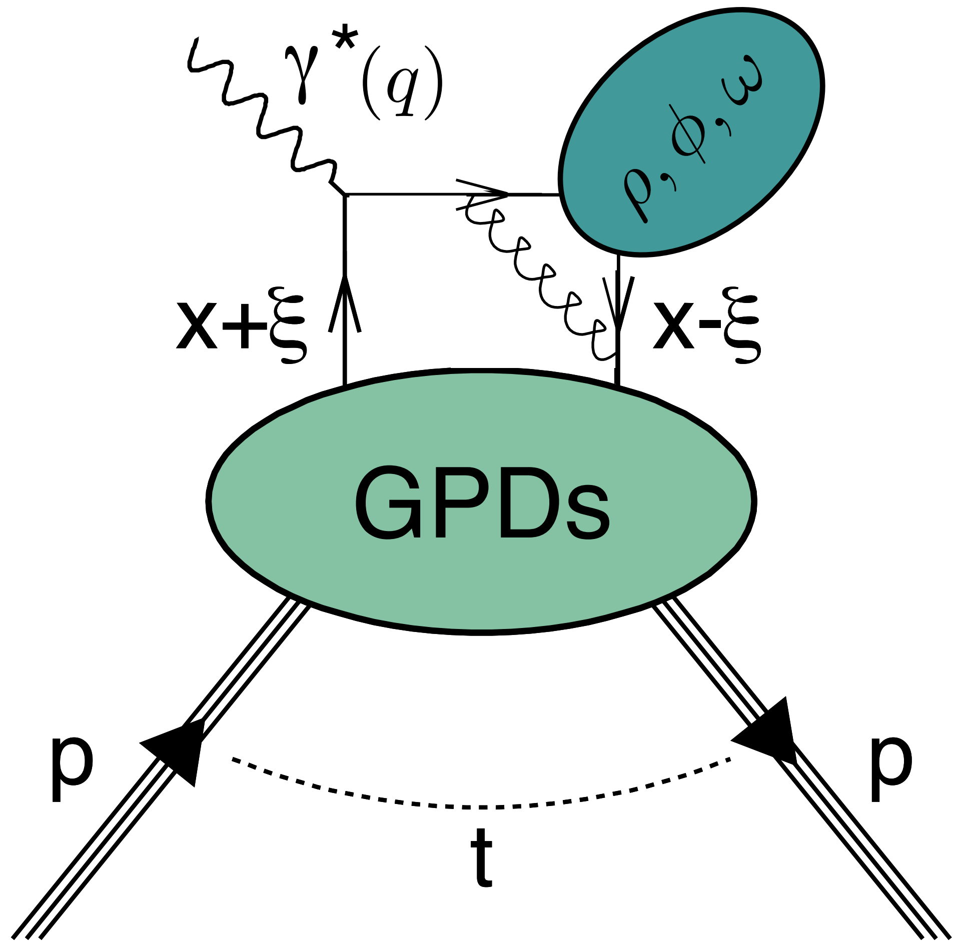
Exclusive reactions at LHCb

Charlotte Van Hulse, on behalf of LHCb
University Alcala de Henares, University Santiago de Compostela

Towards improved hadron femtography with hard exclusive reactions
July 18-22, 2022
Virginia Tech
Blacksburg, VA, USA

AdTCAM

Experimental access to GPDs



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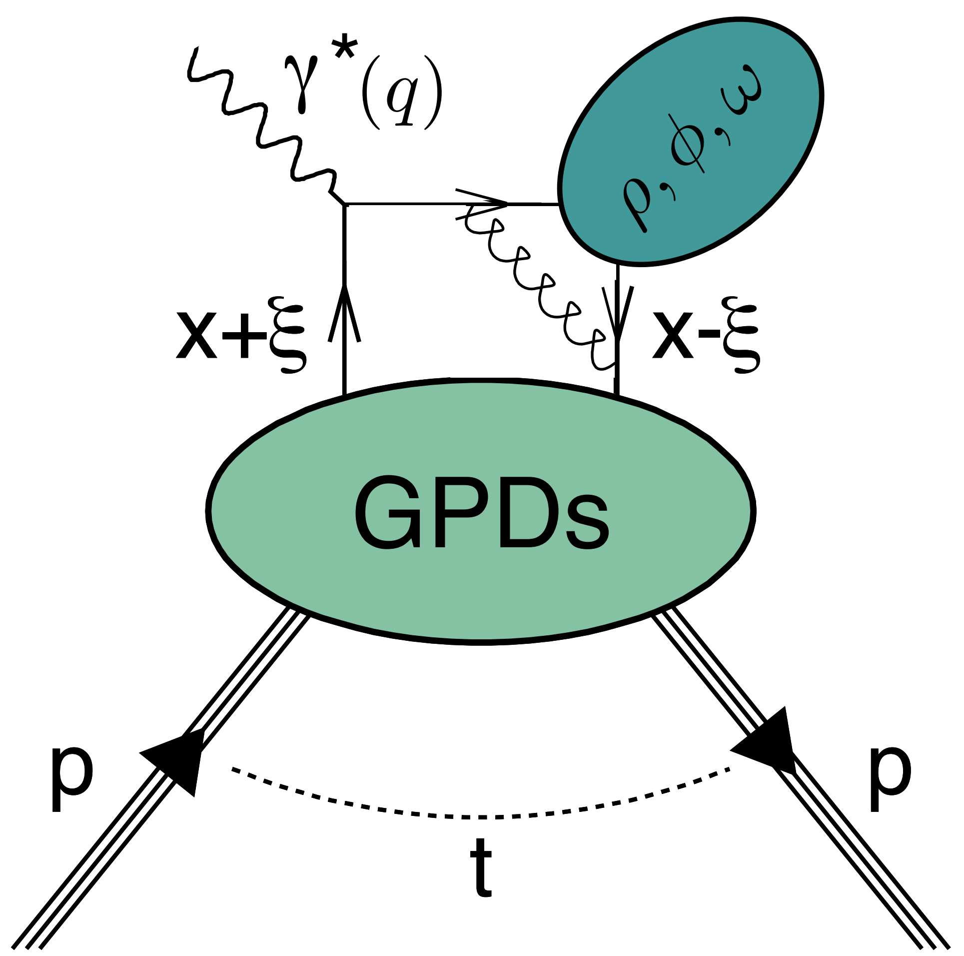
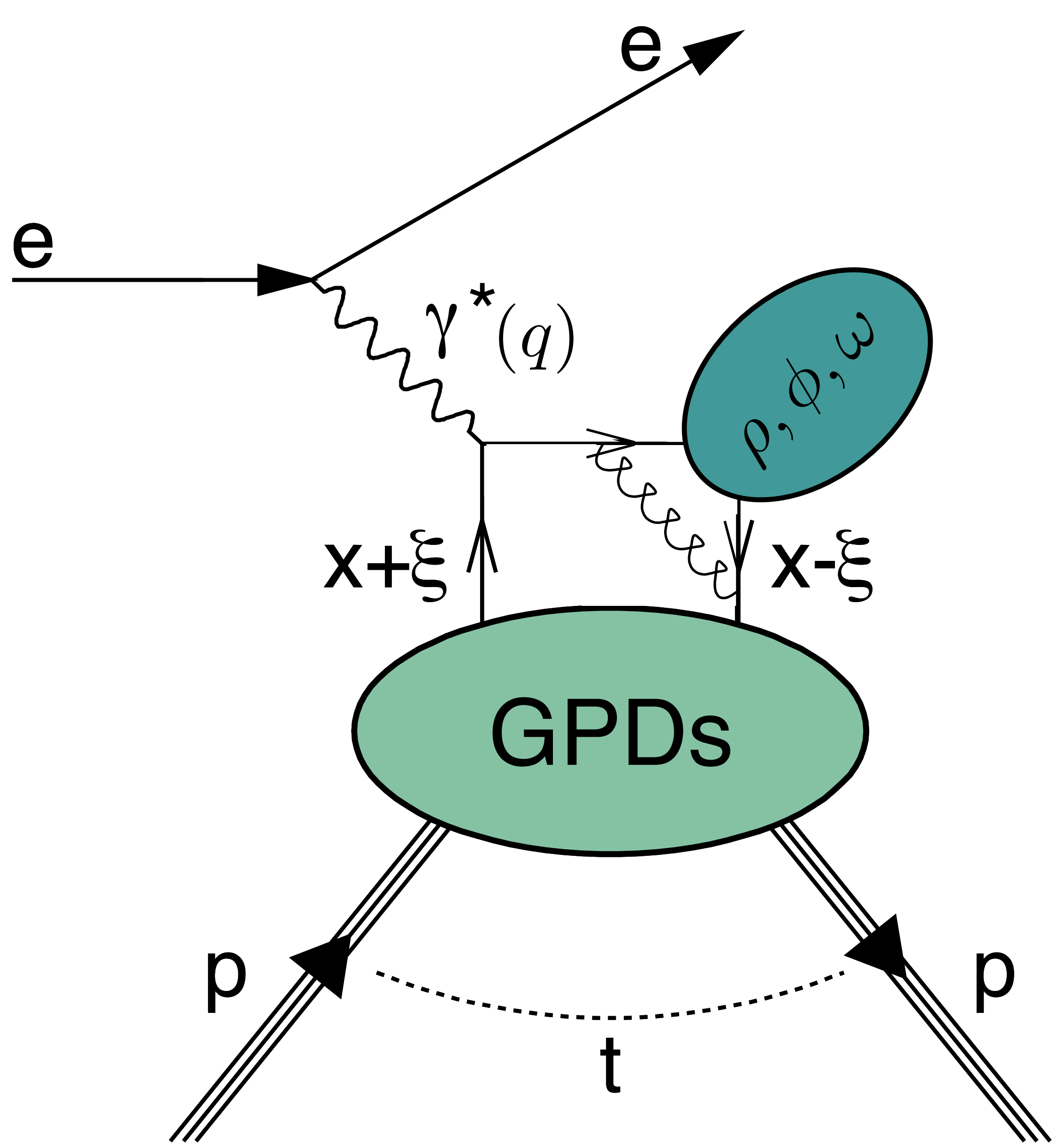


Hard exclusive meson production

hard scale = large Q^2 ($Q^2=-q^2$)

Experimental access to GPDs



Hard exclusive meson production

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CLAS – PRC 95 ('17) 035207; 95 (2017) 035202

COMPASS – PLB 731 ('14) 19; NPB 915 ('17) 454

JLab Hall A Collaboration – PRC 83 ('11) 025201

HERMES – EPJ C 74 ('14) 3110; 75 ('15) 600; 77 ('17) 378

H1 – JHEP 05('10)032; EPJ C 46 ('06) 585

ZEUS – PMC Phys. A1 ('07) 6; NPB 695 ('04) 3

colliders, small x_B, gluons

fixed target: medium/large x_B , quarks

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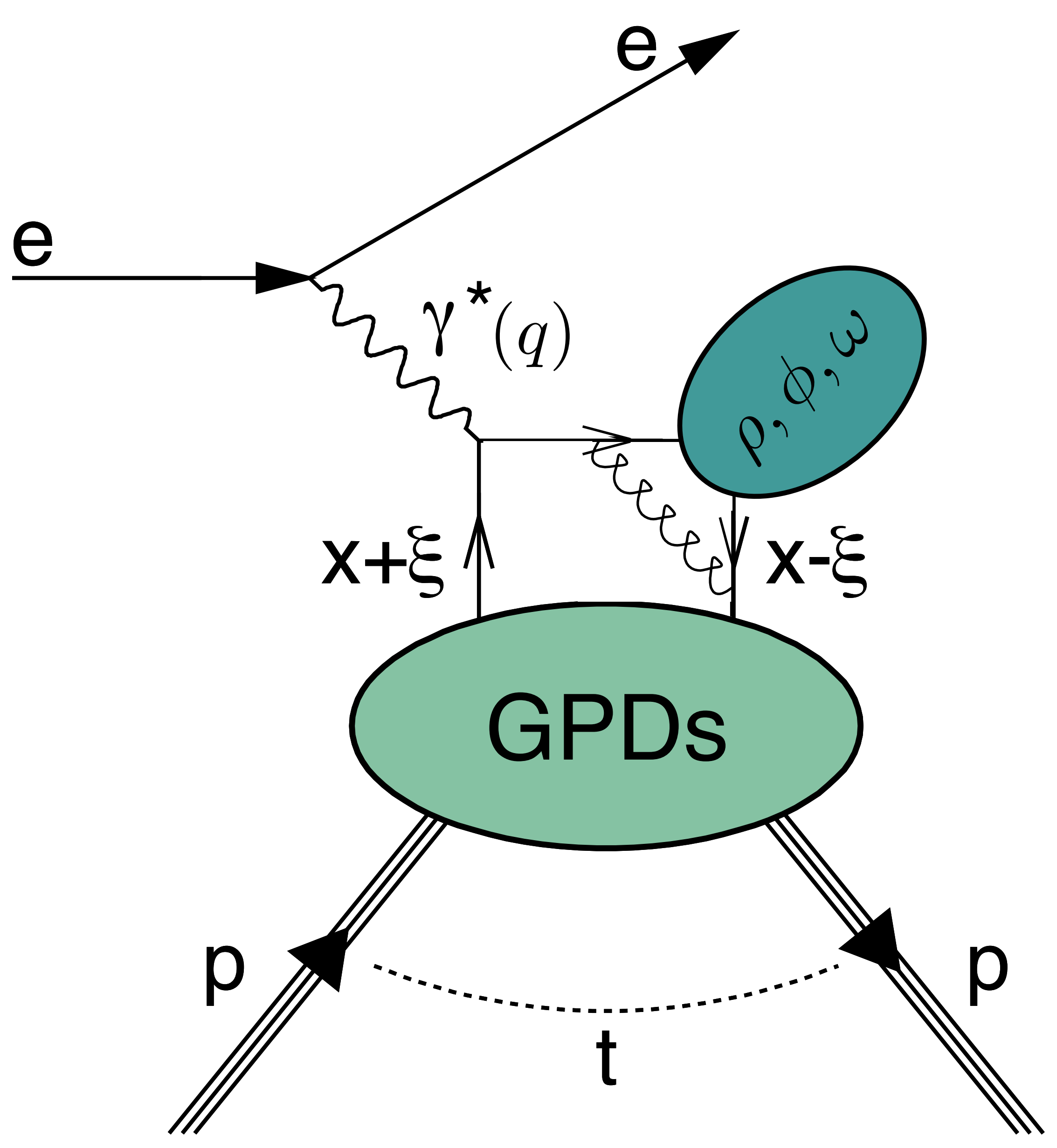

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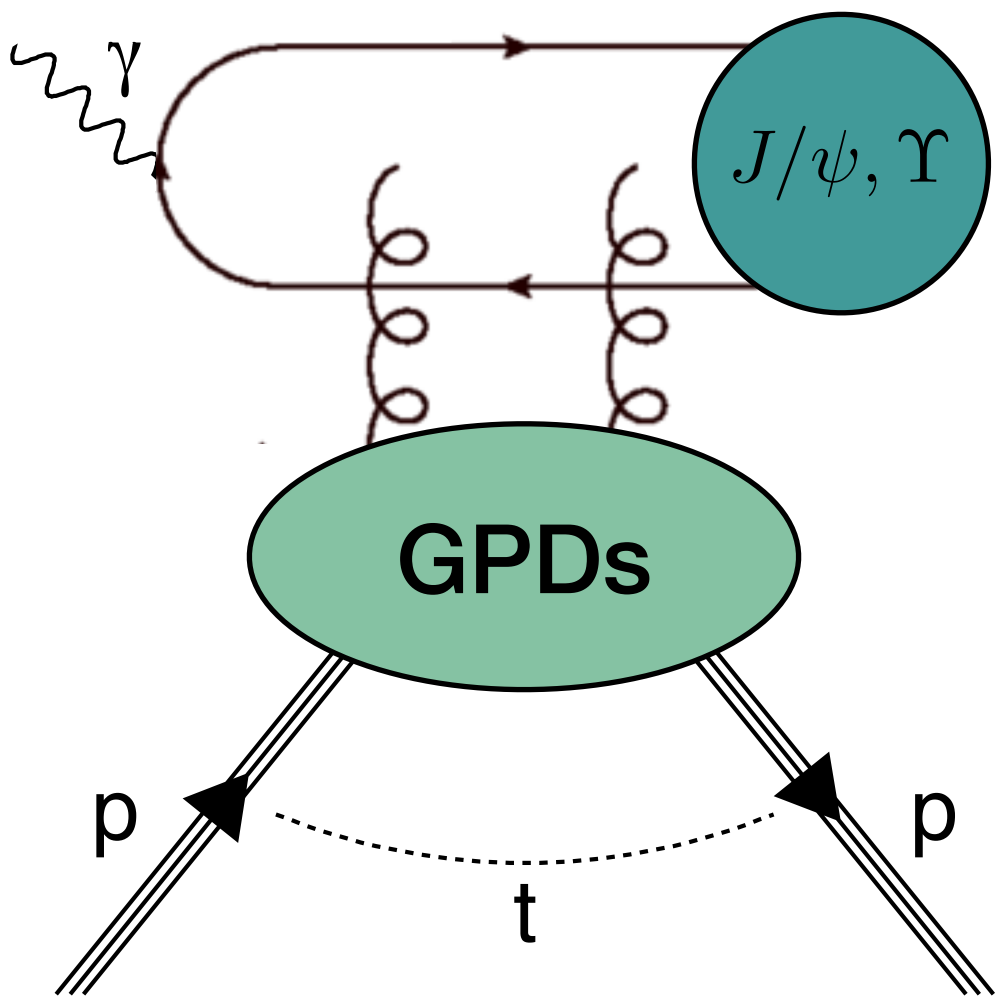

Exclusive meson photoproduction

hard scale = large quark mass

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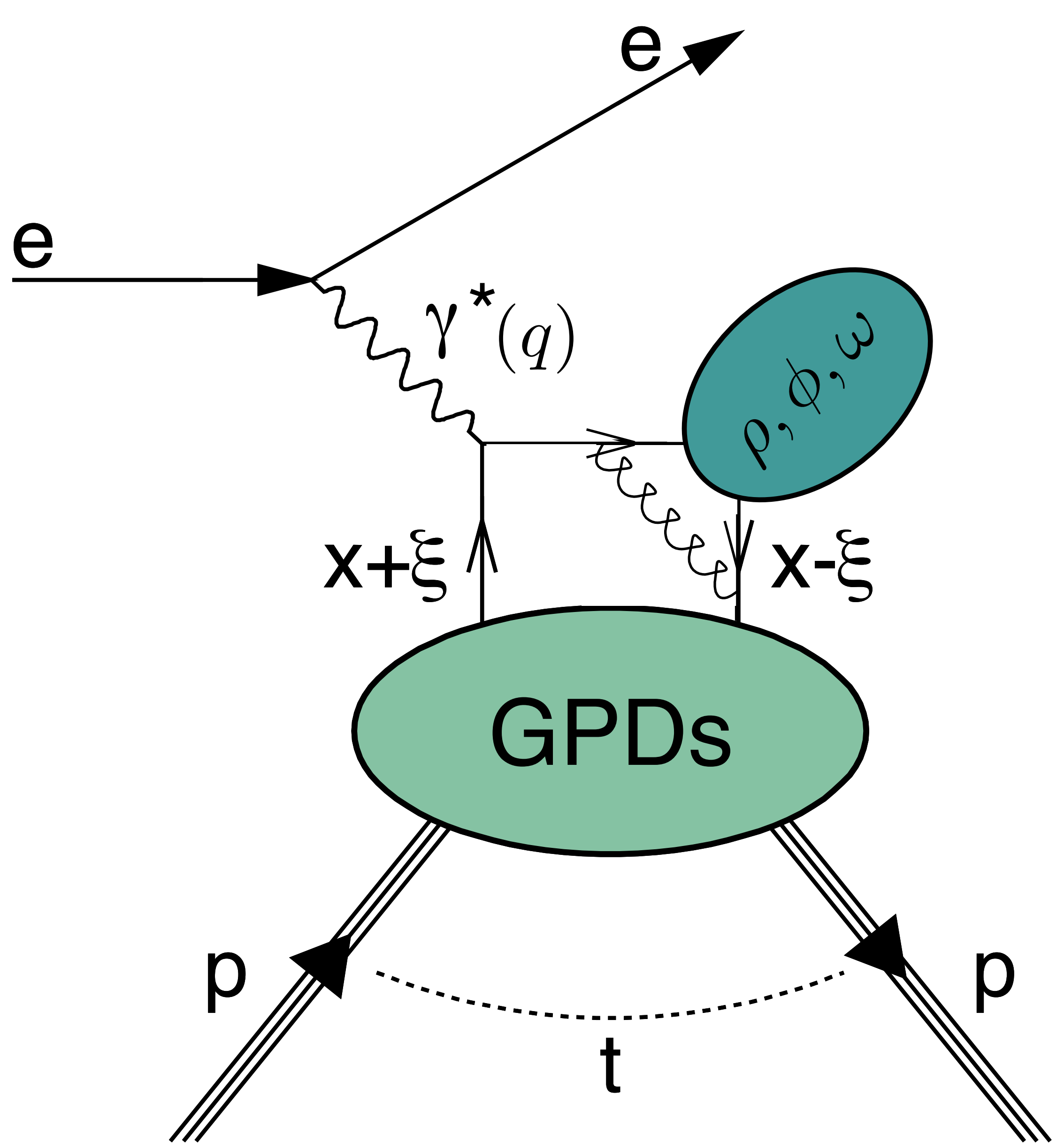

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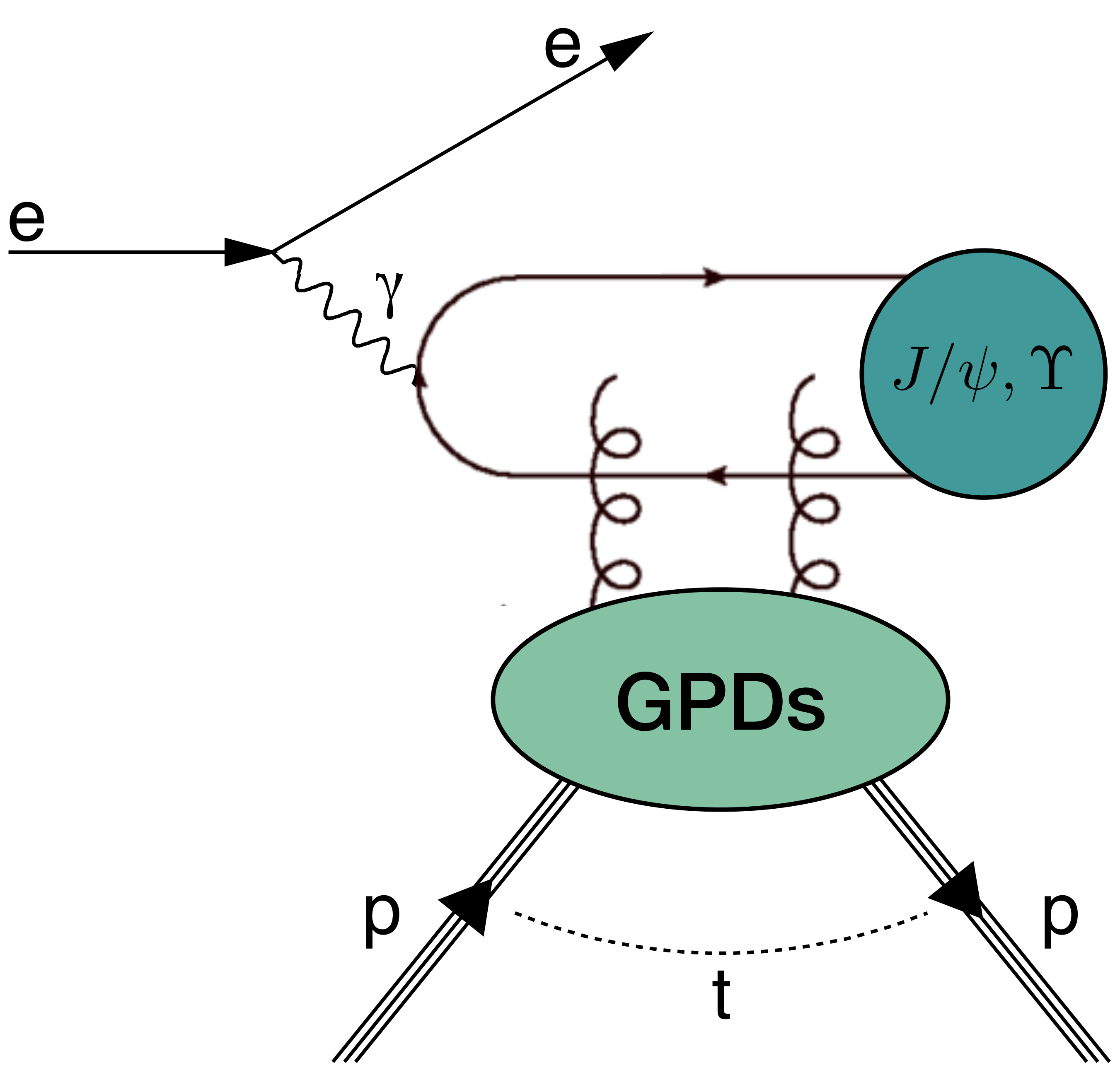

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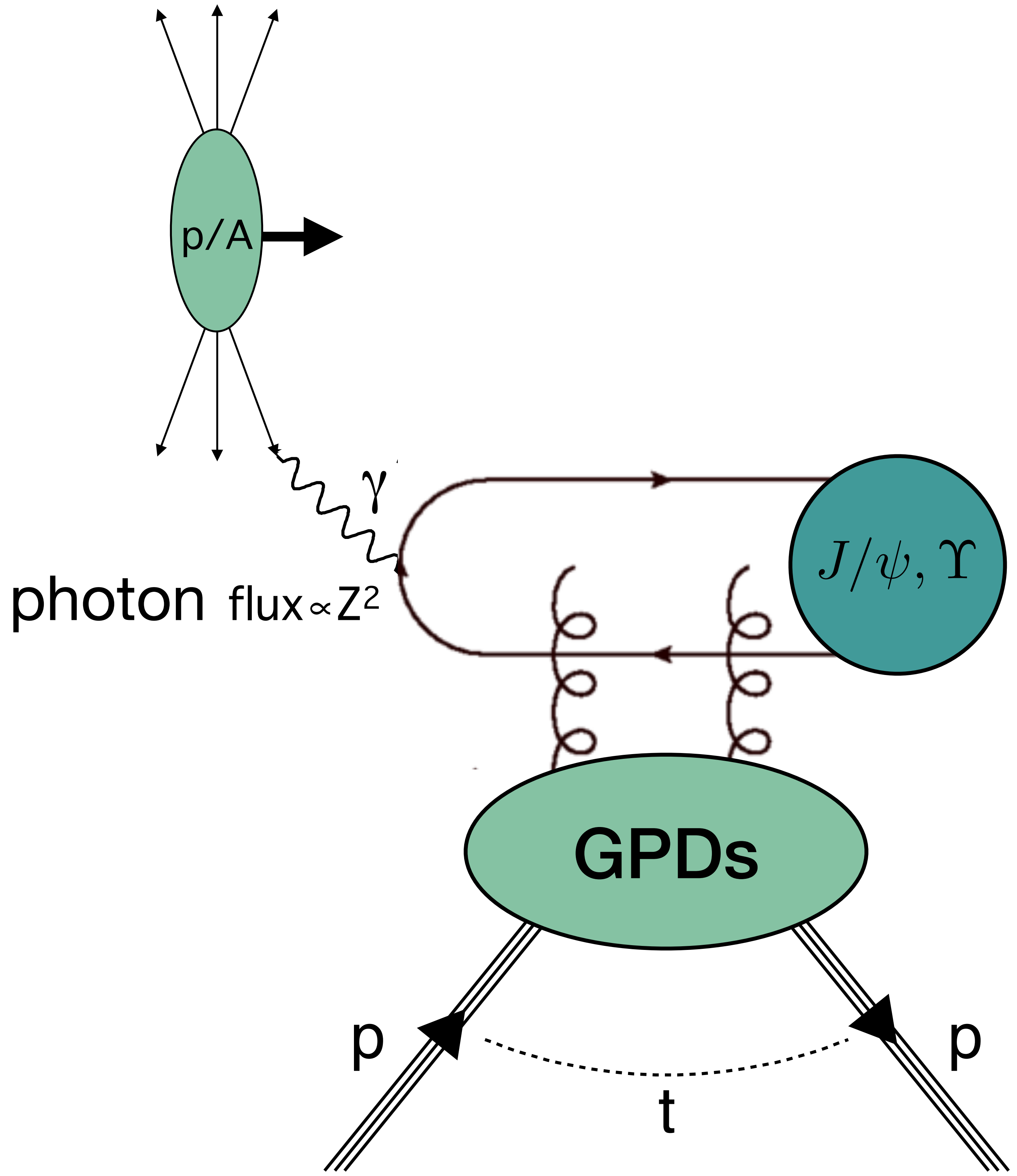
H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251

ZEUS – Nucl. Phys. B 695 ('04) 3; PLB 680 ('09) 4

$$W_{\gamma p} = [30, 300]\ \mathrm{GeV}$$

Ultra-peripheral exclusive quarkonia production

large–impact-parameter interactions (> sum of radii):
hadronic interactions strongly suppressed,
in favour of electromagnetic interactions



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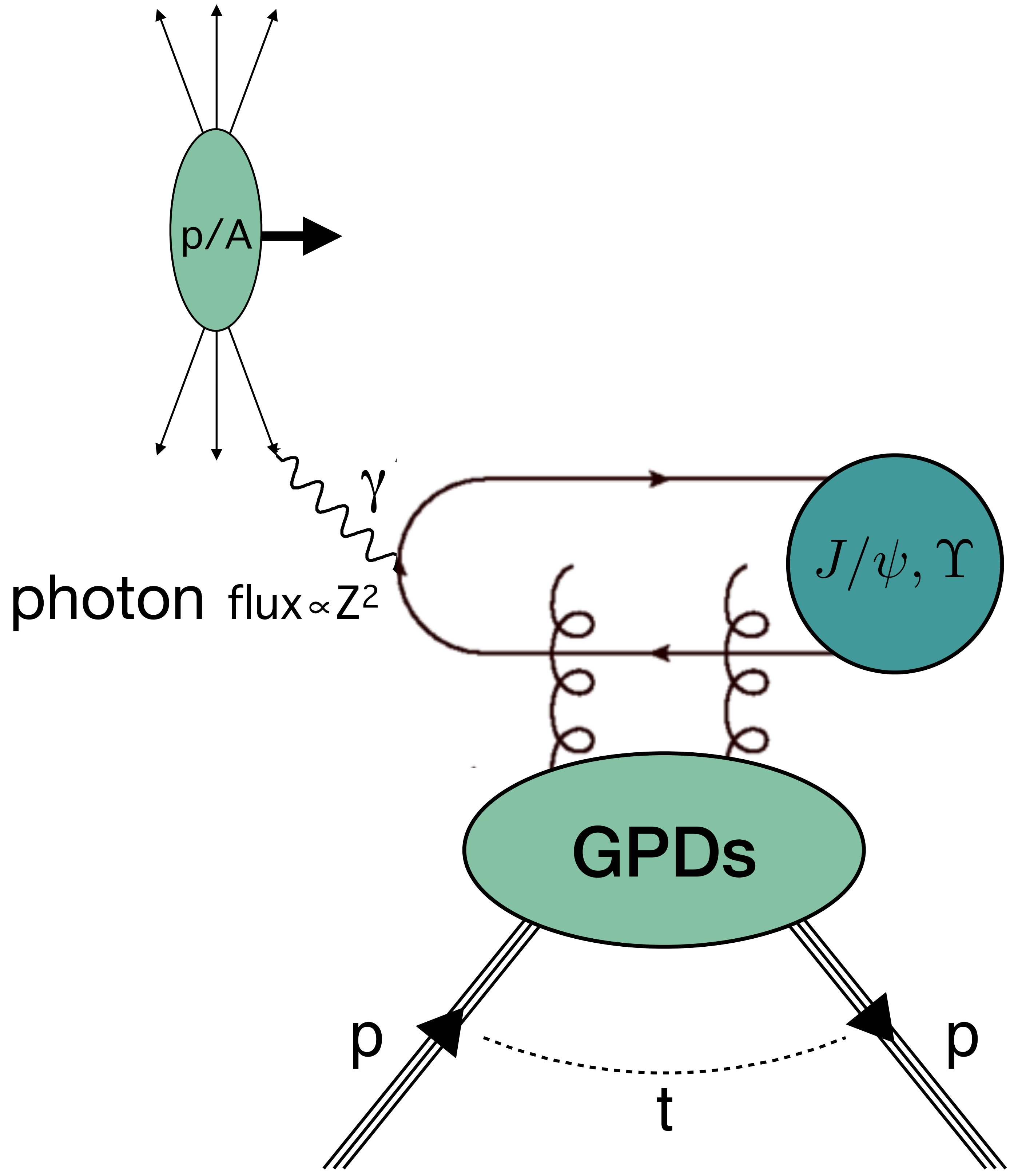

$W_{\gamma N}^{\max} = 34$ GeV ↓ $W_{\gamma p}^{\max} = 1.5$ TeV

- PHENIX: Au-Au – Phys. Lett. B **679** ('09) 321
- CDF: p-p̄ – Phys. Rev. Lett. **102** ('09) 242001
- CMS, PbPb: Phys. Lett. B **772** ('17) 489
- CMS, pPb: Eur. Phys. J. C **79** ('19) 277
- ALICE: Pb-Pb – Eur. Phys. J. C **73** ('13) 2617; Phys. Lett. B **718** ('13) 1273; Phys. Lett. B **751** ('15) 358; Phys. Lett. B **798** ('19) 134926; Eur. Phys. J. C **81** (2021) 712; Phys. Lett. B 817 (2021) 136280.
- ALICE: p-Pb – Phys. Rev. Lett. **113** ('14) 232504; Eur. Phys. J. C **79** ('19) 402
- LHCb: PbPb – CERN-LHCb-CONF-2018-003
- LHCb: pp – J. Phys. G: Nucl. Part. Phys. **40** ('13) 045001; **41** ('14) 055002; JHEP 1509 ('15) 084); JHEP10('18)167

Coherent production – low x_B

At LHCb: low x_B! Down to 10^{-5} or 10^{-6}, depending on beam E.

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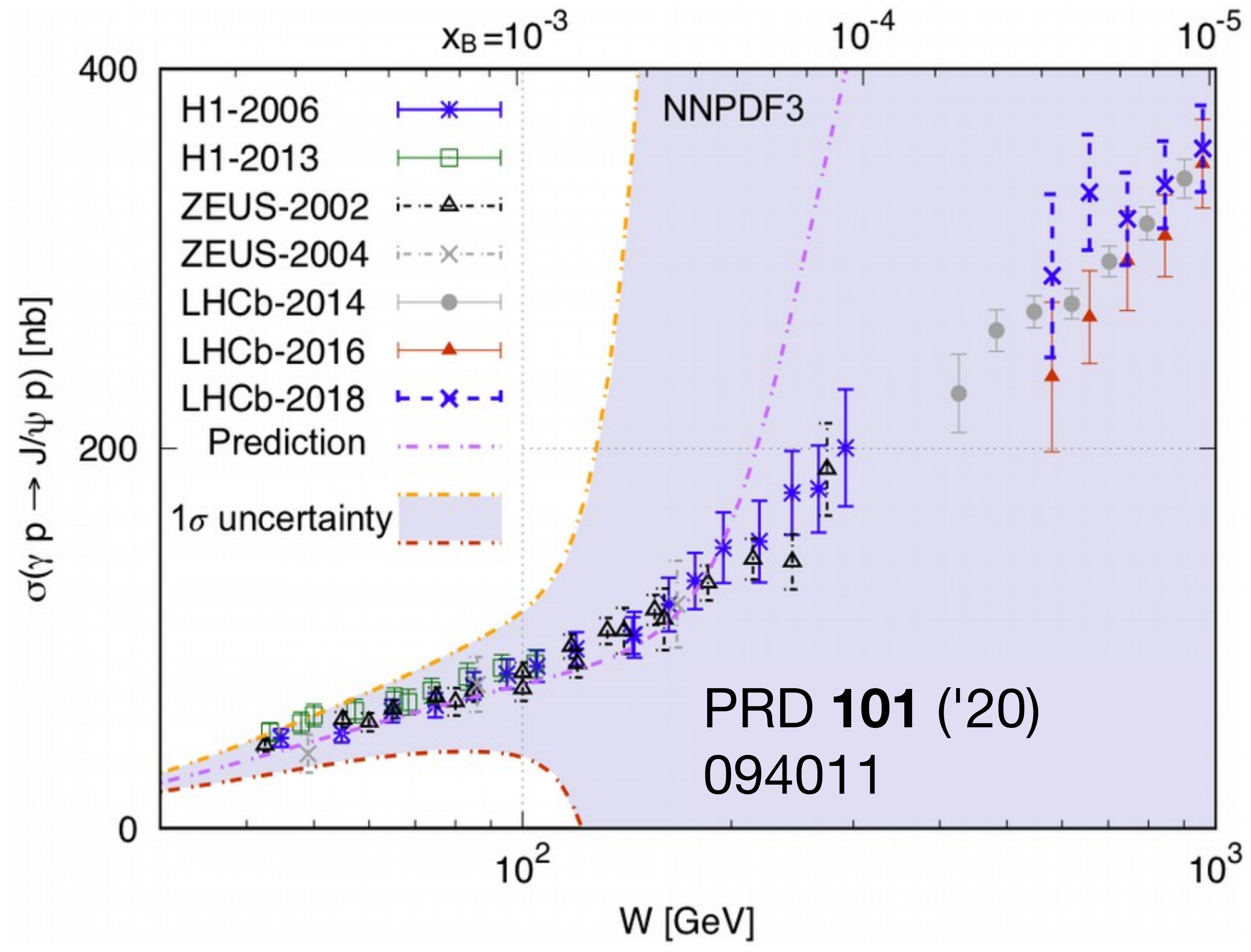
approximate GPDs to gluon PDF

$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto [g(x_B)]^2$$

Z. Phys. C**57** ('93) 89–92;
arXiv:1609.09738

Impact of LHCb data for nucleon PDFs



PRD **101** ('20)
094011

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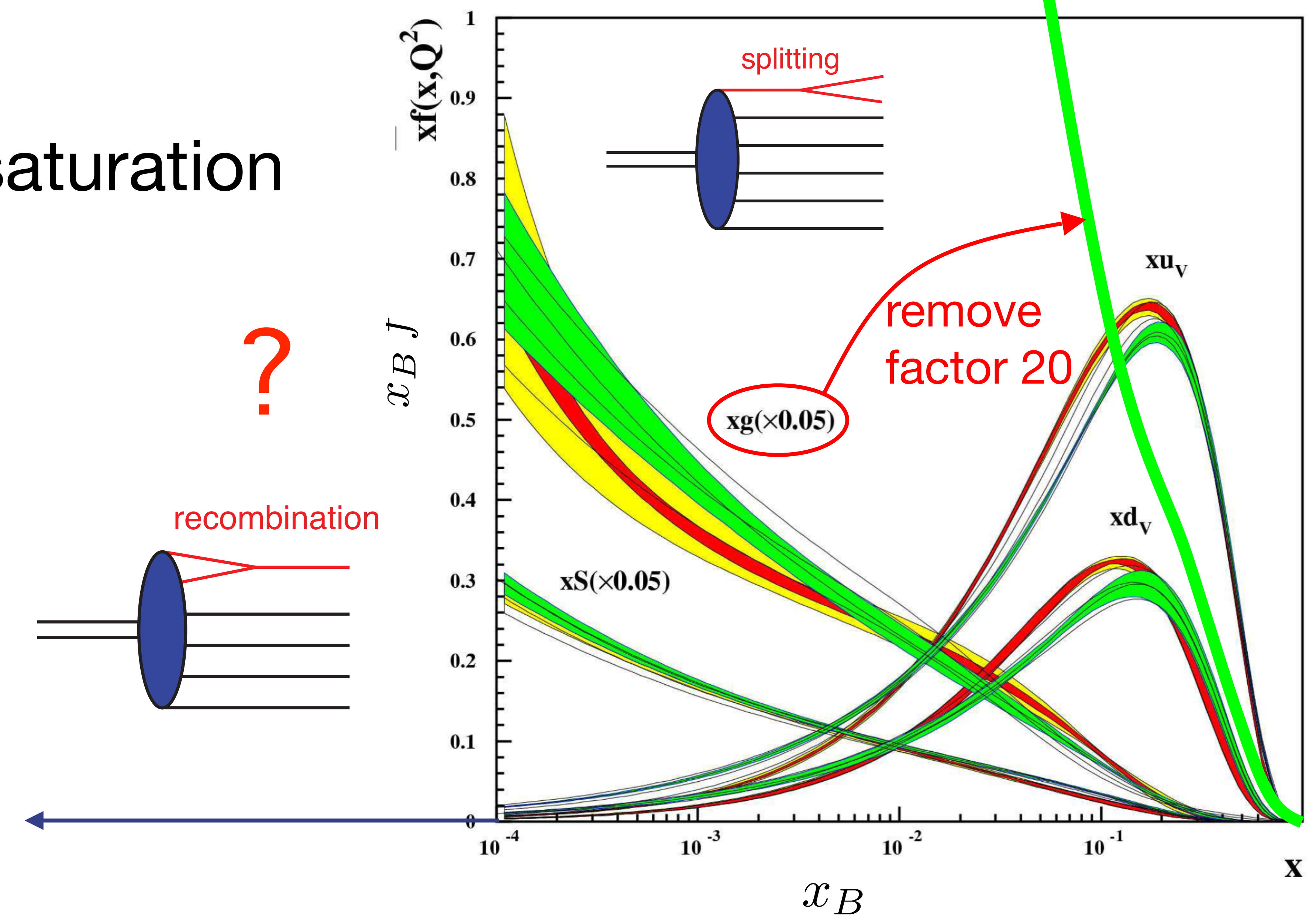
test saturation

?



