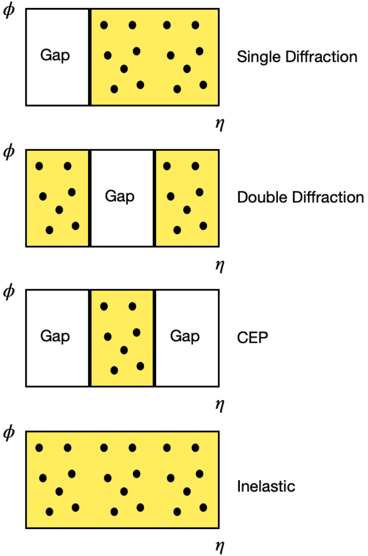
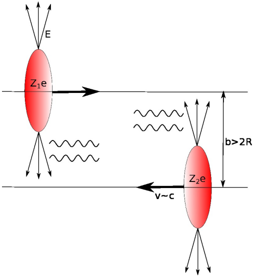
Recent LHCb results on forward physics and diffraction

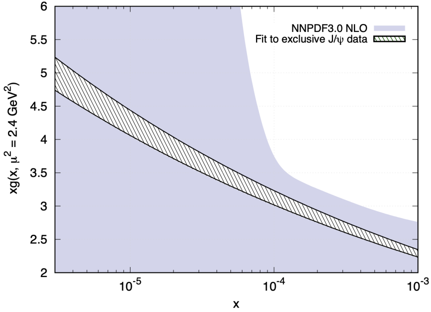
Luke McConnell

on behalf of the LHCb Collaboration





CEP useful for constraining gluon pdf and probing low x behaviour

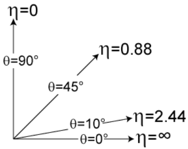


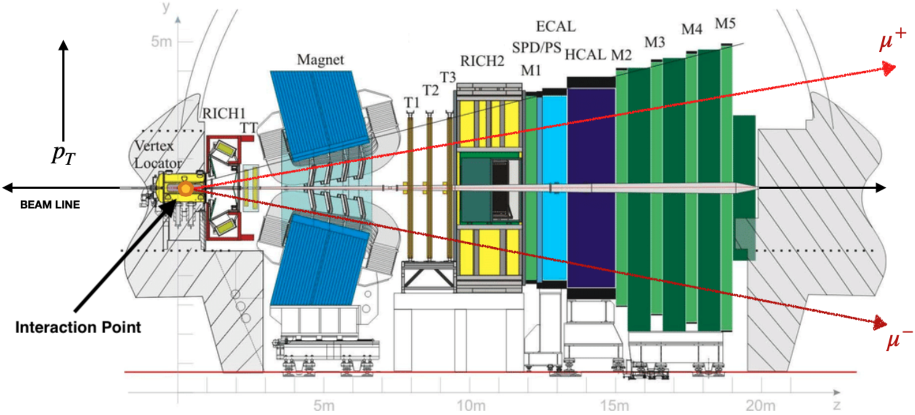
[1]

CEP mediated by pomeron

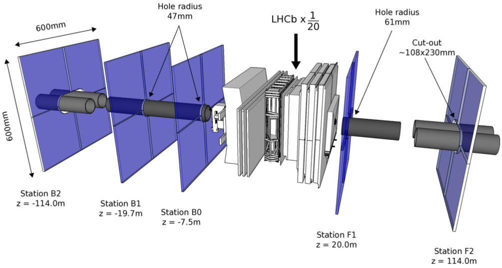
$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\eta = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$



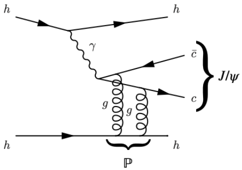


[2]

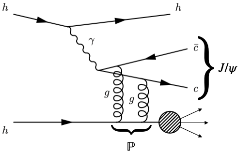


[3]

