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http://charm18.inp.nsk.su/

Quarkonium production in *p*A and *d*A collisions

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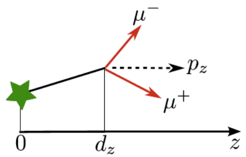
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Study of quarkonium in *p*(*d*)A collisions

- Quarkonium states reconstructed in di-lepton final states: e^+e^- (ALICE, PHENIX) and $\mu^+\mu^-$ final states.
- In a wide acceptance range, thanks to complementarity of experiments.
- Depending on detector, vertex information to separate *prompt* production and production from *B* decays. If not, inclusive production is measured.

$$t_z(J/\psi) = \frac{d_z \times M_{J/\psi}}{p_z}$$



- At various energies and with different collision systems:

Energy $\sqrt{s_{\mathrm{NN}}}$	**86.6 GeV**	**110 GeV**	**200 GeV**	**5.02 TeV**	**8 TeV**	**8.16 TeV**
	LHCb: *p*He	LHCb: *p*Ar	RHIC: *pp*, *p*Al, *p*Au, *d*Au, He^{3}Au	LHC: *pp*, *p*Pb	LHC: *pp*	LHC: *p*Pb

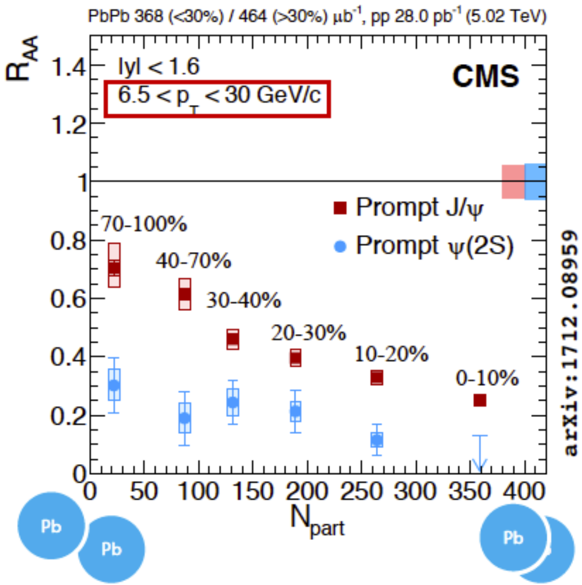
Motivations

- Understanding of QGP properties requires caracterisation of effects that can mimick it: suppression of charmonium production is one important observable to study.
- This can be done with *p* or *d* collisions with heavy ions, comparing with reference from *pp* collisions.
- Several cold nuclear matter effects identified:
  - Modification of the parton density functions in nuclei,
  - Energy loss of the partons in the medium,
  - Color Glass Condensate or gluon density saturation,
  - Comovers: comoving hadrons perturbing the final states,
  - Break-up in the nuclei.

Initial state

Final state

- Changing type of ions or study different final states: final state effects.
- Changing energy or acceptance: initial state effects.

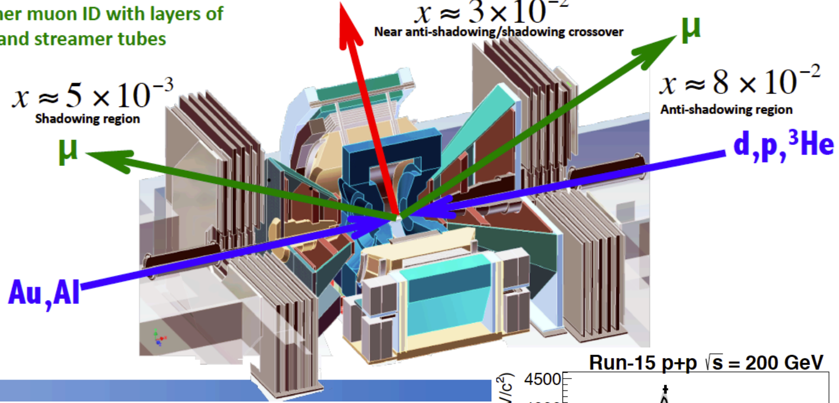


[arXiv:1712.08959]

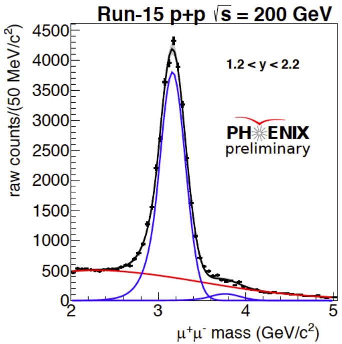
Experimental Facilities (RHIC)

Muons: 1.2 < |y| < 2.2,
-Tracked with silicon,wire chambers
-Further muon ID with layers of
steel and streamer tubes

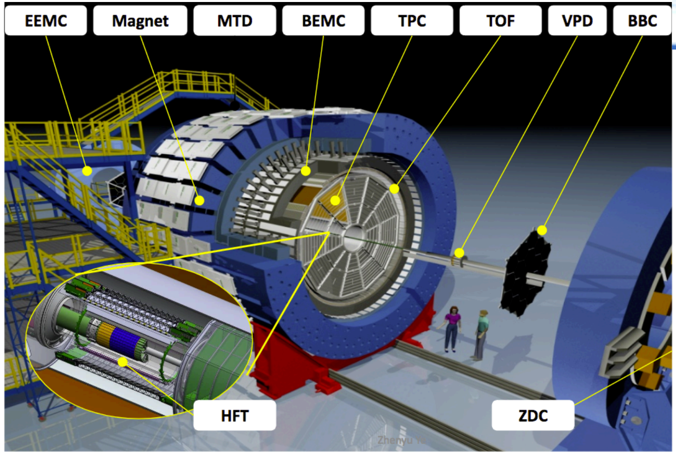
Electrons: |y| <0.35,
-Tracked with DC,PC
-ID with RICH, EmCal

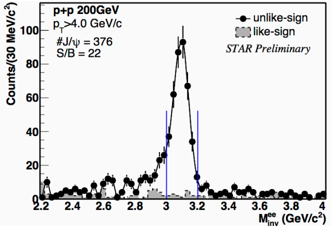


PHENIX



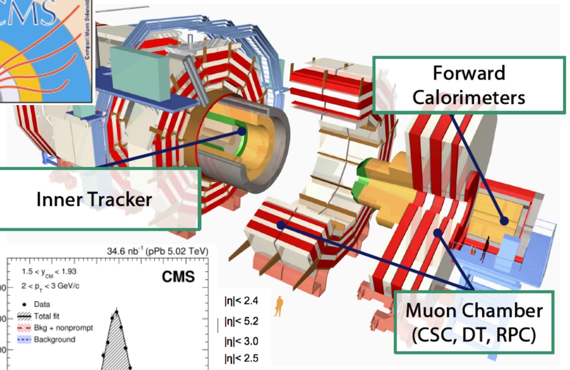
STAR

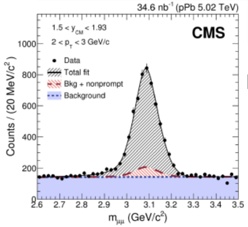


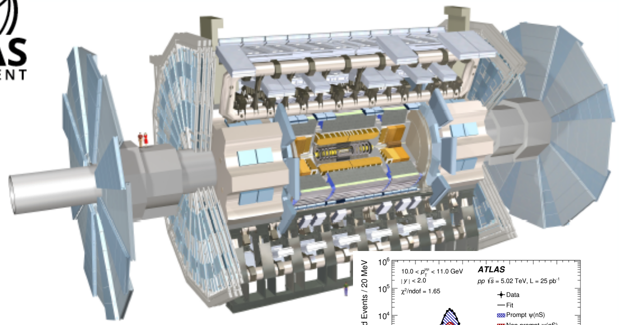


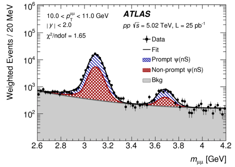
TPC: $|\eta| < 1$
TOF: $|\eta| < 1$
BEMC: $|\eta| < 1$
EEMC: $1 < \eta < 2$
HFT (2014-2016): $|\eta| < 1$
MTD (2014+): $|\eta| < 0.5$