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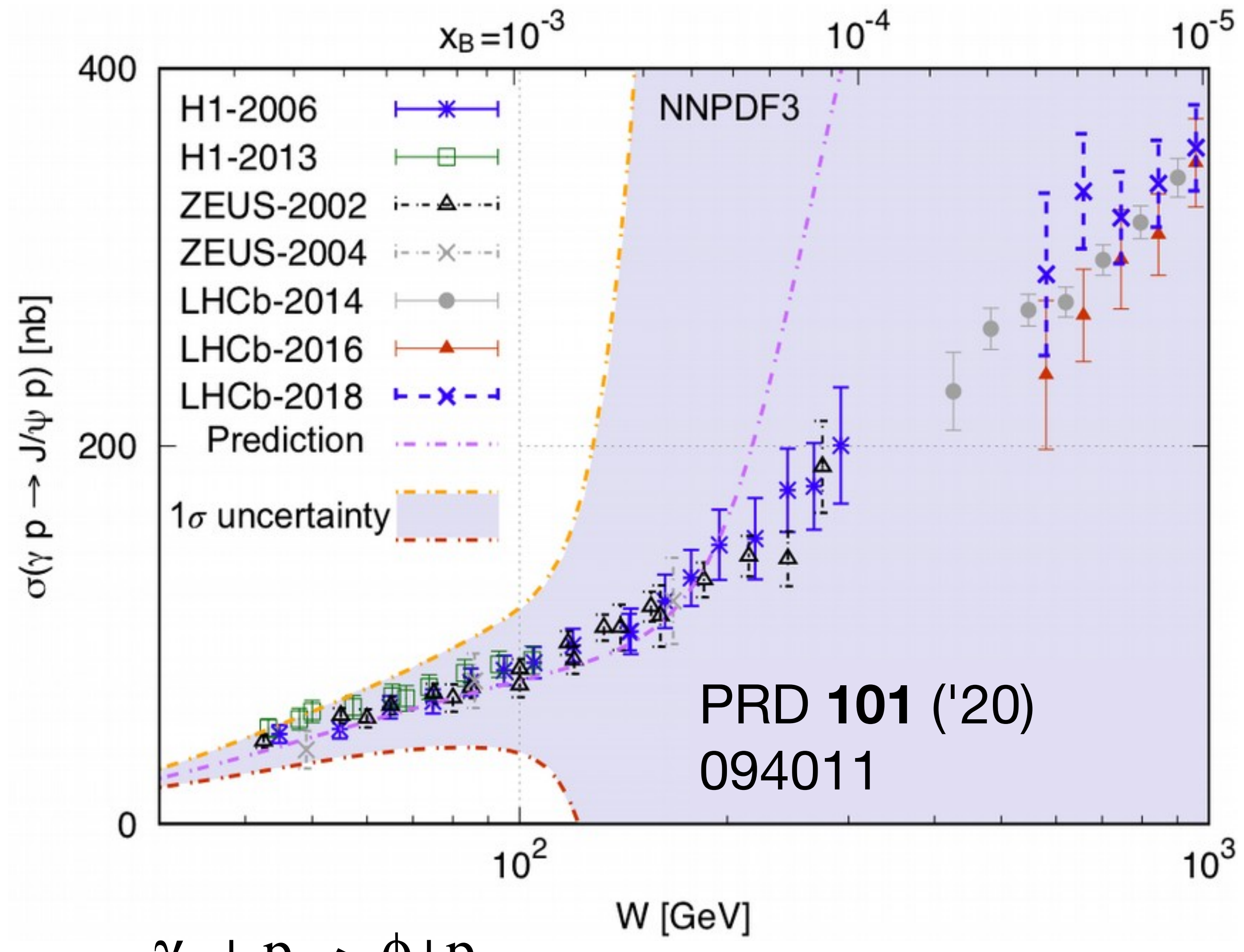
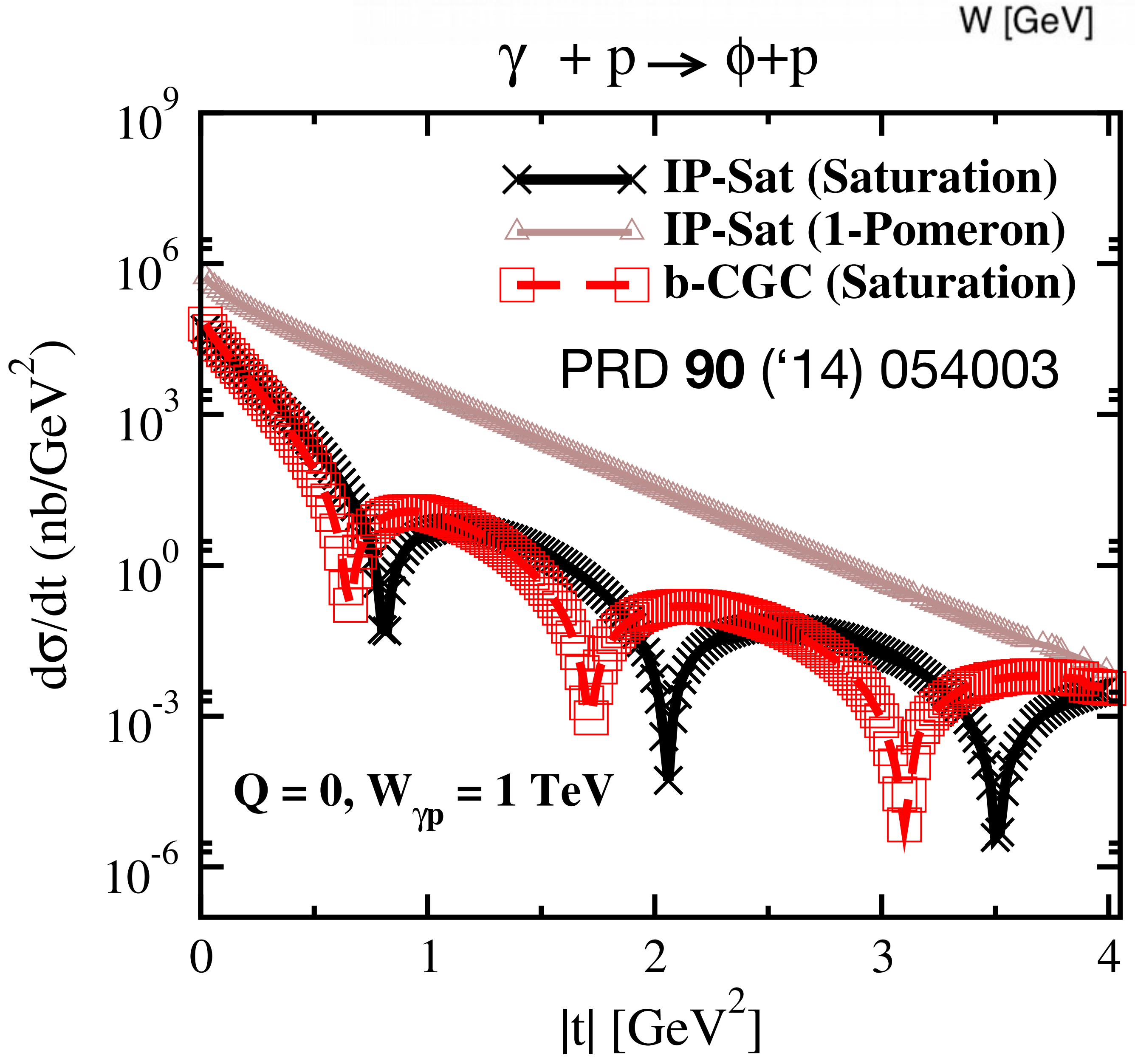
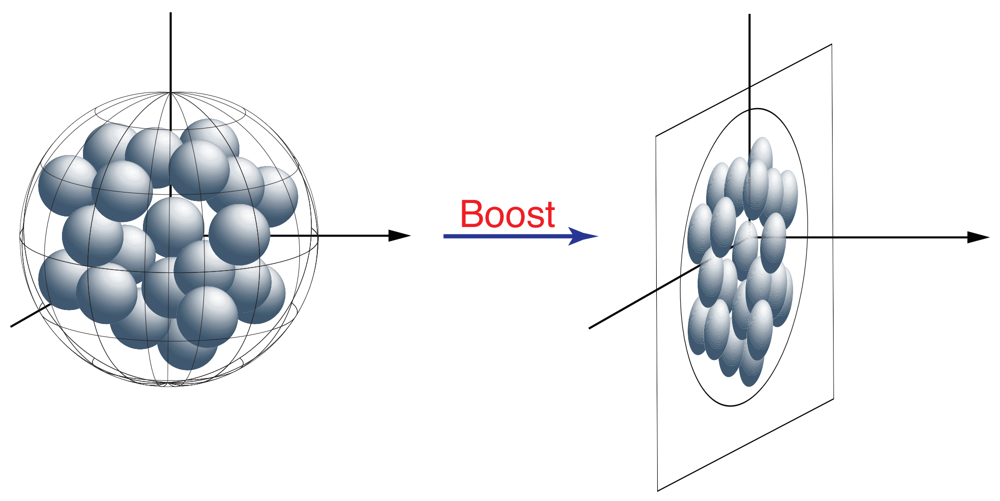
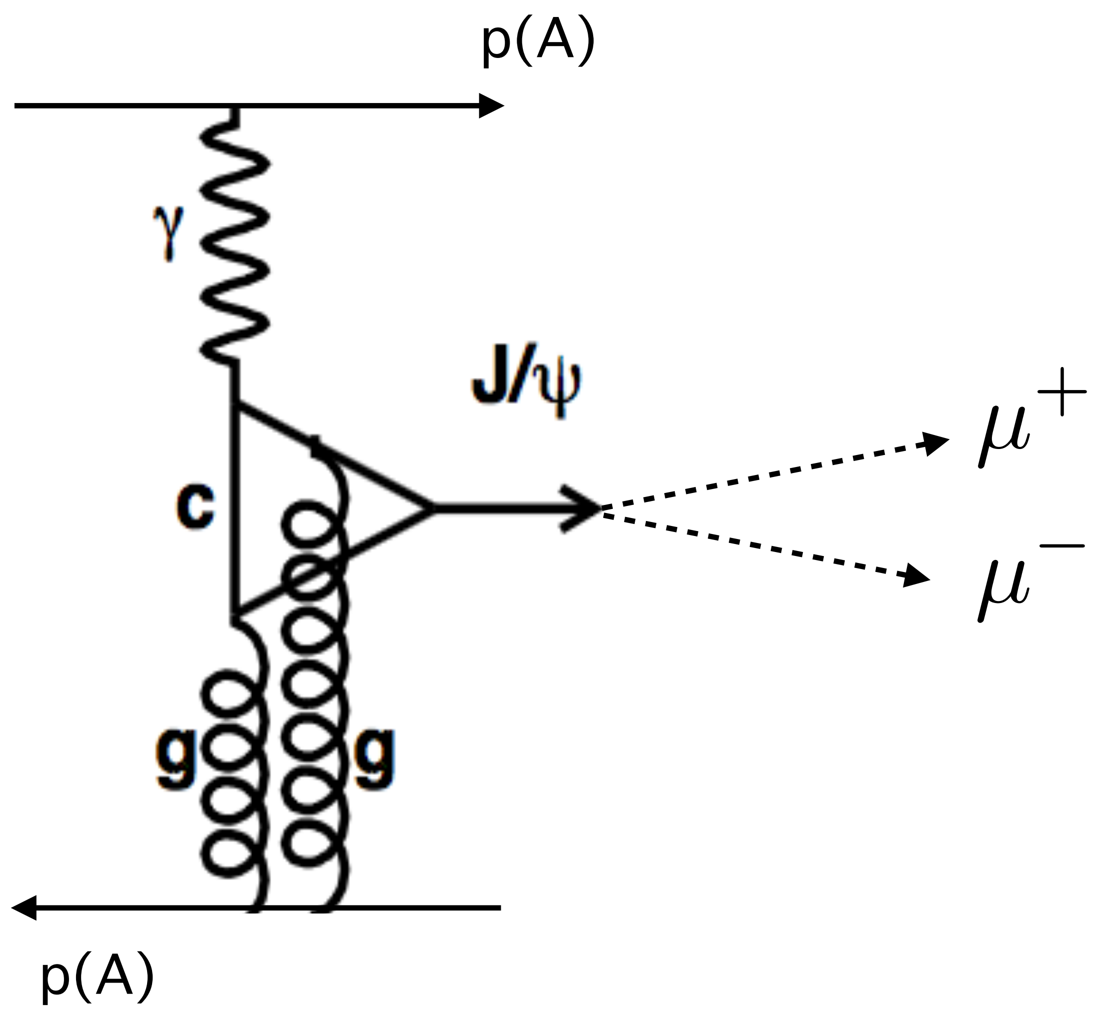






$A^{1/3}$ enhancement of saturation effect

Central exclusive production



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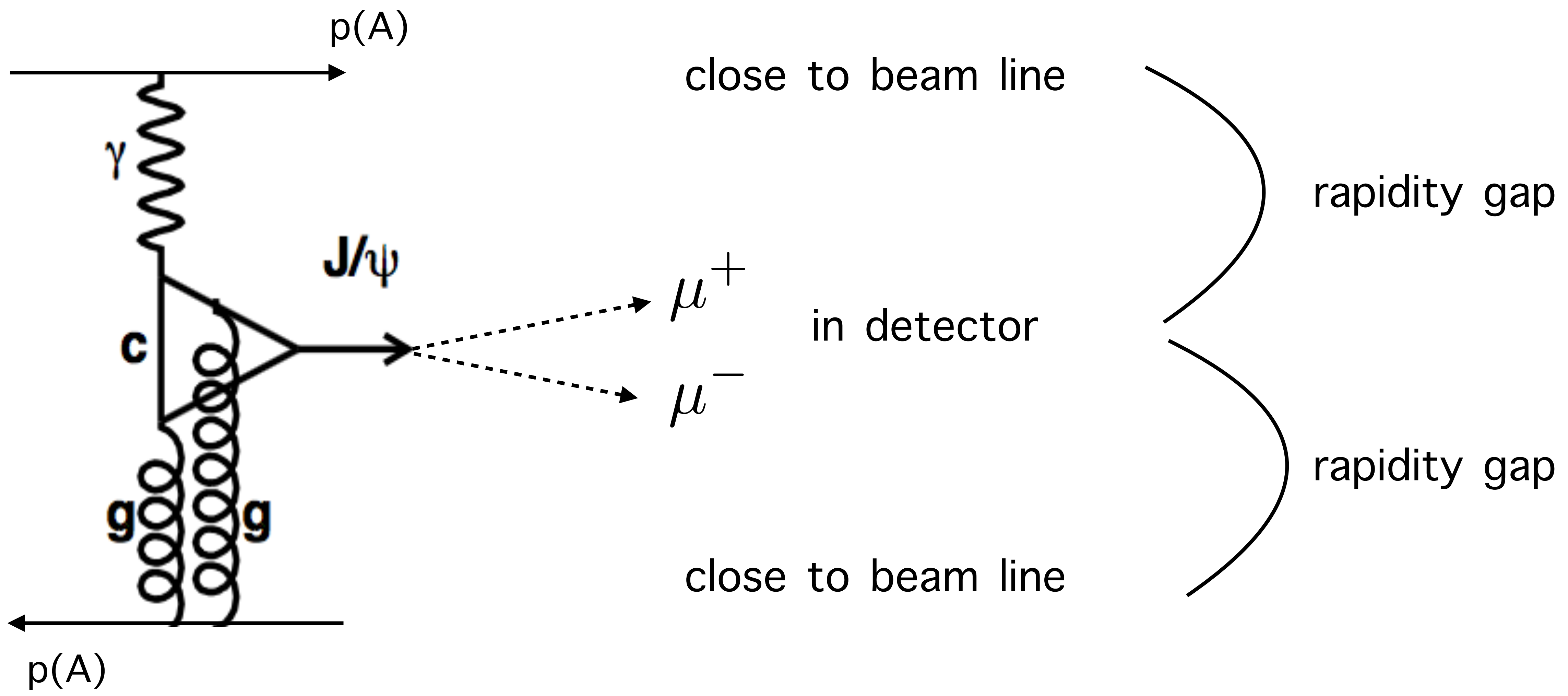

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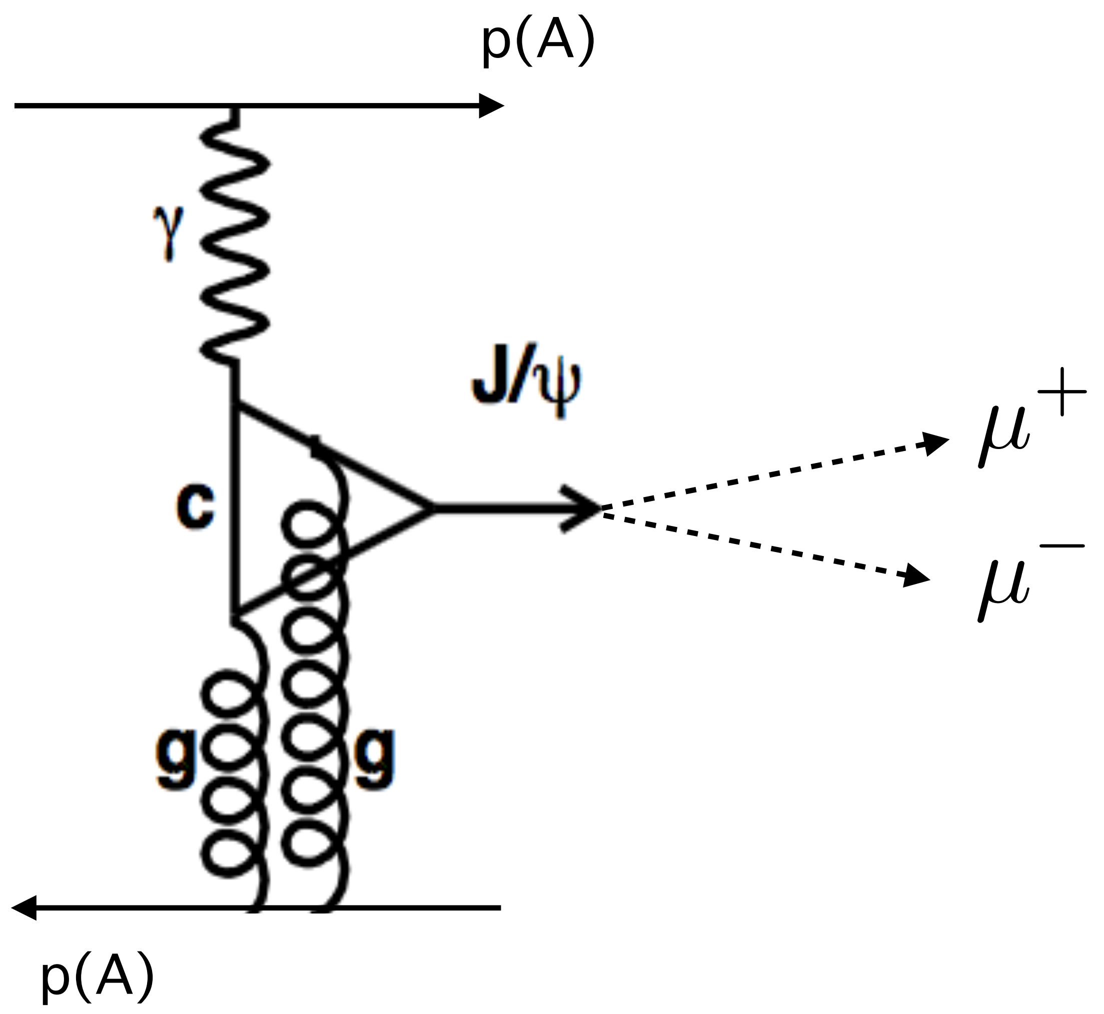
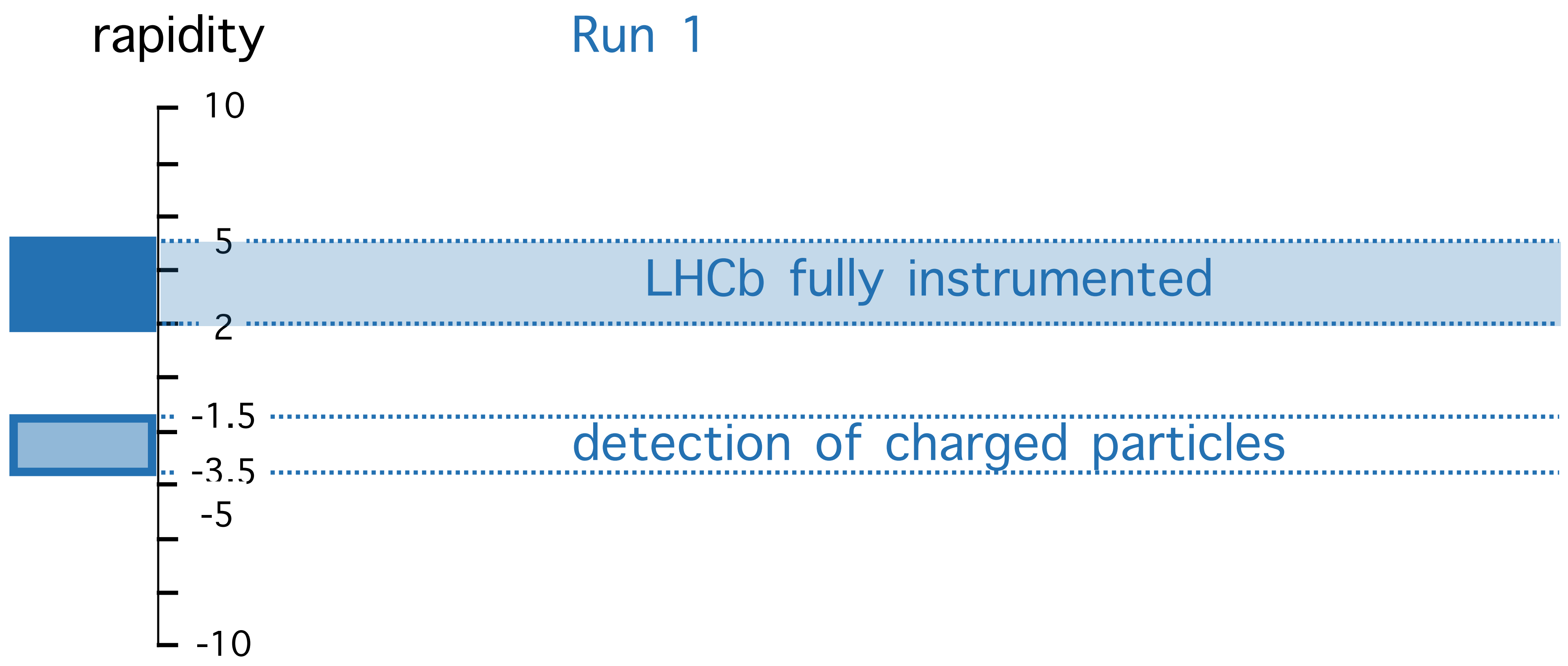
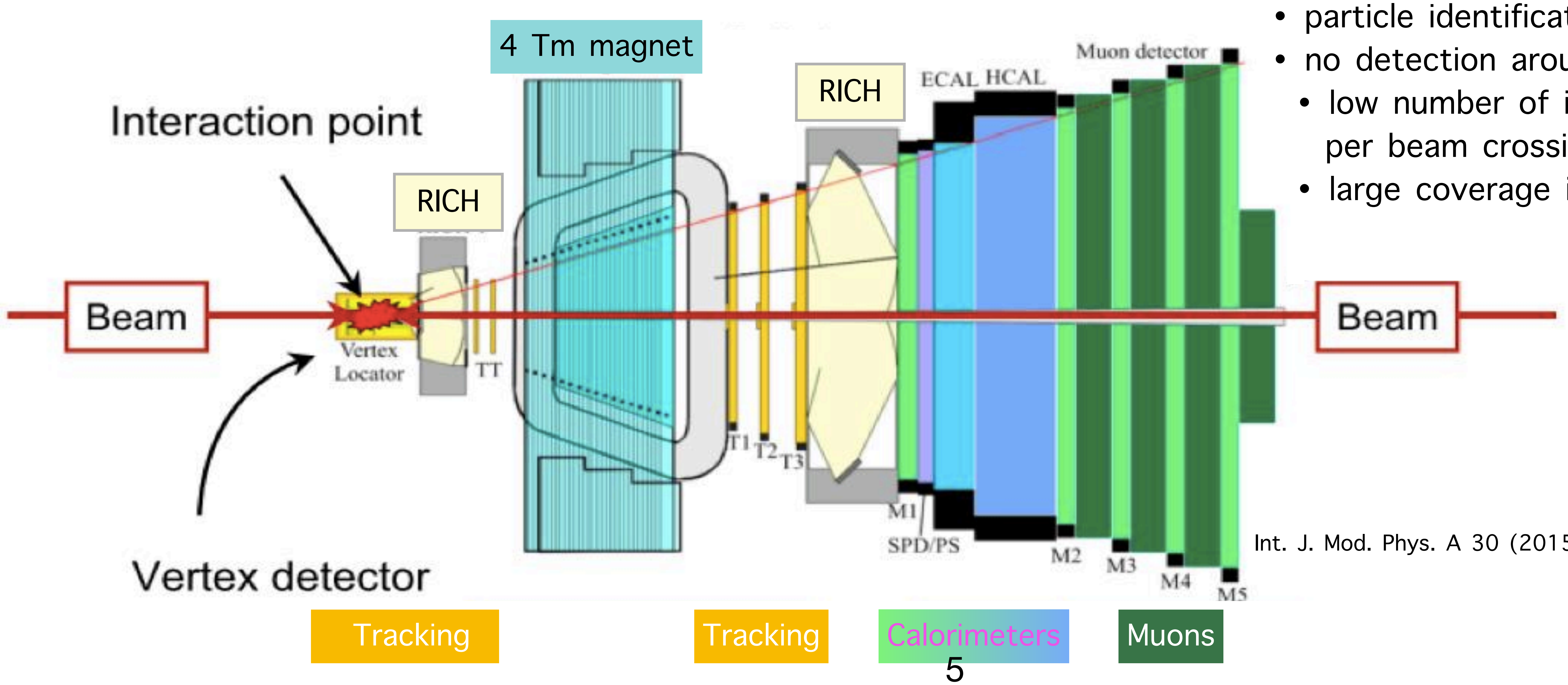




- low p_T threshold: p_T>400 MeV
- particle identification
- no detection around beam line but
  - low number of interactions per beam crossing: 1.1–1.5
  - large coverage in rapidity



Int. J. Mod. Phys. A 30 (2015) 1530022

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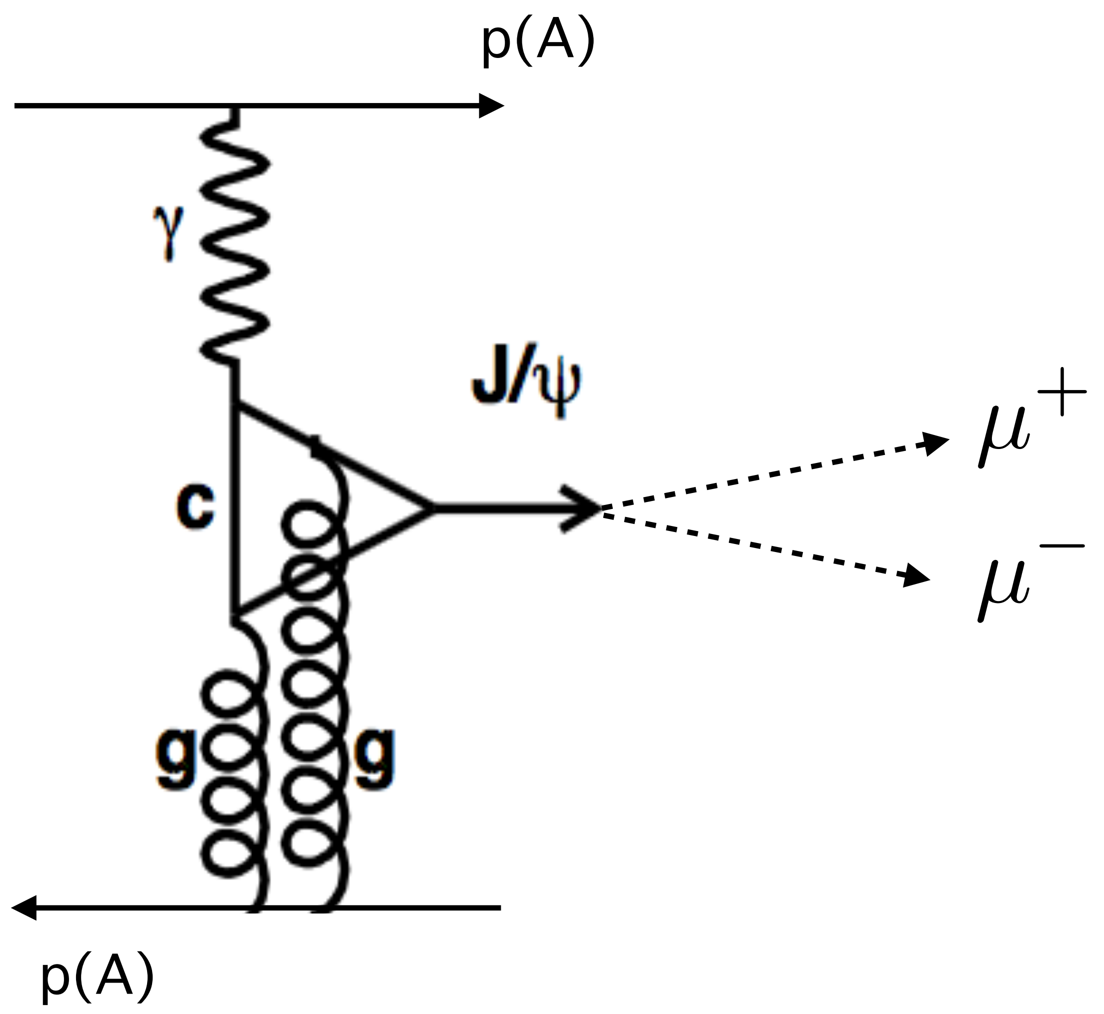

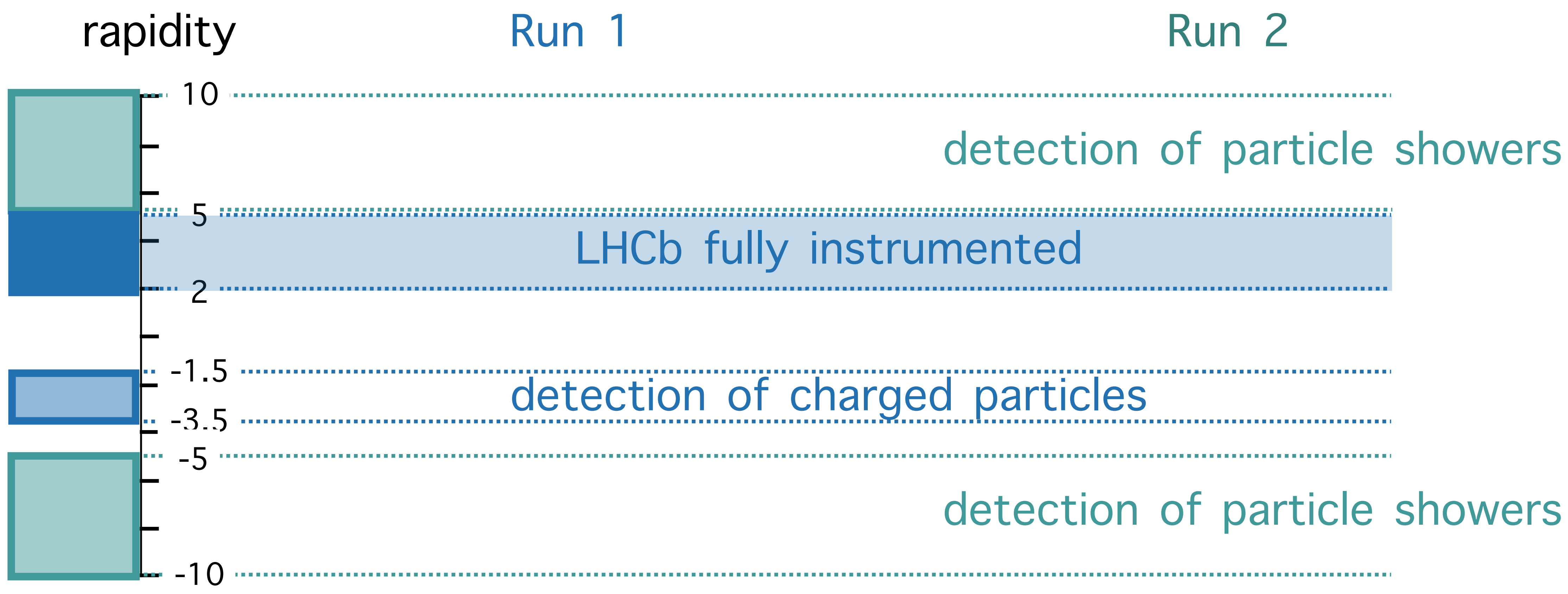

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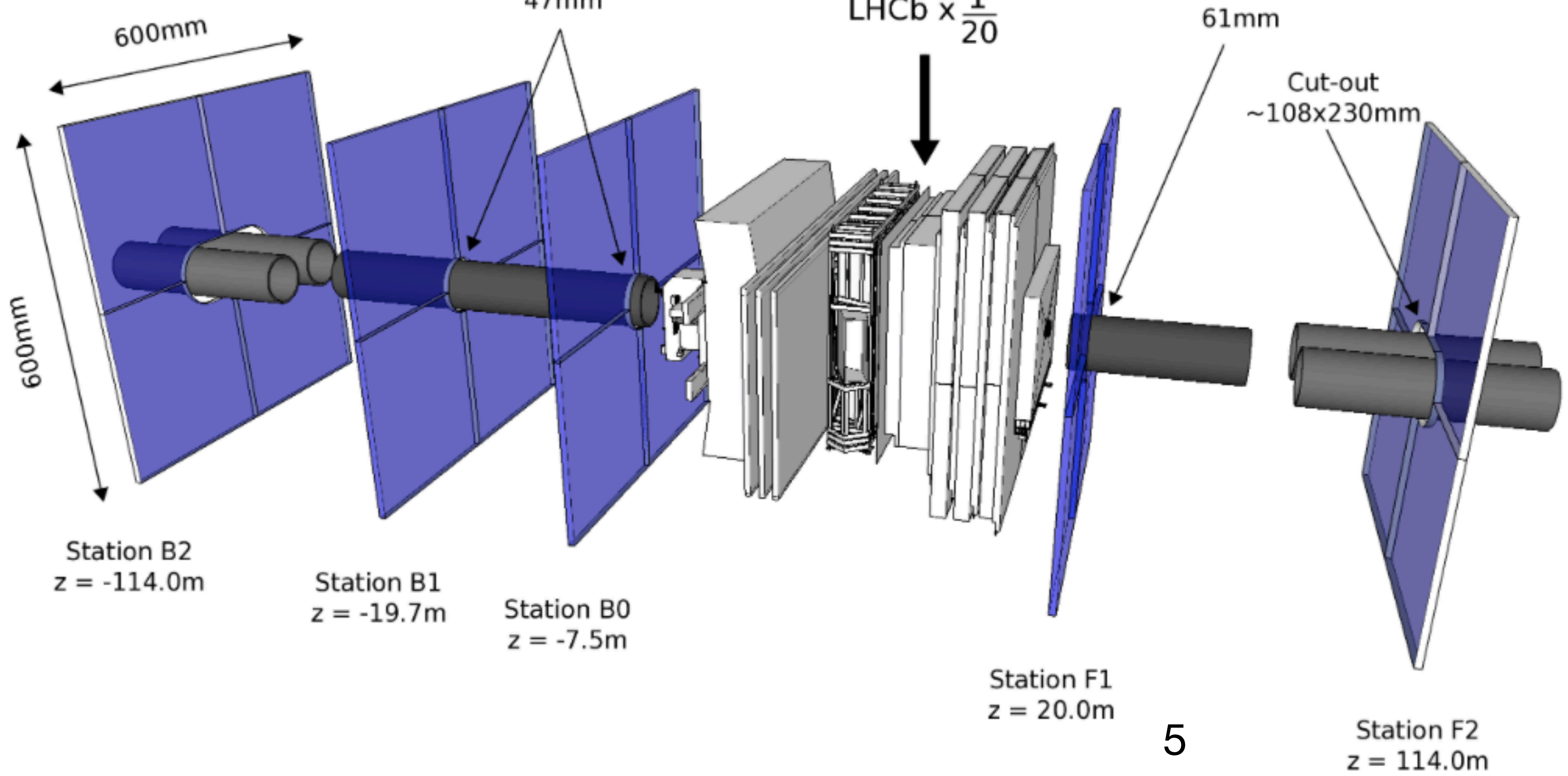
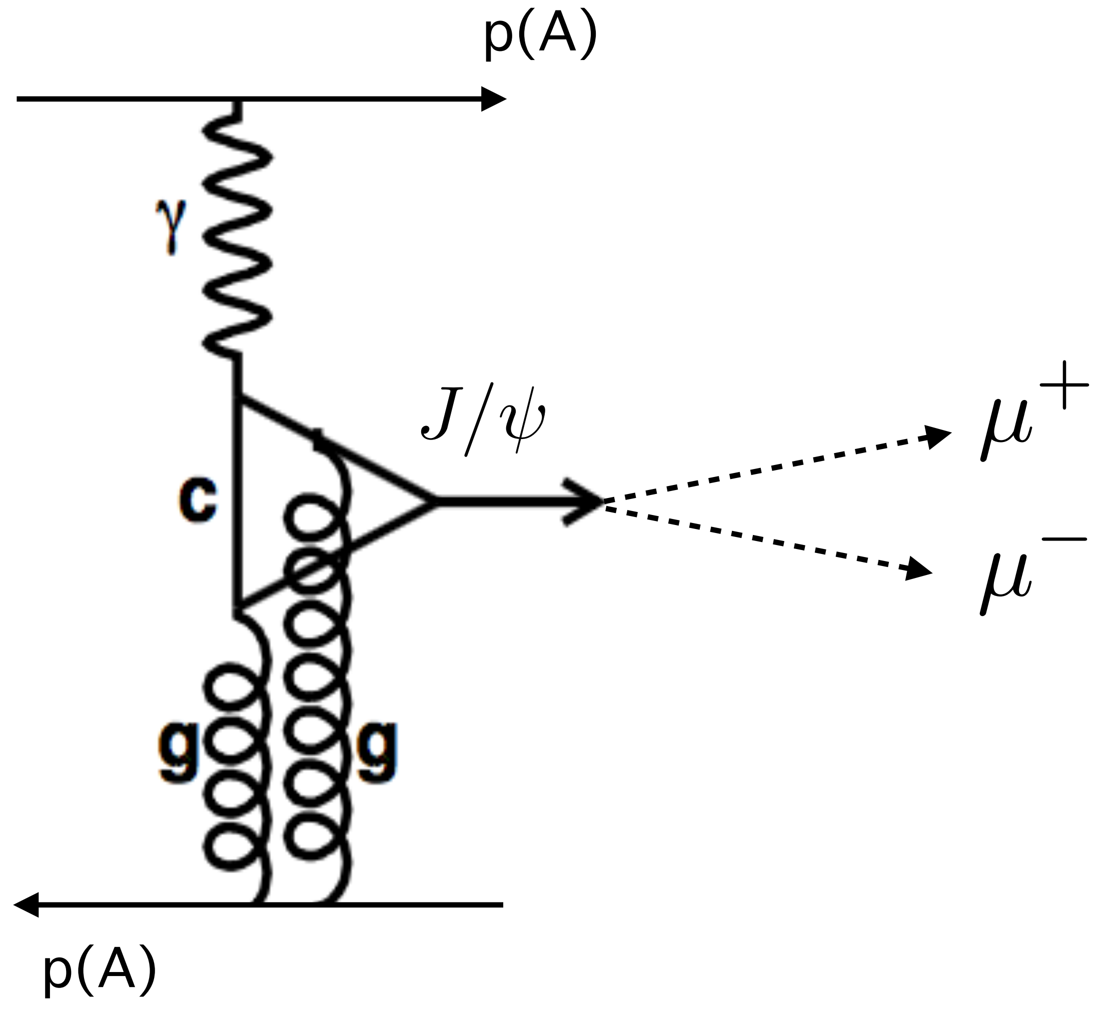


