Accessing GPDs at the LHC

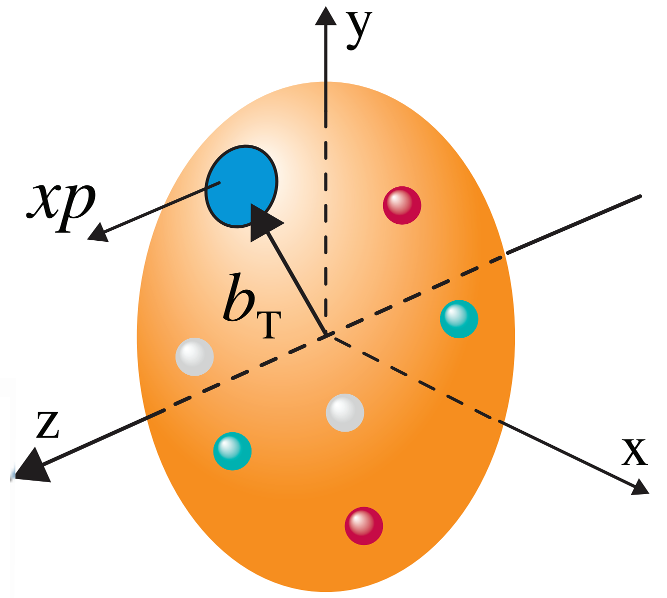
Charlotte Van Hulse
University of Alcalá

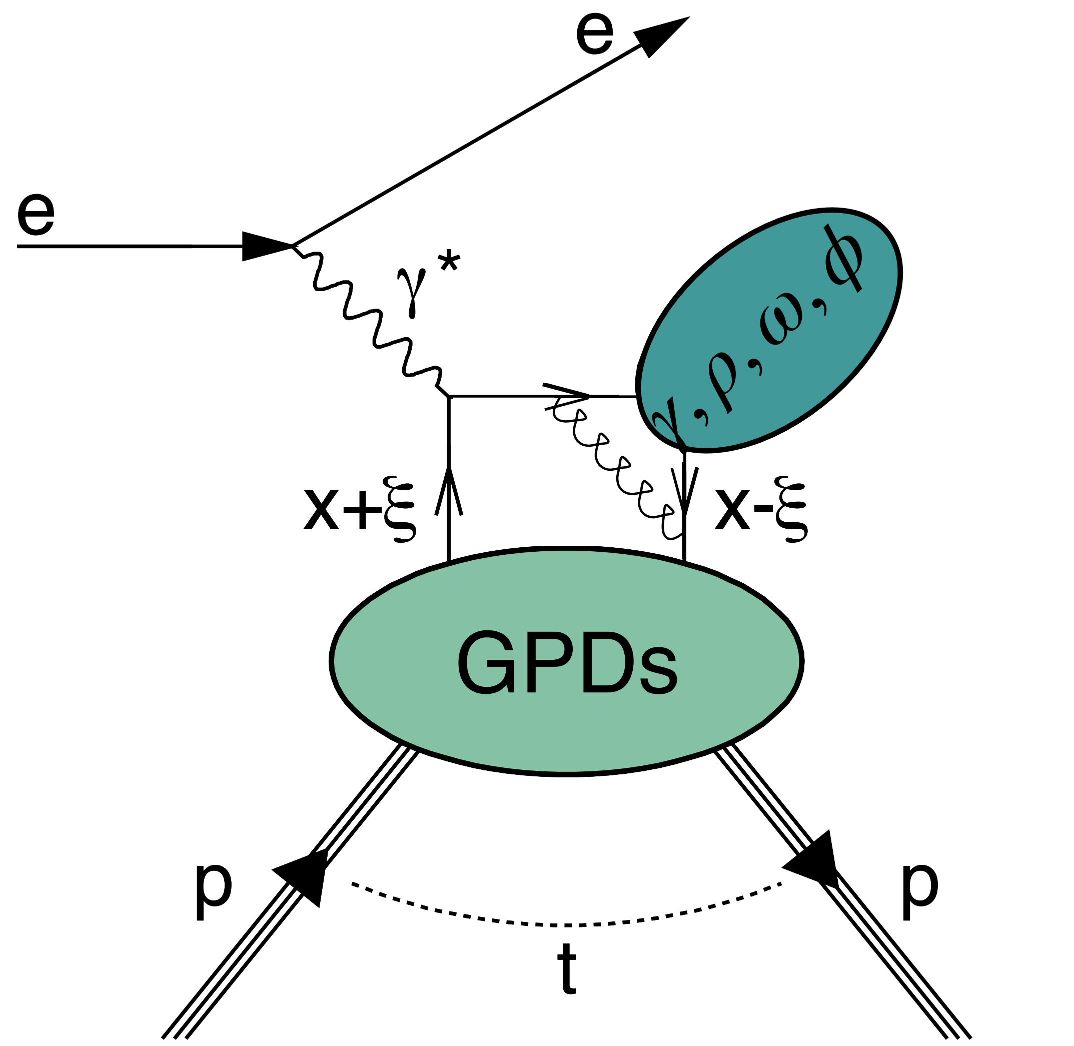
AdT

Comunidad de Madrid

20th IWHSS – 5th CPHI
30 Sep – 04 Oct 2024
Yerevan, Armenia

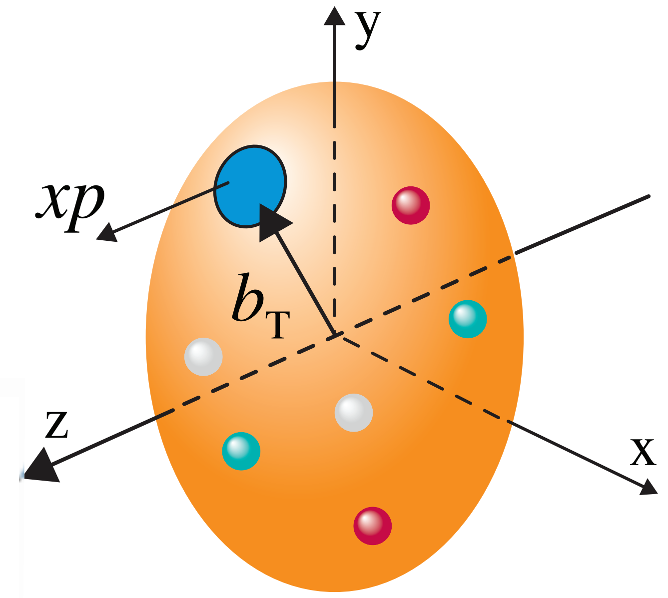
Exclusive processes

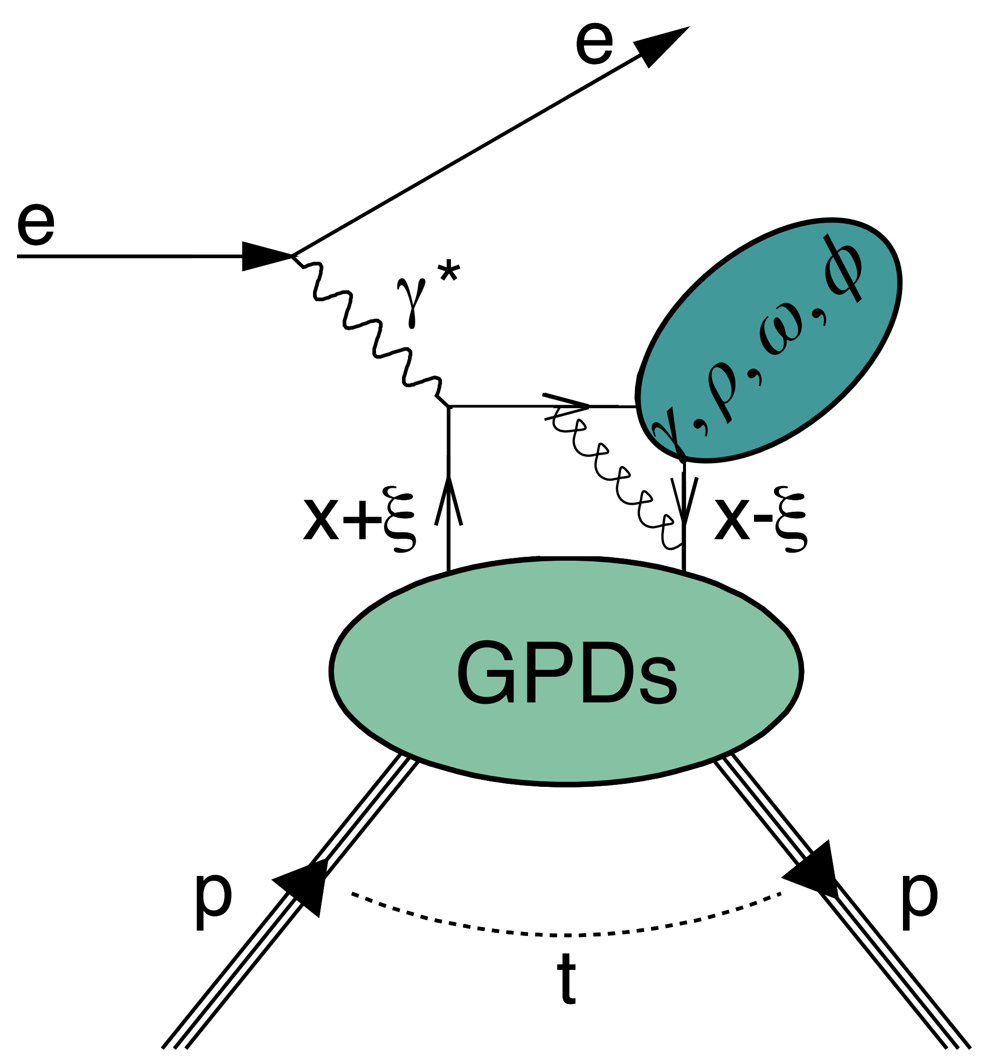




Hard exclusive meson production
Hard scale=large Q^2

Exclusive processes





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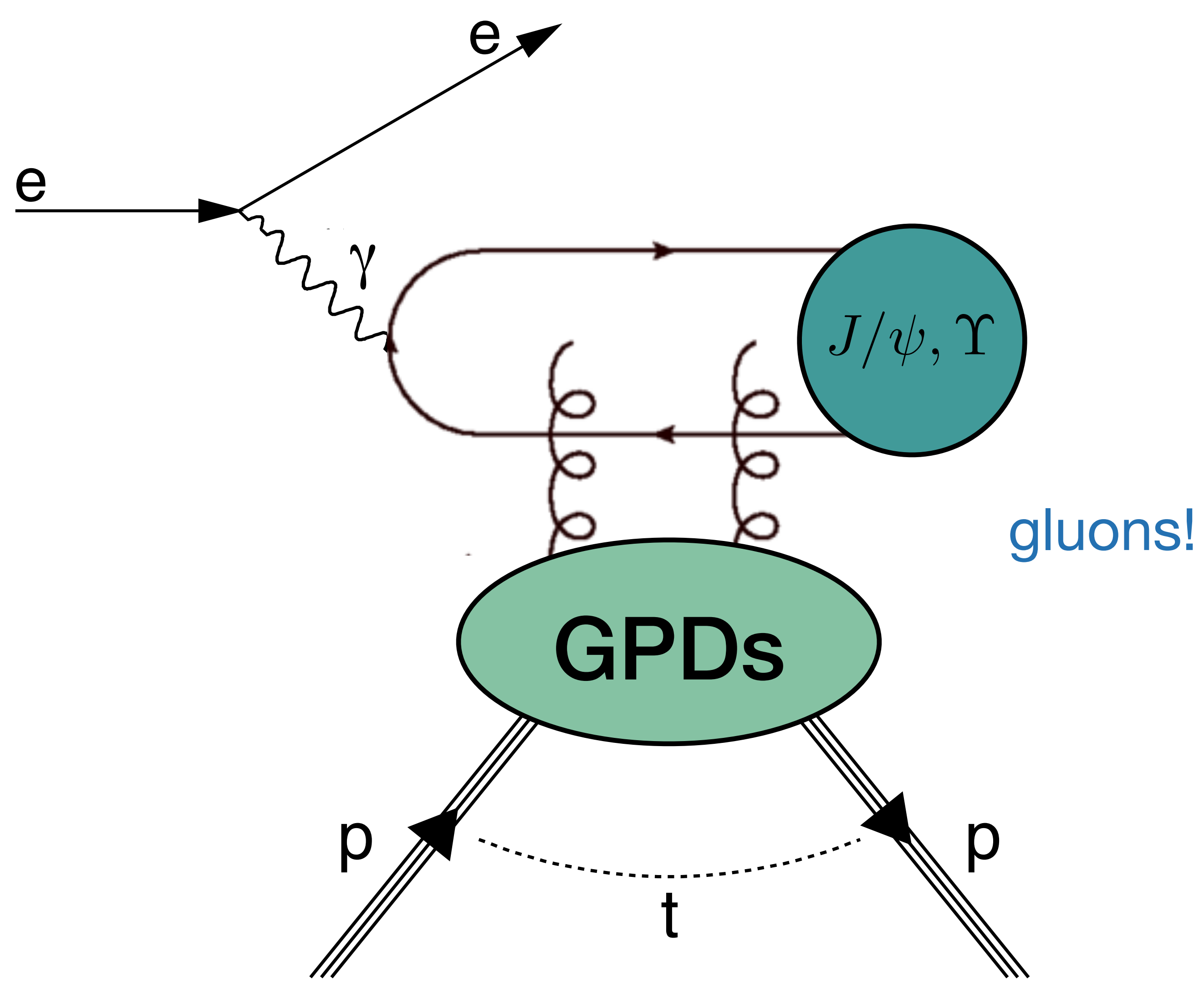

Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

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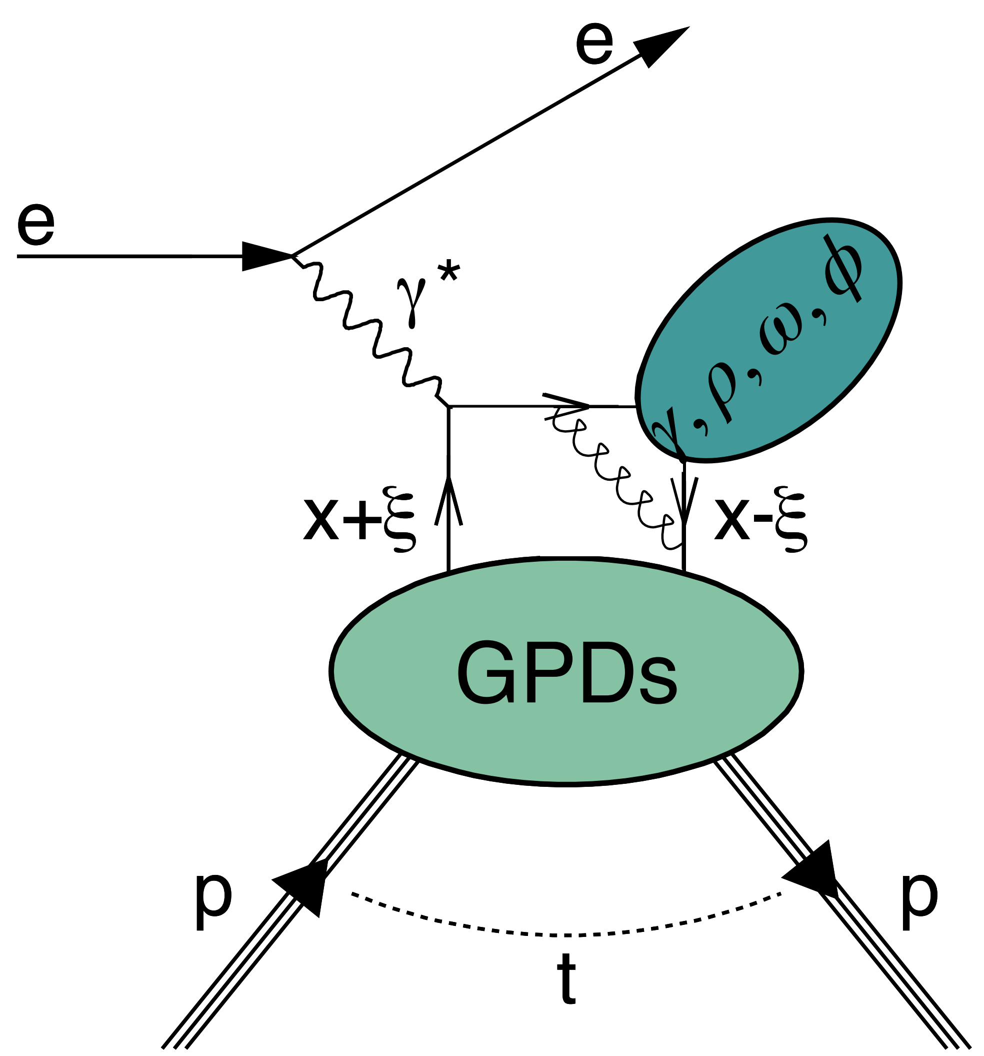

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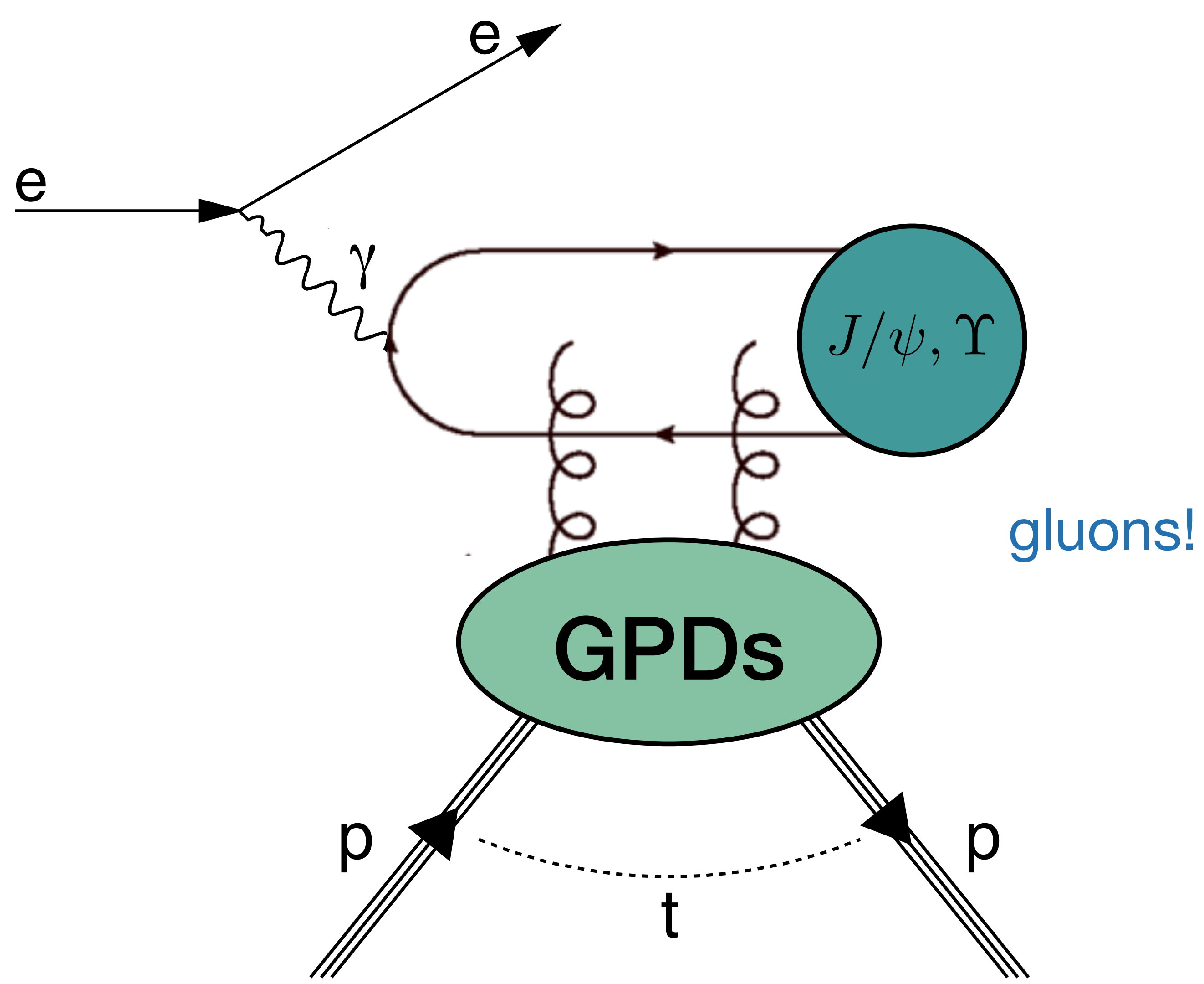

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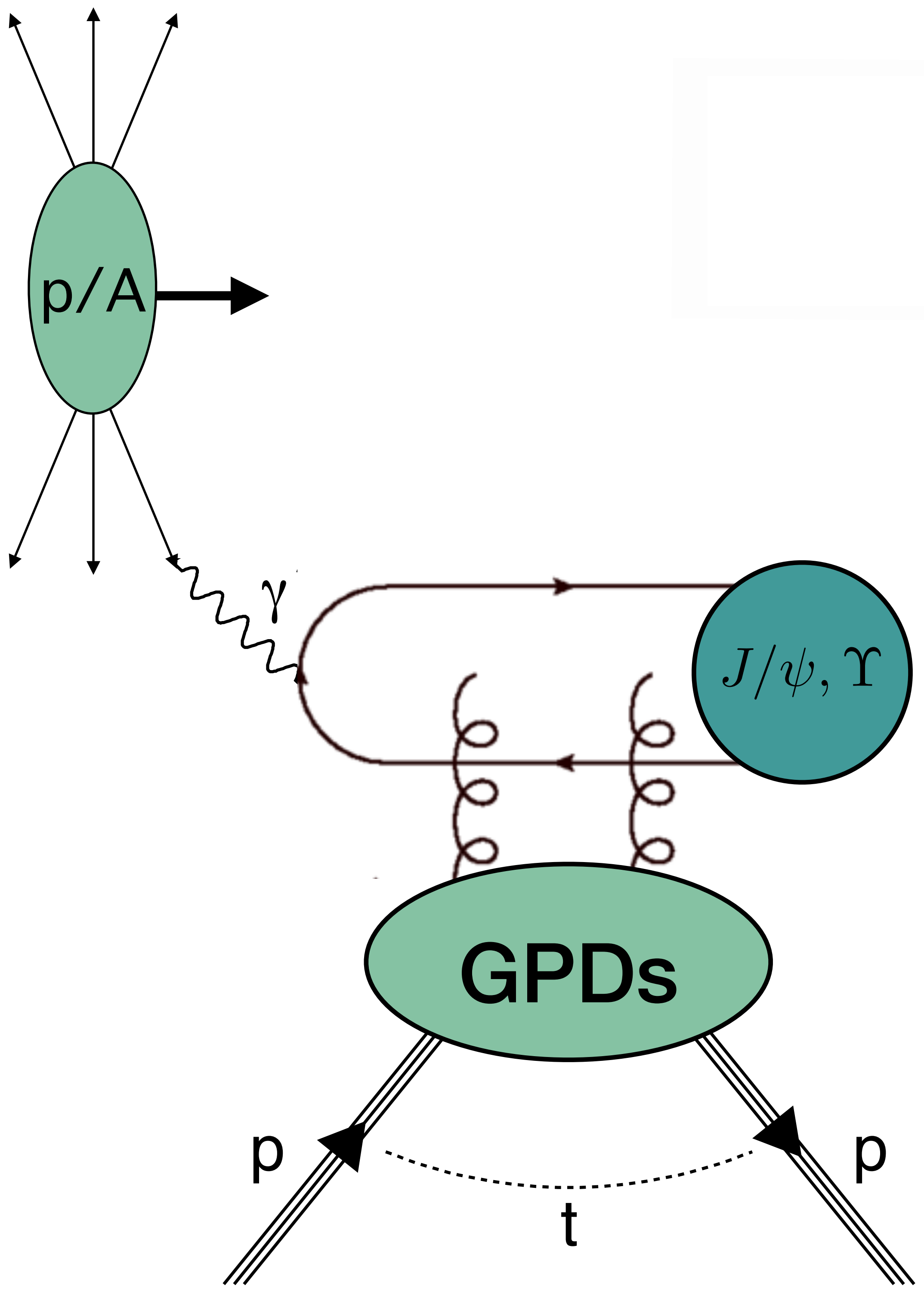

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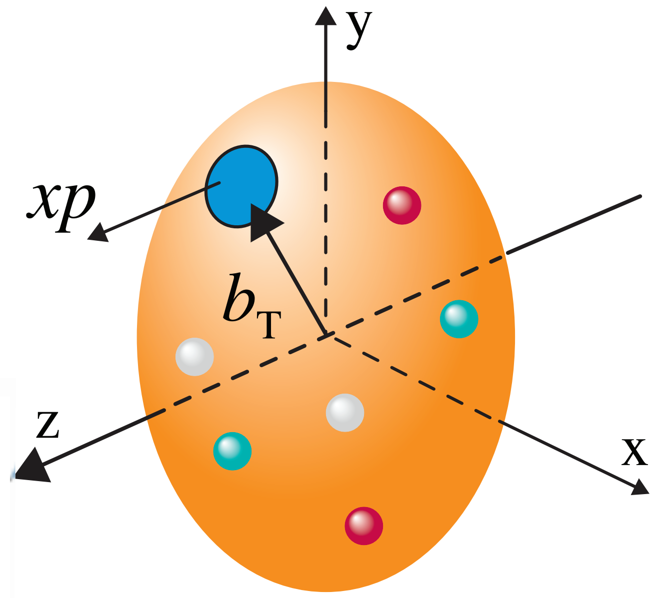

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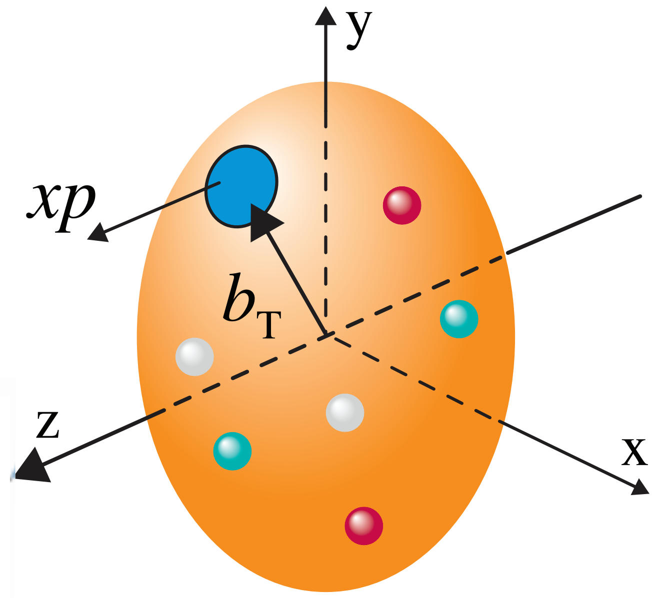

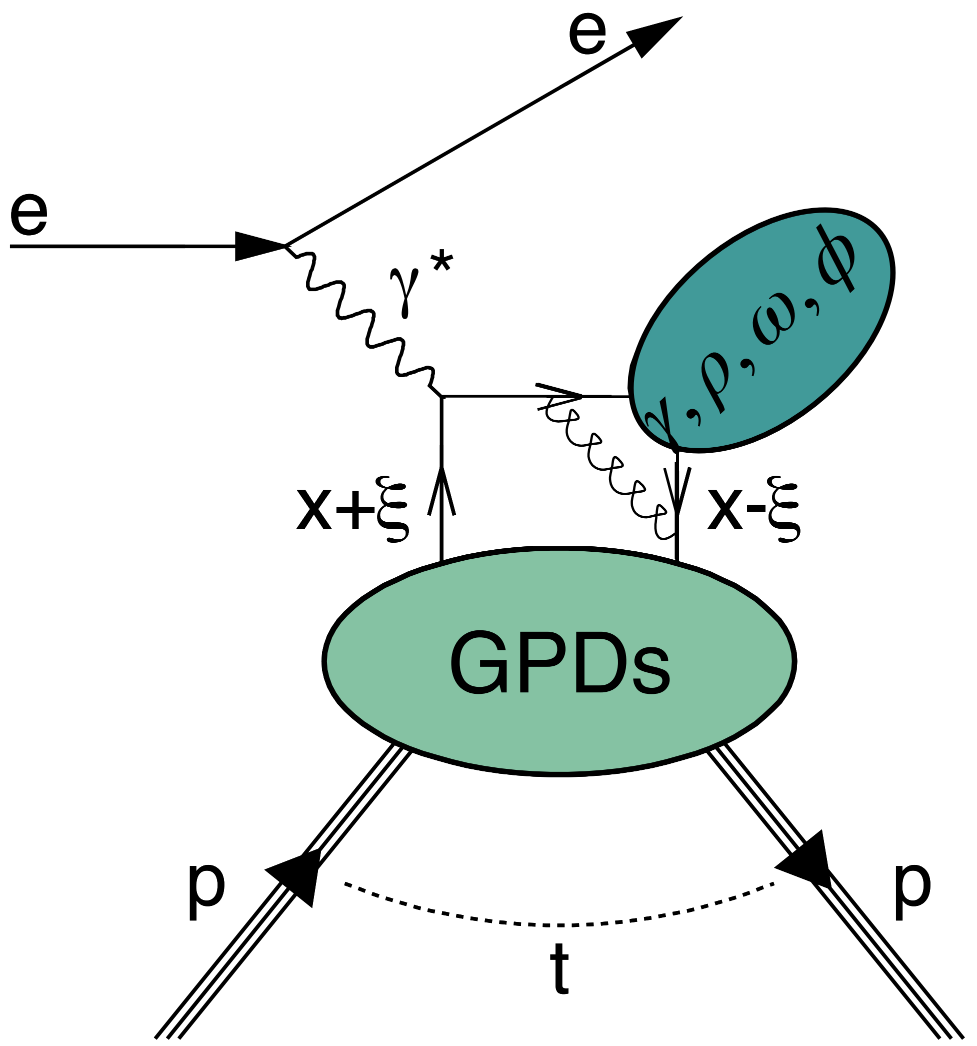

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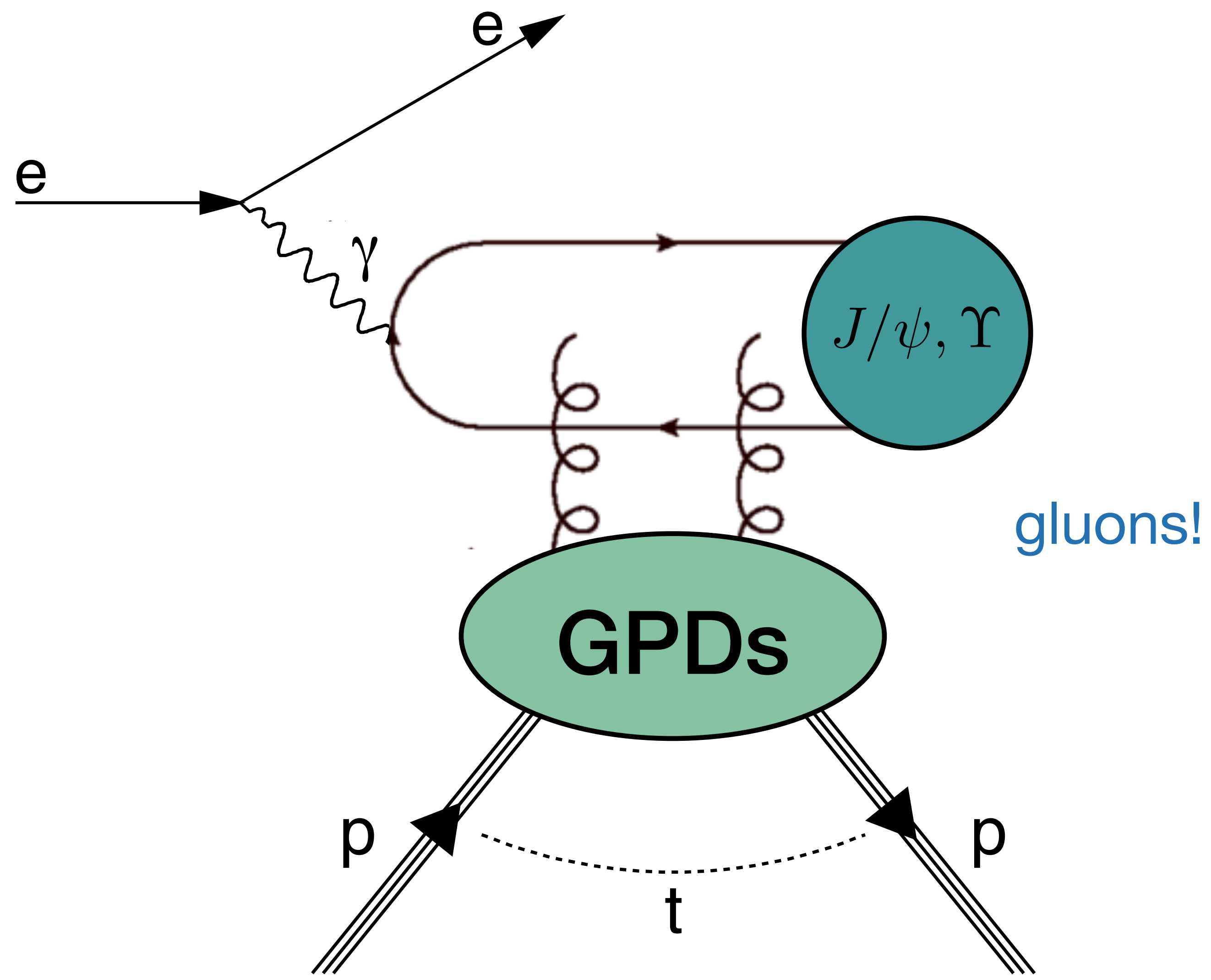

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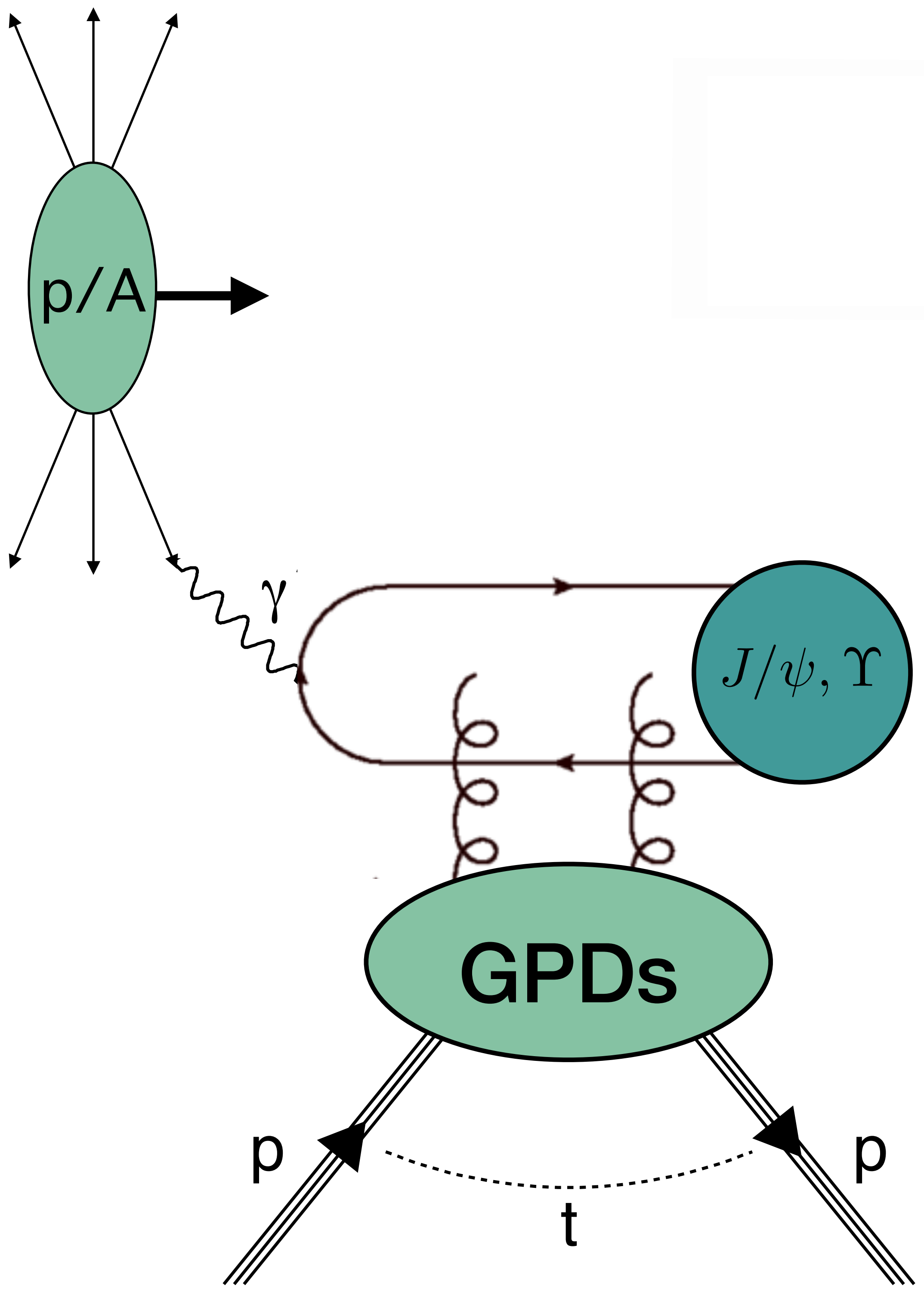


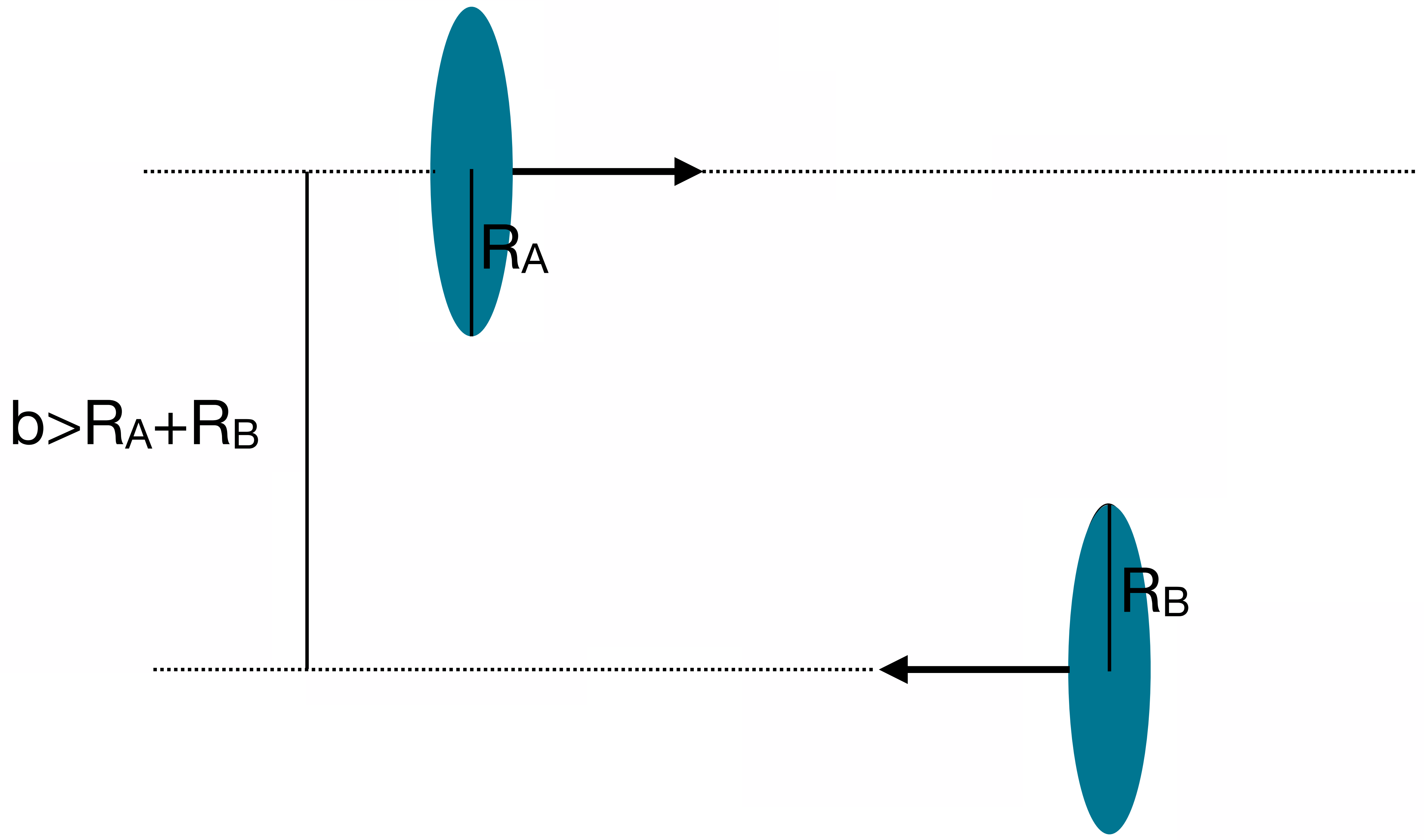
Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

down to $x_B=10^{-4}$ at HERA/EIC in ep
$x_B=10^{-3}$ at EIC in eA

down to $x_B=10^{-6}$ at LHC in pp
$x_B=10^{-5}$ at LHC in pA

Ultra-peripheral collisions (UPCs)

large–impact-parameter interactions

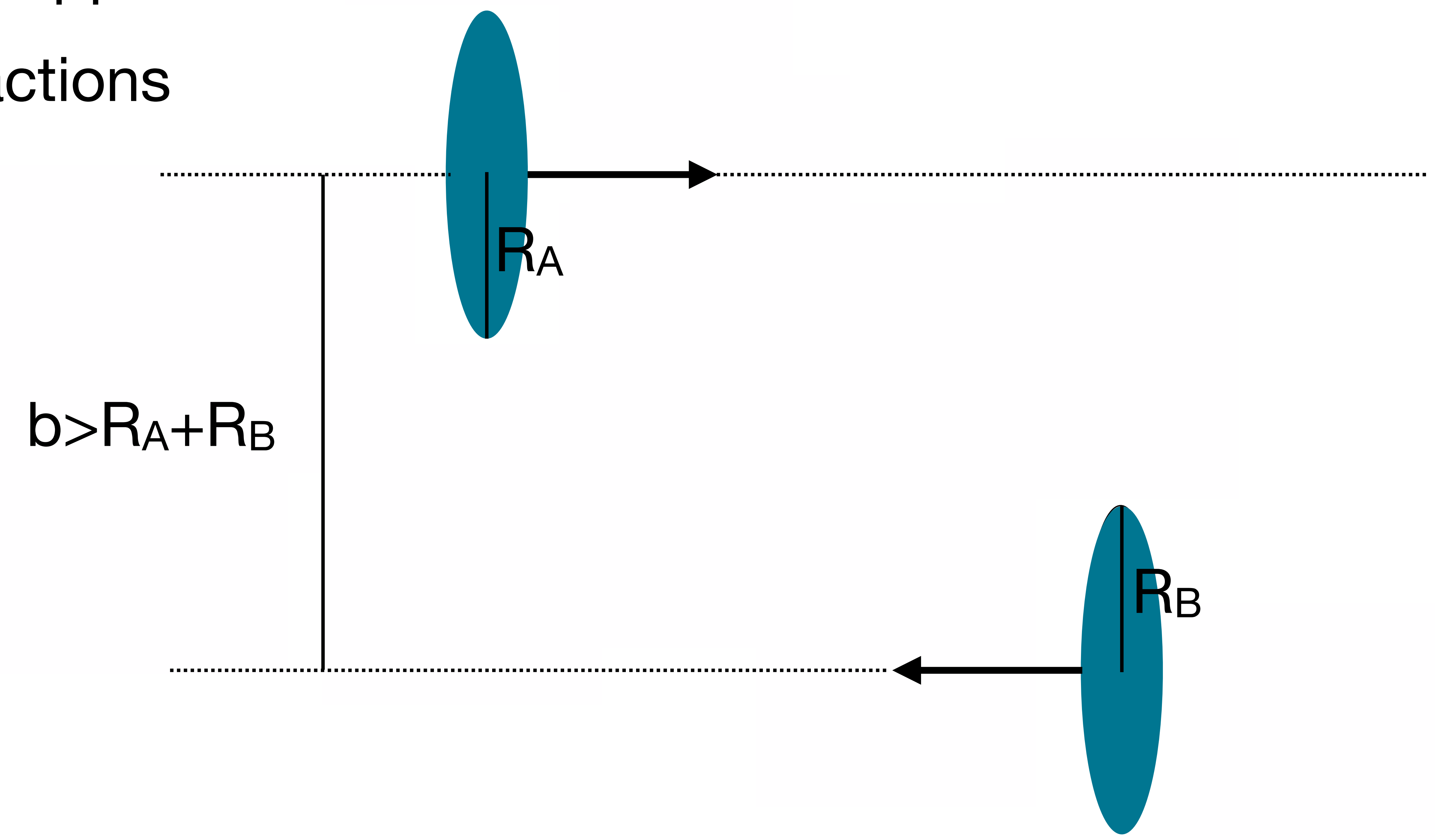


Ultra-peripheral collisions (UPCs)

large–impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions



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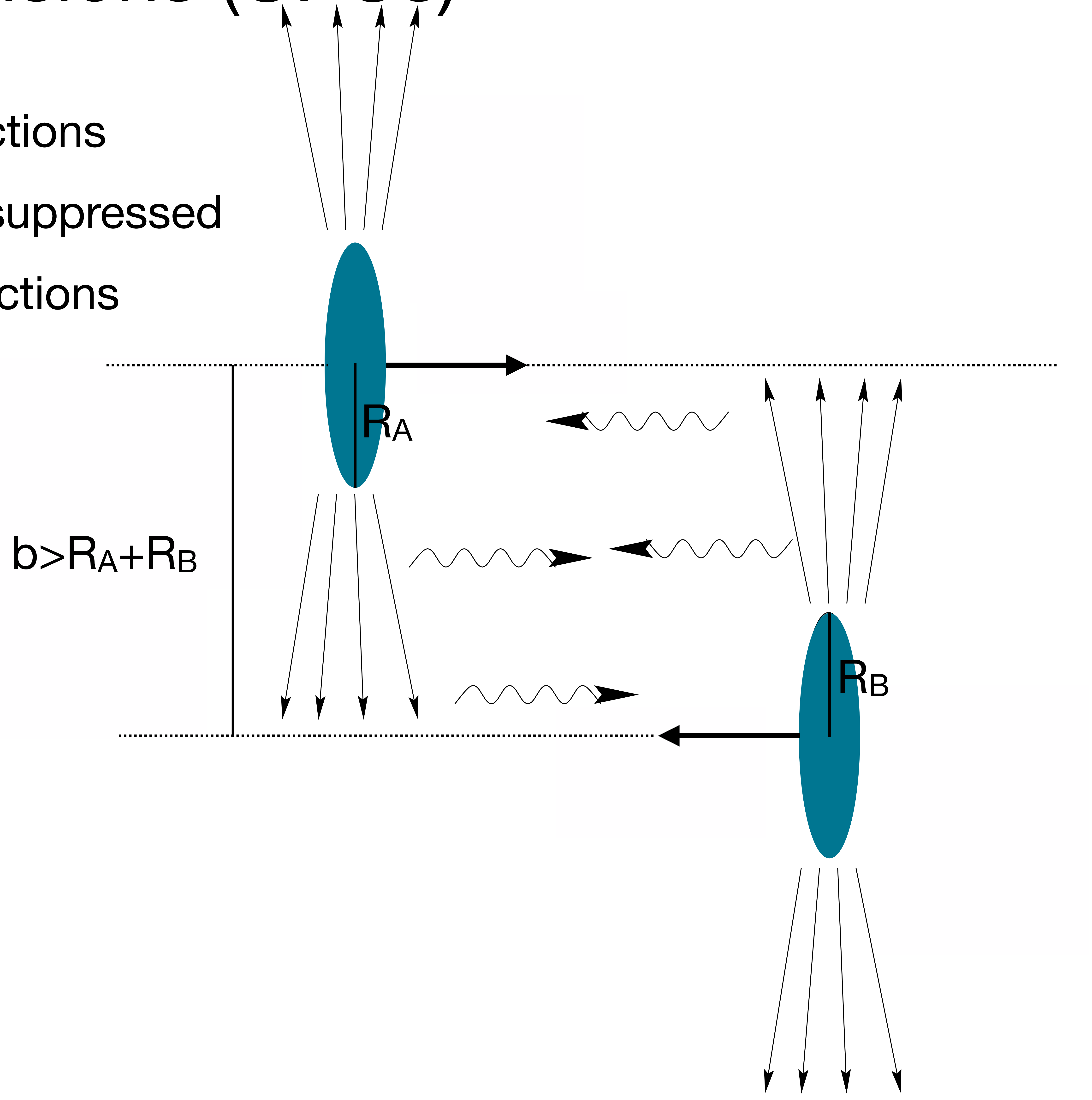