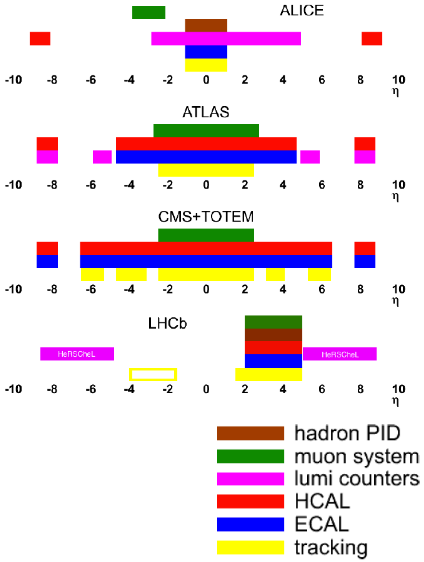
Experimental Facilities (LHC)

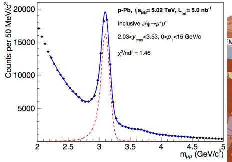


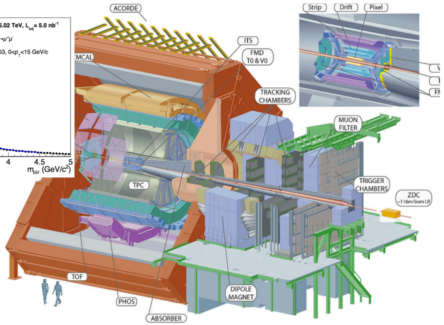


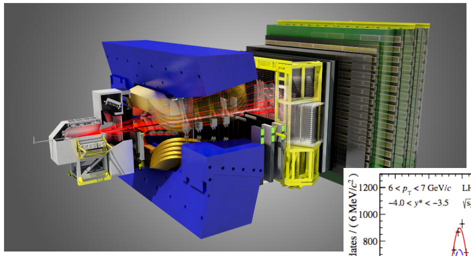


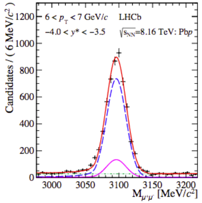








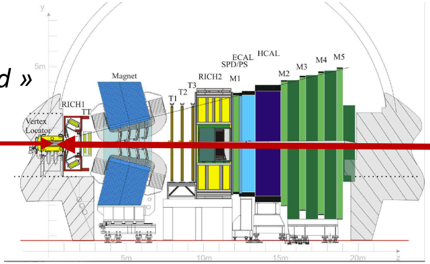




Experimental Facilities (LHC)

- Due to the asymmetry of the detector acceptance and the possibility of the LHC to revert the beams, ALICE and LHCb cover also negative rapidities in the center of mass frame of the collision.

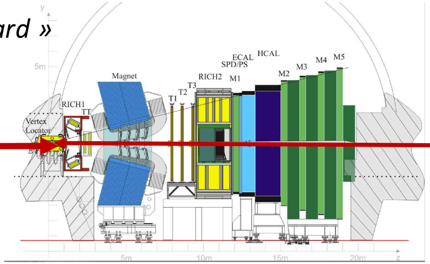
pPb « *forward* »



p → ← Pb

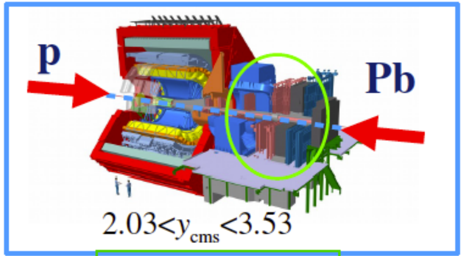
1.5 < *y** < 4.5

Pbp « *backward* »

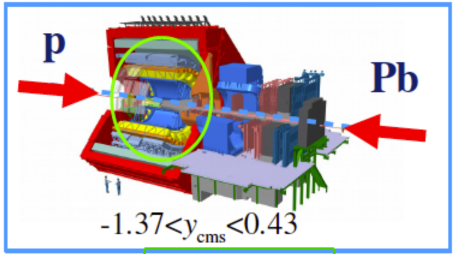


Pb → ← *p*

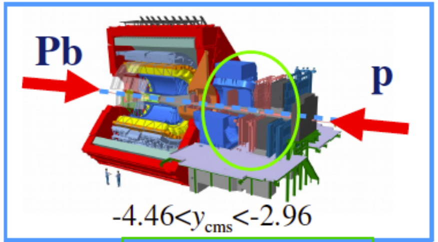
-5.5 < *y** < -2.5



Forward rapidity



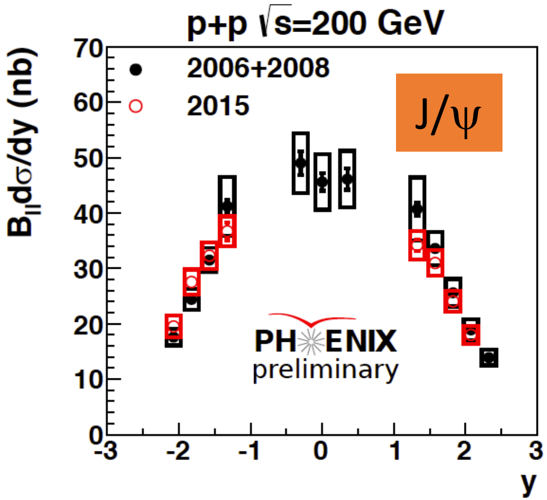
Mid rapidity

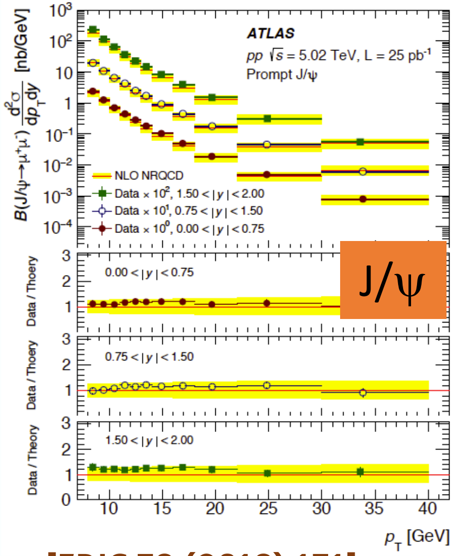


Backward rapidity

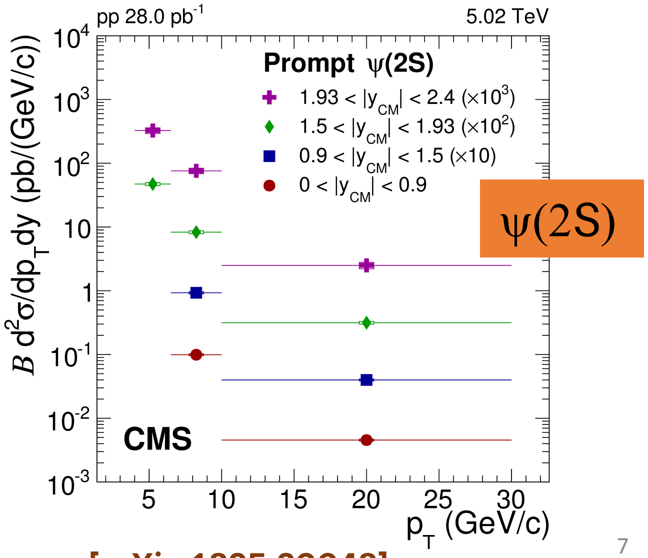
pp reference cross-sections

- In *pp* collisions, no nuclear matter effects are expected: reference for all measurements.
- The reference center of mass energy must be the same than the *p*(*d*)A measurement: special runs
- If they don't exist, rely on extrapolations of cross-sections (for example 8 TeV → 8.16 TeV)





