

Complementarity between EIC and LHC for diffractive / exclusive studies (with quarkonia)

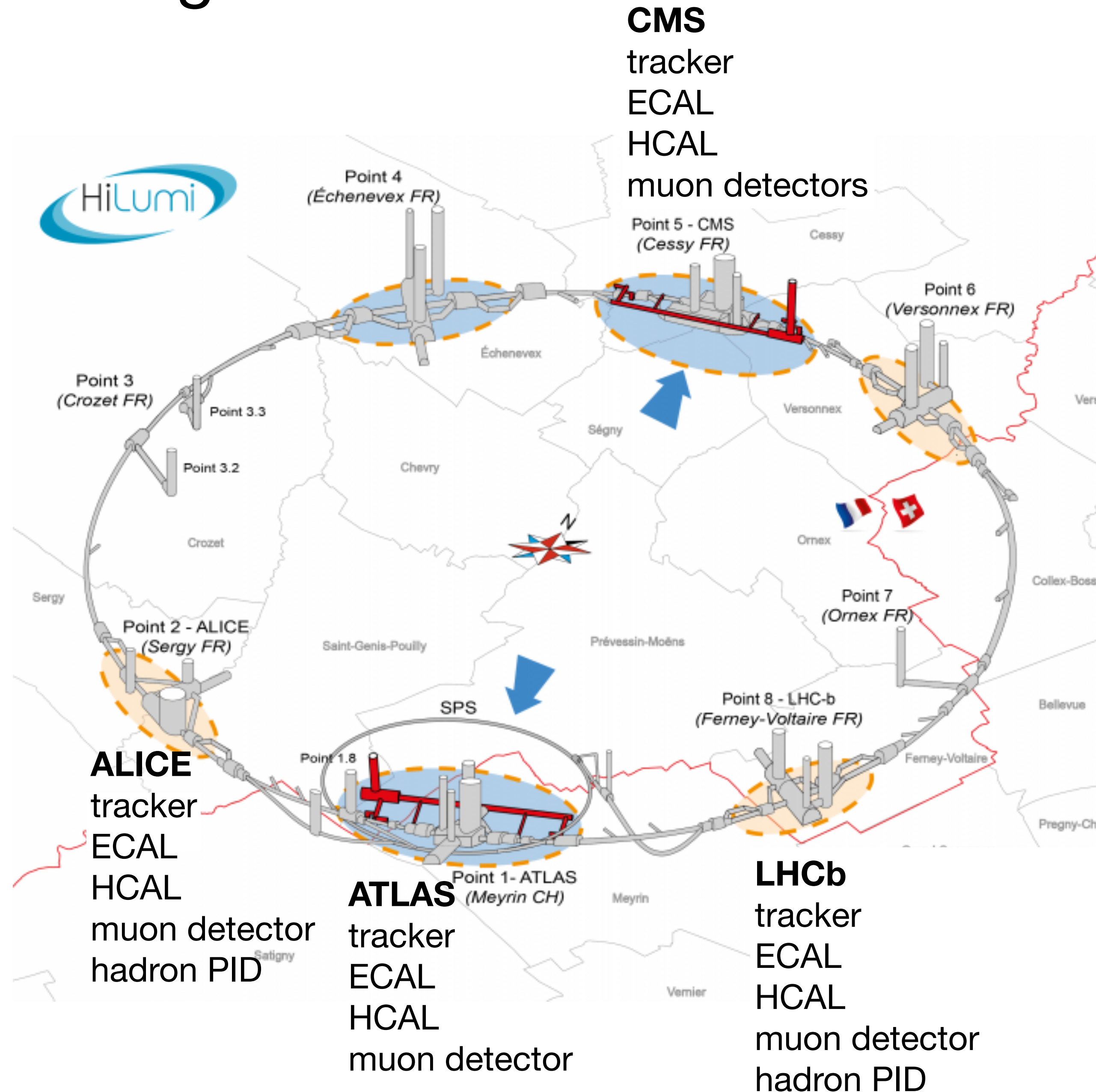
Charlotte Van Hulse
University of Alcalá



Synergies between LHC and EIC for quarkonium physics
8–12 July 2024
ECT* Trento, Italy

The high-lumi LHC

A. Dainese et al., CERN Yellow Reports: Vol. 7 (2019)



pp collisions

$$\sqrt{s} = 14 \text{ TeV}$$

$$\text{ATLAS/CMS } \mathcal{L} : 5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow \mathcal{L}_{\text{int}} : 3000 \text{ fb}^{-1}$$

$$\text{LHCb } \mathcal{L} : 2 \cdot 10^{33} / 2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow \mathcal{L}_{\text{int}} : 300 \text{ fb}^{-1}$$

PbPb collisions

$$\sqrt{s_{NN}} = 5.5 \text{ TeV}$$

$$\text{ALICE/ATLAS/CMS RUN4: } \mathcal{L}_{\text{int}} : 6.8 \text{ nb}^{-1}$$

$$\text{LHCb RUN4: } \mathcal{L}_{\text{int}} : 1.0 \text{ nb}^{-1}$$

pPb collisions

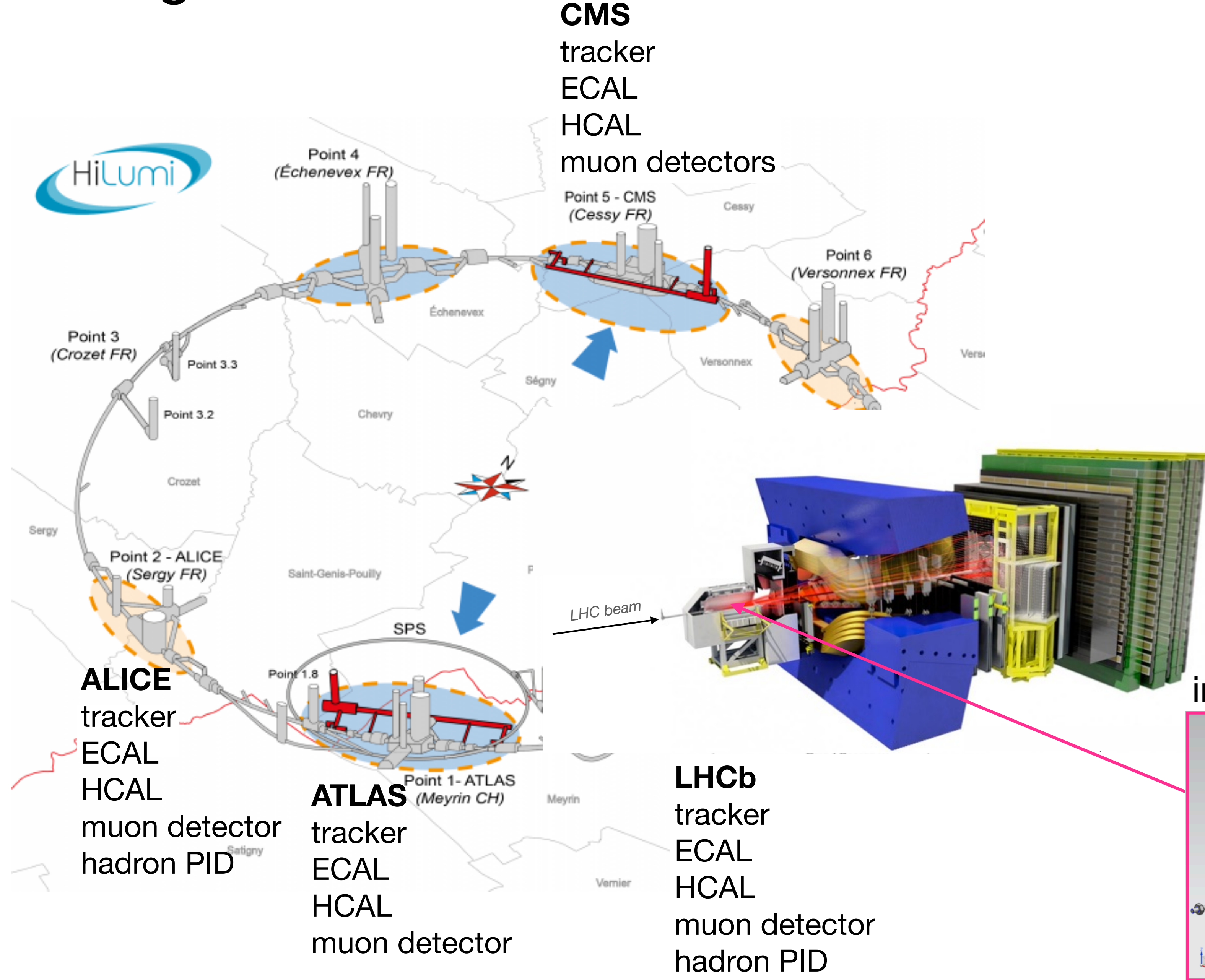
$$\sqrt{s_{NN}} = 8.8 \text{ TeV}$$

$$\text{ATLAS/CMS RUN4: } \mathcal{L}_{\text{int}} : 0.6 \text{ pb}^{-1}$$

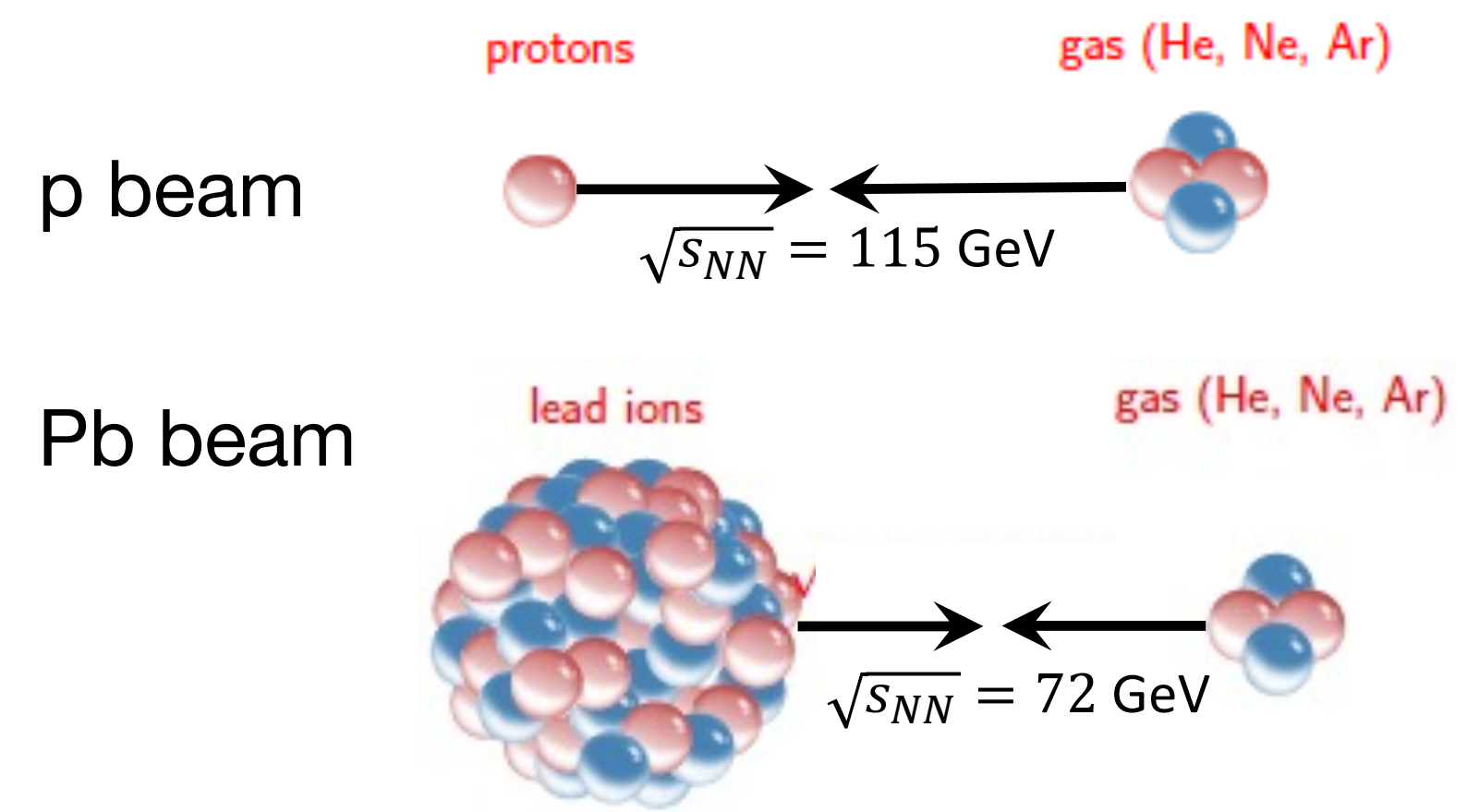
$$\text{ALICE/LHCb RUN4: } \mathcal{L}_{\text{int}} : 0.3 \text{ pb}^{-1}$$

Also p0 and 00 runs and possibly other intermediate-mass nuclei such as Ar-Ar

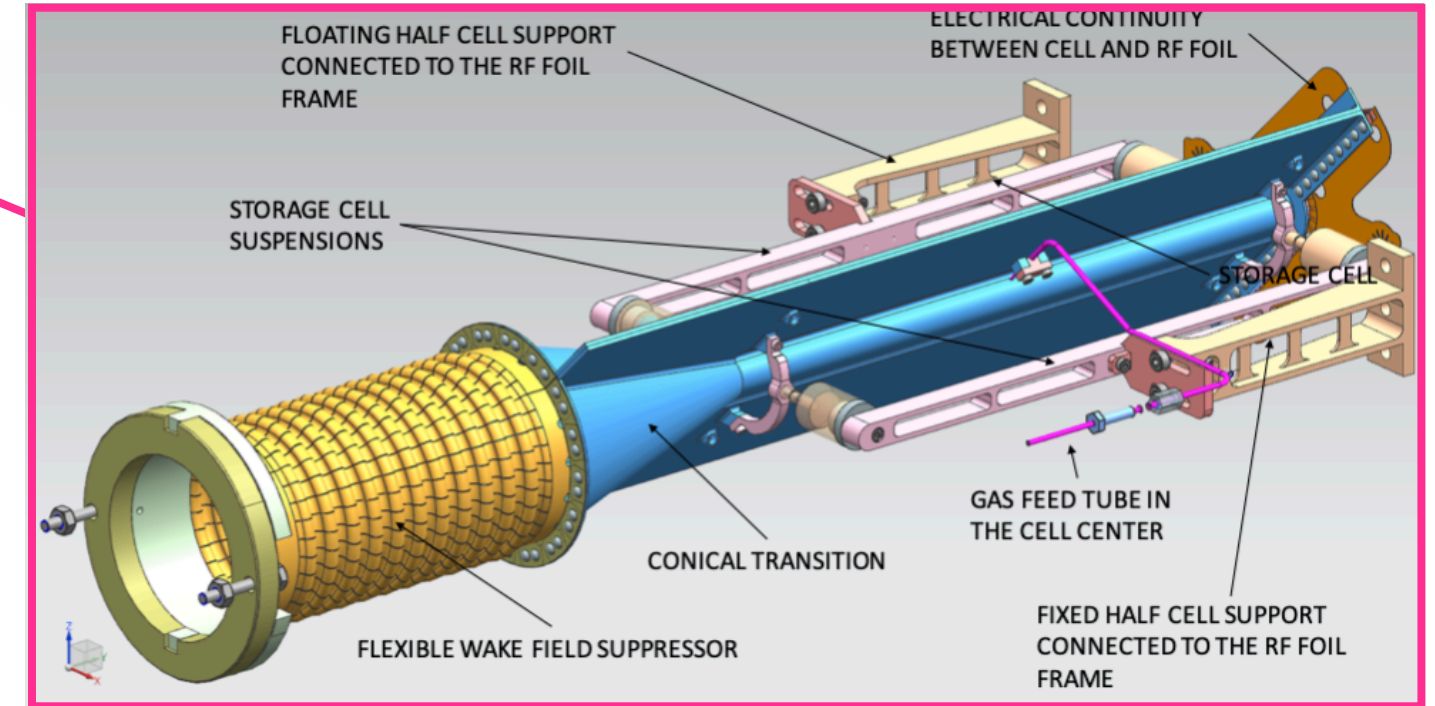
The high-lumi LHC



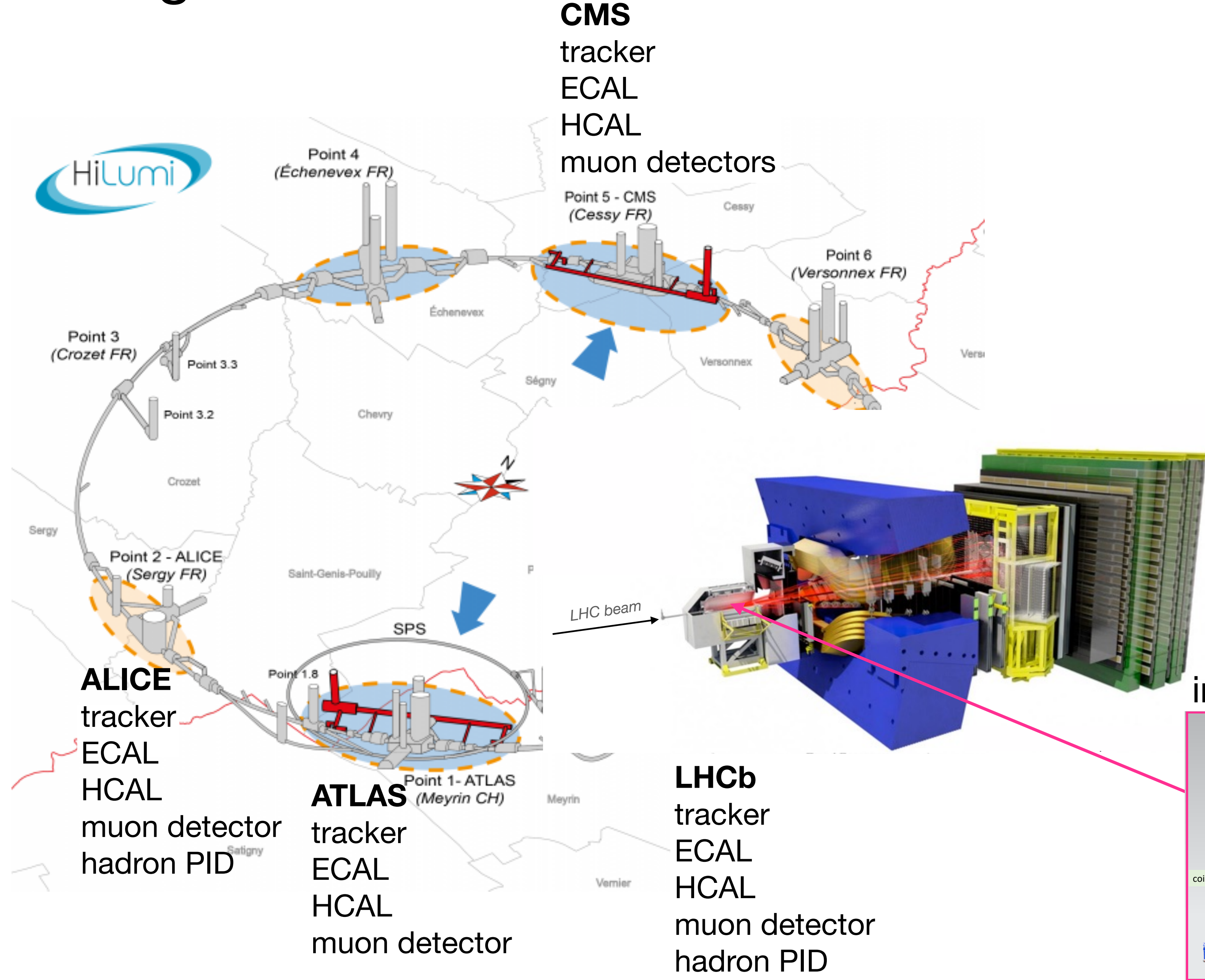
Fixed target – SMOG2



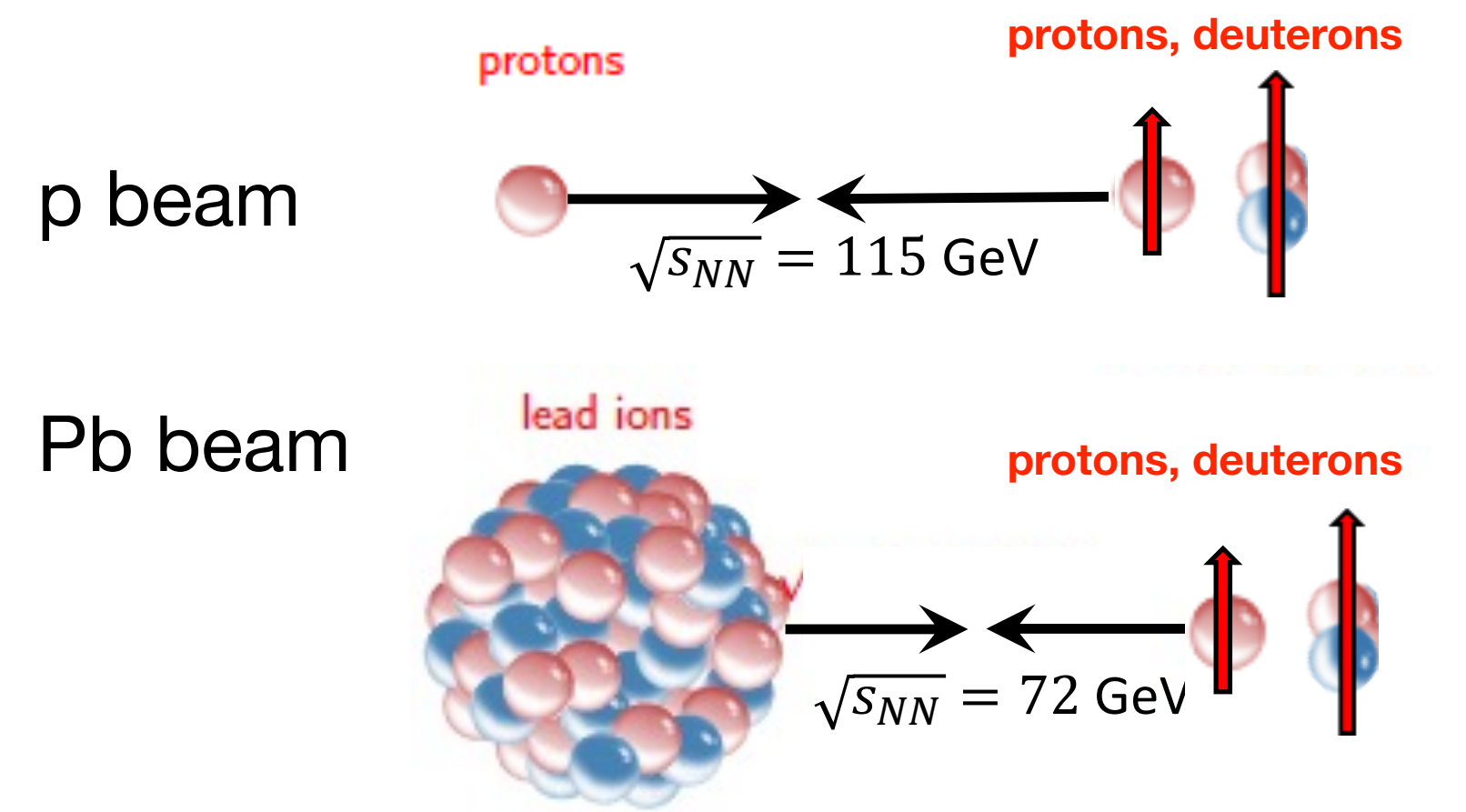
inject gas: He, Ne, Ar, and H₂, D₂



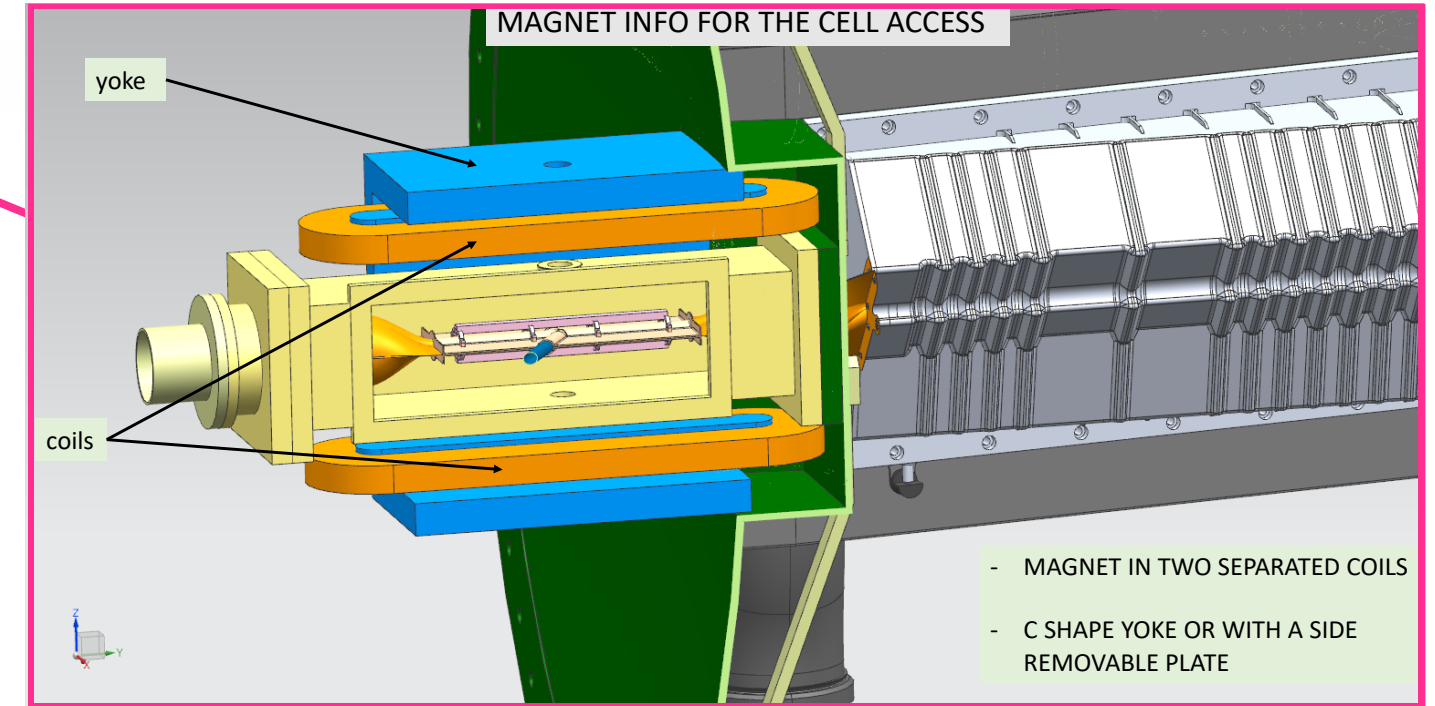
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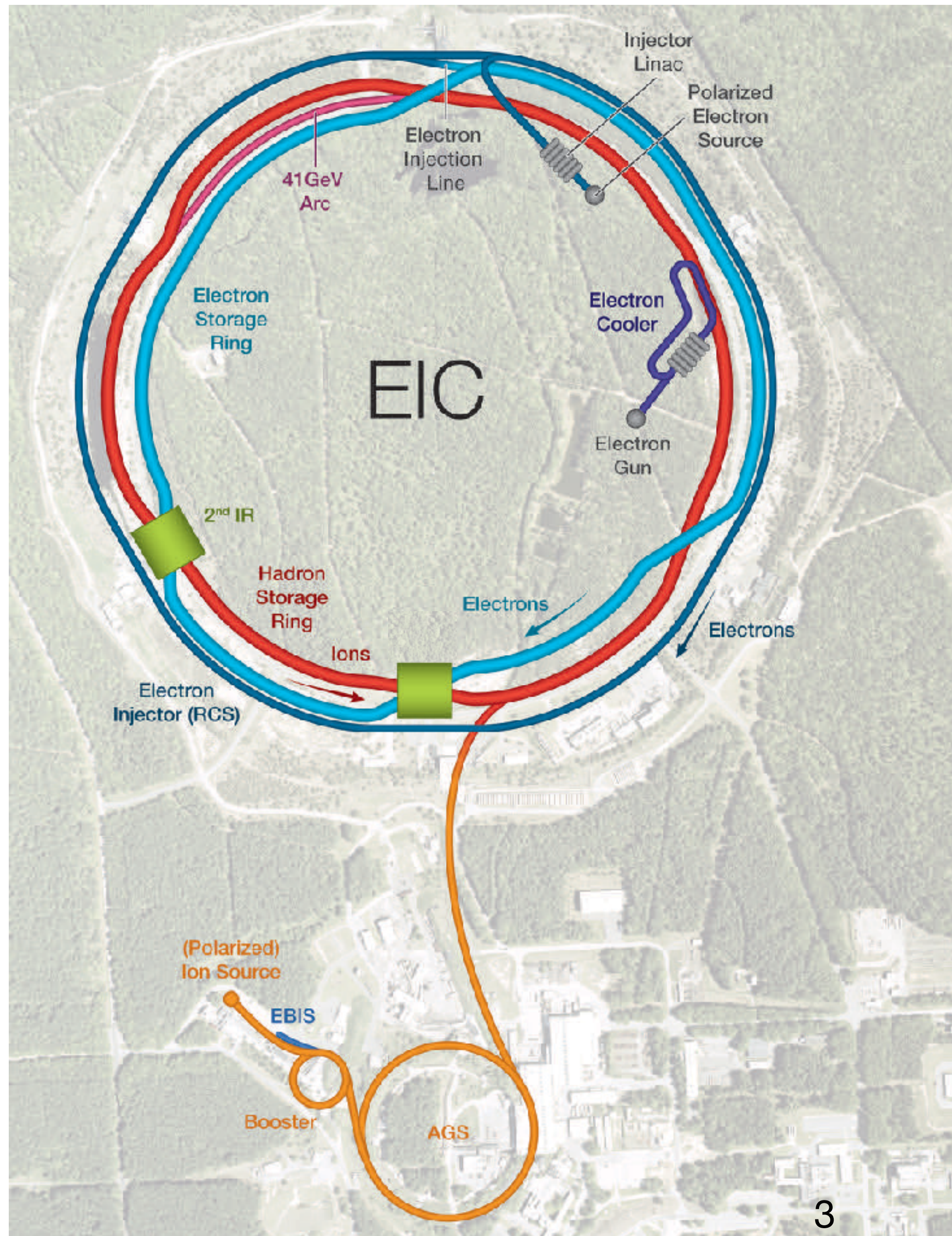
Fixed target – LHCSpin proposed for Run5



inject gas: He, Ne, Ar, and H₂, D₂

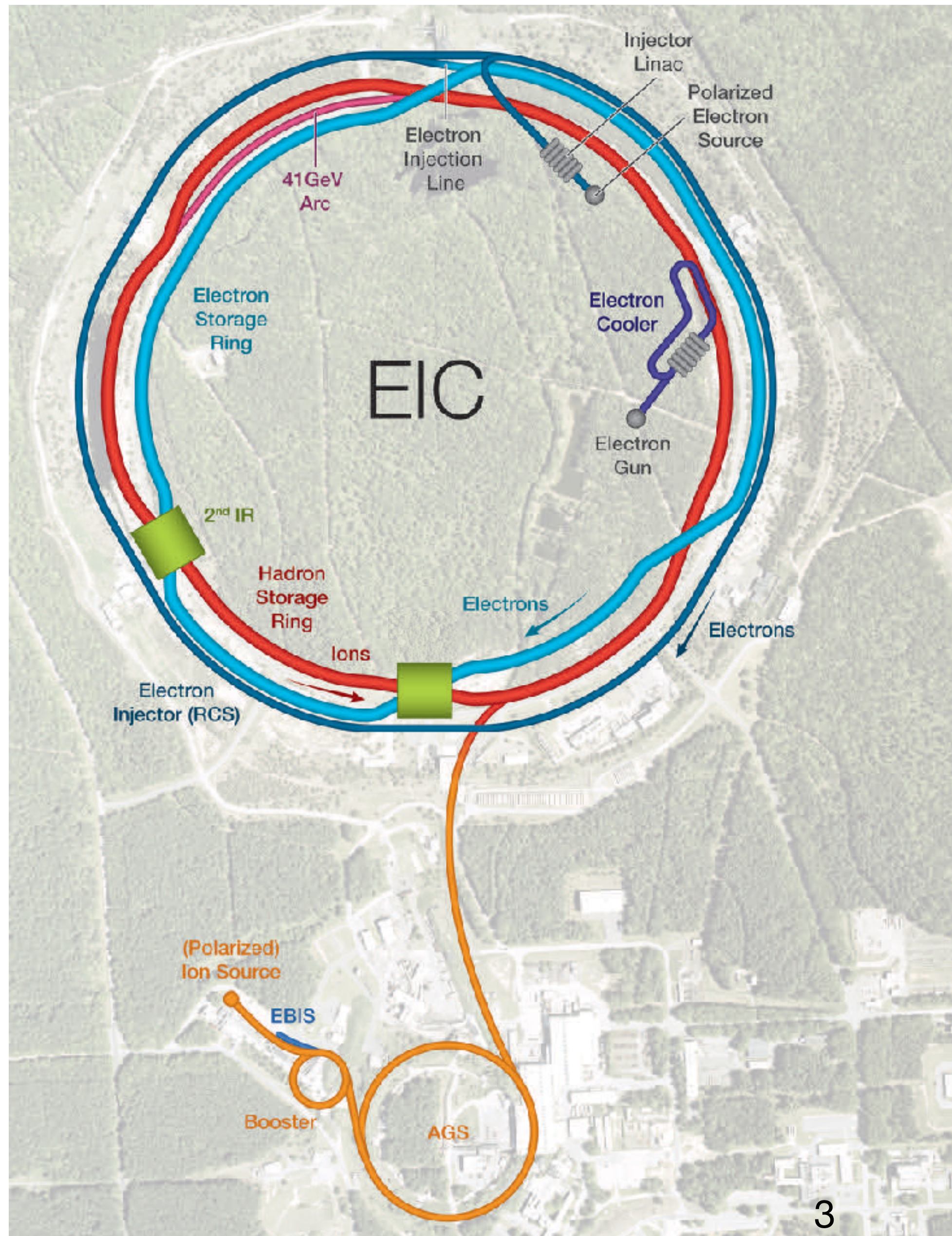


The electron-ion collider



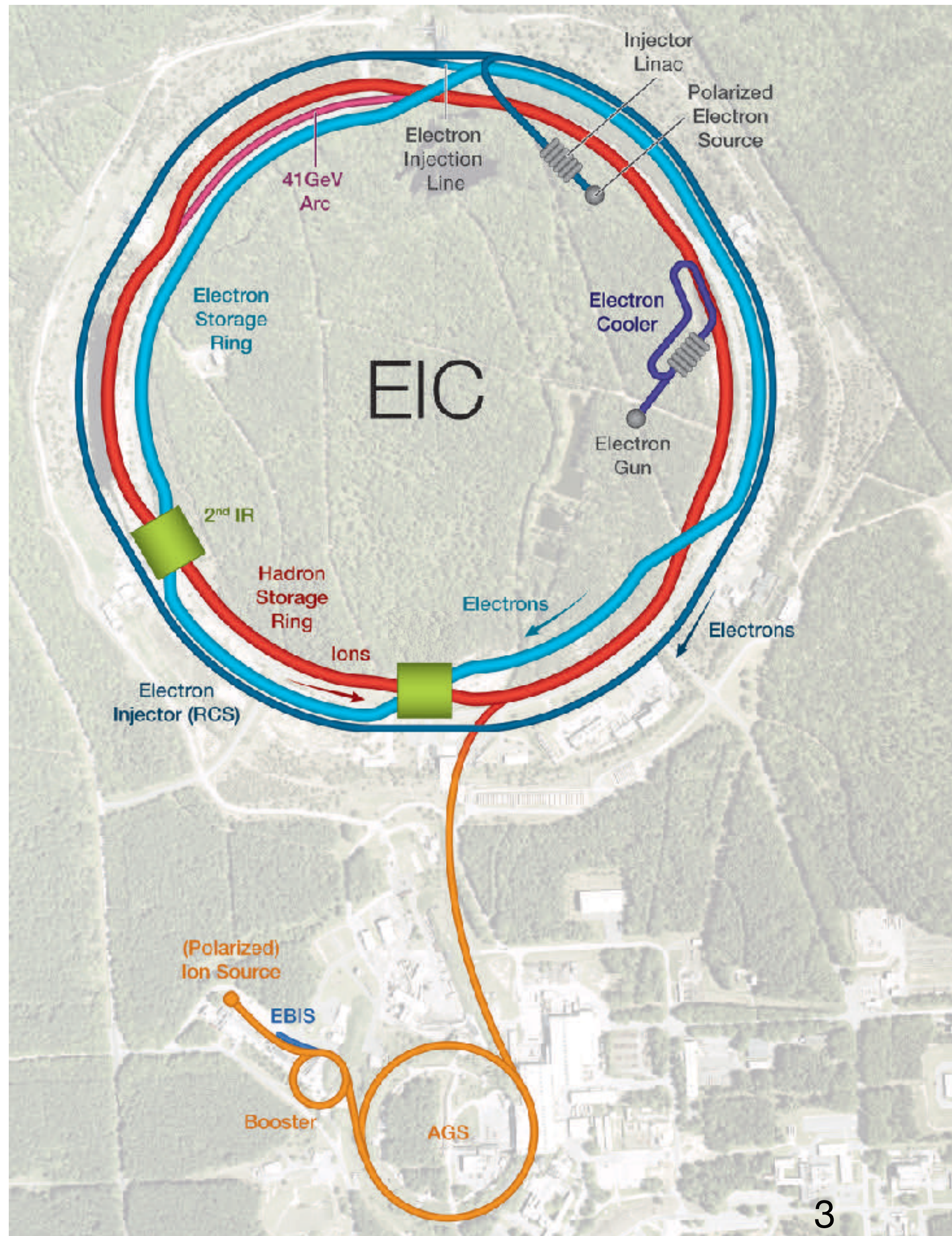
- Based on RHIC:
 - use existing hadron storage ring energy: 41–275 GeV
 - add electron storage ring in RHIC tunnel energy: 5–18 GeV
- $\sqrt{s} = 29 - 141$ GeV

The electron-ion collider



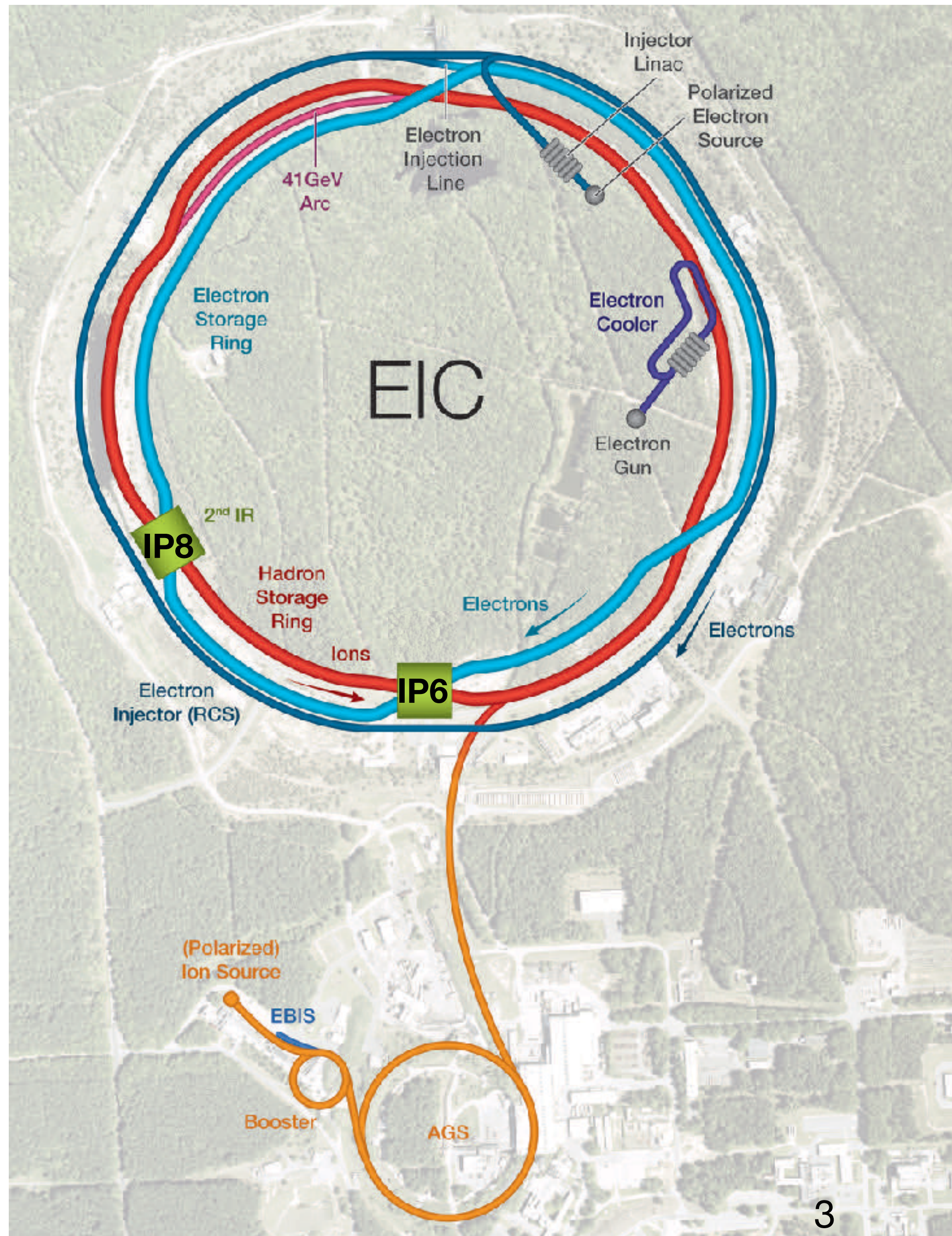
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~ 70% polarisation

The electron-ion collider



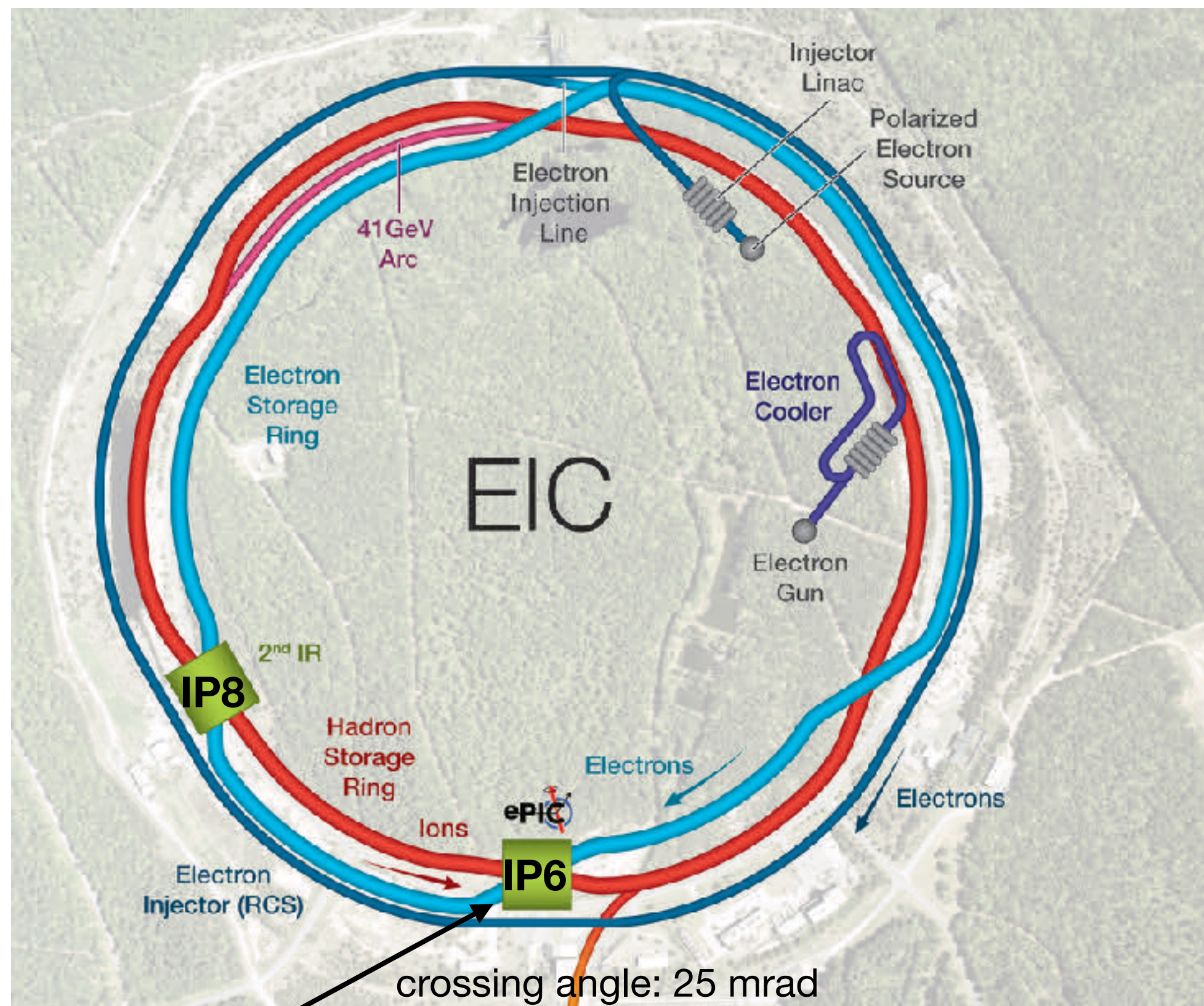
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- ep: $\mathcal{L} = 10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$
 $\leftrightarrow \mathcal{L}_{\text{int}} = 10 - 100 \text{ fb}^{-1}/\text{year}$
- eA: $\mathcal{L} = 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
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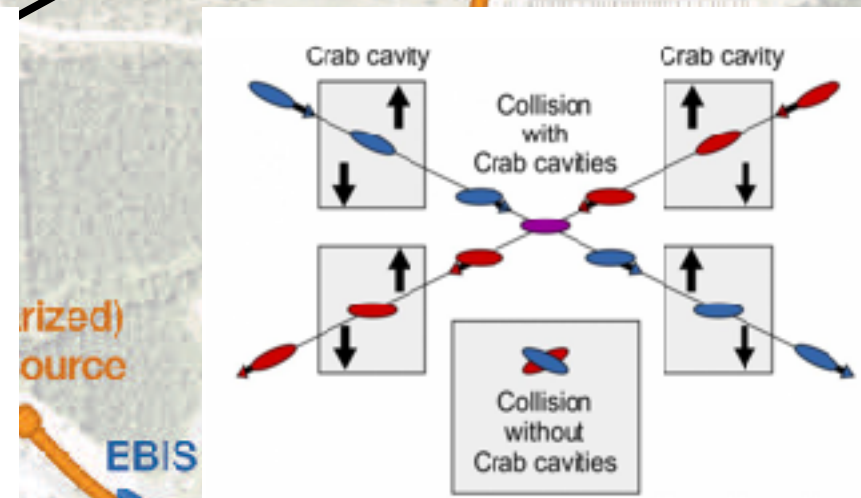
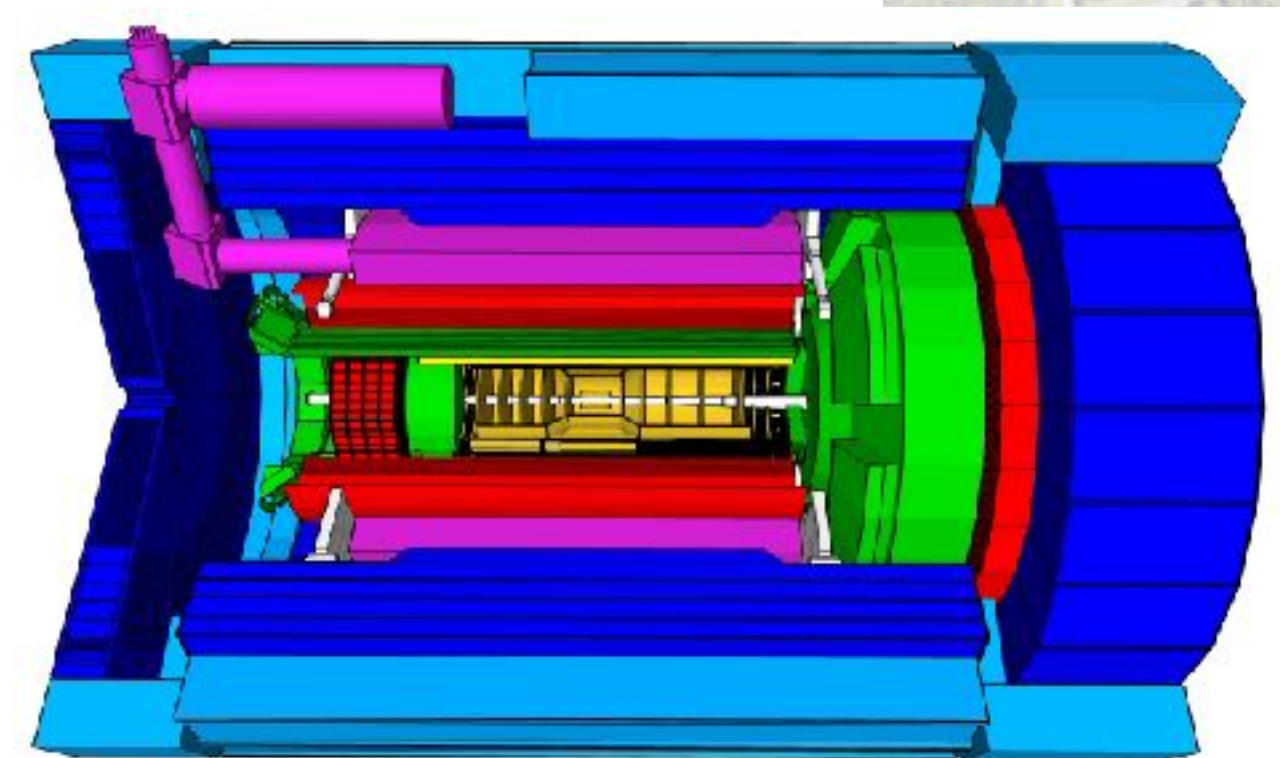


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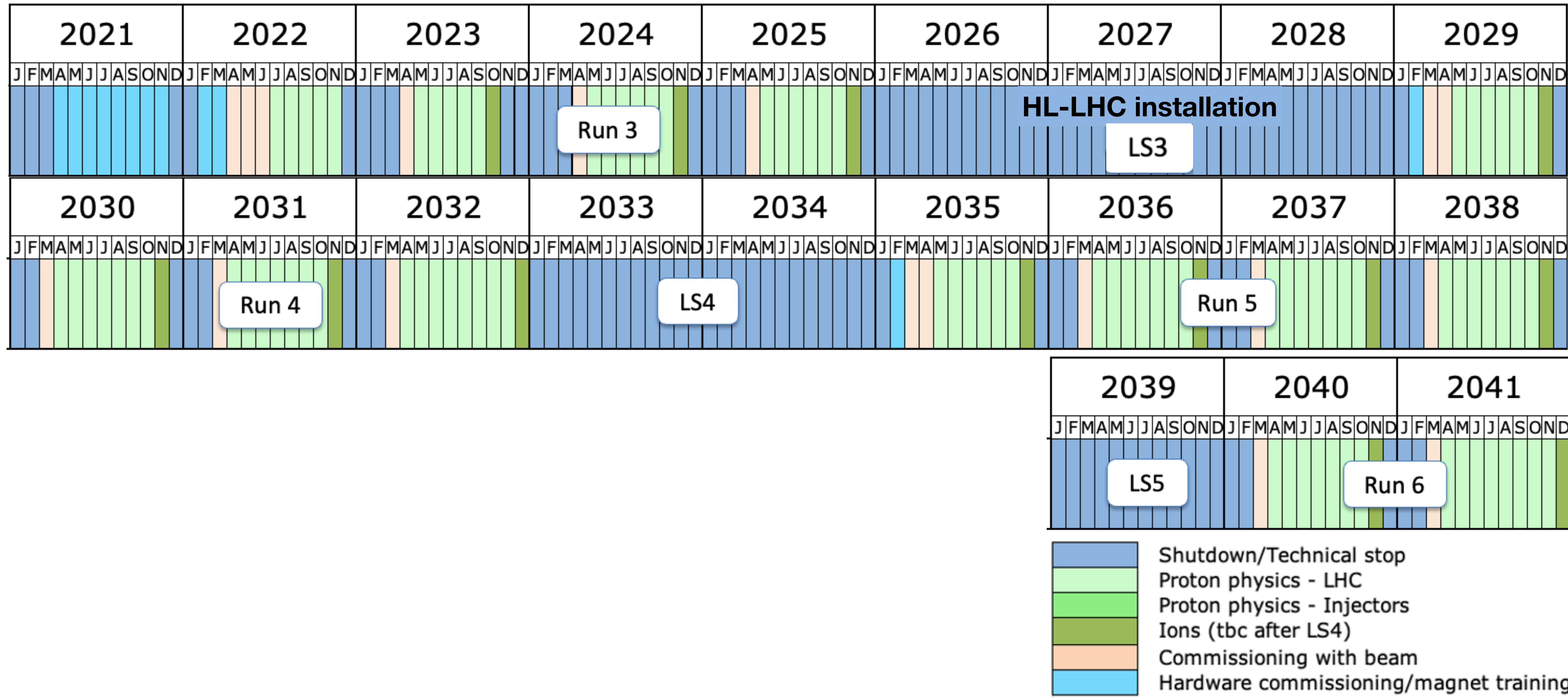
crossing angle: 25 mrad



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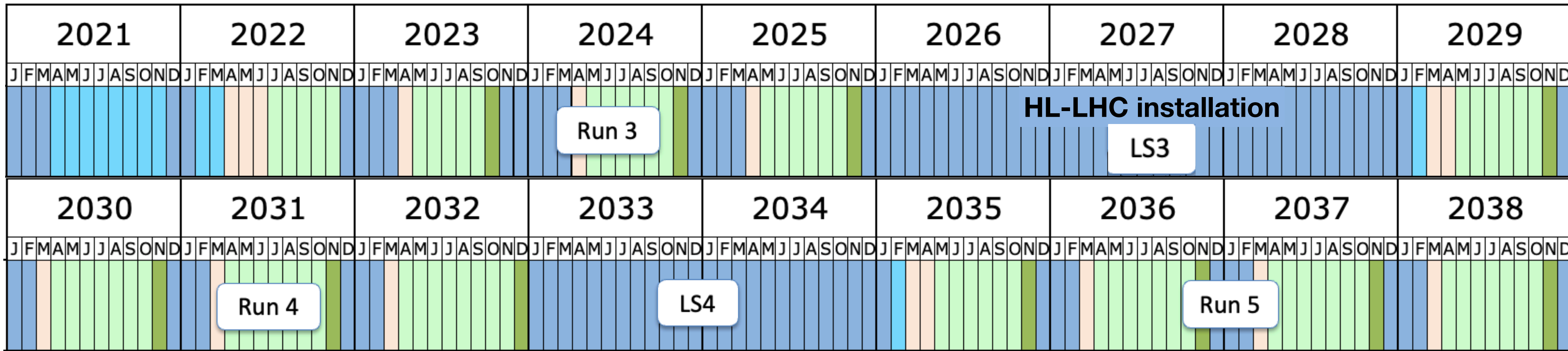
Timelines