Central exclusive quarkonium production and its backgrounds



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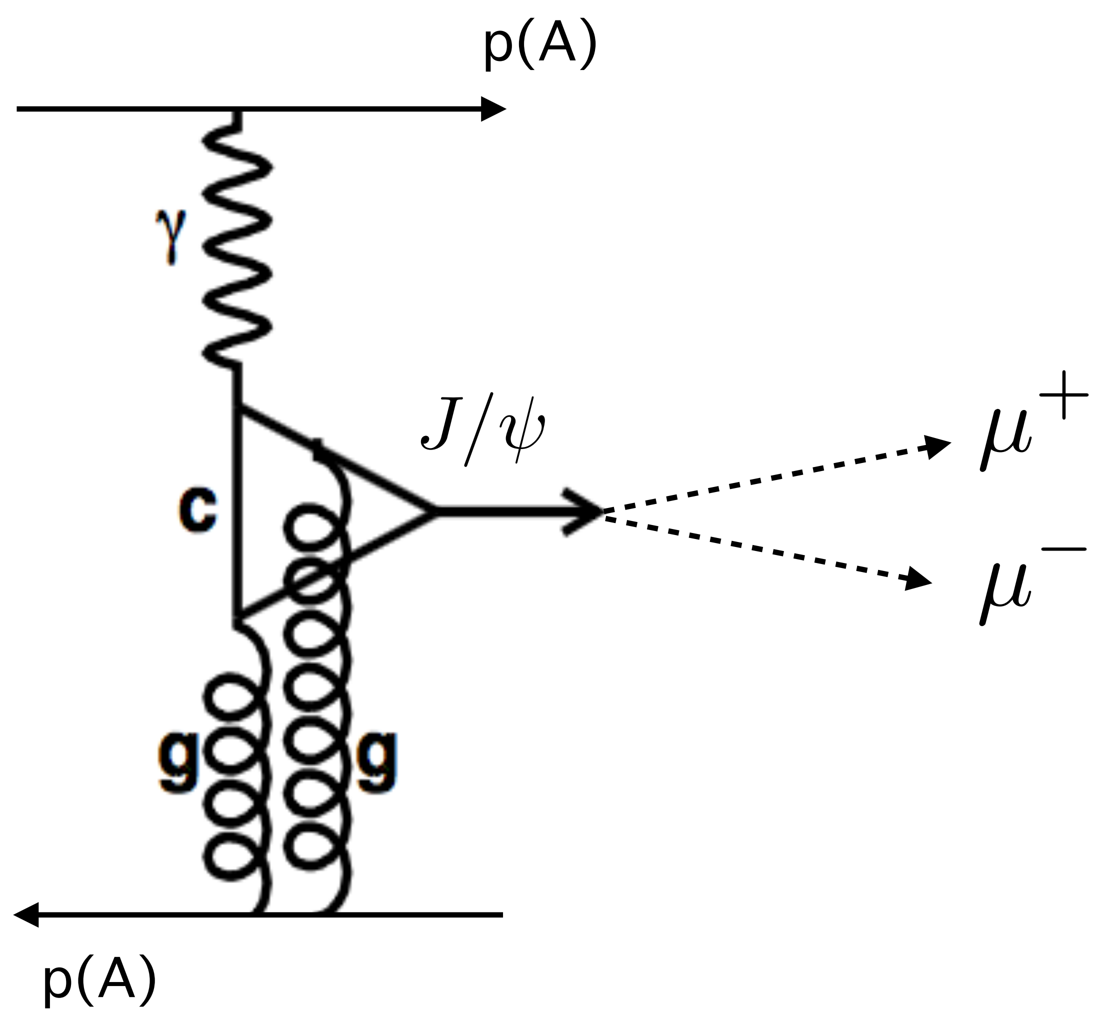

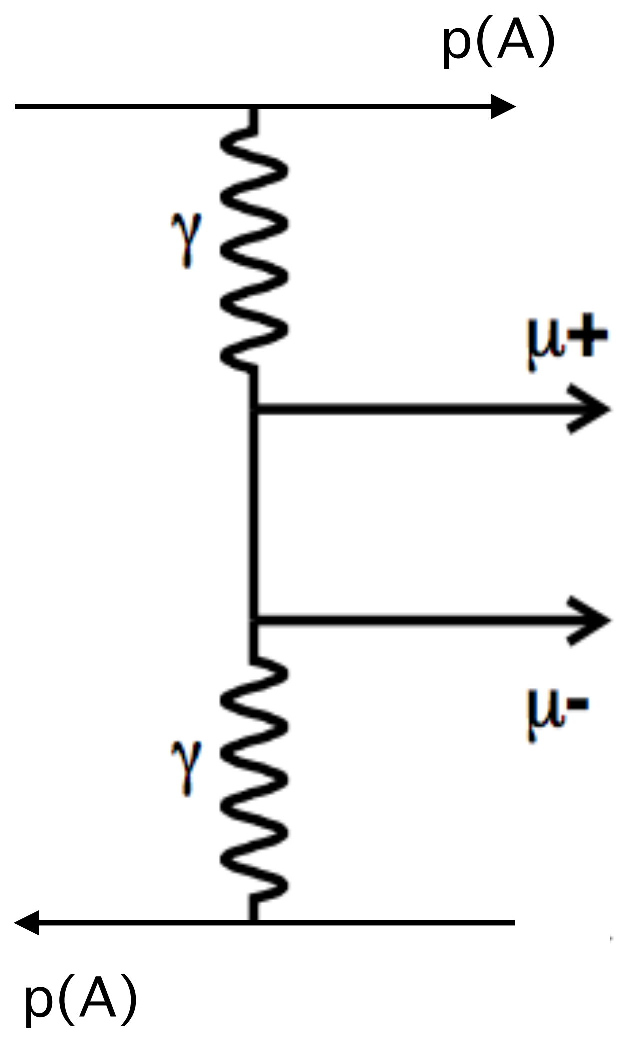

Bethe-Heitler process

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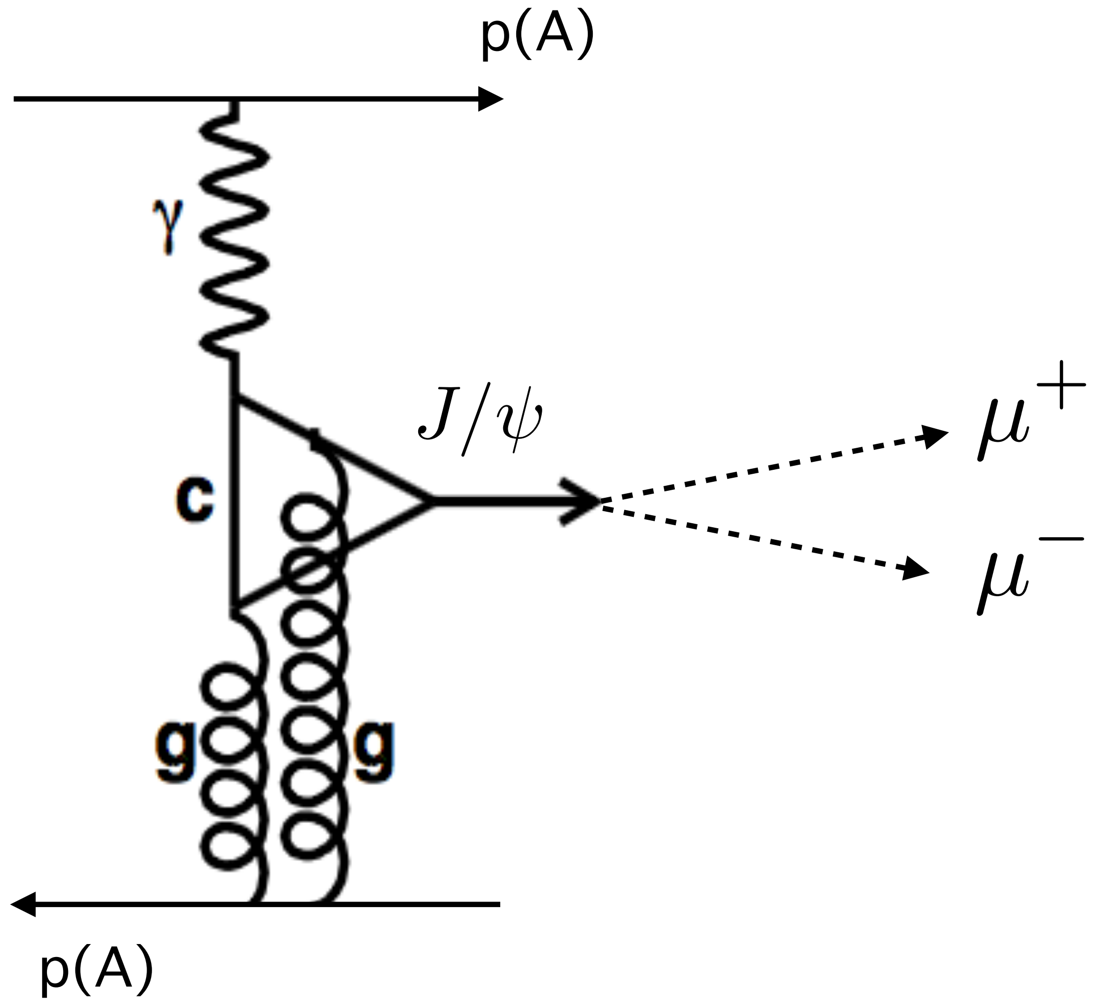

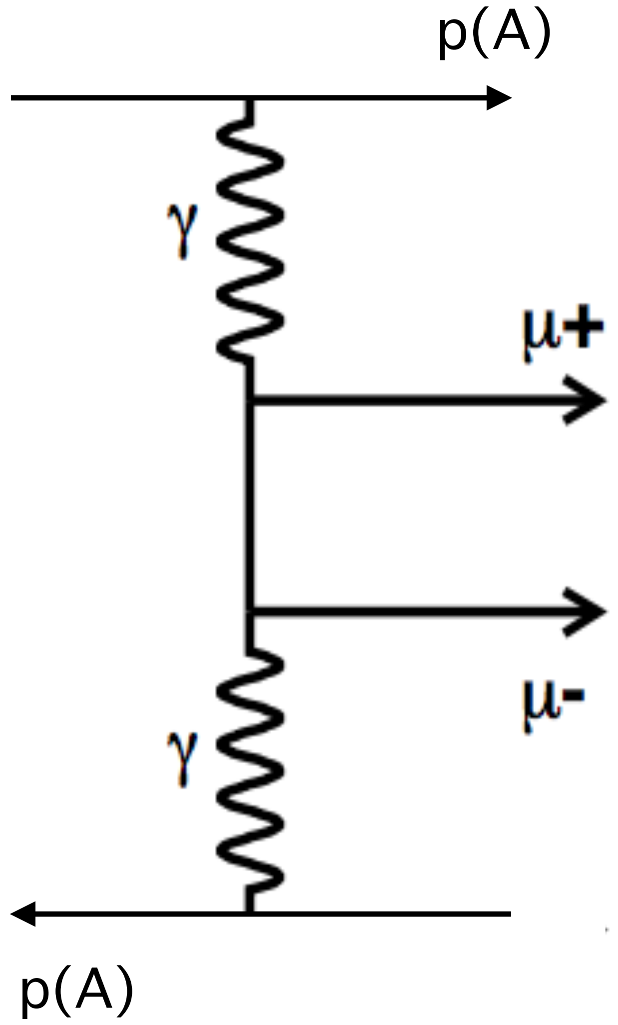

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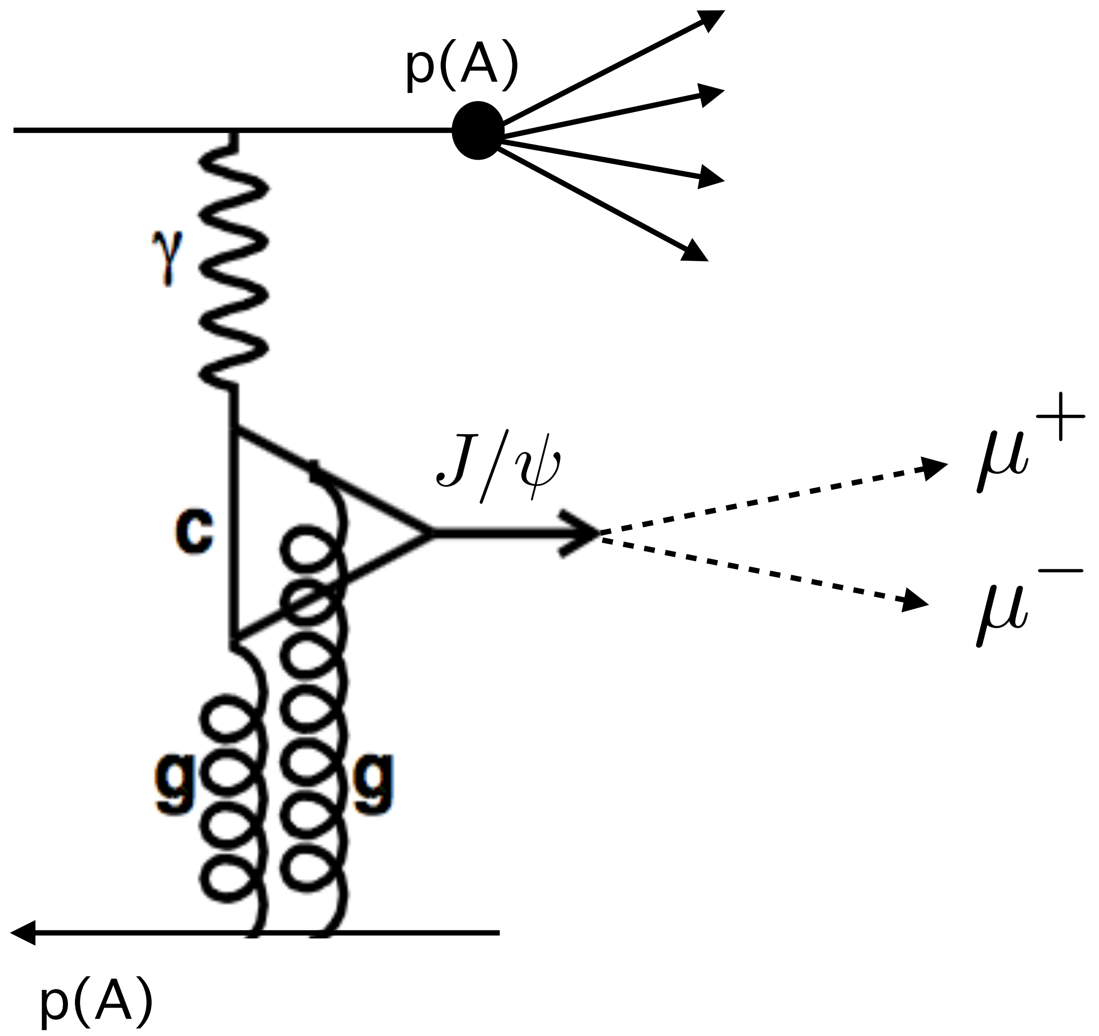

proton/ion dissociation

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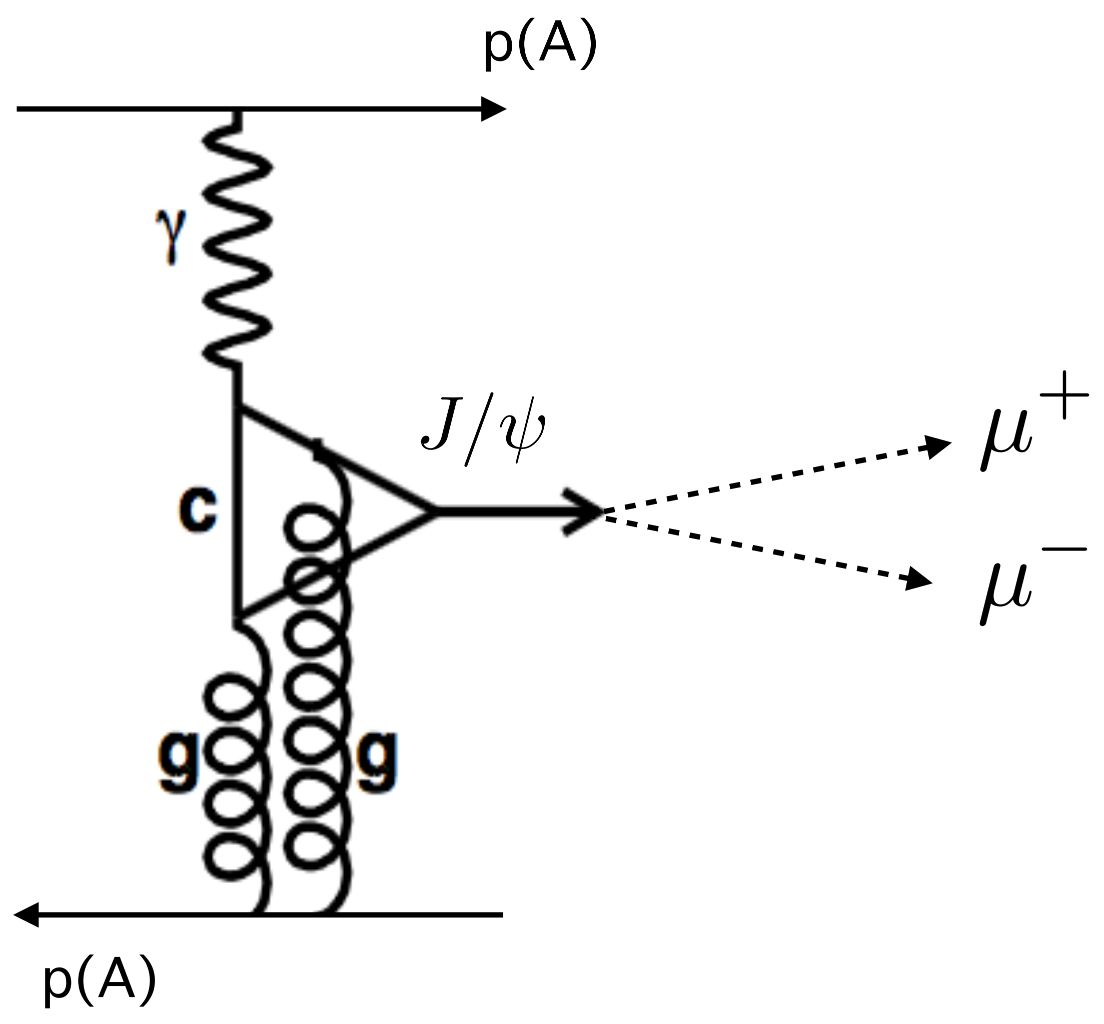

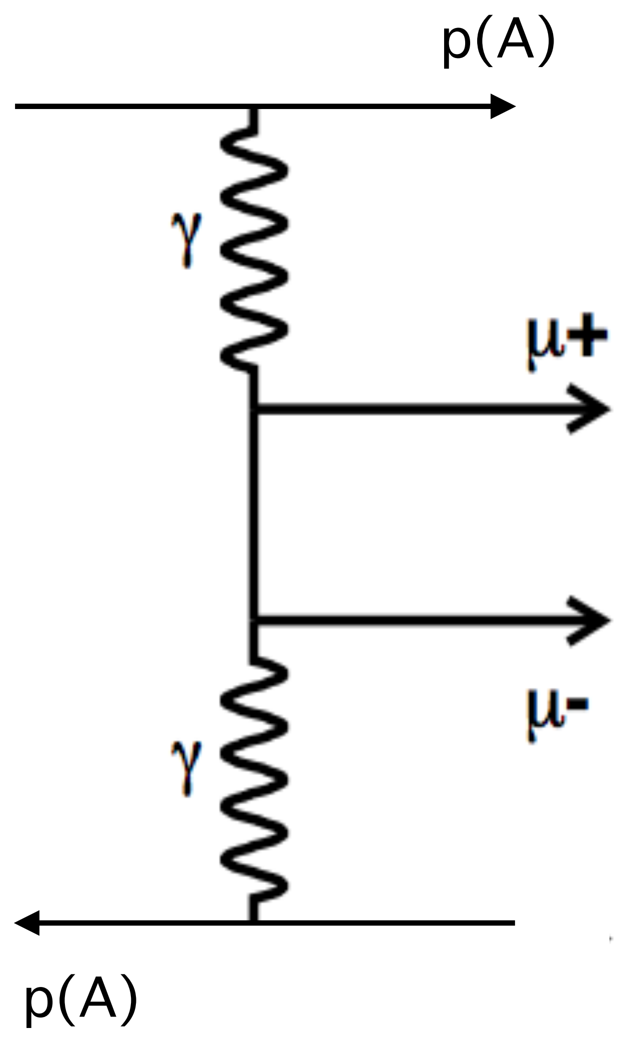

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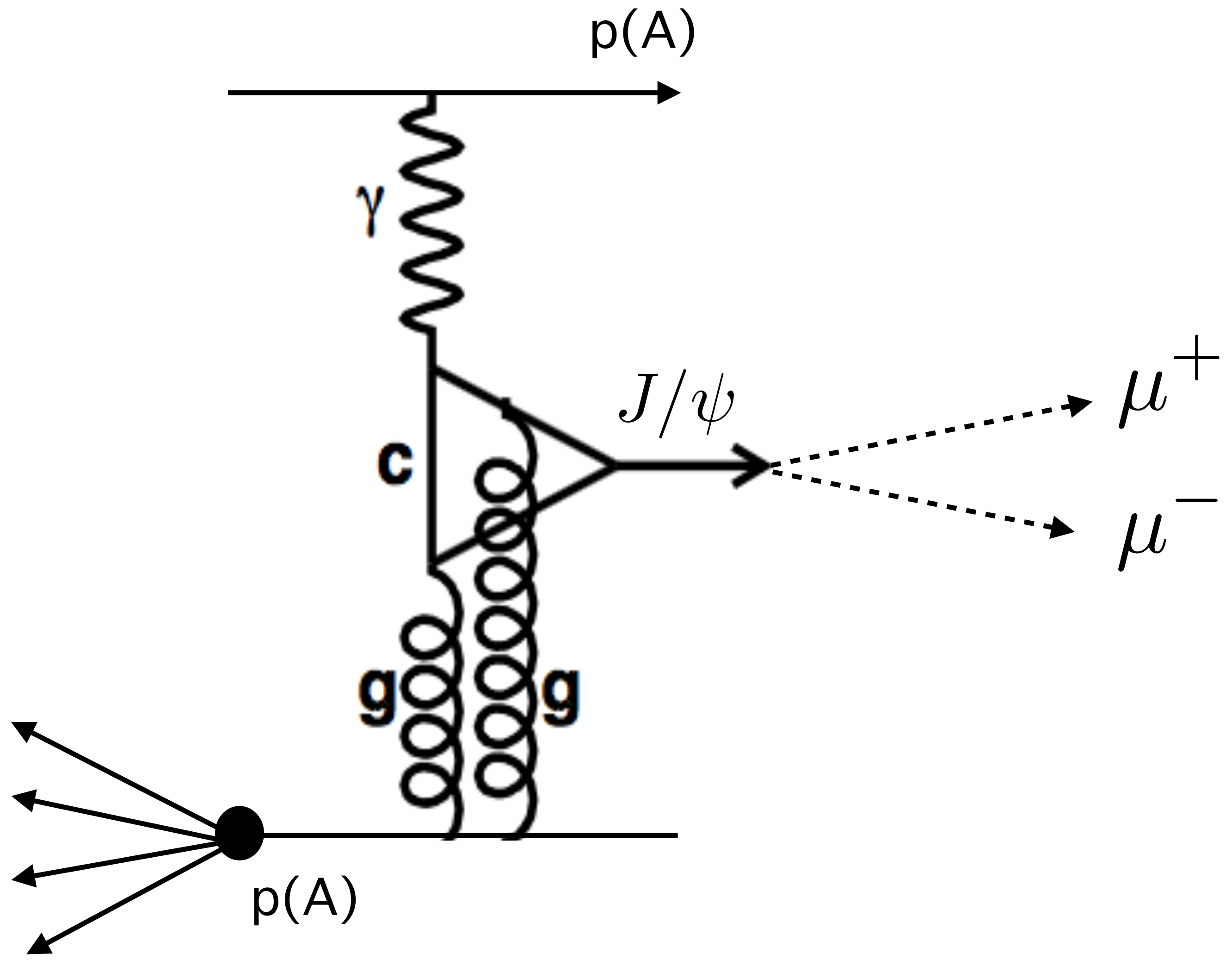

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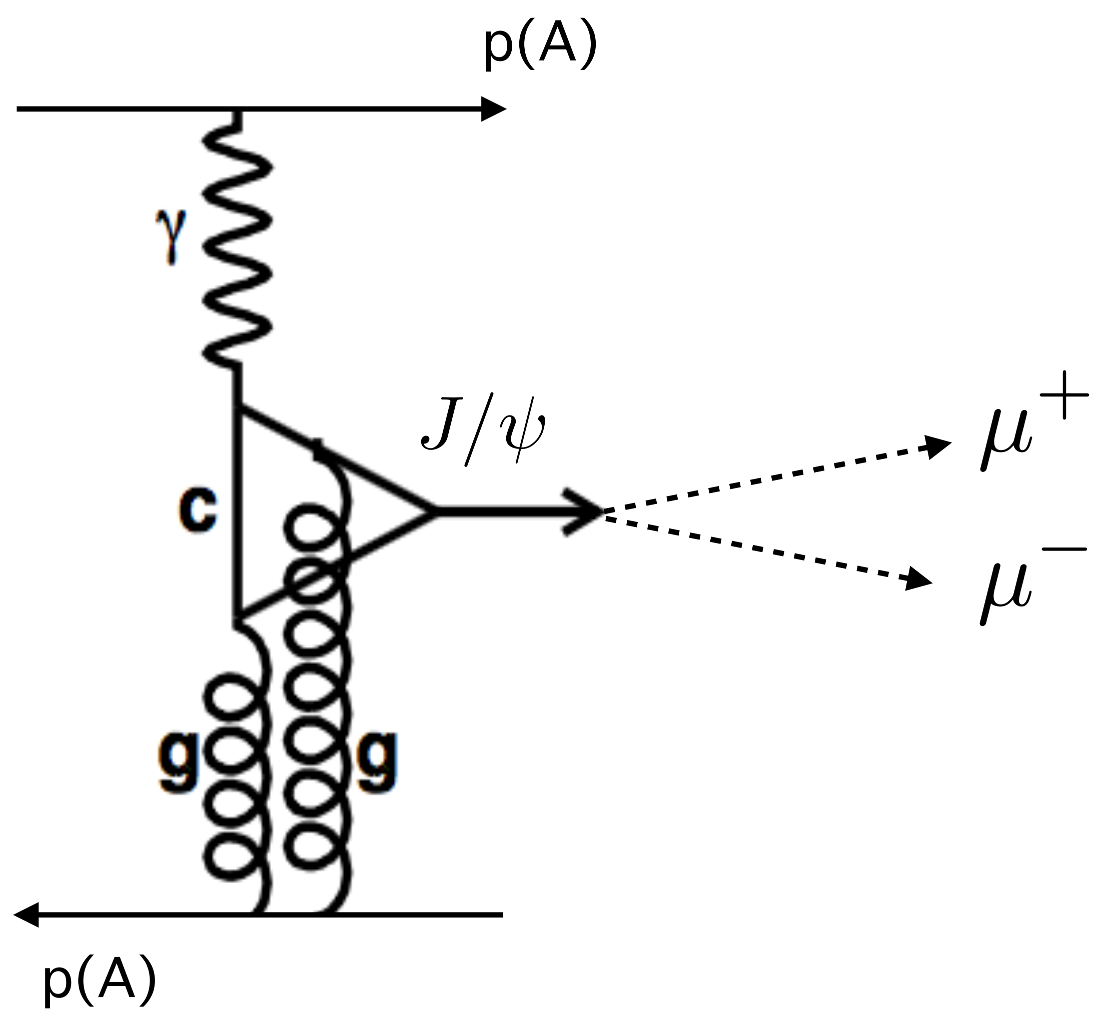

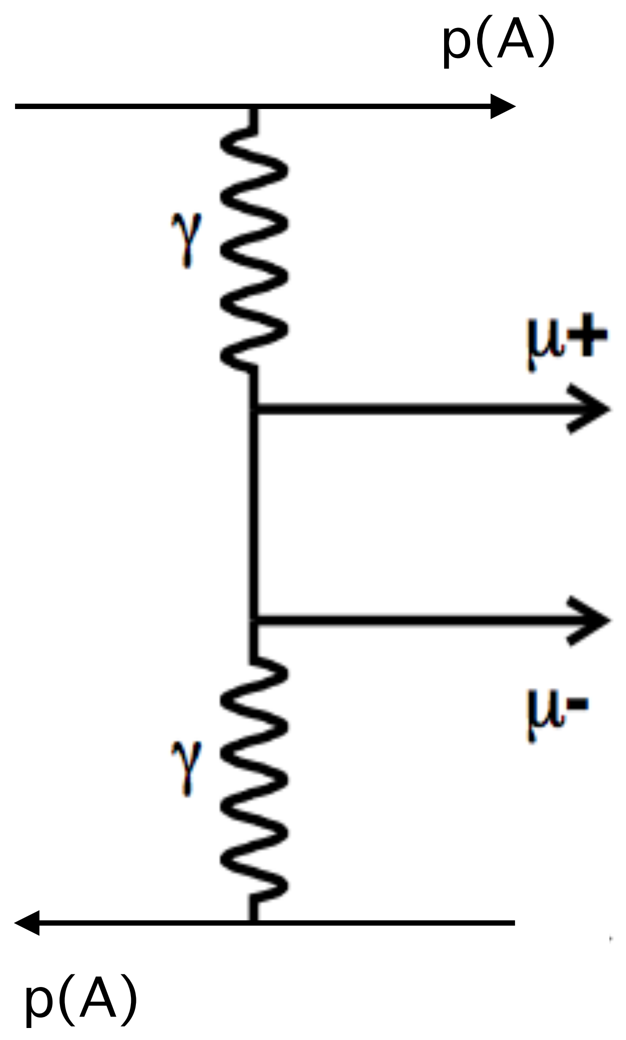

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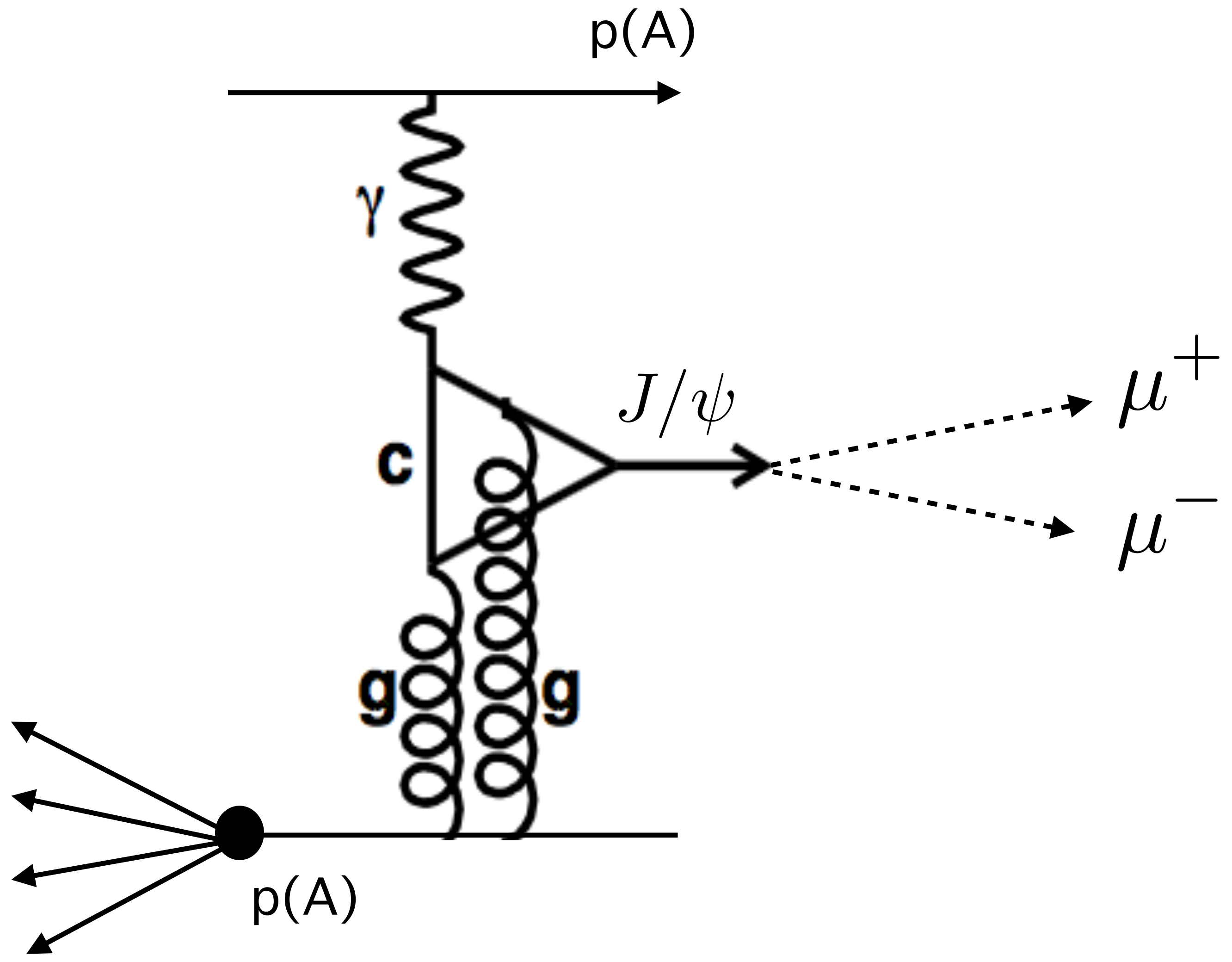

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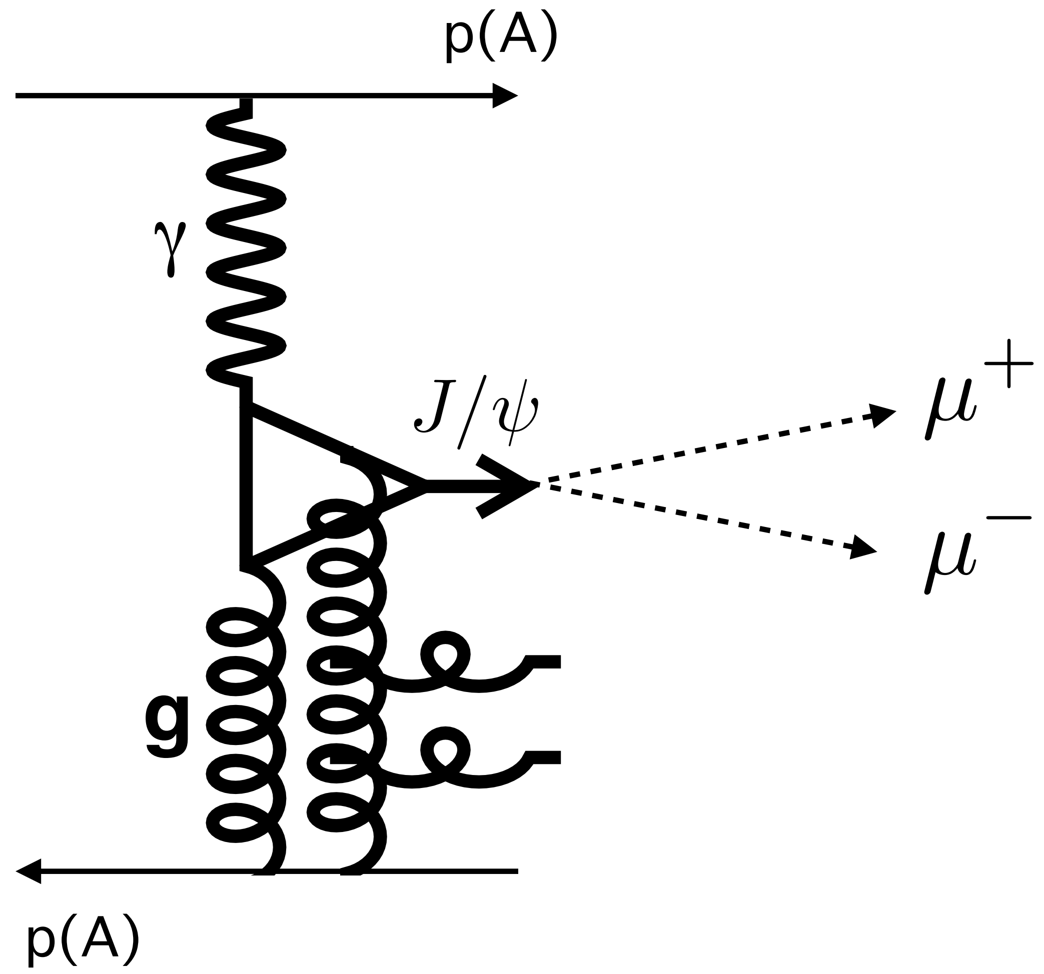
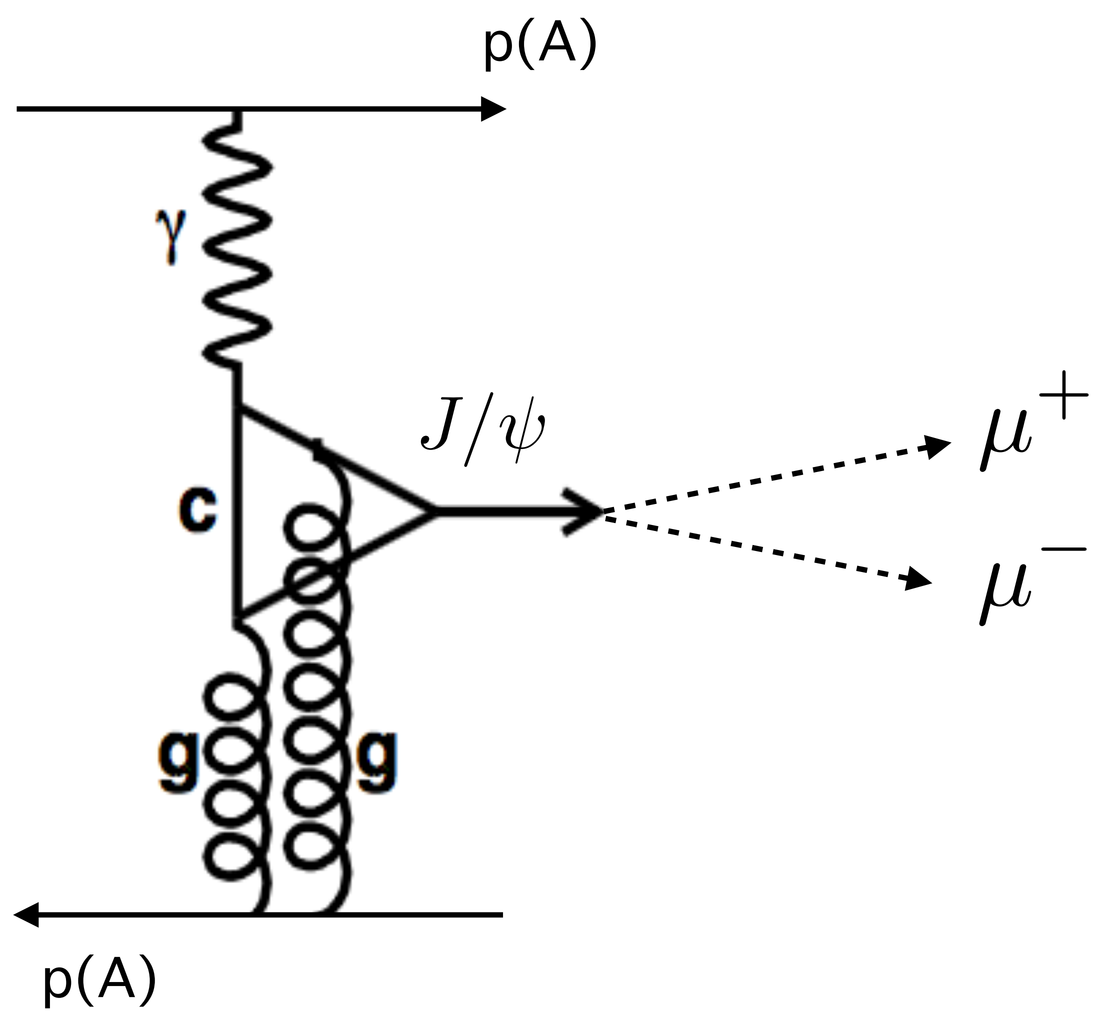
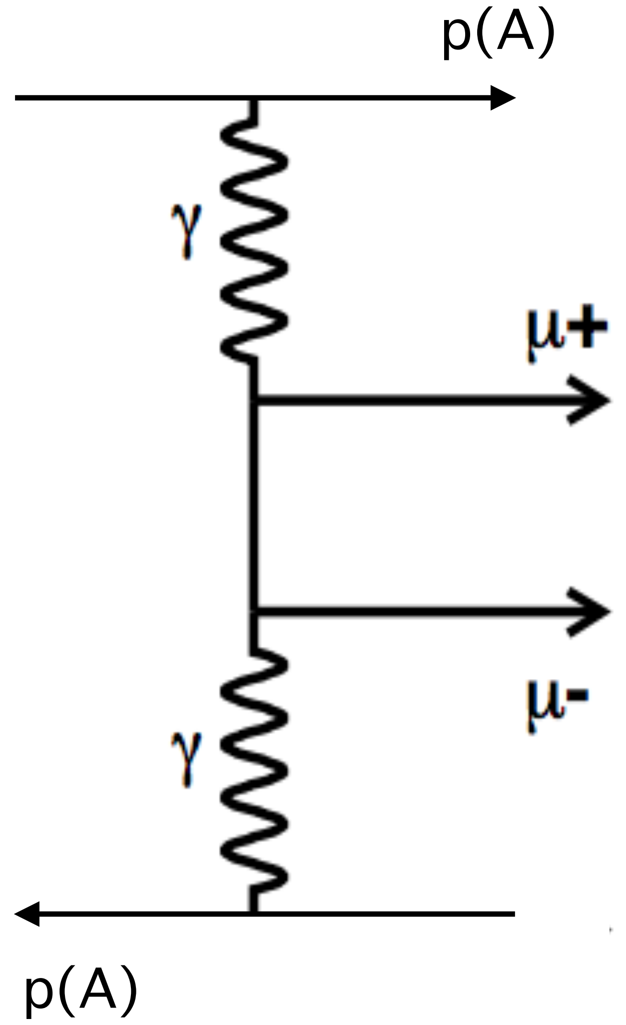