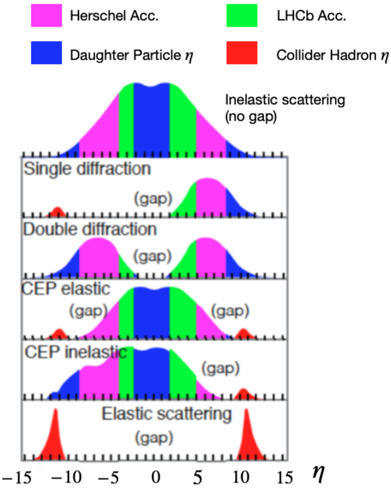
CEP: $p + p \to p + X + p$



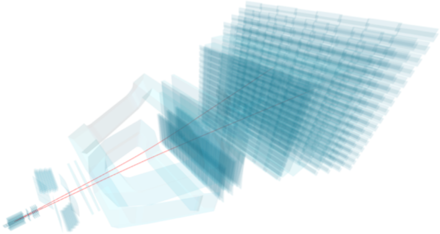
(a) CEP Elastic



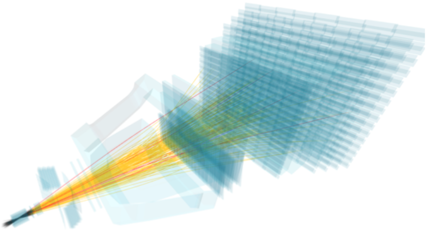
(b) CEP Inelastic



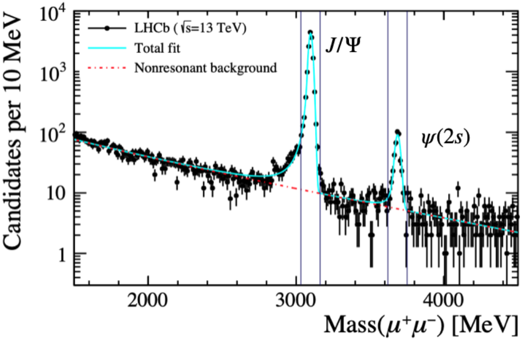
CEP of J/Ψ and $\psi(2s)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV



CEP, $\psi \to \mu^+ + \mu^-$



Inelastic

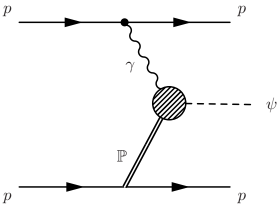


$\psi \to \mu^+\mu^-$: Event Selection

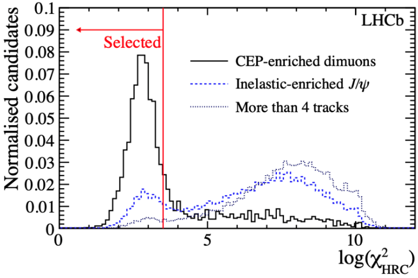
- Exactly two reconstructed tracks
- $2 < \eta_{\mu^+\mu^-} < 4.5$
- $m_{\mu^+\mu^-}$ within ±65 MeV of J/Ψ and $\psi(2s)$ masses
- $p_T^2 < 0.8$ GeV^2
- Herschel for inelastic background

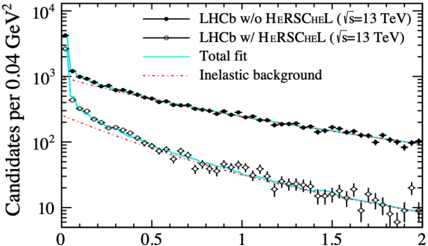
Backgrounds

- Continuum Dimuon Production ($\gamma\gamma$ fusion)
- Feed-down from χ_{c_J} ($\mathbb{PP}$ fusion) and $\psi(2s)$ ($\gamma\mathbb{P}$ fusion)
- Inelastic production



Signal Process





Total Fit includes both signal (described using sim) and inelastic bkg (modelled as exp+exp)

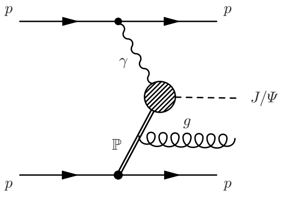
$\log\left(\chi^2_{HRC}\right)$ related to measured Herschel activity

Herschel Cut

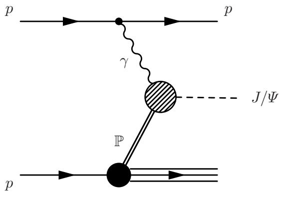
$\log\left(\chi^2_{HRC}\right) < 3.5$

Herschel Efficiency

$\varepsilon = 0.723 \pm 0.008$



Gluon Emission



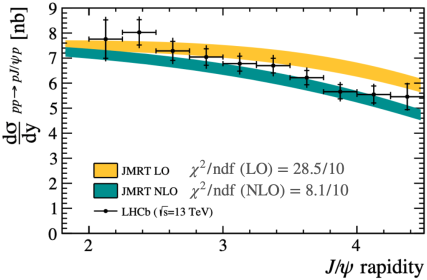
Proton Dissociation

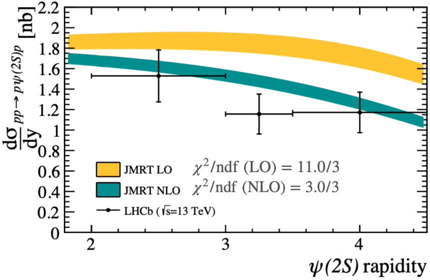
CEP of J/Ψ and $\psi(2s)$ mesons in pp collisions at $\sqrt{s} = 13$ TeV [JHEP 10 (2018) 167]