LHC

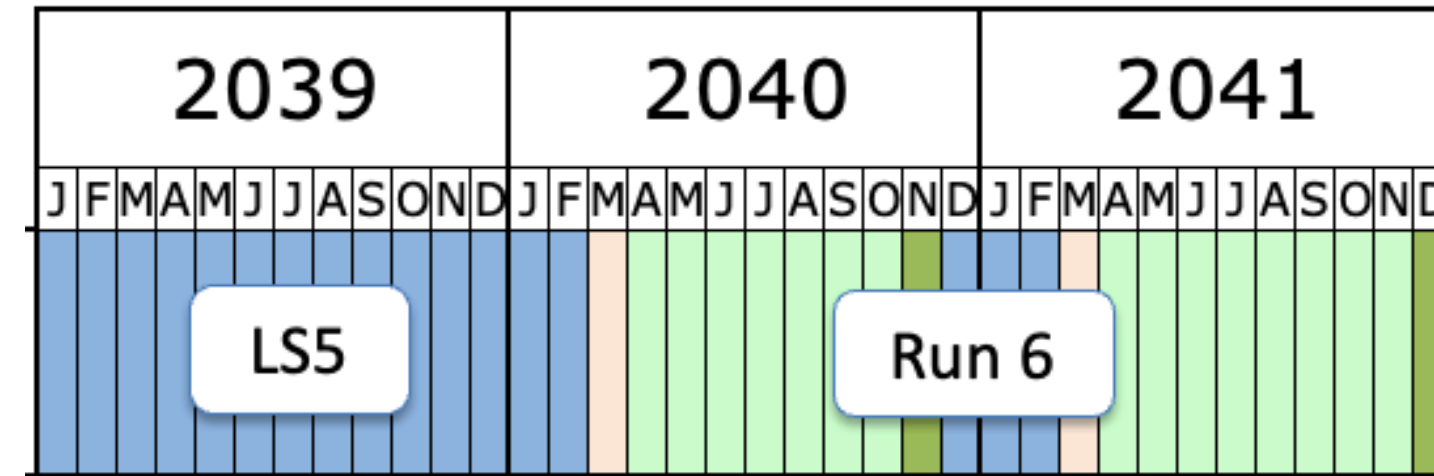
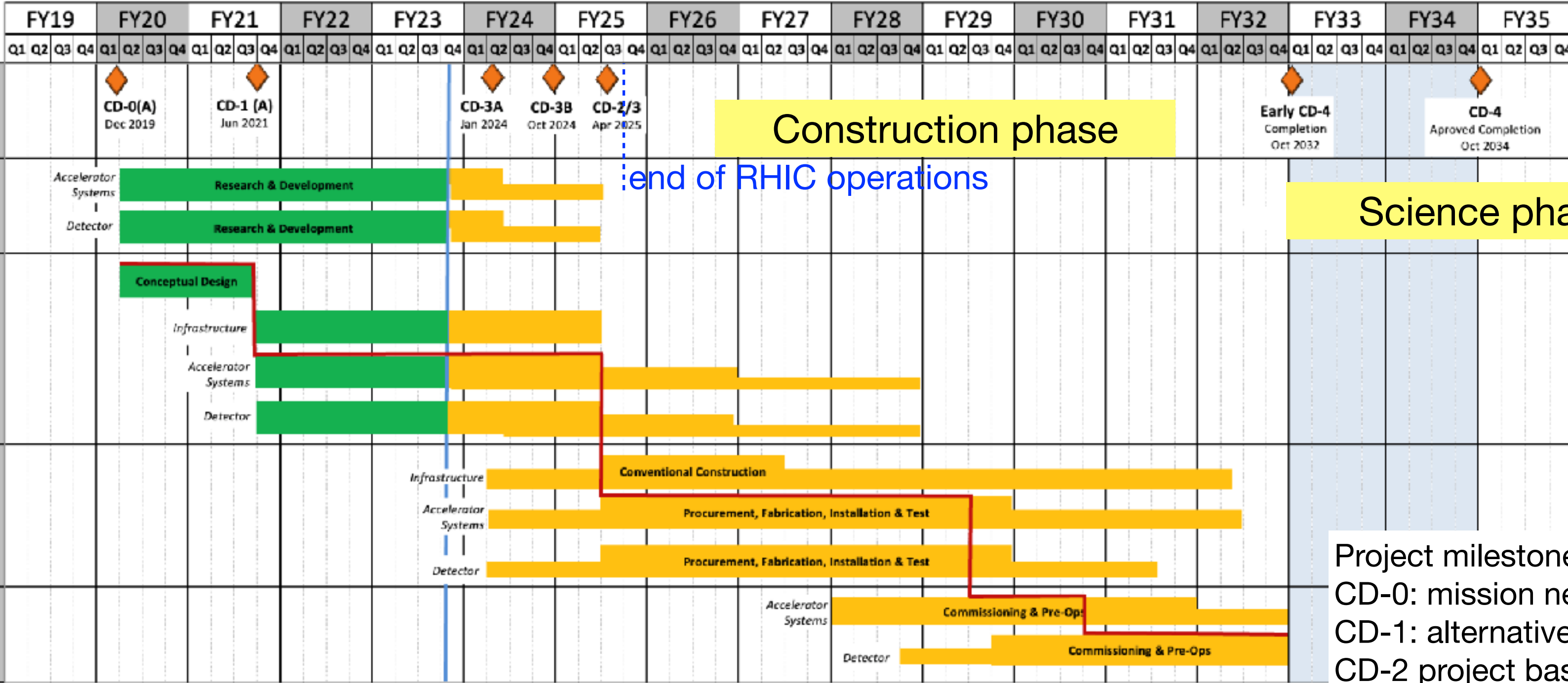


Timelines

LHC



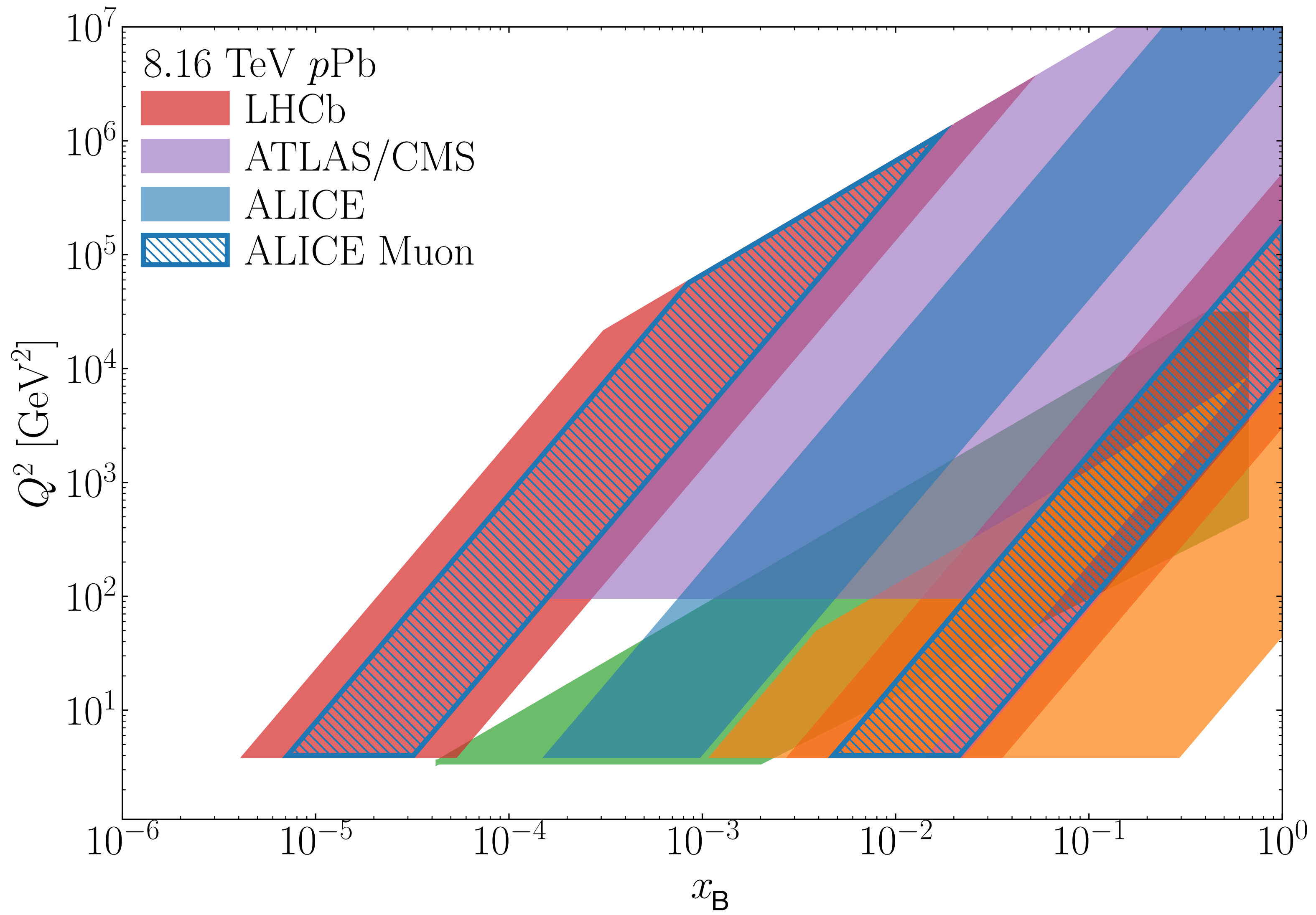
EIC



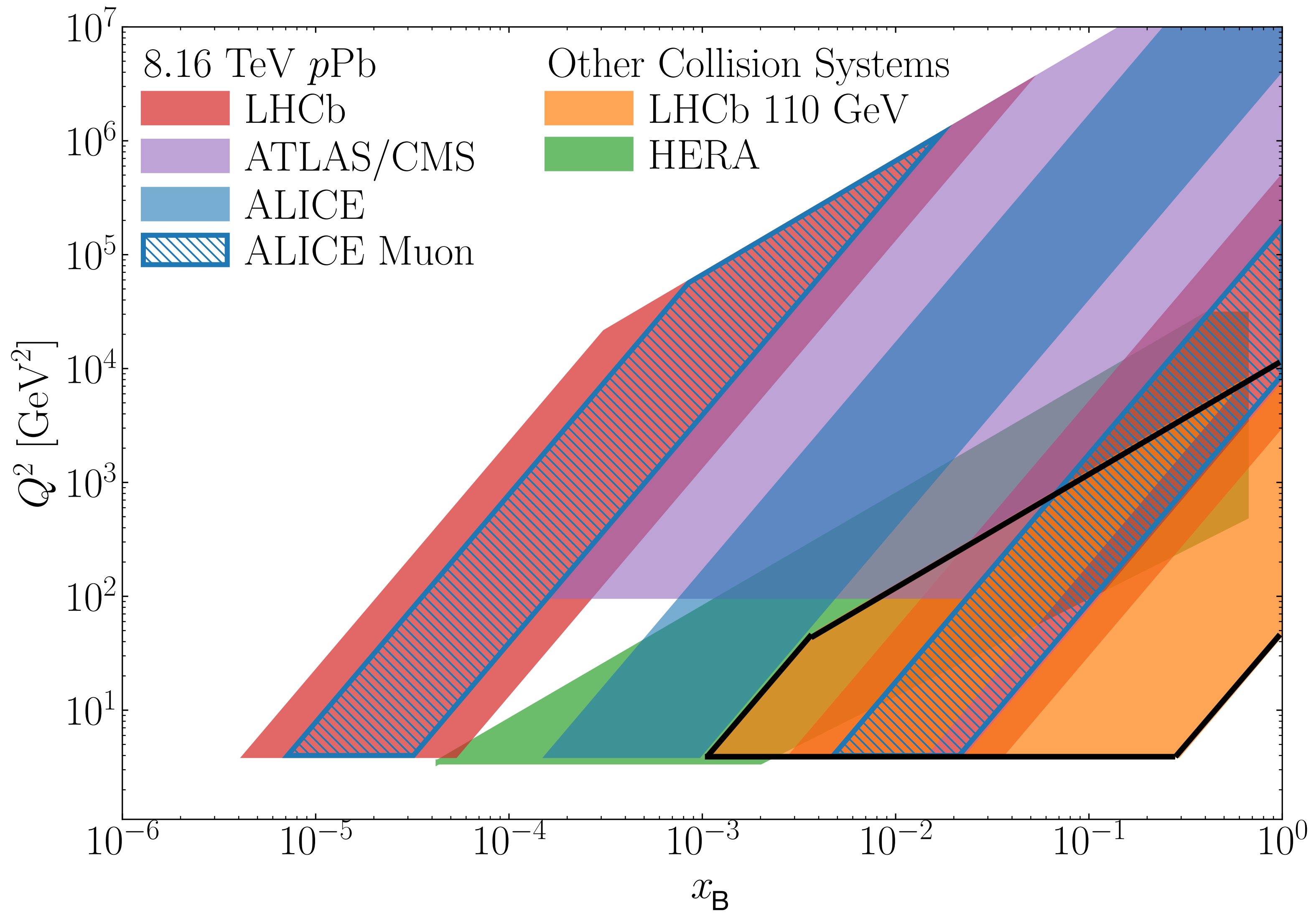
- Shutdown/Technical stop
- Proton physics - LHC
- Proton physics - Injectors
- Ions (tbc after LS4)
- Commissioning with beam
- Hardware commissioning/magnet training

Project milestones
 CD-0: mission need
 CD-1: alternative selection, cost range
 CD-2 project baseline
 CD-3: start of construction
 CD-4: project completion, start of operation

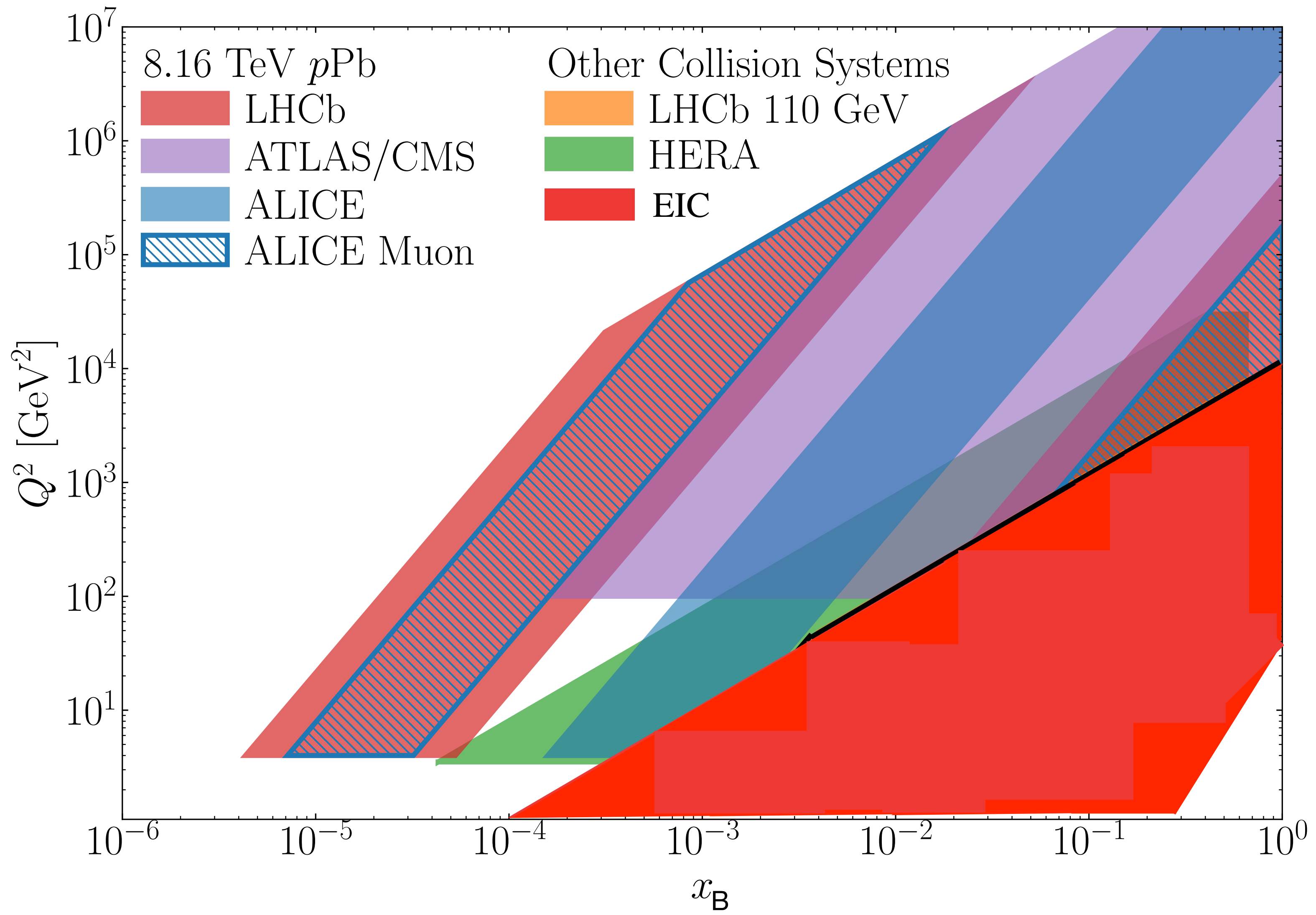
Kinematic coverage



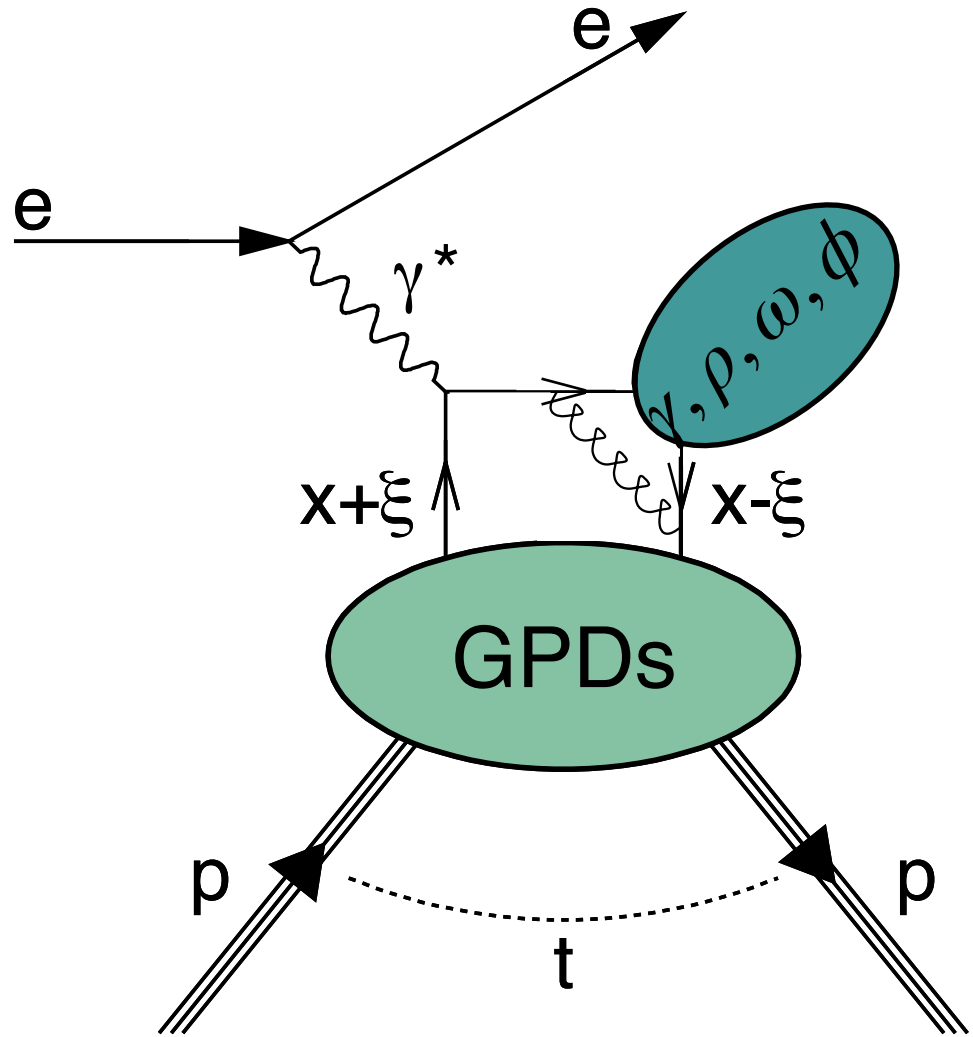
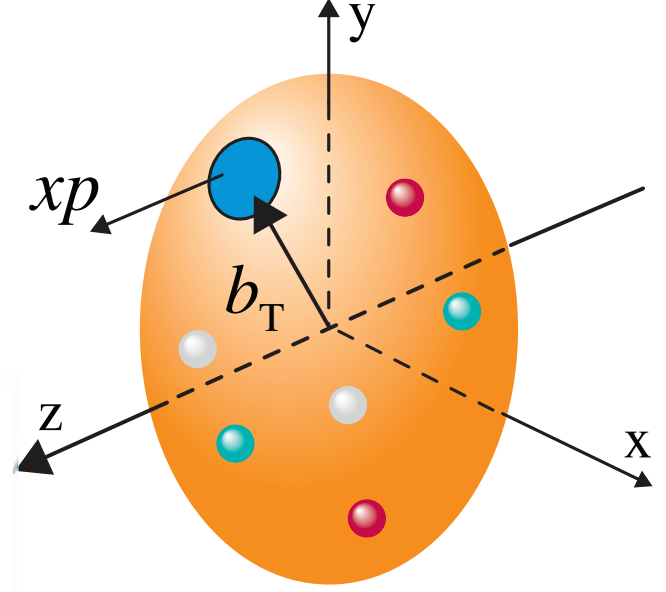
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Kinematic coverage

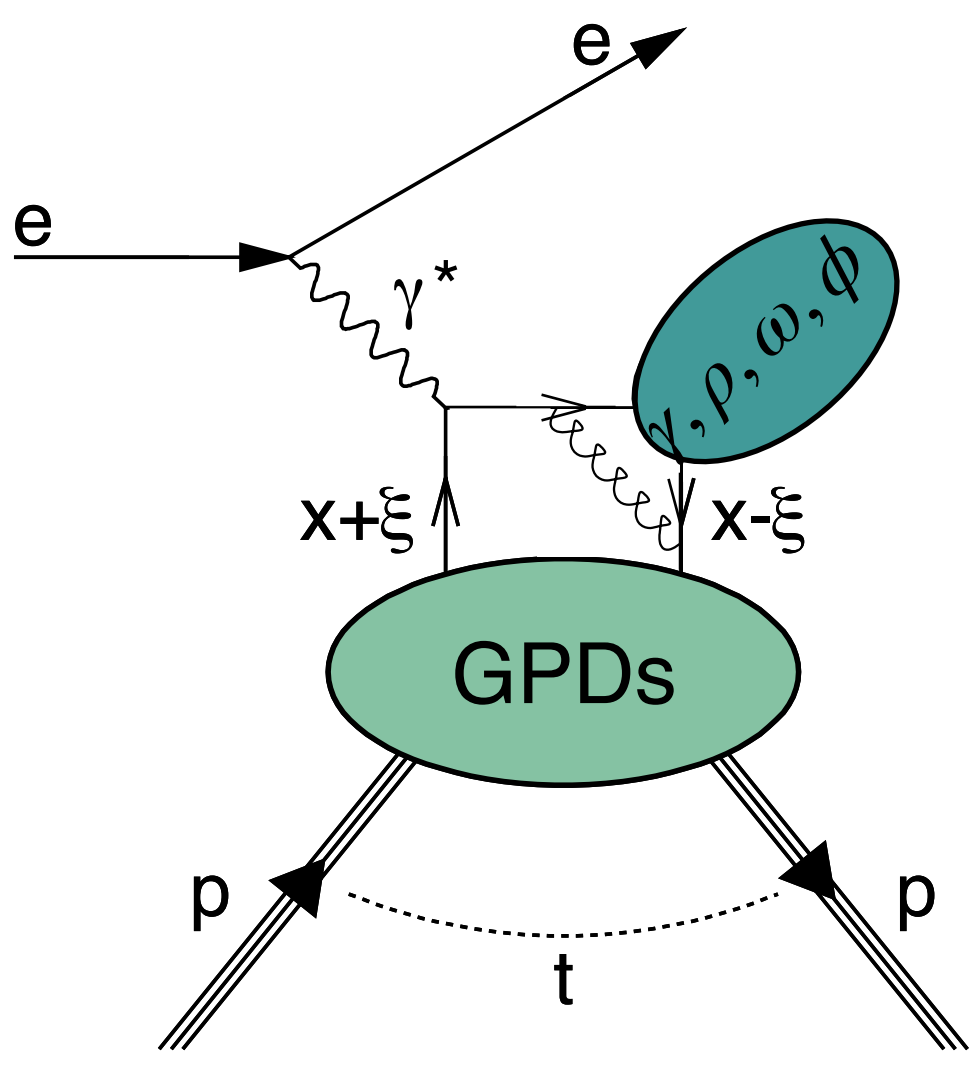
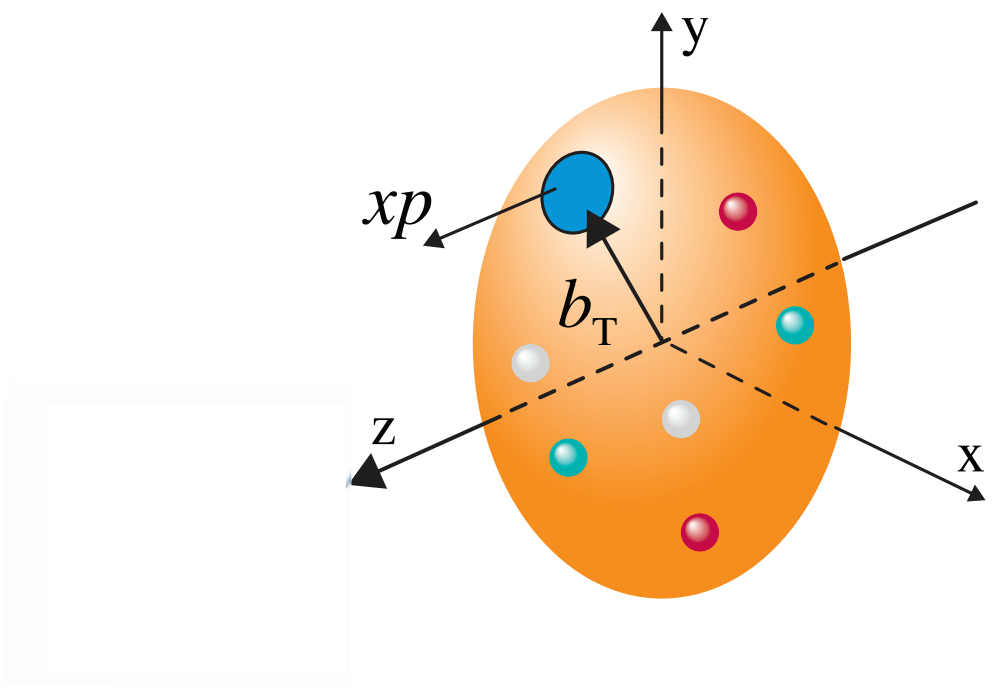


Exclusive processes at the EIC and LHC

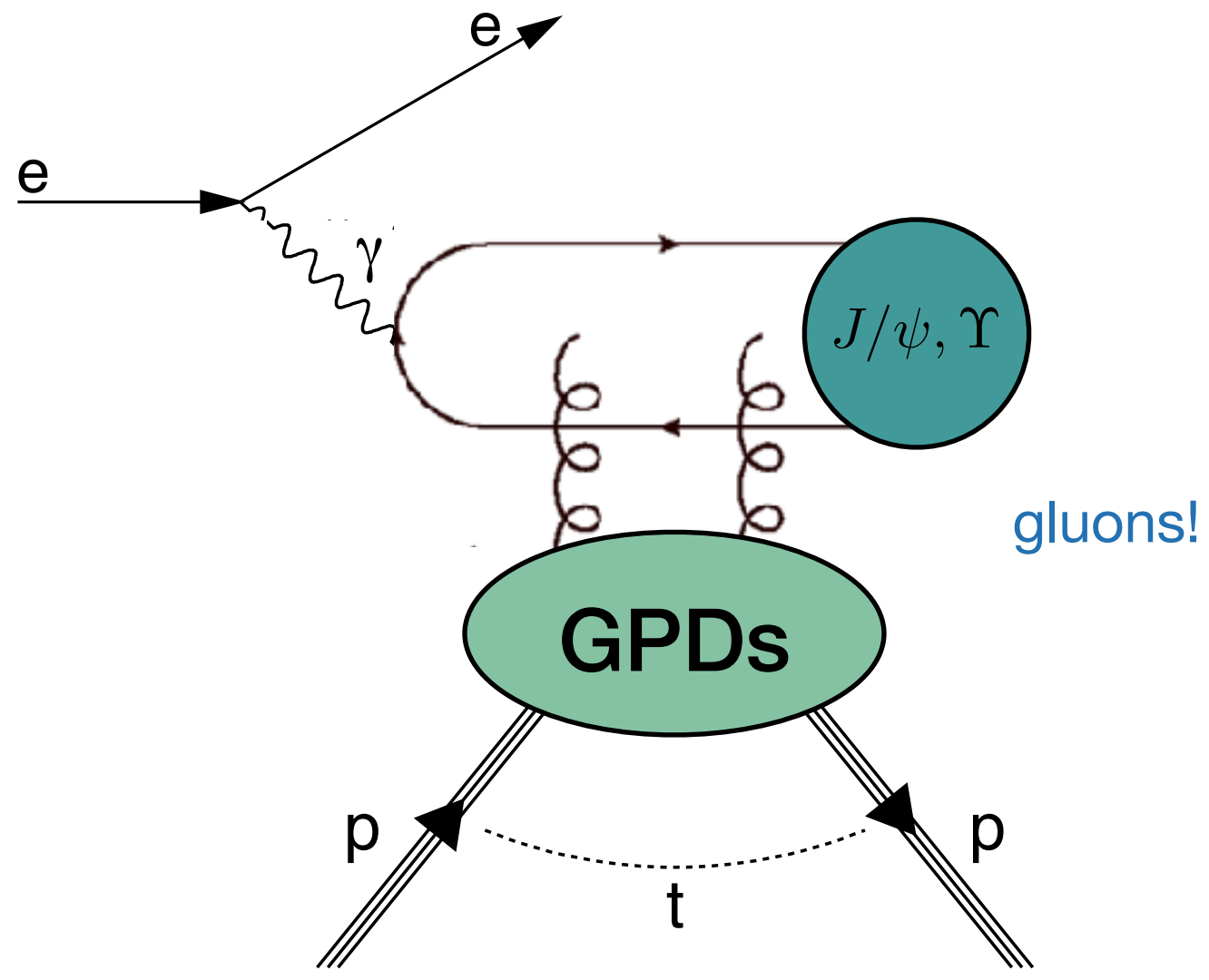


Hard exclusive meson production
Hard scale=large Q^2

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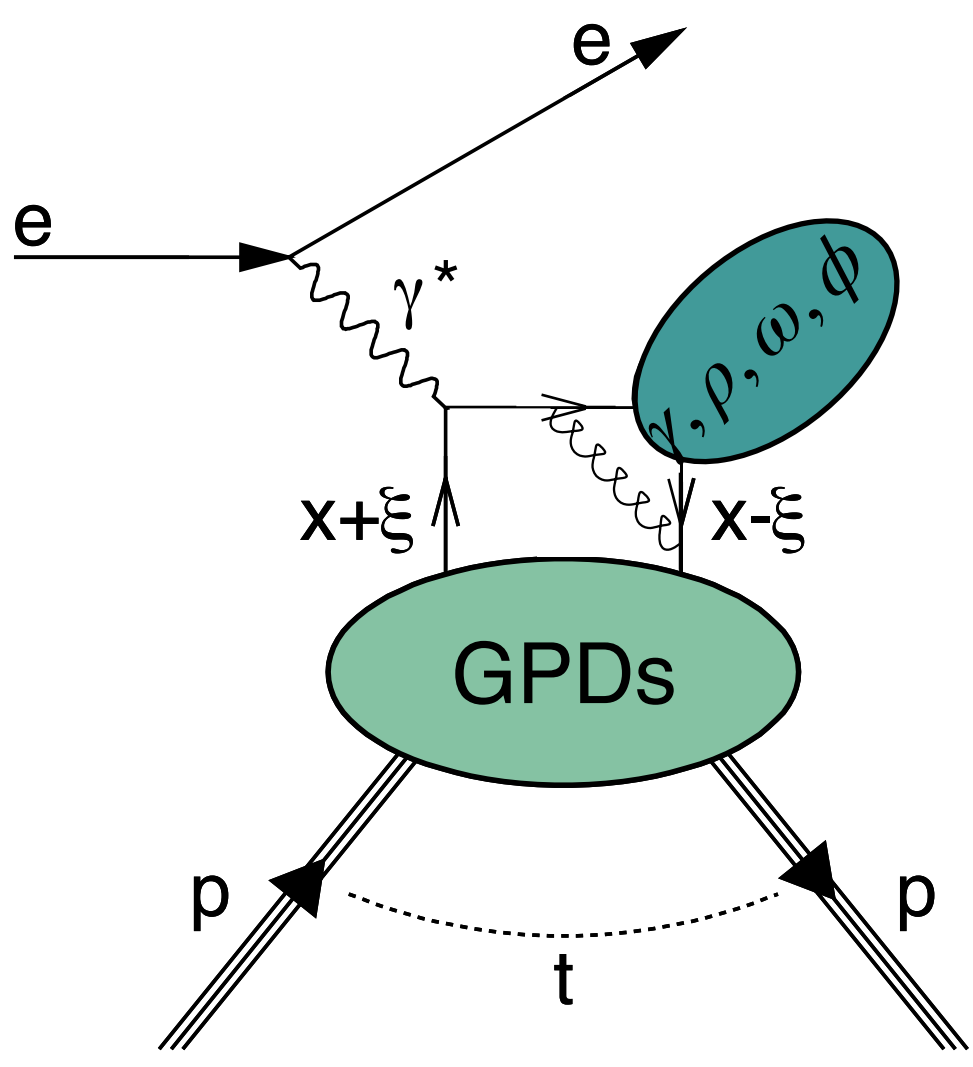
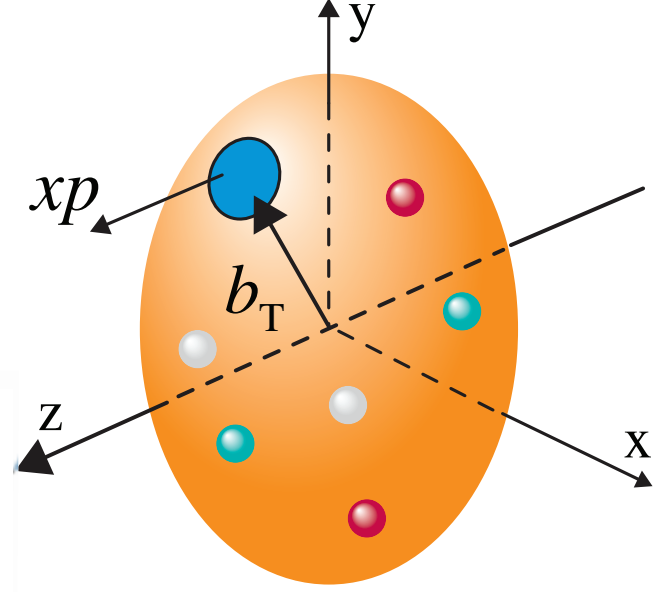


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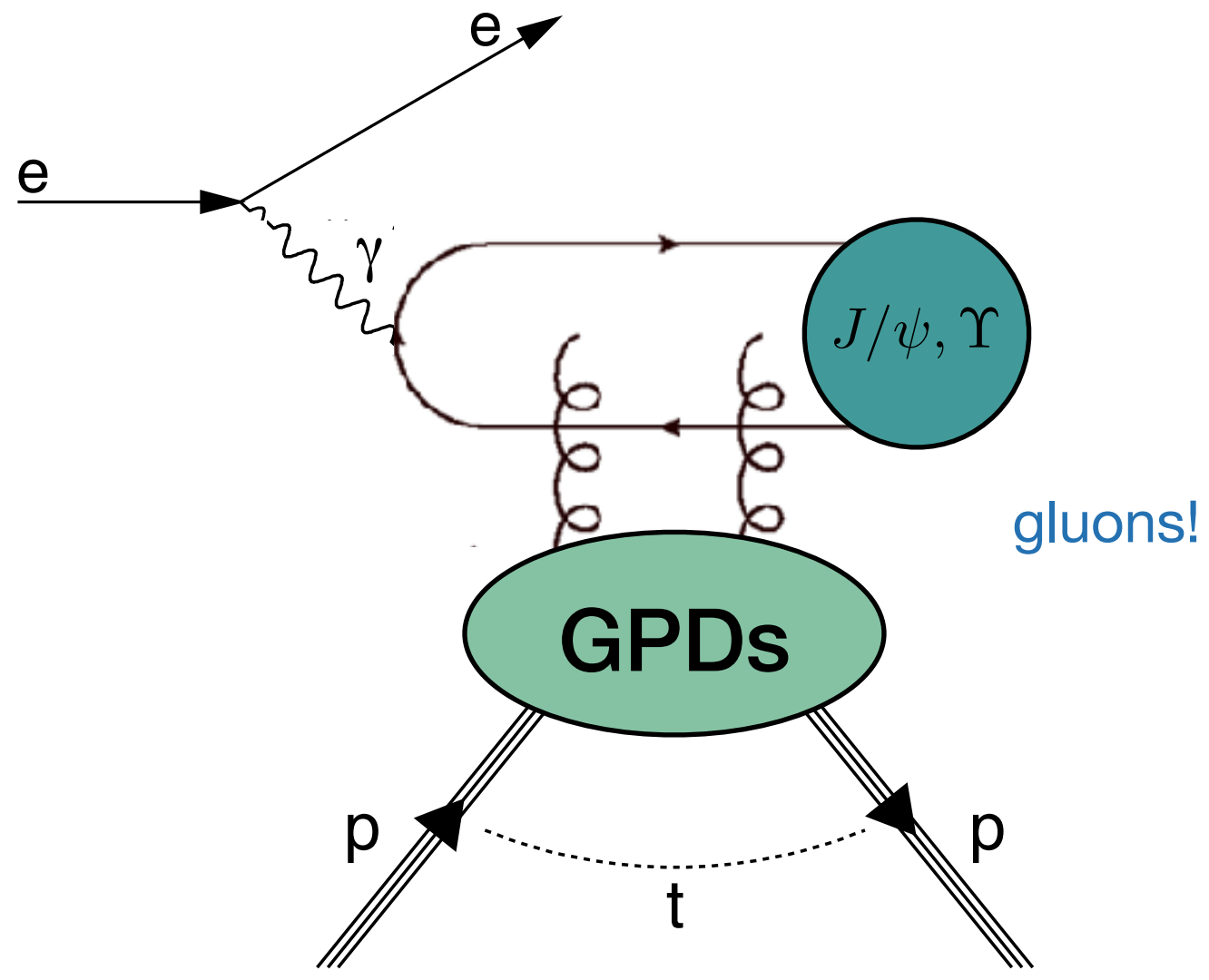


Exclusive meson photoproduction
Hard scale = large charm/bottom-quark mass

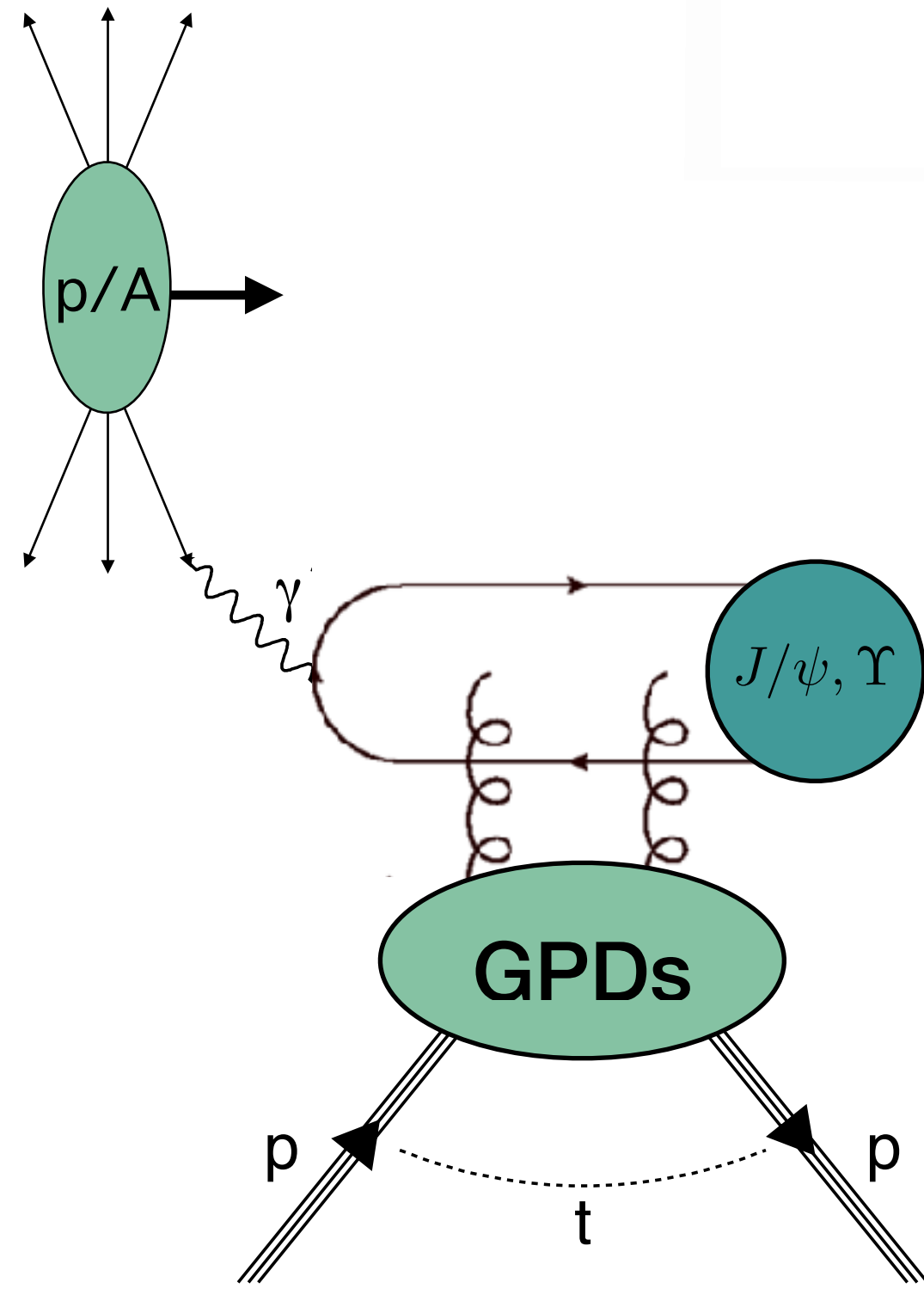
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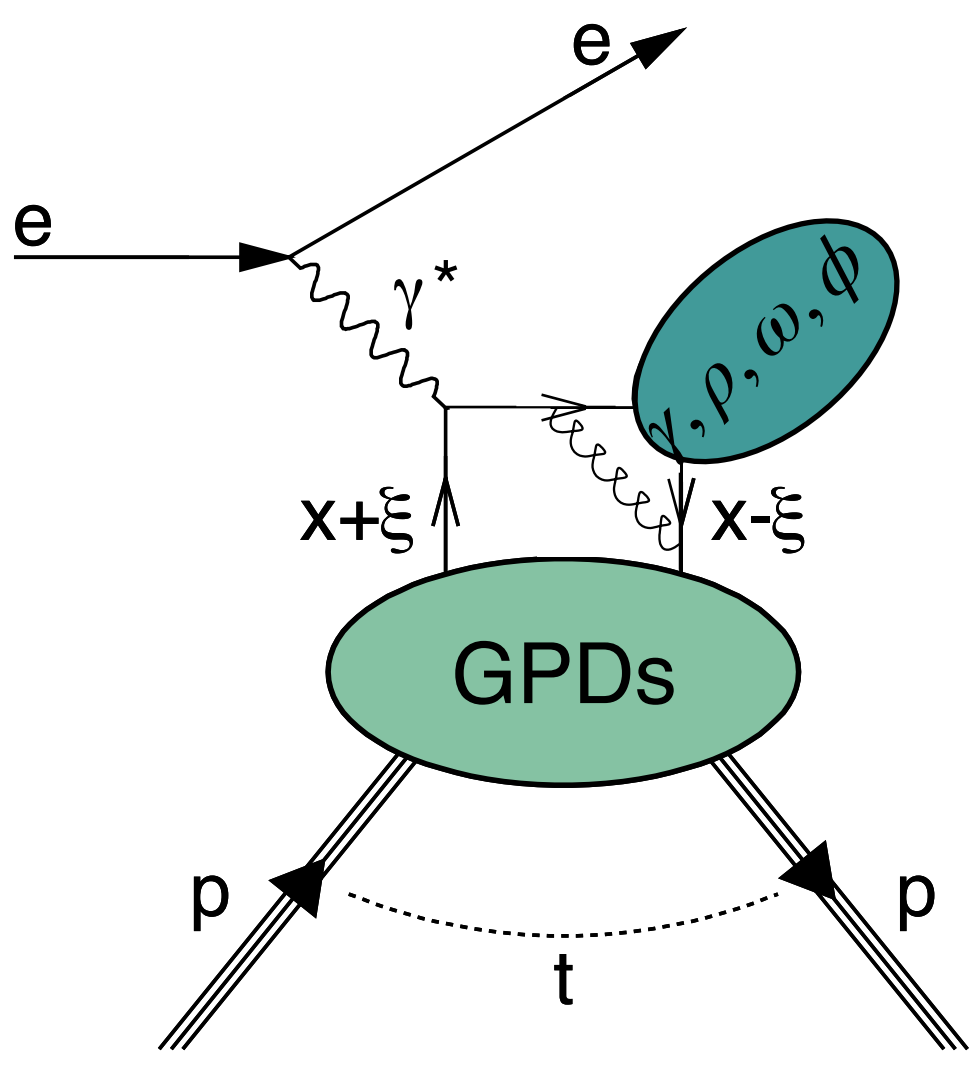
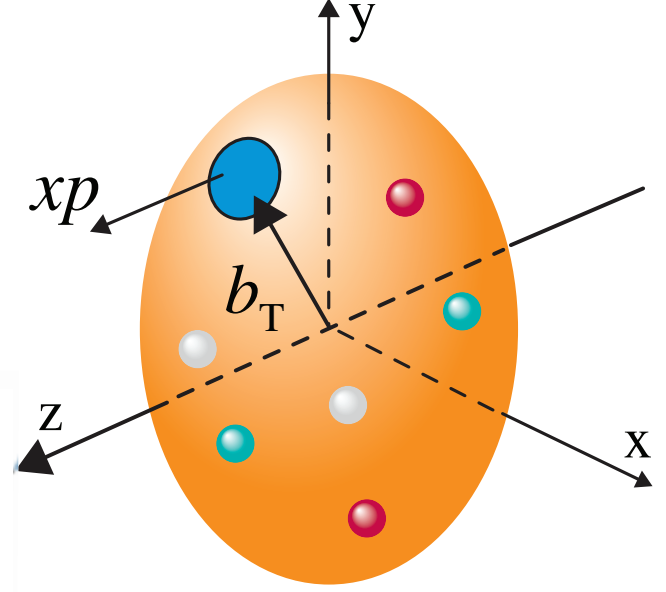


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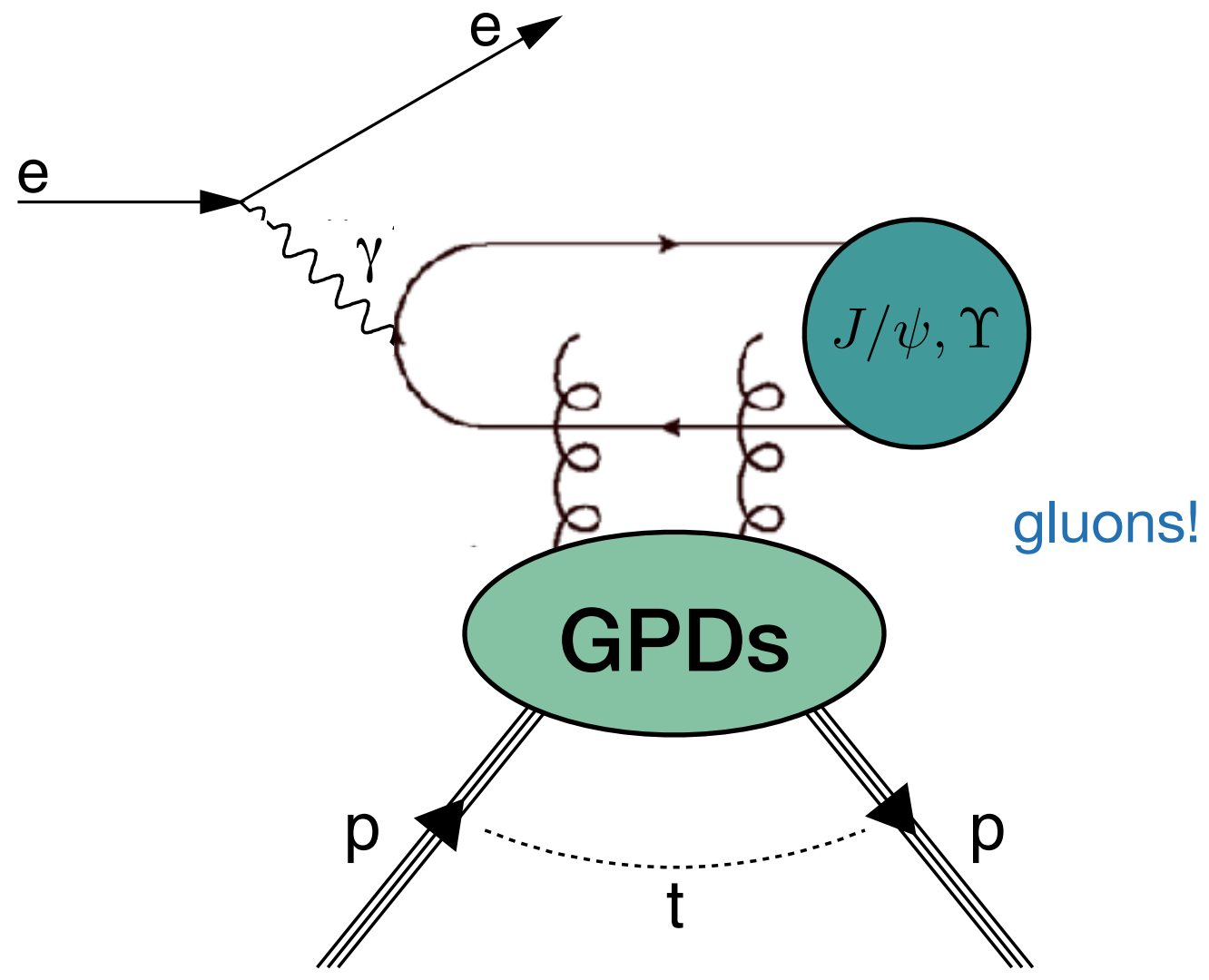


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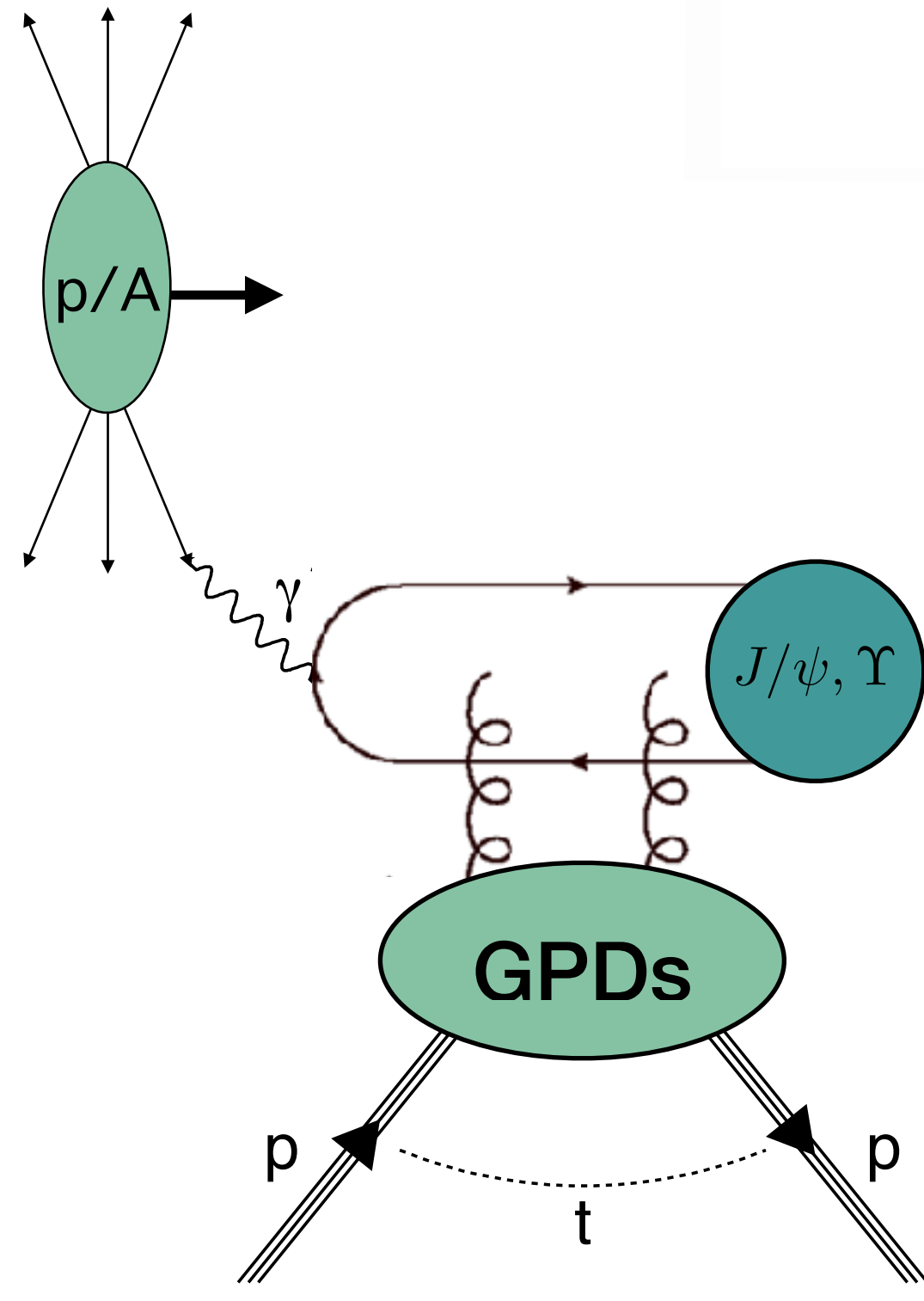
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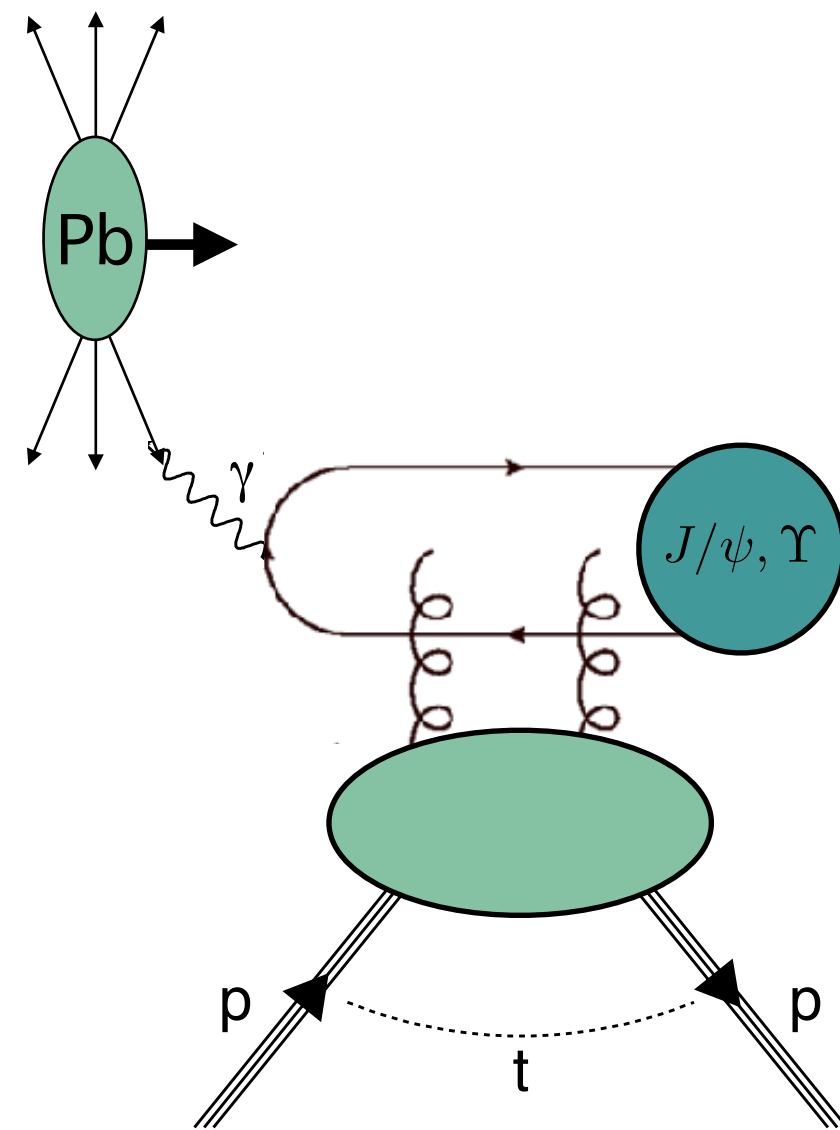
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down to $x_B=10^{-4}$ at HERA/EIC in ep
 $x_B=10^{-3}$ at EIC in eA

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

What are we probing in UPCs?