inelastic production

Central exclusive quarkonium production and its backgrounds





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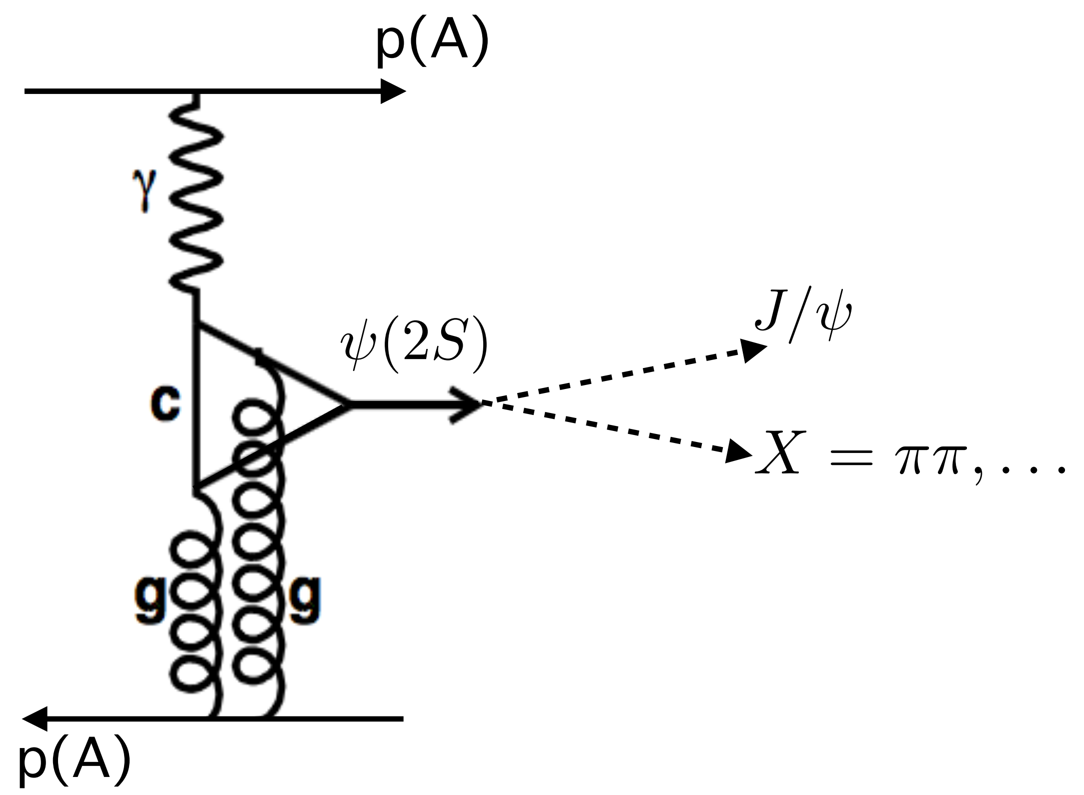
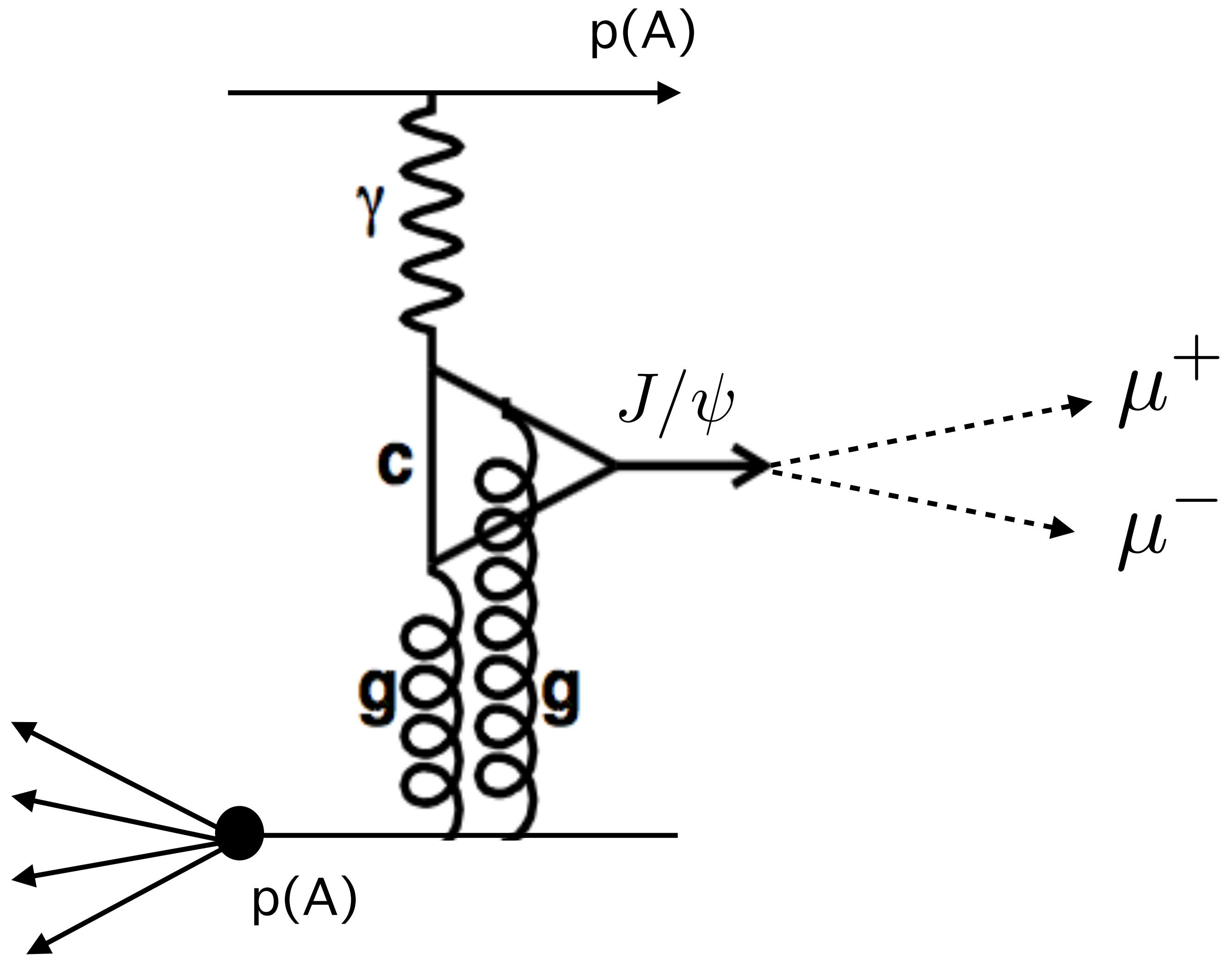


feed down



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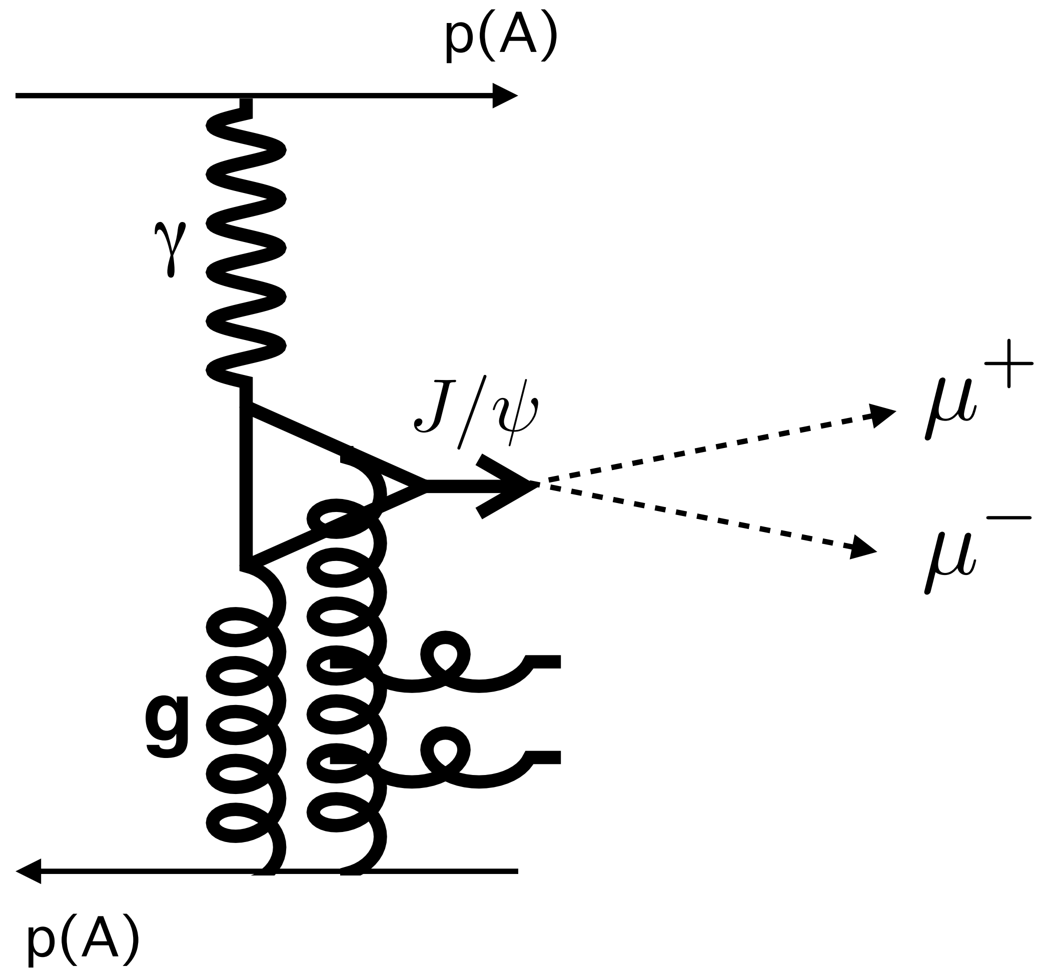

inelastic production

Exclusive single-quarkonium production in pp

- Exclusive J/ψ and ψ(2S): $\sqrt{s} = 7$ TeV and part of $\sqrt{s} = 13$ TeV data (from 2015) → x_B down to 2×10^{-6}
- Exclusive ϒ: $\sqrt{s} = 7$ and 8 TeV data.
- Reconstruction via dimuon decay, with $2<\eta<4.5$.
- Quarkonium: $2<y<4.5$ and $p_T^2<0.8$ GeV^2

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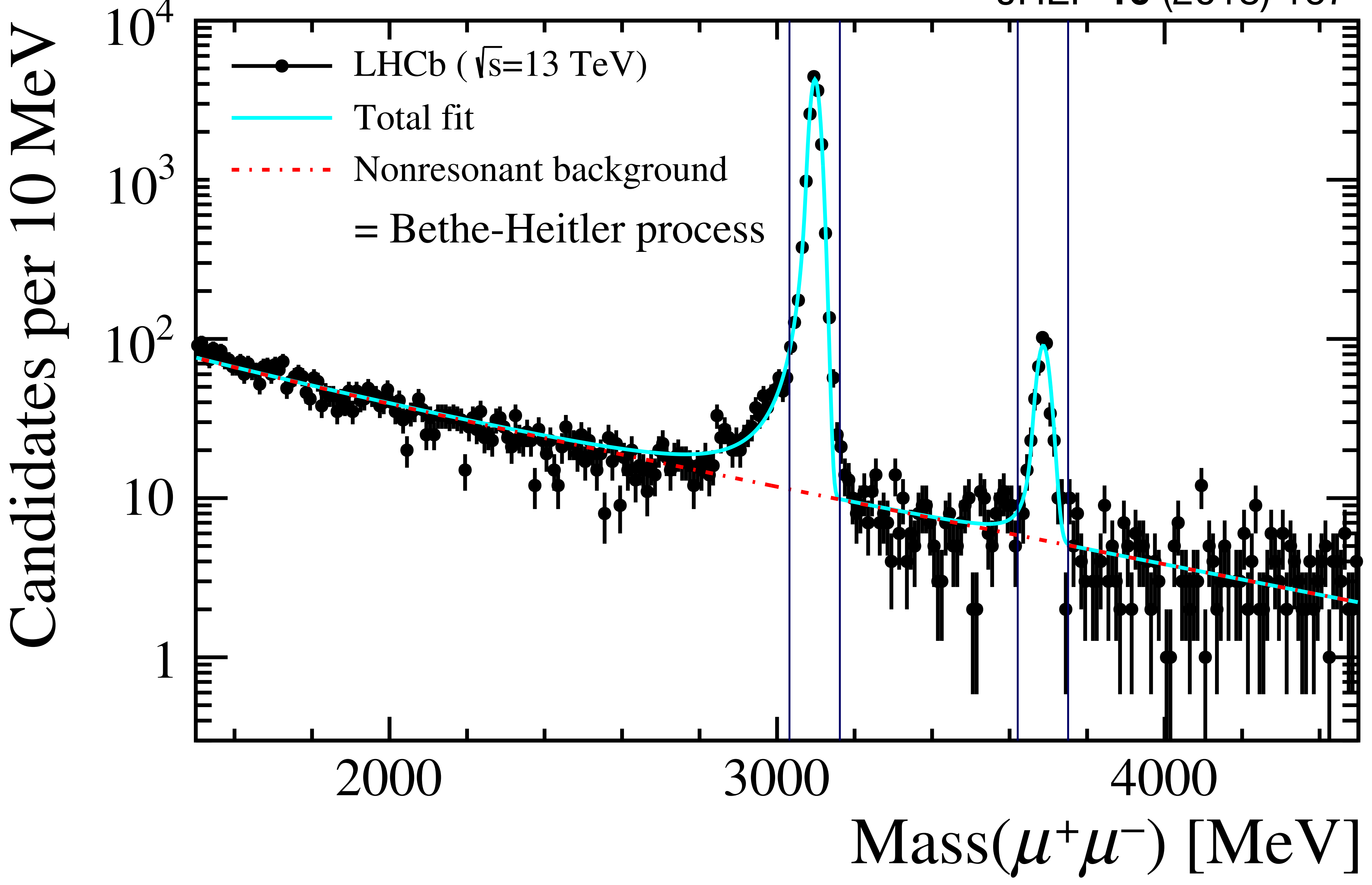
J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002

JHEP **10** (2018) 167



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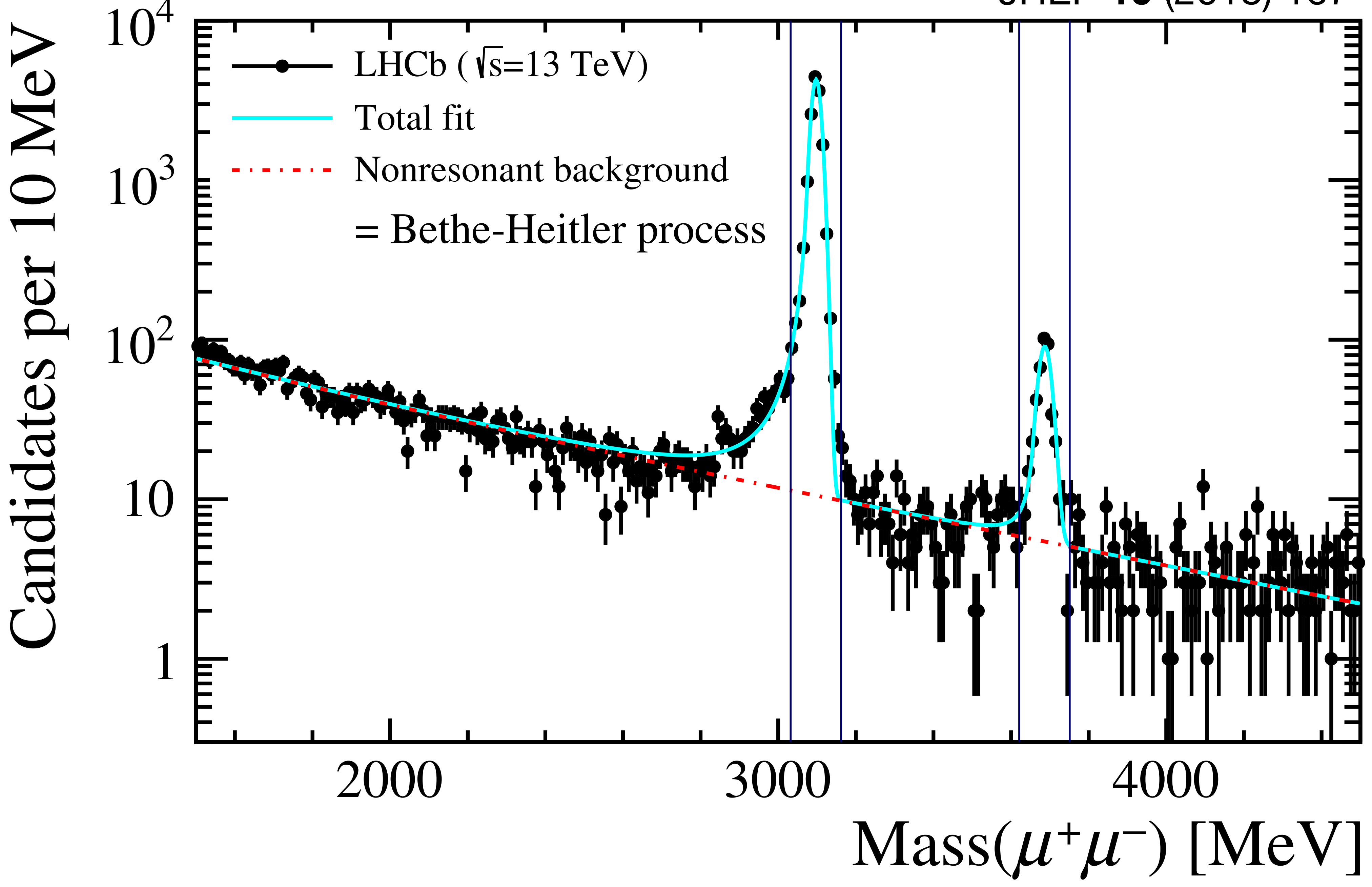
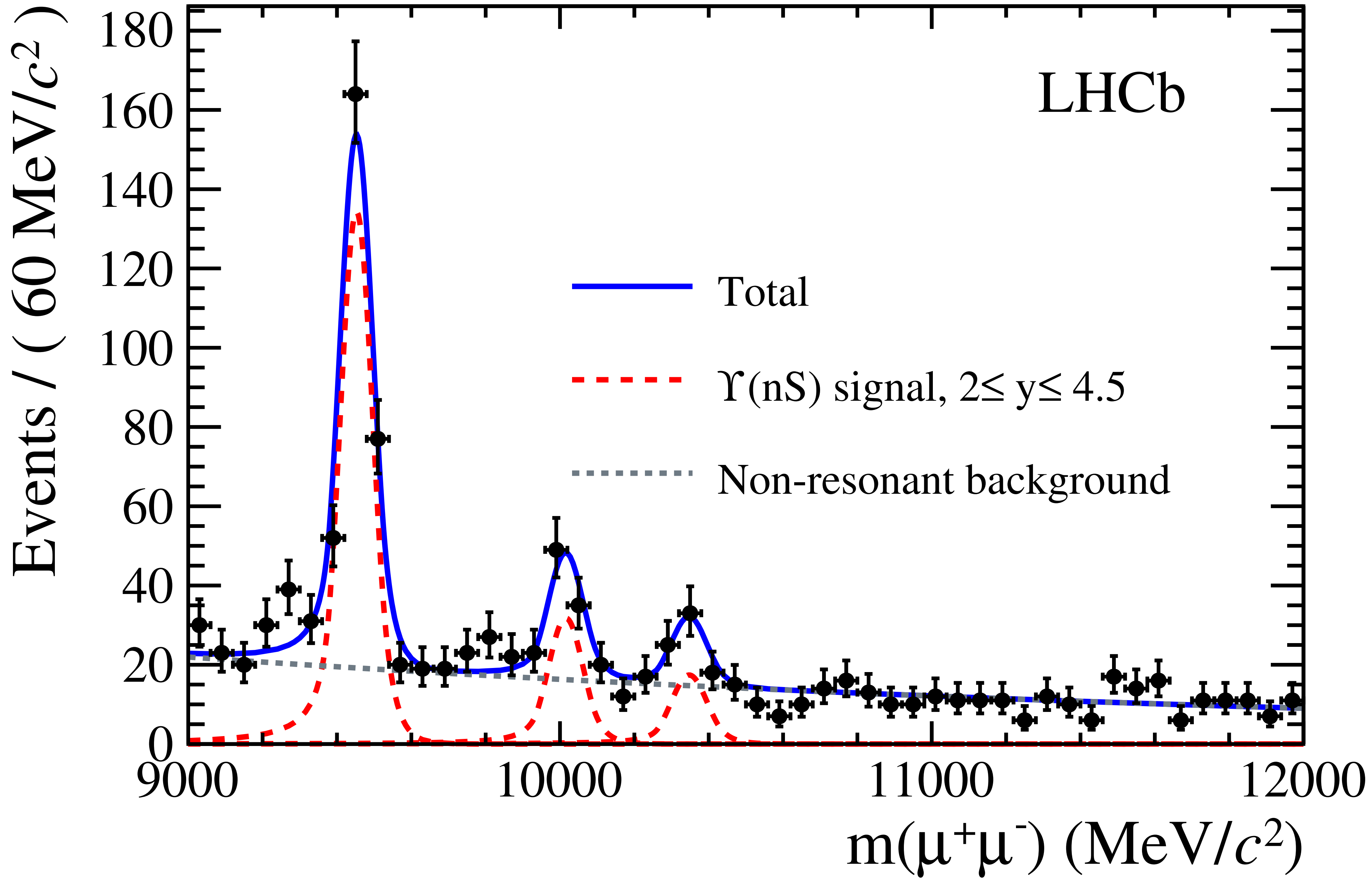


JHEP11(2013)085



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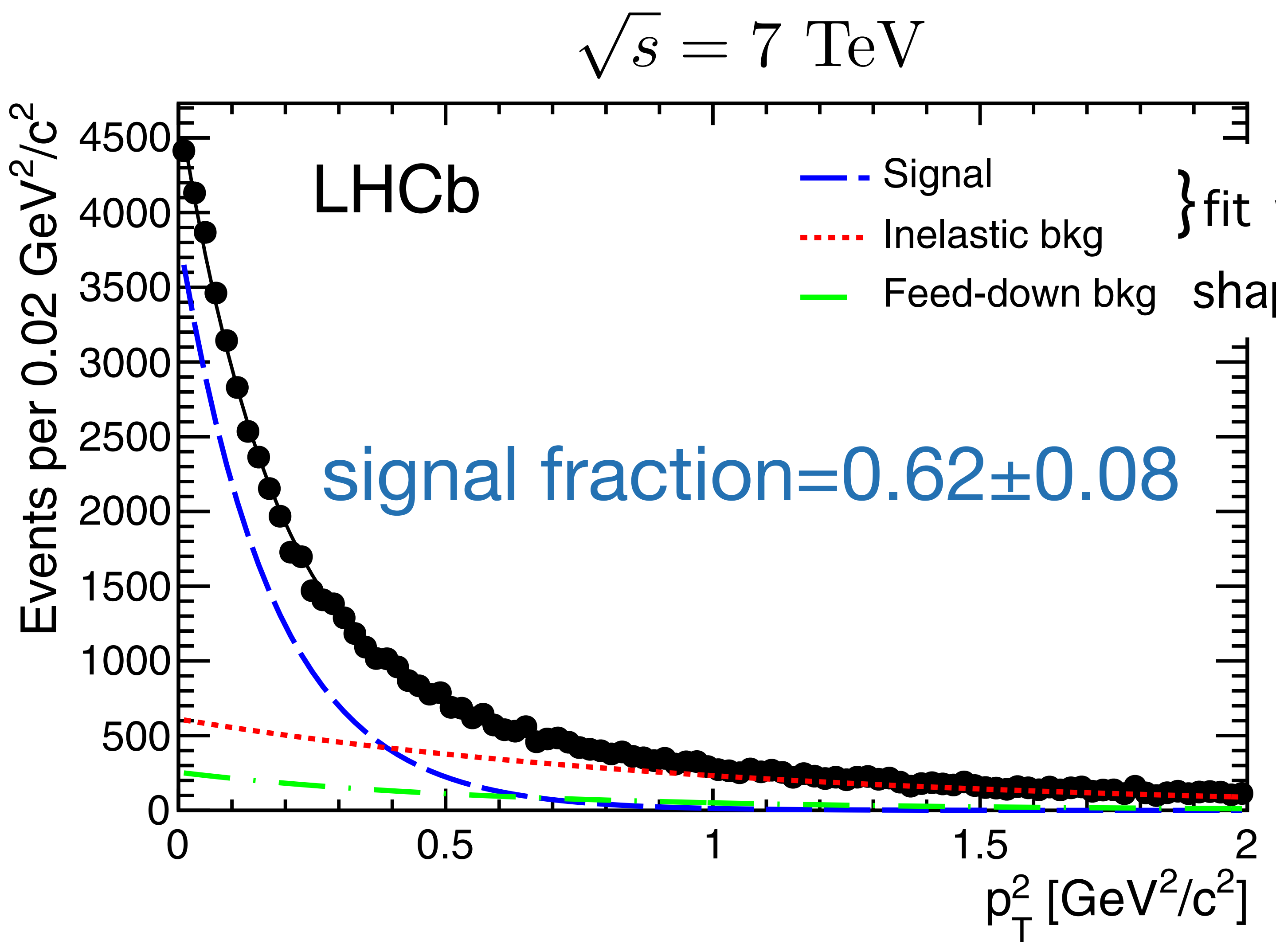
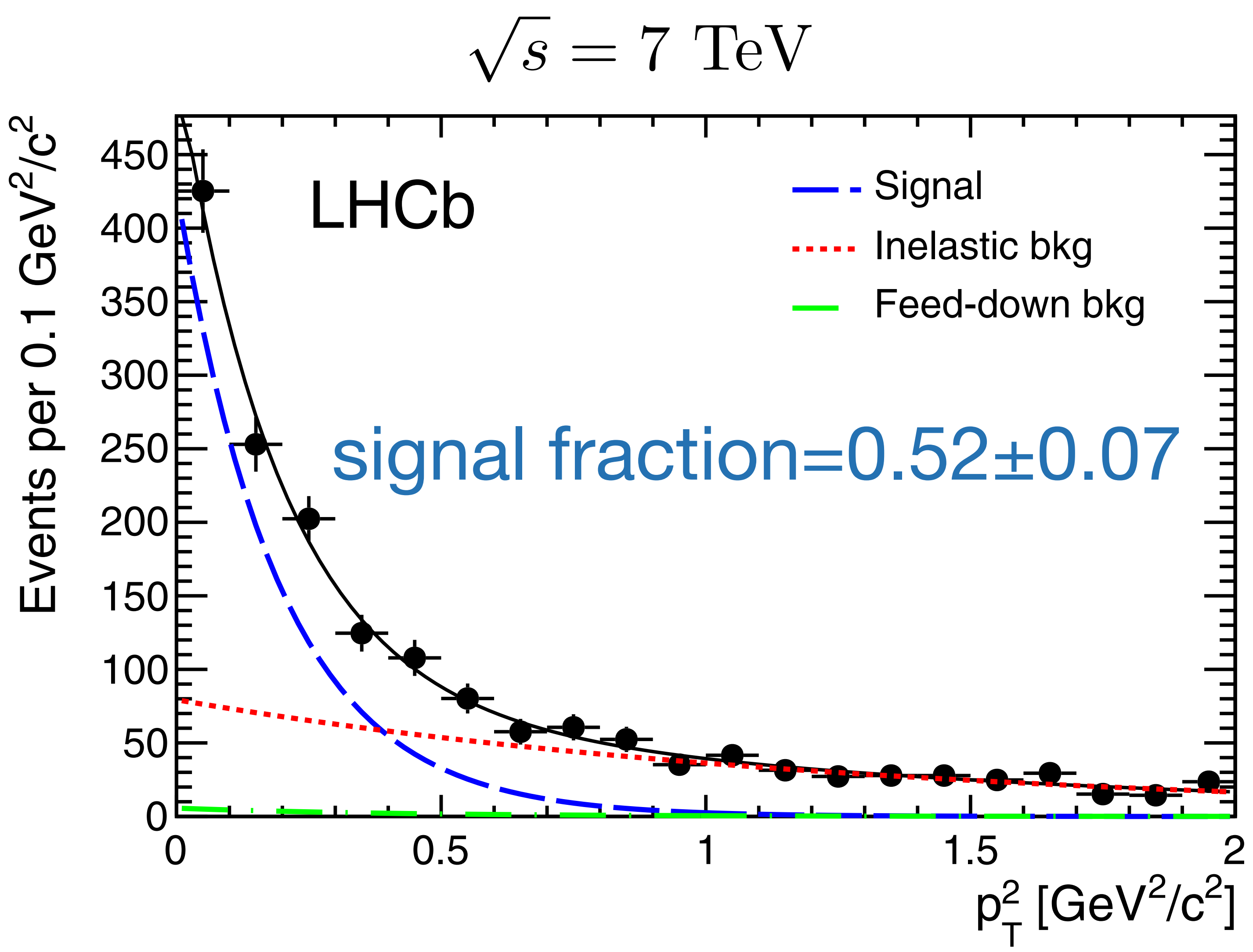
Proton dissociation and feed down

J/ψ feed-down background: ψ(2S)



}fit with exponential shape from data

Expected ψ(2S) feed-down background: $\chi_c(2P)$ and $X(3872)$



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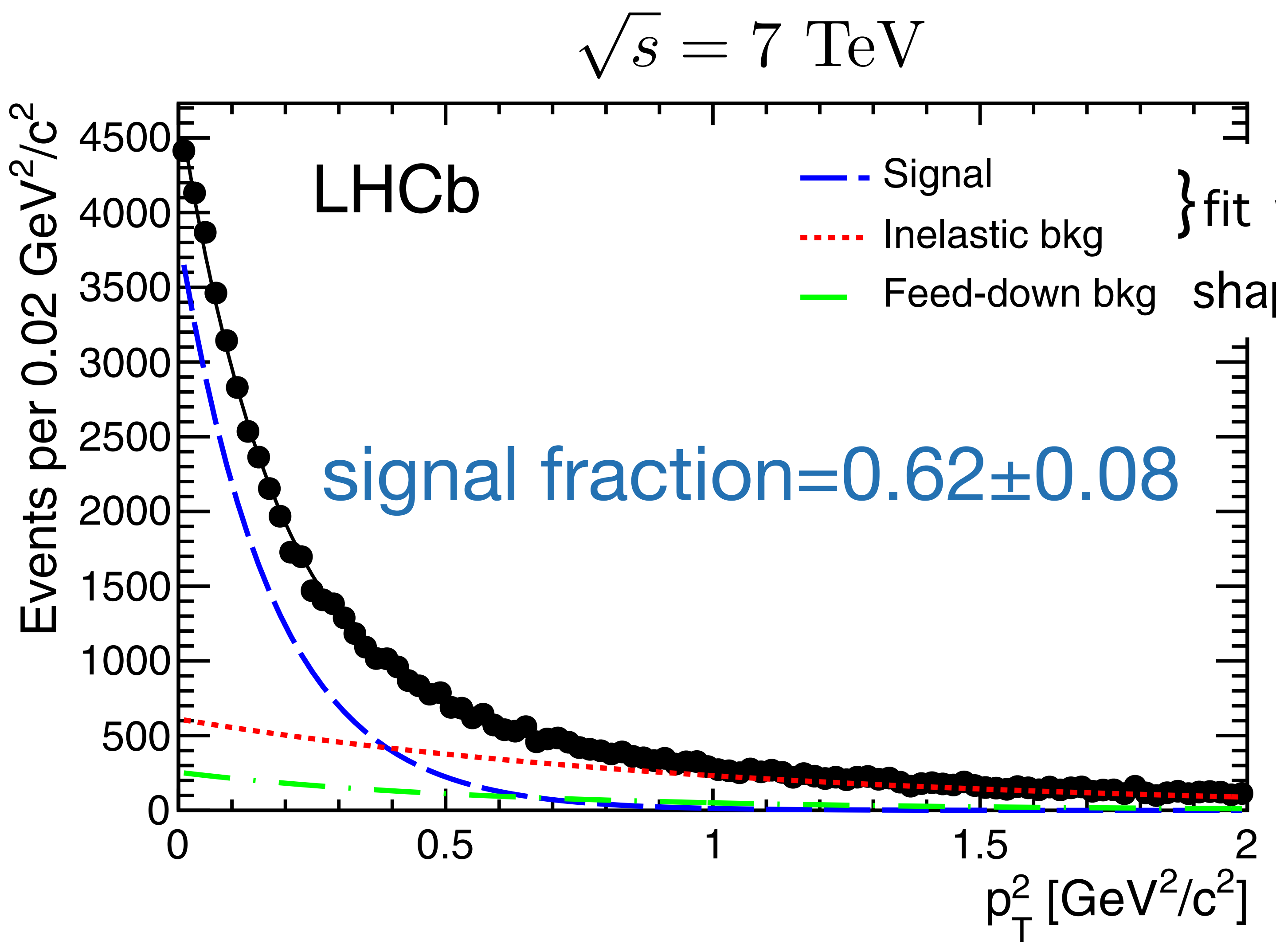

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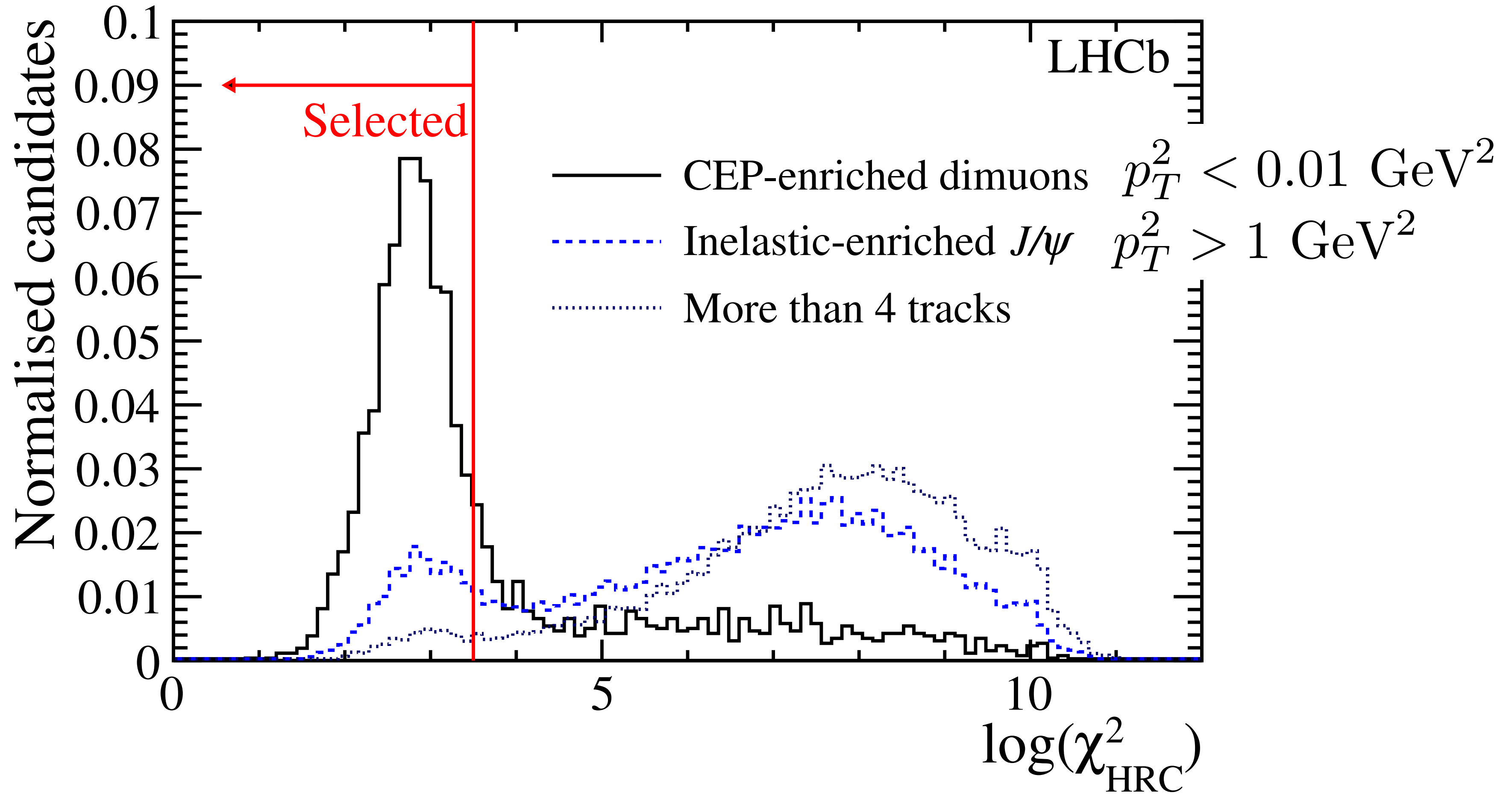
Herschel



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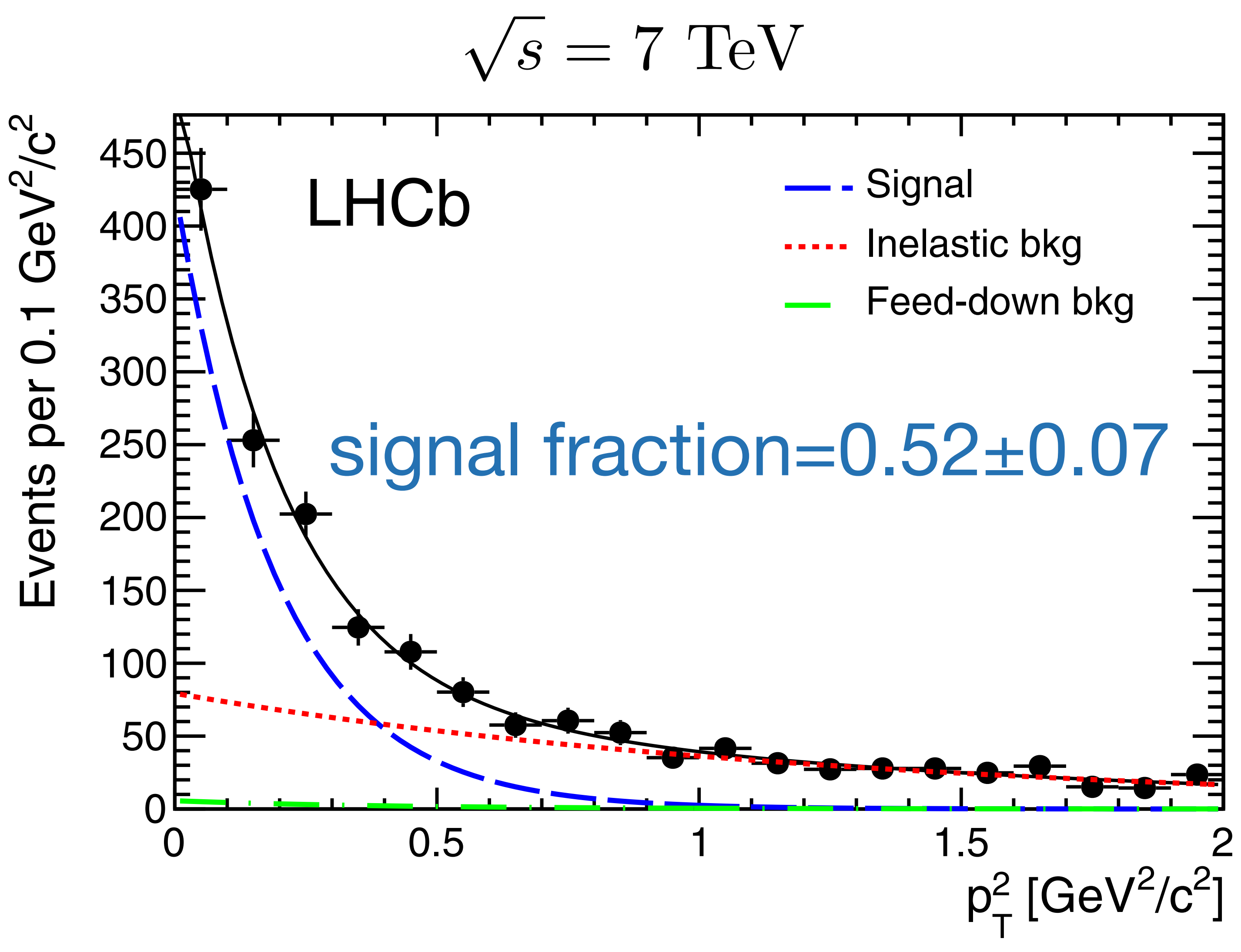

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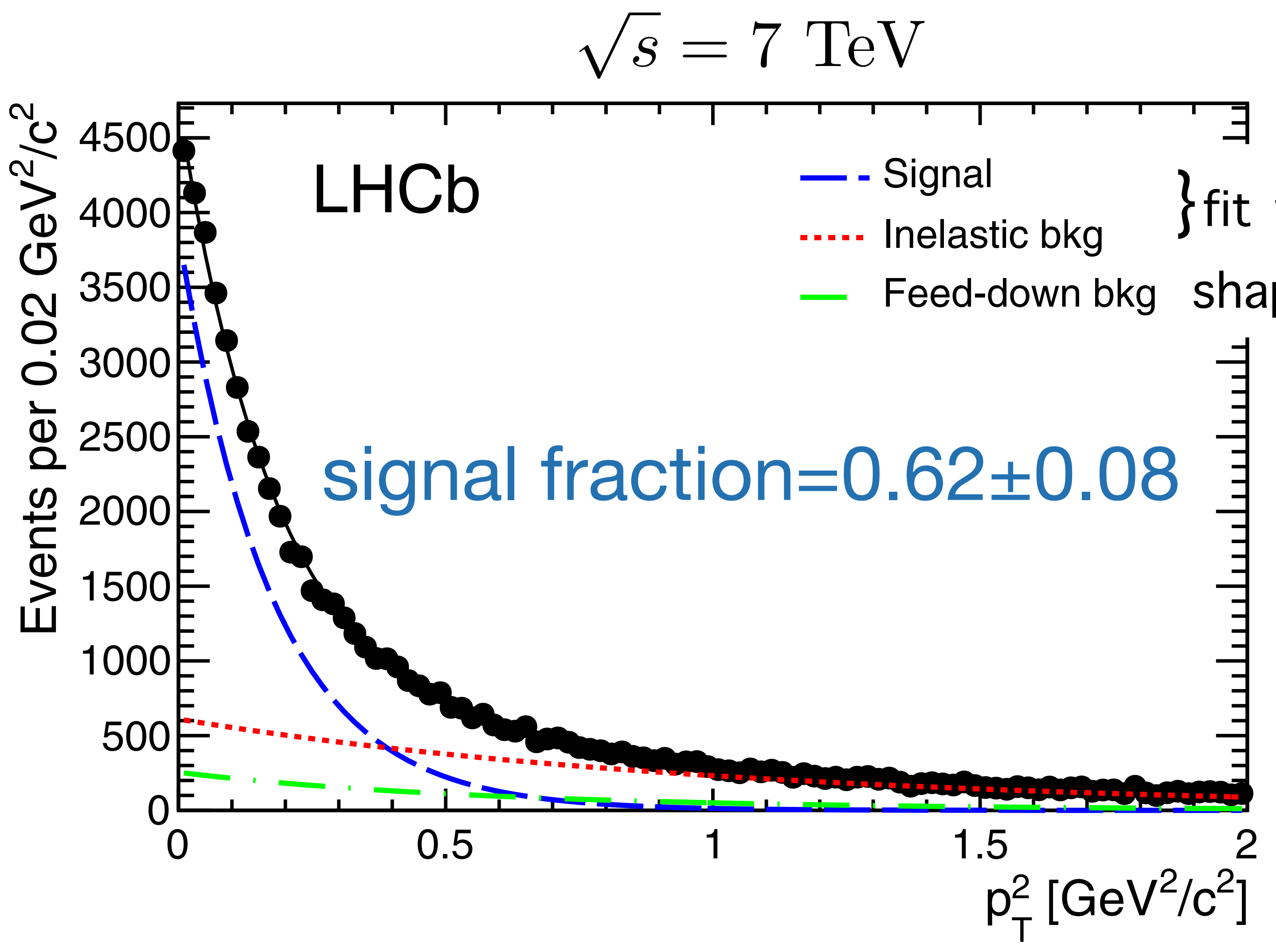

