Exclusive measurements at LHC sensitive to GPDs

Charlotte Van Hulse
University of Alcalá

AdT

Comunidad de Madrid

IWHSS
Prague, Czech Republic
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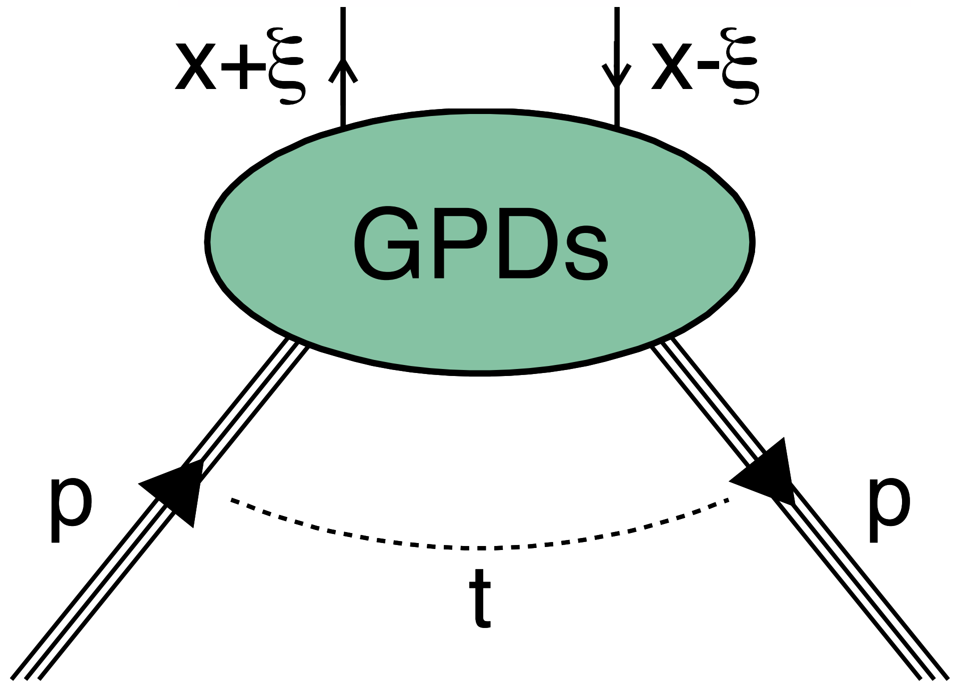
Experimental access to GPDs



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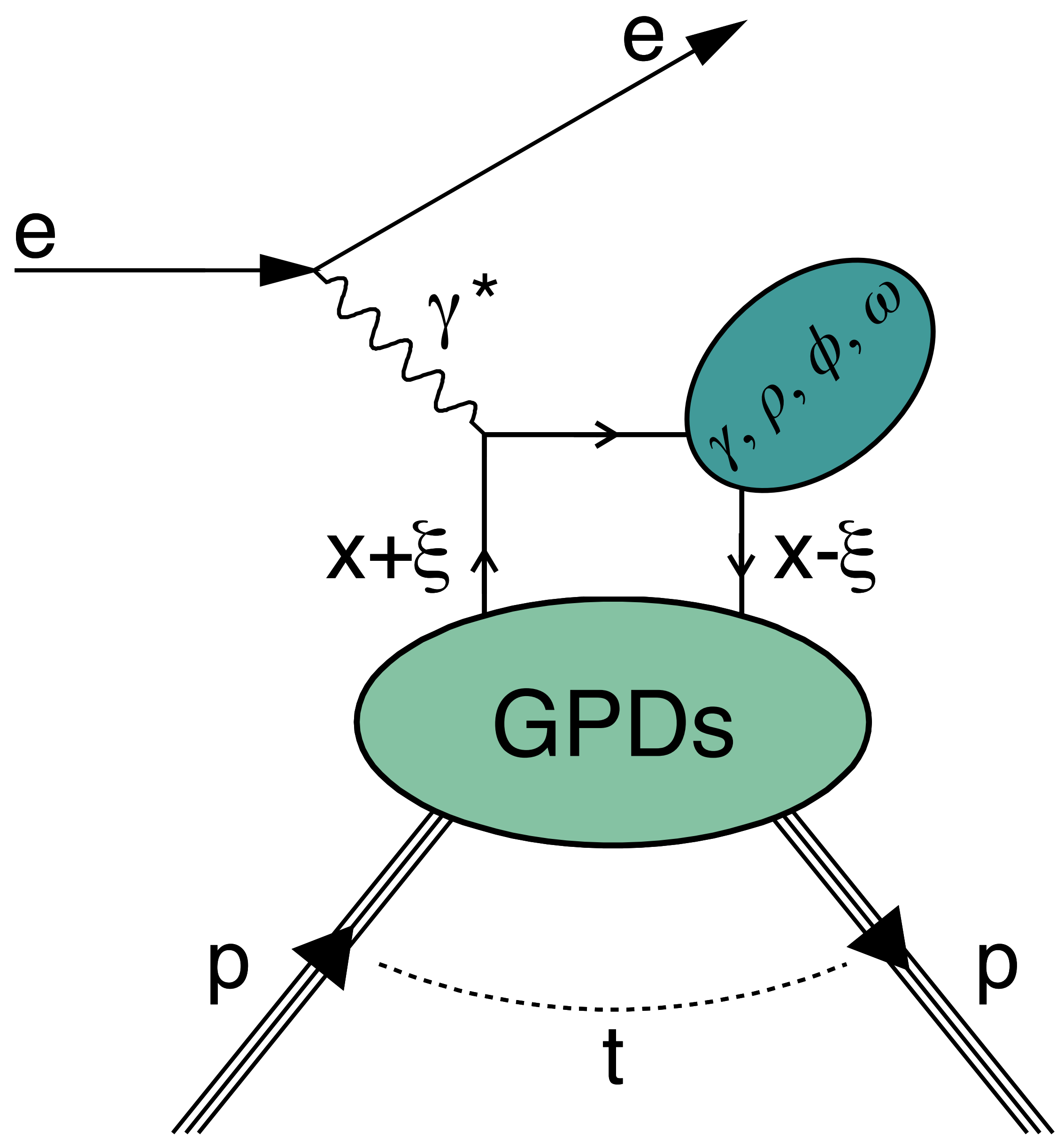

Hard scale=large Q^2

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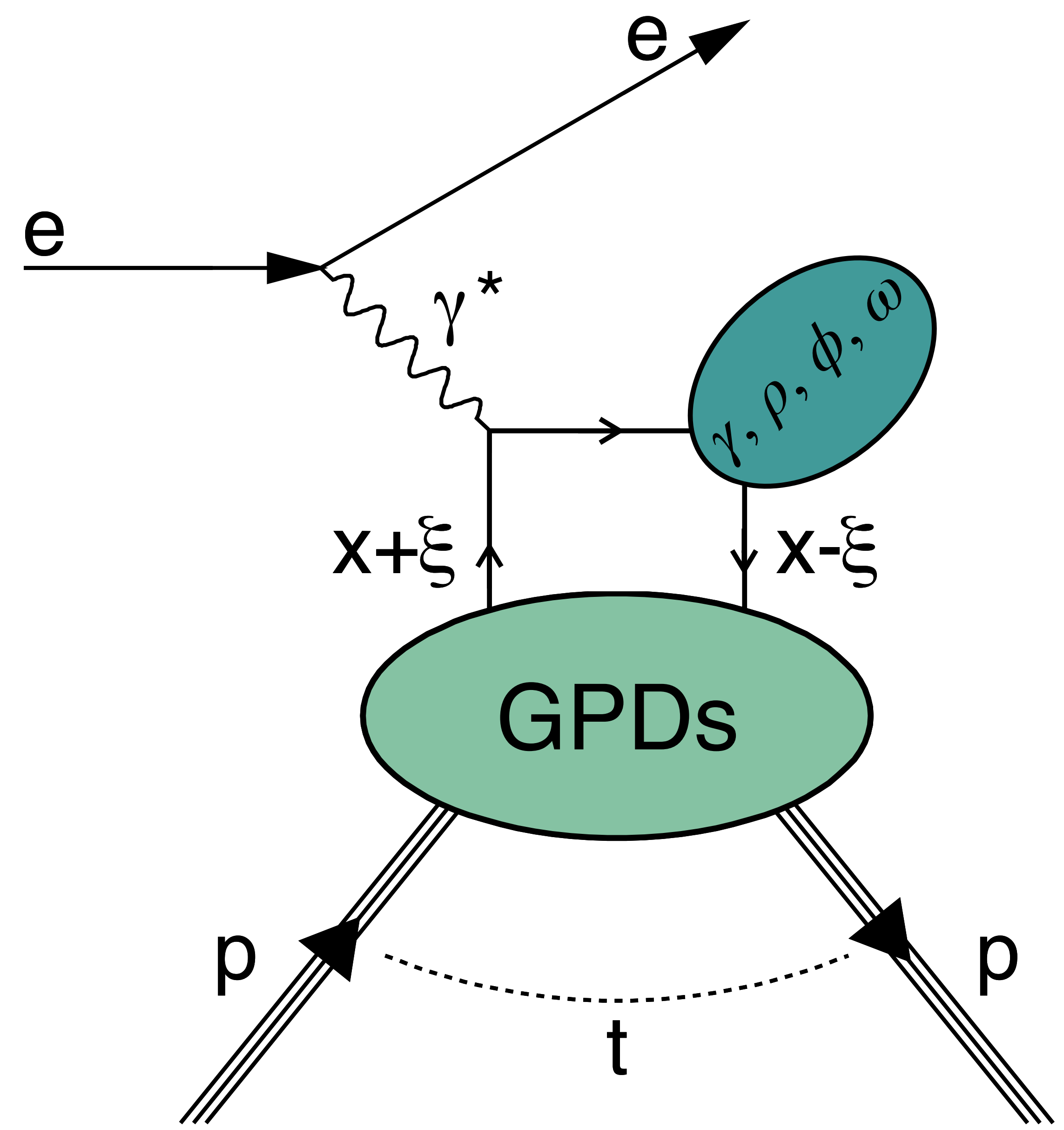


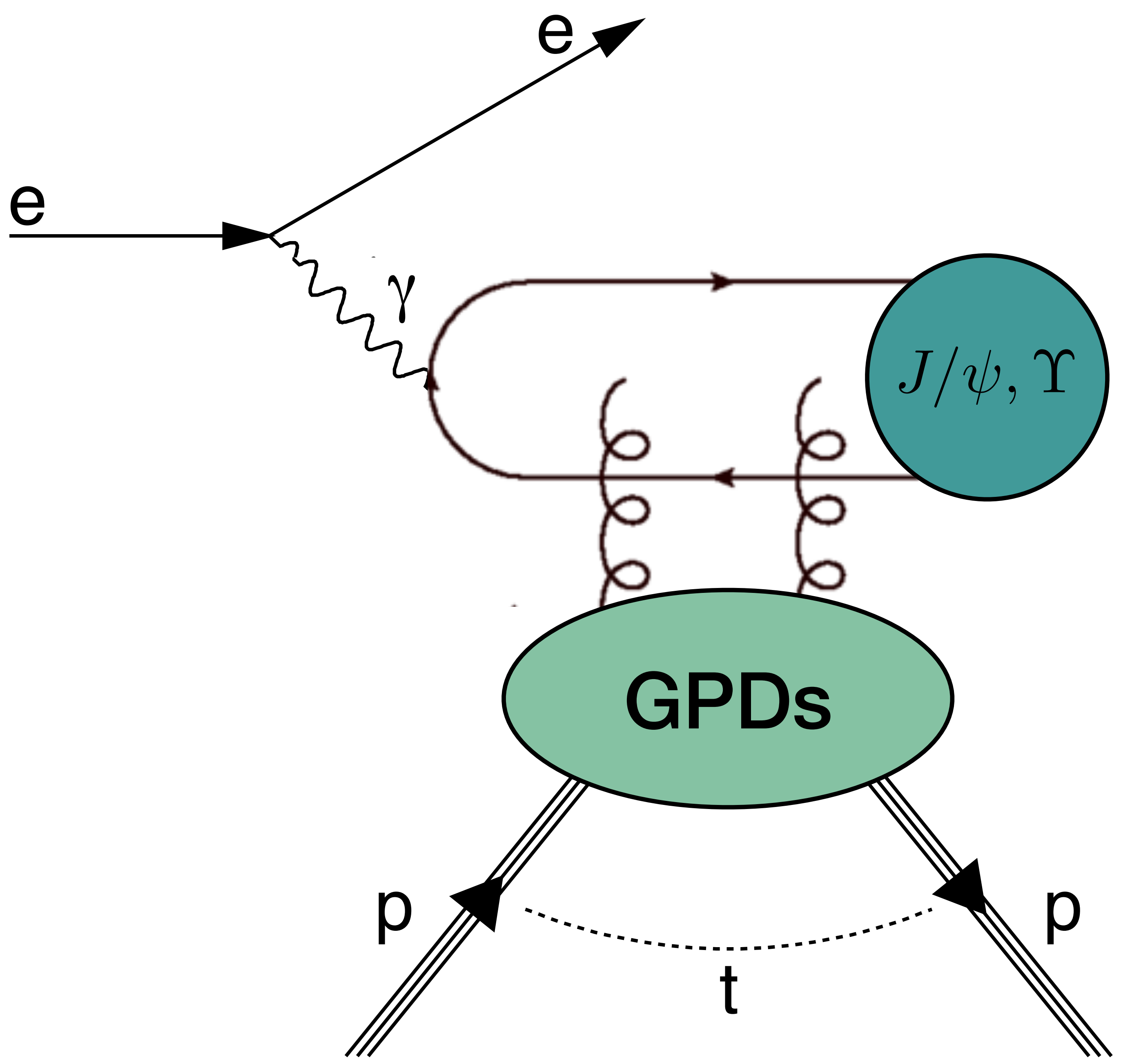
Hard scale=large Q^2

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

Experimental access to GPDs



Hard scale = large charm/bottom-quark mass

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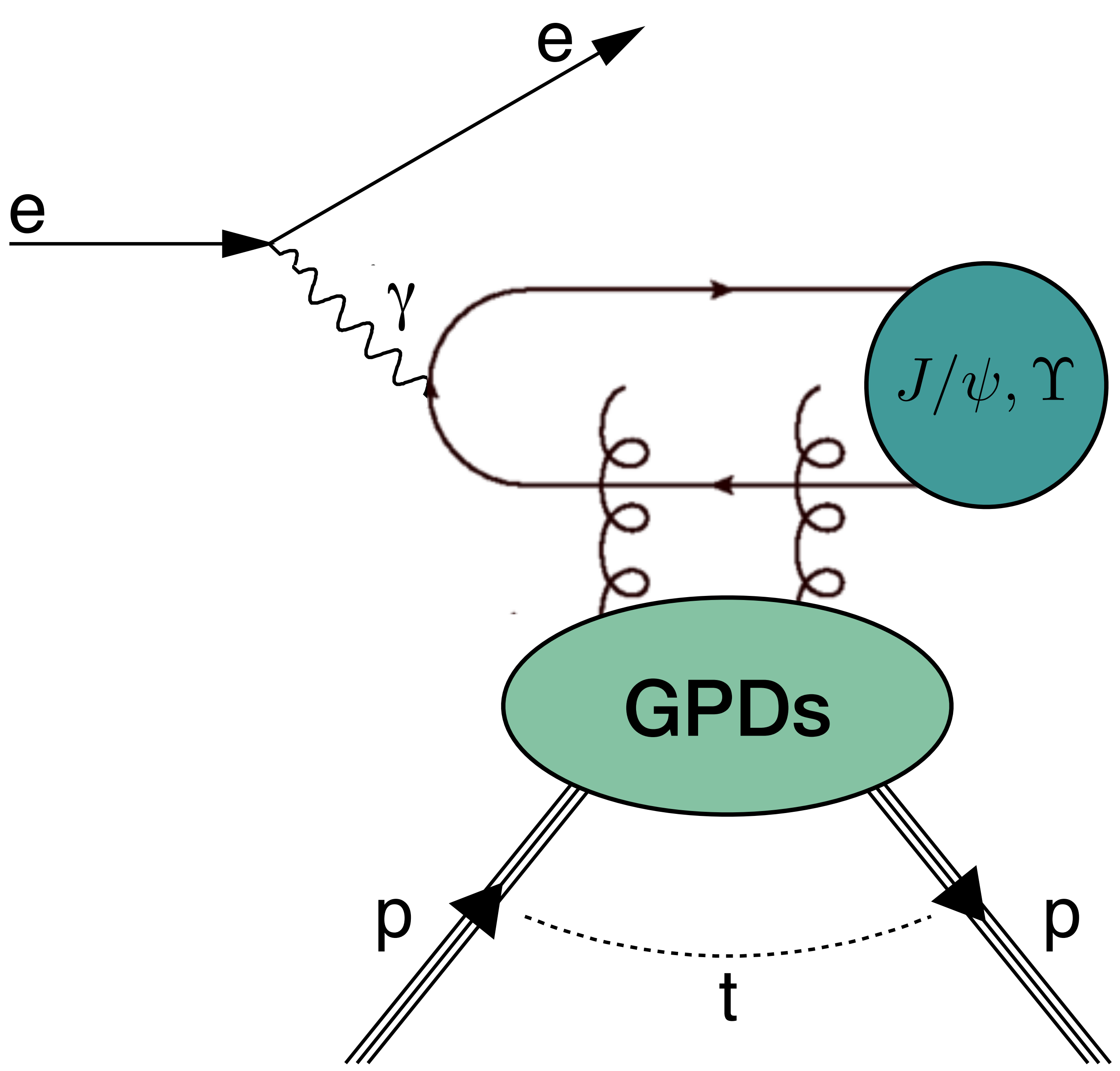

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H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251

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

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

down to $x_B = 10^{-4}$

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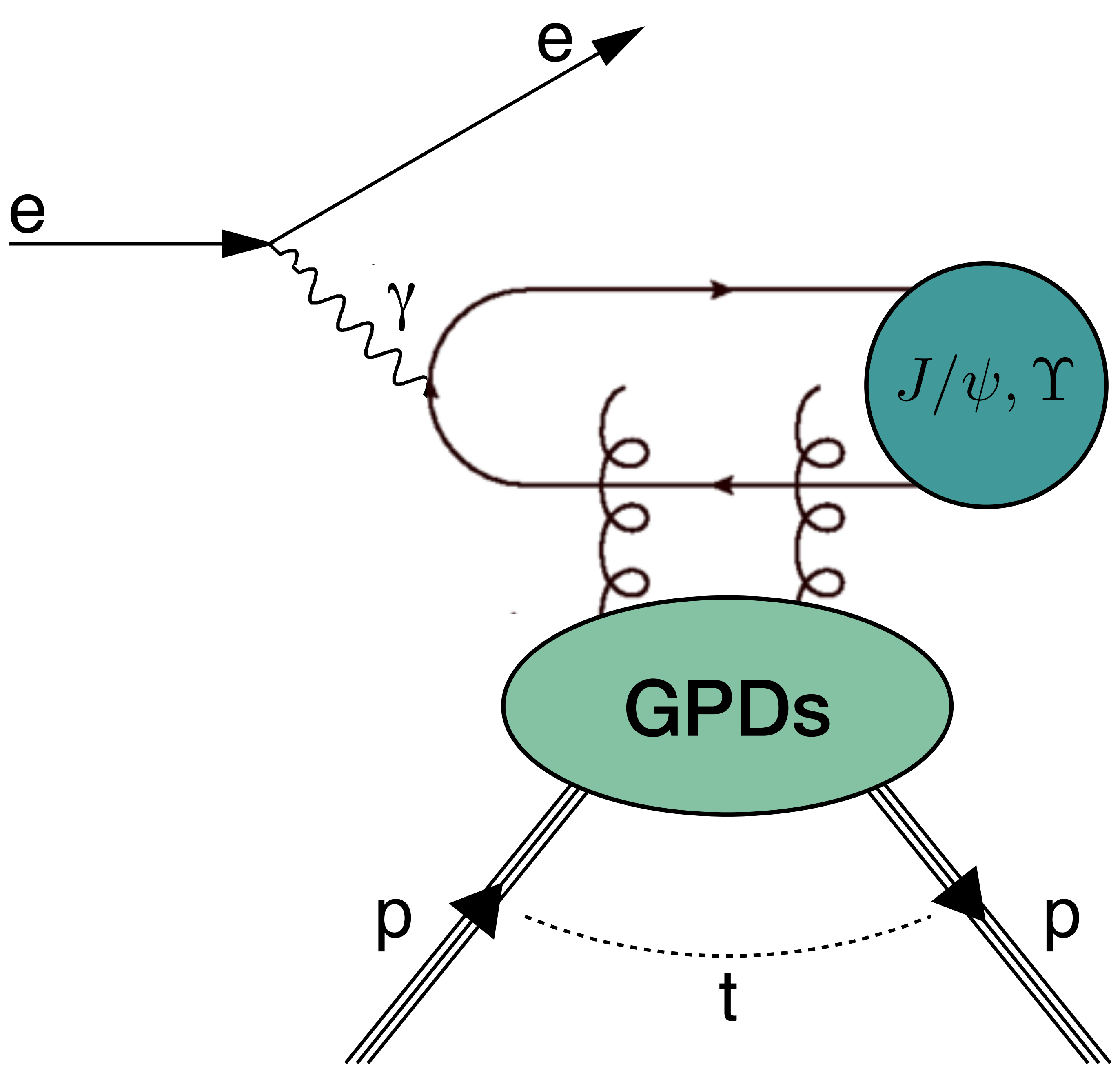

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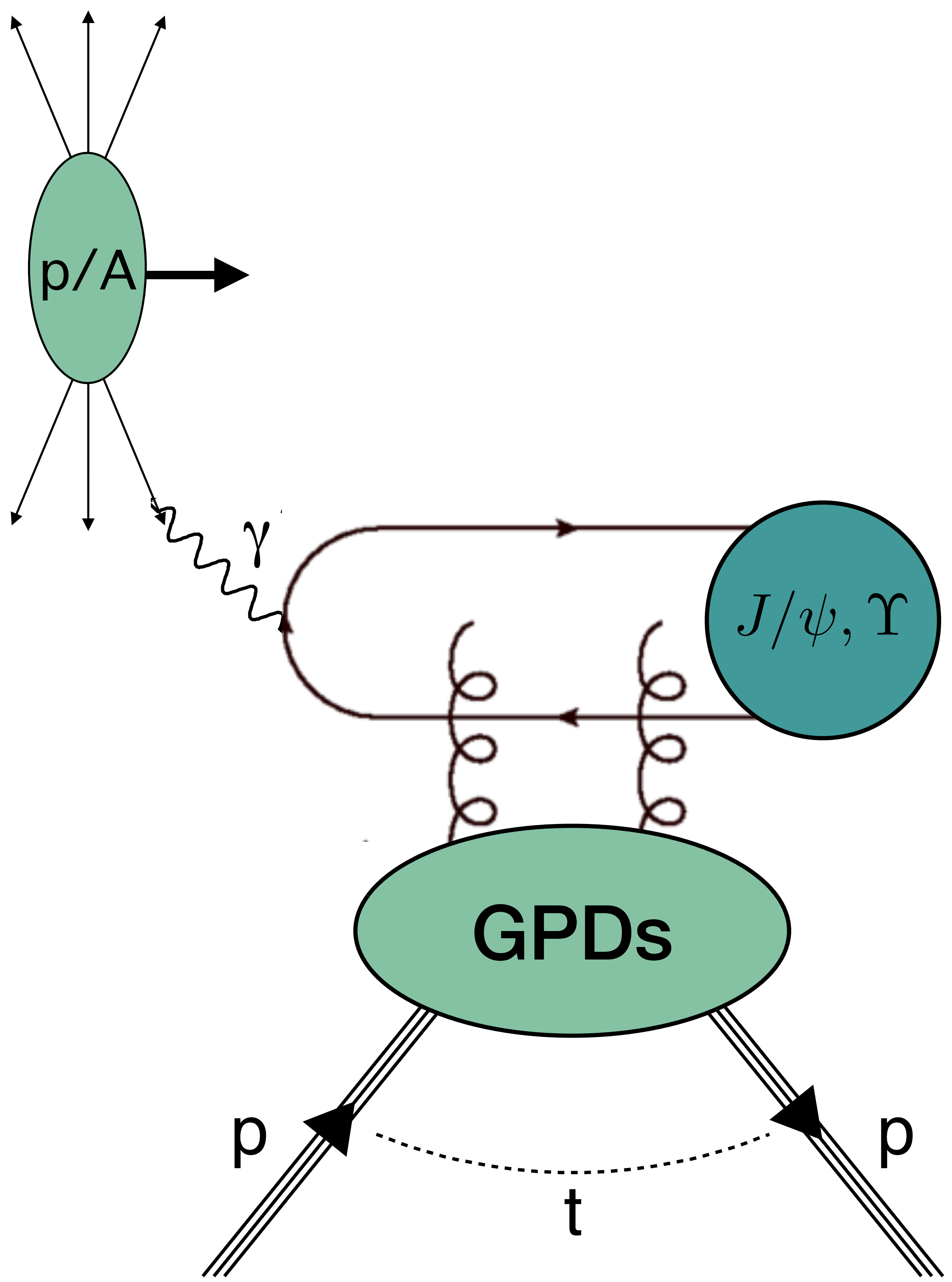

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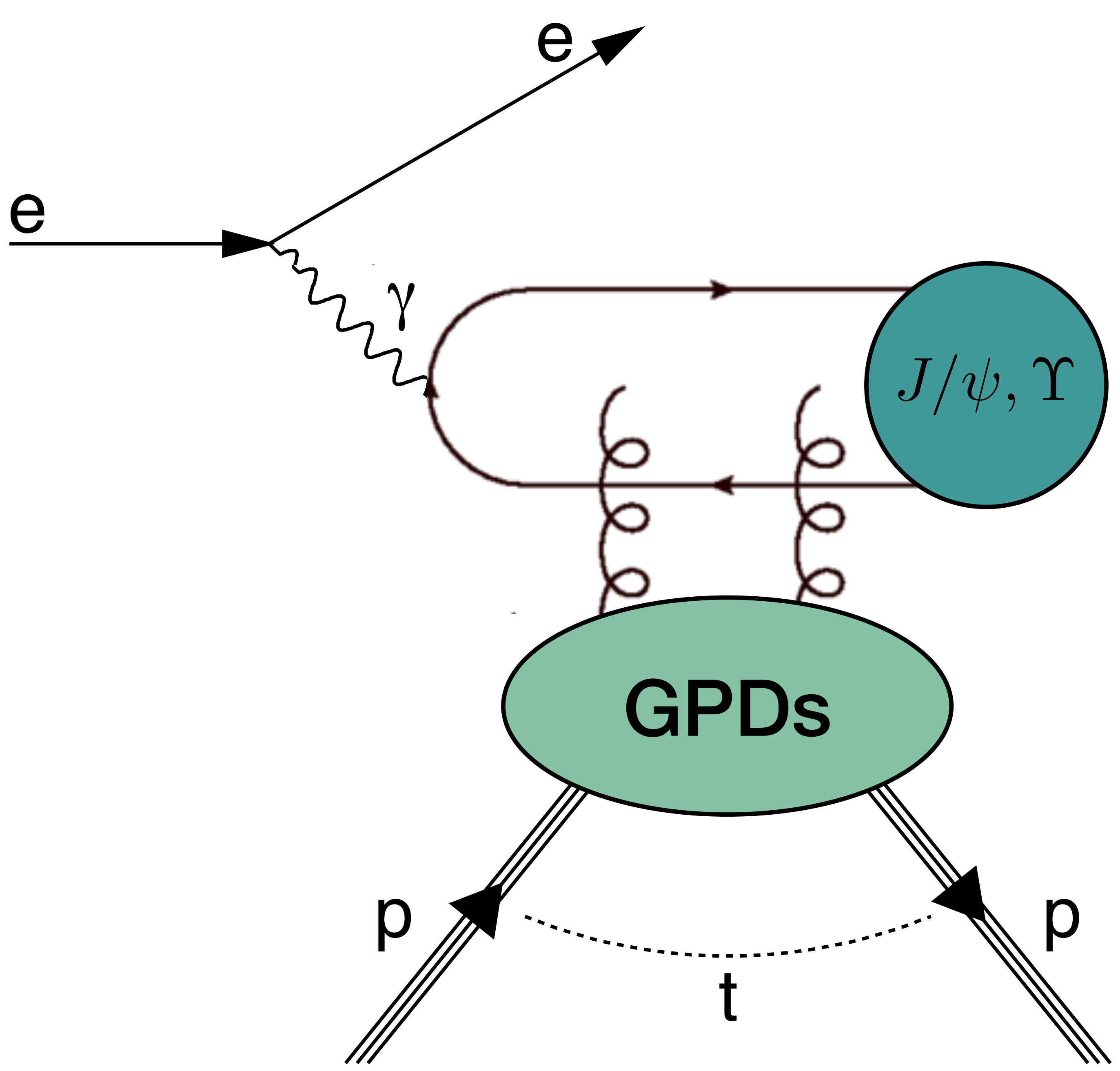

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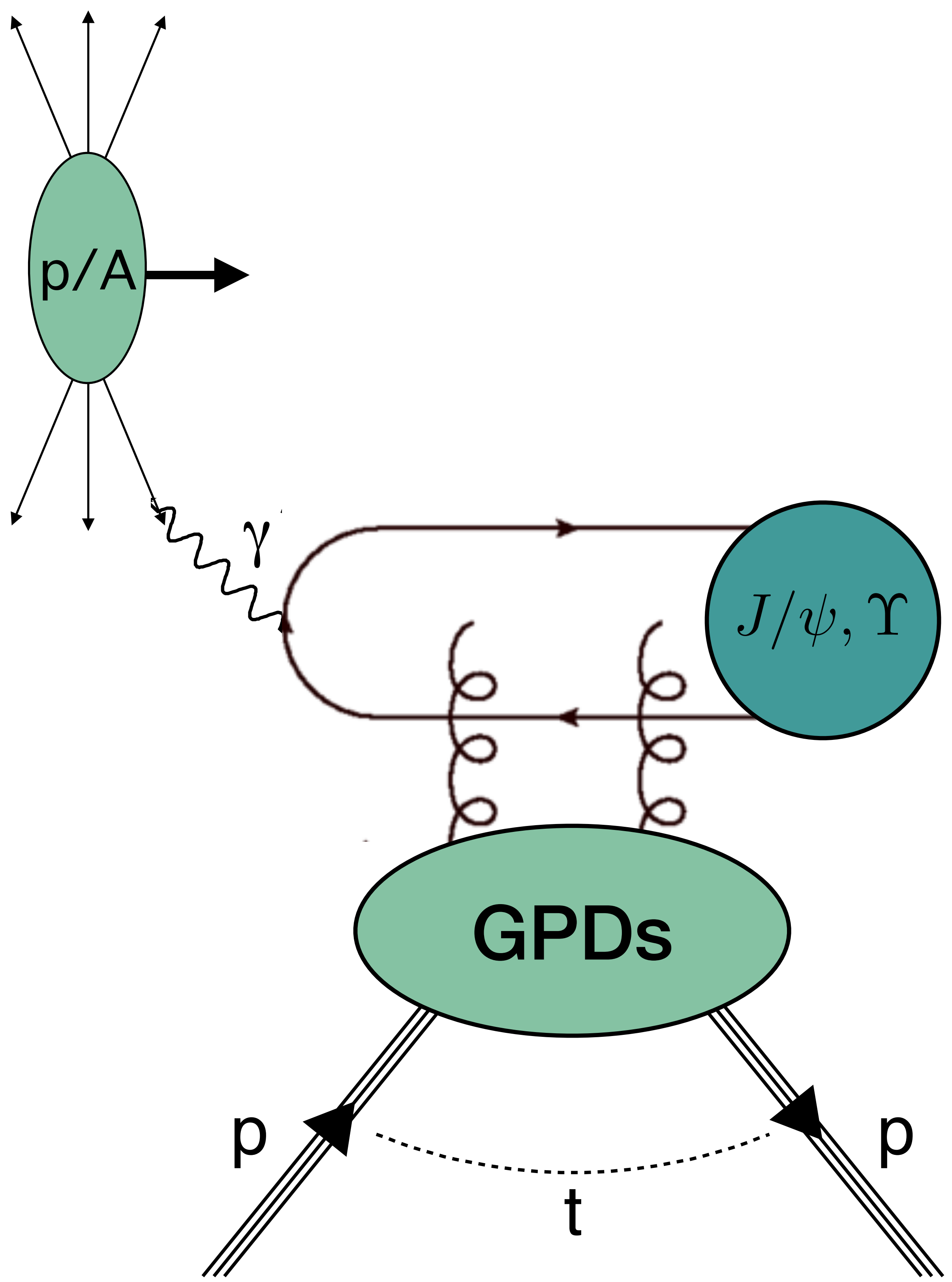


$W_{\gamma N}^{\max} = 34$ GeV

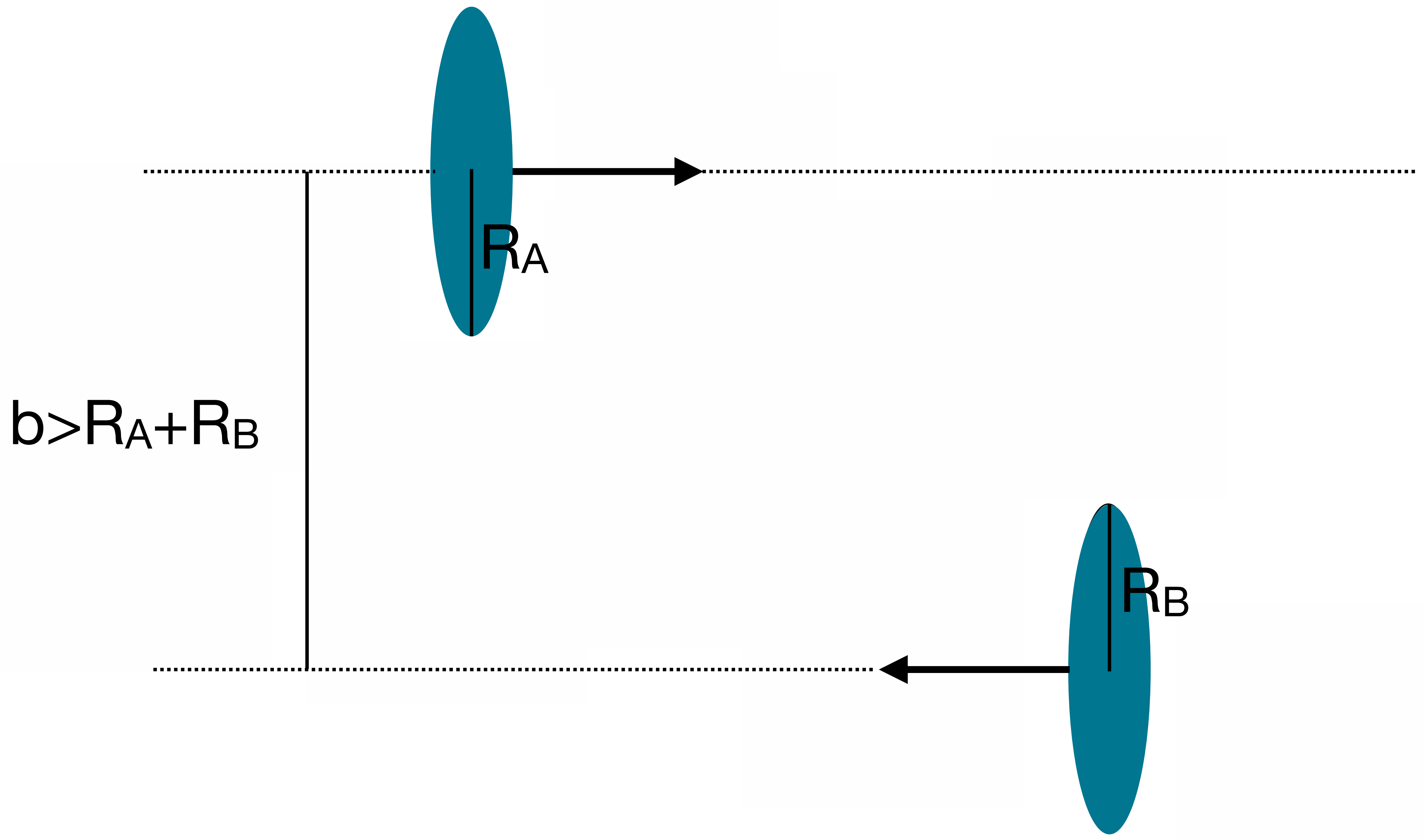
PHENIX: Au-Au – Phys. Lett. B **679** ('09) 321
CDF: p-p̄ – Phys. Rev. Lett. **102** ('09) 242001
CMS, PbPb: Phys. Lett. B **772** ('17) 489
CMS, pPb: Eur. Phys. J. C **79** ('19) 277
ALICE: Pb-Pb – Eur. Phys. J. C **73** ('13) 2617; Phys. Lett. B **718** ('13) 1273; Phys. Lett. B **751** ('15) 358; Phys. Lett. B **798** ('19) 134926.
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

$W_{\gamma p}^{\max} = 1.5$ TeV

down to $x_B=10^{-6}$

Ultra-peripheral collisions

large–impact-parameter interactions

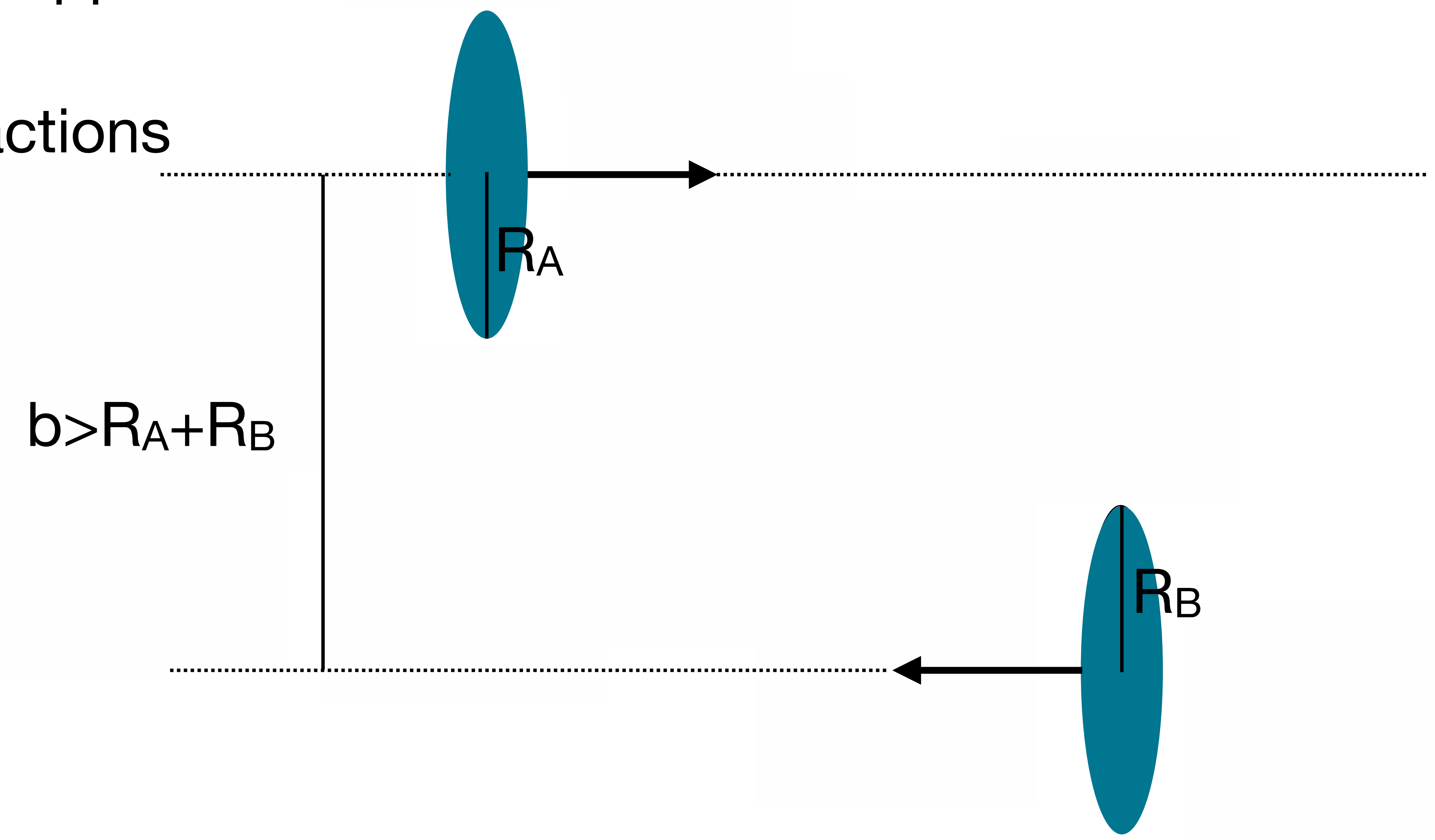


Ultra-peripheral collisions

large–impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions



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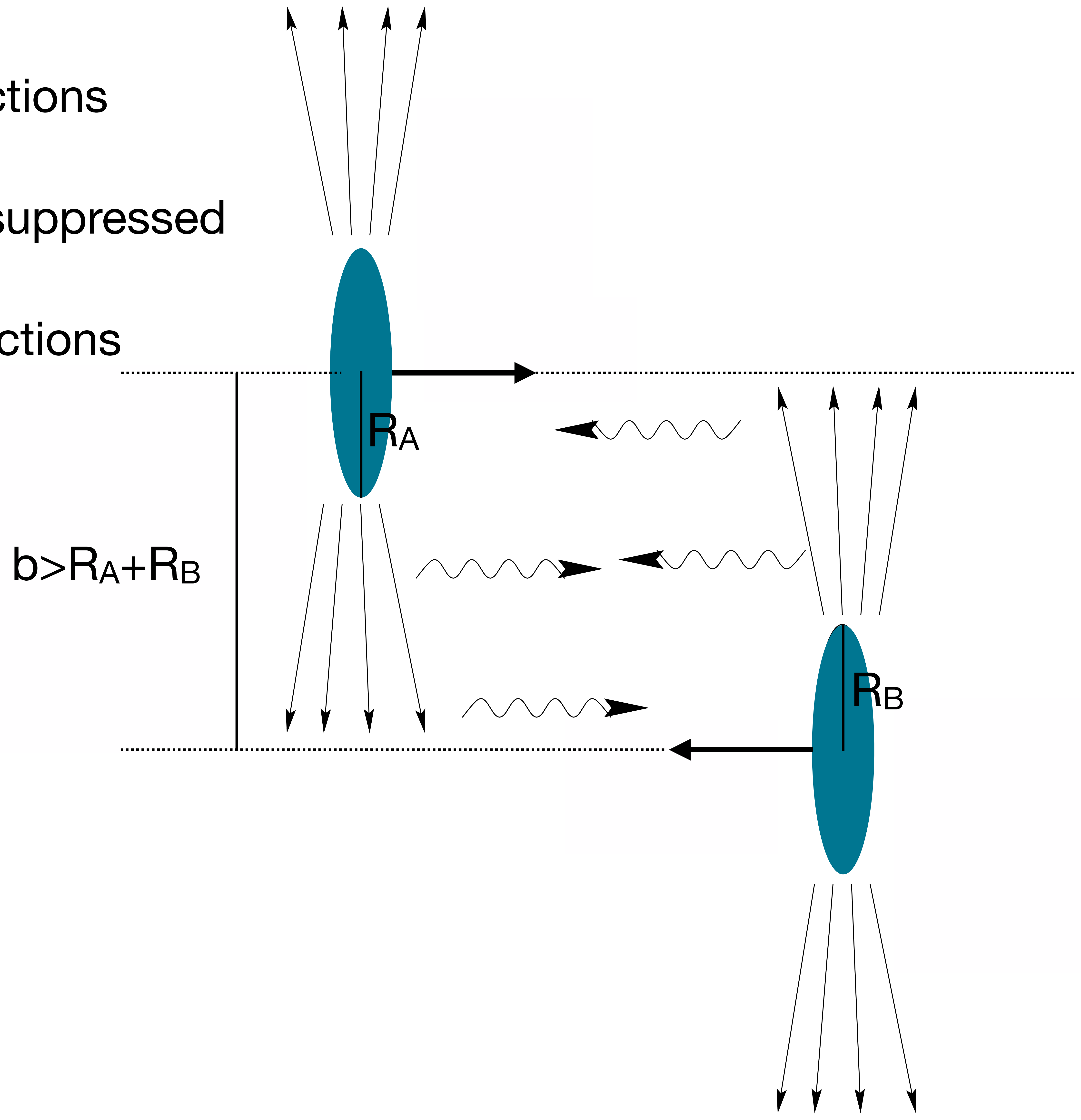

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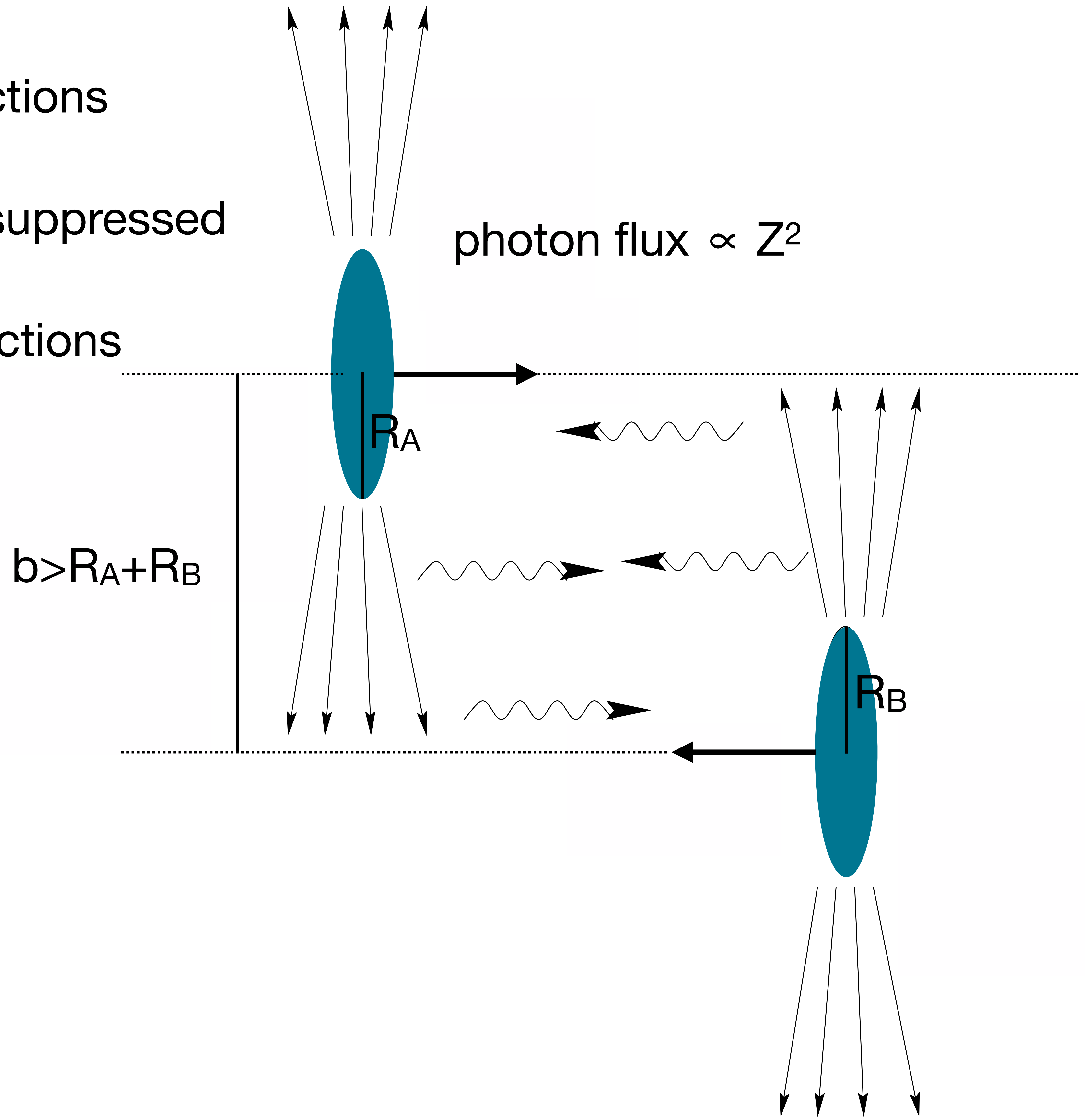