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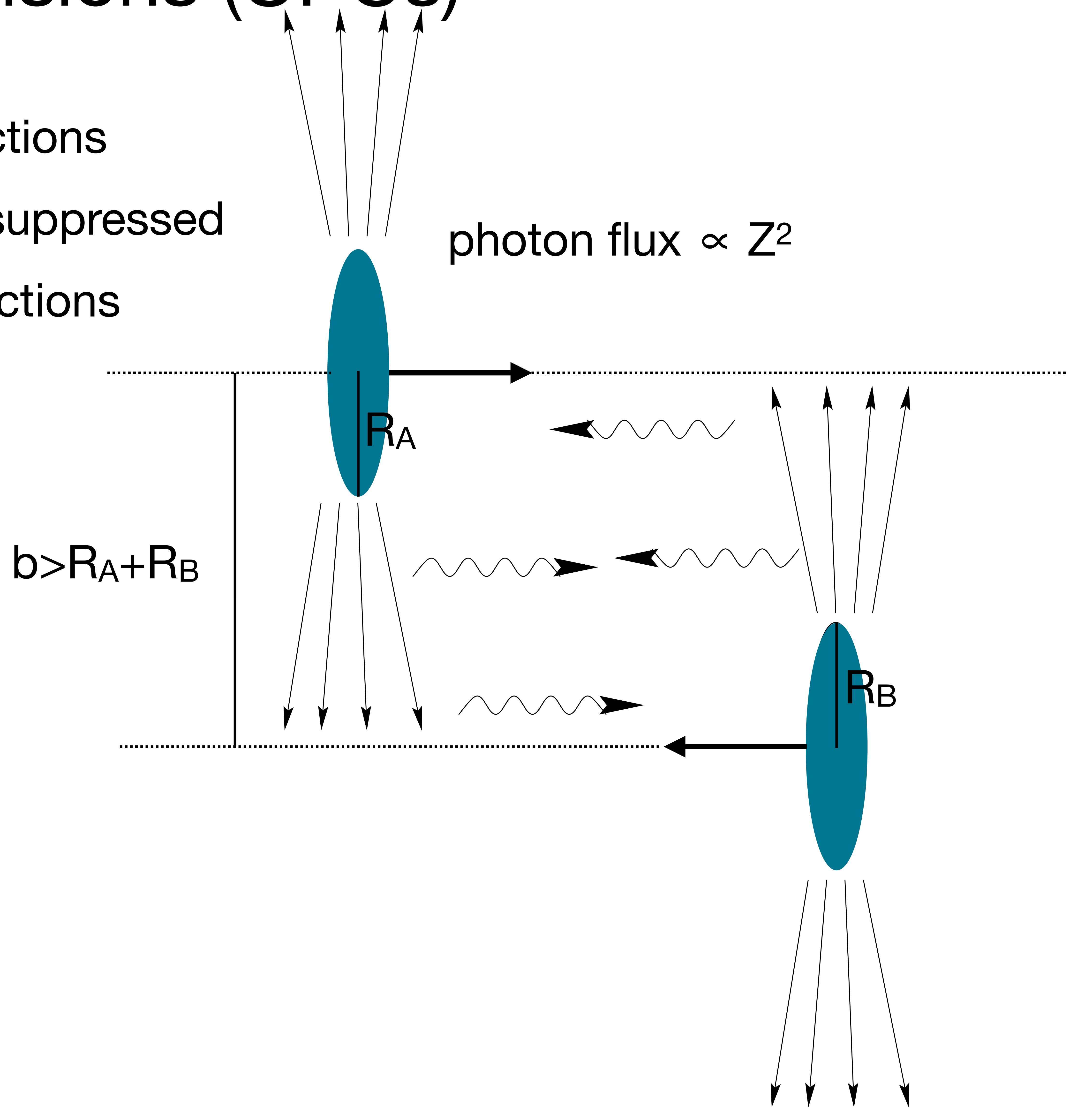

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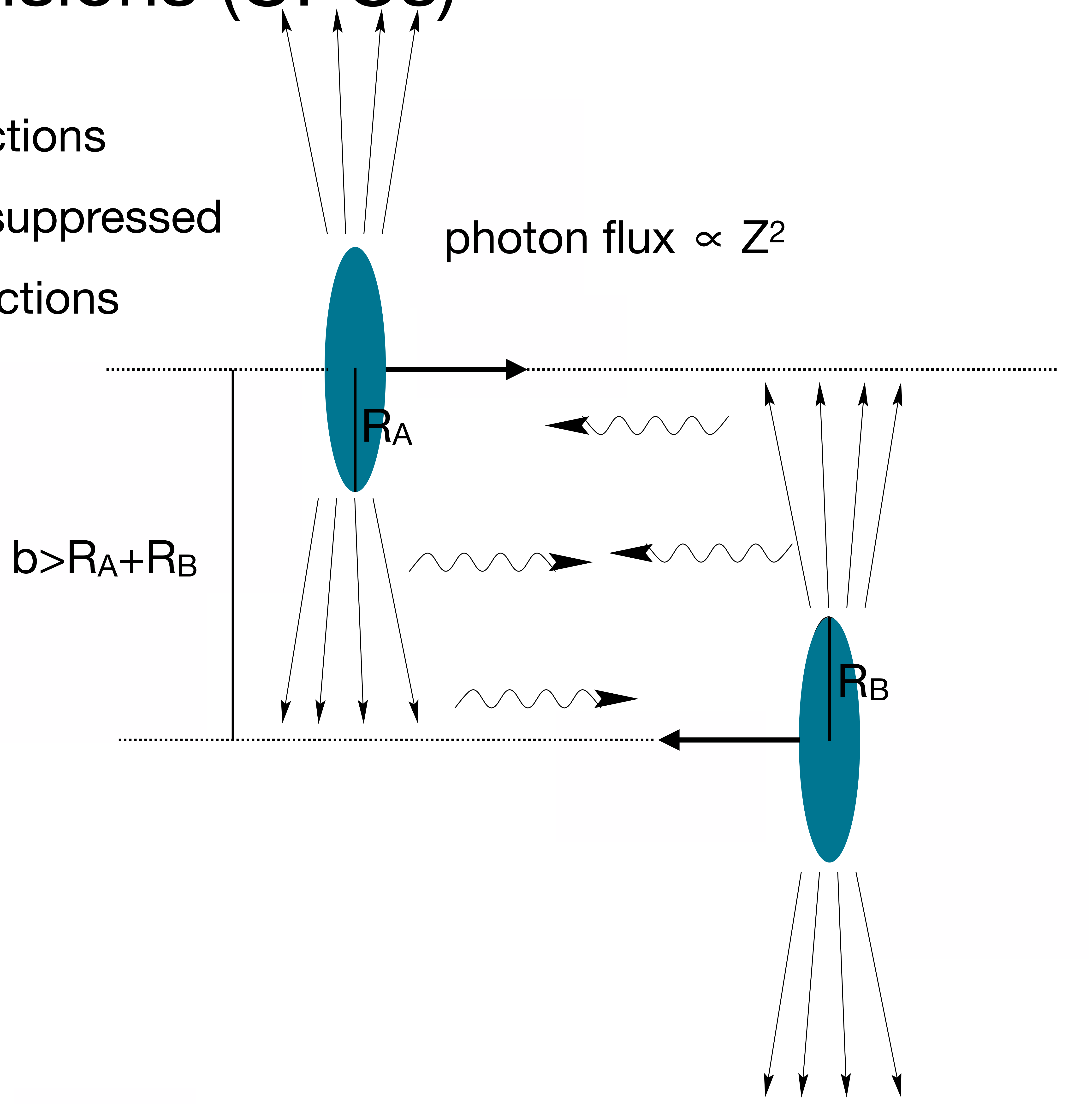

photon virtuality $Q^2 < \left(\frac{\hbar c}{R_A}\right)^2$

→ quasi-real photons

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

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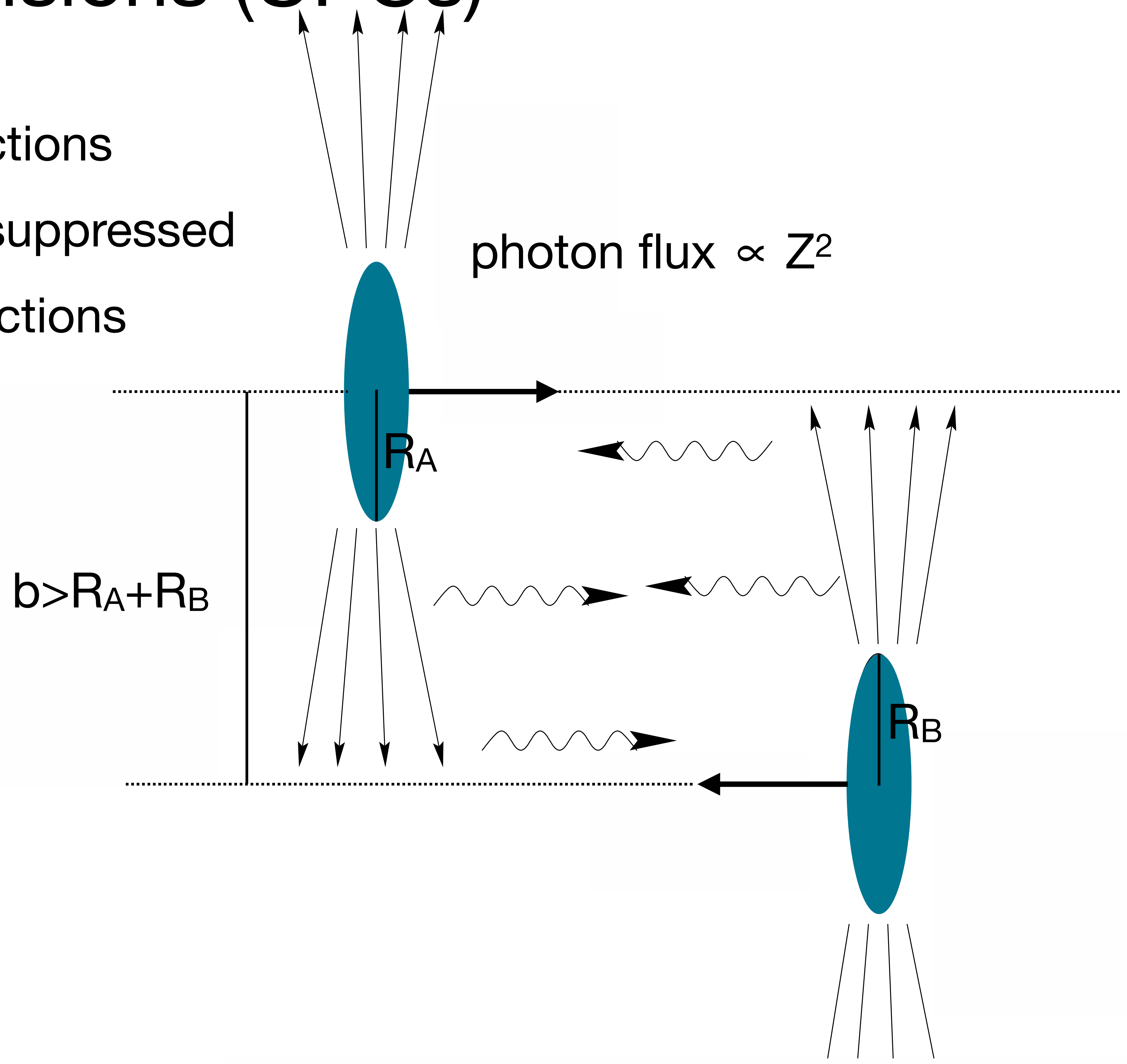

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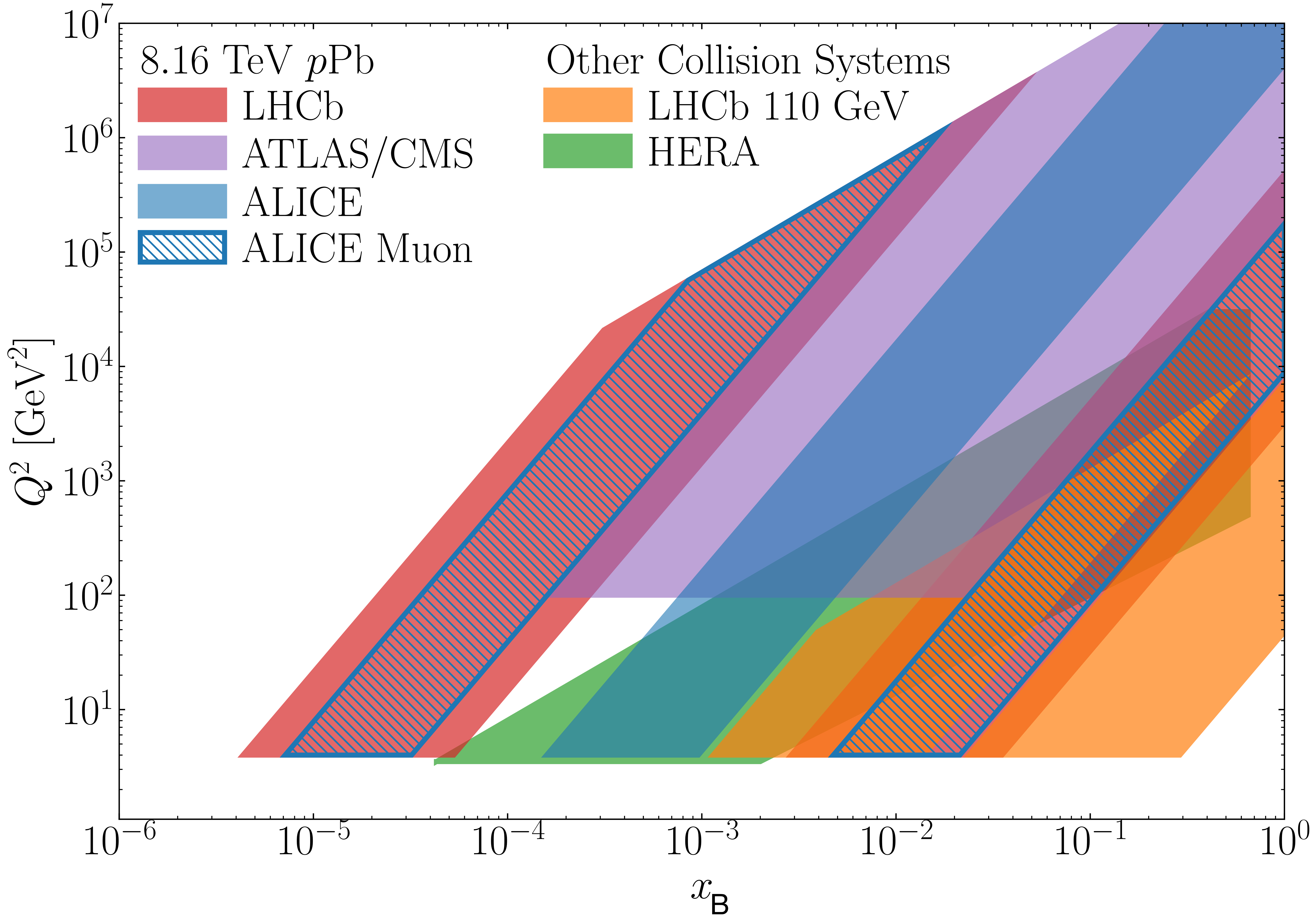
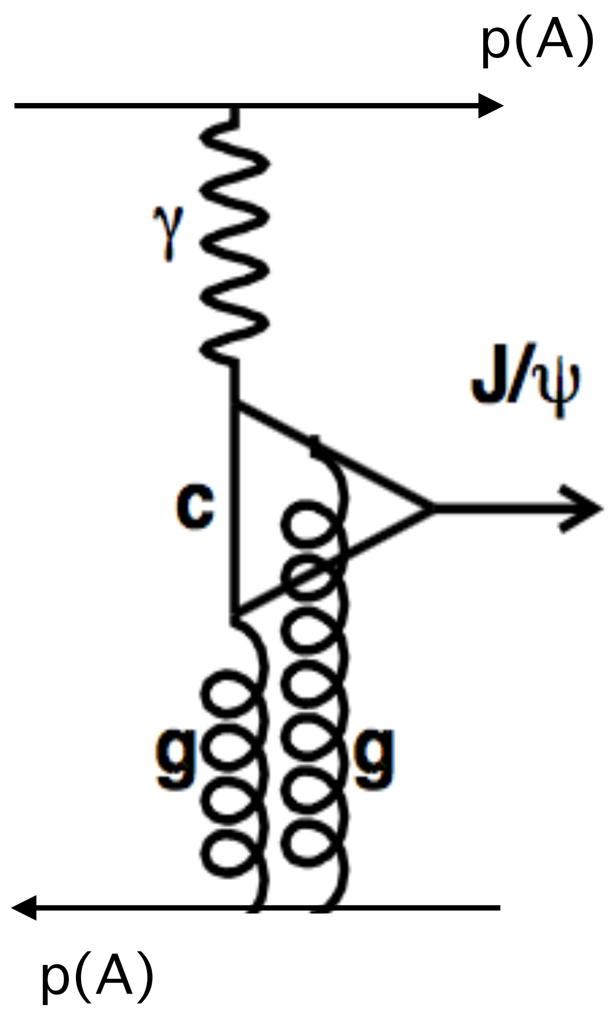
System	$\sqrt{s_{AB}}$	E_A	E_B	(a) $\gamma_{A\leftrightarrow B}$	(b) $E_{\gamma Max}$	(c) $E^{rest}_{\gamma Max}$	(d) $W^{max}_{\gamma p}$
pPb	5.02 TeV	4 TeV	1.567 TeV	1.43×10^7	28 MeV	0.4 PeV	0.86 TeV
pPb	8.16 TeV	6.5 TeV	2.56 TeV	3.78×10^7	28 MeV	1 PeV	1.4 TeV
pp	13 TeV	6.5 TeV	6.5 TeV	9.6×10^7	116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

table: K. Lynch

Kinematic coverage



Measurement of exclusive production on proton: example LHCb



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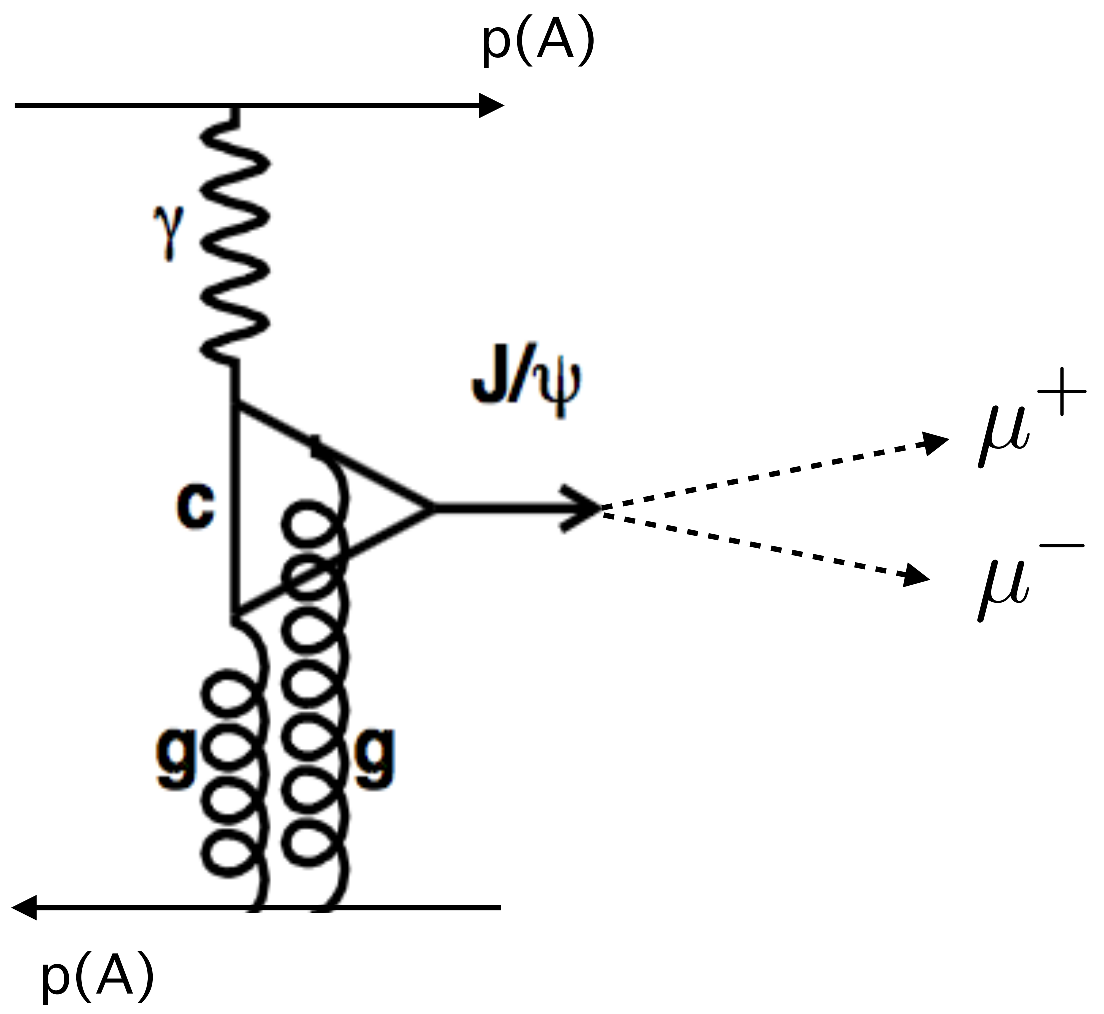

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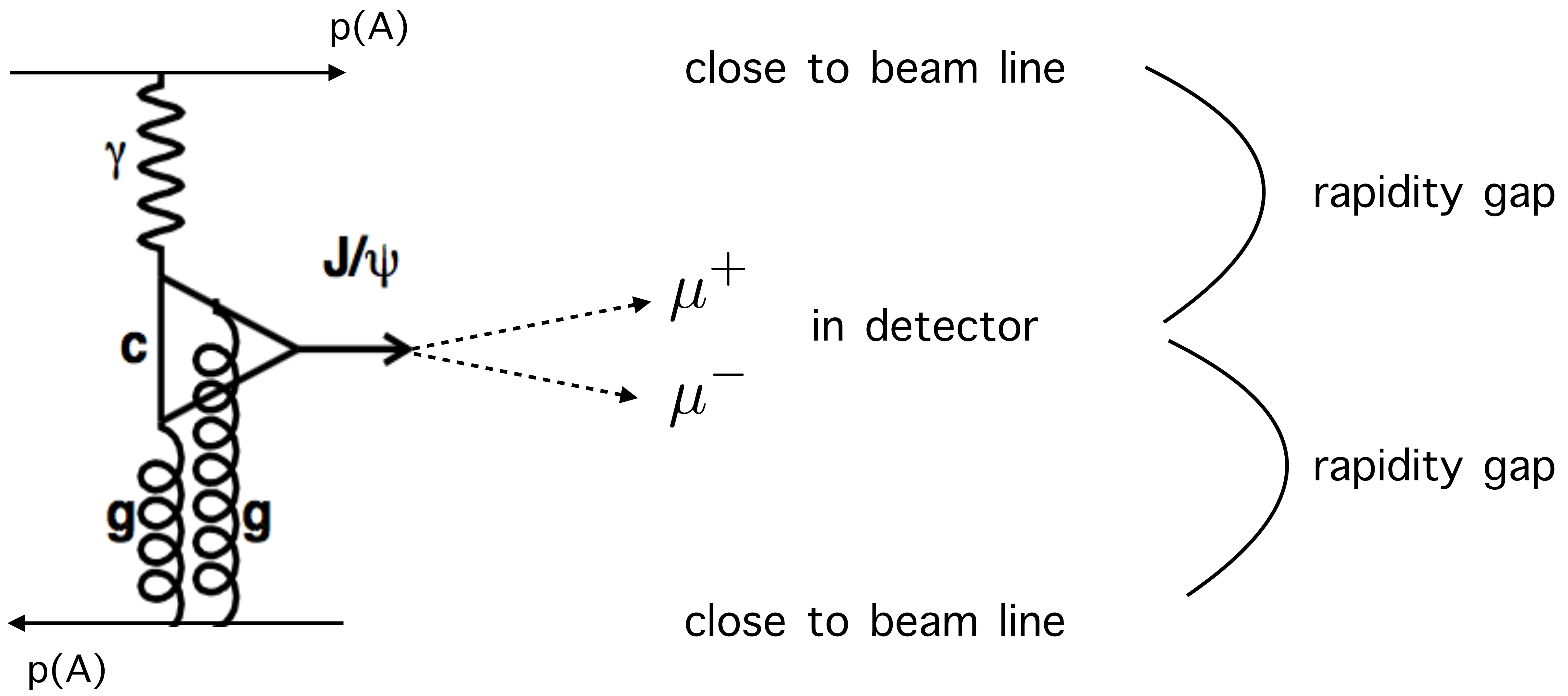

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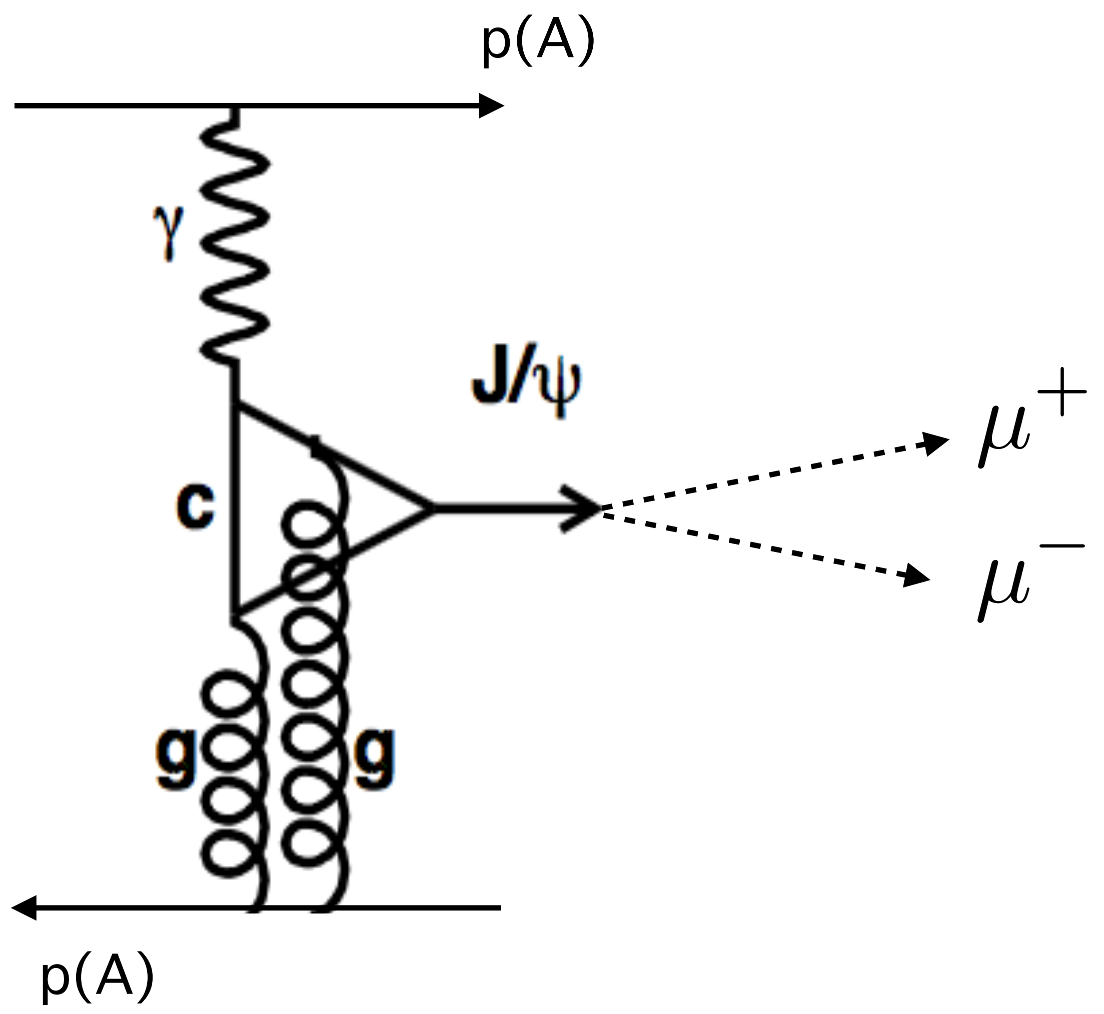

