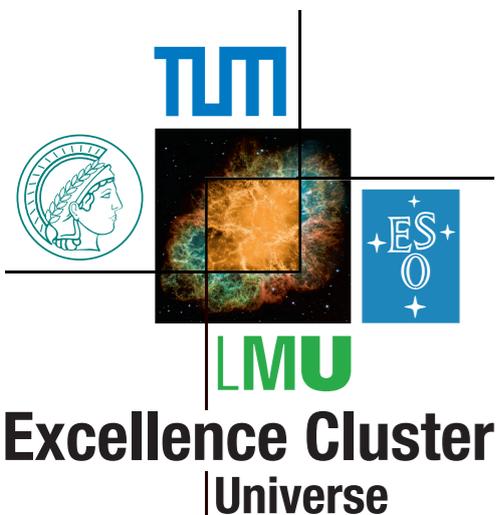


Open and Hidden Heavy Flavor Results from the LHC

– Torsten Dahms –
Excellence Cluster “Universe” - TUM

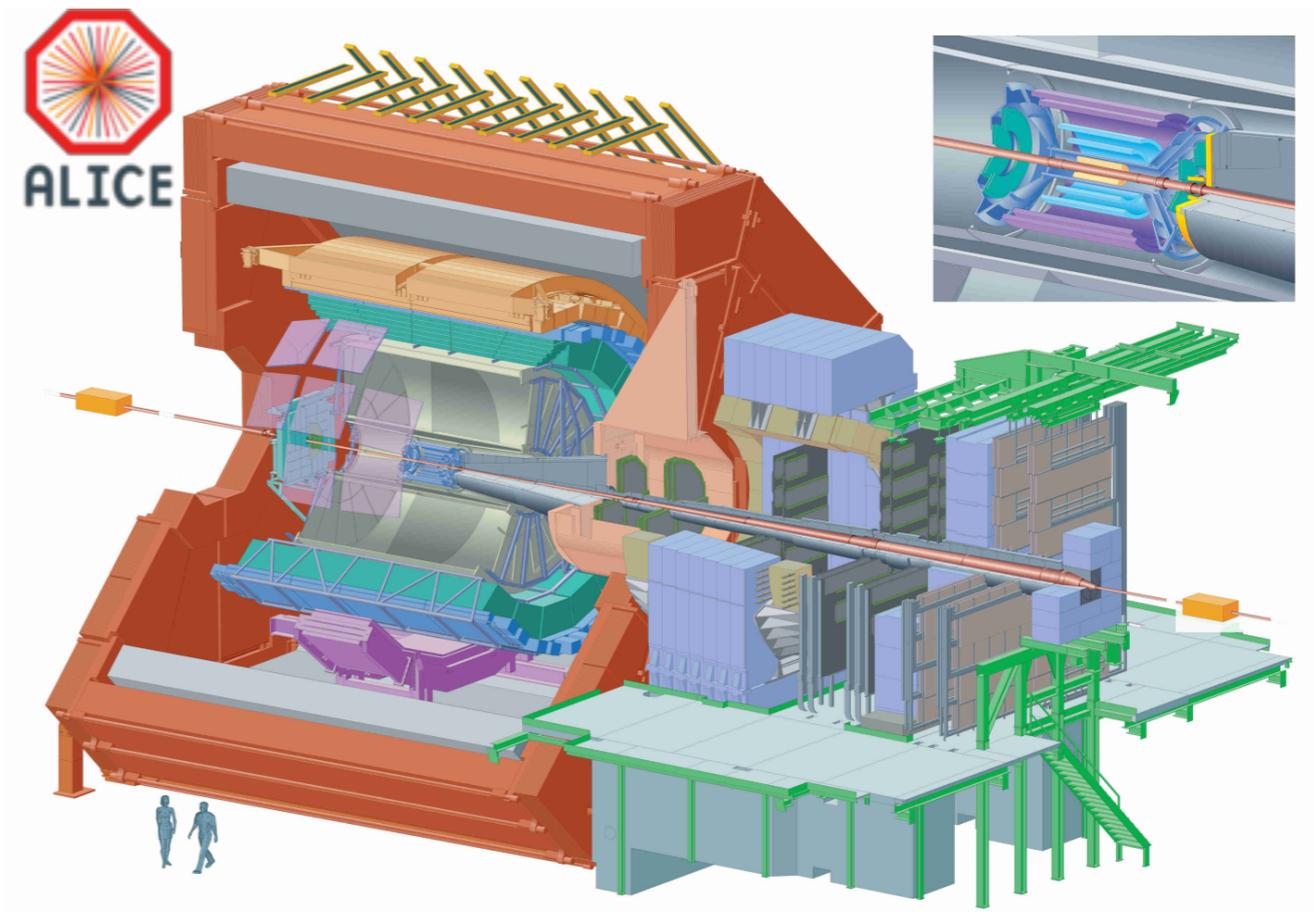
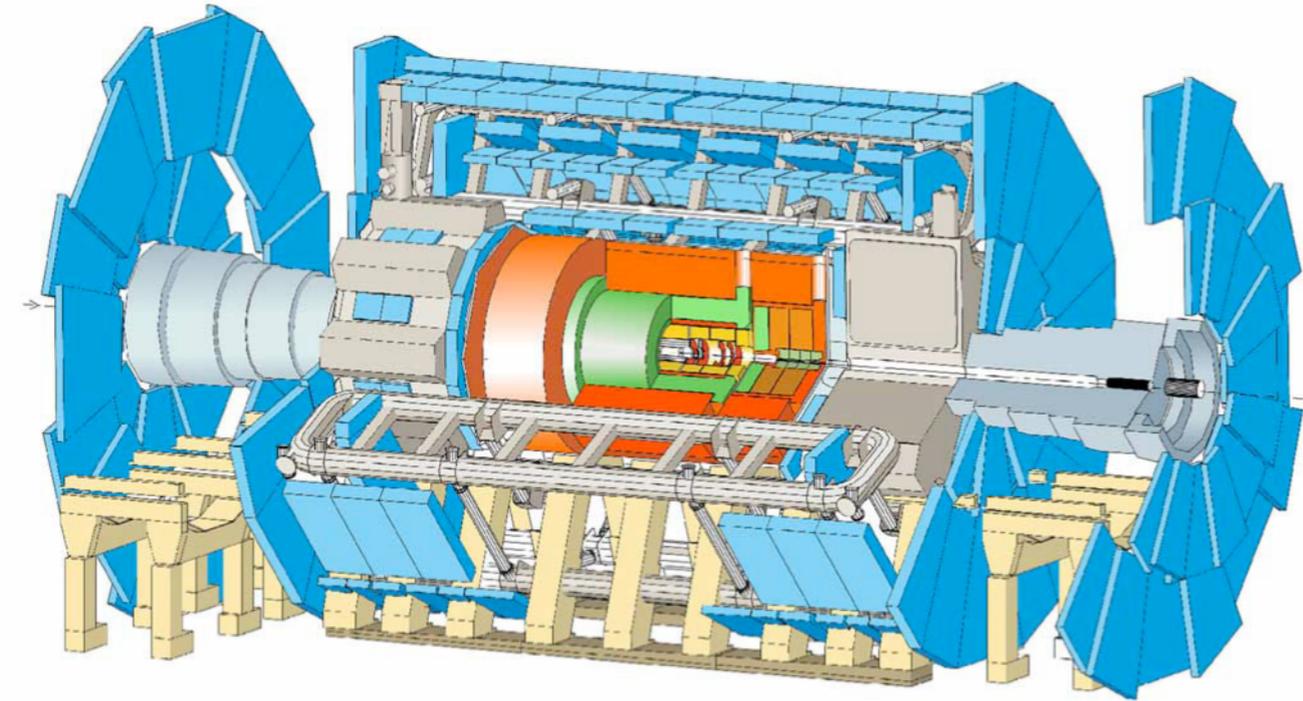
RHIC & AGS Users’ Meeting
Brookhaven National Laboratory
June 7th, 2016



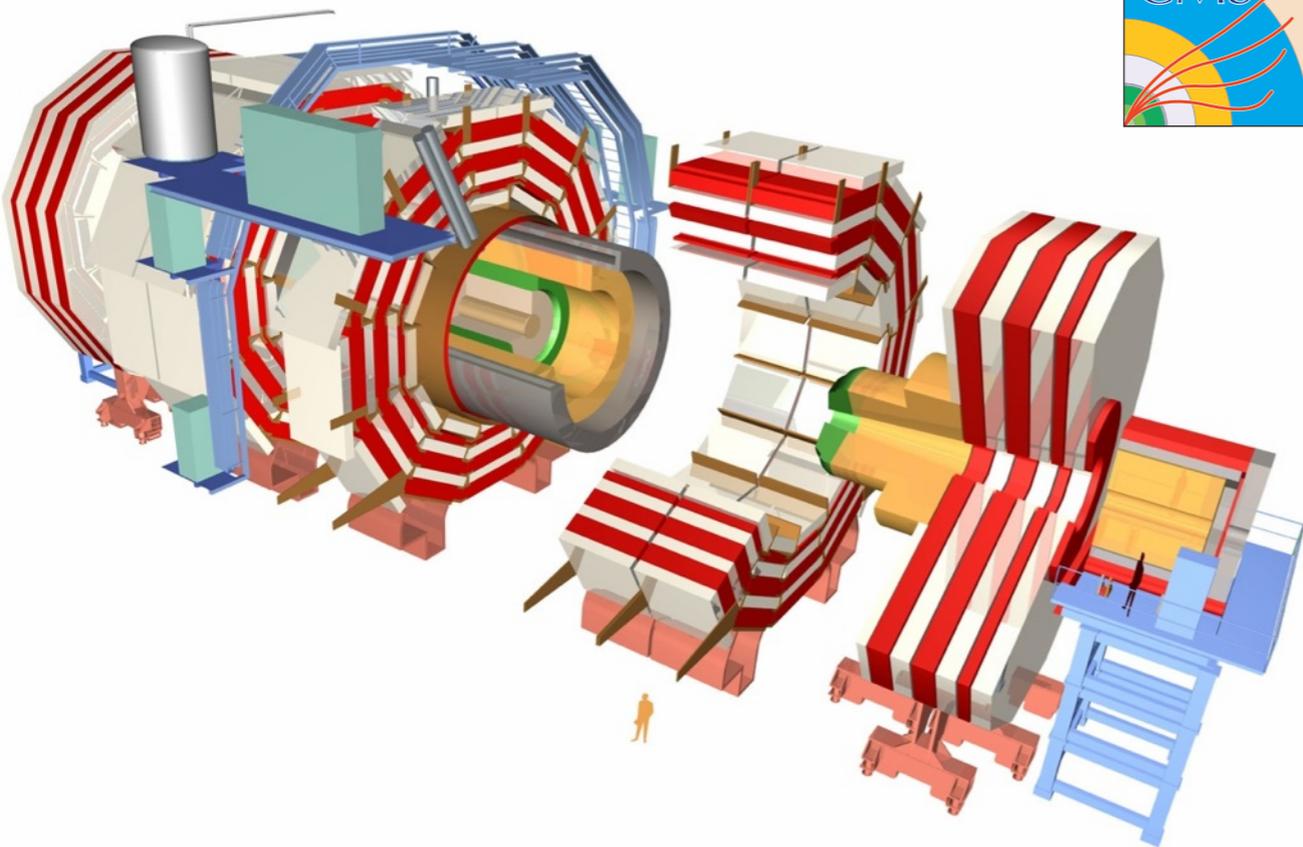
Technische Universität München

LHC experiments taking heavy-ion data

ATLAS
EXPERIMENT

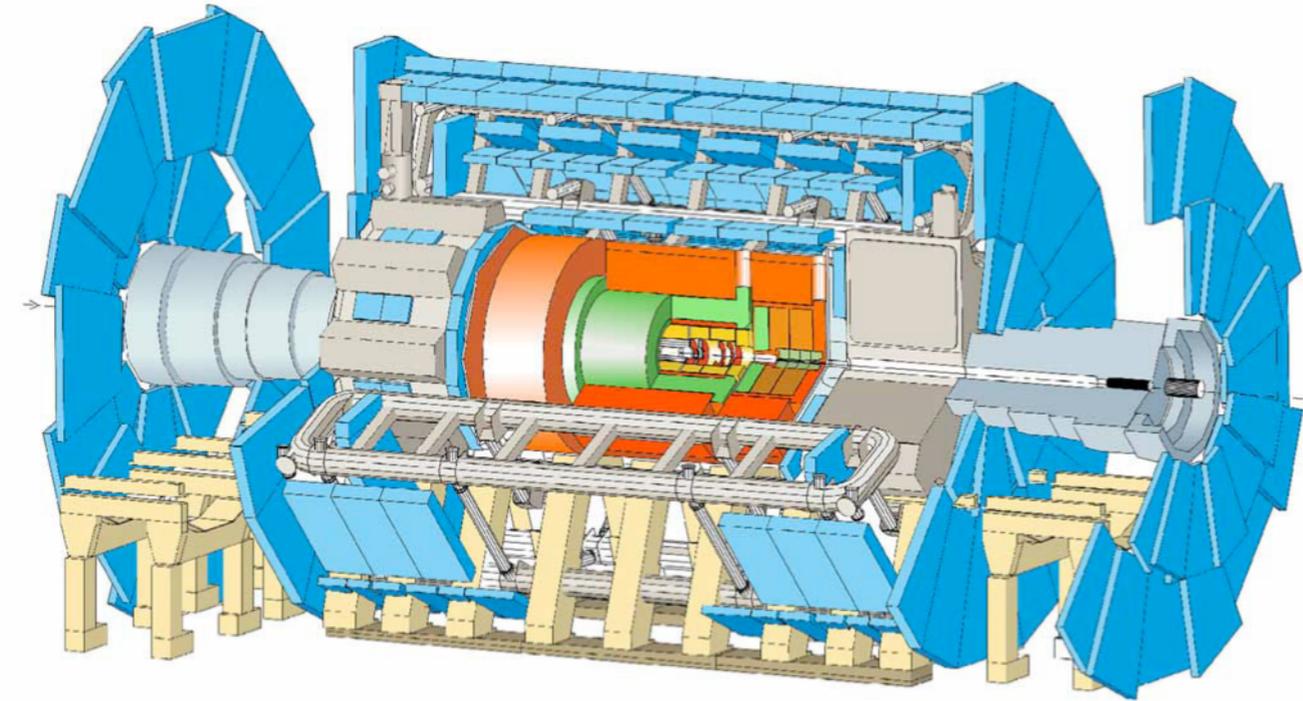


CMS

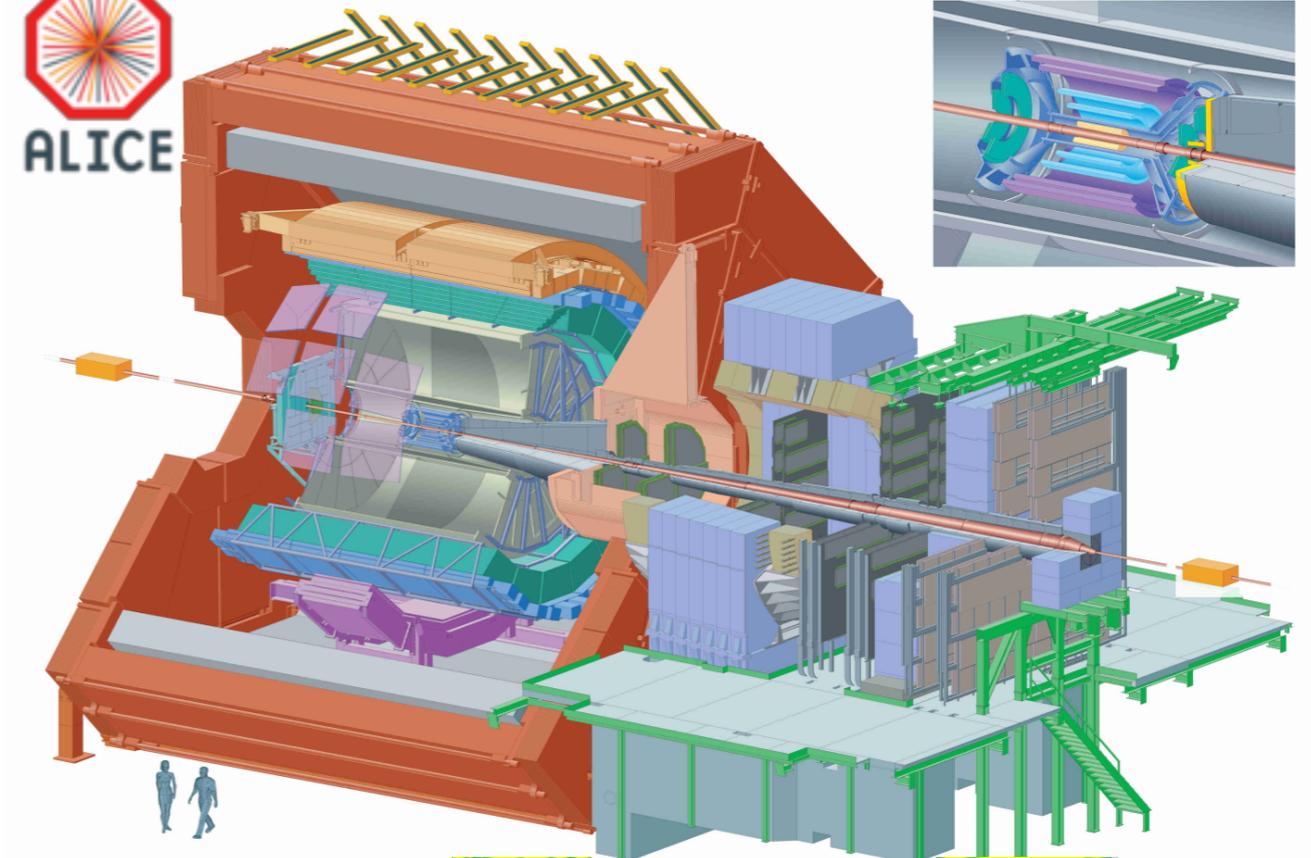


LHC experiments taking heavy-ion data

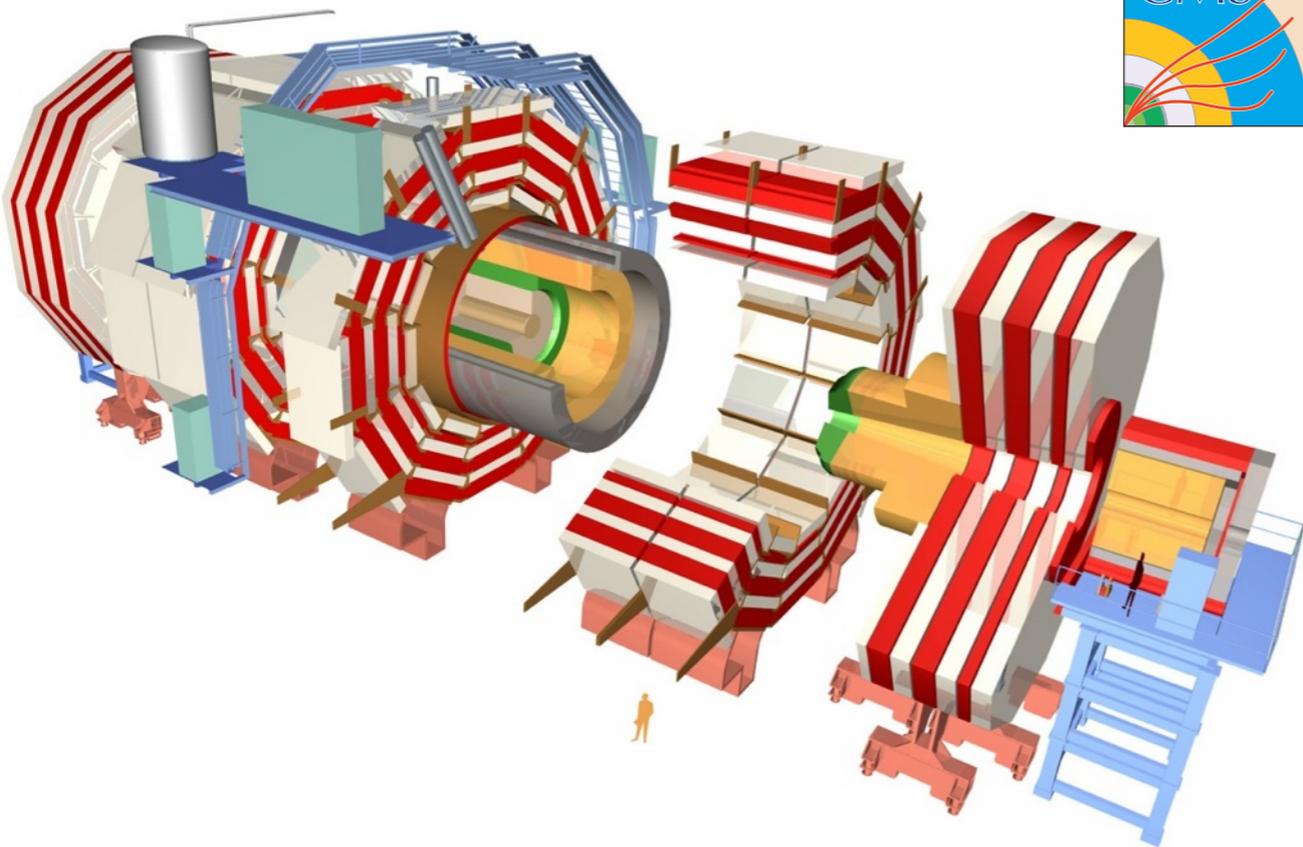
ATLAS
EXPERIMENT



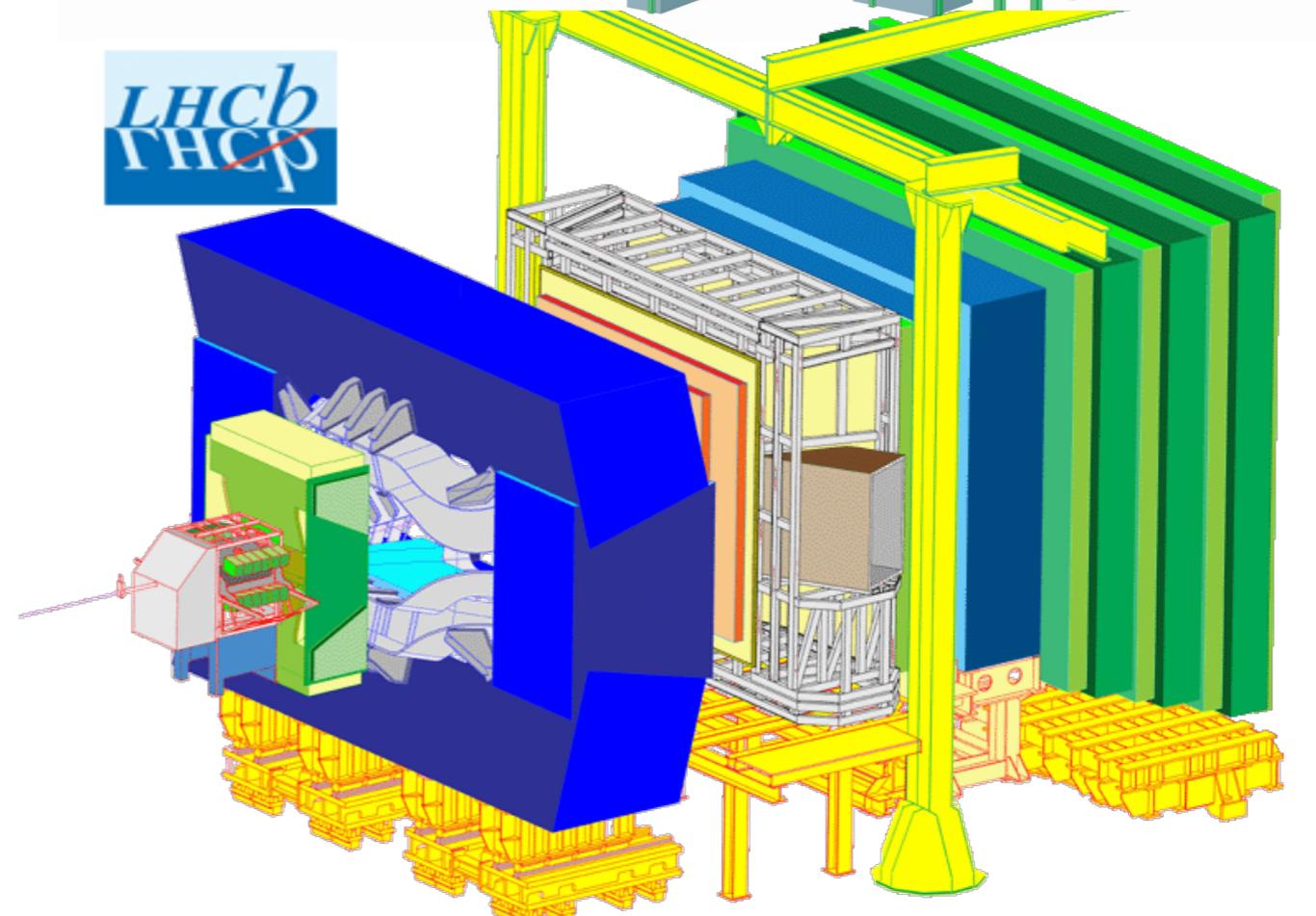

ALICE



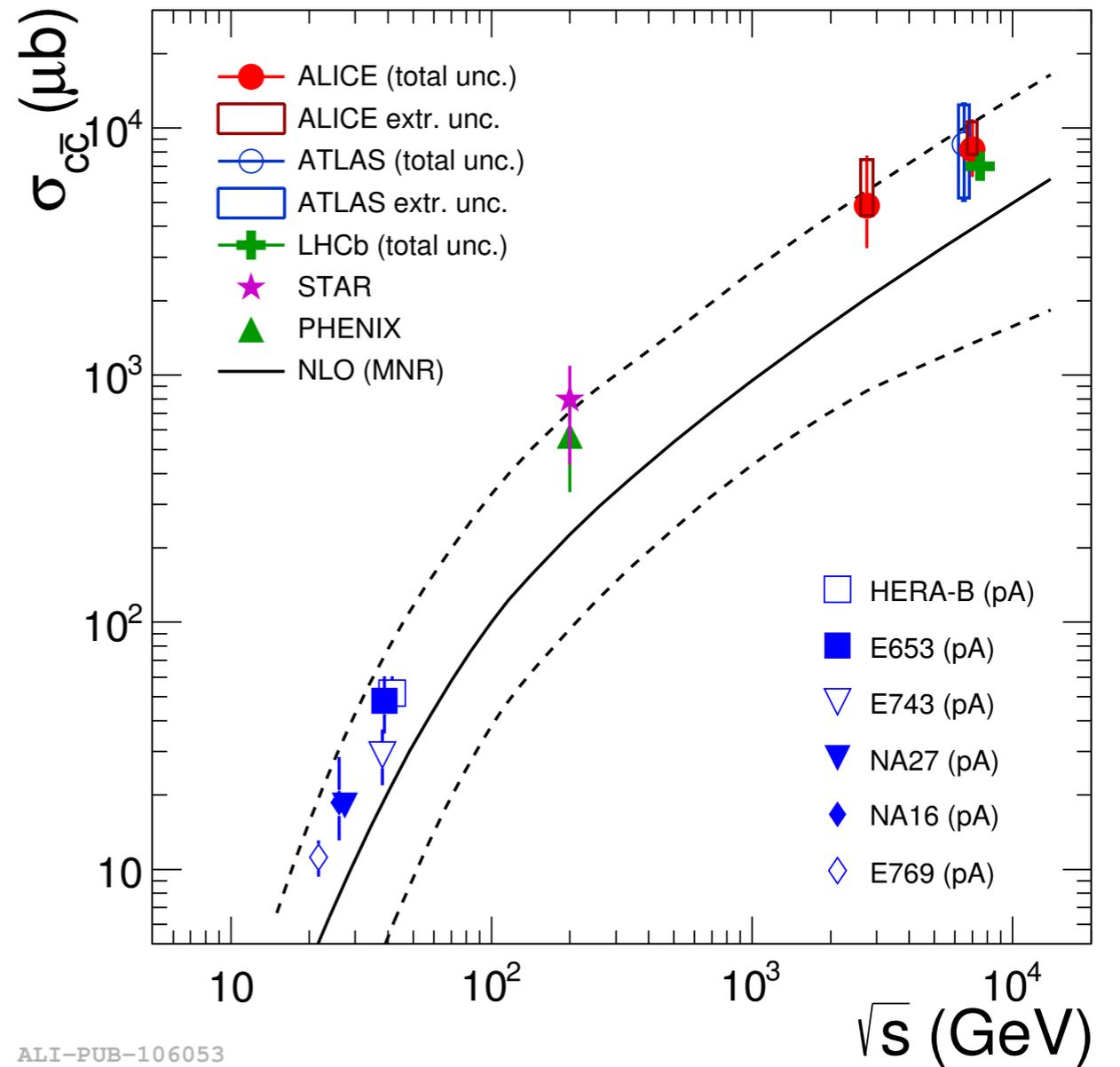
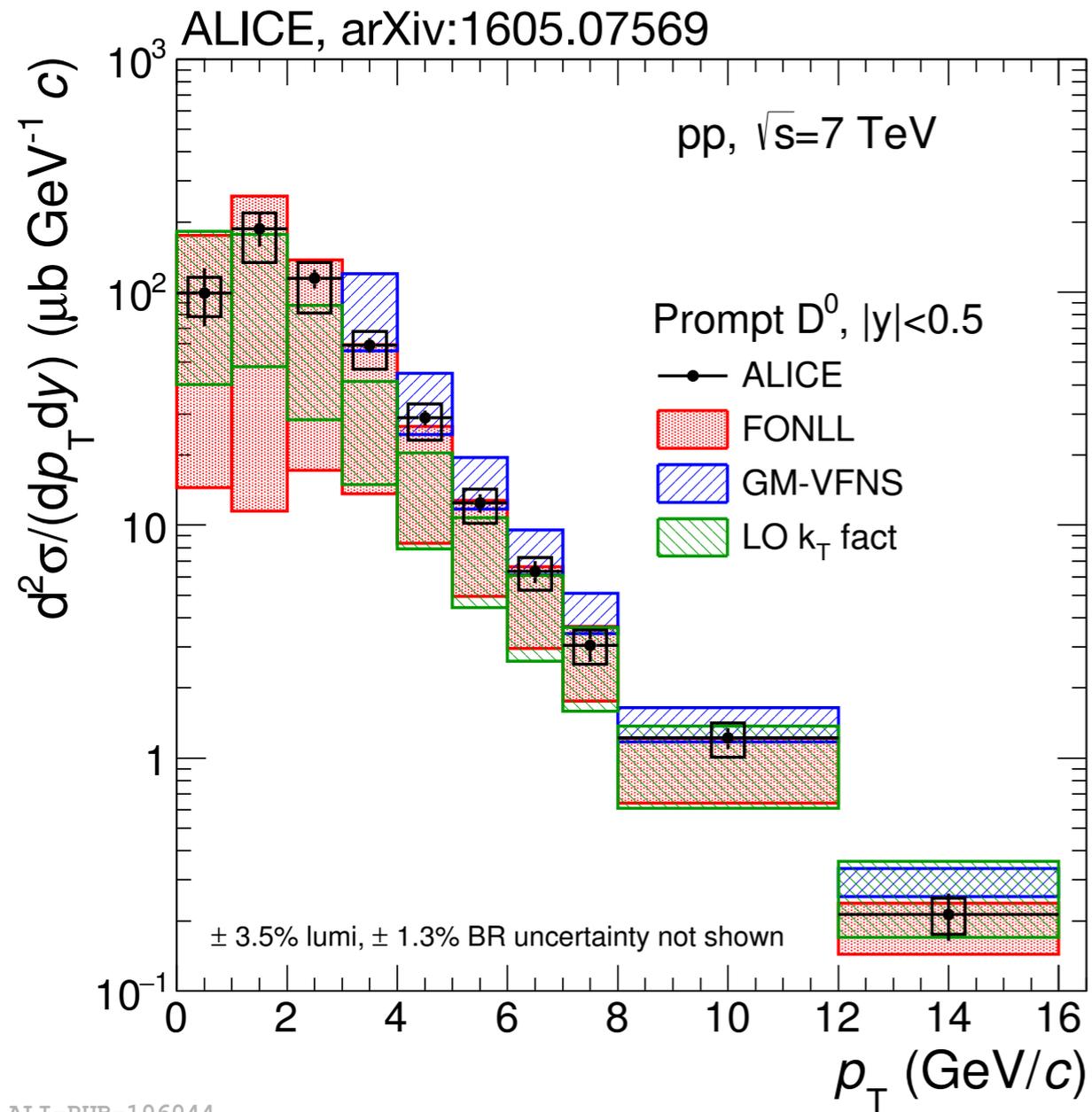
CMS



LHCb
ГHCР



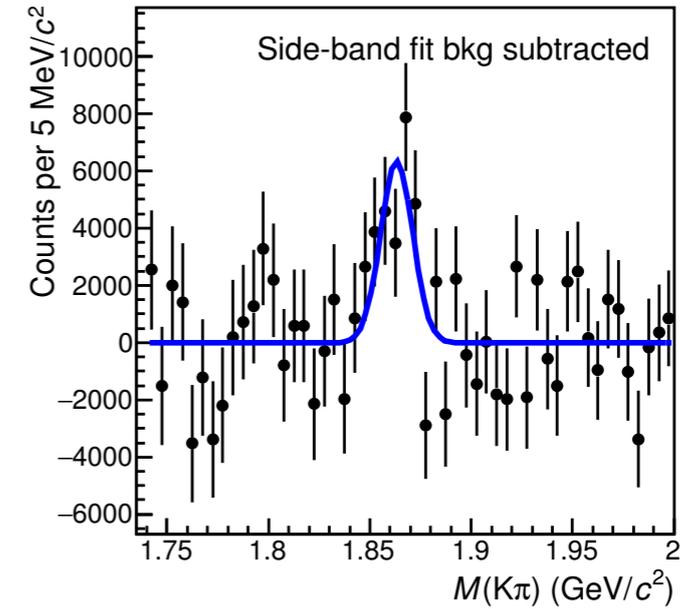
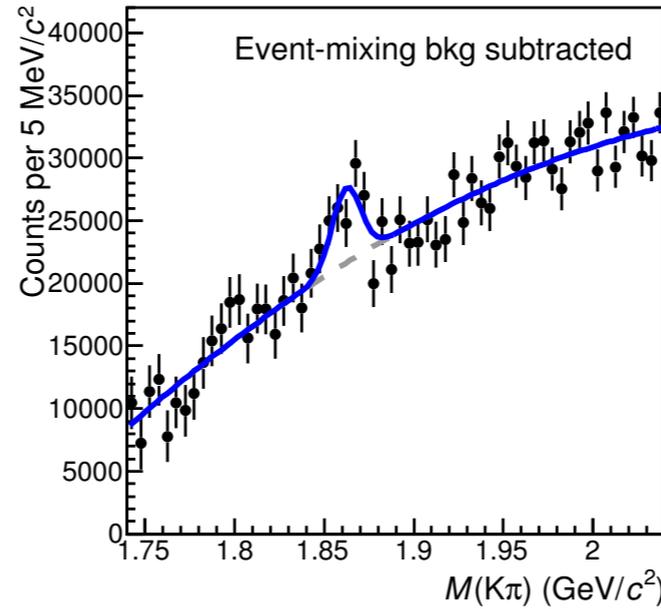
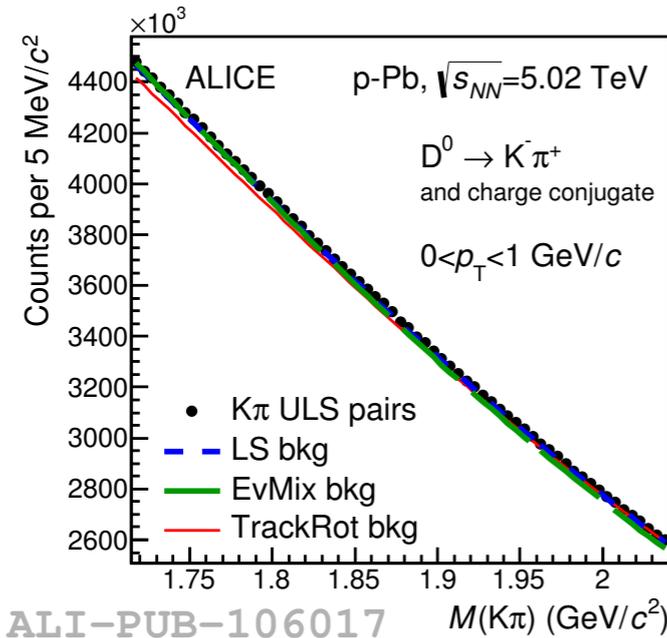
The reference: D in pp



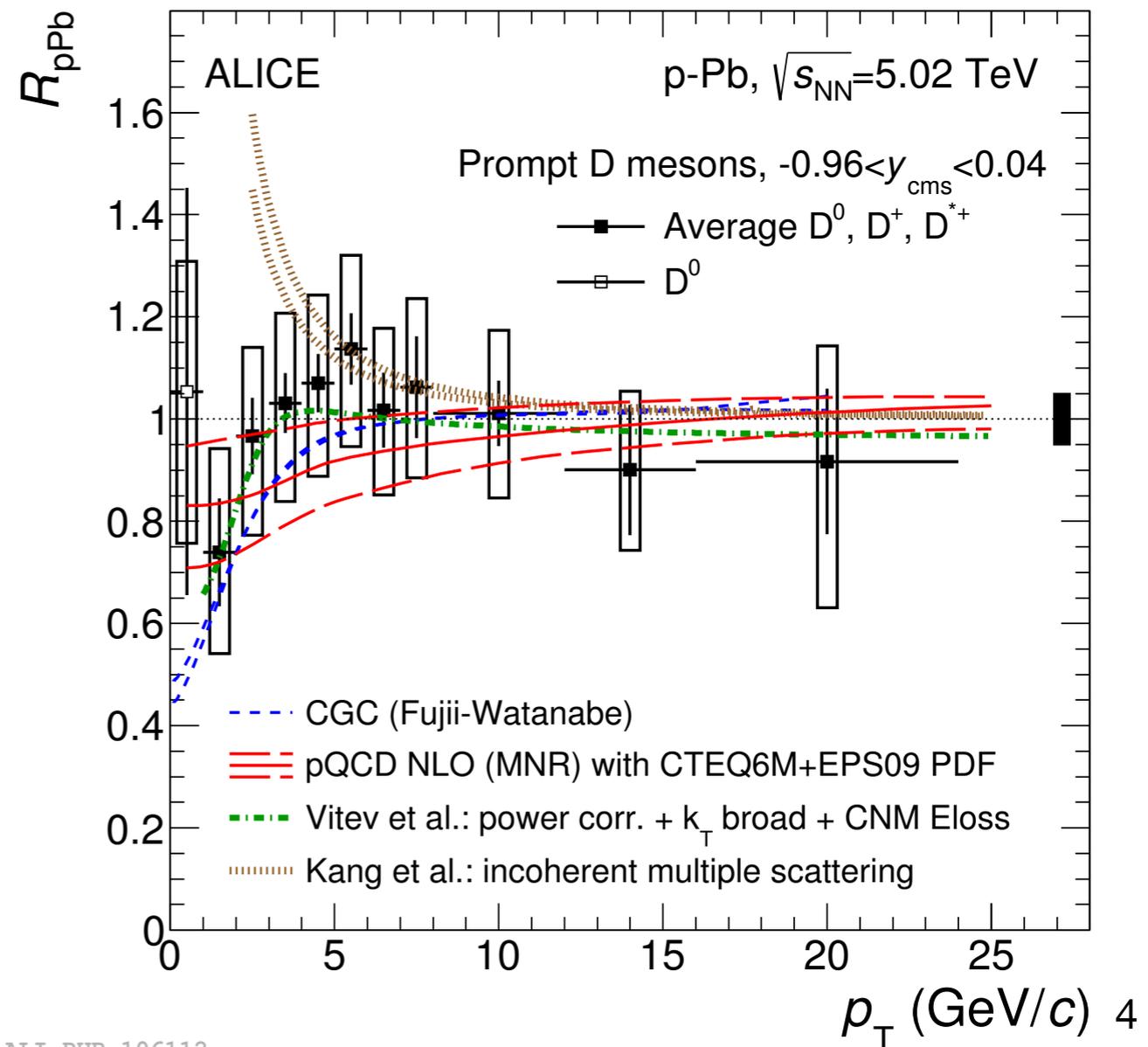
- D^0 measured to $p_T=0$
- Any hope for the theory uncertainties to decrease in the future?

D in p-Pb

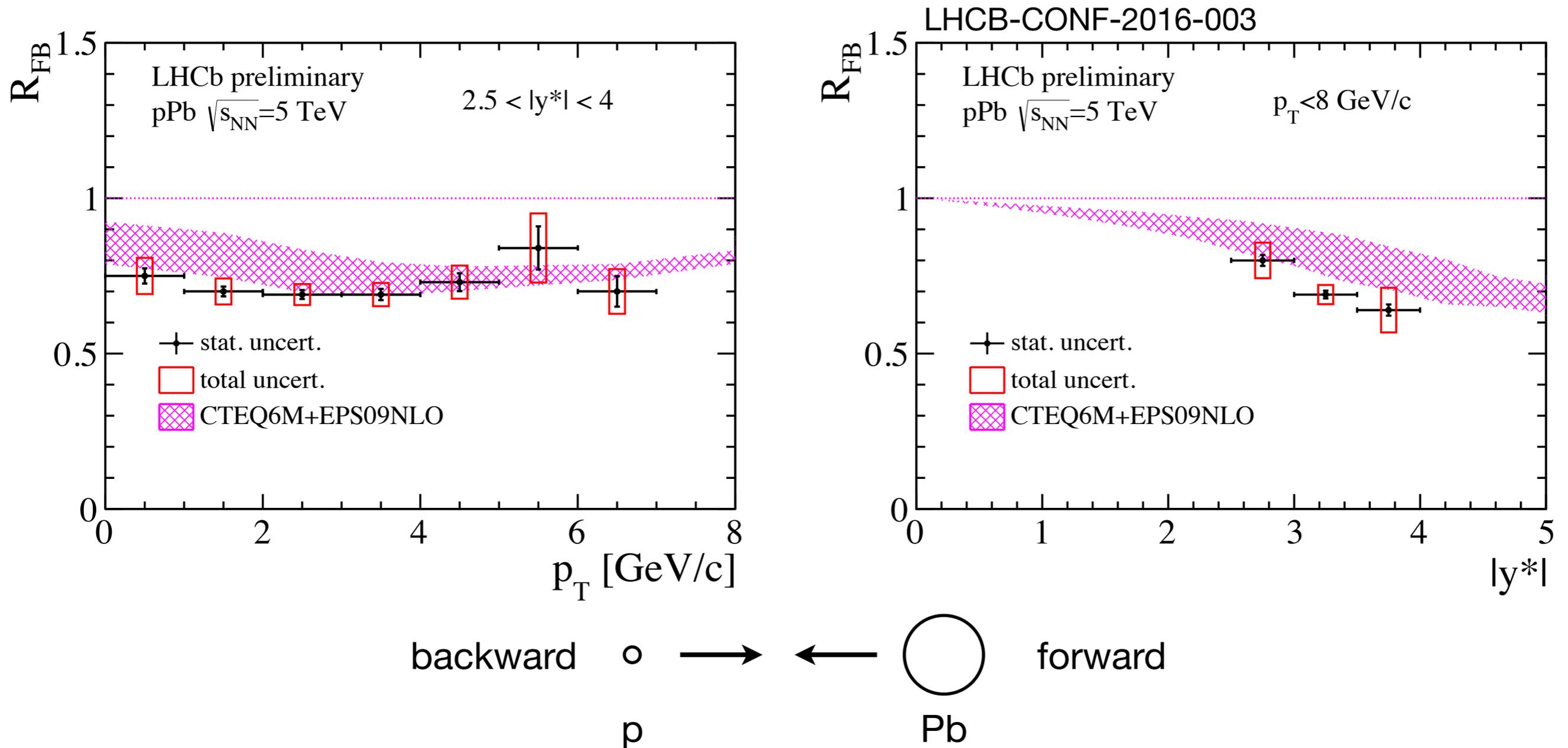
ALICE, arXiv:1605.07569



- D^0 to $p_T=0$ also in p-Pb
- Binary scaling of total charm cross section seems to hold in p-Pb
 - yet beware of large uncertainties
- R_{pPb} compatible with CNM models

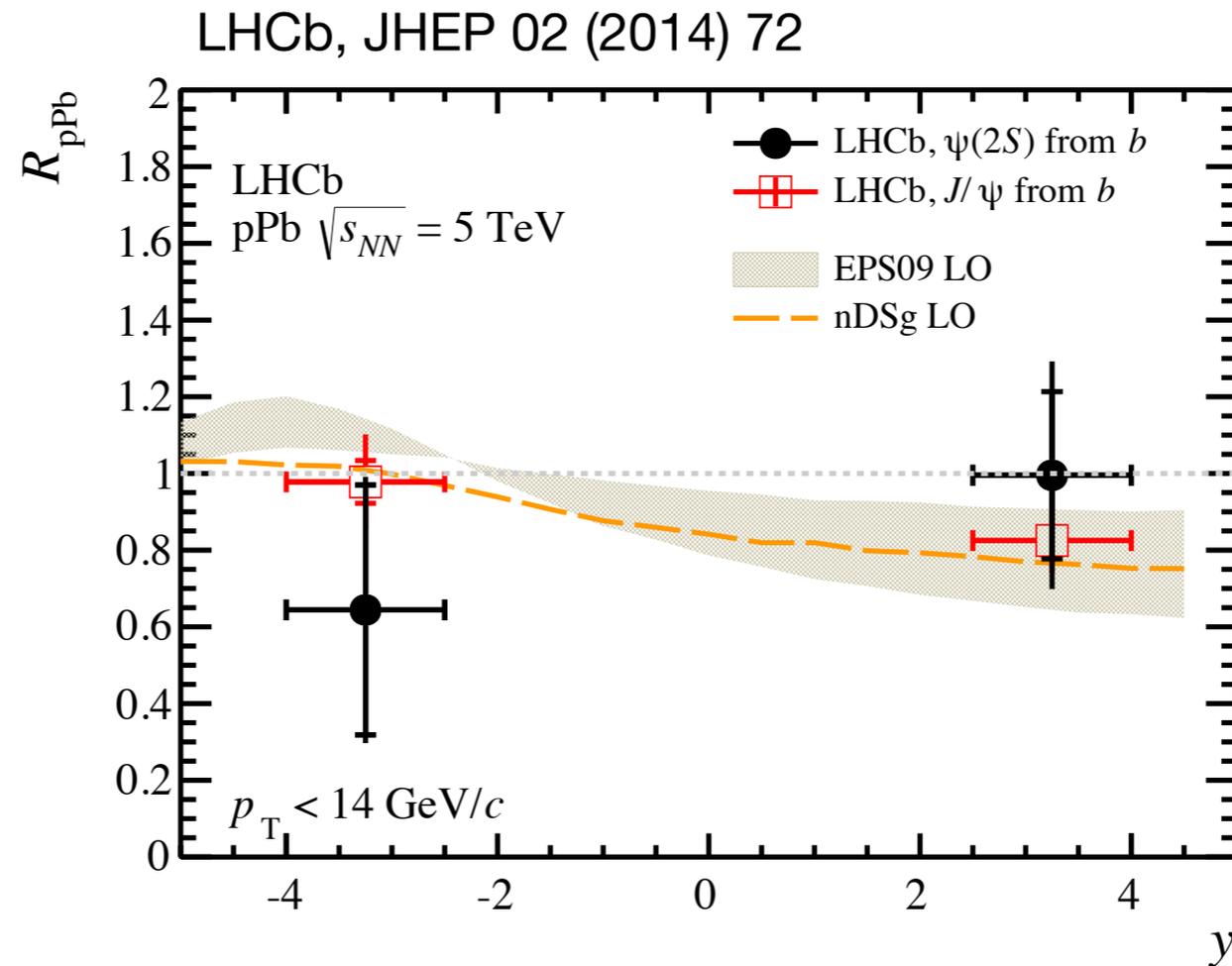


D at forward rapidity in p-Pb



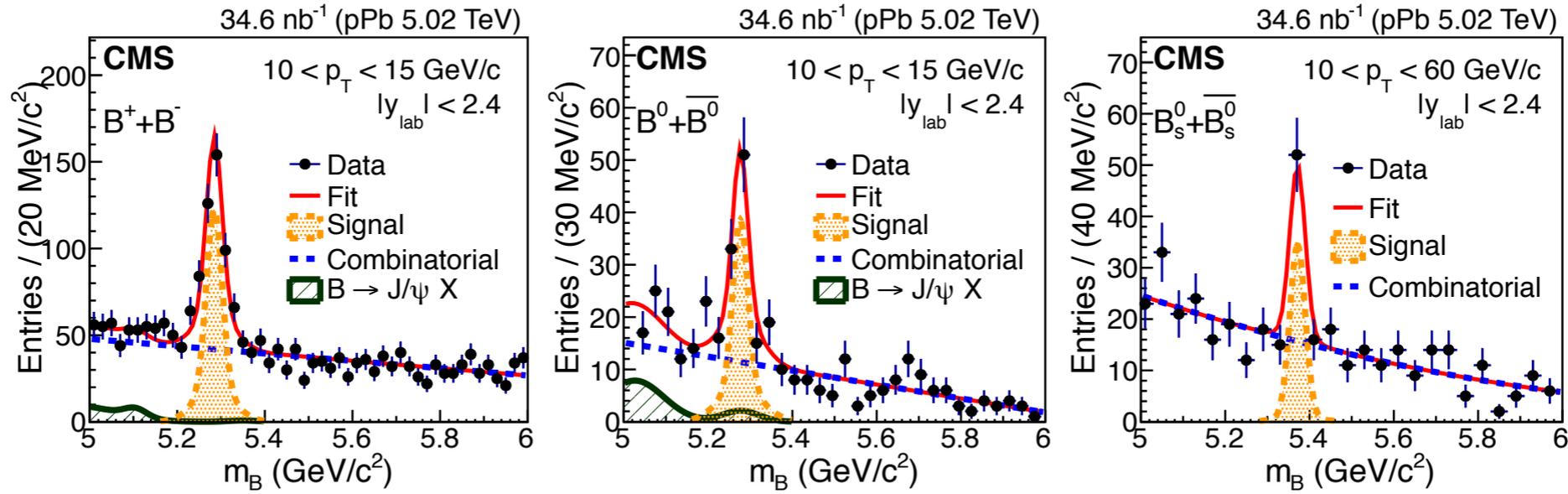
- LHCb measured sizable suppression at forward rapidity independent of p_T
- Consistent with shadowing (EPS09)