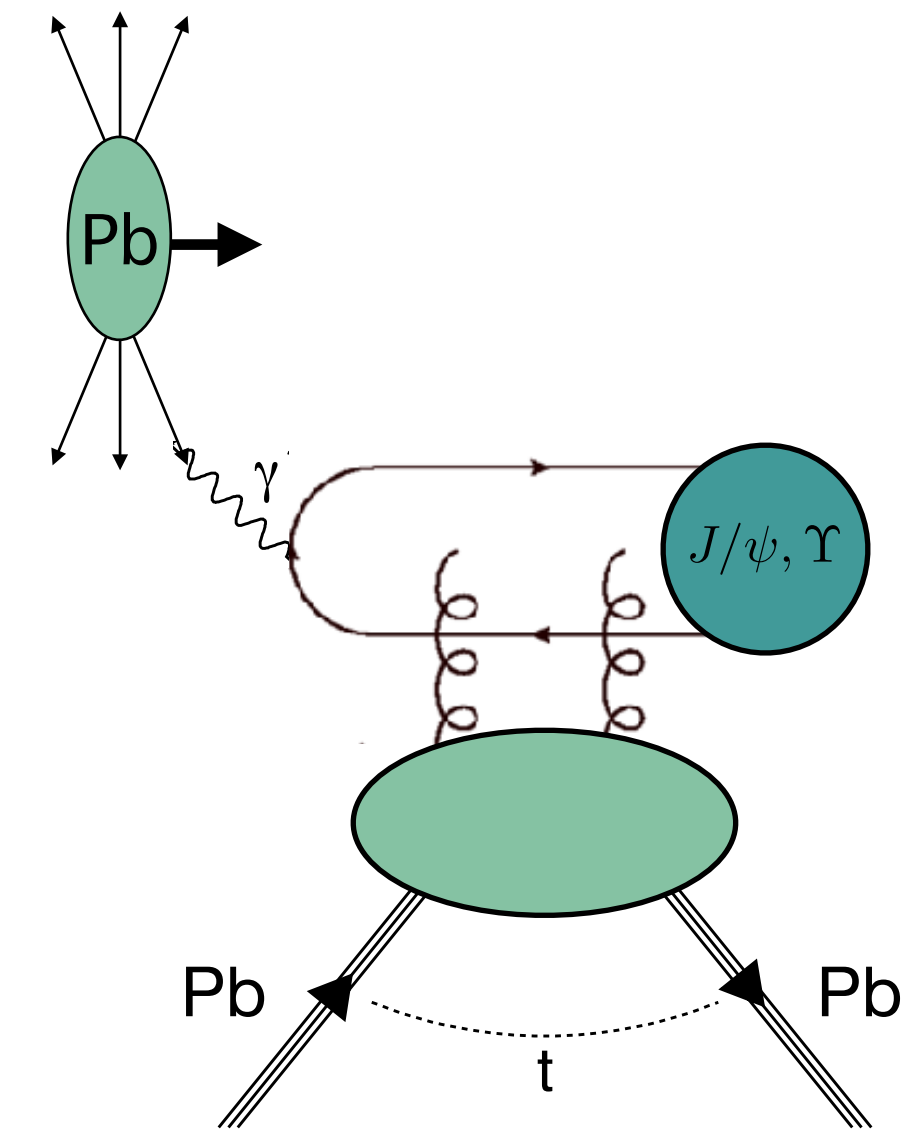
proton-proton and proton-lead collisions



probing proton

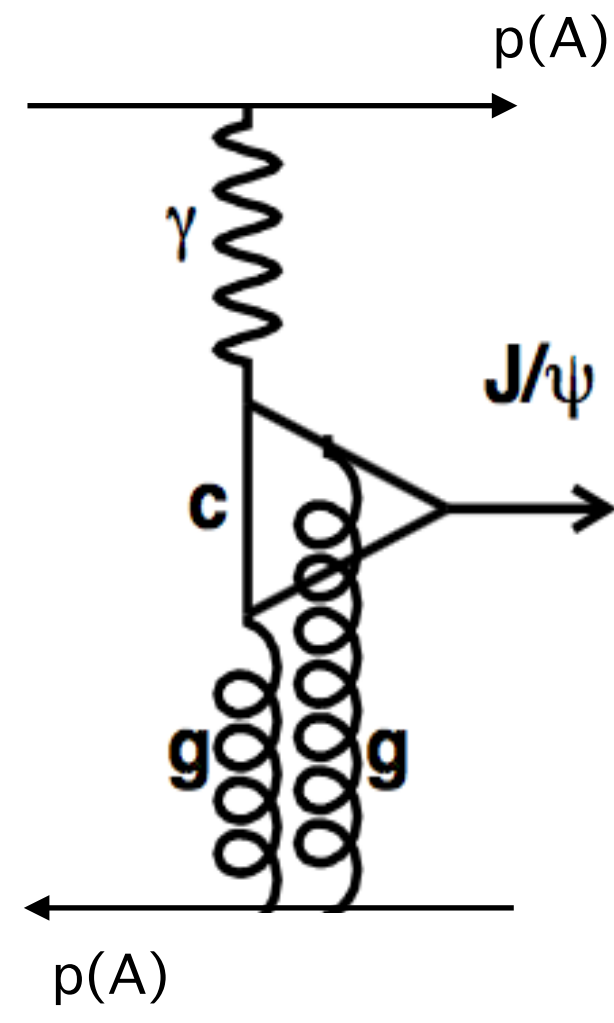
proton-lead: Z^2 dependence of photon flux
→ predominantly probing proton

lead-lead collisions

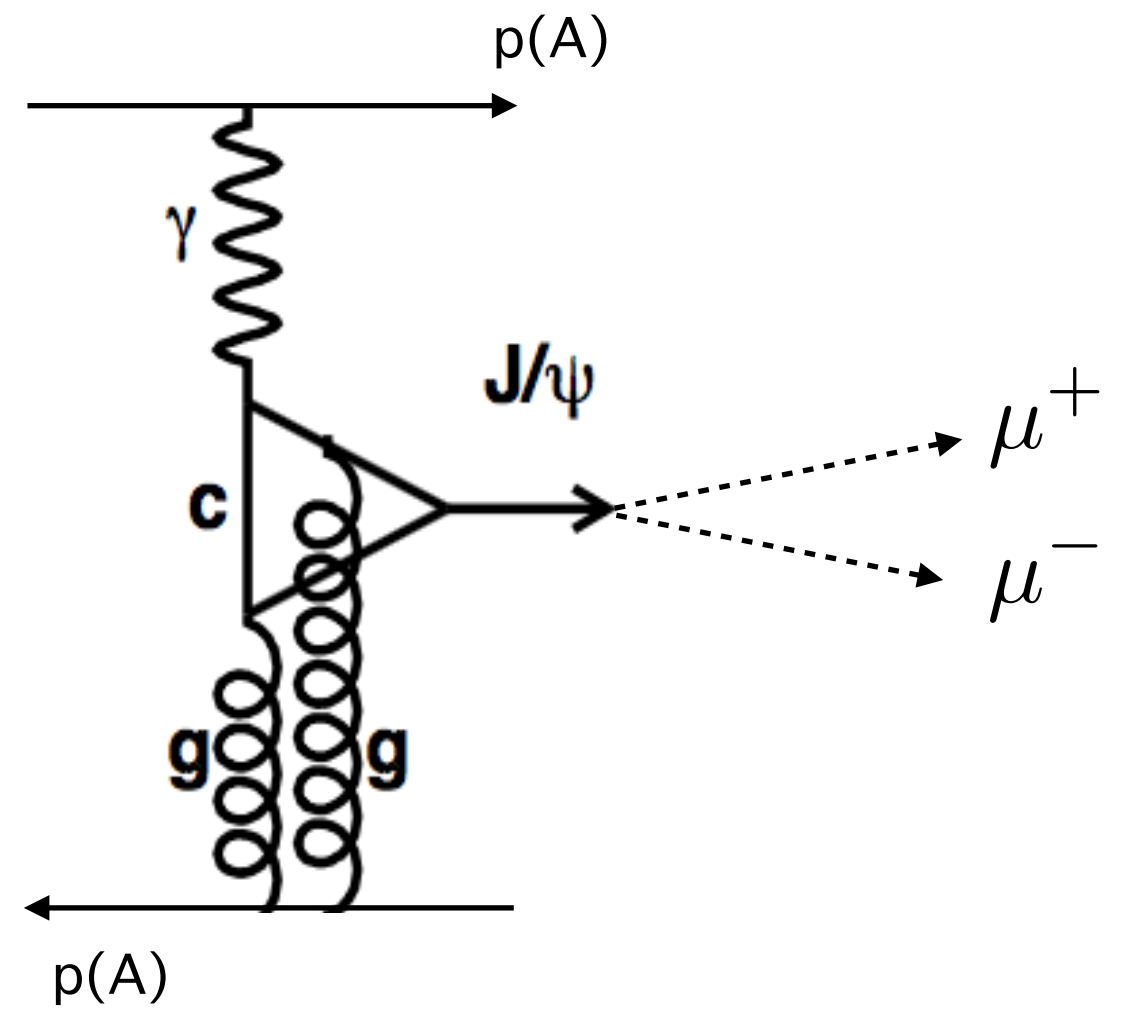


probing ion

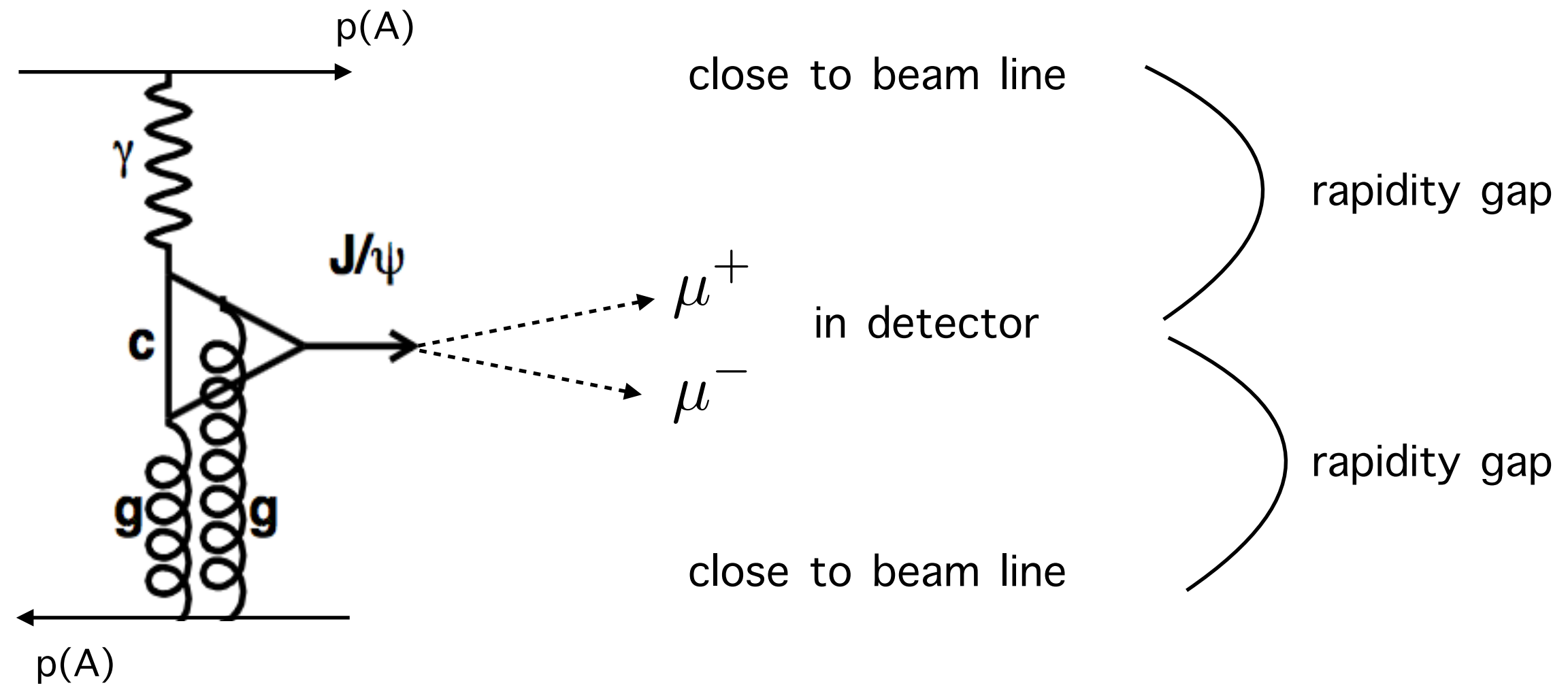
Measurement of exclusive production on proton at LHC: example LHCb



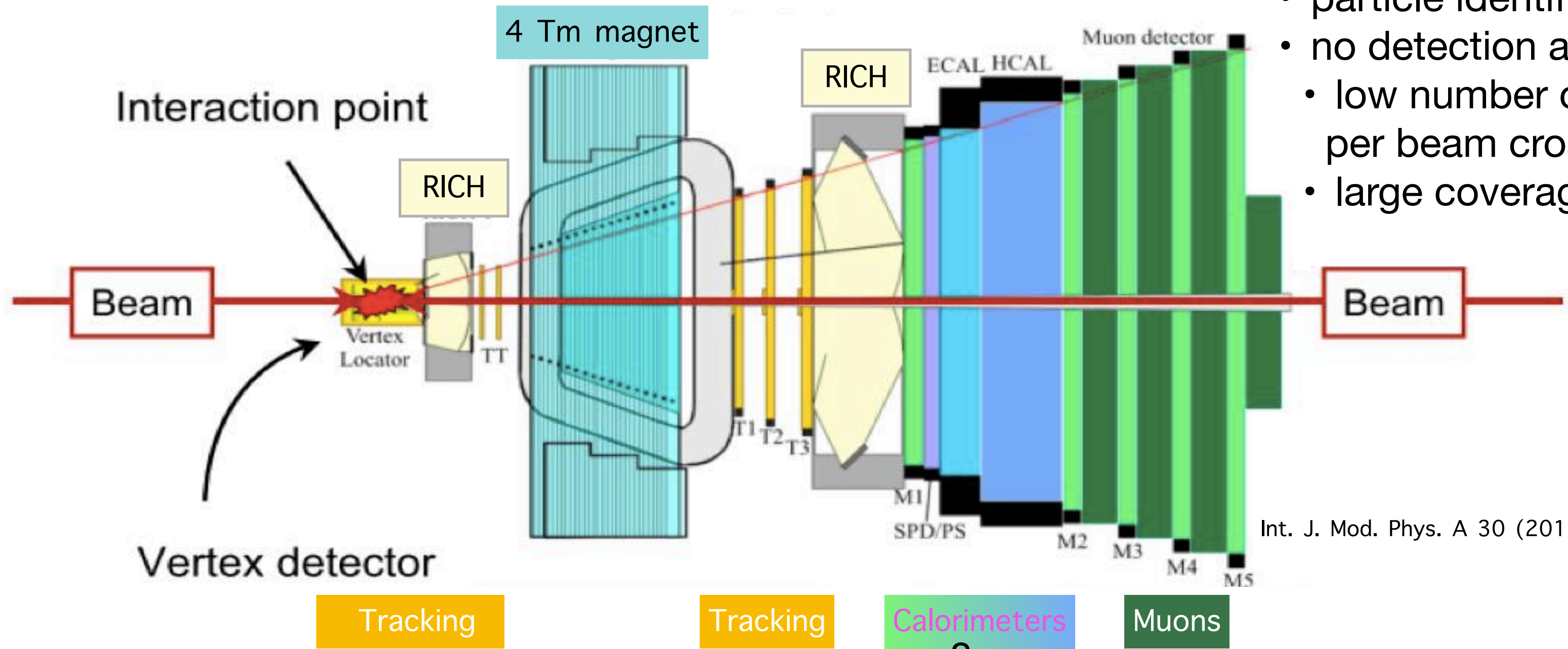
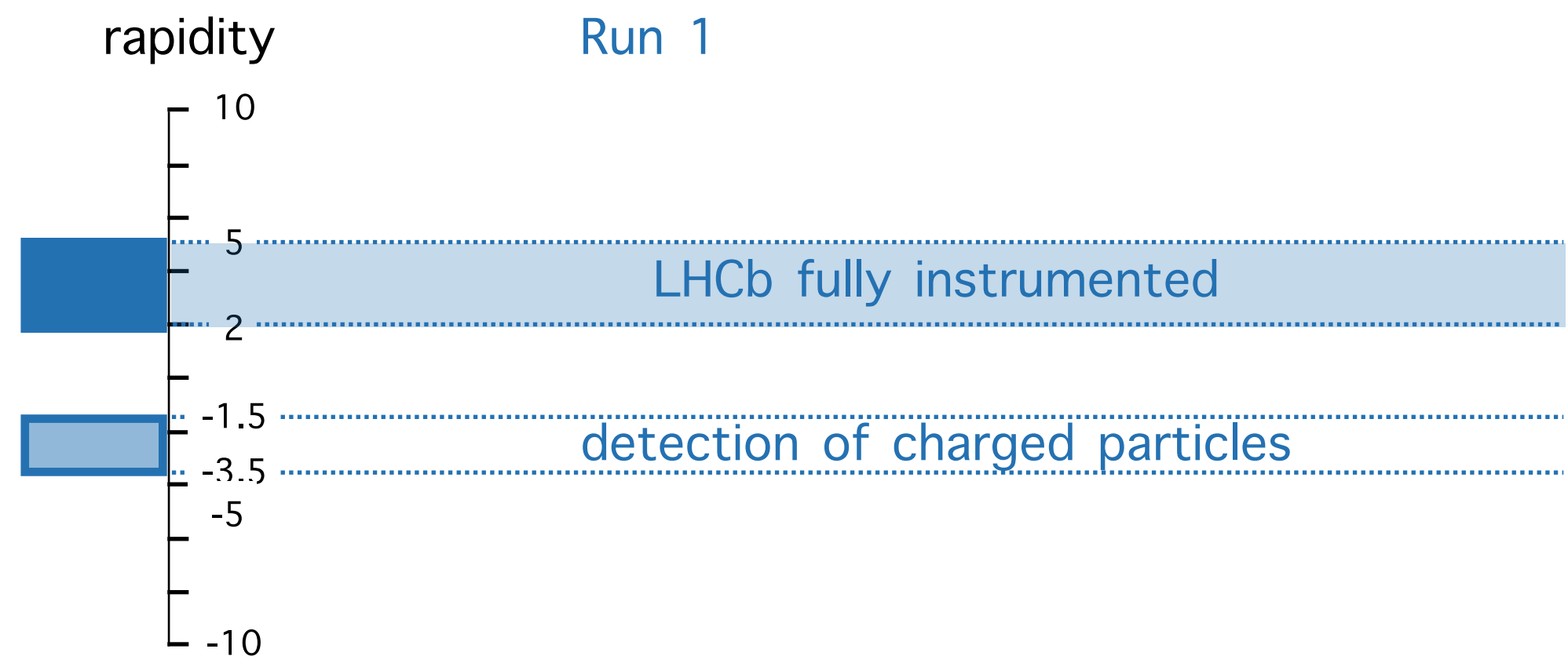
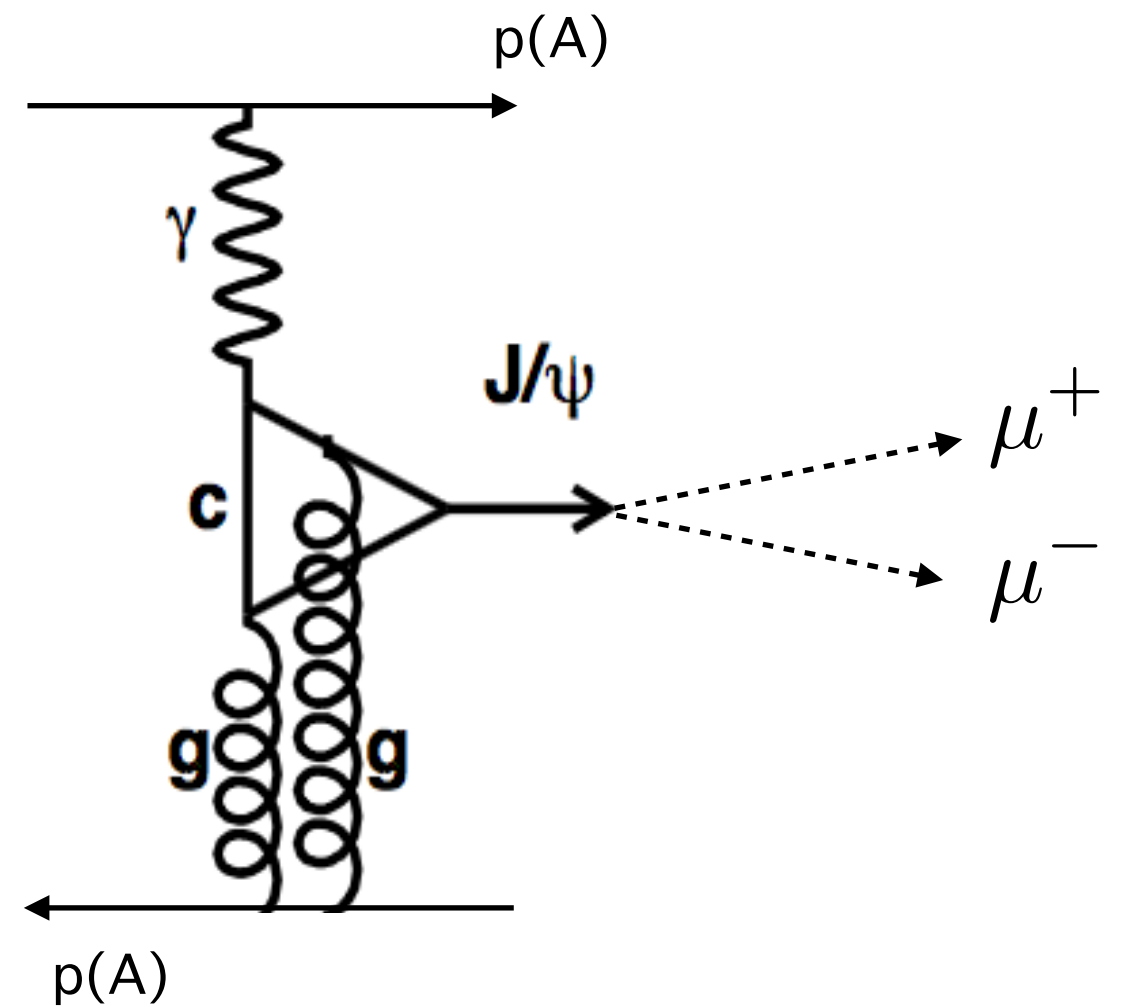
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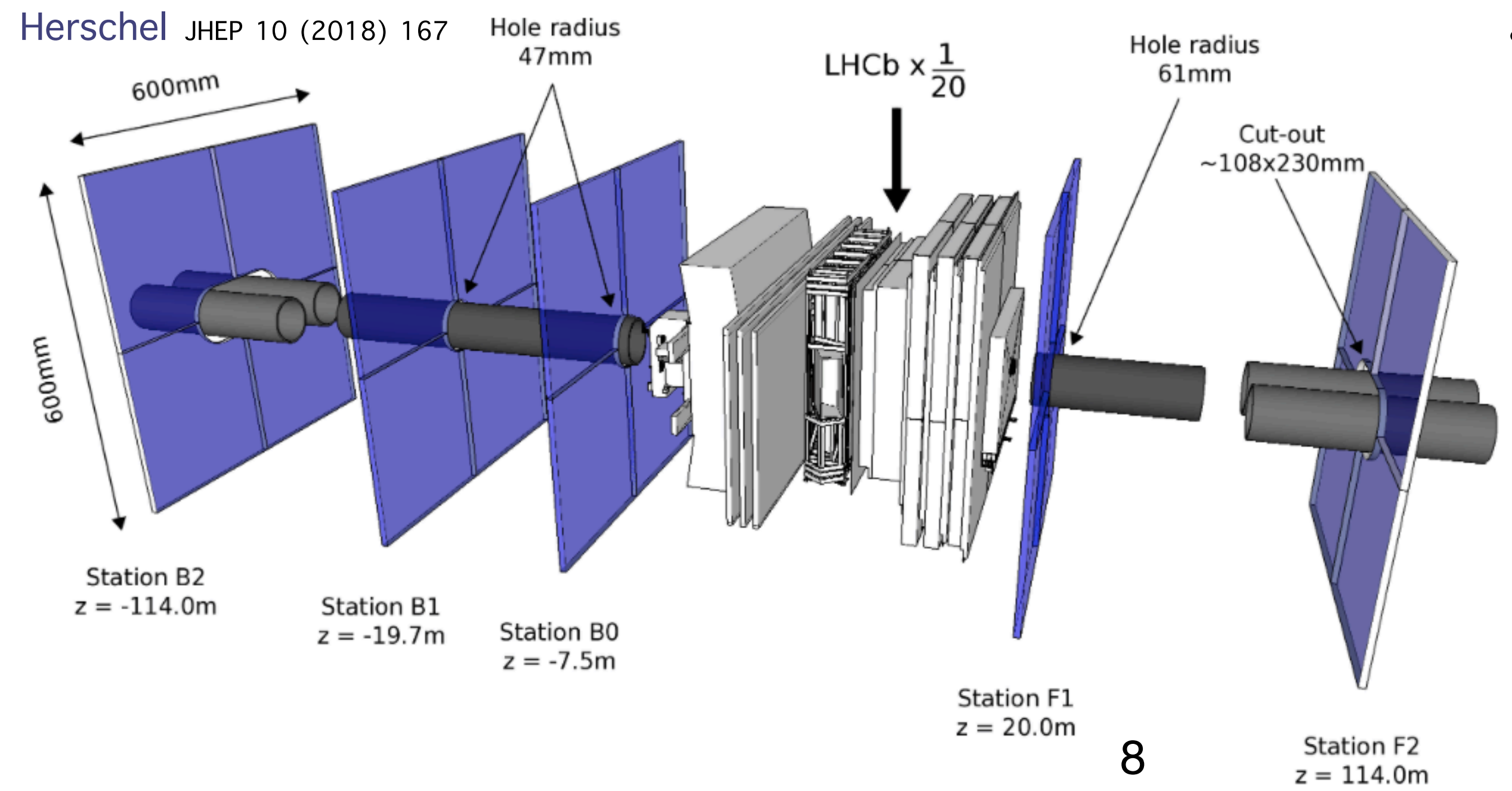
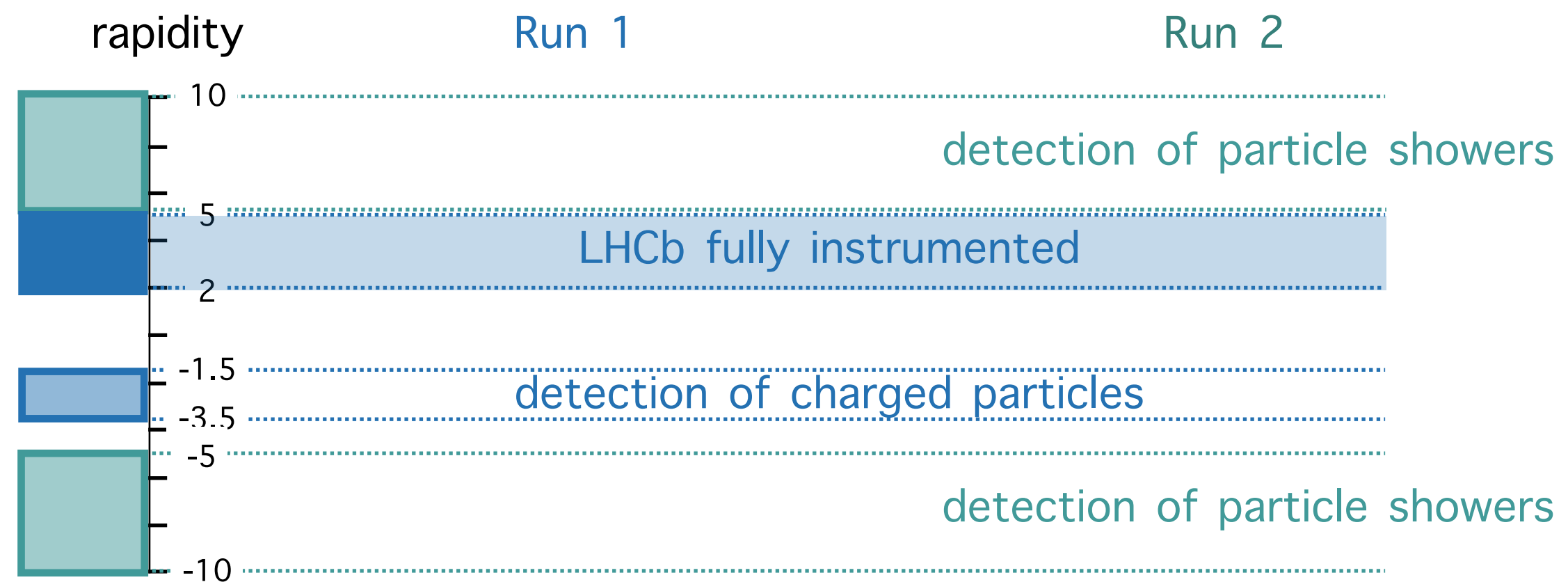
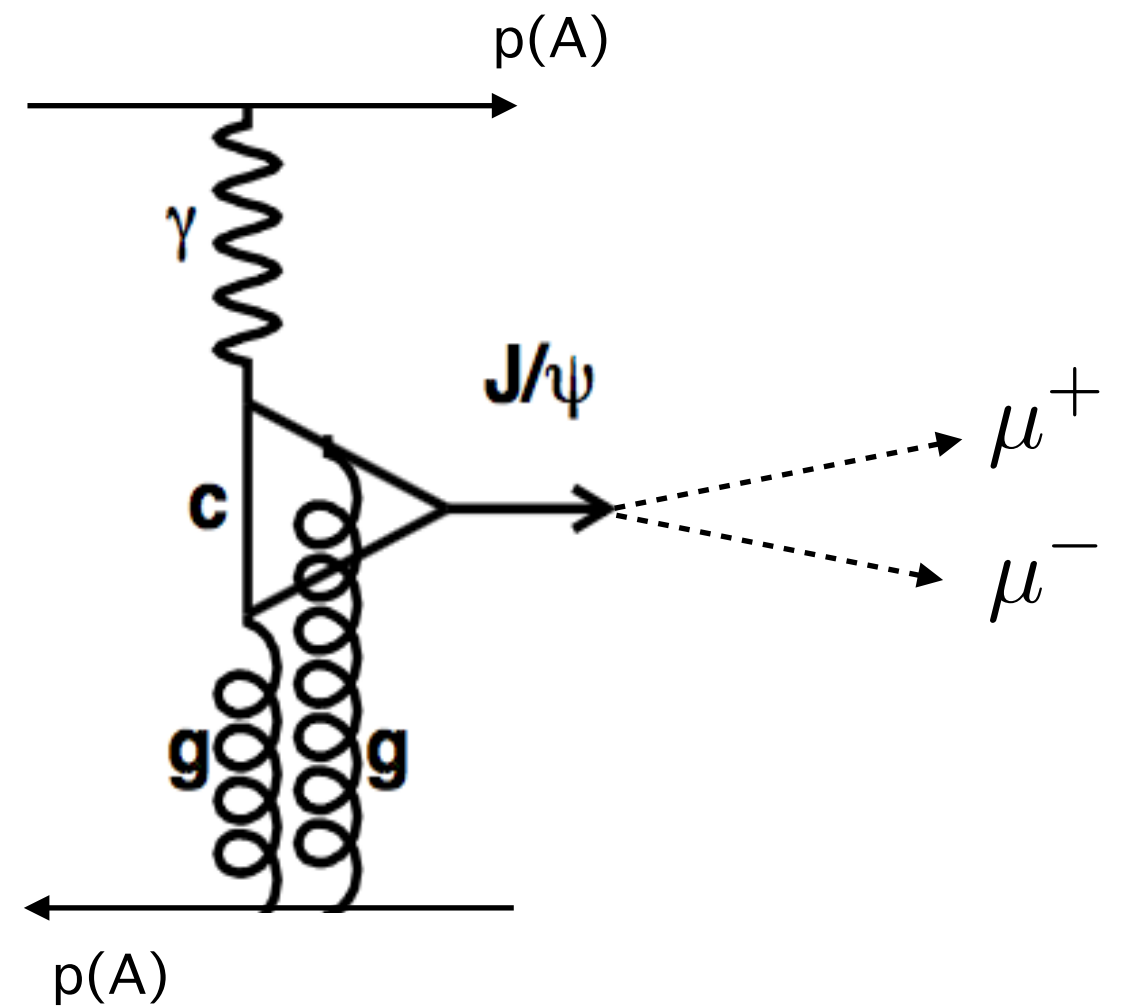
Measurement of exclusive production on proton at LHC: example LHCb



- 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

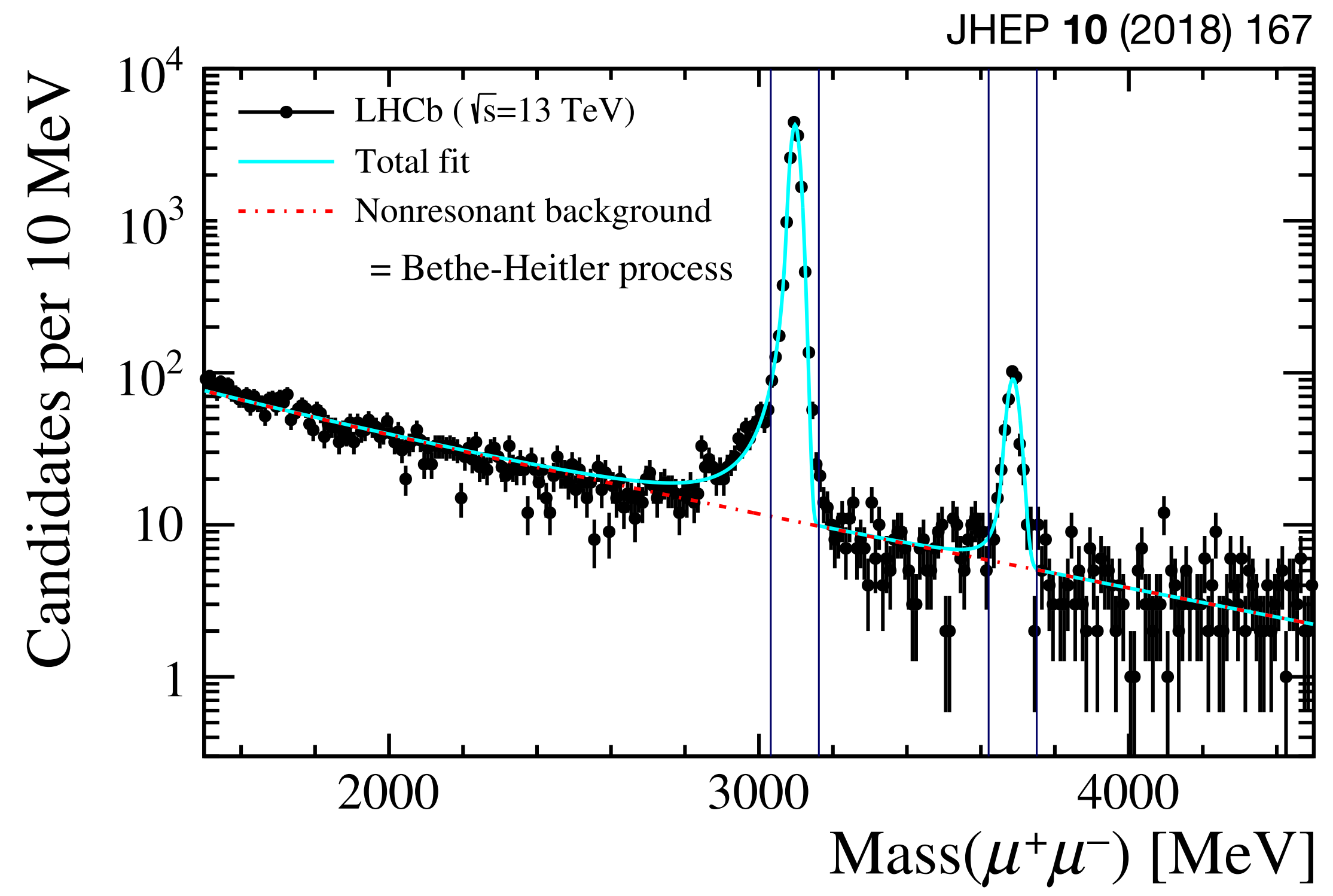
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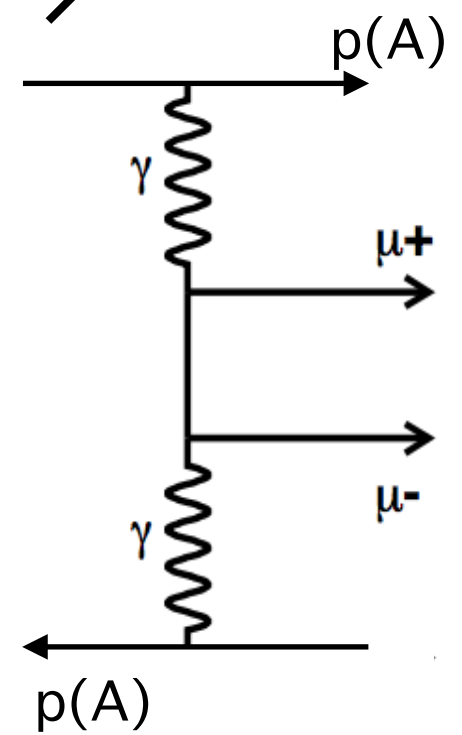
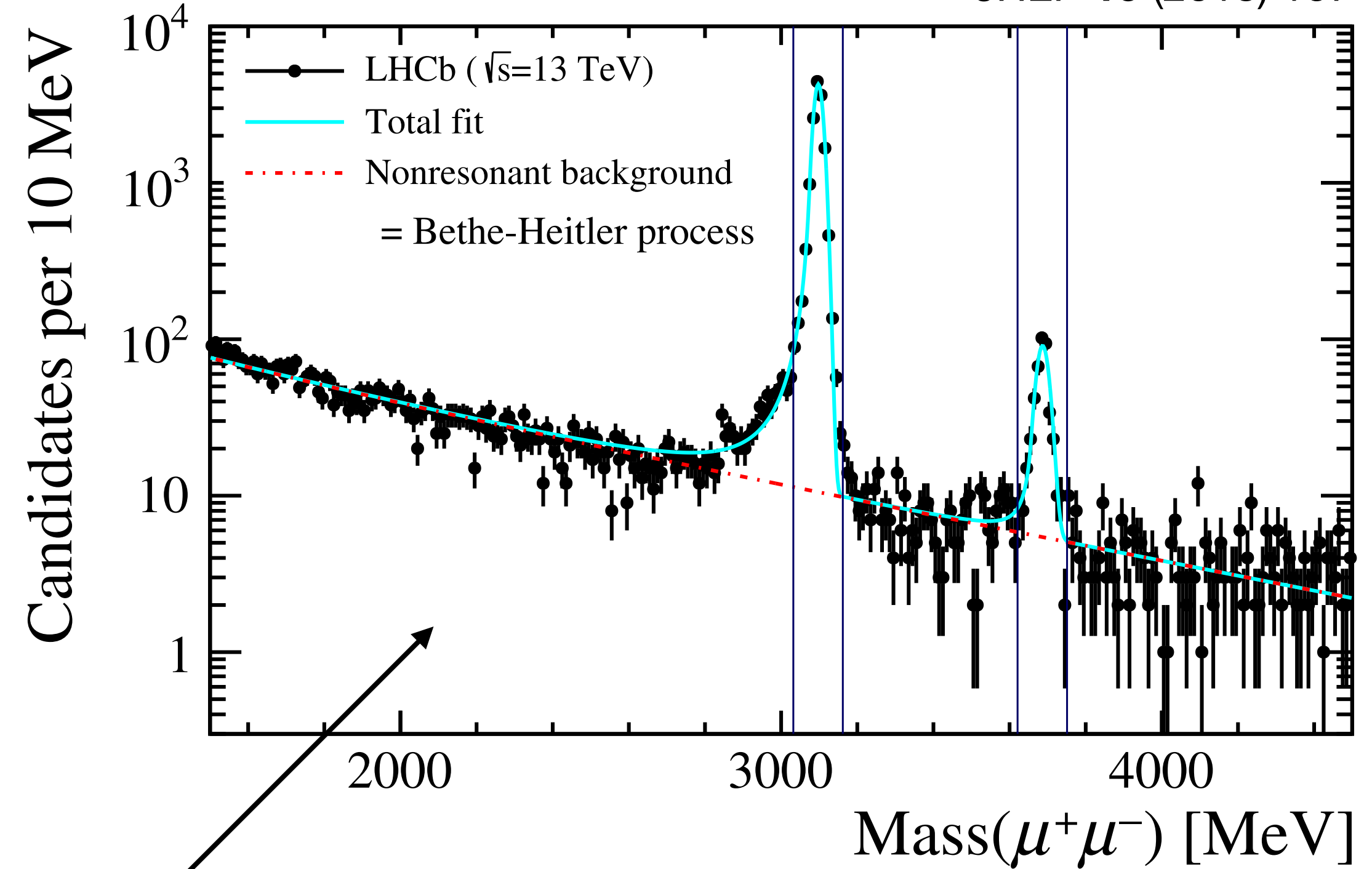
proton-proton collisions



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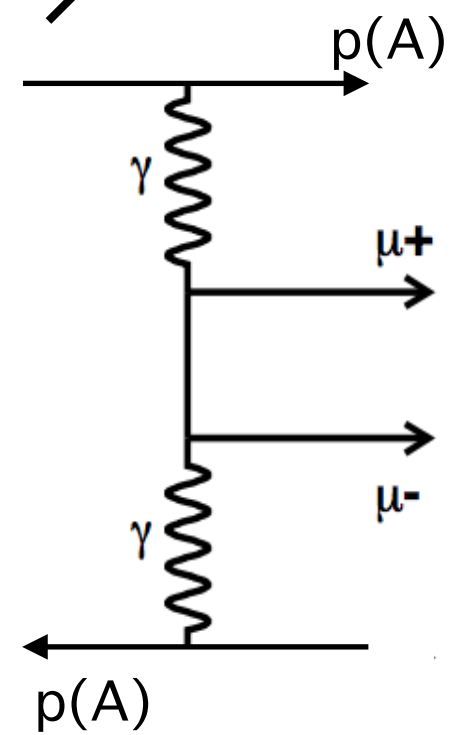
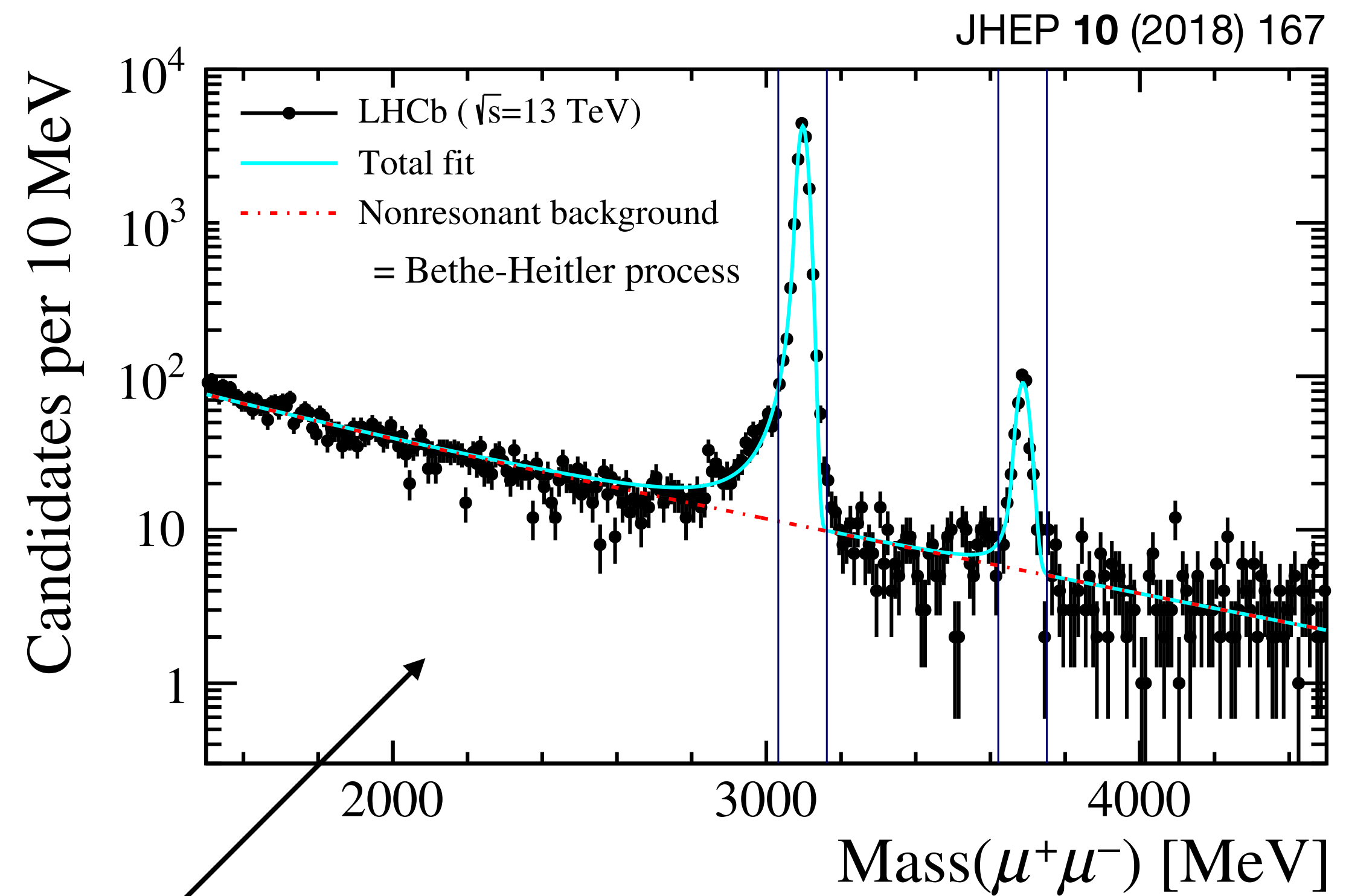
JHEP 10 (2018) 167



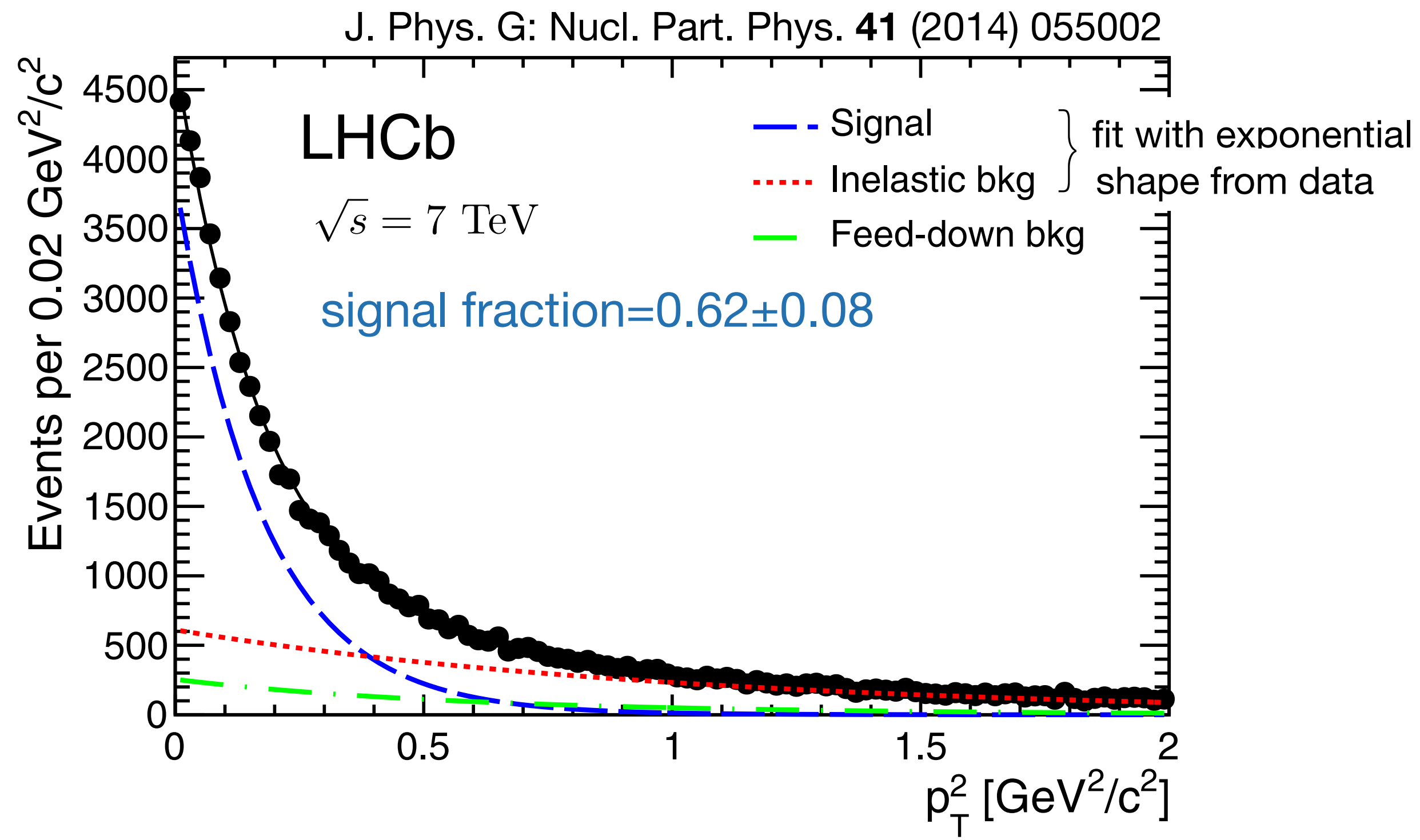
Bethe-Heitler process

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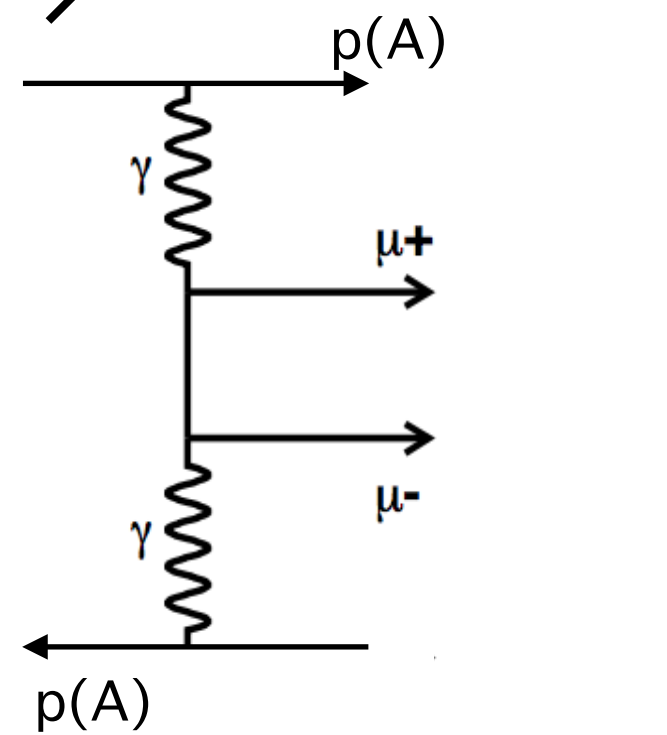
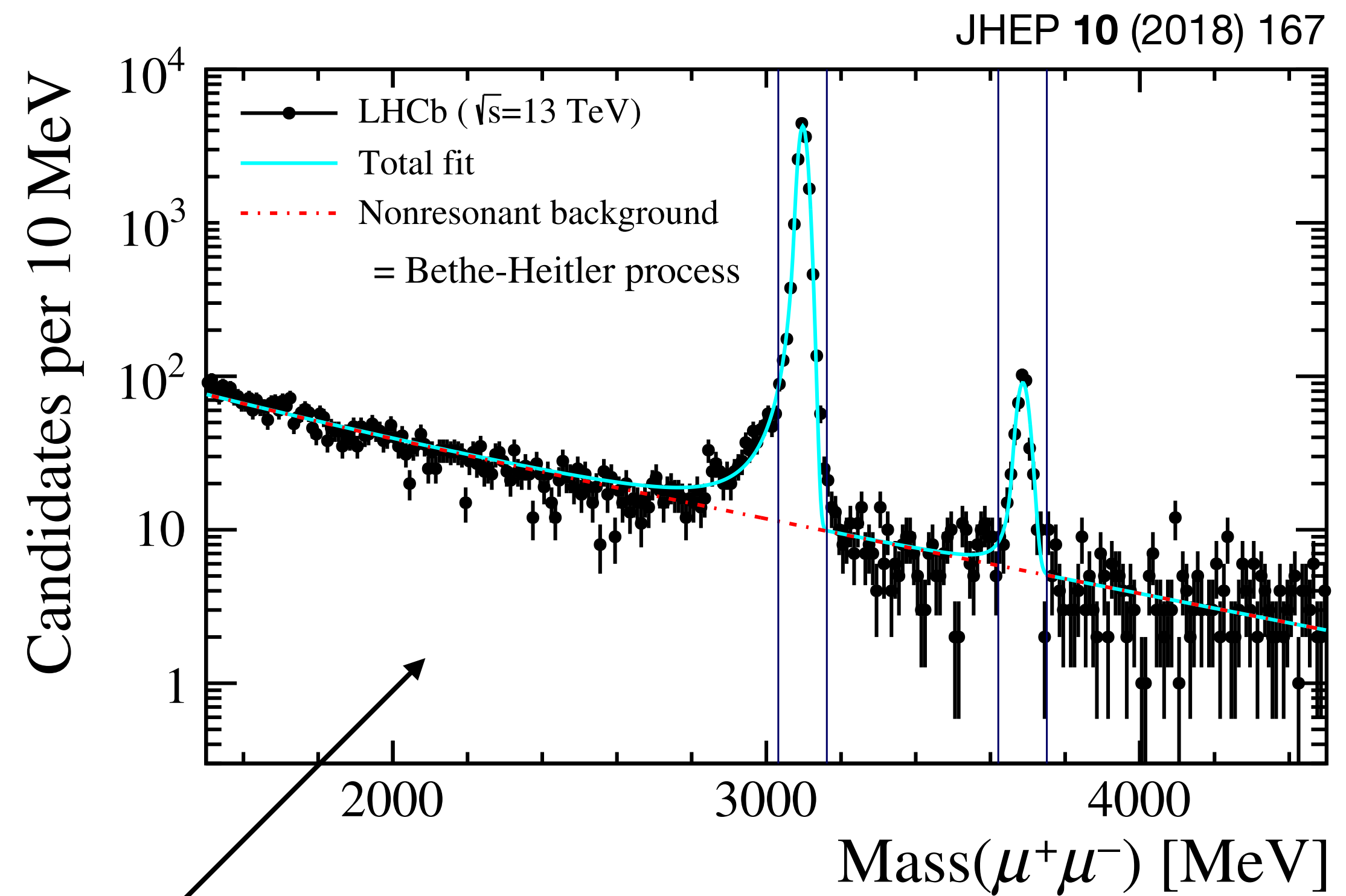


