Latest measurements on exclusive meson production at LHC

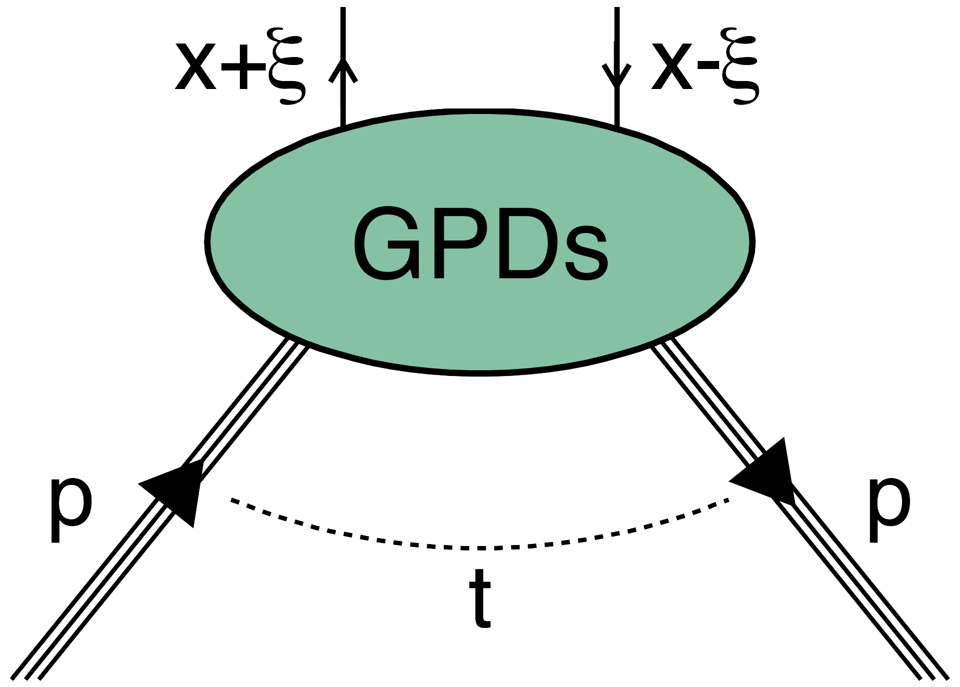
Charlotte Van Hulse
University of Alcalá

AdT

Comunidad de Madrid

Towards improved hadron femtography with hard exclusive reactions 2023
Jefferson Lab, Newport News, VA
August 07–11, 2023

Experimental access to GPDs



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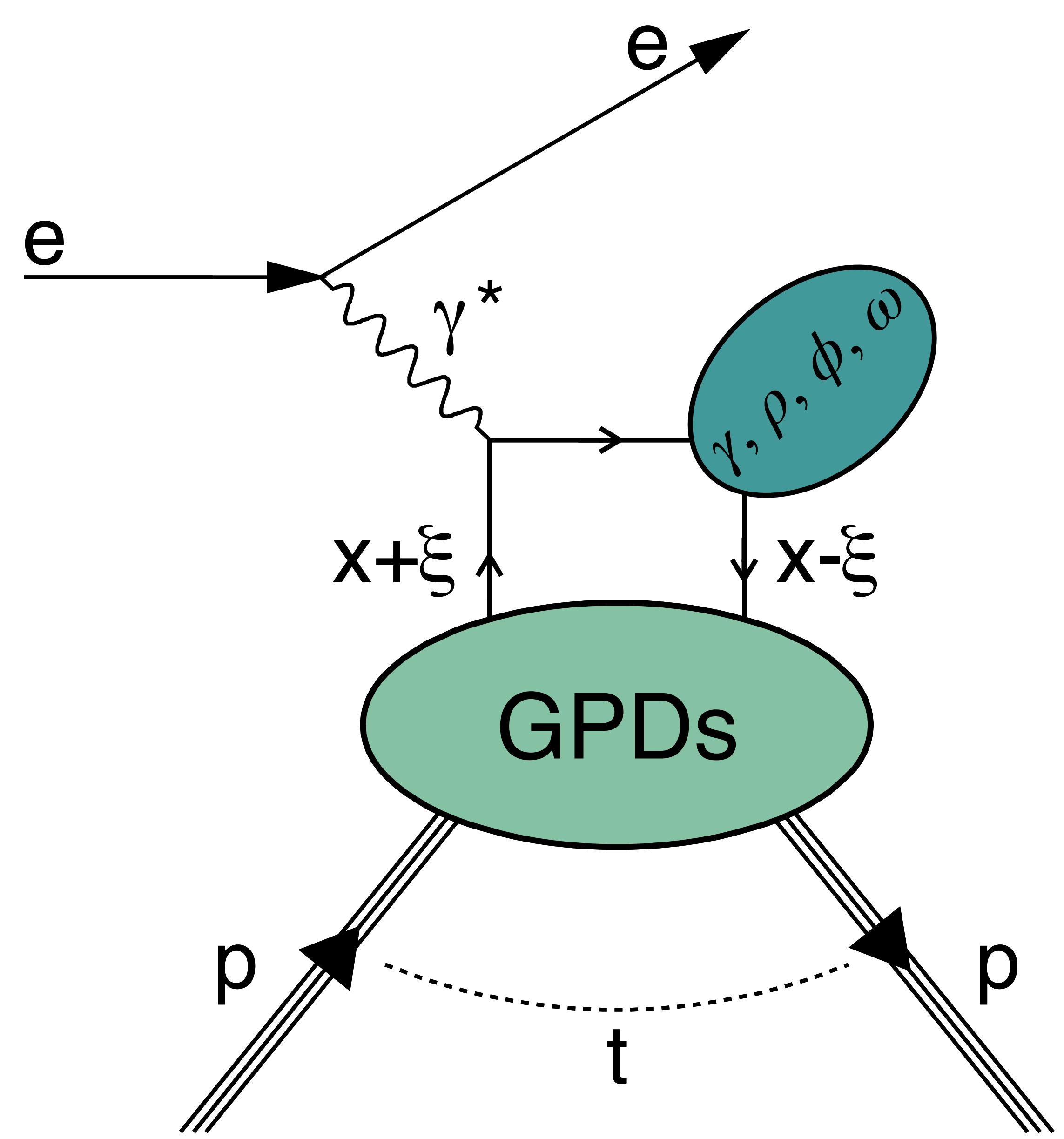

Hard scale=large Q^2

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

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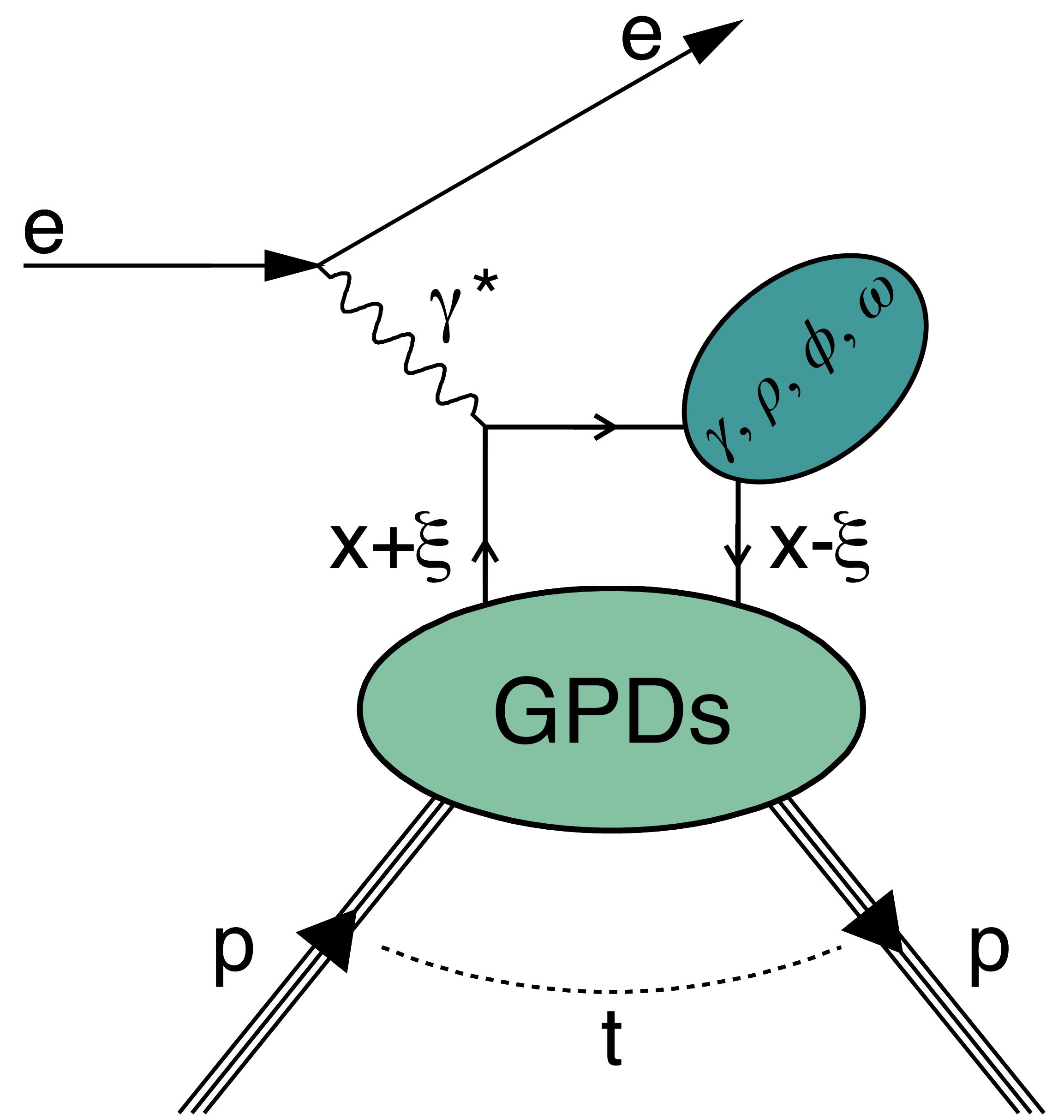

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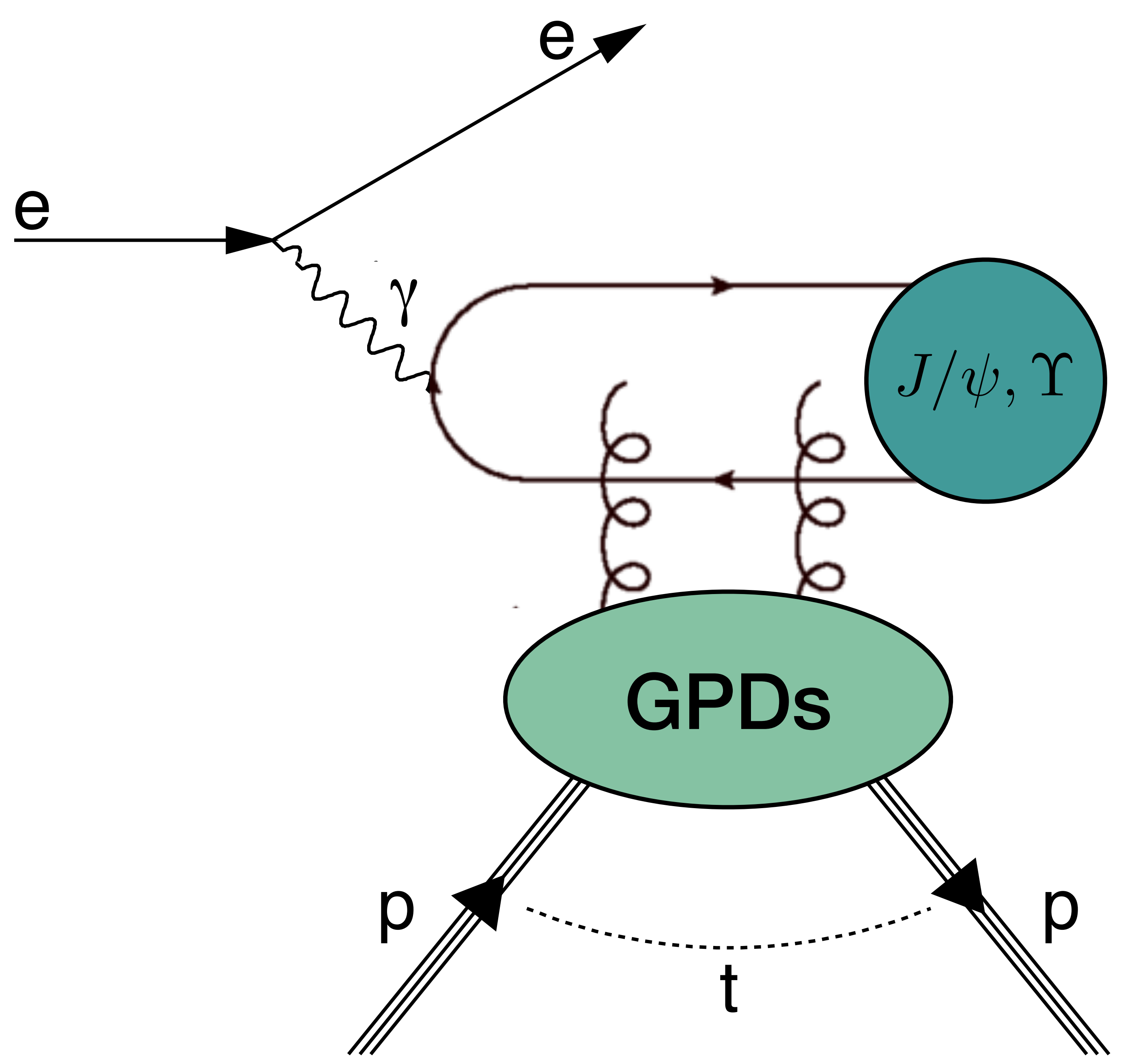

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H1 – EPJ C 46 ('06) 585; 73 ('13) 2466; PLB 541 ('02) 251
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$$W_{\gamma p} = [30, 300] \text{ GeV}$$

down to x_B=10^{-4}

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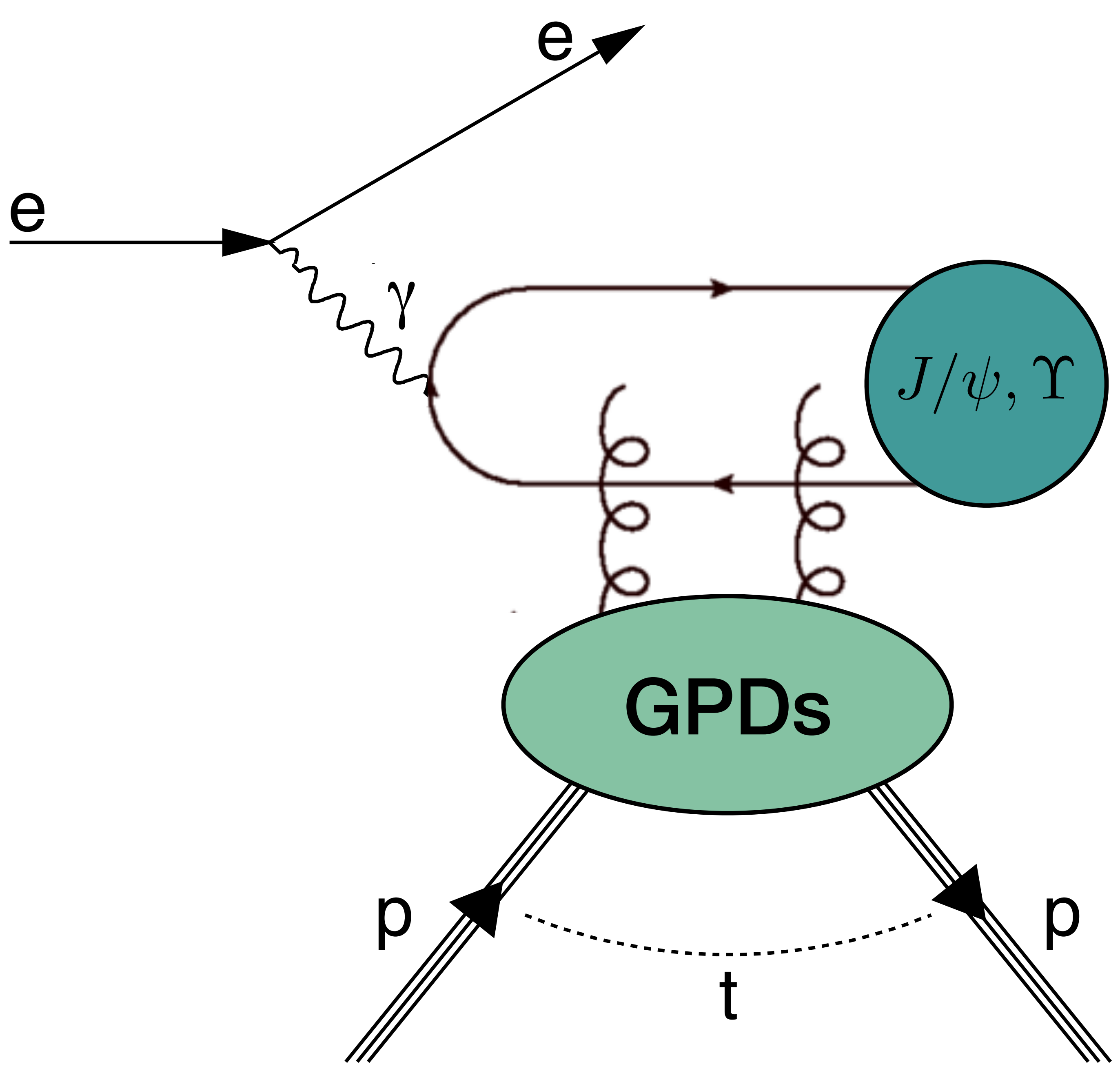

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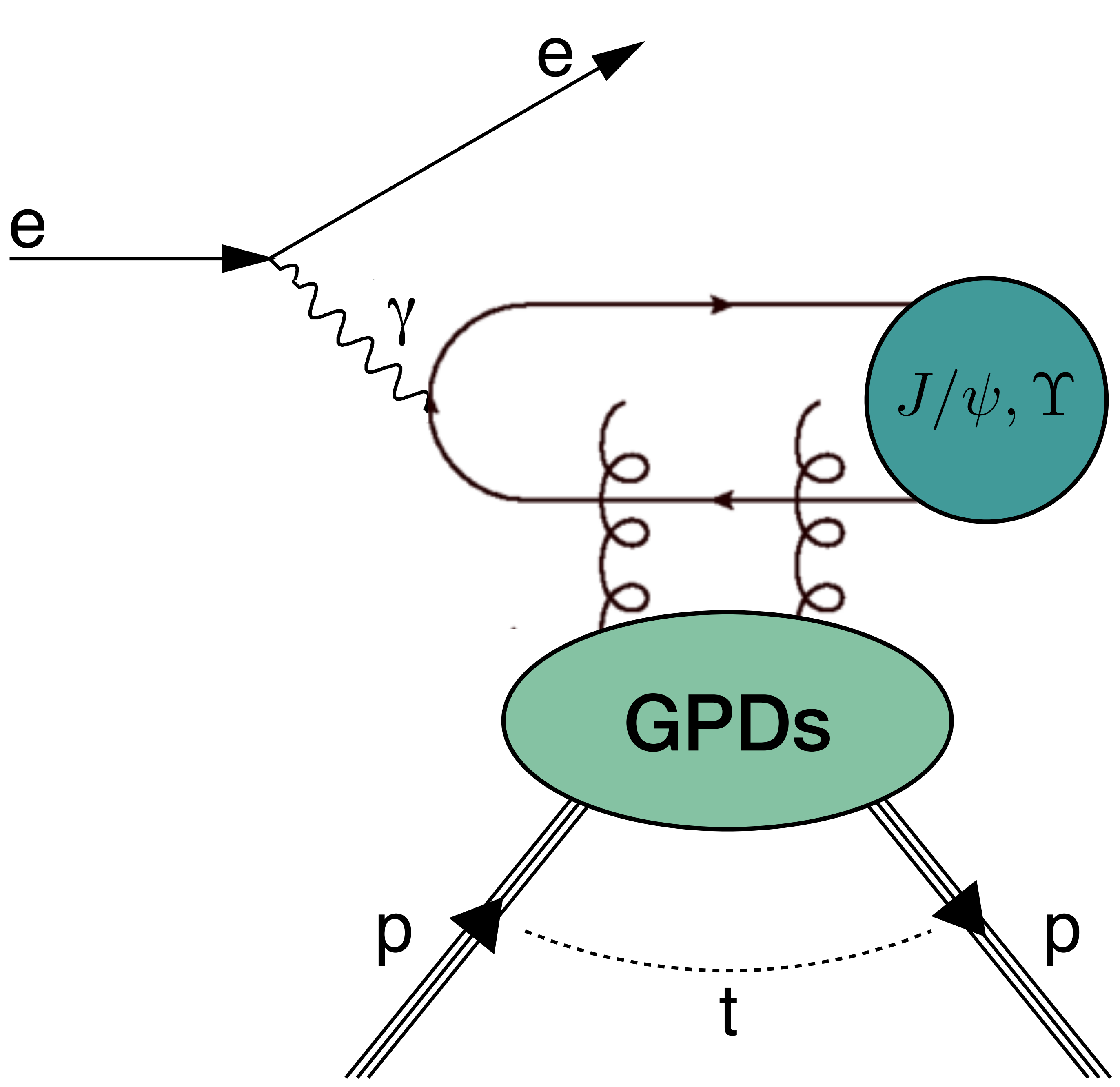

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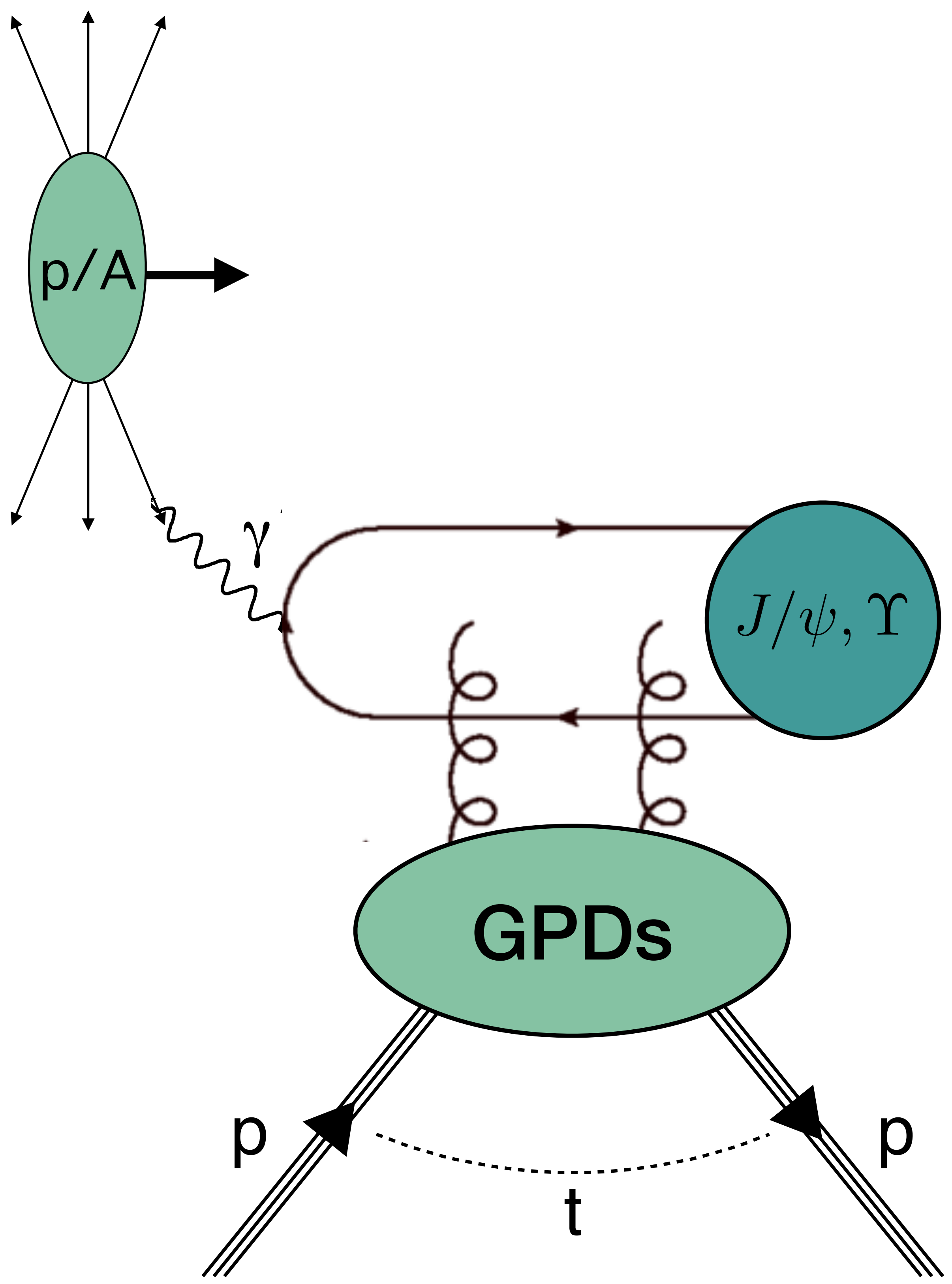

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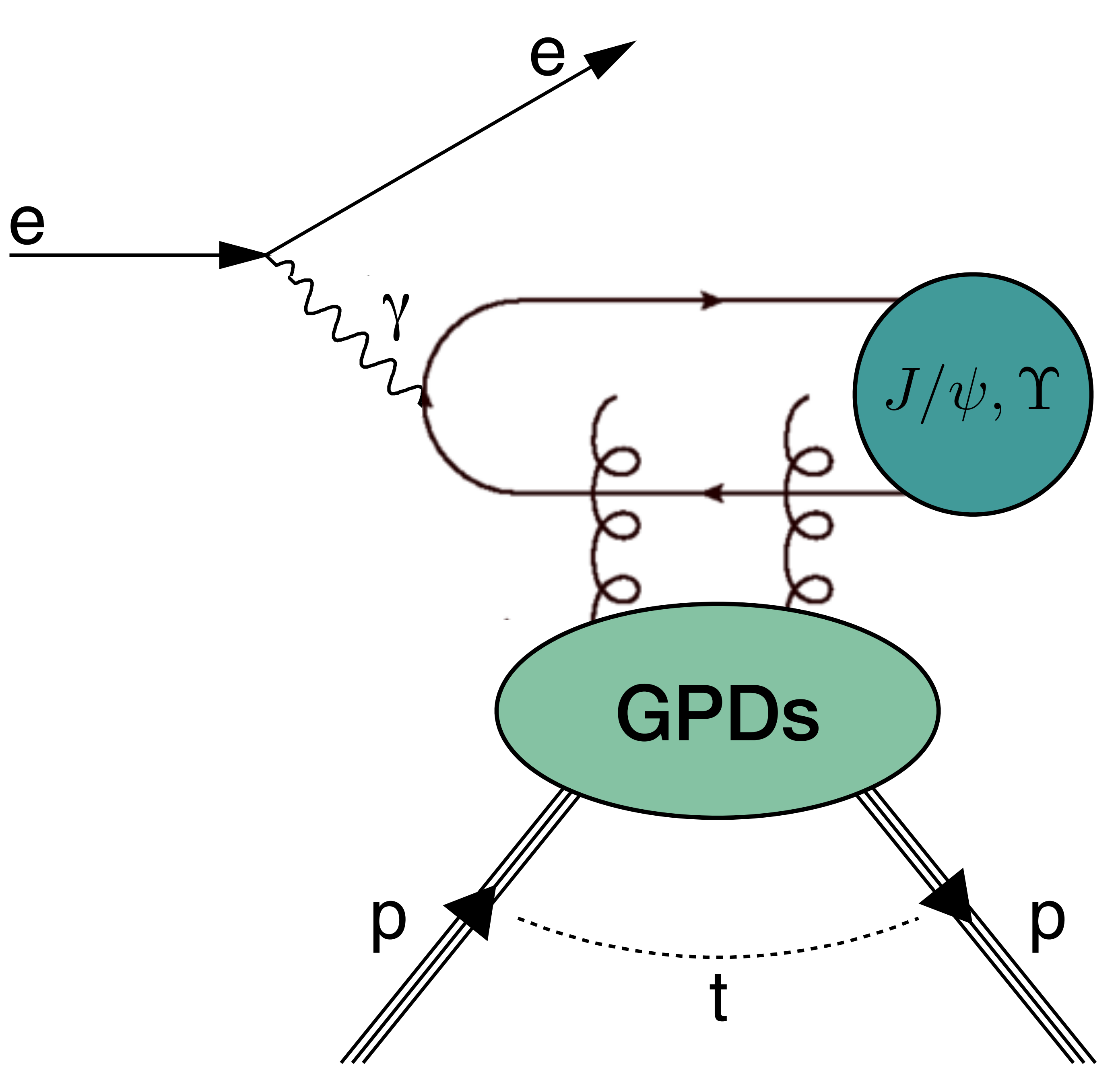

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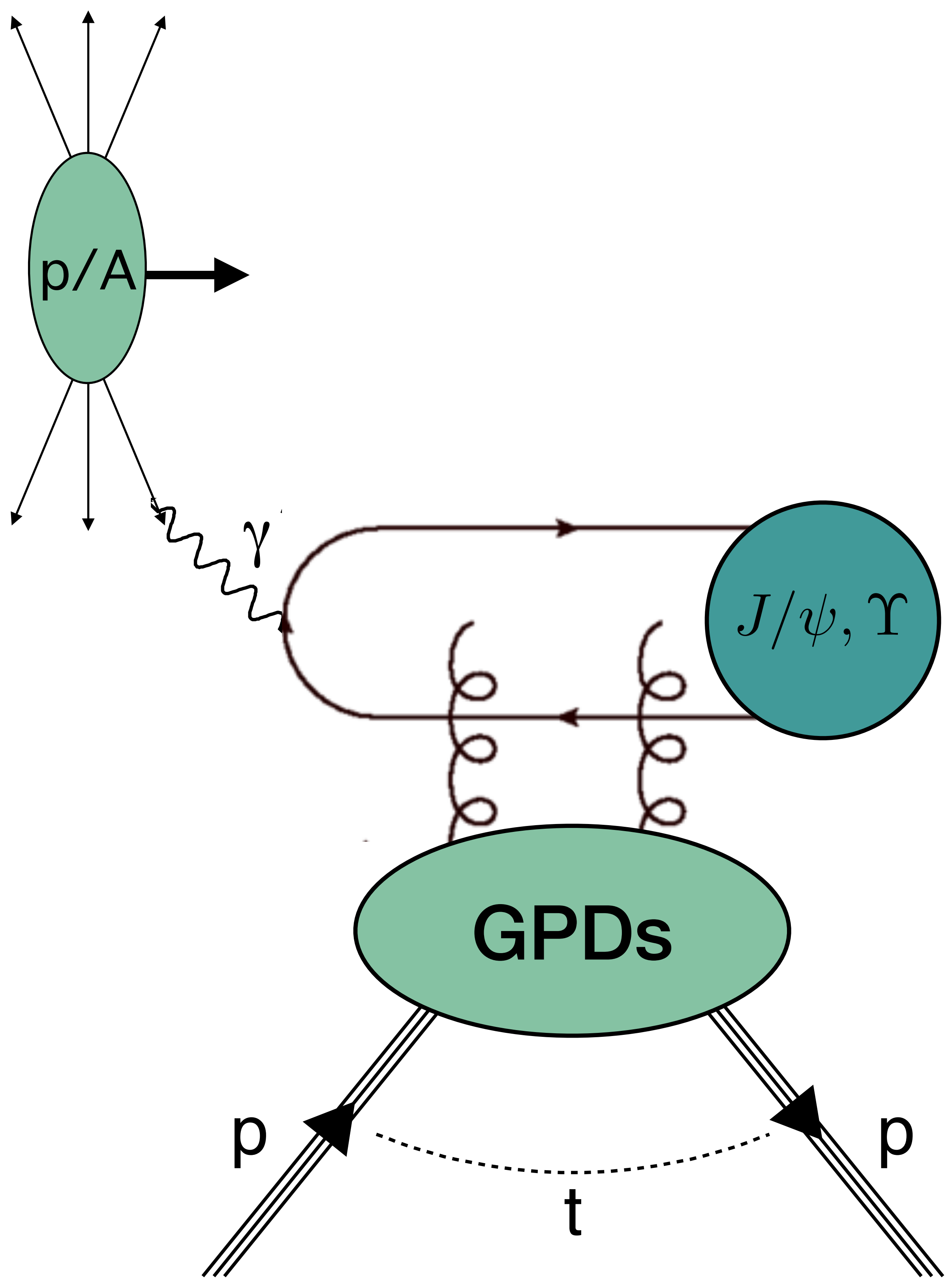


$W_{\gamma N}^{\max} = 34$ GeV

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

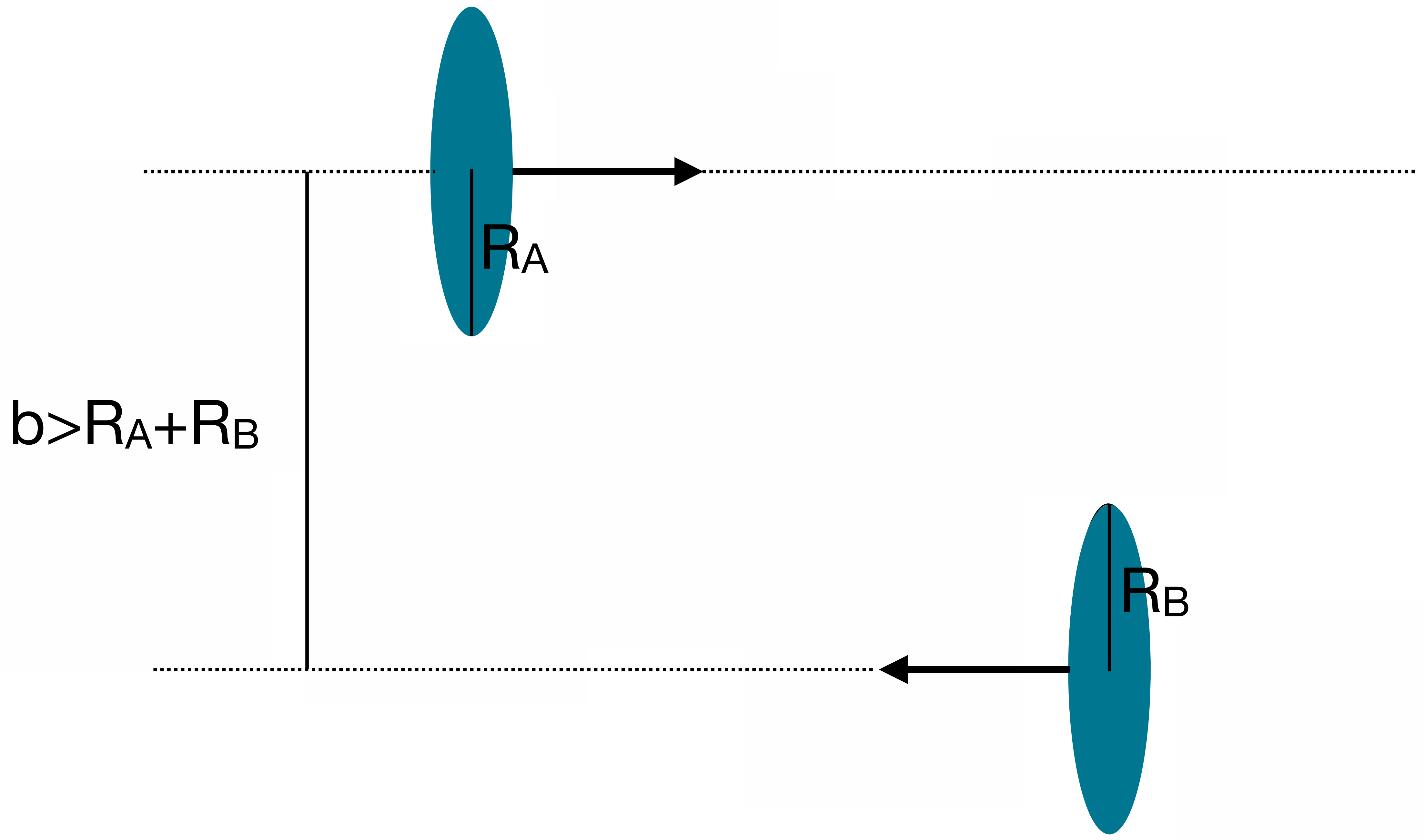
$W_{\gamma p}^{\max} = 1.5$ TeV

LHCb: pp – J. Phys. G: Nucl. Part. Phys. **40** ('13) 045001; **41** ('14) 055002; JHEP 1509 ('15) 084); JHEP10('18)167

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

Ultra-peripheral collisions

large–impact-parameter interactions



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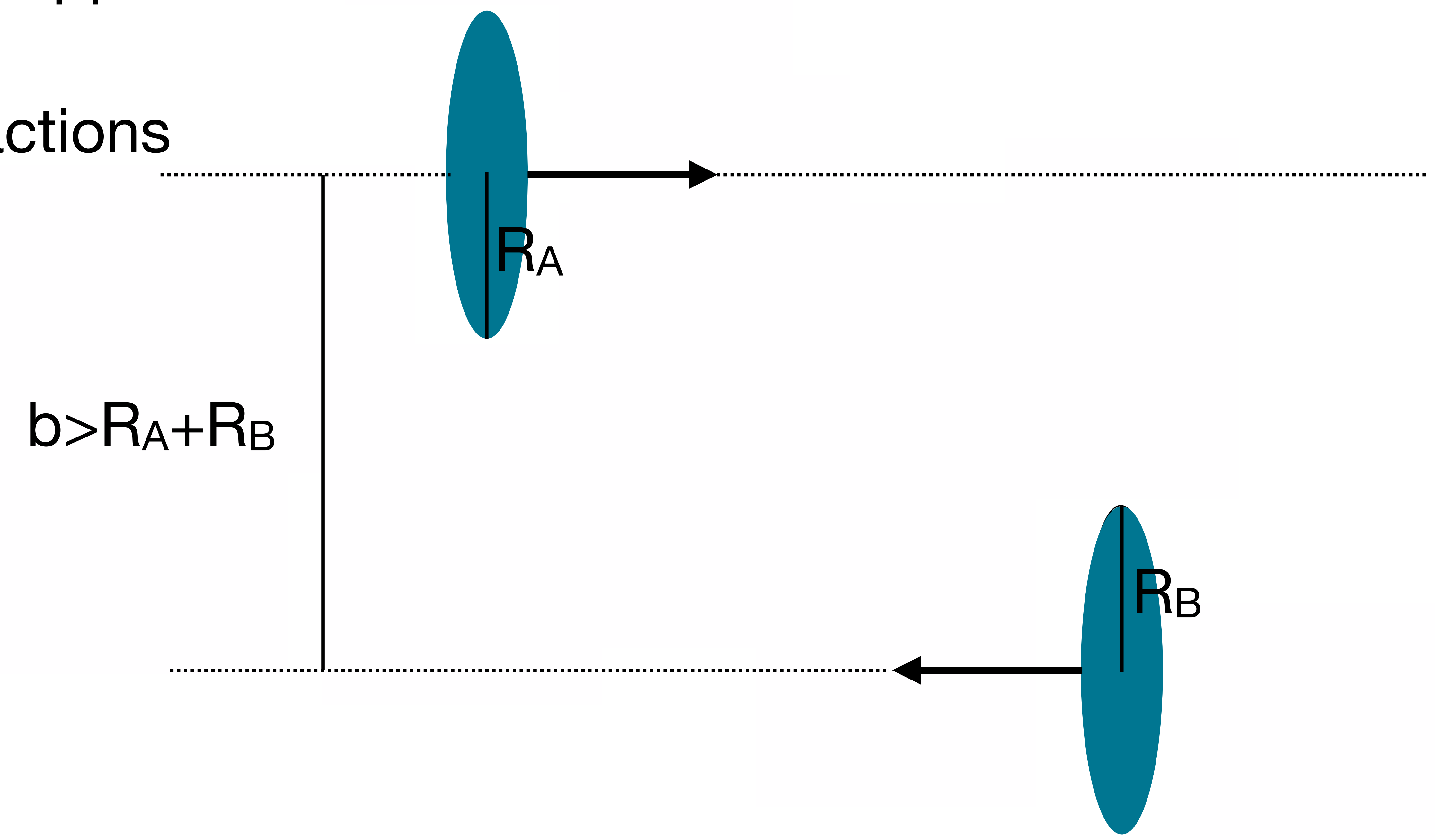
hadronic interactions strongly suppressed

instead: electromagnetic interactions



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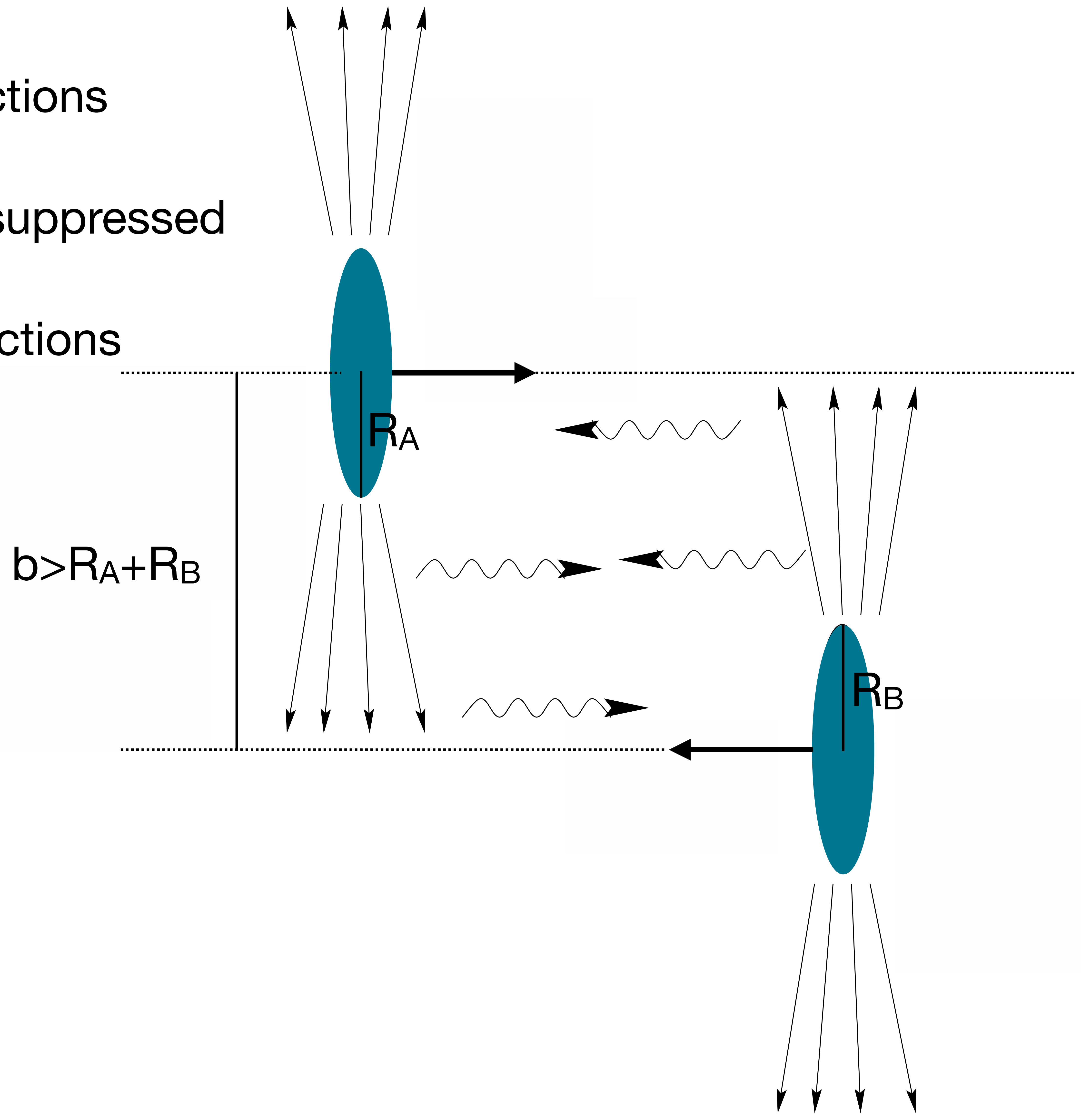

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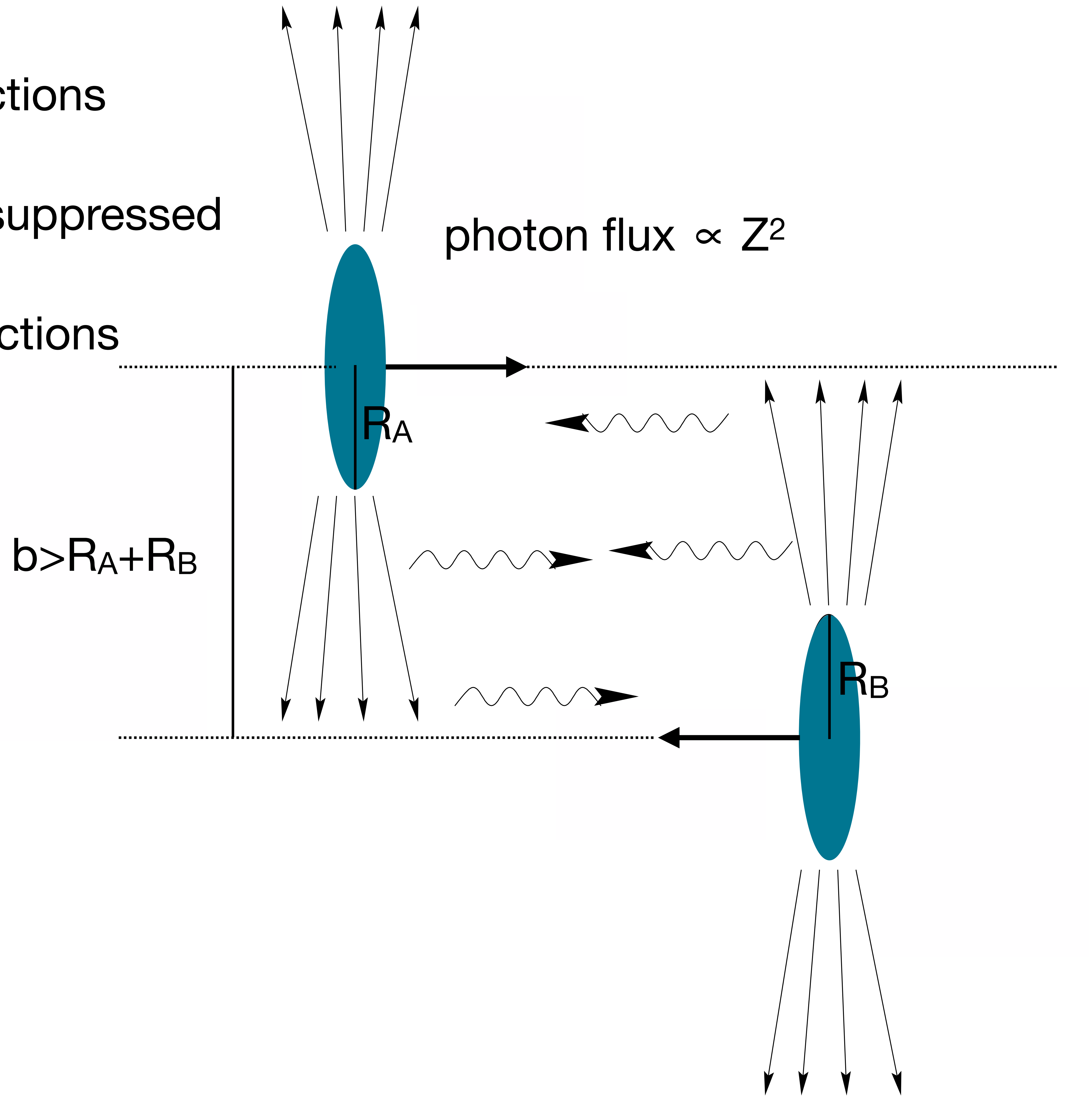