B at forward rapidity in p-Pb

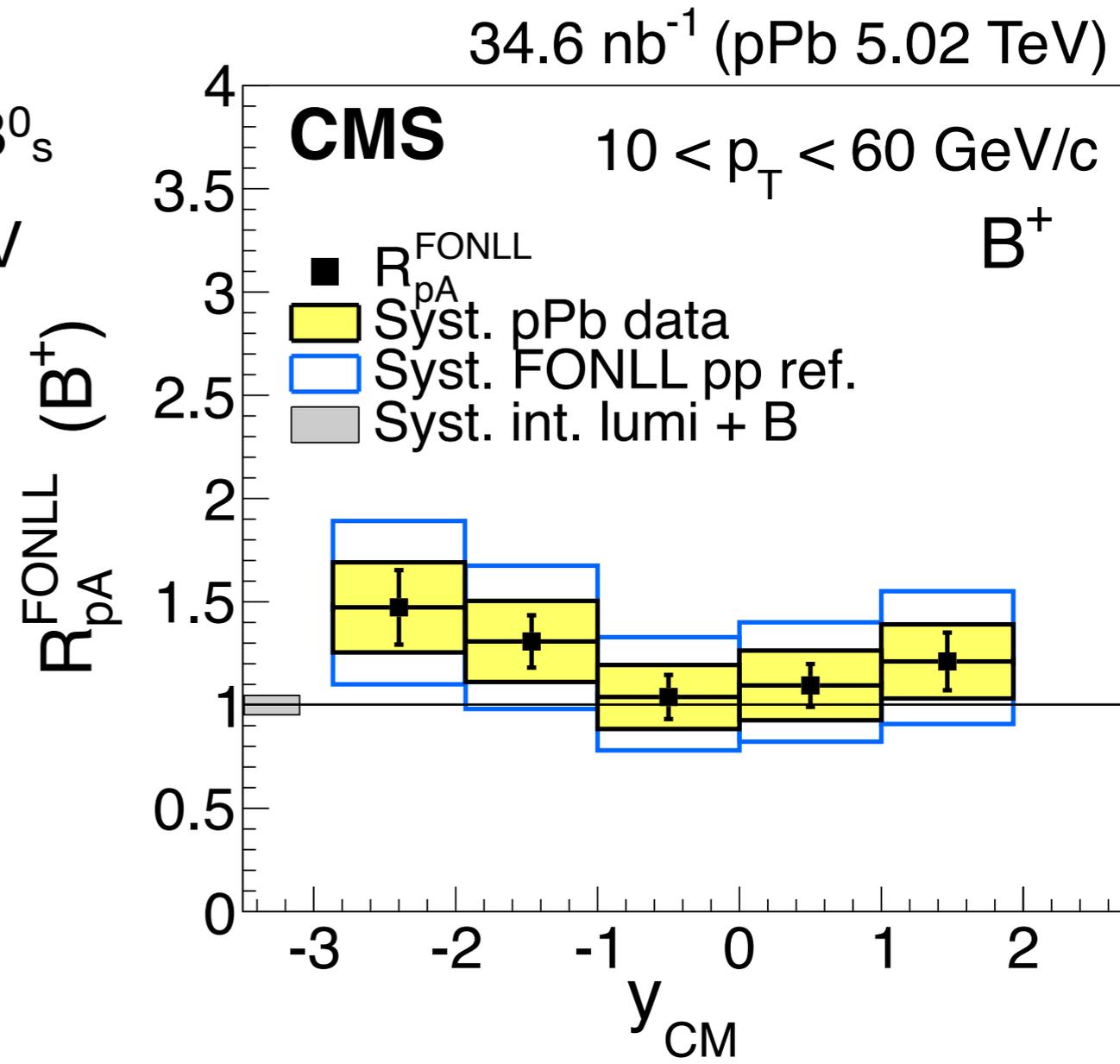


- Measured via non-prompt charmonia
- No strong modifications at forward nor backward y

High- p_T B in p-Pb

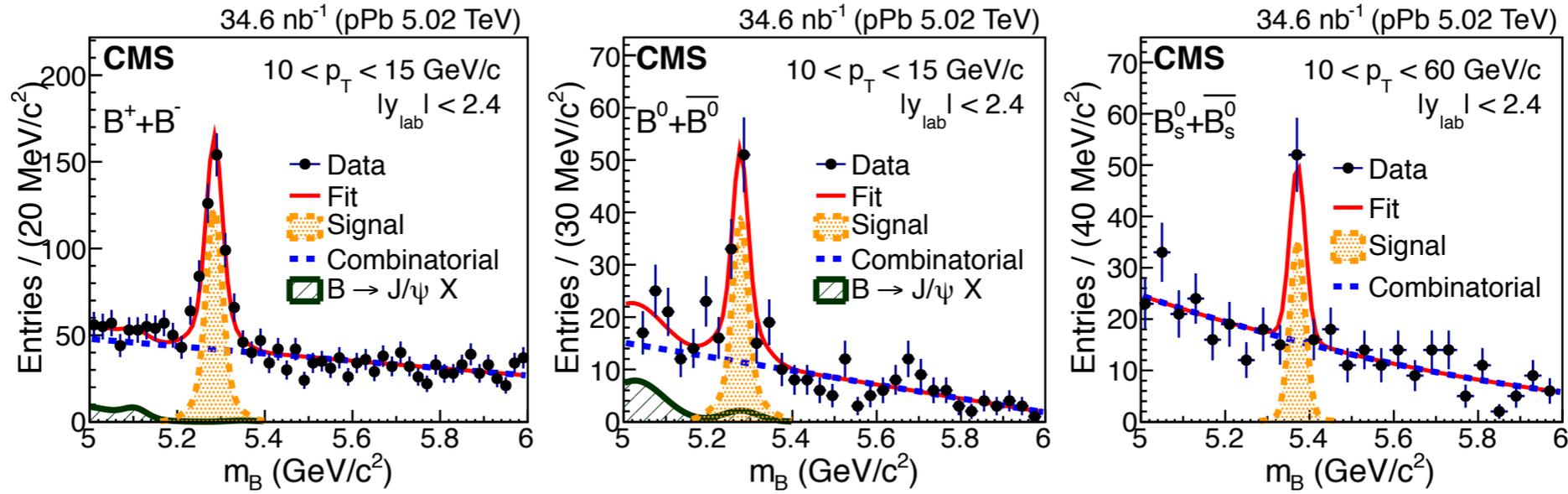


- CMS fully reconstructed B^+ , B^0 and B^0_s
- No strong CNM effects for $p_T > 10$ GeV
 - ▶ also for inclusive B via non-prompt J/ψ
 - ▶ anything happening towards low p_T ?

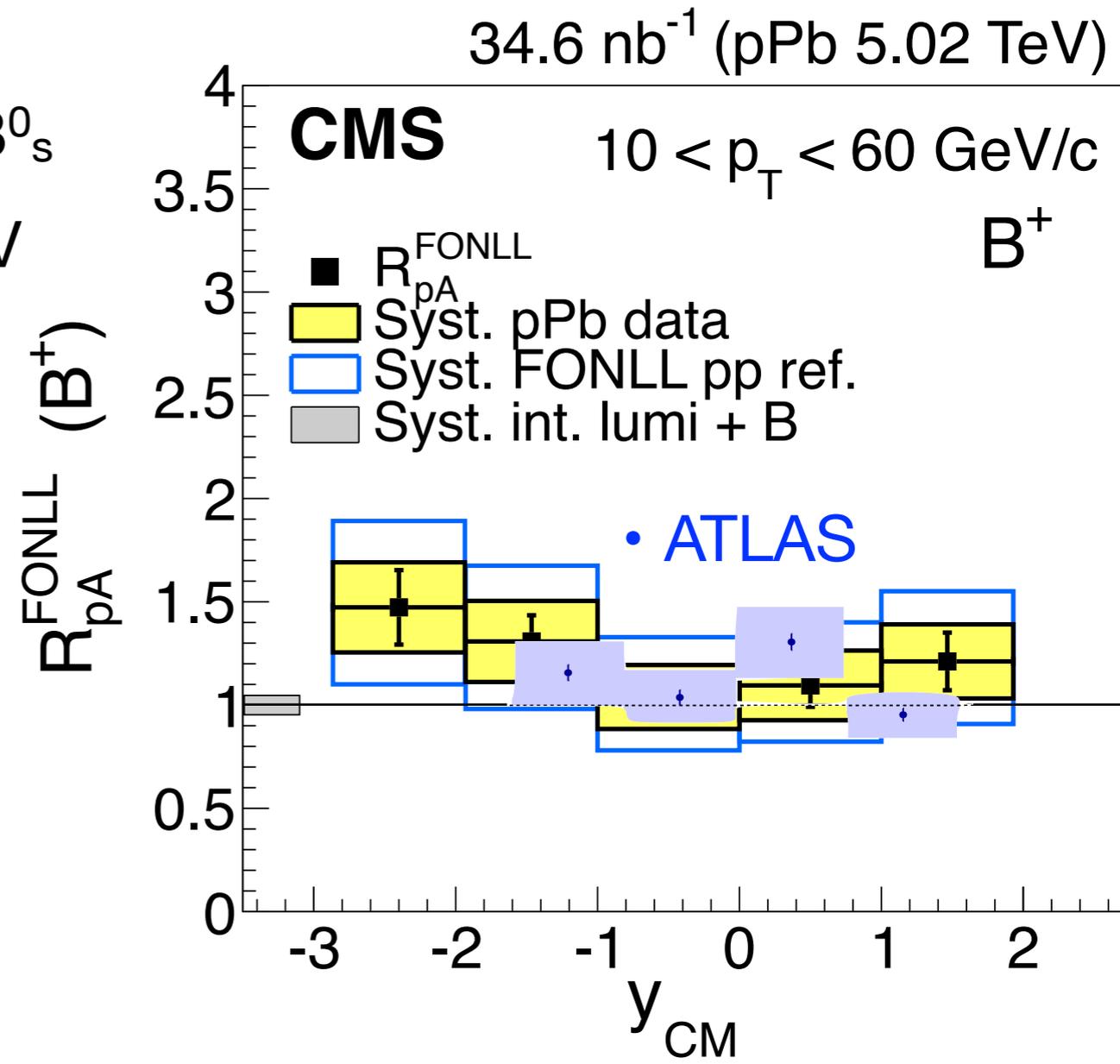


CMS, PRL 116 (2016) 032301
 CMS-PAS-HIN-14-009
 ATLAS, PRC 92 (2015) 034904

High- p_T B in p-Pb

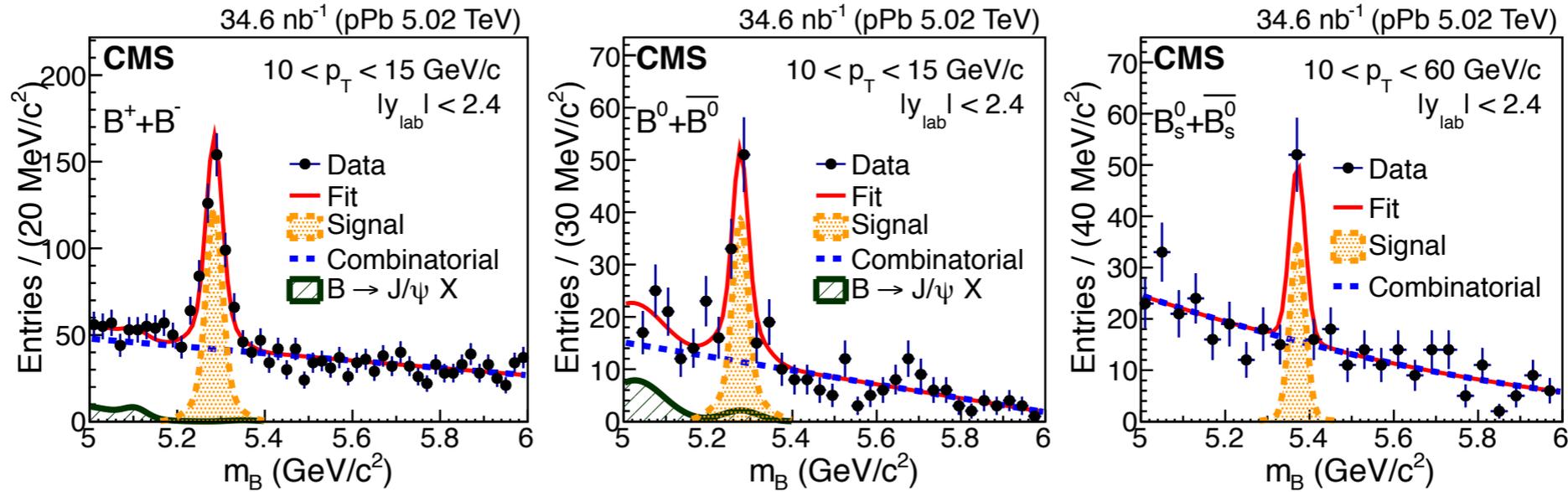


- CMS fully reconstructed B^+ , B^0 and B^0_s
- No strong CNM effects for $p_T > 10$ GeV
 - ▶ also for inclusive B via non-prompt J/ψ
 - ▶ anything happening towards low p_T ?

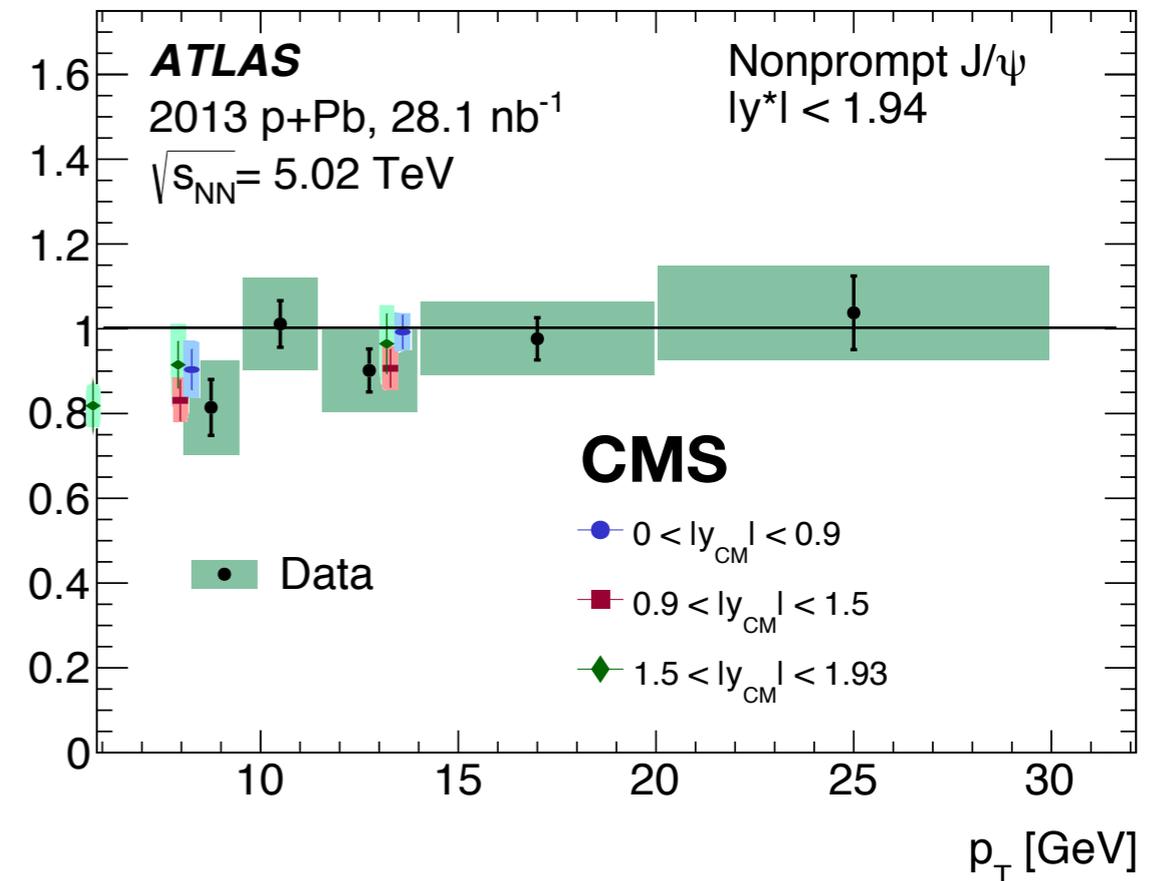


CMS, PRL 116 (2016) 032301
 CMS-PAS-HIN-14-009
 ATLAS, PRC 92 (2015) 034904

High- p_T B in p-Pb



- CMS fully reconstructed B^+ , B^0 and B_s^0
- No strong CNM effects for $p_T > 10$ GeV R_{FB}
 - ▶ also for inclusive B via non-prompt J/ψ
 - ▶ anything happening towards low p_T ?

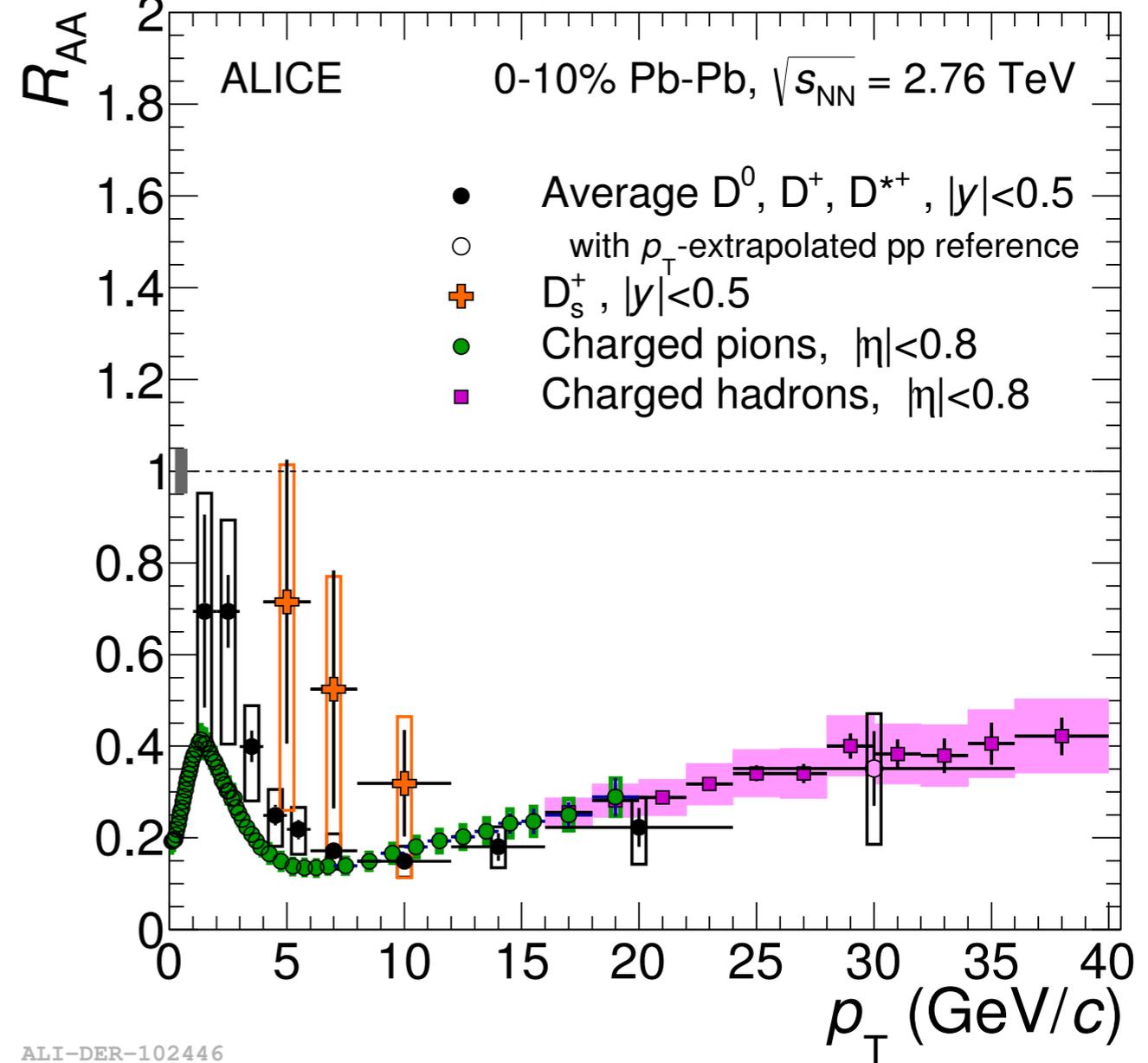
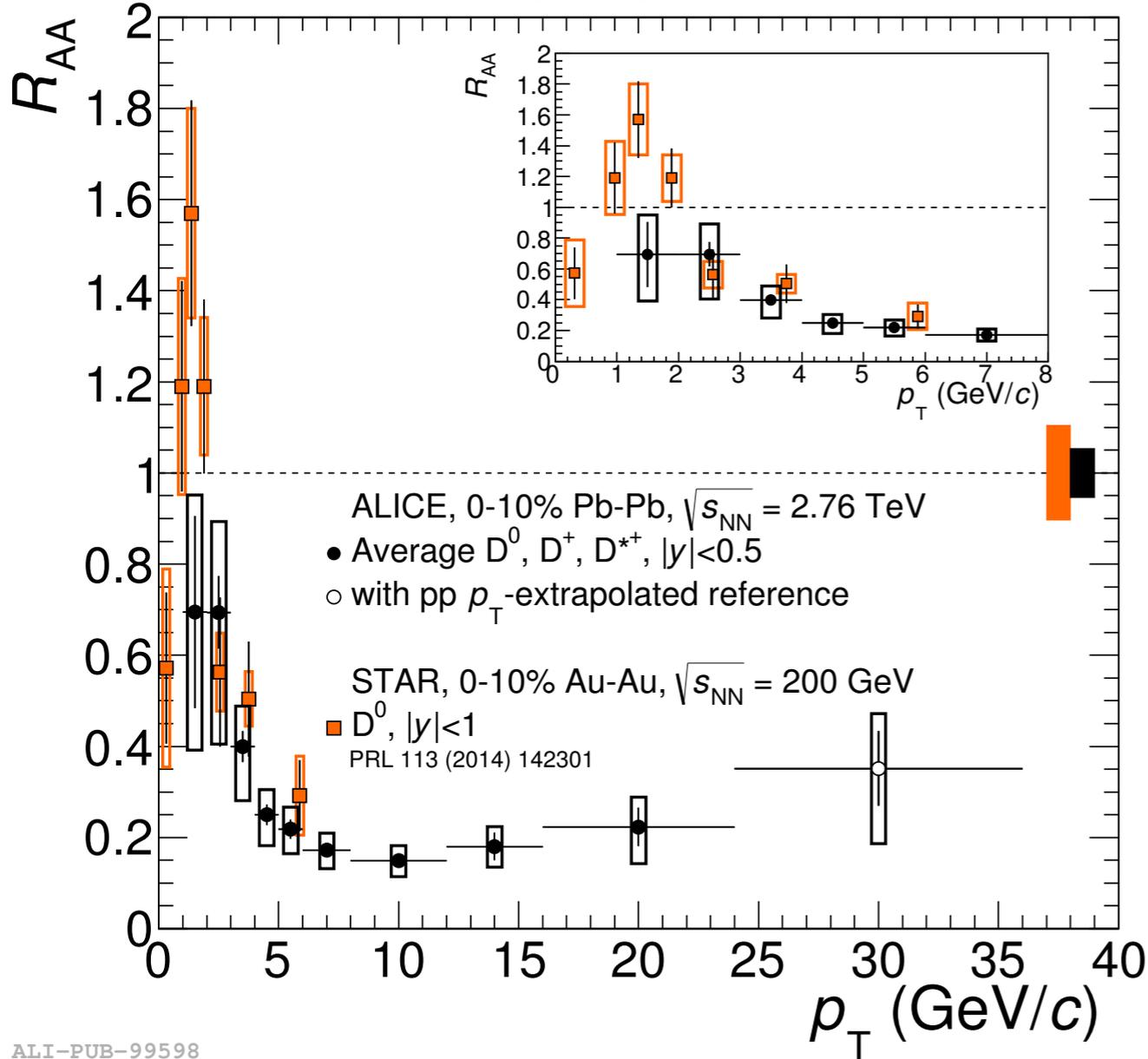


CMS, PRL 116 (2016) 032301
 CMS-PAS-HIN-14-009
 ATLAS, PRC 92 (2015) 034904

D R_{AA} in Pb-Pb

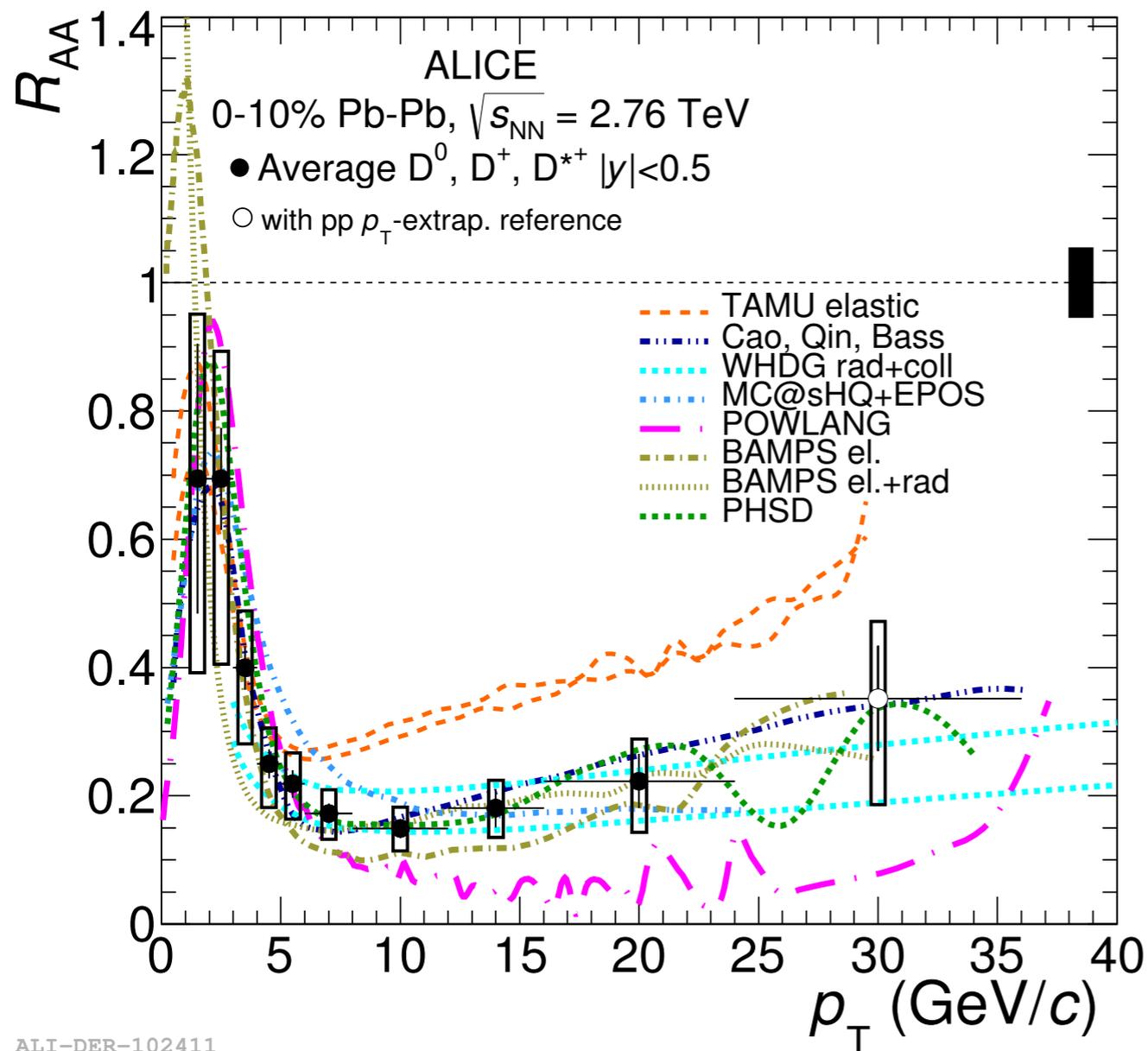
ALICE, JHEP 03 (2016) 081

ALICE, JHEP 03 (2016) 082

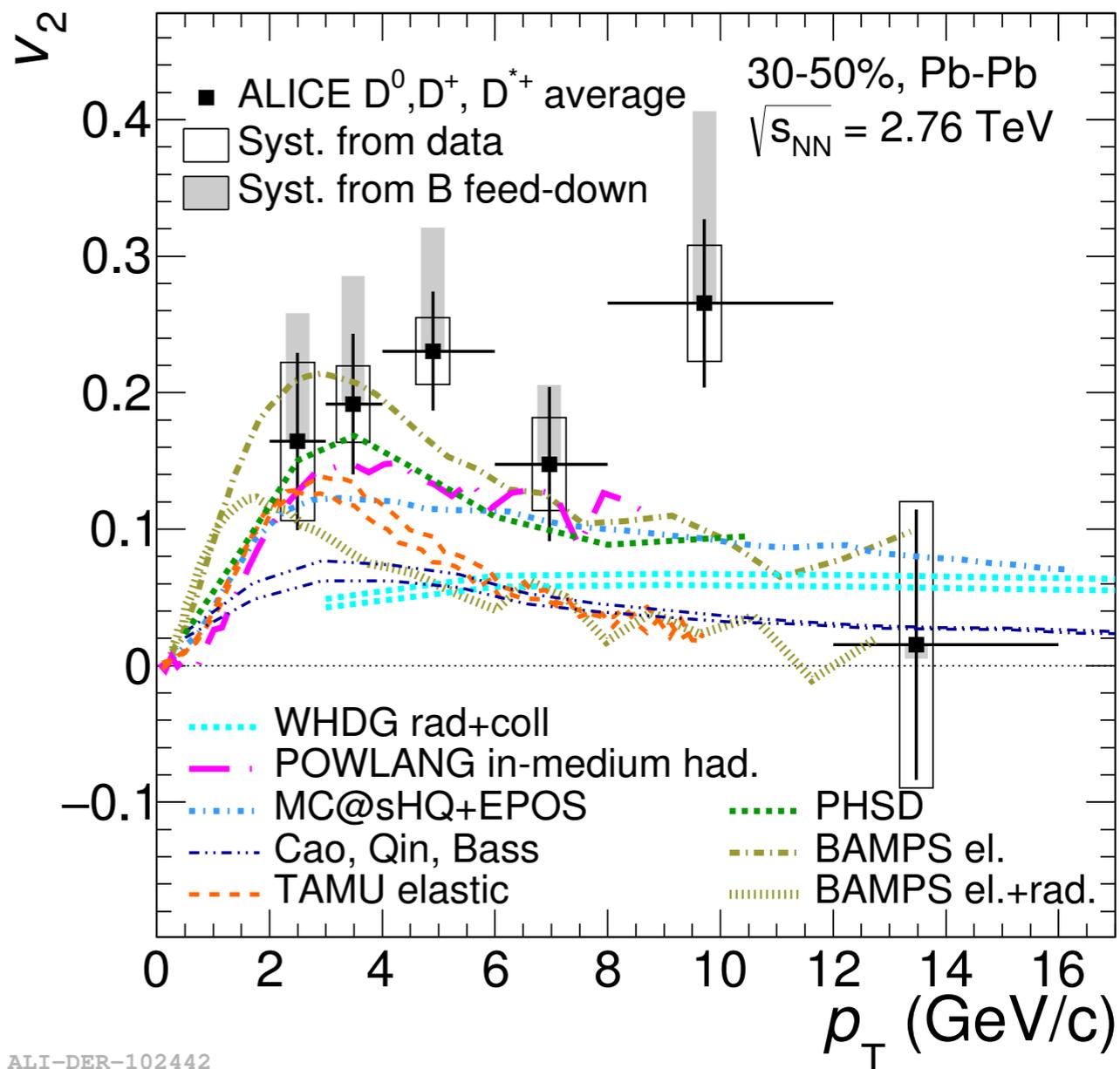


- At RHIC: $R_{AA} > 1$ at low p_T a sign of radial flow, what about LHC?
- Mass ordering at low p_T (as expected for QGP energy loss)
- Indication of less suppression for D_s (canonical suppression of s in pp)
- Heavy and light flavor exhibit same suppression at high p_T

D R_{AA} vs. v_2



ALI-DER-102411



ALI-DER-102442

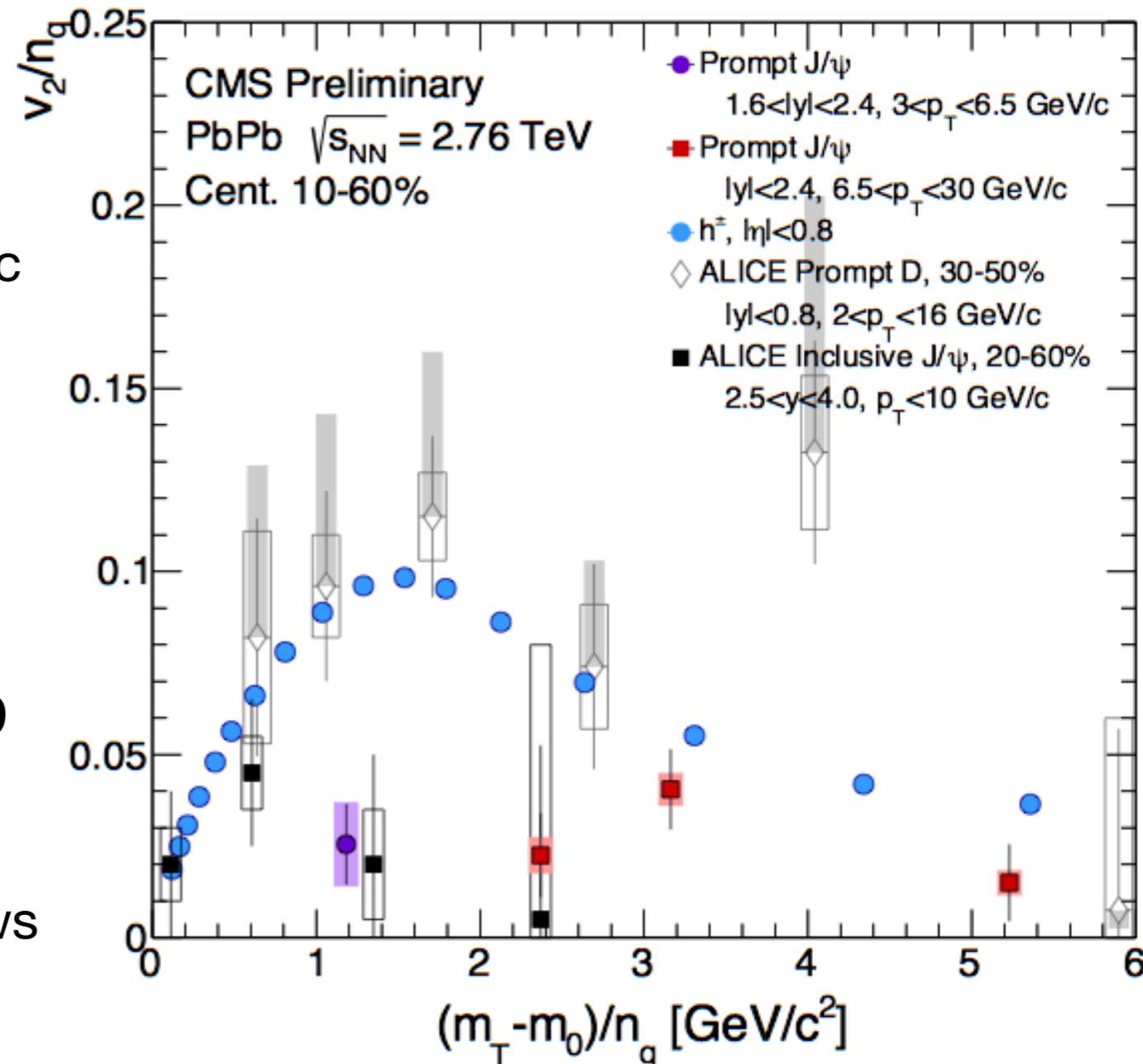
- Collisional energy loss models produce a lot of v_2 but overestimate R_{AA}
- Adding radiational energy loss helps for R_{AA} but underestimates v_2

ALICE, PRC 90 (2014) 034904

ALICE, JHEP 03 (2016) 081

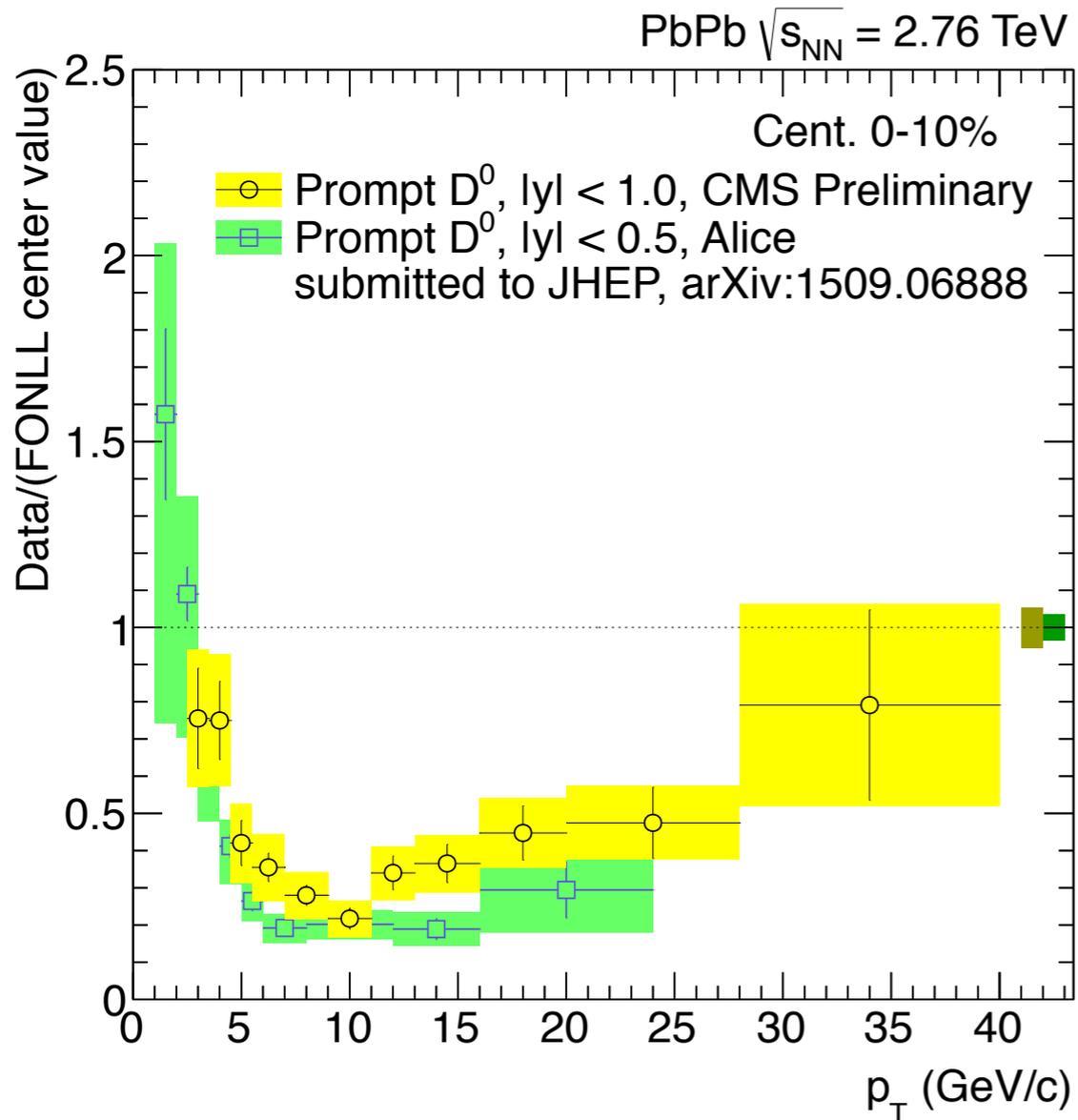
J/ψ & D v_2 scaling?

- ALICE found “hint of v_2 ”
 - ▶ as expected for recombination
- CMS measured significant v_2
 - ▶ though only above 6.5 GeV/c
 - ▶ measurement also for $3 < p_T < 6.5$ GeV/c
 - ▶ high- p_T $v_2 \rightarrow$ path-length dependent suppression
- Taking all results together
 - ▶ J/ψ has non-zero v_2
- Comparison to light hadrons and D
- What about the n_q scaling?
 - ▶ approximate scaling for D (charm flows as much as the light quark?)
 - ▶ no such scaling for J/ψ above 1 GeV
 - ▶ I am completely ignoring uncertainties ☺

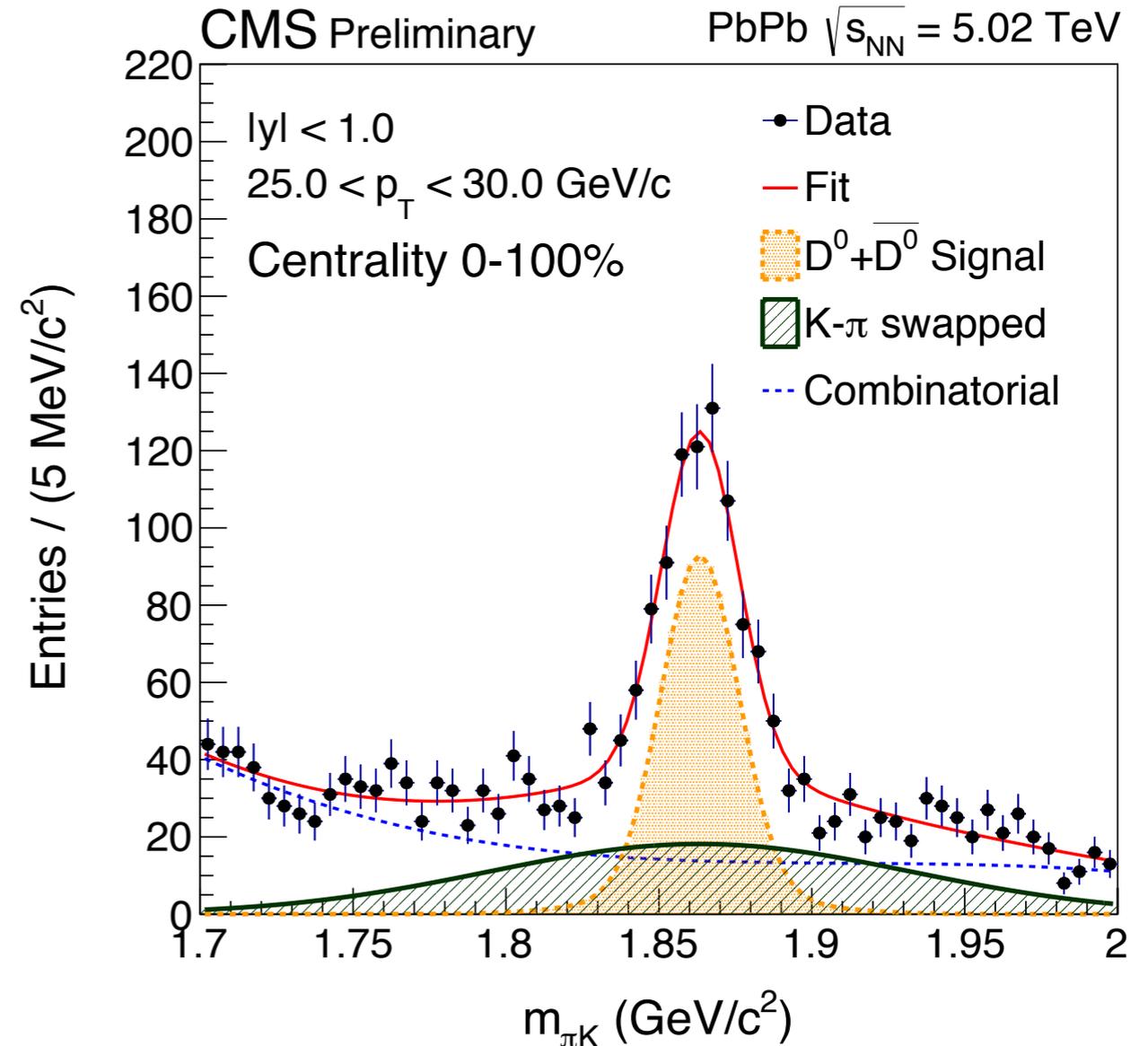


“High- p_T ” $D R_{AA}$

CMS-PAS-HIN-15-005



CMS-PAS-HIN-16-001

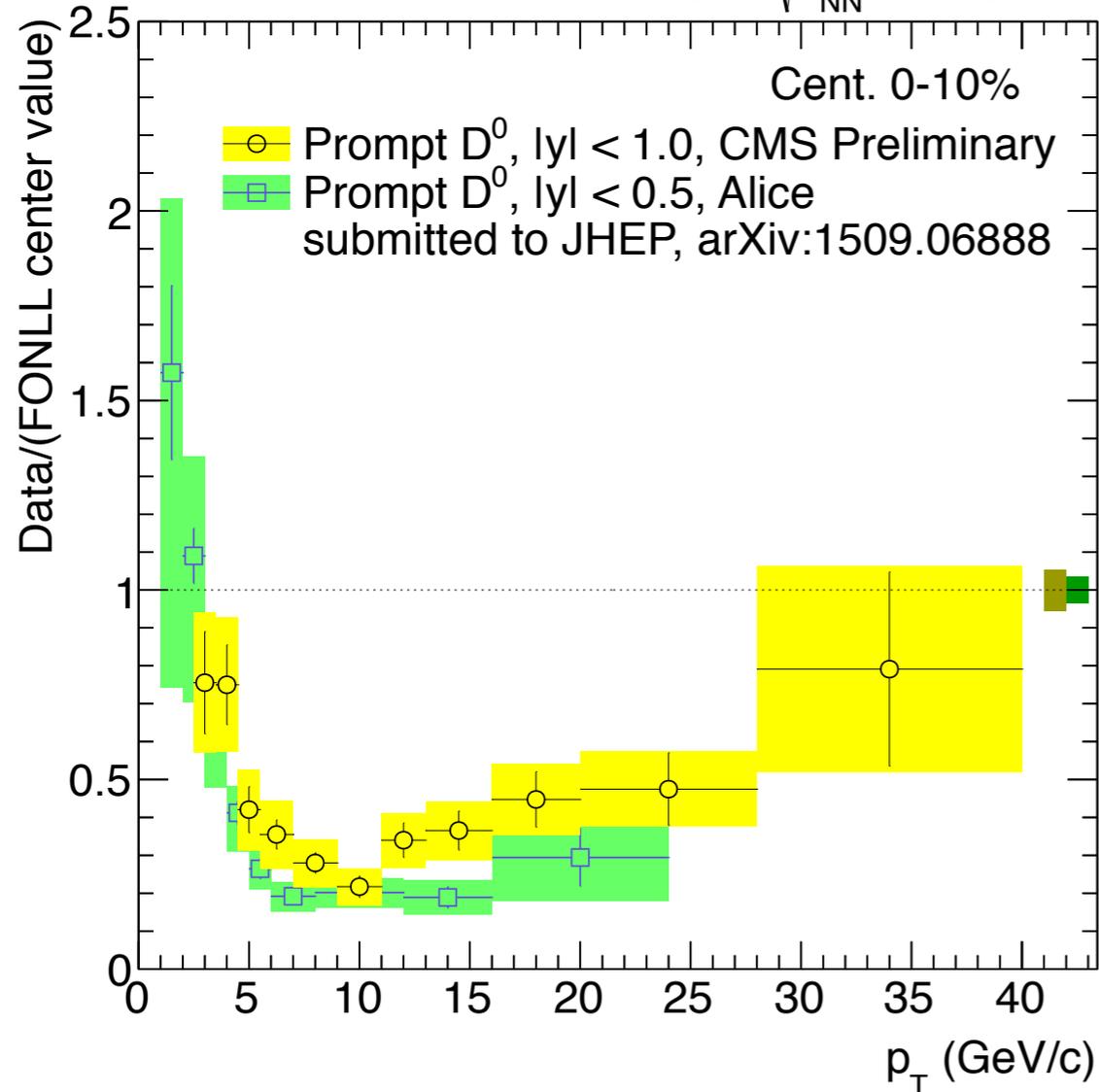


- CMS reconstructed D mesons down to $p_T=2.5$ GeV
 - slight discrepancy with ALICE in Pb-Pb at 2.76 TeV when using the same reference
- Run-II: D^0 trigger with online reconstruction in the HLT
 - extending measurement to 2 to 100 GeV