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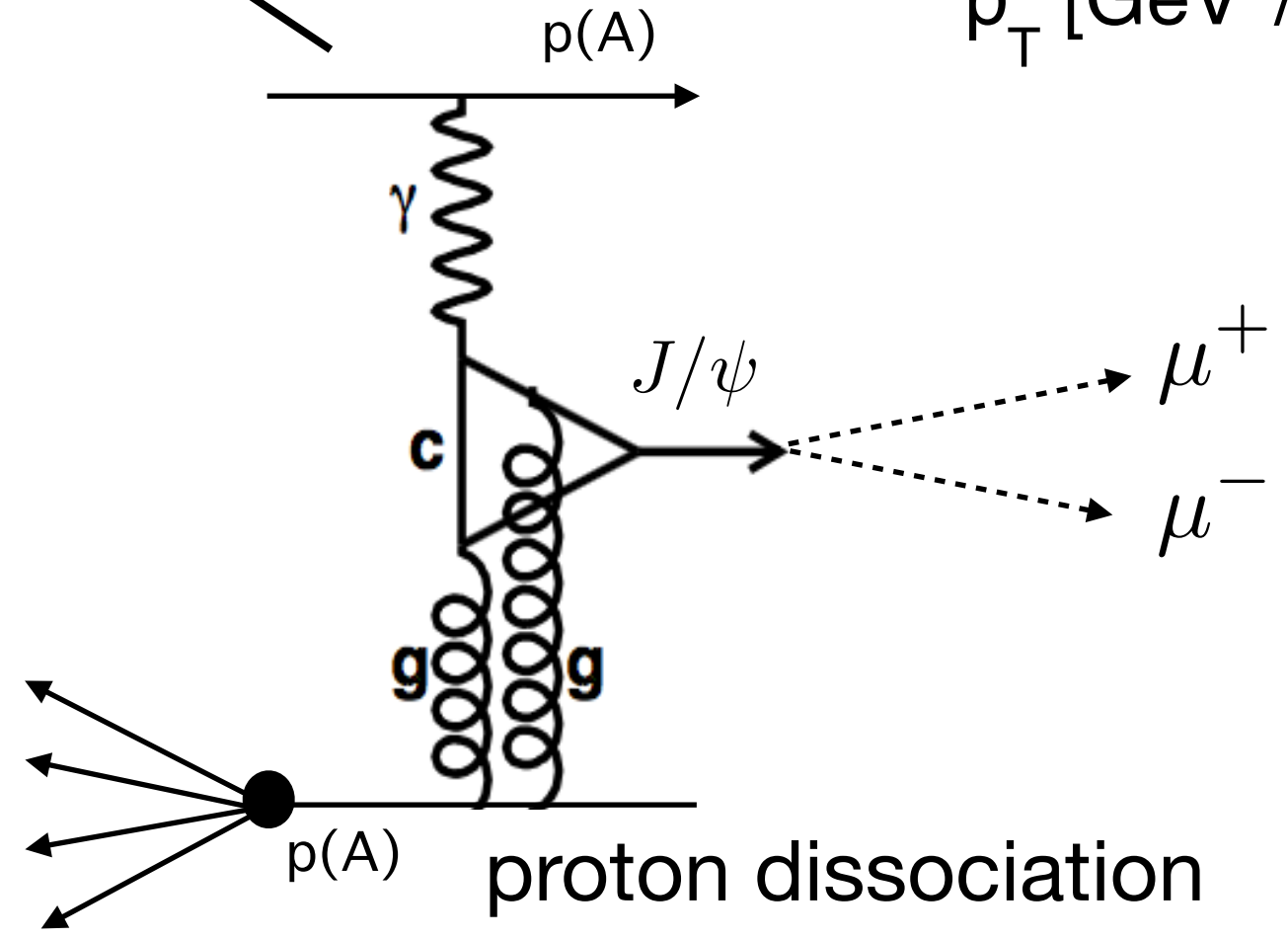
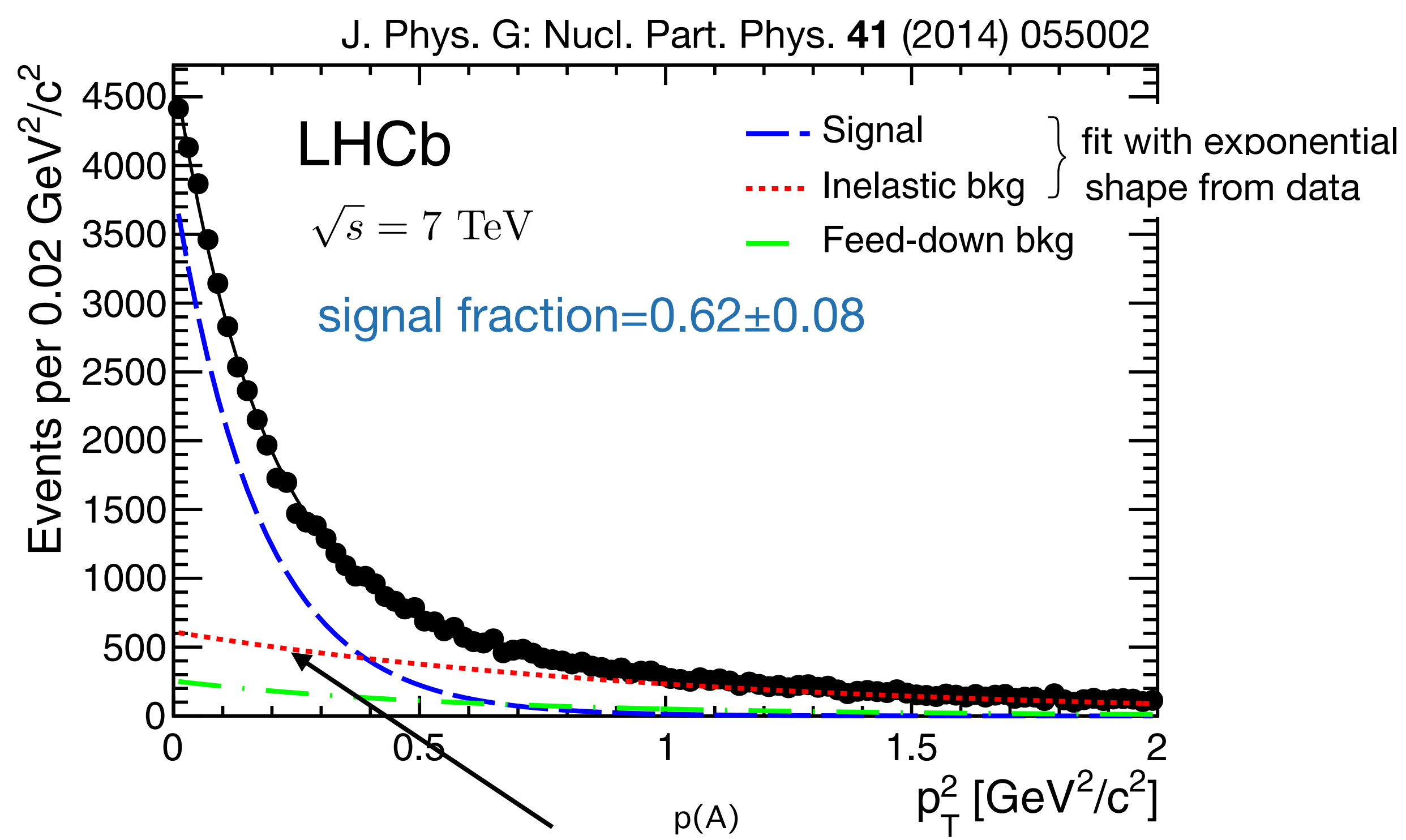


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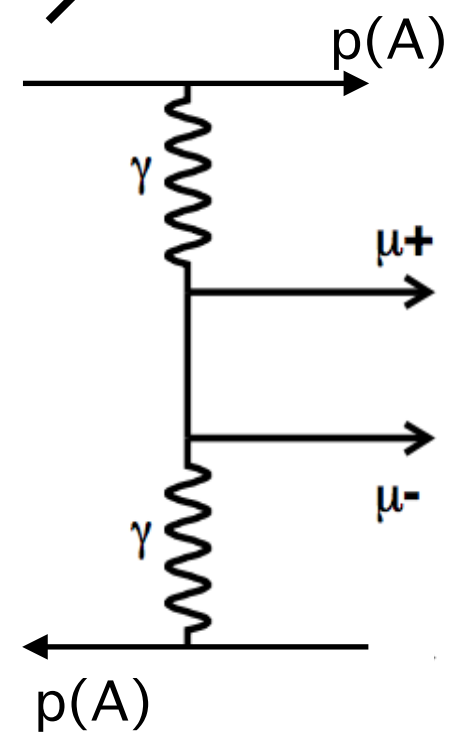
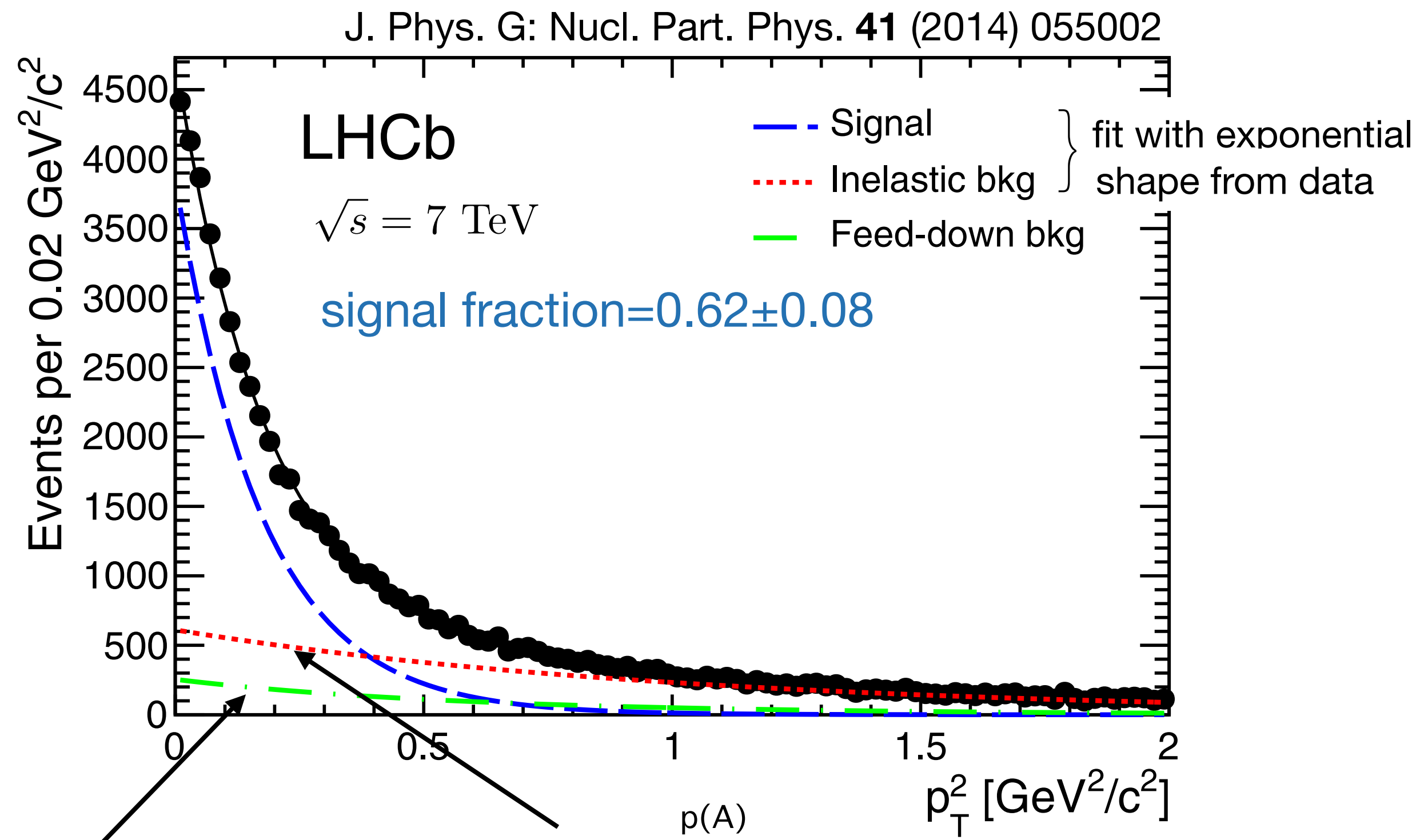
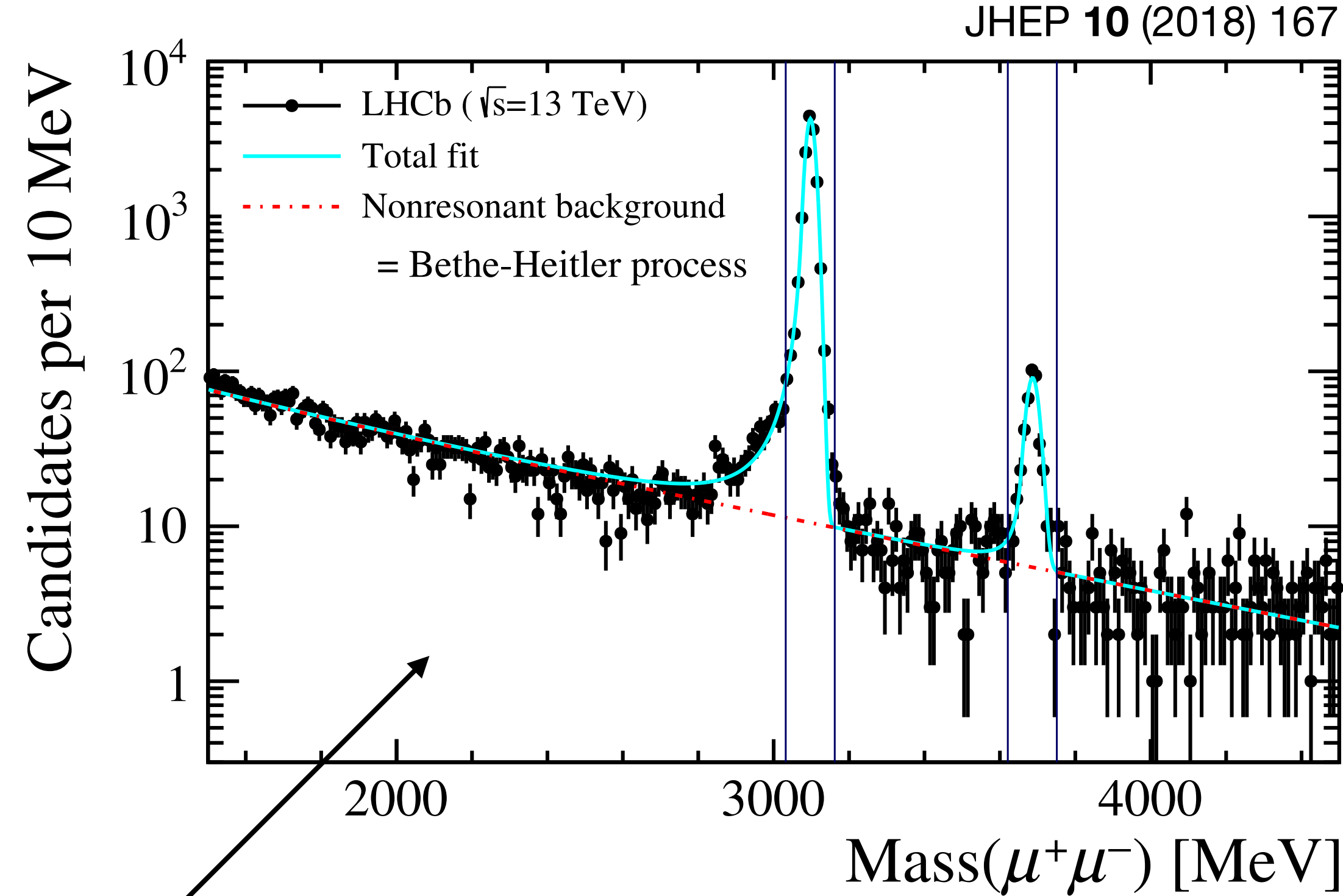


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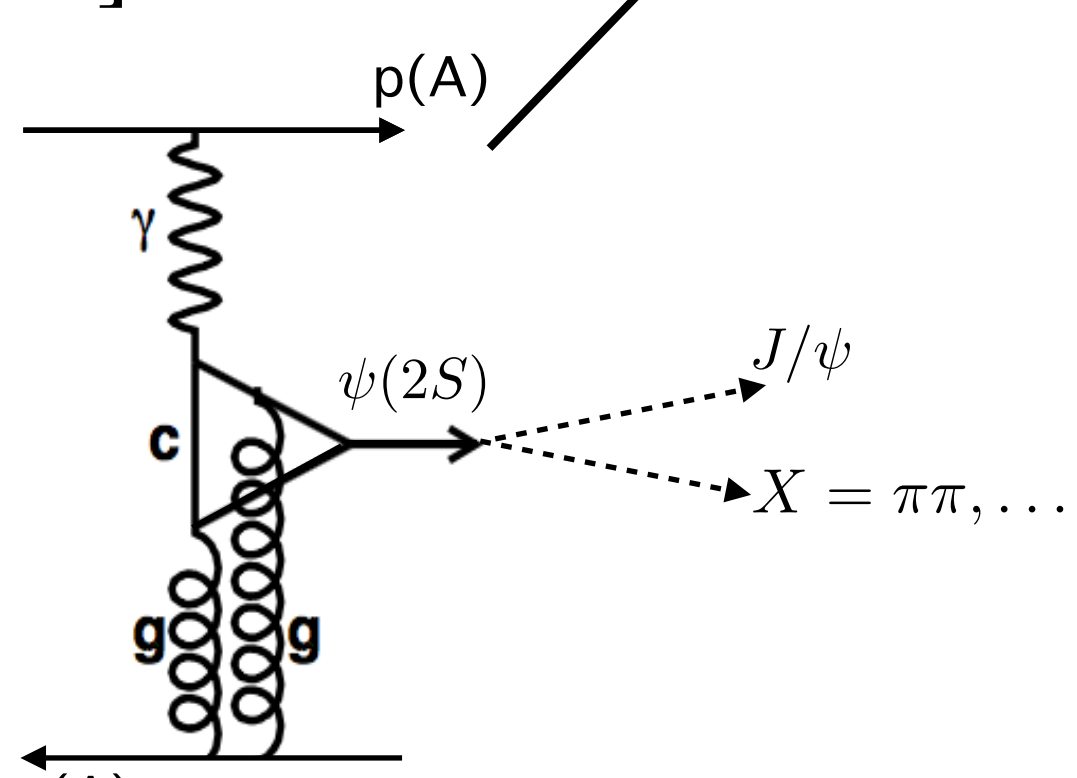


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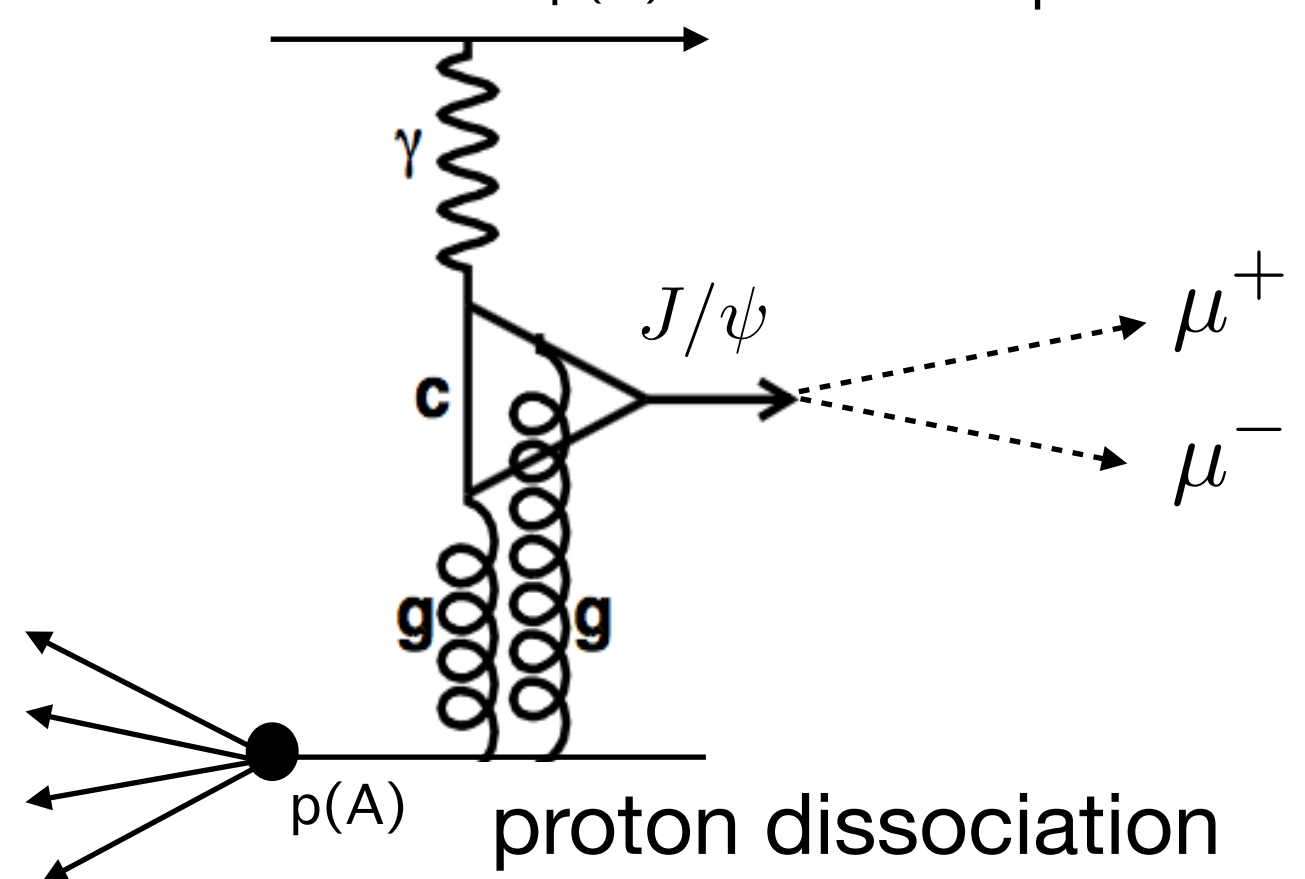
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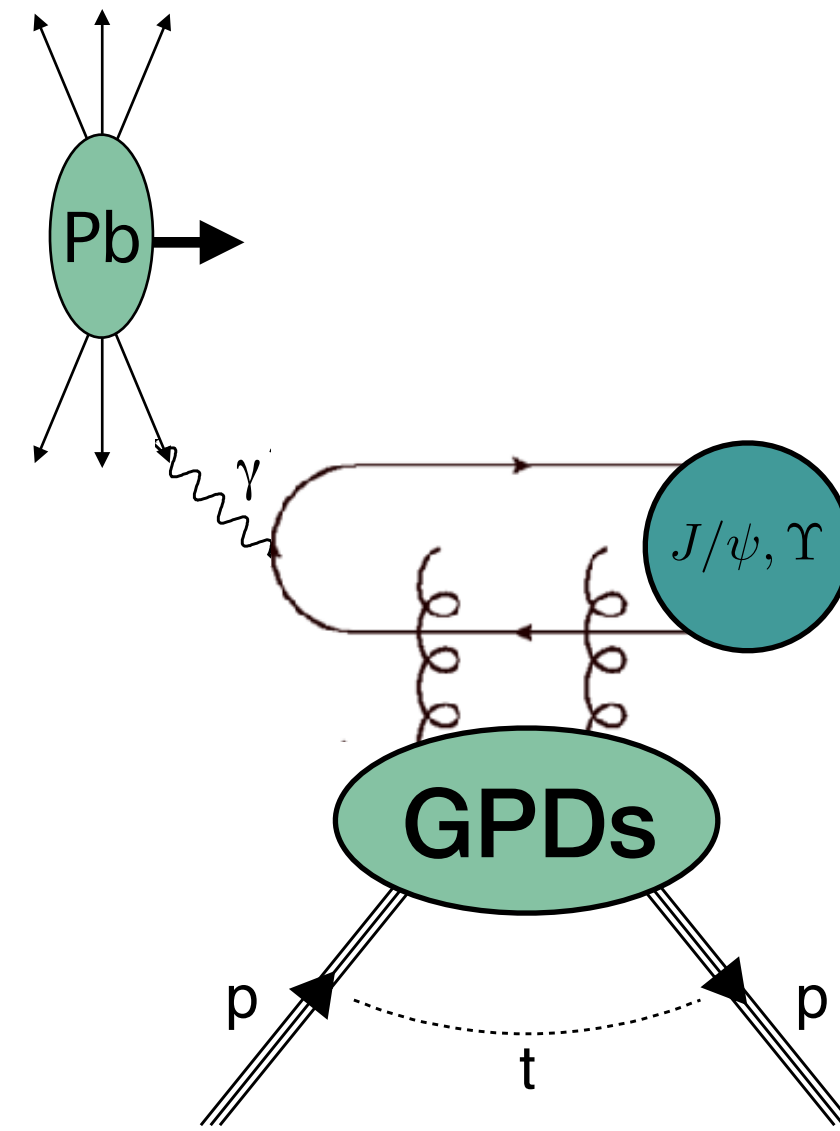


feed down



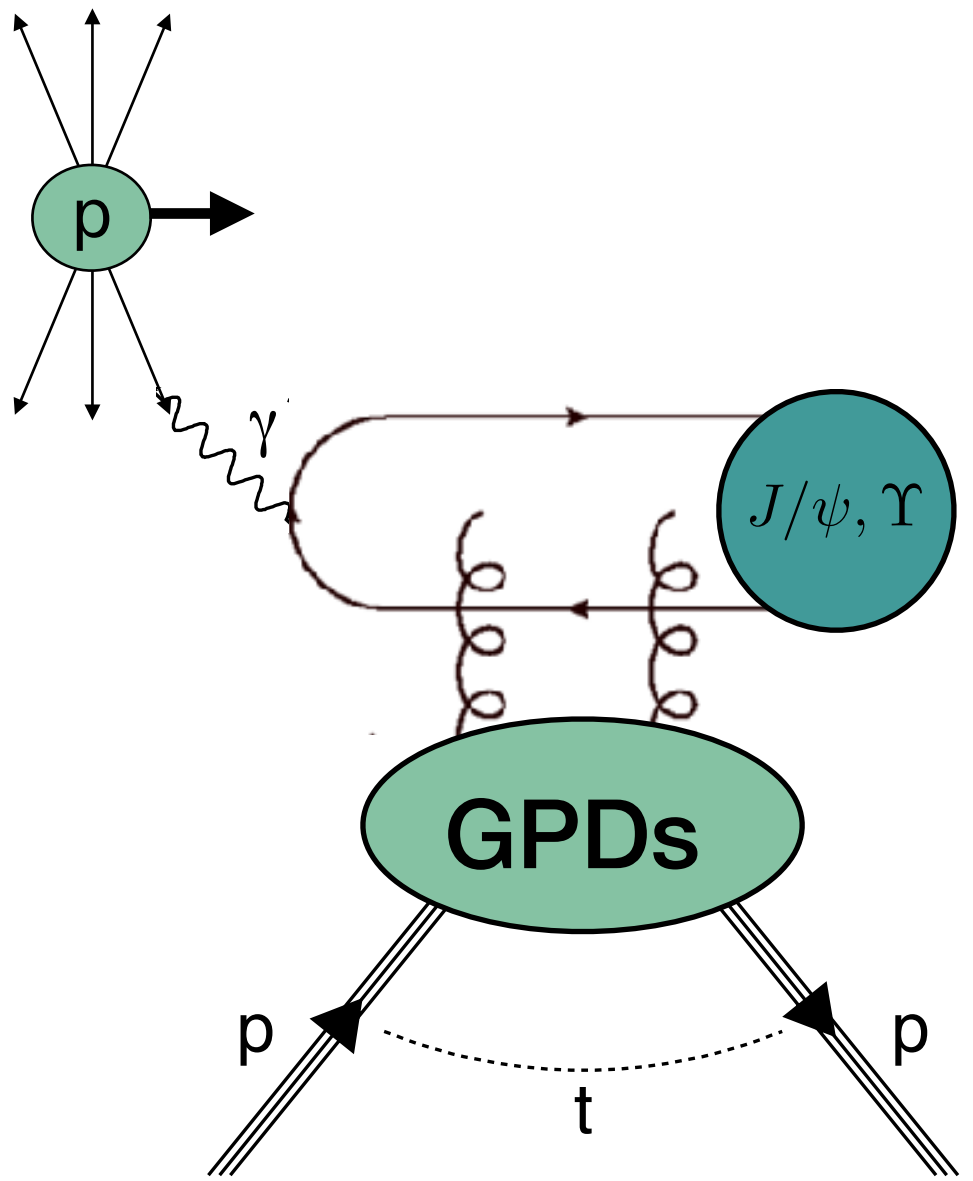
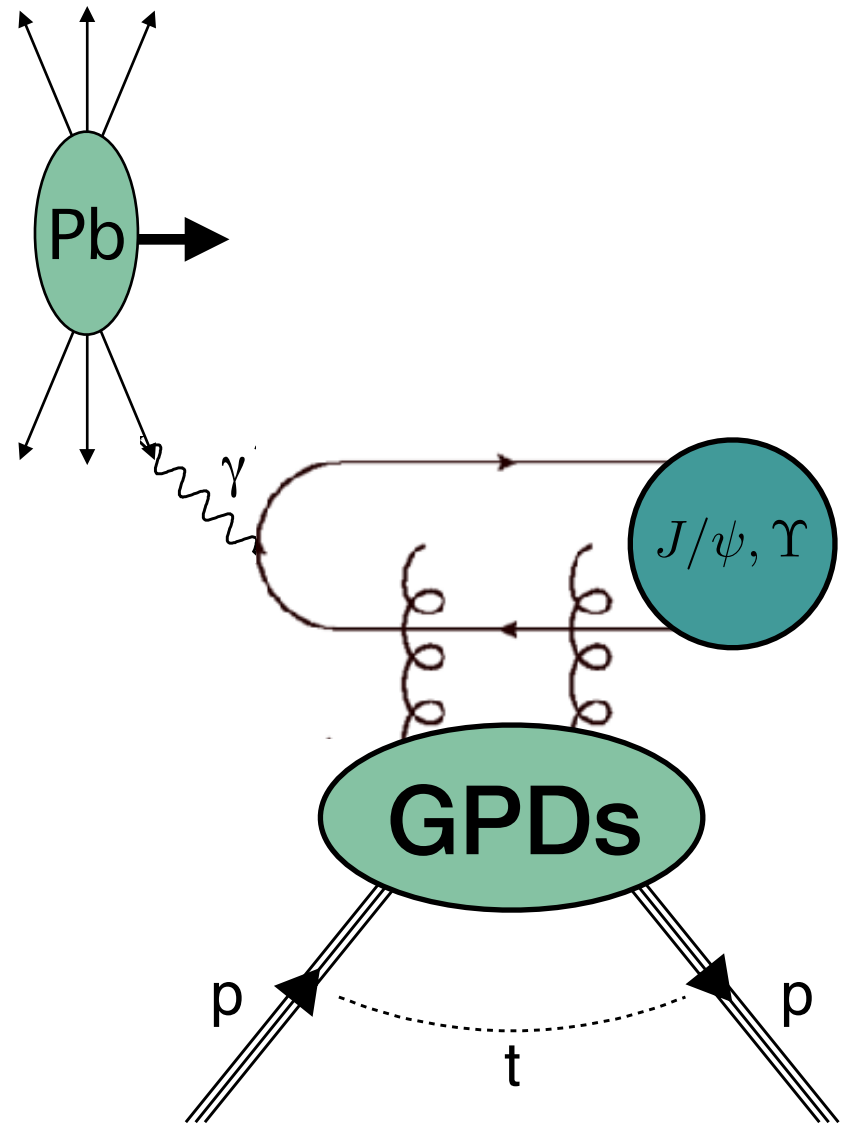
proton dissociation

Extraction of the J/ψ photoproduction



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

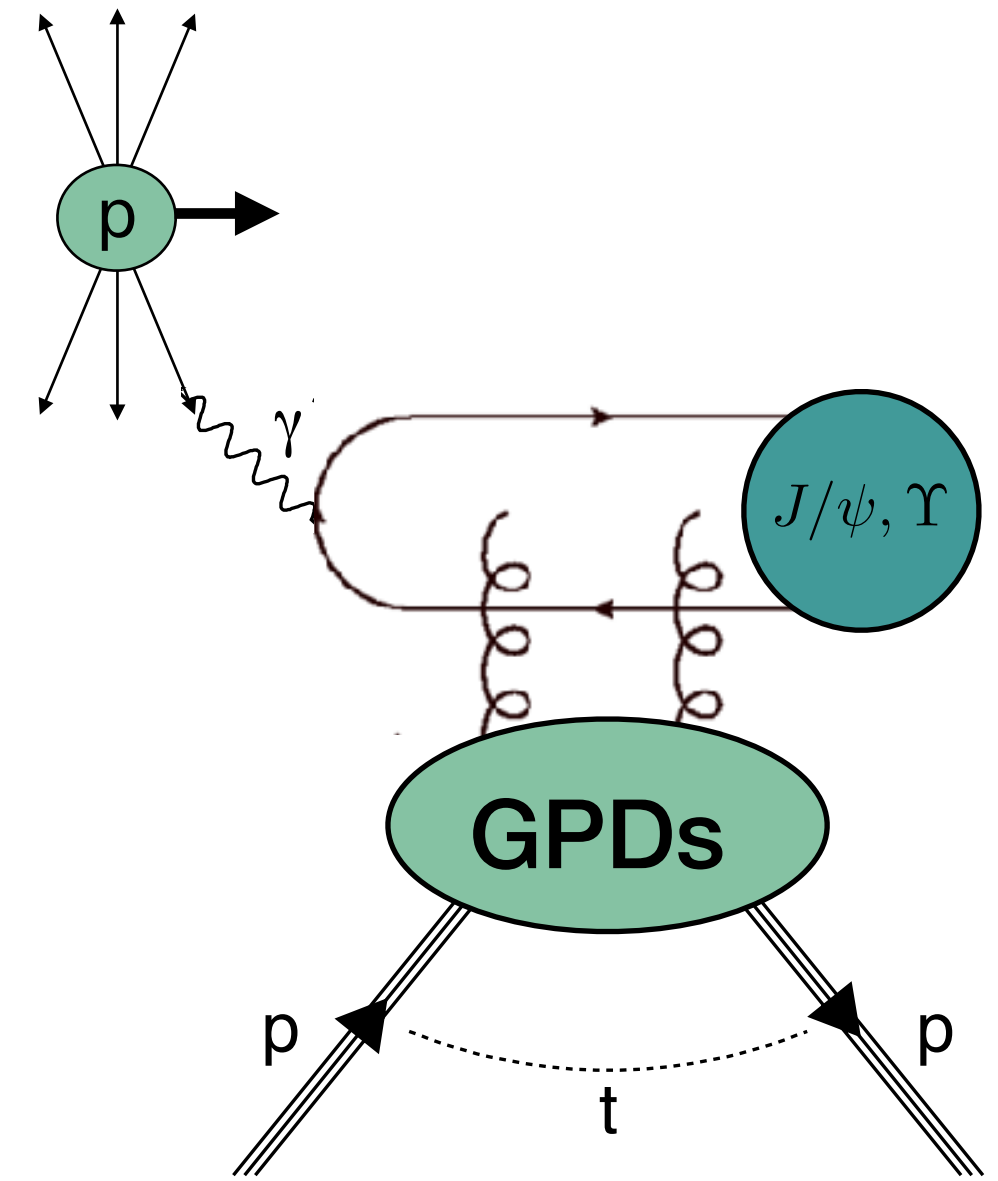
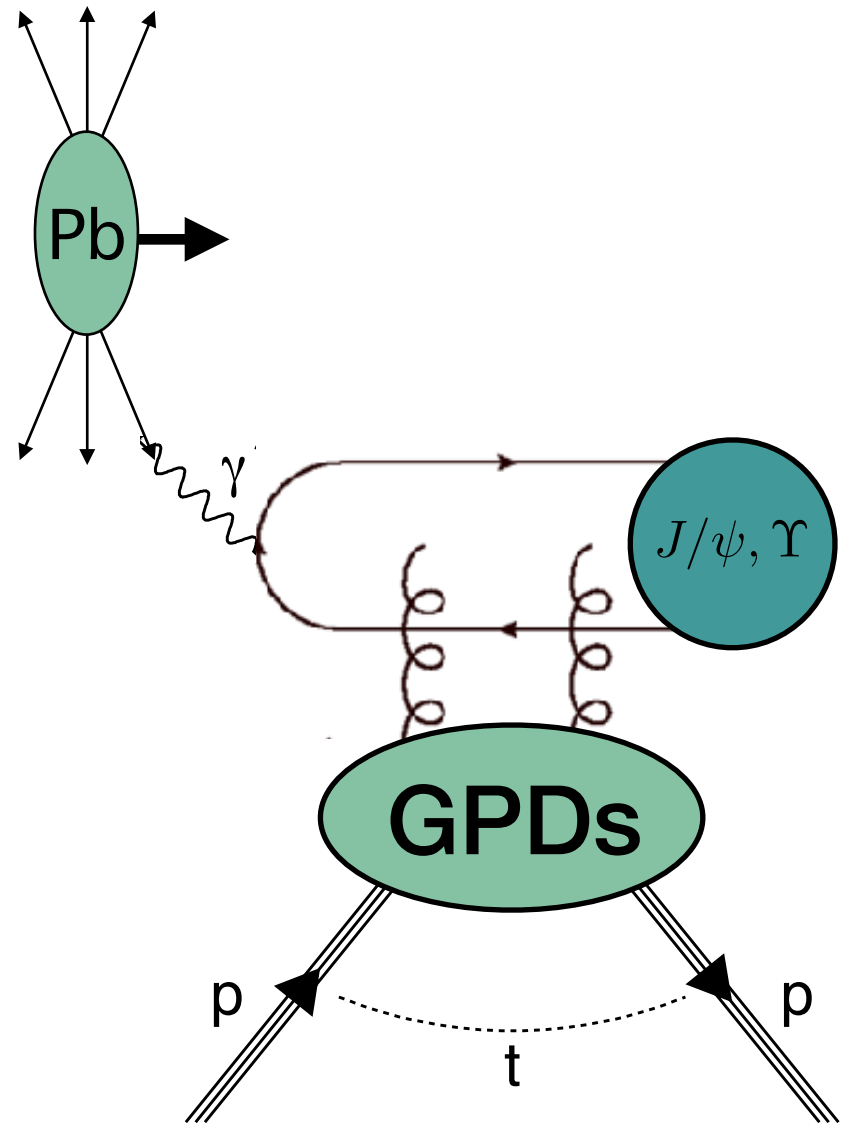
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pp: ambiguity in ID of photon emitter

Extraction of the J/ψ photoproduction



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

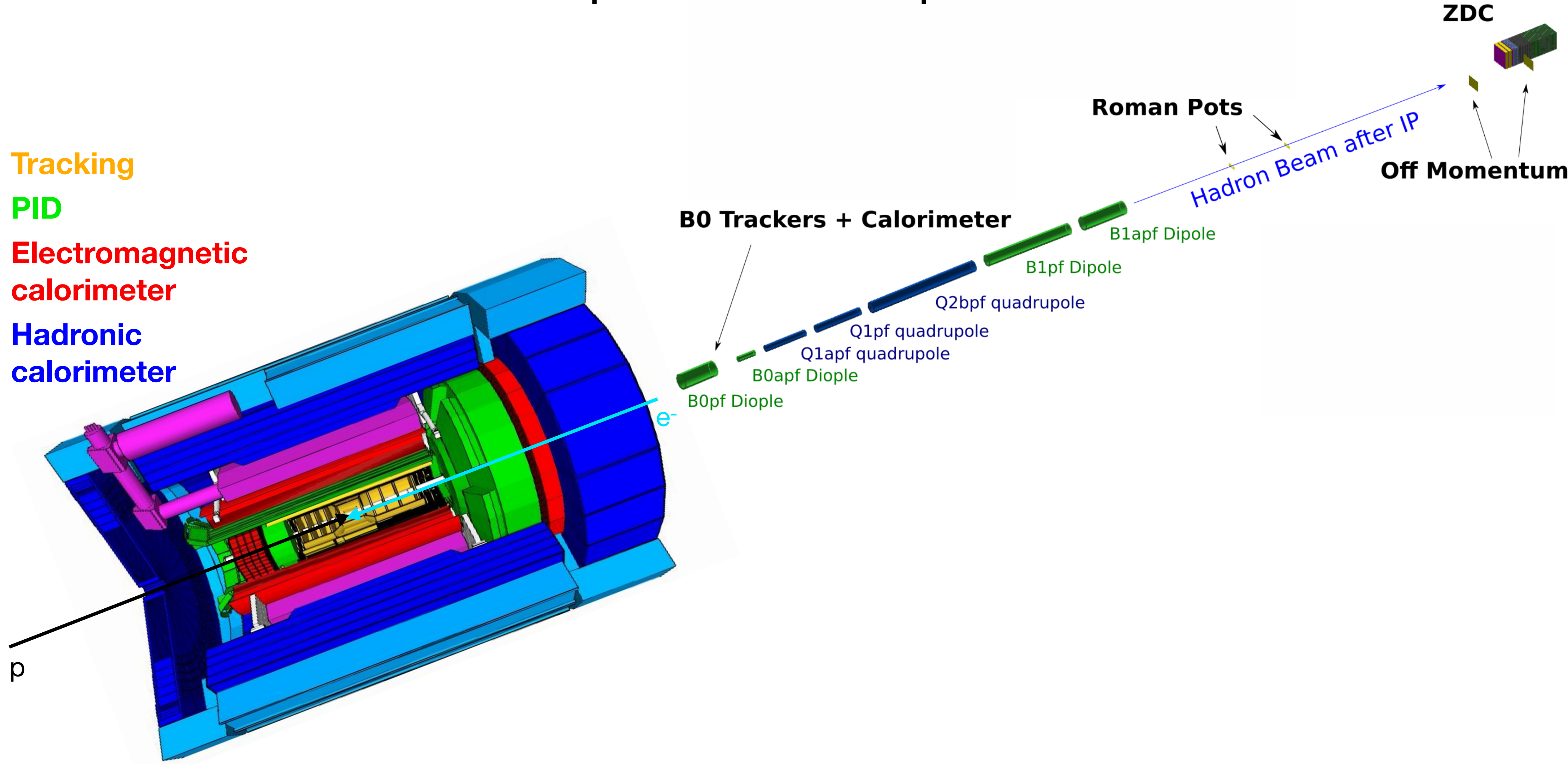
relation pp and γp cross section:

$$\sigma_{pp \rightarrow p\psi p} = r(W_+) k_+ \frac{dn}{dk_+} \sigma_{\gamma p \rightarrow \psi p}(W_+) + r(W_-) k_- \frac{dn}{dk_-} \sigma_{\gamma p \rightarrow \psi p}(W_-)$$

LHCb used HERA data for low- E_{γ} (W_-) contribution.

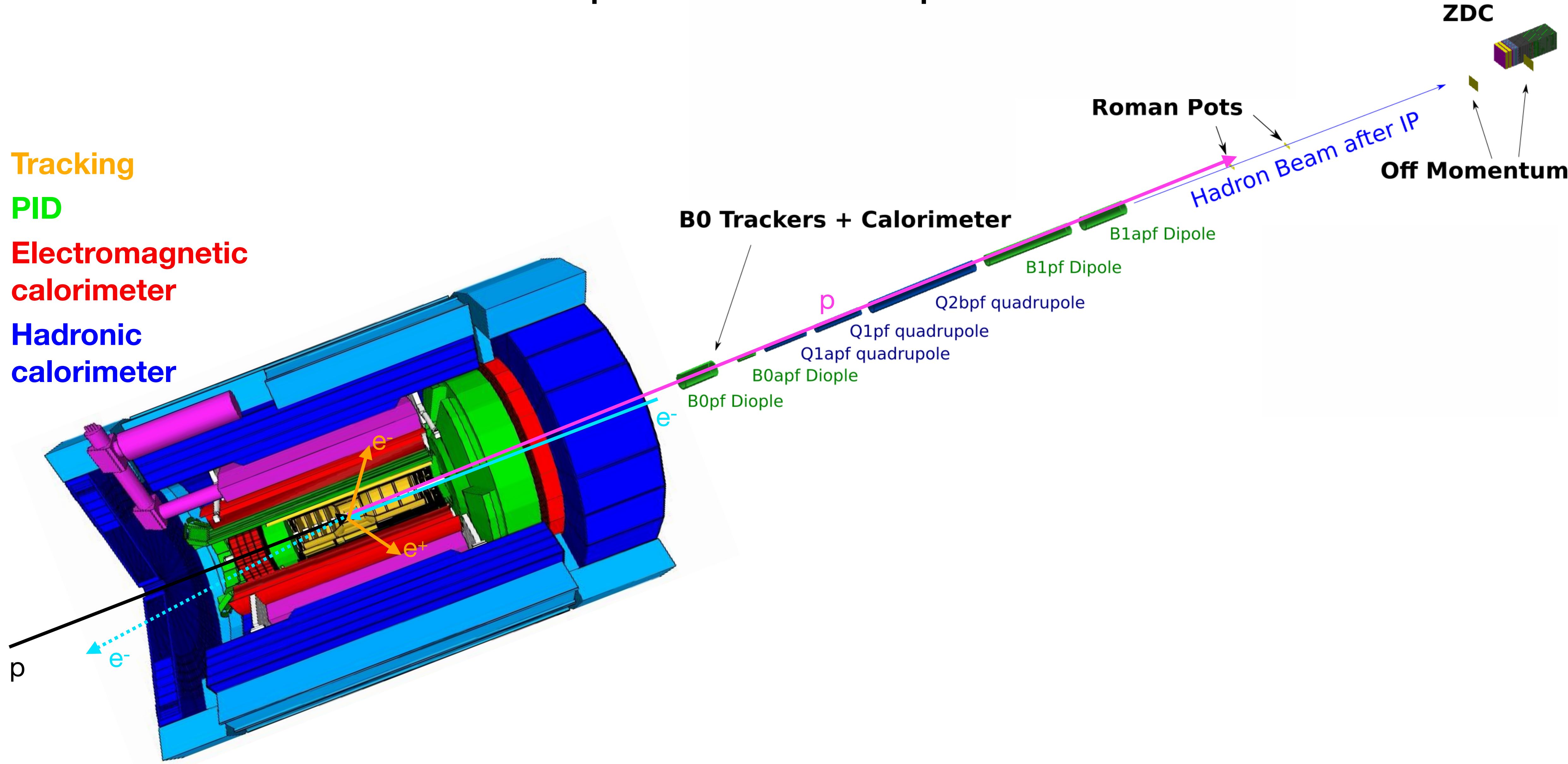
Measurement of exclusive production on proton at EIC