[EPJC 78 (2018) 171]

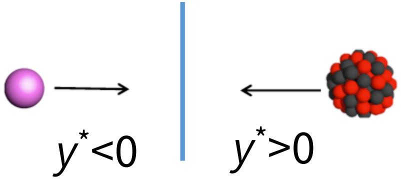


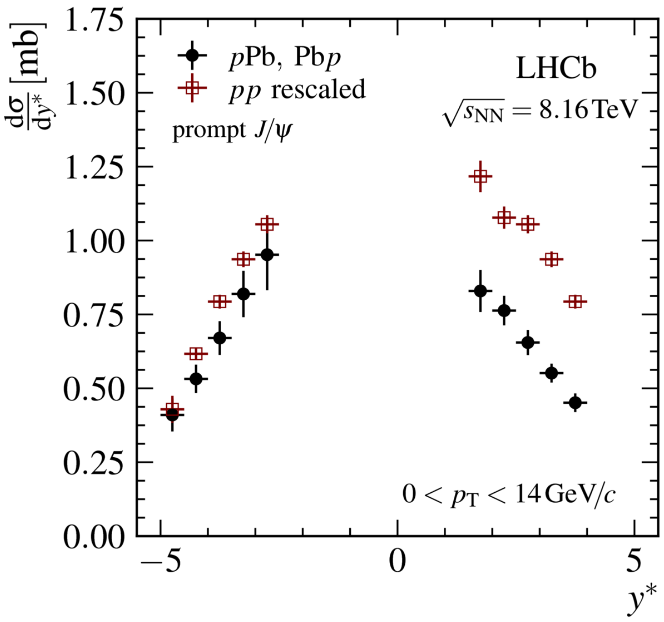
[arXiv:1805.02248]

Modification of J/ψ production in *p*A

- Compare production with *pp* reference cross-section at the same energy, scaled by *A*
- This is quantified in R_{pA}, which is unity in the absence of effects :

$$\boxed{R_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^{*}) = \frac{1}{A}\frac{\mathrm{d}^{2}\sigma_{p\mathrm{Pb}}(p_{\mathrm{T}}, y^{*})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^{*}}{\mathrm{d}^{2}\sigma_{pp}(p_{\mathrm{T}}, y^{*})/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^{*}}}$$

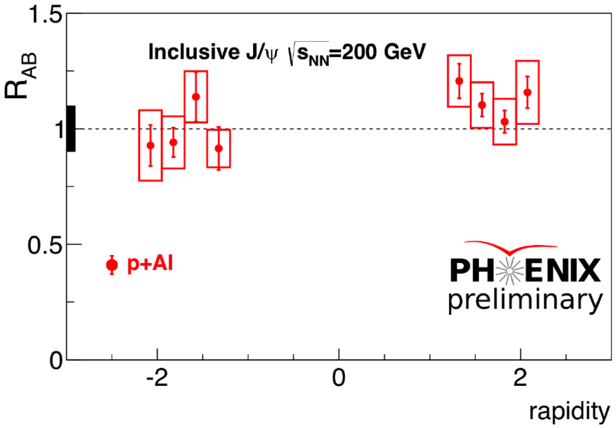


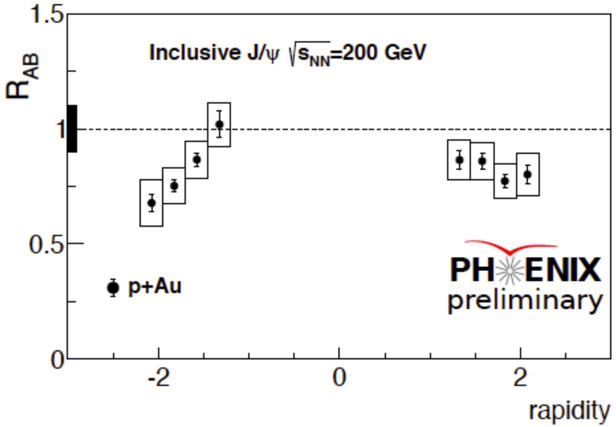


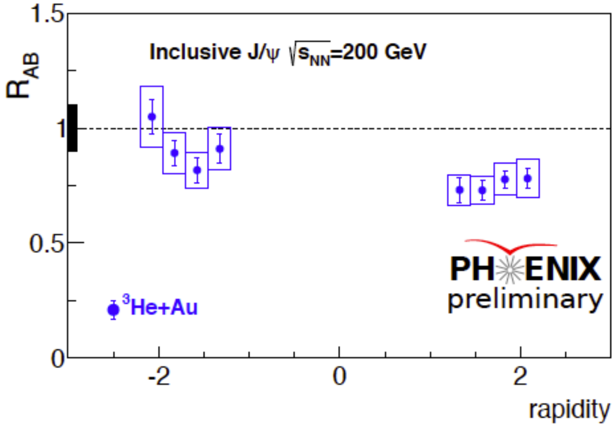
[PLB 774 (2017) 159]

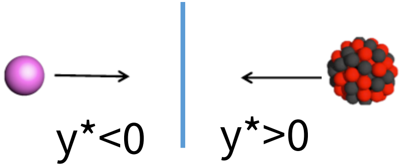
Modification of J/ψ production

- At 200 GeV, small effect, of a suppression in the forward region.



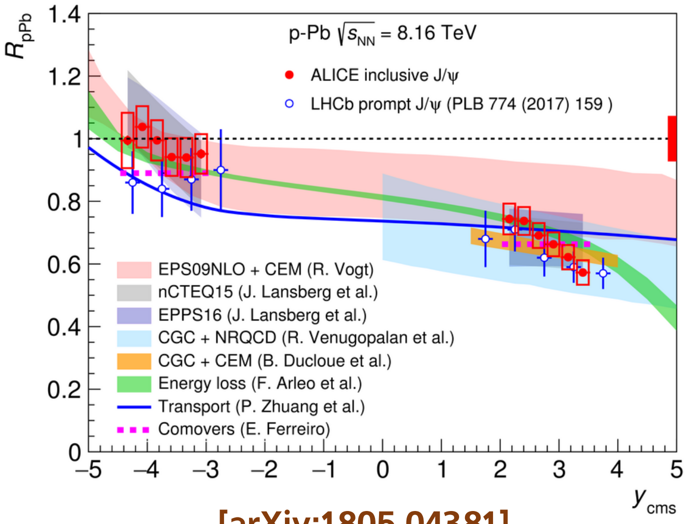






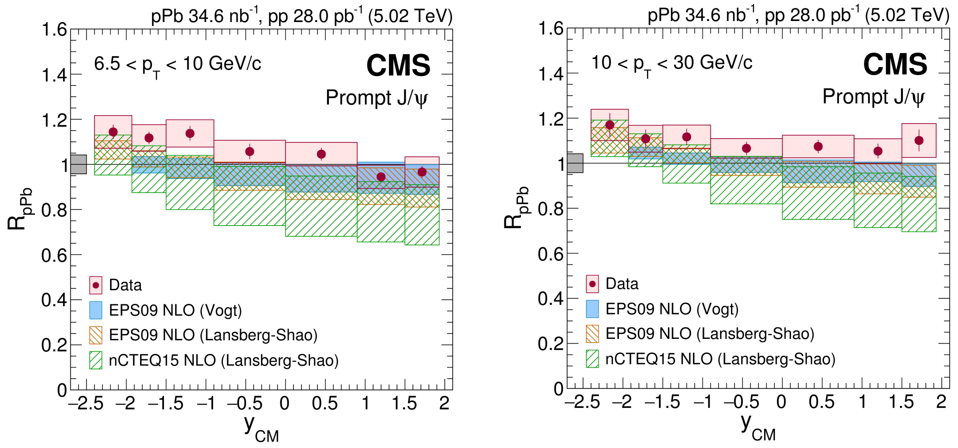
Modification of J/ψ production

- Larger suppression when going more foward.
- Compatible with no suppression at mid-rapidity and large p_T, y~0, similar to RHIC data.
- These features are well reproduced by several models, based on nuclear PDF modification (with CEM or HELAC-Onia for cross-section in *pp* collisions), color glass condensate, energy loss, comovers and transport model.



