Complementarities between the HL-LHC pPb and fixed-target runs and EIC

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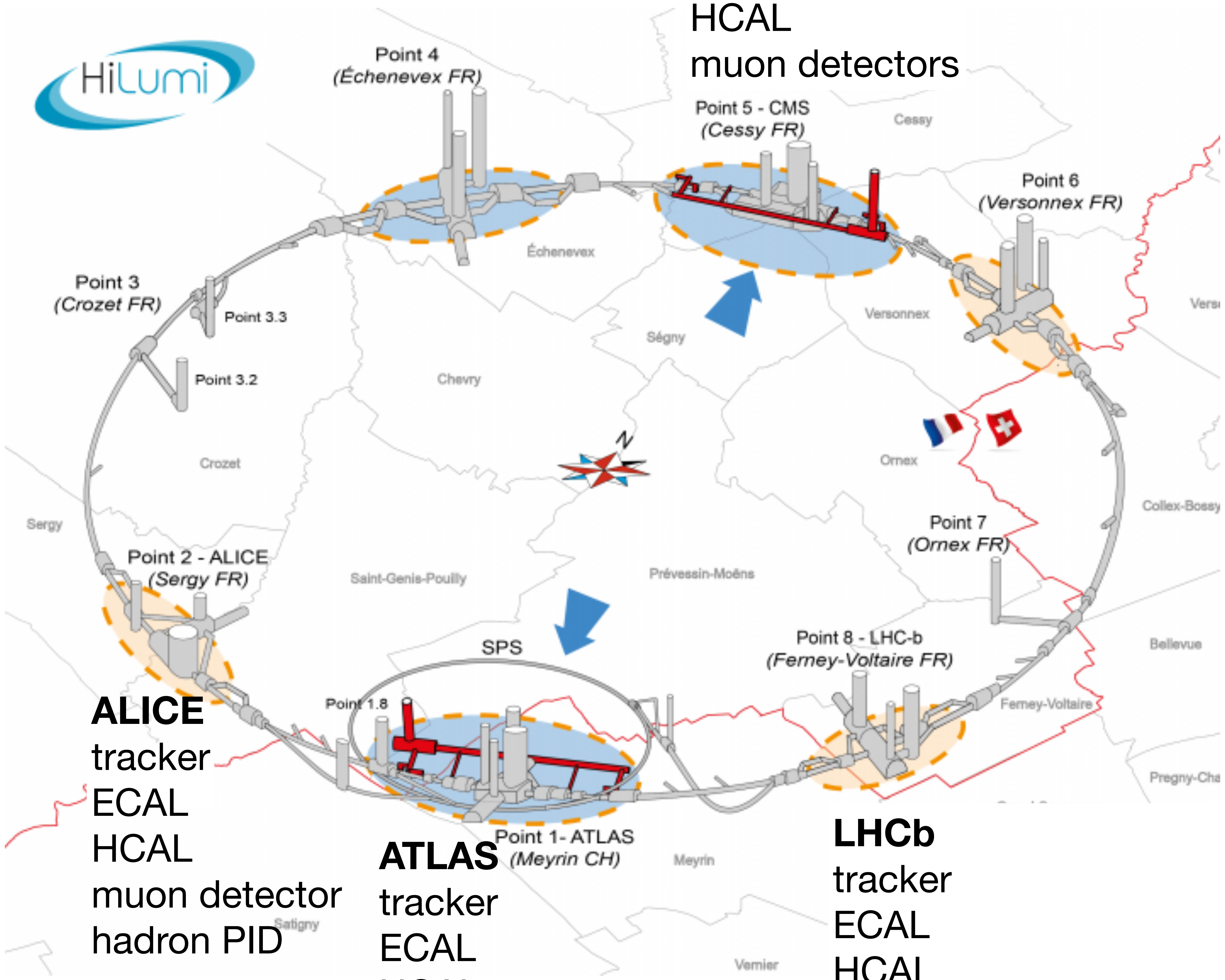
University of Alcalá

AdT

Comunidad
de Madrid

Physics with high-luminosity proton-nucleus collisions at the LHC
4–5 July 2024
CERN, Switzerland

The high-lumi LHC



CMS
tracker
ECAL
HCAL
muon detectors

ALICE
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ECAL
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hadron PID

ATLAS
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pPb collisions

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

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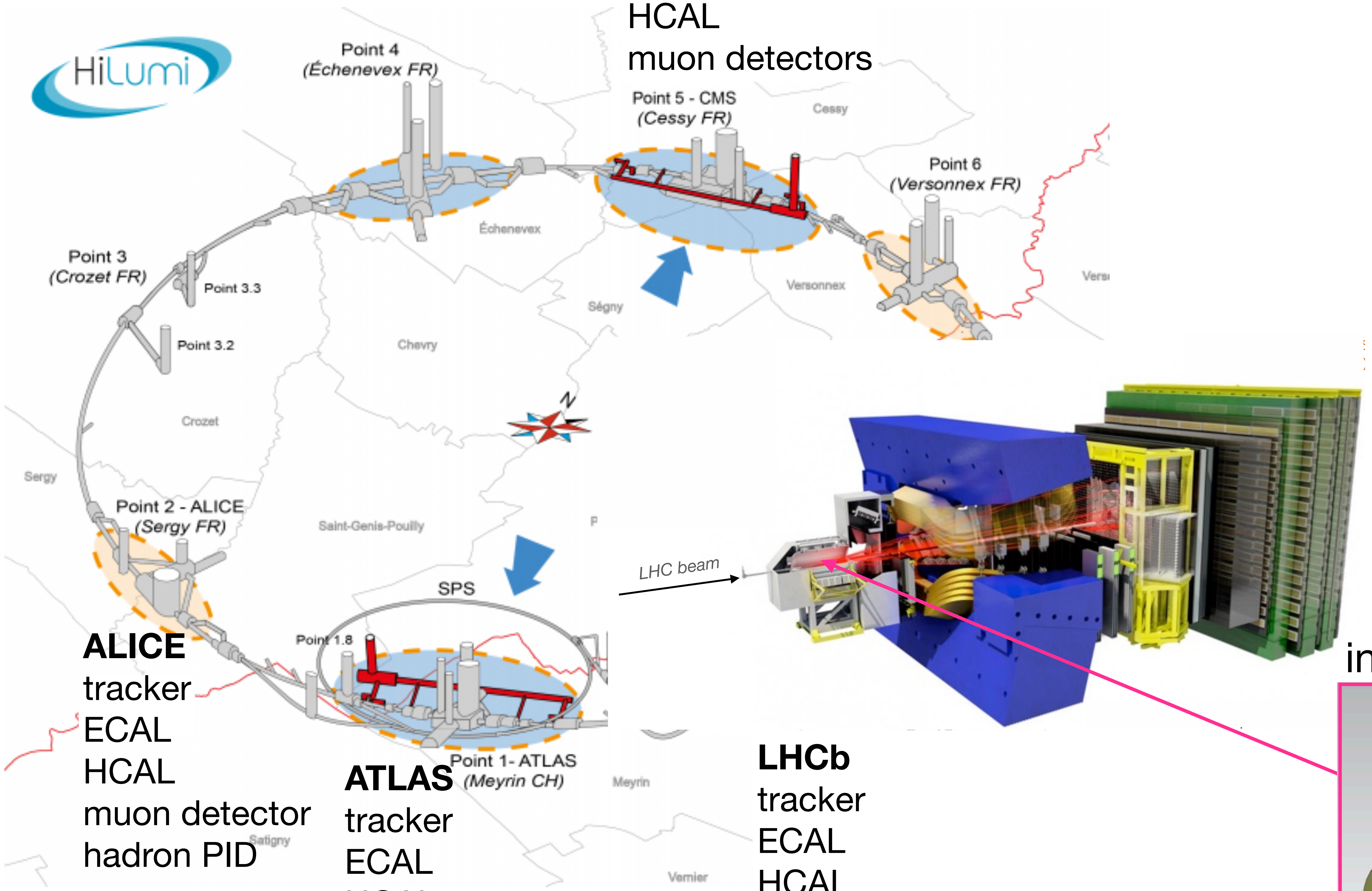

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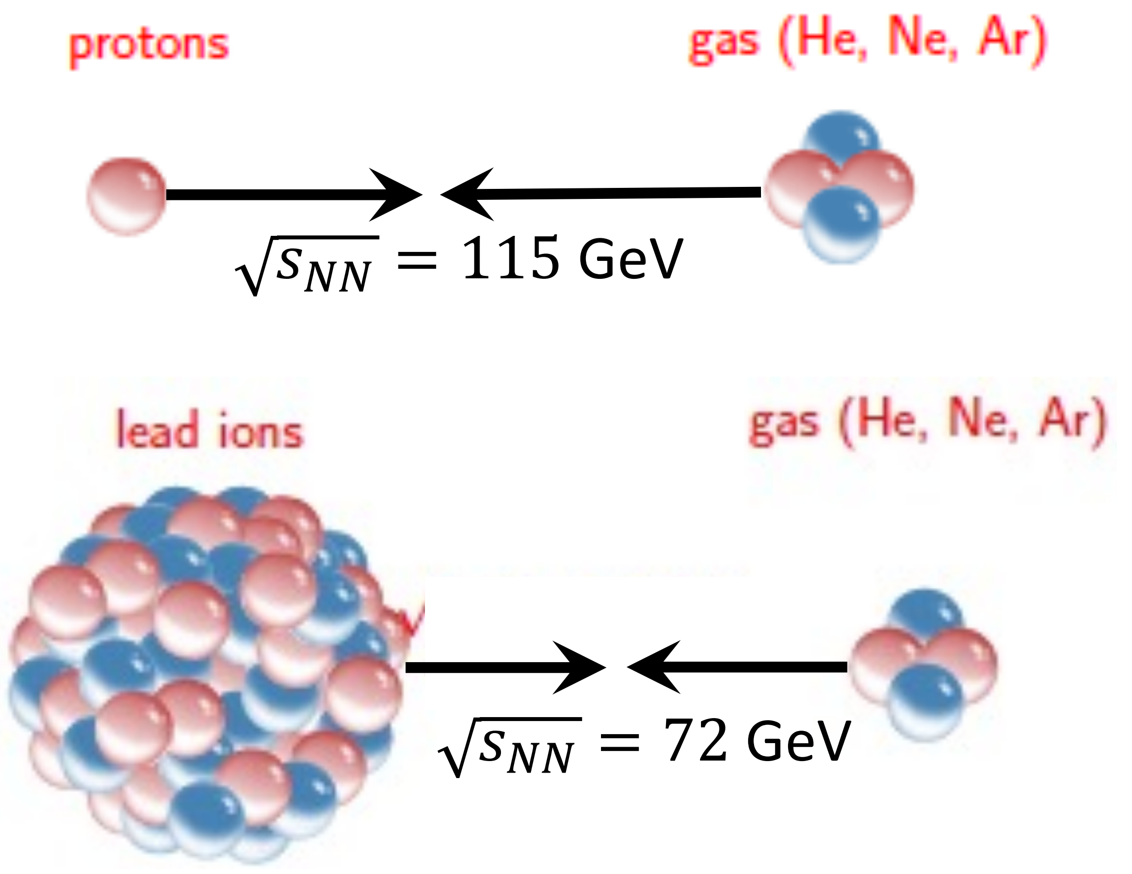
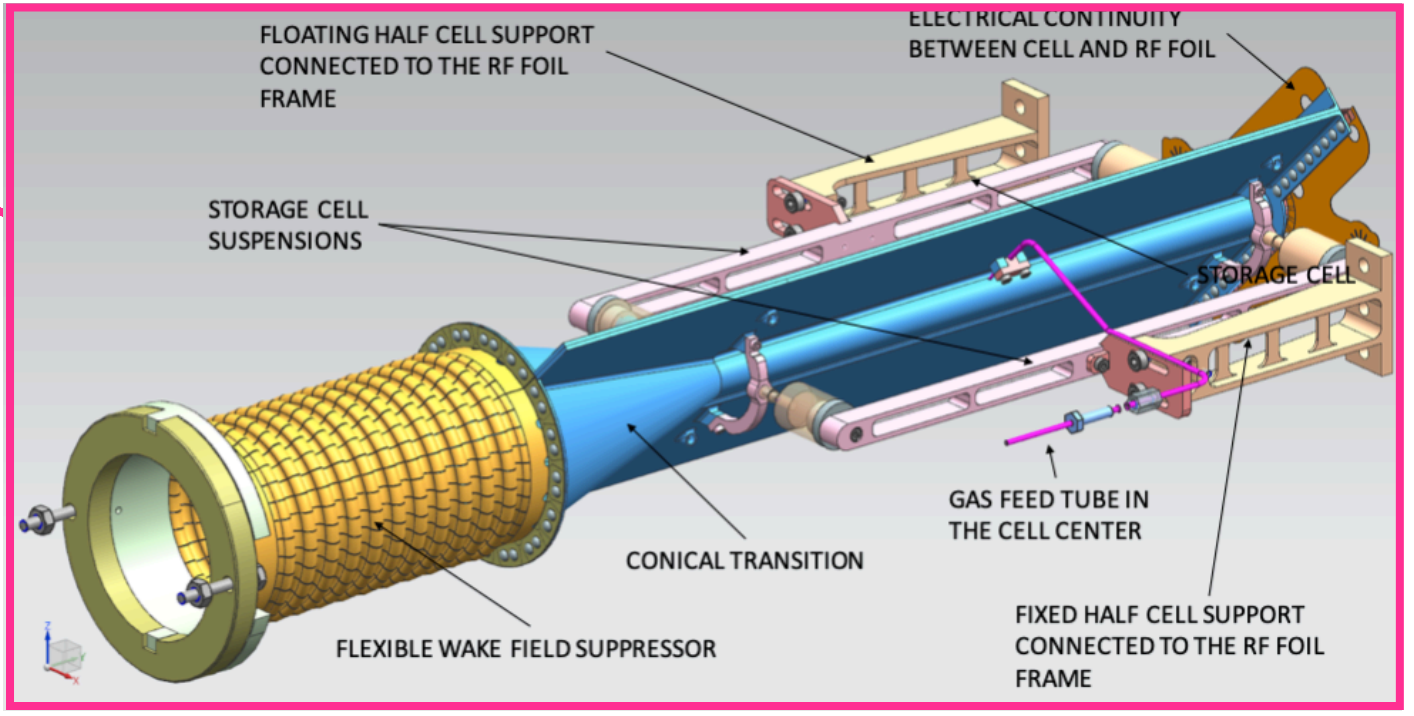
Fixed target – SMOG2



p beam $\sqrt{s_{NN}} = 115$ GeV

Pb beam $\sqrt{s_{NN}} = 72$ GeV

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



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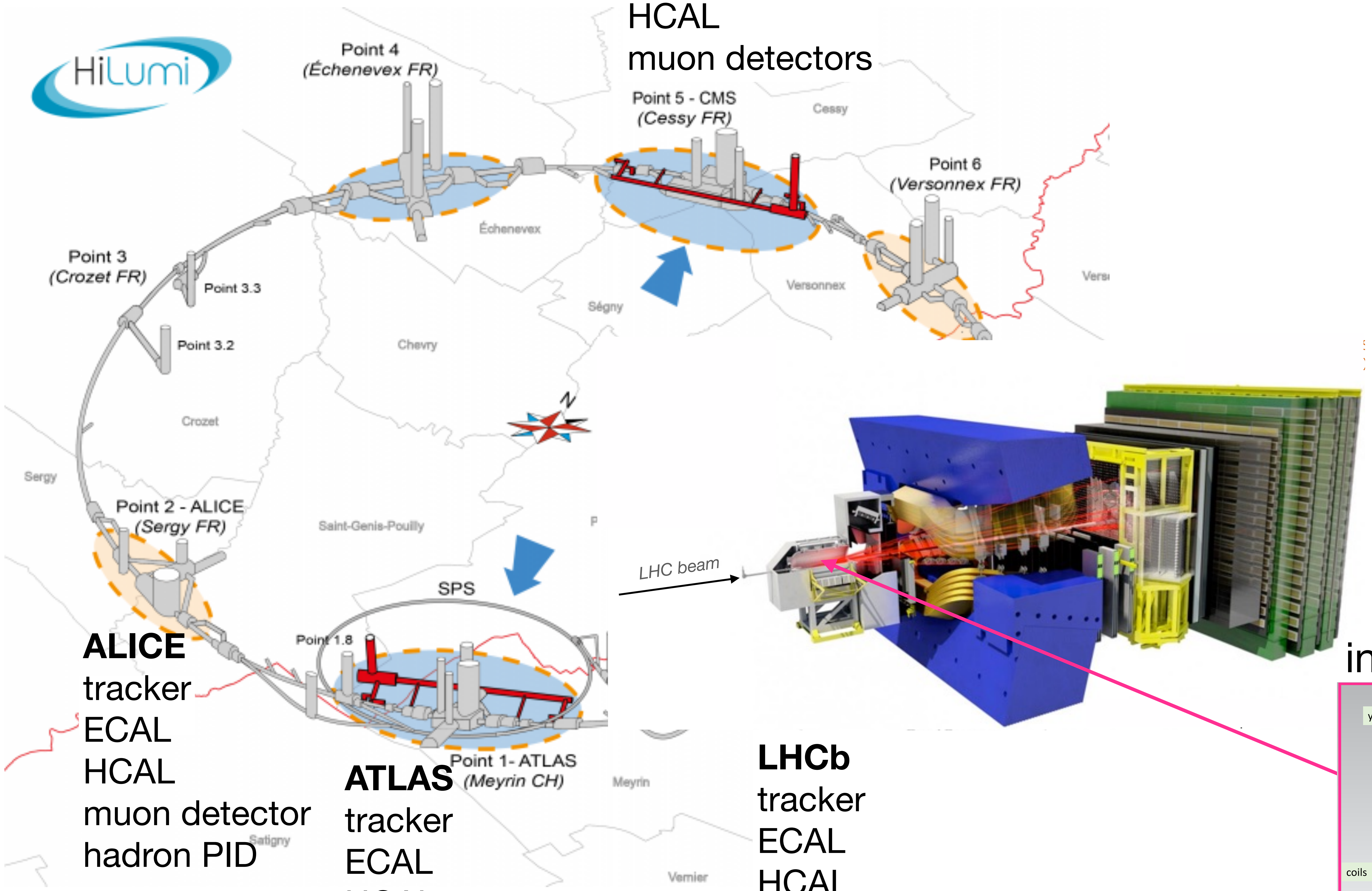

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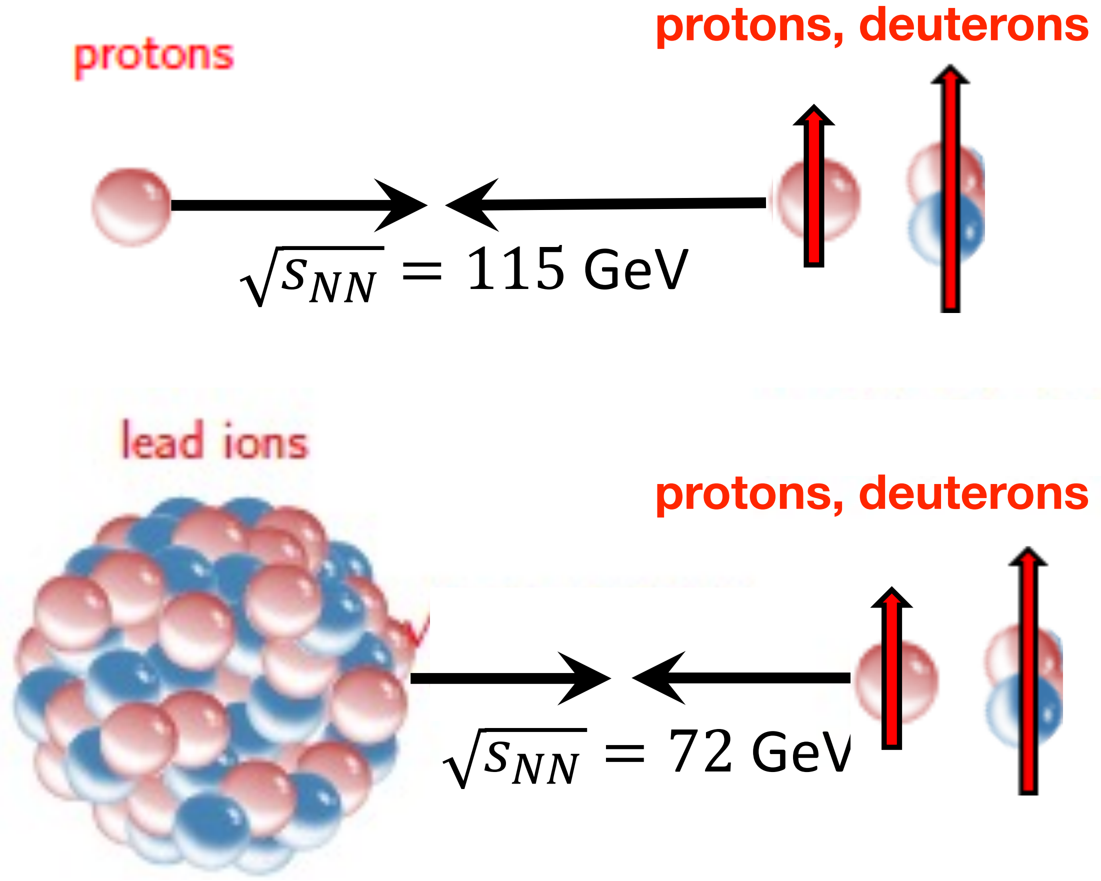
Fixed target – LHCSpin
proposed for Run5

p beam

Pb beam



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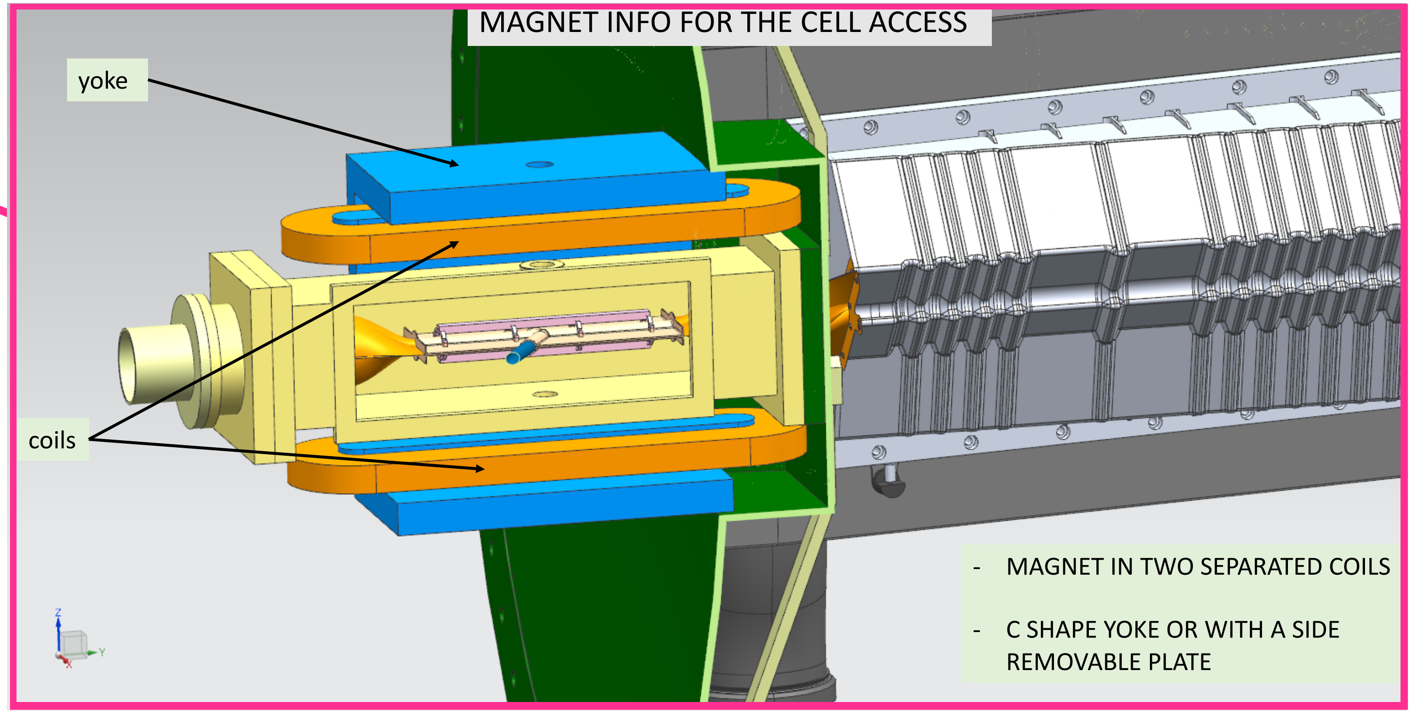
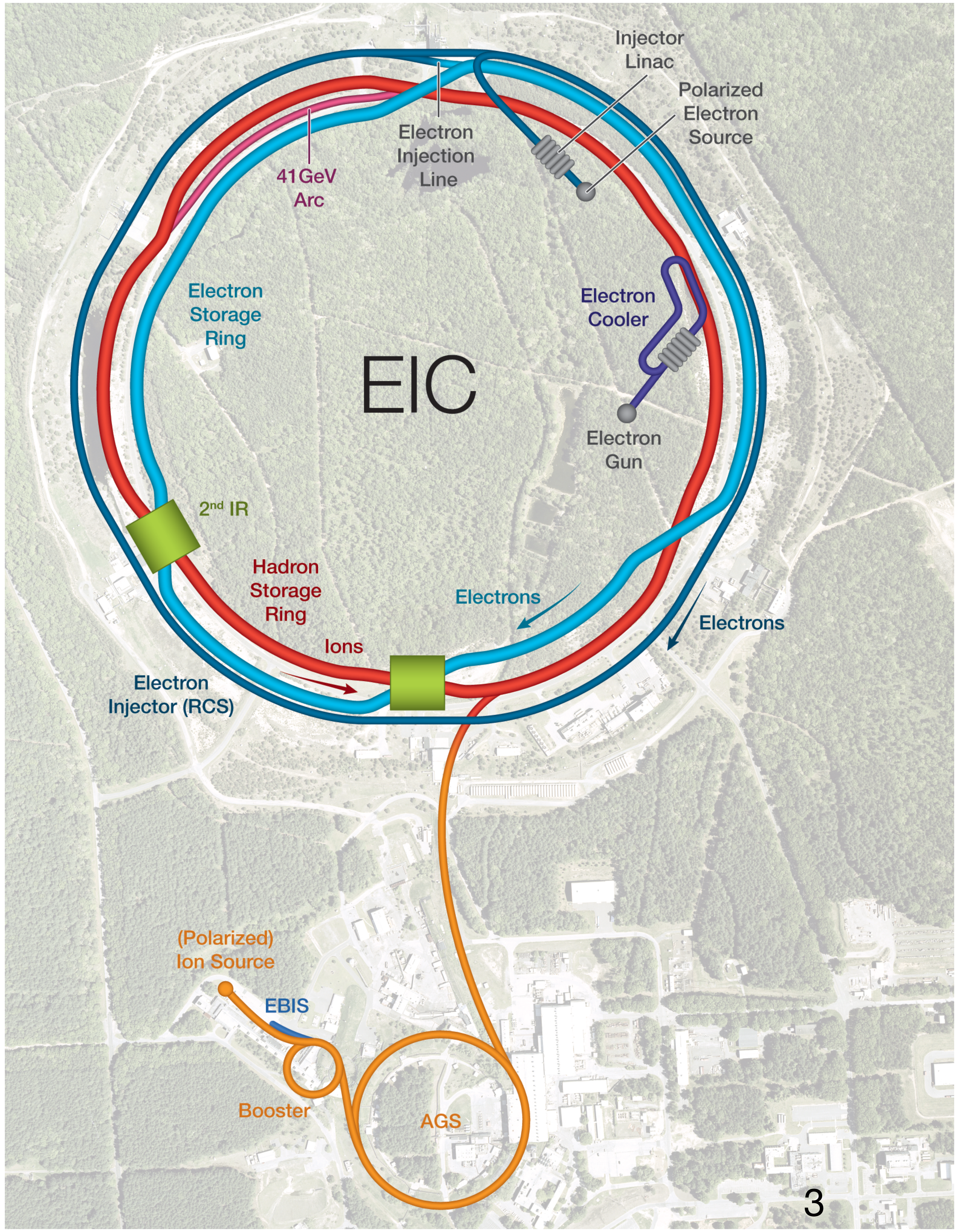


The electron-ion collider



- Based on RHIC:
  - use existing hadron storage ring
    energy: 41–275 GeV
  - add electron storage ring in RHIC tunnel
    energy: 5–18 GeV

$\rightarrow \sqrt{s} = 29 - 141$ GeV

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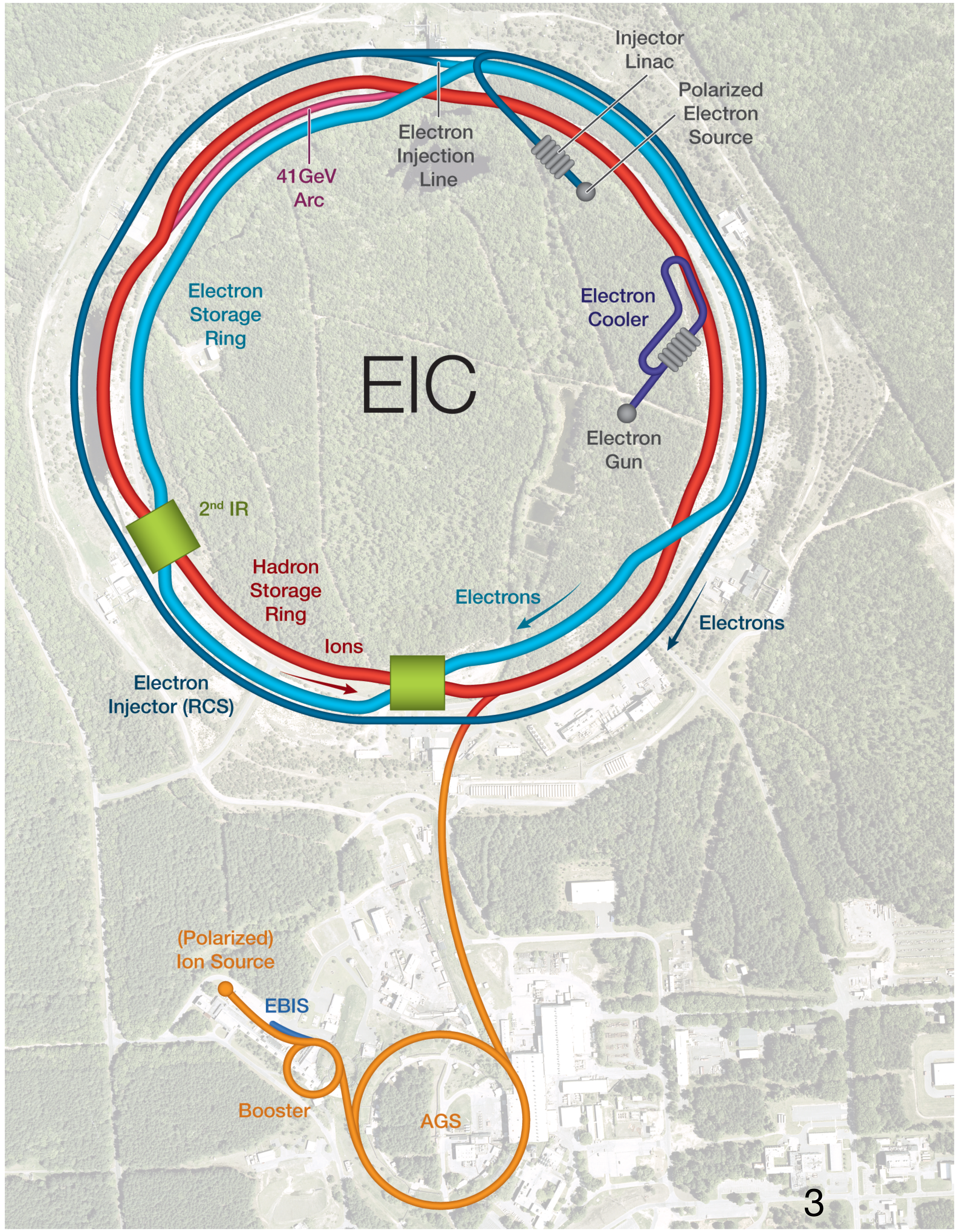

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~ 70% polarisation

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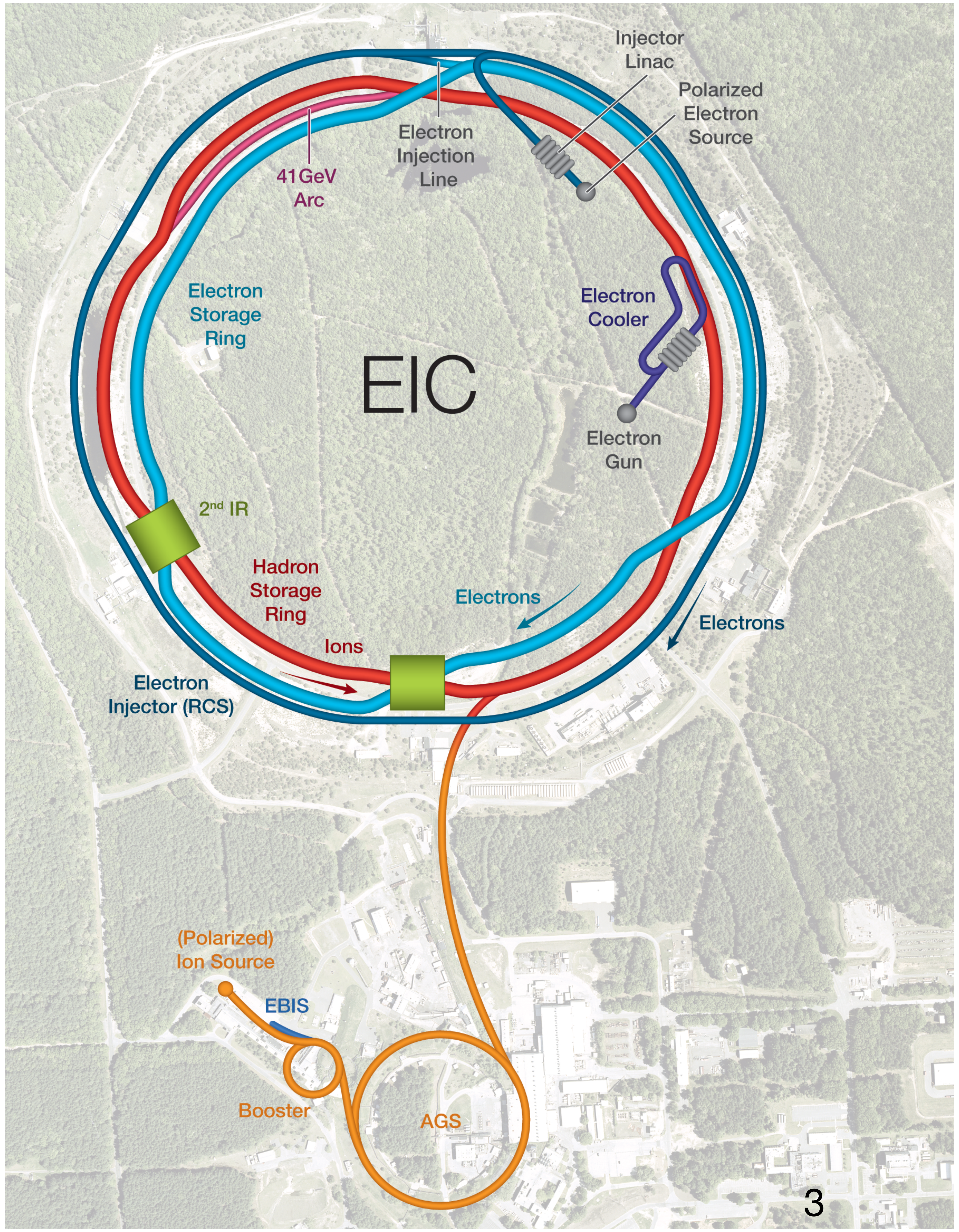

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- ep: $\mathscr{L} = 10^{33-34}$ cm^{-2} s^{-1}

  $\leftrightarrow \mathscr{L}_{\text{int}} = 10 - 100$ fb^{-1}/year

- eA: $\mathscr{L} = 10^{32}$ cm^{-2} s^{-1}

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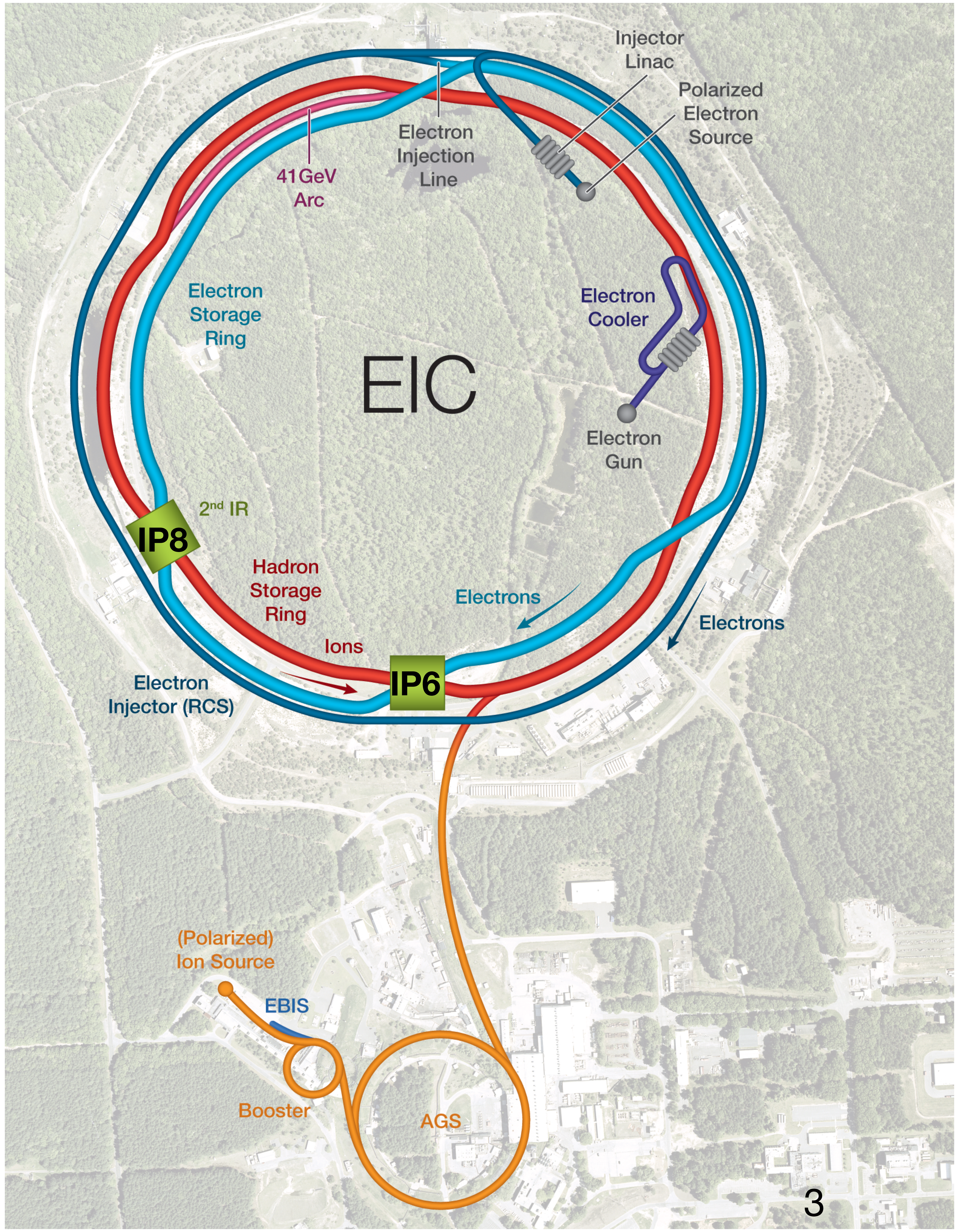