“High- p_T ” $D R_{AA}$

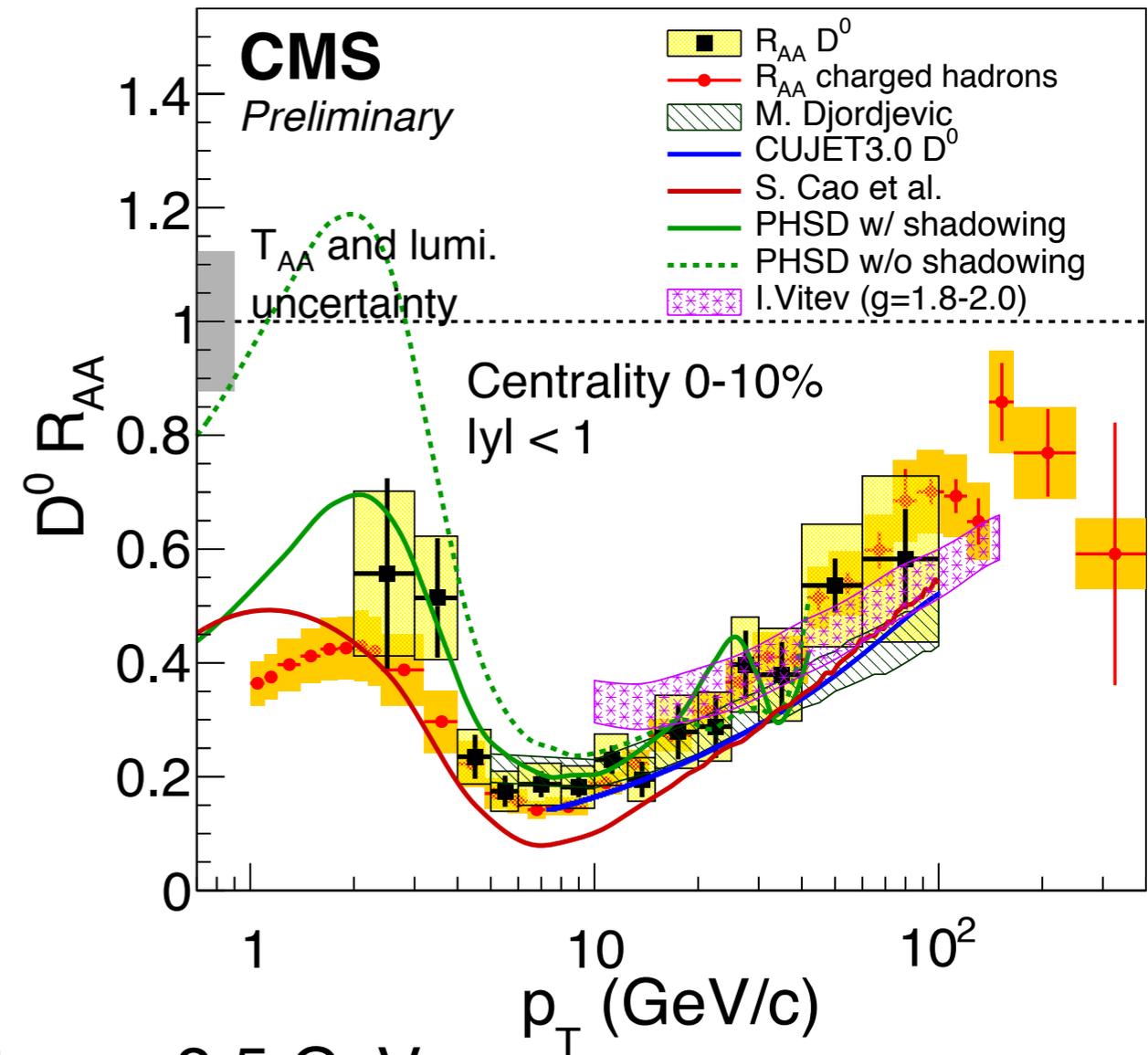
CMS-PAS-HIN-15-005

PbPb $\sqrt{s_{NN}} = 2.76$ TeV



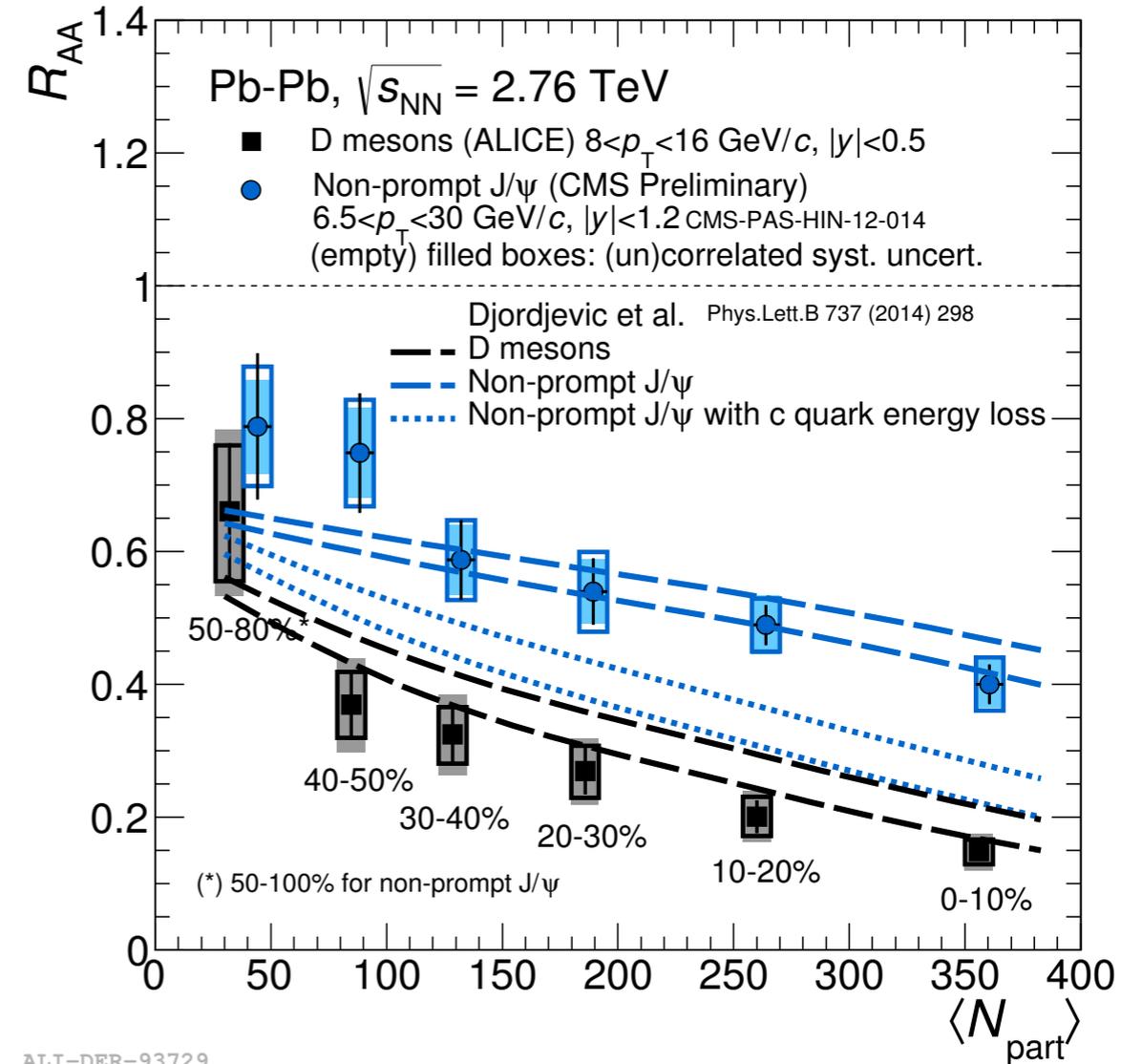
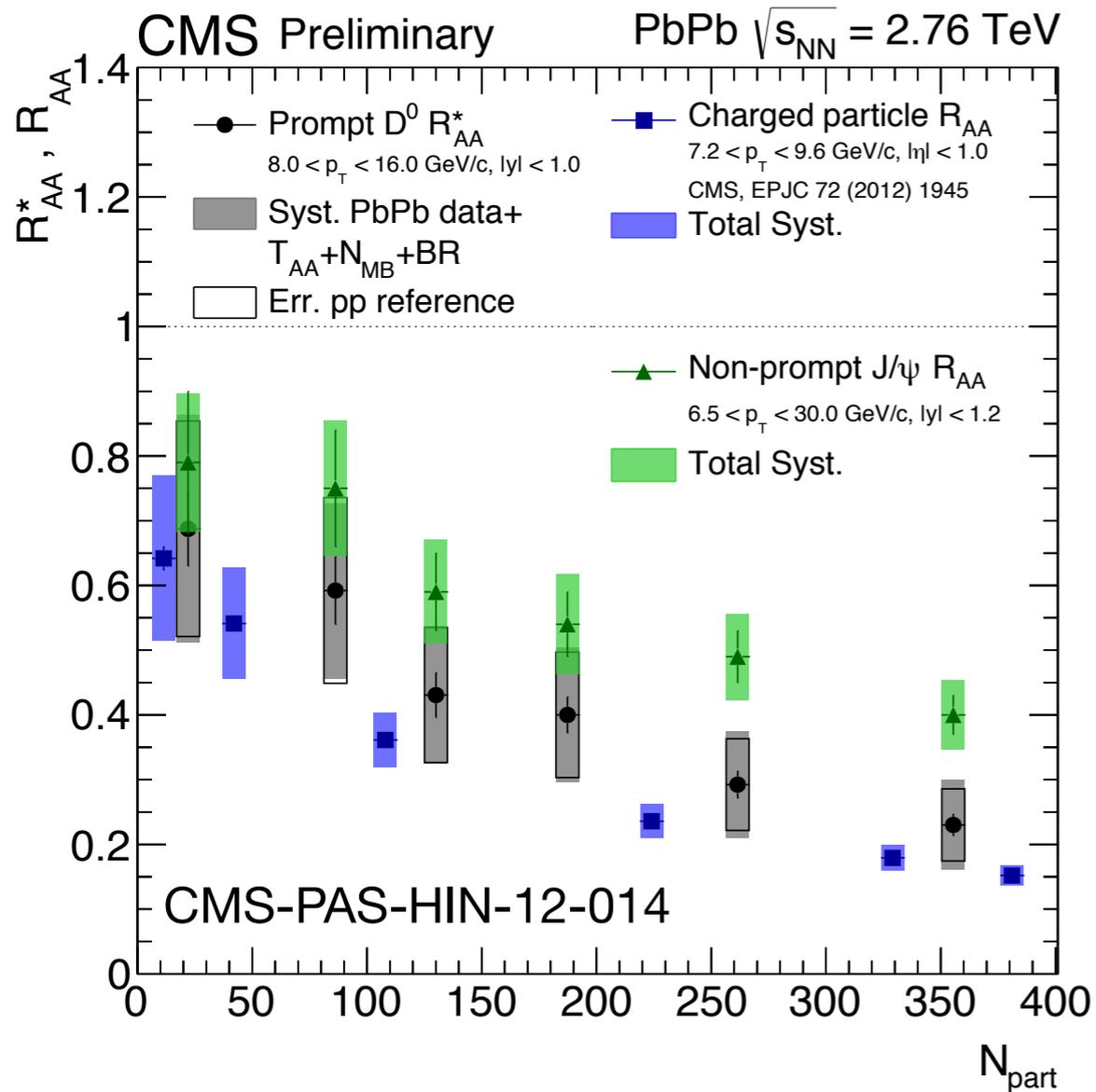
CMS-PAS-HIN-16-001

25.8 pb⁻¹ (5.02 TeV pp) + 404 μ b⁻¹ (5.02 TeV PbPb)



- CMS reconstructed D mesons down to $p_T=2.5$ GeV
 - slight discrepancy with ALICE in Pb-Pb at 2.76 TeV when using the same reference
- Run-II: D^0 trigger with online reconstruction in the HLT
 - extending measurement to 2 to 100 GeV

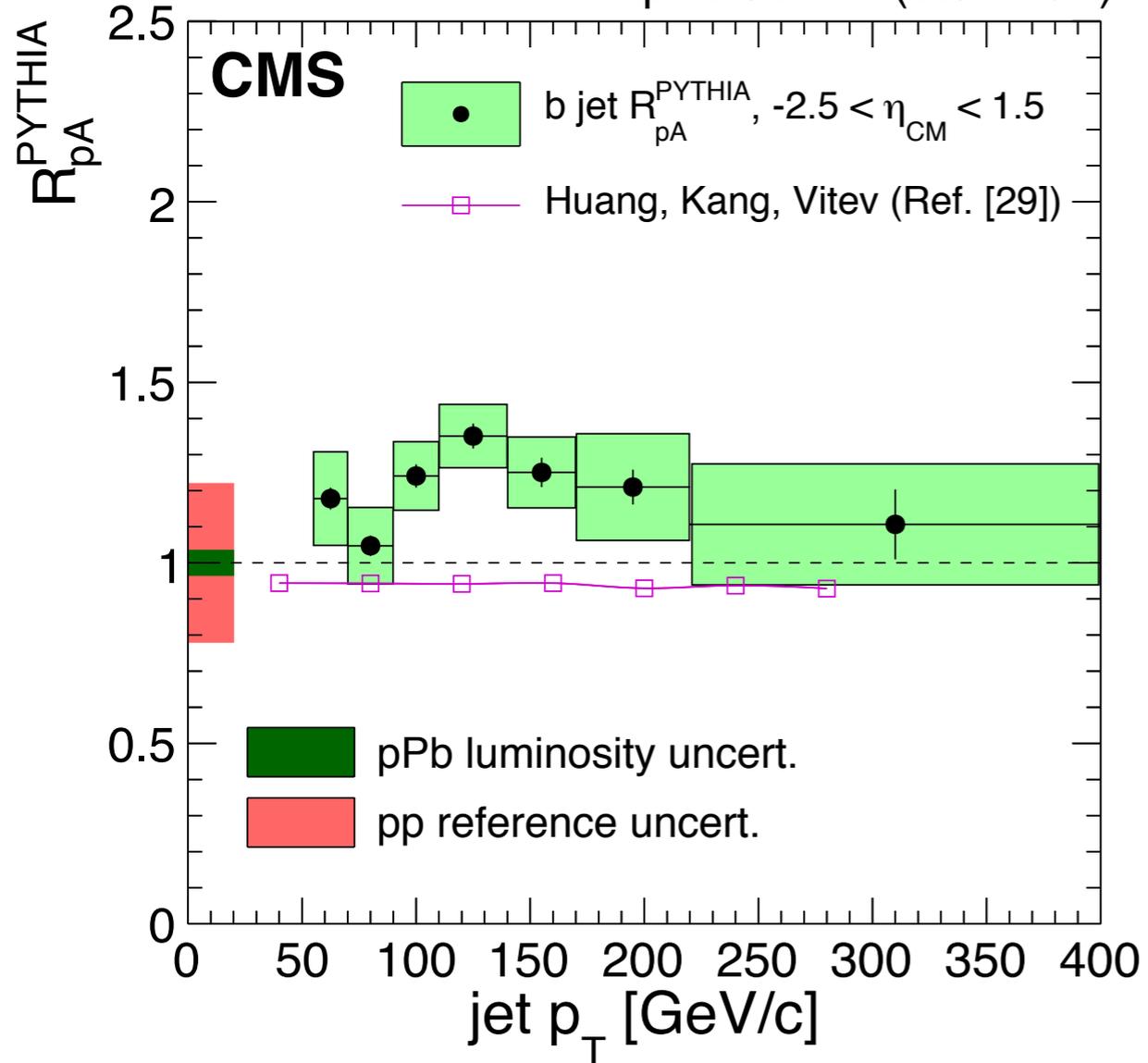
B R_{AA}



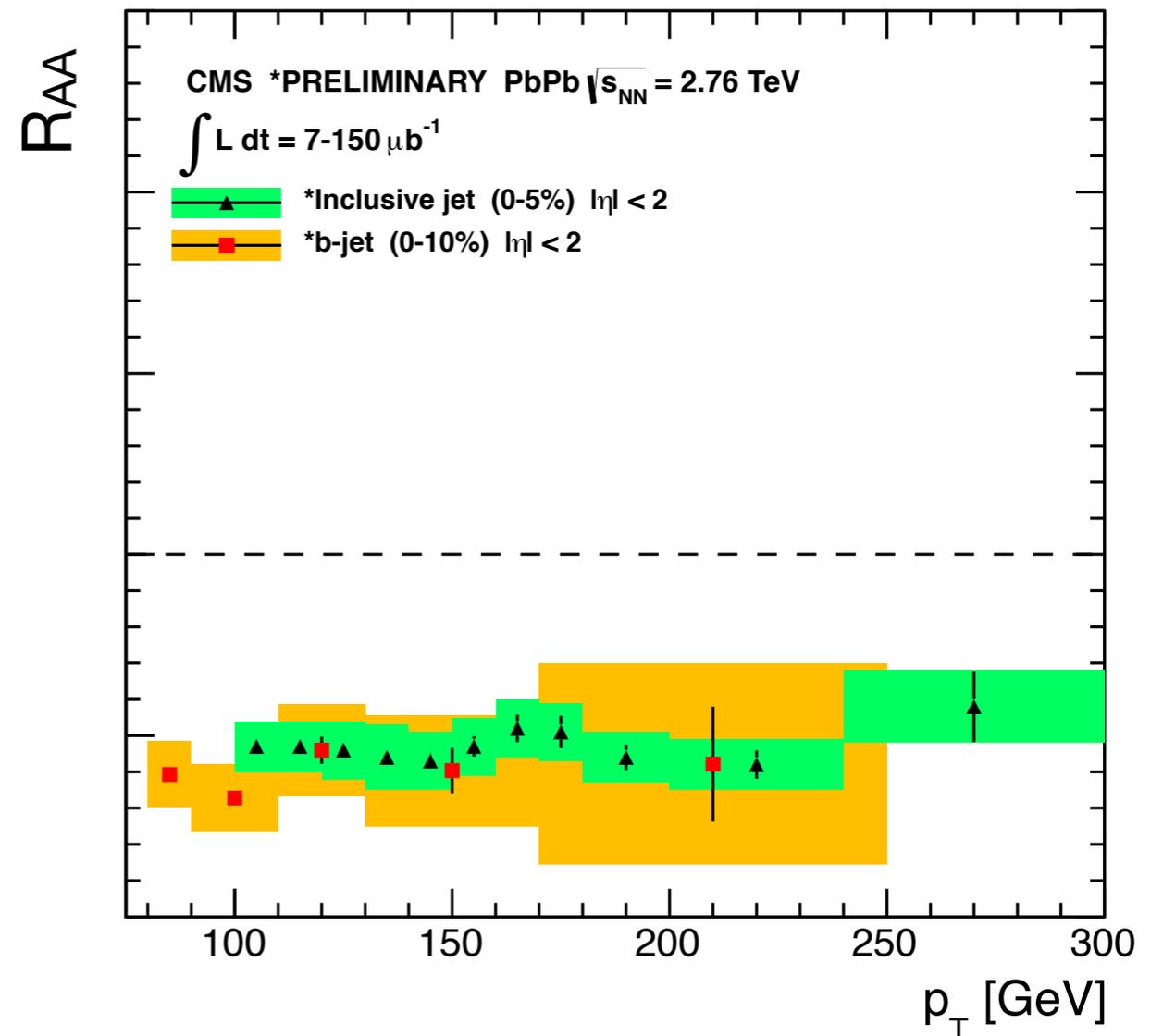
- Clear mass ordering for $p_T > 7$ GeV
- Difference between D and B well explained by quark mass dependence of energy loss

HF Jets in p-Pb and Pb-Pb

CMS, PLB 754 (2016) 59 pPb 35 nb⁻¹ (5.02 TeV)

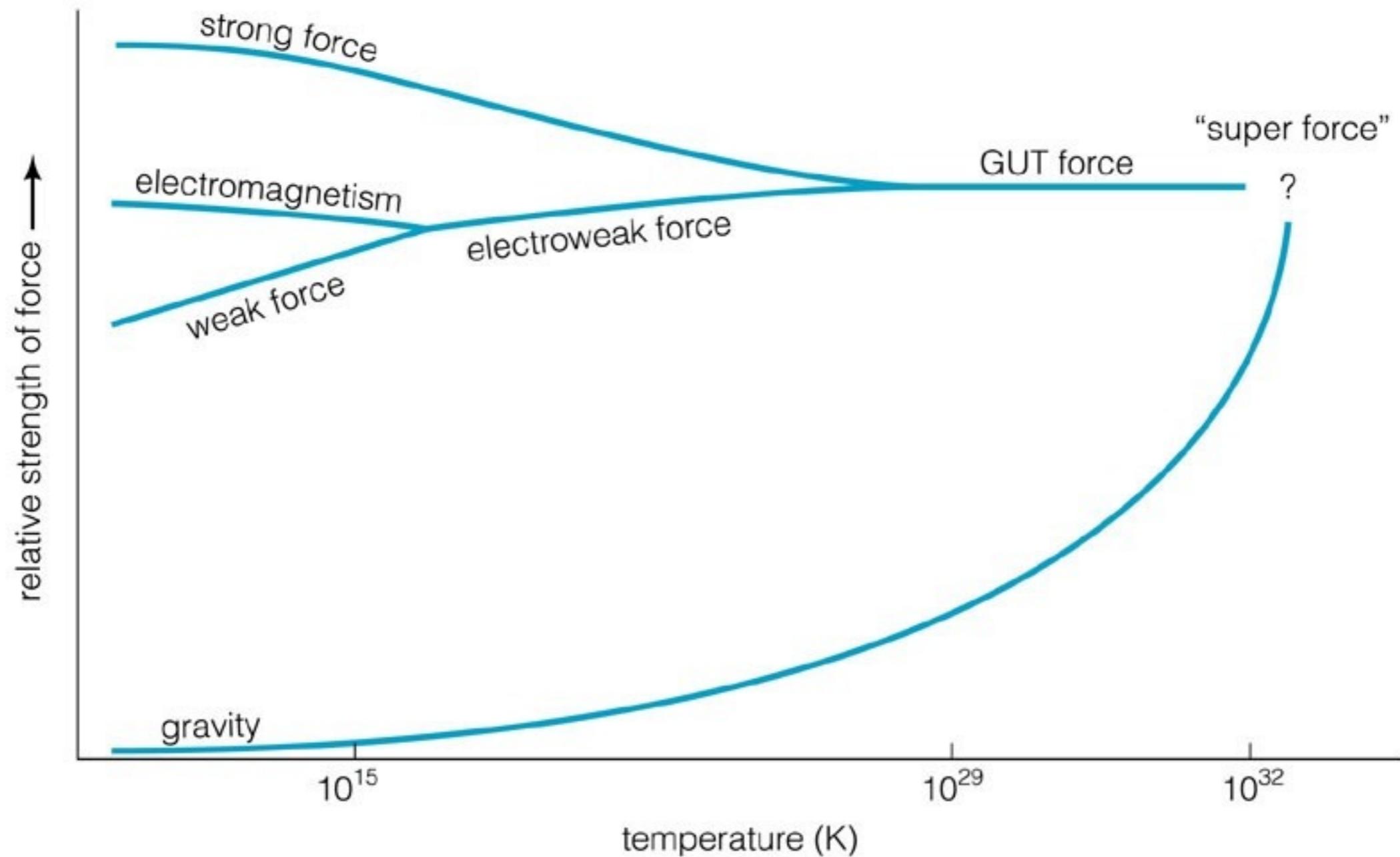


CMS, PRL 113 (2014) 132301



- No significant modification of bottom jets in p-Pb within large uncertainty of pp reference
- Suppression of b jets in Pb-Pb as strong as light jets
 - ▶ might see mostly gluon splitting, need to look for b dijets...

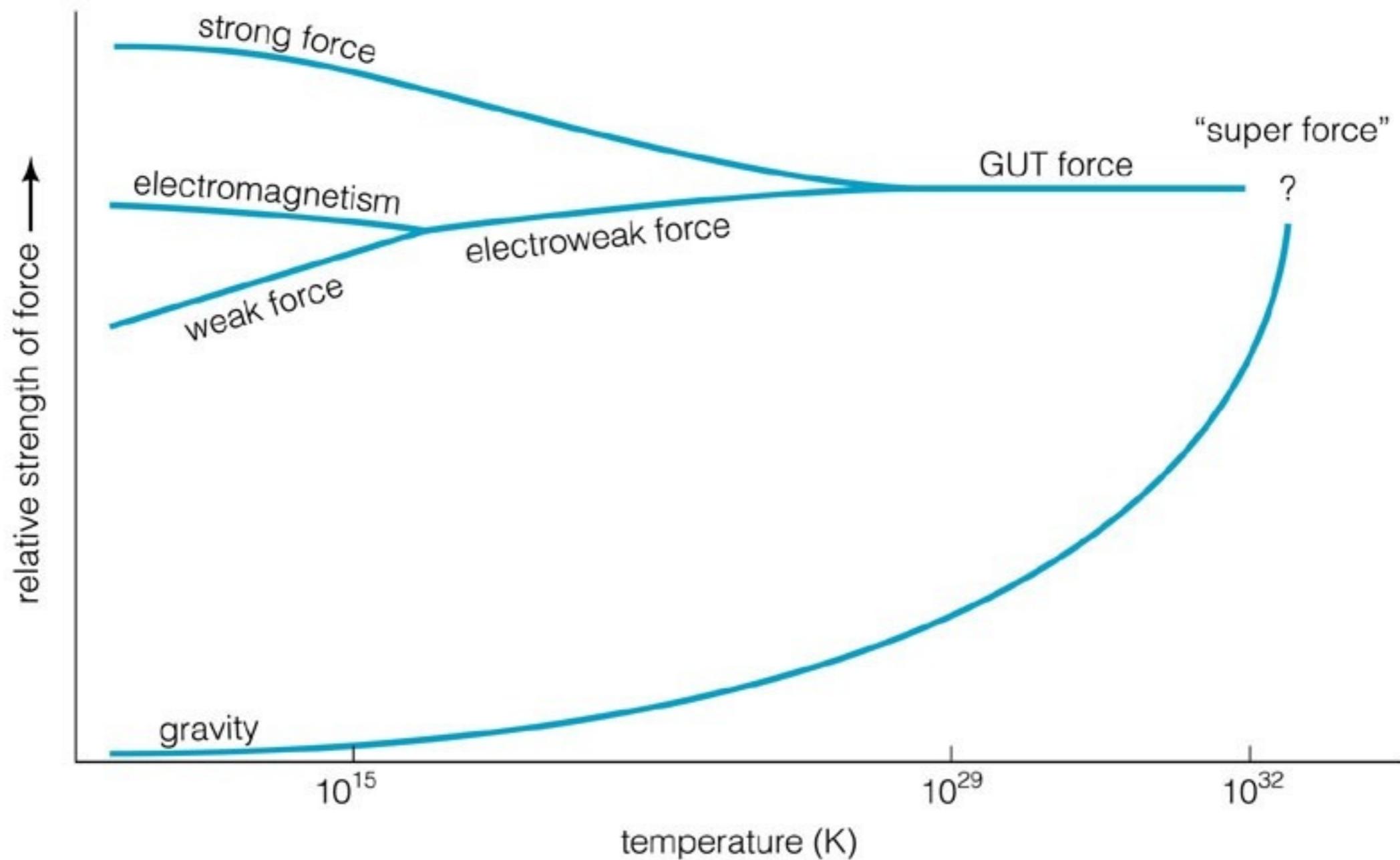
The GUT of heavy-ion physics



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The GUT of heavy-ion physics

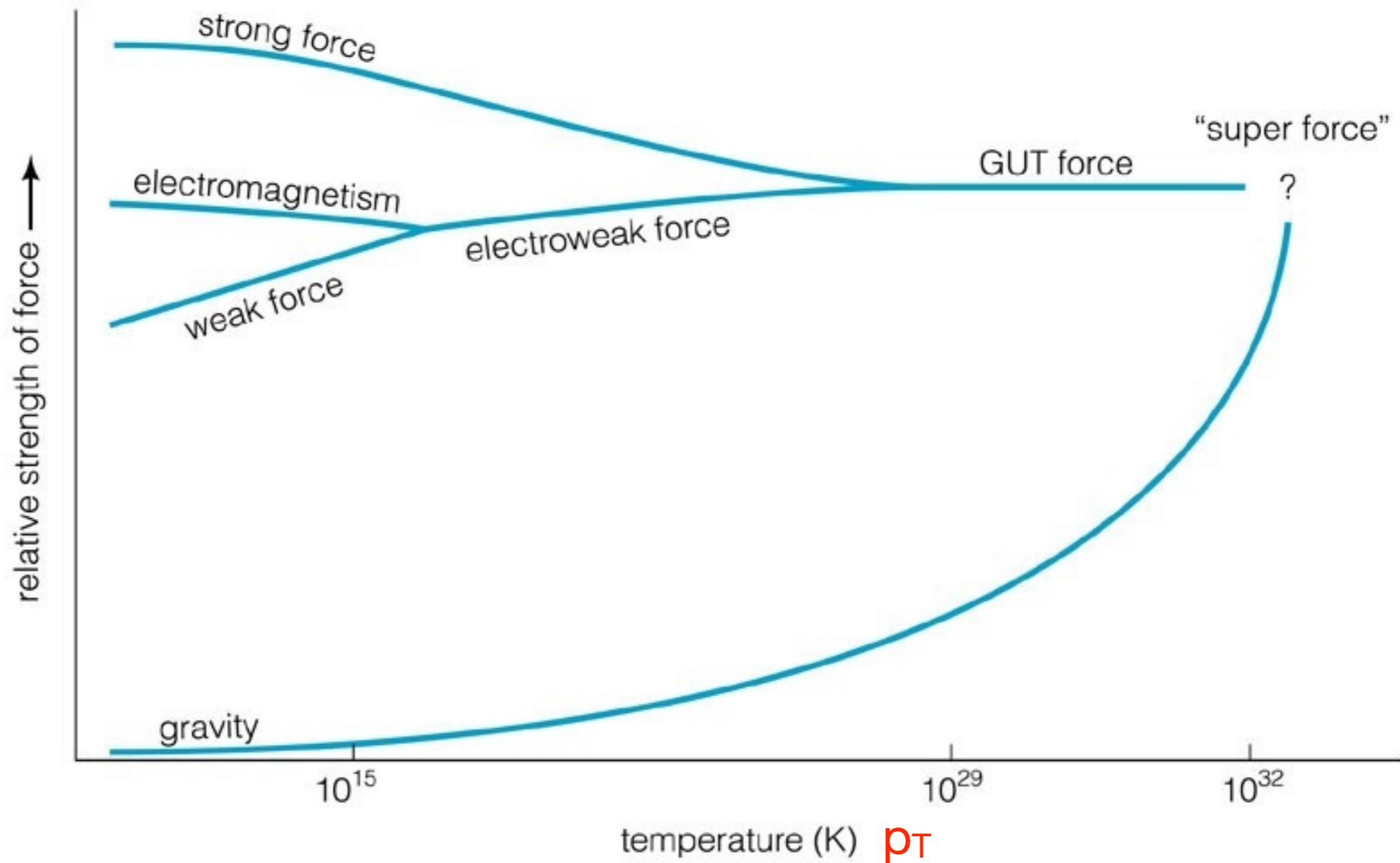
interaction strength with QGP



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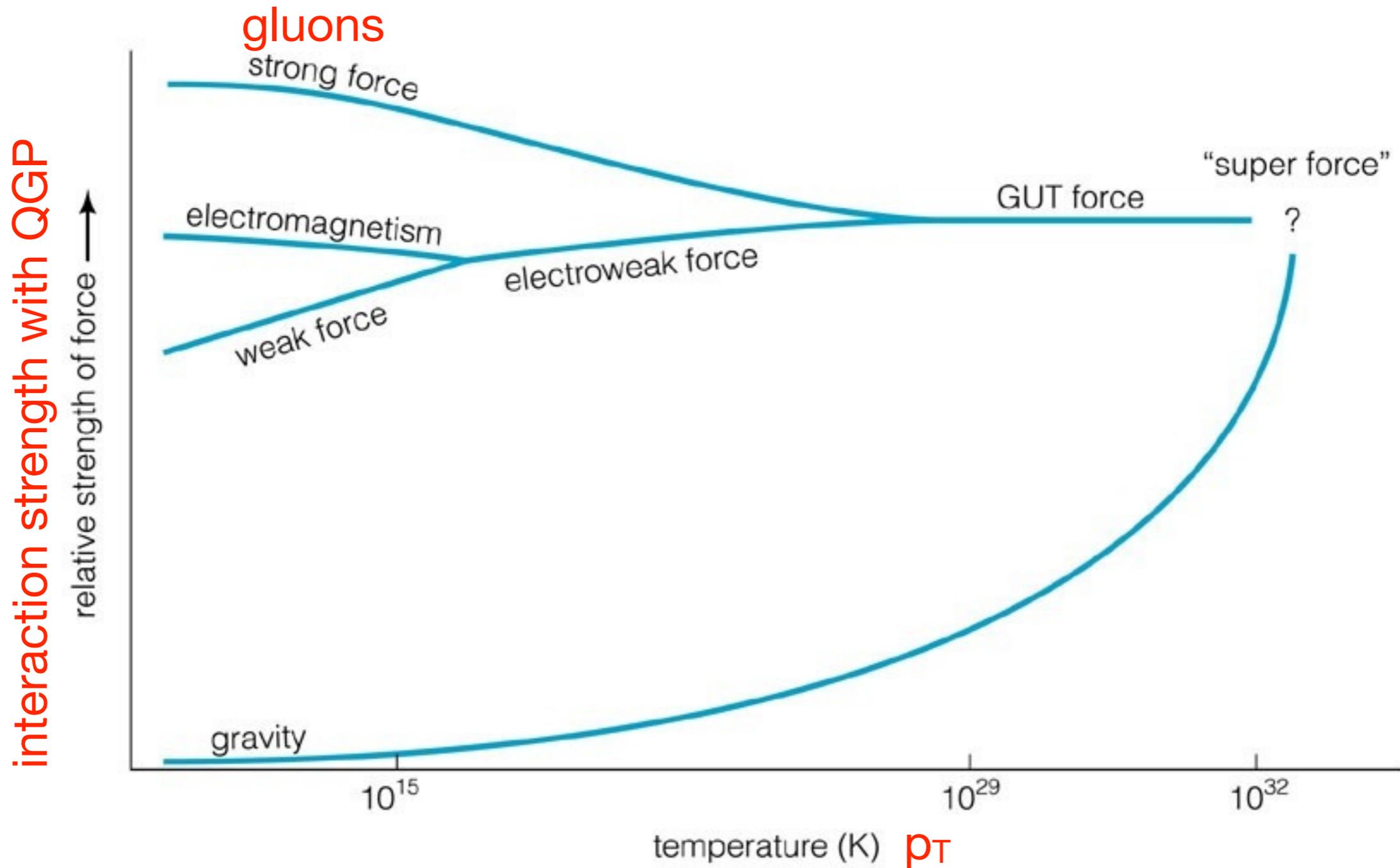
The GUT of heavy-ion physics

interaction strength with QGP



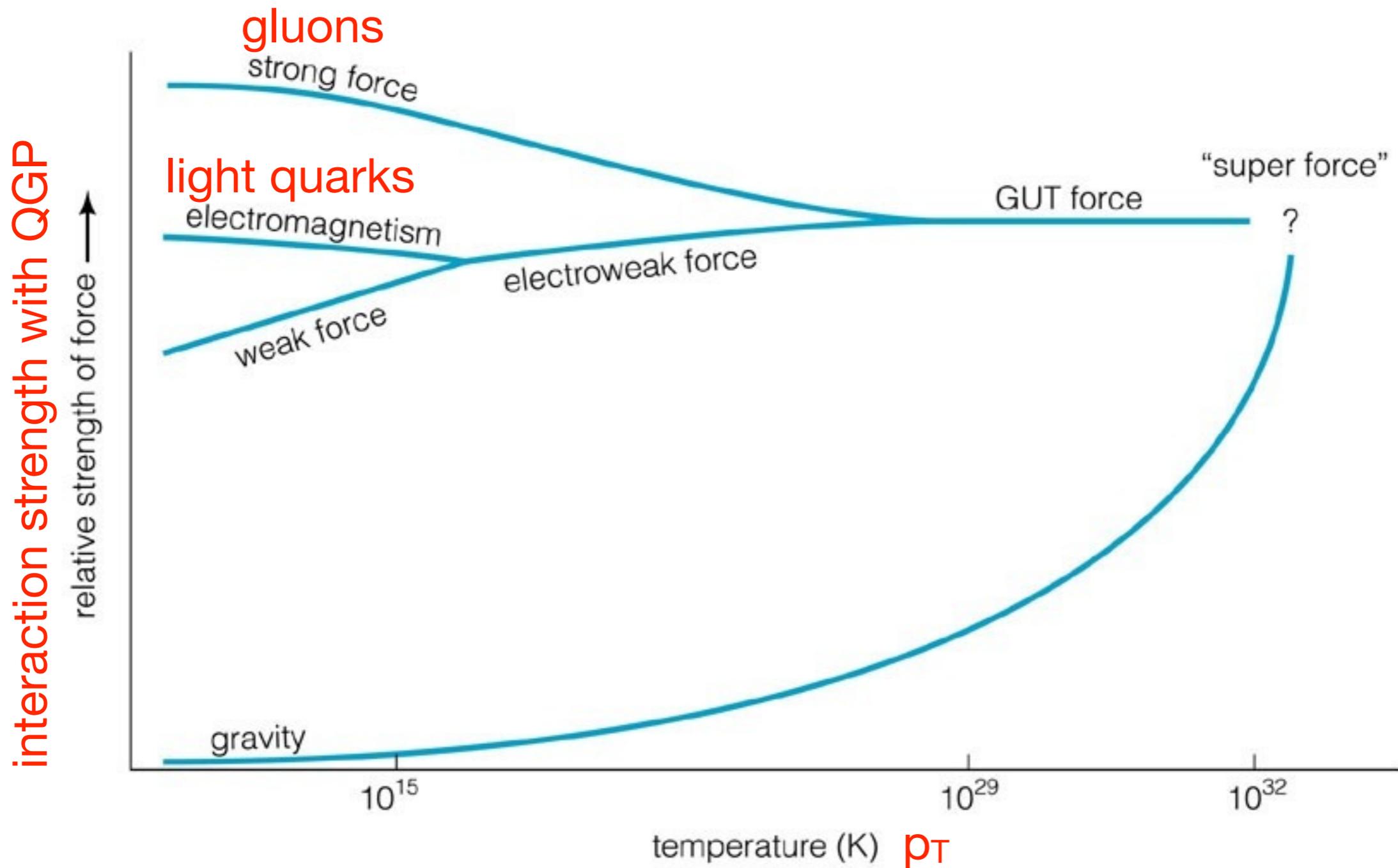
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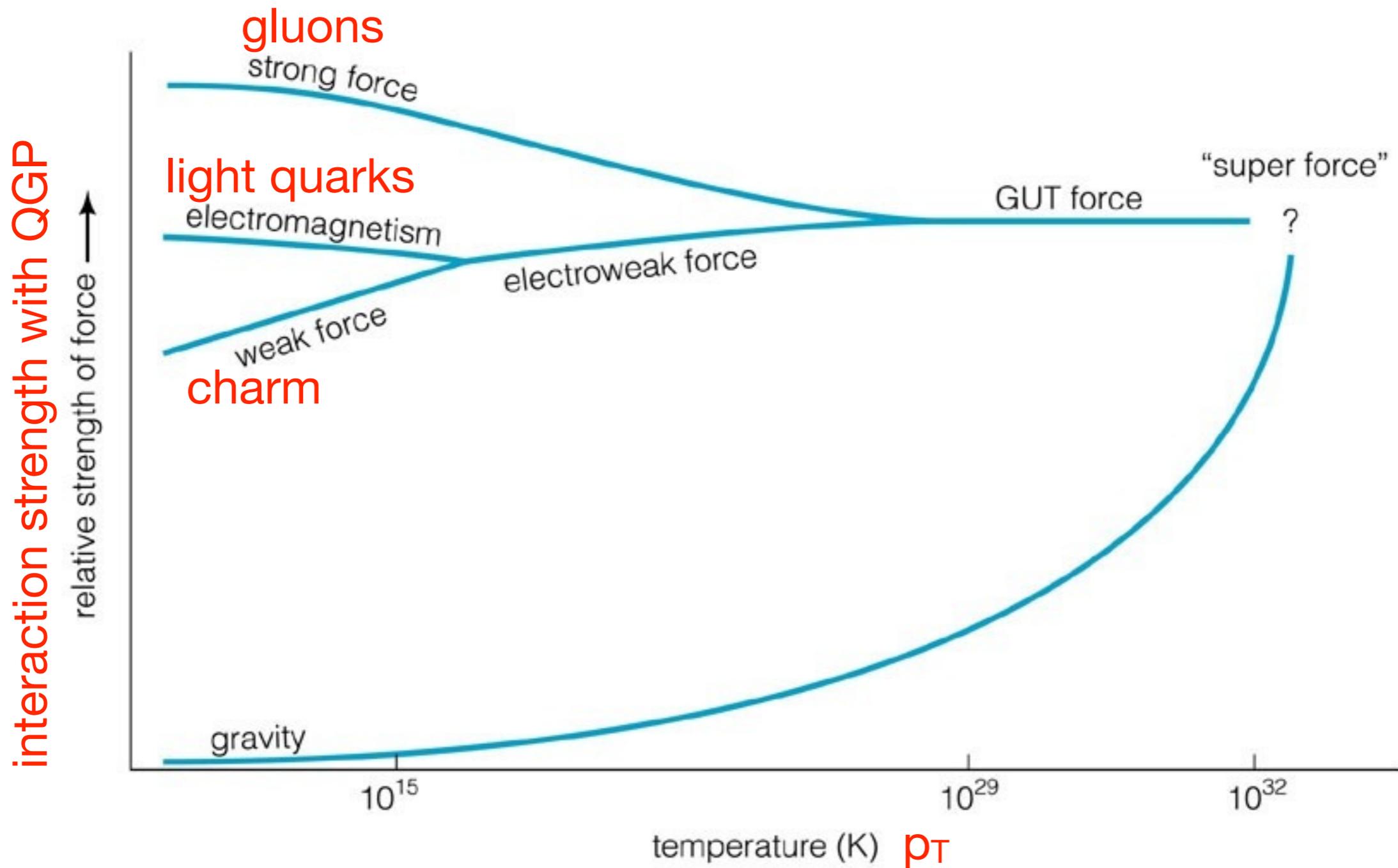
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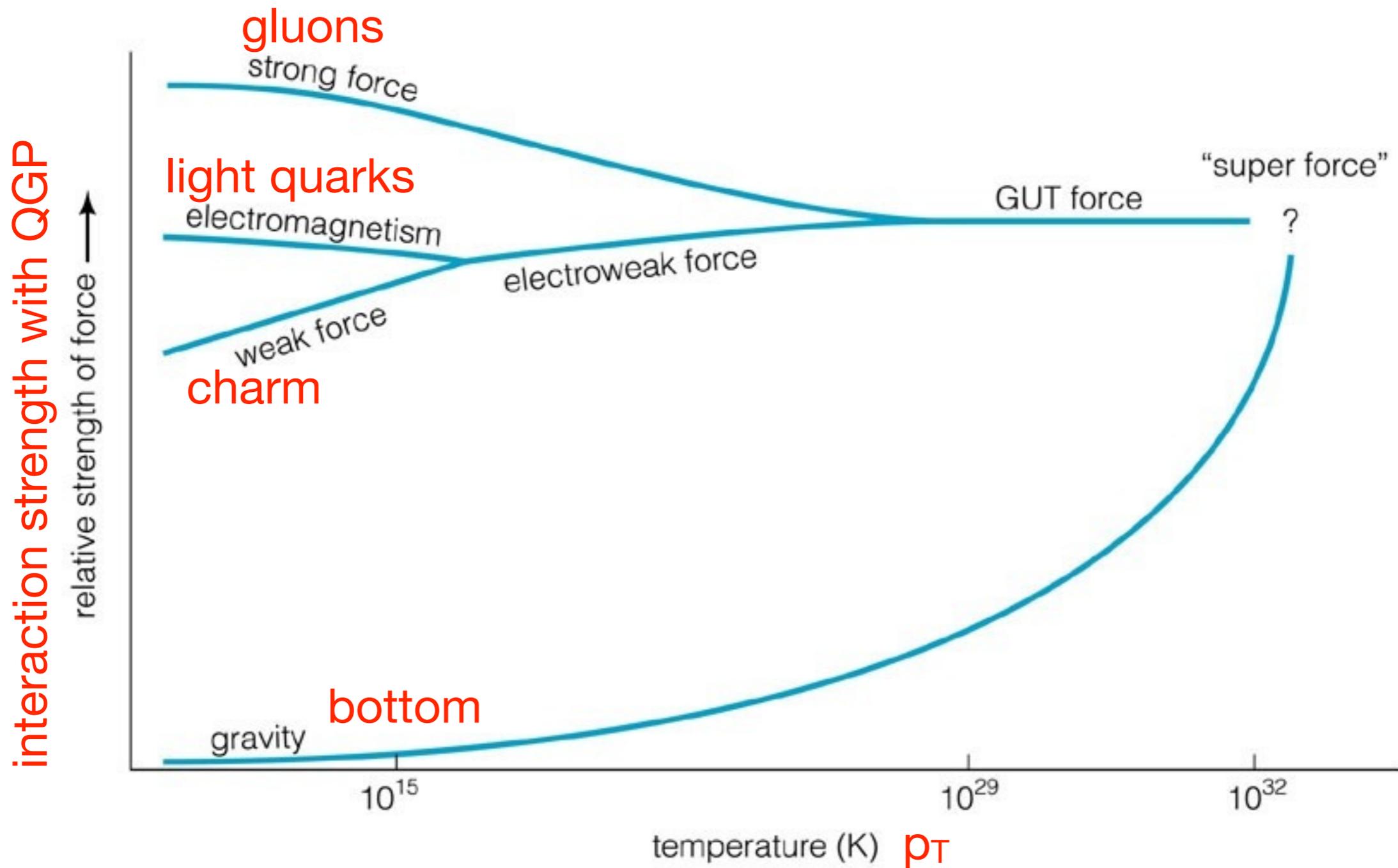
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The GUT of heavy-ion physics



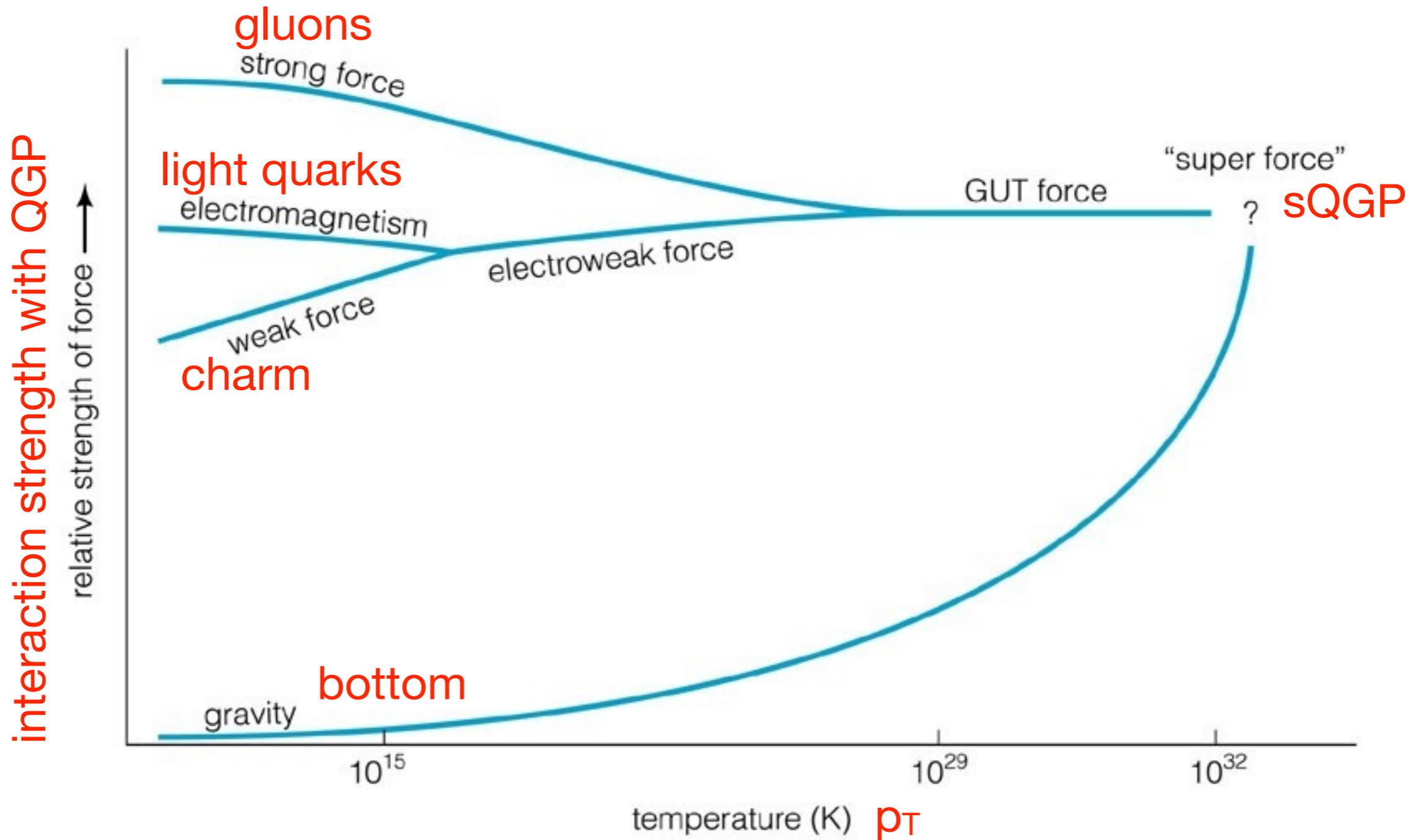
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Quarkonia

