

LHCb highlights in heavy-ion collisions

Samuel Belin on behalf of the LHCb collaboration

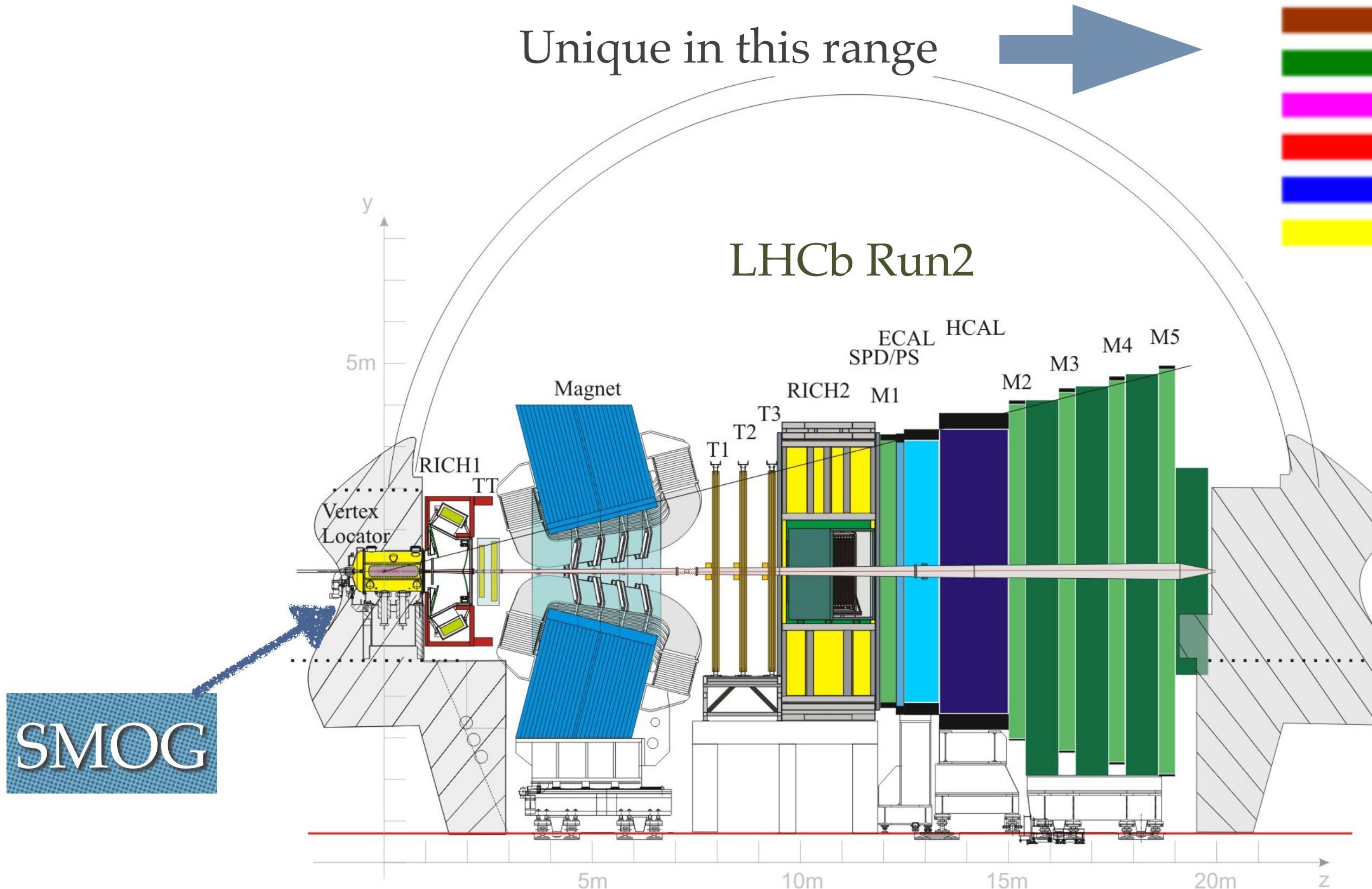
Many New results !

Outline

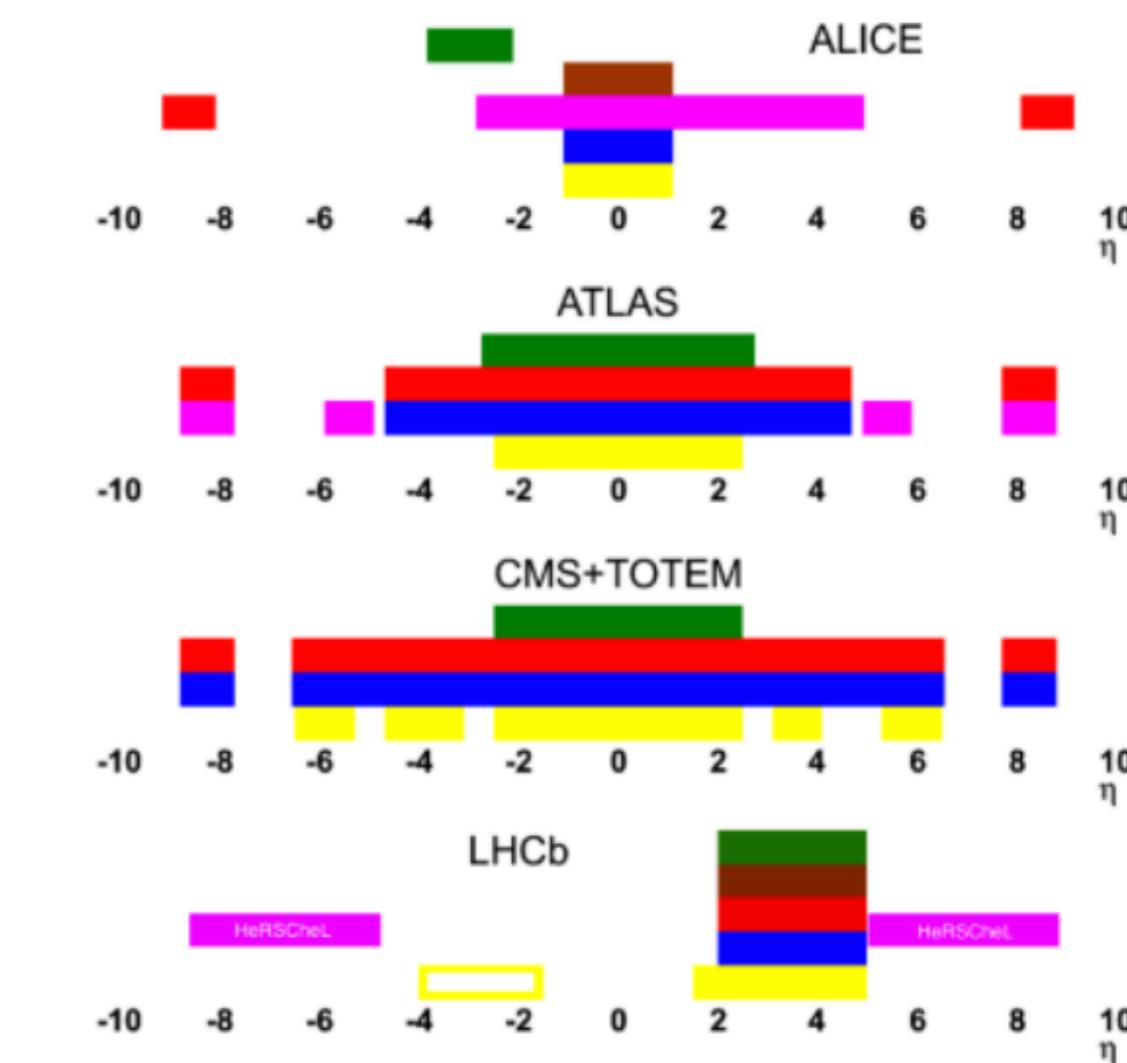
- ❖ Nuclear modification factor of π^0 in $p\text{Pb}$ @8TeV
- ❖ Prompt D^0 mesons in $p\text{Pb}$ @8TeV
- ❖ Z boson in $p\text{Pb}$ @8TeV
- ❖ J/ψ , $\psi(2S)$ production in PbPb Ultra-Peripheral Collisions (UPC) @5TeV
- ❖ Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production
- ❖ Λ_c/D^0 in peripheral PbPb collisions @5TeV
- ❖ Open charm production in $p\text{Ne}$ @68 GeV
- ❖ Charmonium production in $p\text{Ne}$ @68 GeV
- ❖ Charm production in PbNe @68 GeV
- ❖ Antiproton in $p\text{He}$ @110 GeV

The LHCb detector

Single arm spectrometer fully instrumented in pseudorapidity range $2 < \eta < 5$



- hadron PID
- muon system
- lumi counters
- HCAL
- ECAL
- tracking



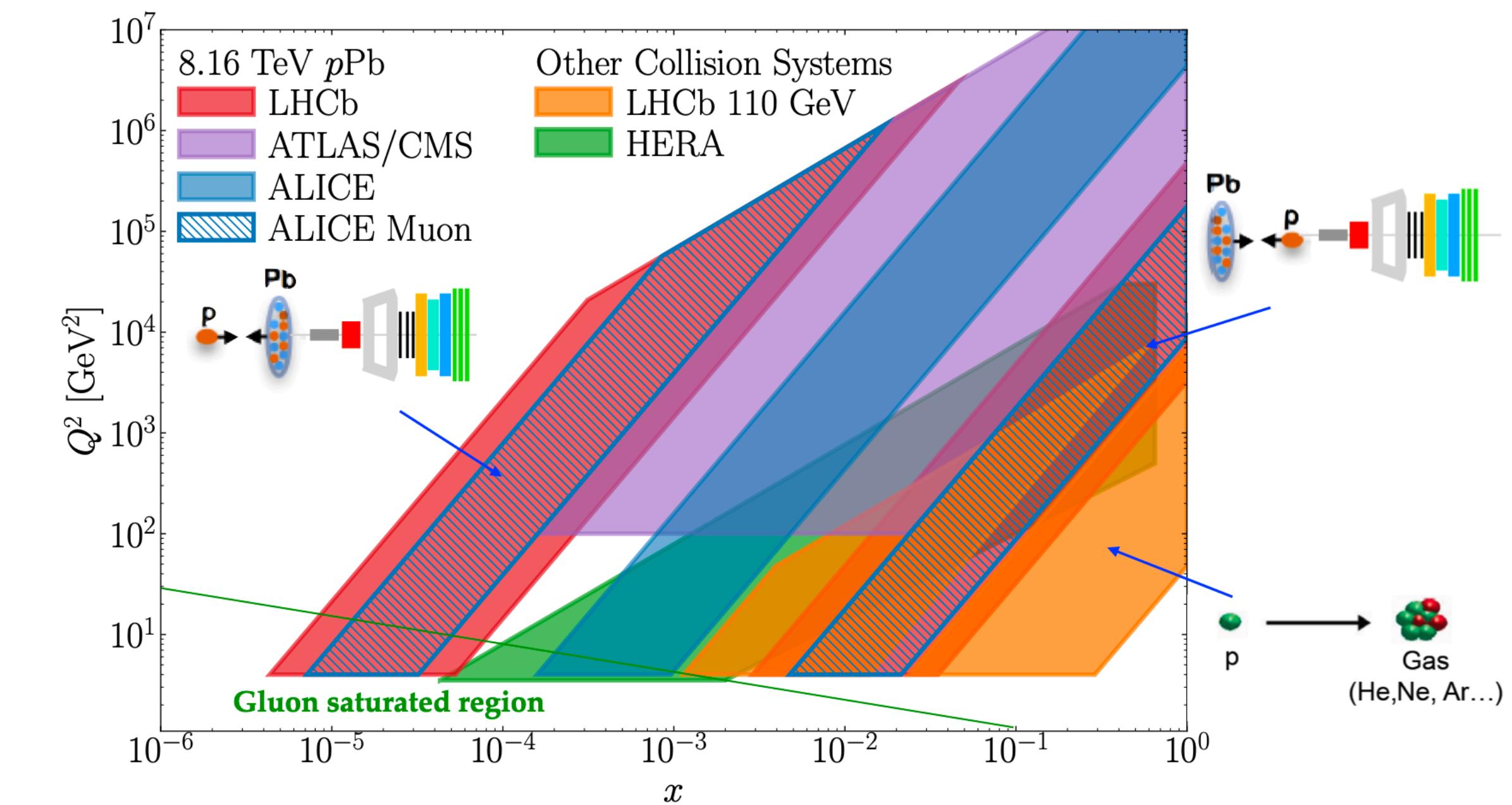
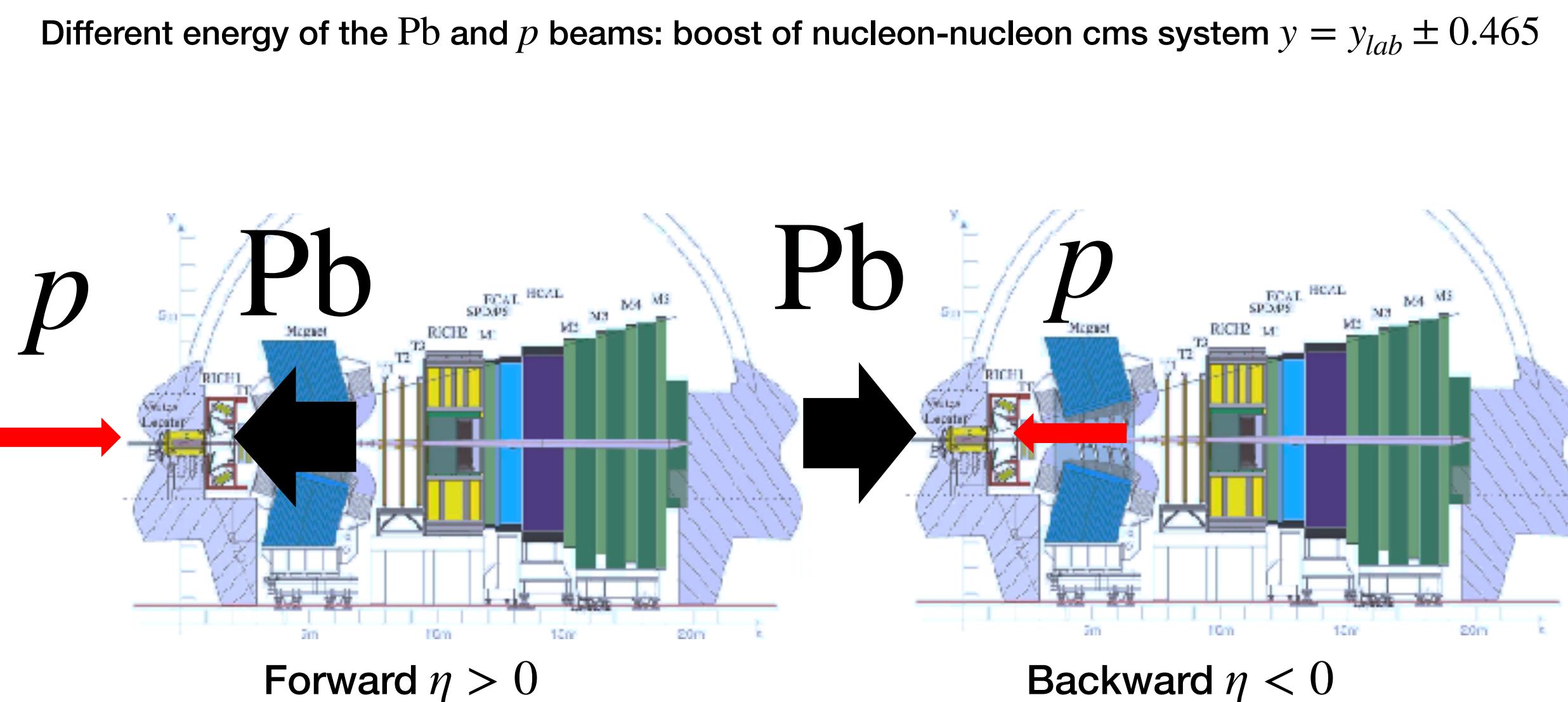
- ❖ Excellent tracking down to $p_T=0$.
- ❖ Excellent particle identification.
- ❖ Excellent primary vertex determination.

JINST 3 (2008) S08005

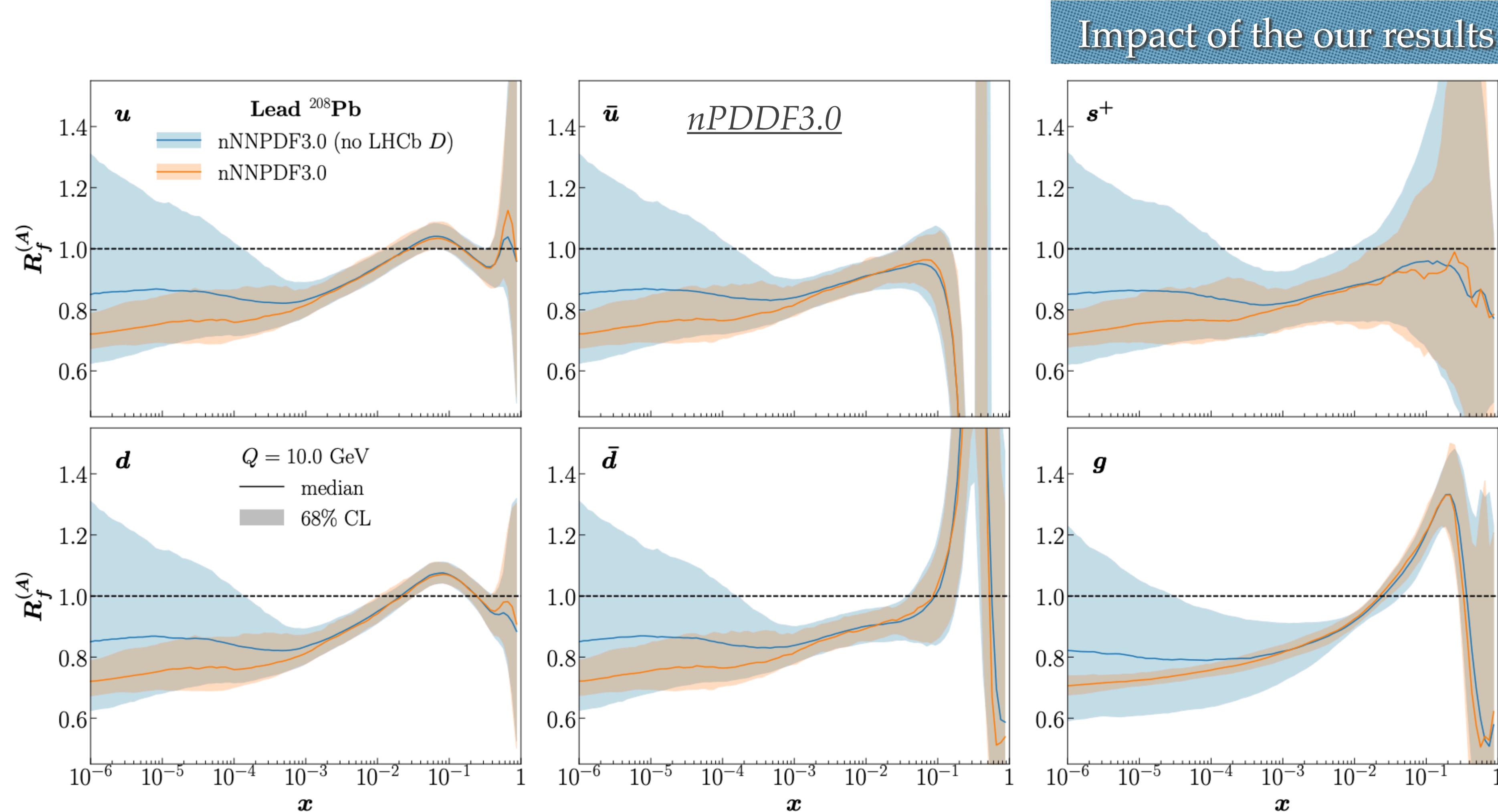
Int. J. Mod. Phys. 734 A30 (2015) 1530022