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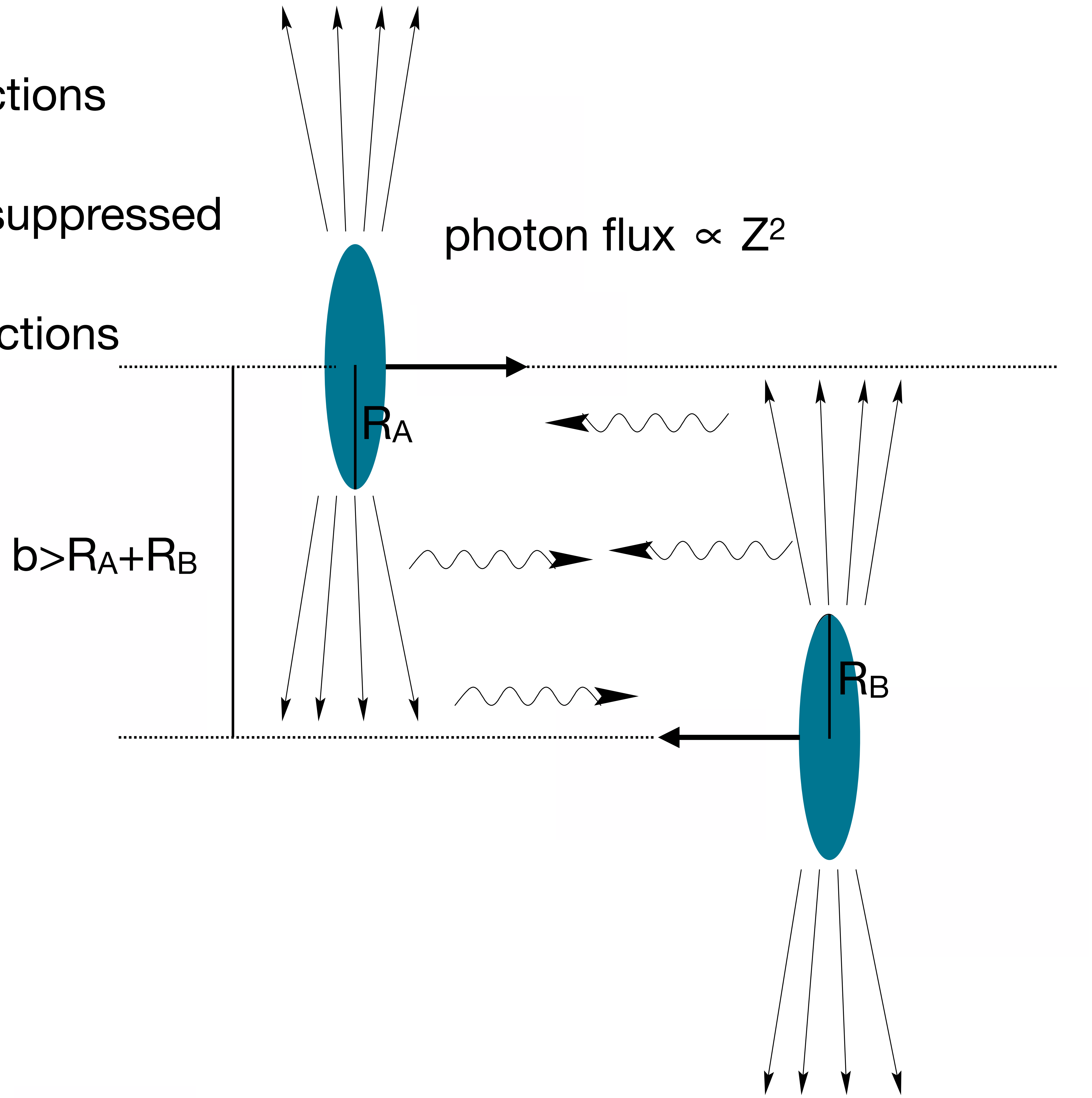

photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$

$\rightarrow$ quasi-real photons

maximum photon energy = $\frac{2\gamma\hbar c}{b_{\min}}$

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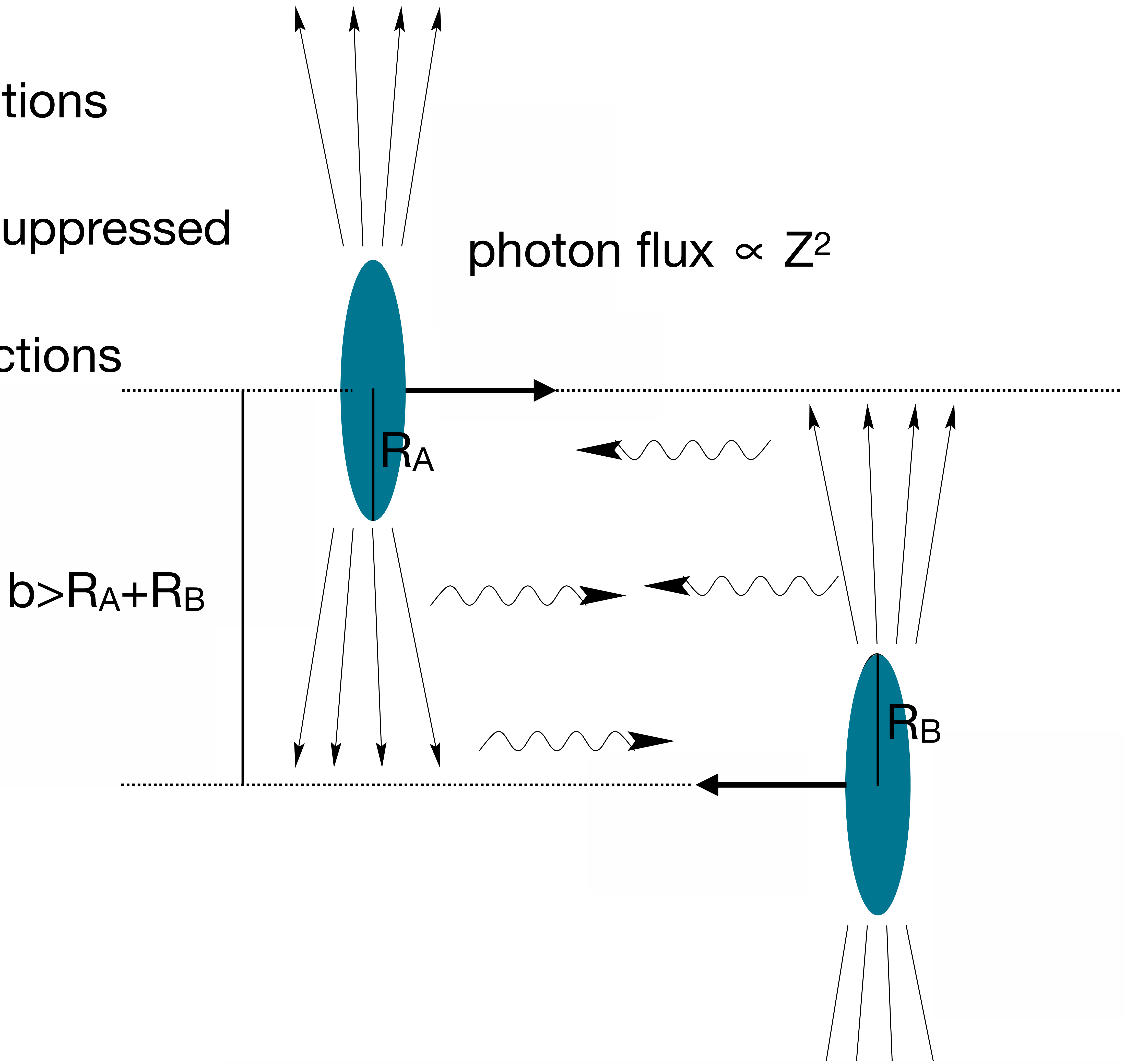

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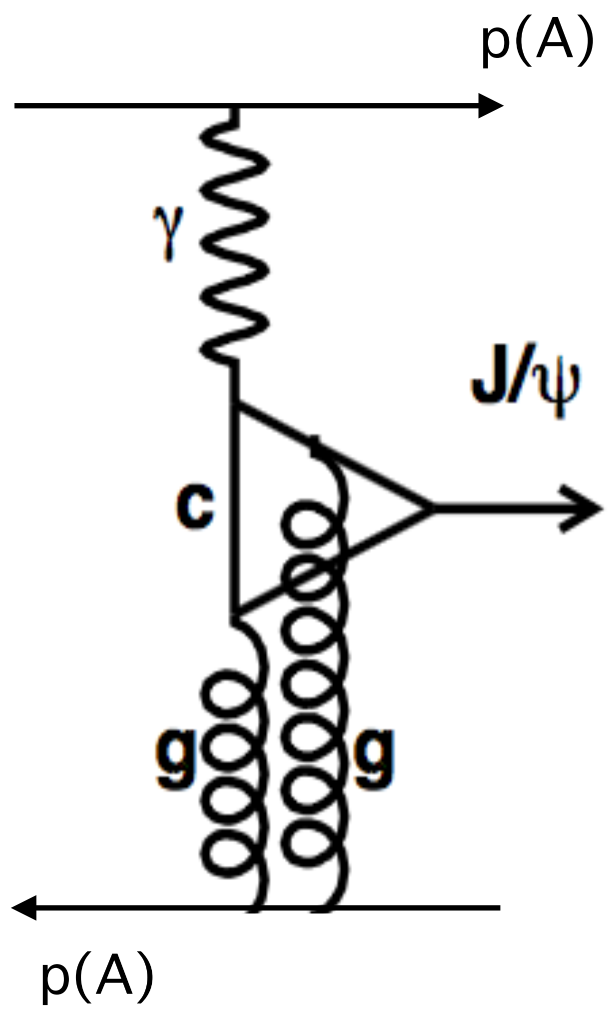
System	$\sqrt{s_{AB}}$	E_A	E_B	(a) $\gamma_{A\leftrightarrow B}$	(b) $E_{\gamma Max}$	(c) $E^{rest}_{\gamma Max}$	(d) $W^{max}_{\gamma p}$
pPb	5.02 TeV	4 TeV	1.567 TeV	1.43×10^7	28 MeV	0.4 PeV	0.86 TeV
pPb	8.16 TeV	6.5 TeV	2.56 TeV	3.78×10^7	28 MeV	1 PeV	1.4 TeV
pp	13 TeV	6.5 TeV	6.5 TeV	9.6×10^7	116 MeV	11 PeV	4.6 TeV

table: K. Lynch

Measurement of exclusive production at LHCb



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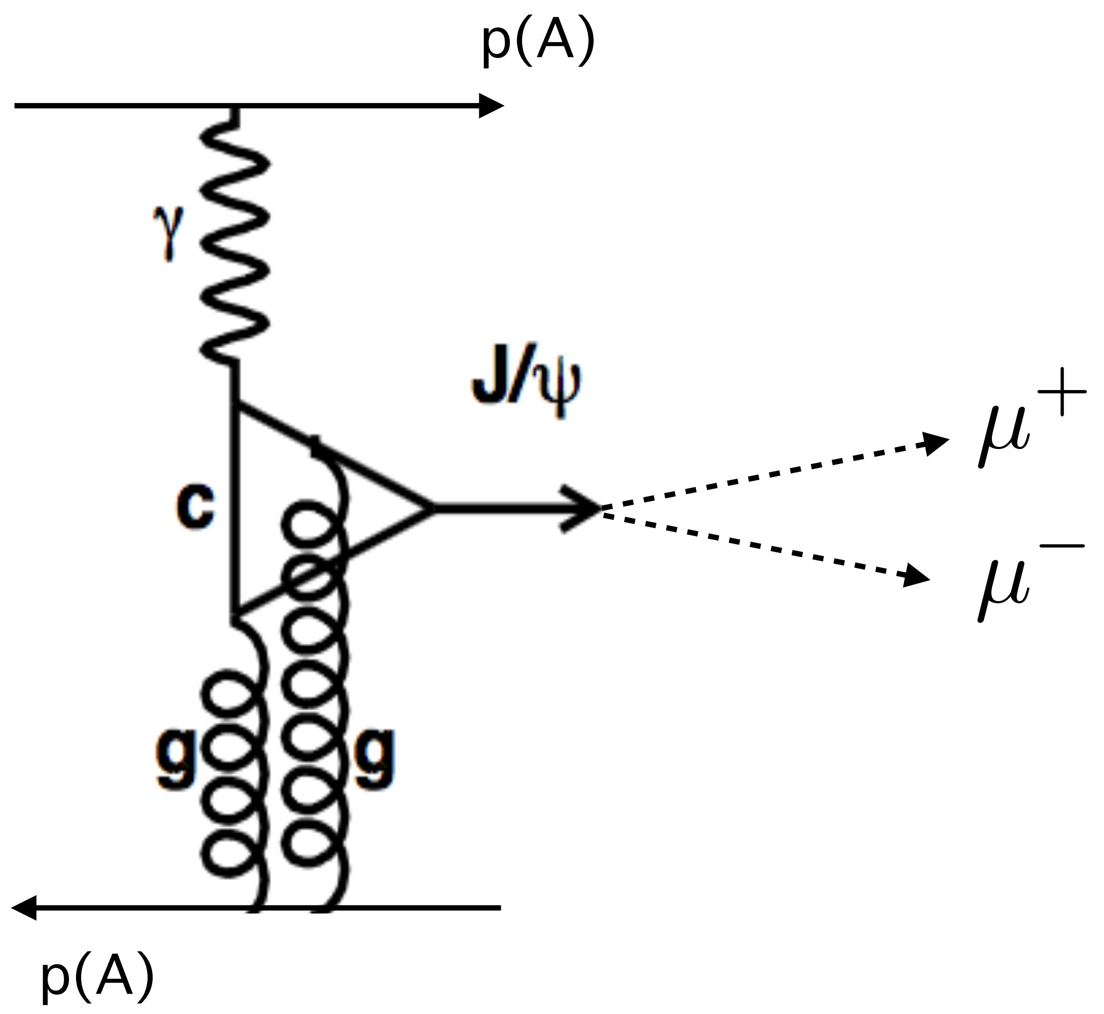

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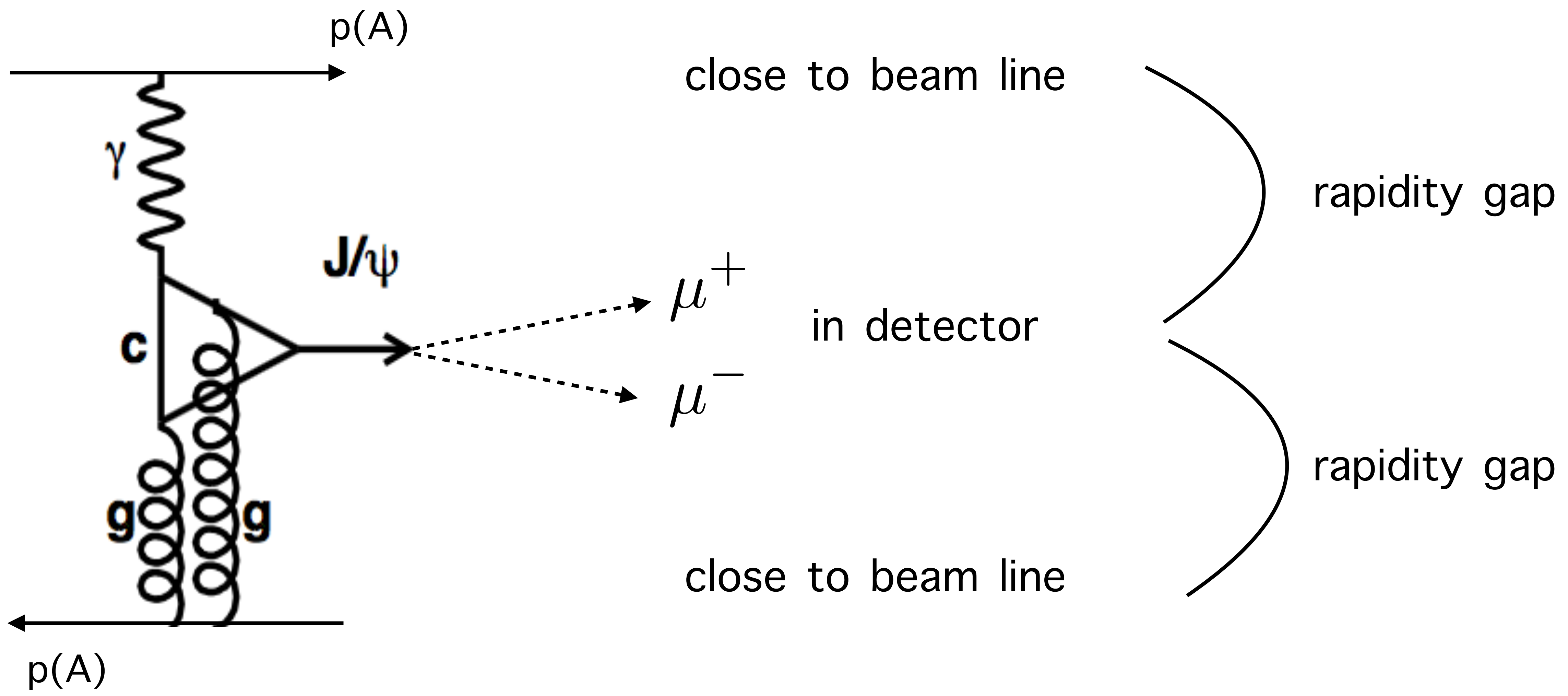

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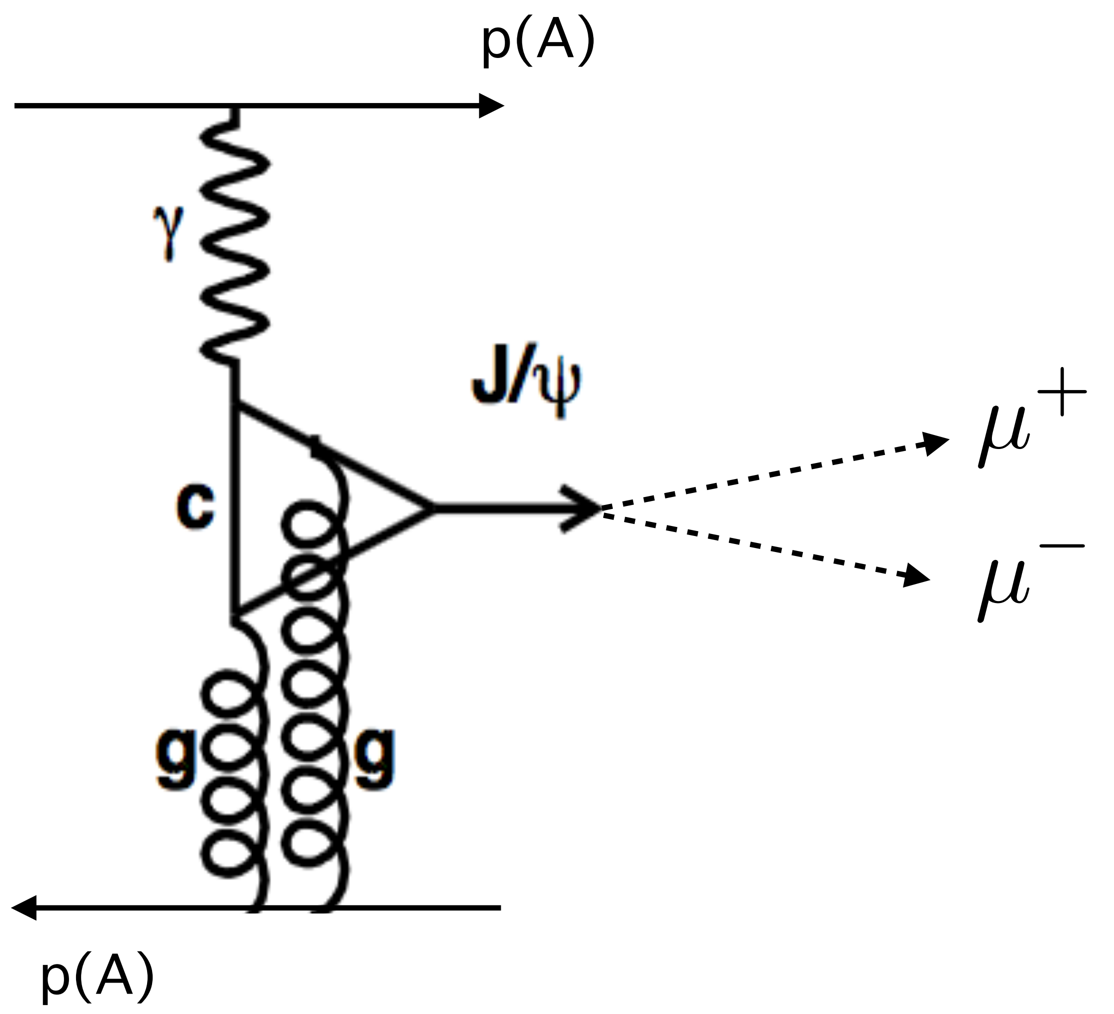
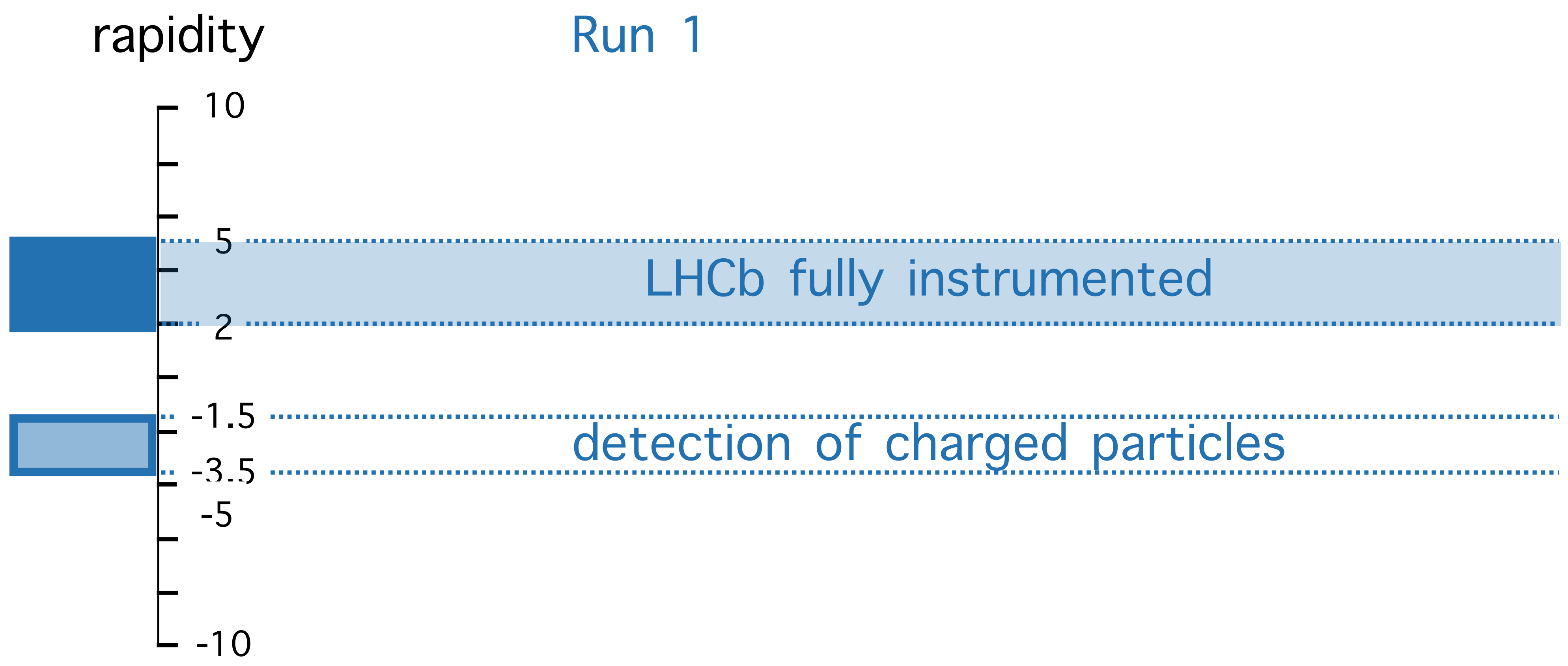
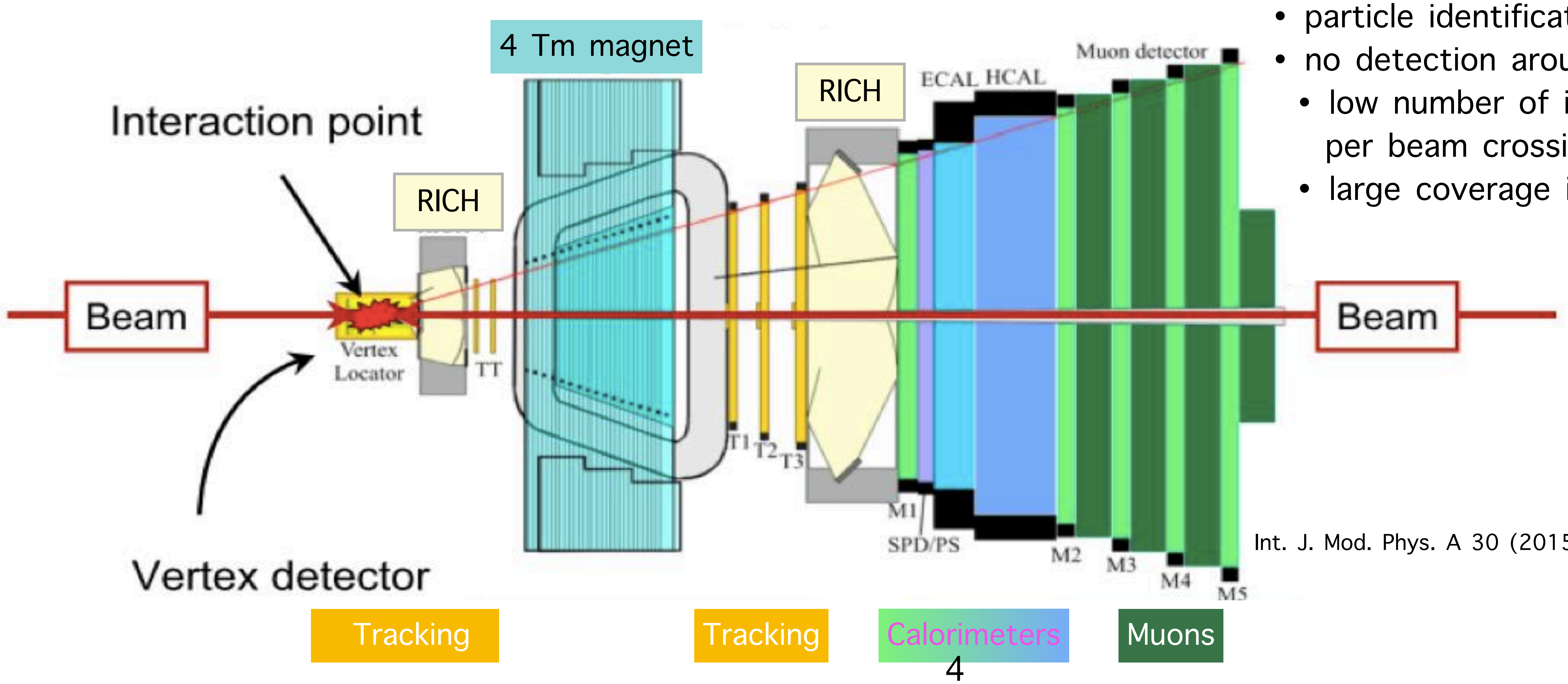




- low p_T threshold: p_T>400 MeV
- particle identification
- no detection around beam line but
  - low number of interactions per beam crossing: 1.1–1.5
  - large coverage in rapidity



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

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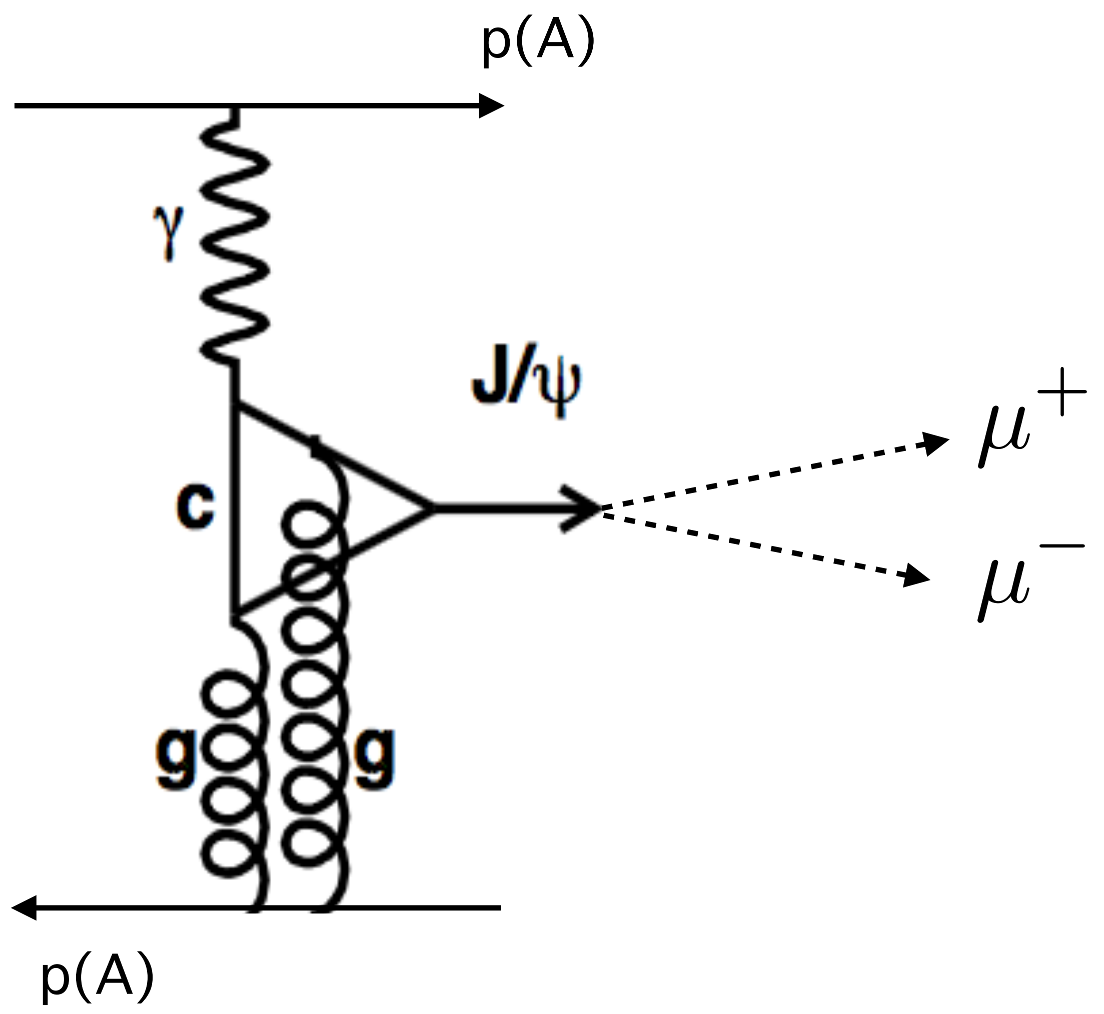

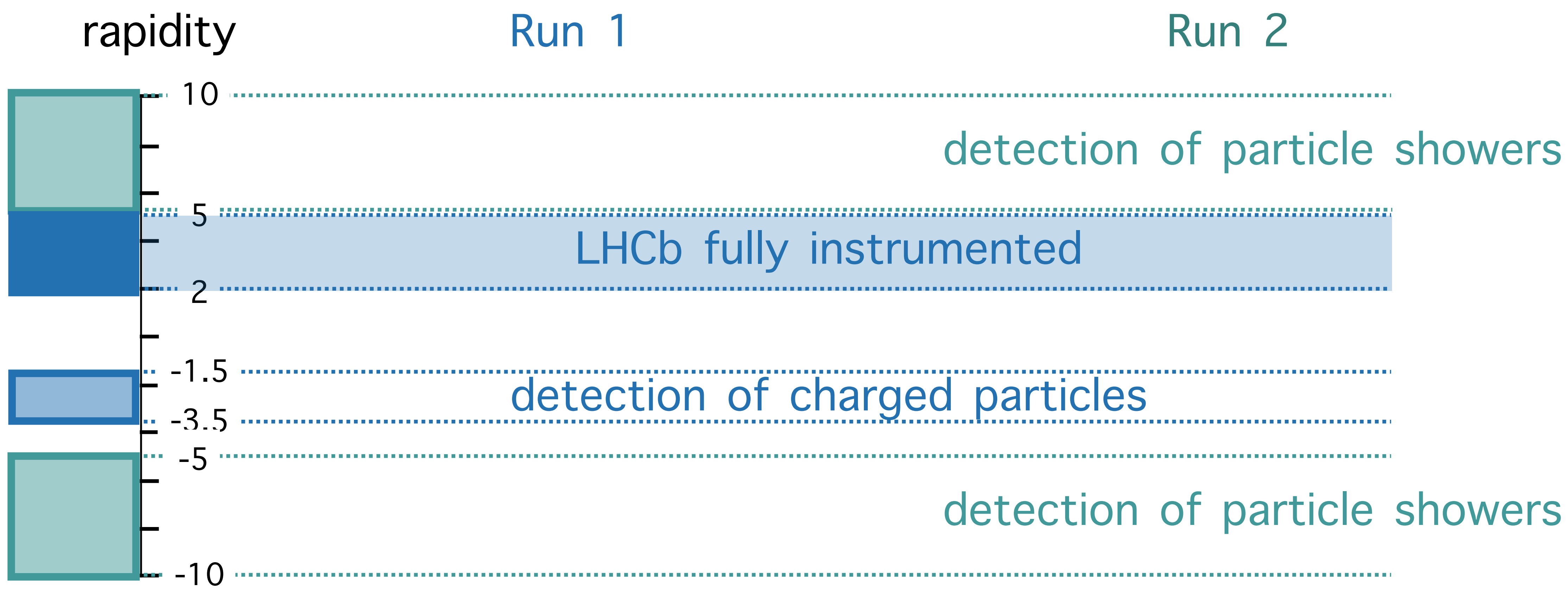

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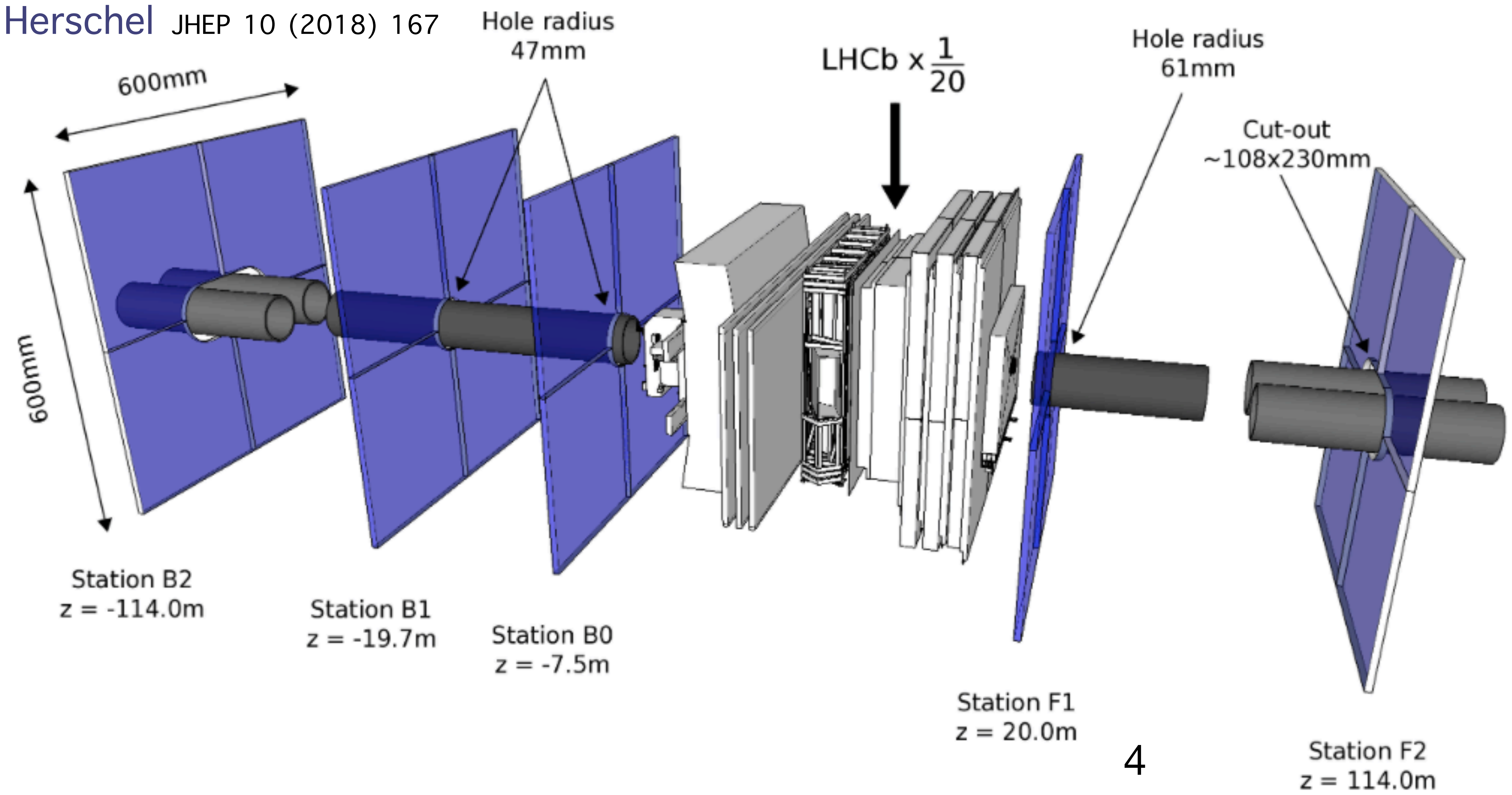
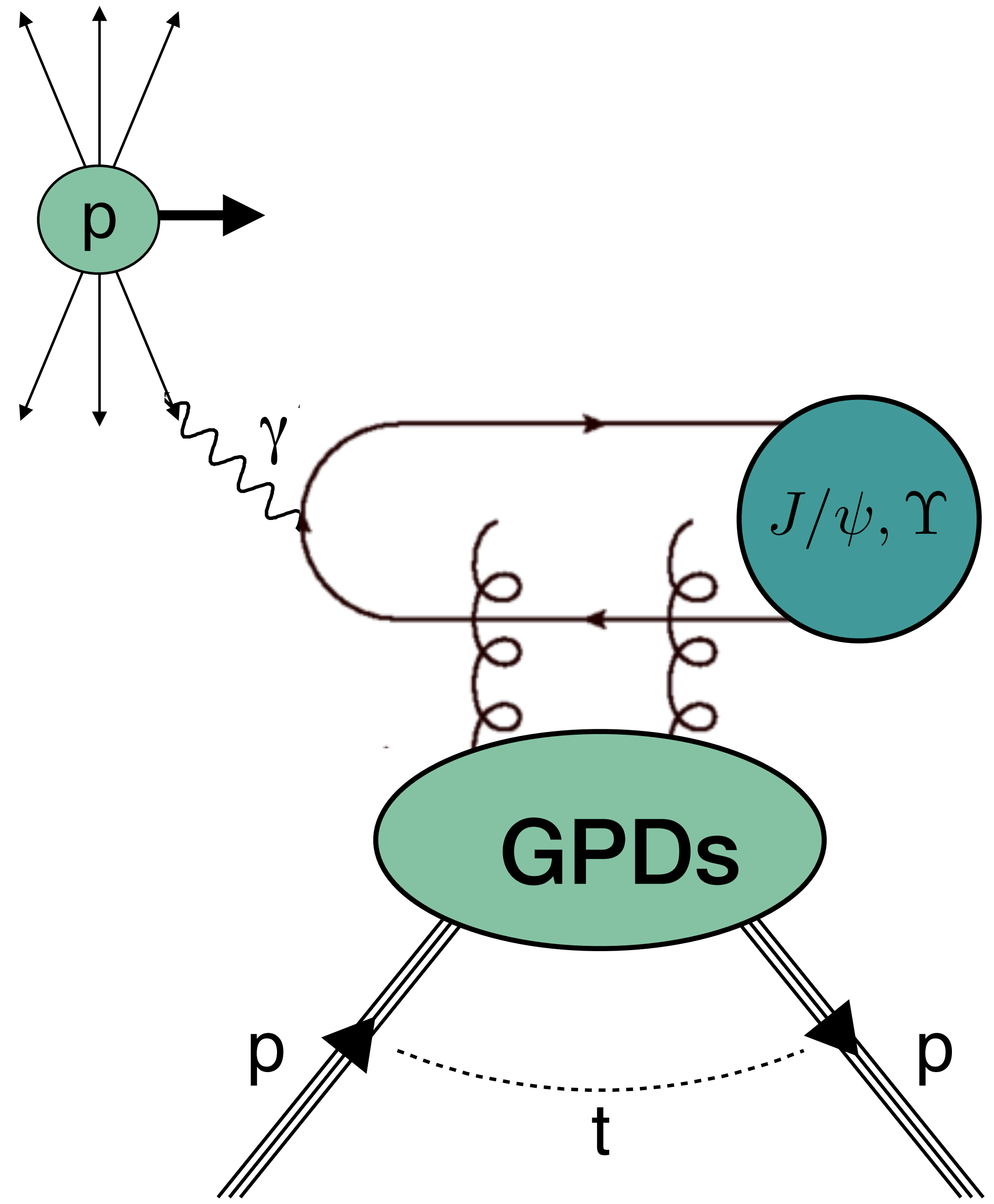
Herschel JHEP 10 (2018) 167



Exclusive single ψ production in pp collisions



- Exclusive J/ψ and ψ(2S): $\sqrt{s} =$ 7 TeV and part of $\sqrt{s} =$13 TeV data (from 2015)

  → x_B down to $2\text{x}10^{-6}$

- Reconstruction via dimuon decay, with 2<η<4.5.
- No other detector activity.
- Quarkonia J//ψ and ψ(2S): 2<y<4.5 and p_T^2<0.8 GeV^2

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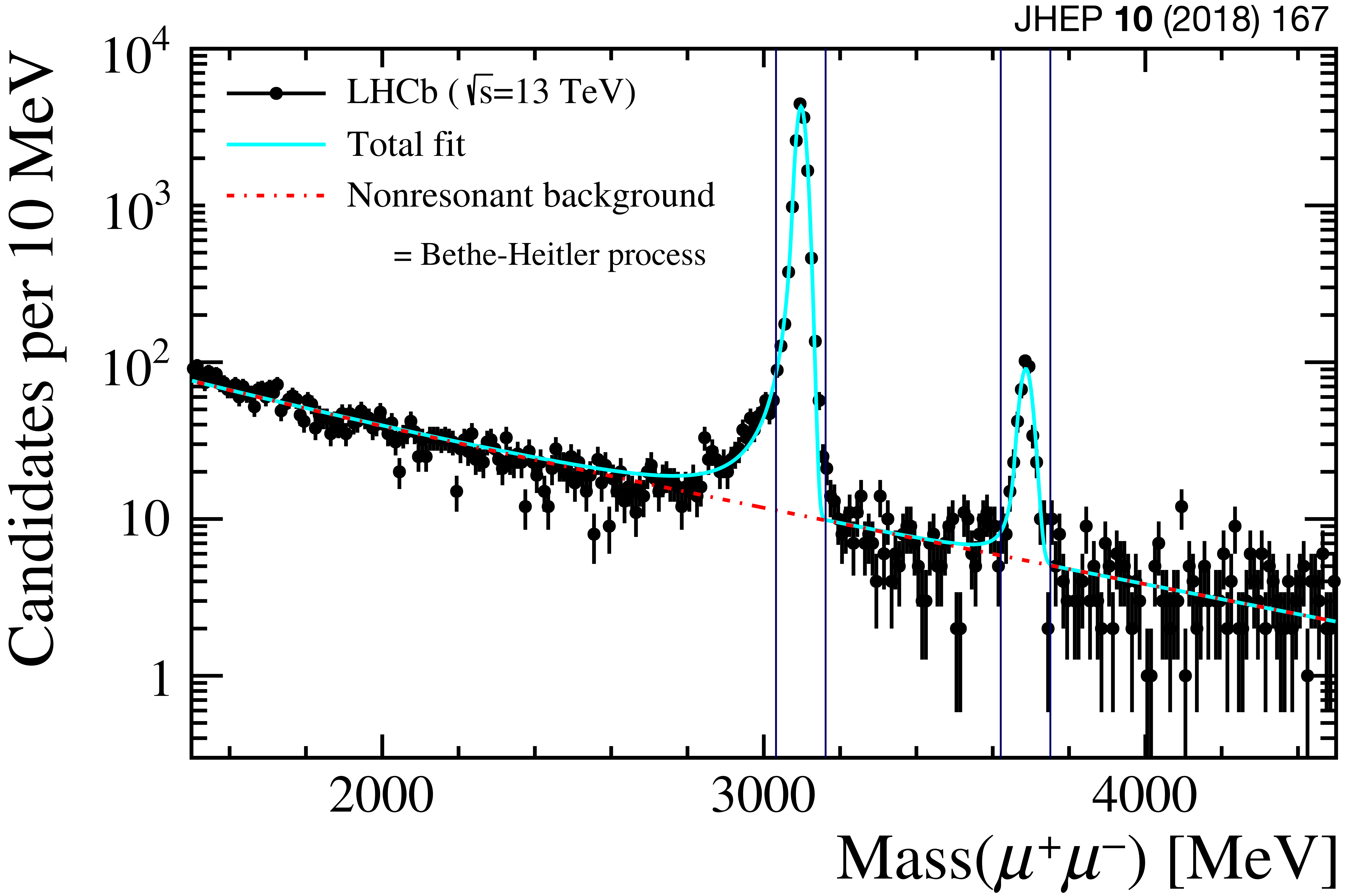