J/ψ in p-Pb $\sqrt{s_{NN}} = 5$ TeV

- Measured R_{pA} at forward and backward rapidity

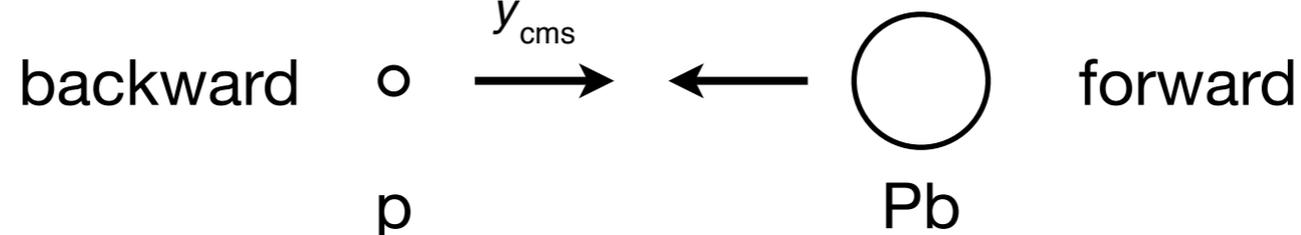
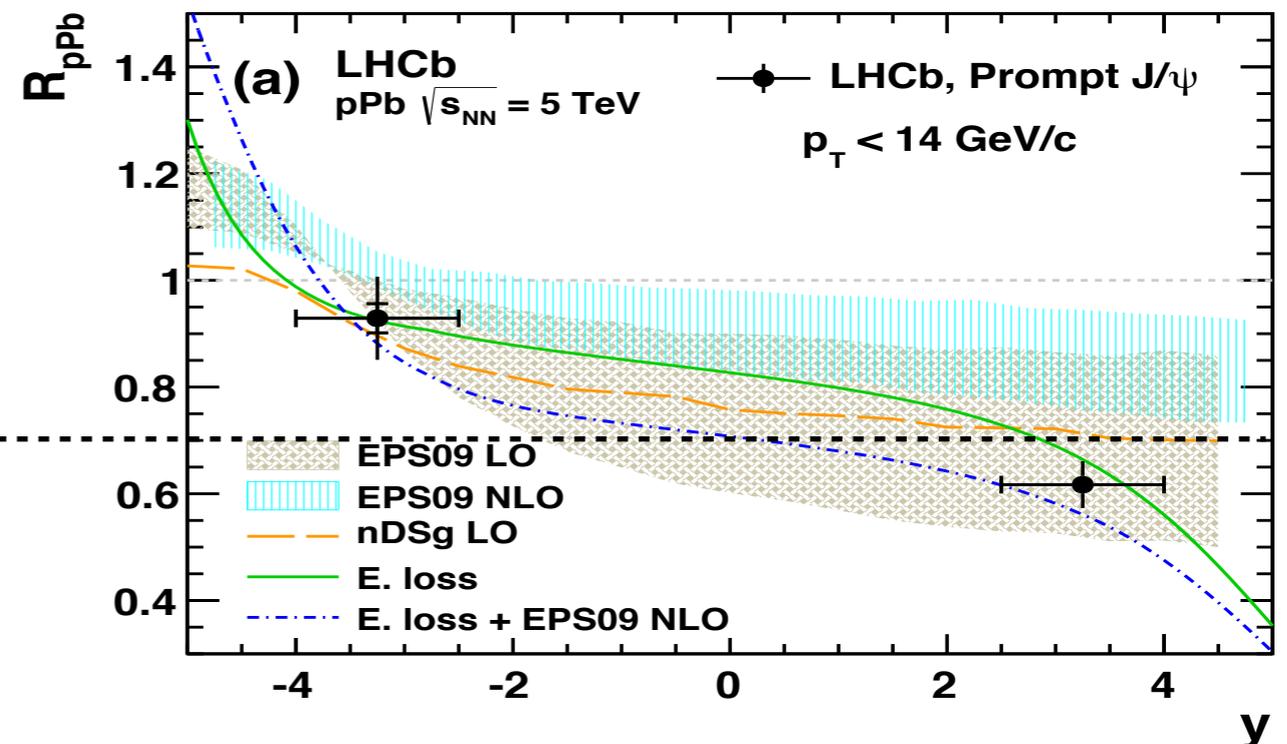
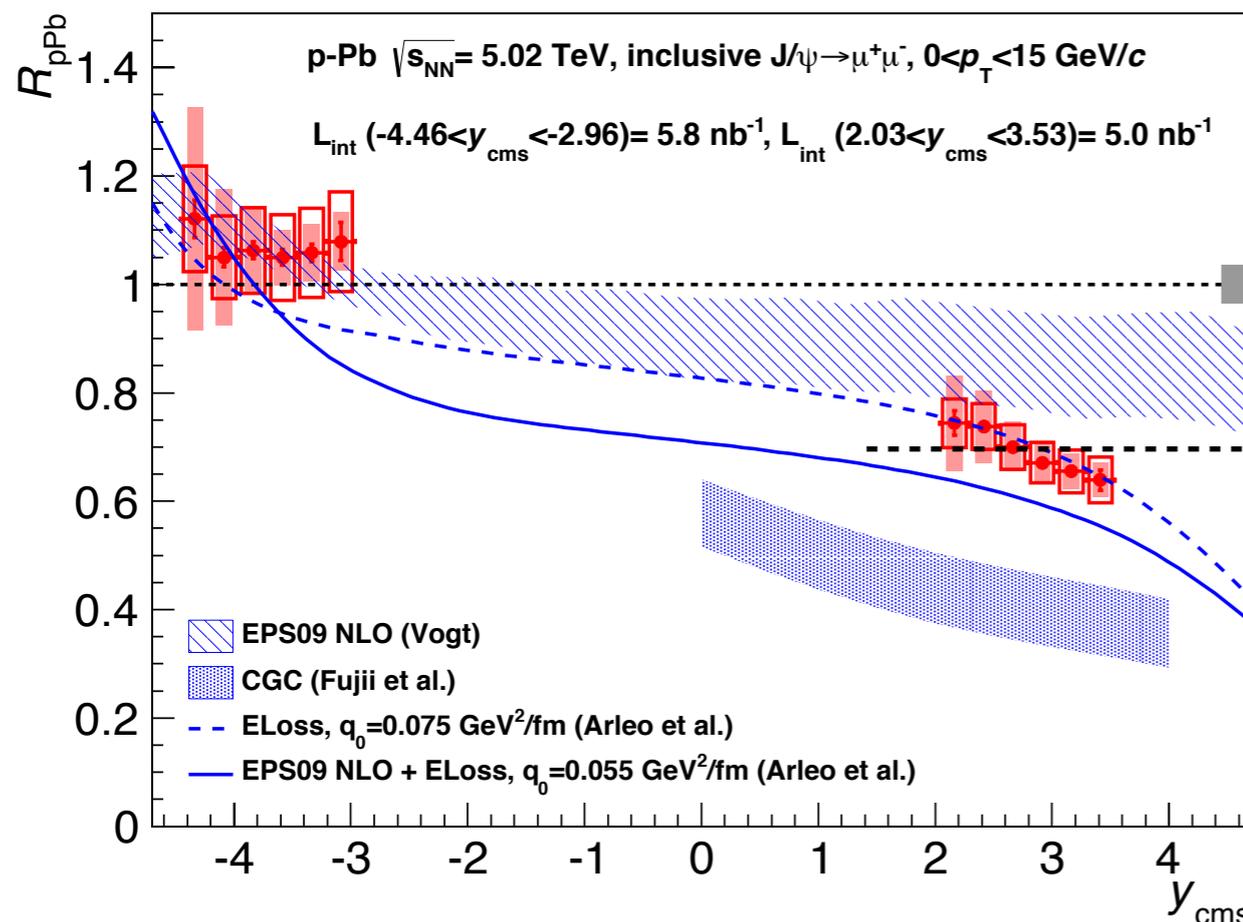
- no pp data at 5 TeV, reference from interpolation

- ALICE and LHCb roughly agree

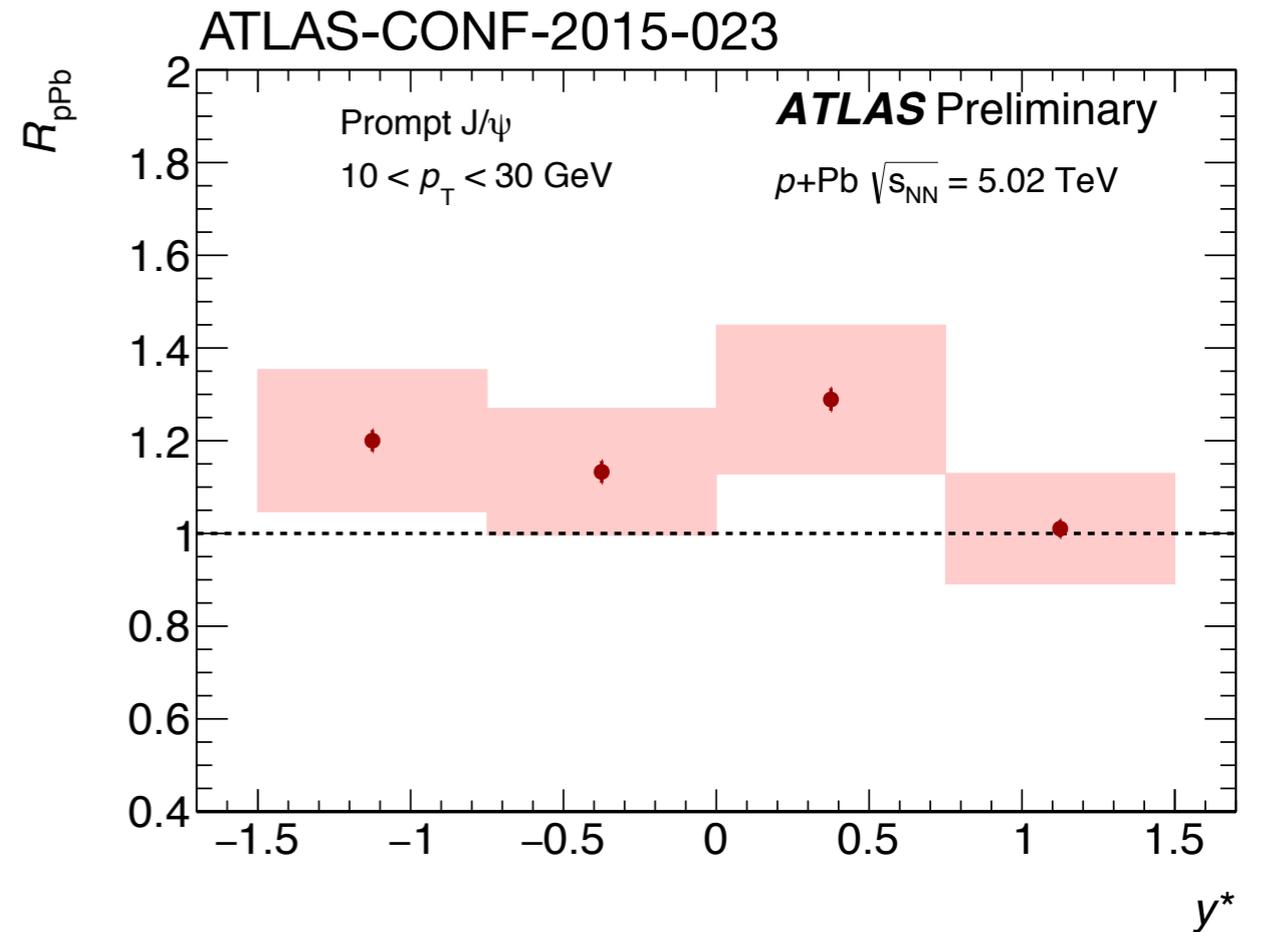
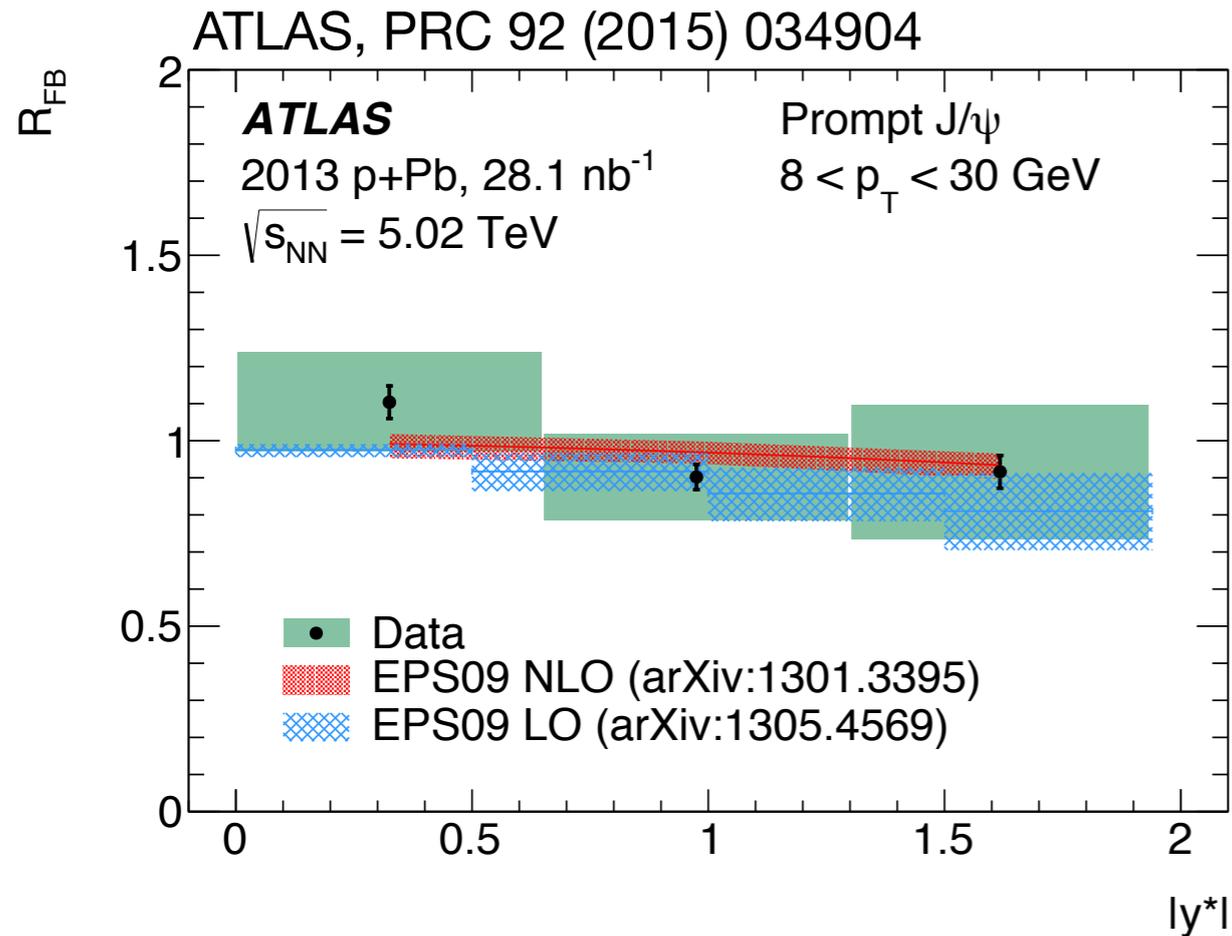
- strong suppression at forward

- agreement with shadowing only, but also with models that include parton energy loss

- no strong suppression/enhancement in the backward region

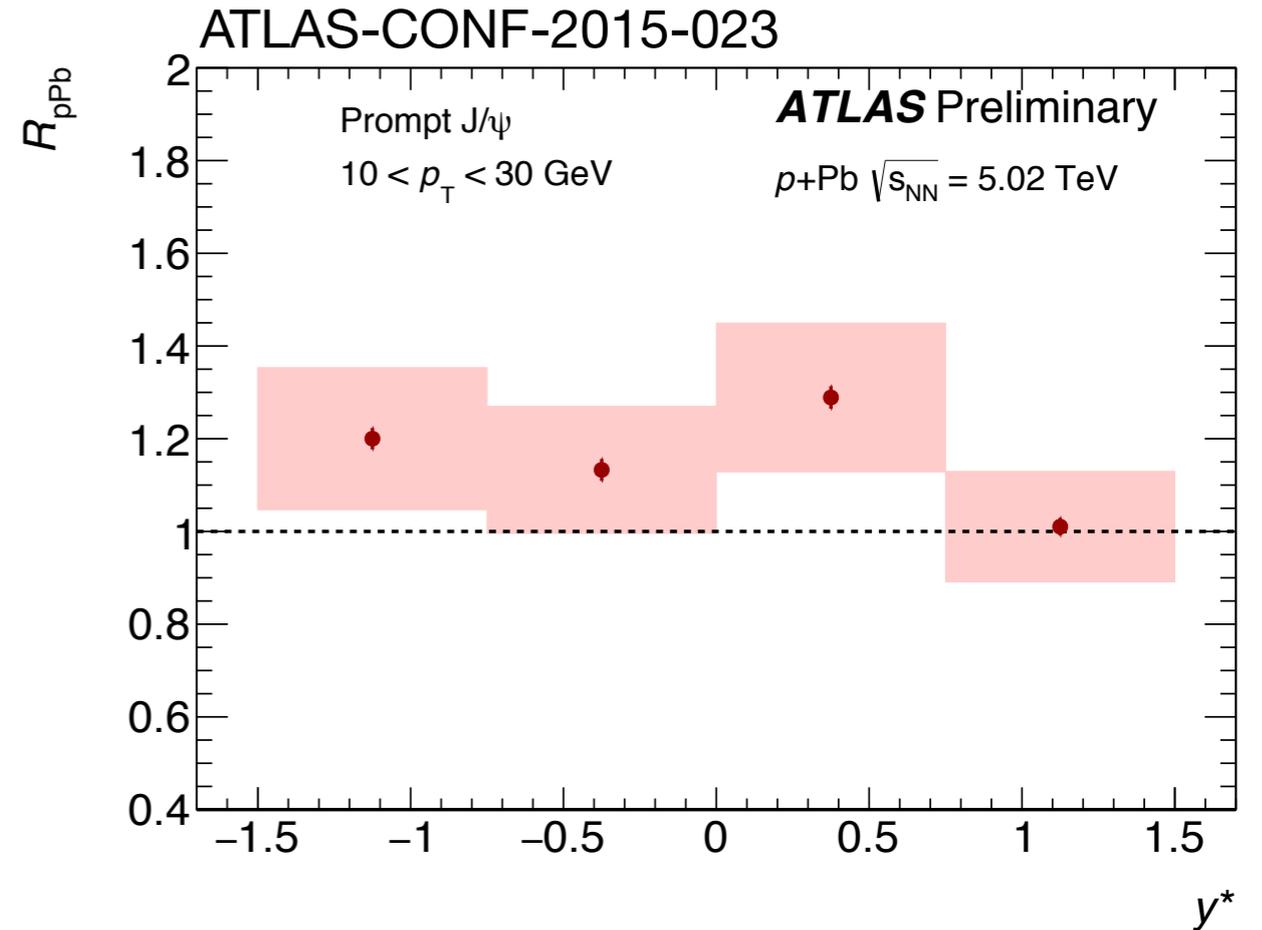
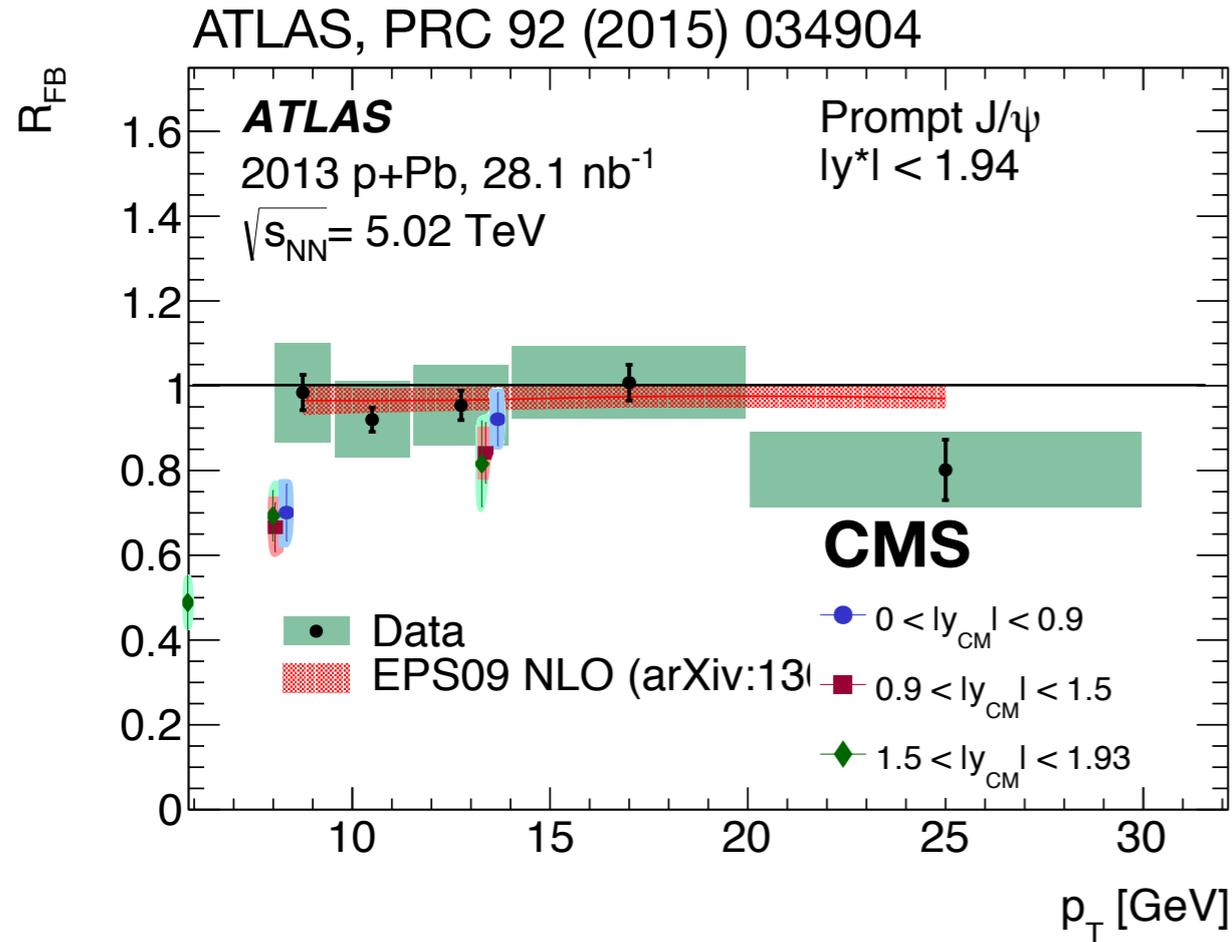


High- p_T J/ψ in p -Pb



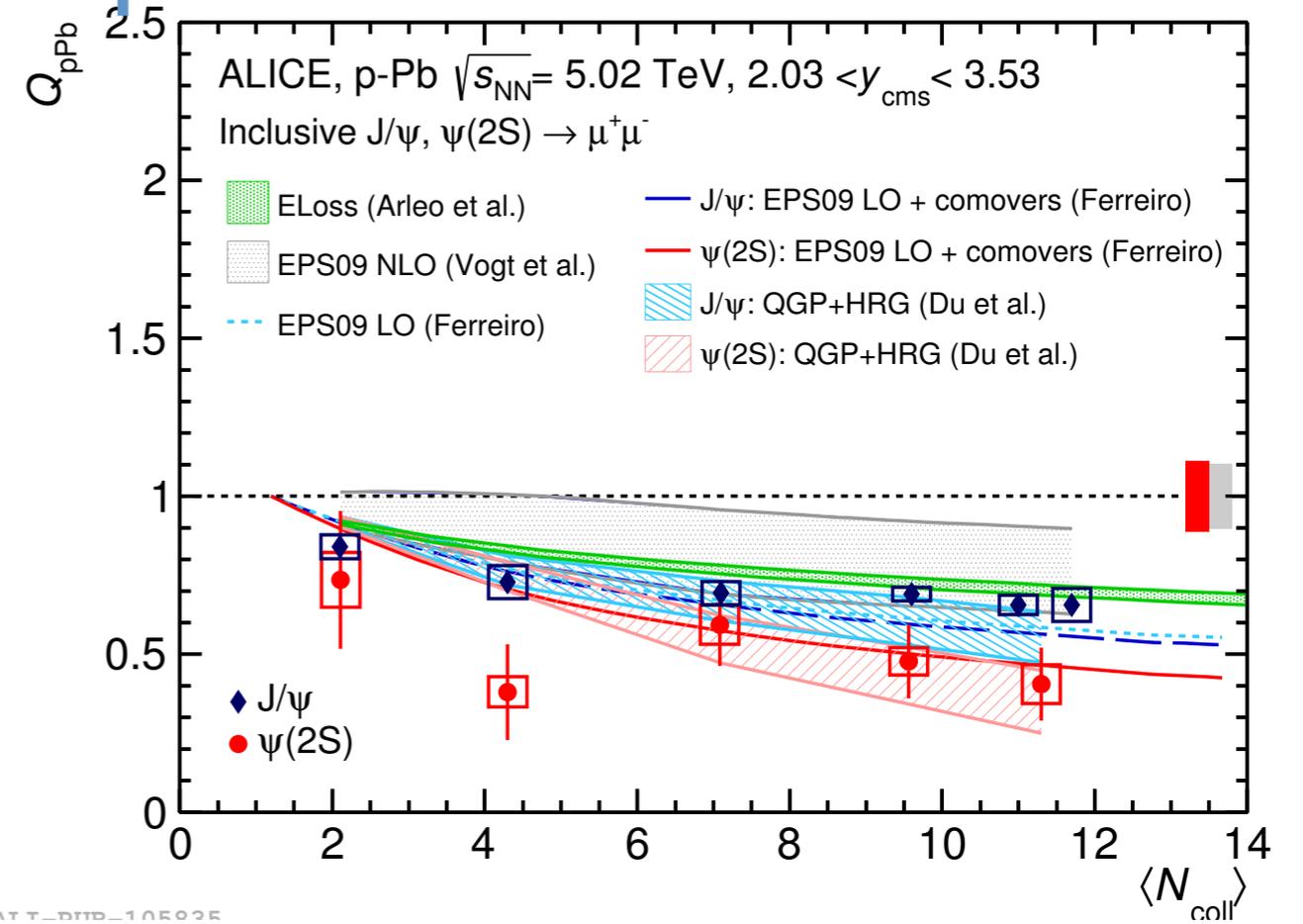
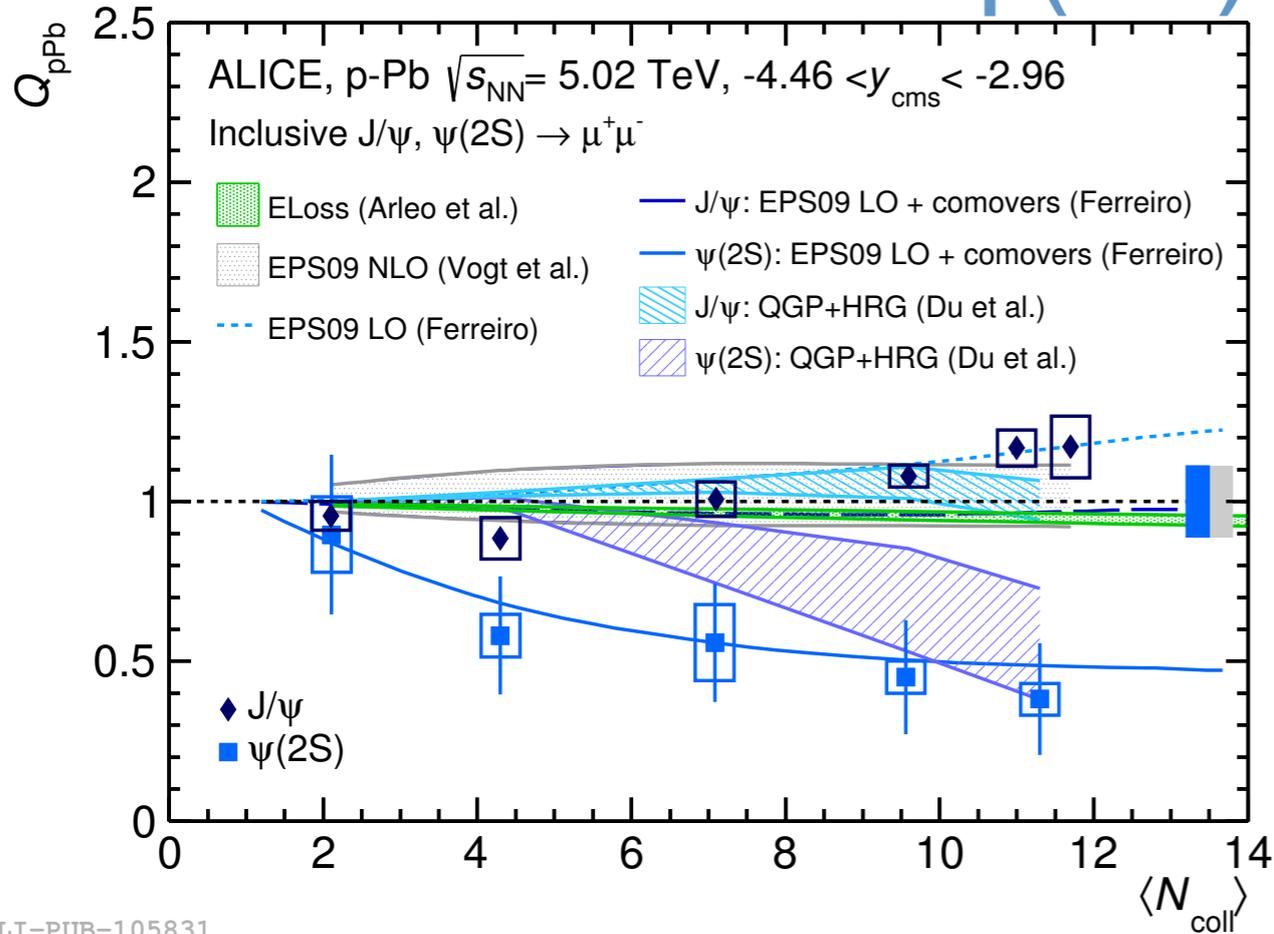
- No significant CNM effects at high p_T (none expected)
 - discrepancy between ATLAS and CMS at intermediate p_T ($< 10 \text{ GeV}$)?
- R_{pPb} based on interpolation with large uncertainties
 - wait for update based on pp measurement at proper energy

High- p_T J/ψ in p -Pb

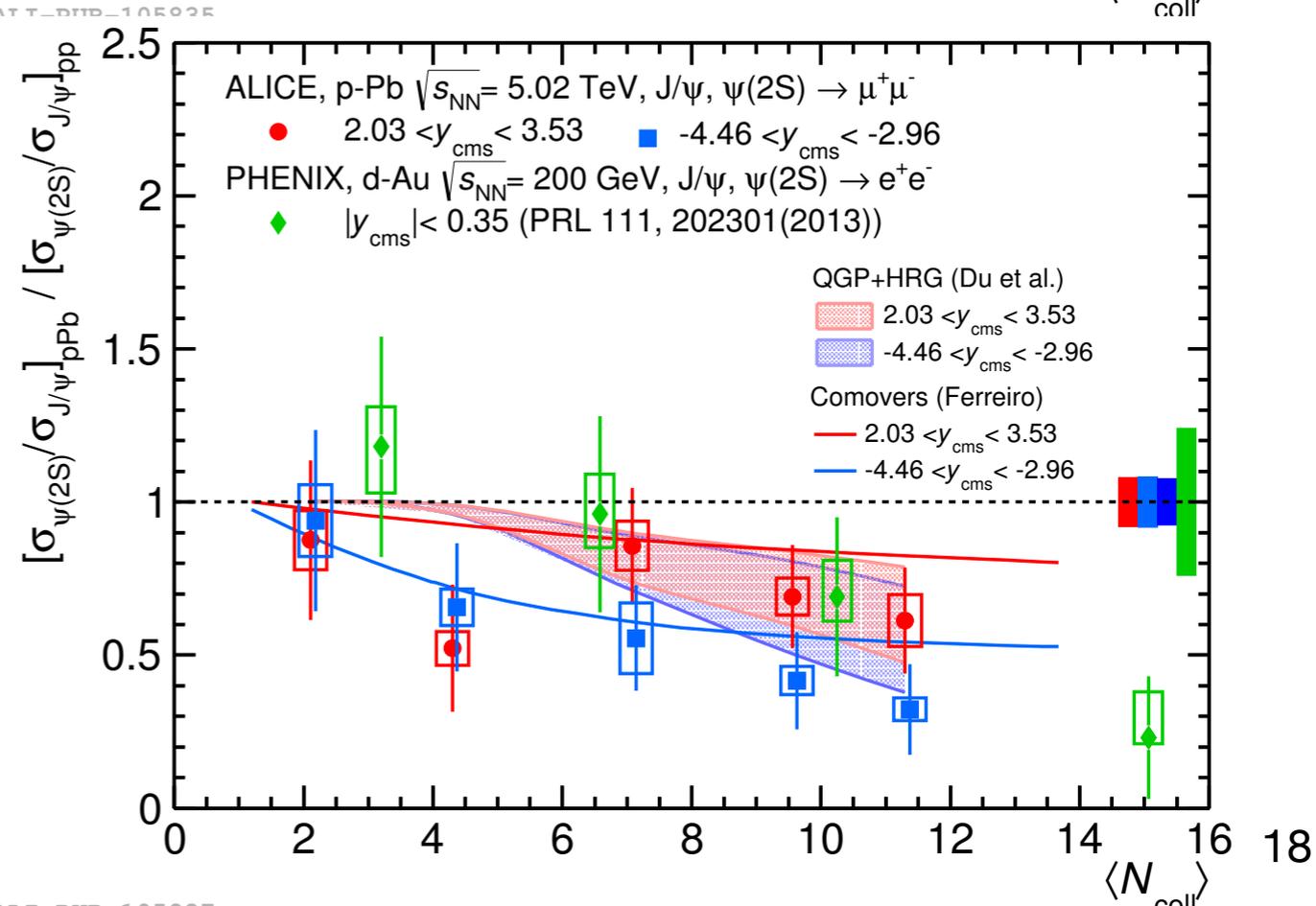


- No significant CNM effects at high p_T (none expected)
 - discrepancy between ATLAS and CMS at intermediate p_T (<10 GeV)?
- R_{pPb} based on interpolation with large uncertainties
 - wait for update based on pp measurement at proper energy

$\psi(2S)$ in p-Pb



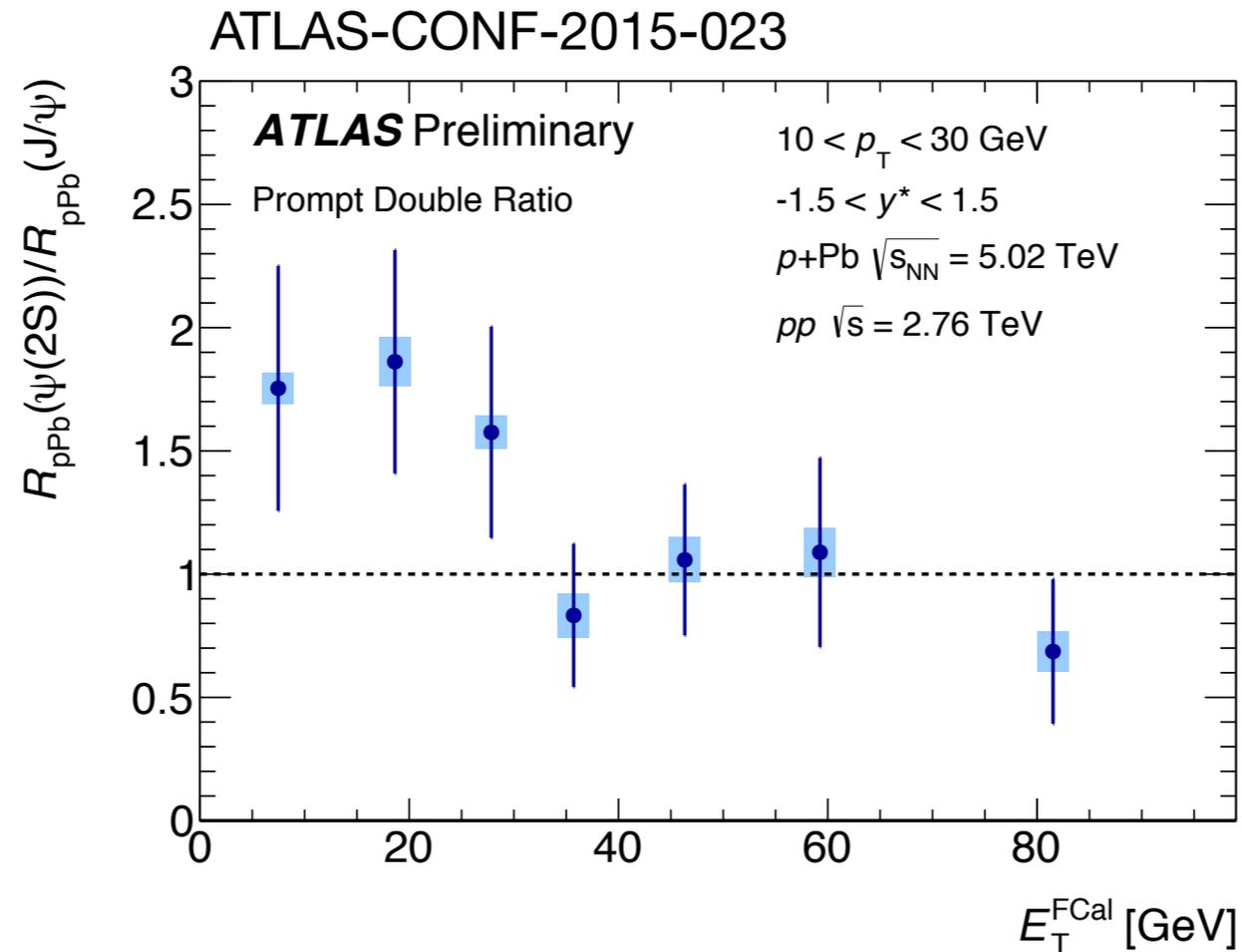
- **Backward:** suppression of $\psi(2S)$, none for J/ψ
 - ▶ J/ψ maybe enhanced in central p-Pb
- **Forward:** suppression of $\psi(2S)$ and J/ψ almost the same
- Comover interaction model qualitatively describes patterns



ALICE, arXiv:1603.02816

also see: LHCb, JHEP 03 (2016) 133

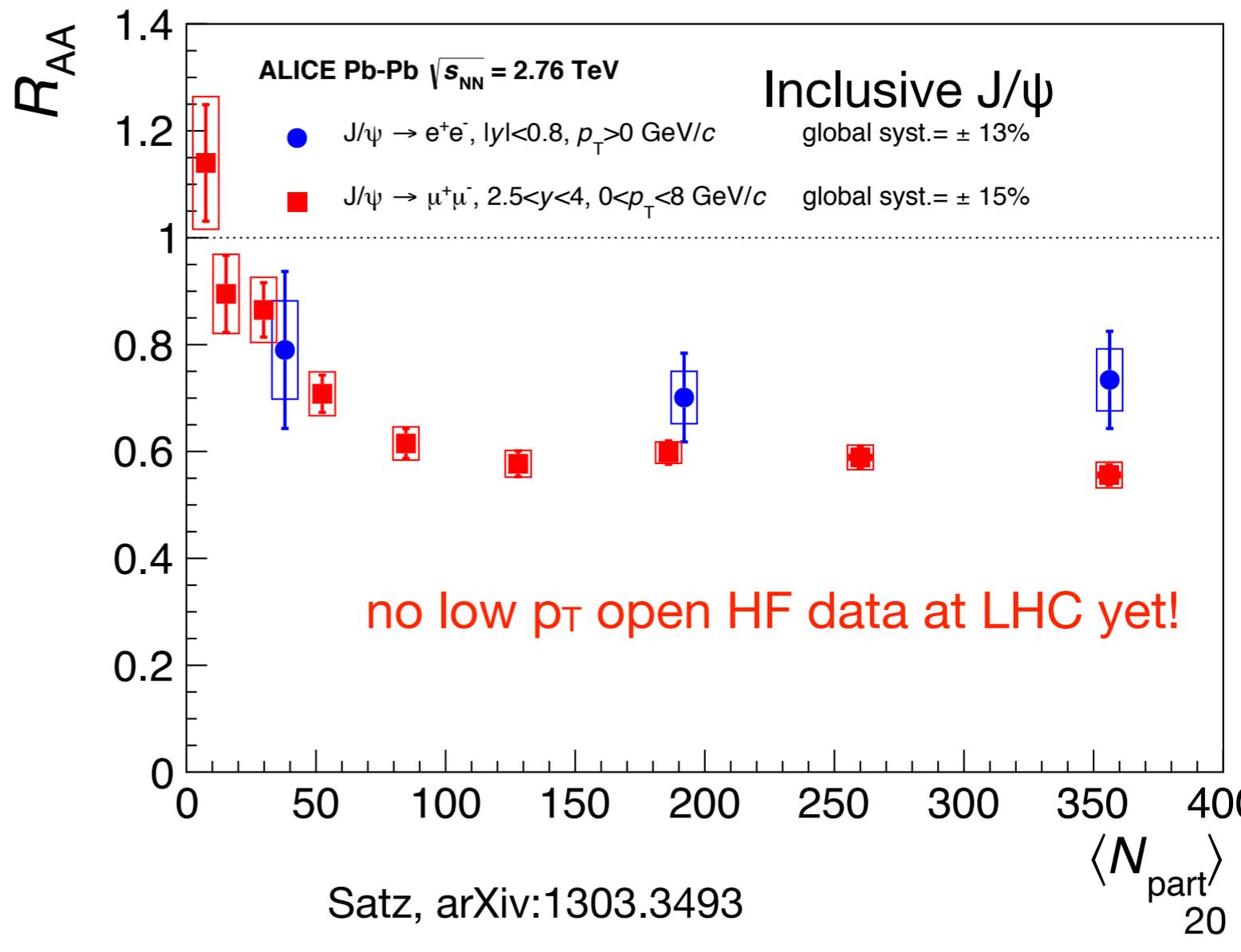
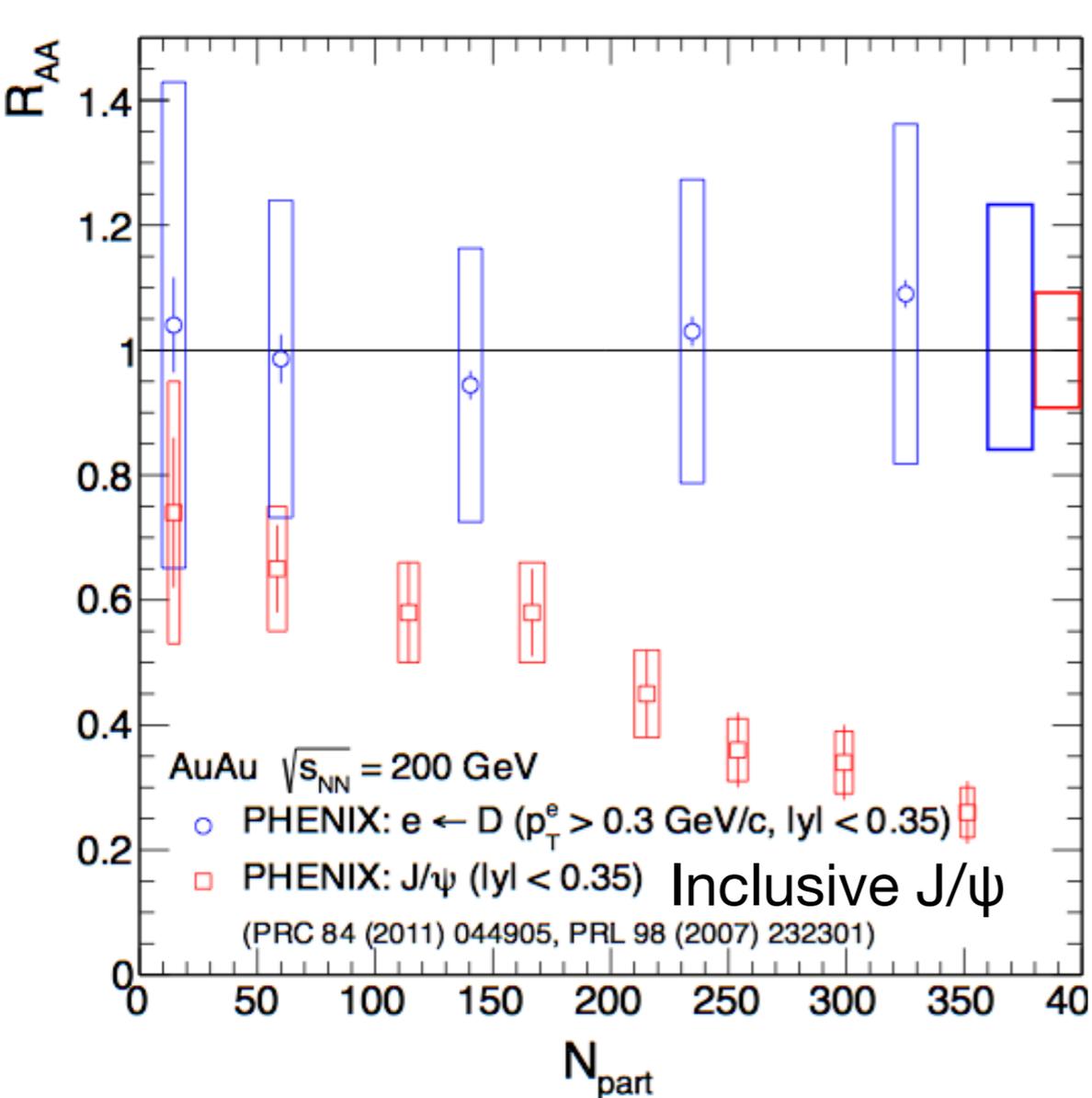
High- p_T $\psi(2S)$ in p-Pb



- At high p_T and midrapidity: hint of opposite behavior of $\psi(2S)$ to J/ψ double ratio in peripheral p-Pb collisions
 - ▶ disappears in central collisions