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signal fraction=0.62±0.08

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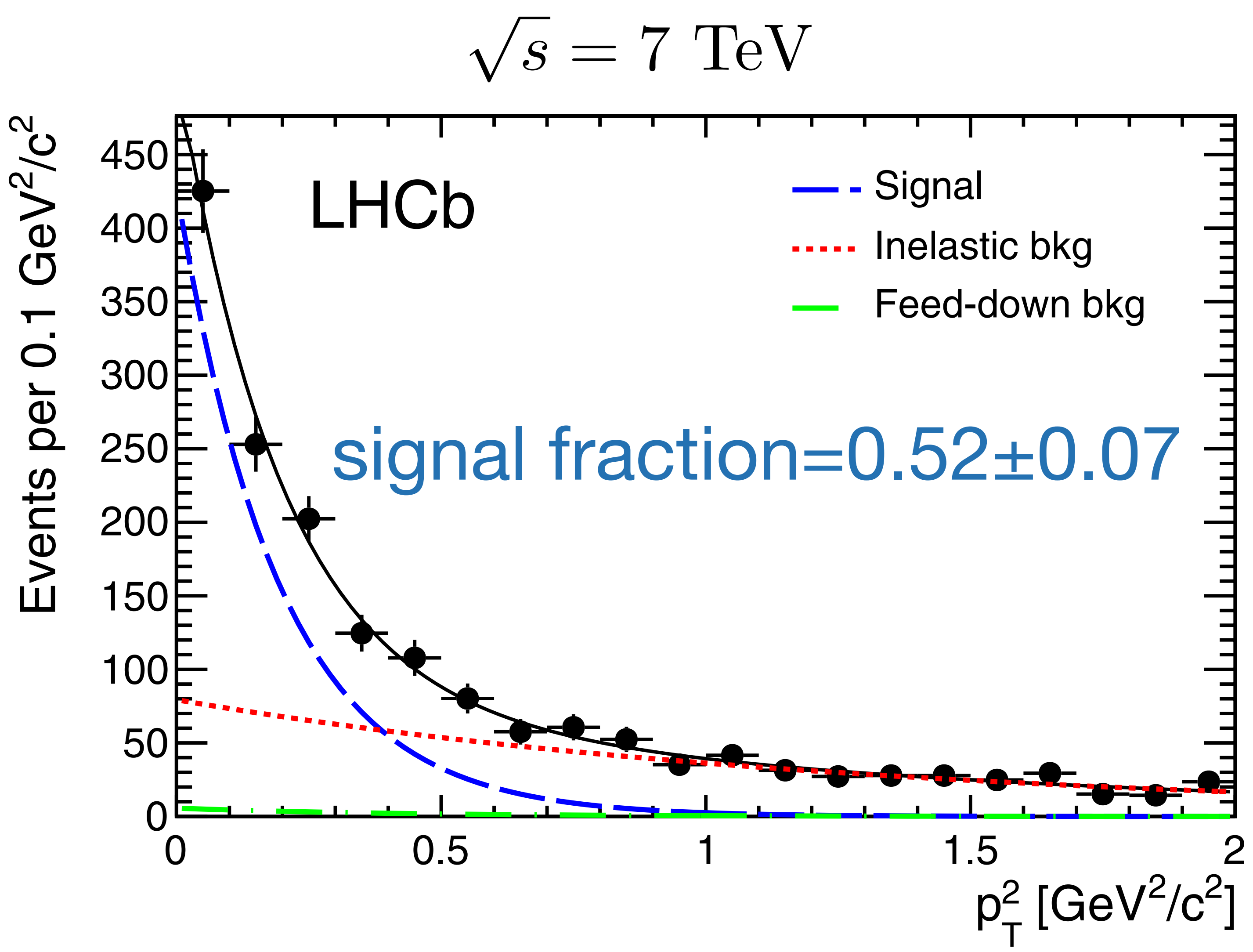
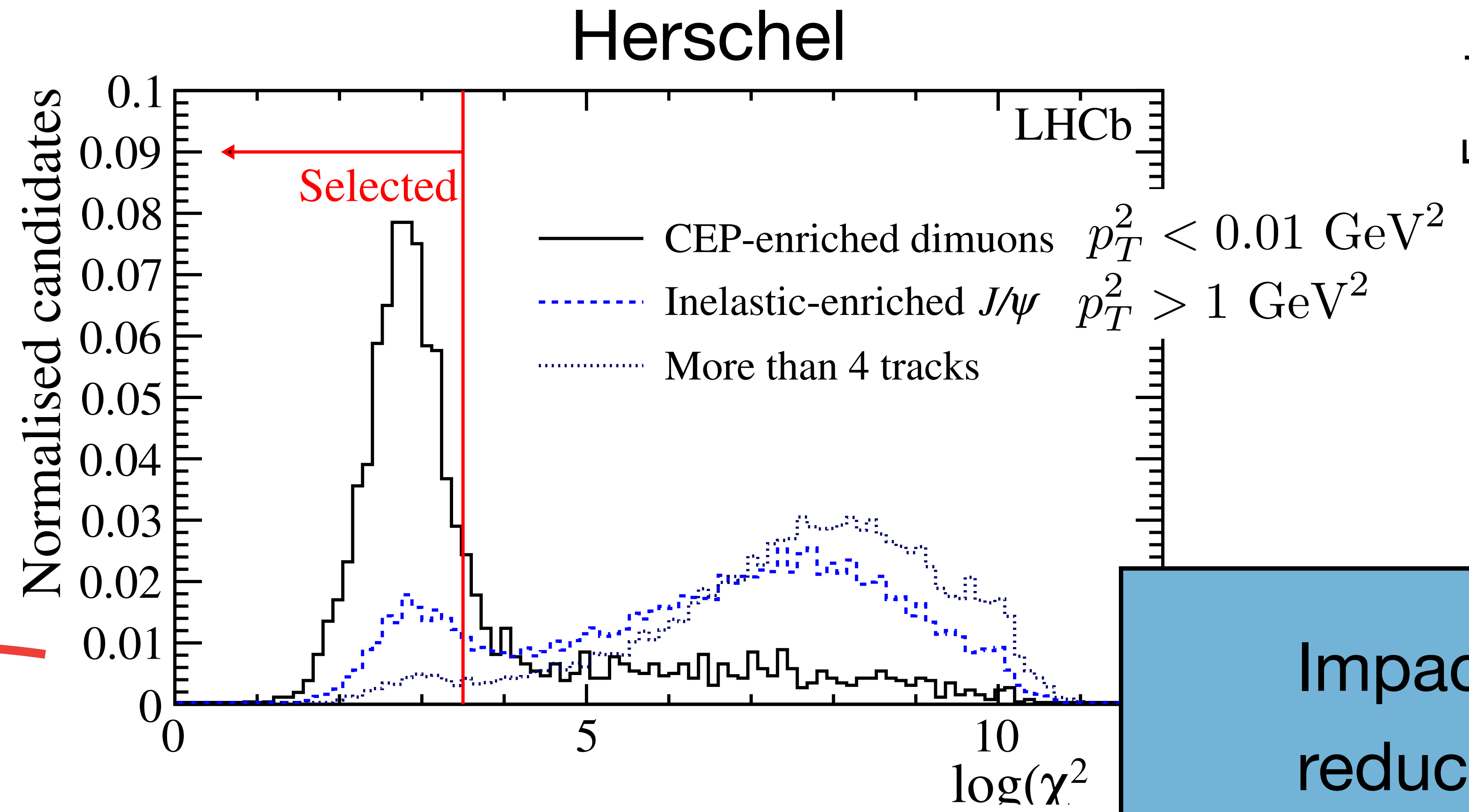
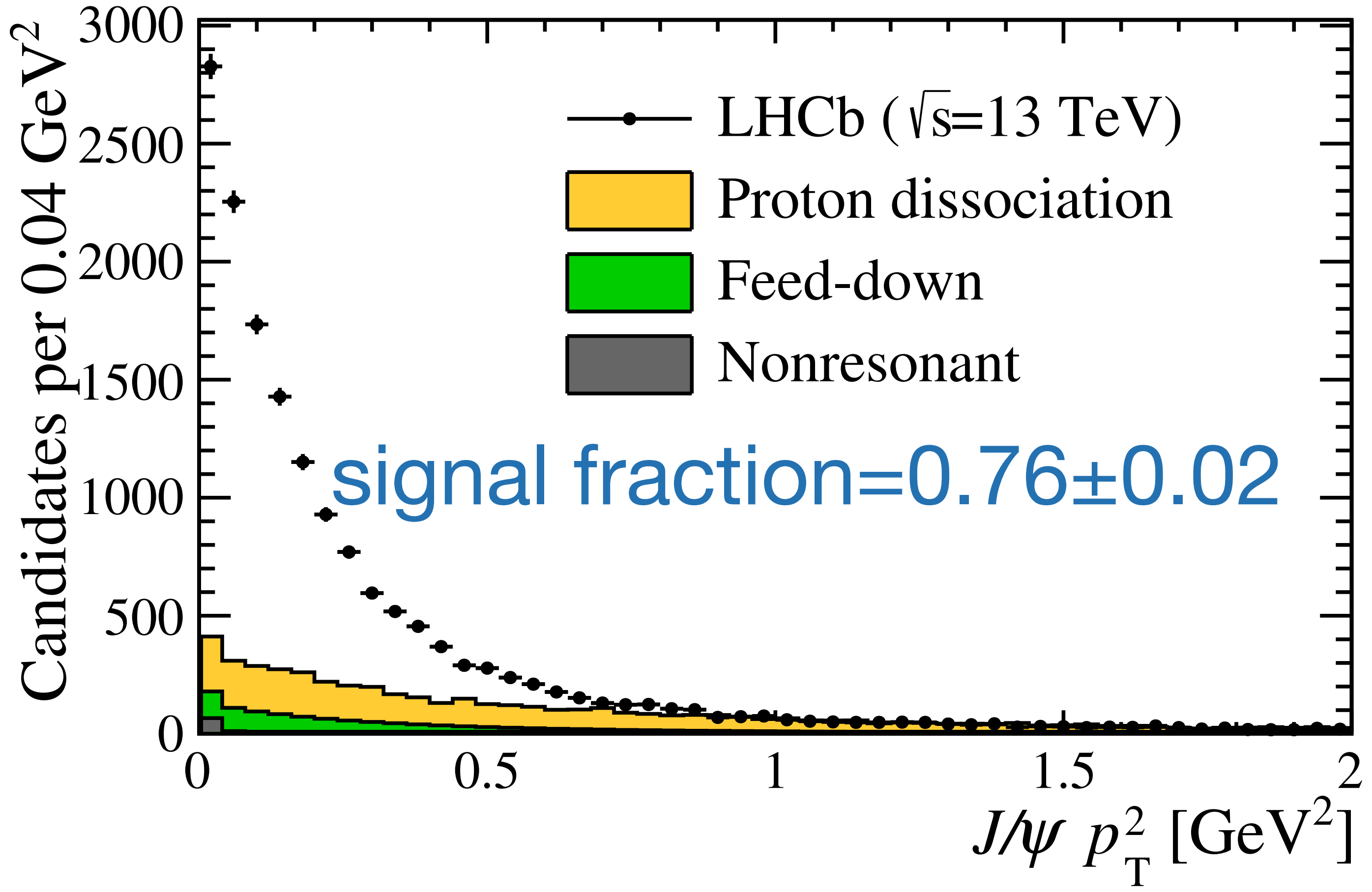


signal fraction=0.52±0.07

Herschel

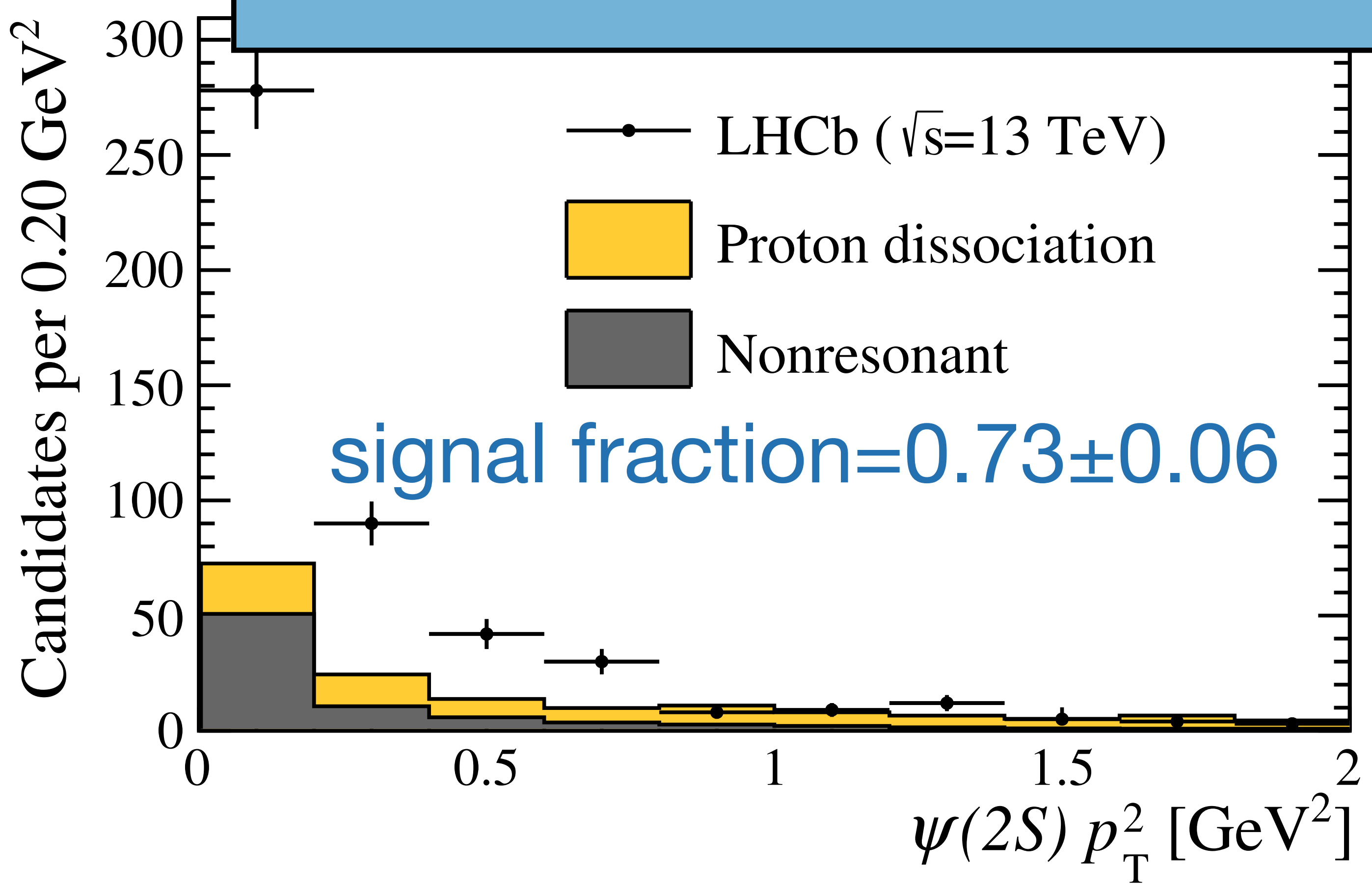


Impact from HERSCHEL:
reduction in inelastic background by ~50%.



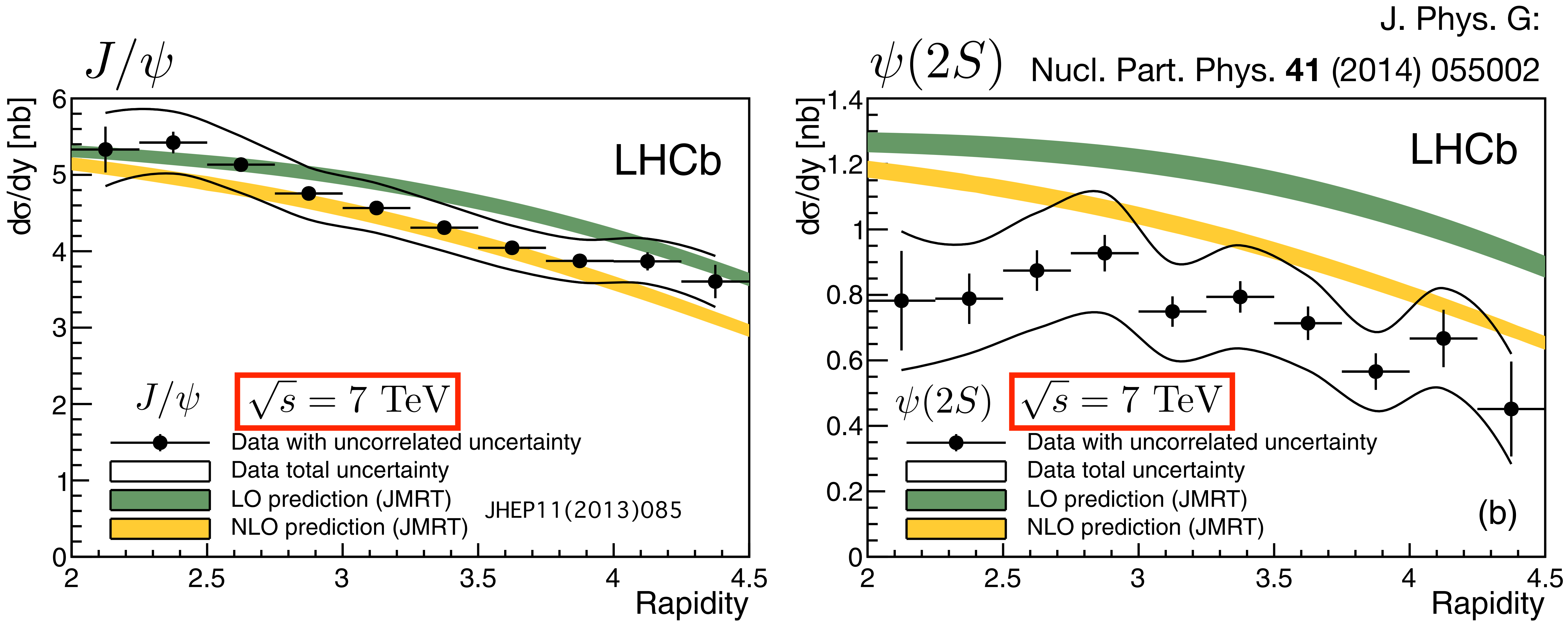
signal fraction=0.76±0.02

shape of background from data



signal fraction=0.73±0.06

pp cross section



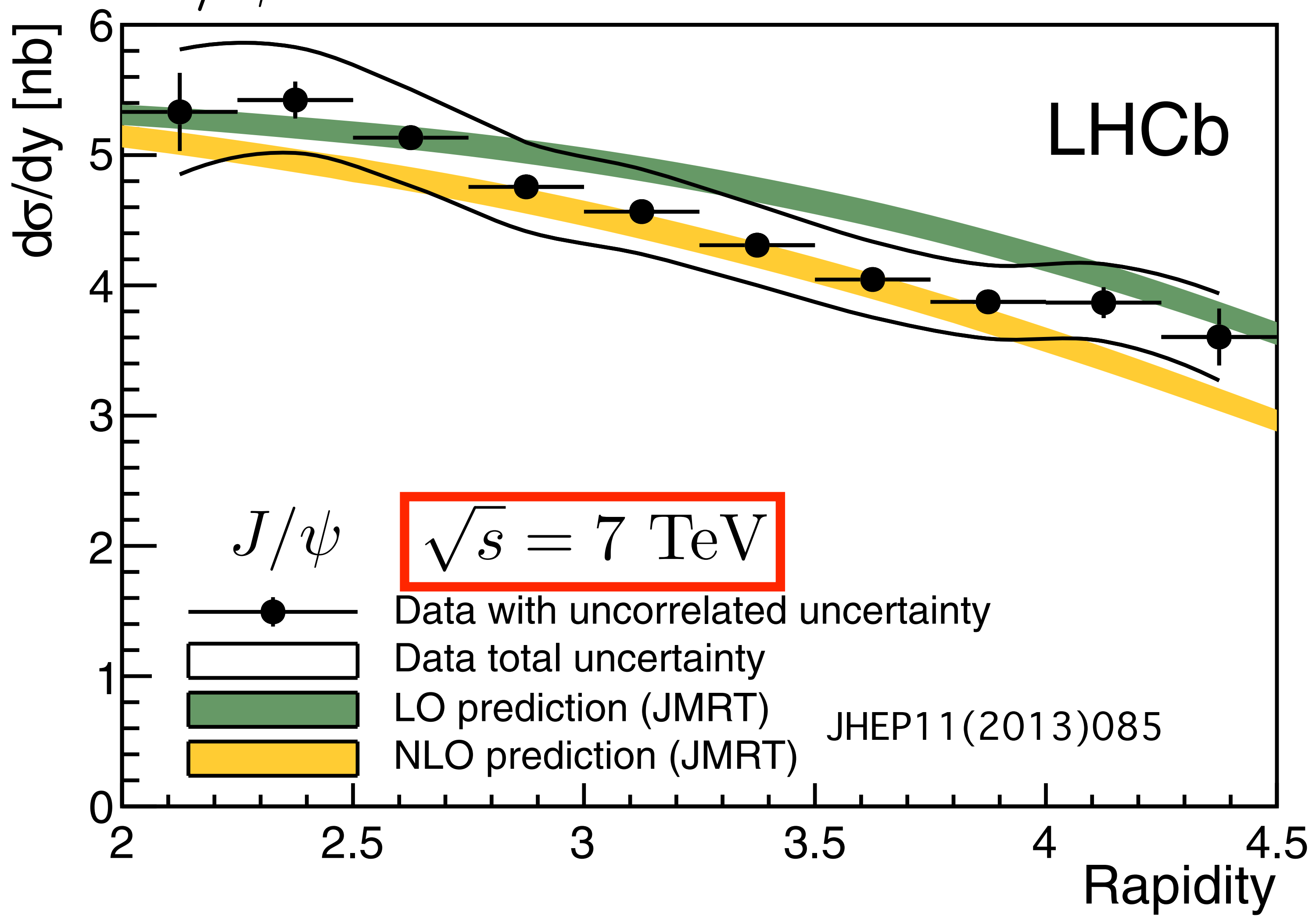
$$\frac{d\sigma_{p\psi p}}{dy} = \frac{\mathcal{P}N}{\epsilon \Delta y \mathcal{L}\mathcal{B}}$$

JMRT prediction: based on gluon PDF

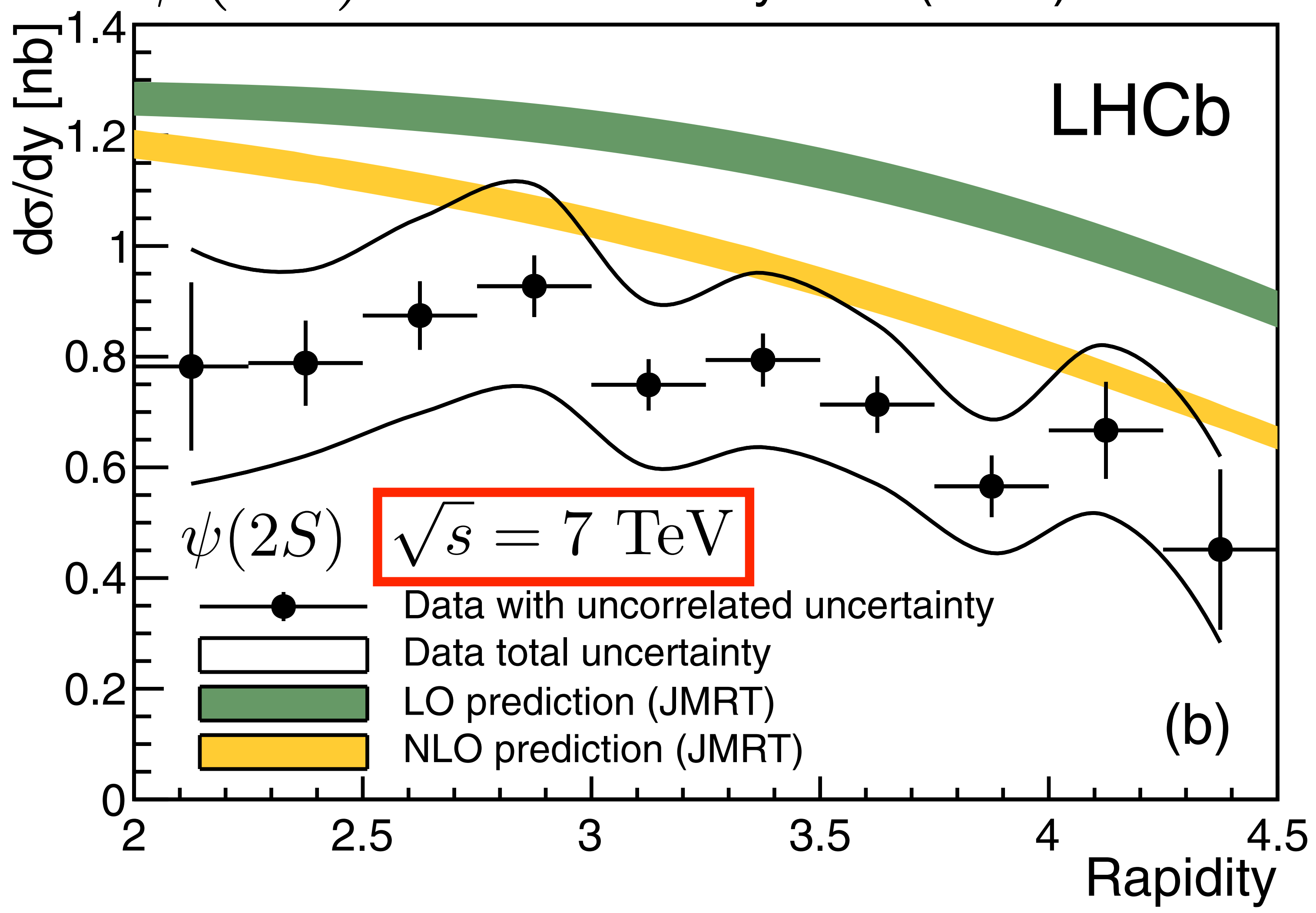
pp cross section

$$\frac{d\sigma_{p\psi p}}{dy} = \frac{\mathcal{P}N}{\epsilon \Delta y \mathcal{L}\mathcal{B}}$$

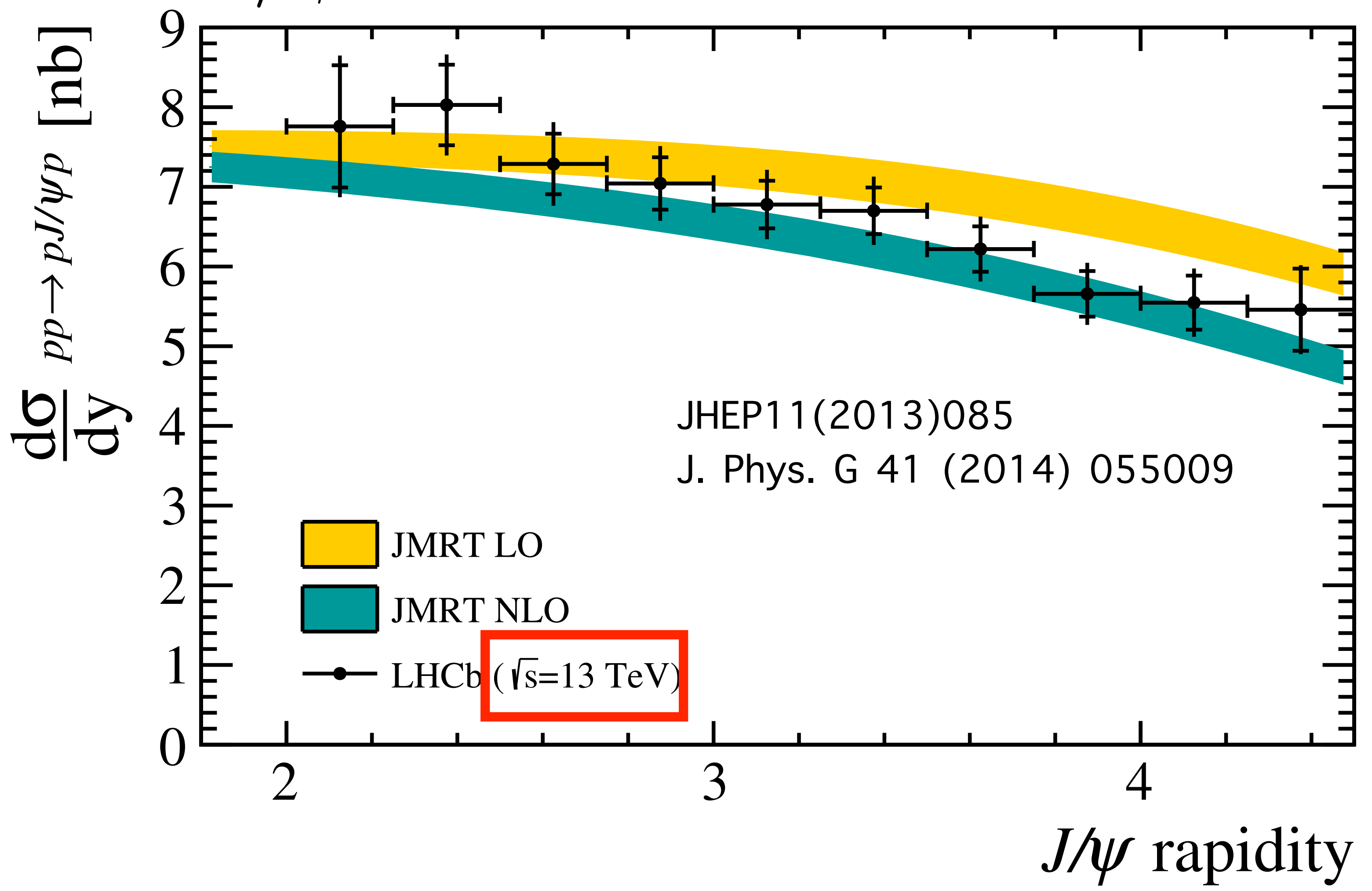
J/ψ



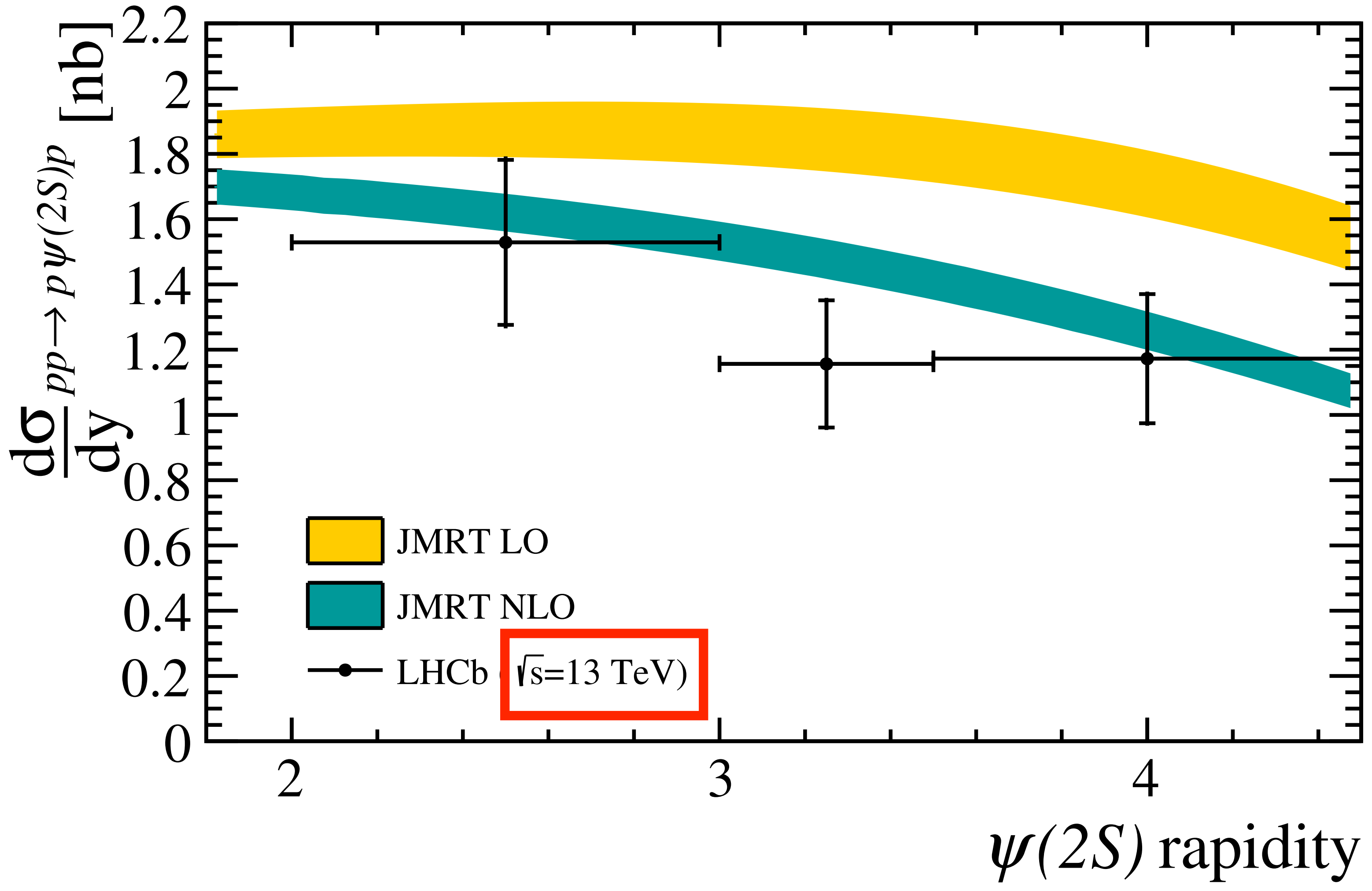
$\psi(2S)$ J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002



J/ψ



$\psi(2S)$ JHEP 10 (2018) 167



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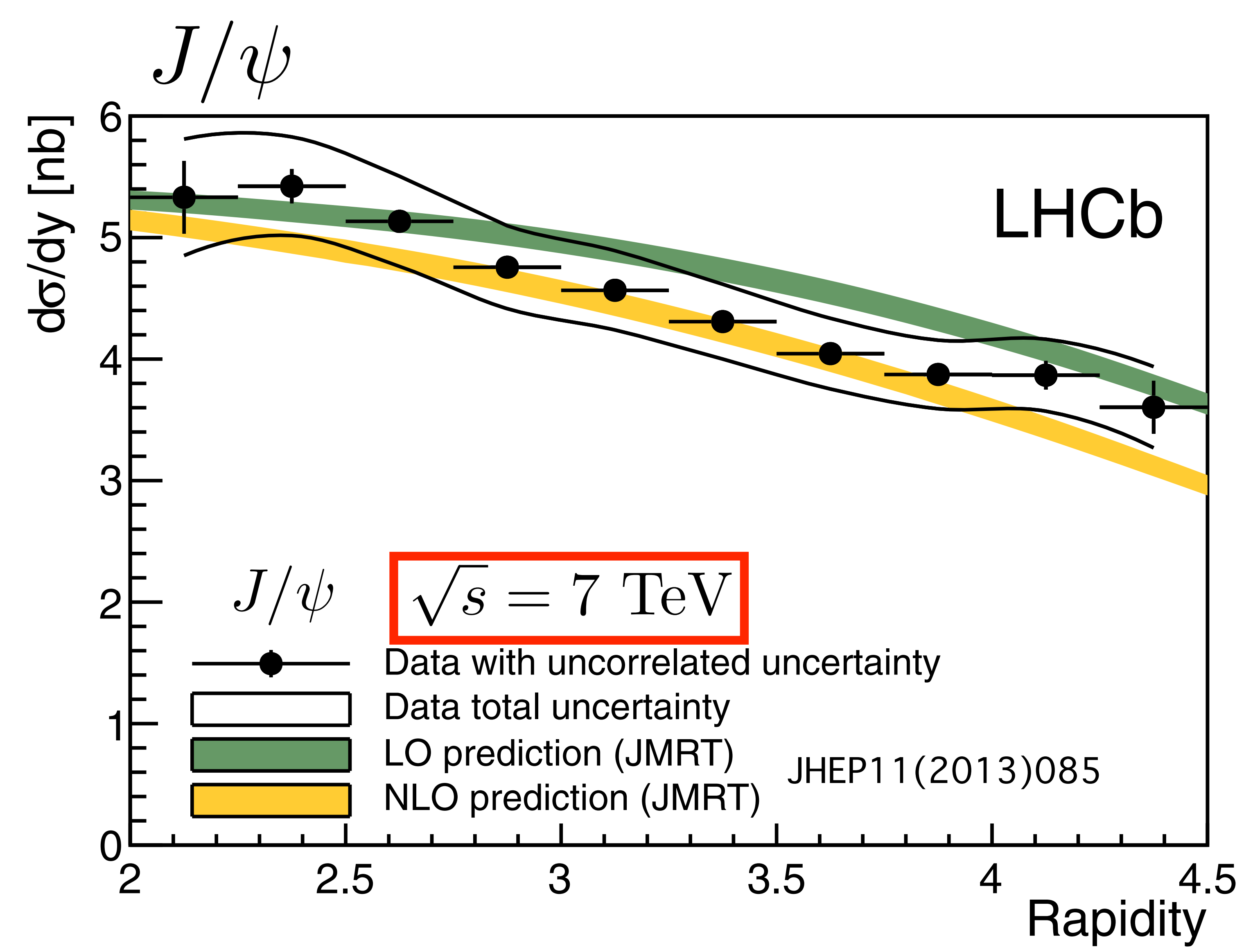
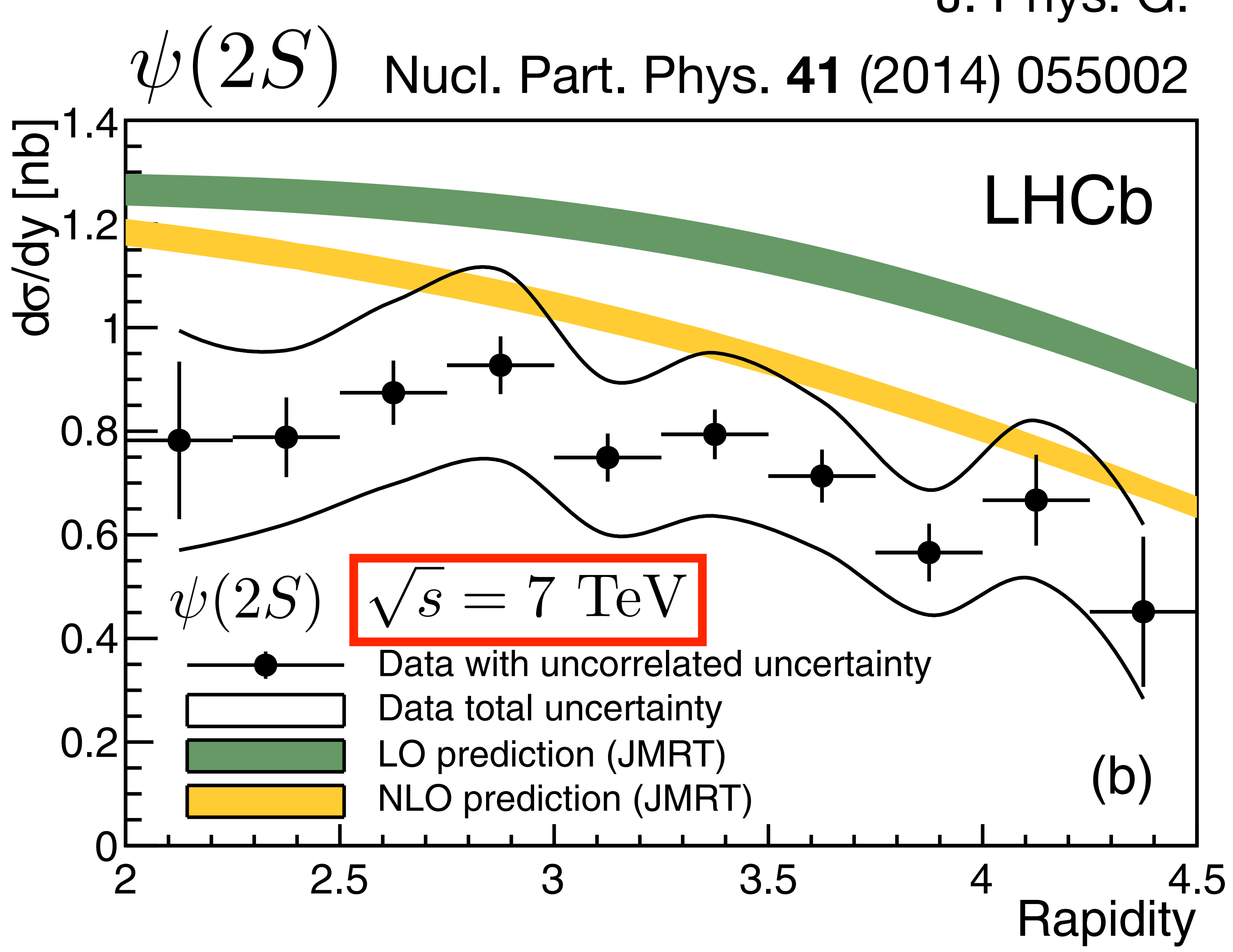
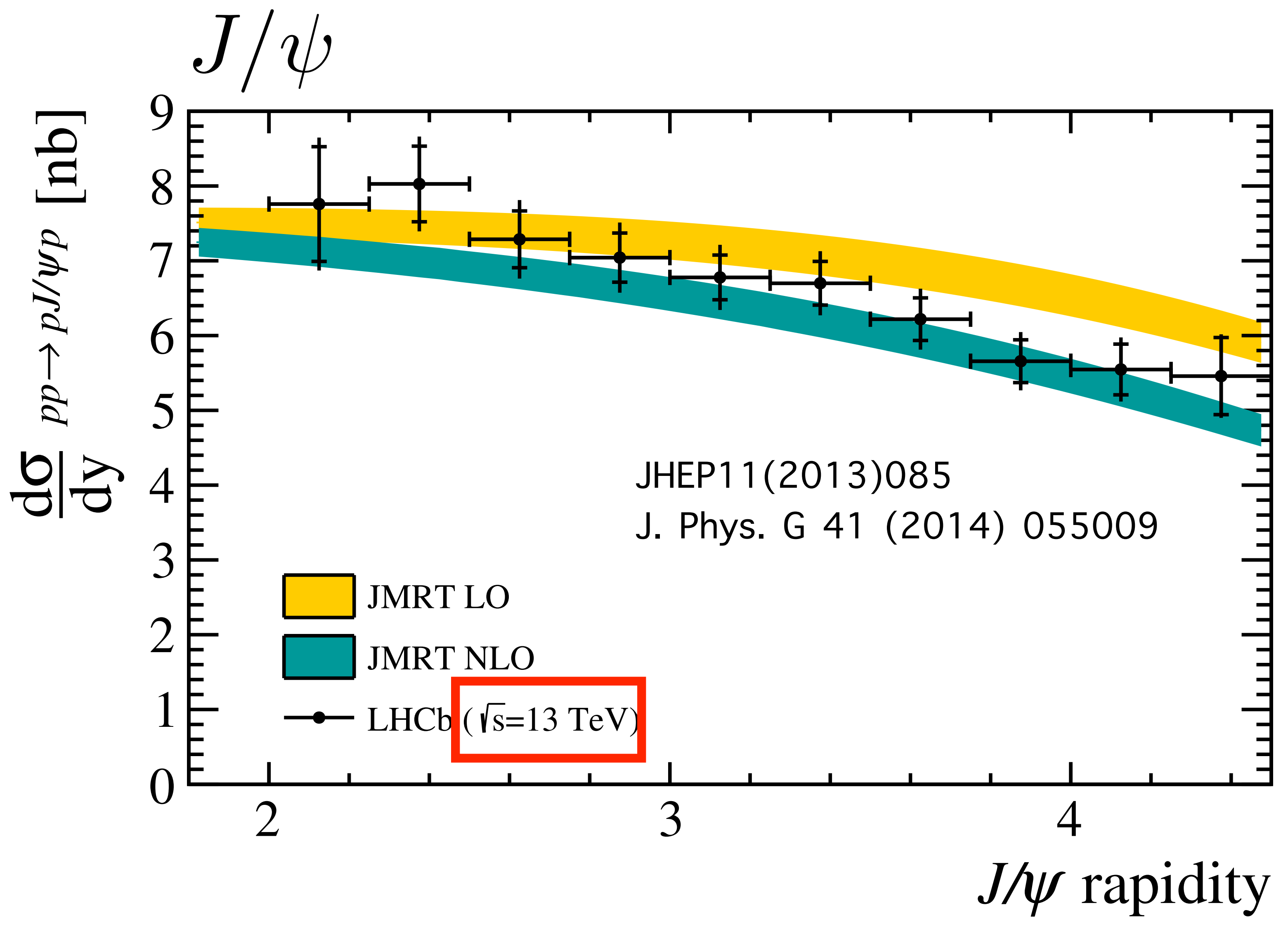