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy} = \frac{N_{sig}}{\varepsilon_{tot}\cdot\Delta y\cdot\varepsilon_{single}\cdot\mathcal{L}_{tot}}$$

$$\mathcal{L}_{tot} = 204 \pm 8 \text{ pb}^{-1}$$

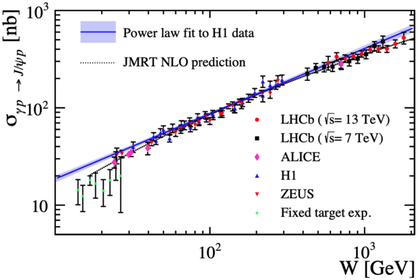
Both results have better agreement with NLO JMRT



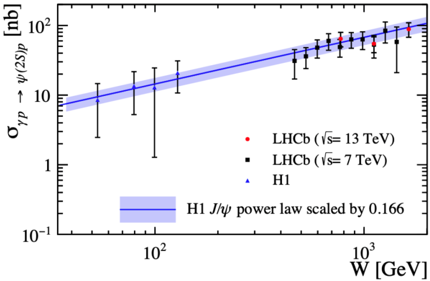


$$\sigma_{J/\Psi\to\mu^+\mu^-} = 435 \pm 18 \text{ (stat.)} \pm 11 \text{ (sys.)} \pm 17 \text{ (lumi) pb}$$

$$\sigma_{\psi(2s)\to\mu^+\mu^-} = 11.1 \pm 1.1 \text{ (stat.)} \pm 0.3 \text{ (sys.)} \pm 0.4 \text{ (lumi) pb}$$



Deviation at high W

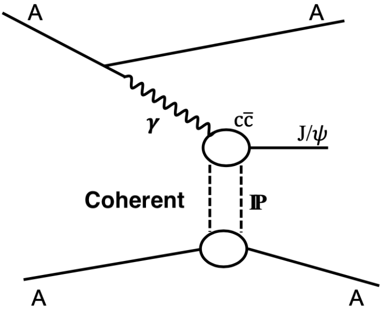


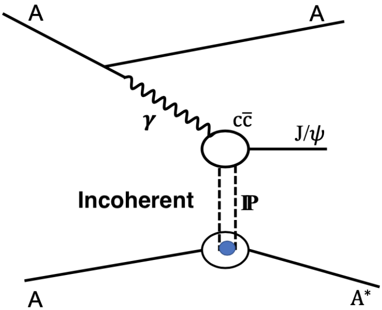
Consistent, but needs more data

$$\underbrace{\sigma_{pp \to p\Psi p}}_{\text{LHCb data}} = r\left(W_+\right) k_+ \frac{dn}{dk_+} \underbrace{\sigma_{\gamma p \to \Psi p}\left(W_+\right)}_{\textit{calculated}} + r\left(W_-\right) k_- \frac{dn}{dk_-} \underbrace{\sigma_{\gamma p \to \Psi p}\left(W_-\right)}_{\text{from HERA}}$$

- $r\left(W_\pm\right)$ is the gap survival factor
- $k_\pm = M_\psi / 2e^{\pm y}$ is the photon energy
- $dn/dk_\pm$ is the photon flux
- $W_\pm$ is the γp system invariant mass

Study of the coherent charmonium production in ultra-peripheral lead-lead collisions





probe nuclear-gluon dsitribution at $Q \sim m^2/4$

measurement depends on $x \approx \left(m/\sqrt{s_{NN}}\right) e^{\pm y}$

Useful in study of nuclear shadowing effects and initial states of collisions with small x

