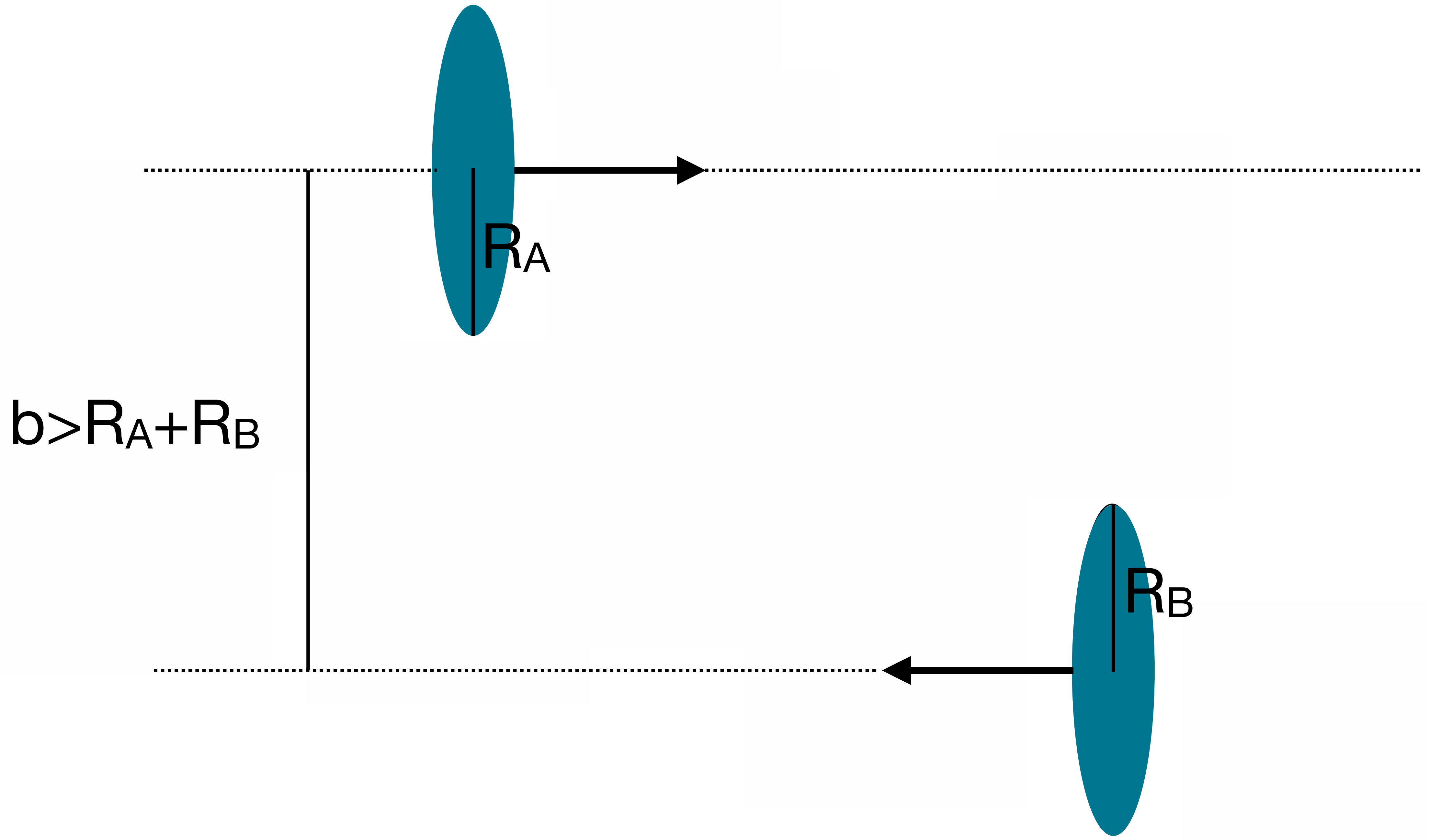
Overview on UPC and perspectives in LHC Run 3 and 4

Charlotte Van Hulse

Heavy-ion meeting 10 December 2020
Orsay

Ultra-peripheral collisions

large–impact-parameter interactions

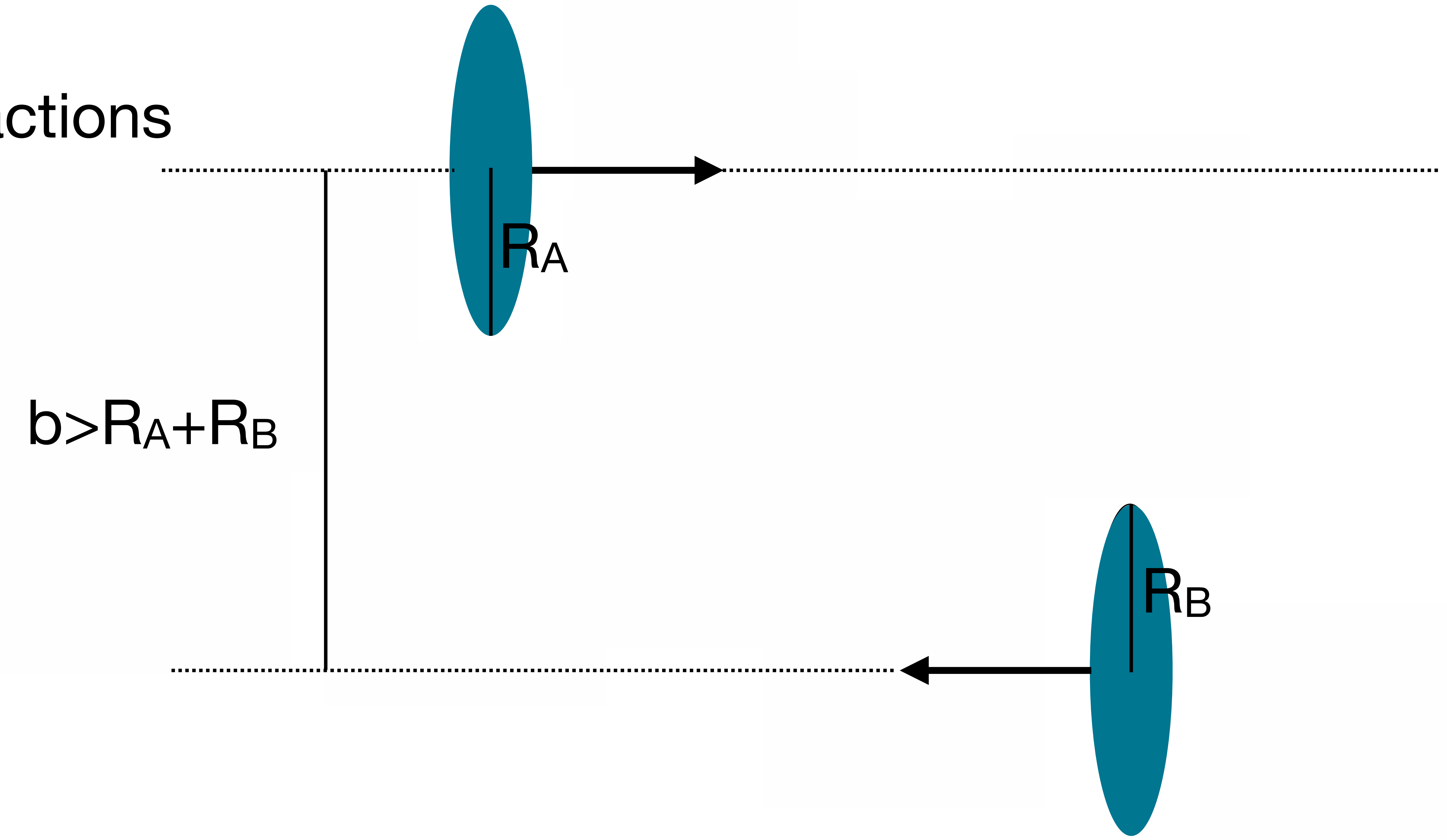


Ultra-peripheral collisions

large–impact-parameter interactions

hadronic interactions strongly suppressed

instead: electromagnetic interactions



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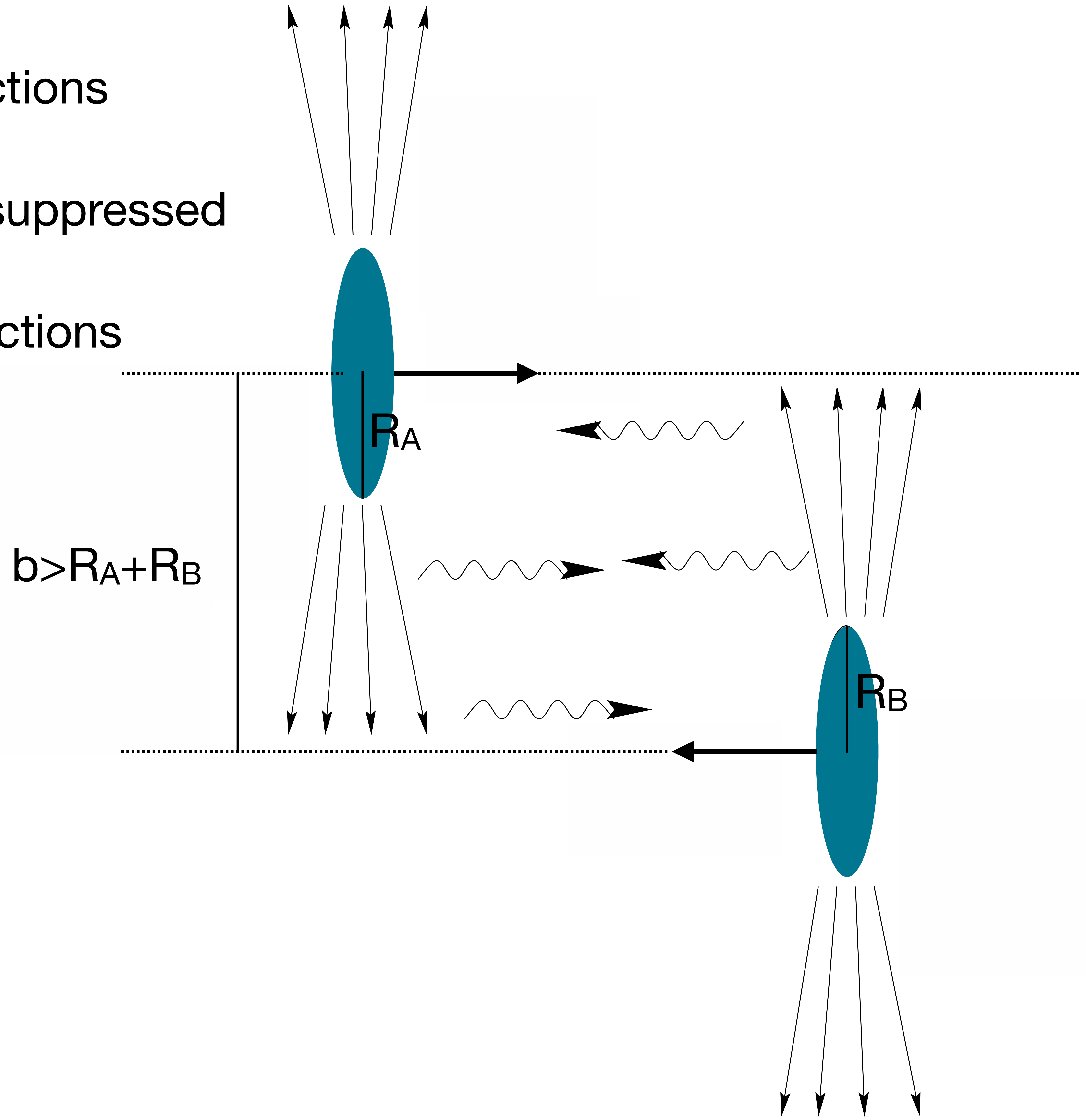

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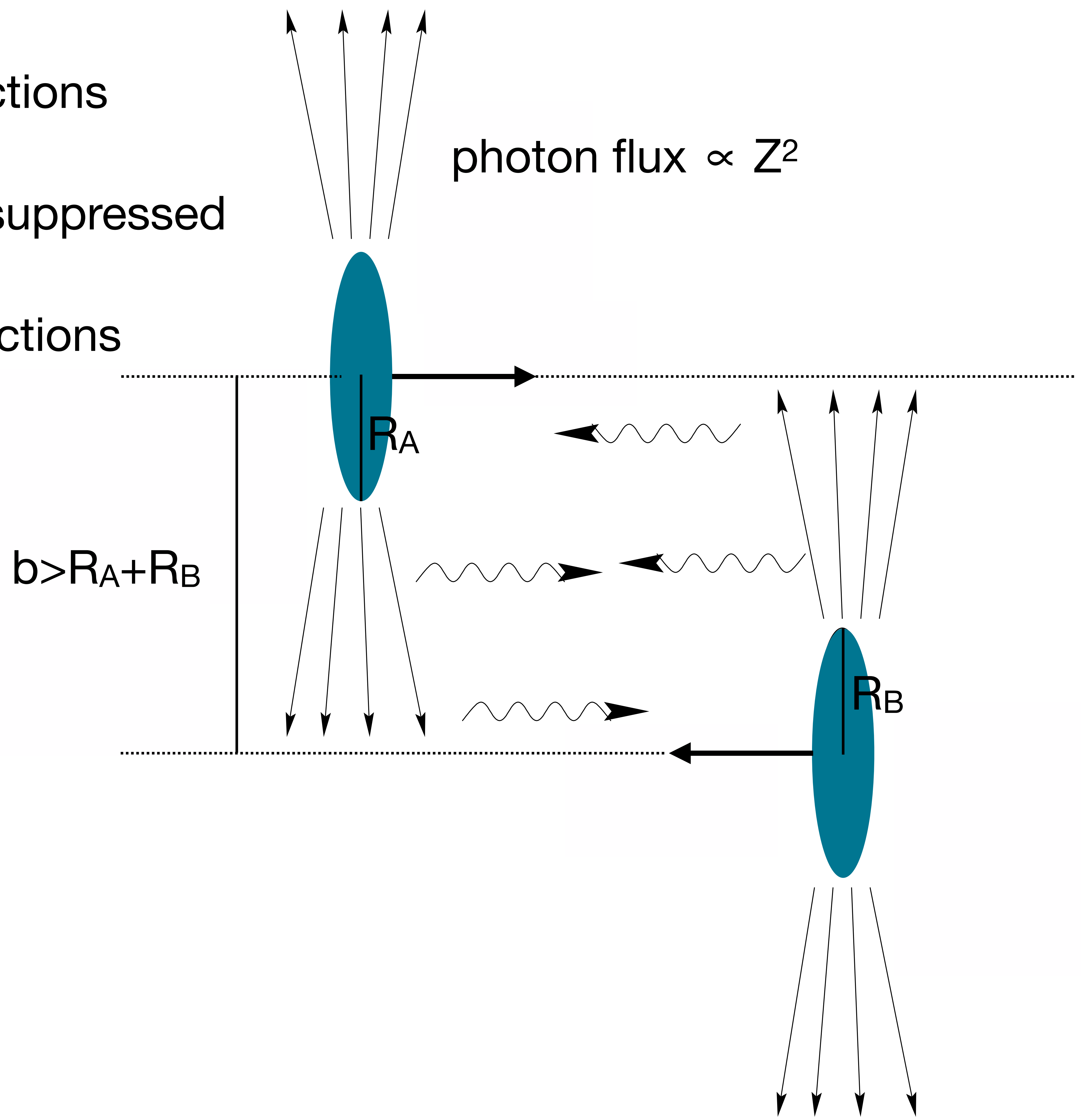
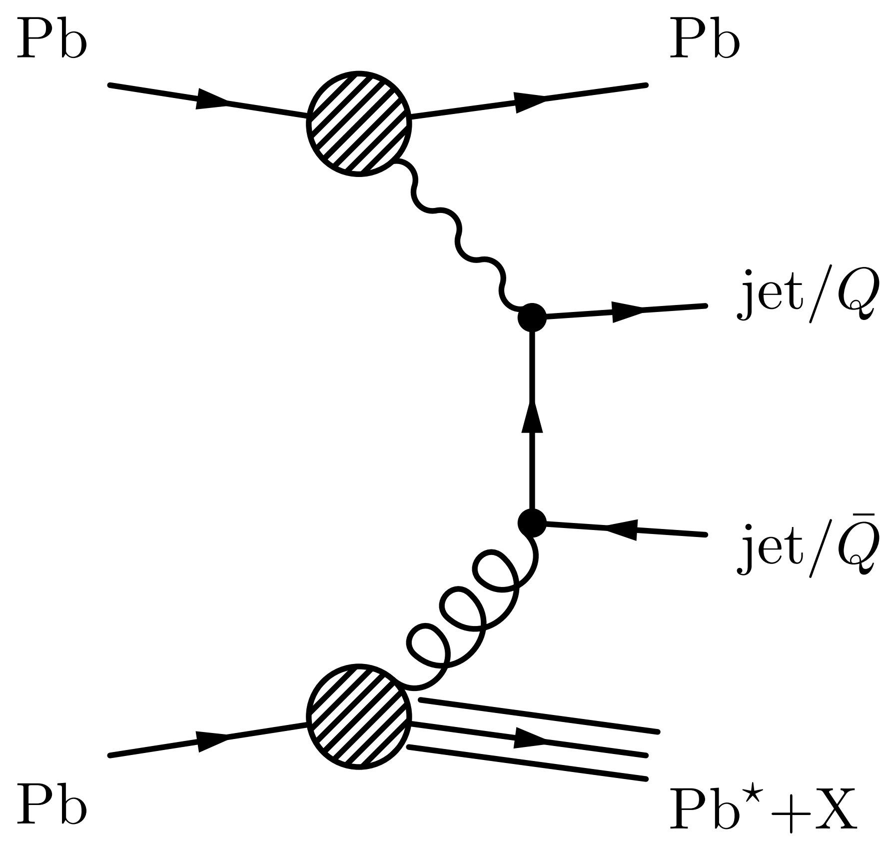


Presented measurements



inclusive and exclusive dijets

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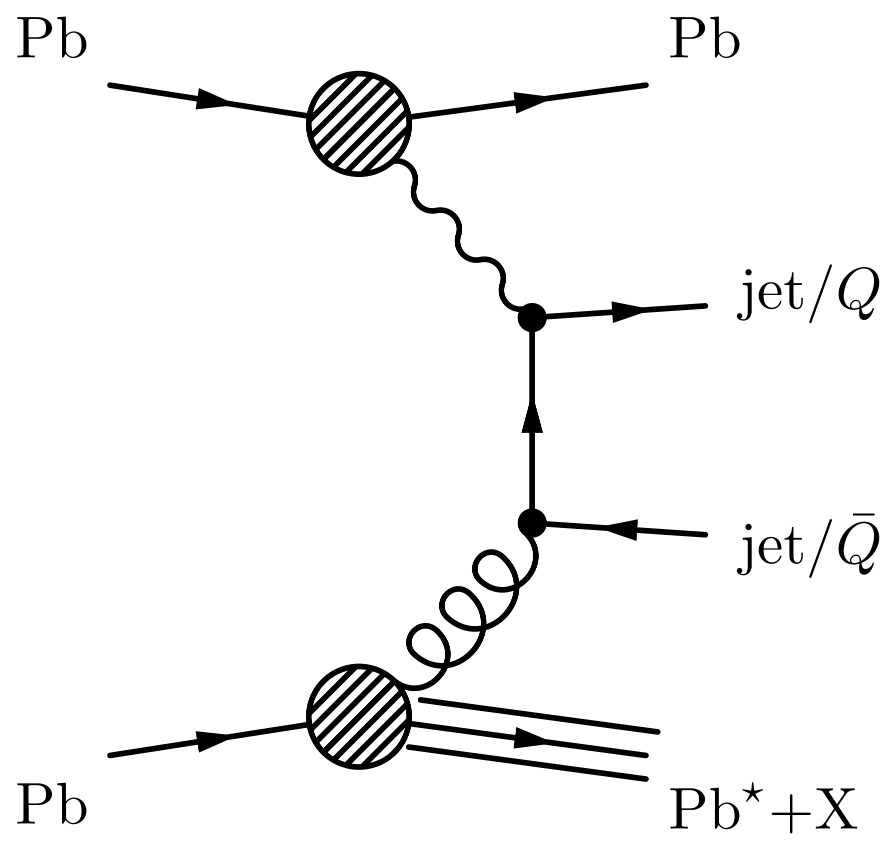

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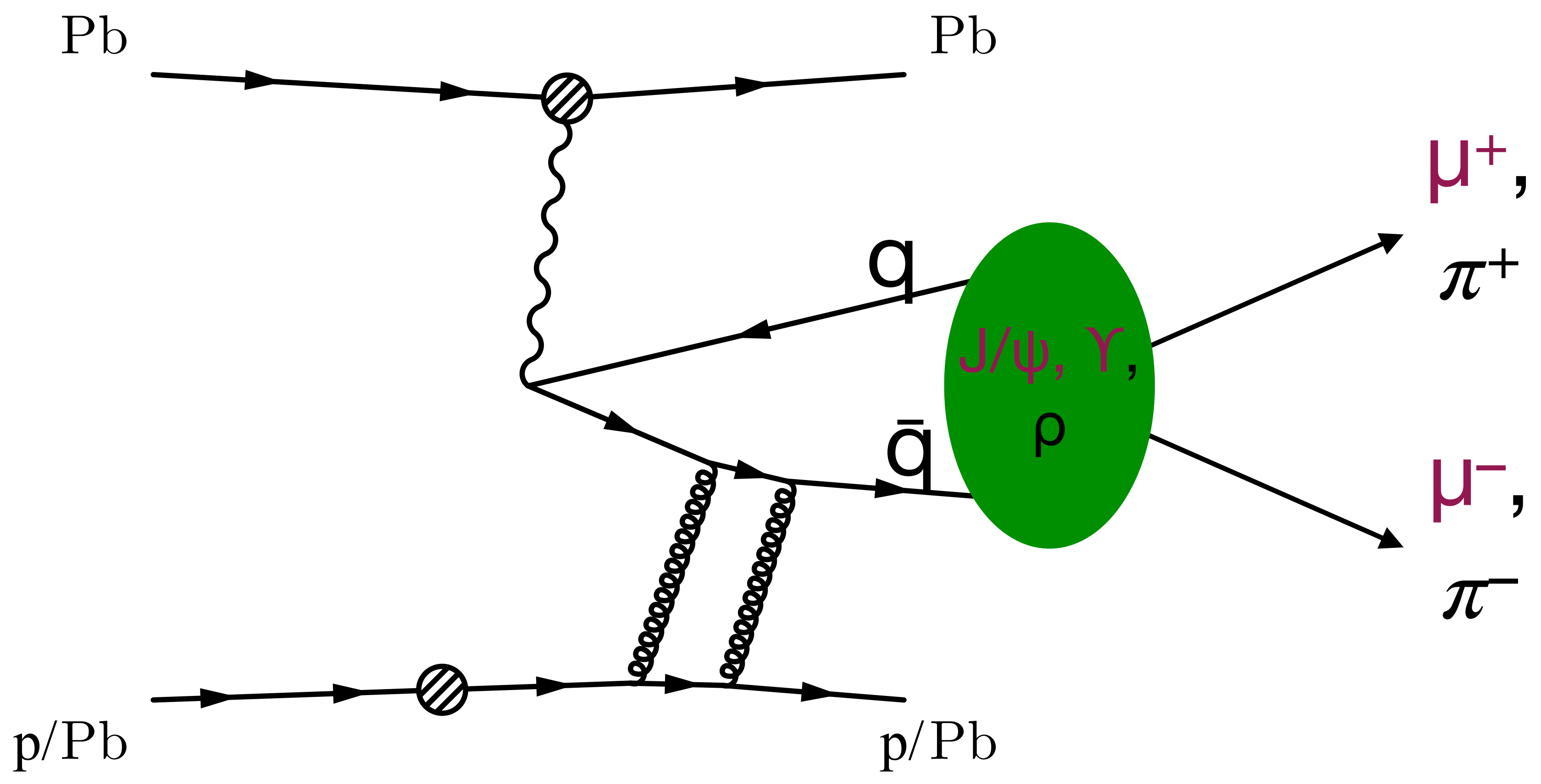

exclusive vector-meson production

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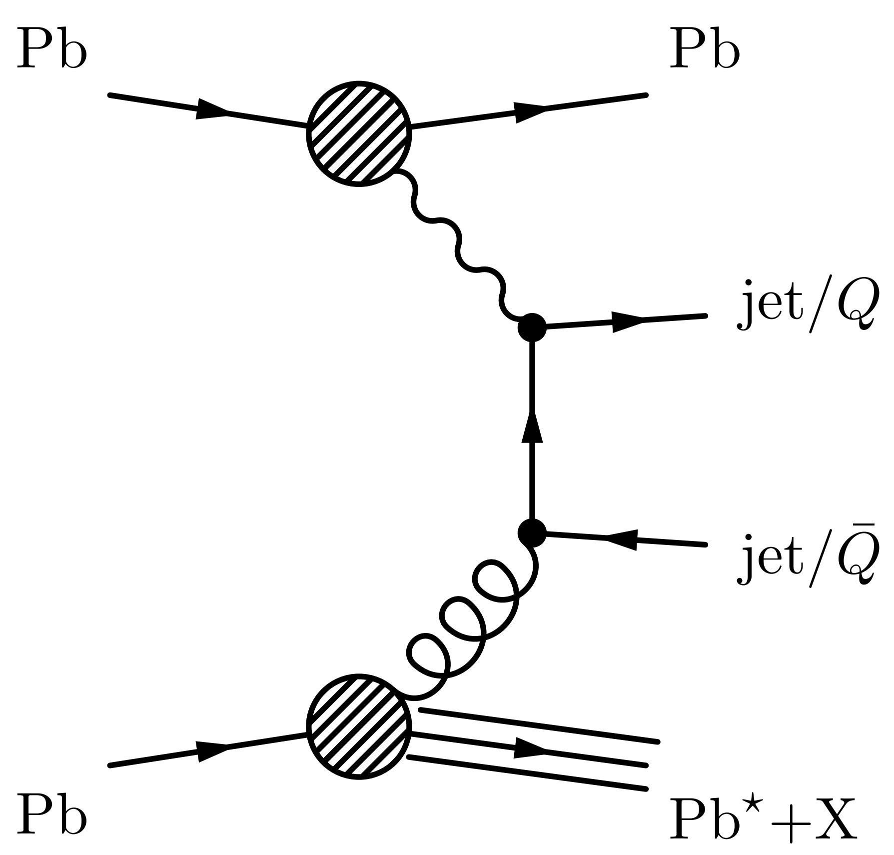

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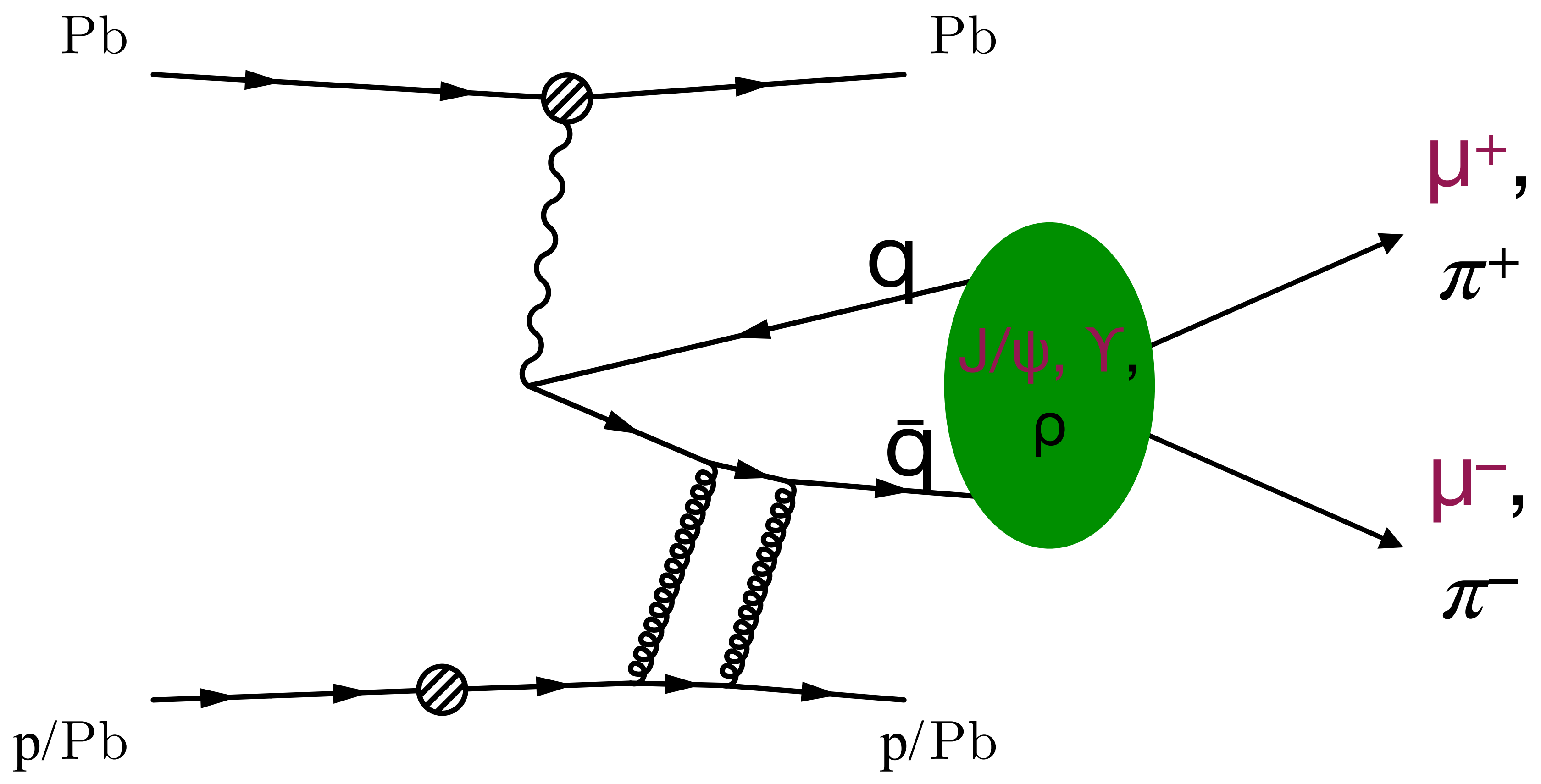

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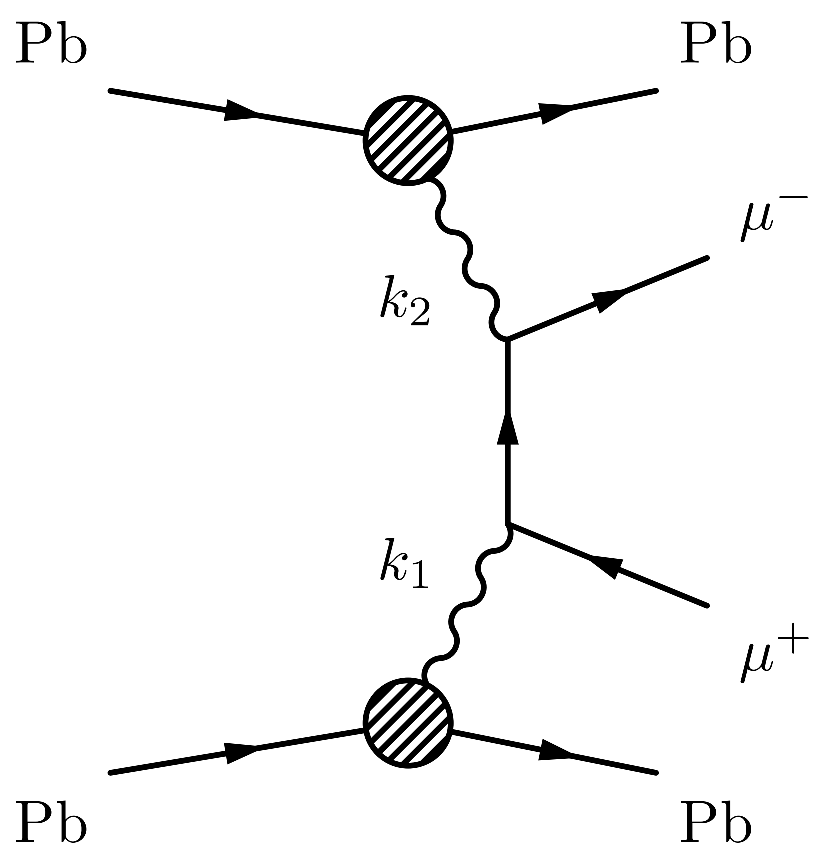

exclusive continuous dilepton production

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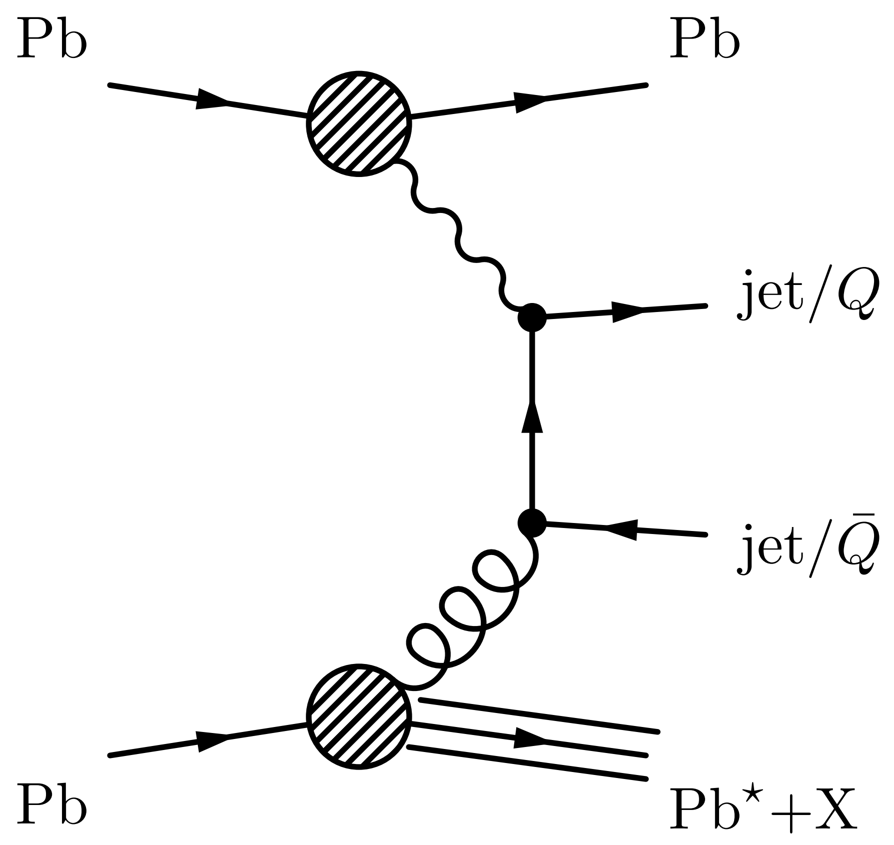

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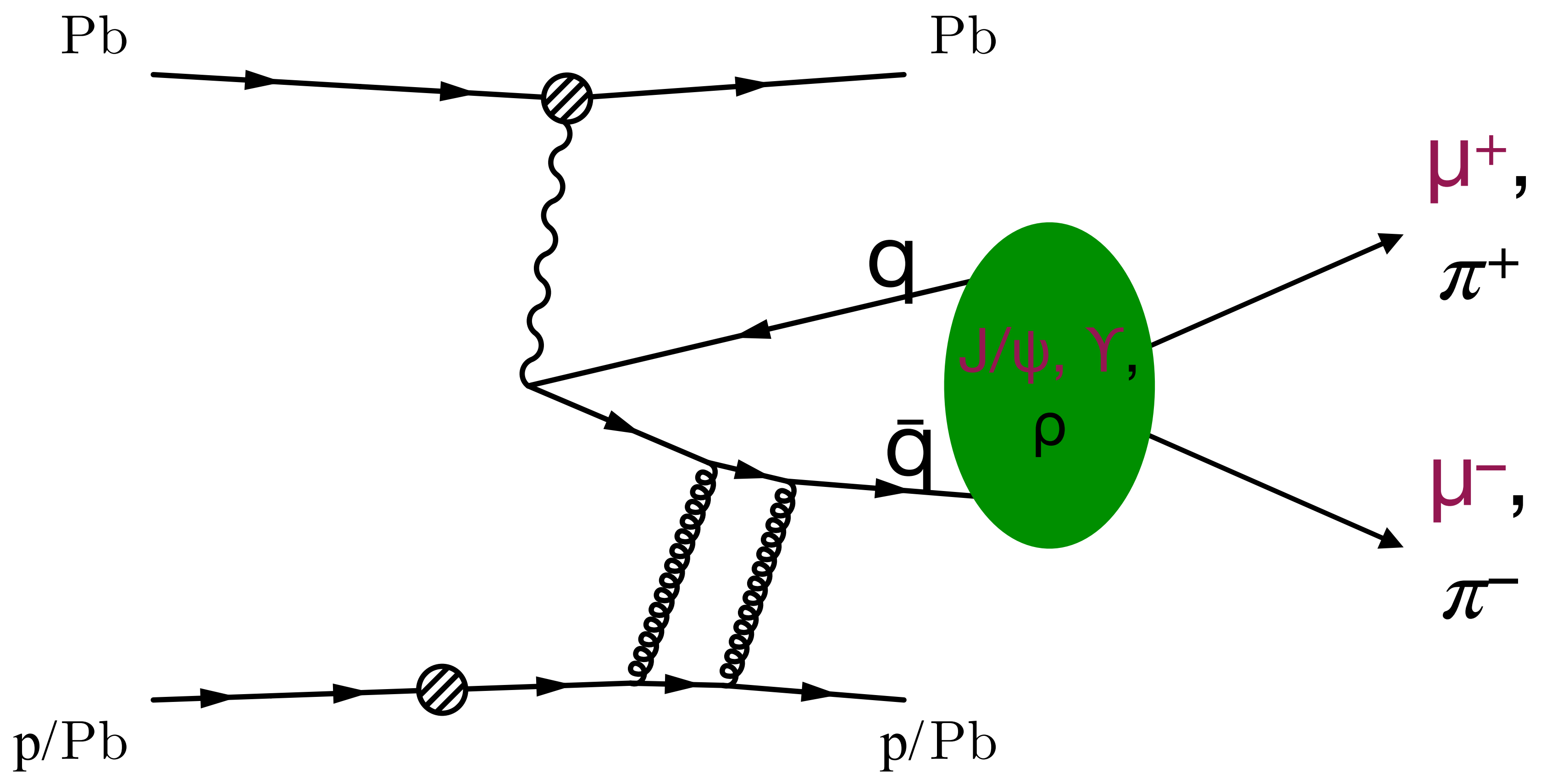

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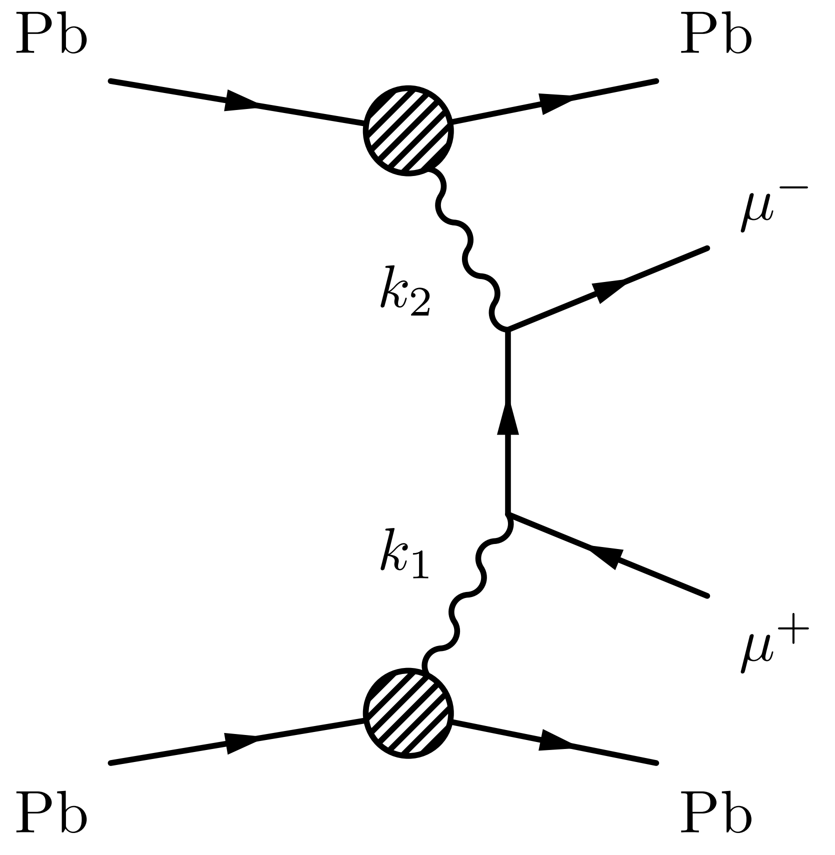

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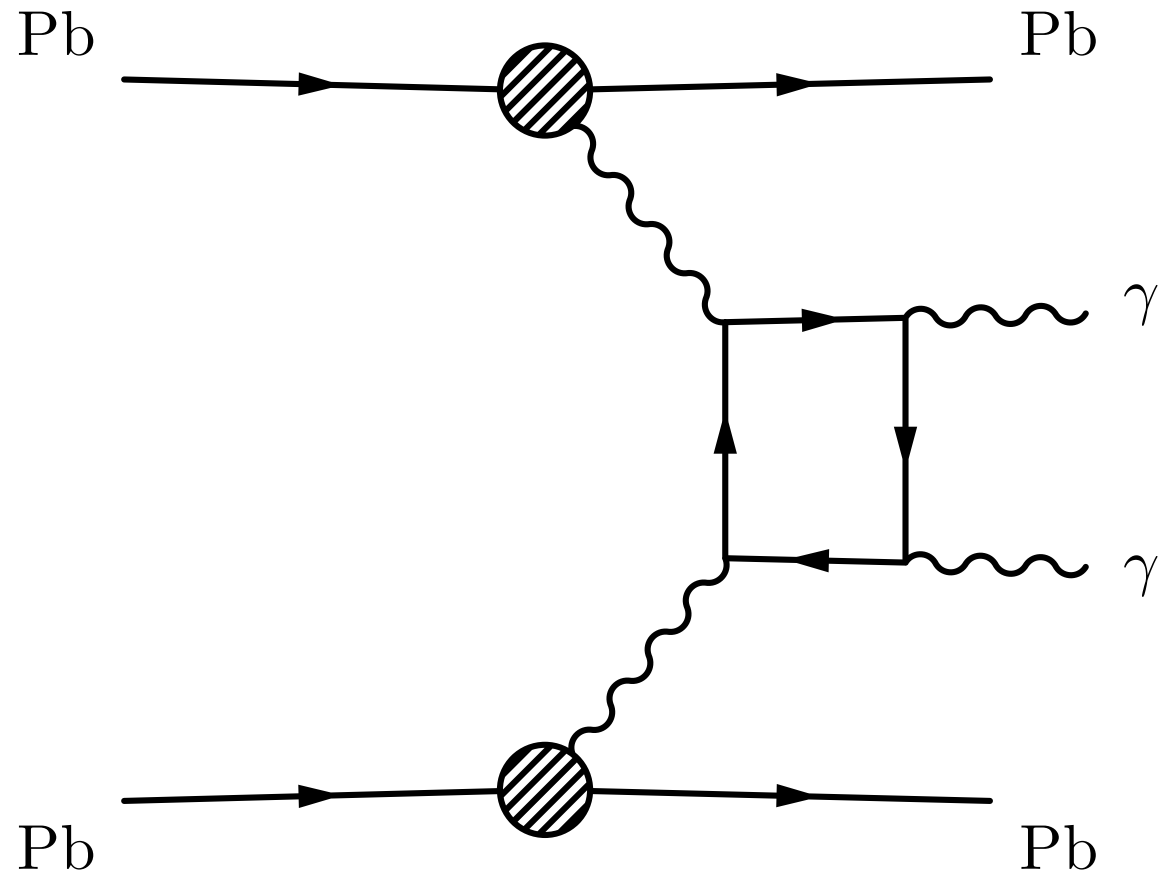
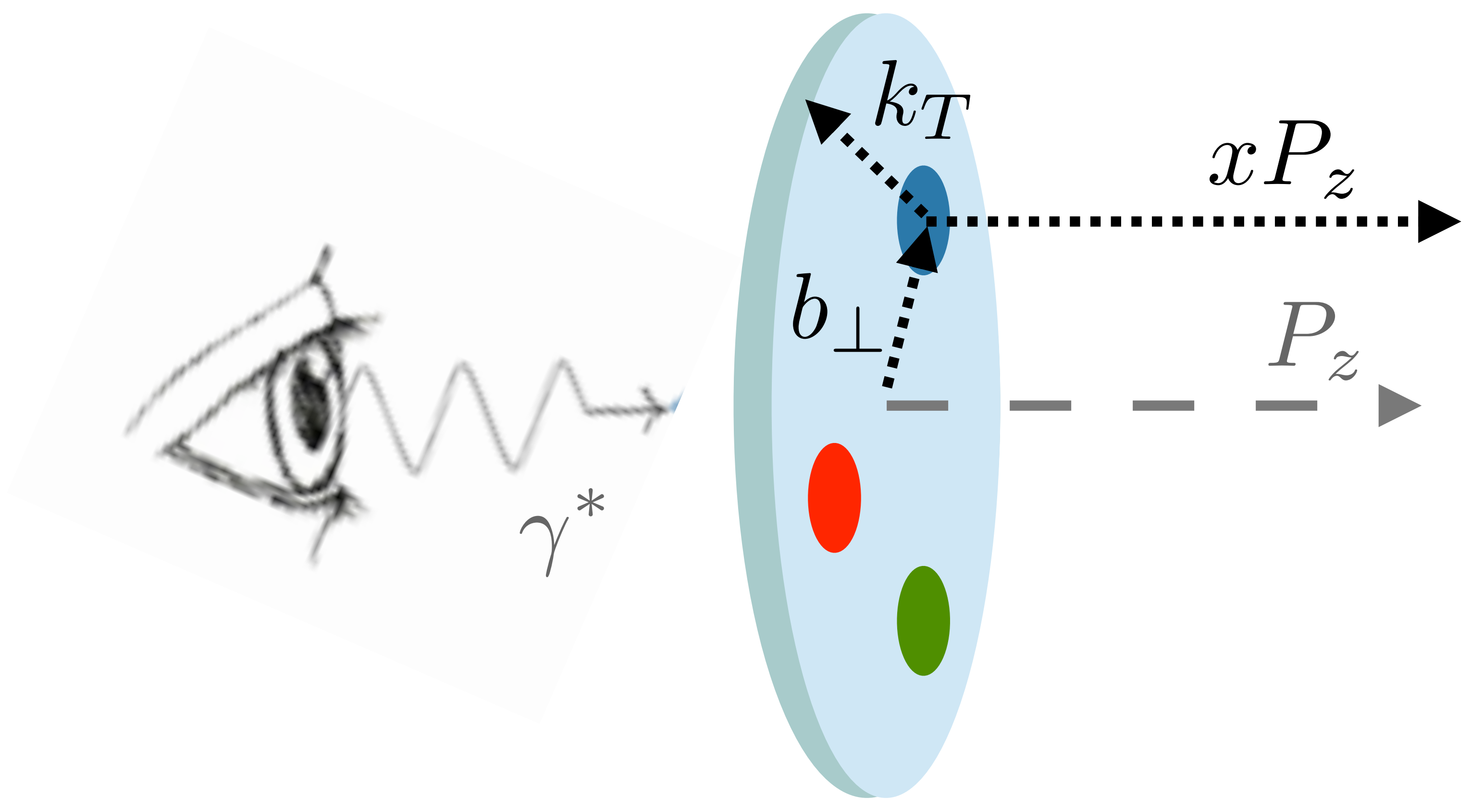


light-by-light scattering

Probing nucleons and nuclei

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$



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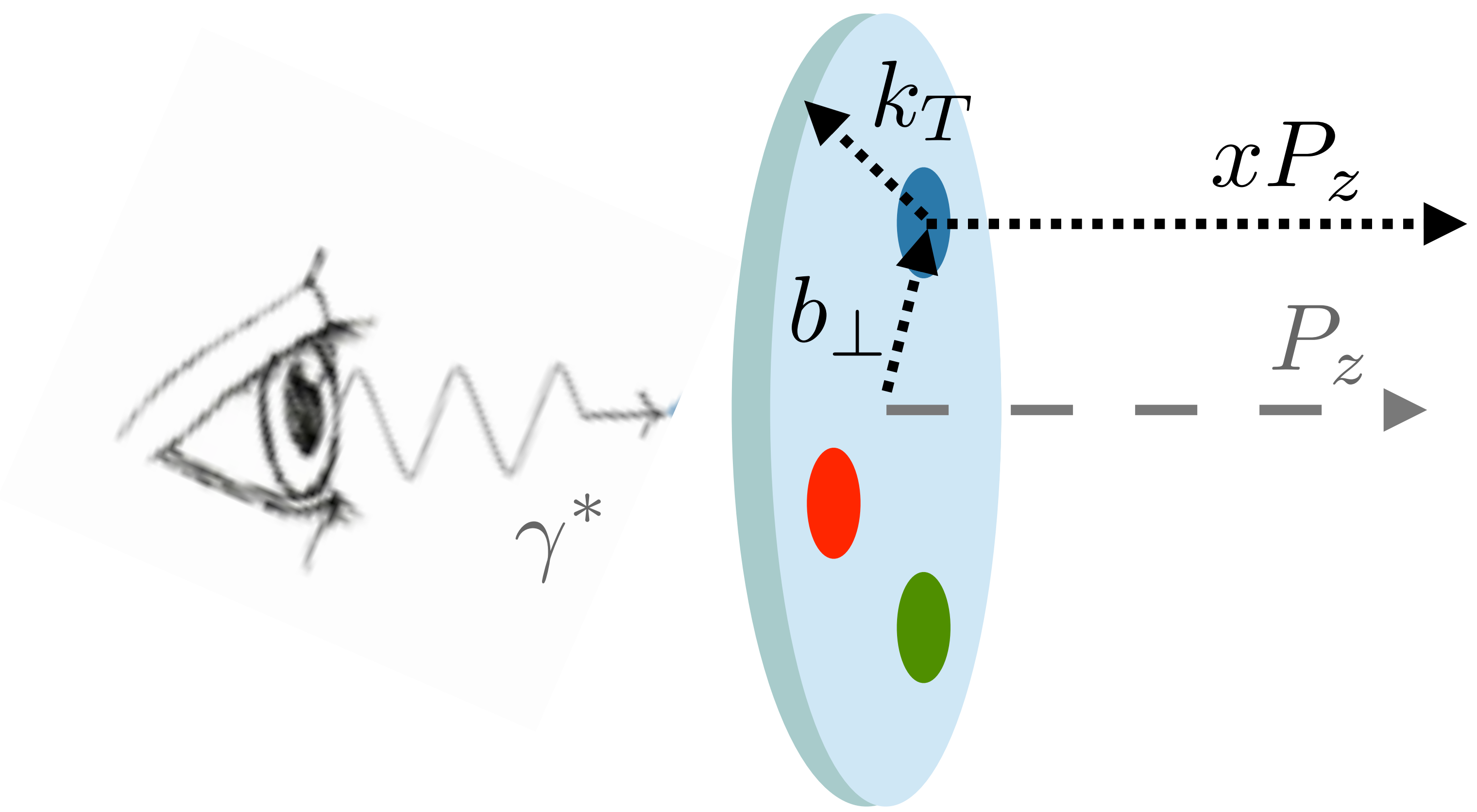
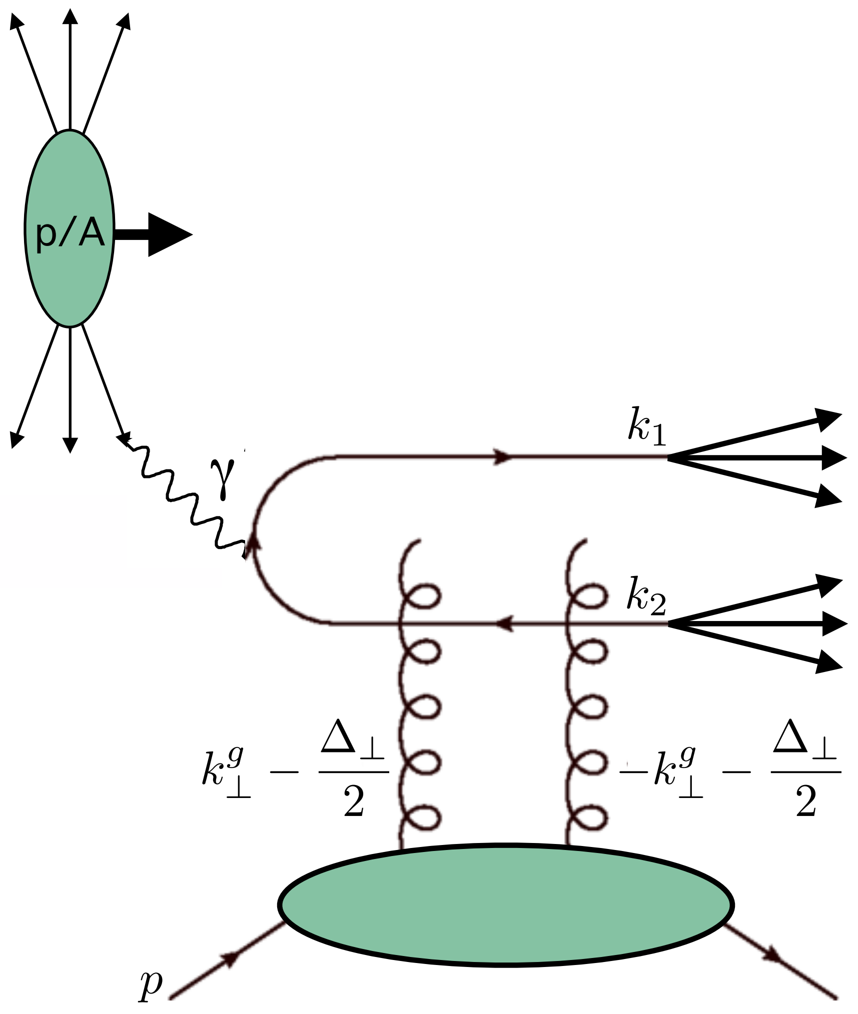




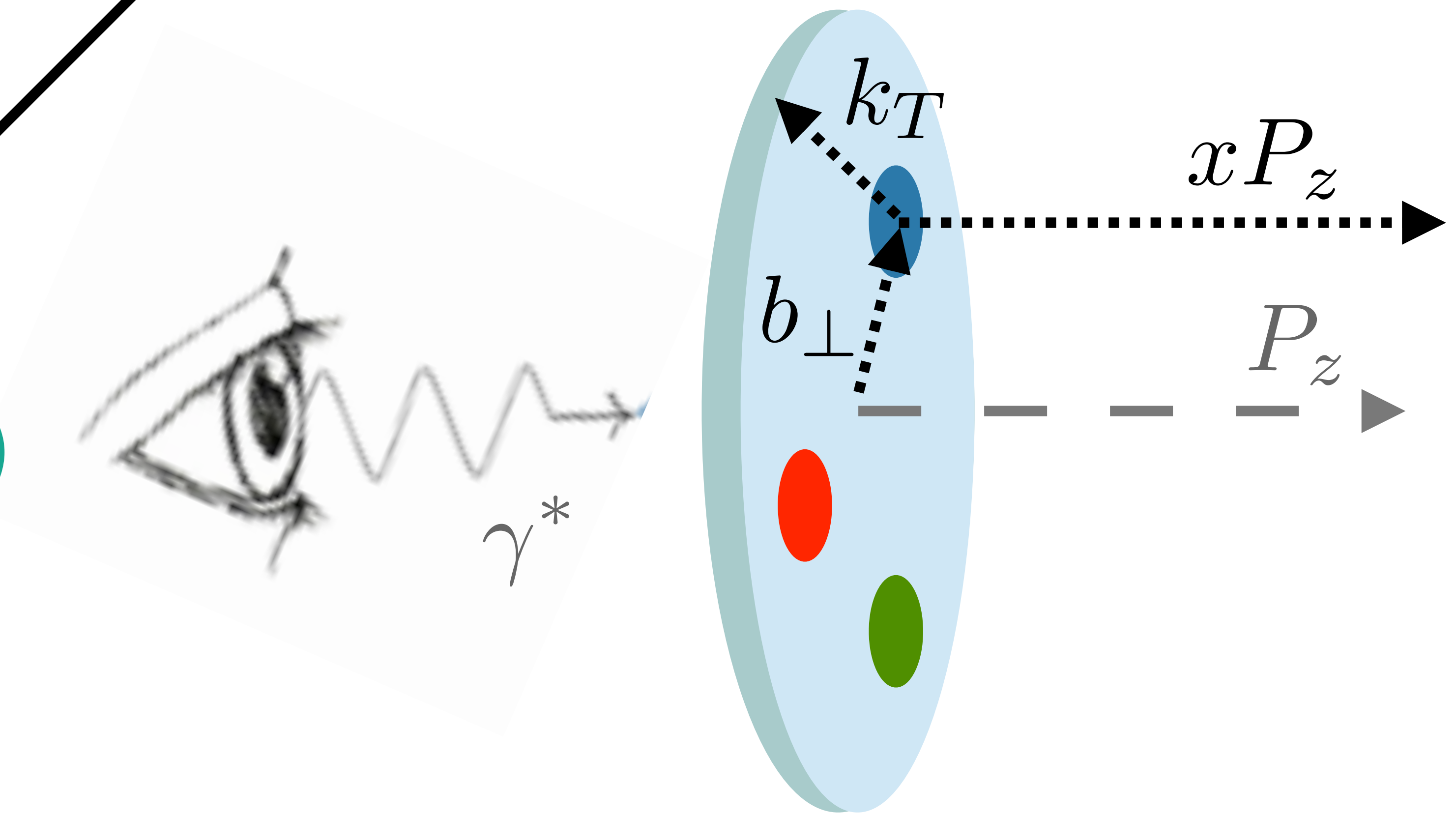
Exclusive dijets and heavy-meson pairs in UPCs
PRD **96** ('17) 034009; PRD **99** ('19) 034016

Probing nucleons and nuclei

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$

transverse-momentum dependent PDFs (TMDs)



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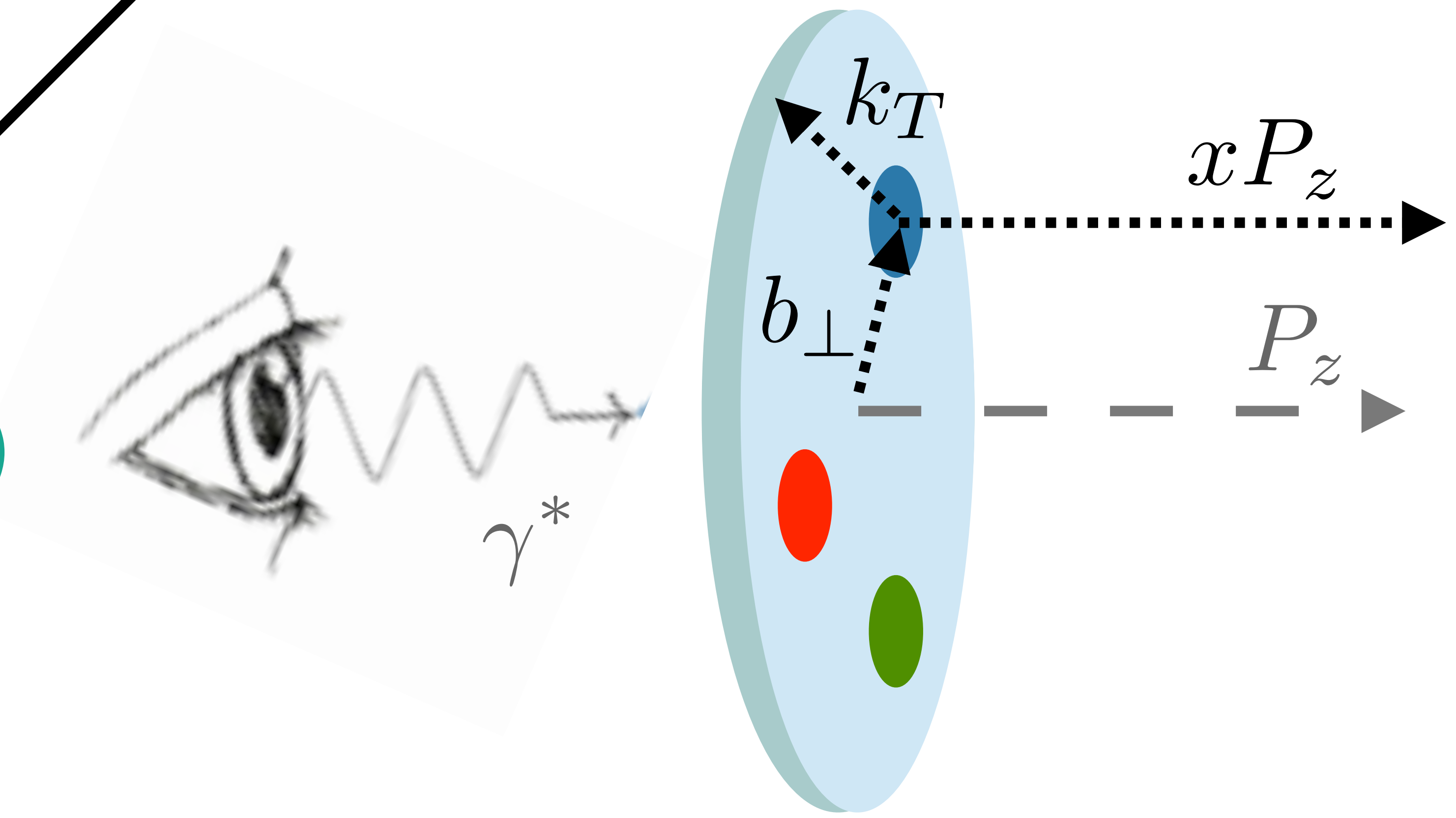