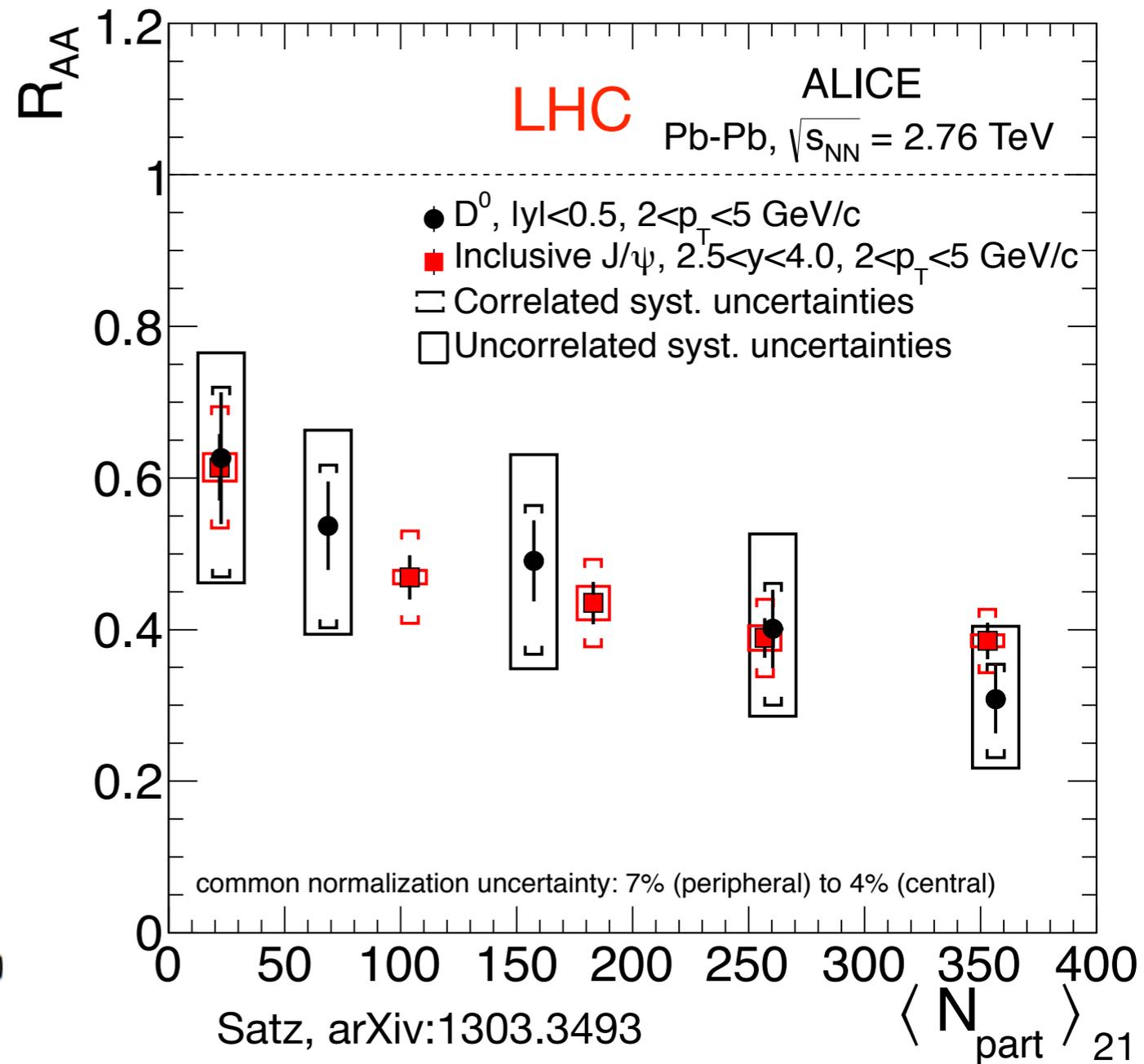
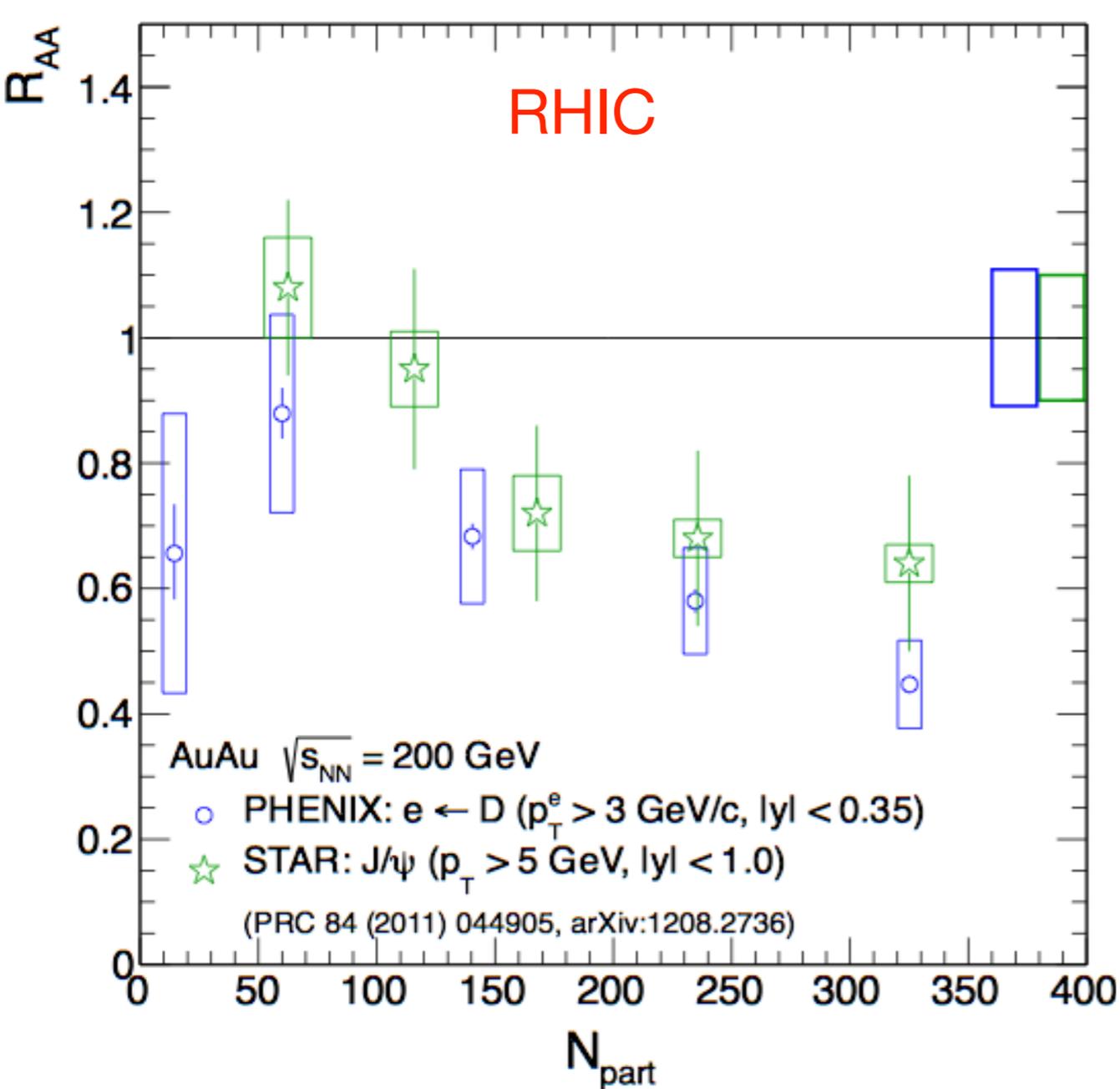
Open vs. Hidden HF in AA

- A brief reminder: Sequential melting a la Satz:
 - ▶ less closed than open HF
 - ▶ not: less closed HF in AA than in pp
- At RHIC: open charm scales with $N_{\text{coll}} \rightarrow R_{\text{AA}}(\text{J}/\psi) = \text{J}/\psi / D$ in PbPb
 - ▶ ignoring the large uncertainties on open charm

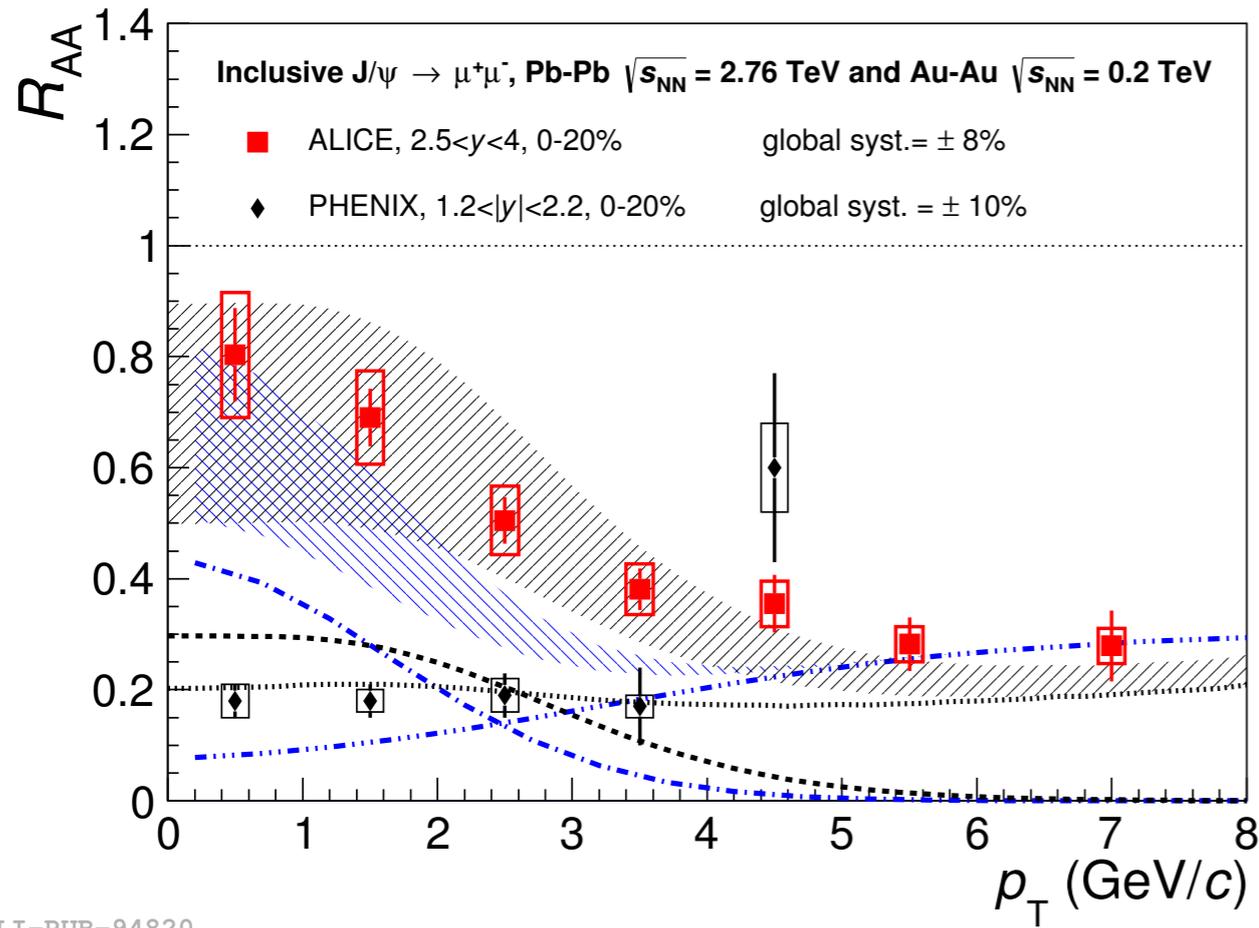


Open vs. Hidden HF in AA: high p_T

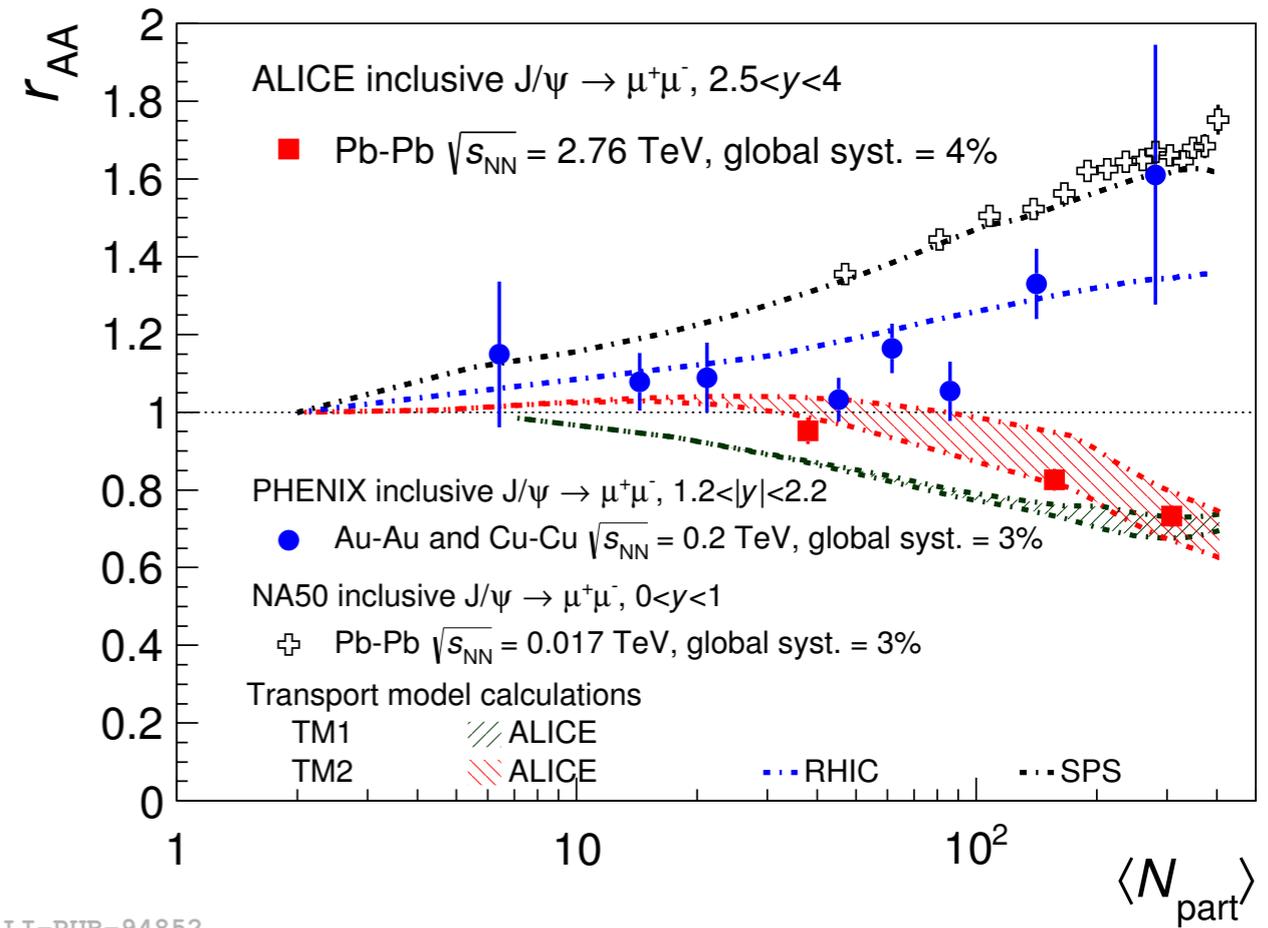
- But how to compare open and closed HF with p_T cuts?
 - ▶ not trivial to select kinematic region of interest: same quark p_T , same hadron p_T , ...?
- Similar suppression for “high- p_T ” D and J/ ψ (energy loss rather than screening?)



J/ψ in Pb-Pb



ALI-PUB-94820

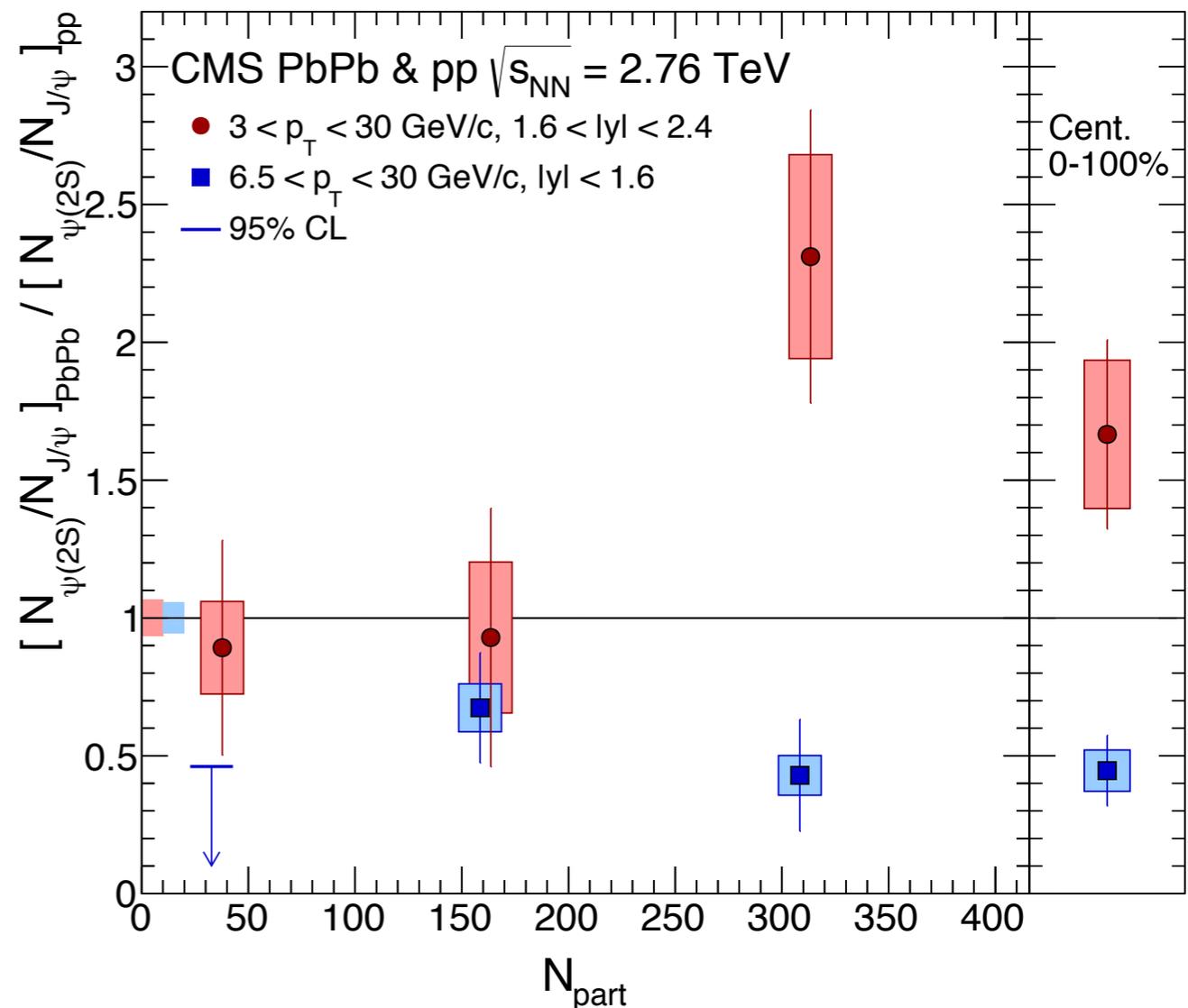


ALI-PUB-94852

- First time that J/ψ are less suppressed at low p_T than high p_T
- Also visible in $r_{AA} = \langle p_T \rangle_{AA} / \langle p_T \rangle_{pp}$
- Models including regeneration component describe data well

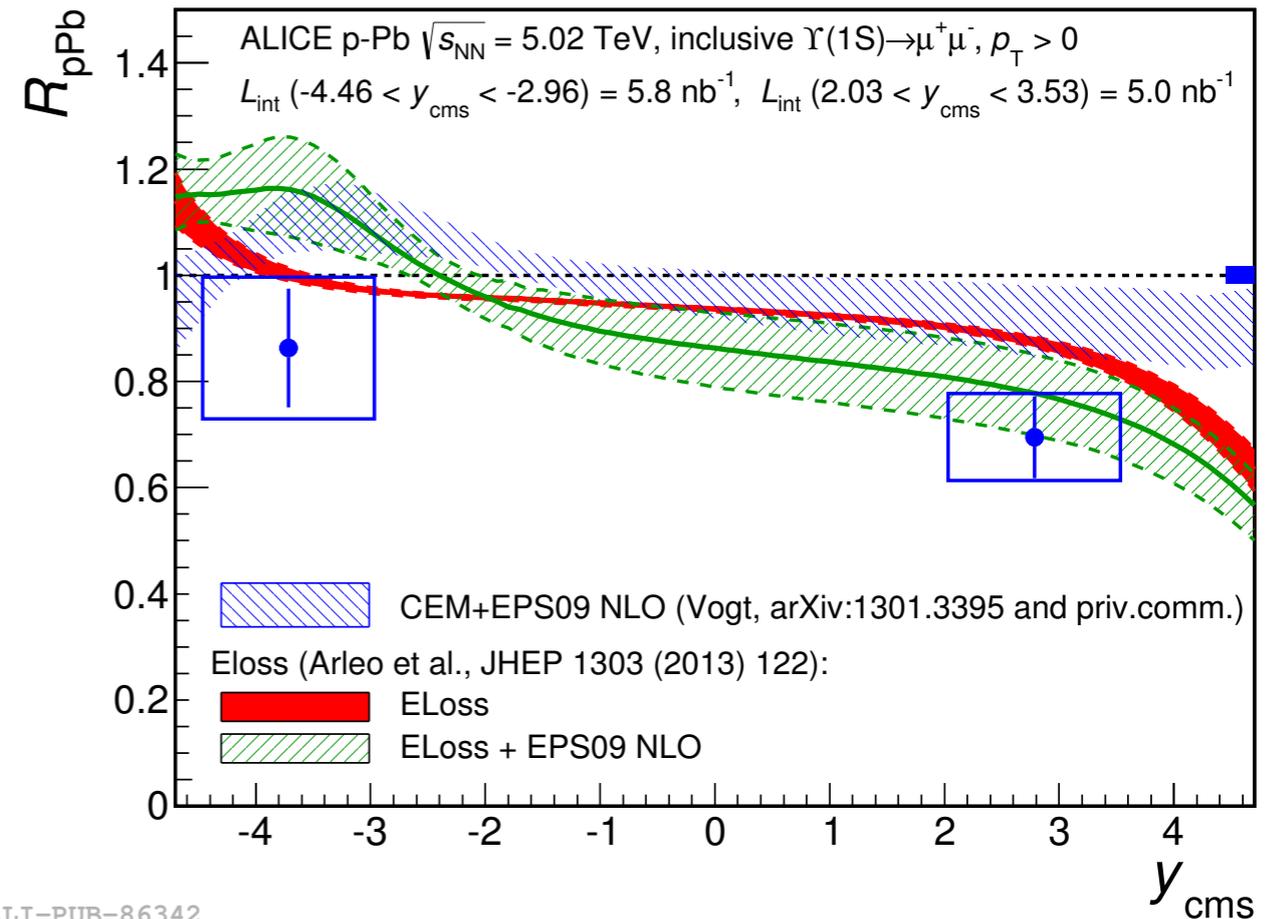
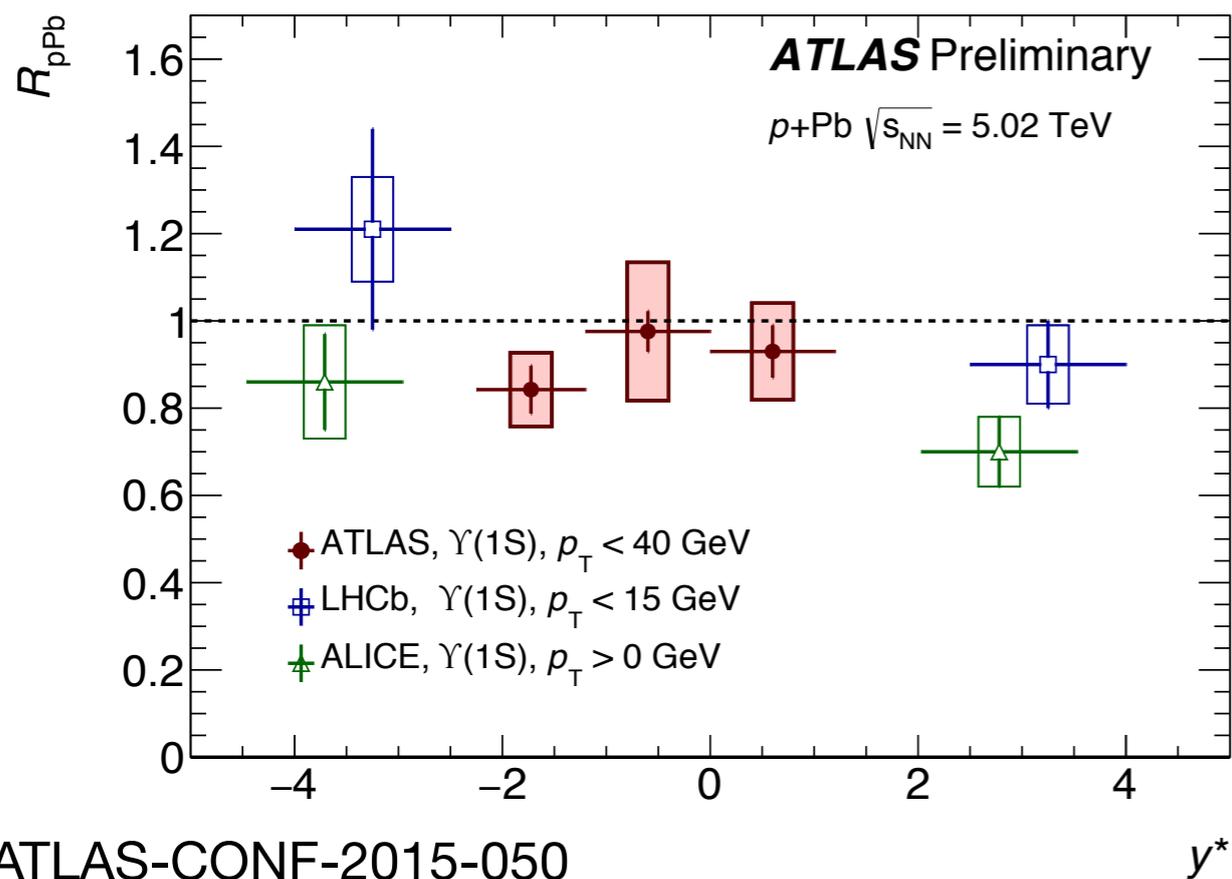
$\psi(2S)$ in Pb-Pb

- Puzzling results from CMS
 - ▶ high p_T and midrapidity: as expected
 - ▶ more forward rapidity and $p_T > 3$ GeV: hint of relative enhancement
 - ▶ Data not precise enough to conclude yet
- ALICE data not precise enough either to confirm or rule out
- What will happen at 5 TeV?
- Regeneration in hadronic phase would favor $\psi(2S)$:
 - ▶ PBM and K. Redlich, EPJ C16 (2000) 519
 - ▶ Xiaojian Du and R. Rapp, NPA 943 (2015) 147

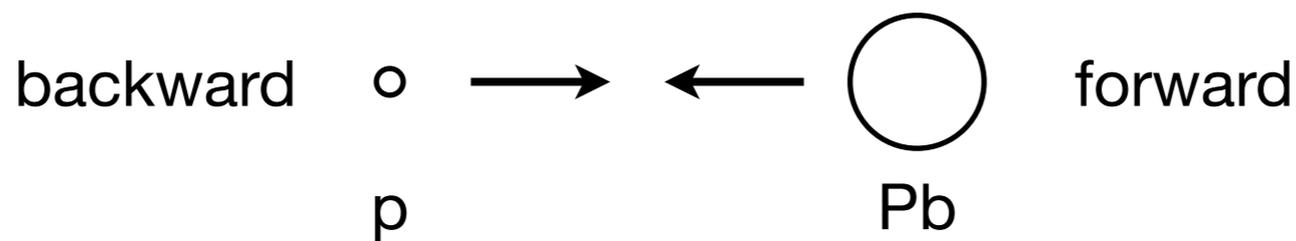


CMS, PRL 113 (2014) 262301
ALICE, arXiv:1506.08804

Υ in p-Pb



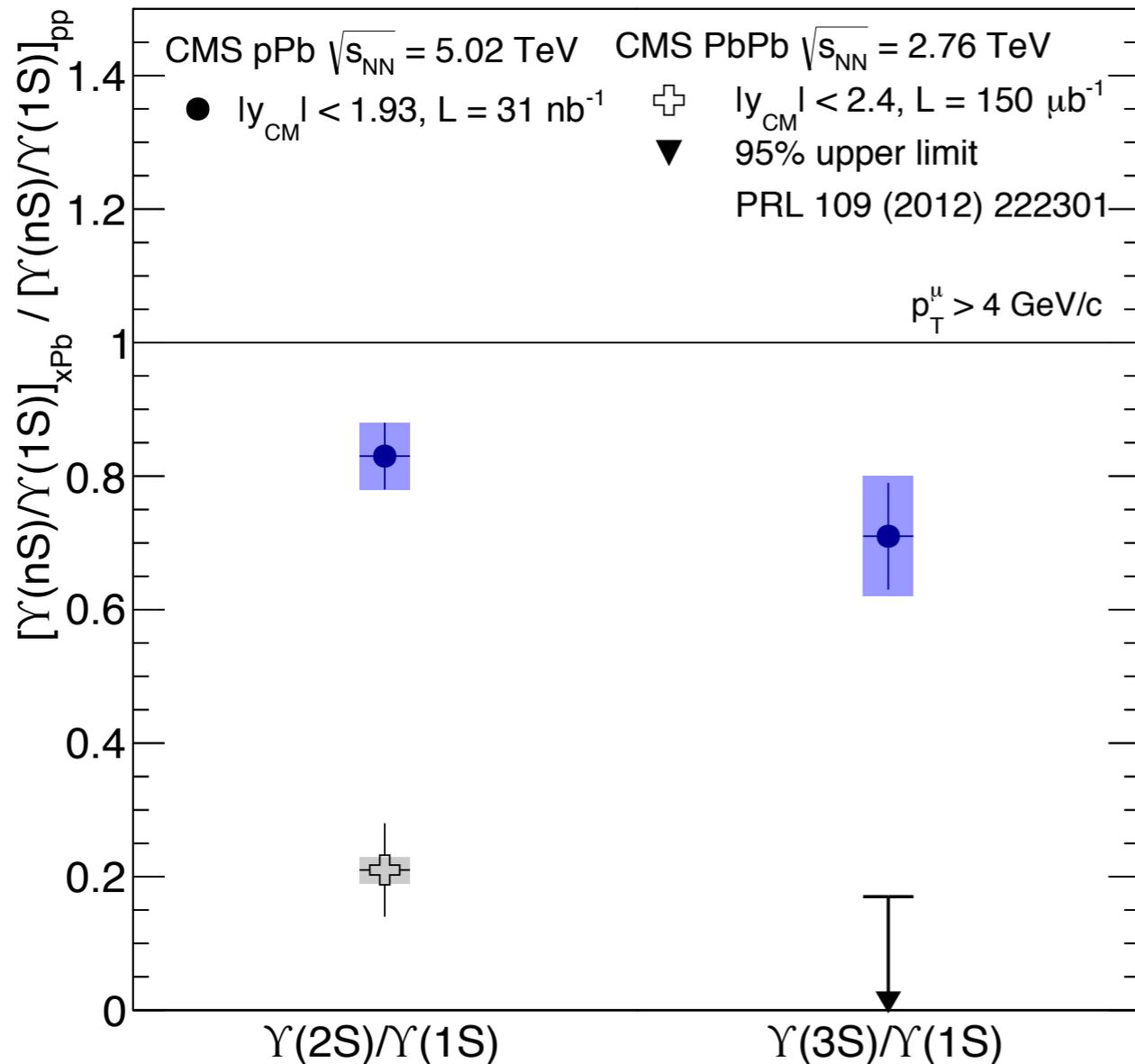
ATLAS-CONF-2015-050
 ALICE, PLB 740 (2015) 105
 LHCb, JHEP 07 (2014) 094



- Observed suppressions consistent with shadowing
- LHCb and ALICE results seem to give different message but agree within uncertainties

$\Upsilon(nS)/\Upsilon(1S)$ Double Ratio in pPb

CMS, JHEP 04 (2014) 103

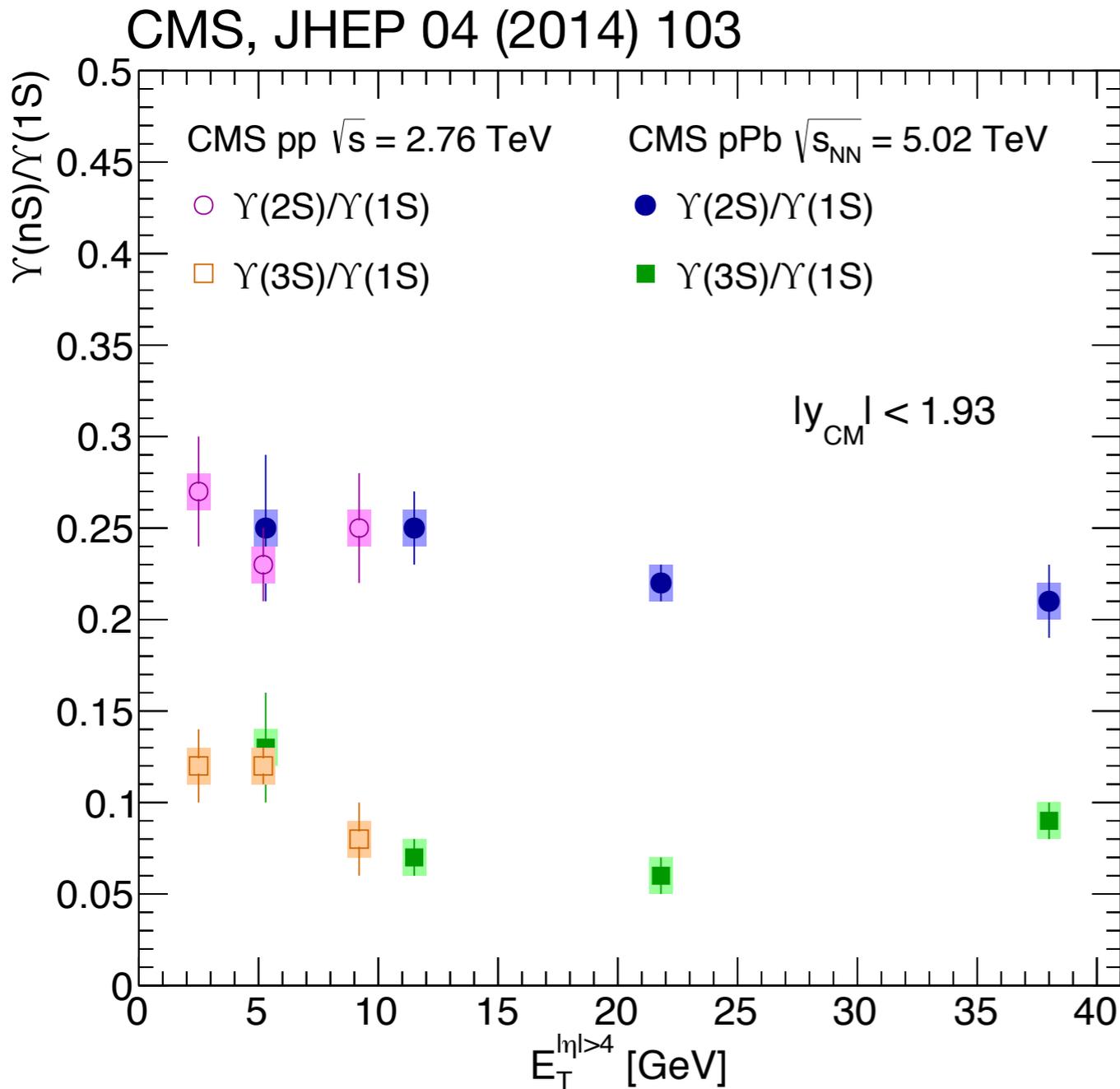


- Pb-Pb: PRL 109 (2012)
 - ▶ slightly different rapidity ($|y_{CM}| < 2.4$)
 - ▶ 2011 pp dataset
- Double ratios in p-Pb larger than in PbPb
 - ▶ suggests additional final effects in PbPb
 - ▶ but: model dependent extrapolation from pPb to PbPb
- p-Pb vs pp:
 - ▶ double ratio less than unity (significance $< 3\sigma$)

$\Upsilon(nS)/\Upsilon(1S)$ vs. “event activity”

Measure event activity at

- Forward rapidity ($4 < |\eta_{\text{lab}}| < 5.2$)
 - ▶ $\sum E_T$ in Hadronic Forward Calorimeter
 - ▶ **weak dependence**
 - ▶ independent sets consistent with flat



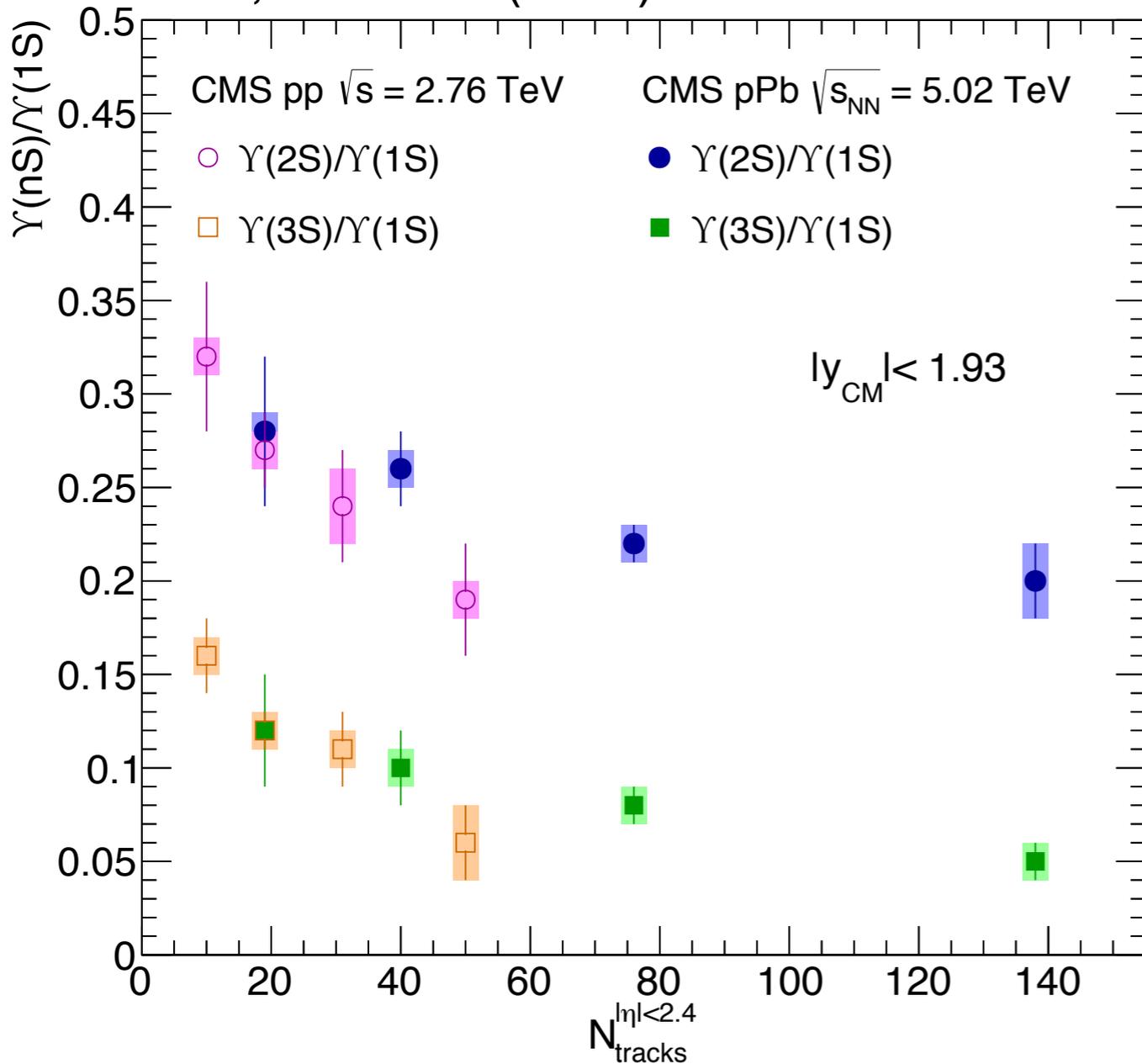
Single Ratios corrected for acceptance and efficiency

$\Upsilon(nS)/\Upsilon(1S)$ vs. “event activity”

Measure event activity at

- Forward rapidity ($4 < |\eta_{\text{lab}}| < 5.2$)
 - ▶ $\sum E_T$ in Hadronic Forward Calorimeter
 - ▶ weak dependence
 - ▶ independent sets consistent with flat
- Midrapidity ($|\eta_{\text{lab}}| < 2.4$)
 - ▶ N_{tracks} : multiplicity in silicon tracker
 - ▶ significant decrease with multiplicity
- Two options to explain results at midrapidity:
 - ▶ Υ affects multiplicity
 - ground states comes with 2 tracks more than excited state
 - ▶ multiplicity affects Υ
 - activity around the Υ breaks the state (comovers?)
- Consequences for PbPb?!

CMS, JHEP 04 (2014) 103



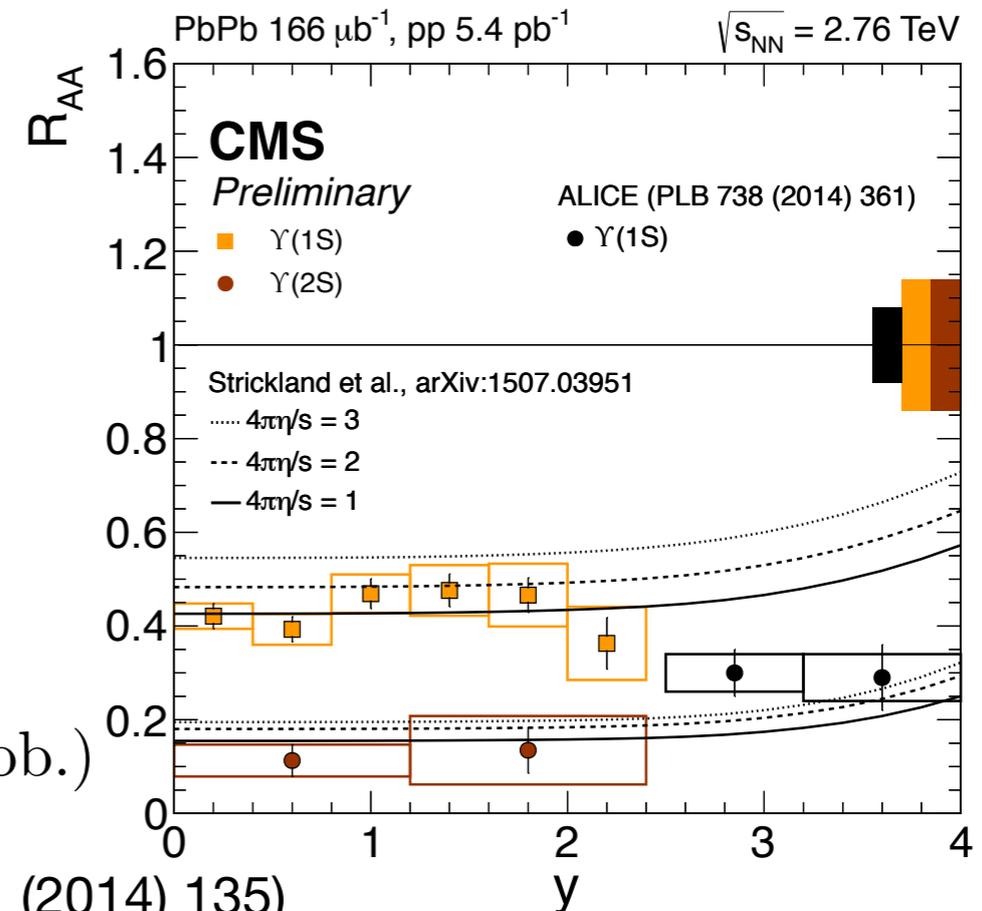
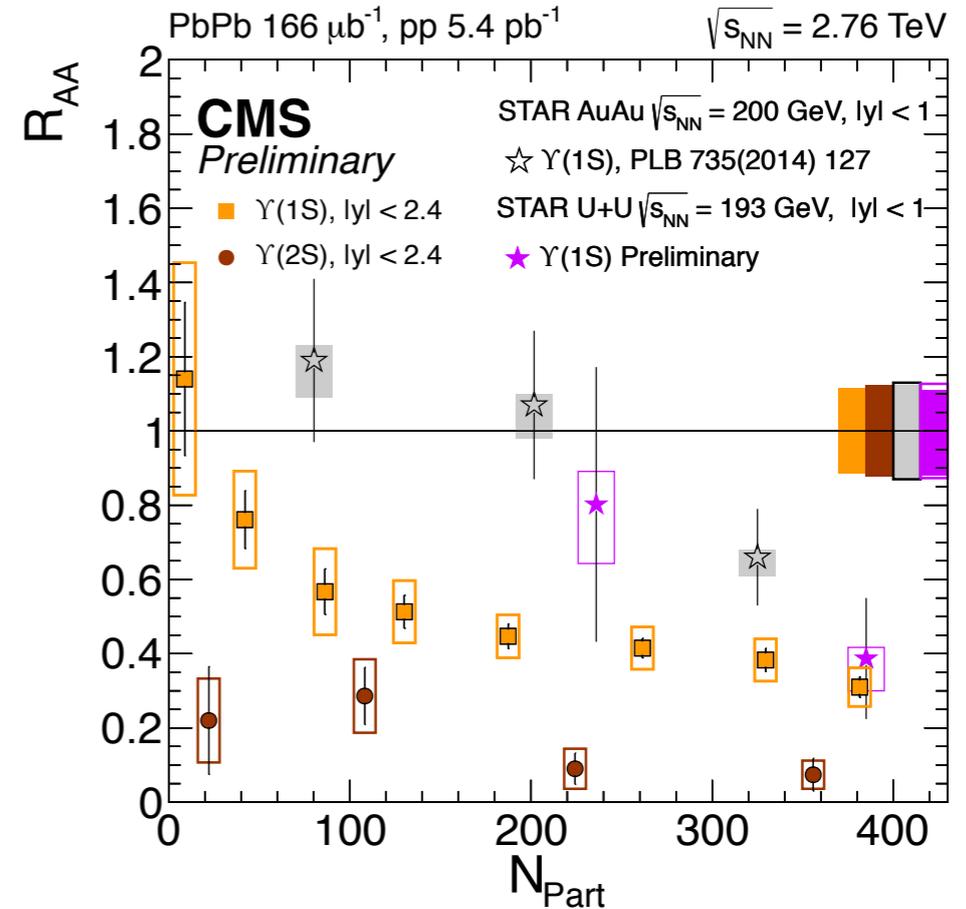
Single Ratios corrected for acceptance and efficiency

$\Upsilon(nS)$ in Pb-Pb

- At the LHC, $\Upsilon(1S)$ already suppressed in semi-peripheral collisions
 - ▶ at RHIC only in central collisions
- $\Upsilon(1S)$ suppression in most central collisions might be larger than just lack of feed-down
 - ▶ feed-down fraction 30–40% but large uncertainties
- More suppression at forward than at midrapidity
 - ▶ Same story as charmonia at RHIC?
 - ▶ recombination also for bottomonia
 - ▶ ~ 2 bb pairs per event but 10x smaller closed/open ratio than charm
- Note on $\Upsilon(2S)$, CMS measured:

$$\frac{\sigma(\Upsilon(2S))}{\sigma(\Upsilon(1S))} = 0.09 \pm 0.02(\text{stat.}) \pm 0.02(\text{syst.}) \pm 0.01(\text{glob.})$$

- ▶ stat. hadronization: 0.032 (Andronic, NPA 931 (2014) 135)