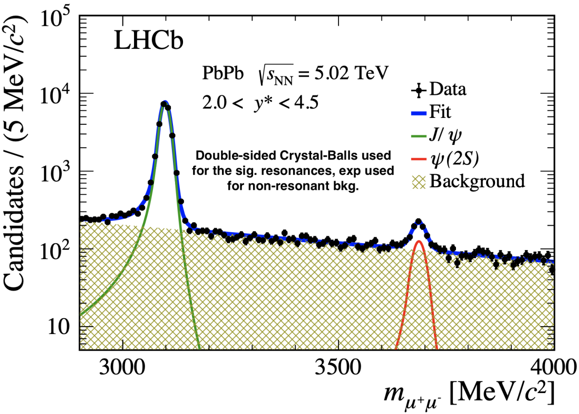
Event Selection

- two reco. muons
- $700 < p_T^{\mu^\pm}$ MeV
- $2 < \eta^{\mu^\pm} < 4.5$
- $m_{\mu^+\mu^-}$ within ±65 MeV of $m(\psi)$
- $p_T^{\psi} < 1$ GeV
- $2 < y^{\psi} < 4.5$
- Herschel requirement

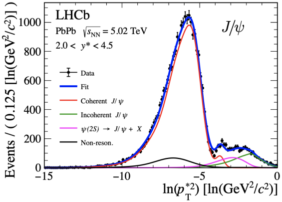
Resonant Backgrounds

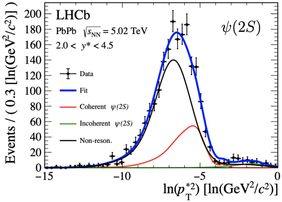
- incoherent prod.
- for the J/Ψ: feed-down from $\psi(2s)$ (in)coherent prod.

$\mathcal{L}_{int} = 228 \pm 10\ \mu b^{-1}$

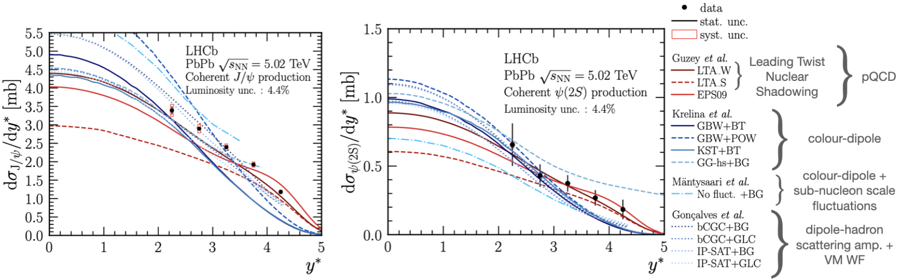


Double-sided Crystal-Balls used for the sig. resonances, exp used for non-resonant bkg.



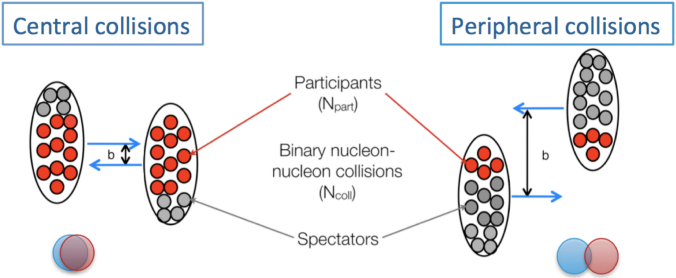


$$\frac{d\sigma^{\psi}}{dy} = \frac{N_{coh}}{\varepsilon_{tot} \cdot \Delta y \cdot \mathcal{L}_{int} \cdot \mathrm{Br}\left(\psi \to \mu^{+}\mu^{-}\right)}$$

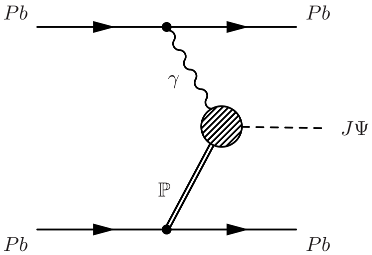


- pQCD models compatible, good at high y^{*}, slight underestimation at low y^{*}
- CGC models all compatible, variations between them, better agreement at low y^{*} than at high y^{*}

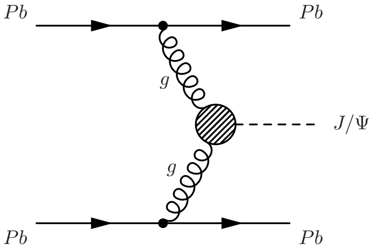
J/Ψ photo-production in Pb-Pb peripheral collisions at $\sqrt{s_{NN}} = 5$ TeV



- Different from UPCs
- $R < b < 2R$
- Hadron dissociates
- Varying number of participating nucleons N_{part}
- Again $J/\Psi \to \mu^+ + \mu^-$