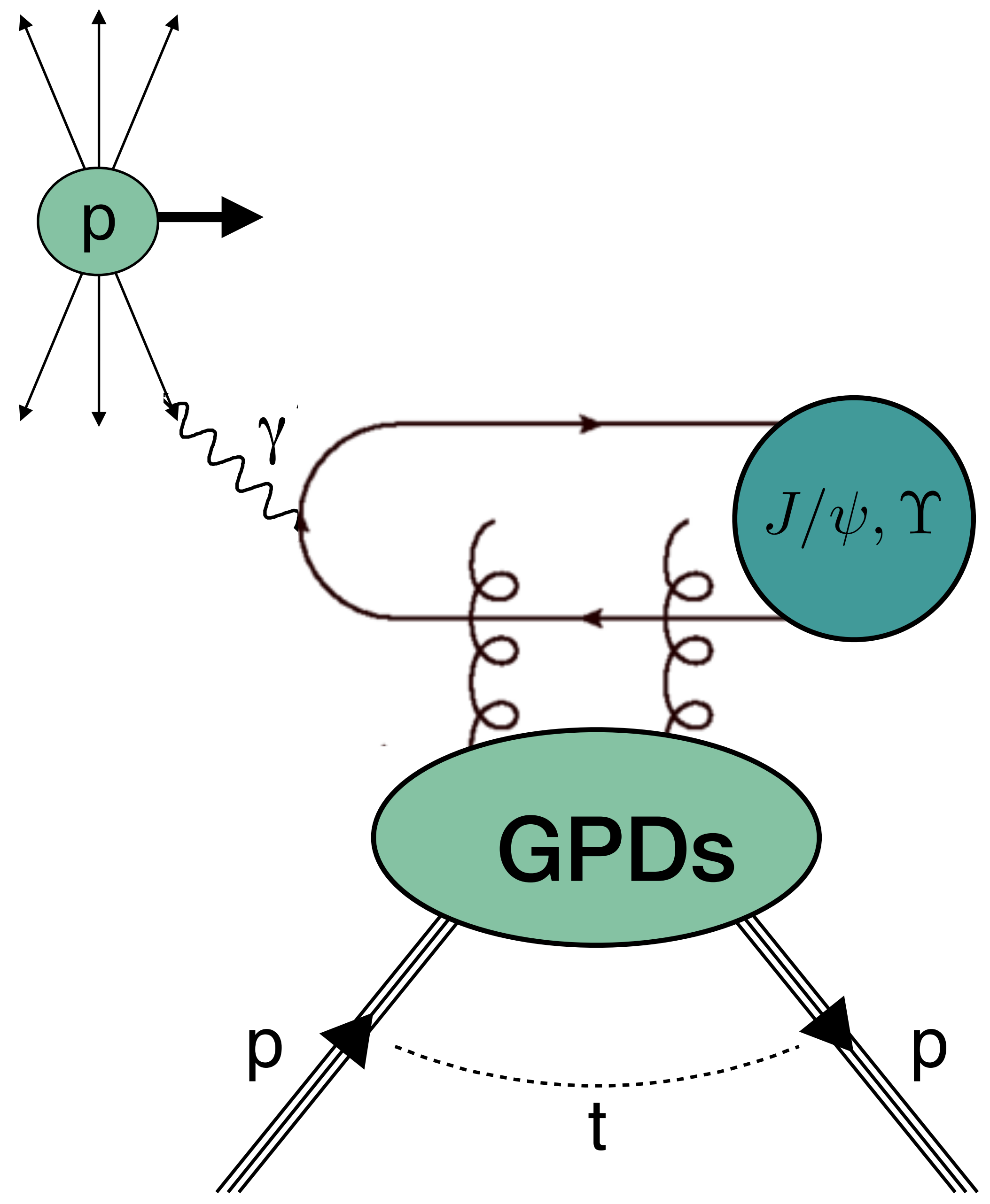

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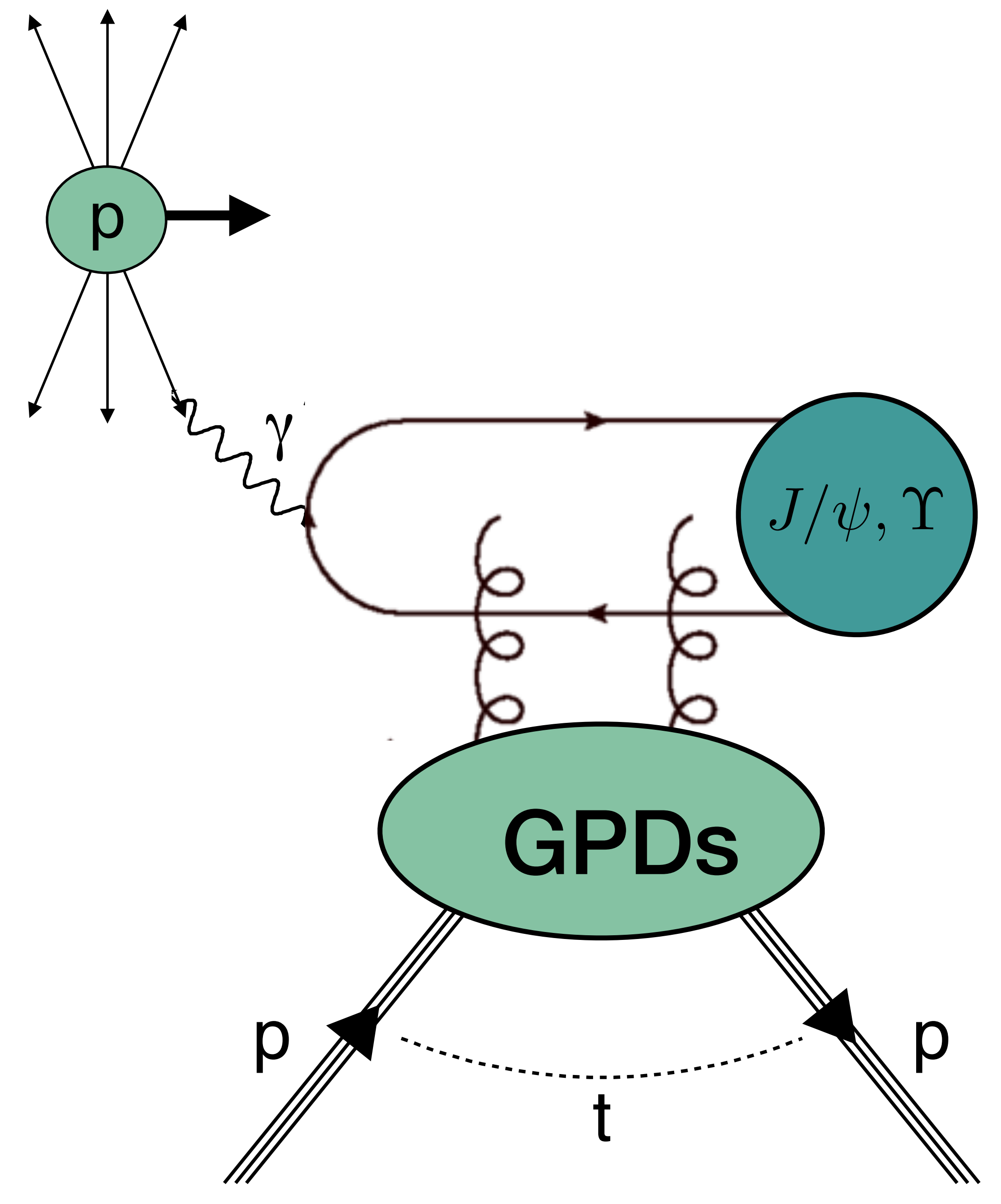

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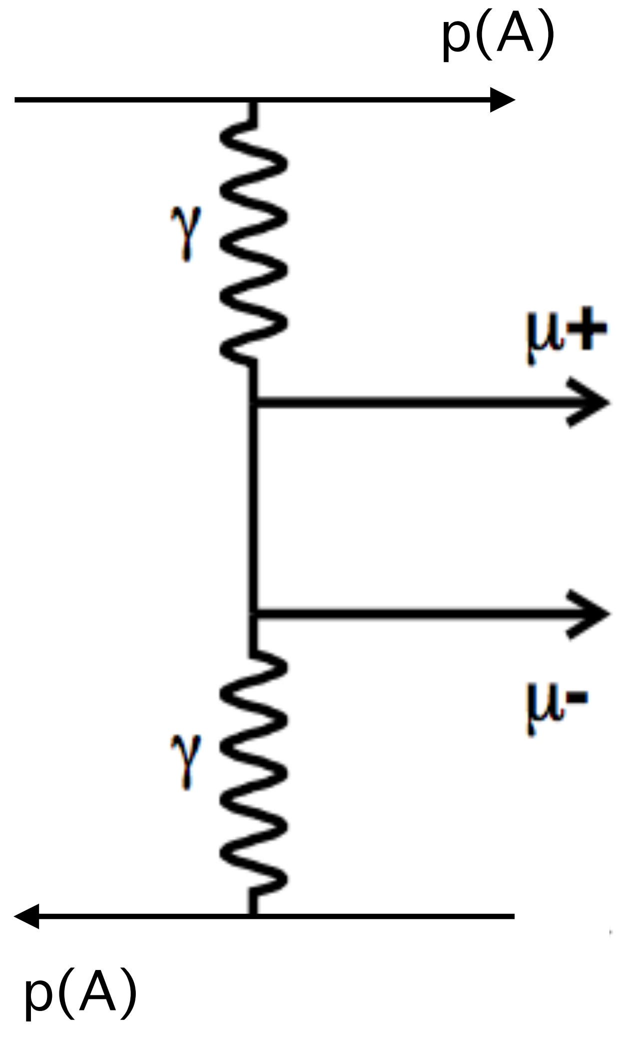
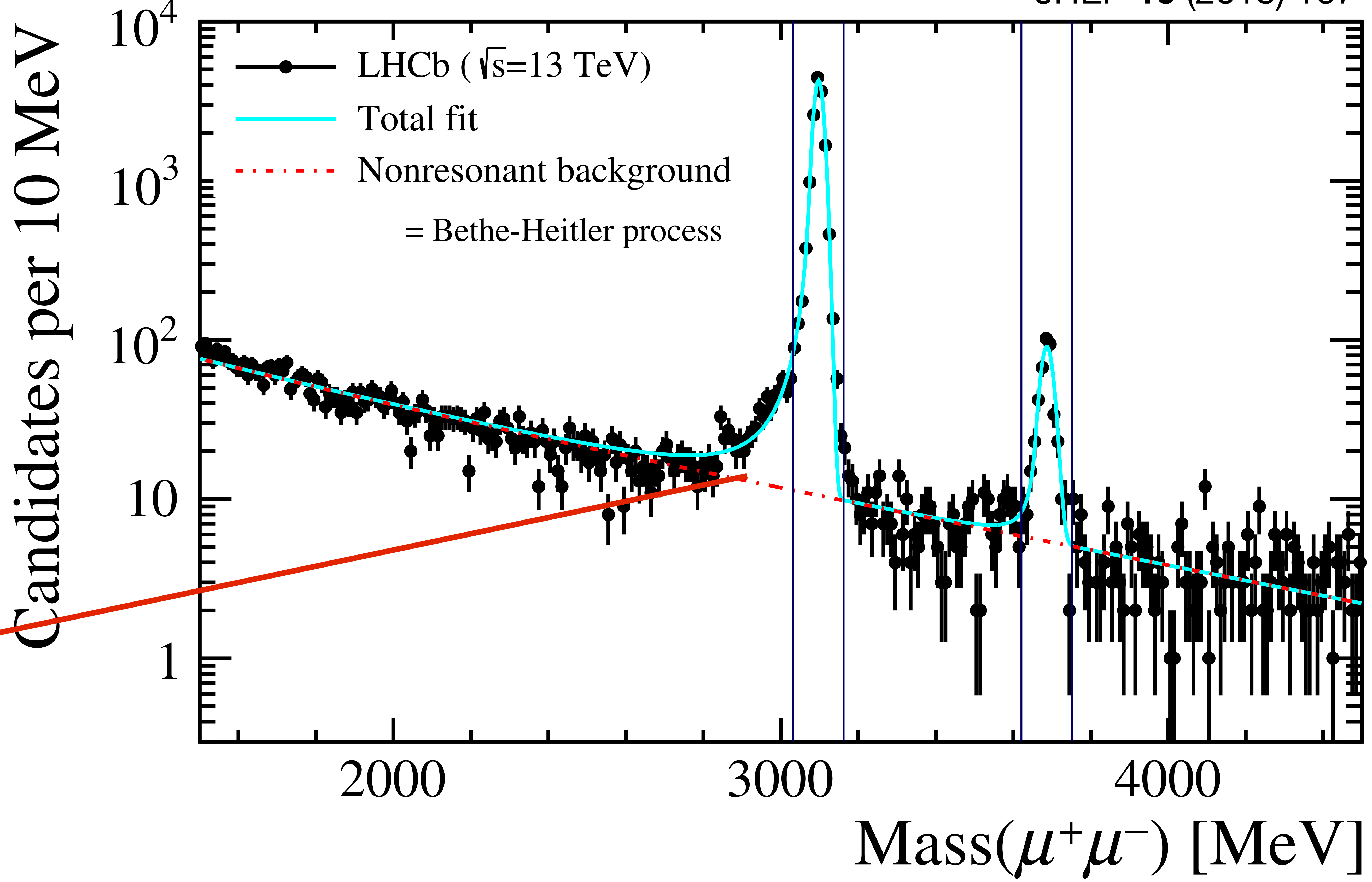


Bethe-Heitler process

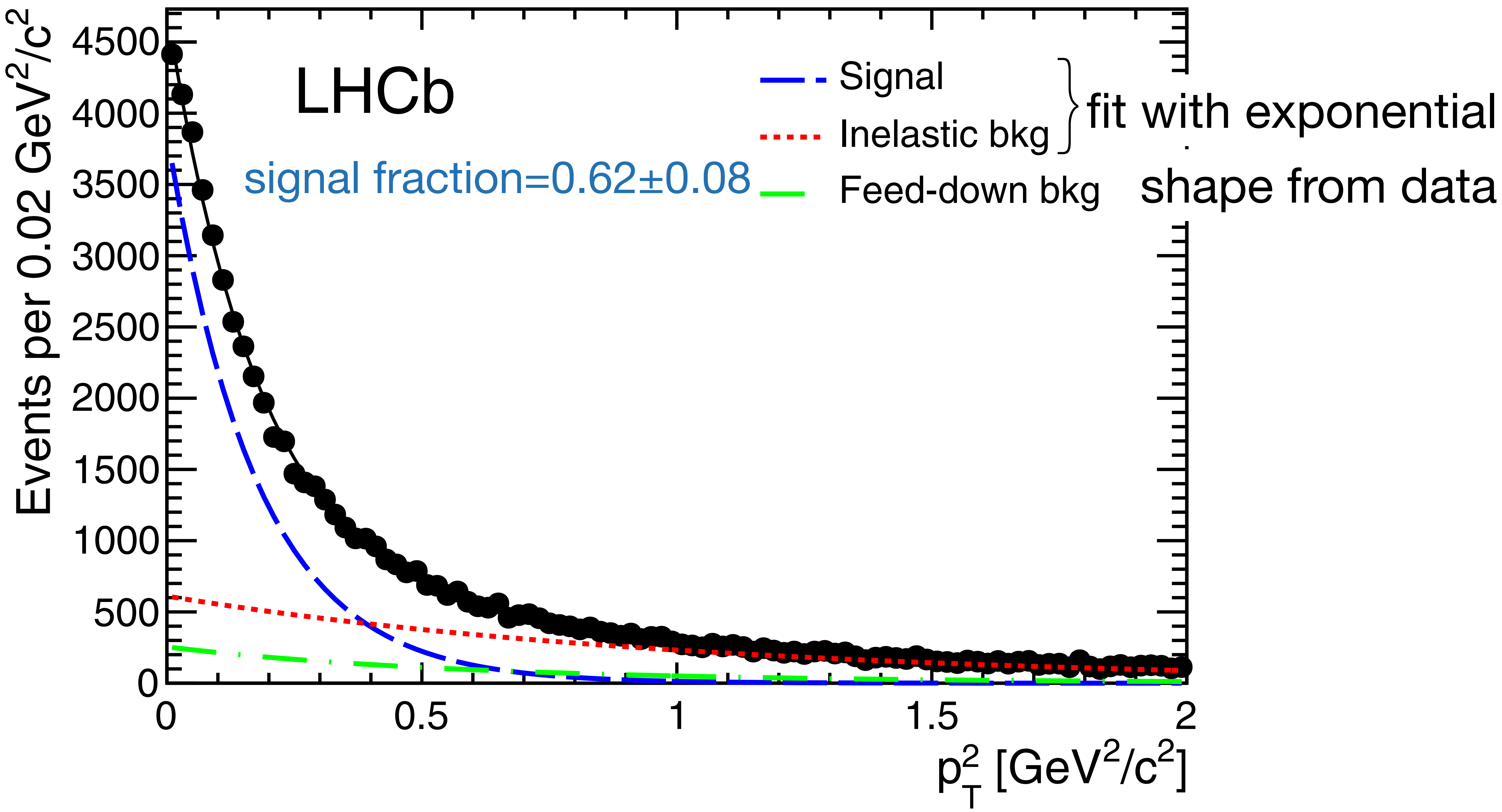
JHEP **10** (2018) 167



Background: feed down and proton dissociation

$\sqrt{s} = 7$ TeV

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



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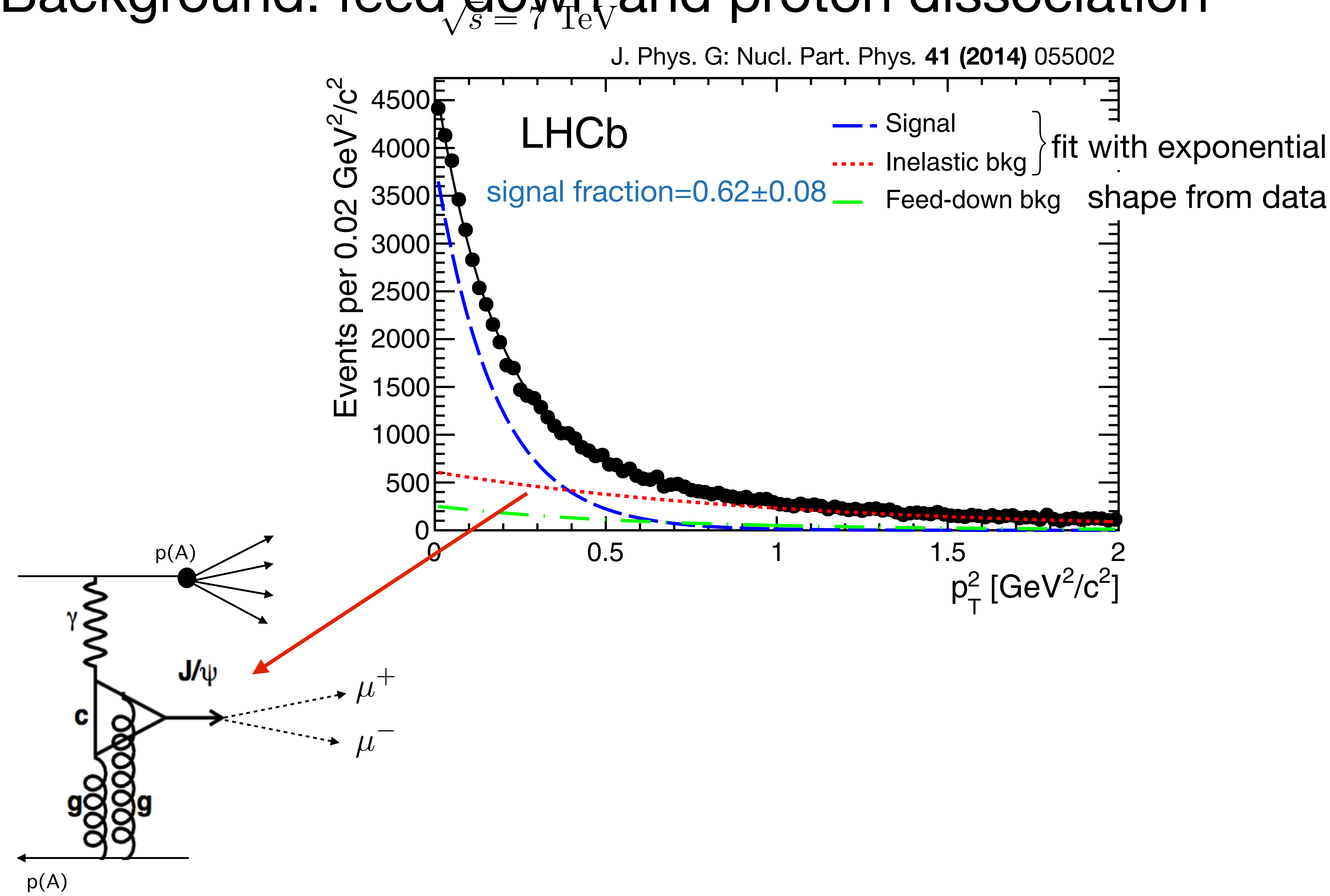

proton/ion dissociation

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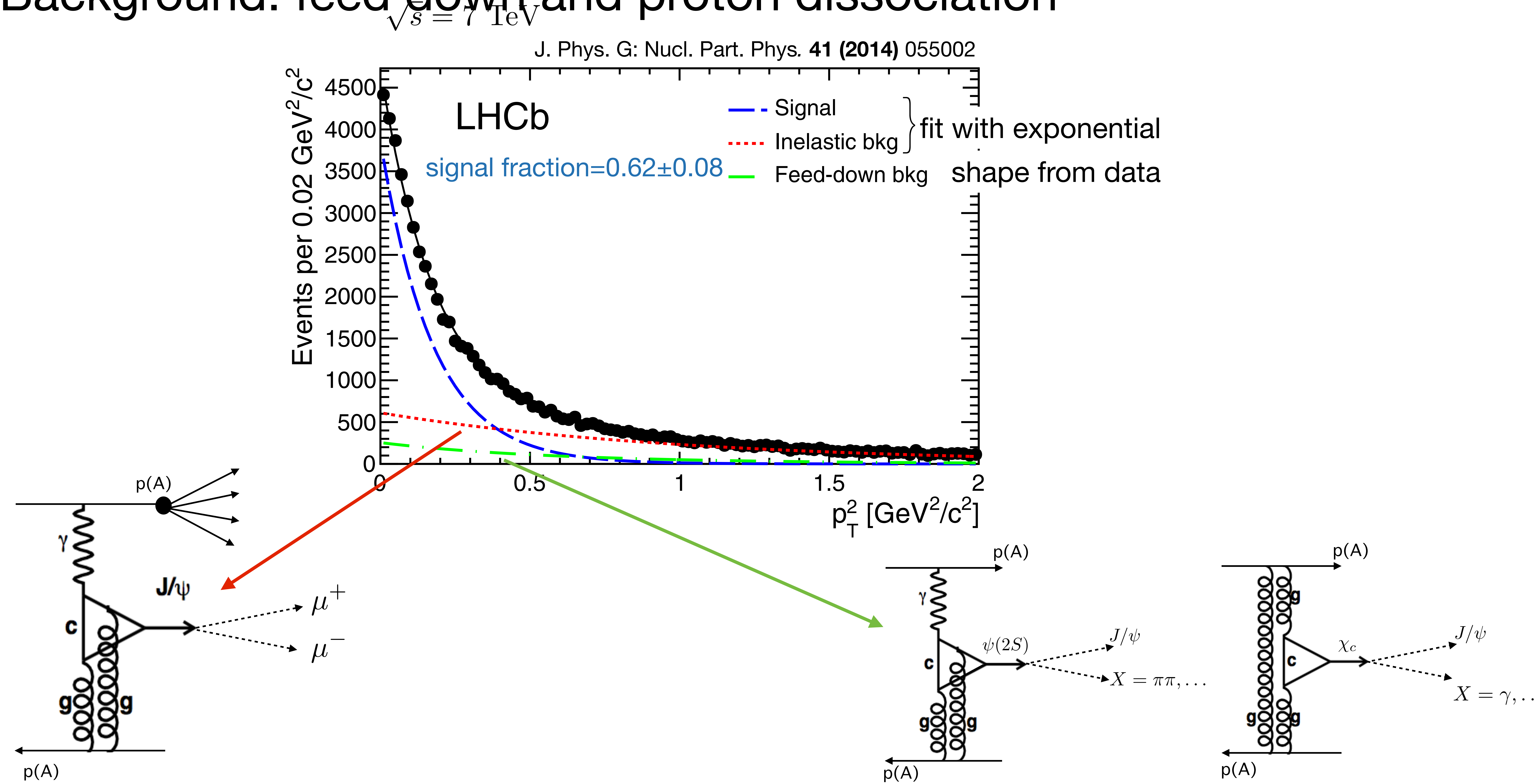
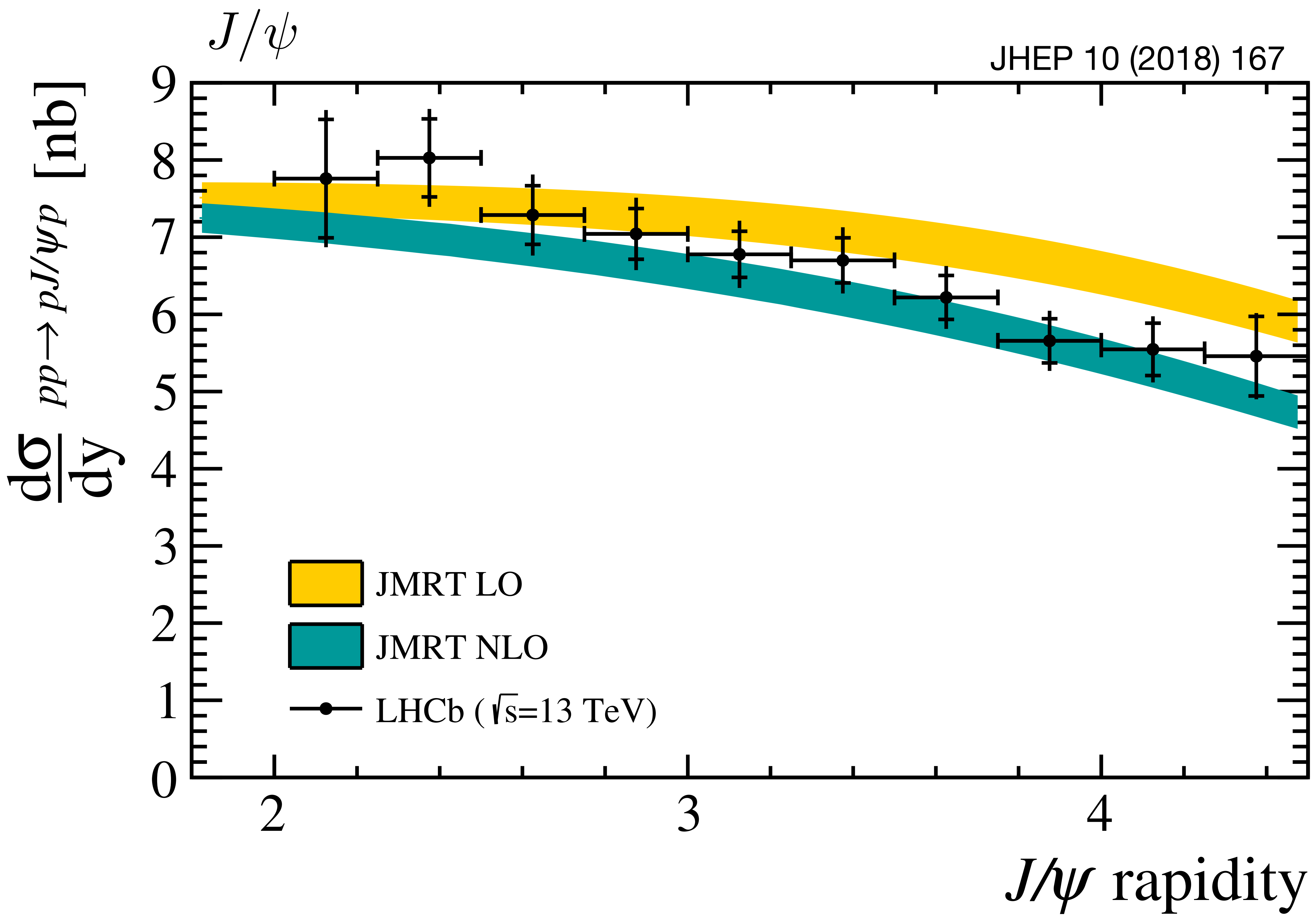


proton/ion dissociation

J/ψ feed-down background

pp cross section



JMRT prediction, based on gluon PDF:

At low x_B, approximate GPD 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

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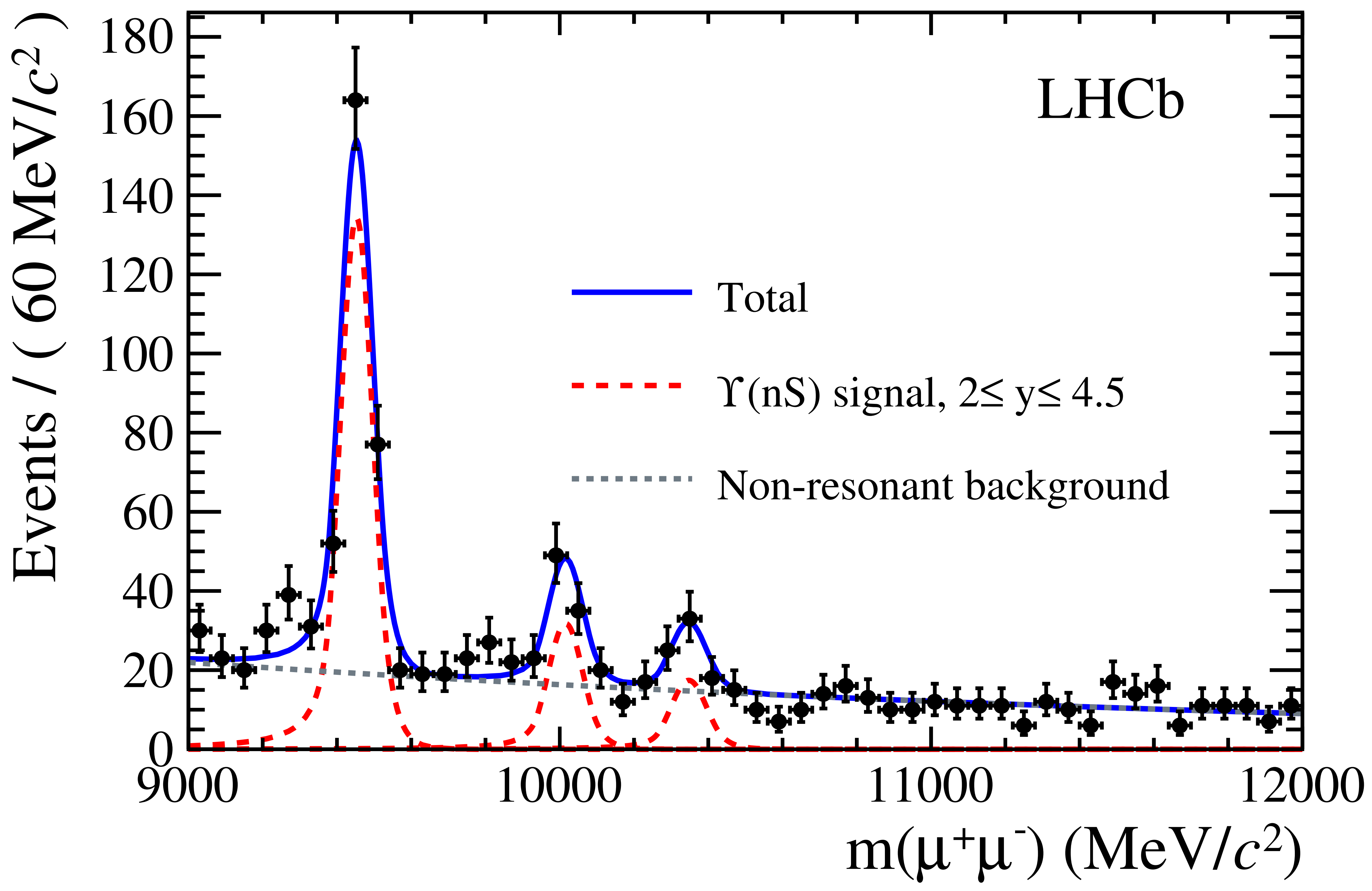
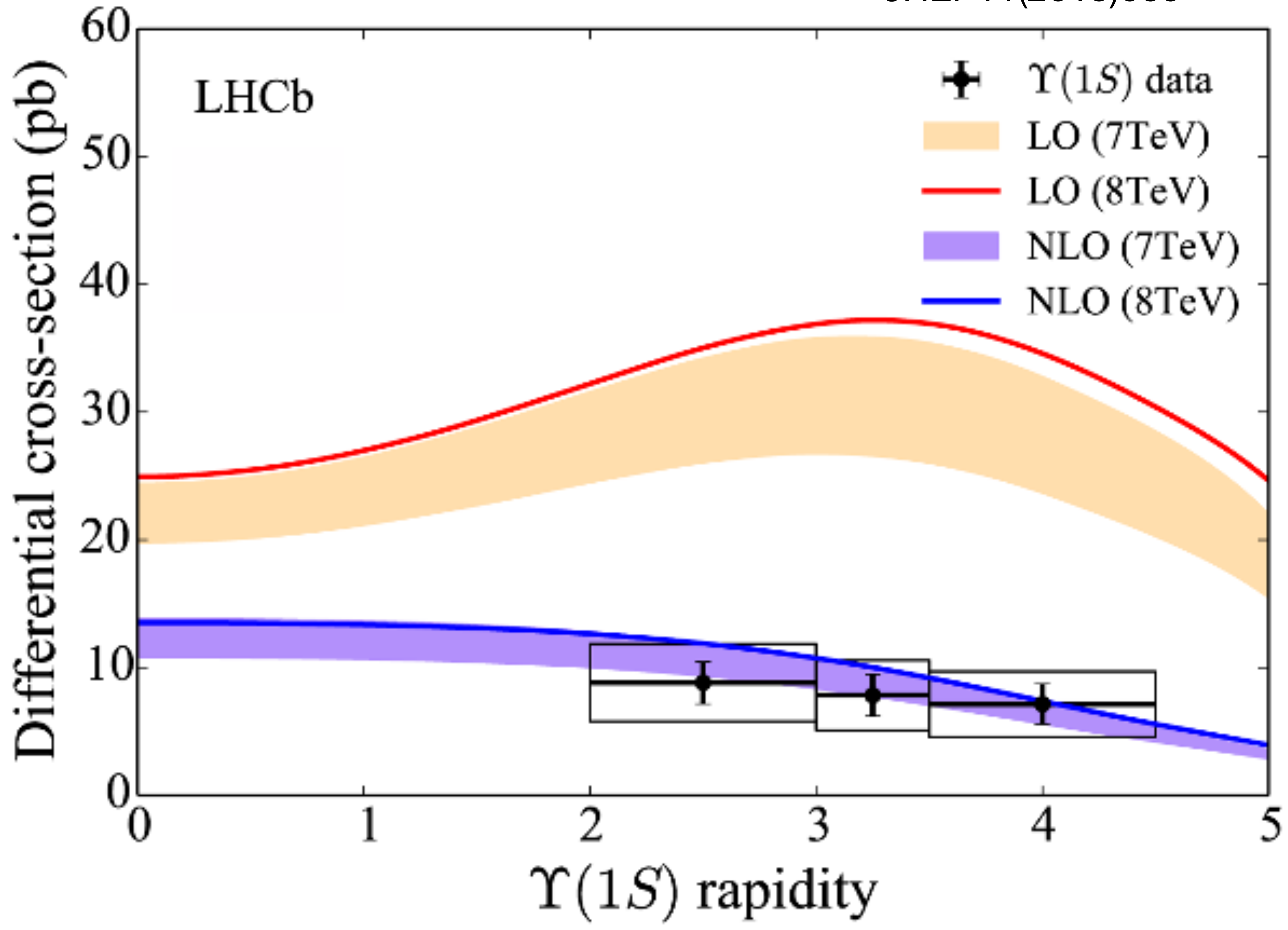
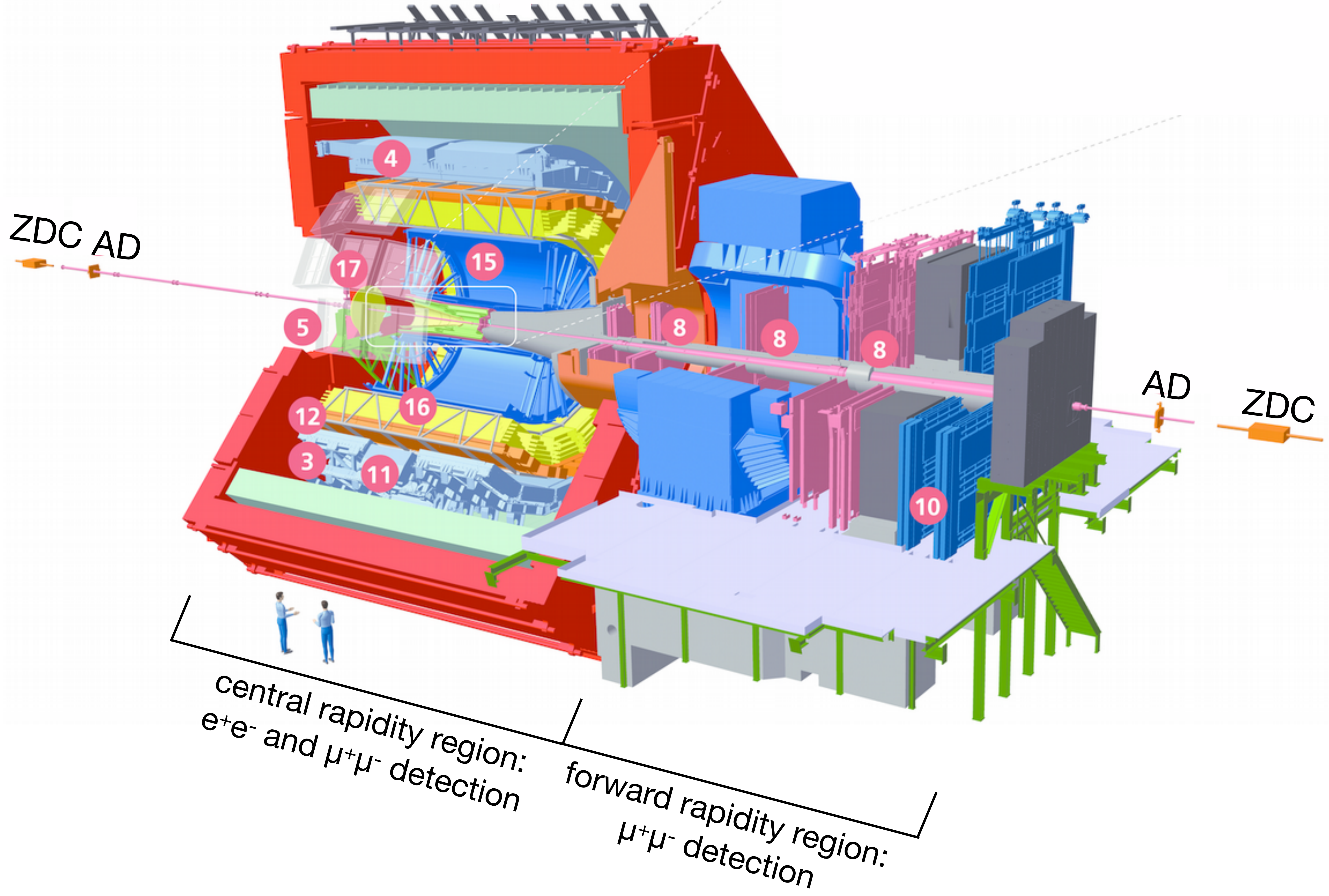


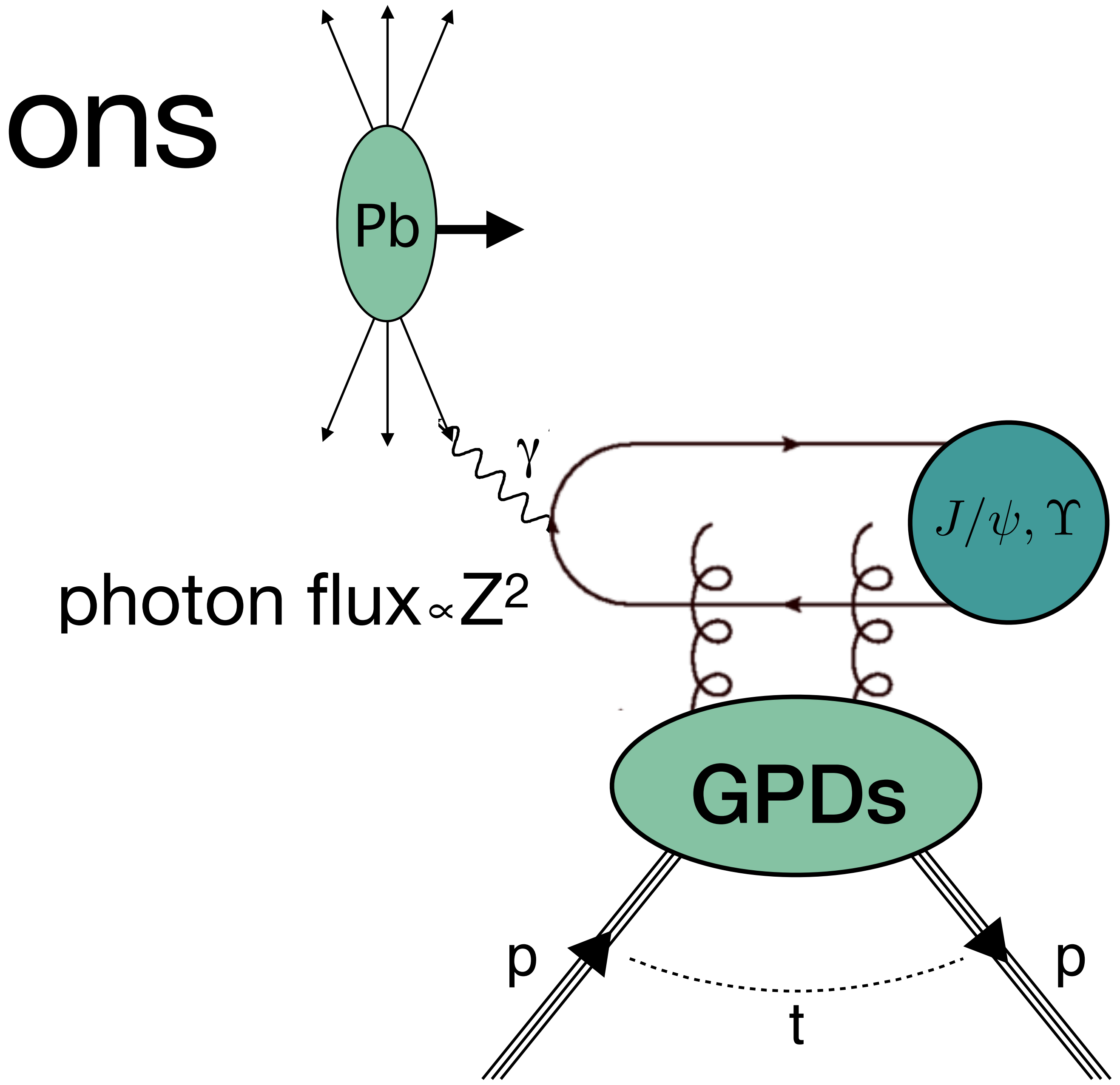
JHEP11(2013)085



higher Q^2 scale

ALICE: exclusive single-J/ψ production in pPb collisions





+ Requirement on forward/backward scintillators and far-foward/backward neutron zero-degree calorimeters (ZDCs)

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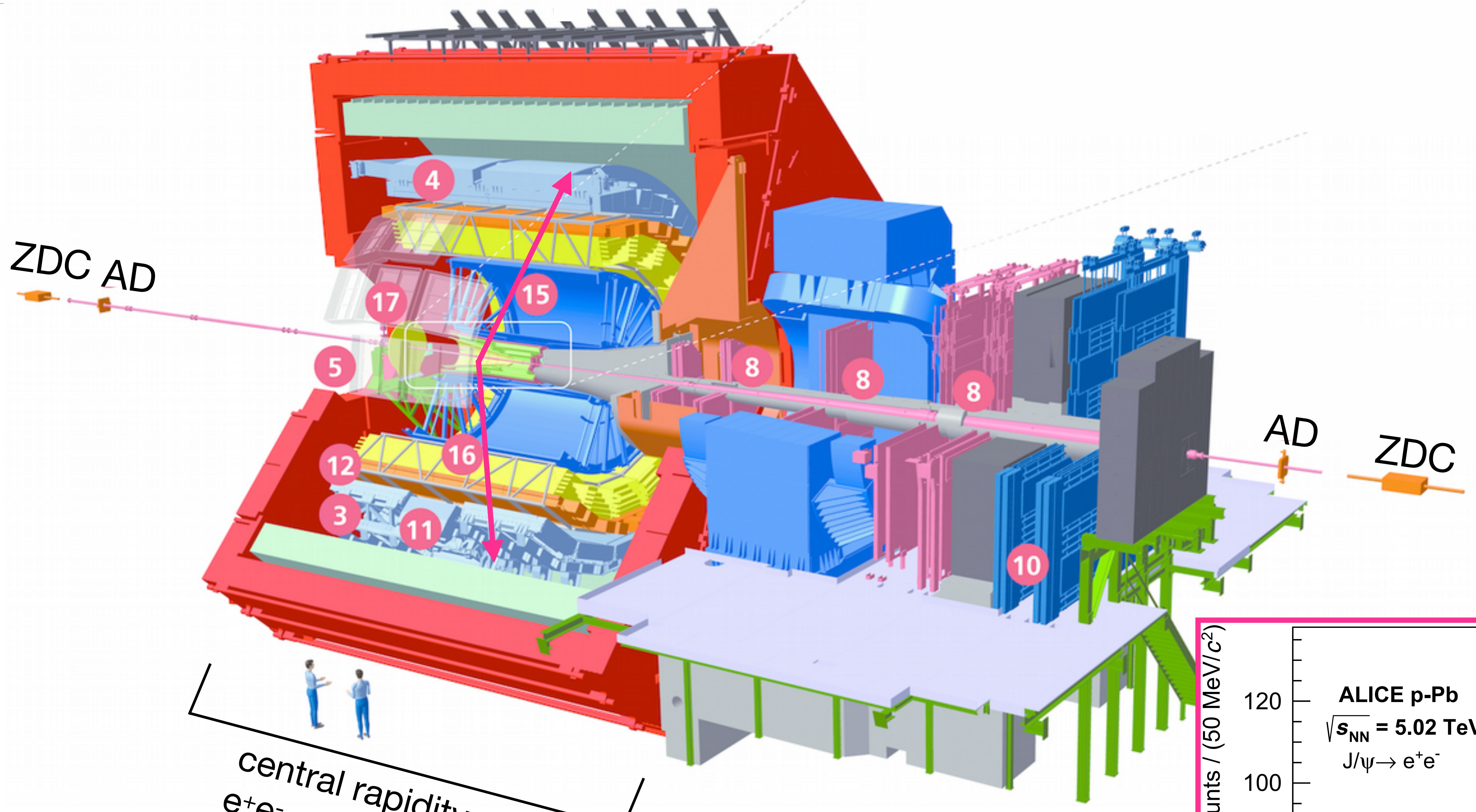