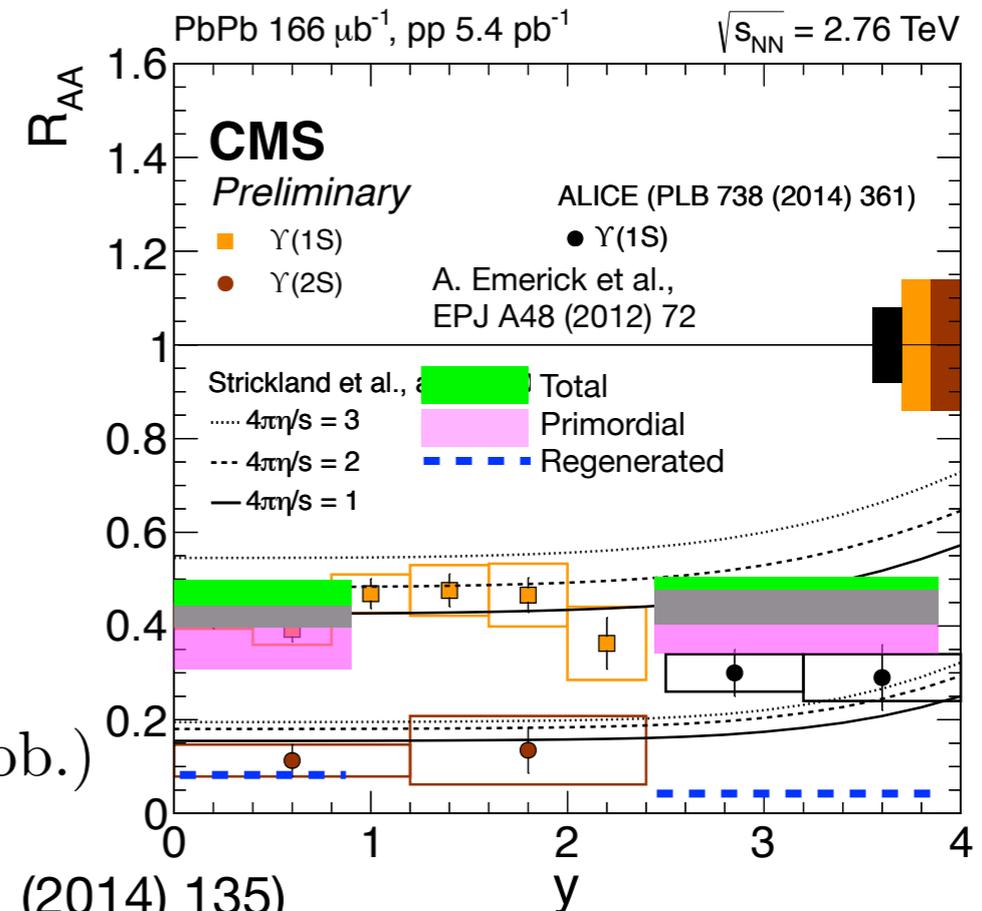
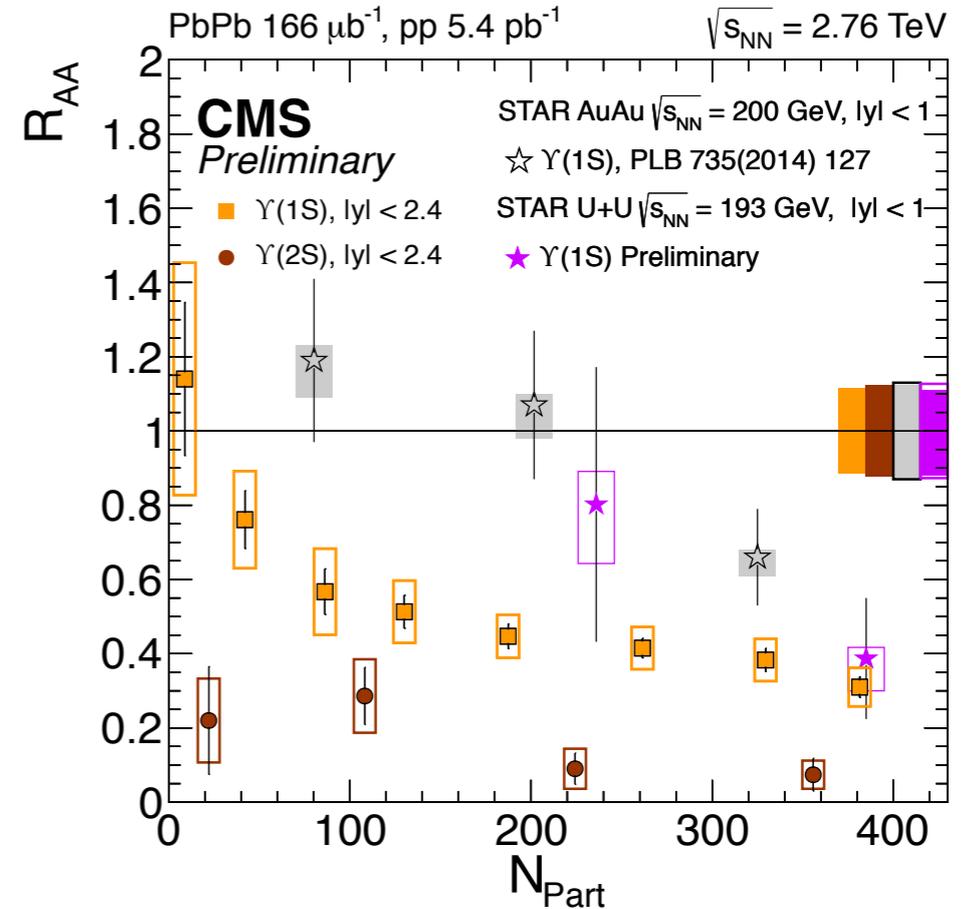


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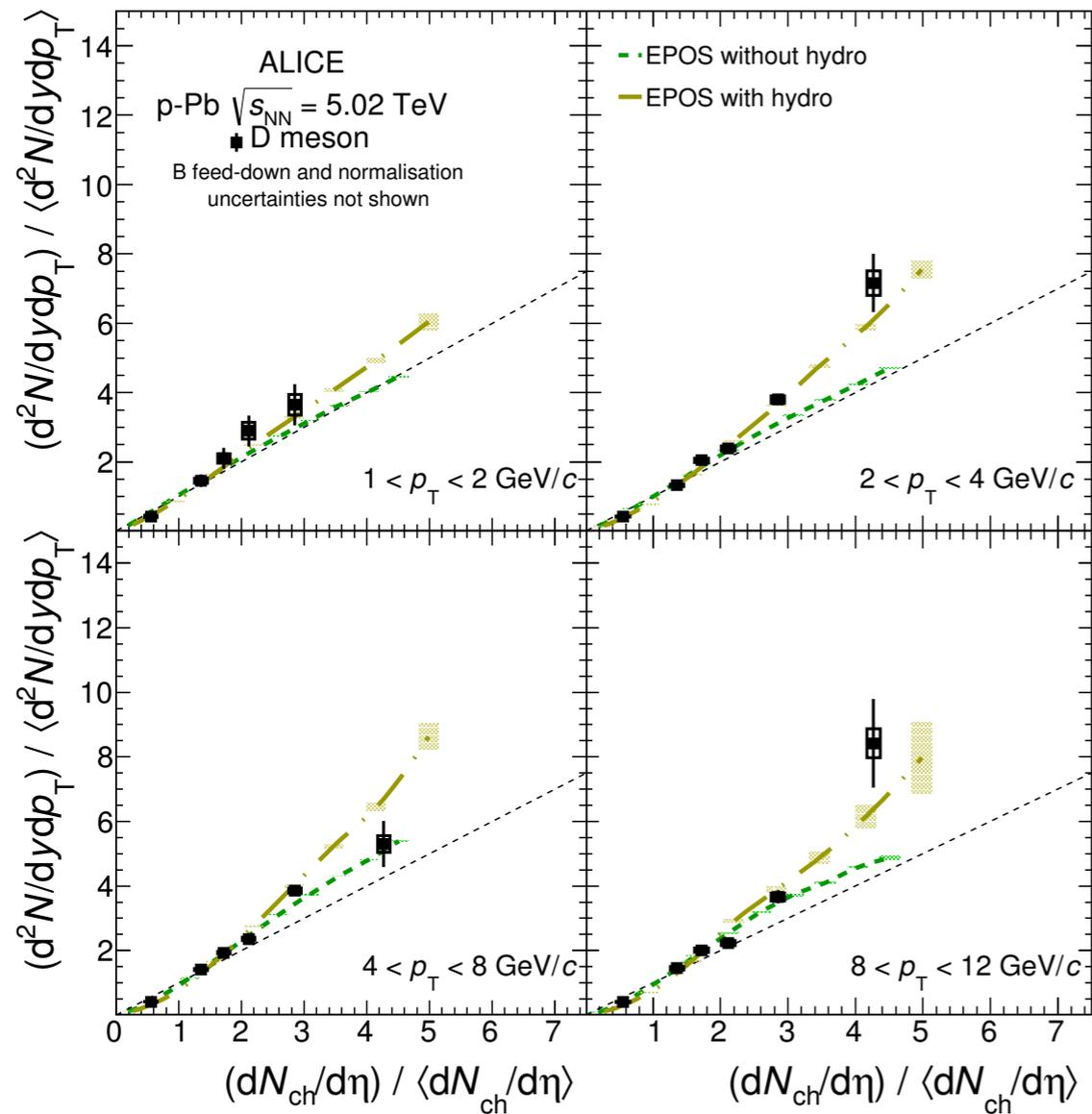


Summary

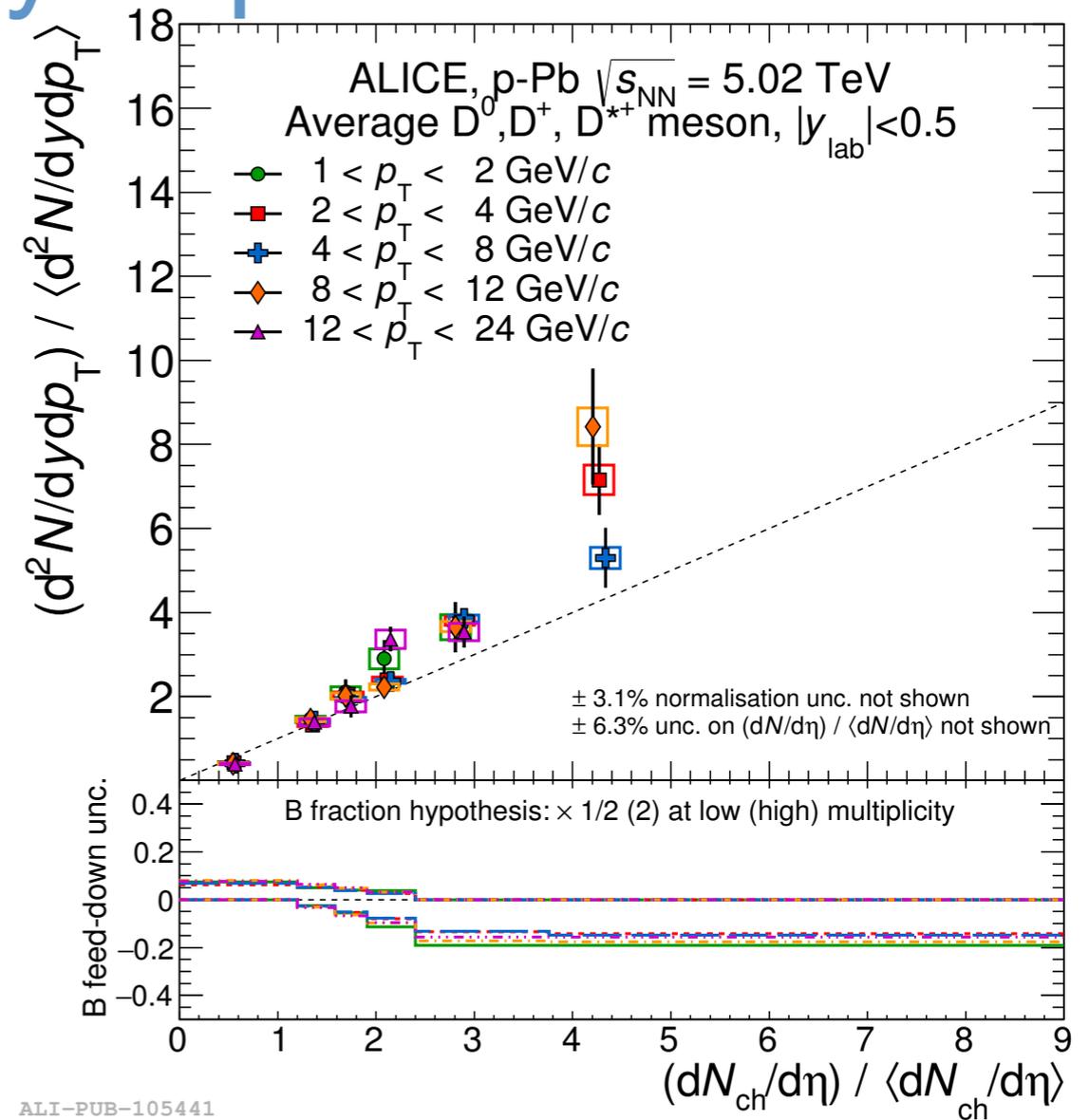
- Things I didn't have time to talk about:
 - ▶ (di)leptons from semileptonic HF decays
 - ▶ D-hadron correlations
 - ▶ Multiplicity dependence of HF production...
- Open Heavy Flavor
 - ▶ p-Pb data consistent with gluon shadowing
 - ▶ mass dependent heavy quark energy loss models well observed D and B R_{AA}
 - ▶ high p_T charm looks "light"
- Quarkonia
 - ▶ p-Pb: quarkonium data point towards some kind of comover effects
 - ▶ Pb-Pb: some form of regeneration seems present, precise measurements of excited states crucial to kill models
 - ▶ Is the $\Upsilon(1S)$ the new J/ψ ?
- Last but not least:
 - ▶ interesting program started at LHCb using SMOG: LHCb as a fixed-target experiment at midrapidity with p-gas and Pb-gas collisions in RHIC energy range

Backup

D vs. multiplicity in p-Pb

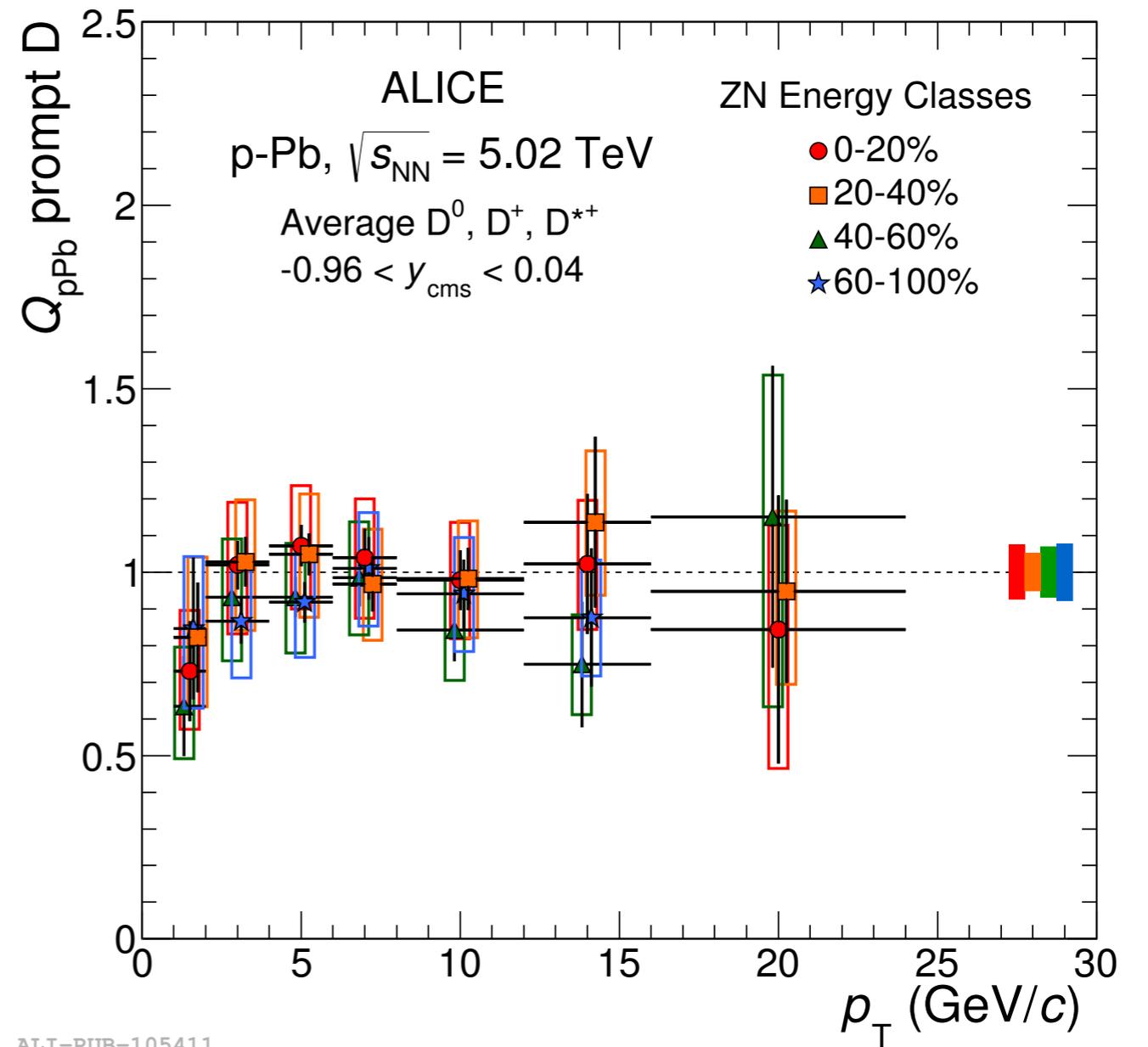


ALI-PUB-105465

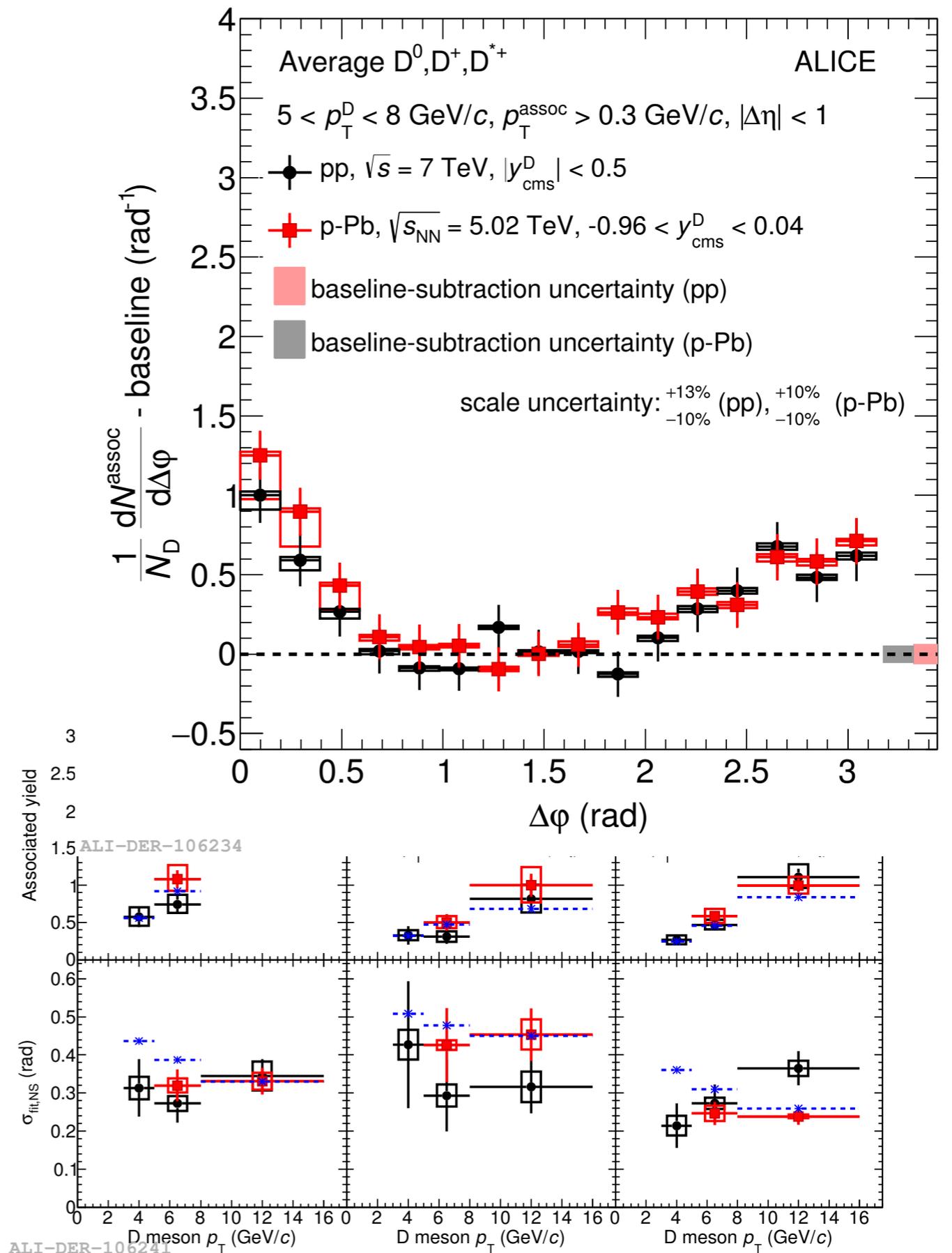


ALI-PUB-105441

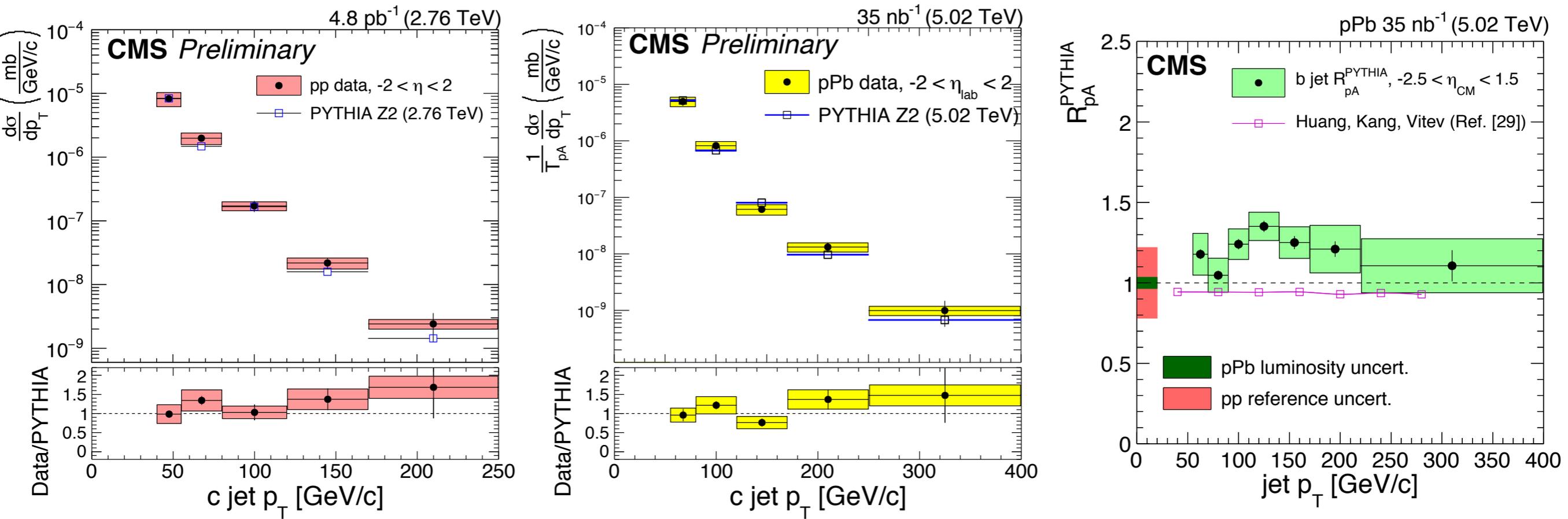
ALICE: D centrality dependence in



ALICE: D-h correlations in pp and p-Pb

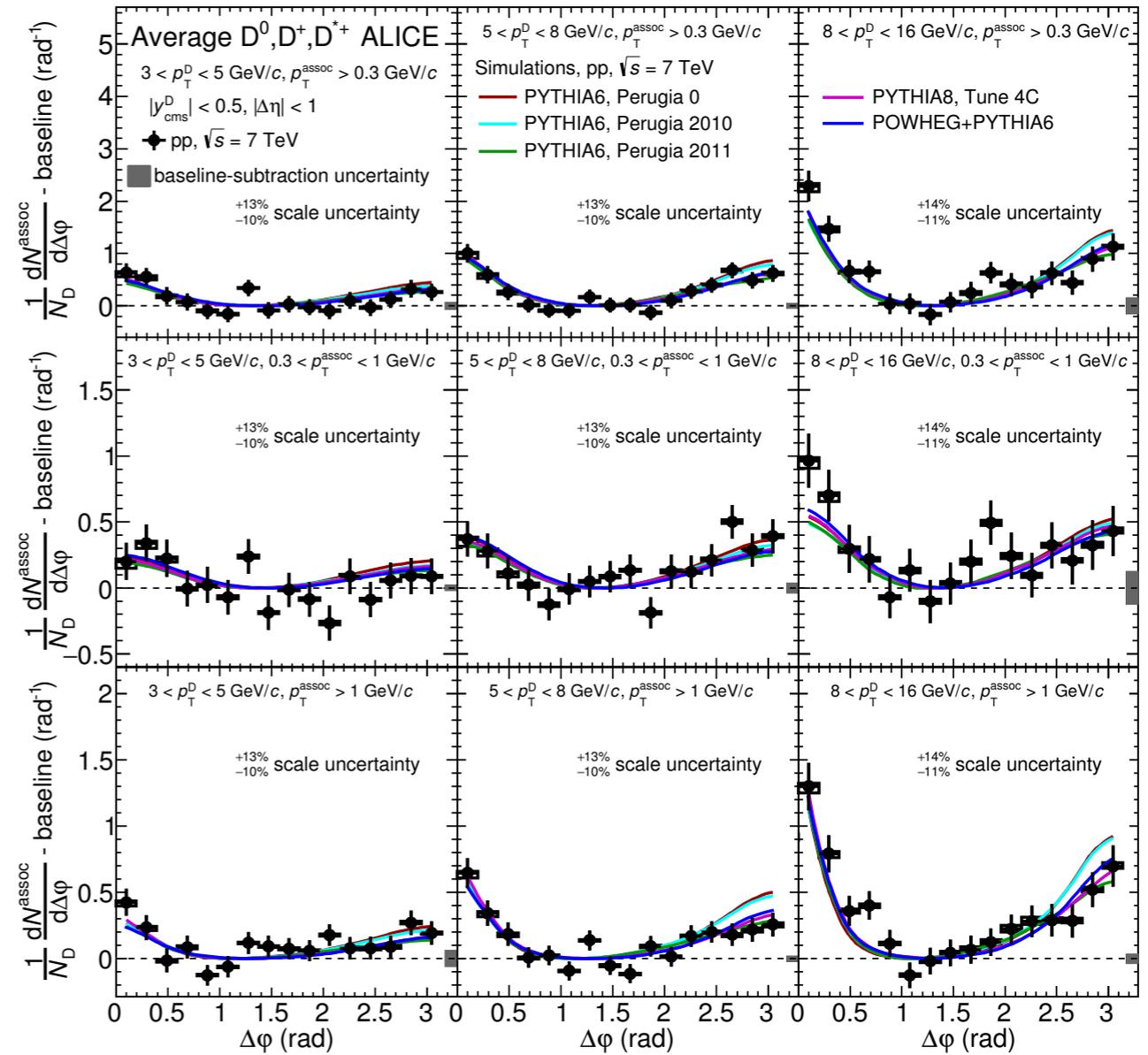


Heavy Flavor Jets in p-Pb



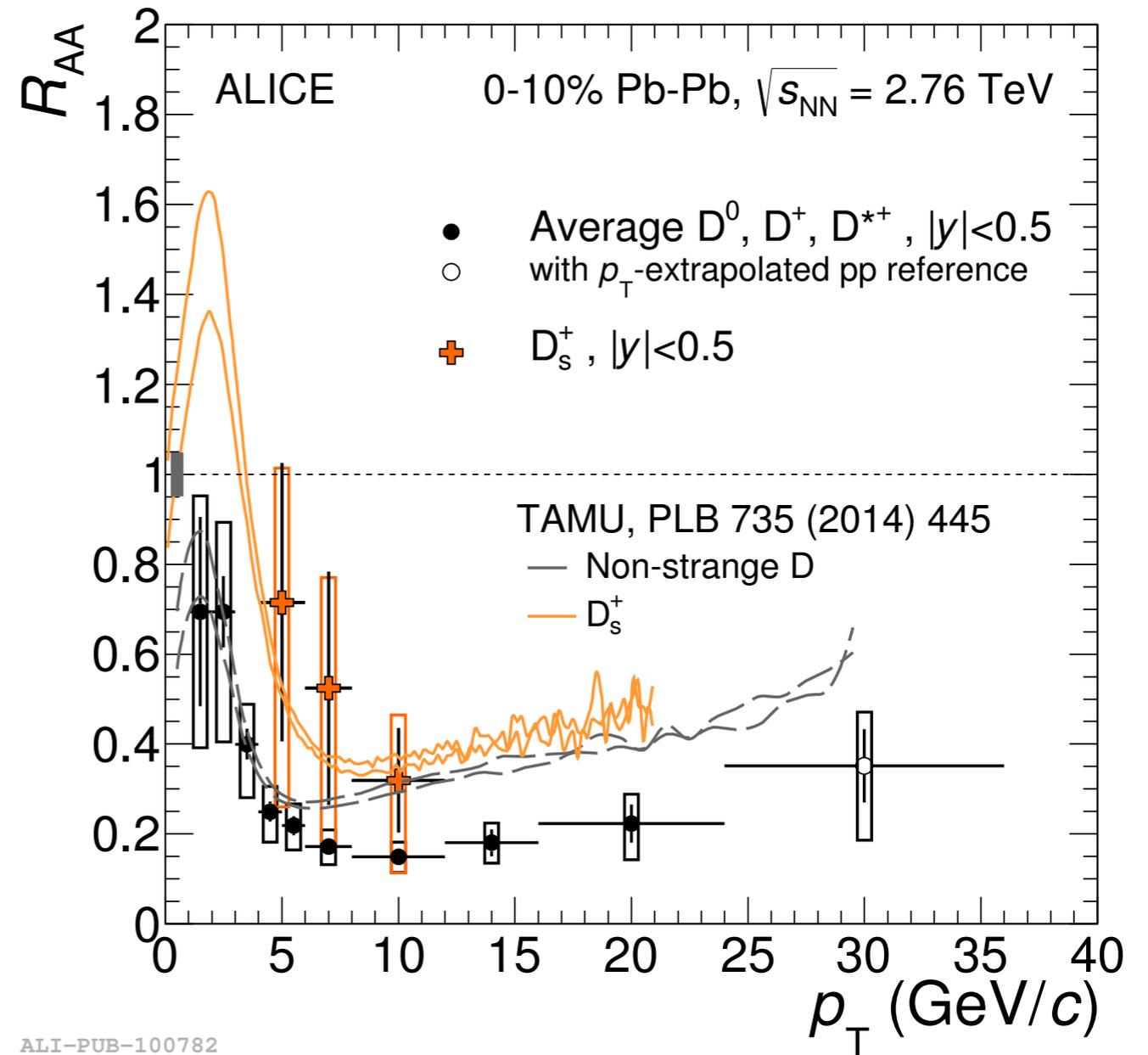
- No significant modification of charm jets in p-Pb
- No significant modification of bottom jets in p-Pb within large uncertainty of pp reference

ALICE: D-h correlations



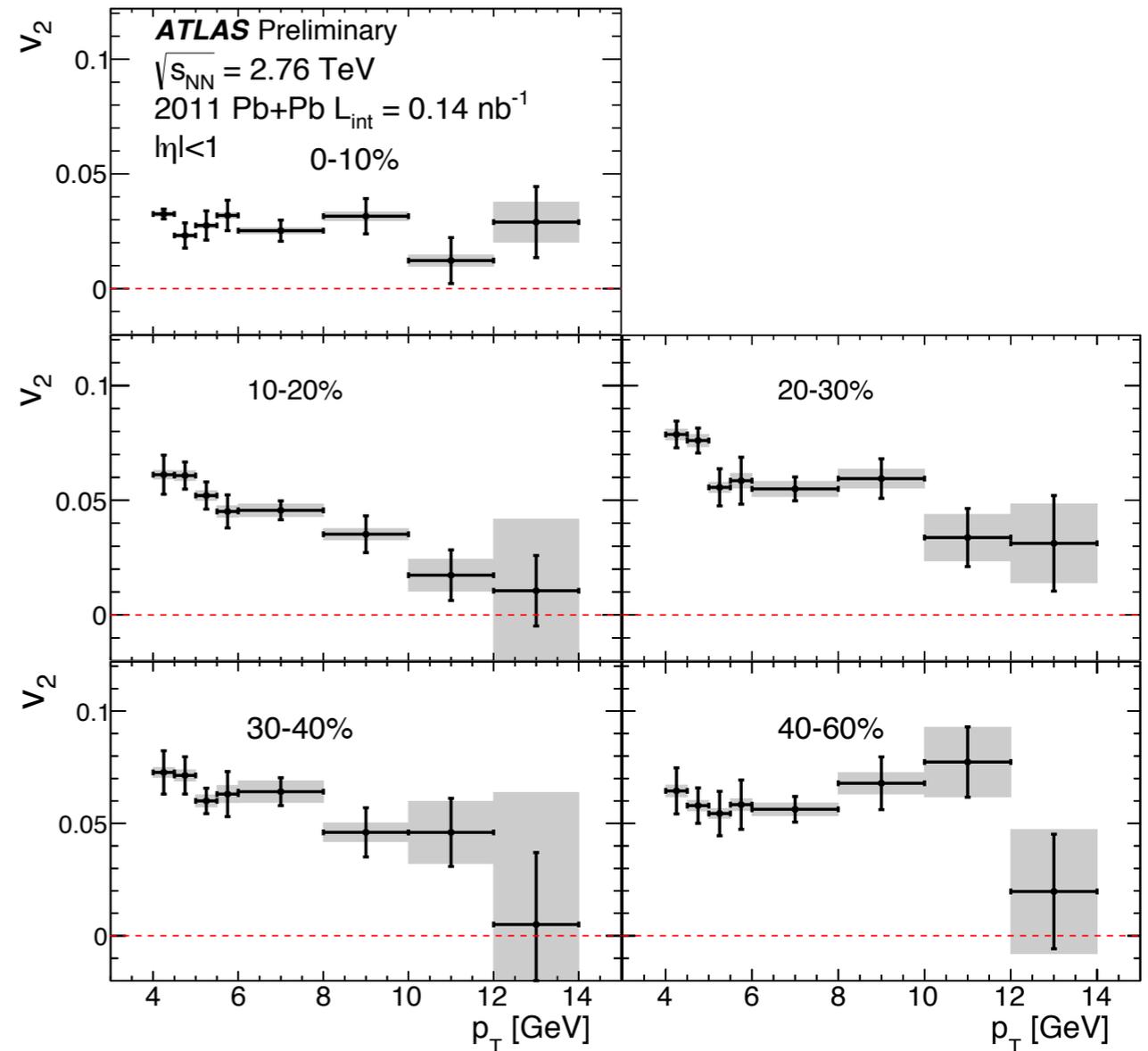
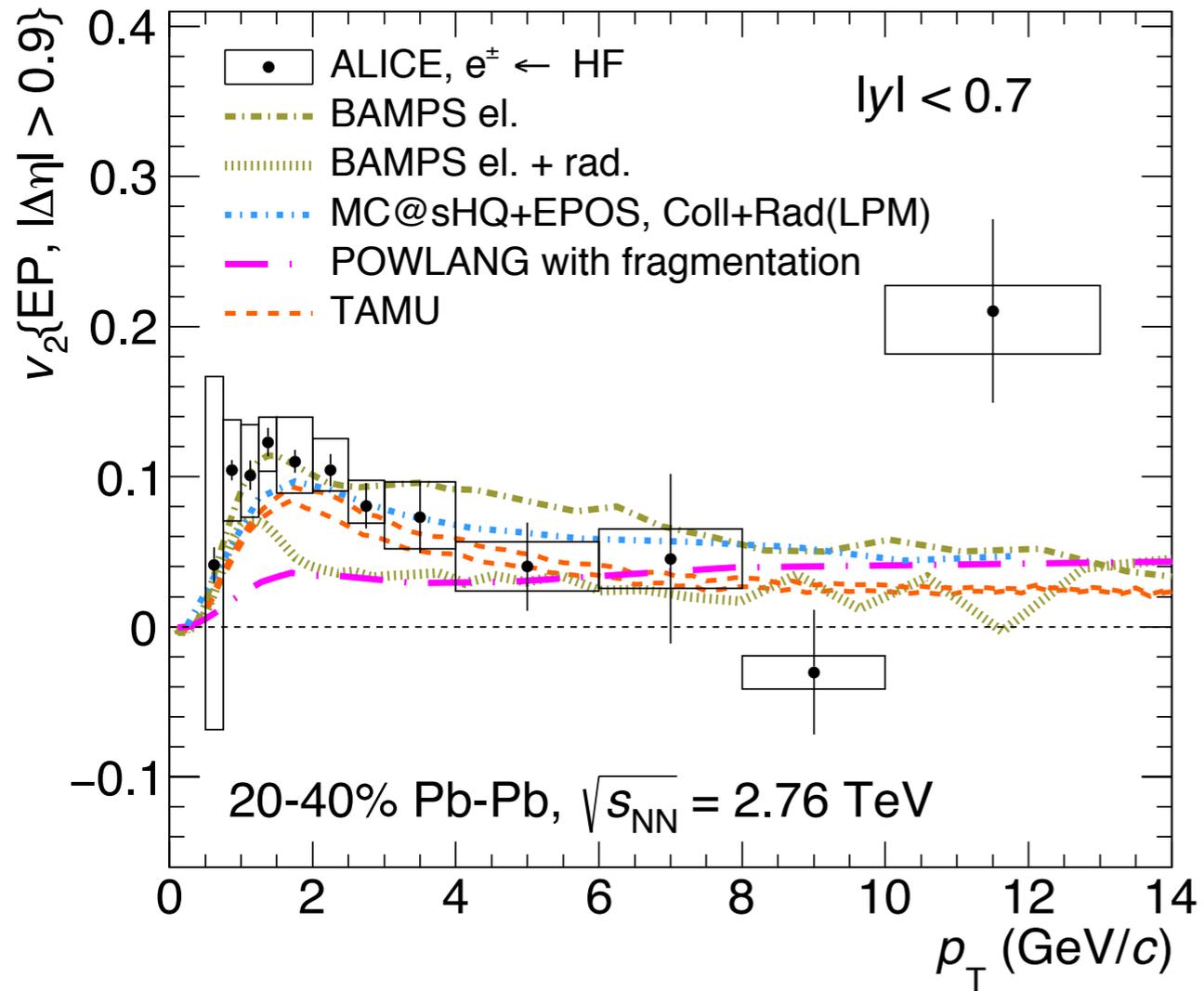
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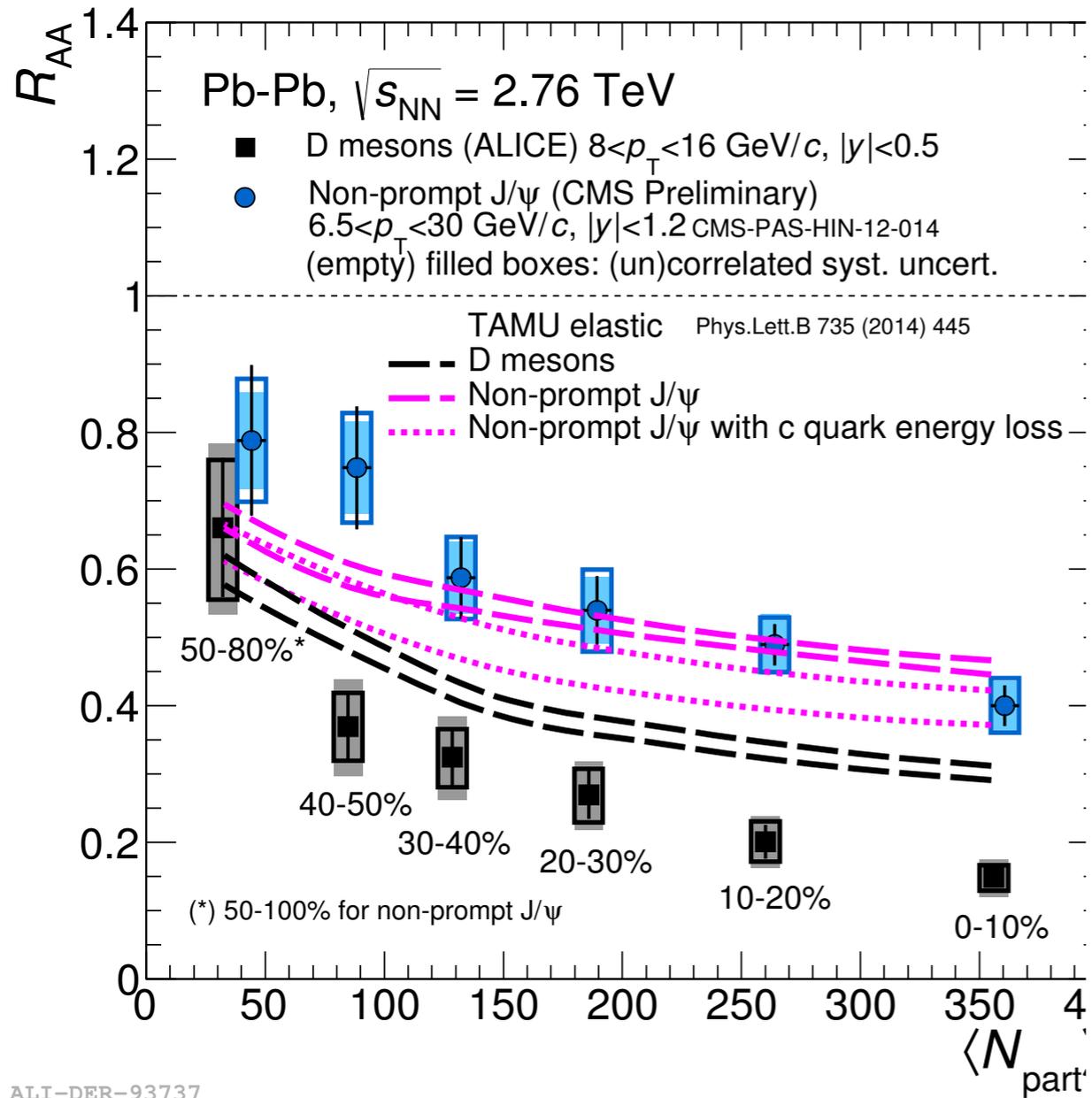
Model comparison: D vs Ds R_{AA}



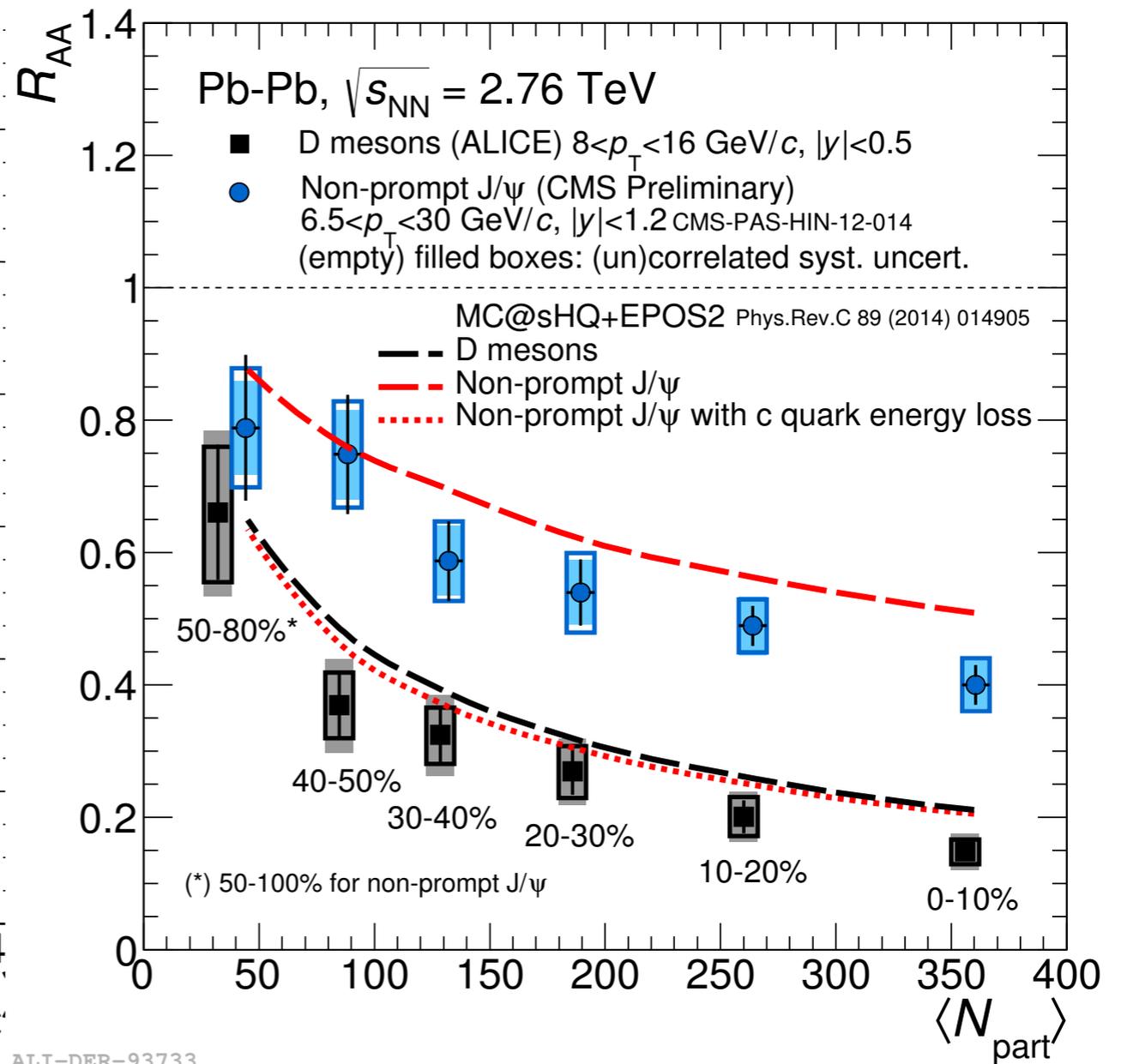
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Electrons from HF decays