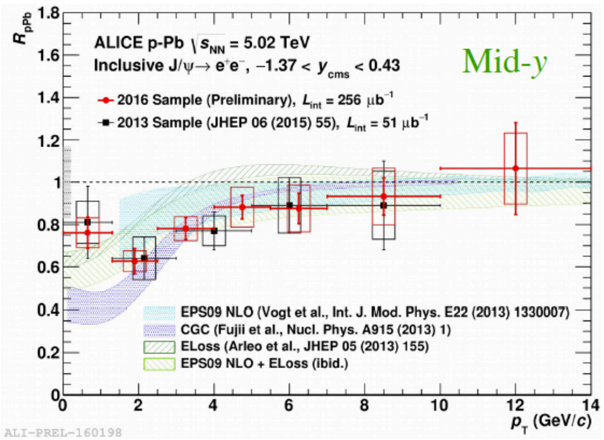
[arXiv:1805.04381]

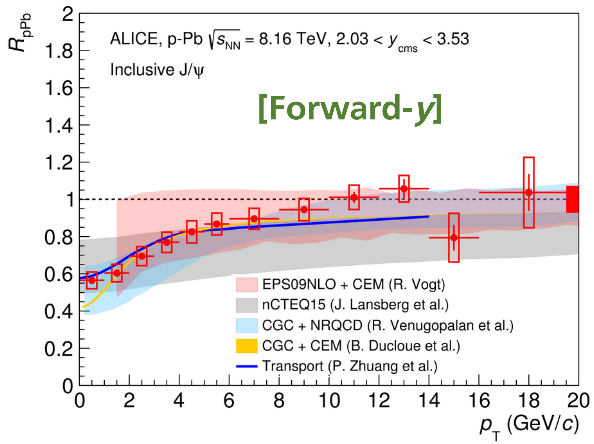
[EPJC 77 (2017) 269]

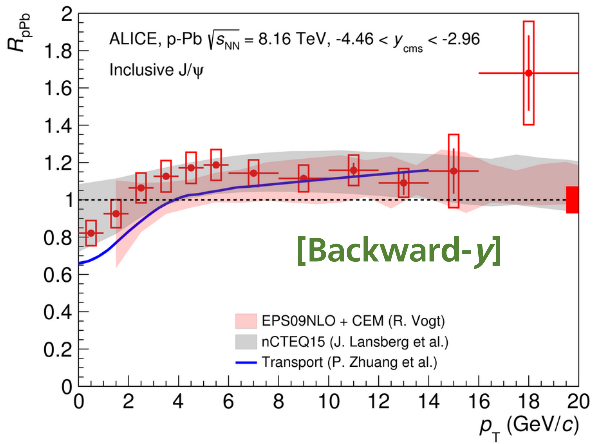


Modification of J/ψ production: p_T

- Suppression decreases with p_T, for all rapidities.
- Behaviour also well reproduced by theoretical models.







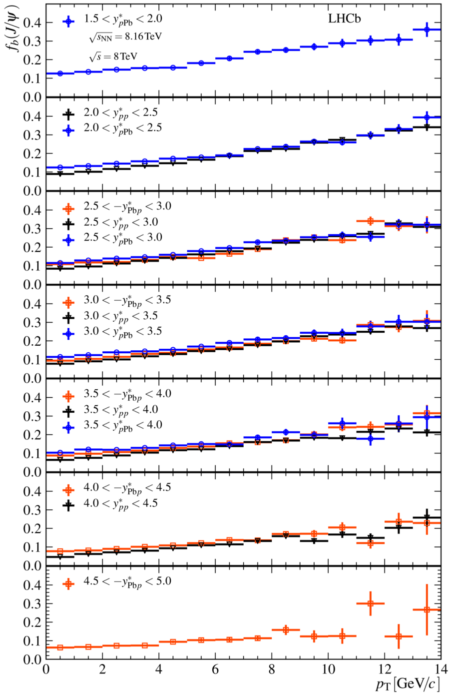
[ALICE-PUBLIC-2018-007]

[arXiv:1805.04381]

Modification of J/ψ from *B* production

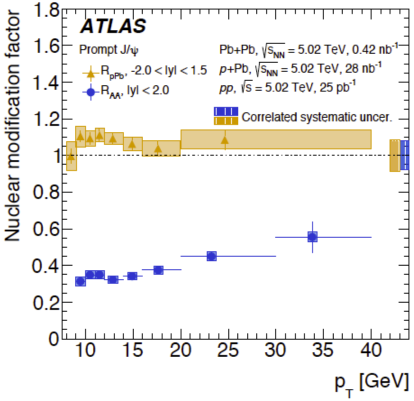
- J/ψ from *B* probe *b* production: same features are observed, but suppression is much less that for *c* production.
- Globally suppression seen in *p*A collisions is much less than suppression seen in PbPb collisions: a lot of room for hot nuclear matter effects, caracteristic of formation of a Quark Gluon Plasma.

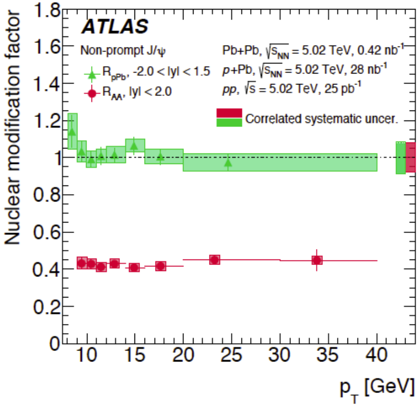
Fraction of *J*/ψ from *b*



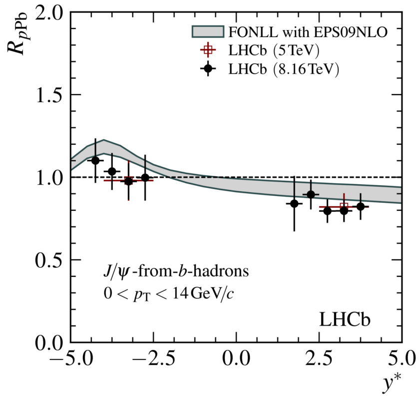
[PLB 774 (2017) 159]

[arXiv:1805.04077]



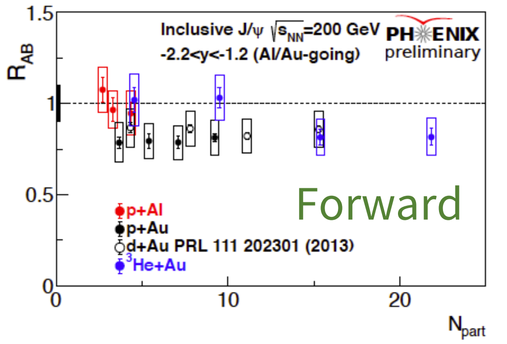


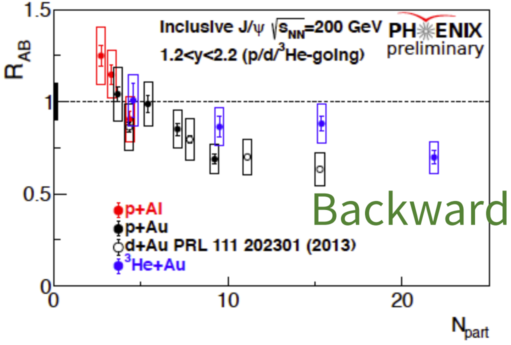
[PLB 774 (2017) 159]