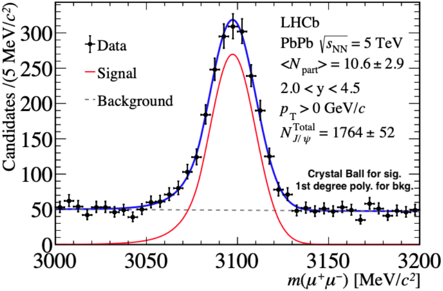


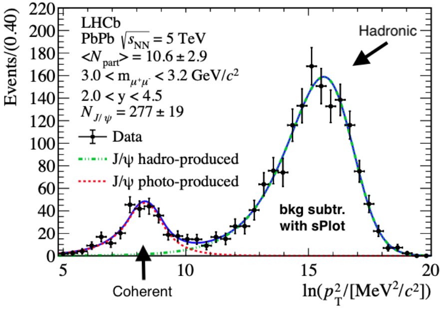
(a) Coherent Process



(b) Hadronic Process

- ALICE and STAR measured excess w.r.t. expectations from purely hadronic J/Ψ production at low p_T
- Posited this is due to photo-production from coherent interactions
- Previously only thought to occur in UPCs
- Presence gives interesting opportunity to examine the profile of the photon flux in *PbPb* PCs





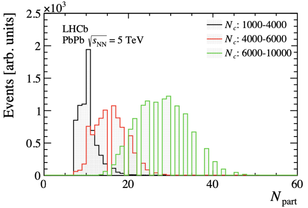
Event Selection

$700 < p_T$, consistent with PV, be muons, min N_c

Backgrounds

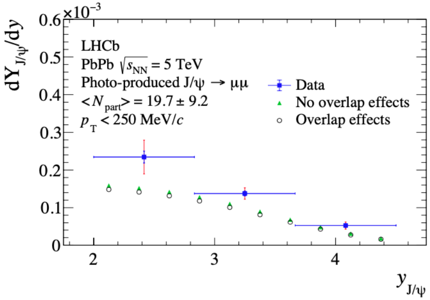
non-prompt (t_z), SMOG (PV), UPCs (Ecal)

N_c	$\langle N_{part} \rangle$	σ_{part}
1000 – 4000	10.6	2.9
4000 – 6000	15.7	4.1
6000 – 10000	27.8	7.2
1000 – 10000	19.7	9.2

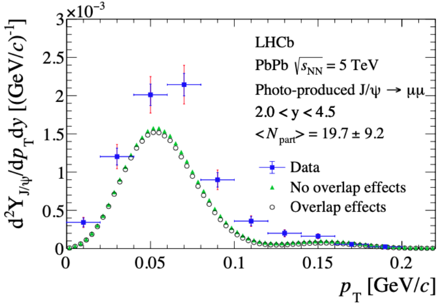


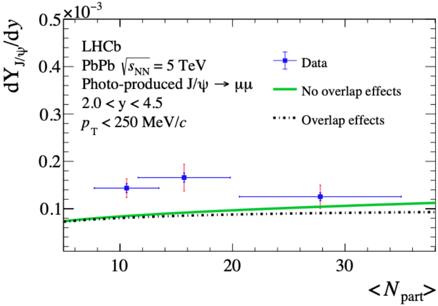
Sig. sample divided into intervals of N_c

J/Ψ photo-production in Pb-Pb peripheral collisions at $\sqrt{s_{NN}} = 5$ TeV [Phys. Rev. C 105 (2022) L032201]



$\mathcal{L}_{int} \approx 210\ \mu b^{-1}$





$$\frac{dY^i_{J/\Psi}}{dy} = \frac{N^i_{J/\Psi}}{\mathcal{B} \cdot N^i_{MB} \cdot \varepsilon^i_{tot} \cdot \Delta y},$$

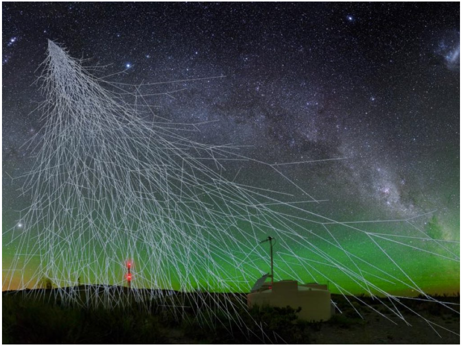
$$\frac{d^2Y}{dydp_T} = \frac{dY^i_{J/\Psi}}{dy}\frac{1}{\Delta p_T}$$

[4, 5]