J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002





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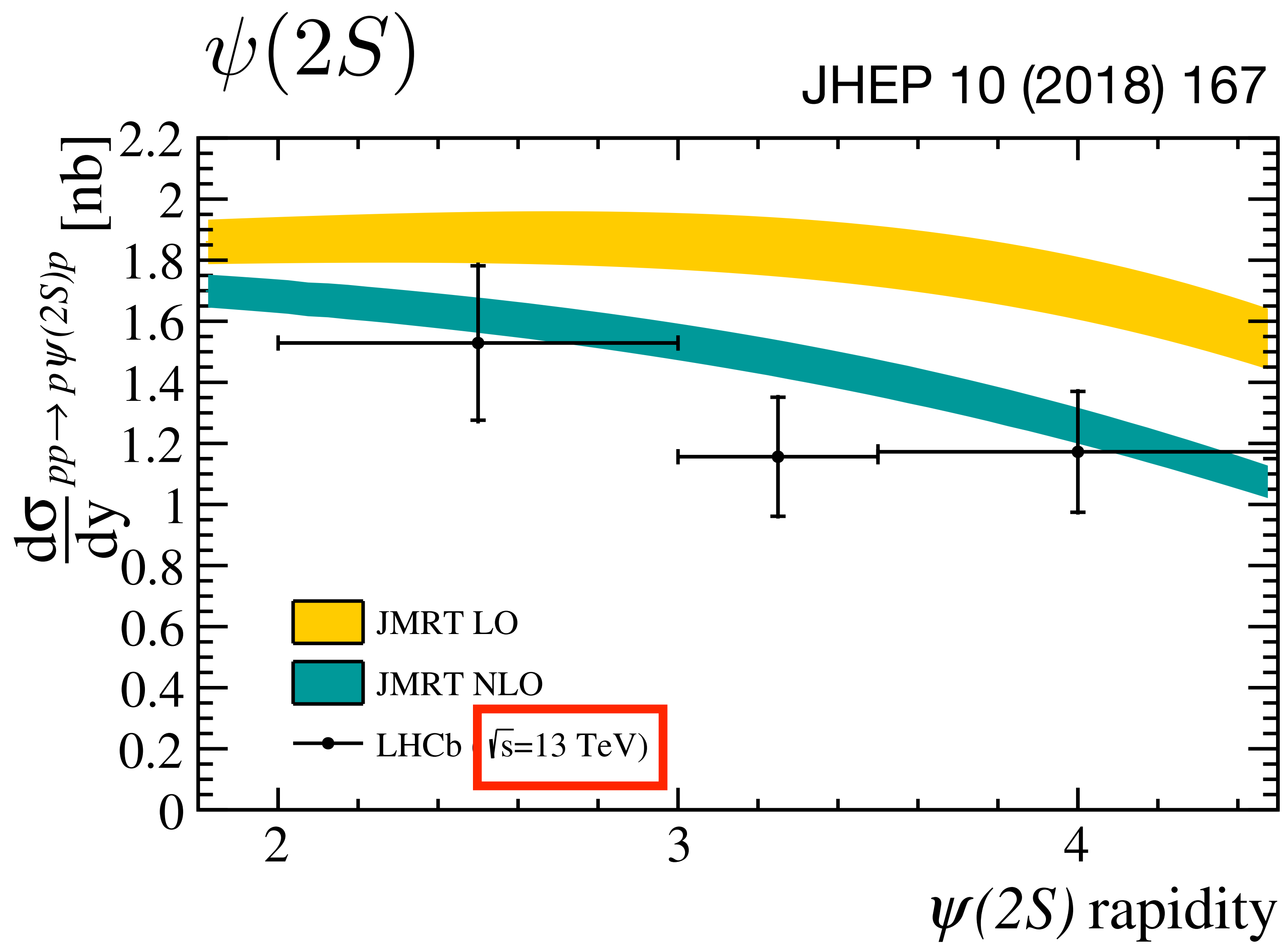

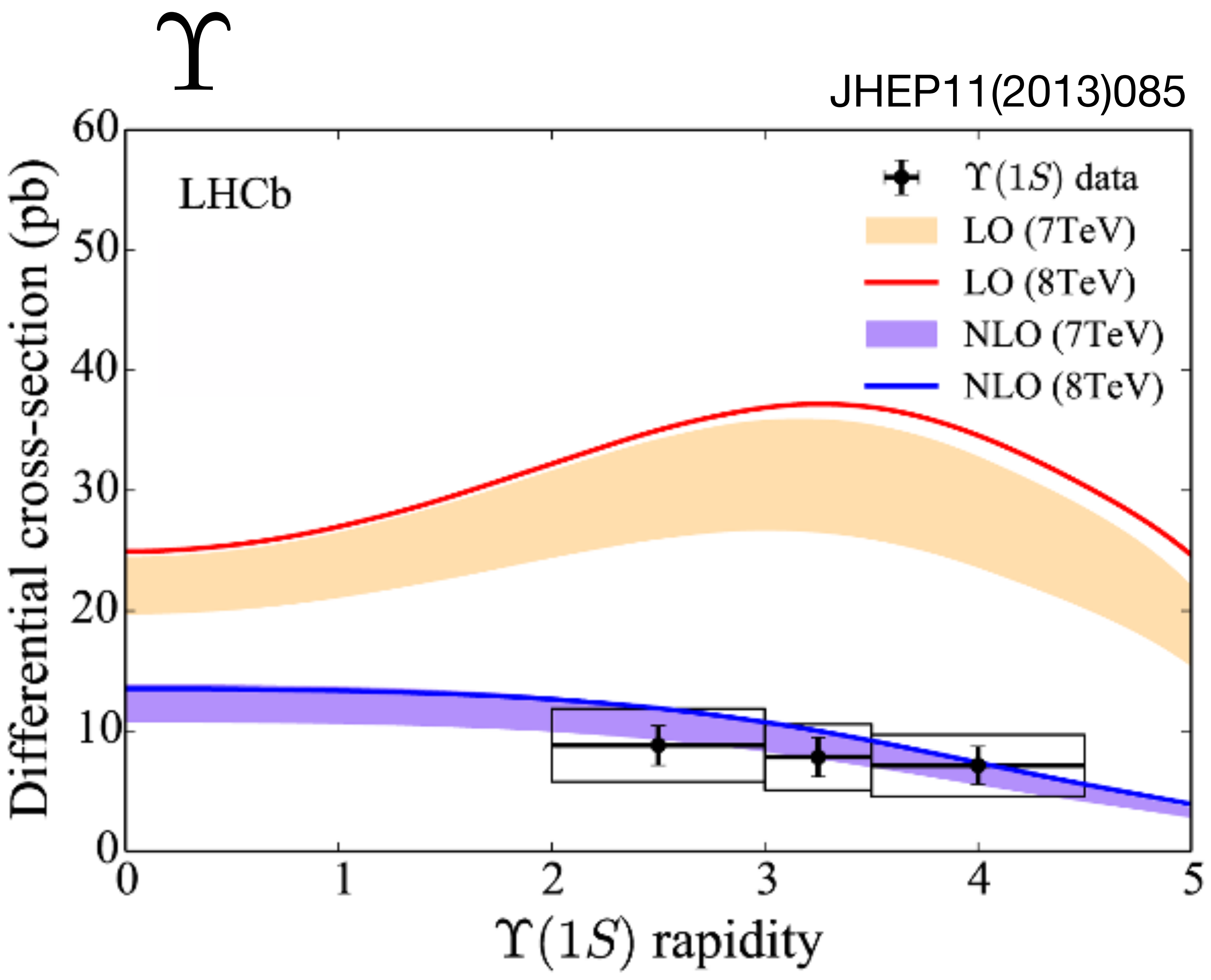

JMRT prediction: based on gluon PDF

γp cross section

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- r = gap survival factor
- $k_\pm = \frac{M_\psi}{2}e^{\pm y}$ = photon energy
- $\frac{dn}{dk_\pm}$ = photon flux
- $W_\pm^2 = 2k_\pm\sqrt{s}$ = photon-proton invariant mass

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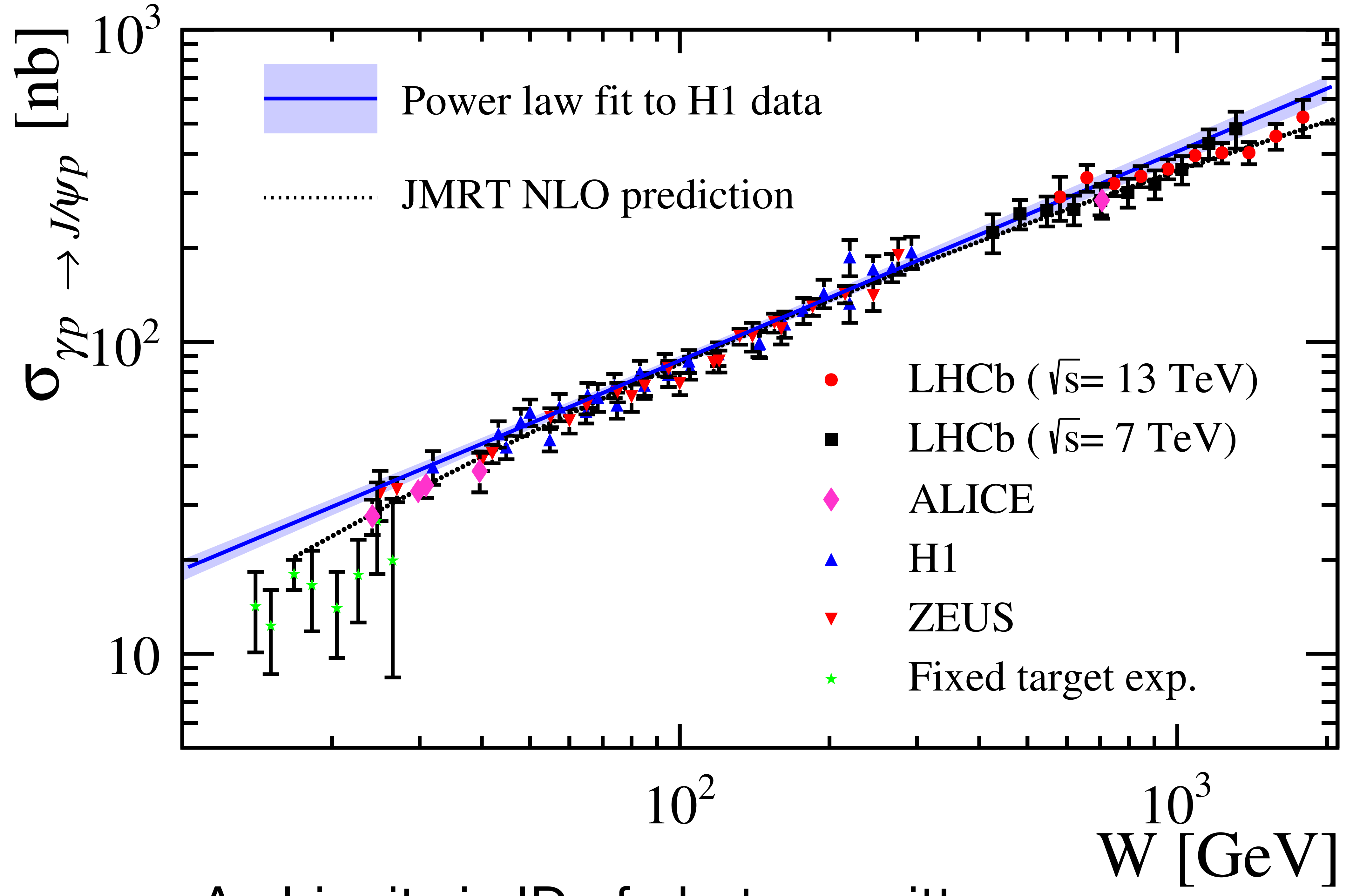

Ambiguity in ID of photon emitter:
use HERA data for low-E$_\gamma$ contribution.

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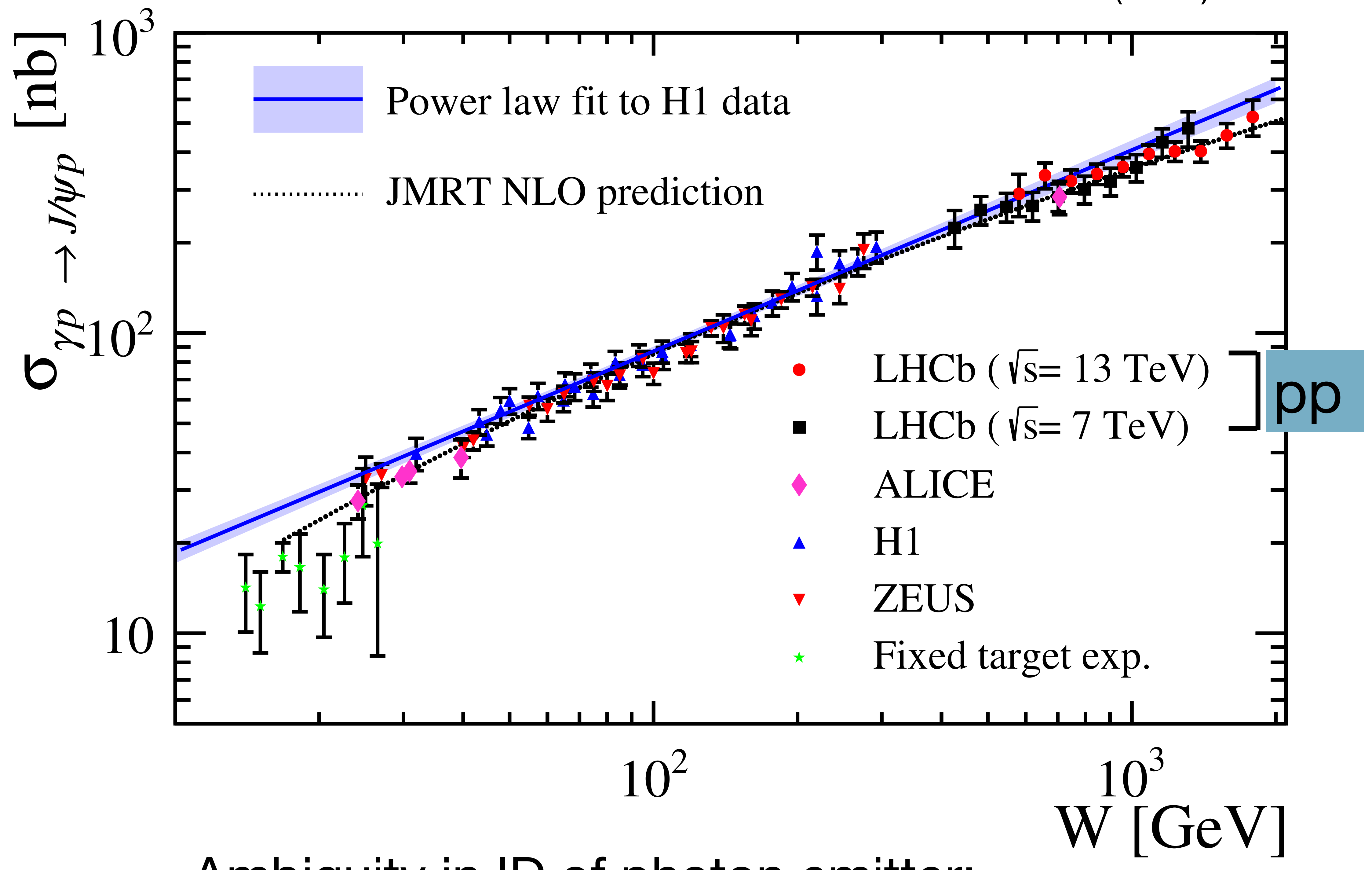

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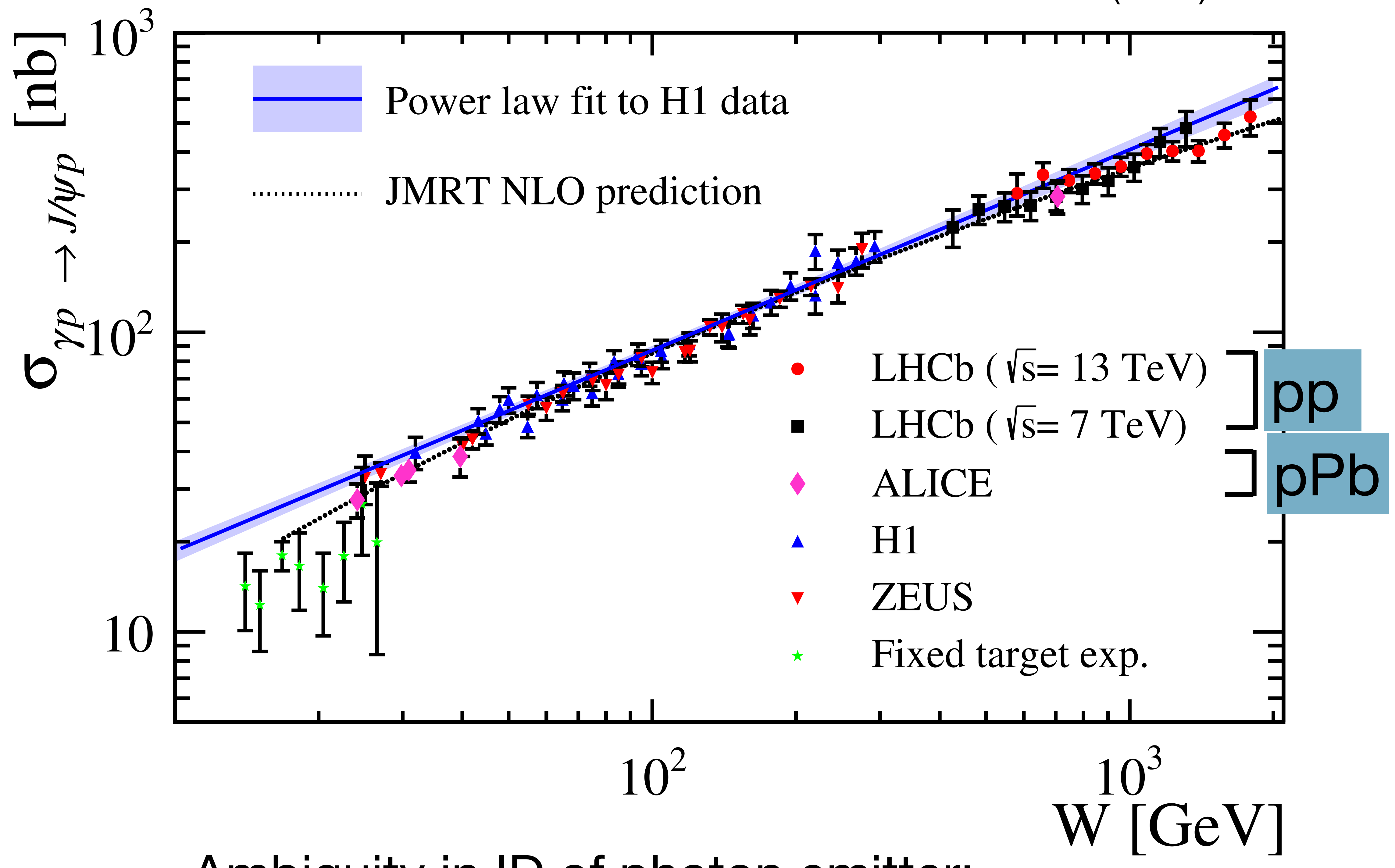

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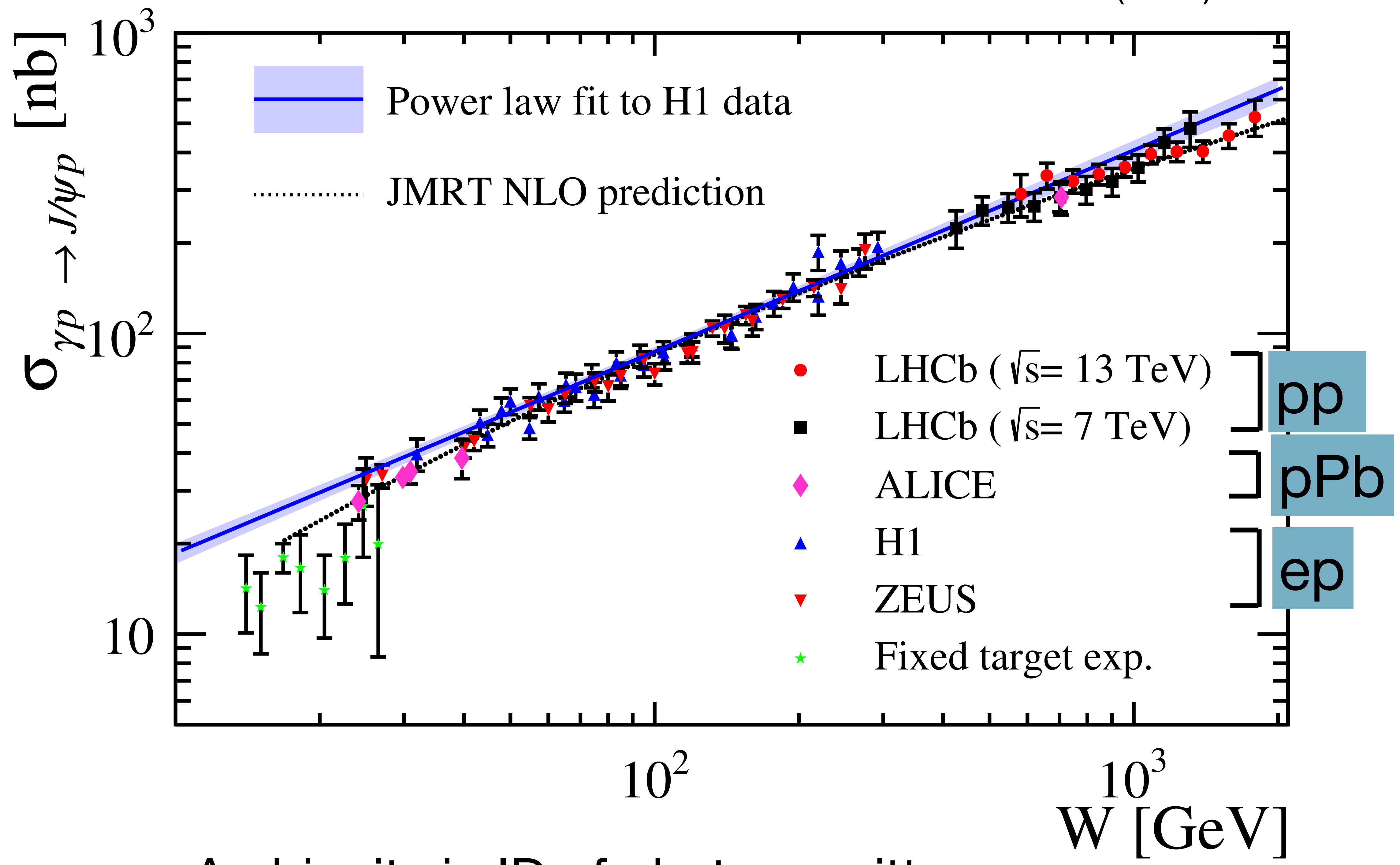

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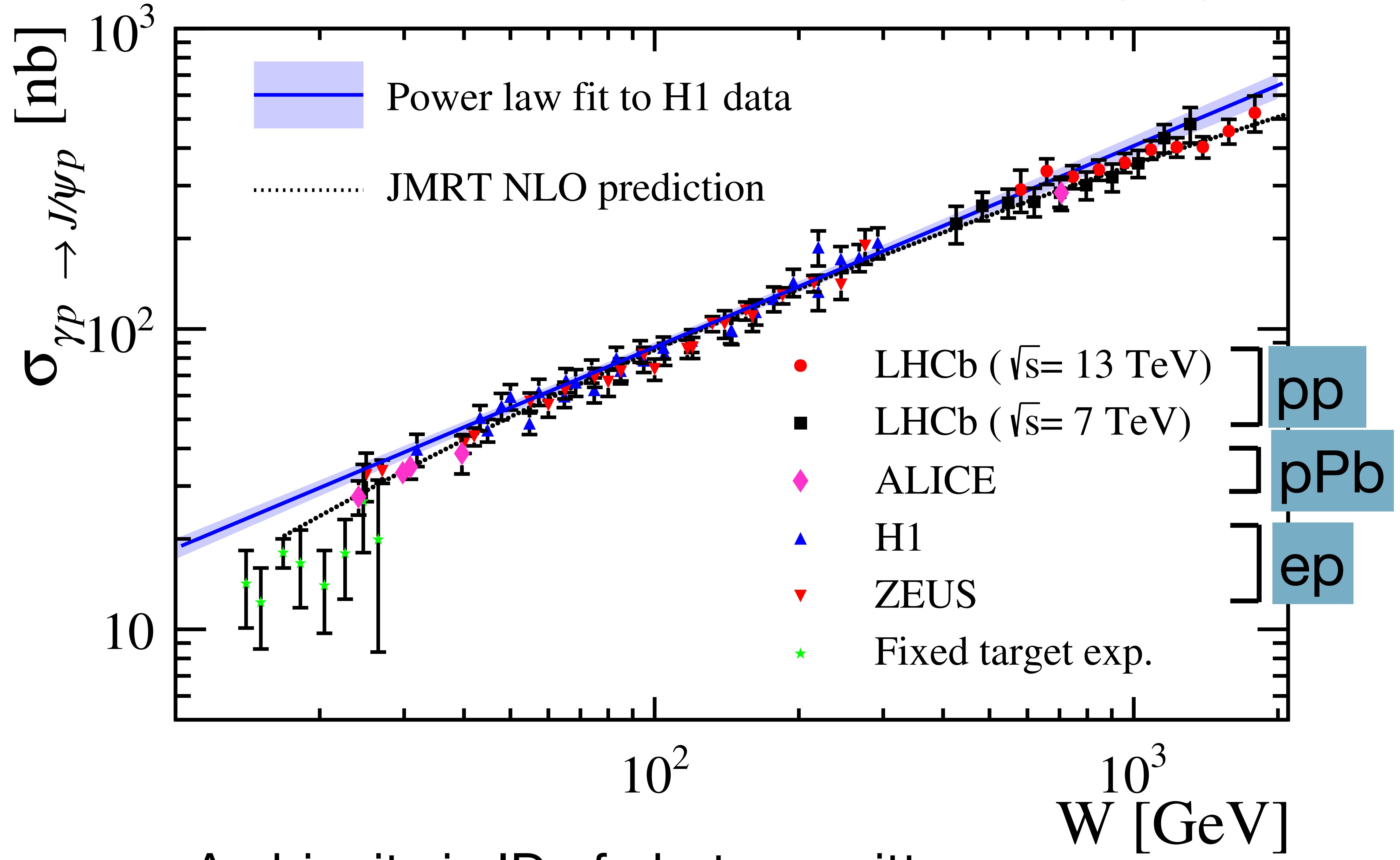

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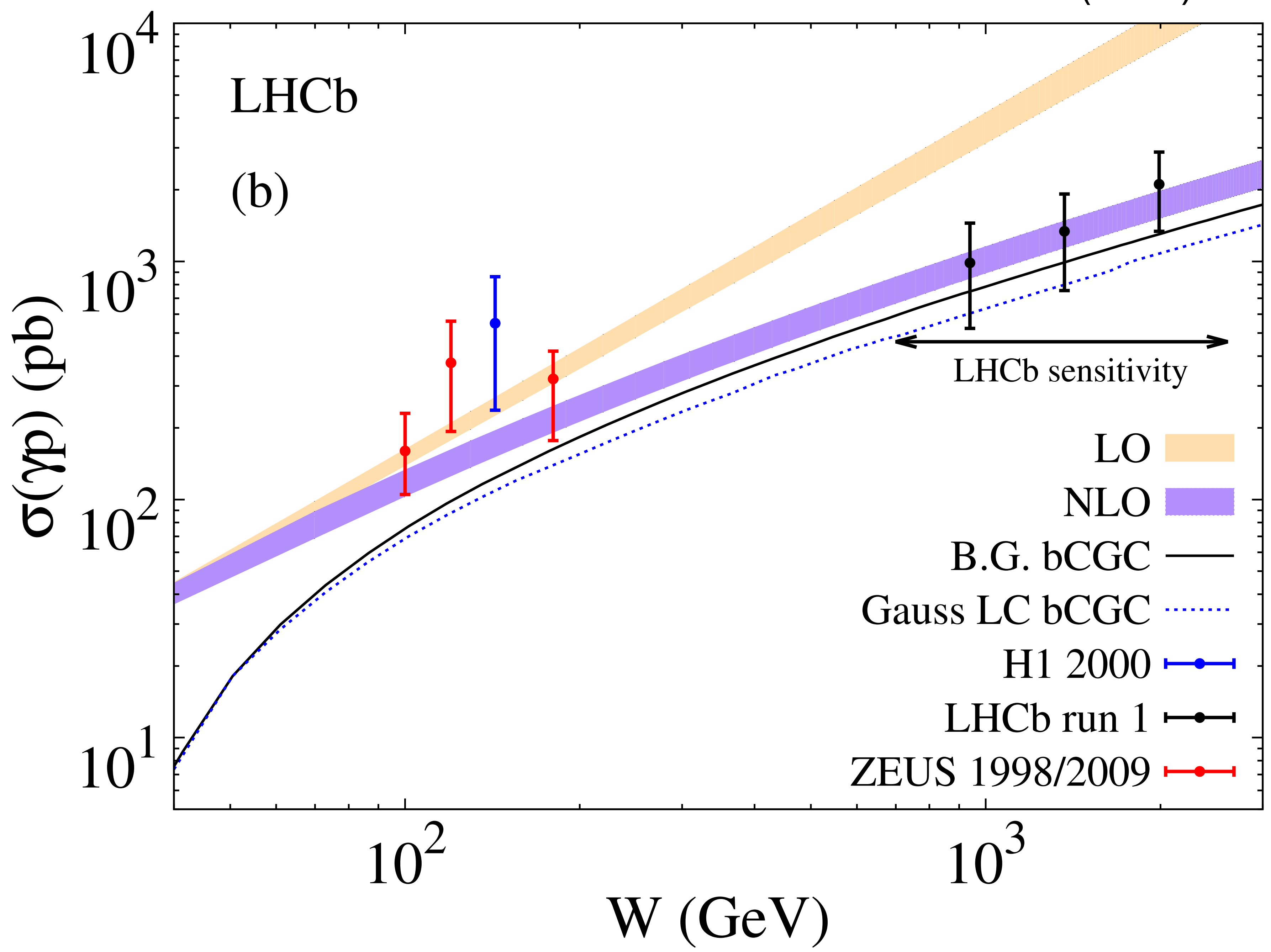
JHEP11(2013)085



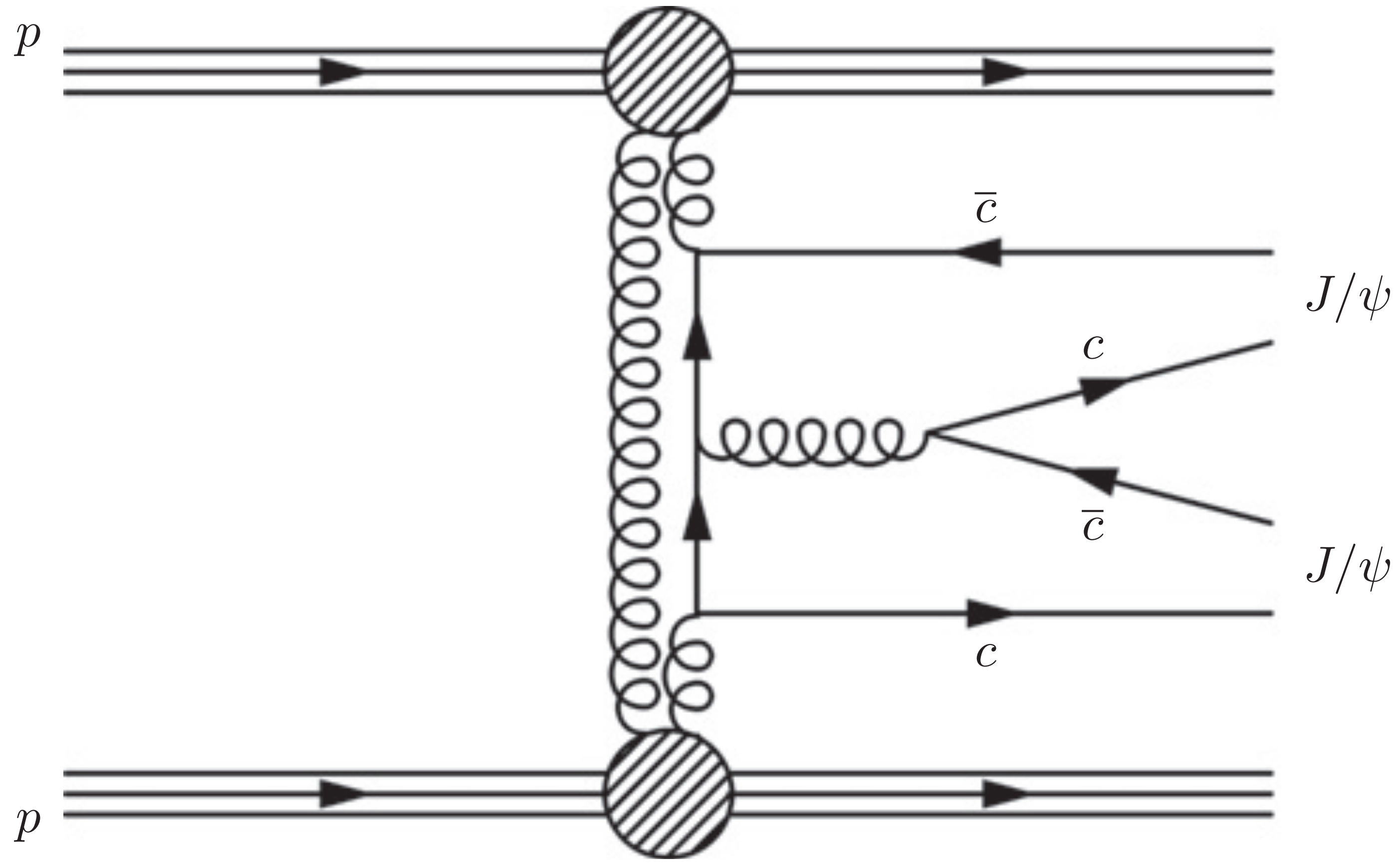
Neglect low-E_γ contribution.