The ultimate nPDF explorer

Excellent possibilities for nuclear physics with $p\text{Pb}$ and SMOG

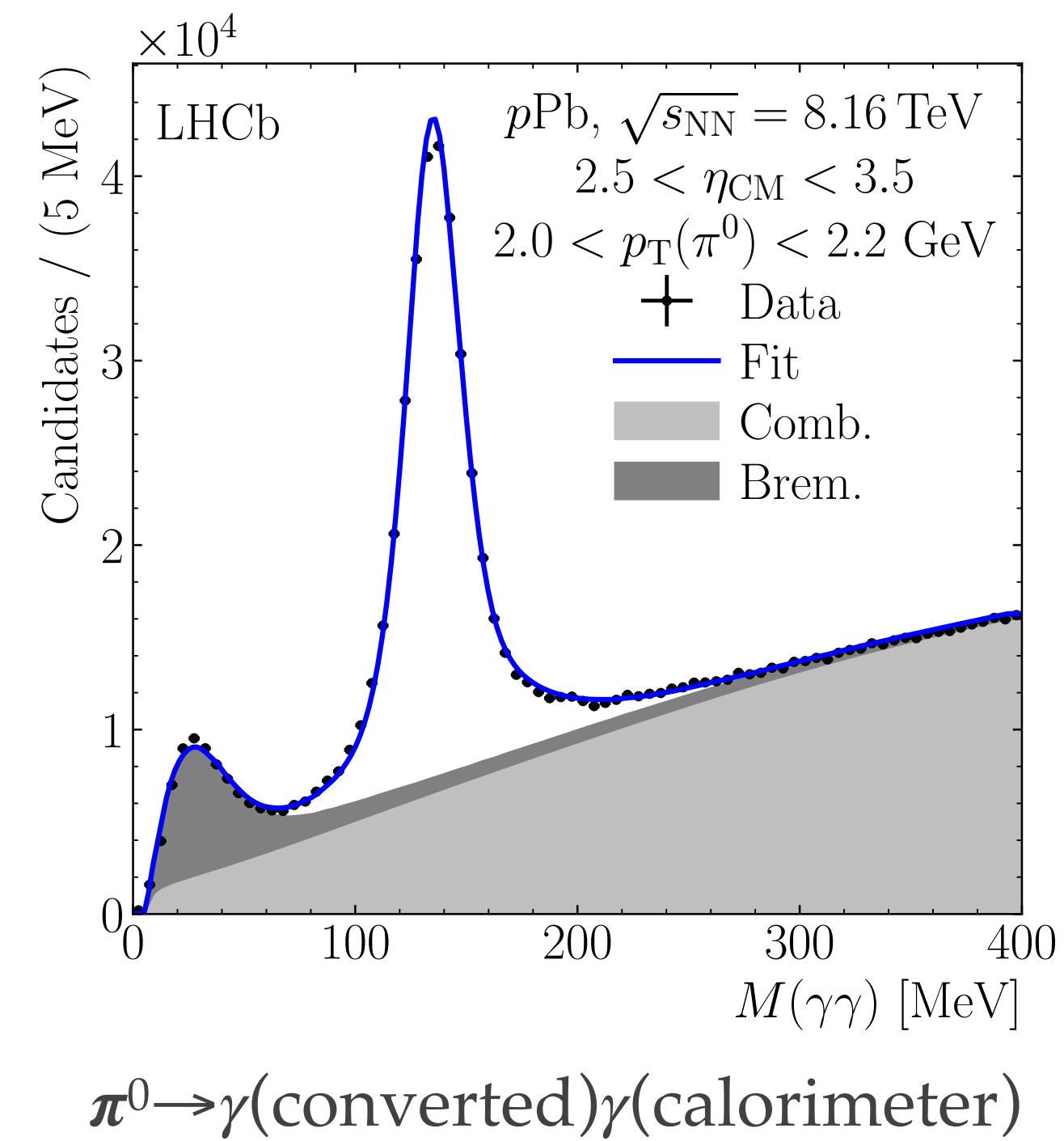


The ultimate nPDF explorer

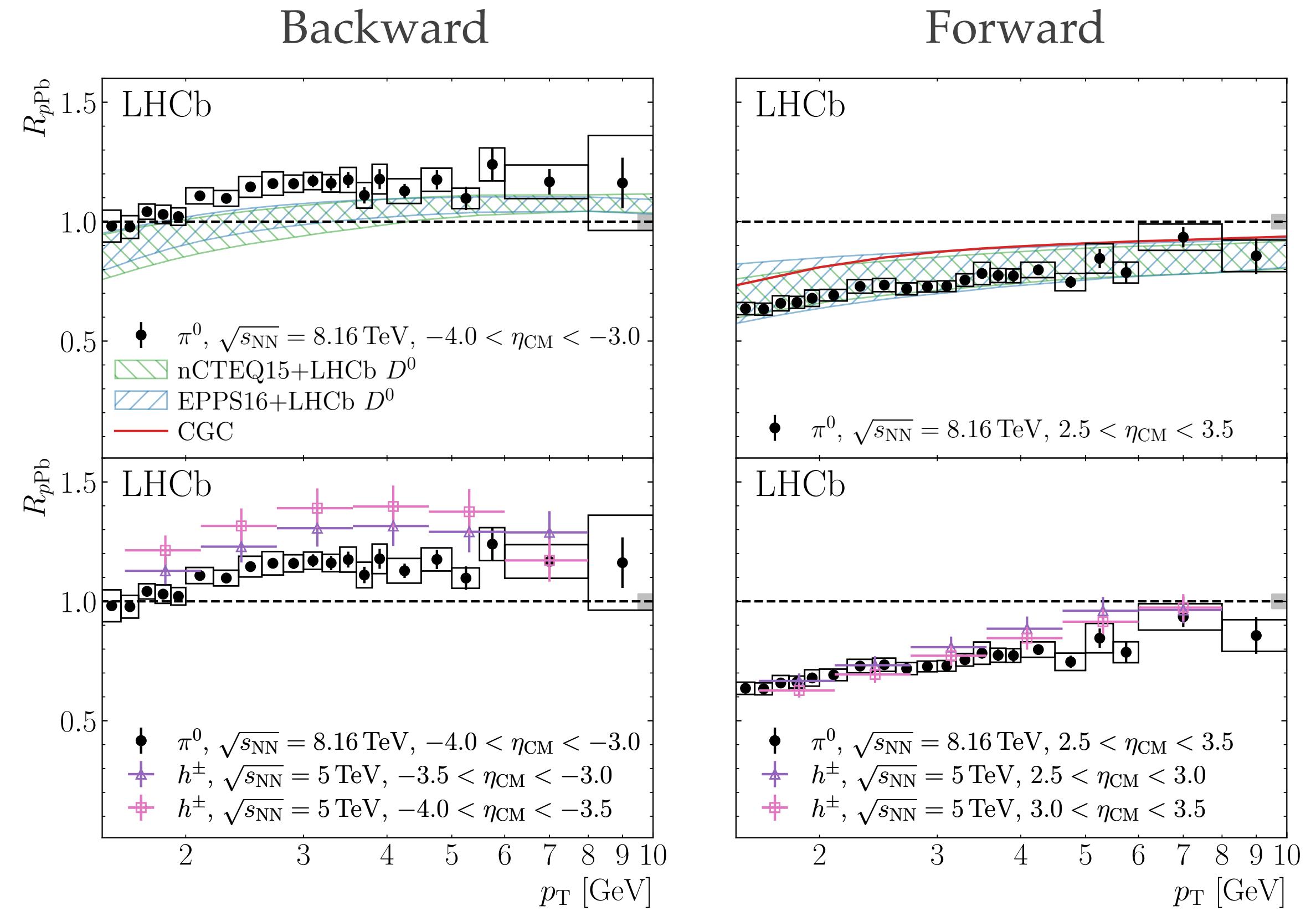


Impact of the our results at 5TeV *LINK*

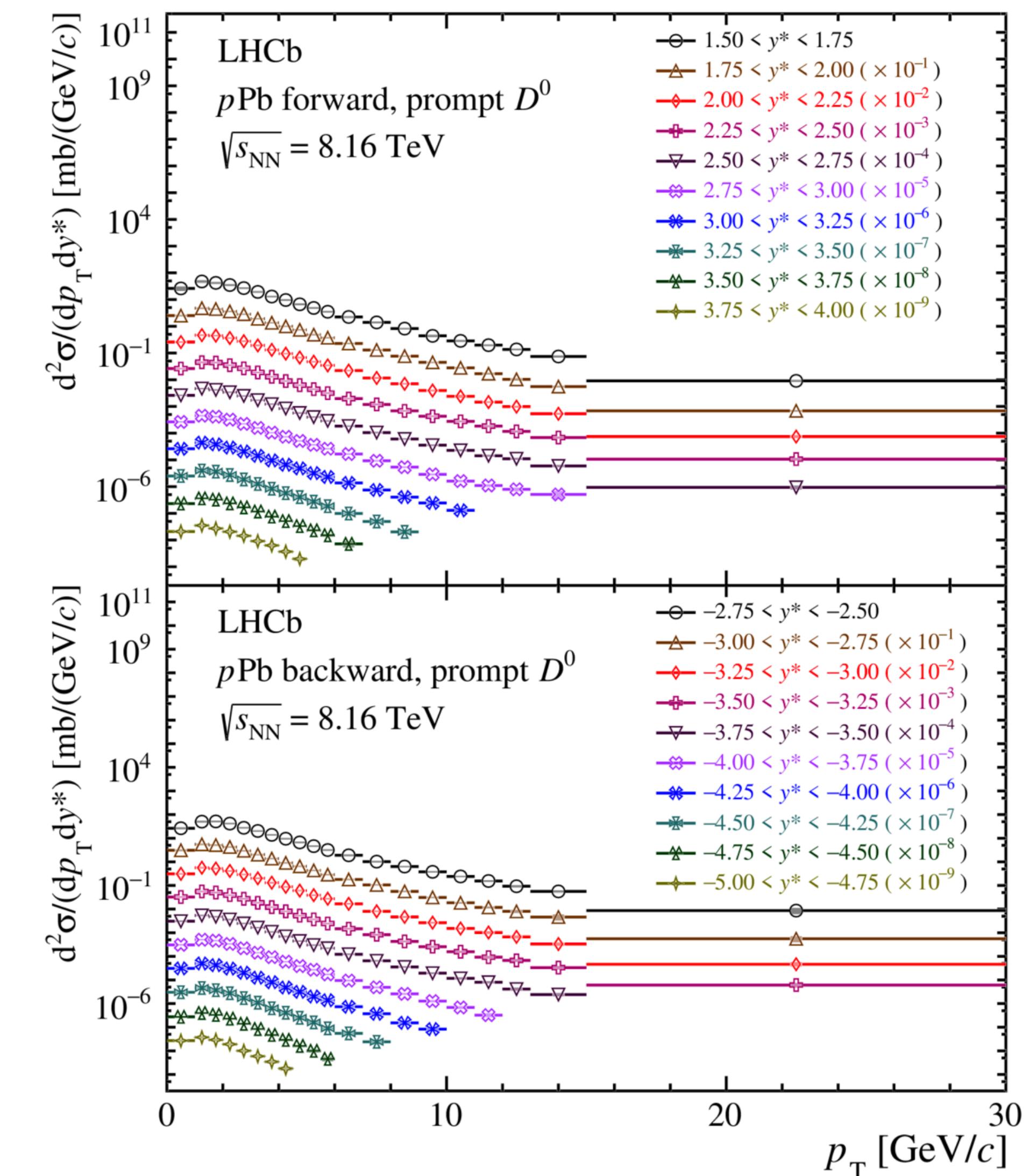
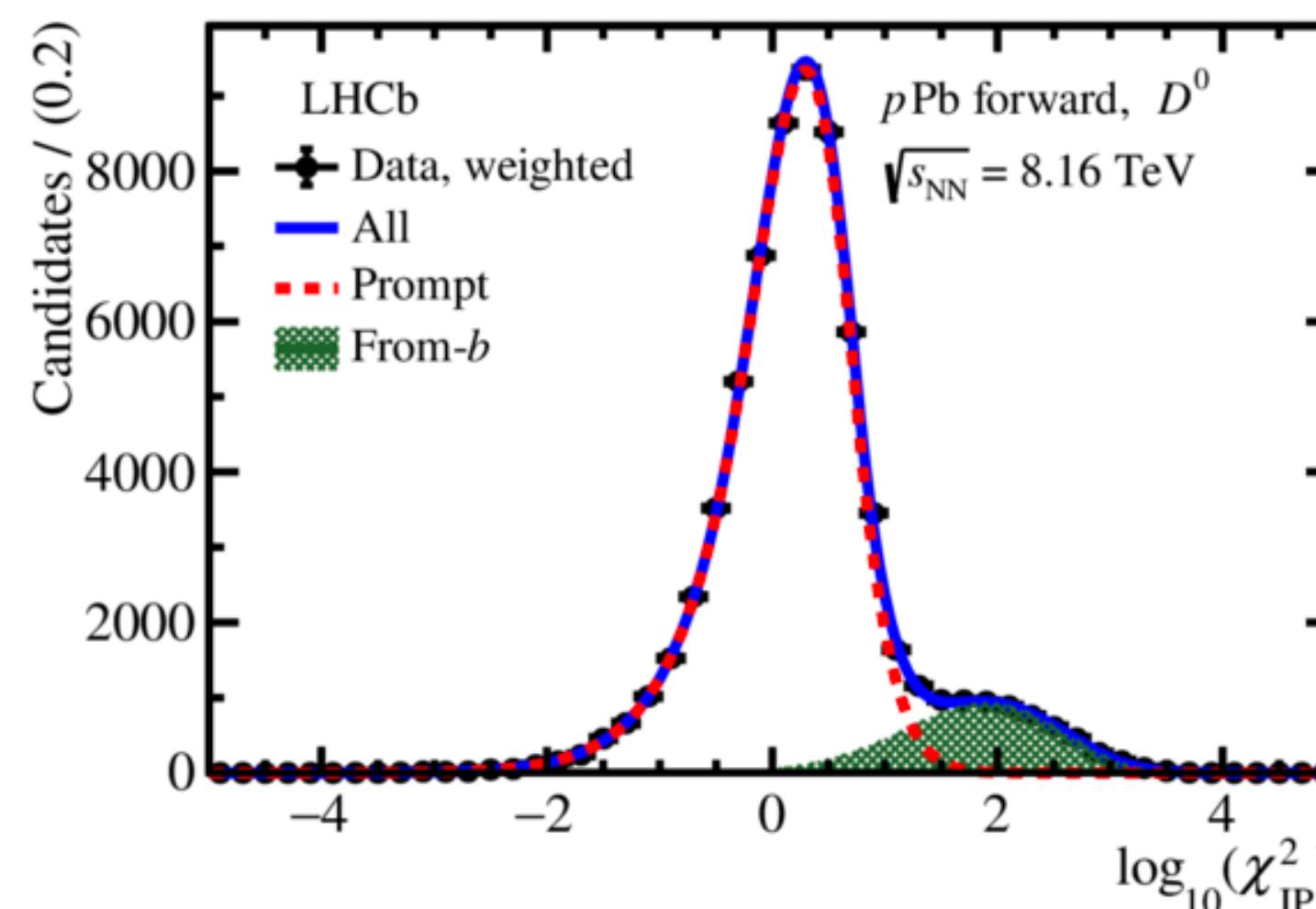
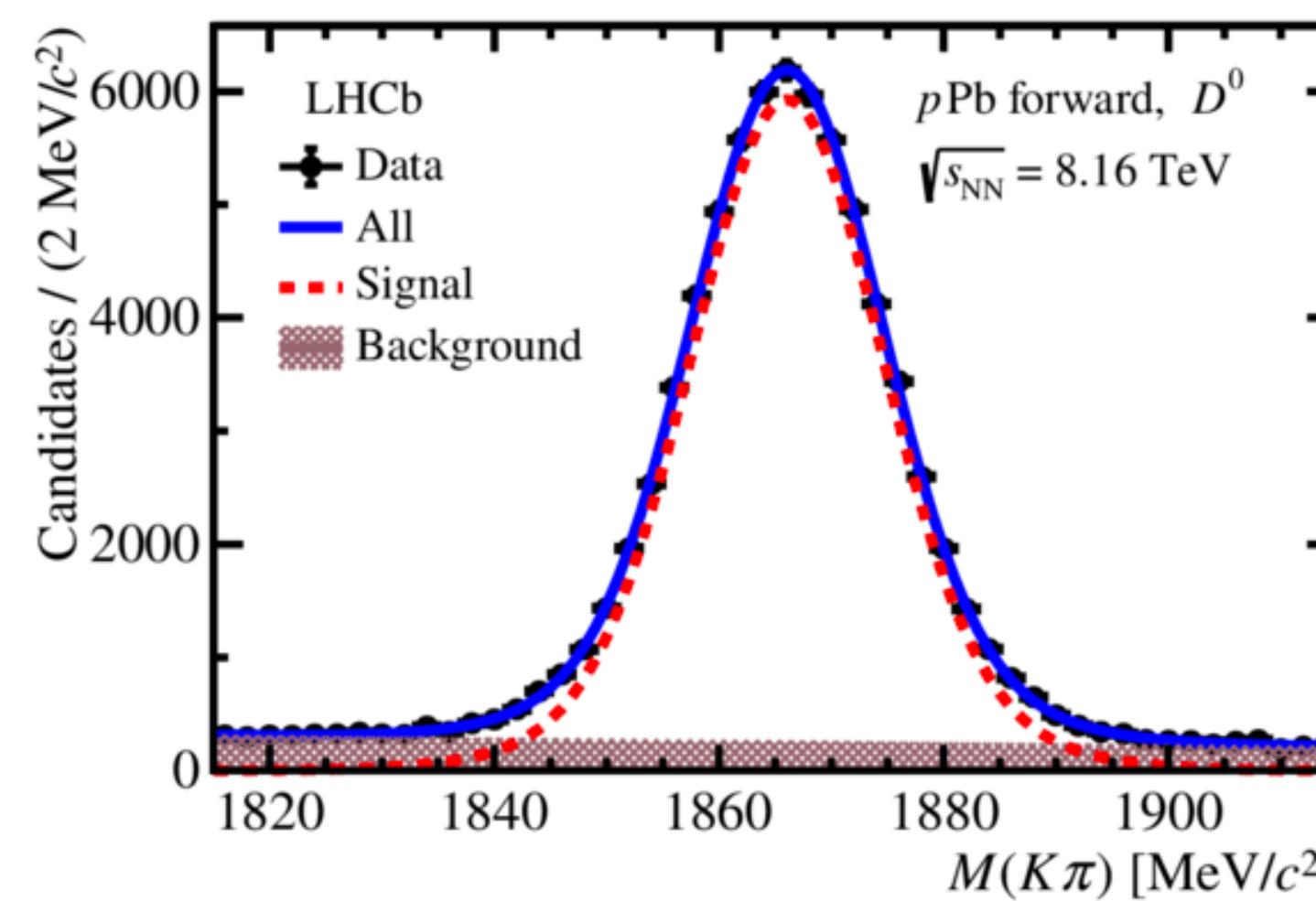
Nuclear modification factor of π^0 in $p\text{Pb}$ @8TeV



- ❖ Constrain nPDF down to $x \sim 10^{-6}$
- ❖ Expected Cronin-like effects in backward and shadowing in forward region
- ❖ Tension in the backward region suggesting additional effects, disagreement with CGC calculations in forward
- ❖ Greater precision than models !

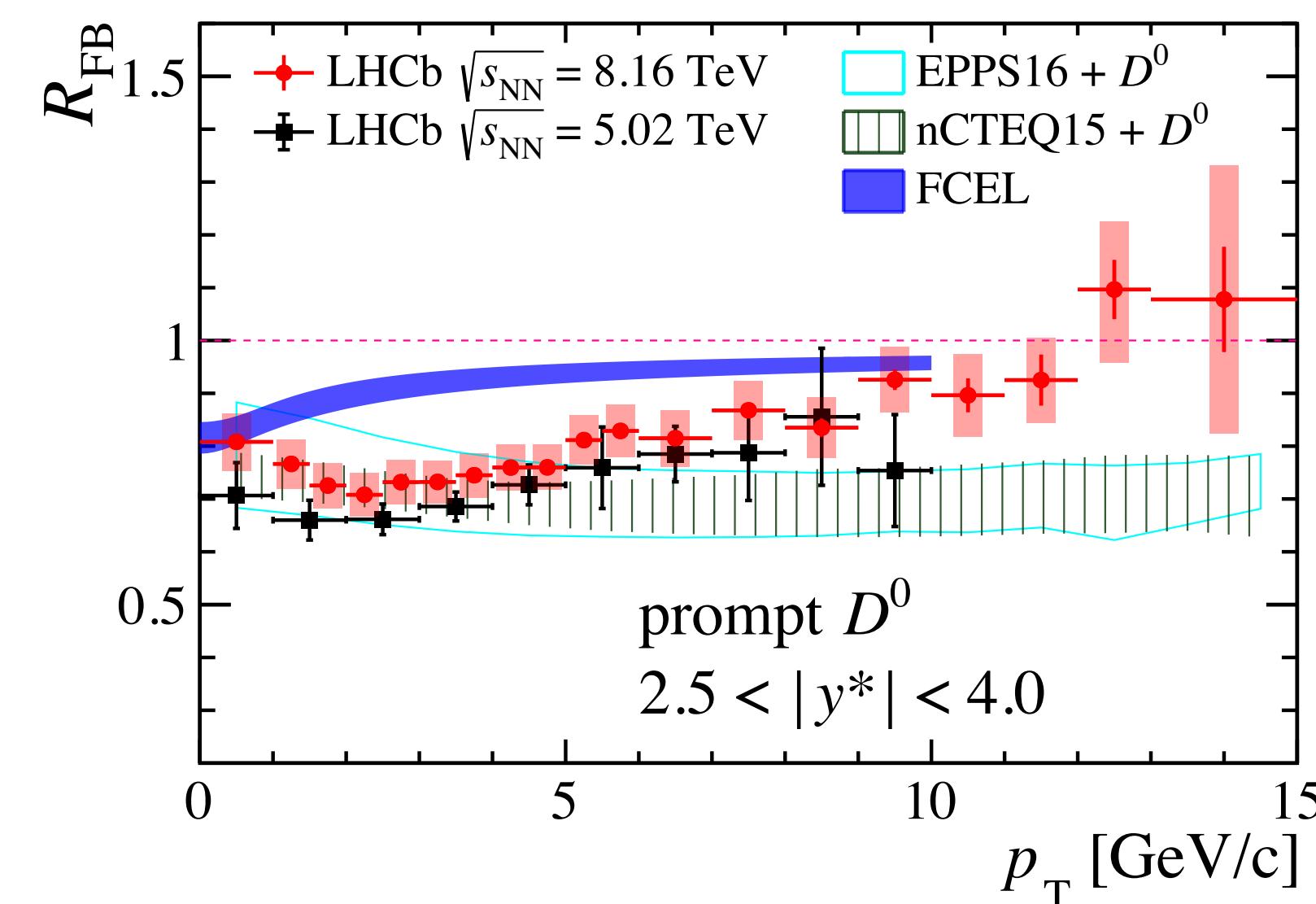
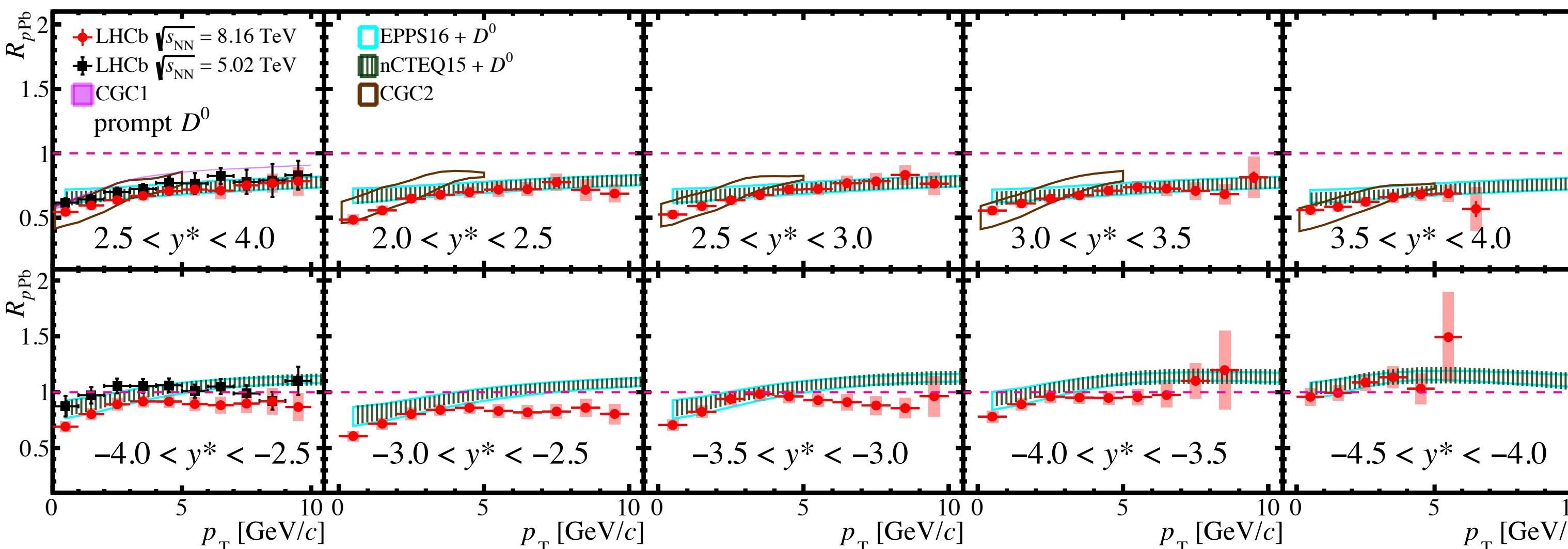


Prompt D^0 mesons in $p\text{Pb}$ @8TeV



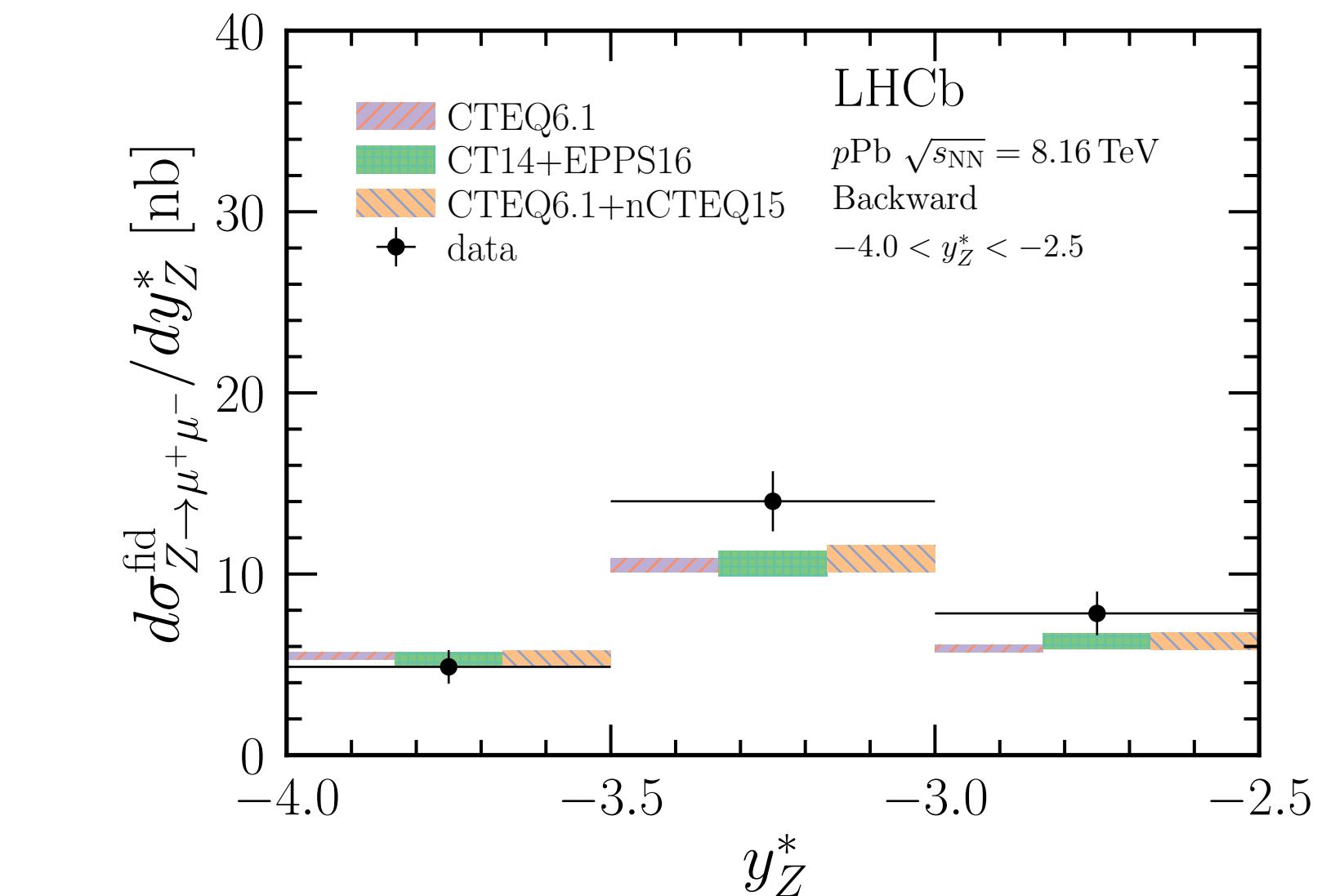
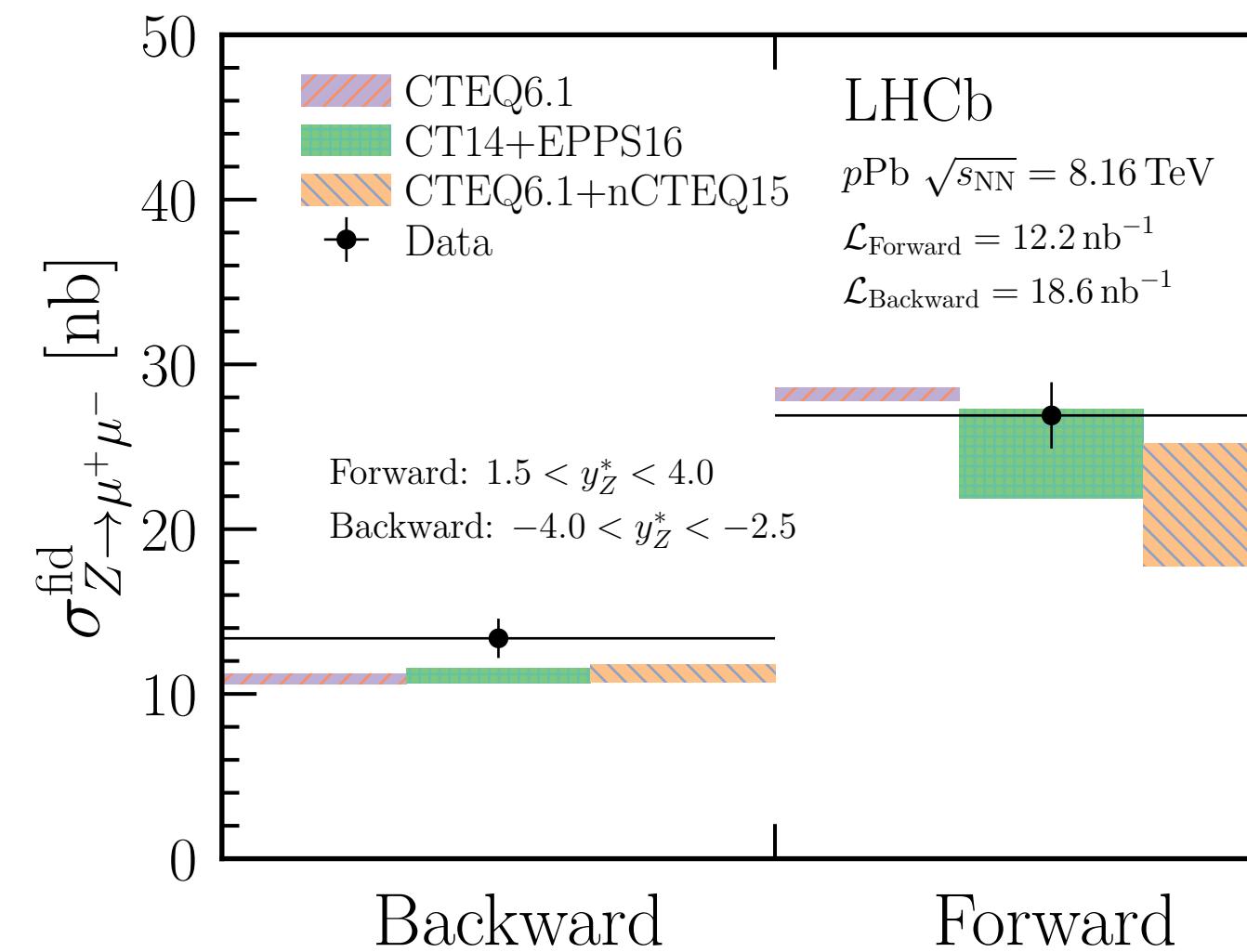
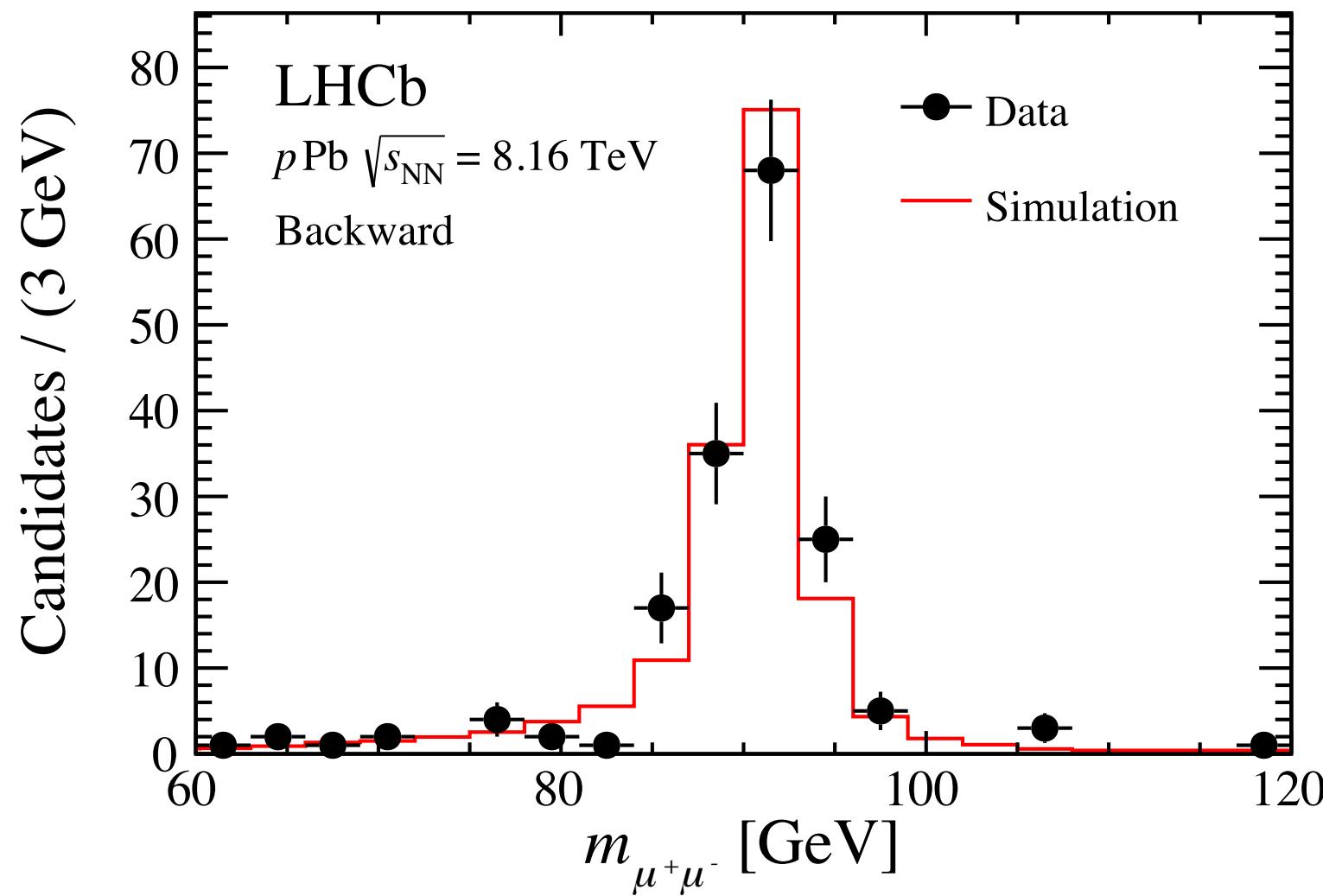
- ❖ Analysis with the high statistic $p\text{Pb}/\text{Pbp}$ 2016 sample
- ❖ Great precision achieved in many bins of p_T and y both in backward and forward
- ❖ Nuclear modification factor computed using interpolation based on LHCb results in pp collisions at 5 and 13 TeV

Prompt D^0 mesons in $p\text{Pb}$ @8TeV



- ❖ Results compared with CGC and nPDFs
- ❖ Overall good agreement, tension at high- p_T suggests an additional effect like energy loss
- ❖ Backward to forward ratio, including medium-induced fully coherent energy loss (FCEL) without nPDFs effects

Z boson in $p\text{Pb}$ @8TeV



Backward $-4.0 < y_Z^* < -2.5$

$$\sigma_{Z \rightarrow \mu^+ \mu^-, p\text{Pb}}^{\text{fid}} = 13.4 \pm 1.0 \pm 0.5 \pm 0.3 \text{ nb}$$