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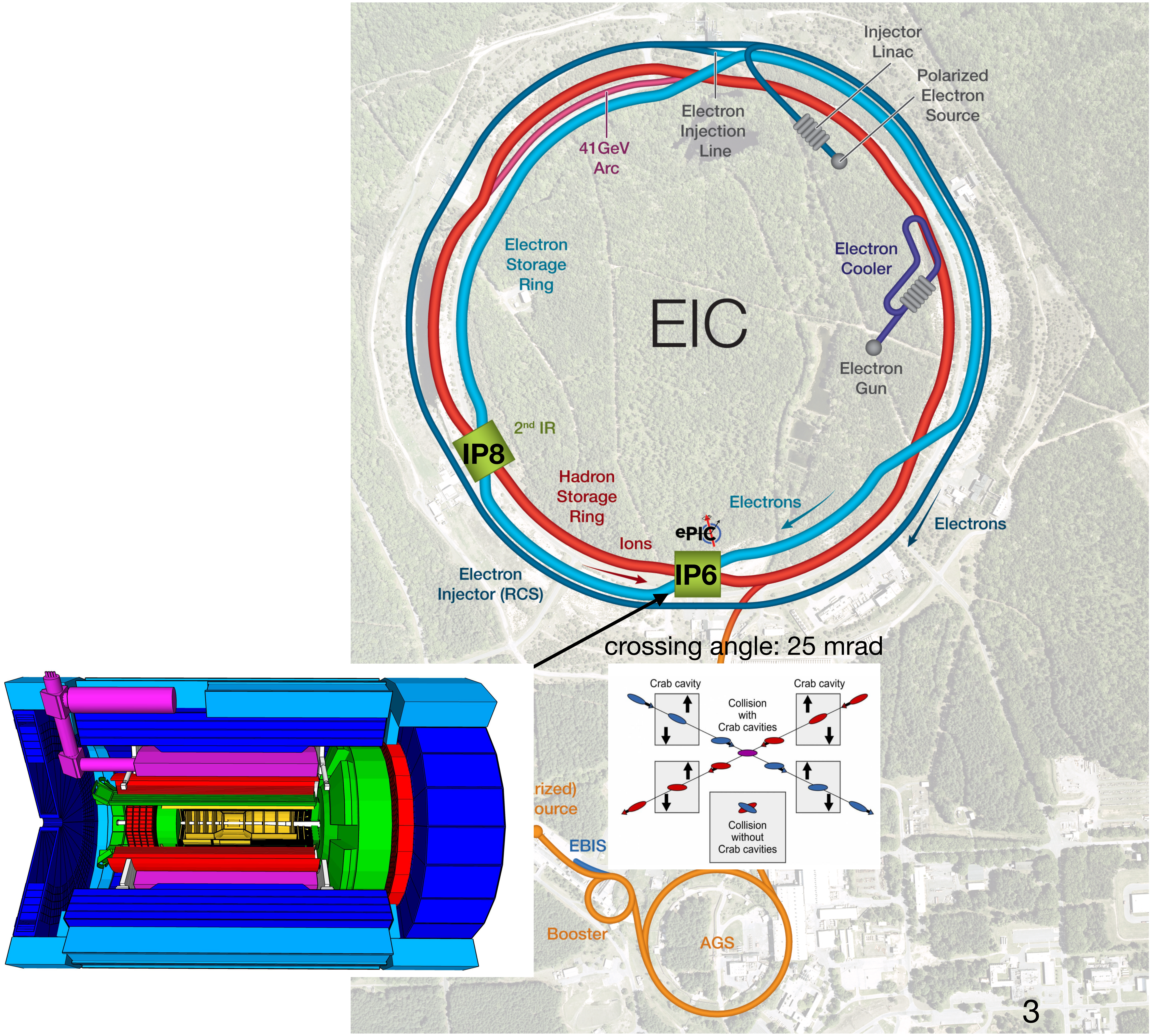

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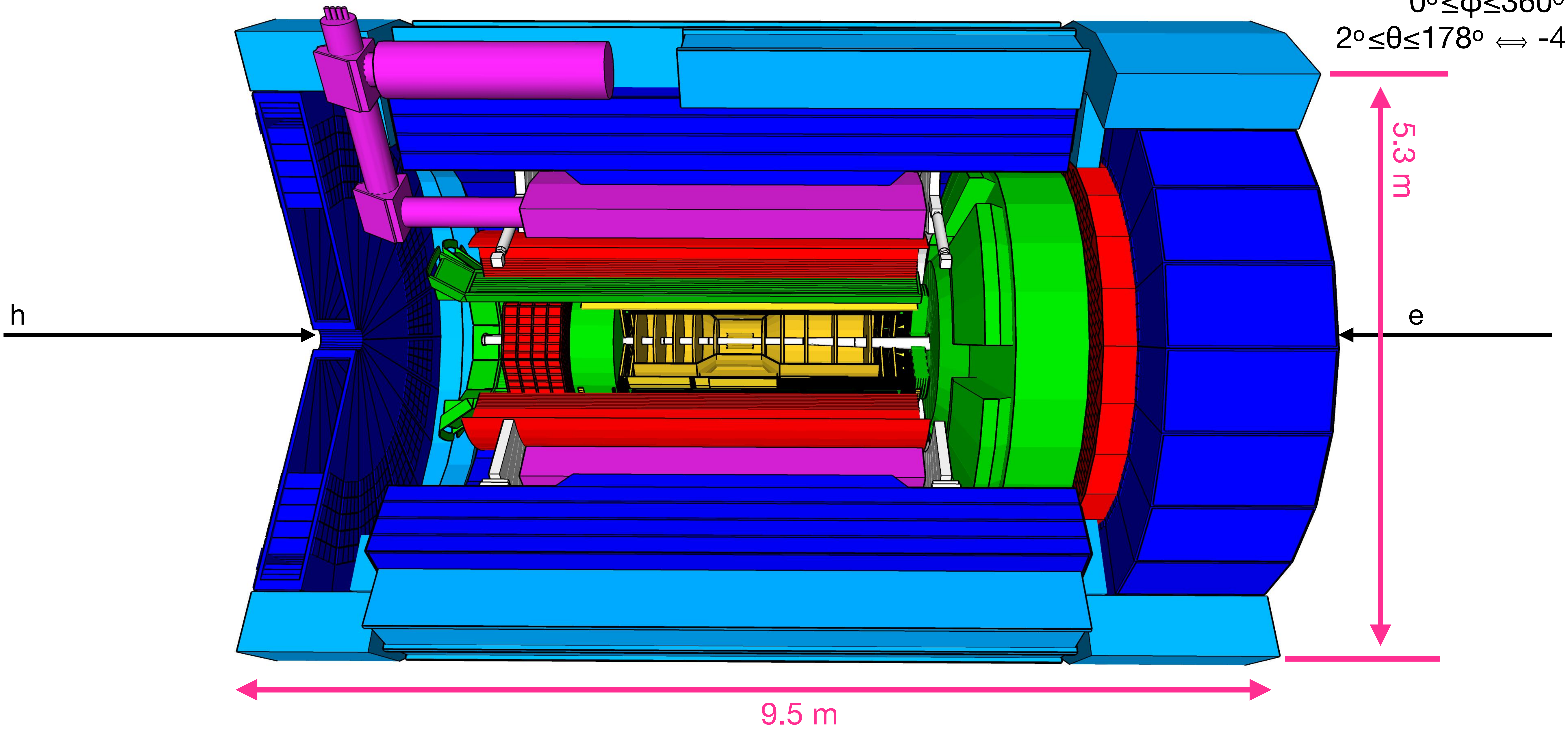
The ePIC detector



hermetic coverage:
$0^o \leq \phi \leq 360^o$
$2^o \leq \theta \leq 178^o \Longleftrightarrow -4 < \eta < 4$

The ePIC detector

- **Tracking**
- **PID**
- **Electromagnetic calorimeter**
- **Hadronic calorimeter**

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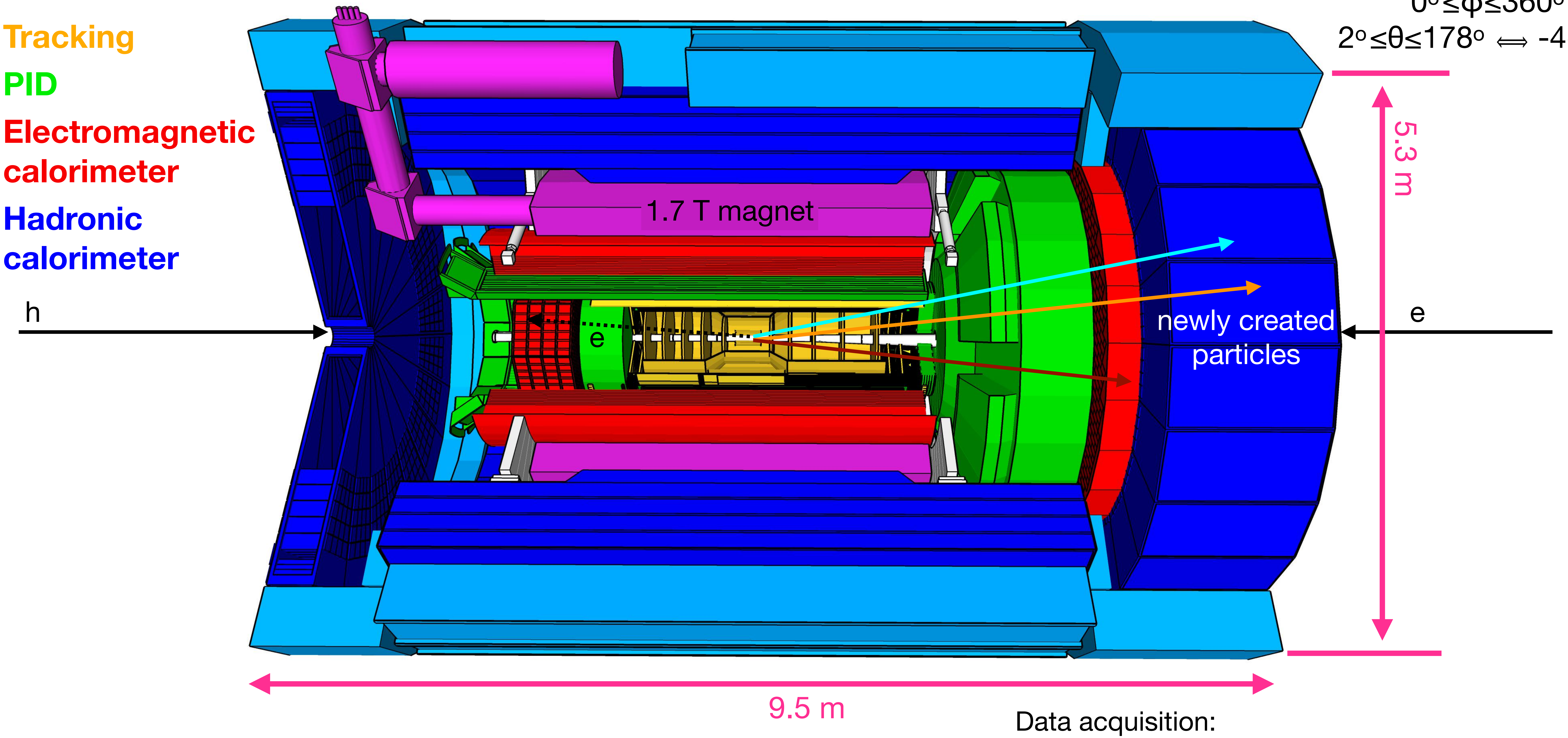

Data acquisition:
no trigger; all collision data is digitised
with strong zero-suppression at front-end electronics

The ePIC detector

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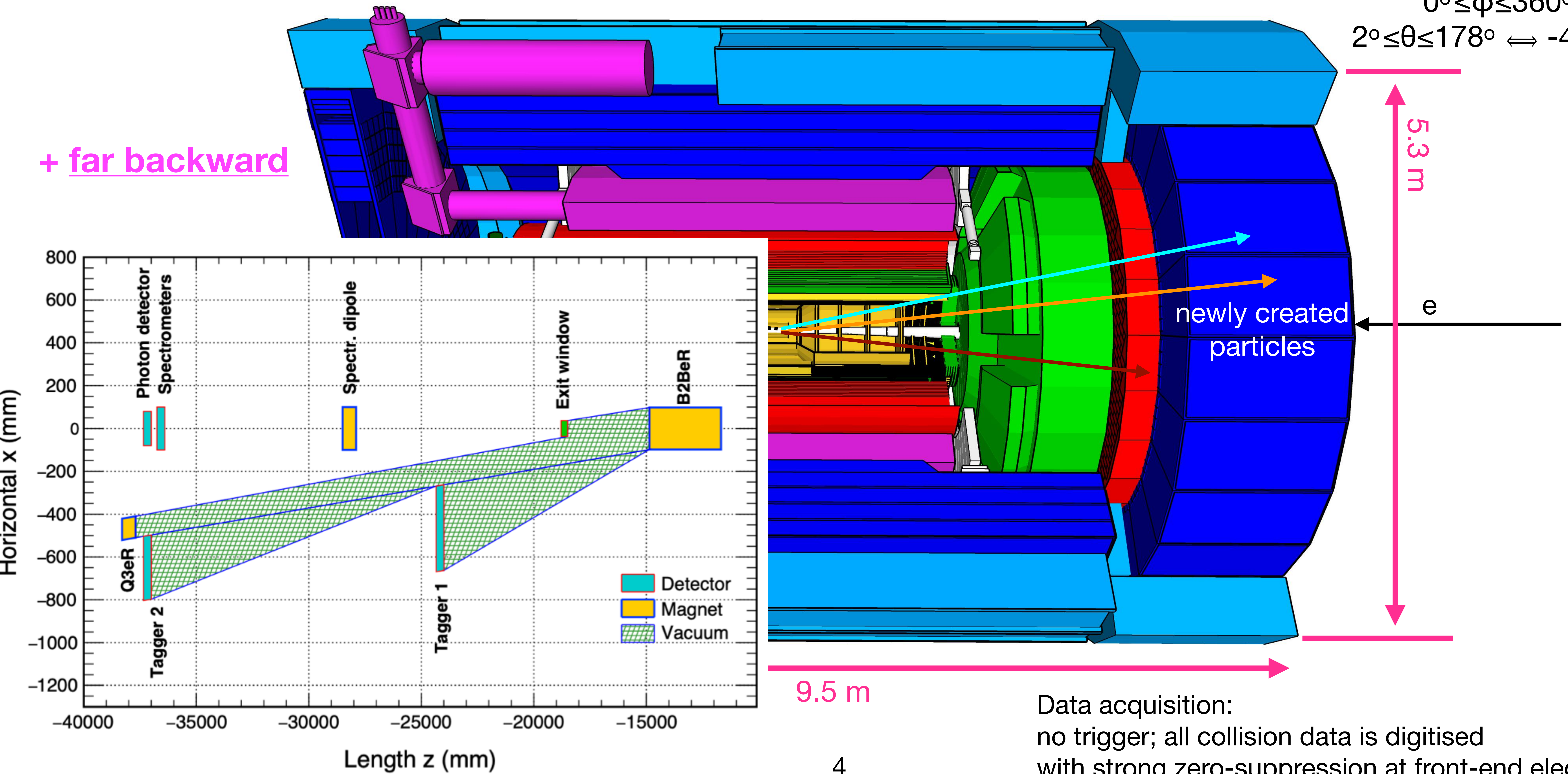
+ far backward



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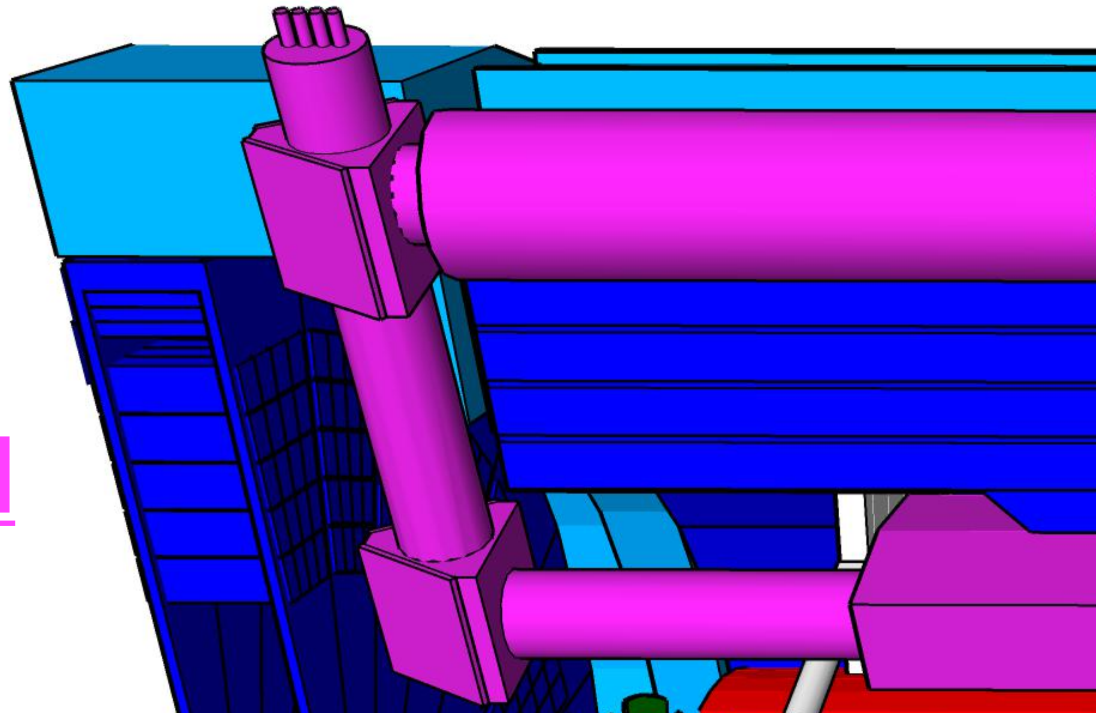

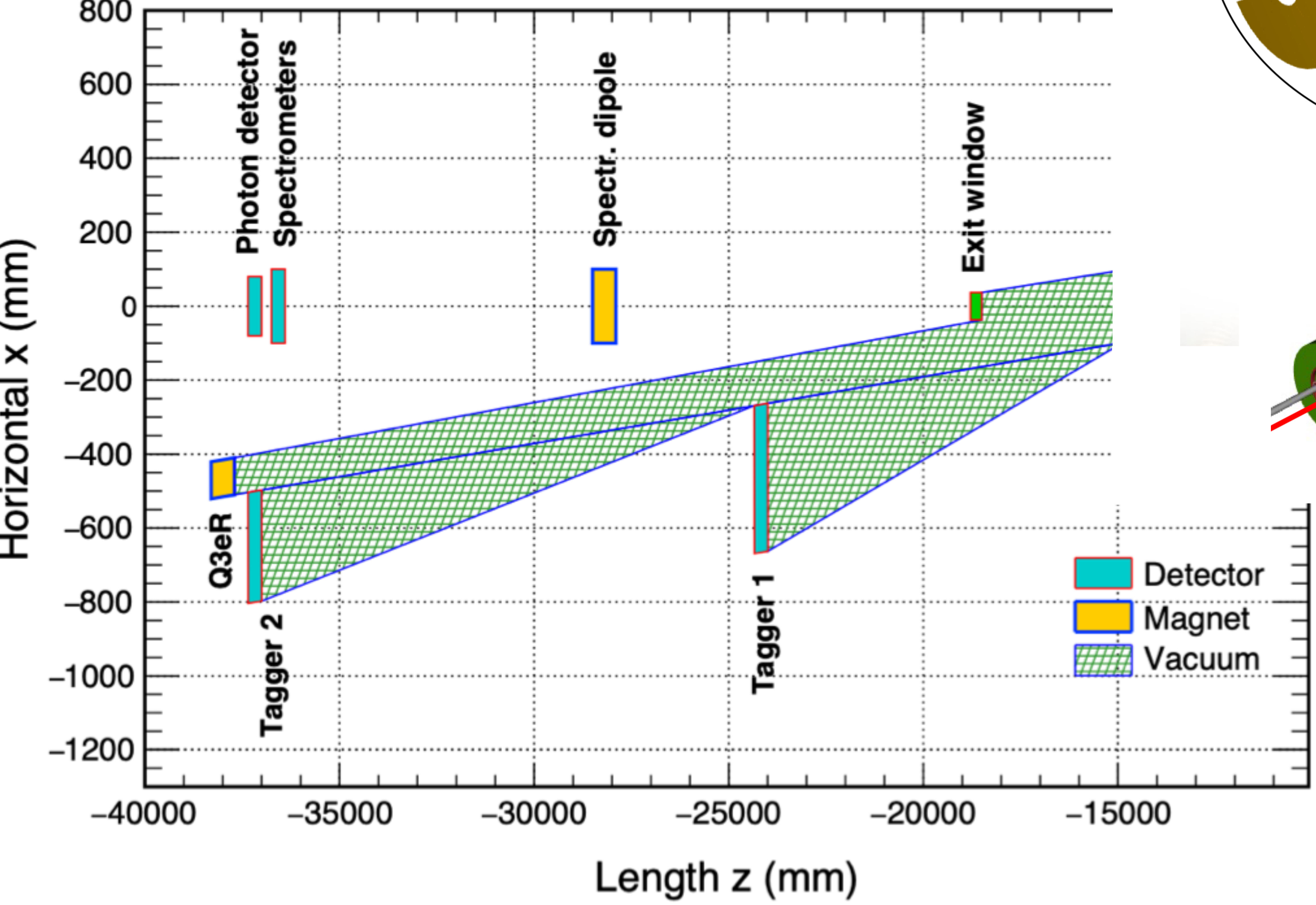

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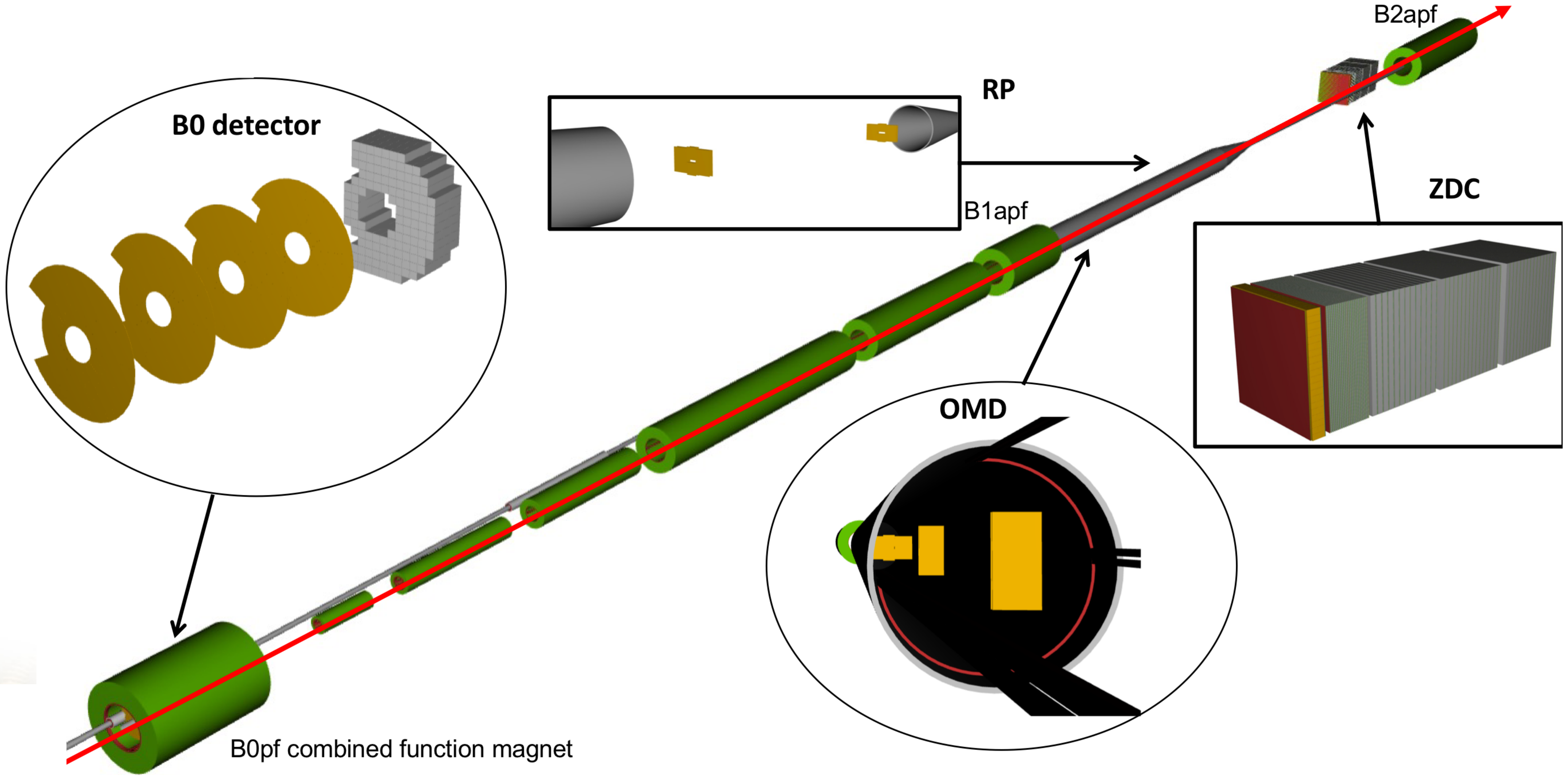

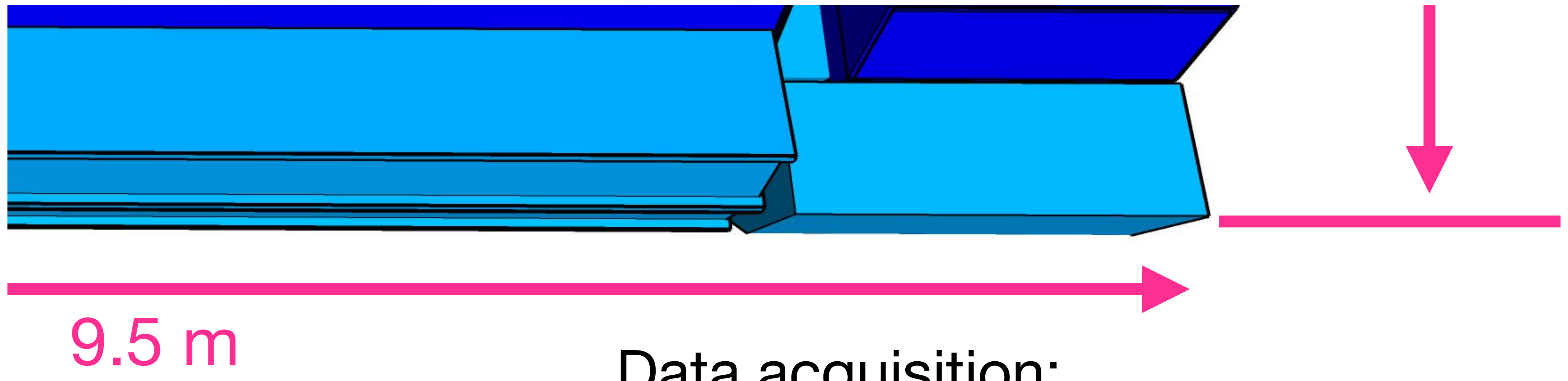

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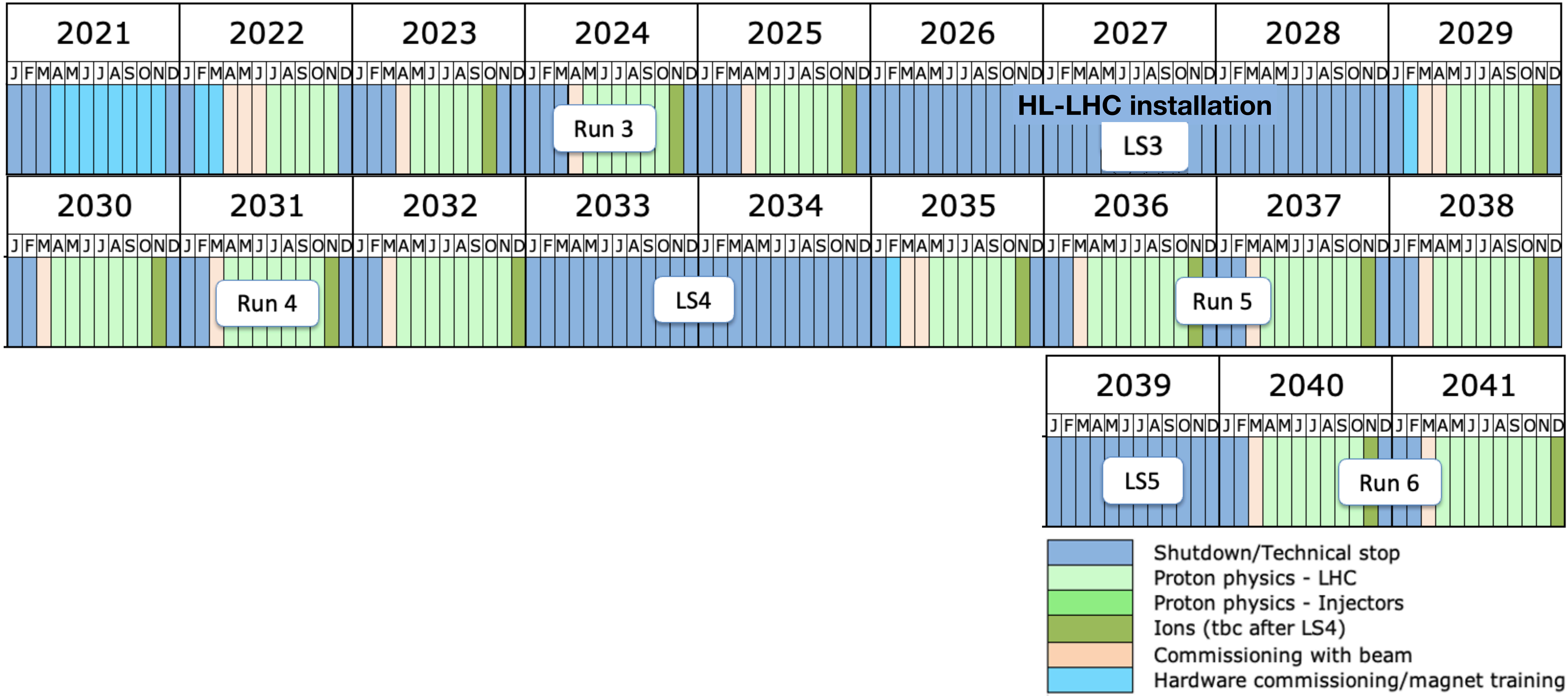
Timelines

LHC



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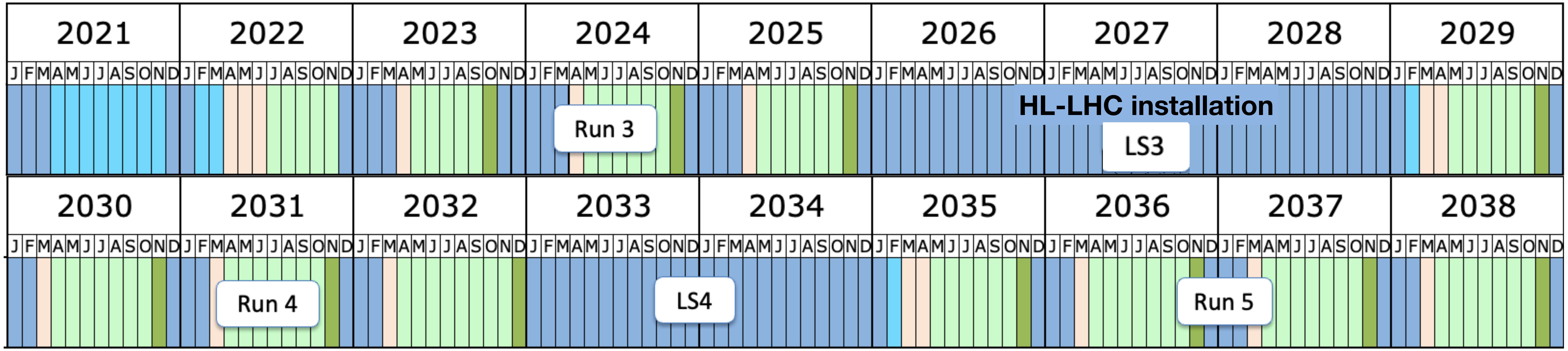
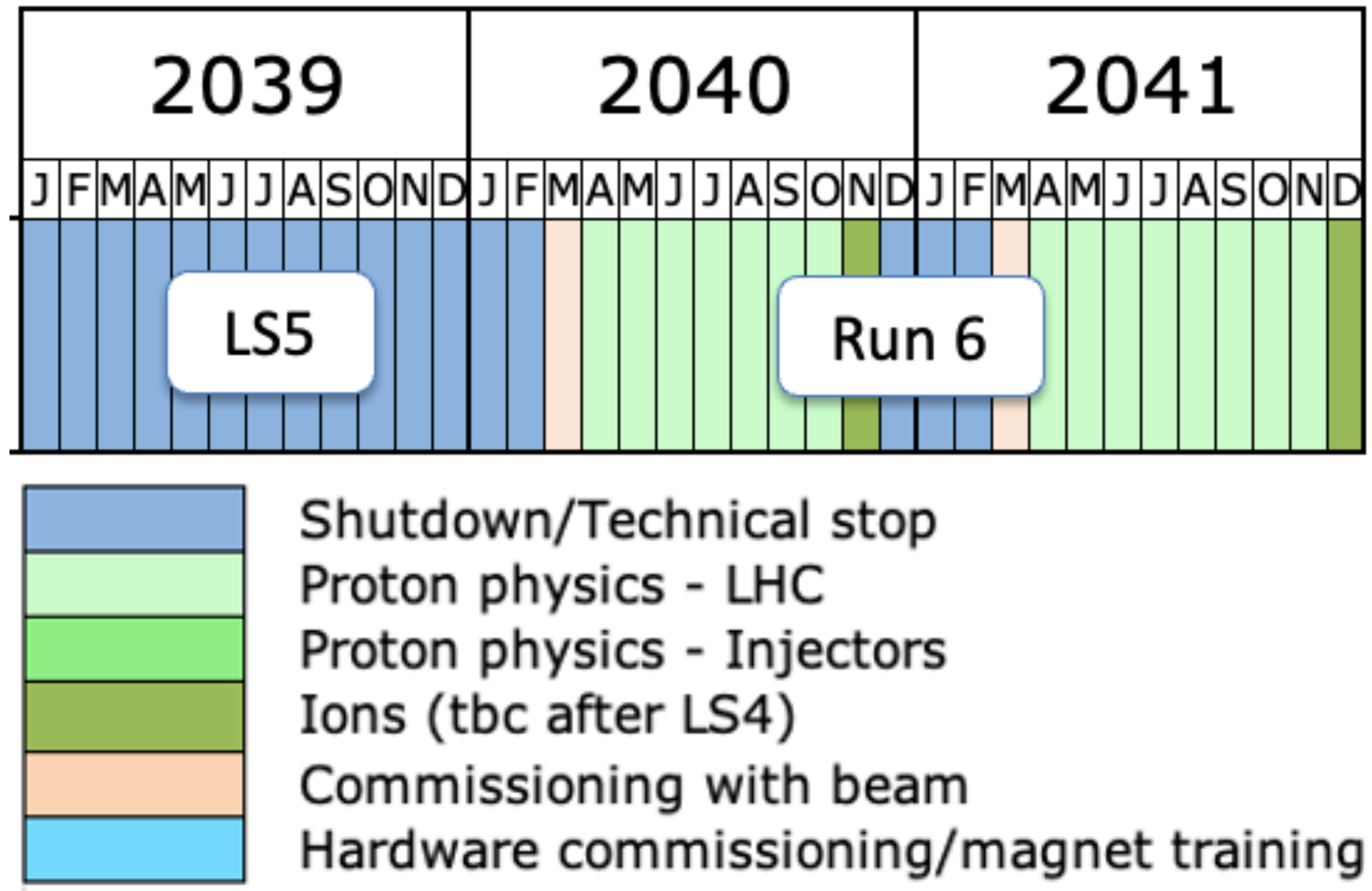
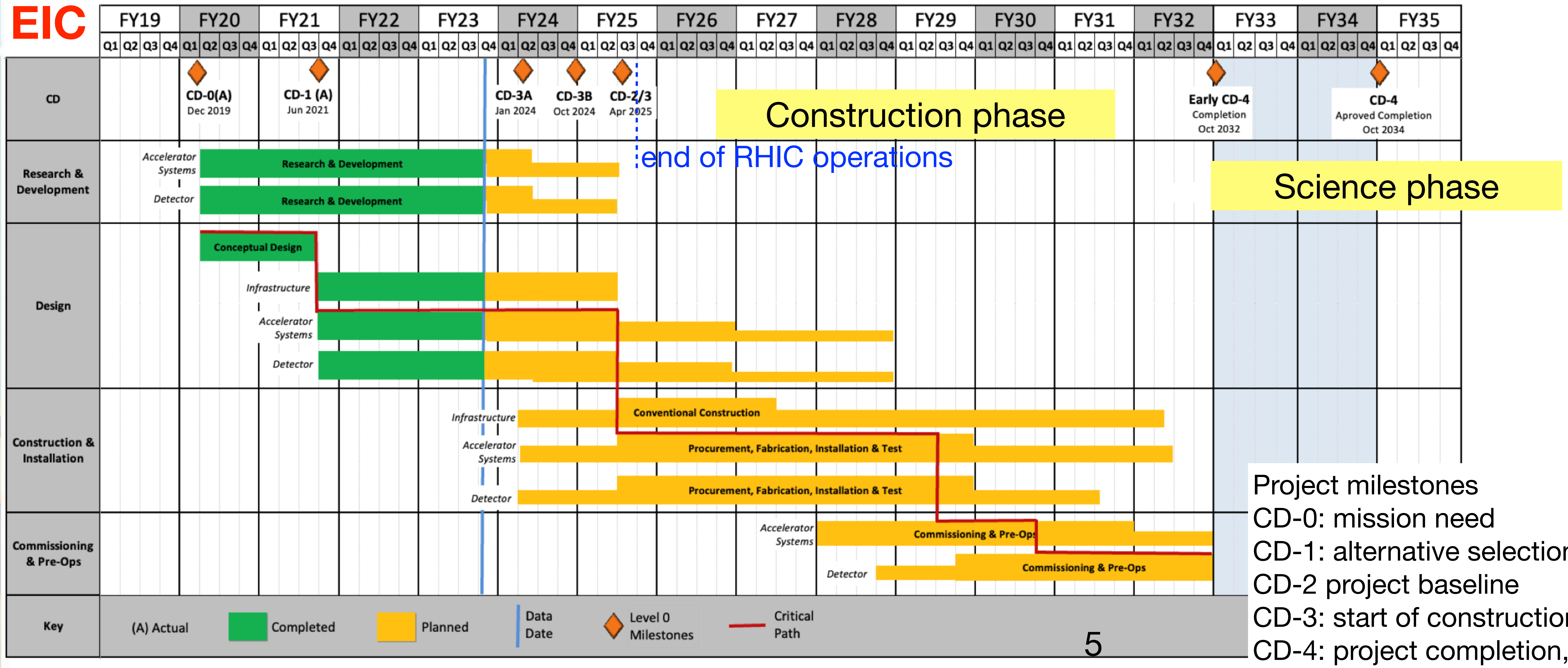


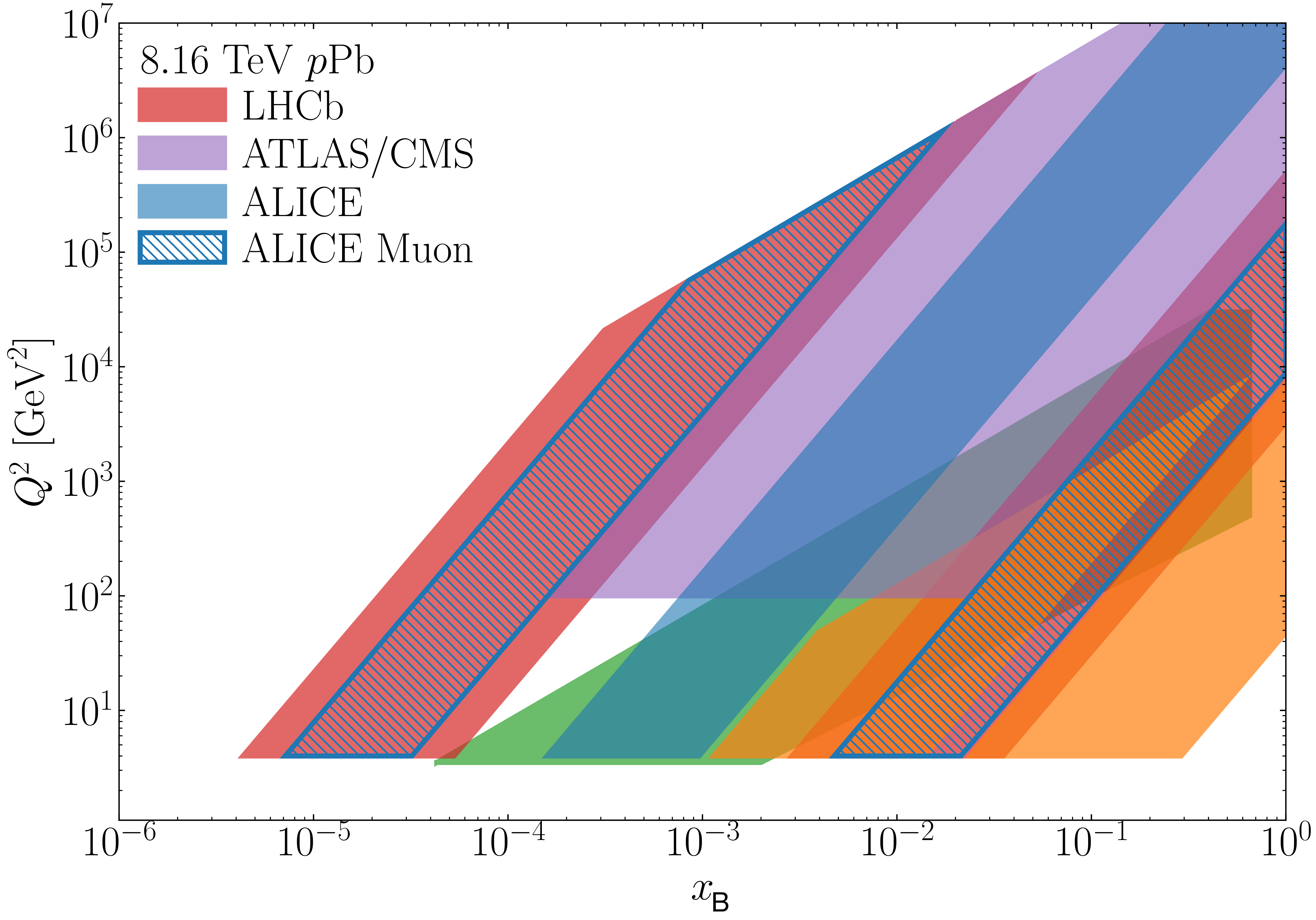


EIC



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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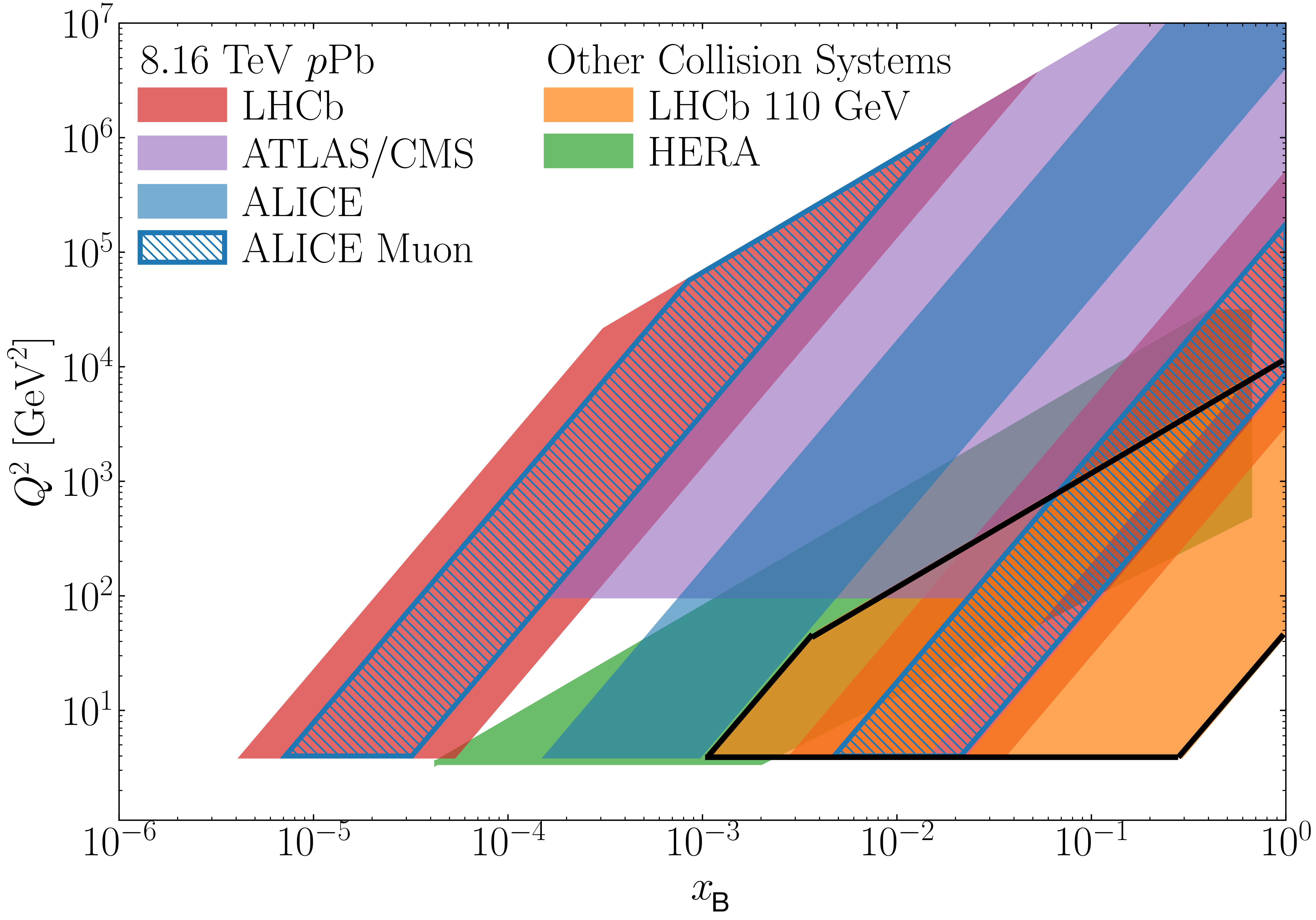