- Tracking
- PID
- Electromagnetic calorimeter
- Hadronic calorimeter



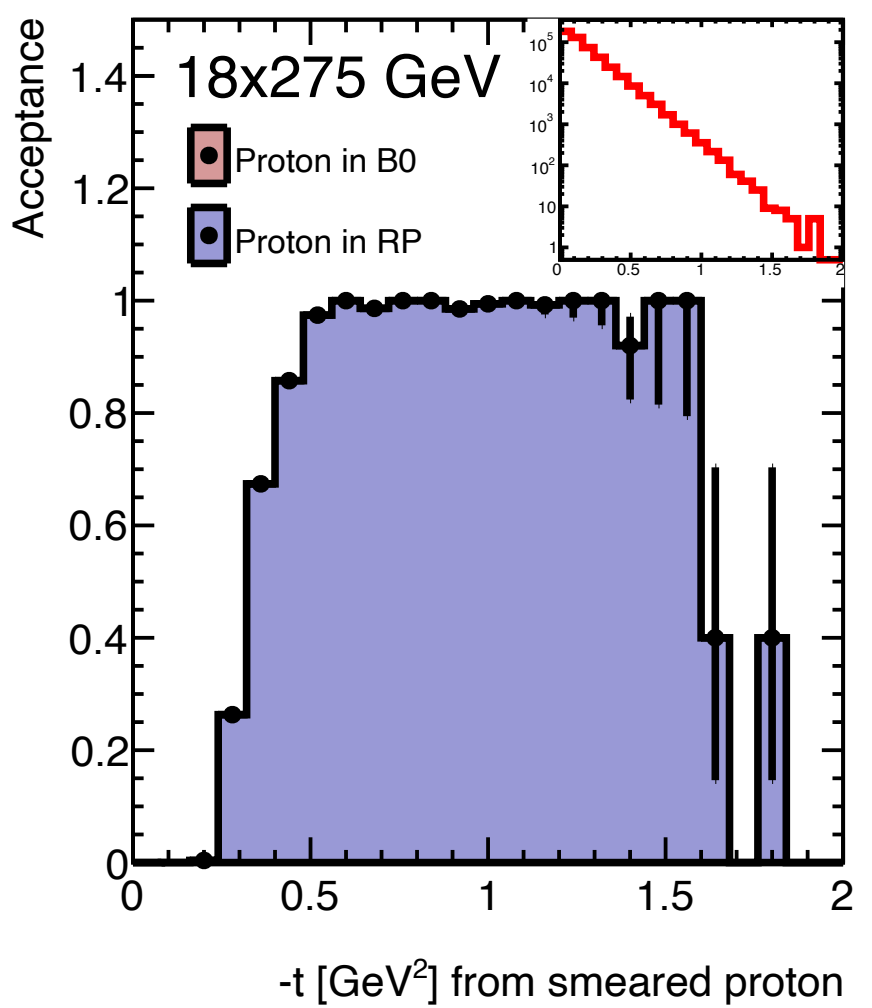
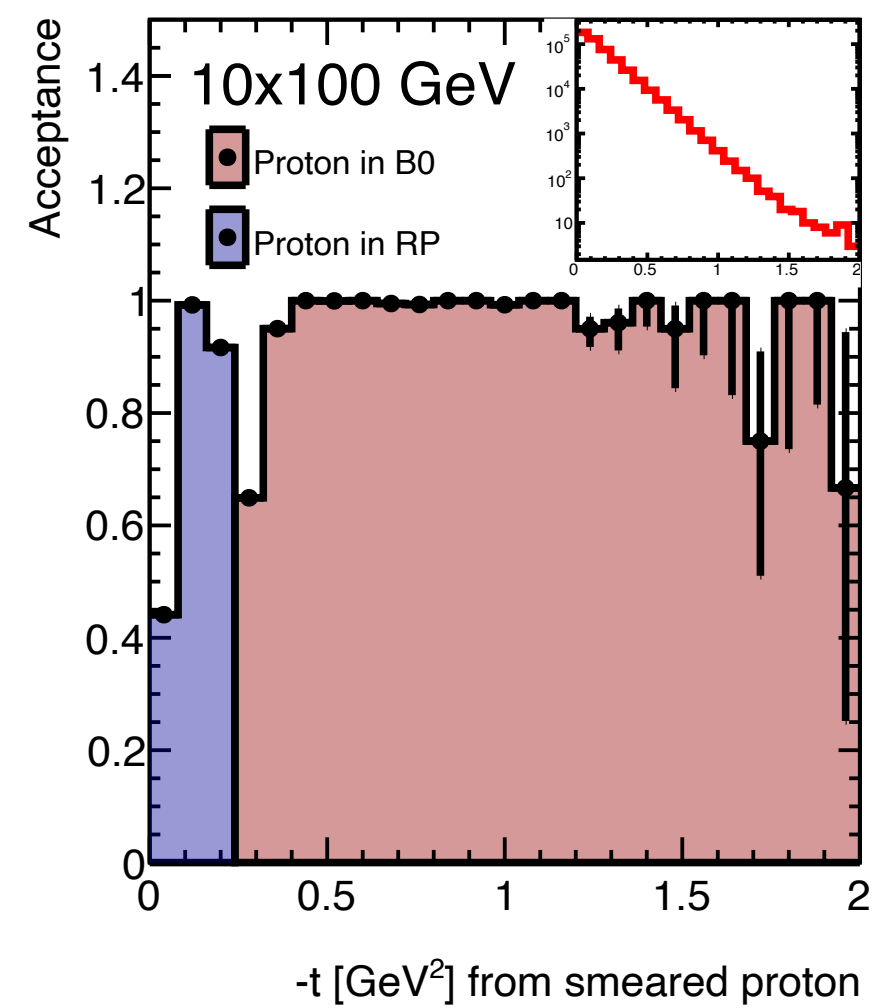
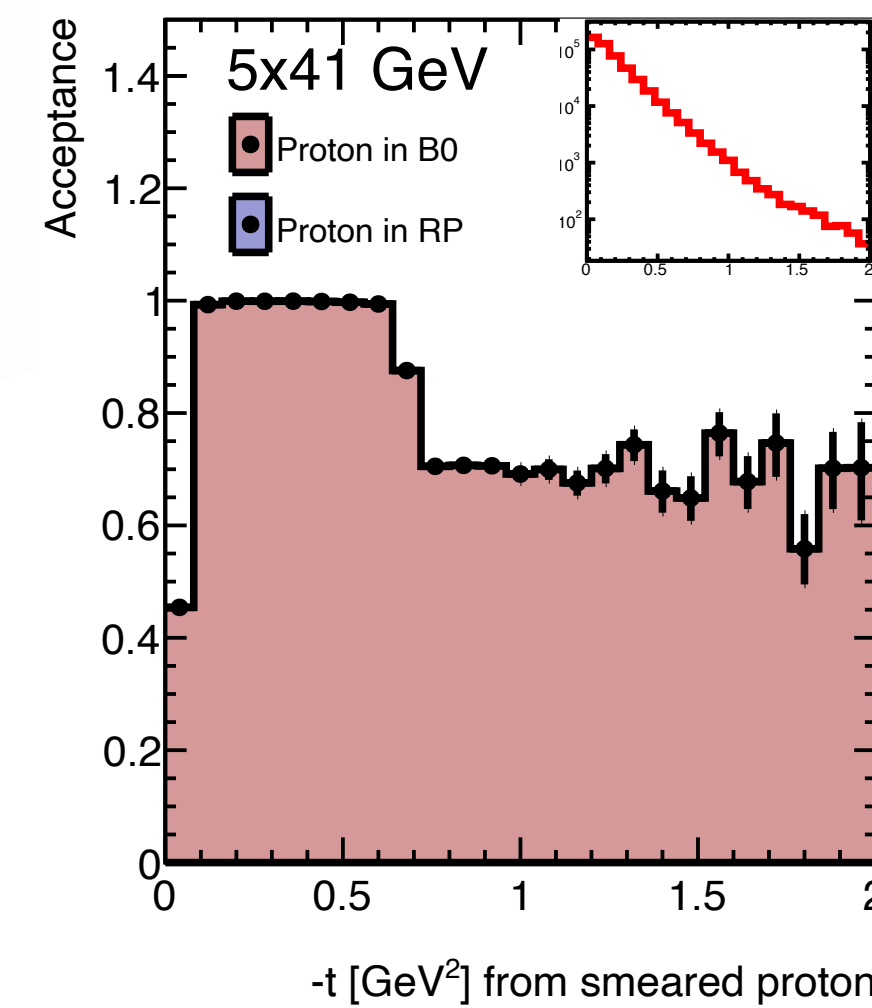
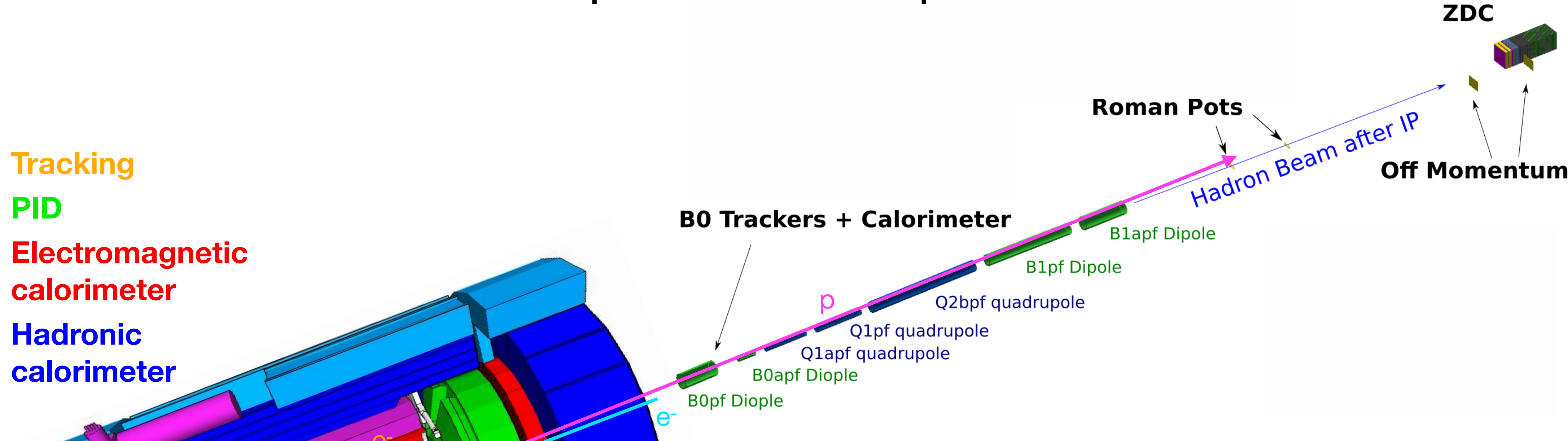
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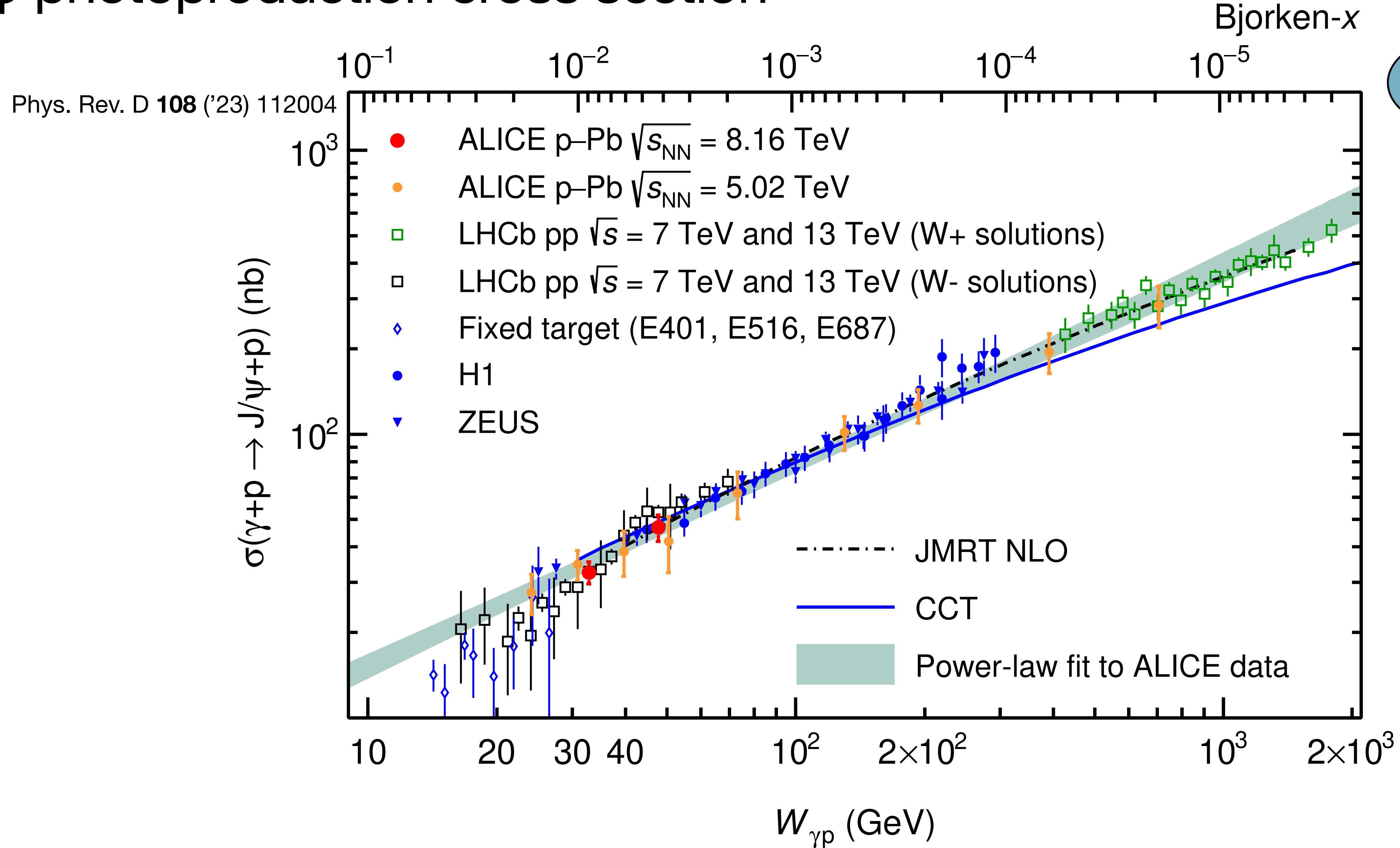


Measurement of exclusive production on proton at EIC

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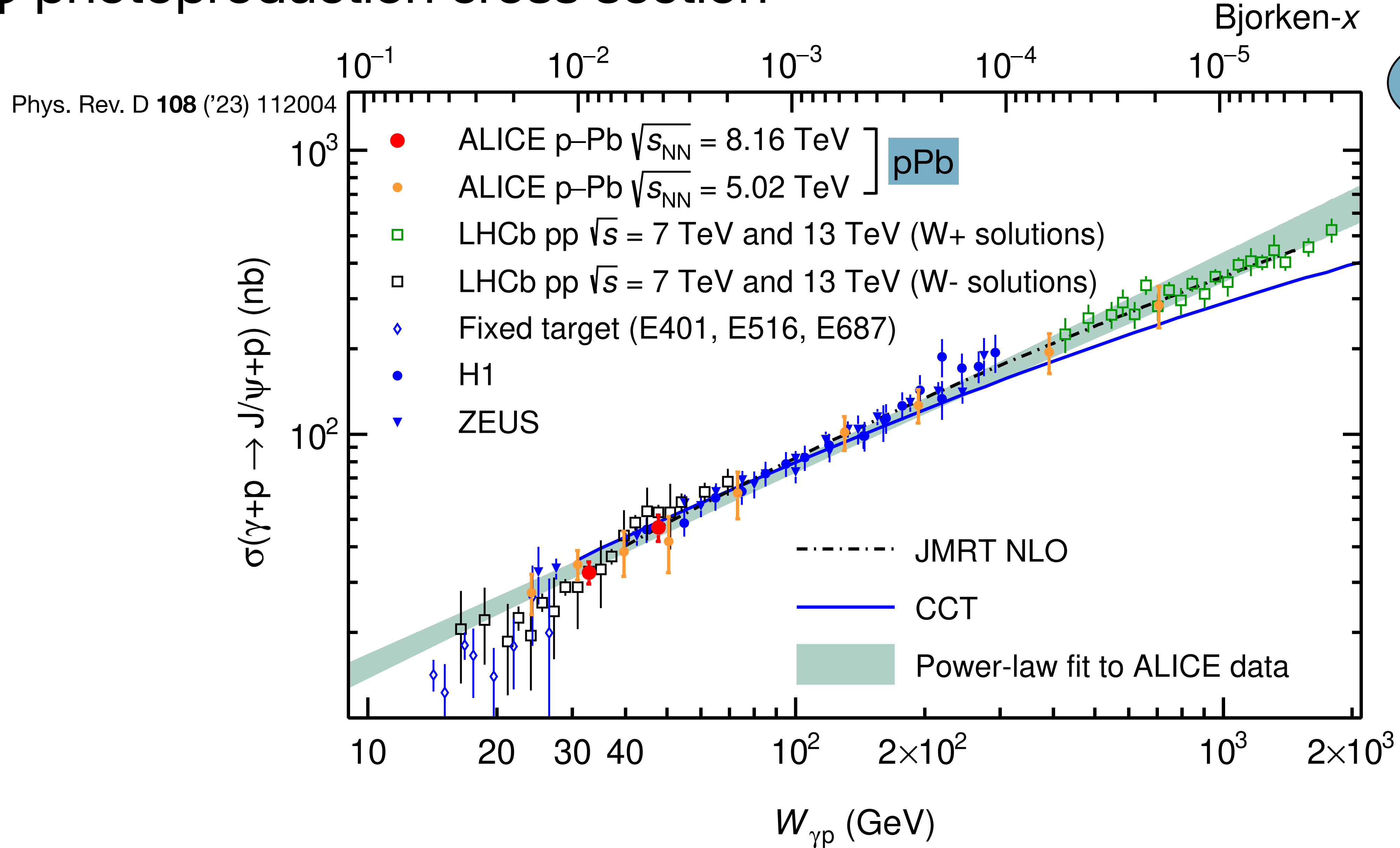


J/ψ photoproduction cross section

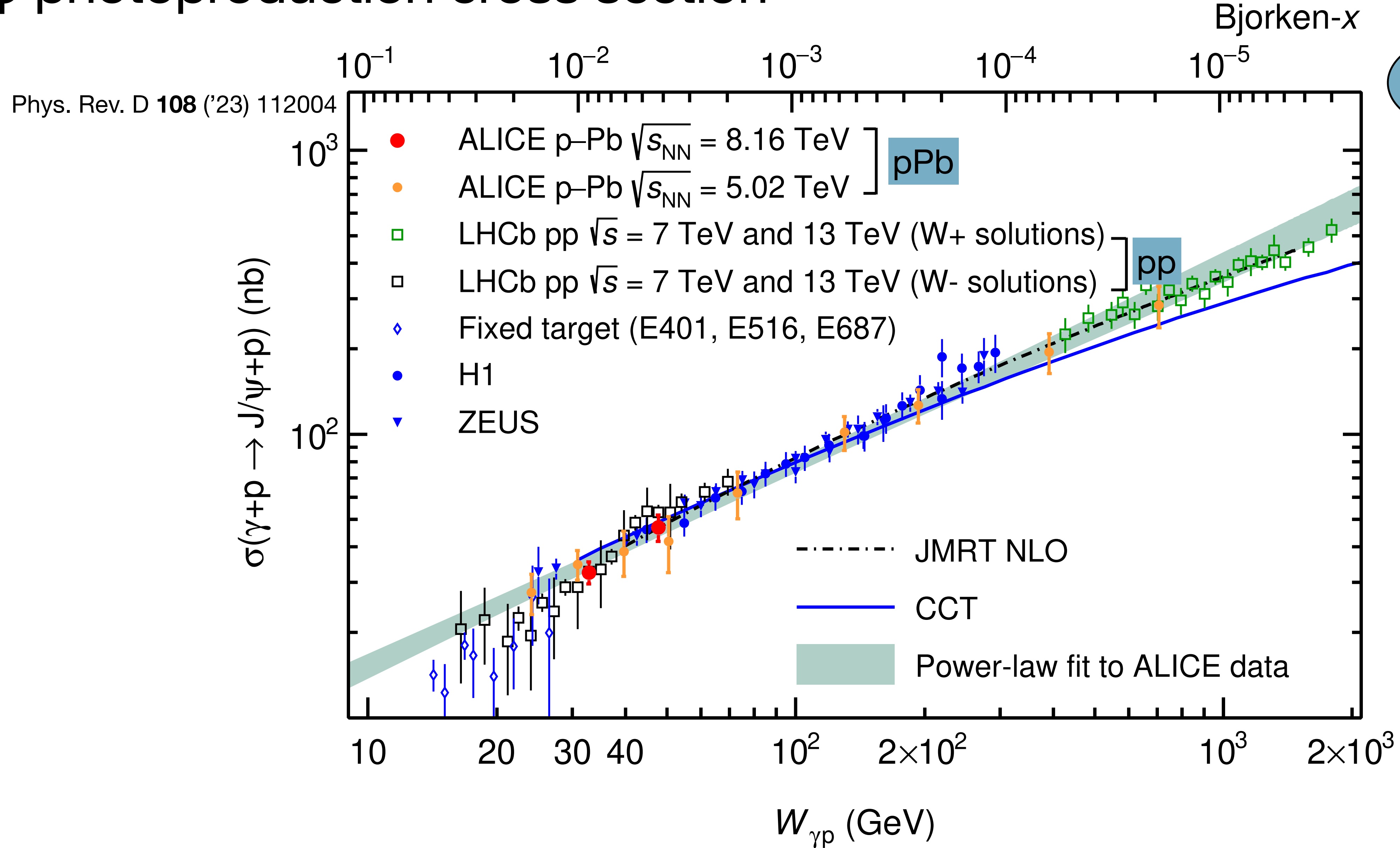


GPD H

J/ψ photoproduction cross section

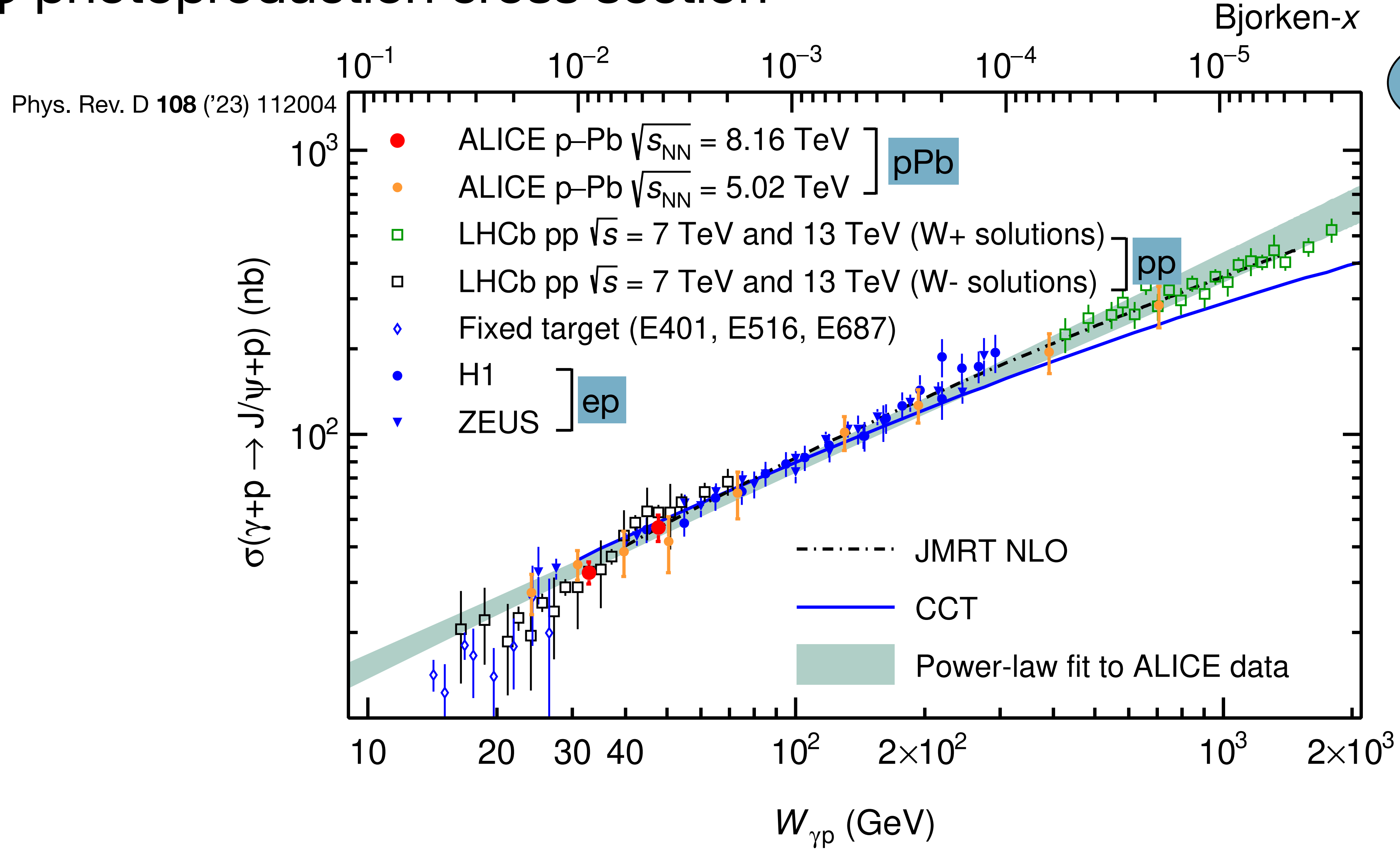


J/ψ photoproduction cross section



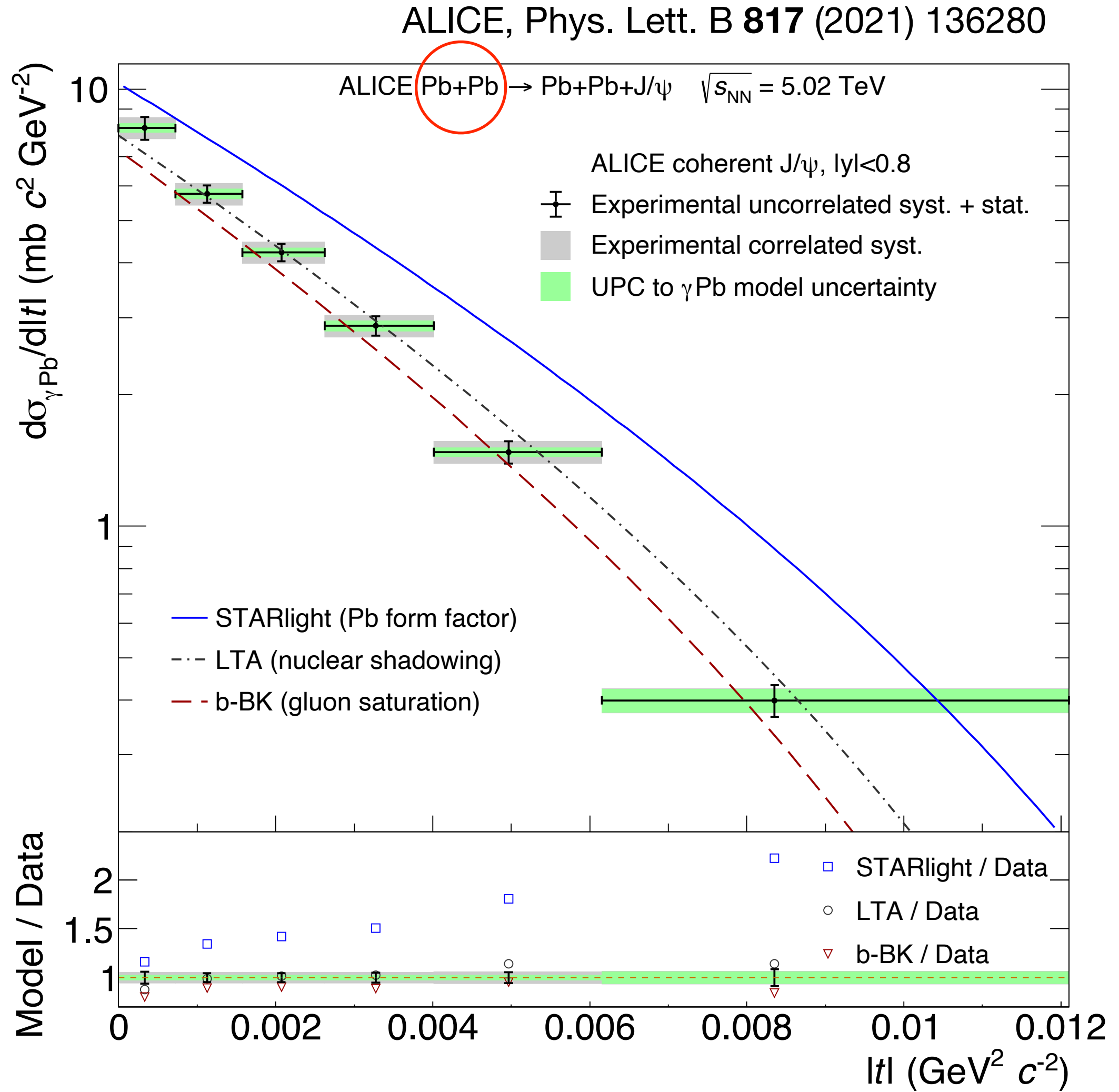
GPD H

J/ψ photoproduction cross section

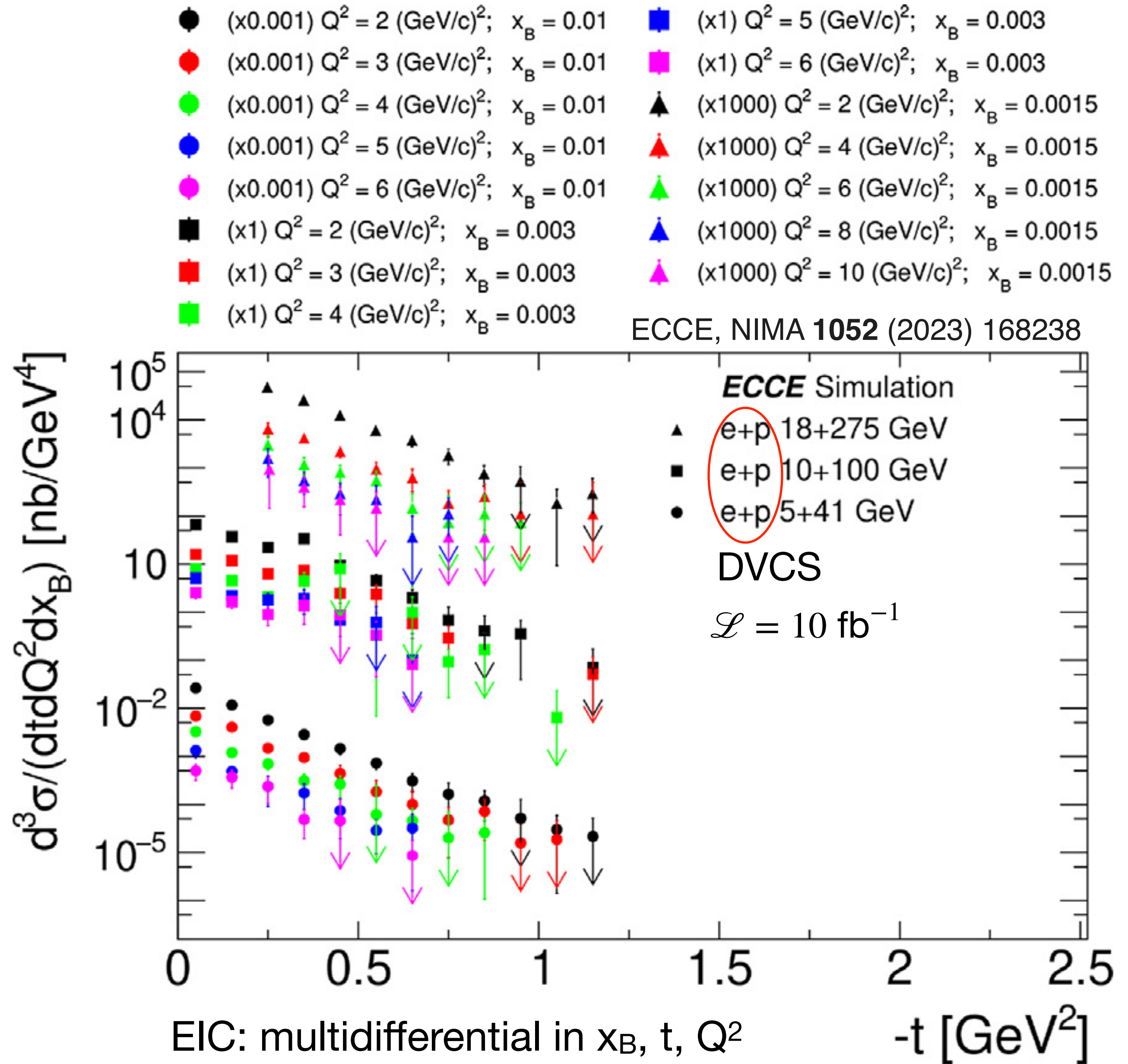
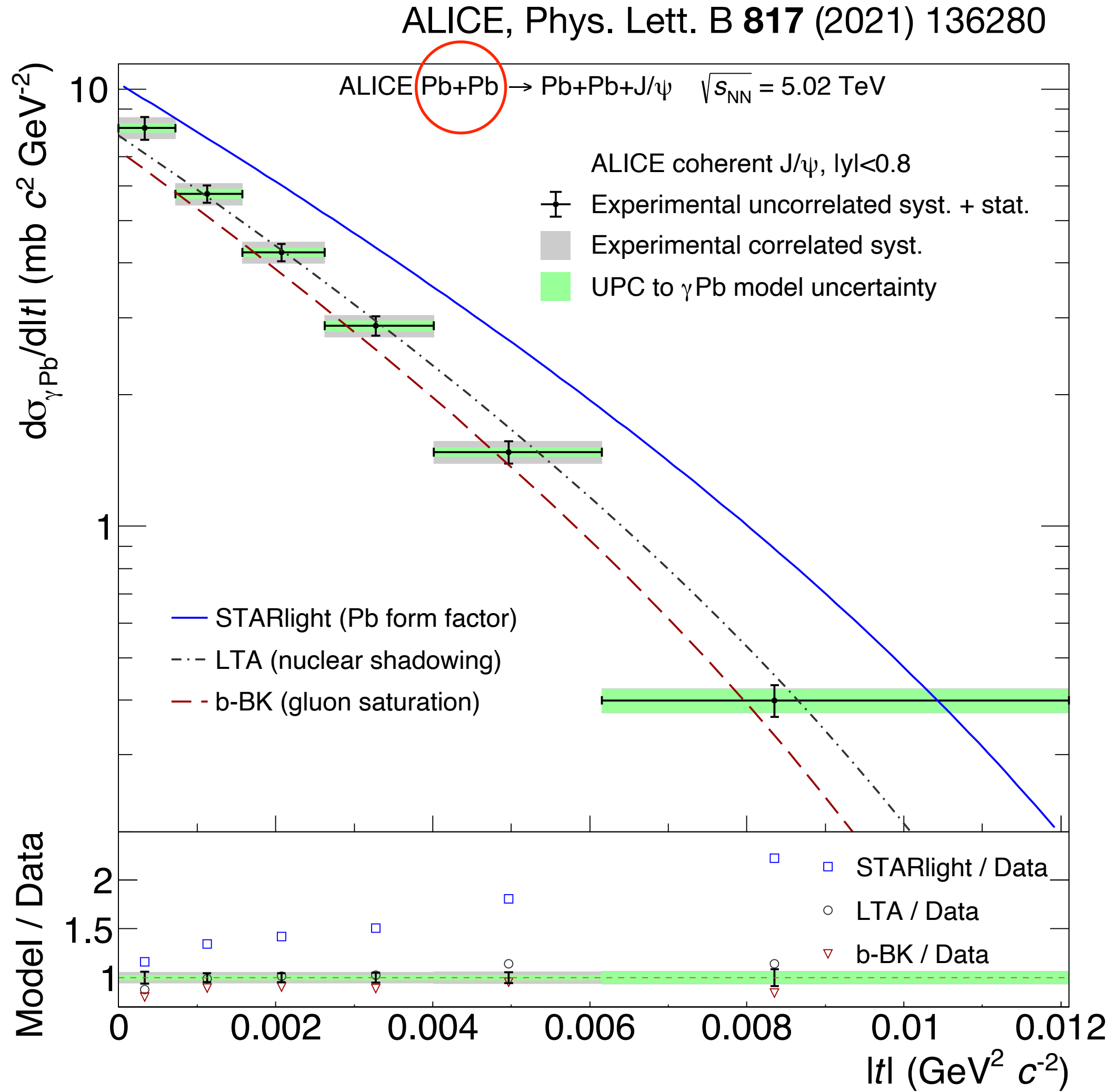


GPD H

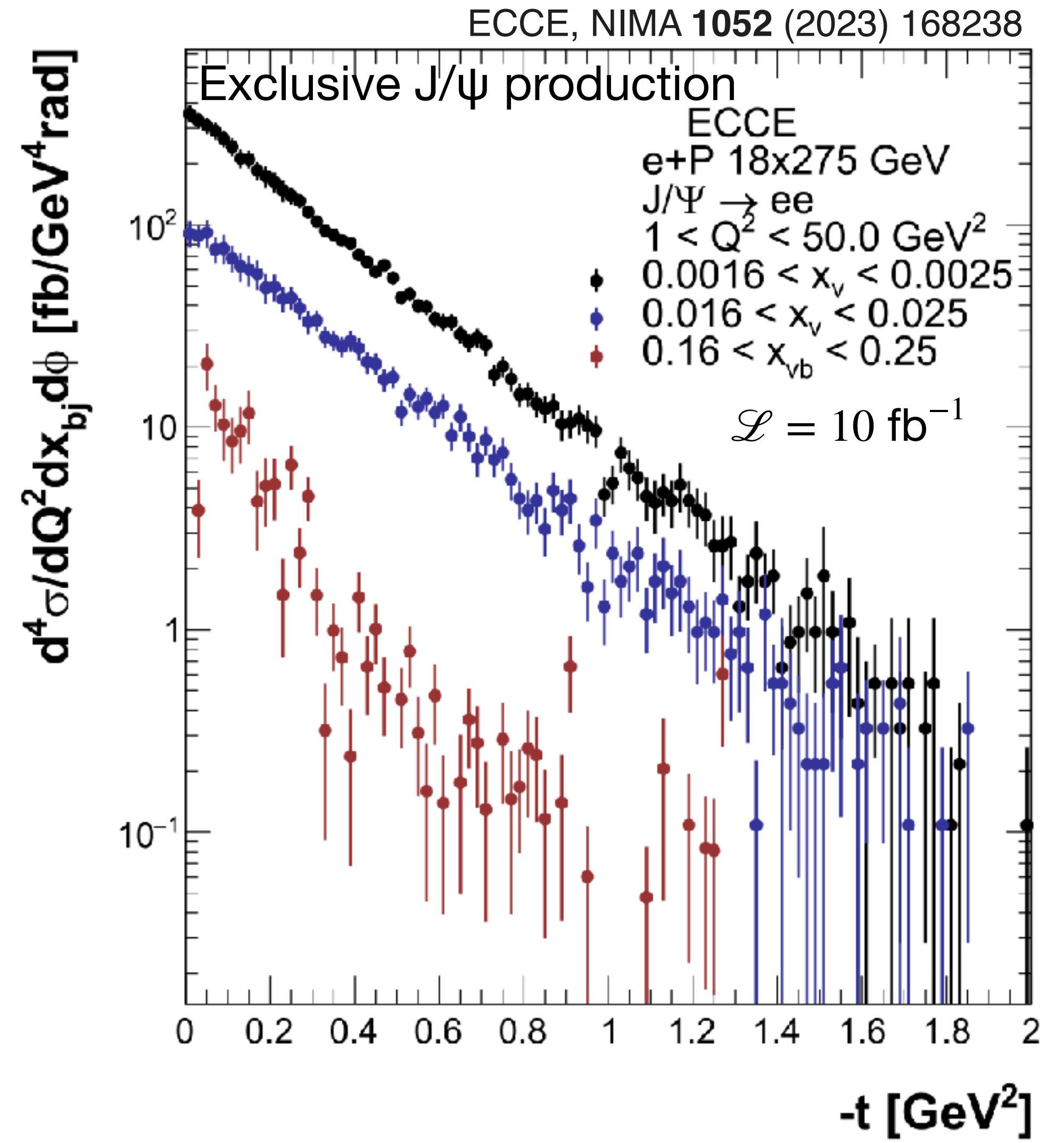
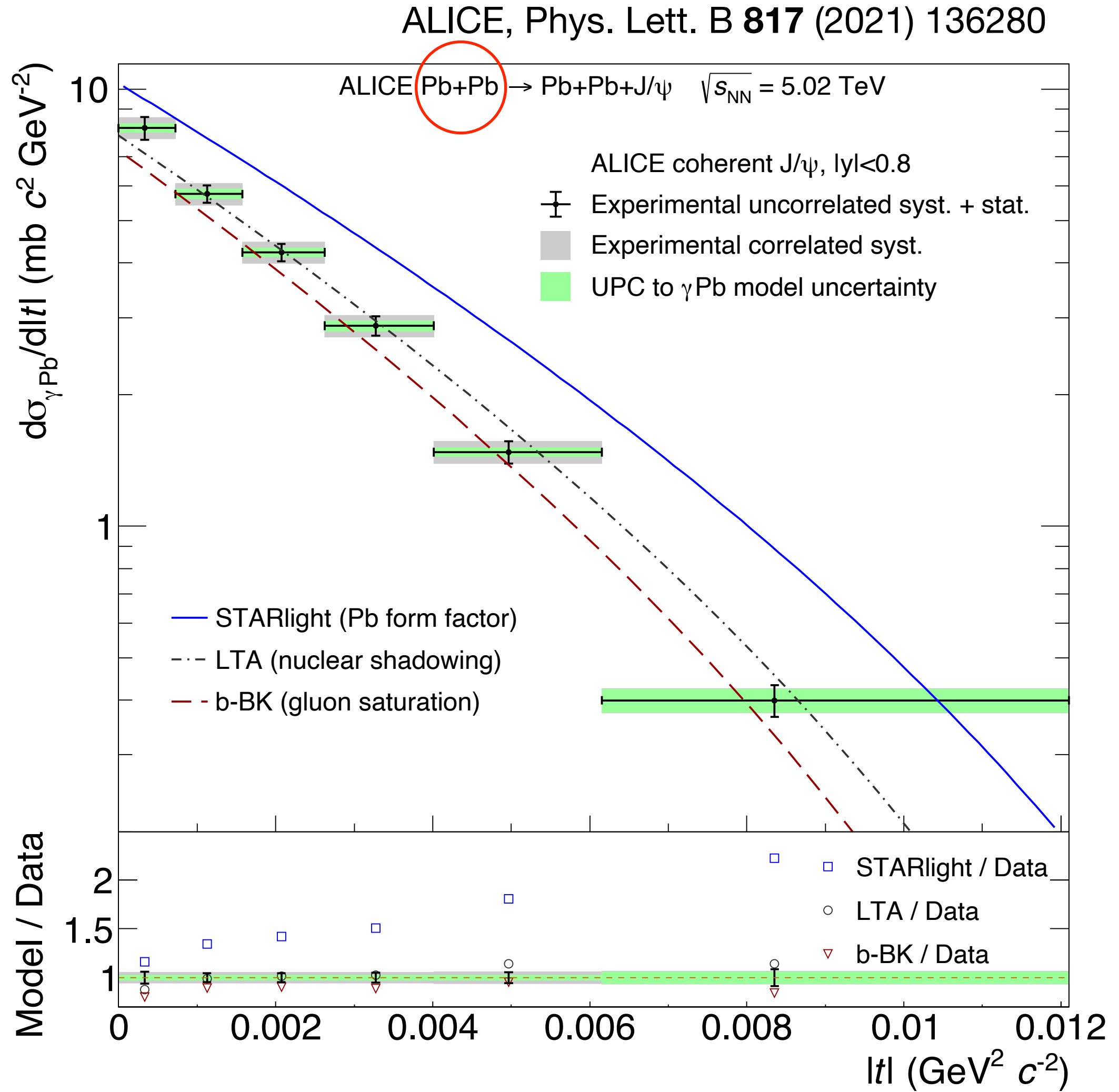
Exclusive measurements on the proton at the LHC and the EIC



Exclusive measurements on the proton at the LHC and the EIC



Exclusive measurements on the proton at the LHC and the EIC



Polarisation and angles

- for spin-1/2 hadron:

Four parton helicity-conserving twist-2 GPDs

$H(x, \xi, t)$	$E(x, \xi, t)$	parton-spin independent
$\tilde{H}(x, \xi, t)$	$\tilde{E}(x, \xi, t)$	parton-spin dependent
proton helicity non flip	proton helicity flip	

Four parton helicity-flip twist-2 GPDs

$H_T(x, \xi, t)$	$E_T(x, \xi, t)$
$\tilde{H}_T(x, \xi, t)$	$\tilde{E}_T(x, \xi, t)$

Polarisation and angles

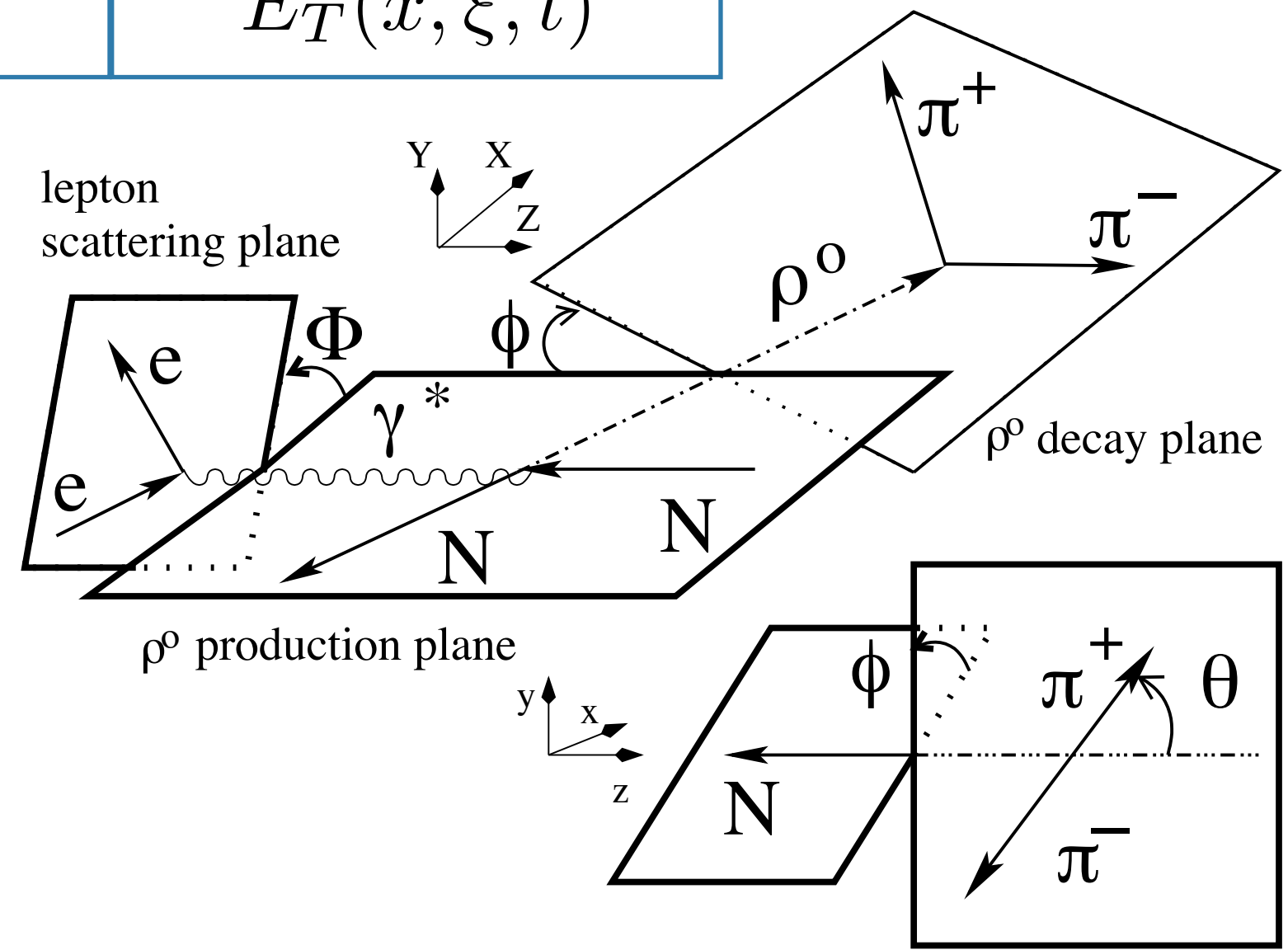
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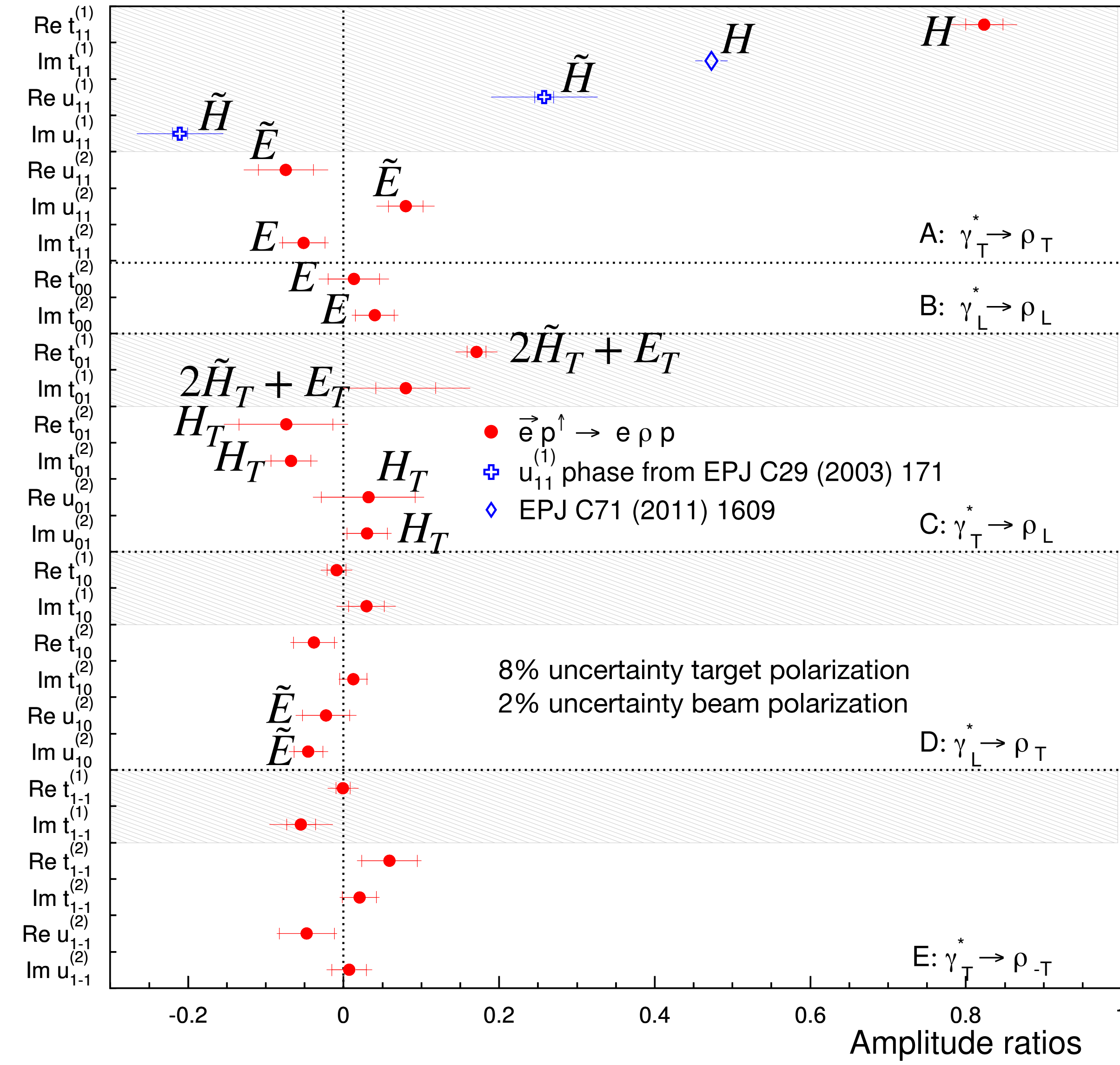
$H_T(x, \xi, t)$	$E_T(x, \xi, t)$
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Exclusive ρ on transversely polarised p

Possible at EIC

HERMES, Eur. Phys. J. C 77 (2017) 378



Polarisation and angles

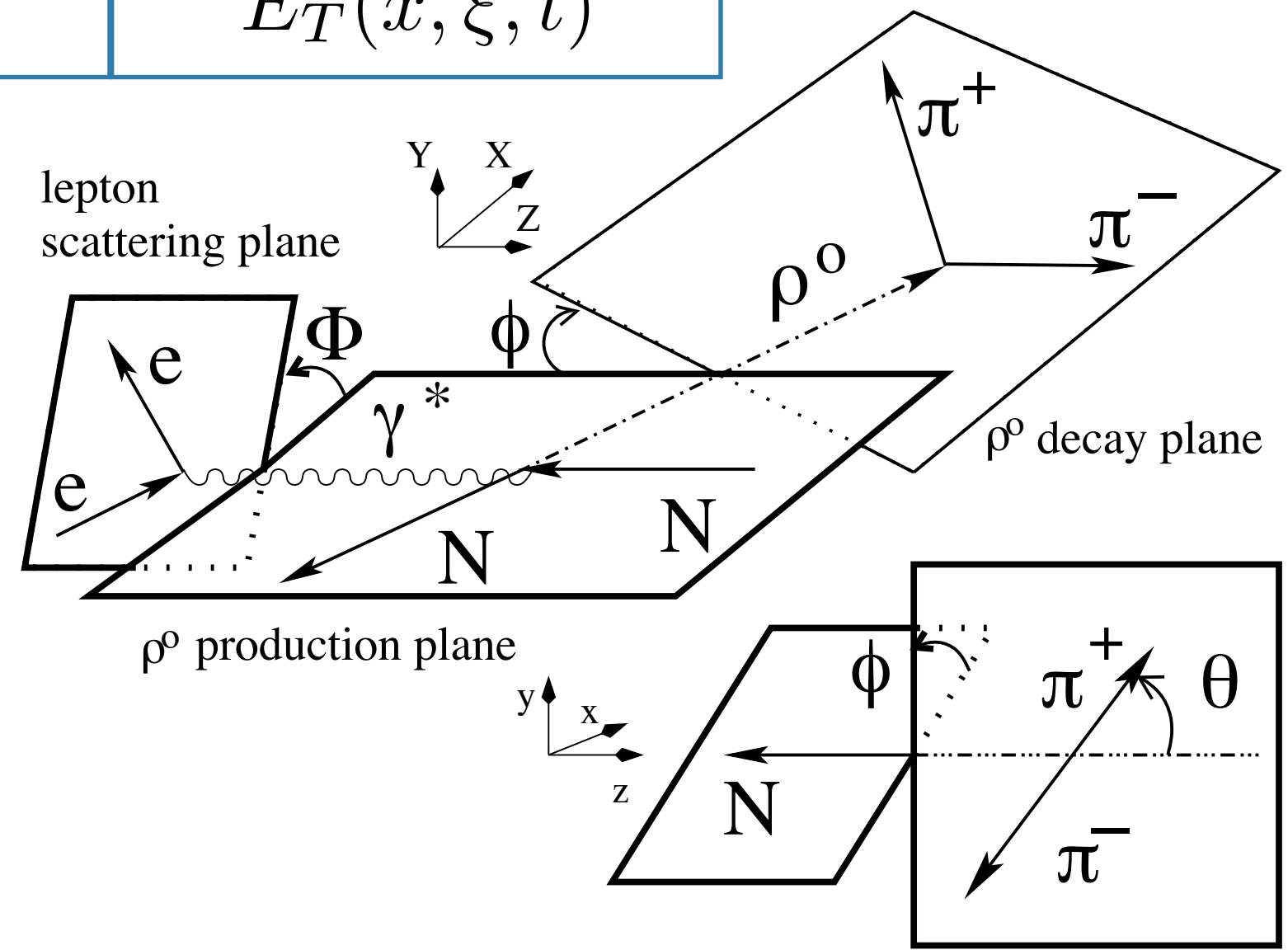
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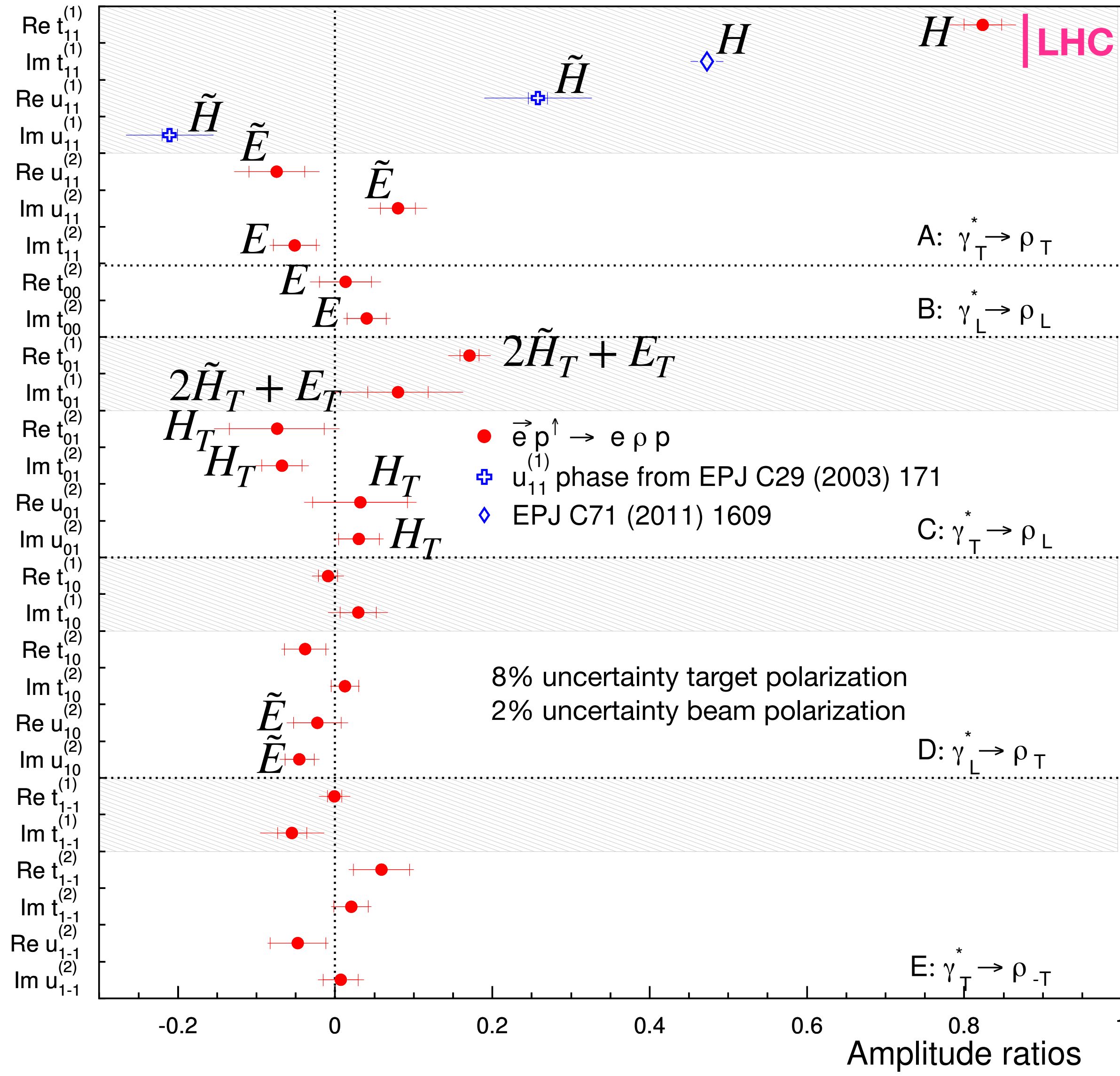
$H_T(x, \xi, t)$	$E_T(x, \xi, t)$
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Exclusive ρ on transversely polarised p