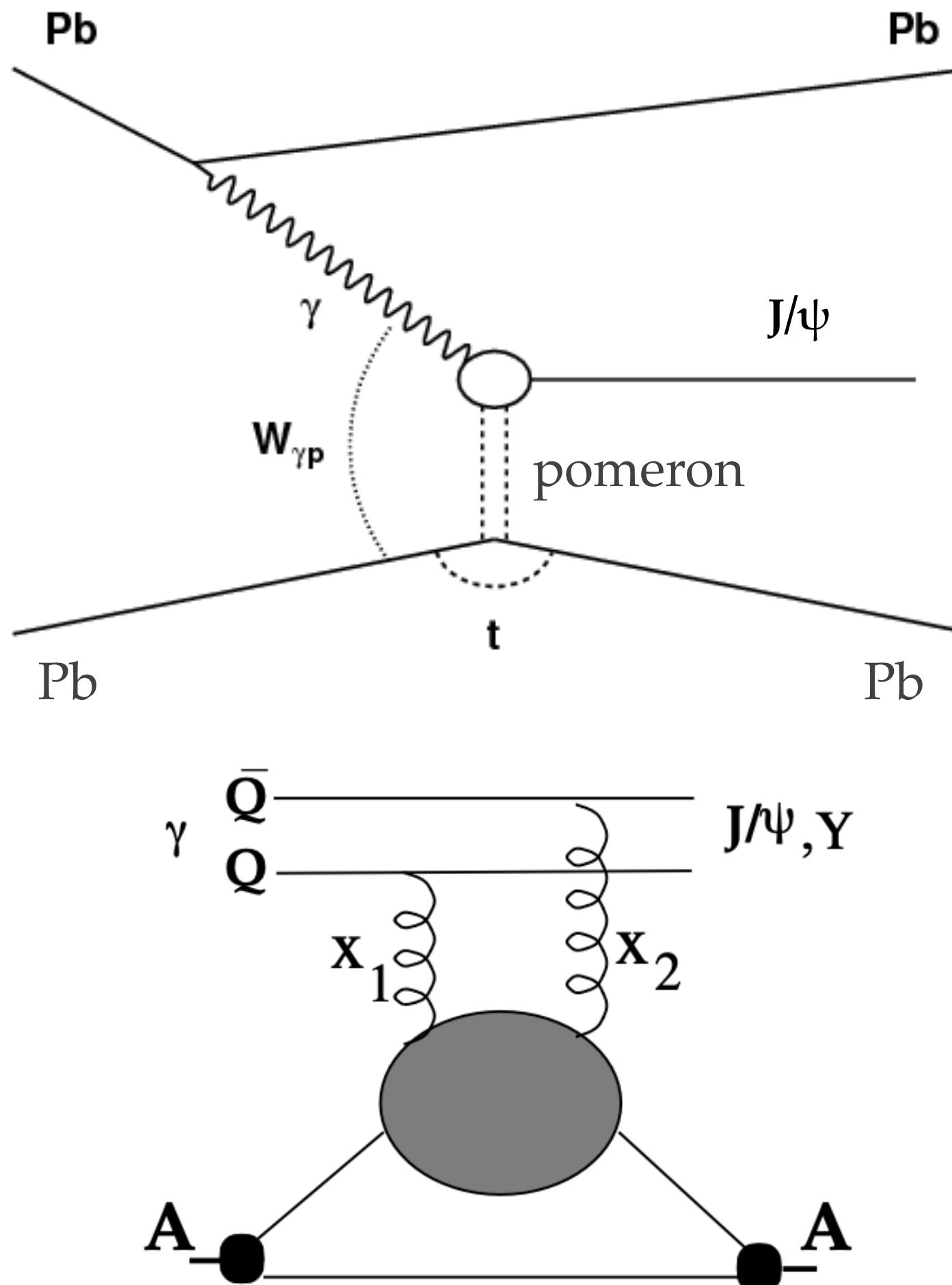
Forward $1.5 < y_Z^* < 4.0$

$$\sigma_{Z \rightarrow \mu^+ \mu^-, p\text{Pb}}^{\text{fid}} = 26.9 \pm 1.6 \pm 0.9 \pm 0.7 \text{ nb}$$

- ❖ Powerful probe to measure nPDF as the hard process is well described by perturbative QCD
- ❖ Results compared to POWHEGBOX predictions using CTEQ6.1, EPPS16 and nCTEQ15 nPDF sets
- ❖ Both regions compatible with the prediction, uncertainty in the forward smaller than the predictions, good constrain on the nPDFs

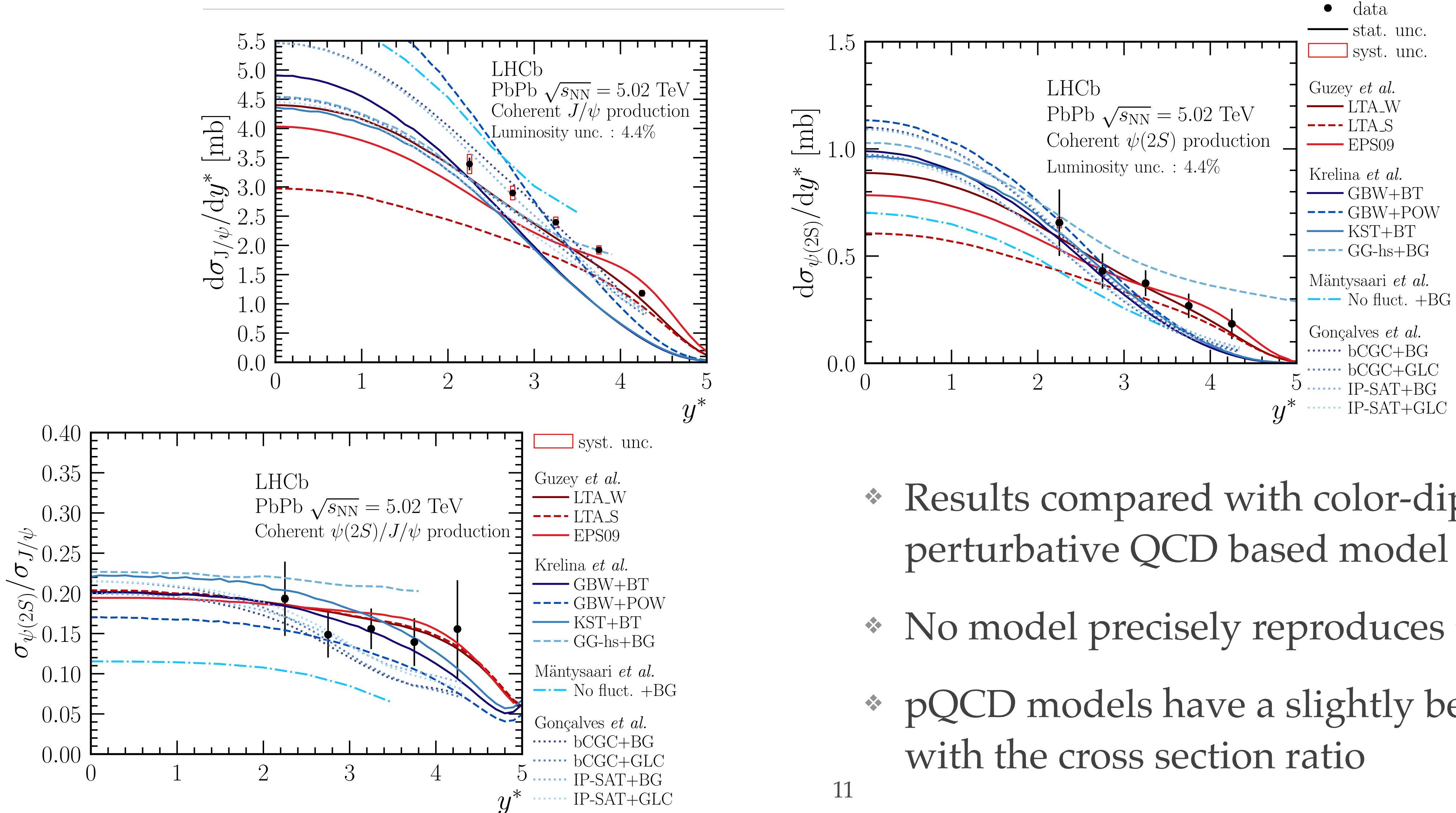
$J/\psi, \psi(2S)$ PbPb UPC @5TeV

Coherent photo-production

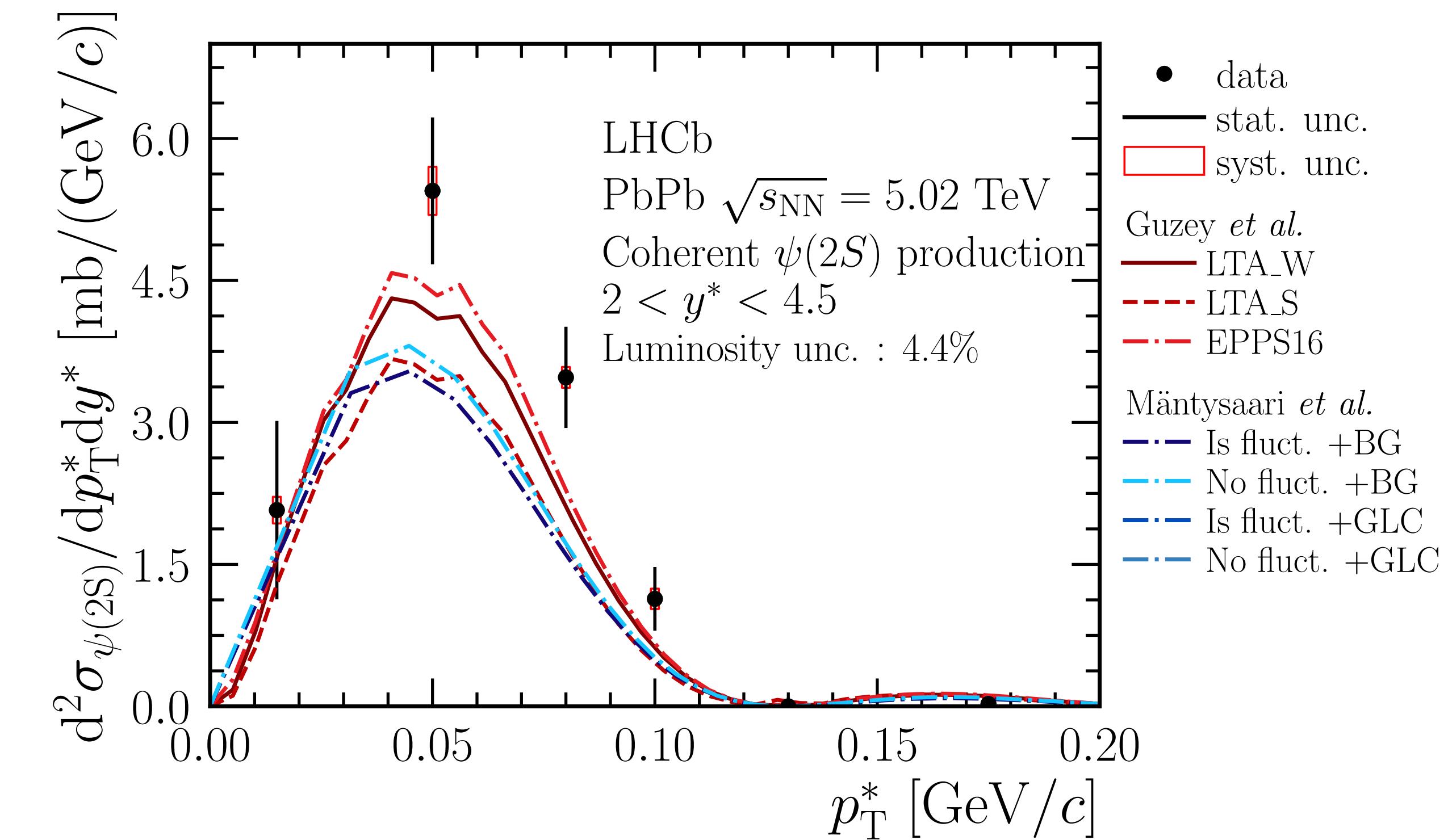
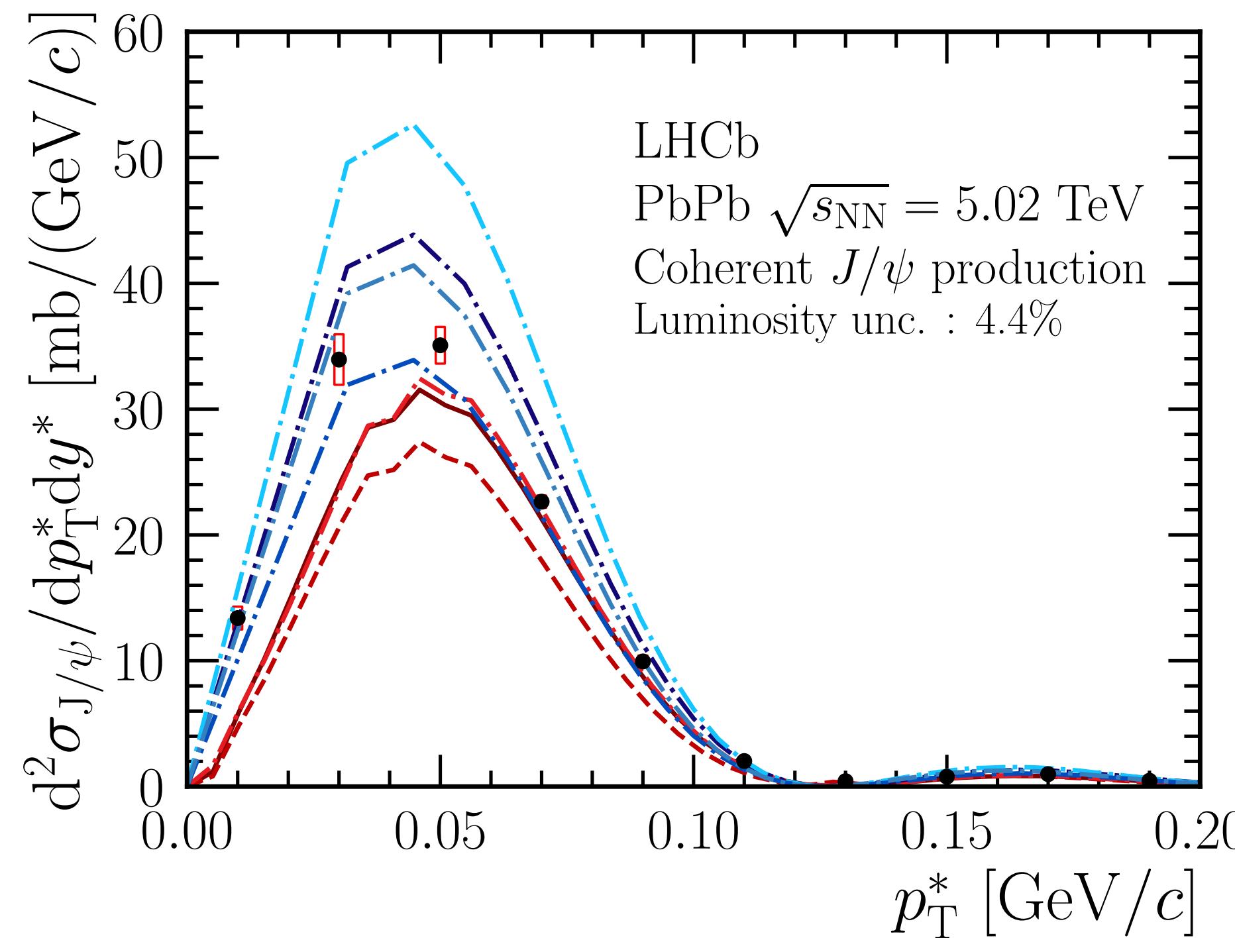


- ❖ Production of vector mesons through the interaction of a photon and a pomeron
- ❖ Amplitude of quarkonium production proportional to the Generalized Parton Distribution functions (GPDs) of the target nucleus $G_A(x_1, x_2, t, Q_{eff}^2)$ at large momentum transfer $Q_{eff}^2 \propto m_Q^2/4$ and low x-Bjorken $10^{-5} < x < 10^{-2}$

$J/\psi, \psi(2S)$ PbPb UPC @5TeV

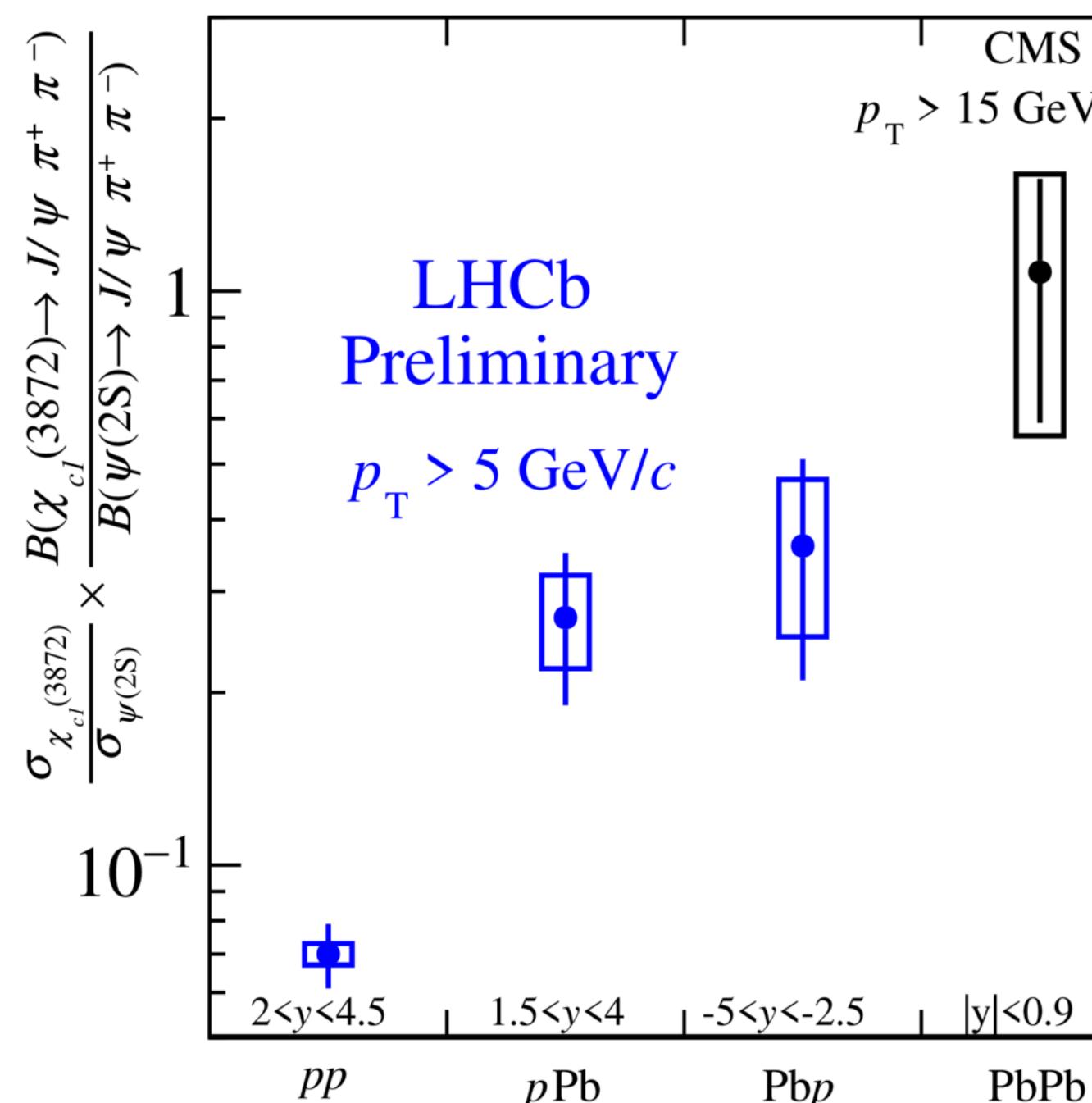
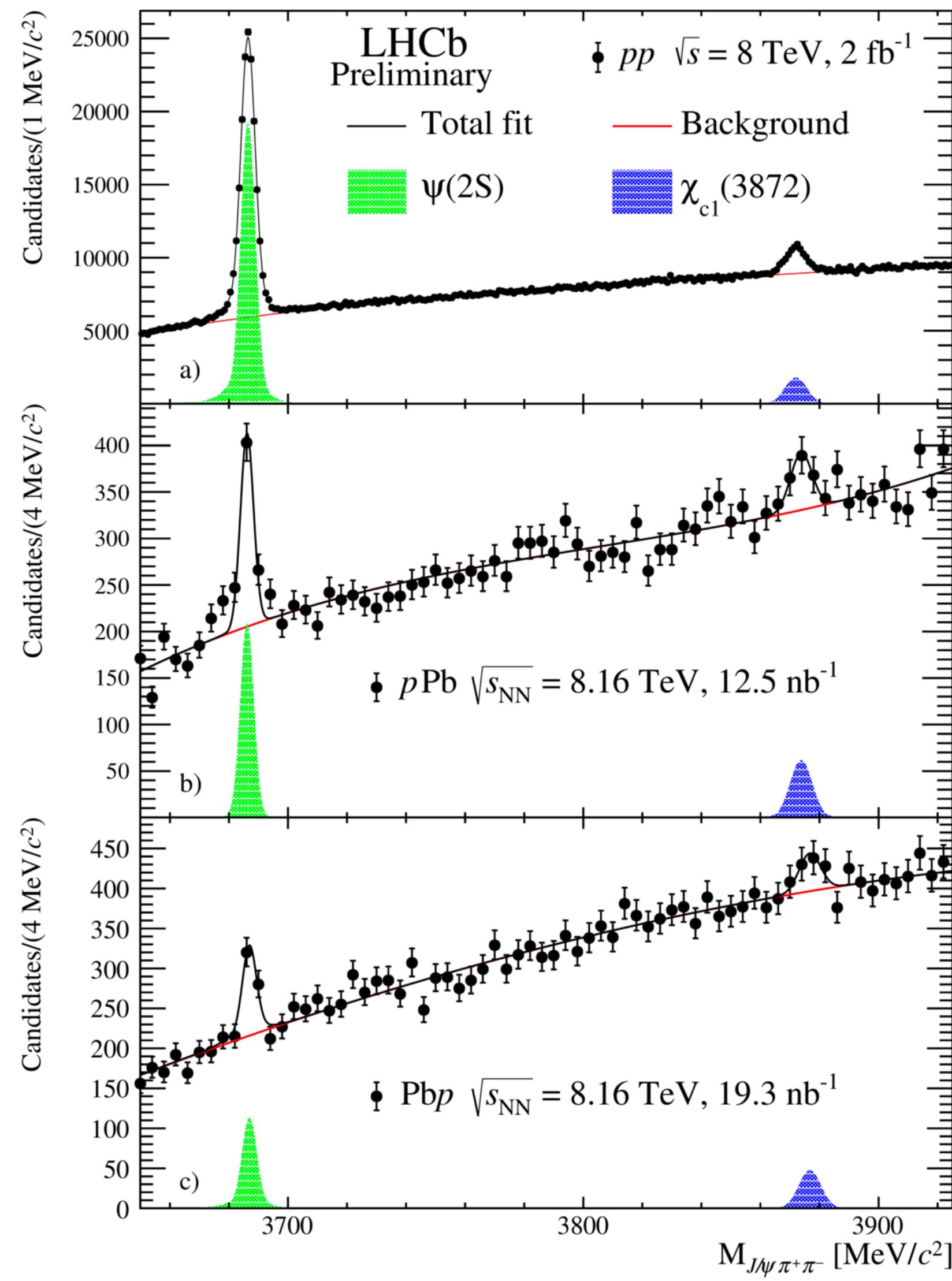


J/ ψ , $\psi(2S)$ PbPb UPC @5TeV



- ❖ Overall shape well reproduced by models but the normalization is less accurate
- ❖ Peaking structure due to destructive interferences (cannot distinguish the photon emitter).

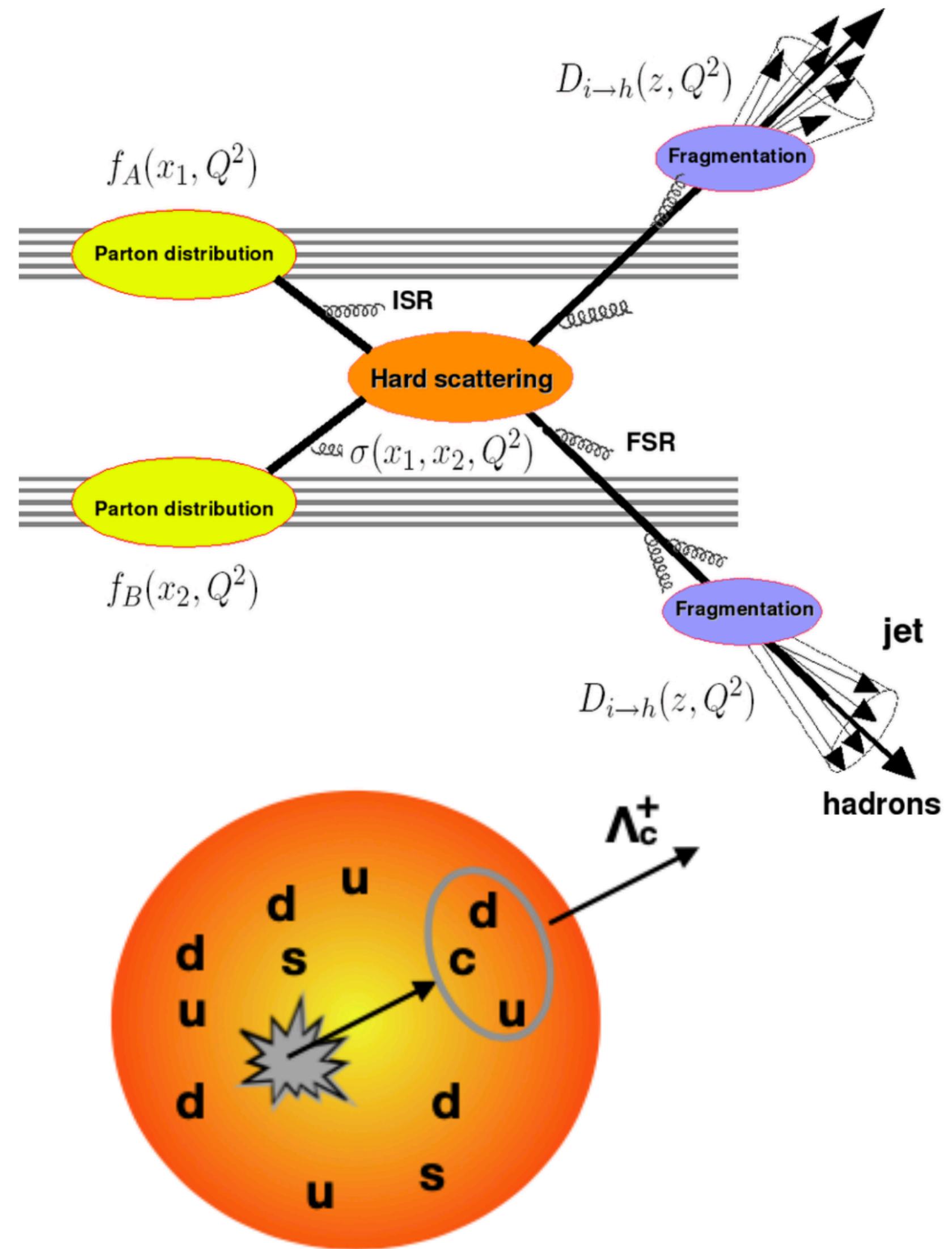
Modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production