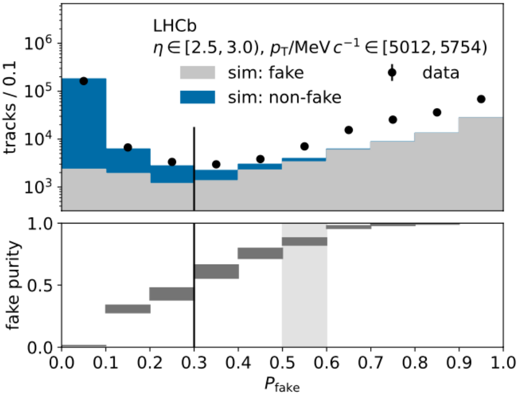
Most precise results to date.

Measurement of prompt charged-particle production in *pp* collisions at $\sqrt{s} = 13$ TeV

- Prod. in inelastic *pp* collisions dominated by soft processes
- Needs models
- MC Generators used for LHC and air showers
- Measurements of light hadron production useful for constraining models
- Prompt long-lived charged particles production good proxy
- Measurement precision essential for improved simulation of underlying events in LHC and air showers.



Air Shower due to Cosmic Rays [6]



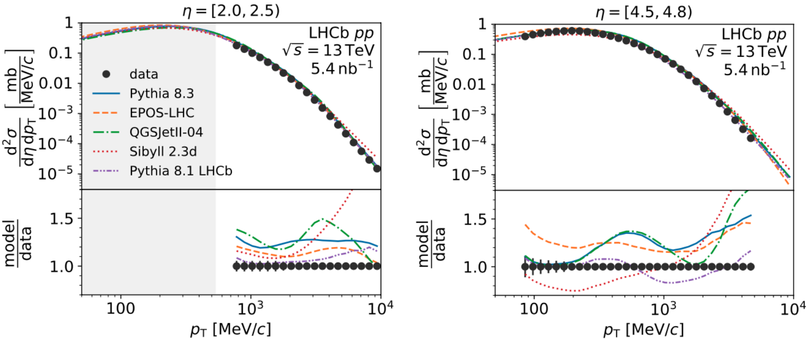
- Unbiased trigger selecting leading bunch crossings
- Tracks with $2 < \eta < 4.5$ and $0.08 < p_T < 10$ GeV
- Loose track selection with high efficiency
- Separated by charge
- Backgrounds: fake tracks, non-prompt tracks (detector material interactions), beam-gas interactions

P_{fake}: fake track probability, obtained with NN classifier.

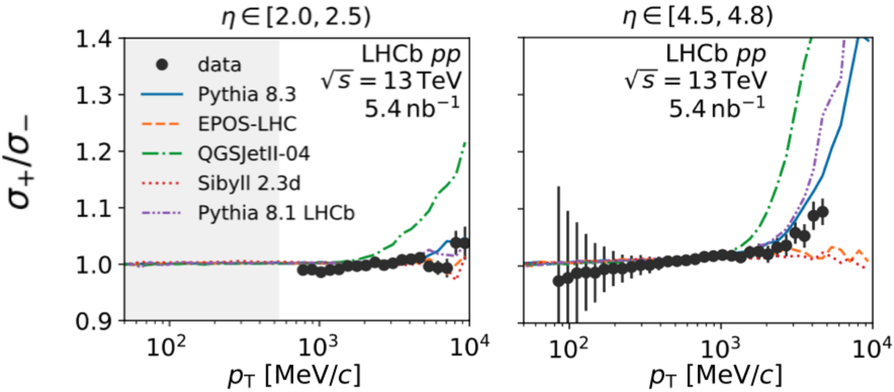
$$\overset{\substack{\text{Candidate tracks}\\ \downarrow}}{n_{cand}} = \underset{\substack{\uparrow\\ \text{Total efficiency}}}{\varepsilon} n + \sum_i \overset{\substack{\text{Background contributions}\\ \downarrow}}{n_{bkg,i}}$$

$$\frac{d^2\sigma}{dp_T d\eta} = \frac{1}{\mathscr{L}} \cdot \frac{n}{\Delta p_T \Delta\eta}$$

$\mathscr{L}$: integrated luminoisty
n : prompt charged particle yield
$\Delta\eta, \Delta p_T$: bin size



- Models mostly overestimate
- Best agreement: EPOS-LHC and Pythia 8-1
- Pythia 8-1 tuned for LHCb, based on occupancy weighting (only deviations in the shape occur)



- $+$ve correlated components of errors cancel in ratio
- For p_T and high η: prod. of $+$ve particles increases as initial state has $+2$ charge, transfers to final state in forward region
- Models predict this to varying degrees, best by Pythia 8.3 (onset of increase is shifted towards lower p_T values)

CEP of J/Ψ and $\psi(2s)$ mesons in *pp* collisions at $\sqrt{s} = 13$ TeV

Photo-production cross sections found to be in good agreement with the JMRT NLO. For J/Ψ there is a deviation from pure power-law extrapolation of H1 data, while $\psi(2s)$ results are consistent although more data is required.