Possible at EIC

HERMES, Eur. Phys. J. C 77 (2017) 378



via unpolarised target

via transversely polarised target

Polarisation and angles

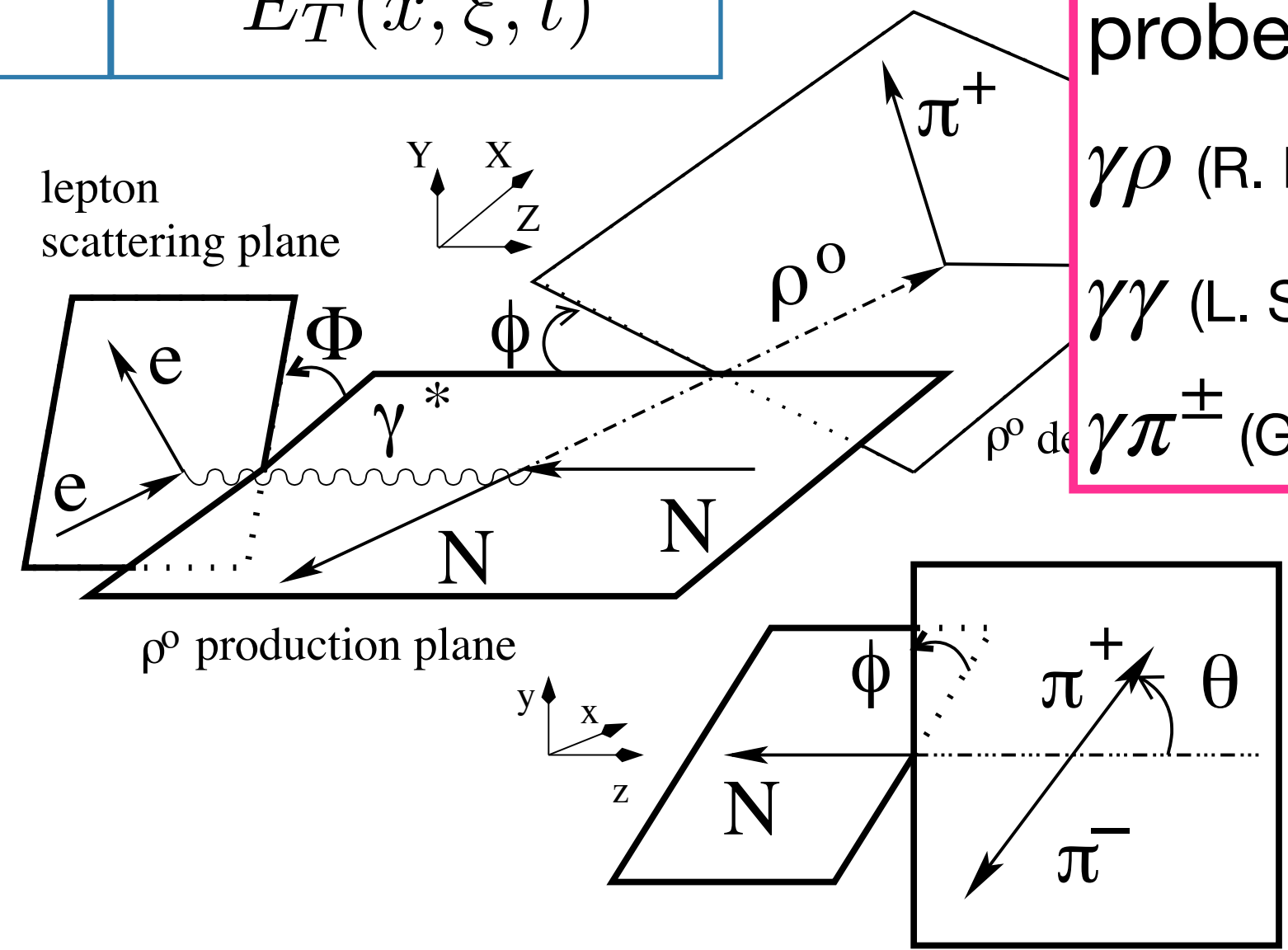
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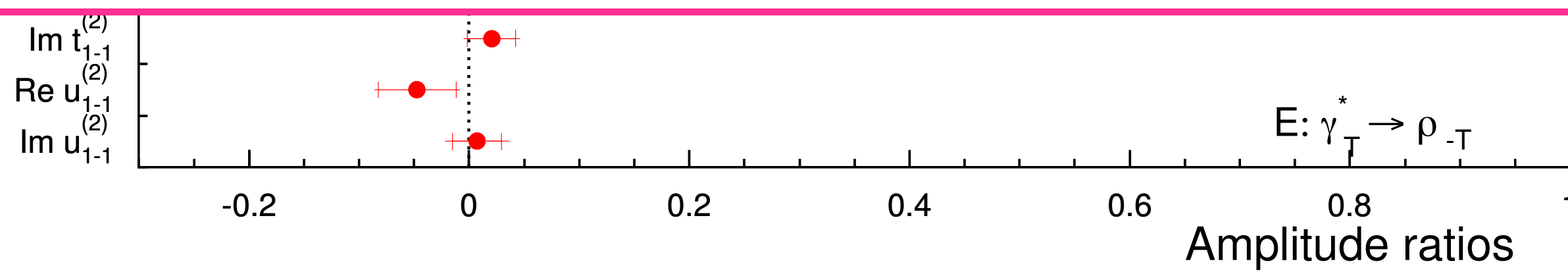
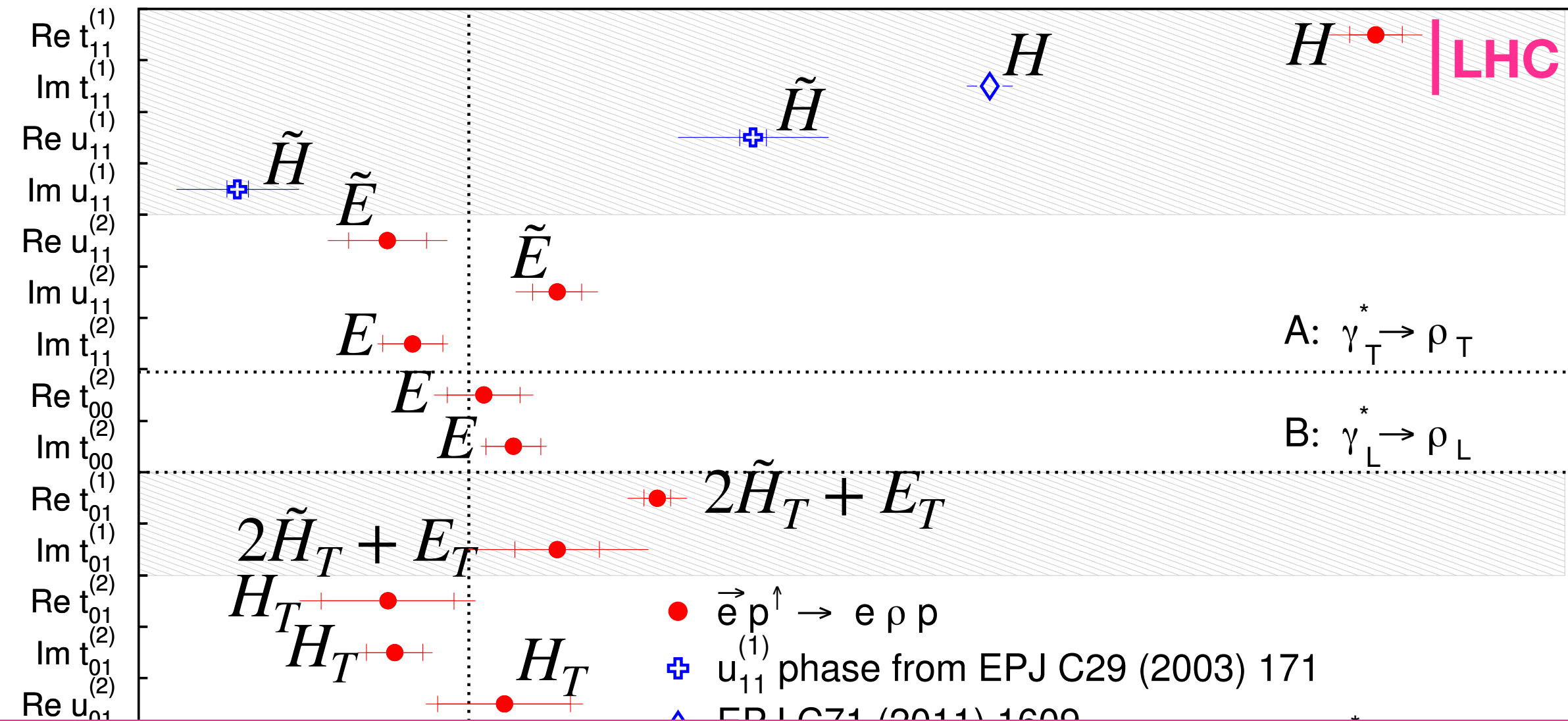


Exclusive production of γ -meson pair in UPCs:
 probe different types of GPDs and access to variety of hard scales.
 $\gamma\rho$ (R. Boussarie et al. JHEP 02 (2017) 054, JHEP 10 (2018) 029)
 $\gamma\gamma$ (L. Szymanowski arXiv:1909.12591)
 $\gamma\pi^\pm$ (G. Duplančić et al. JHEP 03 (2023) 241)

Exclusive ρ on transversely polarised p

Possible at EIC

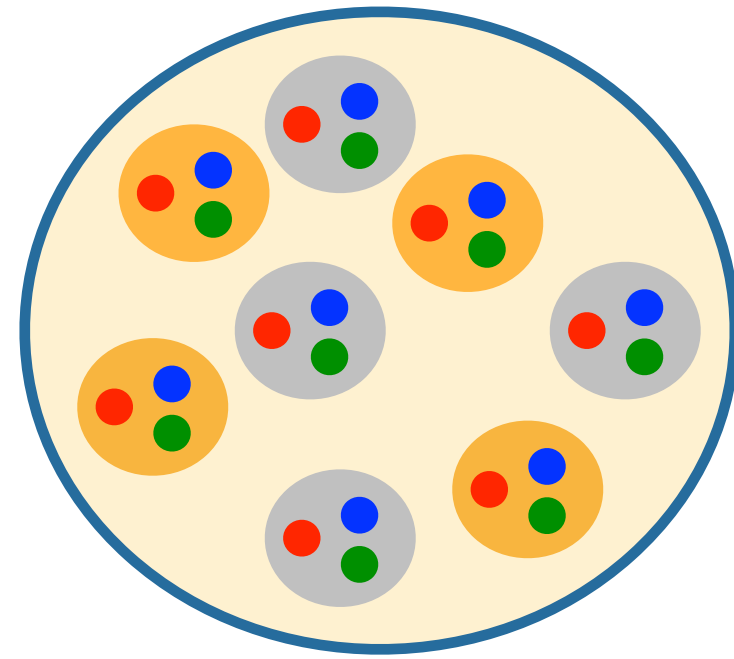
HERMES, Eur. Phys. J. C 77 (2017) 378



via unpolarised target via transversely polarised target

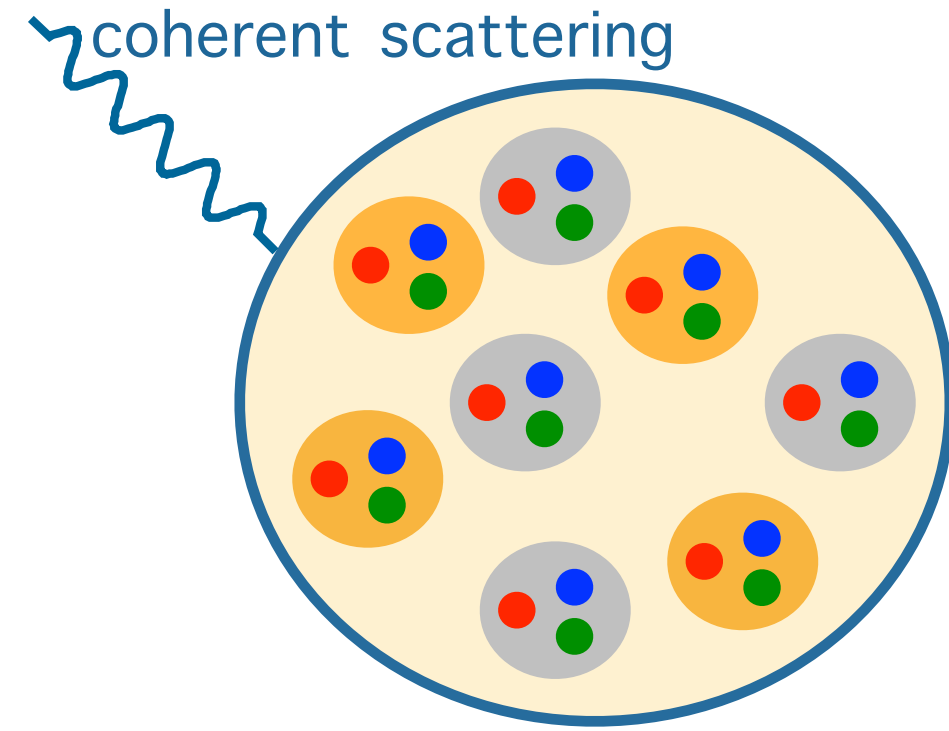
Ultra-peripheral PbPb collisions

What object are we probing?



Ultra-peripheral PbPb collisions

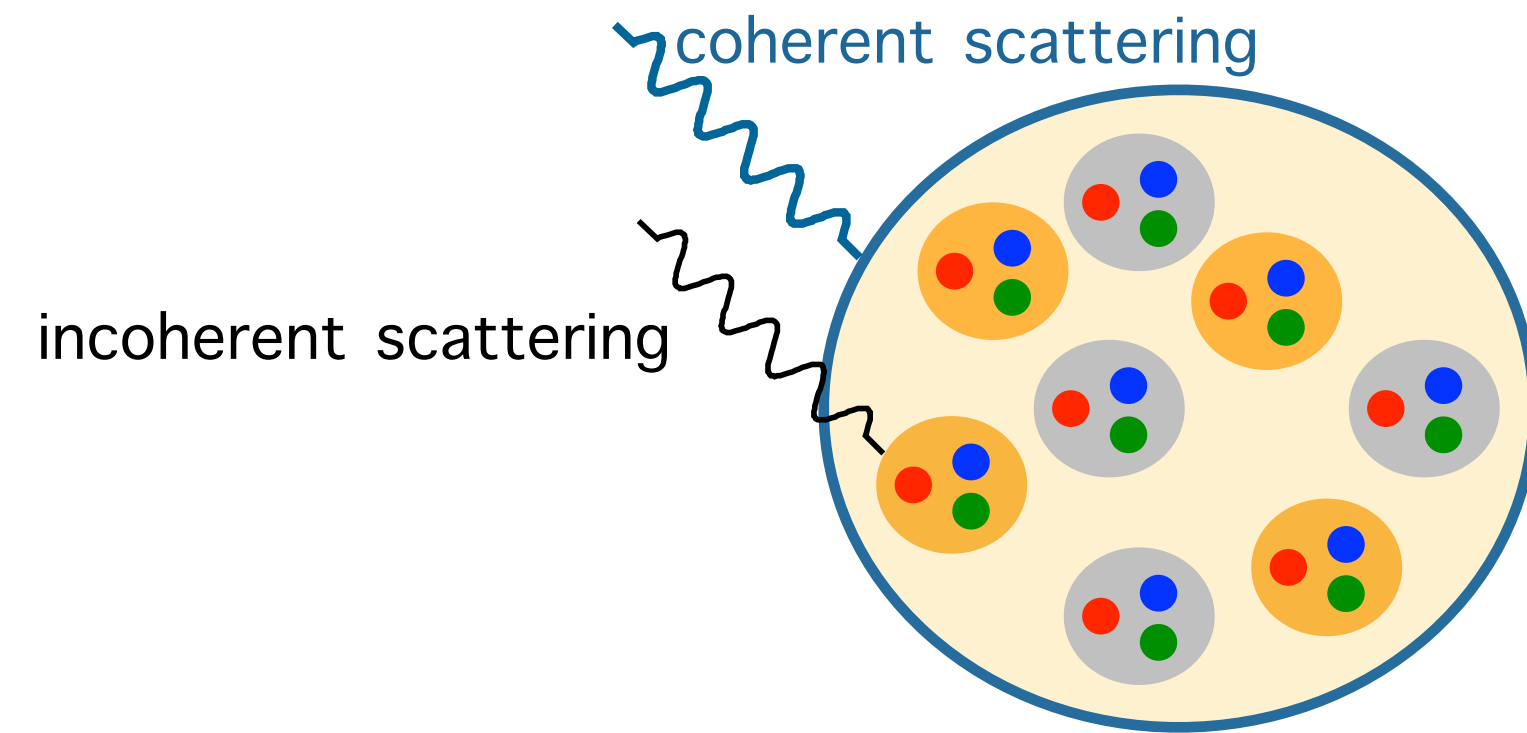
What object are we probing?



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

Ultra-peripheral PbPb collisions

What object are we probing?

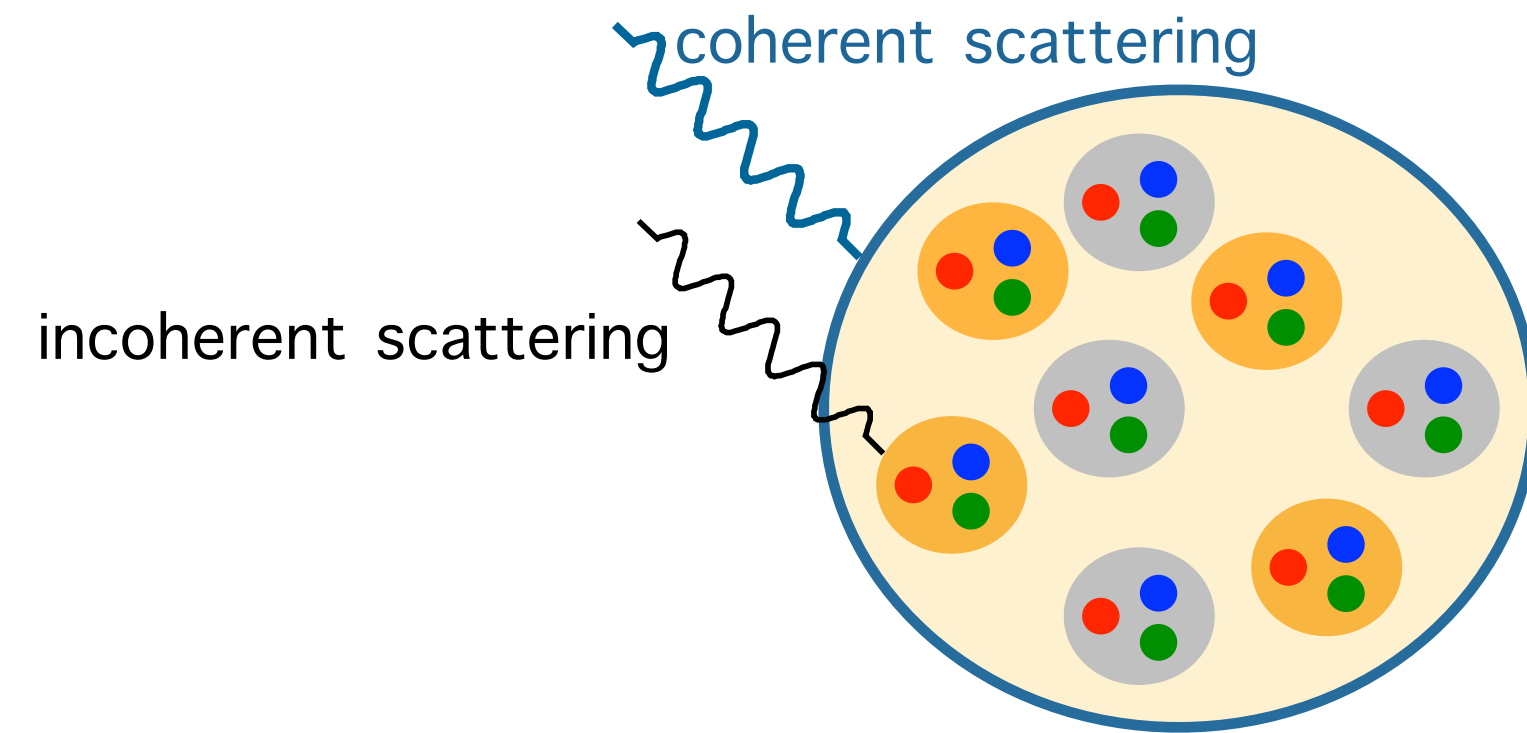


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Incoherent interaction: interaction with constituents inside target.
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Ex.: target dissociation, excitation

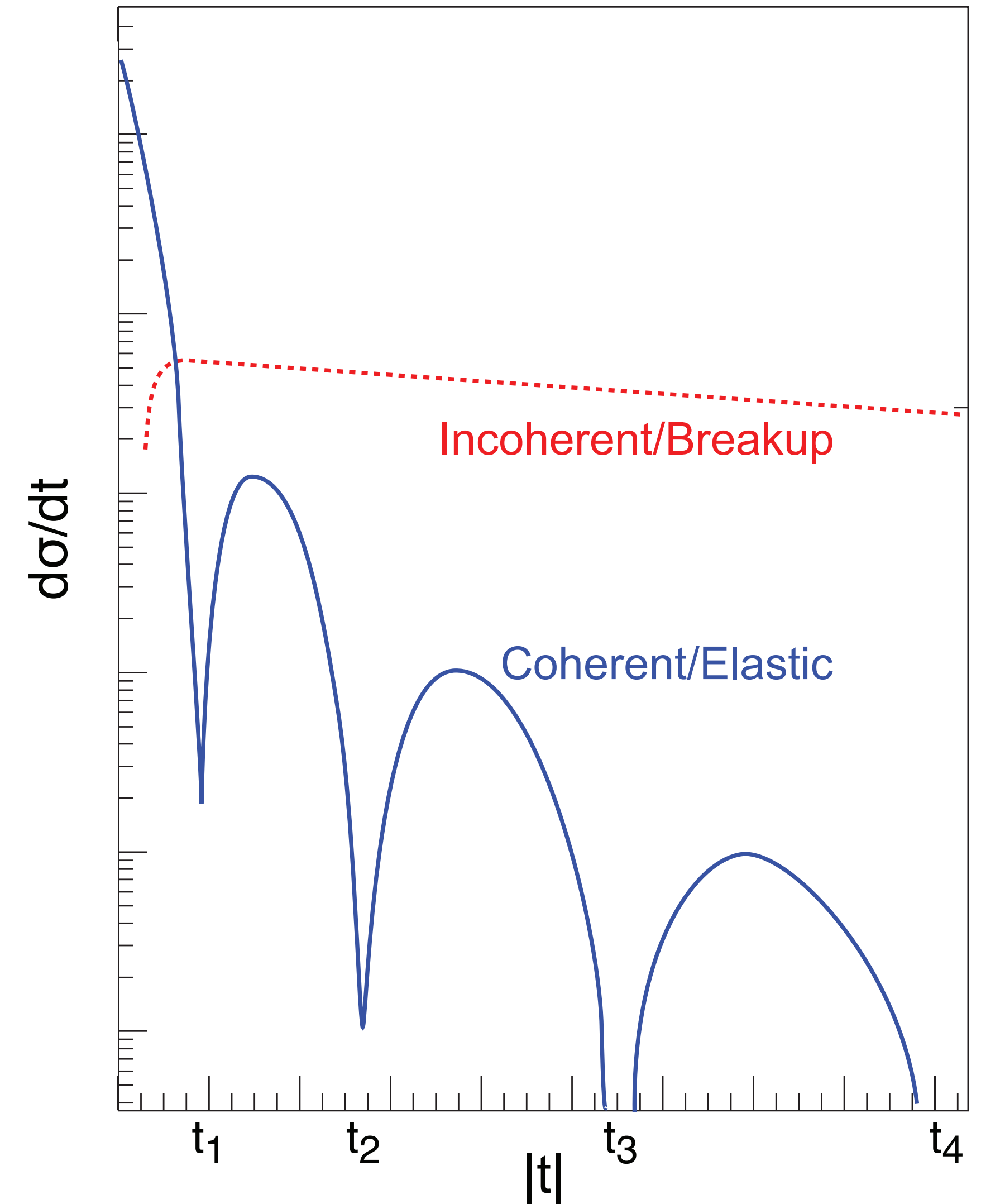
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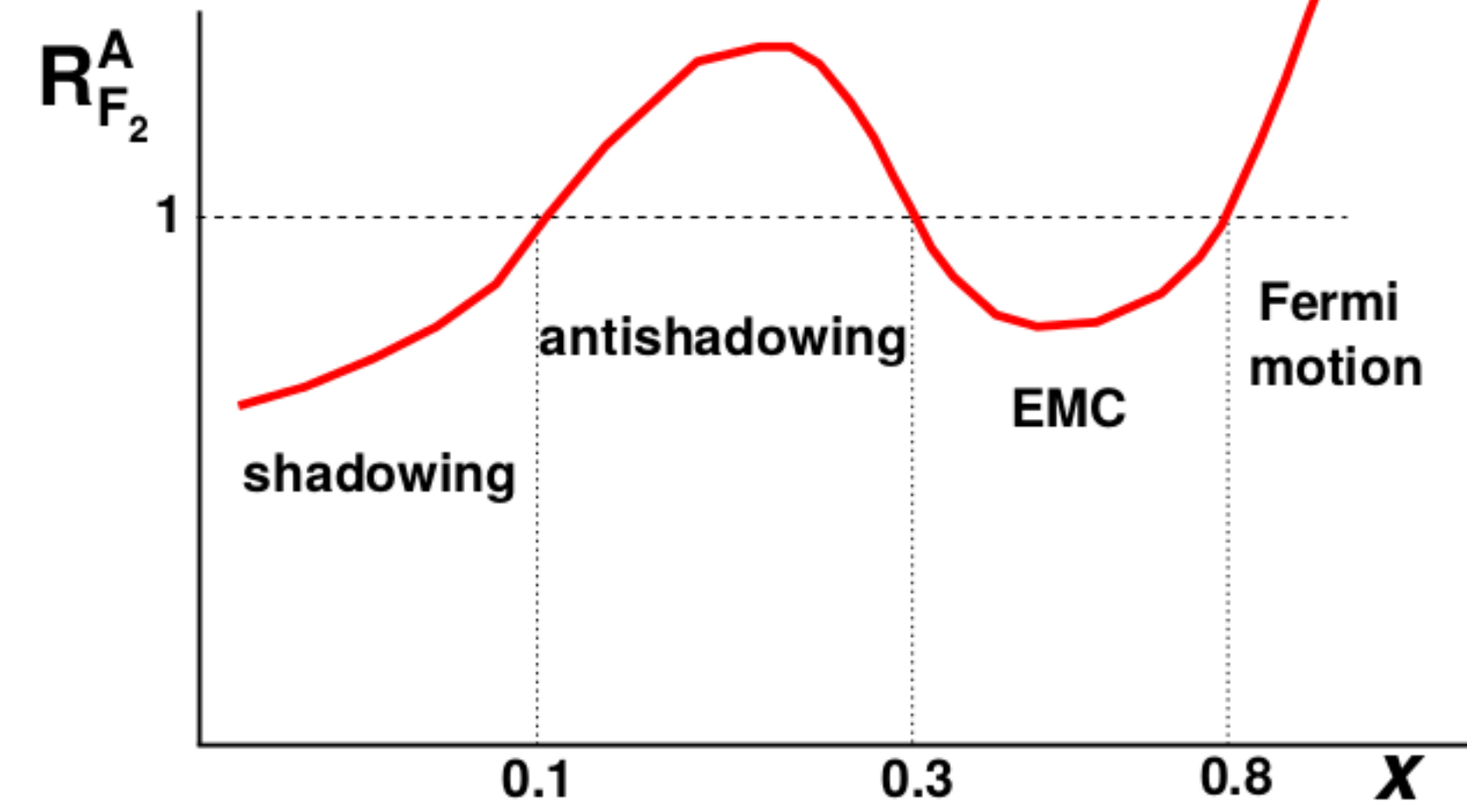
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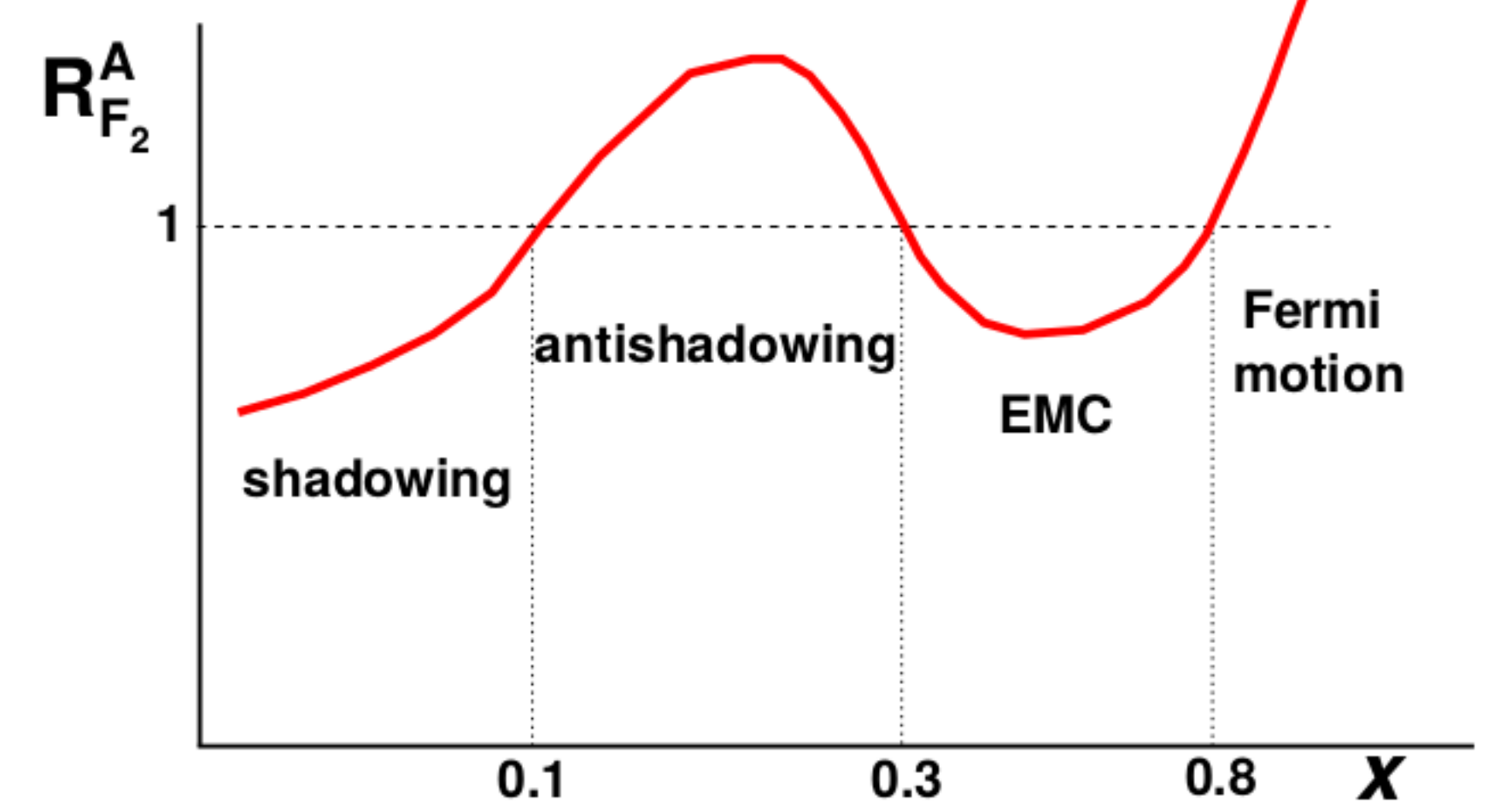
Coherent production

Nuclear GPDs (PDFs at low x_B)

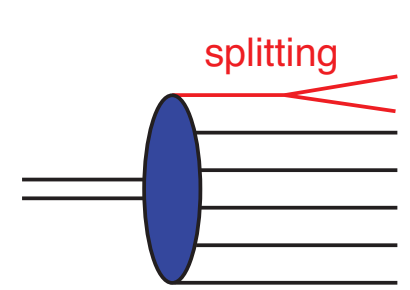


Coherent production

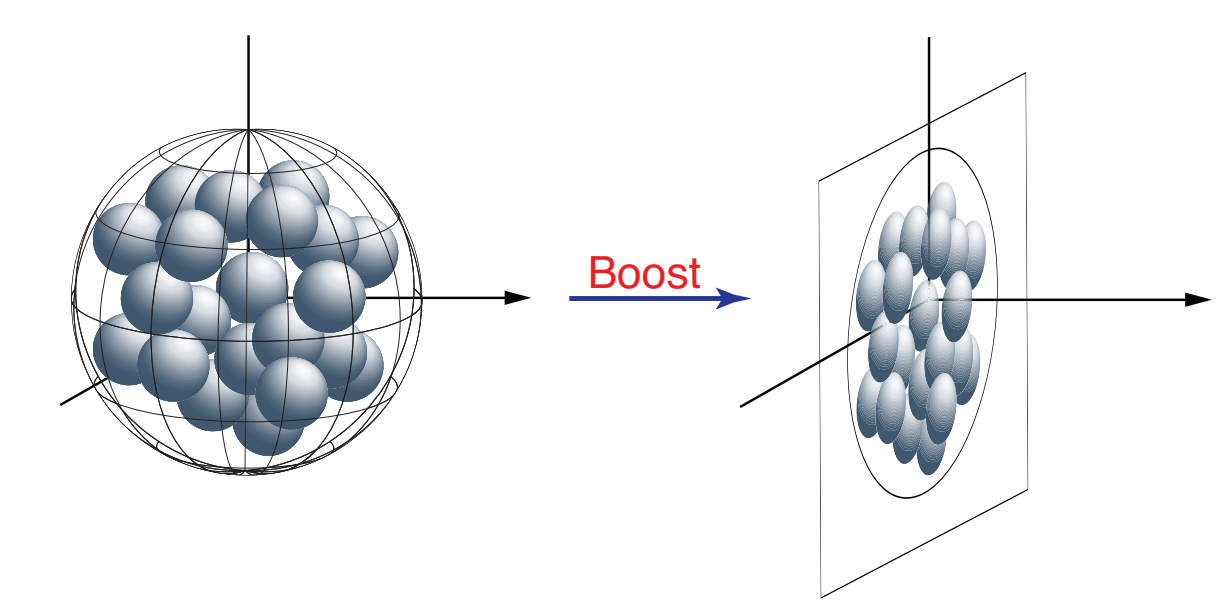
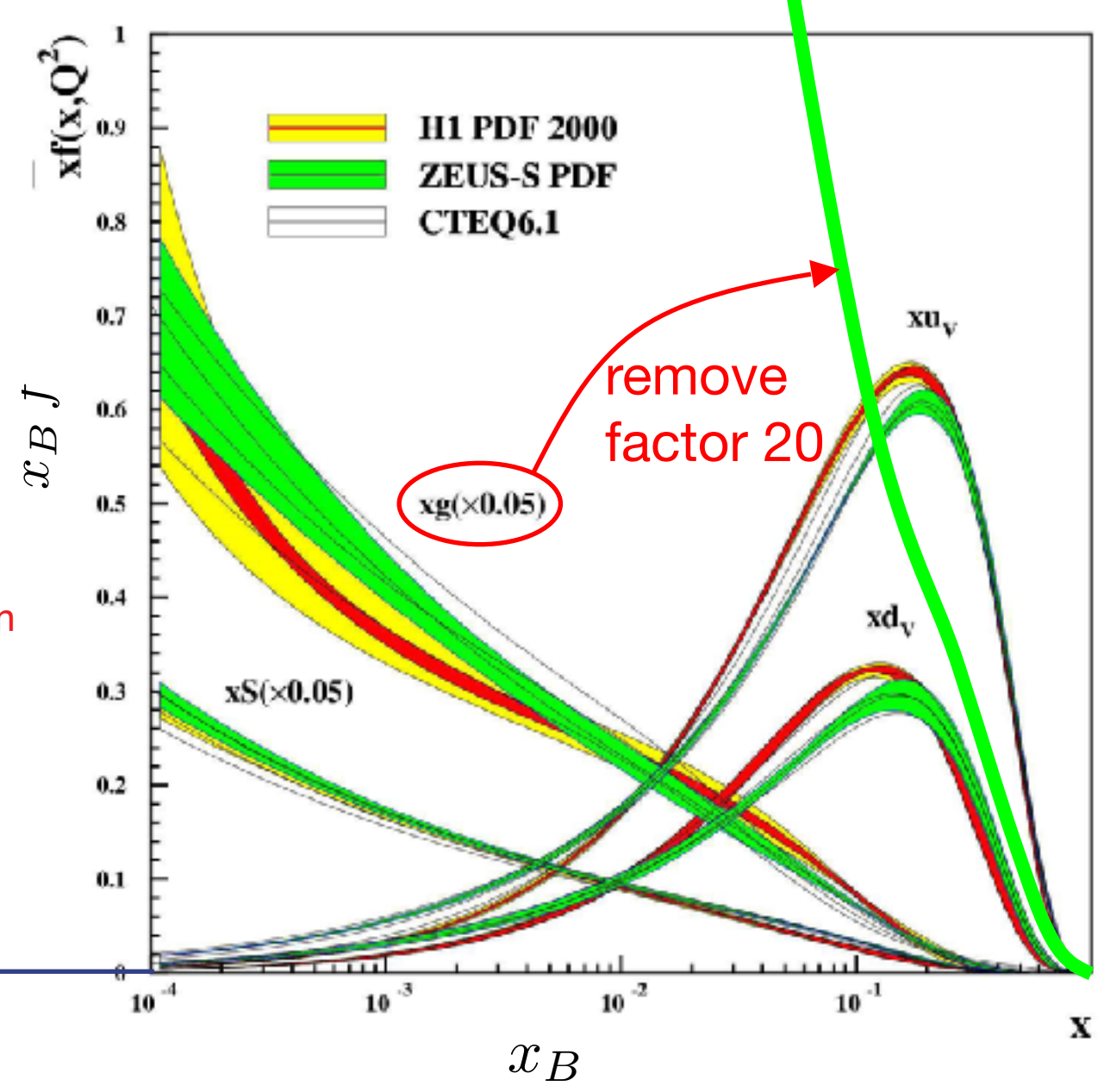
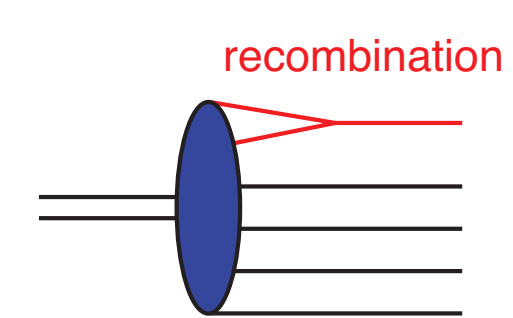
Nuclear GPDs (PDFs at low x_B)



Probing saturation



?

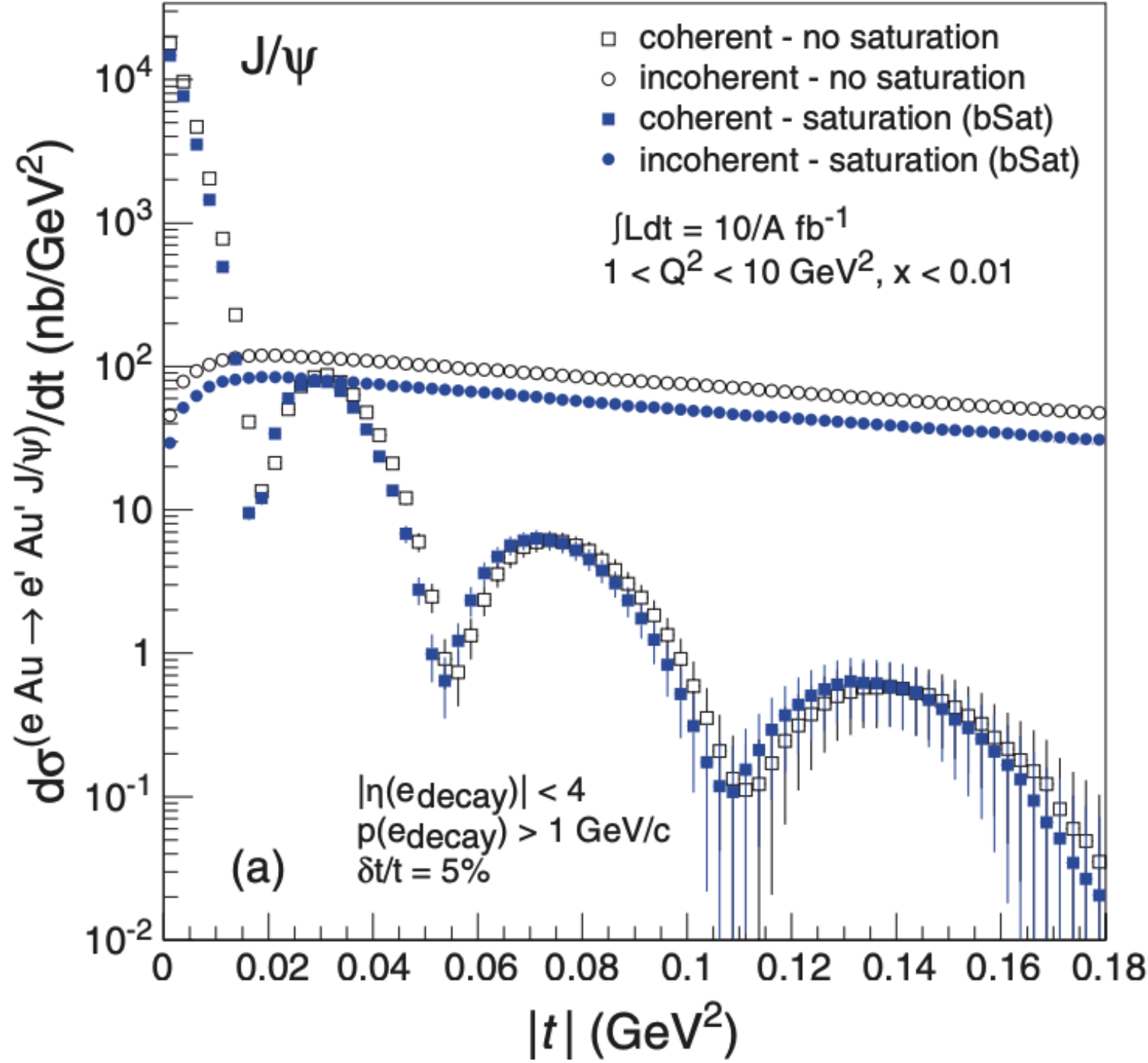


$A^{1/3}$ enhancement of saturation effect for ions

Experimental important points

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

Example at EIC
scattering of Au Toll, Ulrich, PRC **87** (13) 0249



$$-t \approx p_T^2$$

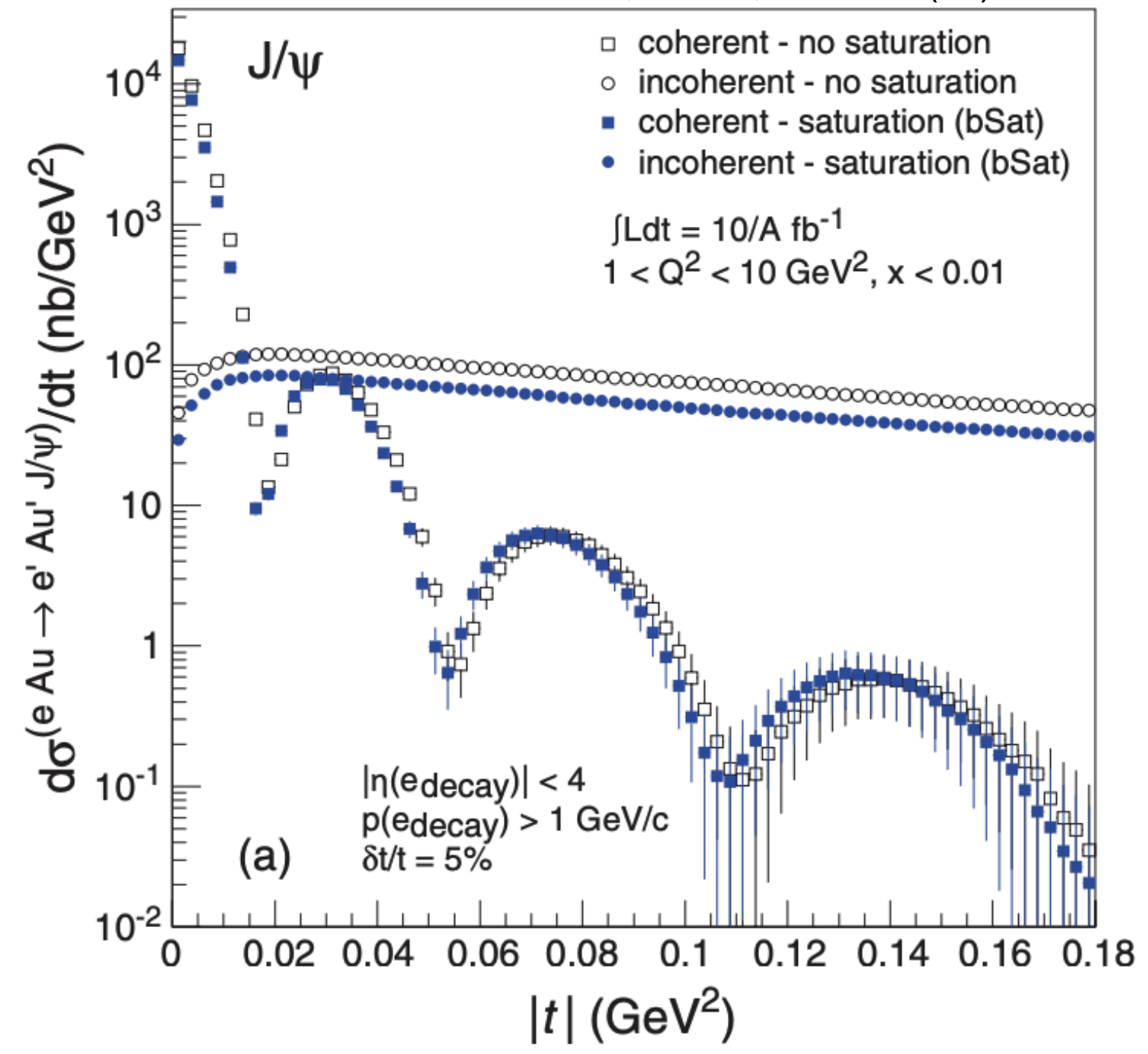
Experimental important points

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

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

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

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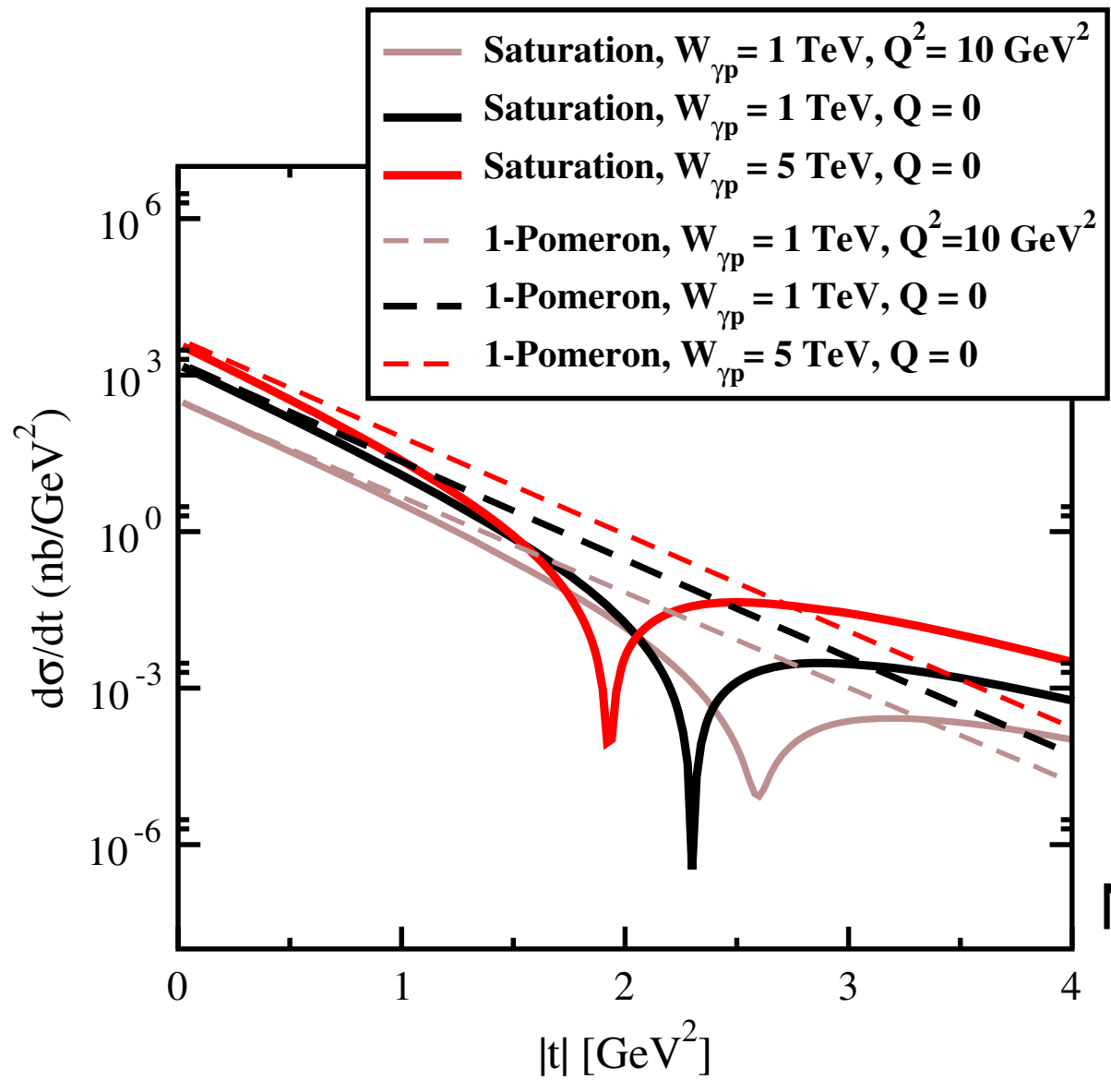
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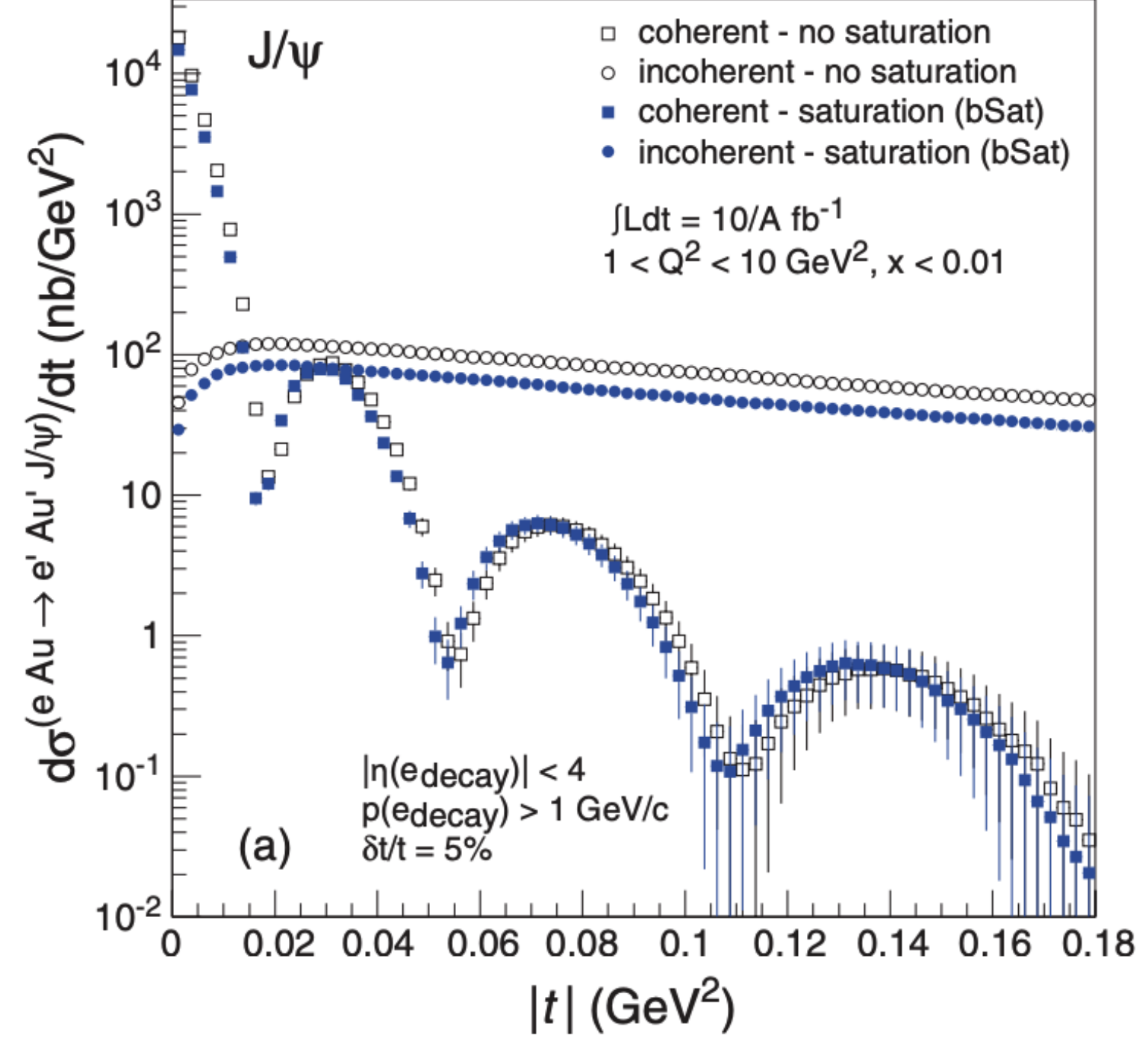
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Experimentally limited by maximum transverse momentum.
 Need to extend p_T range as much as possible in measurement.
 ~third diffractive minimum.

