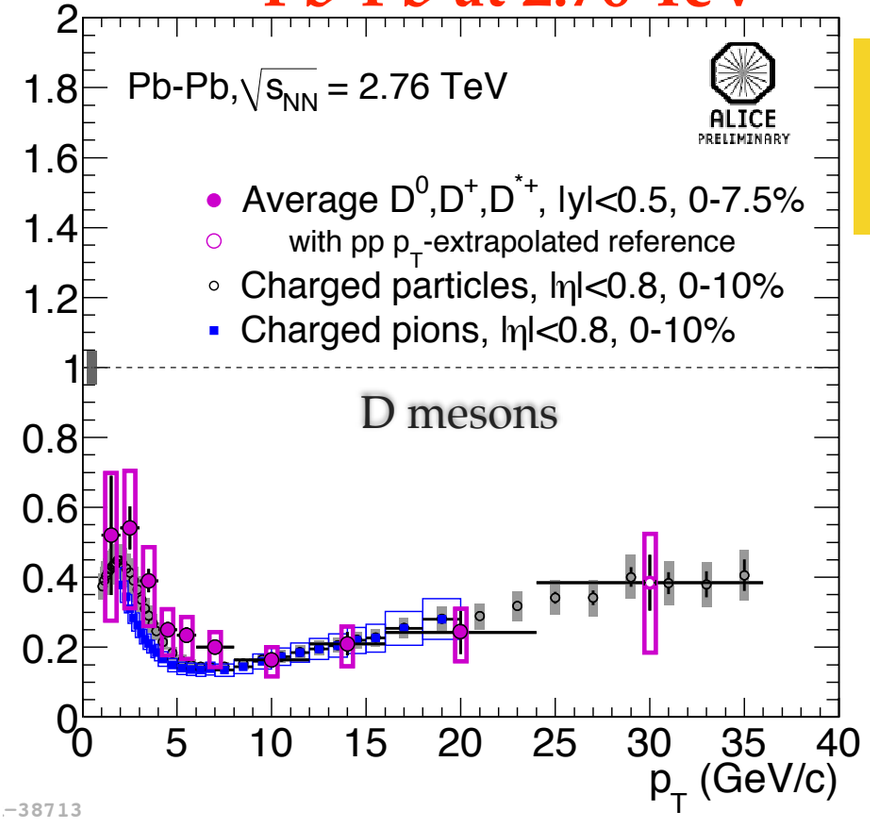
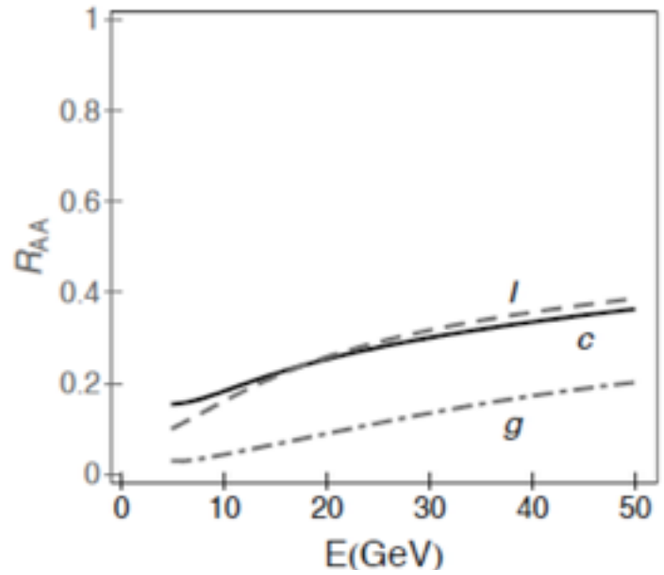
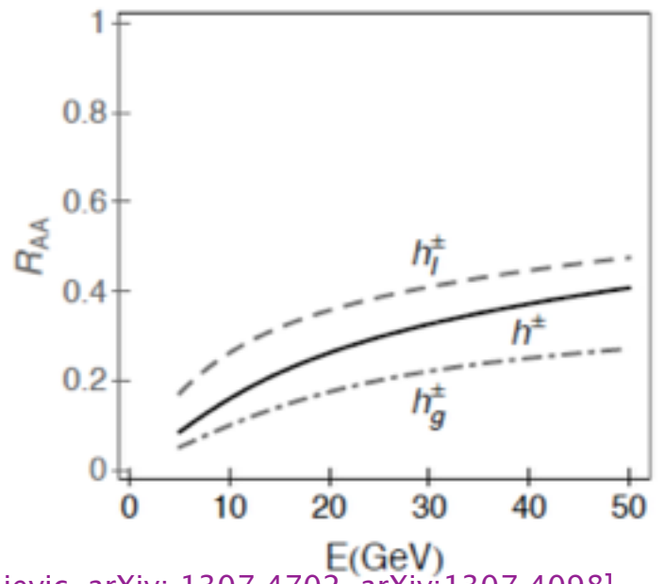


Energy loss color charge dependence, $\Delta E_{u,d,s} < \Delta E_g$?





[M.Djordjevic, arXiv: 1307.4702, arXiv:1307.4098]

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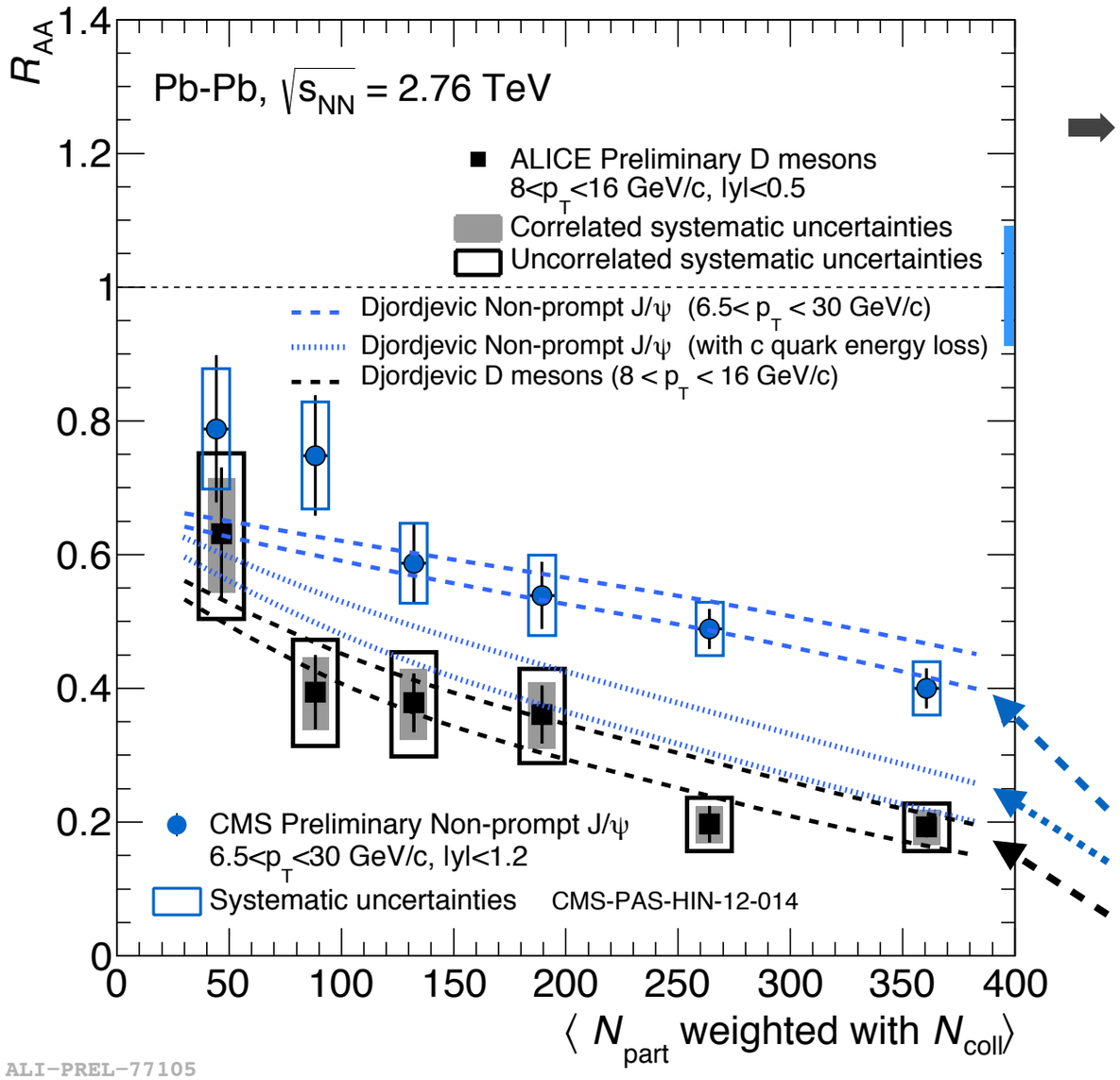
Charm & Beauty at LHC



Pb-Pb at 2.76 TeV

➡ **In central collisions, for p_T>6 GeV, non-prompt J/ψ (CMS) are less suppressed than prompt D mesons, albeit the difference on the b/c average p_T.**

Caveats:
<p_T> B/D hadrons ≠ b/c quarks
fragmentation of b/c
⇨ Need models

non-prompt J/ψ with b-Eloss

non-prompt J/ψ with c-Eloss

D mesons with c-Eloss

Energy loss parton mass dependence, $\Delta E_b < \Delta E_c$?

With this selection:
- **B <p_T> ~ 11 GeV**
- **D <p_T> ~ 10 GeV**

[Djordjevic: private comm (ALICE)]

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
[Vitev: R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C80 (2009) 054902; Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713 (2012) 224]

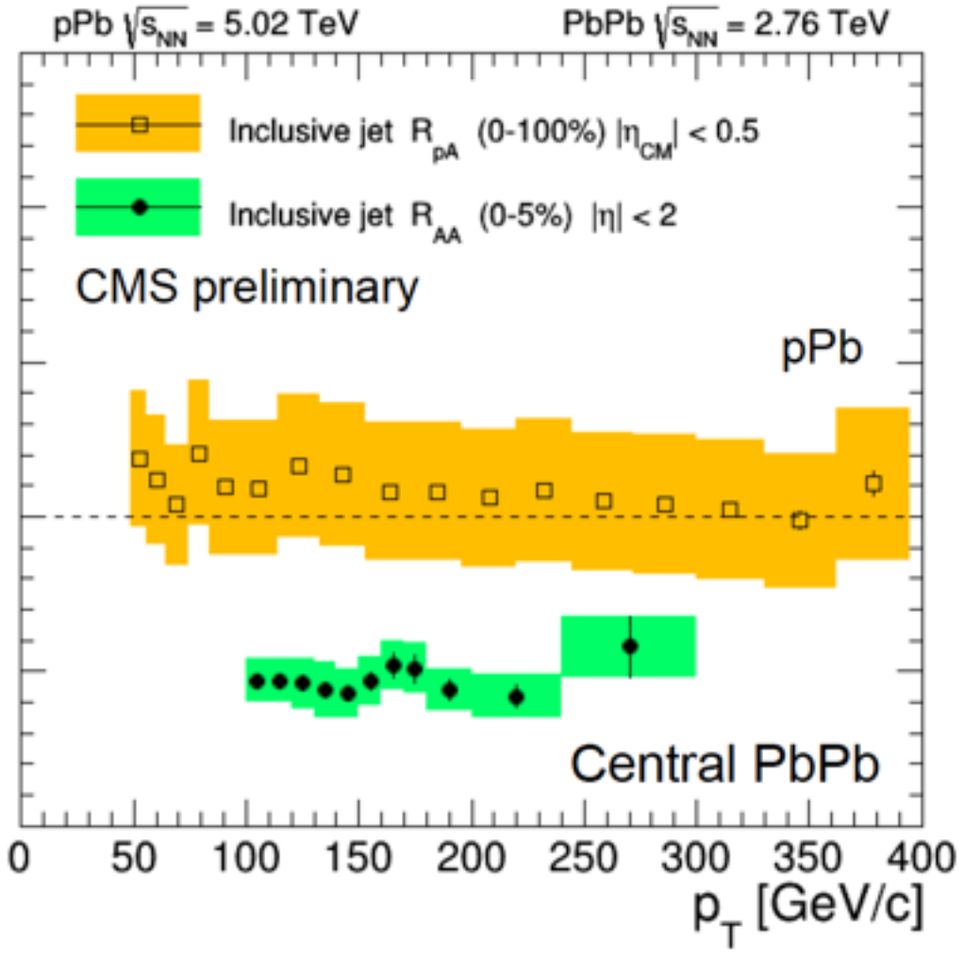
❖ **Consistent with the expectations of mass dependent partonic energy loss**

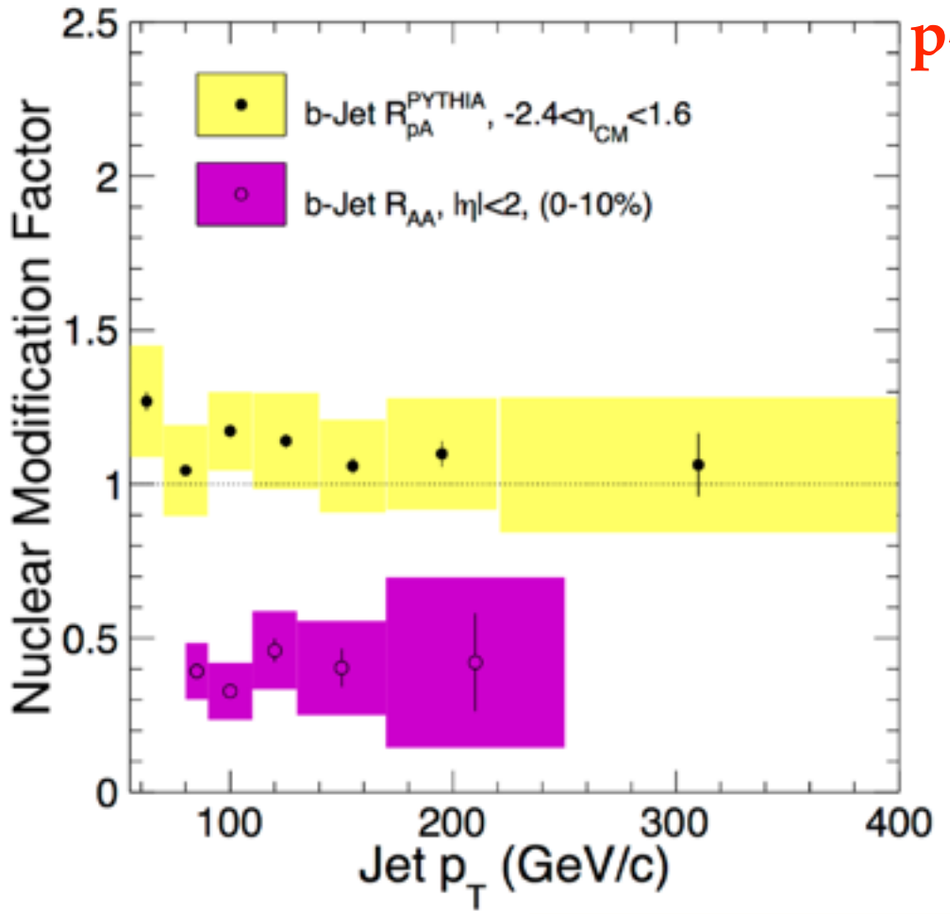
Beauty Jets at LHC

Pb-Pb at 2.76 TeV

p-Pb at 5.02 TeV

CMS-PAS-HIN-14-007



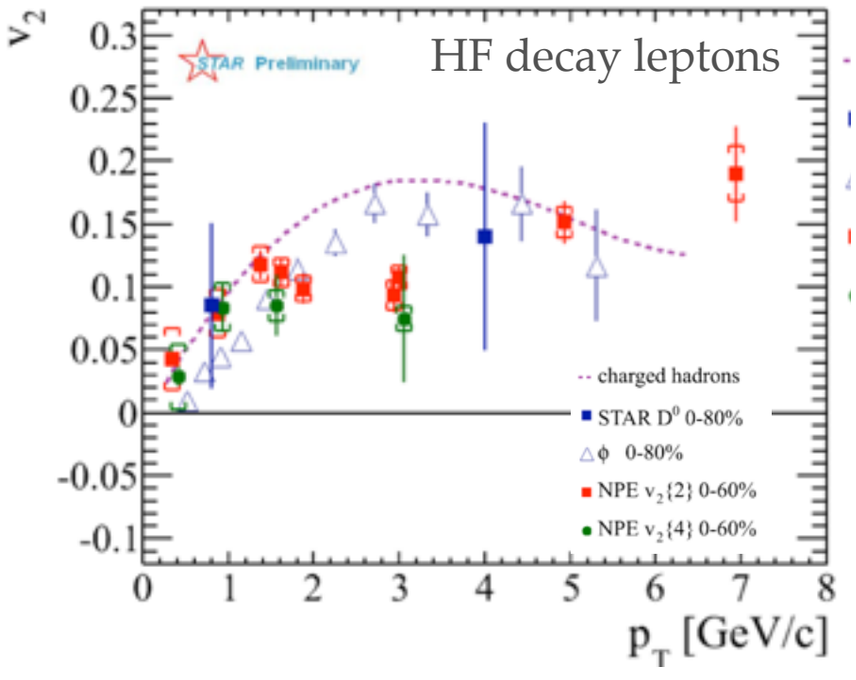


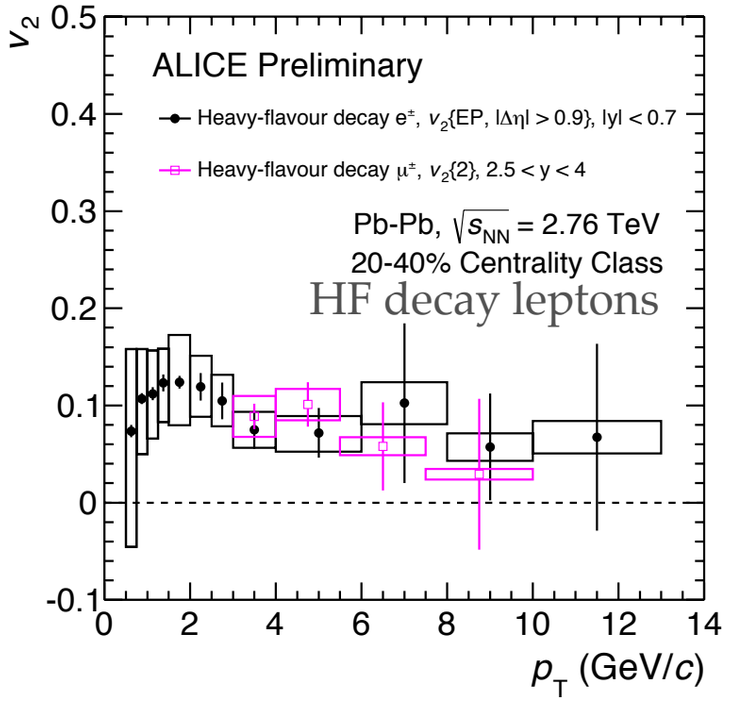
Energy loss parton mass/charge dependence, $\Delta E_b < \Delta E_c < \Delta E_g$?