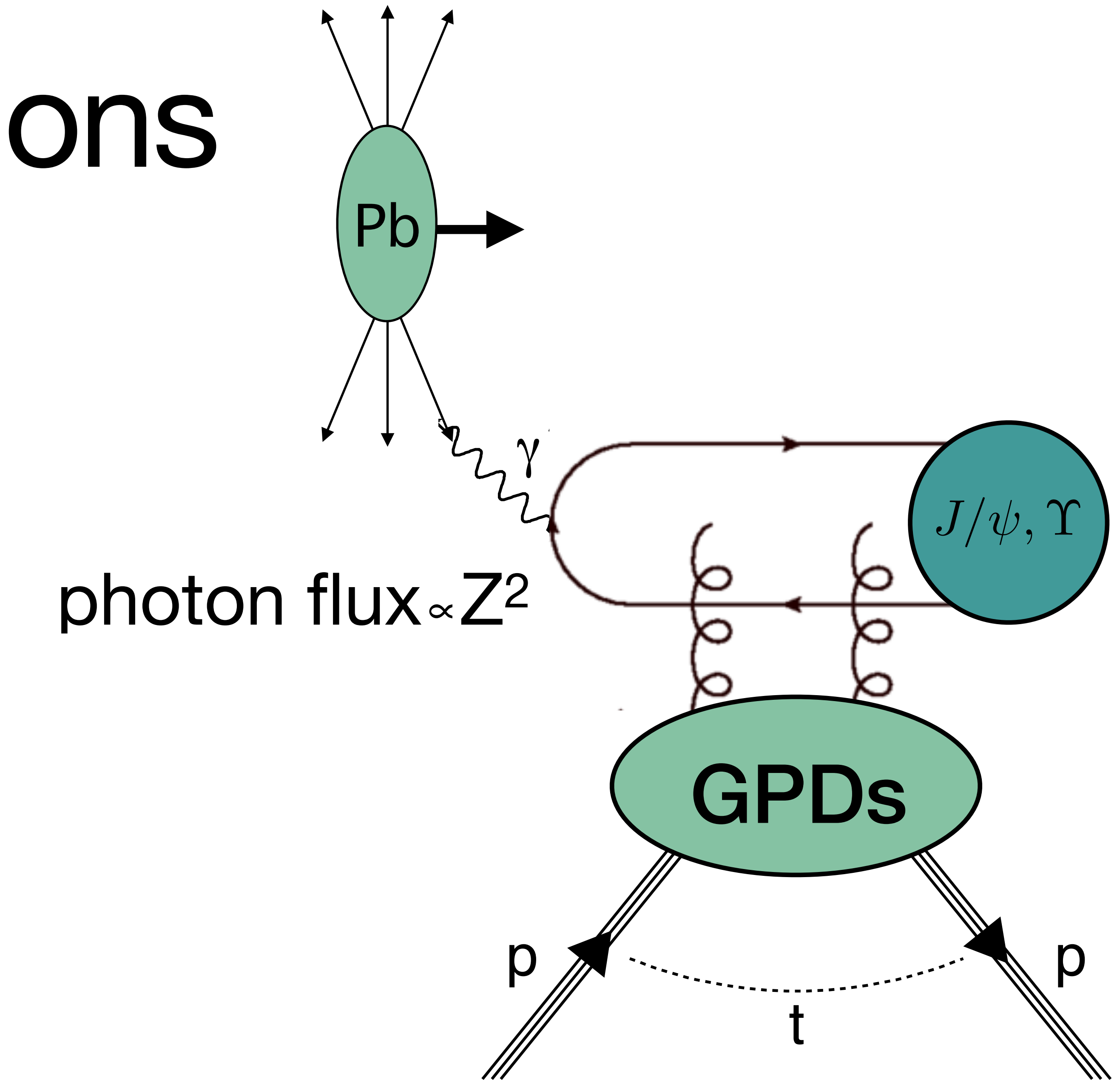

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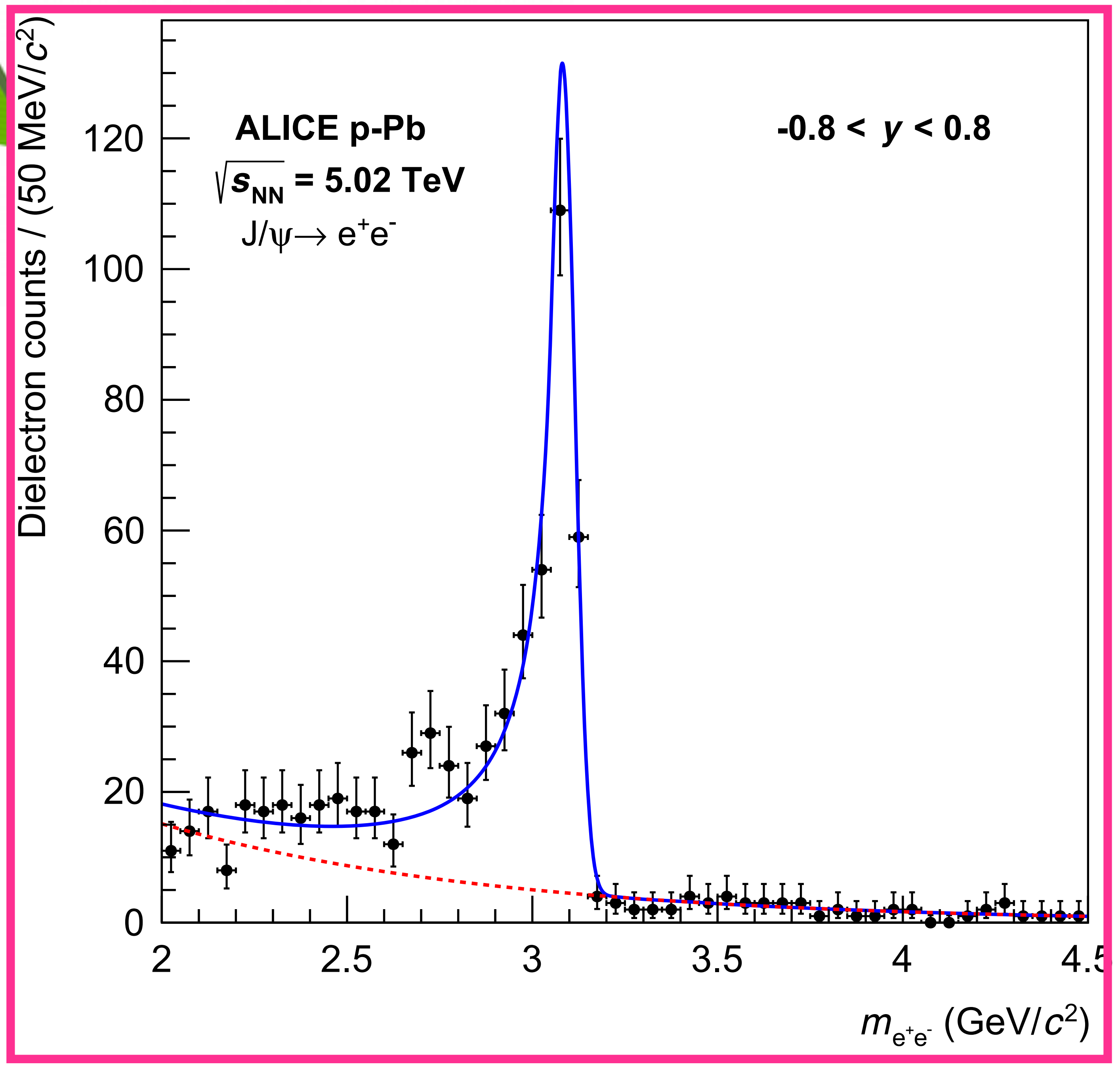

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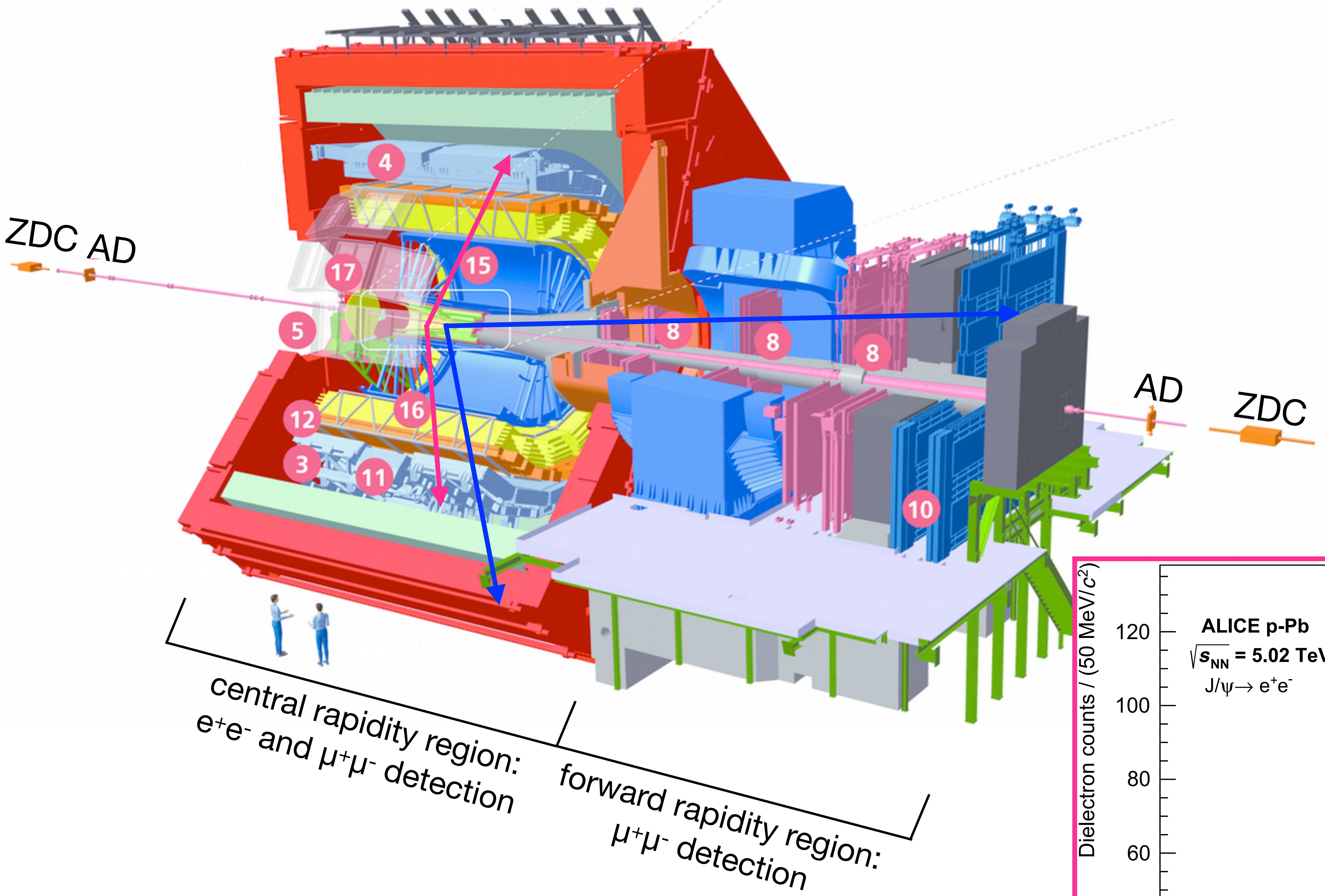

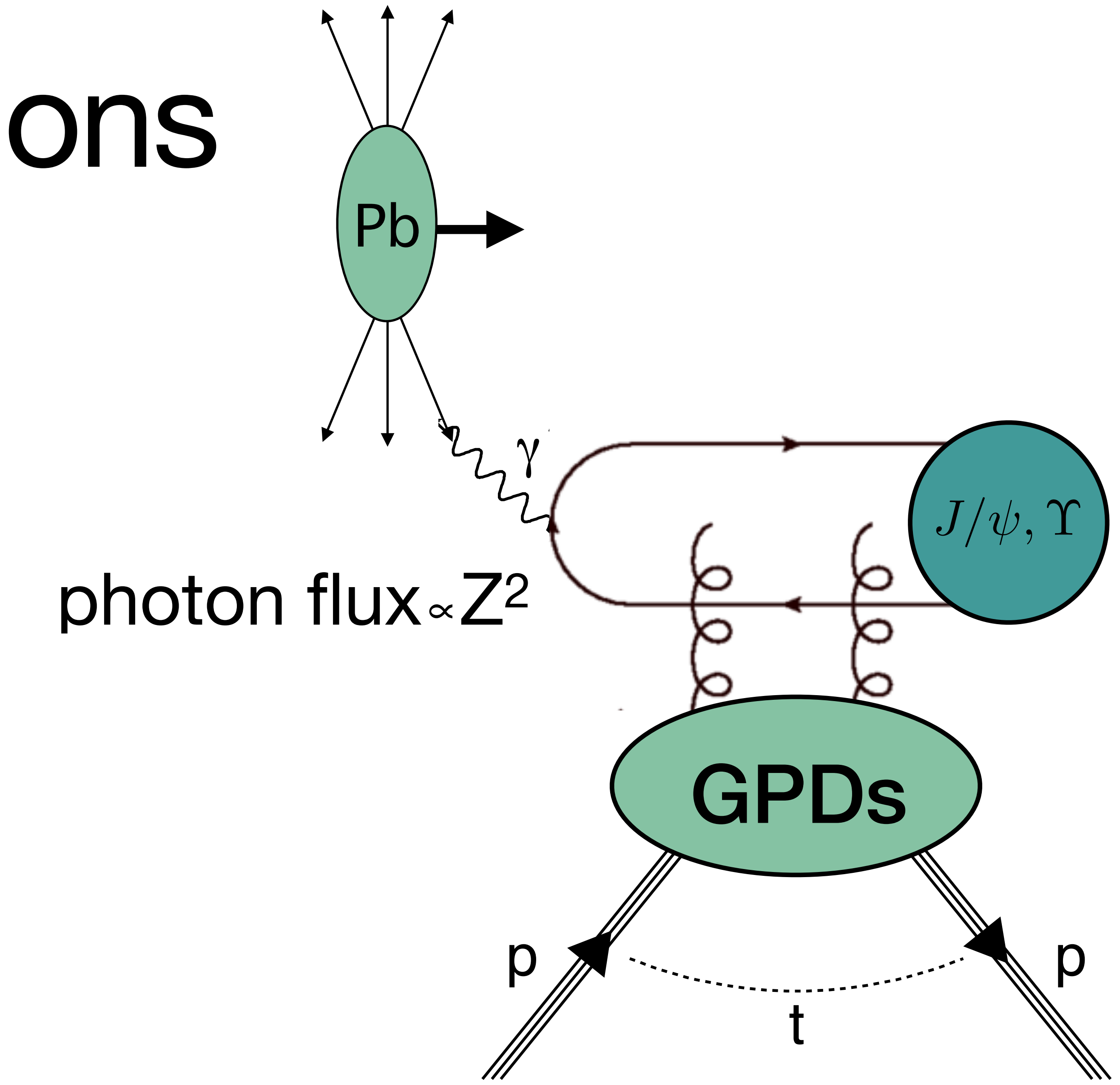

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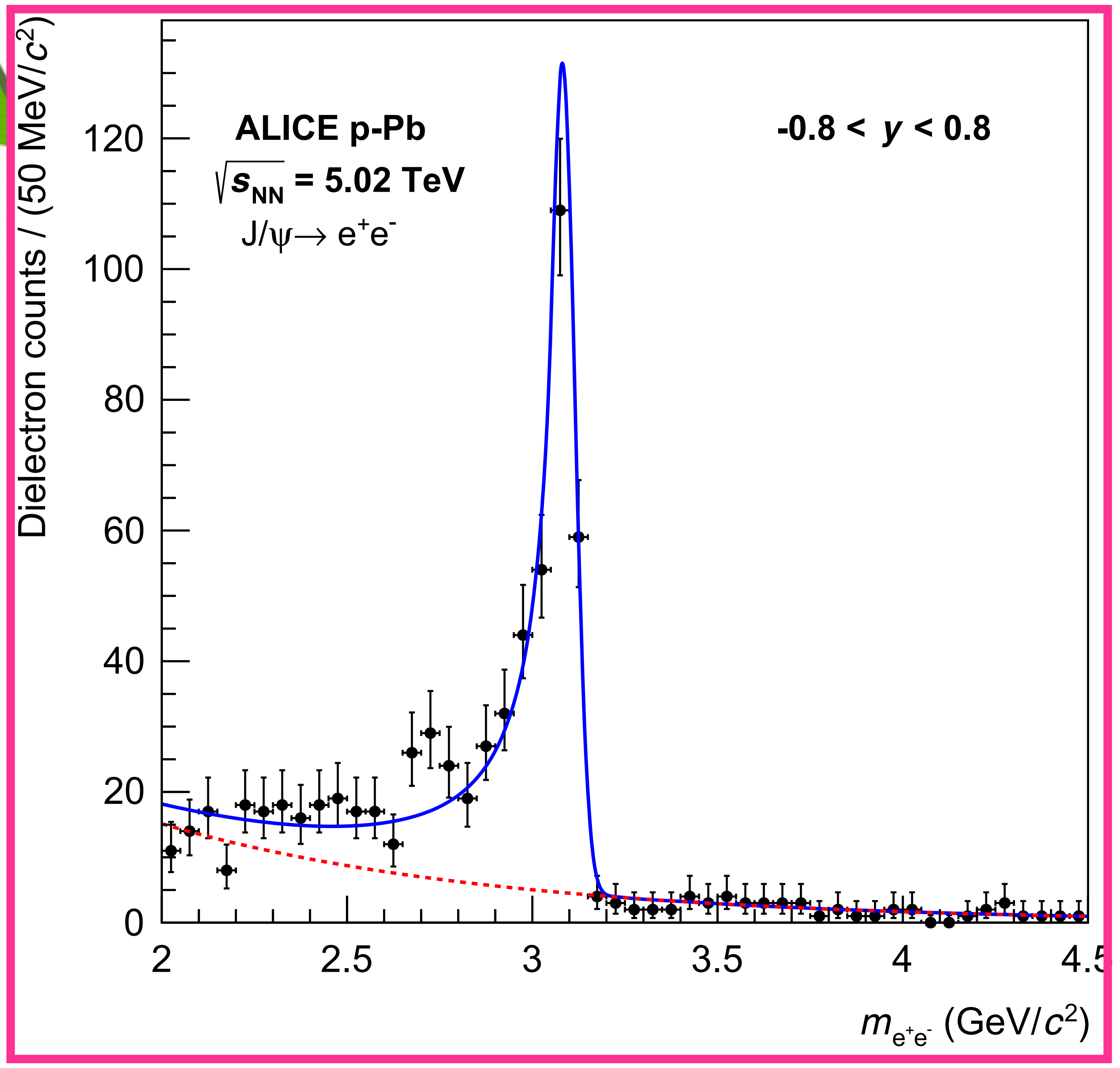
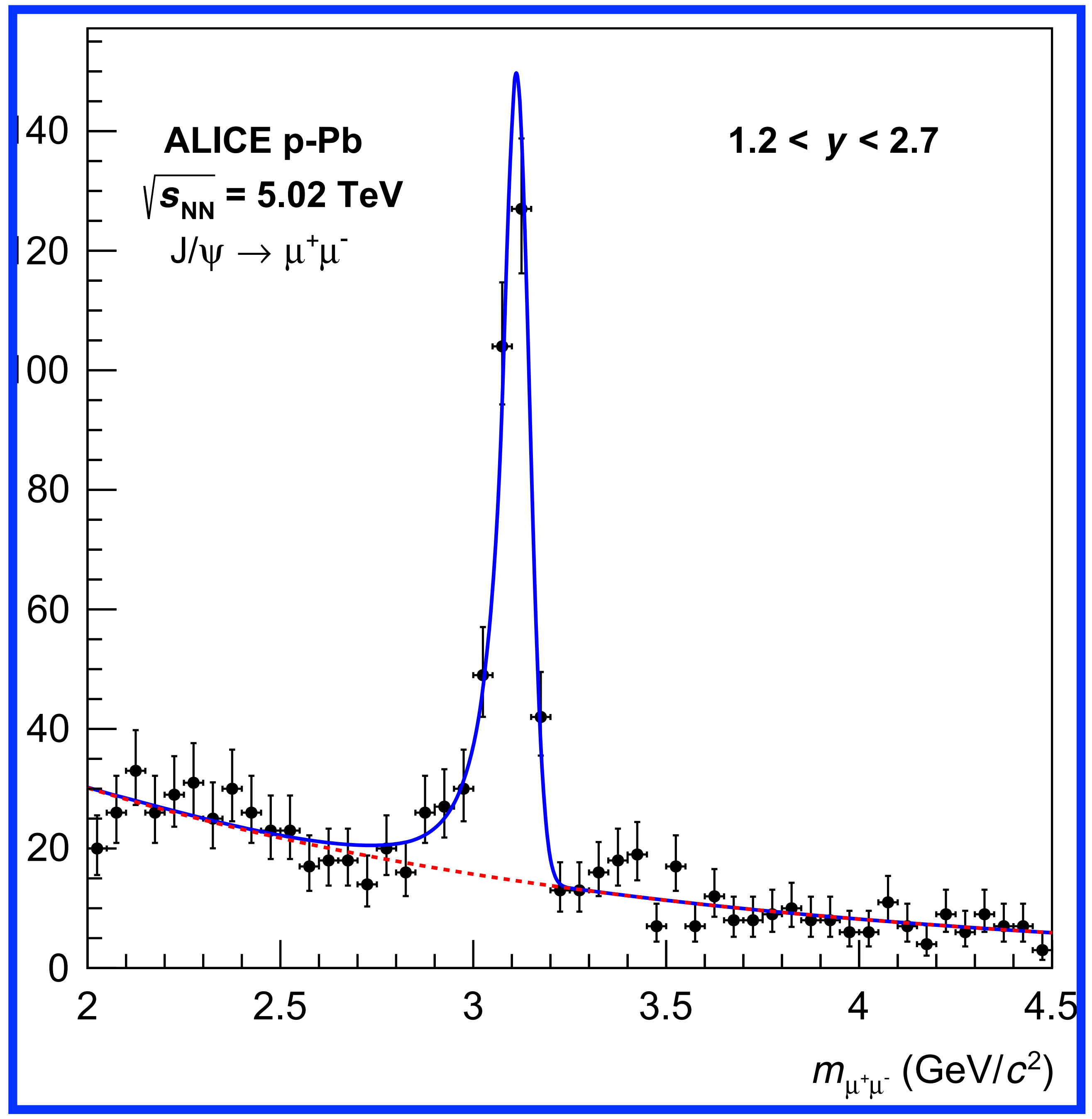
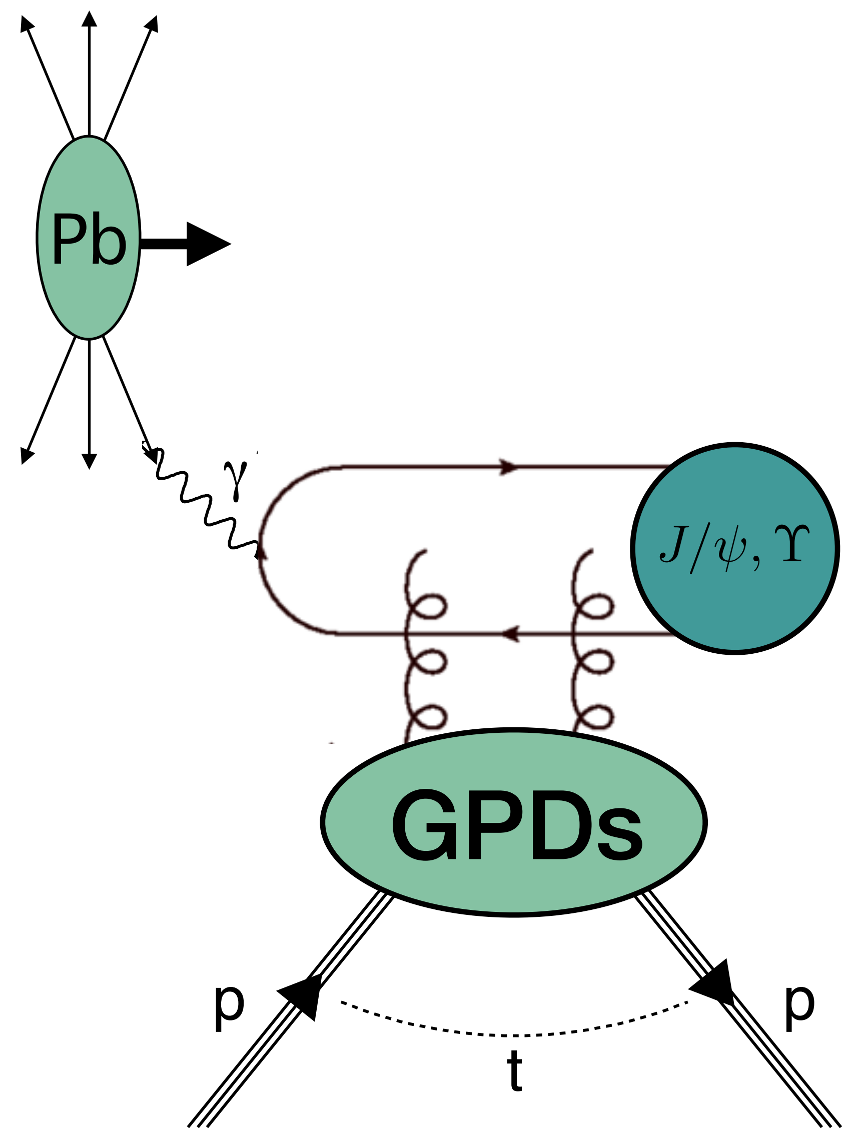




Extraction of the J/ψ photoproduction



pPb: use Z^2 dependence of photon flux

→ Pb is predominantly photon emitter

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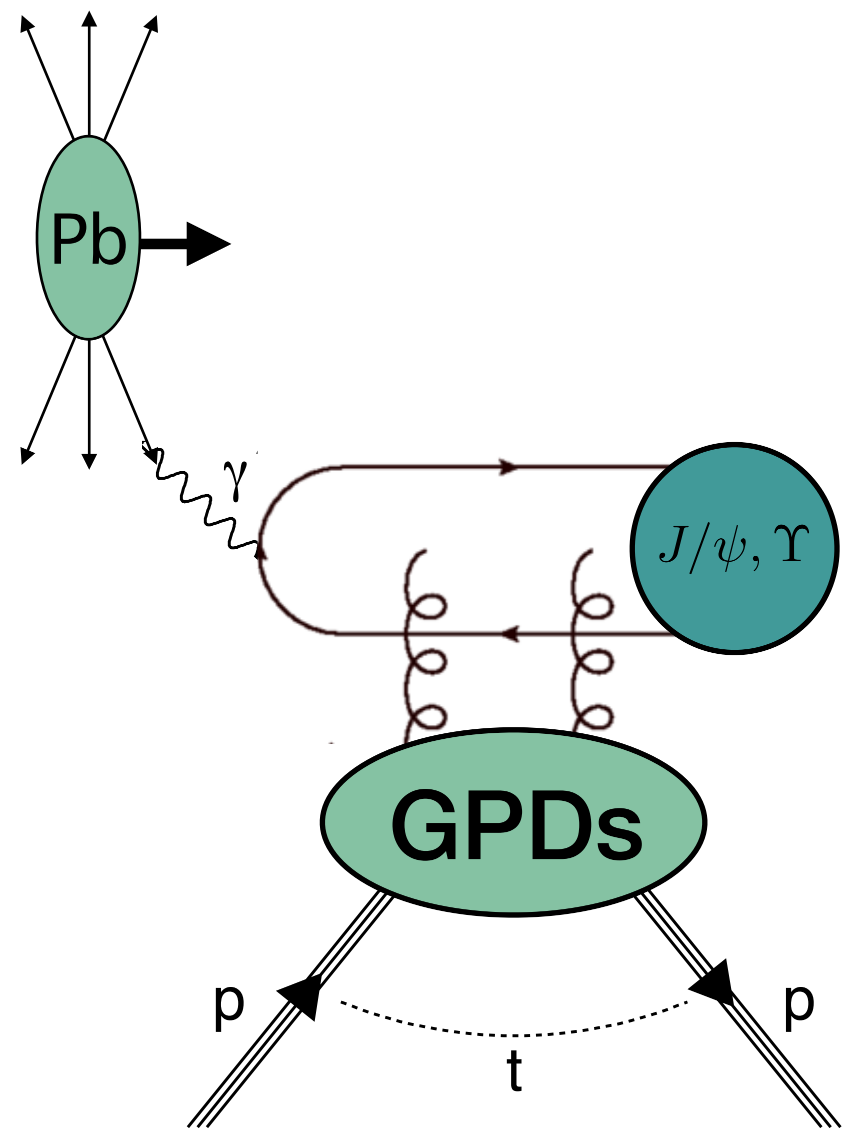

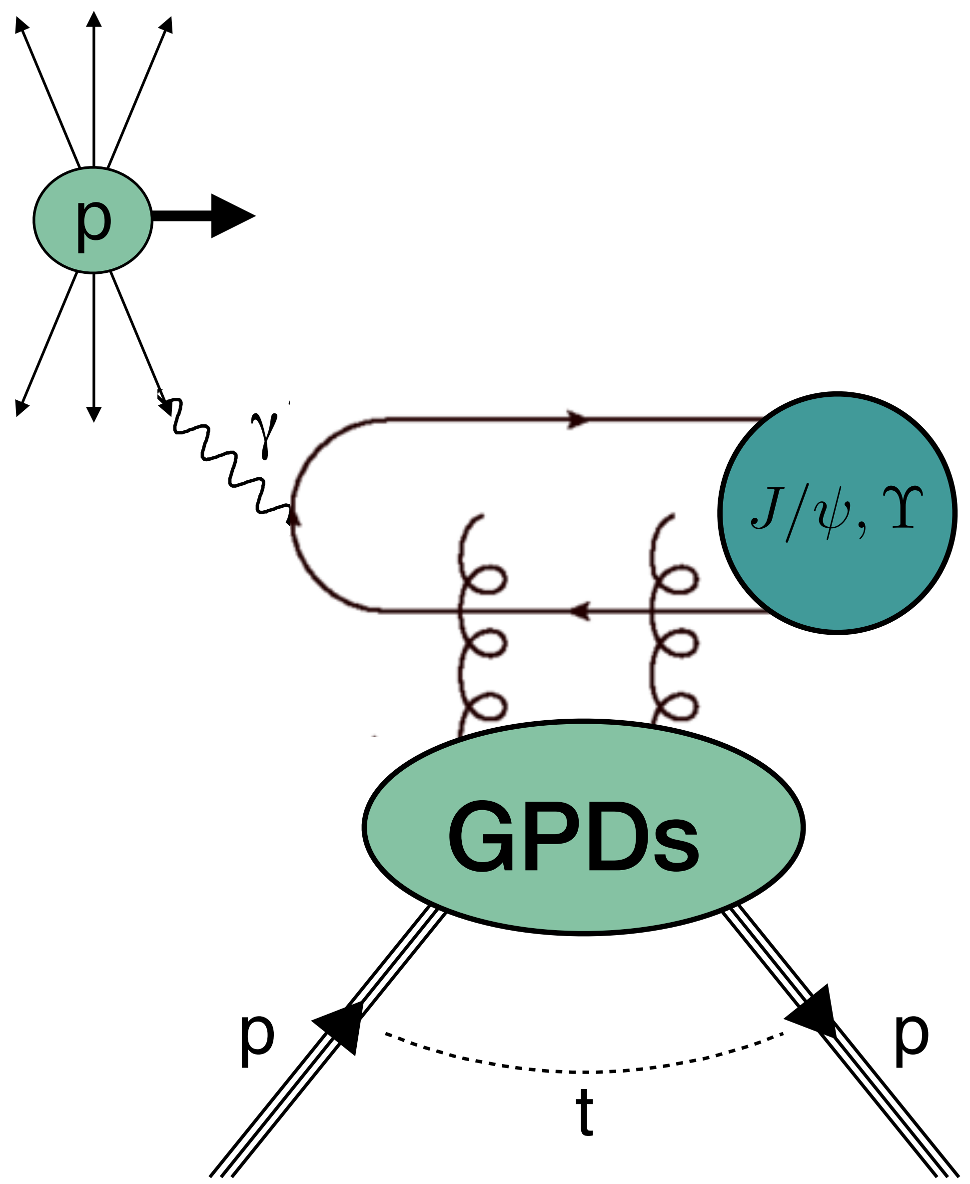

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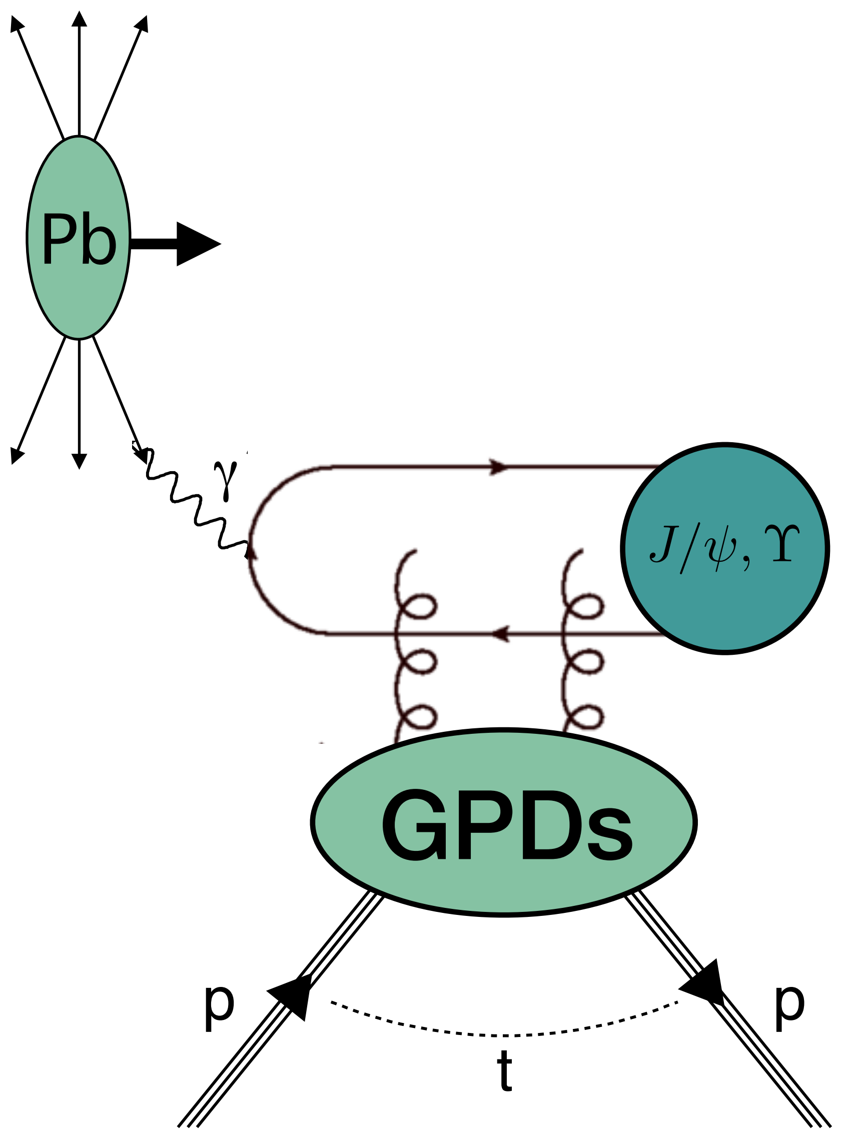

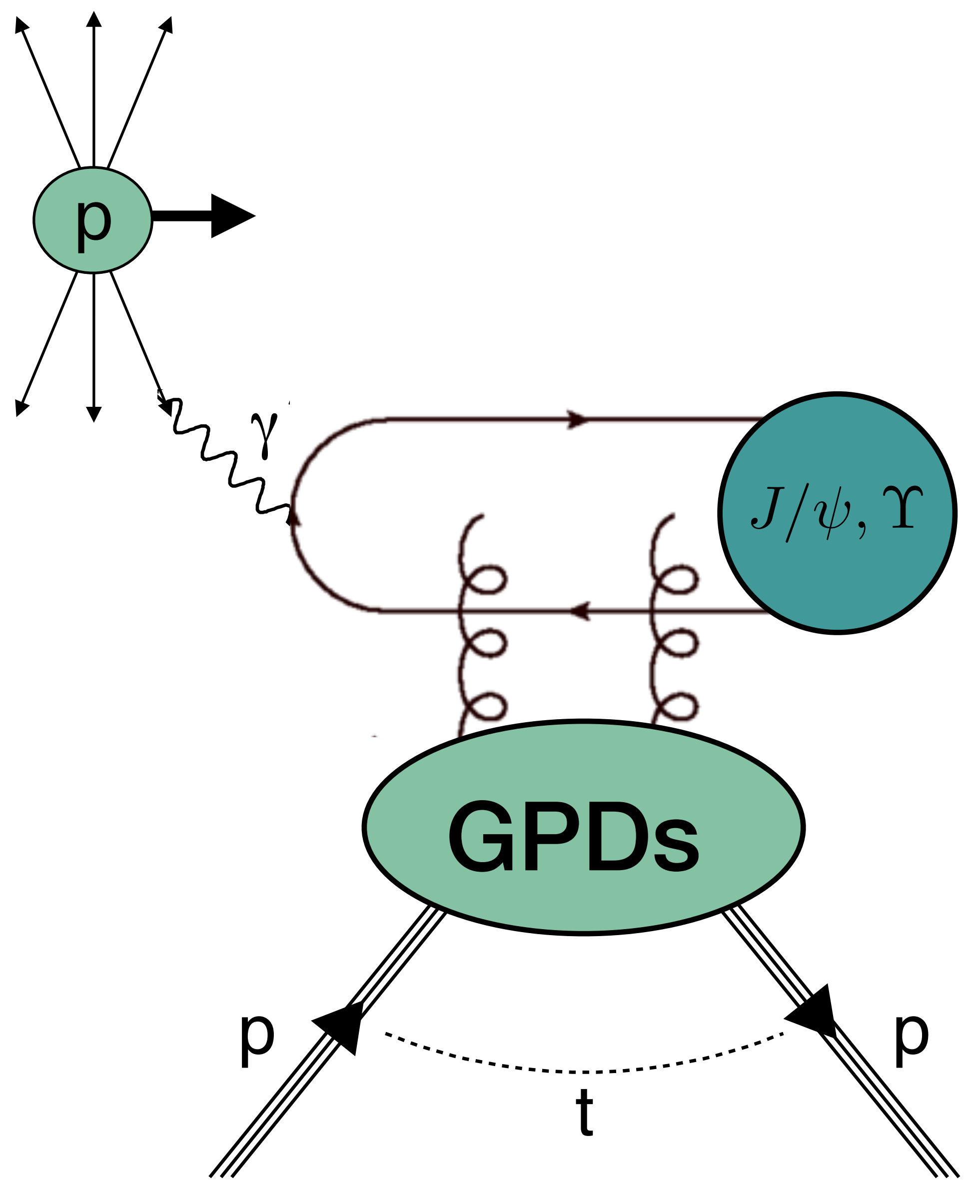

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pp: ambiguity in ID of photon emitter

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

relation pp and γp cross section:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_-\frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

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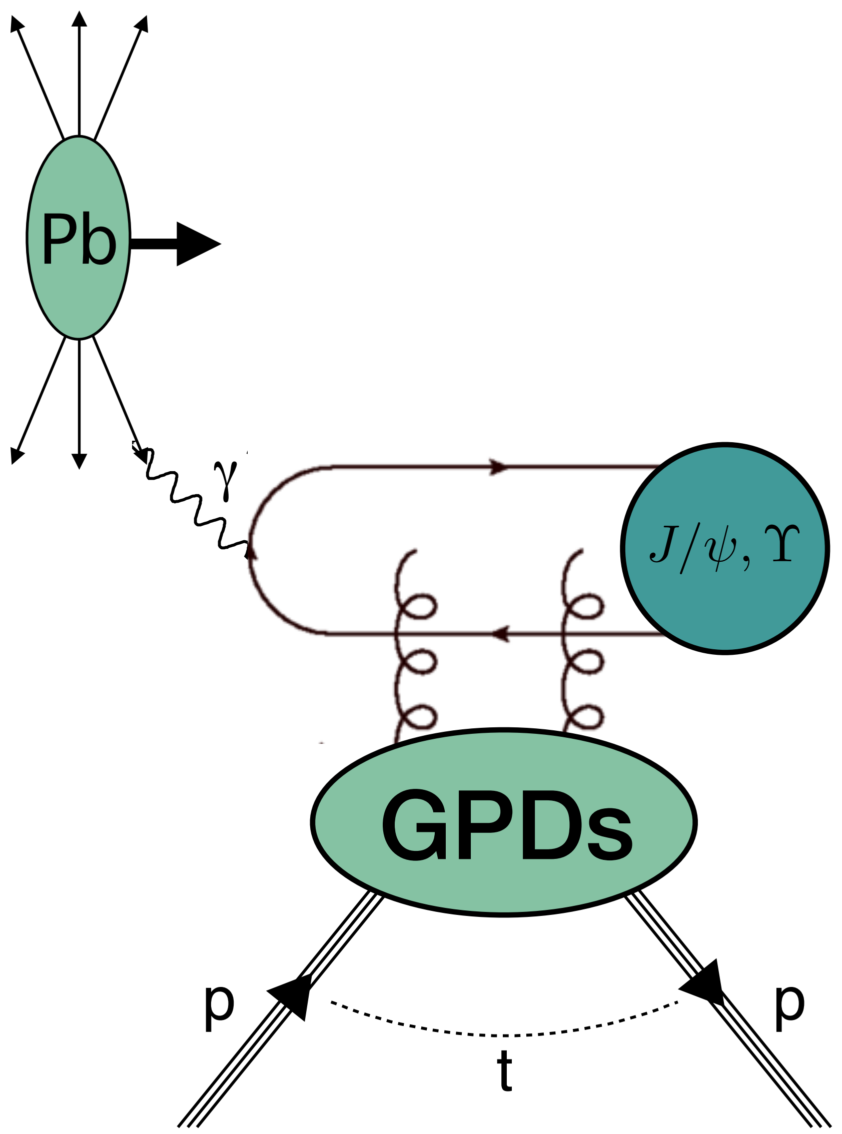

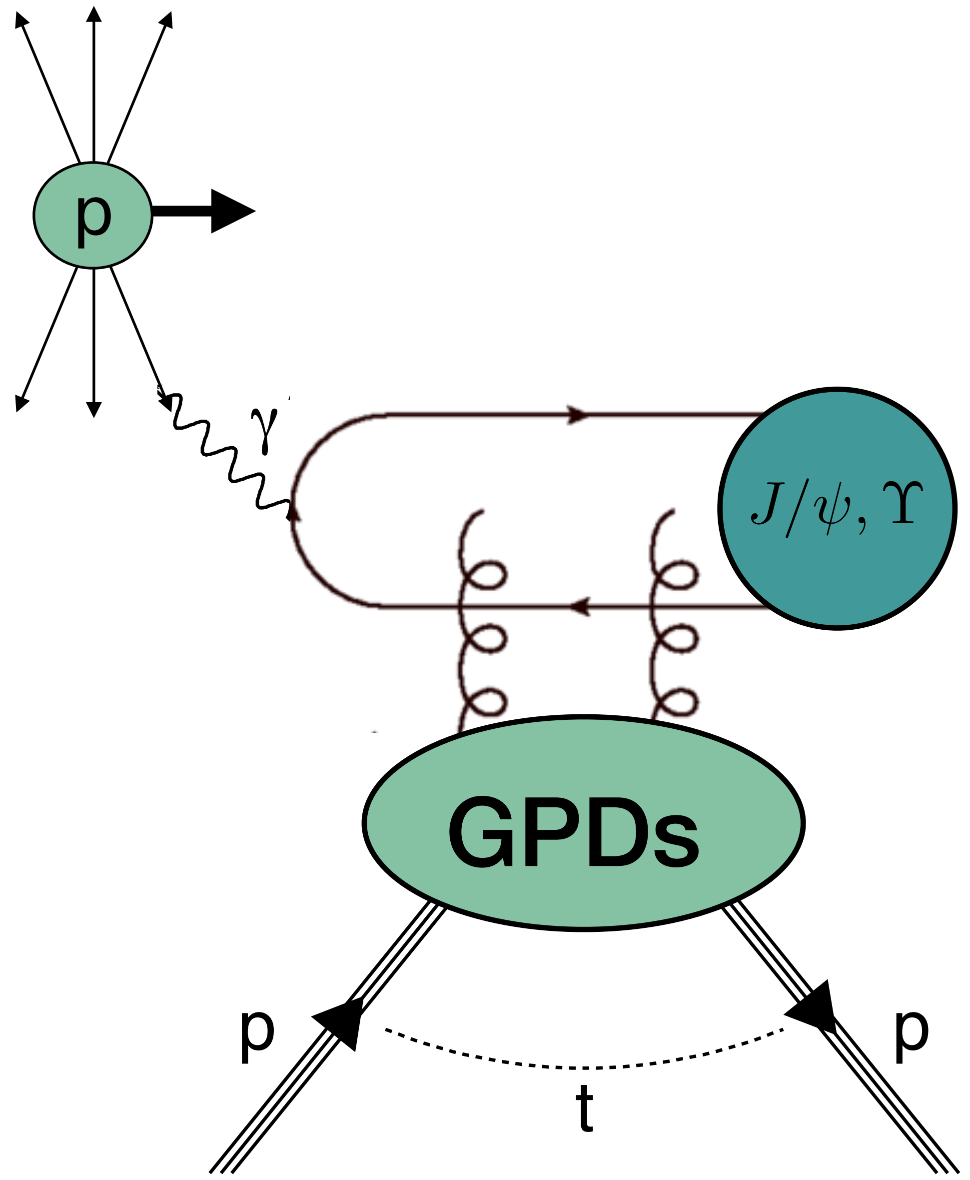

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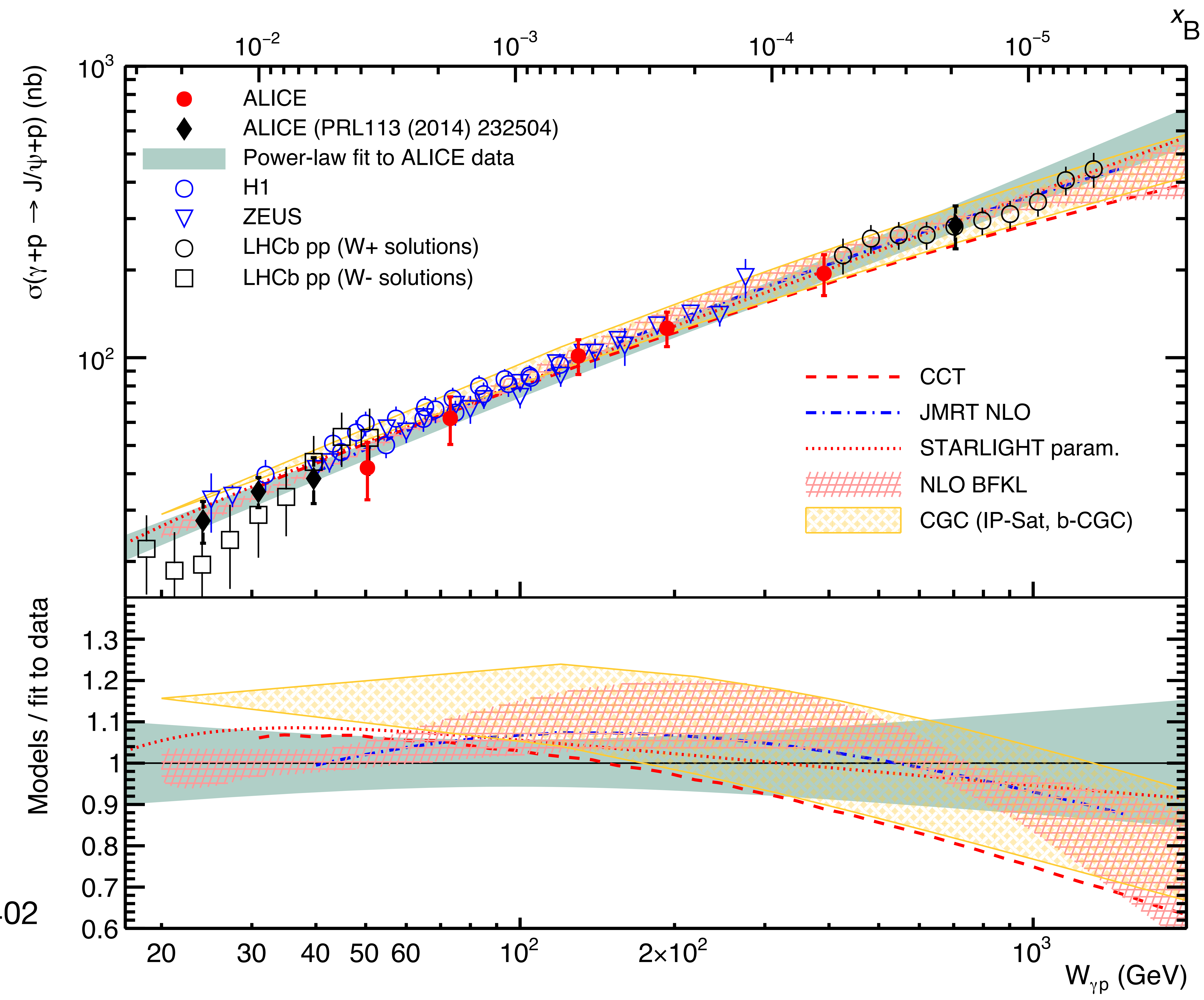
relation pp and γp cross section:

$$\sigma_{pp\to p\psi p} = r(W_+)k_+ \frac{\mathrm{d}n}{\mathrm{d}k_+}\sigma_{\gamma p\to\psi p}(W_+) + r(W_-)k_- \frac{\mathrm{d}n}{\mathrm{d}k_-}\sigma_{\gamma p\to\psi p}(W_-)$$

LHCb used HERA data for low-E_γ (W_-) contribution.