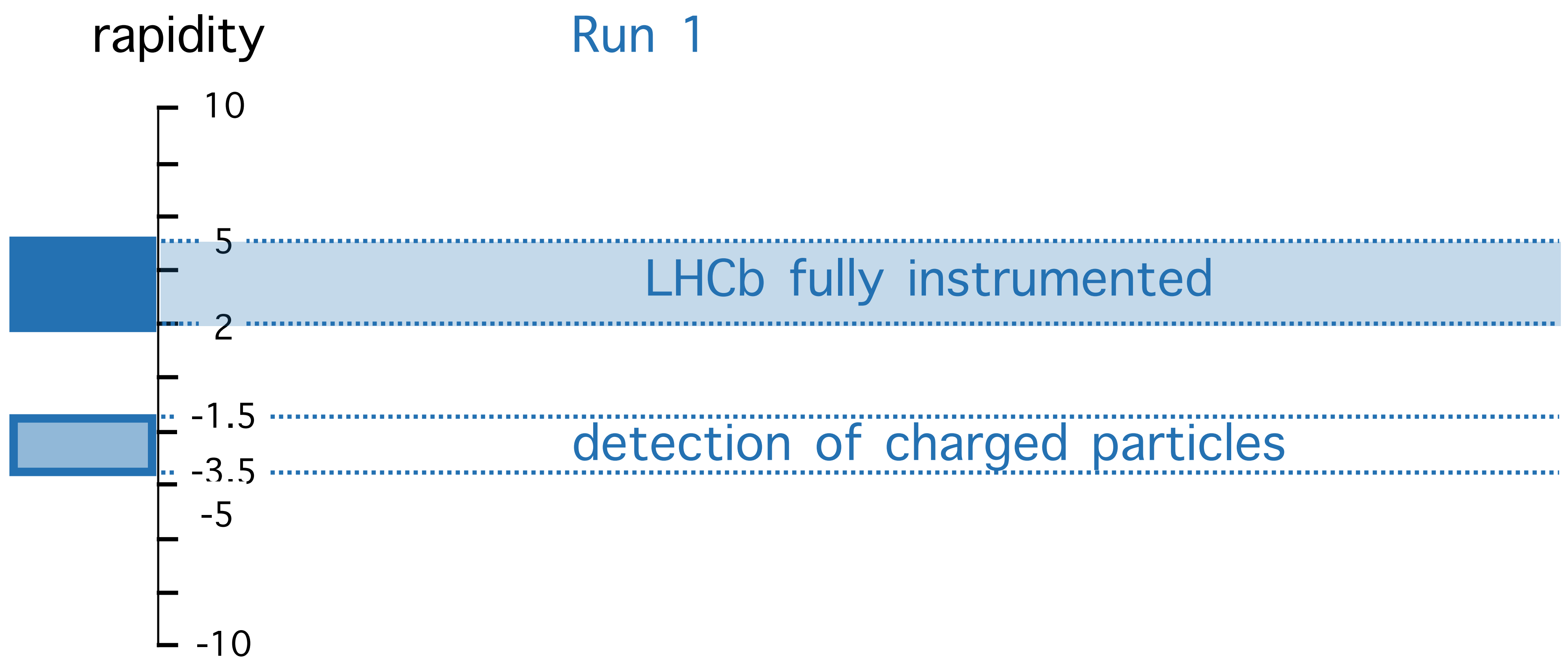

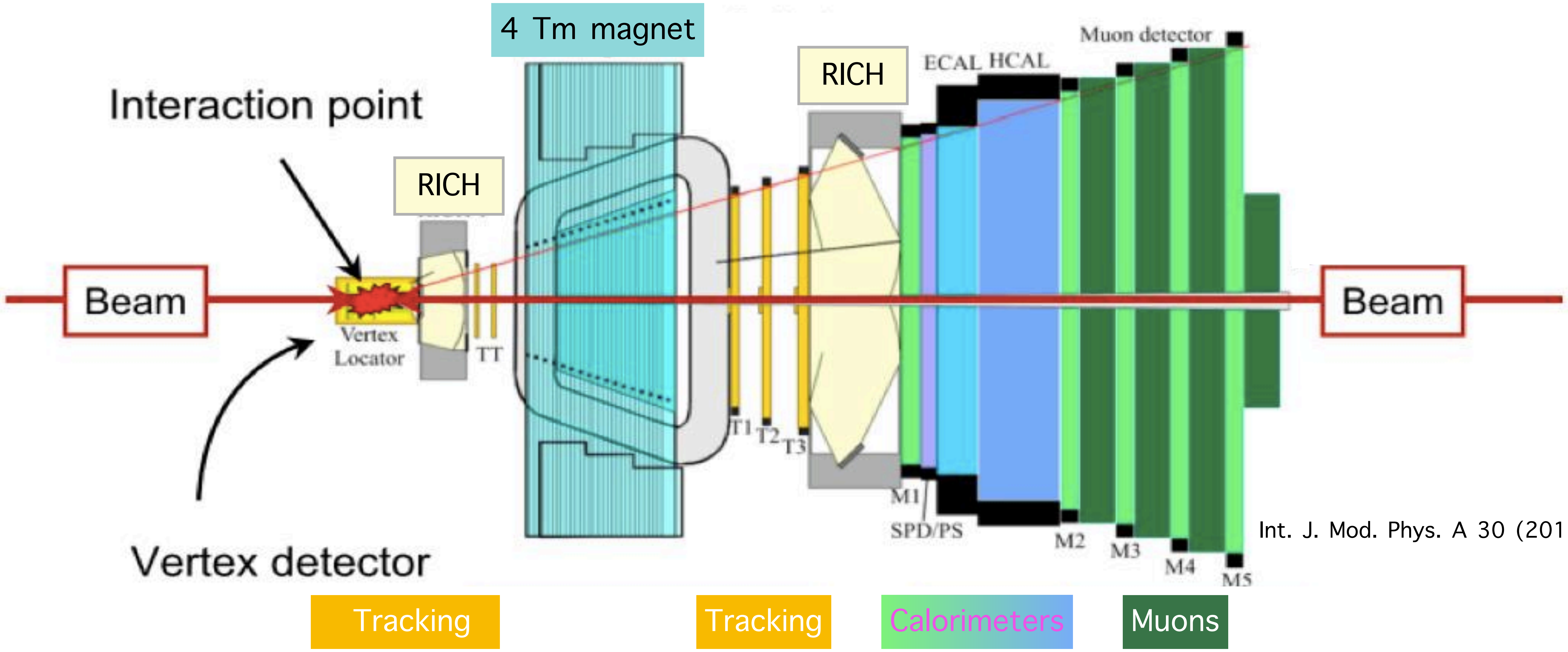

Int. J. Mod. Phys. A 30 (2015) 1530022

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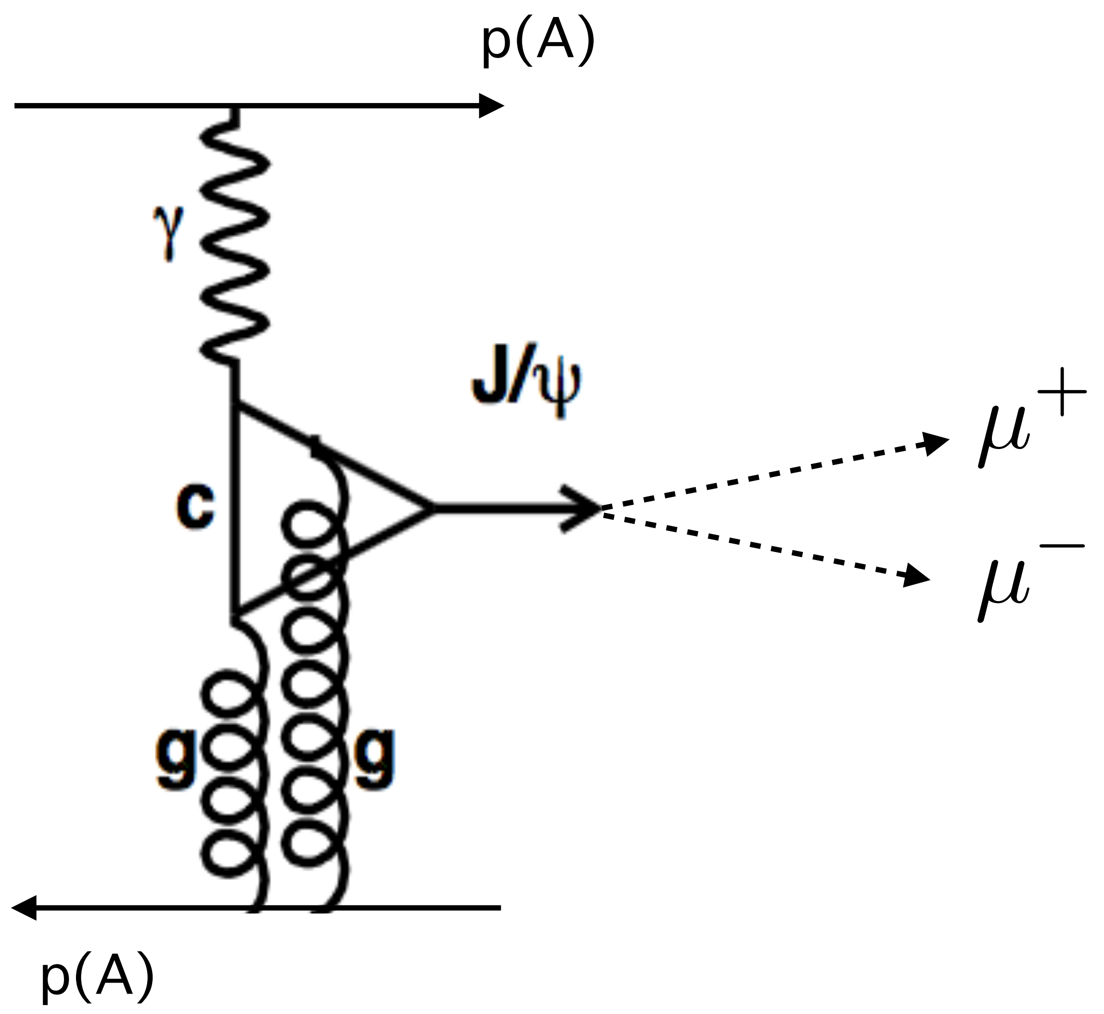
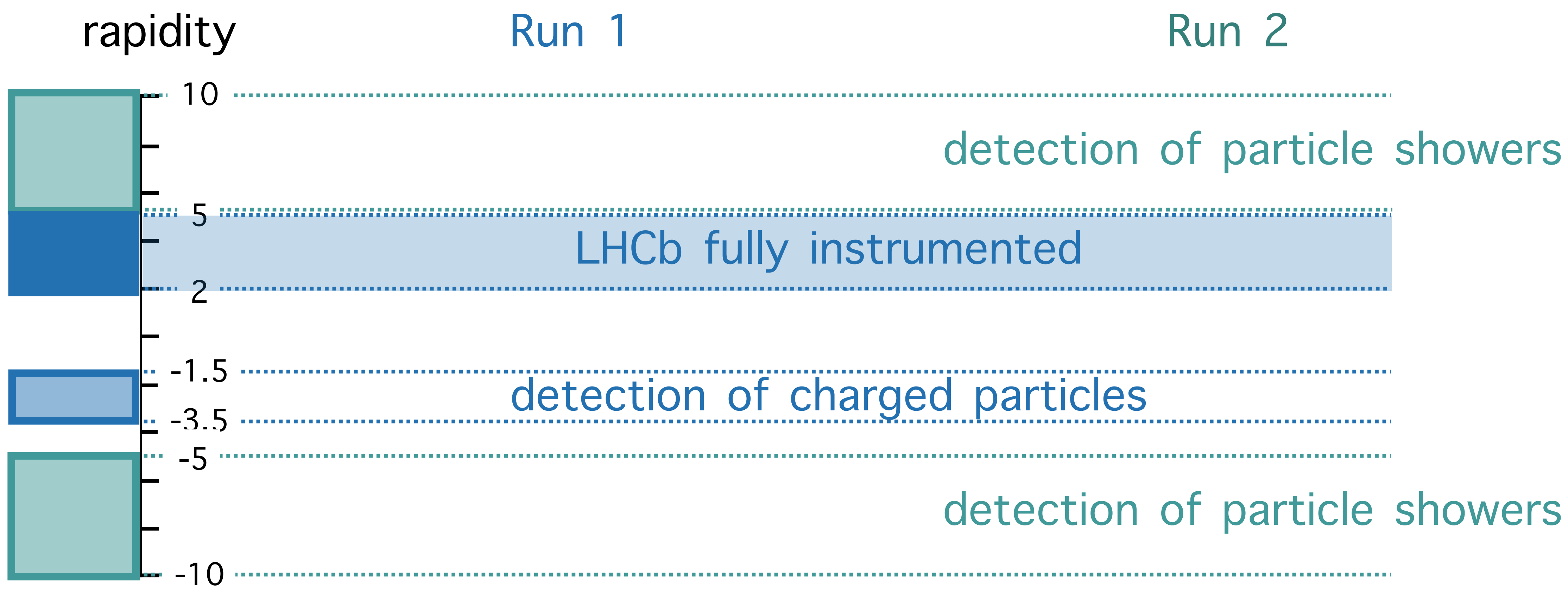
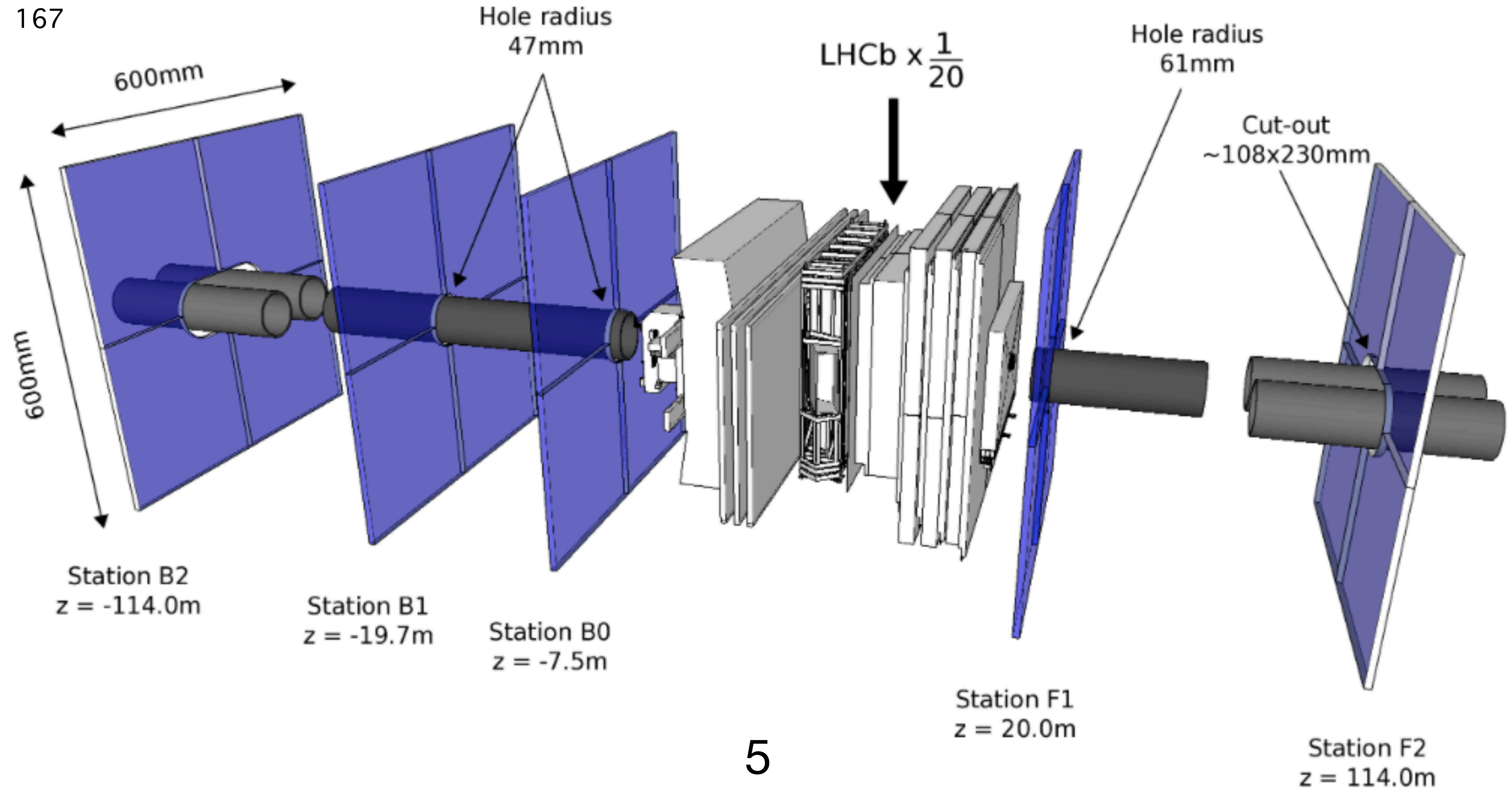




Herschel JHEP 10 (2018) 167



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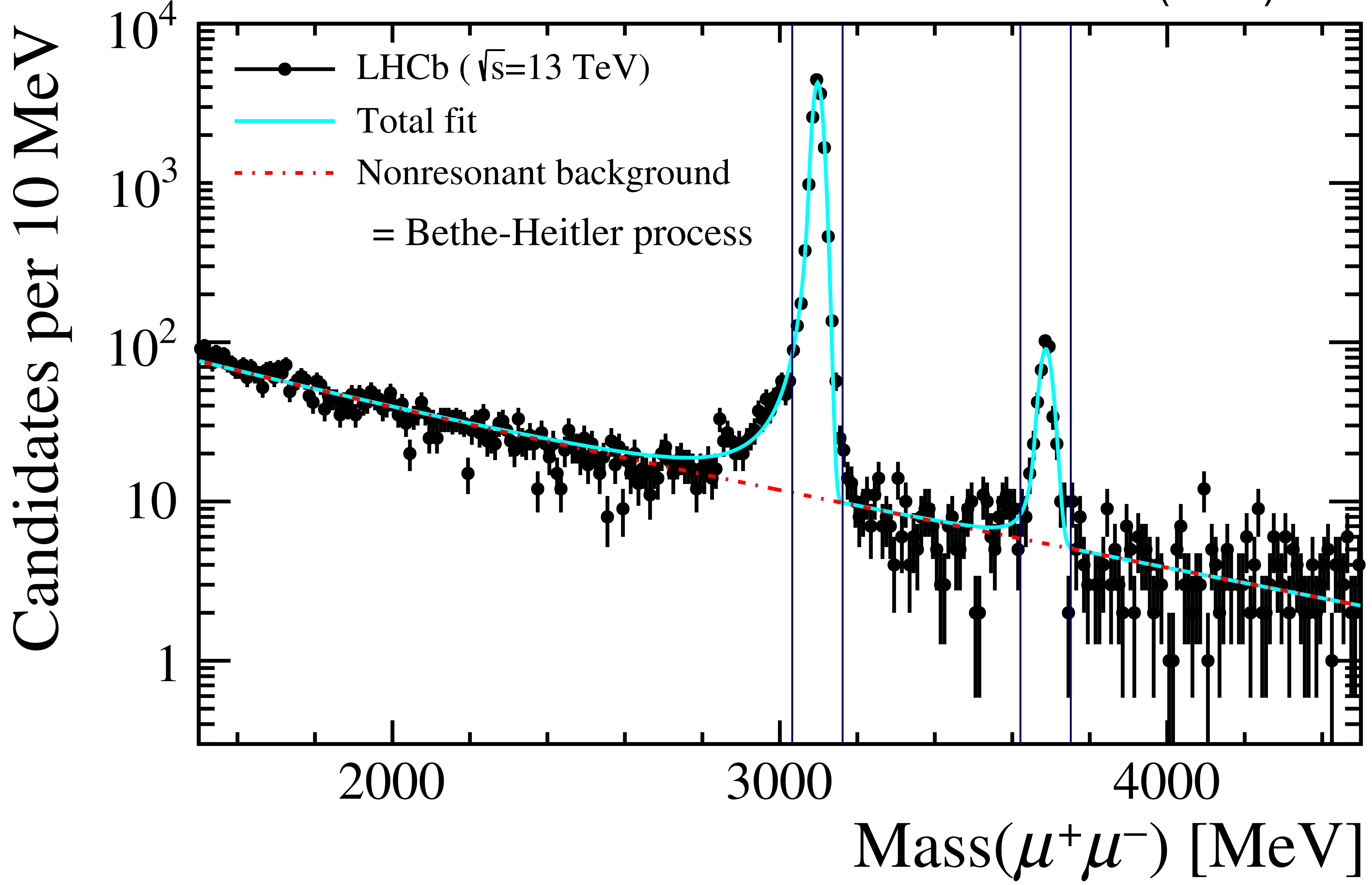
proton-proton collisions

JHEP **10** (2018) 167



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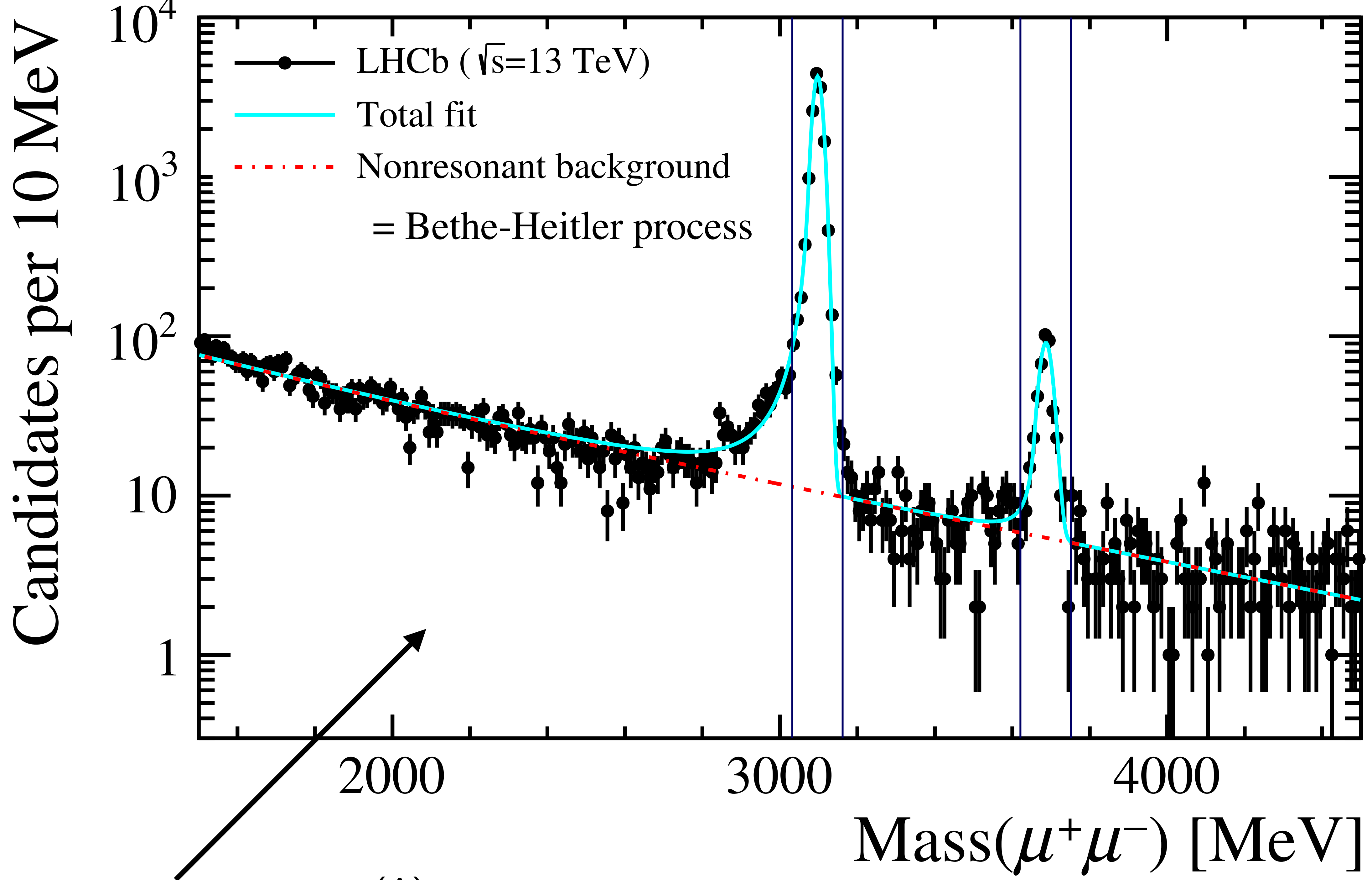

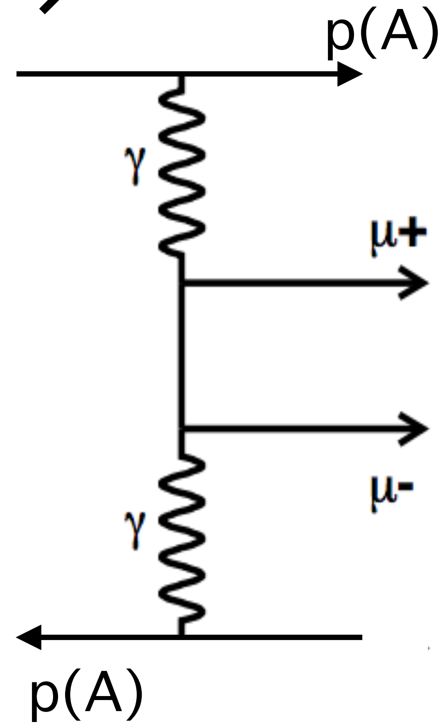

Bethe-Heitler process

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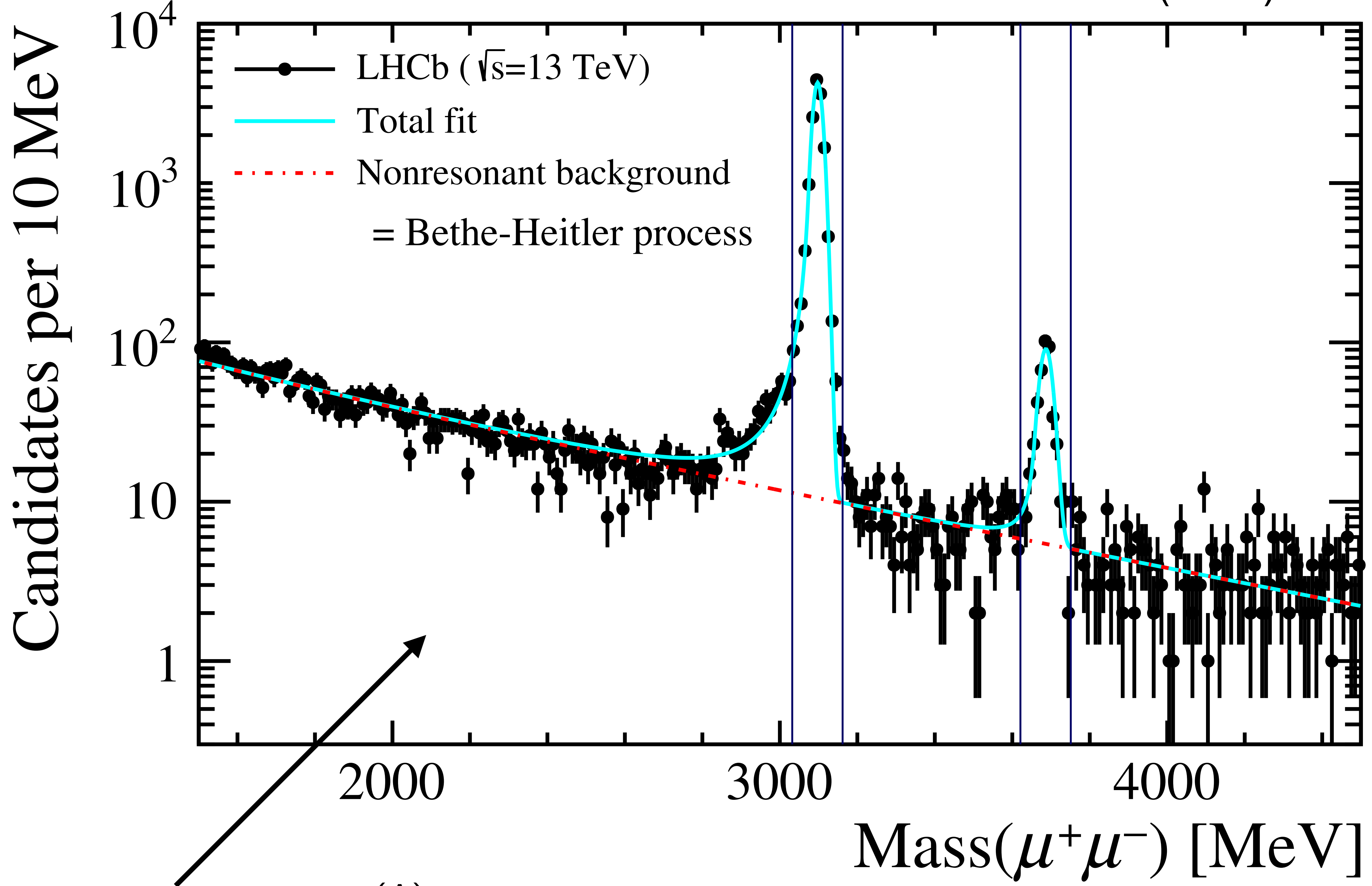

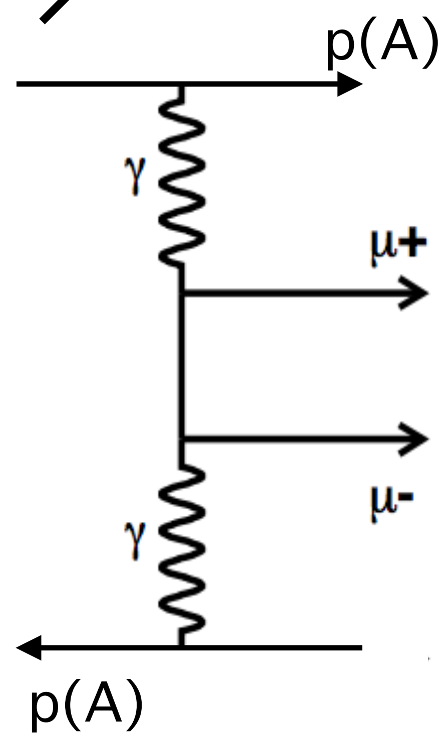

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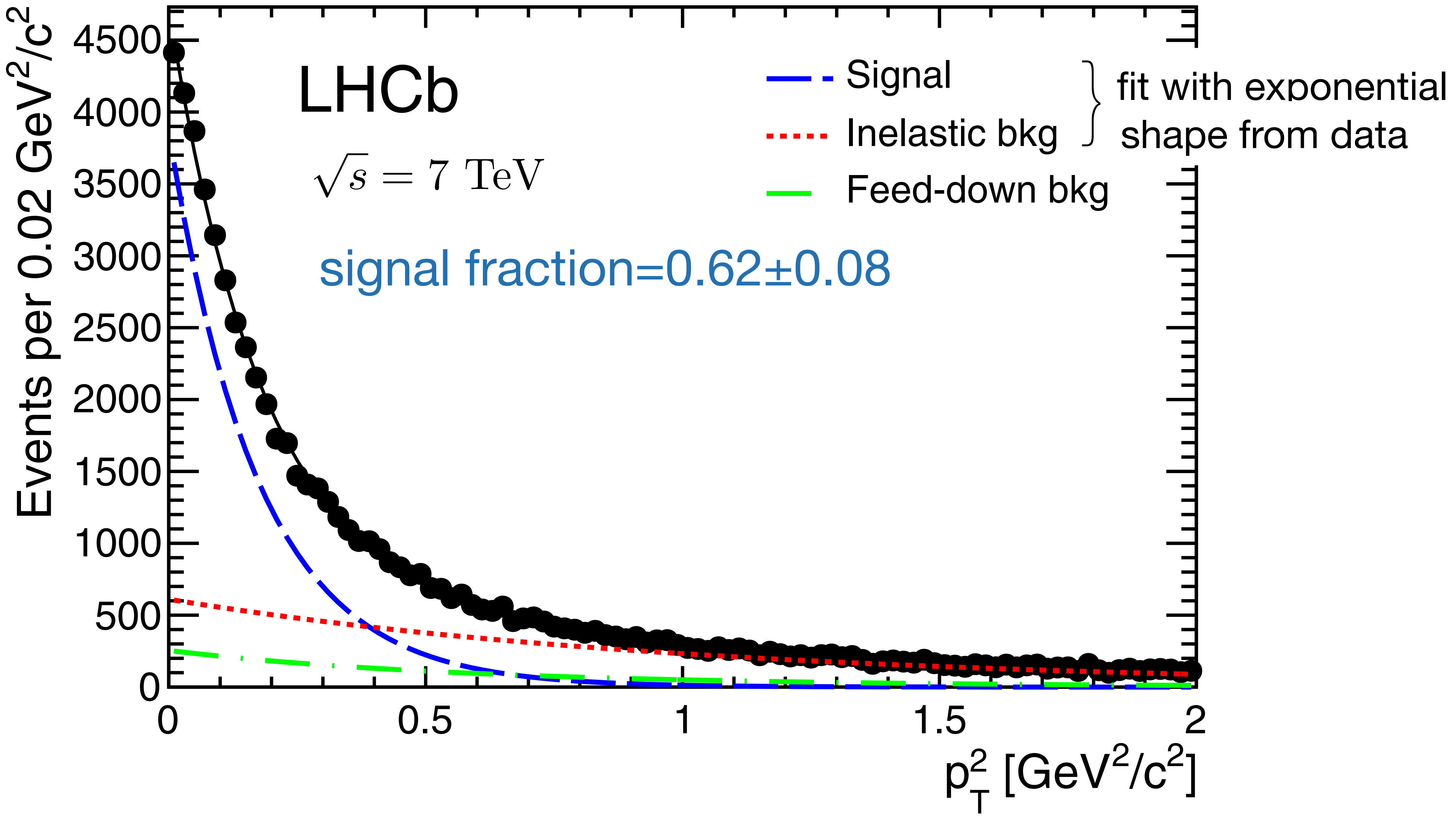
J. Phys. G: Nucl. Part. Phys. **41** (2014) 055002



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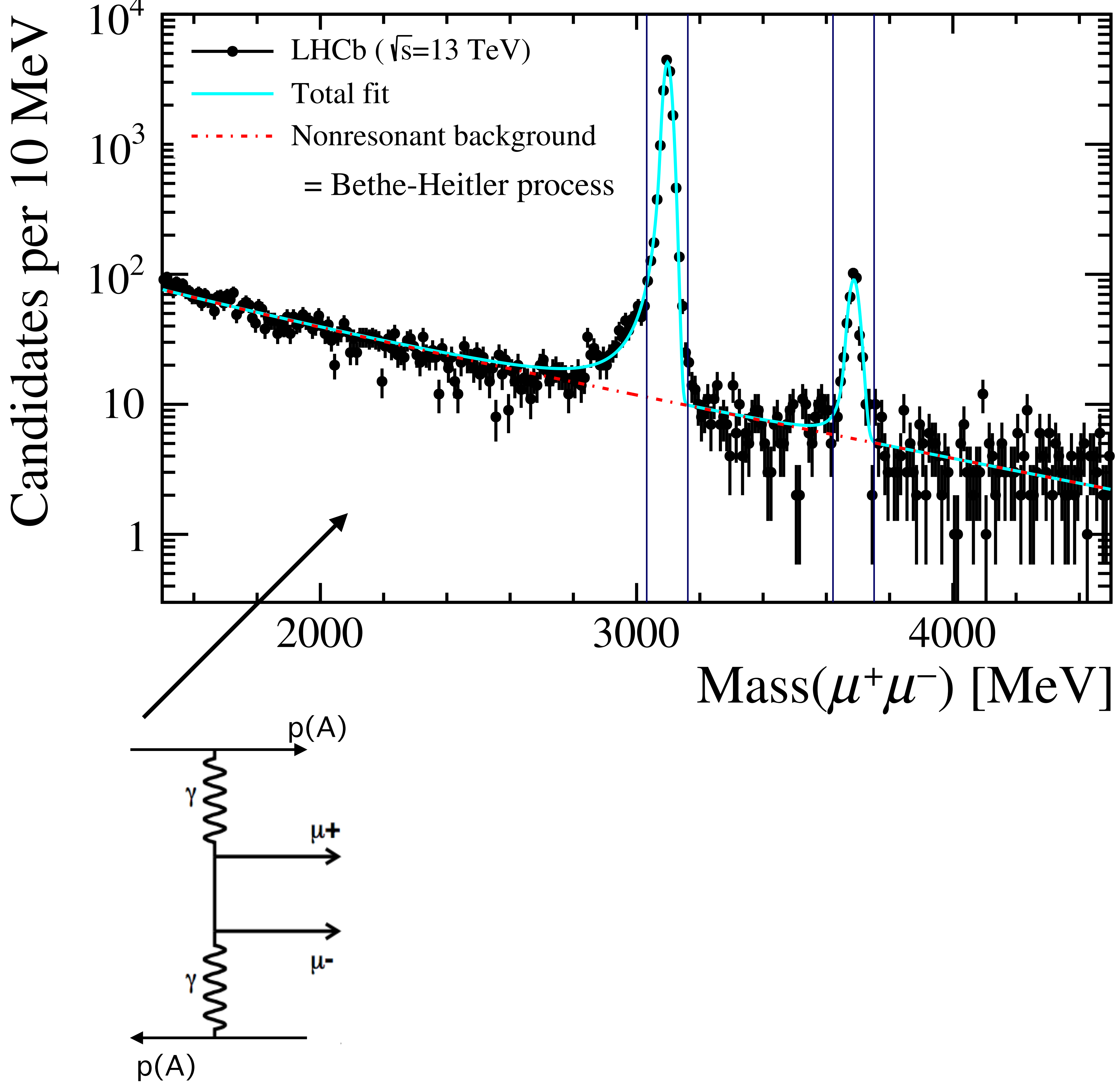

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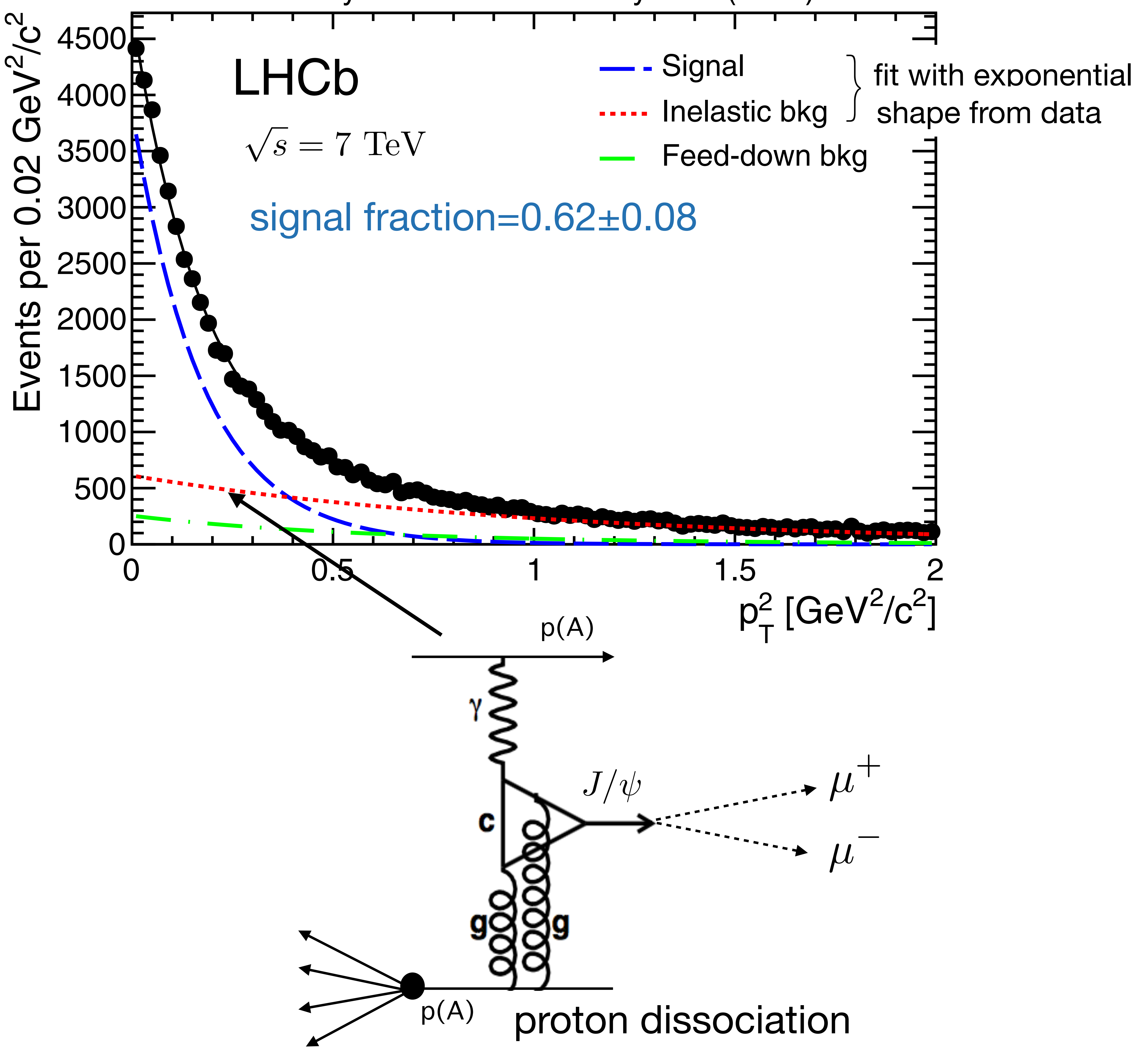

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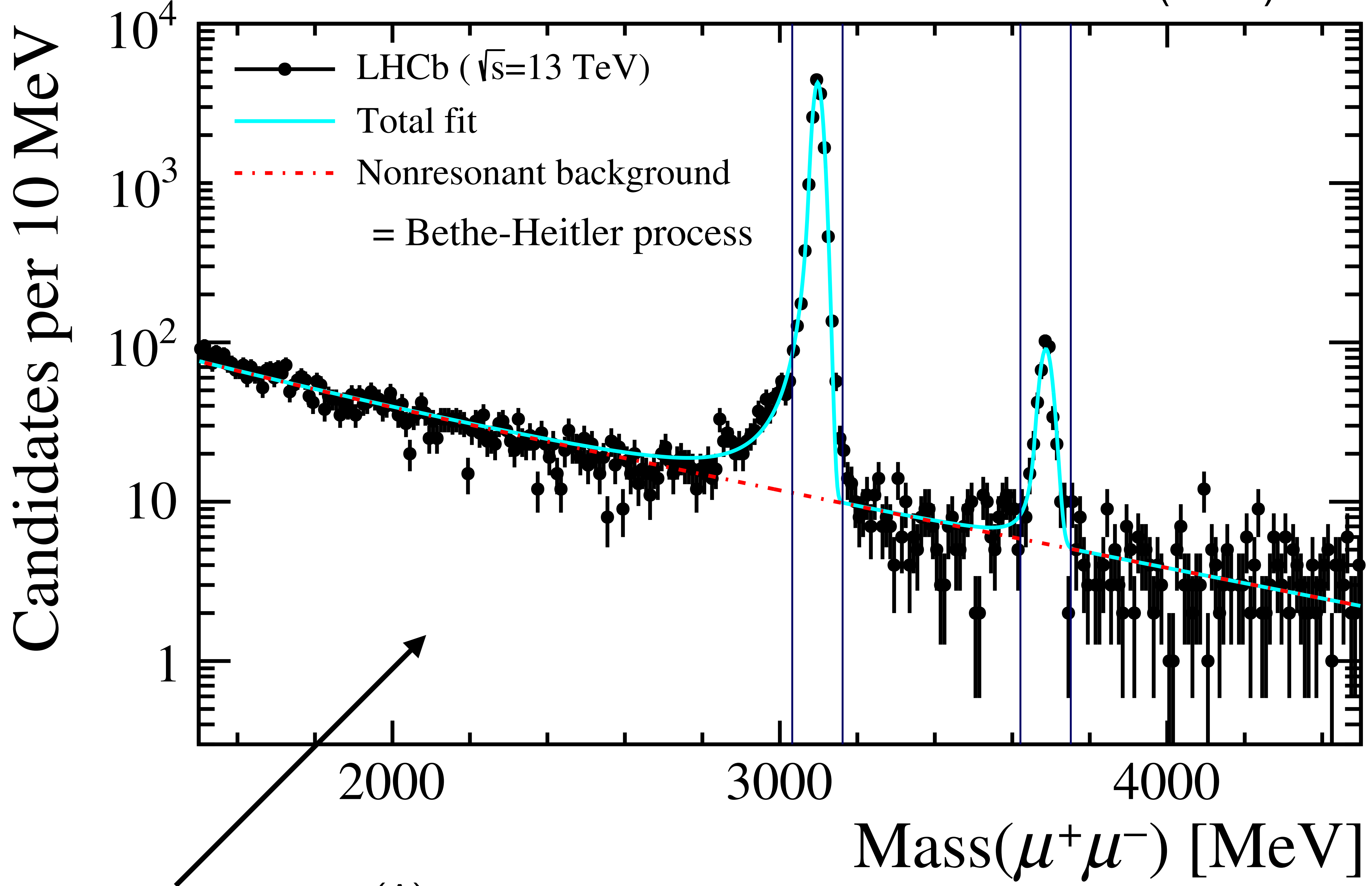

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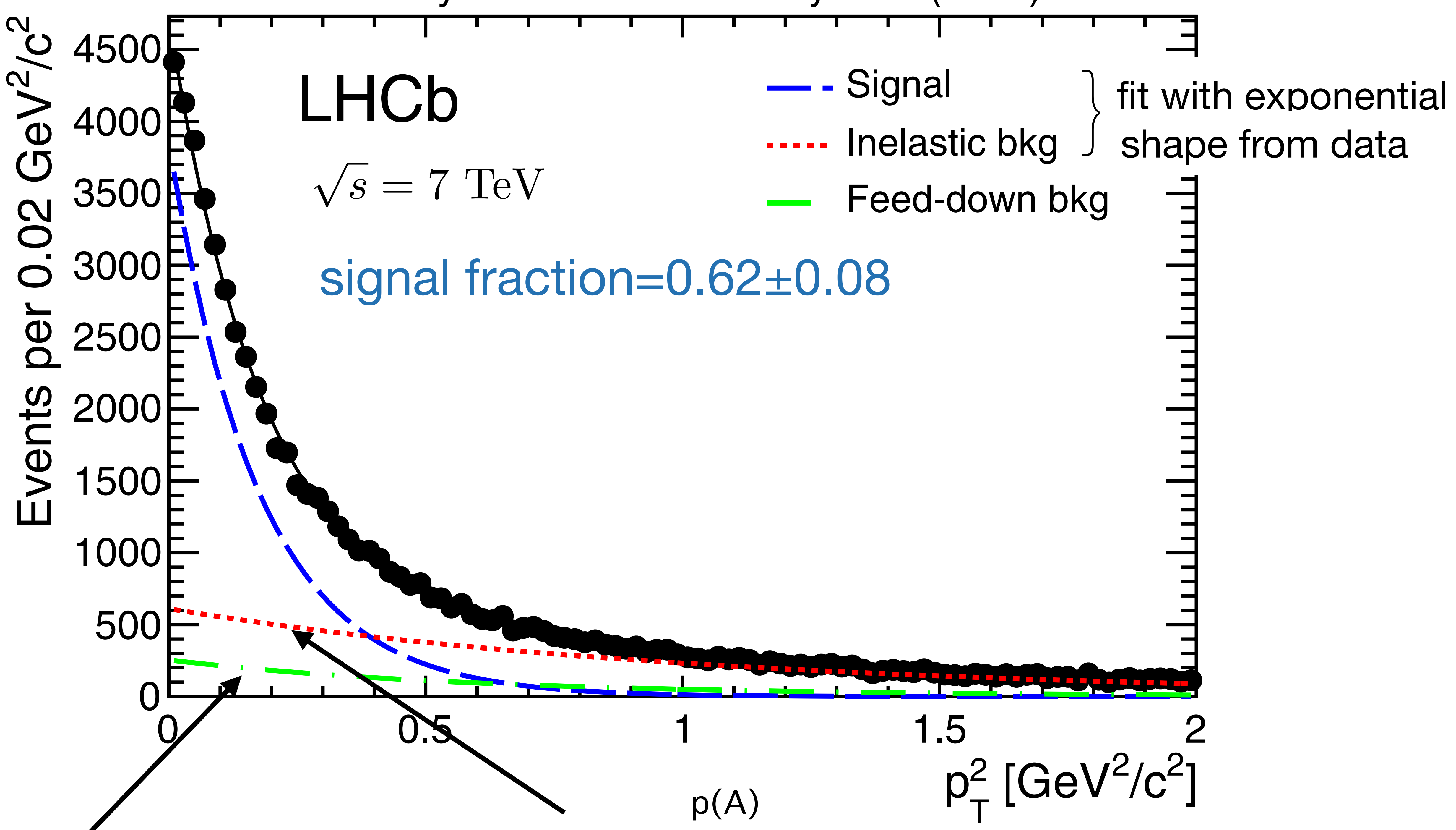