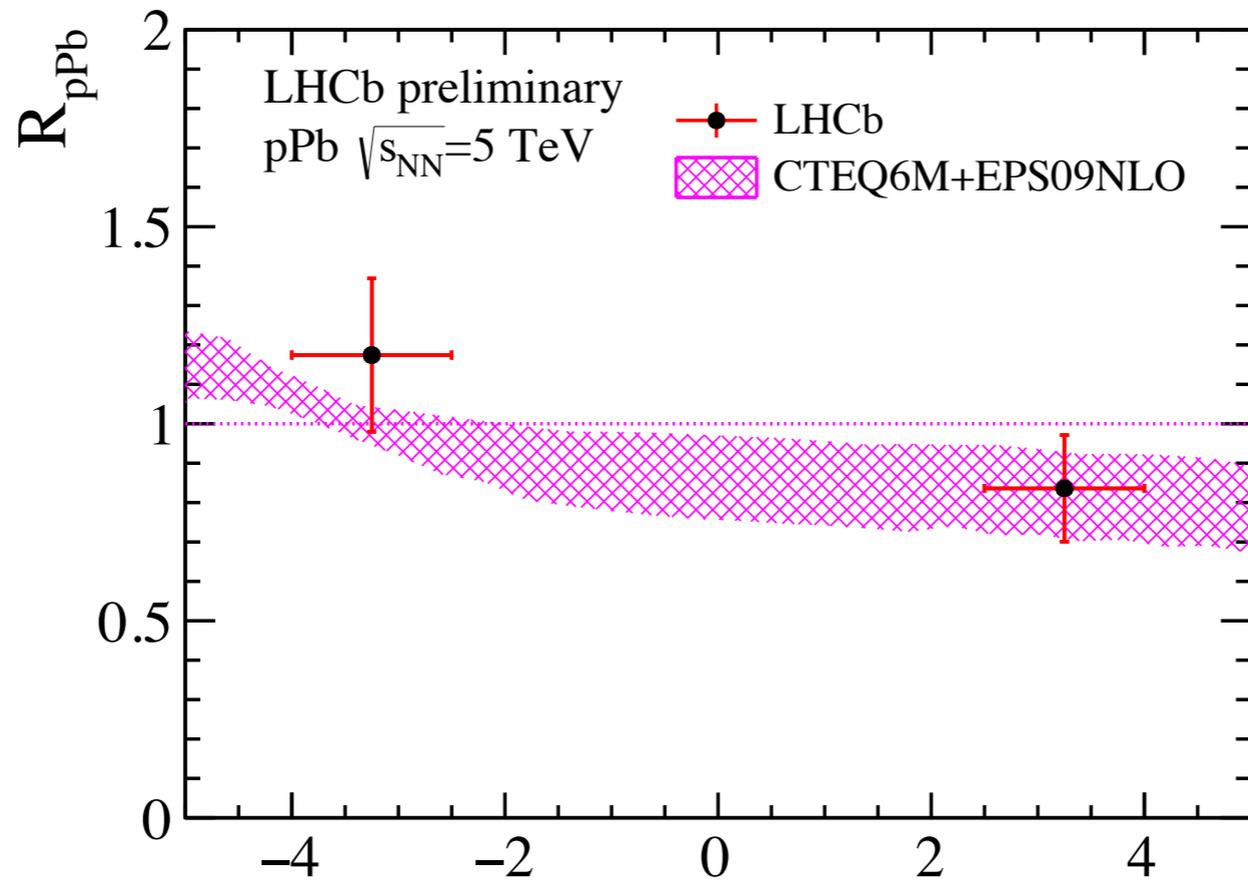
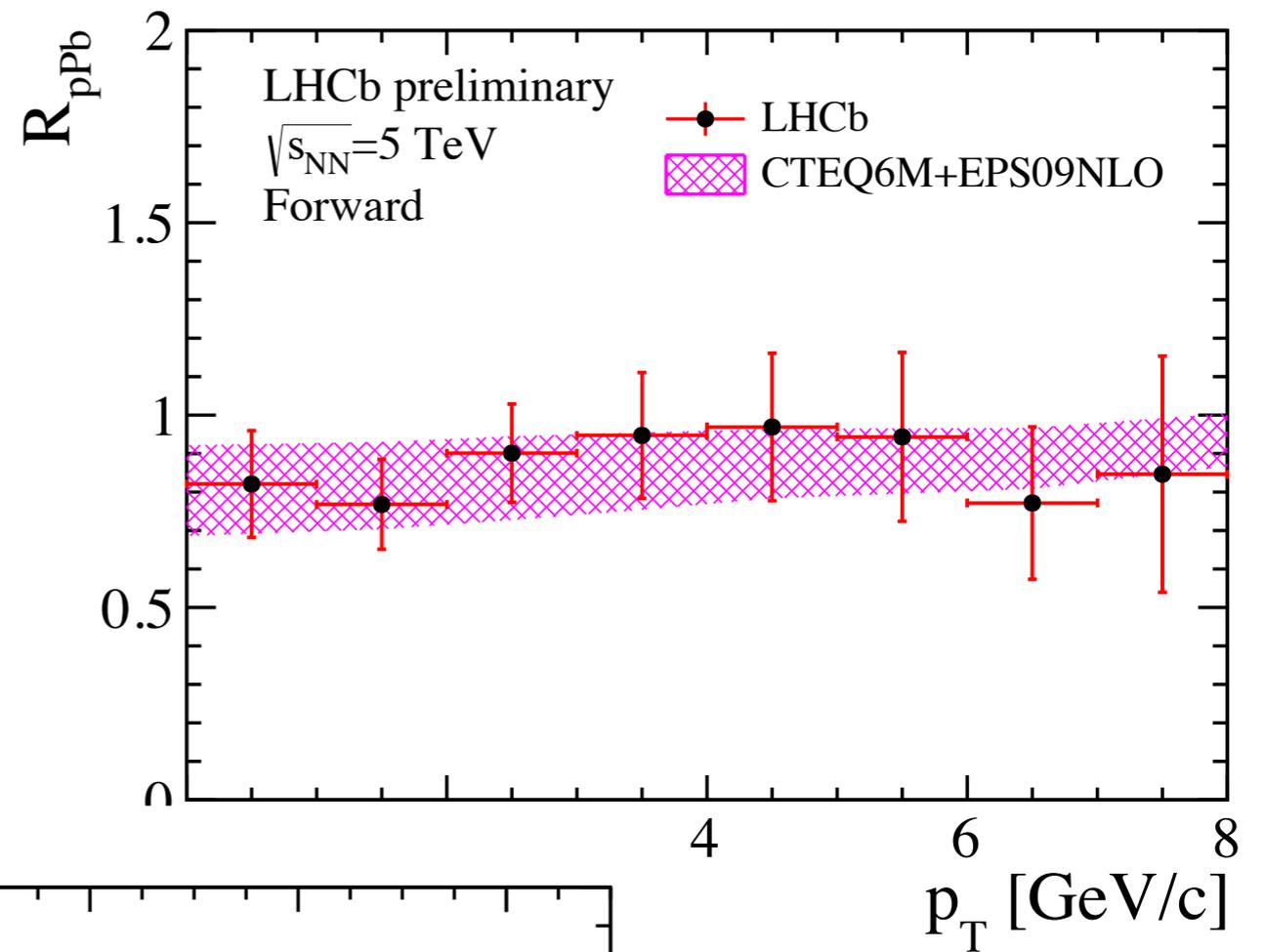
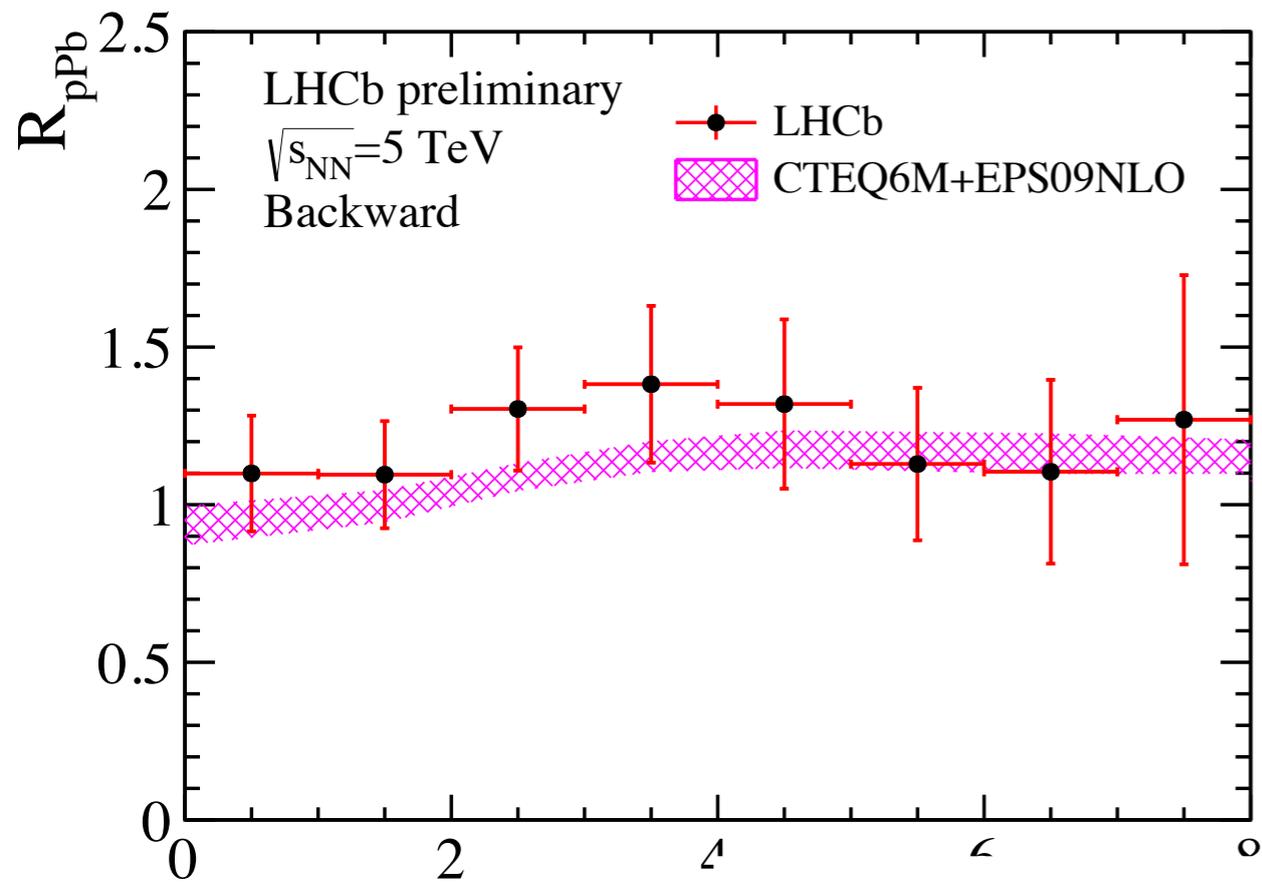


ALI-DER-93737

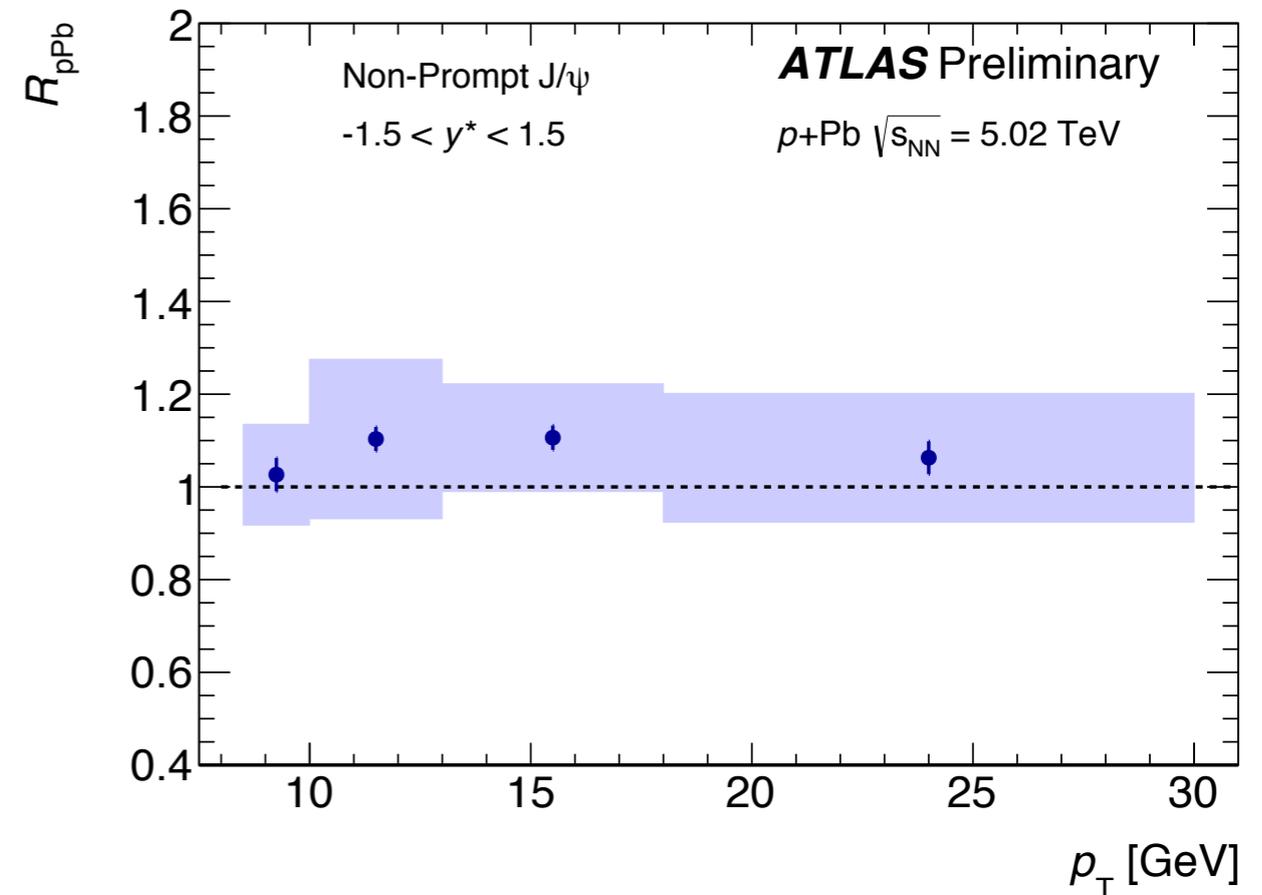
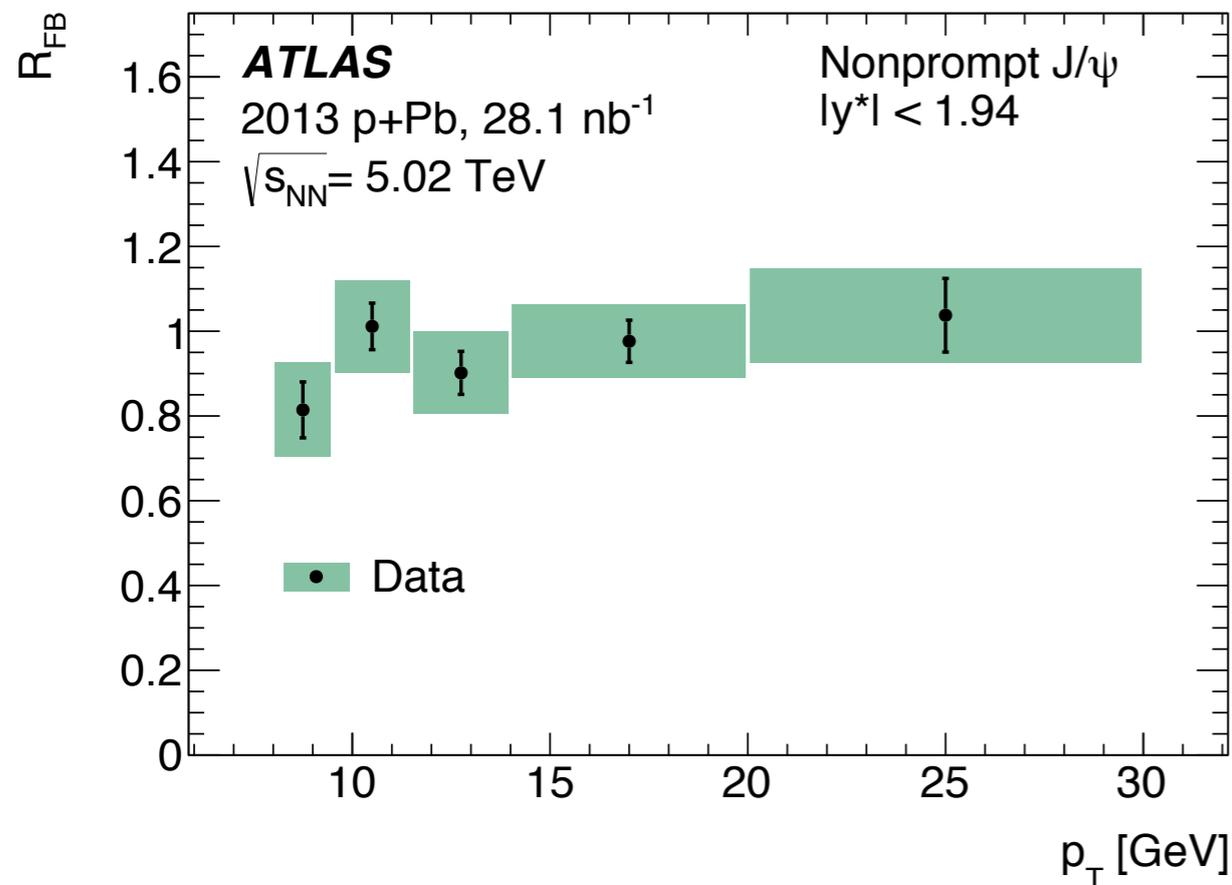
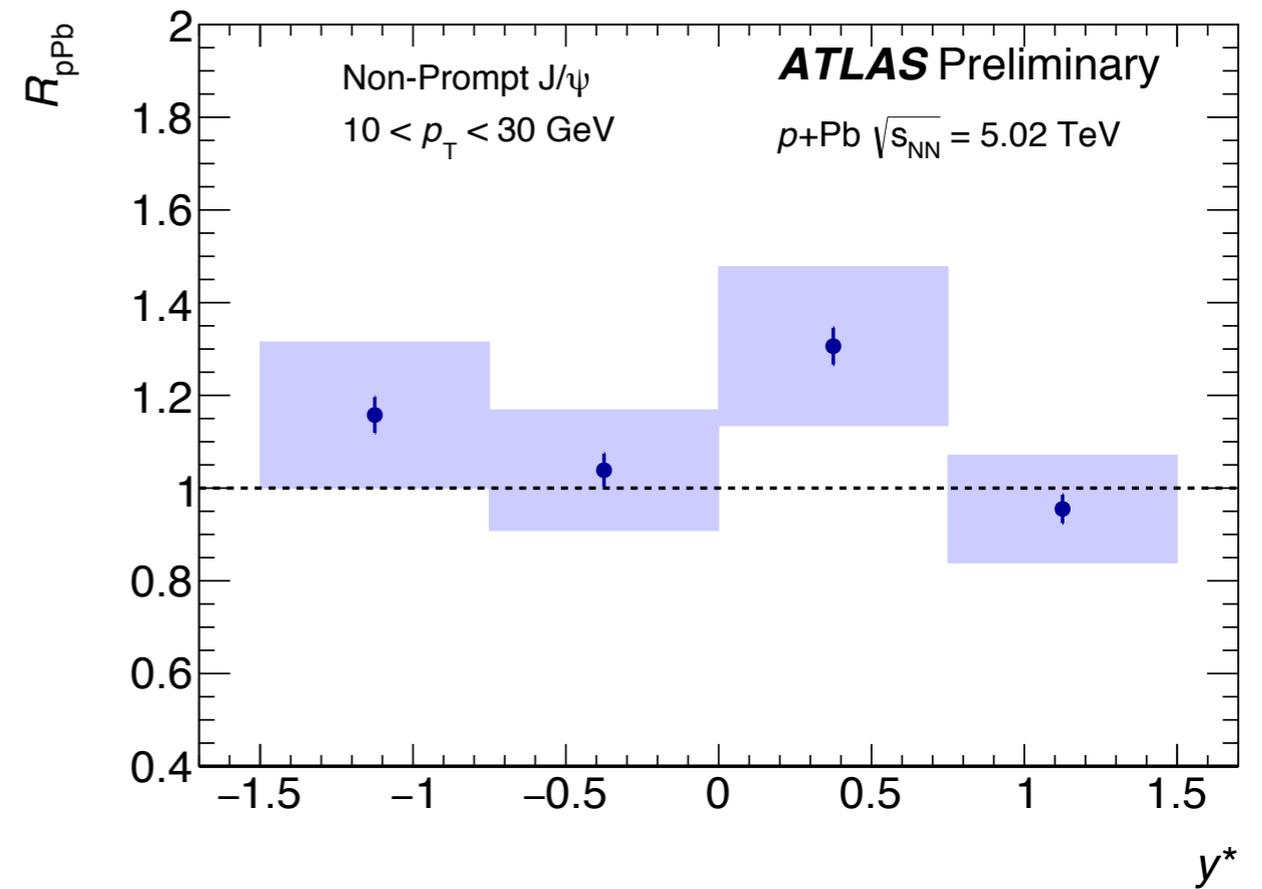
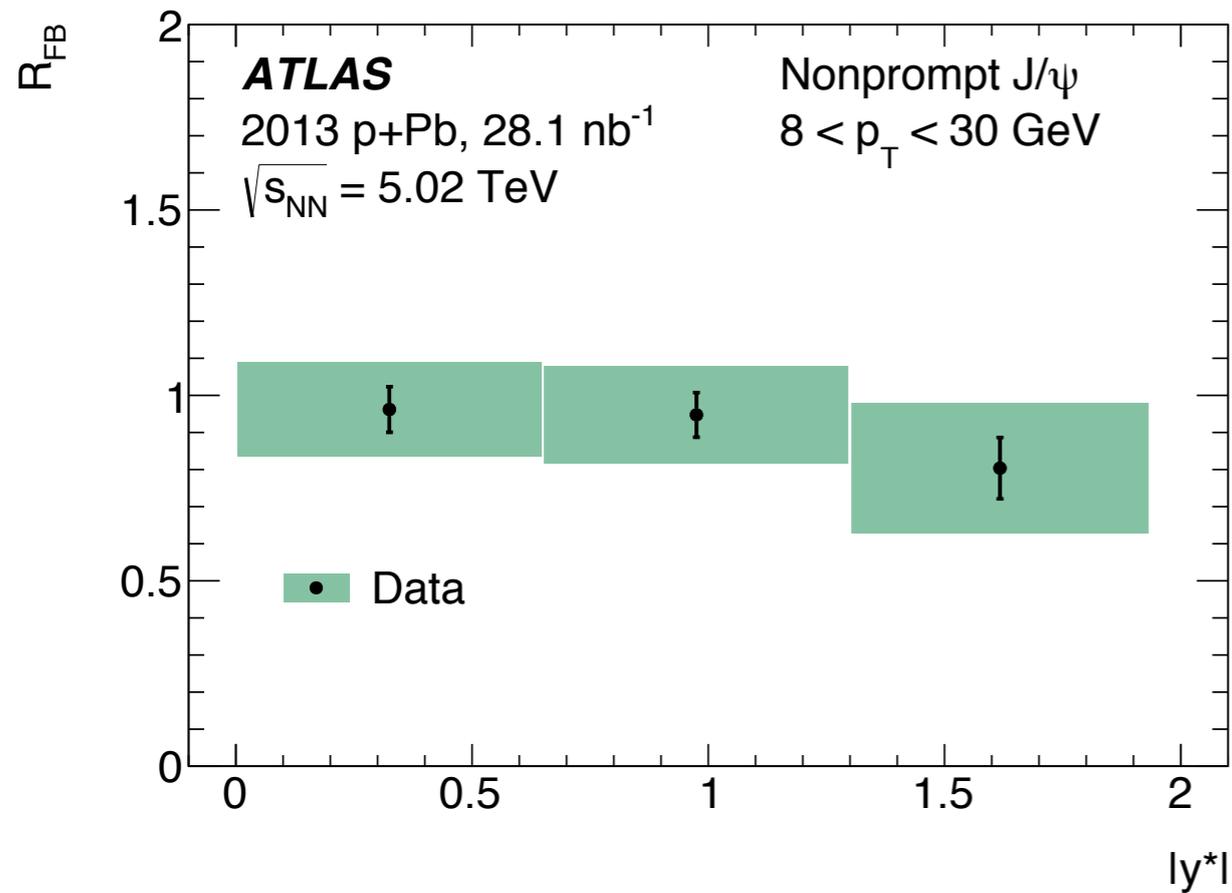


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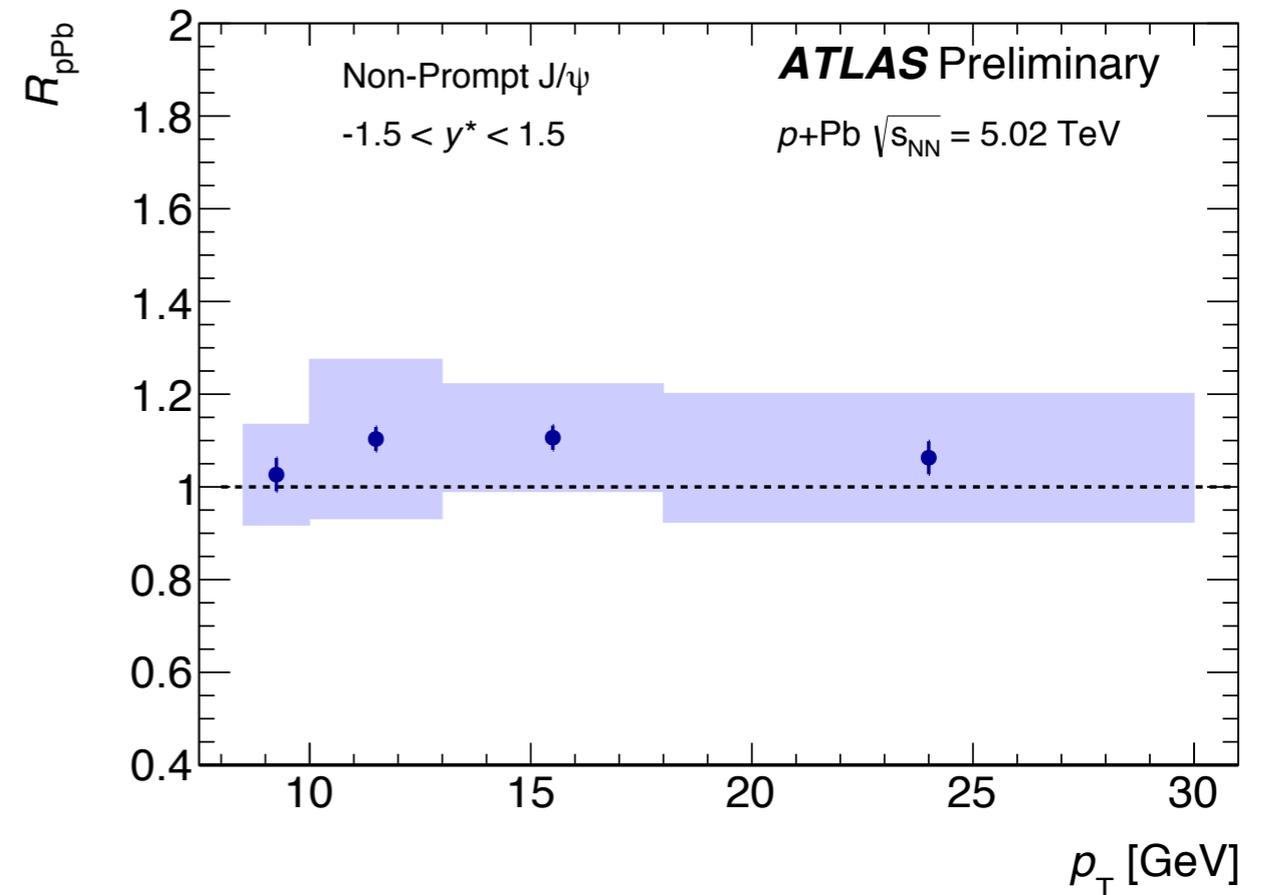
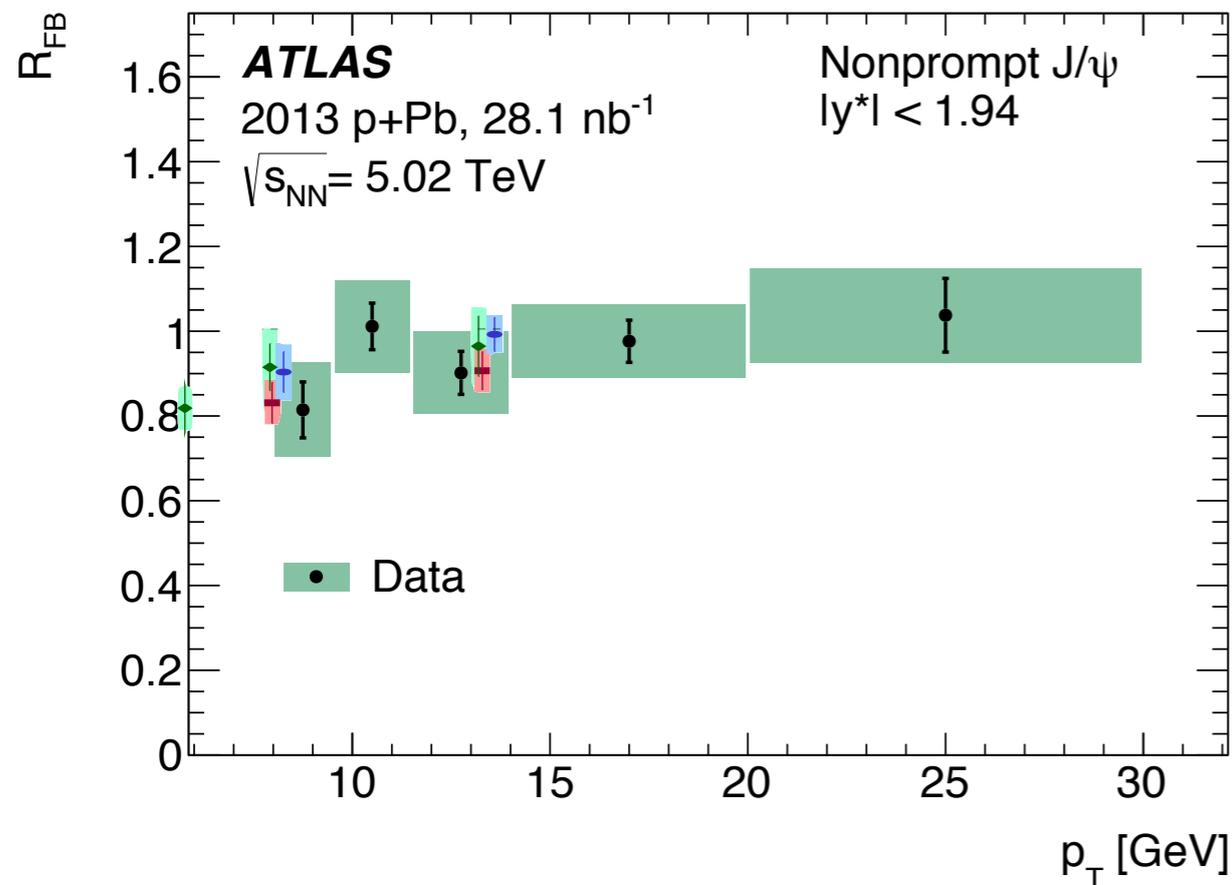
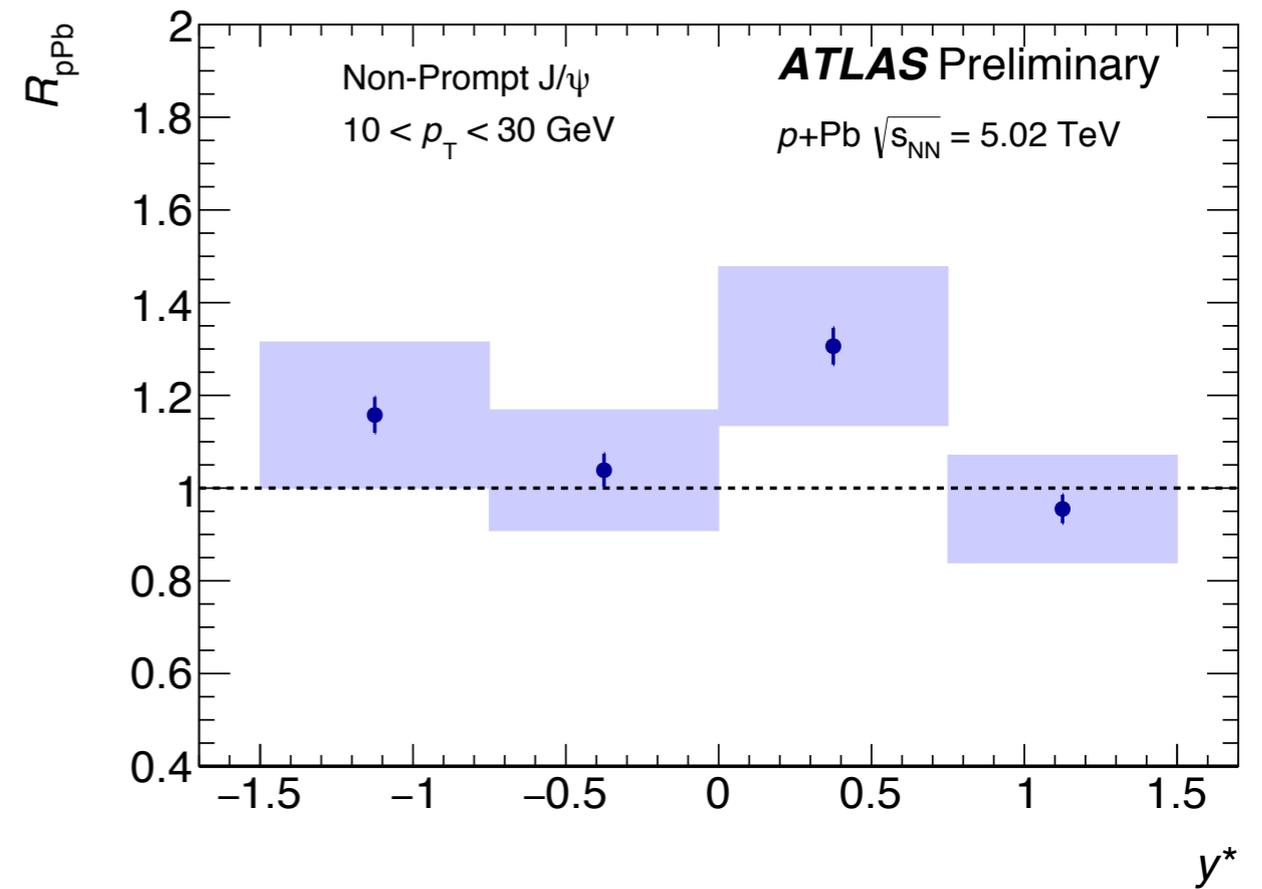
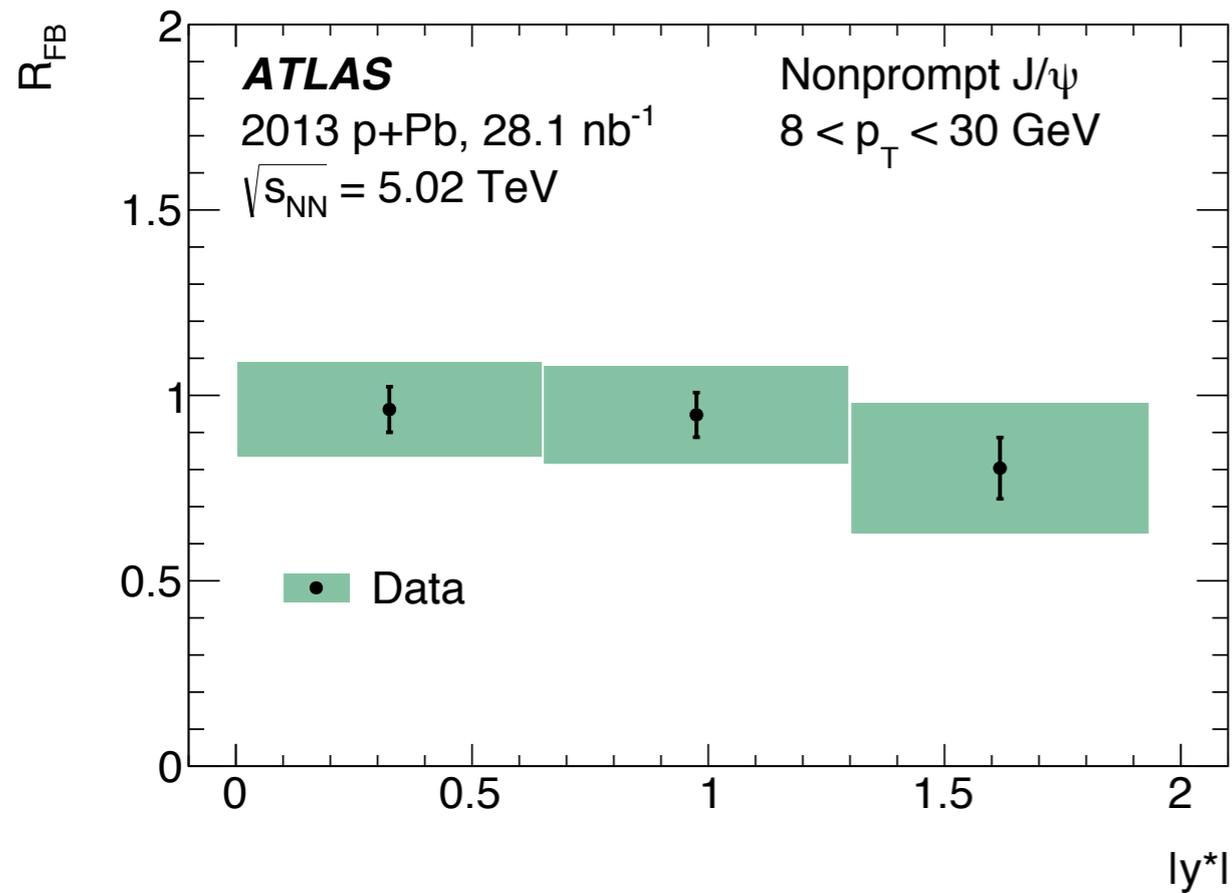
I HCh-D in p-Pb



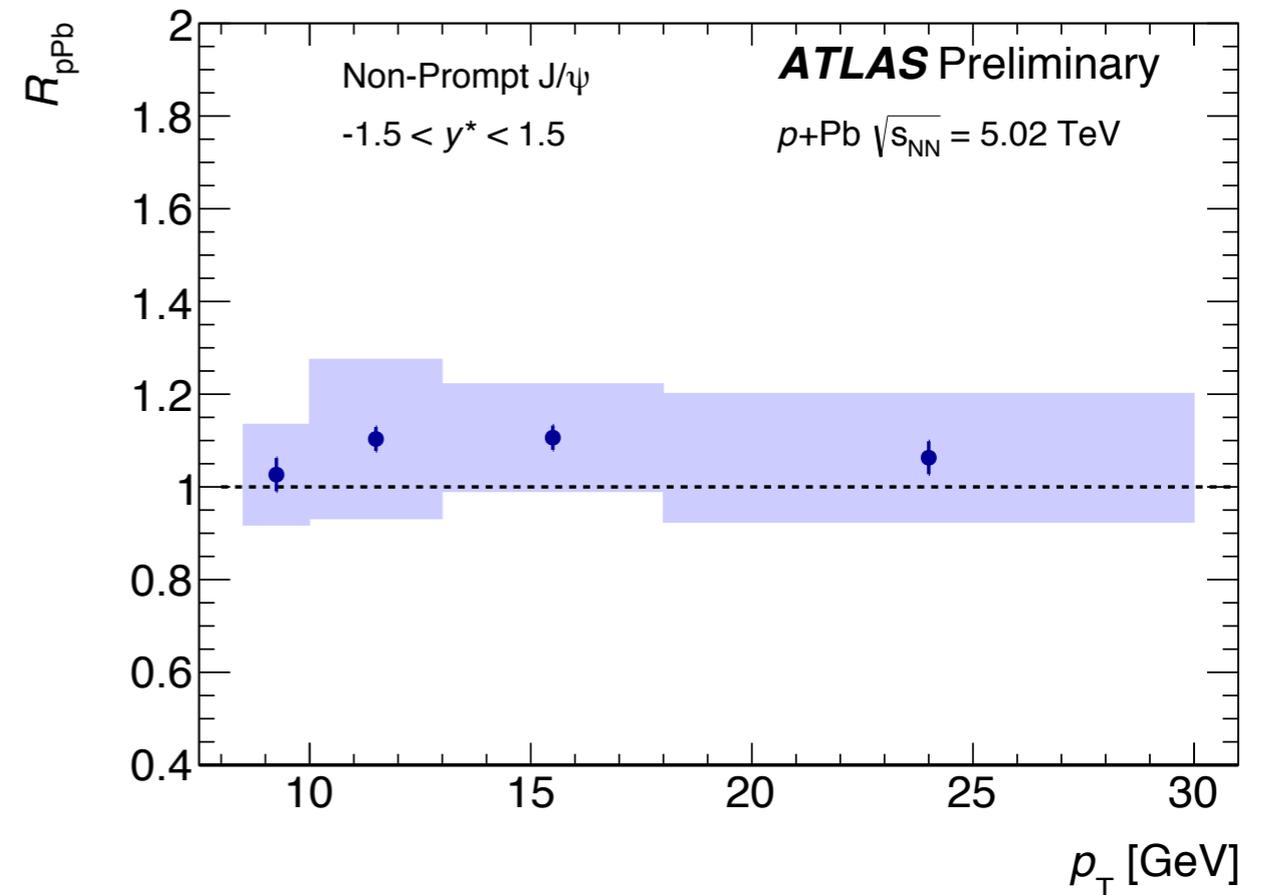
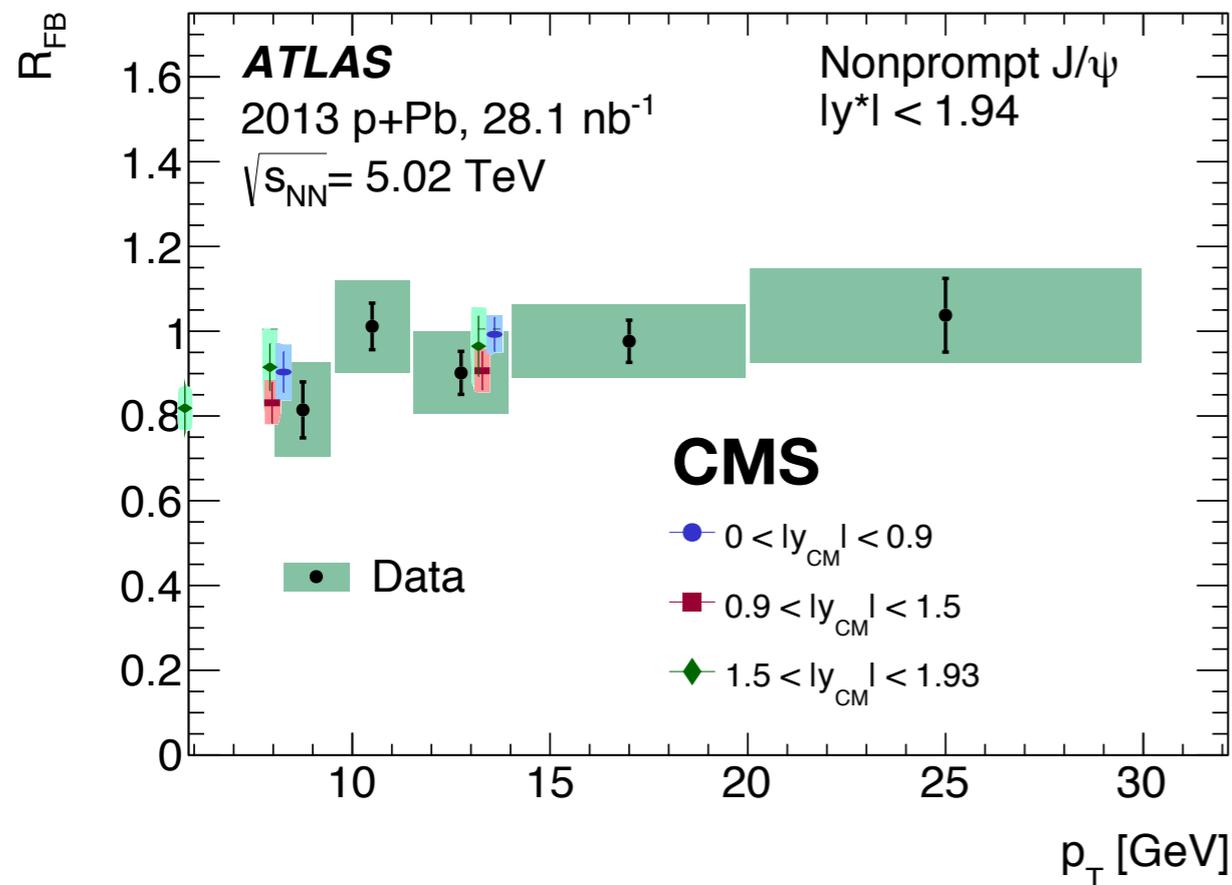
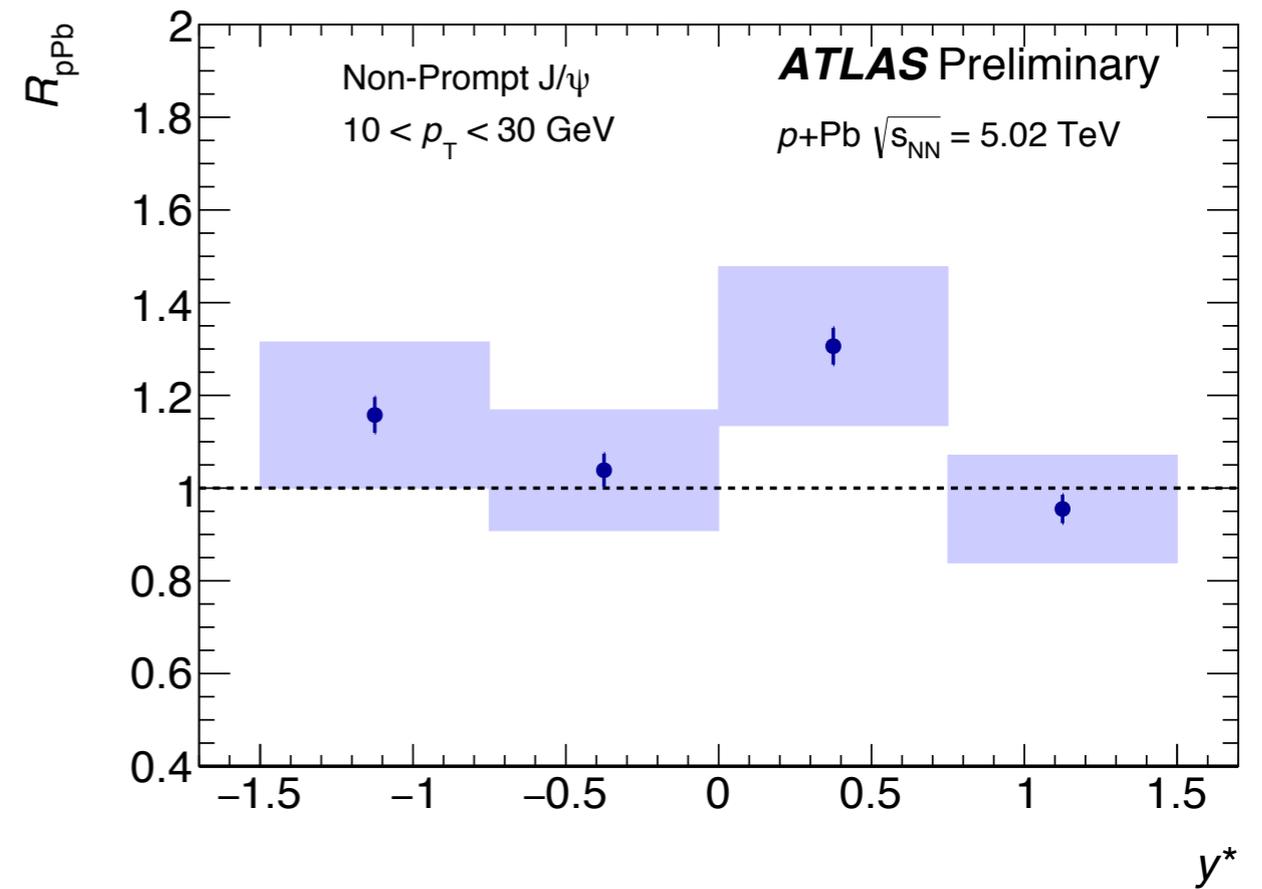
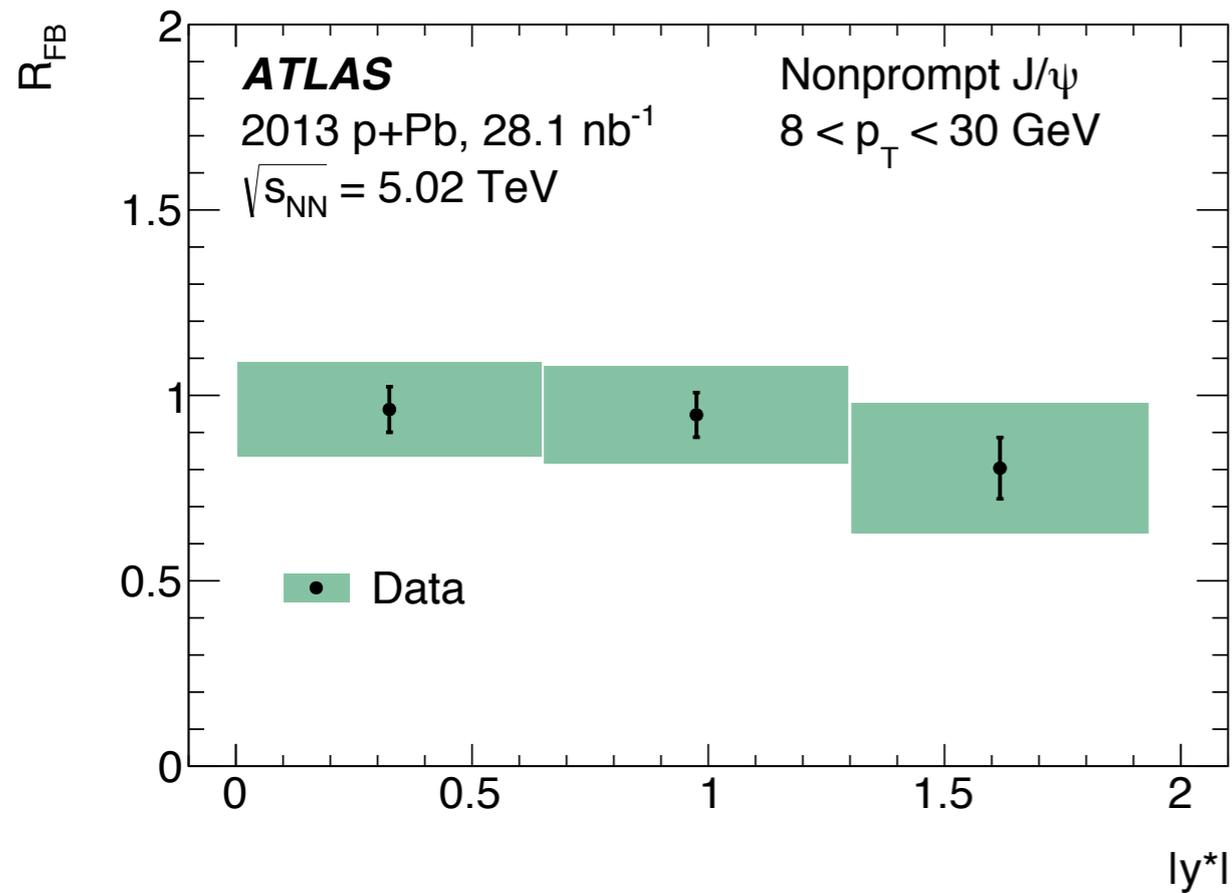
ATLAS: B in pPb