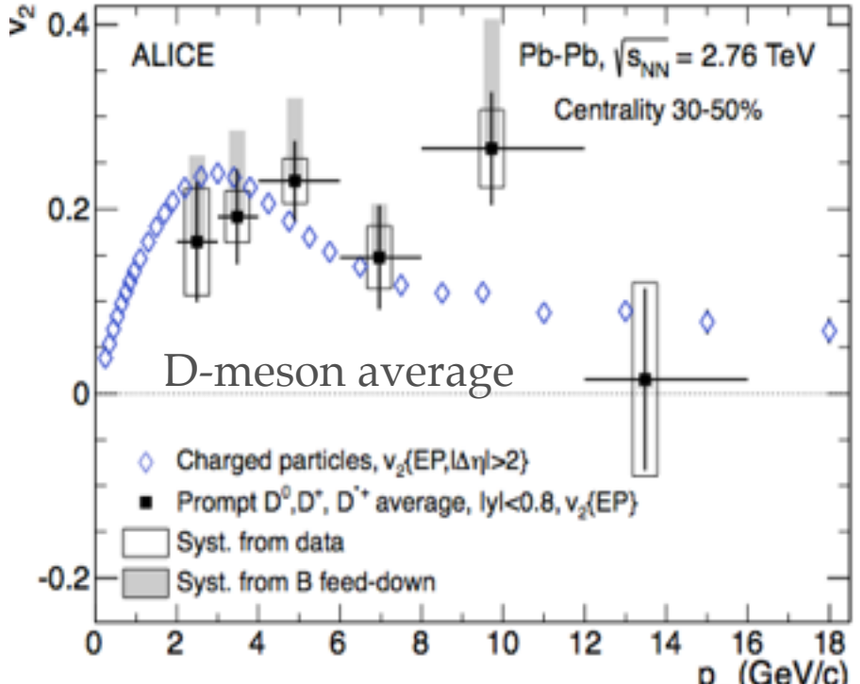
- ➡ **Significant suppression of b-jets up to high p_T**
- ➡ **Similar suppression for b & q/g-jets (as expected at large p_T)**

❖ **Consistent with the expectations of mass dependent partonic energy loss**

Azimuthal anisotropy





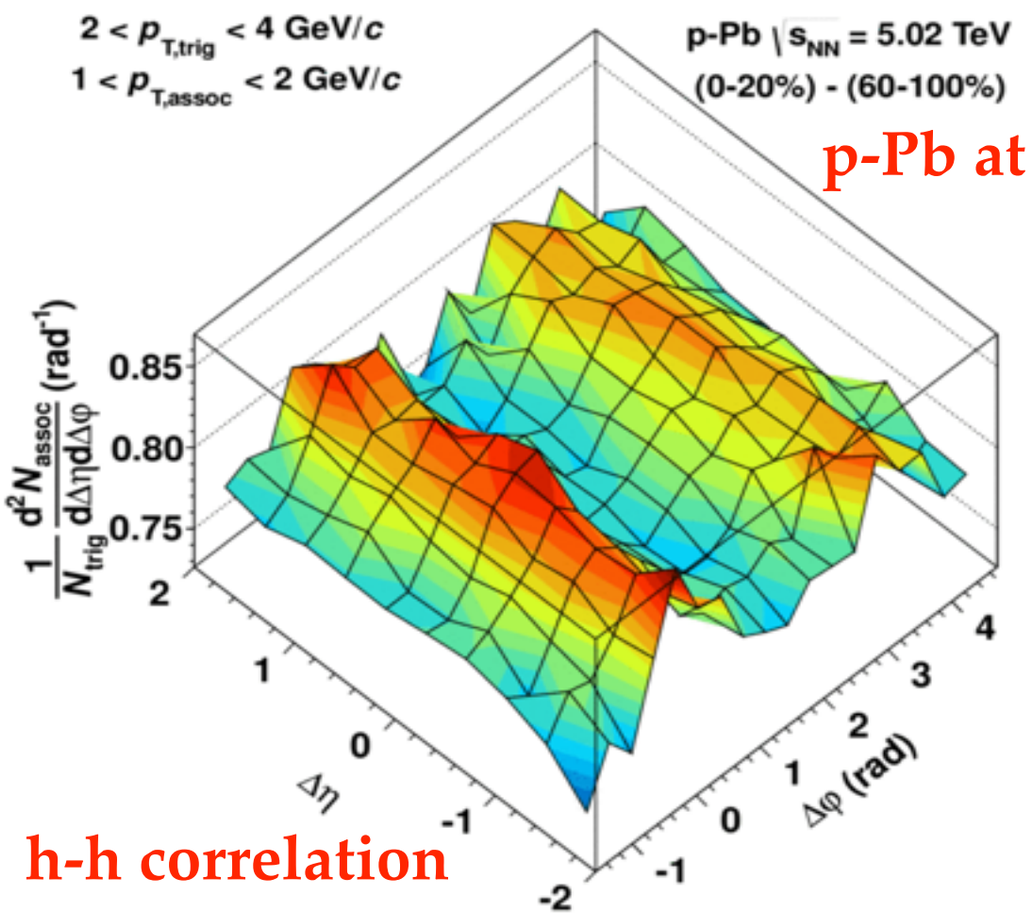


Au-Au at 0.2 TeV | **Pb-Pb at 2.76 TeV**

- ➡ At 200 GeV, $v_2>0$ for $p_T > 3$ GeV/c but smaller than pion v_2
- ➡ Positive open heavy-flavor v_2 in Pb-Pb semi-central collisions at LHC
  - HF decay electrons, >3σ effect for $2<p_T<3$ GeV/c
  - D mesons, 5.7σ effect for $2<p_T<6$ GeV/c
- ➡ Open heavy-flavor v_2 is similar to that of charged particles
- ❖ Suggests that at LHC: Low-p_T charm quarks take part in the collective motion of the system. Intermediate to high-p_T measurements can constrain the path-length dependence of energy loss at high p_T, although we do not have sufficient precision with the current statistics.

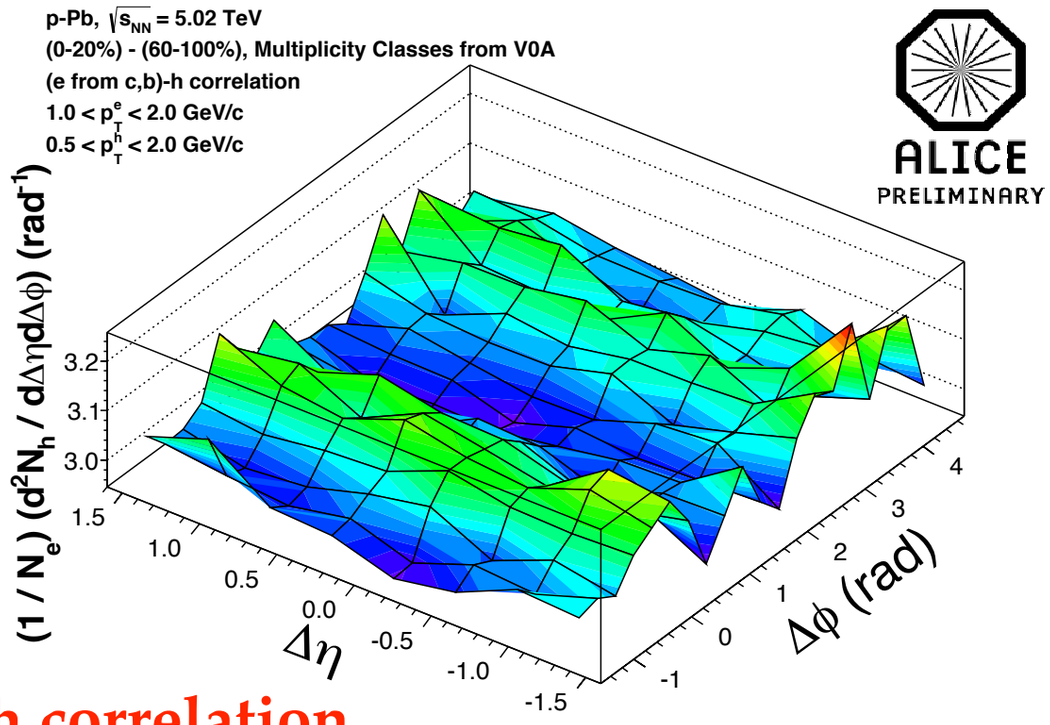
E-H CORRELATIONS IN P-PB DATA

Correlations of the (0-20)% - (60-100)%



p-Pb at 5.023 TeV

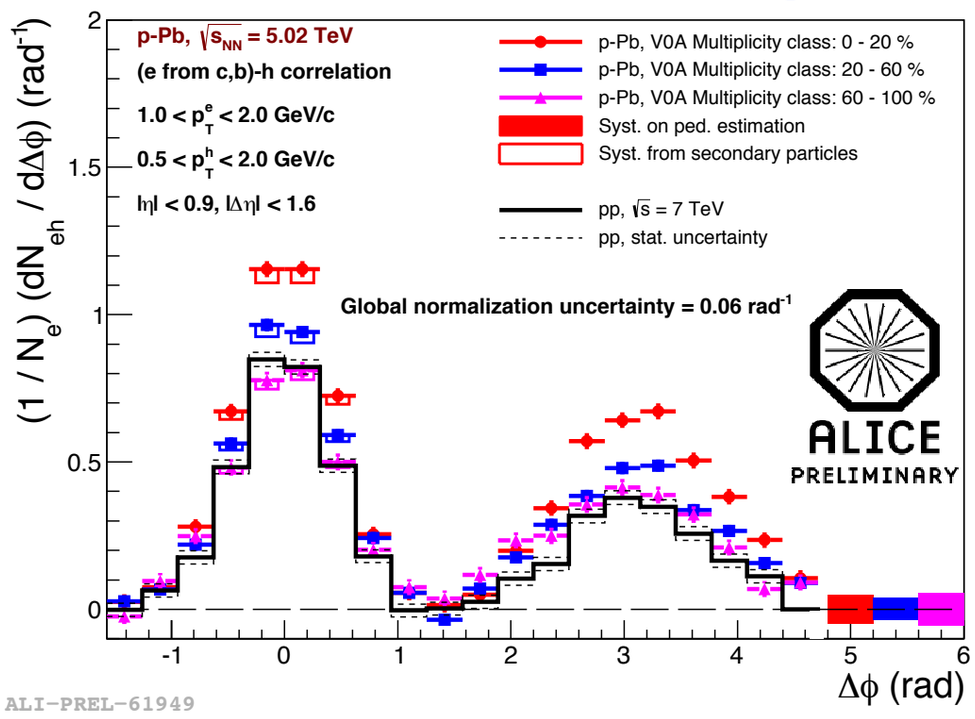
h-h correlation



HFe-h correlation

ALI-PREL-62026

HF decay electrons

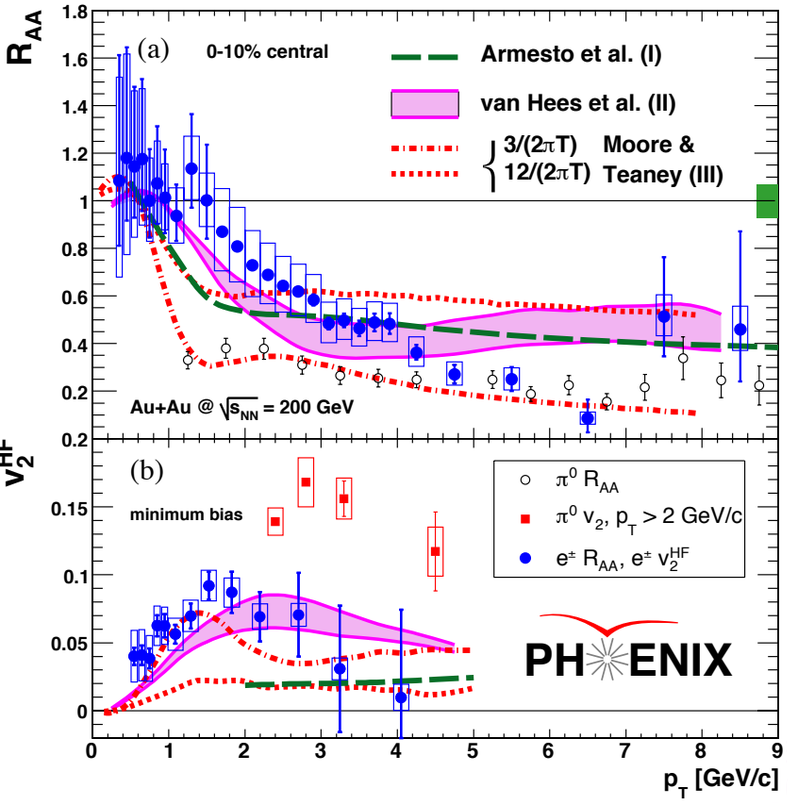


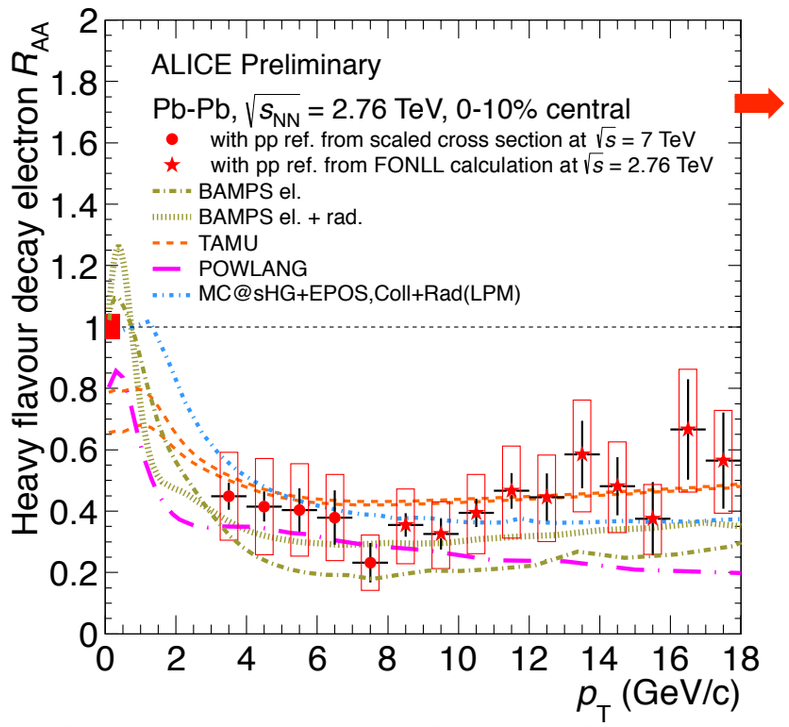
ALI-PREL-61949

➡ **Correlation within HF electrons and hadrons in pPb collisions resemble the double-ridge of hadron-hadron correlation**

E. Pereira de Oliveira Filho, HP13

Open Heavy Flavor R_{AA} & v_2



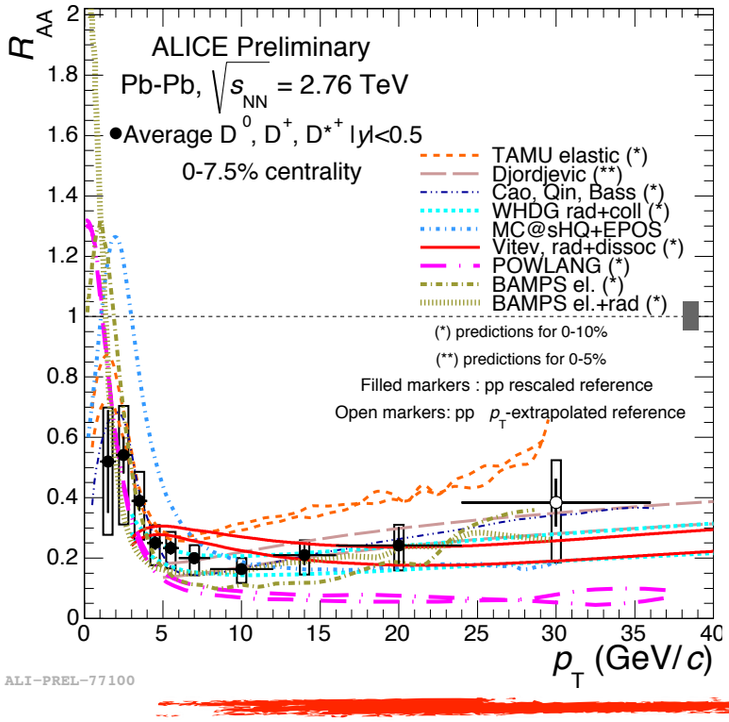


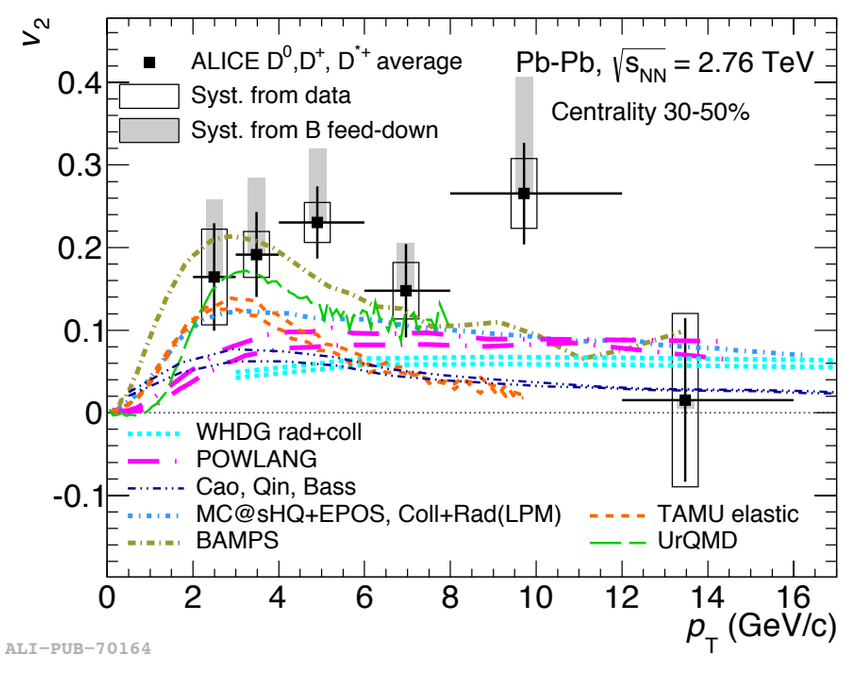
Pb-Pb at 2.76 TeV

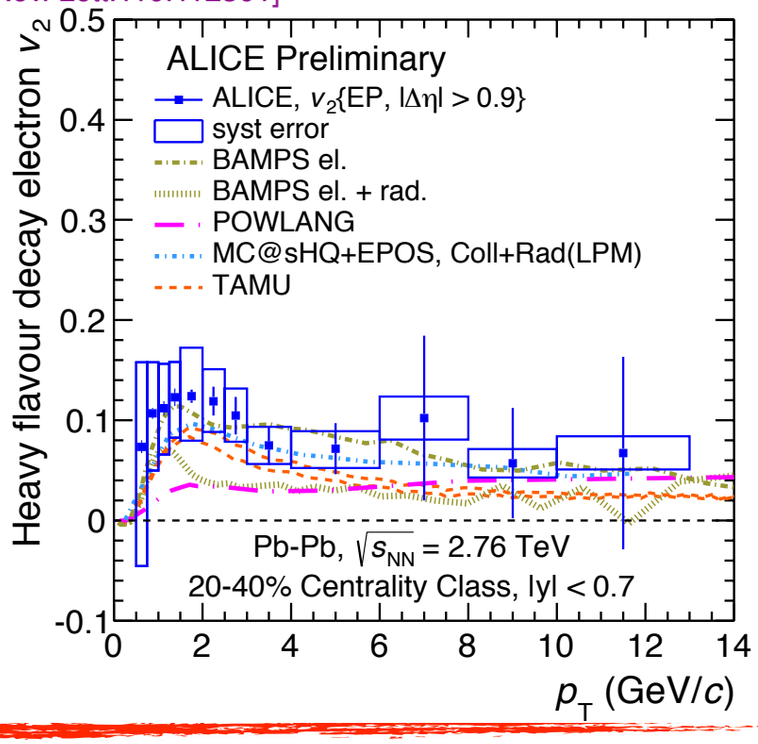
The simultaneous description of open heavy-flavor R_{AA} and v_2 is challenging

⇨ Many models appearing. A more systematic data/ theory comparison might help the interpretation

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
[POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]







Production process
τ_p~0.05-0.15fm/c

DPS (double parton scattering)
& MPI (multiple parton interaction)

D+D or J/ψ+ J/ψ or J/ψ+D production rates
and kine properties in DPS no angular correlation

B and D hadron production rates, ratios, and kinematic properties

+

Nuclear PDFs
gluon shadowing

Saturation
gluon saturation

Eloss by scattering

Multiplicity dependence

k_T broadening

B and D hadron production rates, ratios, and kinematic properties

+

Parton in-medium Eloss
coulour charge C_R=4/3,3
parton mass
$\Delta E_g > \Delta E_c > \Delta E_b$

comovers

hydro?