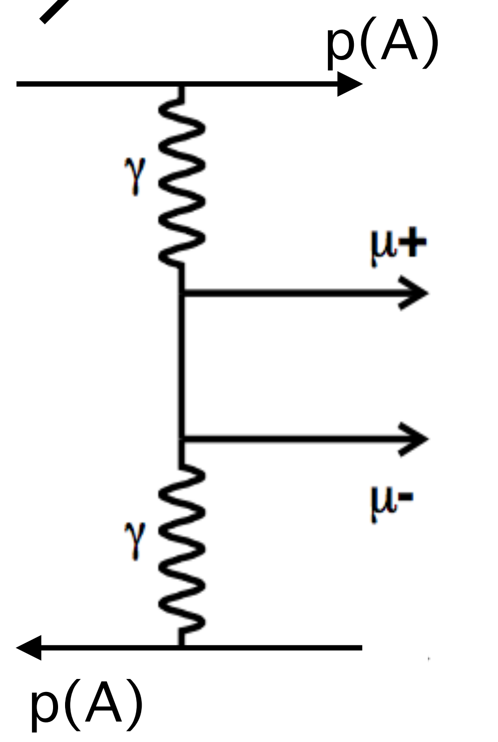

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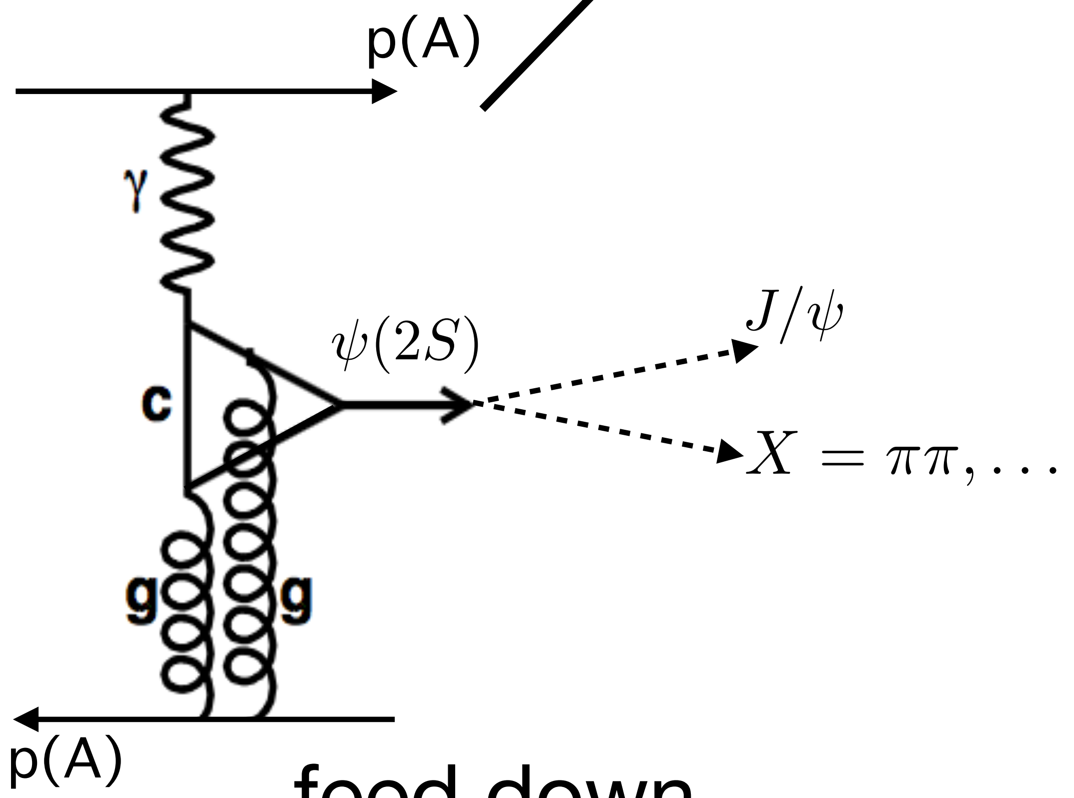
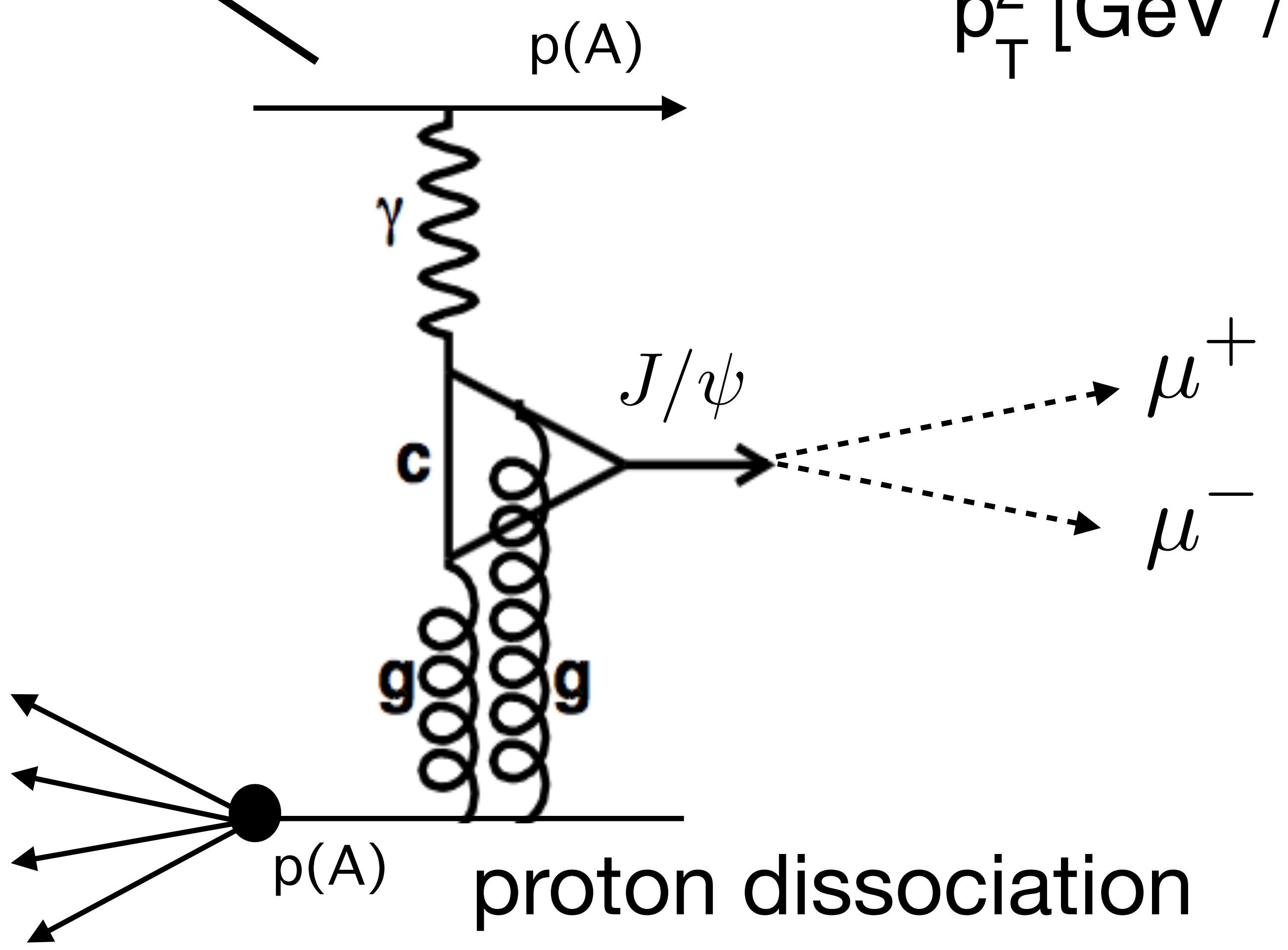
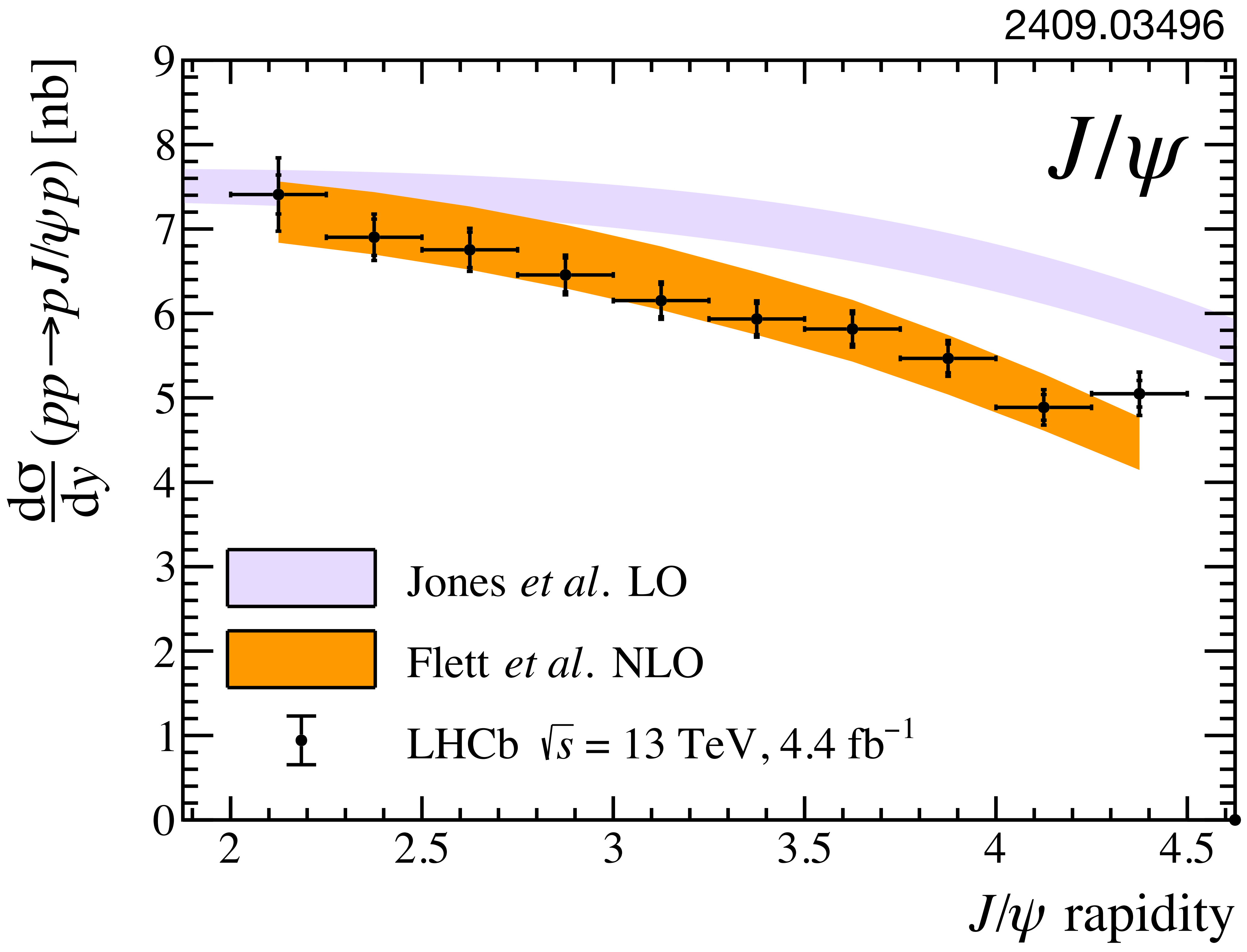


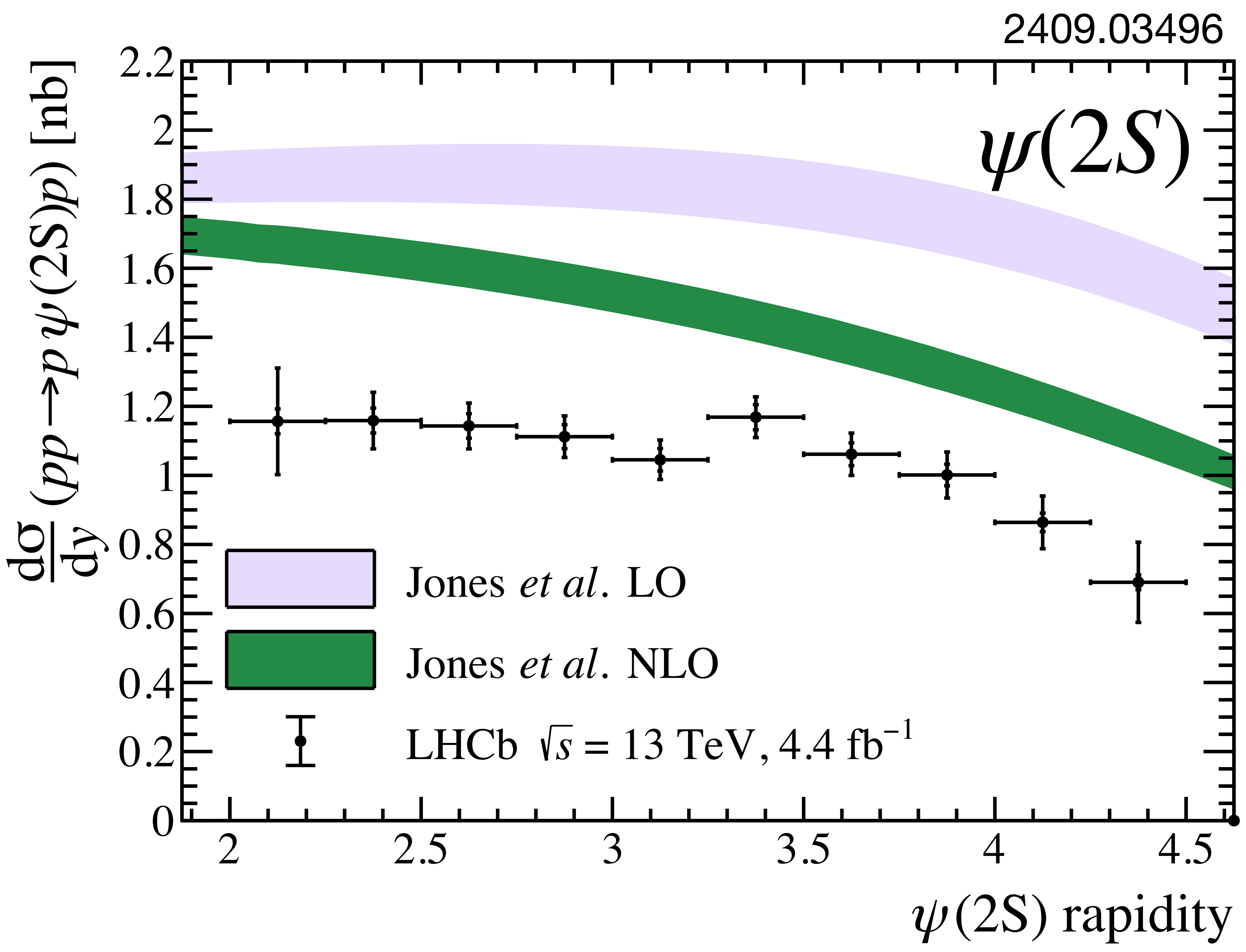
feed down



proton dissociation

Exclusive J/ψ and ψ(2S) production in pp collisions at LHCb





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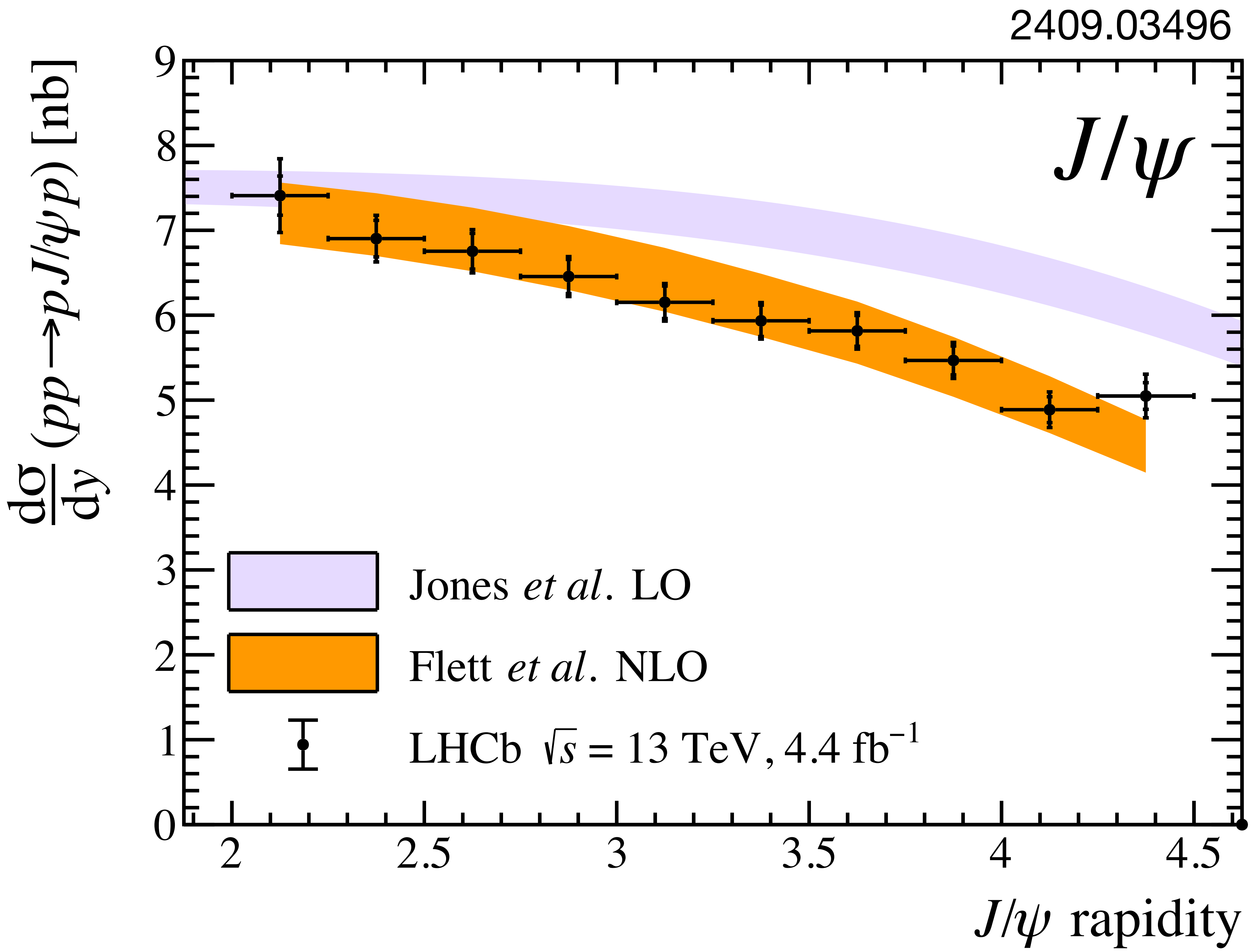
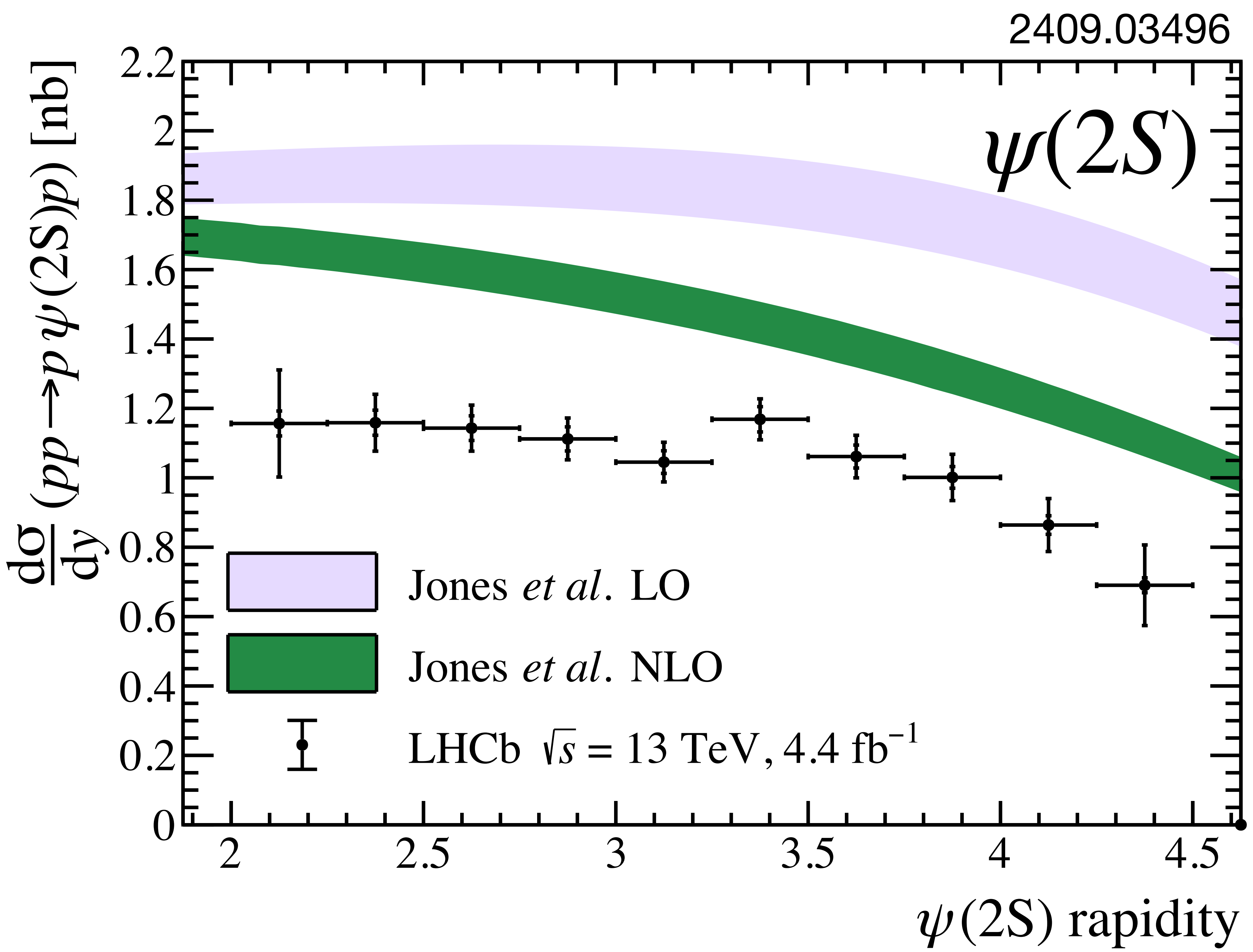


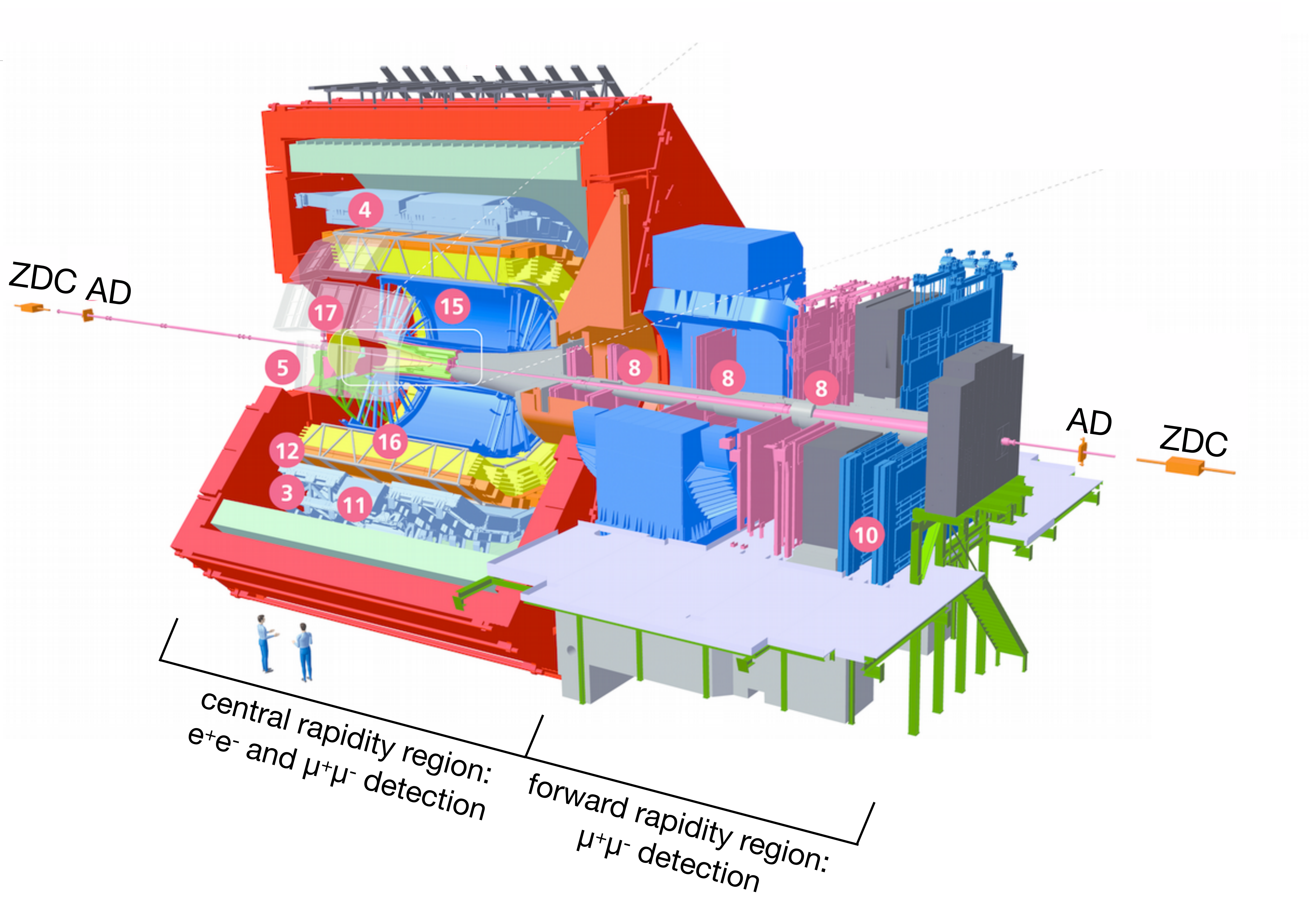


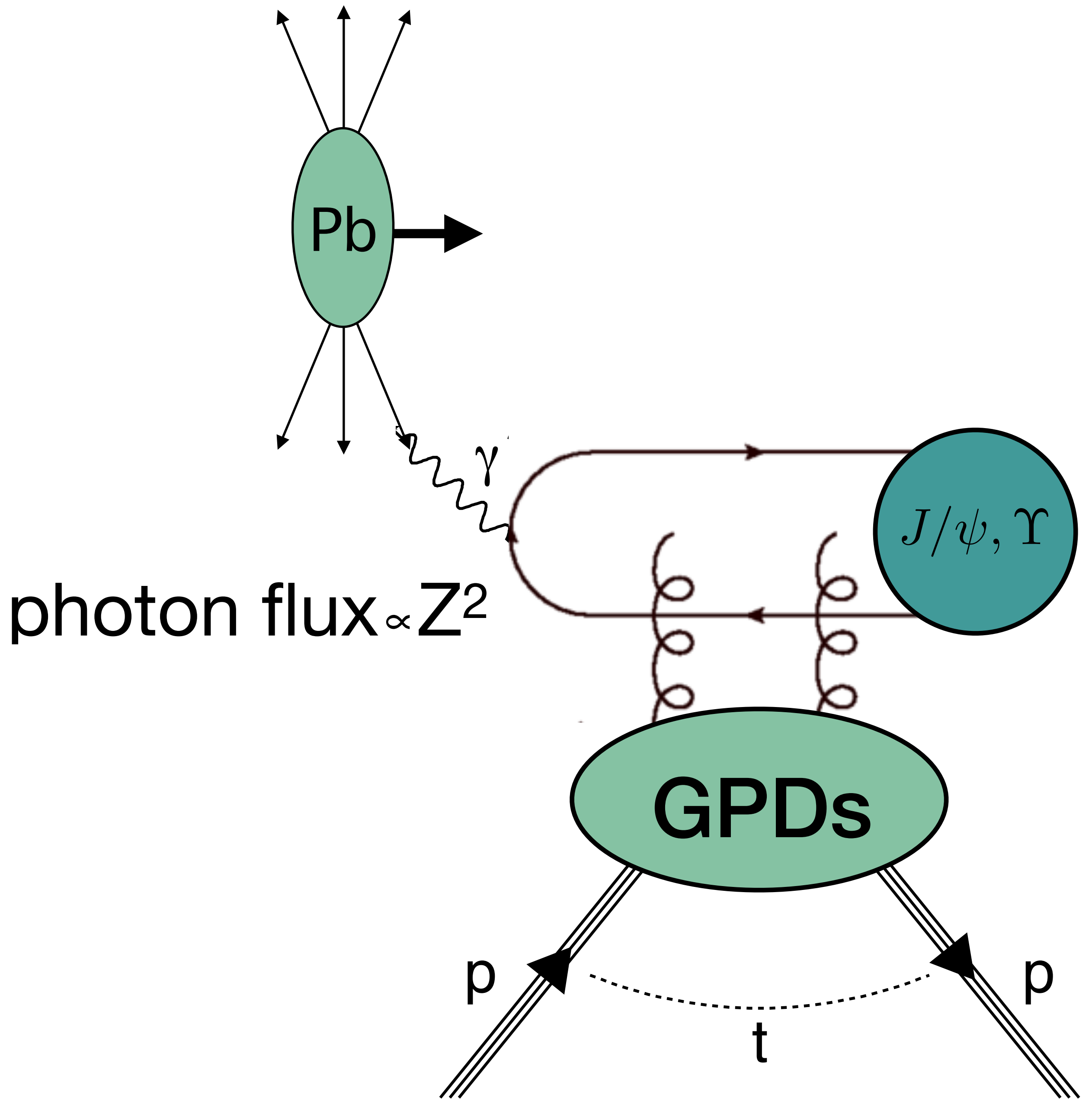
Predictions based on gluon PDF:
At low x_B, approximate GPD to gluon PDF

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

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

Exclusive J/ψ production in pPb collisions at ALICE





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

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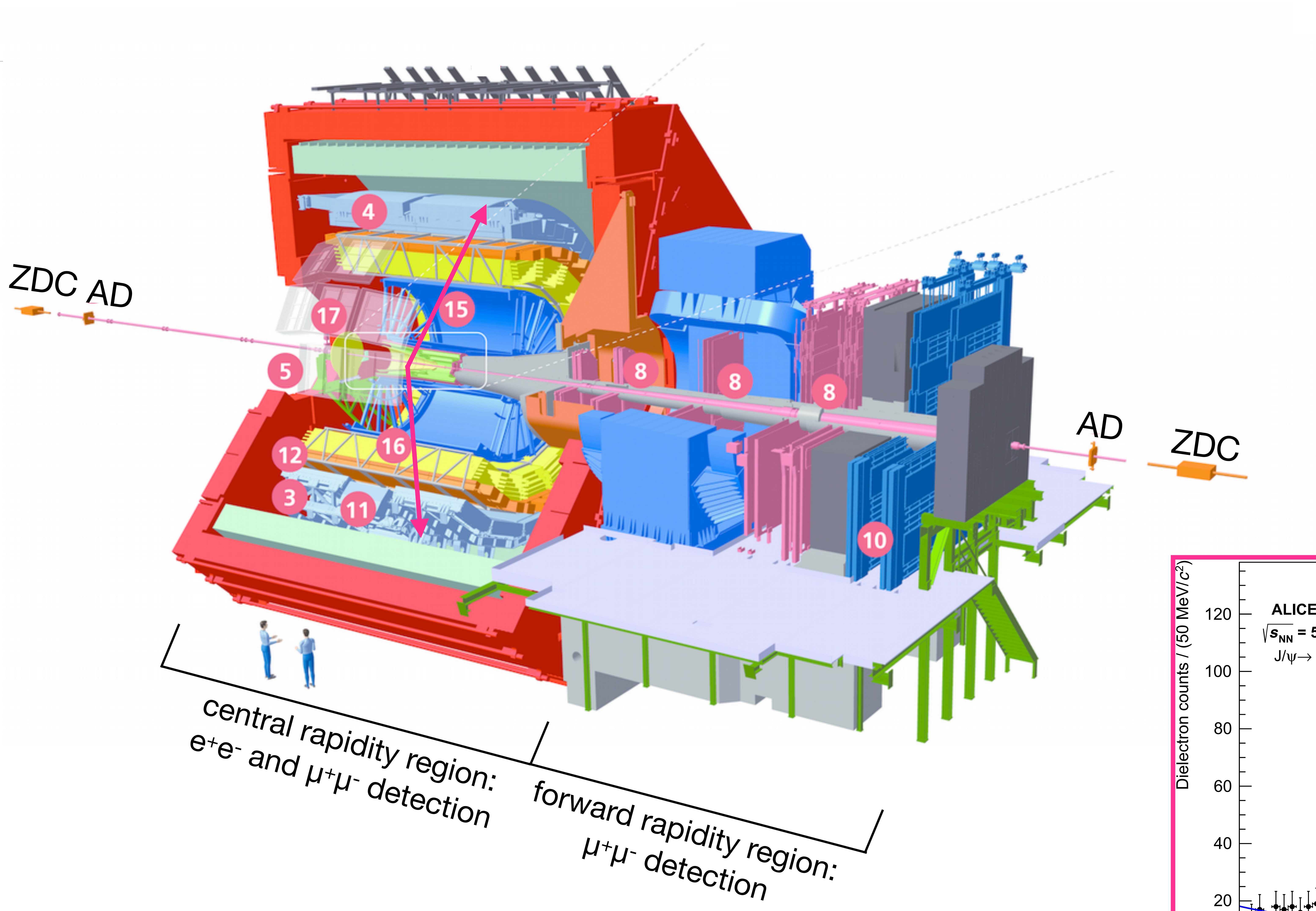

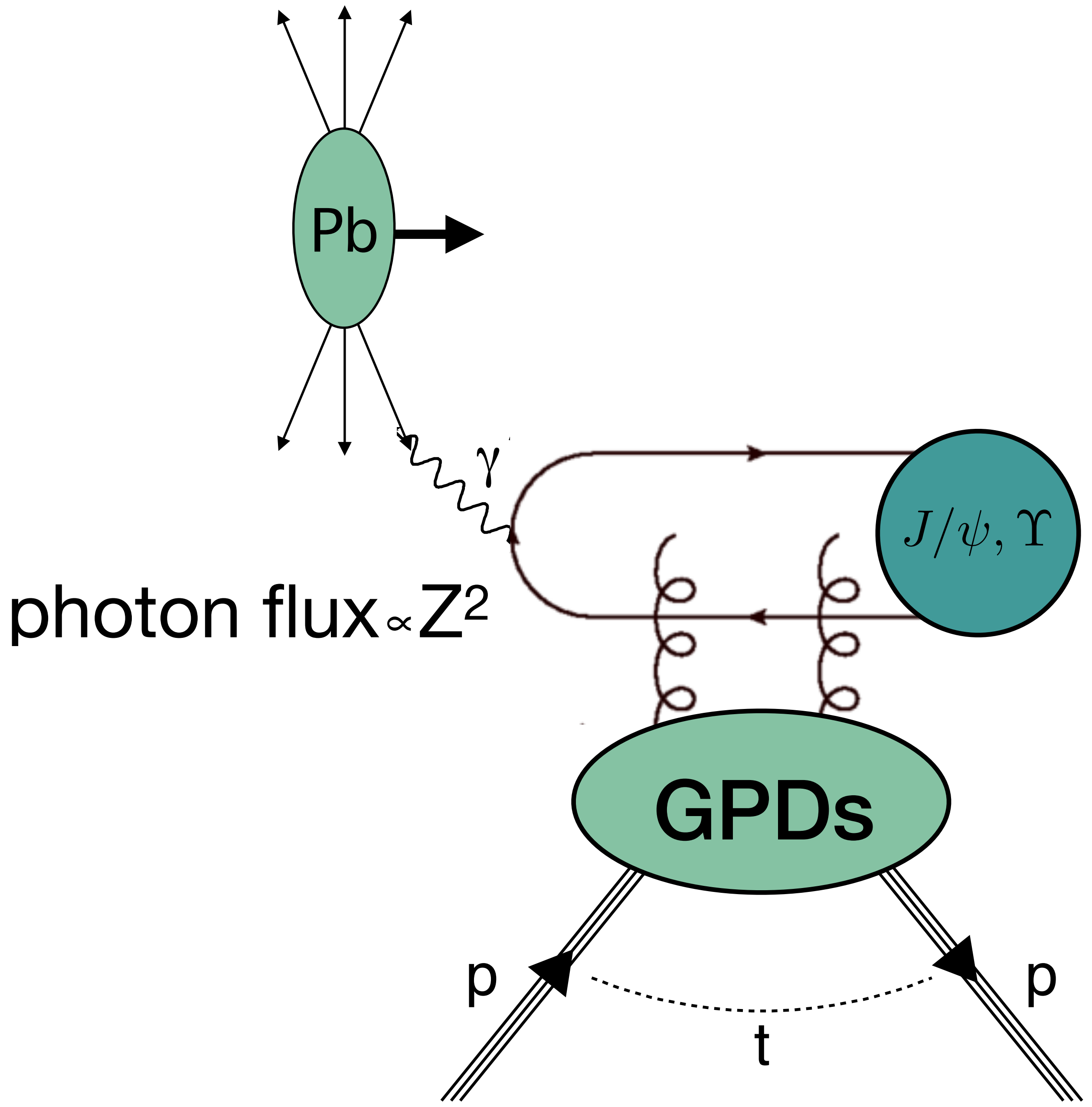

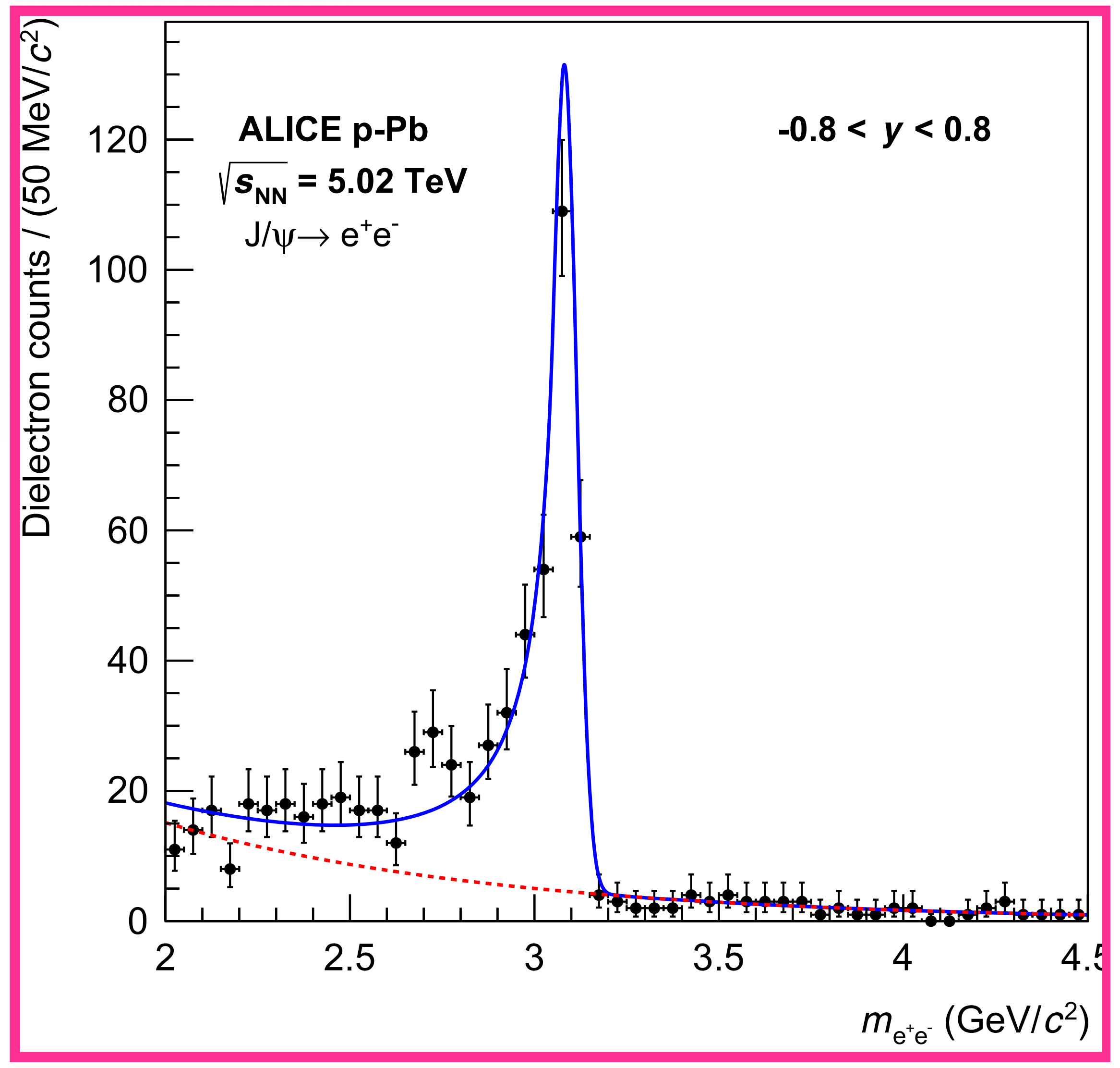

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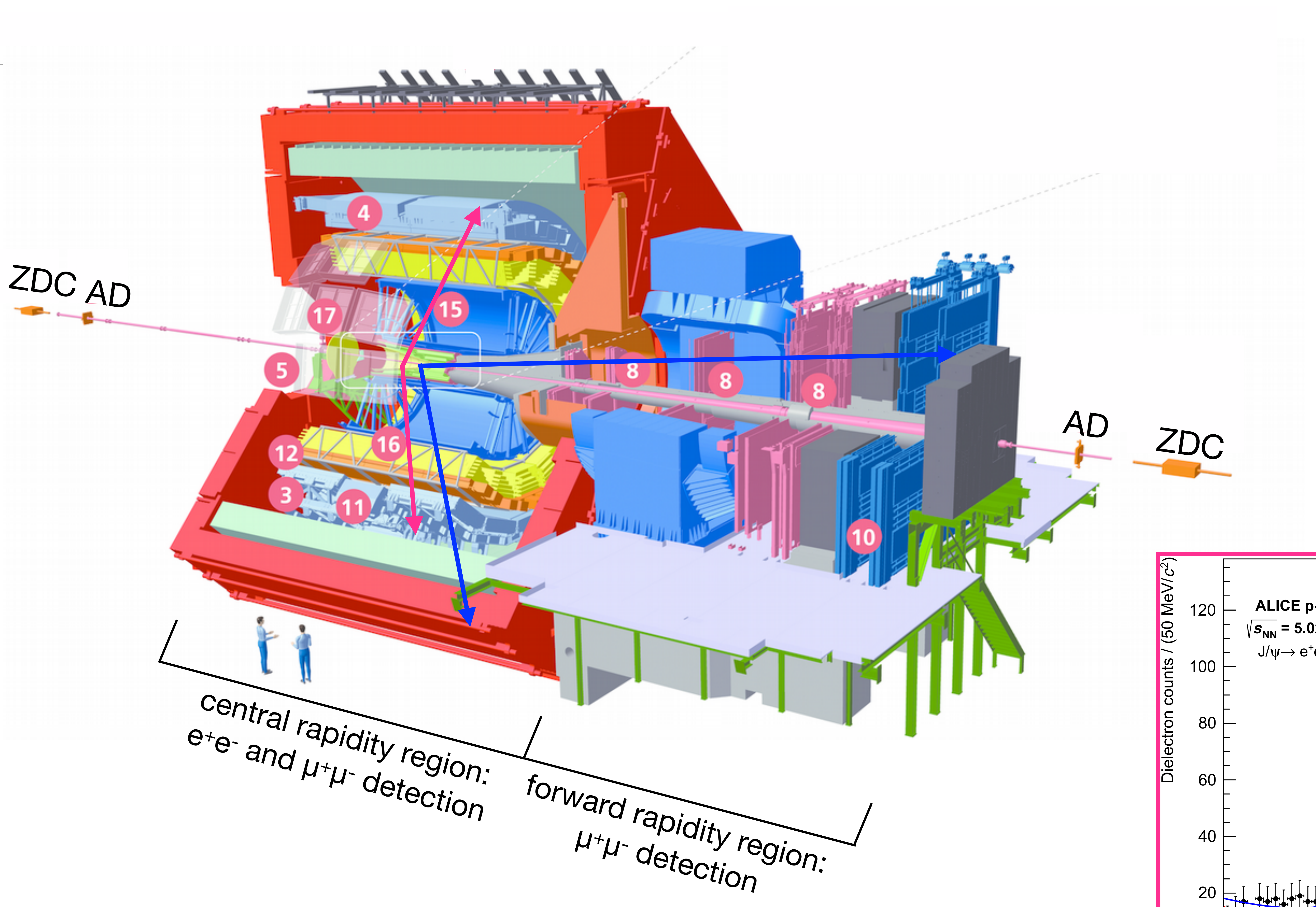