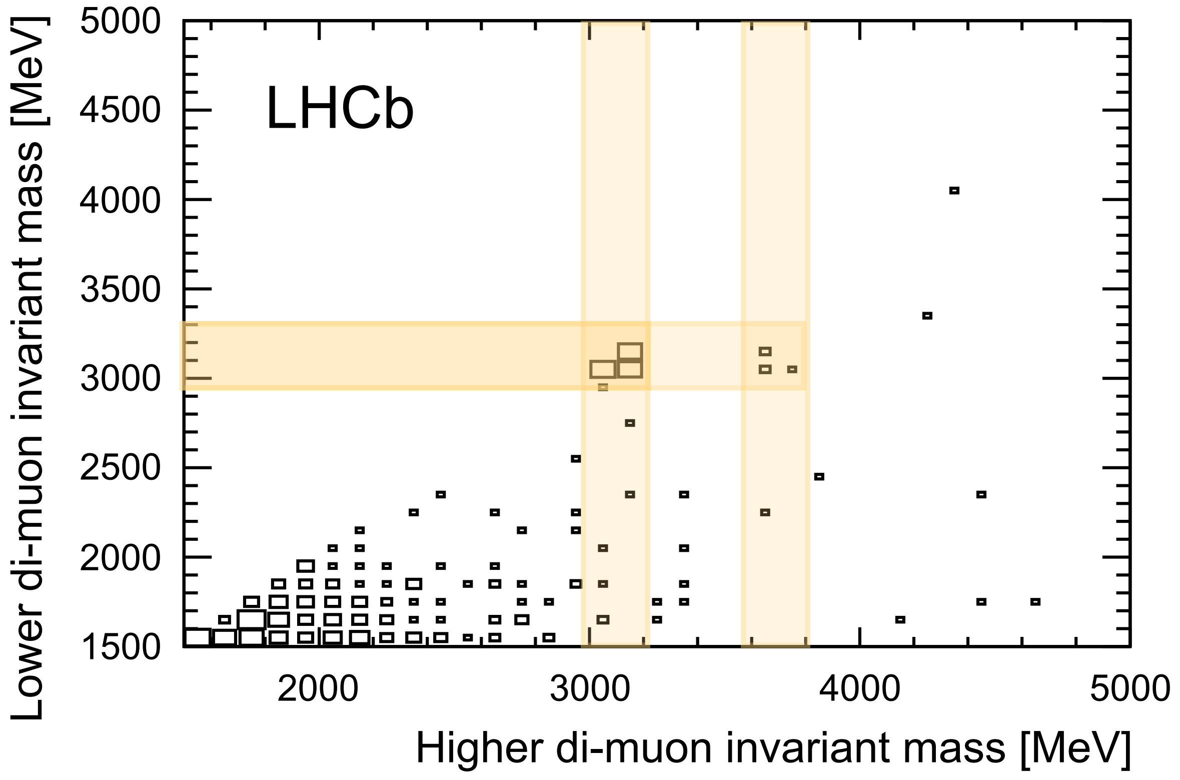
Production of charmonium pairs in pp

- sensitive to glueballs, tetraquarks
- sensitive to gluon distribution $\propto [g(x_B)]^4$

- 7 and 8 TeV data
- $J/\psi J/\psi,\ J/\psi\psi(2S),\ \psi(2S)\psi(2S)$
- $\chi_{c0}\chi_{c0},\ \chi_{c1}\chi_{c1},\ \chi_{c2}\chi_{c2}$

- $\chi_c \to J/\psi\gamma$
- $J/\psi,\ \psi(2S) \to \mu^+\mu^-$
- $2.0 < \eta_{\mu^+\mu^-} < 4.5$





cross sections: not corrected for proton dissociation

$$\sigma^{J/\psi J/\psi} = 58 \pm 10(\text{stat}) \pm 6(\text{syst})\ \text{pb}$$
$$\sigma^{J/\psi\psi(2S)} = 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\ \text{pb}$$
$$\sigma^{\psi(2S)\psi(2S)} < 237\ \text{pb}$$
$$\sigma^{\chi_{c0}\chi_{c0}} < 69\ \text{nb}$$
$$\sigma^{\chi_{c1}\chi_{c1}} < 45\ \text{pb}$$
$$\sigma^{\chi_{c2}\chi_{c2}} < 141\ \text{pb}$$

42% CEP →

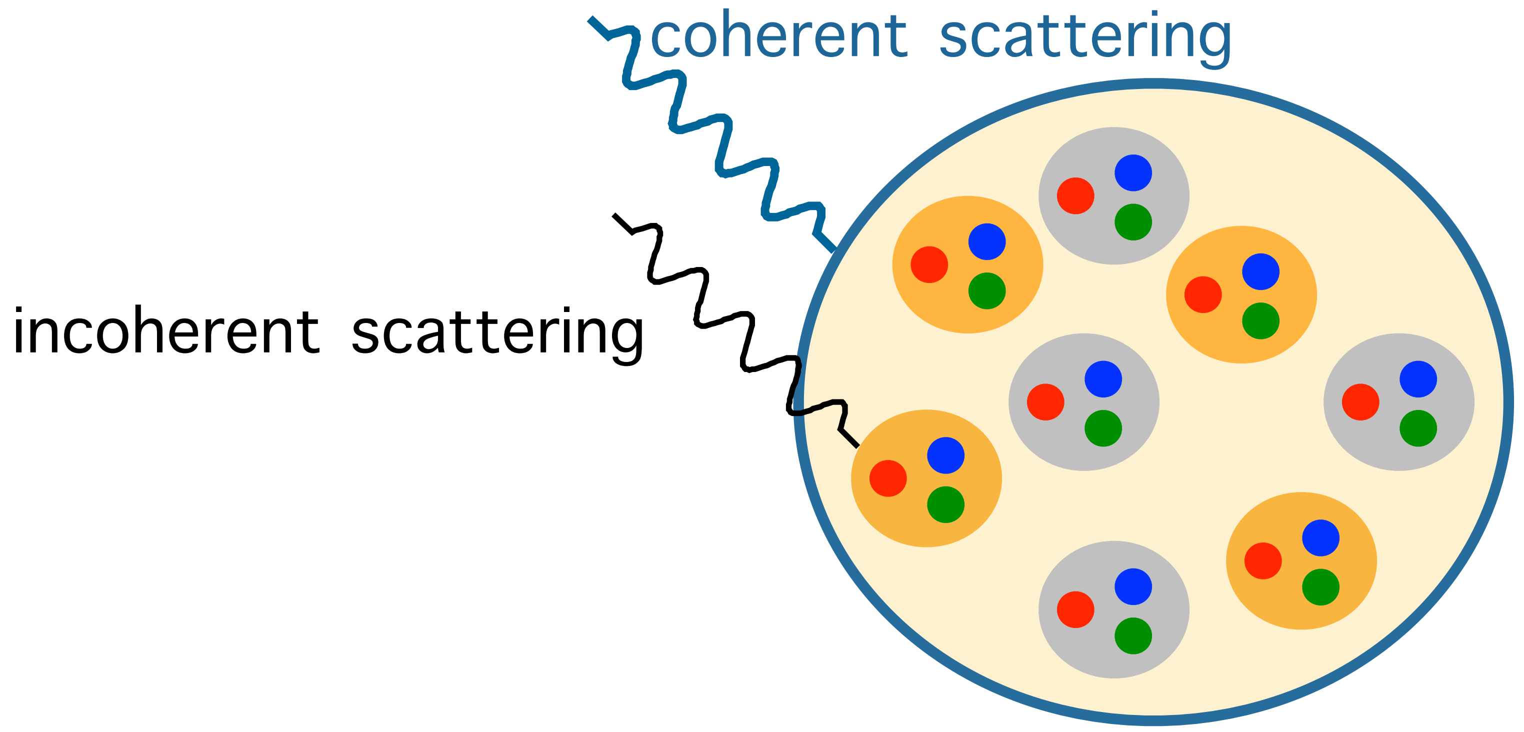
corrected for proton dissociation

$$\sigma^{J/\psi J/\psi} = 24 \pm 9\ \text{pb}$$

J. Phys. G: Nucl. Part. Phys. 41 (2014) 115002

Coherent J/ψ in PbPb UPCs

Coherent J/ψ in PbPb UPCs

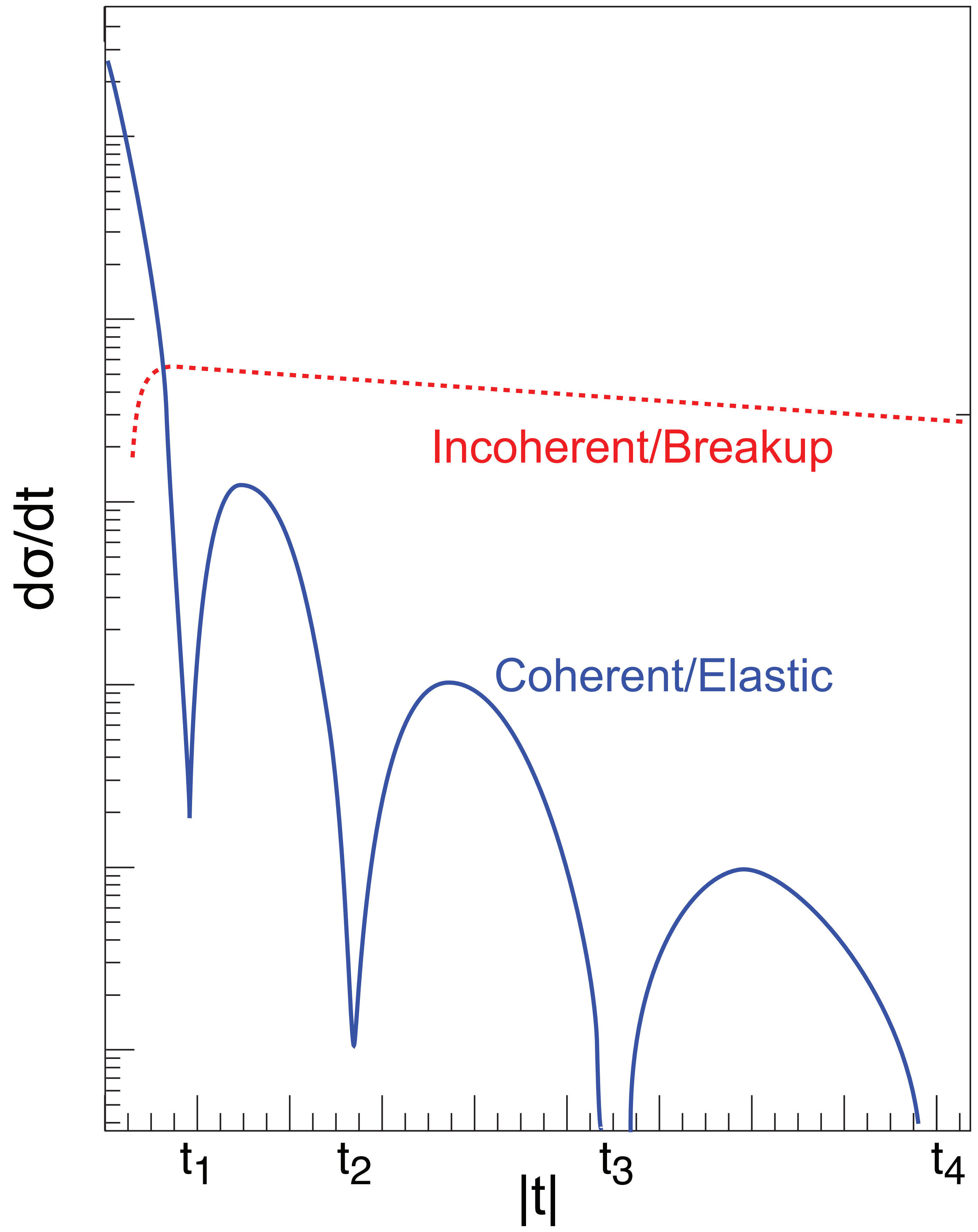


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Incoherent interaction: interaction with constituents inside target.
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

Experimental important points

- Good separation of coherent and incoherent production. Not easy!



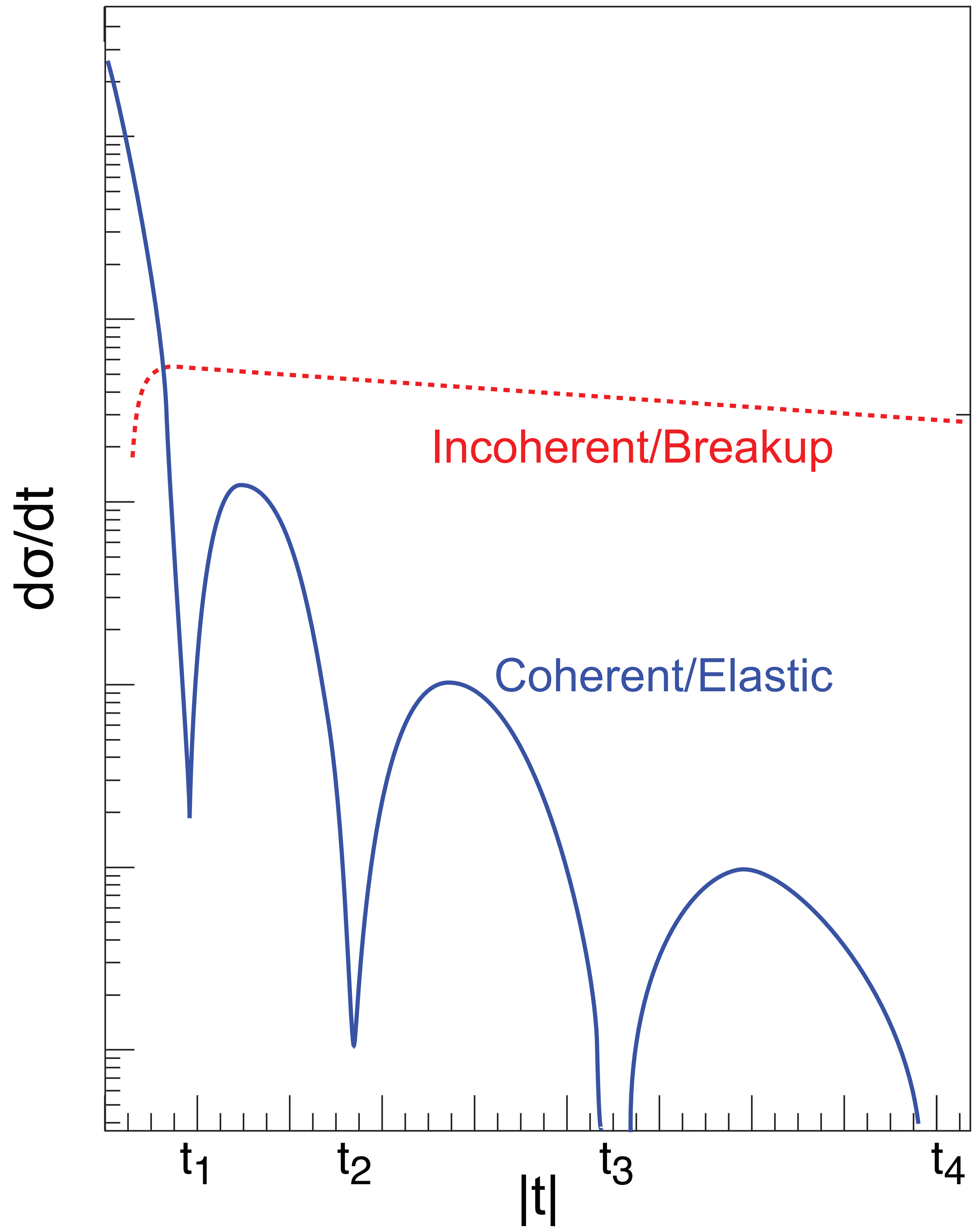
t= squared momentum transfer to target

Experimental important points

- Good separation of coherent and incoherent production. Not easy!
- Coherent production: measurements up to large t:
  - 3D or 2D (x independent) transverse position

$$\int_0^{\infty} d\Delta_\perp \; \mathrm{GPD}(x, 0, \Delta_\perp) \; e^{-ib_\perp \Delta_\perp}$$

Experimentally limited by maximum transverse momentum.
Need to extend p_T range as much as possible in measurement.
~third diffractive minimum.



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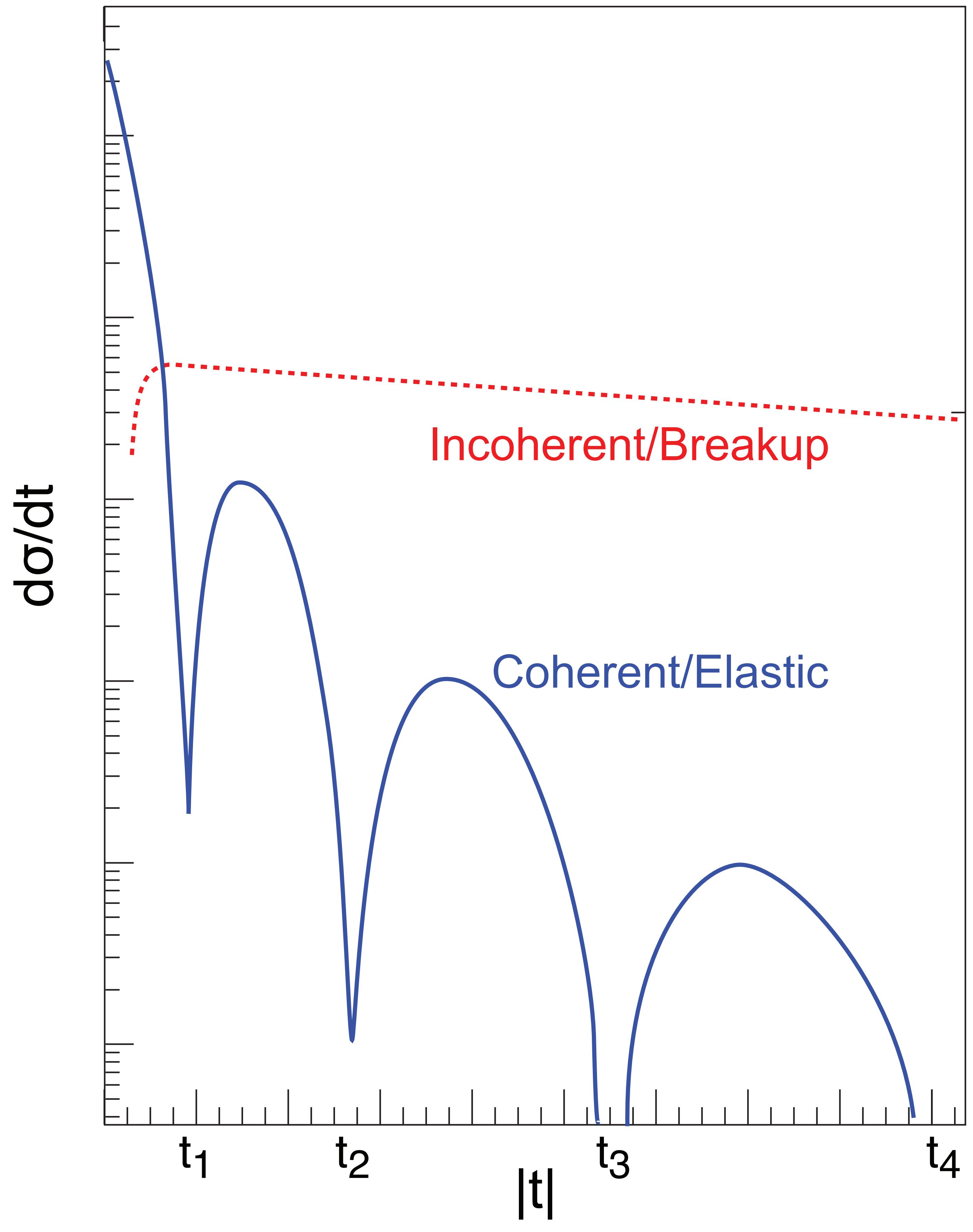
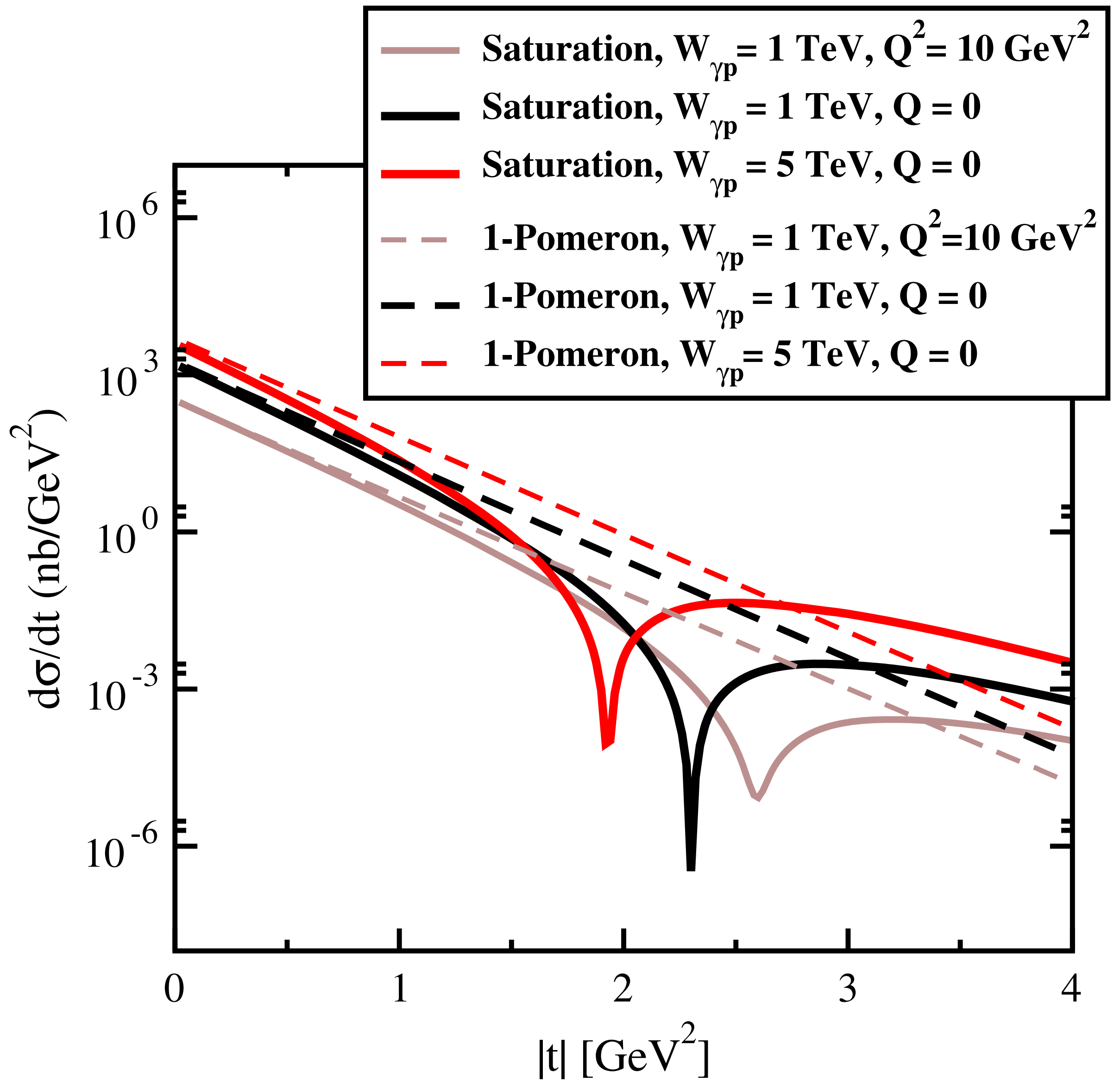


t= squared momentum transfer to target

- Saturation:

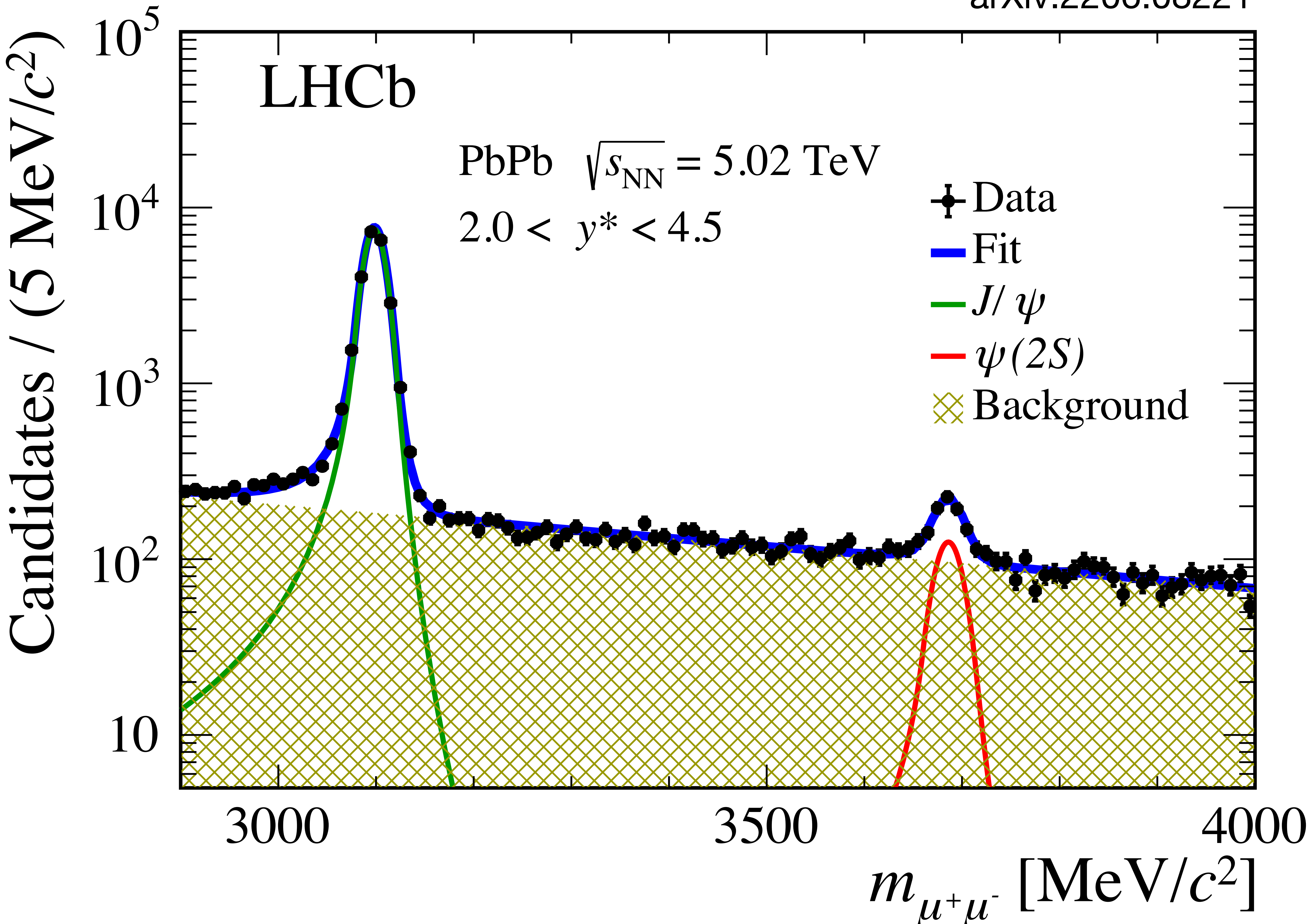
  determine dip position indirectly via slope and probe its dependence With $W_{\gamma p}$



Coherent J/ψ in PbPb UPCs – selection

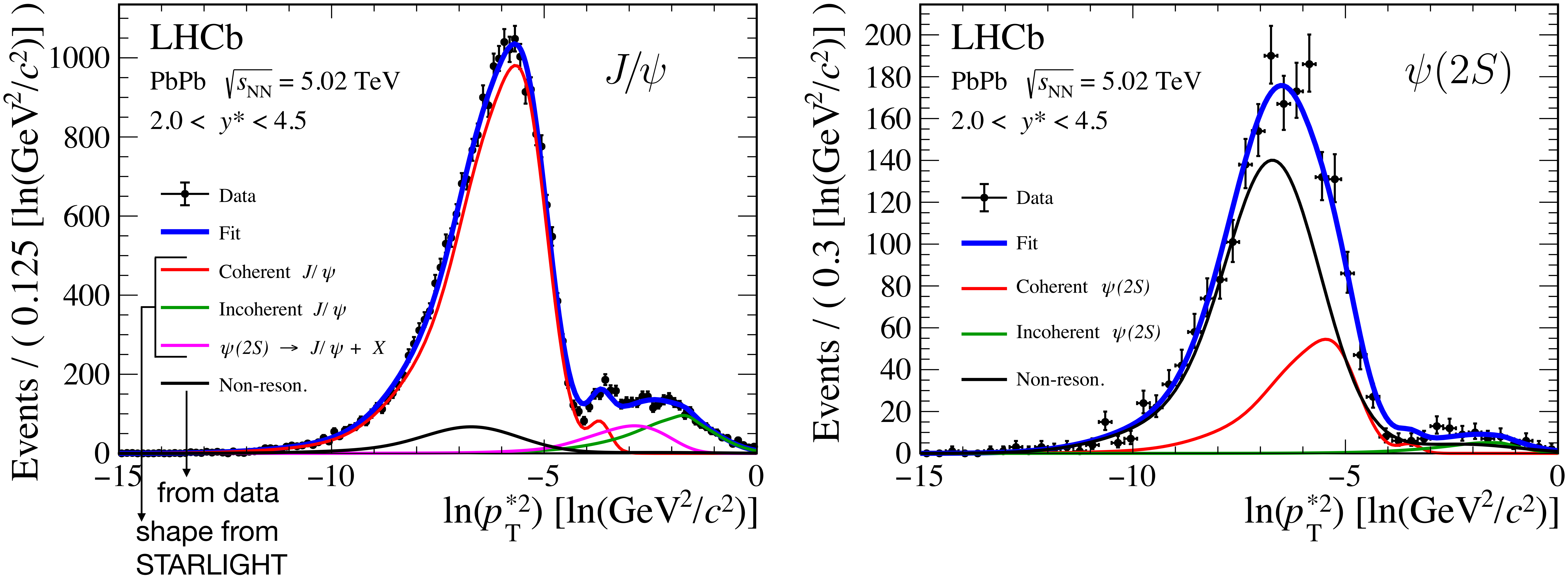
- $\sqrt{s_{NN}} =$ 5.02 TeV data.
- $L_{\rm int} = 228 \pm 10 \mu{\rm b}^{-1}$
- Reconstruction via dimuon decay, with offline selection: $2<\eta_{\mu}<4.5$ and $p_{T,\mu}>$ 700 MeV
- $2<y_{J/\psi}<4.5$ → x_B down to 10^{-5}
- $p_T<1$ GeV

arXiv:2206.08221



Coherent J/ψ in PbPb UPCs – p_T distribution

arXiv:2206.08221



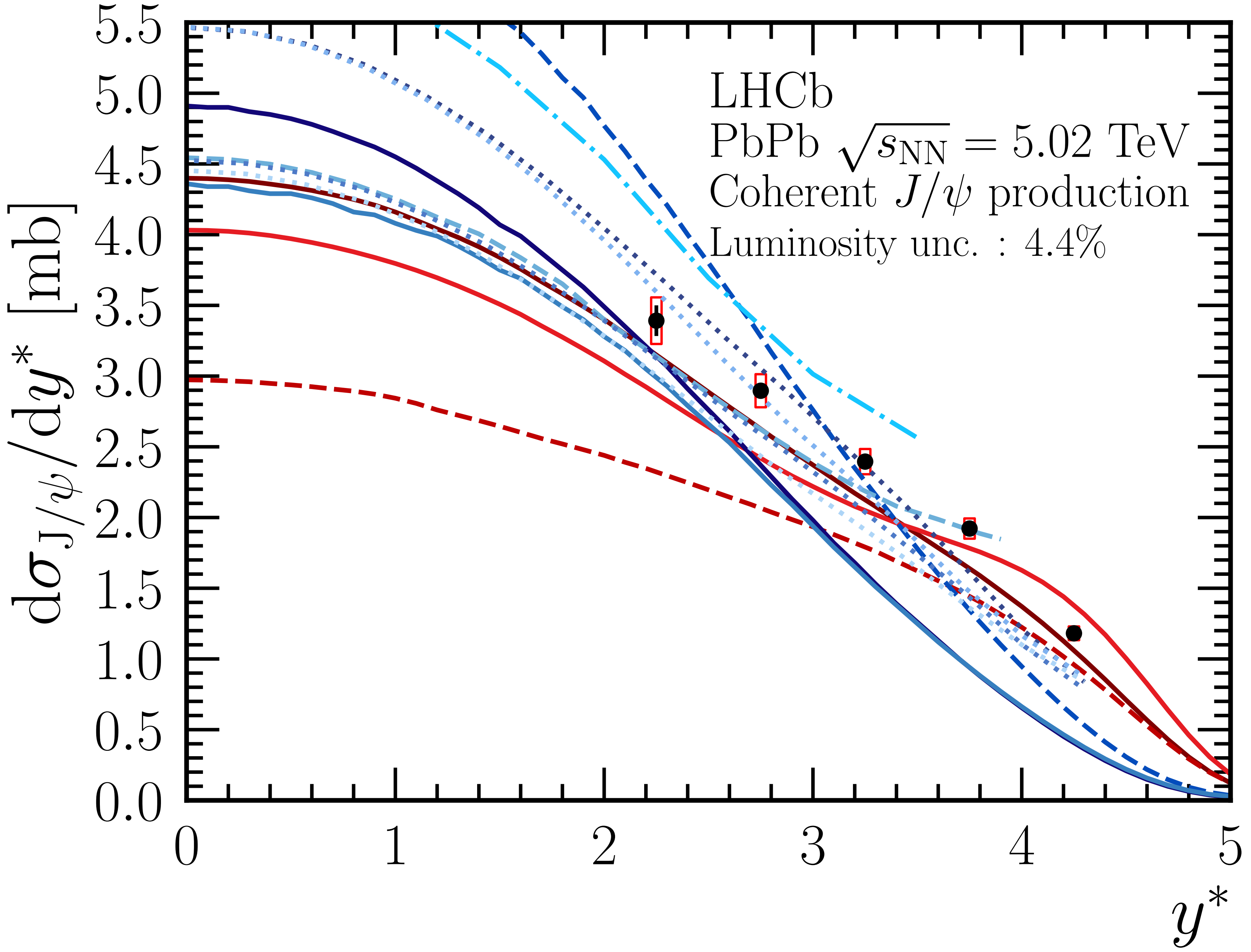
(y-dependent) PbPb cross section of coherent ψ production

$$\frac{d\sigma}{dy} = \frac{n_{\text{coh}}}{\varepsilon_y \, \Delta y \, \mathcal{L} \, \mathcal{B}}$$

efficiency

Luminosity sys. unc. 4.4%

$$\sigma^{\text{coh}}_{J/\psi} = 5.965 \pm 0.059 \pm 0.232 \pm 0.262 \, \text{mb}$$
$$\sigma^{\text{coh}}_{\psi(2S)} = 0.923 \pm 0.086 \pm 0.028 \pm 0.040 \, \text{mb}$$



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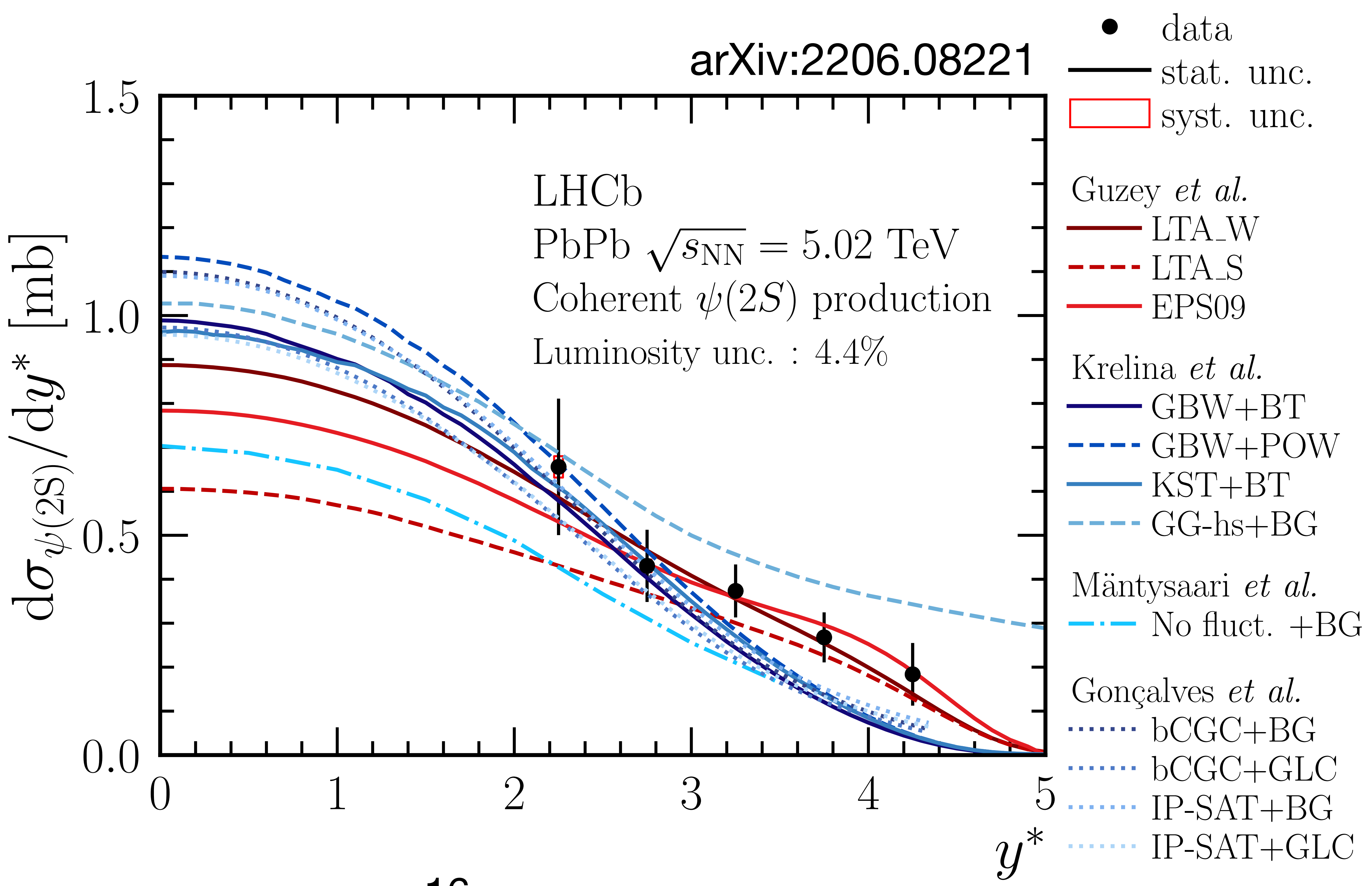

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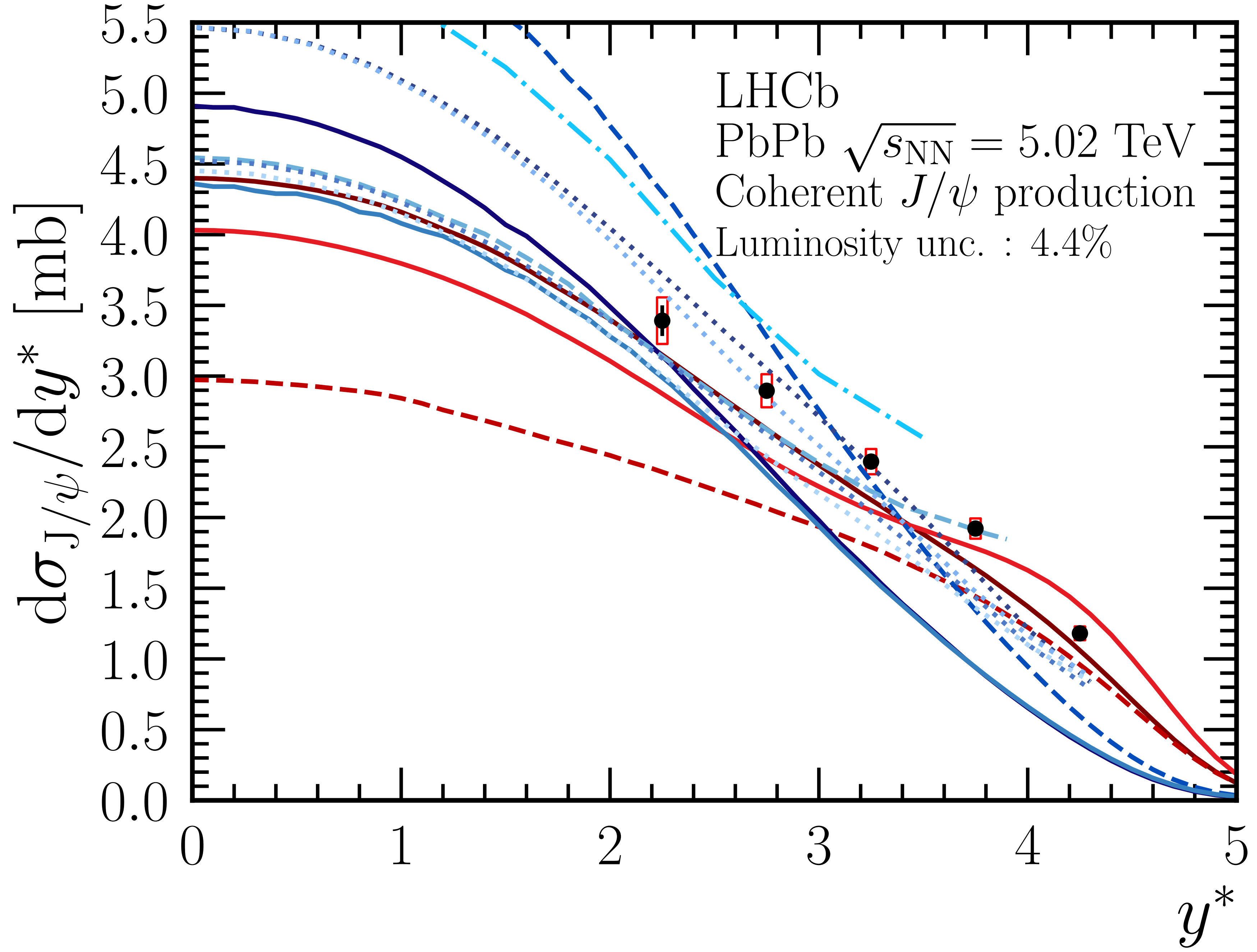

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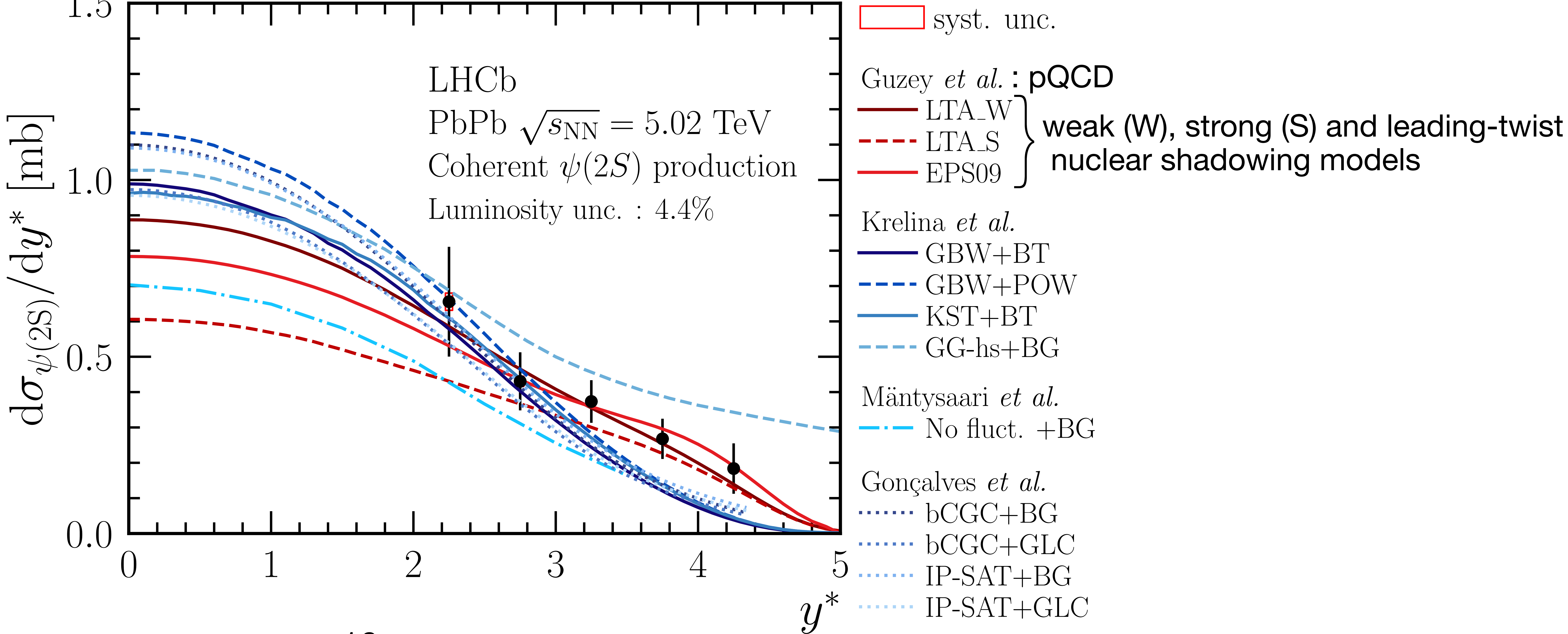