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



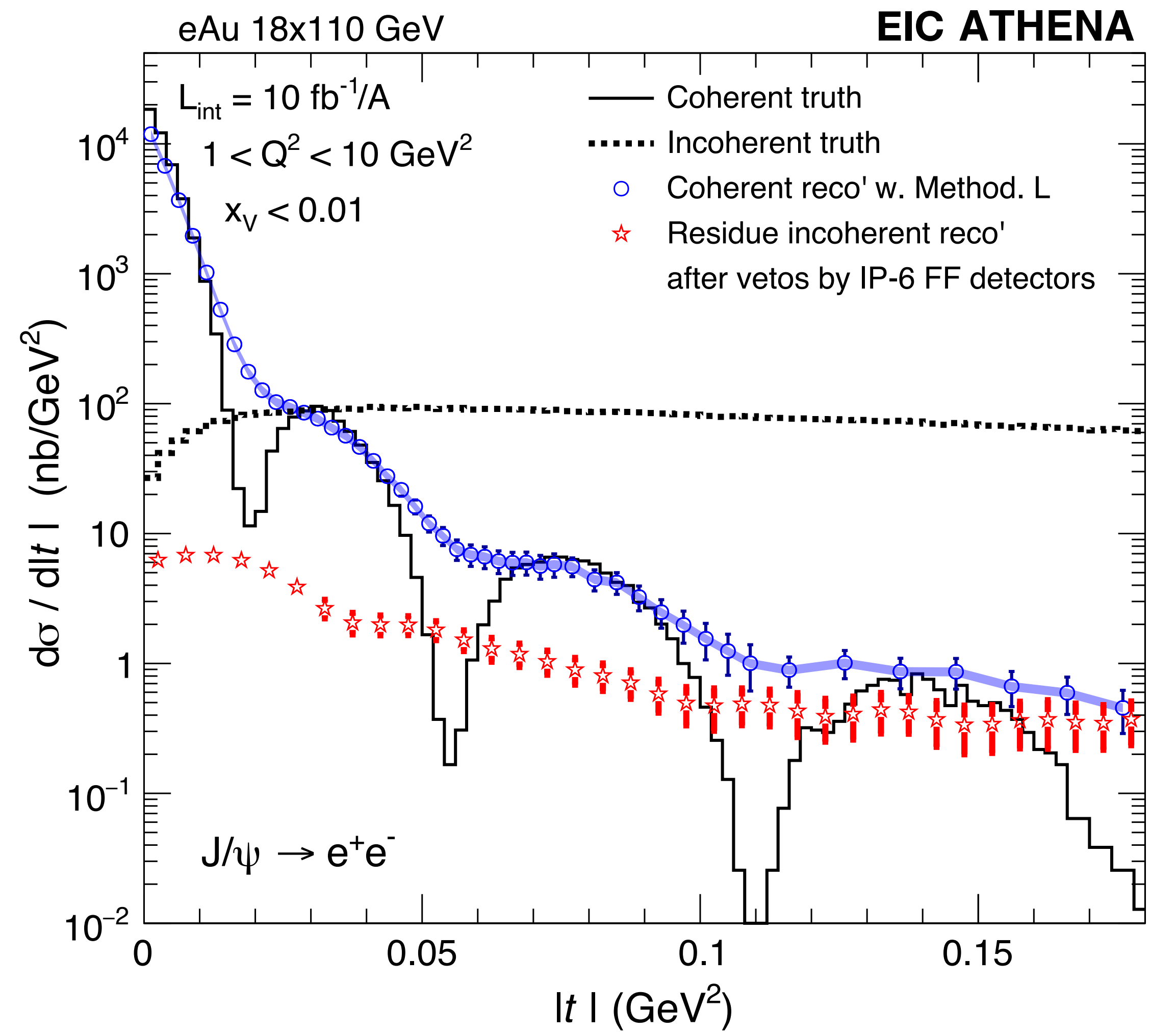
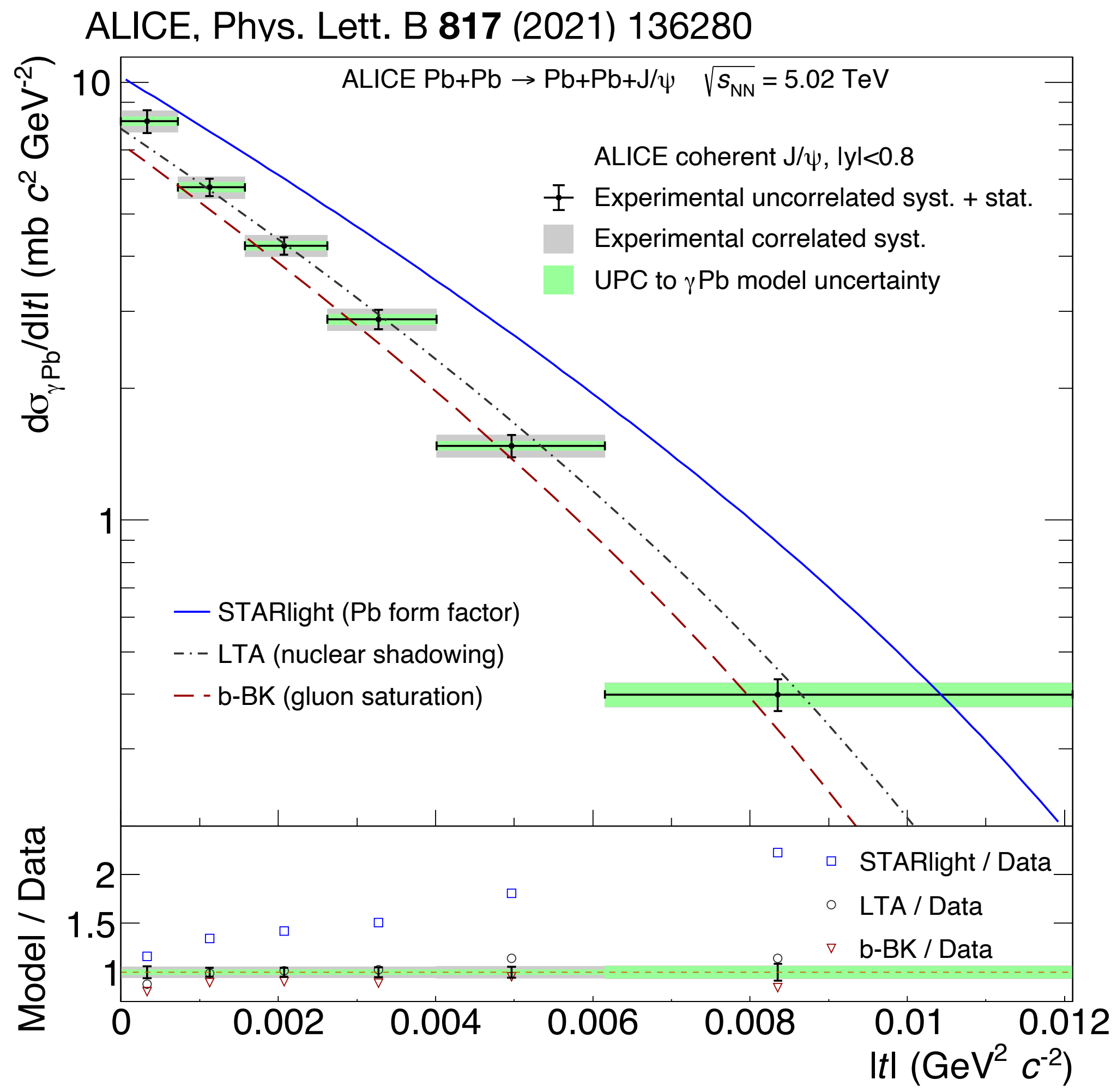
Example at EIC scattering of Au Toll, Ulrich, PRC 87 (13) 0249



$$-t \approx p_T^2$$

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

Diffractive measurements on nuclei



Incoherent production

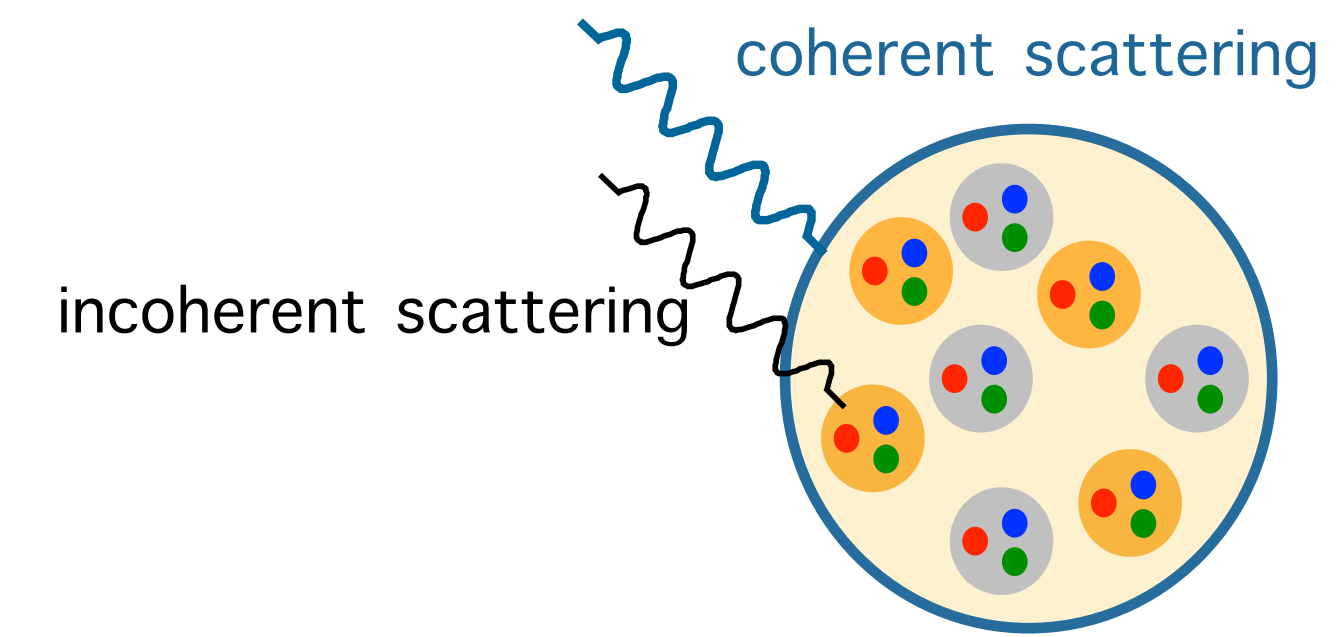
$$\sigma_{\text{tot}} \sim \langle |A|^2 \rangle$$

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

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

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

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

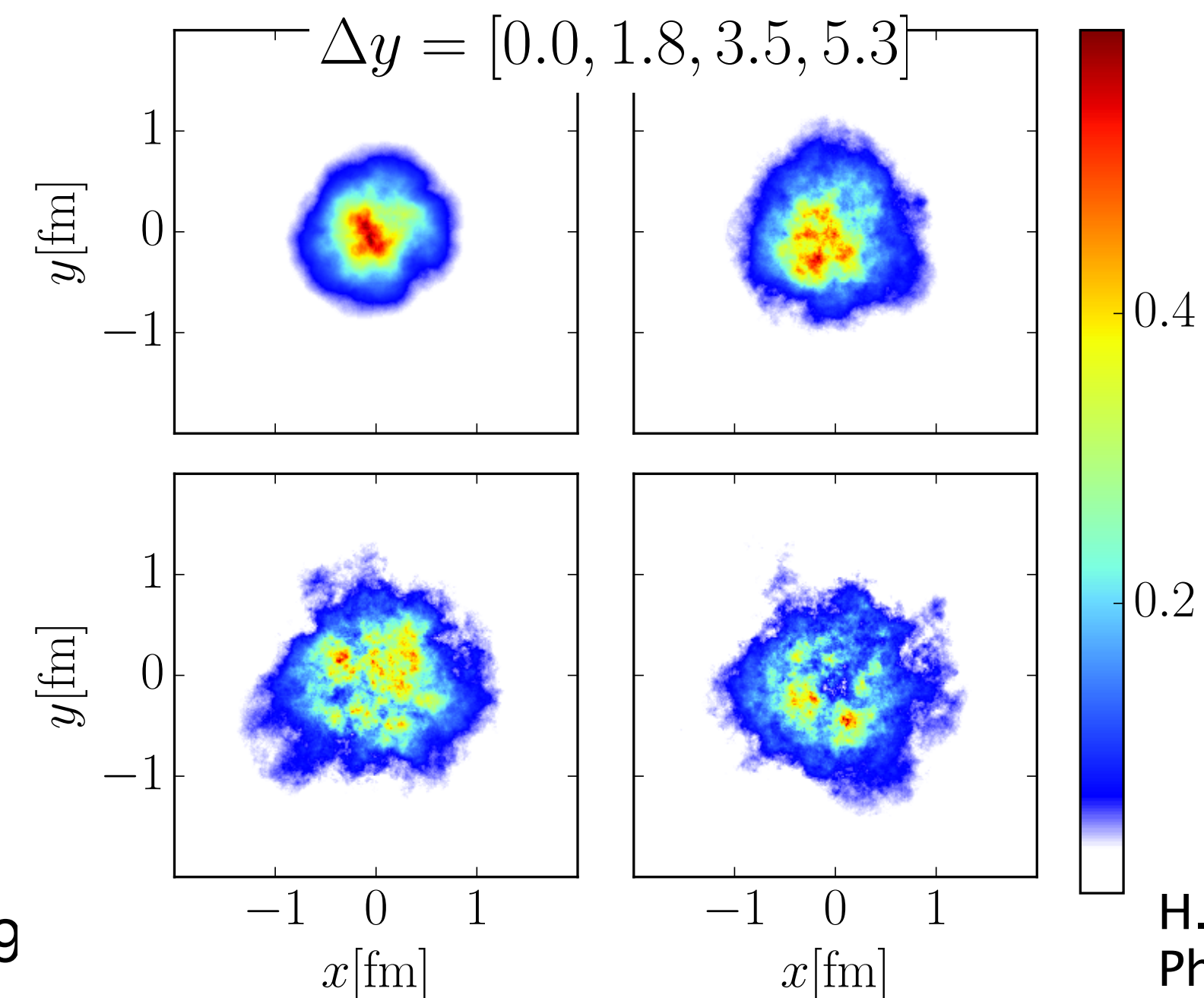


average cross sections

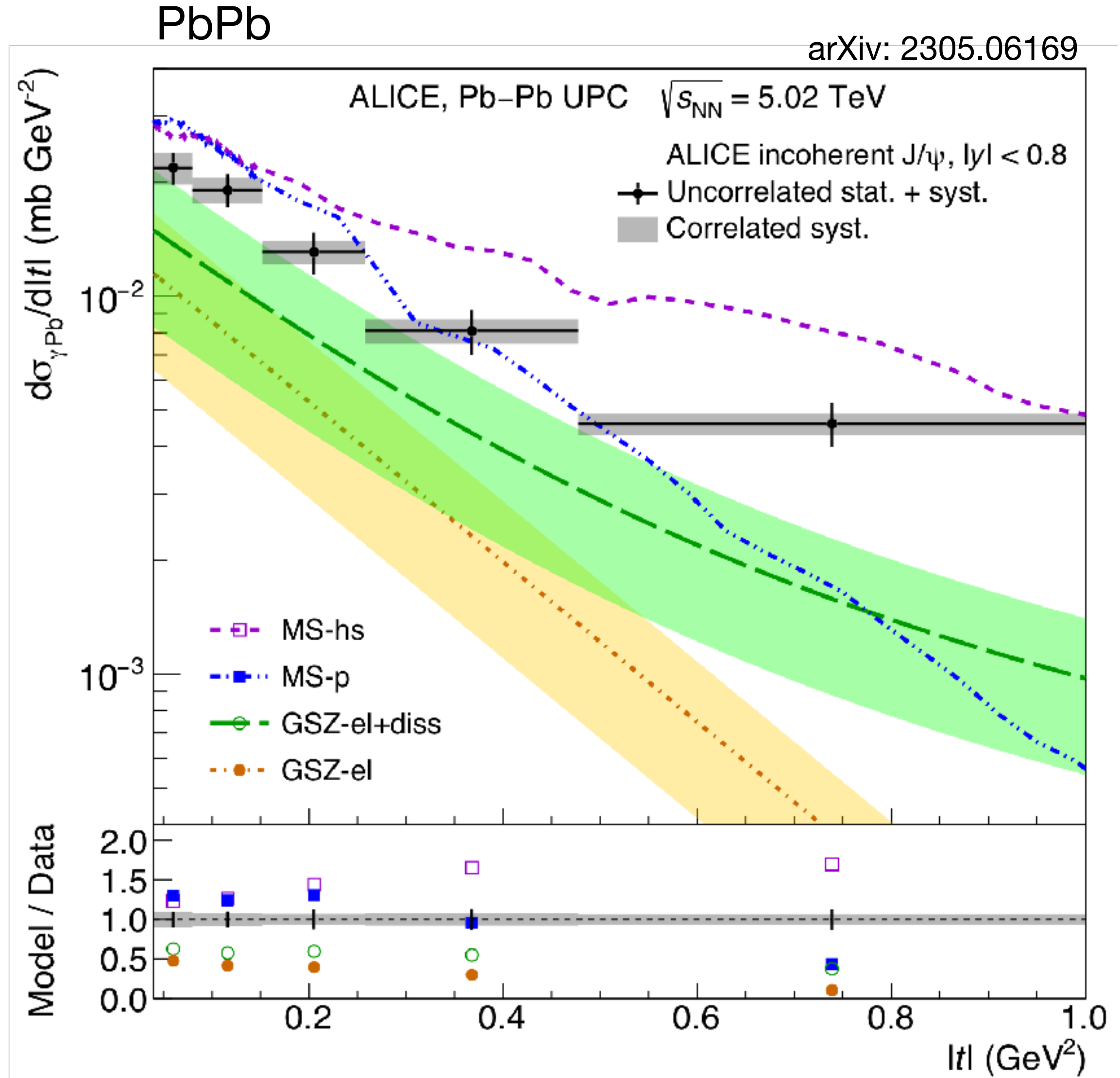
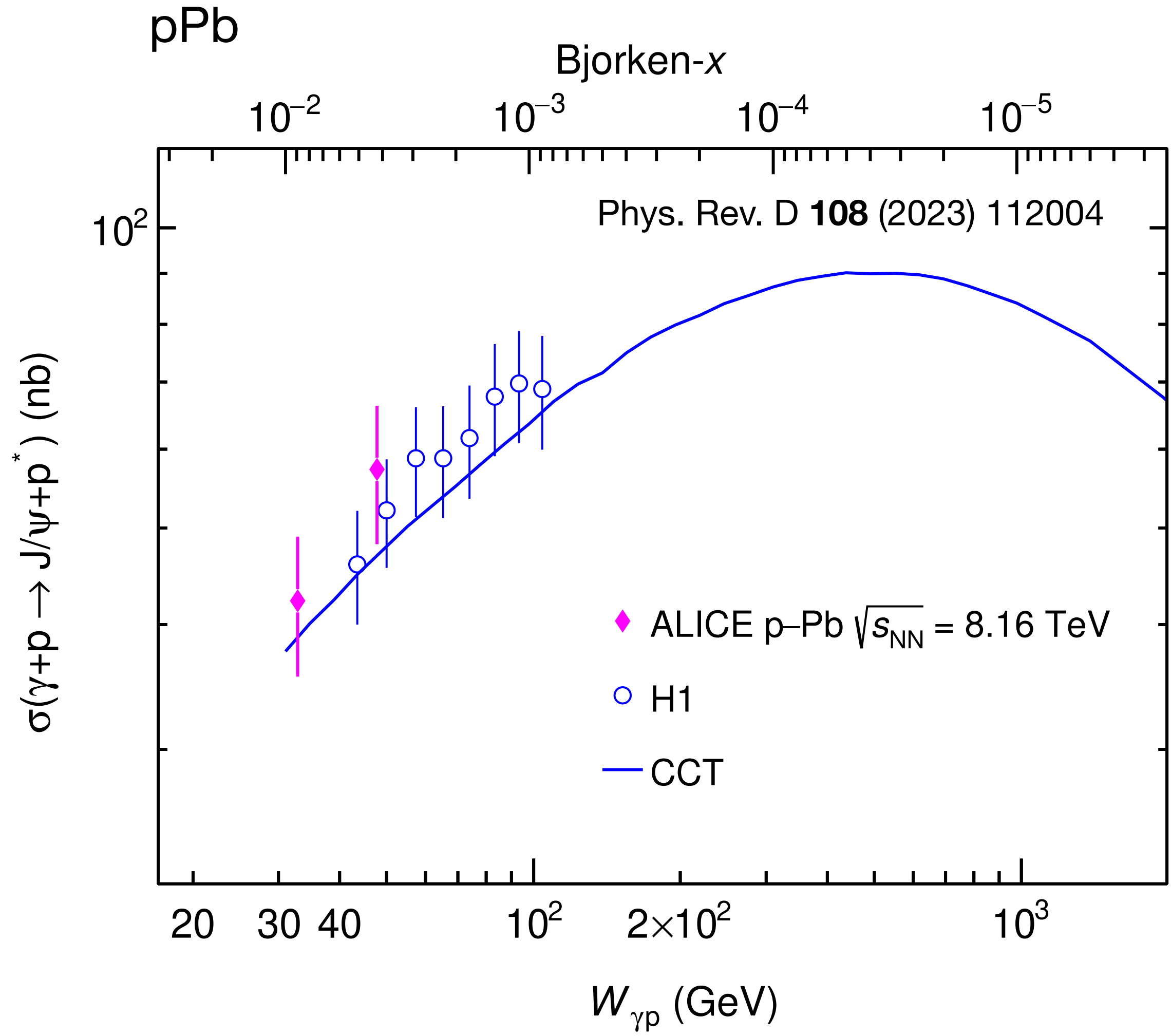
average amplitude over target configurations:
probes average distributions

Incoherent

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

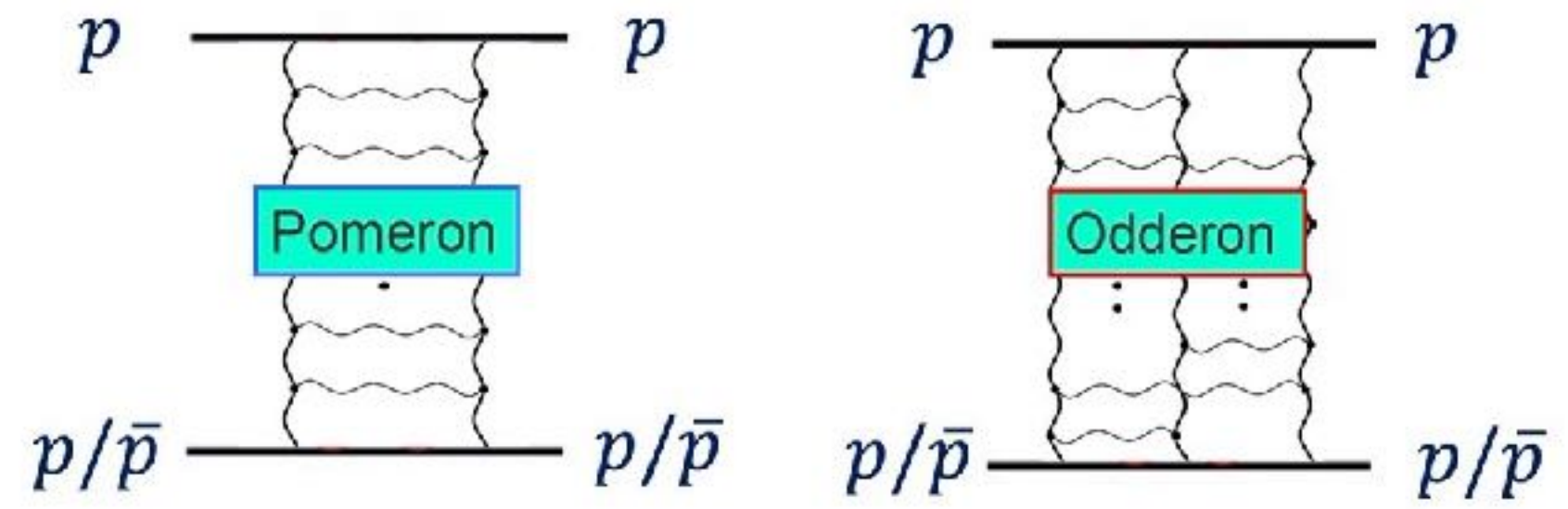


Dissociative production measured by ALICE

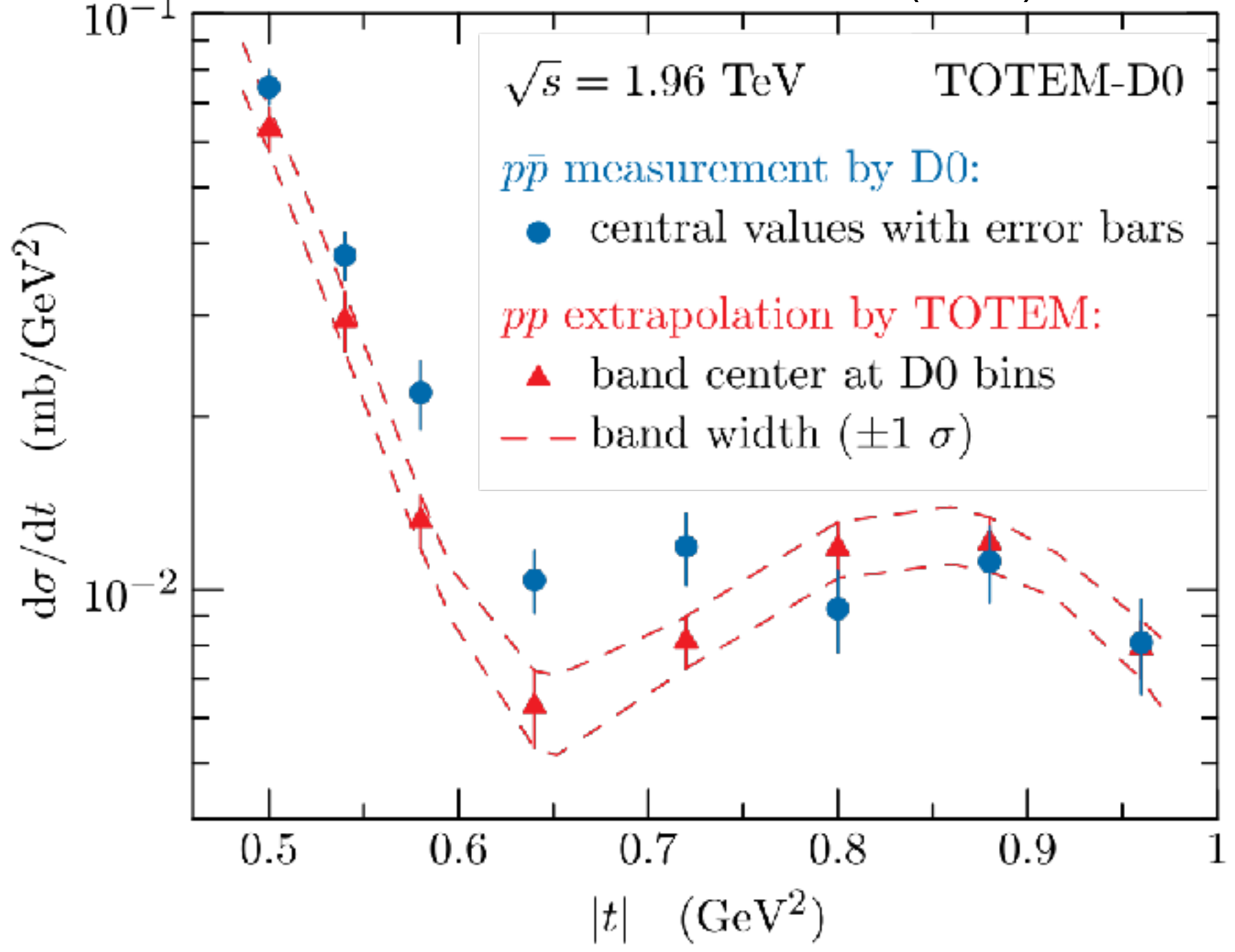


Search for the Odderon

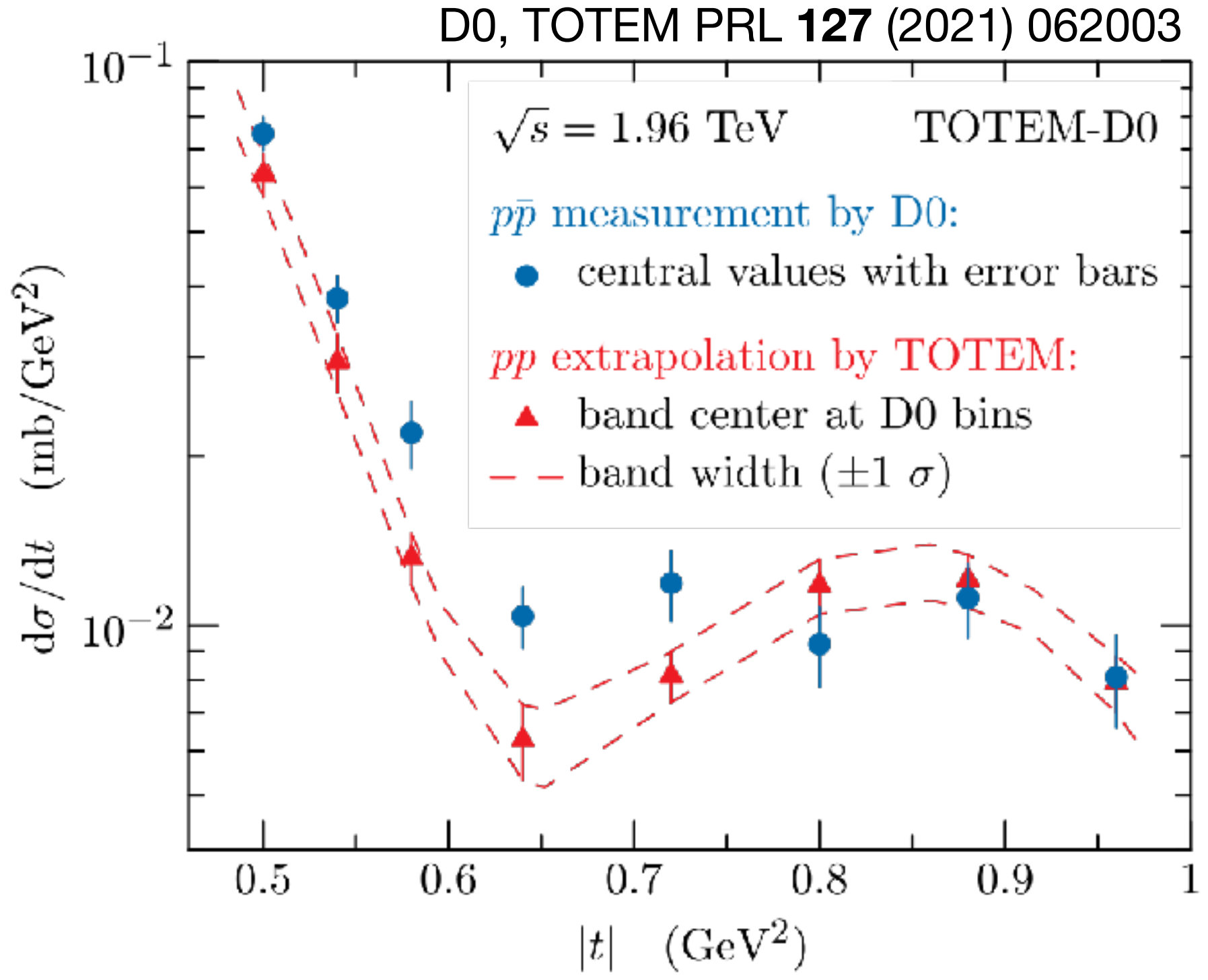
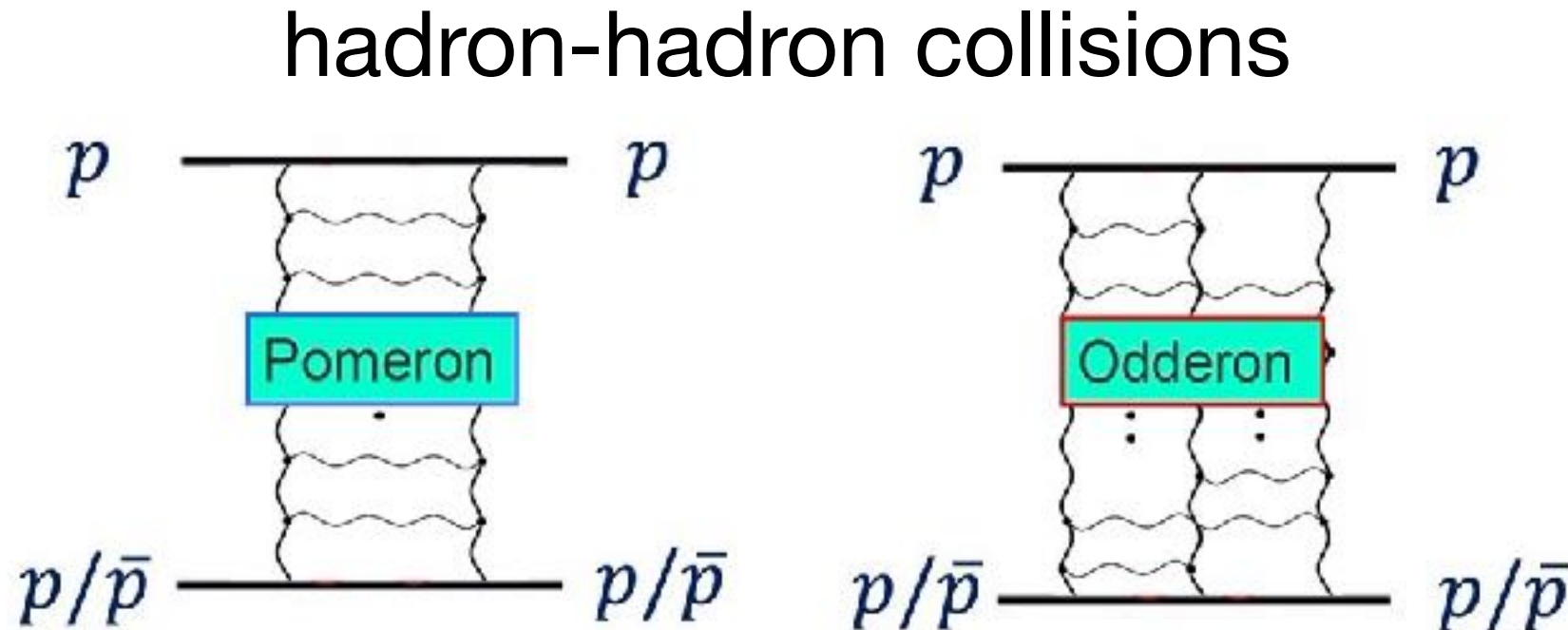
hadron-hadron collisions



D0, TOTEM PRL **127** (2021) 062003



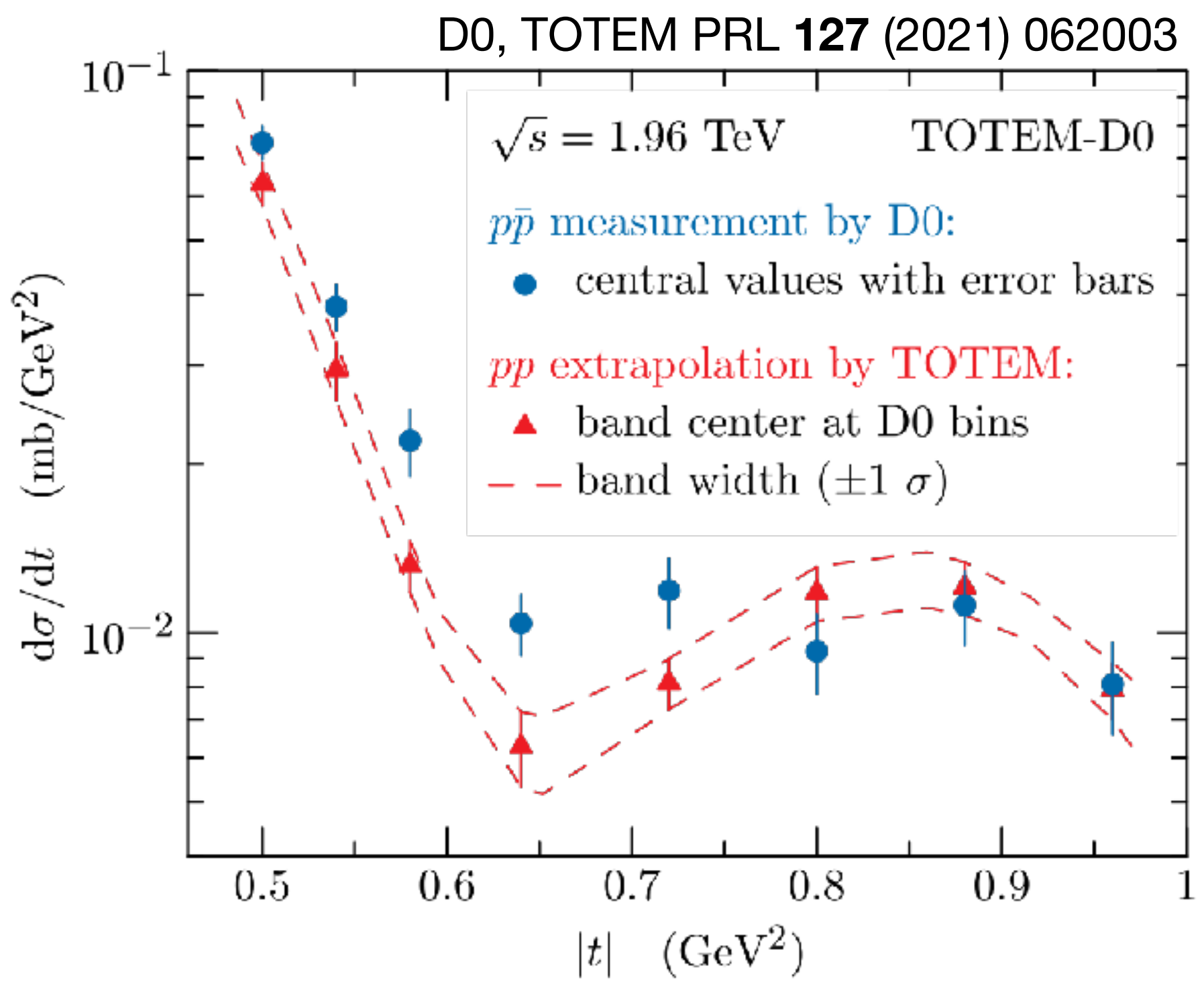
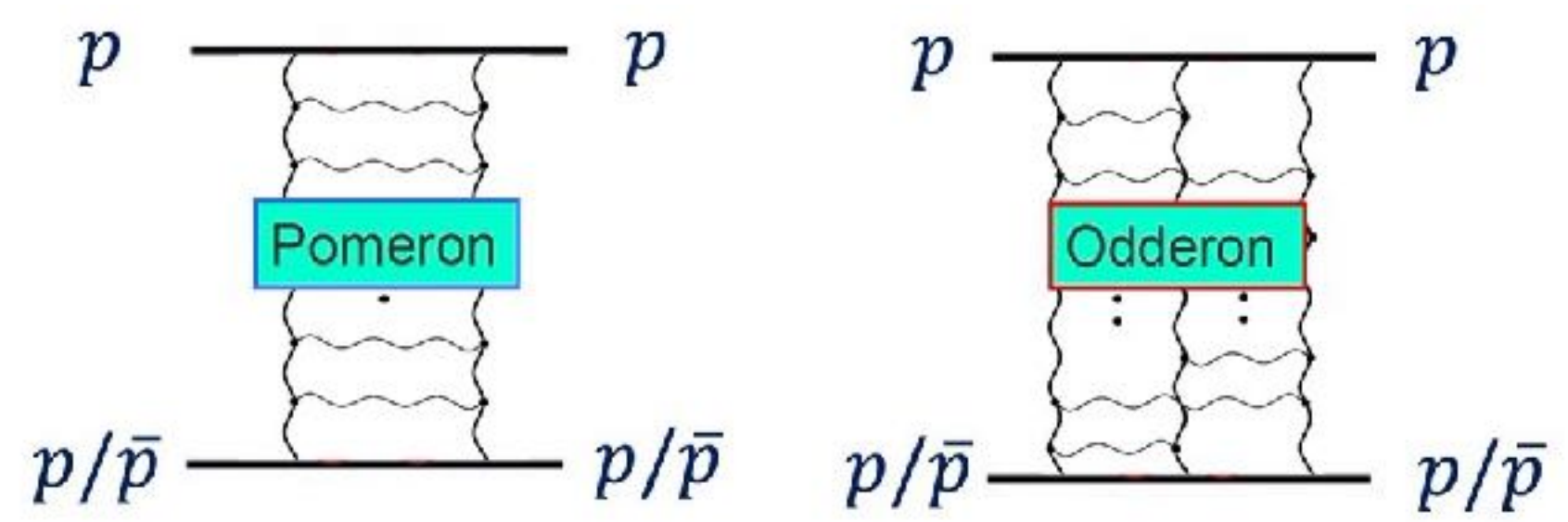
Search for the Odderon



also e.g., f_2 in pA and AA collisions

Search for the Odderon

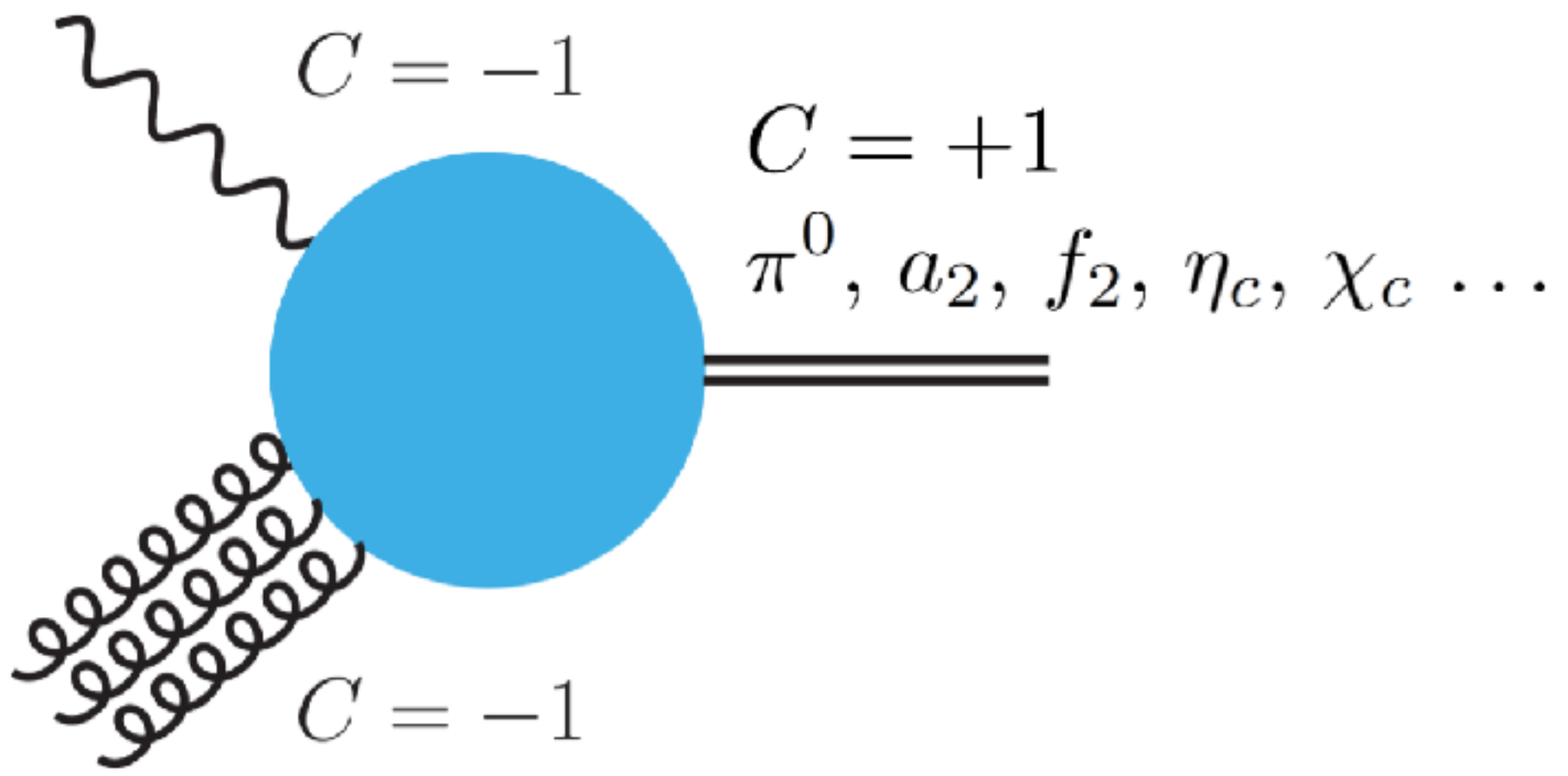
hadron-hadron collisions



also e.g., f_2 in pA and AA collisions

R. McNulty et al., EPJC **80** (2020) 288

deep-inelastic scattering



offers more theoretical control

Measurement by H1

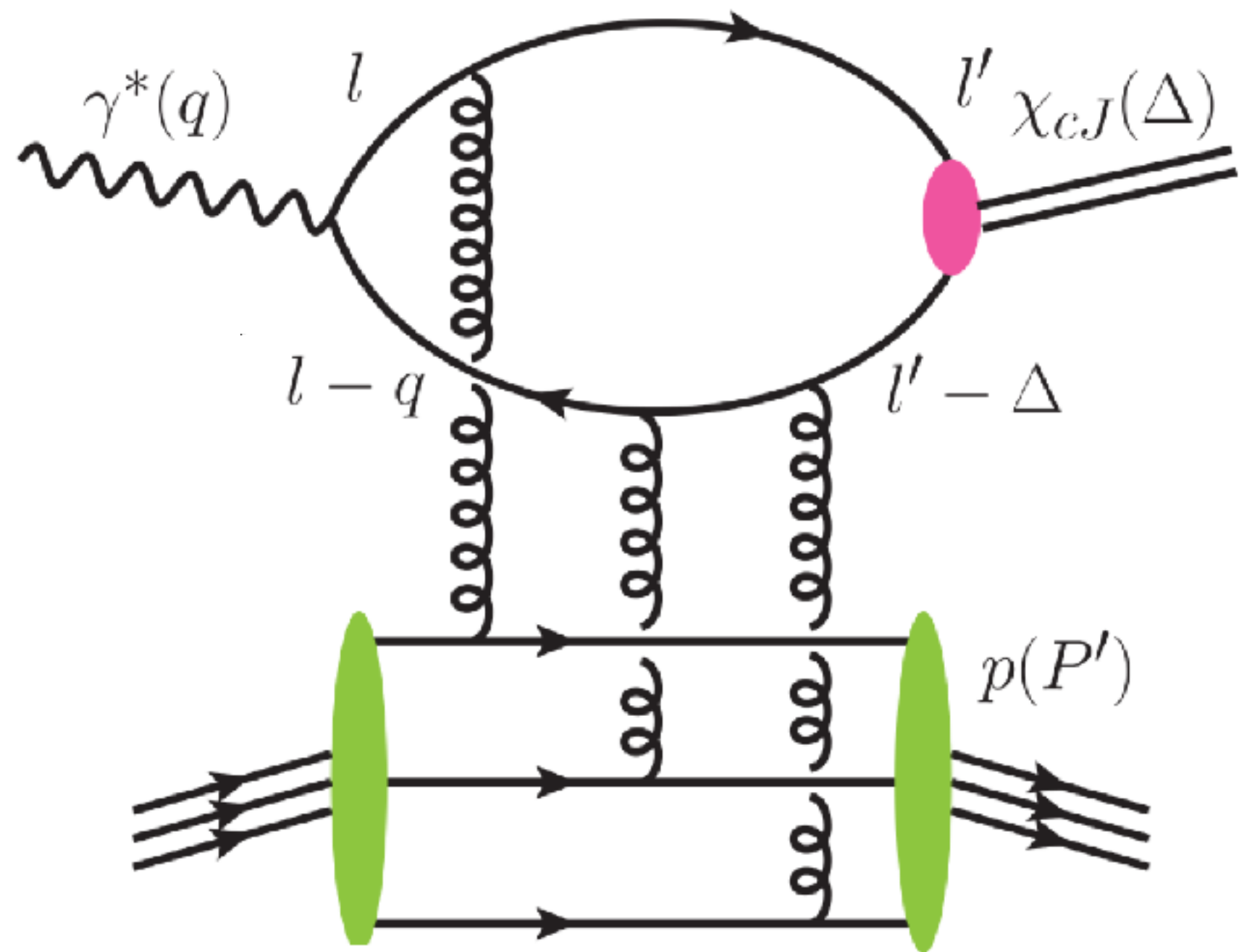
Phys. Lett. B **544** (2002) 35–43

$\sigma(\gamma^* p \rightarrow \pi^0 N^*) < 39 \text{ nb}$

$\sigma(\gamma^* p \rightarrow f_2 X) < 16 \text{ nb}$

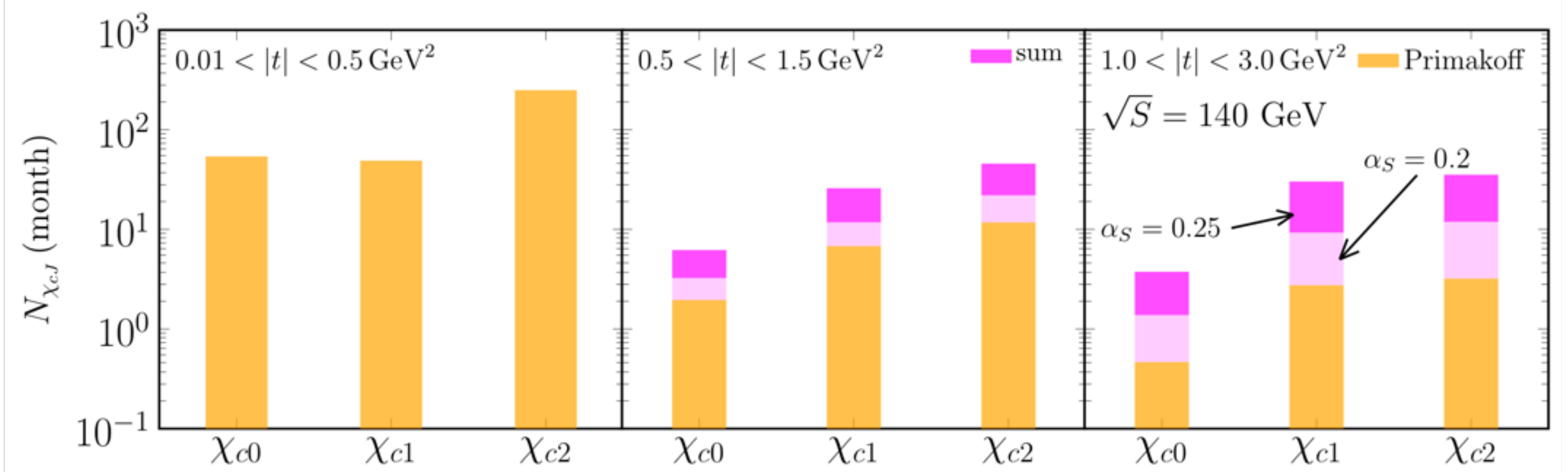
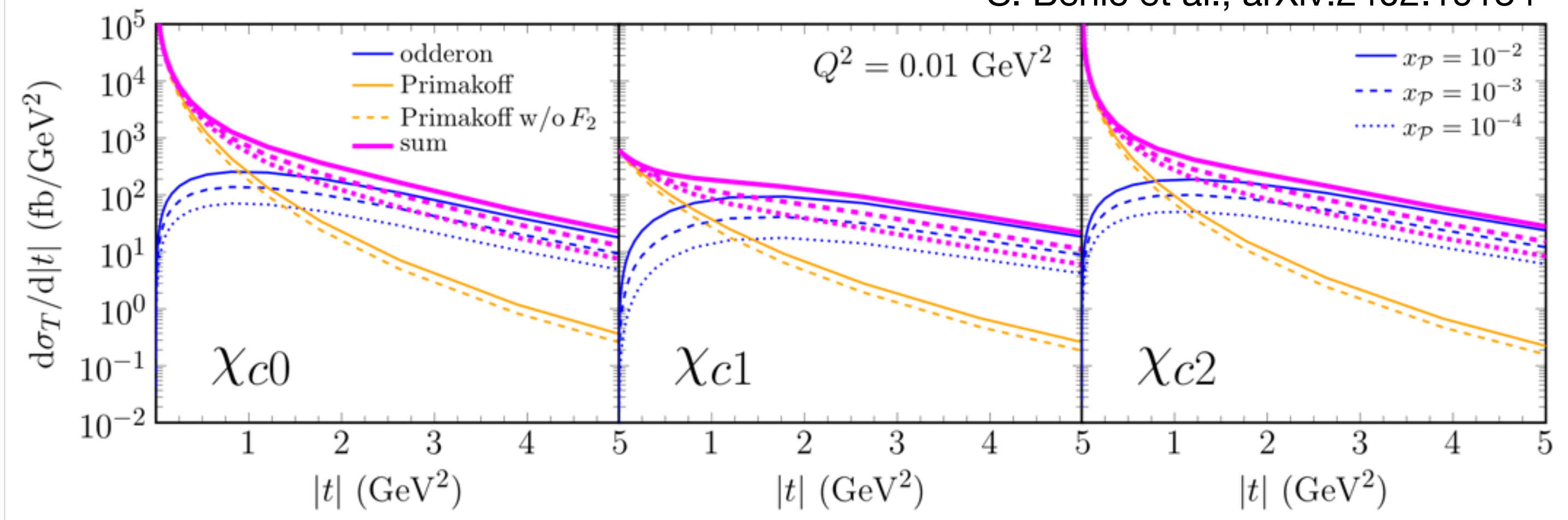
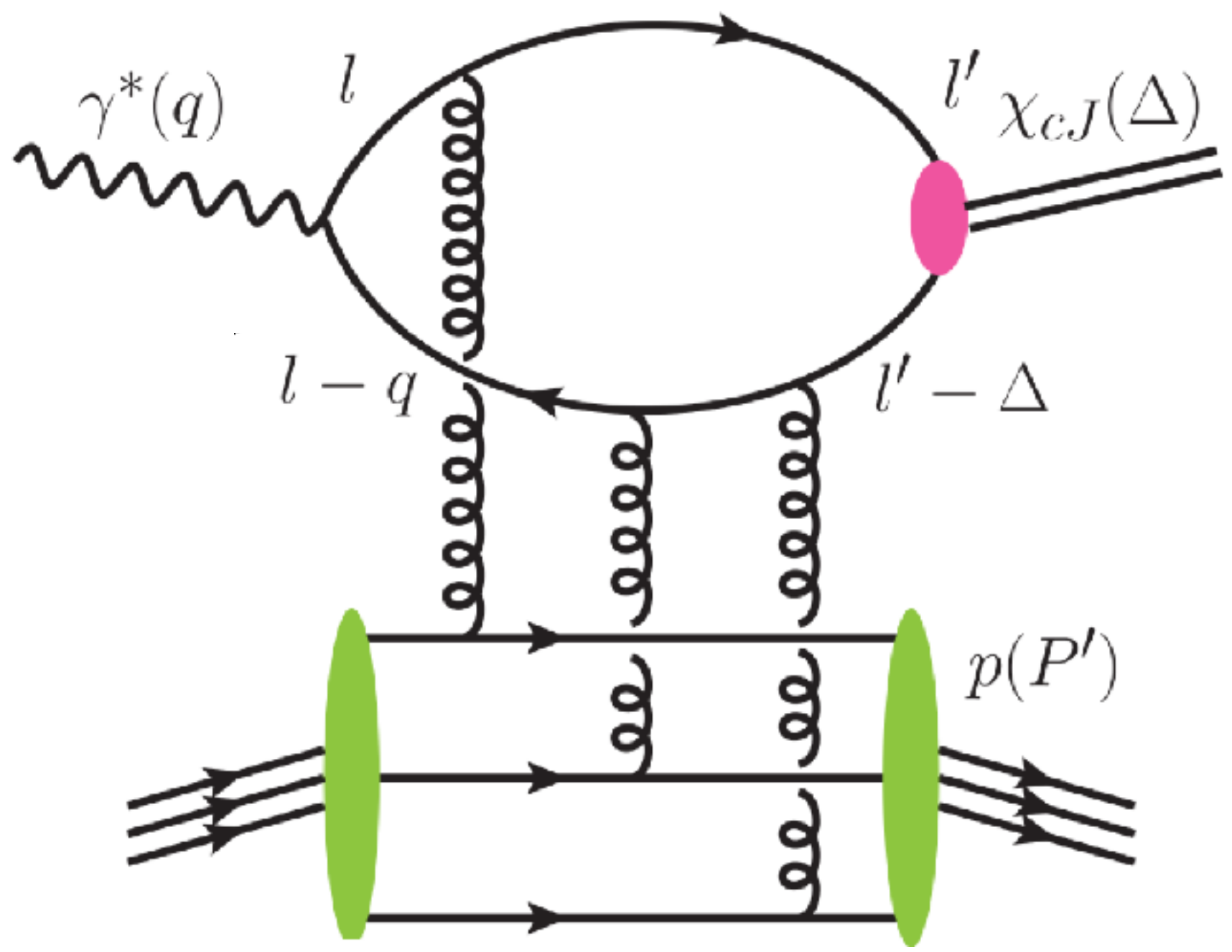
$\sigma(\gamma^* p \rightarrow a_2 X) < 96 \text{ nb}$