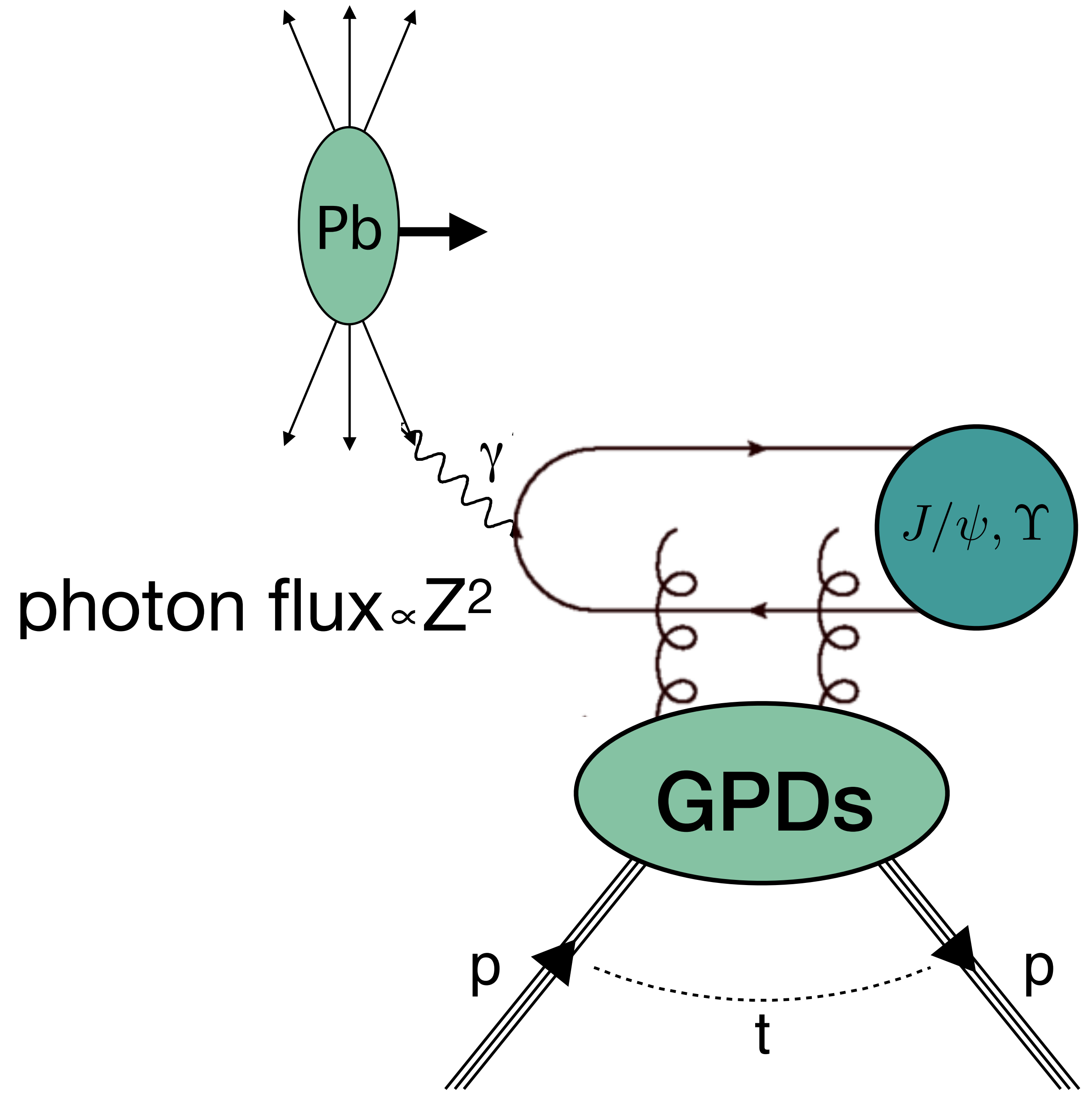

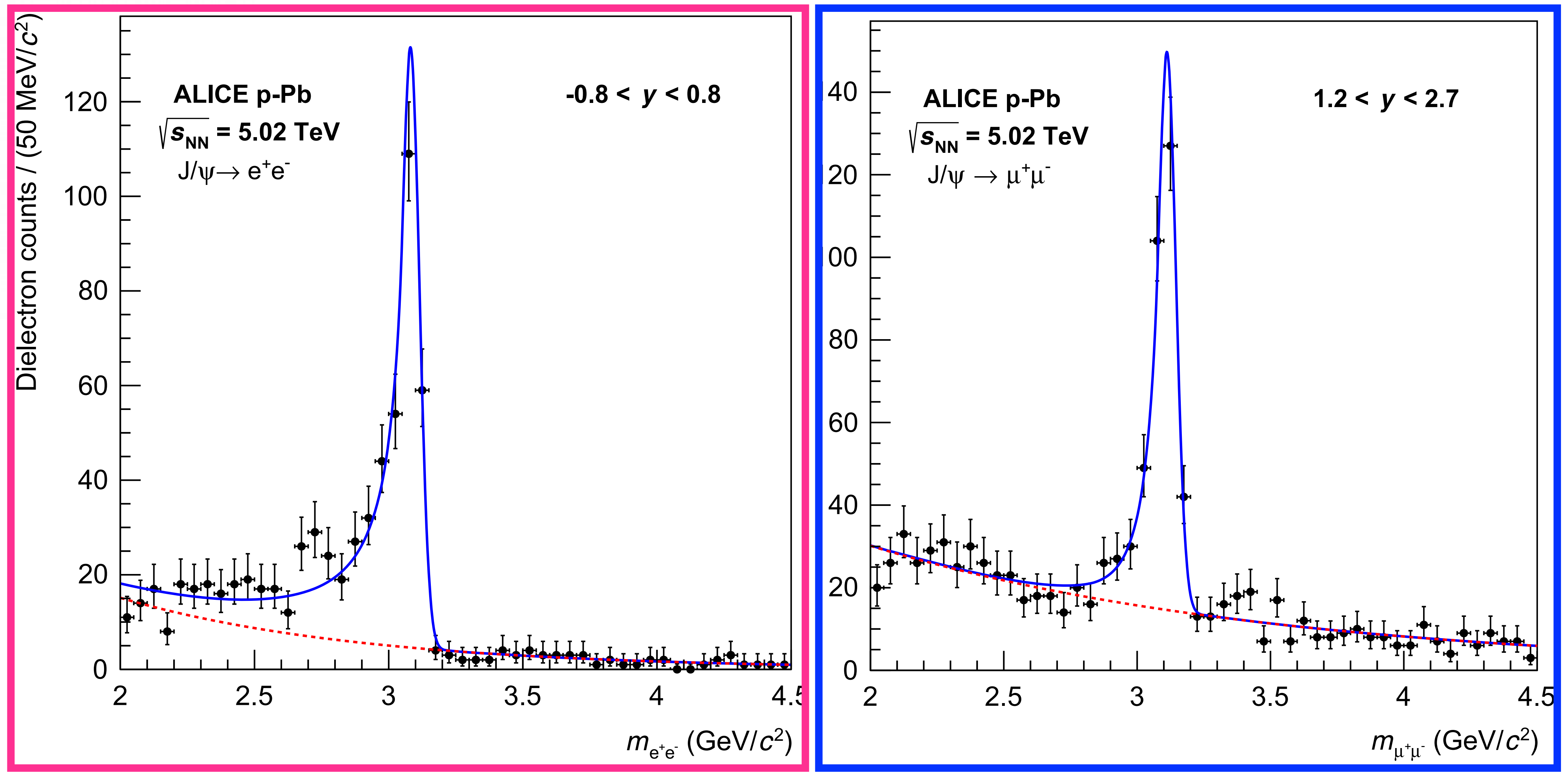

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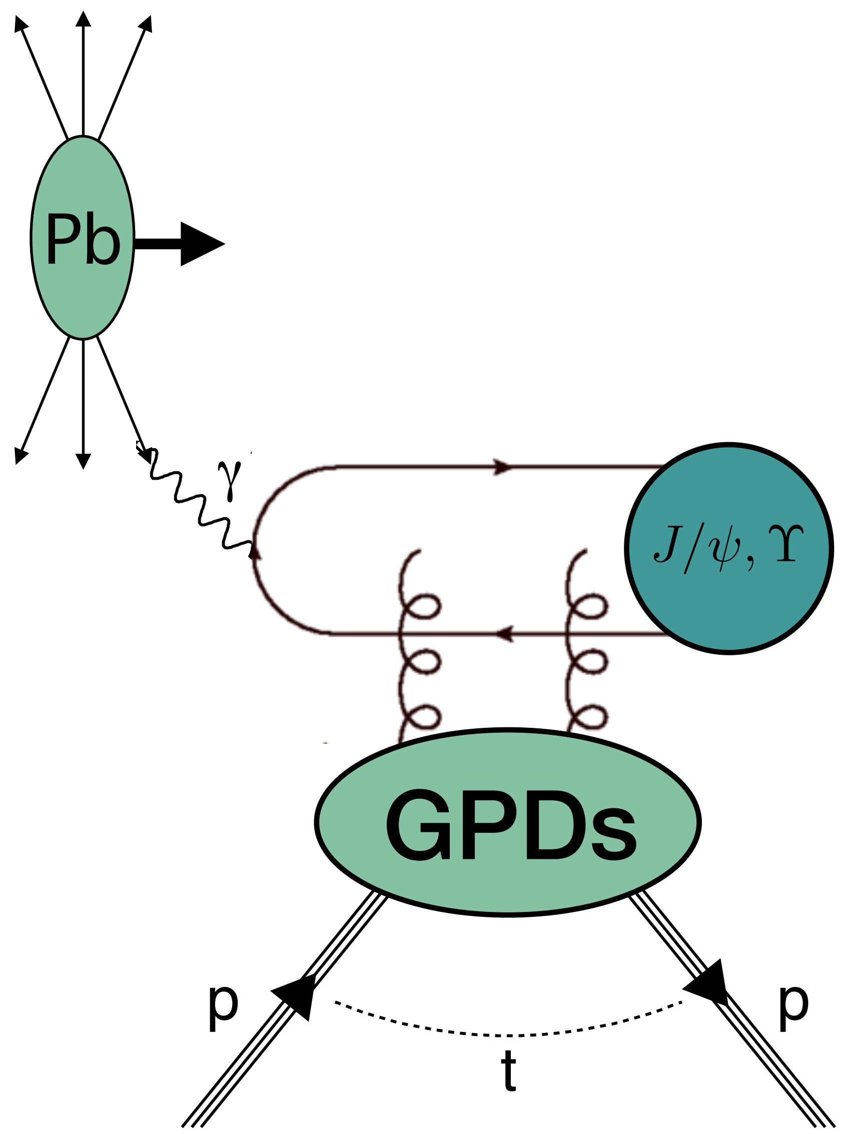
Extraction of the J/ψ photoproduction



pPb: use Z^2 dependence of photon flux
→ Pb is predominantly photon emitter

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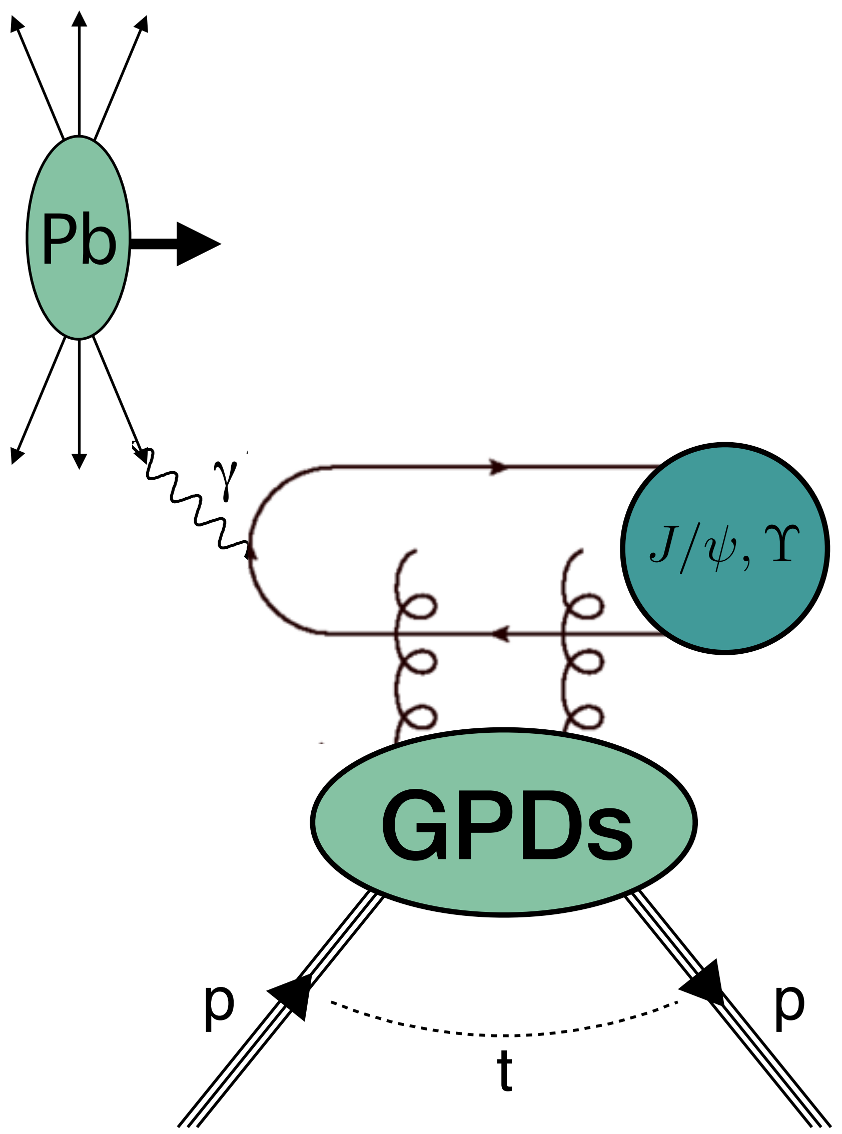

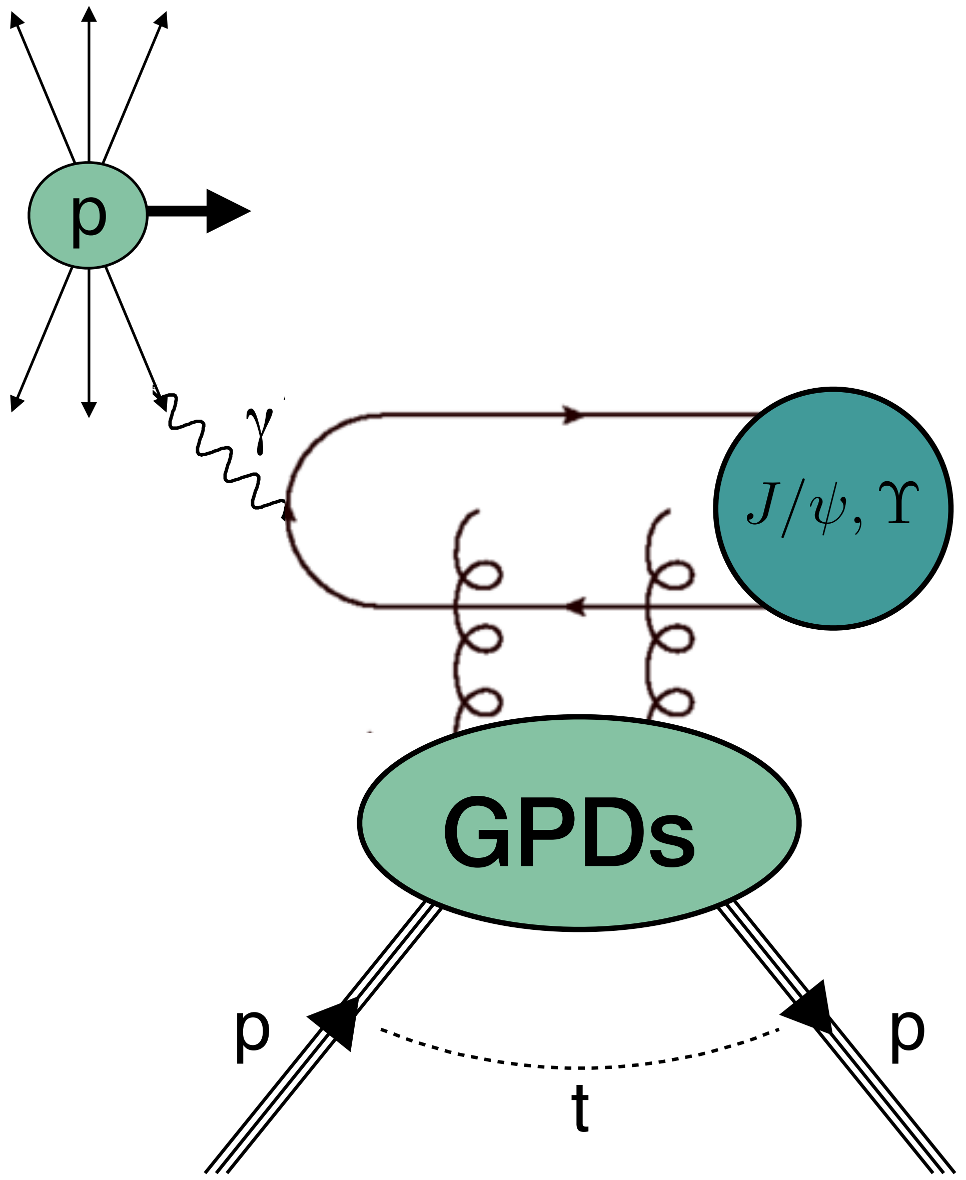

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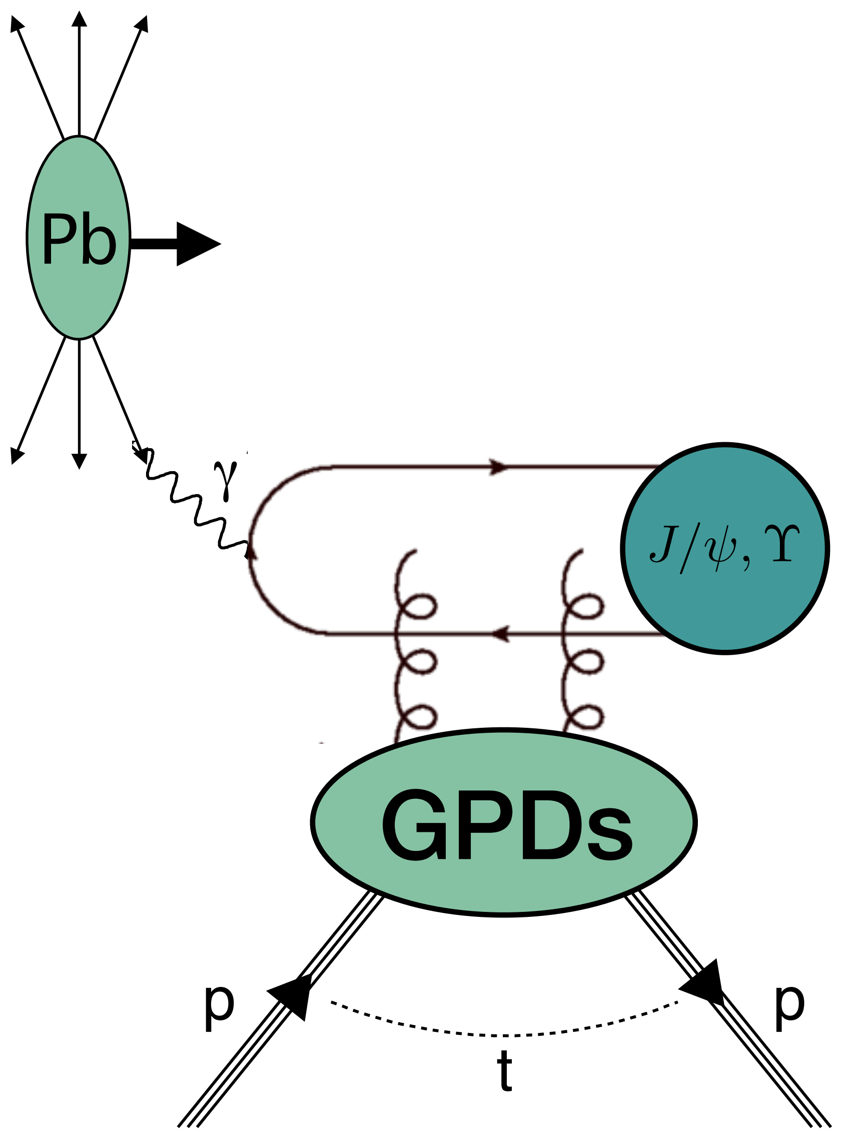

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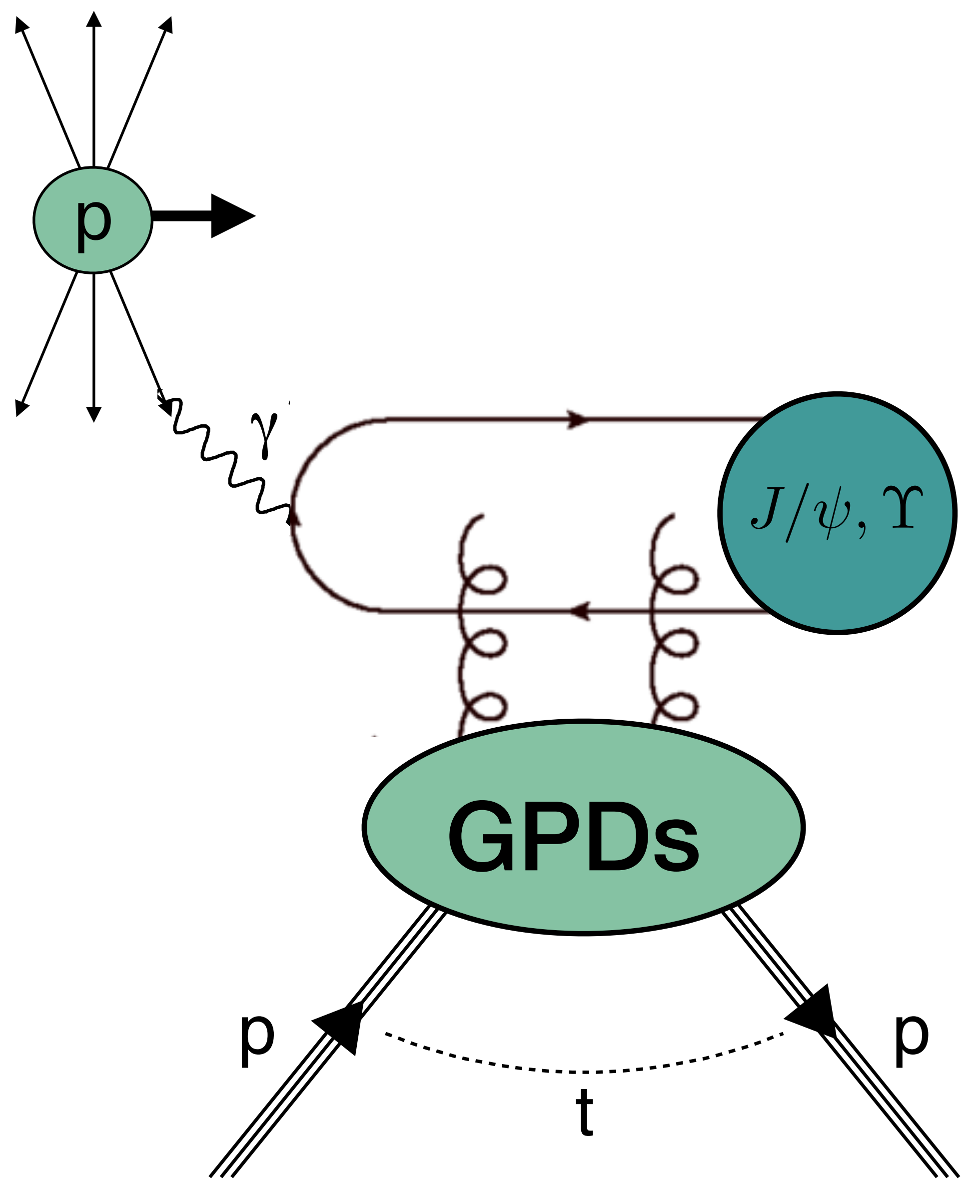


pp: ambiguity in ID of photon emitter

- 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

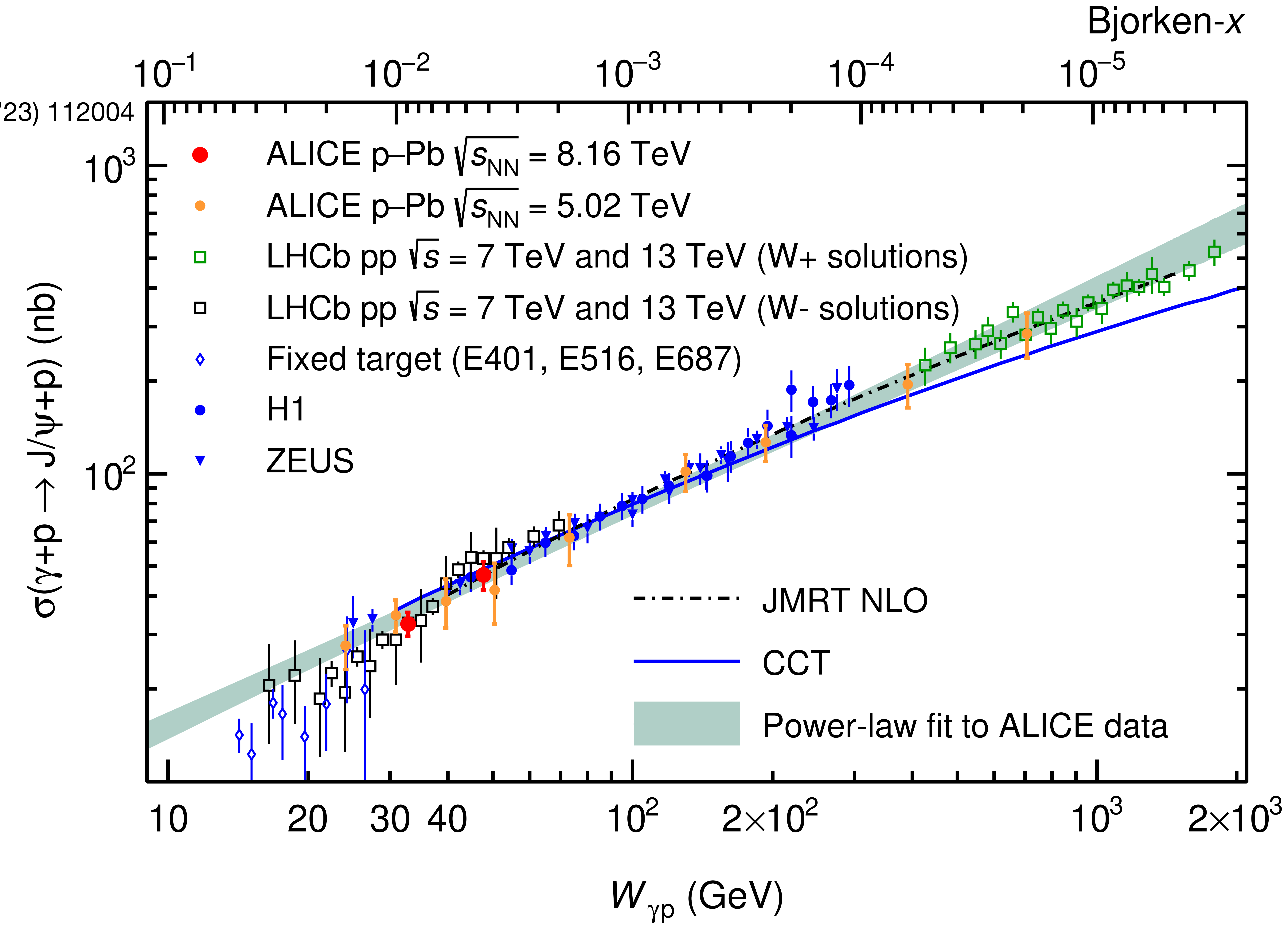
relation pp and γp cross section:

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

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

J/ψ photoproduction cross section

Phys. Rev. D **108** ('23) 112004



GPD H

J/ψ photoproduction cross section

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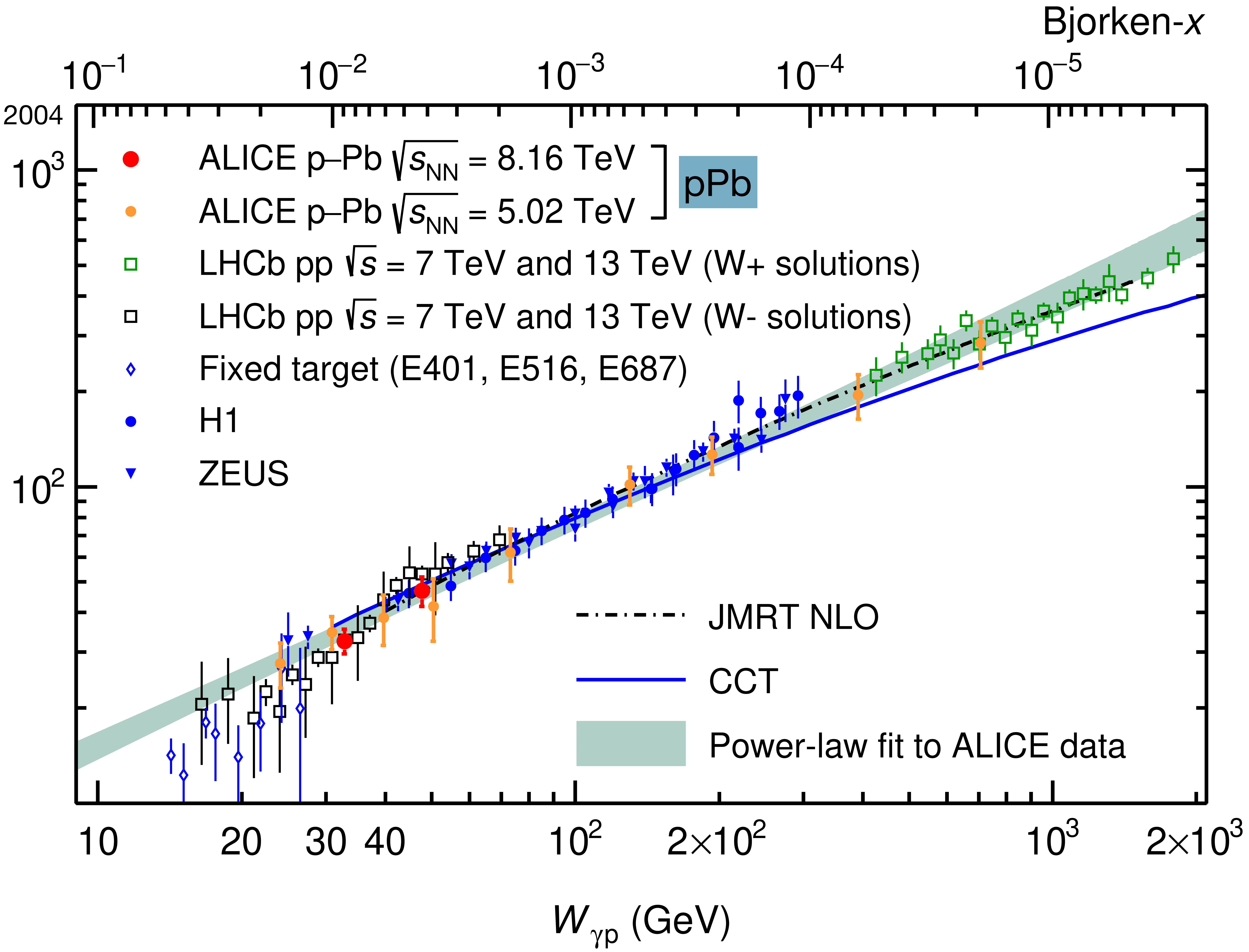
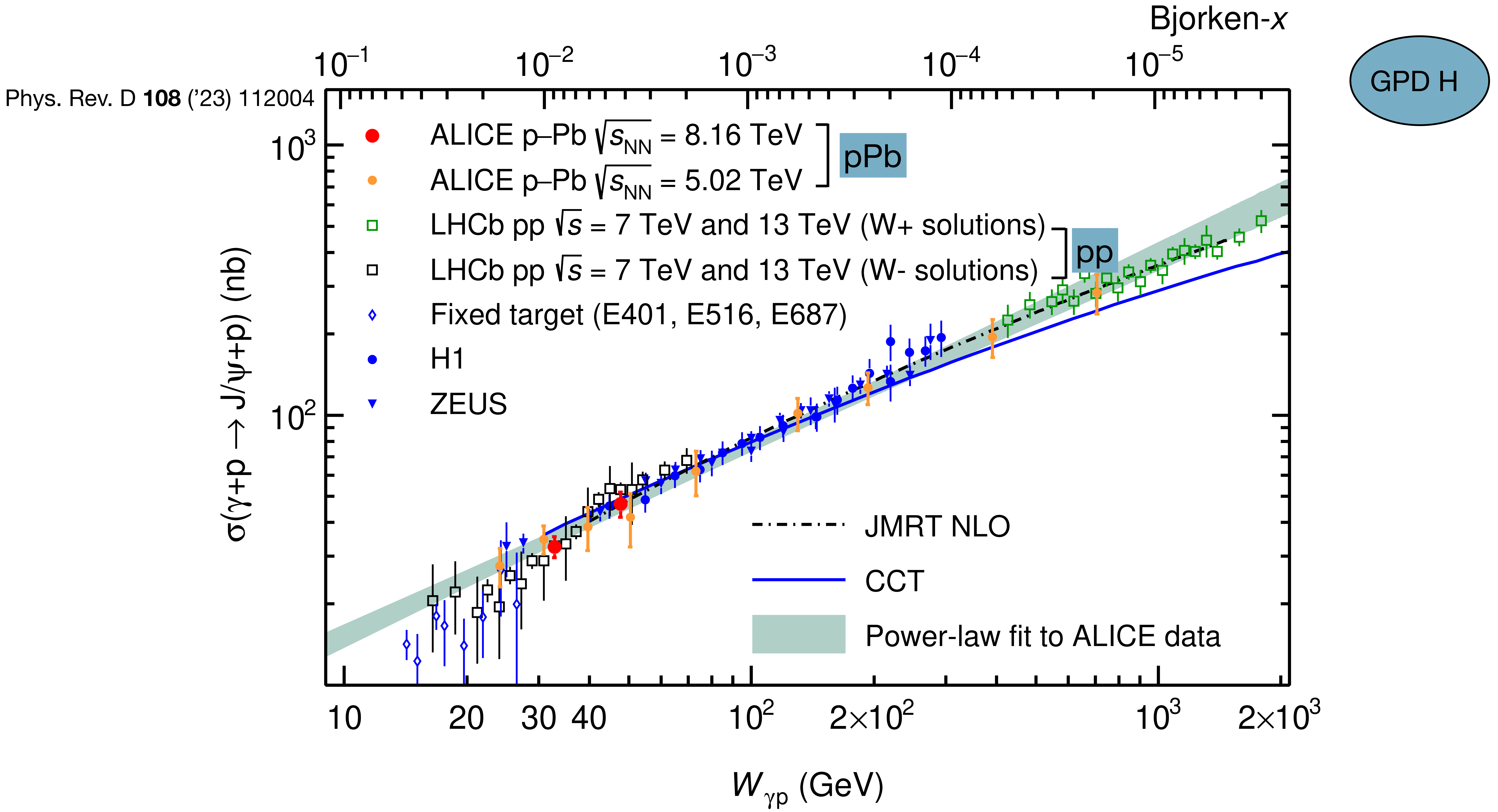


GPD H

J/ψ photoproduction cross section



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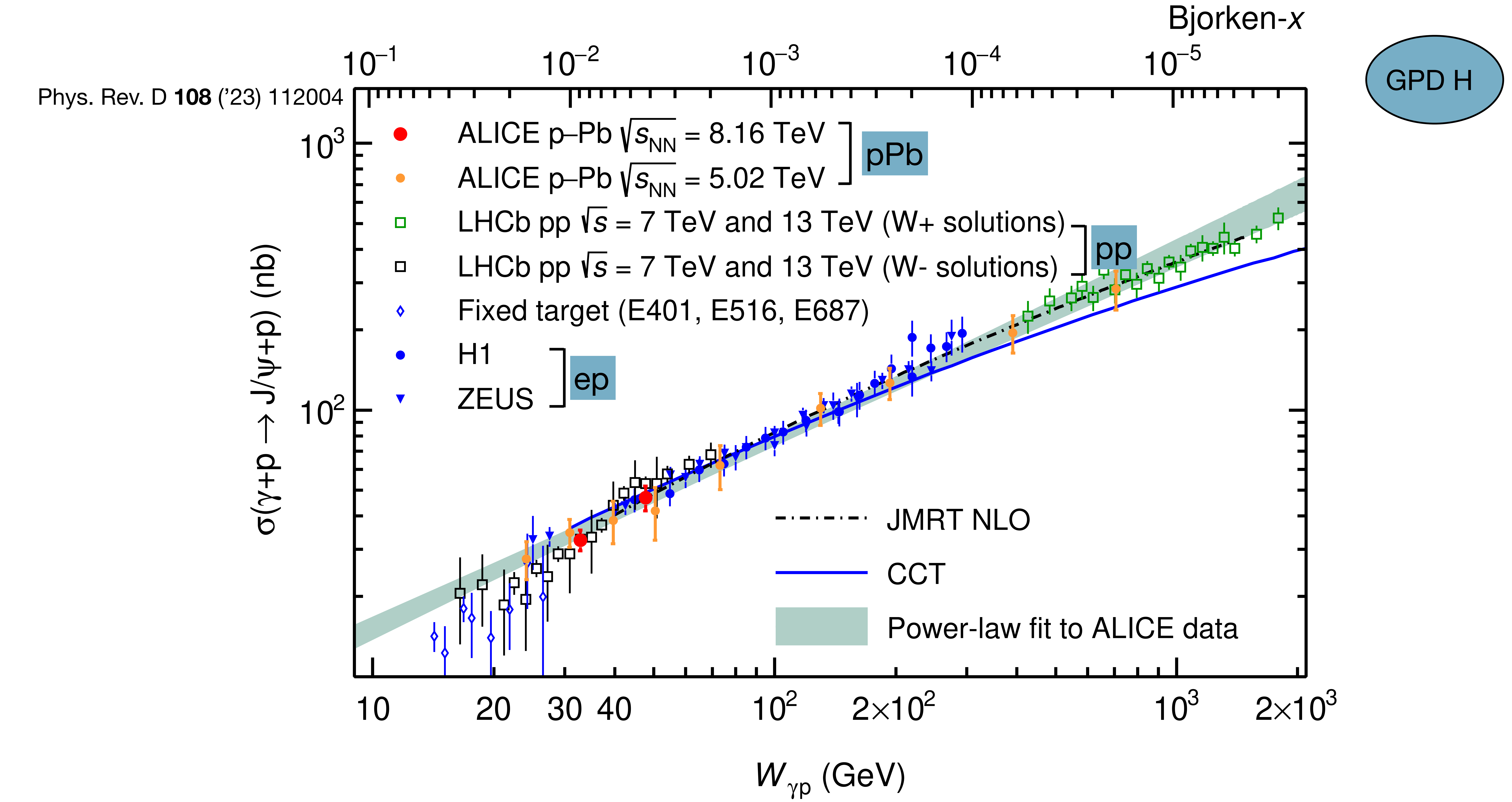

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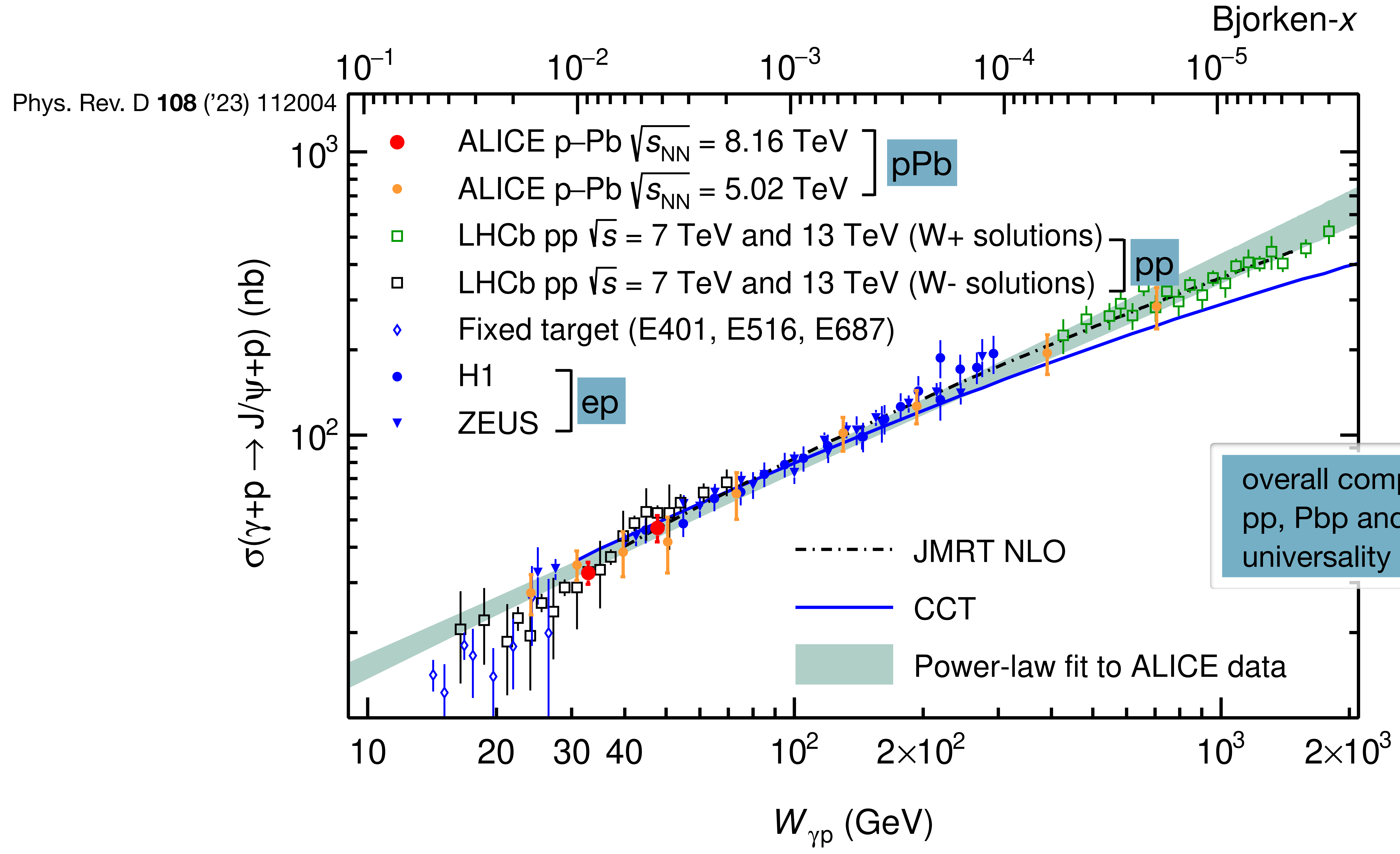
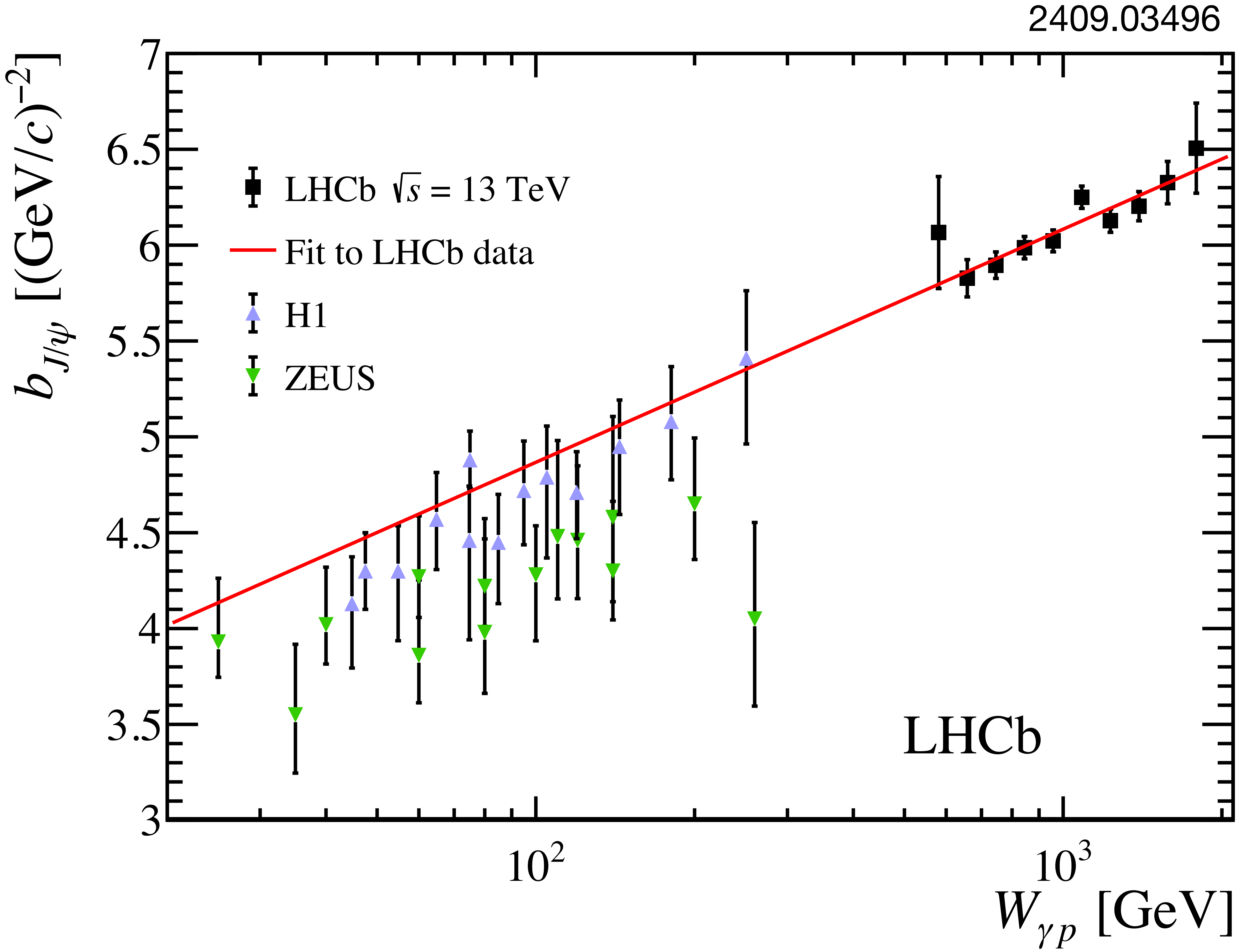