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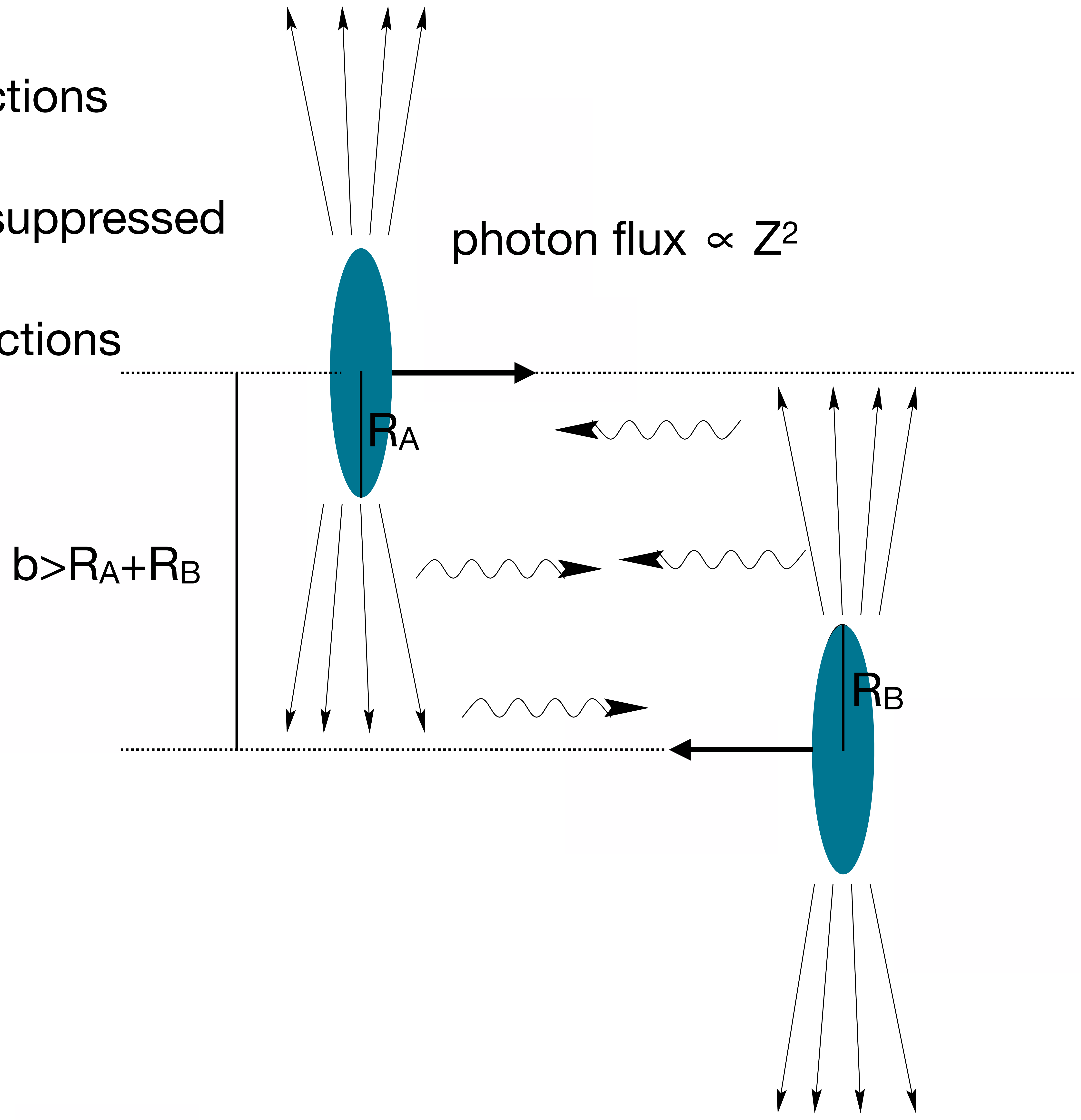

photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$

→ quasi-real photons

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

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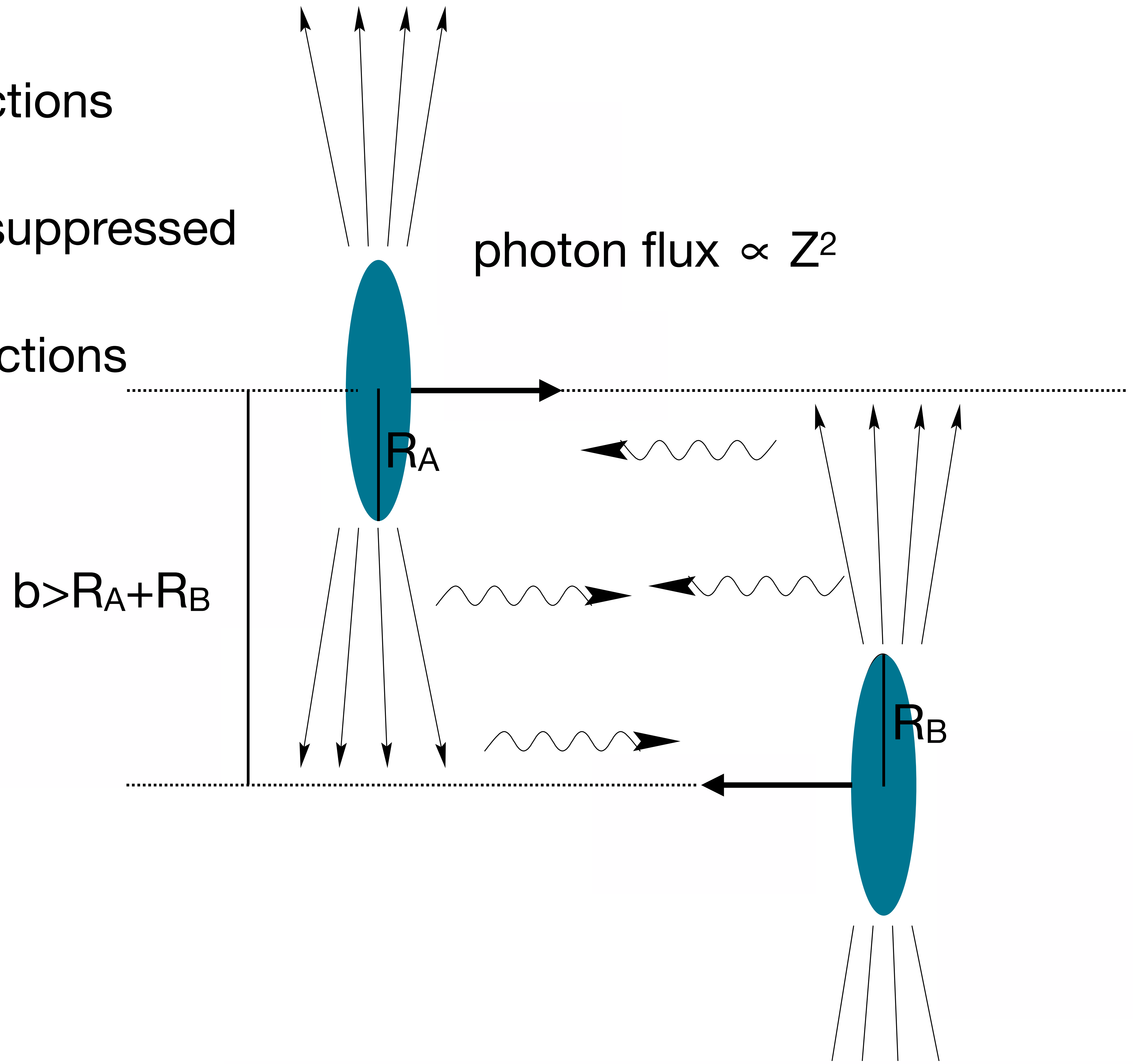

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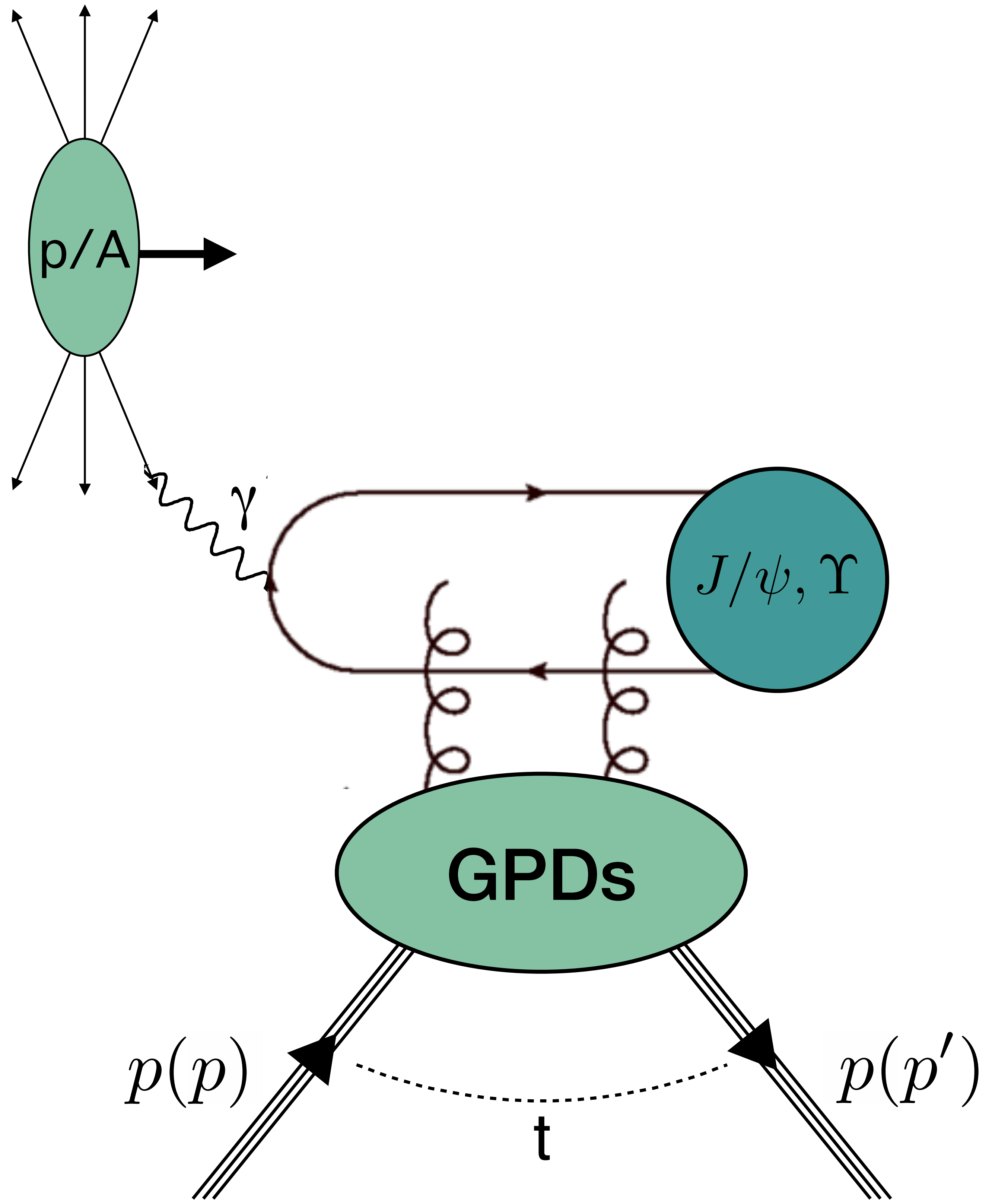
System	$\sqrt{s_{AB}}$	E_A	E_B	(a) $\gamma_{A\leftrightarrow B}$	(b) $E_{\gamma Max}$	(c) $E^{rest}_{\gamma Max}$	(d) $W^{max}_{\gamma p}$
pPb	5.02 TeV	4 TeV	1.567 TeV	1.43×10^7	28 MeV	0.4 PeV	0.86 TeV
pPb	8.16 TeV	6.5 TeV	2.56 TeV	3.78×10^7	28 MeV	1 PeV	1.4 TeV
pp	13 TeV	6.5 TeV	6.5 TeV	9.6×10^7	116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

table: K. Lynch

Exclusive quarkonium photoproduction: kinematics



Kinematic variables

- hardness scale of the interaction:

$$\bar{Q}^2 = \frac{Q^2 + M_V^2}{4} = \frac{M_V^2}{4}$$

photoproduction

- Bjorken-x variable:

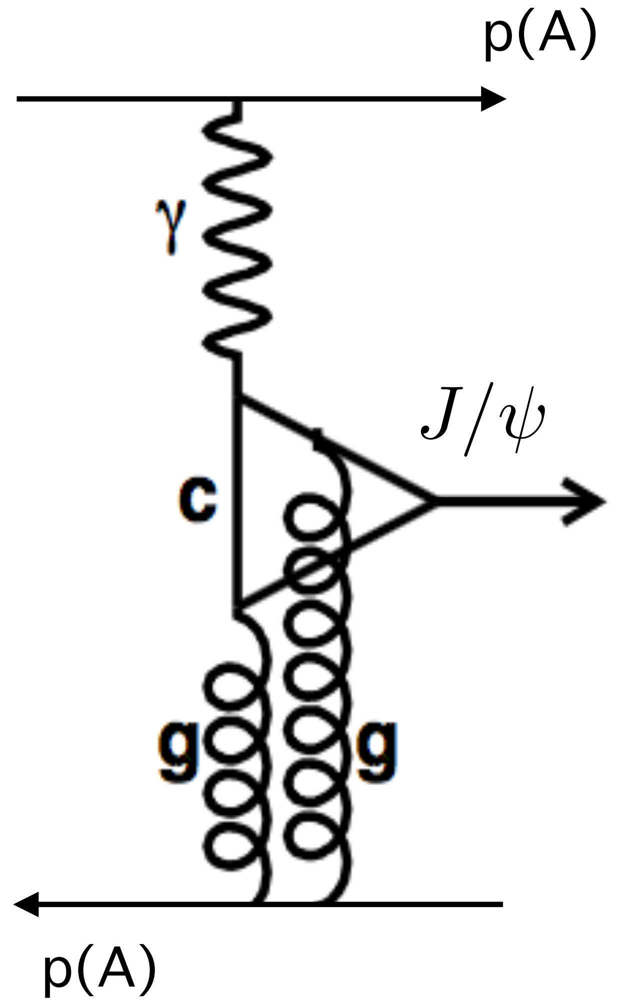
$$x_B = \frac{Q^2 + M_V^2}{W_{\gamma p}^2 + Q^2} = \frac{M_V^2}{W_{\gamma p}^2}$$

$$= \frac{M_V}{\sqrt{s_{NN}}} e^{\pm y} \approx \frac{2\xi}{1-\xi}$$

- Mandelstam variable:

$$t = (p - p')^2 \approx -p_{T,J/\psi}^2$$

Exclusive quarkonium production and its backgrounds



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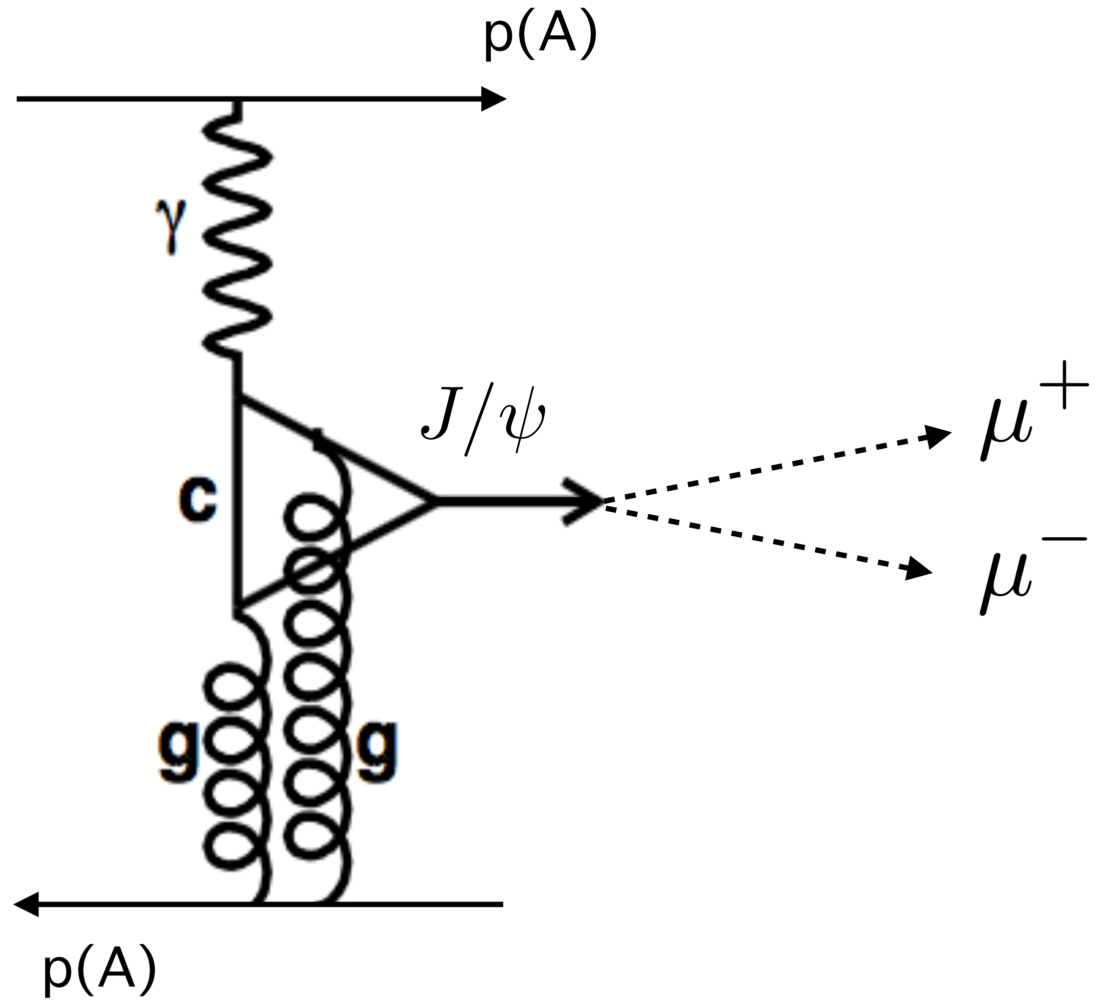

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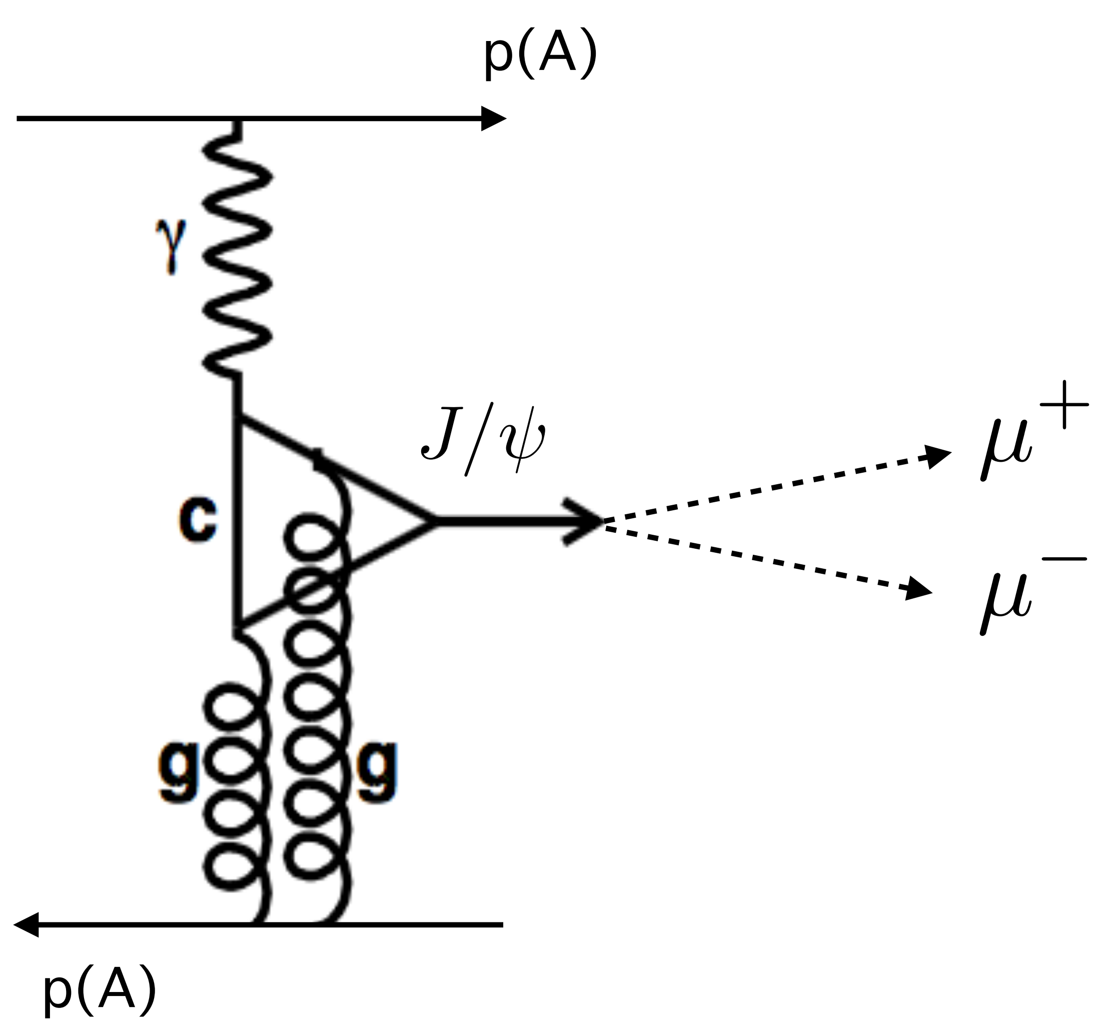

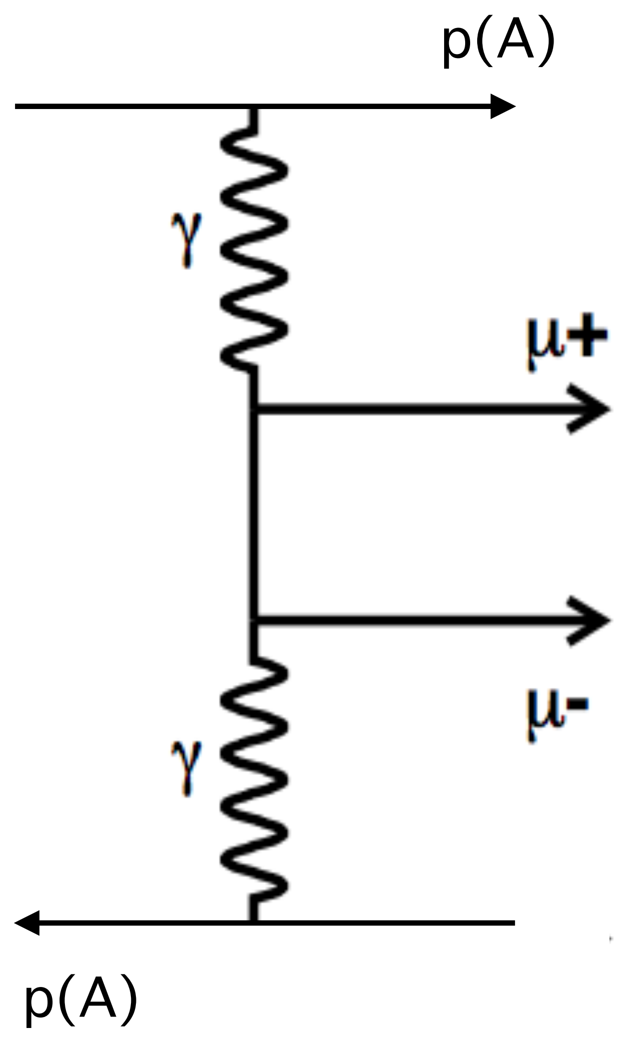

Bethe-Heitler process

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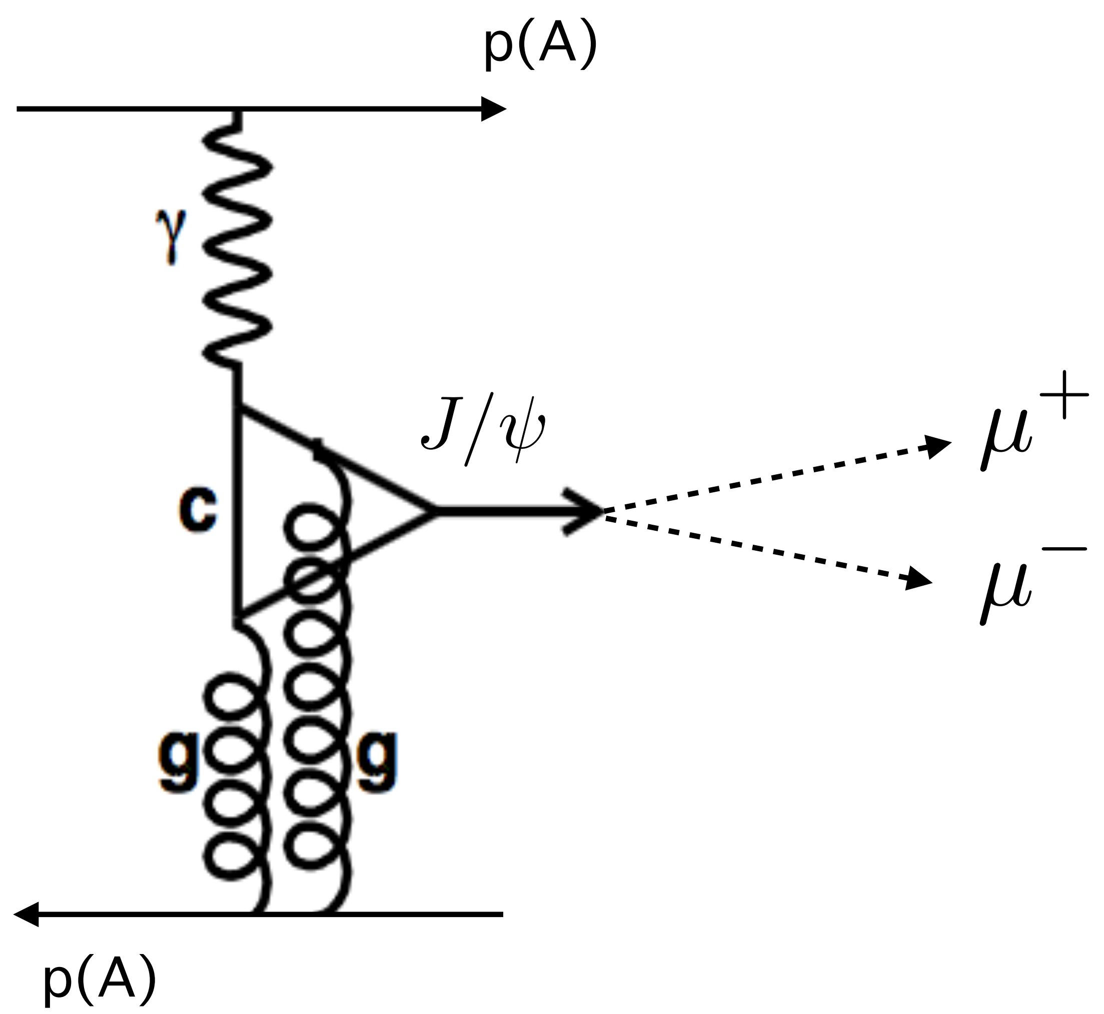

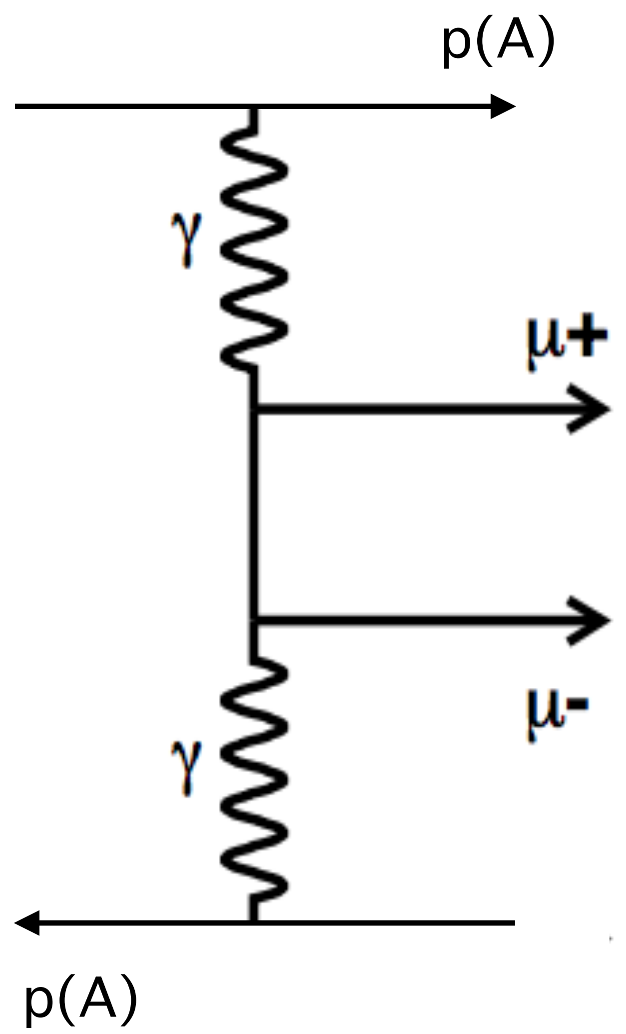

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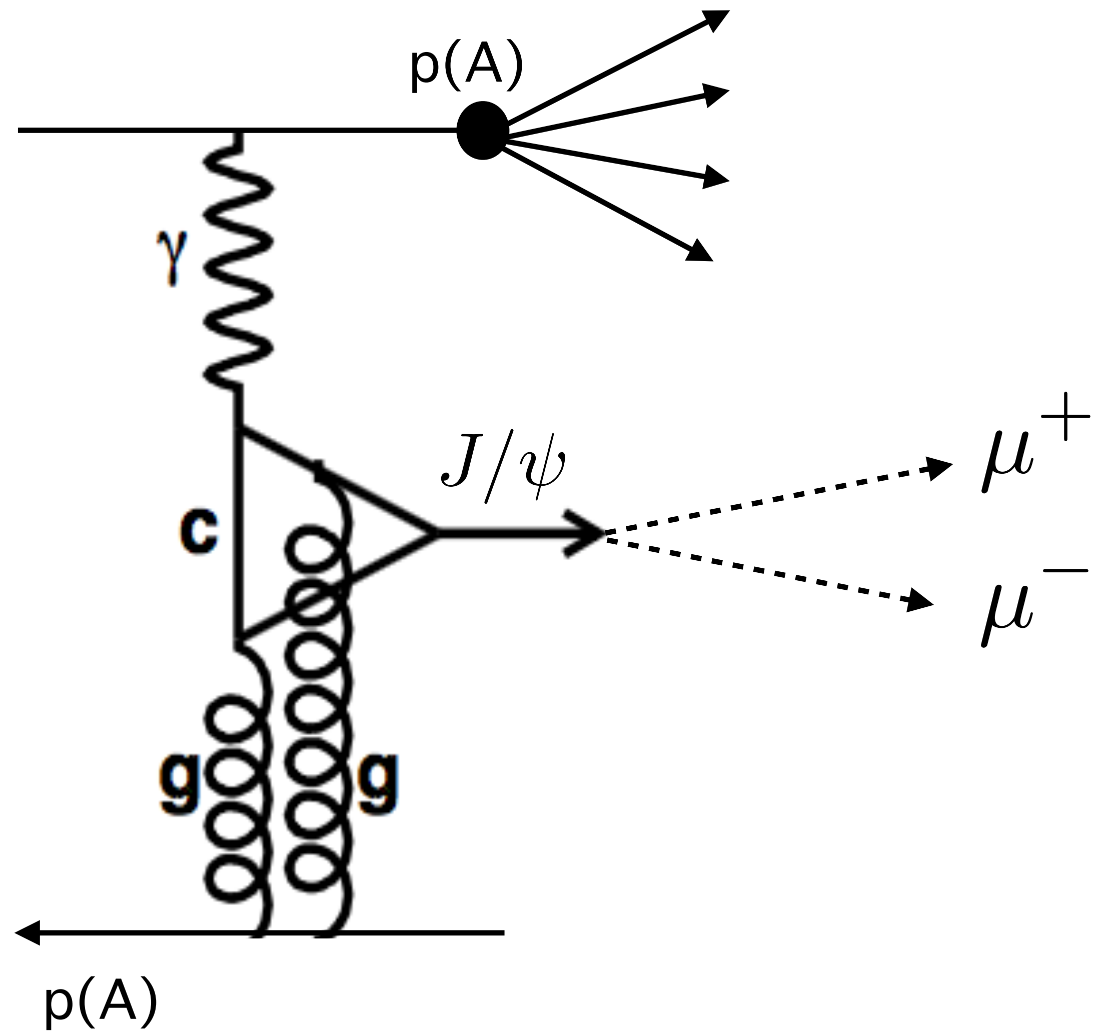

proton/ion dissociation

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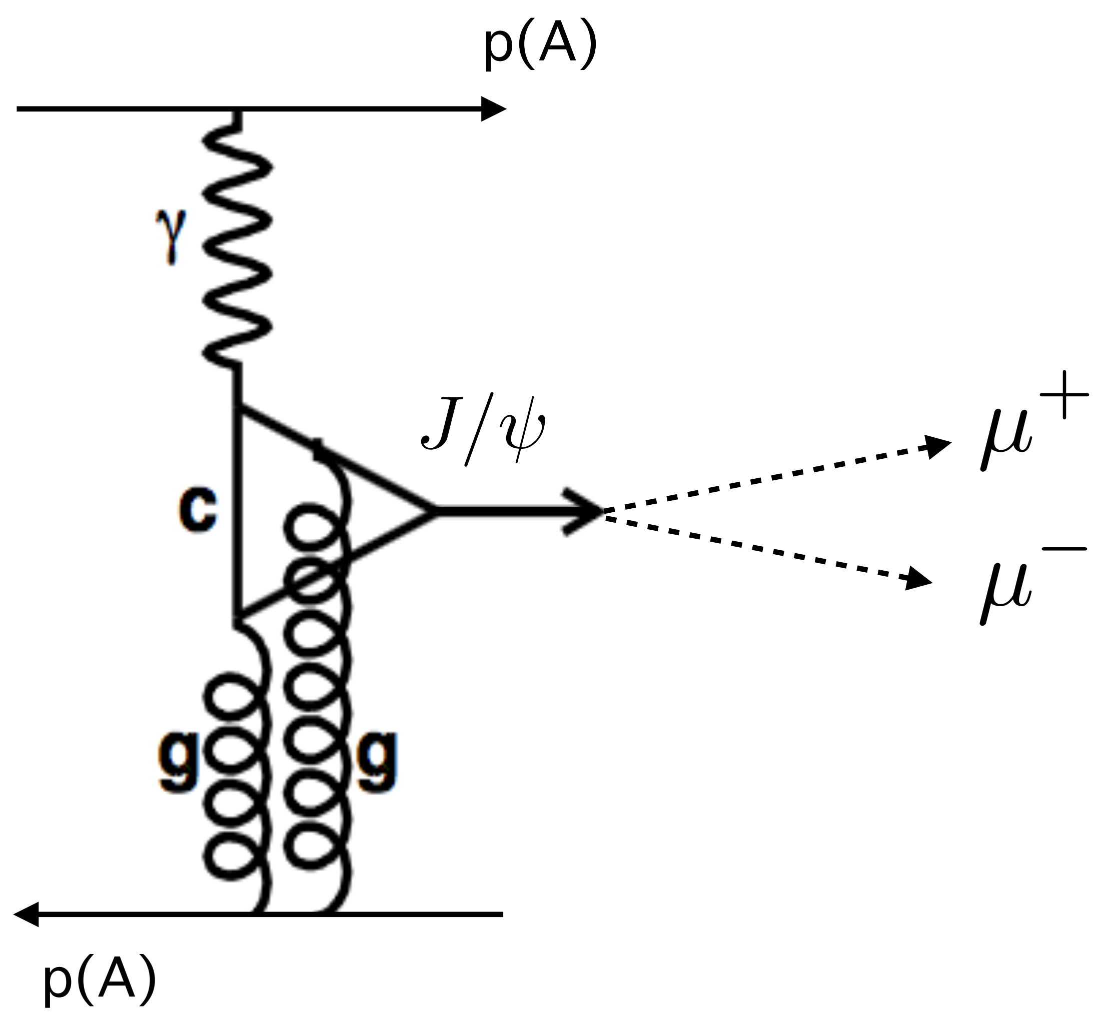

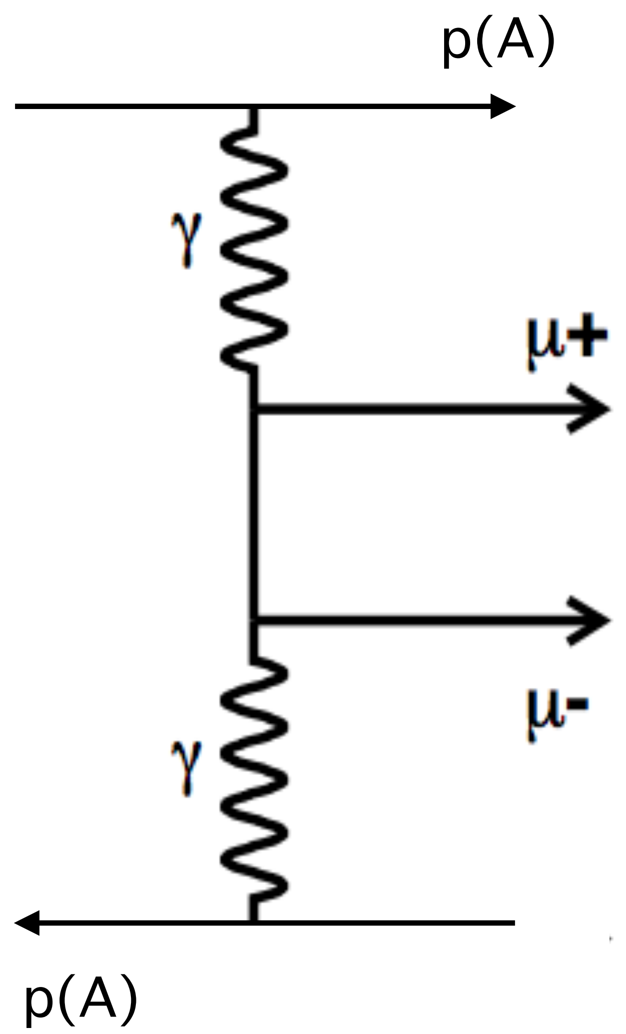

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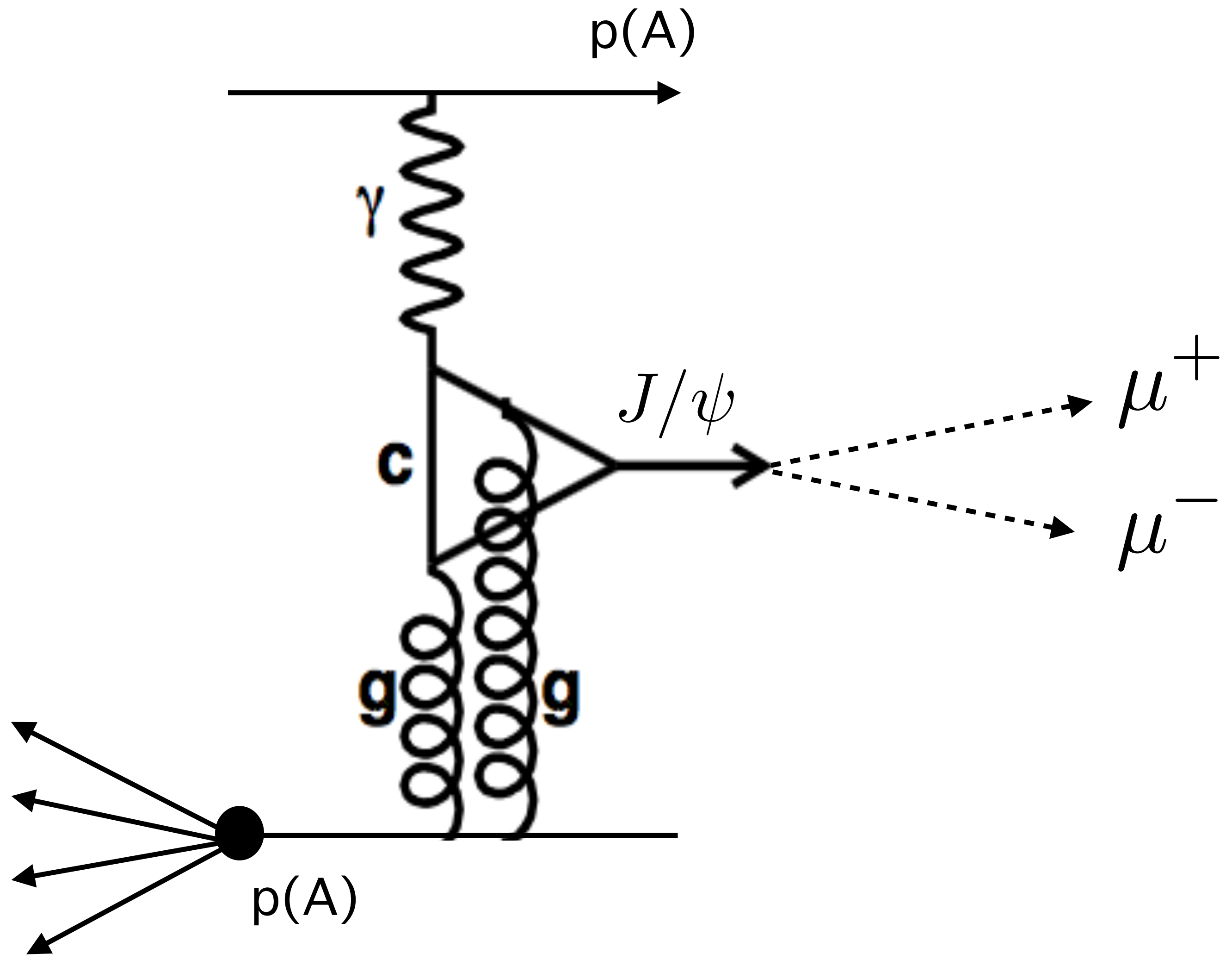

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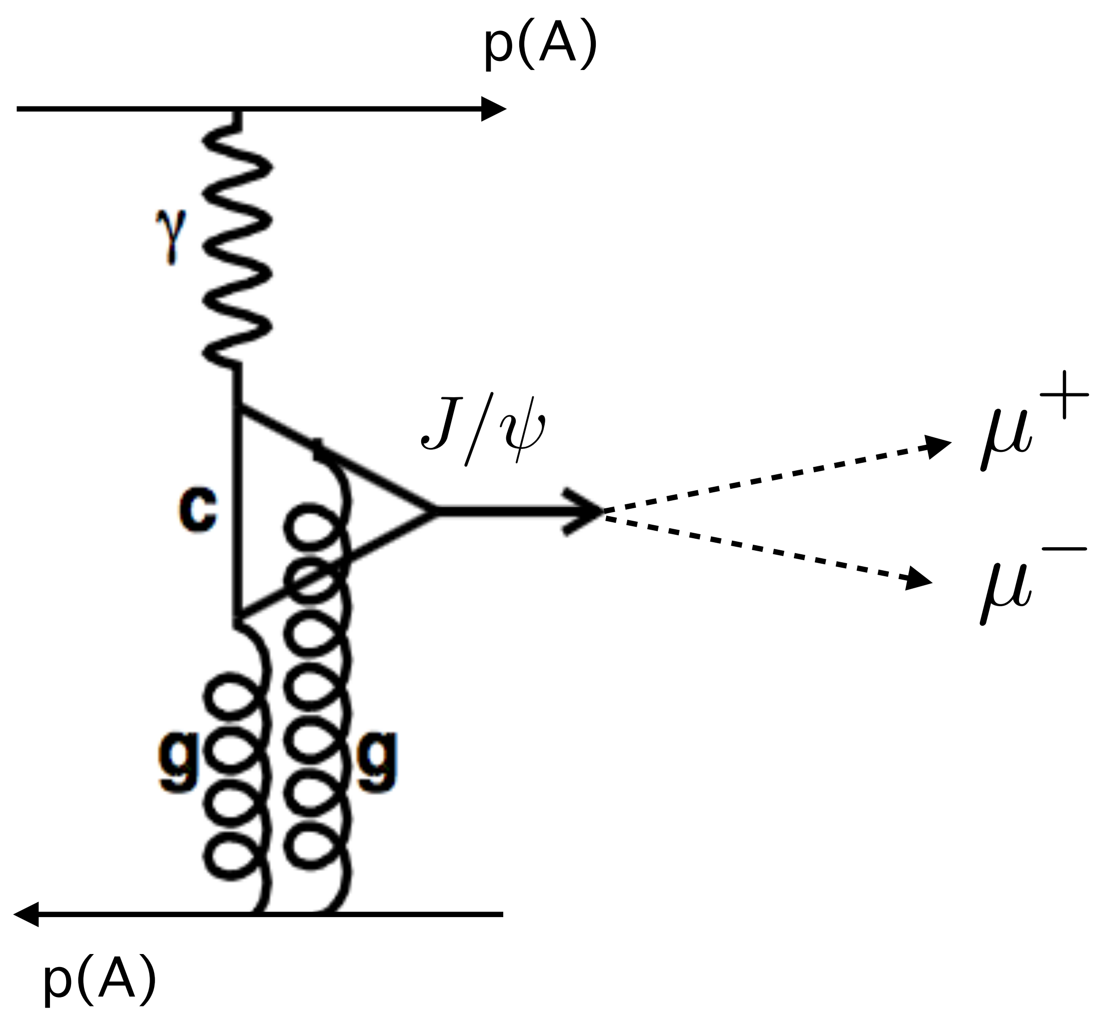