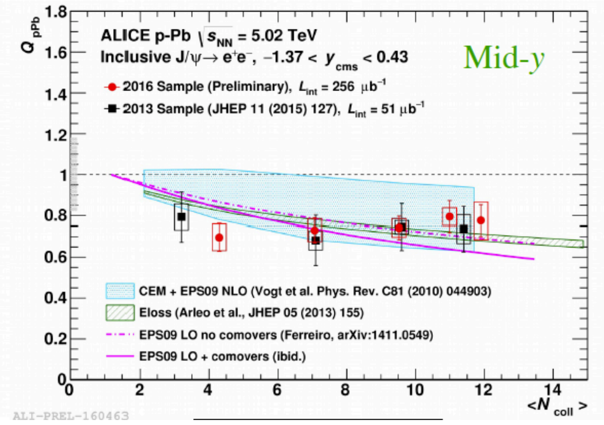


Modification of J/ψ: multiplicity

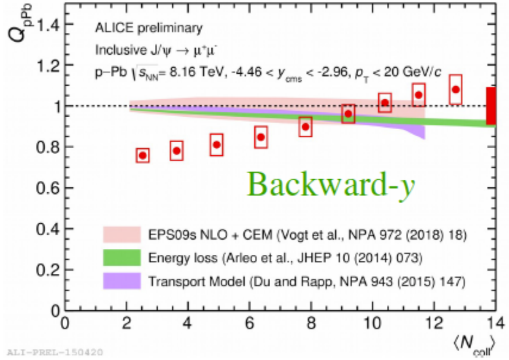
- One way to distinguish models and to compare various collision systems or energies is to measure the suppression as a function of the multiplicity.

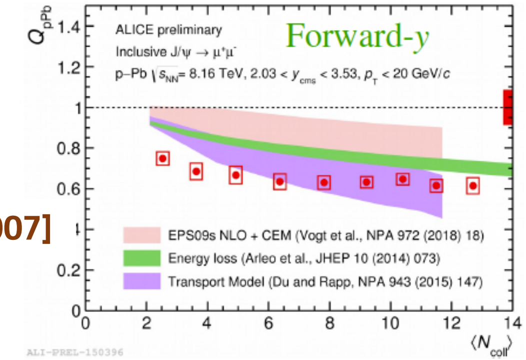






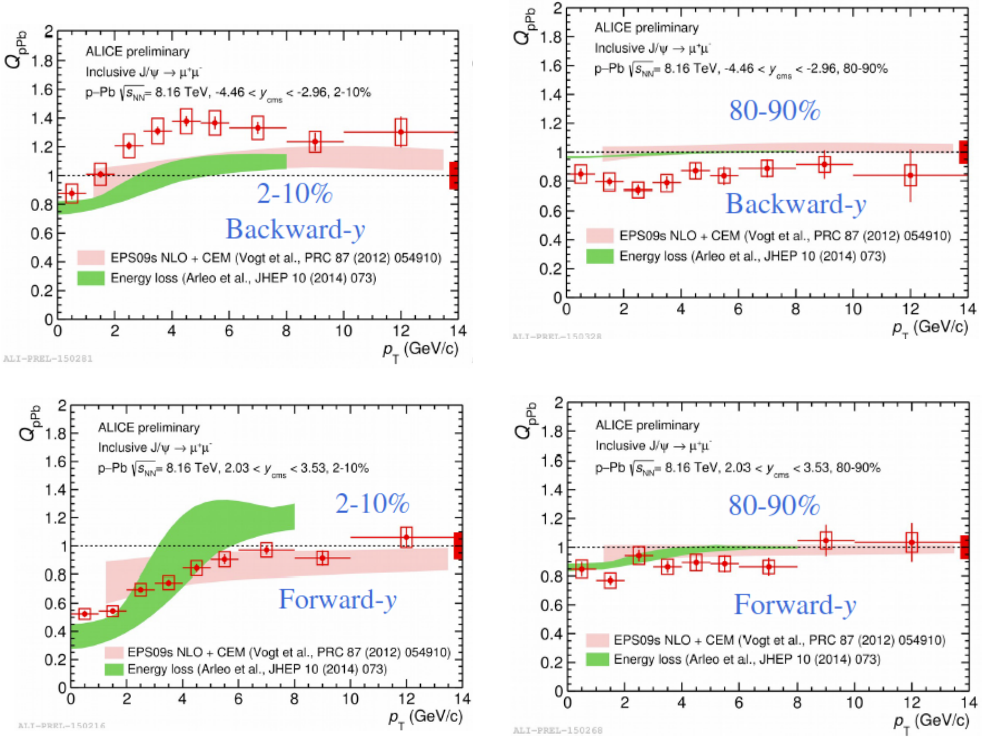
[ALICE-PUBLIC-2017-007]





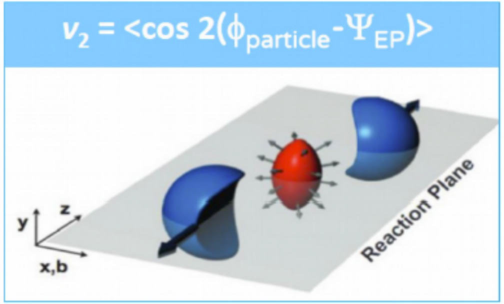
pA J/ψ multiplicity and p_T

- Behaviour in the backward region seems not to follow theory.
- But data are so precise now that multidimensional dependence can be obtained, as a function of p_T and multiplicity for example, where agreement is good.
- [NB: $Q_{p\mathrm{Pb}} = \frac{R_{p\mathrm{Pb}}}{\langle T_{p\mathrm{Pb}}^{\mathrm{mult}} \rangle}$ where $\langle T_{p\mathrm{Pb}}^{\mathrm{mult}} \rangle$ is the average nuclear overlap function]

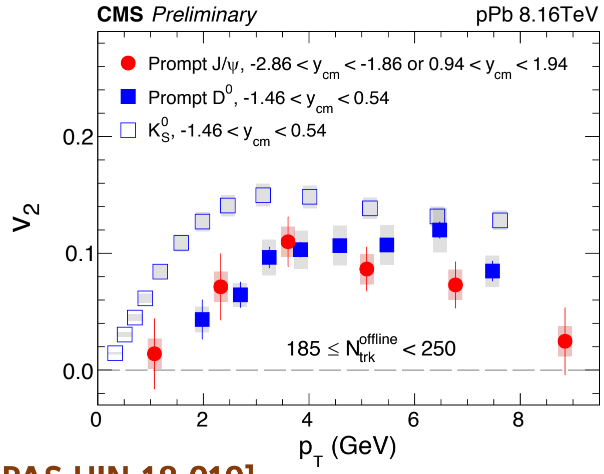


[ALICE-PUBLIC-2017-007]

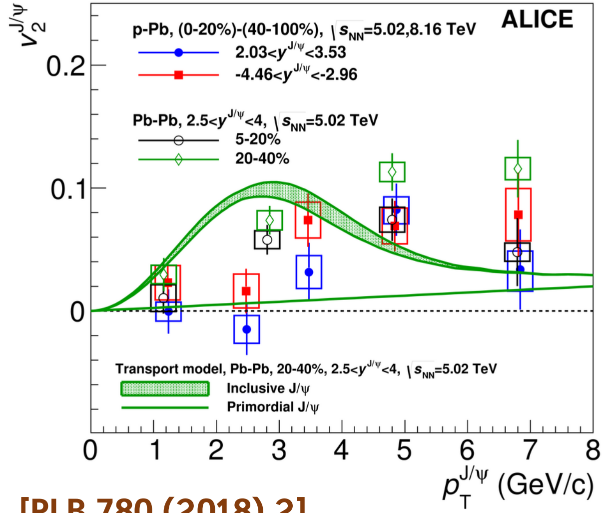
J/ψ azimuthal anisotropy



- In a strongly interacting medium, pressure gradients convert any initial spatial anisotropy into a momentum anisotropy
- Collective effects ($v_2 \neq 0$) seen in D^0, J/ψ v_2 completes picture of PbPb: evidence for charm quark – medium interaction but its origin is not yet understood.