Study of the coherent charmonium production in lead-lead UPCs

Measurements of differential cross section as a function of y (and p_T) for the J/Ψ and $\psi(2s)$ are found to be in compatible with theoretical models.

J/Ψ photo-production in Pb-Pb peripheral collisions at $\sqrt{s_{NN}} = 5$ TeV

Most precise results yet. Supports the hypothesis of coherent J/Ψ photo-production in peripheral hadronic collisions. Results are qualitatively described by the theoretical prediction.

Measurement of prompt charged-particle production in *pp* collisions at $\sqrt{s} = 13$ TeV

Results compared with predictions. Models mostly overestimate differential cross-section. Smallest deviations are observed for EPOS-LHC, ratio of the differential cross-sections best predicted by PYTHIA 8.3.

Thank you for your attention.

References

[1] C. A. Flett, doi:10.17638/03123138

[2] JINST **3** (2008), S08005 doi:10.1088/1748-0221/3/08/S08005

[3] JINST **13** (2018) no.04, P04017 doi:10.1088/1748-0221/13/04/P04017 [arXiv:1801.04281 [physics.ins-det]].

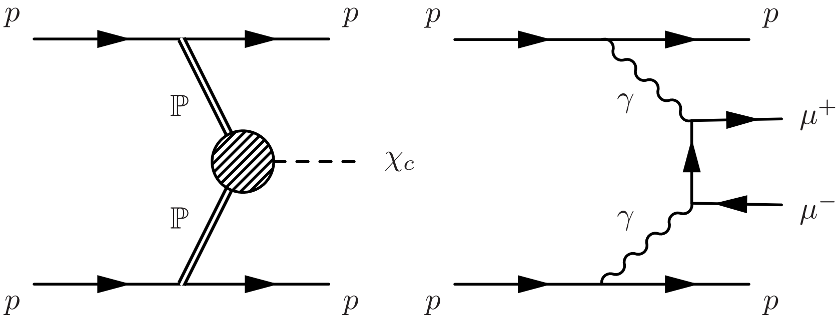
[4] W. Zha, S. R. Klein, R. Ma, L. Ruan, T. Todoroki, Z. Tang, Z. Xu, C. Yang, Q. Yang and S. Yang, Phys. Rev. C **97** (2018) no.4, 044910 doi:10.1103/PhysRevC.97.044910 [arXiv:1705.01460 [nucl-th]]

[5] W. Zha, L. Ruan, Z. Tang, Z. Xu and S. Yang, Phys. Rev. C **99** (2019) no.6, 061901 doi:10.1103/PhysRevC.99.061901 [arXiv:1810.10694 [hep-ph]]

[6] J. Albrecht, L. Cazon, H. Dembinski, A. Fedynitch, K. H. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan and R. Ulrich, *et al.* Astrophys. Space Sci. **367** (2022) no.3, 27 doi:10.1007/s10509-022-04054-5 [arXiv:2105.06148 [astro-ph.HE]]

Back-up

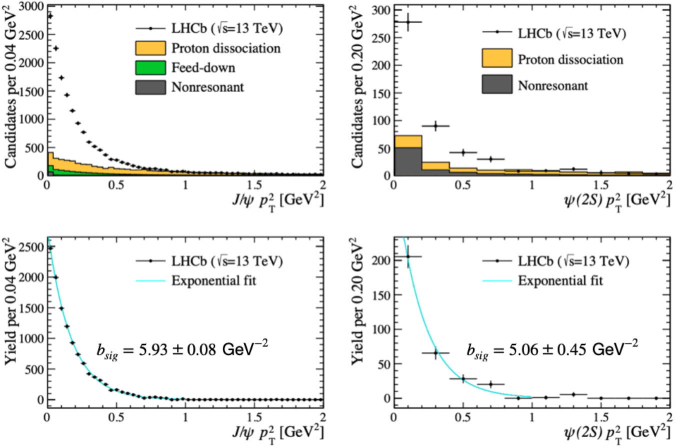
Paper 1: Backgrounds



(a) Feed-down from χ_{c^J} ($\mathbb{PP}$)