Transport properties

B and D hadron production rates, ratios, and kinematic properties

+

Baryon / meson contribution
(might vary the p_T trend)

Decay kinematics
(fetch hadron and parton p_T)

B and D hadron
$d^2\sigma/dp_Tdy$
vs dN/dη
+ azimuthal
(baryon/meson)

D+D & J/ψ+ J/ψ
& J/ψ+D
$d^2\sigma/dp_Tdy$

Summary

- **HF production (pp) is described relatively well by pQCD**
  - **But some model refinements are still needed. Charm-normalization, very high p_T, DPS, MPI...**

- **Complete modeling of the p-A-like effects might require, in addition to shadowing (EPS09) or CGC calculations, k_T broadening, fragmentation, Eloss, flow contributions ?**

- **Heavy flavor production is suppressed in the most central collisions**
  - **Both at RHIC and LHC**
    ⇨ Suffer from parton energy loss
  - **Similar for pions and D mesons for p_T >5 GeV/c**
    ⇨ Consistent with colour charge dependence
  - **Larger for D mesons than for non-prompt J/ψ for p_T >6 GeV/c**
    ⇨ Consistent with expected parton mass dependence
  - **Positive v_2 for p_T>2. D-meson v_2 similar to that of light hadrons**
    ⇨ c-quarks participate to the system collective motion

Extra To Do List

- **Precise measurements of heavy flavor production down to p_T~0 in both pA and AA and over a wide y-range are missing**
  - **Missing the very low p_T (0-1 GeV)**

- **A full understanding of picture would require models describing at the same time pA and AA measurements: p_T, y, v_2 and their centrality dependence.**
  - **Quarkonia models should also be able to reproduce HF behaviour**

Thanks for your attention !

... THE MEASUREMENTS

➡ In p-A-like collisions...

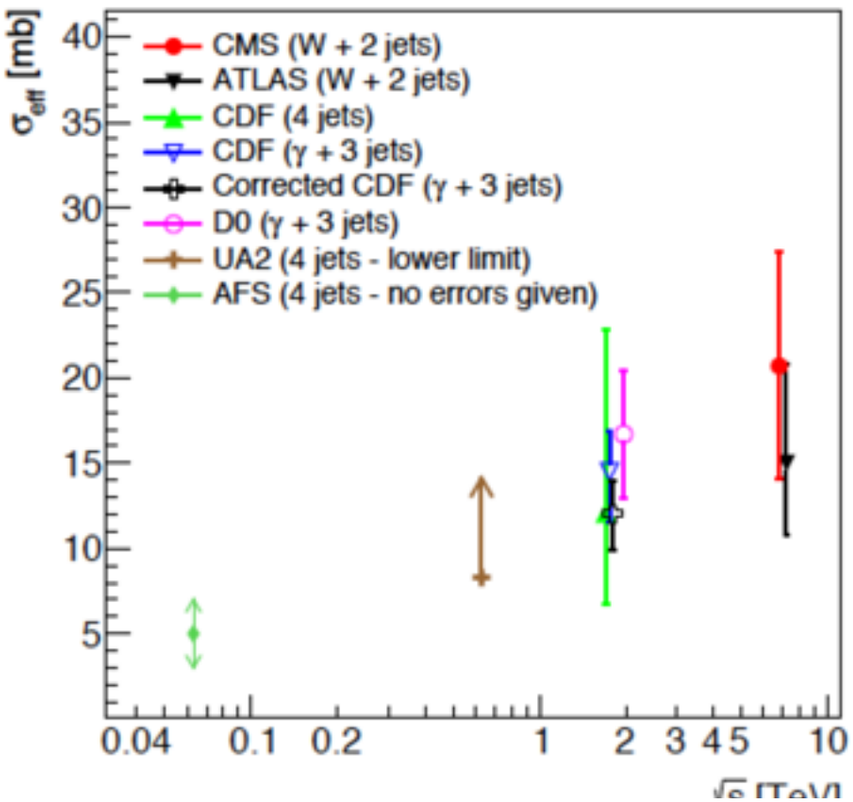
	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF decay electrons	✔	✔	✔			
B-decay electrons	?					
HF decay muons	✔		?			
D		✔	✔			
D			✔			
B→J/ψ			?		?	✔
B hadrons					✔	
B jets					?	

✳ In heavy-ion collisions...

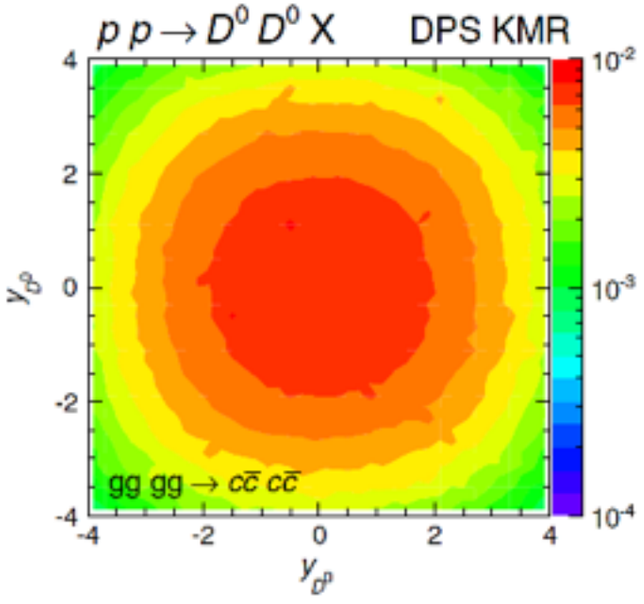
	PHENIX	STAR	ALICE	ATLAS	CMS	LHCb
HF decay electrons	✔	✔	✔			
B-decay electrons	?					
HF decay muons	?		✔	✔		
D		✔	✔			
D			✔			
B→J/ψ					✔	
B hadrons						
B jets					✔	

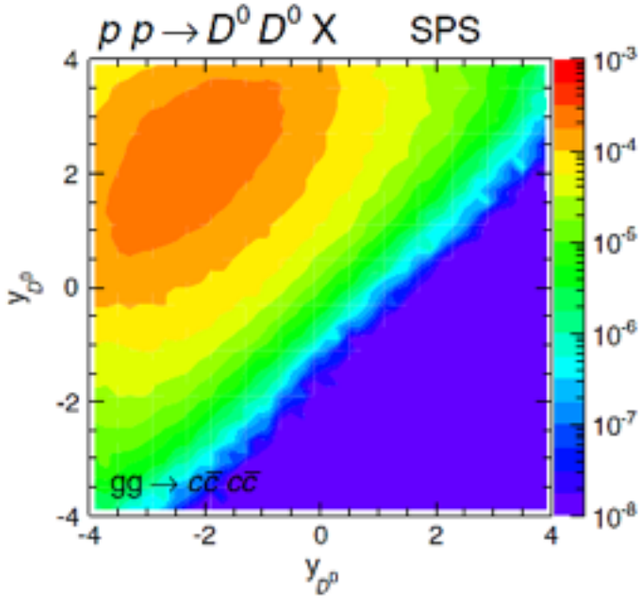
Multi-Parton Interactions

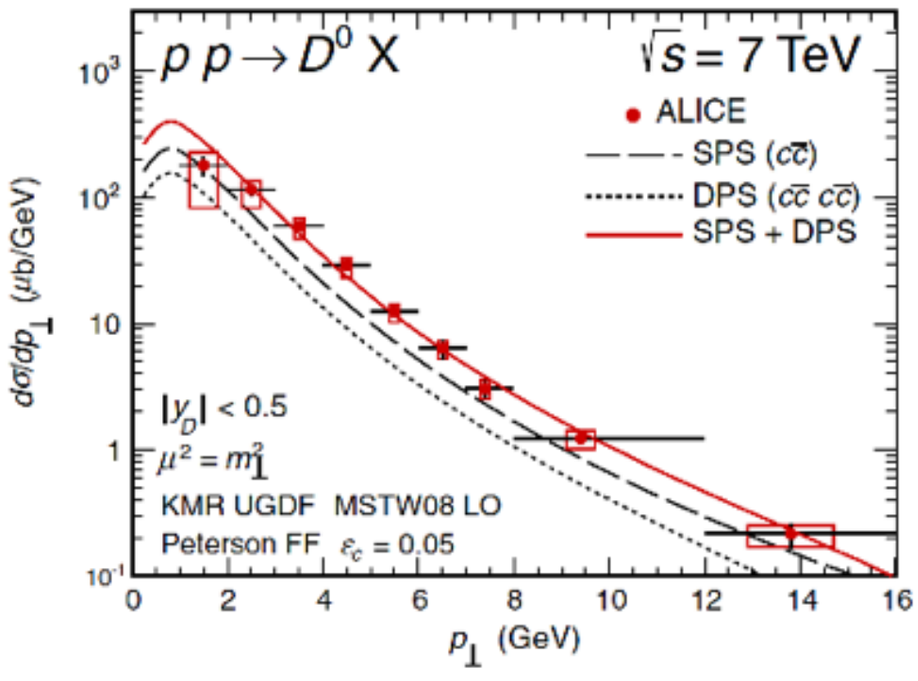
CMS, JHEP 03 (2014) 032



D0,	Z/γ+b/c	PRD87 092010 (2013); PRL 112 042001 (2014); arXiv:1405.3964
CDF,	W/Z+ ϒ/D*	CDF Note 11099 & 11087 (2014)
LHCb,	J/ψ+ C and CC,	JHEP06 (2012) 141; JHEP03 (2014) 108 (Addendum)
LHCb	Z+C	JHEP04 (2014) 91
ATLAS	W+2 jets	New J. Phys. 15 (2013) 033038
CMS	W+2 jets	JHEP03 (2014) 032



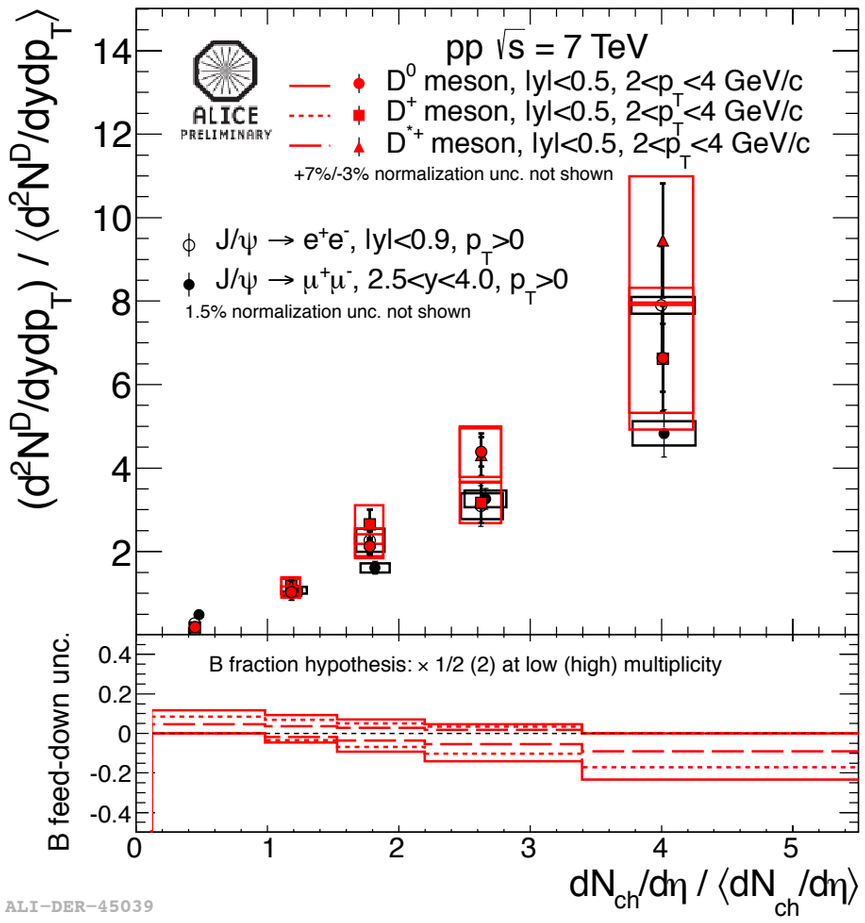




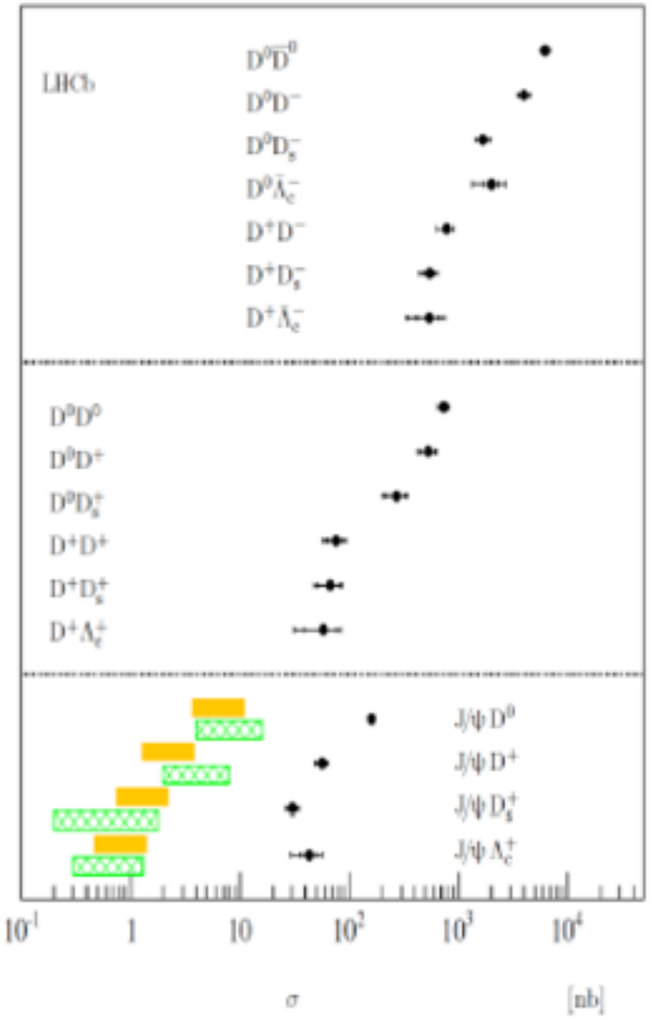
M. Maciula, A. Szczurek, Phys. Rev. D 87 094022 (2013)
A. Hameren, M. Maciula, A. Szczurek, arXiv:1402.6972 (2014)

More differential measurements

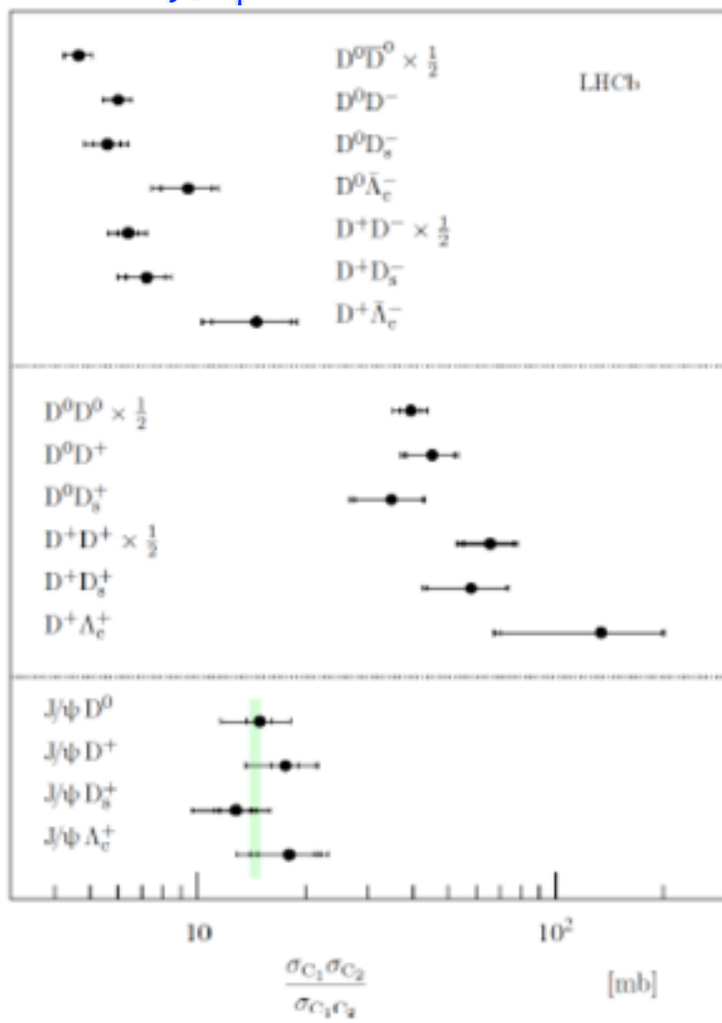
pp at 7 TeV



D mesons



J/ψ mesons



- Similar increase of prompt-D and J/ψ production vs multiplicity
- **Hints for multi-parton interactions at a hard scale in pp collisions**