[CMS PAS HIN-18-010]

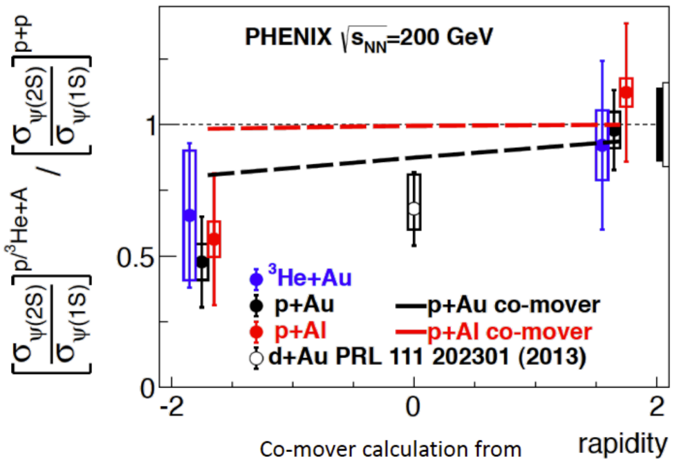


[PLB 780 (2018) 2]

ψ(2S) suppression

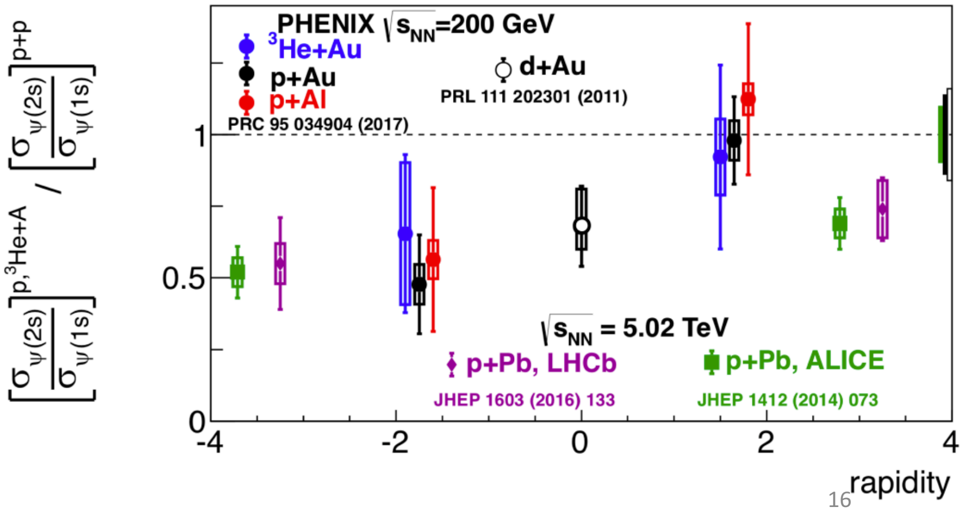
- ψ(2S) is more suppressed than J/ψ: suggests final state effect and that factorisation with respect to final state is broken.
- Not expected from only initial effects: comover model in particular describes data well.

[PRC 95 (2017) 034904]



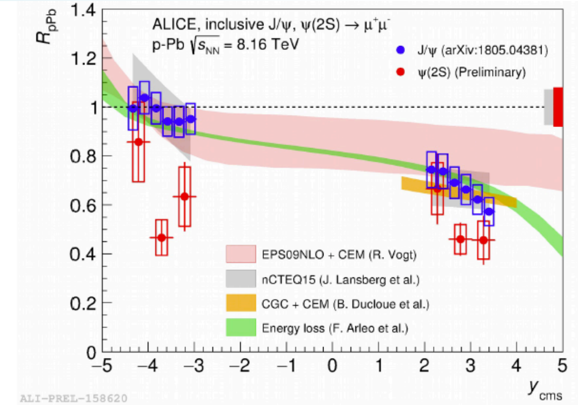
Co-mover calculation from
E. Ferreiro, PLB 749 (2015)

[PRC 95 (2017) 034904]

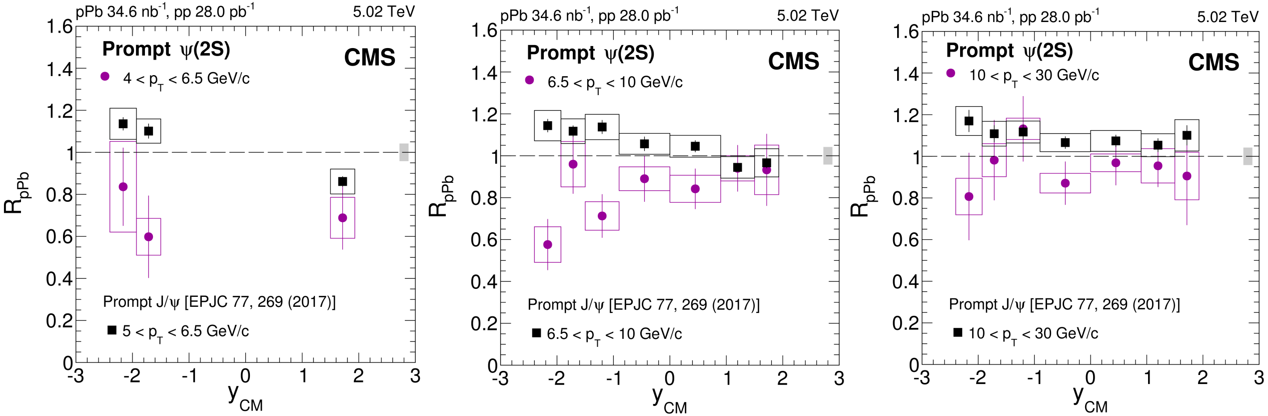


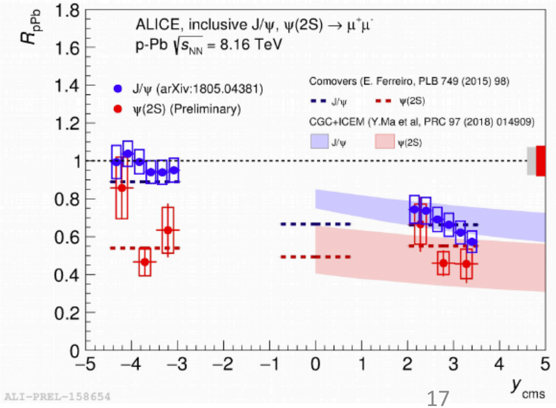
ψ(2S) suppression

- Effect also seen, but less pronounced at mid-rapidity at the LHC.
- More precise measurements at 8.16 TeV.



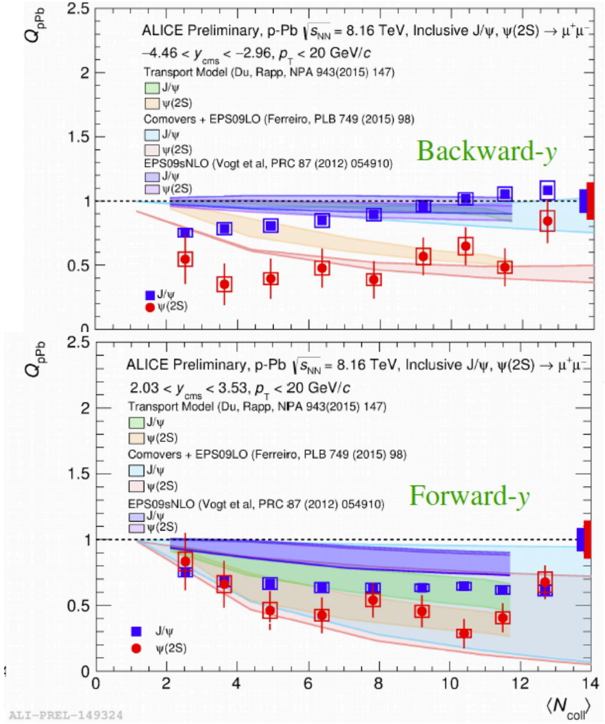
[arXiv:1805.02248]