Search for the Odderon at the EIC



Search for the Odderon at the EIC

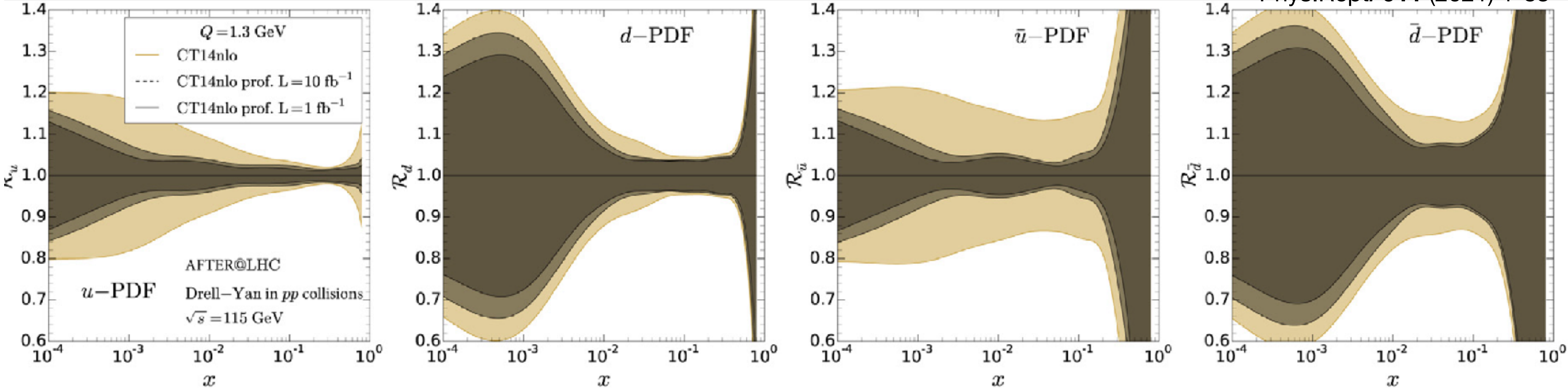
S. Benić et al., arXiv:2402.19134



Fixed target and nucleon PDFs

C. Hadjidakis et al.,
 Phys.Rept. **911** (2021) 1-83

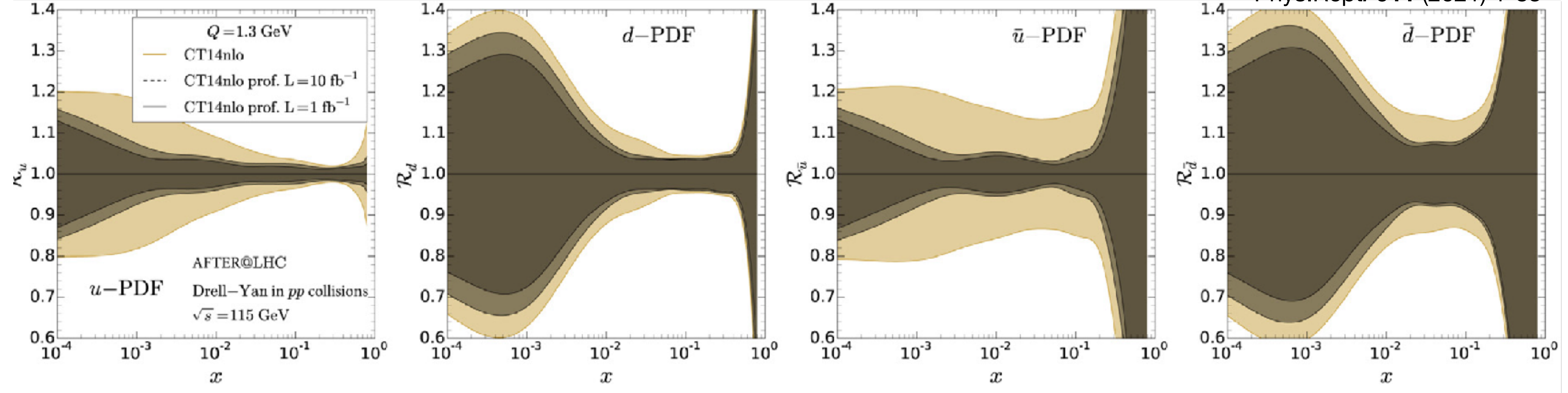
Drell-Yan impact on nucleon PDFs



Fixed target and nucleon PDFs

C. Hadjidakis et al.,
Phys.Rept. **911** (2021) 1-83

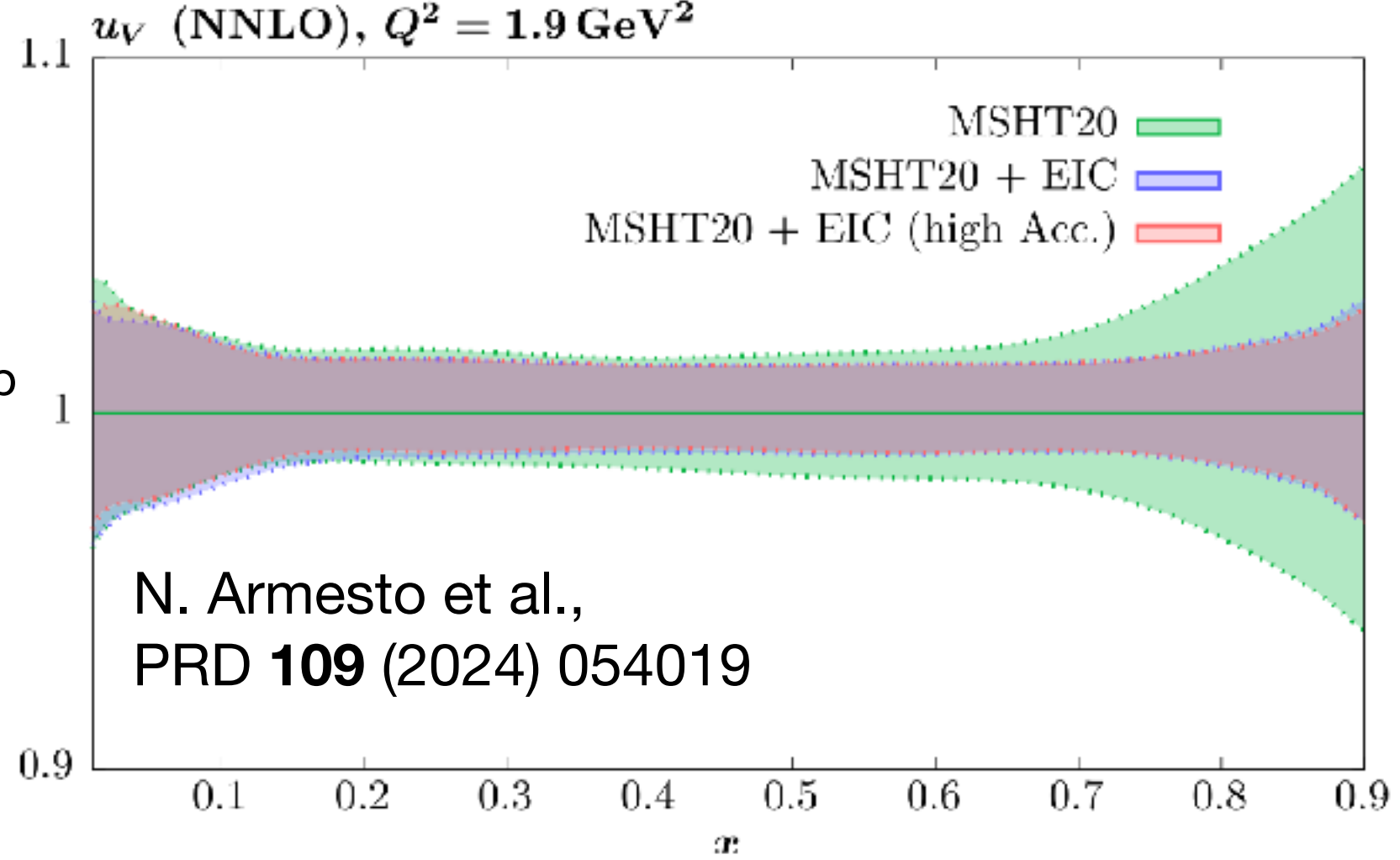
Drell-Yan impact on nucleon PDFs



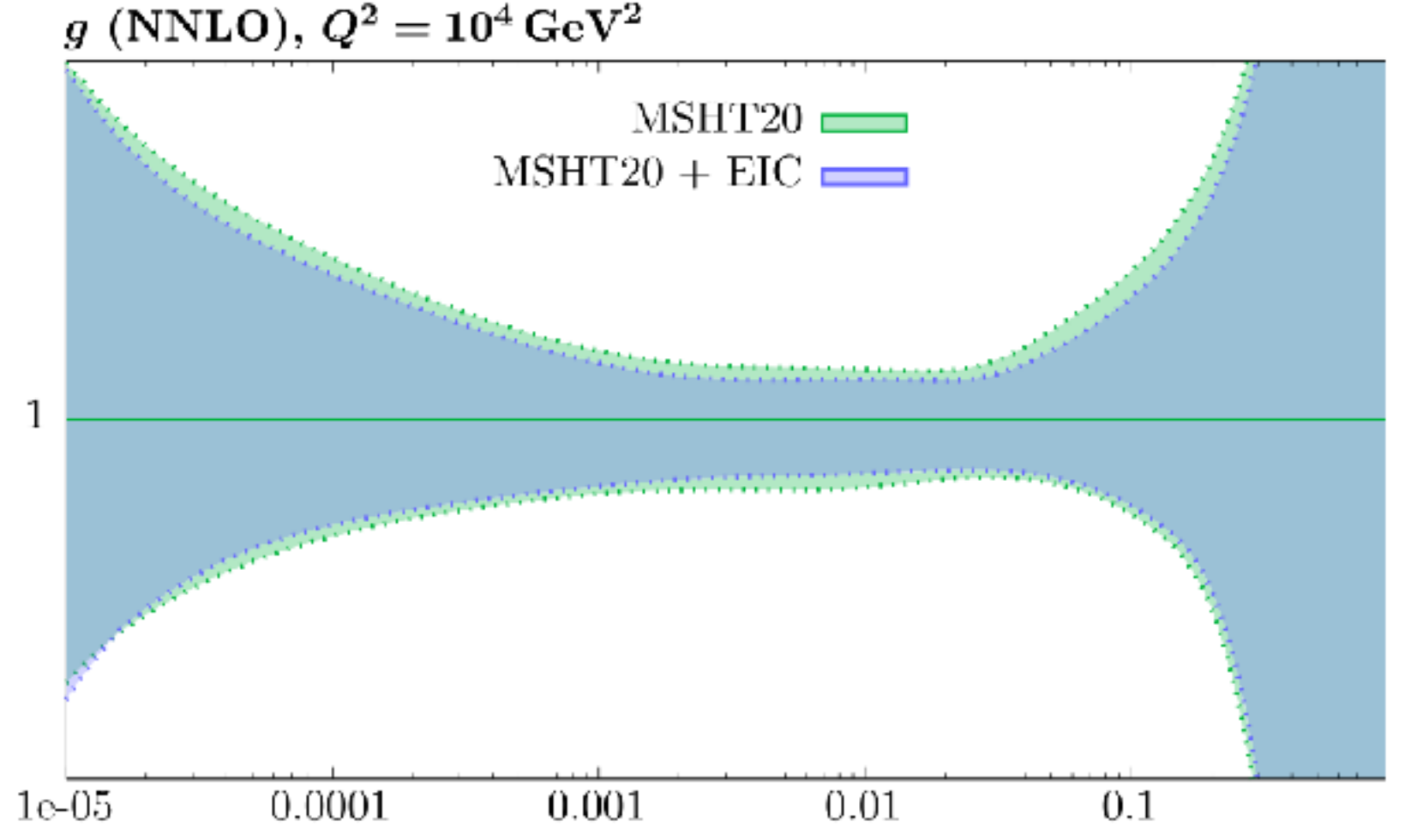
Inclusive e-p data only

E_{ep} : 18x275, 10x275, 10x100
5x100, 5x41

\mathcal{L} : 1 year of data collection for each E_{ep}



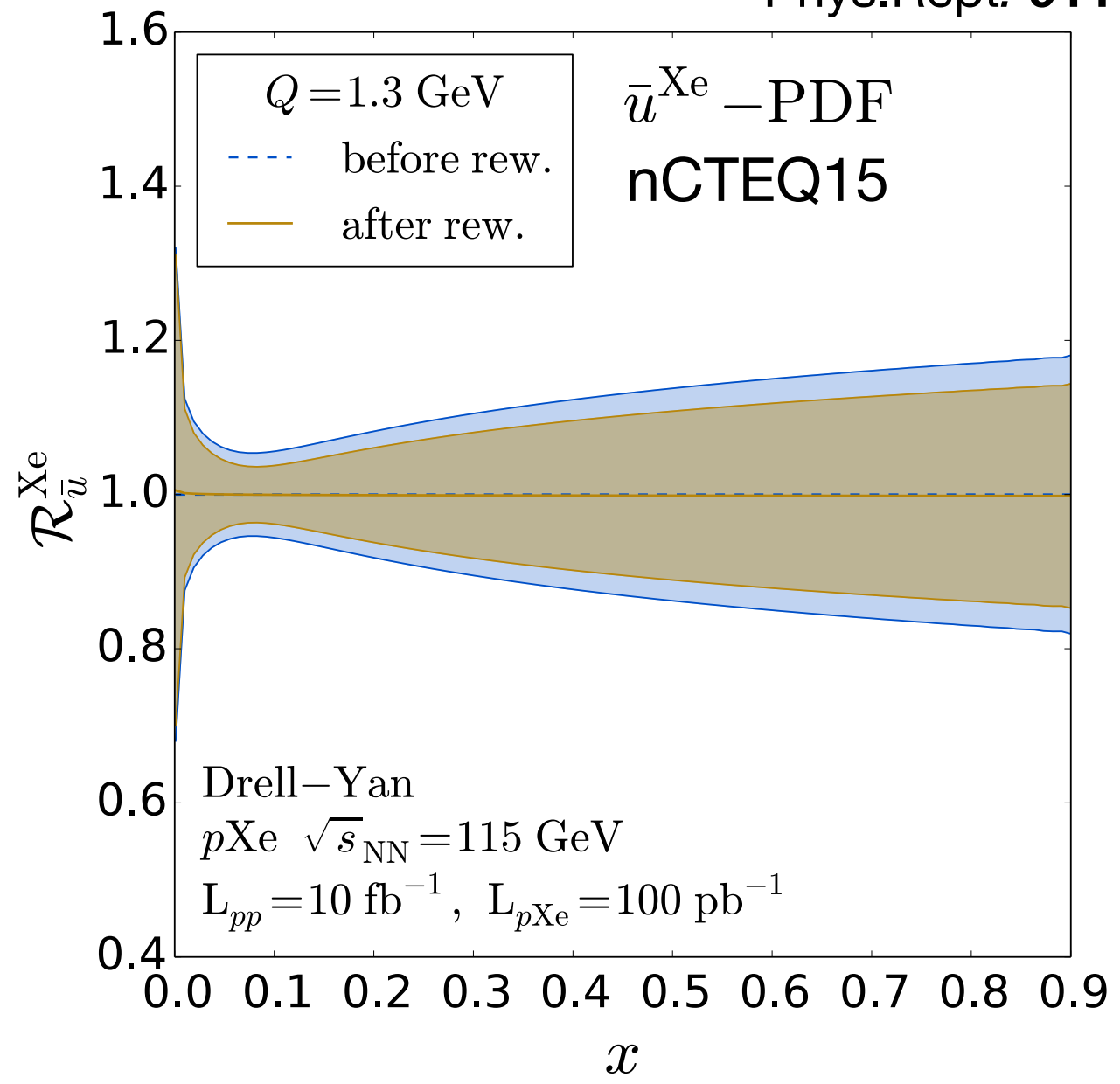
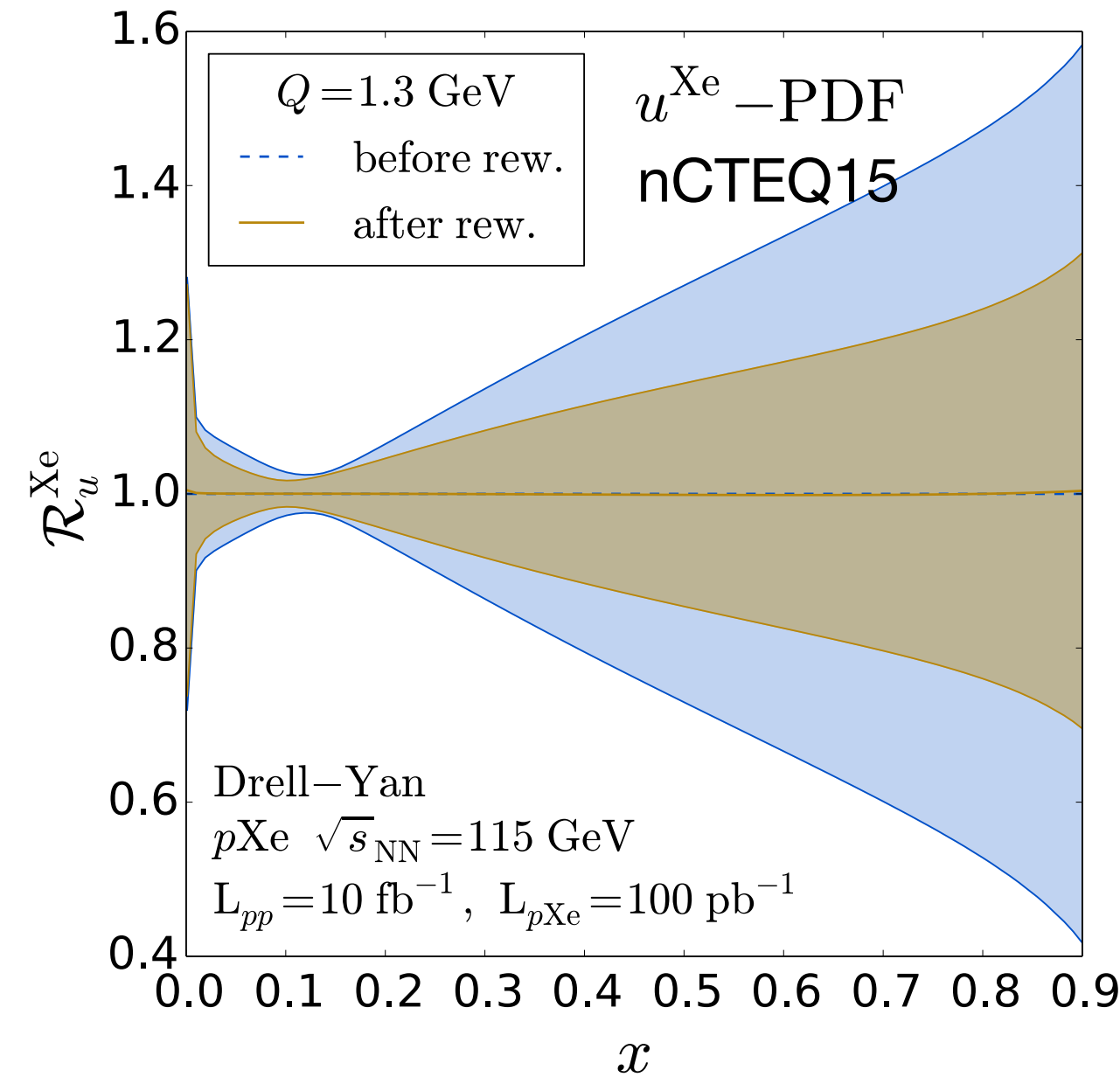
N. Armesto et al.,
PRD **109** (2024) 054019



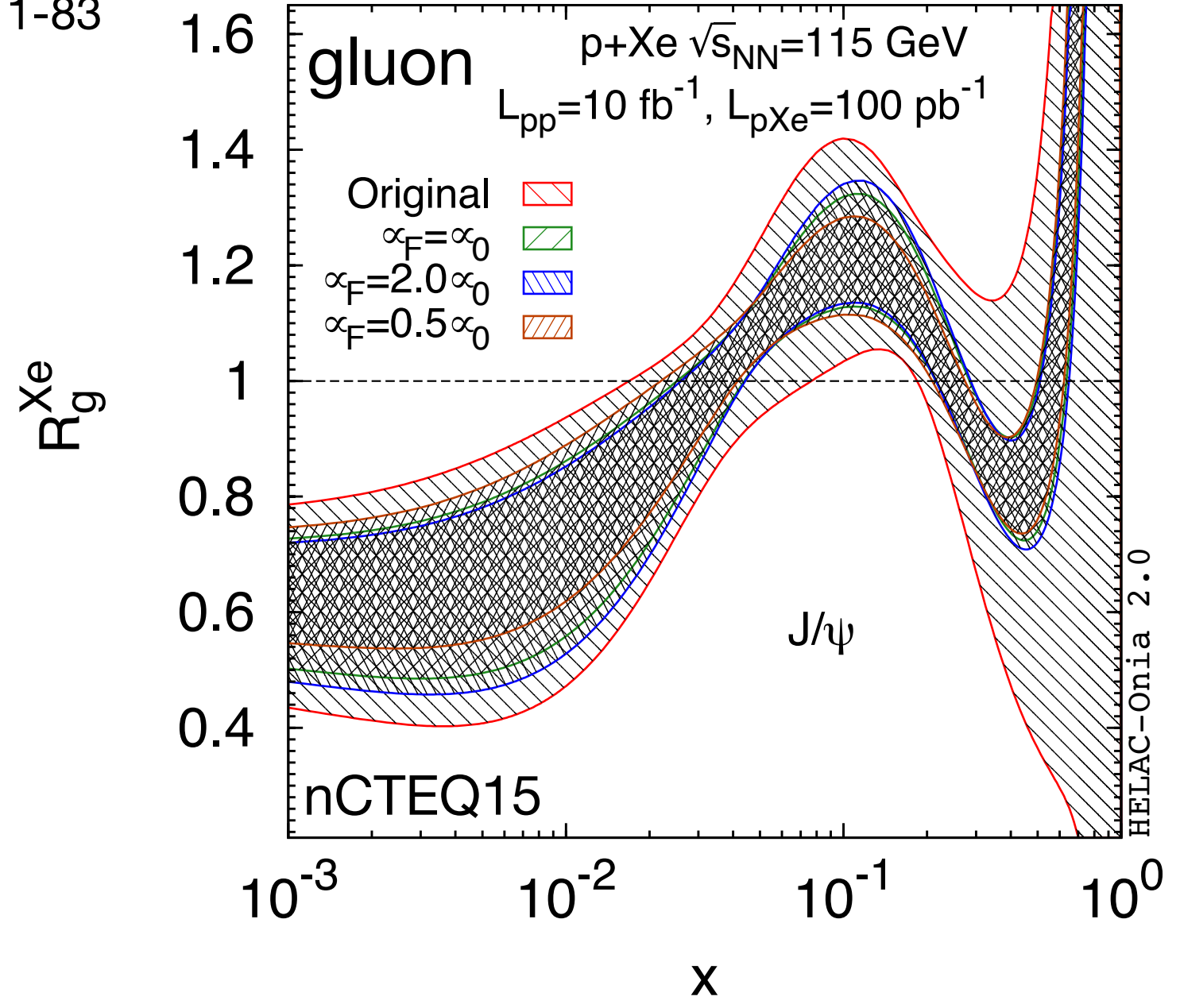
Fixed target and nuclear PDFs

Fixed-target Drell-Yan

C. Hadjidakis et al.,
Phys.Rept. **911** (2021) 1-83



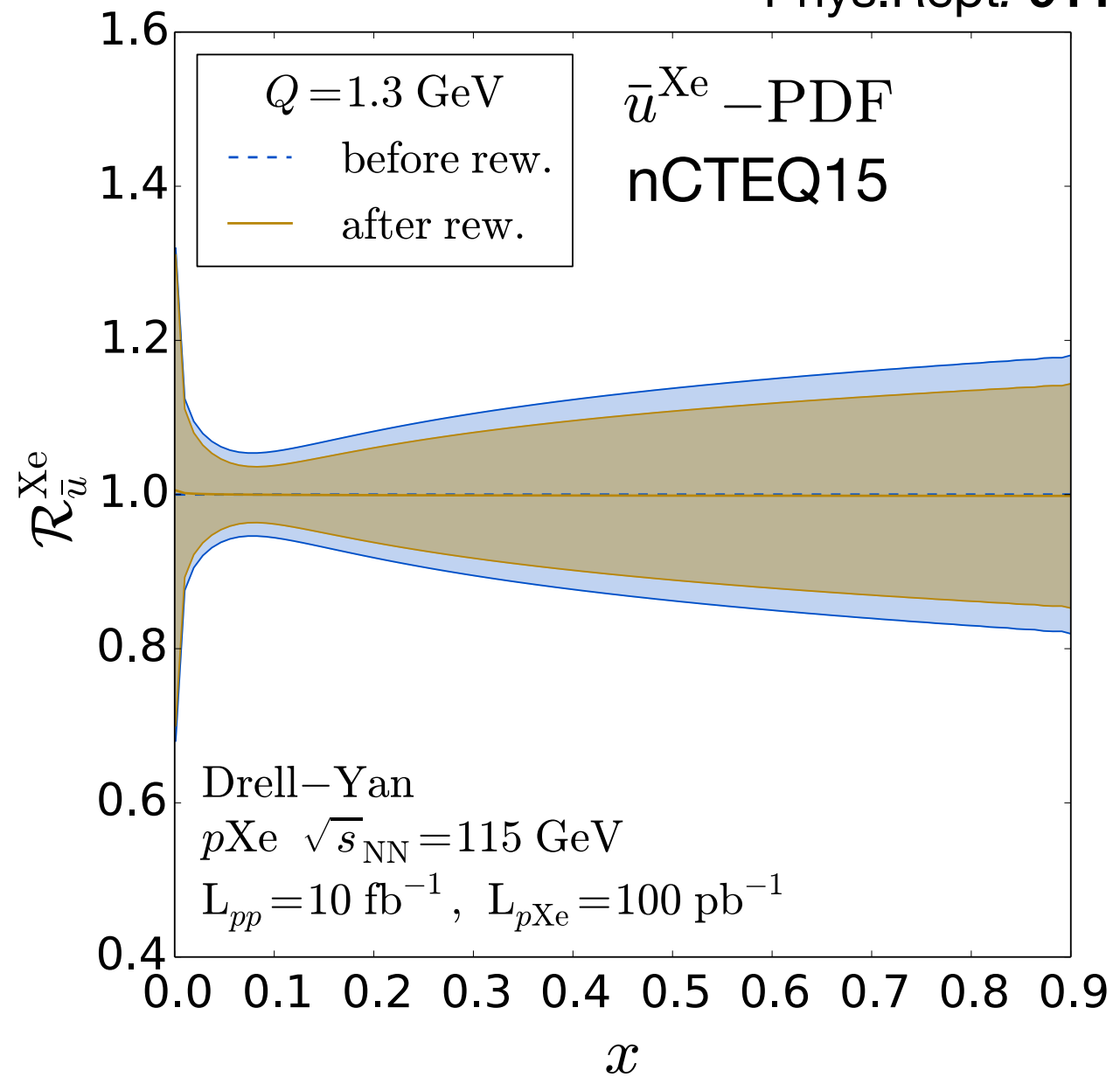
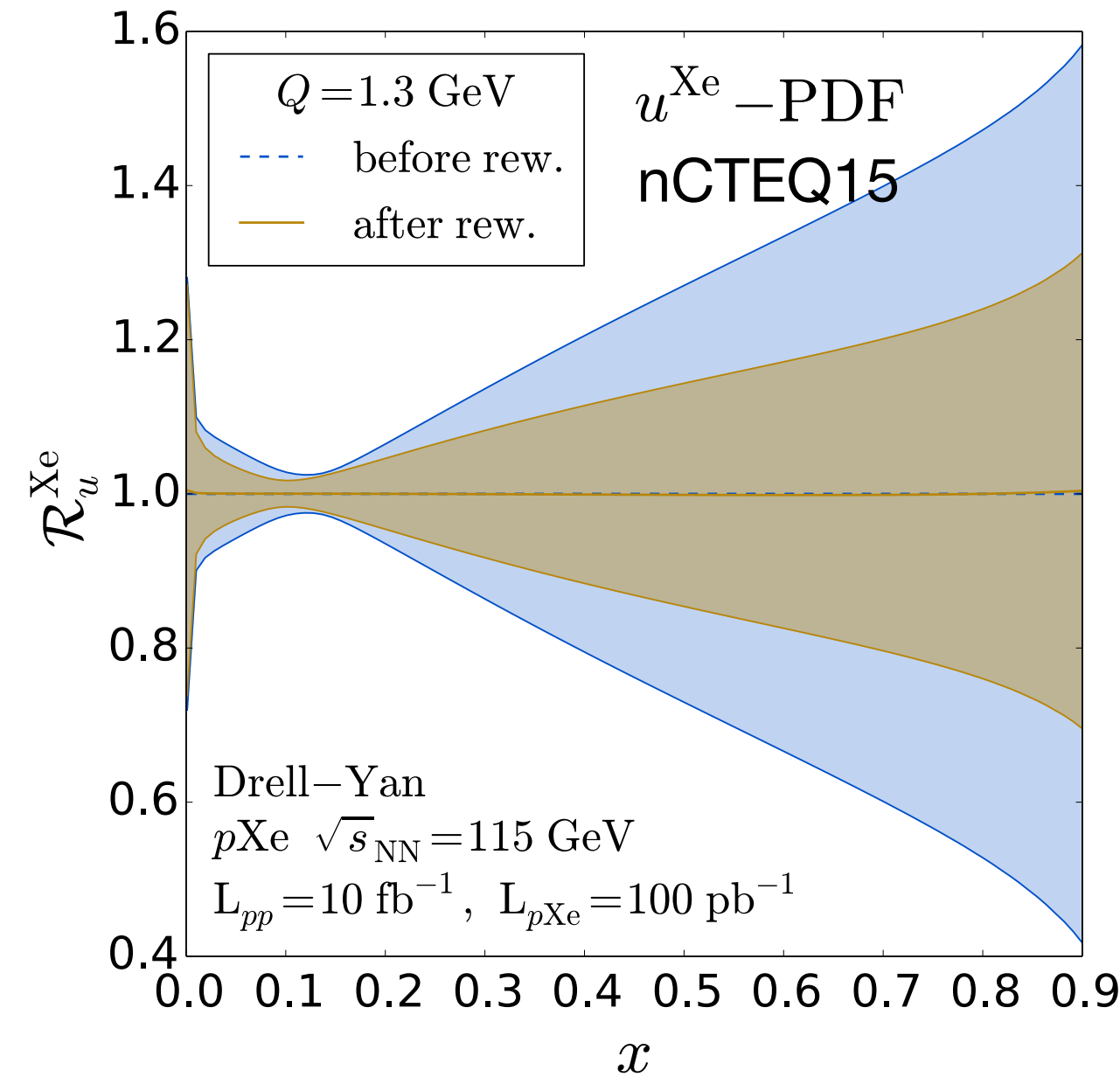
Fixed-target J/ψ production



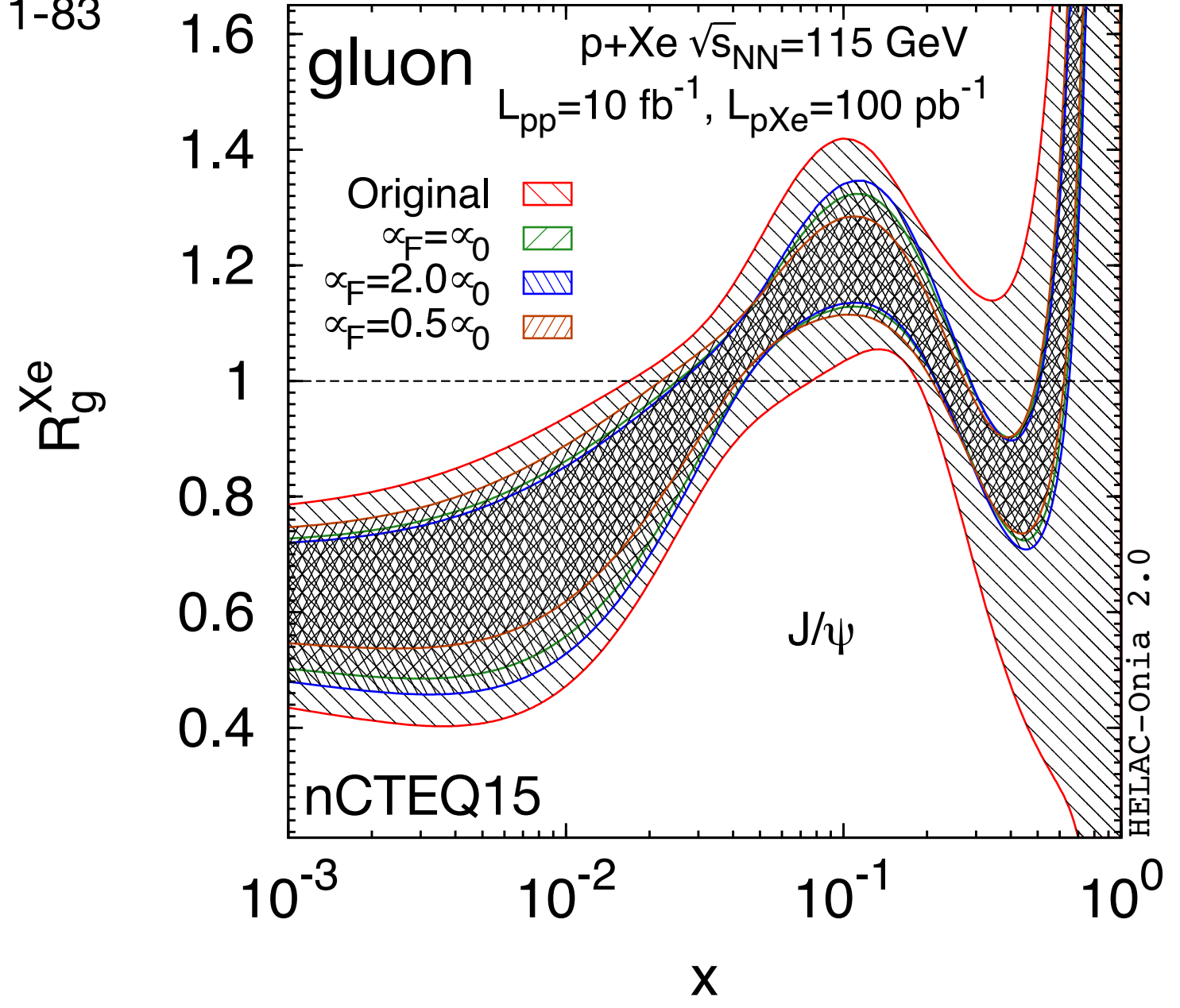
Fixed target and nuclear PDFs

Fixed-target Drell-Yan

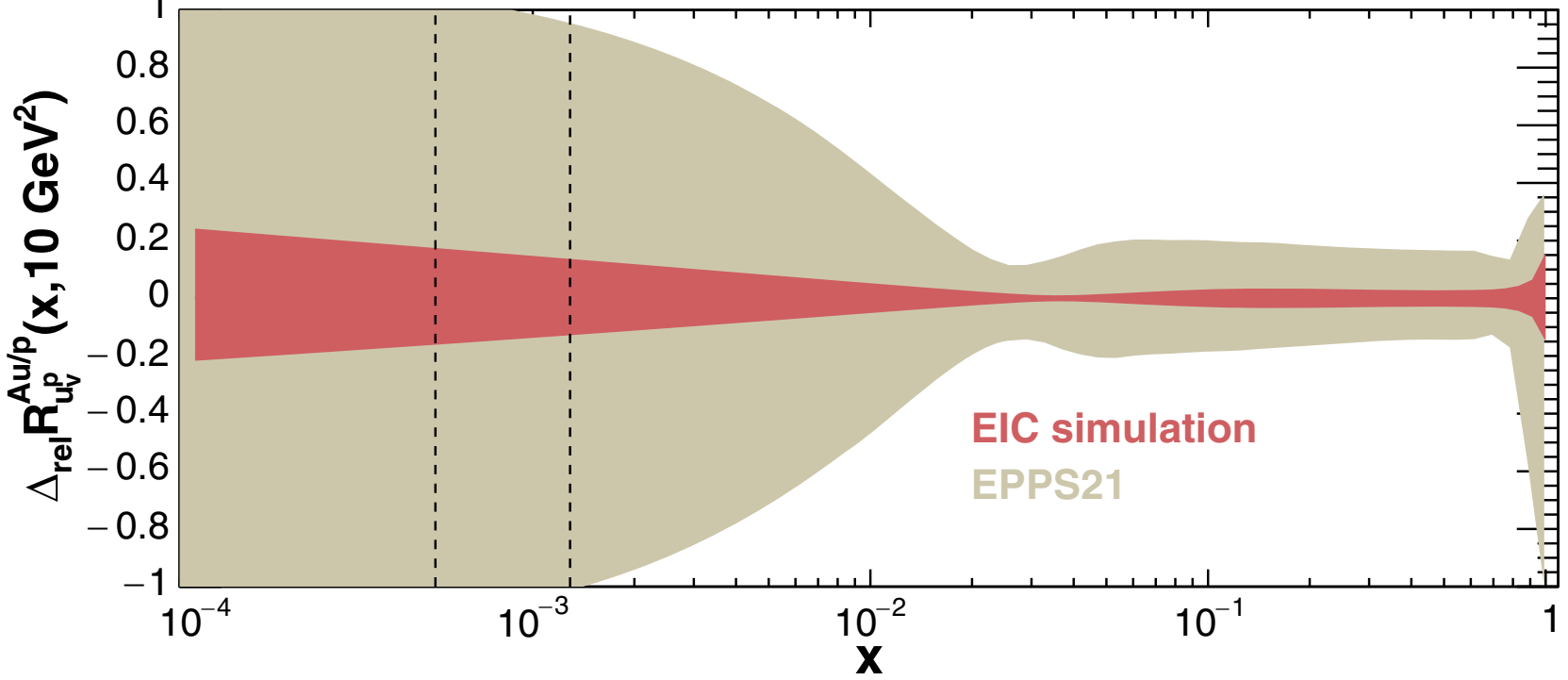
C. Hadjidakis et al.,
Phys.Rept. **911** (2021) 1-83



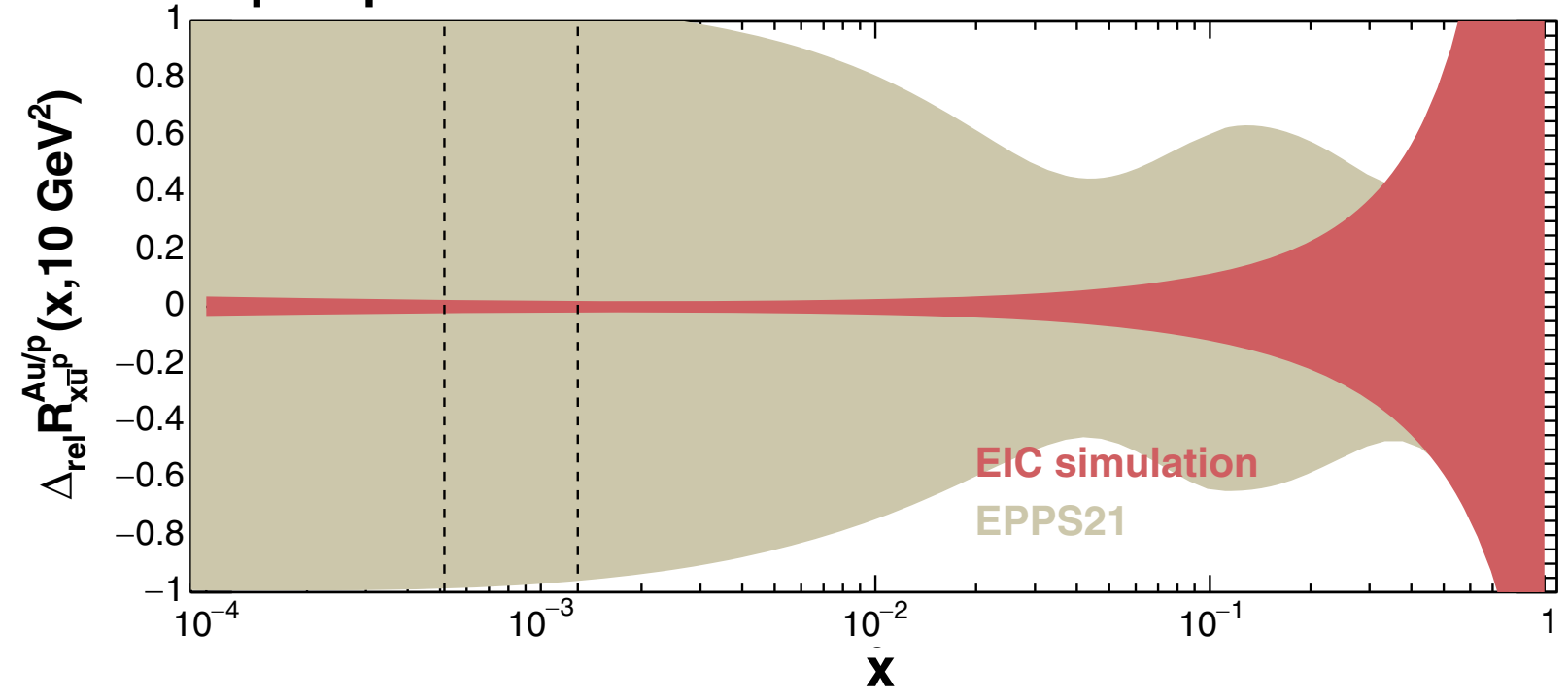
Fixed-target J/ψ production



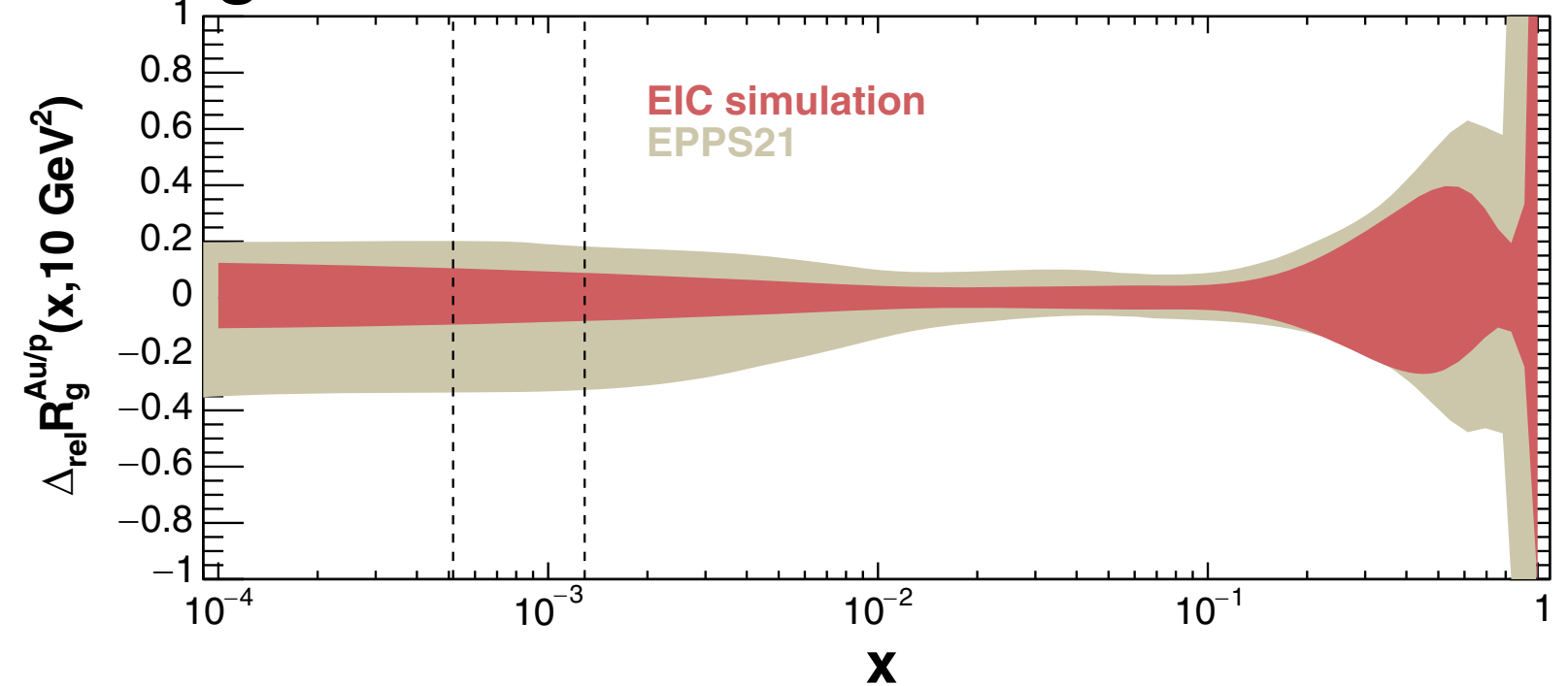
up-quark valence



up-quark sea



gluon
N. Armesto et al.,
PRD **109** (2024) 054019



Fixed target

SMOG2:

exclusive measurements with SMOG2 (RUN3):

	pp	pHe	pXe
special runs {	continuous $\mu^+\mu^-$ $\sigma = 61.931 \text{ pb} = 686 \text{ evts}$	$\sigma = 113.6 \text{ pb} = 0 \text{ evts}$	$\sigma = 17.6 \text{ nb} = 29 \cdot 10^3 \text{ evts}$
data collection in {	$J/\psi \rightarrow \mu^+\mu^-$ $\sigma = 20.467 \text{ pb} = 2302 \text{ evts}$	$\sigma = 27.3 \text{ pb} = 0 \text{ evts}$	$\sigma = 1.3 \text{ nb} = 21 \cdot 10^3 \text{ evts}$
parallel with pp {	$\phi \rightarrow K^+K^-$ $\sigma = 184 \text{ pb} = 12 \cdot 10^3 \text{ evts}$	$\sigma = 109.4 \text{ pb} = 5 \text{ evts}$	$\sigma = 11.0 \text{ nb} = 102 \cdot 10^3 \text{ evts}$

total uncertainty on cross section: 5-10%

Fixed target

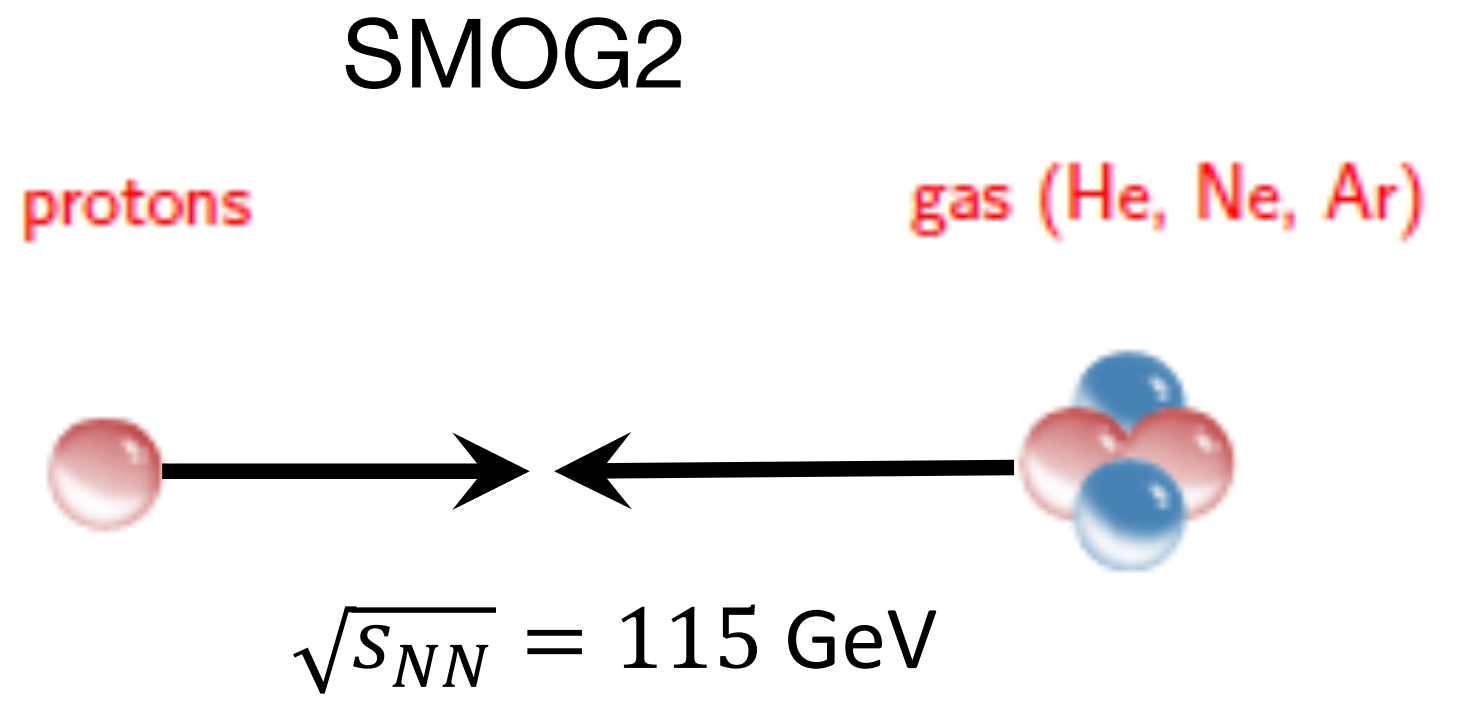
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total uncertainty on cross section: 5-10%

LHCSpin:



Fixed target

SMOG2:

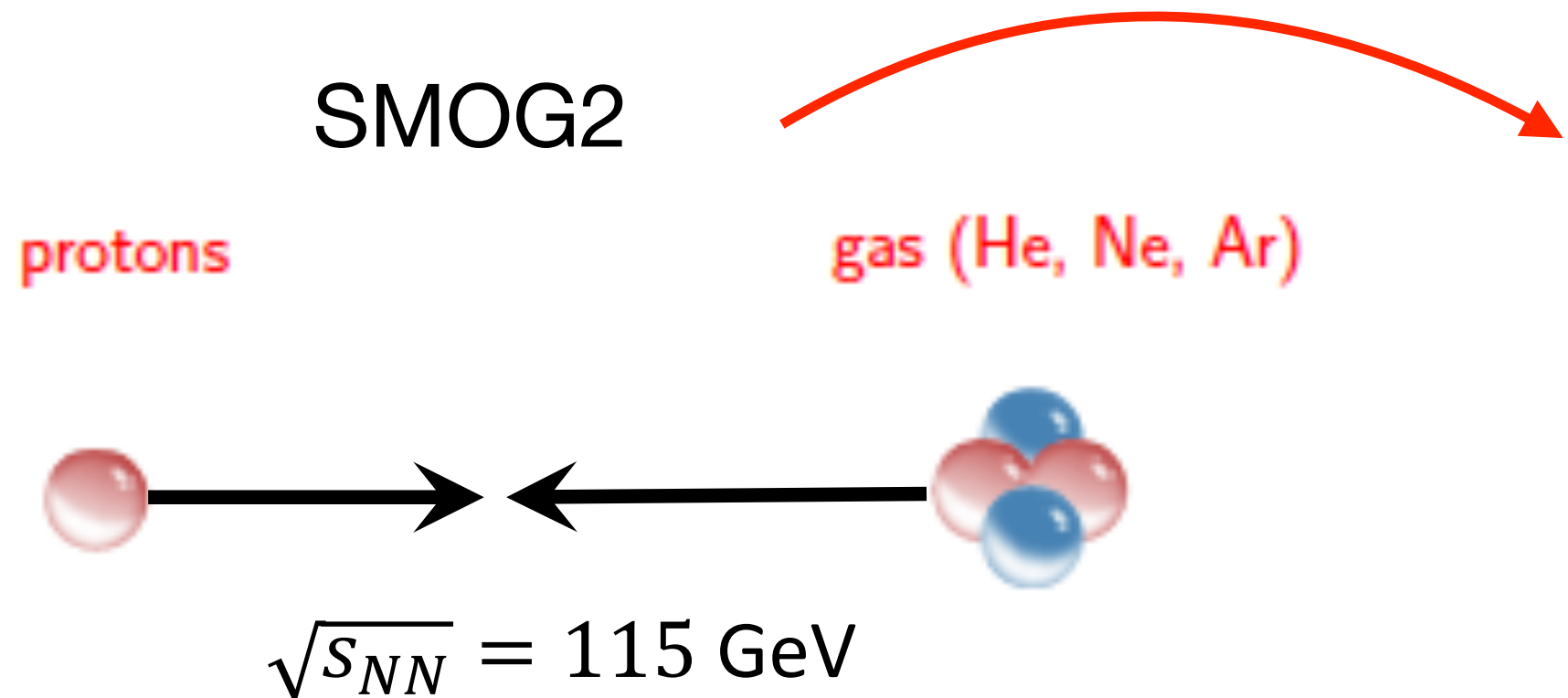
exclusive measurements with SMOG2 (RUN3):

special runs {
data collection in {
parallel with pp {

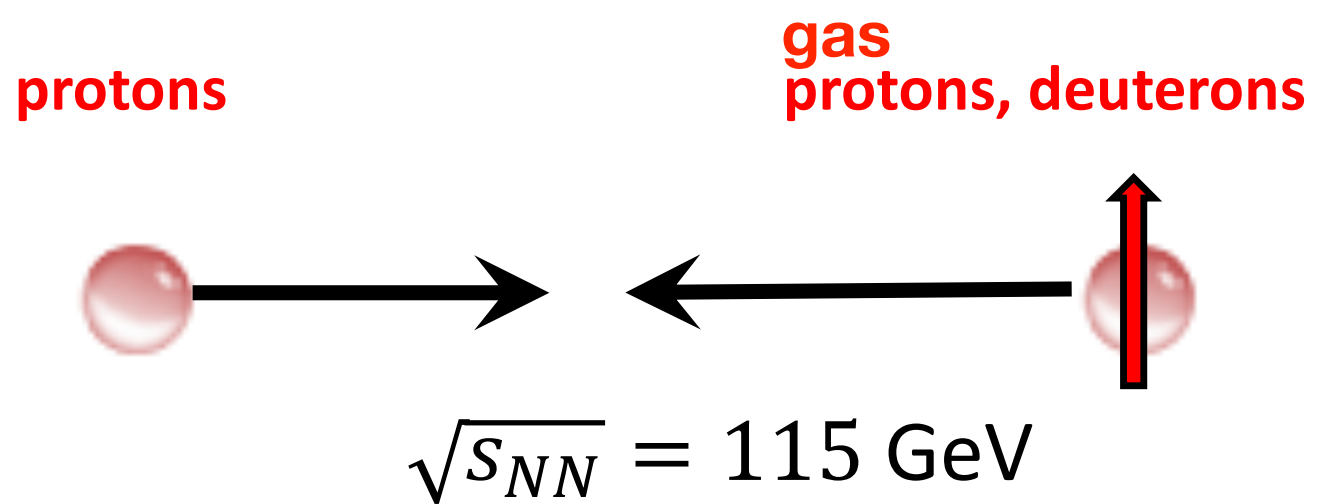
	pp	pHe	pXe
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$J/\psi \rightarrow \mu^+\mu^-$	$\sigma = 20.467 \text{ pb} = 2302 \text{ evts}$	$\sigma = 27.3 \text{ pb} = 0 \text{ evts}$	$\sigma = 1.3 \text{ nb} = 21 \cdot 10^3 \text{ evts}$
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total uncertainty on cross section: 5-10%

LHCSpin:



LHCSPIN: transversely polarised gas target



→ access to spin-dependent GPDs at the LHC

Summary

- Vast complementarity between (HL-)LHC, fixed-target and EIC
- EIC provides high precision and polarisation
- LHC covers otherwise inaccessible low- x_B region
- Fixed target at the LHC covers the large- x_B region
- EIC covers large variety of nuclei
 - > valuable for study of nuclear effects, saturation
- Study of saturation effects: not an easy task: combined LHC and EIC data highly valuable!
- Fixed target also covers variety of nuclei, at large x_B —> complementary channel
- Transversely polarised fixed target would allow to extend the complementarity with EIC