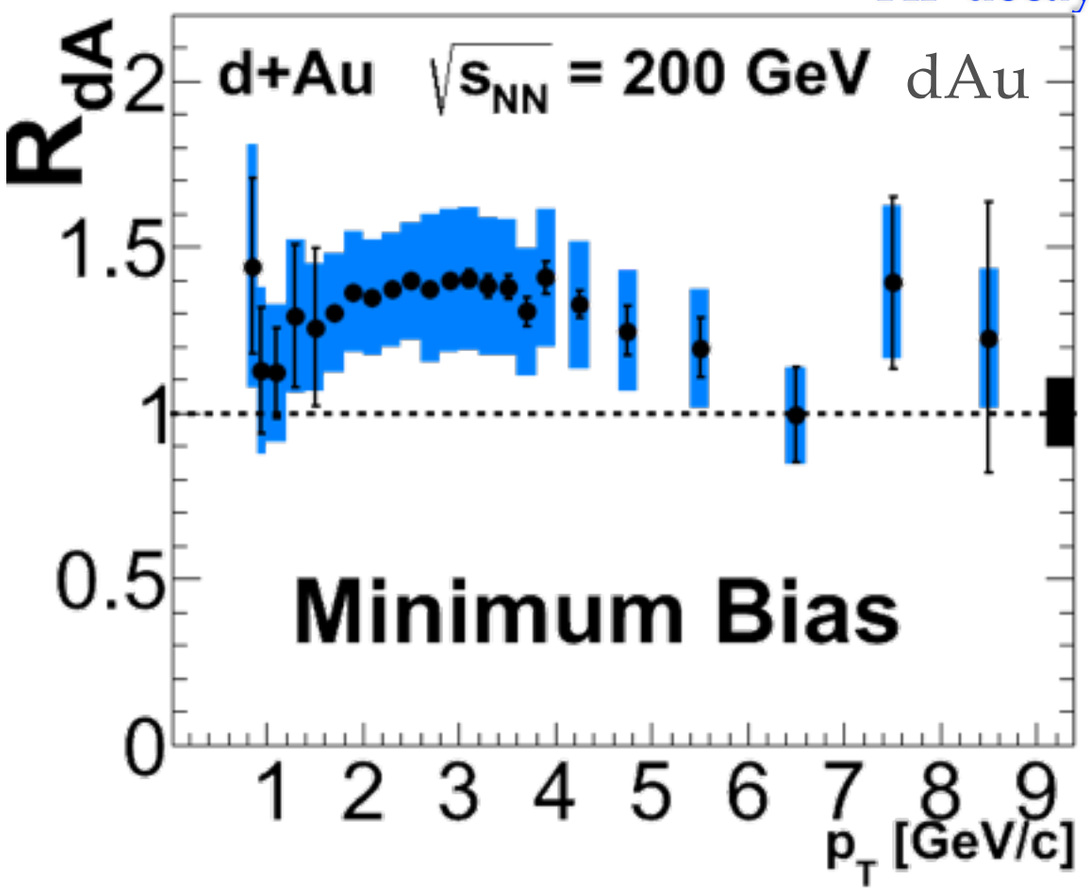
[ALICE Coll, Phys.Lett.B712 (2012) 165-175]

- **Theoretical predictions from gg fusion underestimate J/ψ C cross section**
- **Double Parton Scattering estimates (from CDF multi-jets) agree with J/ψ C cross section**

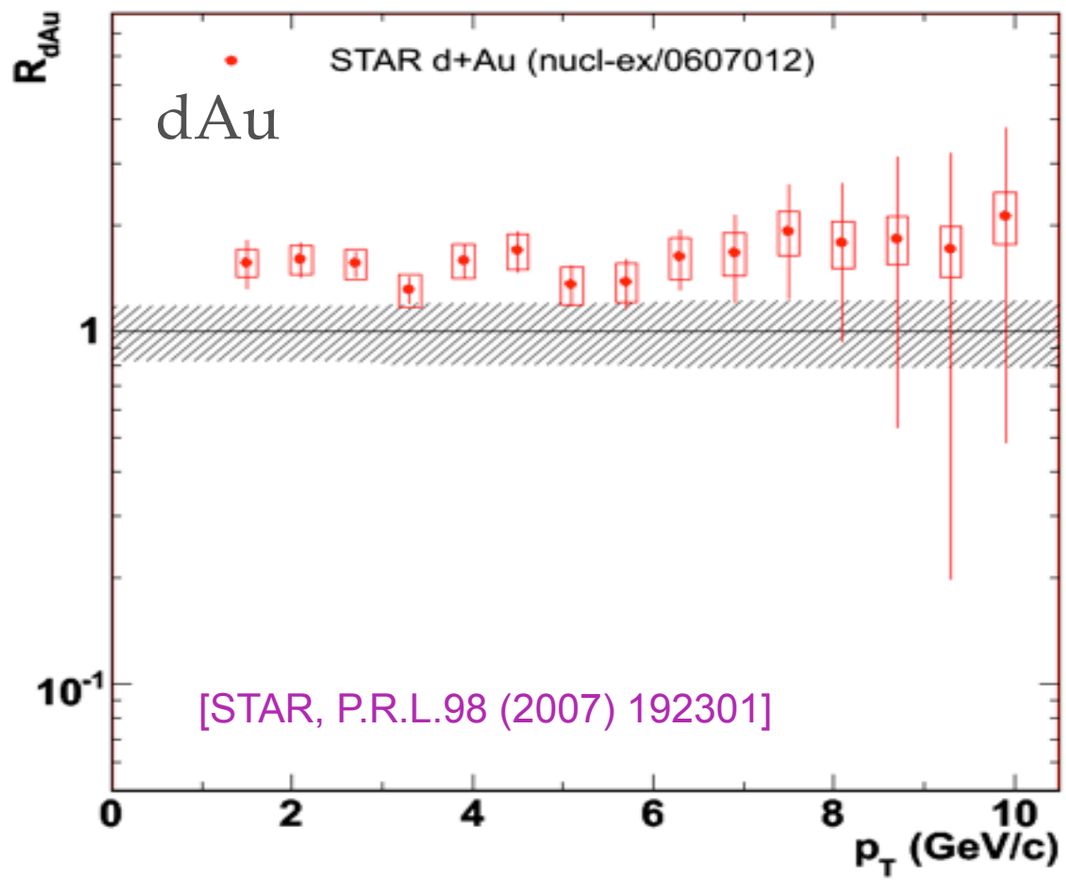
[LHCB, JHEP 06 (2012) 141]
[LHCB, PLB 707 (2012) 52]

HF Decay electrons at RHIC at y~0

HF decay electrons



d-Au at 200 GeV



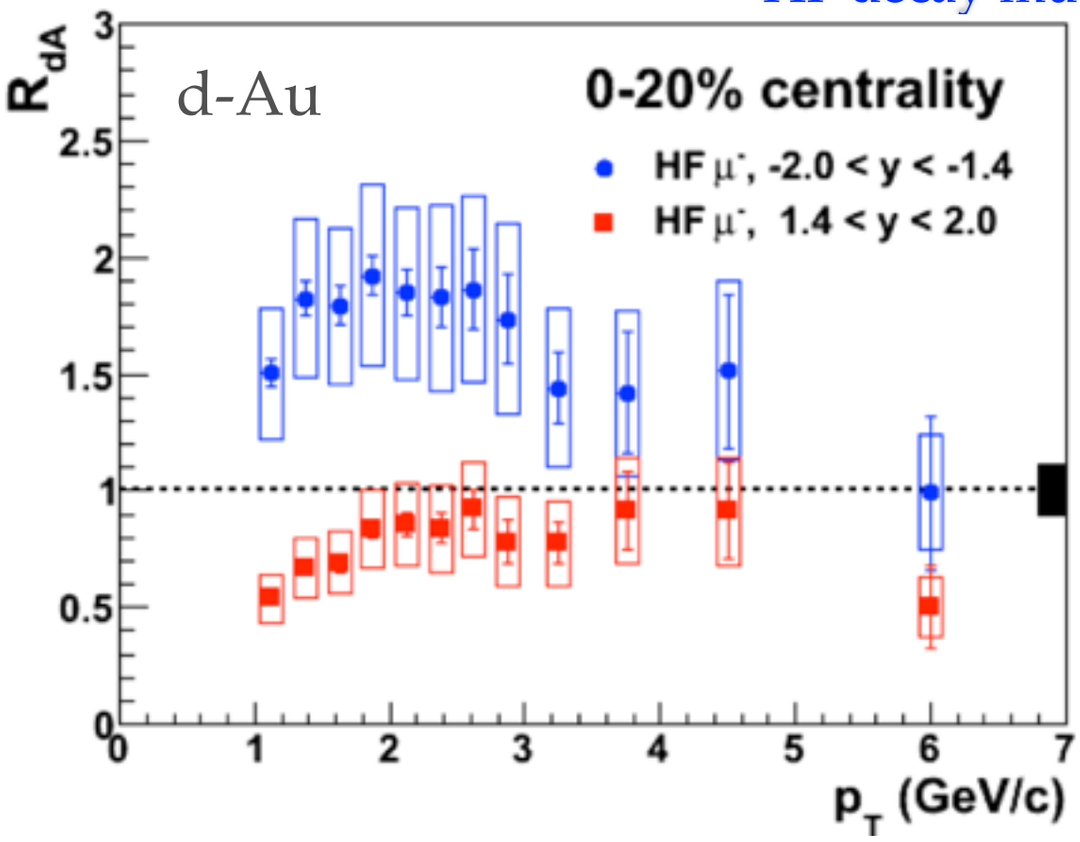
[PHENIX Coll, Phys. Rev. Lett. 109, 242301 (2012)]

➡ No suppression observed for heavy flavor decay electrons at mid-rapidity within uncertainties (flat-like shape)

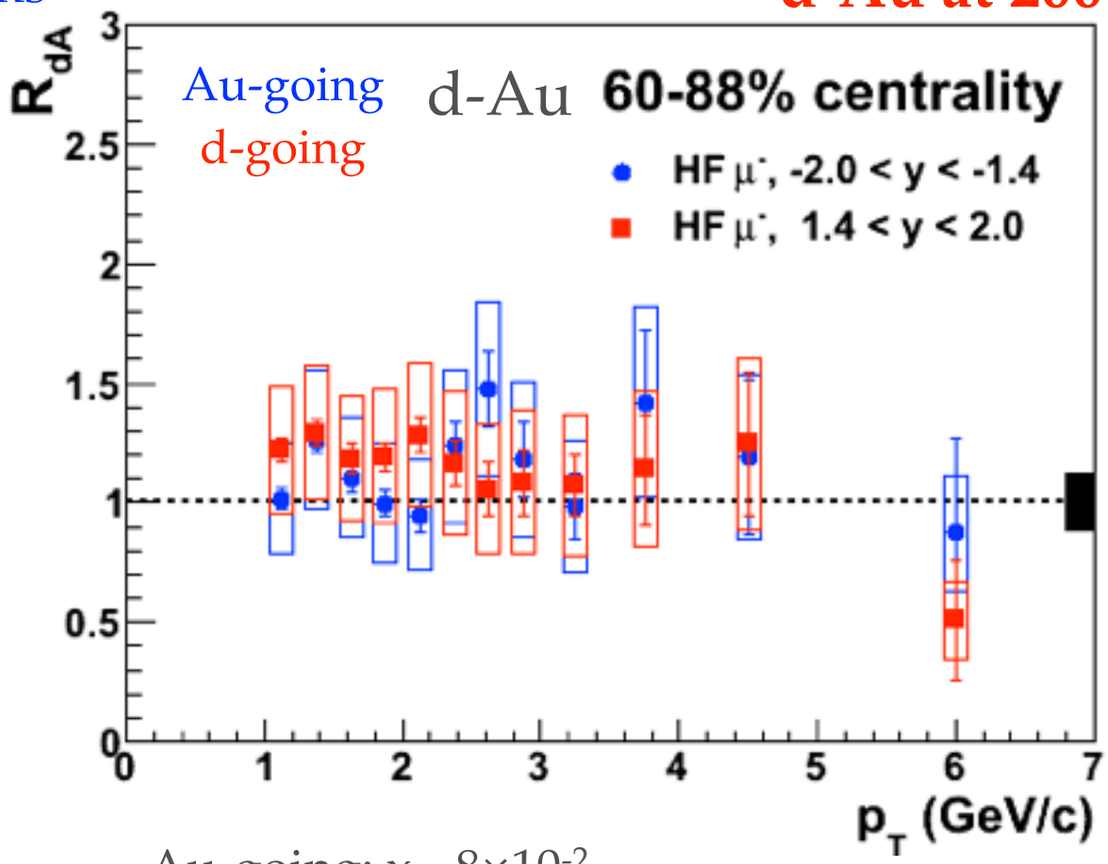
HF Decay Muons at RHIC at |y|~1.7

HF decay muons

d-Au at 200 GeV



[PHENIX Coll, arXiv:1310.1005 (2013)]

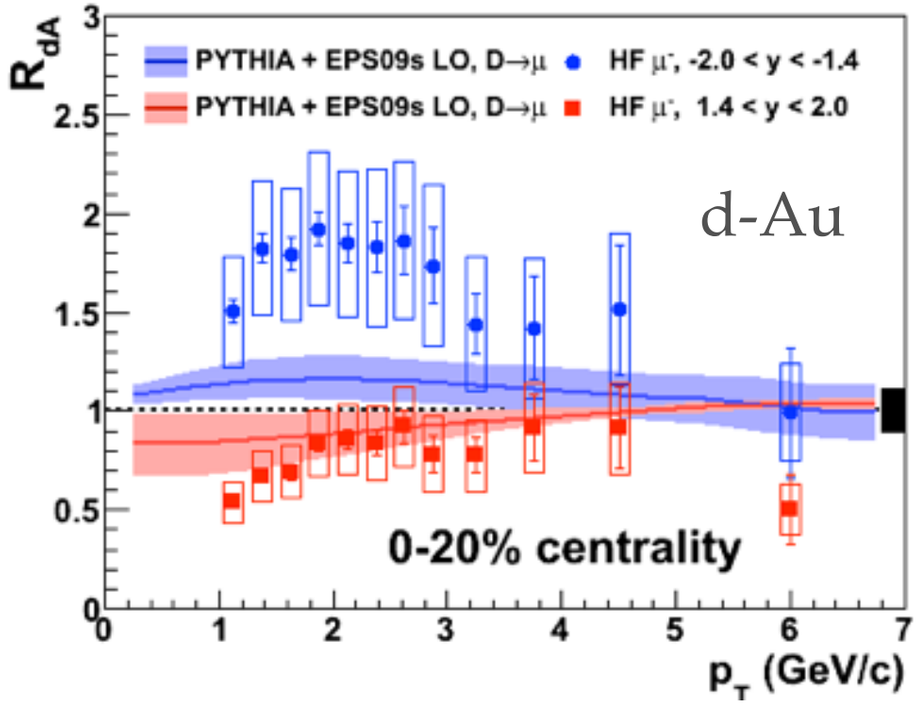


Au-going: $x \sim 8\times10^{-2}$

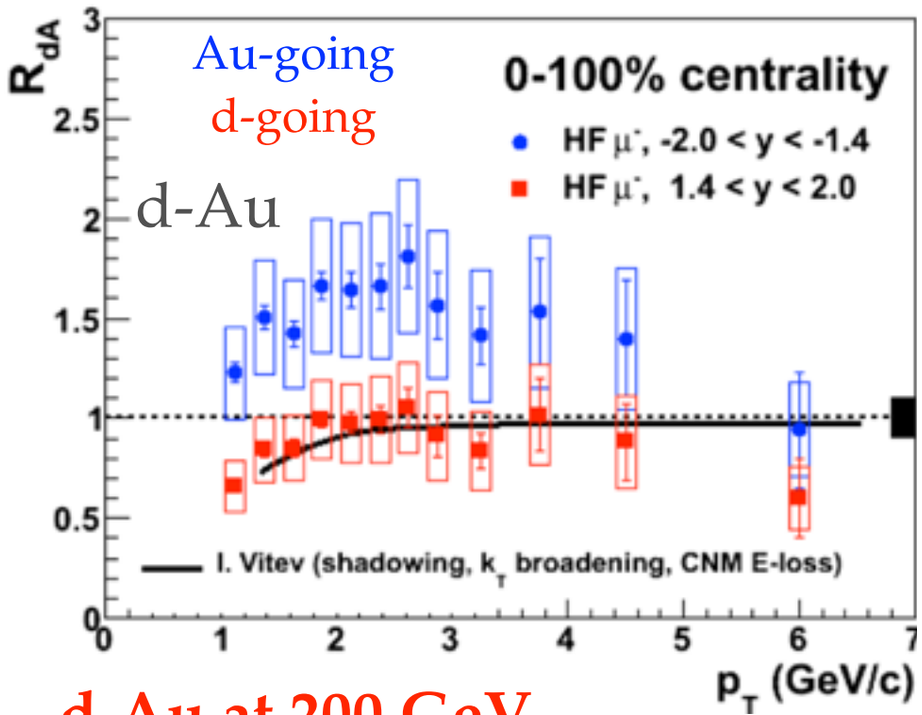
d-going: $x \sim 5\times10^{-3}$

➡ **Different behaviour vs rapidity and centrality**
Mild (strong) rapidity dependence in peripheral (central) collisions

HF Decay Leptons at RHIC



[PHENIX Coll, arXiv:1310.1005 (2013)]



d-Au at 200 GeV

[PHENIX Coll, arXiv:1310.8286 (2013)]

➡ nPDFs do not reproduce backward rapidity results.

- Might impact parameter nPDFs help ?