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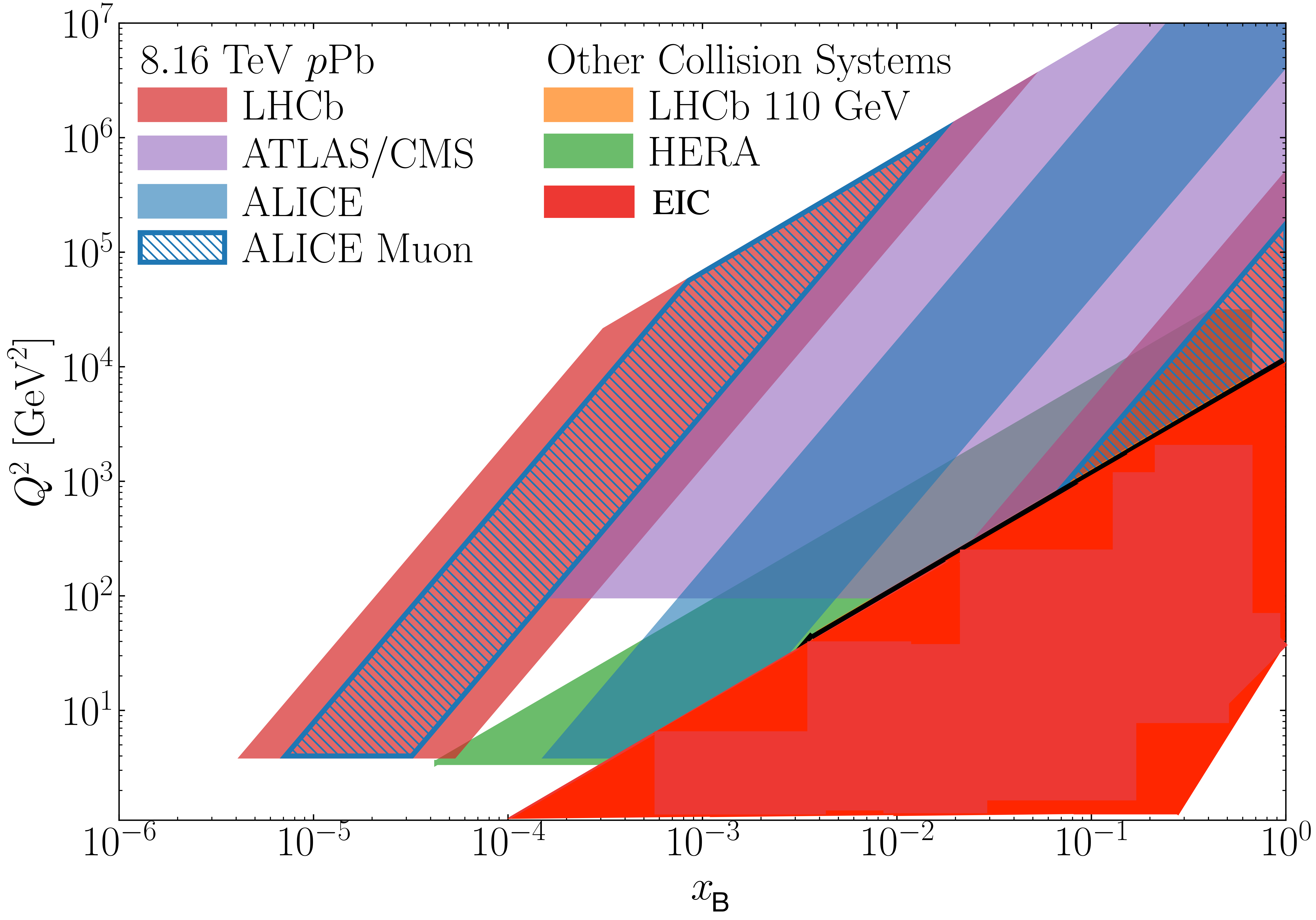
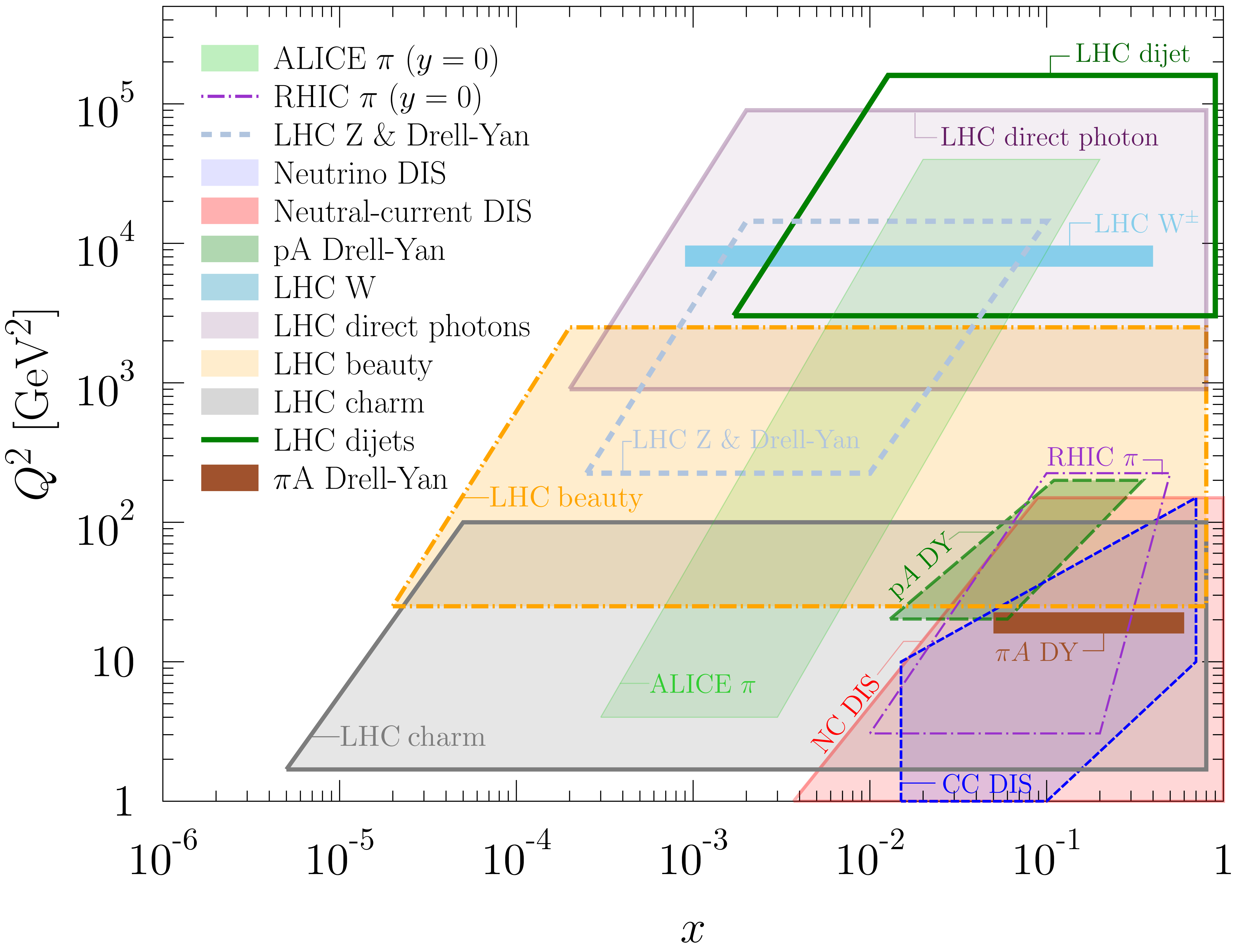
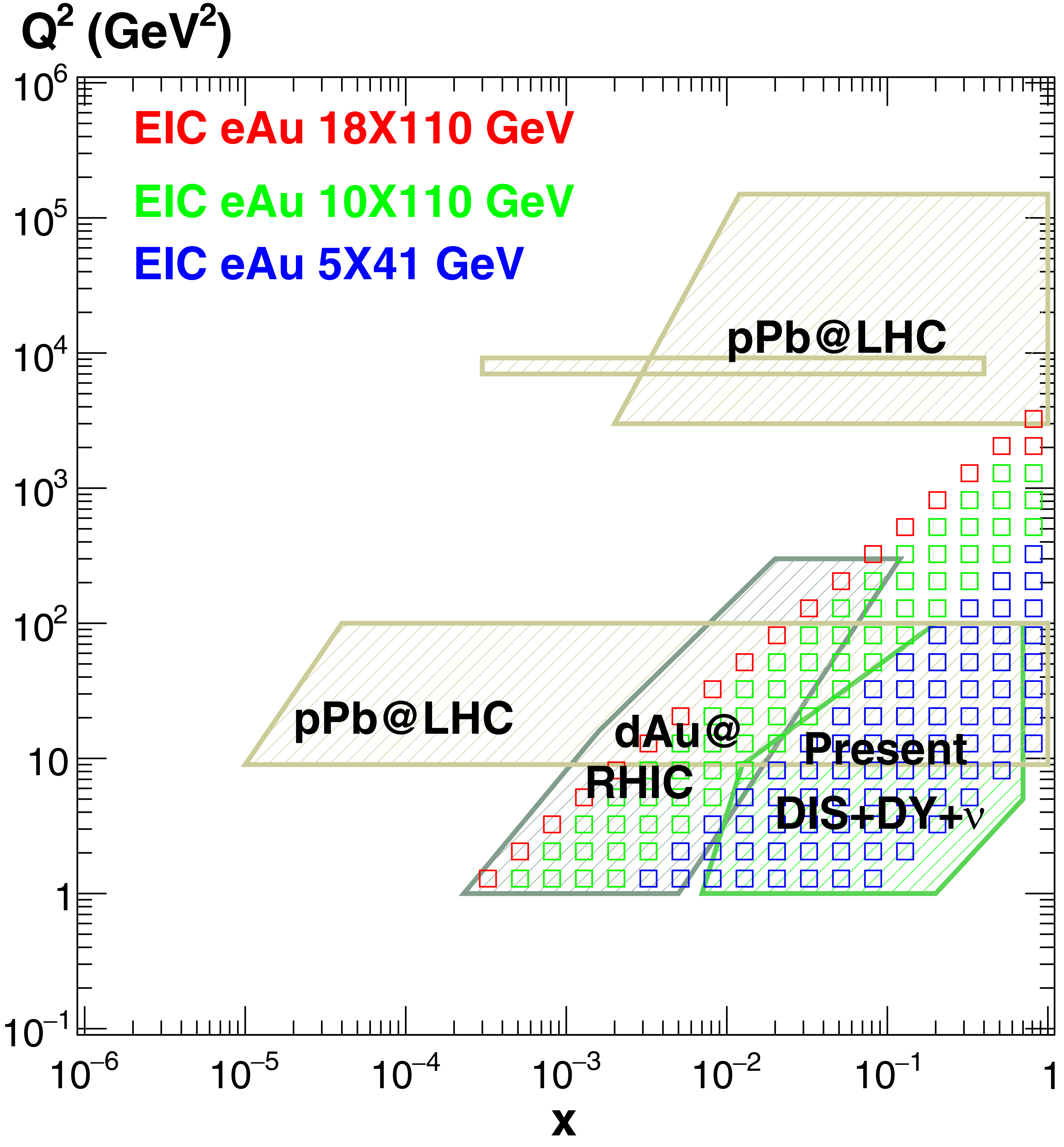


Nuclear PDFs

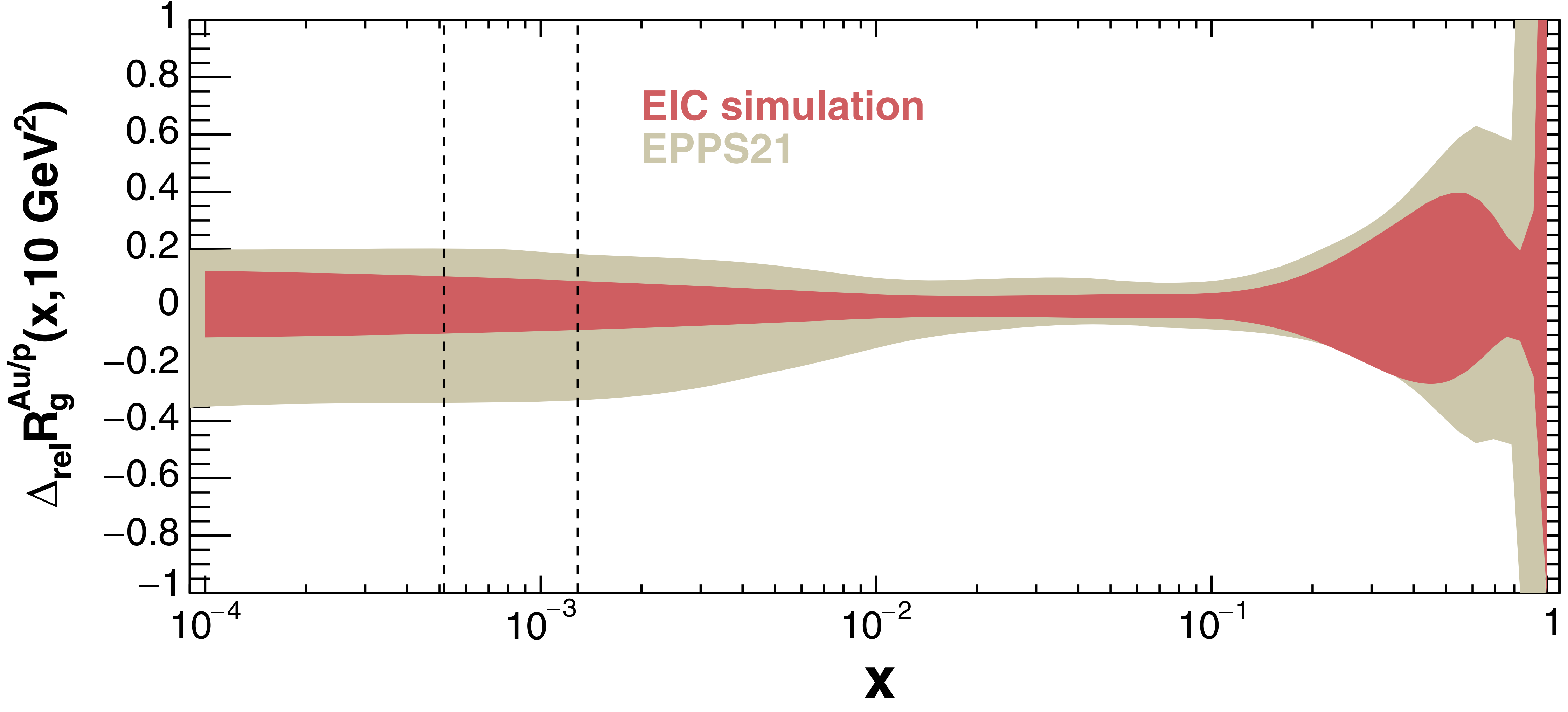




Impact of EIC on nuclear PDFs

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

Uncertainty on gluon distribution in Au/p



Inclusive e-Au data only:
constrain of nuclear PDF one single nucleus!

pPb LHC data: dijet, electro-weak boson, and D-meson

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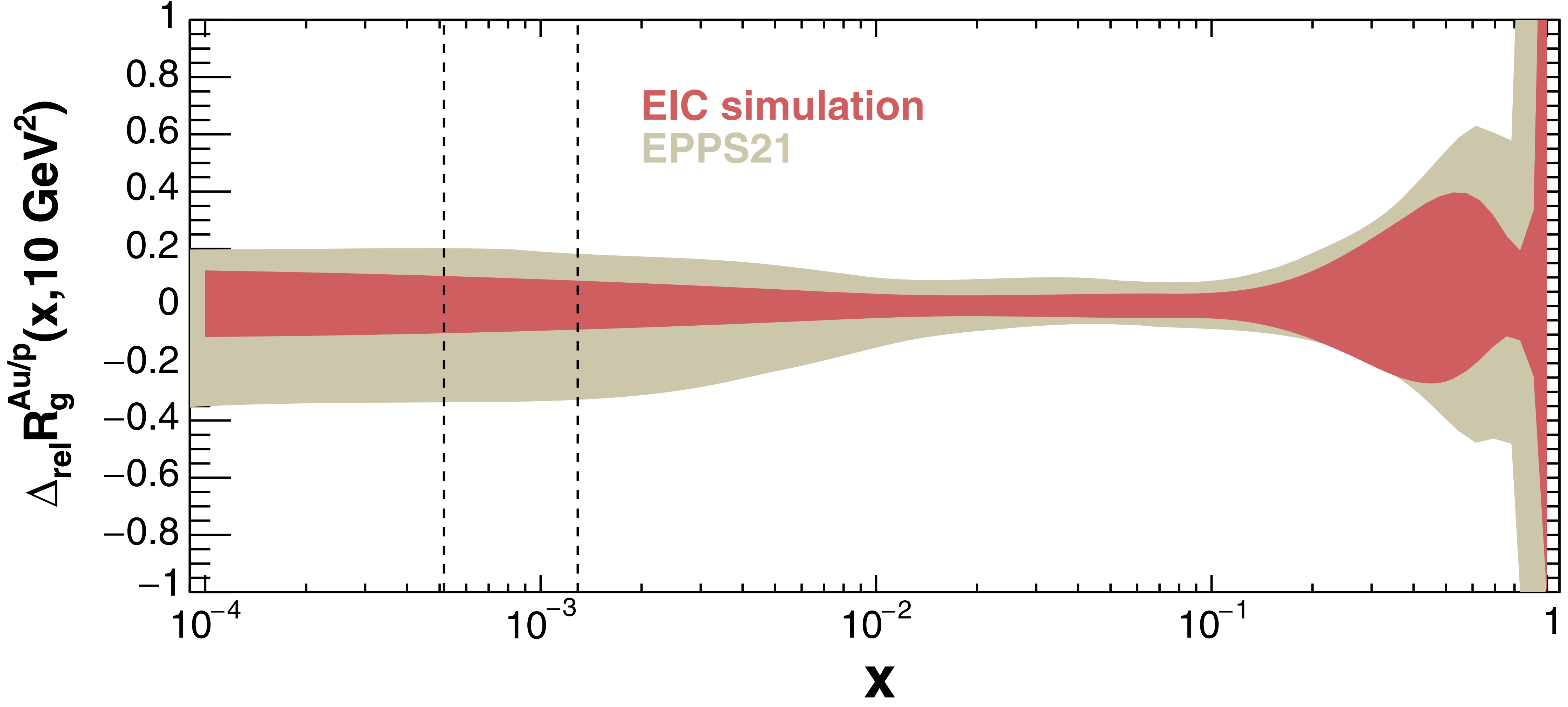
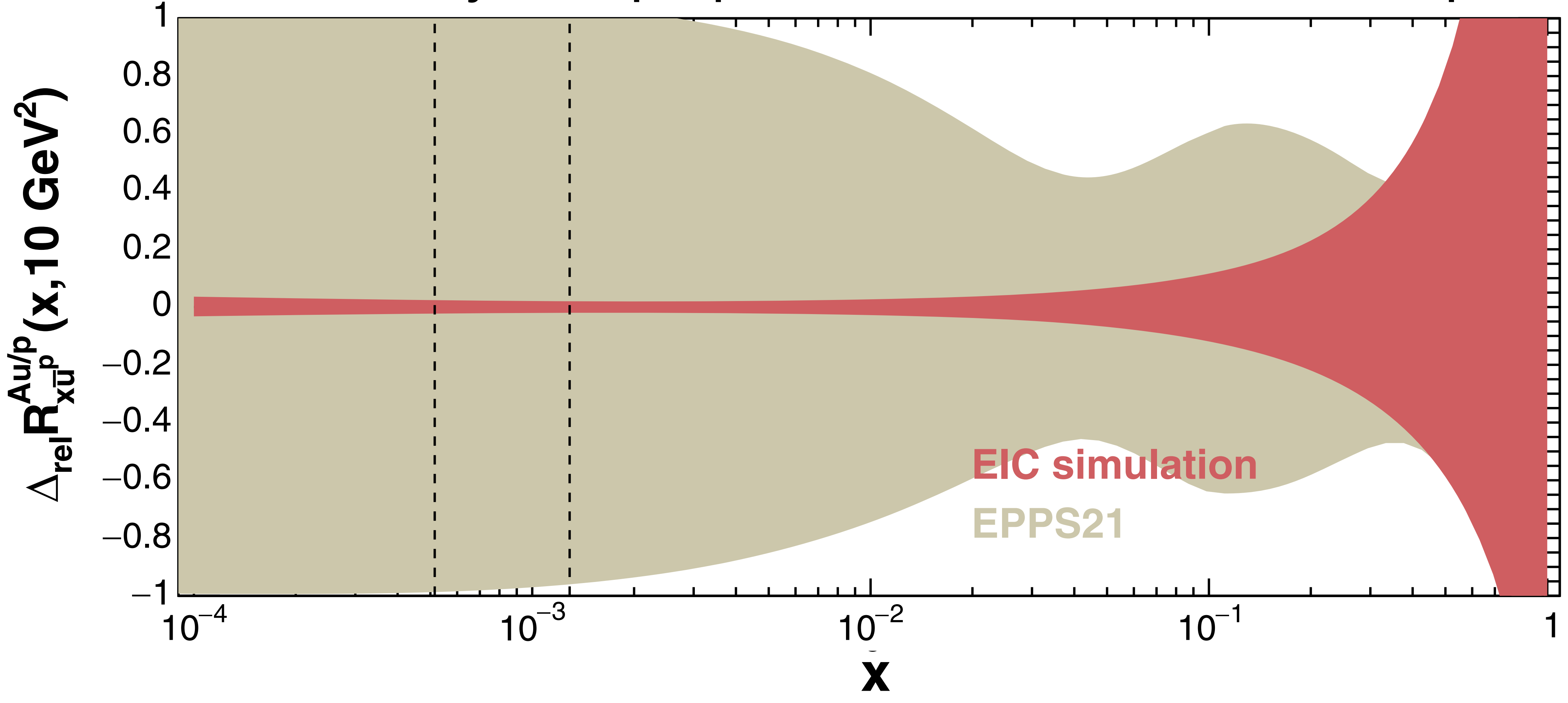
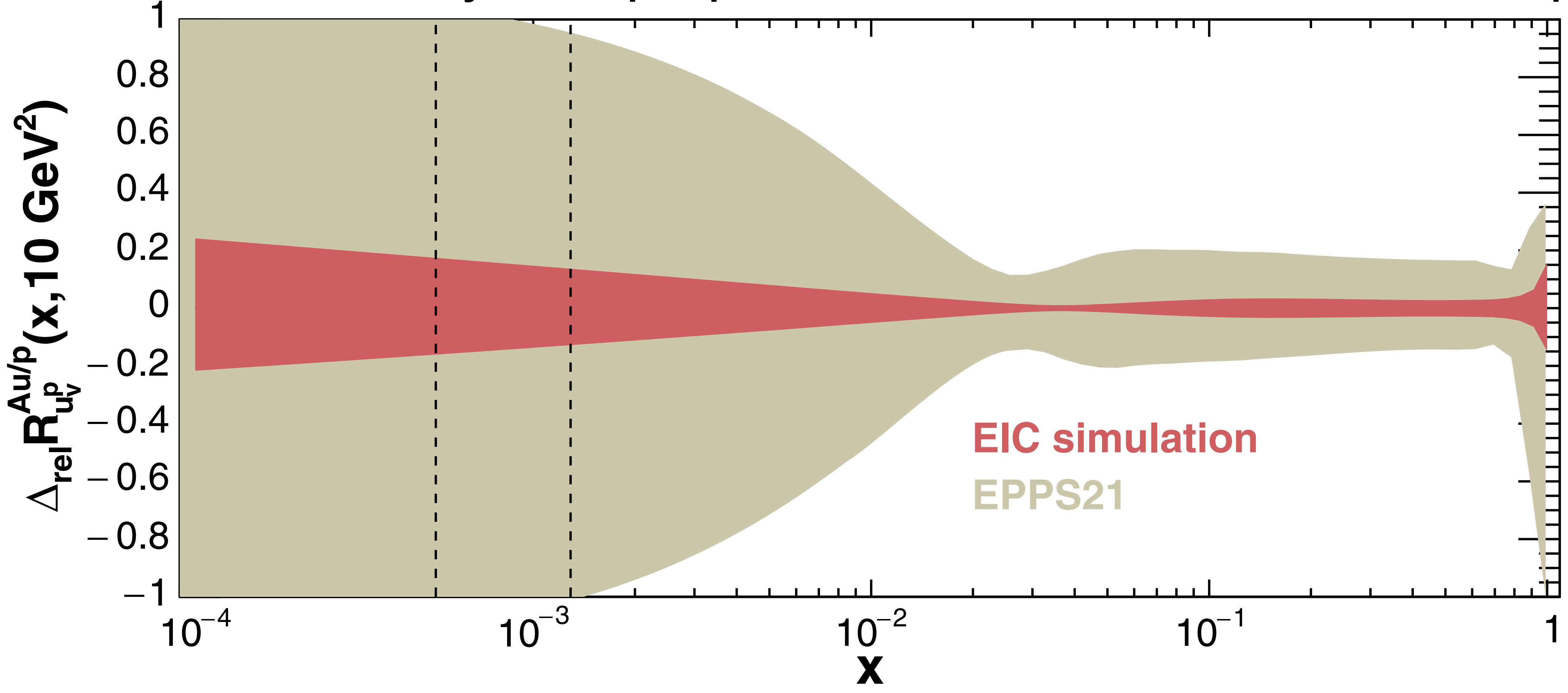


Uncertainty on up-quark sea distribution in Au/p



Uncertainty on up-quark valence distribution in Au/p



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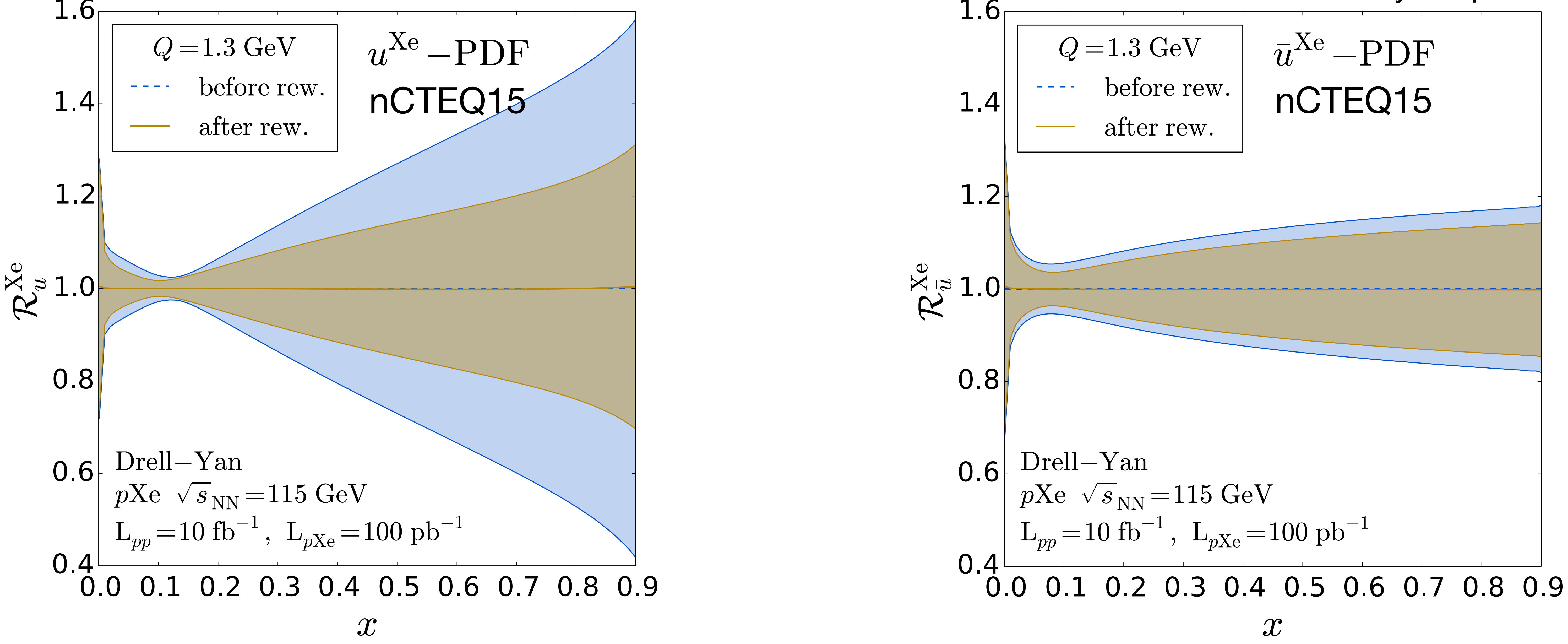
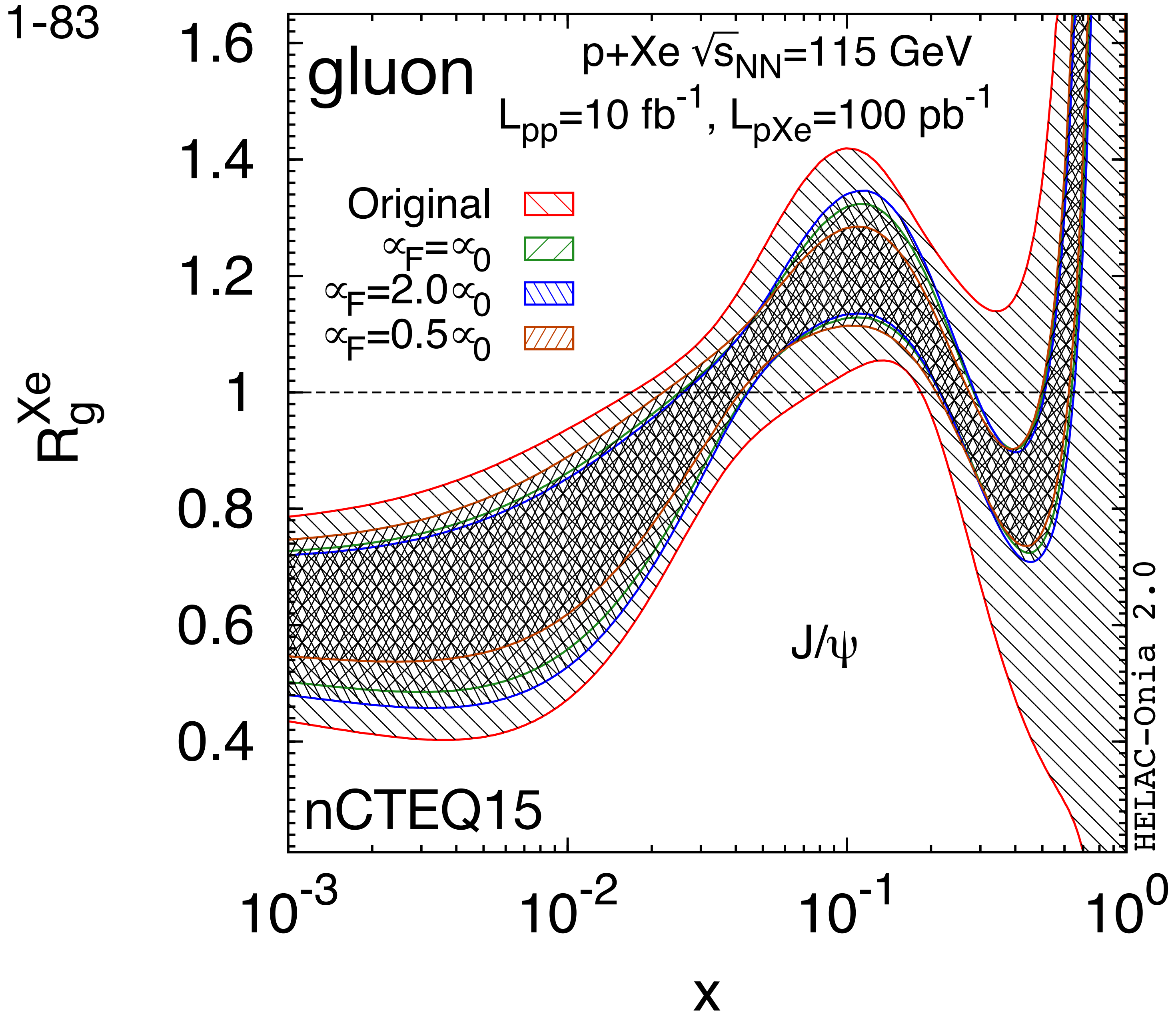
Impact of fixed target on nuclear PDFs

Fixed-target Drell-Yan

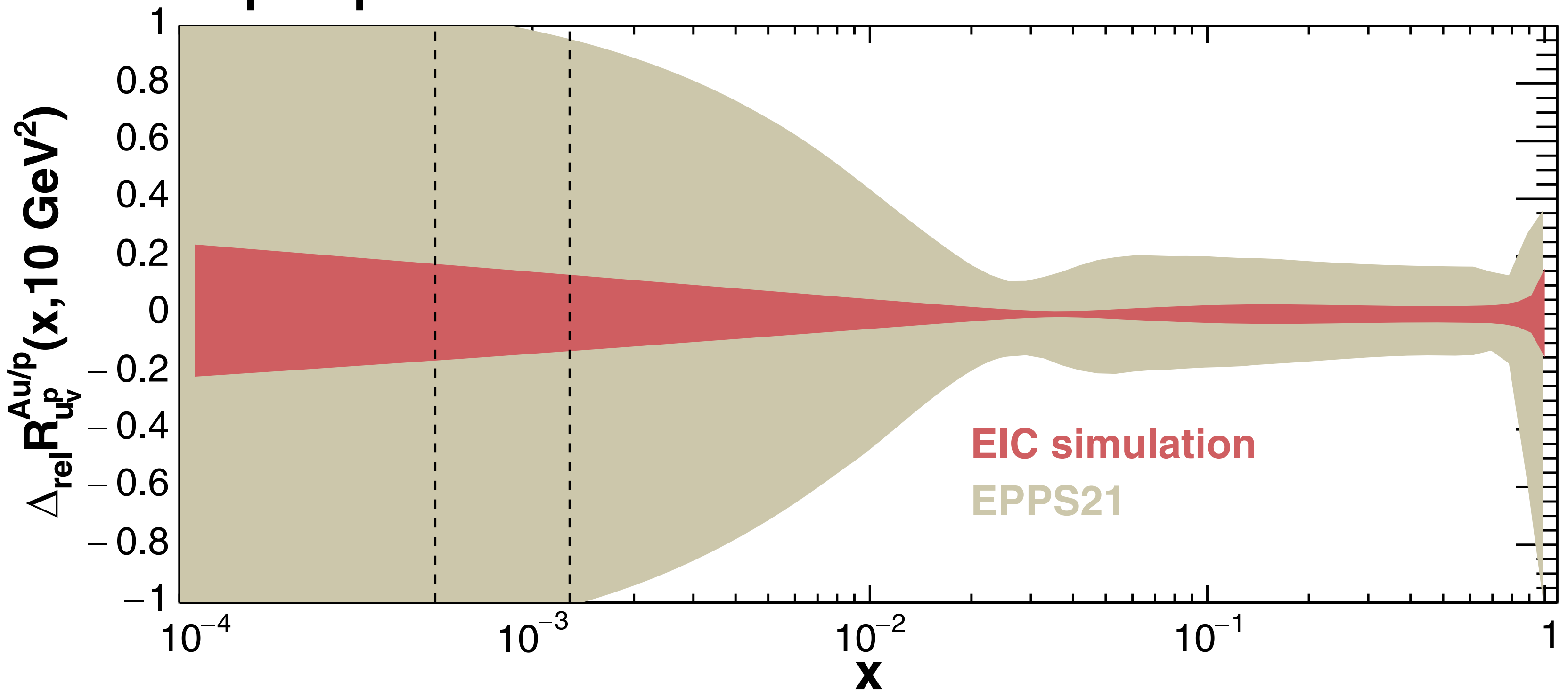
C. Hadjidakis et al.,
Phys.Rept. **911** (2021) 1-83