$\int d^2\vec{k}_T$

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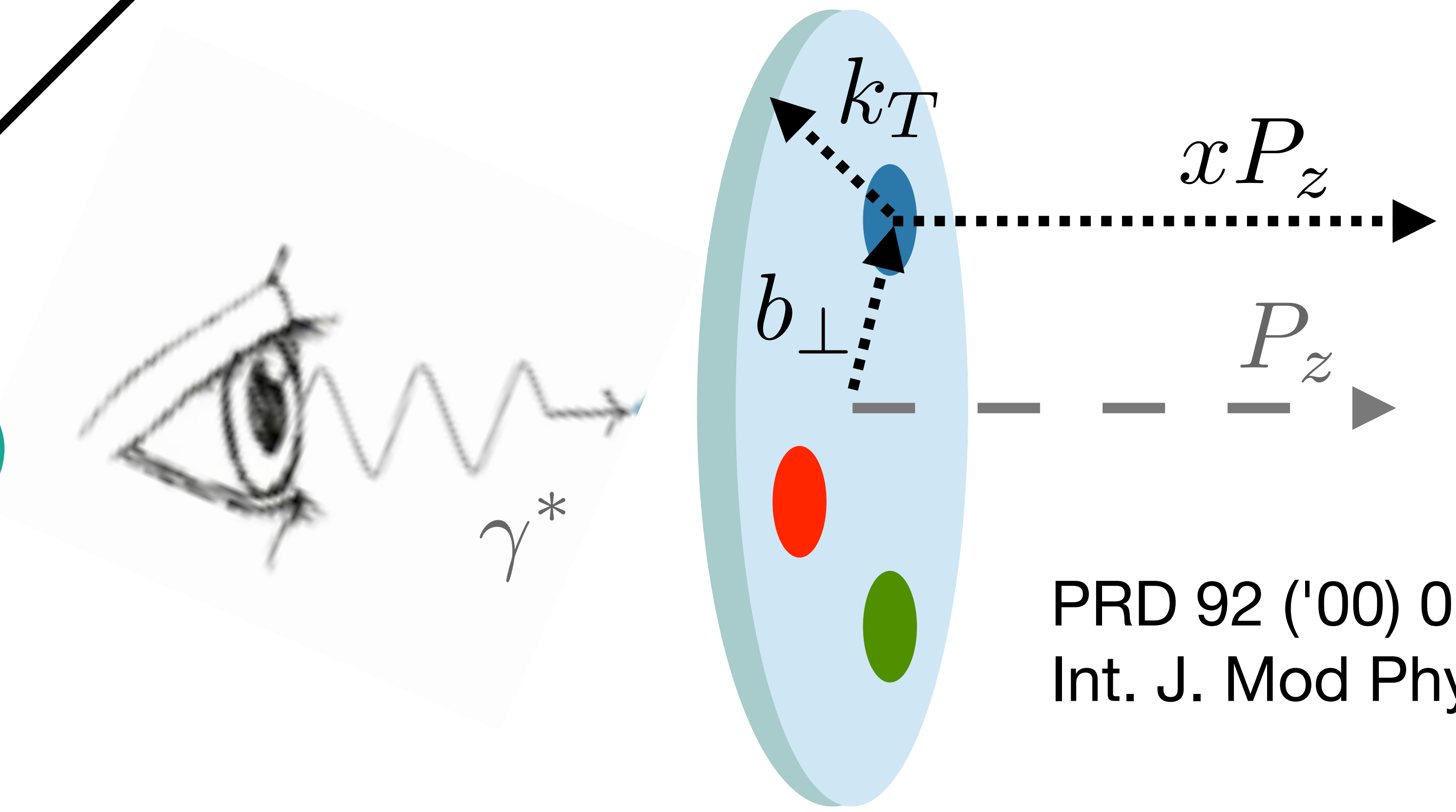

$\int d^2\vec{k}_T$

impact-parameter
dependent distributions

PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173

Fourier
transform

generalised parton
distributions (GPDs)

Probing nucleons and nuclei

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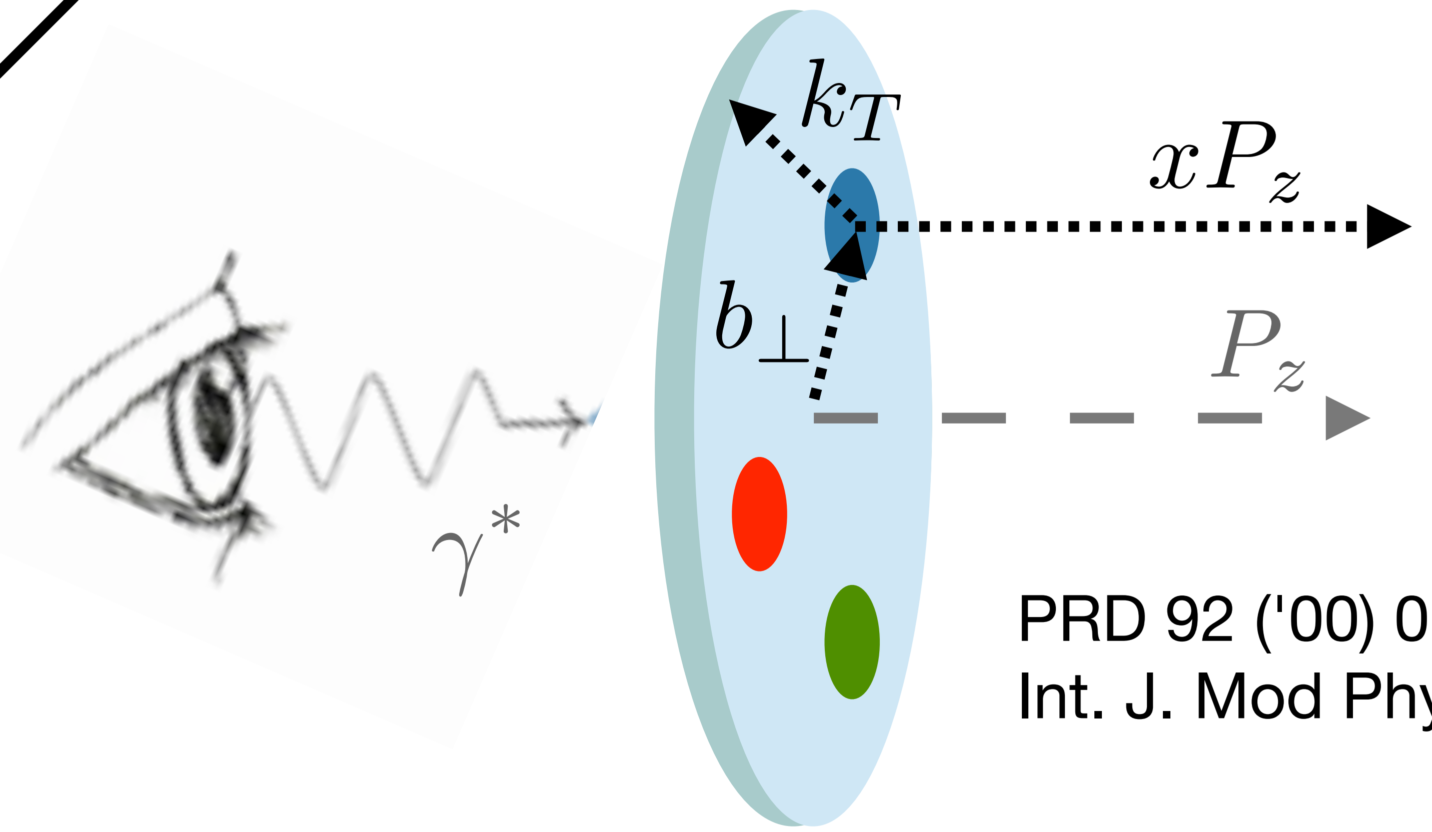

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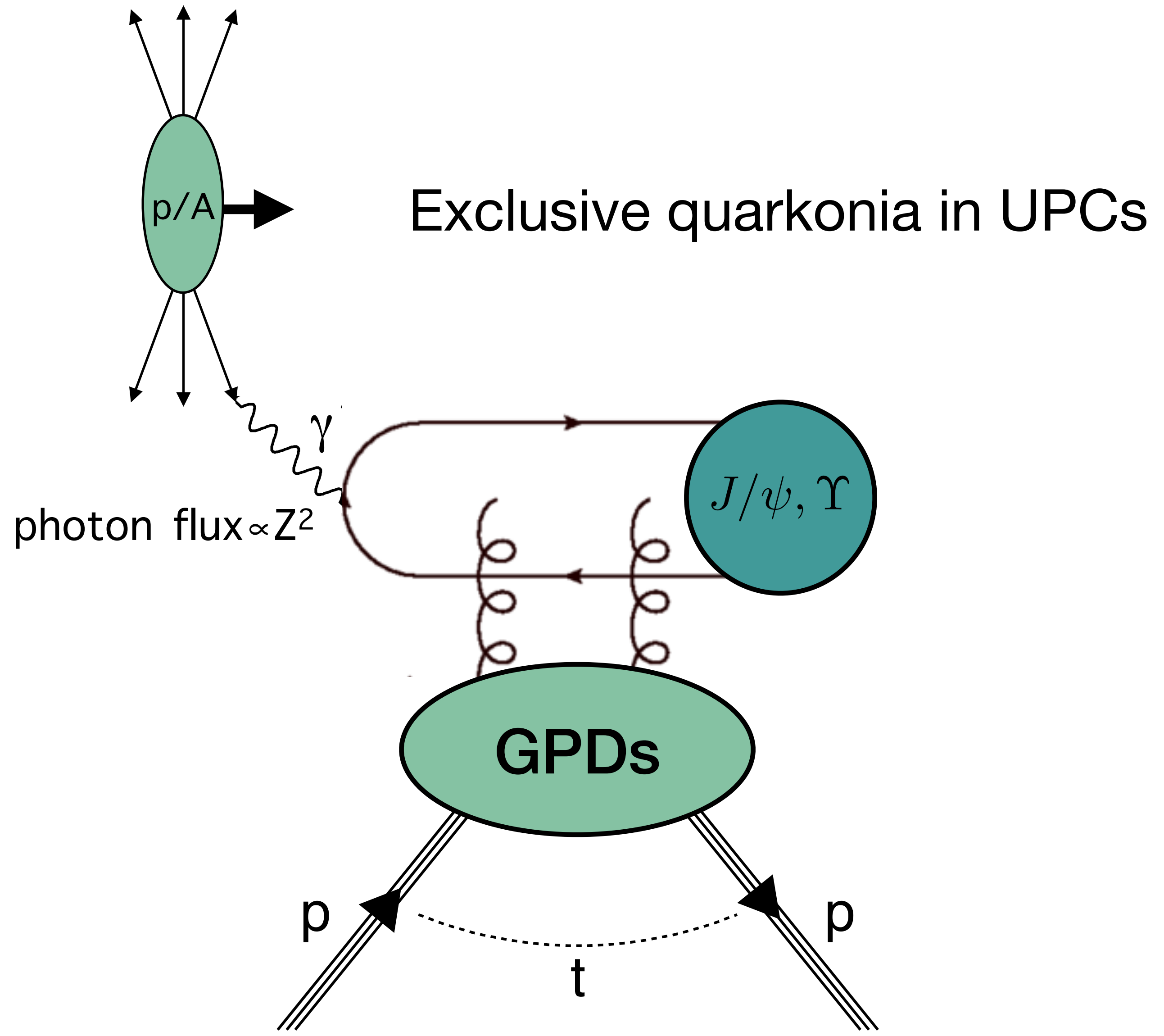


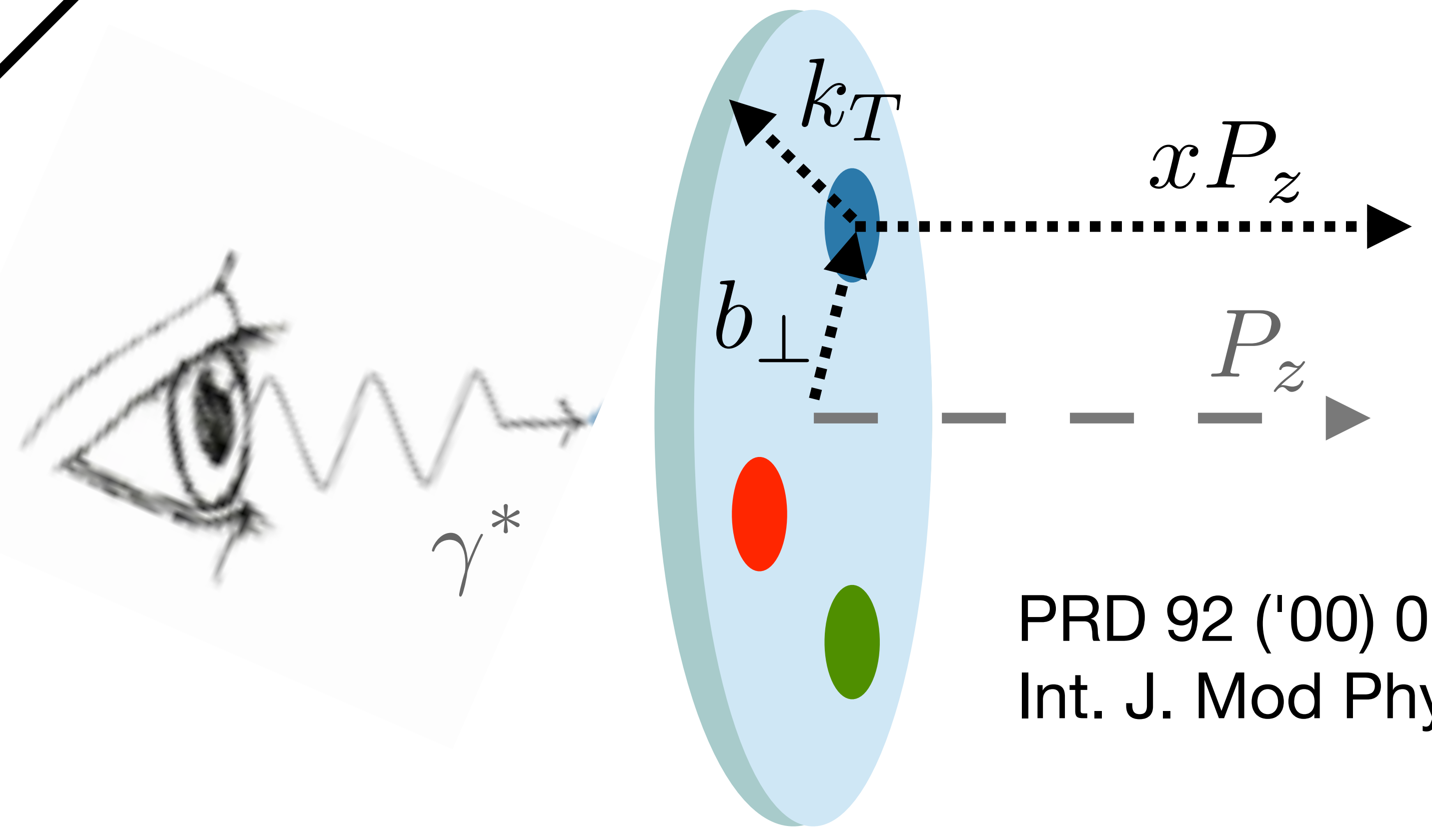
Exclusive quarkonia in UPCs

Probing nucleons and nuclei

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2\vec{b}_\perp$ → transverse-momentum dependent PDFs (TMDs)

$\int d^2\vec{k}_T$ → impact-parameter dependent distributions



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Fourier transform ↓

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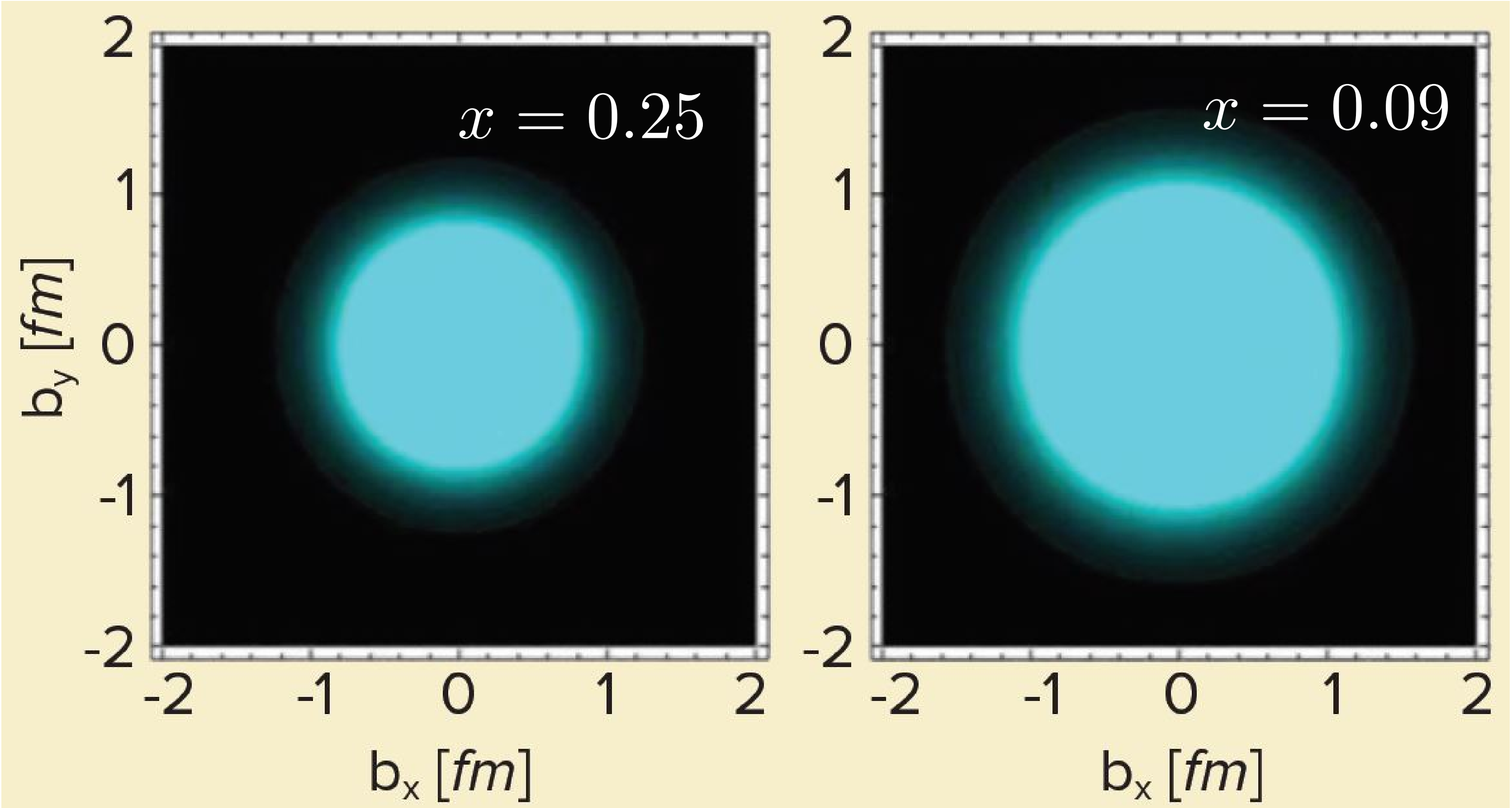

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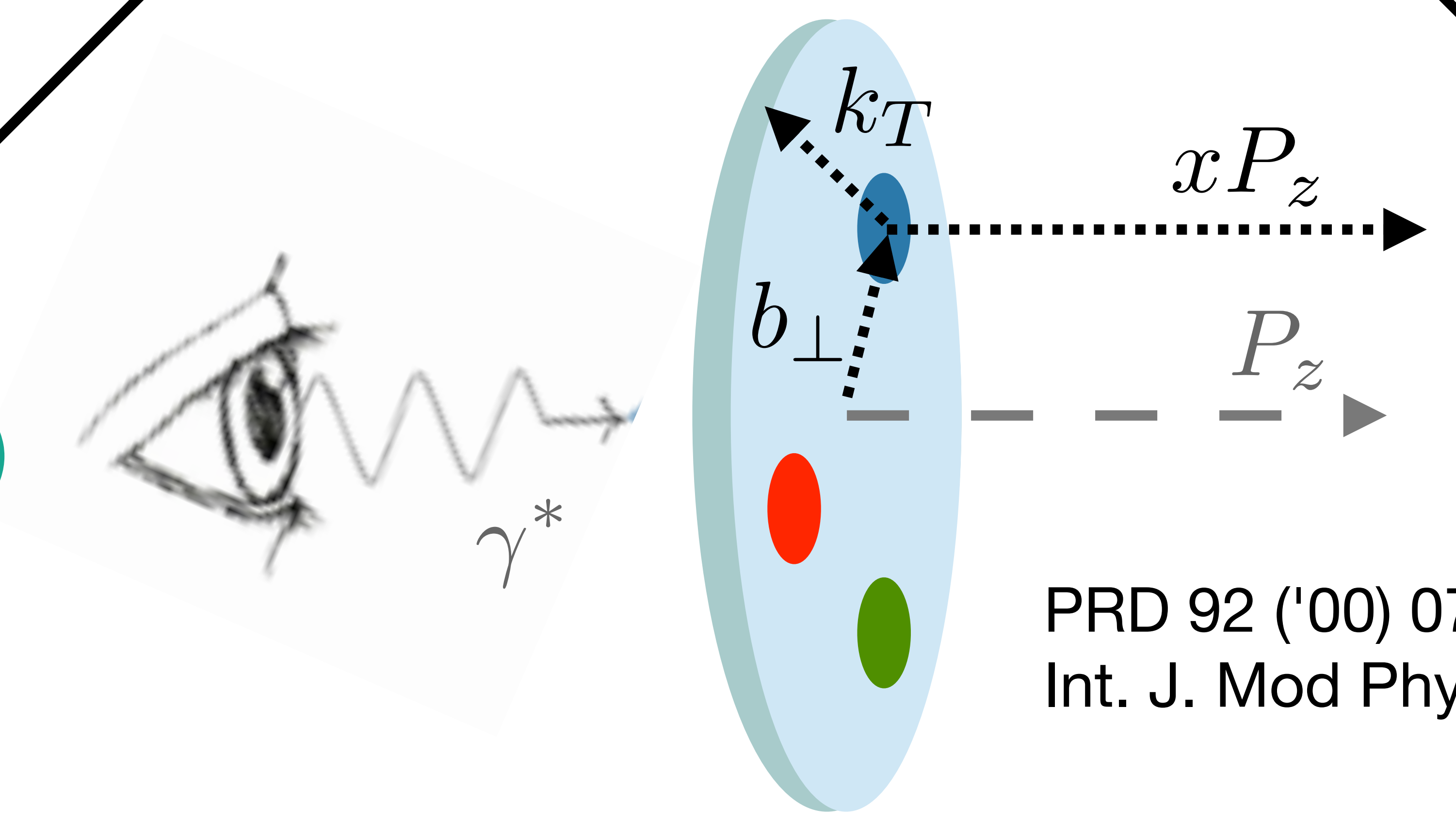


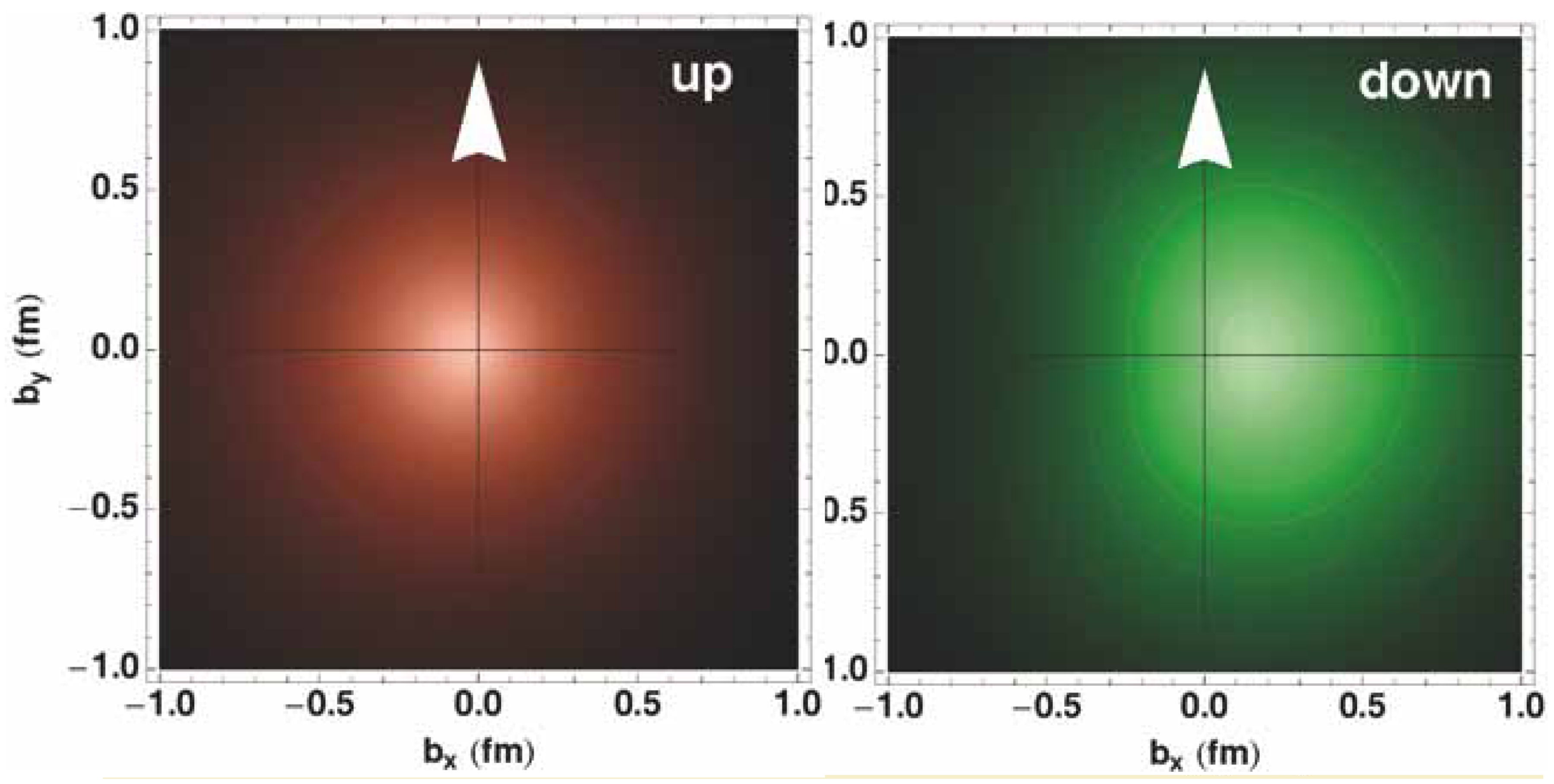
$\int d^2\vec{k}_T$

impact-parameter dependent distributions

Fourier transform

generalised parton distributions (GPDs)

PRD 92 ('00) 071503
Int. J. Mod Phys. A 18 ('03) 173



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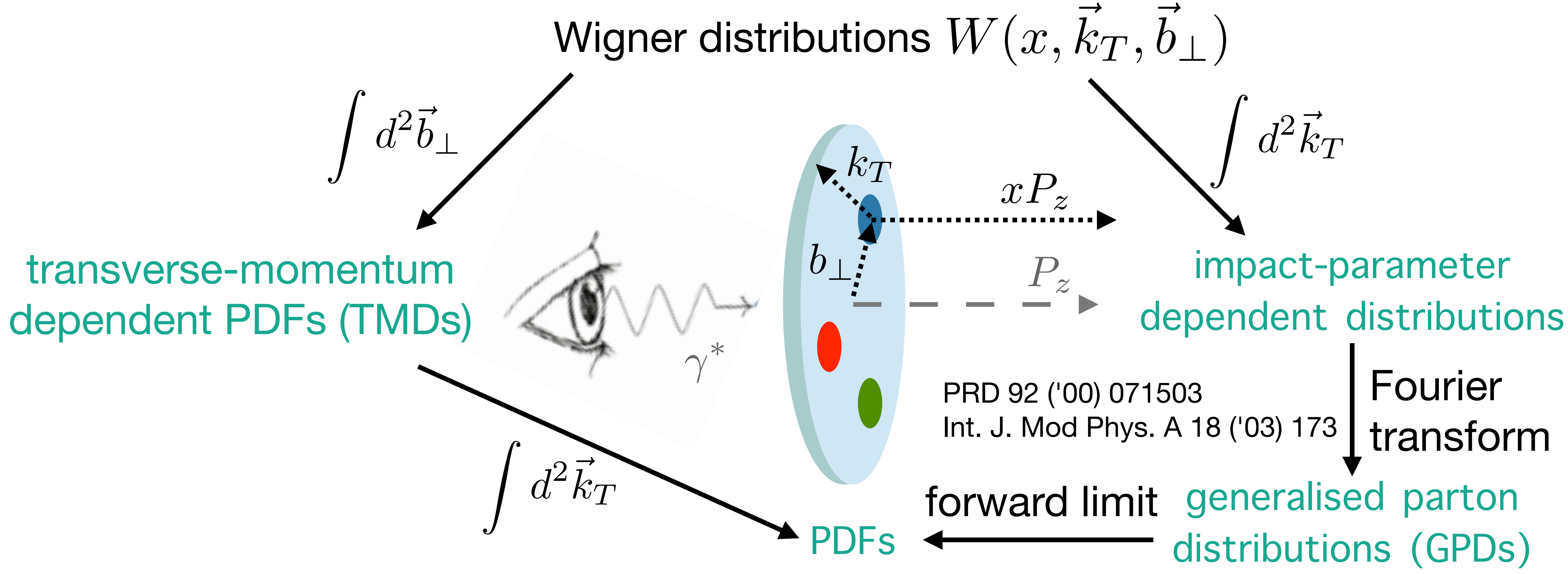

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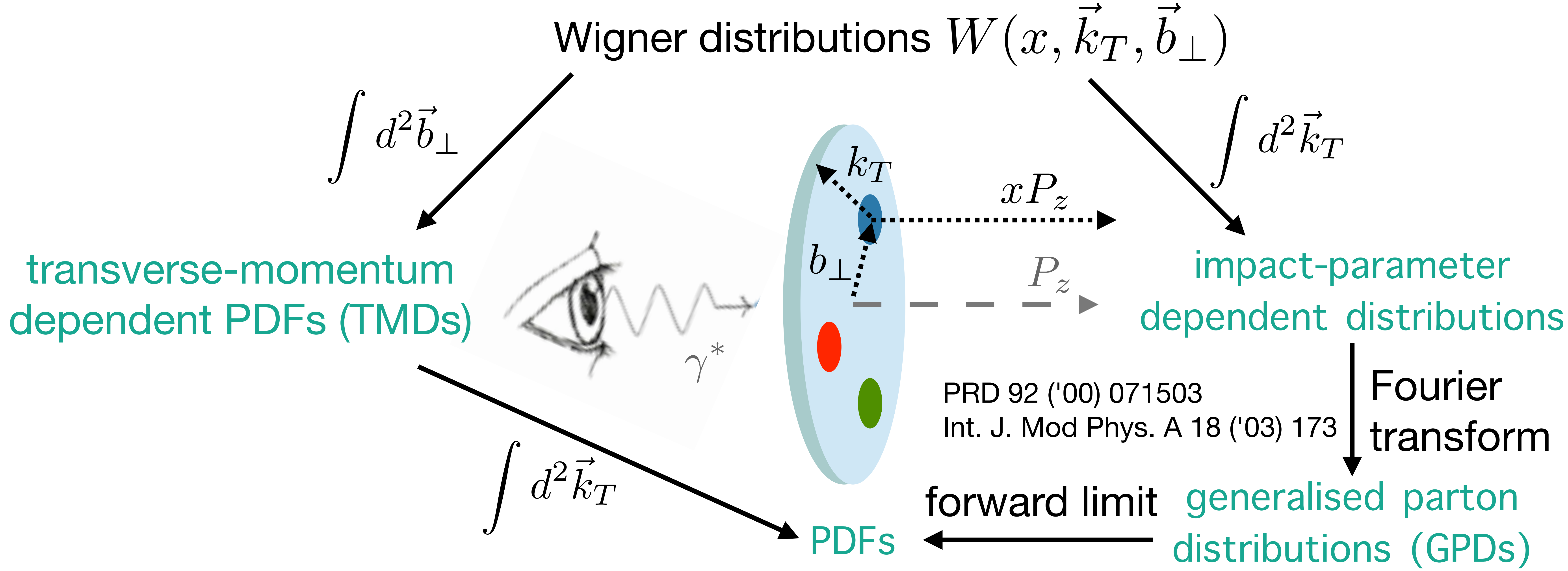
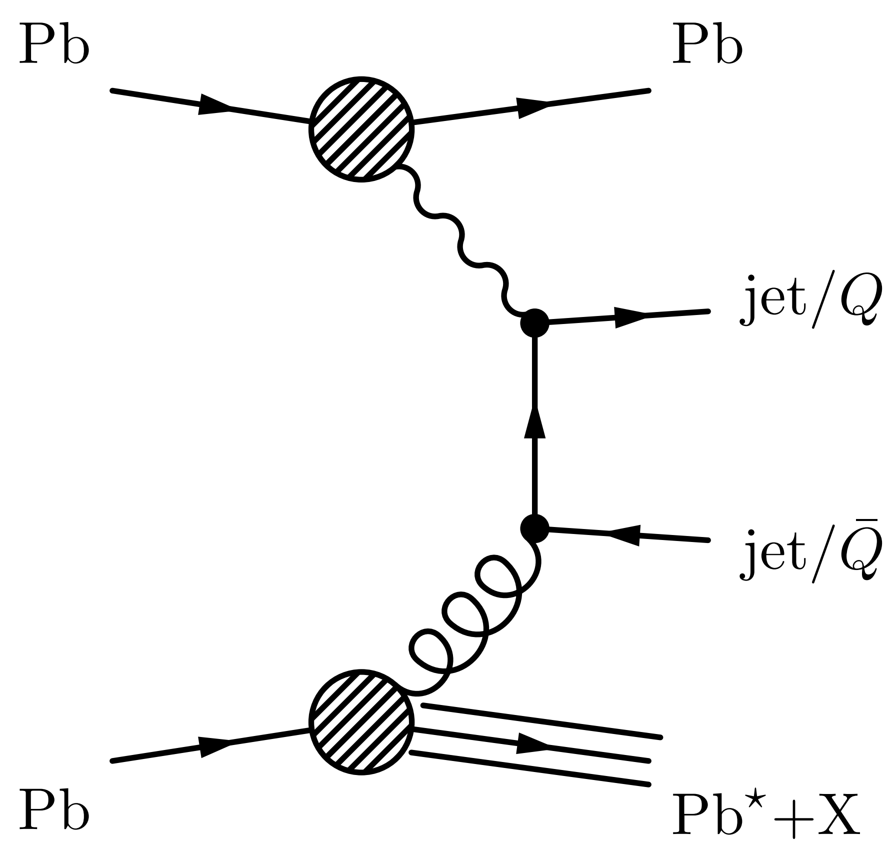
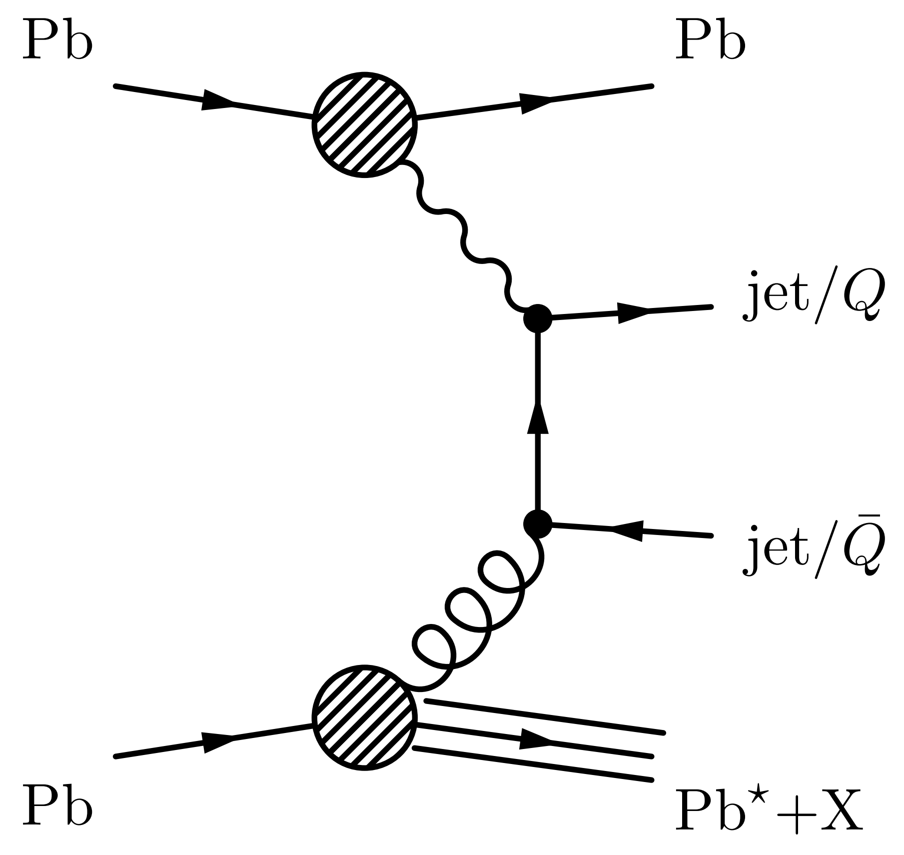




Dijets

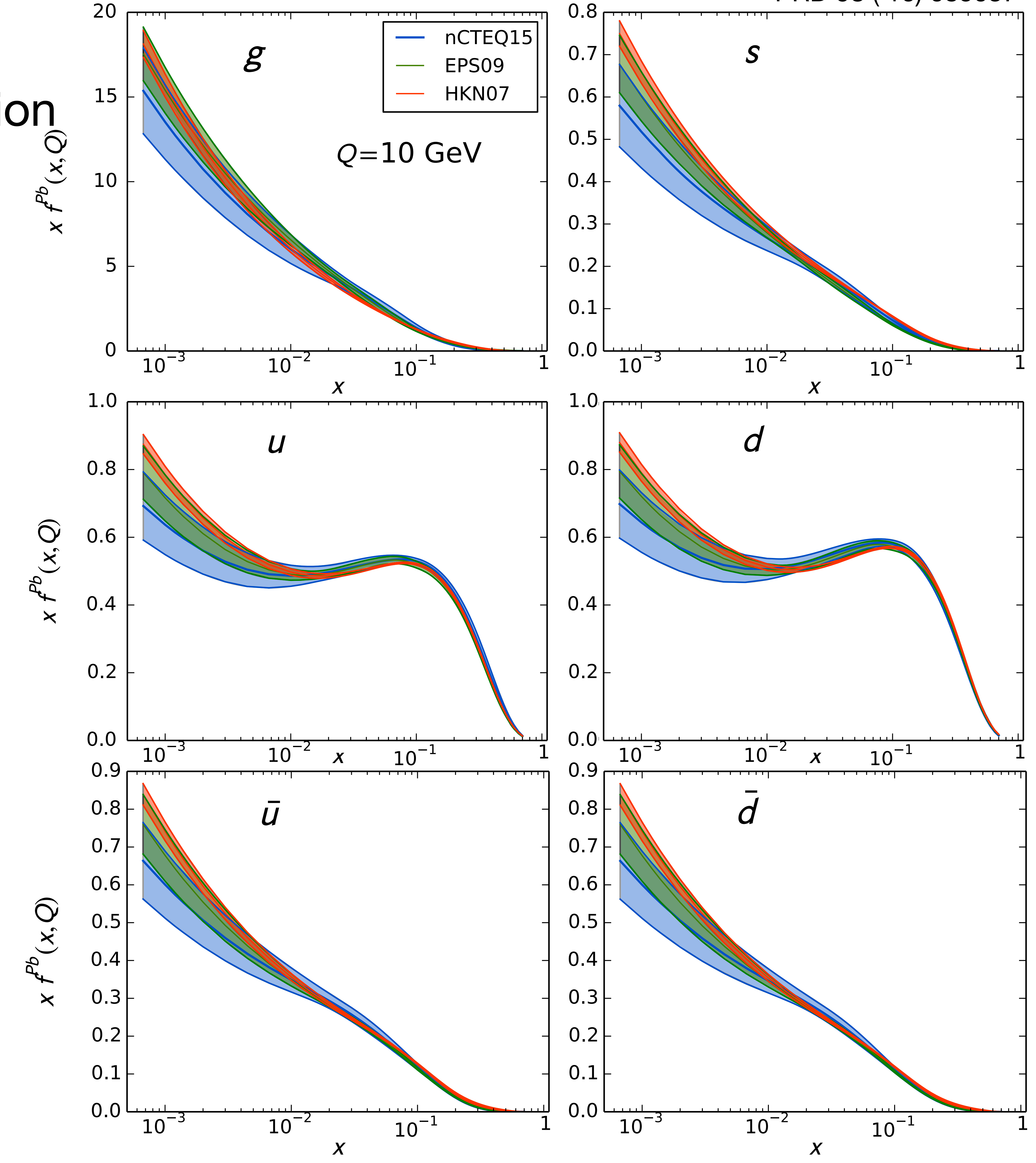


Dijets in photoproduction on Pb

- Access to nuclear PDFs at low x_B, through photon-gluon fusion

  ⟶ constrain nuclear PDFs, where uncertainties are large

PRD **93** ('16) 085037



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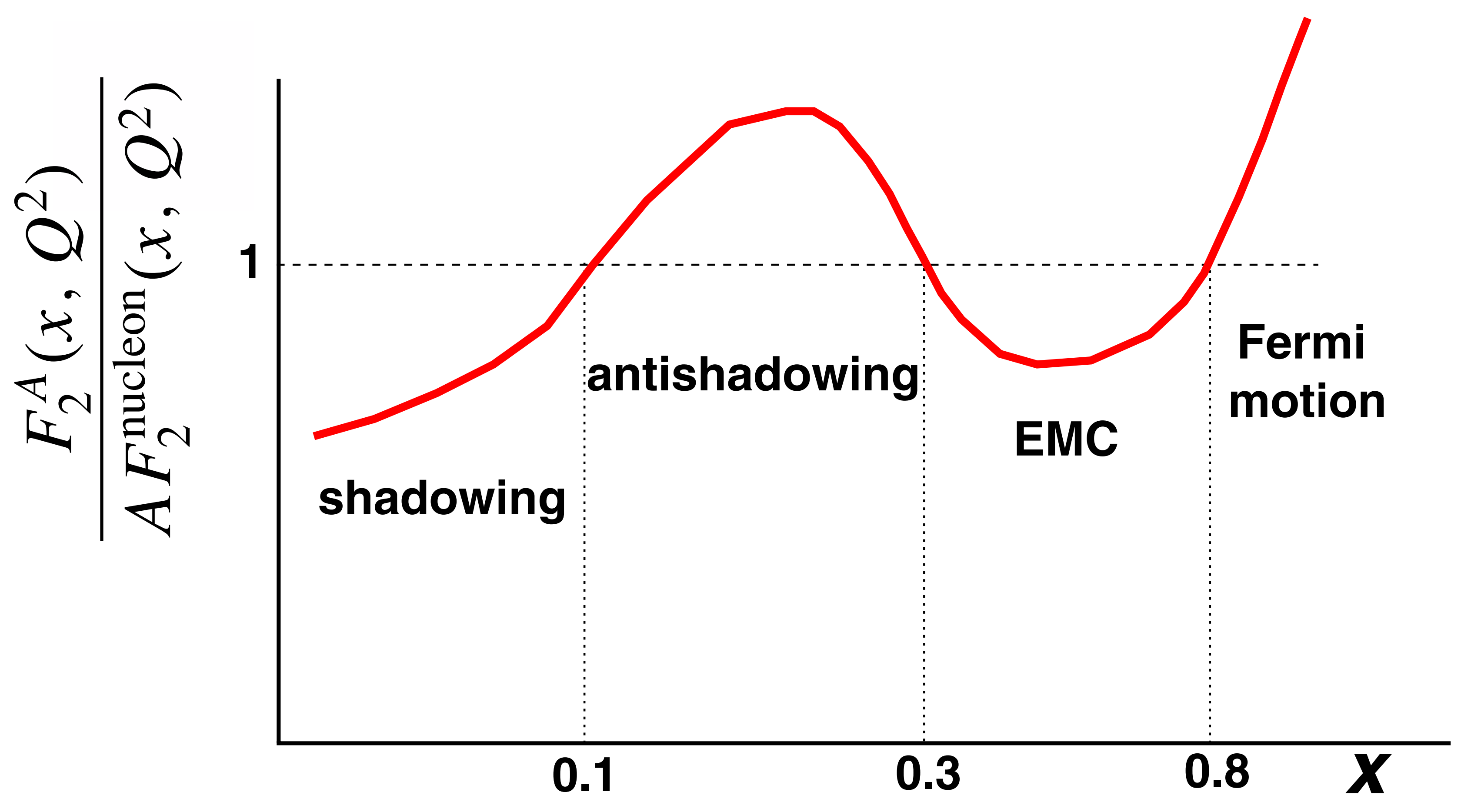

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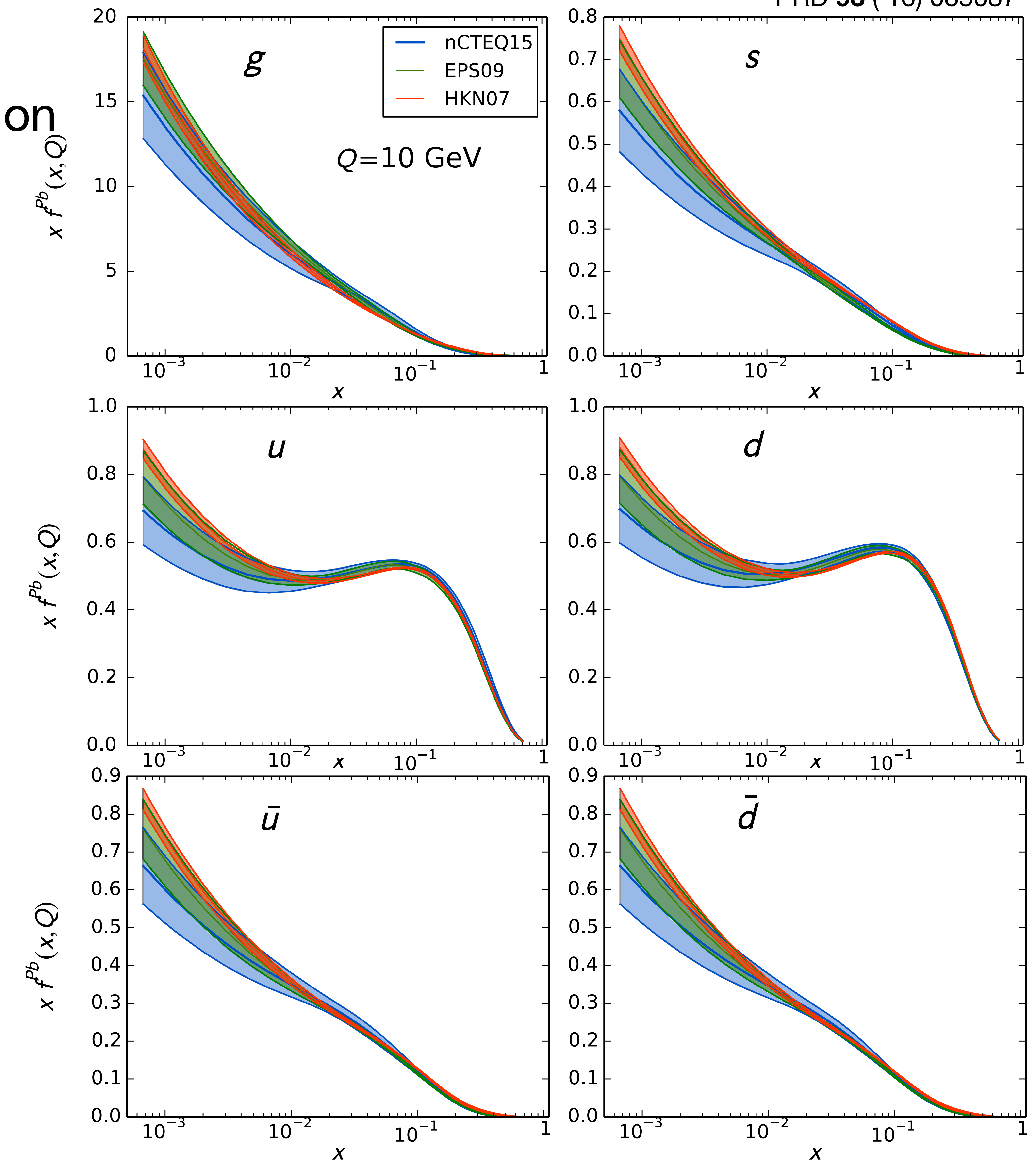

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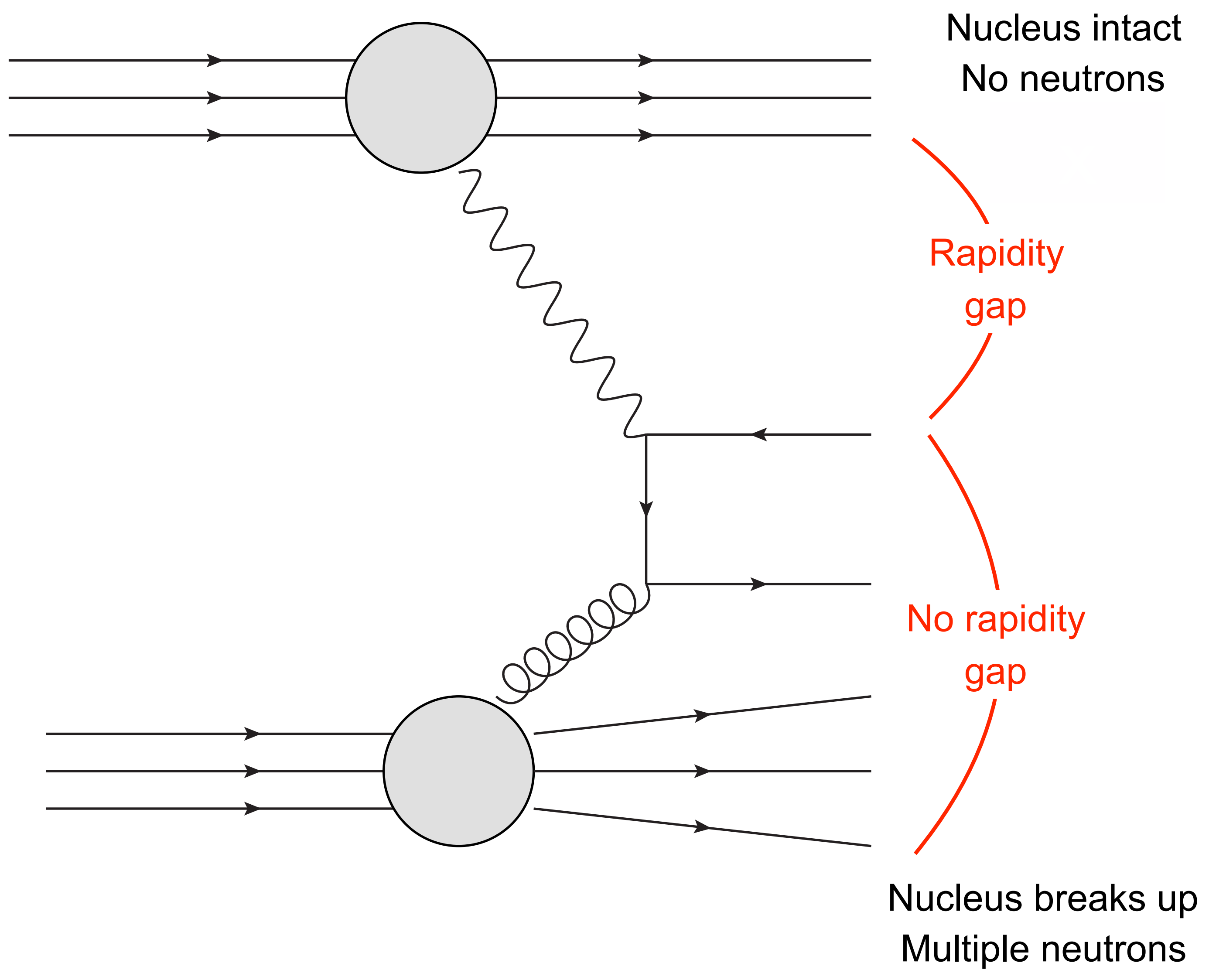

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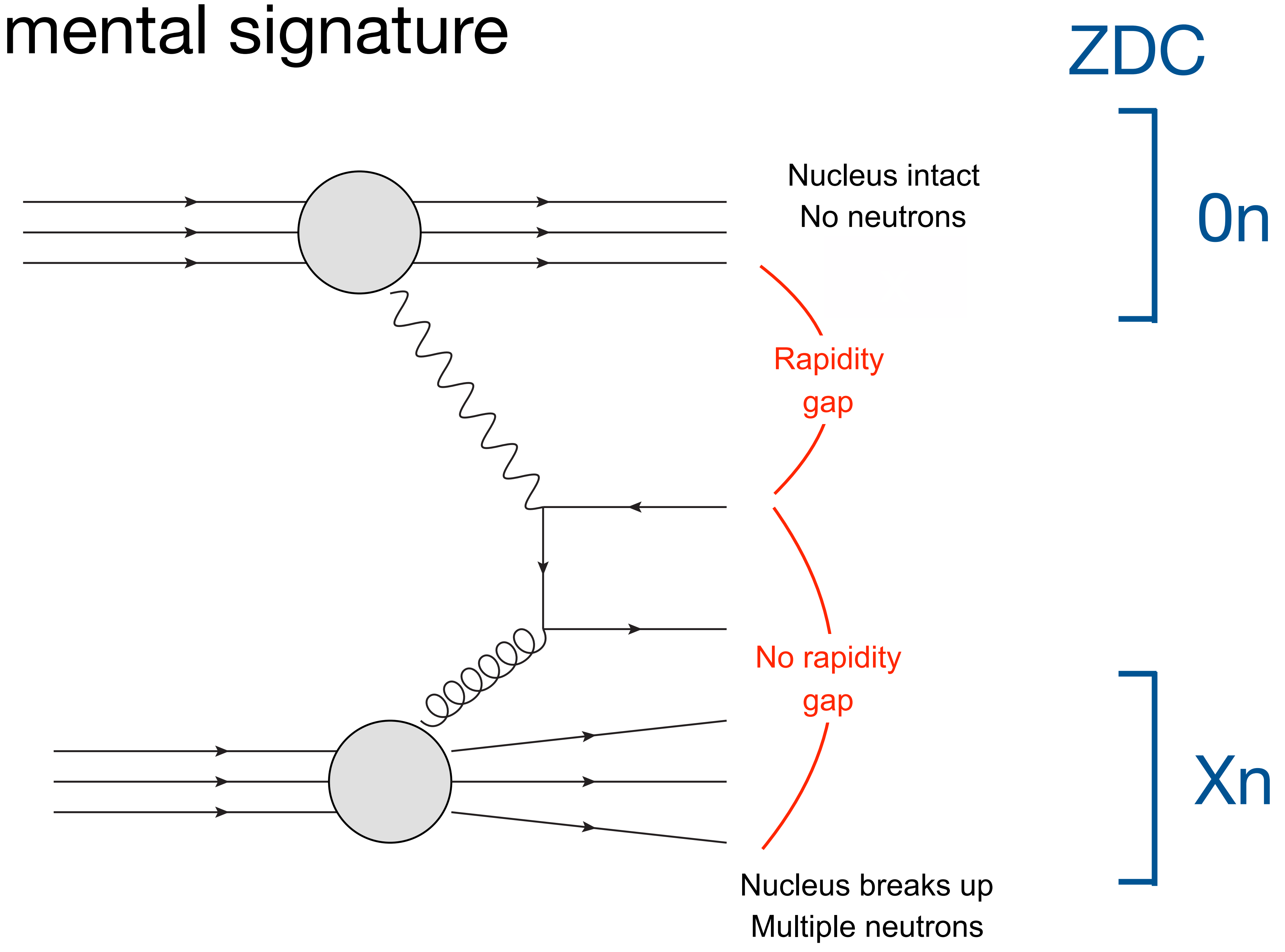

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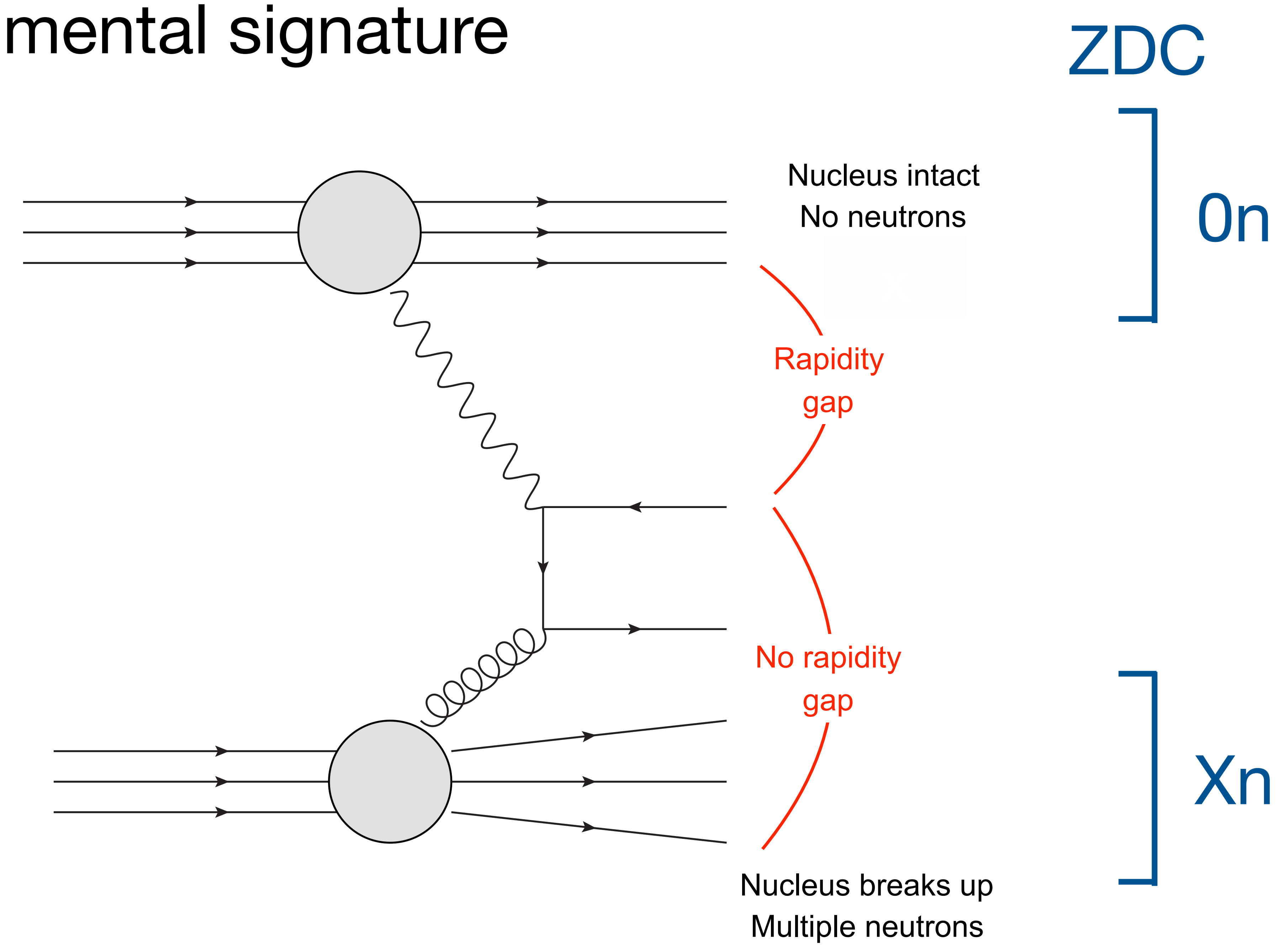
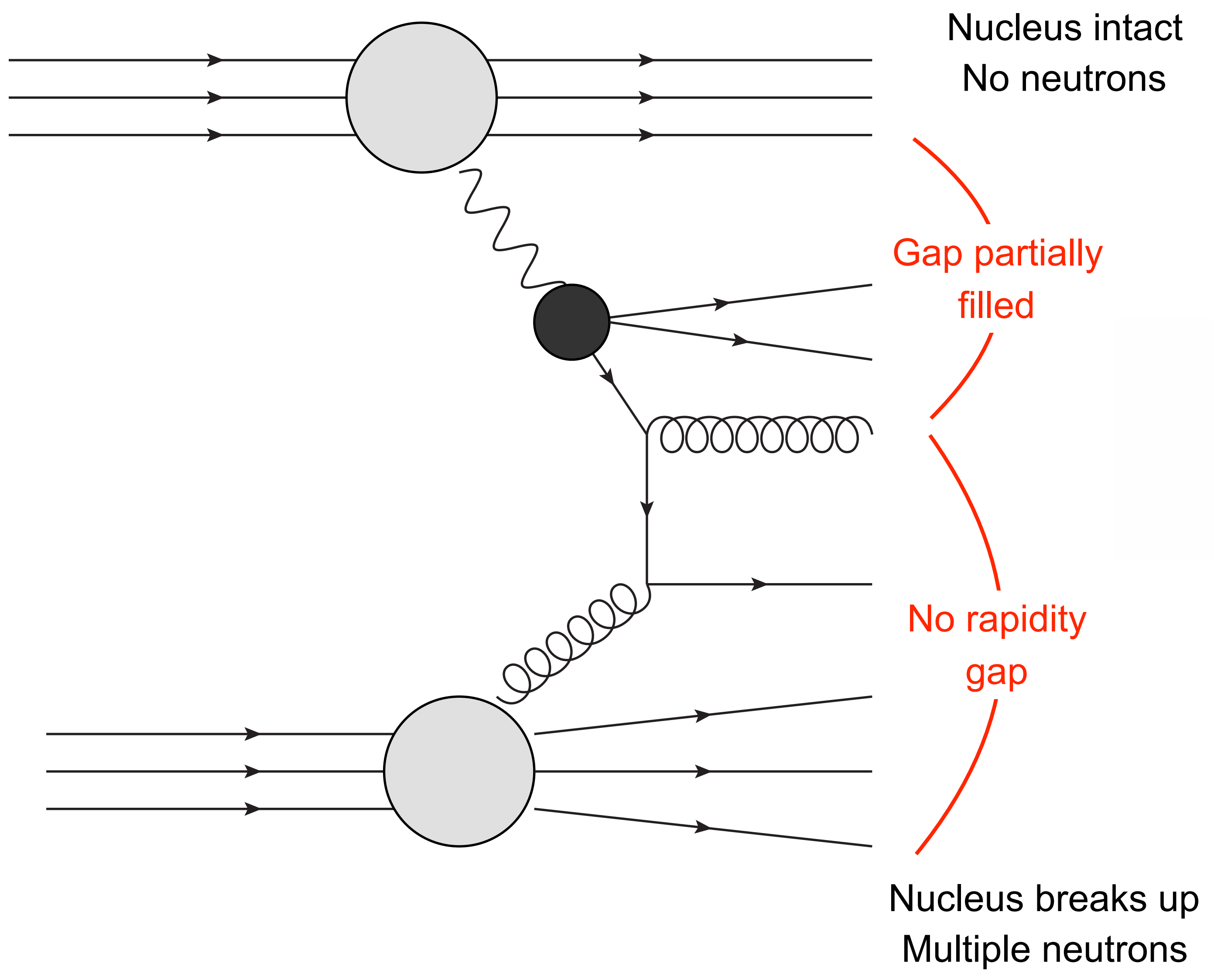


direct photon



resolved photon

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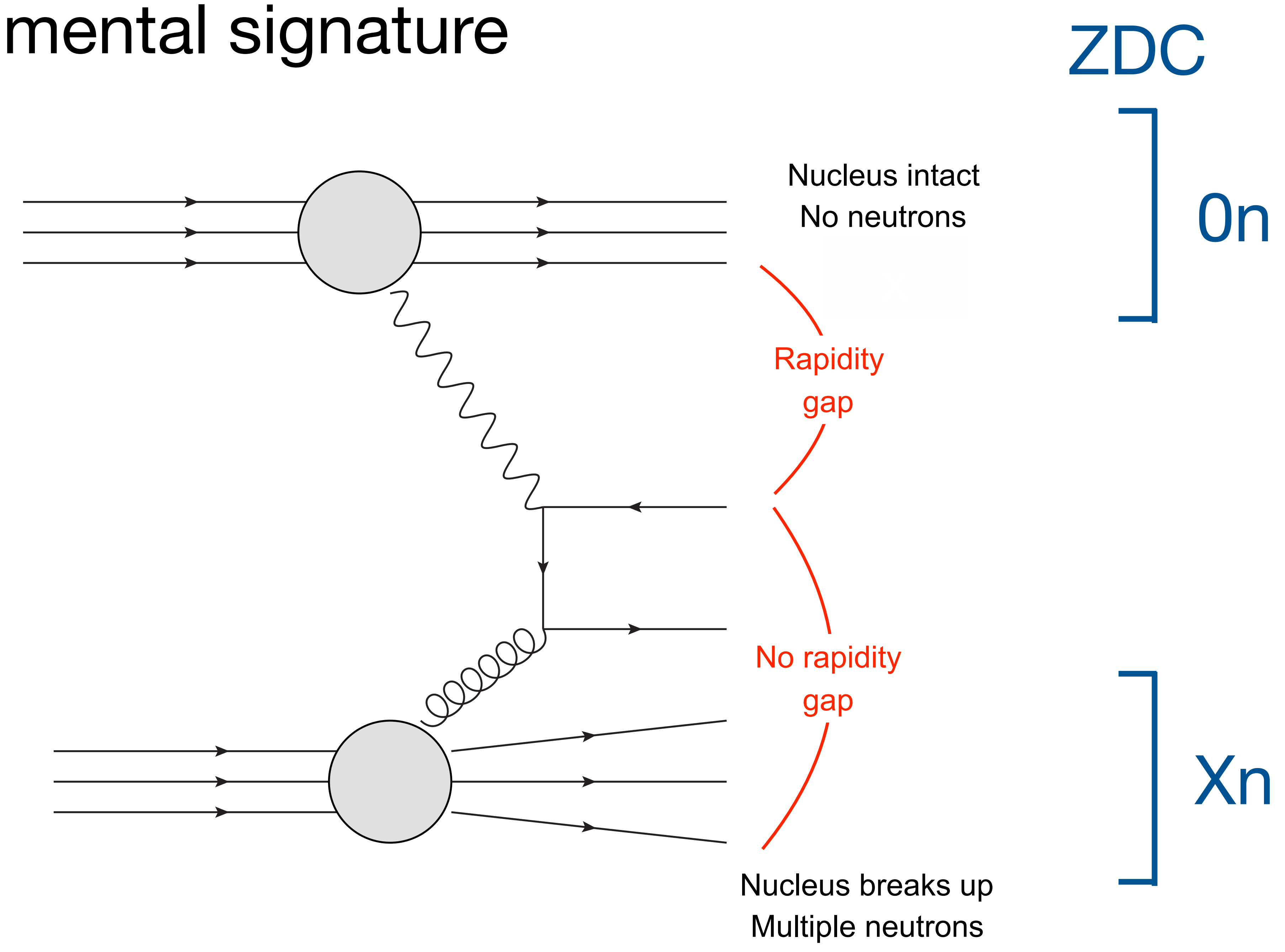