GPD H

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

Exclusive J/ψ photoproduction on the proton: b slope

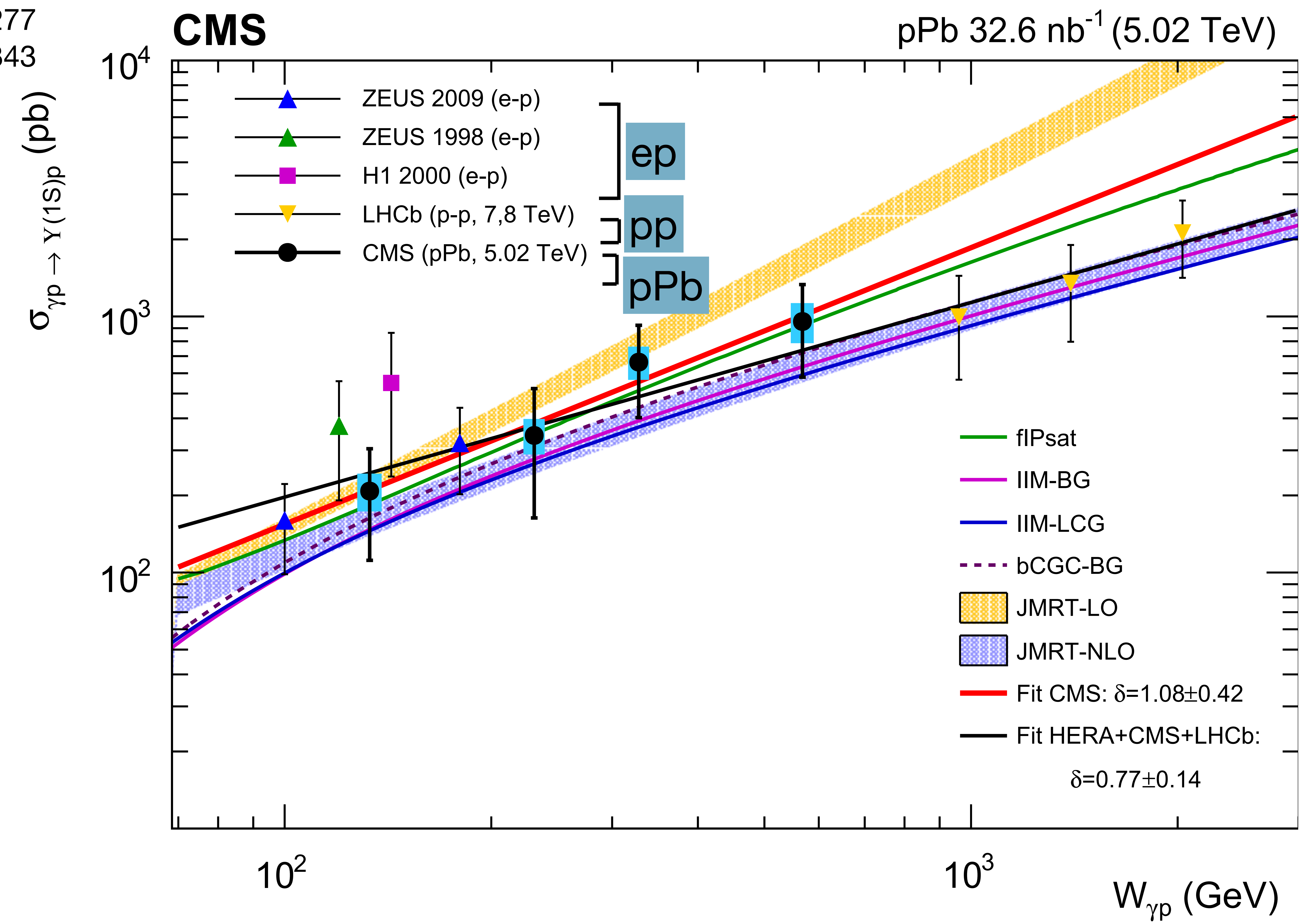


$$\sigma_{\gamma p \to J/\psi p} \propto e^{-b|t|}$$

$$b = b_0 + 4\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)$$

Υ photoproduction cross section

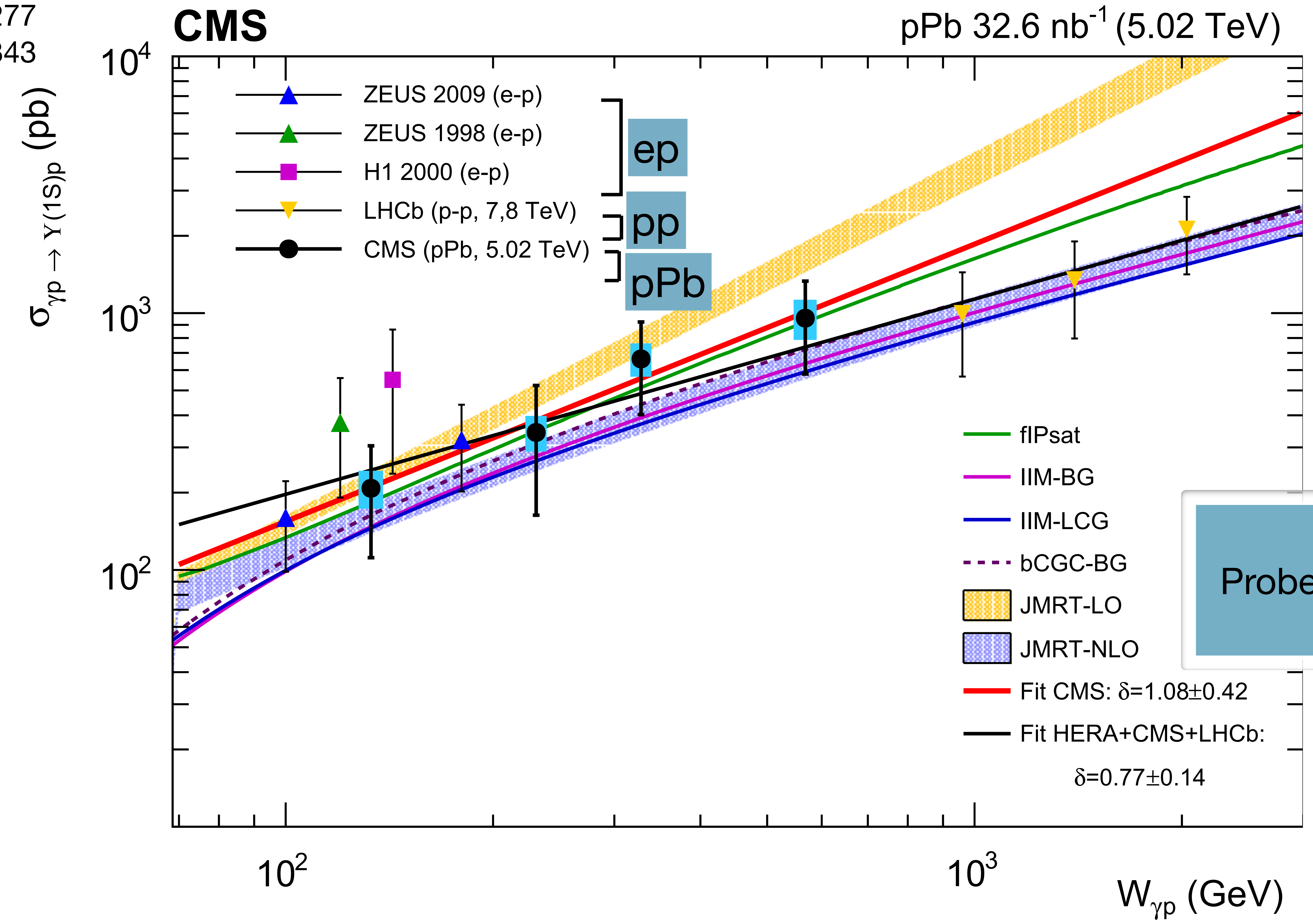
Eur. Phys. J. C **79** (2019) 277
Eur. Phys. J. C **82** (2022) 343



GPD H

Υ photoproduction cross section

Eur. Phys. J. C **79** (2019) 277
Eur. Phys. J. C **82** (2022) 343



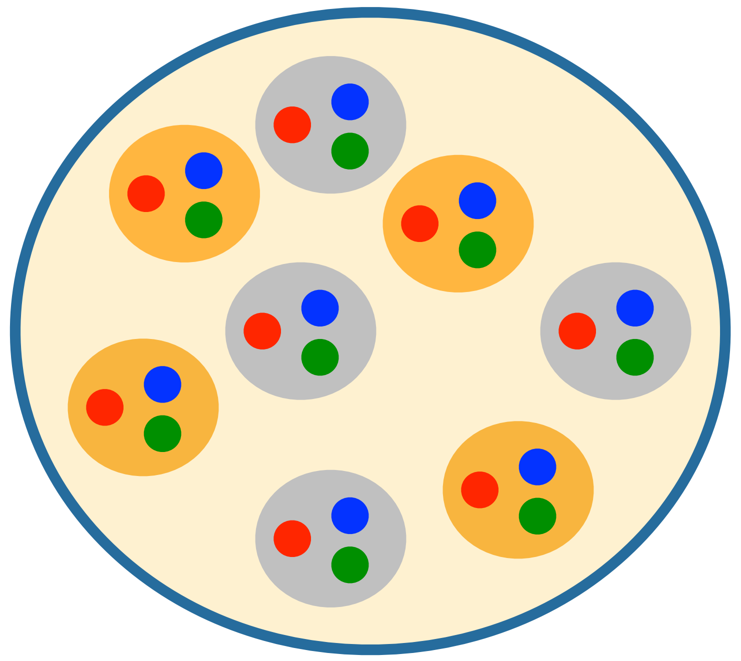
GPD H

Probes GPDs at higher scale.

Ultra-peripheral PbPb collisions

Ultra-peripheral PbPb collisions

What object are we probing?



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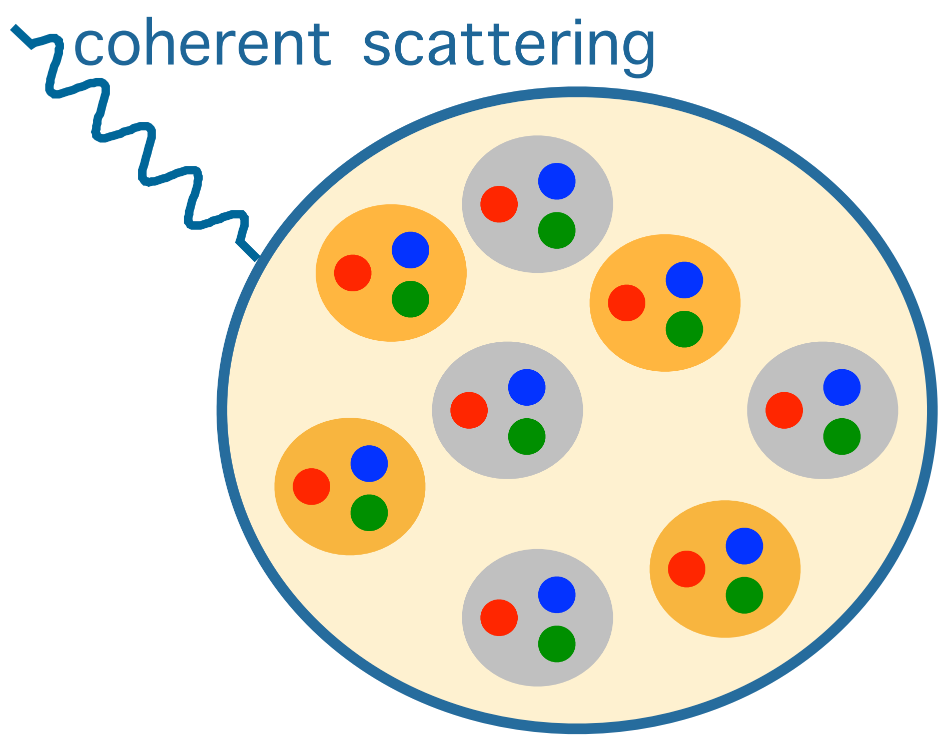
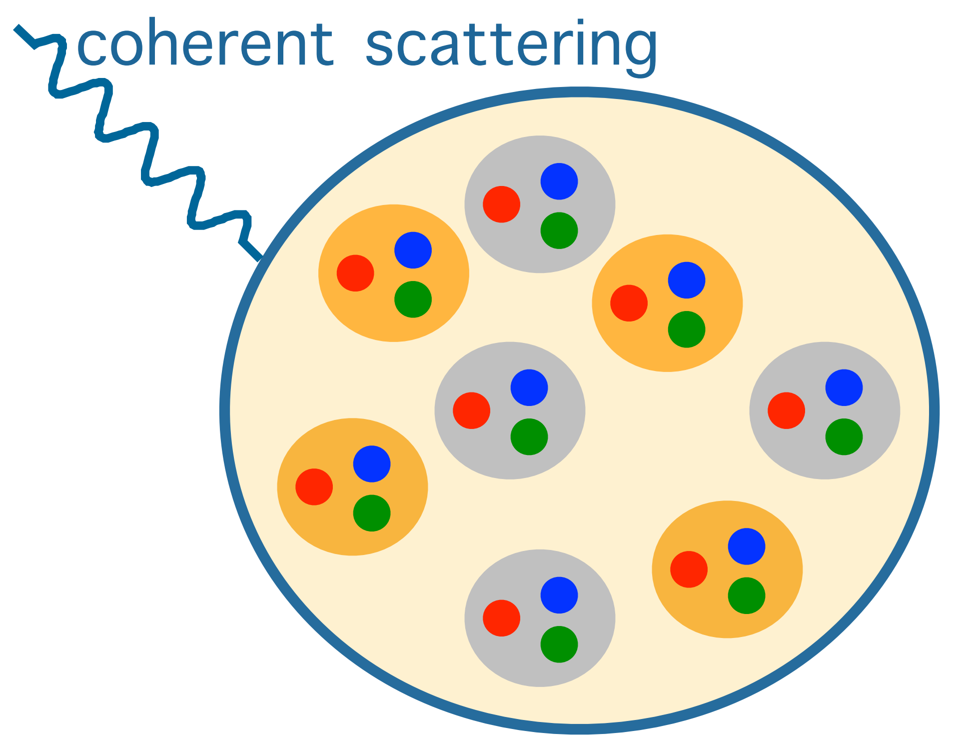


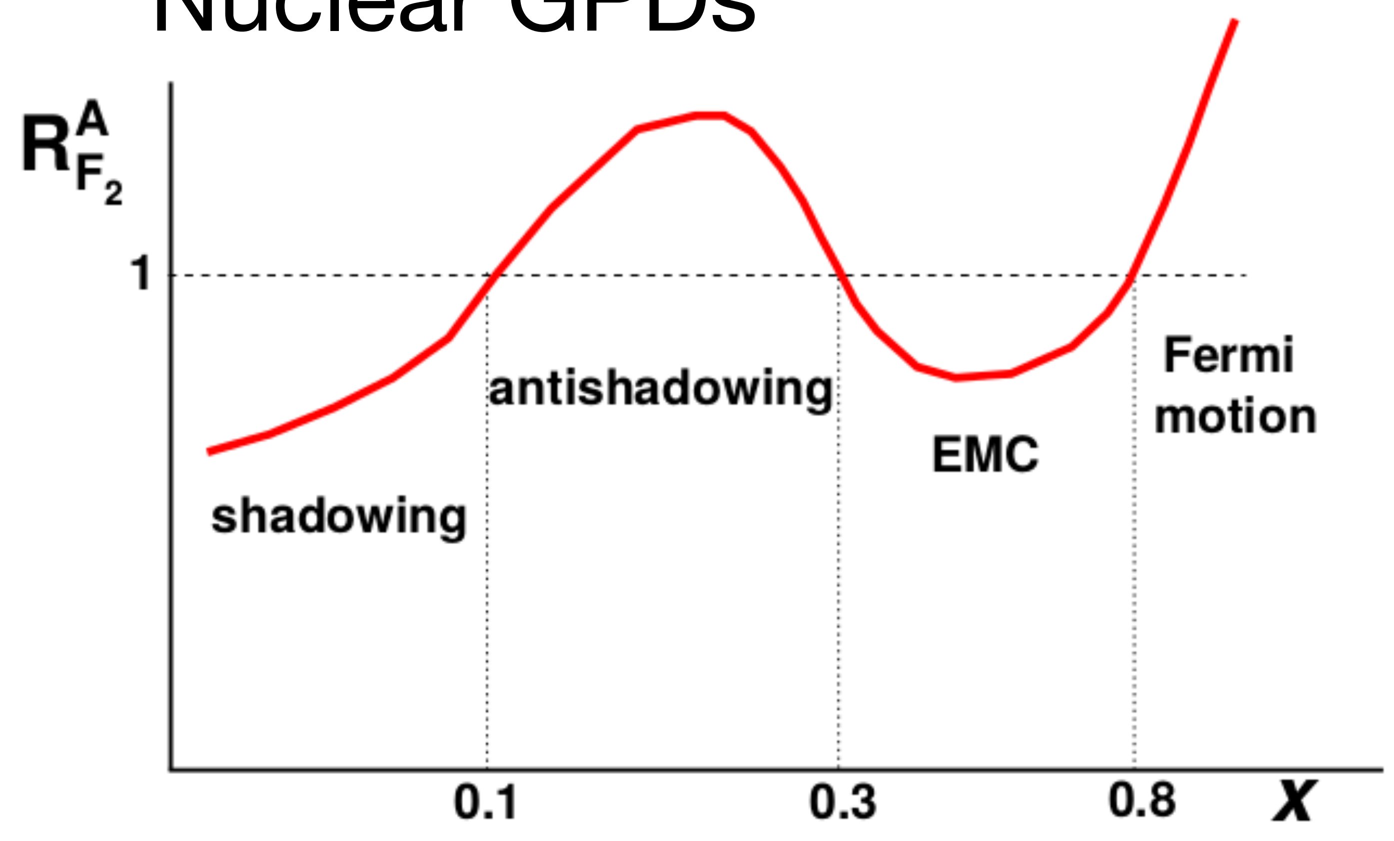
Coherent interaction: interaction with target as a whole.
~ target remains in same quantum state.

Ultra-peripheral PbPb collisions

What object are we probing?



Nuclear GPDs



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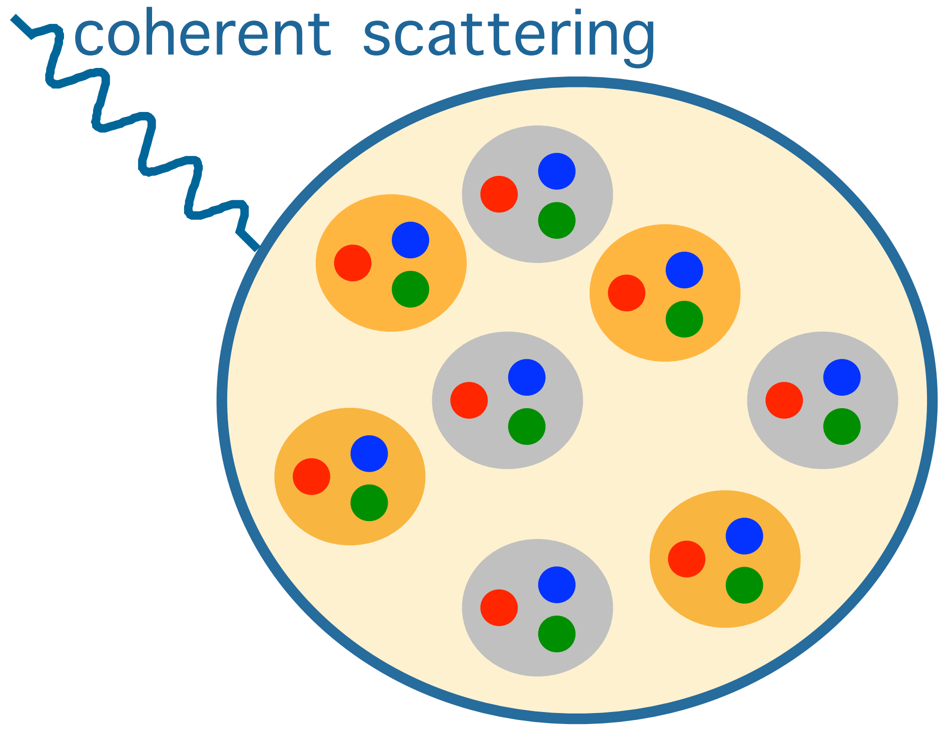

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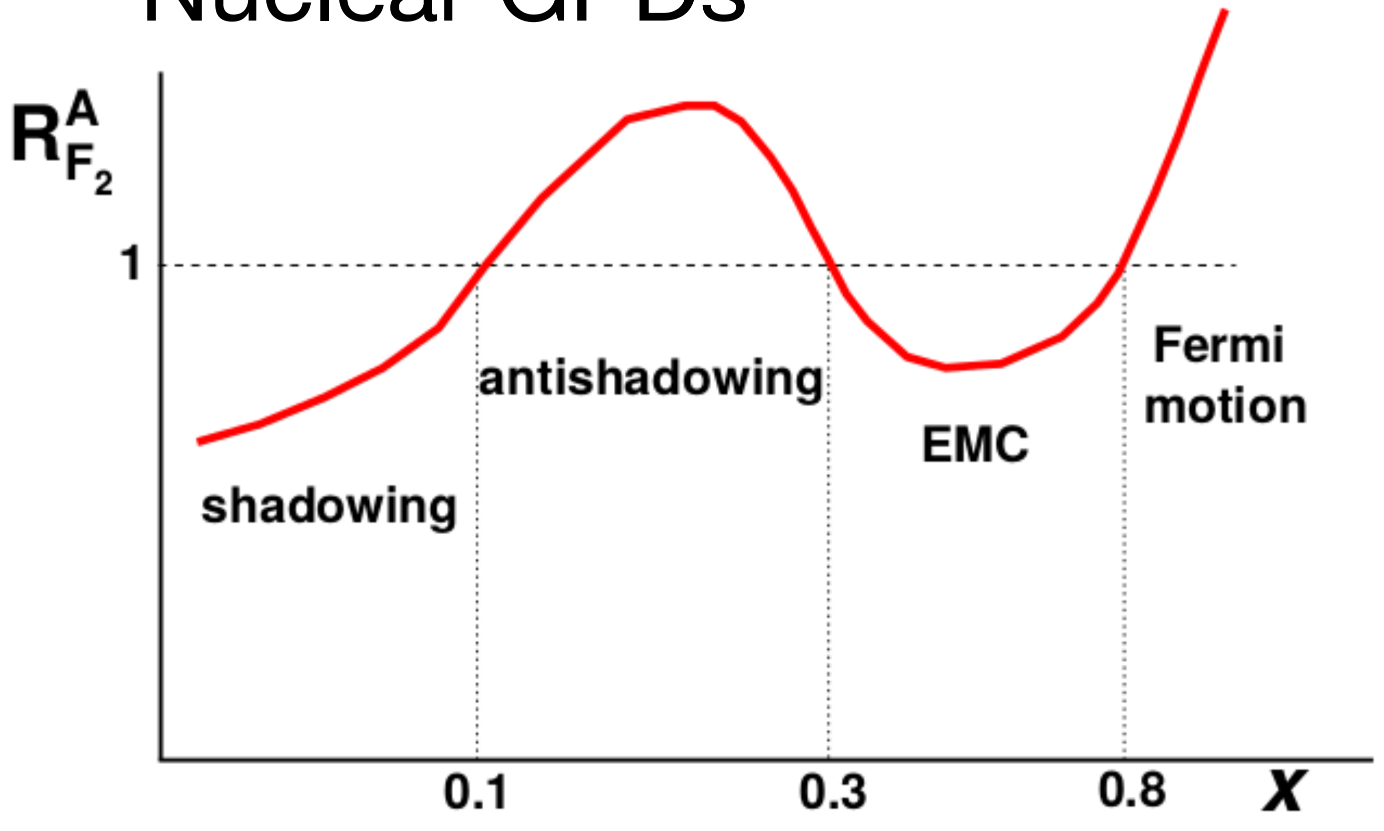
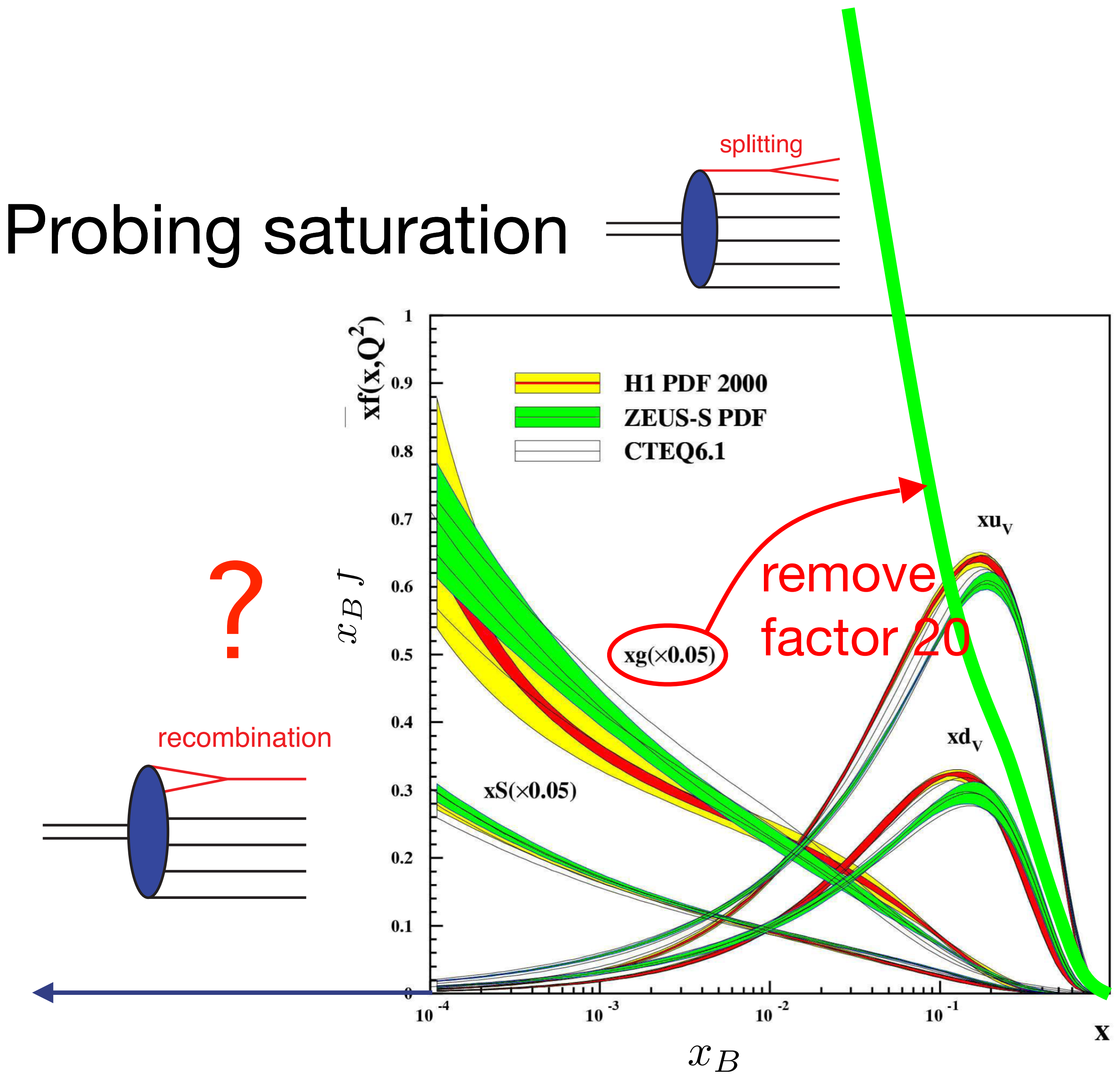


Probing saturation



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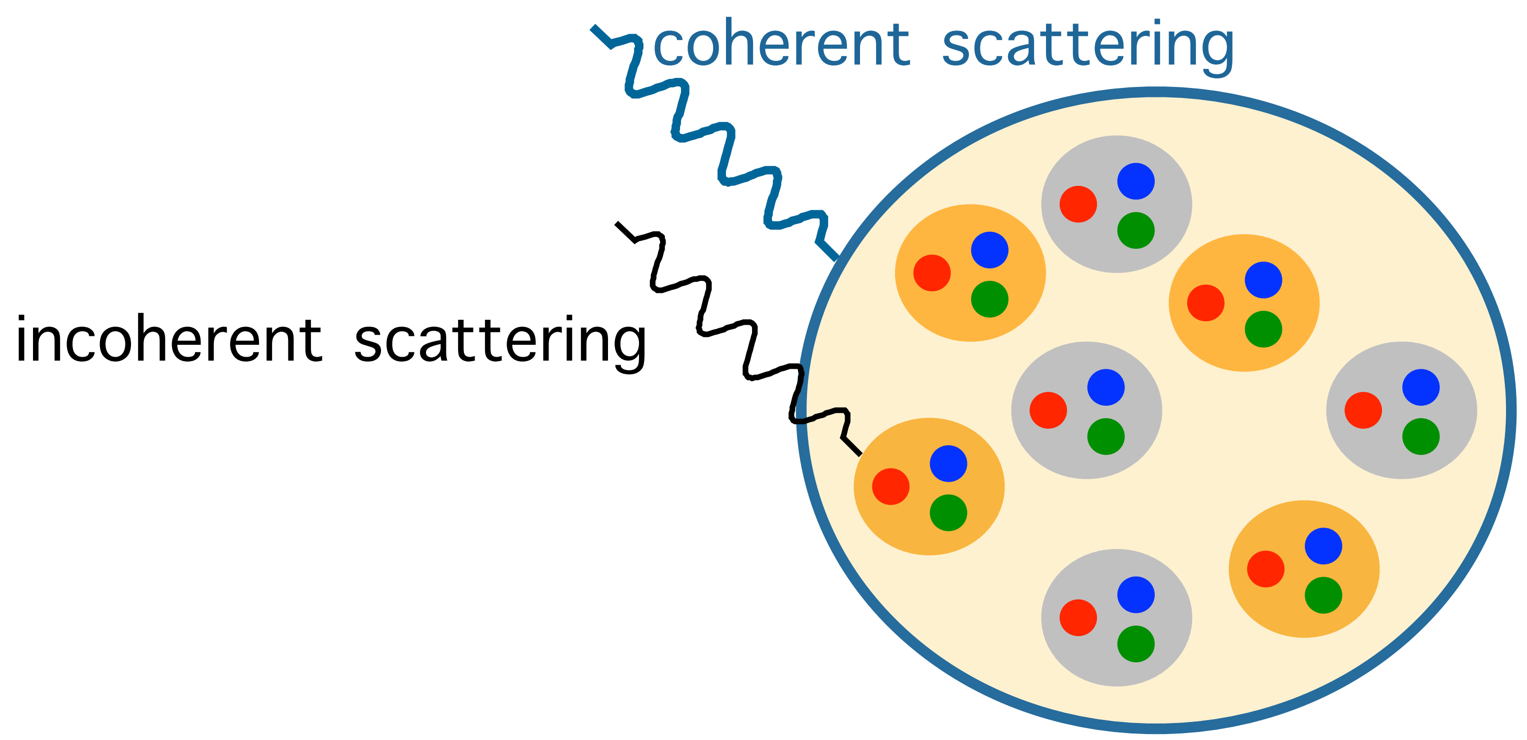

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Incoherent interaction: interaction with constituents inside target.
~ target does not remain in same quantum state.
Ex.: target dissociation, excitation

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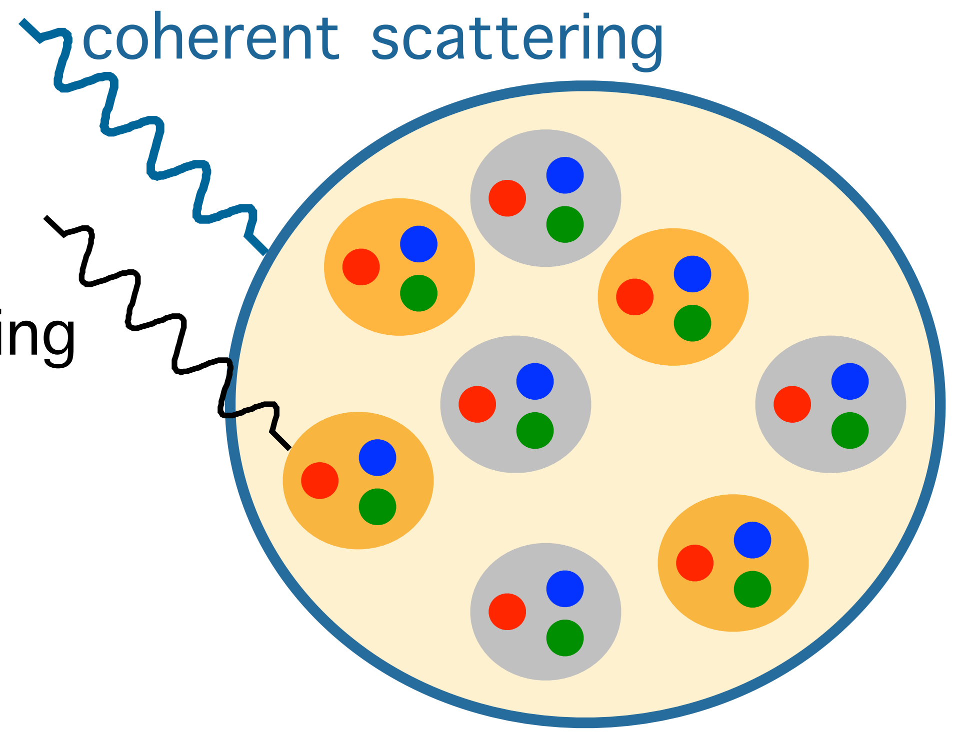

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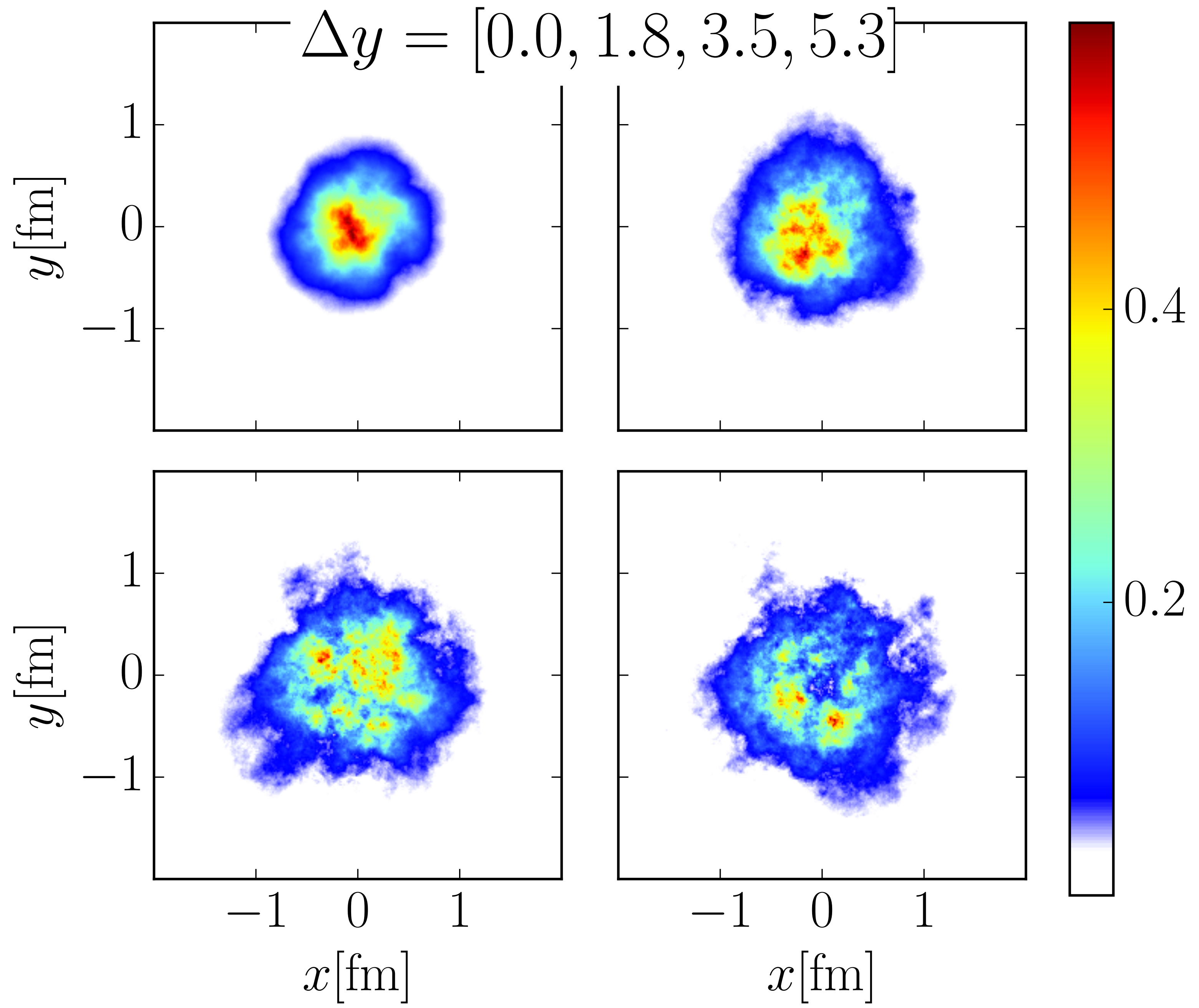
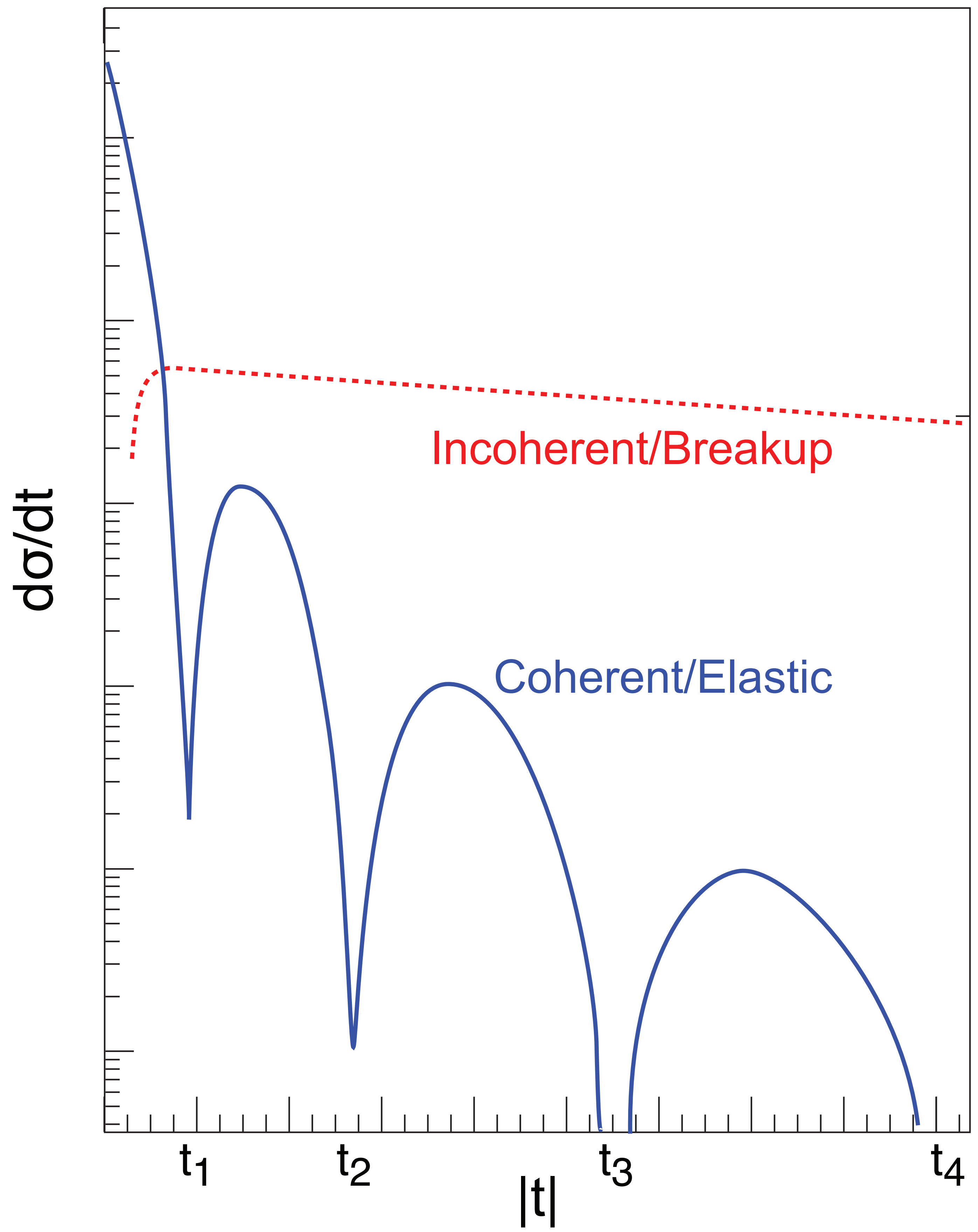
Probing event-by-event fluctuations



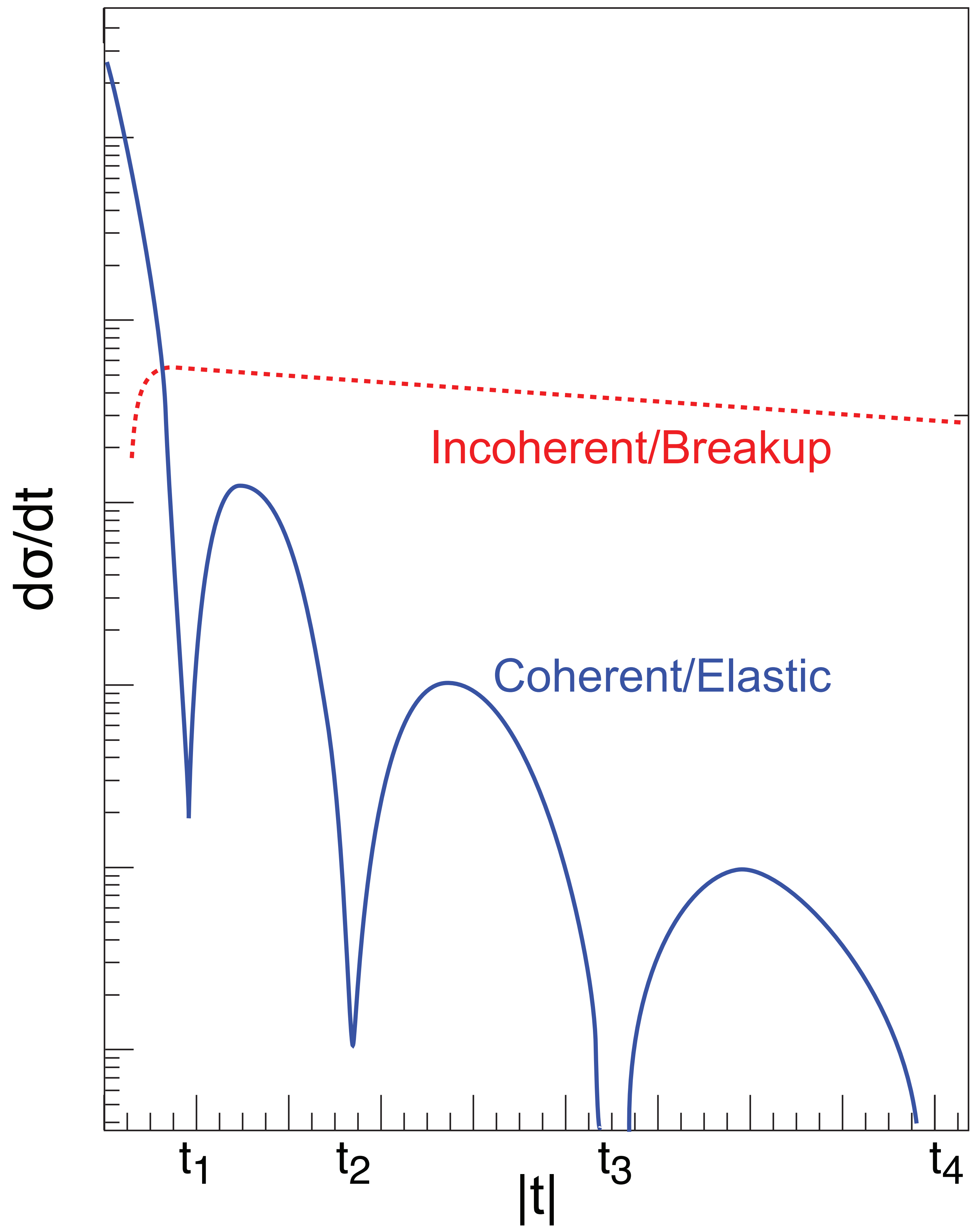
H. Mäntysaari and B. Schenke.
Phys. Rev. D 98, 034013 (2018)

Experimental important points



Experimental important points

- Good separation of coherent and incoherent production: not easy!