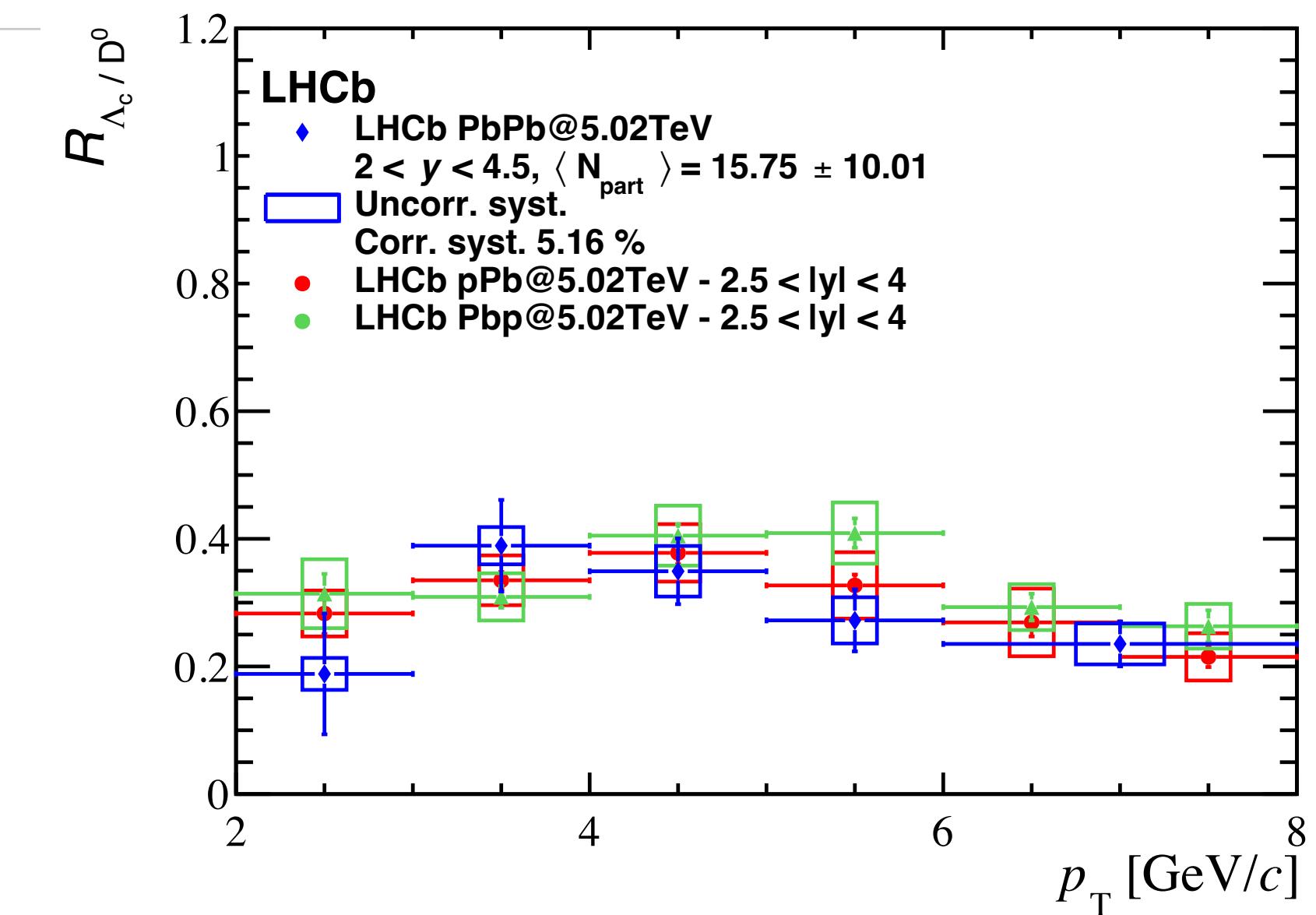
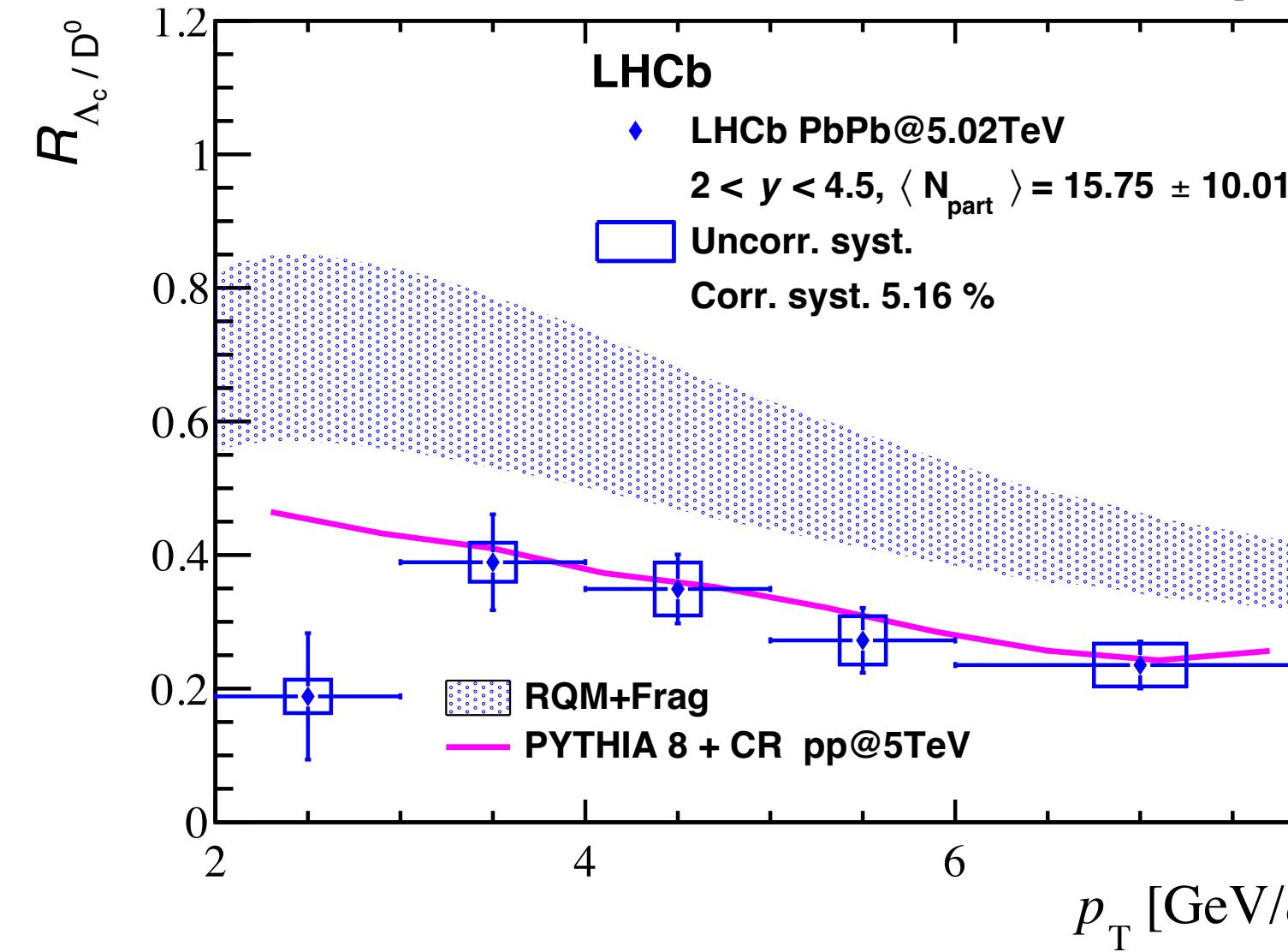
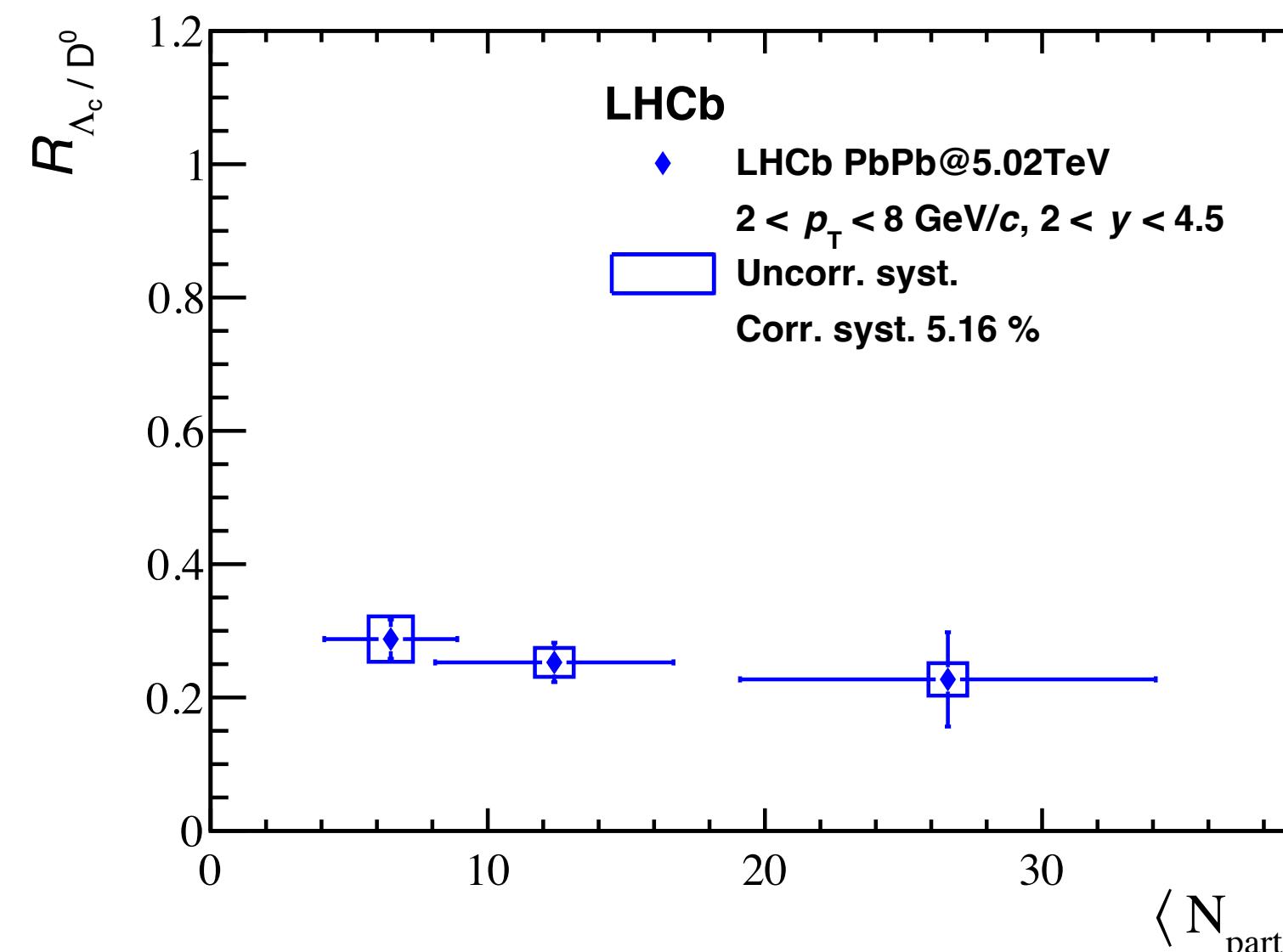
- ❖ Production of the exotic state $\chi_{c1}(3872)$ in $p\text{Pb}$ and Pbp
- ❖ The comparison with $\psi(2S)$ suggests the exotic state experiences different interactions in the nuclear medium
- ❖ Ratio sensitive to final state effects
- ❖ Ratio increasing wrt system size, quark coalescence dominant over $\chi_{c1}(3872)$ comover breakup?

Λ_c^+/\bar{D}^0 in PbPb @ 5TeV

- ❖ Large quark mass -> pQCD calculation
- ❖ Ratio to test pQCD factorisation
- ❖ Probe hadronization mechanisms:
 - ❖ Fragmentation functions
 - ❖ Coalescence:
 - ❖ Occurring in both small and large system?
 - ❖ Multiplicity dependent?



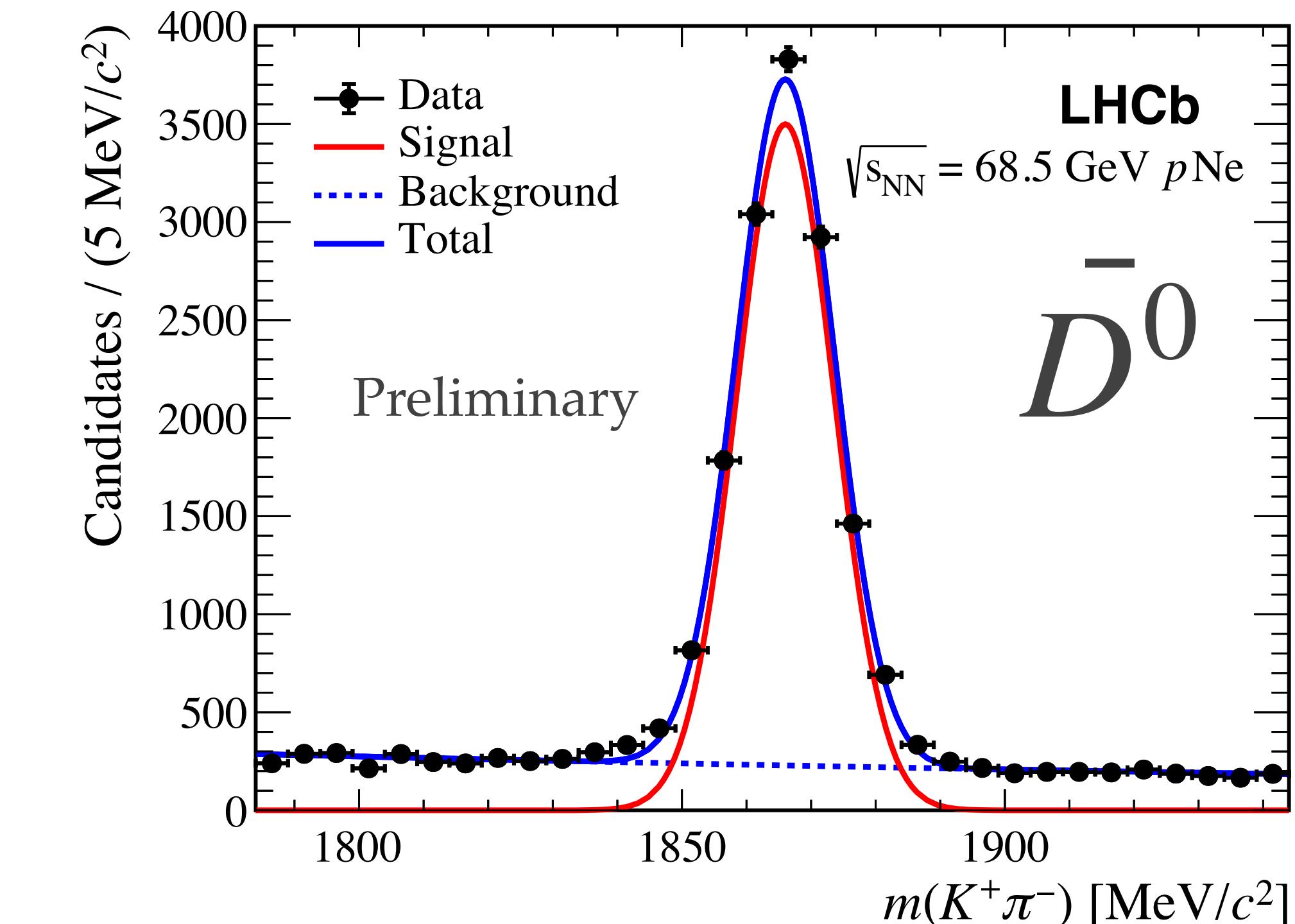
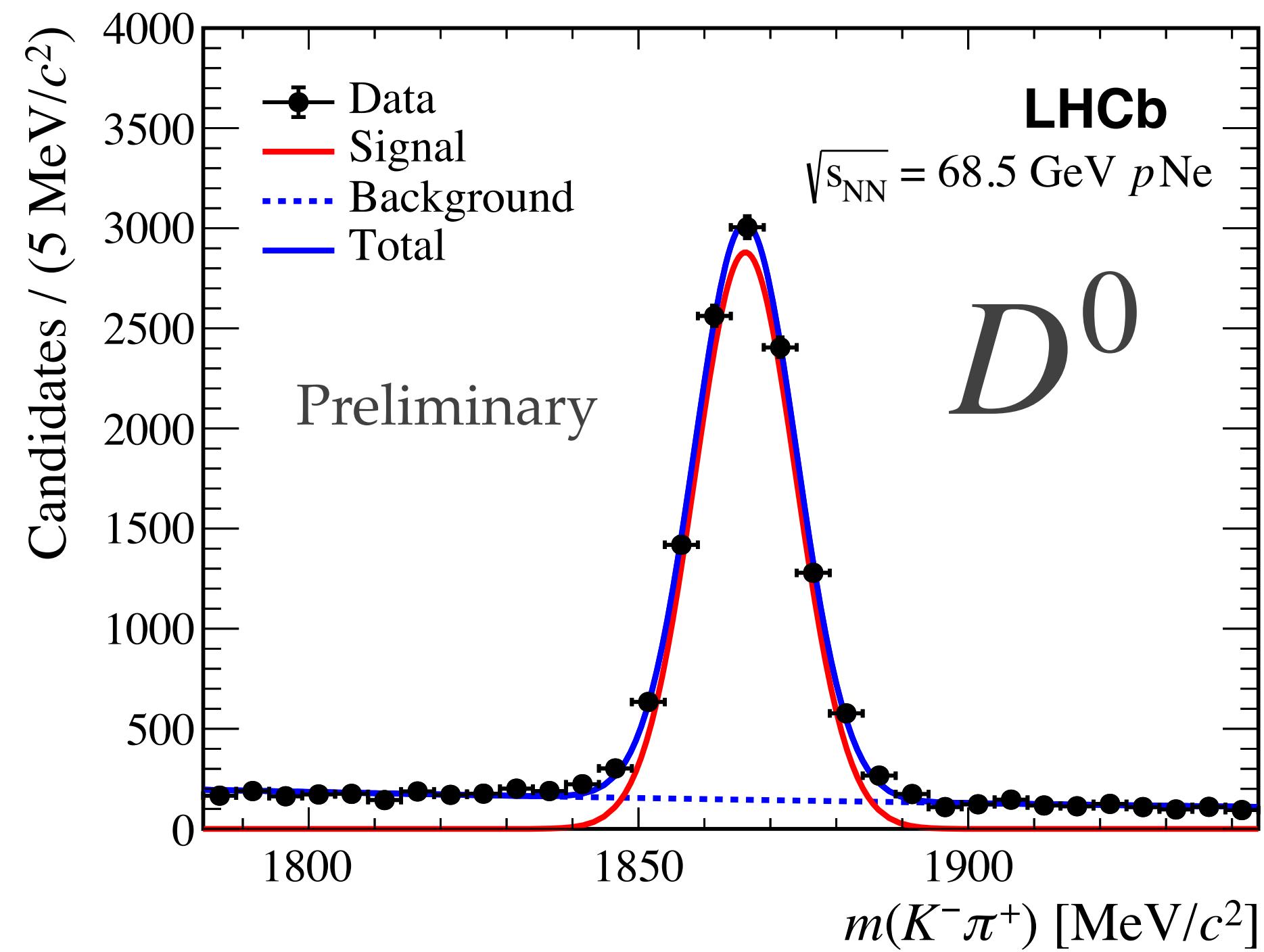
Λ_c^+/D^0 in PbPb @ 5TeV



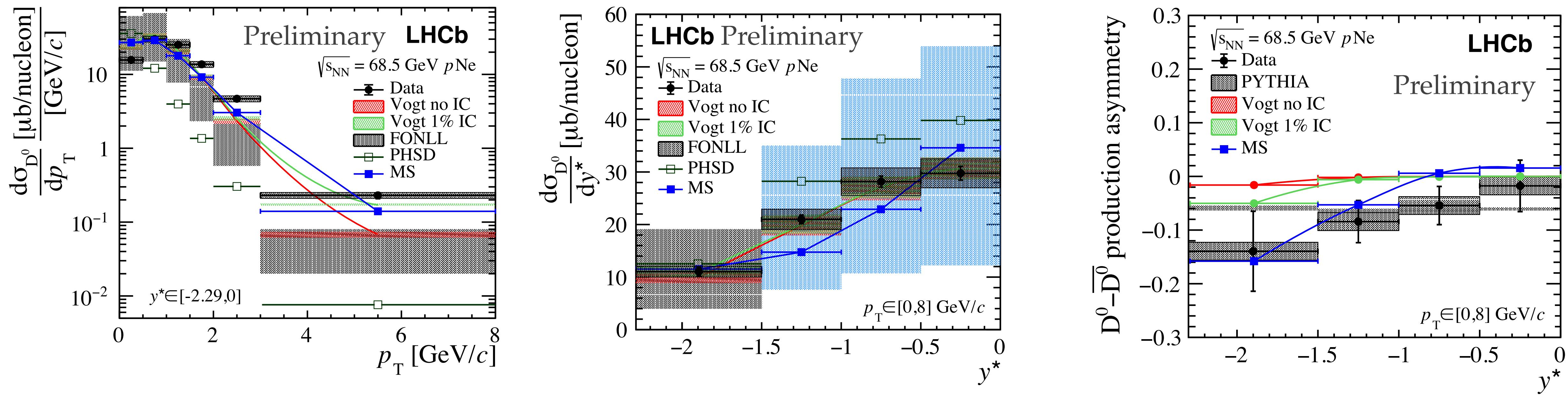
- ❖ Flat dependence vs N_{part}
- ❖ Results compatible with $p\text{Pb}$ results at same energy
- ❖ Decreasing trend toward high p_{T}
- ❖ Compatible with PYTHIA8 and color reconnection ($pp@5\text{TeV}$)

Open charm production in $p\text{Ne}$ @68 GeV

- ❖ Fixed target collisions, centre of mass rapidity [-2.29,0] high x-Bjorken
- ❖ Cross-section measurements compared to models including or not intrinsic charm
- ❖ Largest SMOG sample with $L = 21.7 \pm 1.4 \text{ nb}^{-1}$

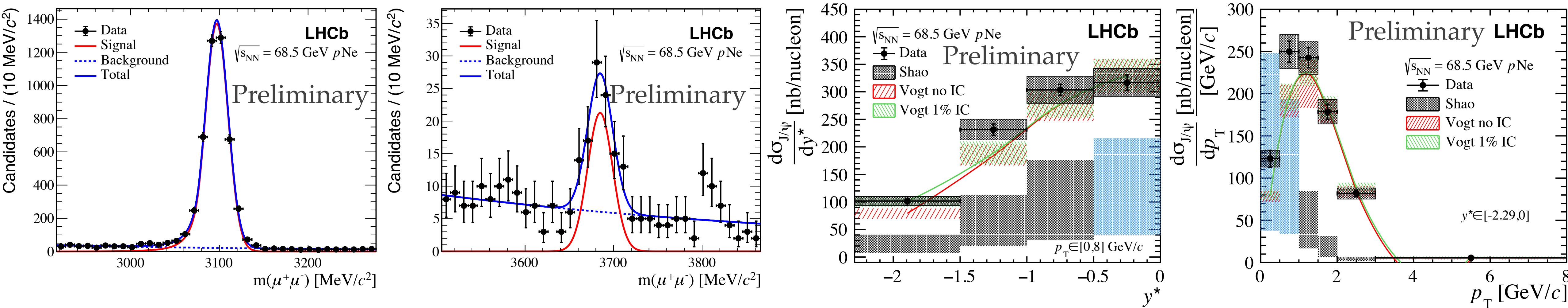


Open charm production in $p\text{Ne}$ @68 GeV



- ❖ Cross-section compared to many models, Vogt and MS model that includes 1% intrinsic charm describe better the data.
- ❖ Asymmetry found, down to -15% at $y^* = -2.29$, compatible with Pythia8 simulation
- ❖ Possible recombination with valence quarks can explain the $D^0 - \bar{D}^0$ asymmetry

Charmonium production in $p\text{Ne}$ @68 GeV

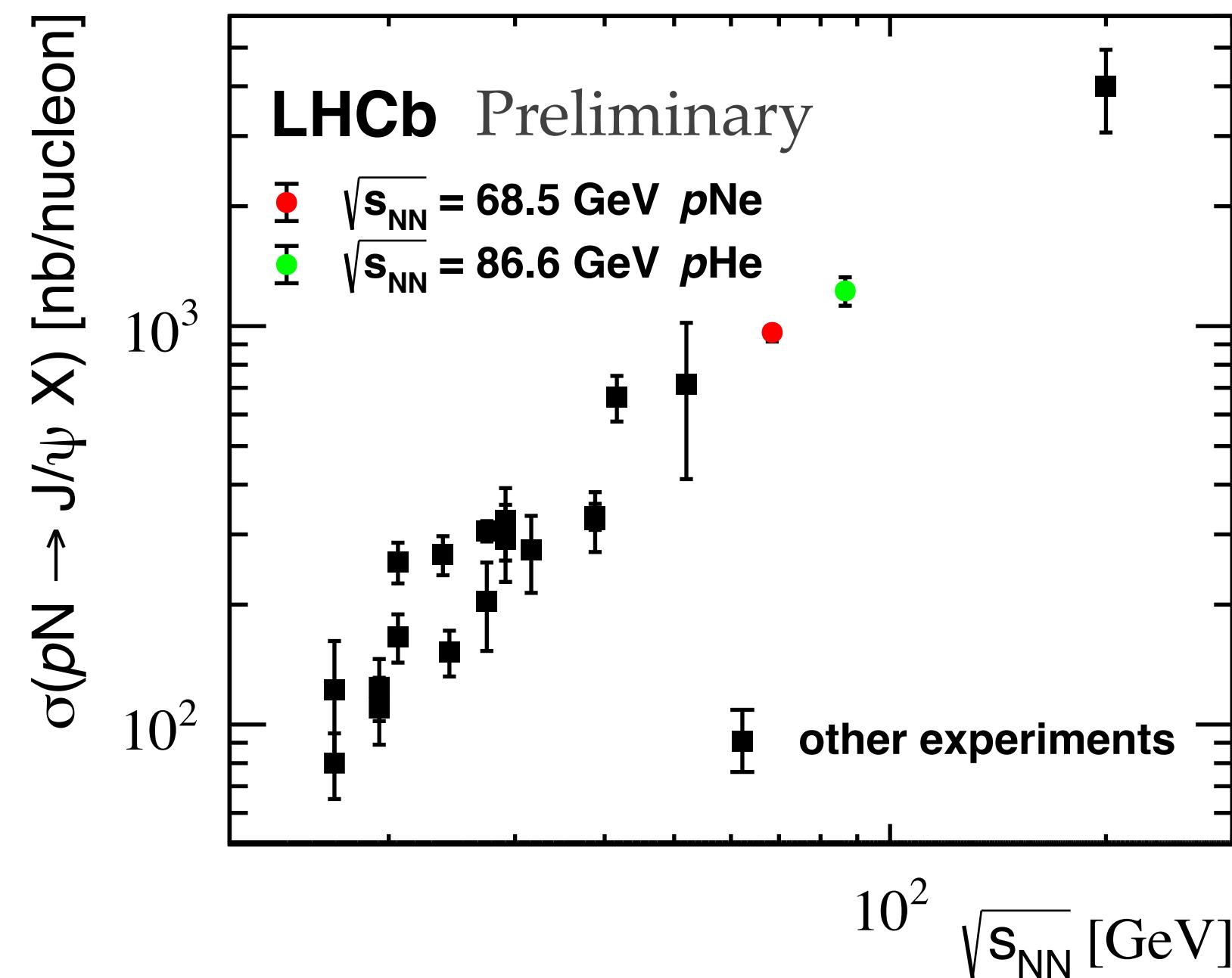


- ❖ Complete the intrinsic charm measurement with J/ψ
- ❖ Again the Vogt model with 1% intrinsic charm seems to better describe the data, but larger samples with the SMOG2 system are needed to draw definitive conclusions

See LHCb intrinsic charm measurement with Z+jet Phys. Rev. Lett. **128**, 082001

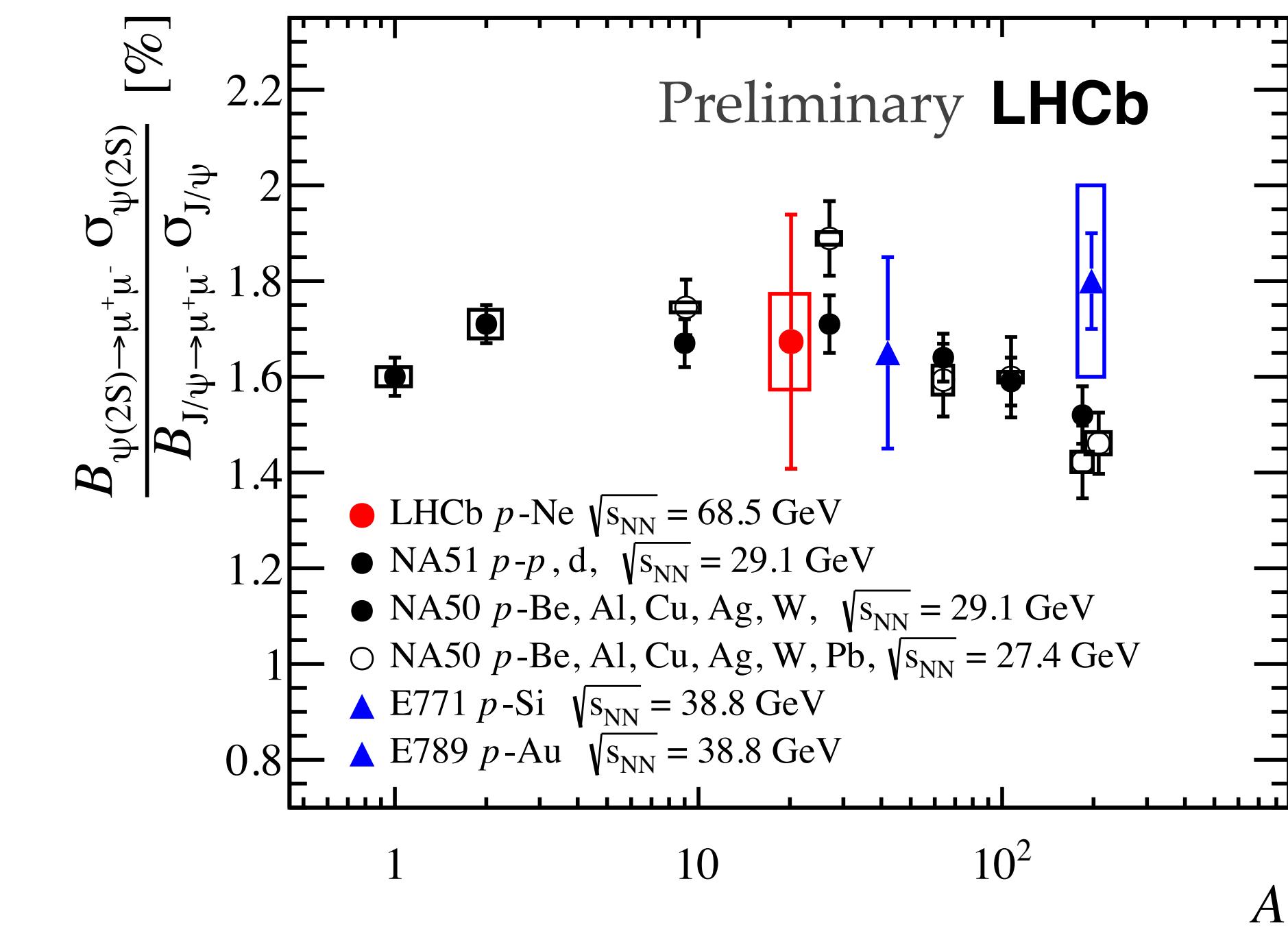
Charmonium production in $p\text{Ne}$ @68 GeV