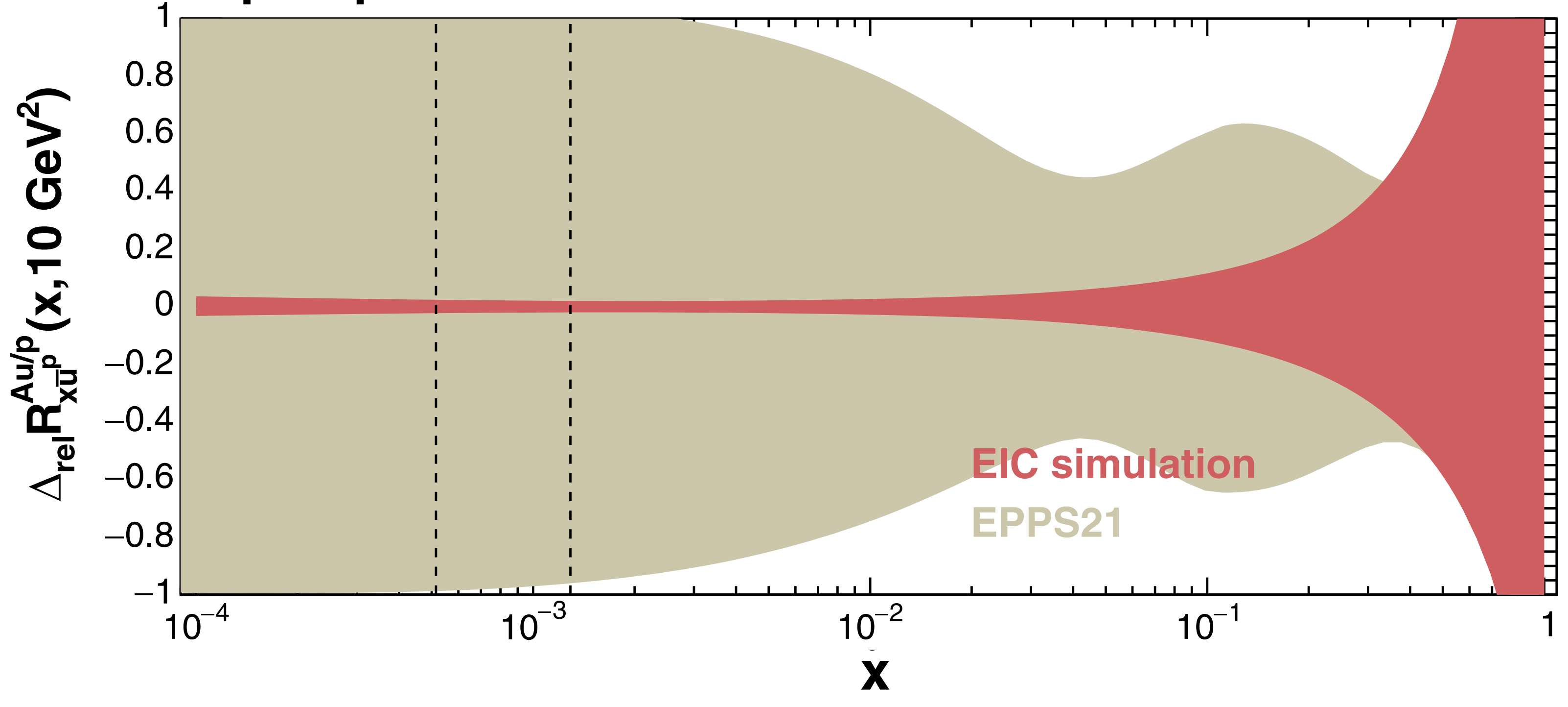
Fixed-target J/ψ production



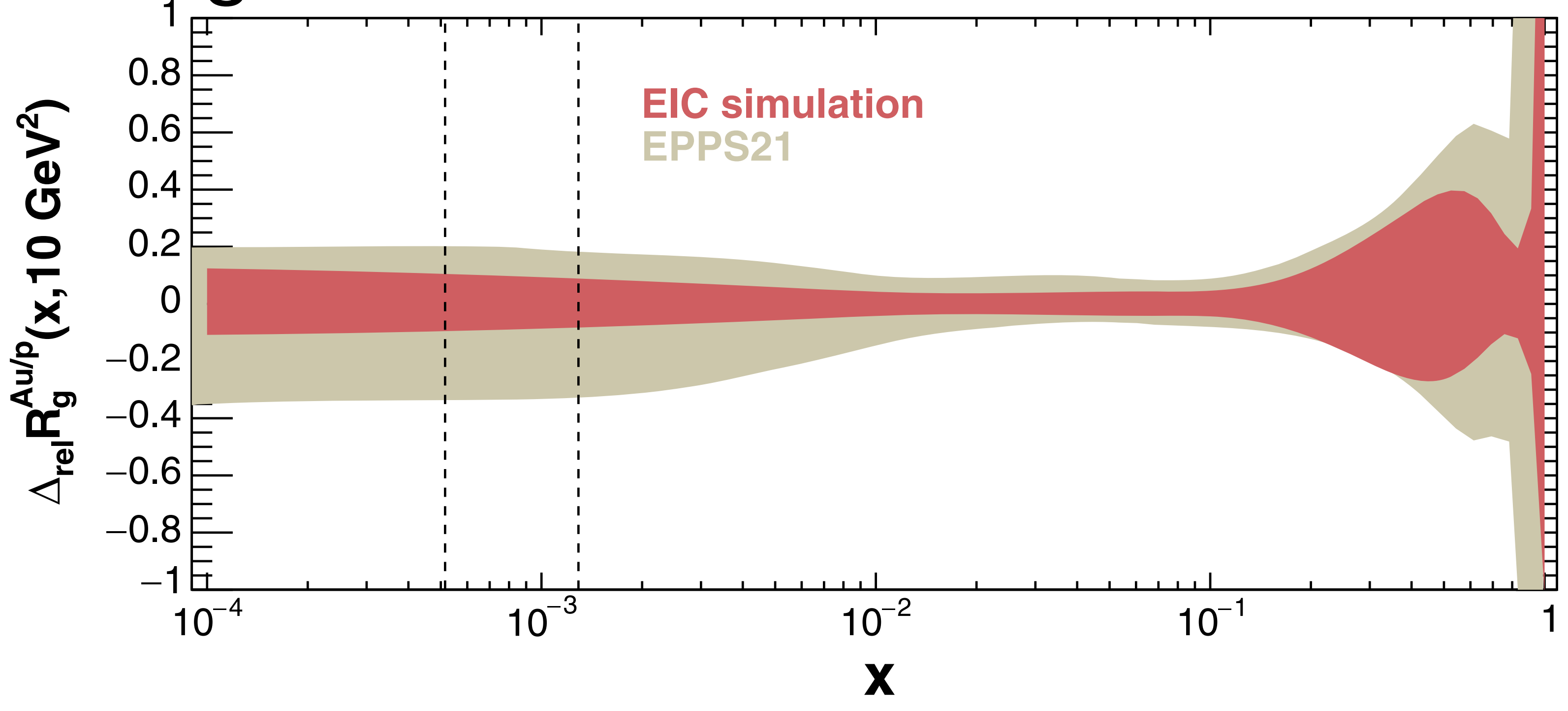
up-quark valence



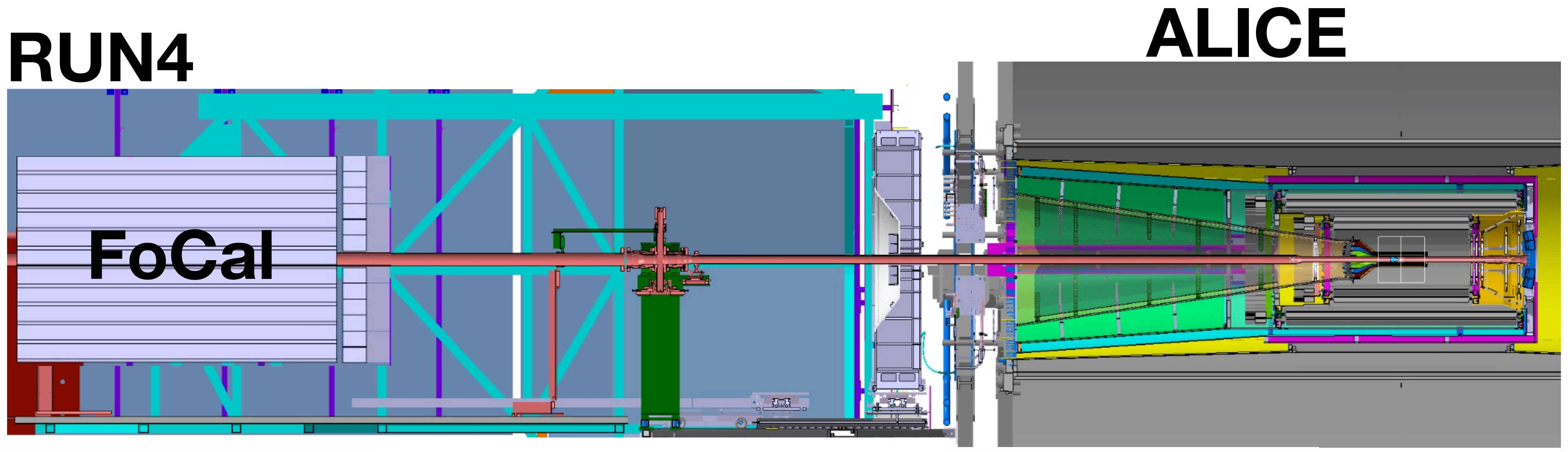
up-quark sea



gluon



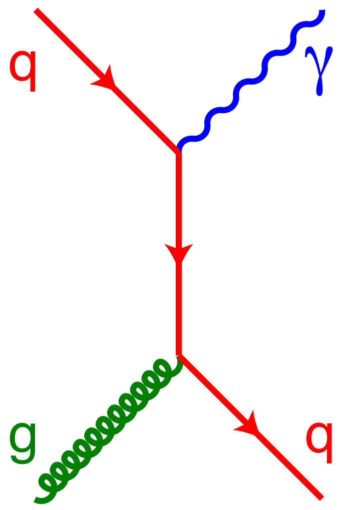
Probing small-x gluon PDFs: Forward Calorimeter (FoCal) at ALICE



EMCal+HCal in $3.4 < \eta < 5.8$

Isolated photons

isolated photons in coincidence with hadrons (π^0): dominated by quark-gluon Compton scattering



Probe (nuclear) gluon PDFs and saturation in x_B down to 10^{-6}

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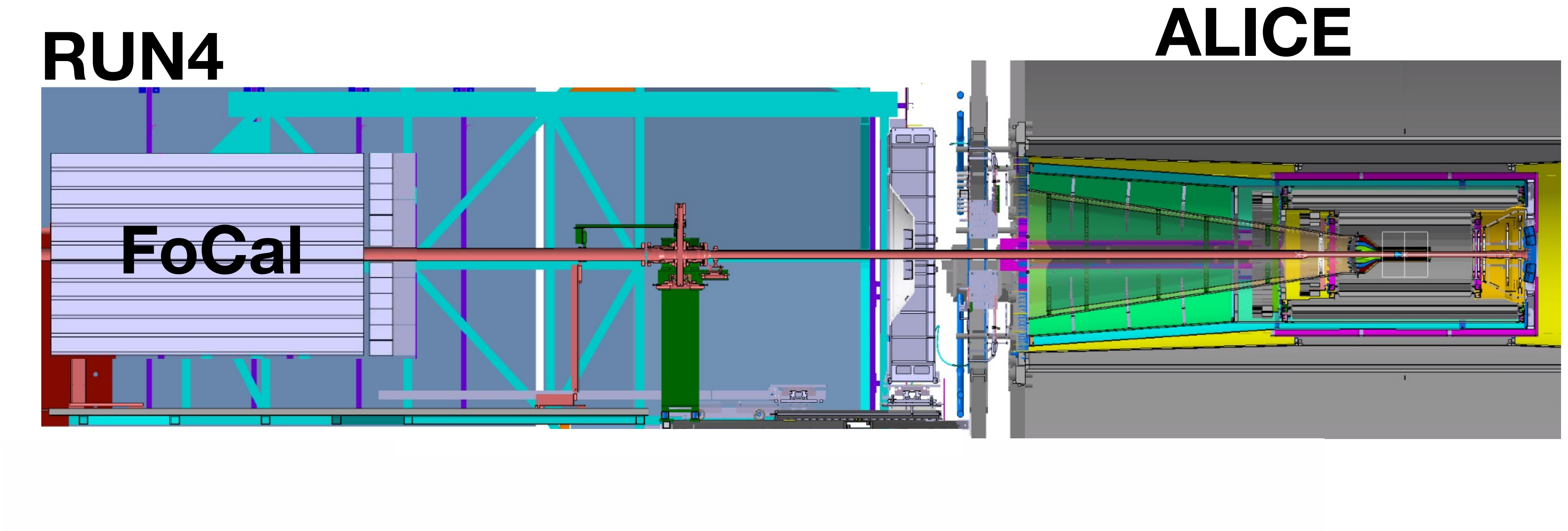

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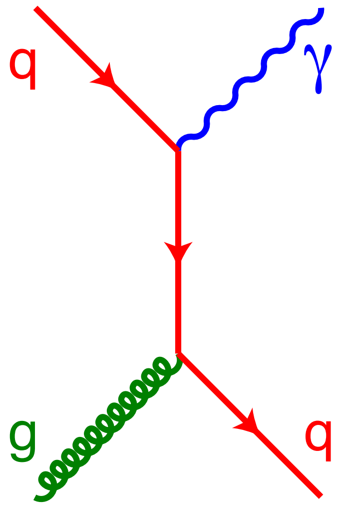
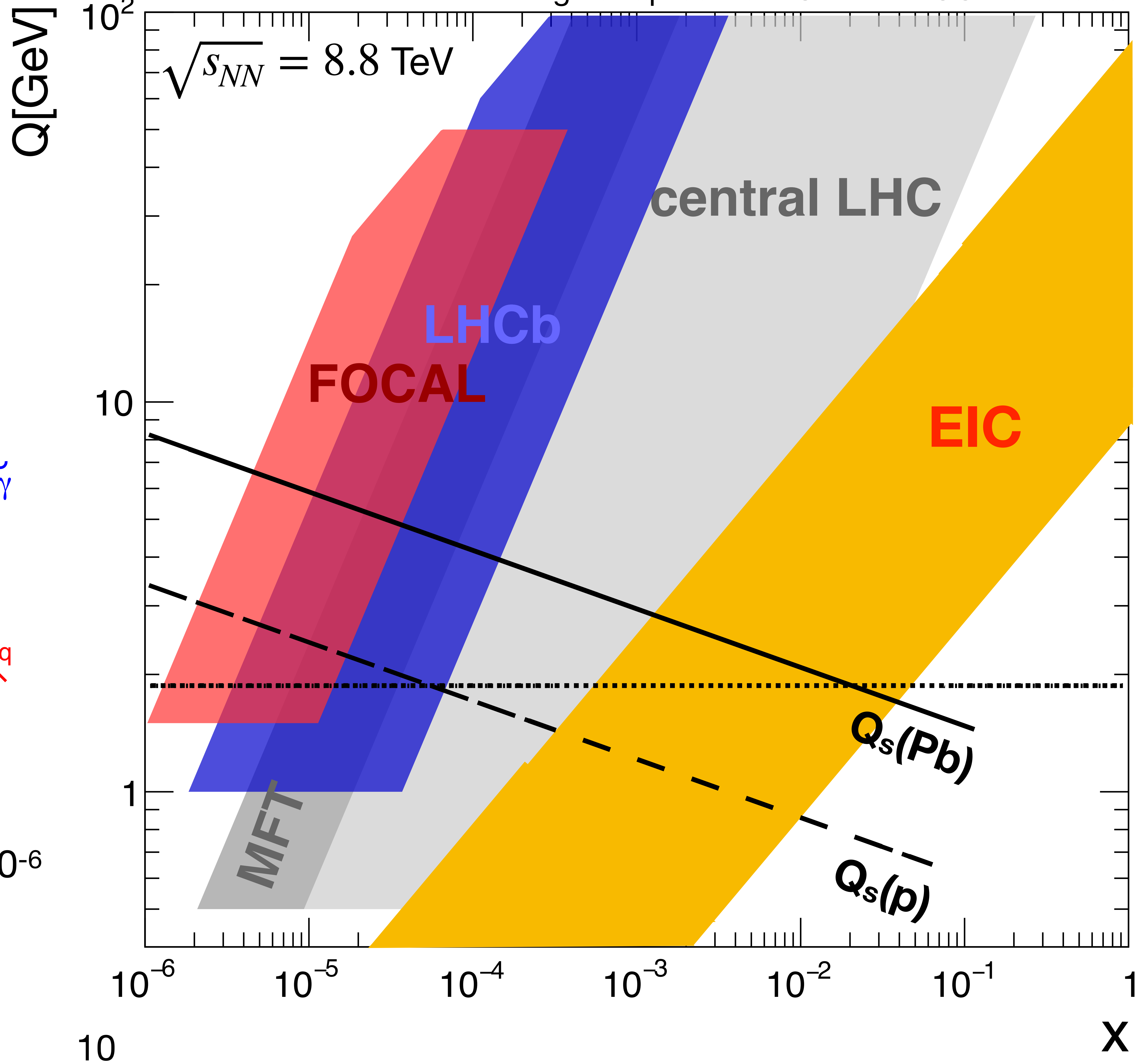
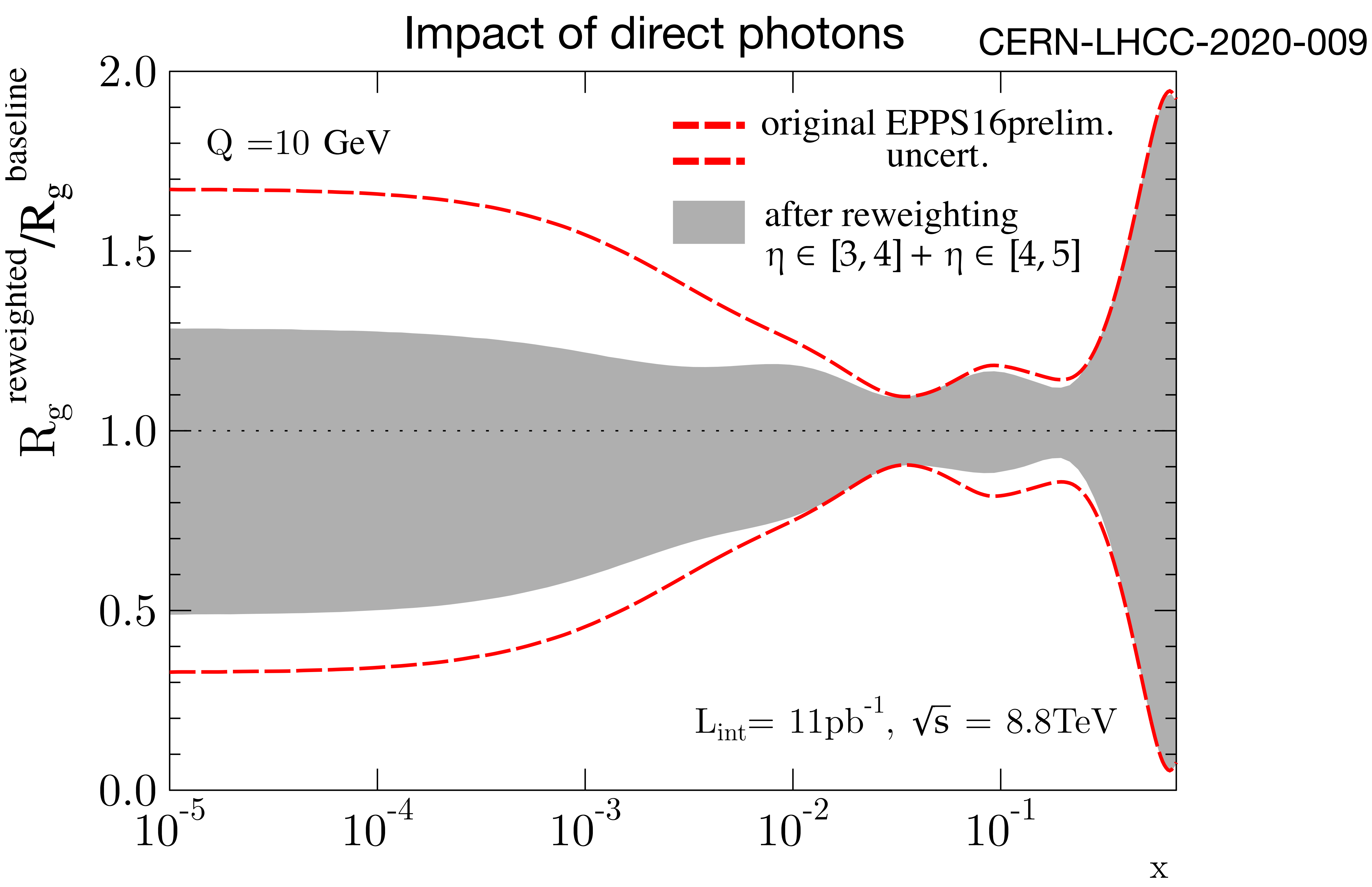


Probe (nuclear) gluon PDFs and saturation in x_B down to 10^{-6}

Fig. adapted from CERN-LHCC-2020-009



Expected impact of FoCal on gluon PDFs



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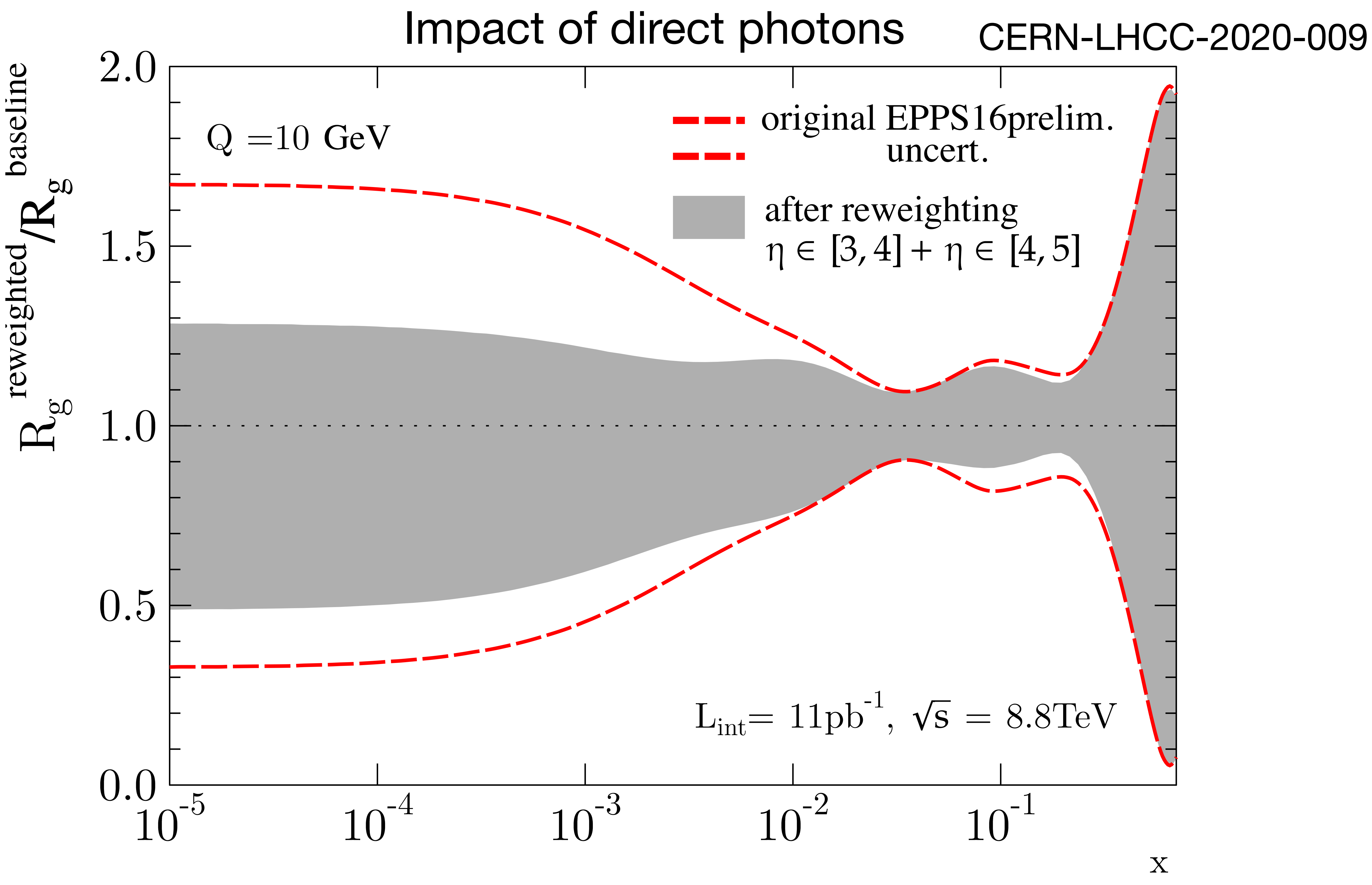
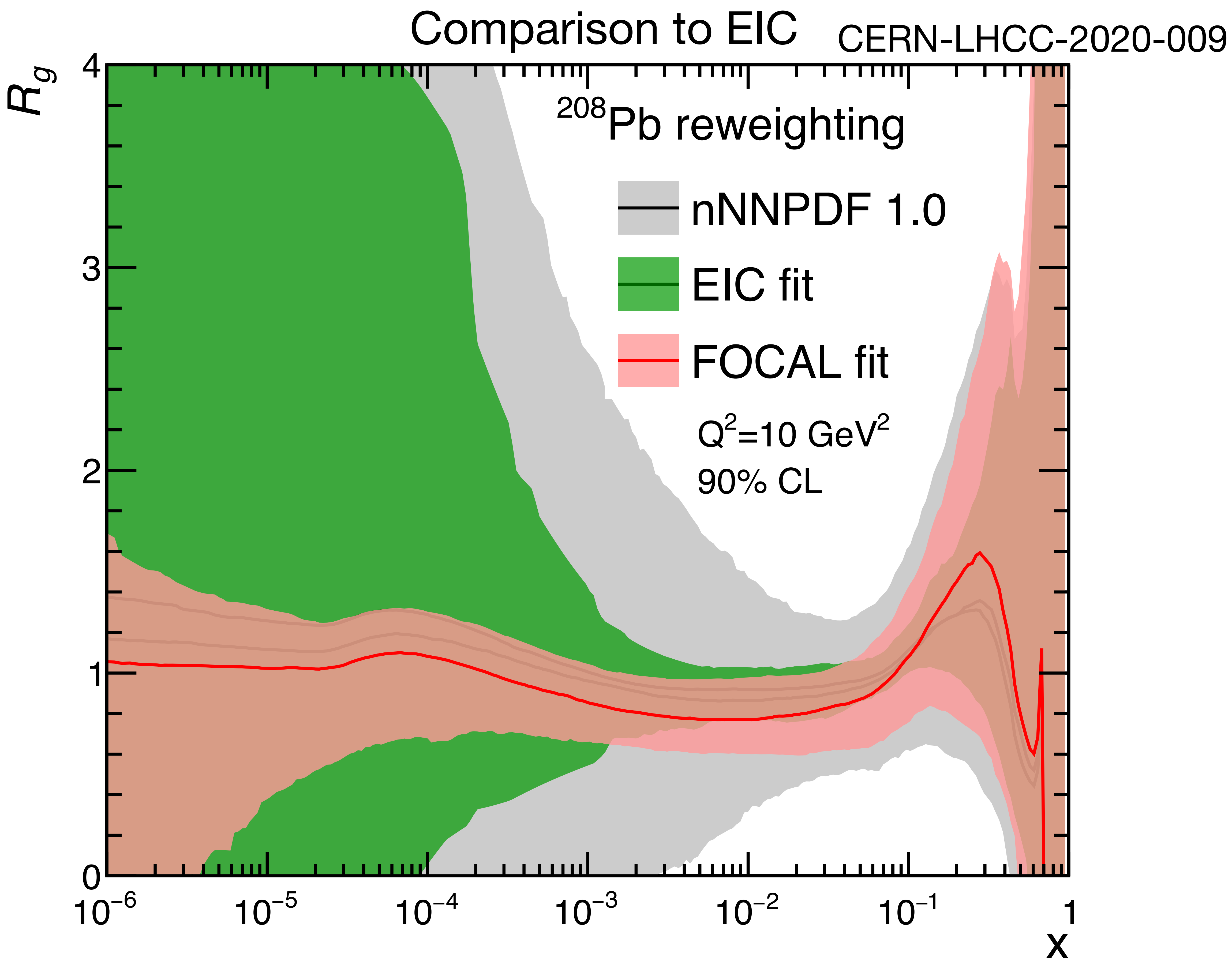
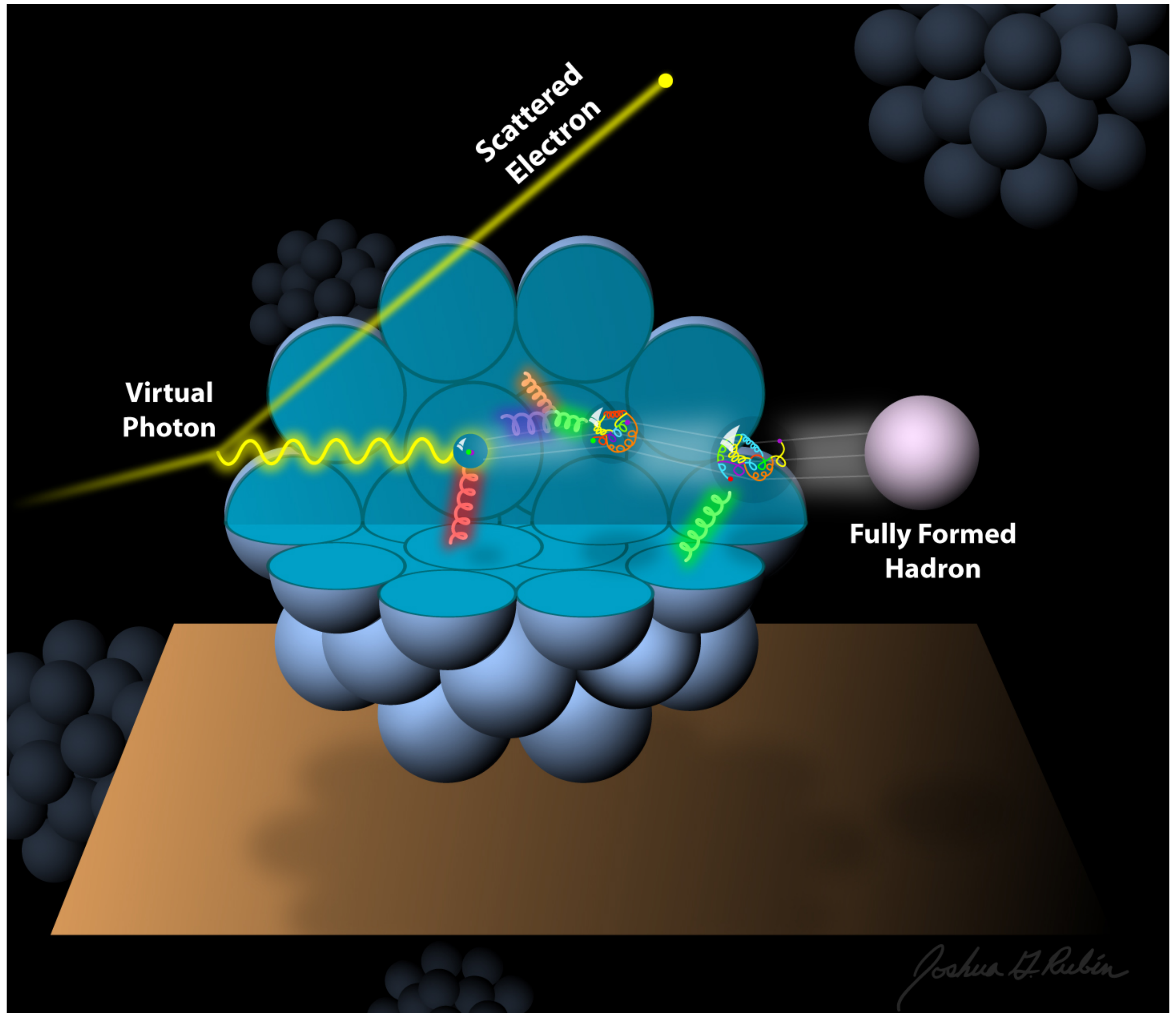




Study of hadronisation



- Energy loss of parton by medium-induced gluon radiation
- Energy loss of (pre-)hadron via absorption and rescattering (small)

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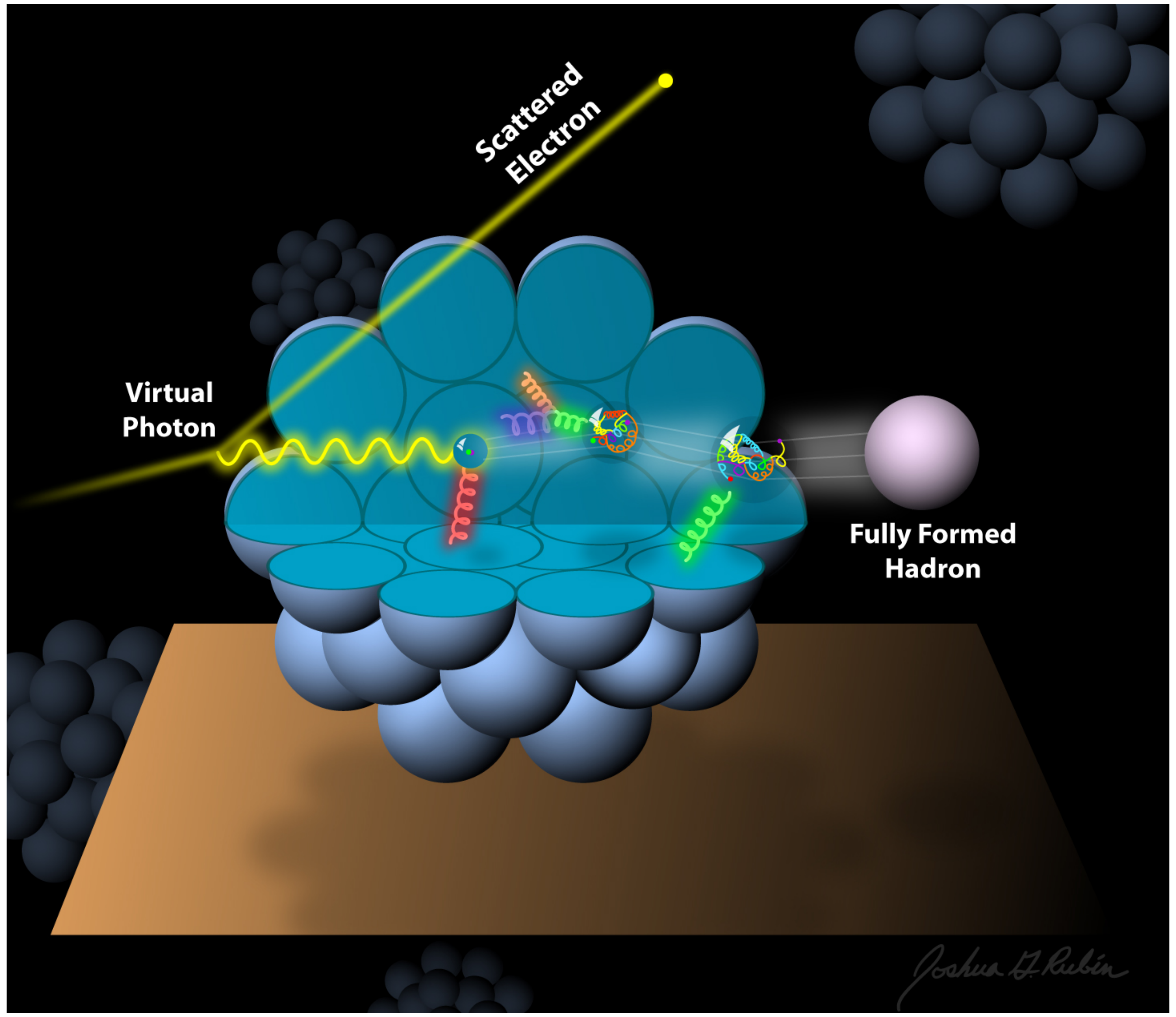

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- Partonic and hadronic processes: different signature

  → using variety of nuclei probe space-time evolution of hadron formation

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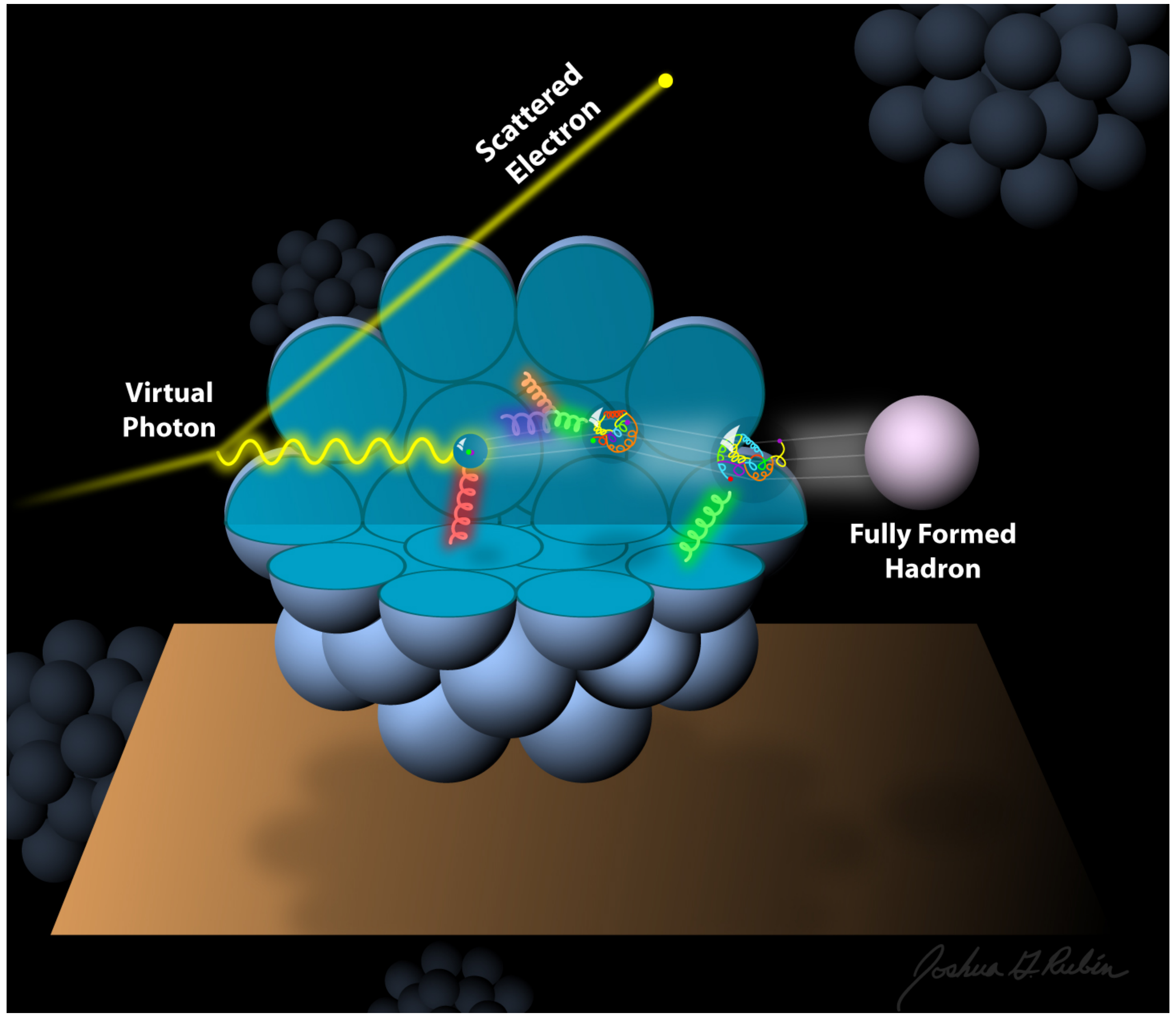

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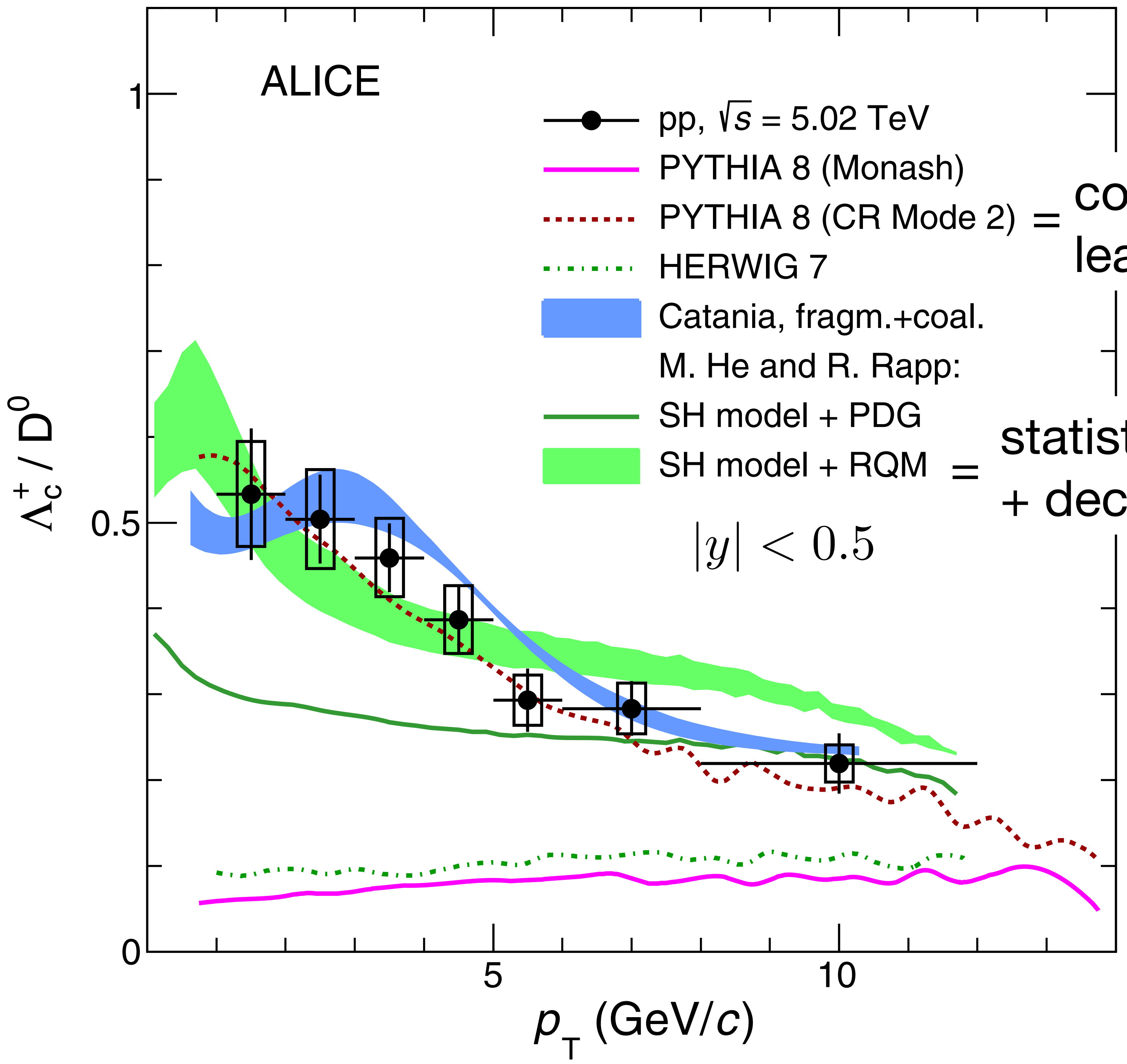
Λ_c^+/D^0