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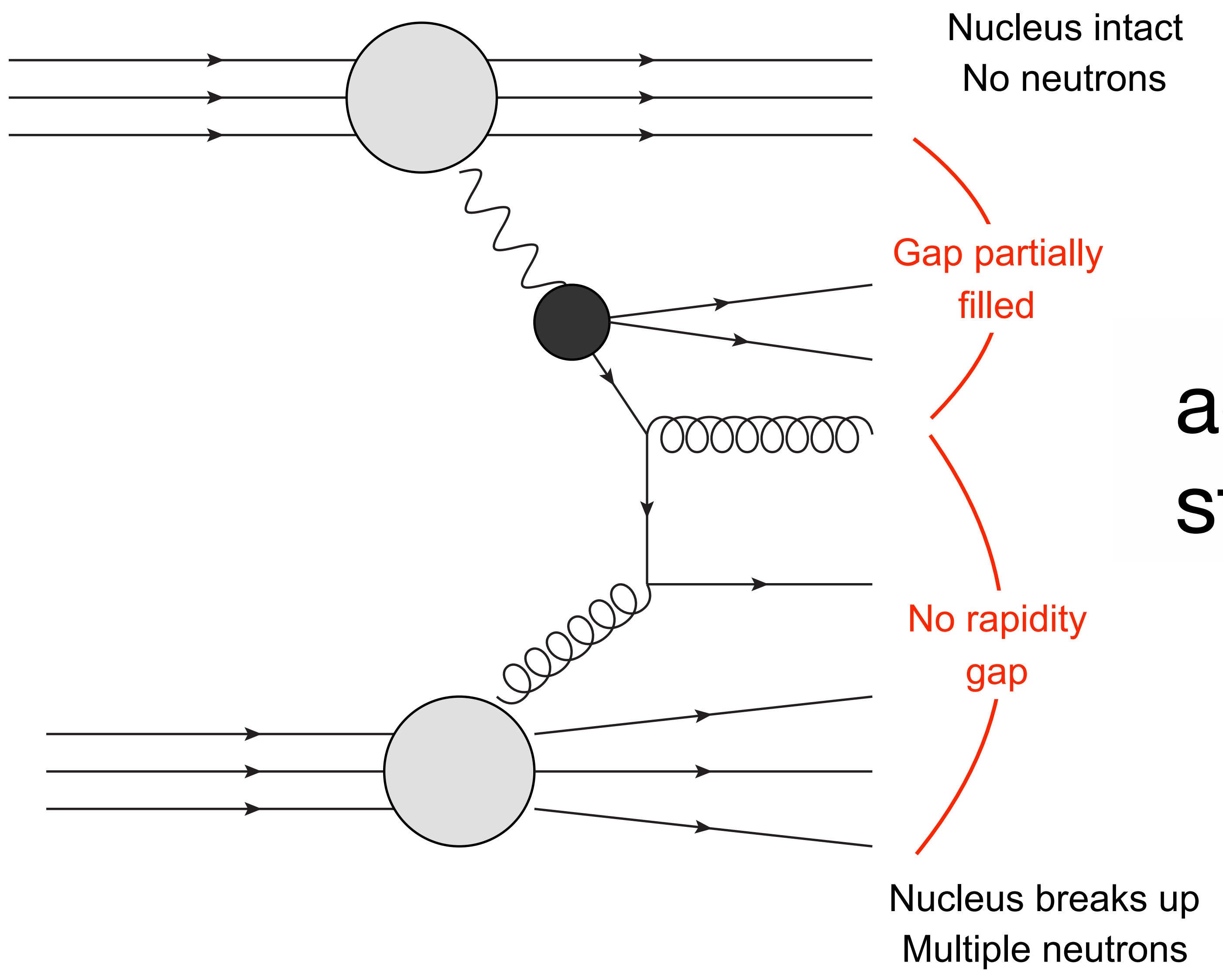

access to partonic structure of photon!

resolved photon

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- measurement:
  - ATLAS preliminary: ATLAS-CONF-2017-011

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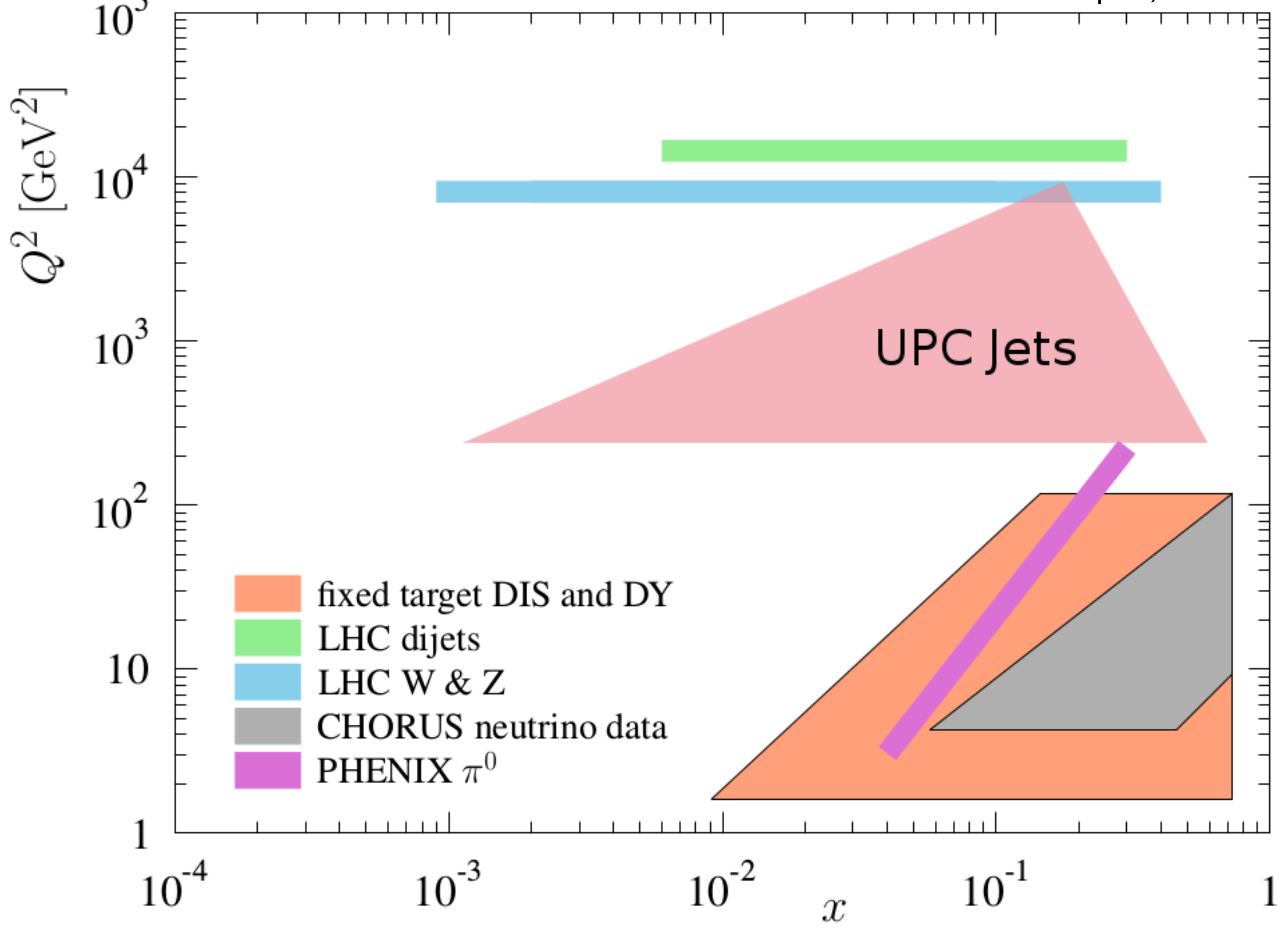
talk Oldrich Kepka, DIS'17



ATLAS measurement

- PbPb at $\sqrt{s_{NN}} = 5.02$ TeV; $\mathscr{L}$=0.38 nb^{-1}
- at least 2 jets
- $p_{T,\text{leading jet}} > 20$ GeV; $p_{T,\text{subleading jet}} > 15$ GeV
- $|\eta_{jet}|<4.4$
- $H_T>40$ GeV; $M_J>35$ GeV
- # neutrons in ZDCs: 0nXn
- $\Sigma\Delta\eta>2$ in 0n (photon) direction; $\Sigma\Delta\eta<3$ in Xn (break-up) direction

$$H_T = \sum_{\text{jet}} p_{T,jet} \xrightarrow{2\to 2} 2Q$$

$$M_J = \sqrt{\left(\sum_{\text{jet}} E_{\text{jet}}\right)^2 - \left|\sum_{\text{jet}} \vec{p}_{\text{jet}}\right|^2}$$

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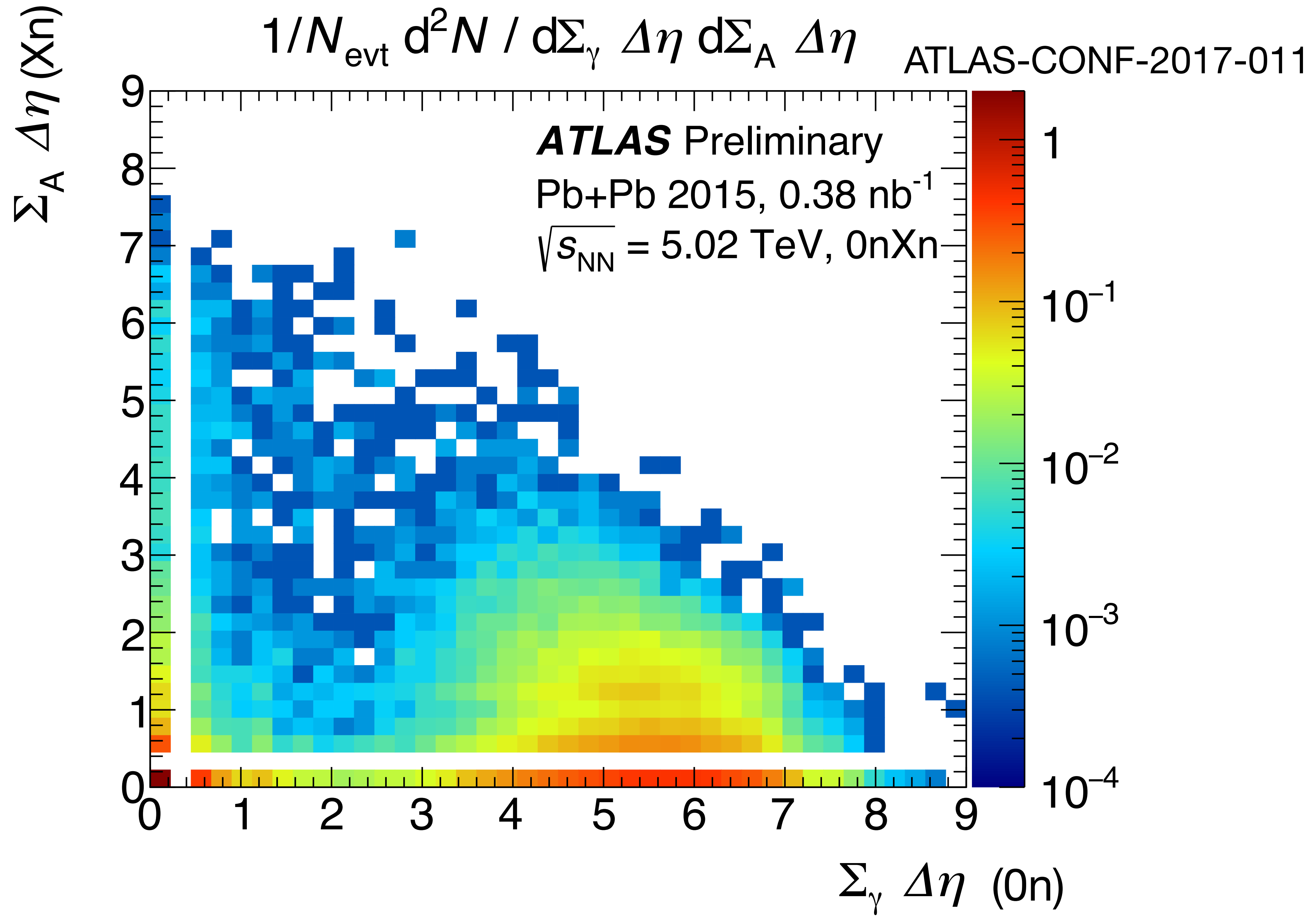

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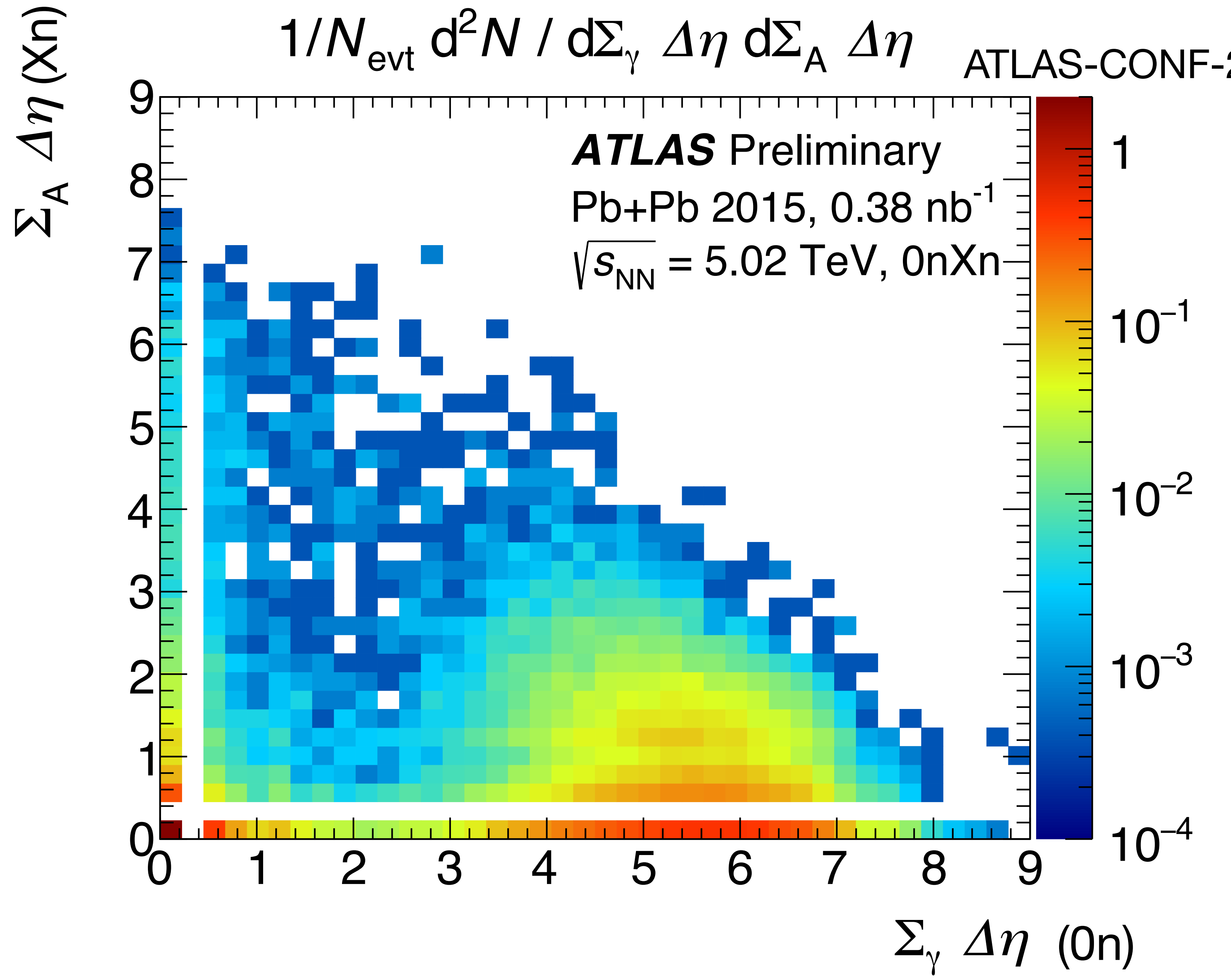
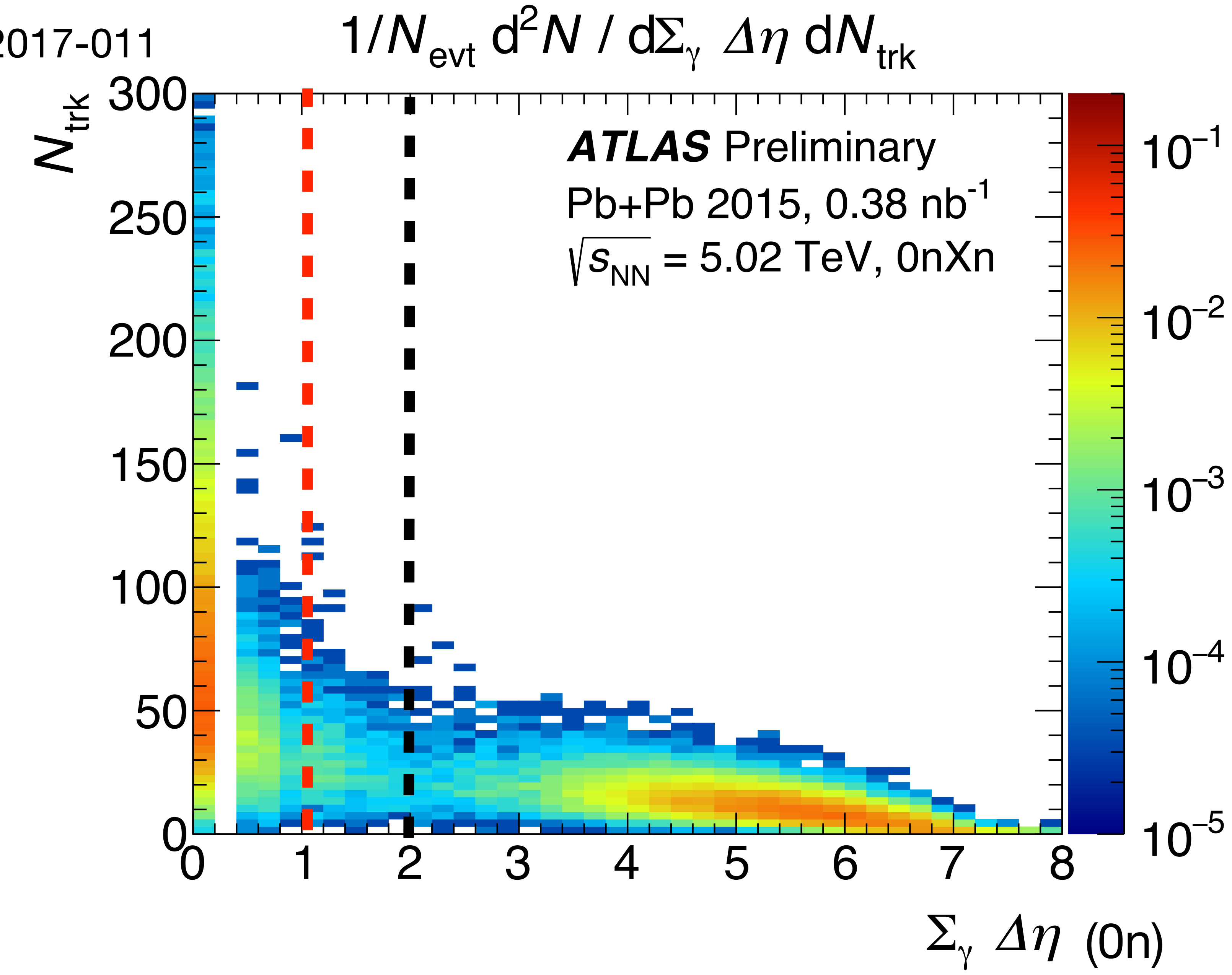
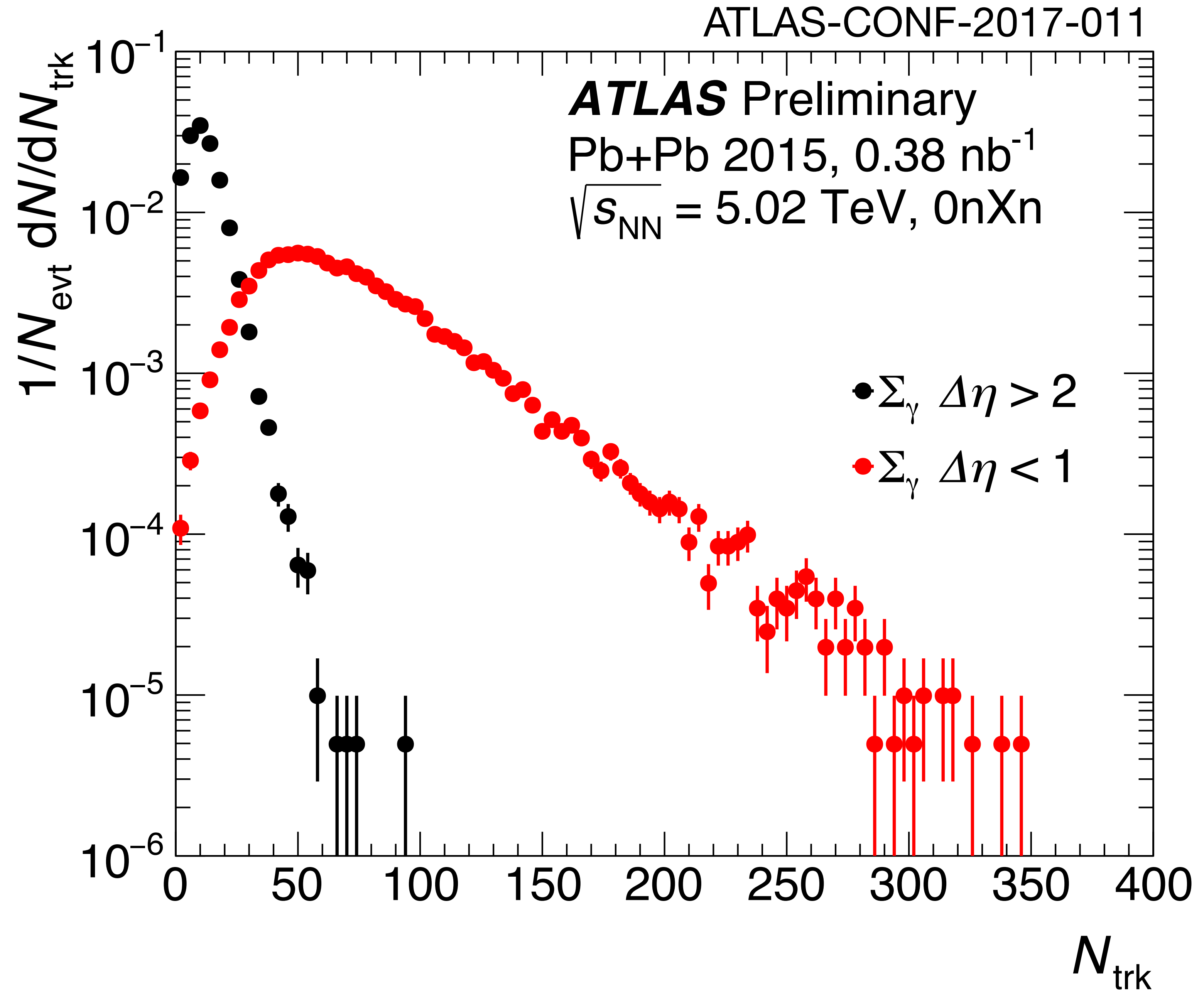




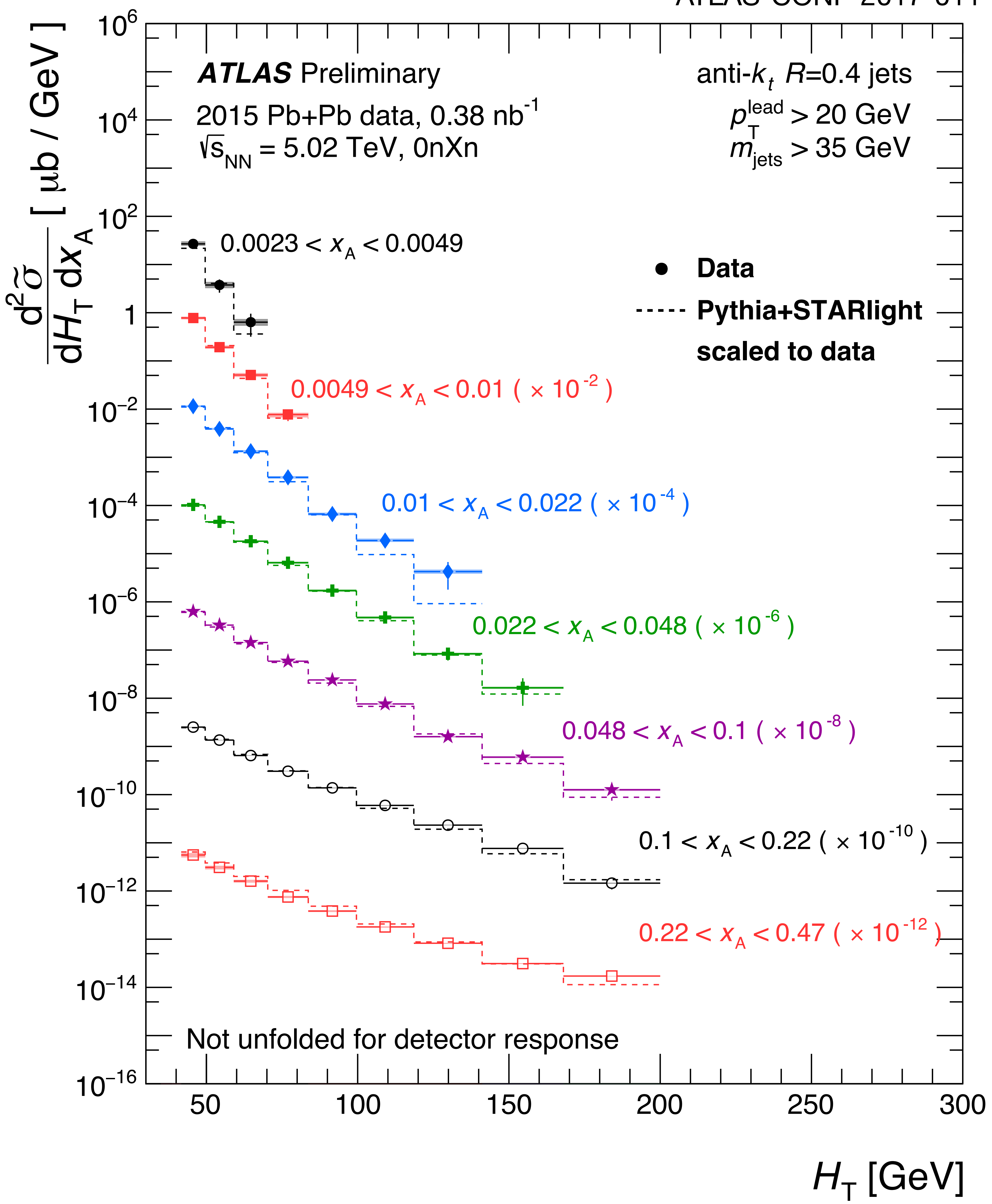


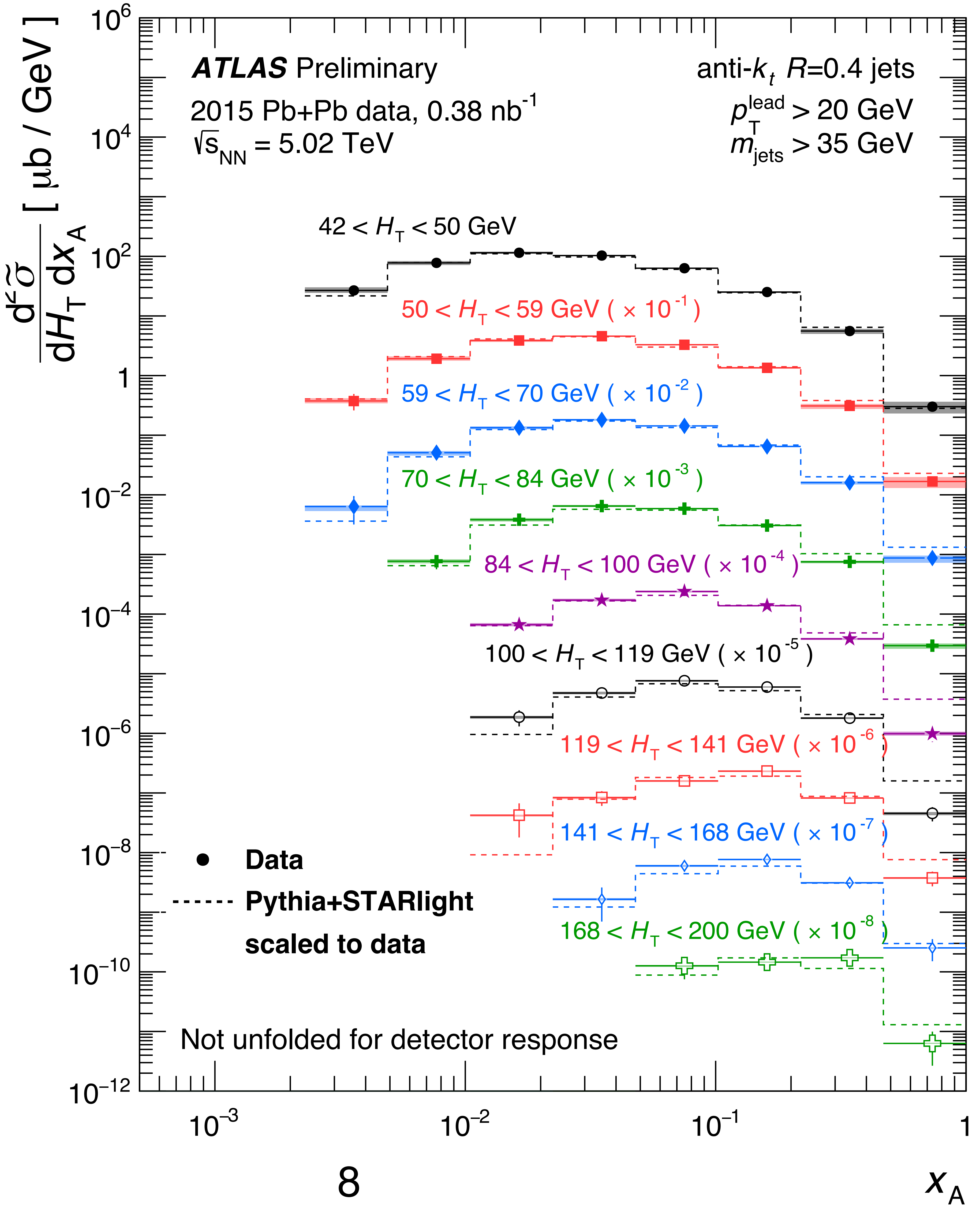
ATLAS measurement: results

$$y_J = \frac{1}{2}\ln\left(\frac{\sum_{\text{jet}} E_{\text{jet}} + \sum_{\text{jet}} p_{z,\text{jet}}}{\sum_{\text{jet}} E_{\text{jet}} - \sum_{\text{jet}} p_{z,\text{jet}}}\right)$$

$$x_A = \frac{M_J}{\sqrt{s}} e^{-y_J} \xrightarrow{2\to 2} \text{parton energy fraction}$$

ATLAS-CONF-2017-011

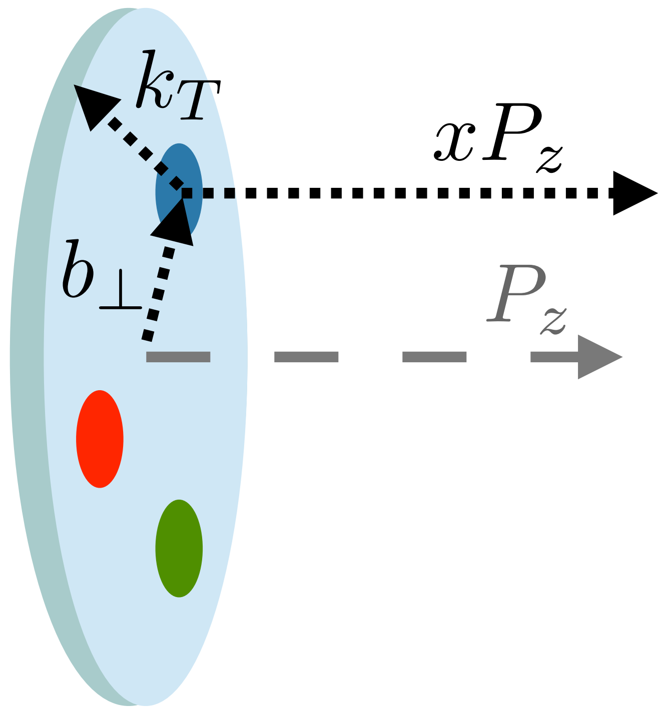




- STARlight: photon flux
- PYTHIA: γ^*+p
  - CTEQ6L1 proton PDF
  - SaS 1D photon PDFs
  - no nuclear modifications

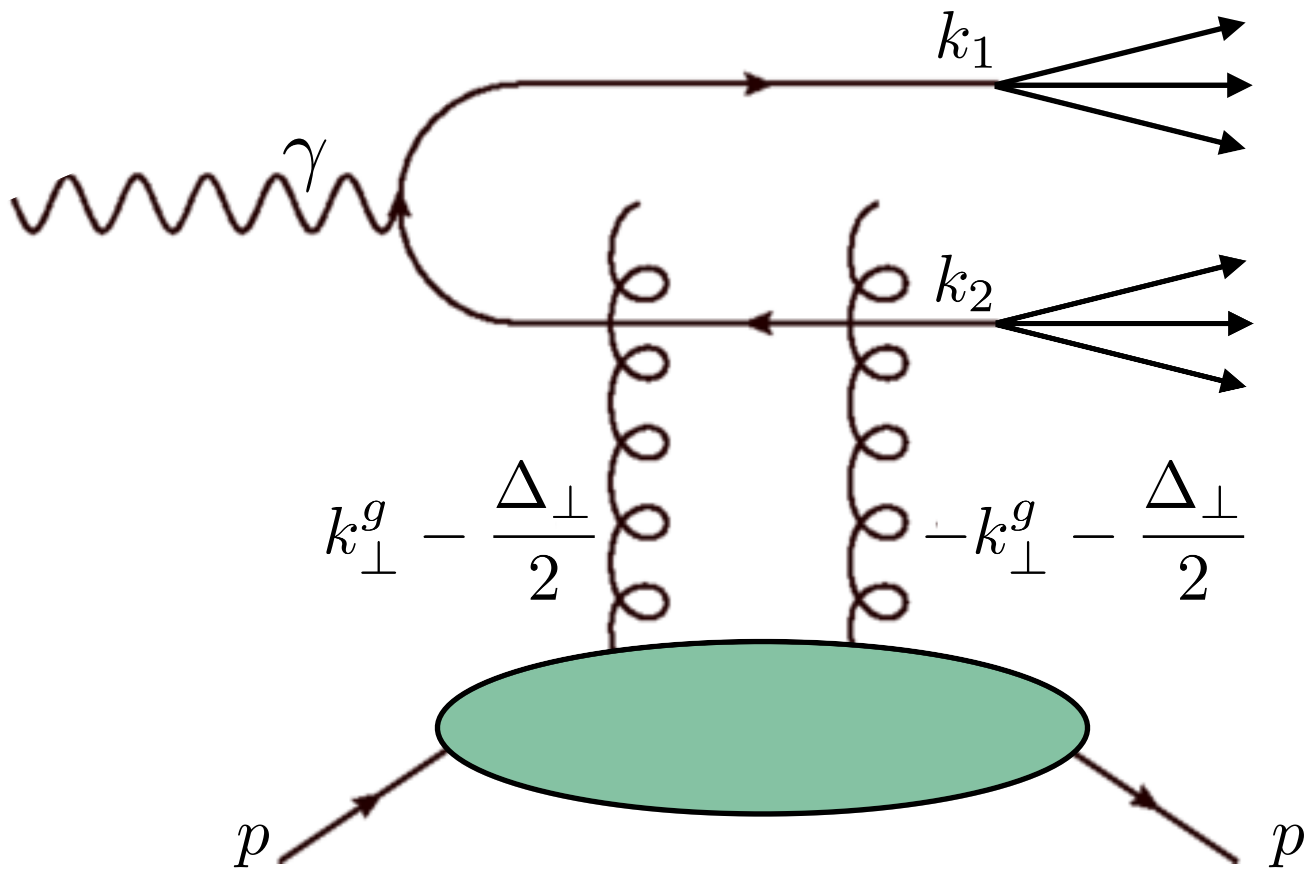
- General good agreement of data and MC
- Proof of principle that photoproduction of jets can be studied in UPCs at LHC!

Exclusive dijets in photoproduction



Gluons, small x

Y. Hatta et al., 116 (2016) 202301
Y. Hagiwara et al., PRD 95 (2017) 114032



- recoil proton momentum
  $$\vec{\Delta}_\perp = -(\vec{k}_{1\perp} + \vec{k}_{2\perp})$$
- relatif dijet momentum
  $$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{1\perp} - \vec{k}_{2\perp})$$
- back-to-back jets
  $$P_\perp \gg \Delta_\perp$$
  Q^2 small: $k_\perp \sim P_\perp$

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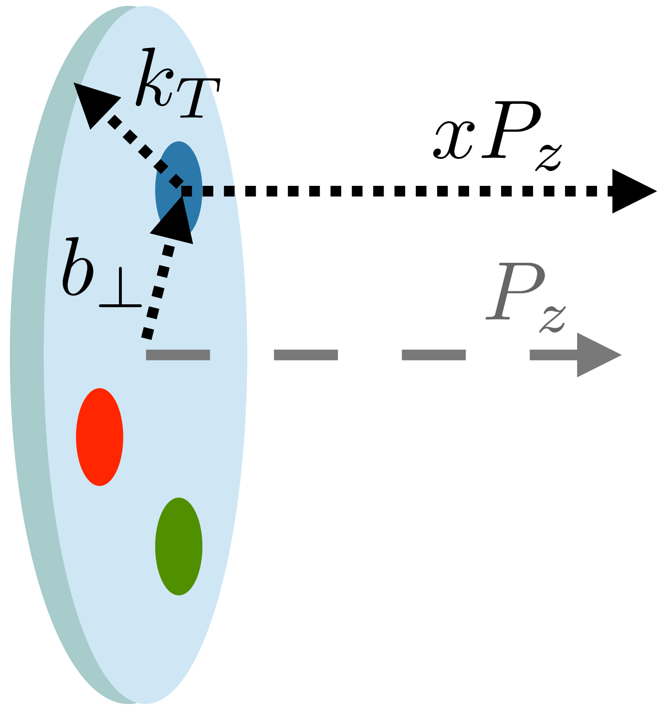

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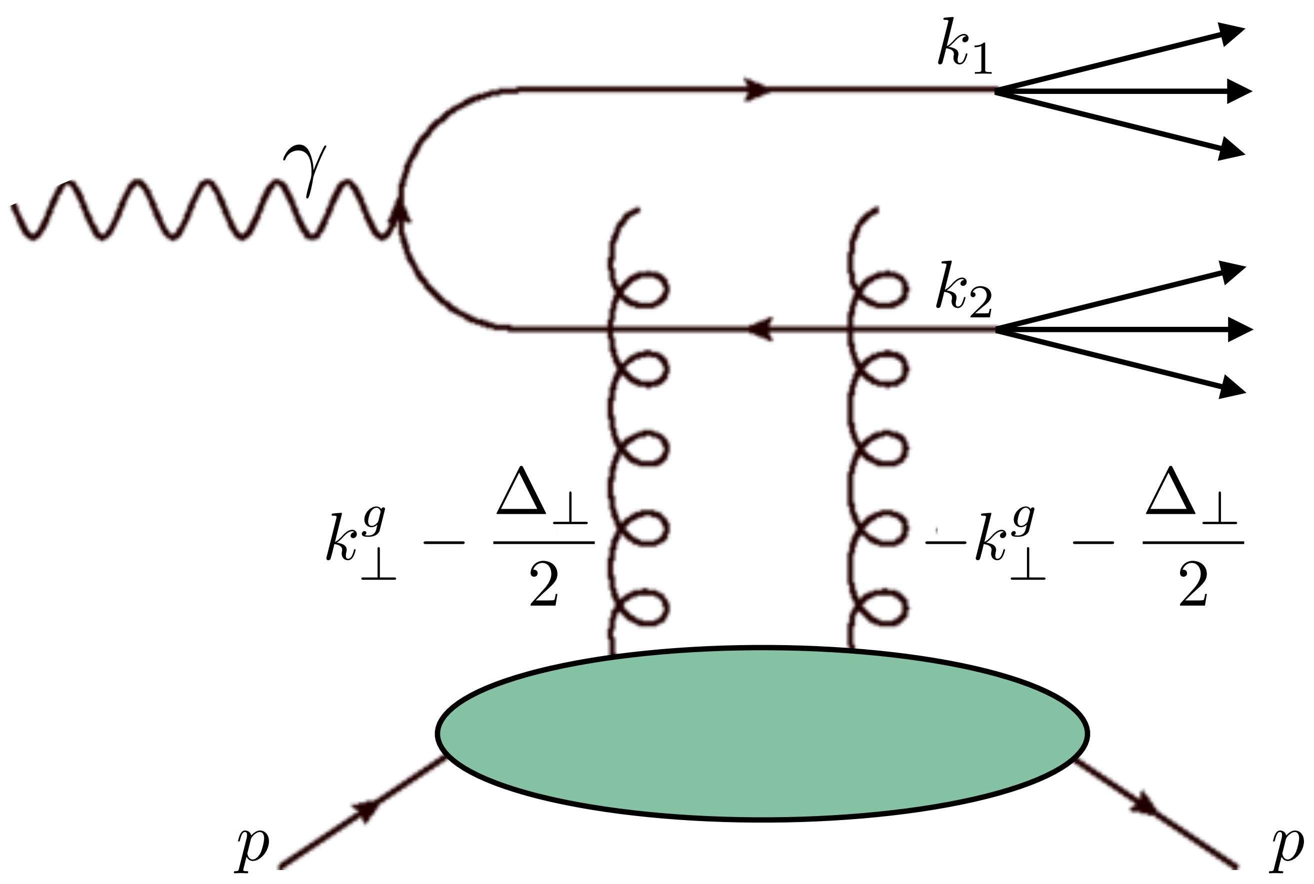

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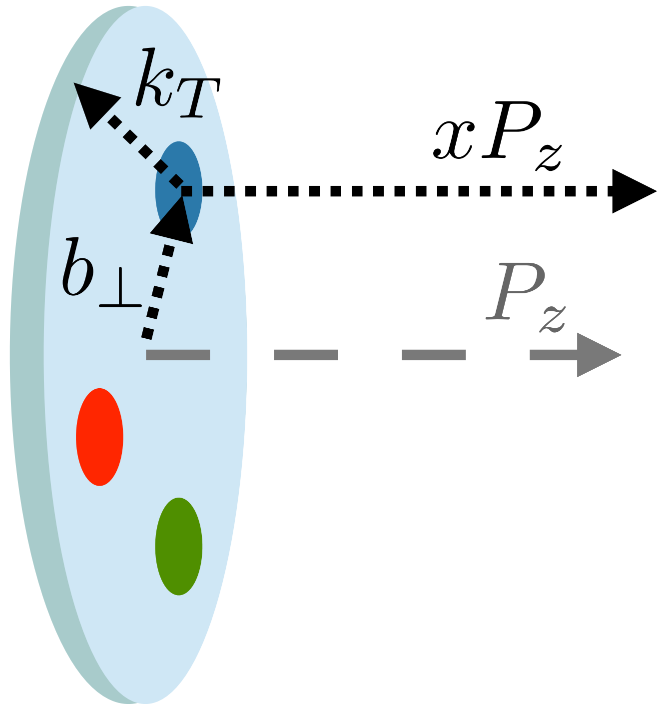
Q^2 small: $k_\perp \sim P_\perp$

small x

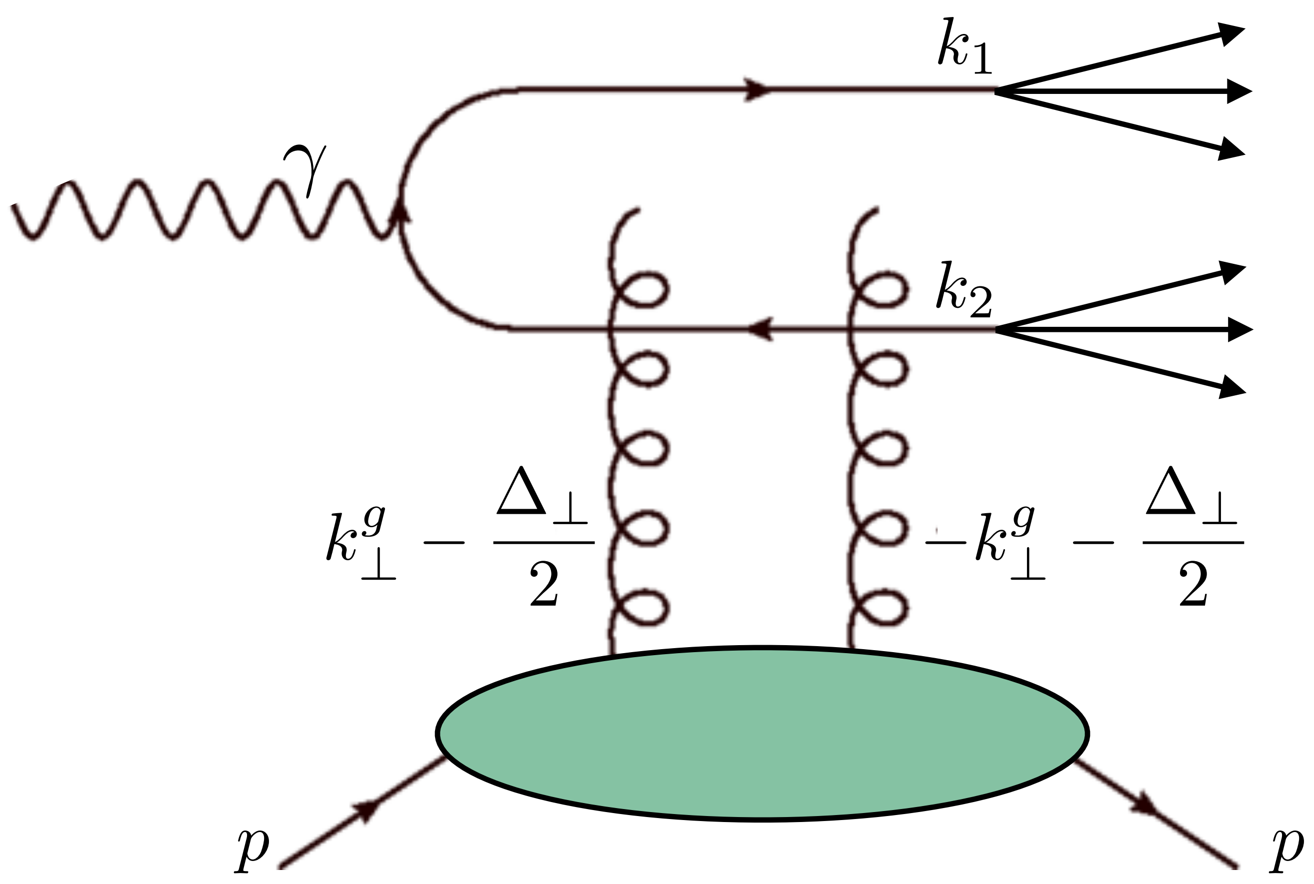
$$W^{DP}(x, \vec{k}_\perp, \vec{b}_\perp) = W_0^{DP}(x, k_\perp, b_\perp) + 2\, W_1^{DP}(x, k_\perp, b_\perp) \cos 2(\phi_{k_\perp} - \phi_{b_\perp}) + \ldots$$

Exclusive dijets in photoproduction



Y. Hatta et al., 116 (2016) 202301
Y. Hagiwara et al., PRD 95 (2017) 114032

Gluons, small x



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- back-to-back jets

$$P_\perp \gg \Delta_\perp$$

Q^2 small: $k_\perp \sim P_\perp$

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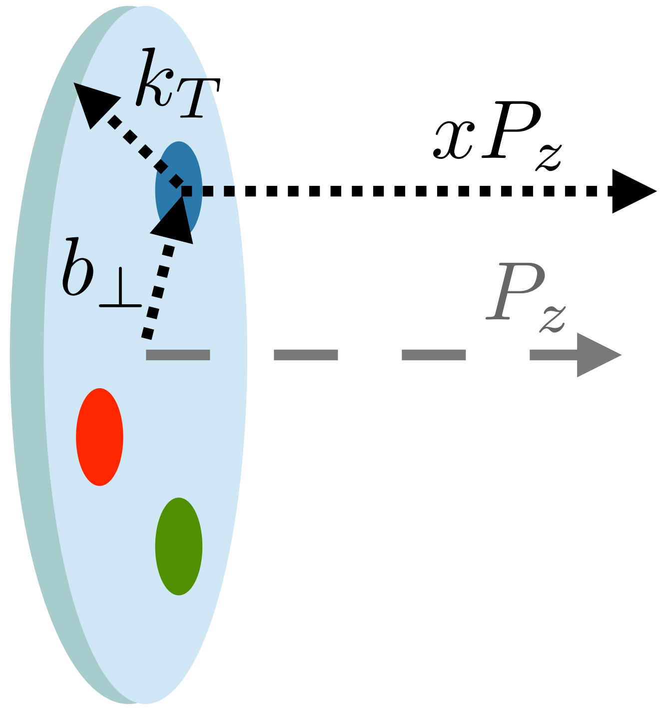

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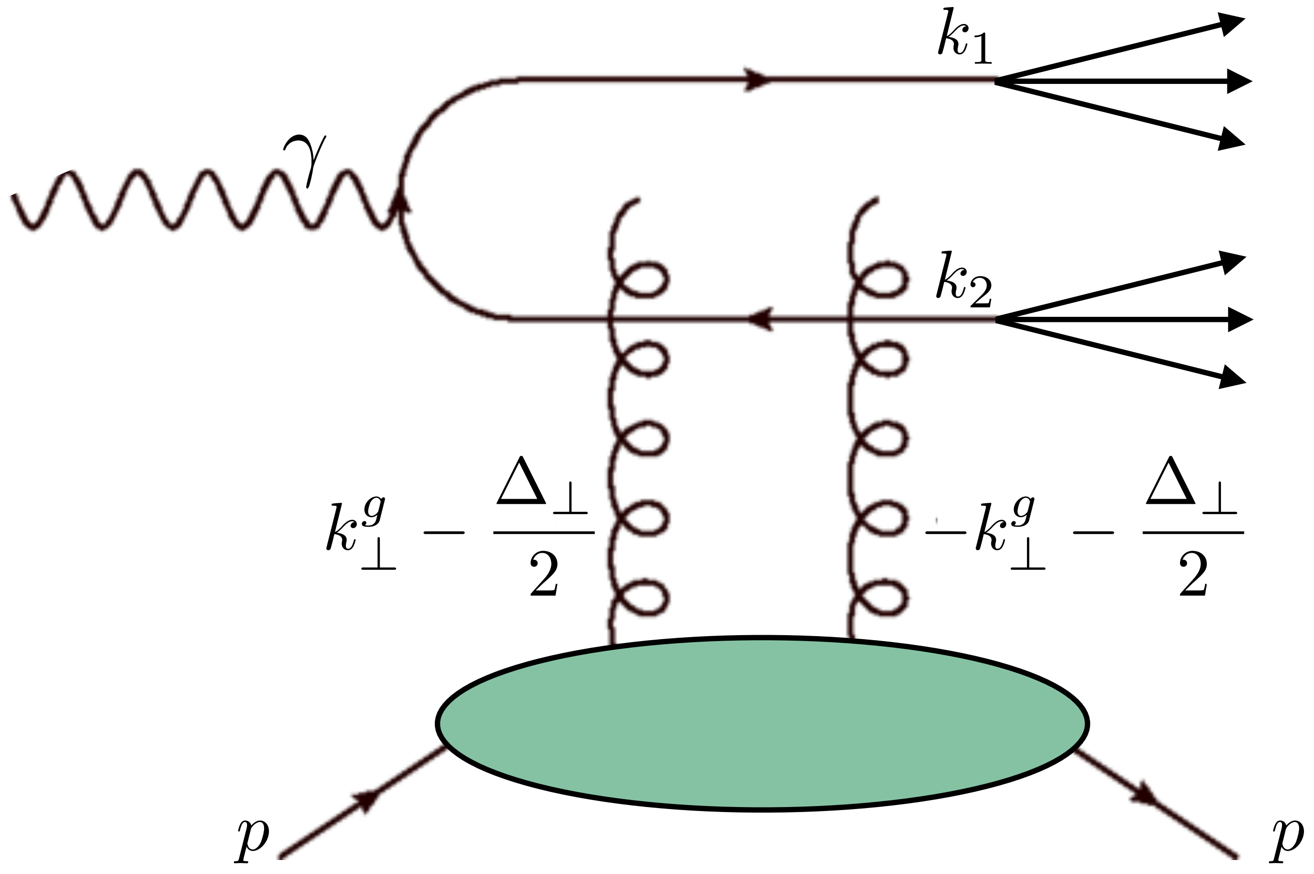

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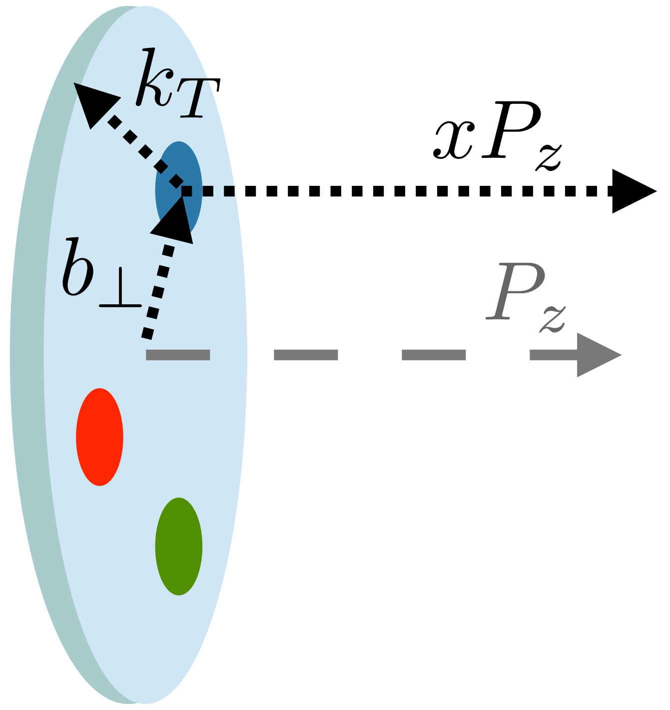

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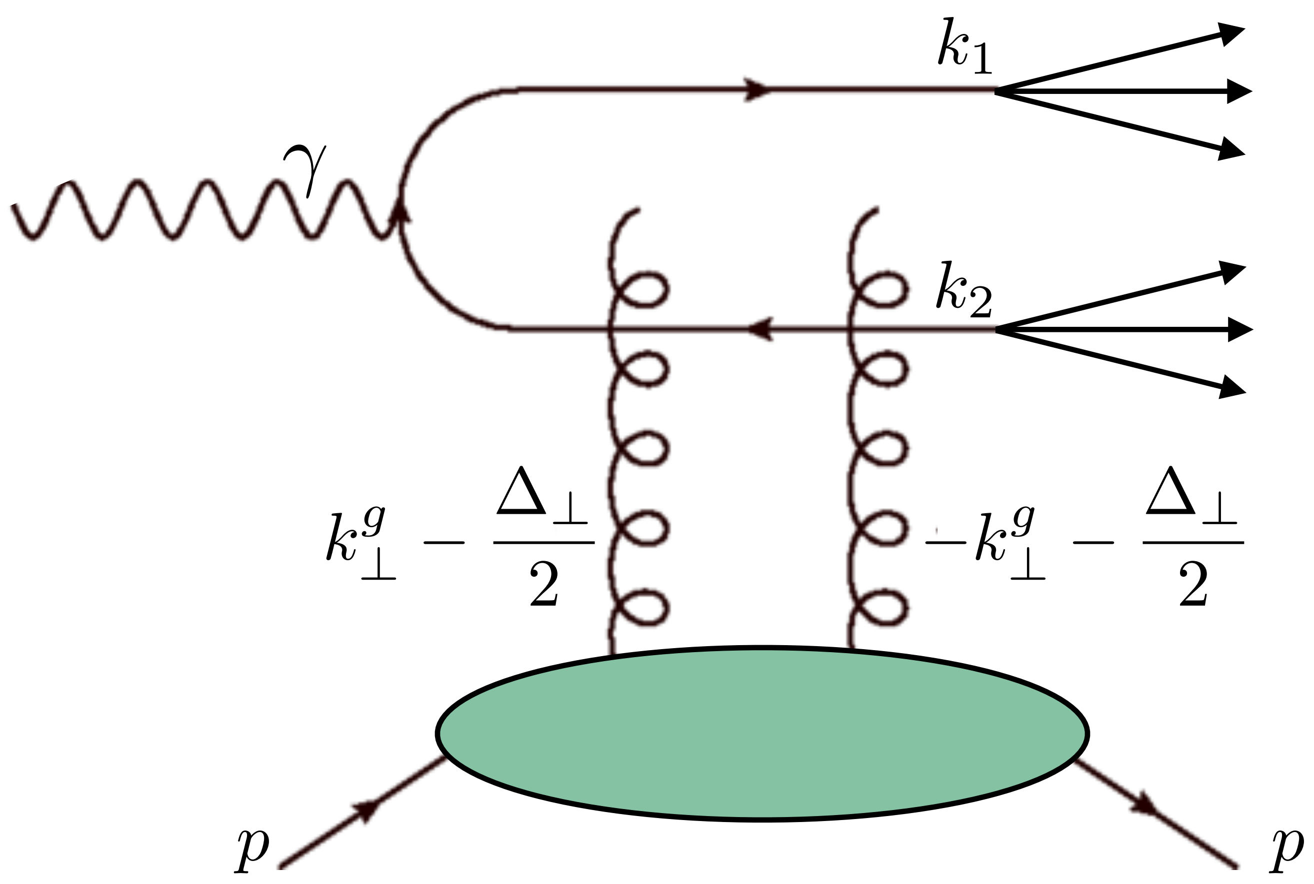

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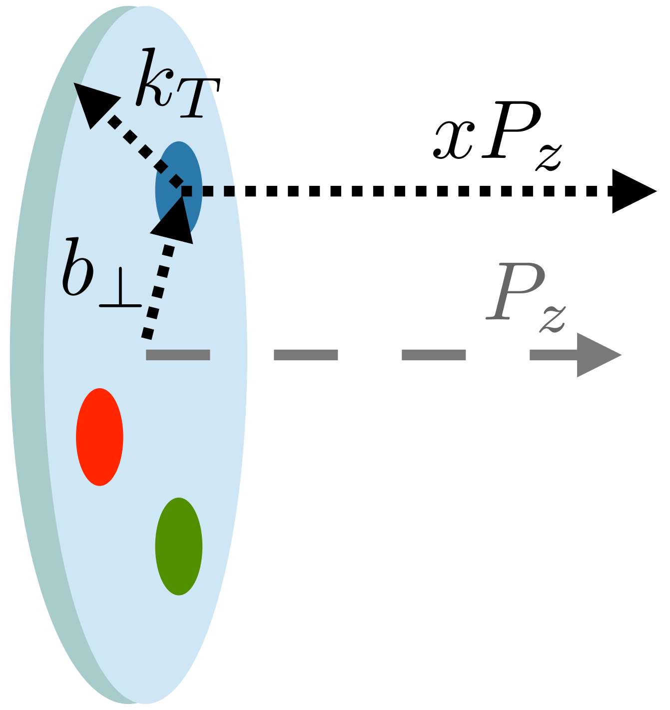