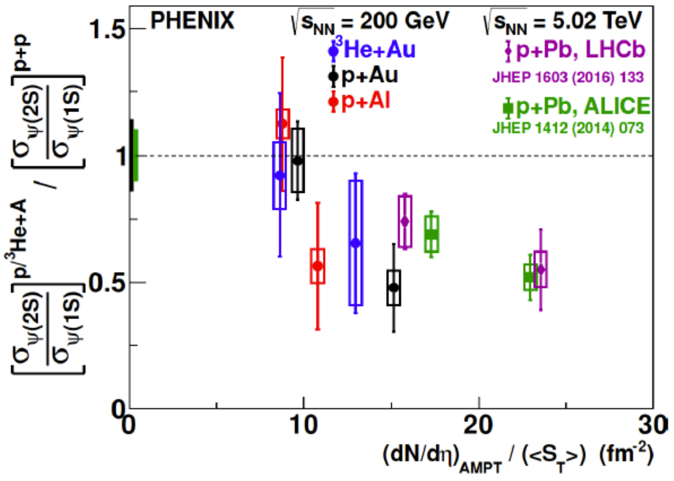


ψ(2S) suppression

- Relevant parameter for comover or transport model is the particle density.



Direct comparison with LHC data as function of comoving particle density

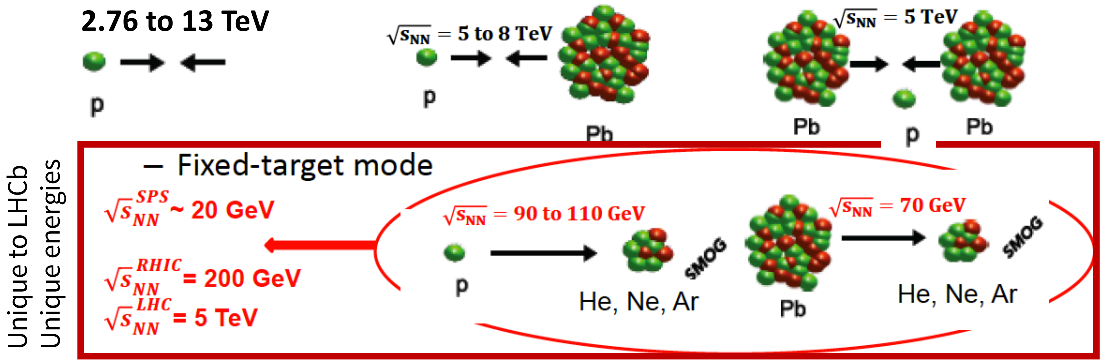


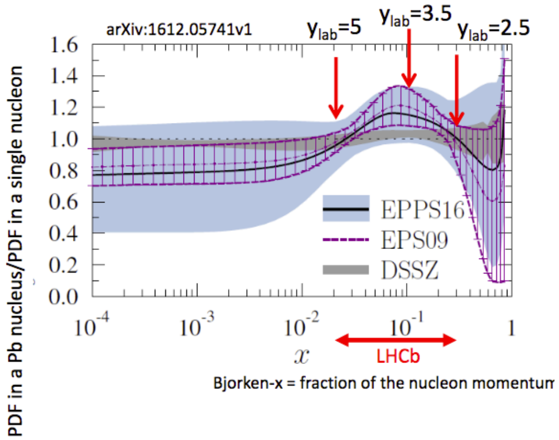
$$< S_T >= 4\pi\sqrt{< x^2 >< y^2 > - < xy >^2}$$

from Glauber model

LHCb operation modes

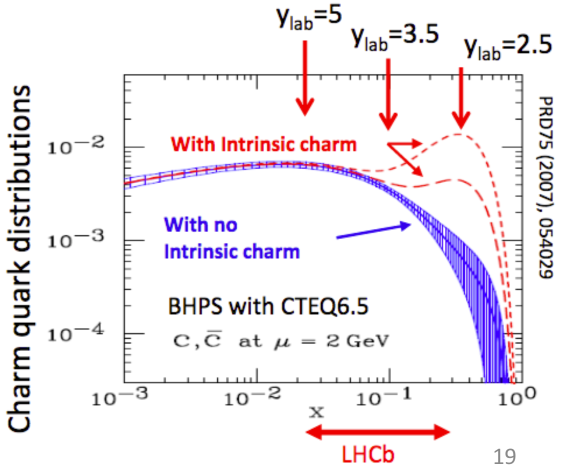
– Collider mode





LHCb rapidity 2.5 < yLHCb < 4.5 $\Longrightarrow \begin{cases} \text{7 TeV beam:} & -2.3 < y^*_{\mathrm{LHCb}} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^*_{\mathrm{LHCb}} < 0.2 \end{cases}$

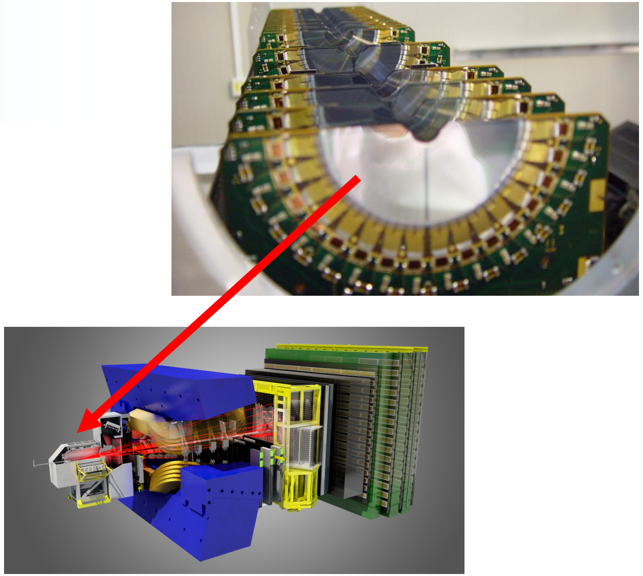
y^*_{LHCb} = rapidity in collision center of mass frame

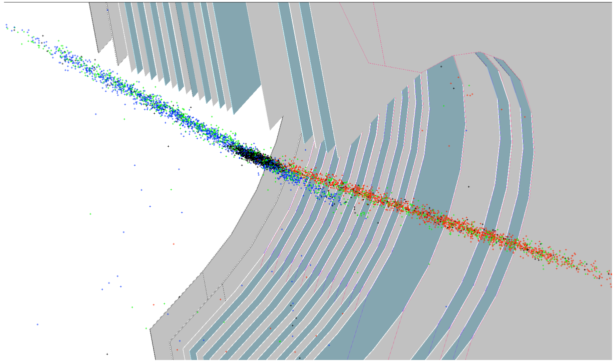


- Fixed target mode gives access to large *x* in target: nuclear PDF anti-shadowing region and intrinsic charm content of the nucleon.

Fixed target mode – SMOG

- Gas can be injected in the interaction region of LHCb, in the VELO vaccuum (*ie* the LHC vaccuum).
- Initially this was designed to measure the luminosity of LHCb, by measuring the beam images with beam-gas vertices: used during LHC van der Meer scan sessions: 1.2% precision on integrated luminosity.
- Other use cases emerged:
  - Measure LHC ghost charge (proportion of particles outside the colliding buckets) for the ALICE, ATLAS and CMS luminosity.
  - Fixed target physics interesting at the LHC [S. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg, Phys. Rep. 522 (2013) 239].