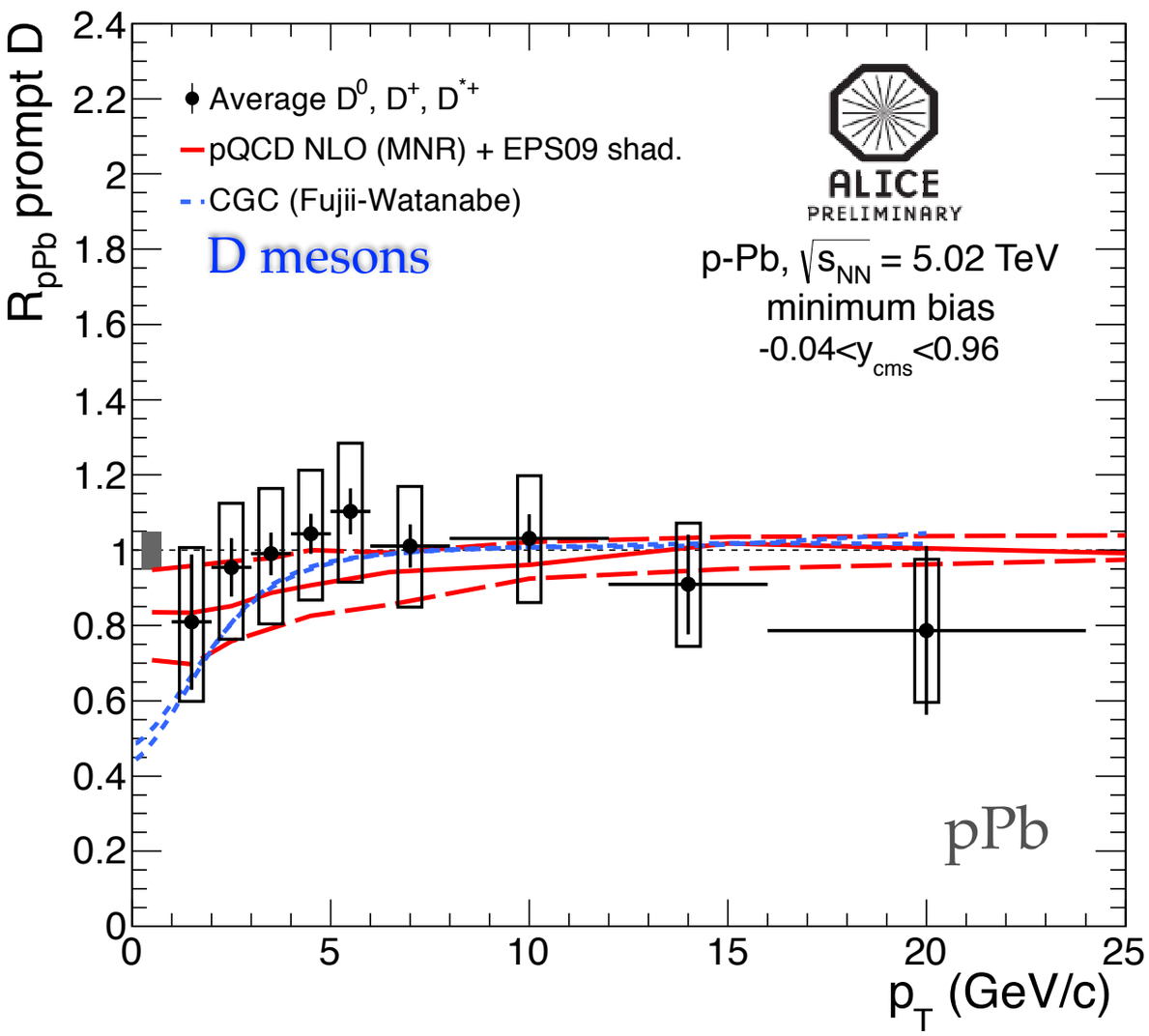
✳ Vitev calculation includes: k_T broadening via parton scattering, gluon shadowing, and partonic energy loss from fragmentation and dissociation

- Seems to overestimate the mid-rapidity central Cu-Cu results

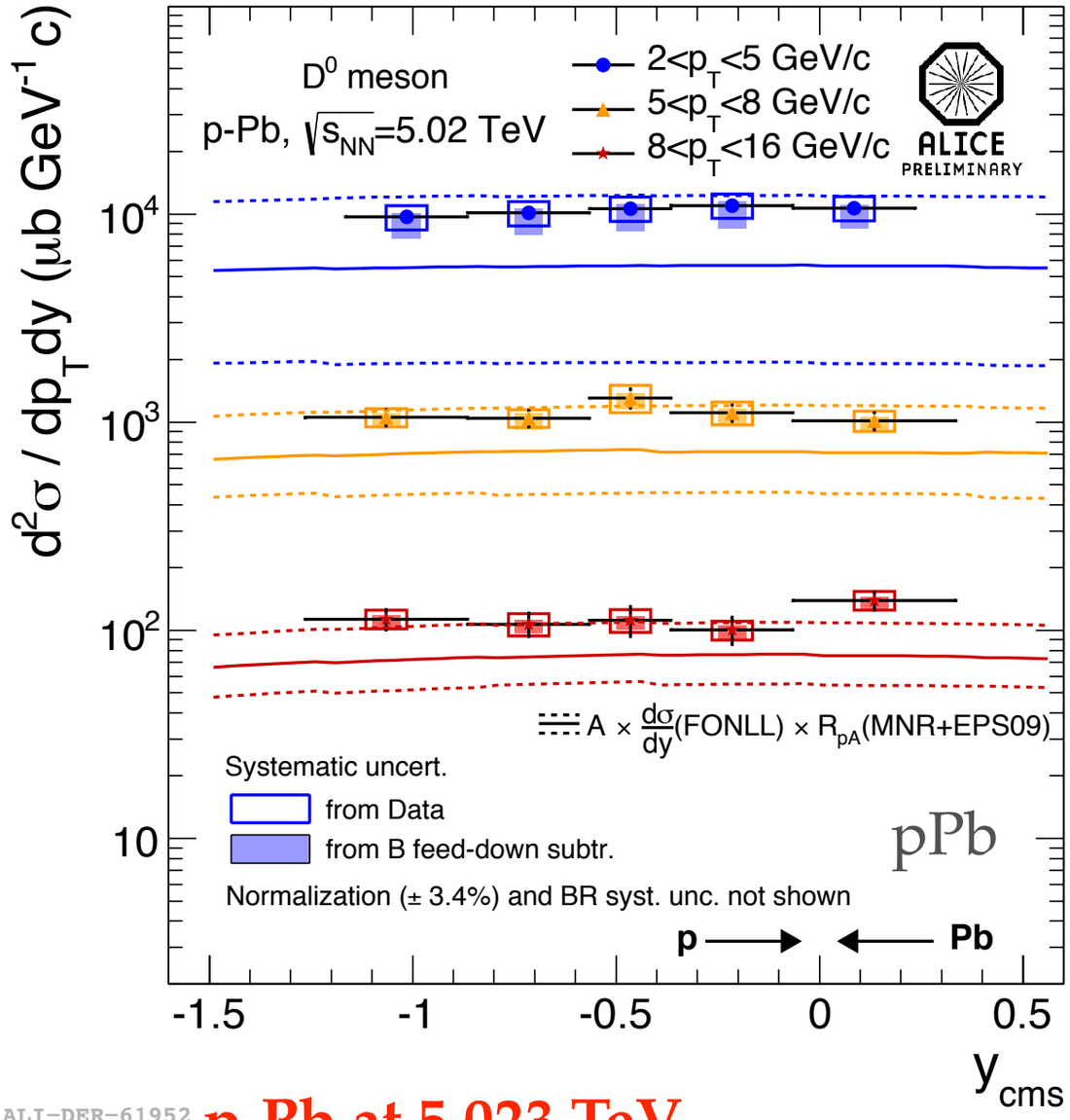
[Vitev, Phys. Rev. C 75, 064906 (2007)]

➡ **Additional effects: k_T broadening, energy loss, comovers, coalescense, hydro may be at play ?**

Charm production at LHC



D. Stocco, SQM13

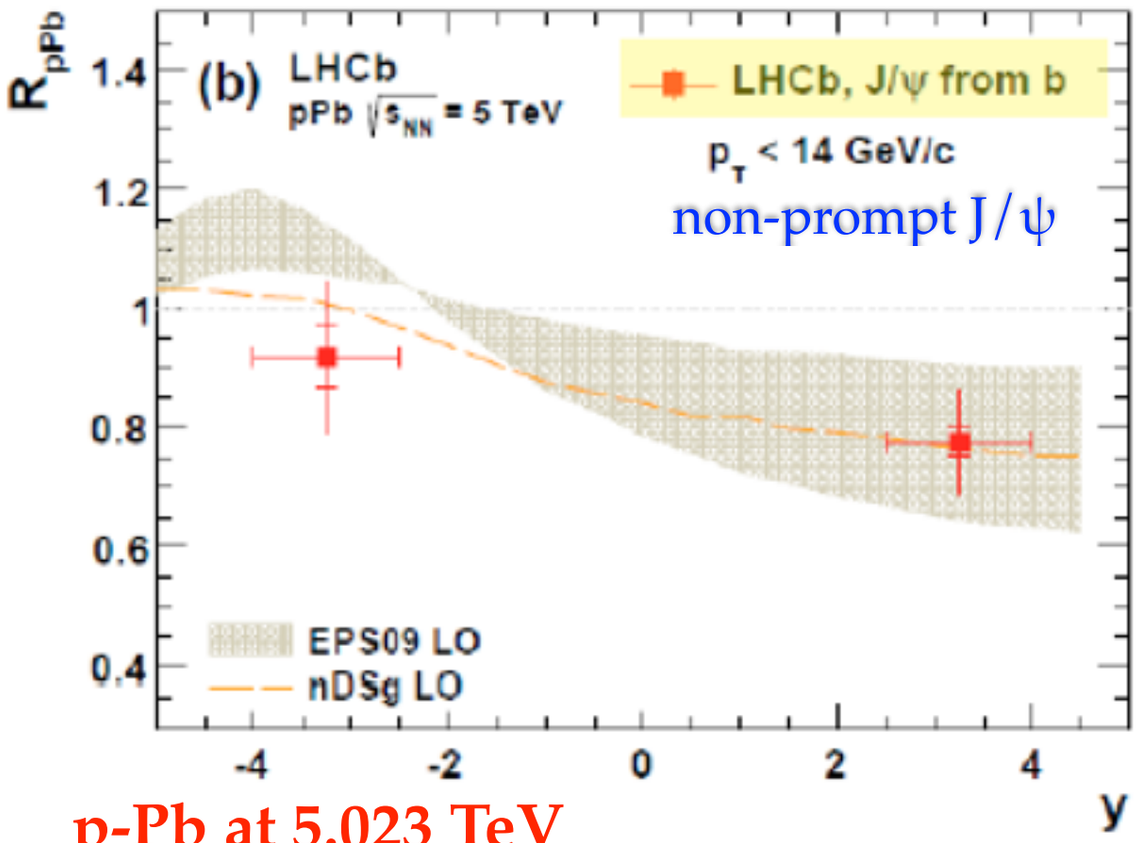


ALI-DER-61952 **p-Pb at 5.023 TeV**

- Good agreement with MNR calculations with EPS09 shadowing
- Also well described by CGC predictions
- Nuclear effects expected to be small for high p_T PbPb collisions

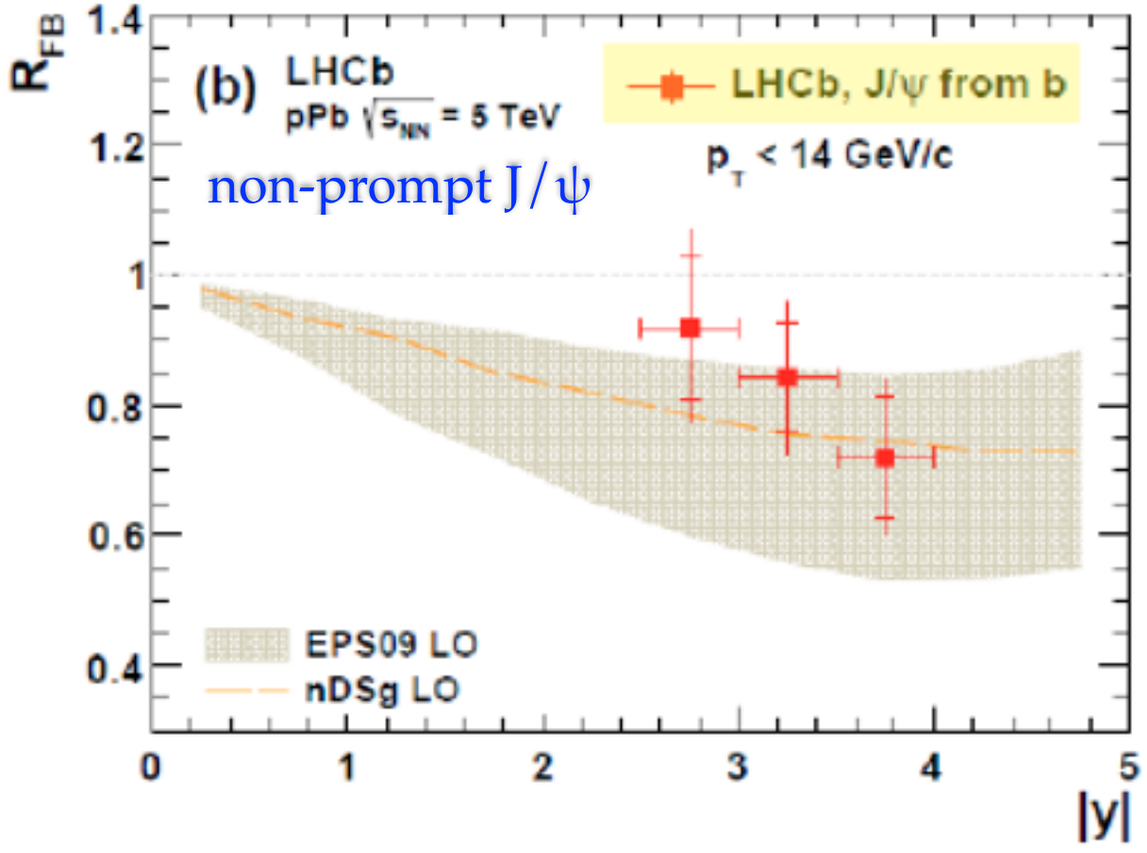
LHCb Beauty production at LHC

Non-Prompt J/ψ R_{pPb}



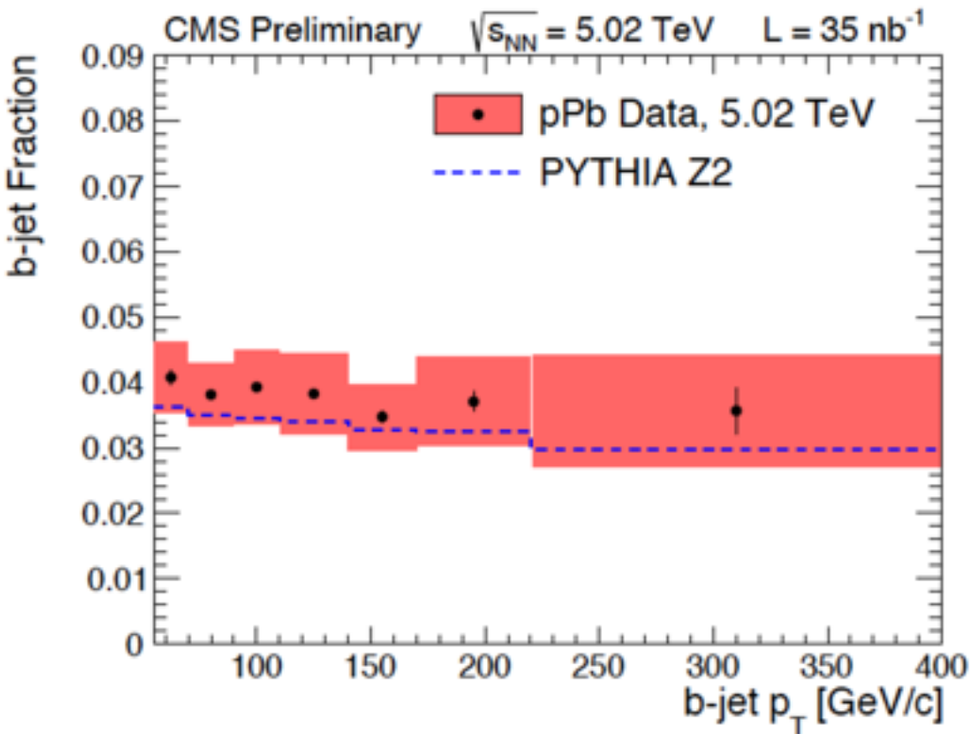
p-Pb at 5.023 TeV

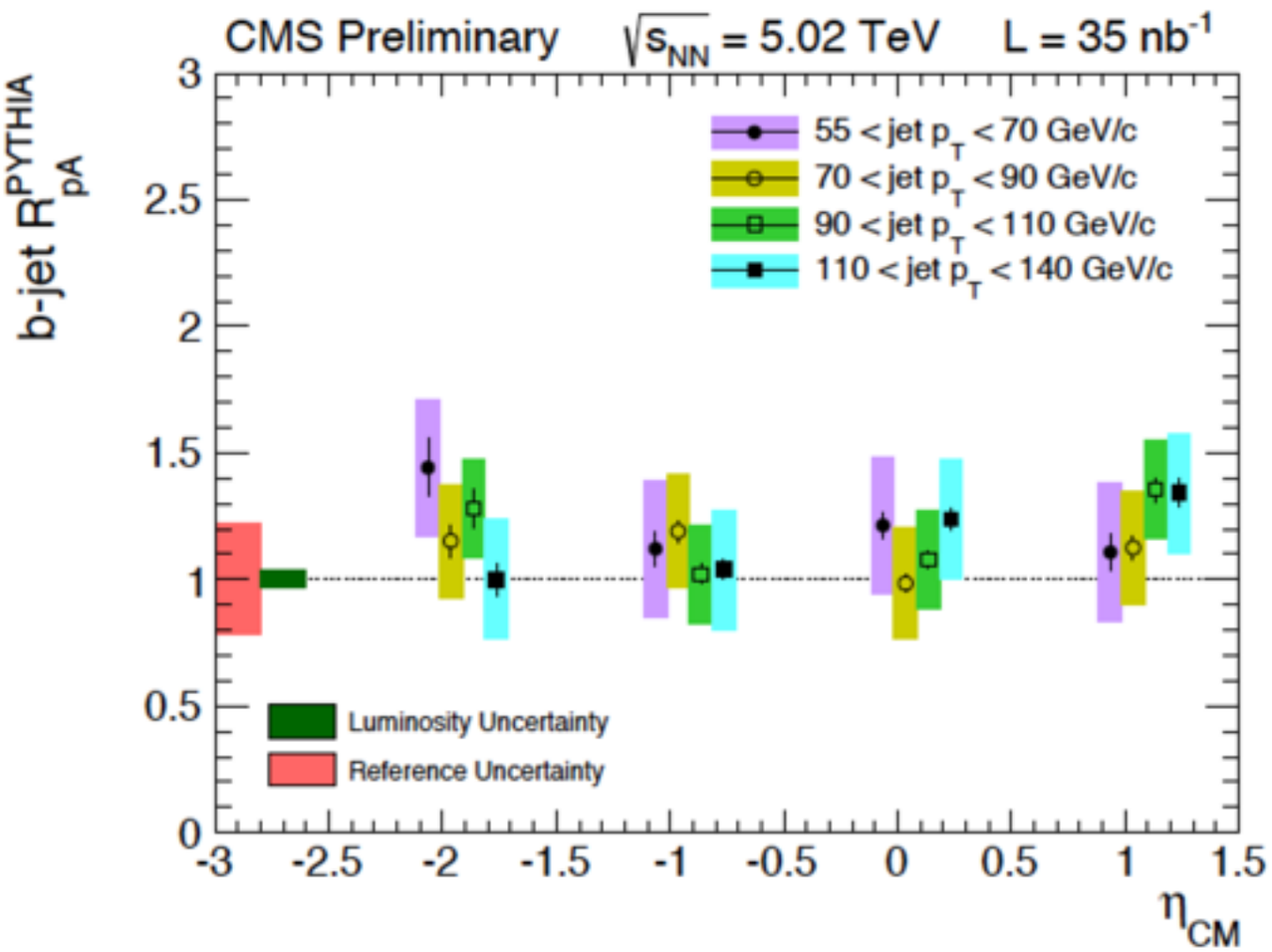
Non-Prompt J/ψ forward to backward ratio