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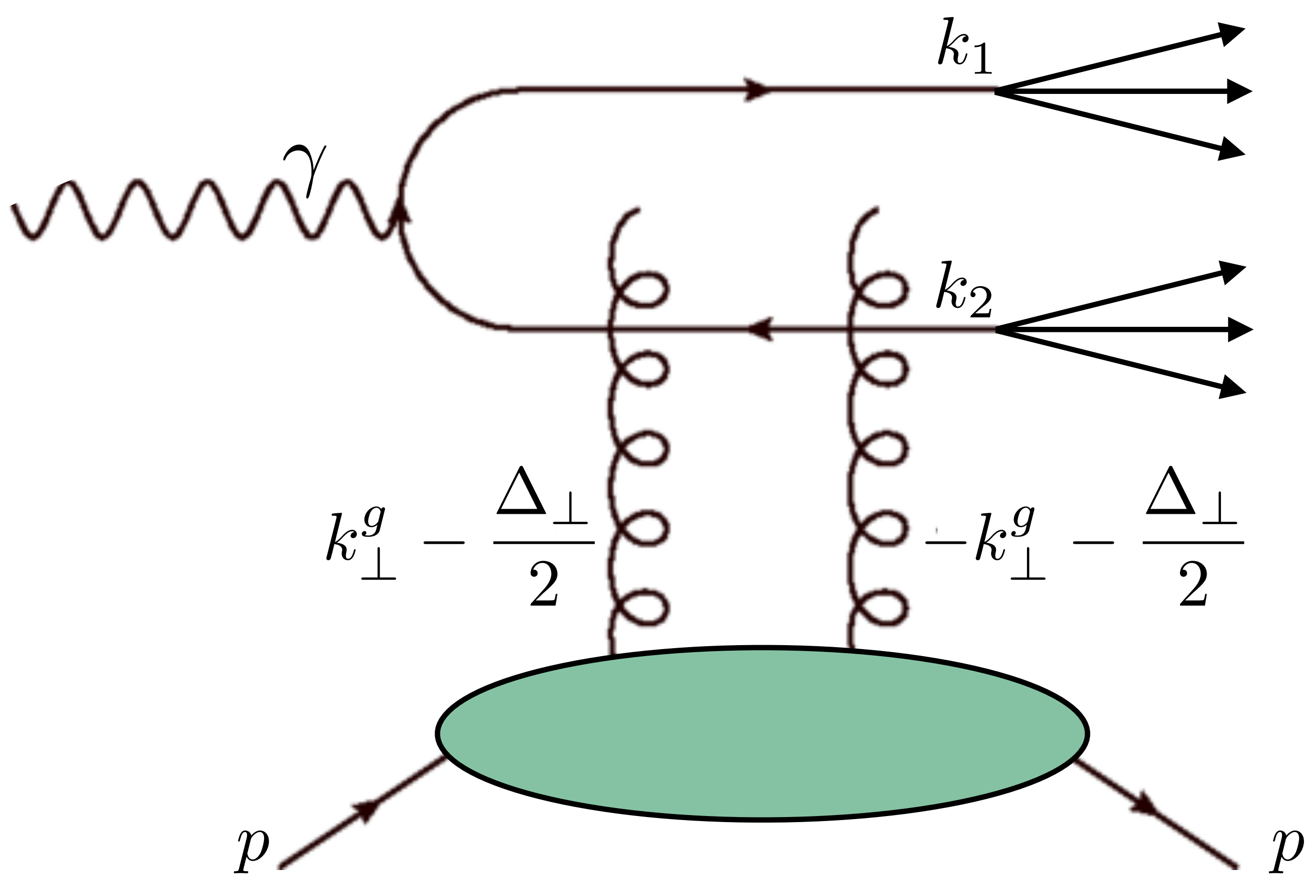

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- DIS: σ∝convolution integral
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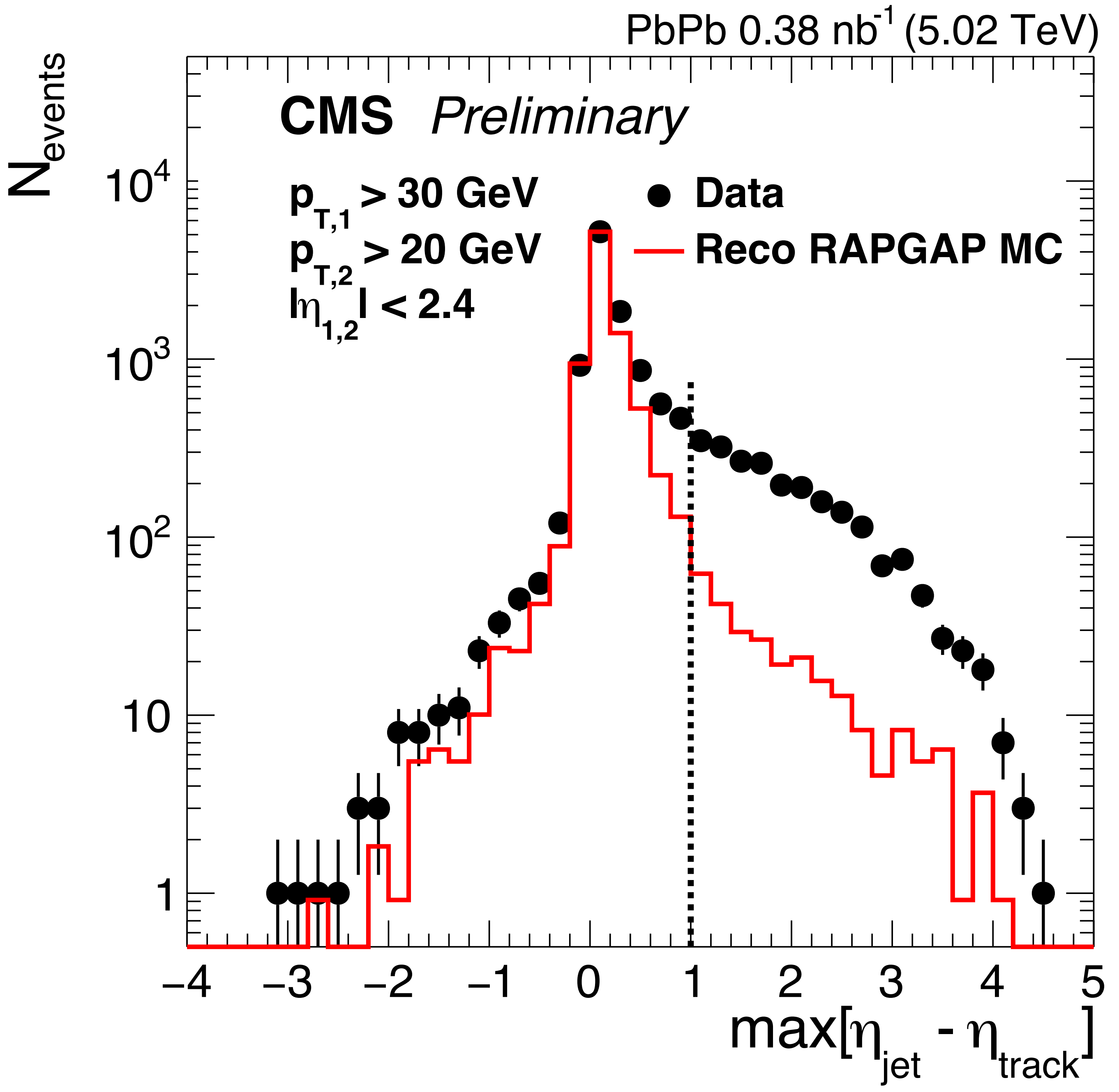
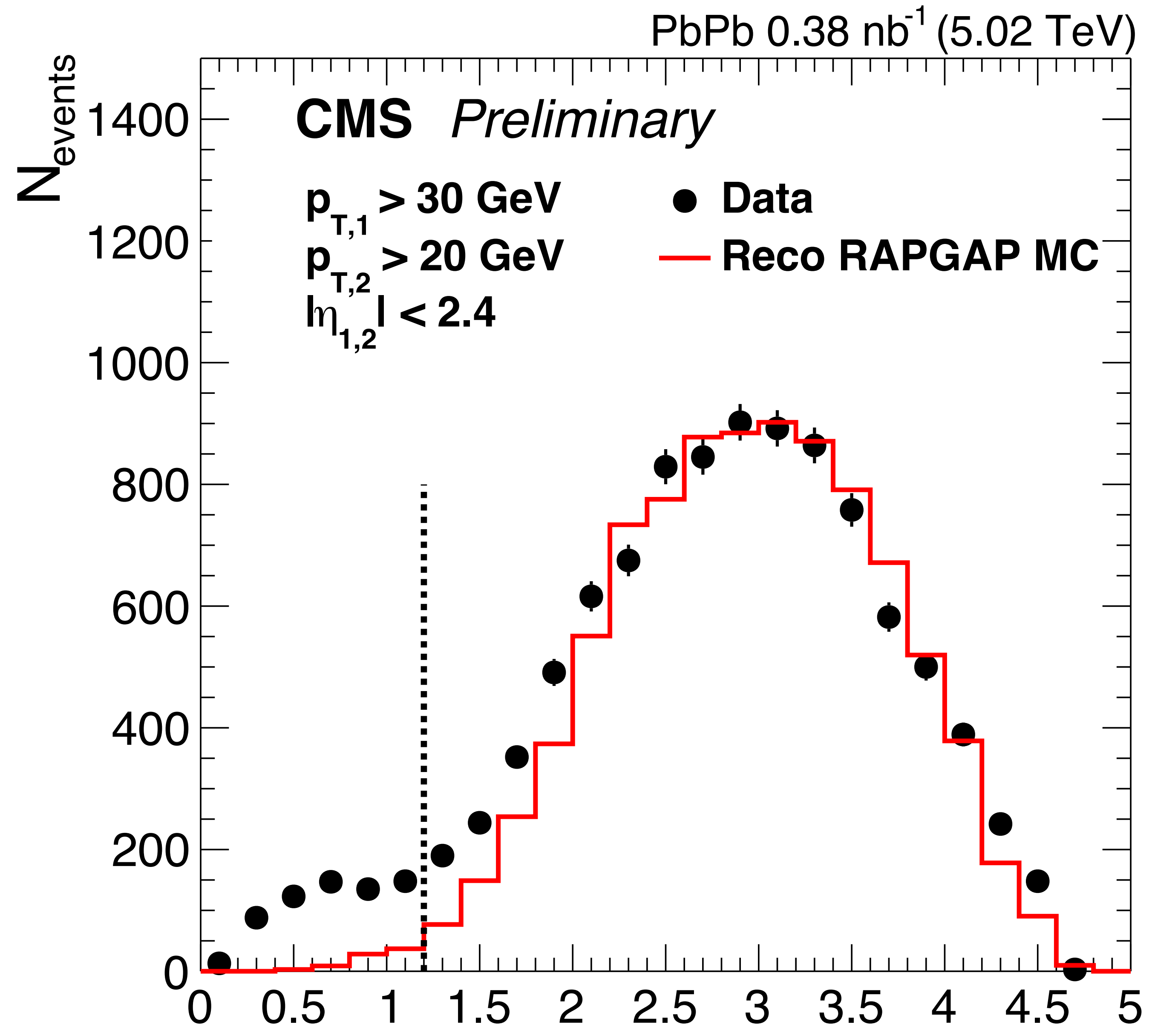
- measurement:
  - CMS preliminary: CMS-PAS-HIN-18-011

CMS measurement

- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=0.38 nb^{-1}
- exactly 2 jets
- $p_{T,\text{leading jet}}$ > 30 GeV; $p_{T,\text{subleading jet}}$ > 20 GeV
- $|\eta_{jet}|<2.4$
- $|\eta_{jet}-\eta_{track}|<1$
- rapidity gap in hemisphere opposite to dijet >1.2
- $P_\perp>\Delta_\perp$





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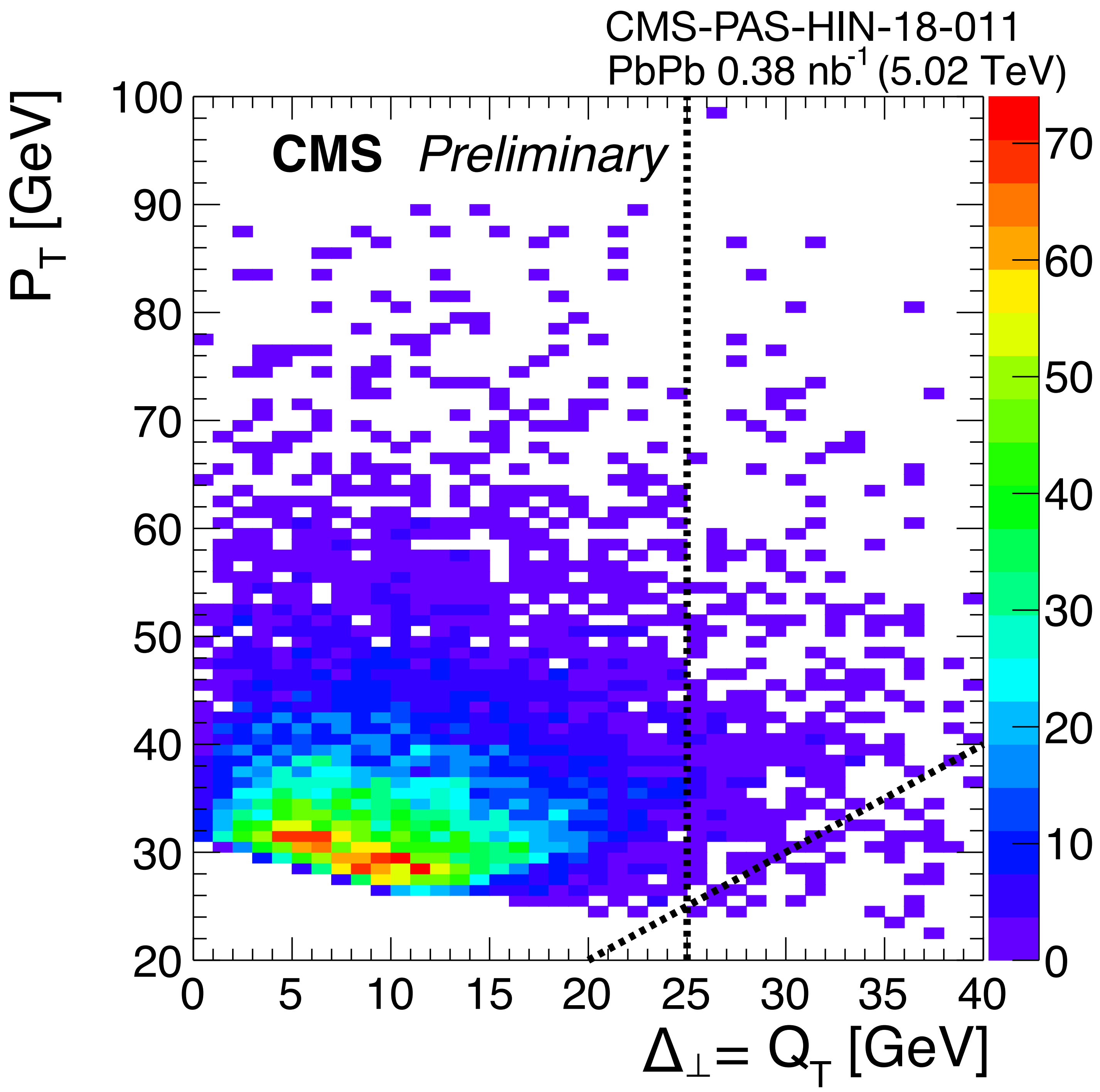
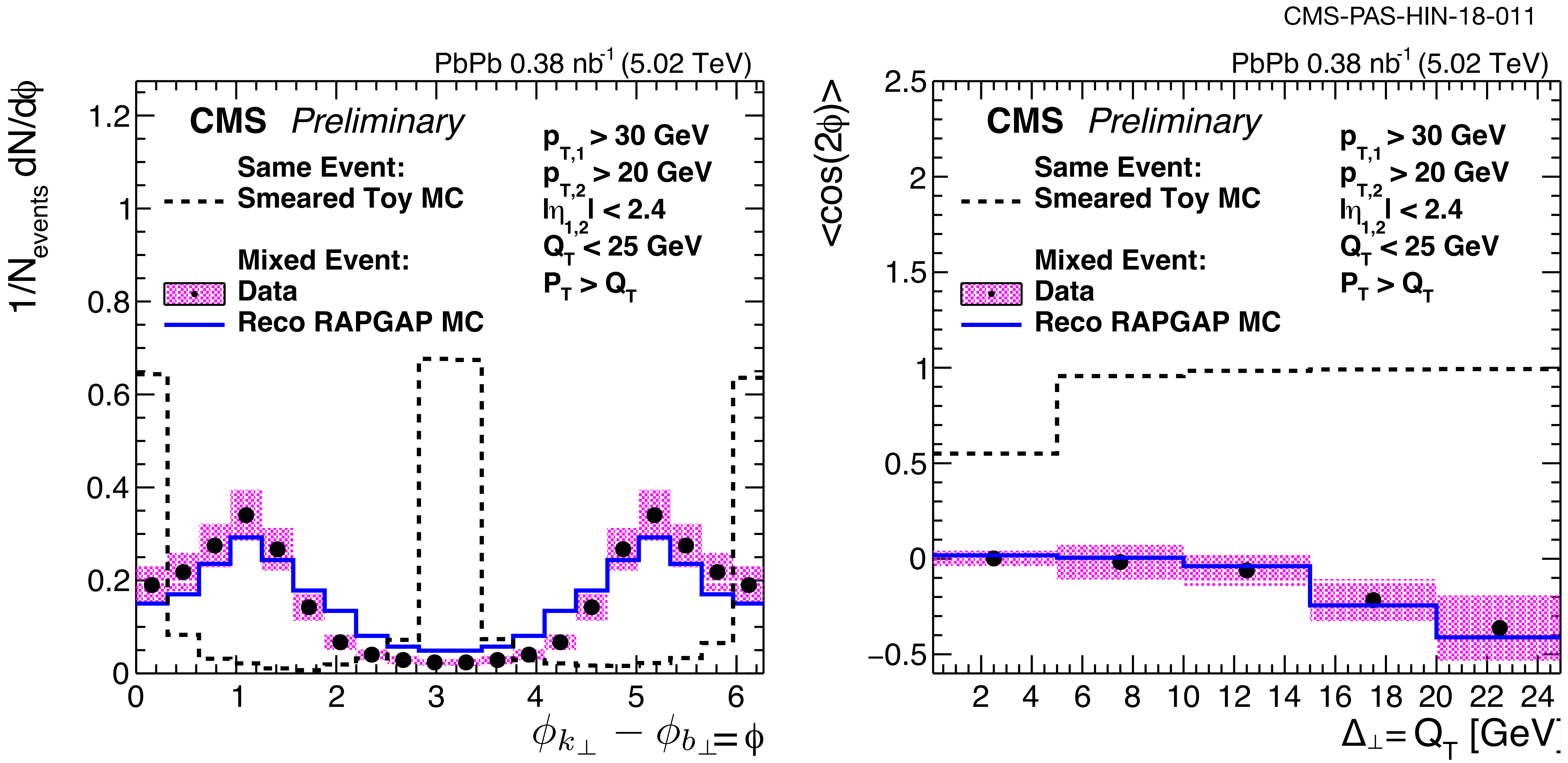


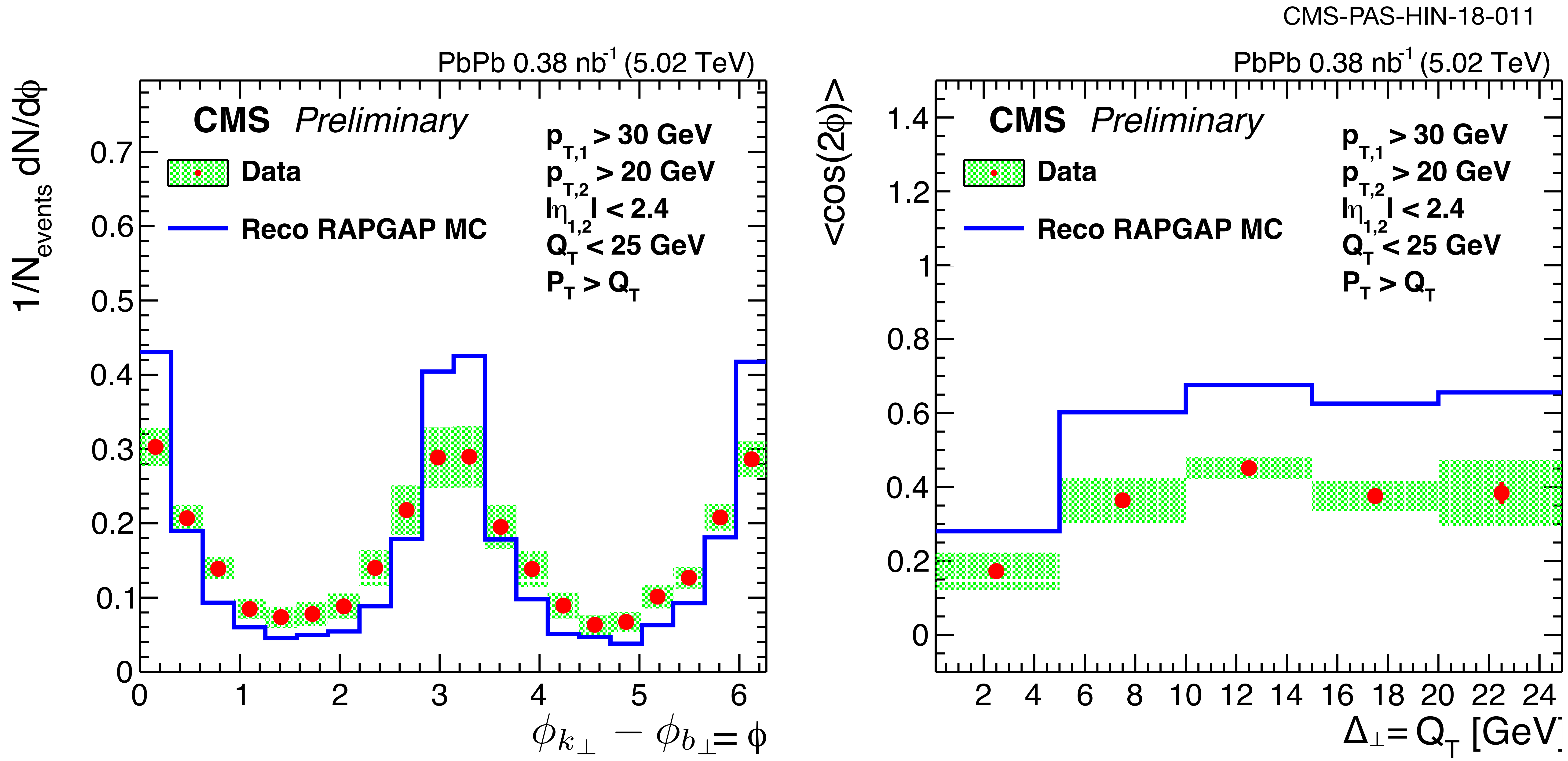
CMS measurement

- Event mixing



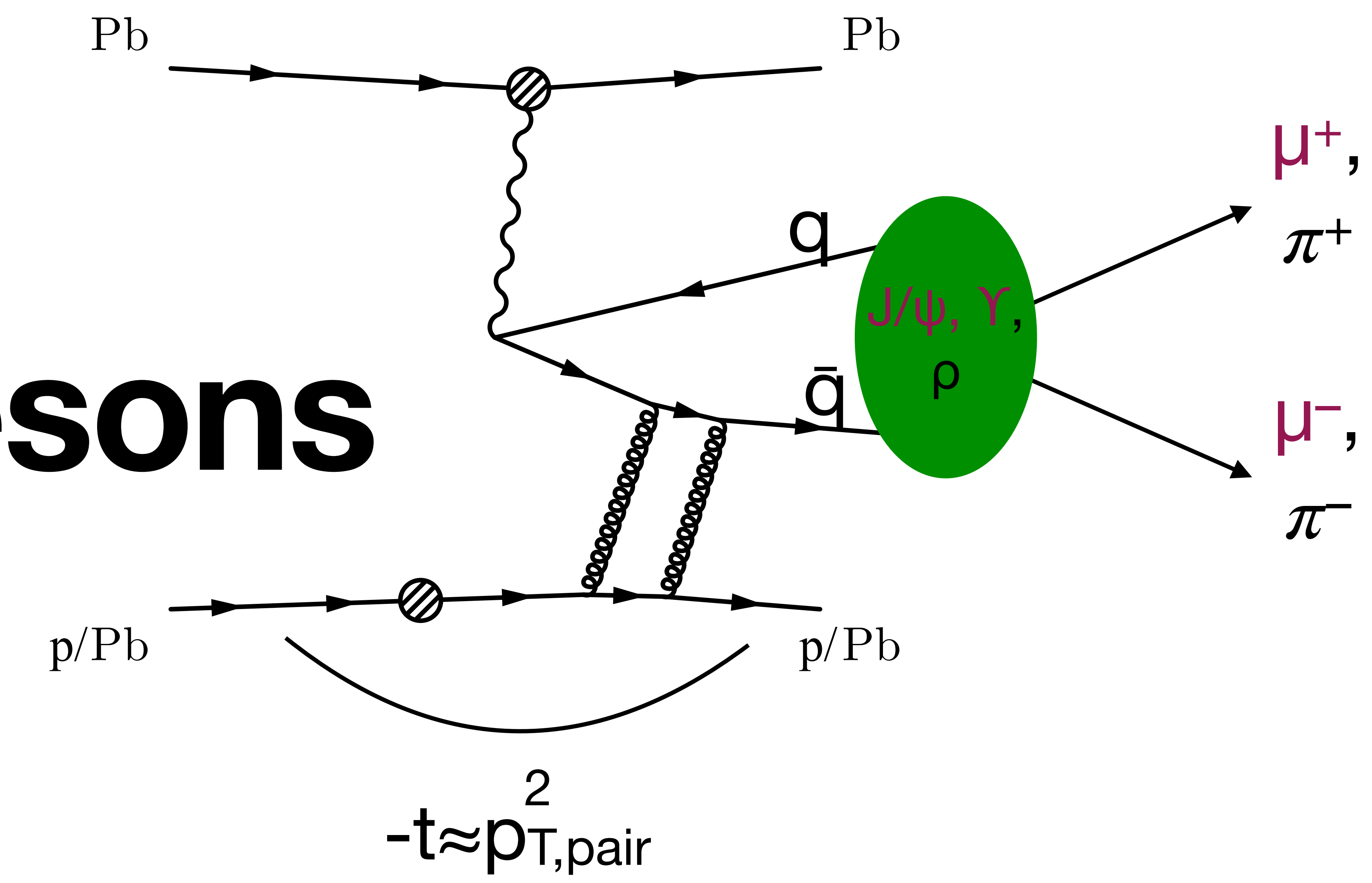
- MC=RAPGAP with photon spectrum from STARlight
- good agreement between MC and data

CMS result



- first extraction of cos(2ϕ) modulation
- results not corrected for instrumental effects
- disagreement between MC and data
- first step towards extraction of Wigner distributions!

Exclusive vector mesons



Exclusive vector-meson production at small x_B

Quarkonia

approximate access to gluon PDF

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

Z. Phys. C**57** ('93) 89–92;
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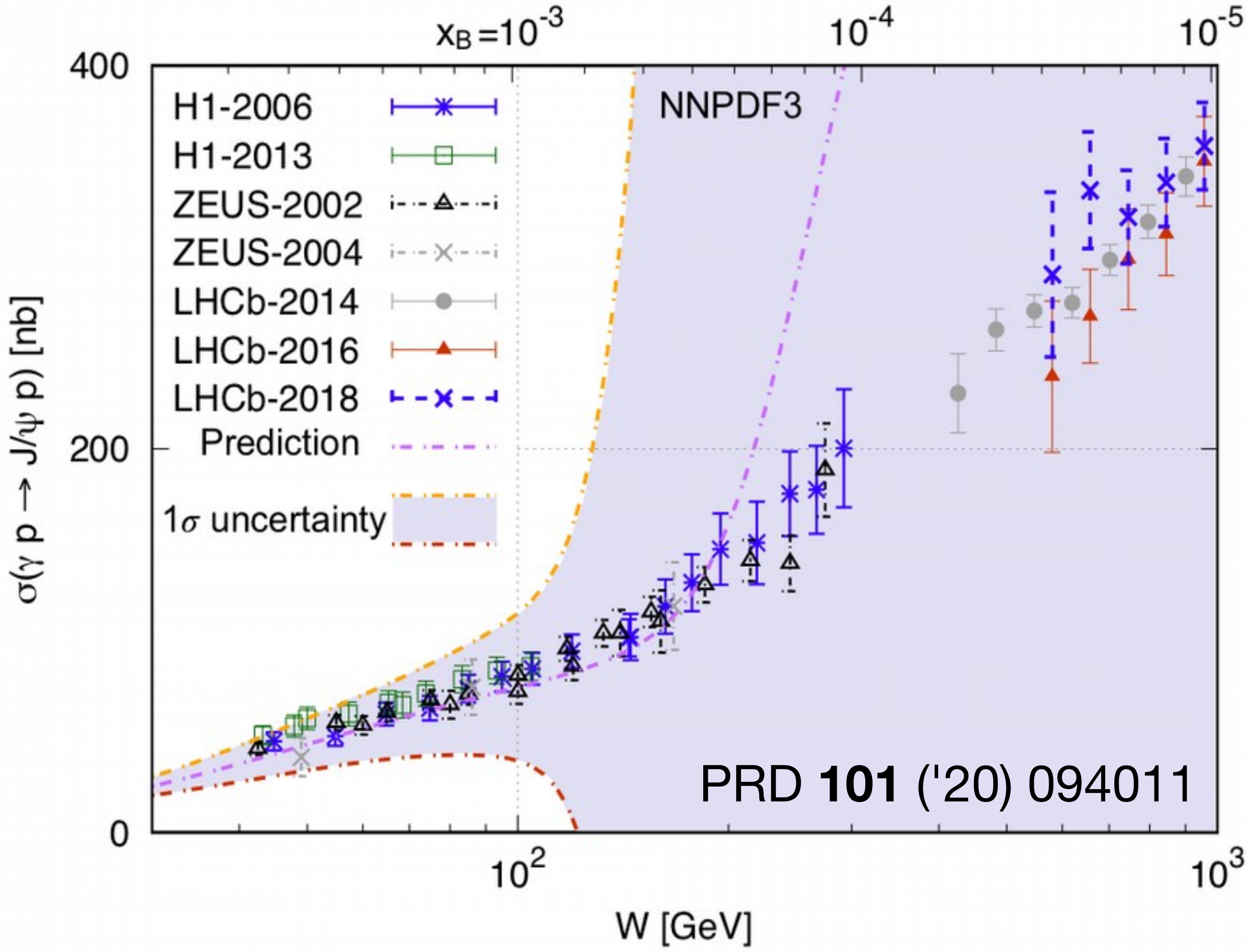

PRD **101** ('20) 094011

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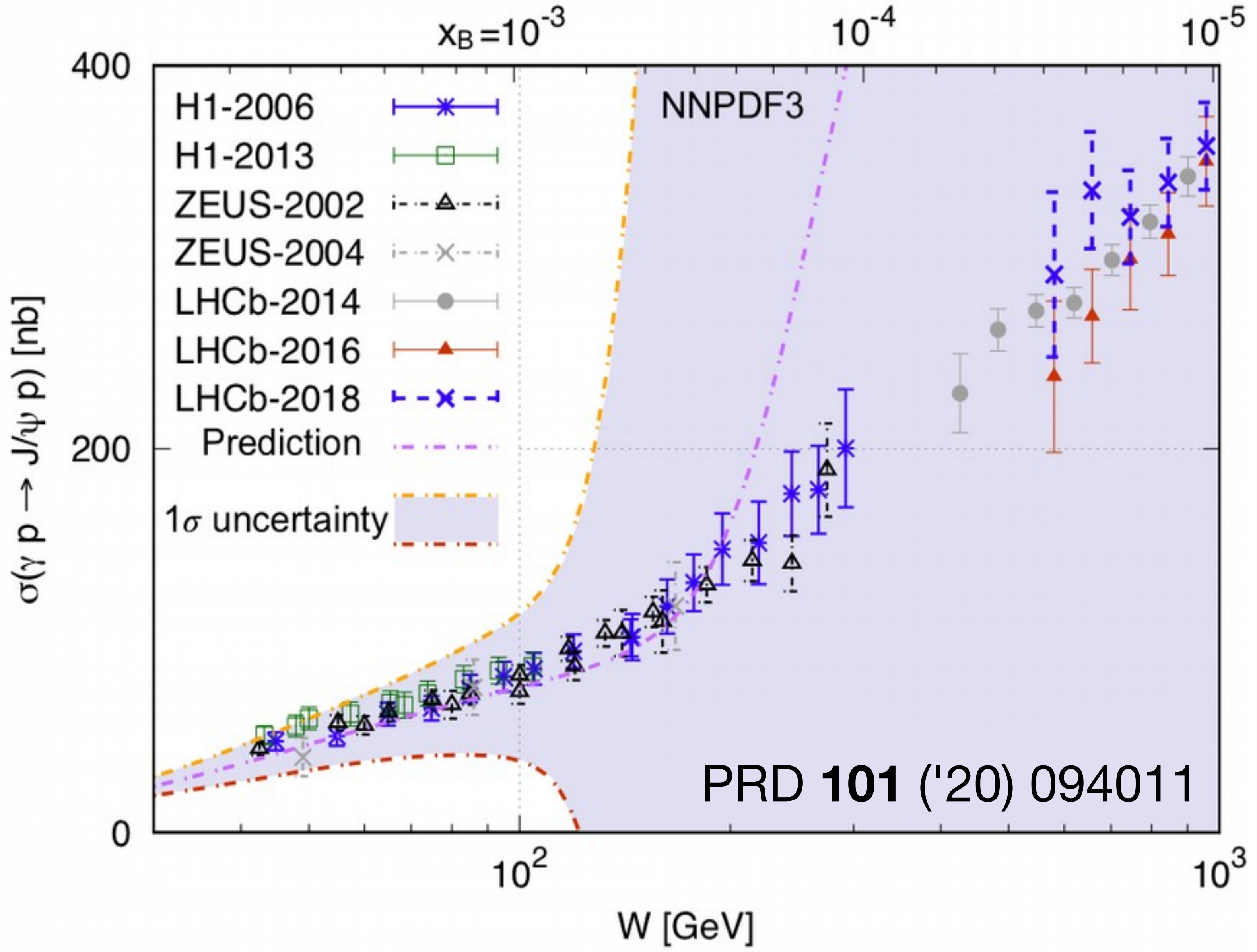

Vector-mesons

test saturation

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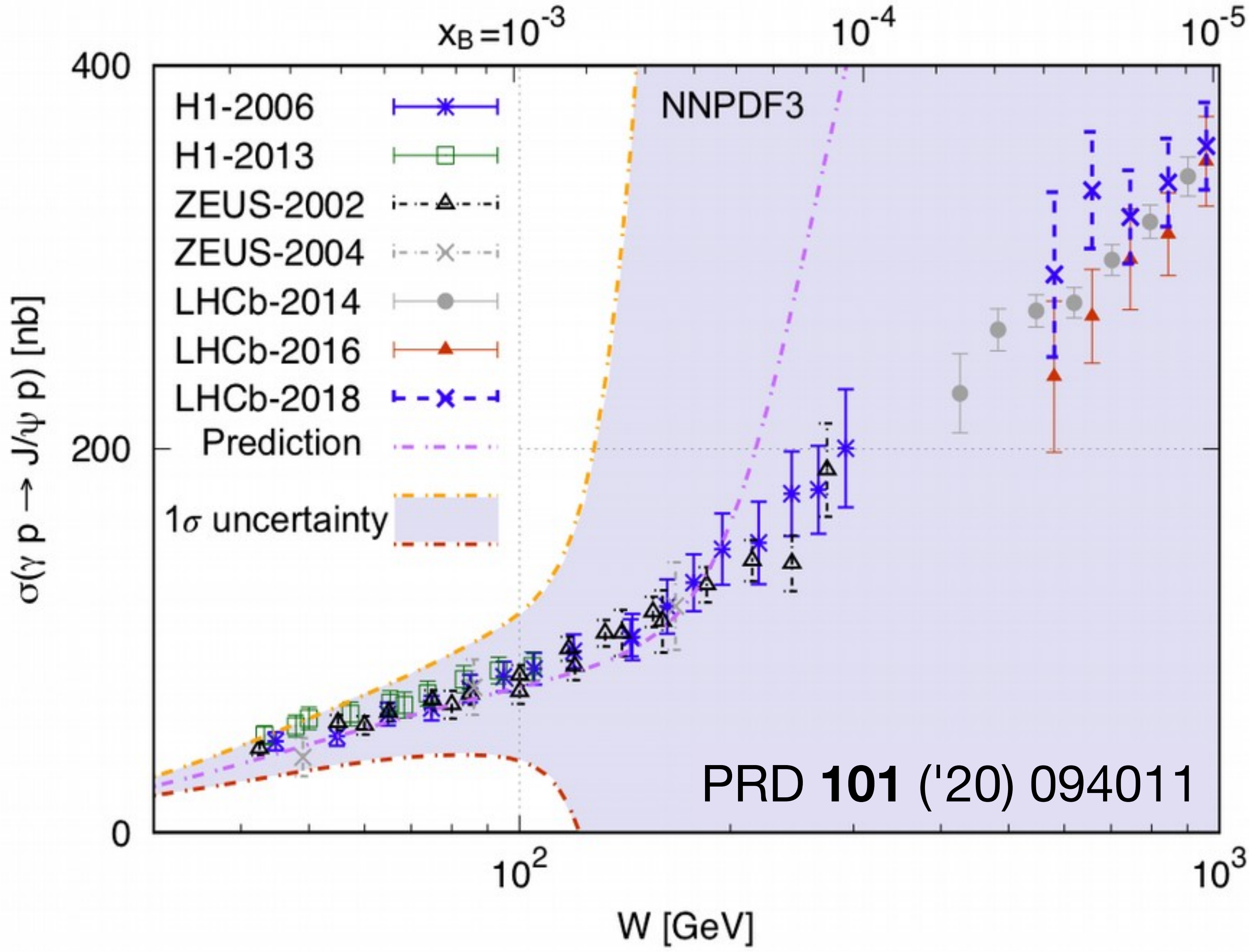

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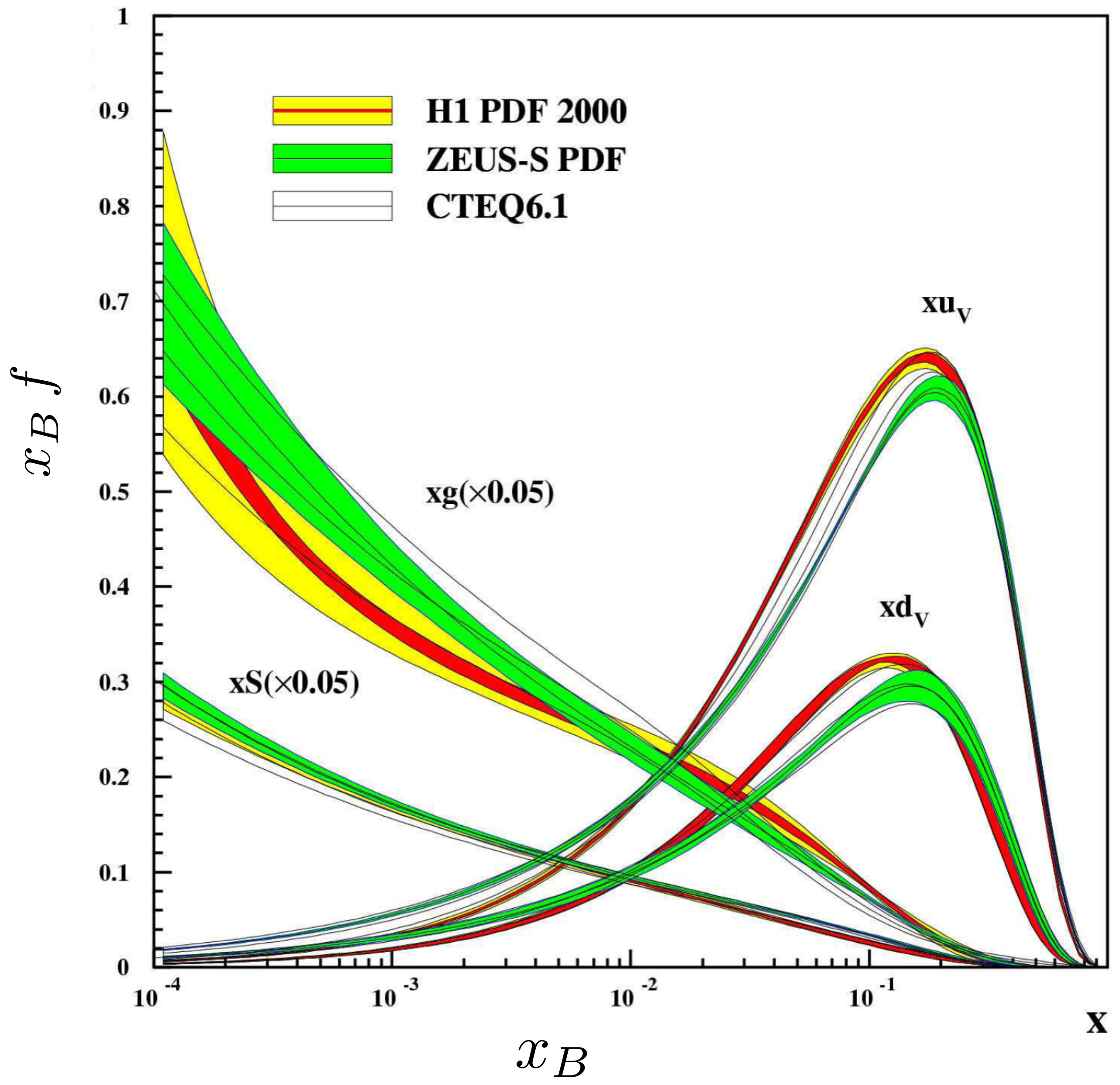

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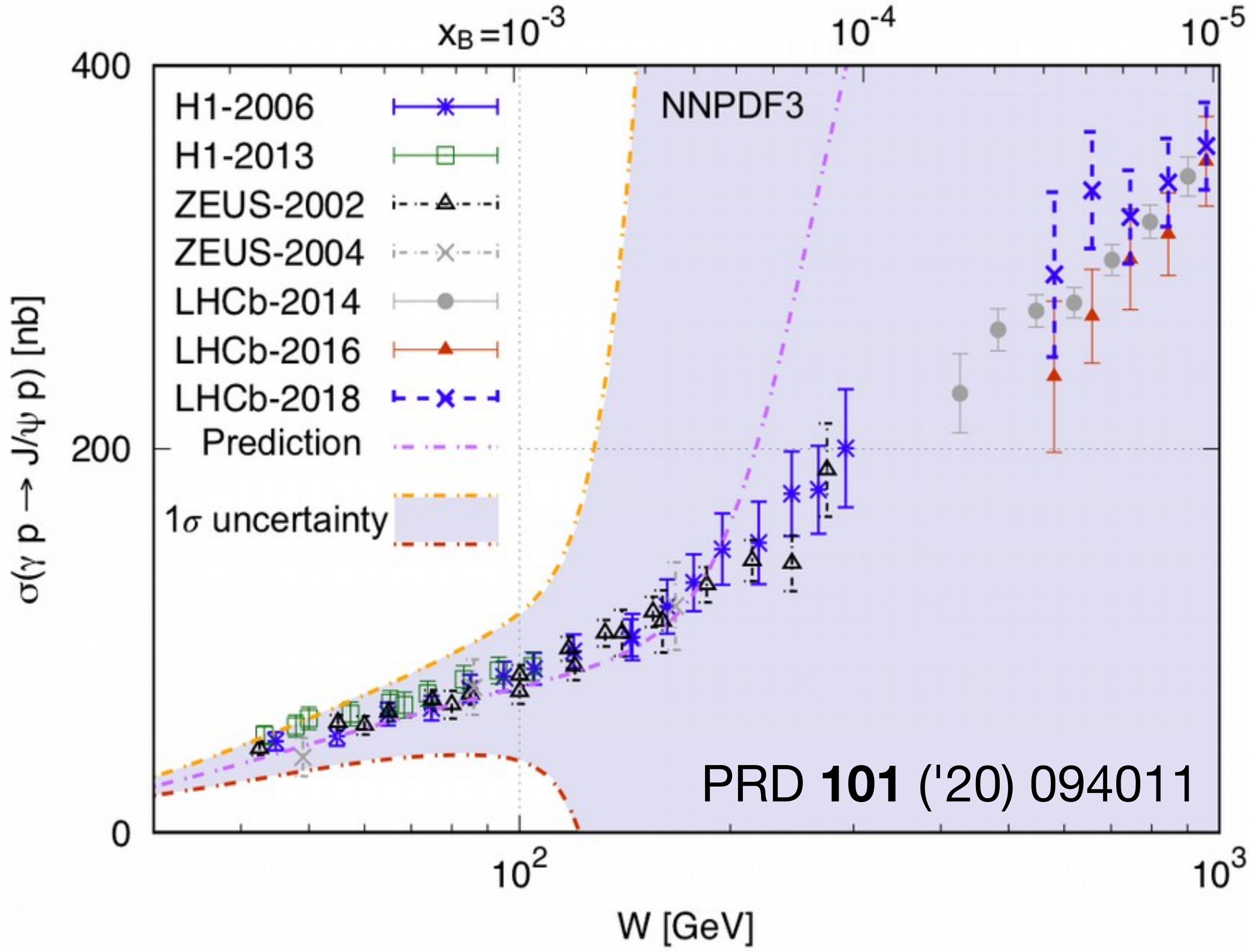

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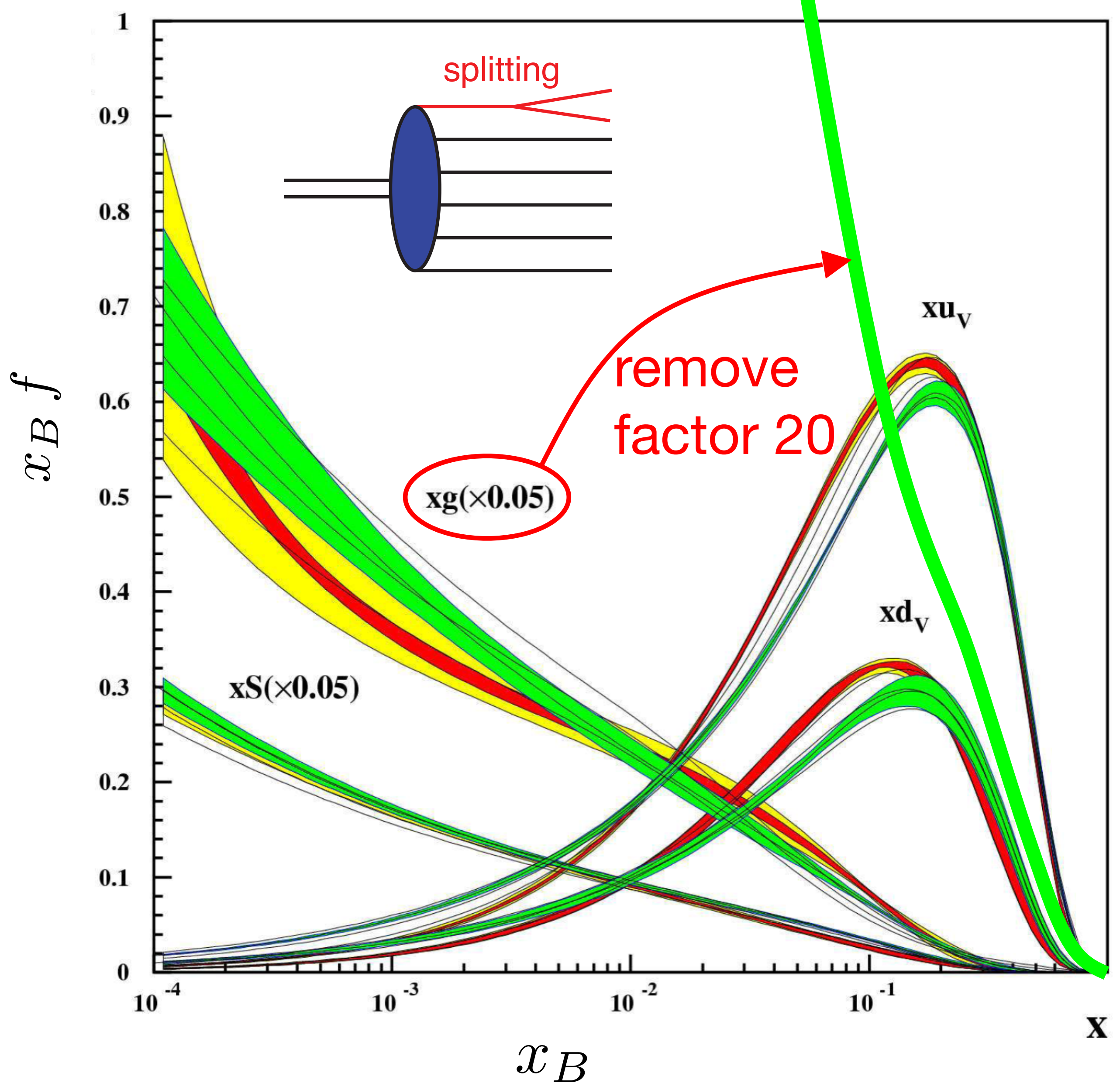

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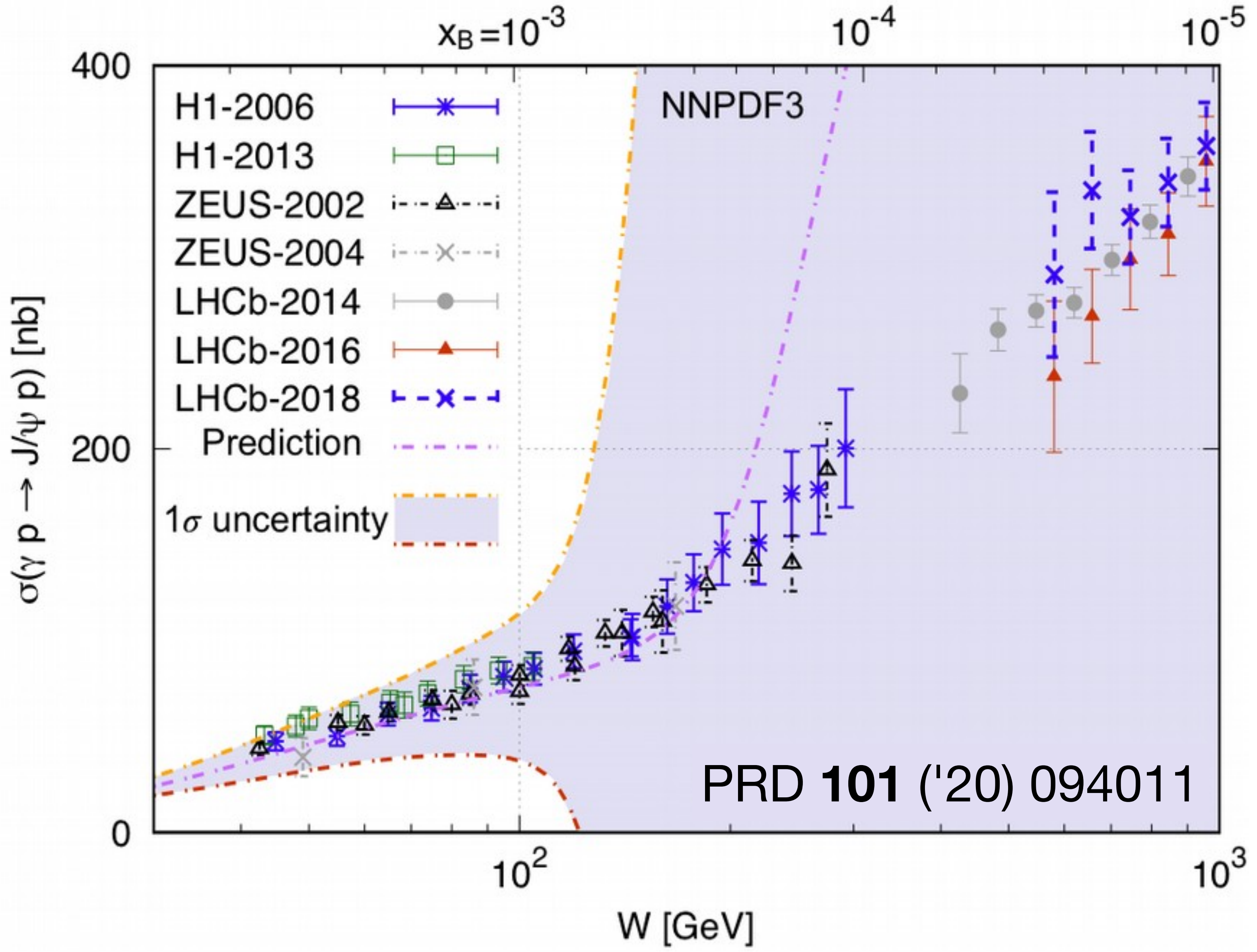

PRD **101** ('20) 094011

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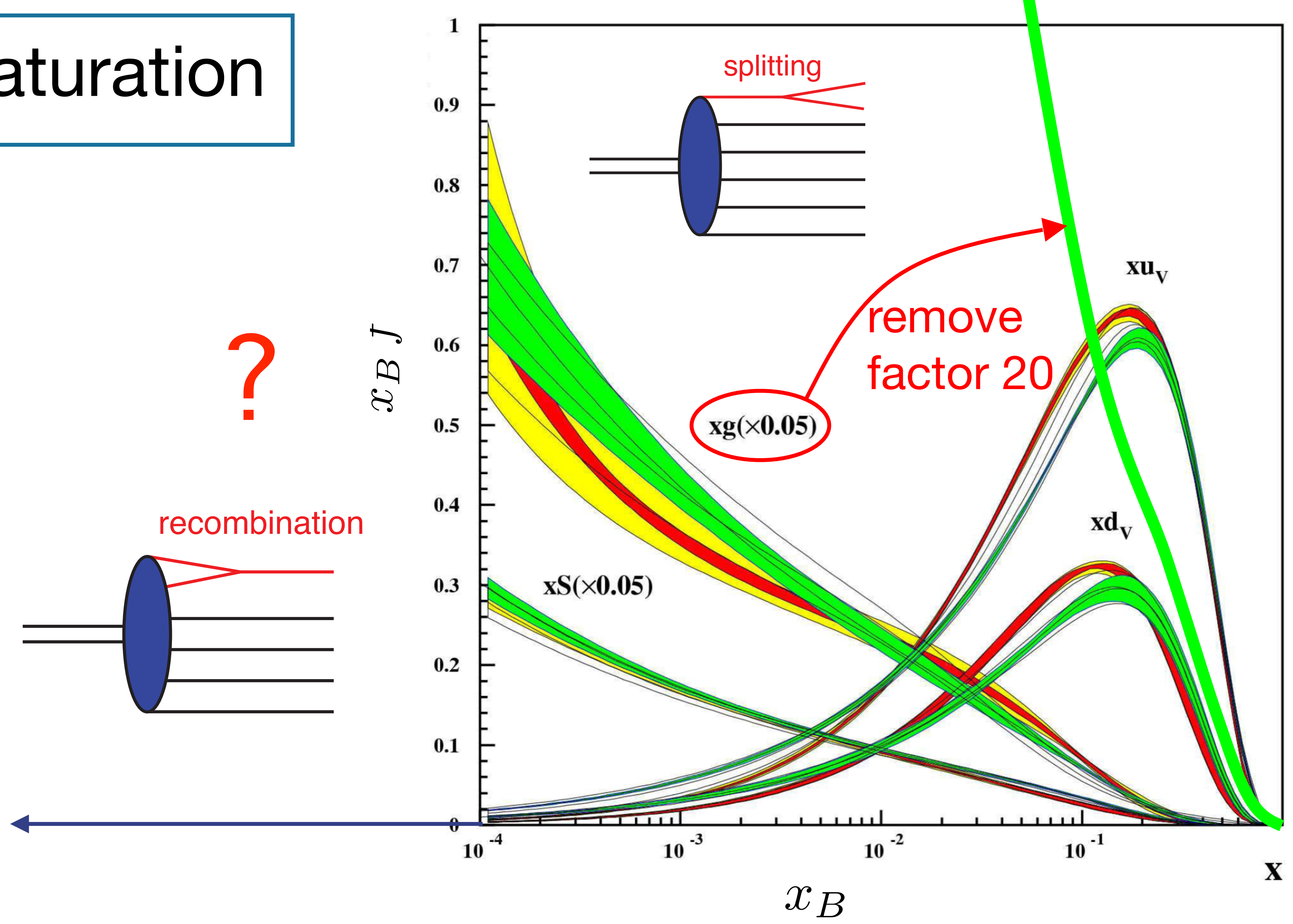

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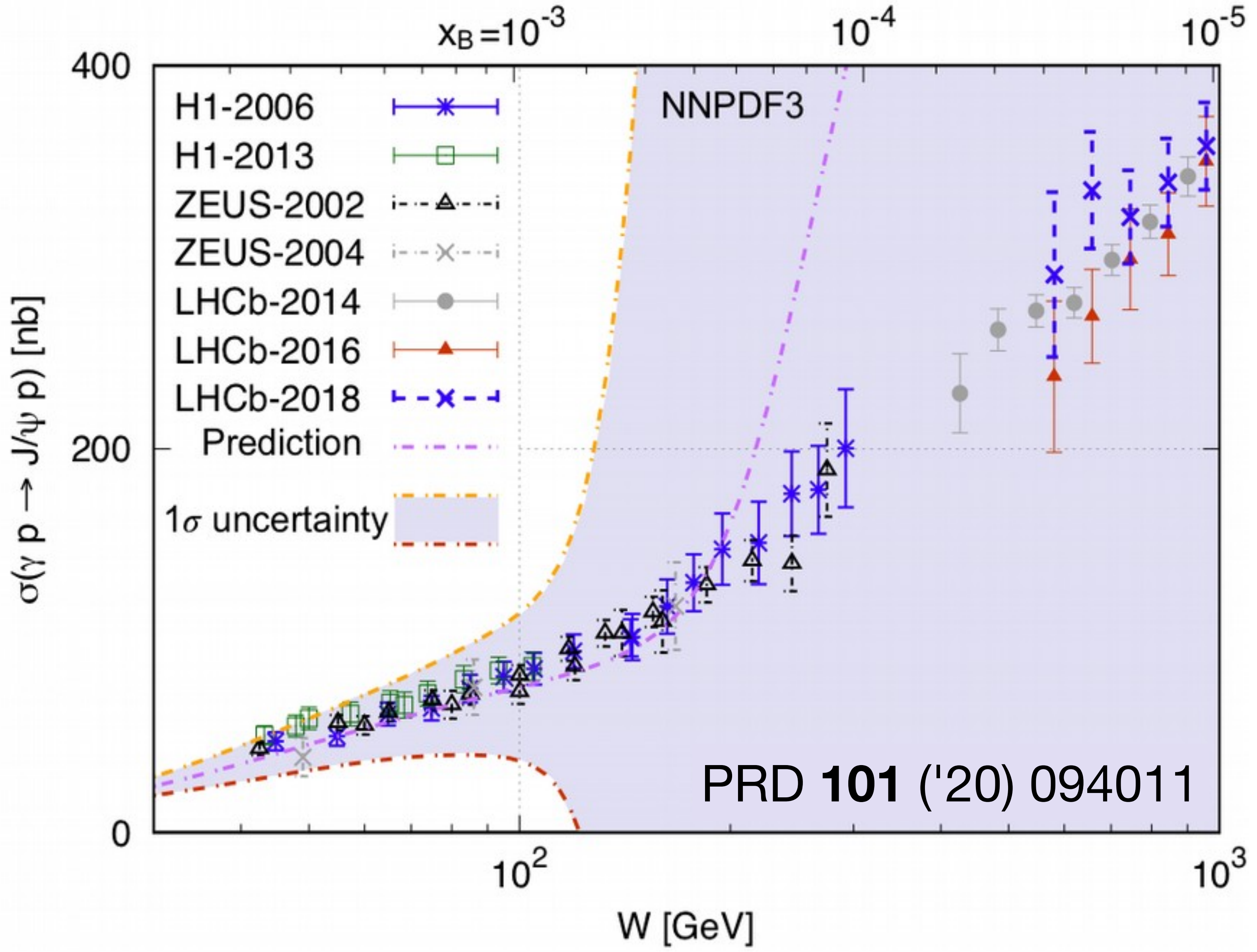

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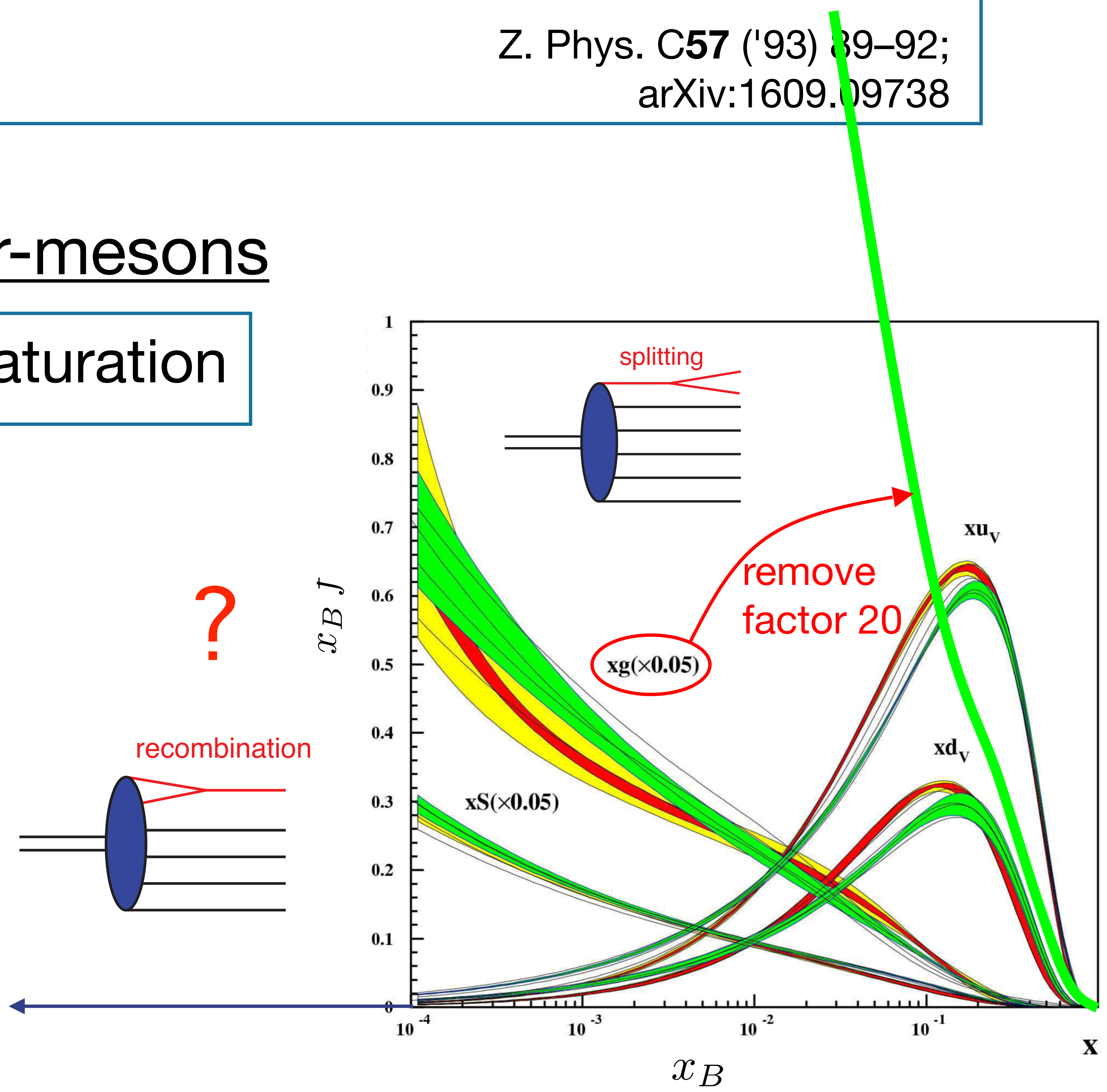