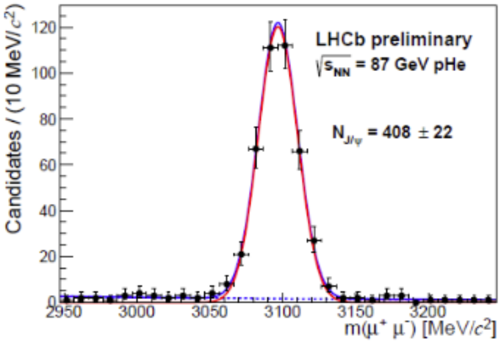


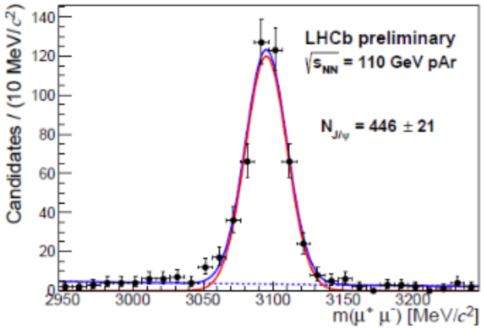


[LHCb-CONF-2017-001]

J/ψ production in *p*Ar and *p*He collisions

- Data taken in 2015 (*p*Ar) and 2016 (*p*He) during special runs of the LHC:
  - pAr: 110 GeV (17h with 4 TeV *p* beam),
  - pHe: 86.6 GeV (87h with 2.56 TeV *p* beam).
- The gas spreads several meters around the interaction point, for this analysis, requires that the collision vertex is within 20cm of the interaction point, to increase detector performances (within 10cm for normal *pp* data taking).
- The total integrated luminosity of the *p*He sample is determined from a process with a precisely known cross-section: scattering of the proton on the electrons of the He atom.
  - $L_{int} = 7.58 \pm 0.09 \pm 0.46\ nb^{-1}$

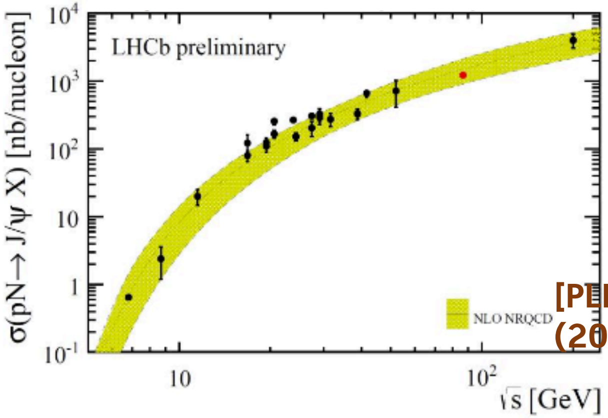




[LHCb-CONF-2017-001]

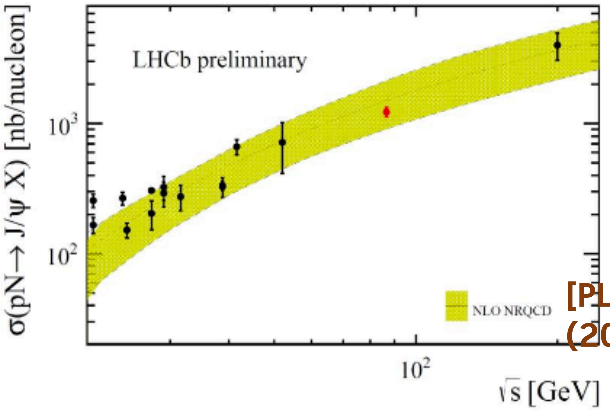
J/ψ production in *p*He collisions @86.6 GeV

- Cross-section measured in acceptance (2<y<4.6) is $\sigma_{J/\psi} = 652 \pm 33(\text{stat}) \pm 42(\text{syst})\ \text{nb/nucleon}$.
- Extrapolated to 4π: $\sigma_{J/\psi} = 1226 \pm 62\ (\text{stat}) \pm 82\ (\text{syst})\ \text{nb/nucleon}$.
- Compared with other experiments at low energies and with NRQCD evolution of the cross-section.



[PLB 638 (2006) 202]

Zoom in

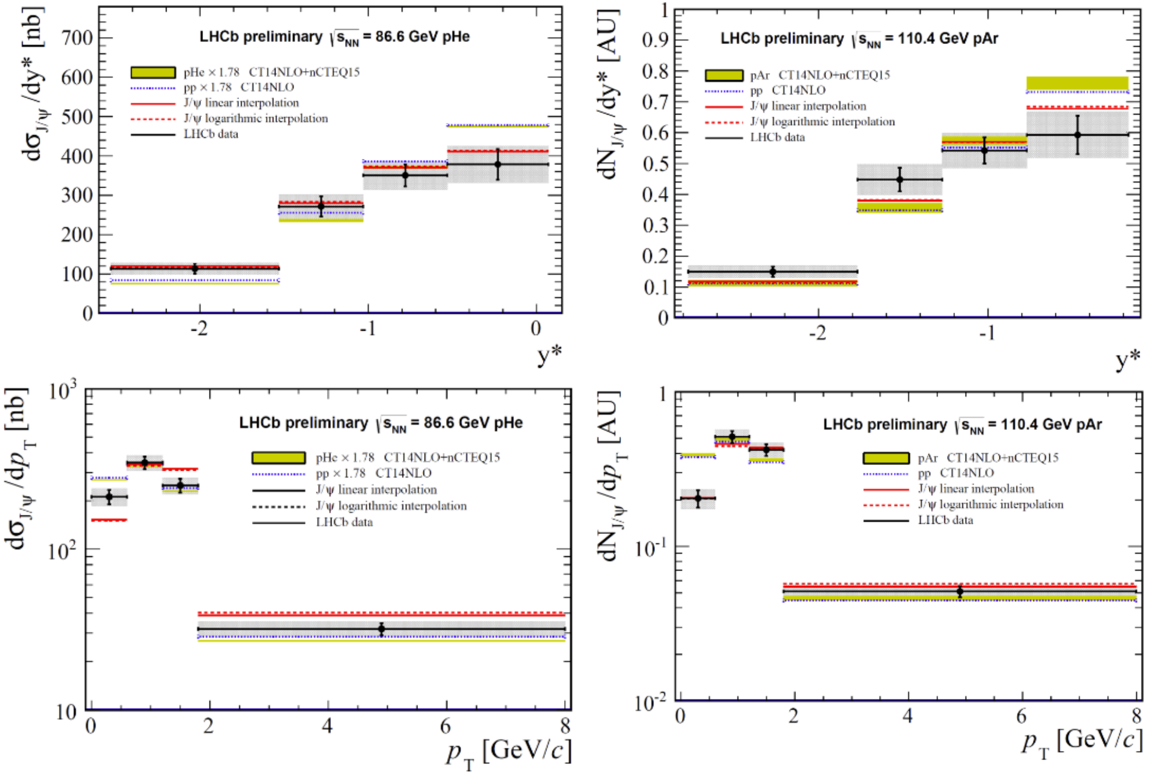


[PLB 638 (2006) 202]

[LHCb-CONF-2017-001]

J/ψ production in *p*Ar and *p*He collisions

- Differential cross-sections (*p*He) or differential efficiency corrected yields normalized to unity (*p*Ar) are compared with:
  - Phenomenological parametrisation: F. Arleo and S. Peigné, [JHEP13 (2013) 122, JHEP13 (2013) 155], with parameters fitted on PHENIX (200 GeV) and HERAB (41.5 GeV) data extrapolated to LHCb energies. No absolute normalization given: fixed to LHCb data.
  - HELAC-Onia: H-S. Shao, J.-P. Lansberg [EPJC 77 (2017) 1], using CT14NLO and nCTEQ15. Underestimates the cross-section by a factor 1.78.



Conclusions

- A lot of new measurements available for charmonium production in p(d)A collisions.
- These precision measurements are necessary to understand fully cold nuclear matter effects.
- Interesting feature of $\psi(2S)$ production bringing a lot of information: future measurements of χ_c production in $p(d)$A collisions are very important.
- Fixed target experiment at the LHC, in LHCb providing the first results on charmonium production.