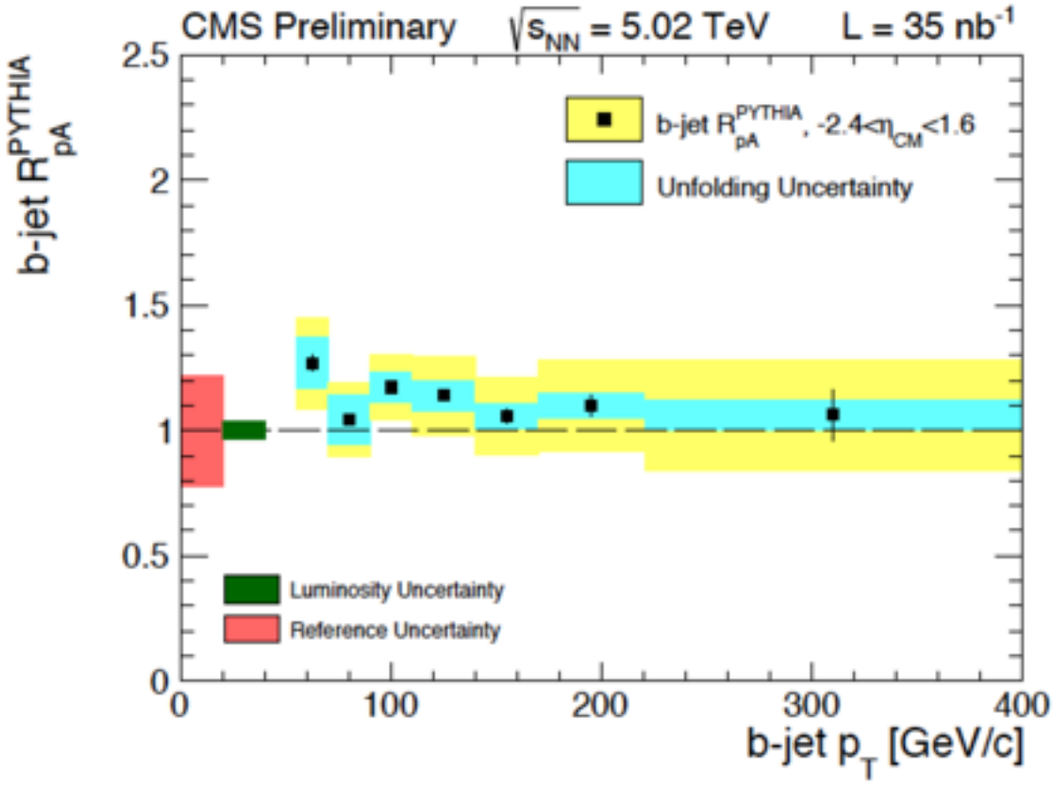


- First measurement of beauty production down to p_T~0 in heavy ion collisions !
- R_{FB} suggests a possible rapidity dependence
- Not negligible nuclear effects expected at low p_T in PbPb collisions
- Reasonable agreement with LO calculations with EPS09 shadowing