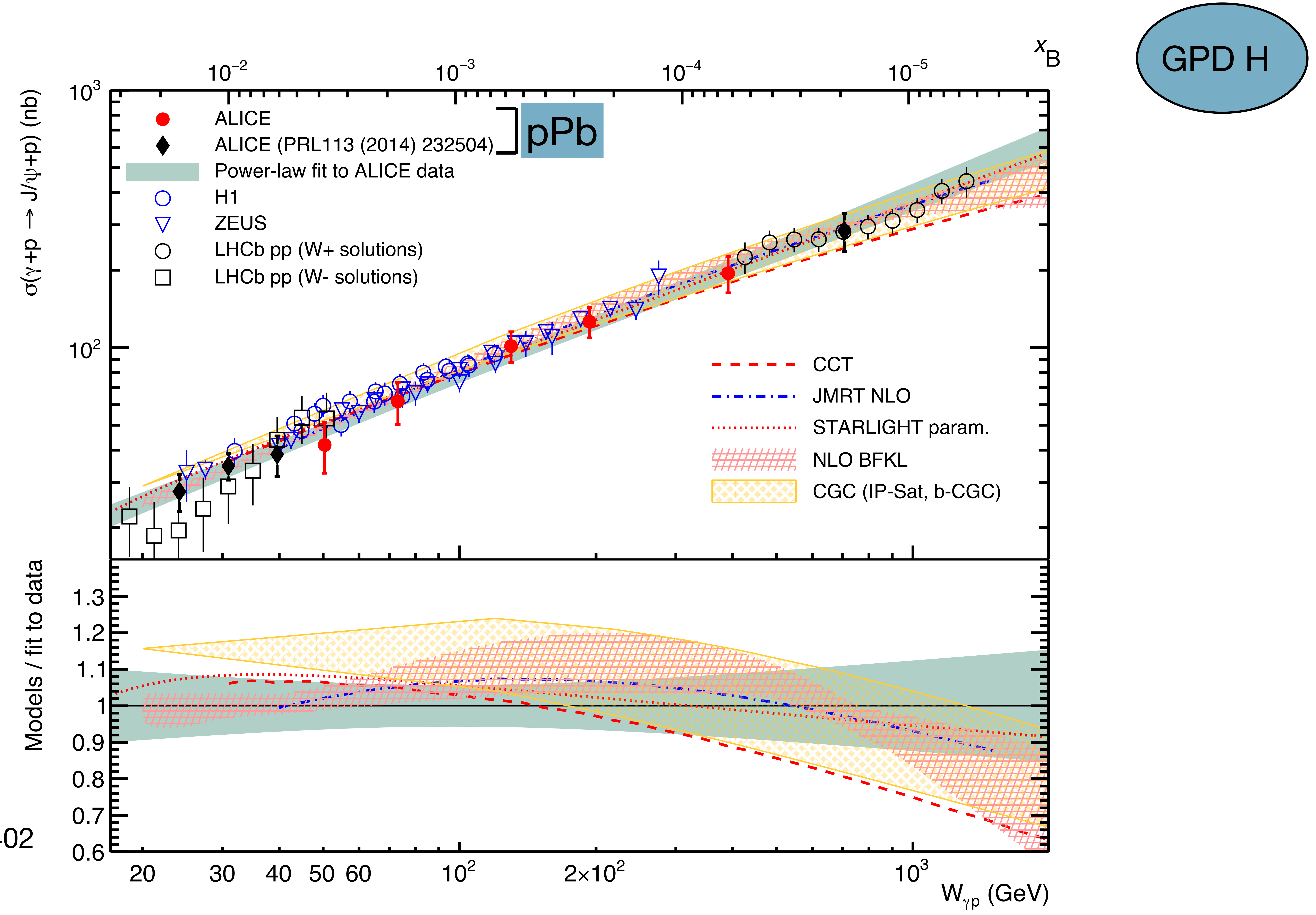
γp cross section: LHC

GPD H



Eur. Phys. J. C **79** ('19) 402

γp cross section: LHC



Eur. Phys. J. C **79** ('19) 402

γp cross section: LHC

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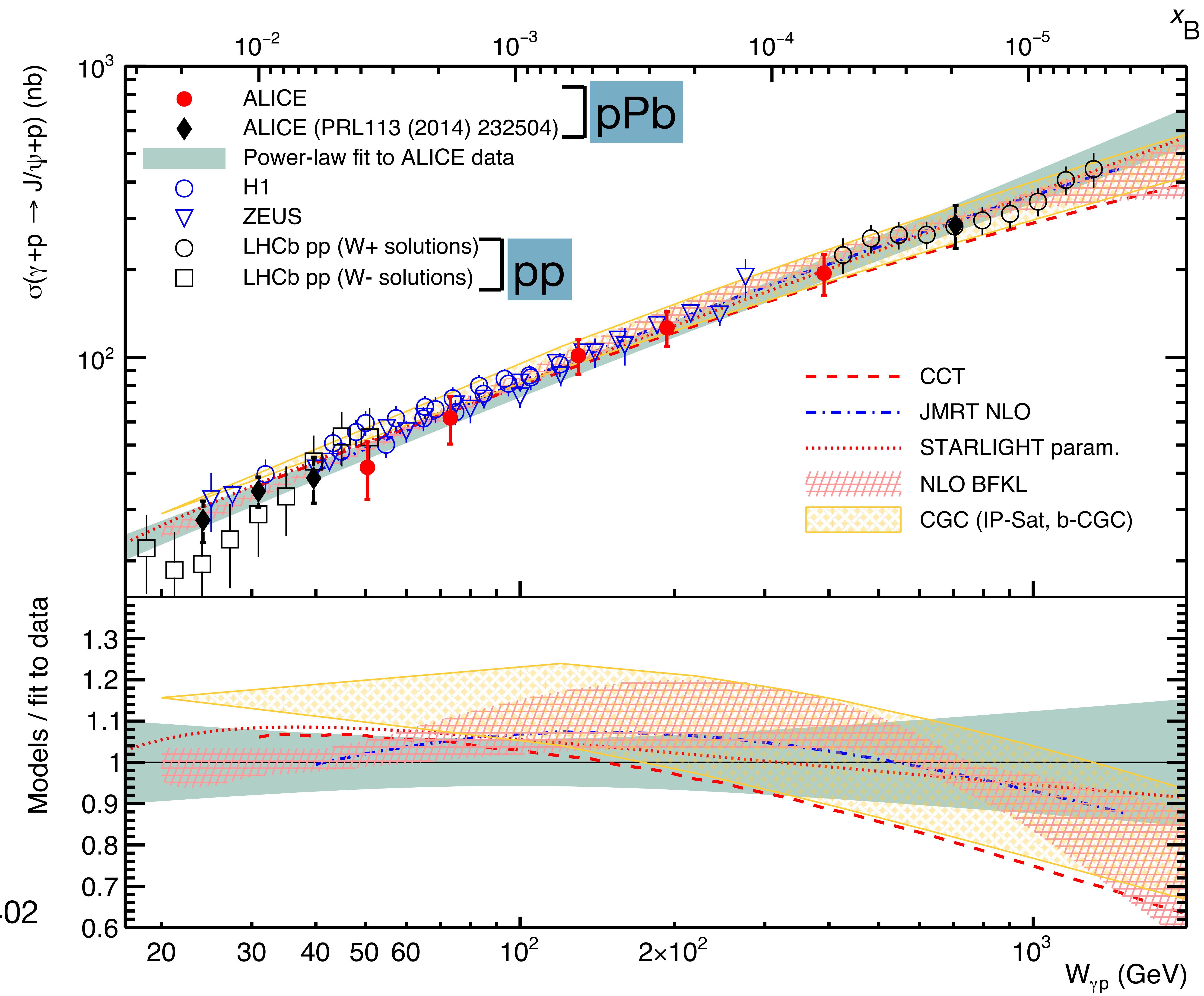
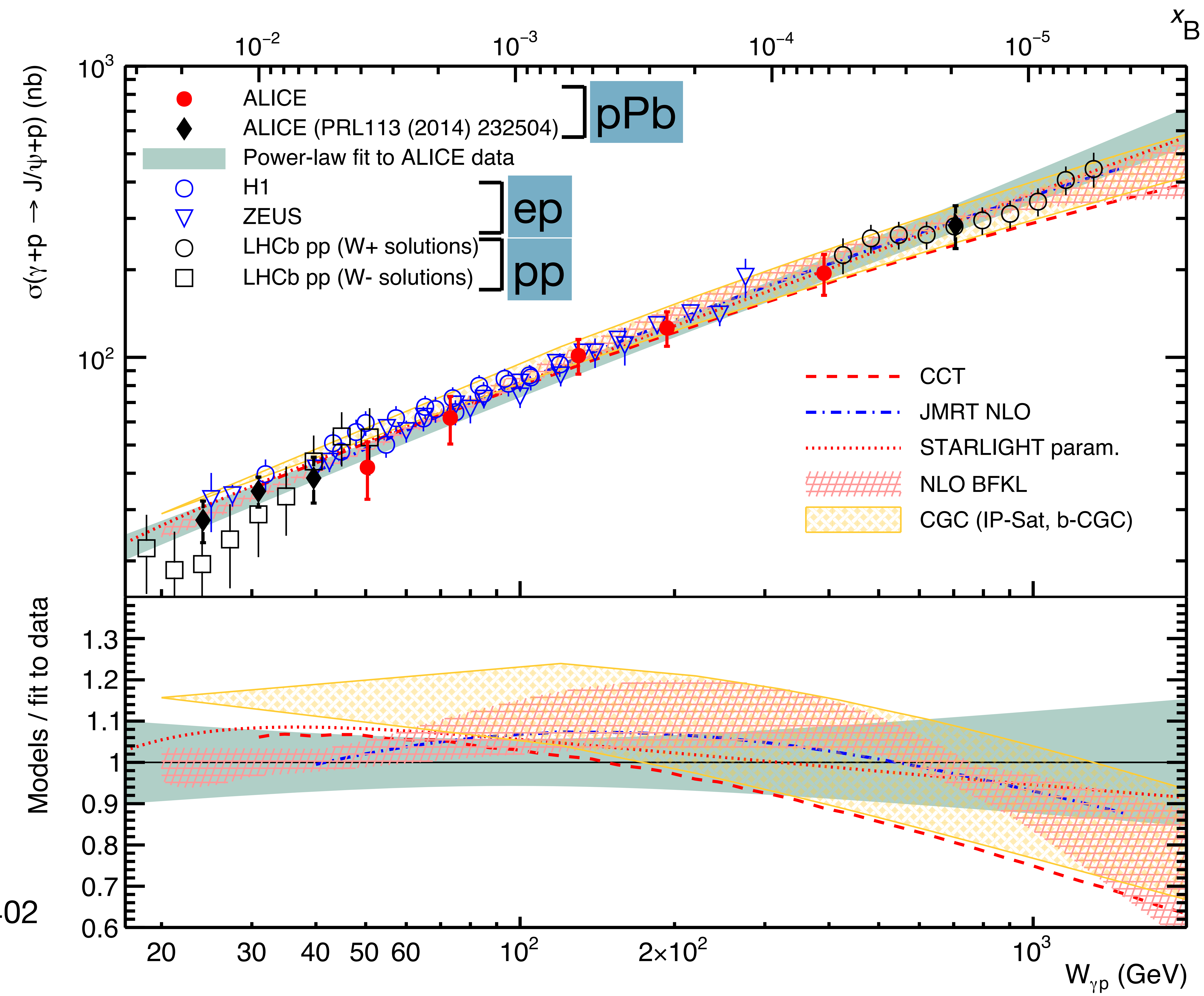


Eur. Phys. J. C **79** ('19) 402

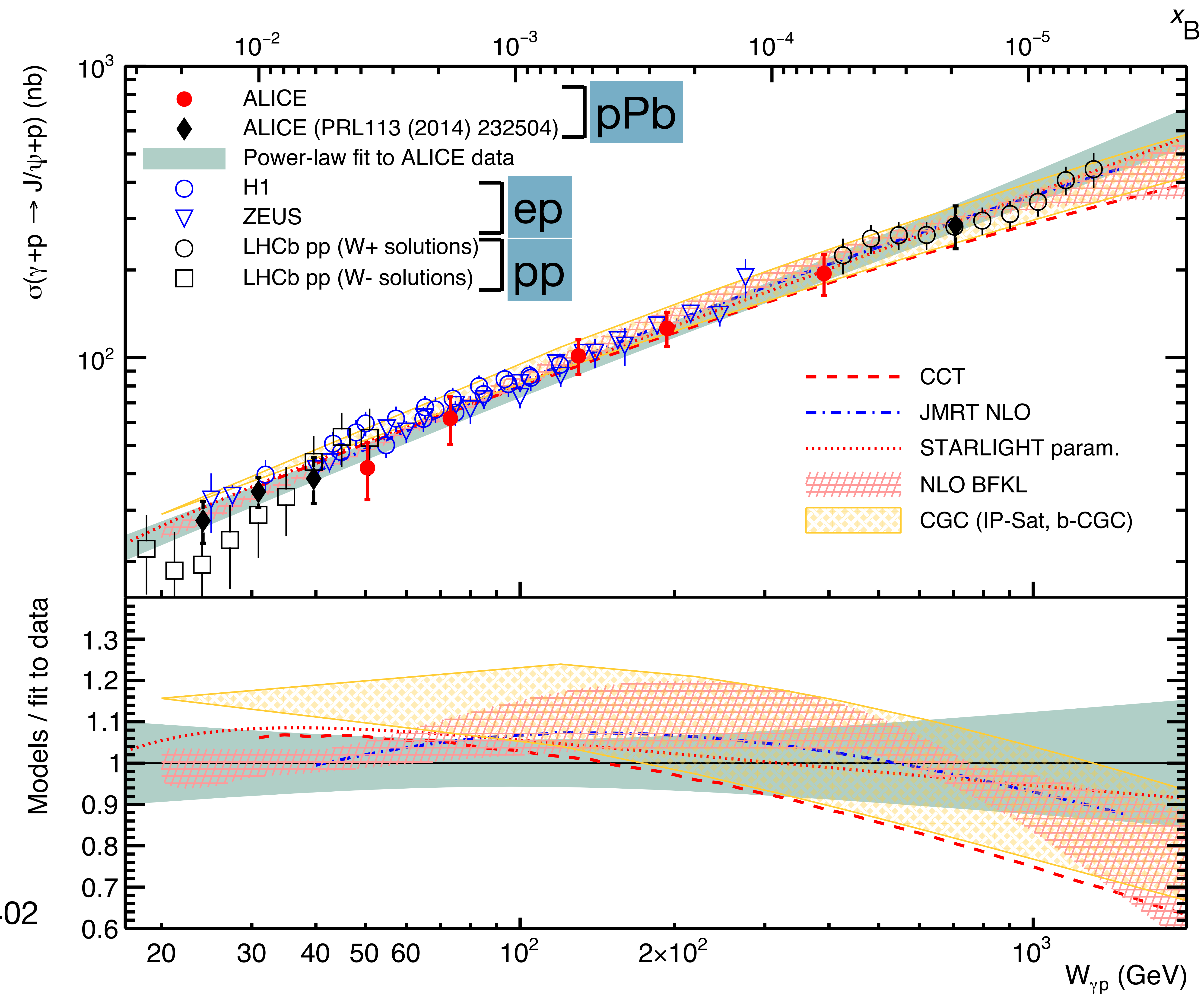
γp cross section: LHC



GPD H

Eur. Phys. J. C **79** ('19) 402

γp cross section: LHC



Eur. Phys. J. C **79** ('19) 402

GPD H

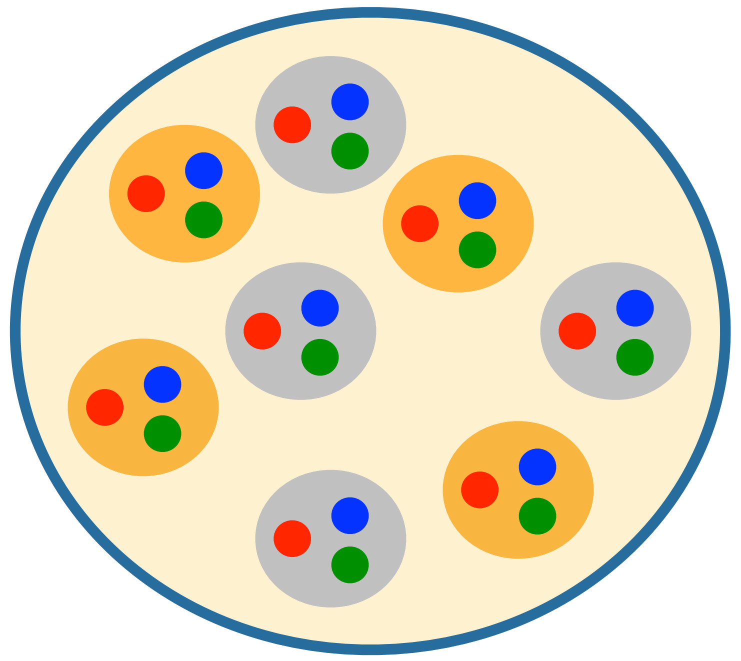
overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

Ultra-peripheral collisions in PbPb

What object are we probing?

Ultra-peripheral collisions in PbPb

What object are we probing?



Ultra-peripheral collisions in PbPb

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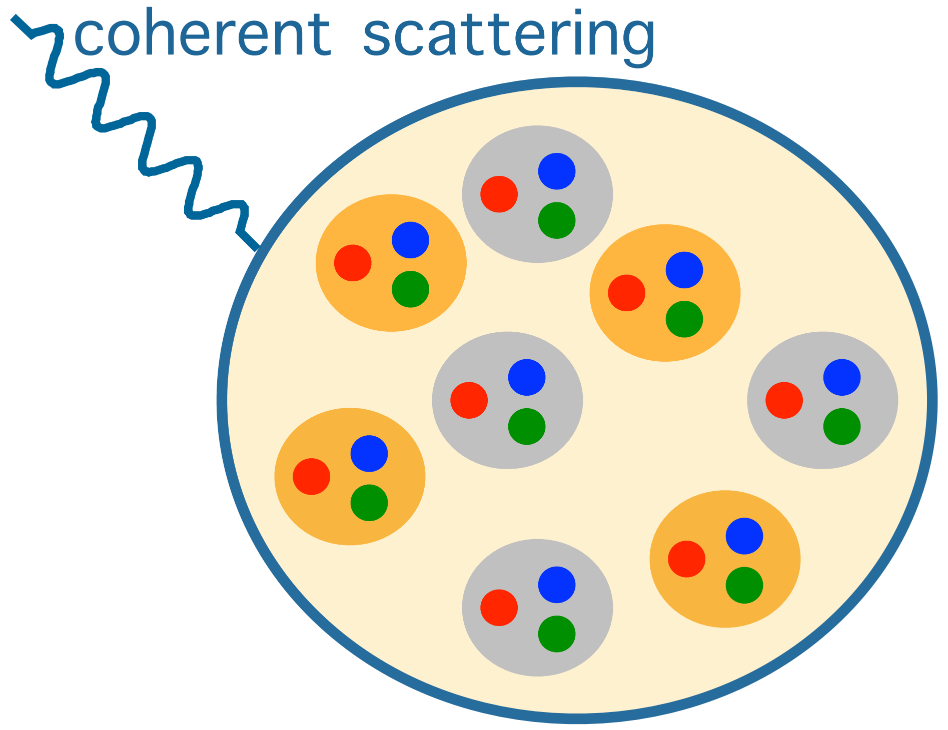

Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Ultra-peripheral collisions in PbPb

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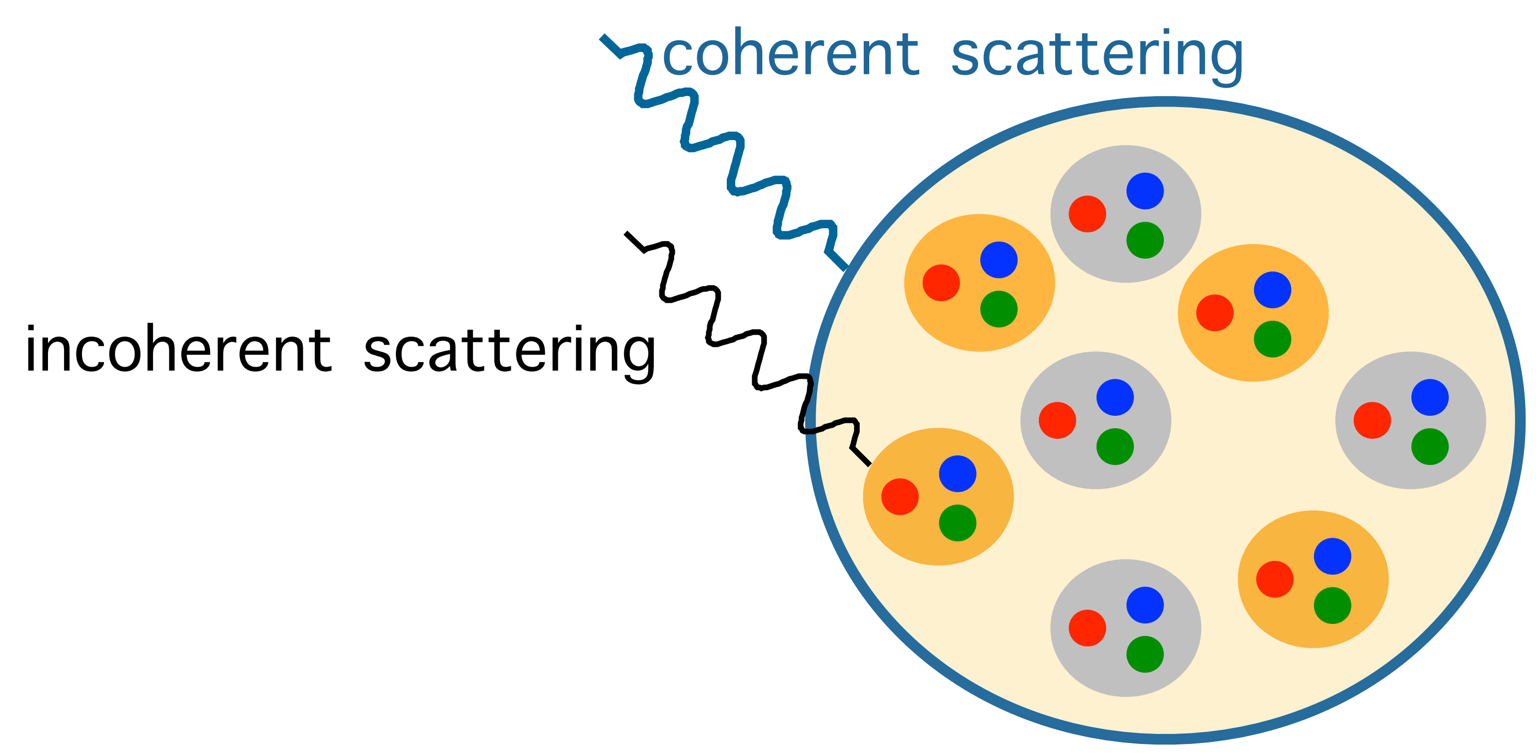
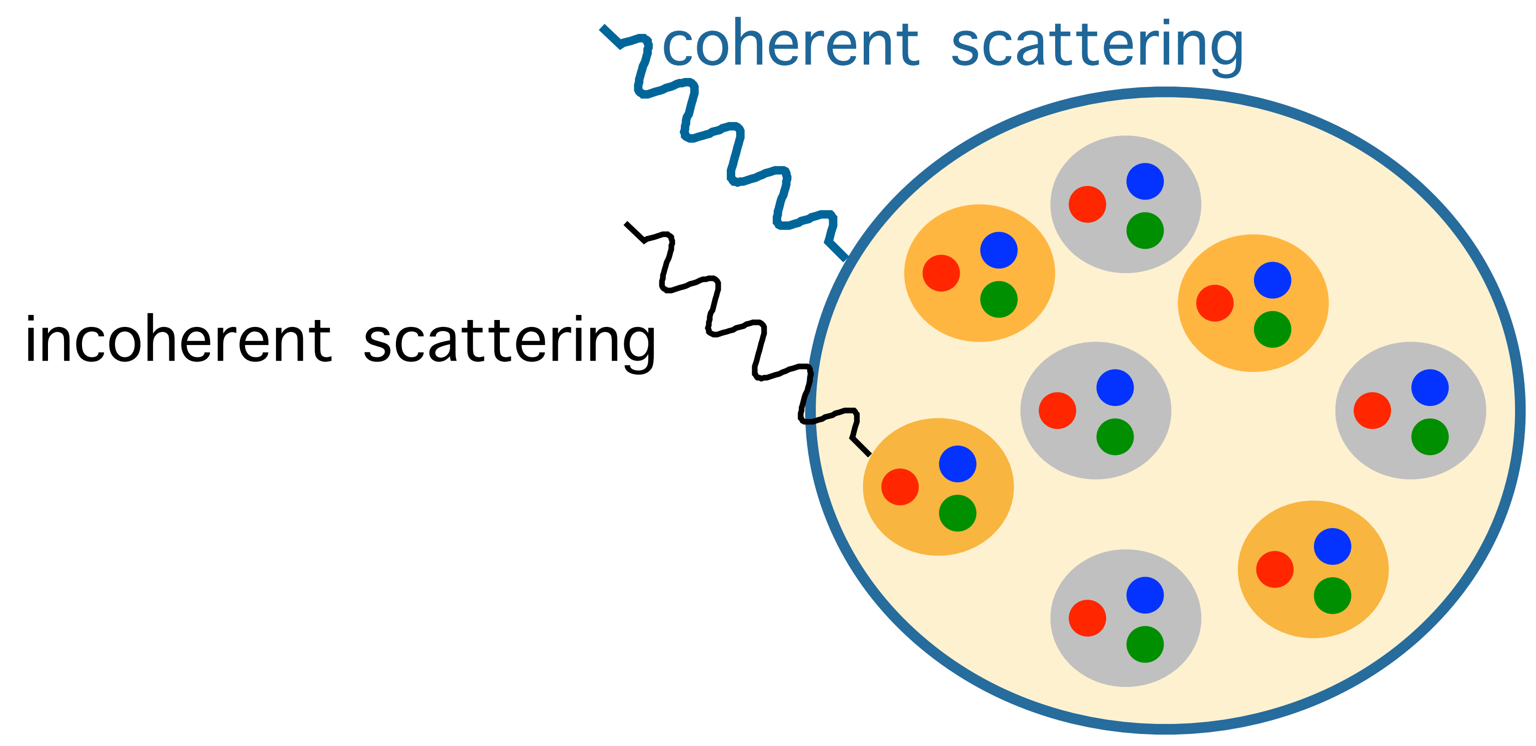


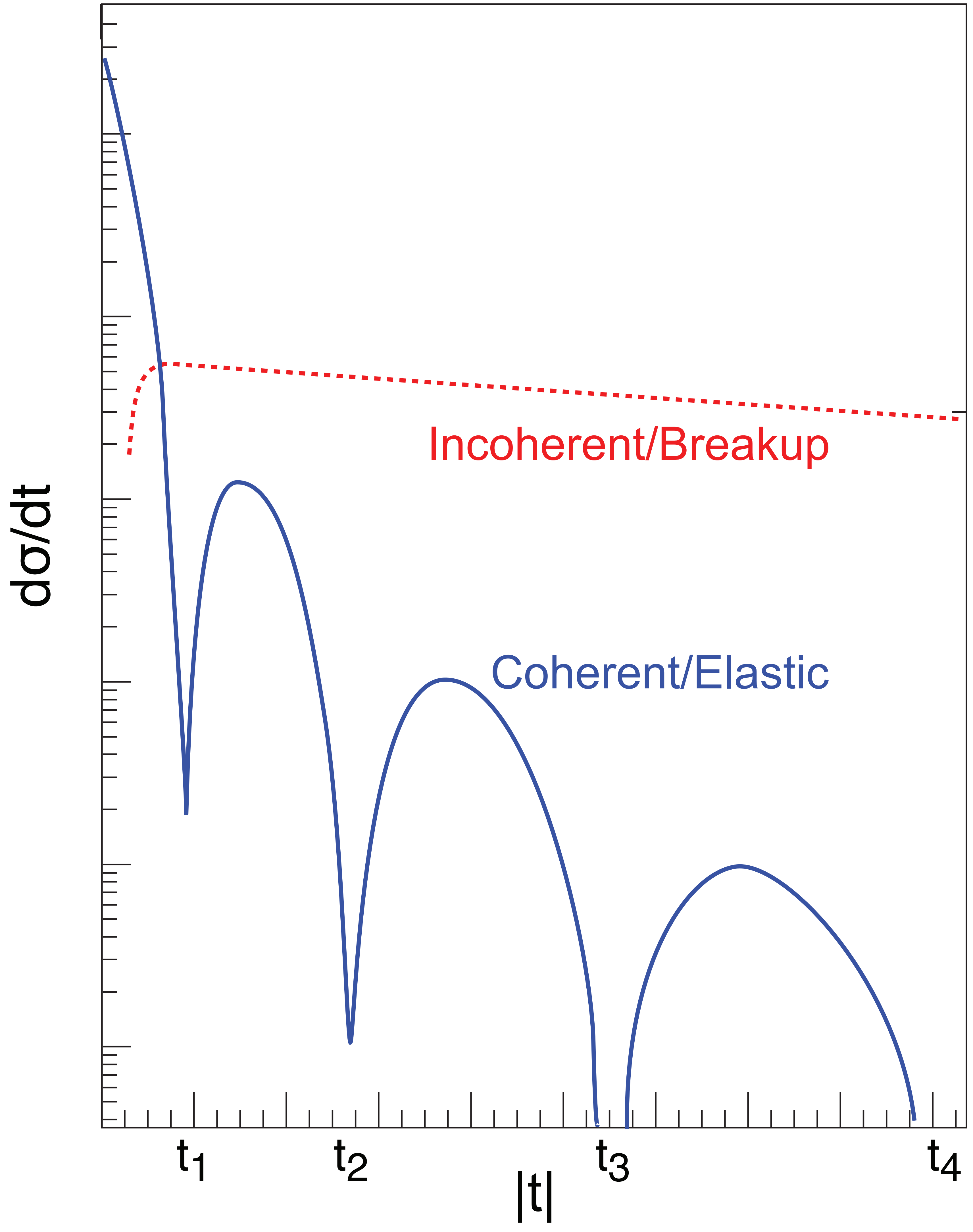
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

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

Ultra-peripheral collisions in PbPb

What object are we probing?





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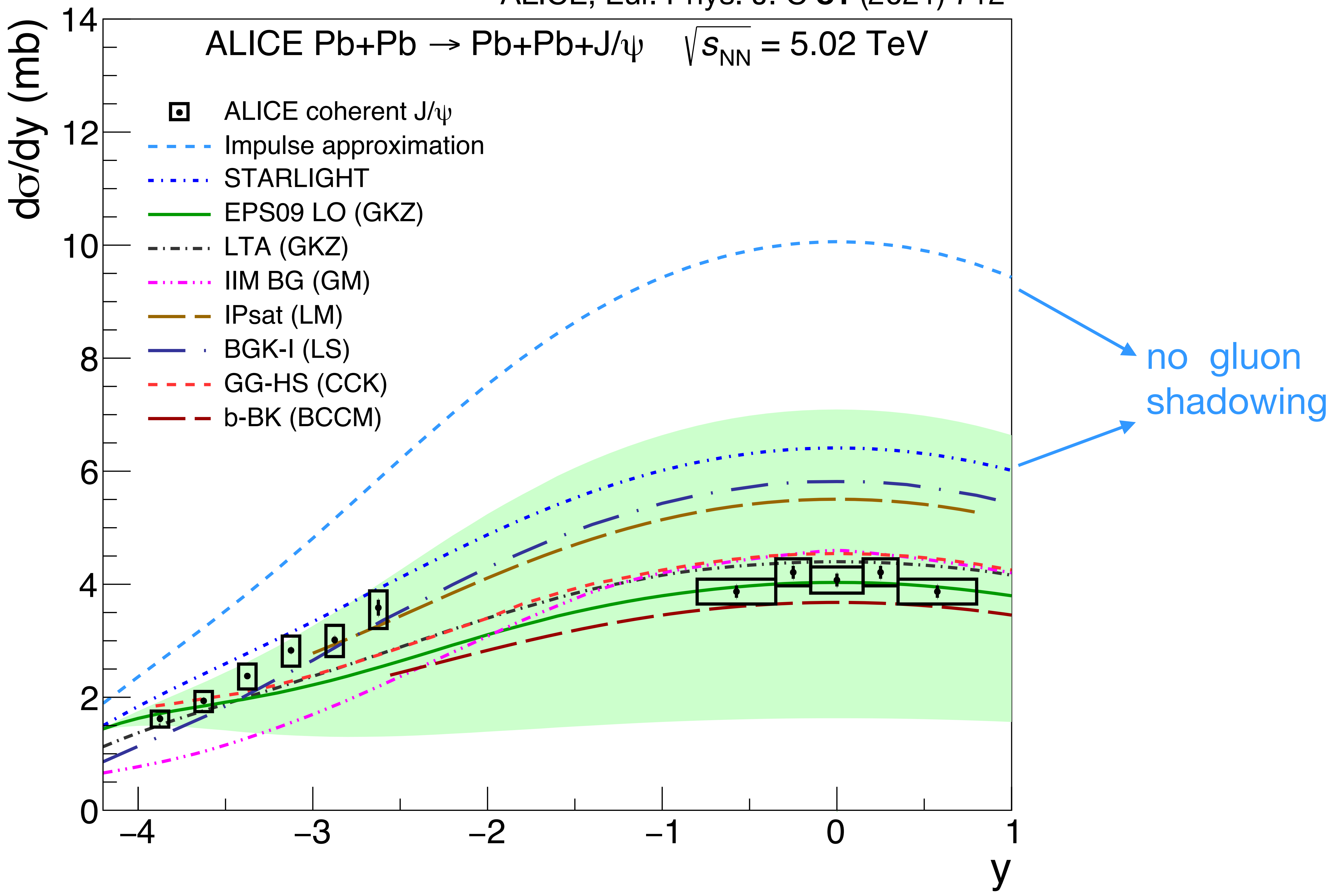
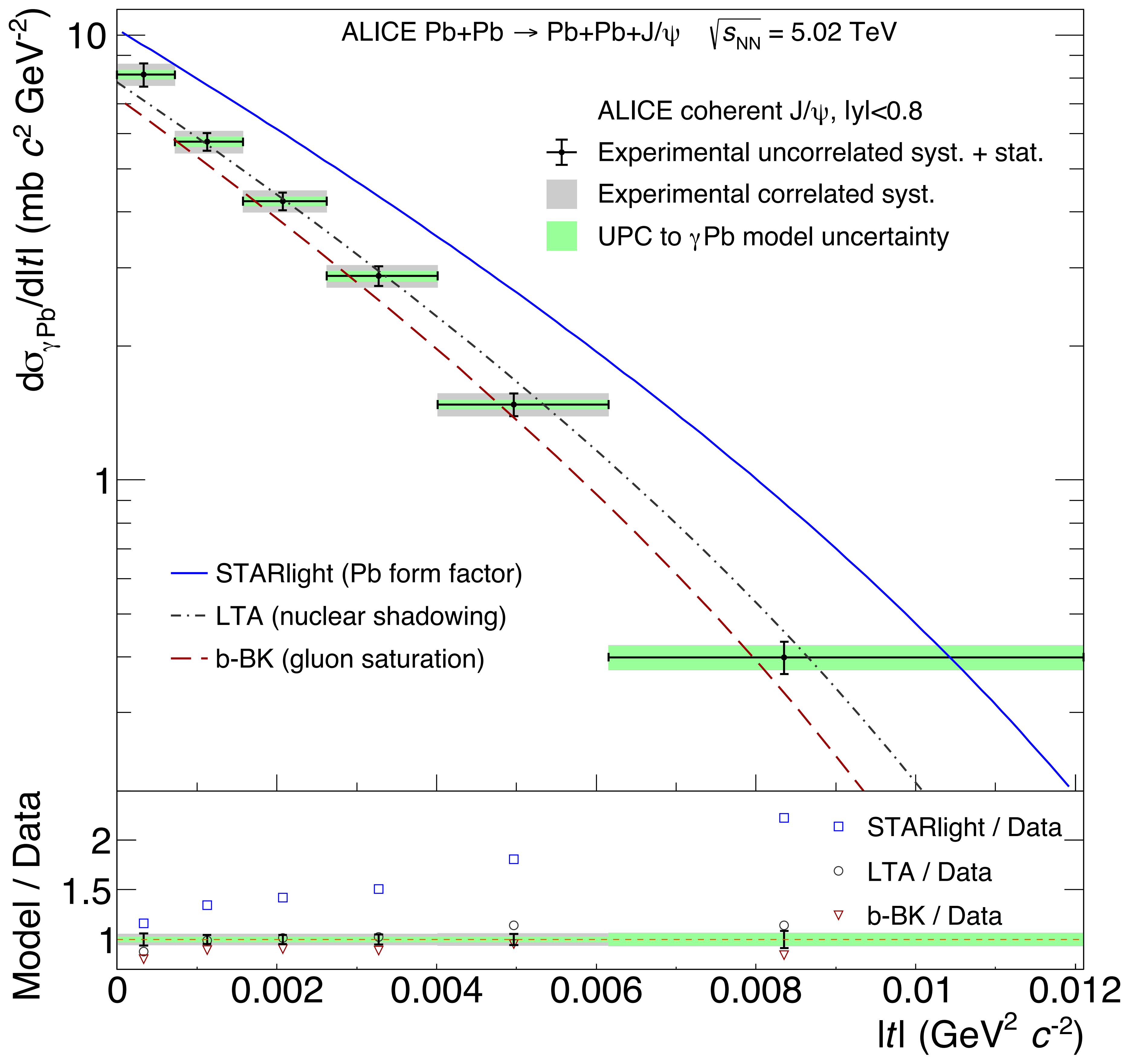
Coherent photoproduction in PbPb at ALICE

ALICE, Eur. Phys. J. C **81** (2021) 712



ALICE, Phys. Lett. B **817** (2021) 136280



$-4.0<y<-2.5$

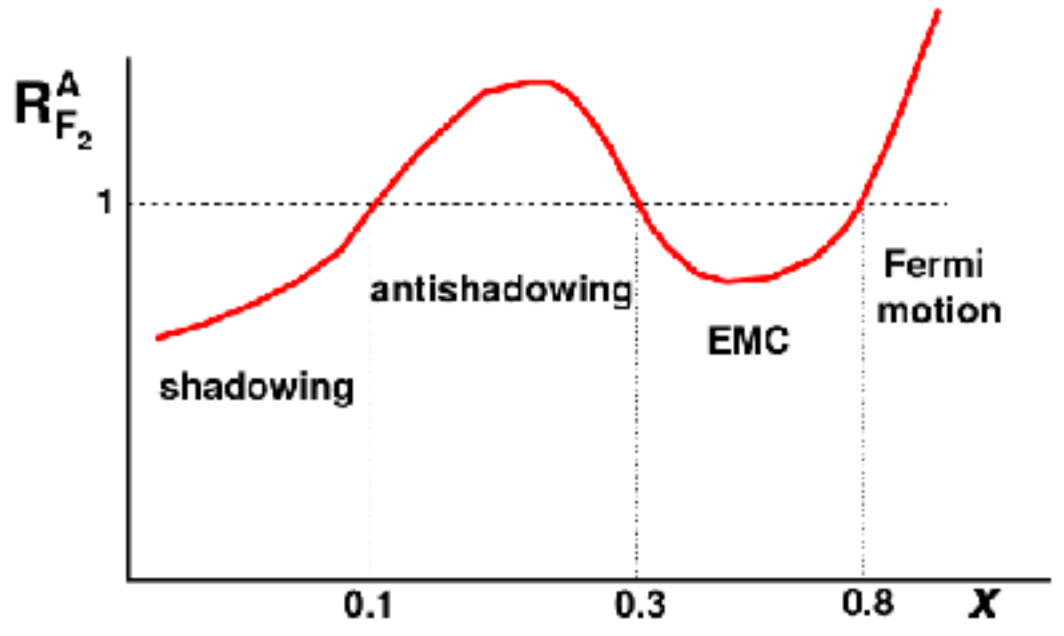
$|y|<0.8 \longleftrightarrow 0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$

$0.7 \times 10^{-2} < x_B < 3.3 \times 10^{-2}$ (dominant)

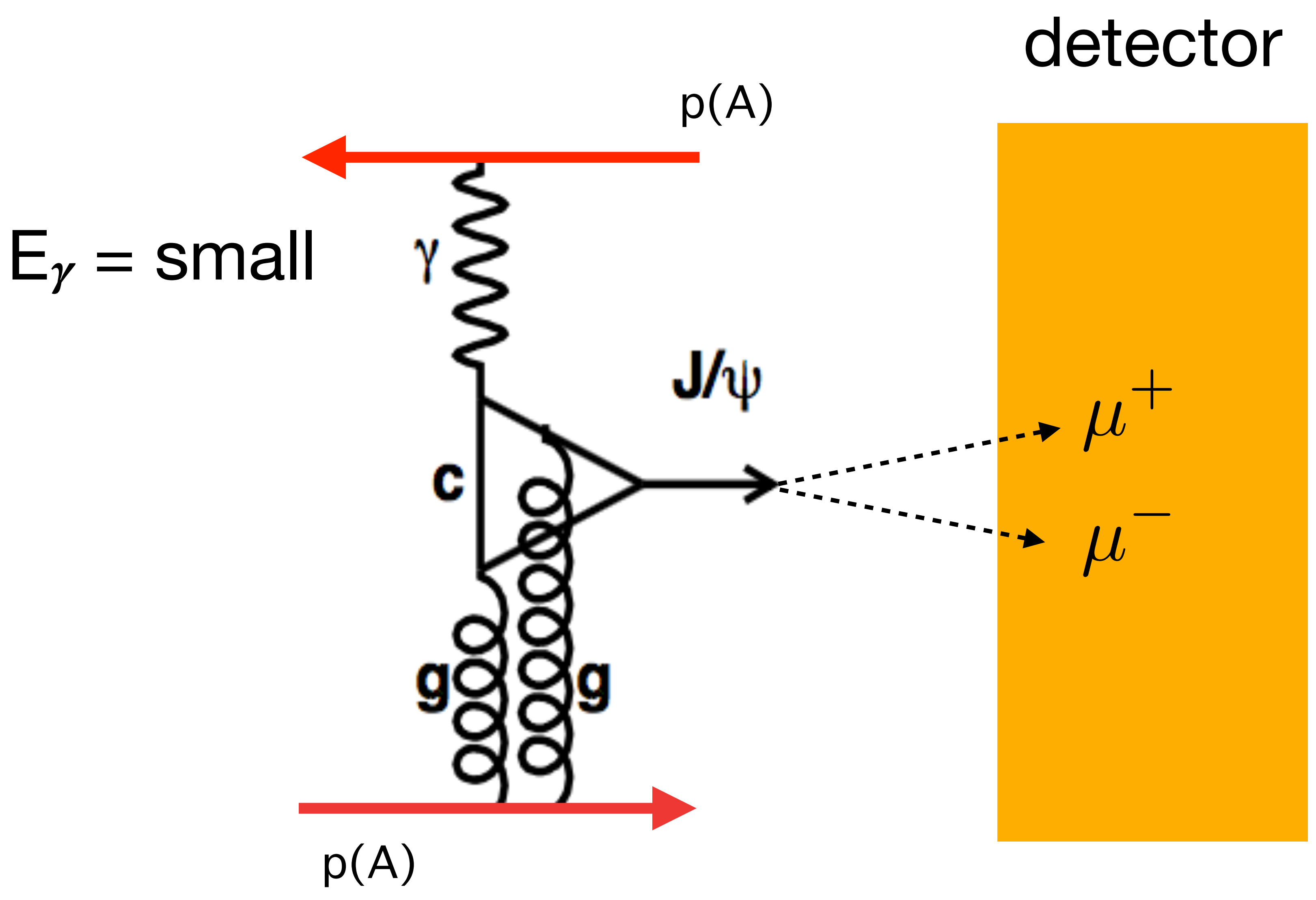
$1.1 \times 10^{-5} < x_B < 5.1 \times 10^{-5}$

Results indicate shadowing in gluon PDF:

$$R_g = \frac{g^{Pb}}{A\, g^p} \approx 0.65 \text{ at } x \approx 10^{-3}$$



Disentangling the ambiguity on the ID of the γ emitter



$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

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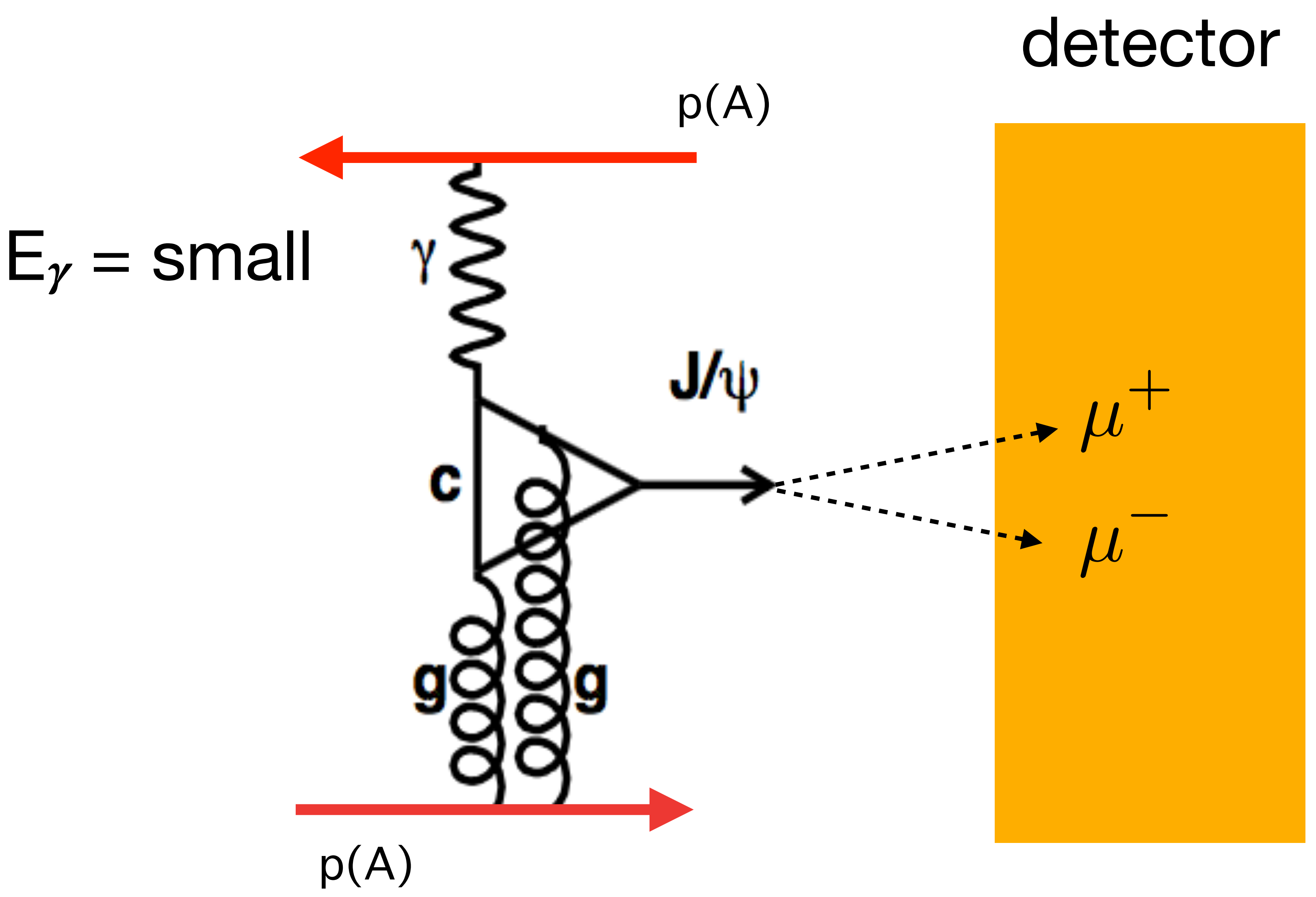