ALICE, Phys. Rev. Lett. **127** (2021) 202301



PYTHIA 8 (CR Mode 2) = colour reconnection beyond the leading-colour approximation

SH model + RQM = statistical hadronisation model + decaying excited states

- Decrease with p_T

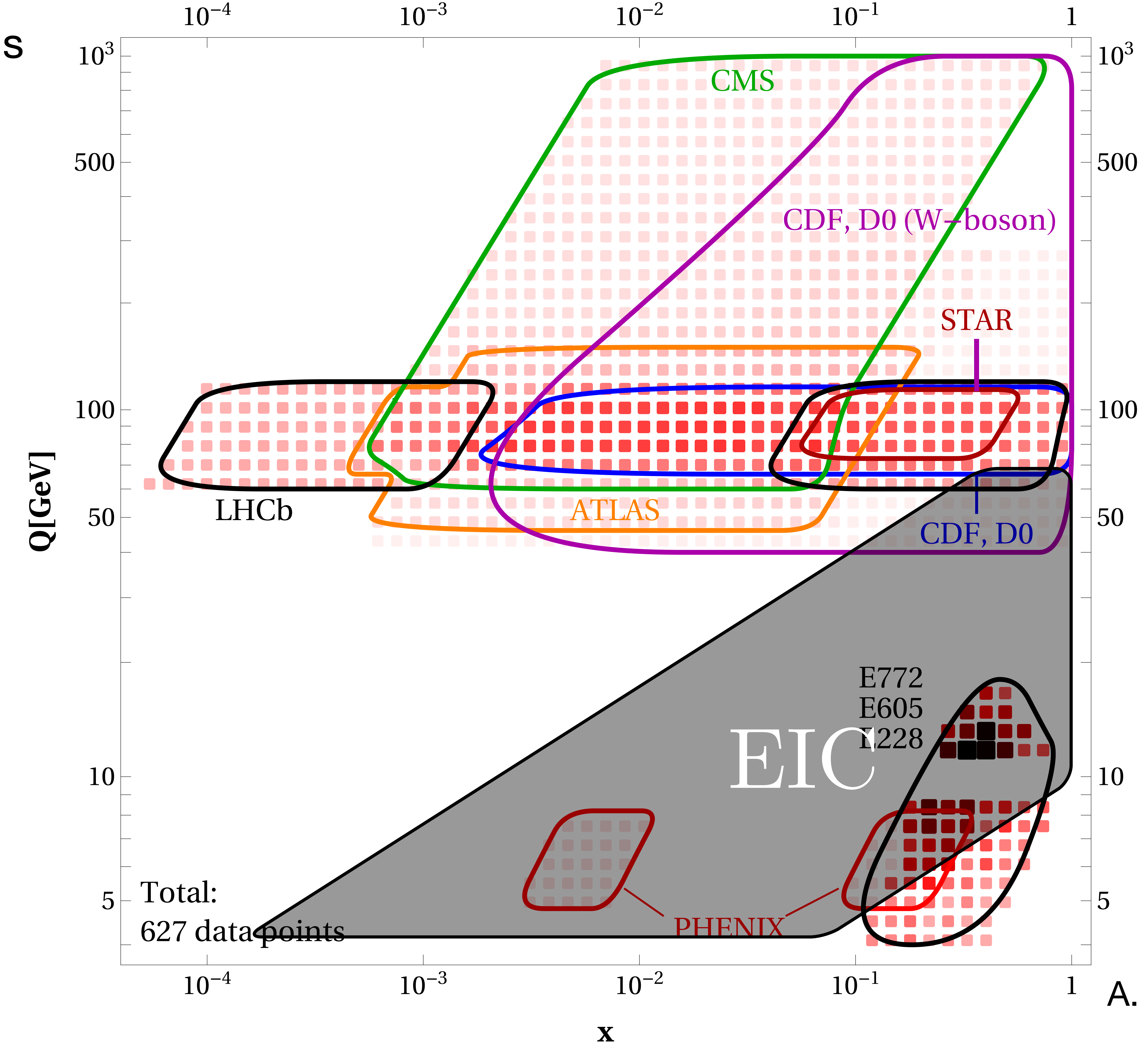
  → suggests difference for meson and baryon formation
- Larger than for e^+e^- and ep measurements

  → suggest additional mechanisms in hadron-hadron collisions

Spin-independent quark TMD PDFs at the LHC and EIC

x-Q coverage for pp/ep collisions

ART34 extraction: at N⁴LL
V.Moos et al., arXiv.:2305.07473



A. Vladimirov

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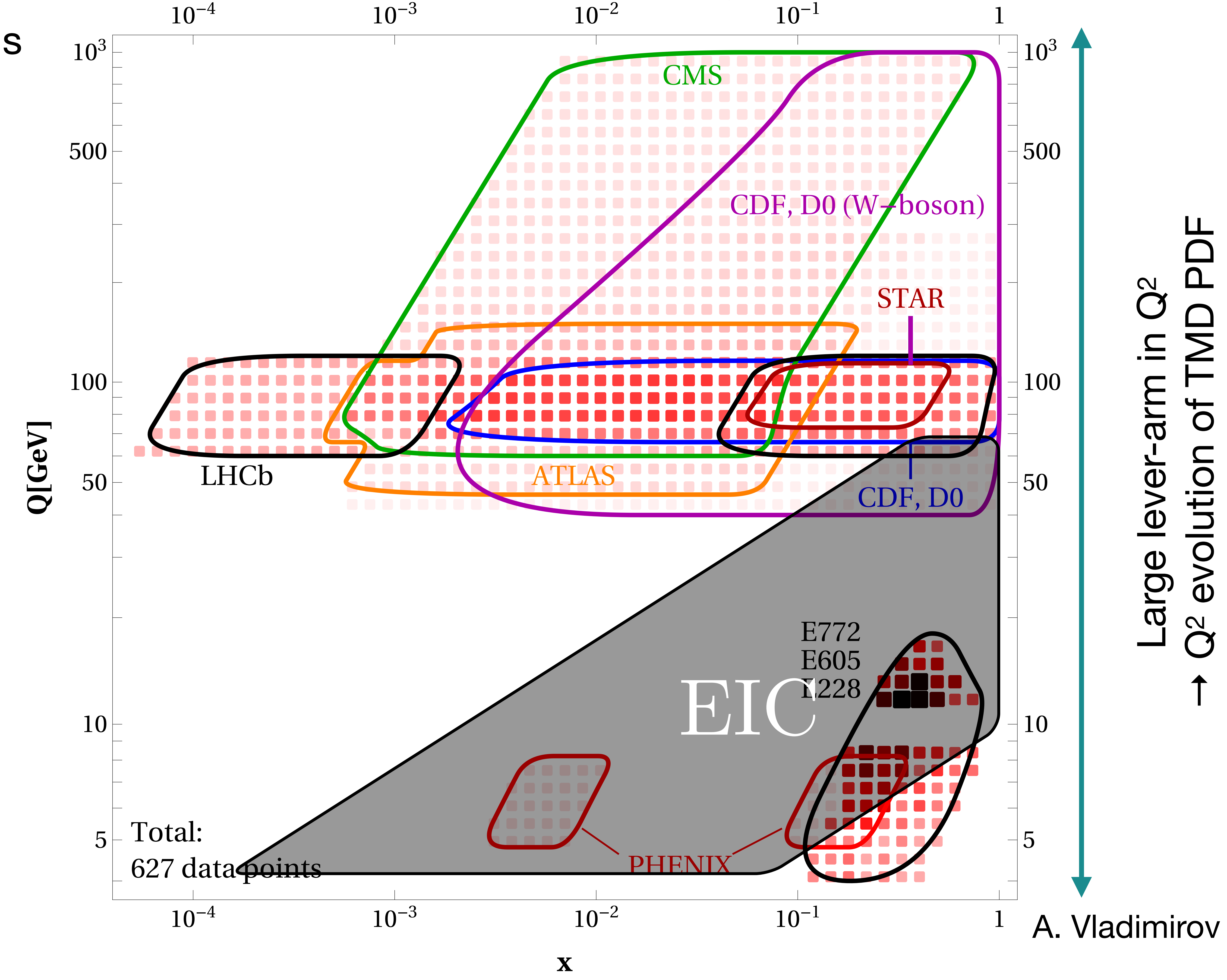


A. Vladimirov

Large lever-arm in Q^2
→ Q^2 evolution of TMD PDF

Nuclear TMD PDFs at the LHC and EIC

quark polarisation

nucleon polarisation

	U	L	T
U	f_1		$h_1^\perp$

gluon polarisation

nucleon polarisation

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$

Nuclear TMD PDFs at the LHC and EIC

quark polarisation

nucleon polarisation

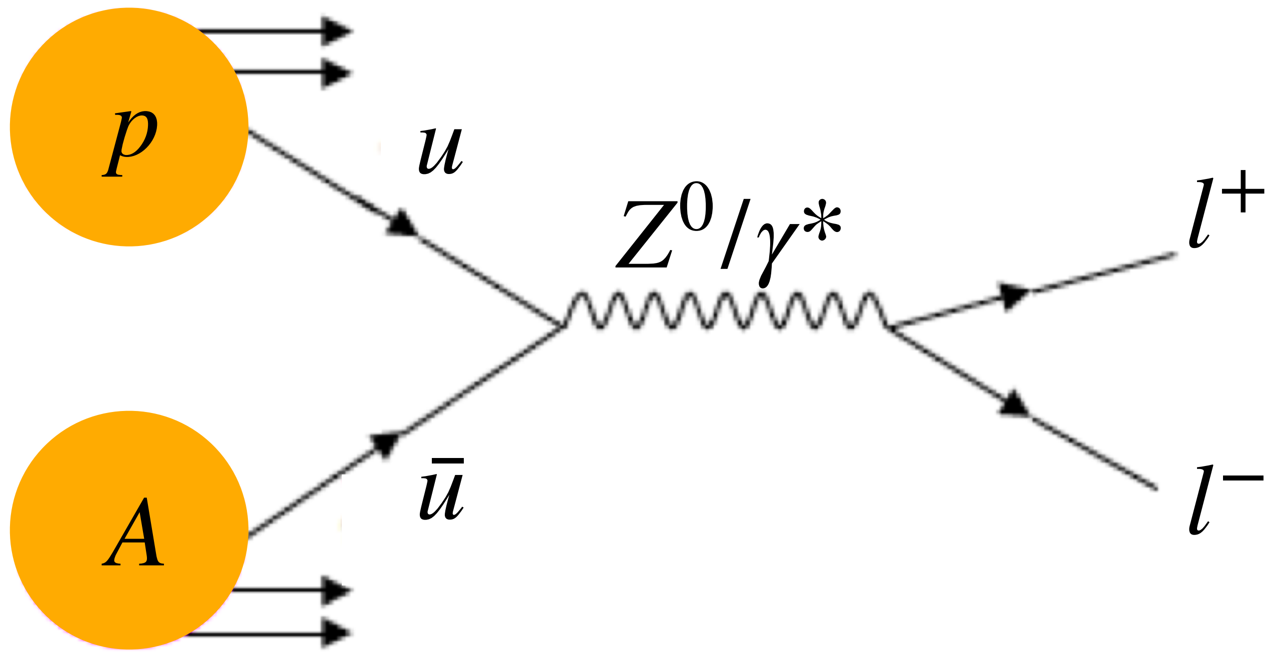
	U	L	T
U	f_1		$h_1^\perp$

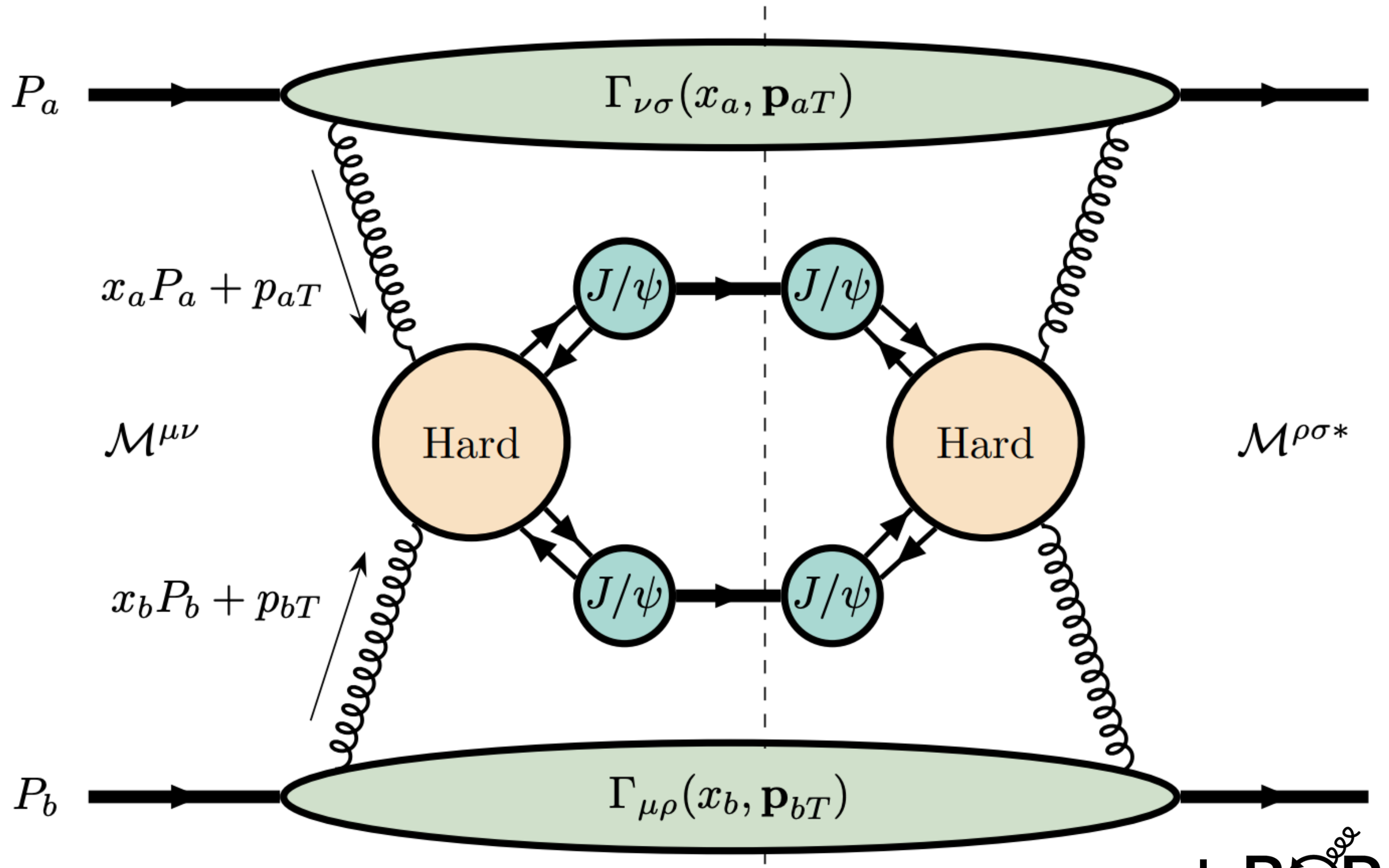
gluon polarisation

nucleon polarisation

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$

LHC





J.BOR

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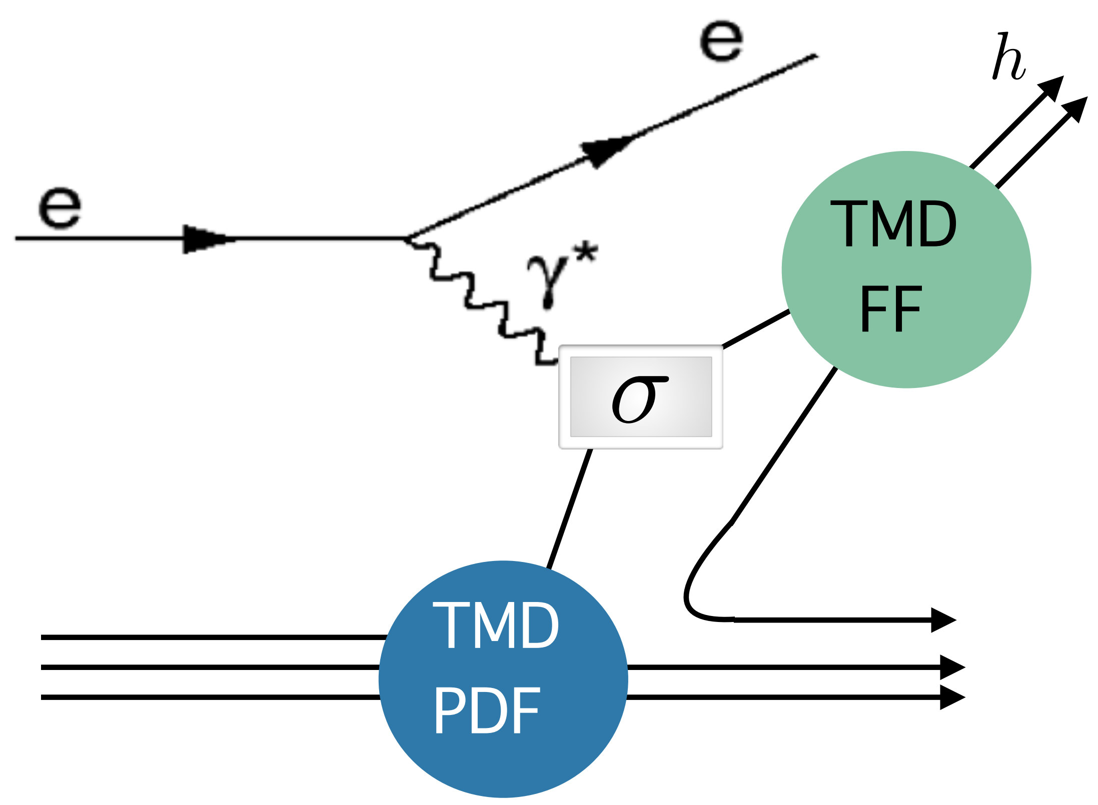
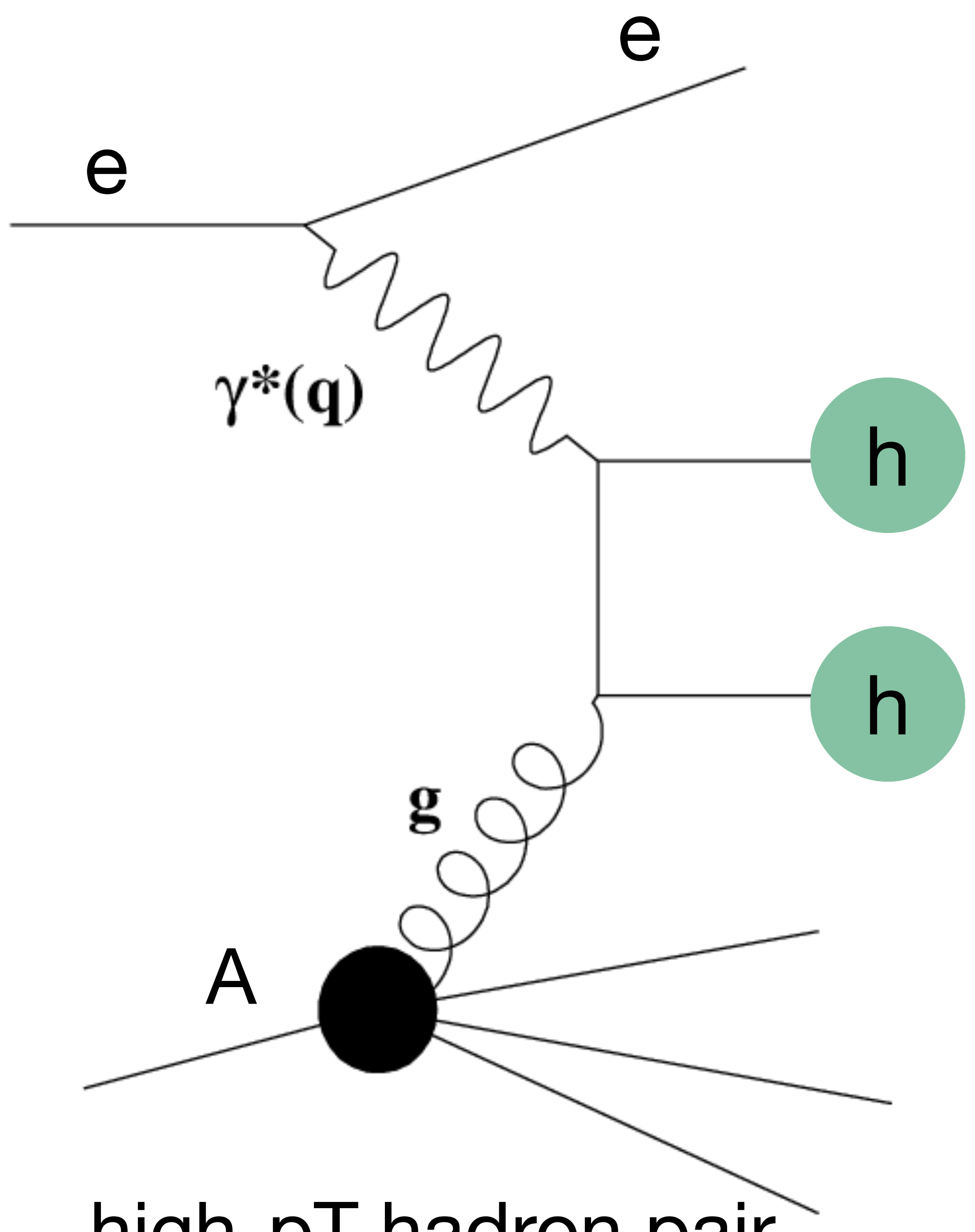
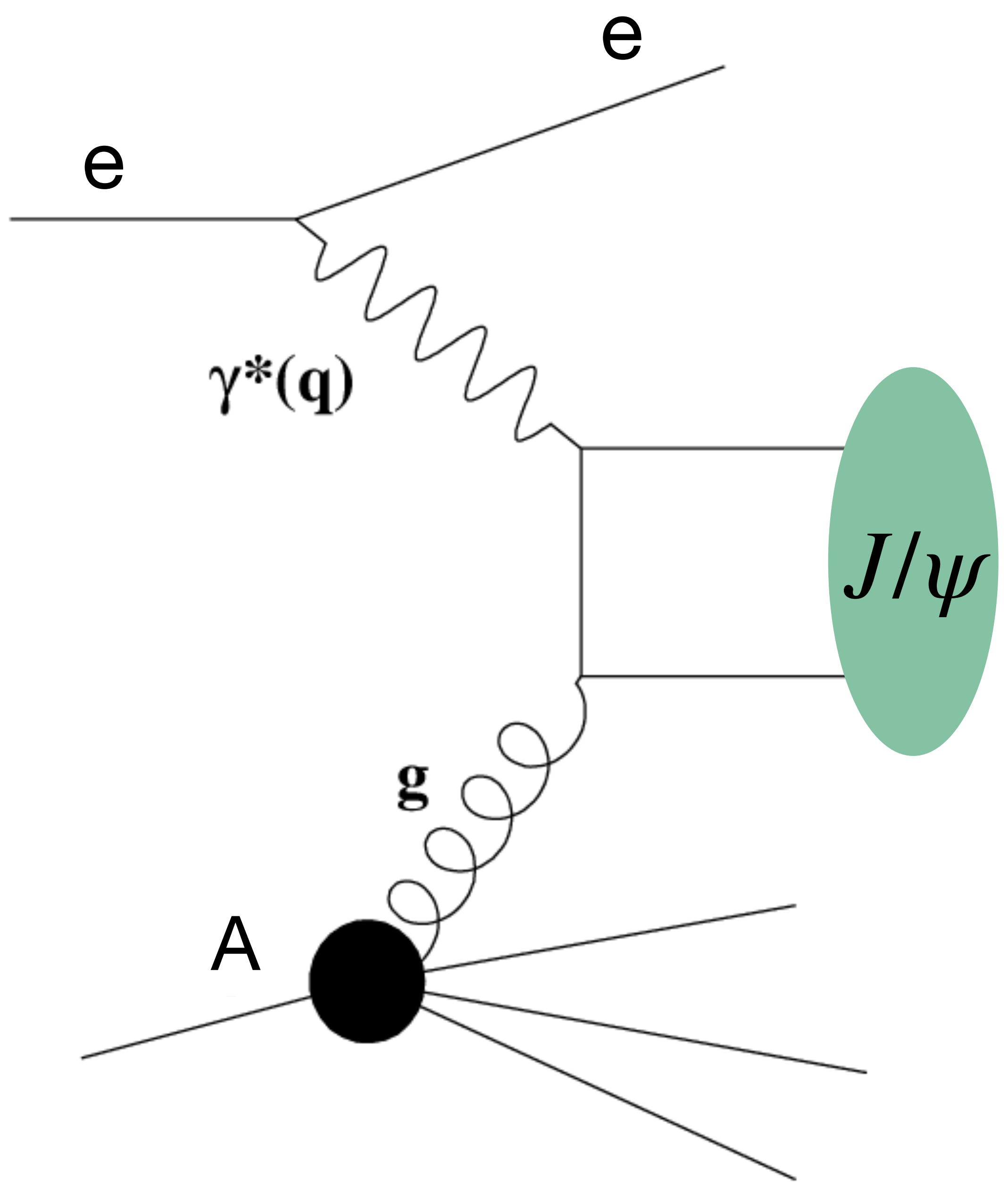
EIC

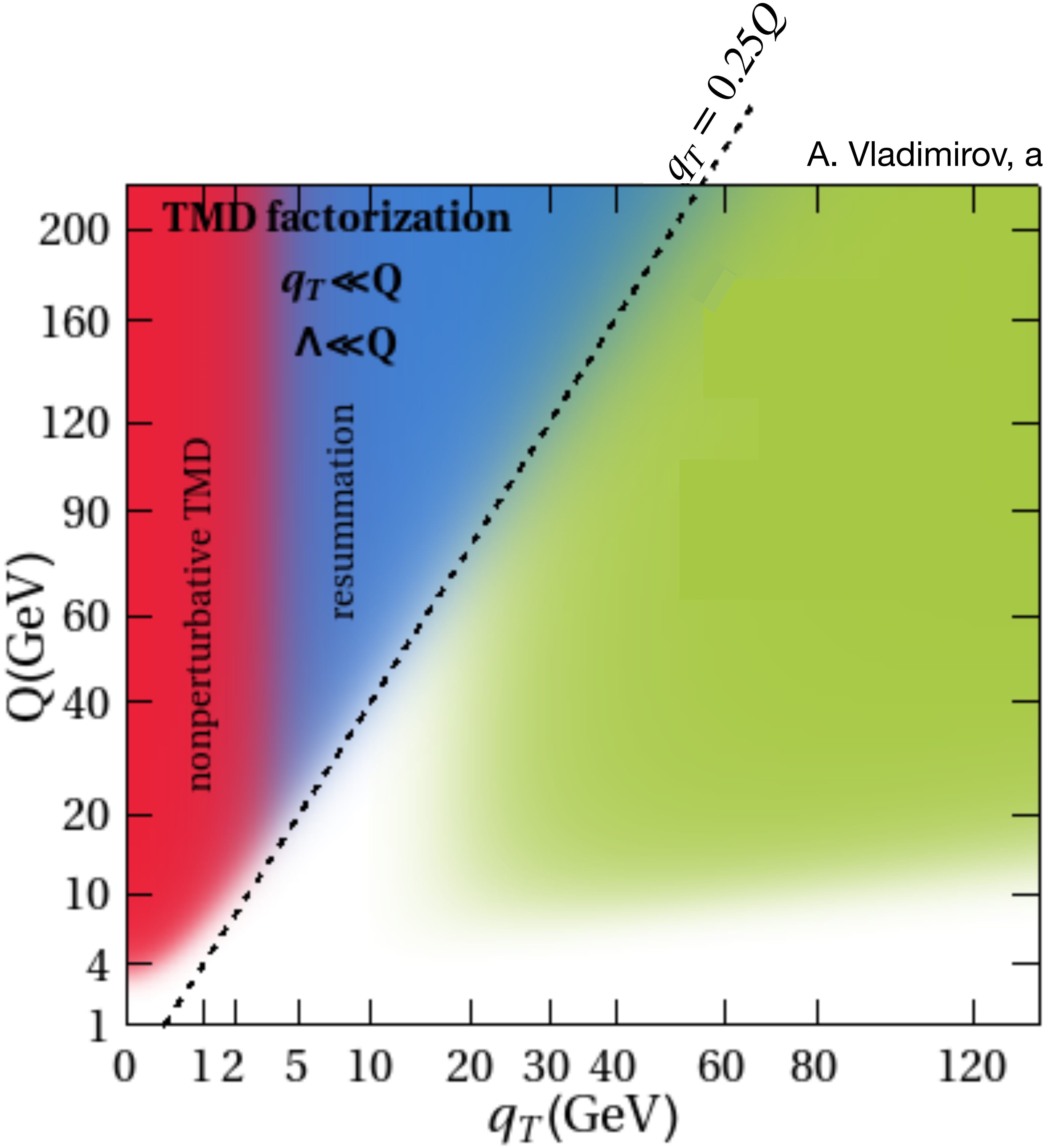




high-pT hadron pair



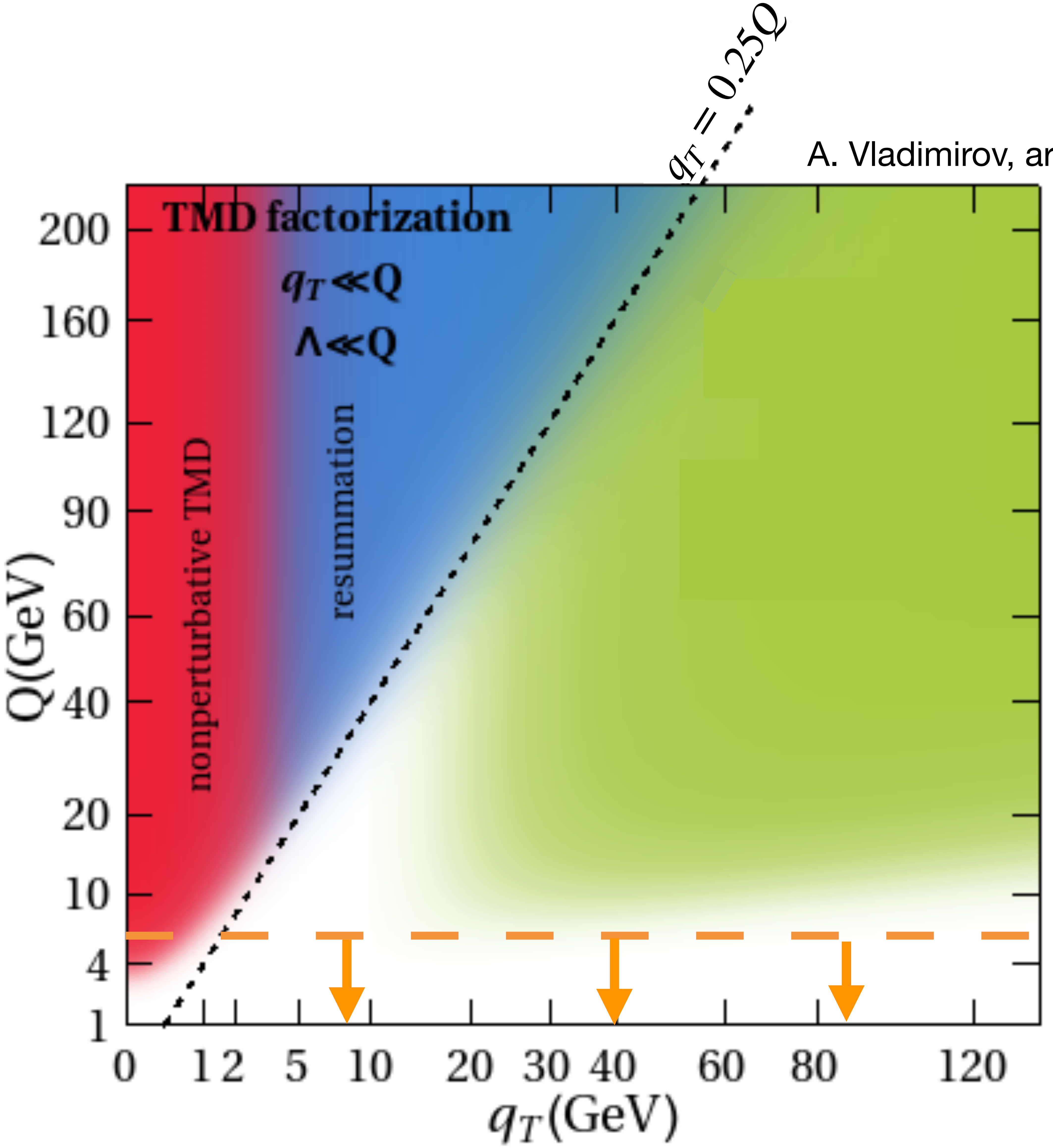
Power corrections at the LHC and EIC



A. Vladimirov, arXiv 2307.13054

Fig. adapted from A. Vladimirov

Power corrections at the LHC and EIC



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Various power corrections:

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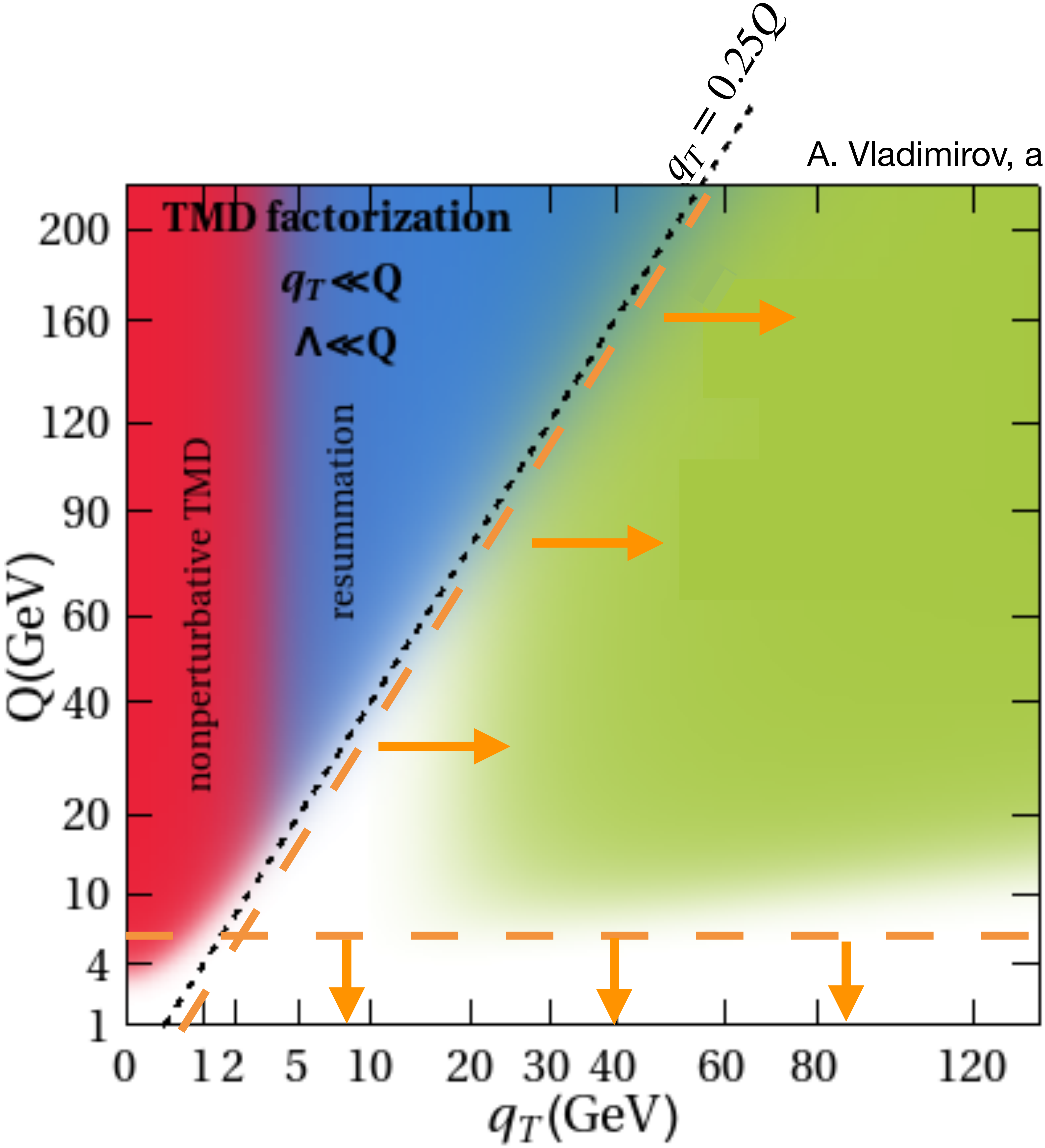
- target-mass corrections

Power corrections at the LHC and EIC



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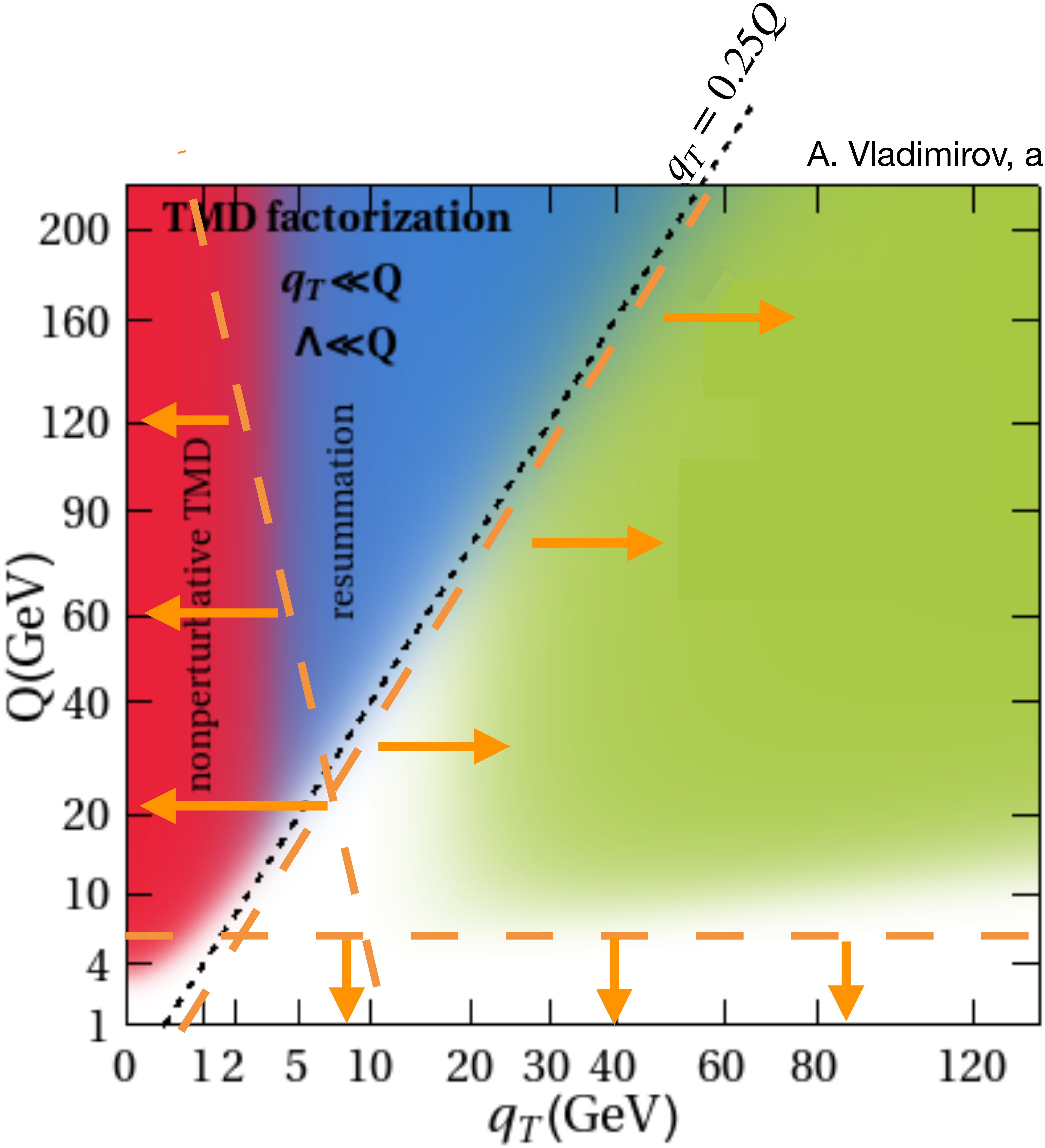