CMS B-Jets in pPb

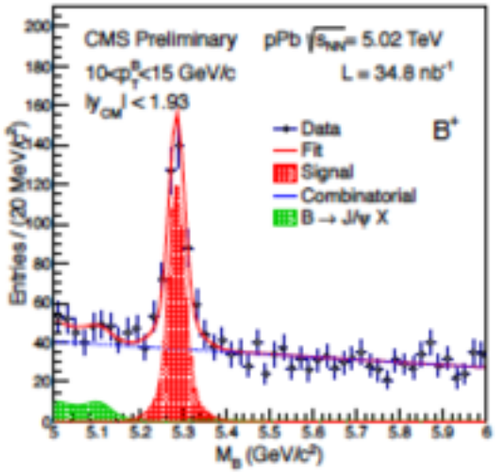


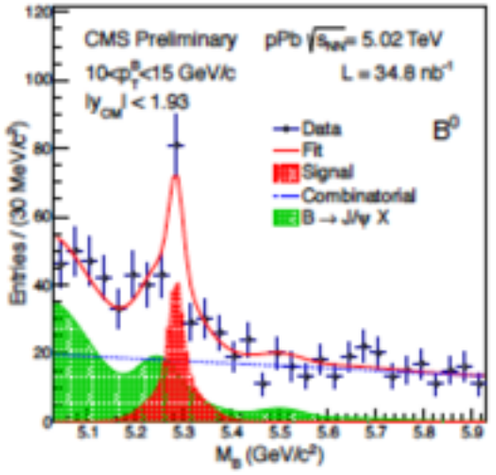


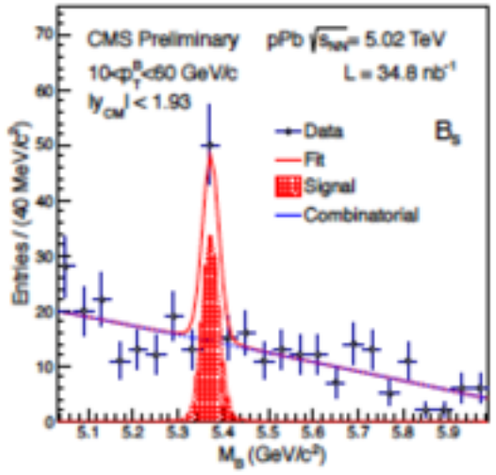


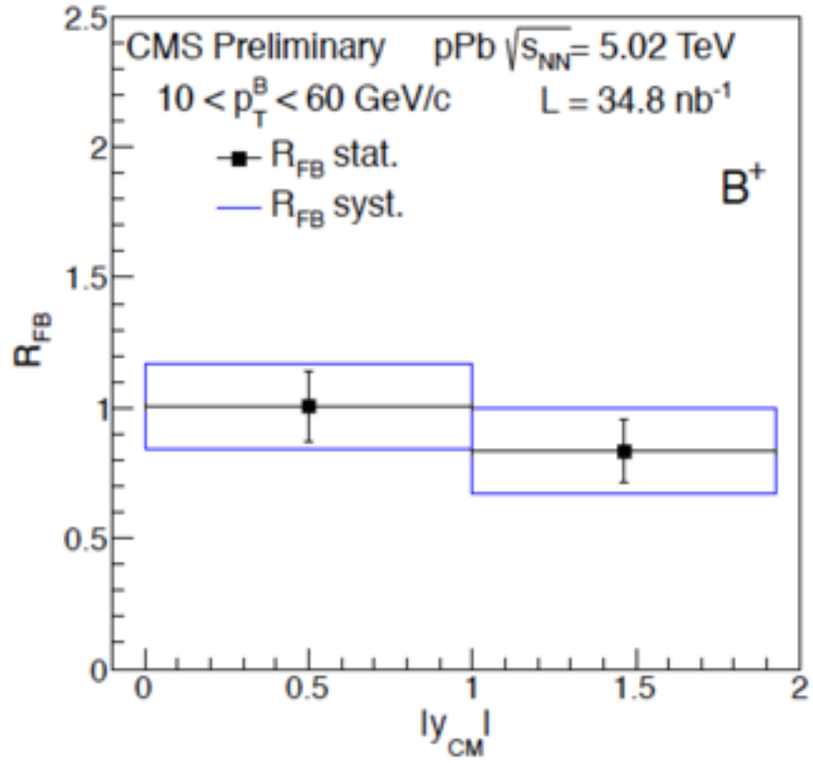
CMS-HIN-14-007-PAS

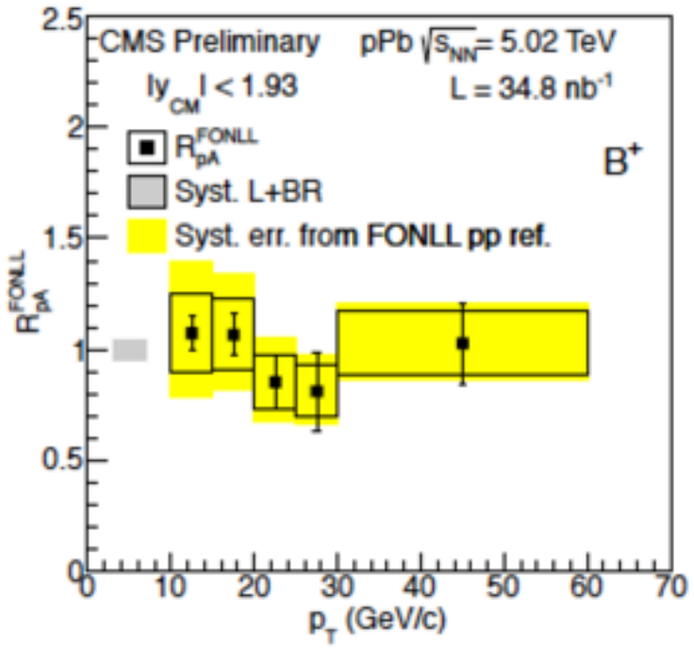
CMS B hadrons in pPb

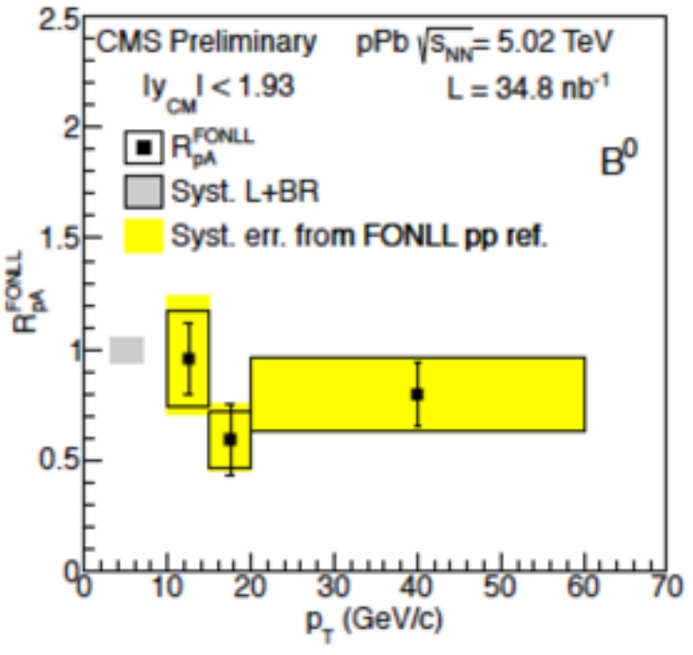


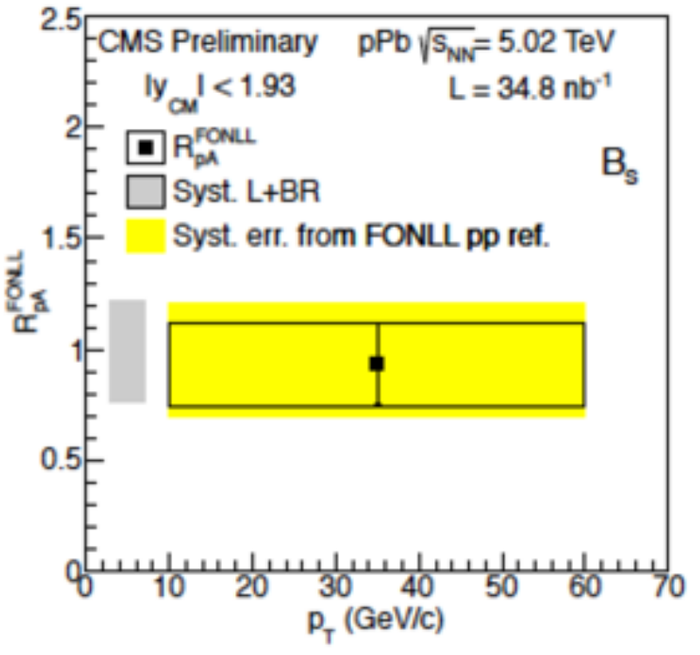






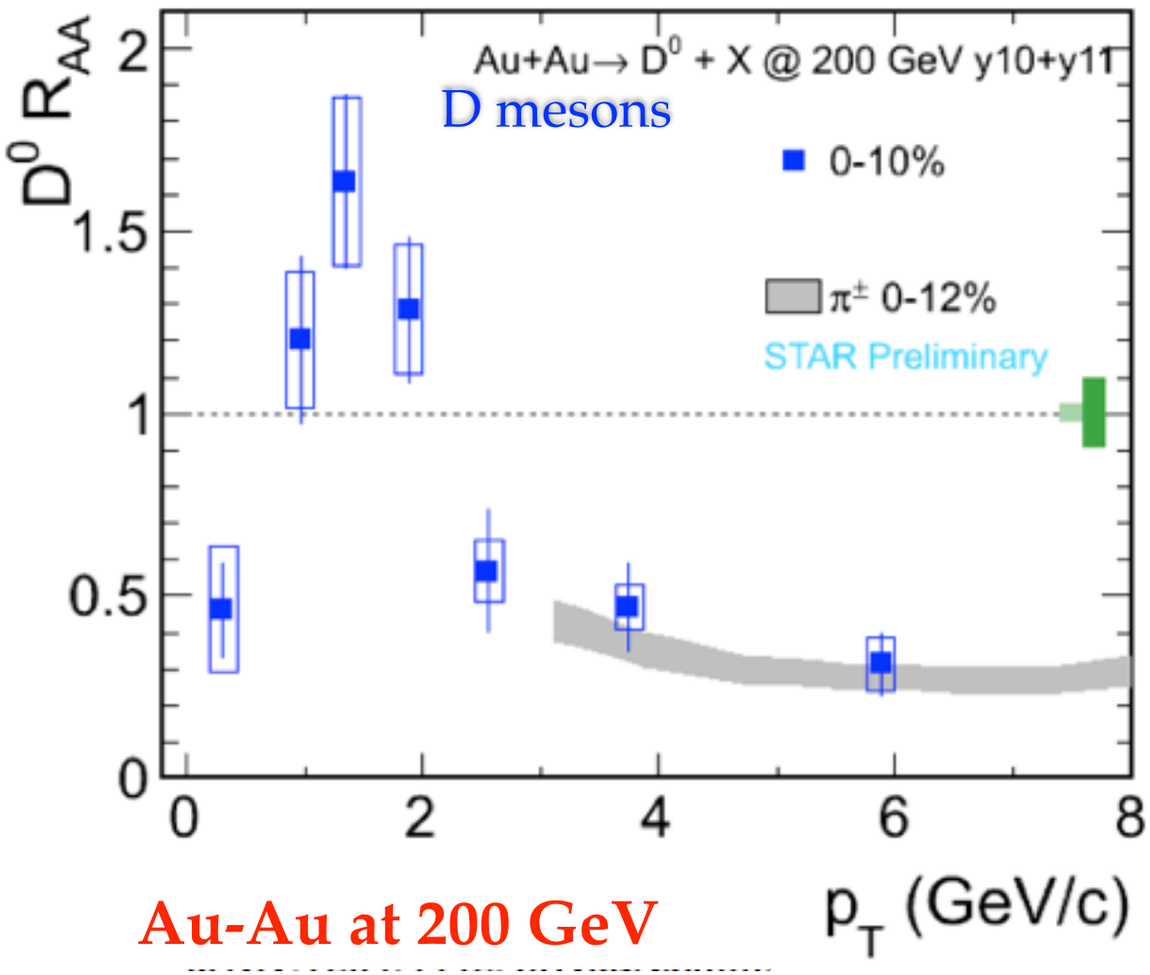




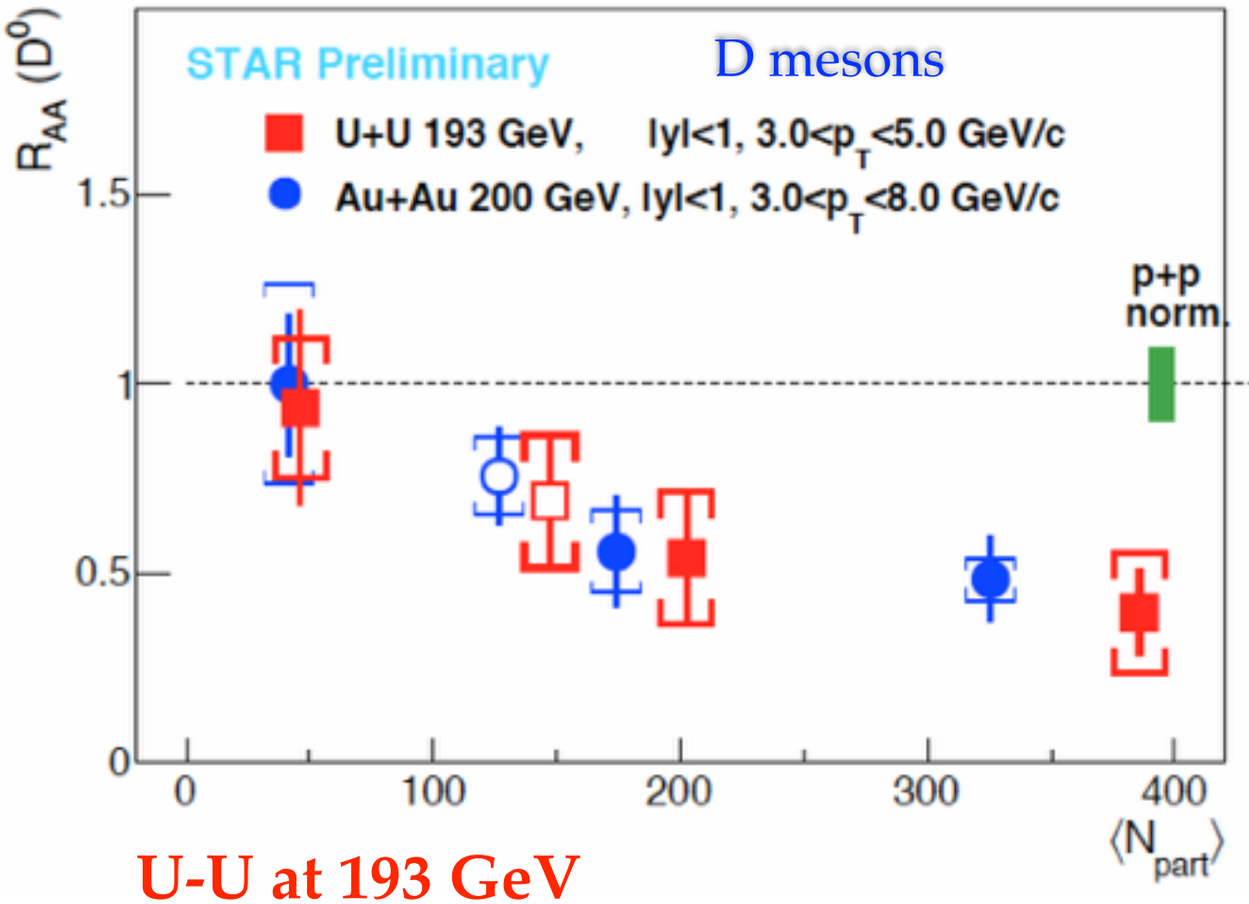


CMS-HIN-14-004-PAS

Charm at RHIC



Au-Au at 200 GeV



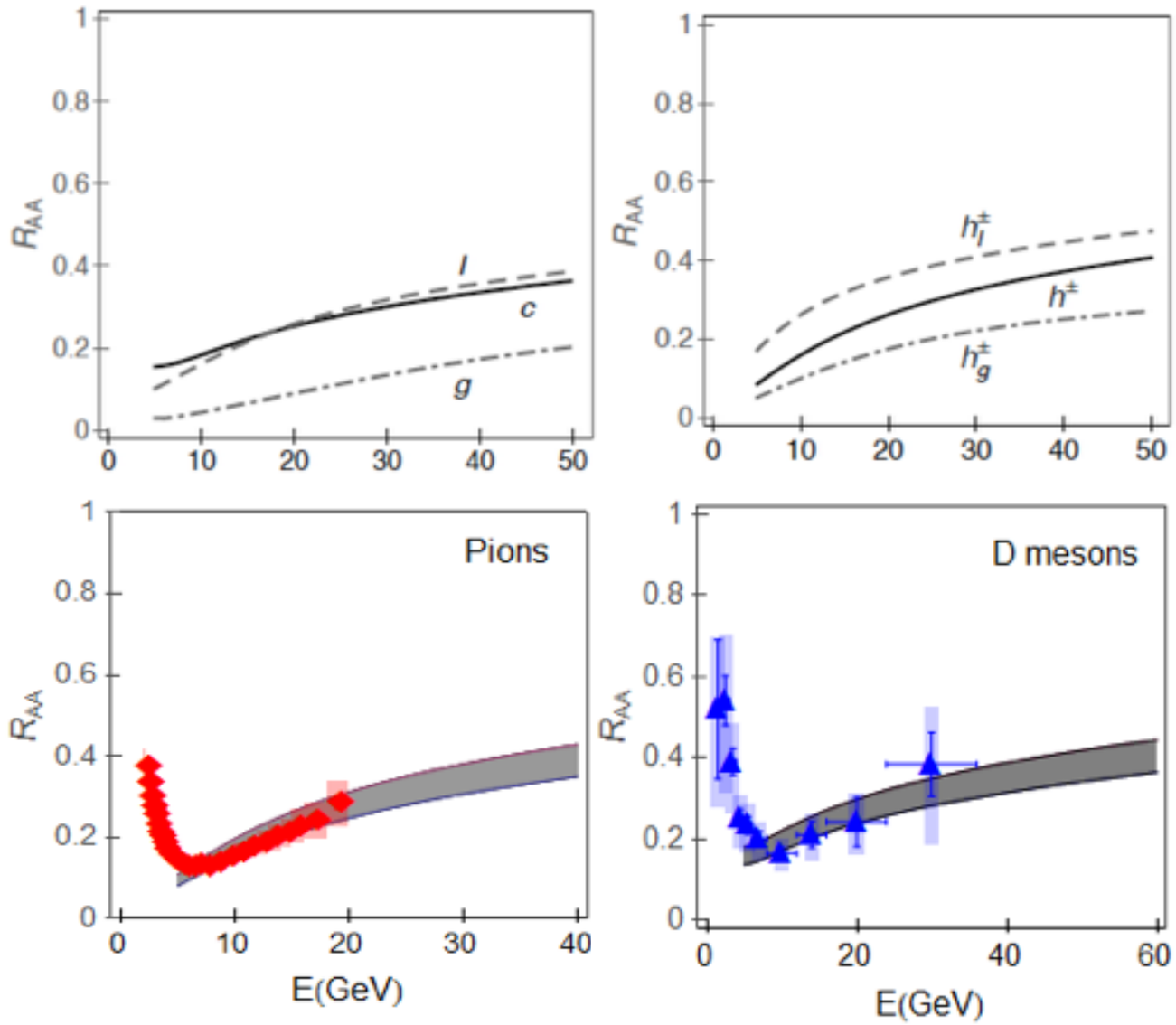
U-U at 193 GeV

Y. Zhenyu, HP13

- Suppression by a factor of 2-2.5 of high p_T D^0 in the most central collisions,
- Clear centrality dependence of the suppression
- while there might be an enhancement at low p_T : radial flow + coalescence ?

Charm & Pion R_{AA} vs p_T

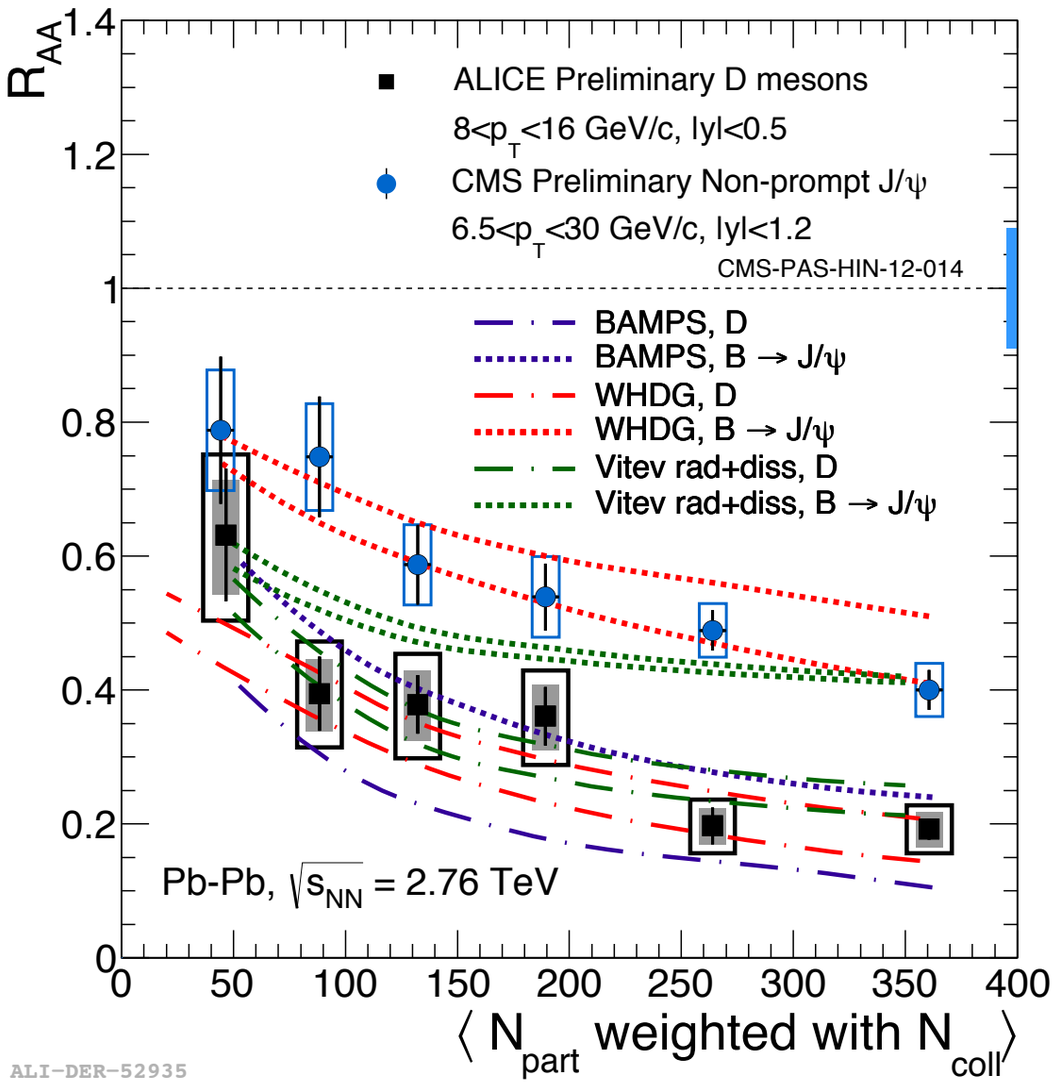
Charm & Pion R_{AA} vs P_T



[M.Djordjevic, arXiv: 1307.4702, arXiv:1307.4098]

Charm & Beauty at LHC

Pb-Pb at 2.76 TeV



➡ **In central collisions, for p_T>6 GeV, non-prompt J/ψ (CMS) are less suppressed than prompt D mesons, albeit the difference on the b/c average p_T.**

Caveats:
<p_T> B/D hadrons ≠ b/c quarks
fragmentation of b/c
⇨ Need models

With this selection:
- **B <p_T> ~ 11 GeV**
- **D <p_T> ~ 10 GeV**

Energy loss parton mass dependence, $\Delta E_b < \Delta E_c$?

BAMPS - collisional energy loss in an expanding medium

It tends to predict larger suppression for both D mesons and non-prompt J/ψ.

WHDG - collisional + radiative energy loss in anisotropic medium

Good agreement with both measurements.

Vitev – radiative + dissociation

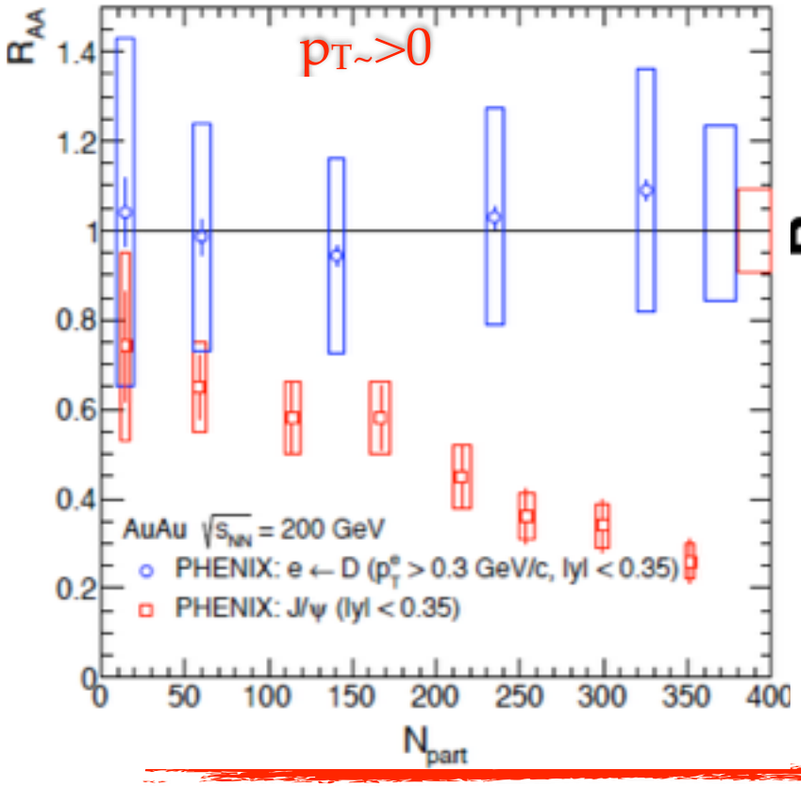
Relative good description, but underestimates non-prompt J/ψ for peripheral classes.

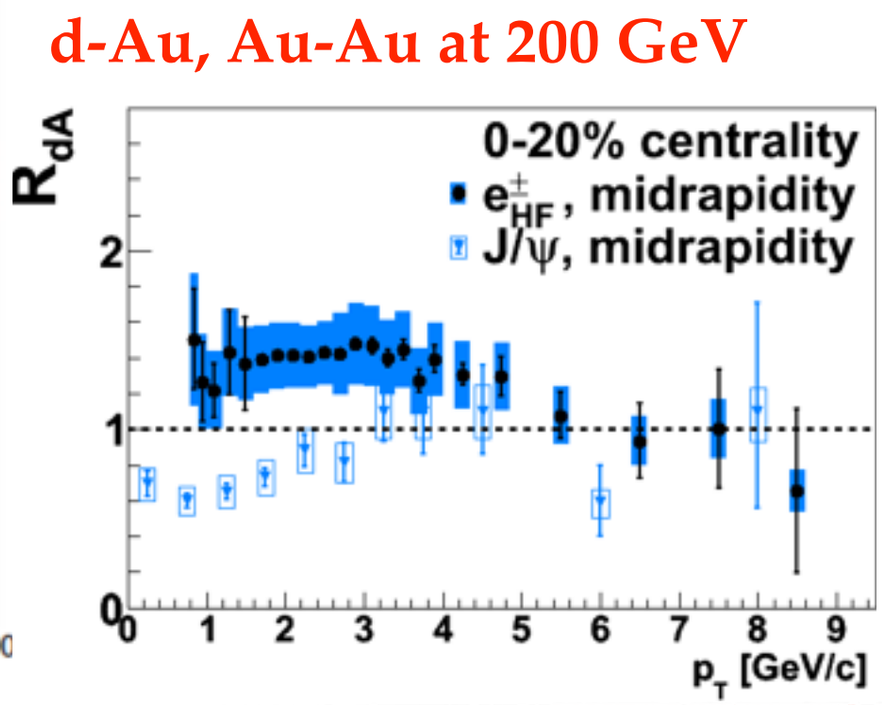
[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
[Vitev: R. Sharma, I. Vitev and B. W. Zhang, Phys. Rev. C80 (2009) 054902; Y. He, I. Vitev and B. -W. Zhang, Phys. Lett. B 713 (2012) 224]

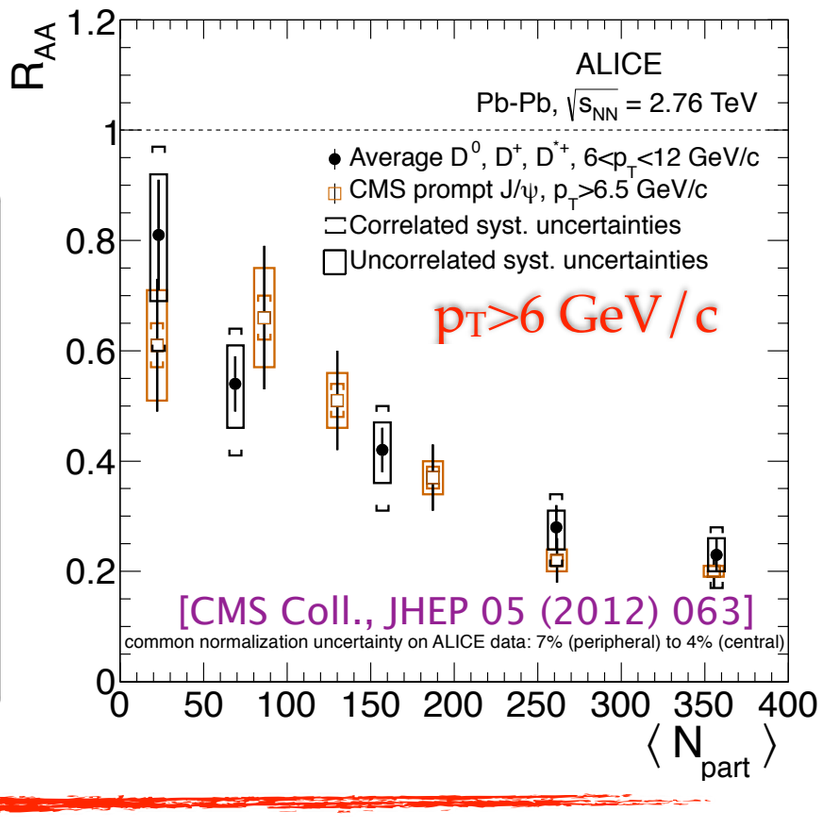
Open and Hidden Charm

- The idea: since quarkonia are formed by pairs of heavy-quarks, heavy-quarks are the natural normalization
- The difficulty: the natural observables would be the p_T-integrated yields, but this is experimentally challenging.
  Comparisons of measurements in different kinematic ranges have to be done with care (different c-quark kinematics involved).
  ⇨ Need of models that take care of these correlations

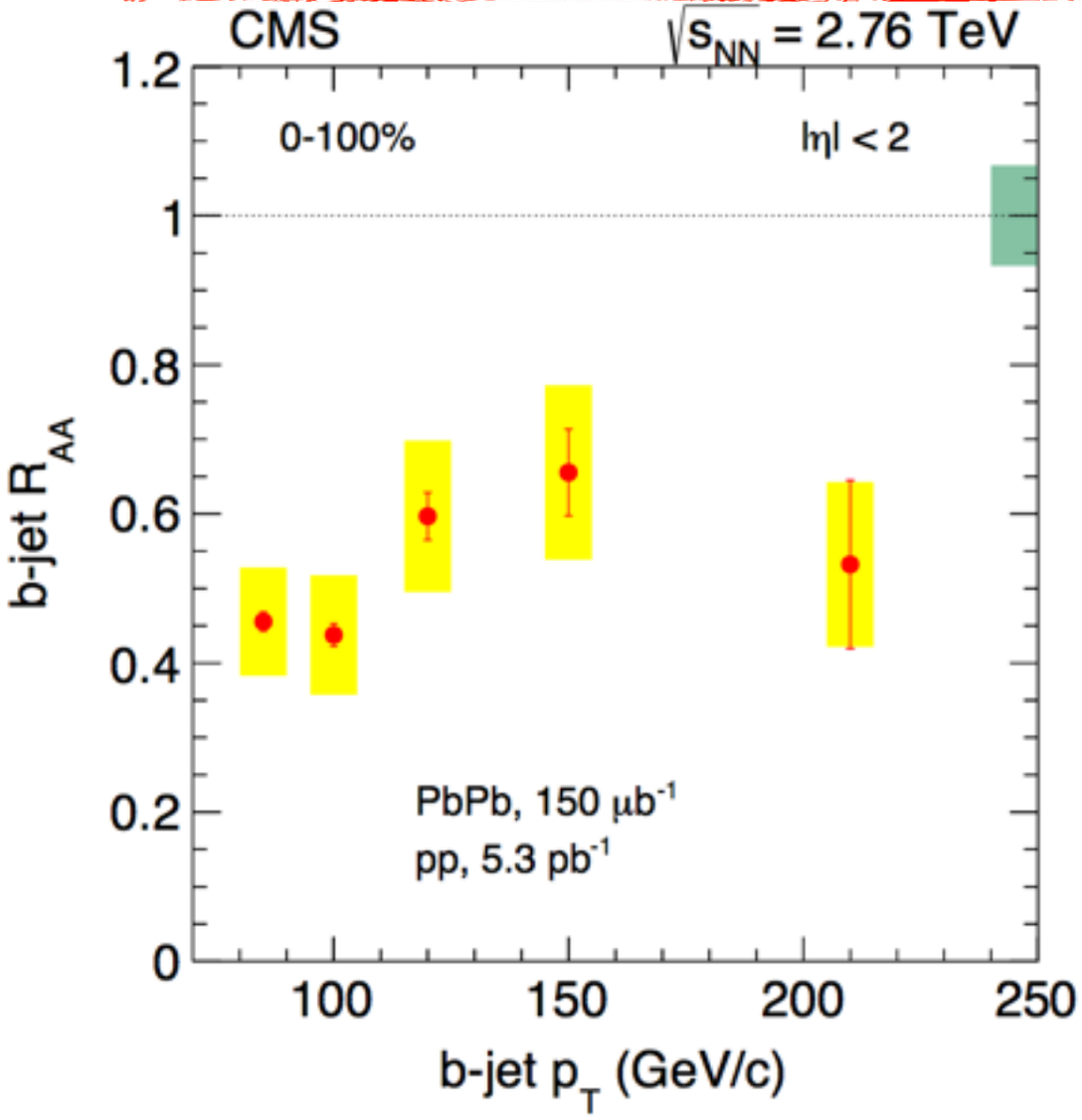
H. Satz, Adv. High Energy Phys. 2013 (2013) 242918, arXiv:1303.3493