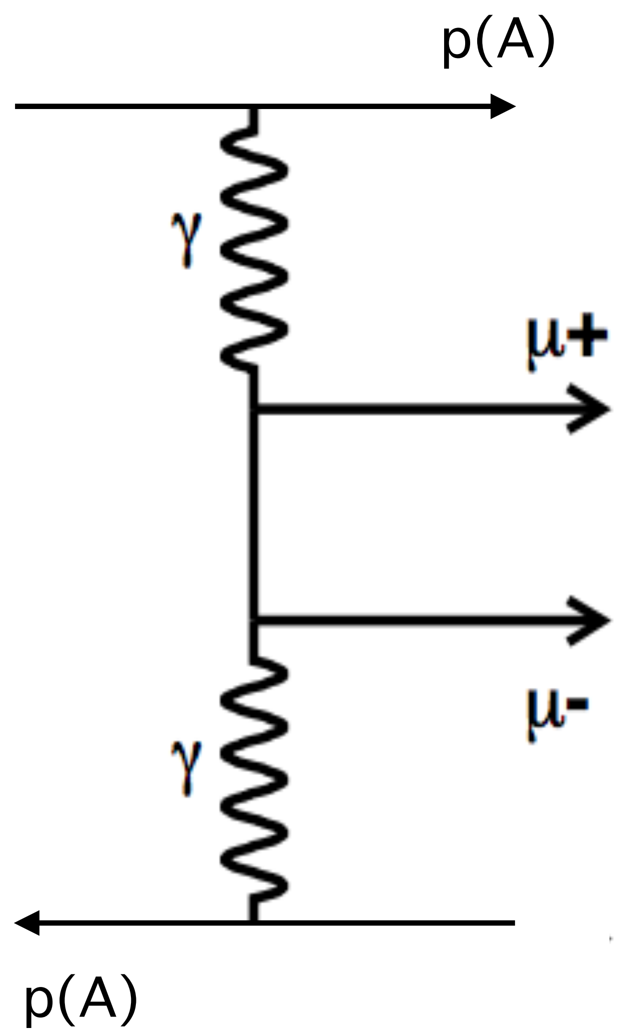

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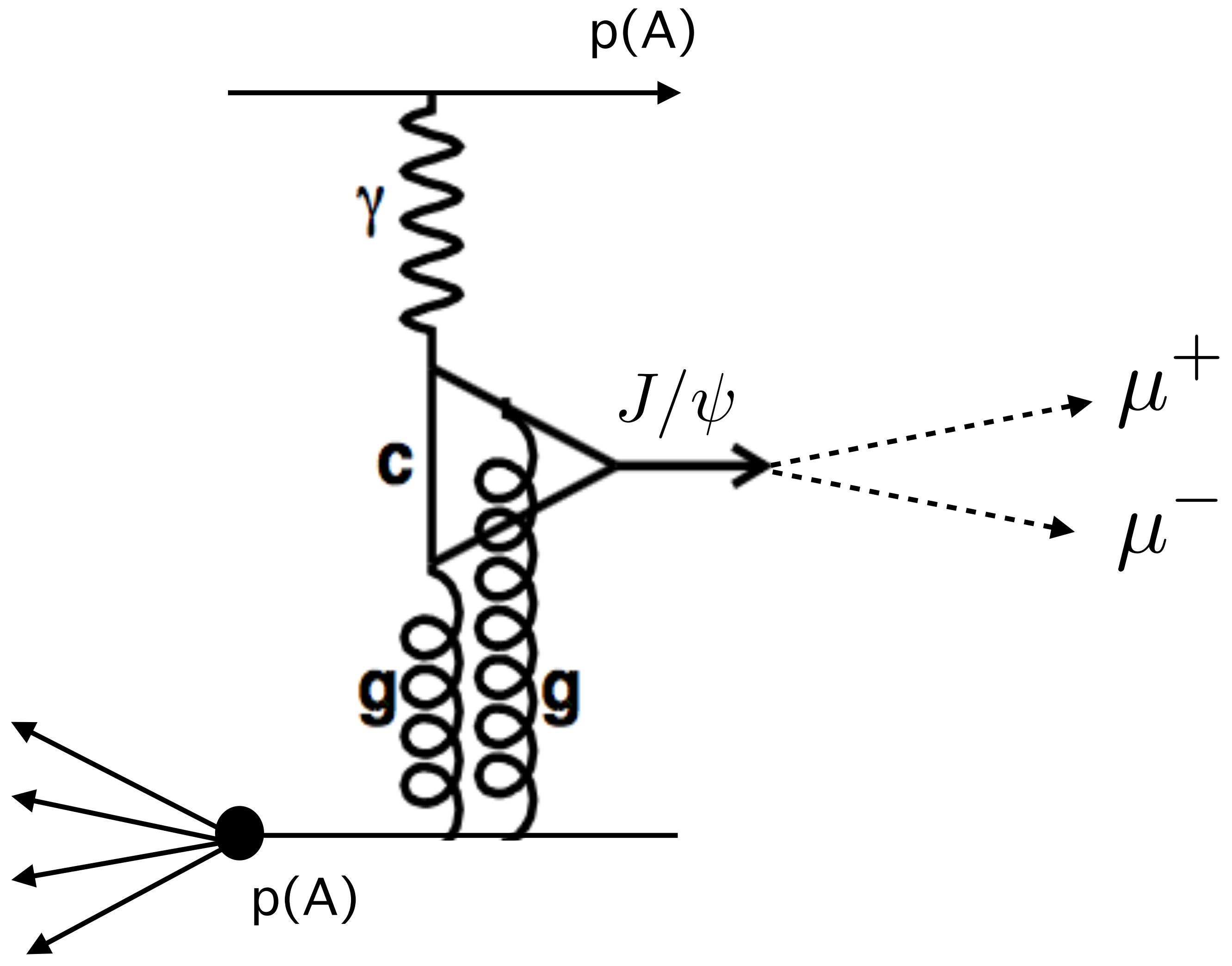

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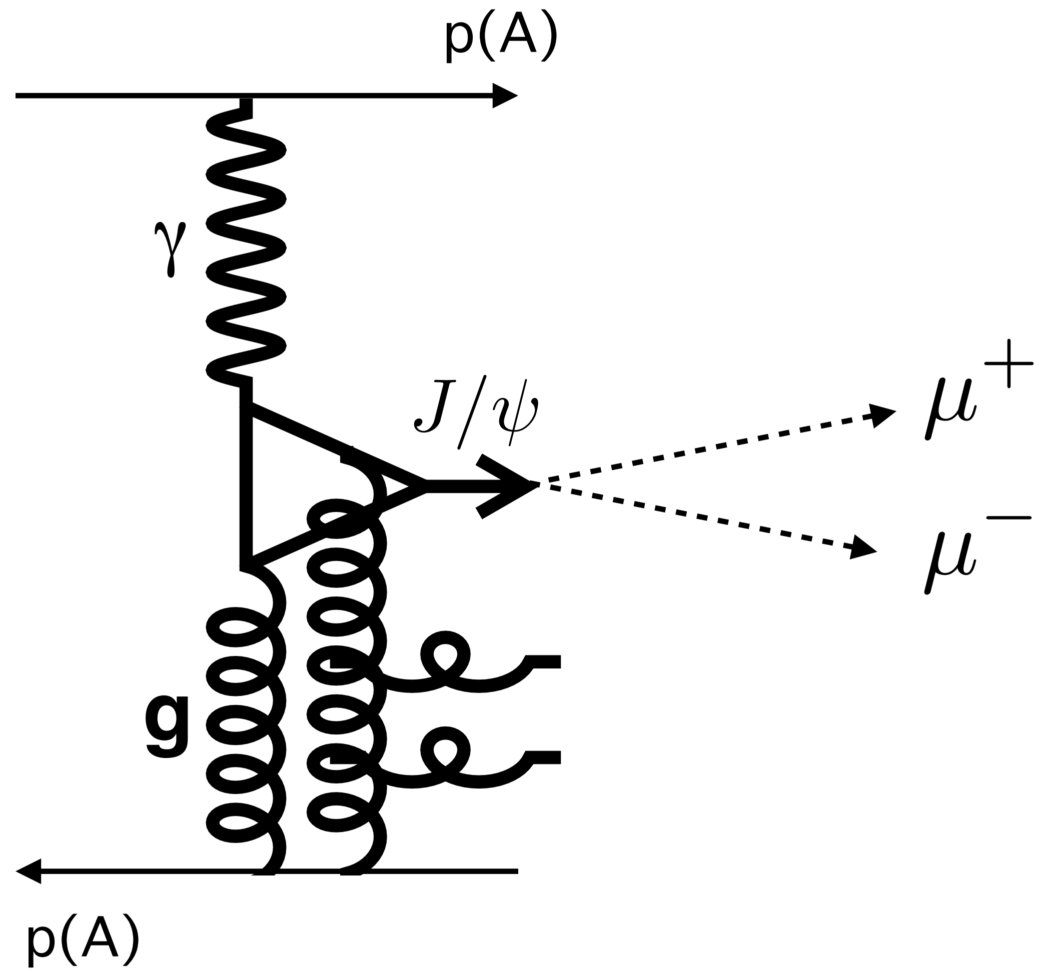

inelastic production

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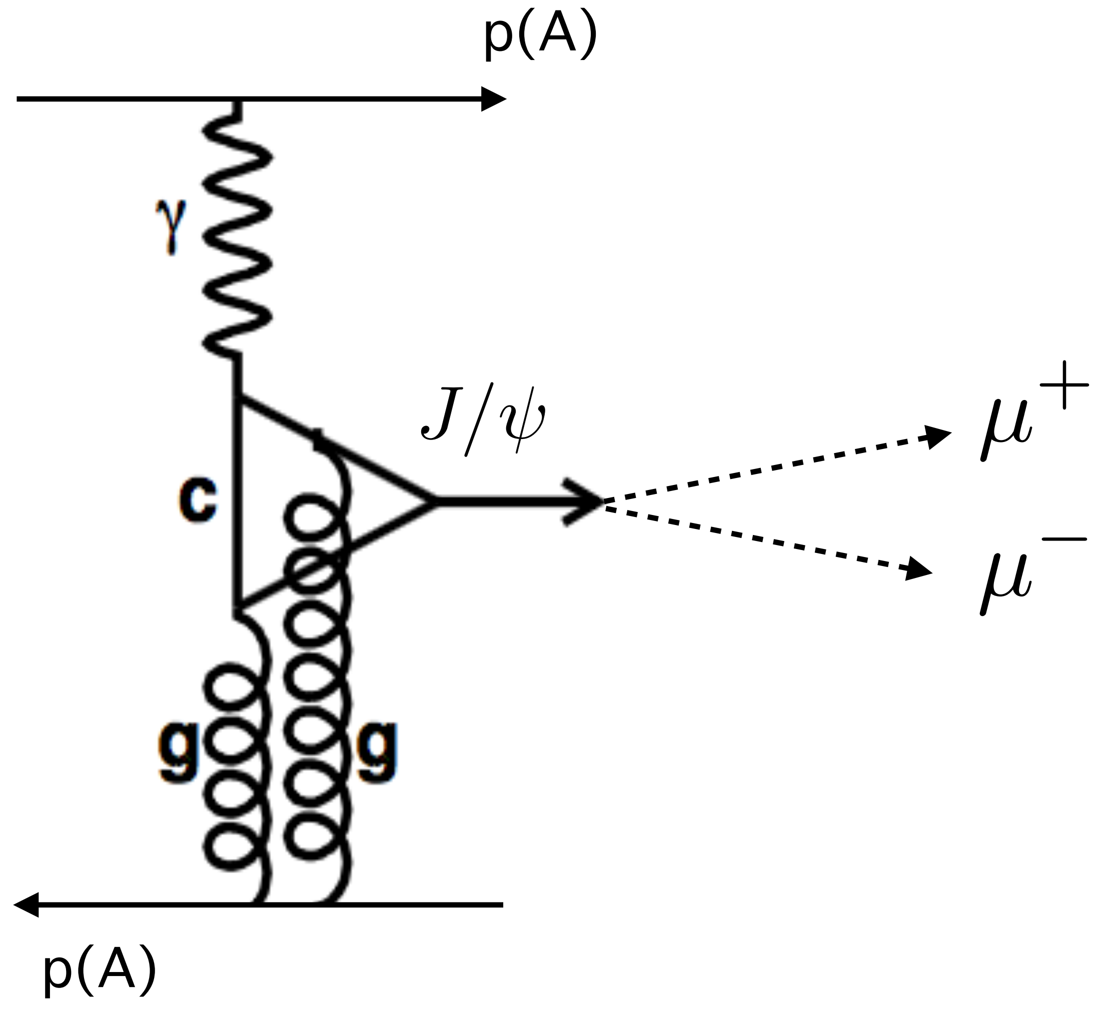

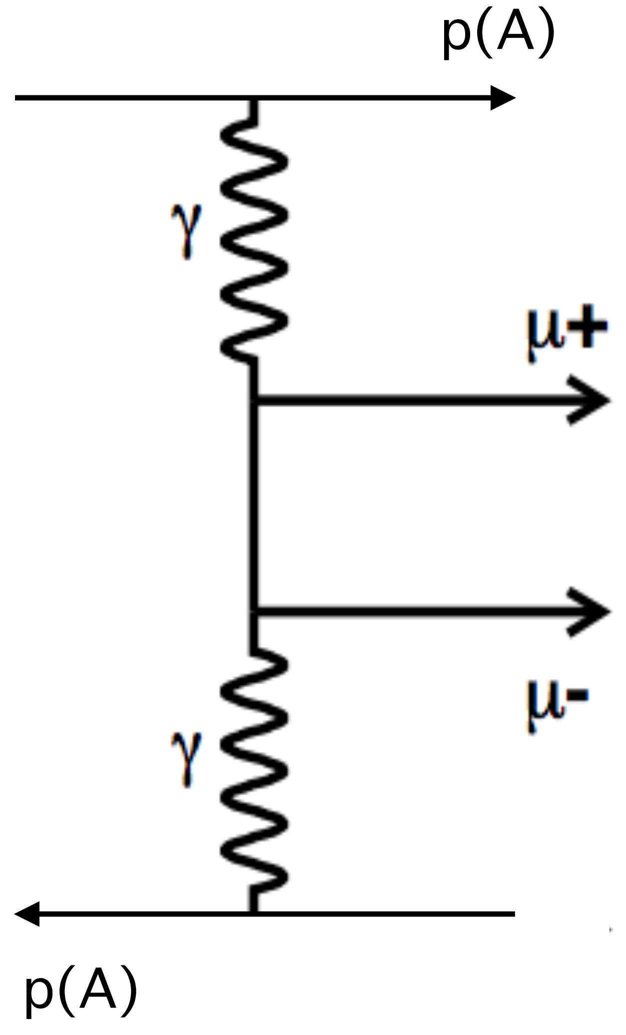

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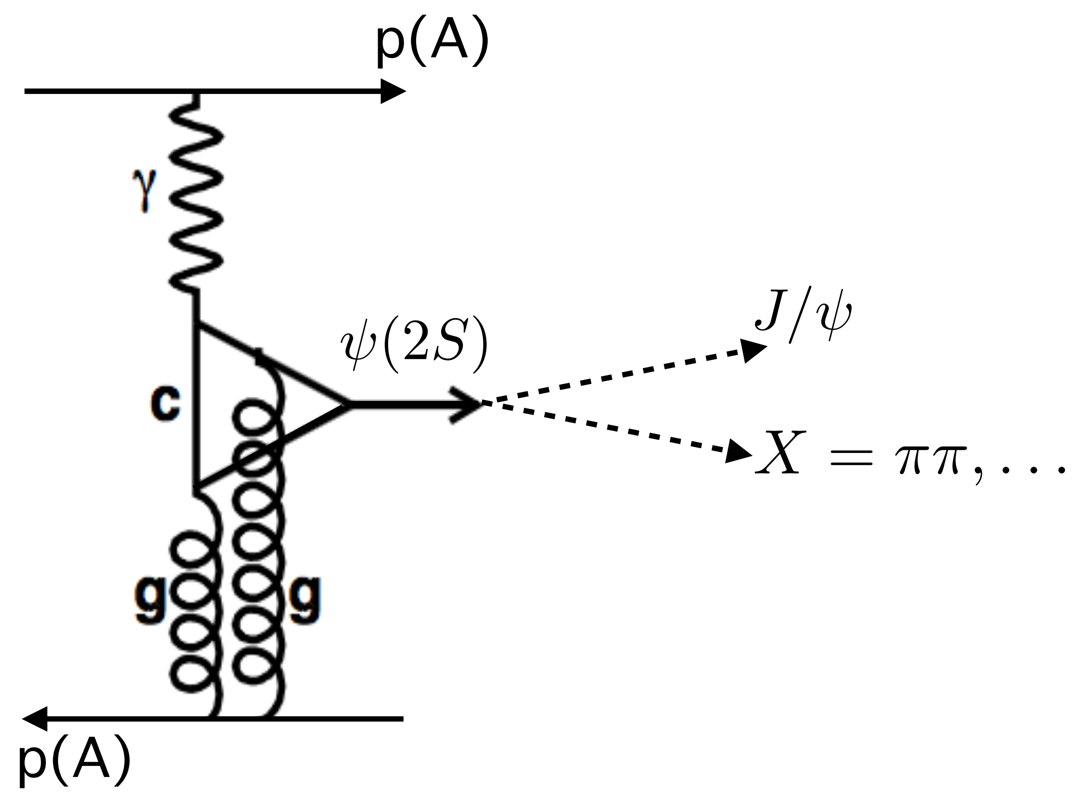
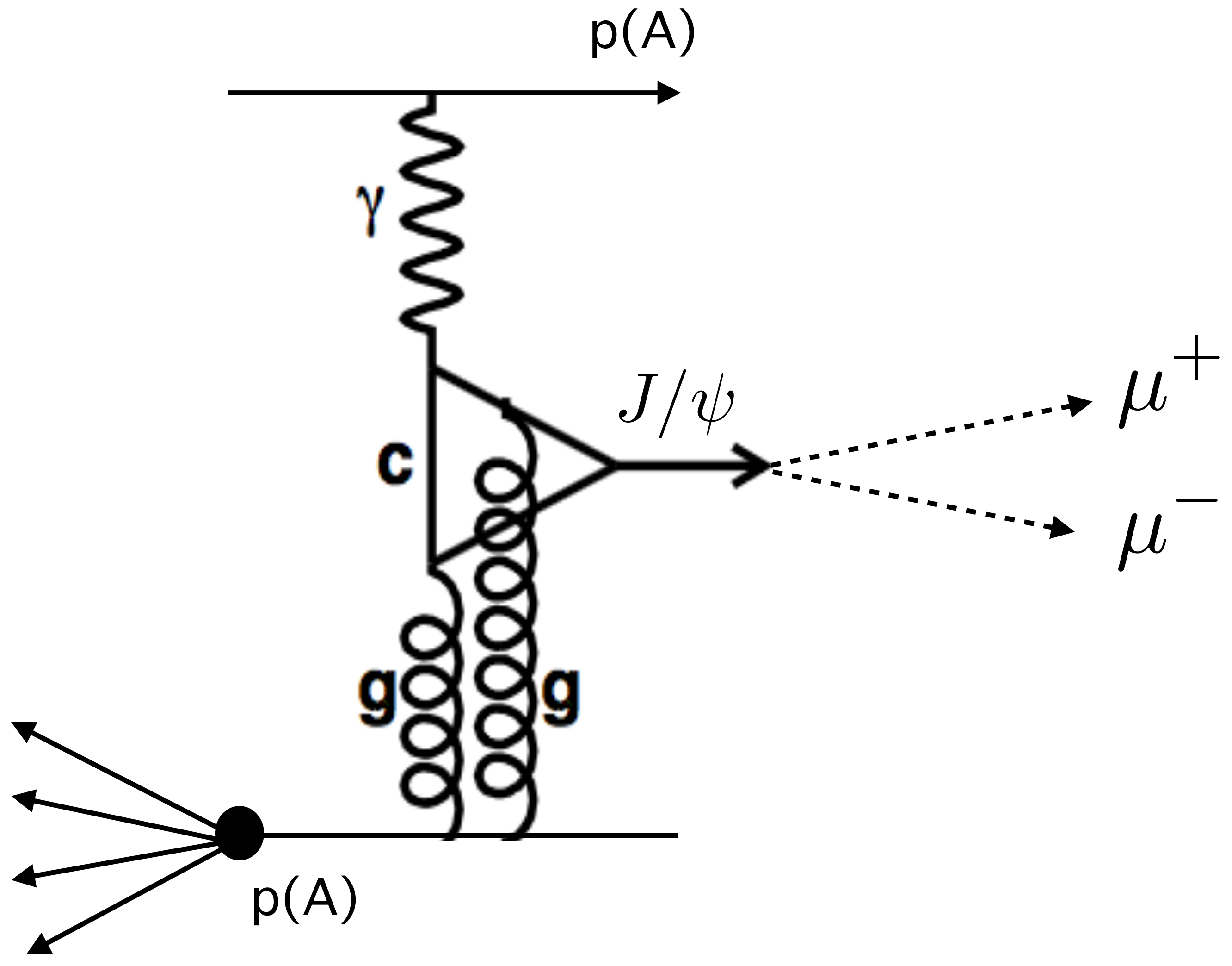


feed down



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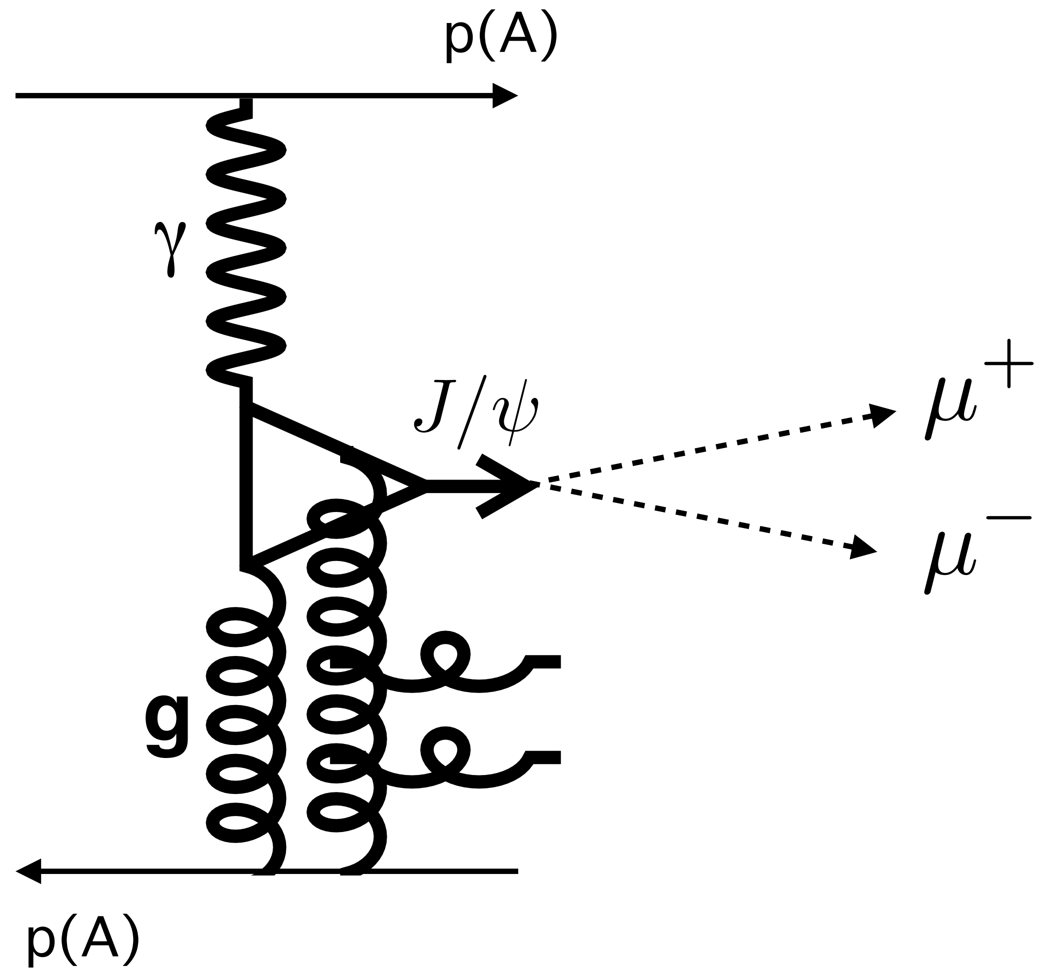

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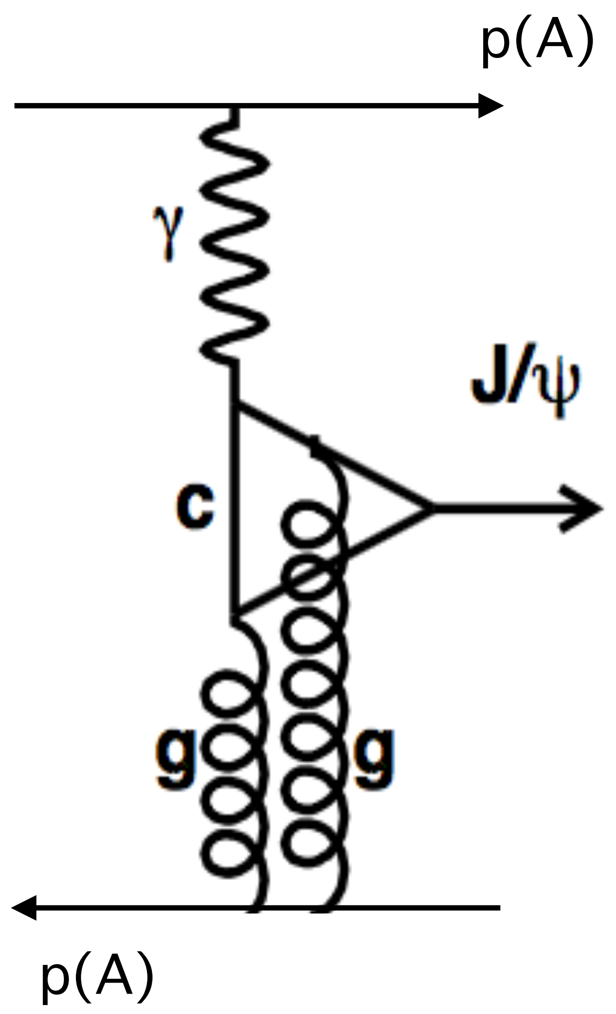
Measurement of exclusive production at LHCb



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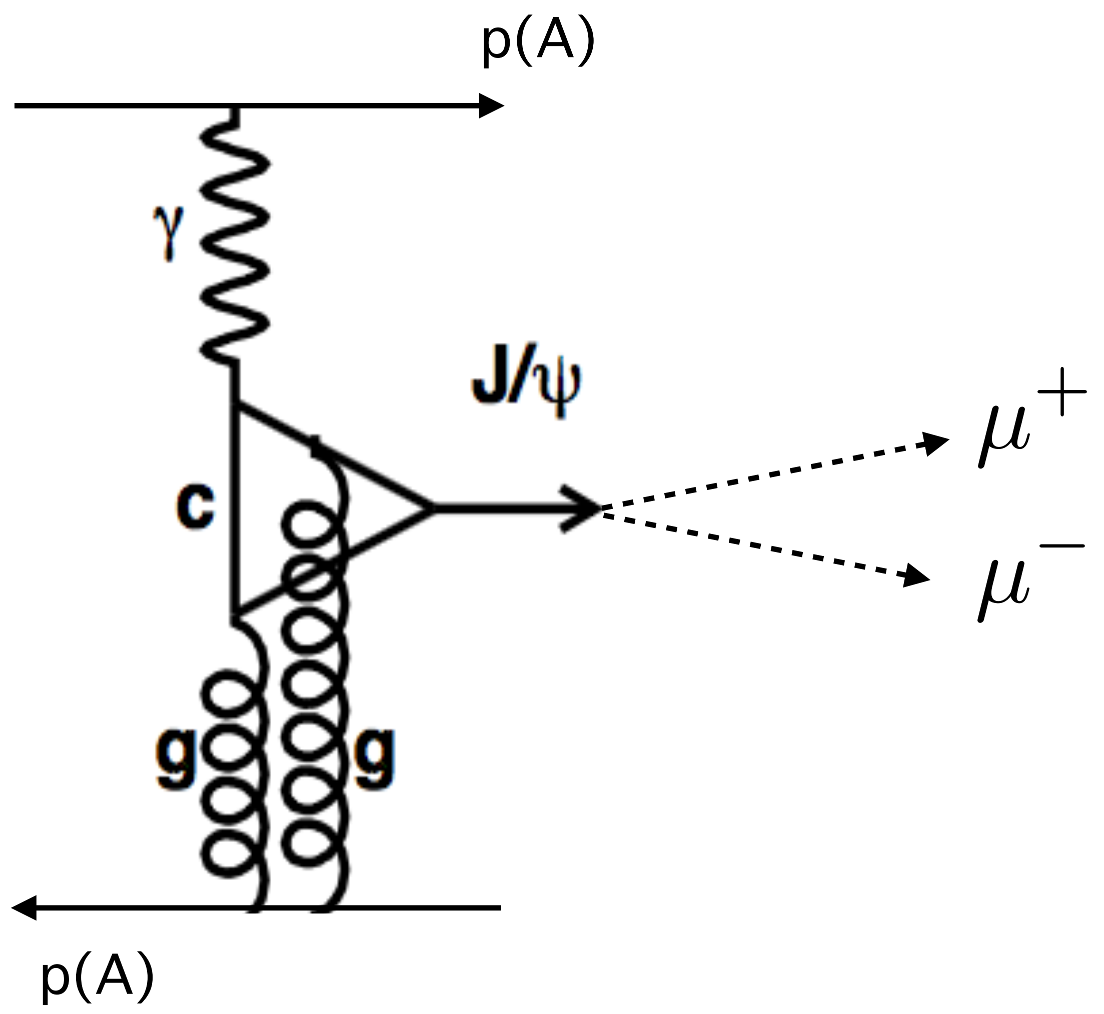

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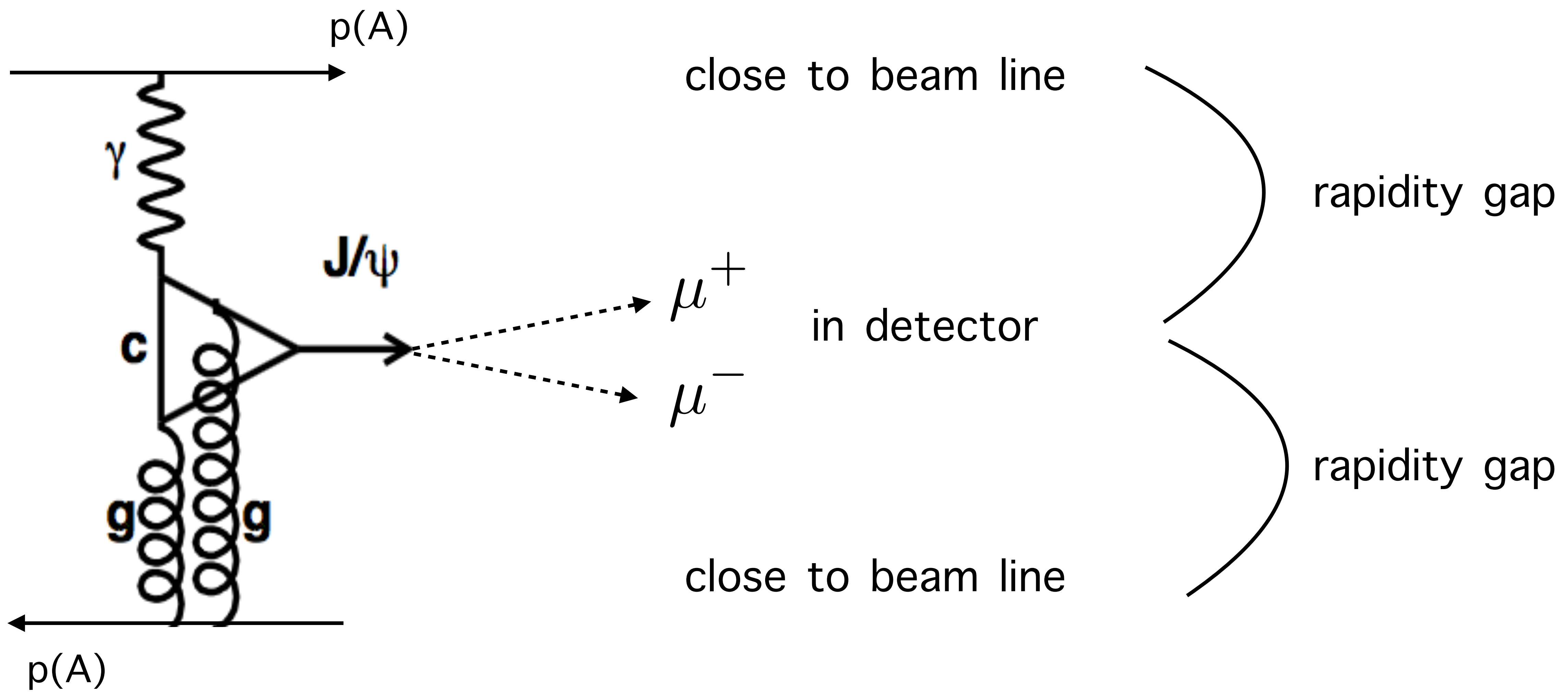

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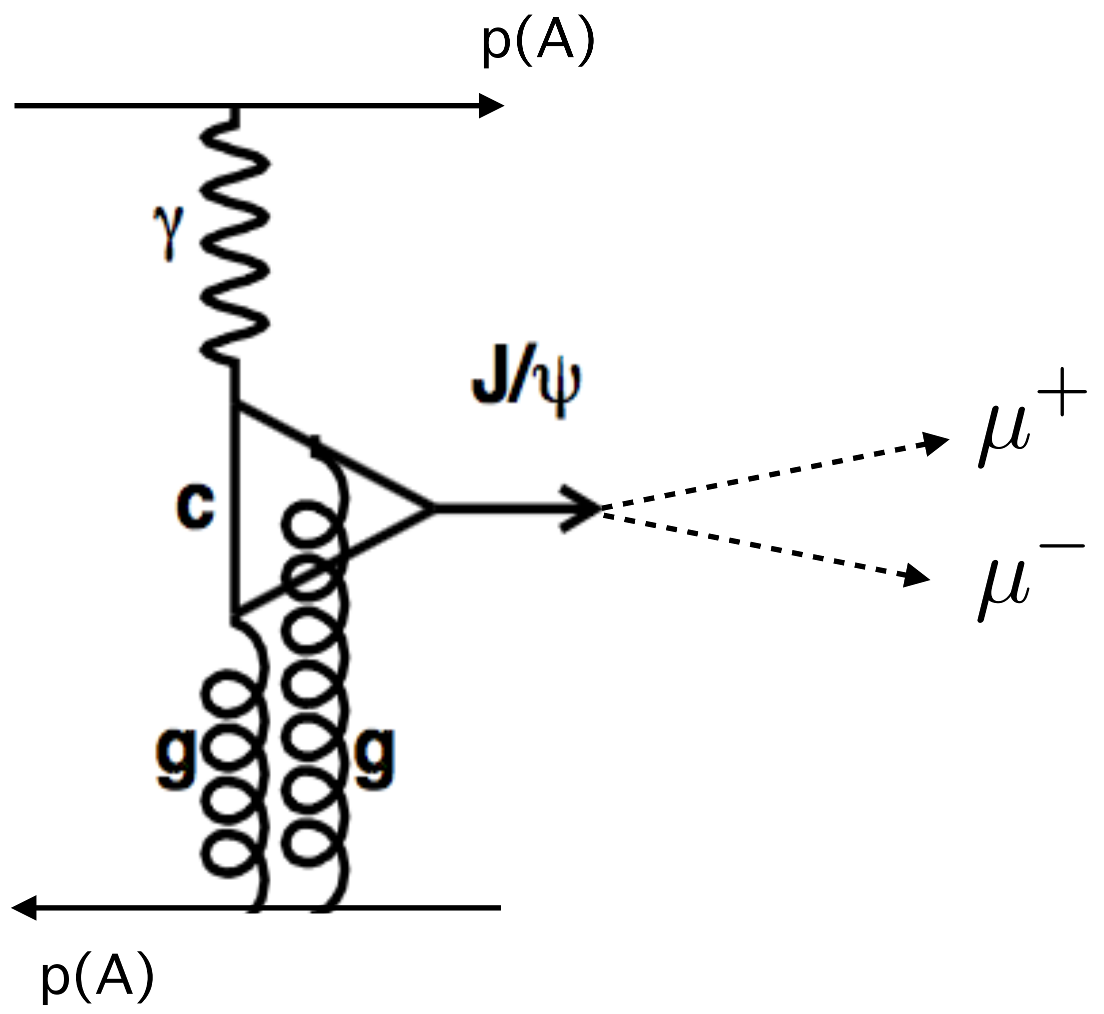

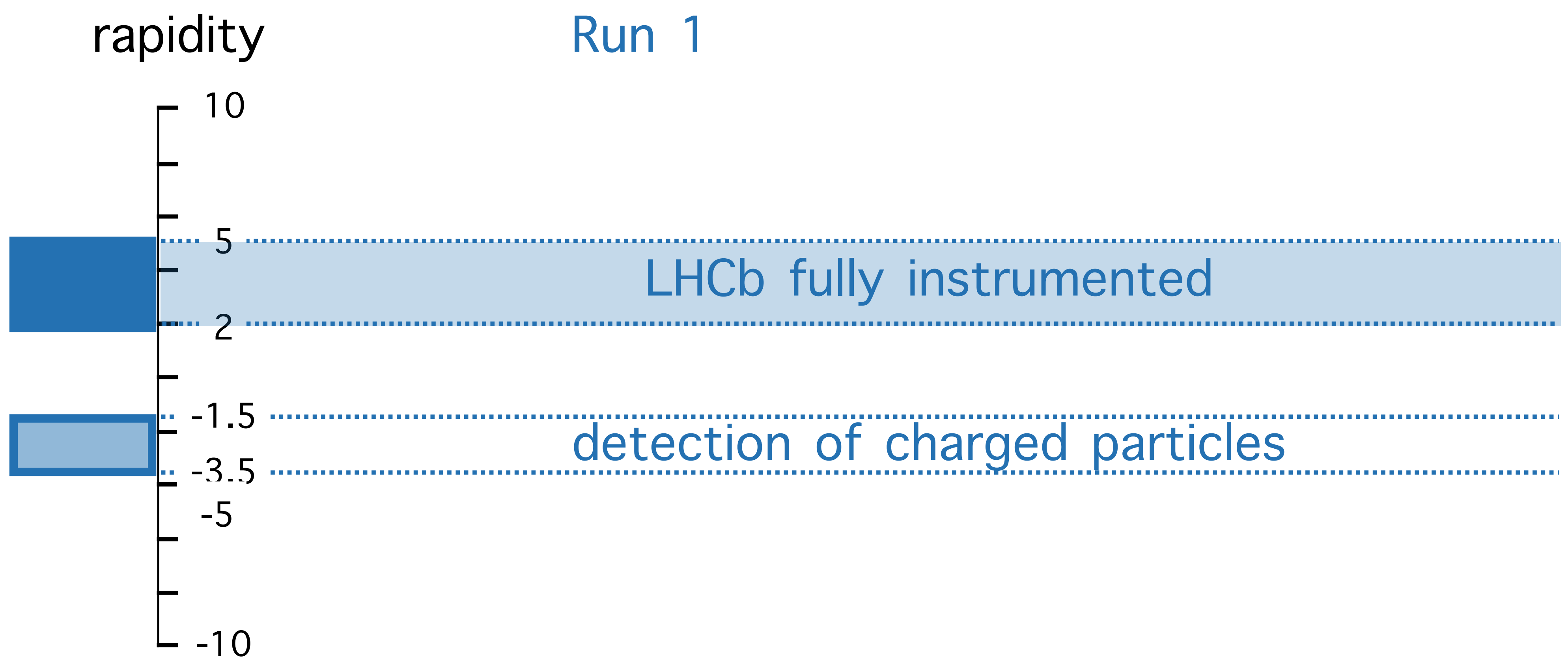

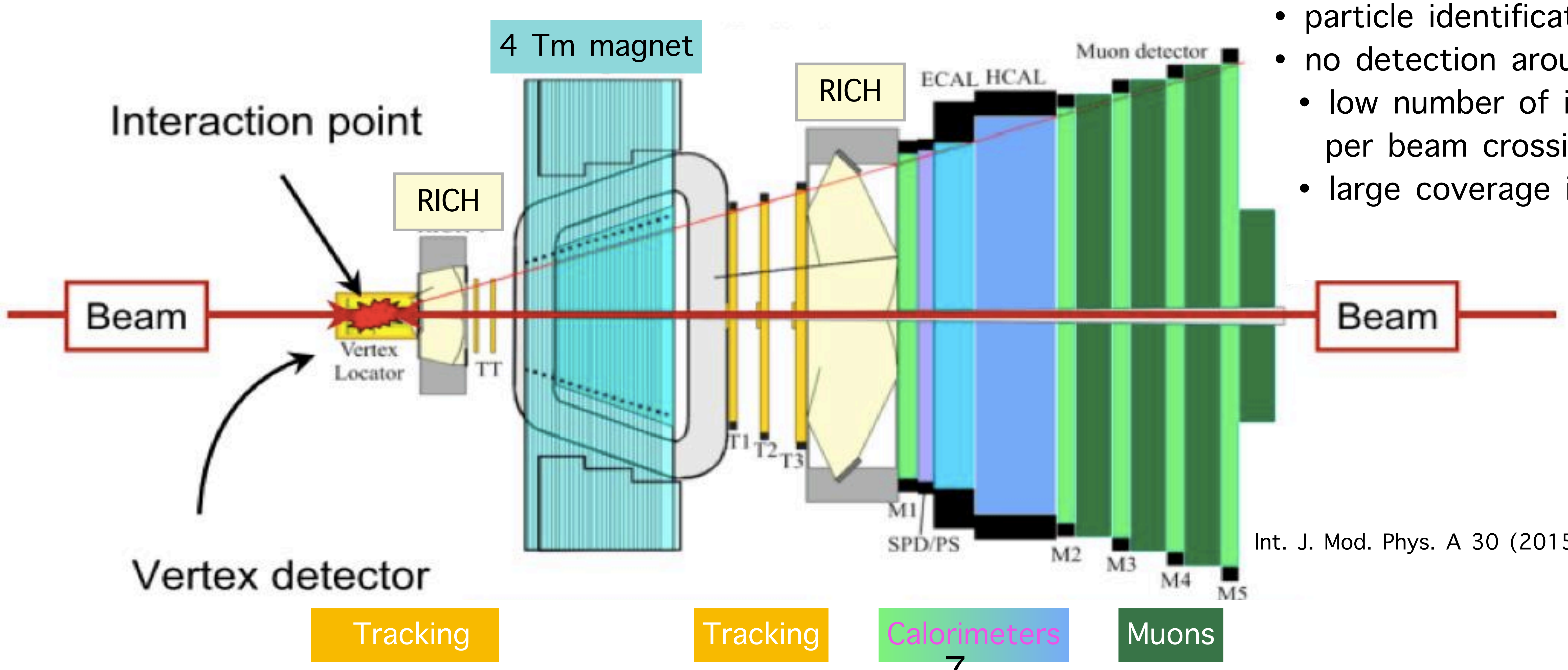

- low p_T threshold: p_T>400 MeV
- particle identification
- no detection around beam line but
  - low number of interactions per beam crossing: 1.1–1.5
  - large coverage in rapidity

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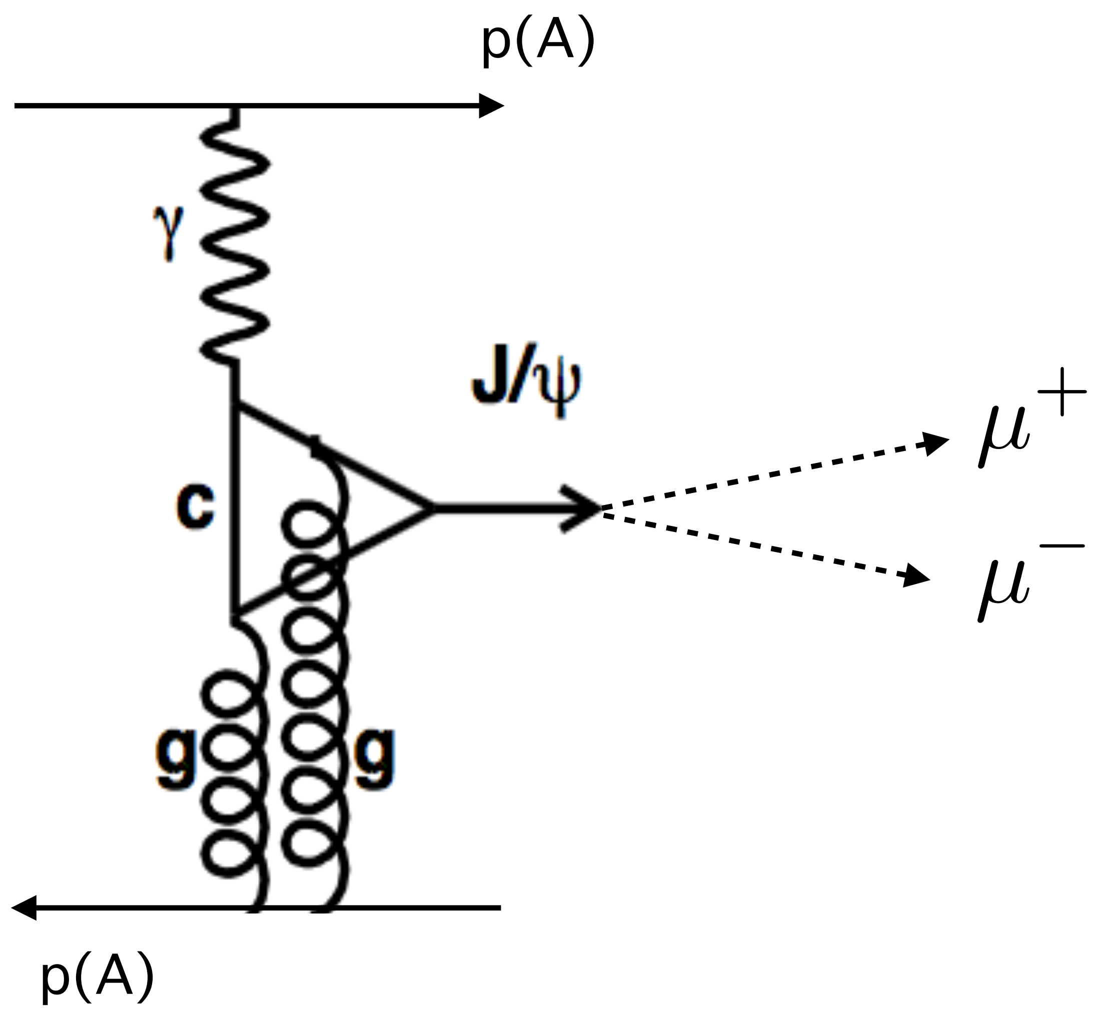