Comparison with previous results



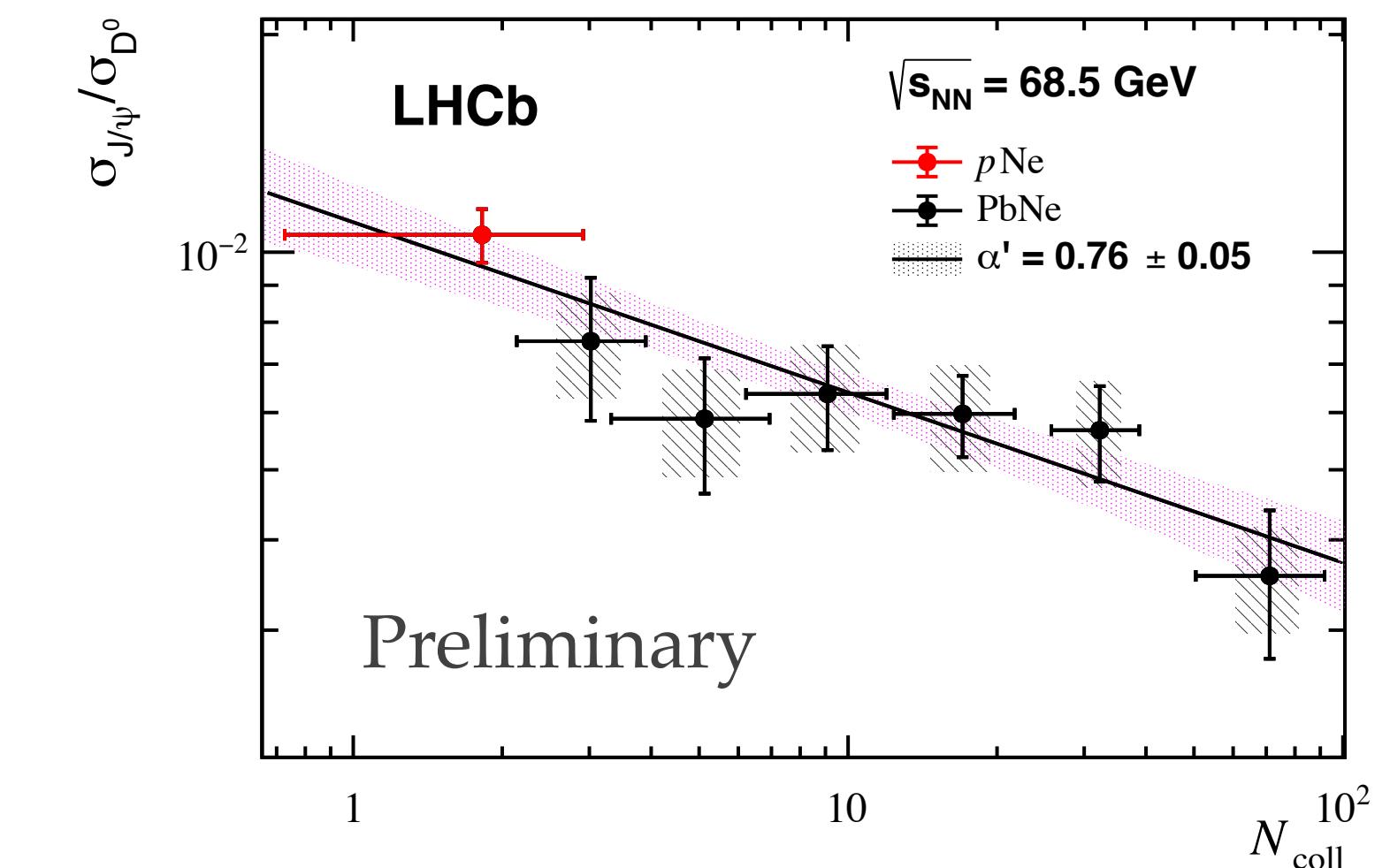
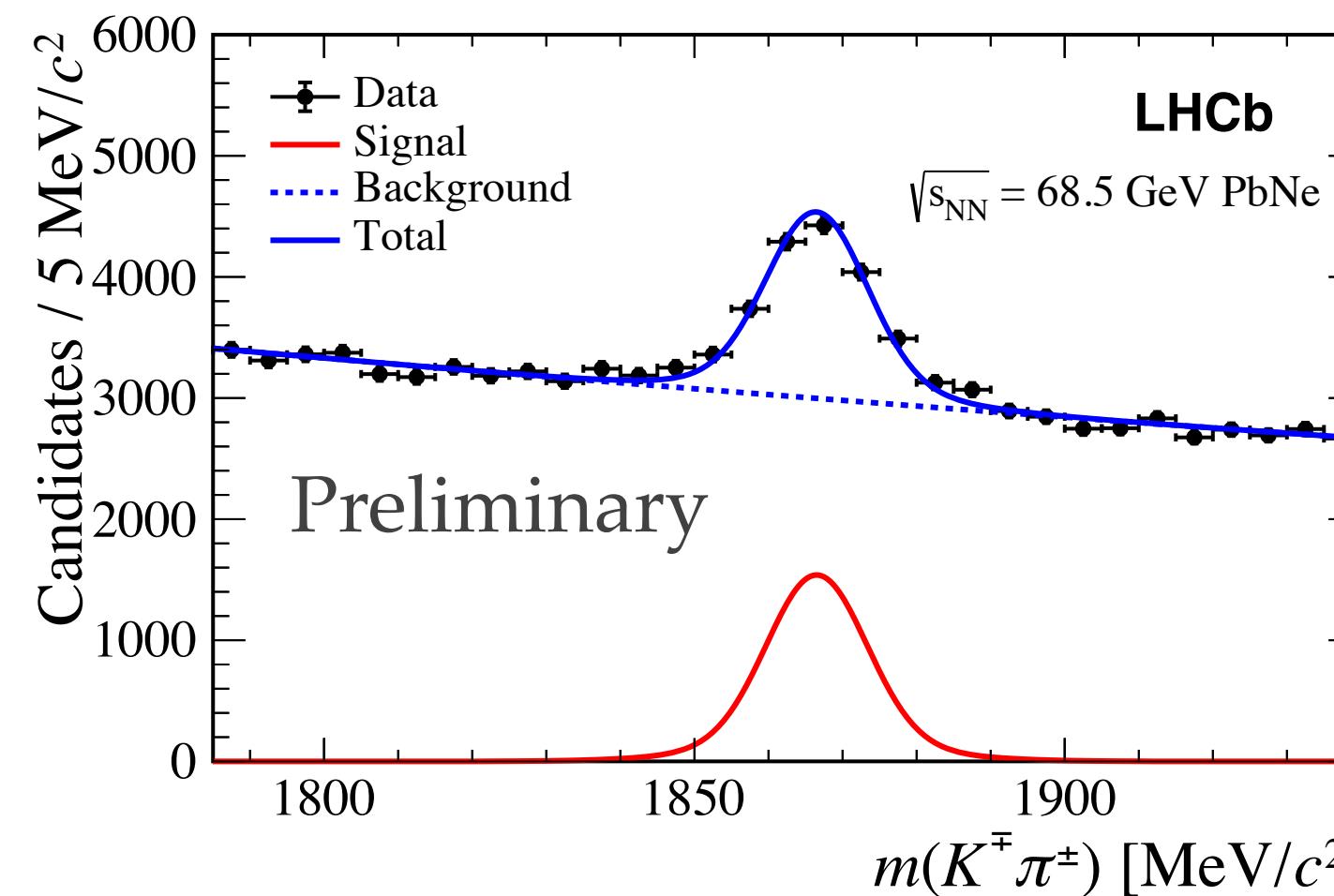
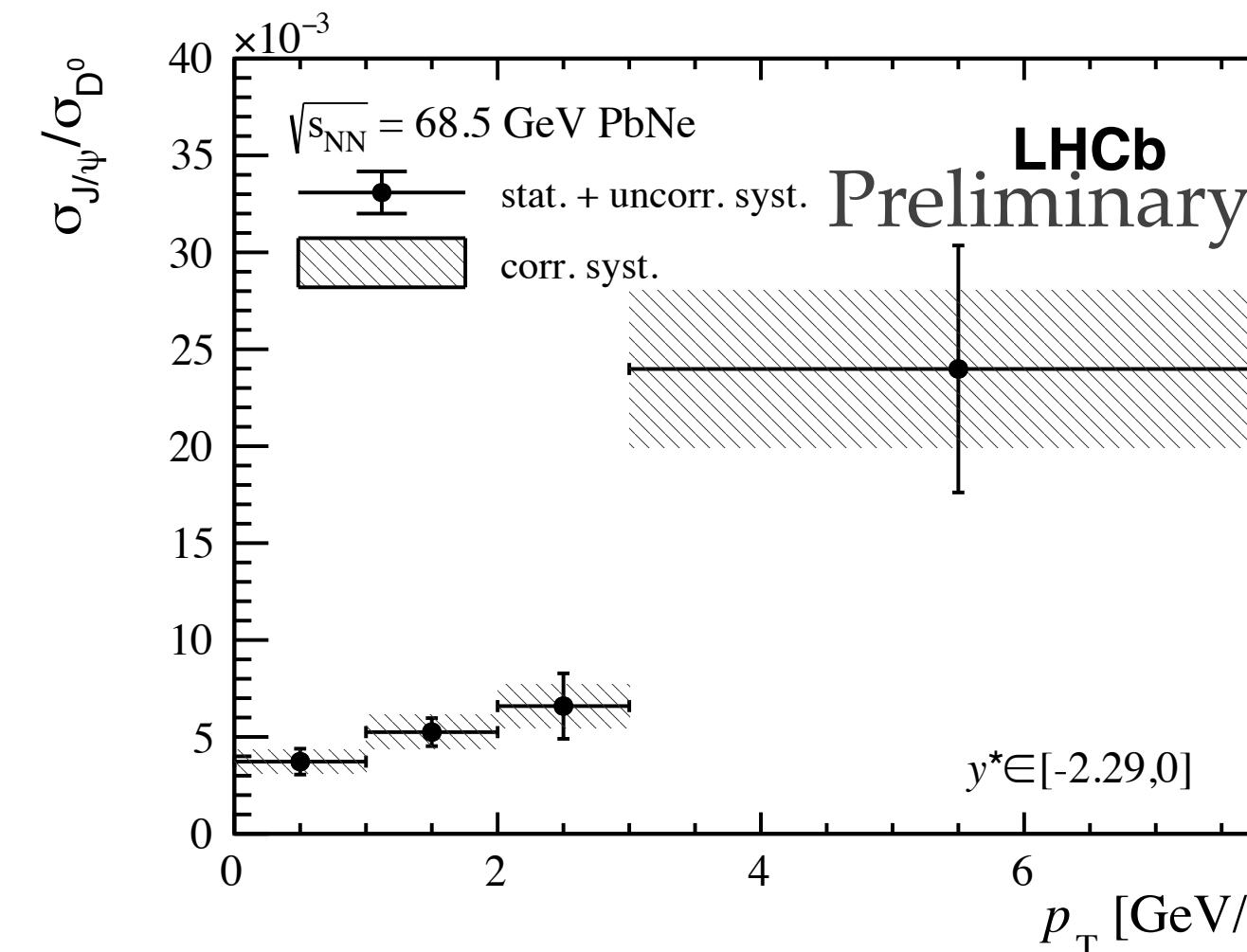
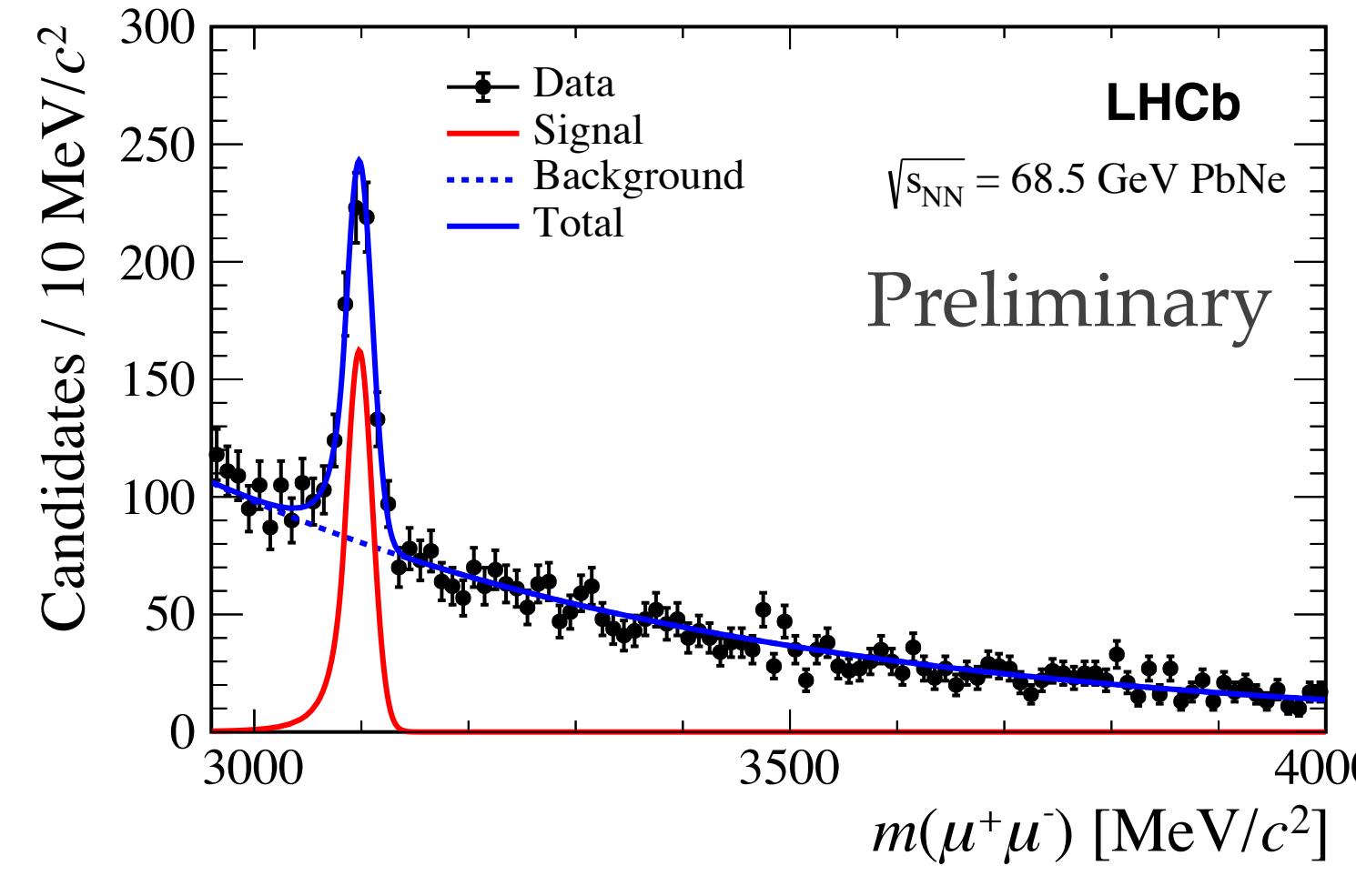
J/ψ 4π extrapolation using Pythia8 with
the CT09MCS PDF set

Power-law dependence with the centre of mass energy



Ratio branching fraction between J/ψ and $\psi(2S)$
compatible with other experiments

Charm production in PbNe @68 GeV



- ❖ Strong p_T dependence
- ❖ Results compared to the $p\text{Ne}$ results and a N_{coll} power law
- ❖ No additional suppression of J/ψ compared to D^0 , no QGP observed

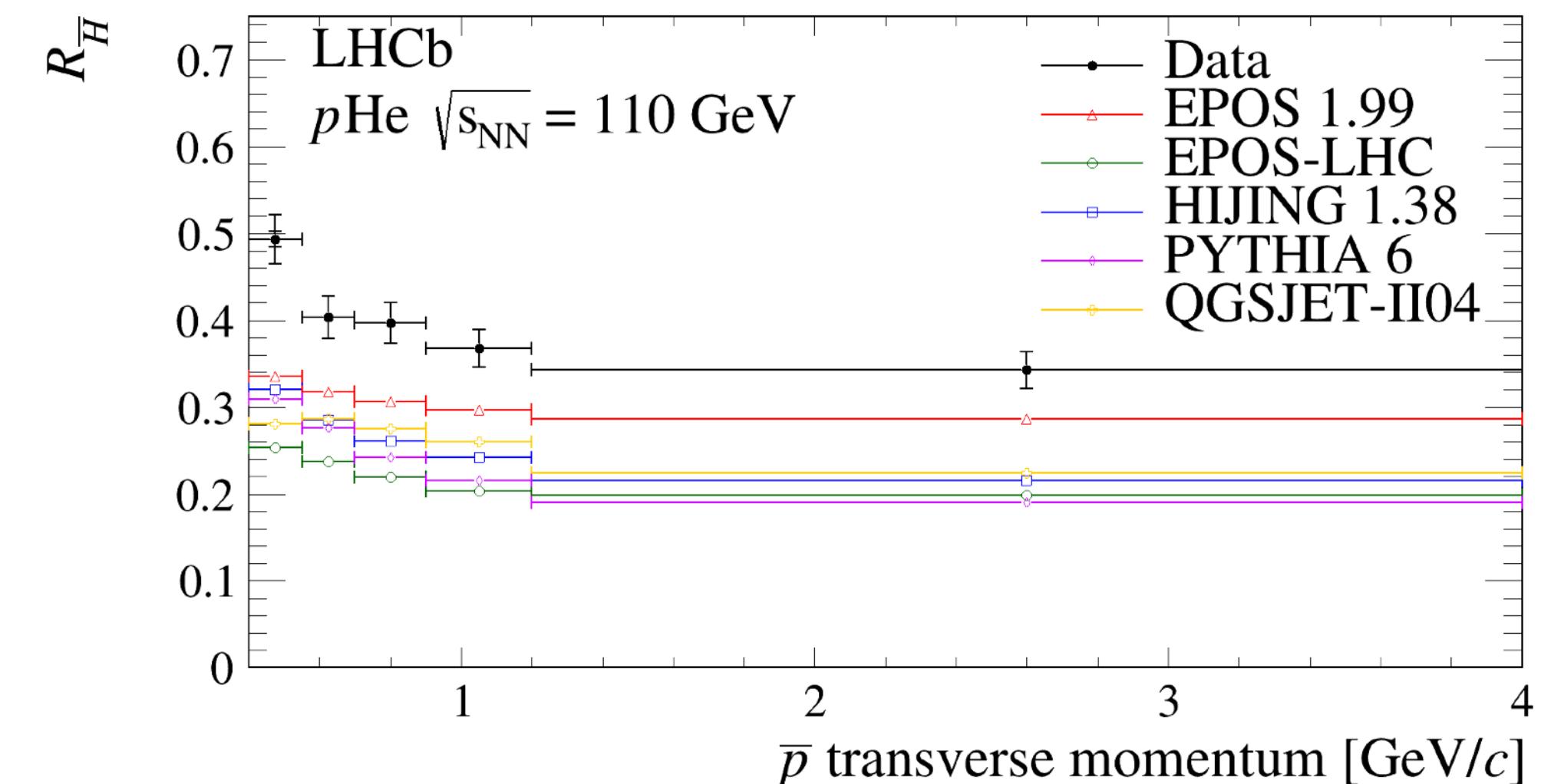
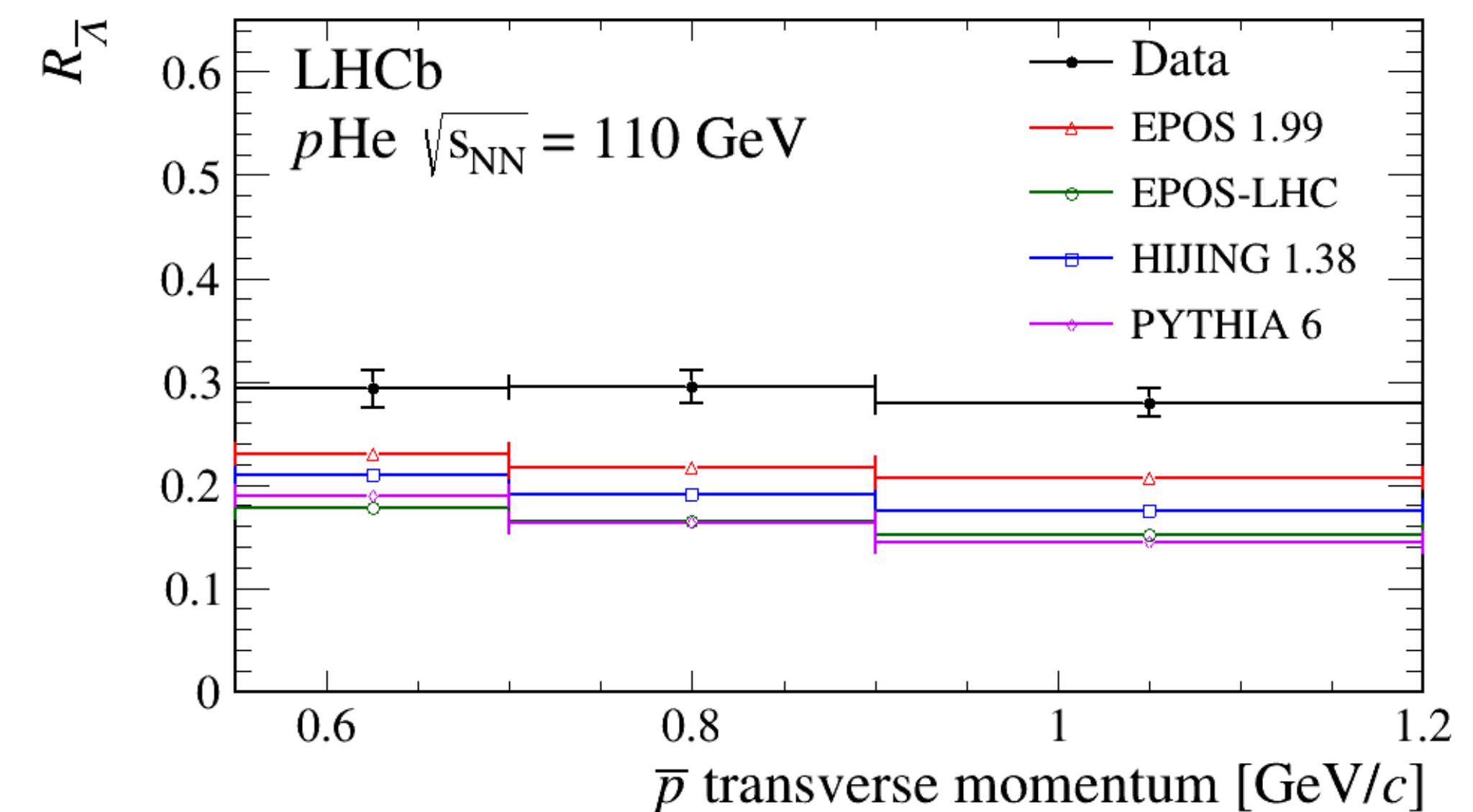
Antiproton in $p\text{He}$ @ 110 GeV

LHCb input for dark matter search !

- ❖ Interpretation of the measured cosmic rays in search of Dark matter limited by our knowledge of anti-matter production
- ❖ Study of the spallation with the InterStellar medium thanks to the SMOG system !
- ❖ Detached-to-prompt antiproton production

$$R_{\bar{H}} = \frac{\sigma(p\text{He} \rightarrow \bar{H}X \rightarrow \bar{p}X)}{\sigma(p\text{He} \rightarrow \bar{p}_{prompt}X)}$$

$$R_{\bar{\Lambda}} = \frac{\sigma(p\text{He} \rightarrow \bar{\Lambda}X \rightarrow \bar{p}X)}{\sigma(p\text{He} \rightarrow \bar{p}_{prompt}X)}$$

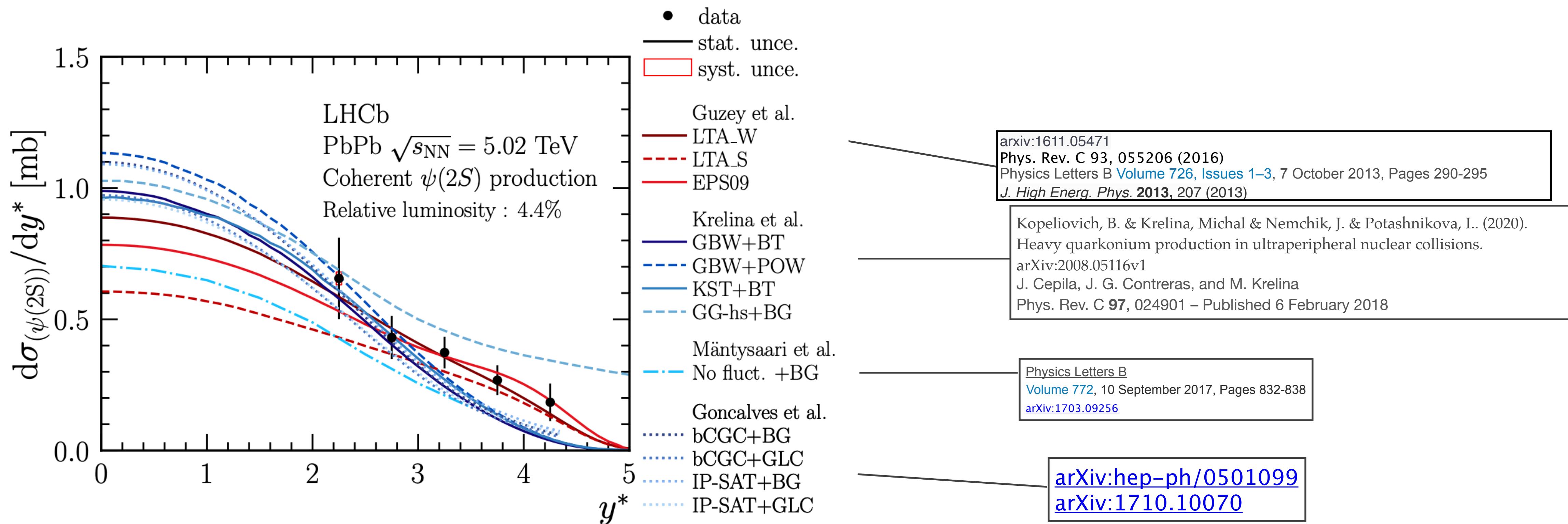


Conclusion

- ❖ LHCb provides many inputs to nPDFs sets through different probes
- ❖ Really precise measurement of coherent J/ψ and $\psi(2S)$ production in UPC PbPb collisions.
- ❖ First measurement of Λ_c/D^0 in PbPb collisions at forward rapidity
- ❖ The fixed-target program gives some original results for nuclear and cosmic ray physics
- ❖ LHCb physics program will continue to evolve next year with new PbPb and fixed-target samples

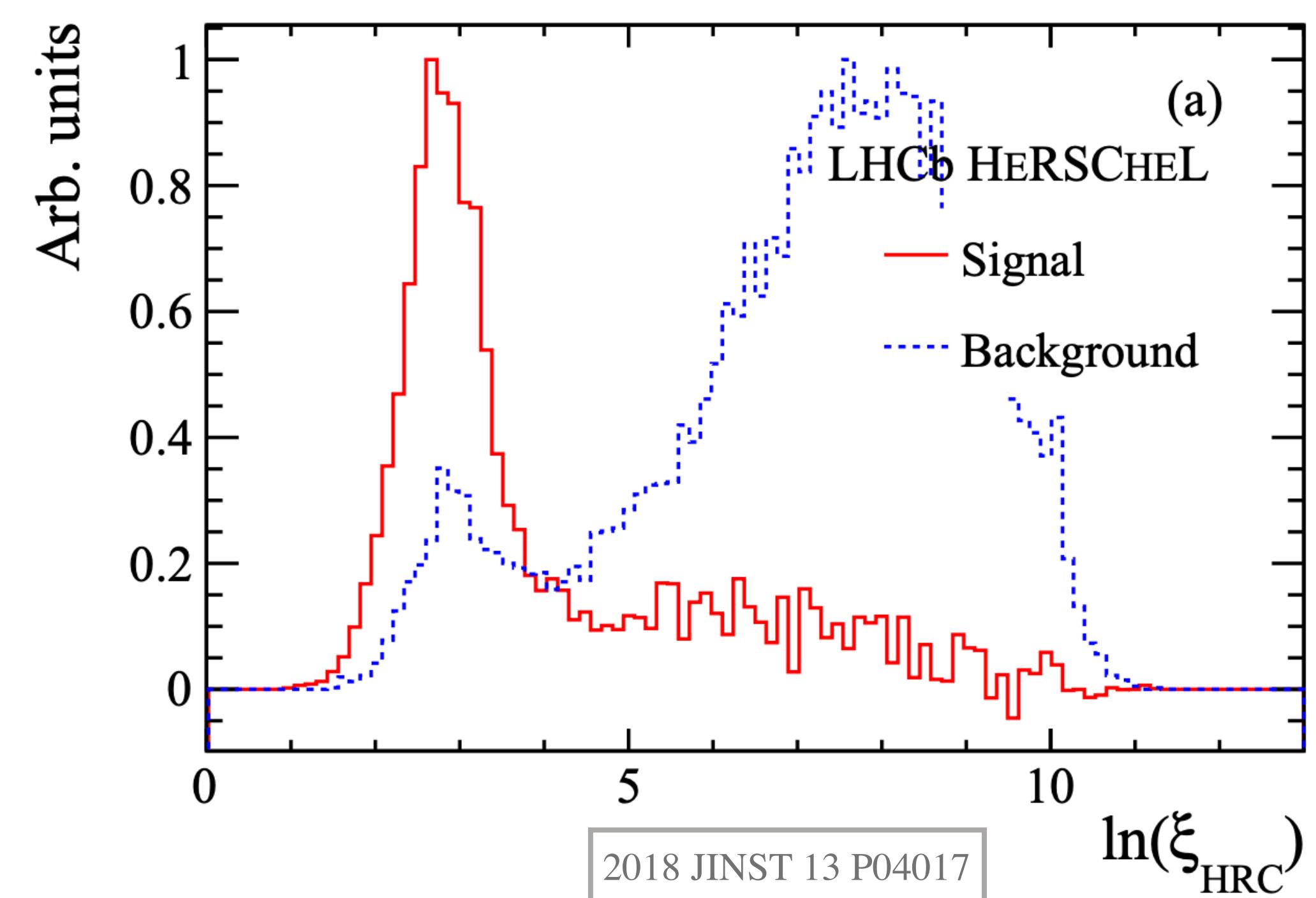
Backup

References of models



J/ ψ , $\psi(2S)$ PbPb UPC @5TeV

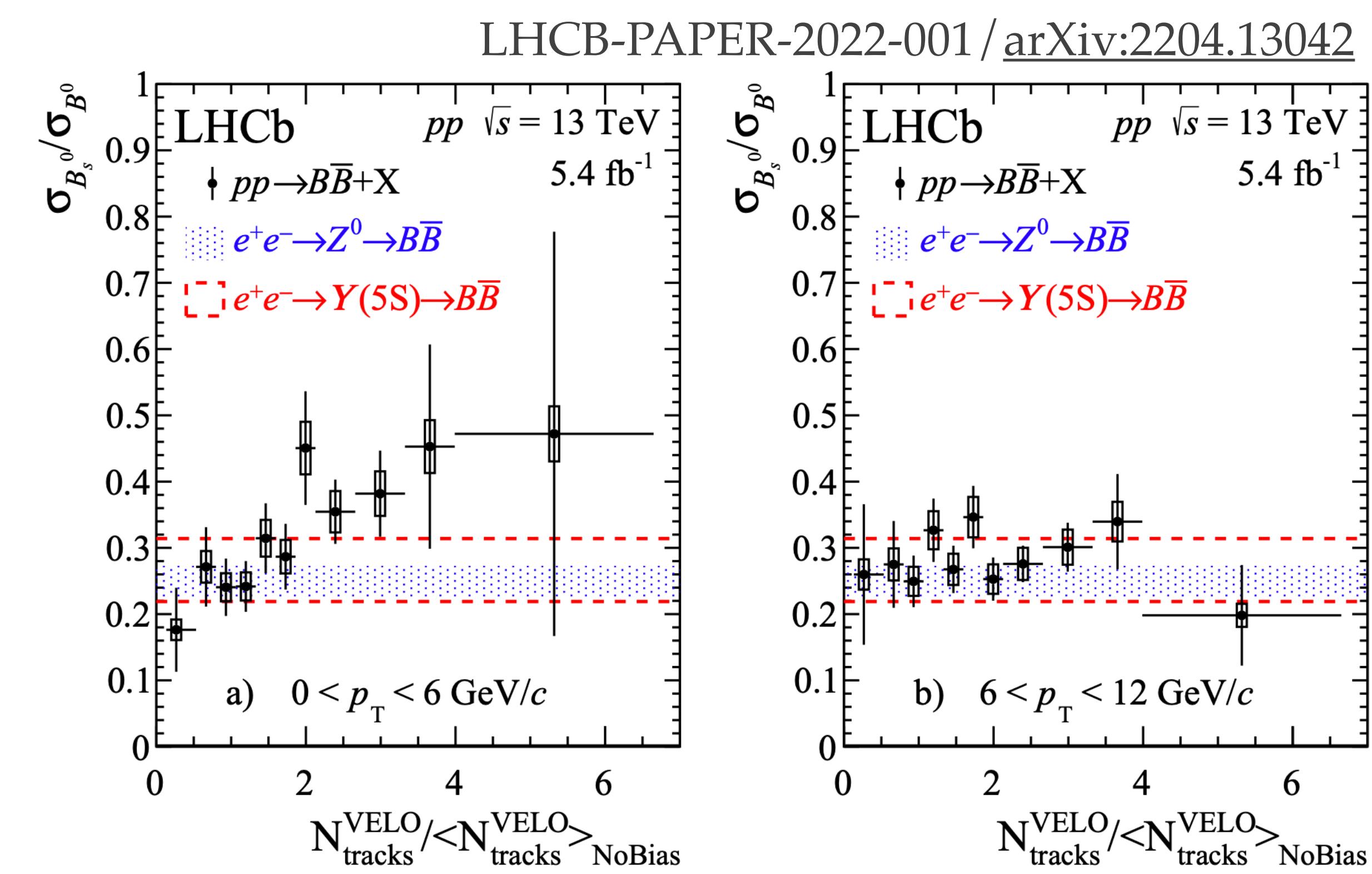
- ❖ PbPb data recorded by the LHCb detector in 2018 with an integrated luminosity of about $\mathcal{L}=228\pm10\mu\text{b}$
- ❖ UPC Event selection:
 - ❖ Veto events with more than 20 hits in the SPD_{SD} calorimeter
 - ❖ Selection thanks to the HeRSChel detector
 - ❖ Candidates reconstructed with the dimuon channel
 - ❖ Two opposite sign μ with $p_T > 700 \text{ MeV}/c$
 - ❖ $p_T^{\mu\mu} < 1 \text{ GeV}/c$ and $\Delta\phi^{\mu\mu} > 0.9\pi$