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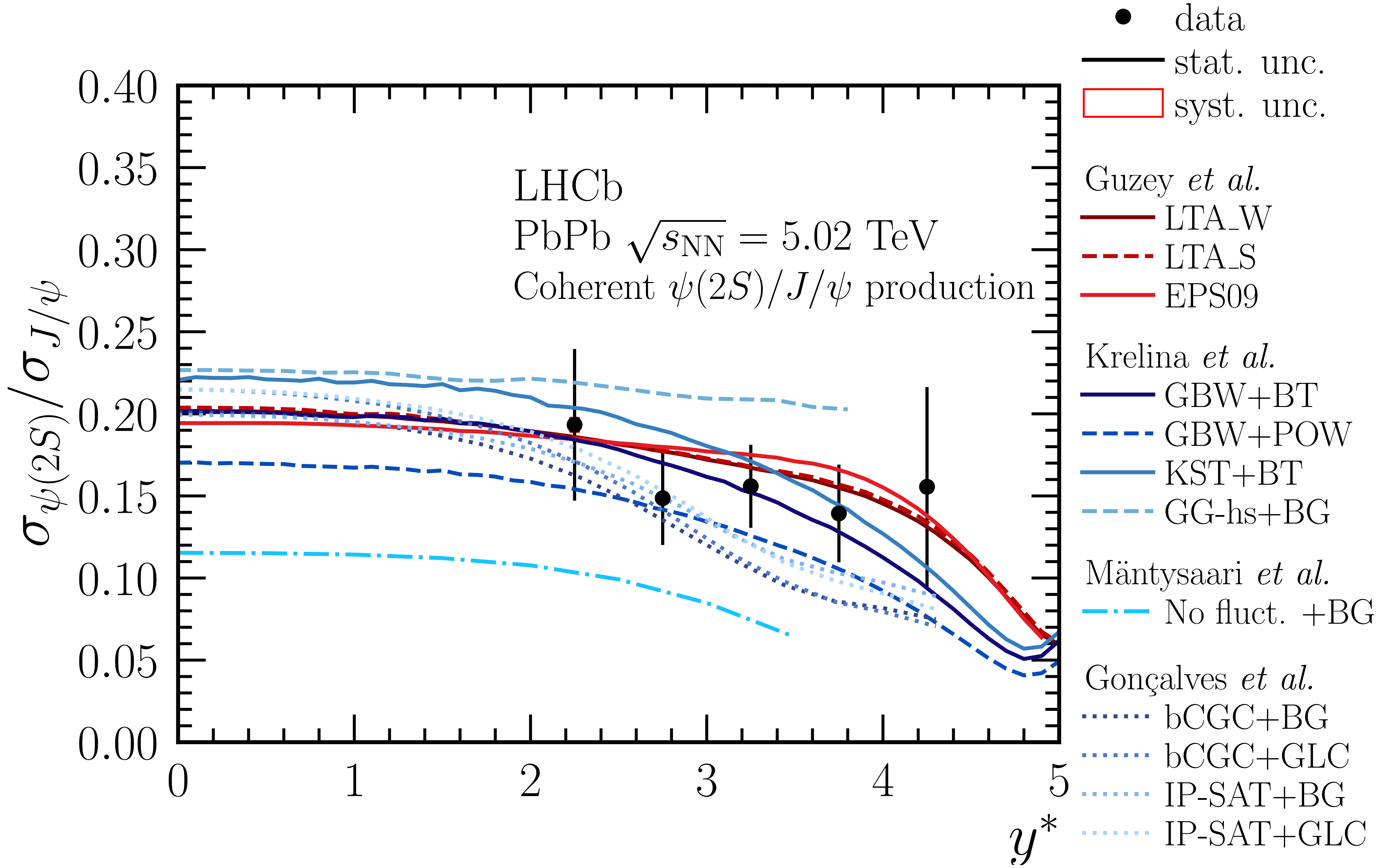
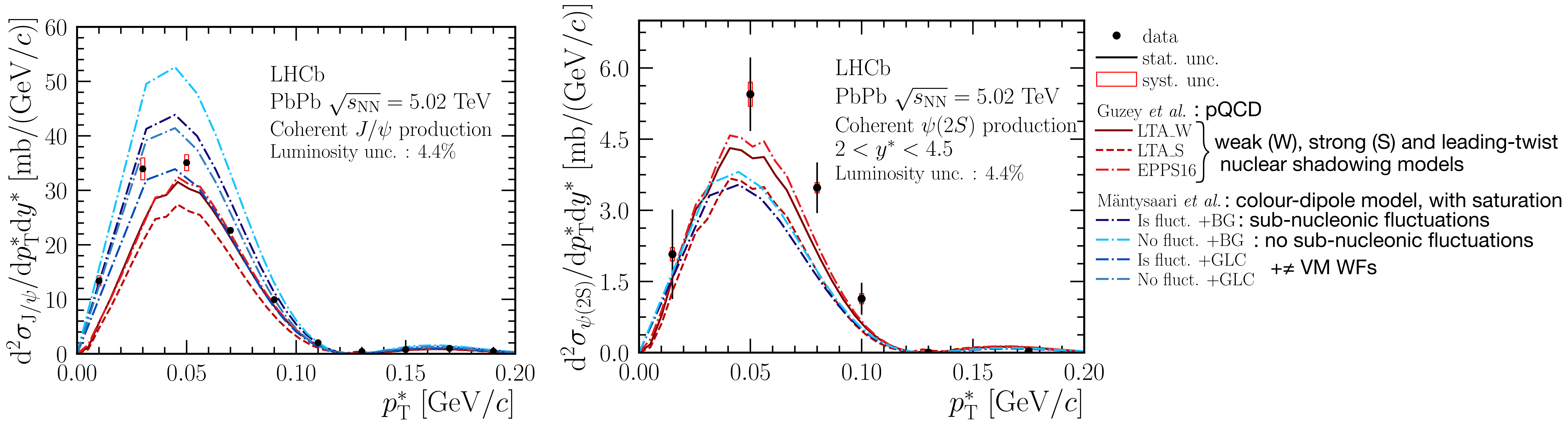
ψ(2S)/J/ψ (y-dependent) cross-section ratio

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

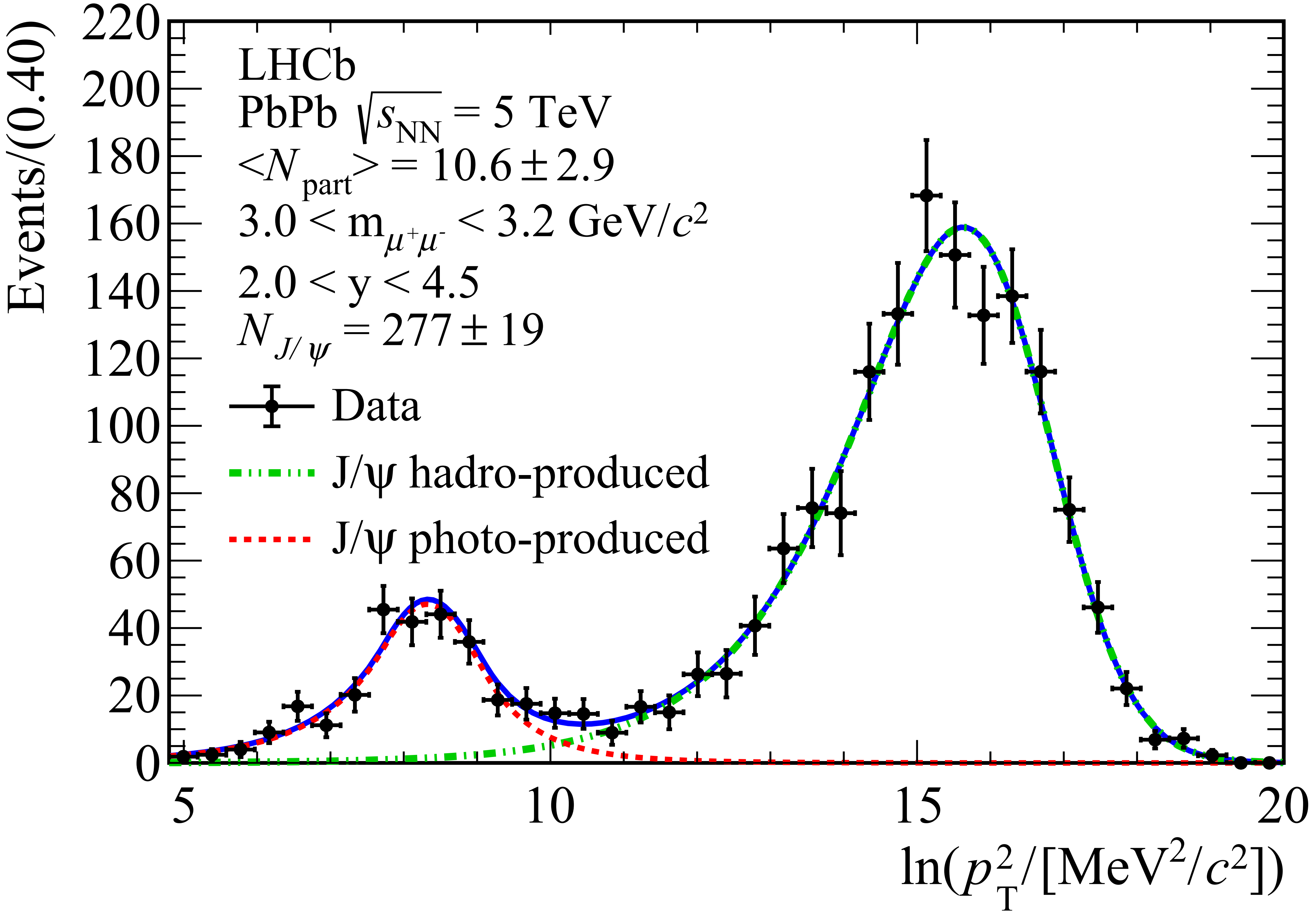


(p_T-dependent) PbPb cross section of coherent J/ψ production



Related: coherent J/ψ production in peripheral PbPb collisions

- $\sqrt{s_{NN}}$ =5 TeV data.
- $L_{\text{int}} = 210\ \mu b^{-1}$
- Reconstruction via dimuon decay, with: $2<\eta_\mu<4.5$
- $2<y_{J/\psi}<4.5$



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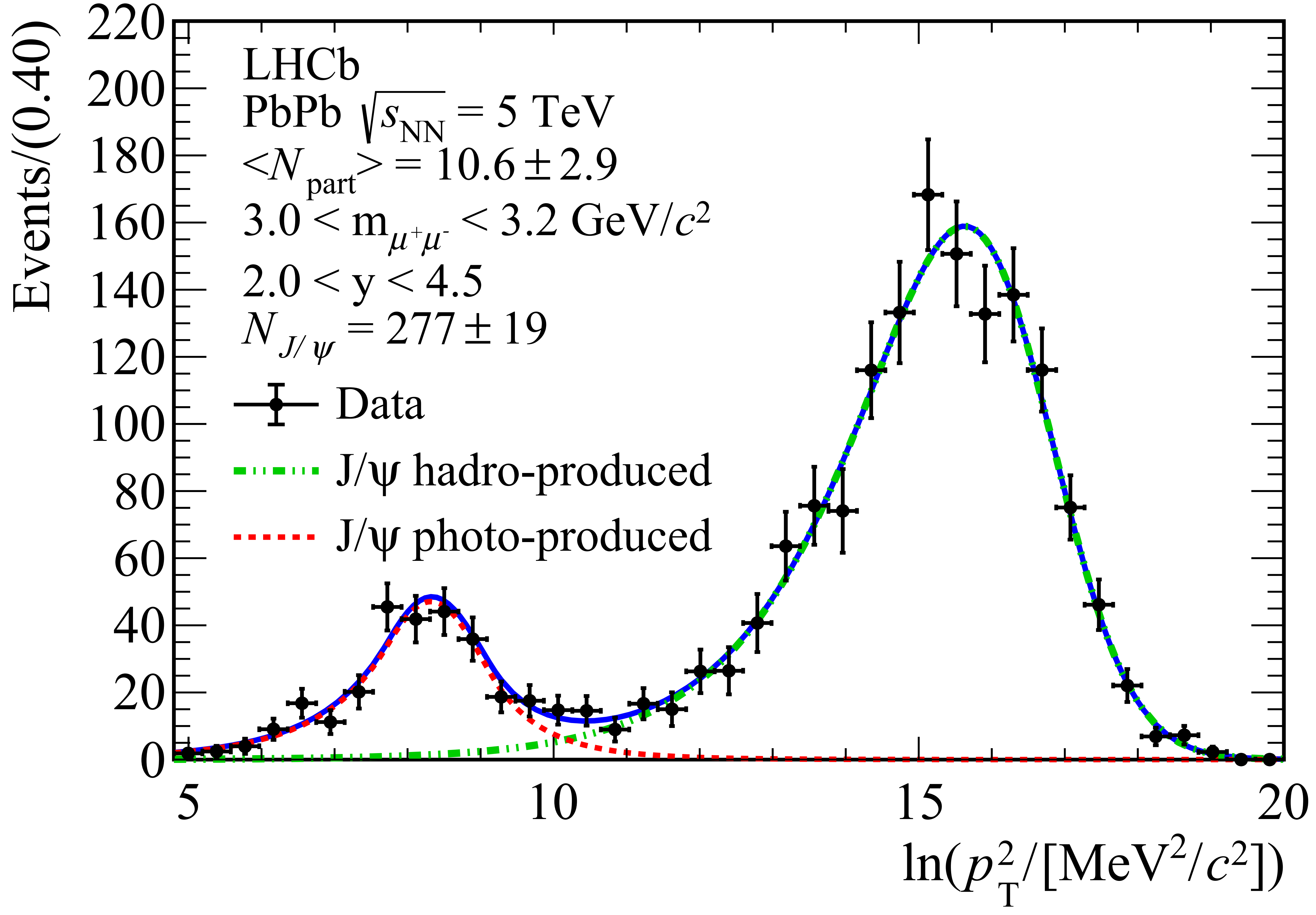
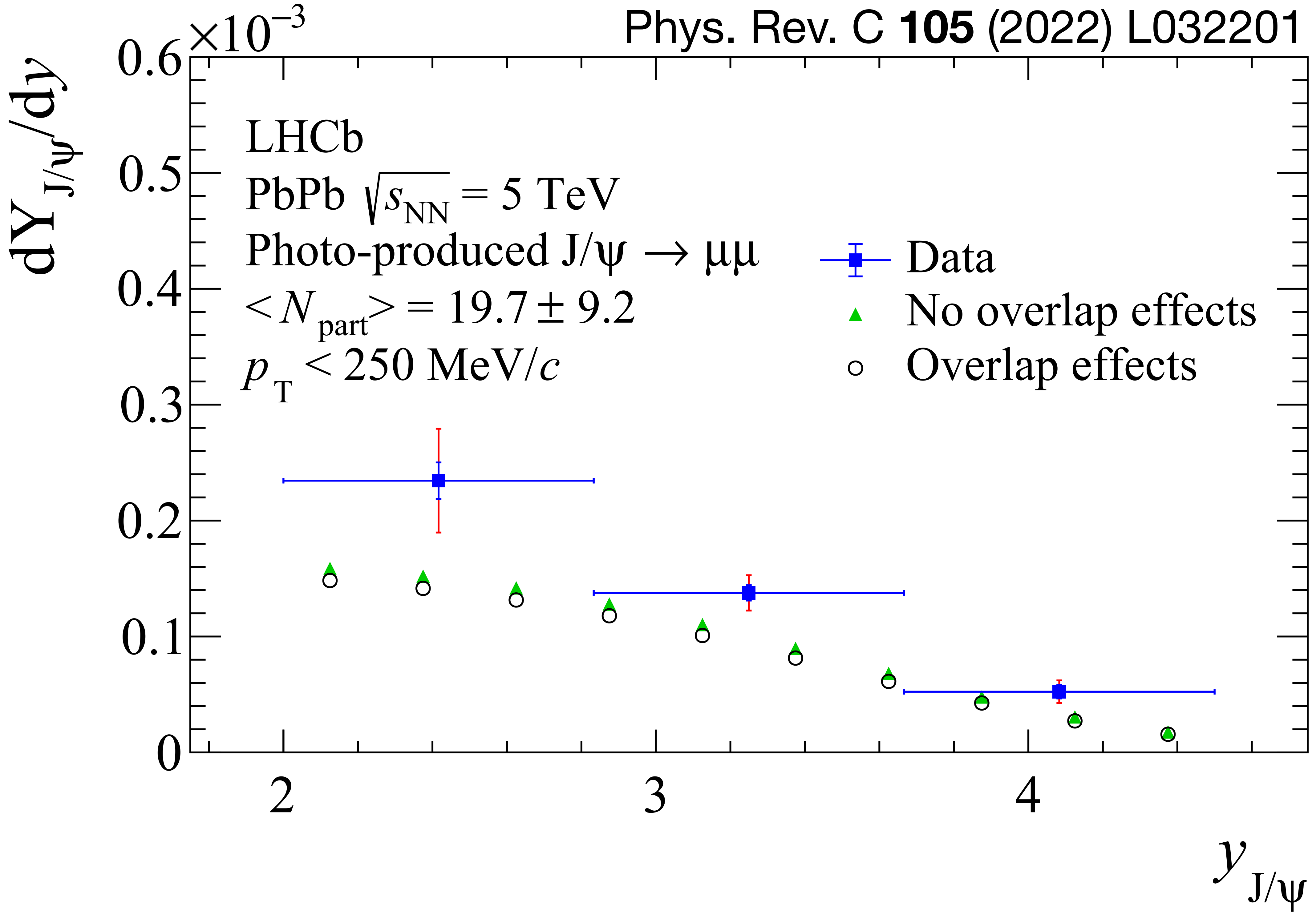




Summary…

- Exclusive production in hadron-hadron collisions: rich field of physics

- Exclusive single-quarkonium production in pp:
  - high potential to constrain GPDs and PDFs at very low-x.
  - probe universality

- Exclusive single-quarkonium production in PbPb:
  - access to nuclear PDFs and GPDs
  - probe to saturation

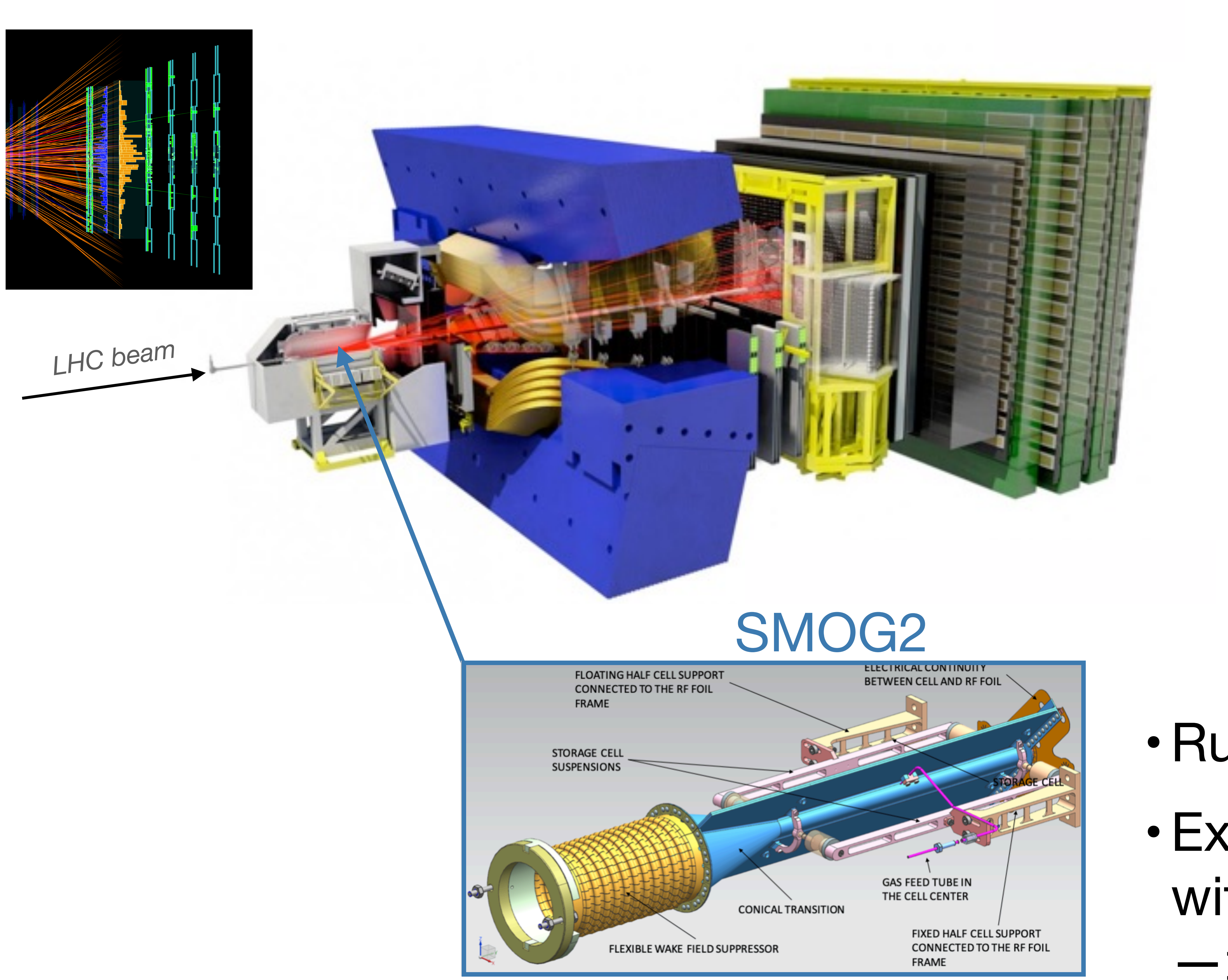
- Additional on-going analysis for exclusive production in pp, pPb and PbPb collisions

and outlook I

- Future data taking for exclusive measurements in hadron-hadron collisions
  - pp collisions: very difficult (impossible?), since too many interactions per bunch crossing. Dedicated runs?
  - pPb collisions: possible and highly desired:
    - Highly reduced ambiguity in ID of photon emitter
    - Direct ratio of Pb to p in same measurements: much cleaner.
  - PbPb collisions: possible and interesting for nuclear studies and potentially saturation
    - Might consider installing a ZDC for improved measurements in purity and t reach

and outlook II

- Future data taking for exclusive measurements in fixed-target mode



- Run 3: injection of unpolarised He, Ne, Ar, and H_2, D_2
- Expected total uncertainty on exclusive cross section with p beam: 5-10%
  —> constrain nucleon and nuclear GPDs in high-x region

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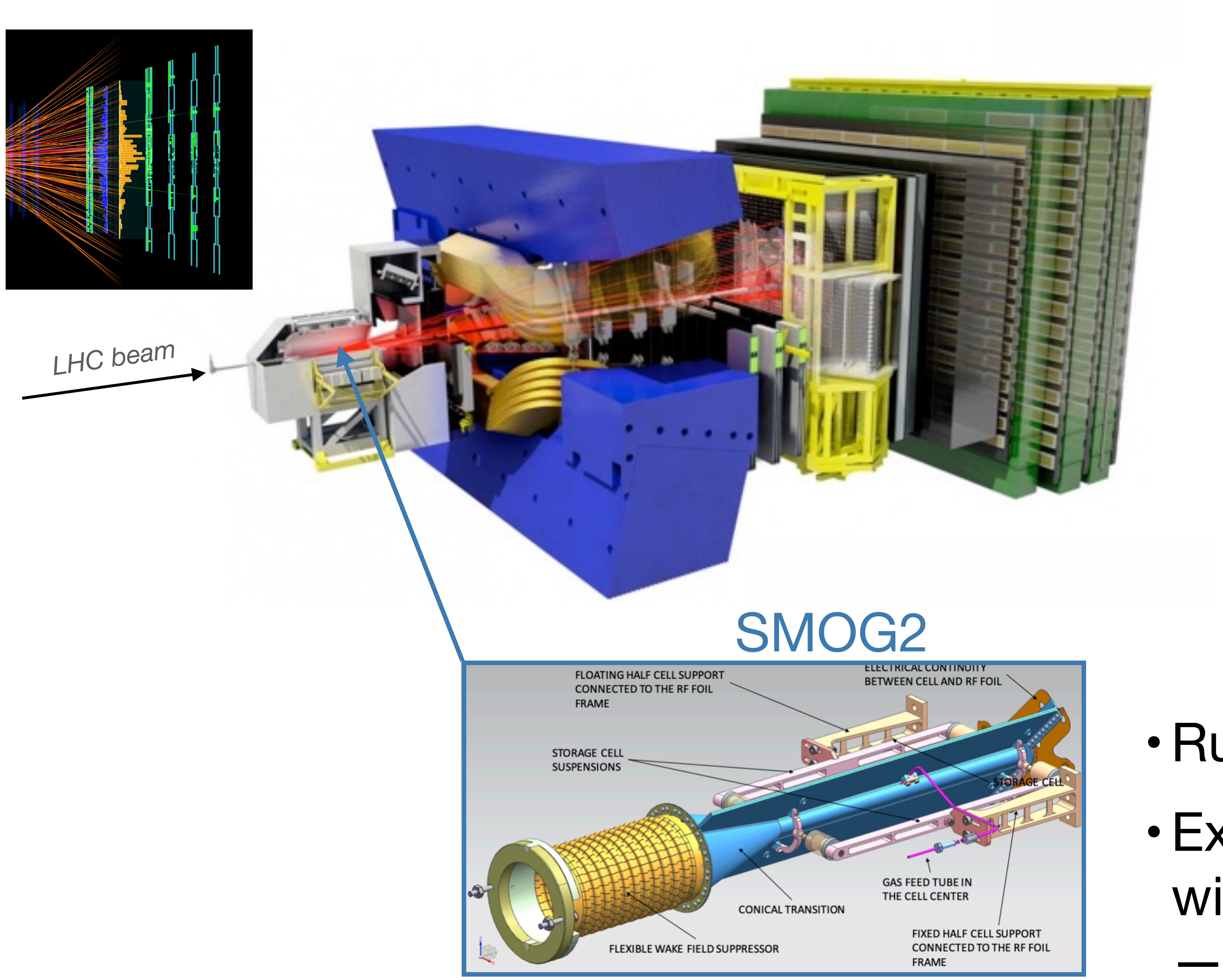
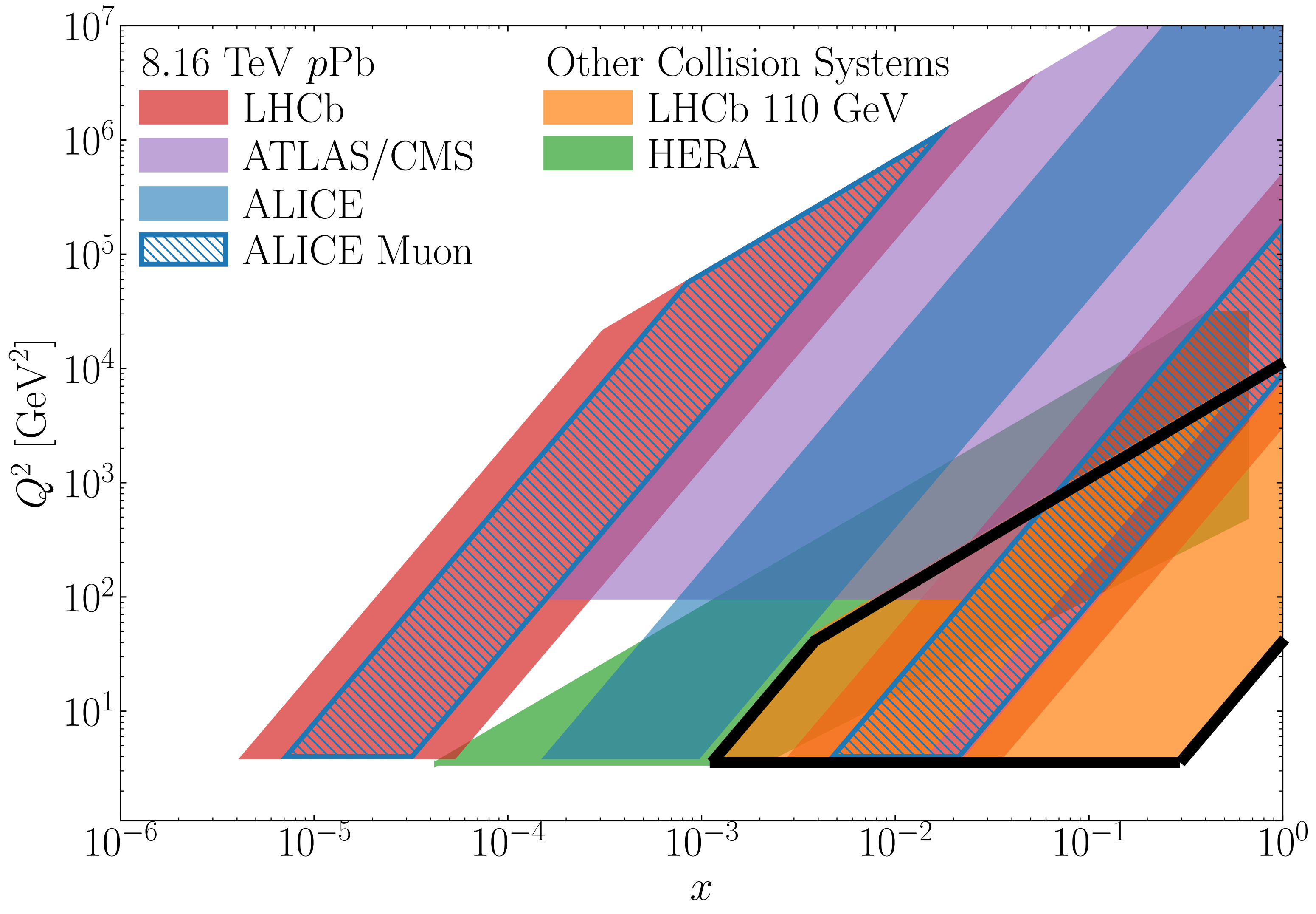


⟶ Access to barely explored high-x region:



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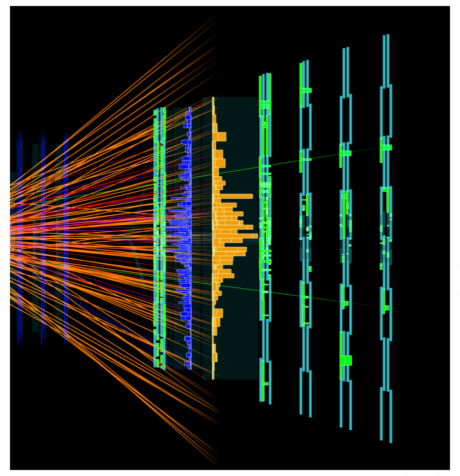
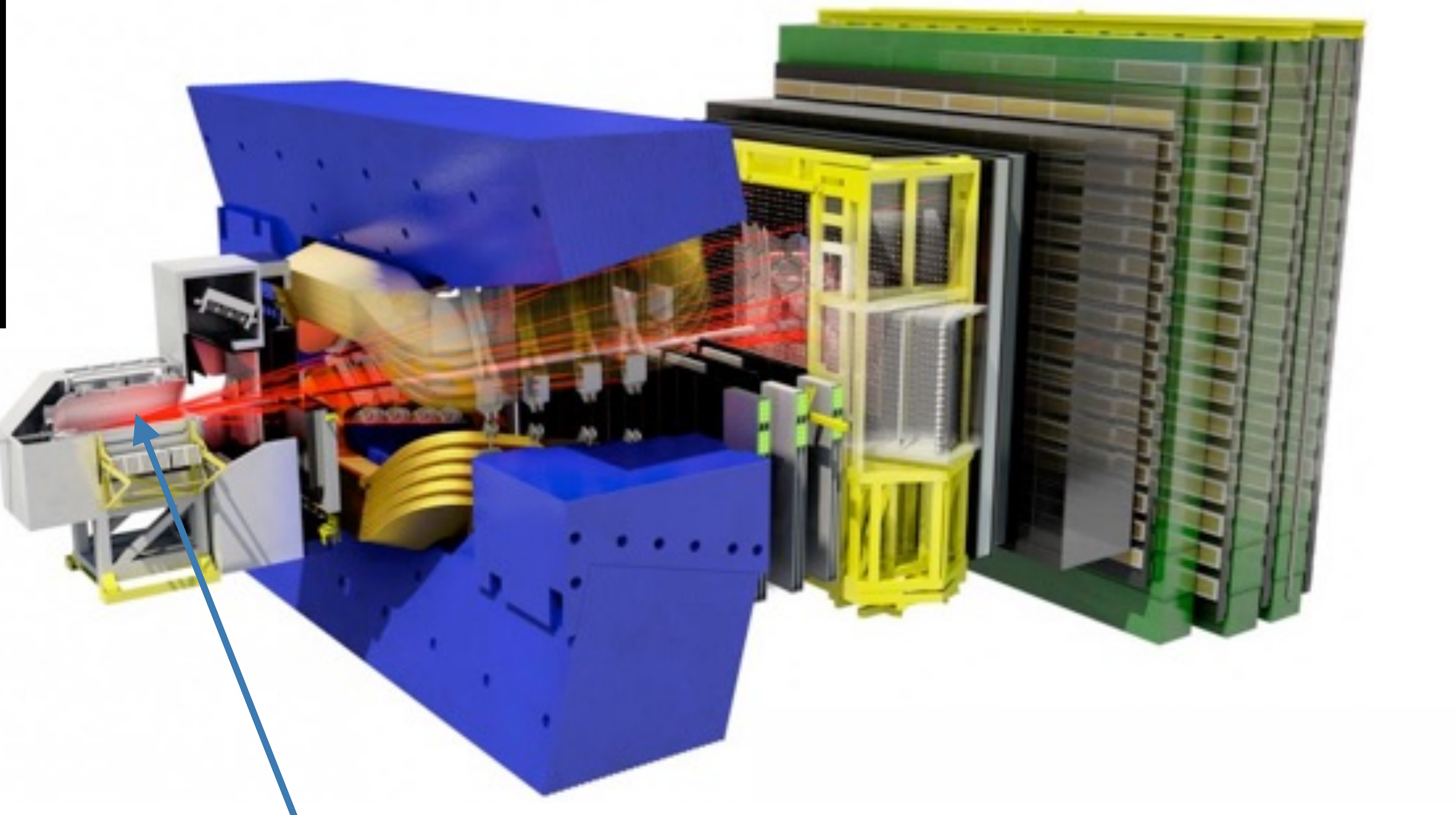
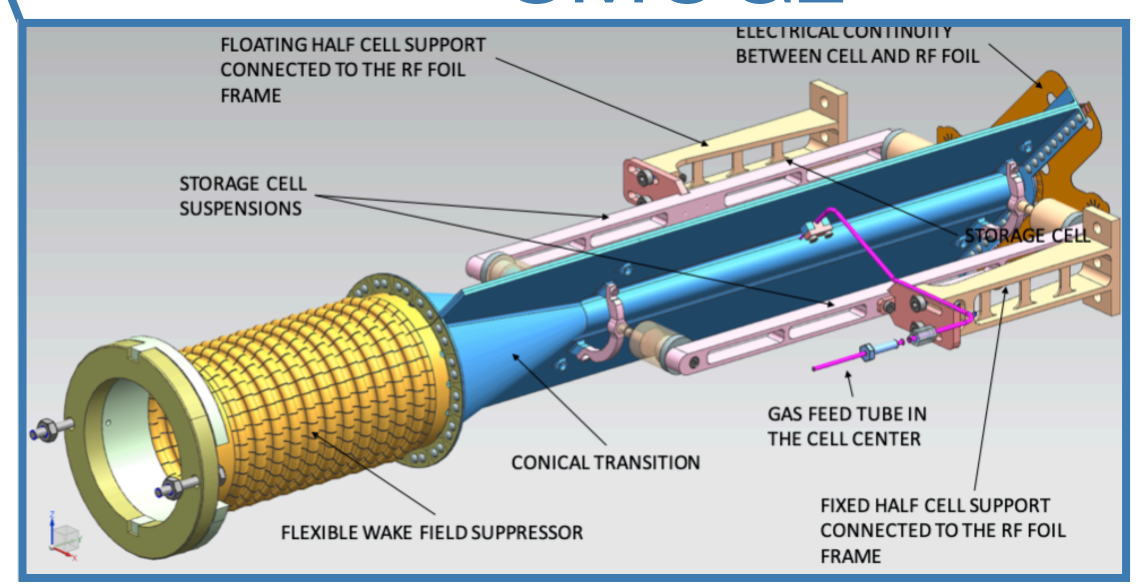




SMOG2



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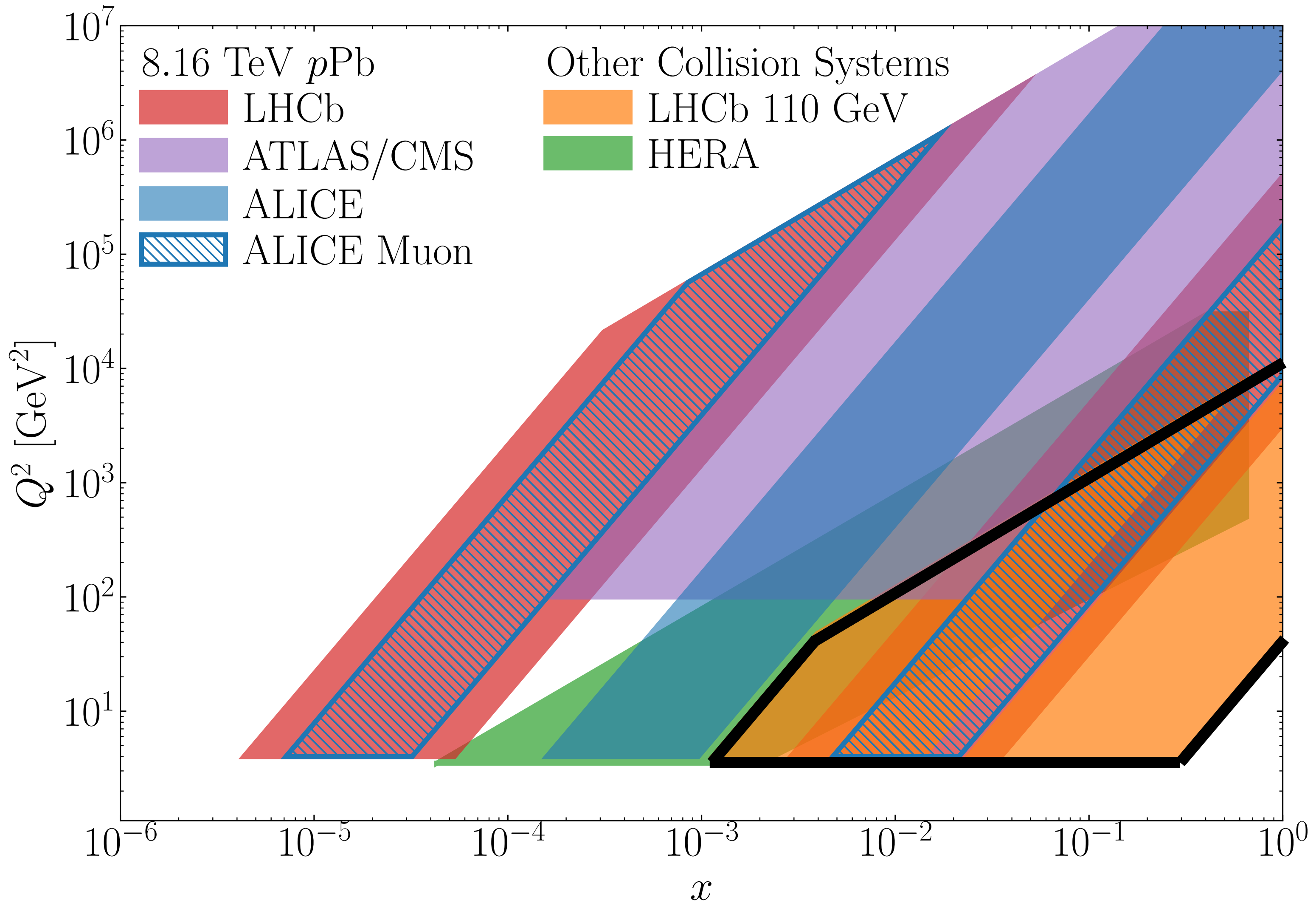

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- Expected total uncertainty on exclusive cross section with p beam: 5-10%
  —> constrain nucleon and nuclear GPDs in high-x region
- Proposal for Run 4:
- LHCSPIN: transversely polarised gas target
  ⟶ access to spin-dependent GPDs
  (orbital angular momentum)