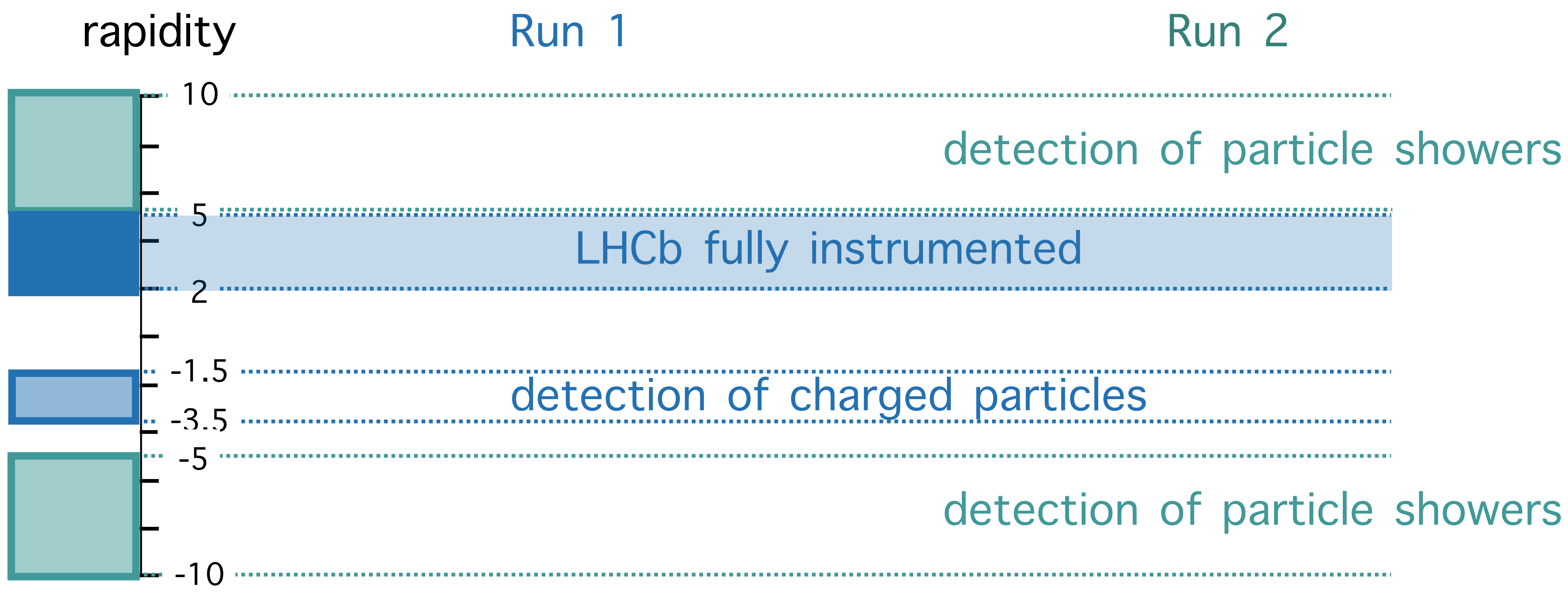

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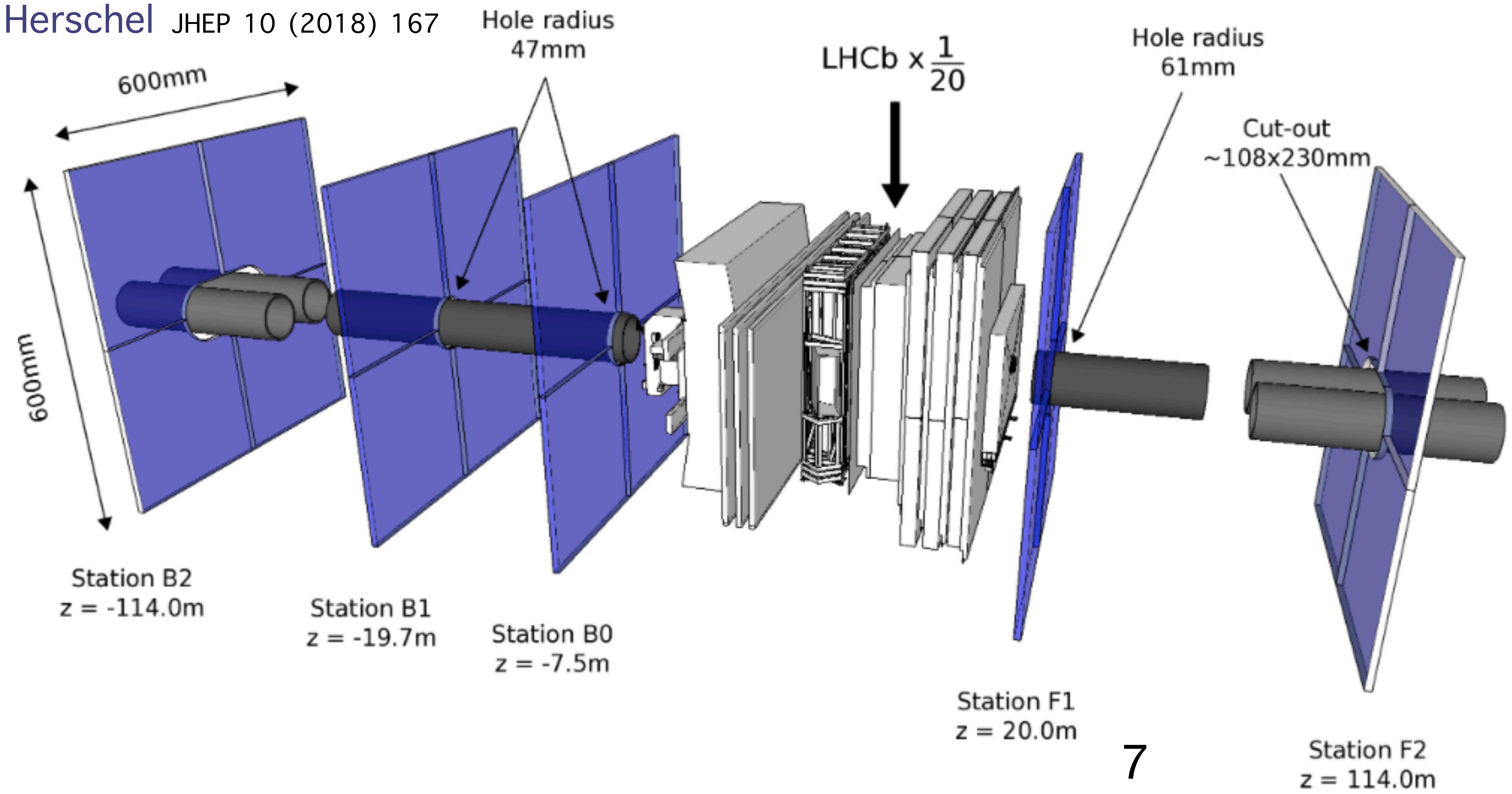
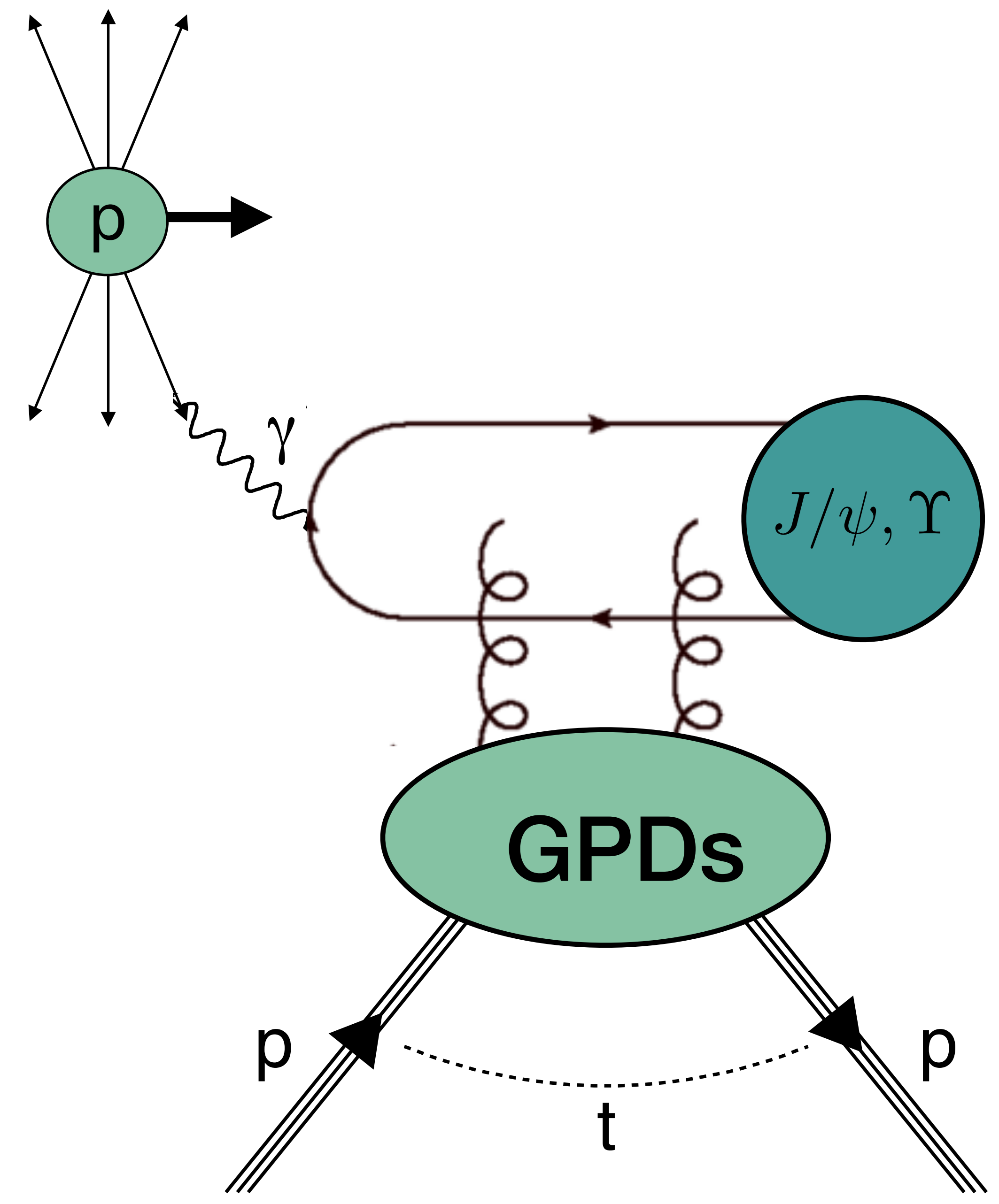


Exclusive single ψ production in pp collisions

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

  → x_B down to $2x10^{-6}$
- 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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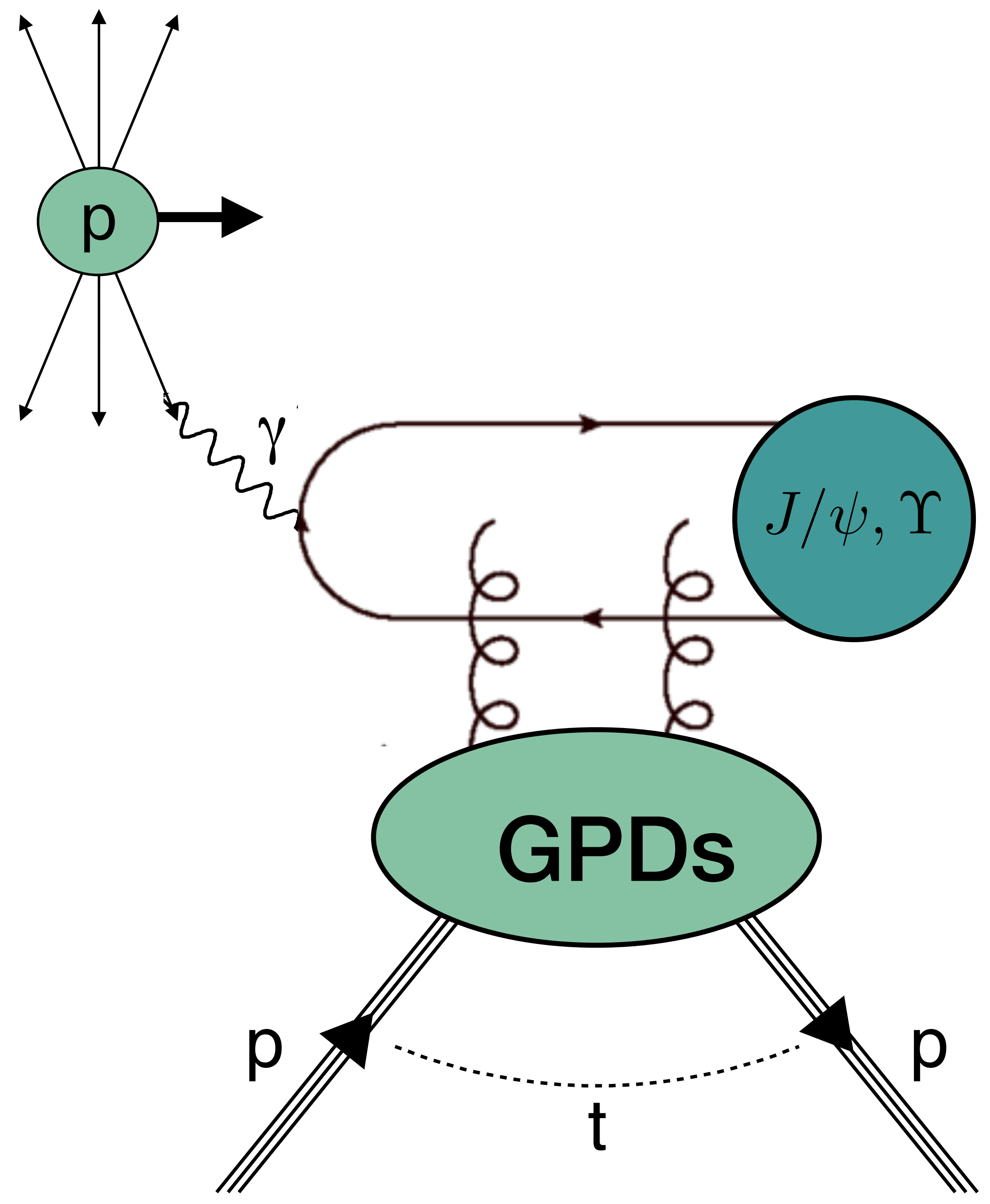

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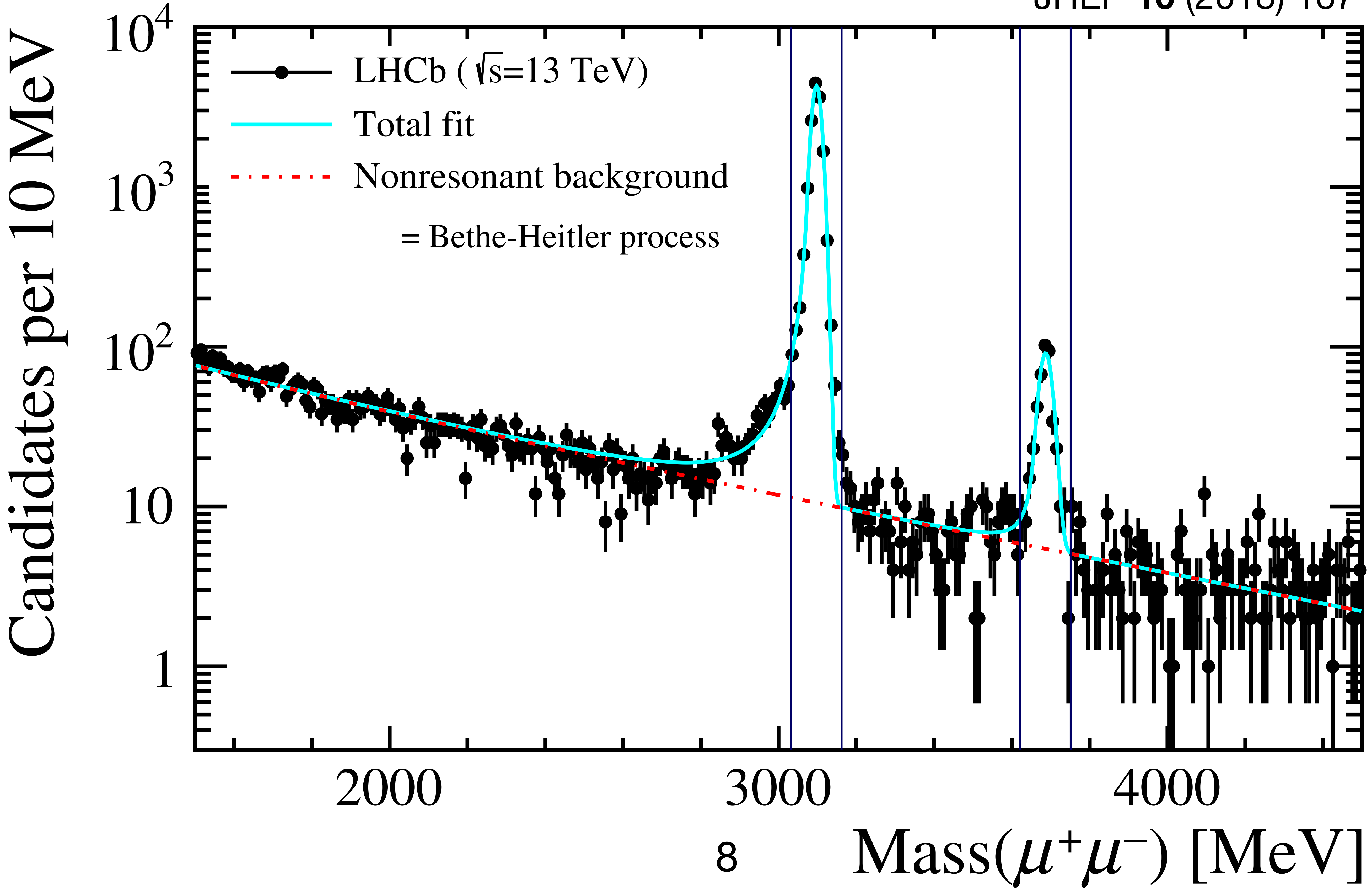

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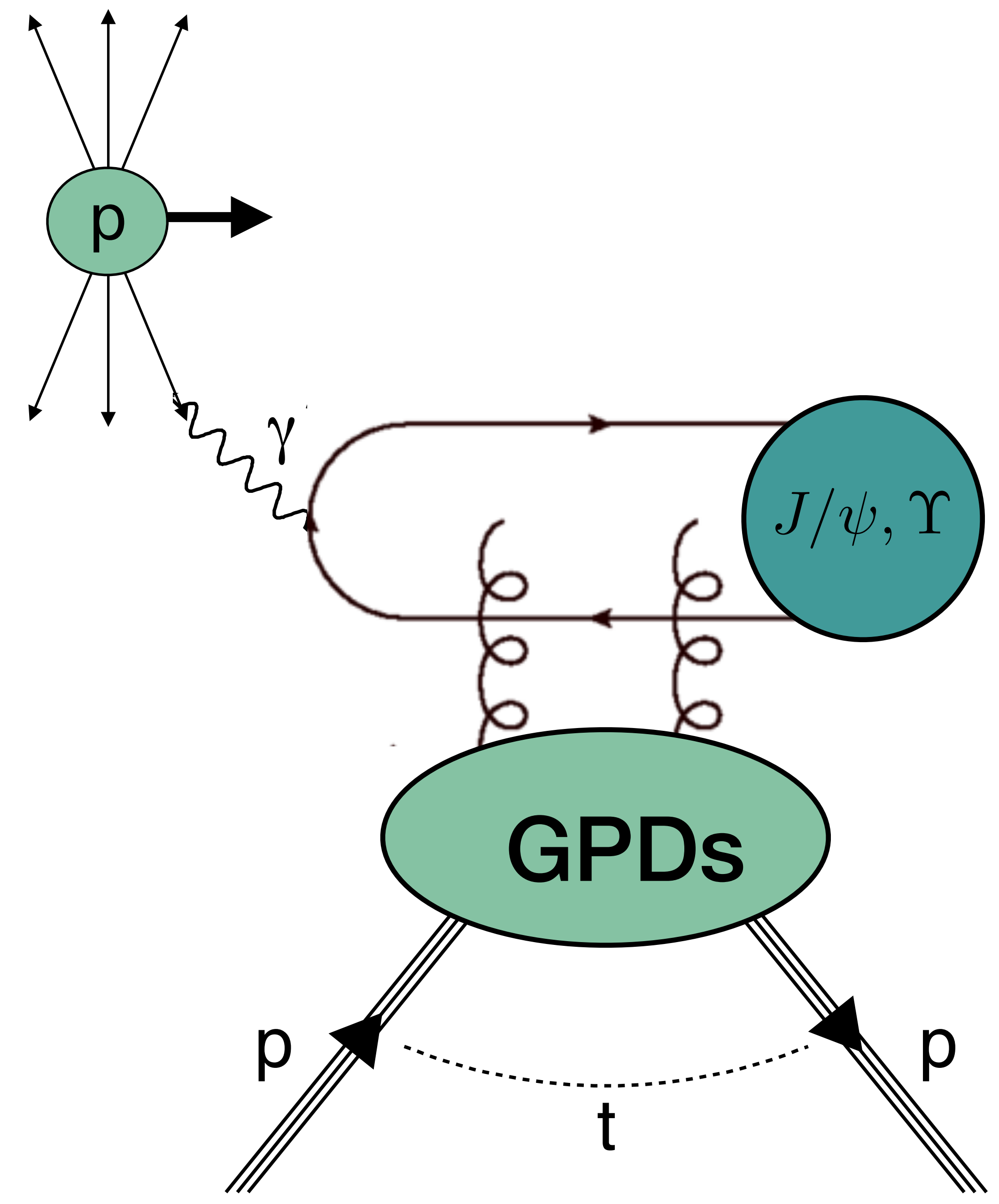

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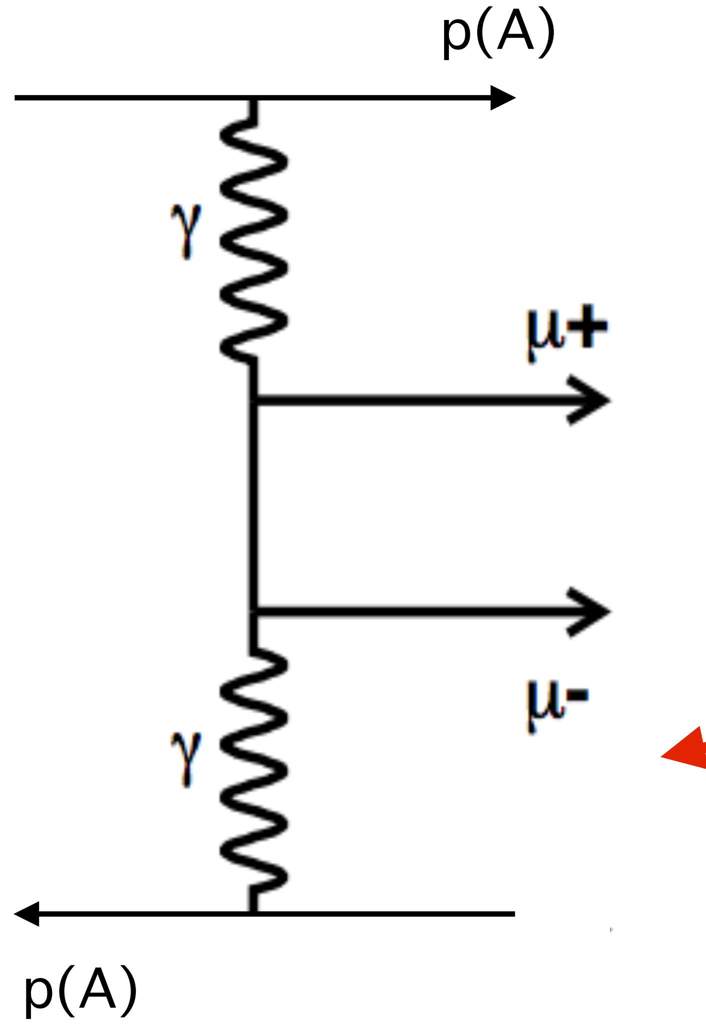

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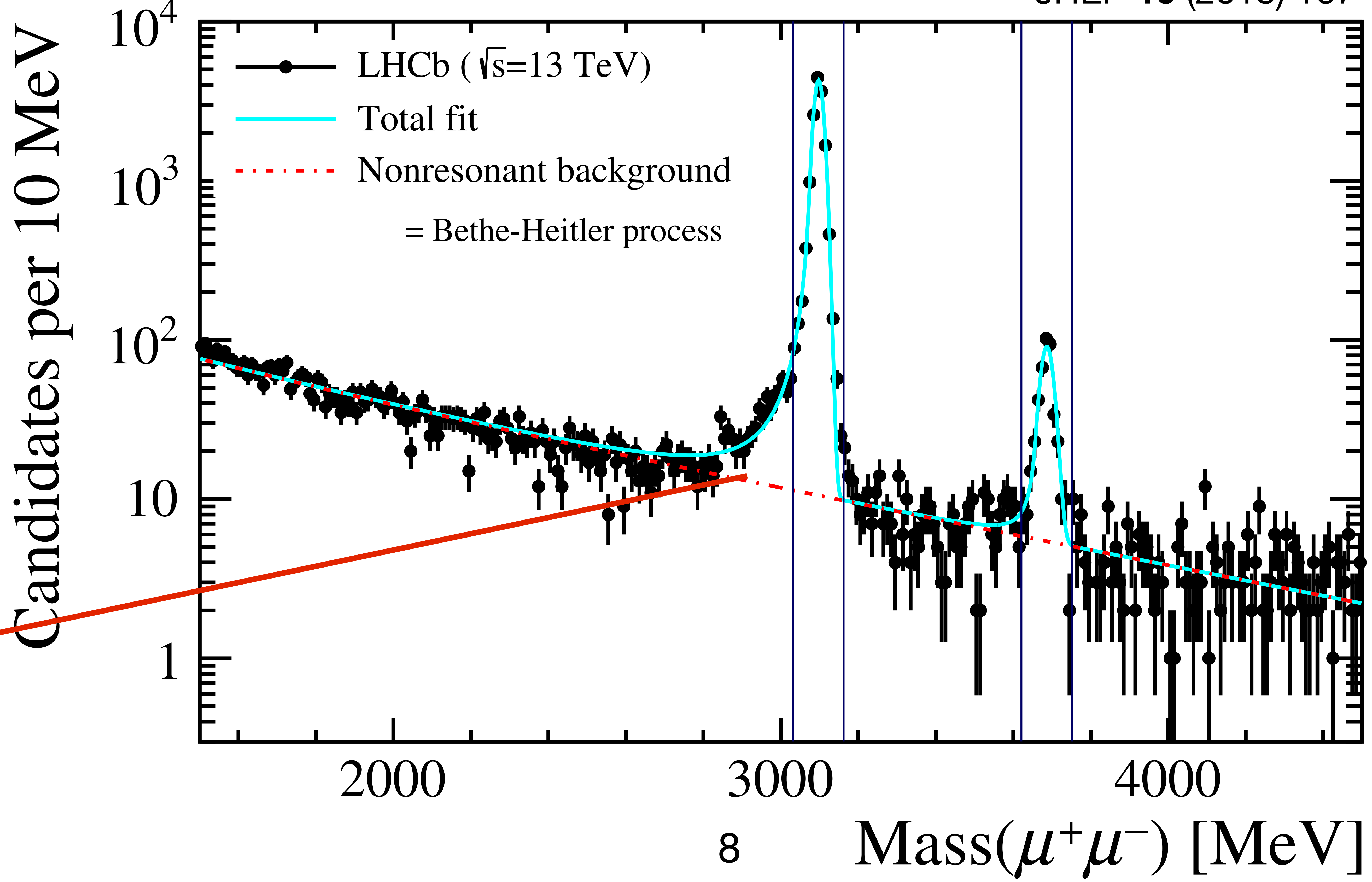
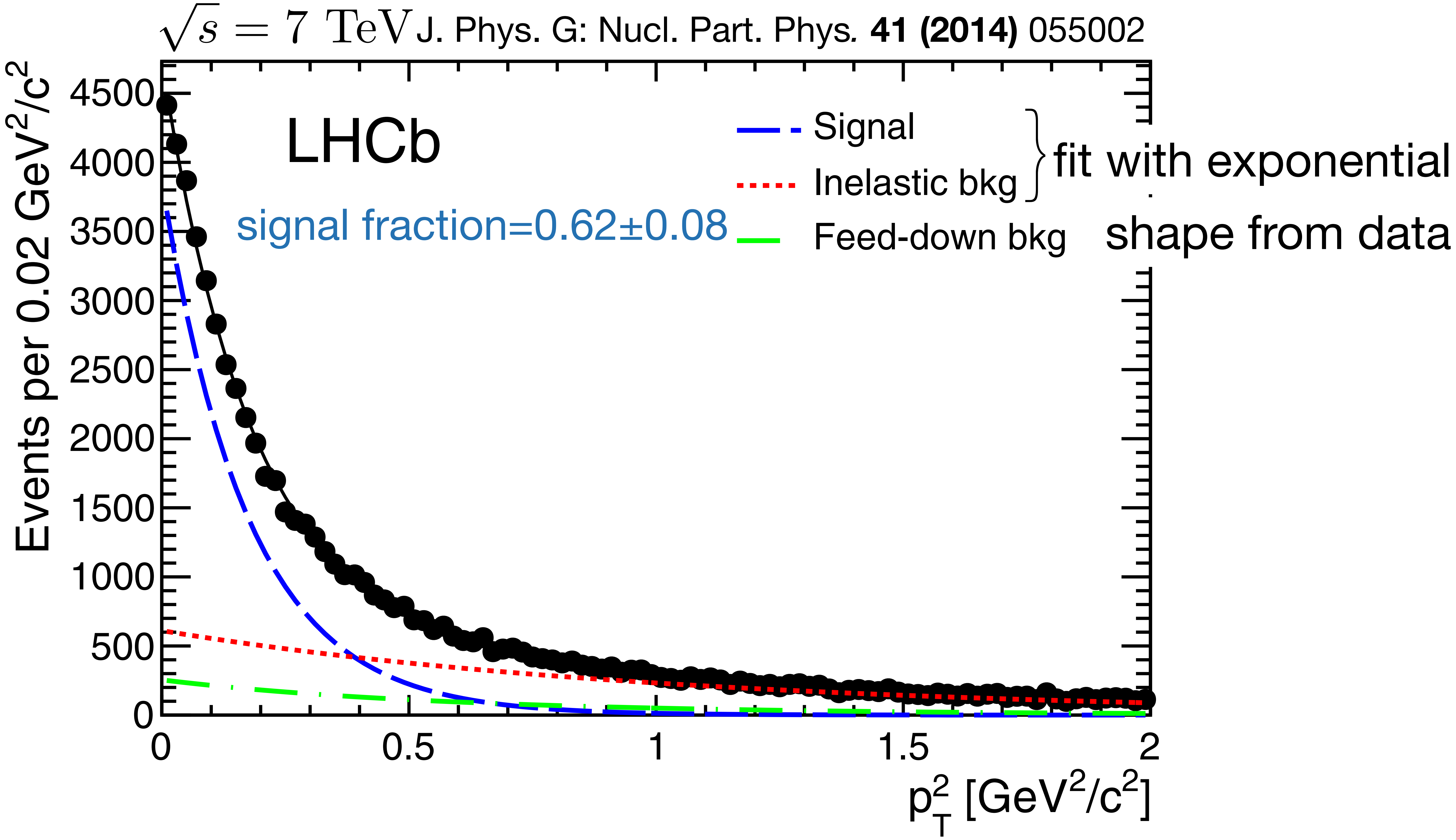
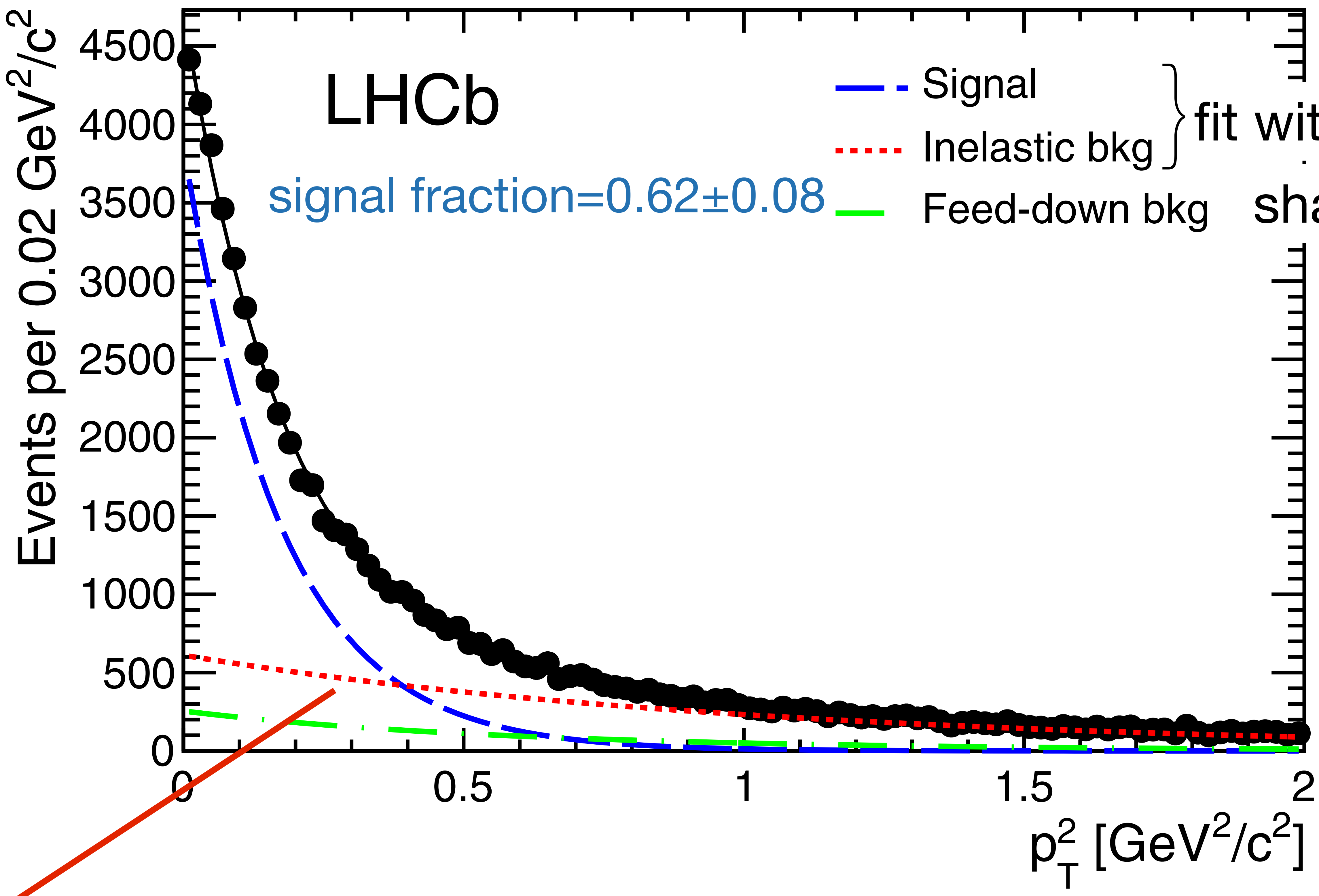


Background: feed down and proton dissociation



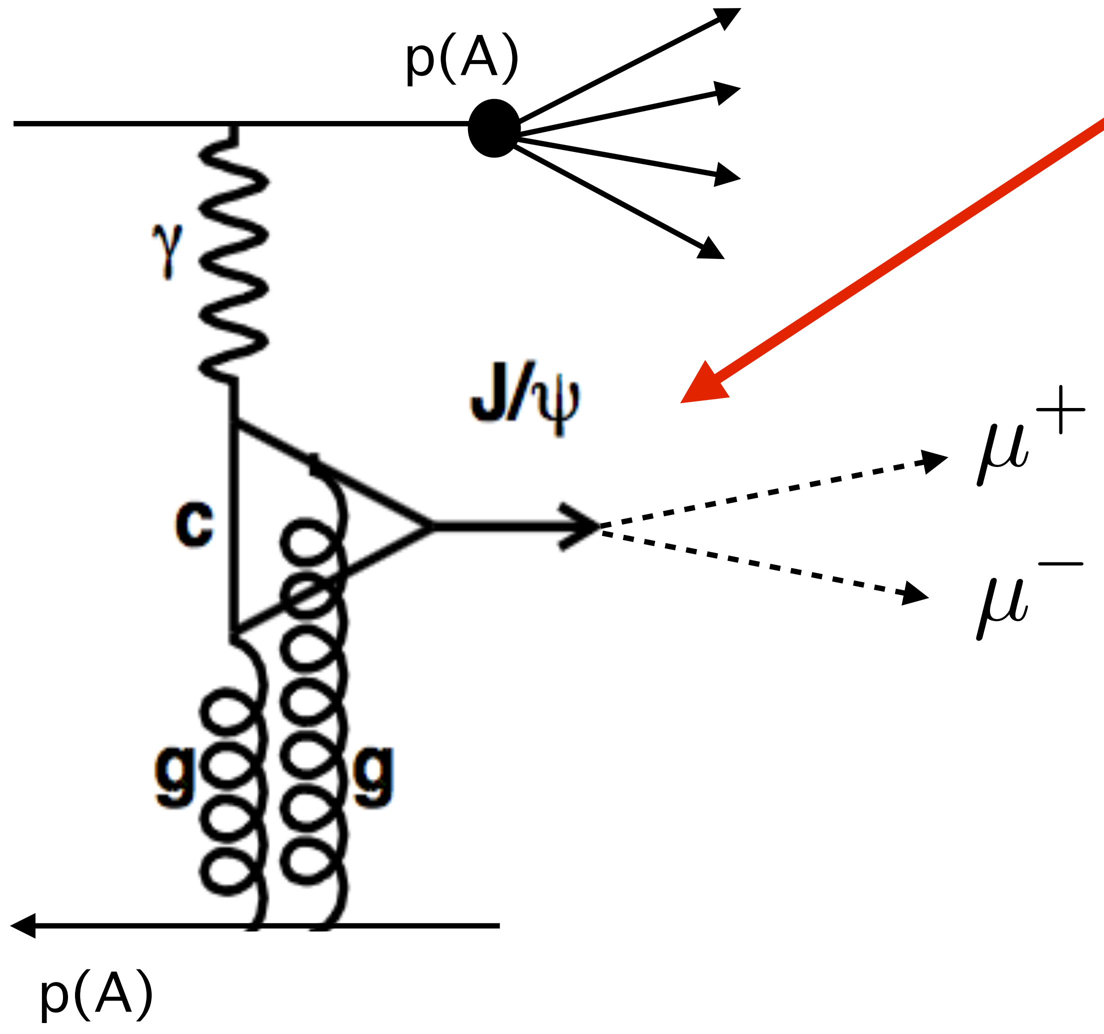
Background: feed down and proton dissociation

$\sqrt{s} = 7\ \mathrm{TeV}$ J. Phys. G: Nucl. Part. Phys. **41 (2014)** 055002



fit with exponential

shape from data



proton/ion dissociation

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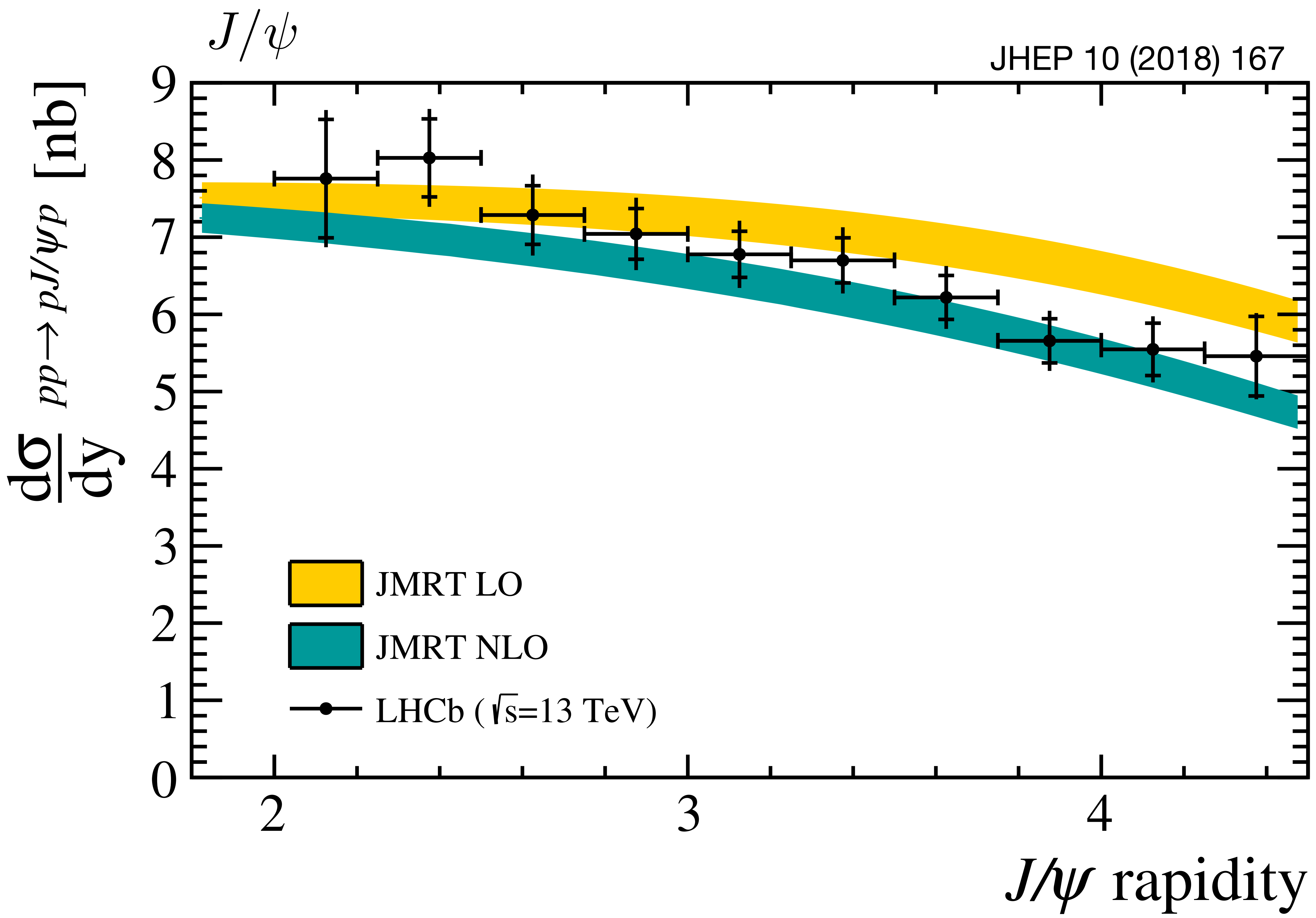
proton/ion dissociation

J/ψ feed-down background

pp cross section



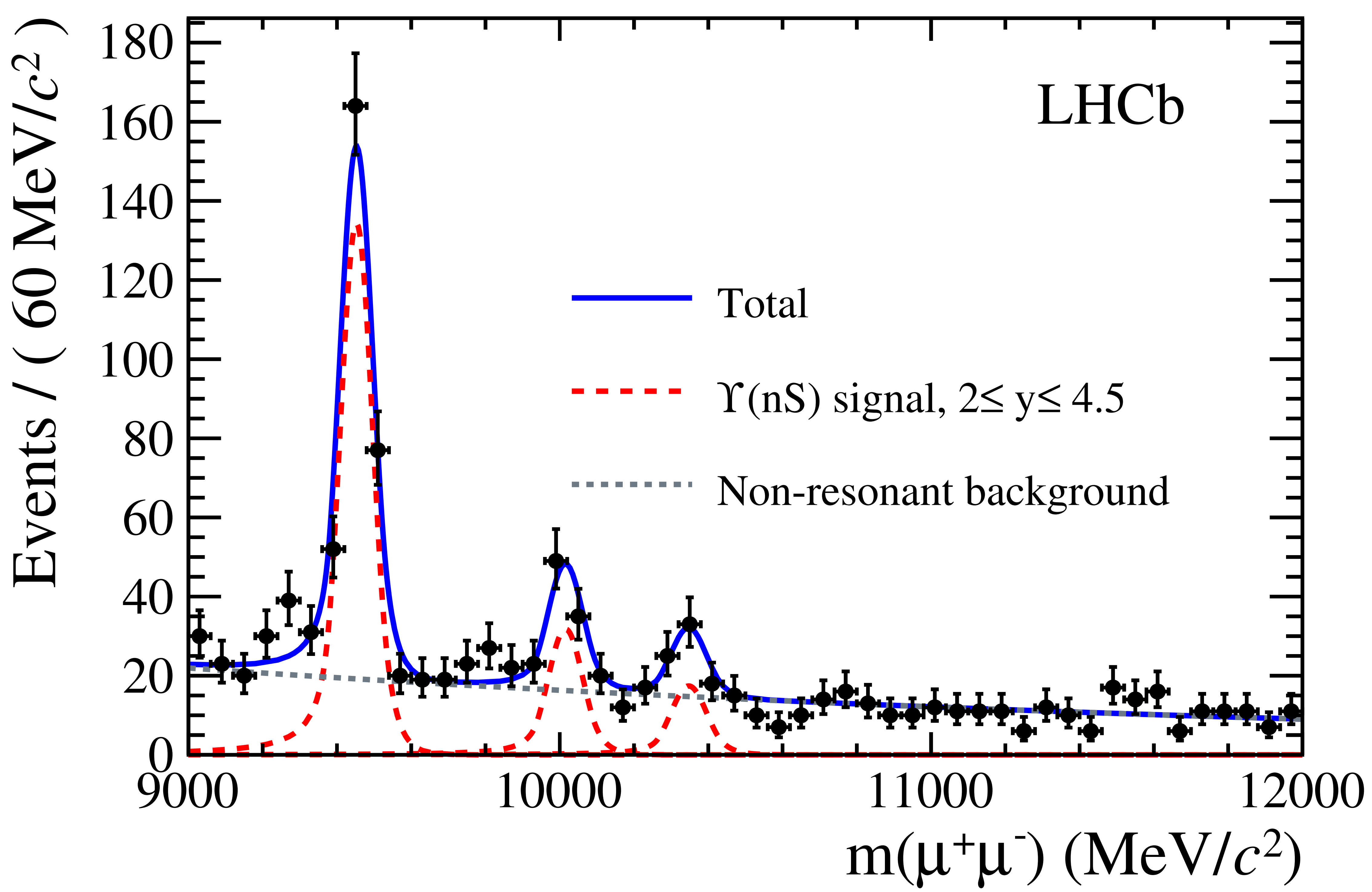
JMRT prediction, based on gluon PDF:

At low x_B, approximate GPD to gluon PDF

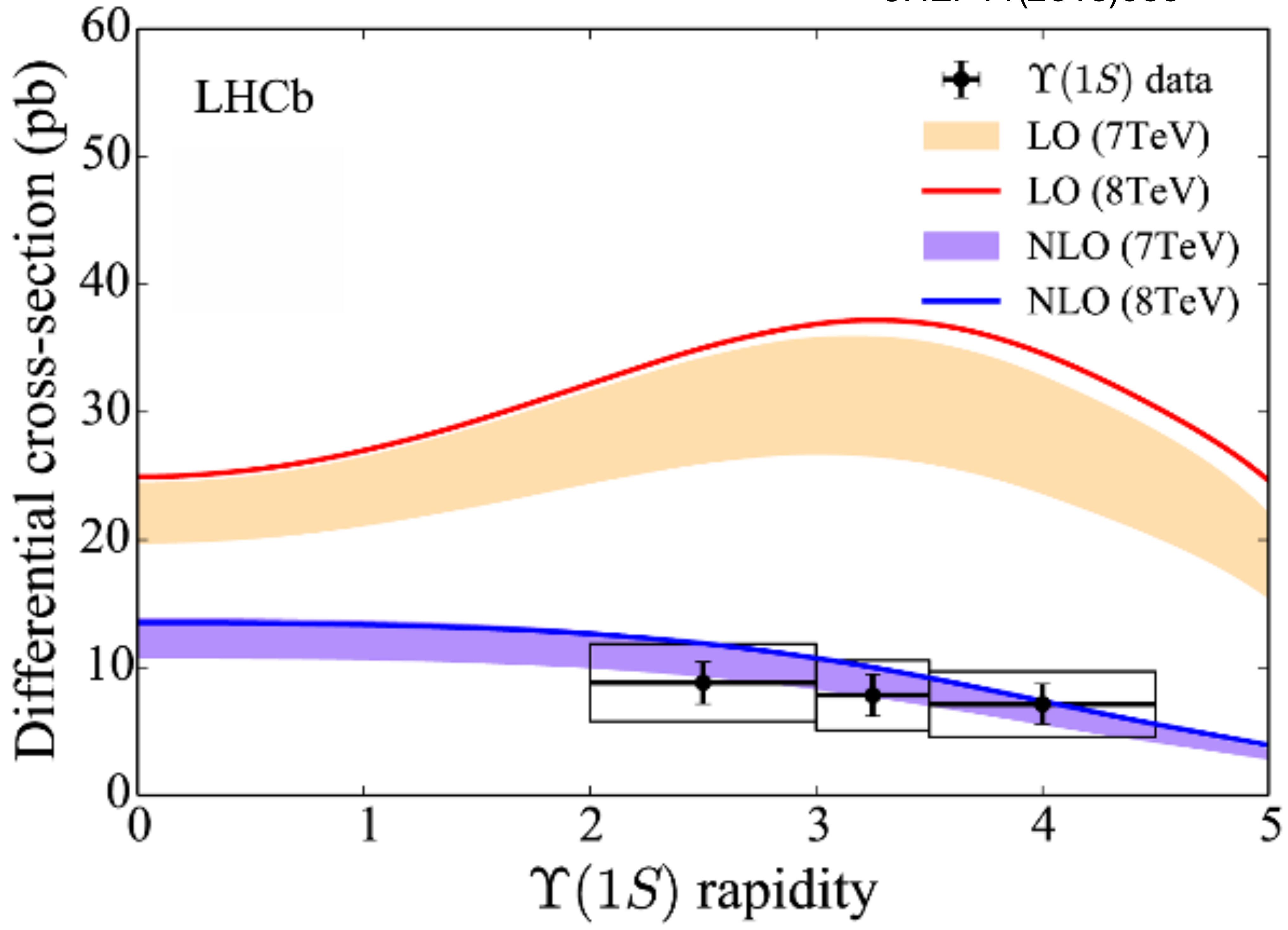
$$\left.\frac{d\sigma}{dt}\right|_{t=0} \propto [g(x_B)]^2$$

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

Exclusive single Υ production in pp collisions

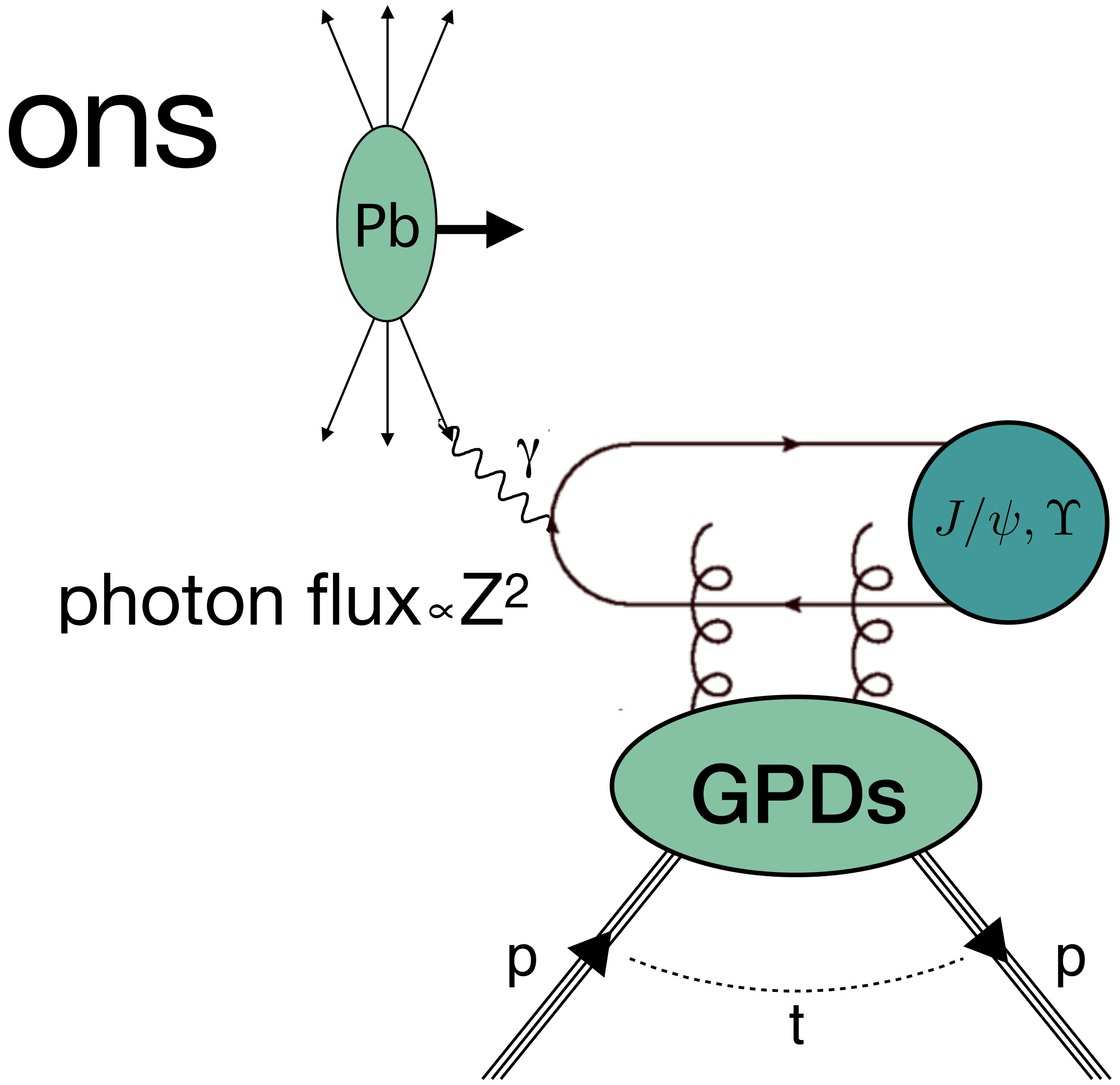


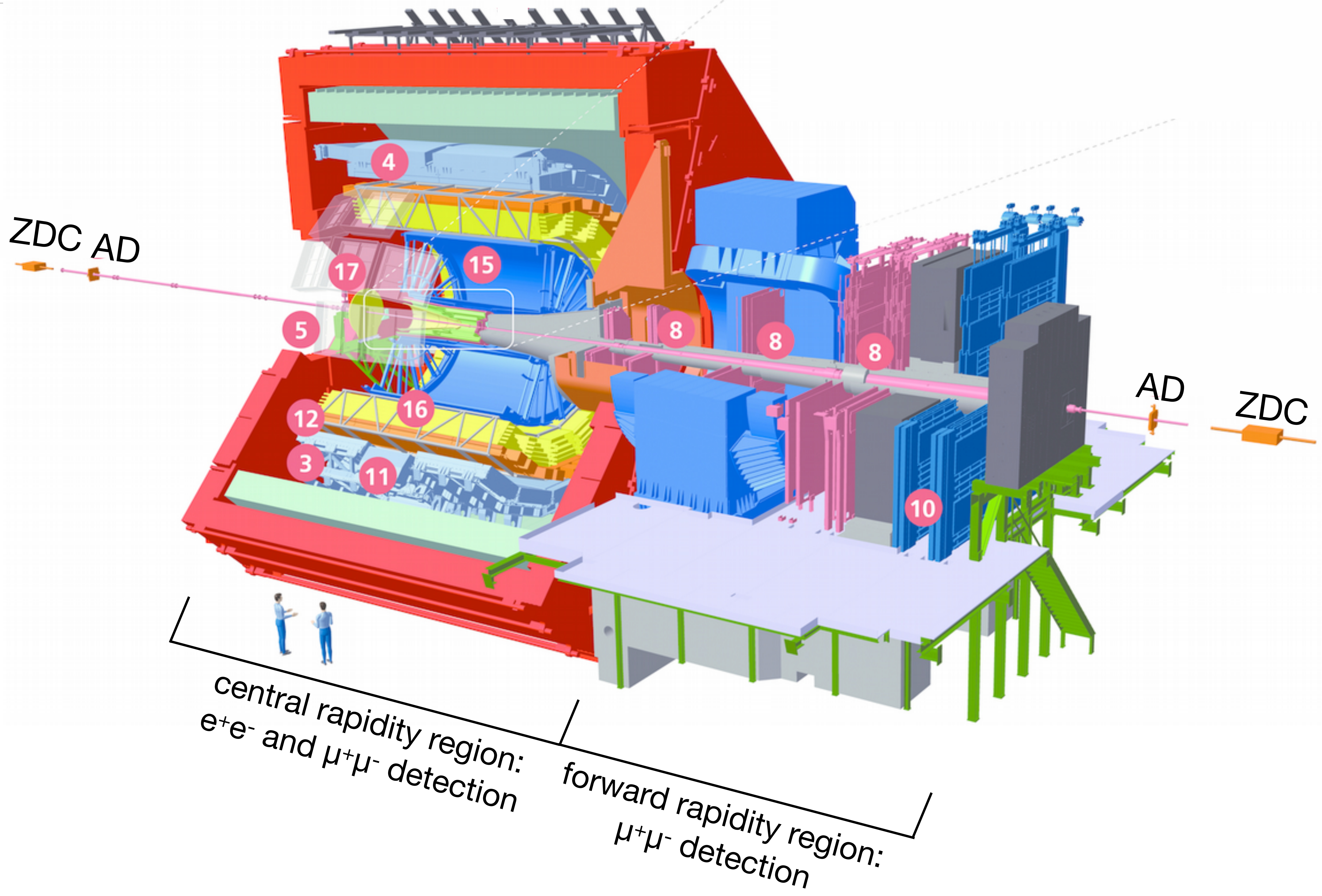
JHEP11(2013)085



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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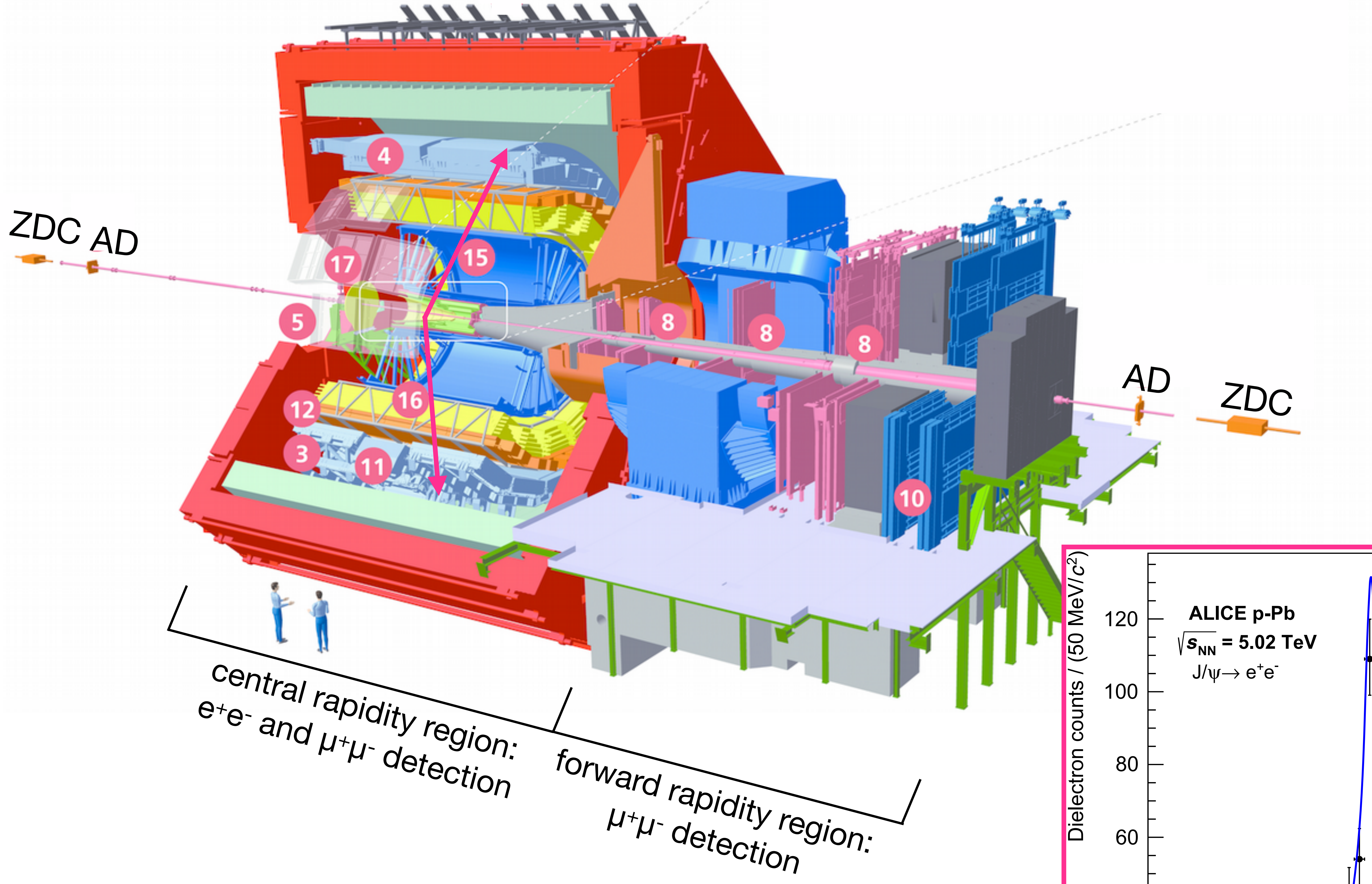

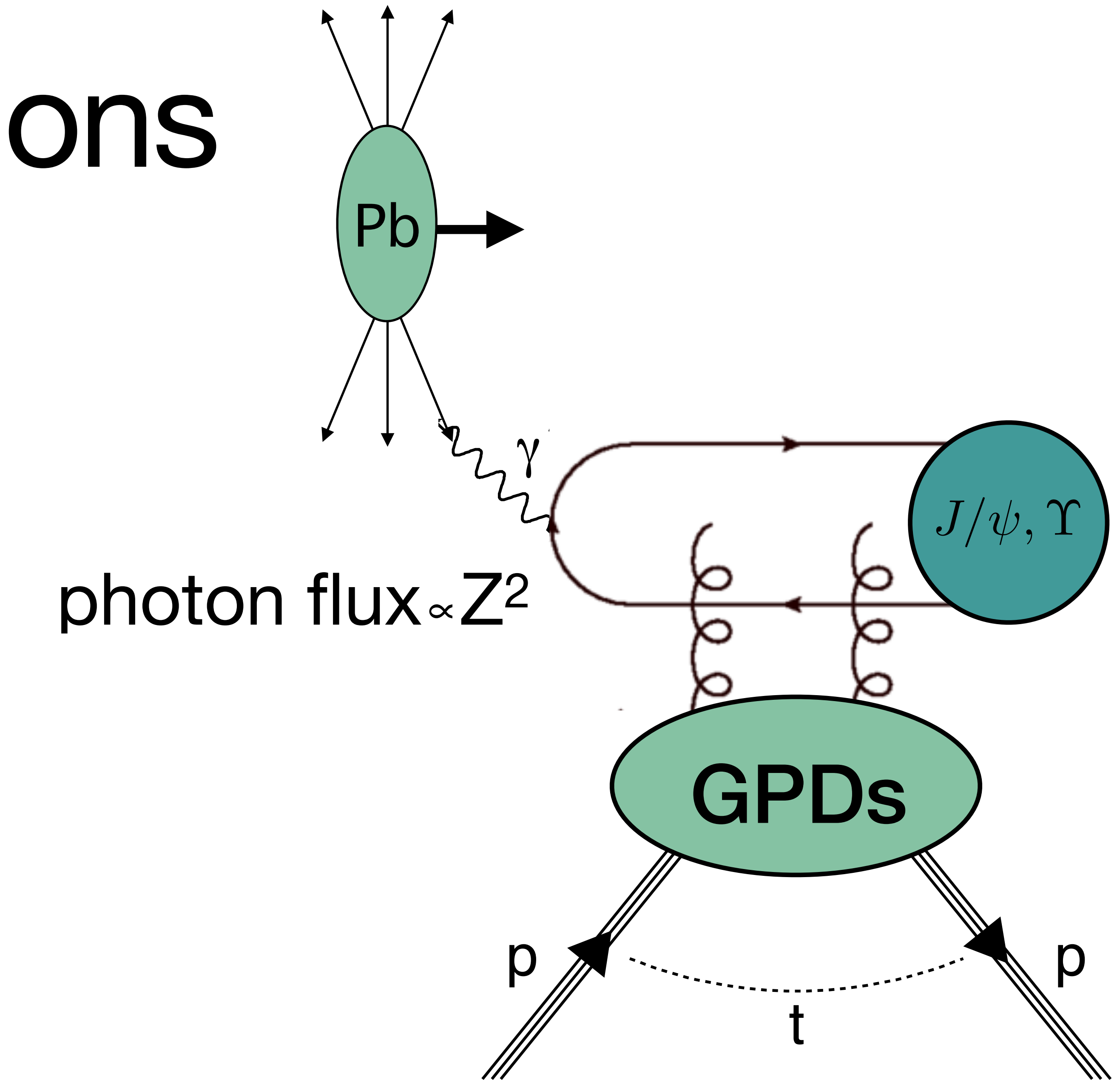

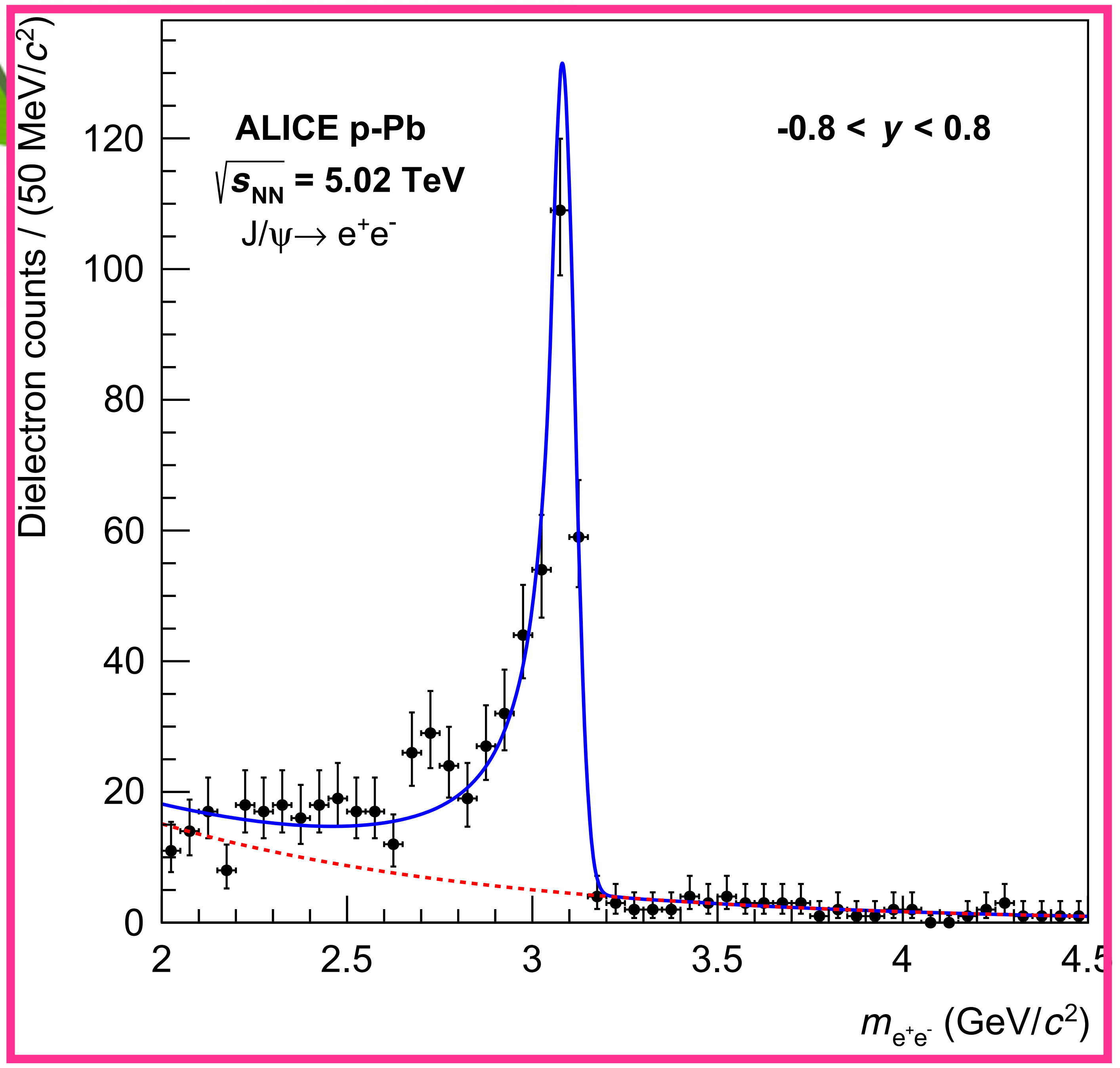

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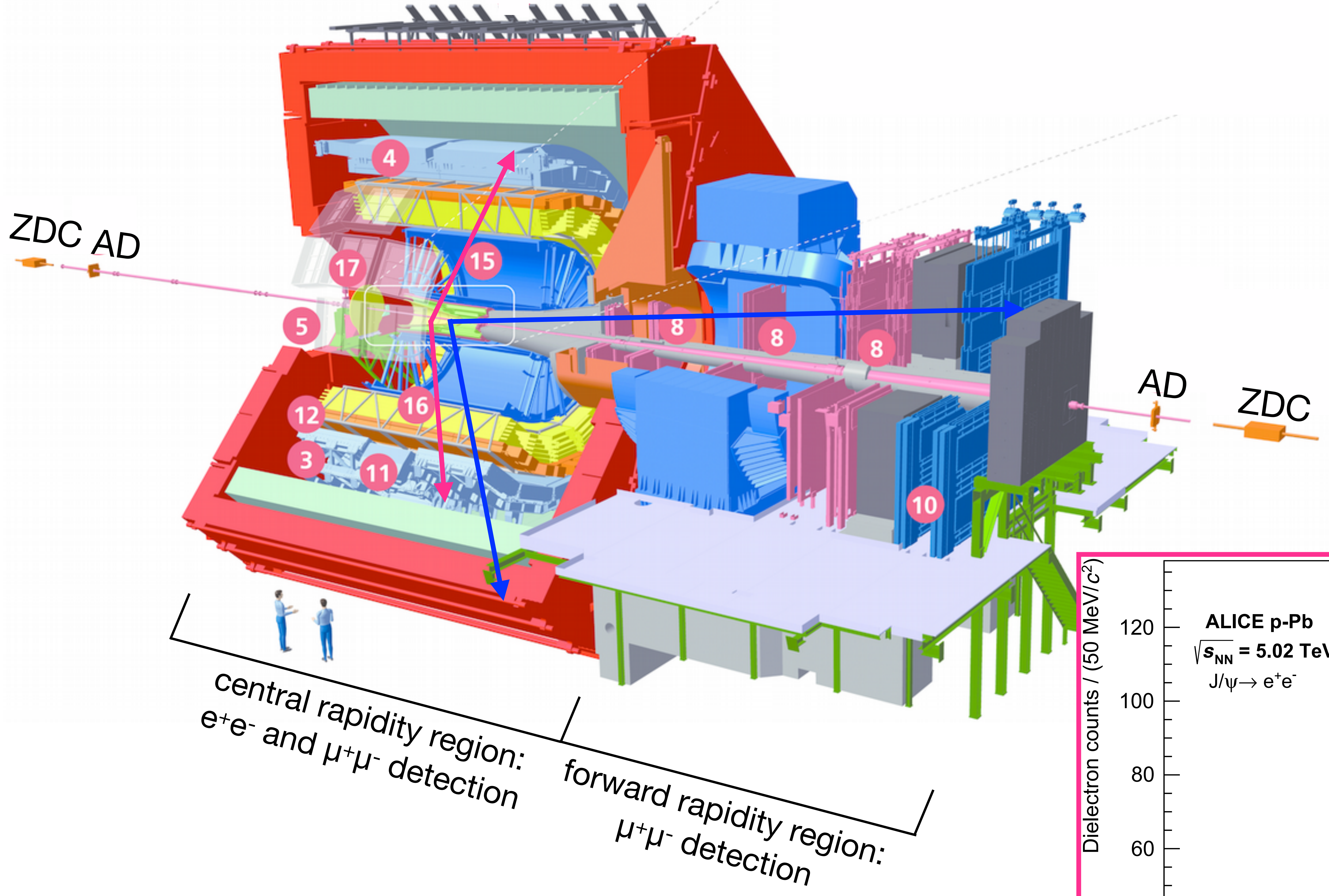

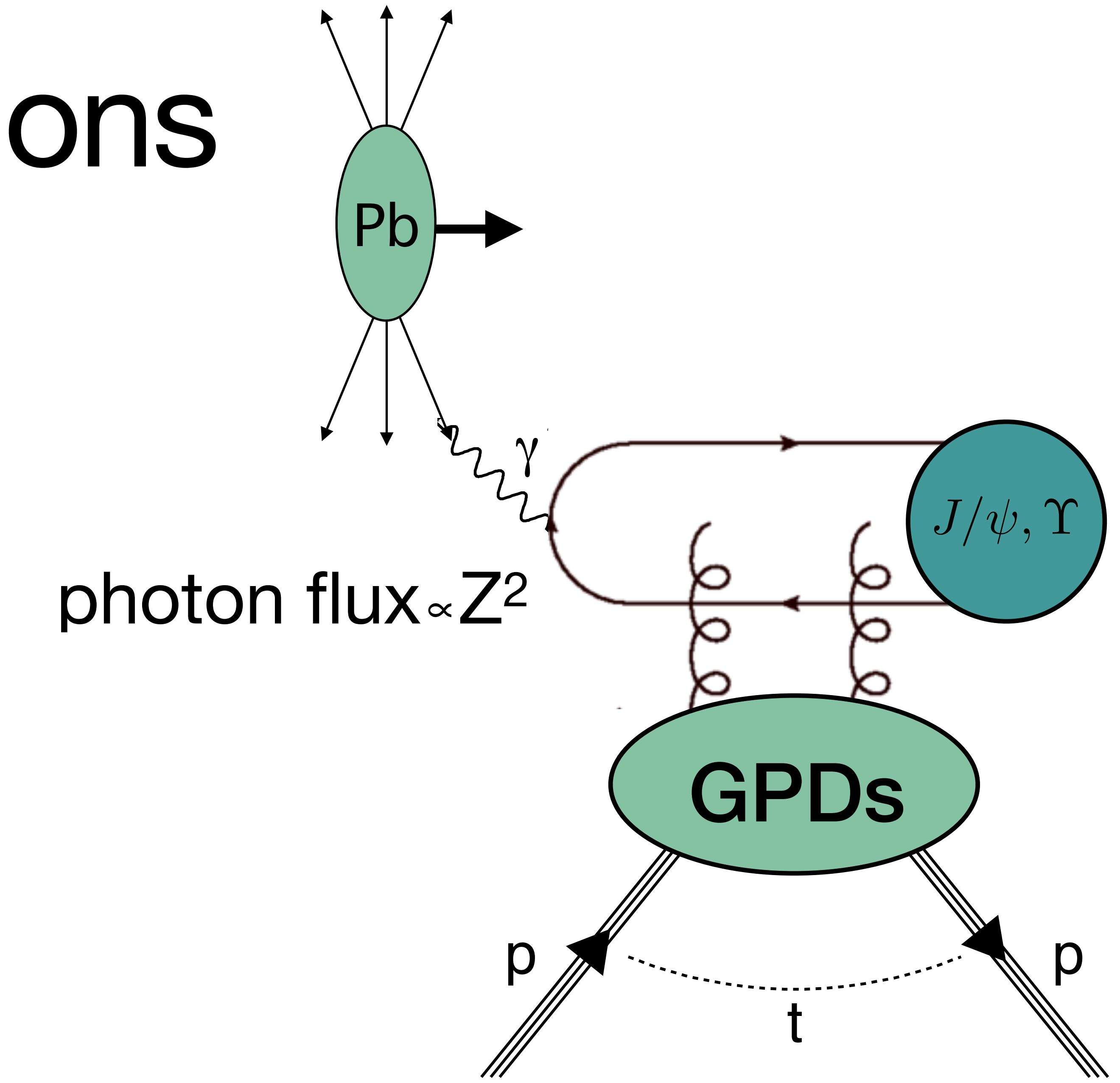

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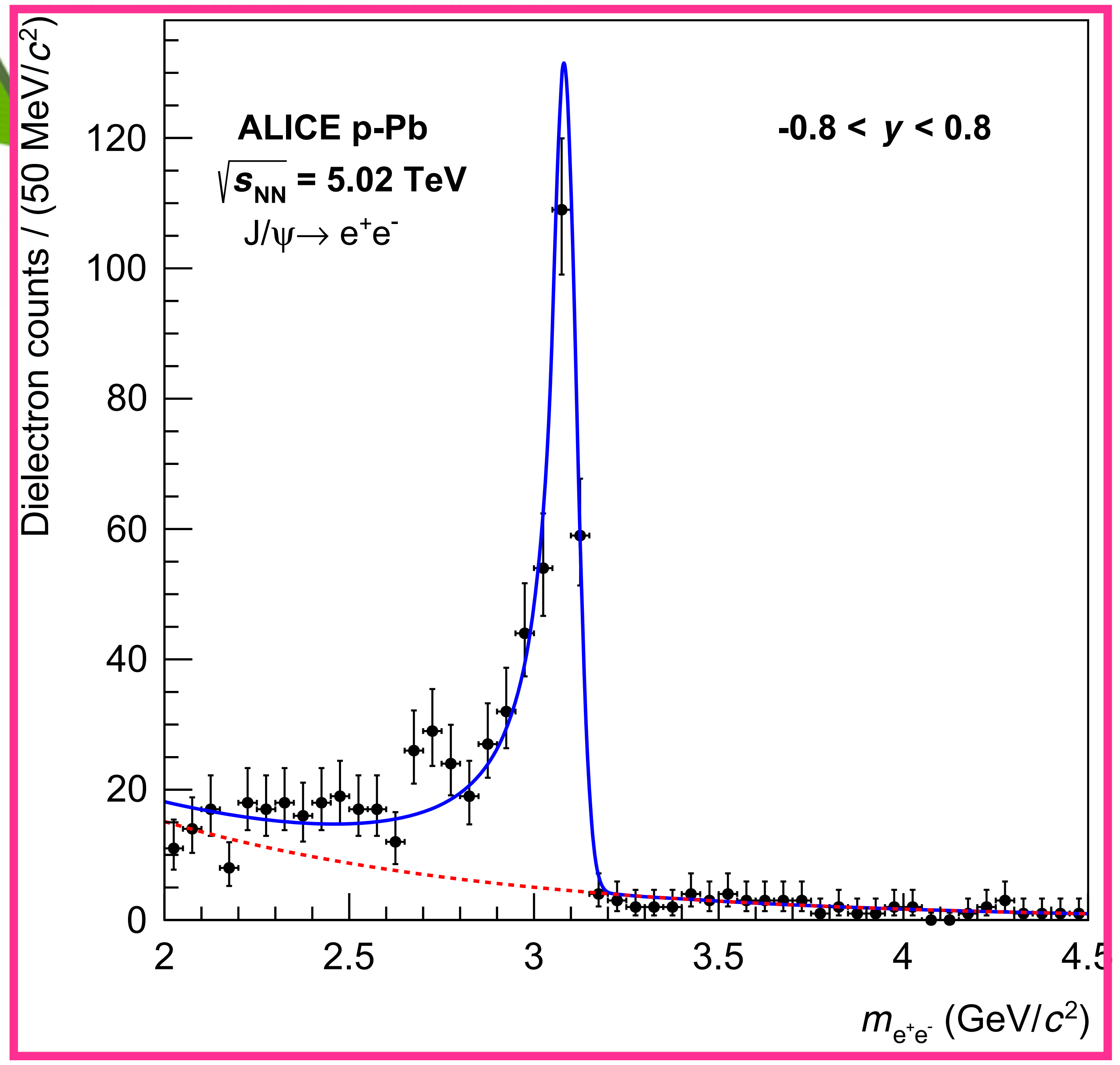
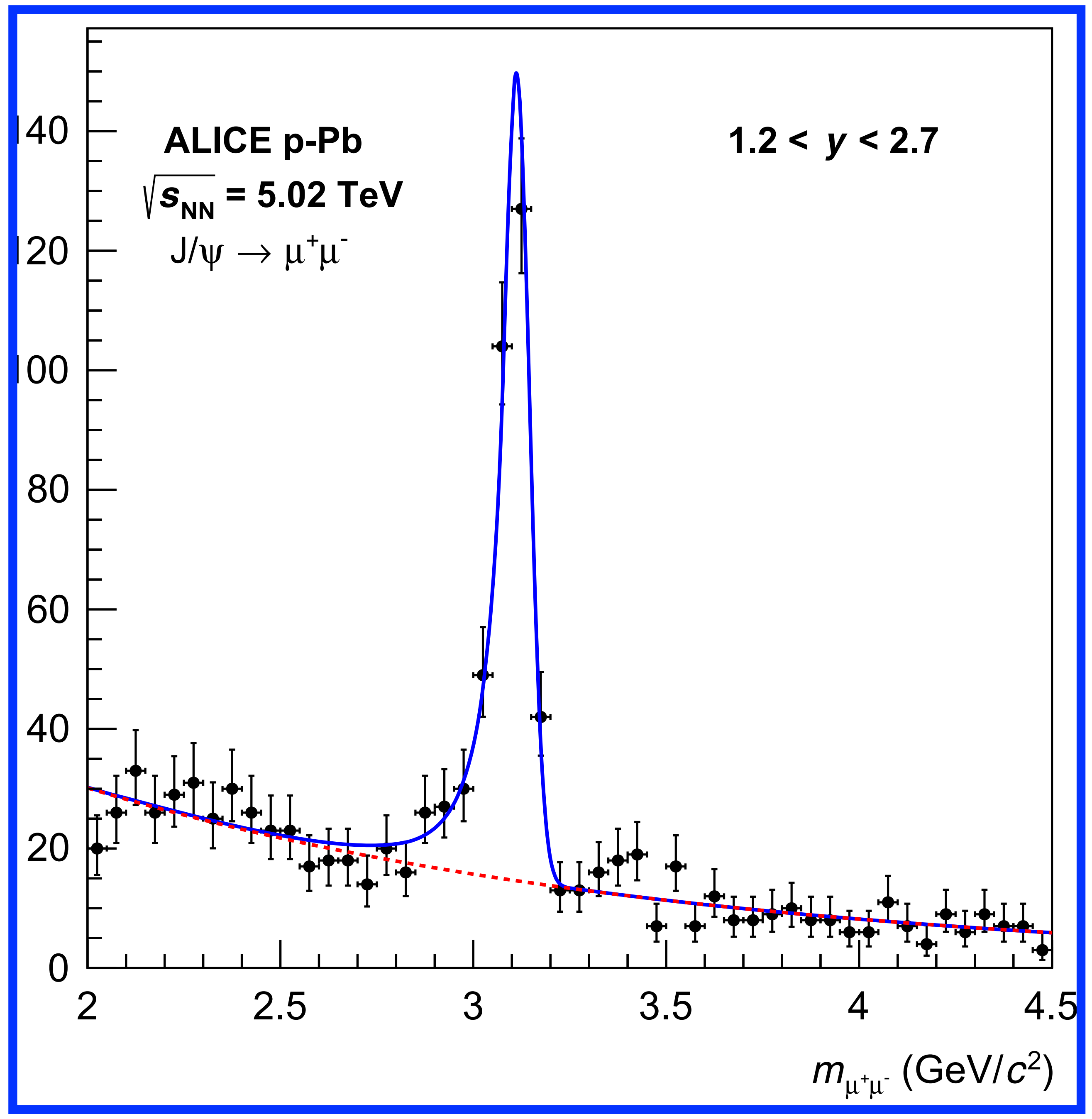
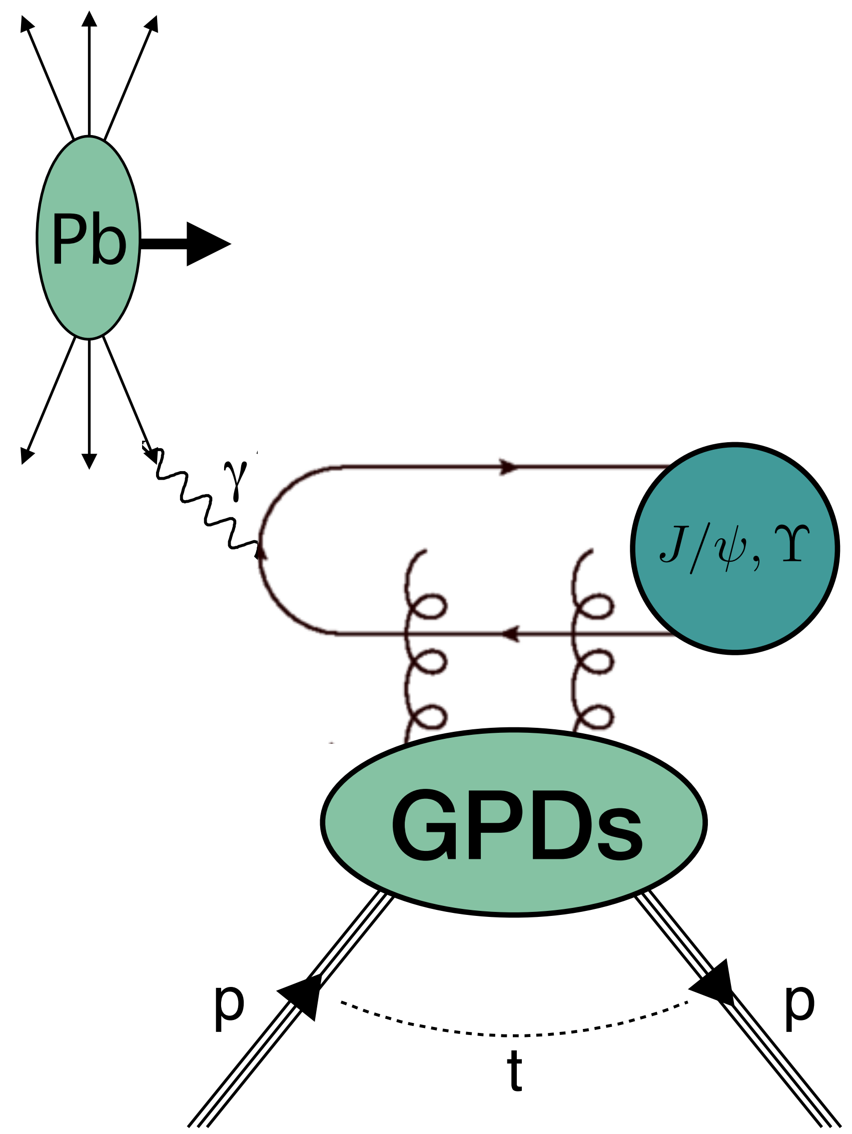




Extraction of the J/ψ photoproduction



pPb: use Z^2 dependence of photon flux

→ Pb is predominantly photon emitter

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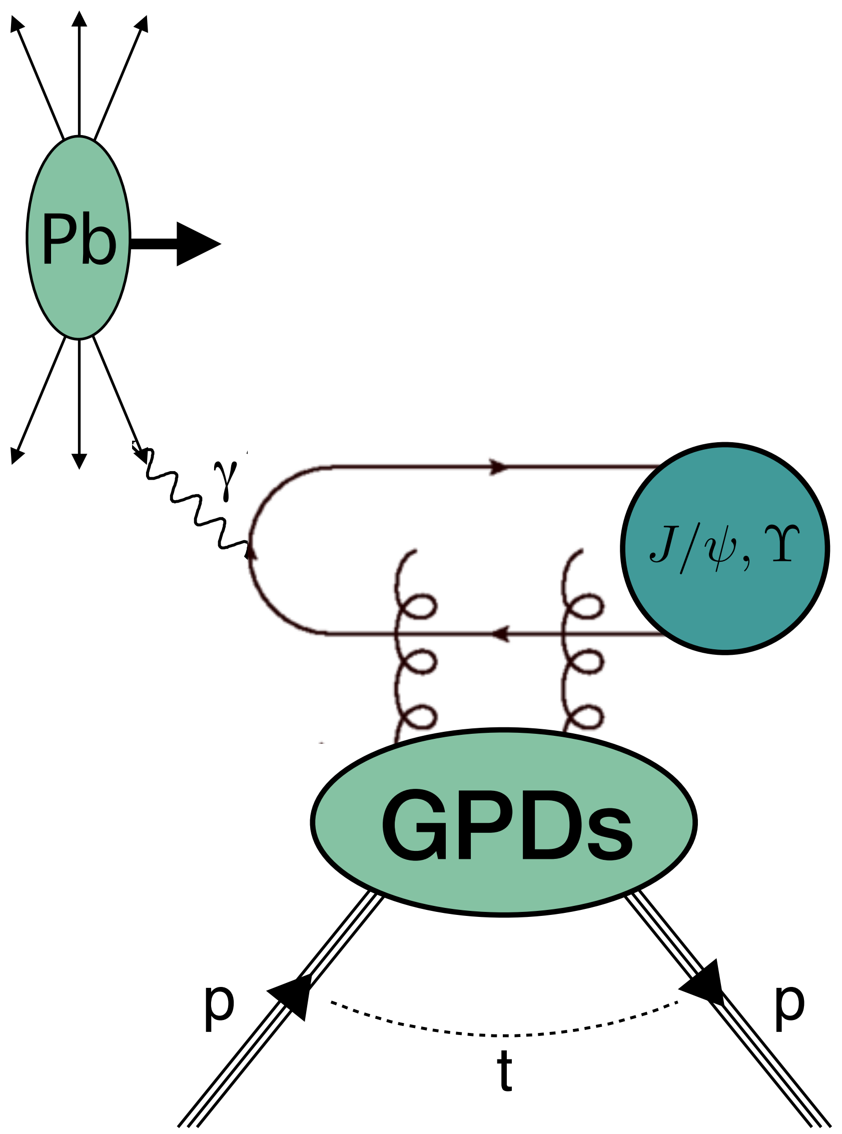