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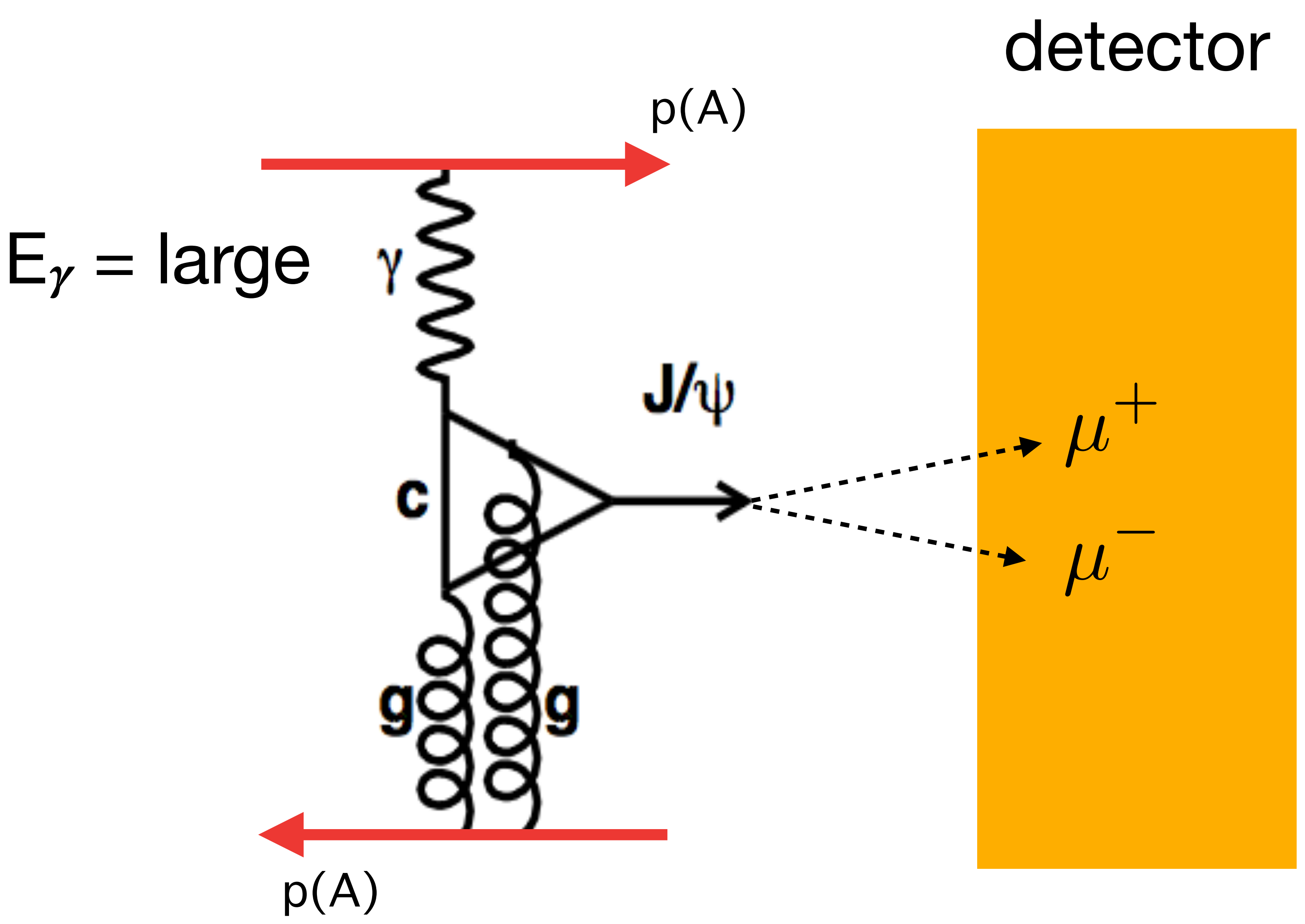
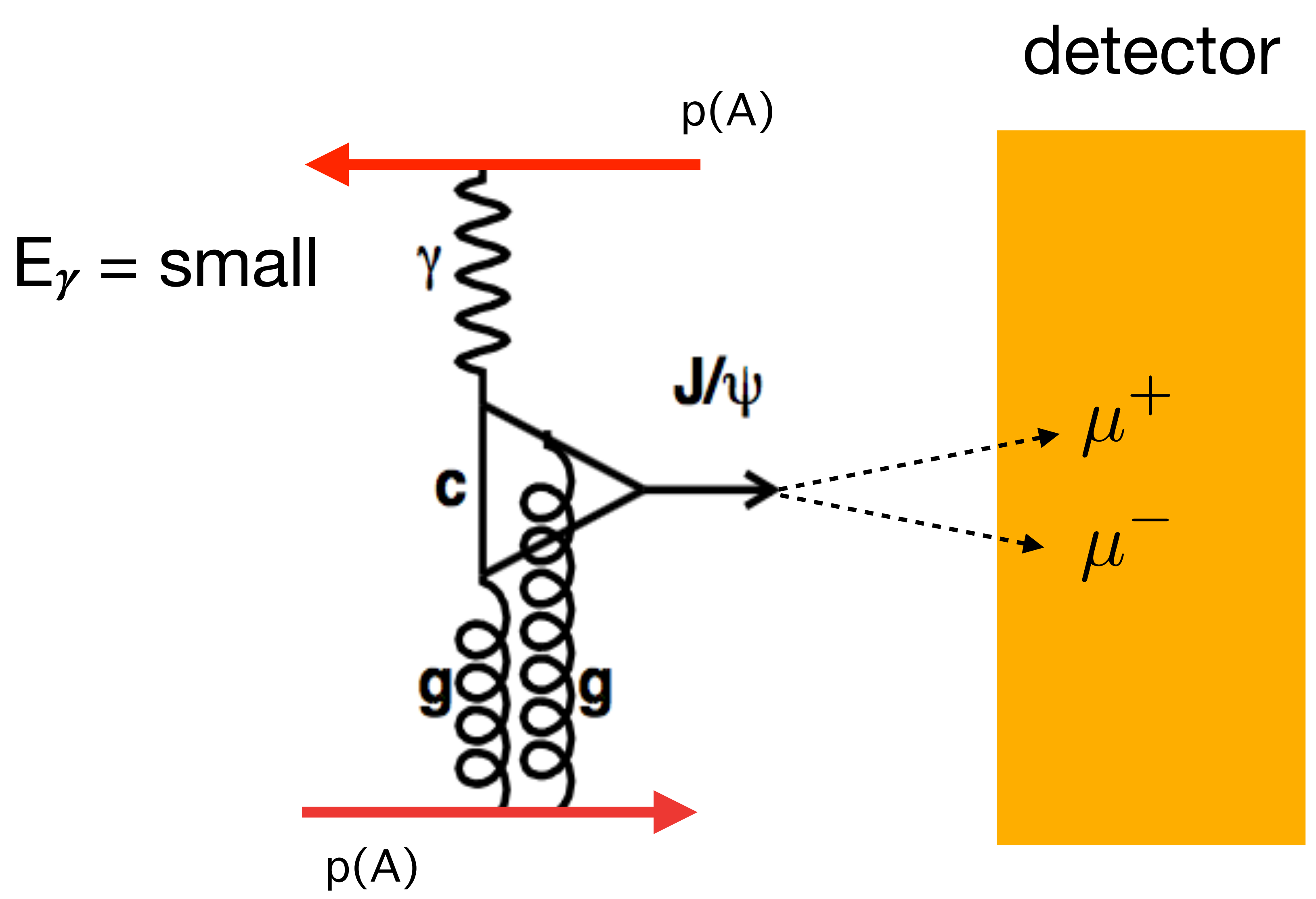
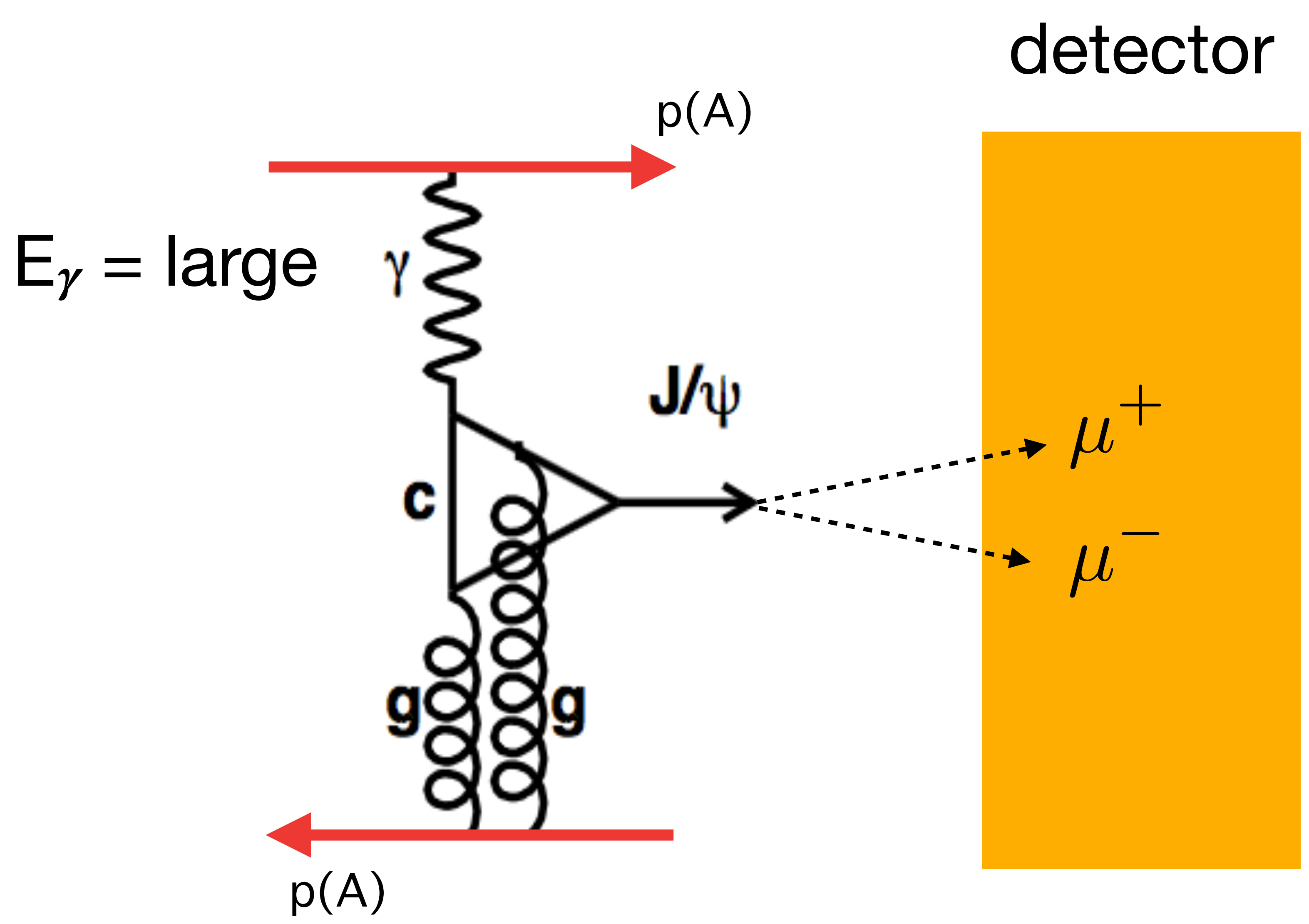


$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

Disentangling the ambiguity on the ID of the γ emitter



$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$



$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

$$\sigma(y) = N_{\gamma/A}(E_{\gamma,s})\, \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}(E_{\gamma,l})\, \sigma_{J/\psi}(E_{\gamma,l})$$

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Photon flux $N_{\gamma/A}(E_\gamma)$ is function of impact parameter:
enhanced for large E_γ at small impact parameter.

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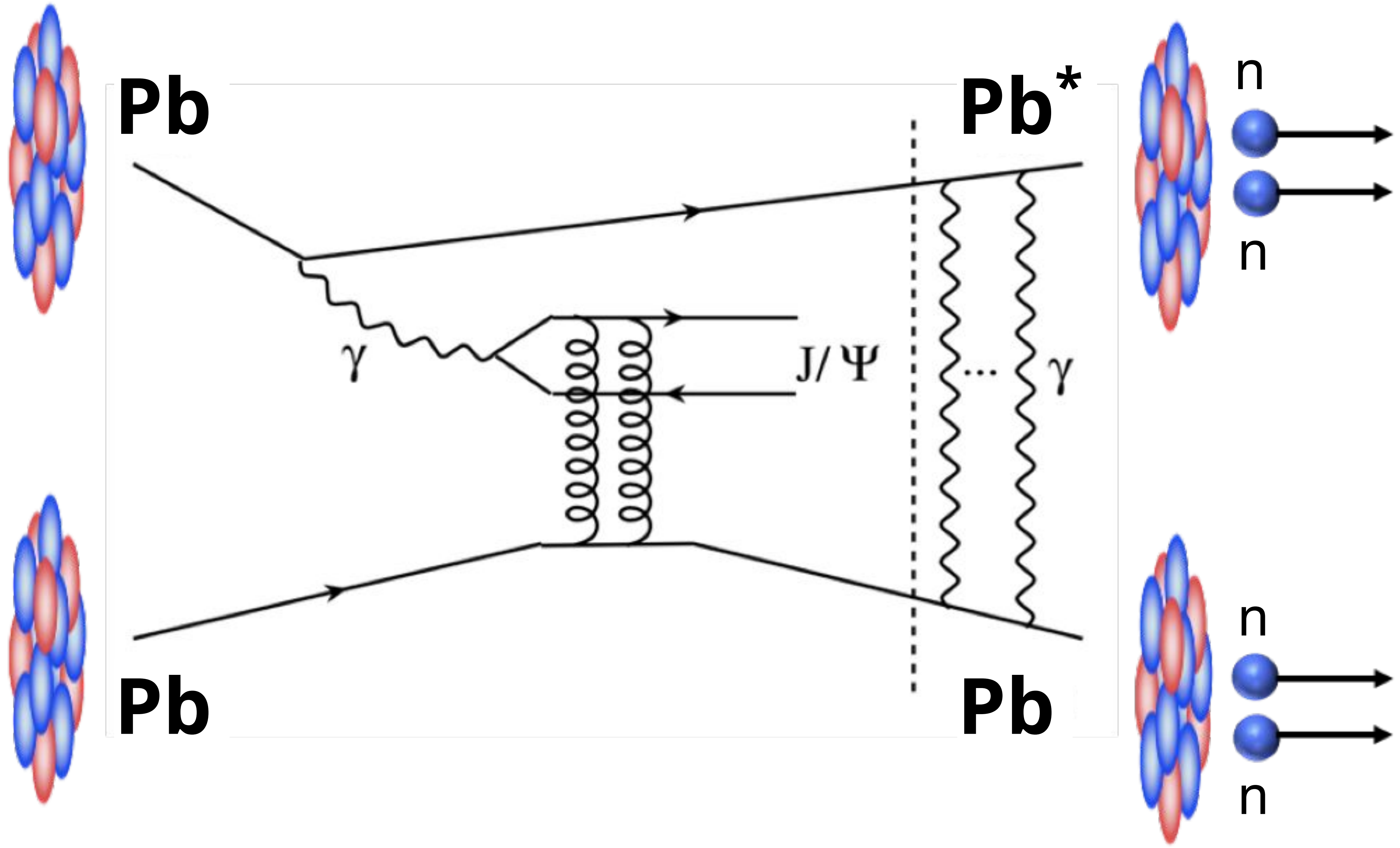
Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.



Picture from André Ståhl

Disentangling the ambiguity on the ID of the γ emitter

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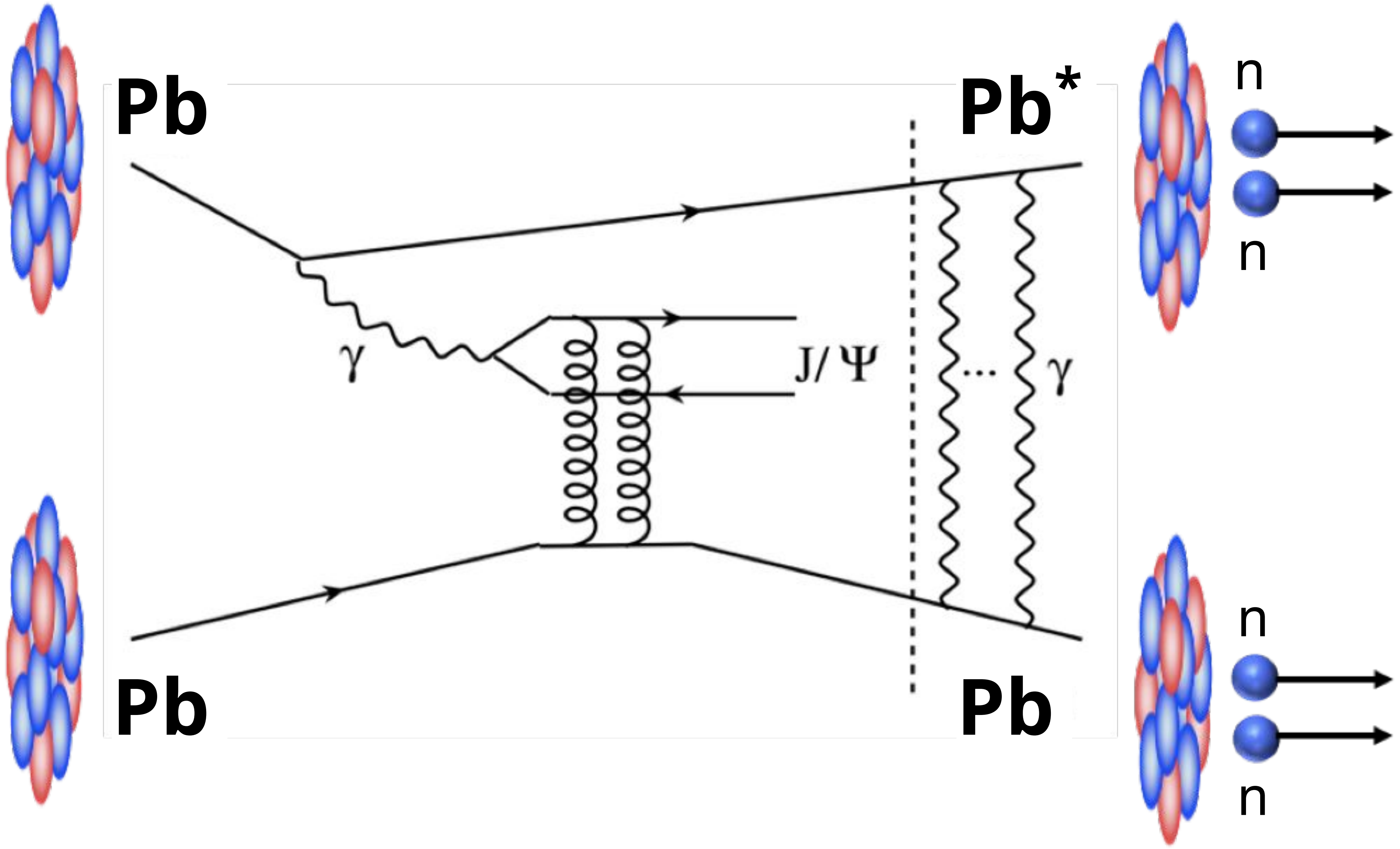
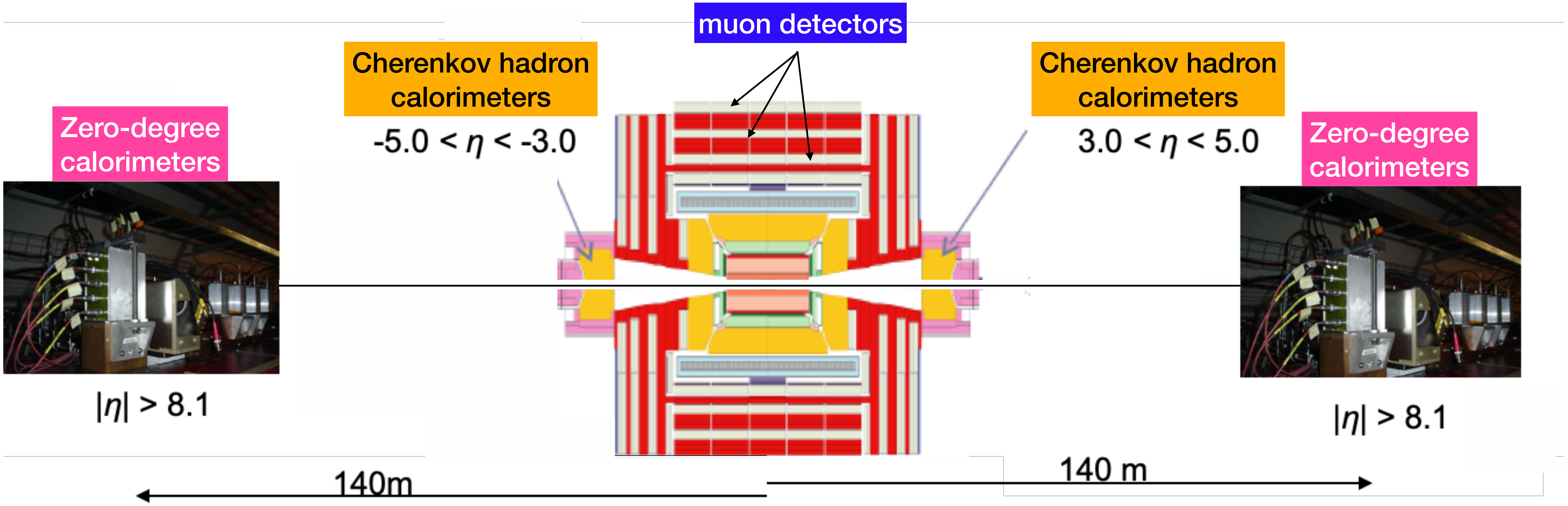


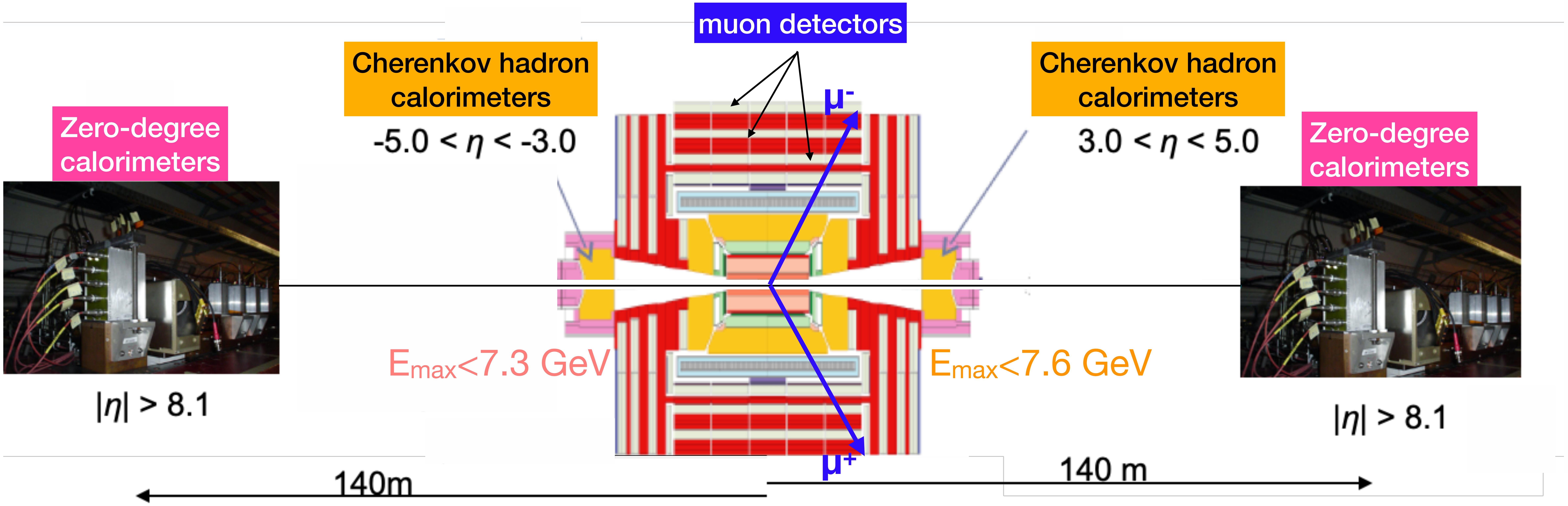
⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS central detector and the (far-)forward region

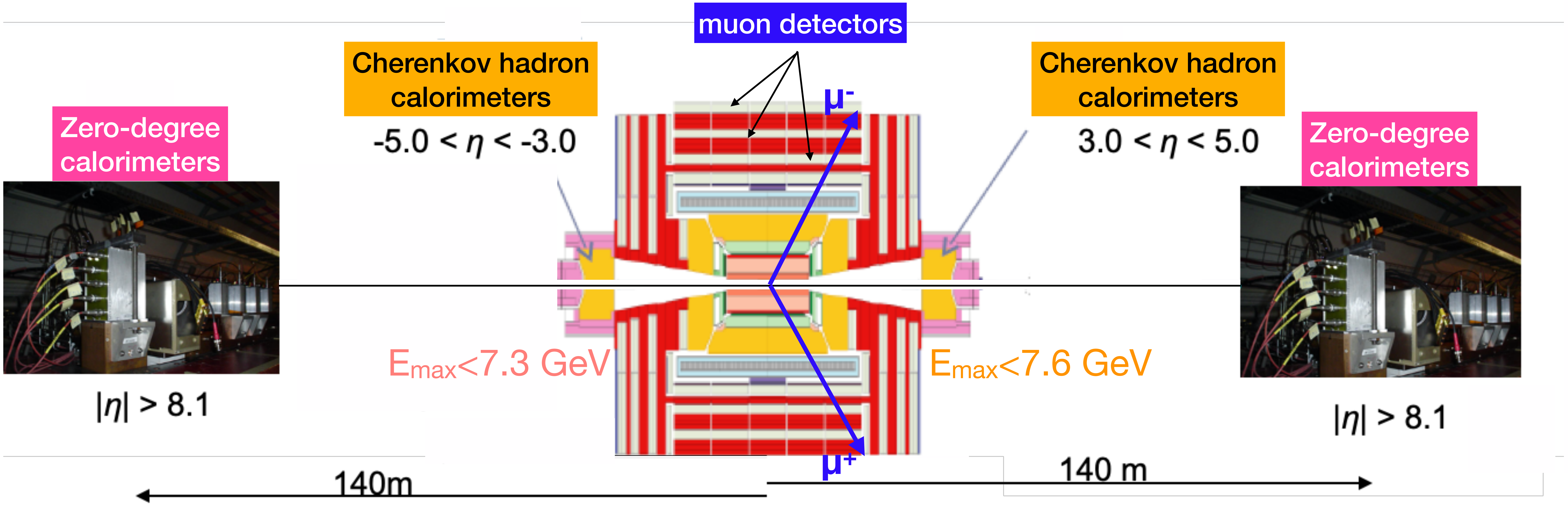


CMS central detector and the (far-)forward region



$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

CMS central detector and the (far-)forward region



$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

0 neutrons
≥1 neutron

0 neutrons
≥1 neutron

0n0n
0nXn
XnXn

Disentangling the ambiguity on the ID of the γ emitter

$$\sigma^{0n0n}(y) = N_{\gamma/A}^{0n0n}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}^{0n0n}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{0nXn}(y) = N_{\gamma/A}^{0nXn}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}^{0nXn}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{XnXn}(y) = N_{\gamma/A}^{XnXn}(E_{\gamma,s})\ \sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}^{XnXn}(E_{\gamma,l})\ \sigma_{J/\psi}(E_{\gamma,l})$$

measured

Disentangling the ambiguity on the ID of the γ emitter

$$\sigma^{0n0n}(y) = N^{0n0n}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0n0n}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

$$\sigma^{0nXn}(y) = N^{0nXn}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0nXn}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

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measured — **computed (StarLight)** — **computed (StarLight)**

Disentangling the ambiguity on the ID of the γ emitter

$$\sigma^{0n0n}(y) = N^{0n0n}_{\gamma/A}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N^{0n0n}_{\gamma/A}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

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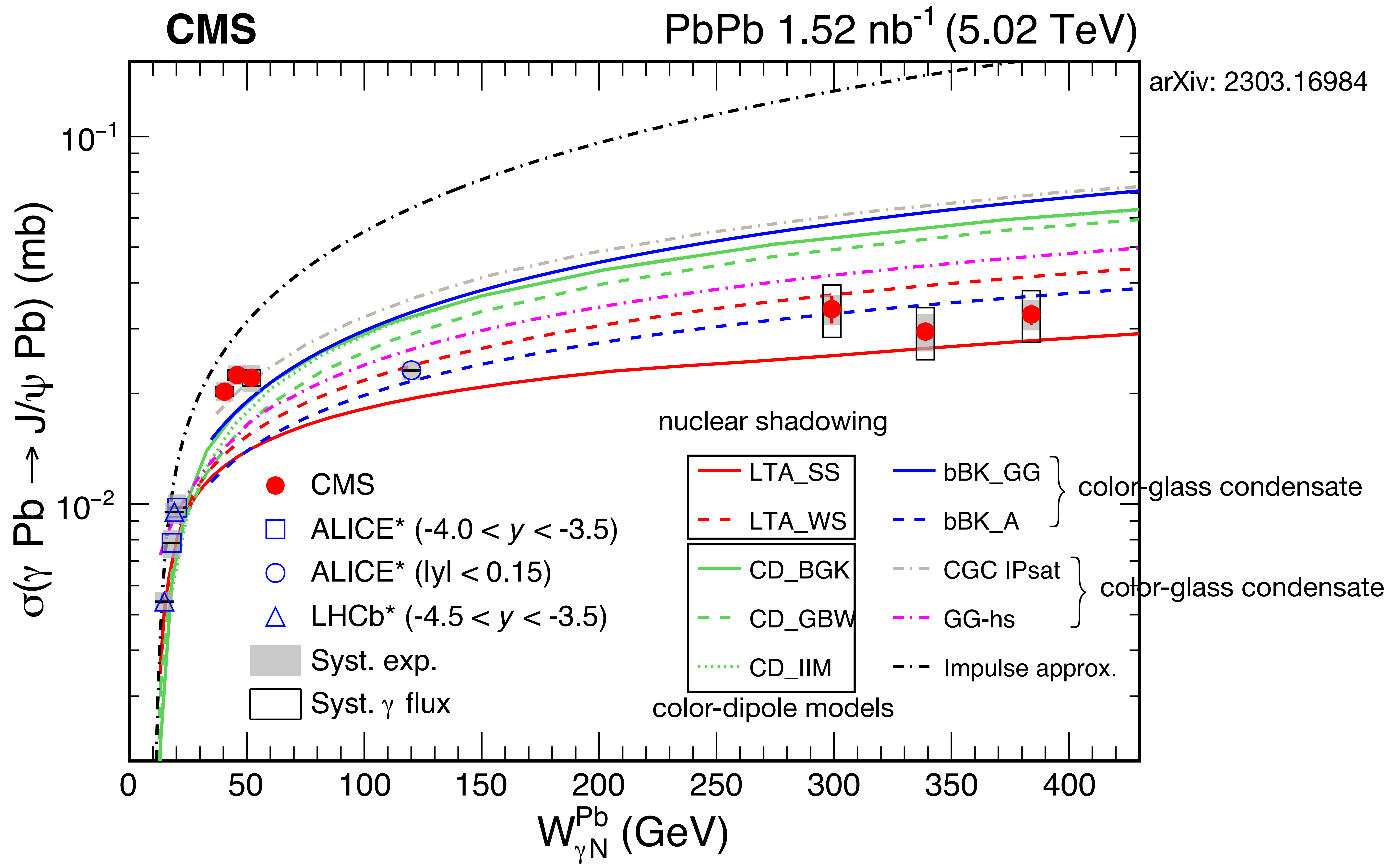
measured | computed (StarLight) | extracted | computed (StarLight) | extracted

CMS: γPb cross section, energy dependence



Summary

- Exclusive single-quarkonium production in pp:
  - unique potential to constrain GPDs at very low x_B, down to 10^{-6}
  - probe universality

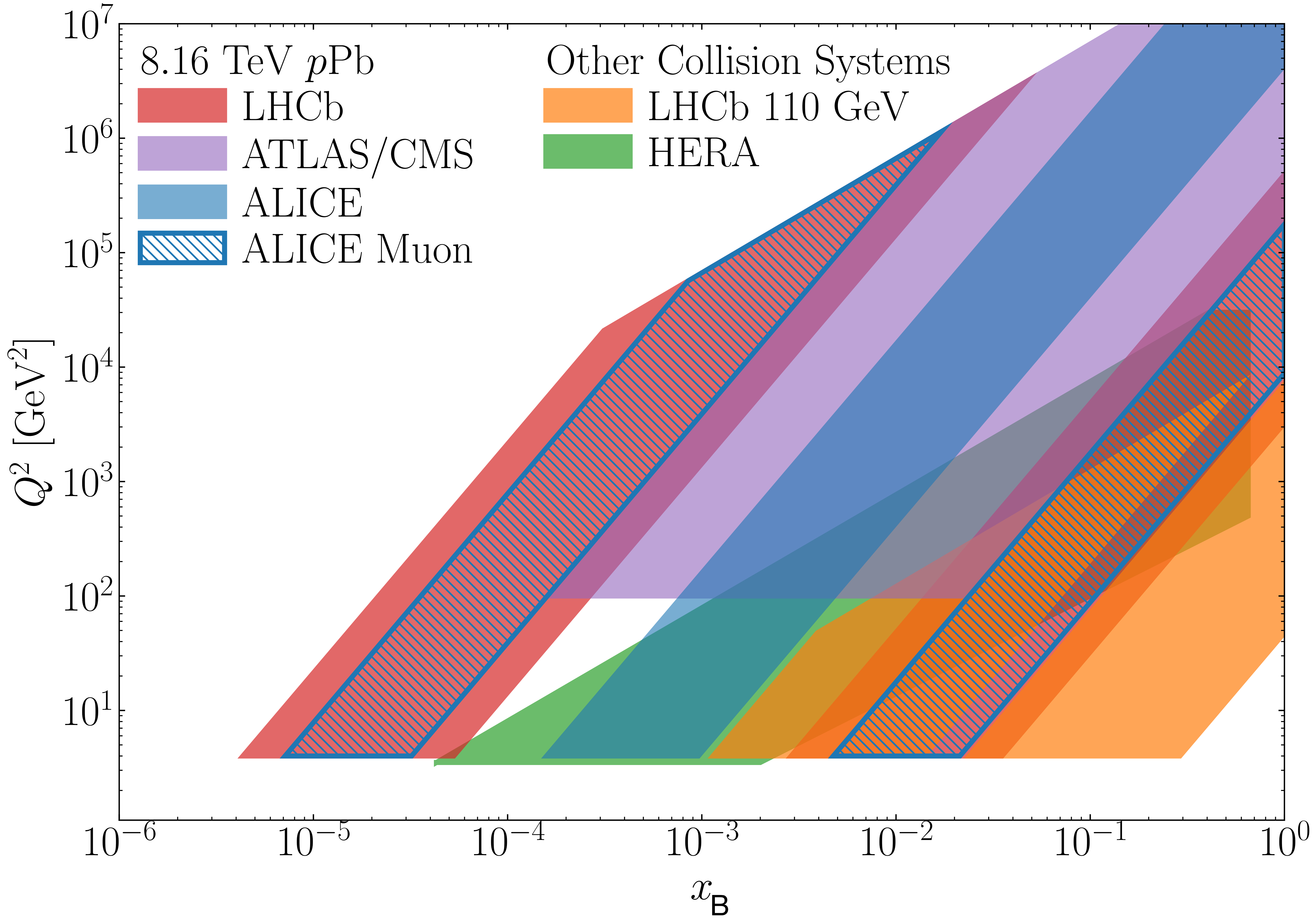
- Exclusive single-quarkonium production in pPb:
  cleanest channel to probe the proton in hadron-hadron collisions, since absence of ambiguity

- Exclusive single-quarkonium production in PbPb:
  - access to nuclear GPDs
  - potential to probe saturation effects
  - neutron tagging by CMS: intriguing small linear rise of cross section for $W_{\gamma N}$>40 GeV

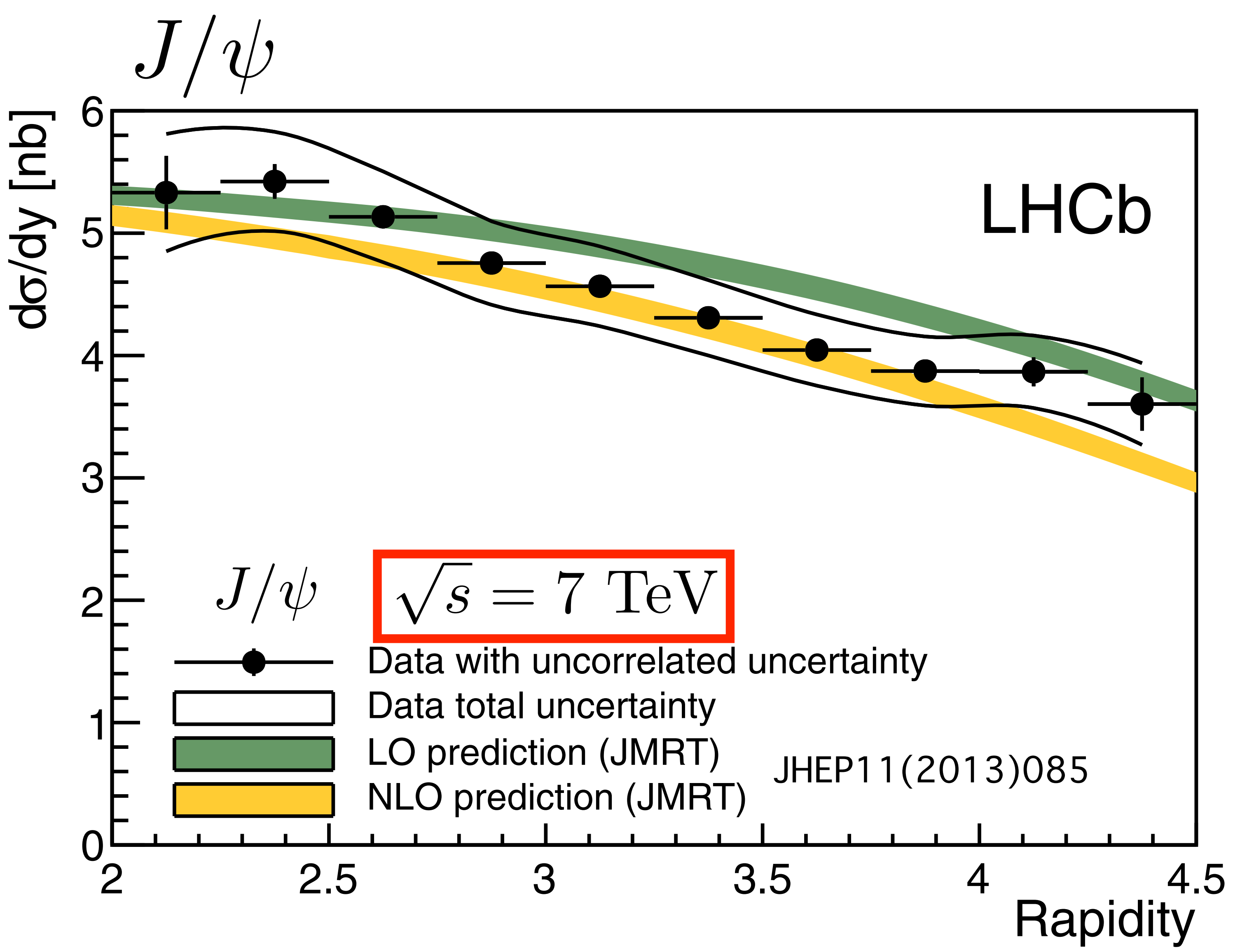
- For all measurements, need double-differential extractions in y and t.