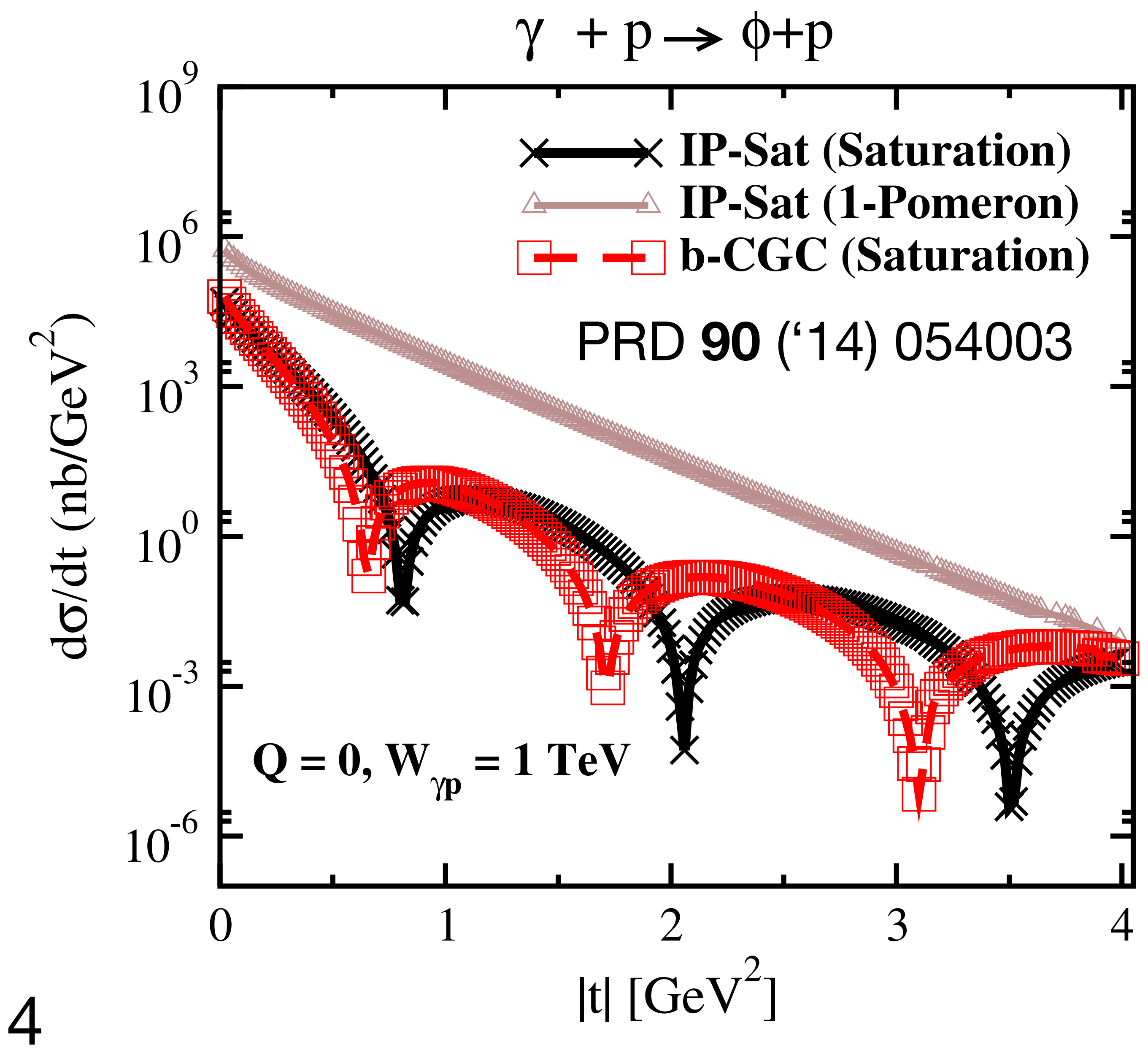

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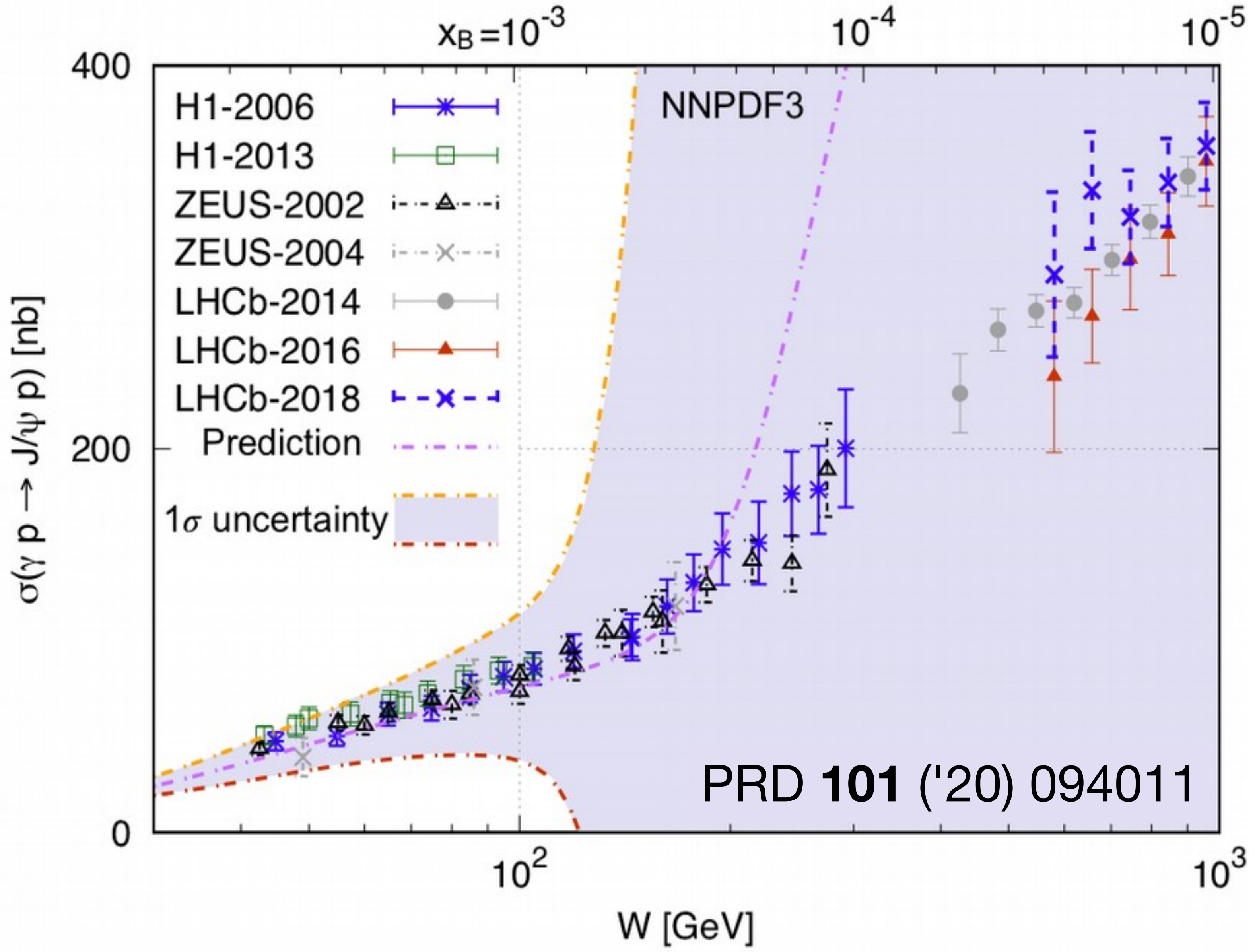

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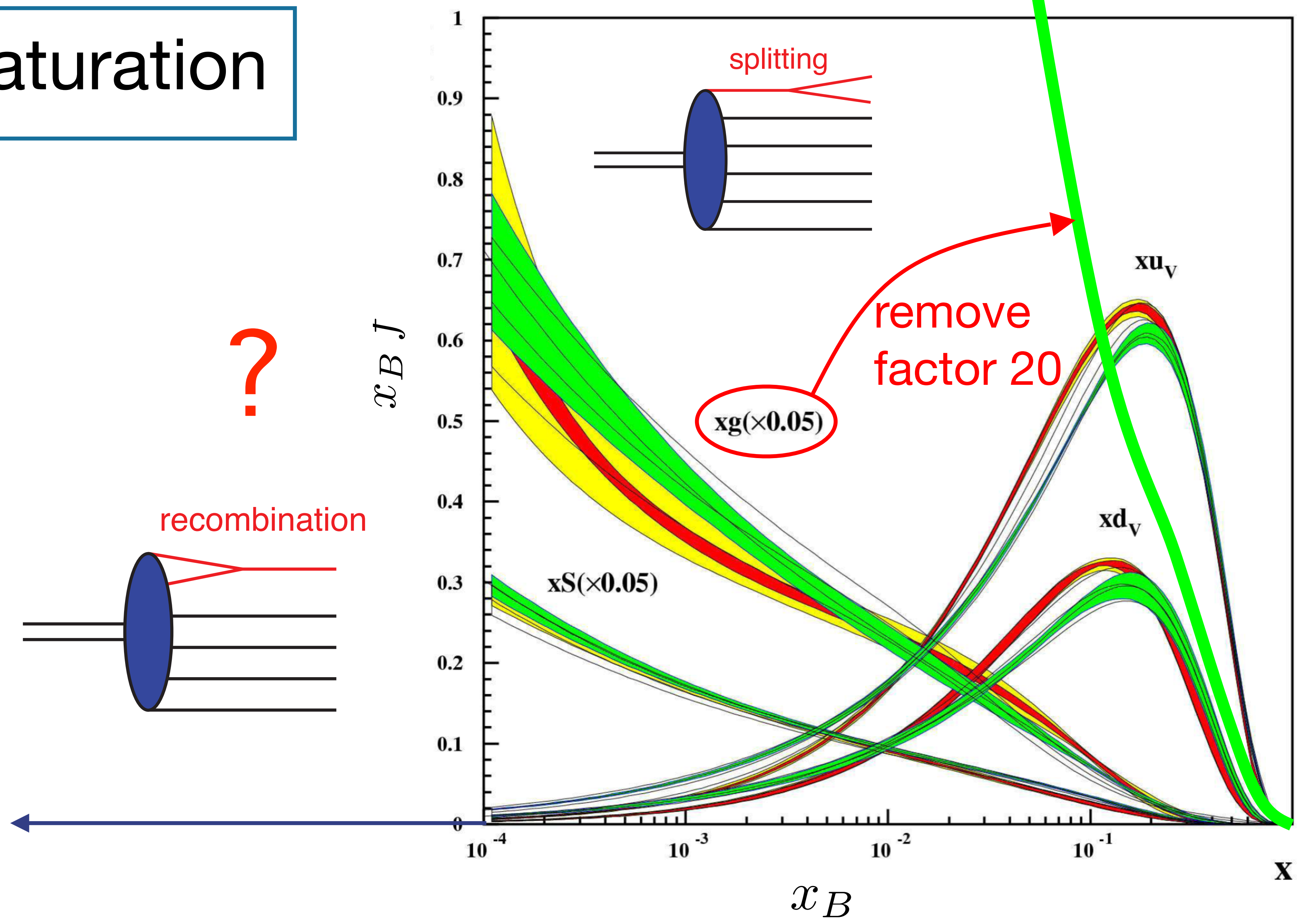
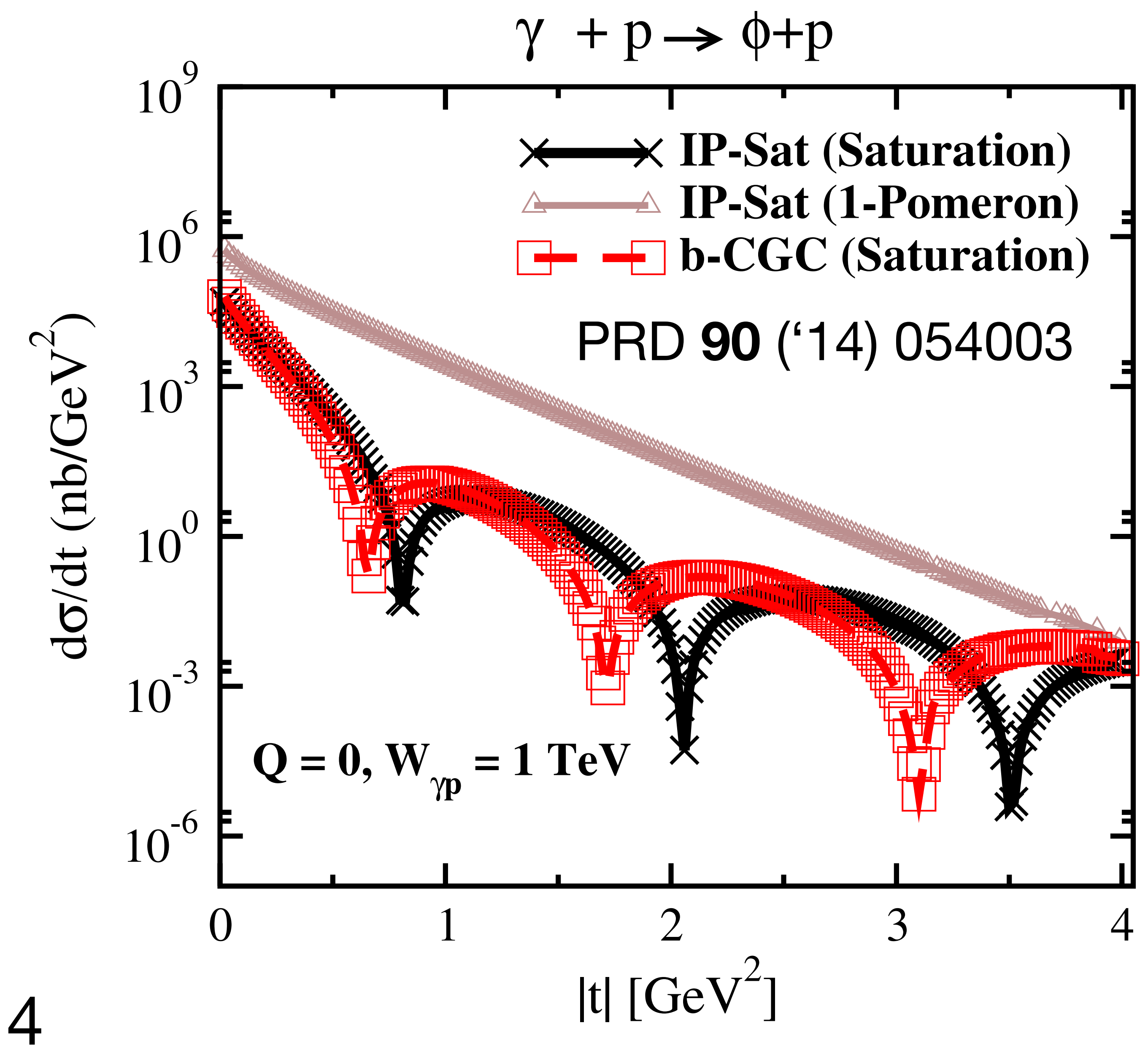
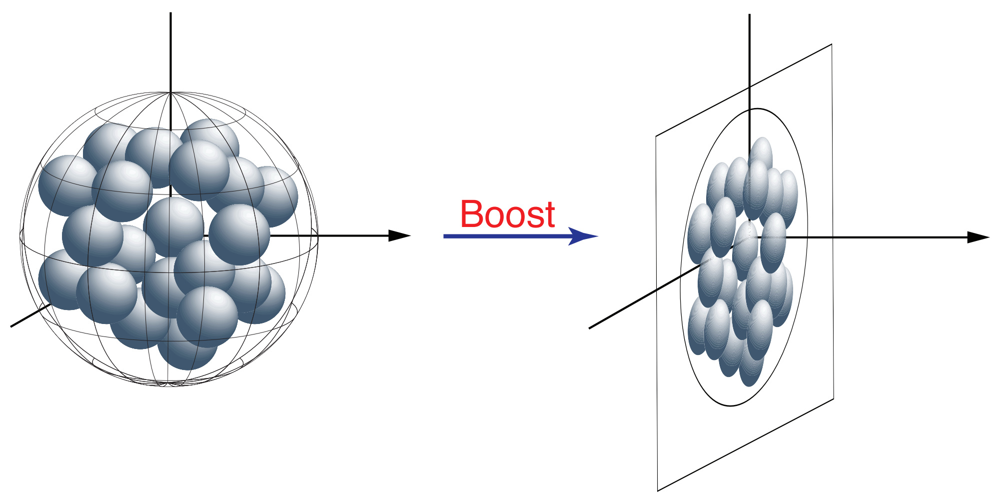
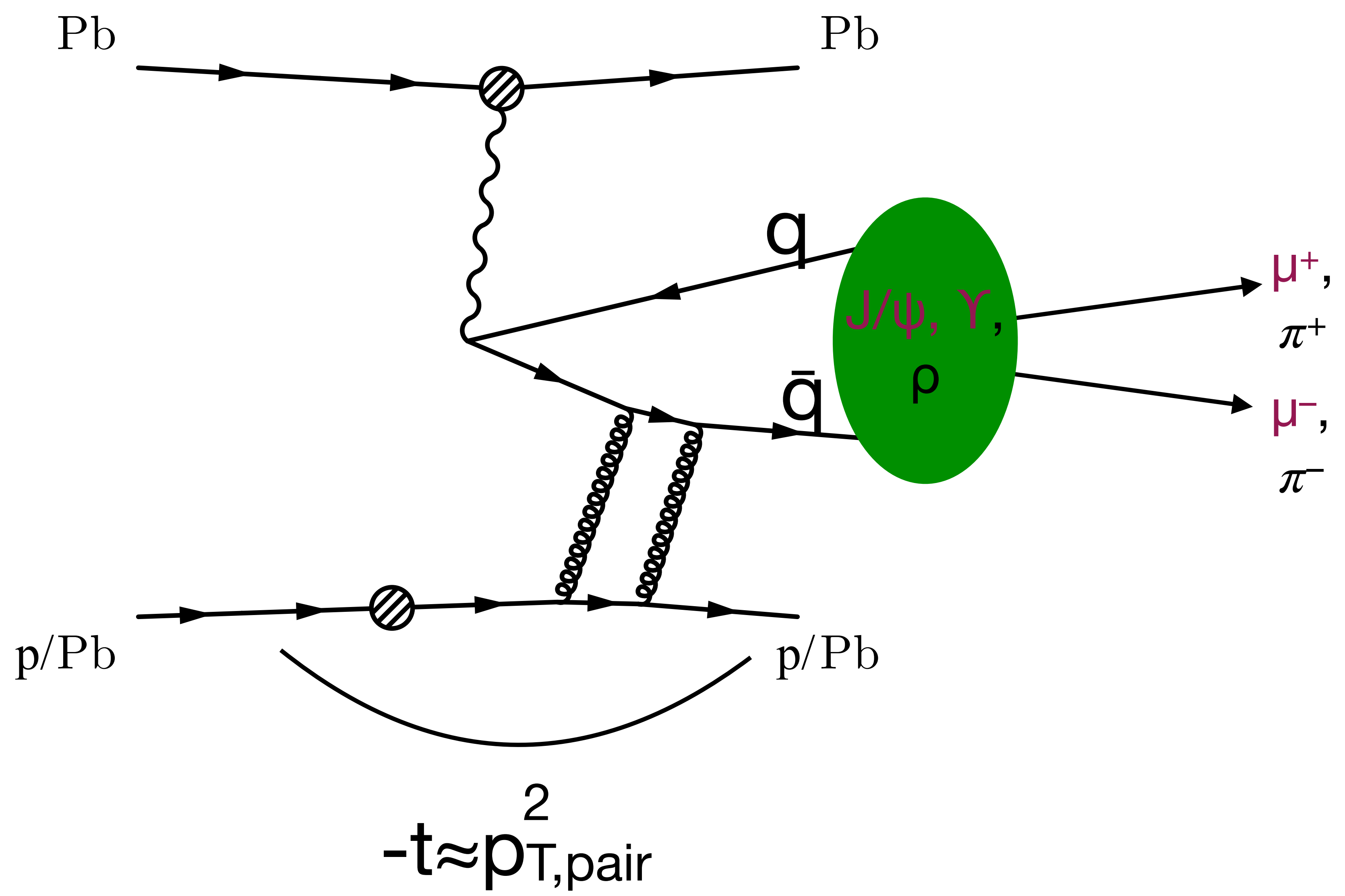






$A^{1/3}$ enhancement of saturation effect

Exclusive vector-meson production



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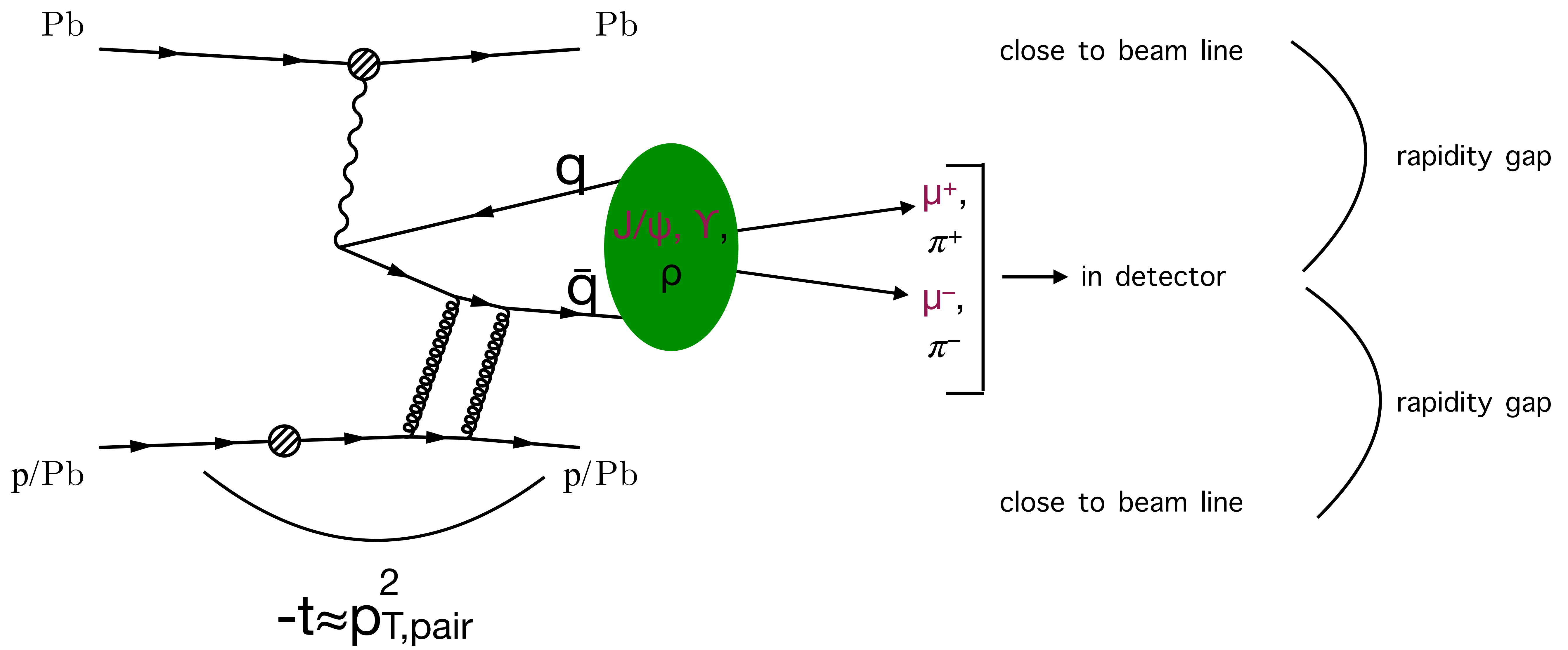

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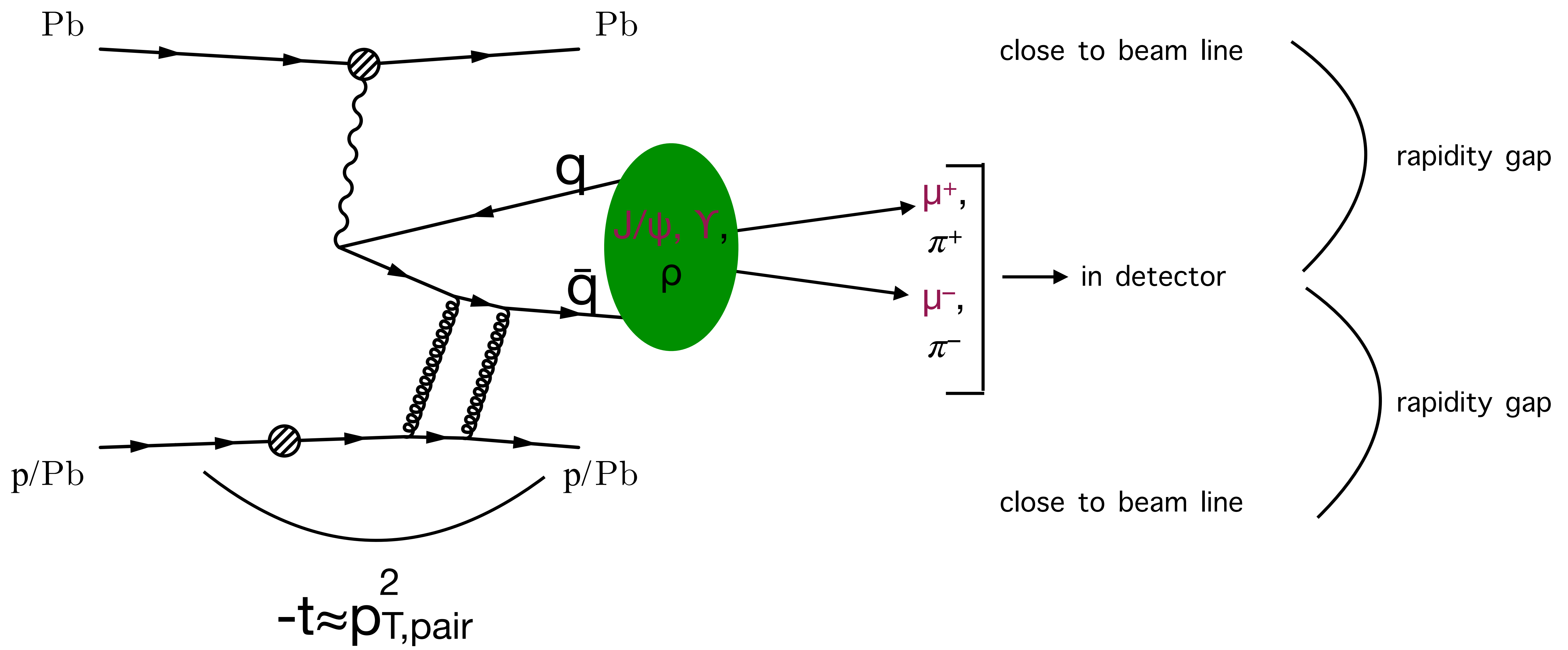

pPb collisions

Z(p)=1

Z(Pb)=82

photon flux ~ Z^2

$\longrightarrow$ Pb ion dominant photon emitter

no ambiguity in identity of photon emitter

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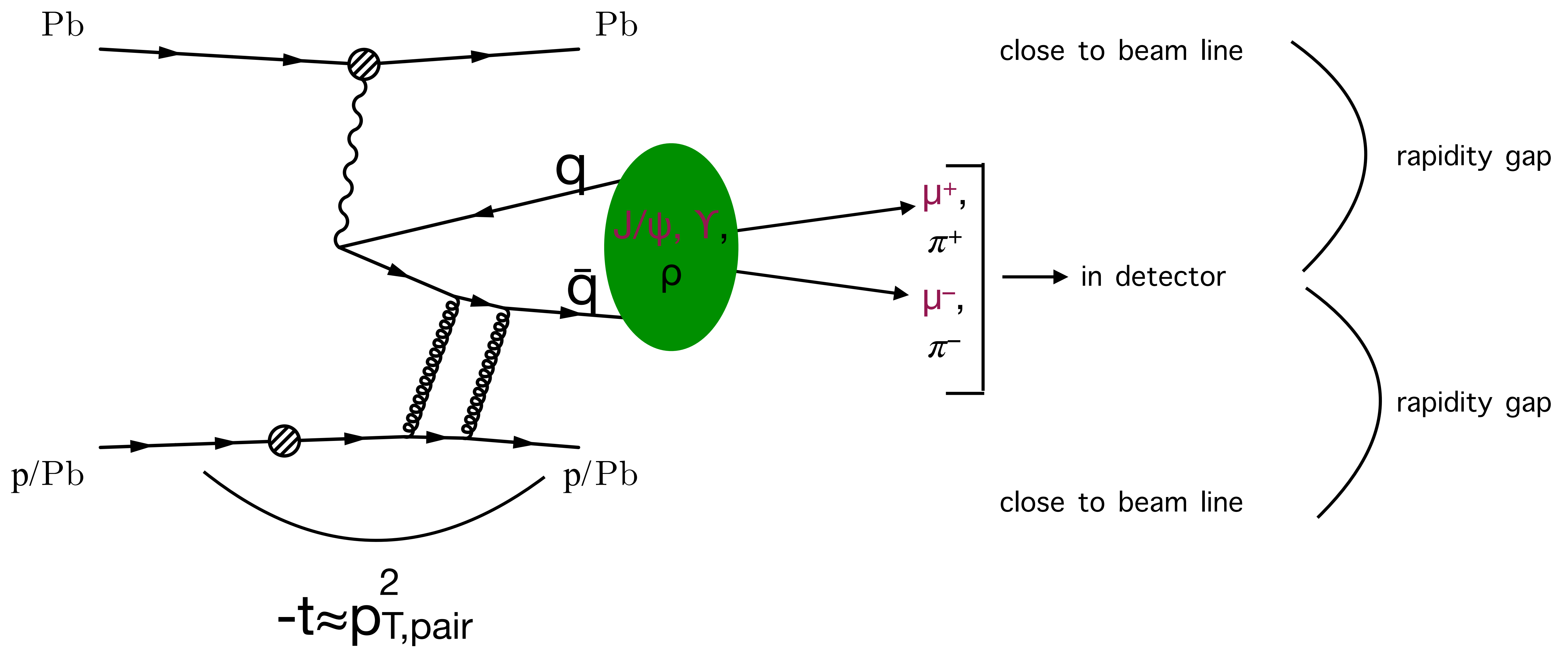

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incoherent interaction: photon interacts with nucleon in Pb (usually break up)

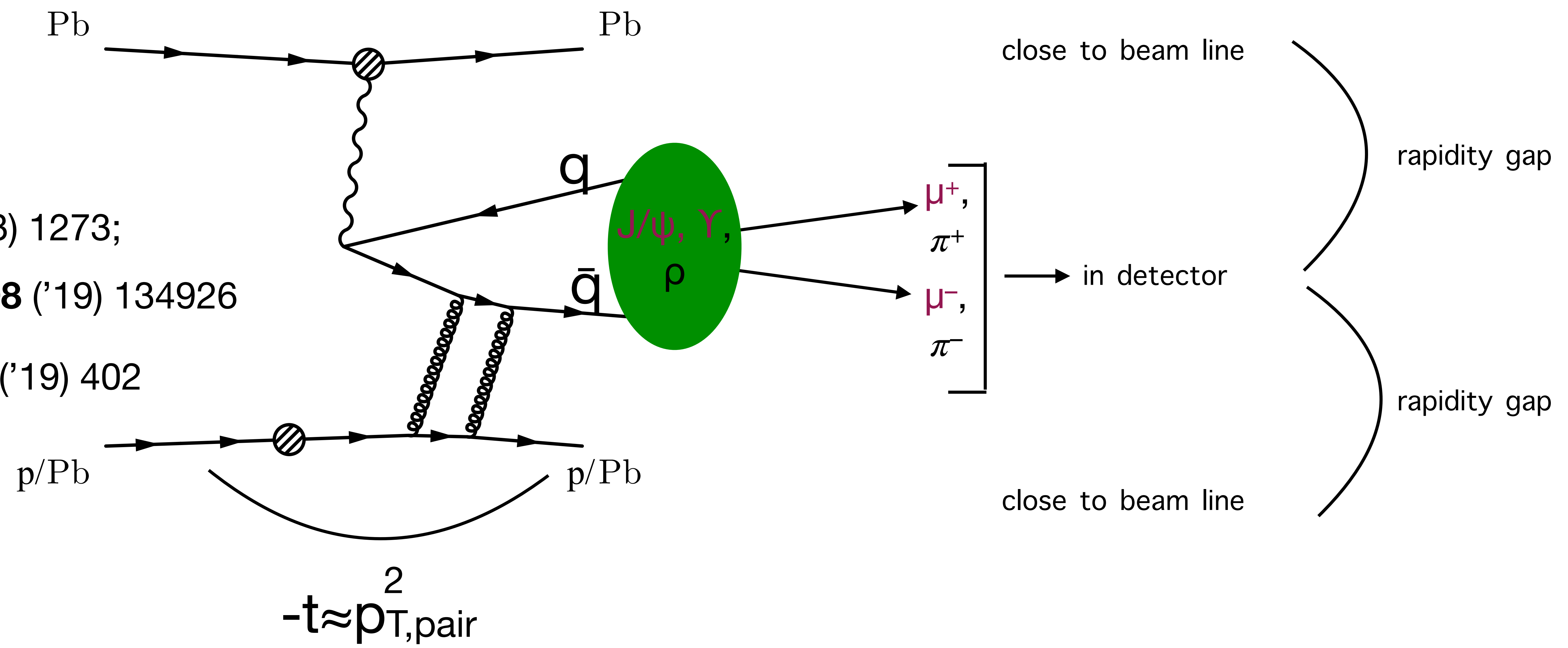
Exclusive vector-meson production

- Measurements:

  J/ψ
  - ALICE, Pb-Pb: Eur. Phys. J. C **73** ('13) 2617; Phys. Lett. B **718** ('13) 1273; Phys. Lett. B **751** ('15) 358 (ψ(2S)); Phys. Lett. B **798** ('19) 134926
  - ALICE, p-Pb: Phys. Rev. Lett. **113** ('14) 232504; Eur. Phys. J. C **79** ('19) 402
  - CMS, PbPb: Phys. Lett. B **772** ('17) 489
  - LHCb, PbPb: CERN-LHCb-CONF-2018-003

  ϒ
  - CMS, pPb: Eur. Phys. J. C **79** ('19) 277

  ρ^0
  - ALICE, PbPb: JHEP **09** ('15) 095
  - CMS, pPb: Eur. Phys. J. C **79** ('19) 702



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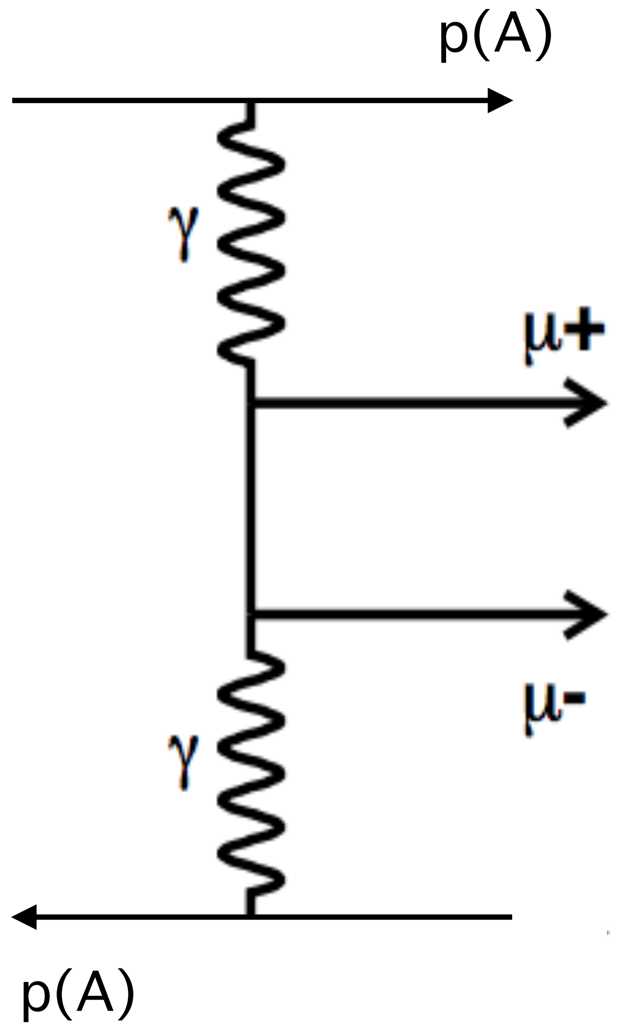

continuous pair production

- remove via fit to invariant mass

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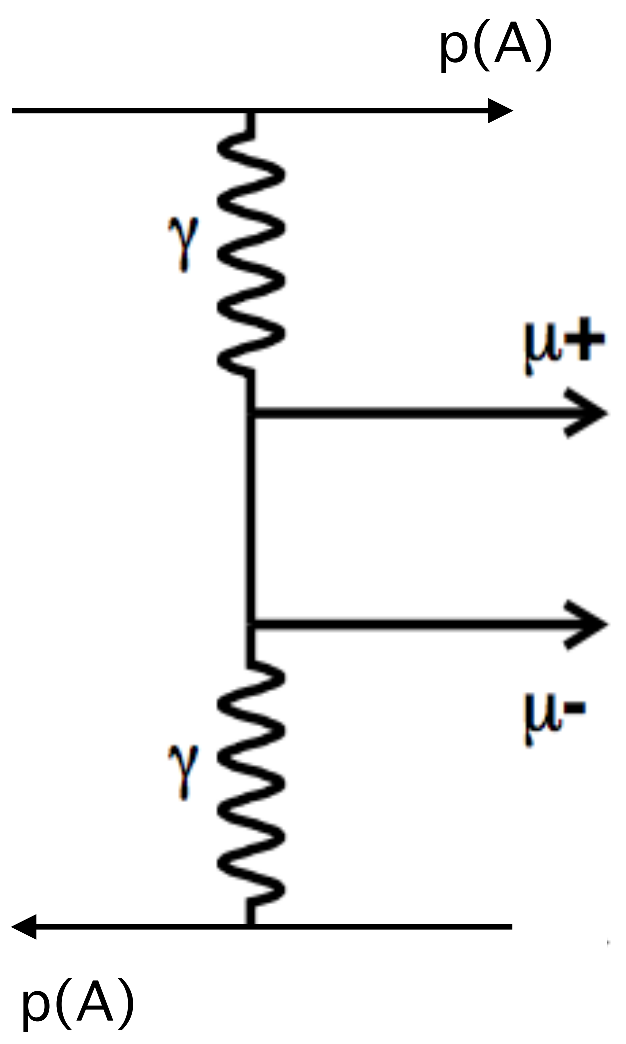

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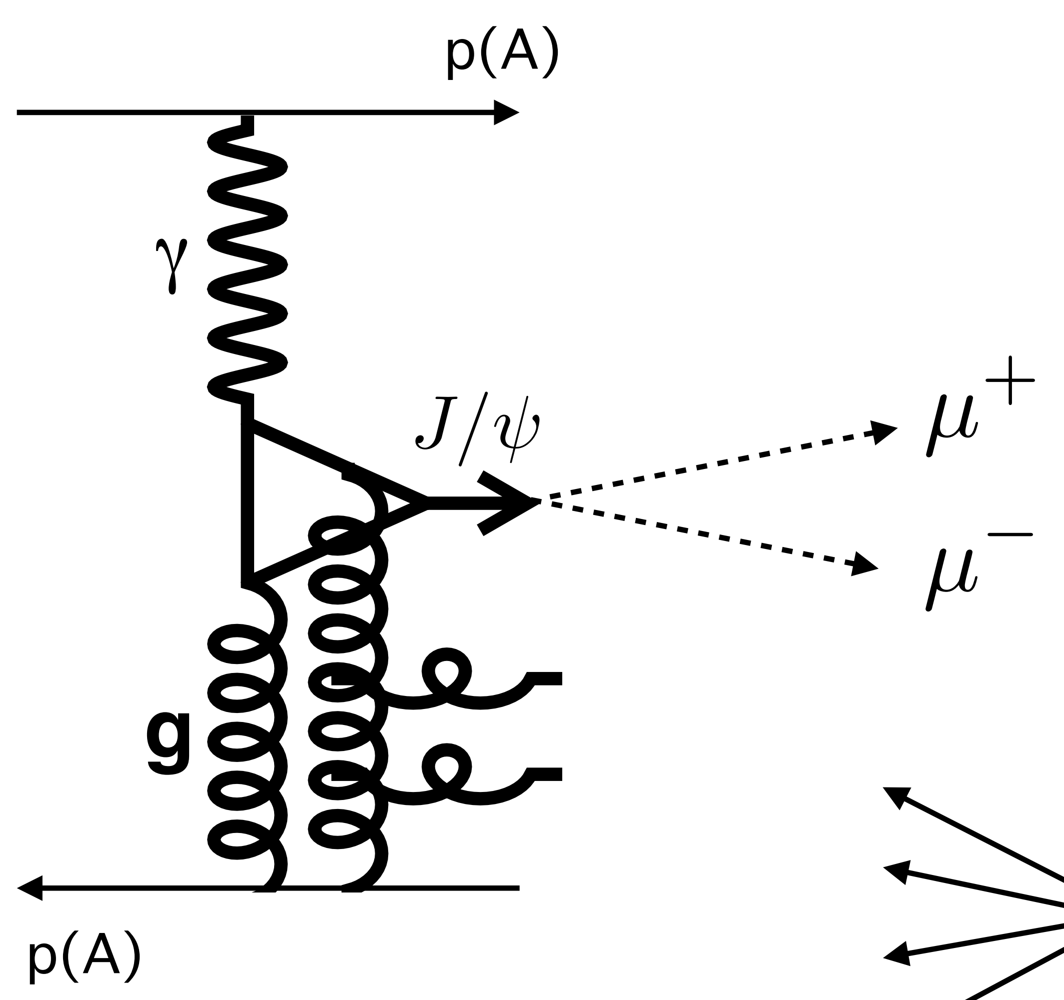
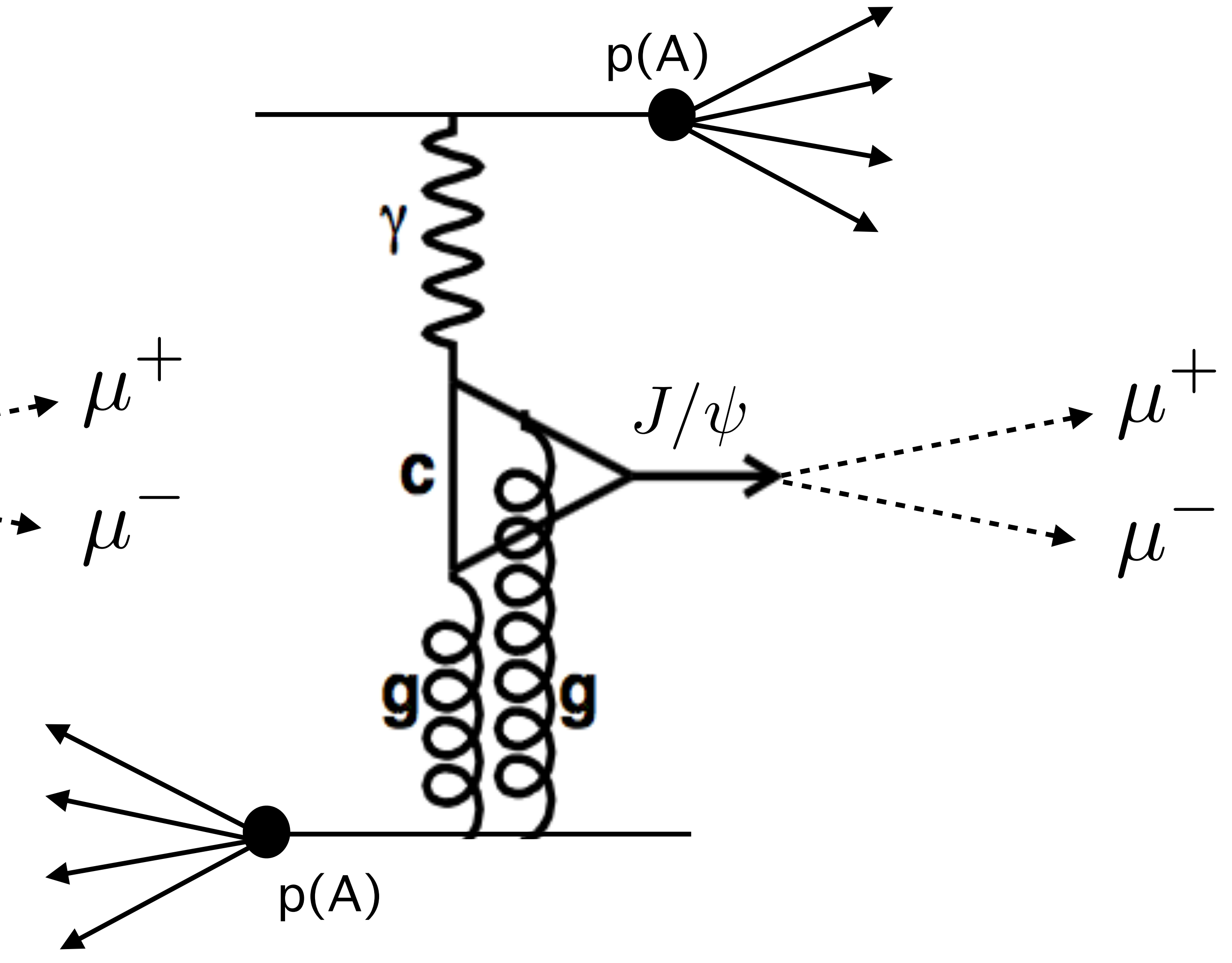


inelastic production

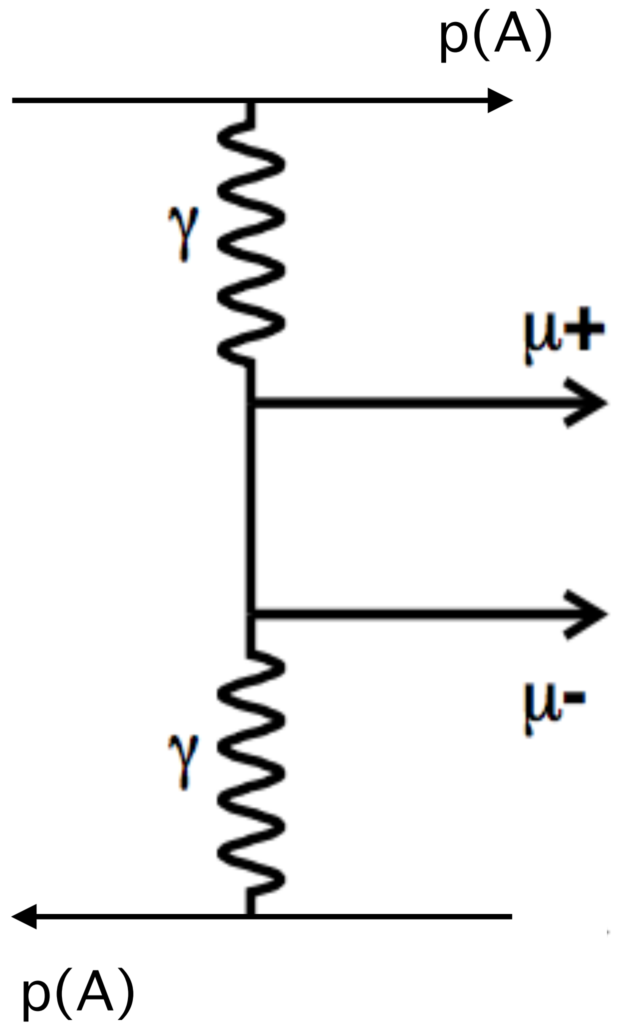


proton/ion dissociation

- remove via fit to invariant mass

- reject via signals in ZDCs, CASTOR, Herschel
- restrict $p_{T,pair}$ to < ~1 GeV
- remove via fit to $p_{T,pair}$
  (model assumption on shape of $p_{T,pair}$ distribution)

Backgrounds to measurements



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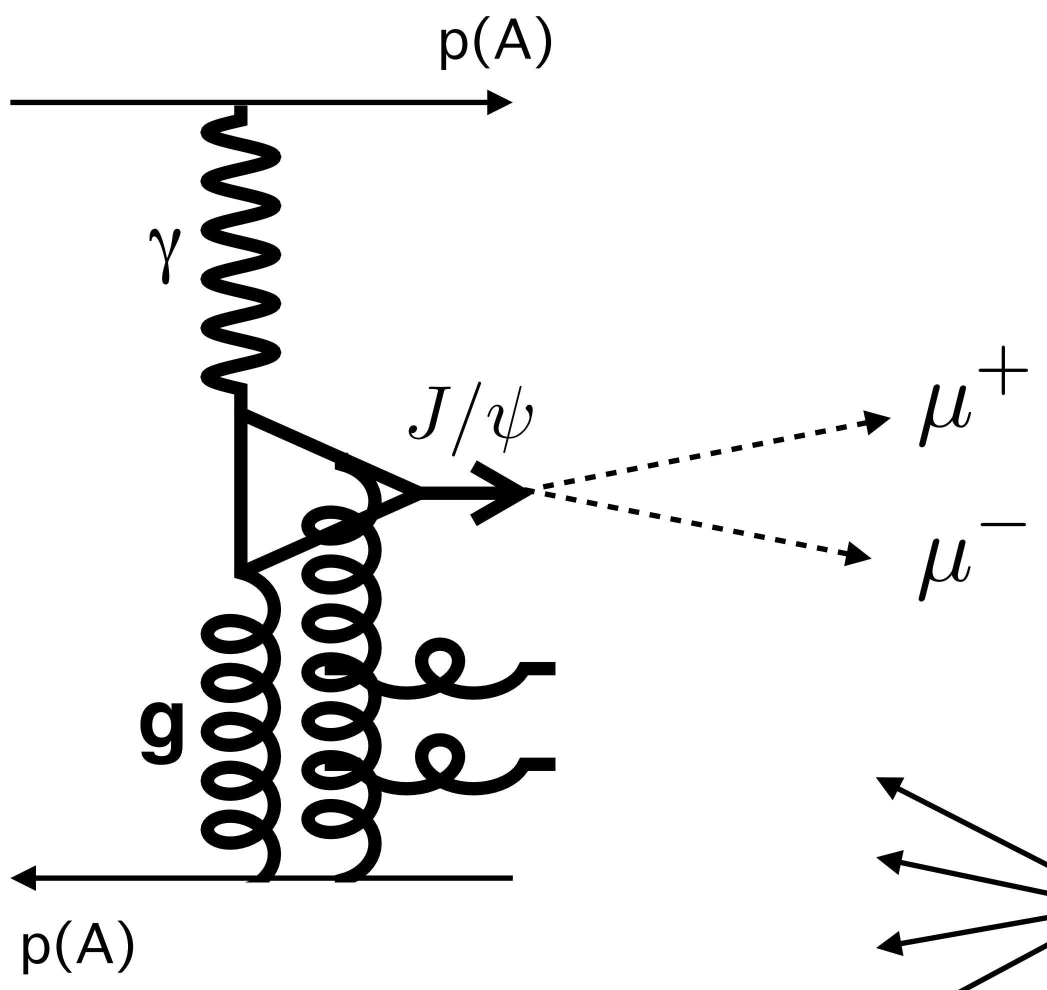

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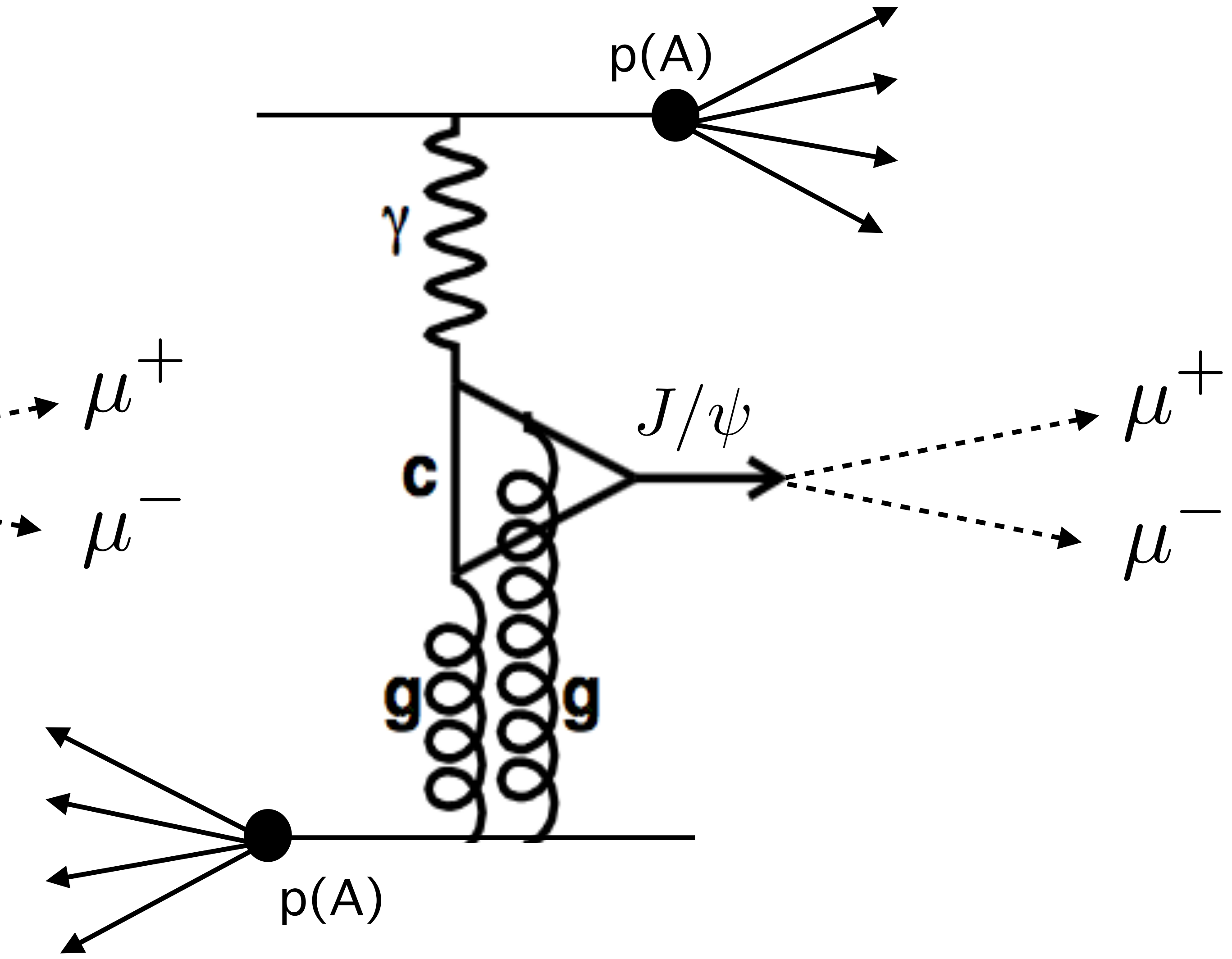

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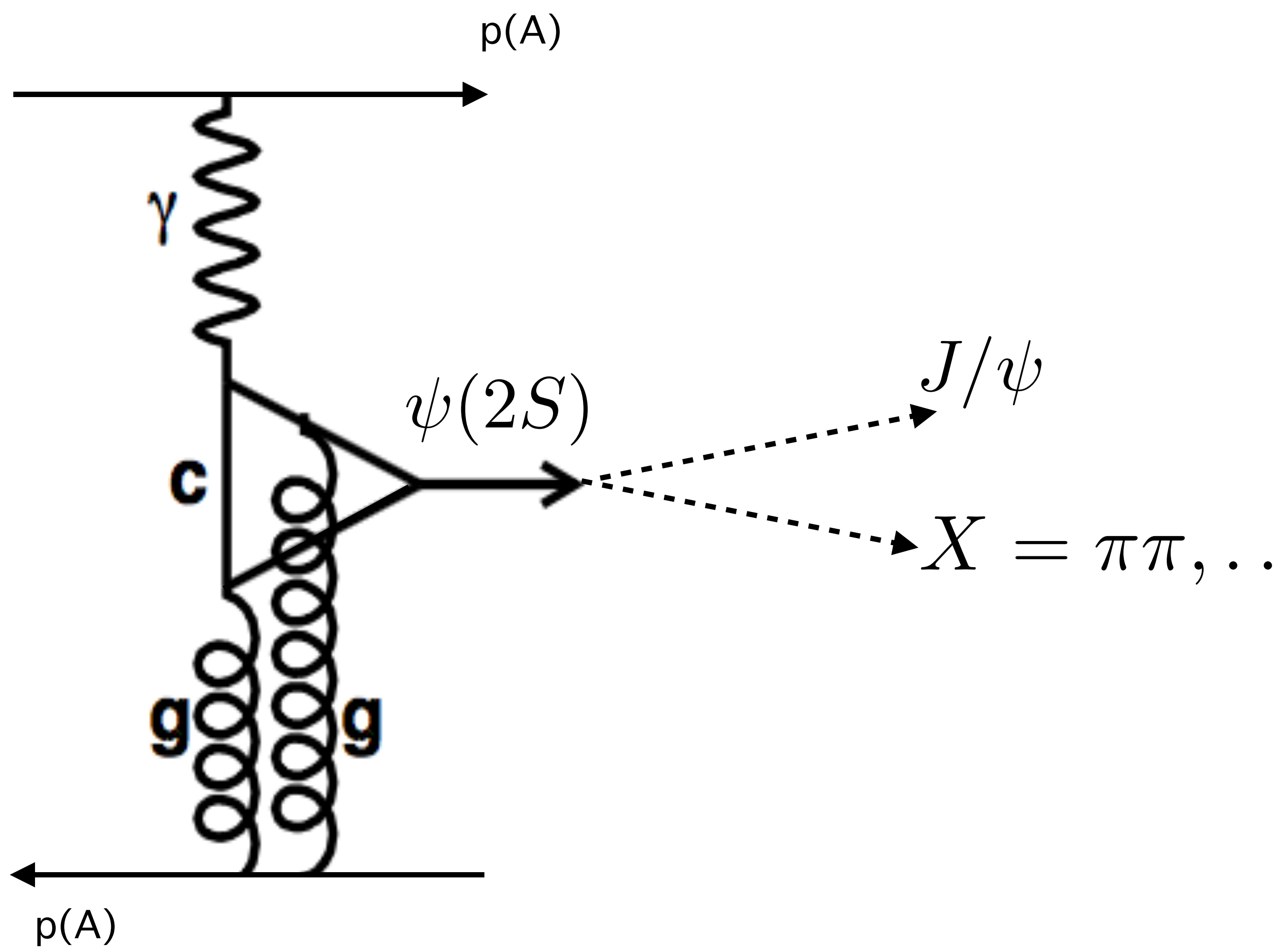

feeddown from higher-mass states

- remove via fit to invariant mass

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  (model assumption on shape of $p_{T,pair}$ distribution)

- reconstruct higher-mass state

Results on J/ψ production in pPb collisions

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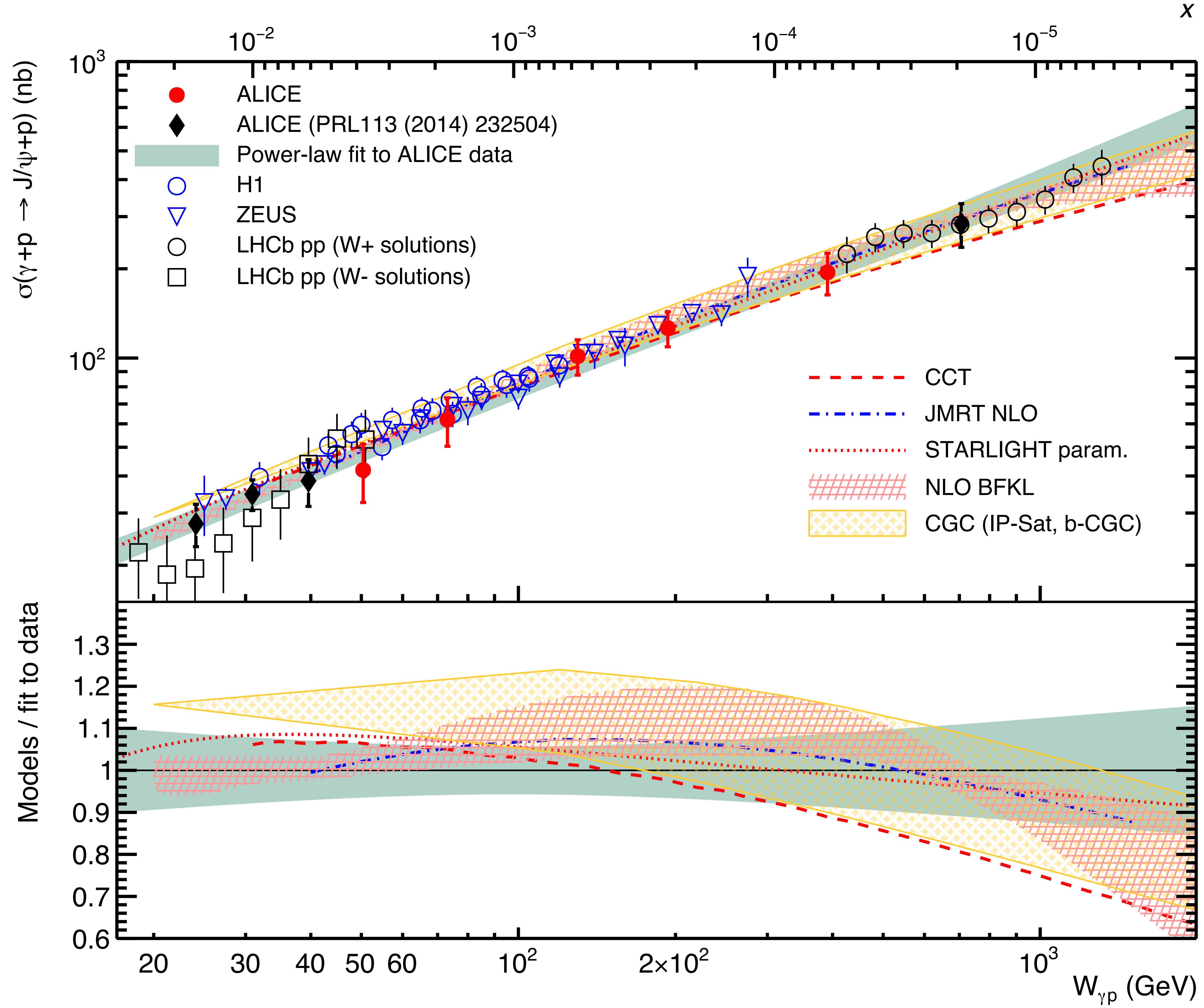
Eur. Phys. J. C **79** ('19) 402