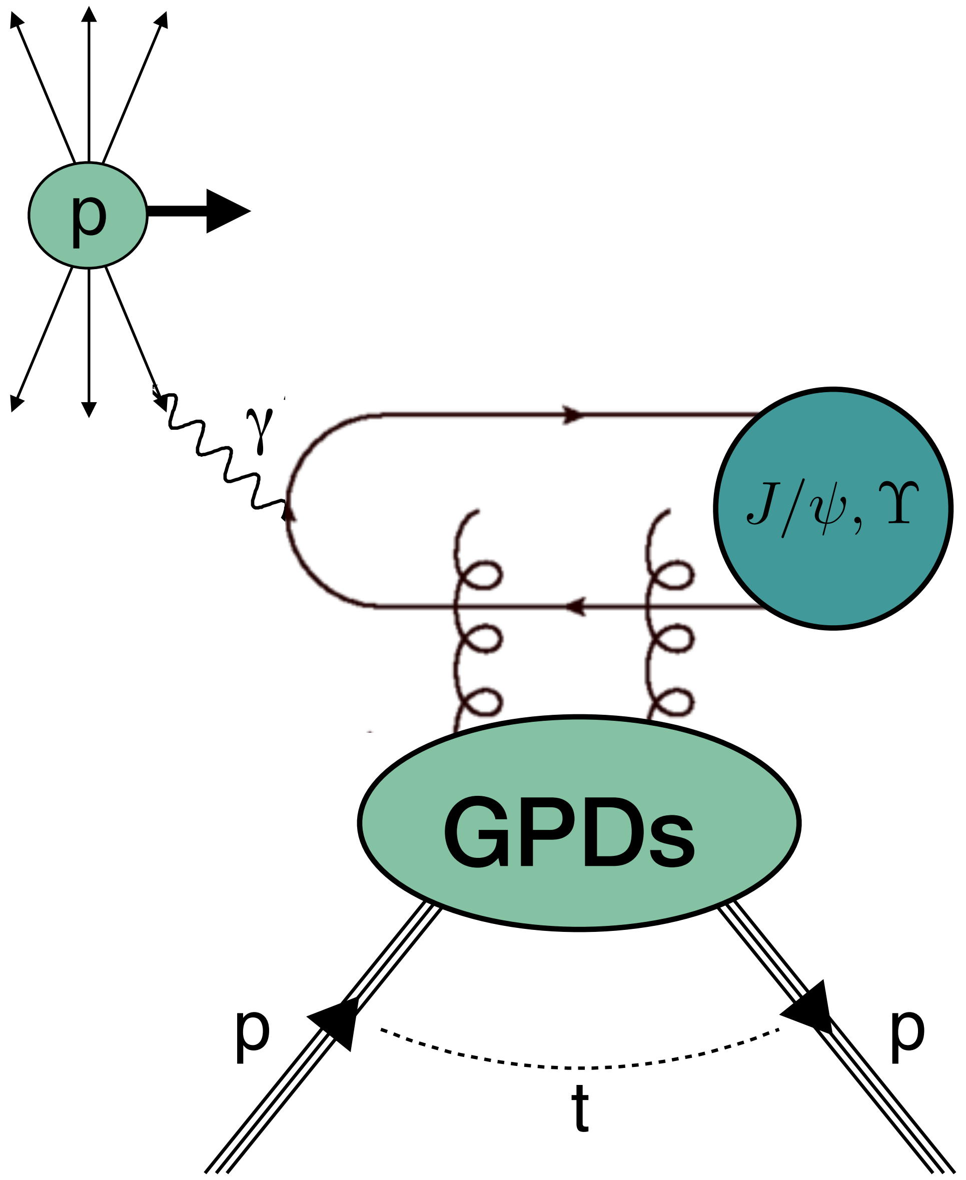

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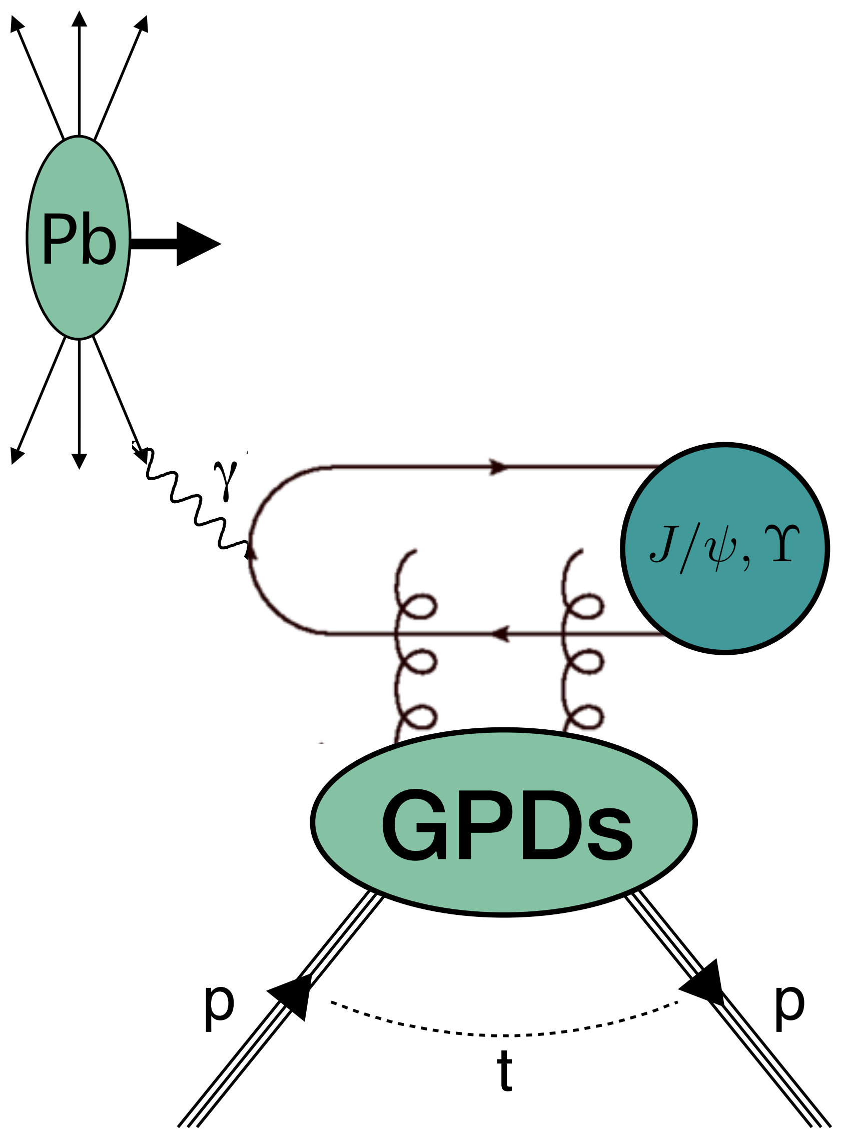

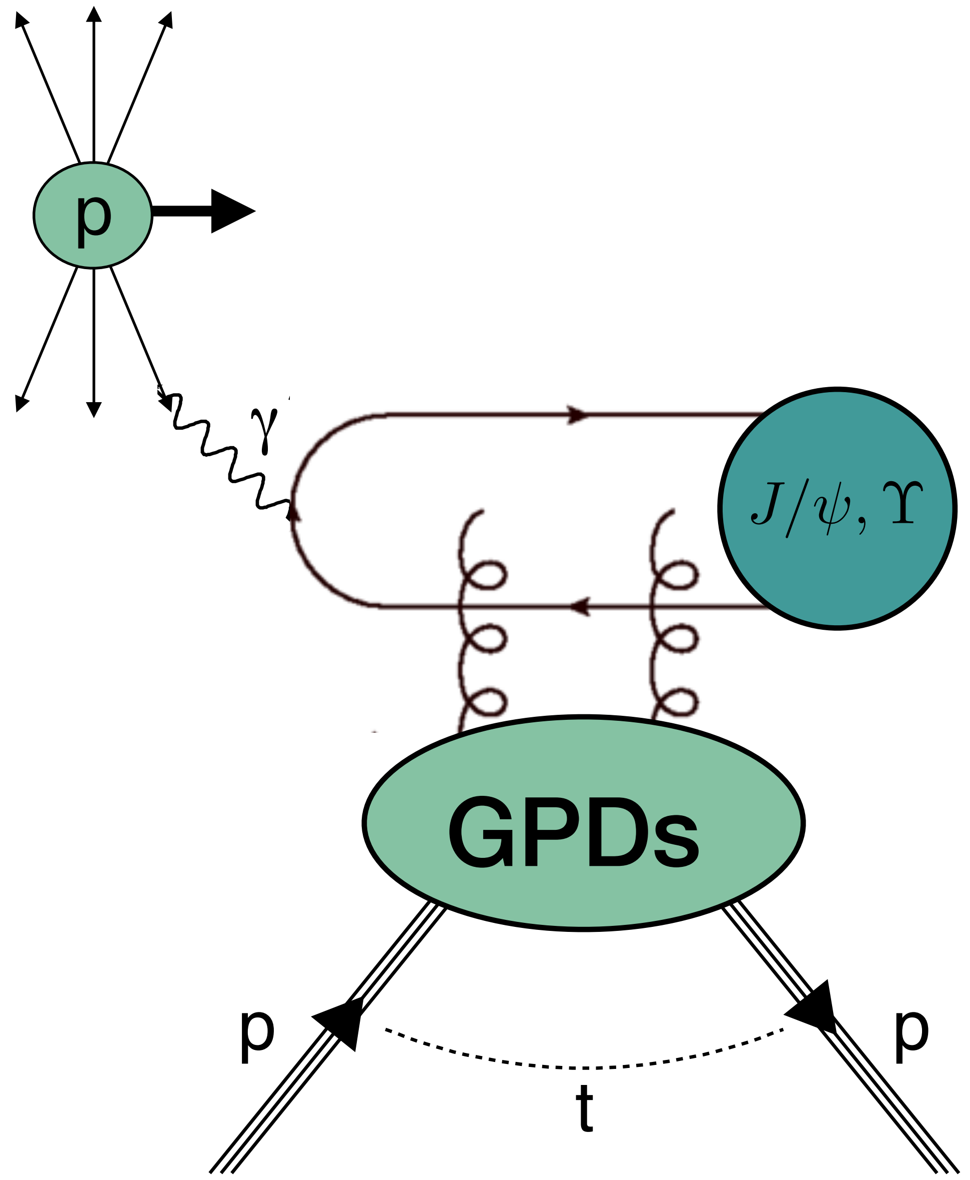

pPb: use Z^2 dependence of photon flux

→ Pb is predominantly photon emitter

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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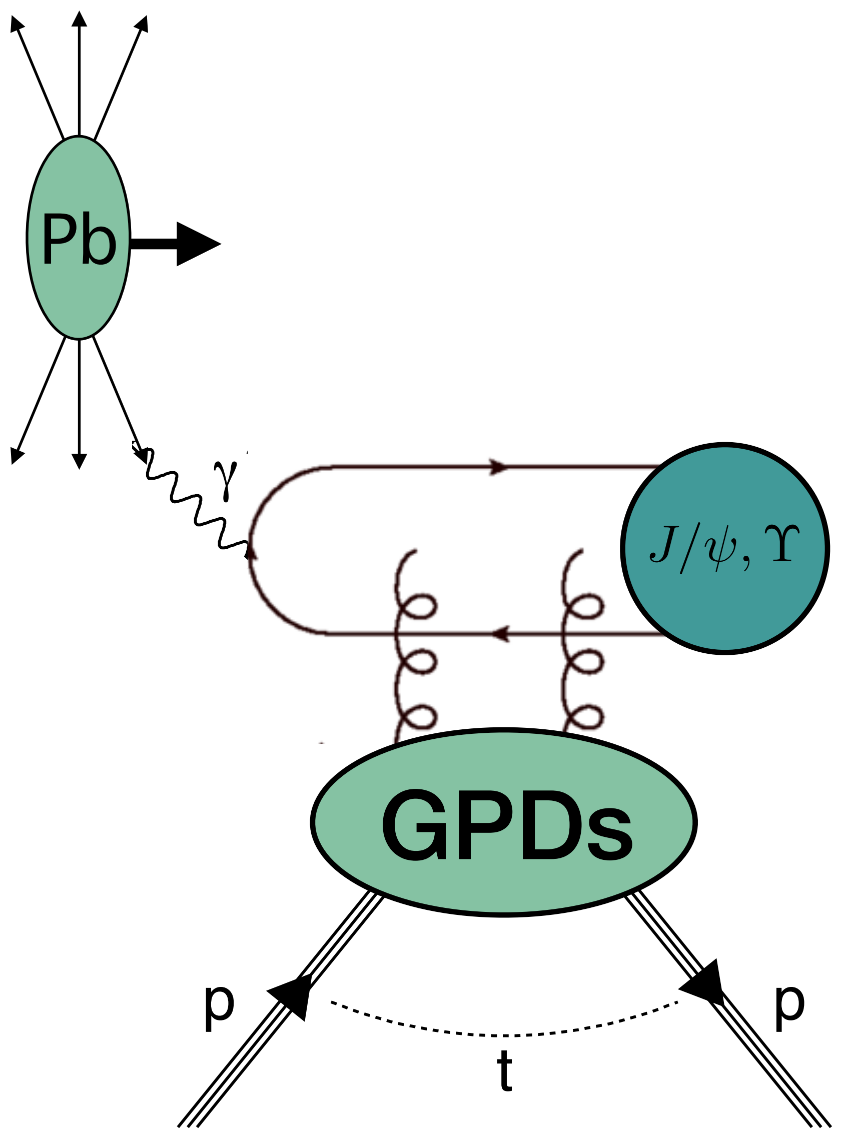

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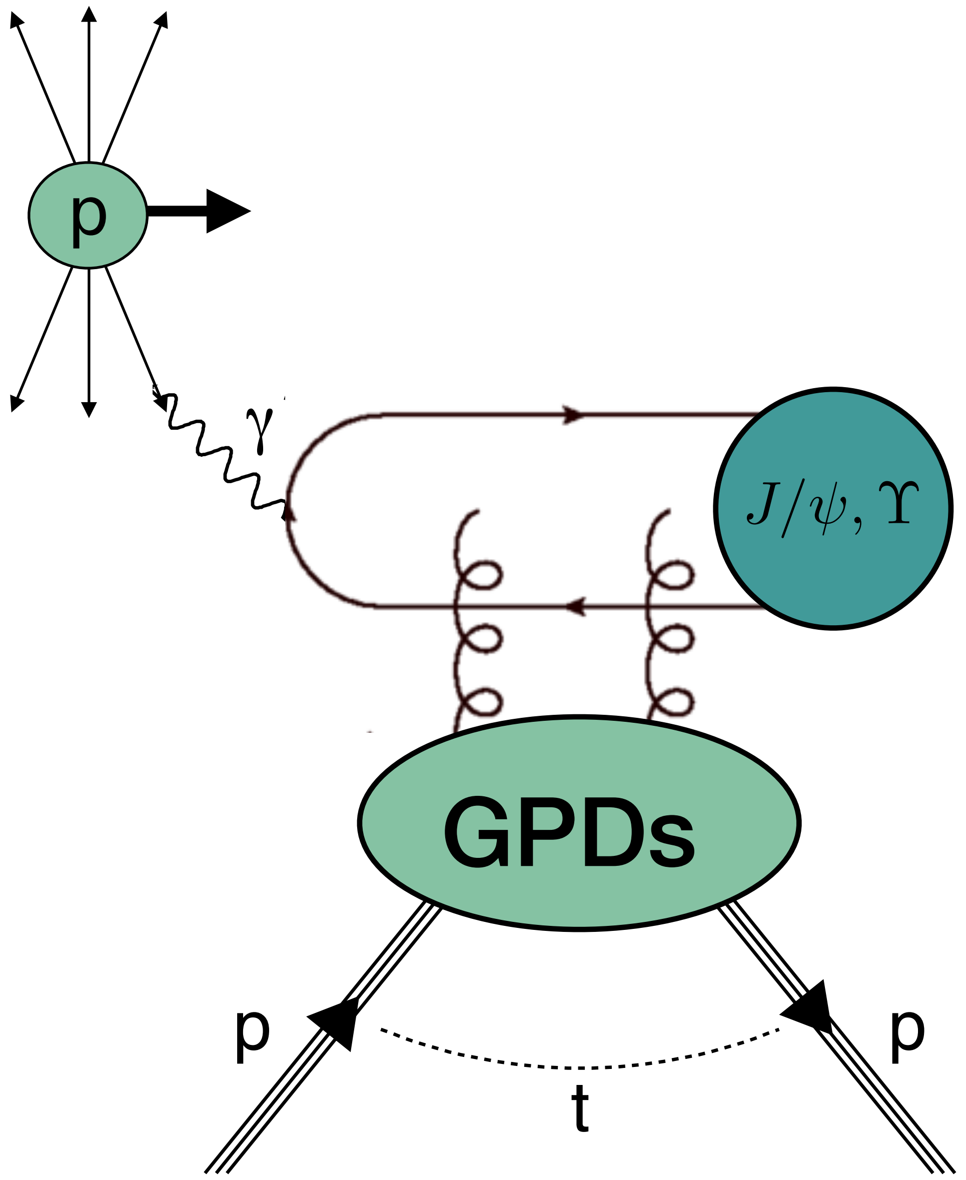

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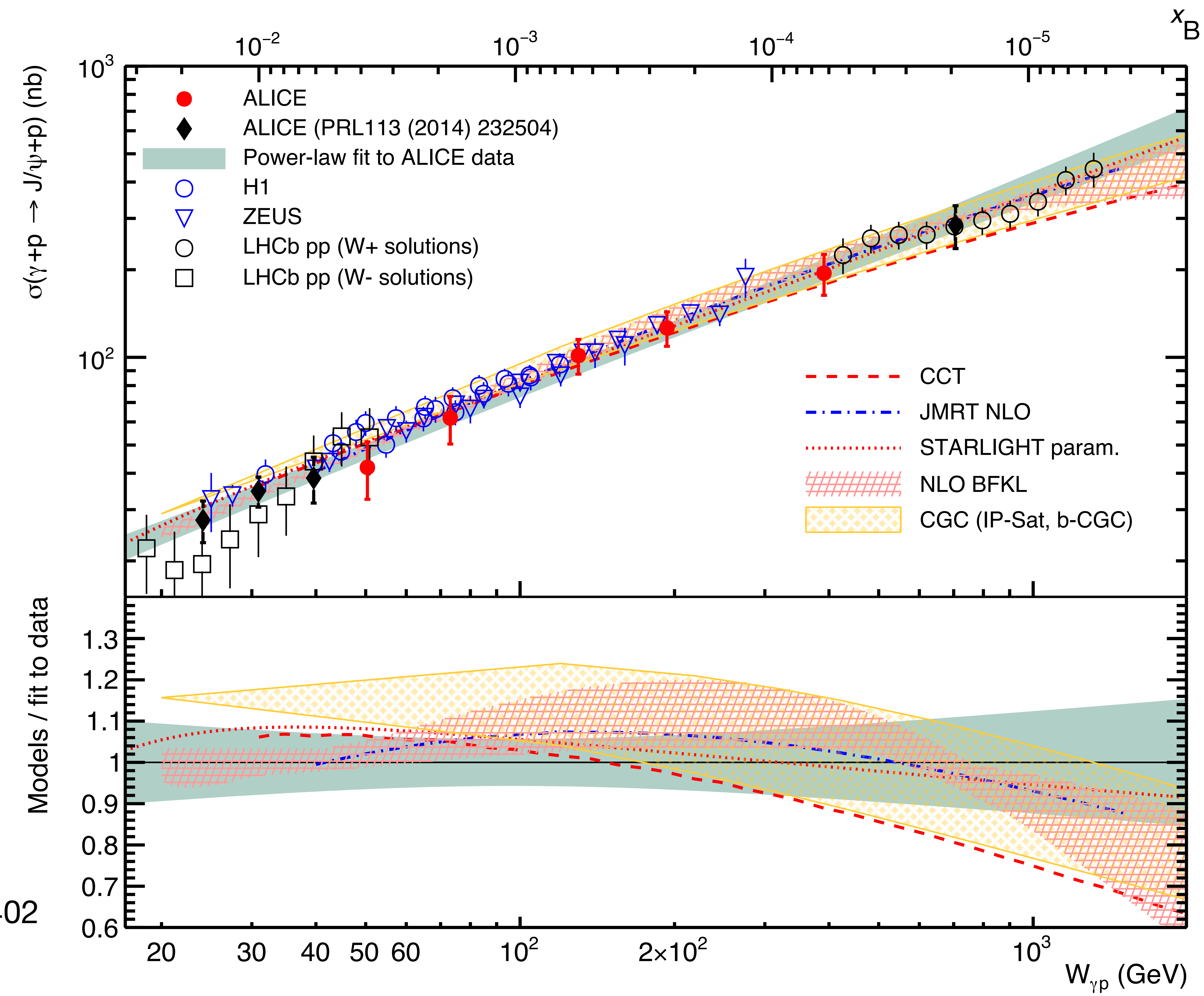
LHCb used HERA data for low-E_γ (W_-) contribution.

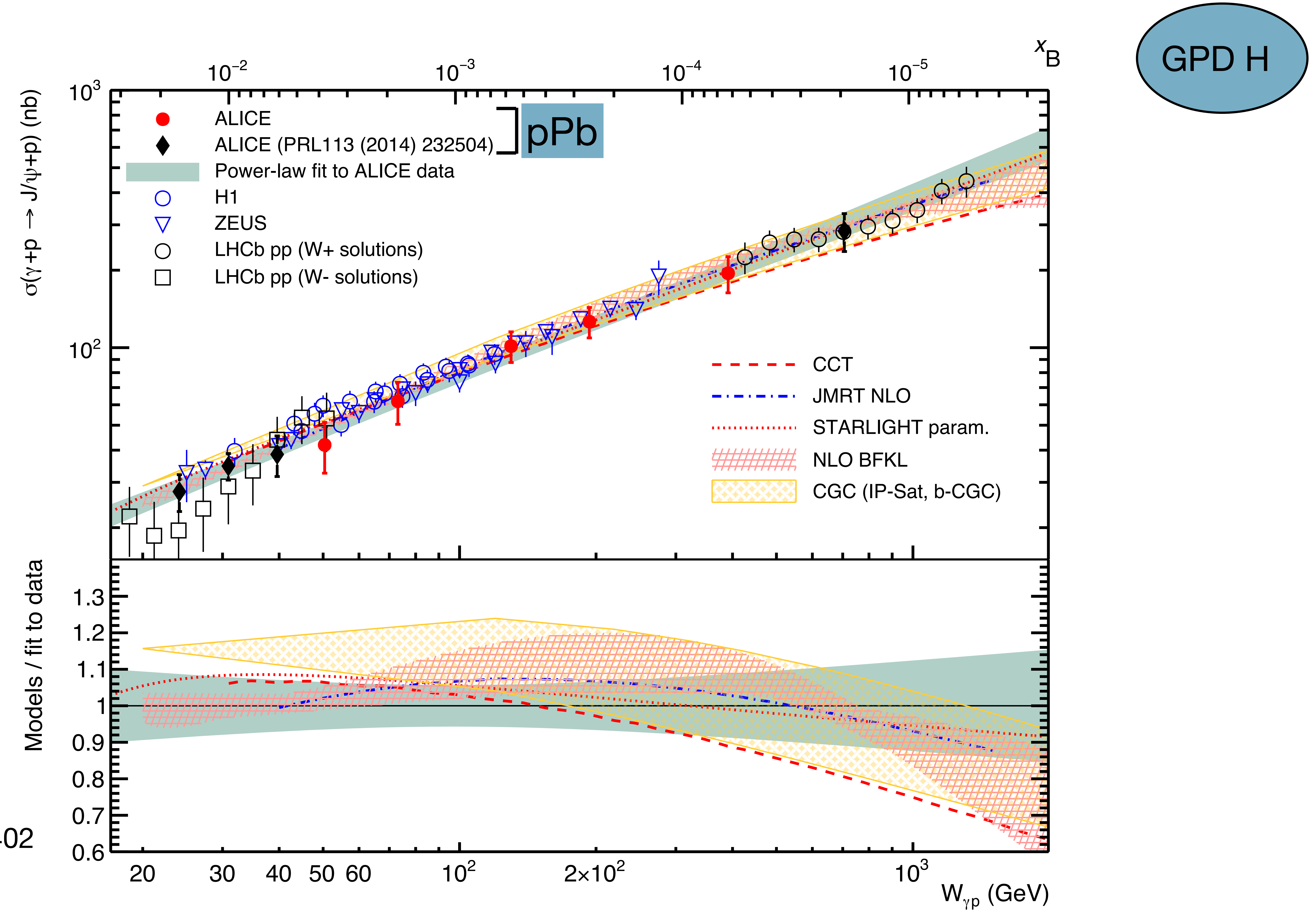
γp cross section: LHC

GPD H



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

γp cross section: LHC



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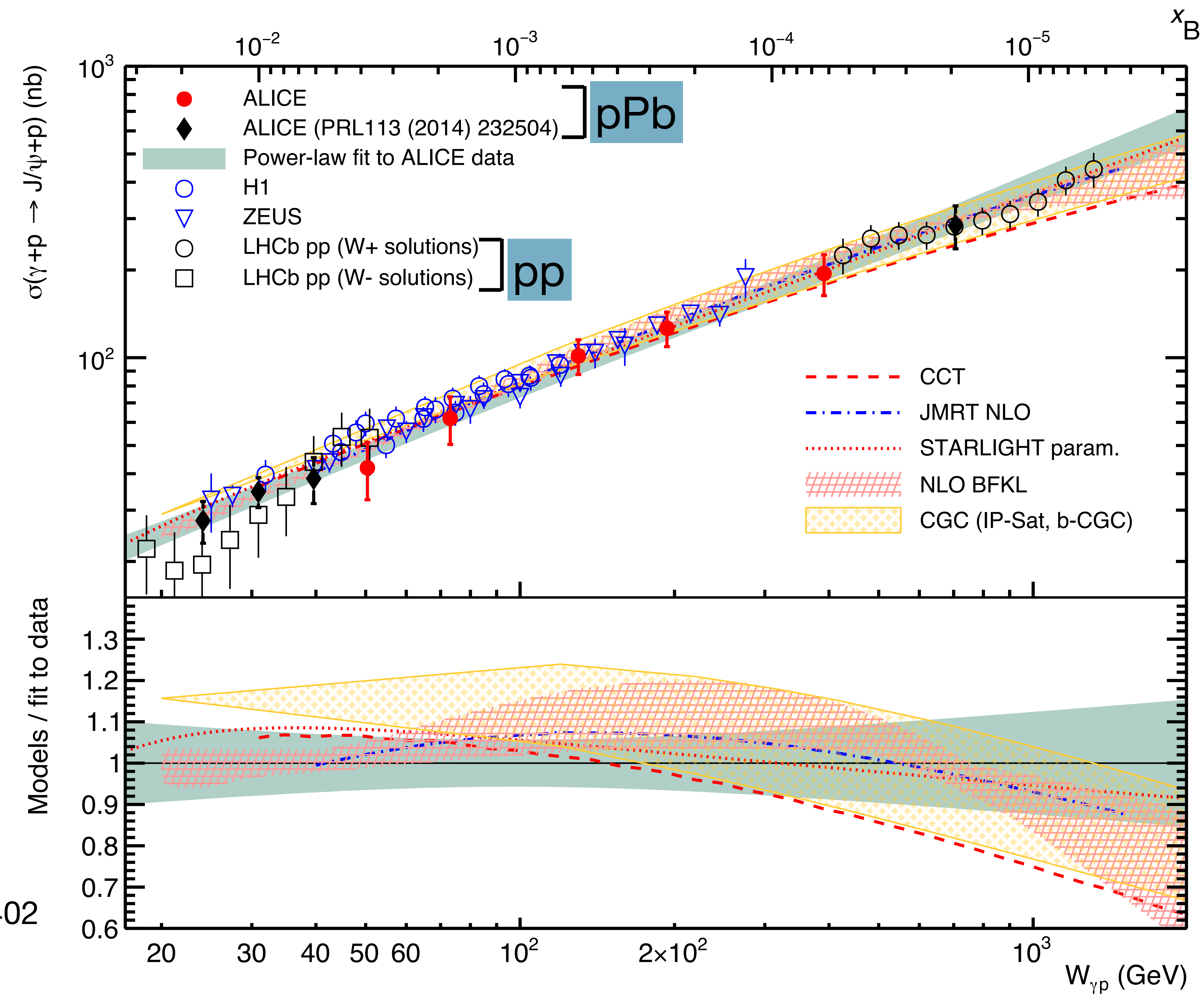
GPD H



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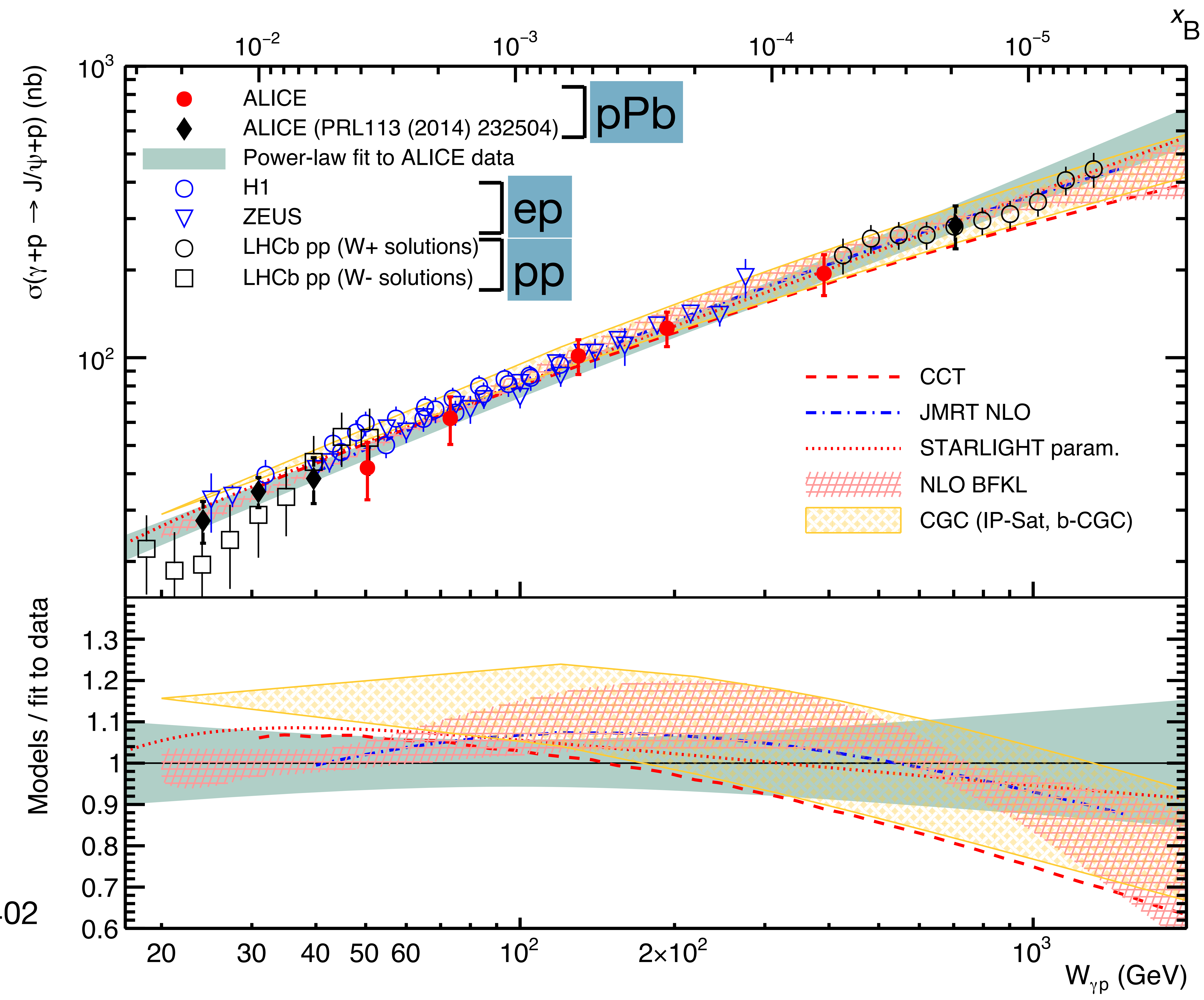
γp cross section: LHC

GPD H



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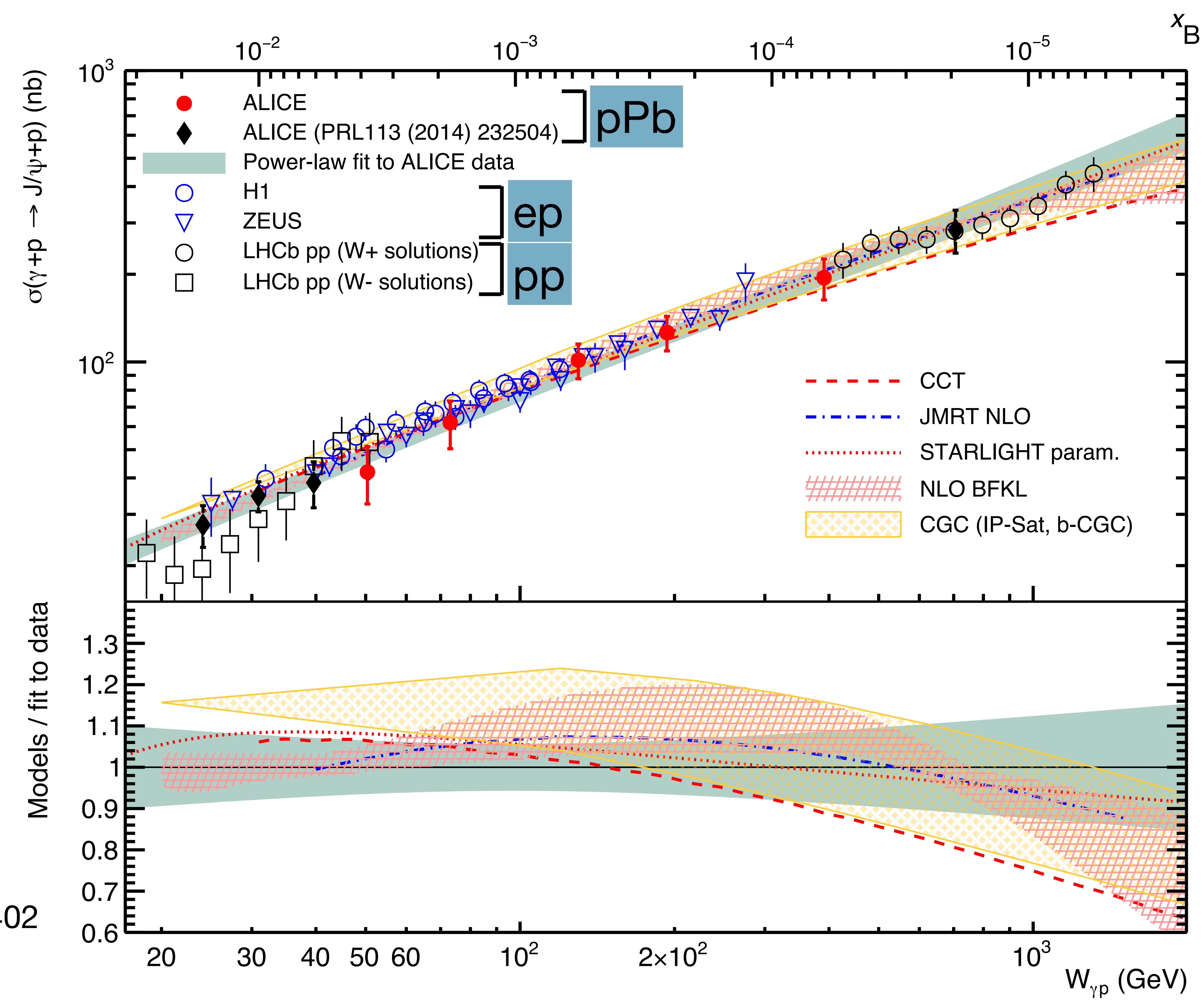

GPD H

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

Ultra-peripheral PbPb collisions

What object are we probing?

Ultra-peripheral PbPb collisions

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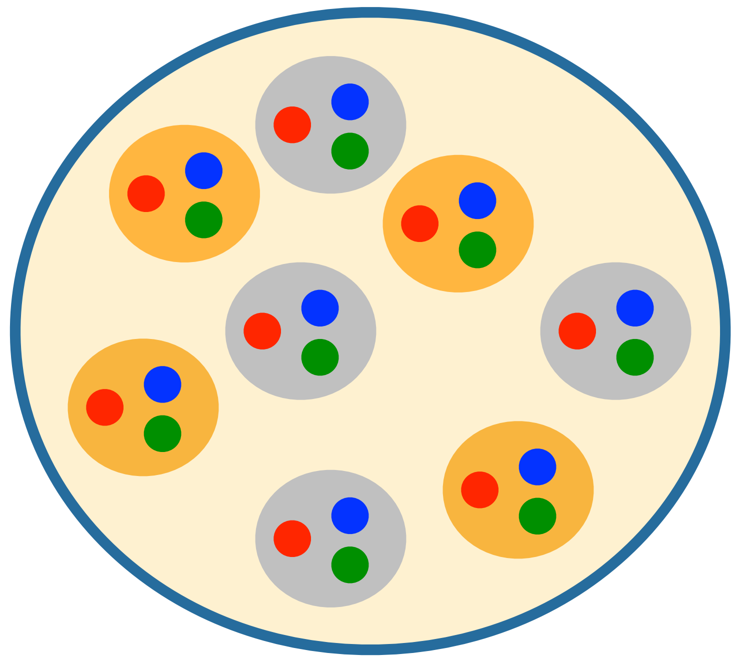

Ultra-peripheral PbPb collisions

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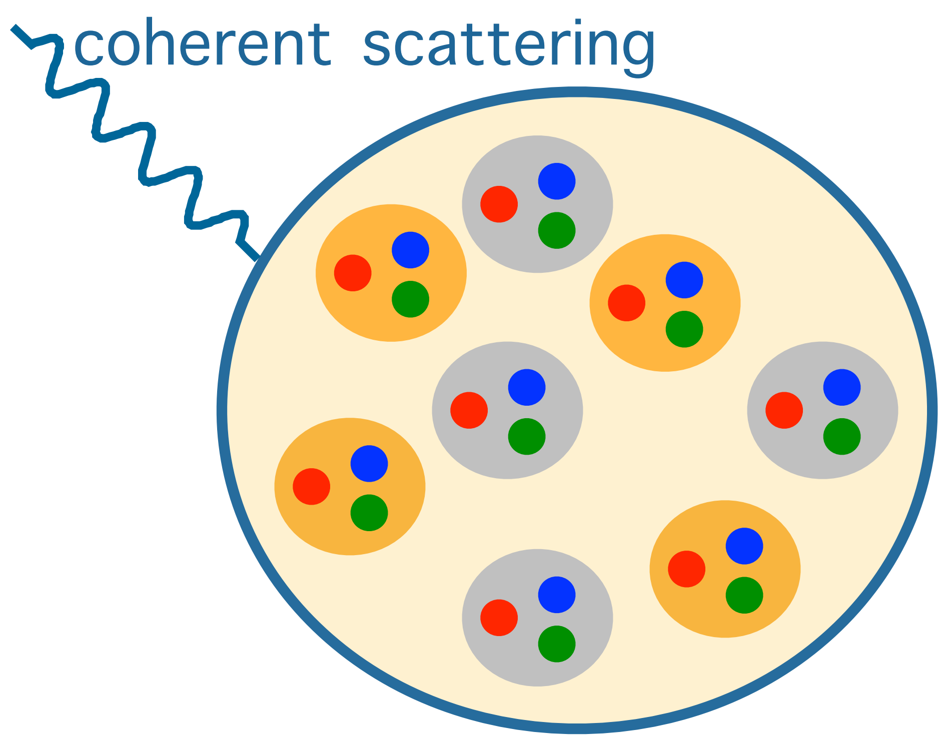
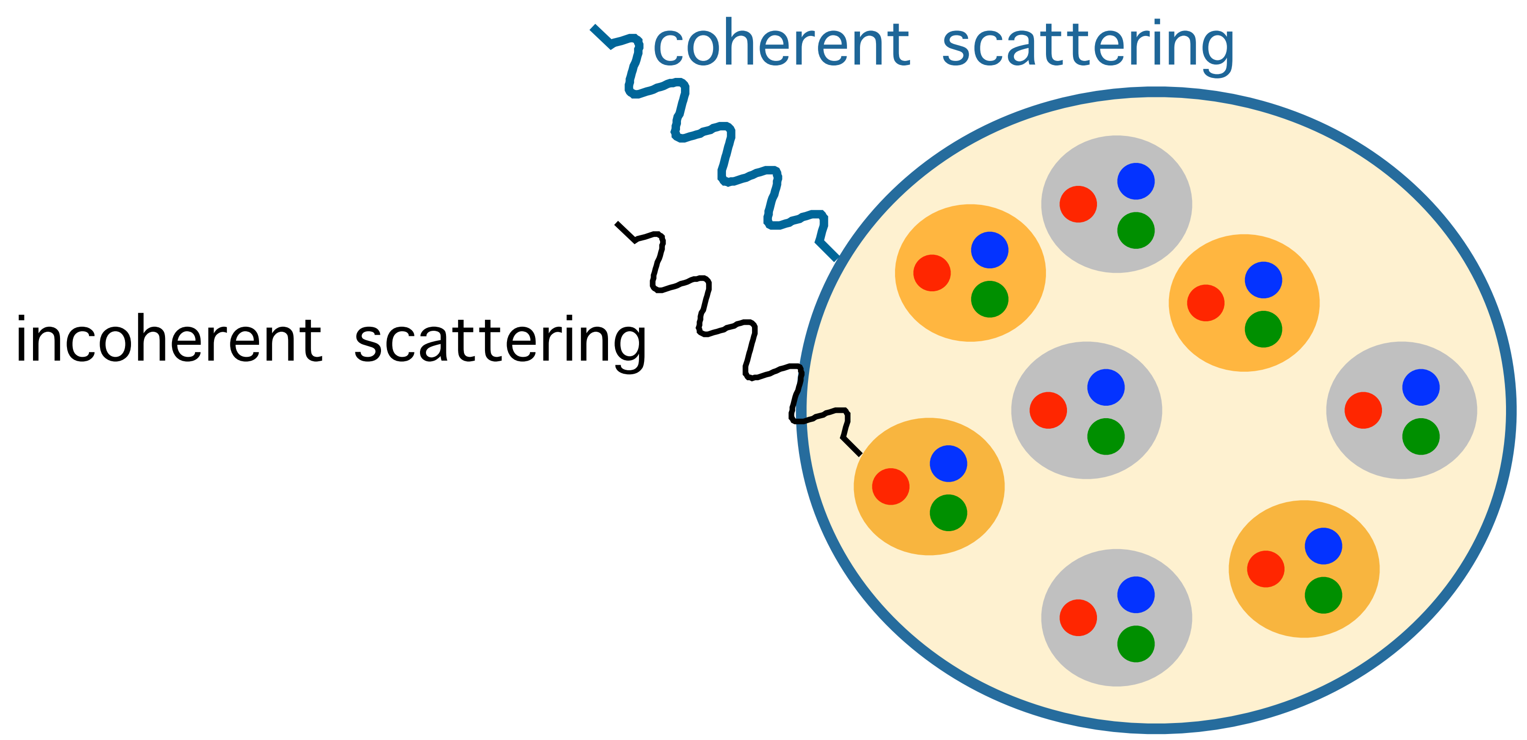


Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Ultra-peripheral PbPb collisions

What object are we probing?