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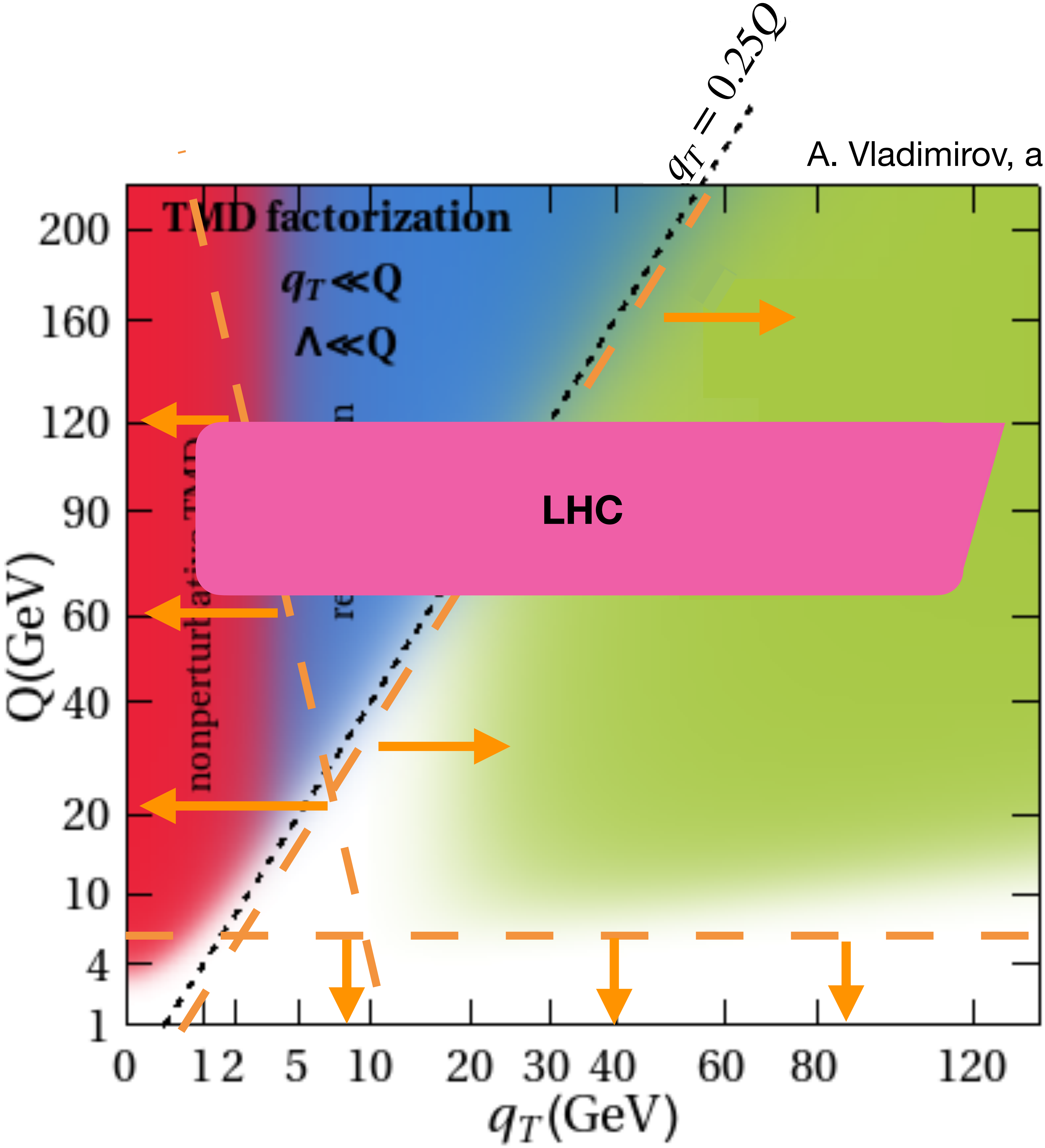

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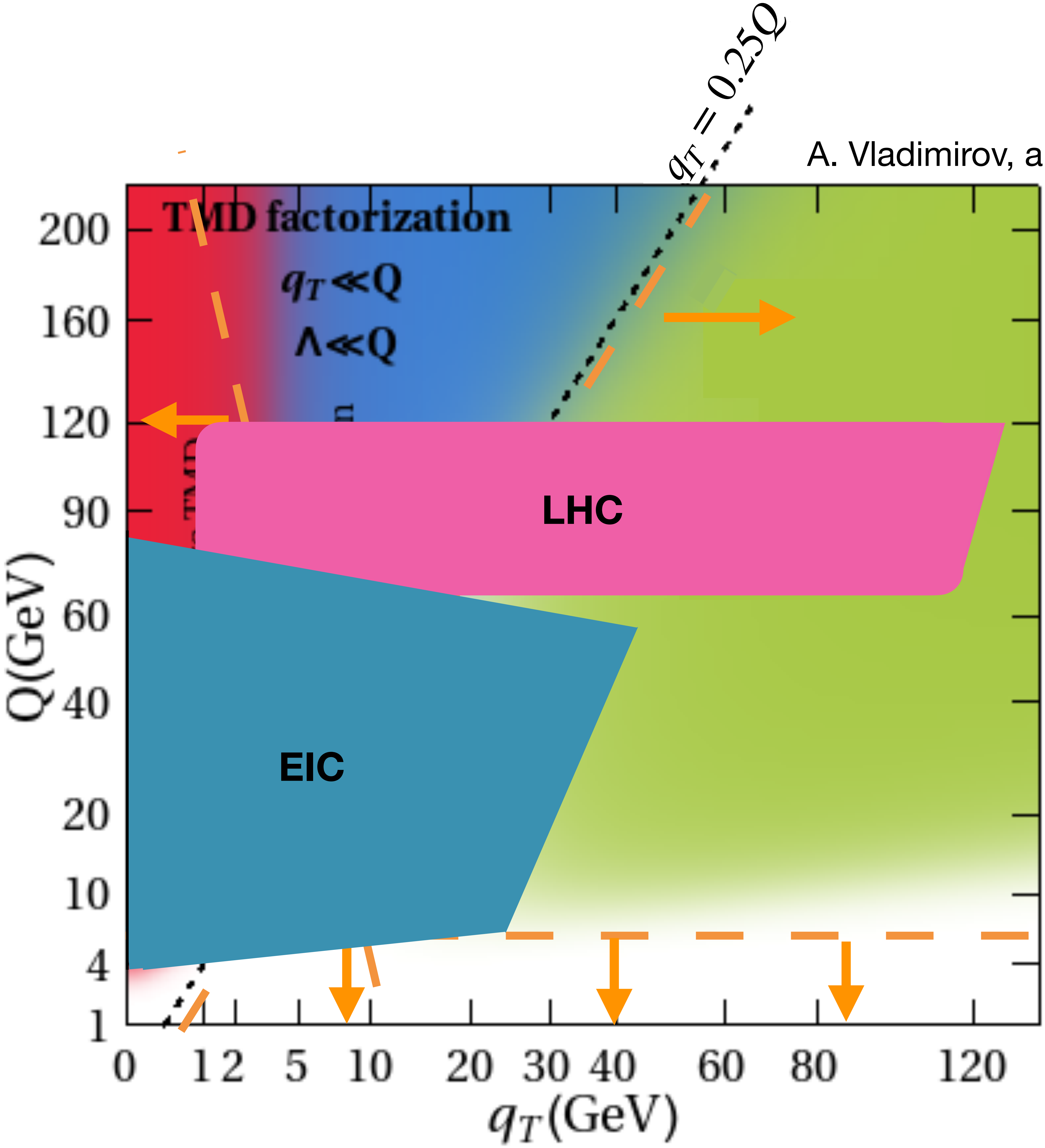

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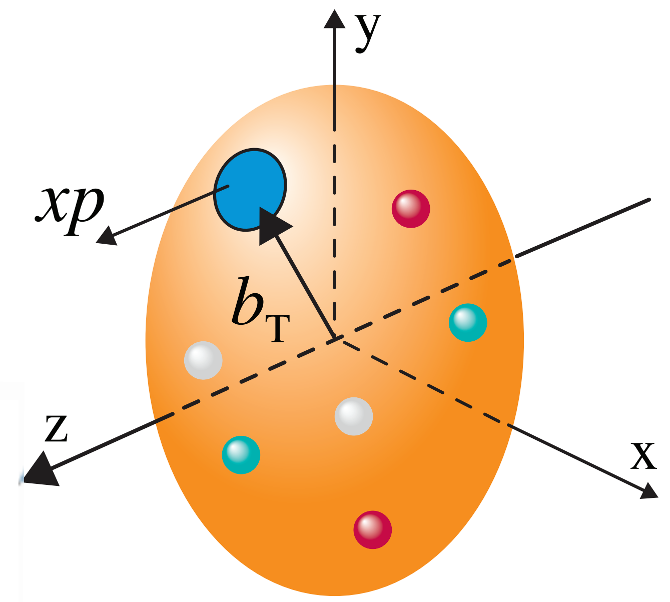
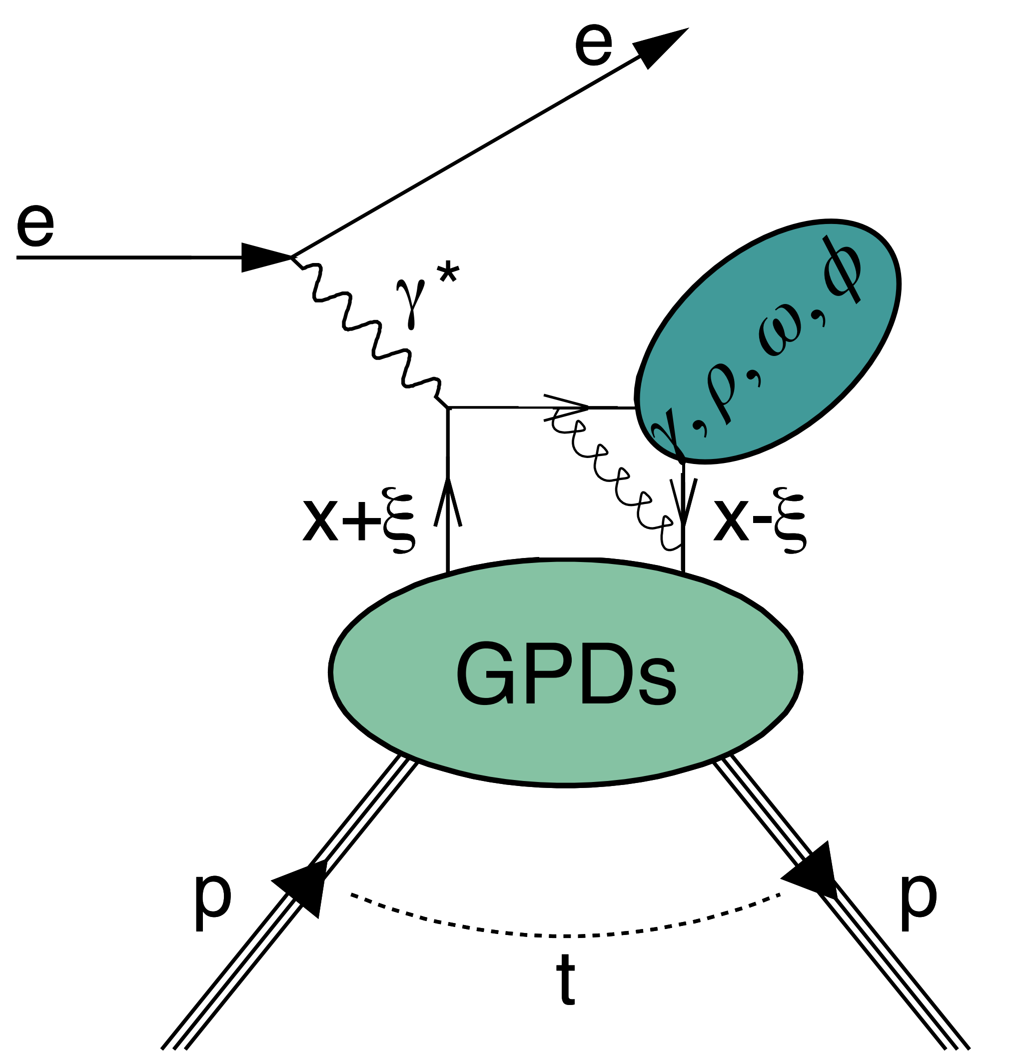
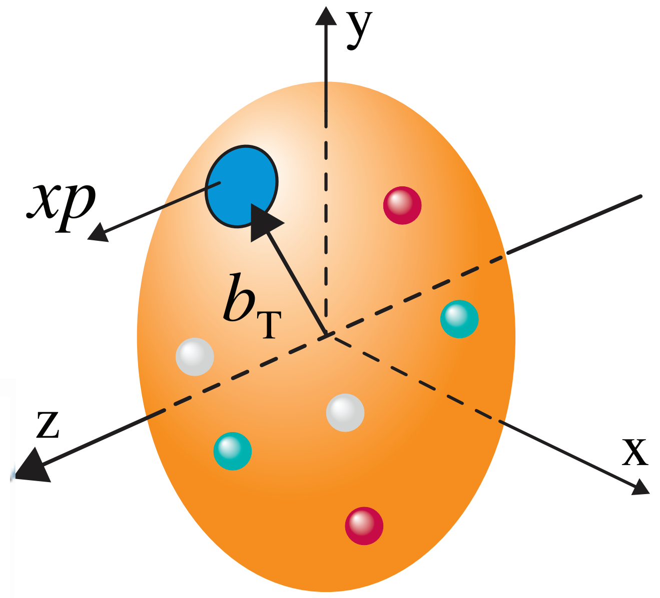
Exclusive processes at the EIC and LHC

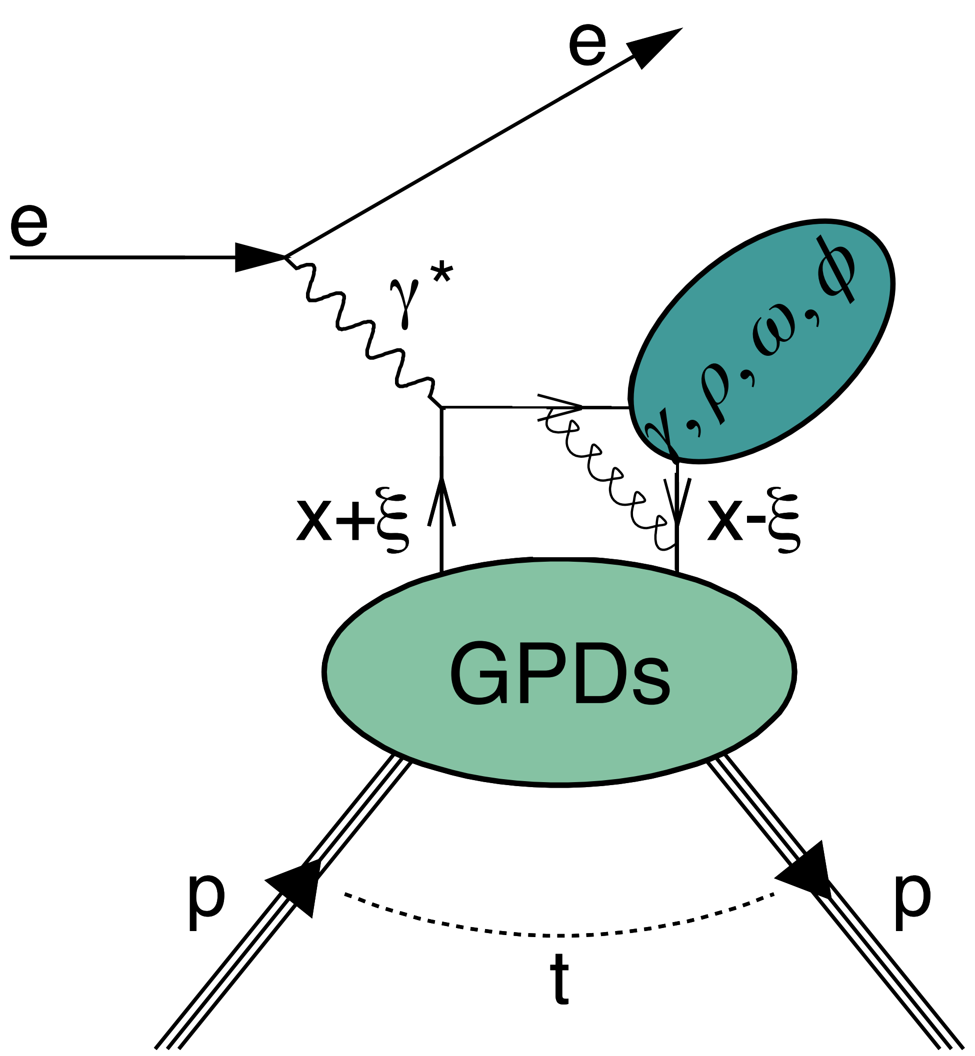




Hard exclusive meson production
Hard scale=large Q^2

Exclusive processes at the EIC and LHC





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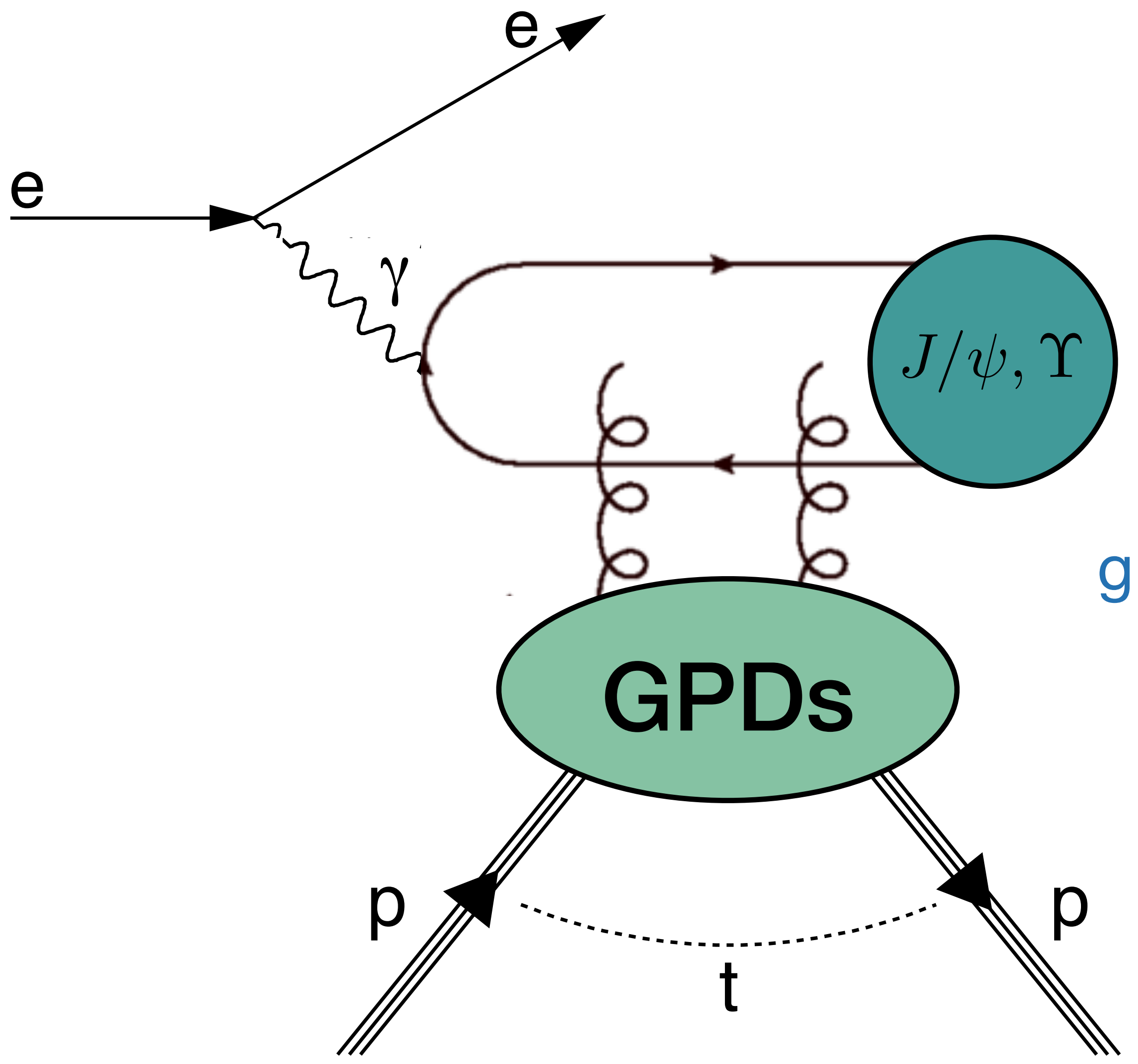

gluons!

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

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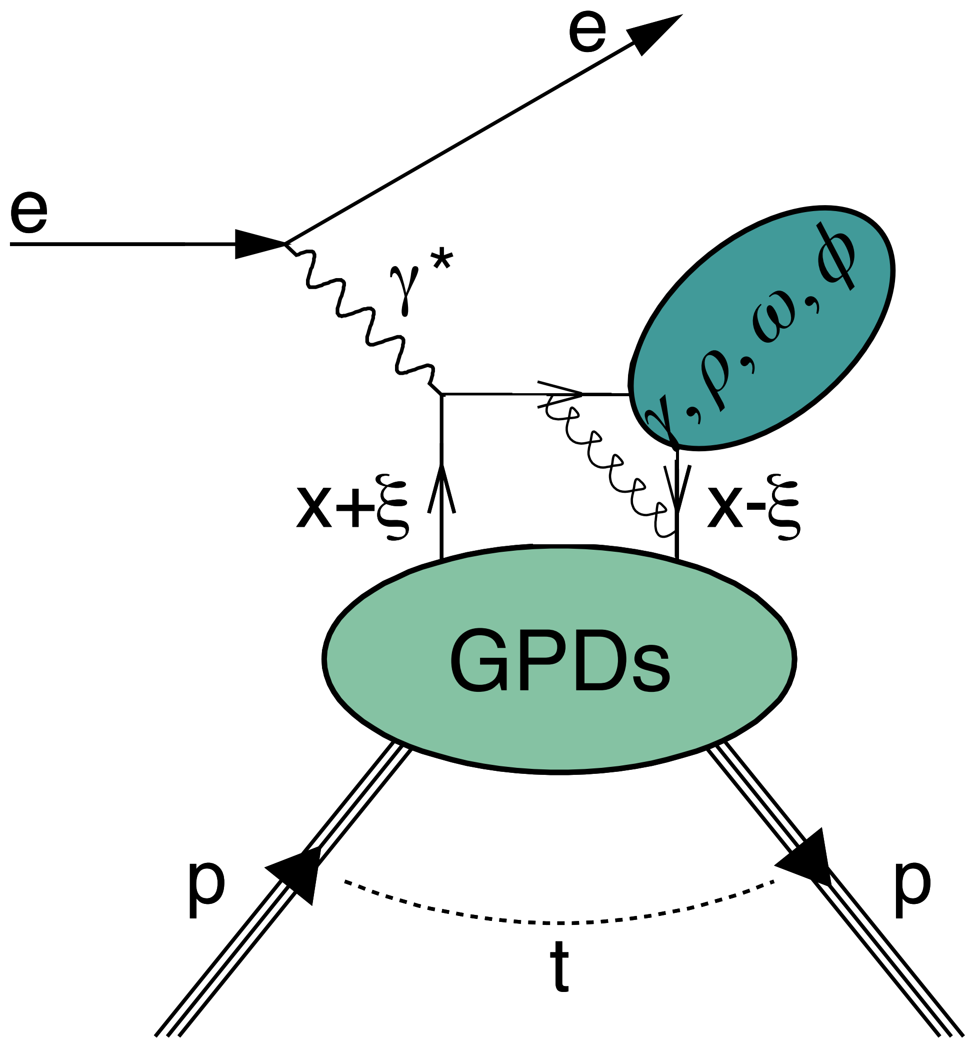

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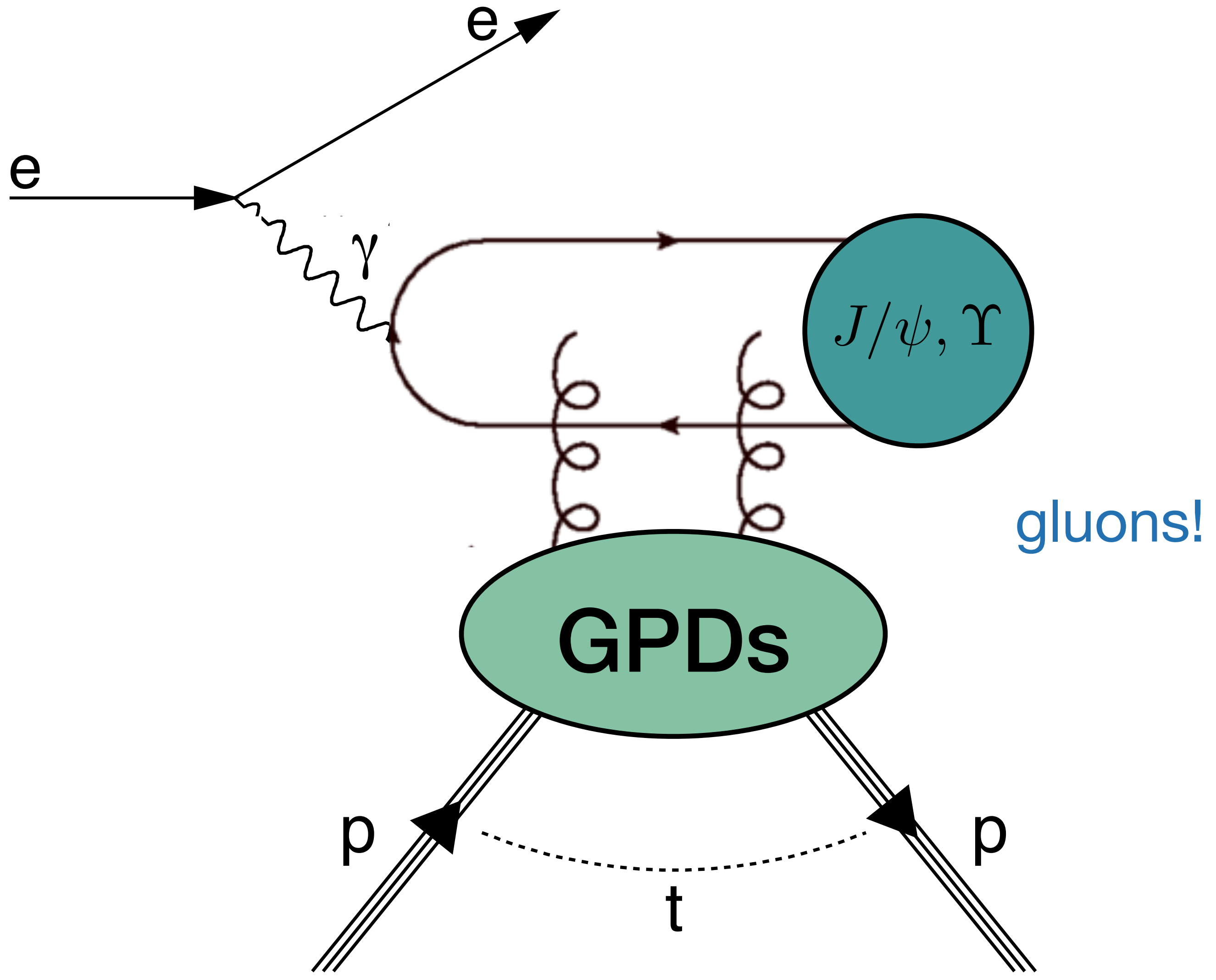

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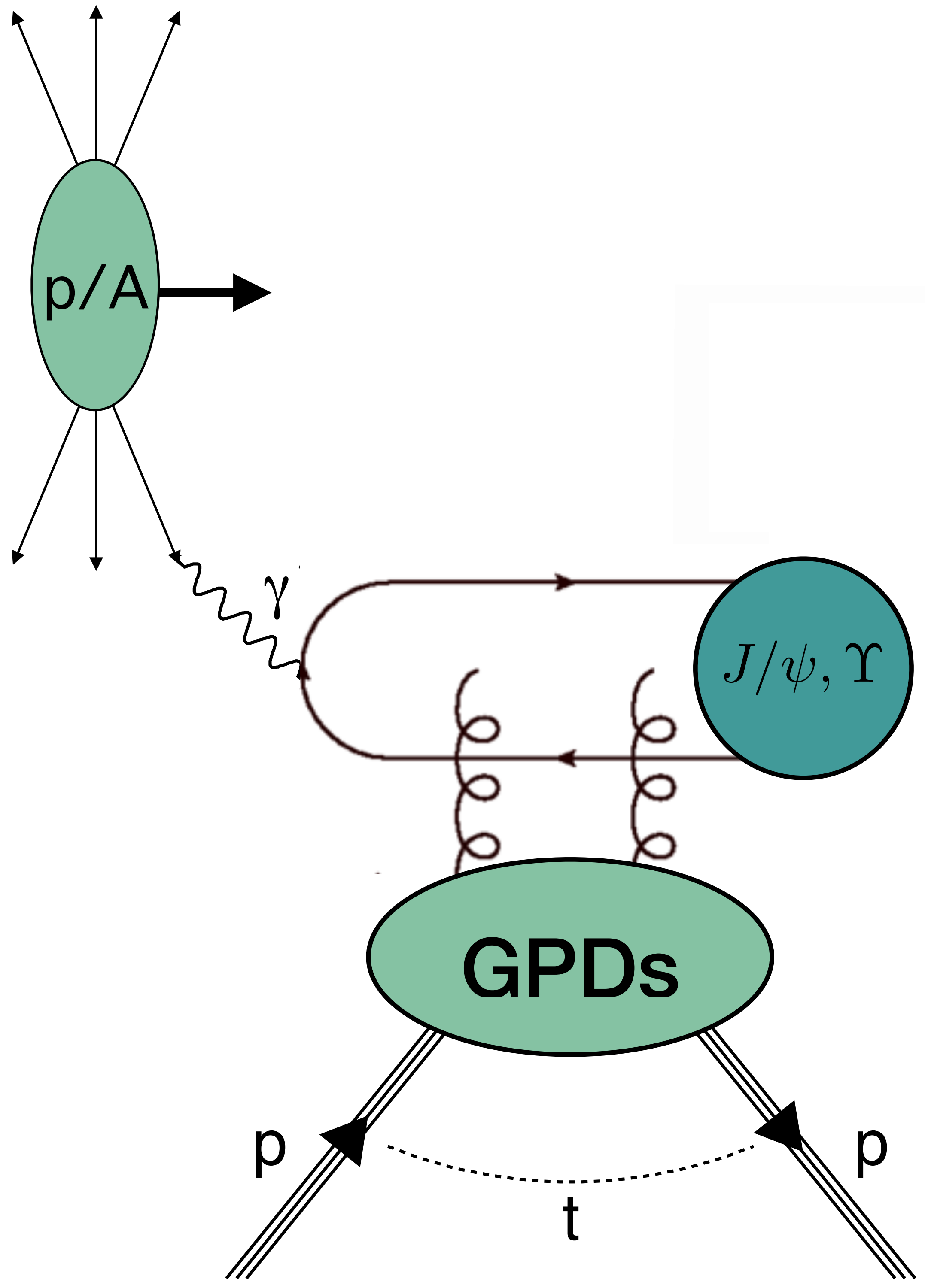

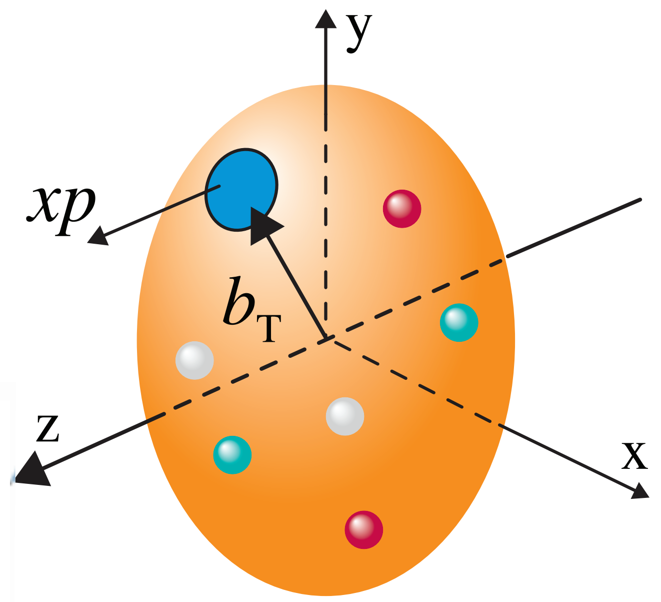

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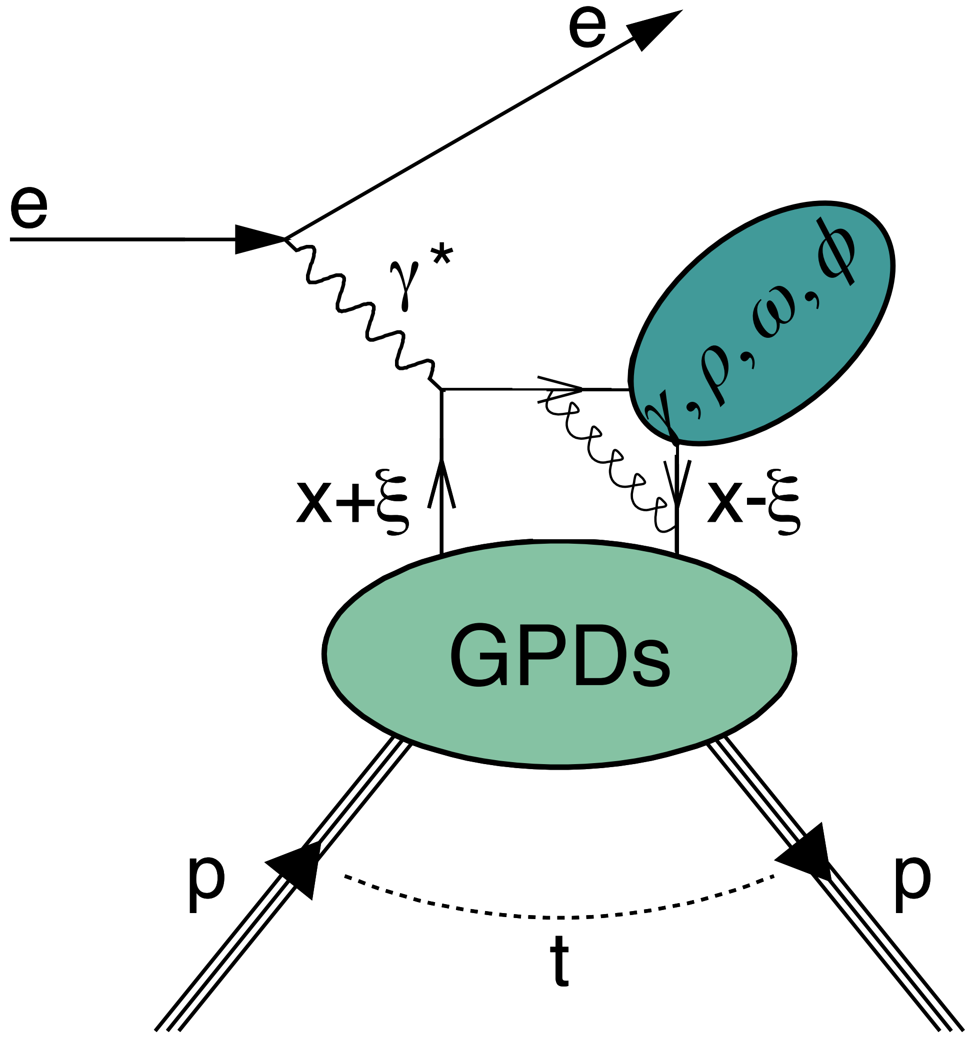

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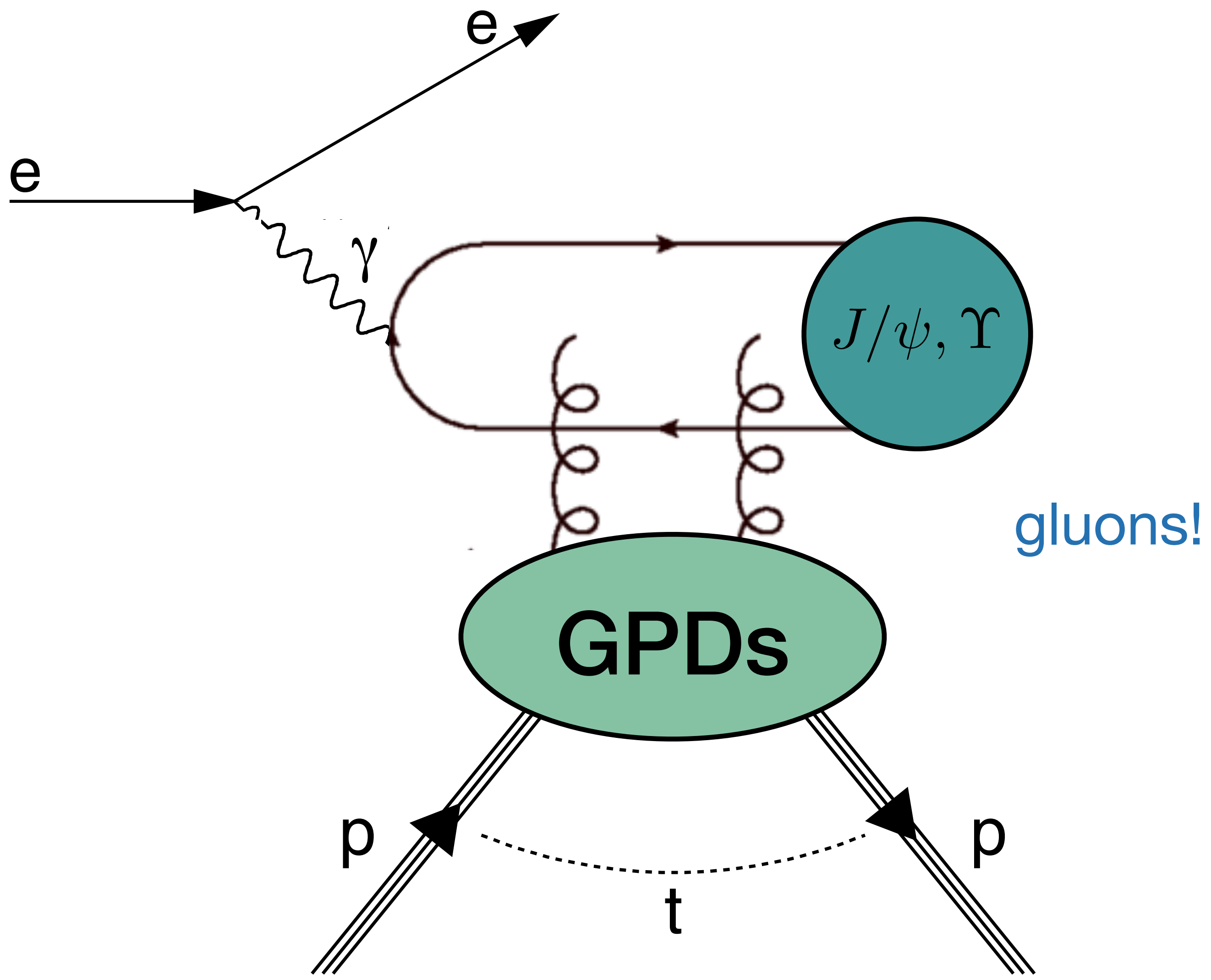

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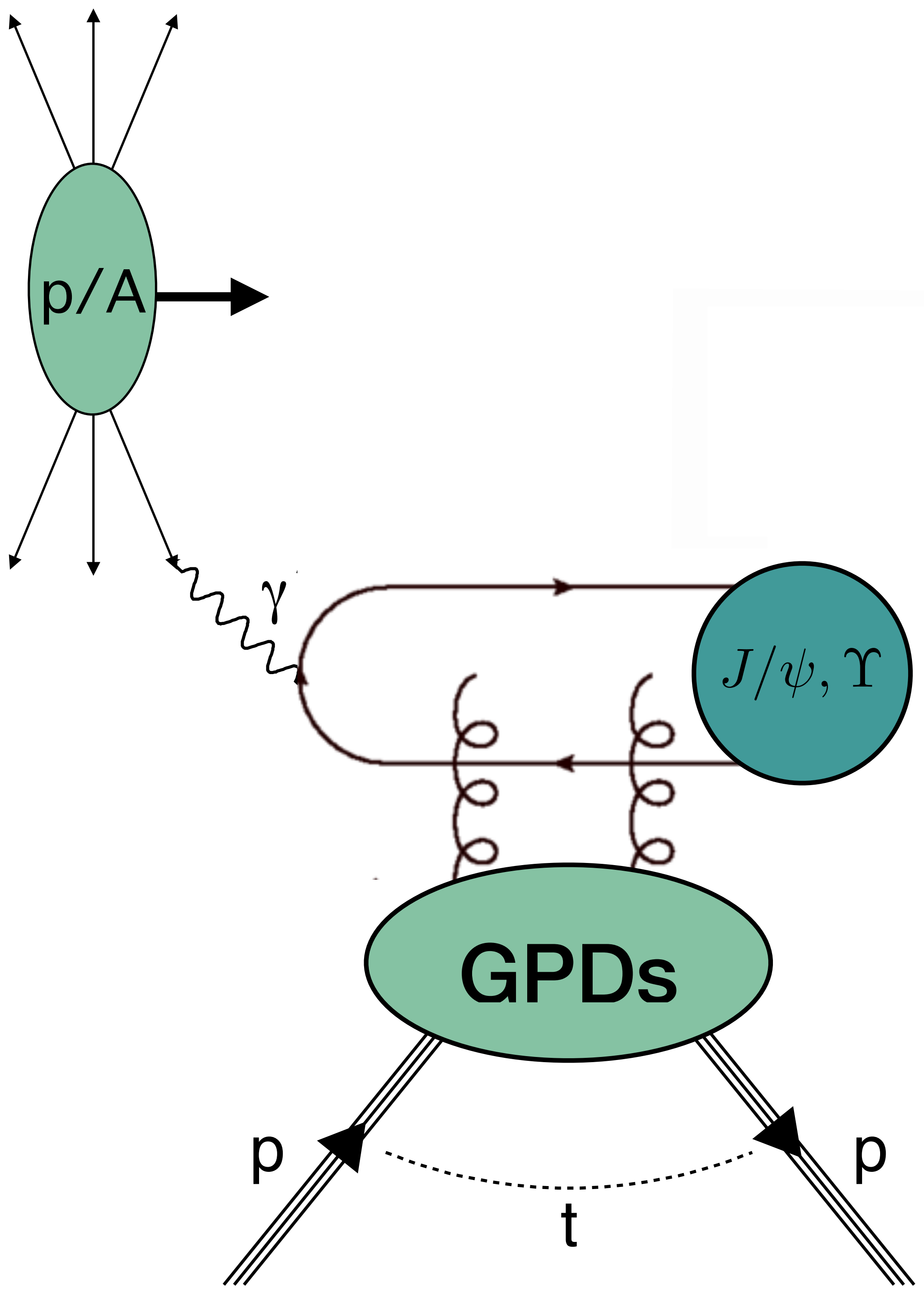