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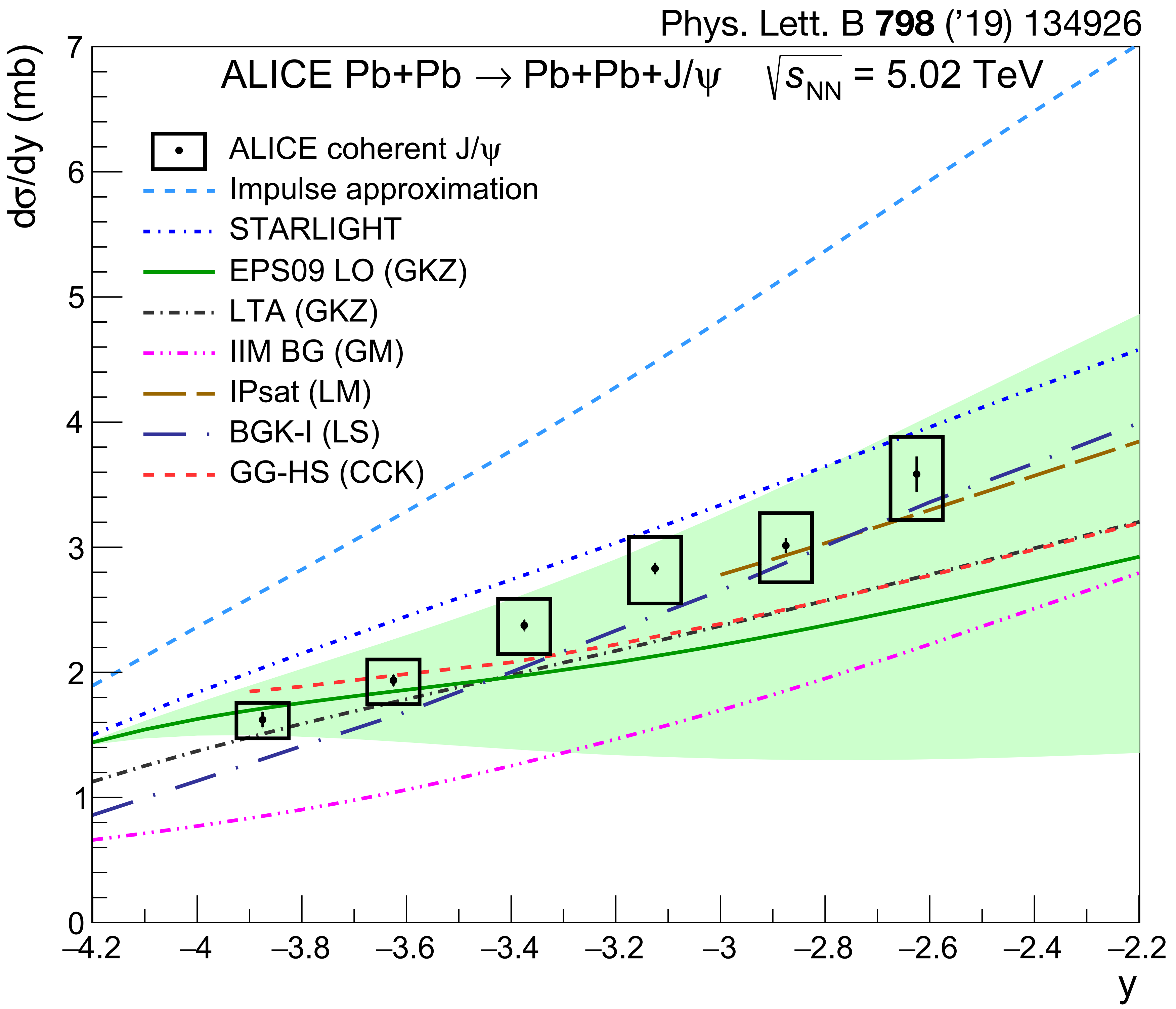

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$0.7 \cdot 10^{-2} < x_B < 3.3 \cdot 10^{-2}$ (dominant)

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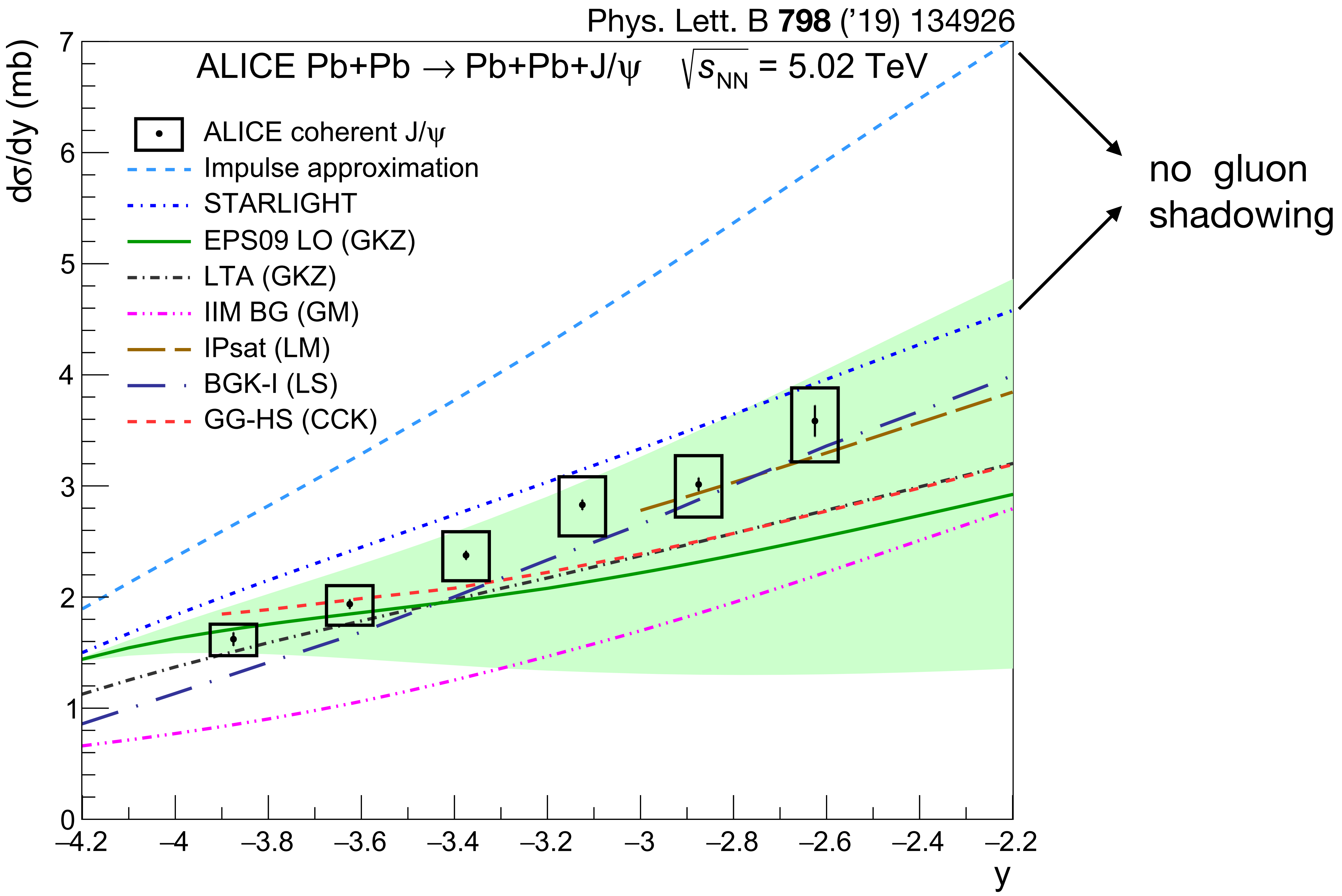

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- access to low-x_B gluon nuclear PDFs
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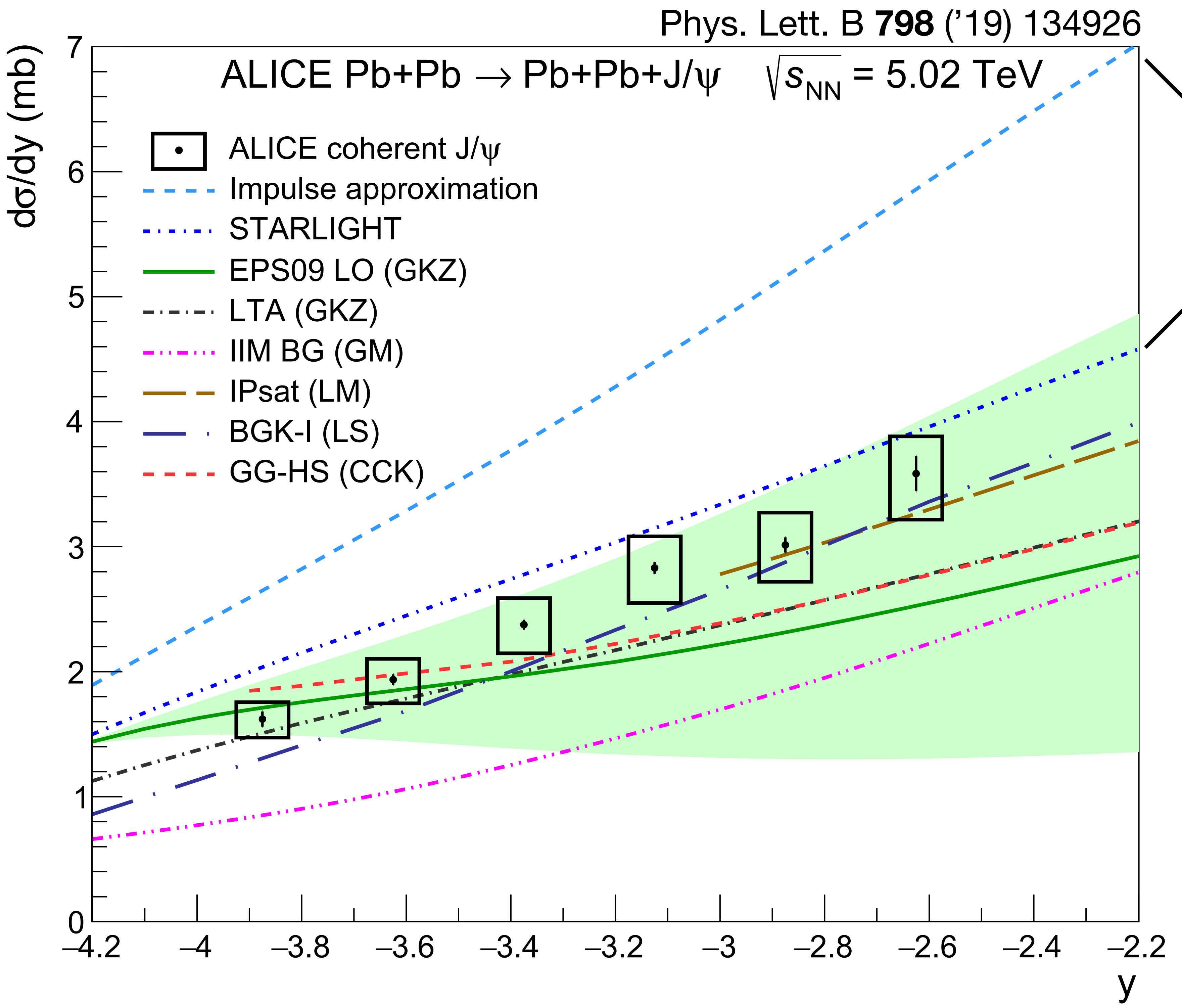
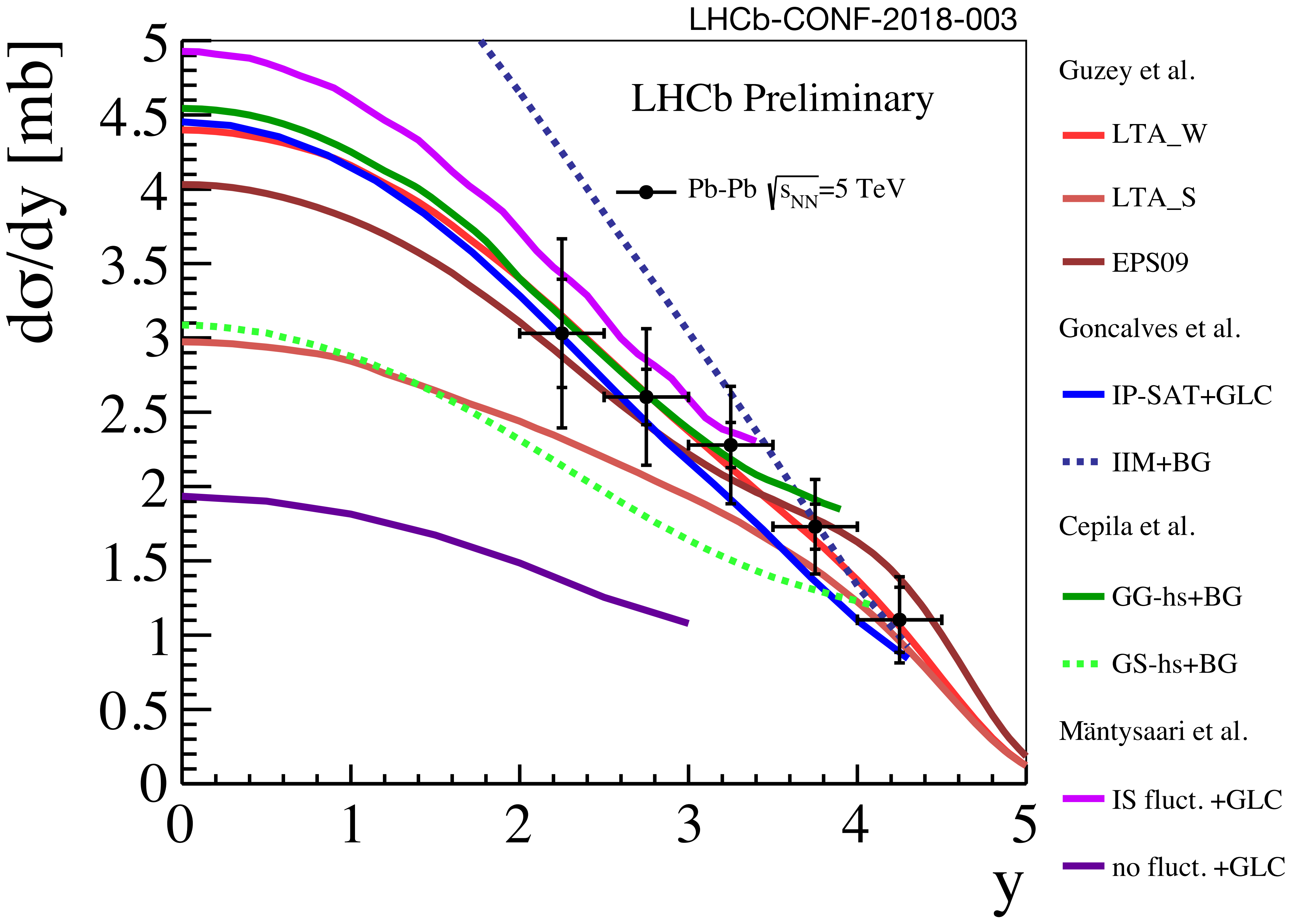


no gluon shadowing



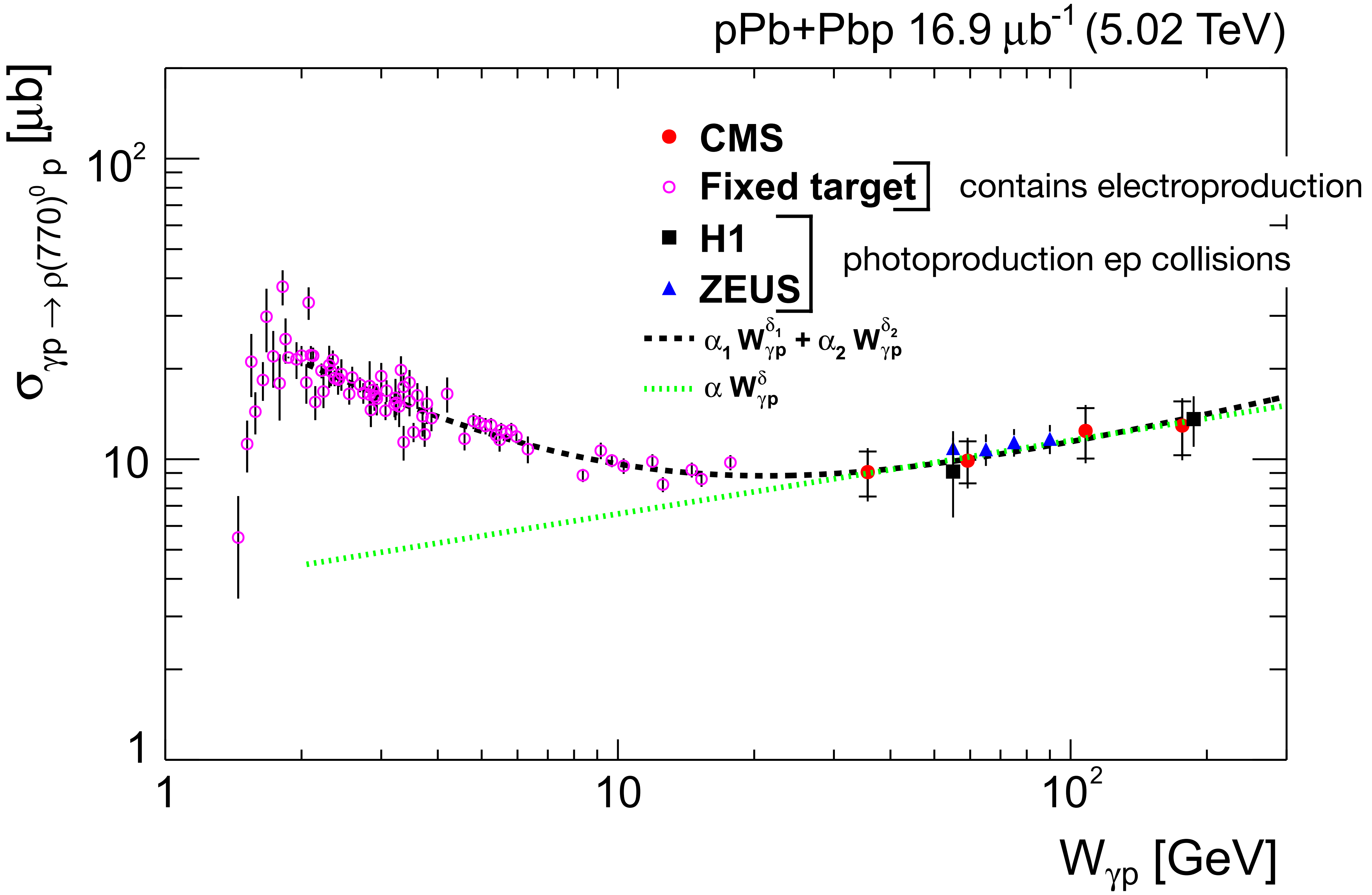
covered x_B region

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

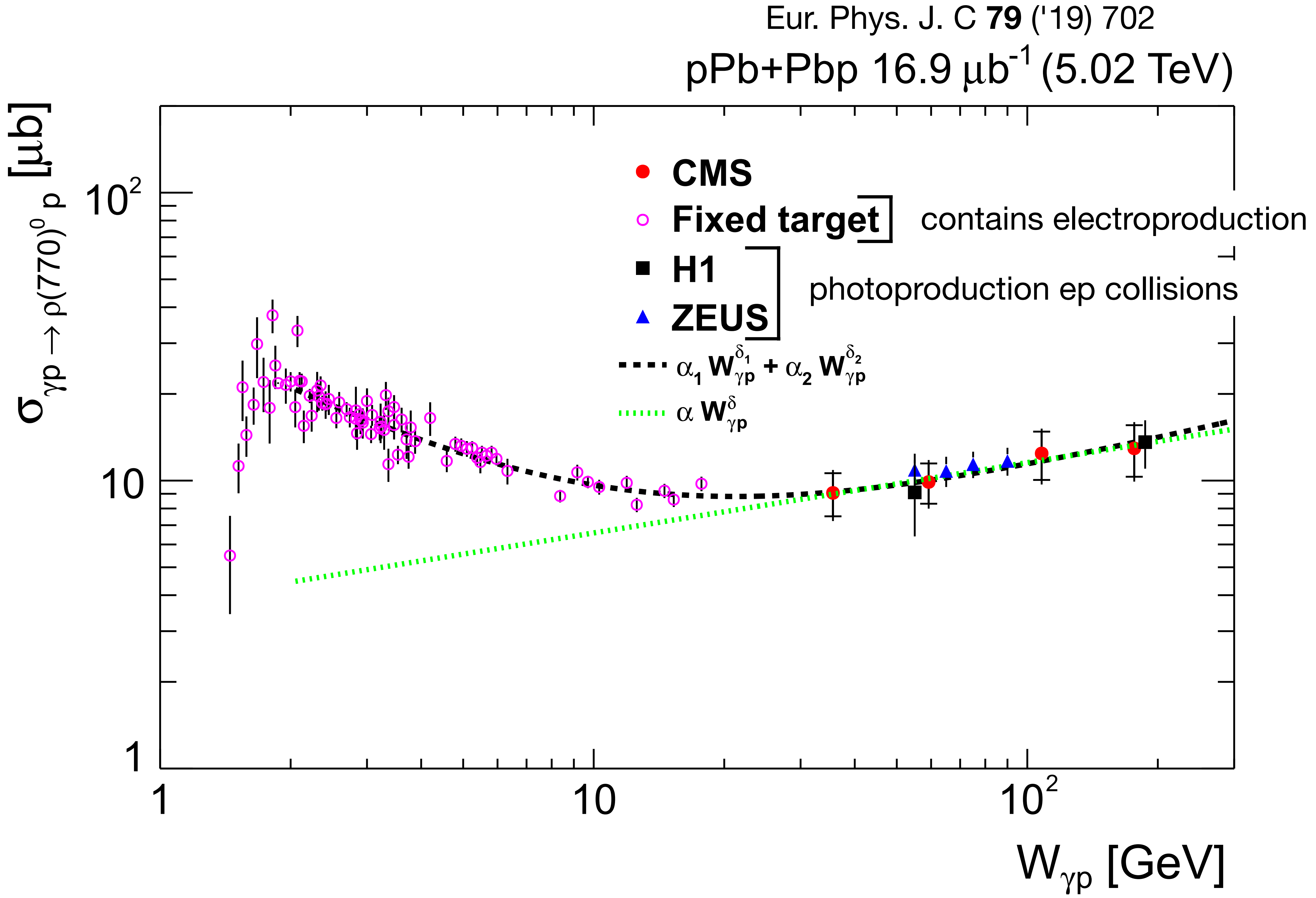
$$1.1 \cdot 10^{-5} < x_B < 5.1 \cdot 10^{-5}$$

Results on ρ^0 in pPb collisions

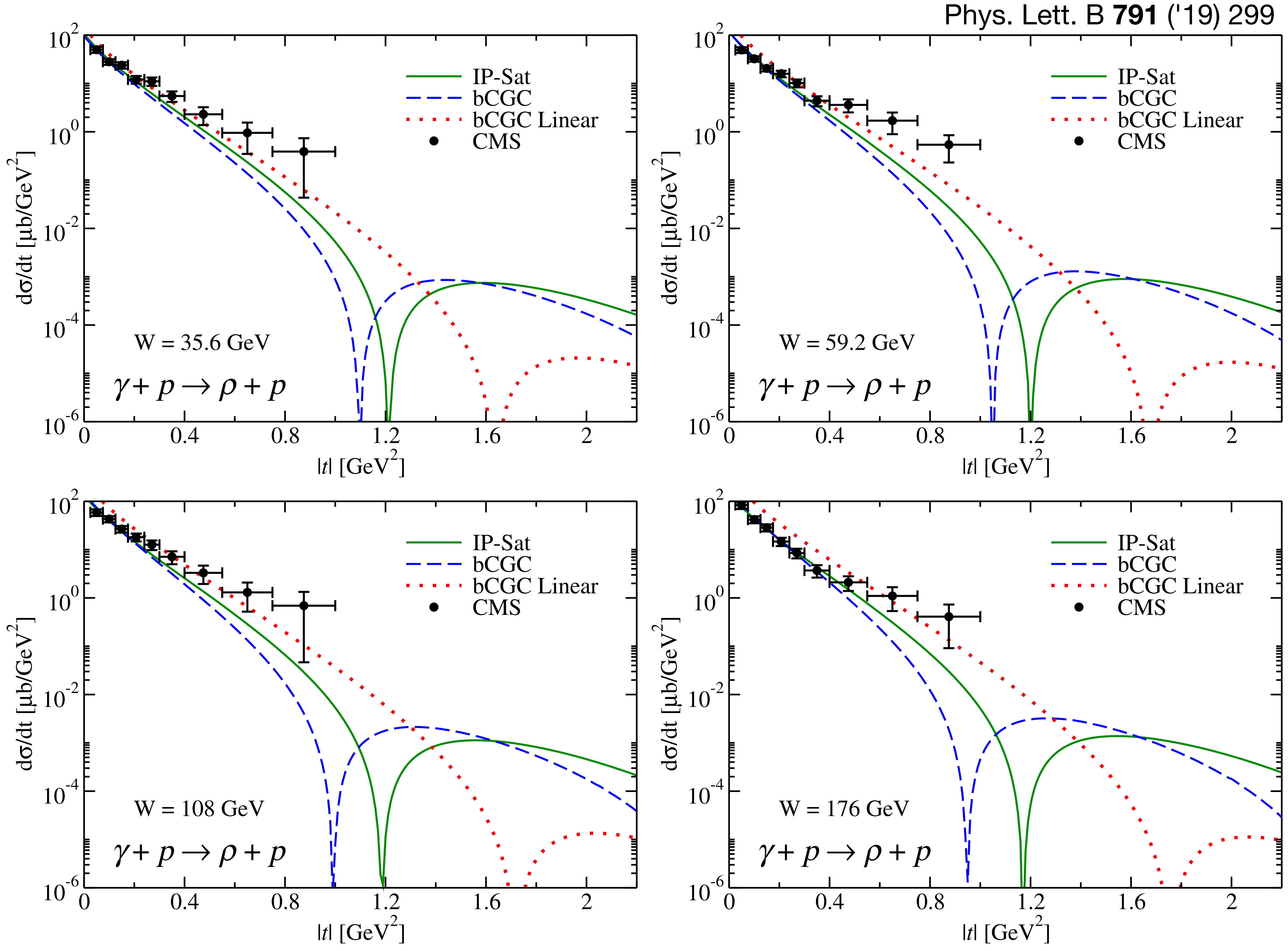
Eur. Phys. J. C **79** ('19) 702



Results on ρ^0 in pPb collisions

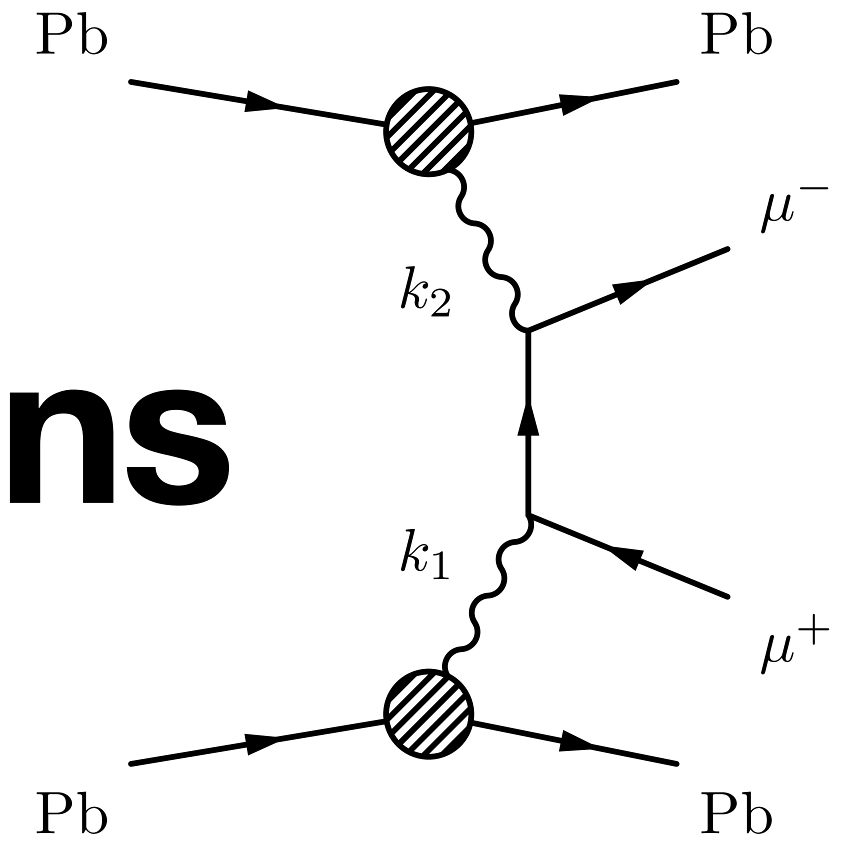


CMS data compared to linear and saturation models



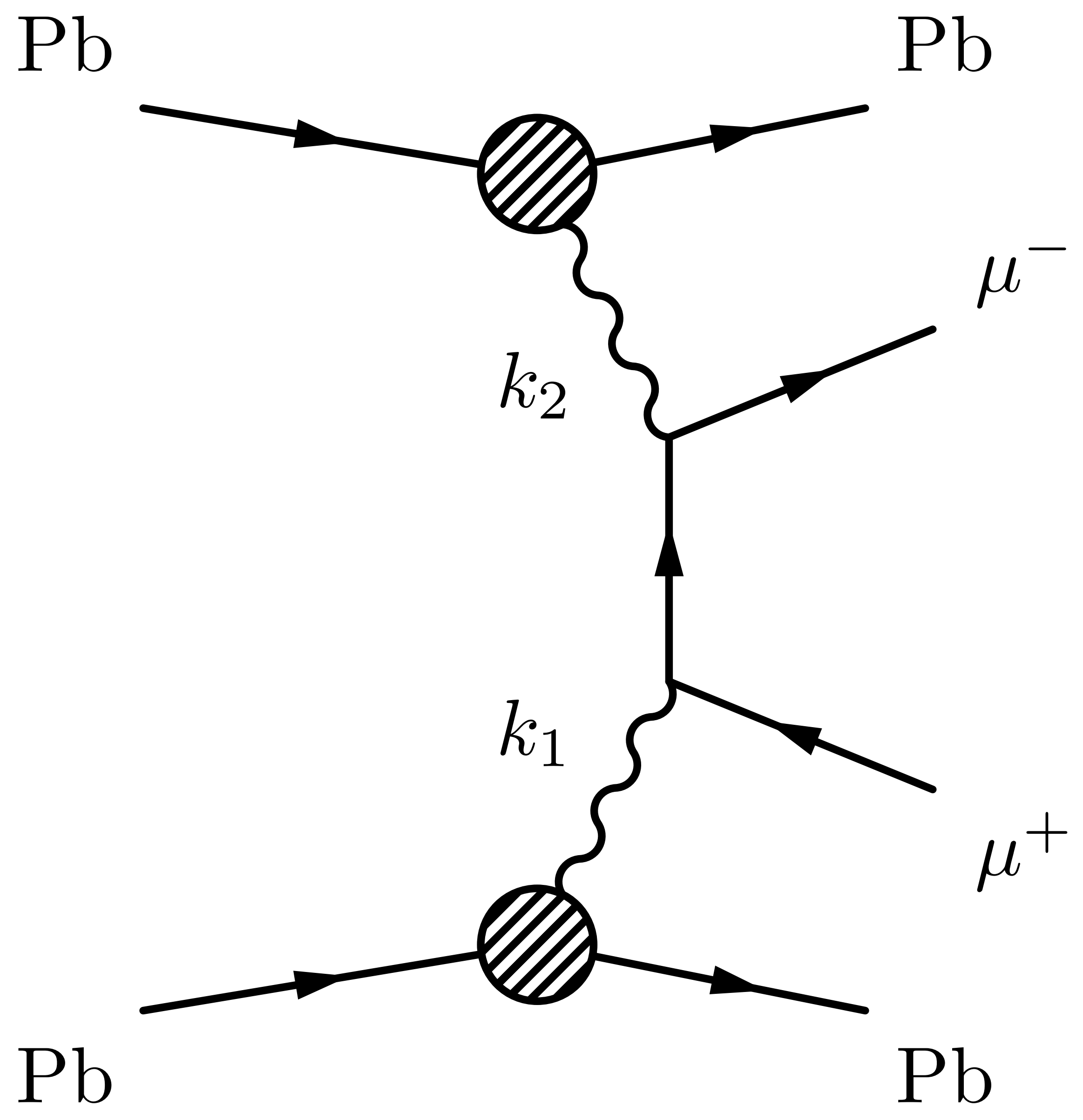
high |t| data needed!

Exclusive continuous dileptons



Exclusive continuous dilepton production

- calibration for
  - photonuclear production of jets, vector mesons, …
  - light-by-light scattering



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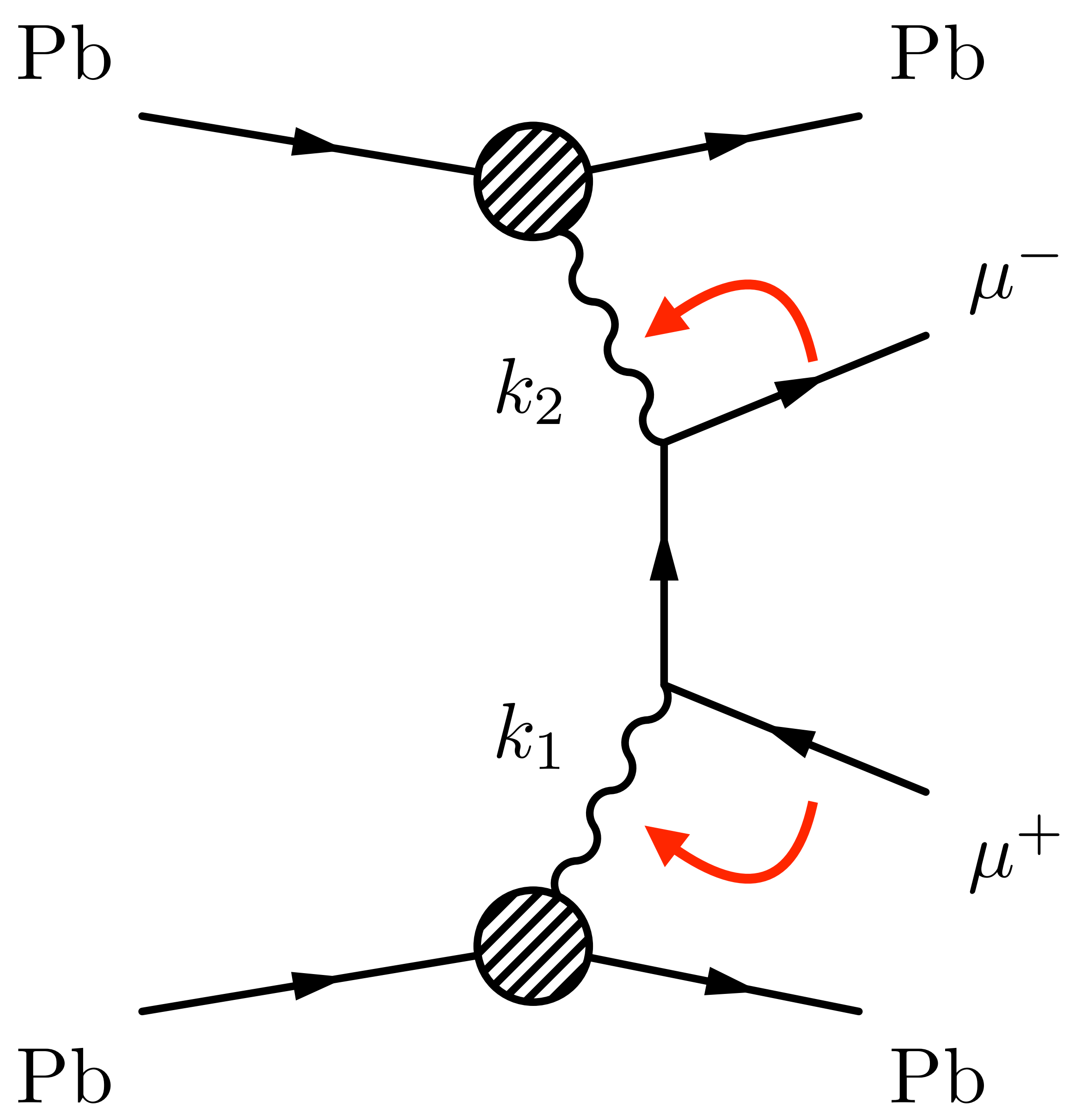

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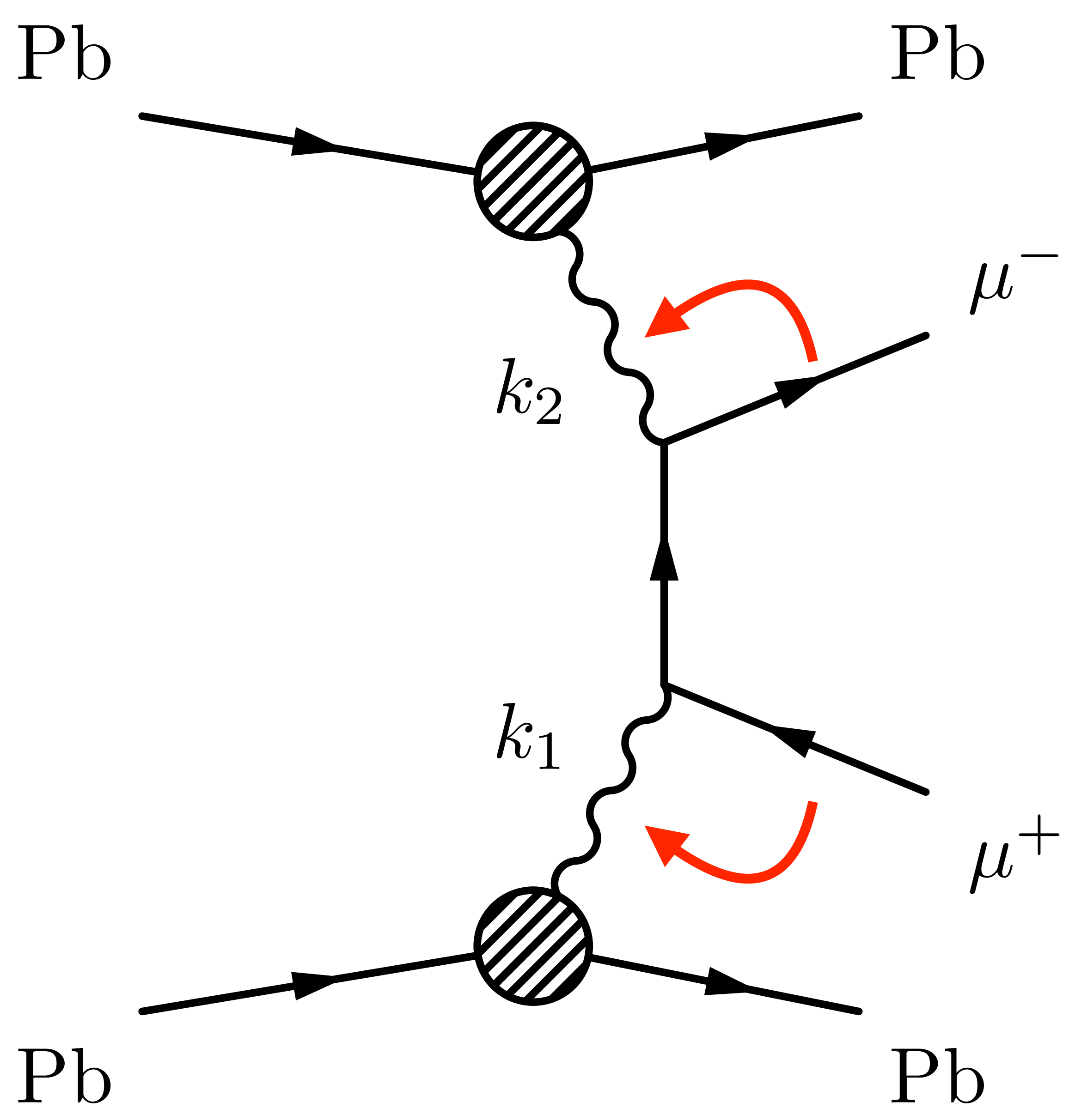

- measurements:
  - ALICE, PbPb (m_{ll}<10 GeV): Eur. Phys. J. C **73** ('13) 2617
  - ATLAS, PbPb (m_{ll}>10 GeV): arXiv:2011.12211
  - ATLAS, pp (m_{ll}>10 GeV): Phys. Lett. B **749** ('15) 242; Phys. Lett. B 777 ('18) 303
  - CMS, pp (m_{ll}<10 GeV): JHEP **1201** ('12) 052

- for m_{ll}>10 GeV: continuous dilepton production is dominant

ATLAS measurement

arXiv:2011.12211

- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=0.48 nb^{-1}
- exactly 2 oppositely charged muons
- $p_{T,\mu} > 4$ GeV
- $|\eta_\mu|<2.4$
- $m_{\mu\mu}>10$ GeV
- $p_{T,\mu\mu}<2$ GeV
- classification of events depending on # neutrons in ZDC

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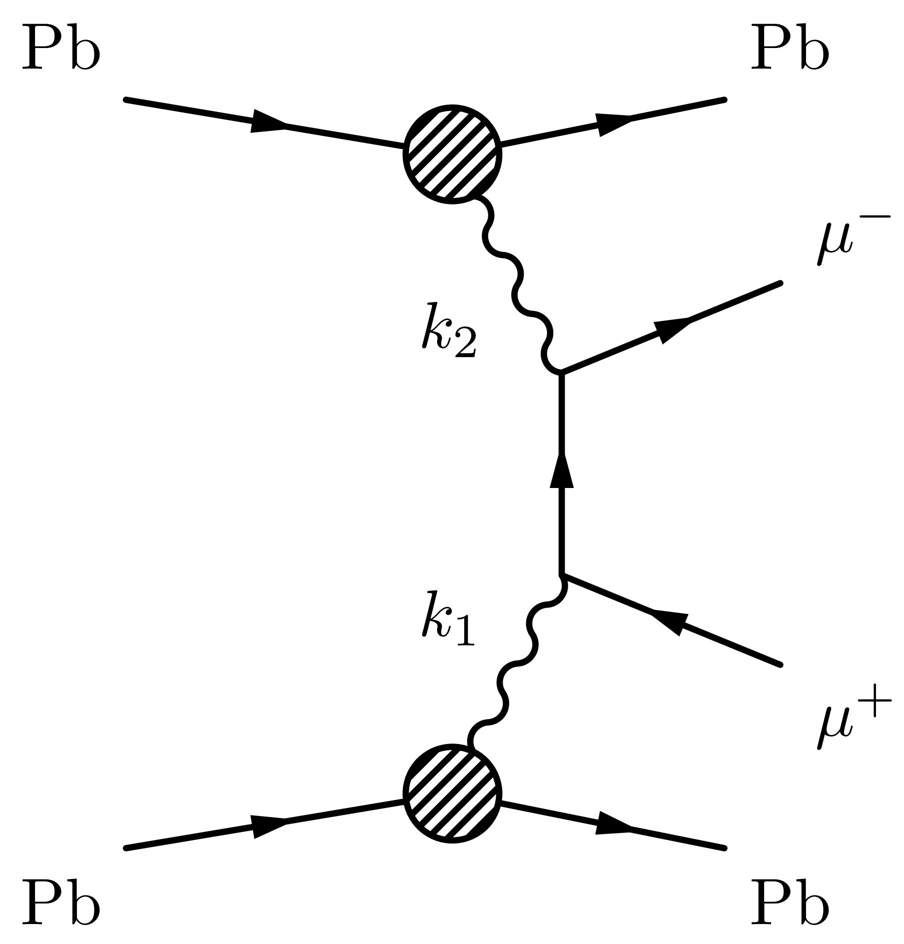
Contributions to event sample



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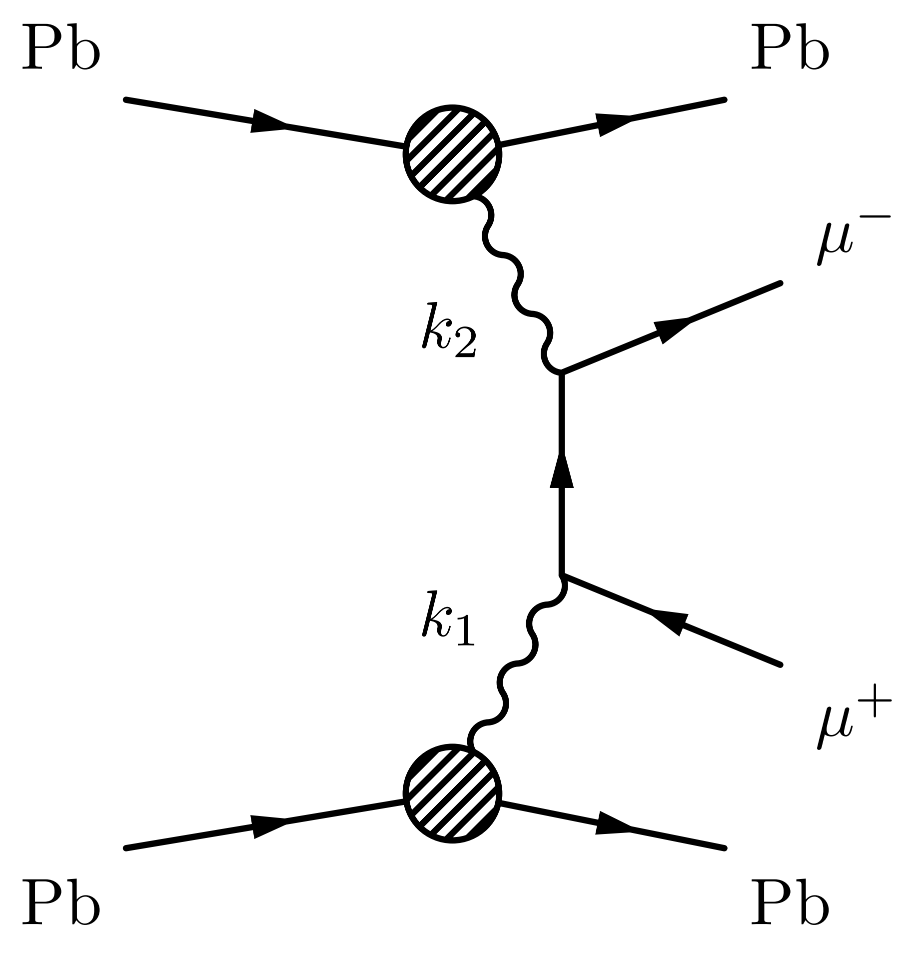
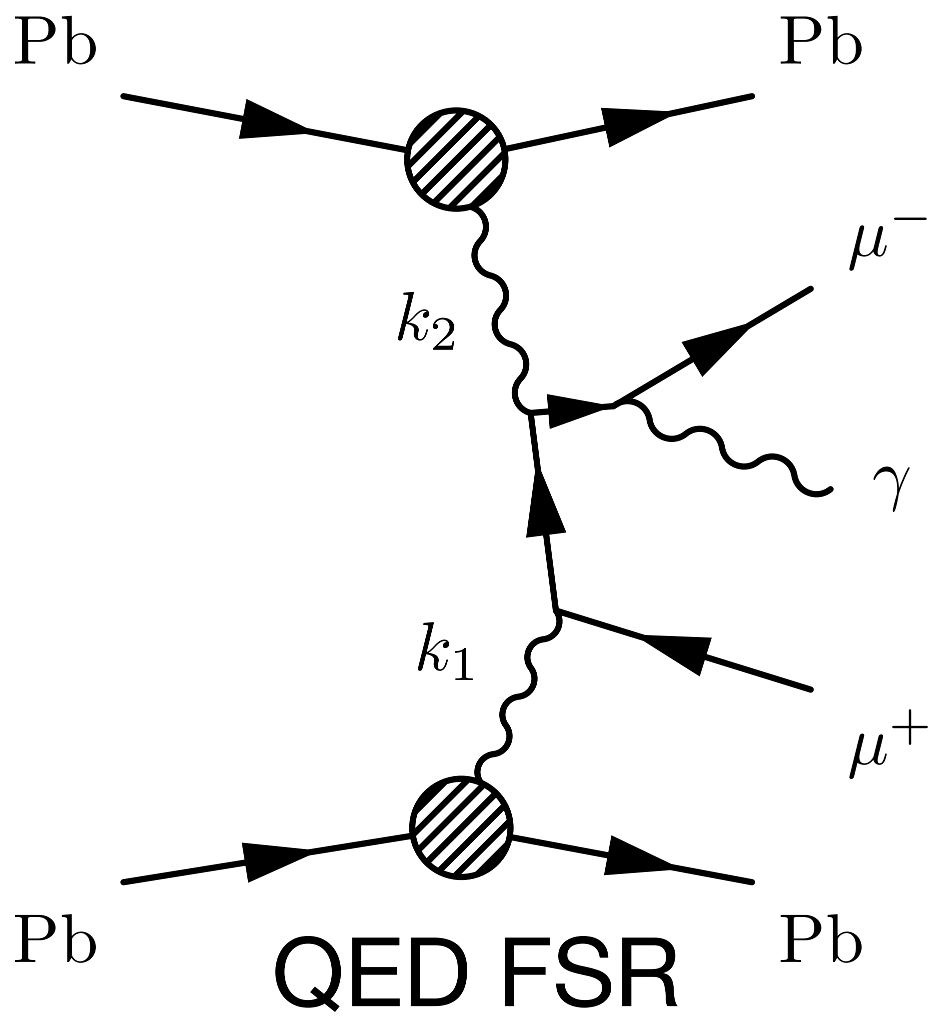
Contributions to event sample

signal





QED FSR

ATLAS measurement

arXiv:2011.12211

- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=0.48 nb^{-1}
- exactly 2 oppositely charged muons
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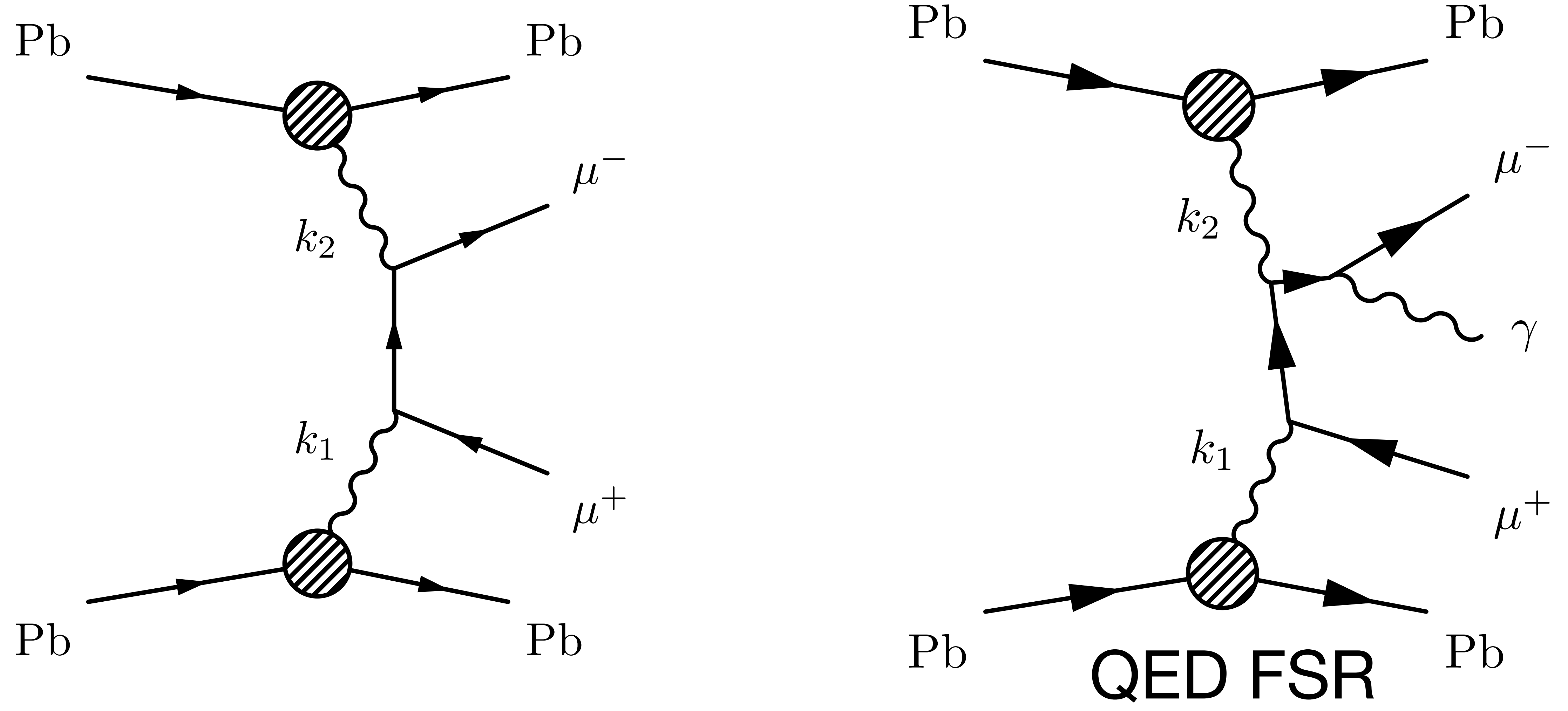
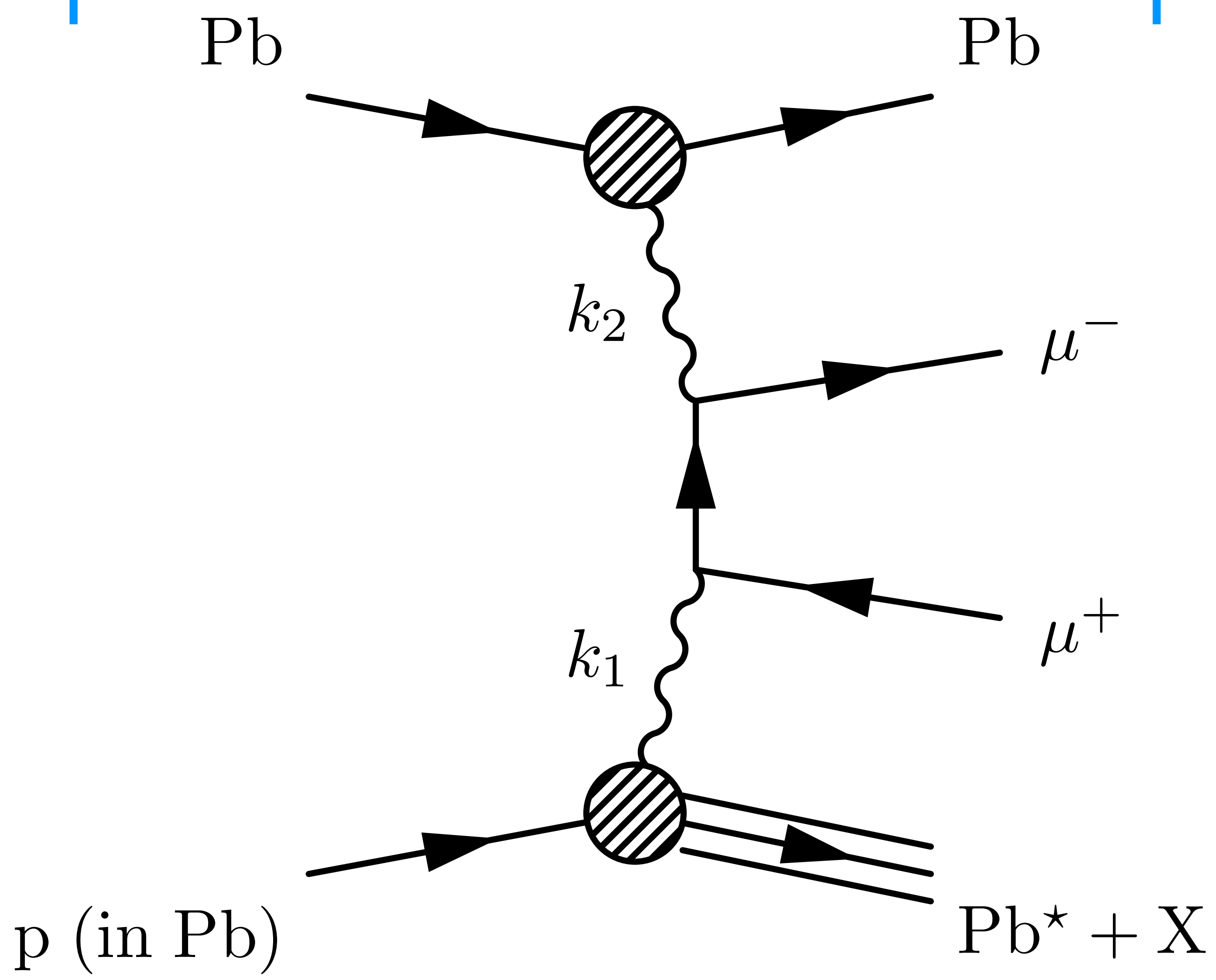
Contributions to event sample

signal



dissociative background correction relies on LPAIR



ATLAS measurement: results

- total fiducial cross section:

$$\sigma_{\text{fid}}^{\mu\mu} = 34.1 \pm 0.3(\text{stat.}) \pm 0.7(\text{syst.})\ \mu\text{b}$$

$$\sigma_{\text{fid}}^{\mu\mu}(\text{STARlight}) = 32.1\ \mu\text{b}$$

$\sigma_{\text{fid}}^{\mu\mu}(\text{STARlight+PYTHIA8}) = 30.8\ \mu\text{b}$ (with QED FSR)

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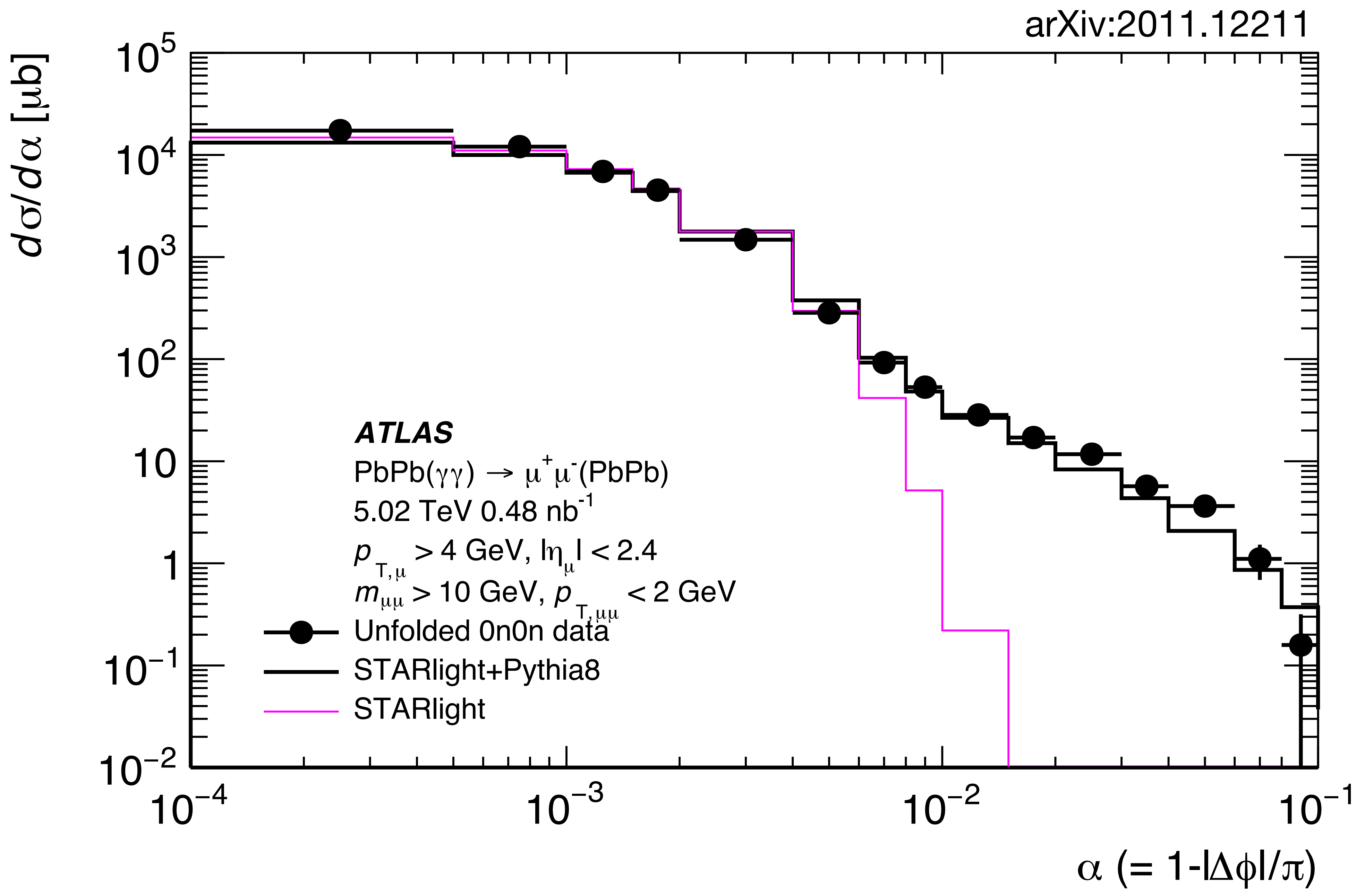
- acoplanarity:



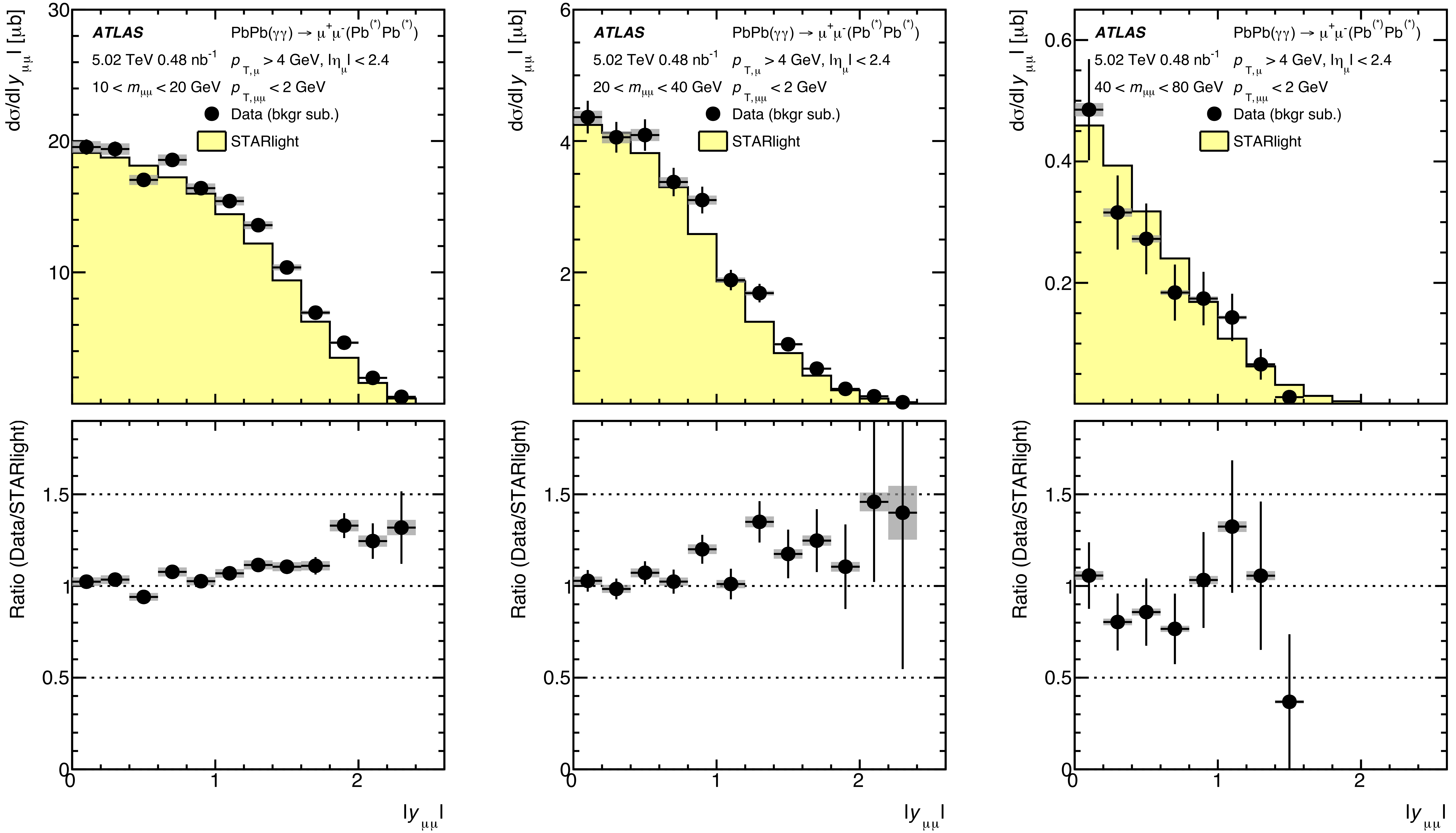
no neutrons in ZDC

⟶ **α**>0.01: higher-order QED

ATLAS measurement: results

- rapidity dependence:

arXiv:2011.12211



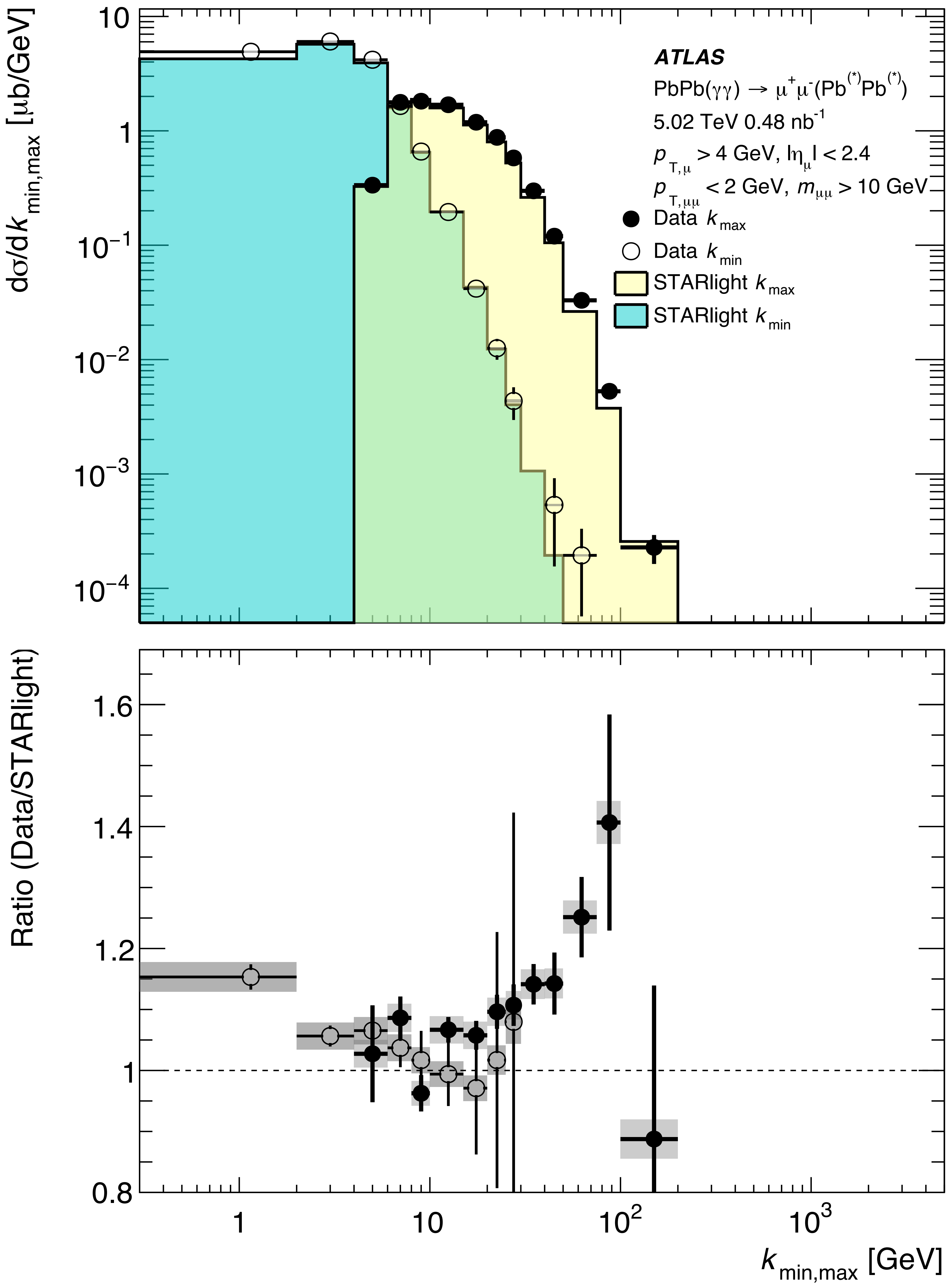
discrepancy at large rapidity

ATLAS measurement: results

- photon-energy dependence:

$$k_{1,2} = \frac{1}{2}\, m_{\mu\mu} e^{\pm y_{\mu\mu}}$$

arXiv:2011.12211



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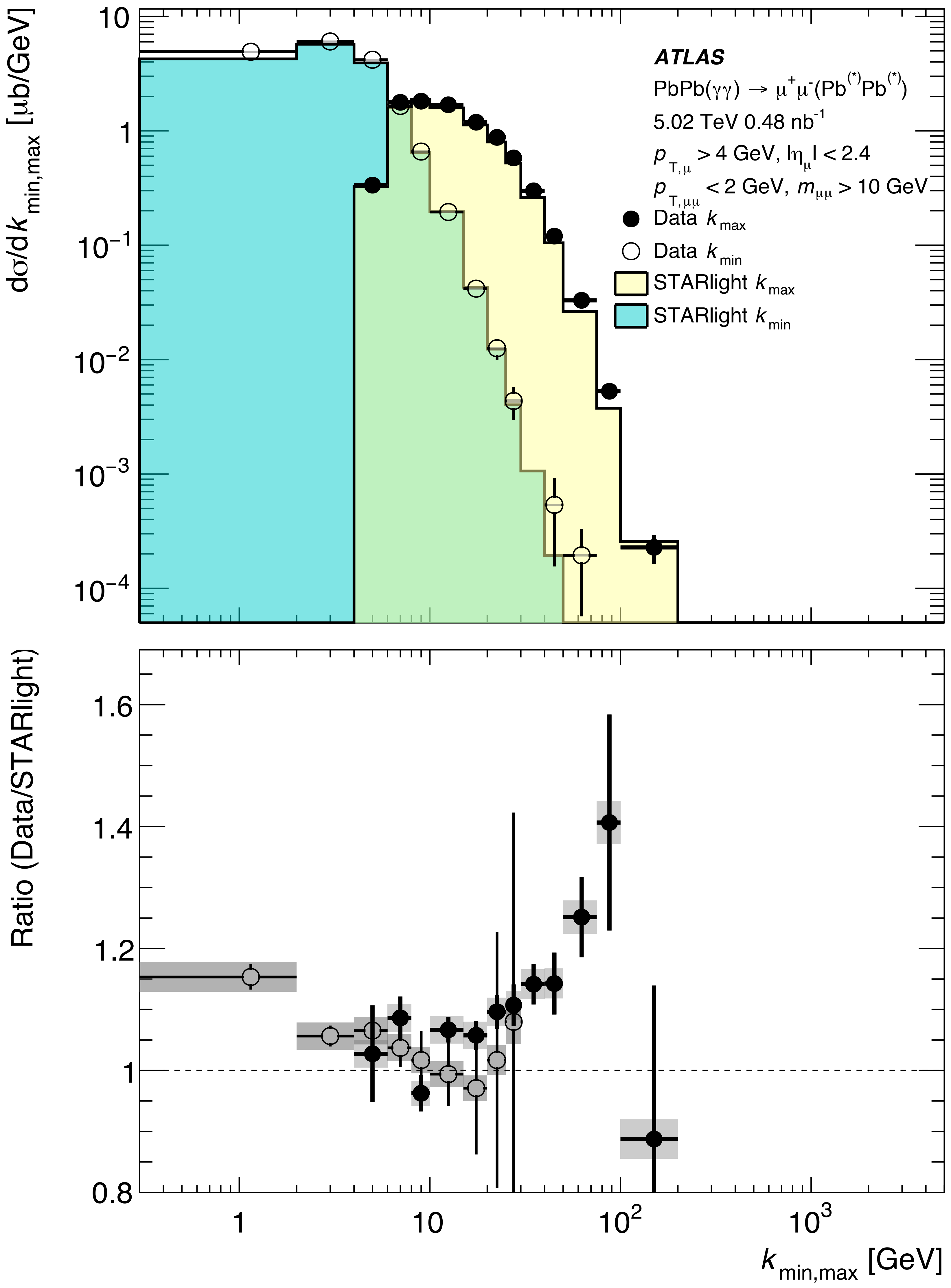
arXiv:2011.12211

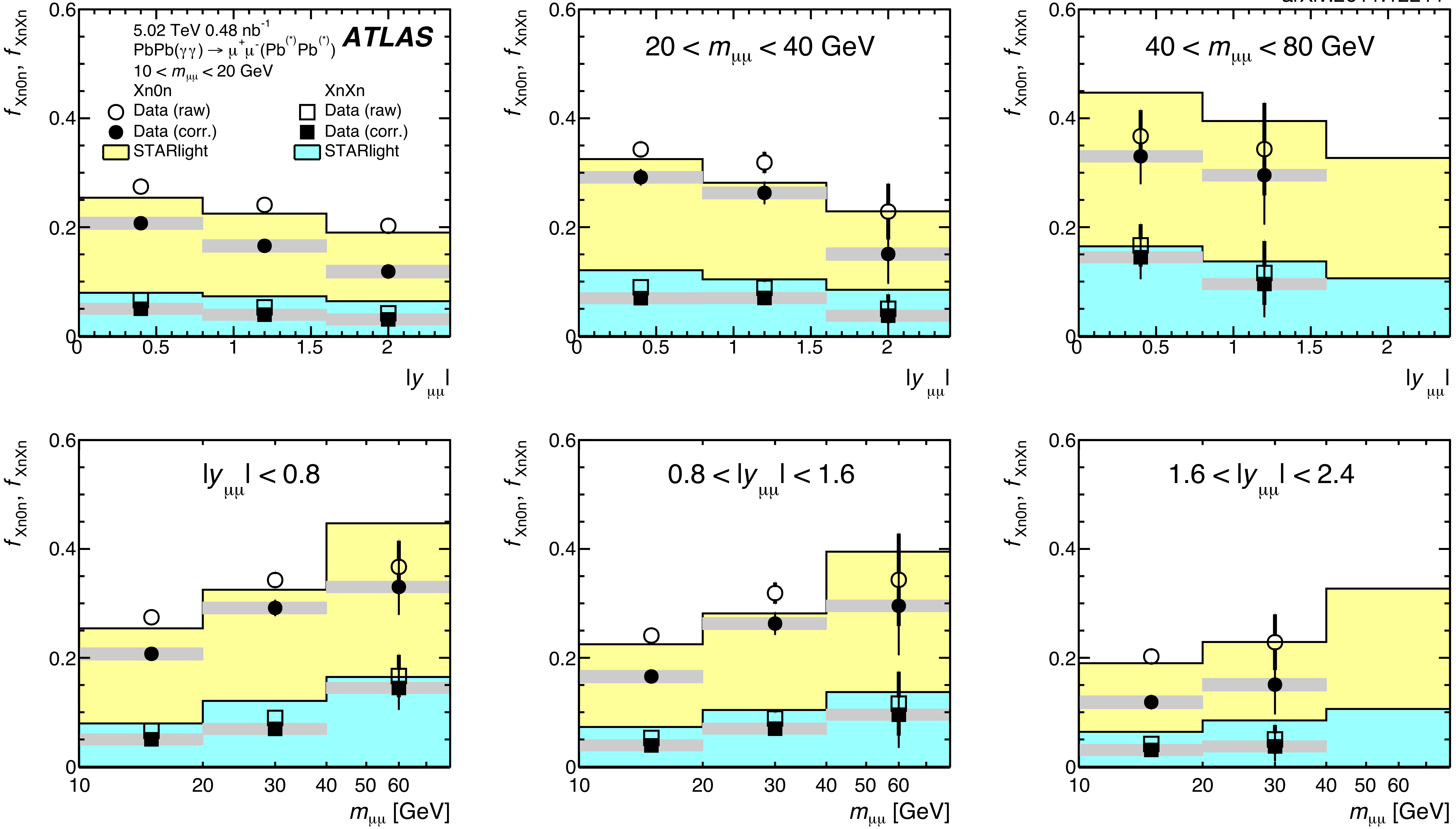


path to reduce discrepancy:
inclusion of **γγ** collisions inside nucleus

ATLAS measurement: results

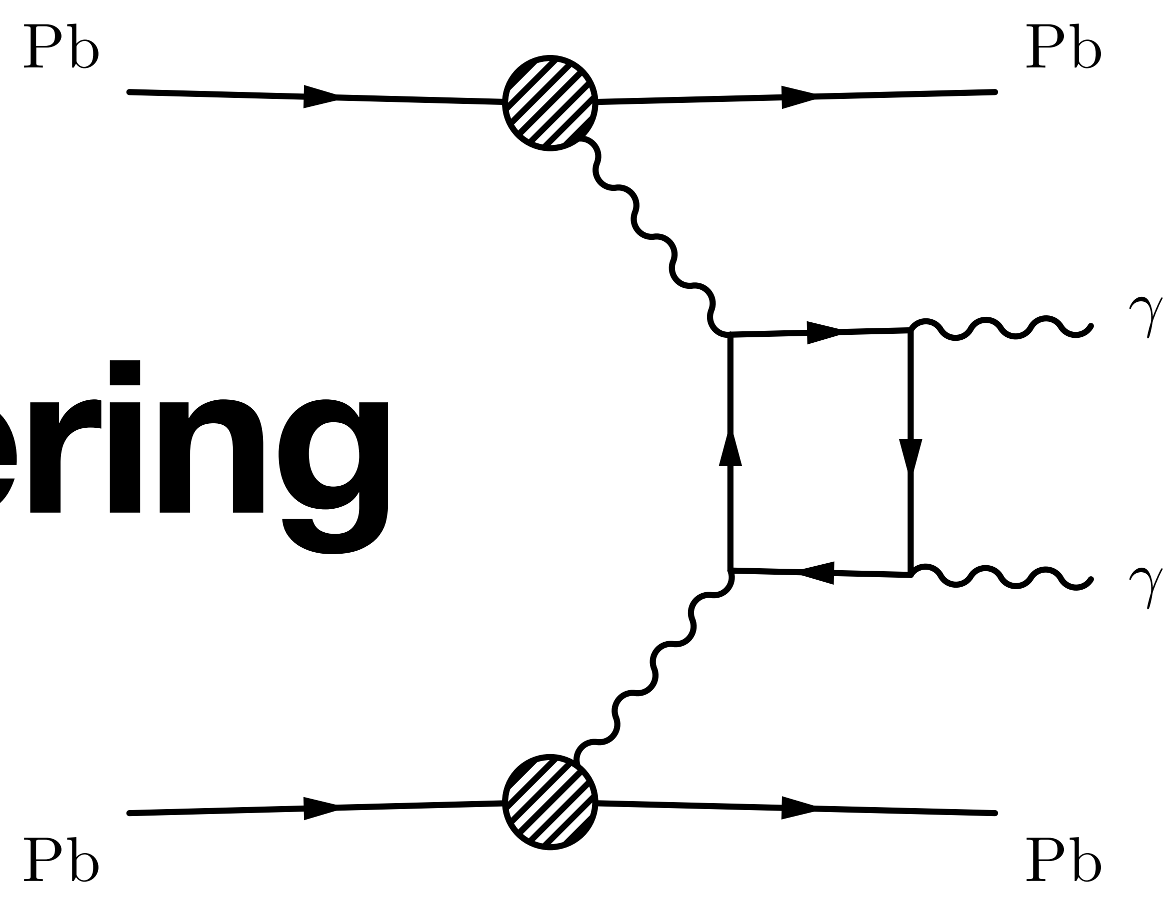
- fractions of events with neutrons in 1 ZDC (Xn0n) and 2 ZDCs (XnXn):

arXiv:2011.12211



STARlight overestimates fractions

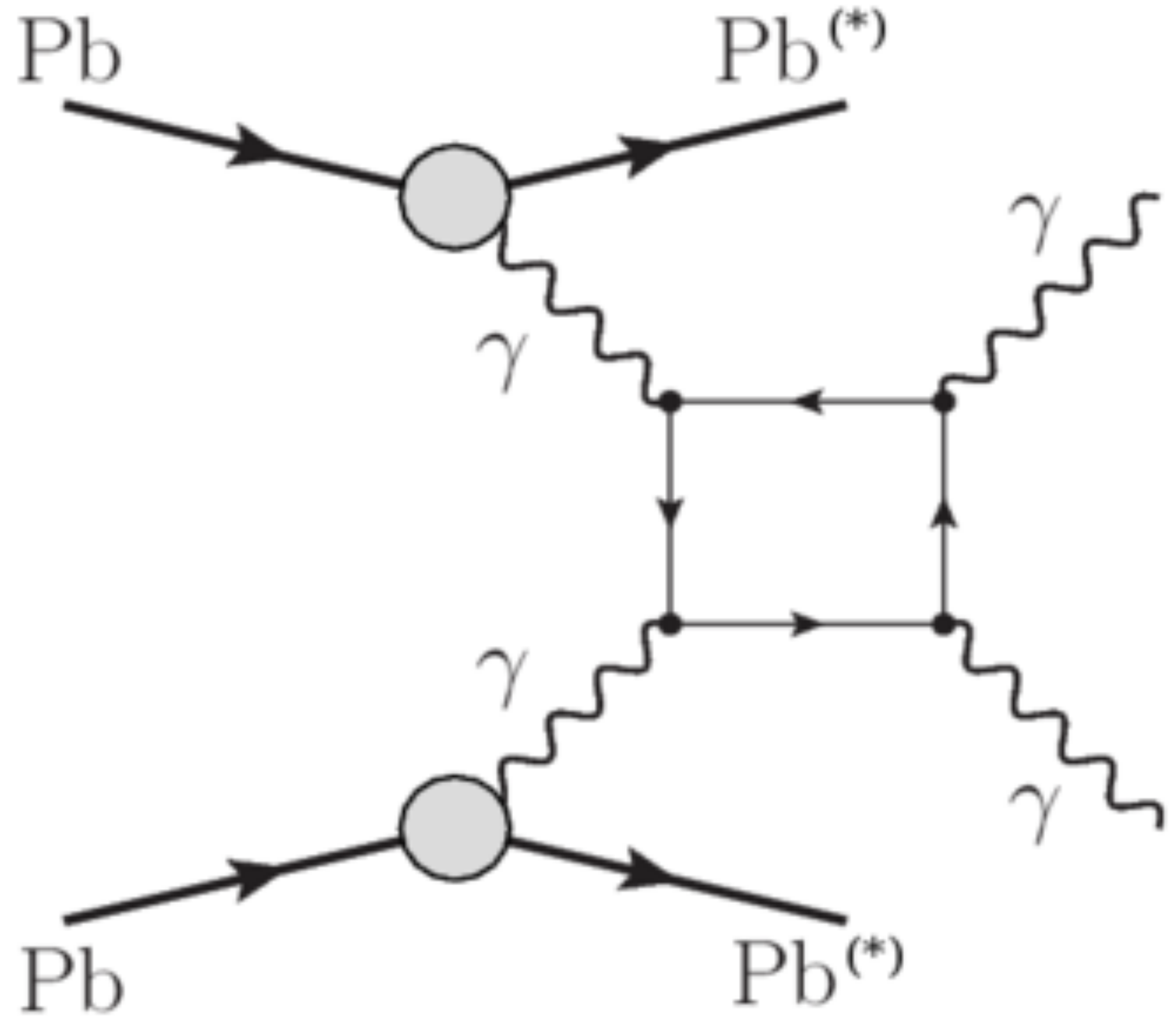
Light-by-light scattering



light-by-light scattering

Light-by-light scattering

- purely quantum-mechanical at $O(\alpha_{EM}^4)$
- substantial QED correction to electron, muon anomalous magnetic moment
- possibly sensitive to new physics (axion-like particles)



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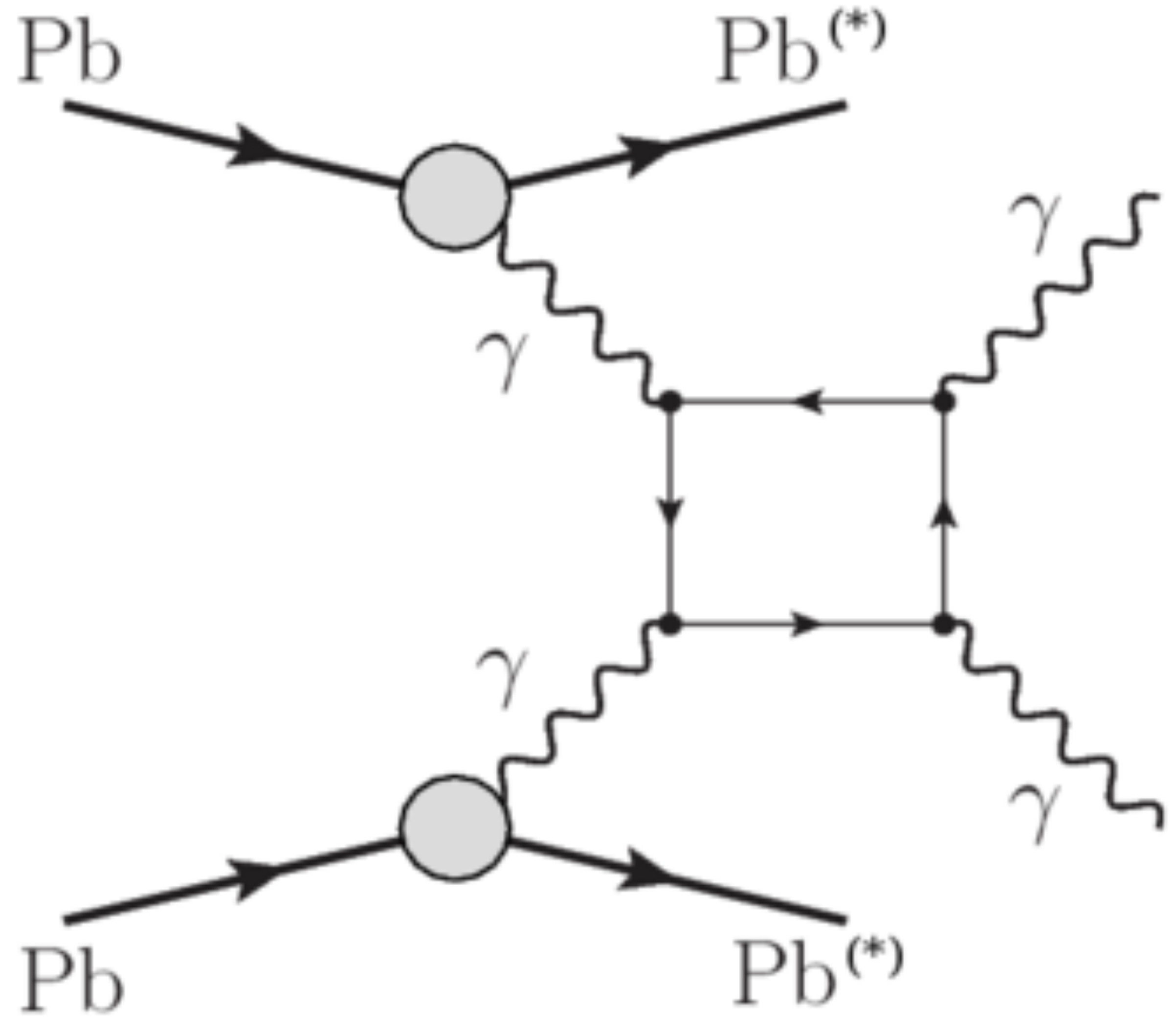

- measurements:
  - ATLAS: Nat. Phys. **13** ('17) 852; Phys. Rev. Lett. **123** ('19) 052001.
  - CMS: Phys. Lett. B 797 ('19) 134826

ATLAS and CMS measurements

ATLAS

- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=1.73 nb^{-1}
- exactly 2 photons
- $E_{T,\gamma} > 3$ GeV; $|\eta_\gamma|<2.4$
- $m_{\gamma\gamma}>6$ GeV
- $p_{T,\gamma\gamma}<1$ GeV or 2 GeV (for $m_{\gamma\gamma}<$ or >12 GeV)
- $(1-|\Delta\phi|/\pi)<0.01$

CMS

- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=390 μb^{-1}
- exactly 2 photons
- $E_{T,\gamma} > 2$ GeV; $|\eta_\gamma|<2.4$
- $m_{\gamma\gamma}>5$ GeV
- $p_{T,\gamma\gamma}<1$ GeV
- $(1-|\Delta\phi|/\pi)<0.01$

ATLAS and CMS measurements

ATLAS

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- exactly 2 photons
- $E_{T,\gamma}$ > 3 GeV; $|\eta_\gamma|$<2.4
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- PbPb at $\sqrt{s_{NN}} = 5.02\ \mathrm{TeV}$; $\mathscr{L}$=390 μb^{-1}
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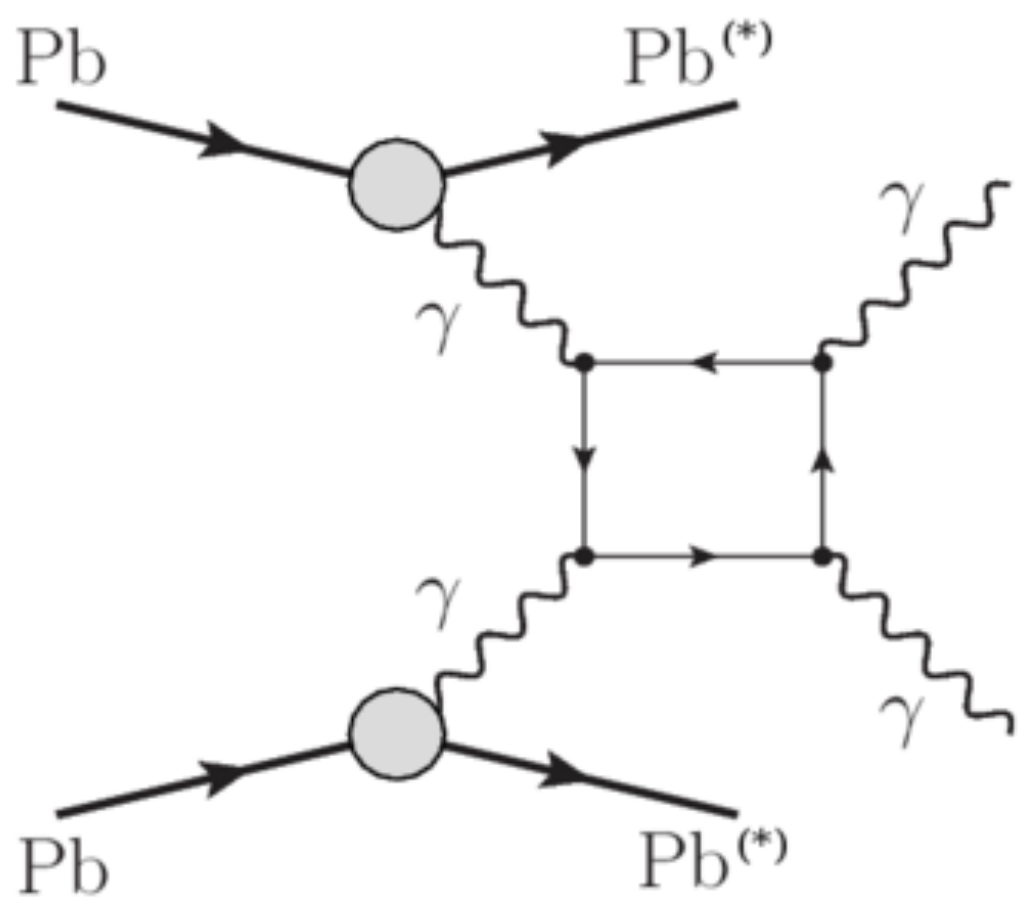
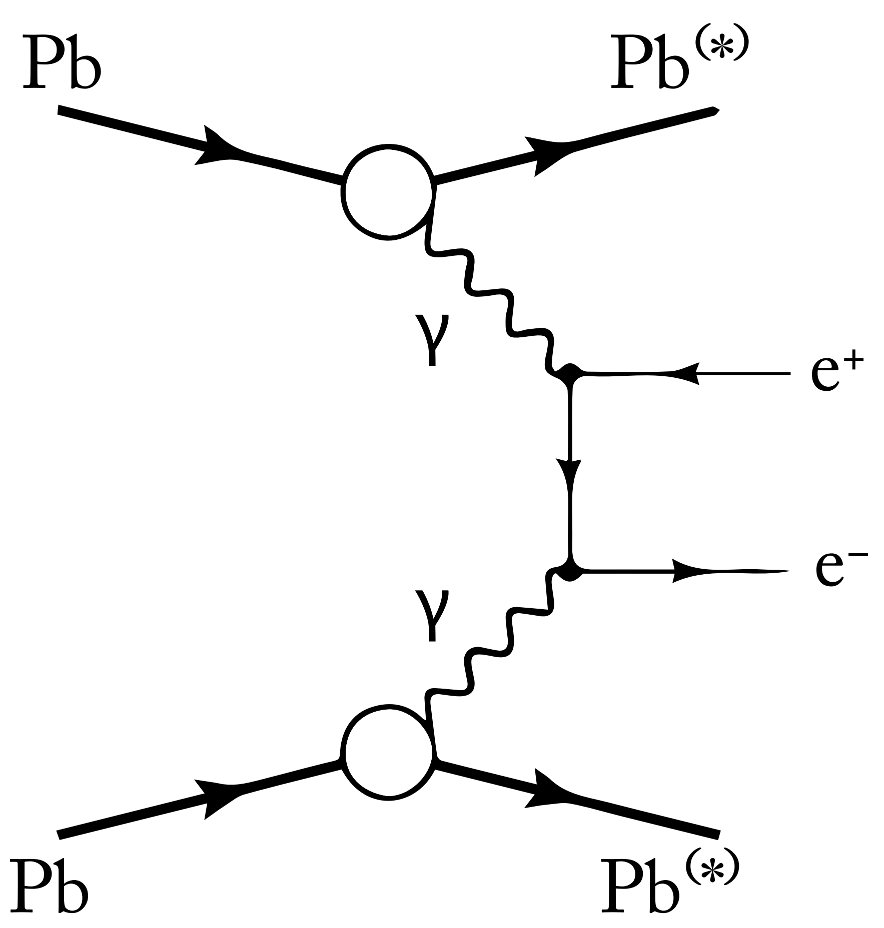
Contributions to event sample

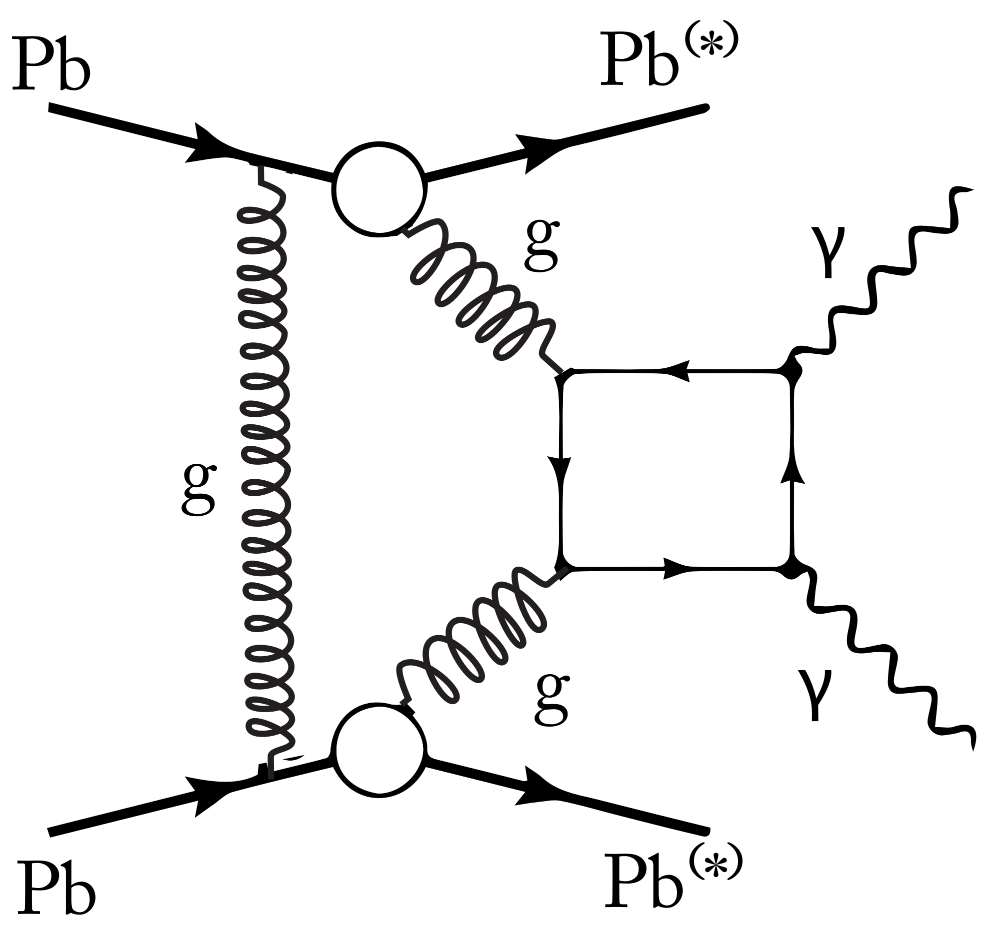
signal



main background contributions



correction via STARlight & data



correction via SuperChic & data

ATLAS and CMS: results

ATLAS

- events observed: 59
- events expected:
  30±4(syst.) signal and 12±1(stat.)±3(syst.) background
- significance excess against background-only=8.2σ

- fiducial cross section

$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 78 \pm 13(\text{stat.}) \pm 7(\text{syst.}) \pm 3(\text{lumi})\ \text{nb}$$

CMS

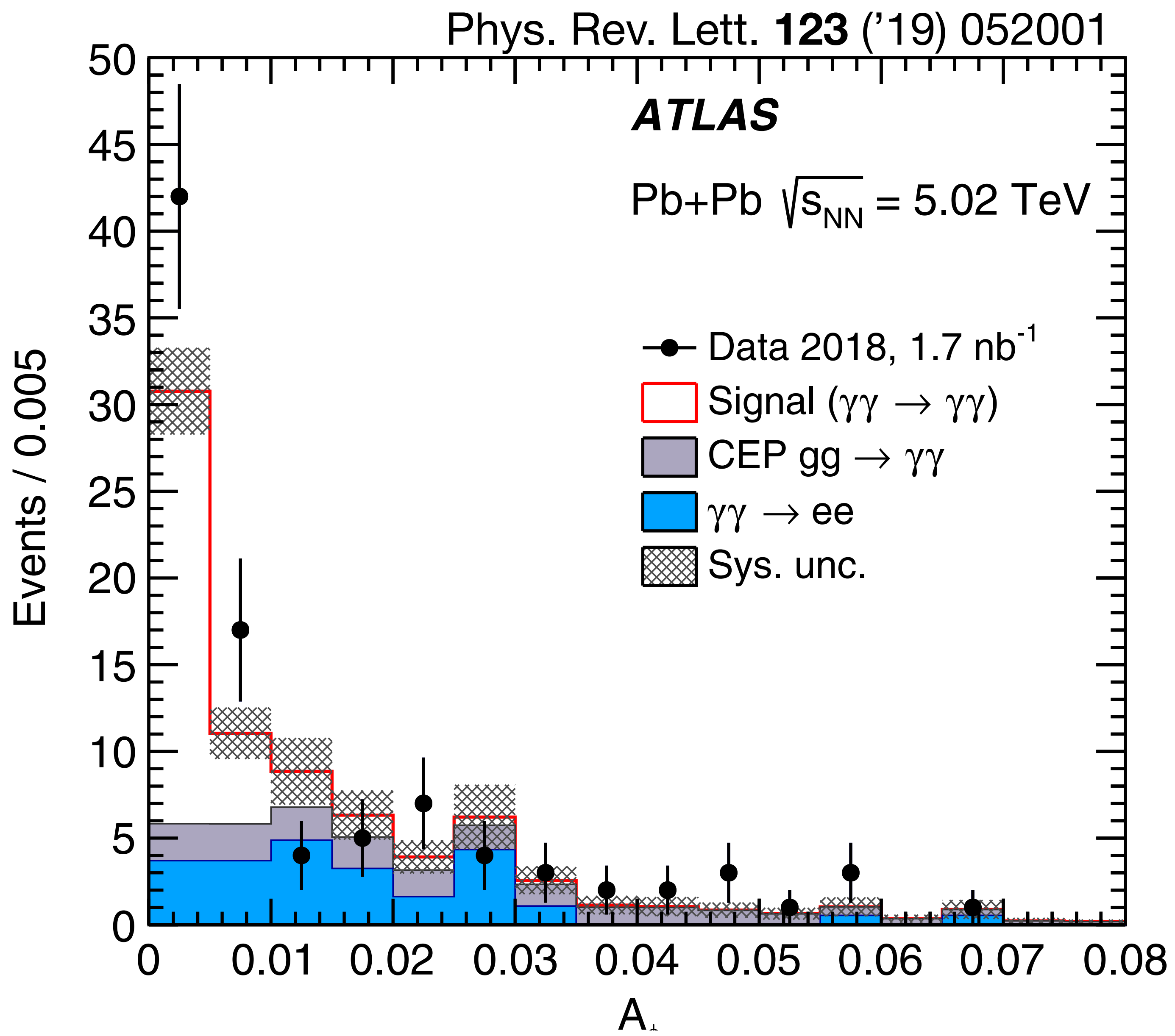
- events observed: 14
- events expected:
  9.0±0.9(theo.) signal and 4.0±1.2(stat.) background
- significance excess against background-only=3.7σ

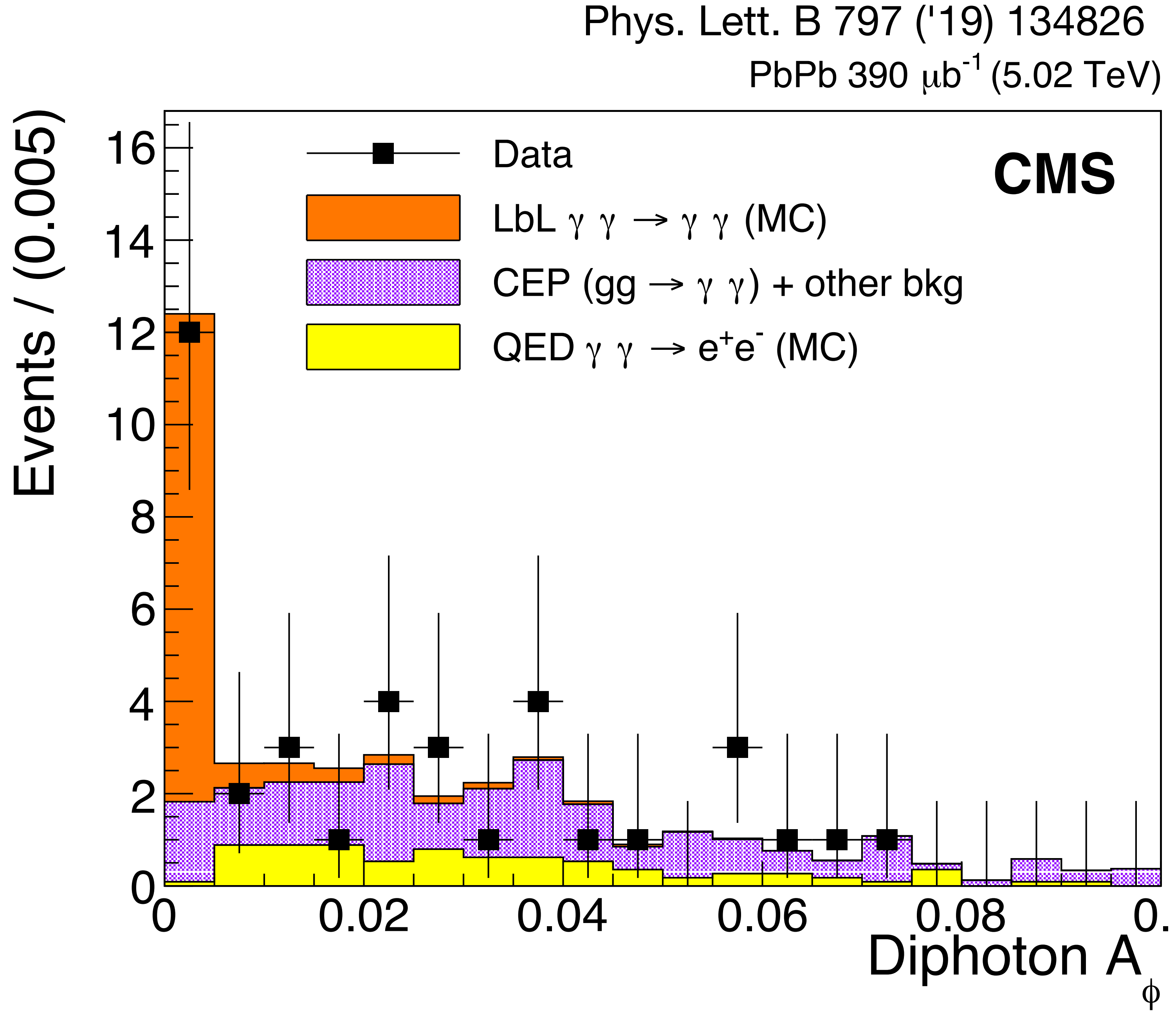
- fiducial cross section

$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = 120 \pm 46(\text{stat.}) \pm 28(\text{syst.}) \pm 12(\text{theo})\ \text{nb}$$

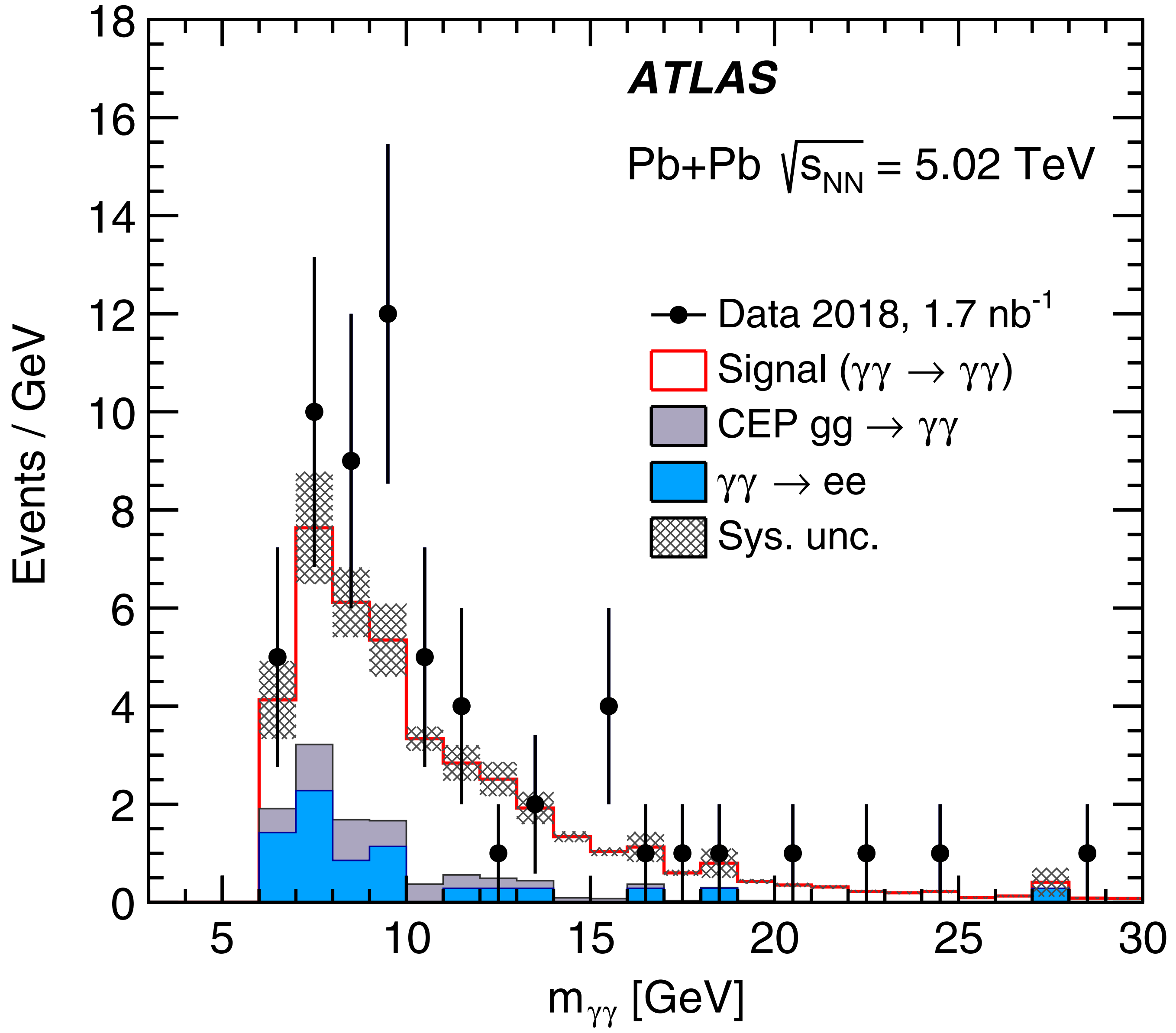
cross sections consistent with standard-model predictions

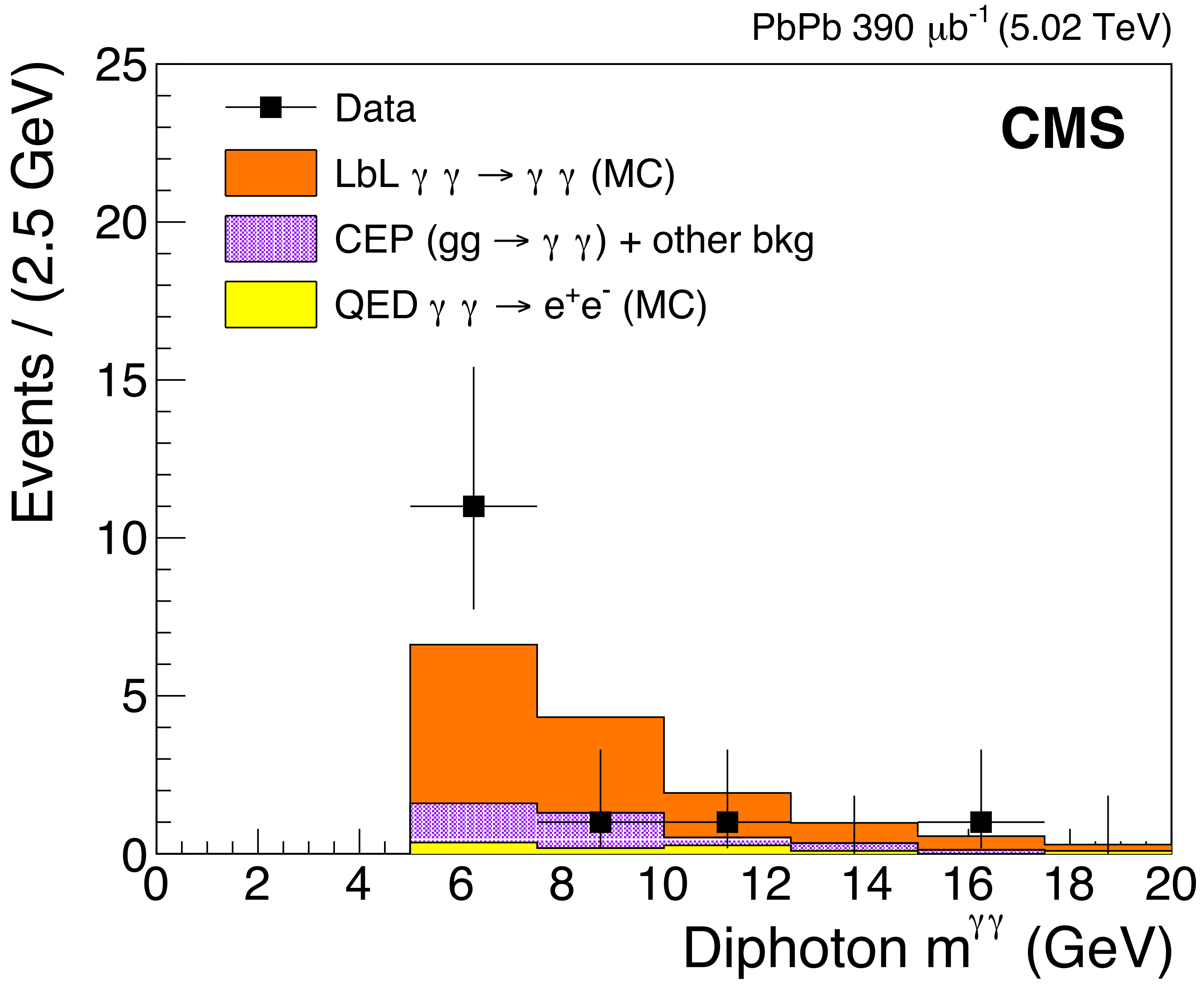
ATLAS and CMS: results



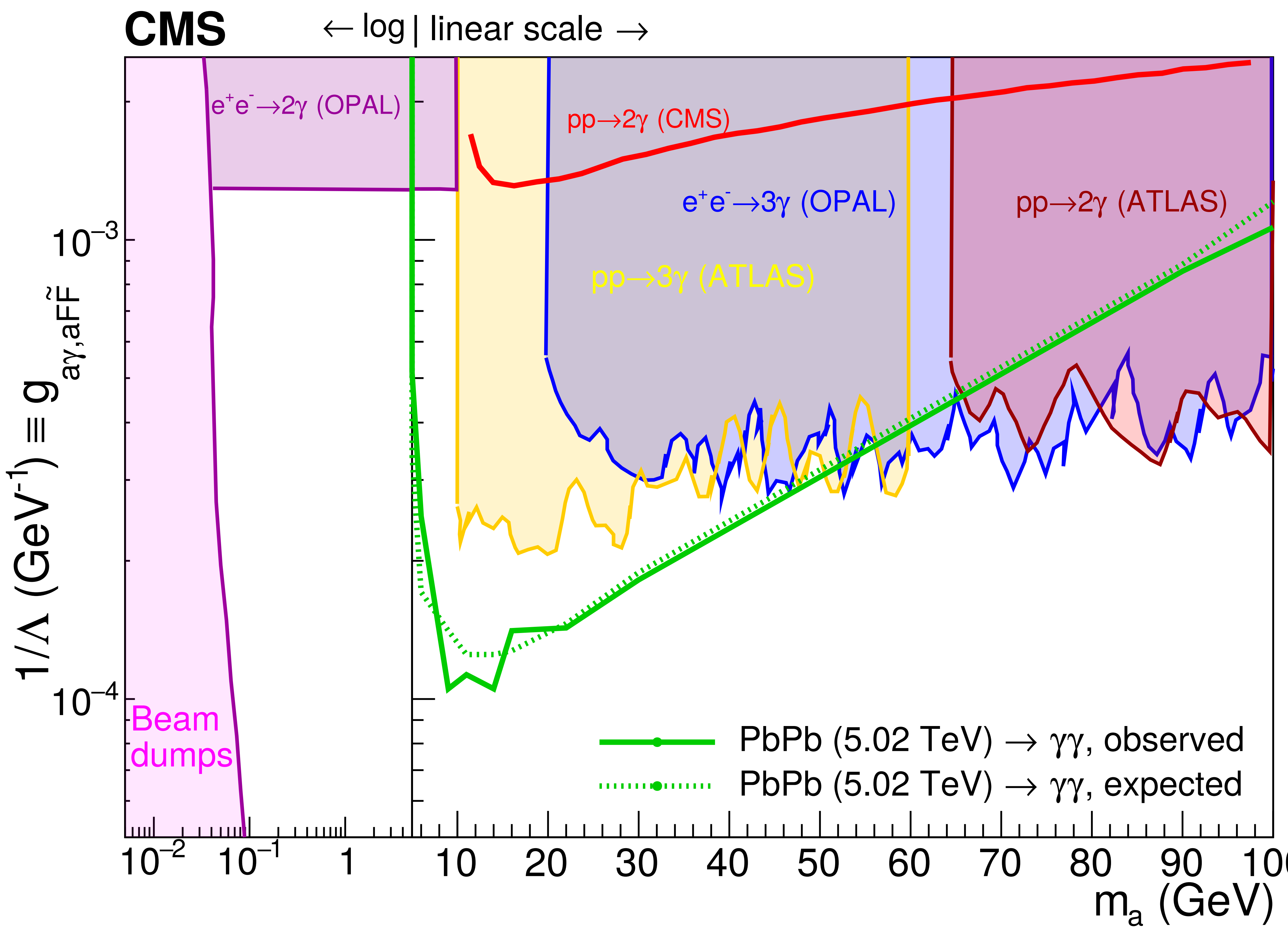


$A_\phi=(1-|\Delta\phi|/\pi)$

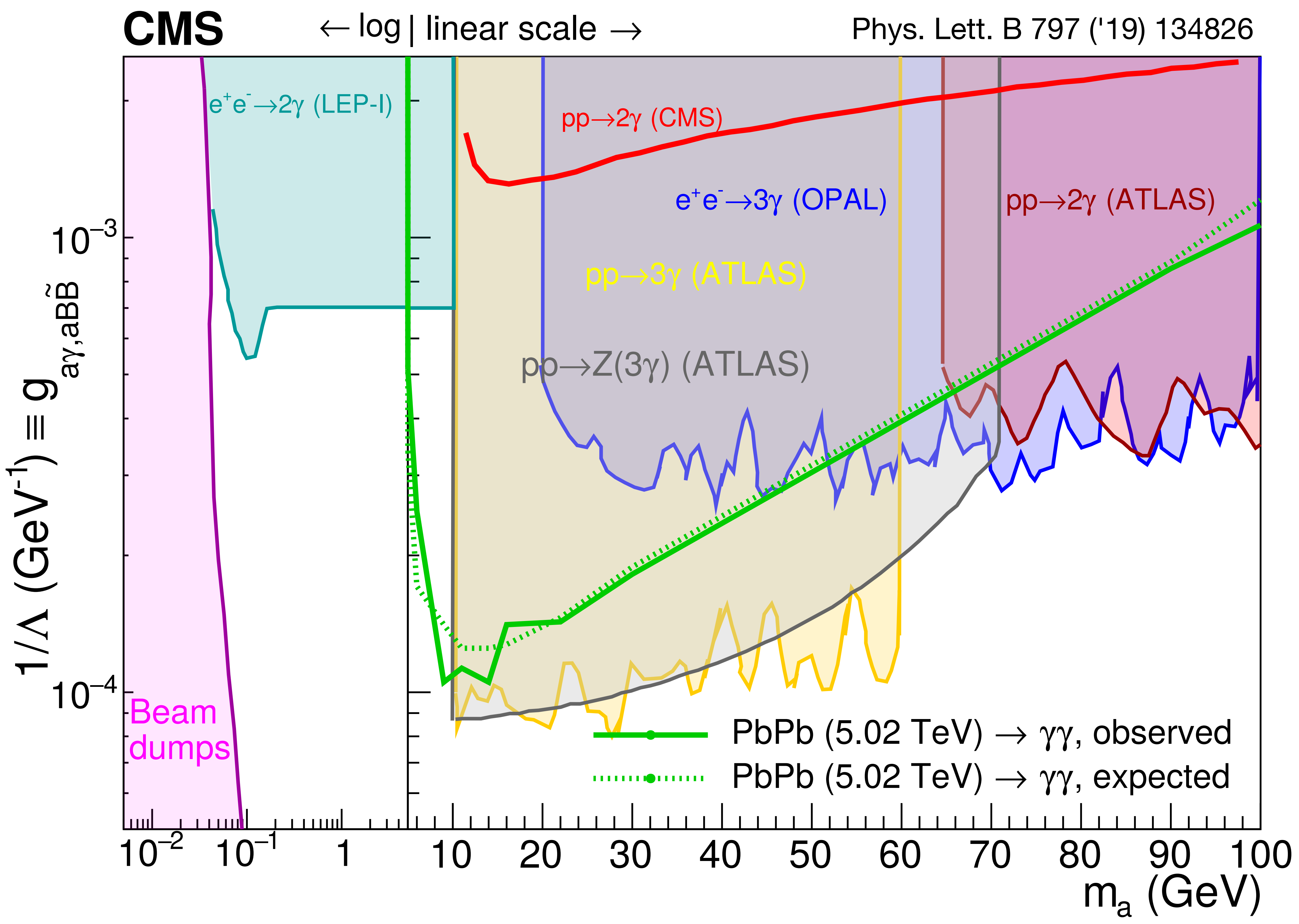




Exclusion limits for axion-like particles



ALP coupling to EM currents



ALP coupling to EM+EW currents

assumption:
100% ALP decay branching fraction to diphotons

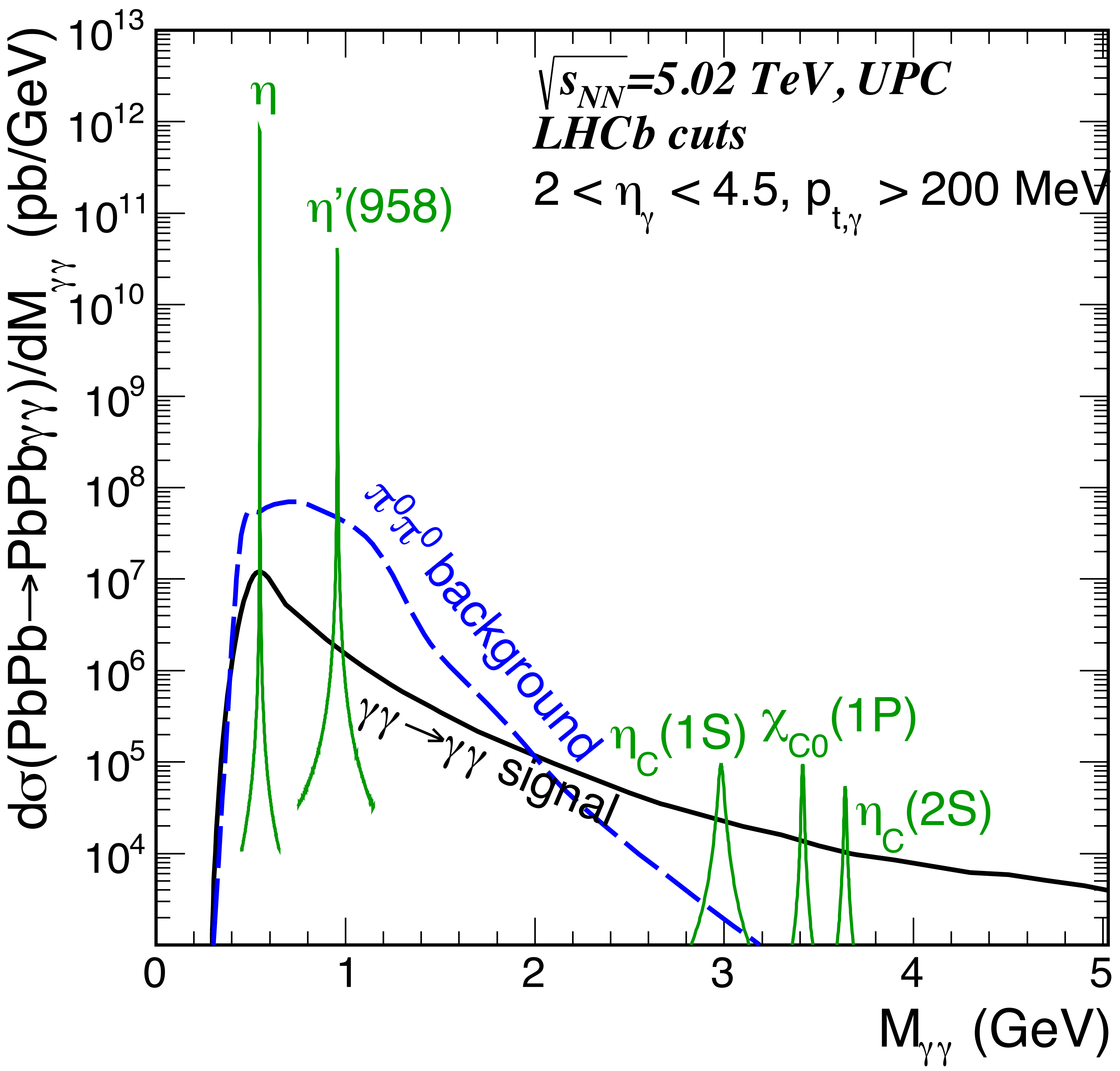
The future

- ! Still Run 2 data to be analysed and explore, e.g., photoproduction of jets
- Runs 3 and 4:
  - 10x data for pPb and PbPb $\longrightarrow$ improve statistically limited measurements
  - upgrade of detectors $\longrightarrow$ improve systematic uncertainties