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 PbPb collisions

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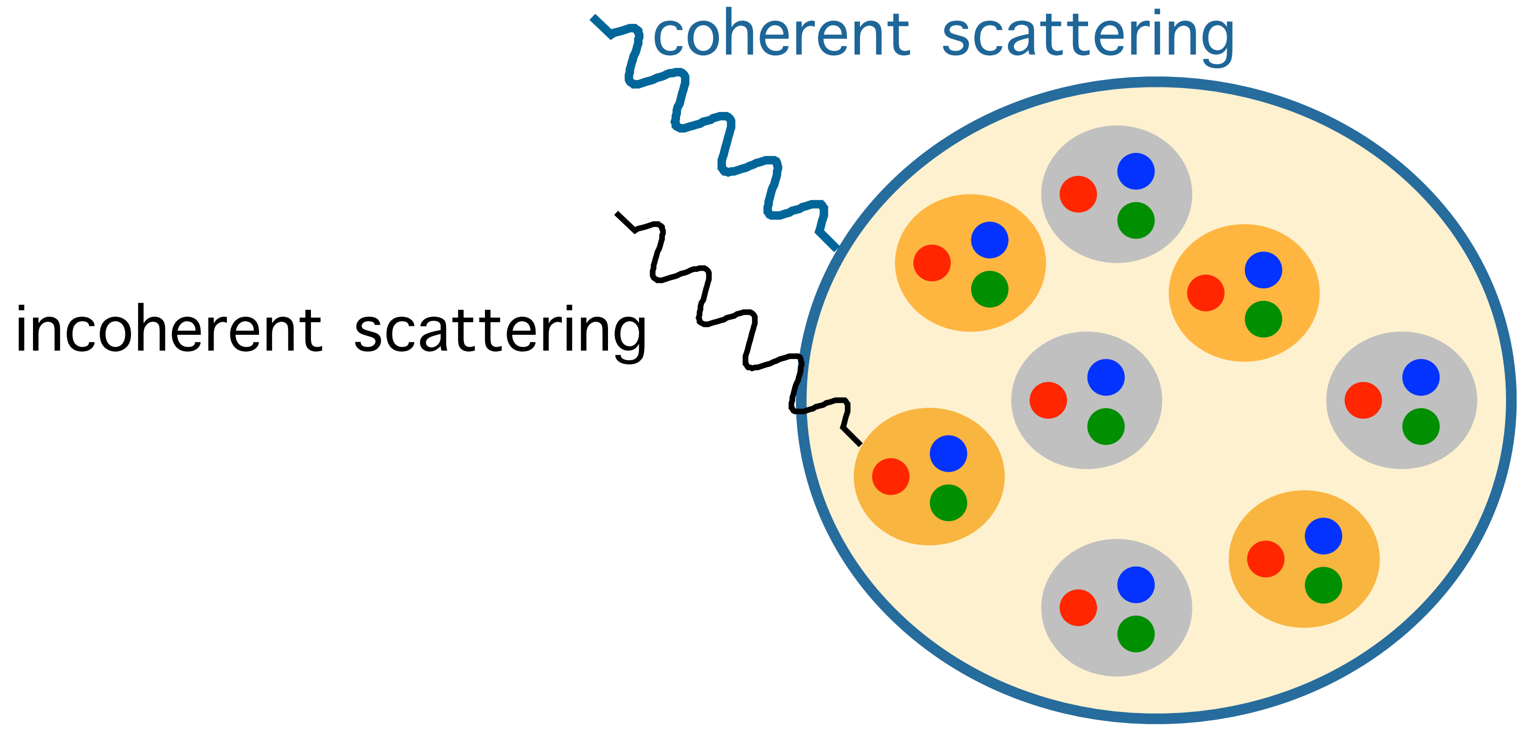

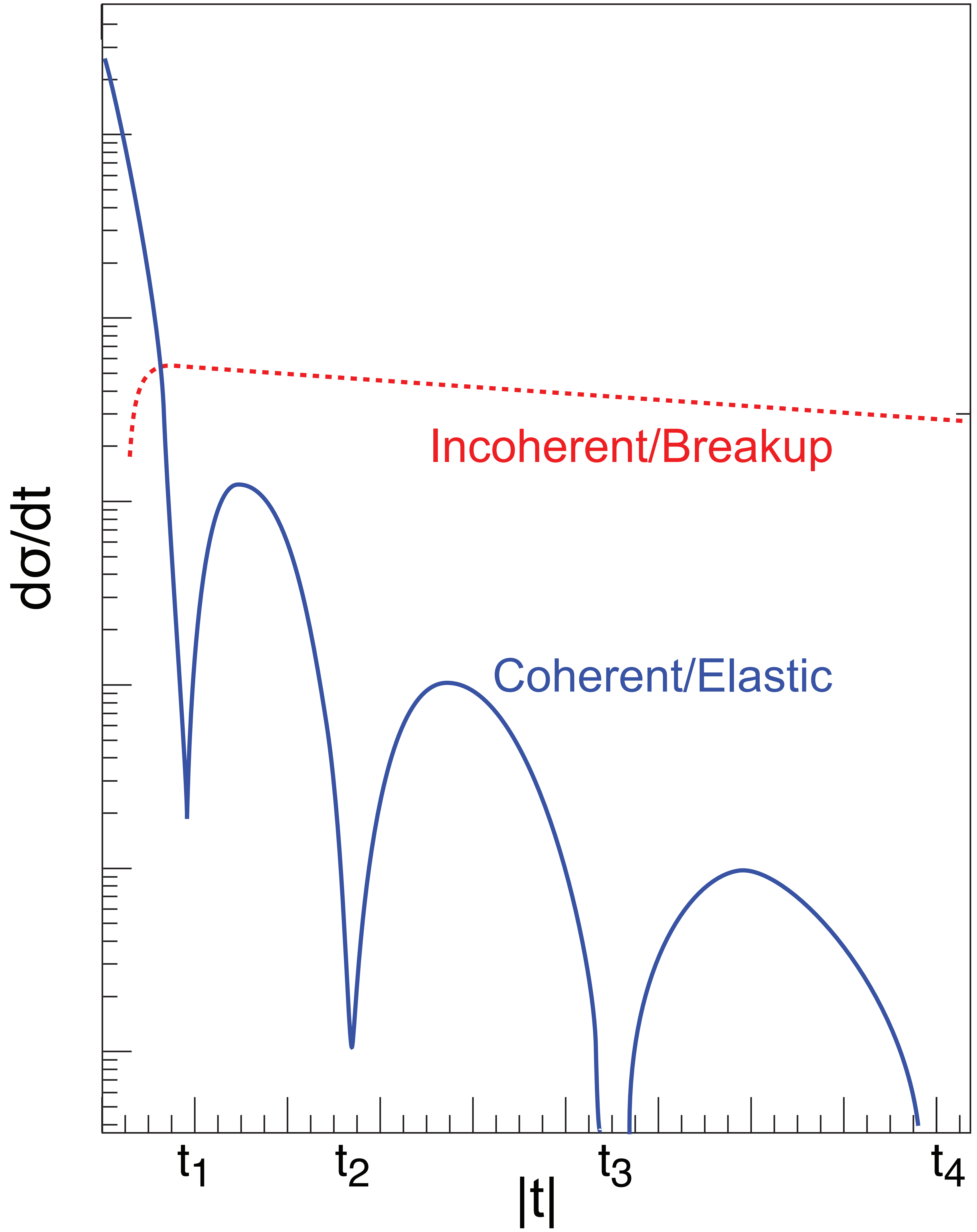

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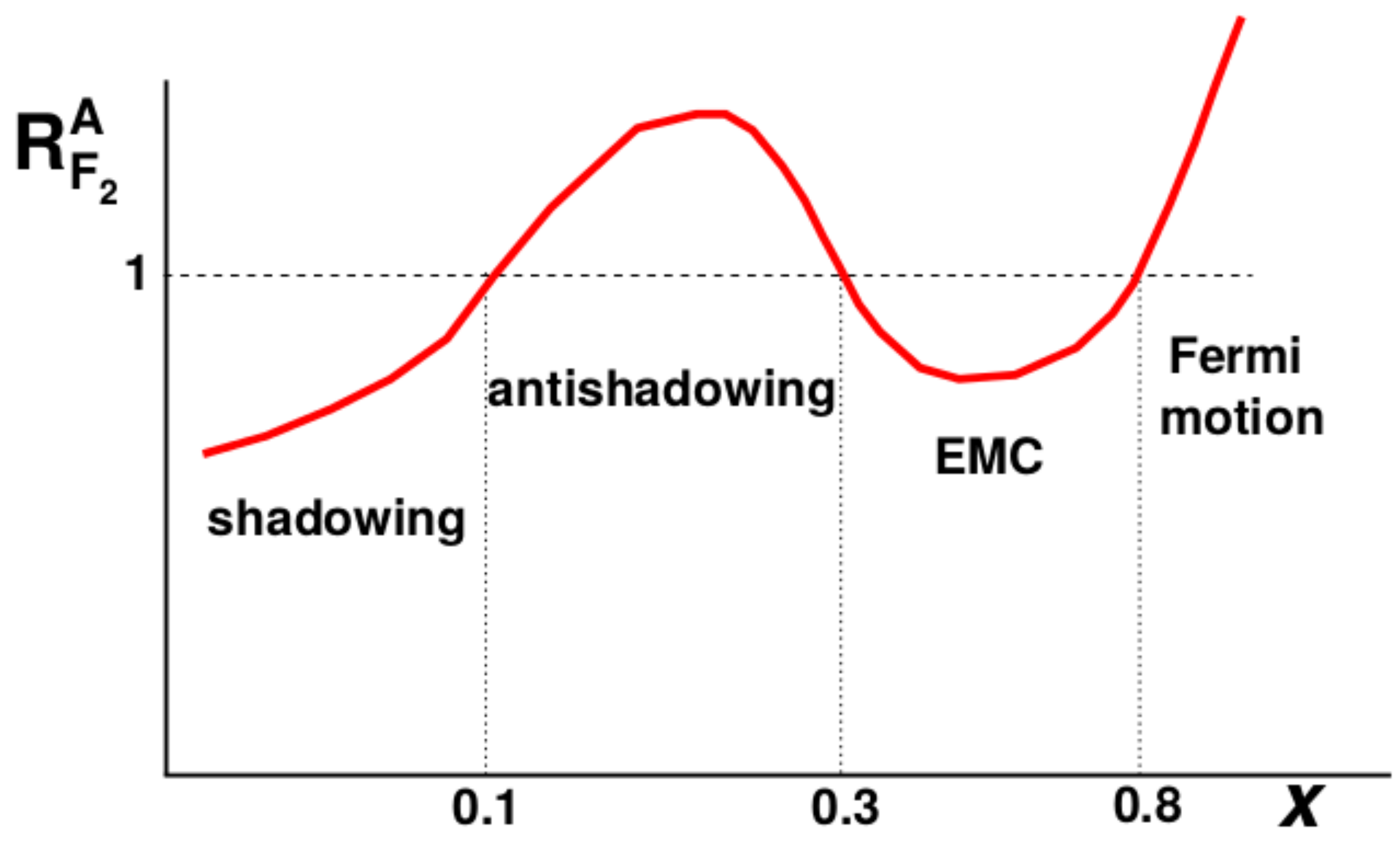
Coherent production

Nuclear GPDs (PDFs at low x_B)



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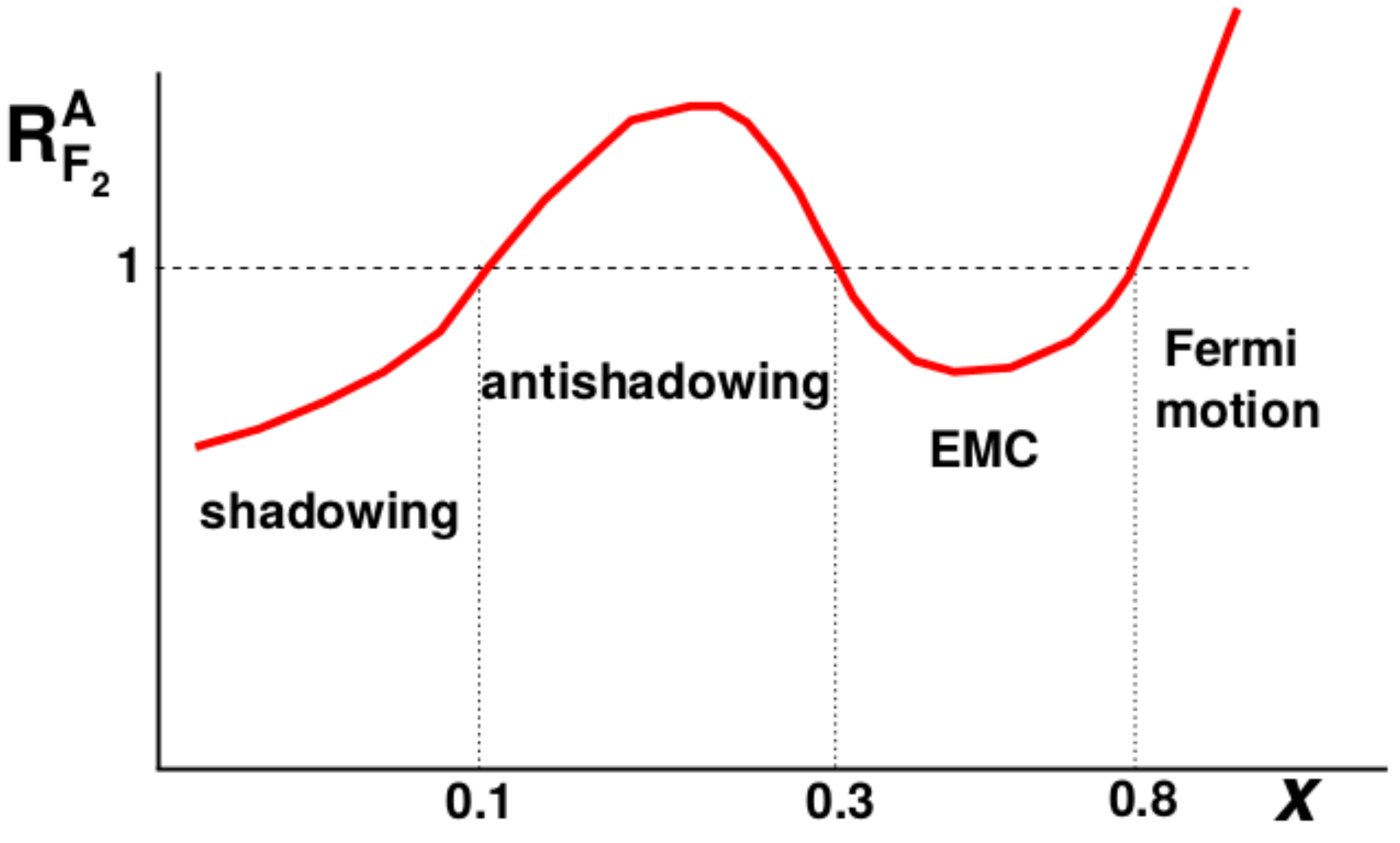
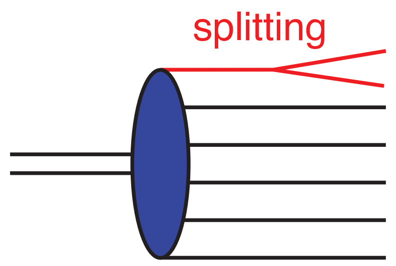
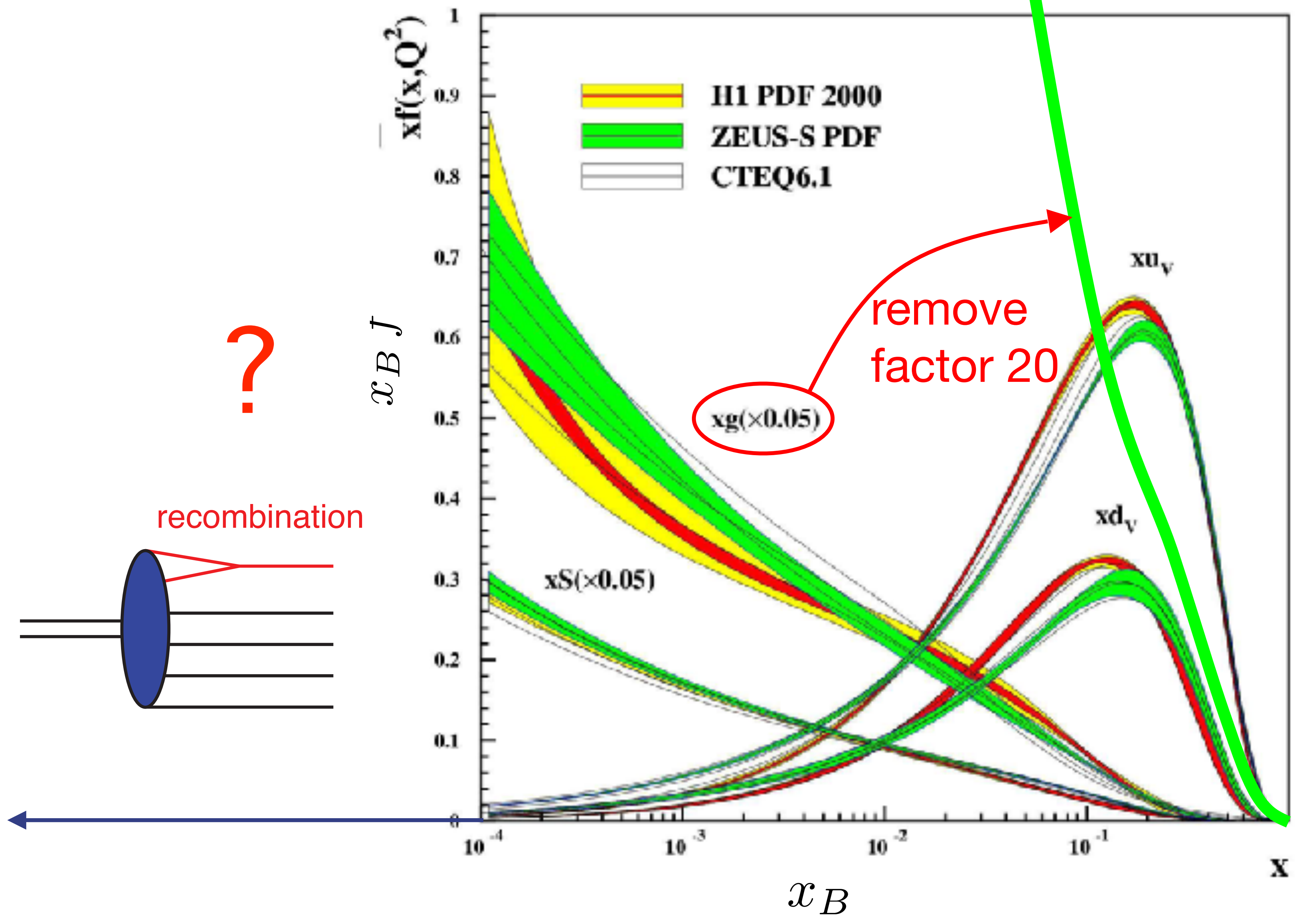
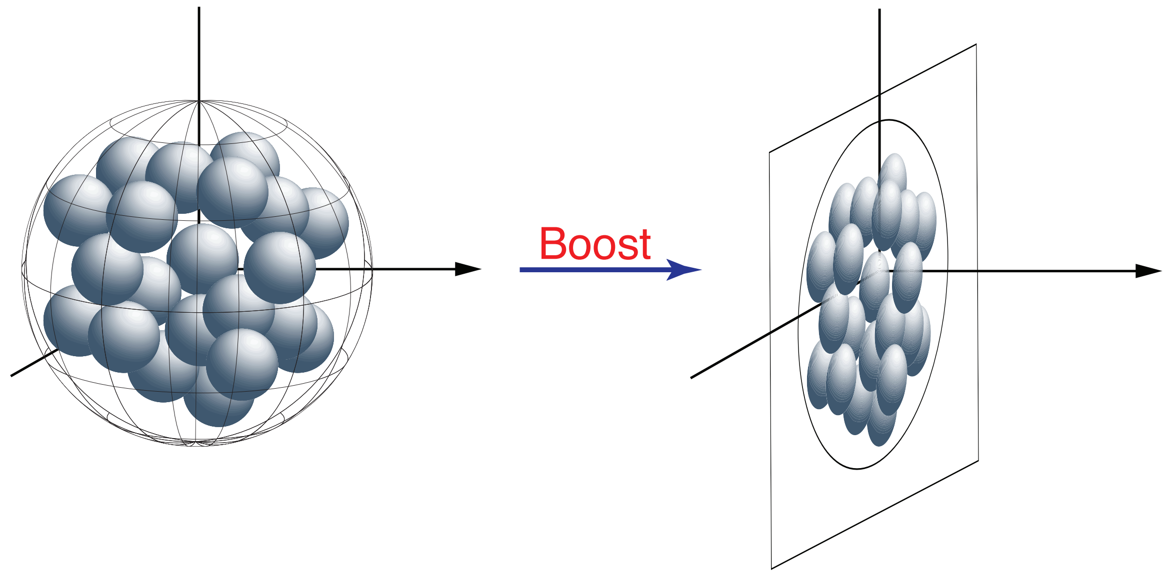


Probing saturation

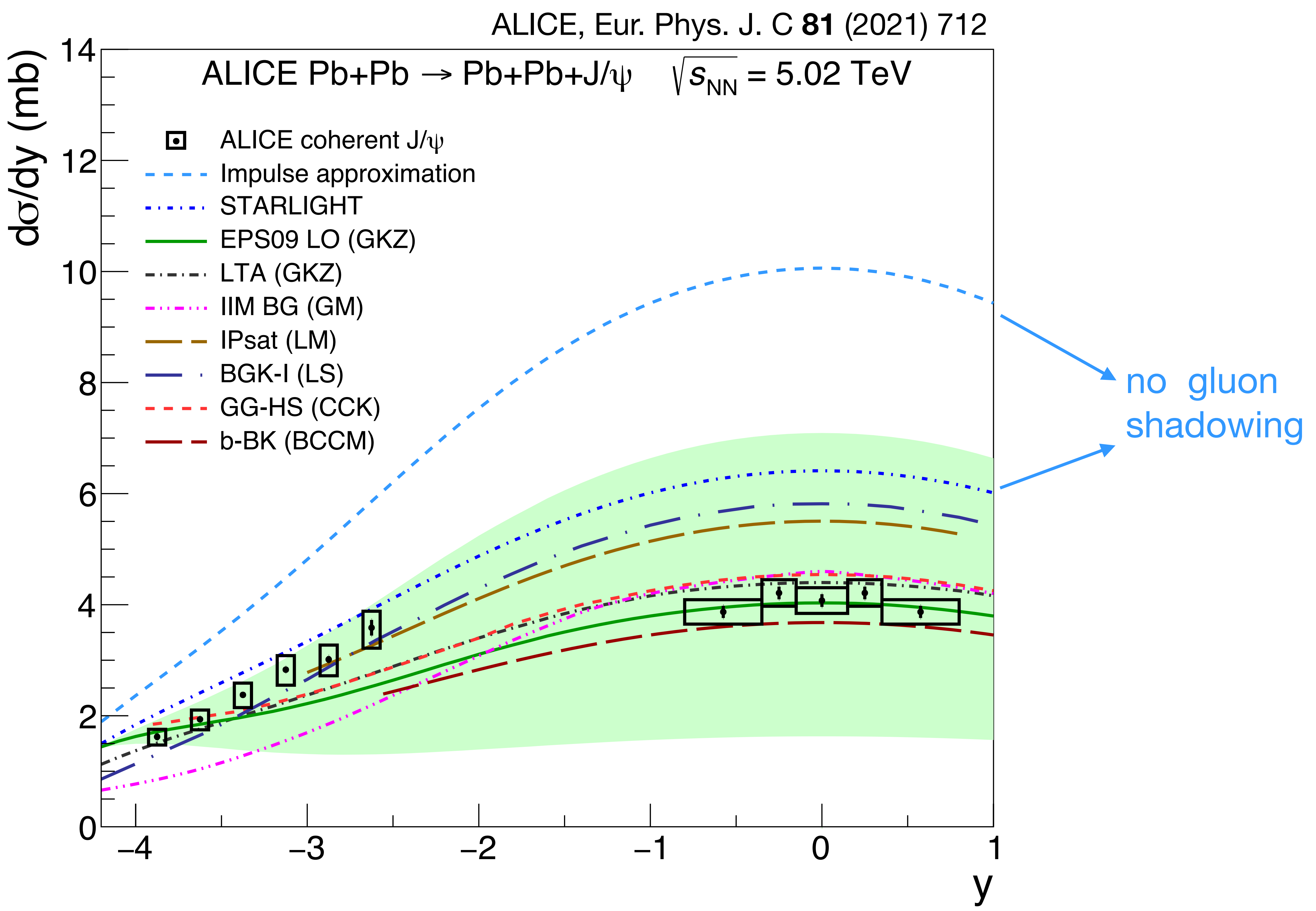




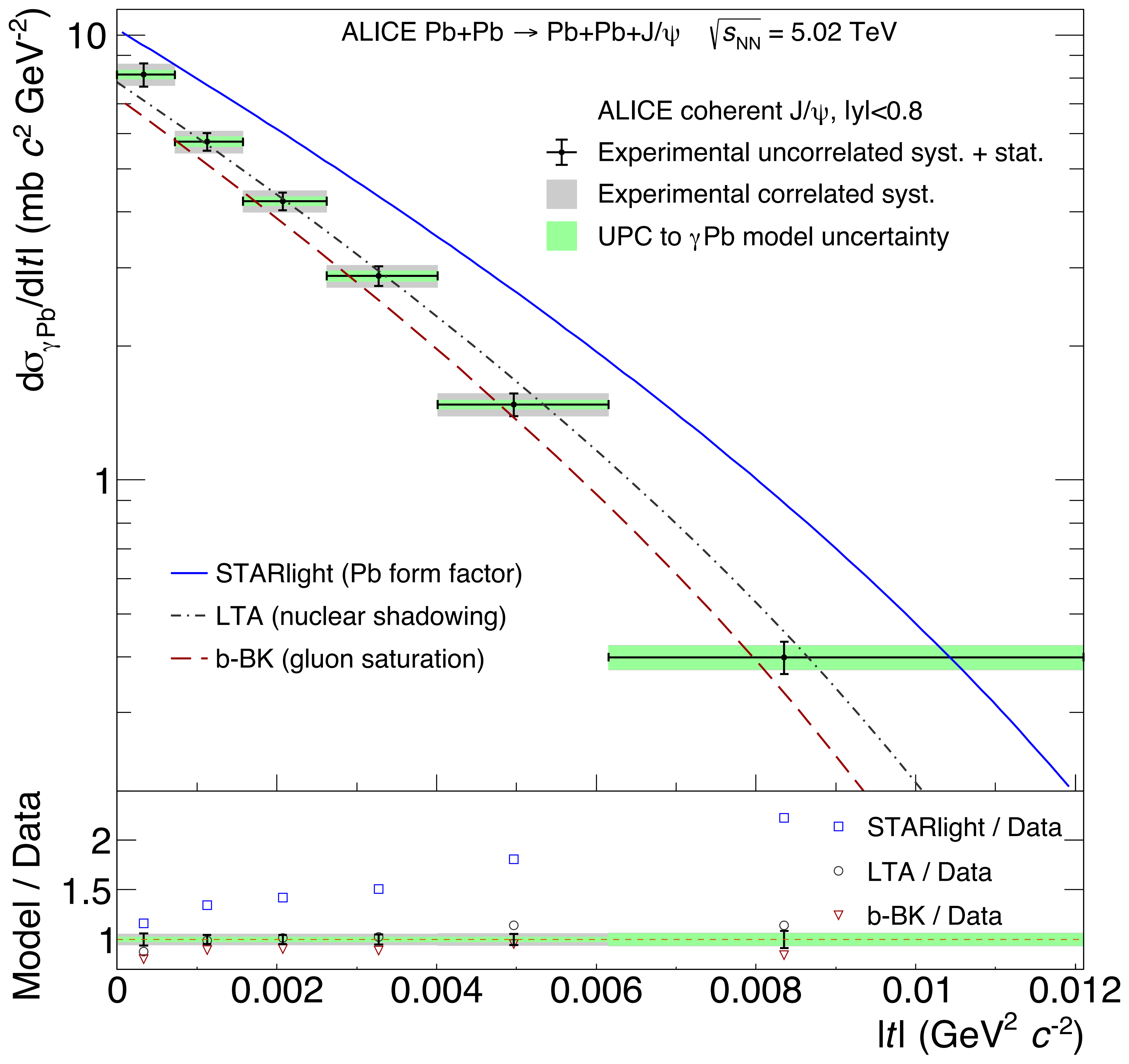


$A^{1/3}$ enhancement
of saturation effect for ions

Coherent photoproduction in PbPb at ALICE



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



$-4.0<y<-2.5$

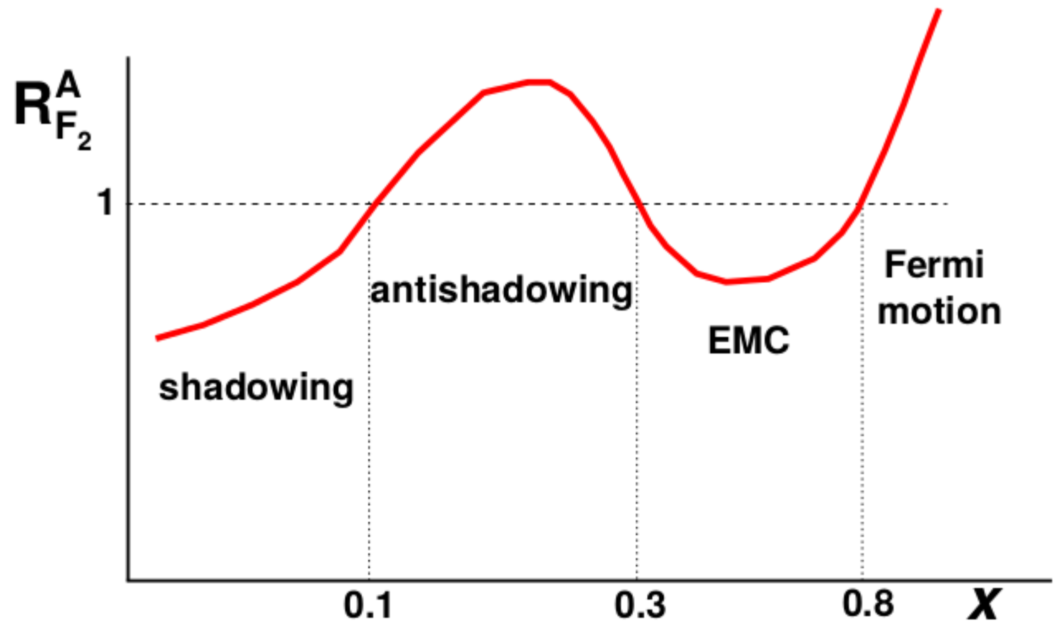
$|y|<0.8 \longleftrightarrow 0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$

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

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

Results indicate shadowing in gluon PDF:

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

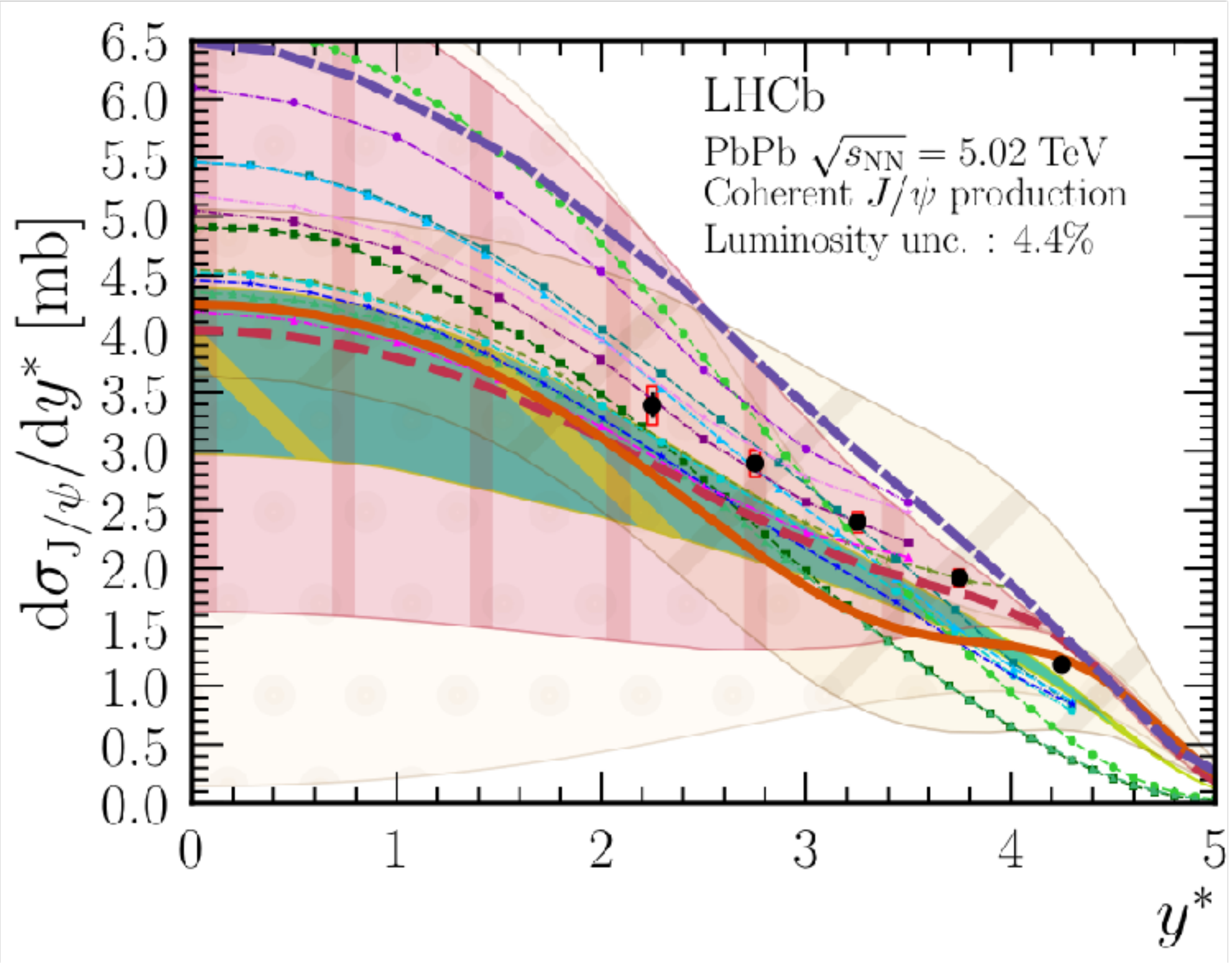


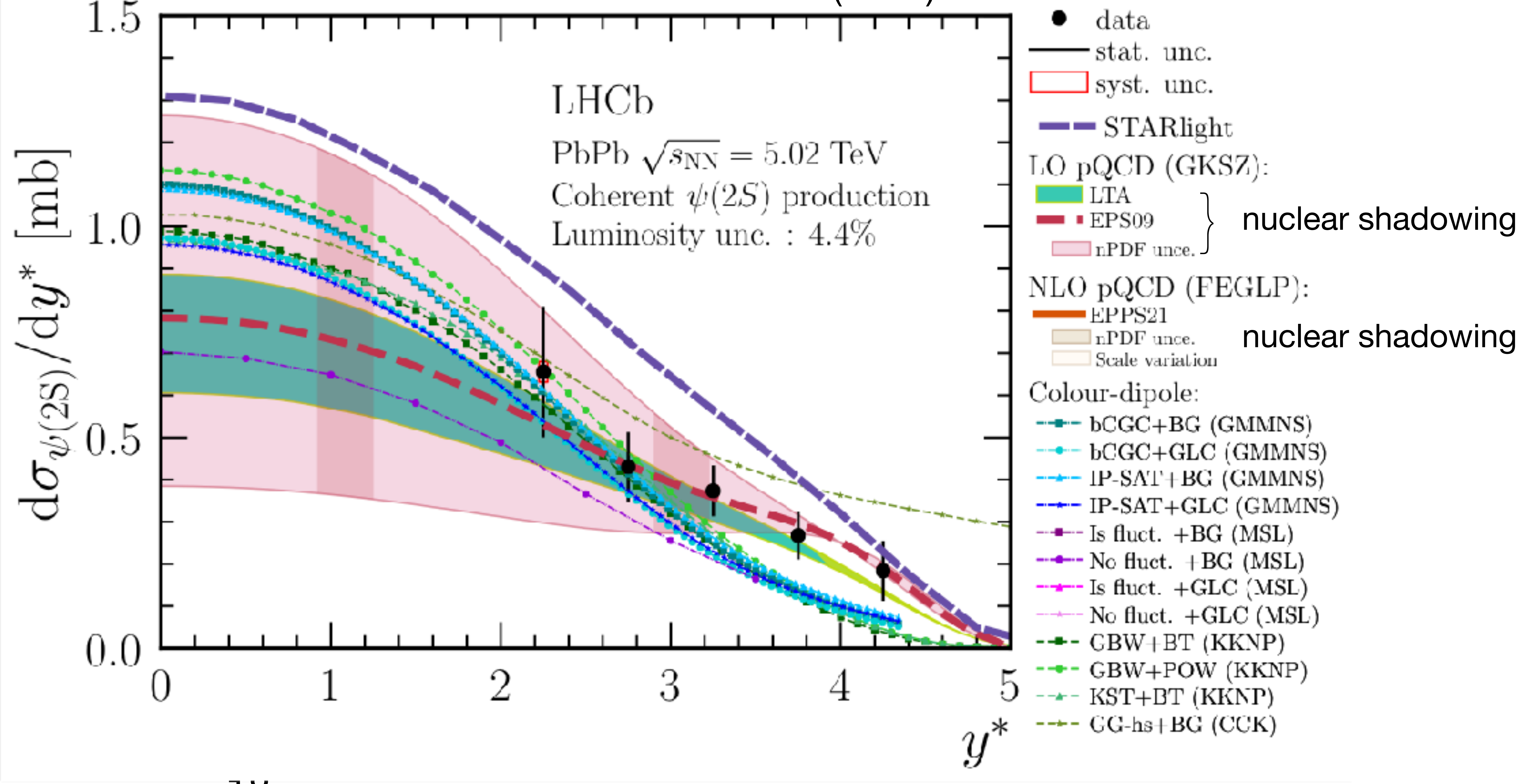
Coherent photoproduction in PbPb at LHCb: y dependence

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

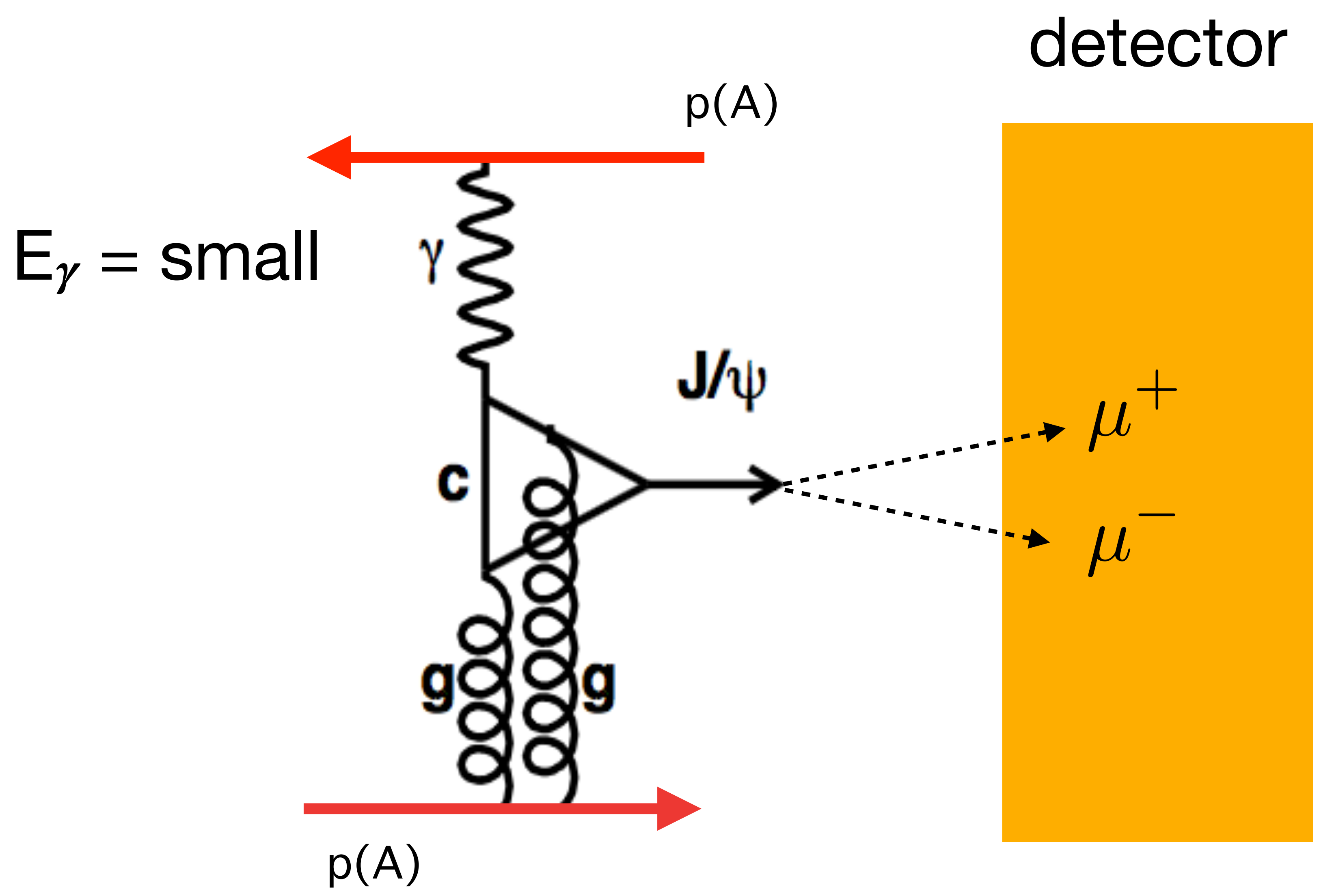
$$\text{Pb} + \text{Pb} \rightarrow \text{Pb} + \text{Pb} + \psi$$

JHEP06(2023)146





Disentangling the ambiguity on the ID of the γ emitter



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

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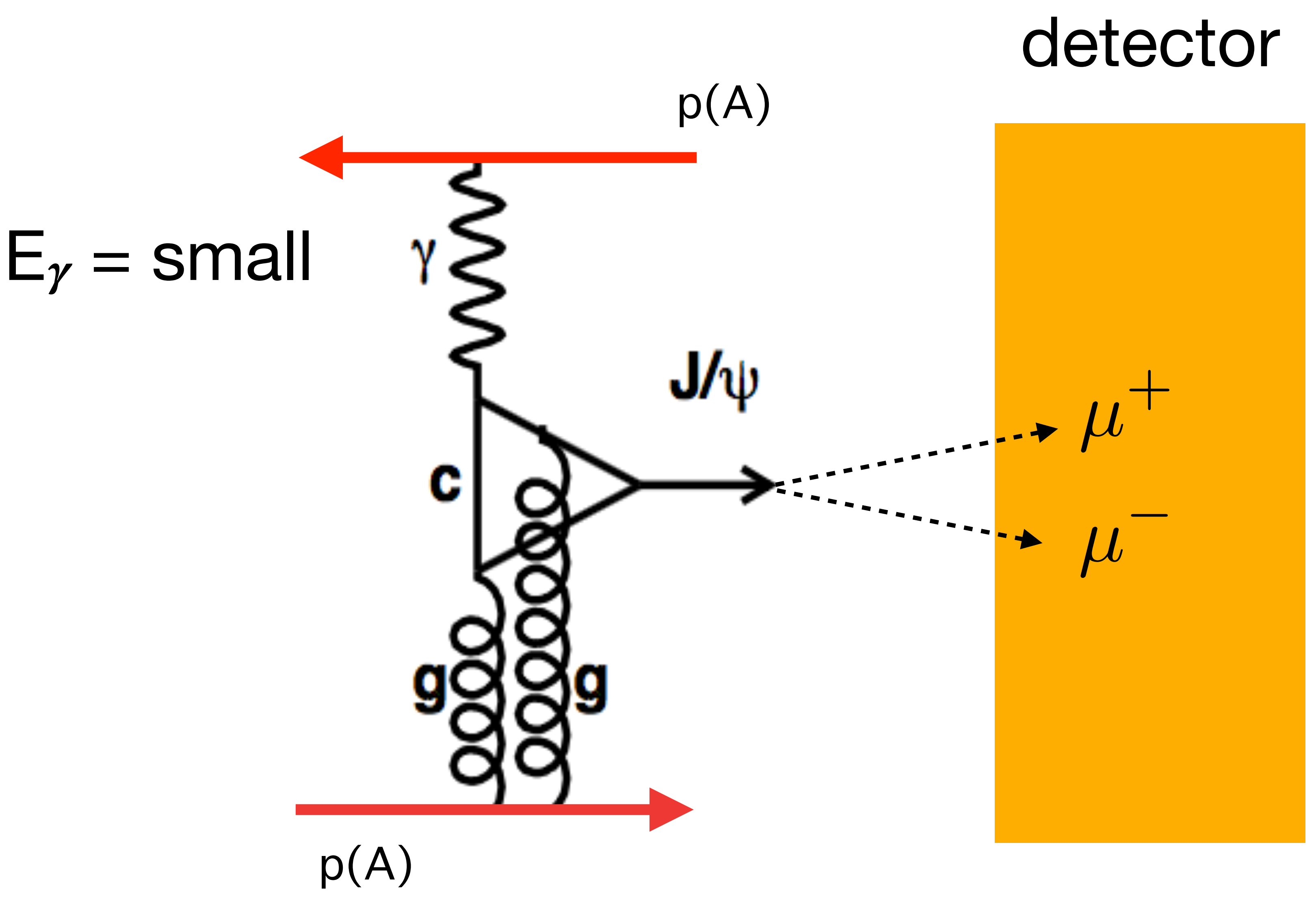

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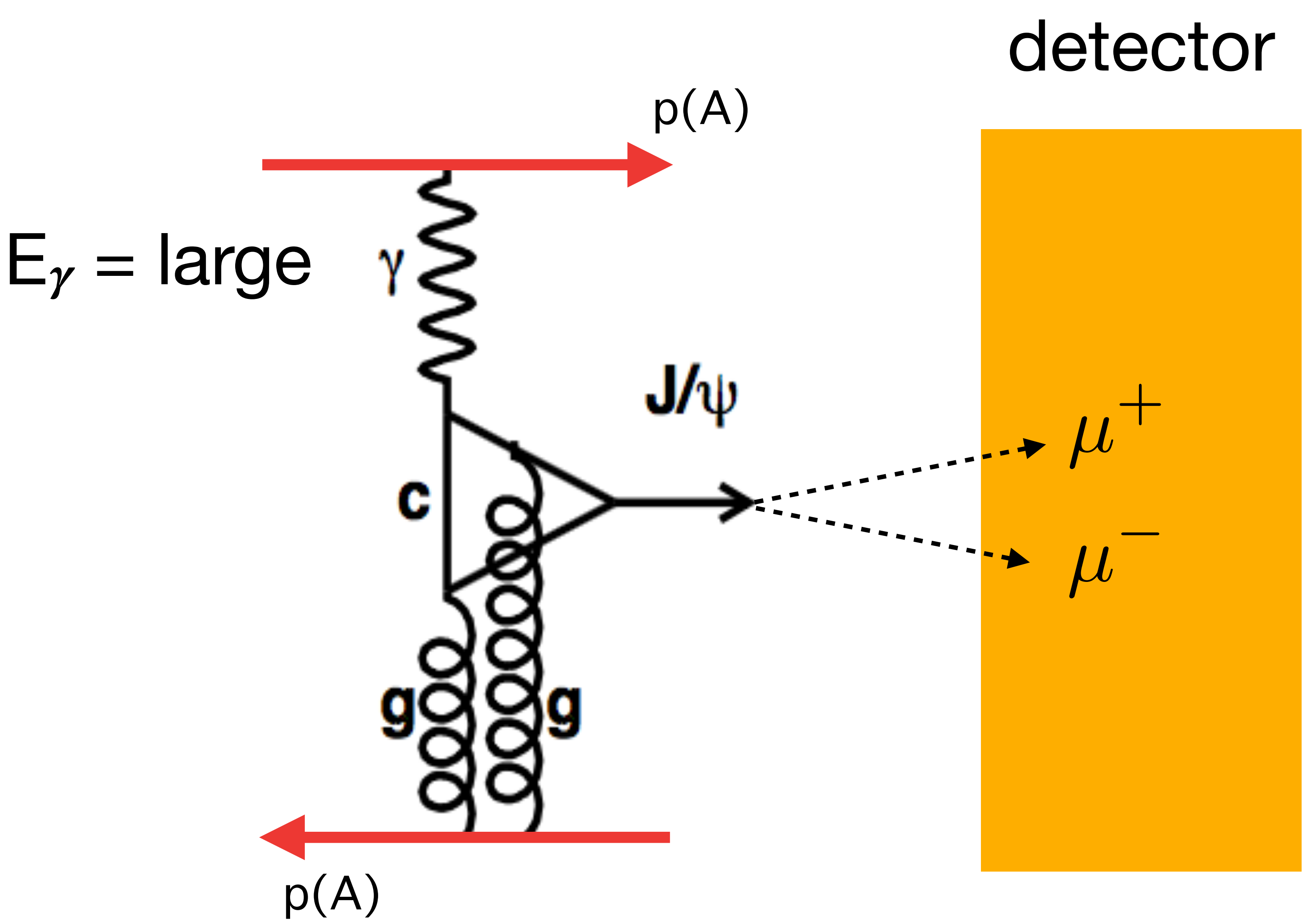

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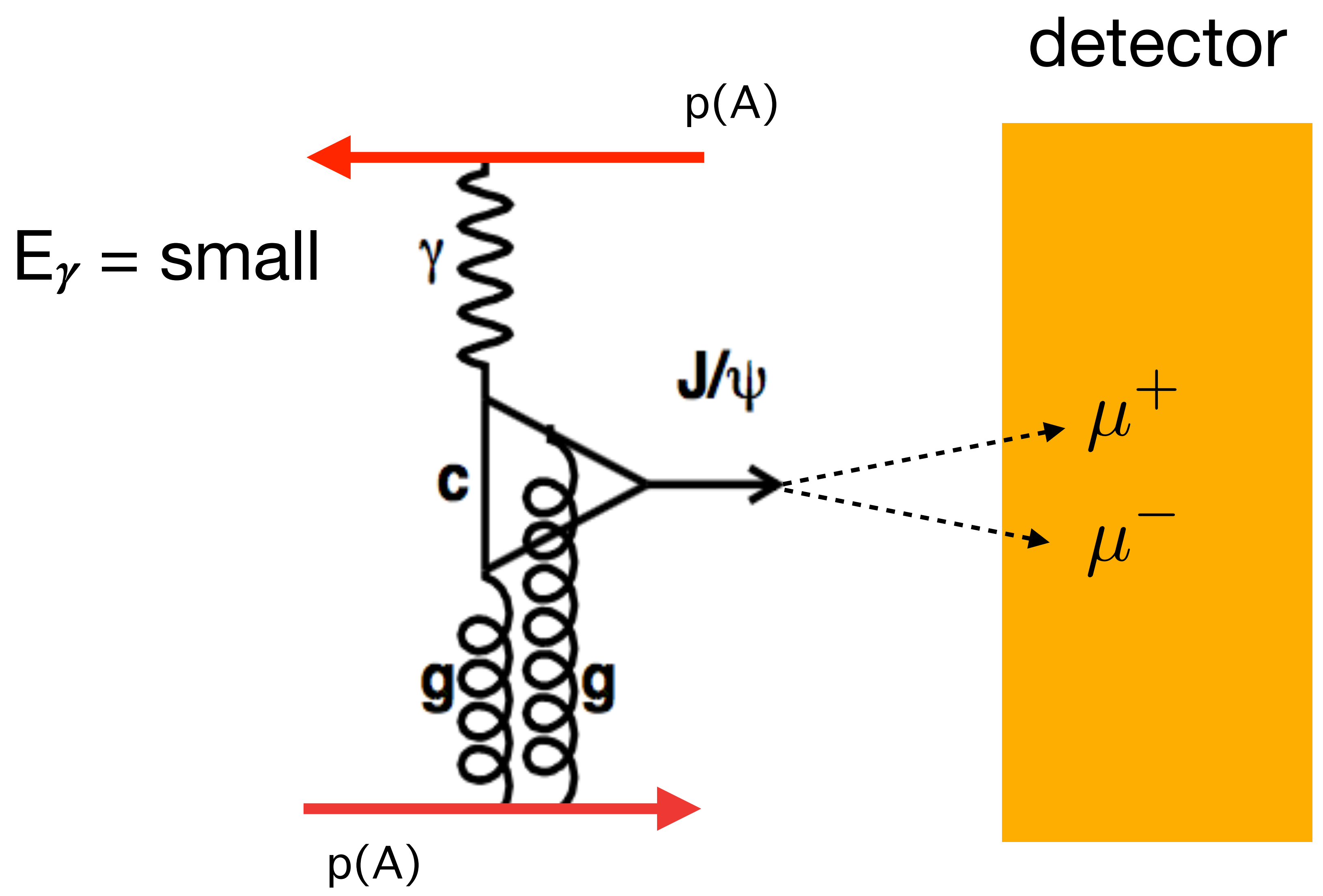

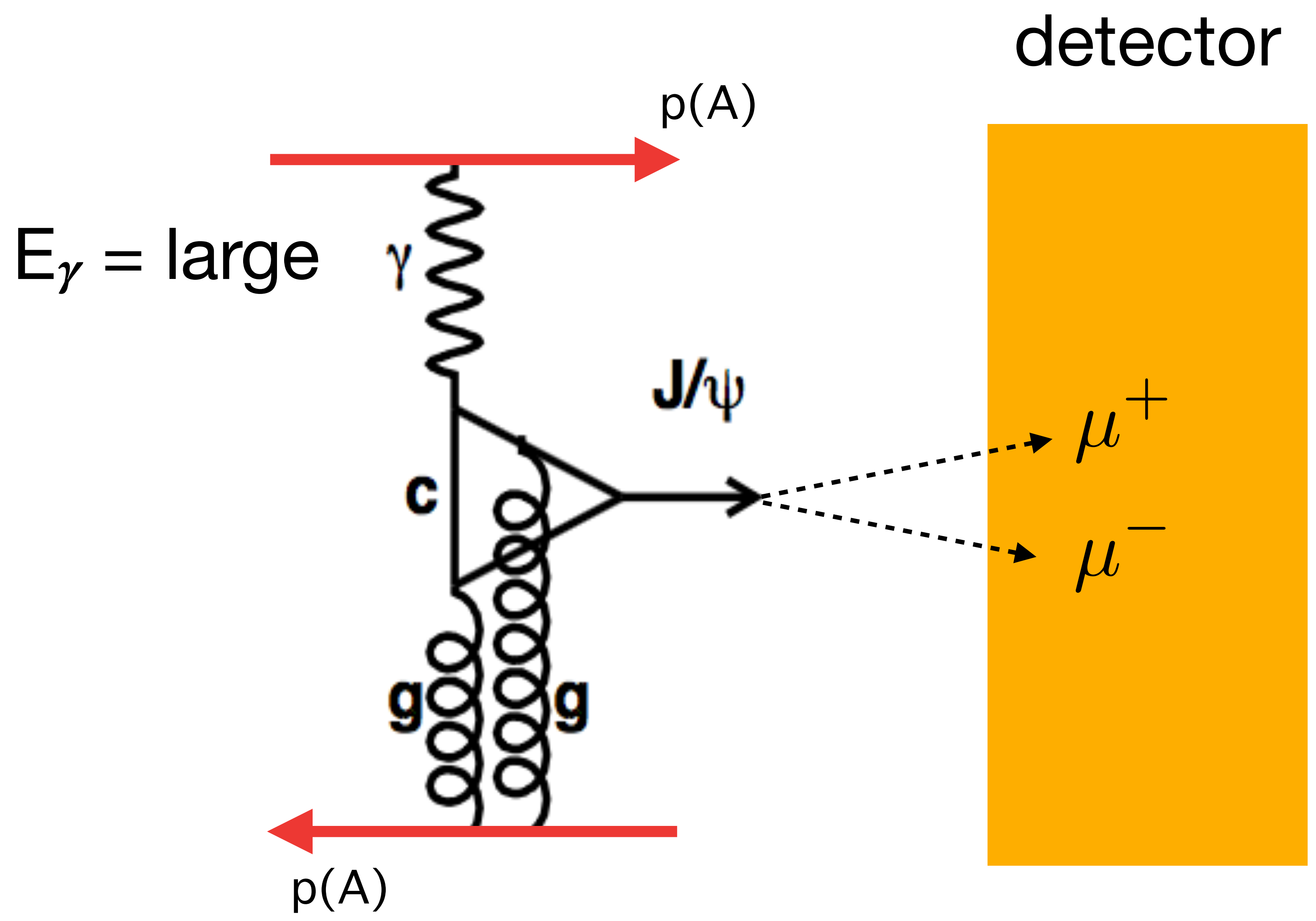

$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

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

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

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Baltz et. al., PRL **89** (2002) 012301
Guzey et. al. EPJC **74** (2014) 7

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enhanced for large E_γ at small impact parameter.