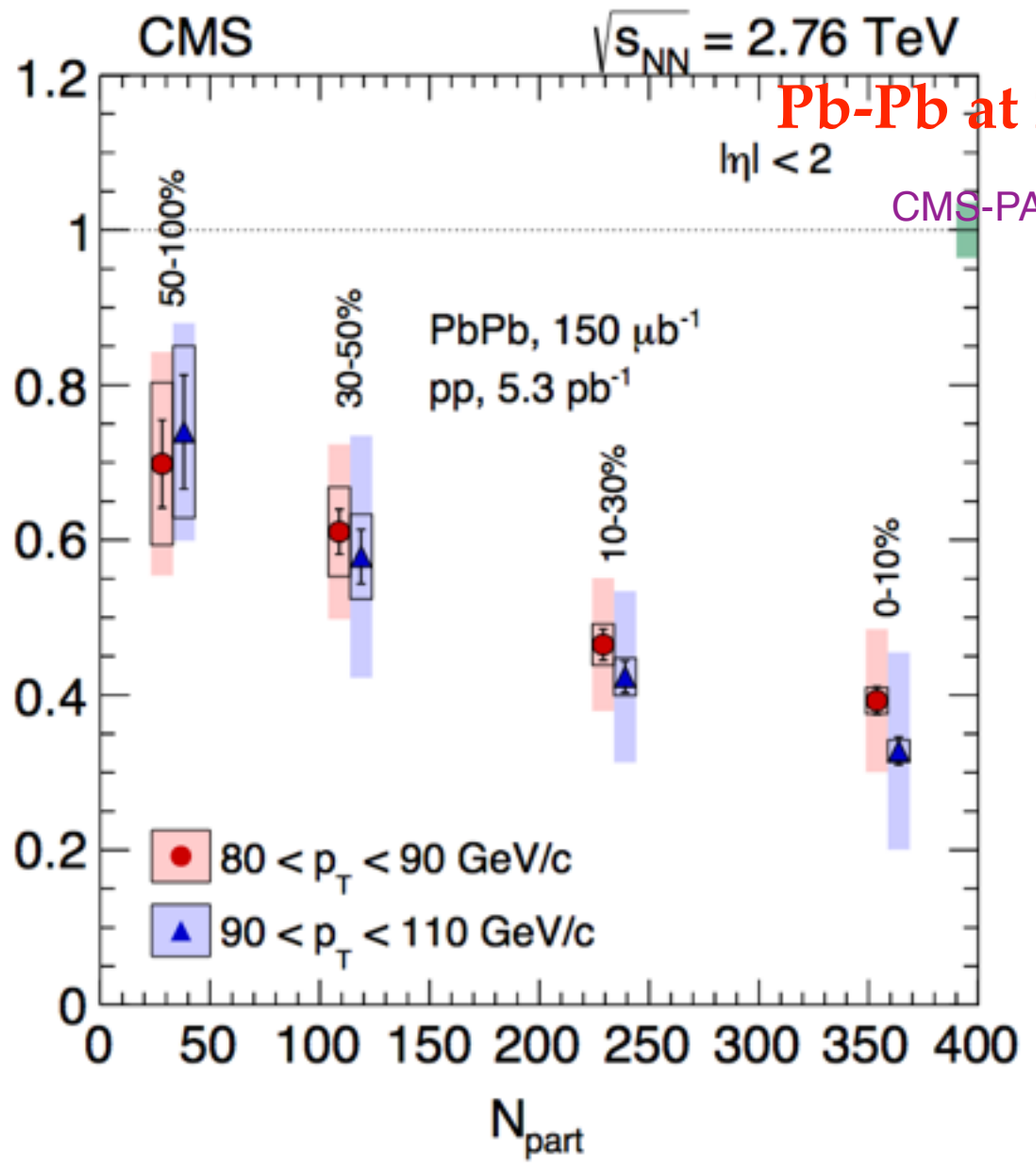






Beauty Jets at LHC





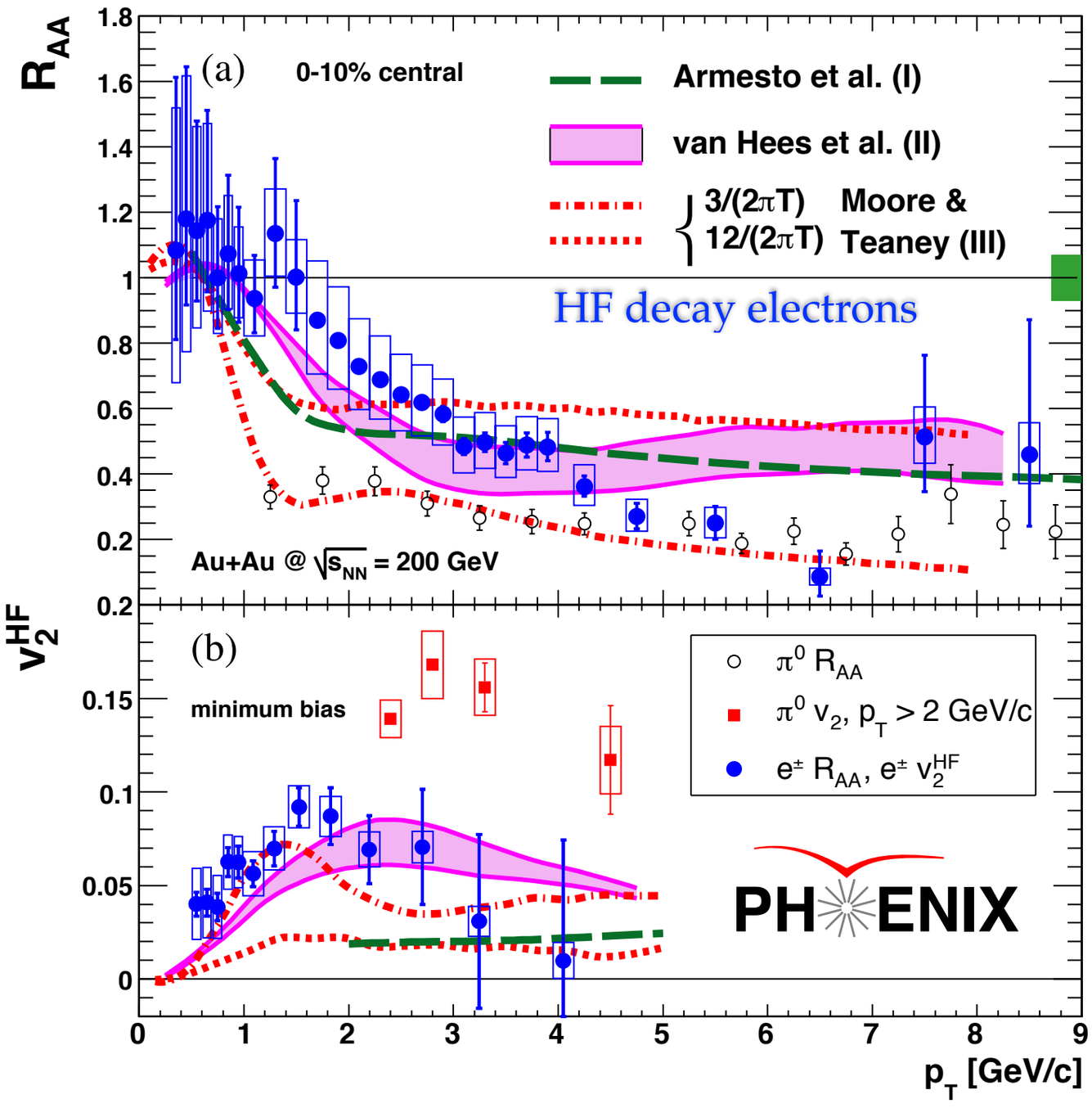
Pb-Pb at 2.76 TeV

CMS-PAS-HIN-14-007

- ➡ First measurement of heavy flavor jet R_{AA}
- ➡ Significant suppression of b-jets up to high p_T
- ➡ Clear centrality dependence of b-jet suppression
- ➡ Similar suppression for b & q/g-jets (as expected at large p_T)

❖ **Consistent with the expectations of mass dependent partonic energy loss**

HF Decay electron R_{AA} & v_2 at RHIC



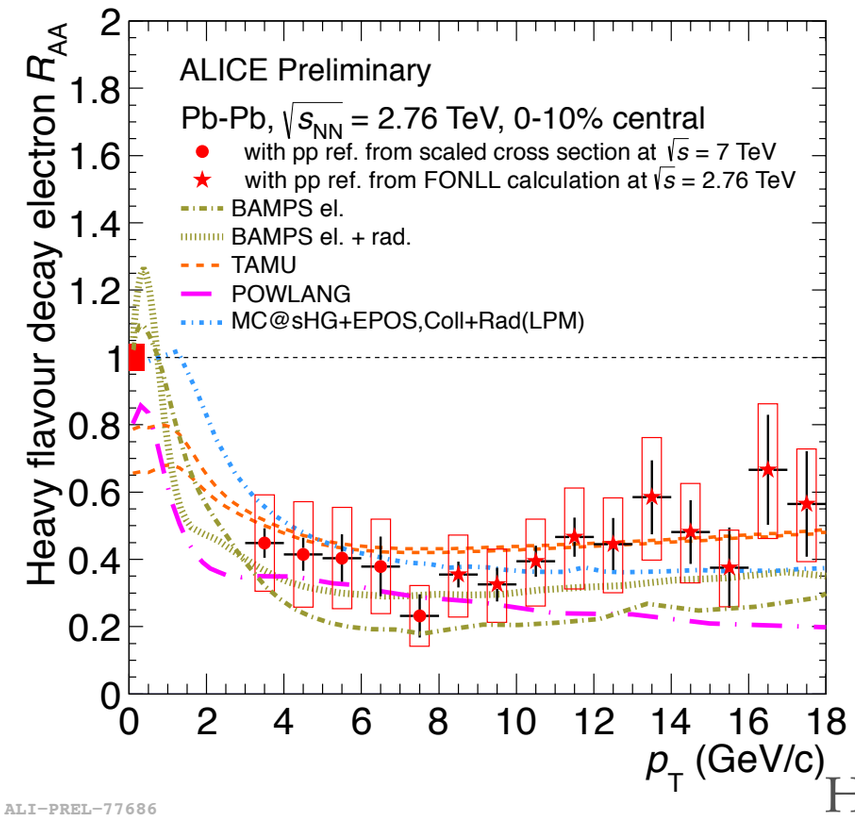
➡ **The simultaneous description of HFe R_{AA} and v_2 is challenging**

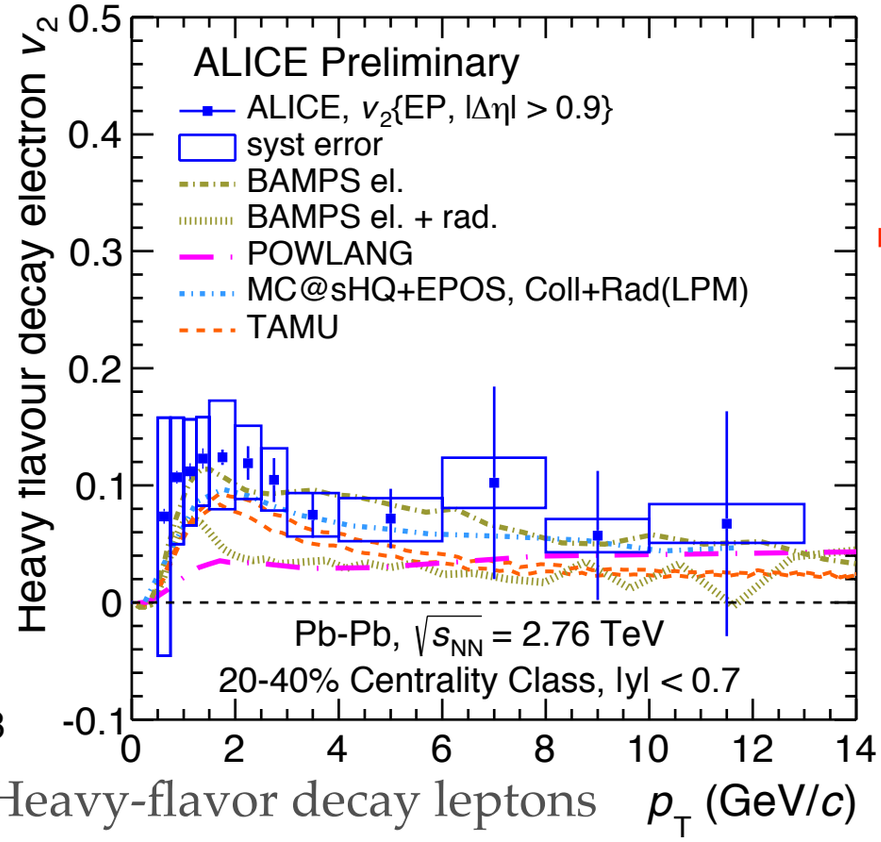
[PHENIX, P.R.L.98 (2007) 172301]
[Armesto et al, P.L.B 637, 362 (2006)]

[H.van de Hees et al, P.R.C 73, 034913 (2006)]
[G.D.Moore et al, P.R.C 71, 064904 (2005)]

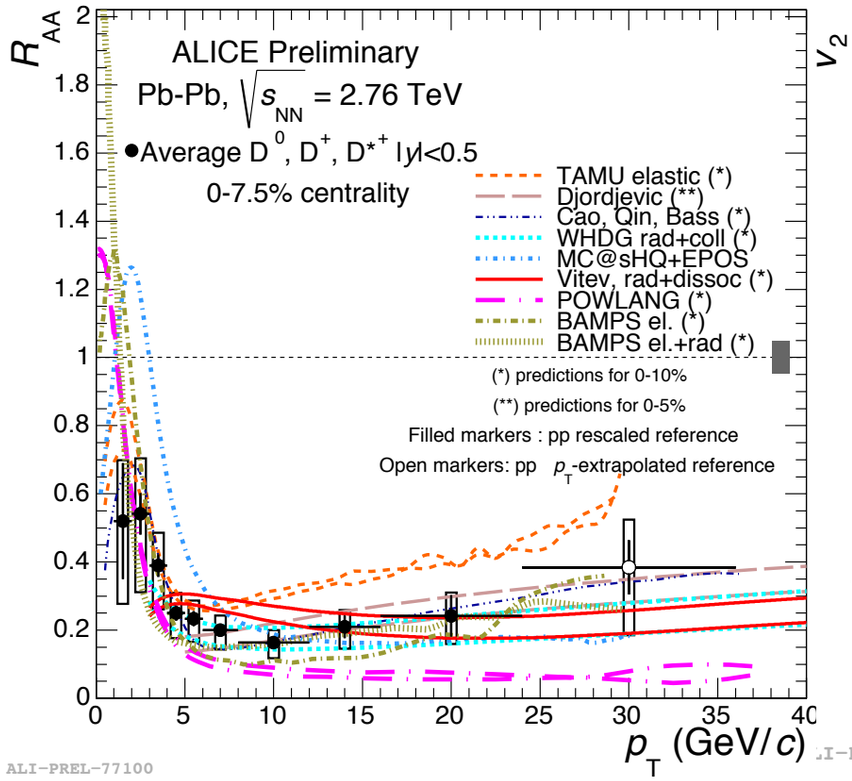
Au-Au at 200 GeV

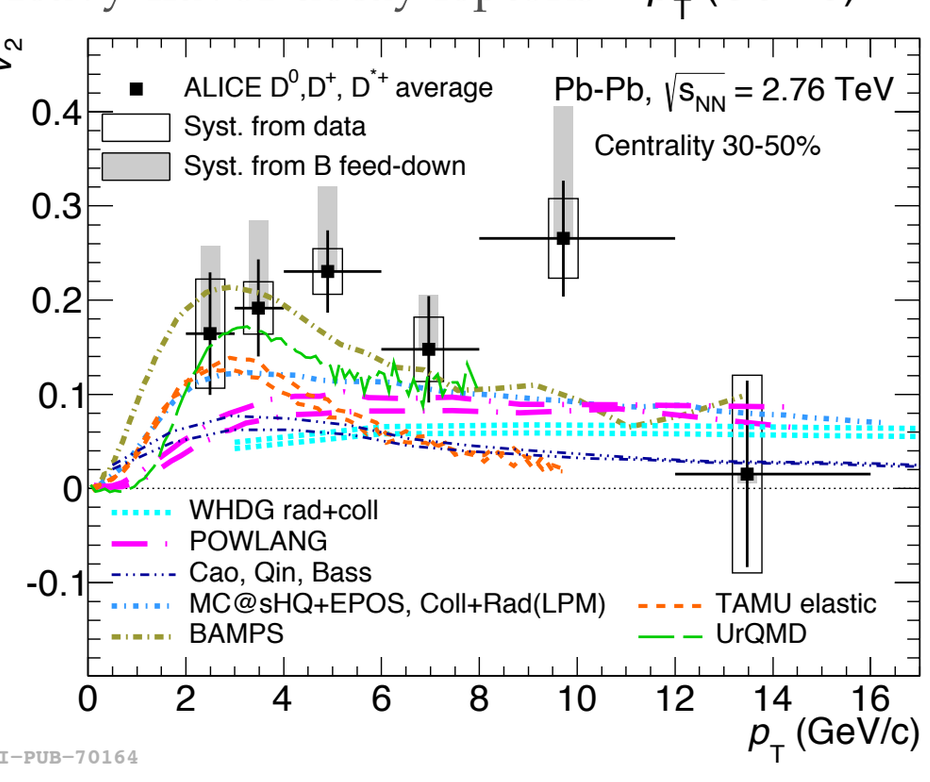
Open Heavy Flavor R_{AA} & v_2





Heavy-flavor decay leptons





Pb-Pb at 2.76 TeV

➡ **The simultaneous description of open heavy-flavor R_{AA} and v_2 is challenging**

⇨ Many models appearing. A more systematic data/ theory comparison might help the interpretation

[BAMPS: J. Phys. G 38 (2011) 124152; Phys. Lett. B 717 (2012) 430]
[WHDG: J. Phys. G 38 (2011) 124114]
POWLANG: Eur. Phys. J C 71 (2011)1666]
[M. He, R. J. Fries and R. Rapp, Phys. Rev. C86 014903; Phys. Rev. Lett.110.112301]