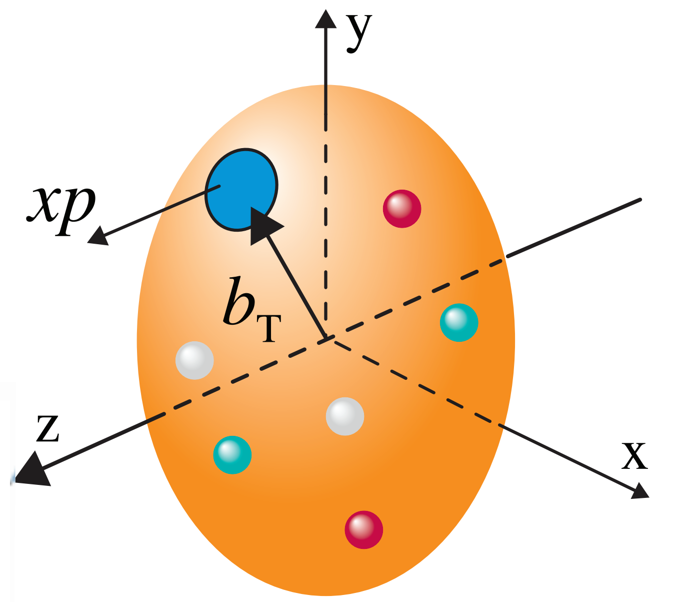

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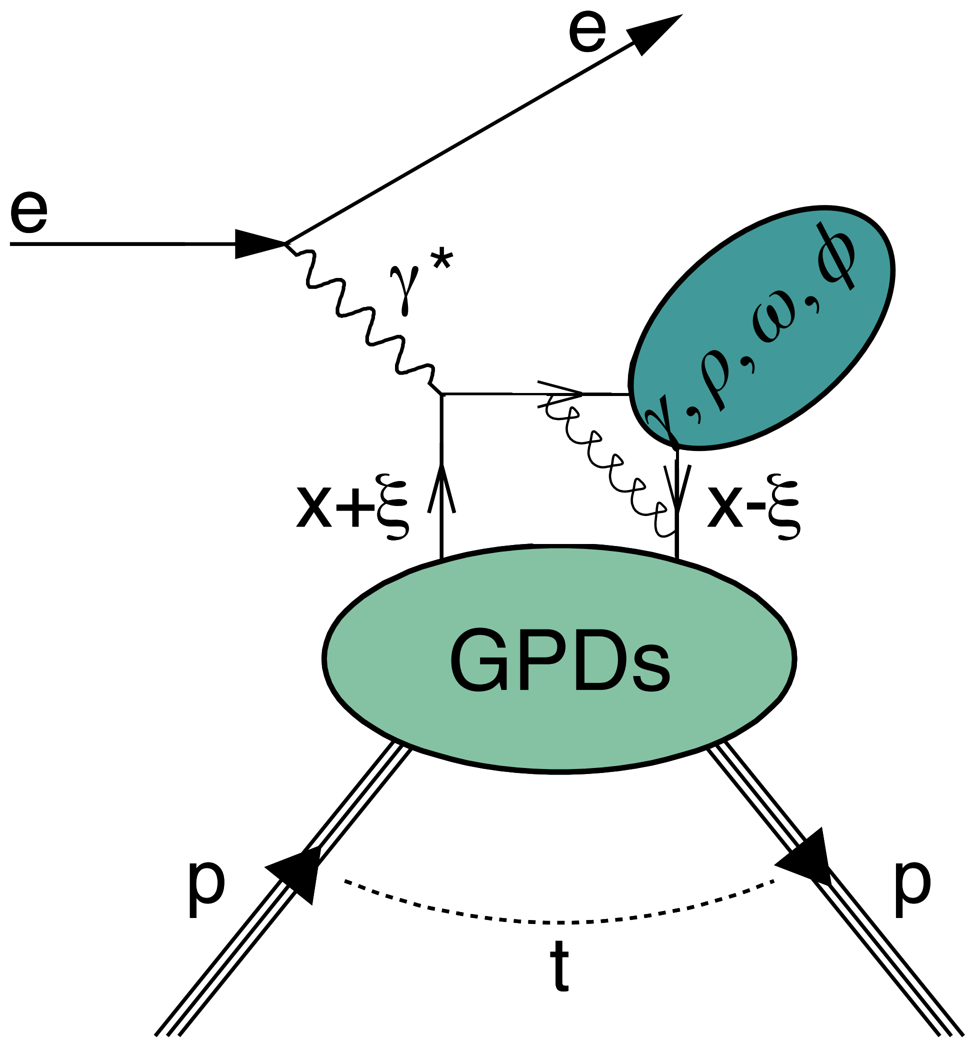
proton-lead: Z^2 dependence of photon flux
→ predominantly probing proton

Exclusive processes at the EIC and LHC



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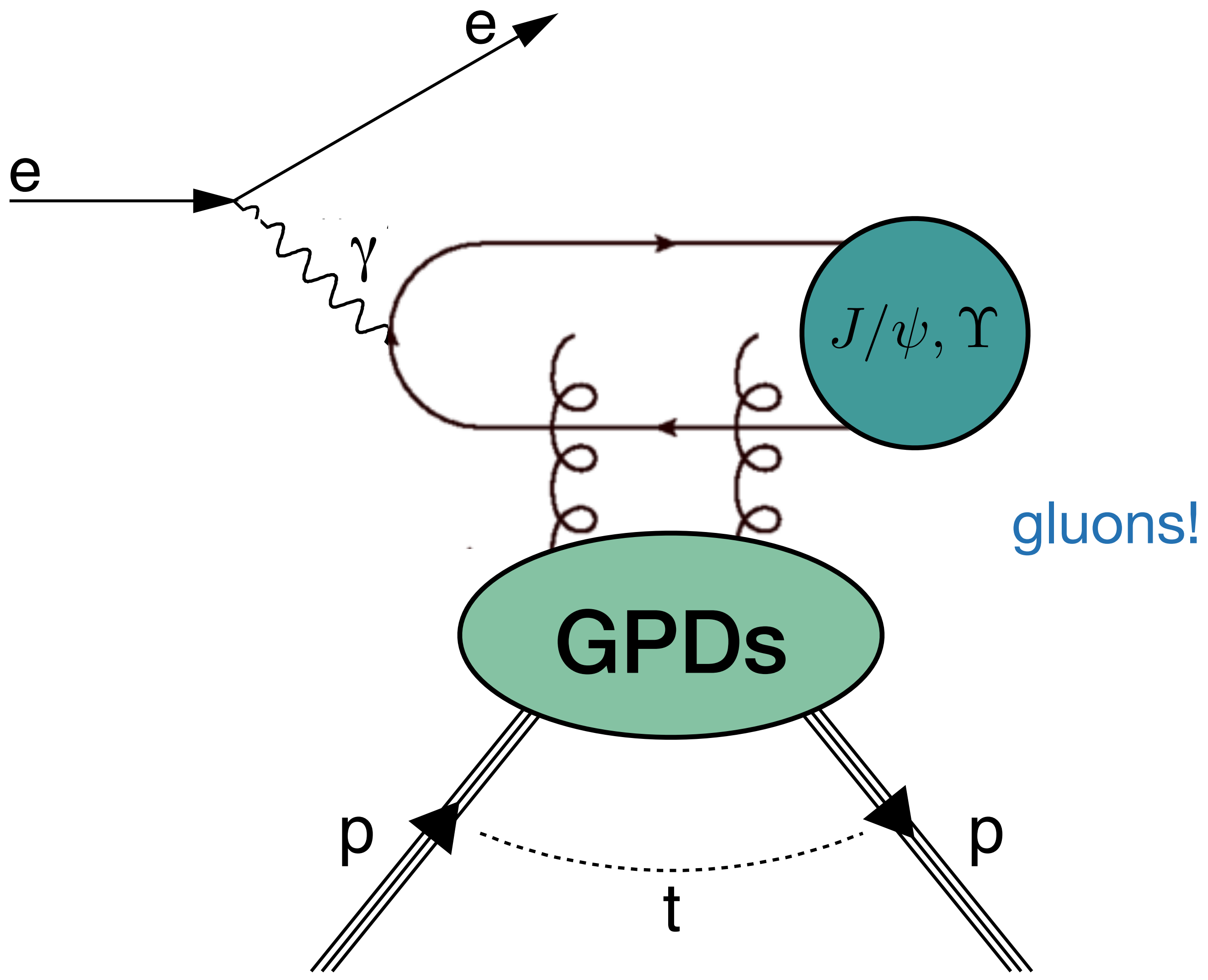

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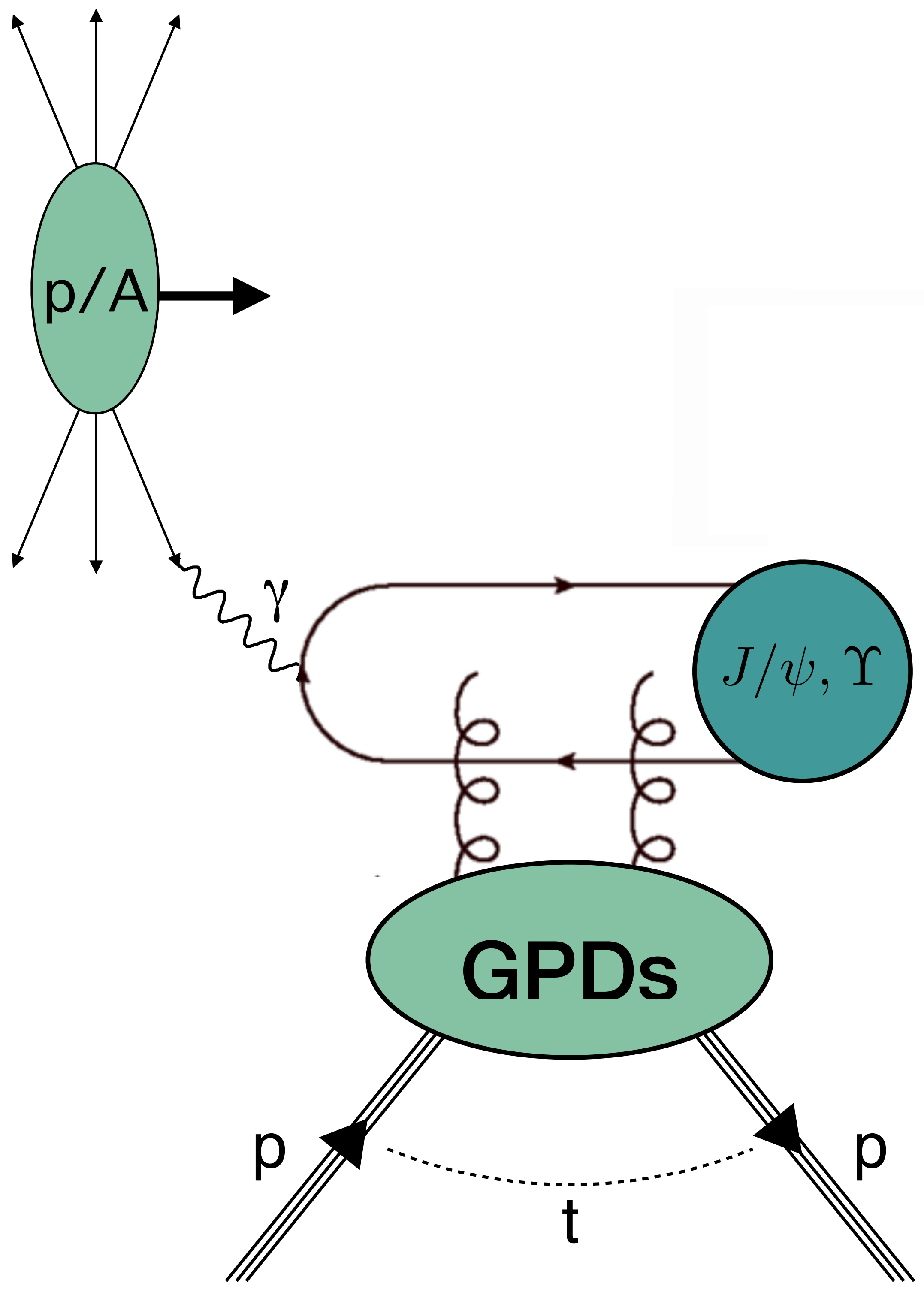

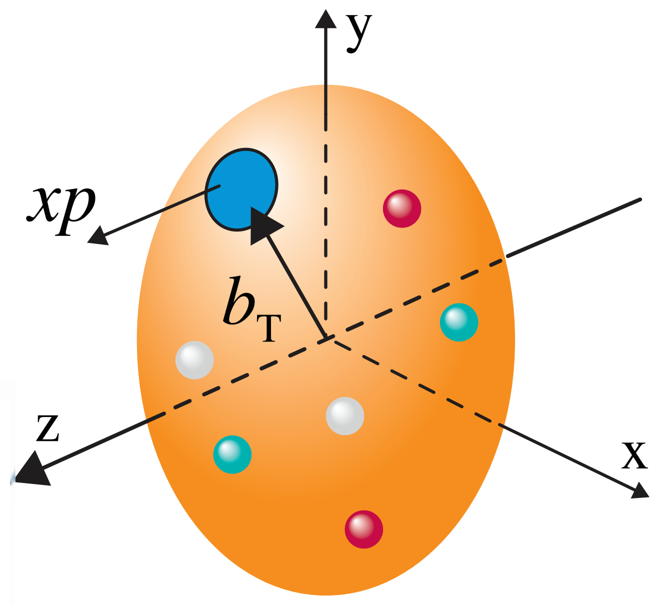

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- probing of p in pp collisions impossible/very difficult since too many interactions/collision
- highly reduced ambiguity in ID of photon emitter compared to pp

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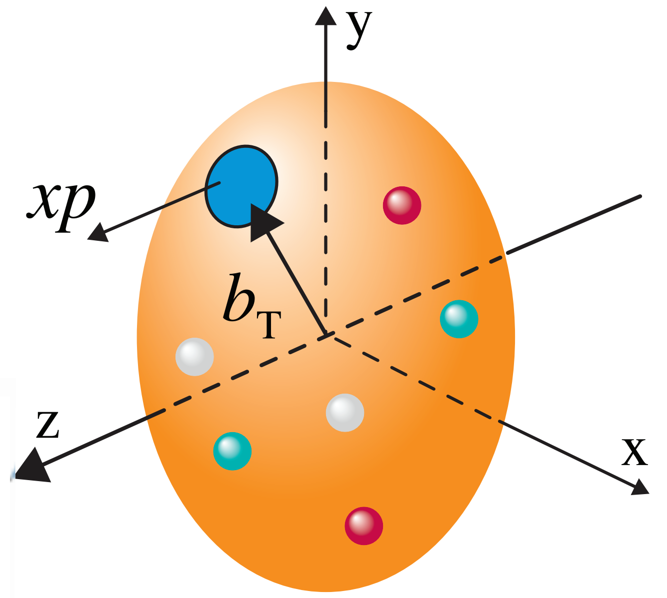

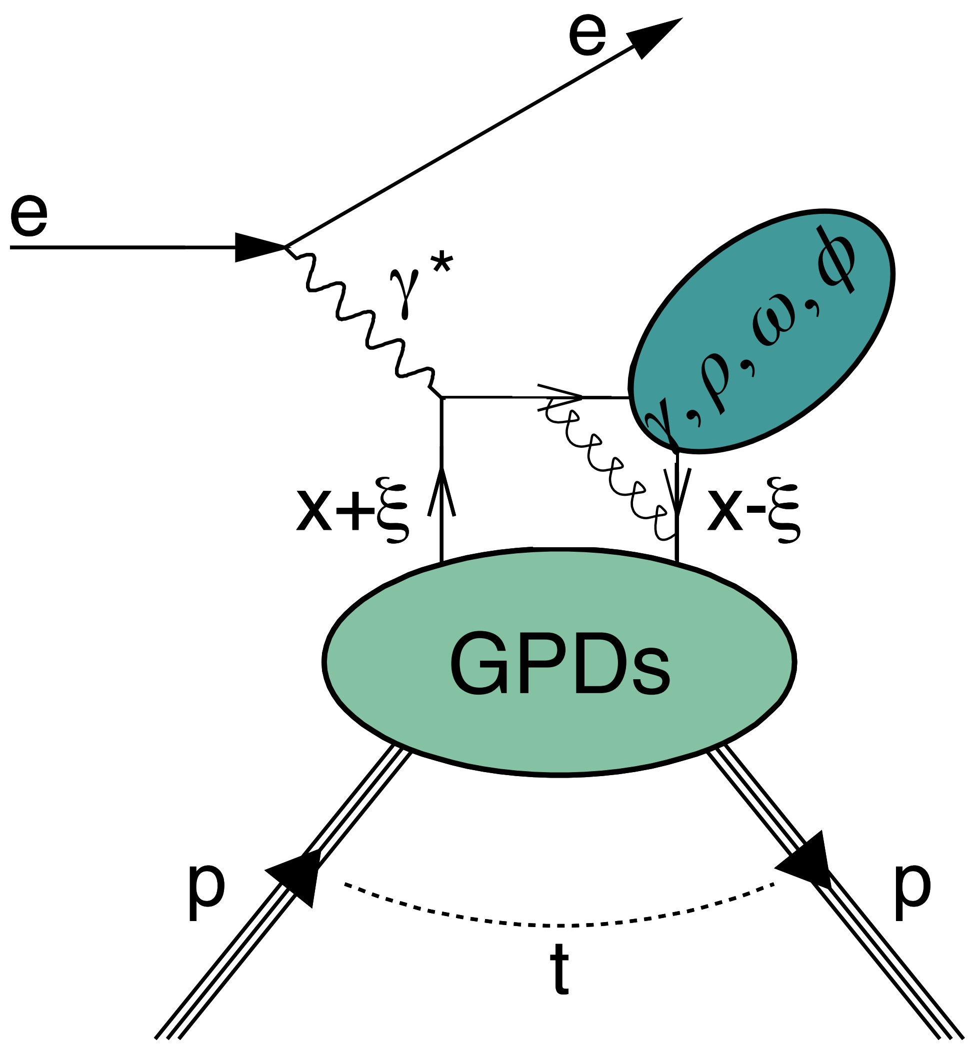

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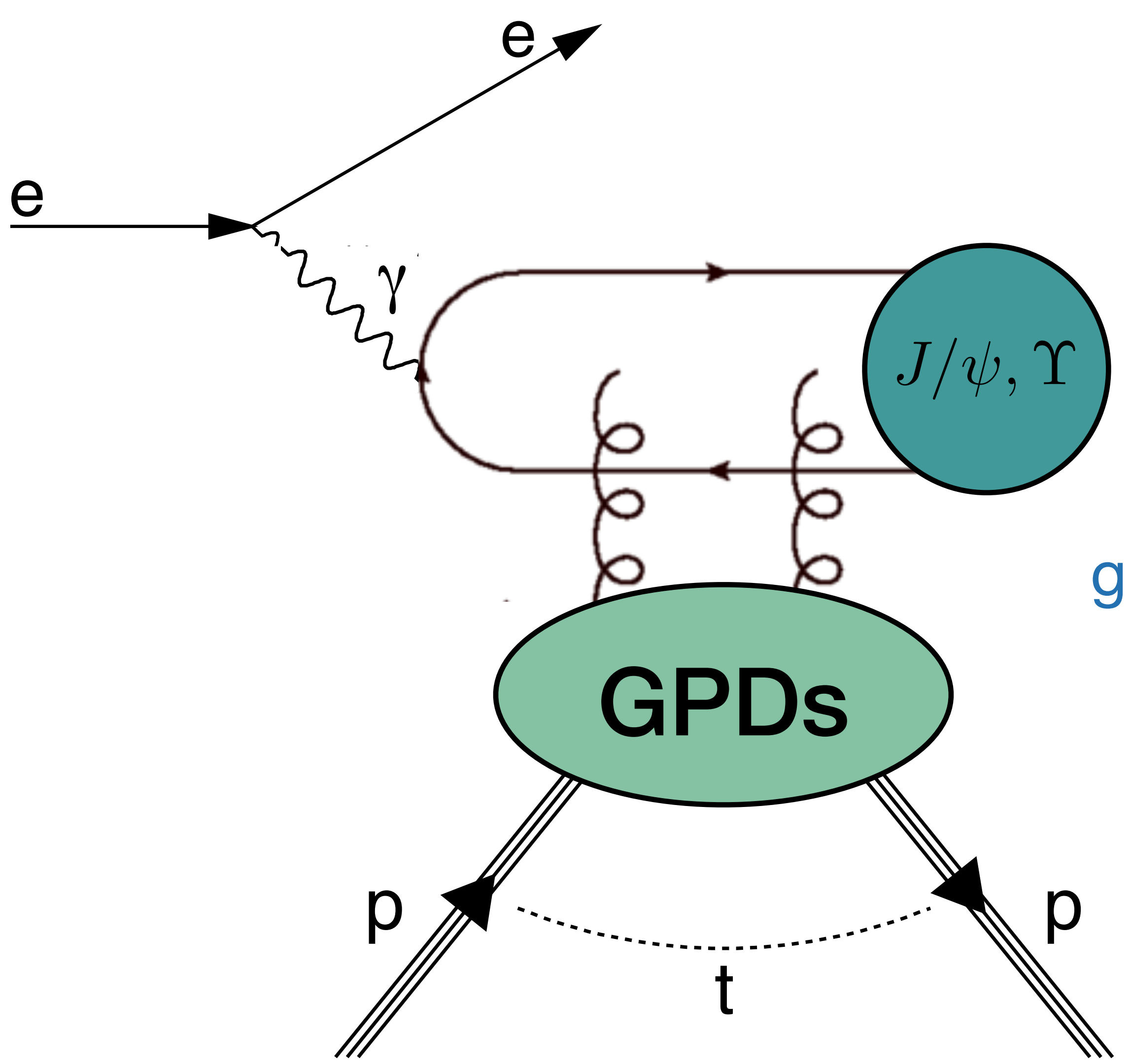

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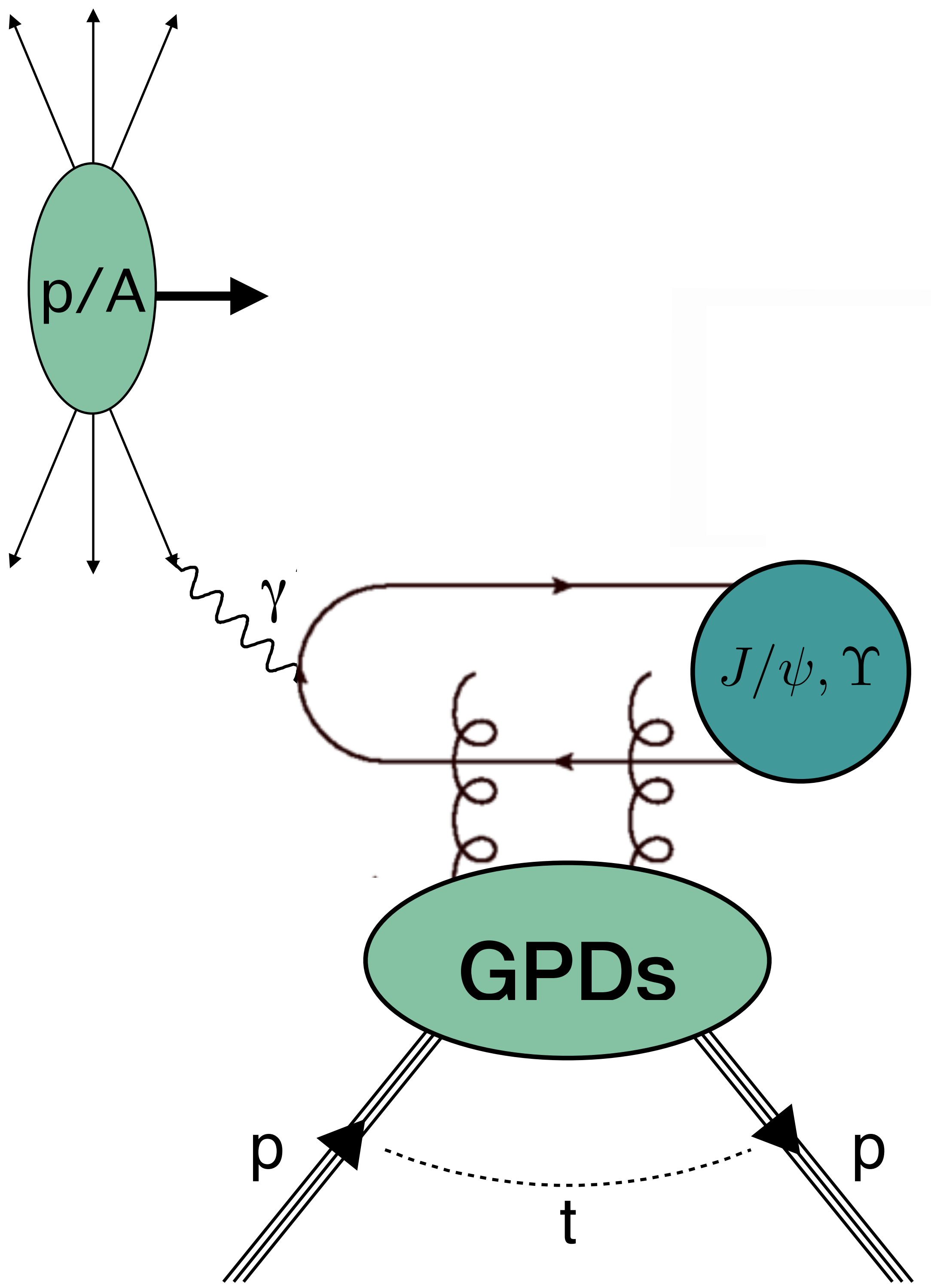

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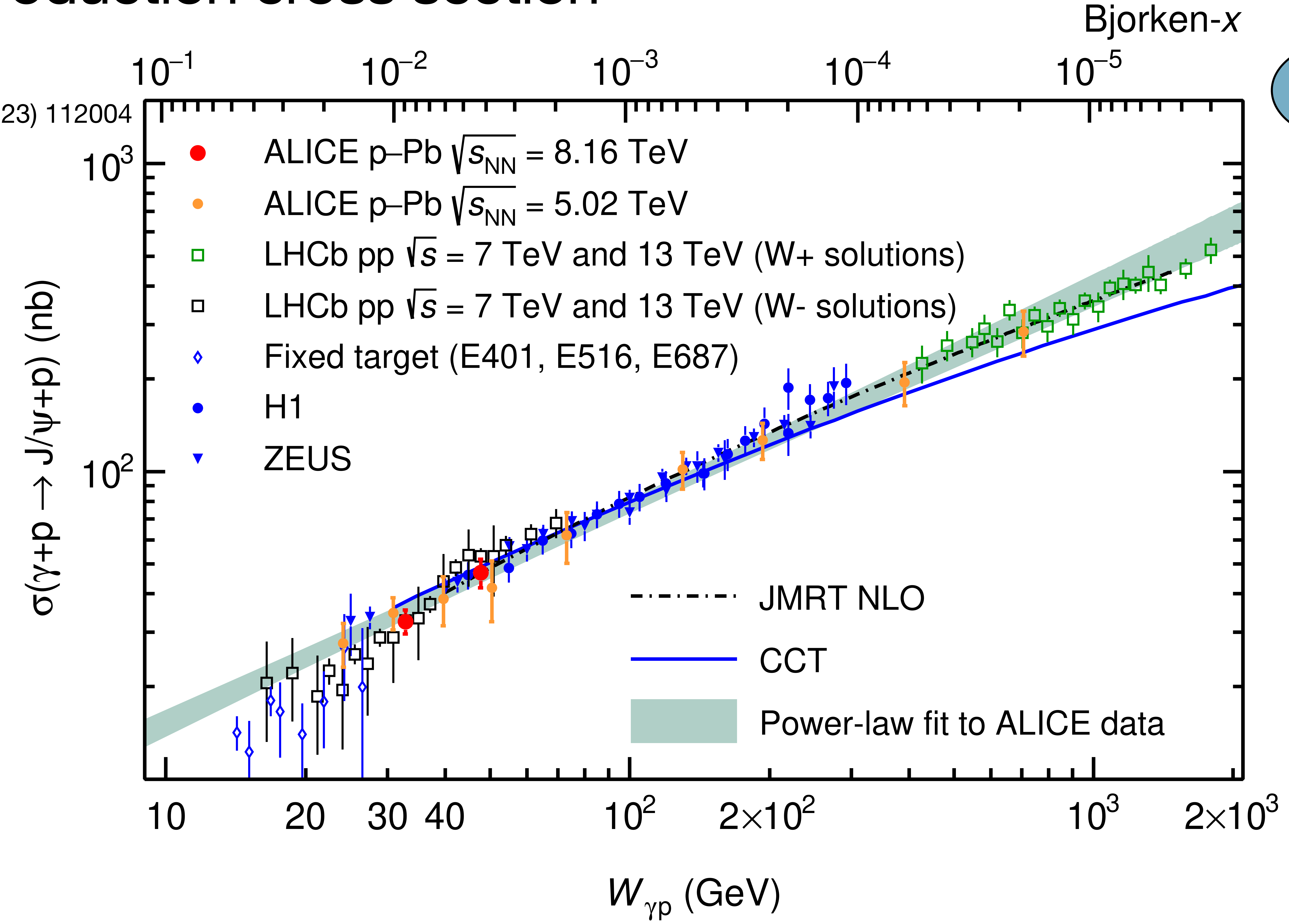
down to $x_B=10^{-4}$ at HERA/EIC in ep
$x_B=10^{-3}$ at EIC in eA

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

J/ψ photoproduction cross section

GPD H

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



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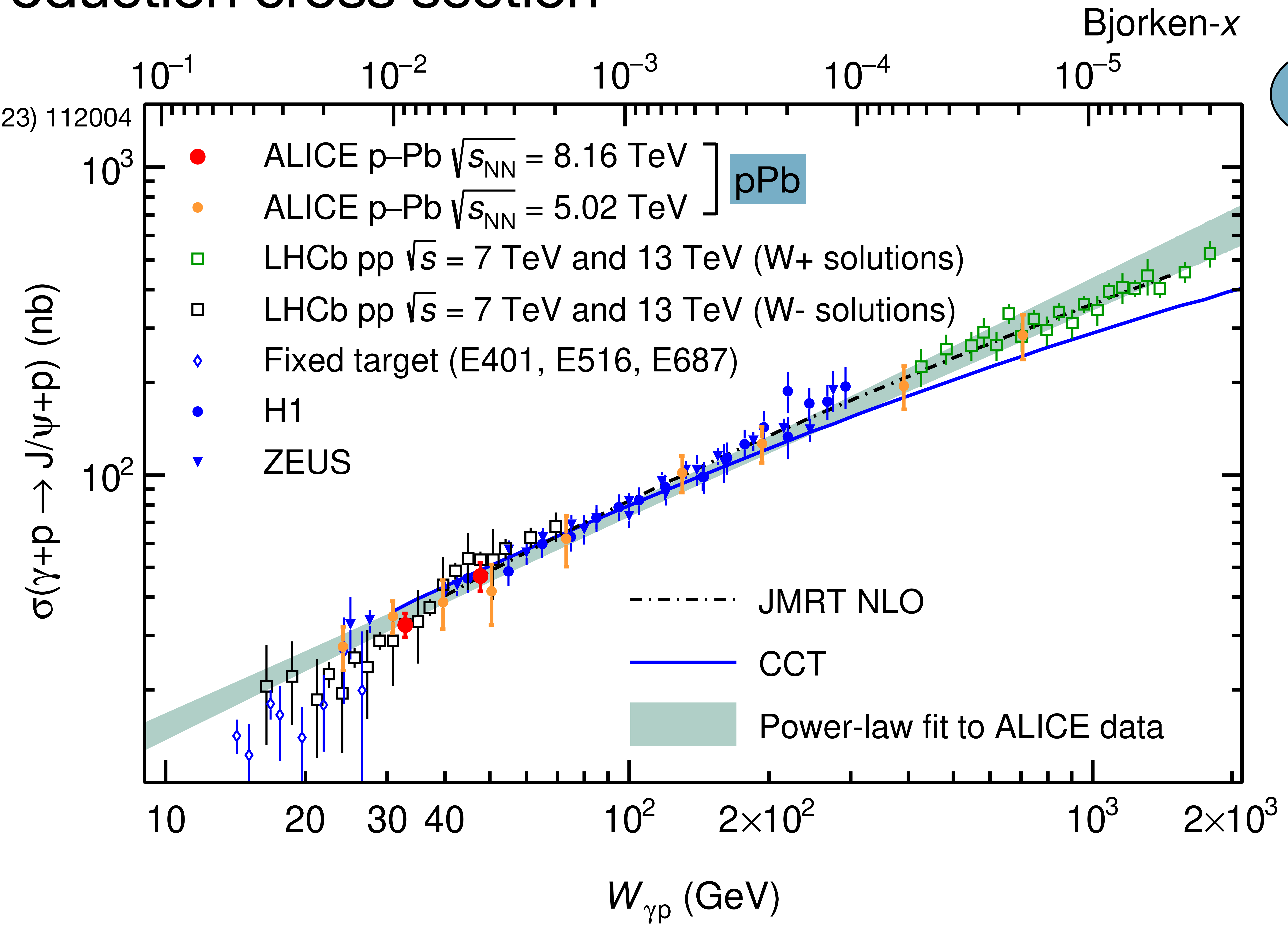

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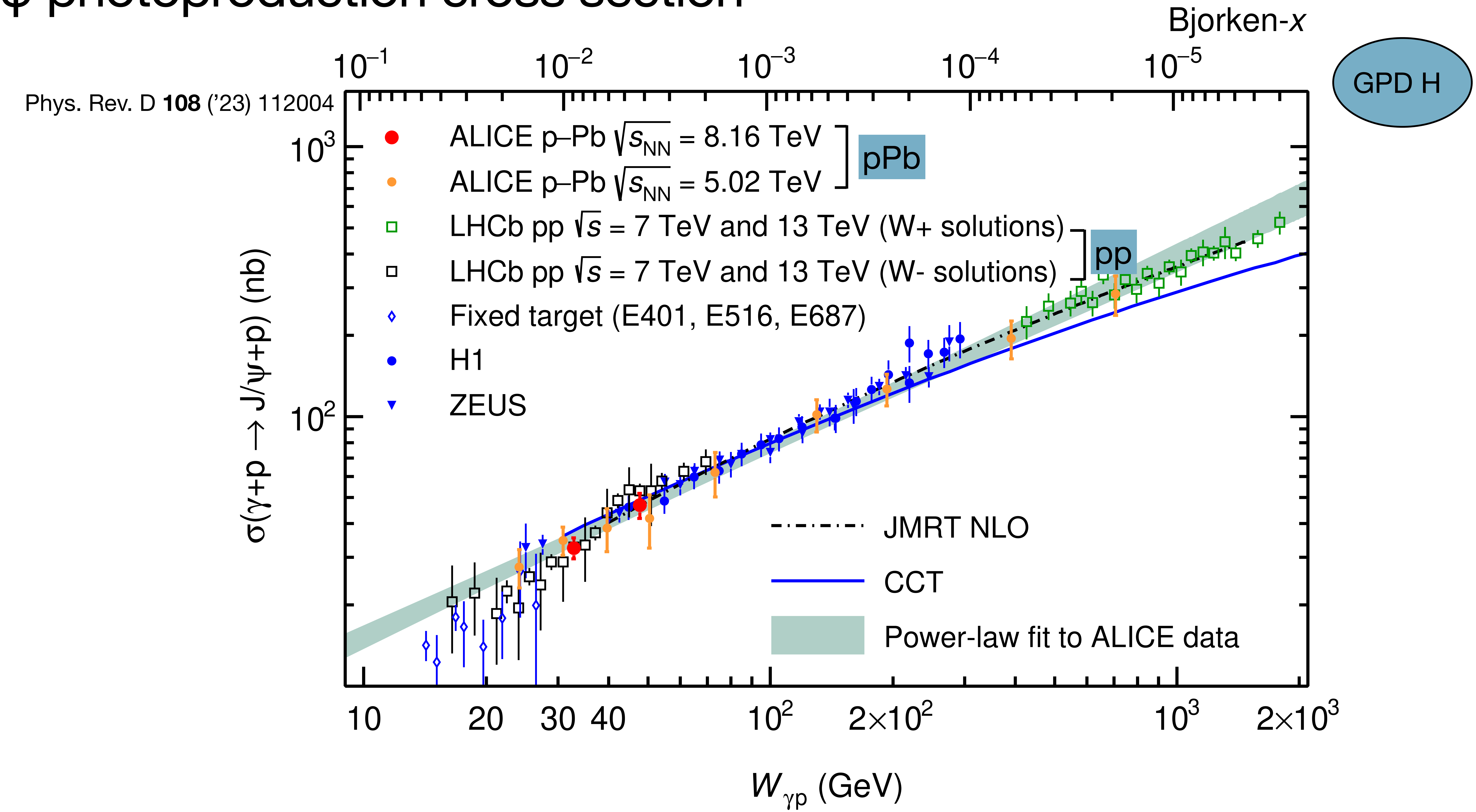

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Phys. Rev. D **108** ('23) 112004

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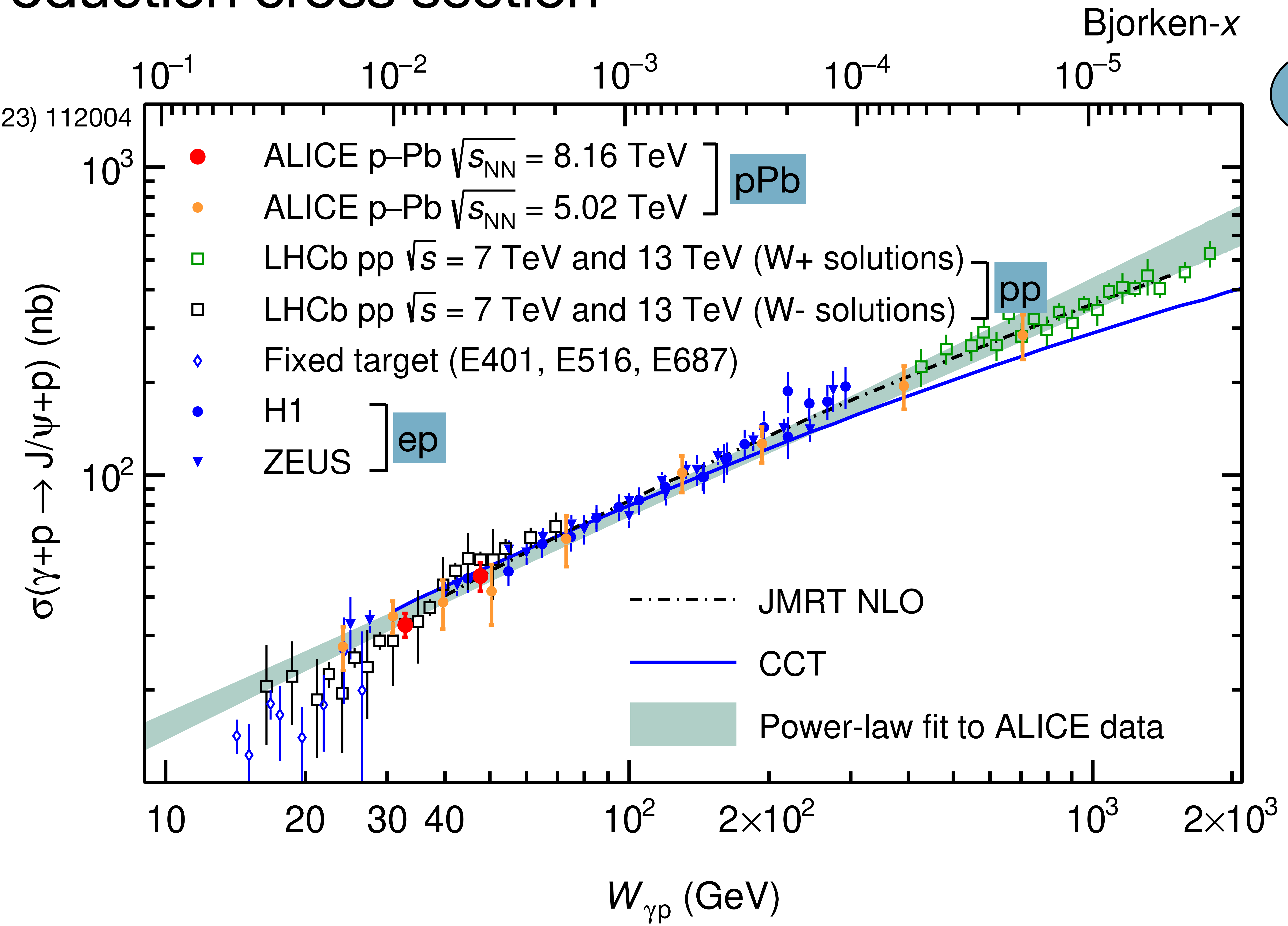