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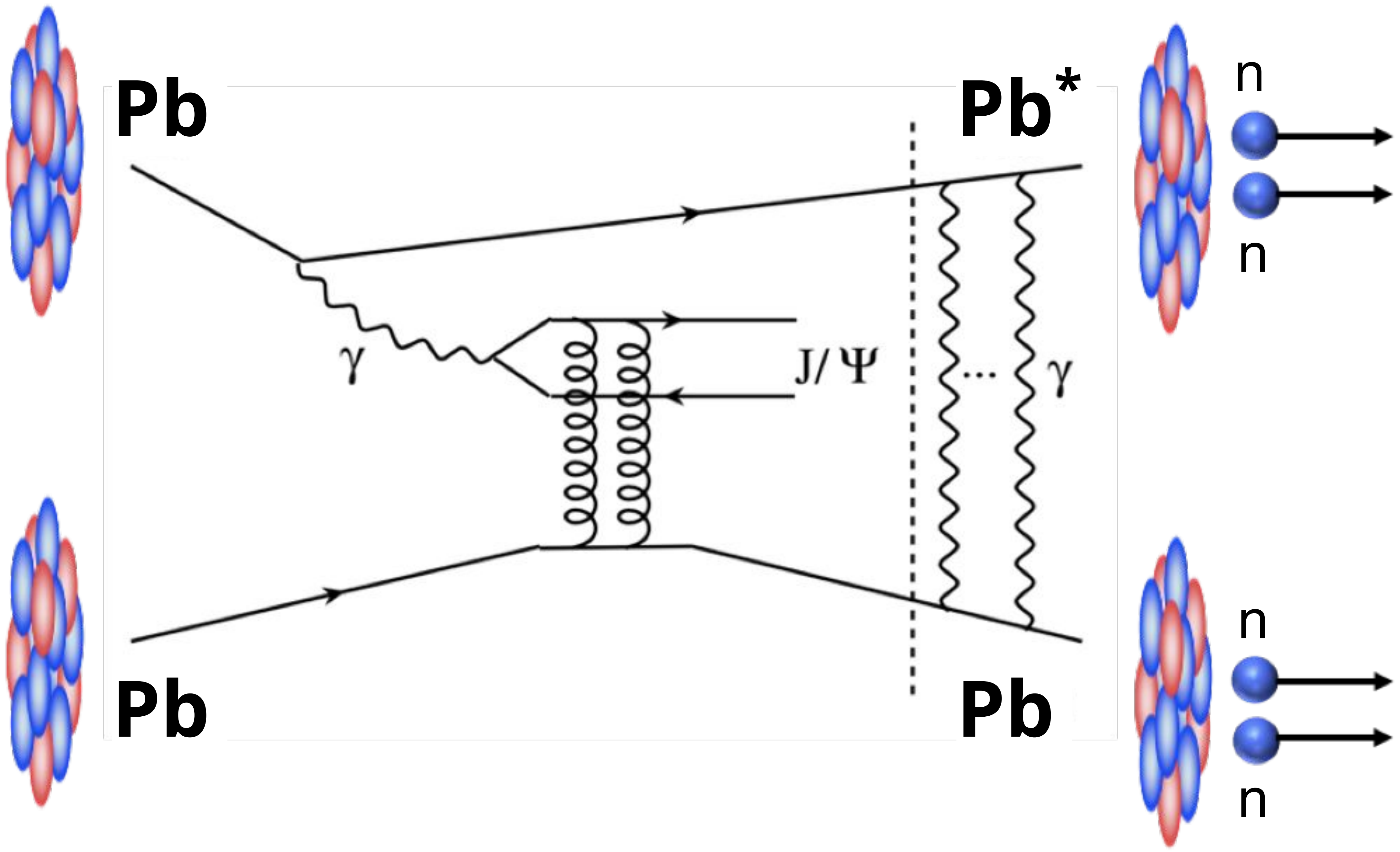
Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.



Picture from André Ståhl

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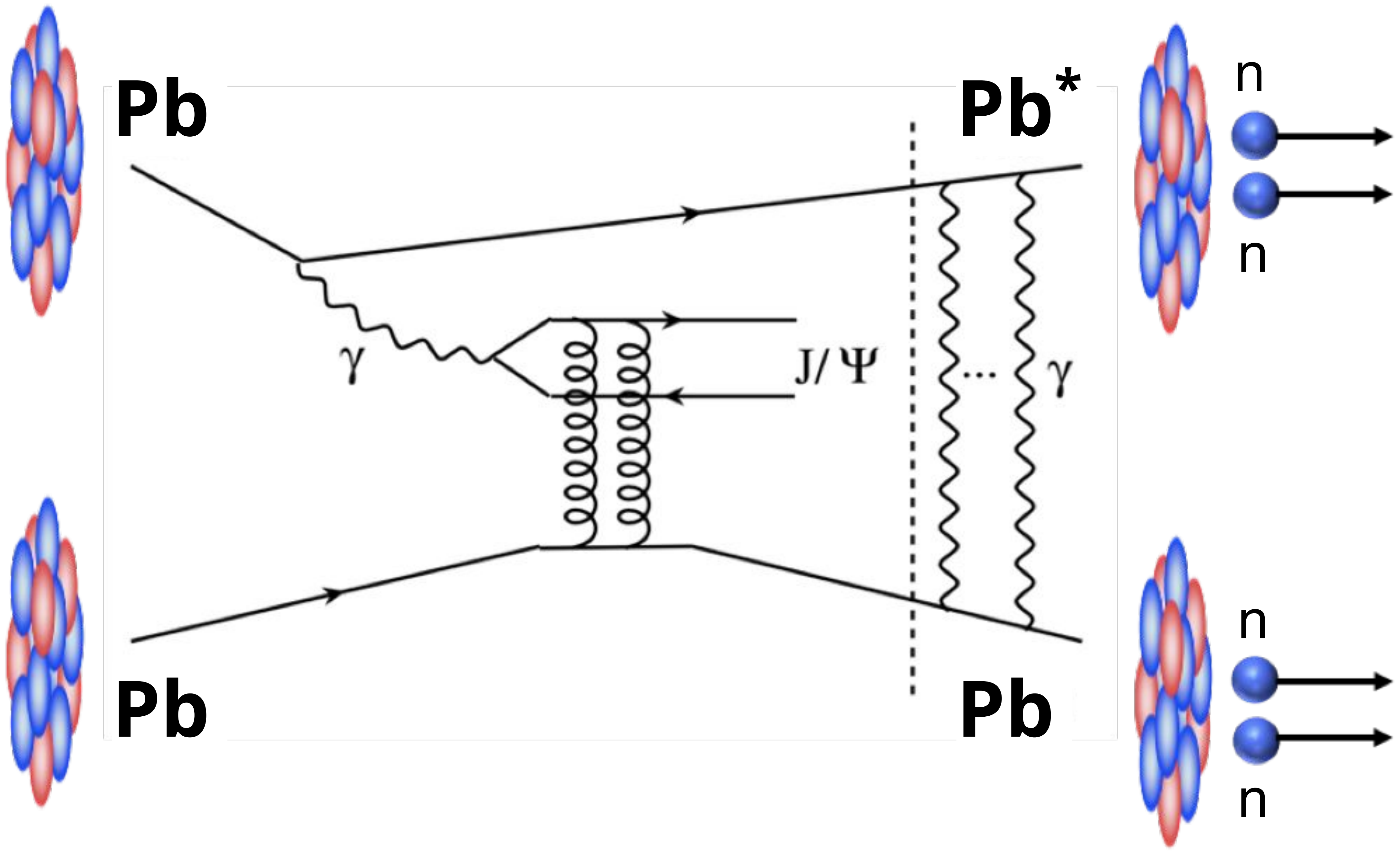
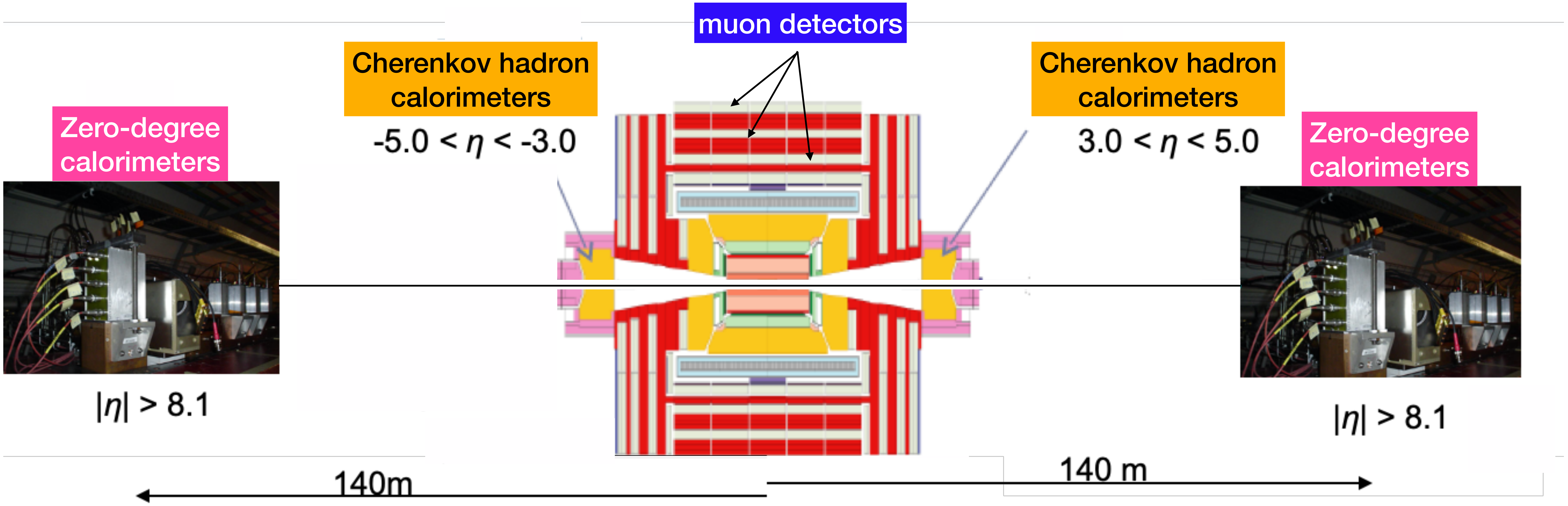


⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS central detector and the (far-)forward region



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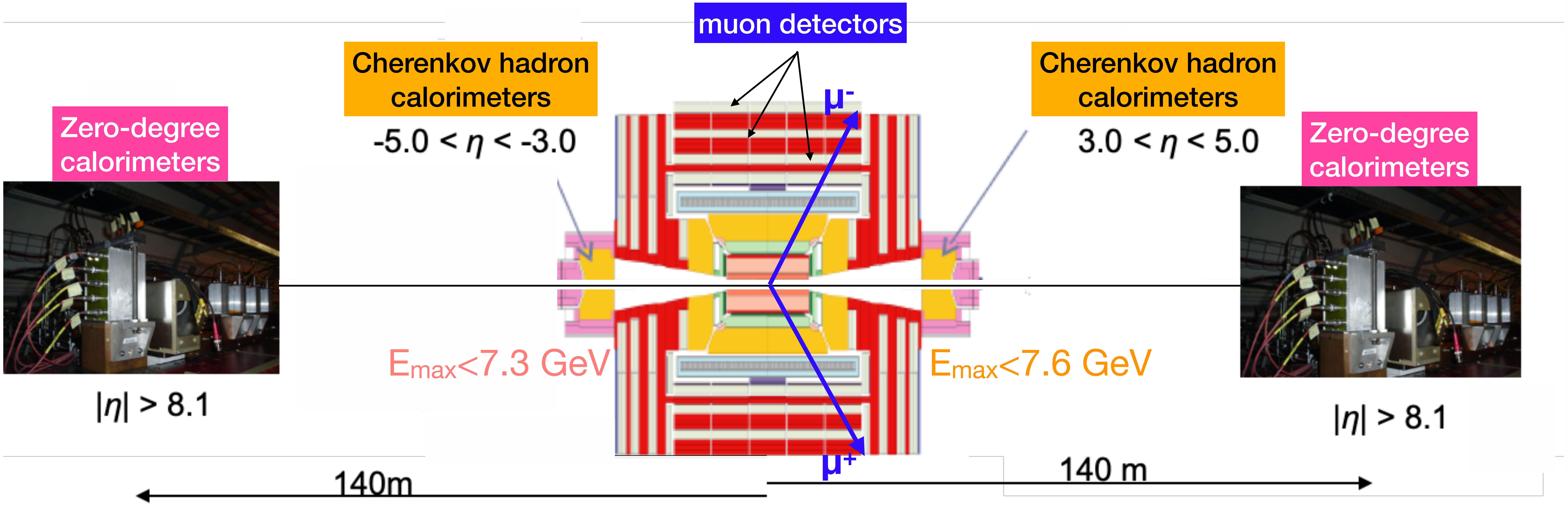

$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

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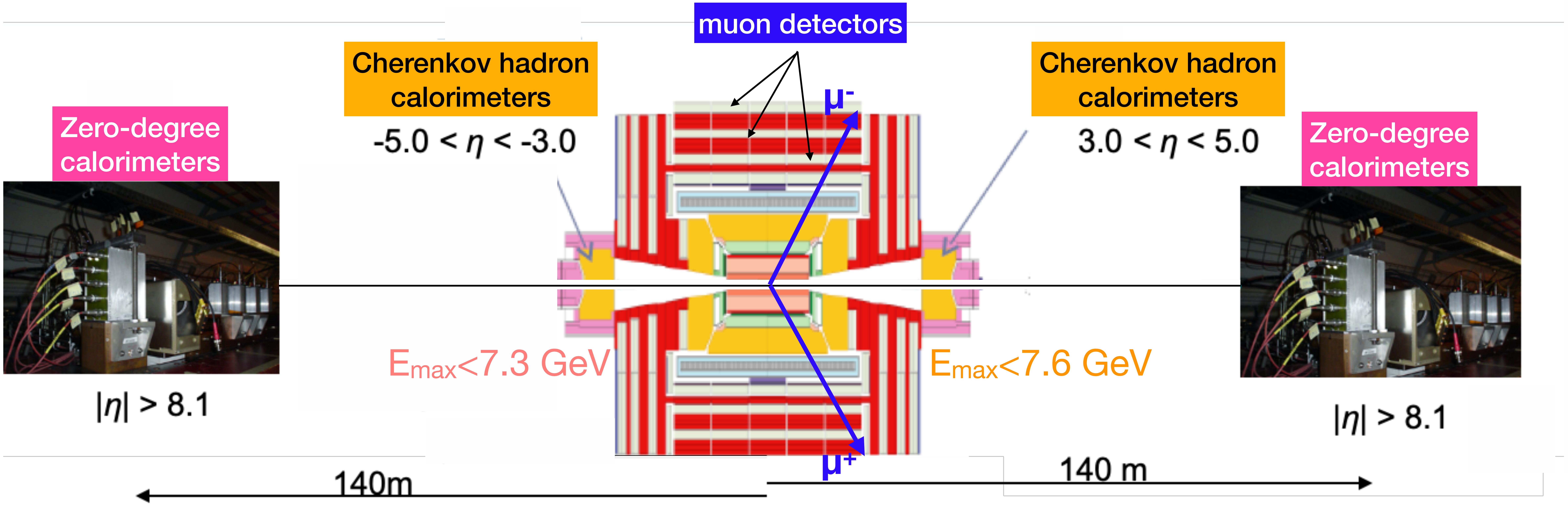

$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

0 neutrons
≥1 neutron

0n0n
0nXn
XnXn

0 neutrons
≥1 neutron

Disentangling the ambiguity on the ID of the γ emitter

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

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

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

measured

Disentangling the ambiguity on the ID of the γ emitter

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

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

Disentangling the ambiguity on the ID of the γ emitter

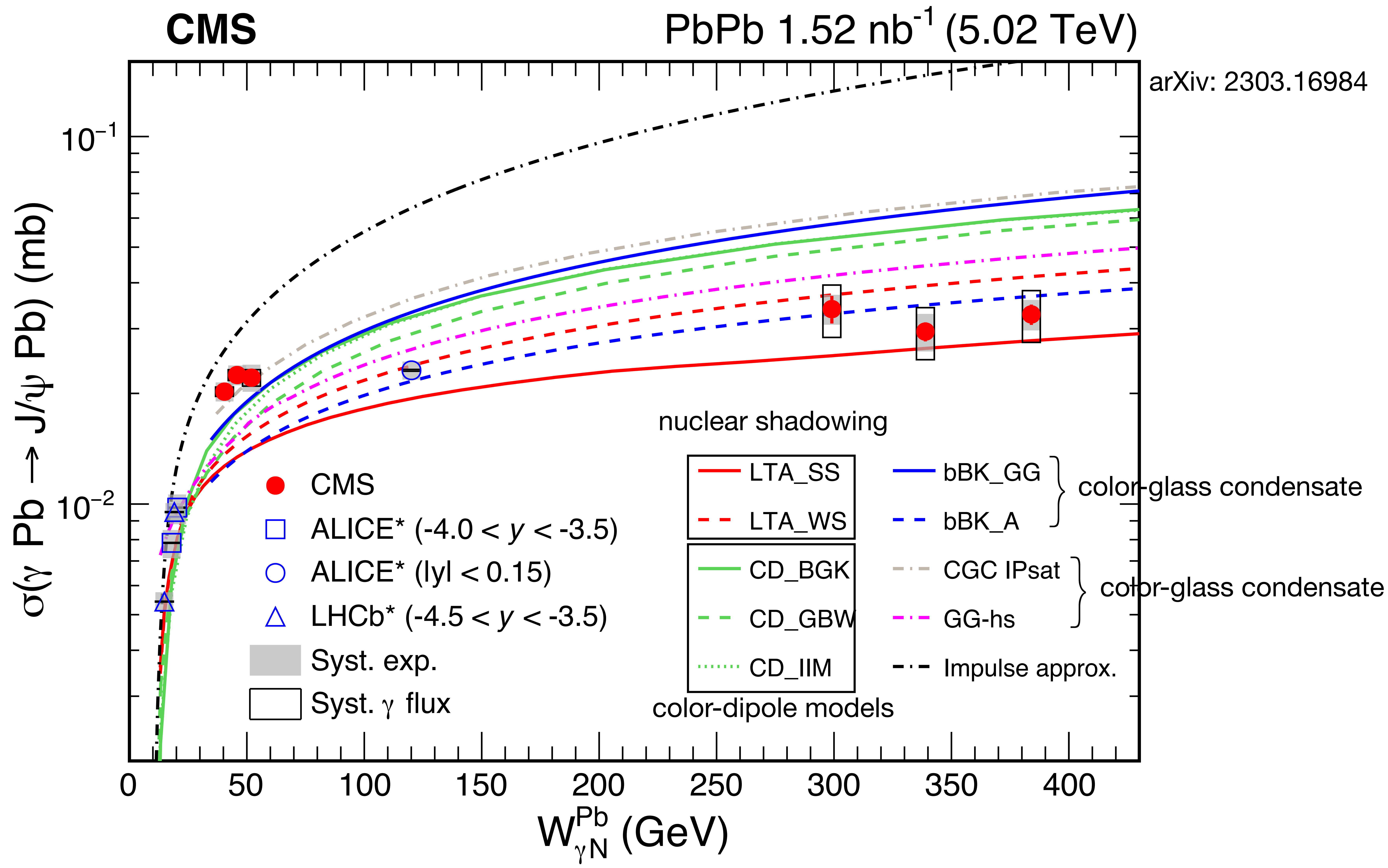
$$\sigma^{0n0n}(y) = N_{\gamma/A}^{0n0n}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}^{0n0n}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

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

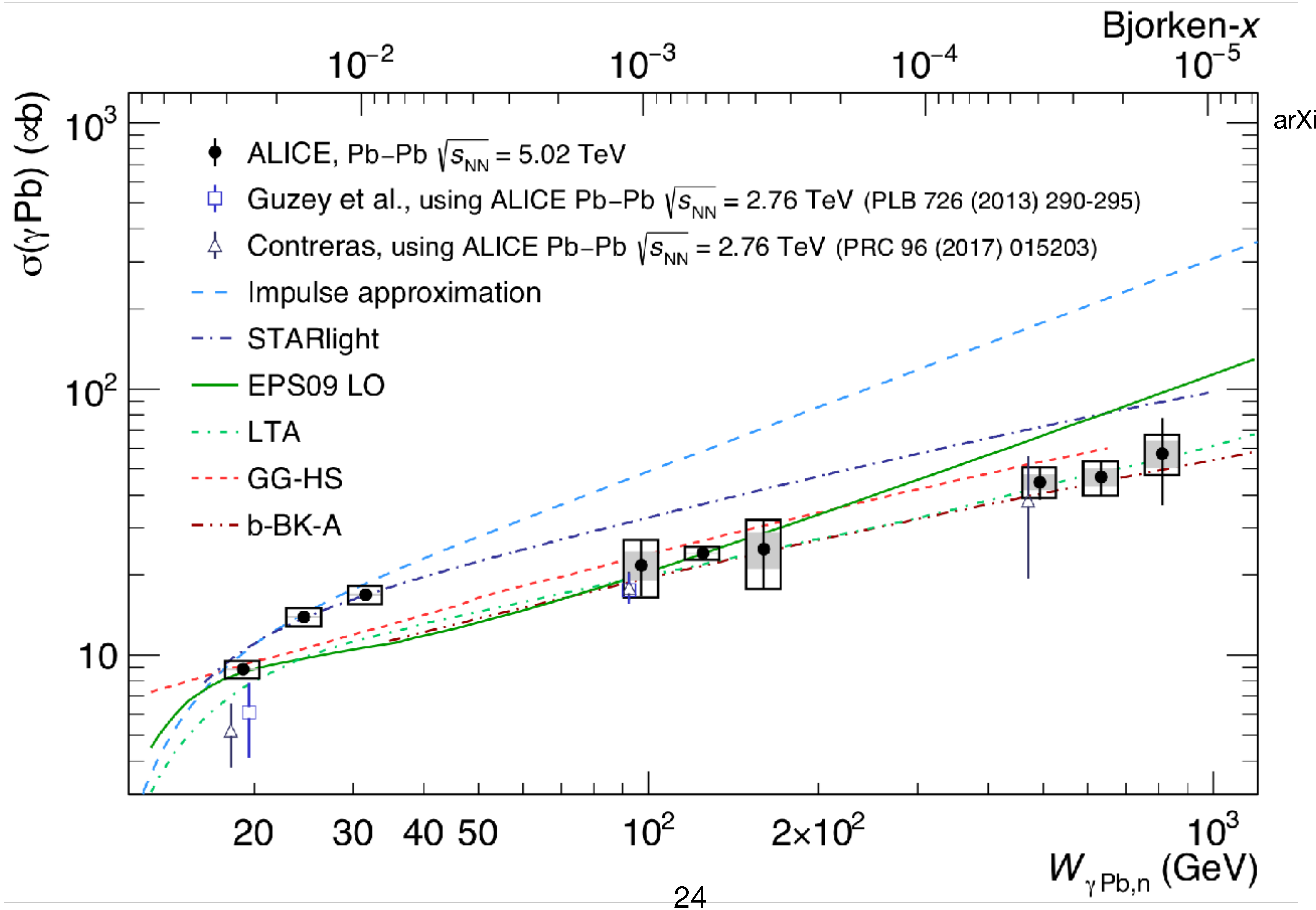
$$\sigma^{XnXn}(y) = N_{\gamma/A}^{XnXn}(E_{\gamma,s})\,\sigma_{J/\psi}(E_{\gamma,s}) + N_{\gamma/A}^{XnXn}(E_{\gamma,l})\,\sigma_{J/\psi}(E_{\gamma,l})$$

measured	computed (StarLight)	extracted	computed (StarLight)	extracted

CMS: γPb cross section, energy dependence

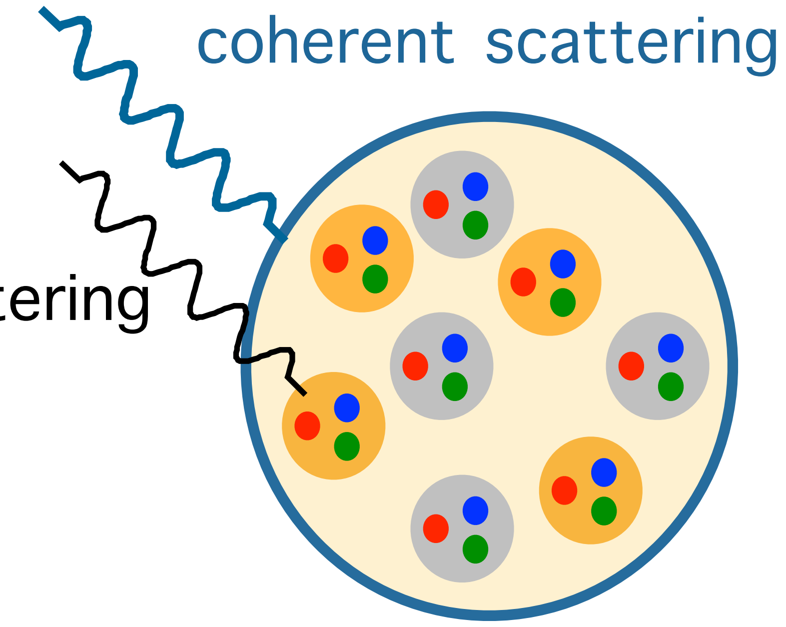


ALICE: γPb cross section, energy dependence



arXiv: 2305.19060

Incoherent production



$$\sigma_{\rm tot} \sim \langle |A|^2 \rangle$$

average cross sections

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

average amplitude over target configurations:
probes average distributions

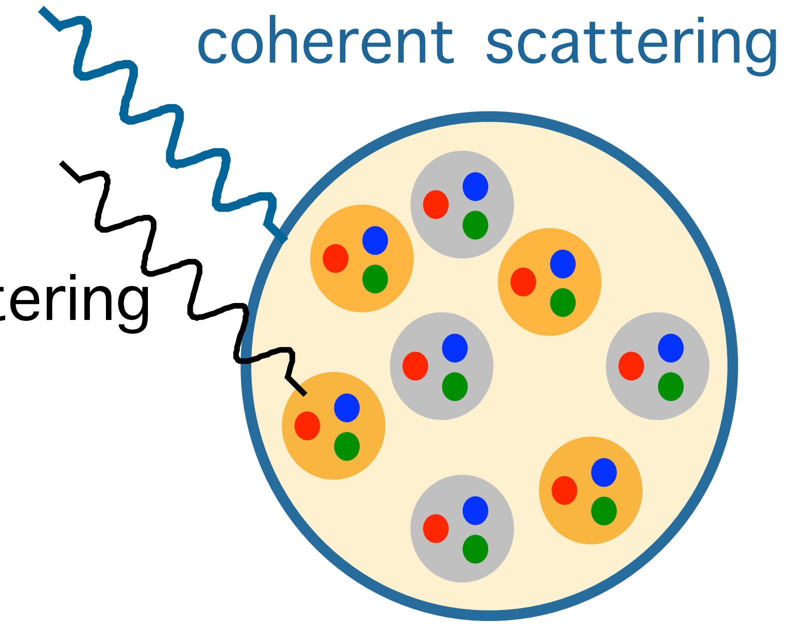
$$\sigma_{\rm incoh} \sim \sum_{f \neq i} |\langle f|A|i\rangle|^2$$

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

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

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

Incoherent production



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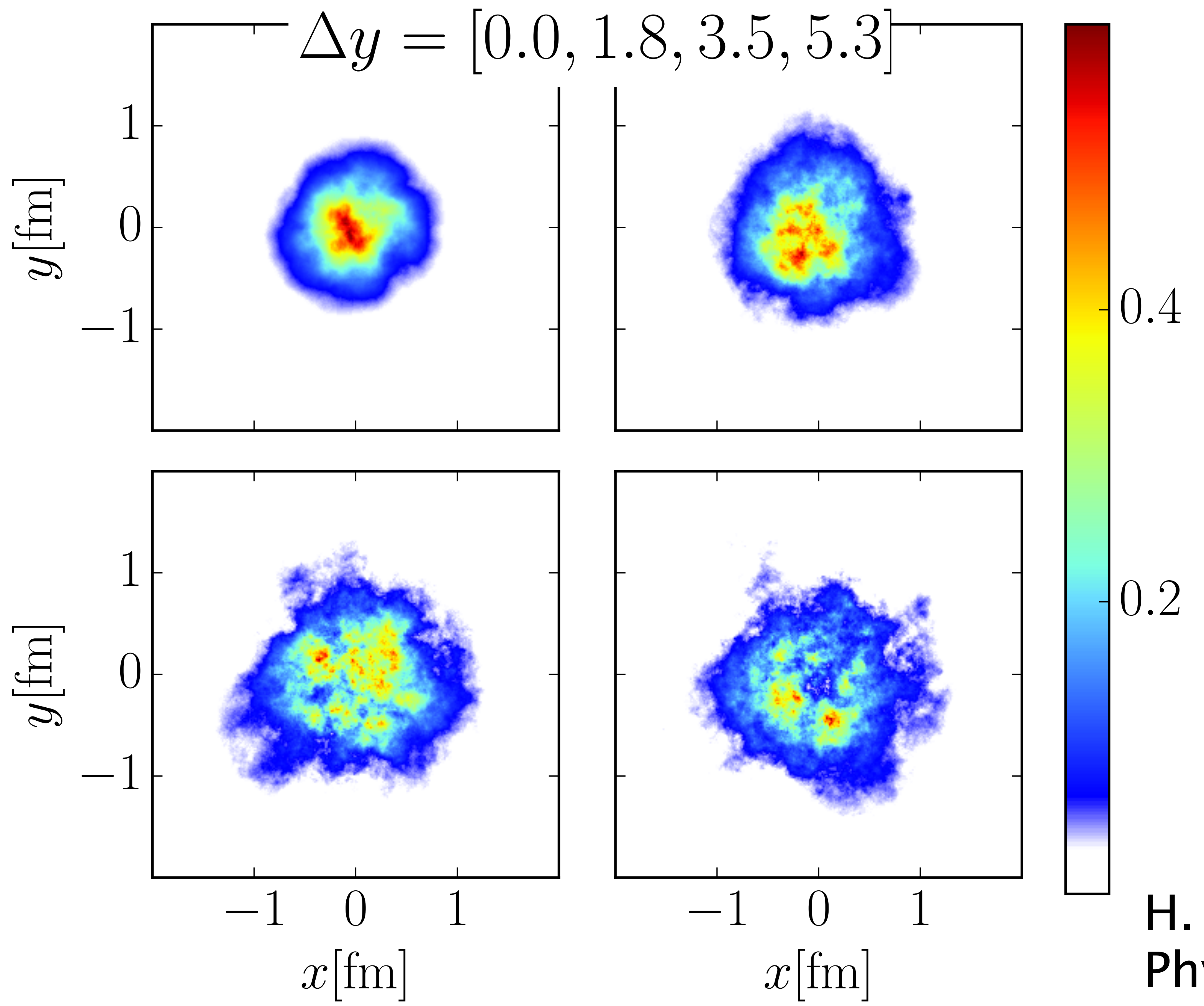
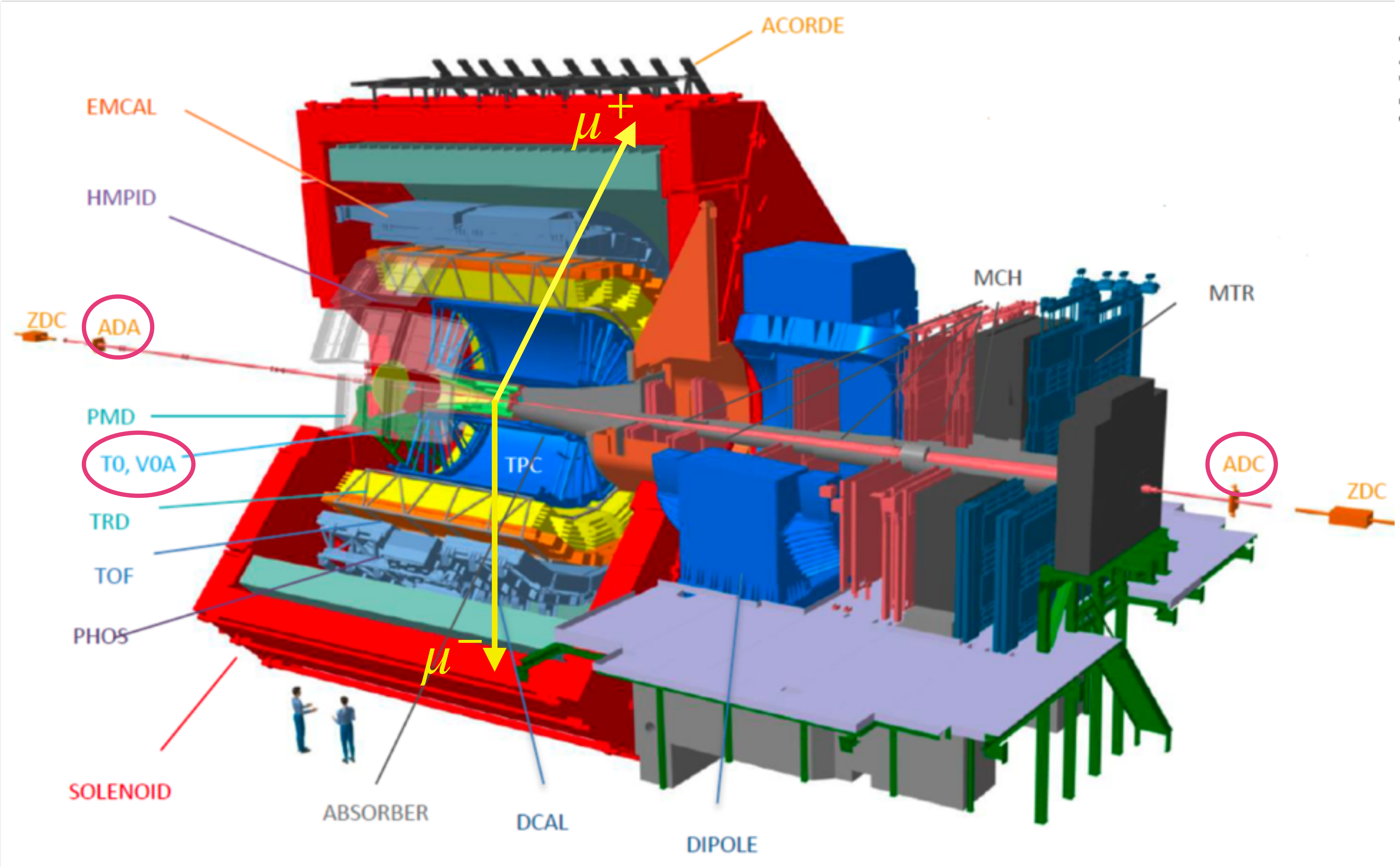
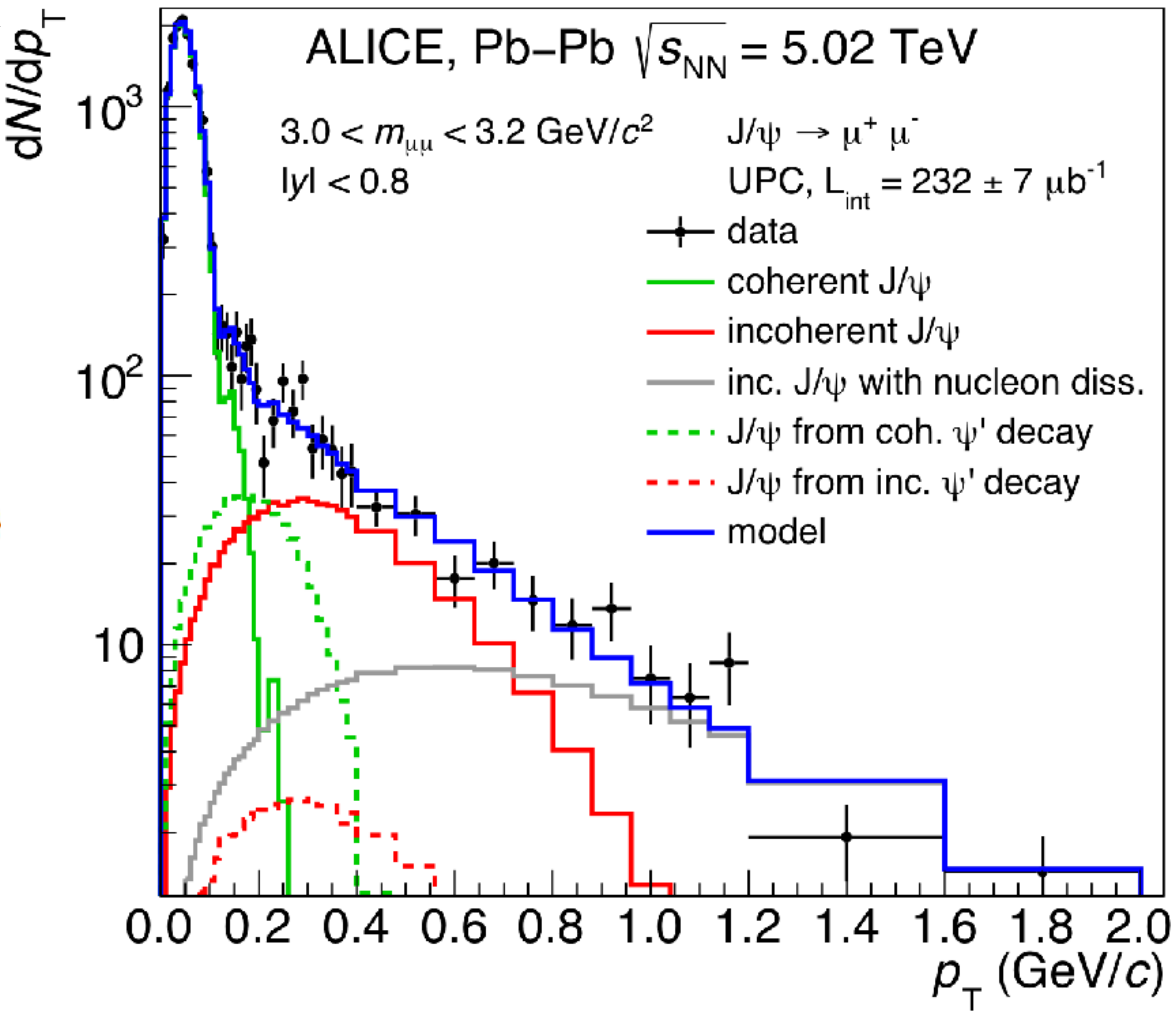


H. Mäntysaari and B. Schenke.
Phys. Rev. D 98, 034013 (2018)

Incoherent production measured by ALICE in PbPb

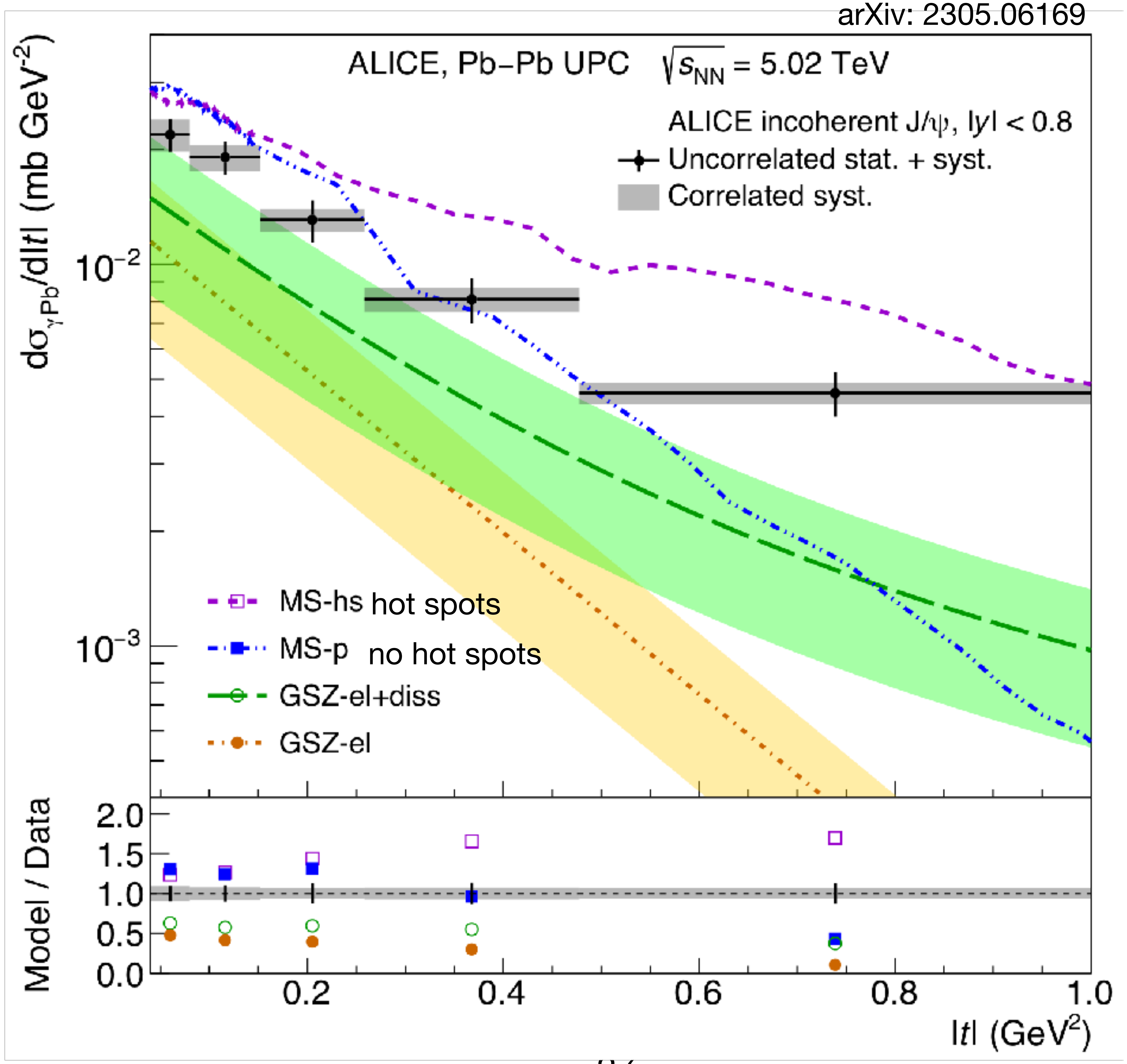


arXiv: 2305.06169



STARlight template+H1parametrisation for dissociation

Incoherent production measured by ALICE in PbPb



$0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$

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 and ALICE: intriguing small linear rise of cross section for $W_{\gamma N}$>40 GeV
  - first measurement of the incoherent photonuclear production of J/ψ by ALICE

- For access to GPDs, need measurements double-differential in y and t.