Back up

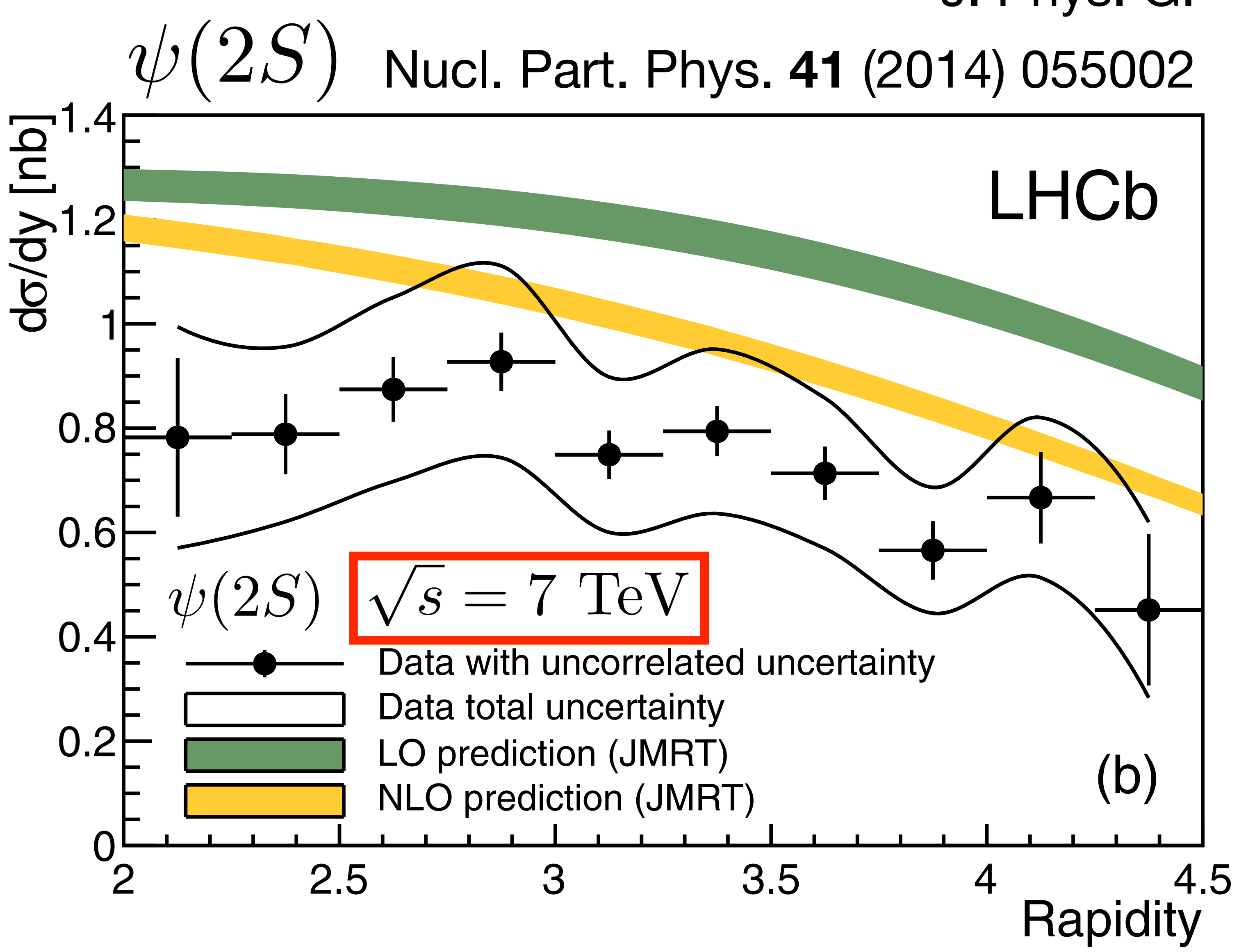
Phase-space covered at the LHC



pp cross section



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



JMRT prediction, based on gluon PDF:

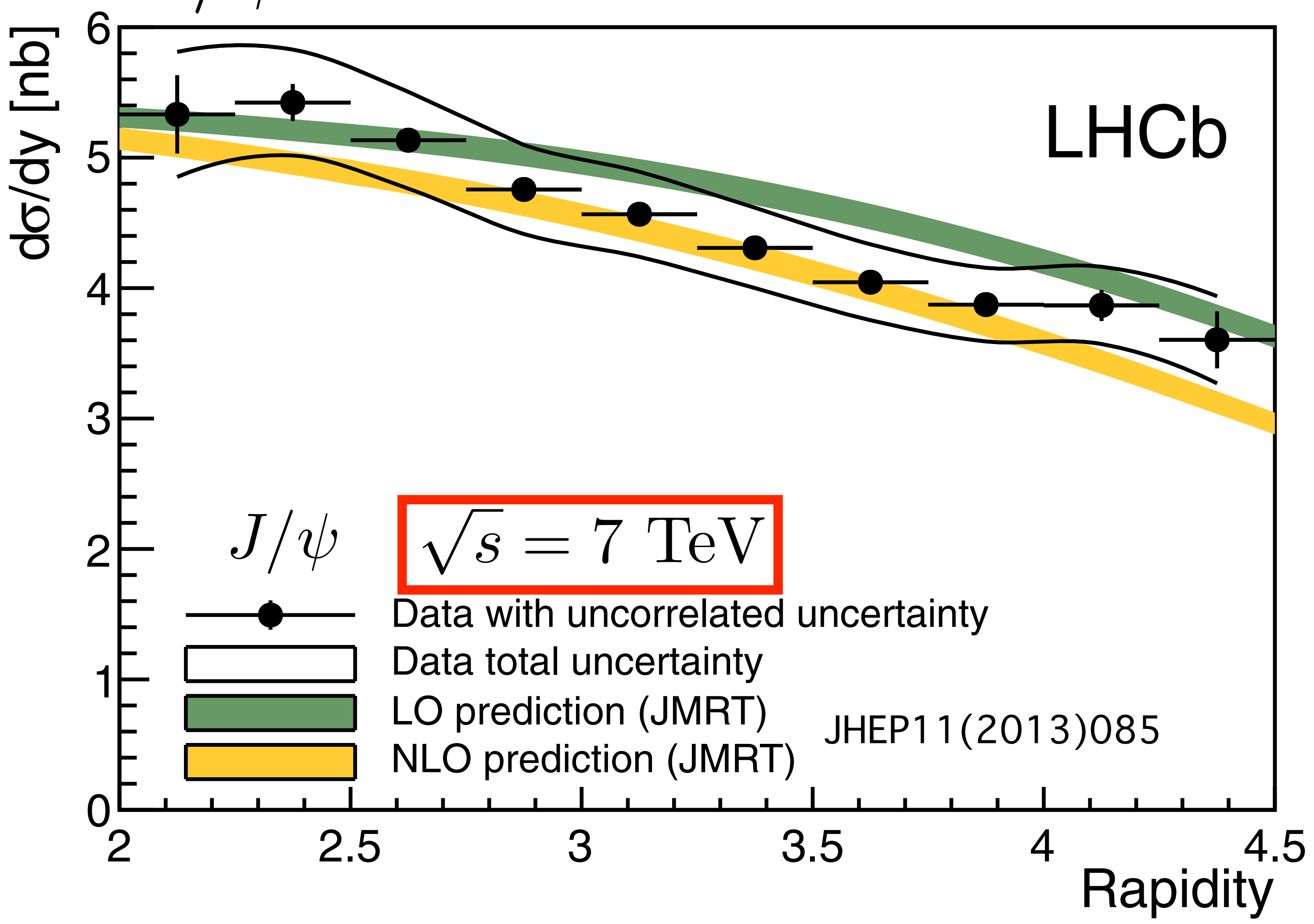
At low x_B, approximate GPD to gluon PDF

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

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

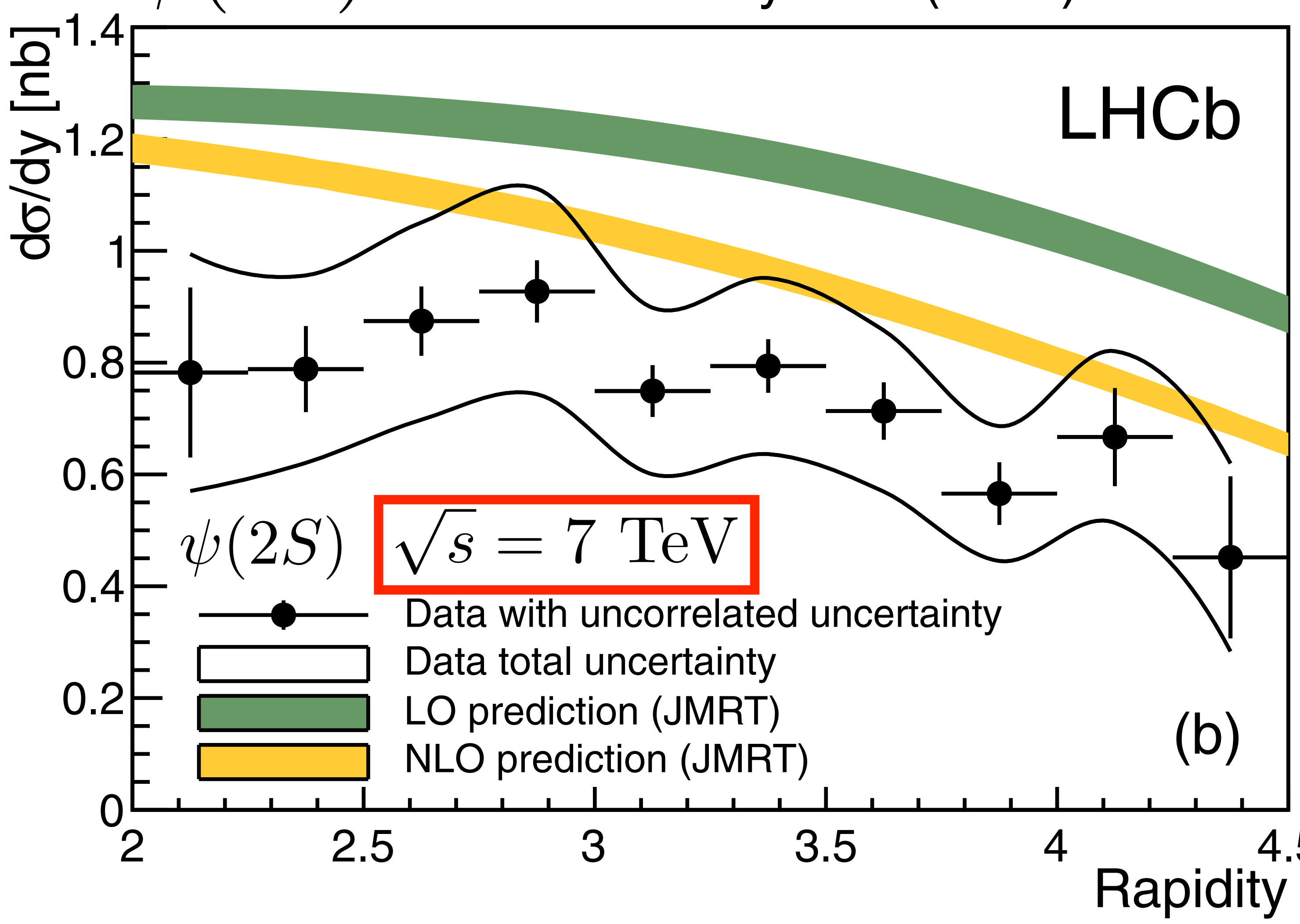
pp cross section

J/ψ



$\psi(2S)$

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



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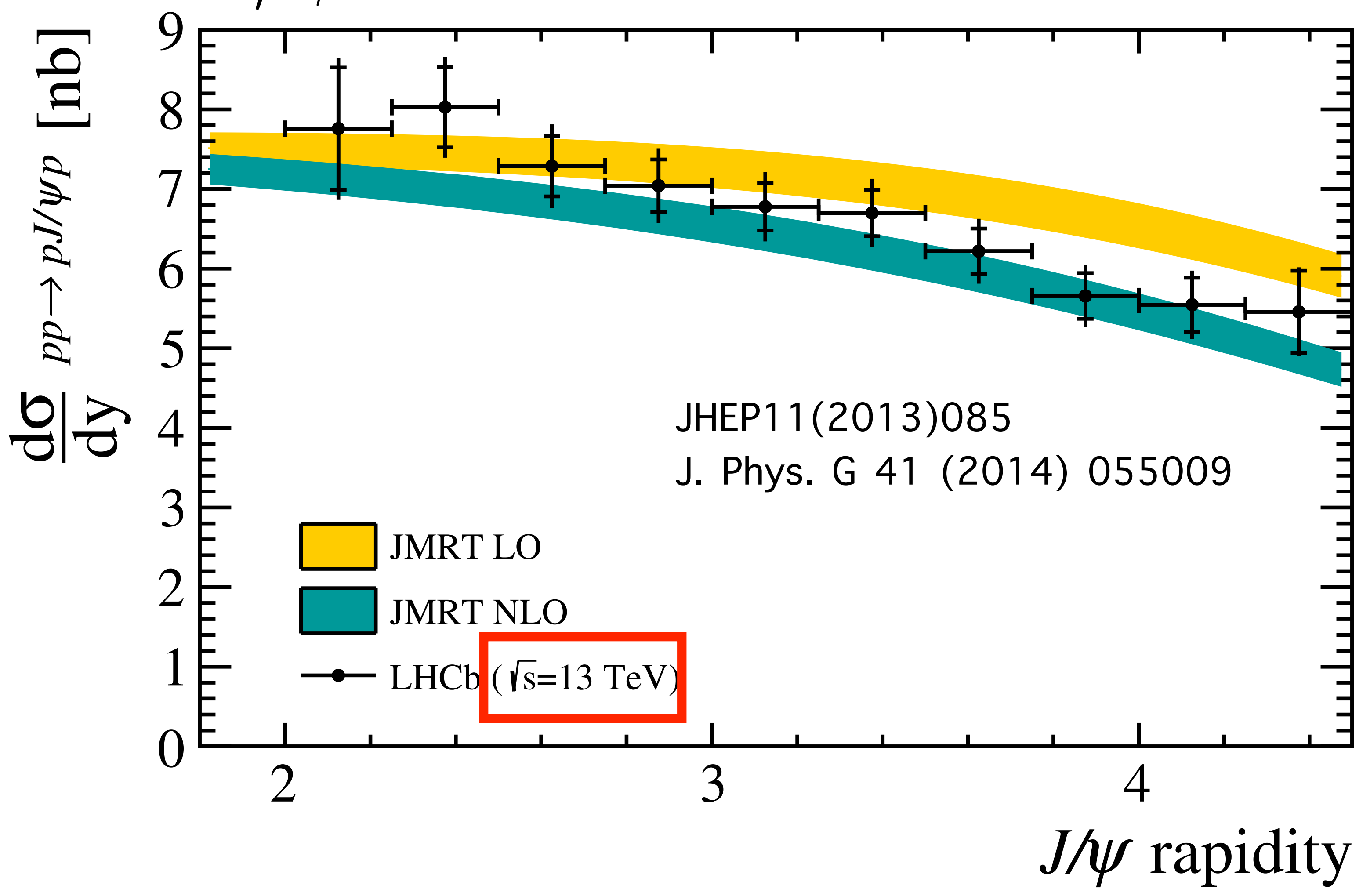

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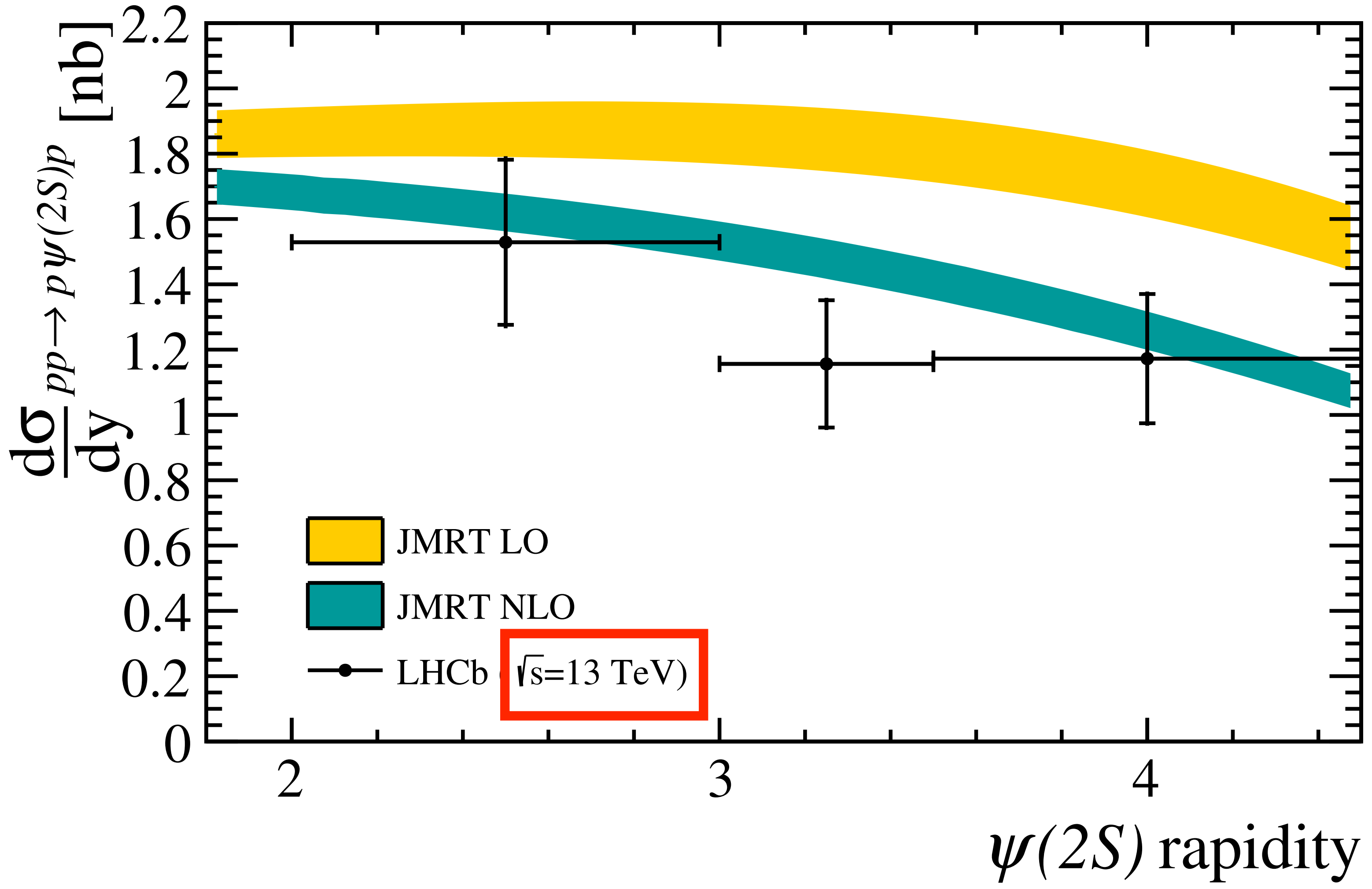
JHEP 10 (2018) 167

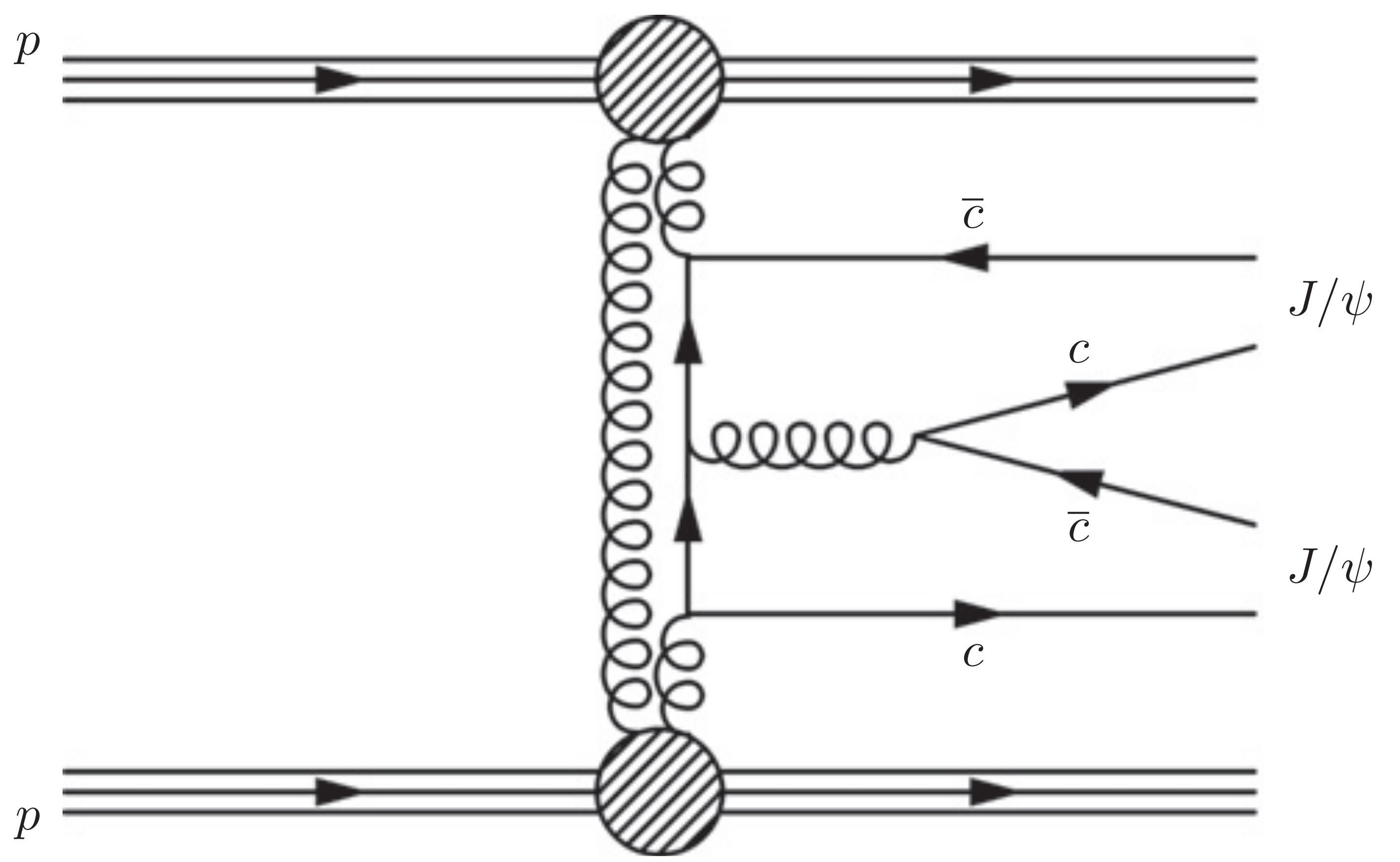


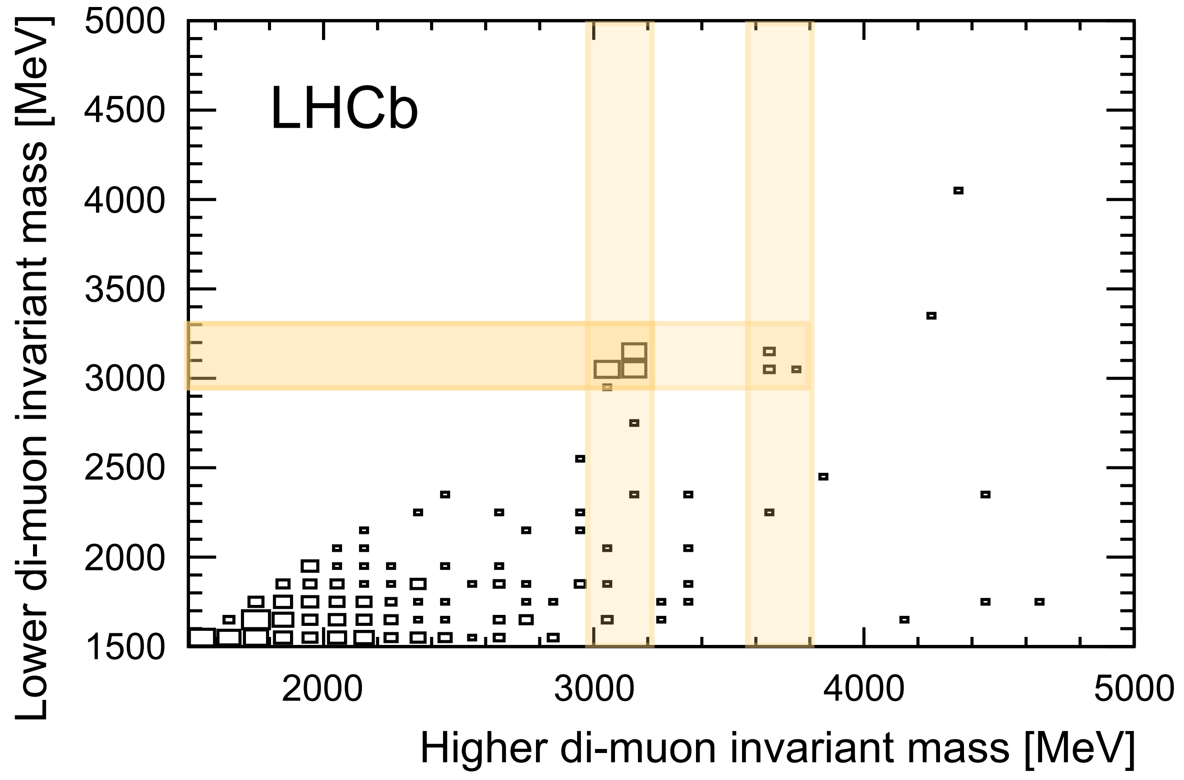
Production of charmonium pairs in pp at LHCb

- 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% exclusive prod. →

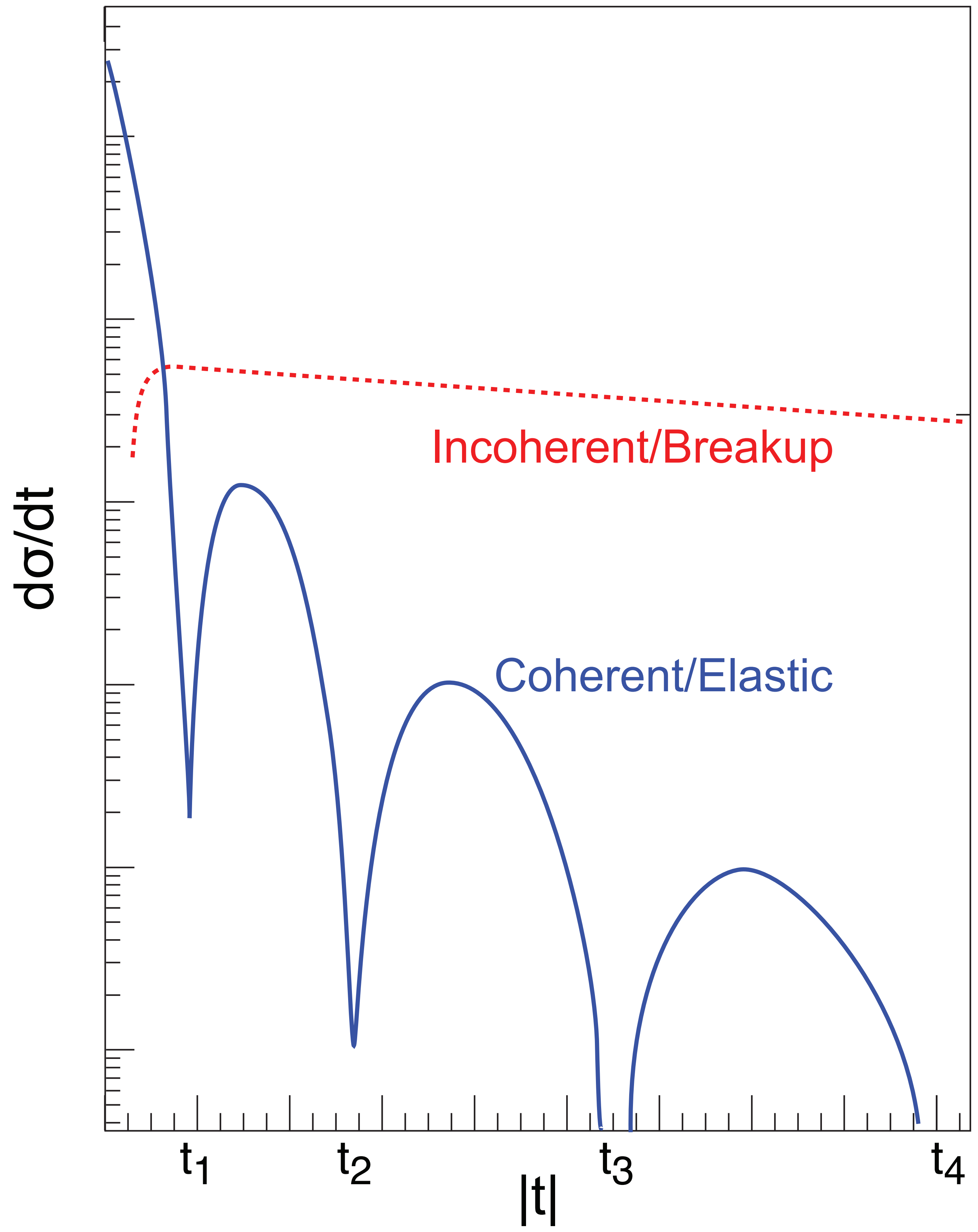
corrected for proton dissociation

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

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

Experimental important points

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



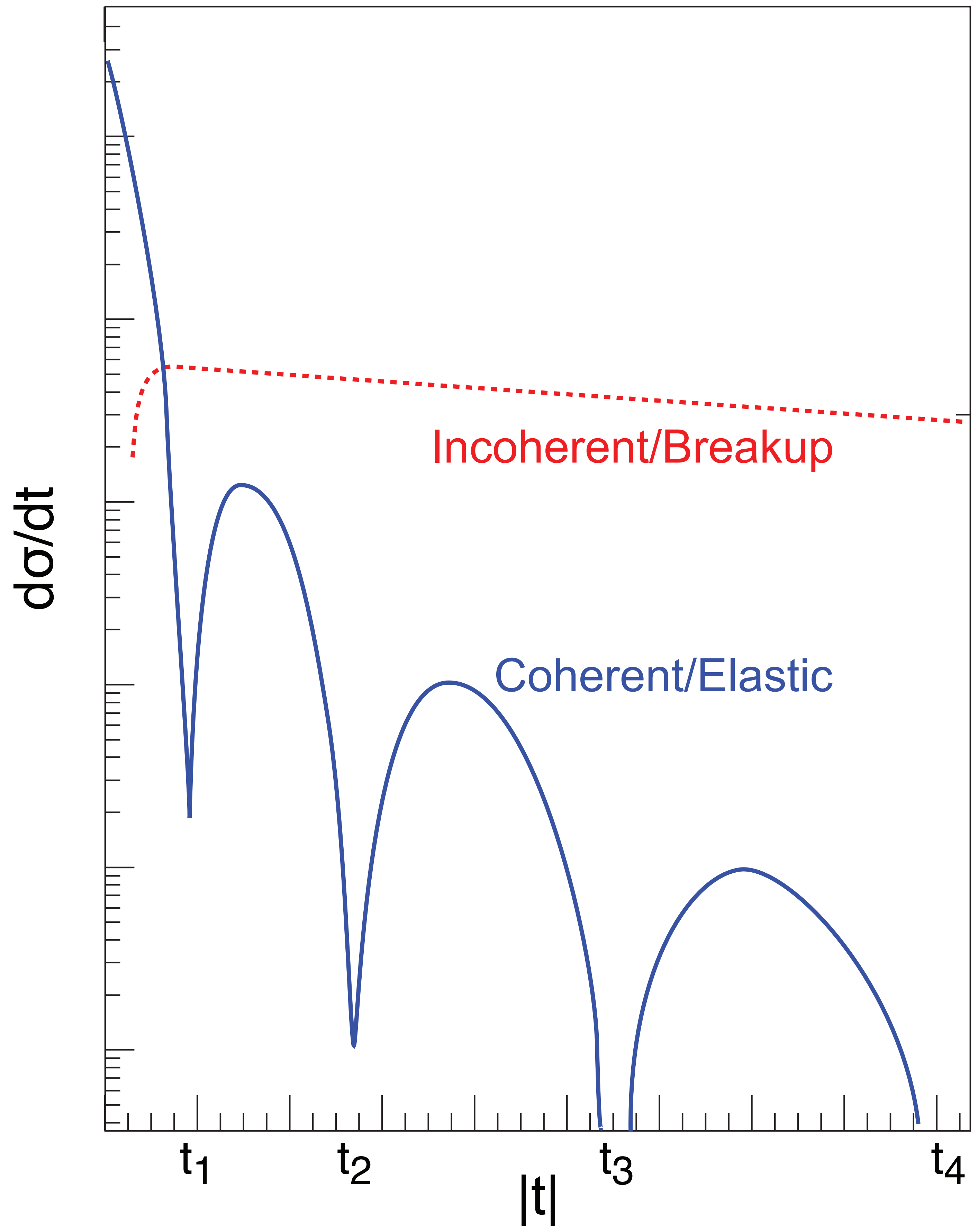
t= squared momentum transfer to target

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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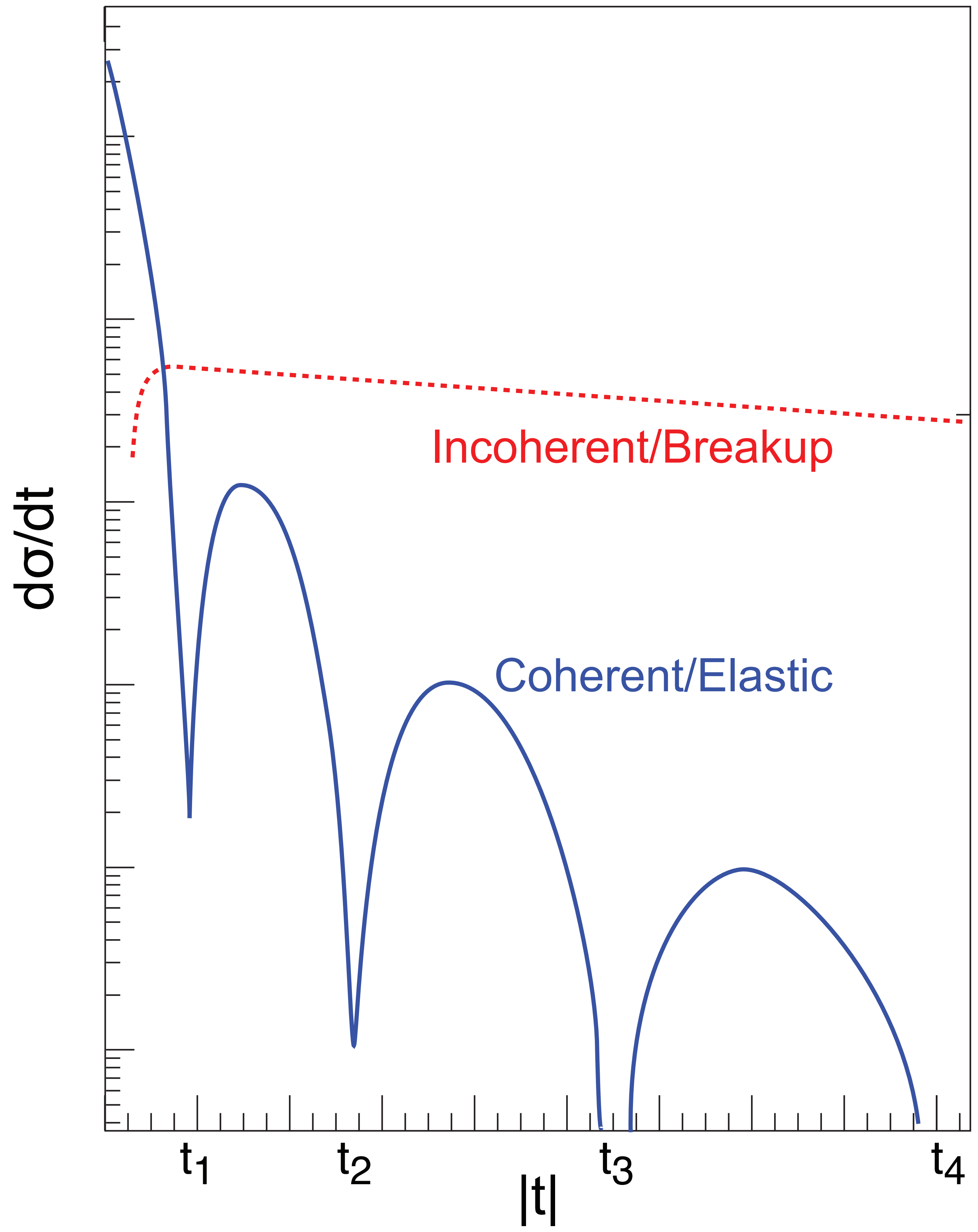
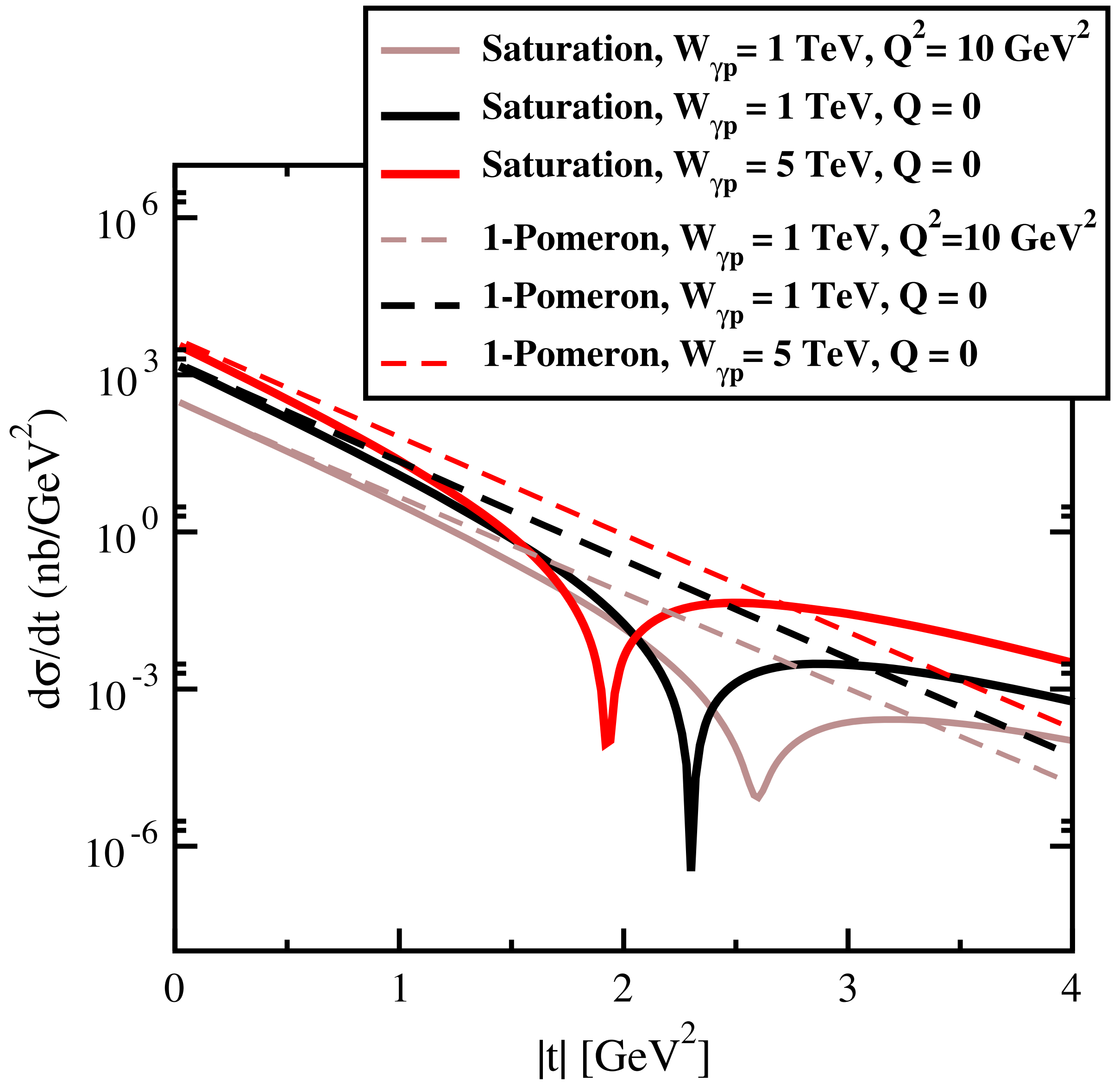


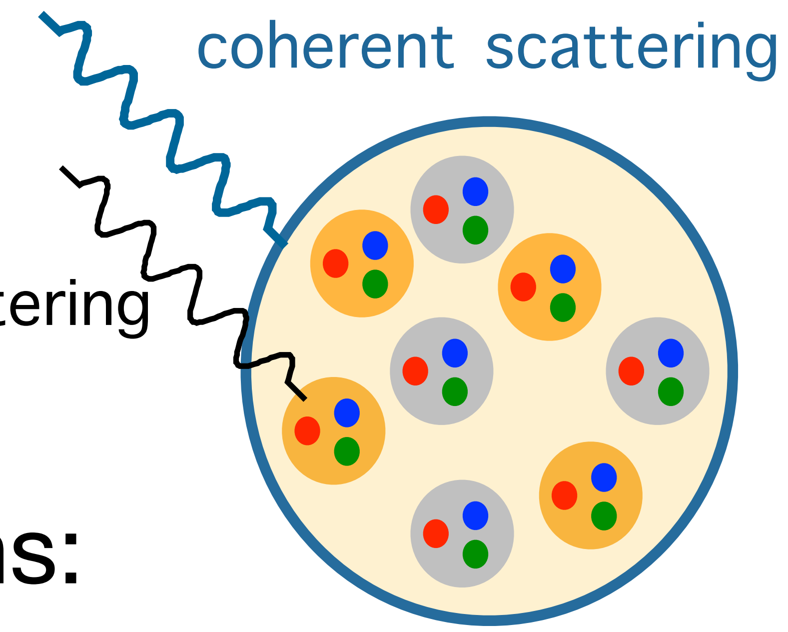
t= squared momentum transfer to target

- Saturation:

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



Incoherent production



$$\sigma_{\text{coh}} \sim |\langle A \rangle|^2$$

average amplitude over target configurations:
probes average distributions

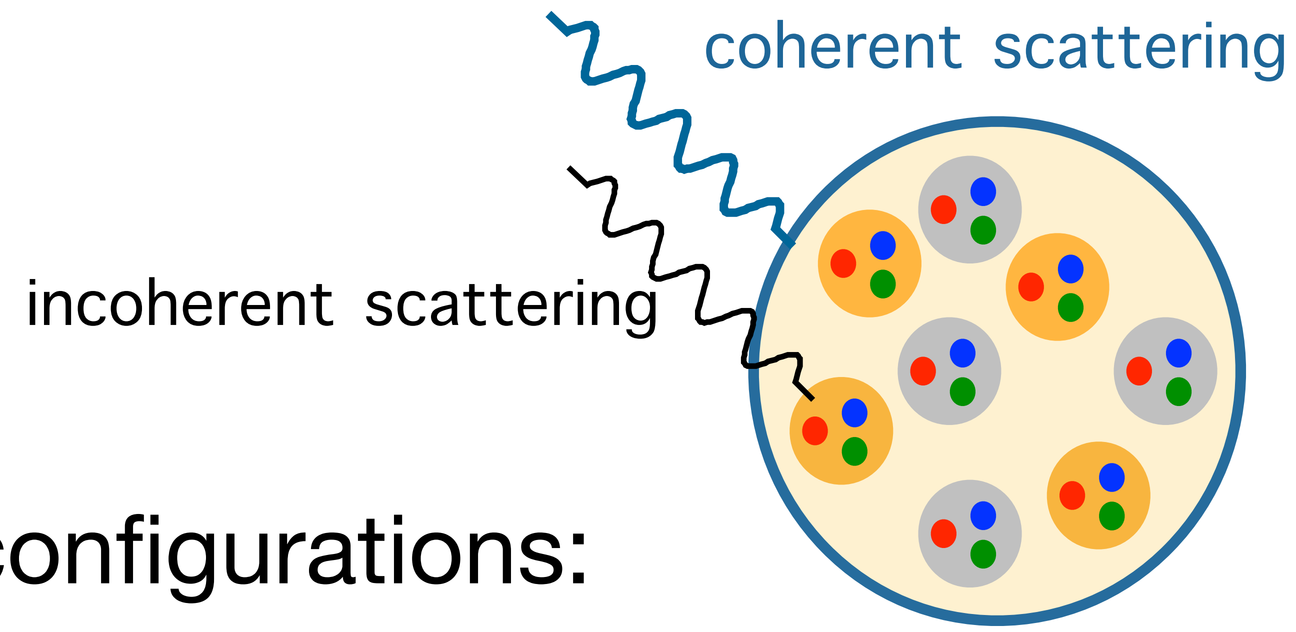
$$\sigma_{\text{incoh}} \sim \sum_{f \neq i} |\langle f|A|i\rangle|^2$$

$$= \sum_f \langle i|A|f\rangle^\dagger \langle f|A|i\rangle - \langle i|A|i\rangle^\dagger \langle i|A|i\rangle$$

$$= \left(\langle |A|^2 \rangle - |\langle A \rangle|^2\right)$$

Incoherent
= difference between both:
probes event-by-event fluctuations

Incoherent production



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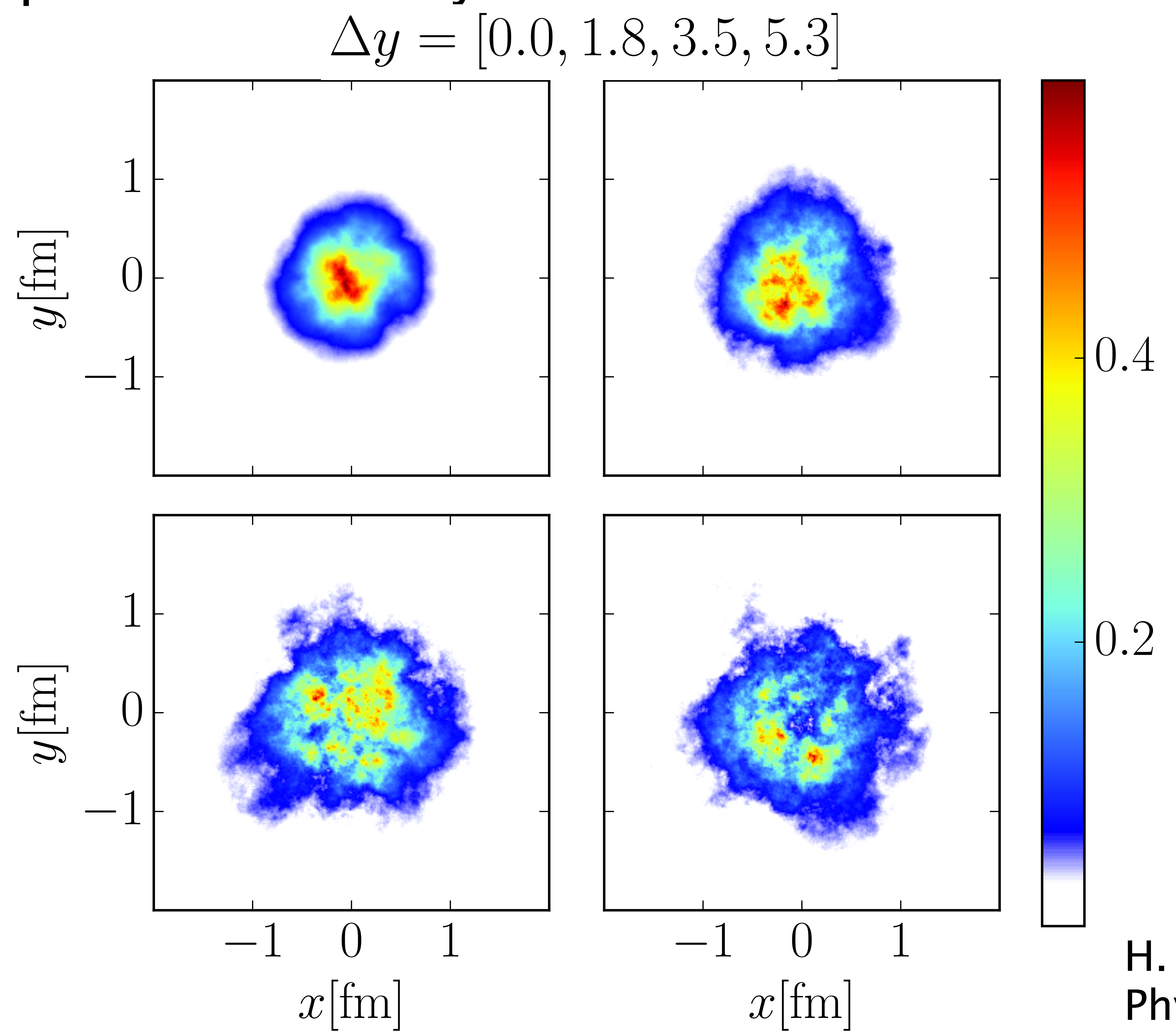
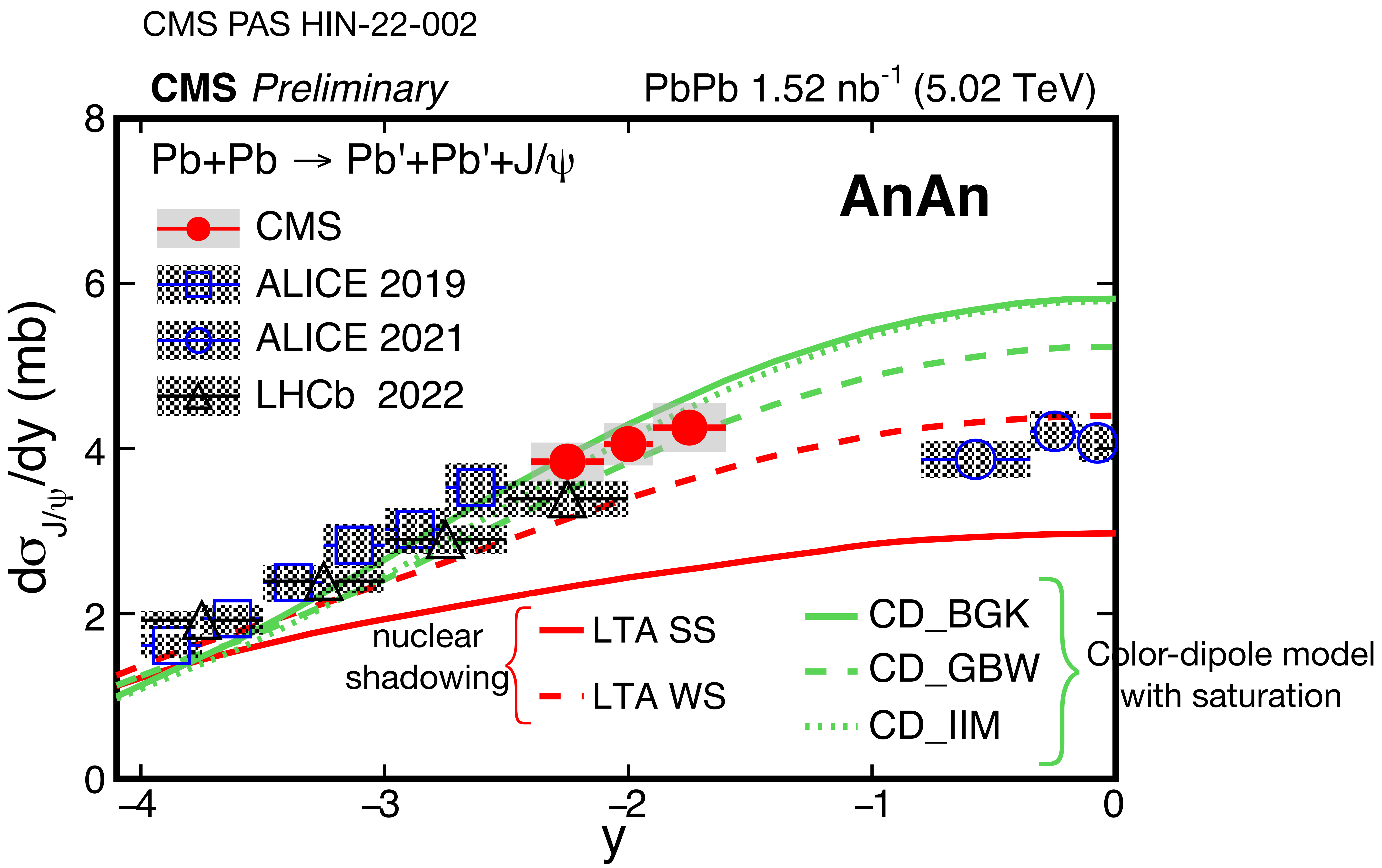