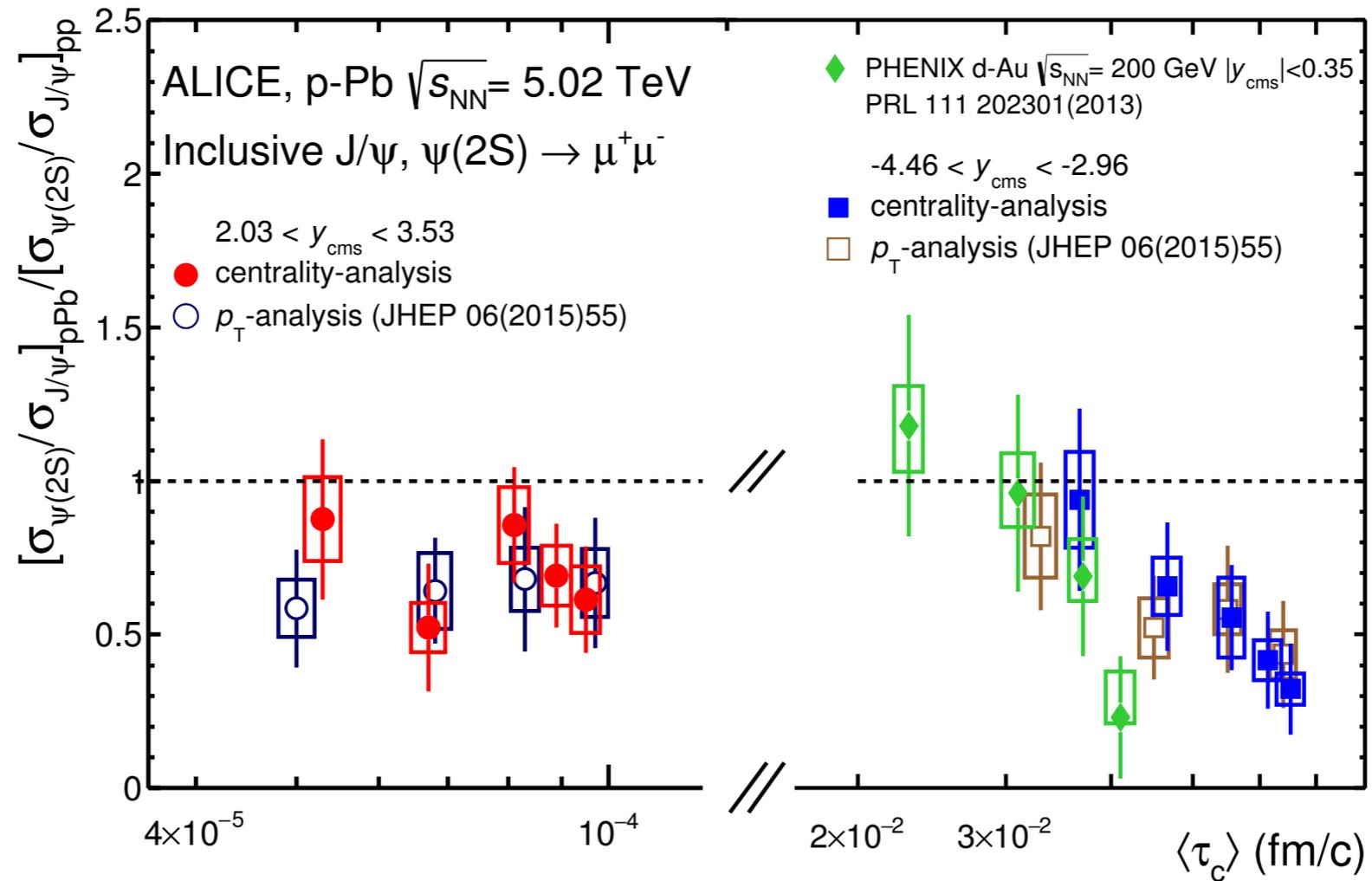
ATLAS: B in pPb



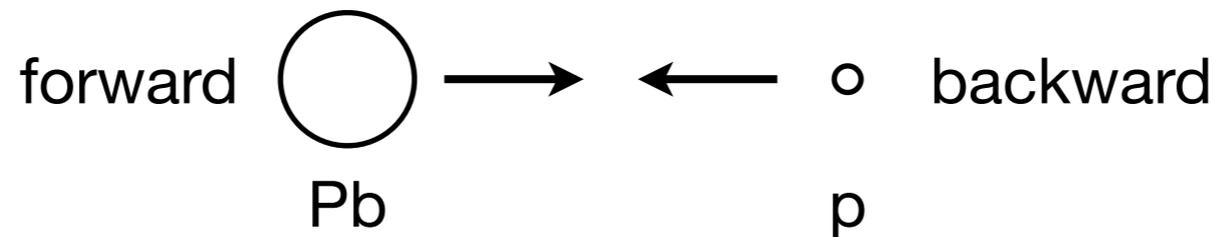
ATLAS: B in pPb



ALICE: $\psi(2S)$ in p-Pb

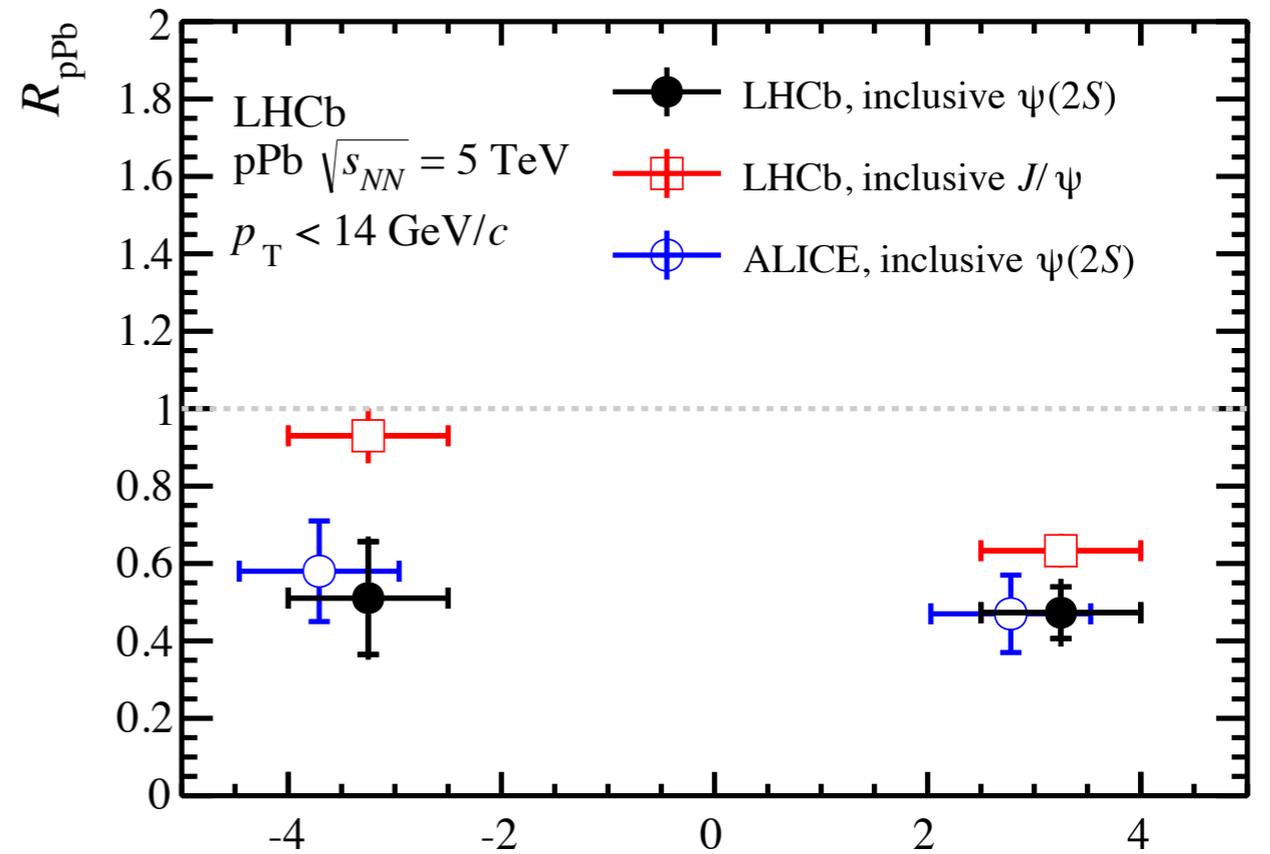
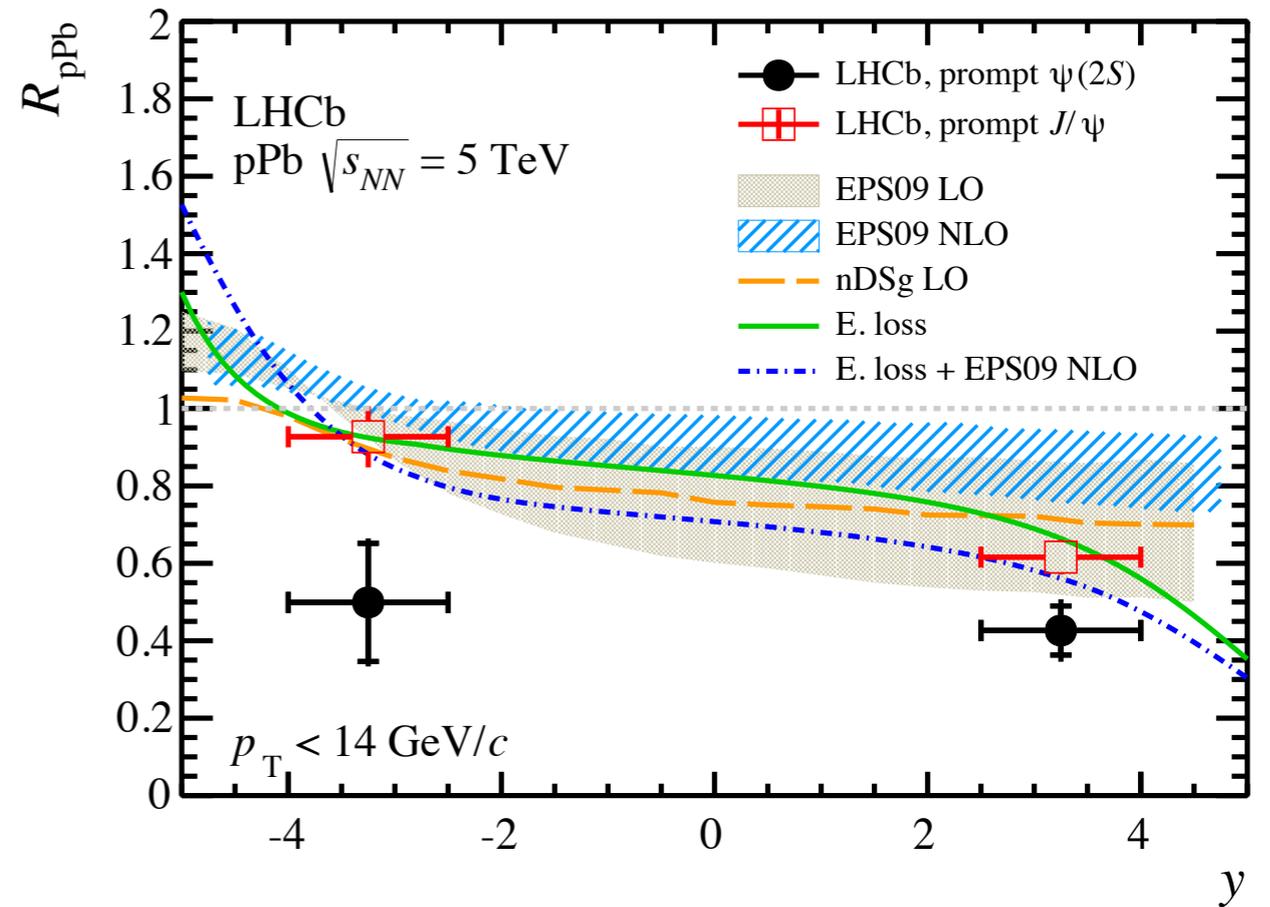
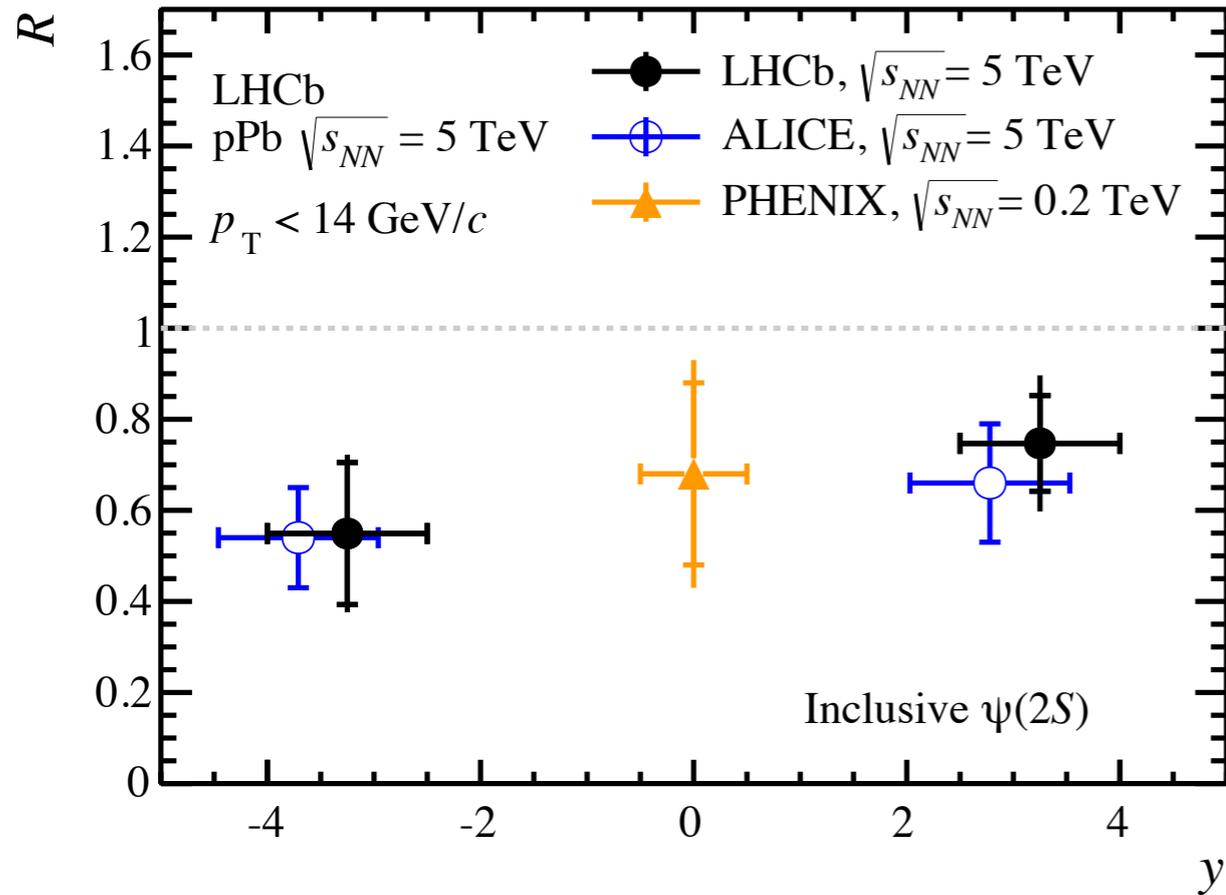


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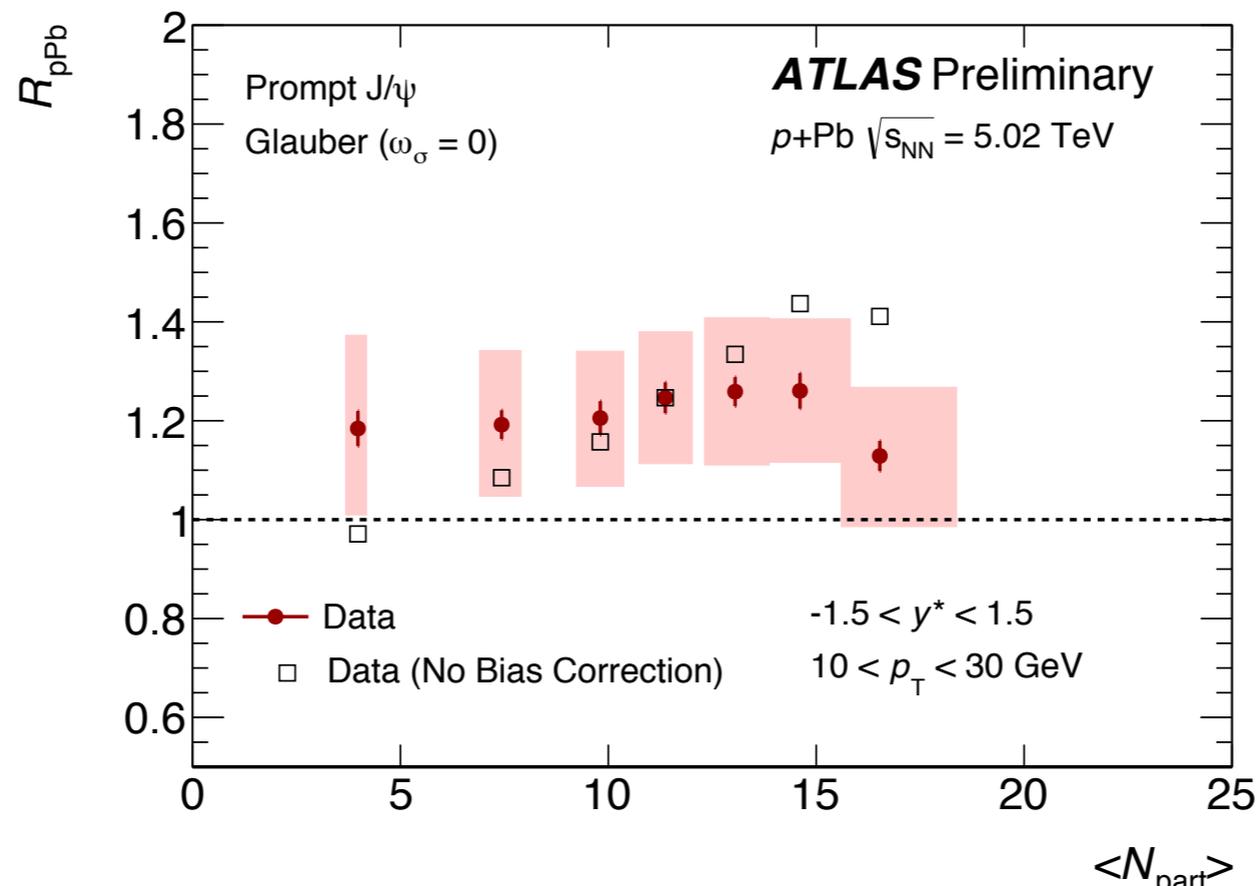
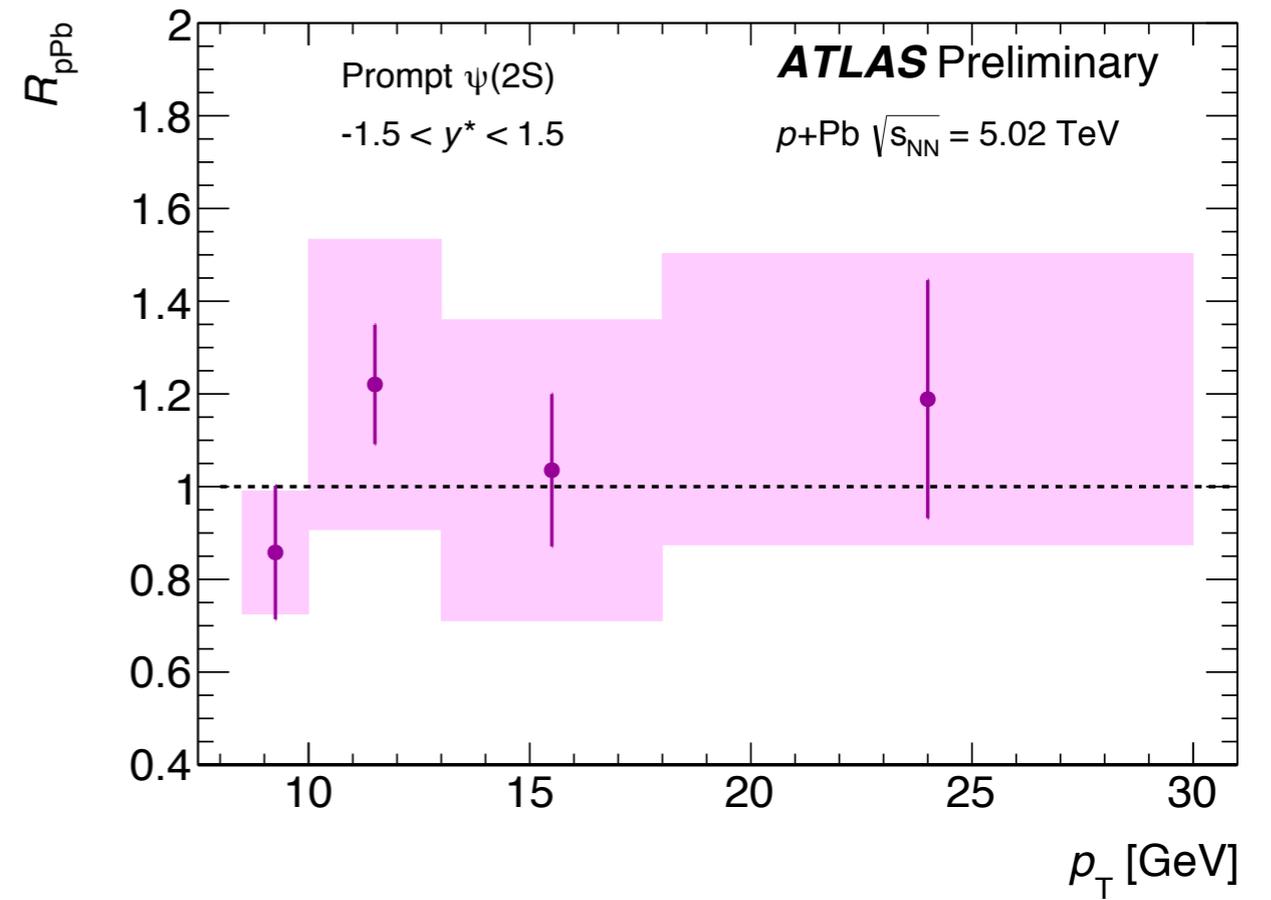
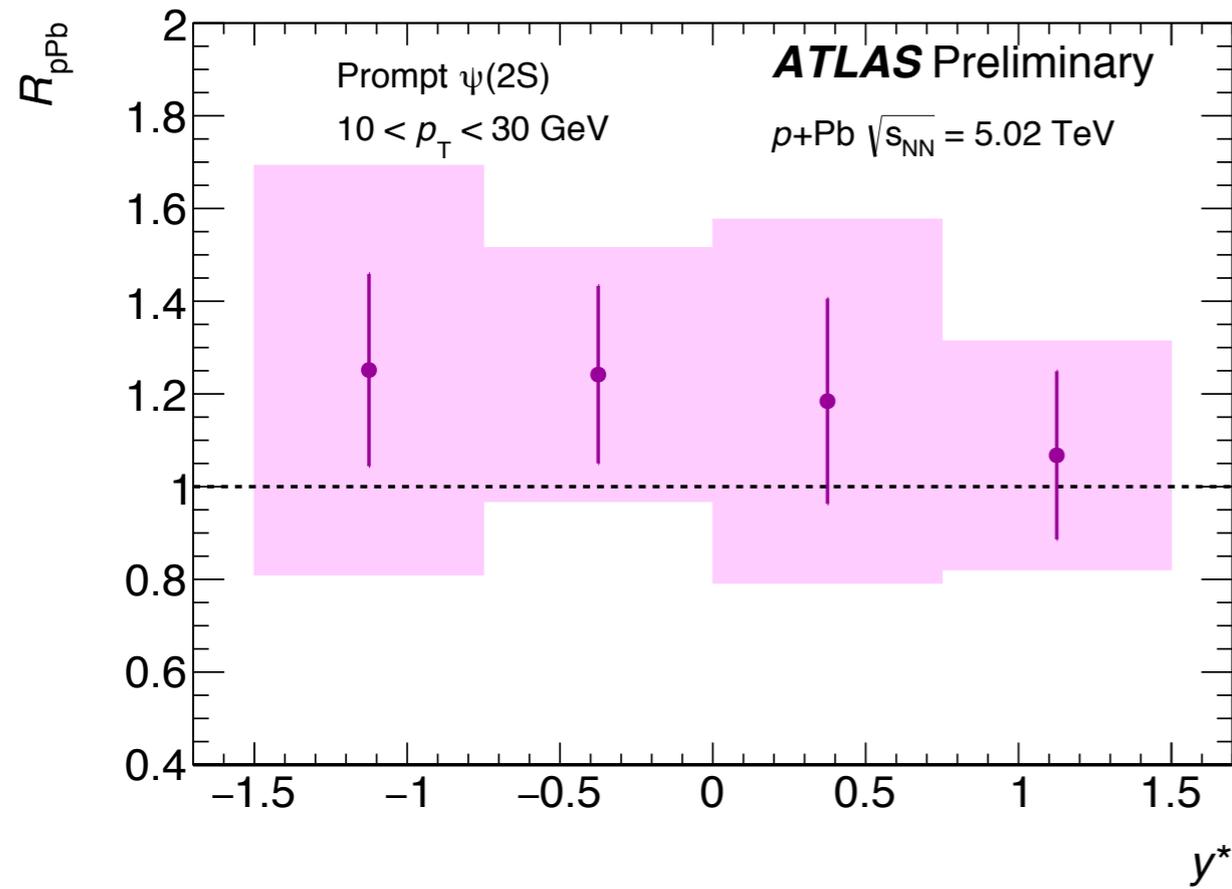


Prompt $\psi(2S)$ in p-Pb

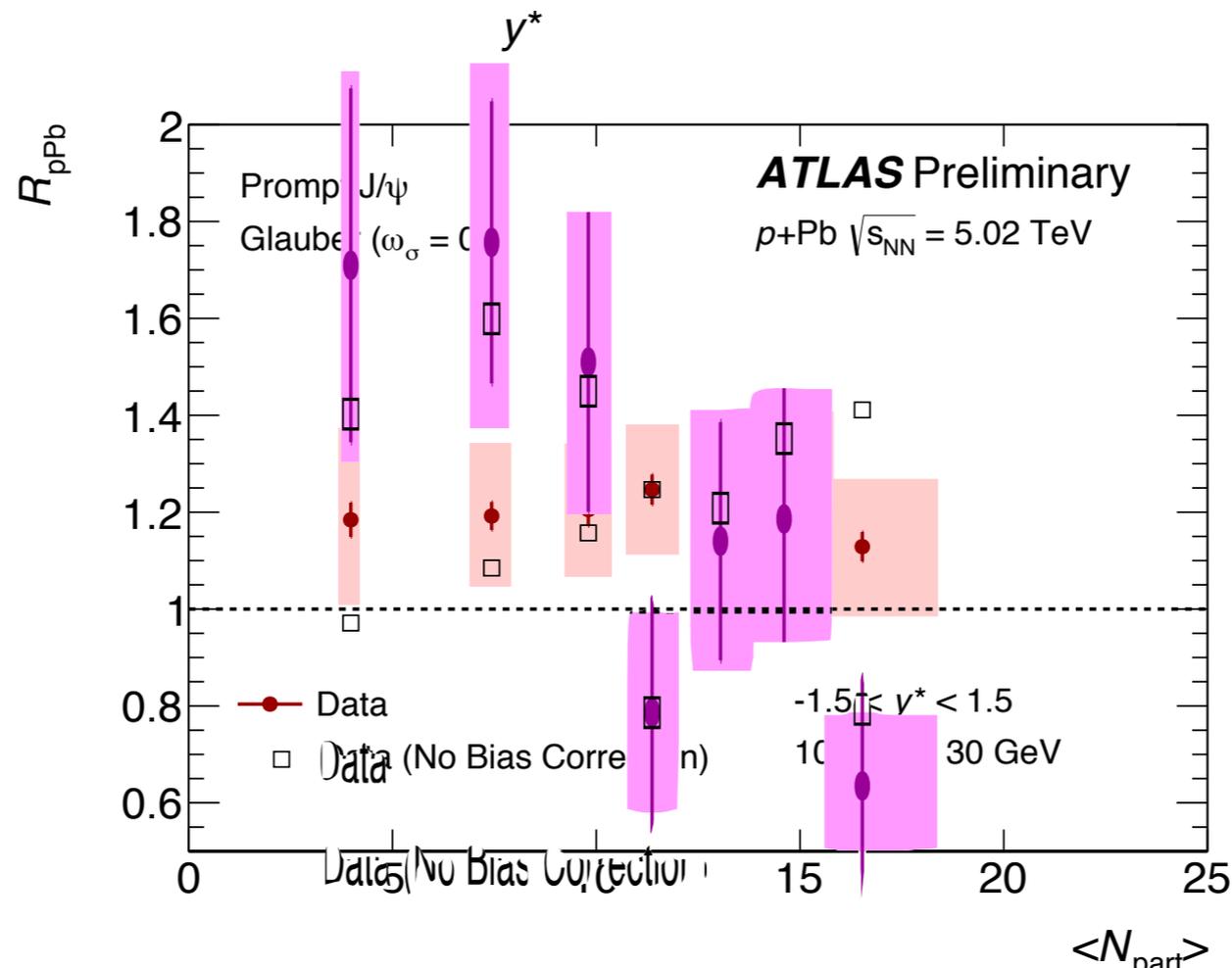
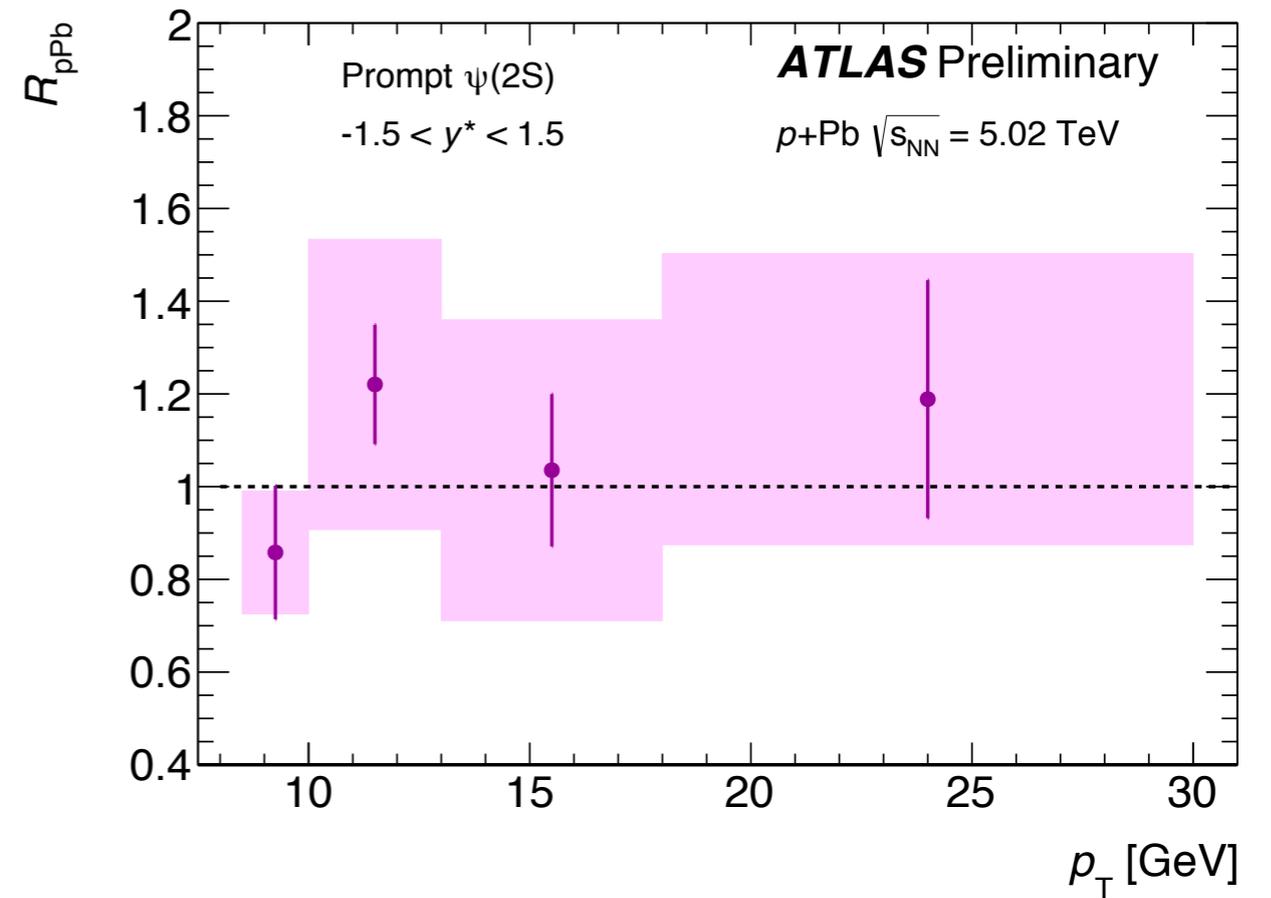
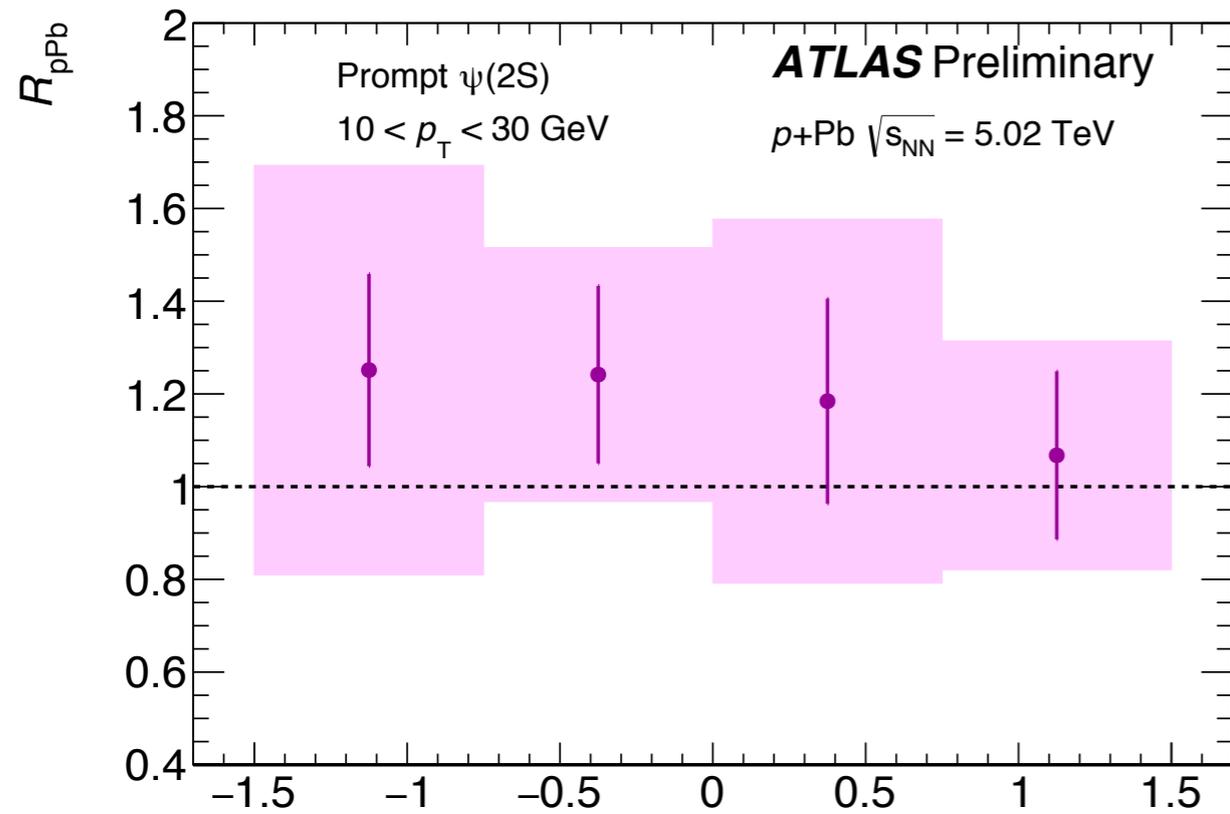
LHCb, JHEP 03 (2016) 133



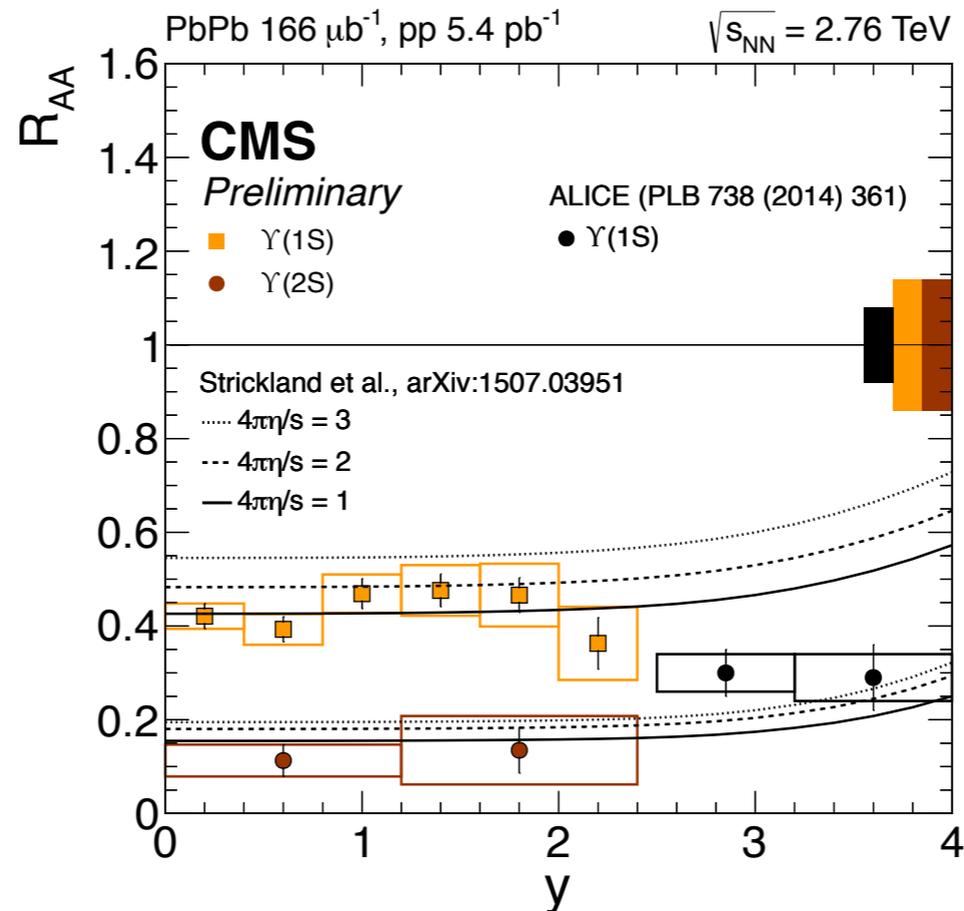
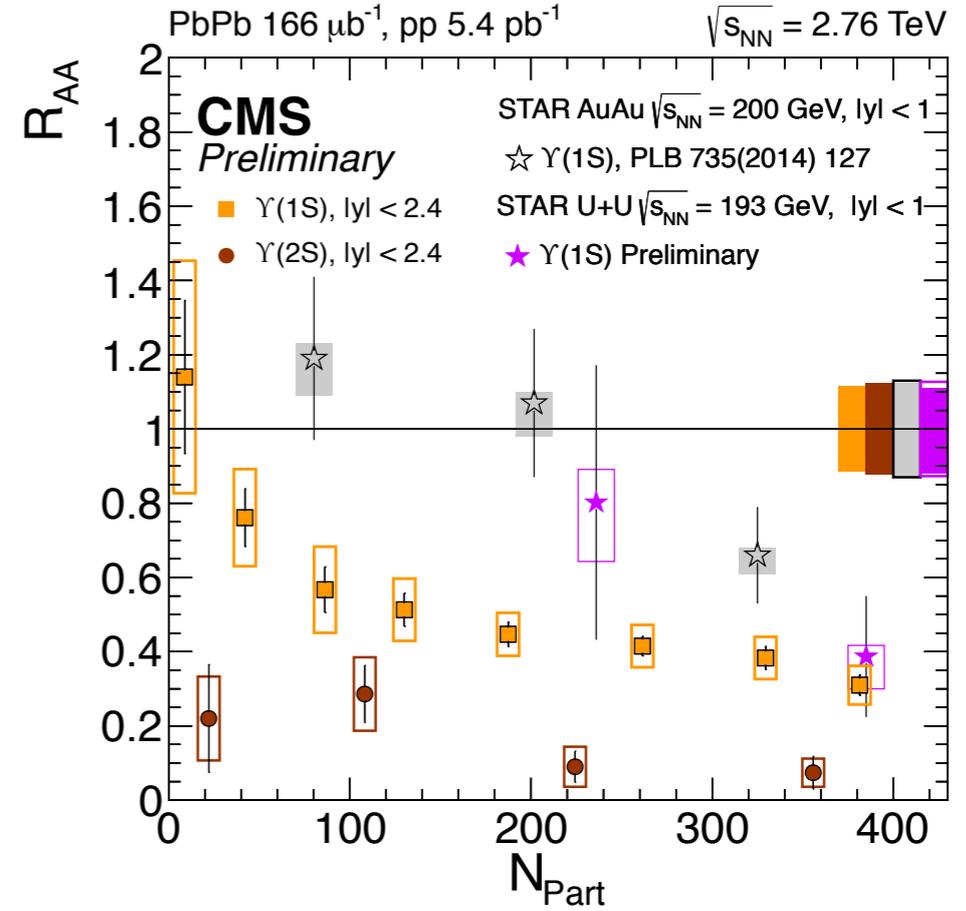
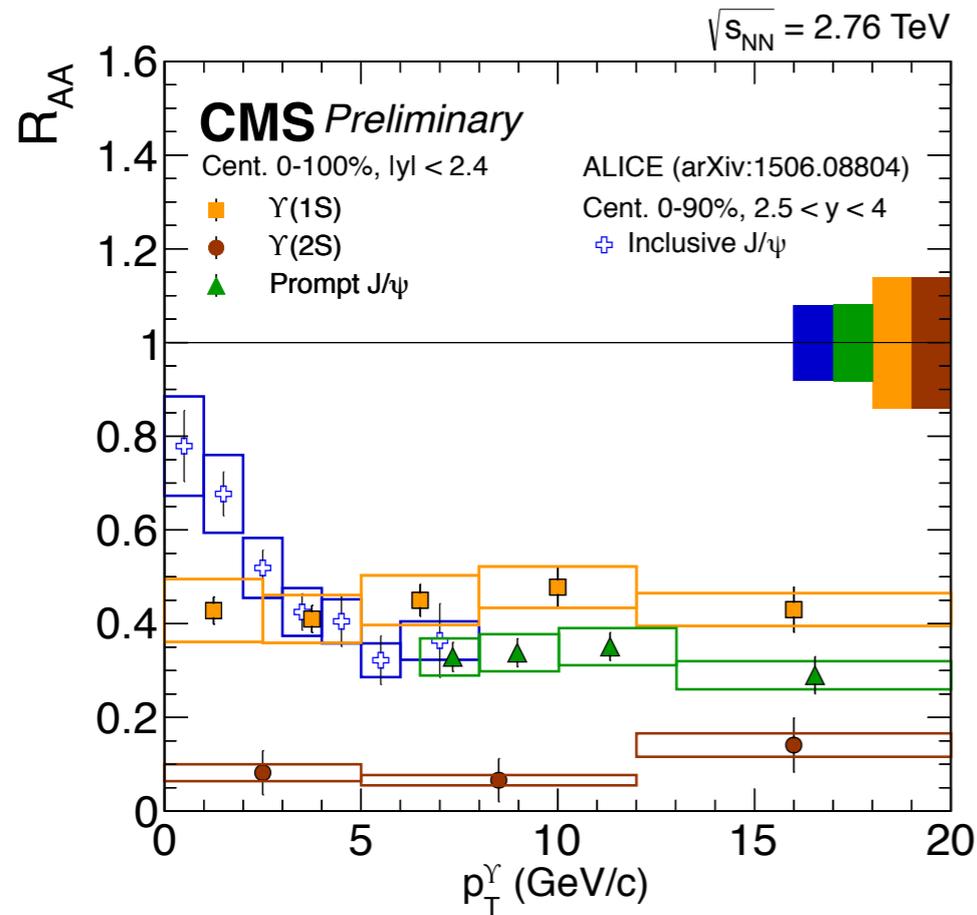
High- p_T $\psi(2S)$ in p-Pb



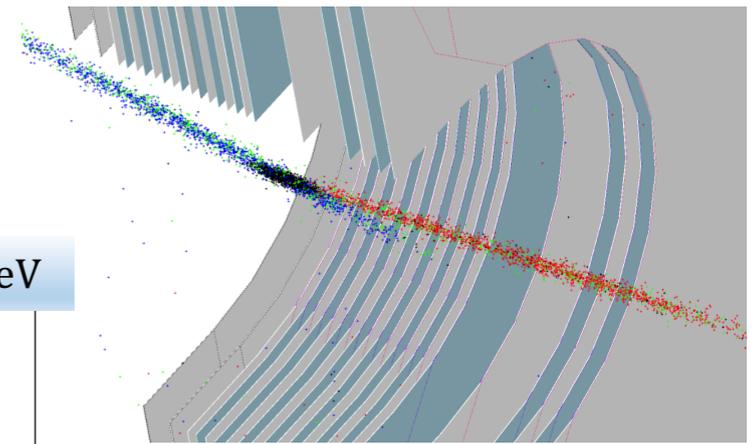
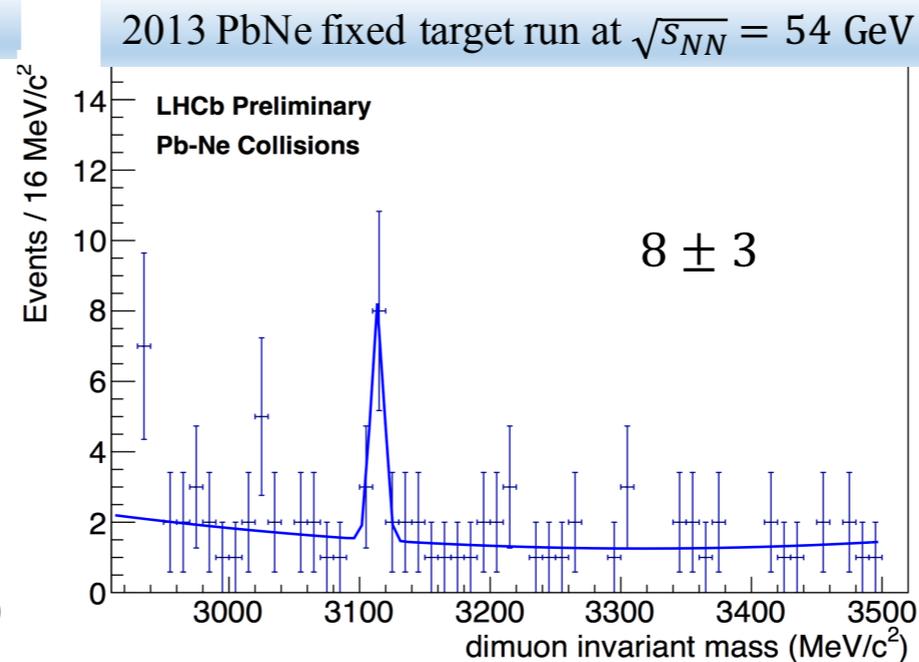
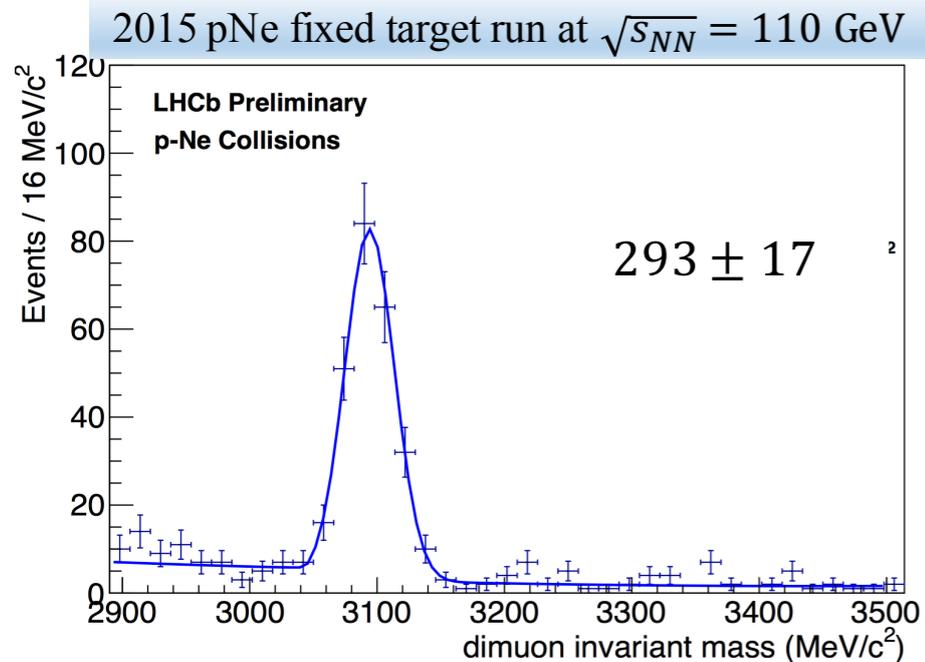
High- p_T $\psi(2S)$ in p-Pb



$\Upsilon(nS)$ in Pb-Pb



LHCb: Prospects with SMOG



Y. Zhang, Moriond (QCD) 2016

- **S**ystem for **M**onitoring the **O**verlap with **G**as
- Injection of noble gas in interaction region
- Provides Pb-gas and p-gas collisions with $\sqrt{s_{NN}}$ in RHIC energy regime