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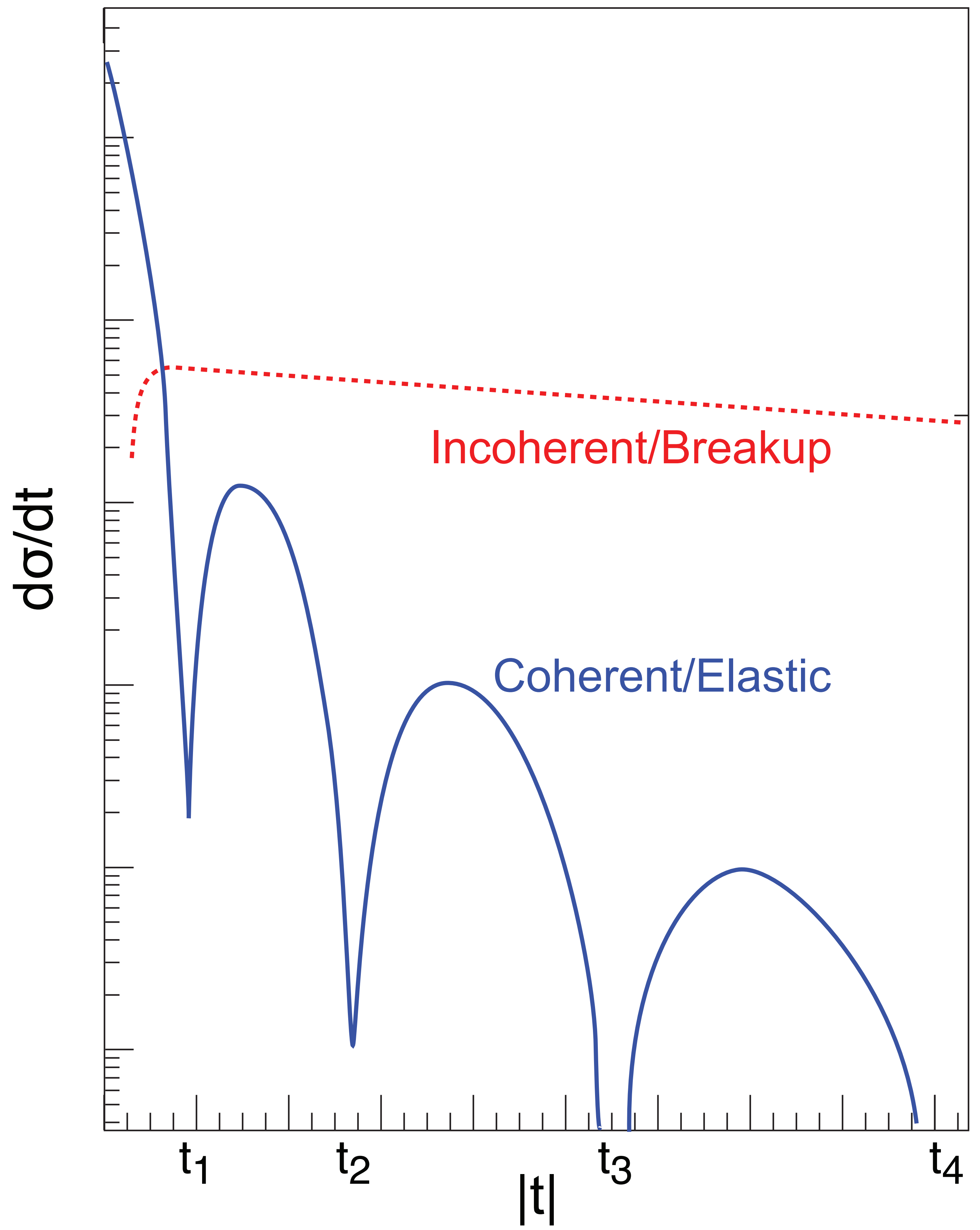
- Good separation of coherent and incoherent production: not easy!
- Coherent production: measurements up to large t:
  - 3D or 2D (x independent) transverse position

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

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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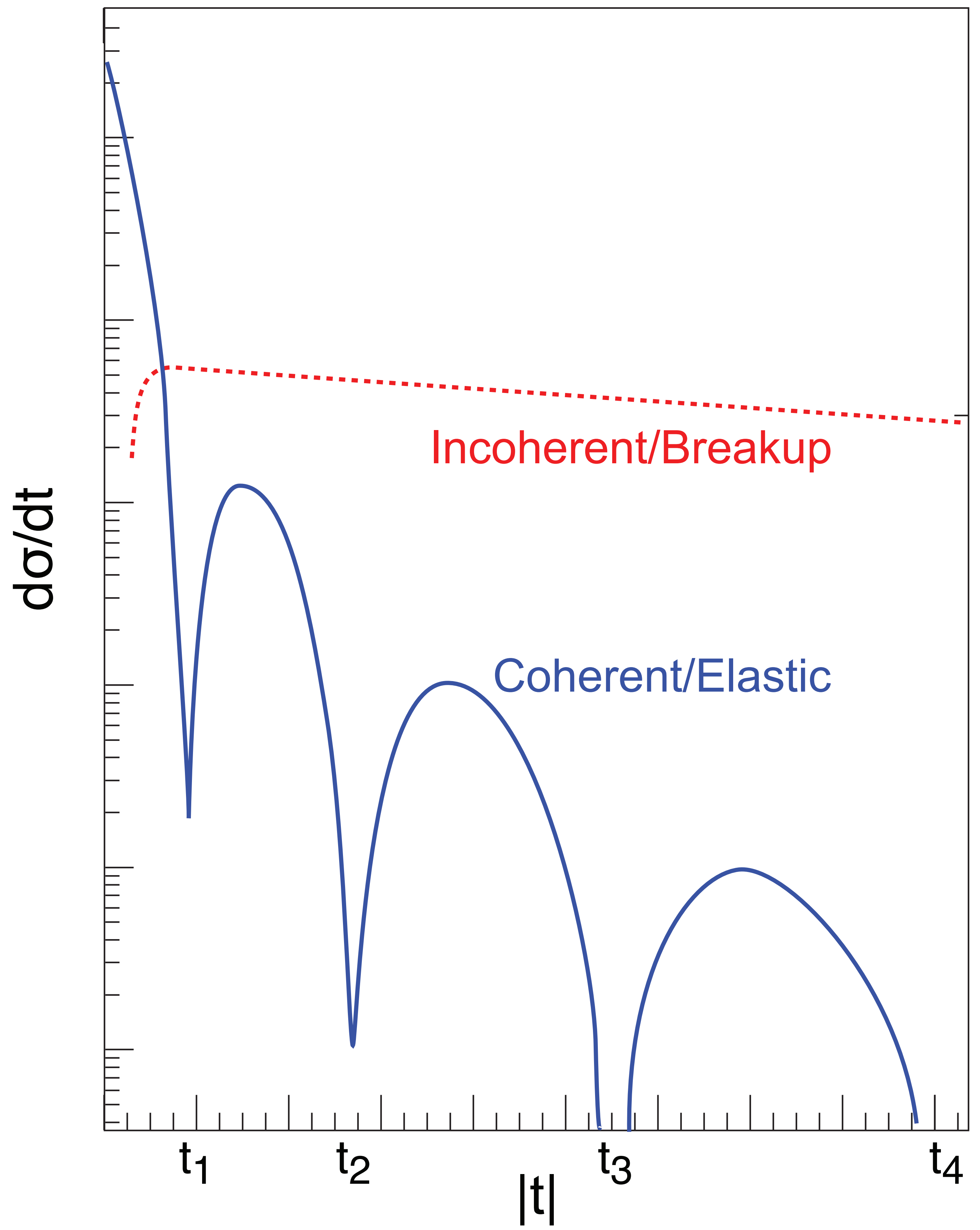
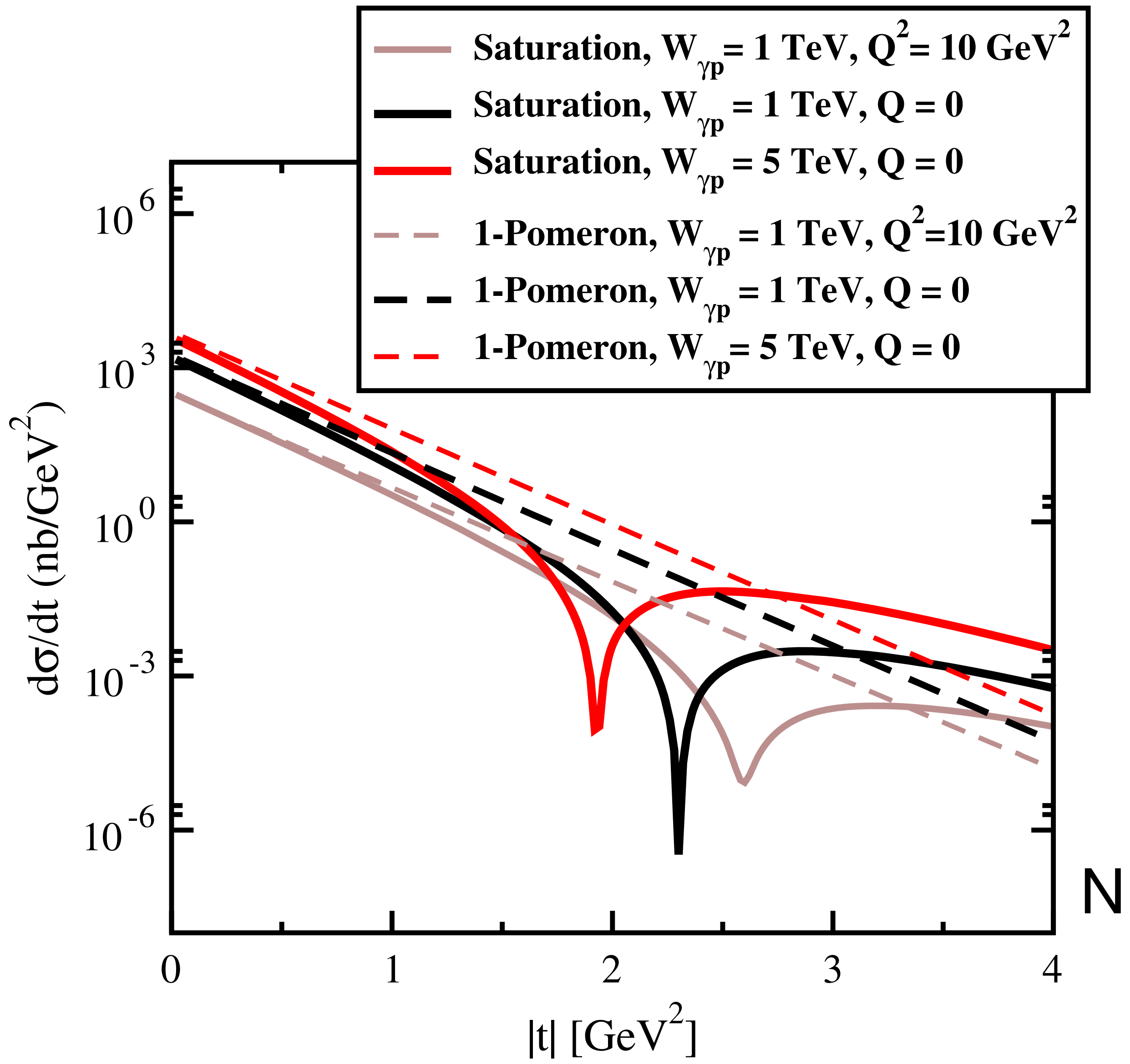


  - Saturation:

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

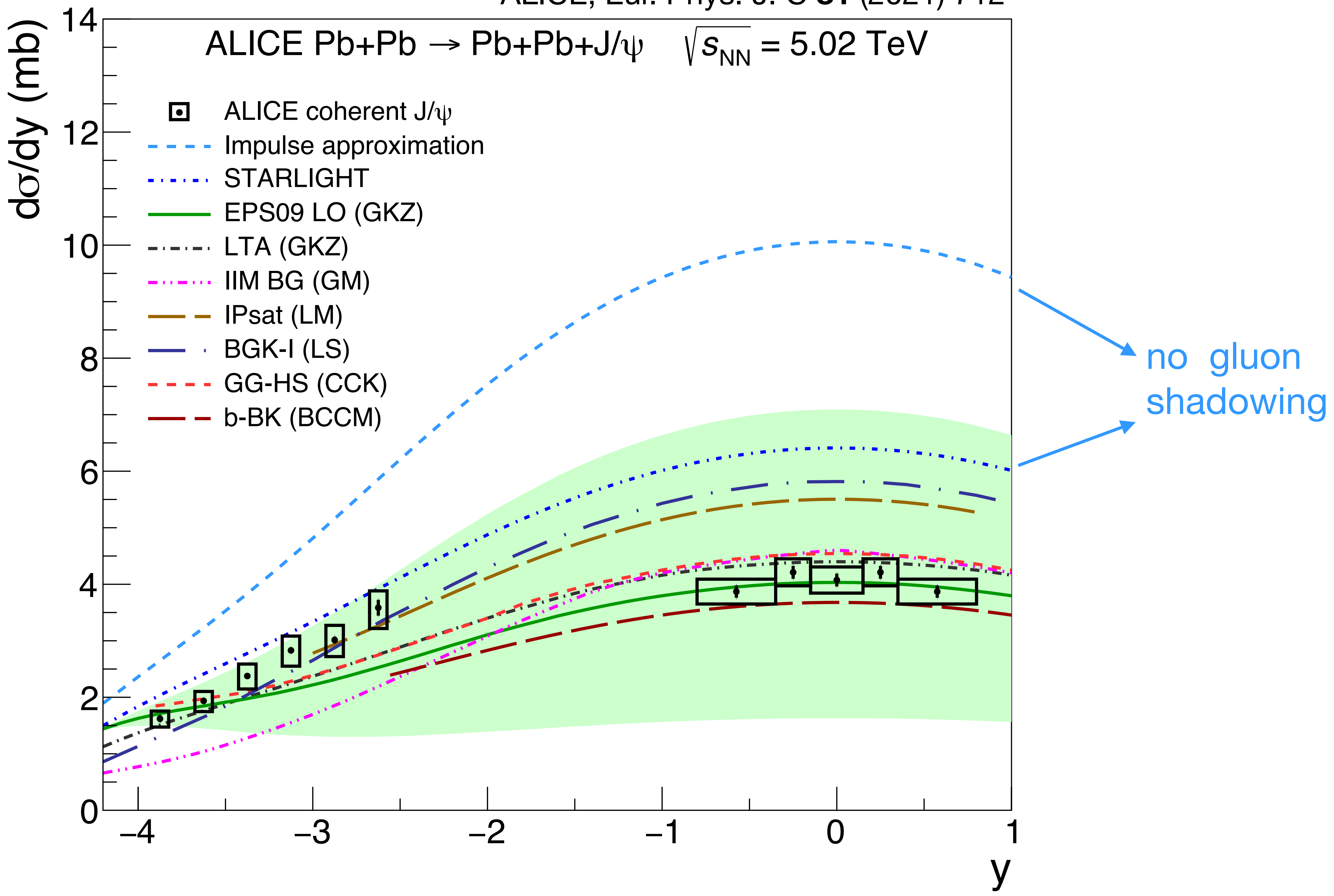


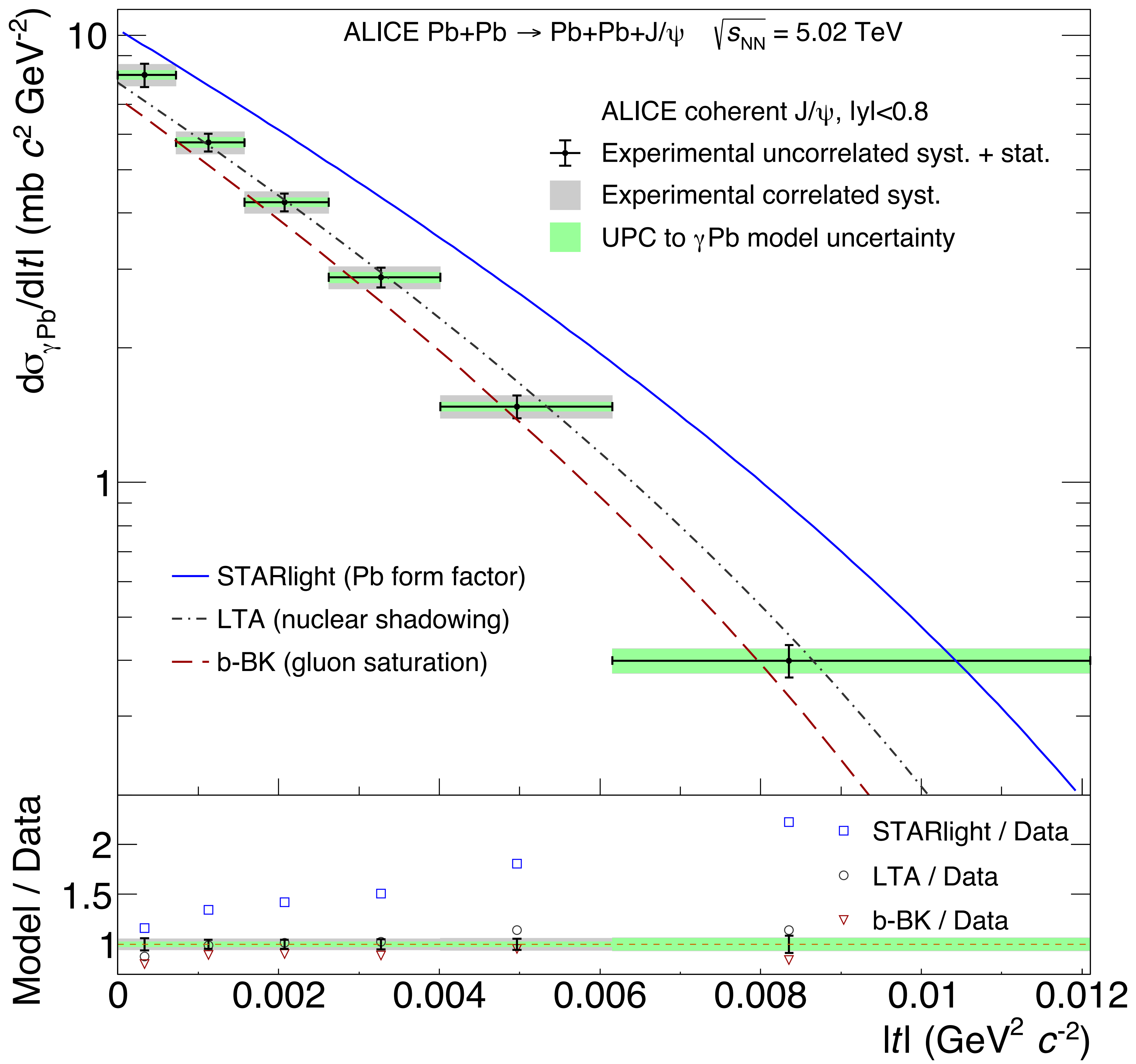
N. Armesto and A. H. Rezaeian, Phys. Rev. D **90** (2014) 054003.

Coherent production in PbPb at ALICE

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

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





-4.0<y<-2.5

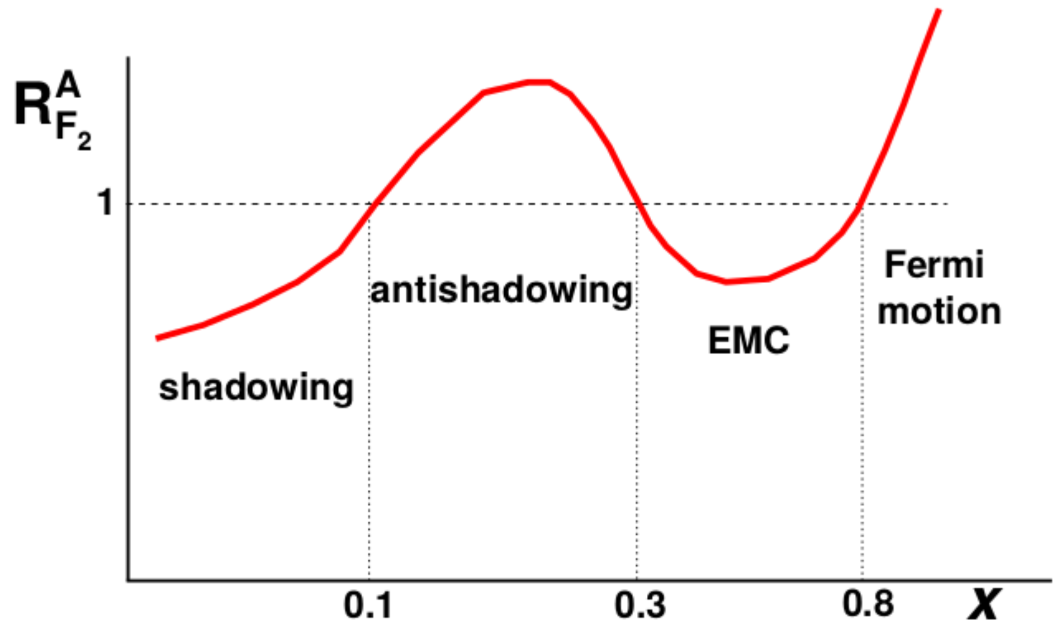
$|y|<0.8 \longleftrightarrow 0.3 \times 10^{-3} < x_B < 1.4 \times 10^{-3}$

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

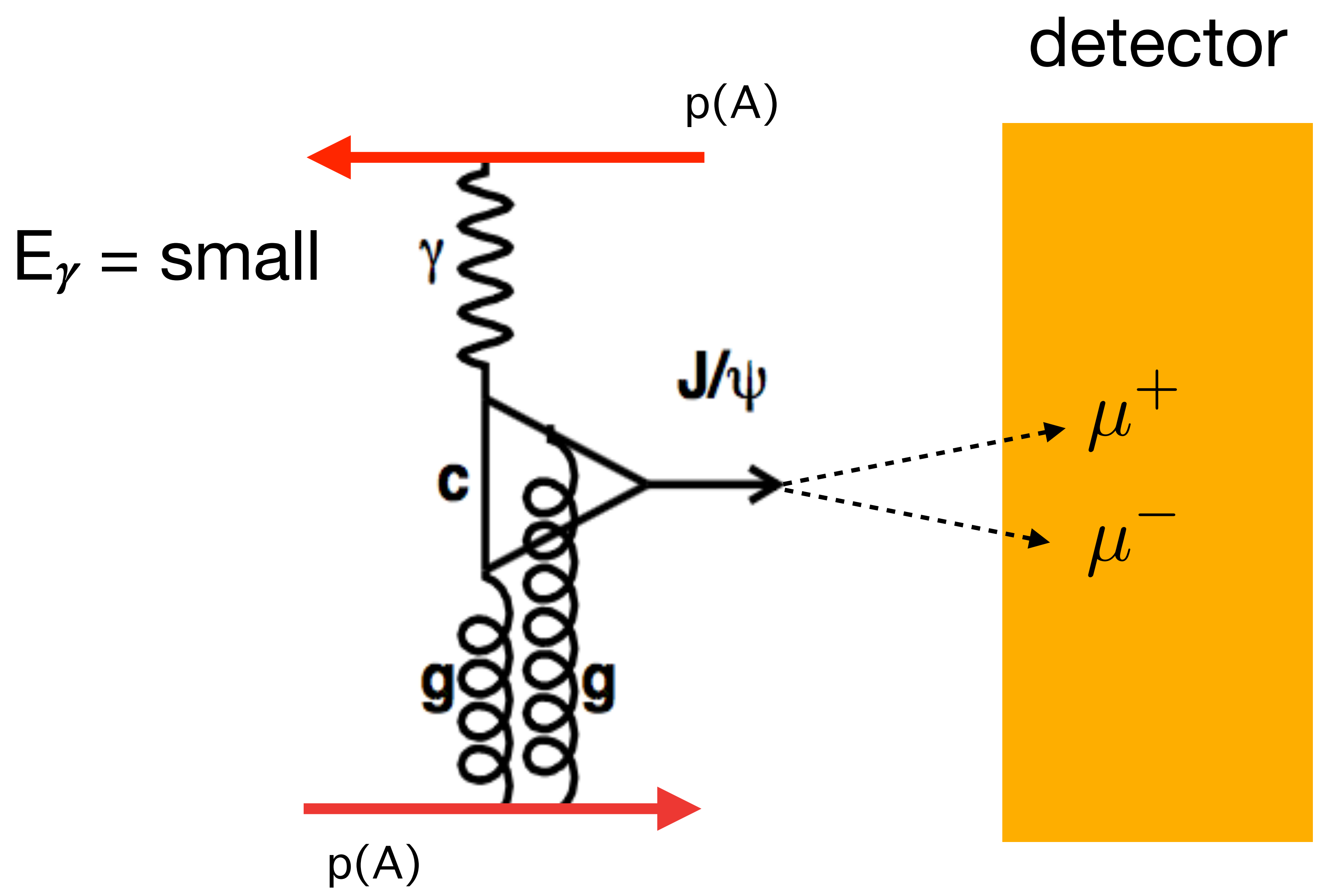
$1.1 \times 10^{-5} < x_B < 5.1 \times 10^{-5}$

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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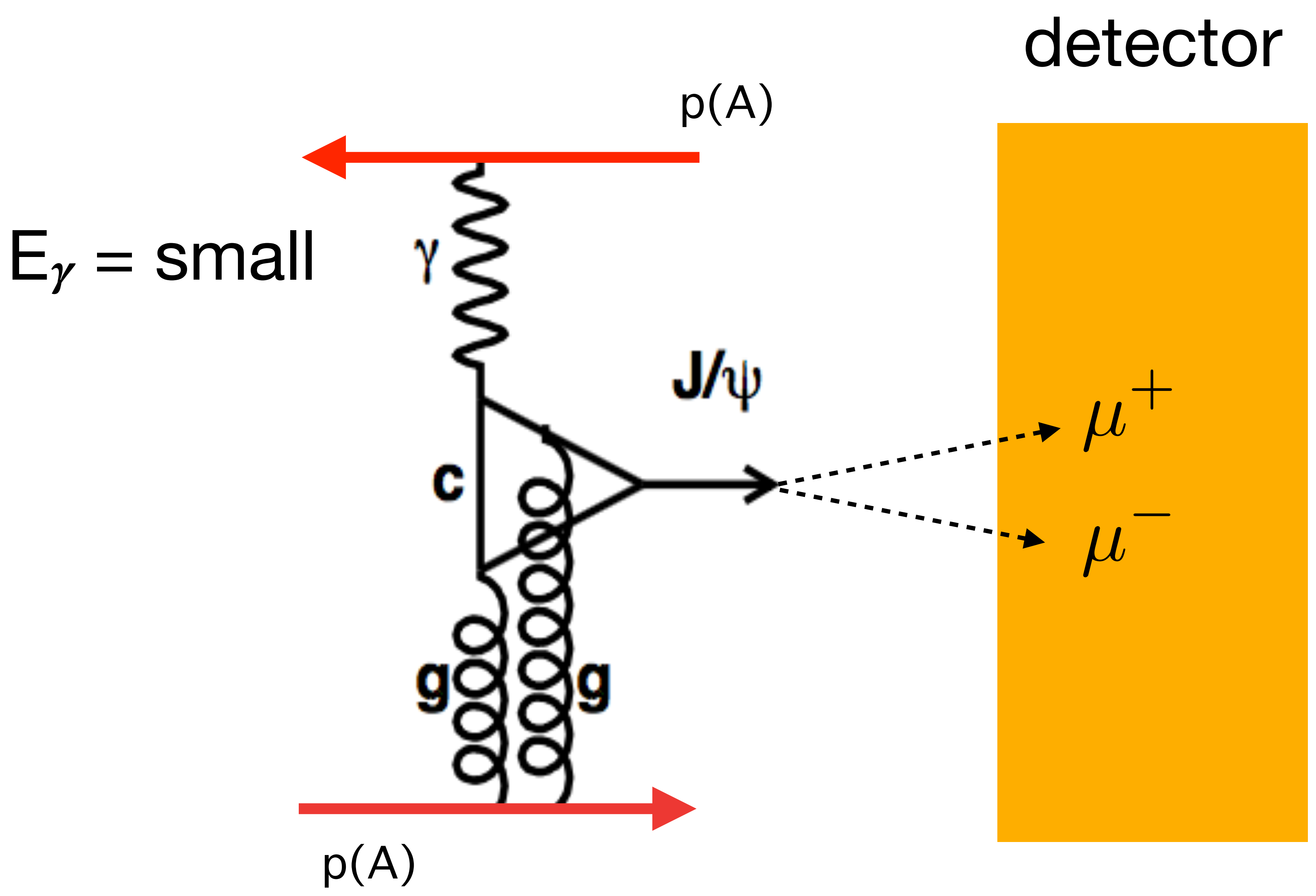

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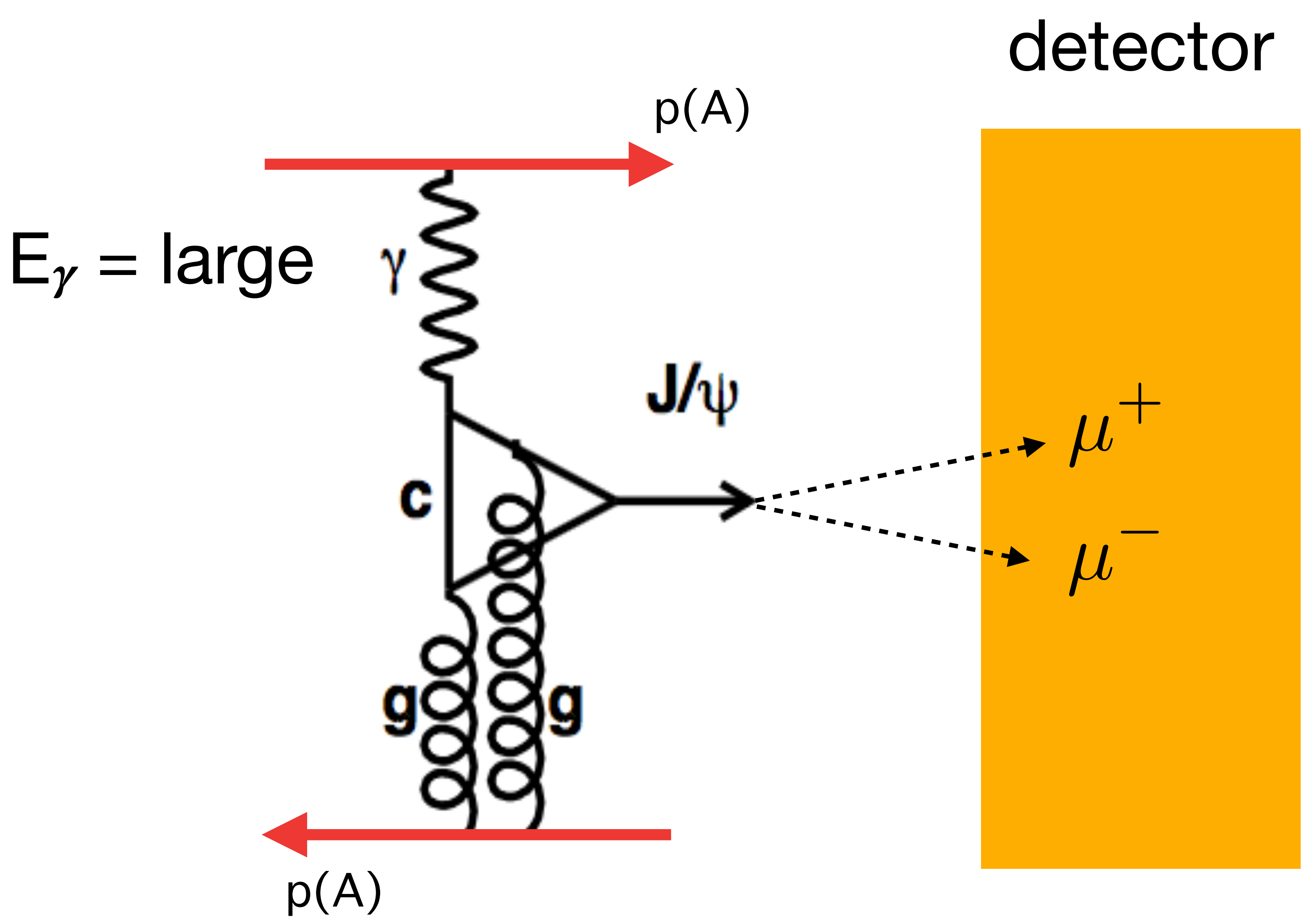

$$E_{\gamma,l} = \frac{M_{J/\psi}}{2} e^{+y}$$

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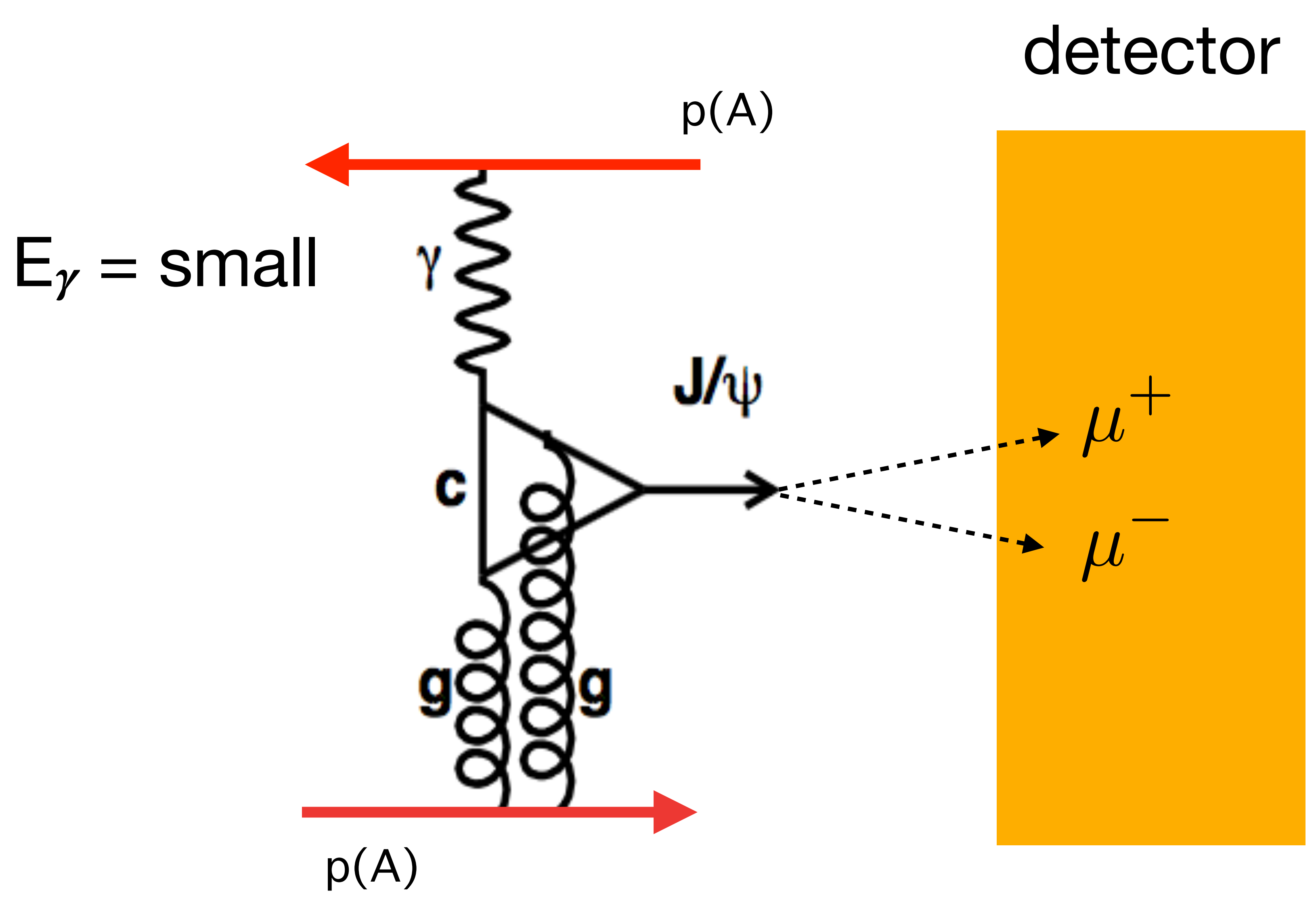

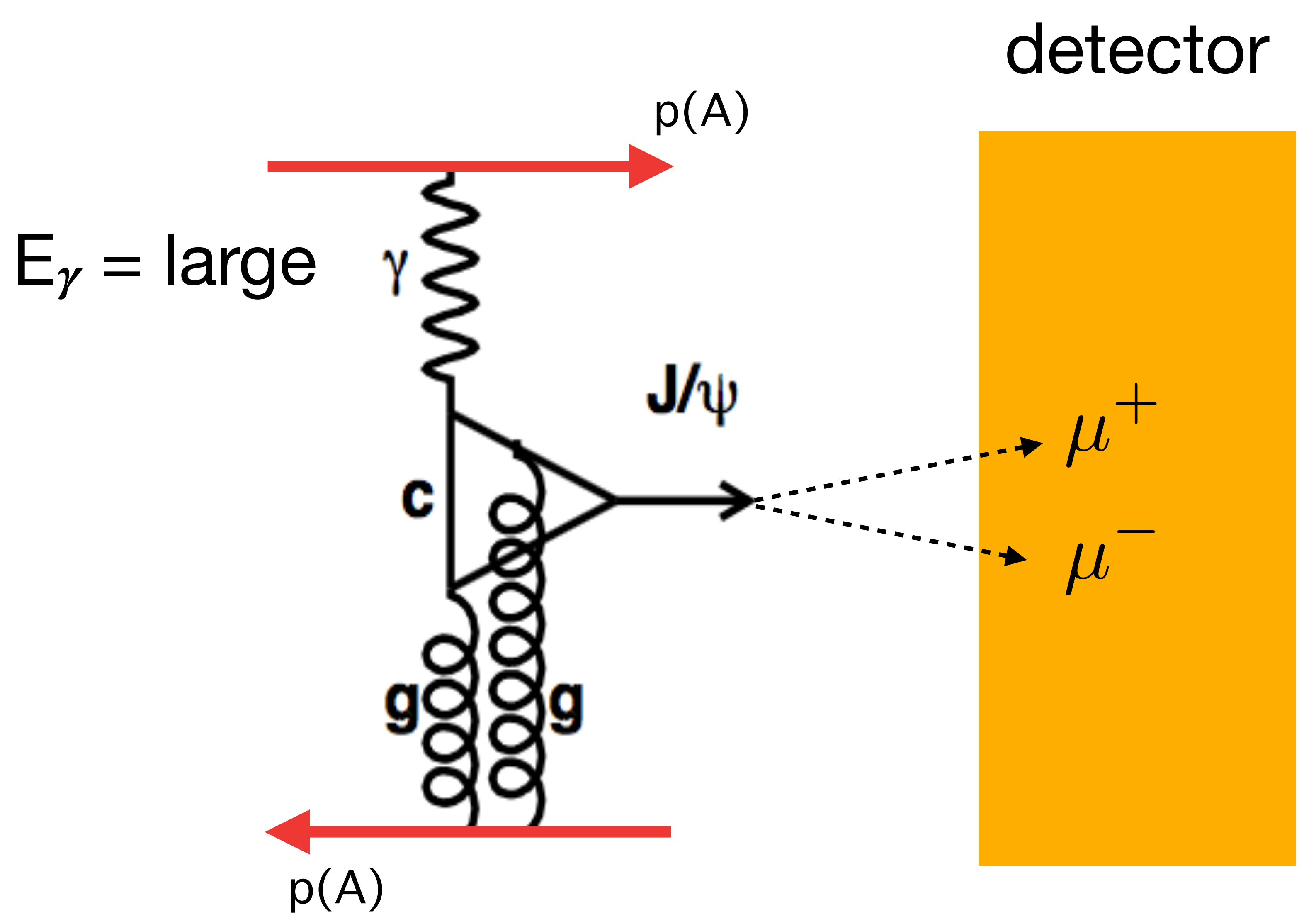

$$E_{\gamma,s} = \frac{M_{J/\psi}}{2} e^{-y}$$

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

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

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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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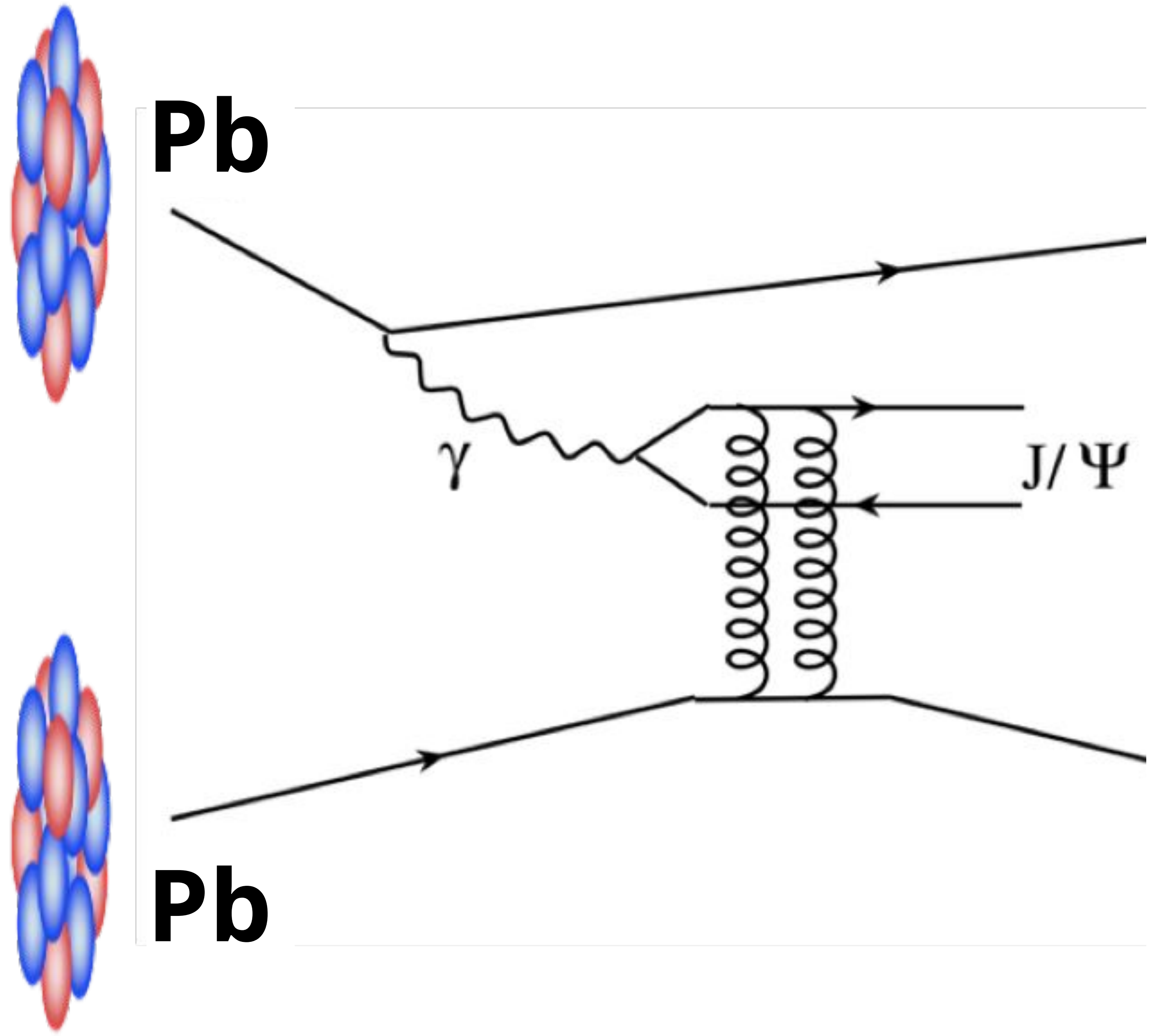

Picture from André Ståhl

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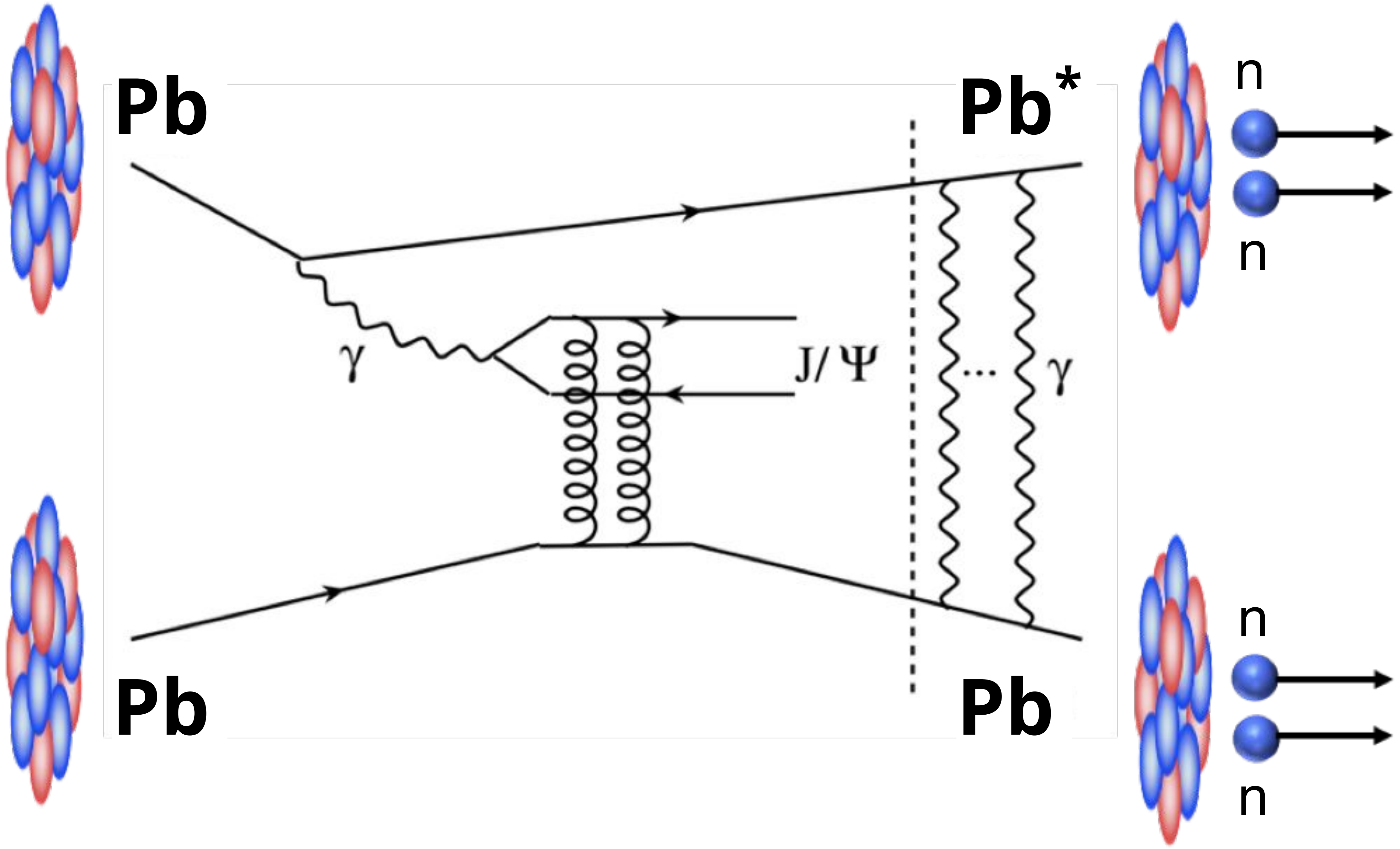
Small impact parameter, b ⟶ higher probability for exciting ($\propto 1/b^2$) ⟶ higher probability to emit neutrons.