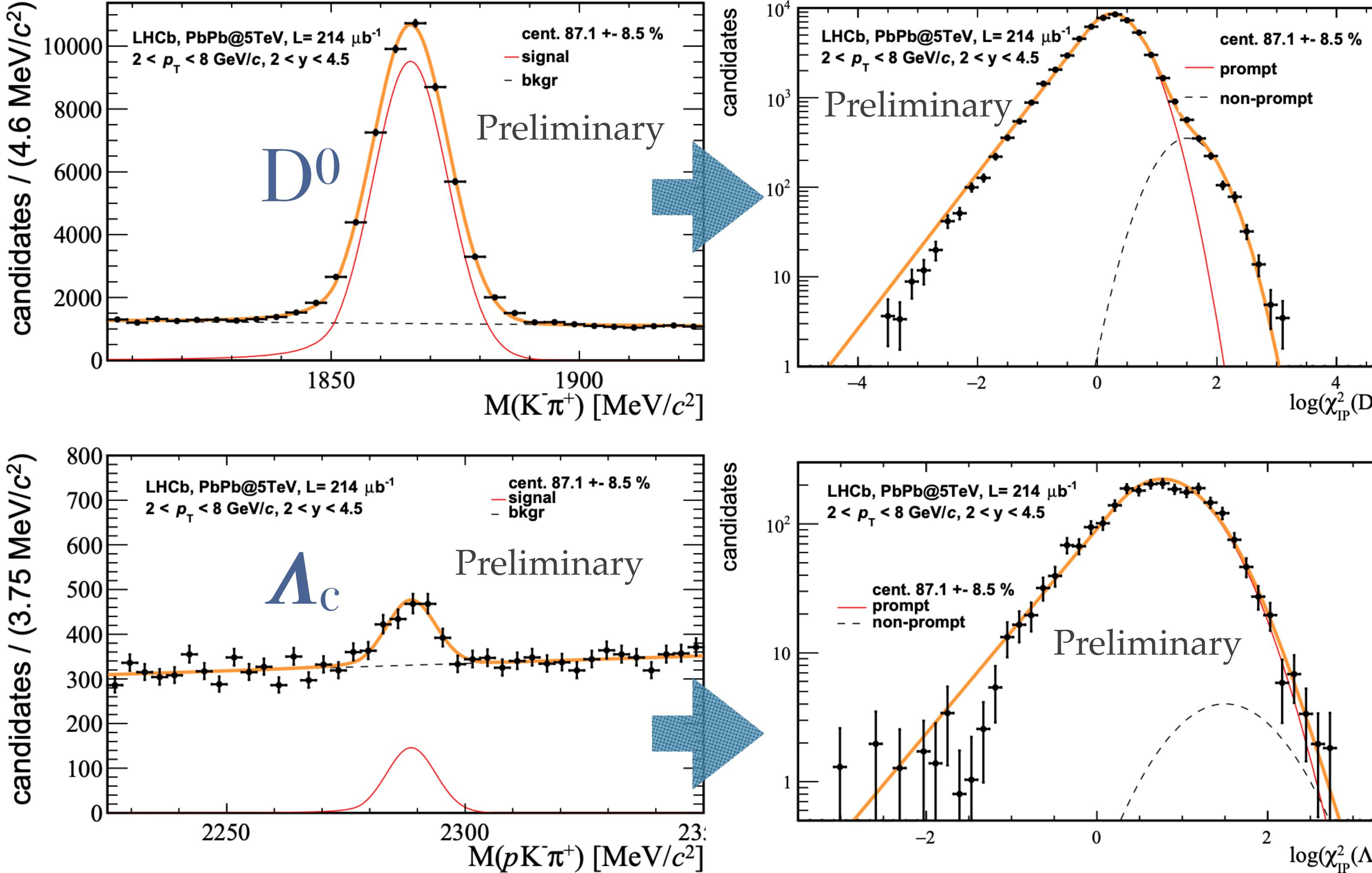
ξ_{HRC} is a χ_2 variable, $\xi_{\text{HRC}} \rightarrow 0$ corresponding to zero or little activity in HerRSChel, compatible with UPC

Λ_c/D^0 in PbPb @ 5TeV

- ❖ Large quark mass -> pQCD calculation
- ❖ Ratio to test pQCD factorisation
- ❖ Probe hadronization mechanisms:
 - ❖ Fragmentation functions
 - ❖ Coalescence:
 - ❖ Occuring in both small and large system?
 - ❖ Multiplicity dependent?



Λ_c/D^0 in PbPb @ 5TeV



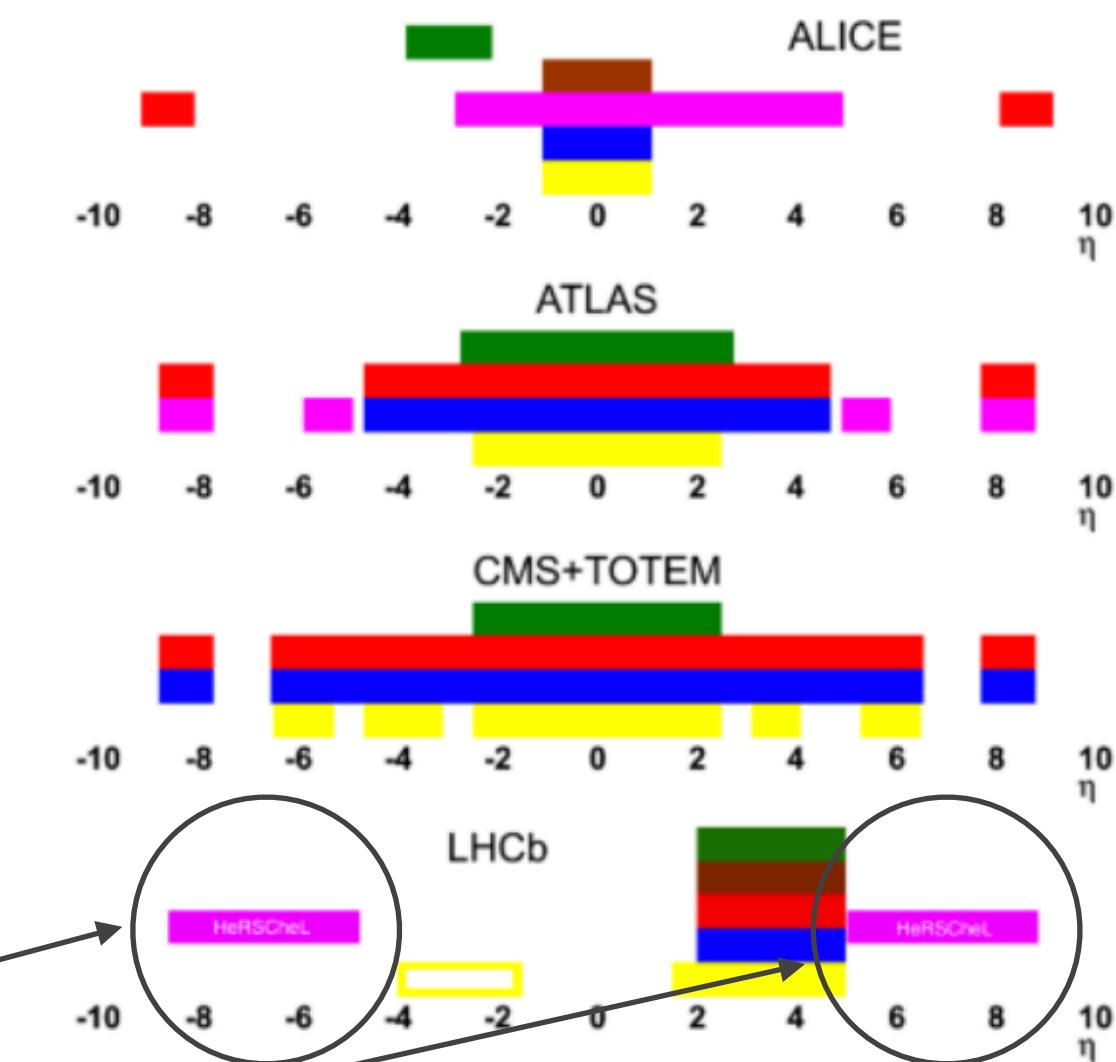
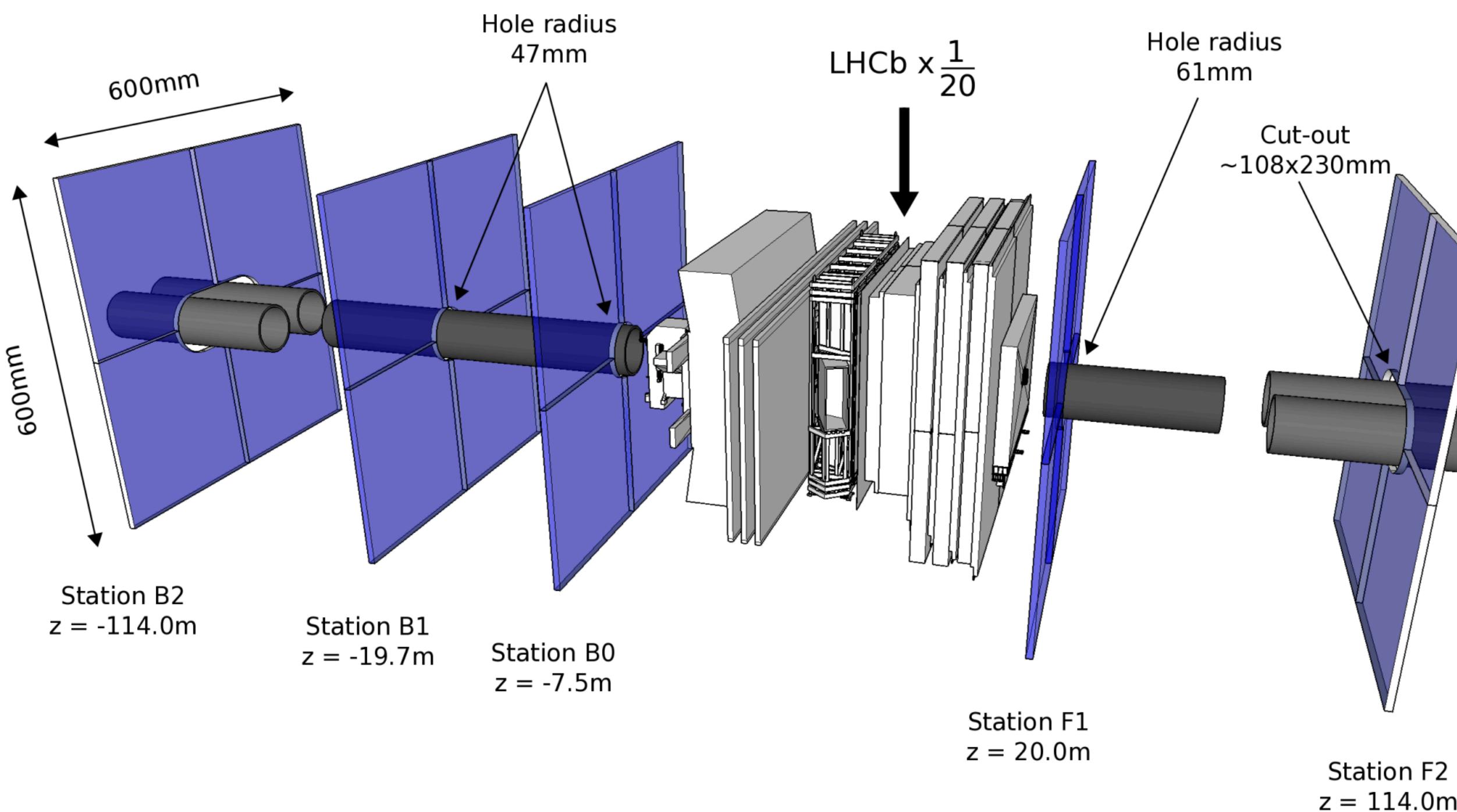
- ❖ $D^0 \rightarrow K\pi$
- ❖ $\Lambda_c \rightarrow pK\pi$
- ❖ Fit to the invariant mass spectrum
- ❖ Fit to the $\log(\chi^2_{\text{IP}})$ (decay vertex compatibility with the primary vertex)

The LHCb detector

Single arm spectrometer fully instrumented in pseudorapidity range $2 < \eta < 5$

2018 JINST 13 P04017

HeRSChel detector, high-rapidity shower counters



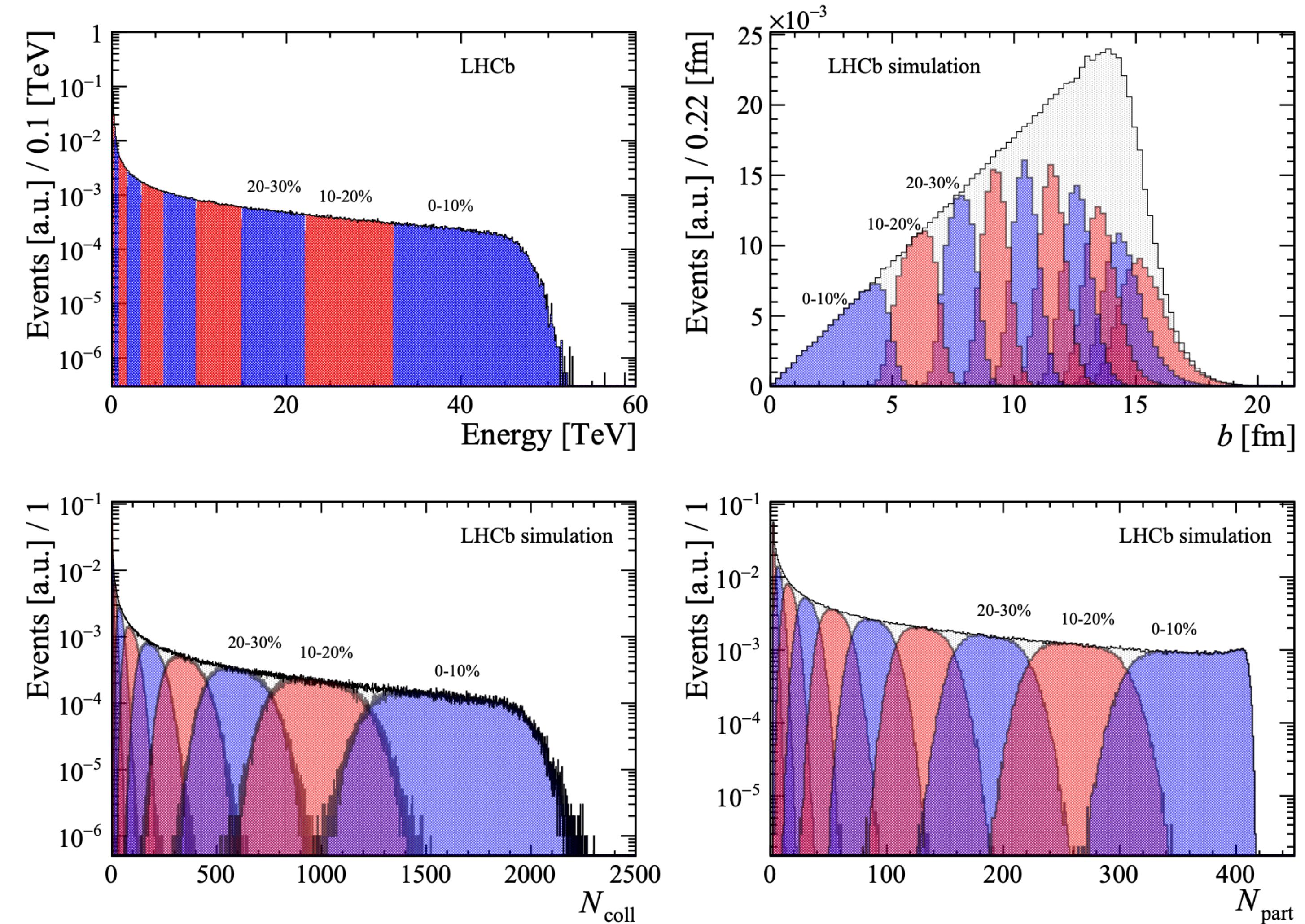
- ❖ Excellent tracking down to $p_T=0$.
- ❖ Excellent particle identification.
- ❖ Excellent primary vertex determination.

Centrality determination

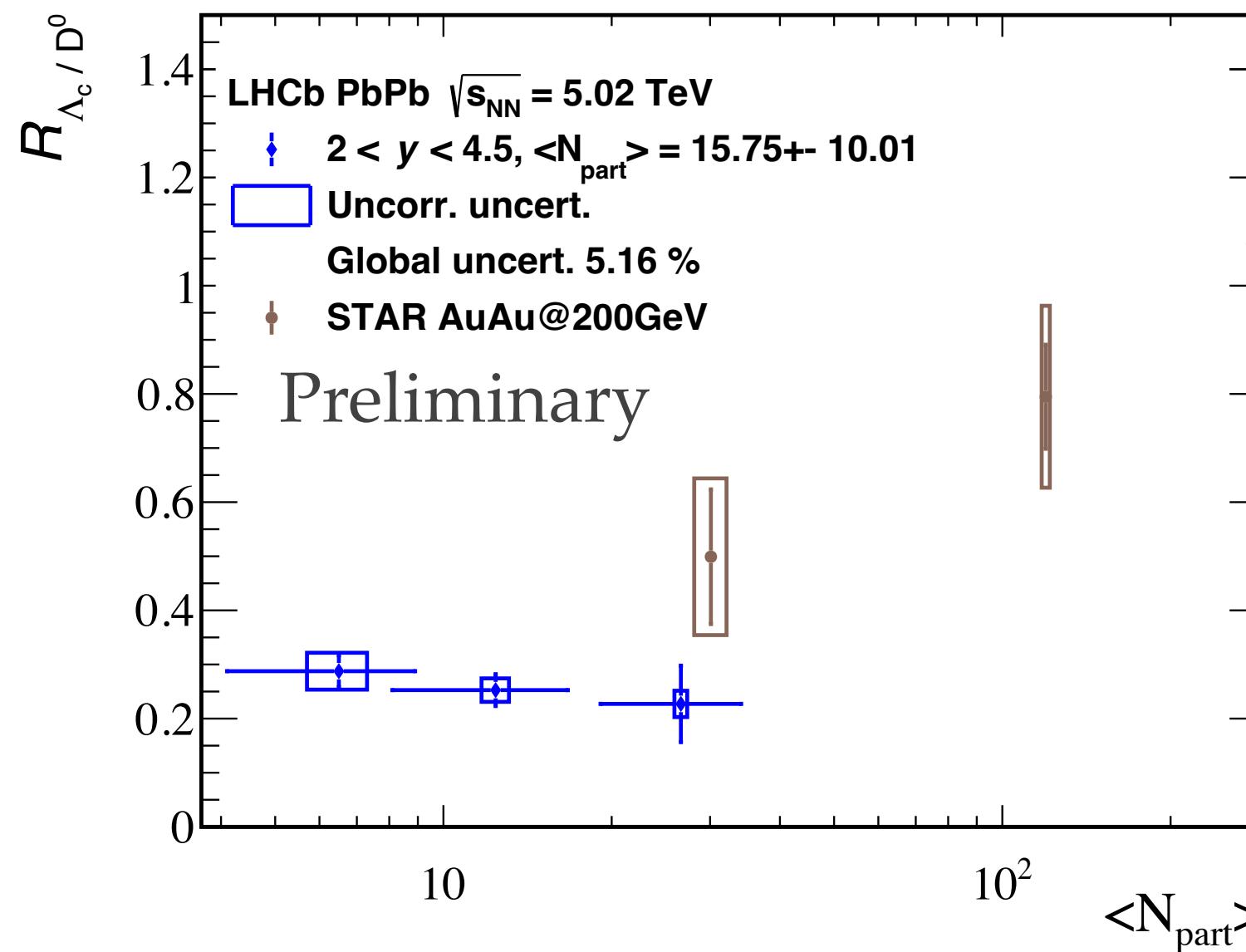
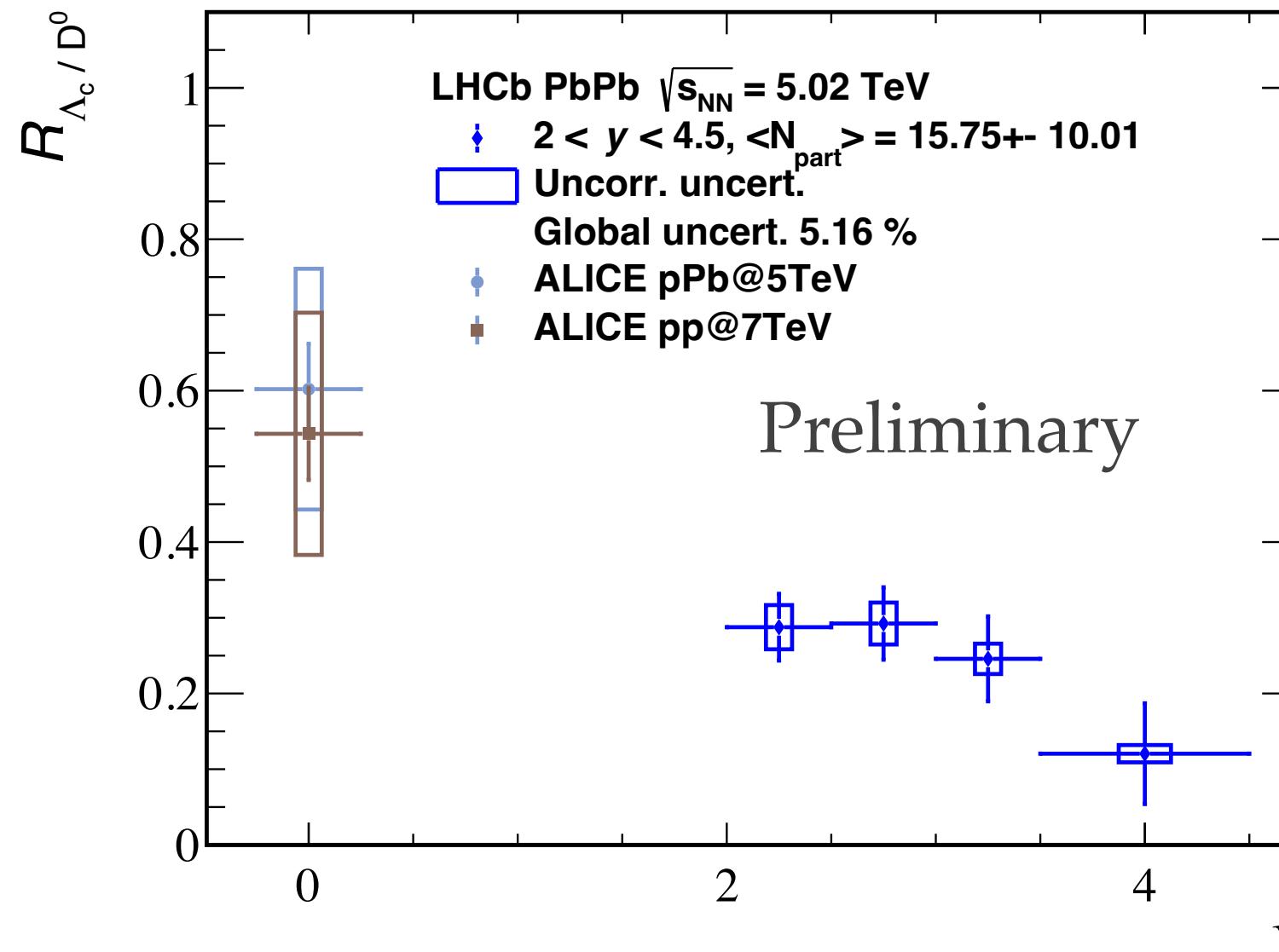
[arXiv:2111.01607](https://arxiv.org/abs/2111.01607)

Centrality determination using MCGLauber model

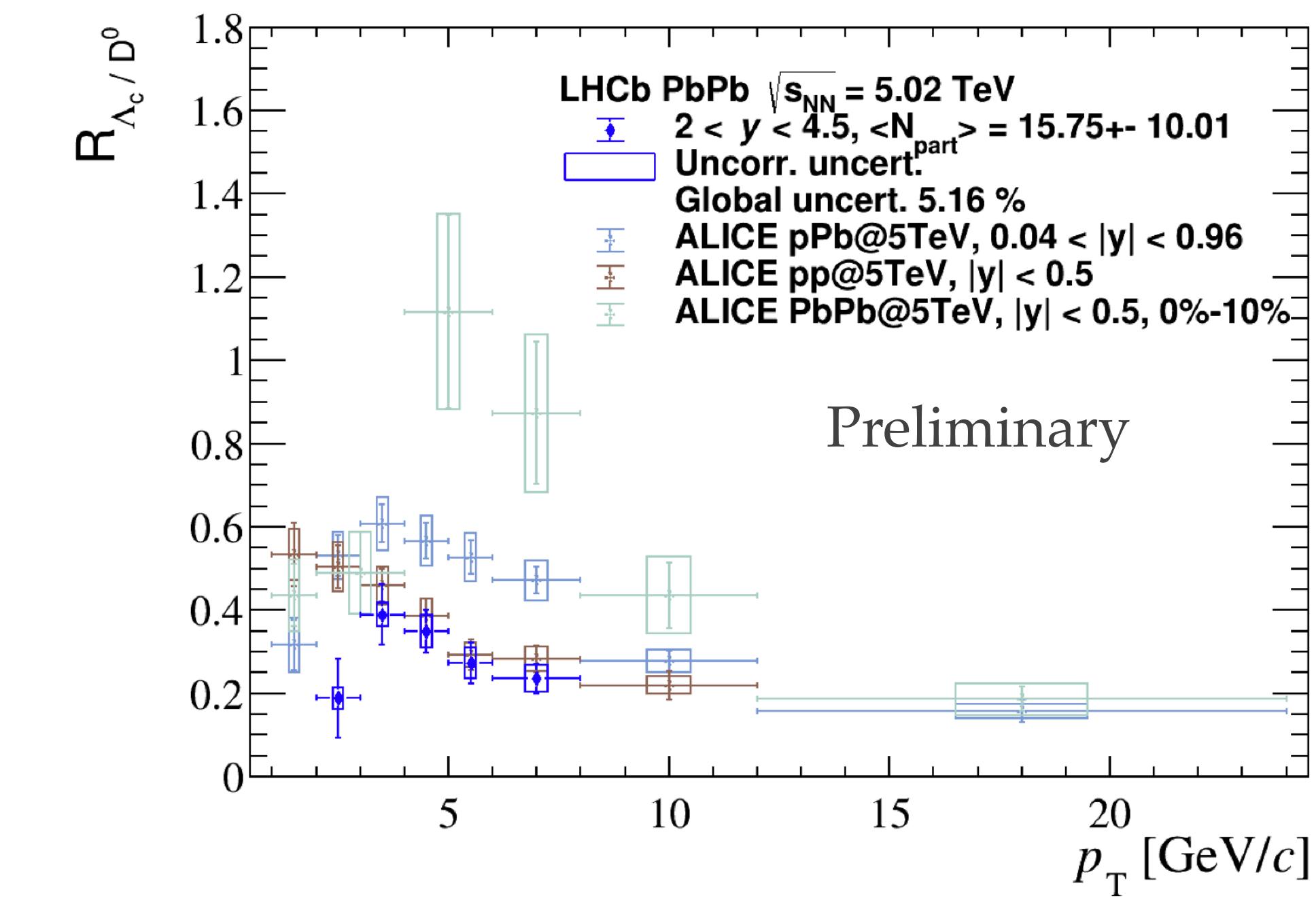
Centrality %	$N_{\text{part}} \pm \sigma$	$N_{\text{coll}} \pm \sigma$	$b \pm \sigma$
100 – 90	2.91 ± 0.54	1.83 ± 0.34	15.41 ± 2.96
90 – 80	7.03 ± 0.78	5.77 ± 0.64	14.56 ± 1.80
80 – 70	15.92 ± 0.64	16.44 ± 0.69	13.59 ± 0.52
70 – 60	31.26 ± 0.67	41.28 ± 0.93	12.61 ± 0.28
60 – 50	54.65 ± 1.13	92.59 ± 2.01	11.59 ± 0.24
50 – 40	87.54 ± 1.01	187.54 ± 2.43	10.47 ± 0.14
40 – 30	131.24 ± 1.15	345.53 ± 3.89	9.23 ± 0.08
30 – 20	188.02 ± 1.49	593.92 ± 6.62	7.80 ± 0.06
20 – 10	261.84 ± 1.83	972.50 ± 10.37	6.02 ± 0.04
10 – 0	357.16 ± 1.70	1570.26 ± 15.56	3.31 ± 0.01