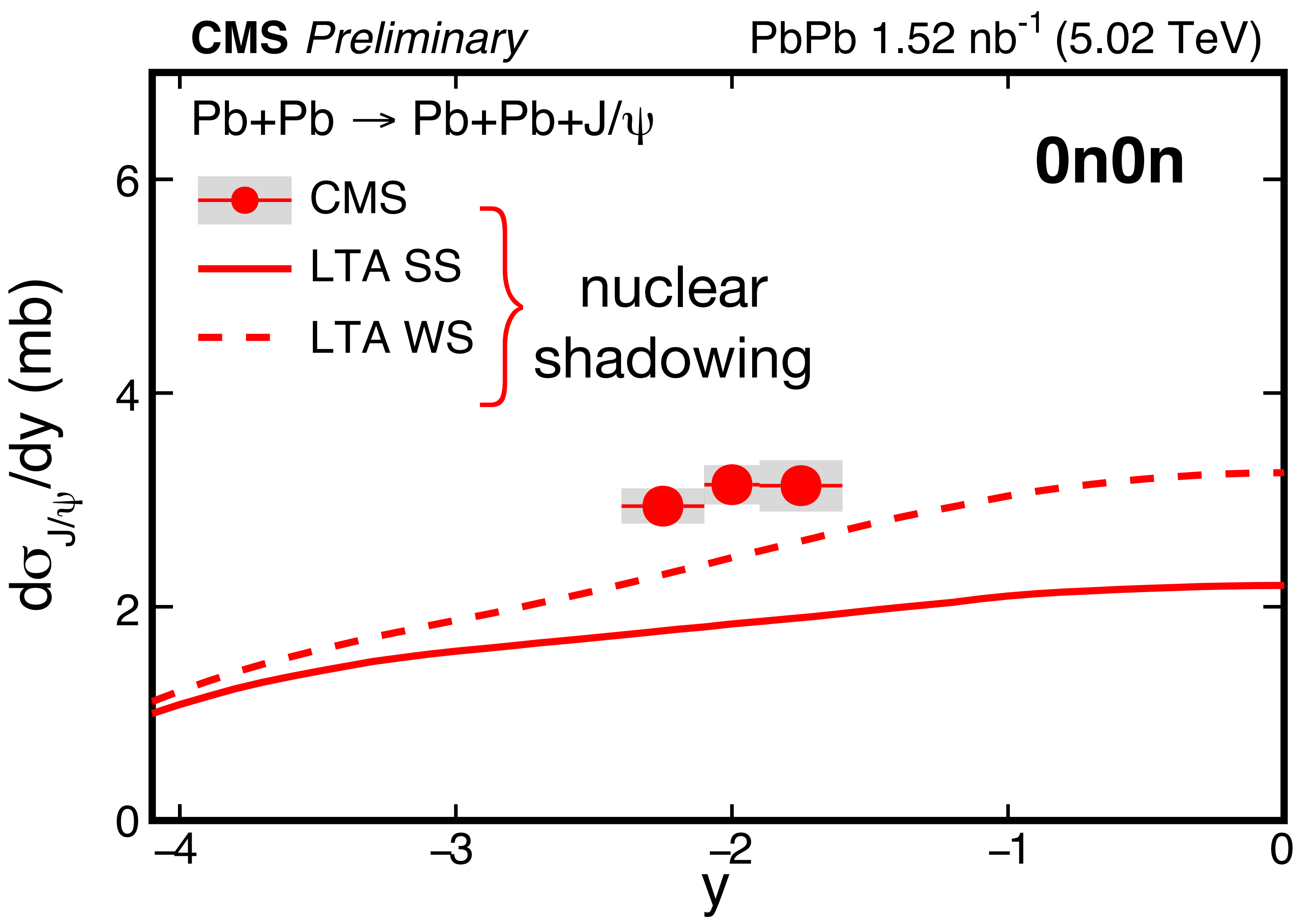
H. Mäntysaari and B. Schenke.
Phys. Rev. D 98, 034013 (2018)

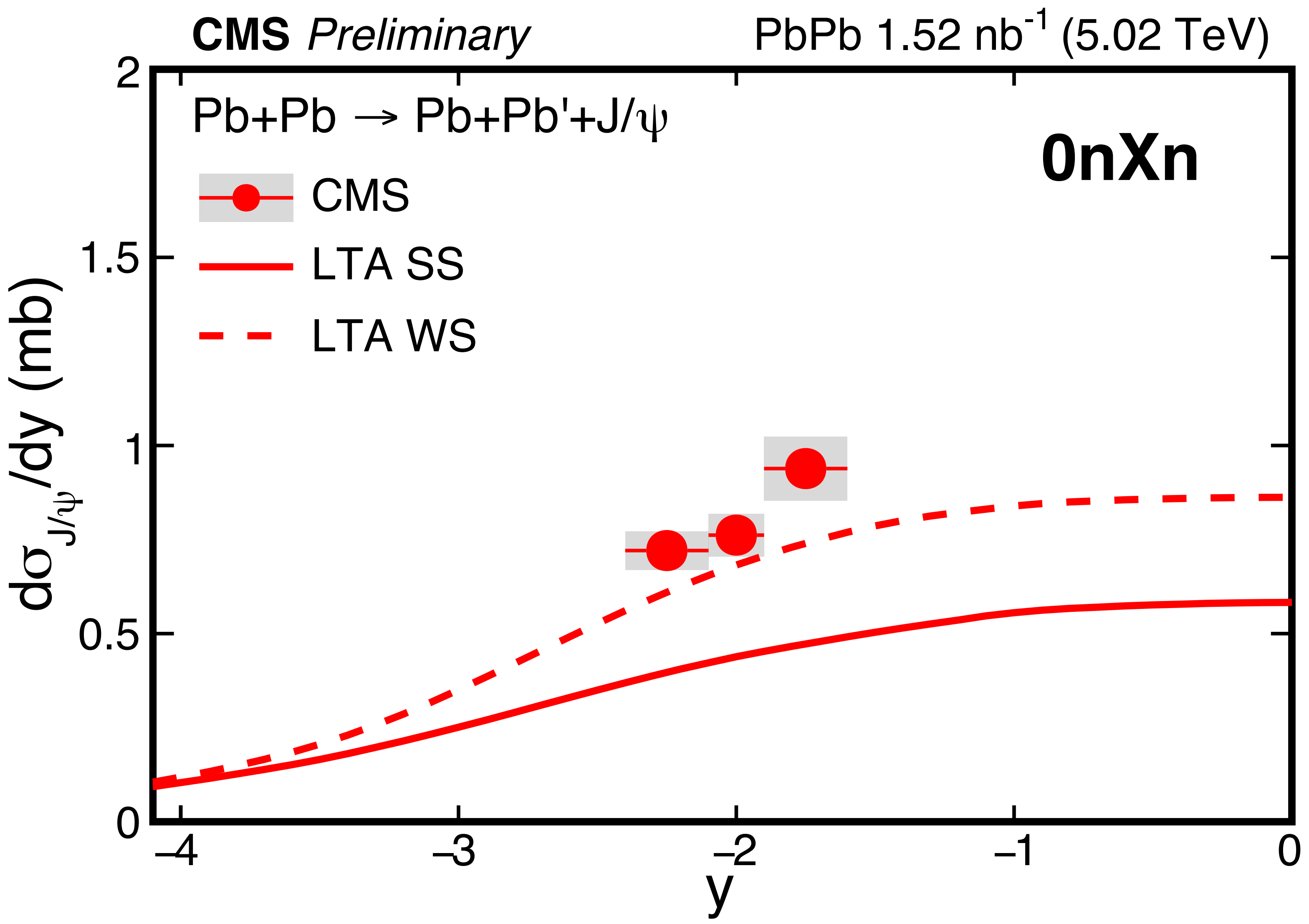
CMS results: no requirement on neutron detection

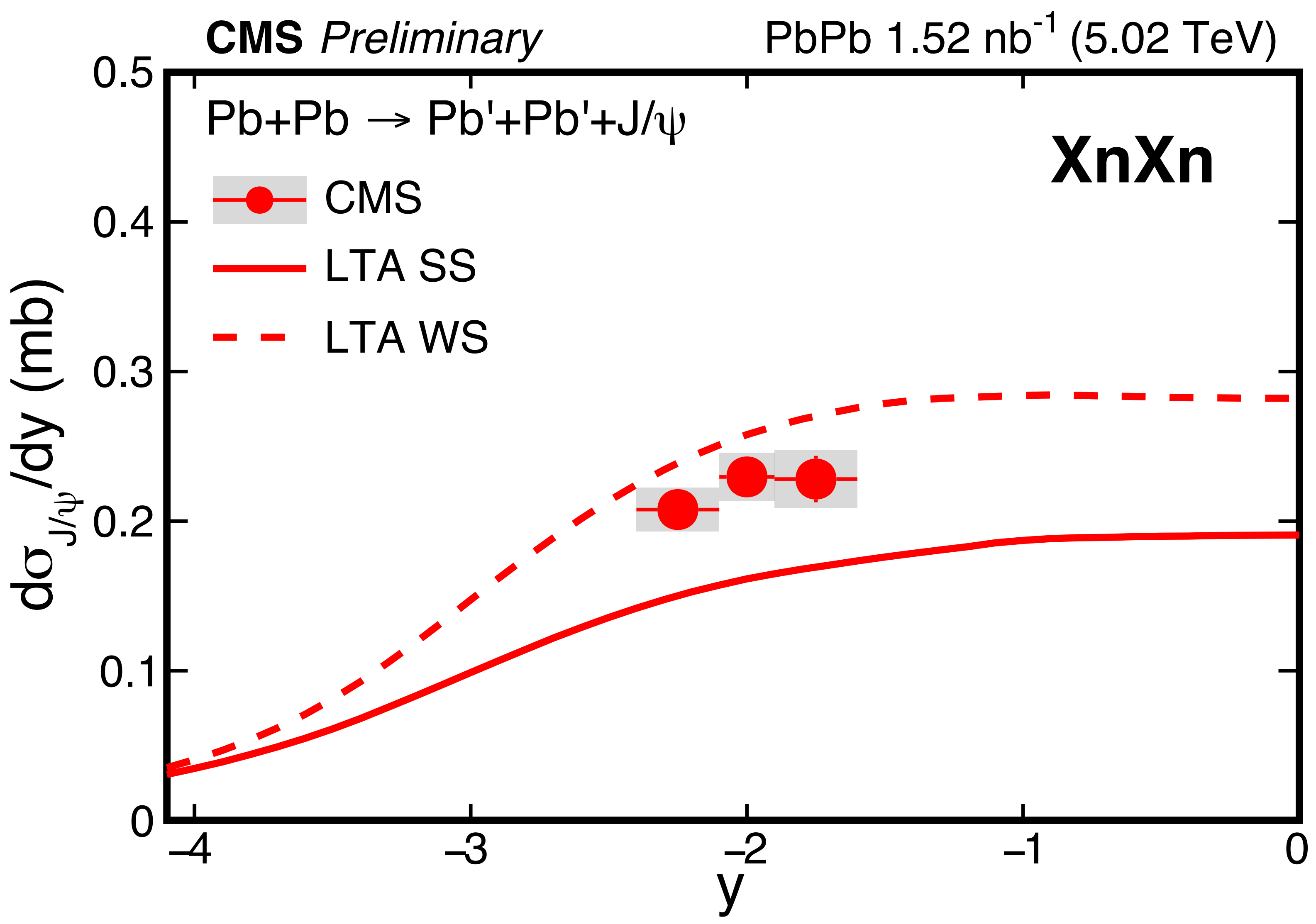


CMS results: different neutron-detection requirements

CMS PAS HIN-22-002







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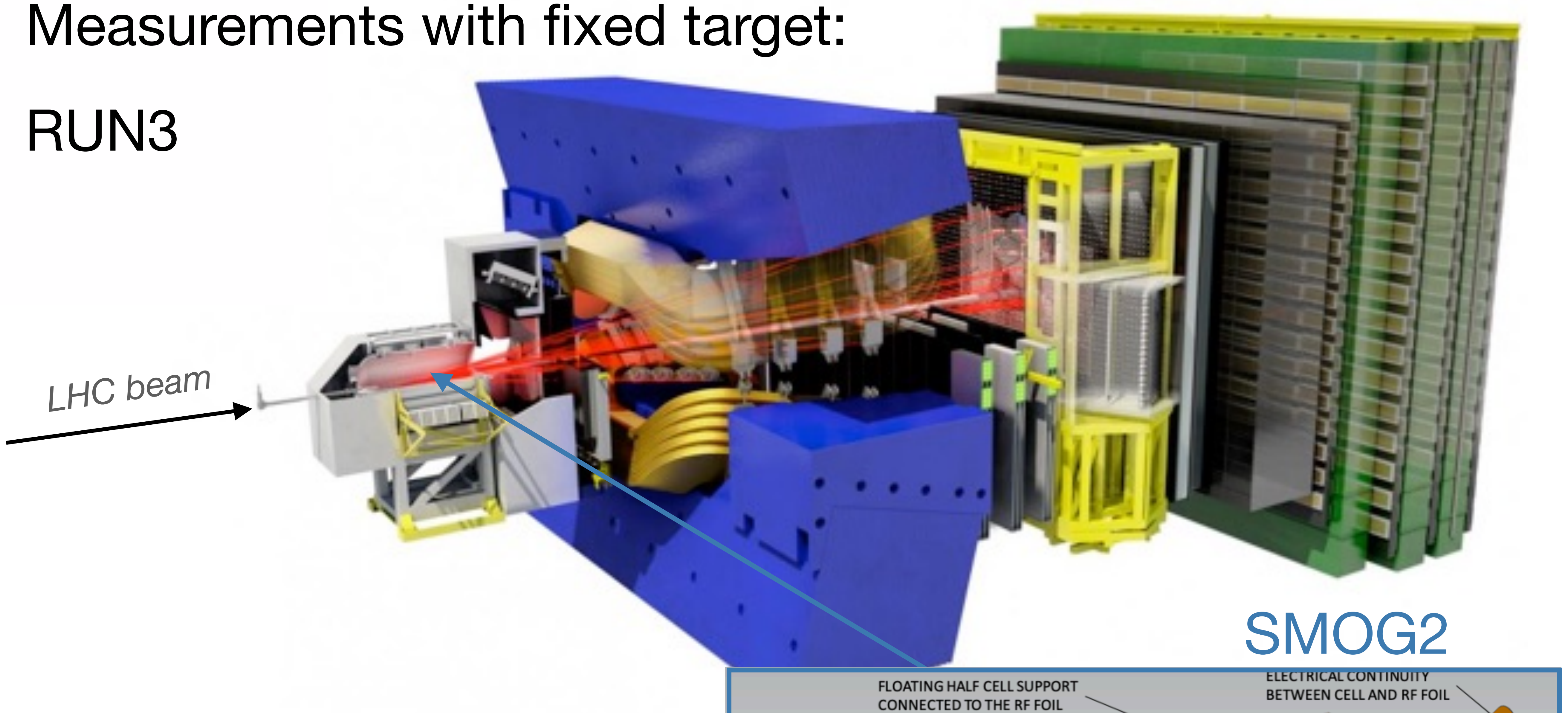
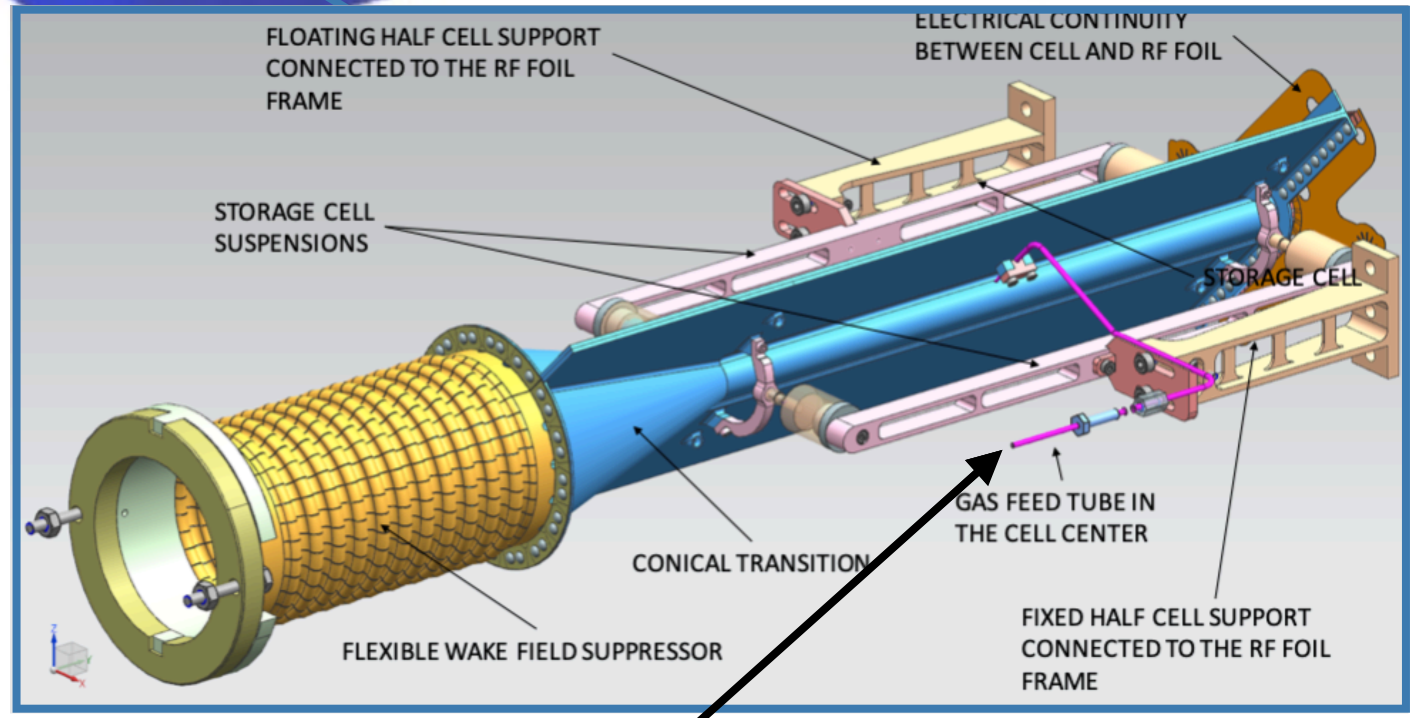
RUN3



SMOG2



inject gas: He, Ne, Ar, and H_2, D_2

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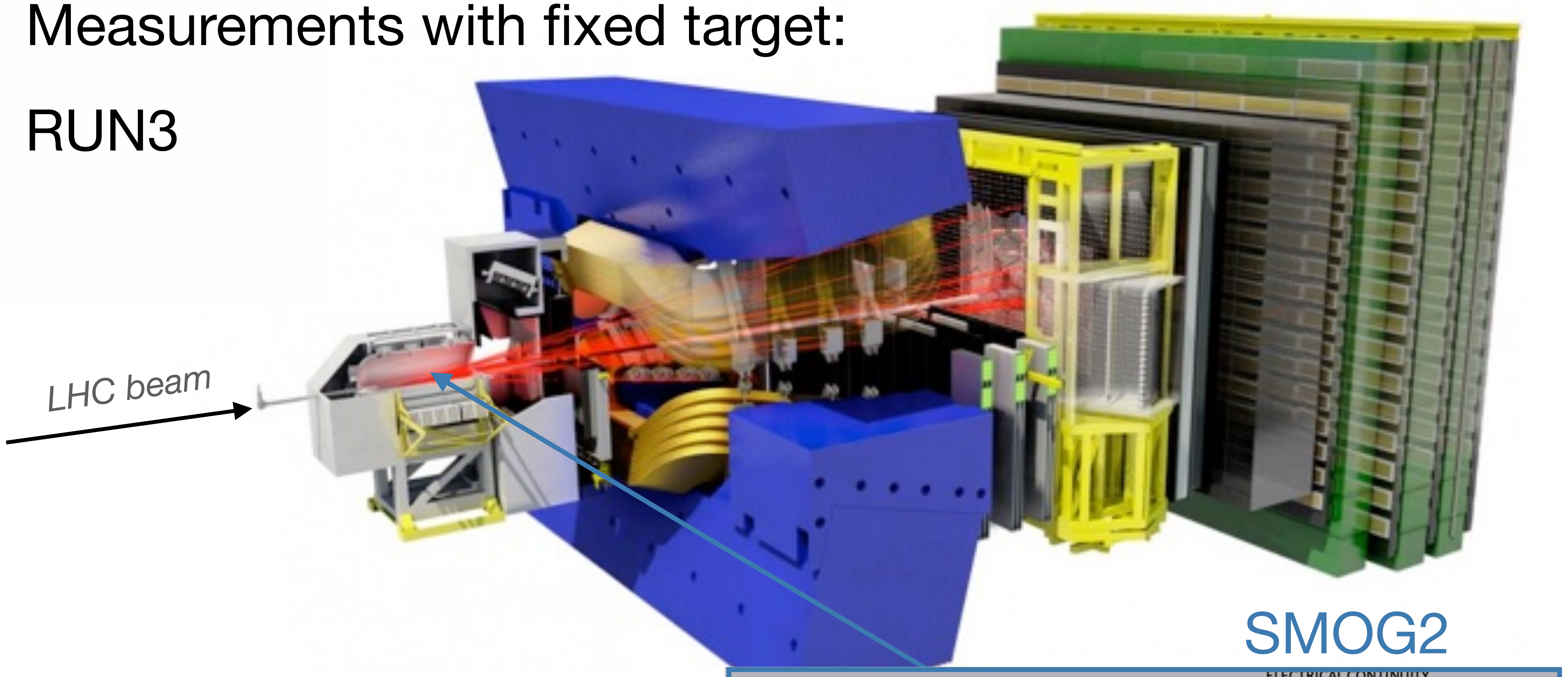

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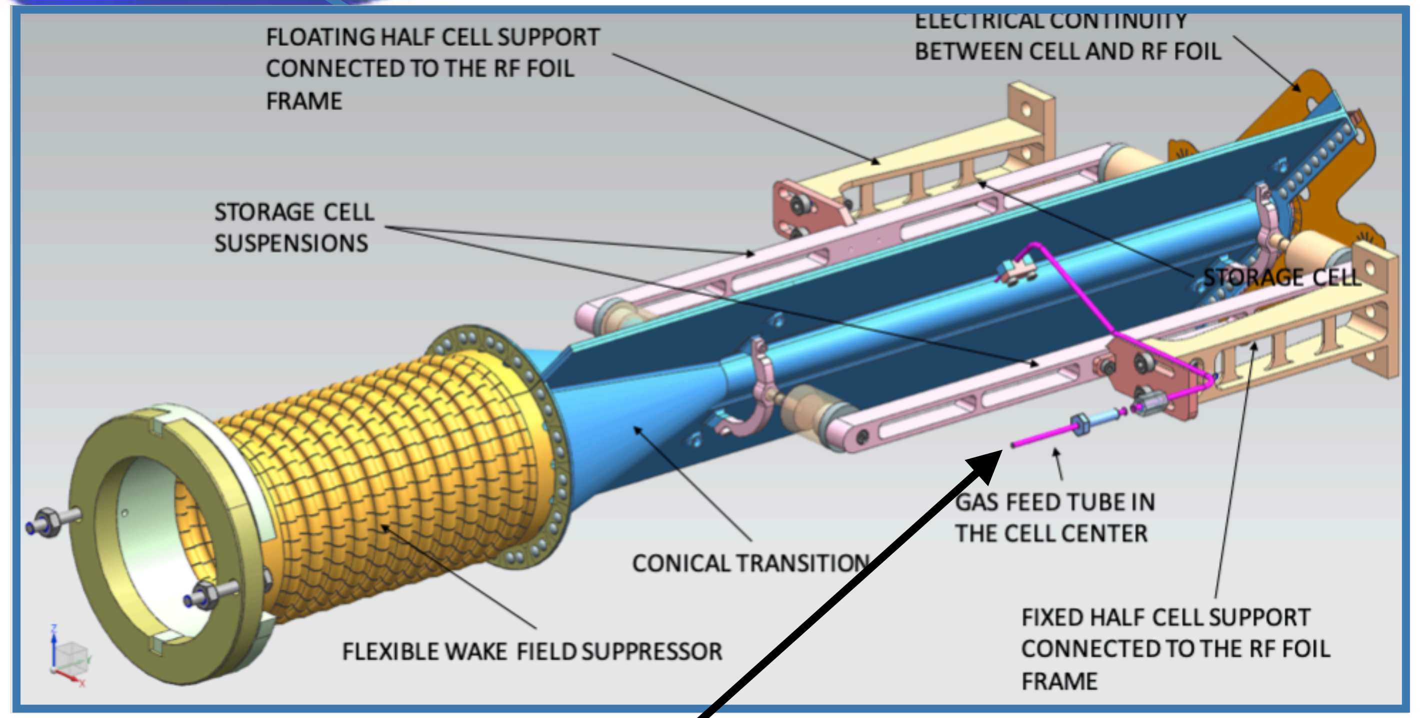

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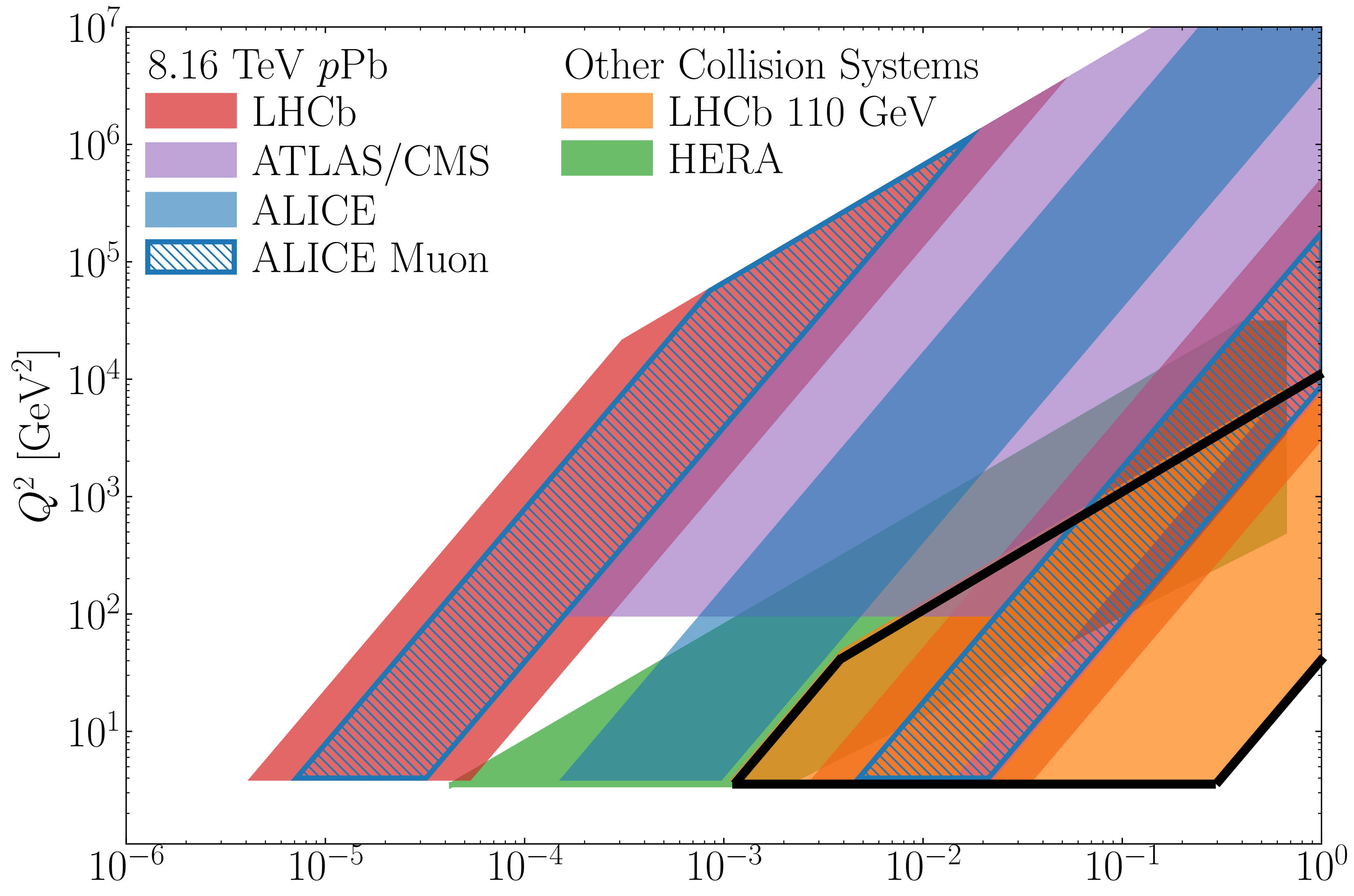
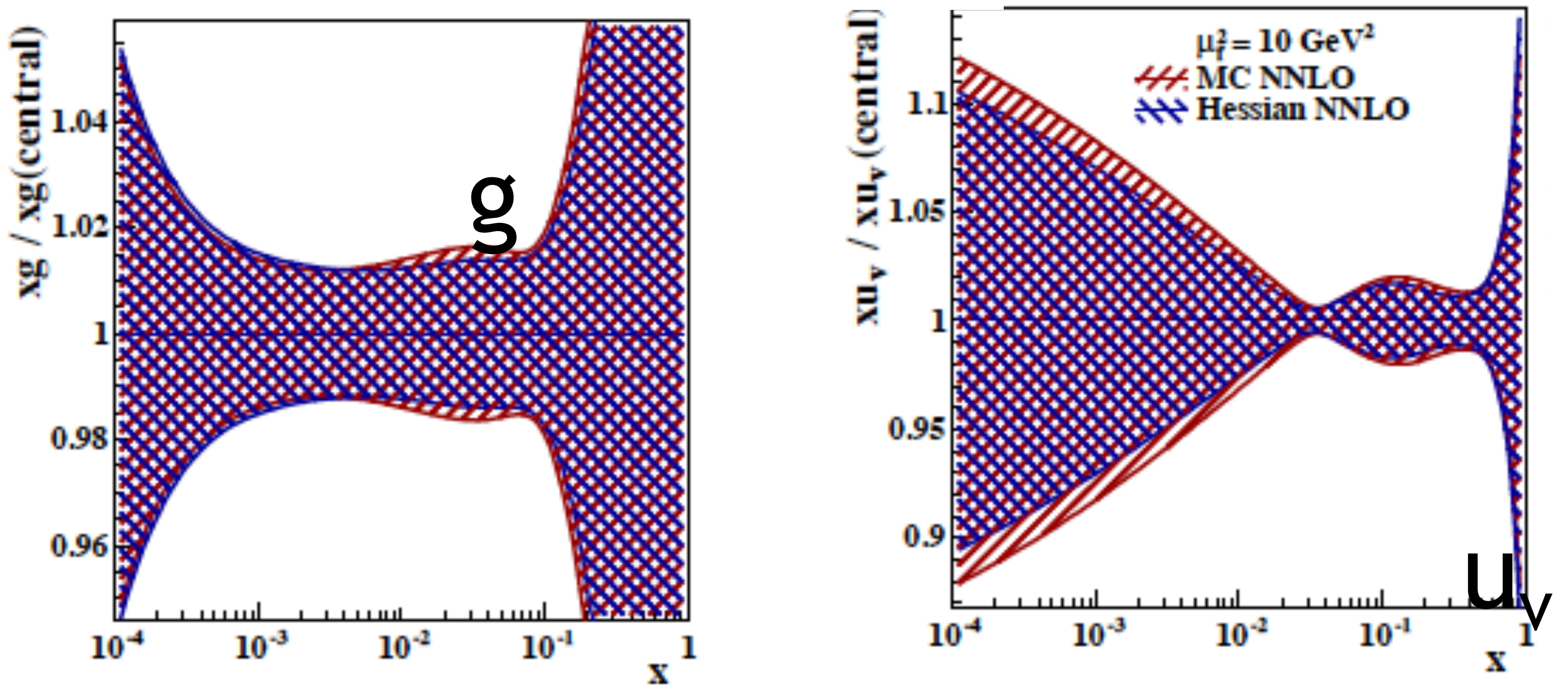


HERAPDF2.0



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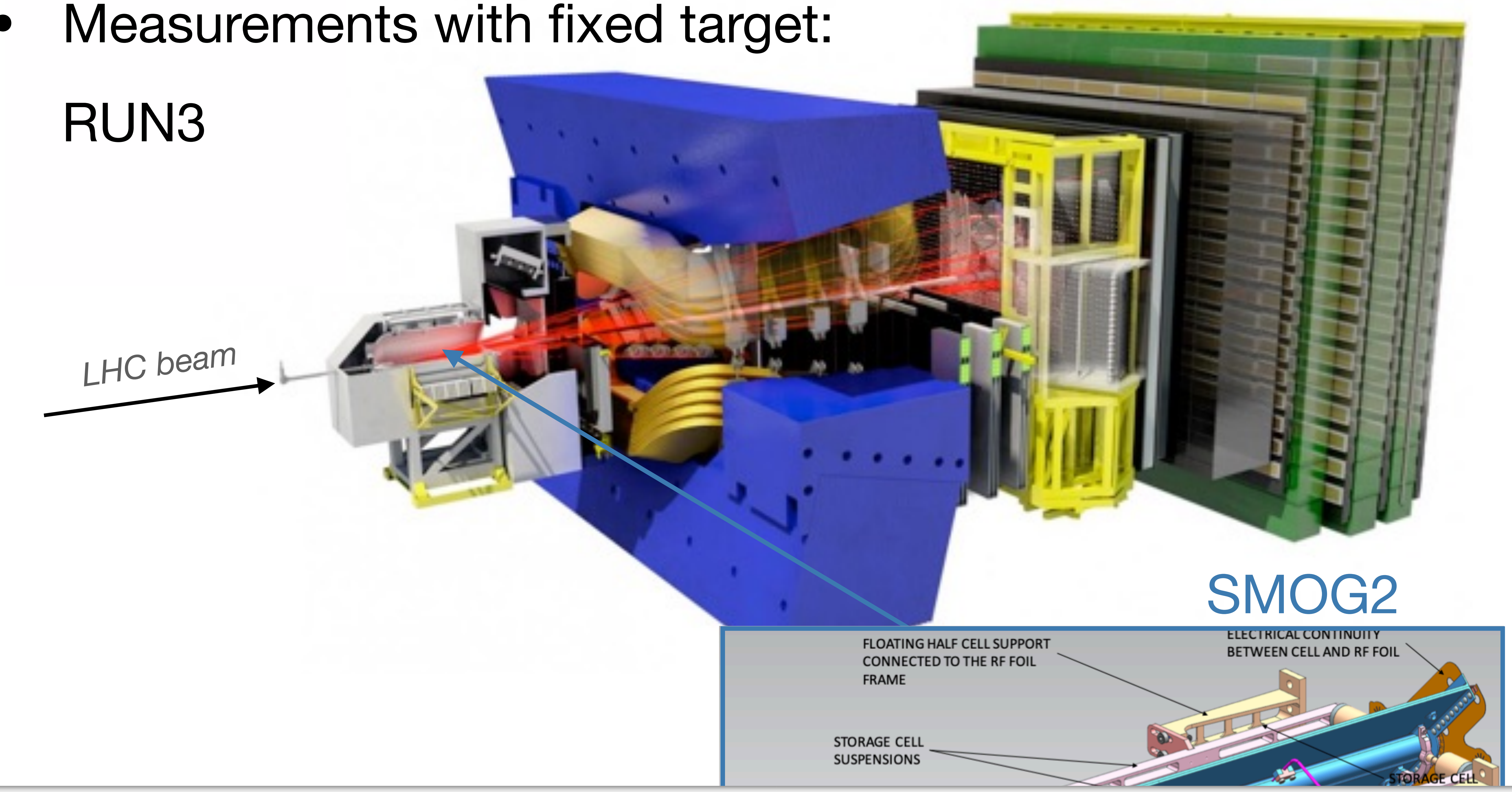

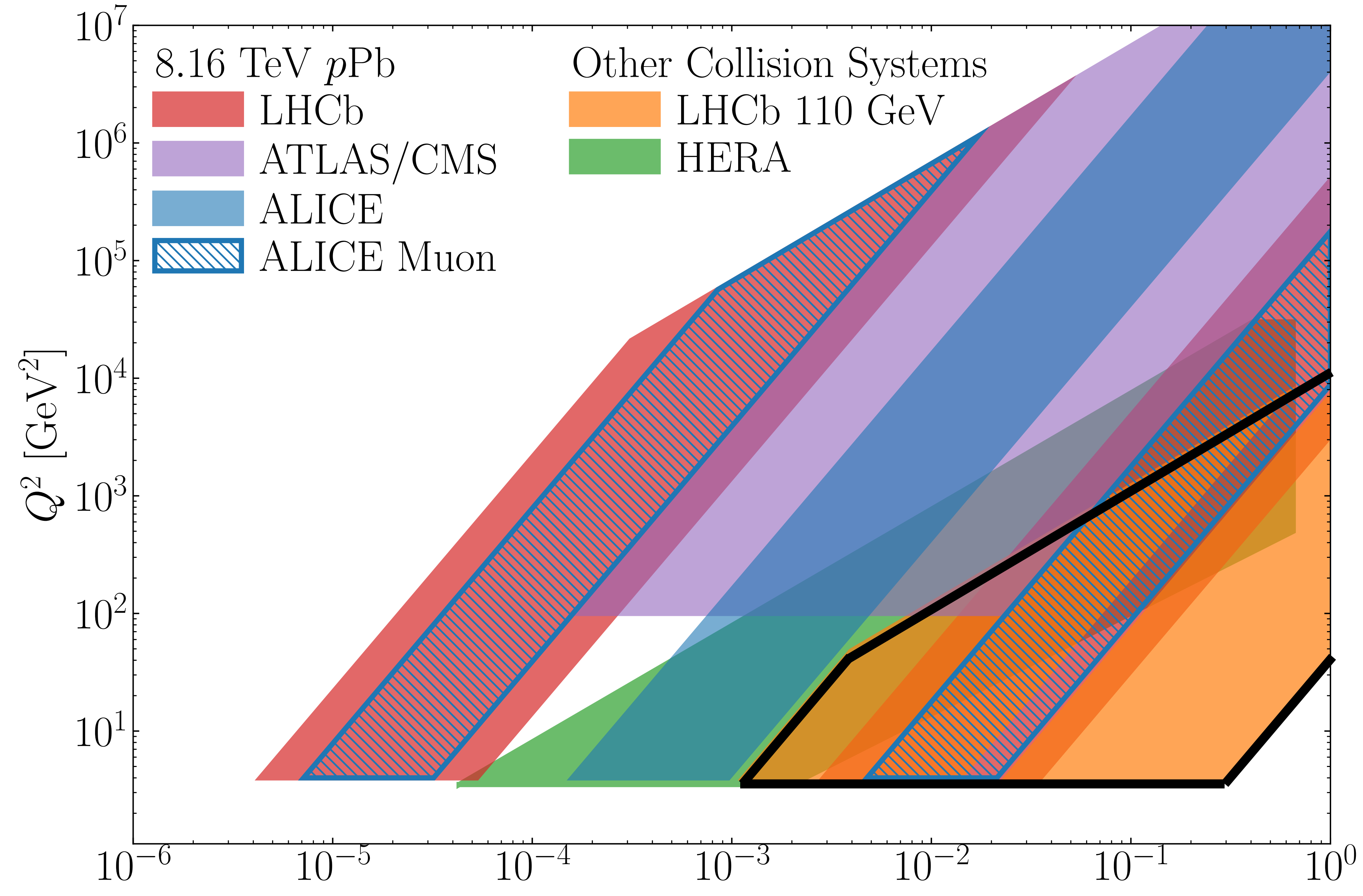

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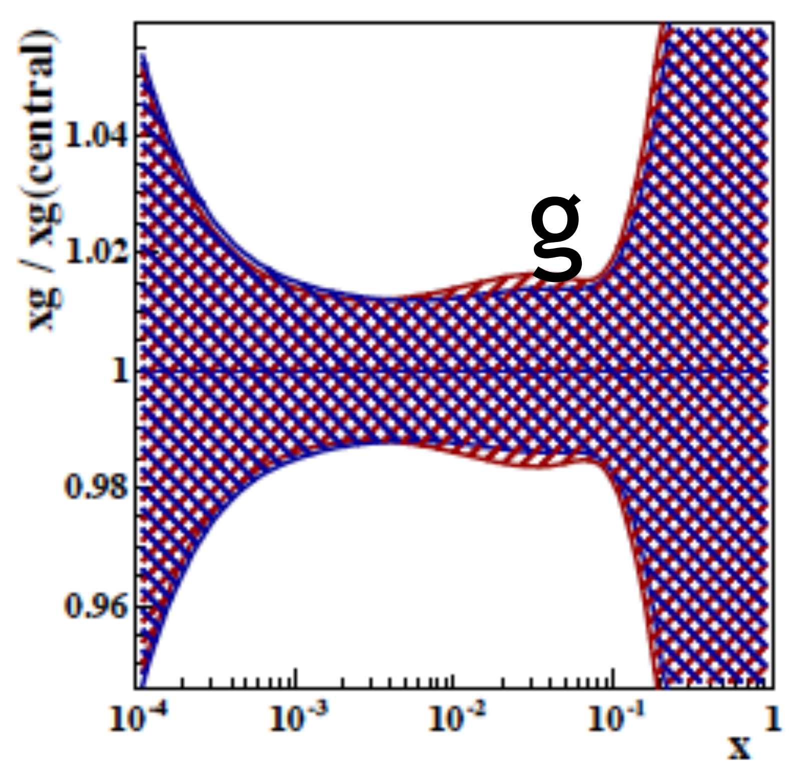
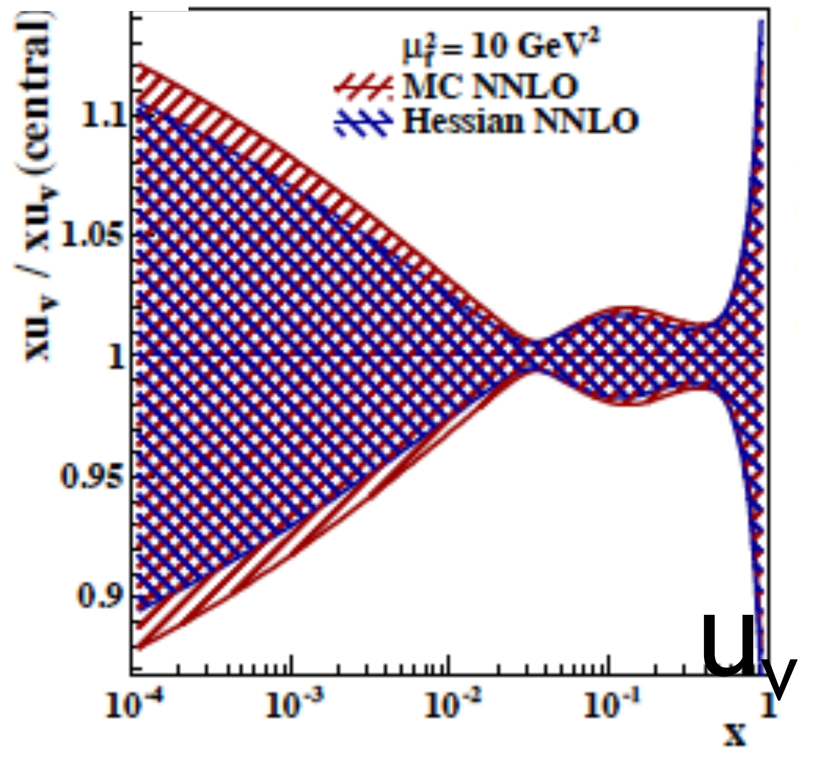
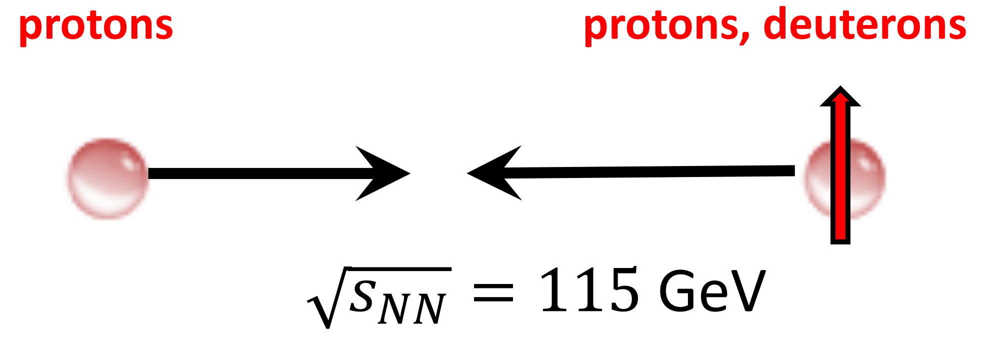
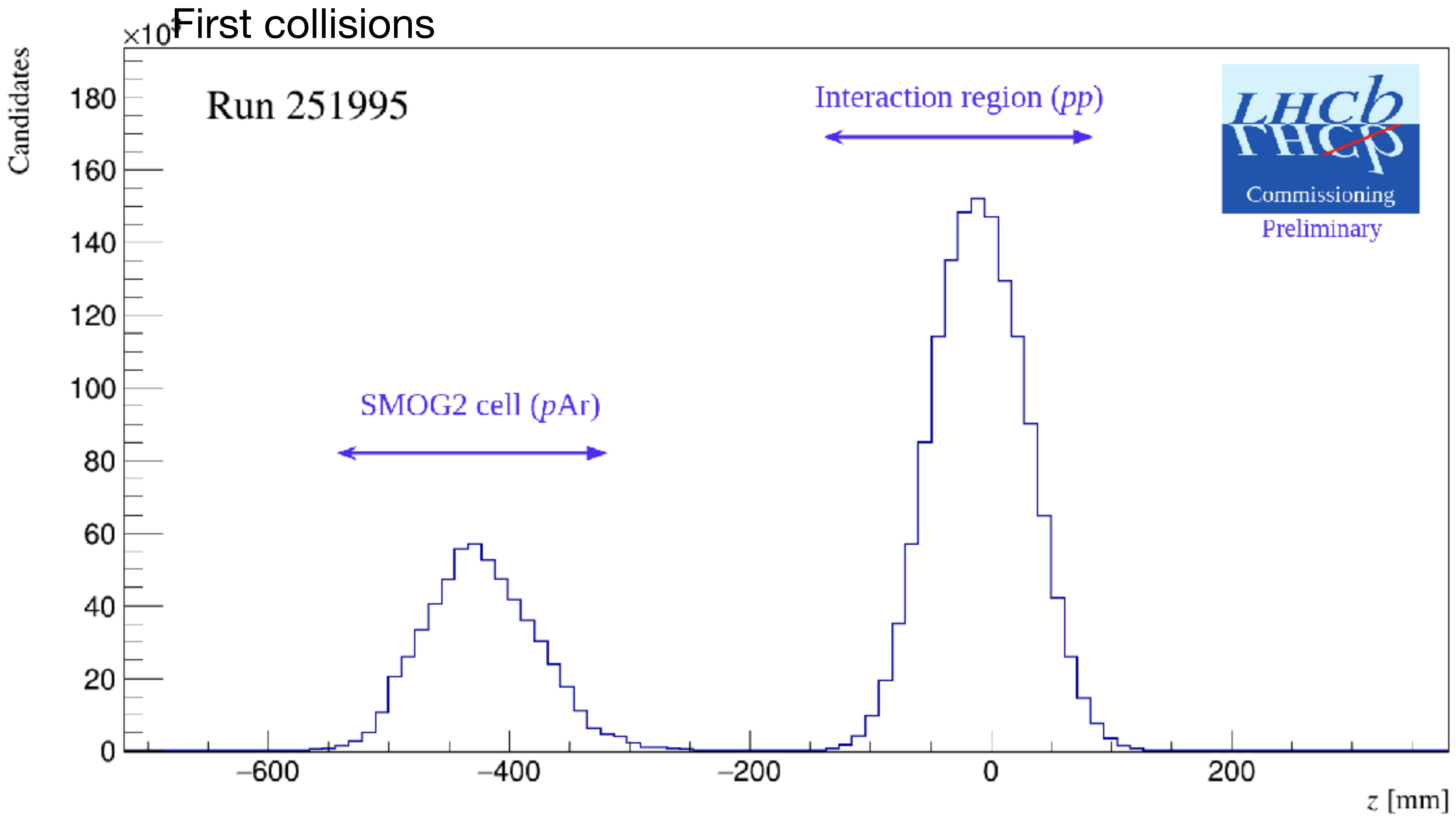




- Proposal for Run 4:
- LHCSPIN: transversely polarised gas target
  → access to spin-dependent GPD E
  (orbital angular momentum)



Interest of fixed target



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