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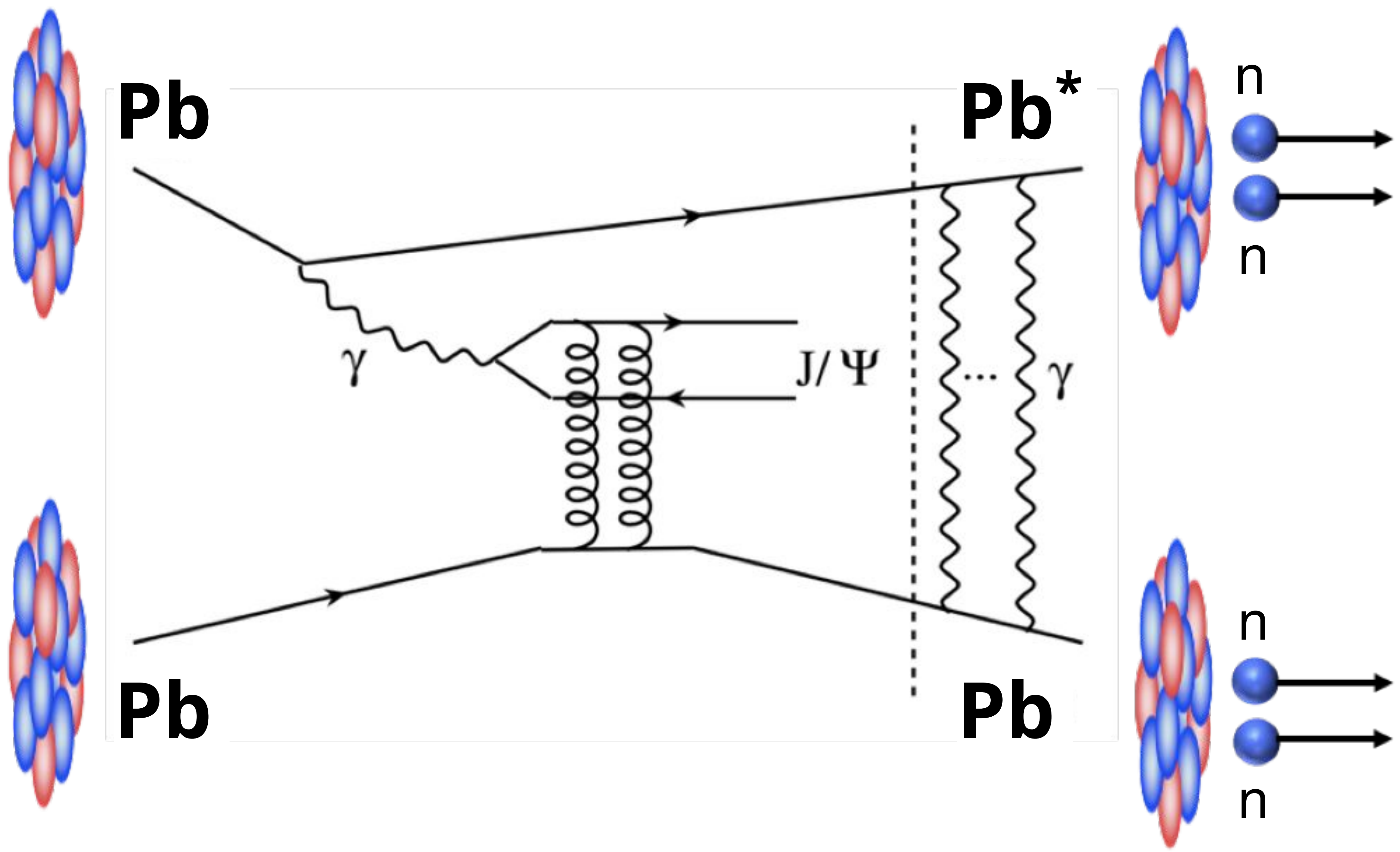
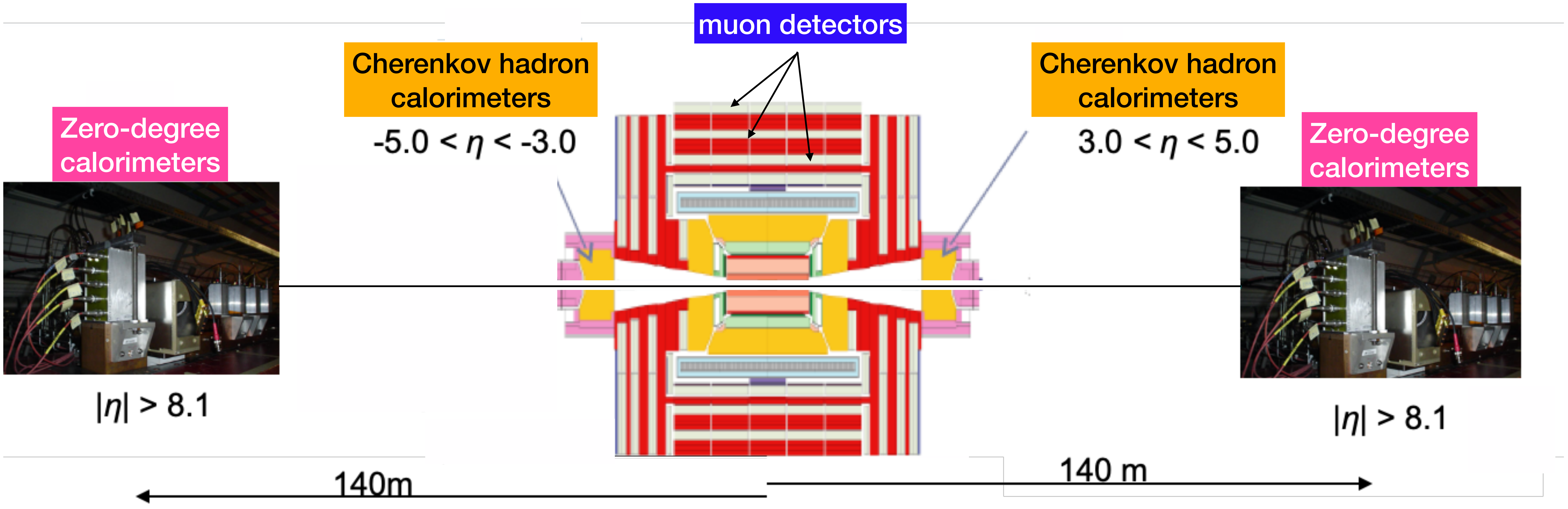


⟶ Make measurement with possibility to detect neutrons

Picture from André Ståhl

CMS central detector and the (far-)forward region



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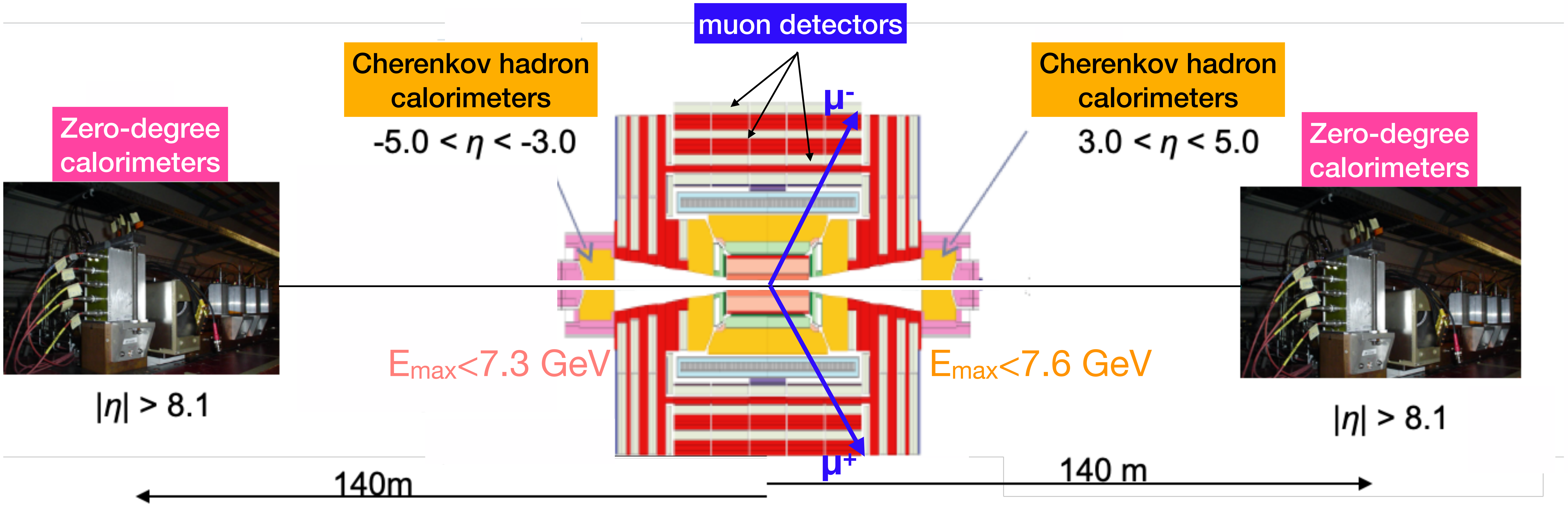
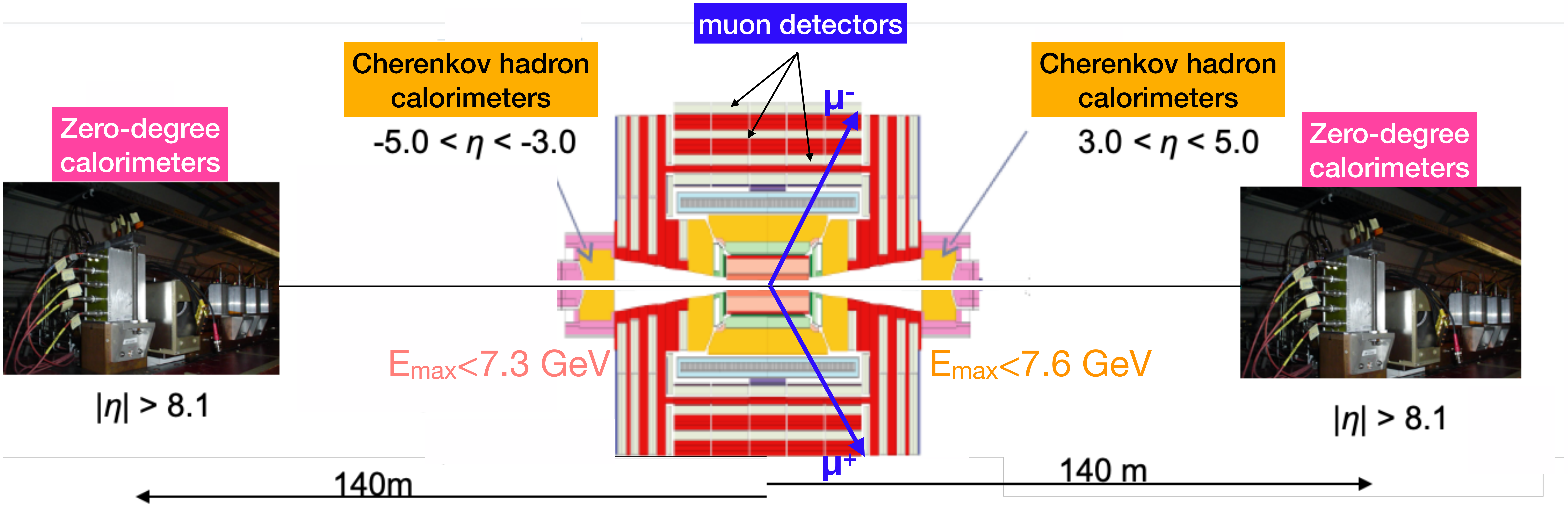


$$1.6 < |y_{\mu^+\mu^-}| < 2.4$$

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

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

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

measured

Disentangling the ambiguity on the ID of the γ emitter

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measured

computed (StarLight)

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Disentangling the ambiguity on the ID of the γ emitter

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measured

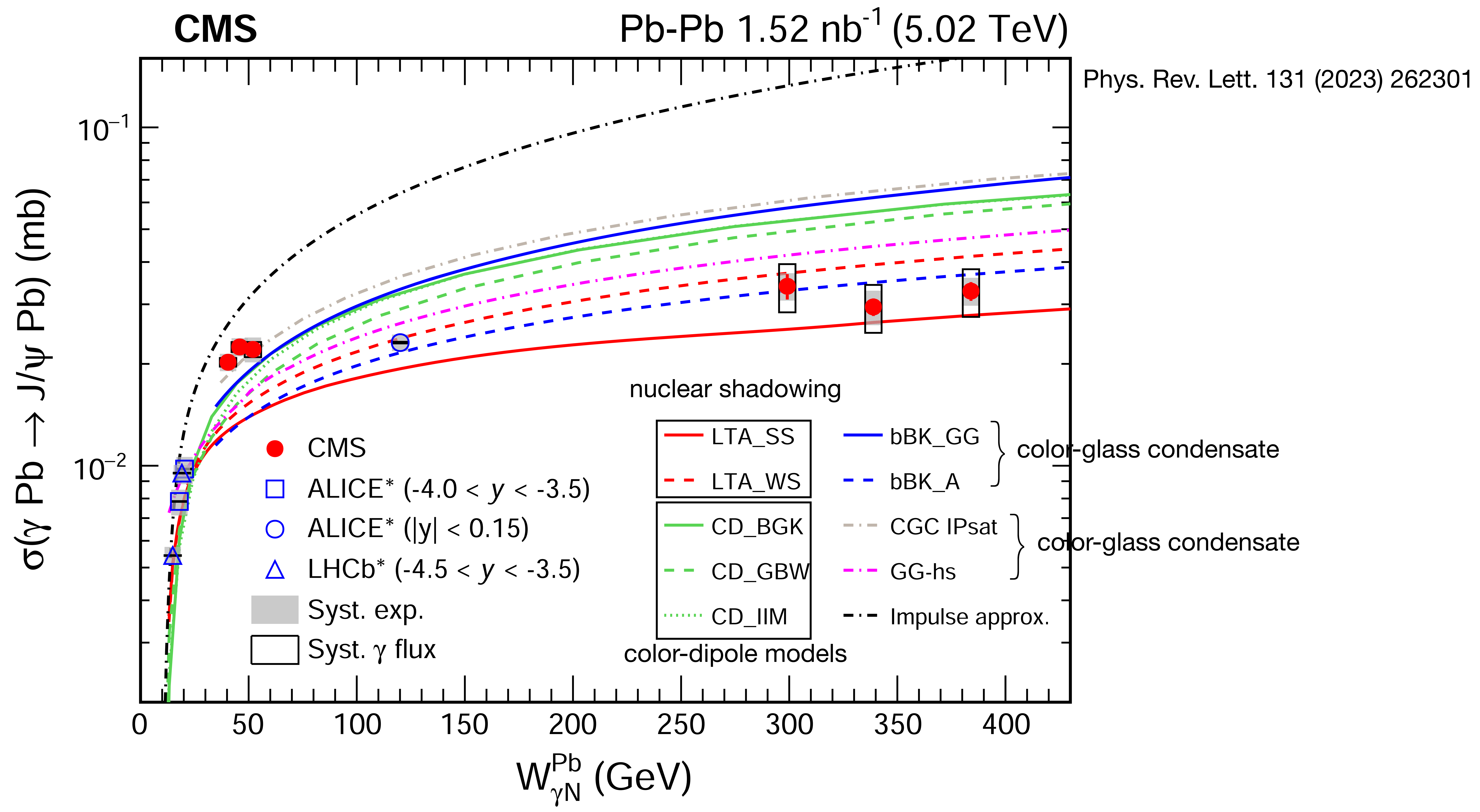
computed (StarLight)

extracted

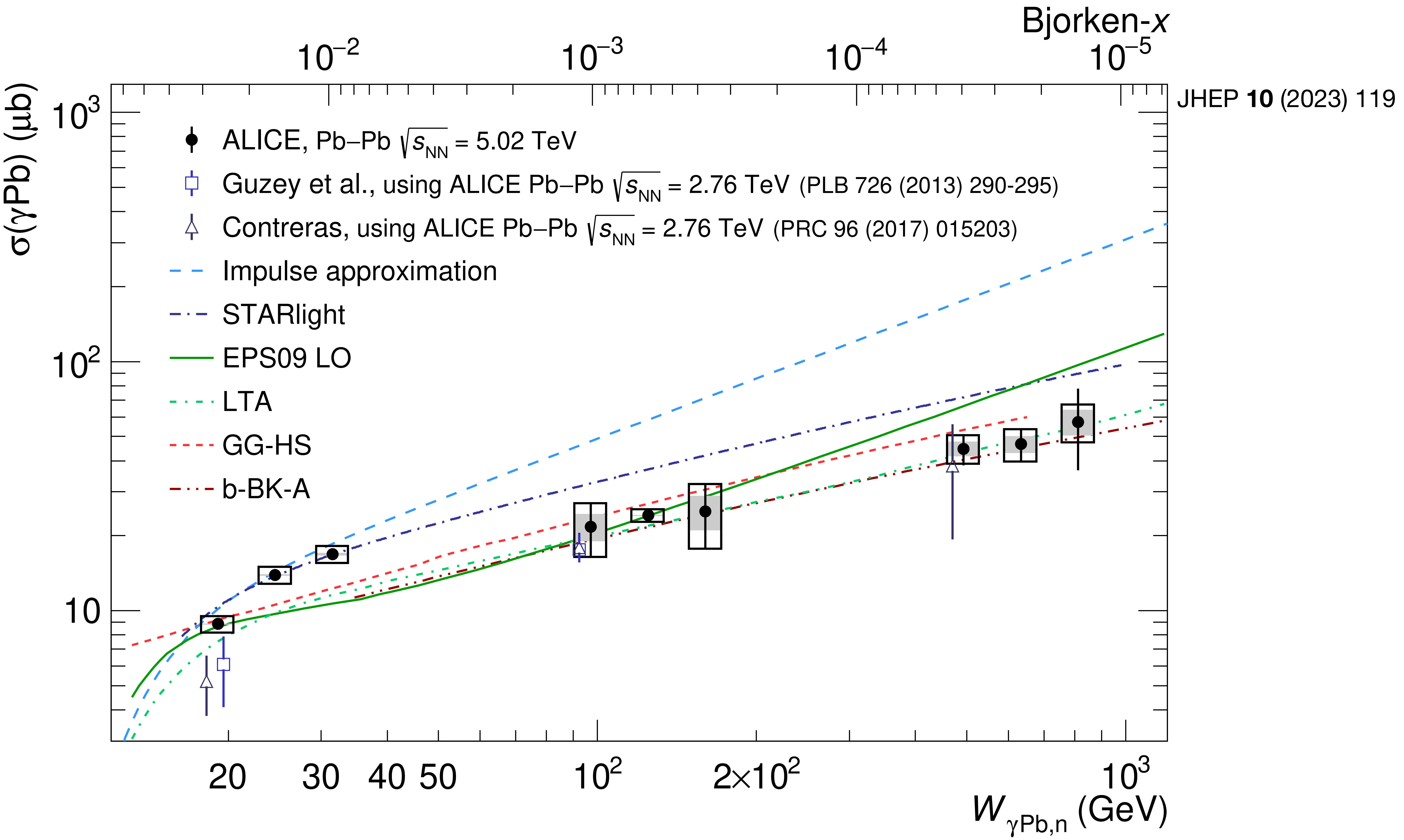
computed (StarLight)

extracted

CMS: γPb cross section, energy dependence



ALICE: 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 and ALICE: intriguing small linear rise of cross section for $W_{\gamma N}$>40 GeV

- Future measurements will allow to probe low x_B and high x_B region (with fixed target)

Back up

Coherent photoproduction in PbPb: y dependence

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

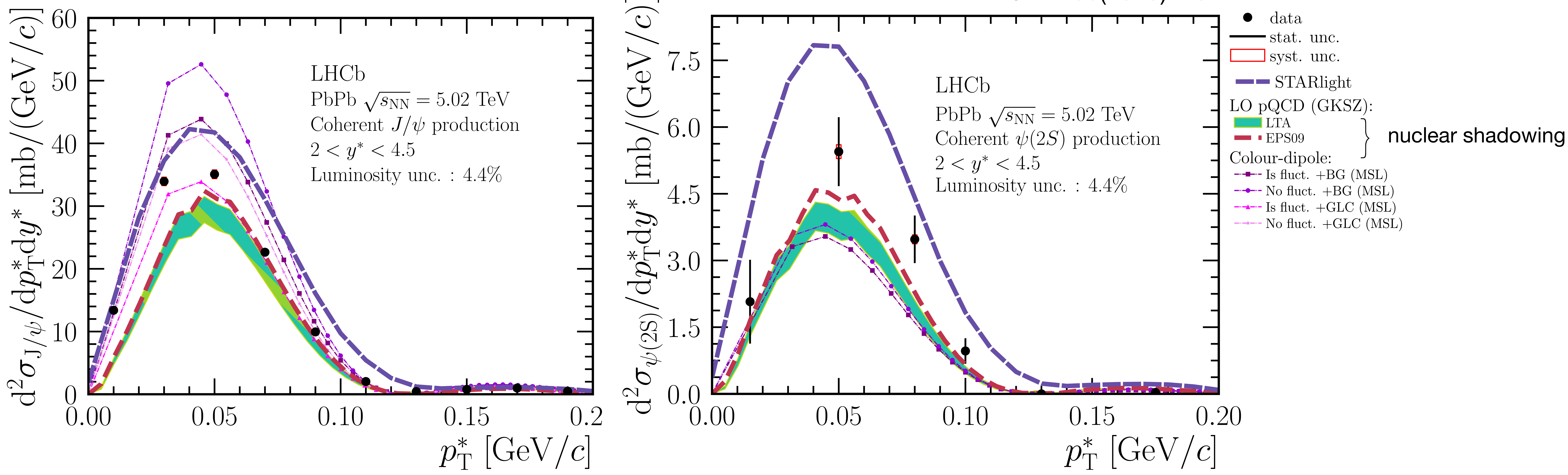
$\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \psi$

JHEP06(2023)146

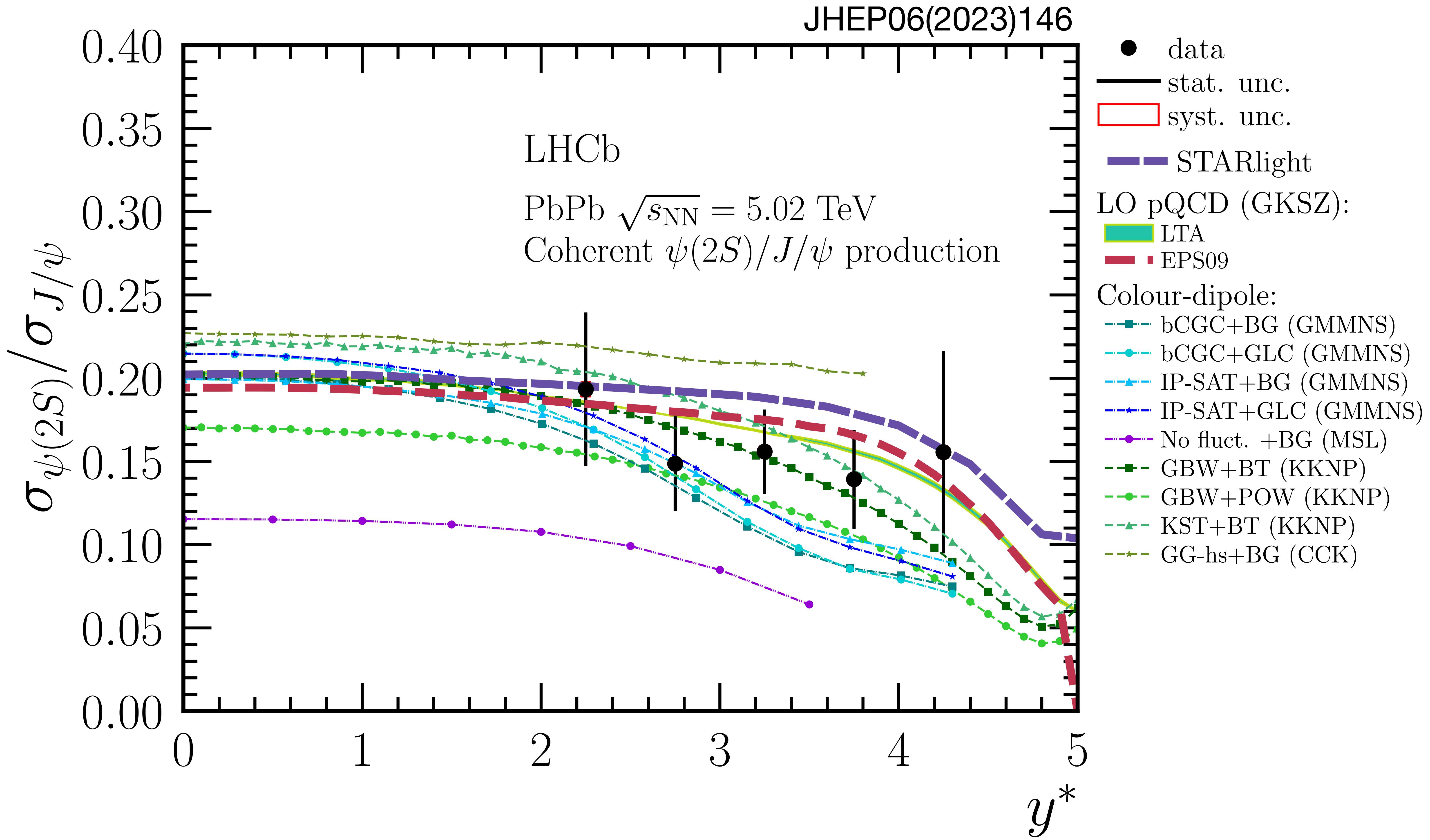
Coherent photoproduction in PbPb: p_T dependence

$$\mathrm{Pb} + \mathrm{Pb} \to \mathrm{Pb} + \mathrm{Pb} + \psi$$

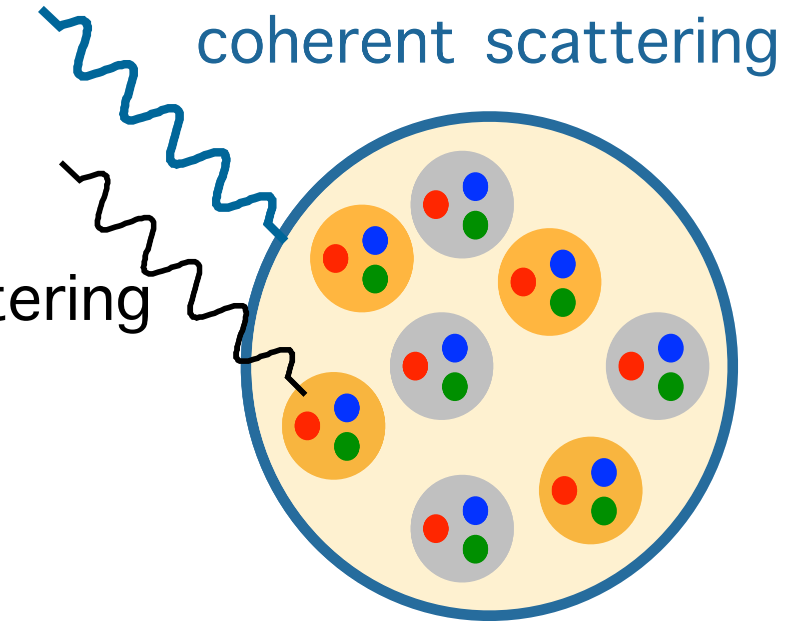
JHEP06(2023)146



Coherent photoproduction in PbPb: $\psi(2S)/J/\psi$



Incoherent production



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

average cross sections

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

average amplitude over target configurations:
probes average distributions

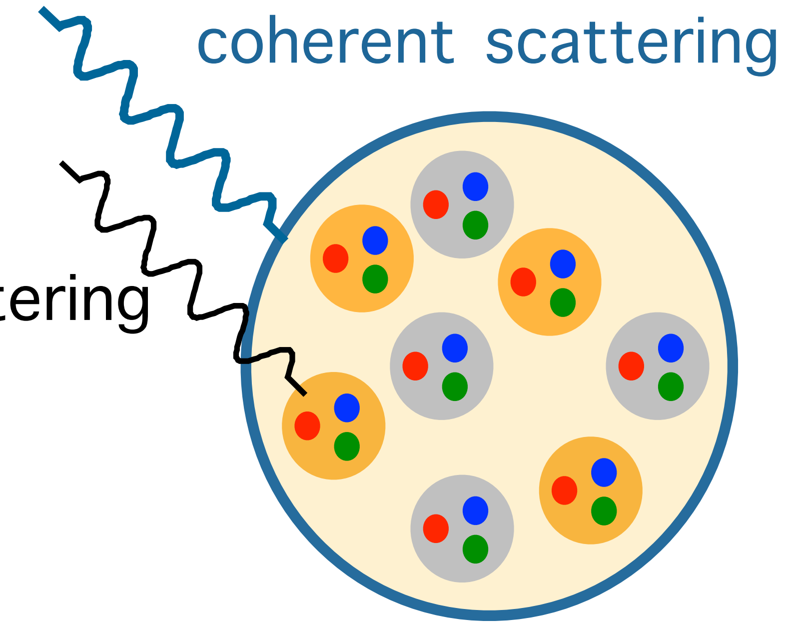
$$\sigma_{\text{incoh}} \sim \sum_{f \neq i} |\langle f|A|i\rangle|^2$$

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

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

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

Incoherent production



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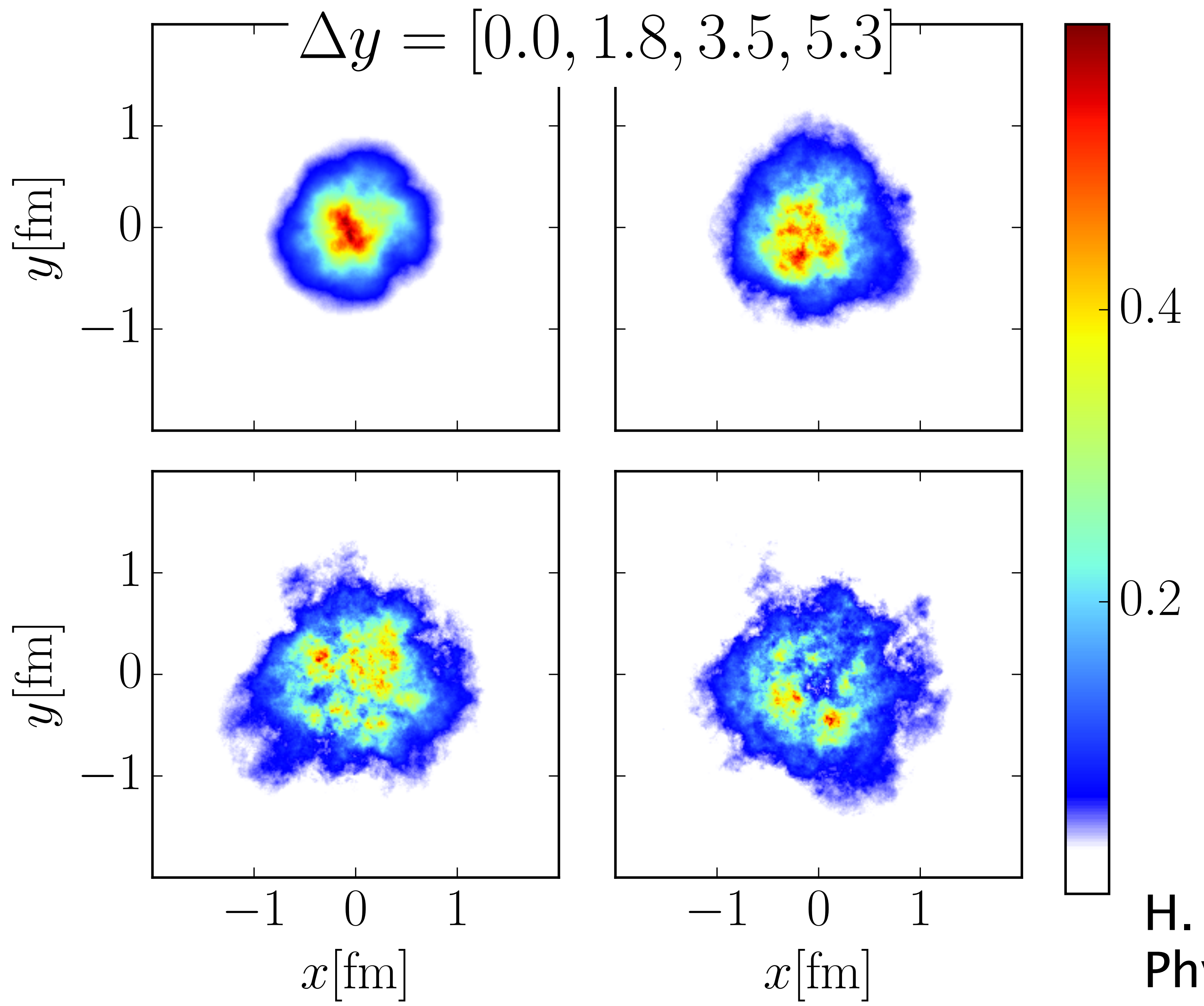
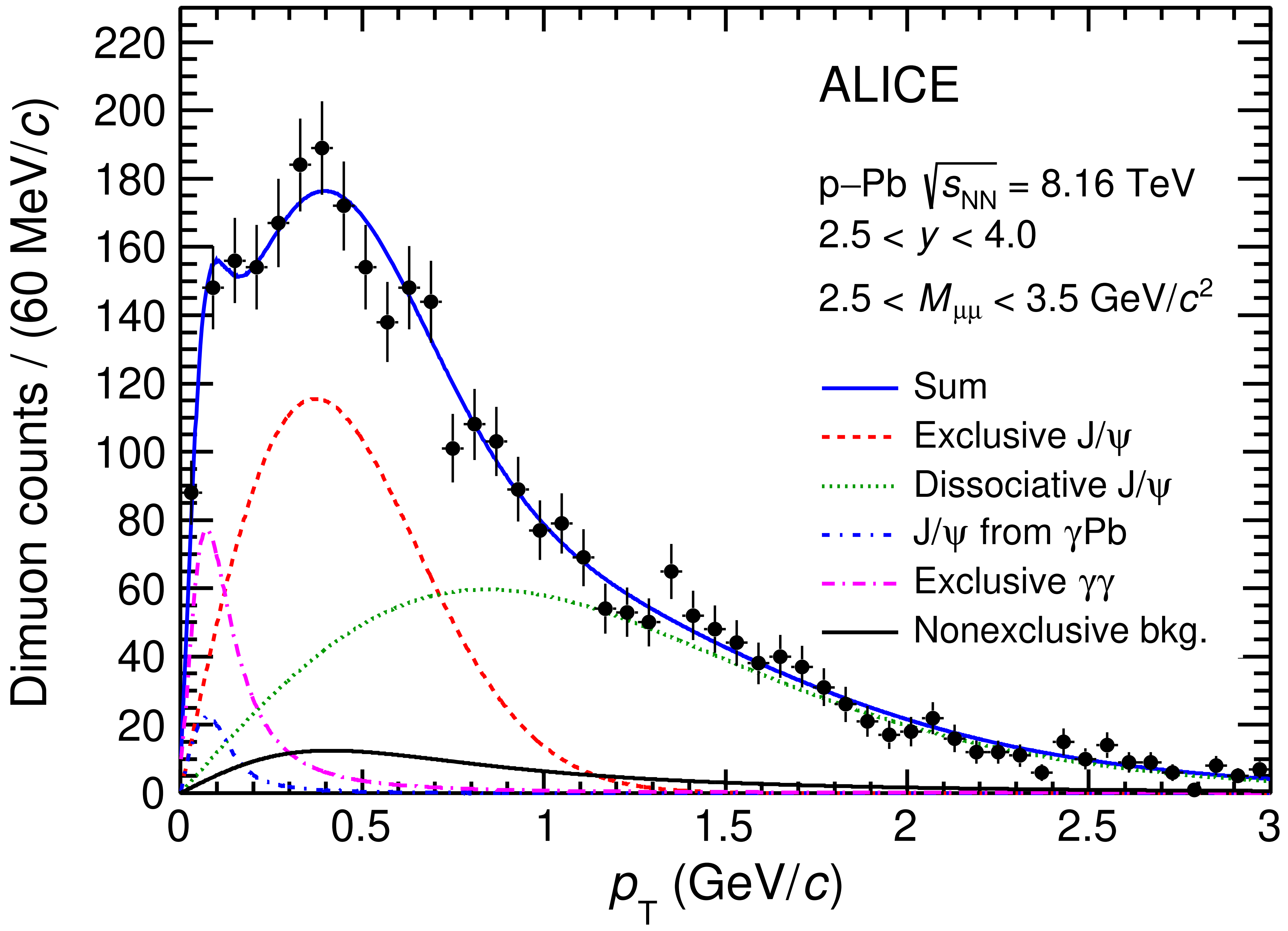


H. Mäntysaari and B. Schenke.
Phys. Rev. D 98, 034013 (2018)

Dissociative production measured by ALICE

pPb



PbPb

arXiv: 2305.06169