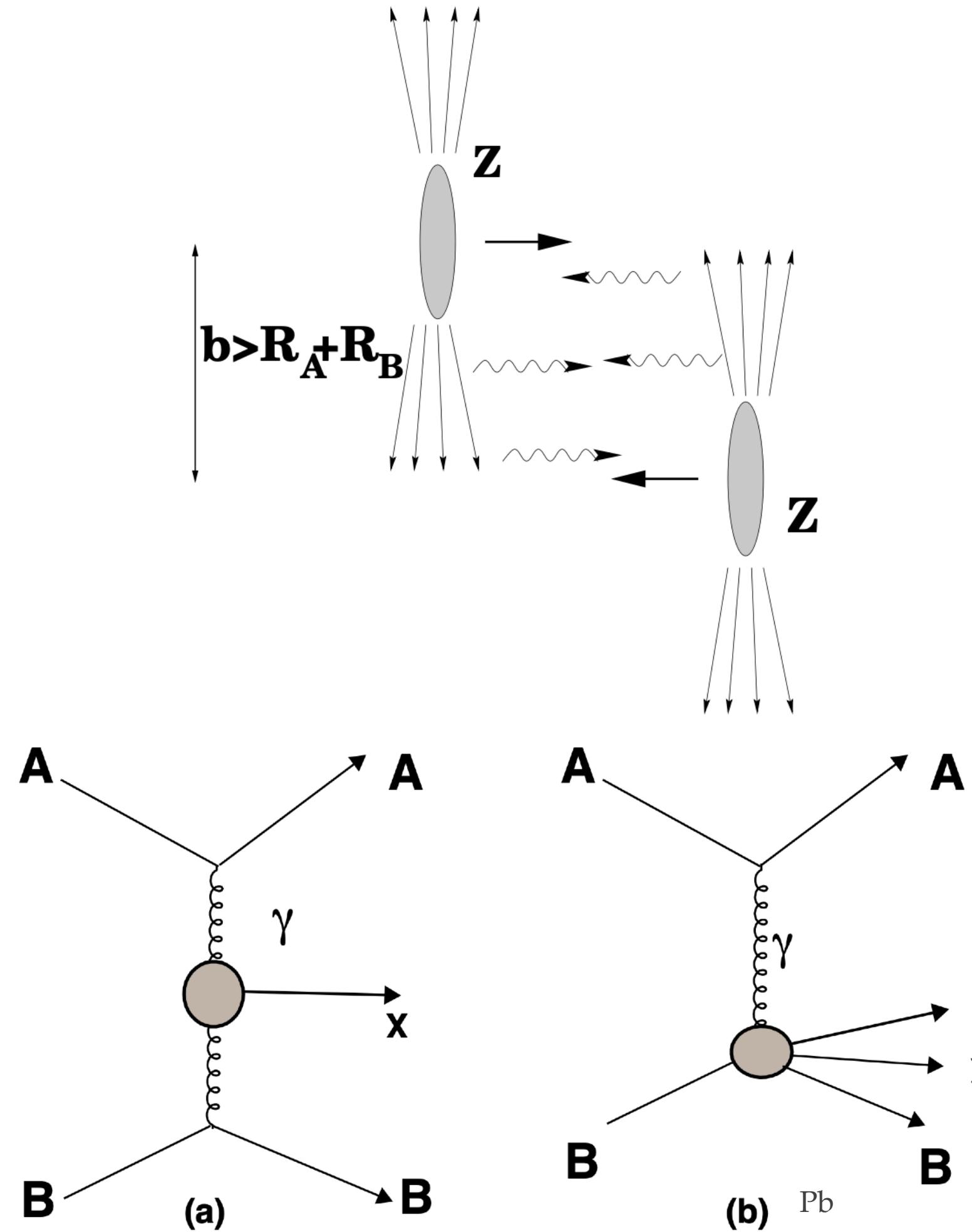
Λ_c/D^0 in PbPb @ 5TeV



- ❖ Confirm tension with ALICE results
- ❖ Rapidity dependence?
- ❖ New results in central PbPb from ALICE
- ❖ Ratio enhanced with QGP formation ?



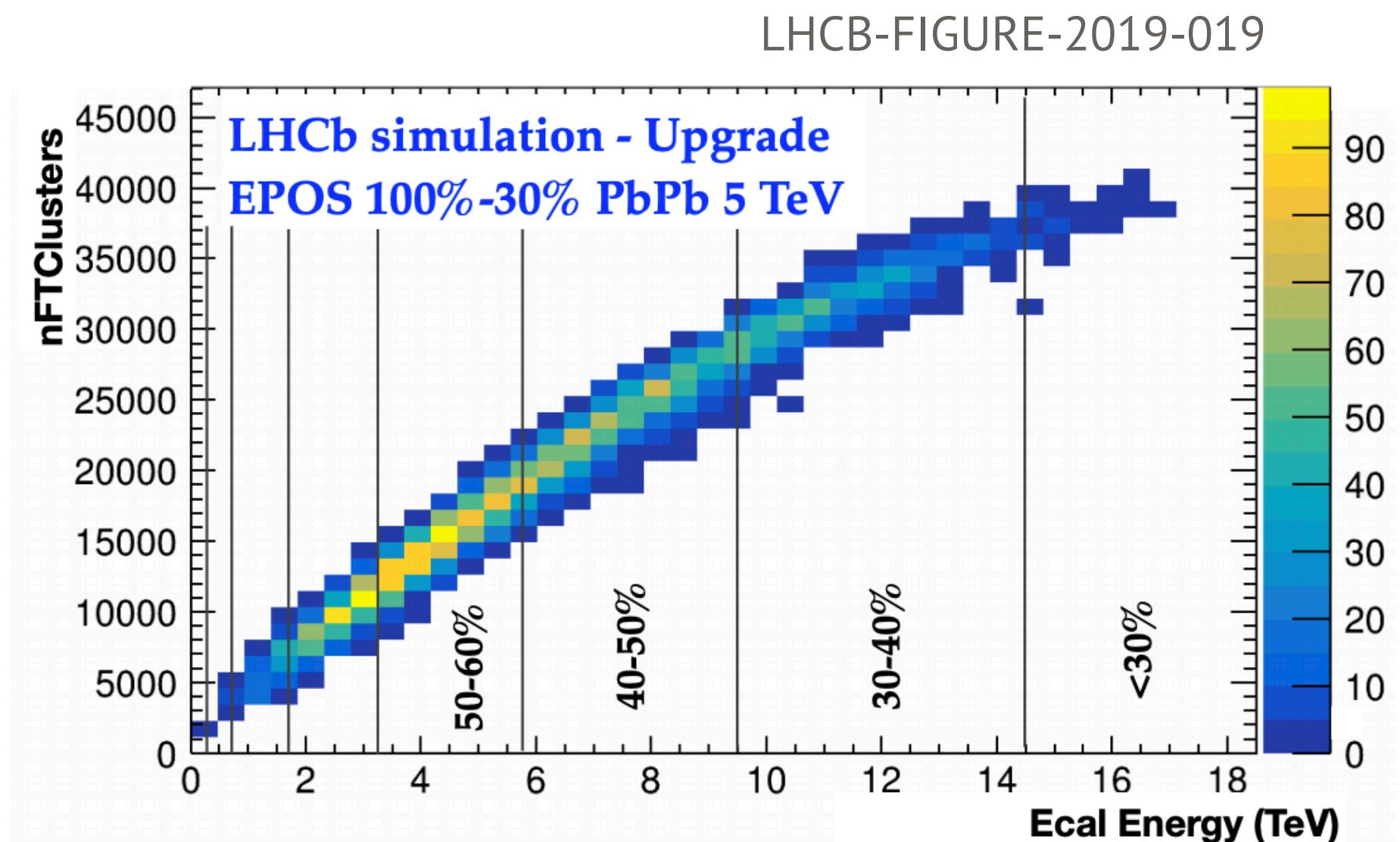
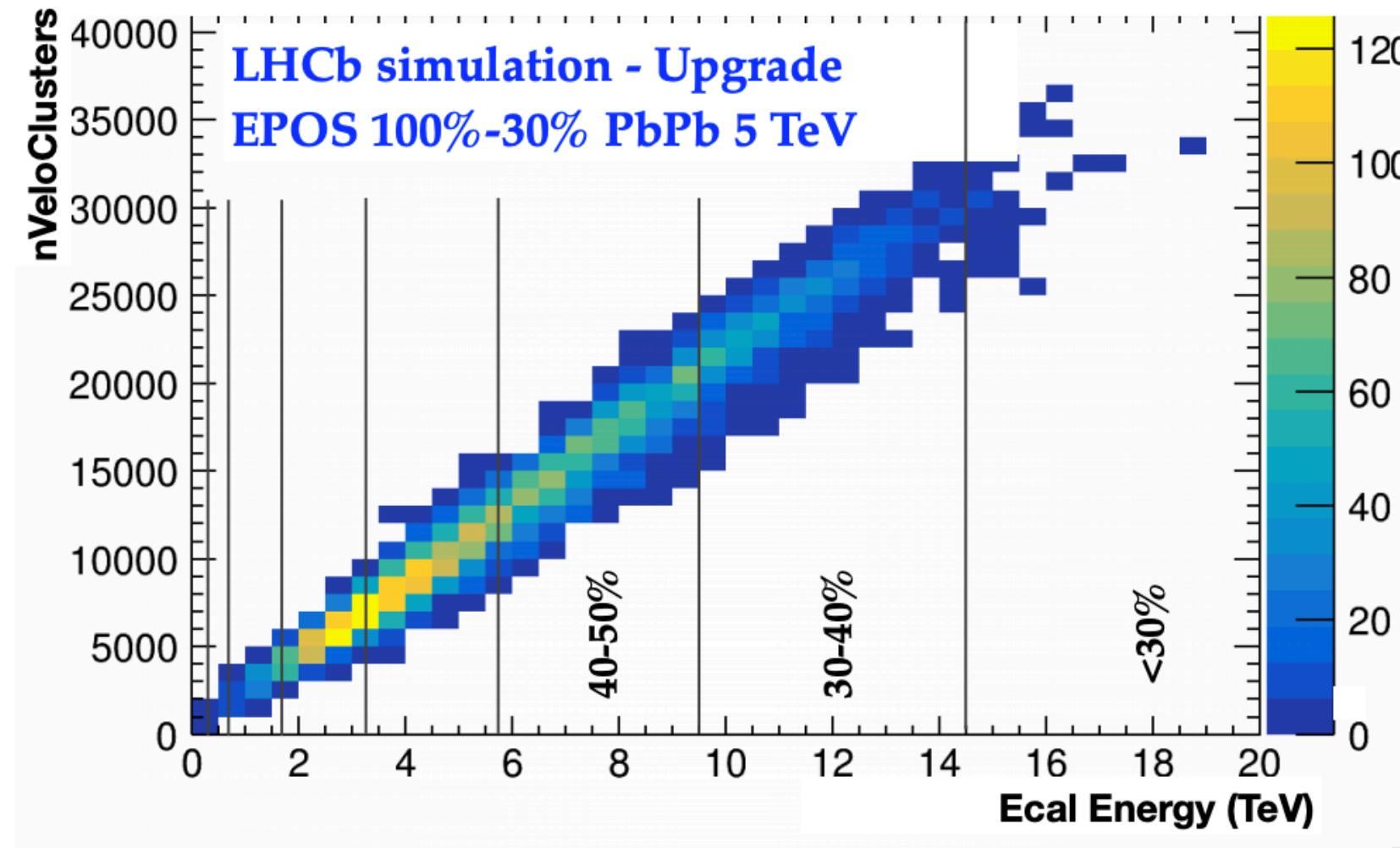
$J/\psi, \psi(2S)$ PbPb UPC @5TeV



- ❖ Impact parameter $b > R_1 + R_2$
- ❖ Interaction between two nuclei with no actual **hadronic collisions**
- ❖ No destruction of the nuclei $A+A \rightarrow A+A+X$
- ❖ Interaction through the quasi real-photon cloud from one or both nuclei.
- ❖ Large reaction rate as photon flux $\propto Z^2$
- ❖ Production of dileptons, vector mesons...

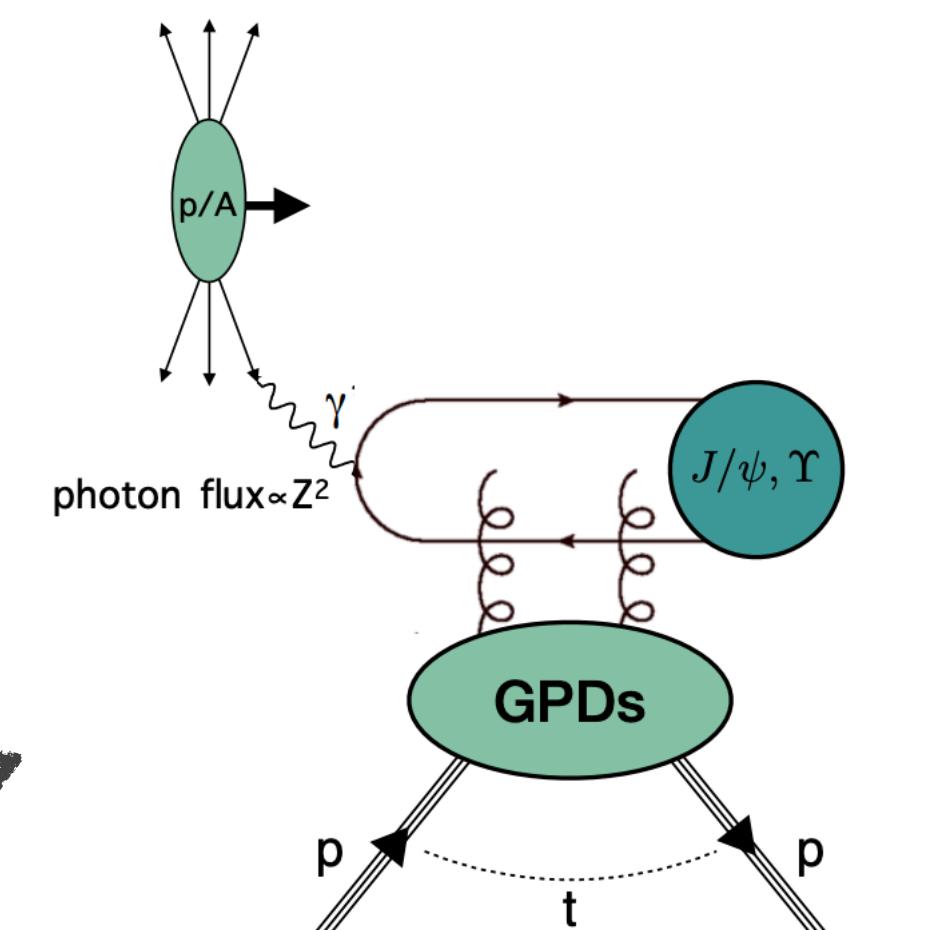
Performances Run 3 PbPb

PbPb collisions

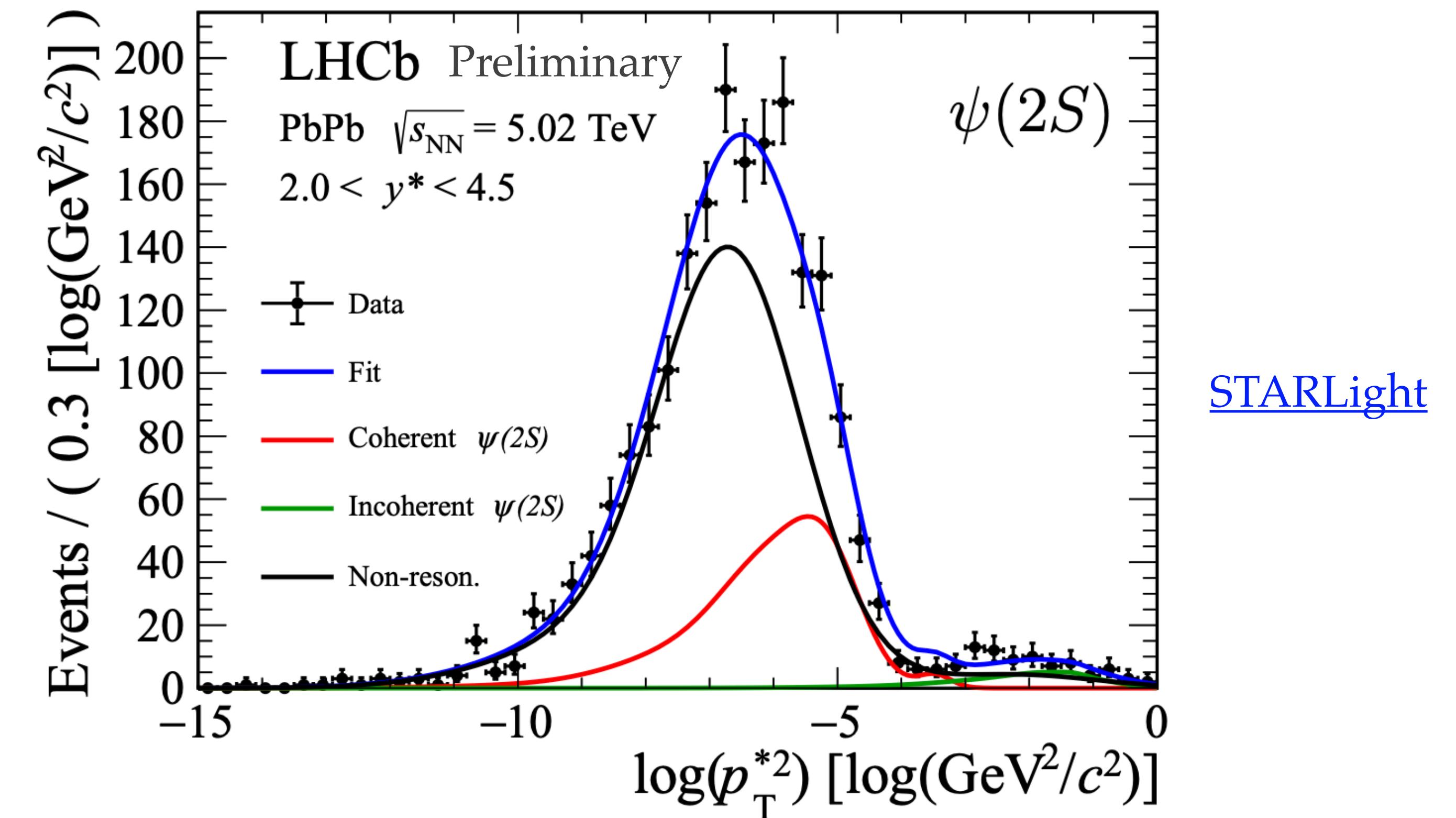
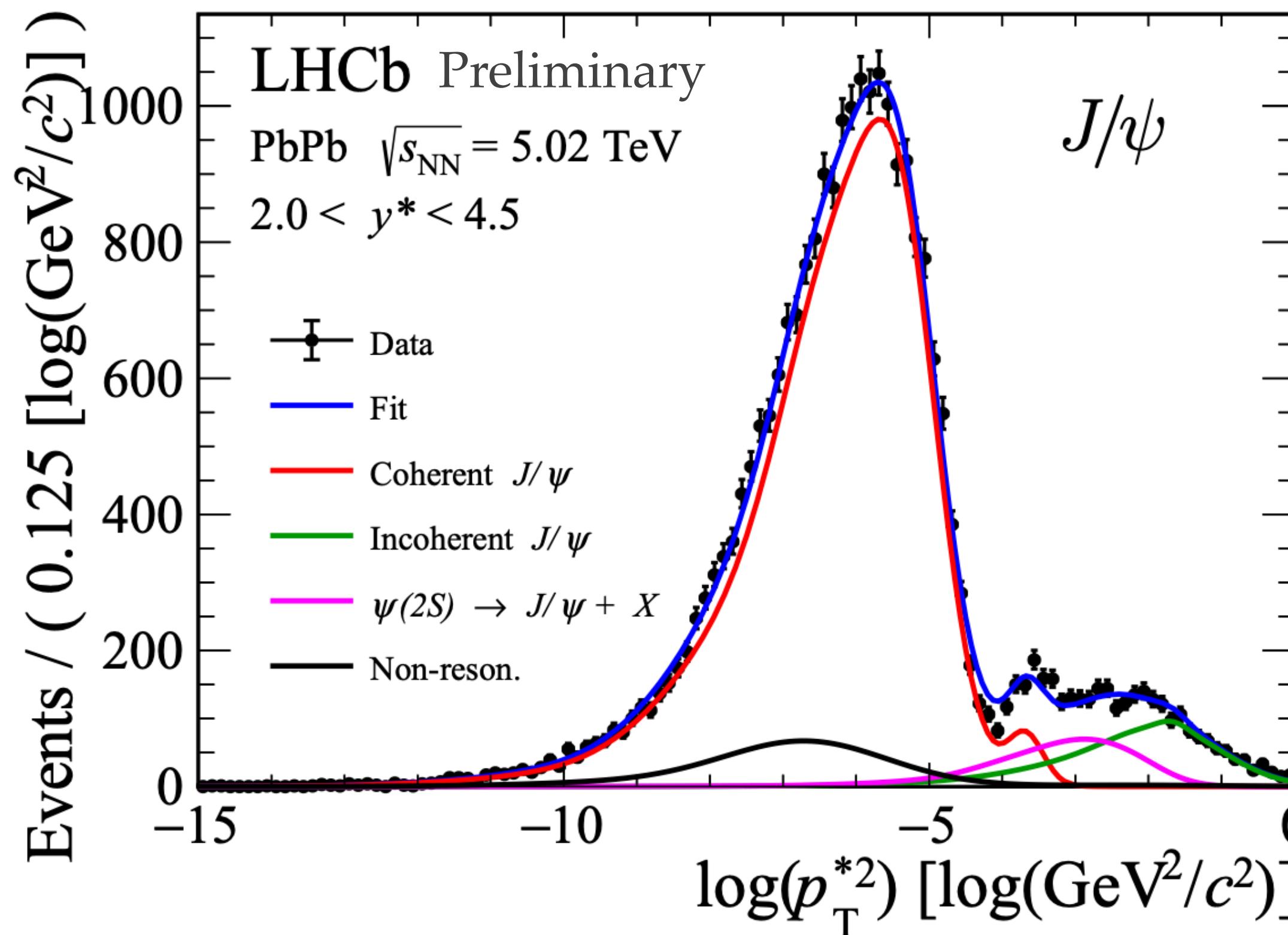


LHCb-FIGURE-2019-019

- ❖ No significant saturation for 70% most peripheral collisions (simulation for higher centralities are being produced), expect almost no saturation for Run4 (90% most peripheral) and no saturation for Run5.
- ❖ Semi-central PbPb collisions soon available : QGP studies for LHCb in run 3 !
- ❖ Increased statistics: improvement of UPC studies.



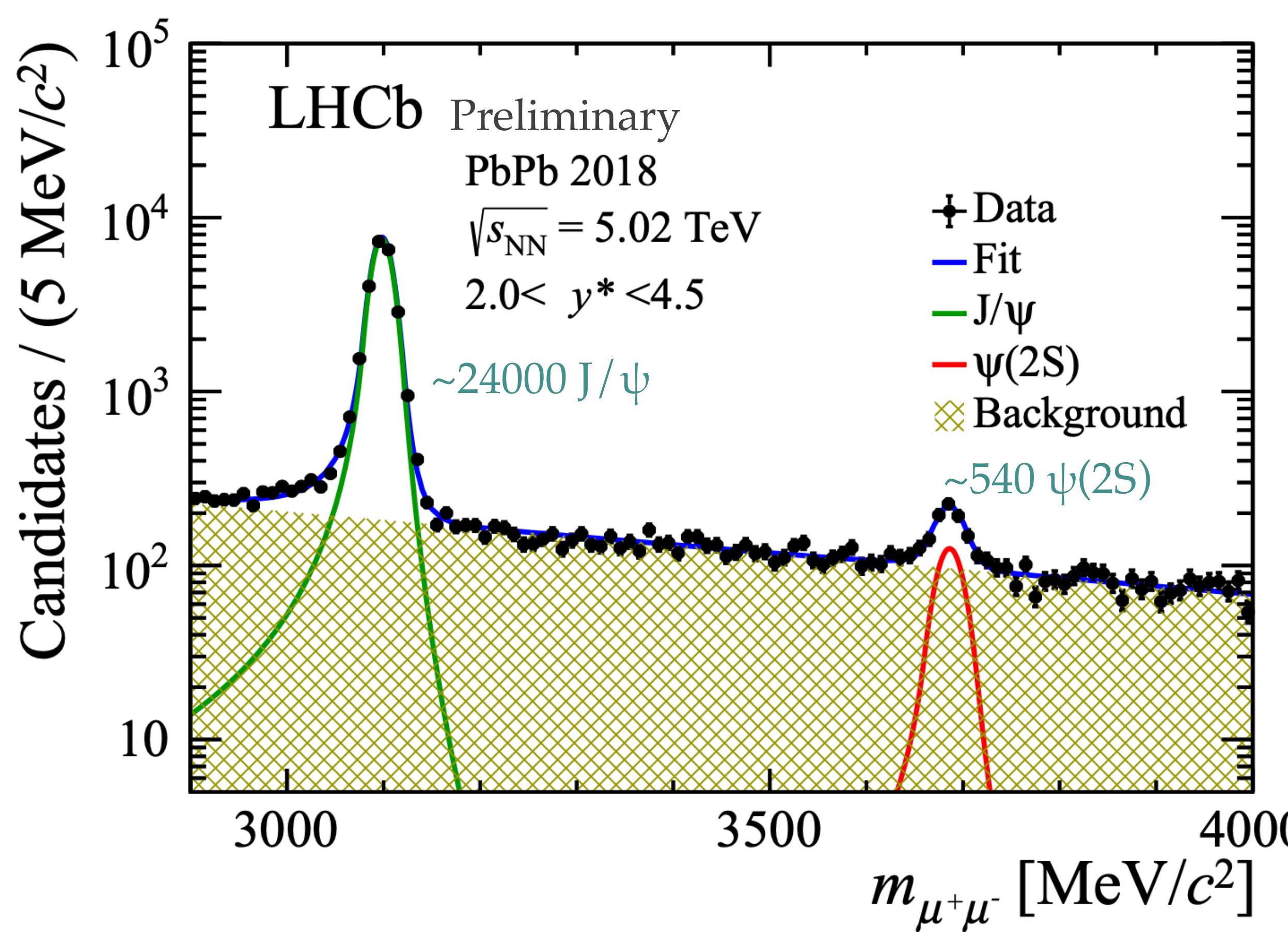
J/ ψ , $\psi(2S)$ PbPb UPC @5TeV



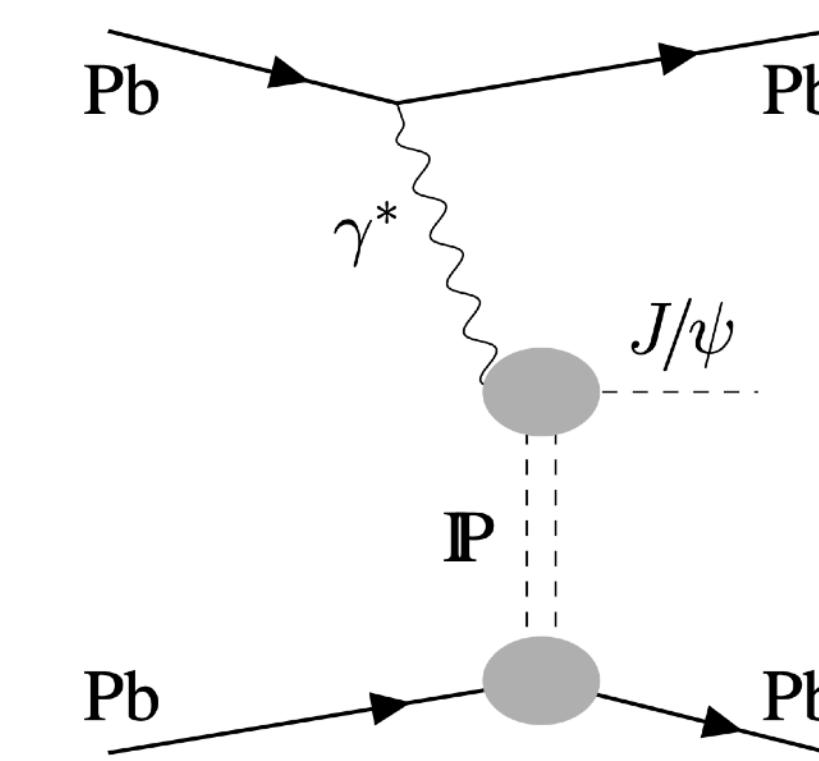
- ❖ Template fit based on the STARLight model
- ❖ Shape of the background taken from the side band method

Excellent resolution !