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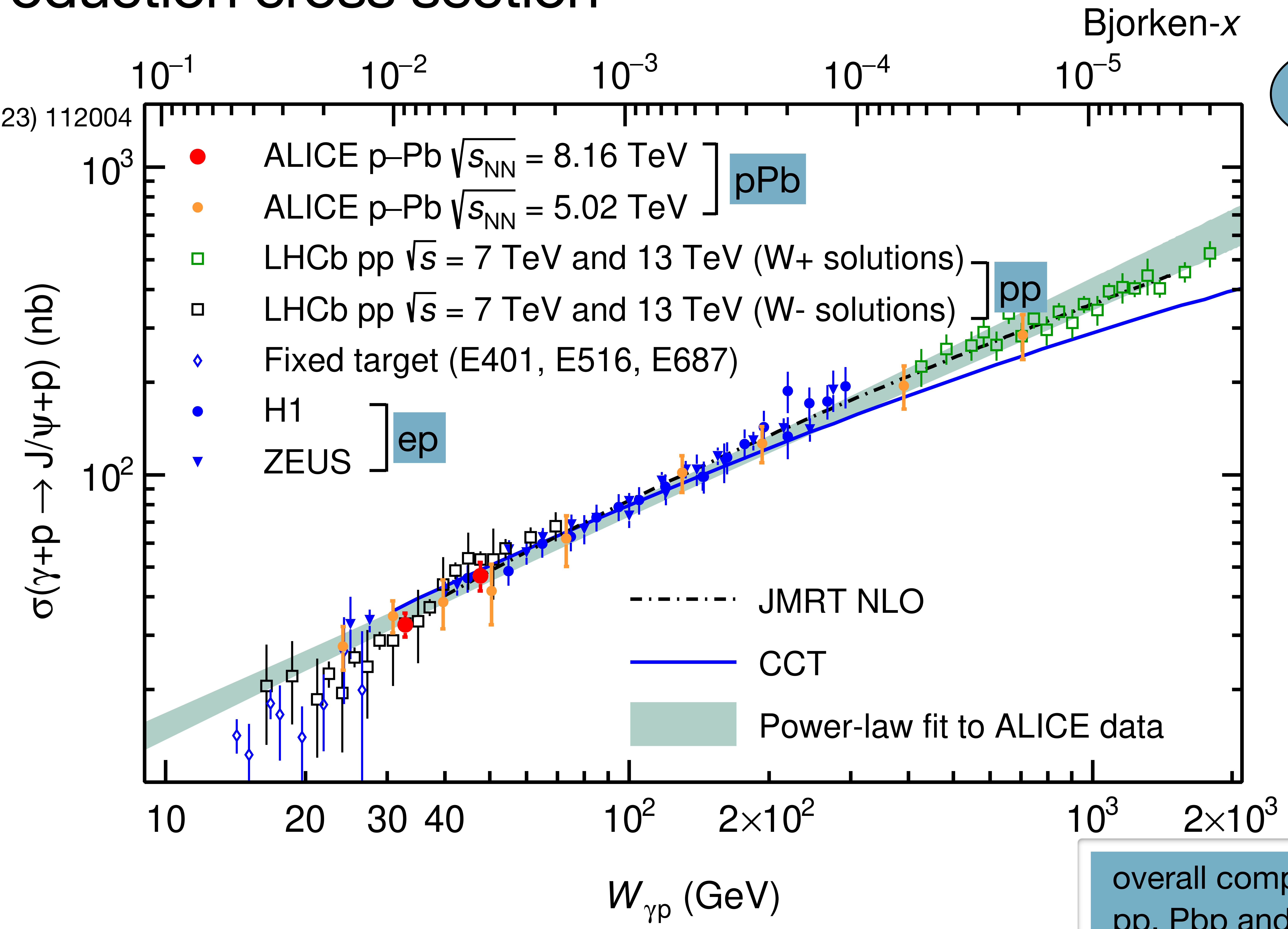
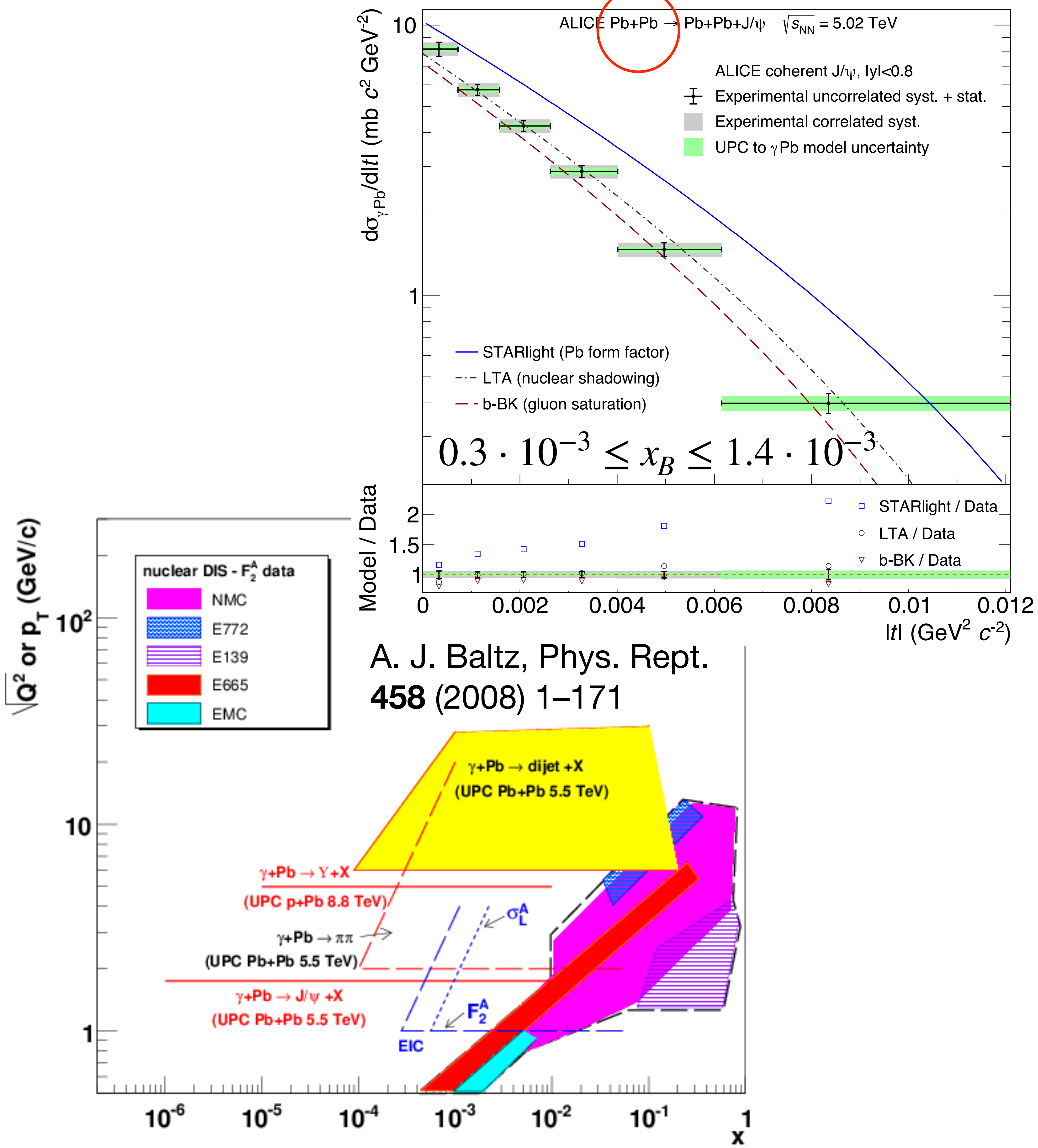


GPD H

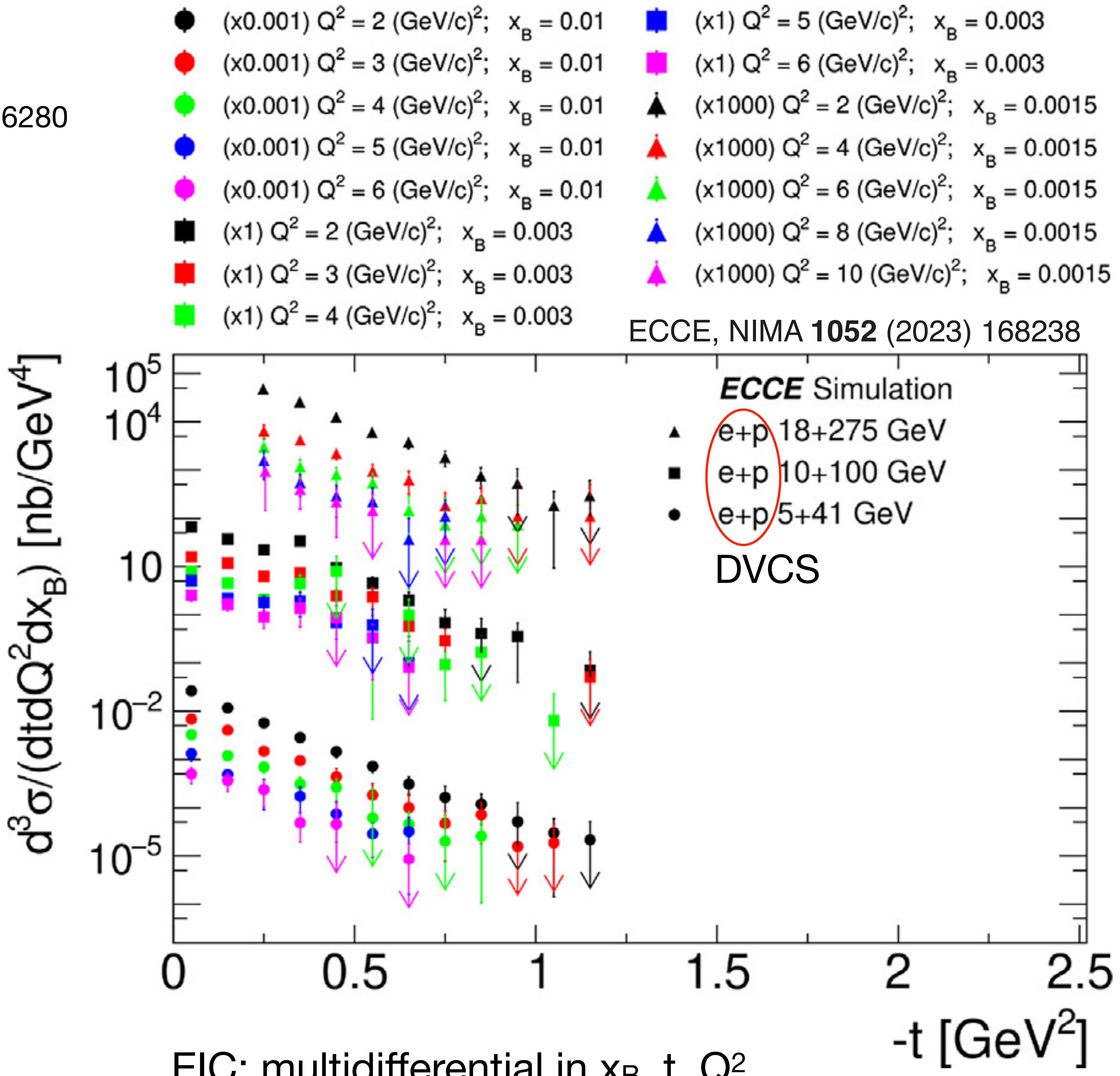
overall compatibility between pp, Pbp and ep data: hint of universality of underlying physics

GPDs at LHC and the EIC



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

A. J. Baltz, Phys. Rept. **458** (2008) 1–171



ECCE, NIMA **1052** (2023) 168238

EIC: multidifferential in x_B, t, Q^2
with detection of scattered proton

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

$H_T(x,\xi,t)$	$E_T(x,\xi,t)$
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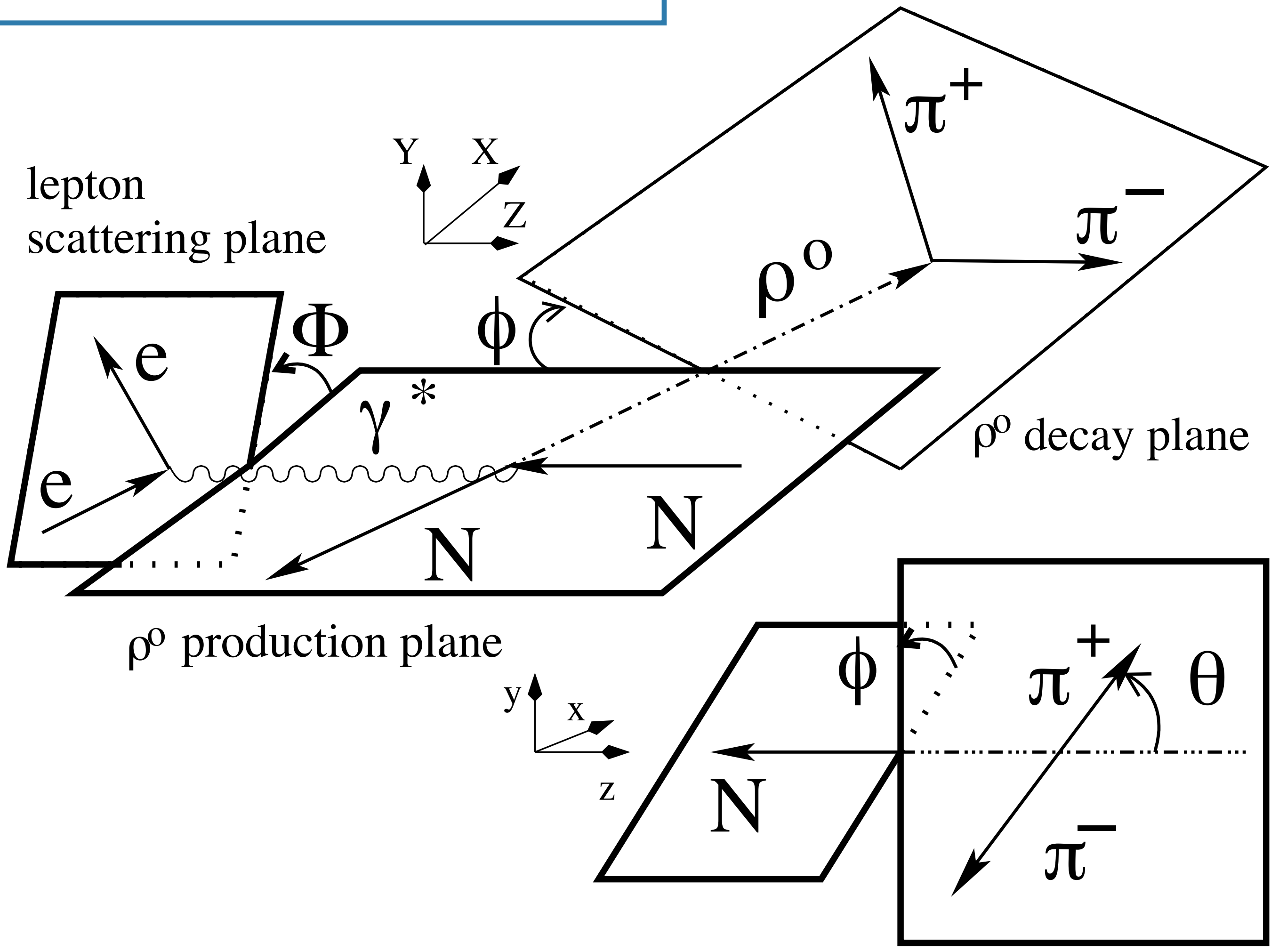
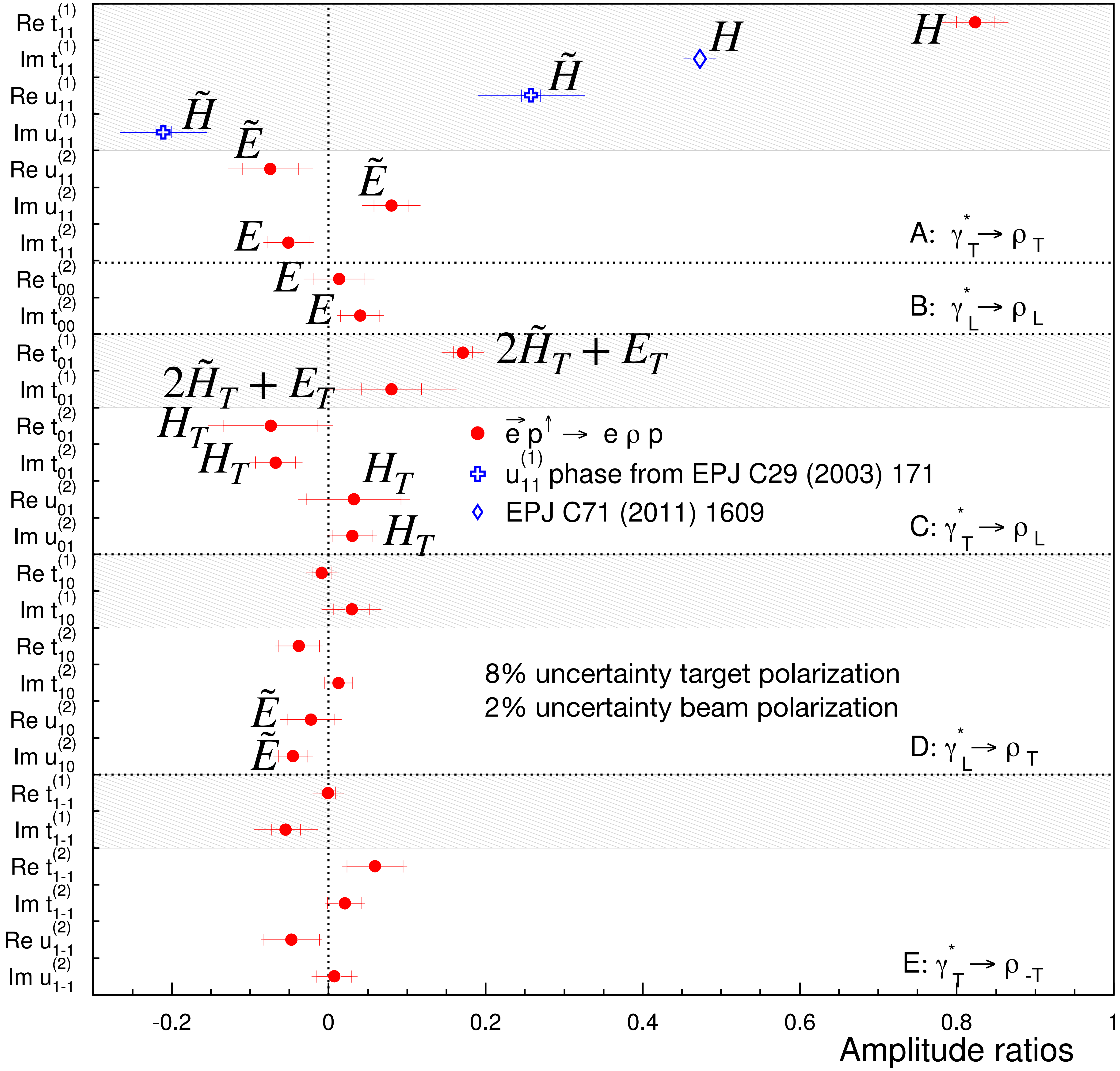


Exclusive ρ on transversely polarised p

Possible at EIC

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



▨ via unpolarised target

☐ via transversely polarised target

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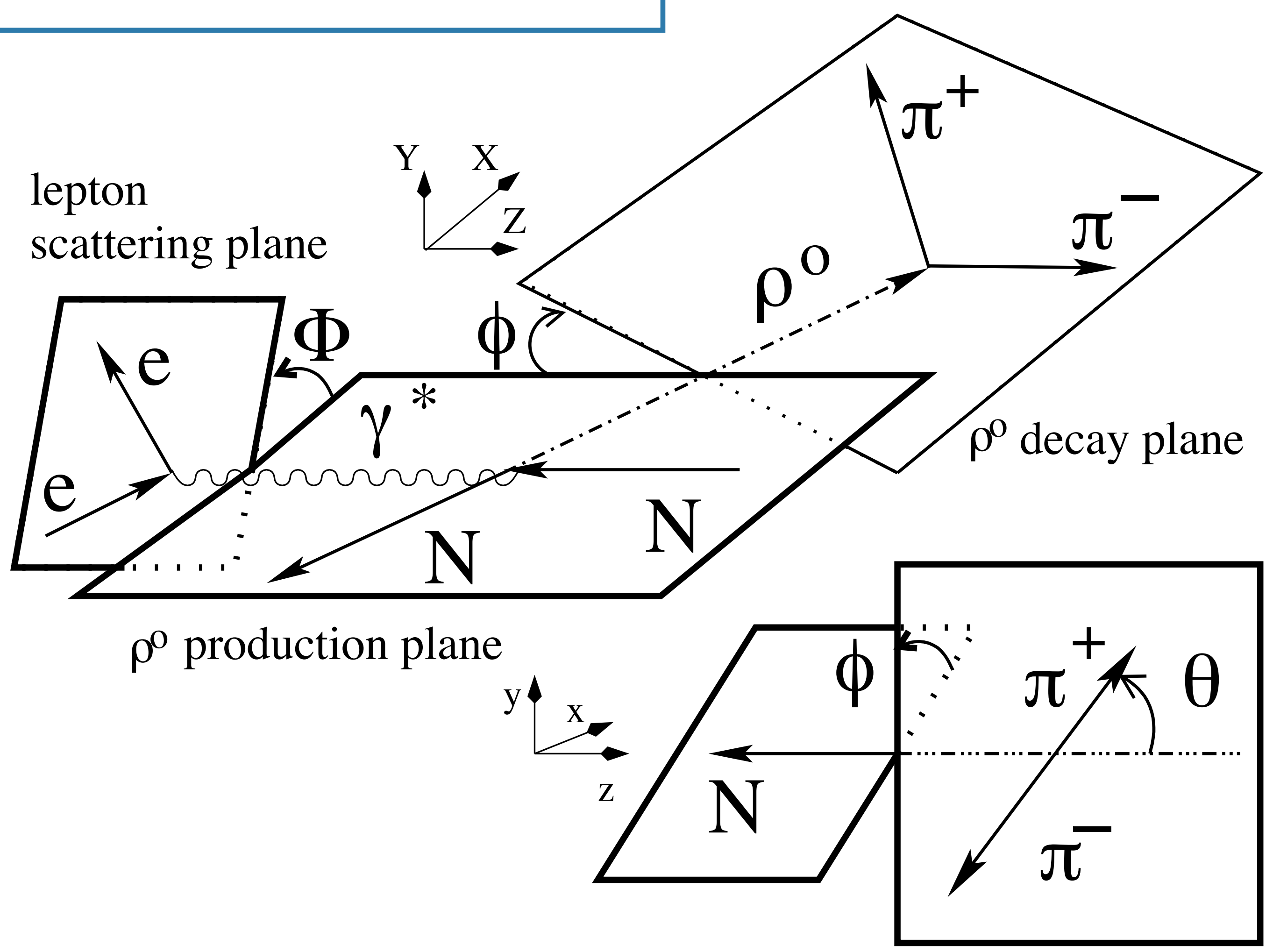

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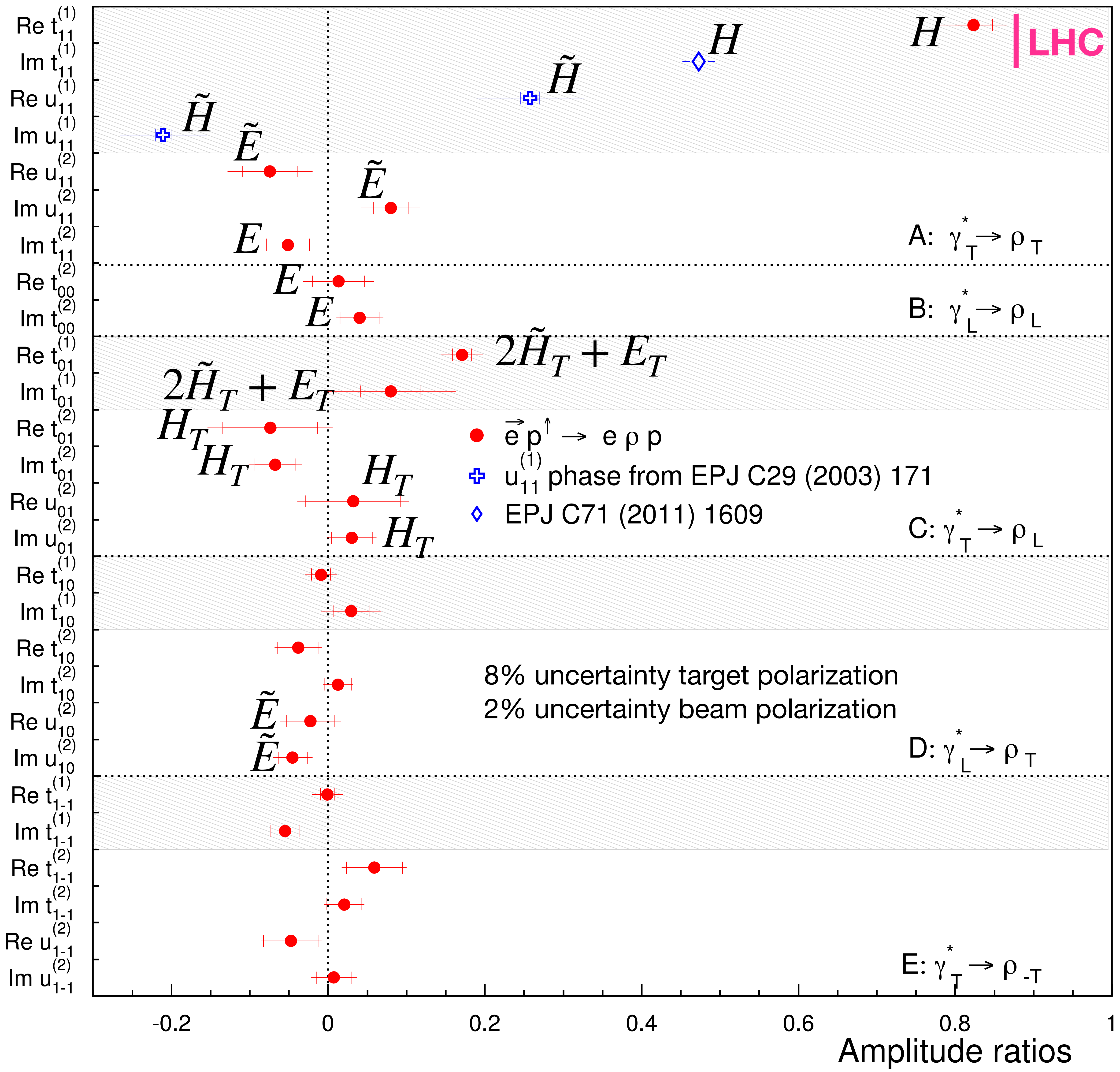

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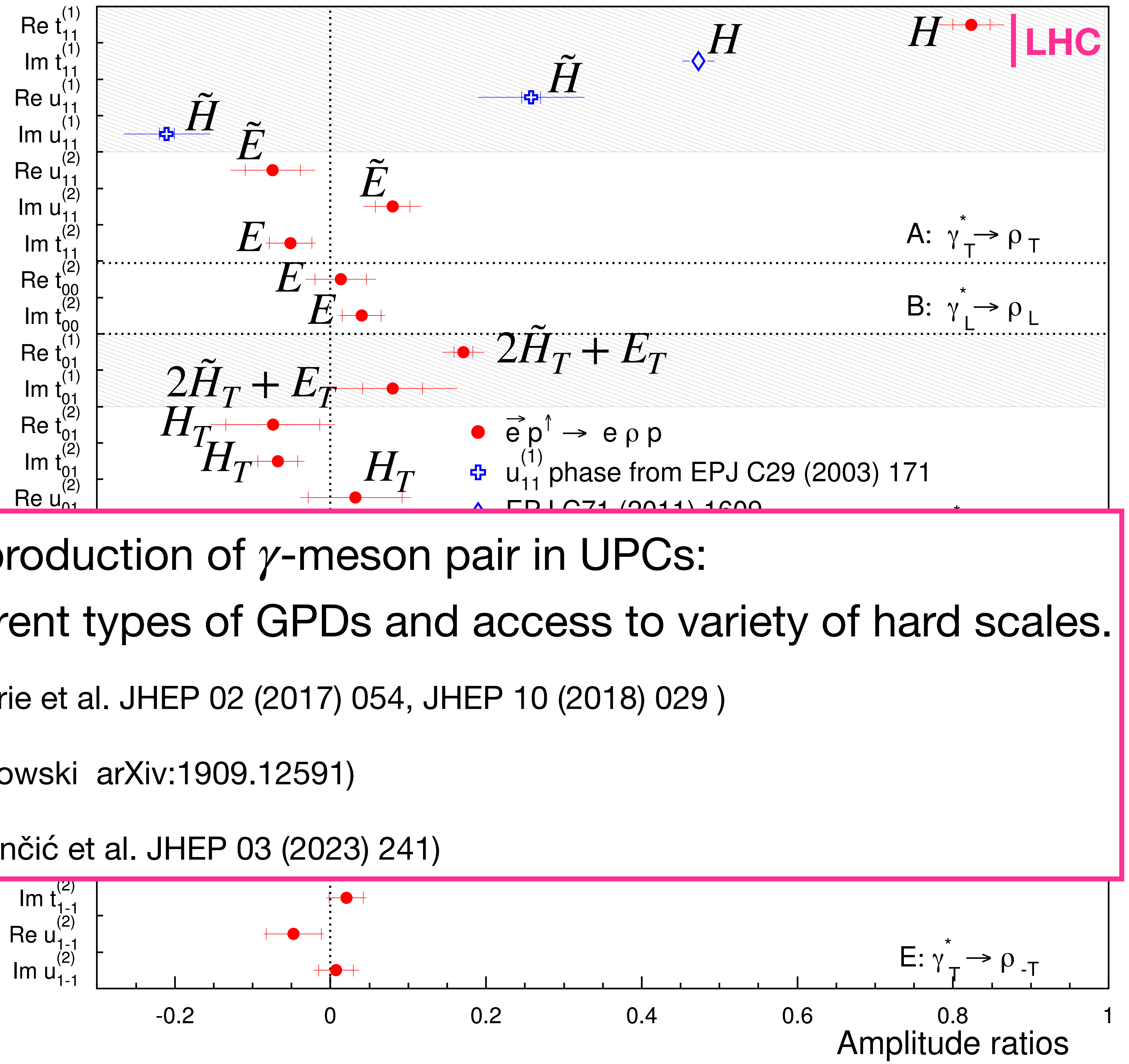
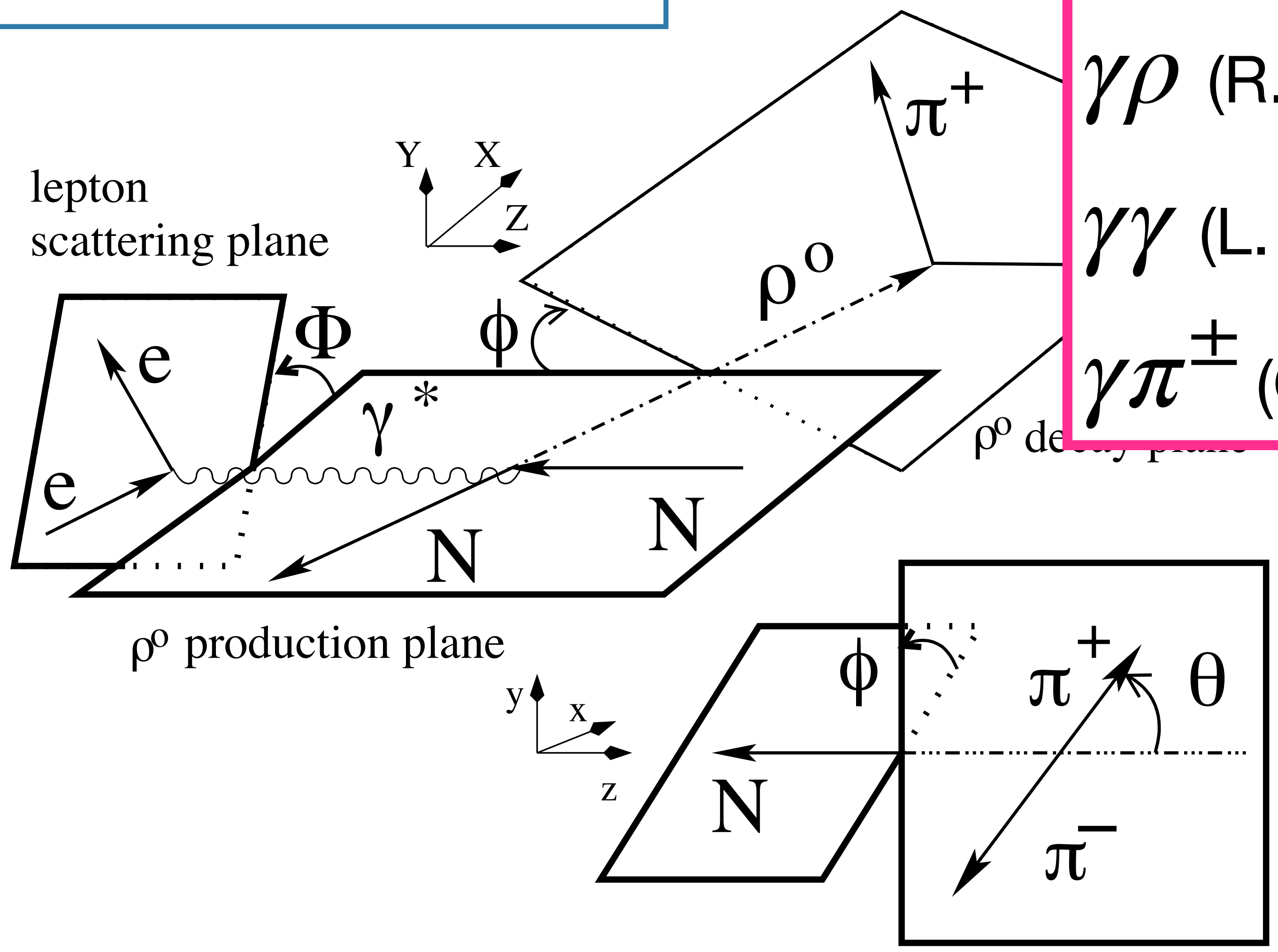


via unpolarised target

via transversely polarised target



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)

Fixed target

SMOG2:

exclusive measurements with SMOG2 (RUN3):

special runs {

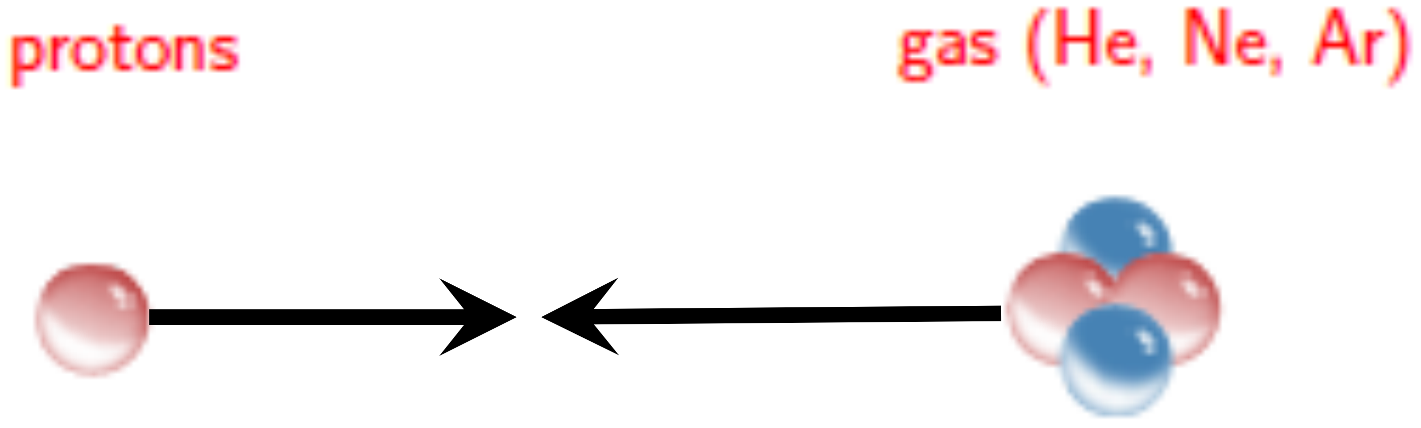
data collection in parallel with pp {

	pp	pHe	pXe
continuous $\mu^+\mu^-$	$\sigma = 61.931$ pb $= 686$ evts	$\sigma = 113.6$ pb $= 0$ evts	$\sigma = 17.6$ nb $= 29\ 10^3$ evts
$J/\psi \to \mu^+\mu^-$	$\sigma = 20.467$ pb $= 2302$ evts	$\sigma = 27.3$ pb $= 0$ evts	$\sigma = 1.3$ nb $= 21\ 10^3$ evts
$\phi \to K^+K^-$	$\sigma = 184$ pb $= 12\ 10^3$ evts	$\sigma = 109.4$ pb $= 5$ evts	$\sigma = 11.0$ nb $= 102\ 10^3$ evts

total uncertainty on cross section: 5-10%

LHCSpin:

SMOG2



$\sqrt{s_{NN}} = 115$ GeV

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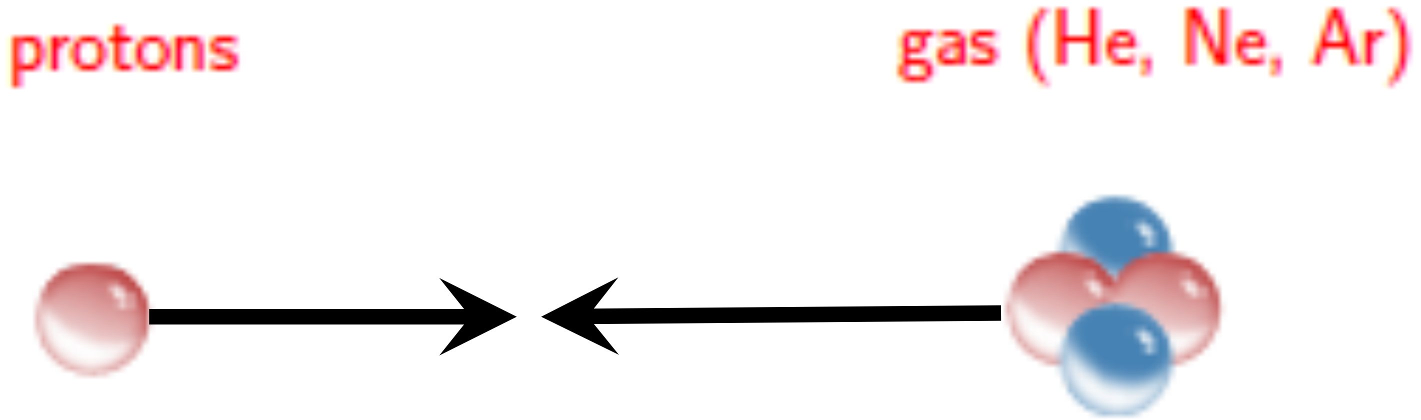
LHCSpin:

SMOG2 → **LHCSPIN**: transversely polarised gas target



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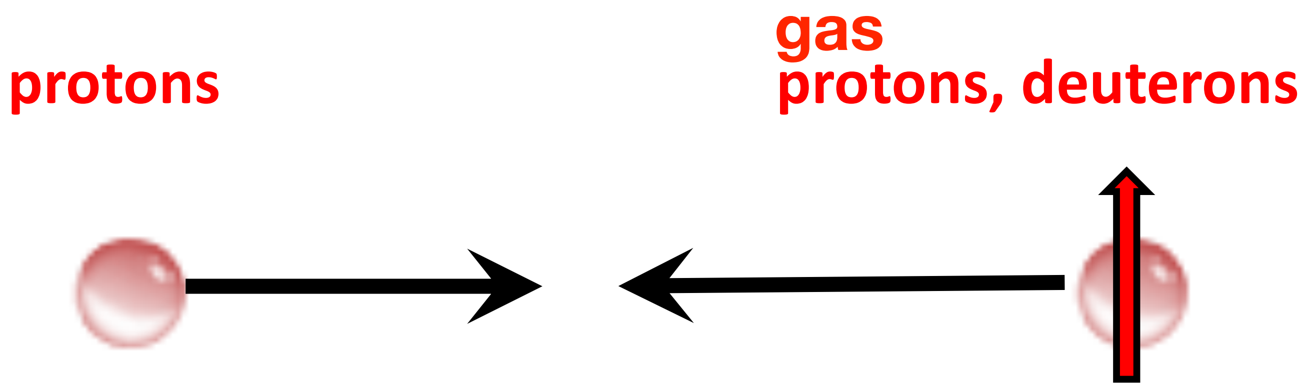

$\sqrt{s_{NN}} = 115$ GeV

⟶ access to spin-dependent GPDs at the LHC

Summary

- Vast complementarity between (HL-)LHC, fixed-target and EIC
- EIC covers large variety of nuclei

  —> valuable input for cold nuclear matter determination and for QGP studies

  —> precise study of hadronisation, can help to understand LHC baryon data
- Fixed target also covers variety of nuclei, at large x_B —> complementary channel
- LHC covers otherwise unaccessible low-x_B regions
- Study of the multi-dimensional nucleon-structure:
  - EIC ep provides high precision and polarisation for nucleon/light nuclei
  - LHC pA covers otherwise unaccessible low-x_B regions