(b) Continuum Dimuon Production ($\gamma\gamma$)

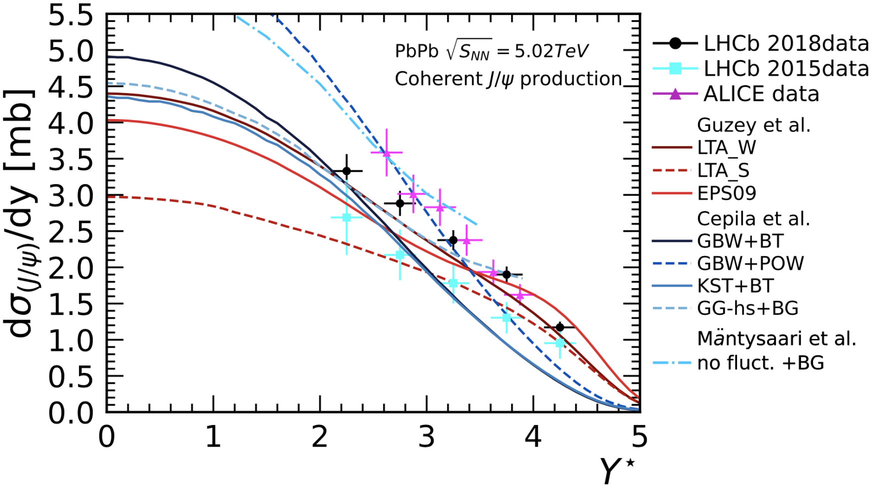
Paper 1: Fitting p_T^2 distributions



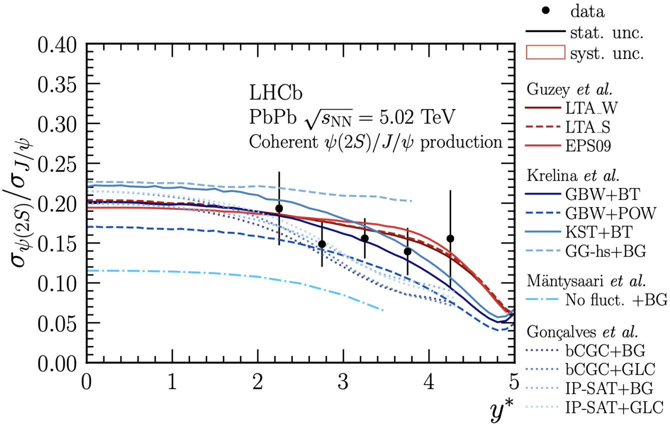
Regge Theory suggests $\frac{d\sigma}{dp_T^2} \sim \exp\left(-b_{sig}\, p_T^2\right)$

$b_{sig} \approx 6$ GeV^{-2} consistent with predictions

Paper 3: Comparison to ALICE

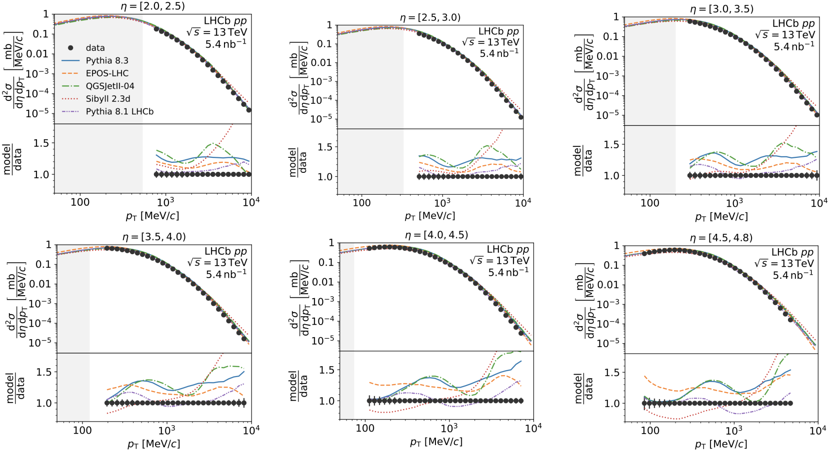


Paper 3: Cross Section Ratio



$$\sigma^{coh}_{\psi(2s)}/\sigma^{coh}_{J/\Psi} = 0.155 \pm 0.014 \pm 0.003$$

Paper 3: All Differential Cross Sections



Paper 4: All Cross Section Ratios