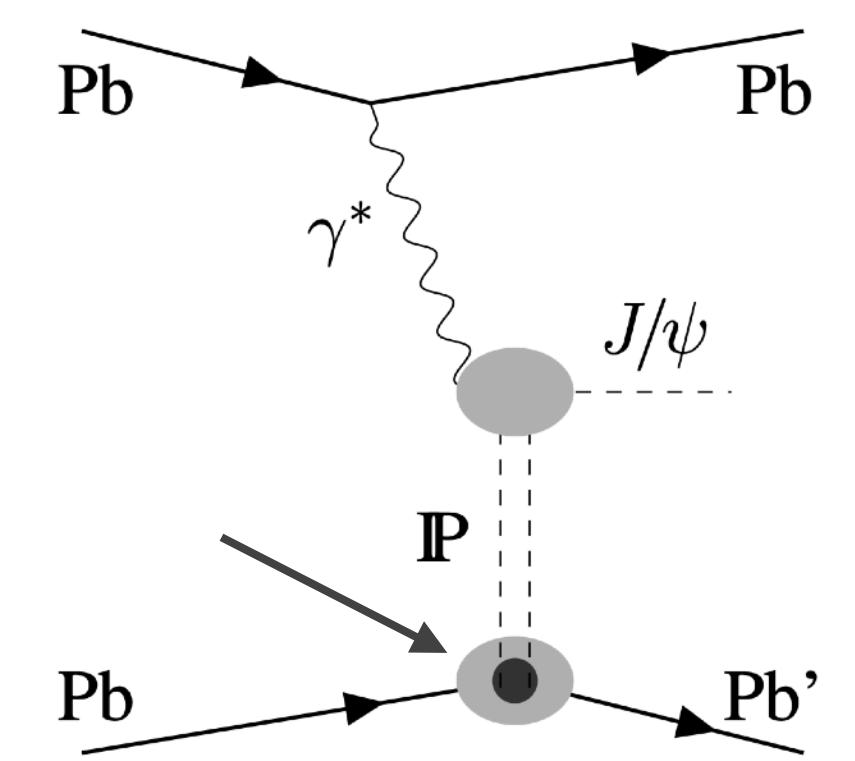
J/ ψ , $\psi(2S)$ PbPb UPC @5TeV



- Both signal contain coherent and incoherent produced candidates
- J/ψ from feed-down from $\psi(2S)$
- Background from $\gamma\gamma \rightarrow \mu\mu$ non-resonant



Coherent



Incoherent

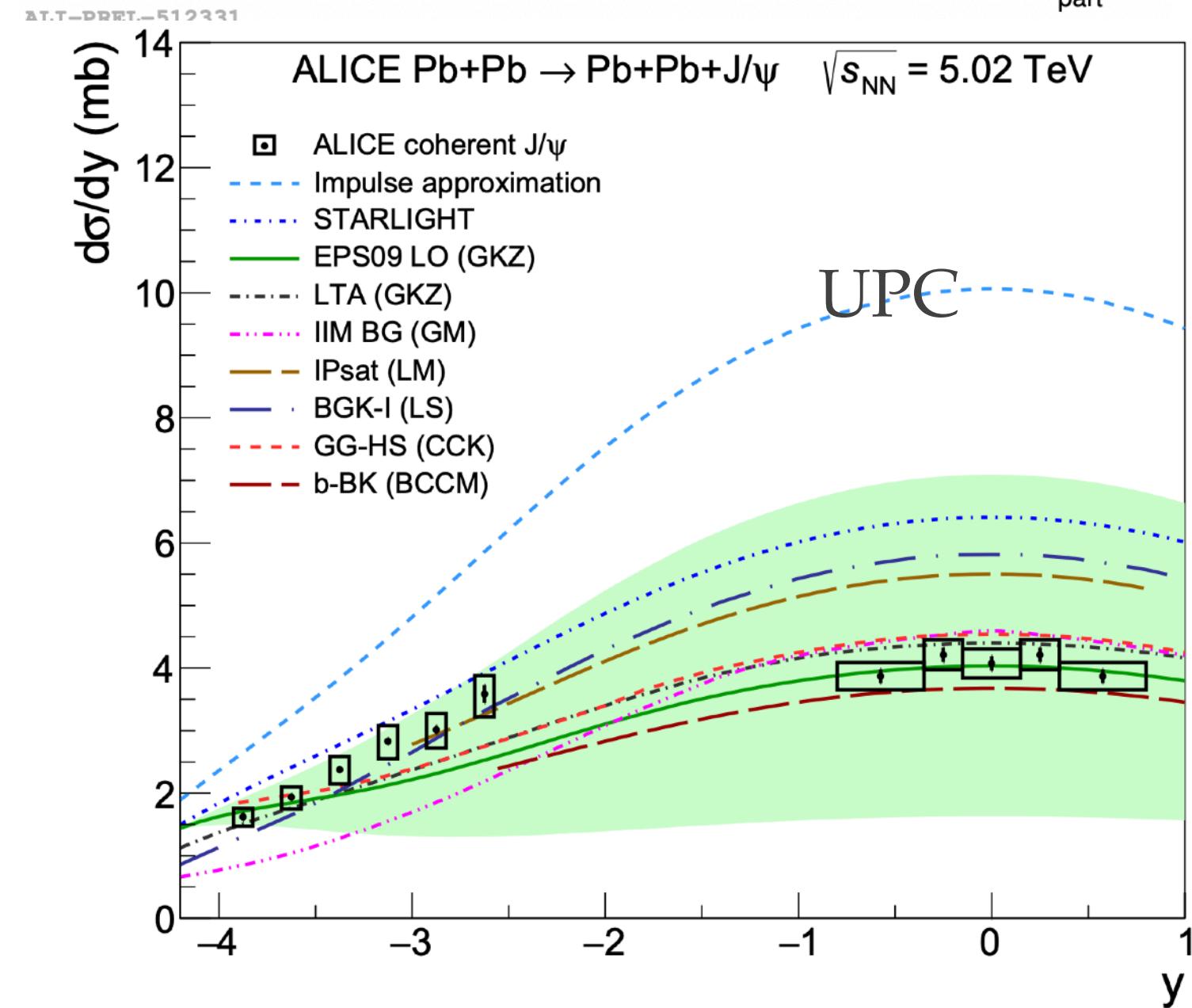
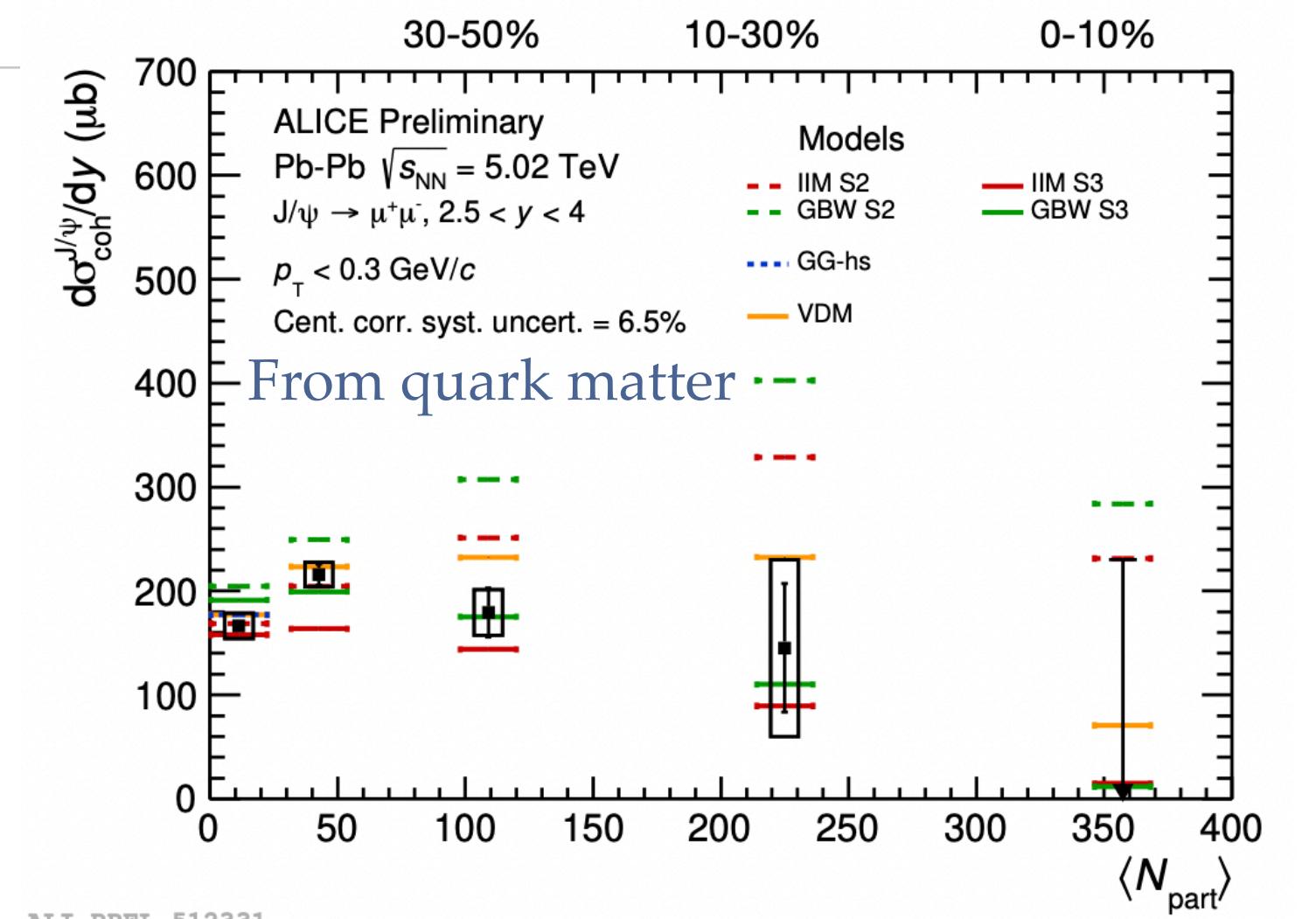
Coherent J/ ψ in PbPb peripheral collisions

- ❖ ALICE as a lesser precision but central measurement
- ❖ Decrease here could be explain by:
 - ❖ Less accessible area for the photon to interact
 - ❖ Melting of the photo produced J/psi, low-pt spectrum not repopulated by (re)combined

Better thermometer for QGP ?

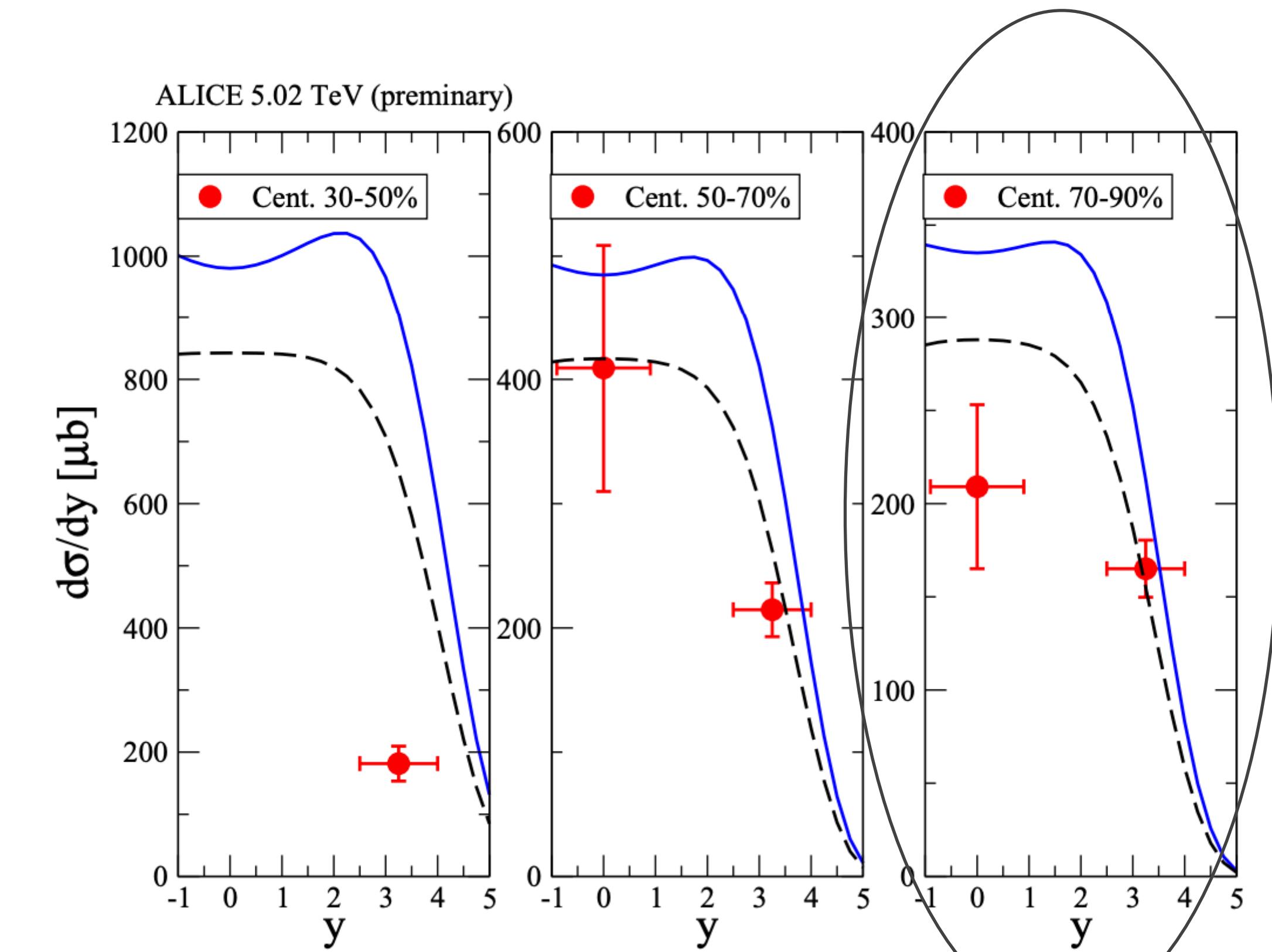
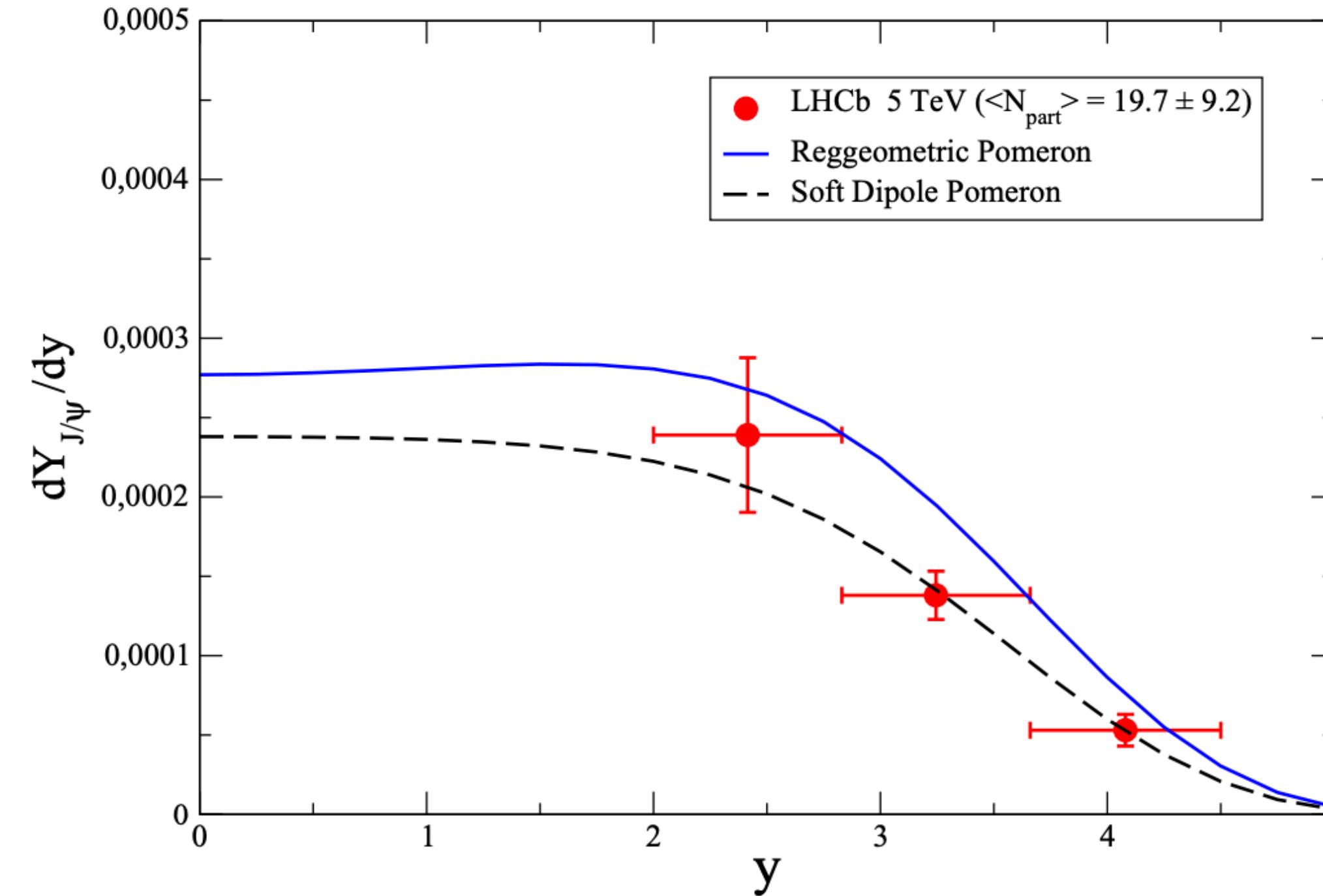
- ❖ Precise measurement with LHCb in run3/4
- ❖ However behavior not clearly understood even in UPC

Precise measurement with run3/4 !



Coherent J/ ψ in PbPb peripheral collisions

Vector Dominance Model + Glauber multiple scattering formalism

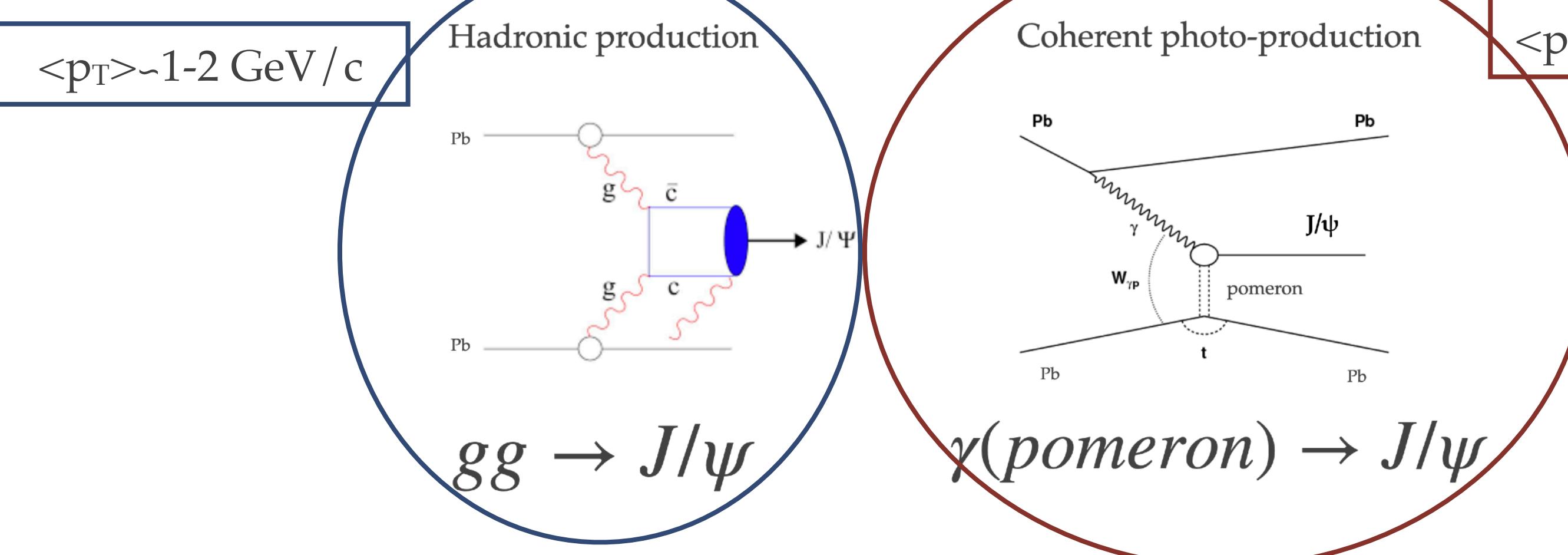


- ❖ Recent preprint shows good agreement with the soft dipole pomeron model
- ❖ Agreement with corresponding results from ALICE

Coherent J/ ψ in PbPb peripheral collisions

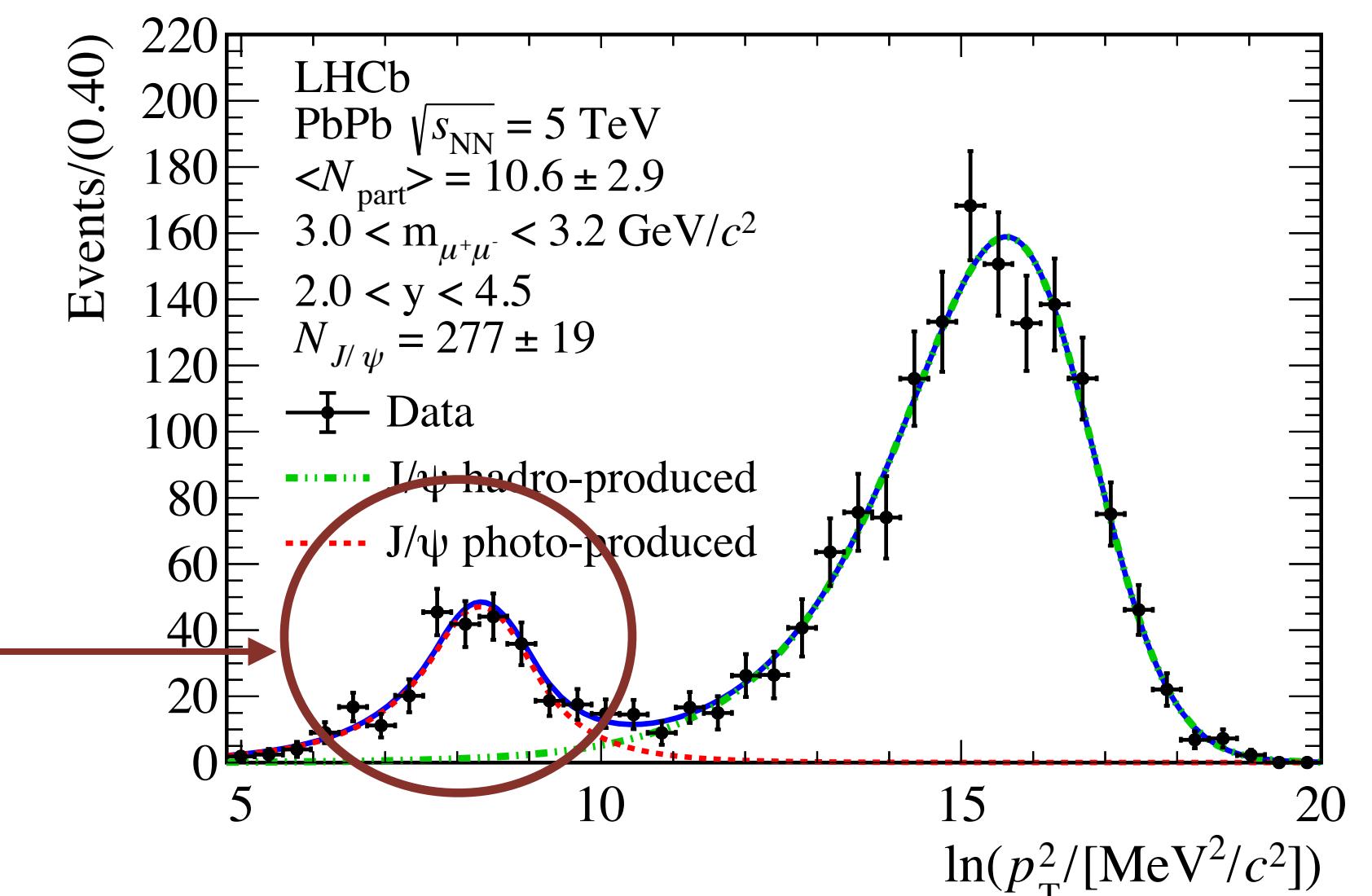
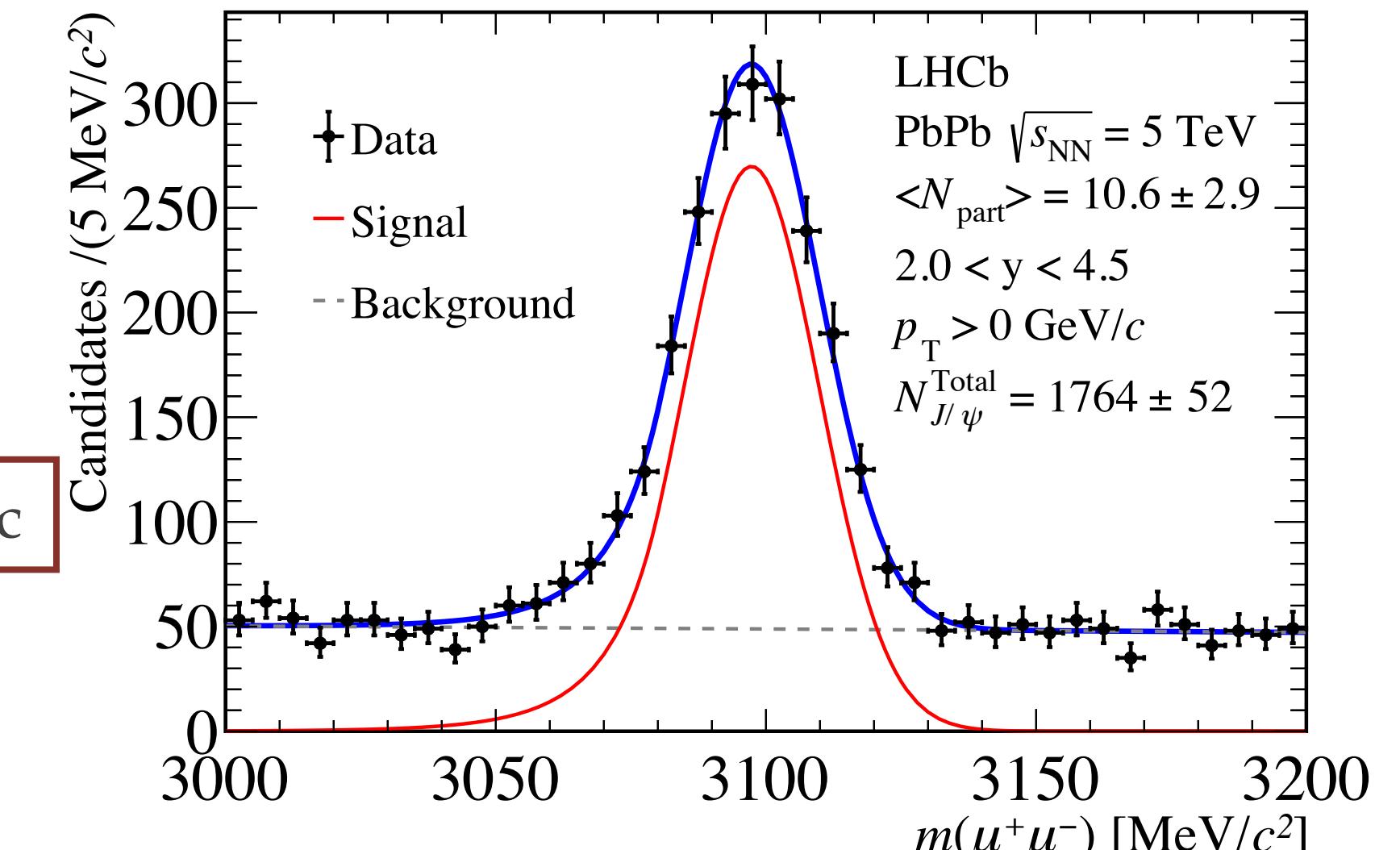
Coherent photo-production in peripheral collisions ? ($b < 2R_{\text{Pb}}$)

- ❖ 2018 PbPb sample at 5.02 TeV, limited to 60-90% centrality



Separate the two contributions through the p_T distribution of the J/ψ

« Excess » of J/ψ with mean p_T around $\sim 70 \text{ MeV}/c$
Compatible with coherent photo-production



Coherent J/ ψ in PbPb peripheral collisions

- ❖ Consistent with J/ ψ photo-production in PbPb hadronic collisions
- ❖ Most precise p_T measurement to date
- ❖ Shape compatible with model, two assumptions:
 - ❖ No effect of the overlap between the nuclei (UPC-like but small IP)
 - ❖ Effect of the overlap

W. Zha et al. Phys. Rev. C97 (2018) 044910 / Phys. Rev. C99, 06901(R)