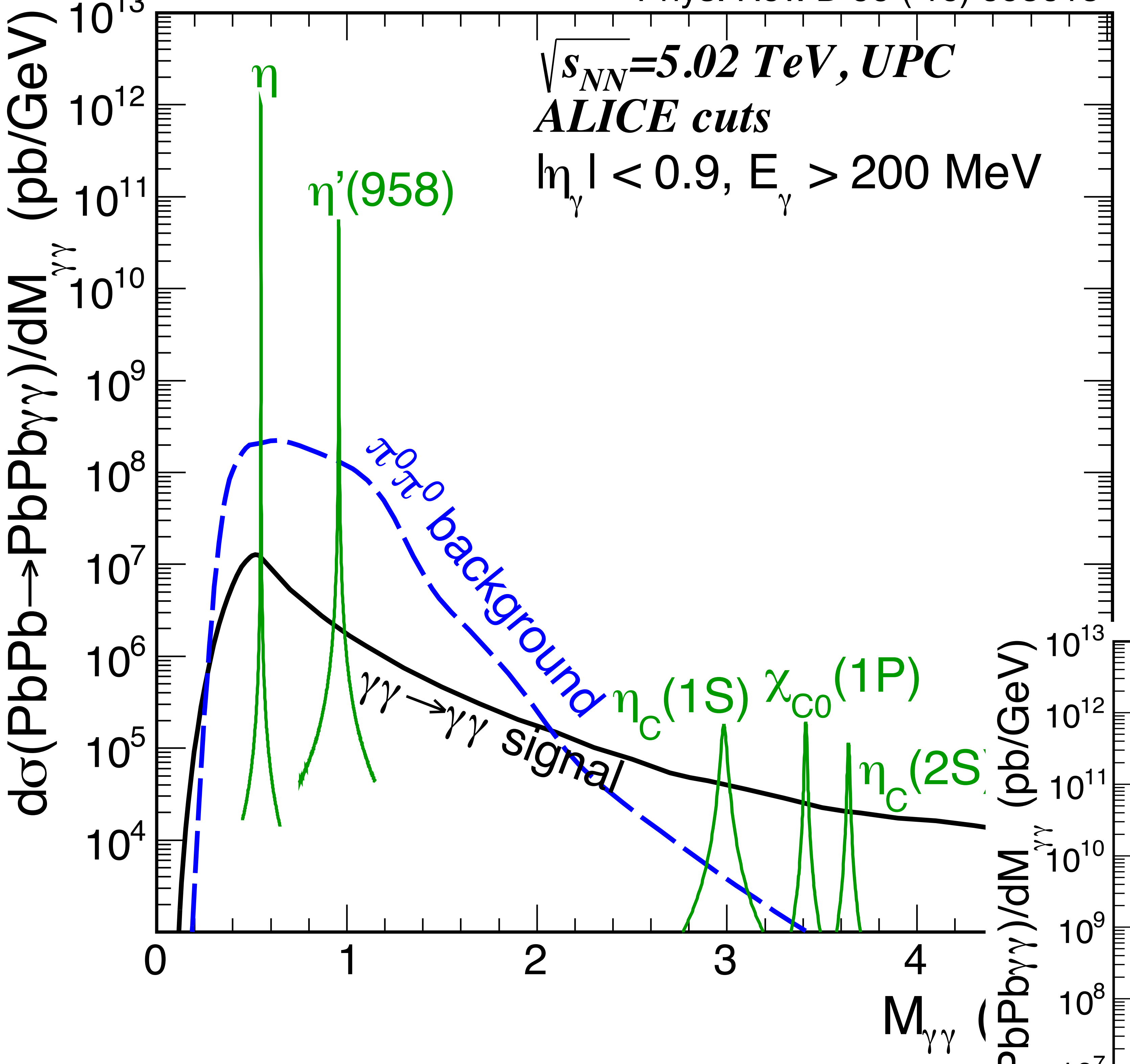
    $\longrightarrow$ extend kinematic reach

The future

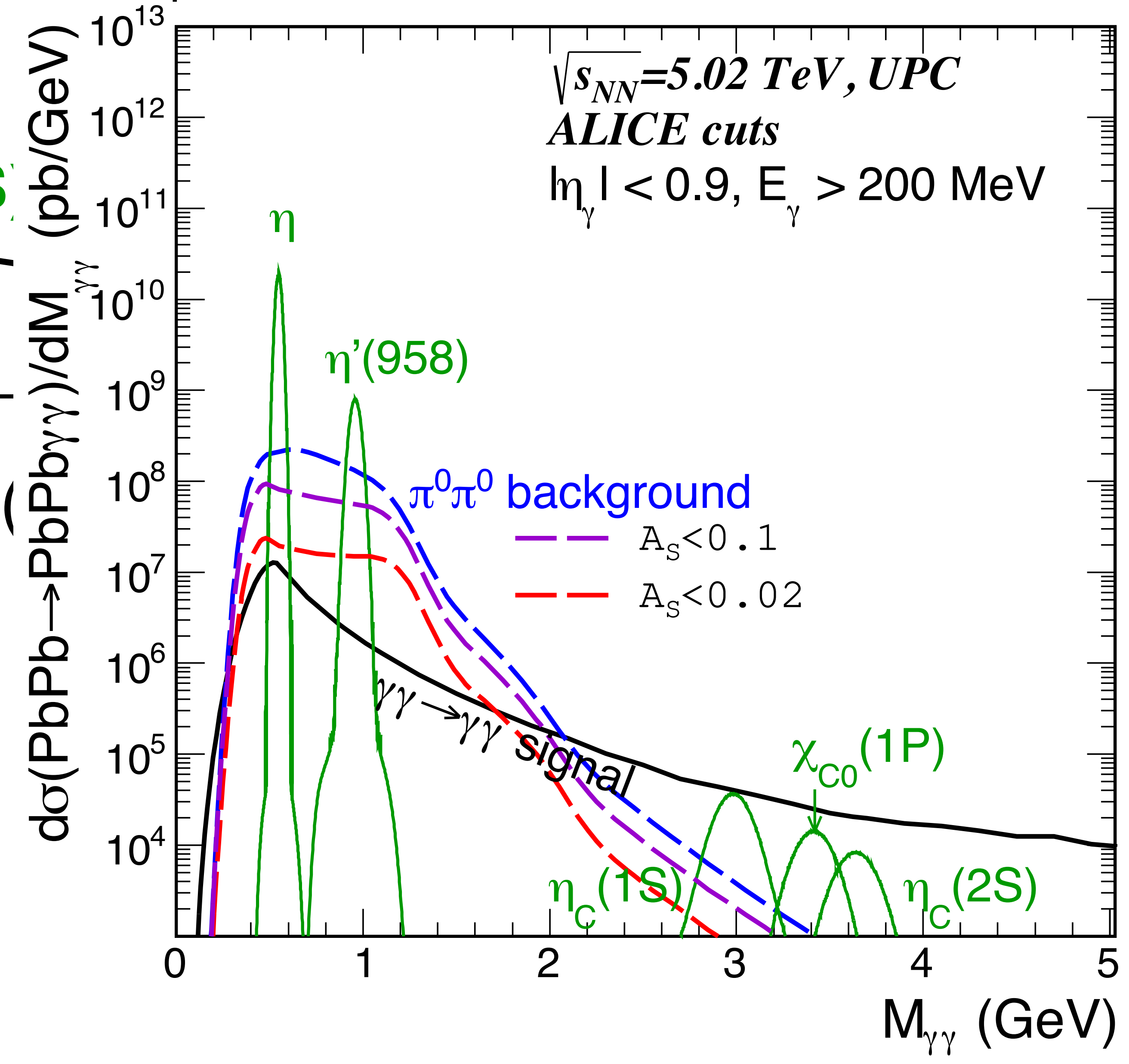
- Light-by-light scattering for $m_{\gamma\gamma}$<5 GeV by ALICE and LHCb in RUN3 and beyond:



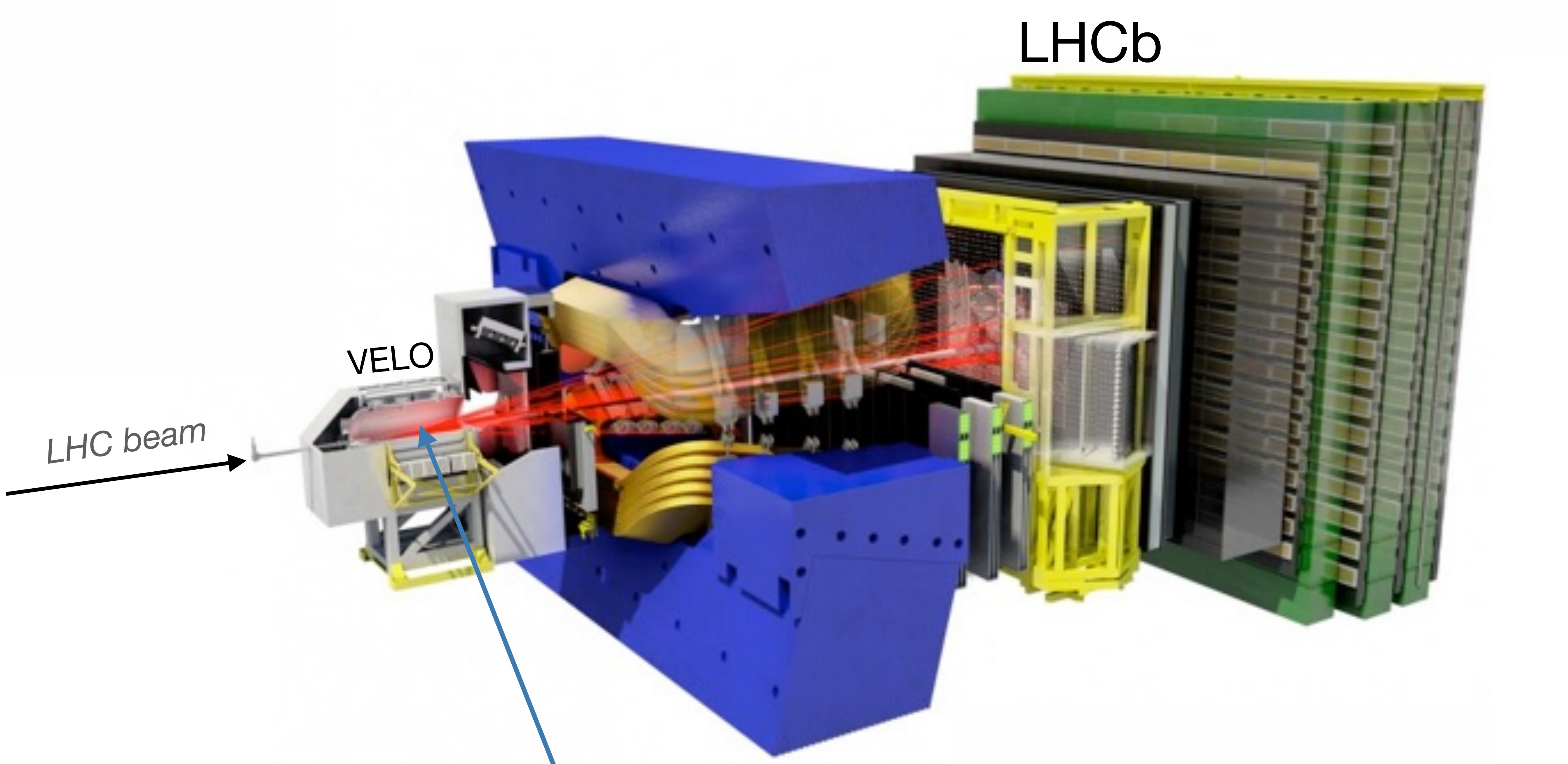
Phys. Rev. D **99** ('19) 093013

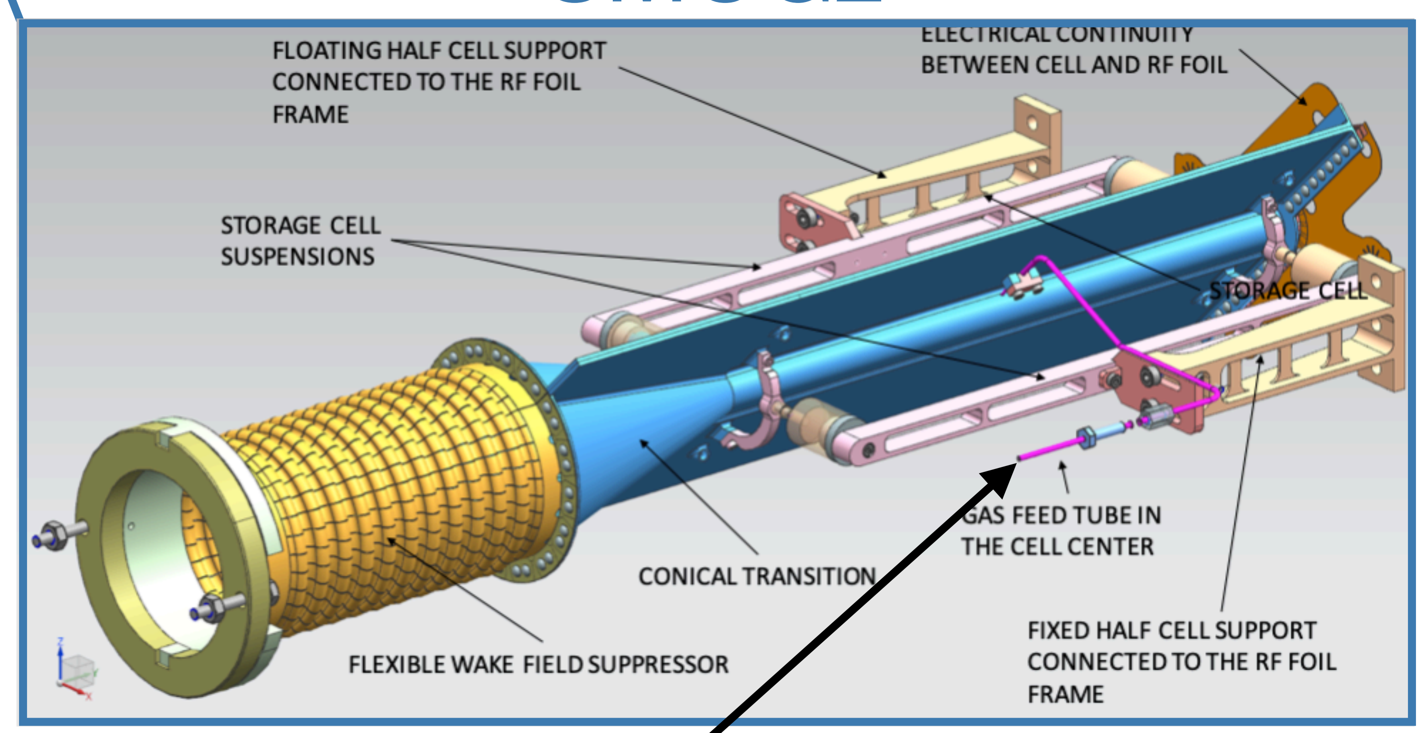


background reduction through kinematic cuts



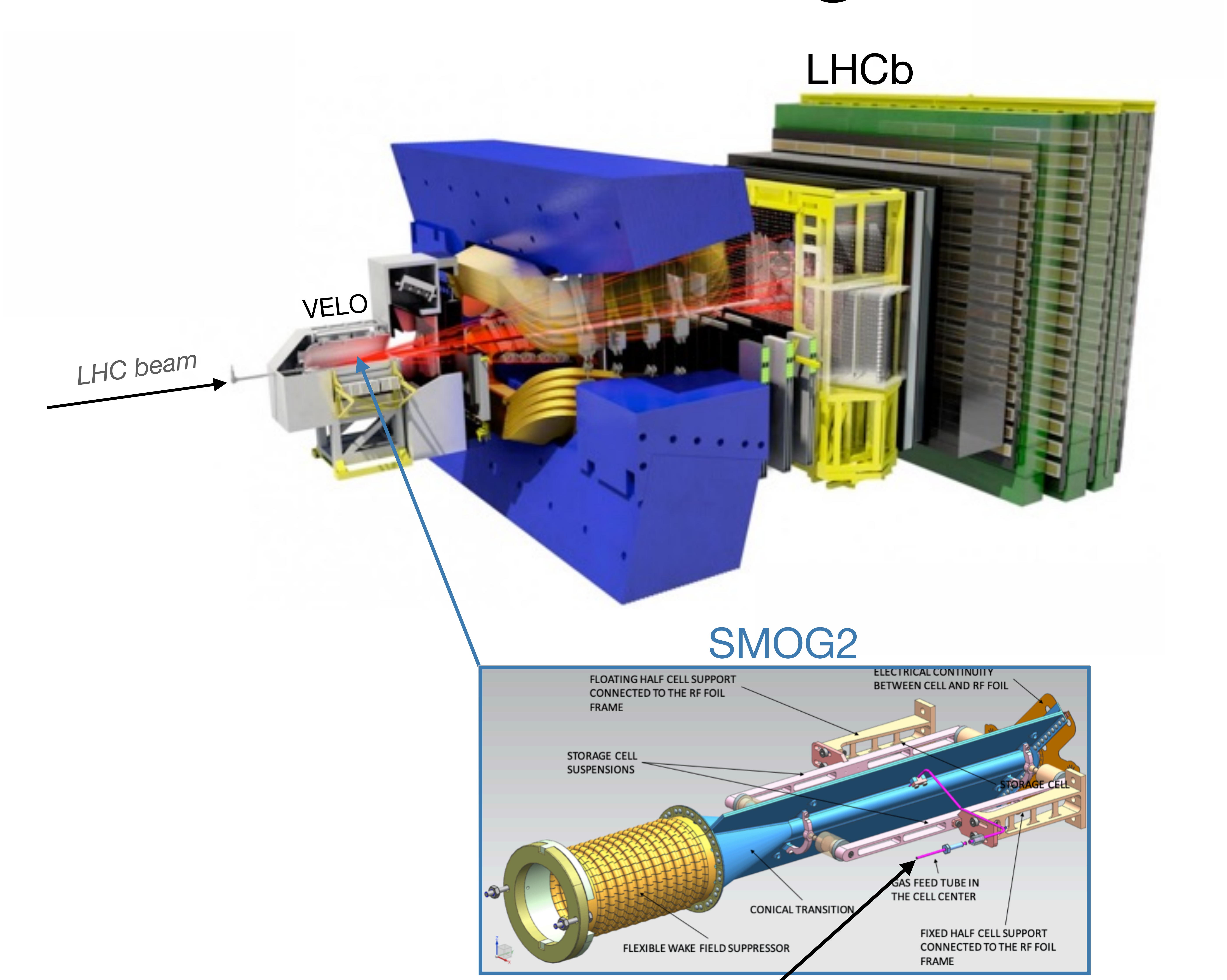
The future: fixed target Run 3





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

The future: fixed target Run 3



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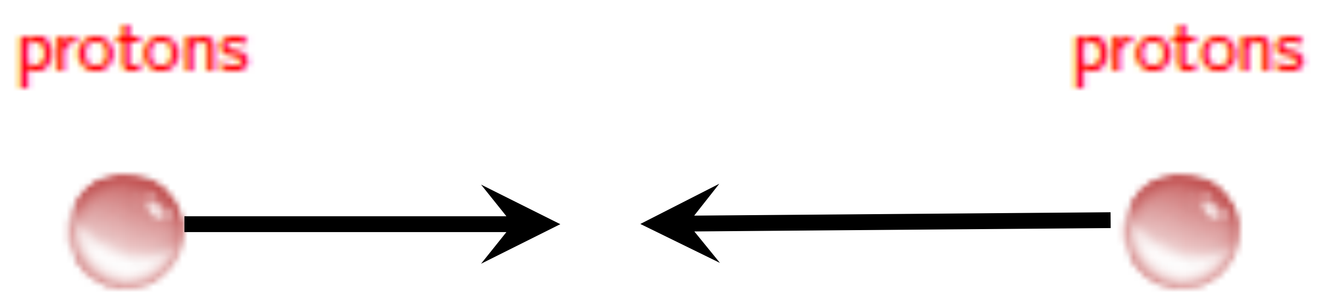
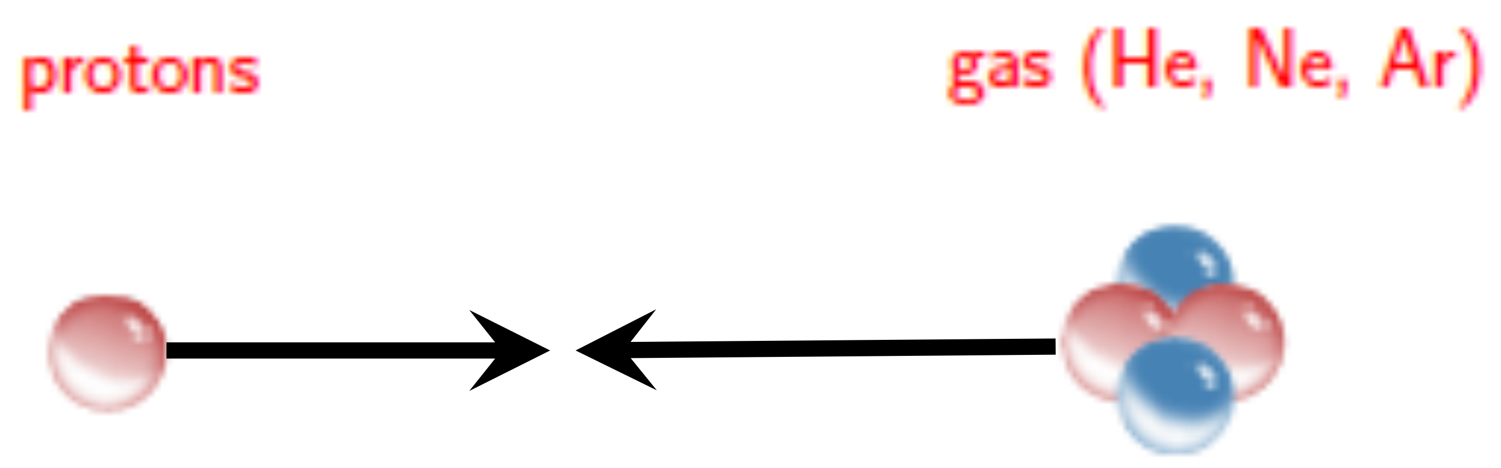


$\sqrt{s} = 13$ TeV

$2 < y_{CM} < 4.5$



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

$-2.78 < y_{CM} < 0.2$

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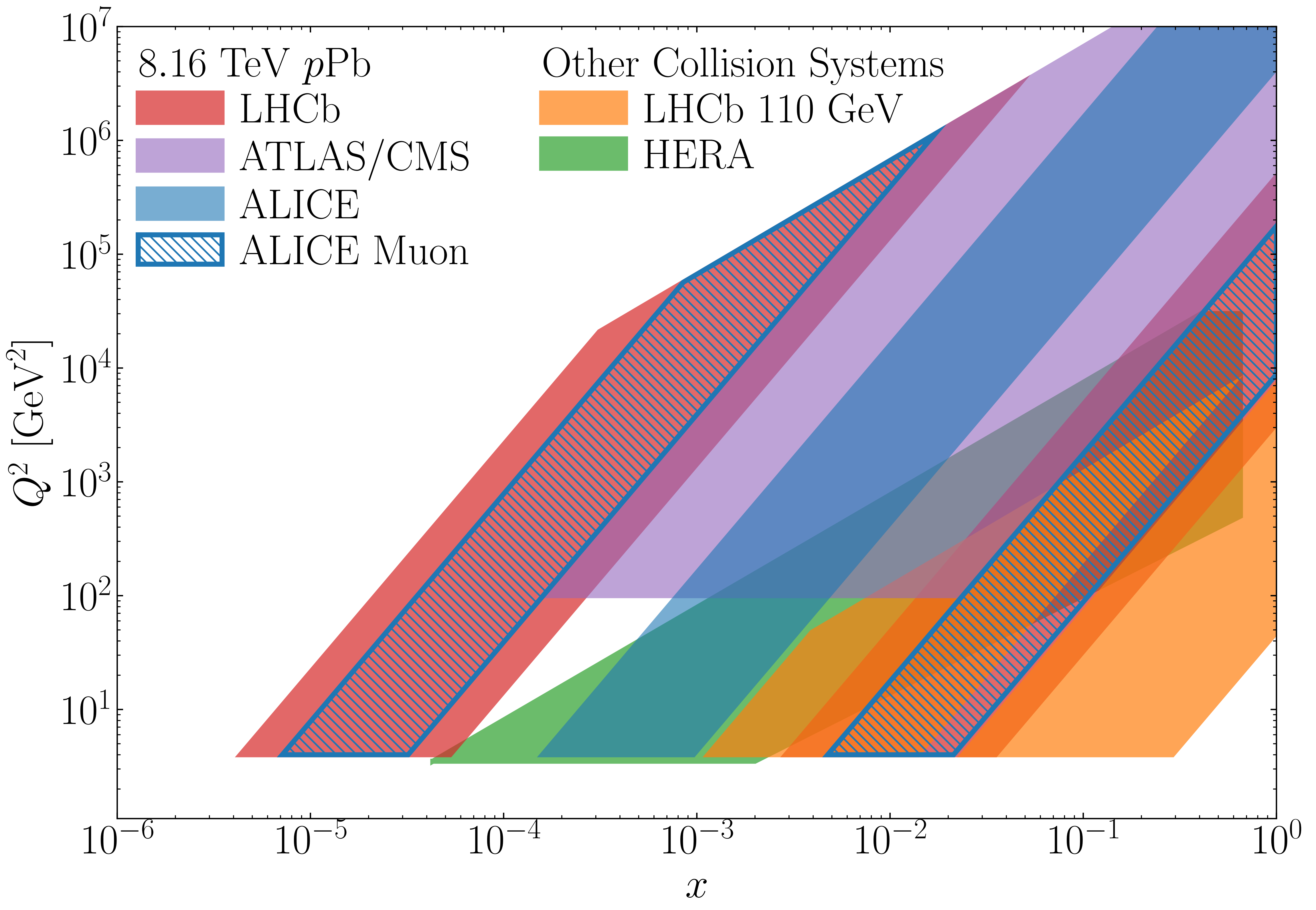

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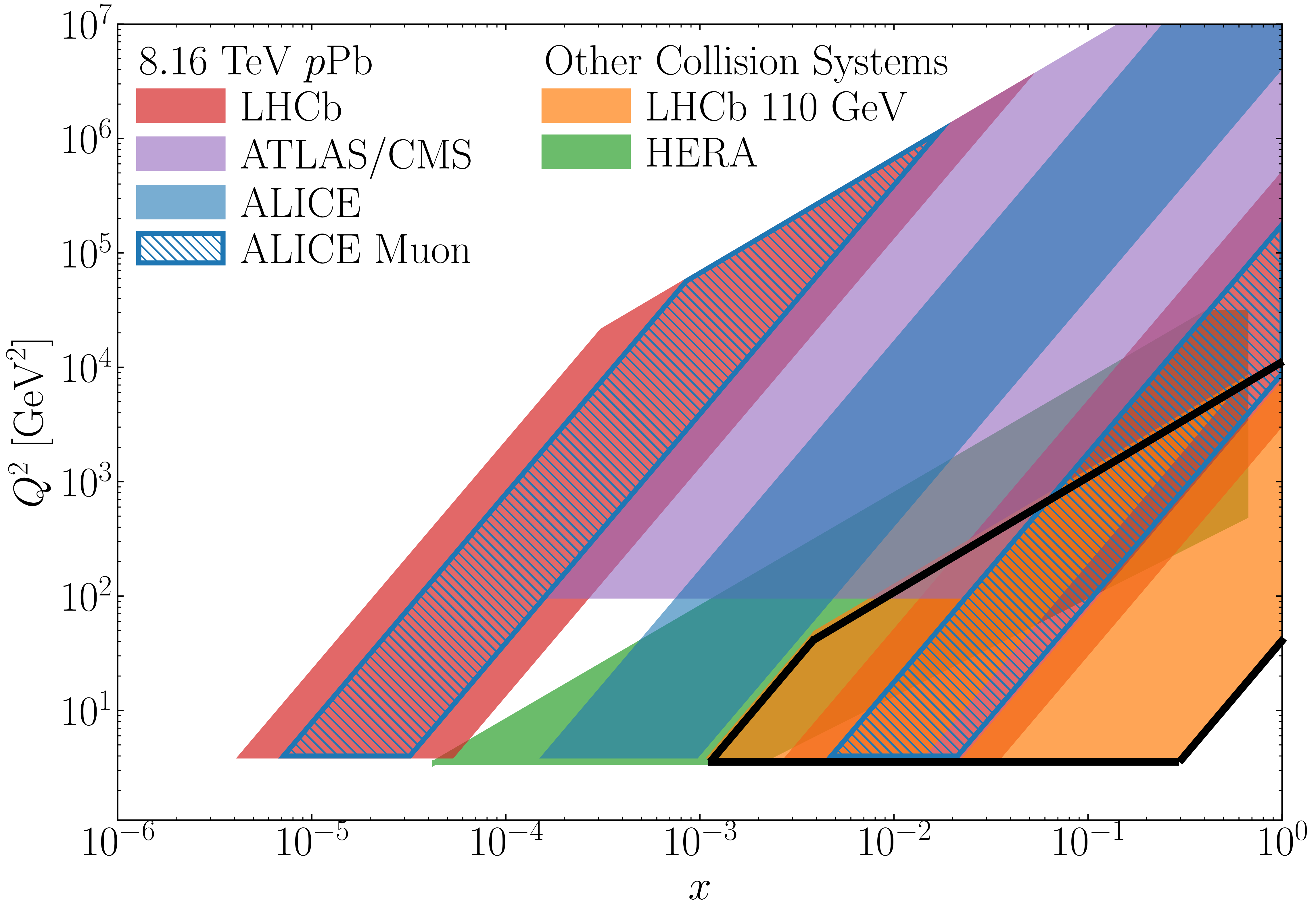
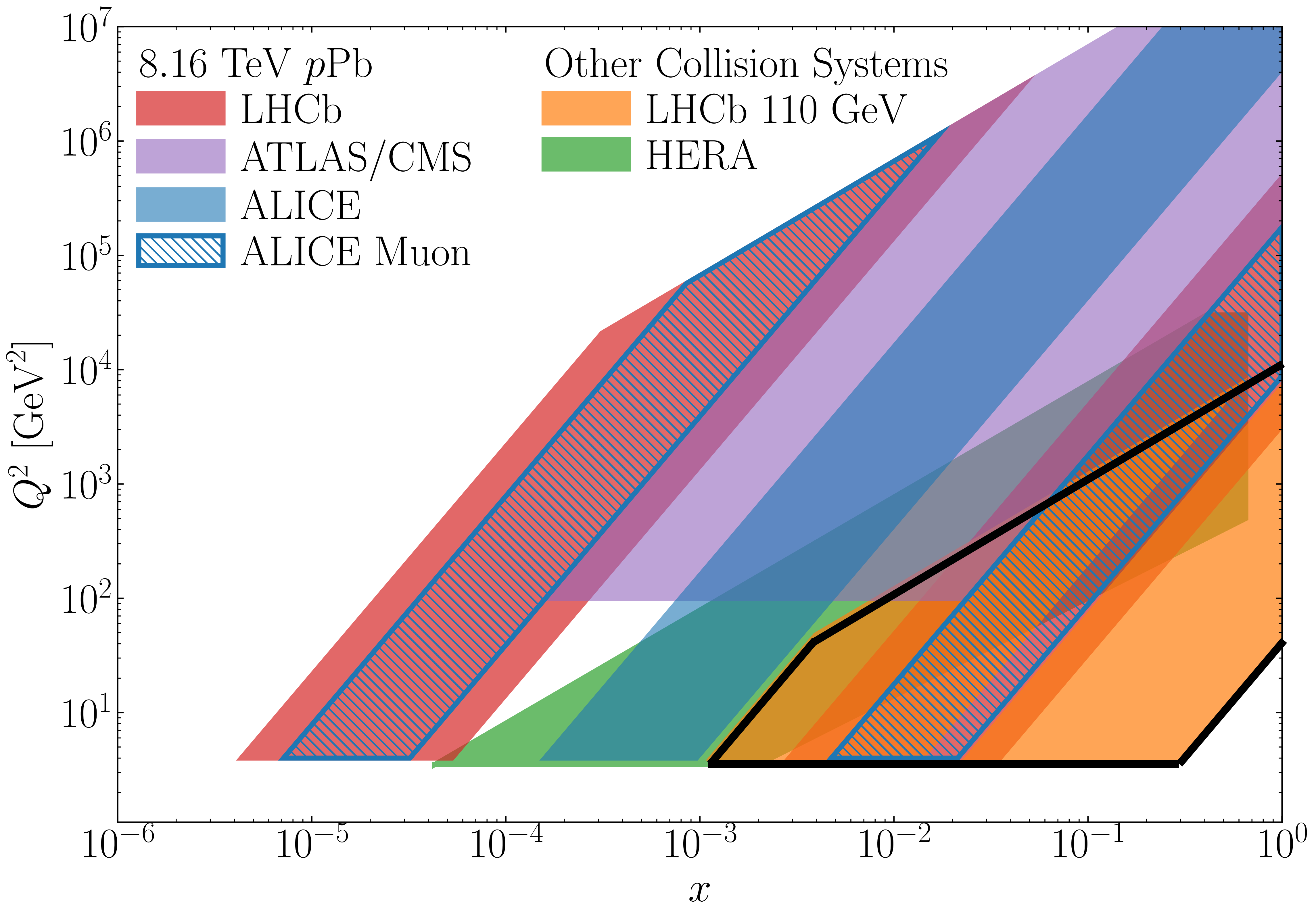


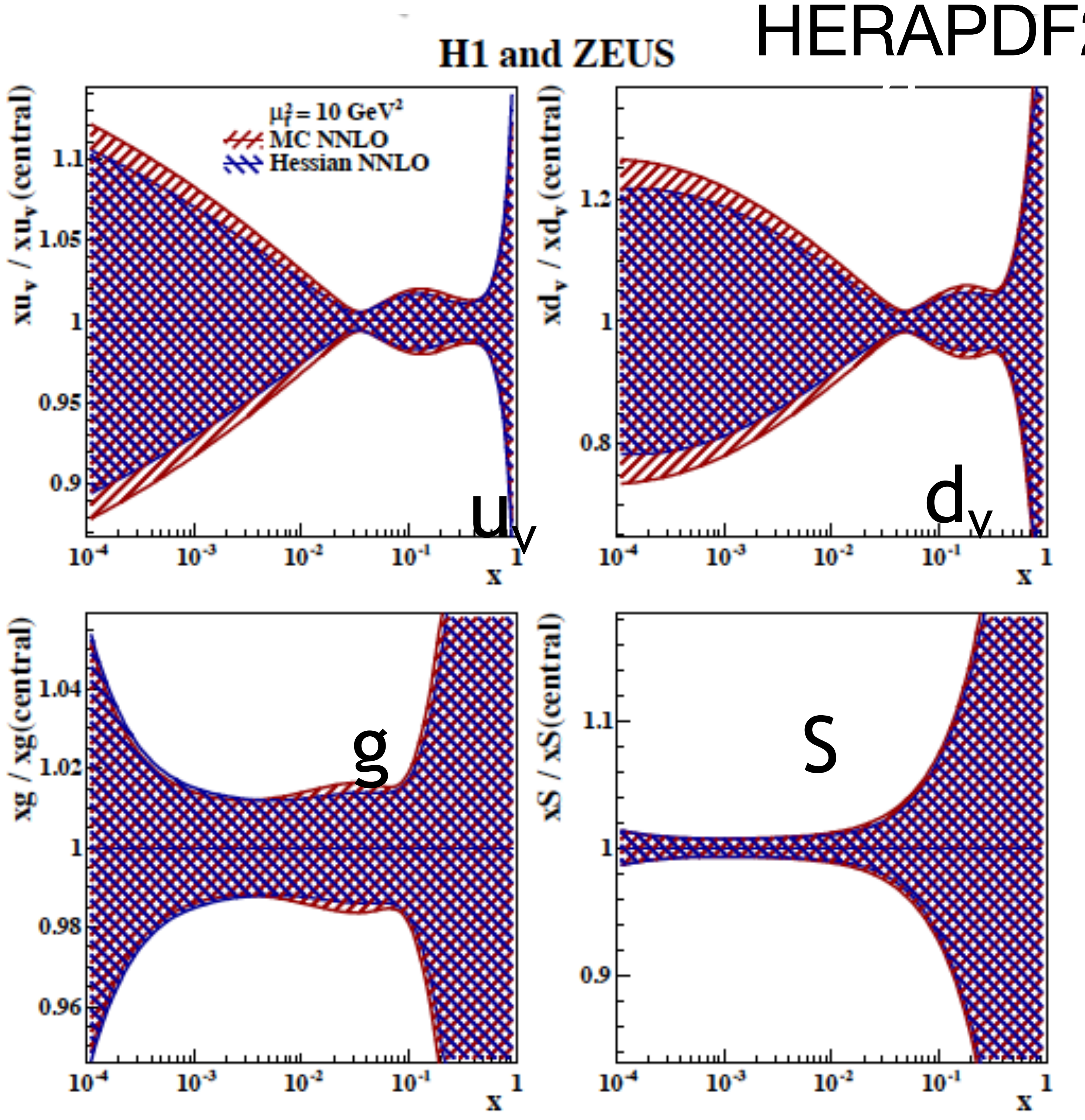
high-x_B region

The future: fixed target Run 3

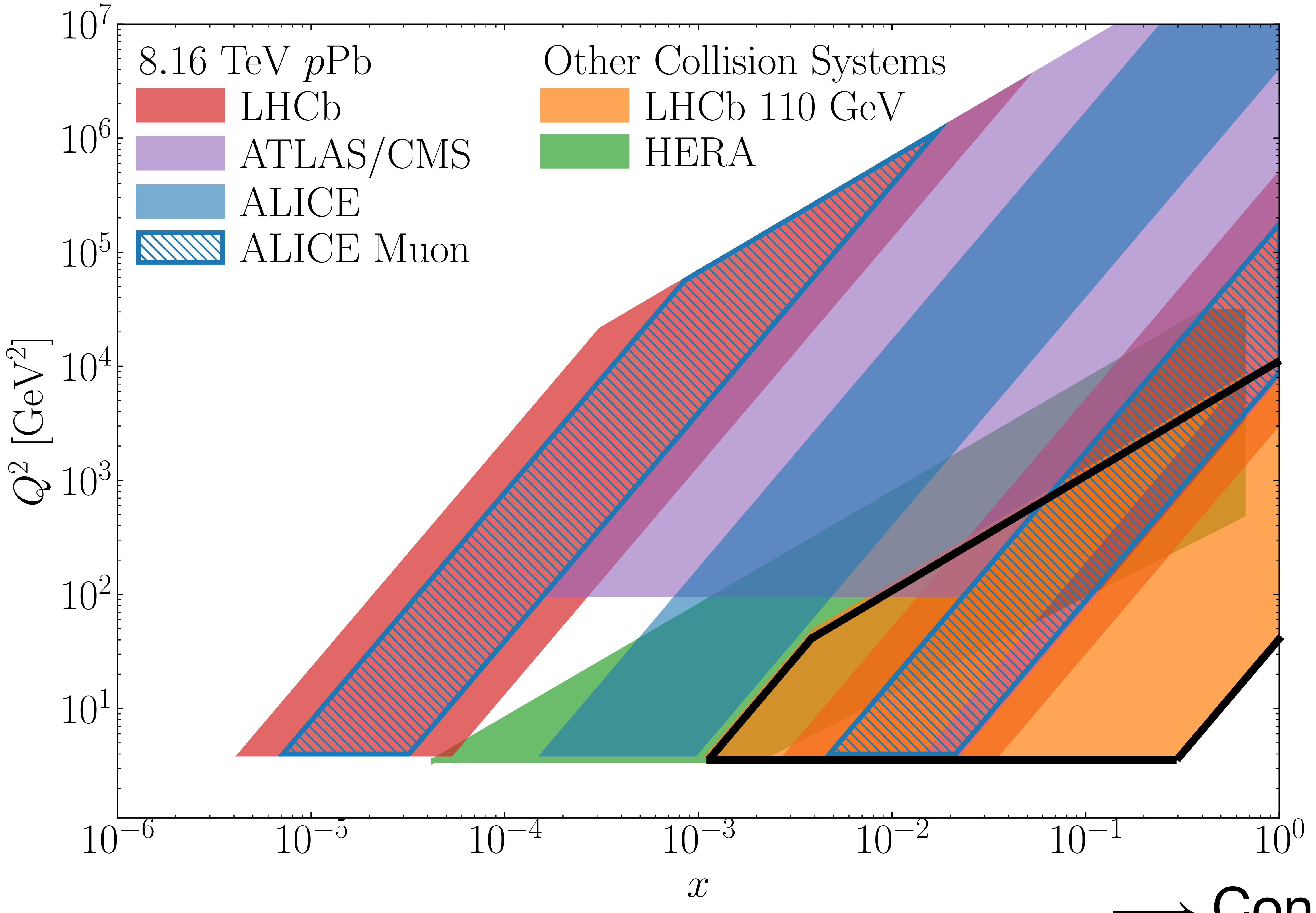


high-x_B region barely explored

HERAPDF2.0



The future: fixed target Run 3



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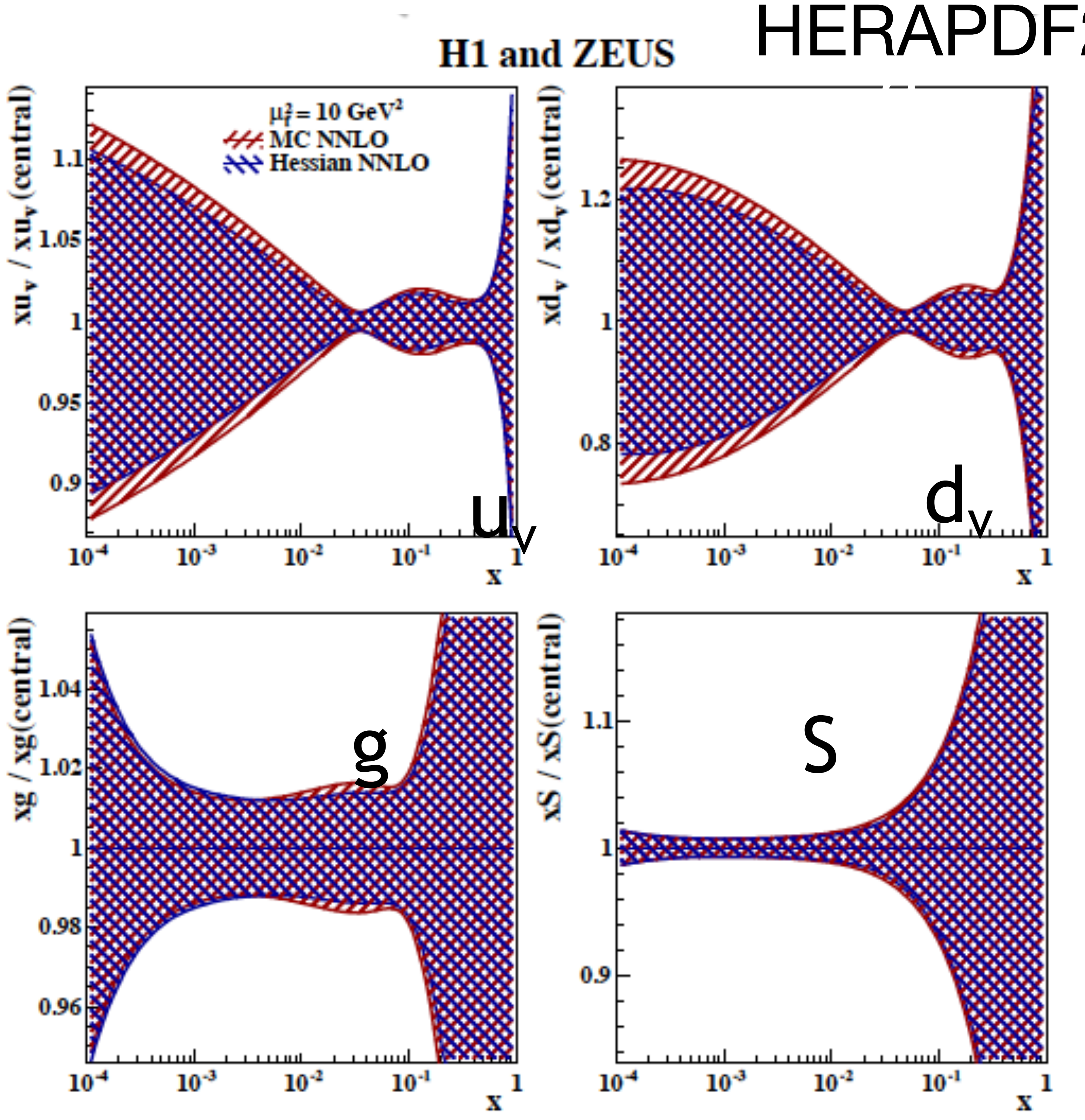
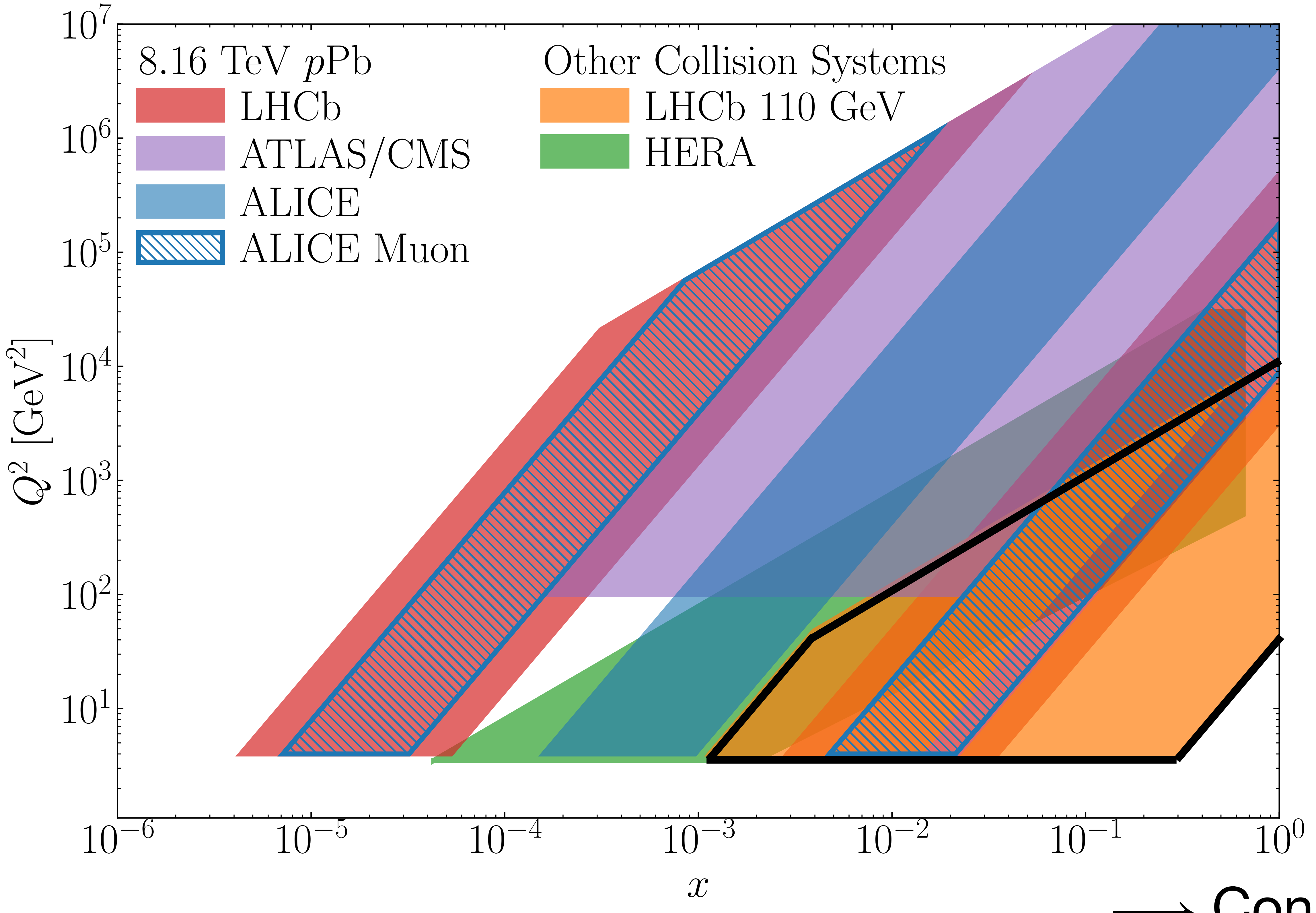
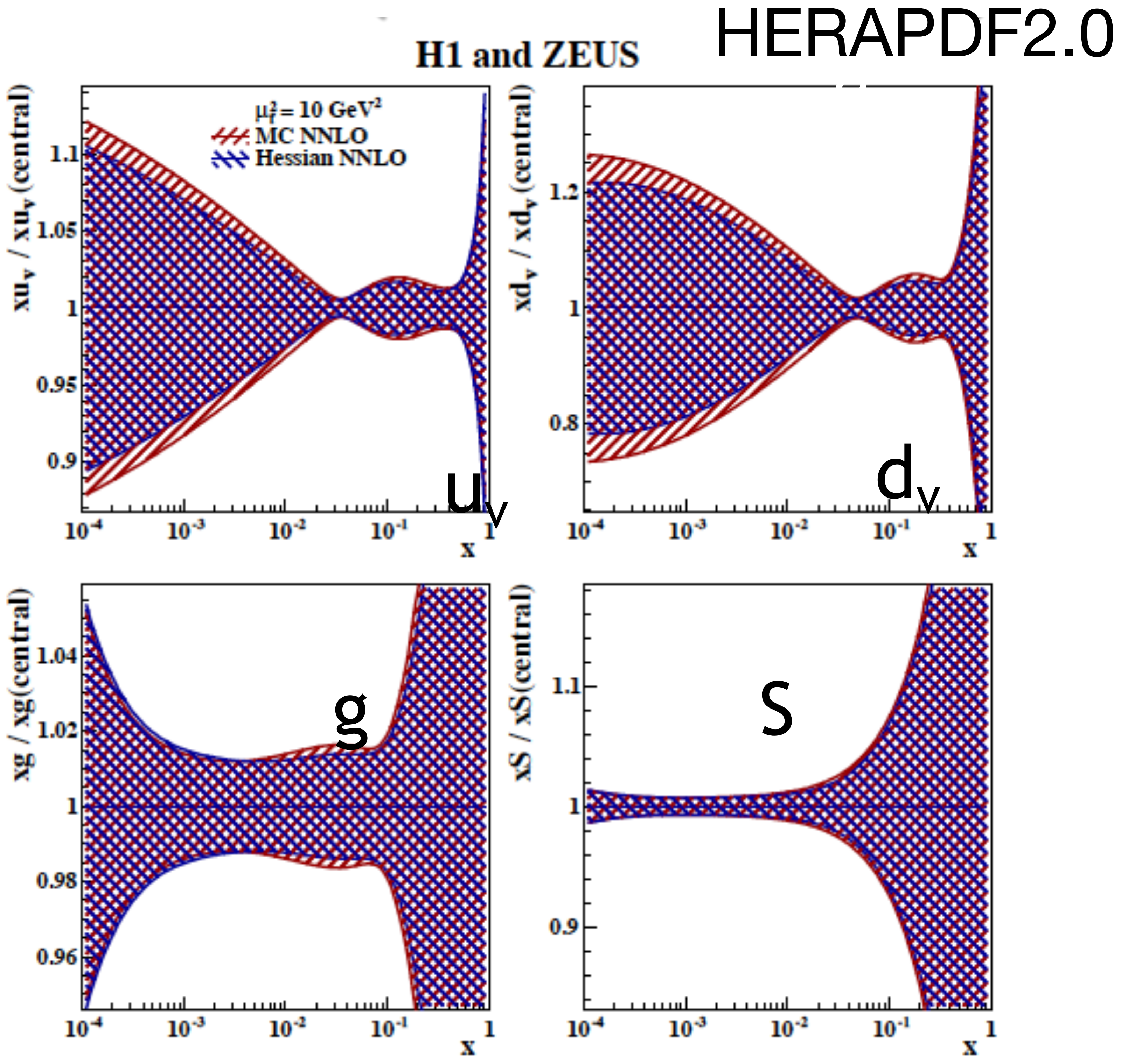


⟶ Constrain nucleon and nuclear GPDs in high-x_B region

The future: fixed target Run 3



high-x_B region barely explored



$\longrightarrow$ Constrain nucleon and nuclear GPDs in high-x_B region

exclusive measurements with SMOG2:

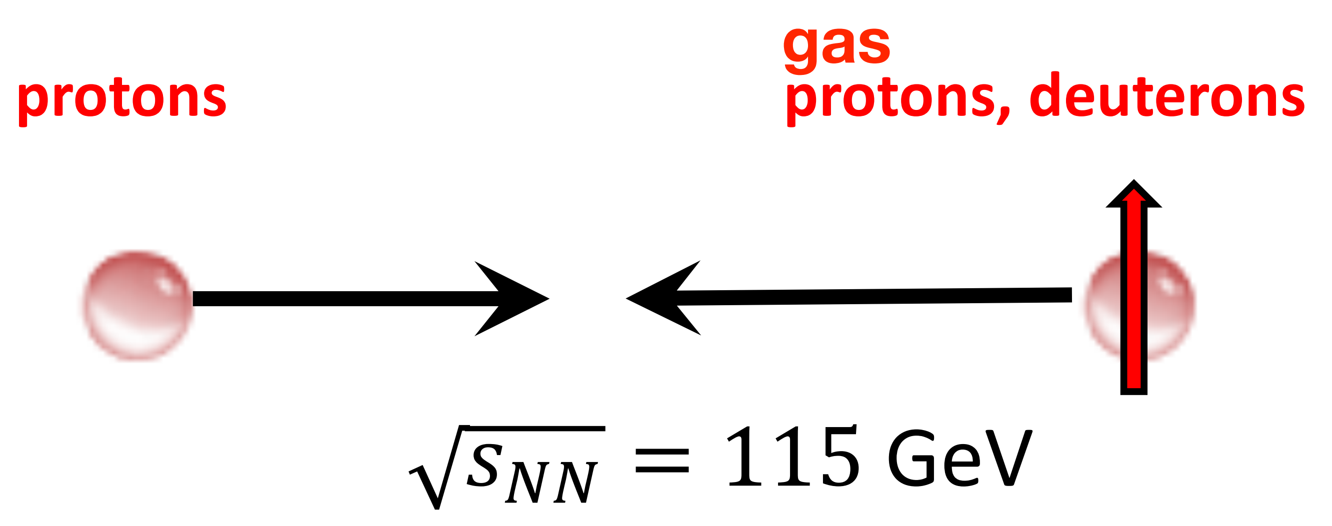
	pp	pHe	pXe
continuous $\mu^+\mu^-$	$\sigma = 61.931$ pb $= 686$ evts	$\sigma = 113.6$ pb $= 0$ evts	$\sigma = 17.6$ nb $= 29\ 10^3$ evts
$J/\psi \to \mu^+\mu^-$	$\sigma = 20.467$ pb $= 2302$ evts	$\sigma = 27.3$ pb $= 0$ evts	$\sigma = 1.3$ nb $= 21\ 10^3$ evts
$\phi \to K^+K^-$	$\sigma = 184$ pb $=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

total uncertainty on cross section: 5-10%

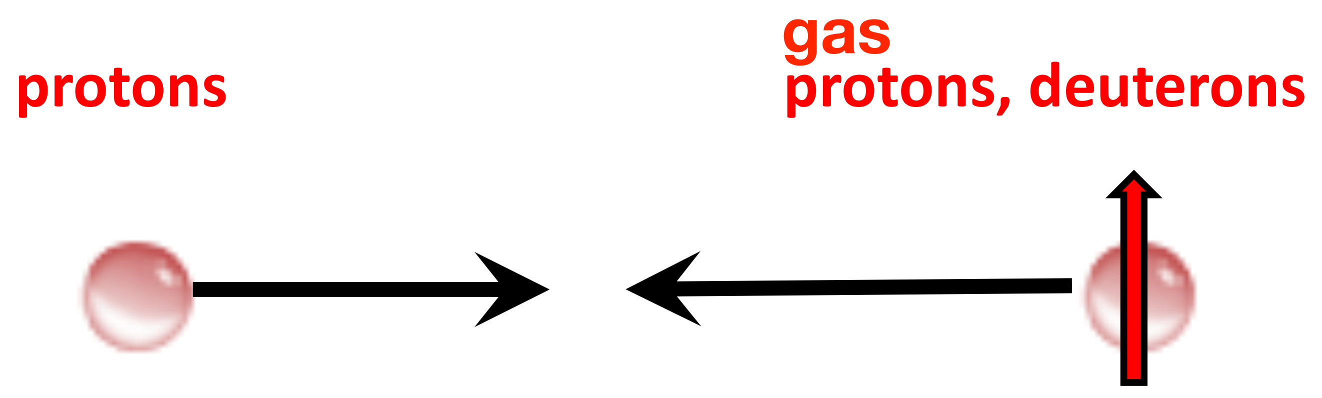
The future: proposed fixed targets Run 4

- SMOG2 LHCSPIN: polarised gas target

  $\longrightarrow$ access to spin-dependent GPDs (orbital angular momentum), PDFs, and TMD PDFs



The future: proposed fixed targets Run 4

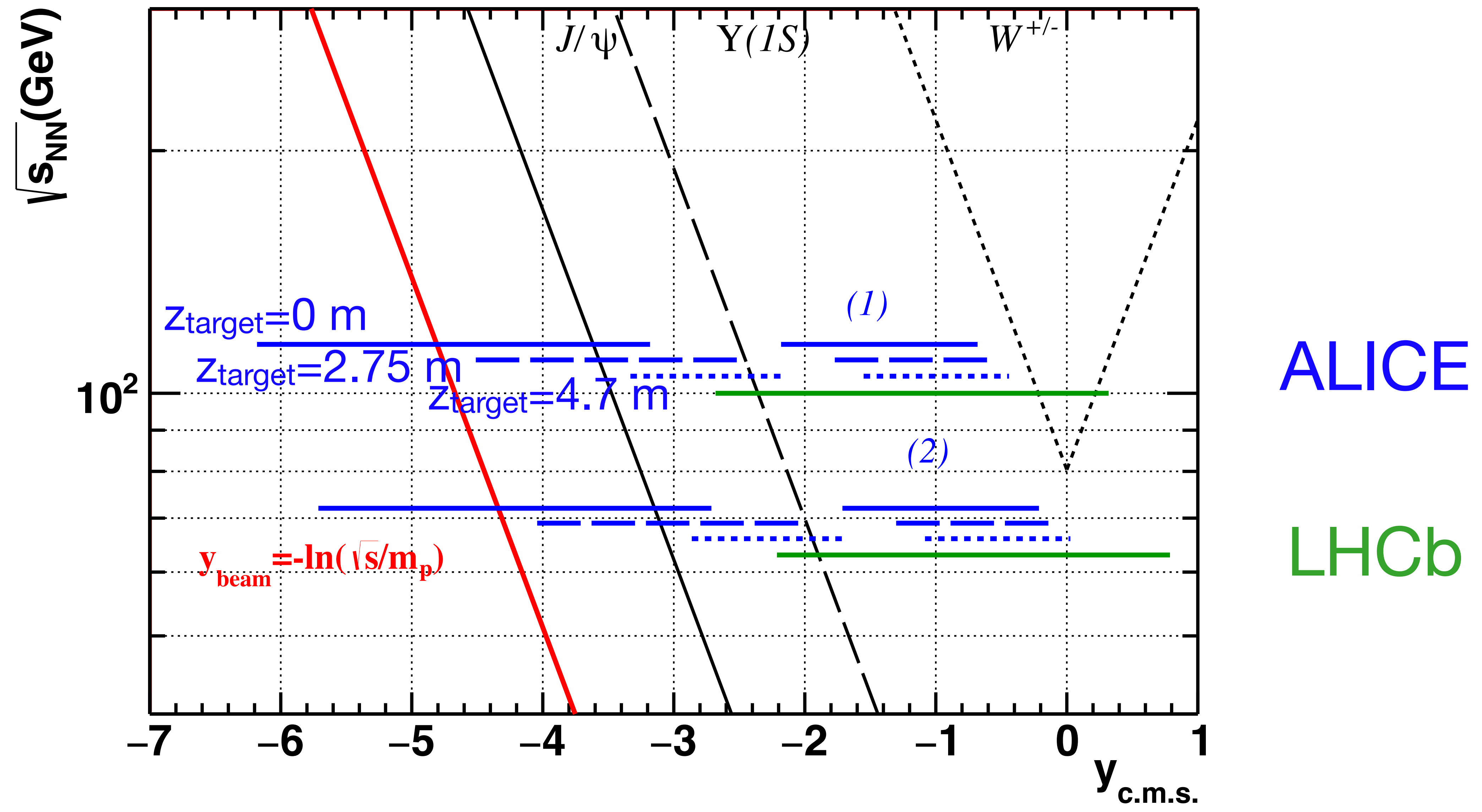


$\sqrt{s_{NN}} = 115$ GeV

- SMOG2 → LHCSPIN: polarised gas target

  ⟶ access to spin-dependent GPDs (orbital angular momentum), PDFs, and TMD PDFs

- solid fixed target at ALICE
  - complementary targets
  - complementary coverage in y_{CM}



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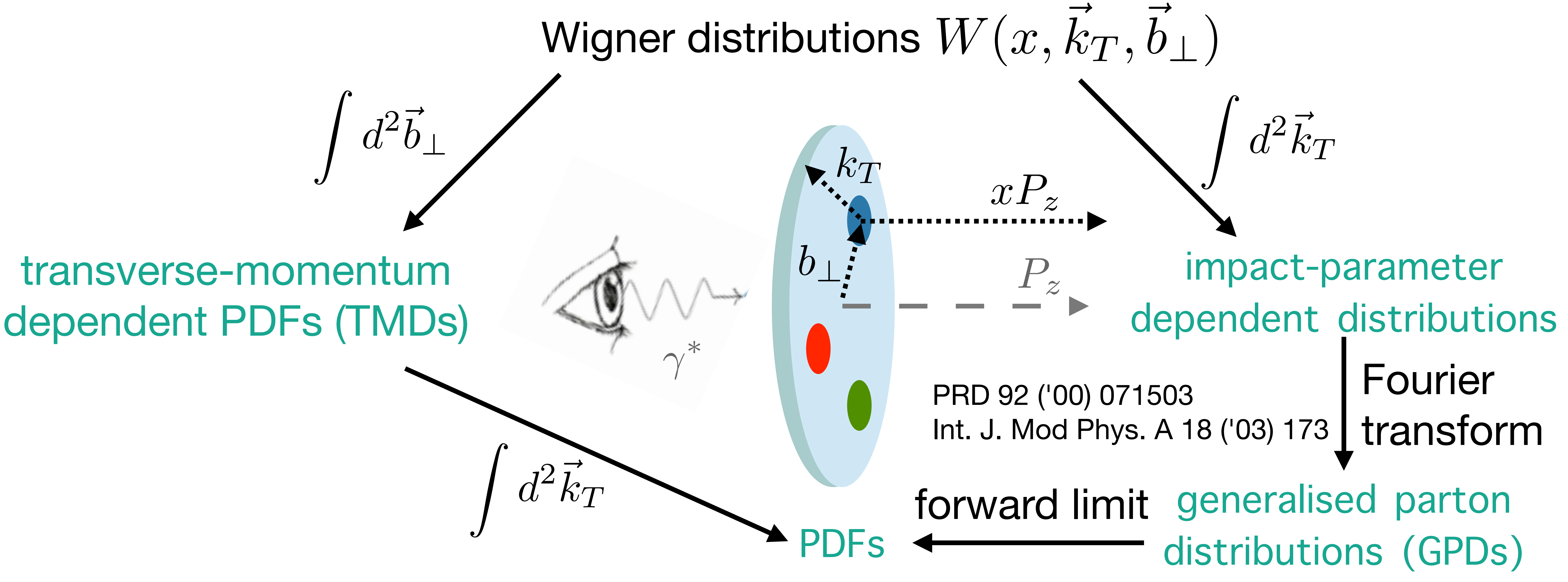

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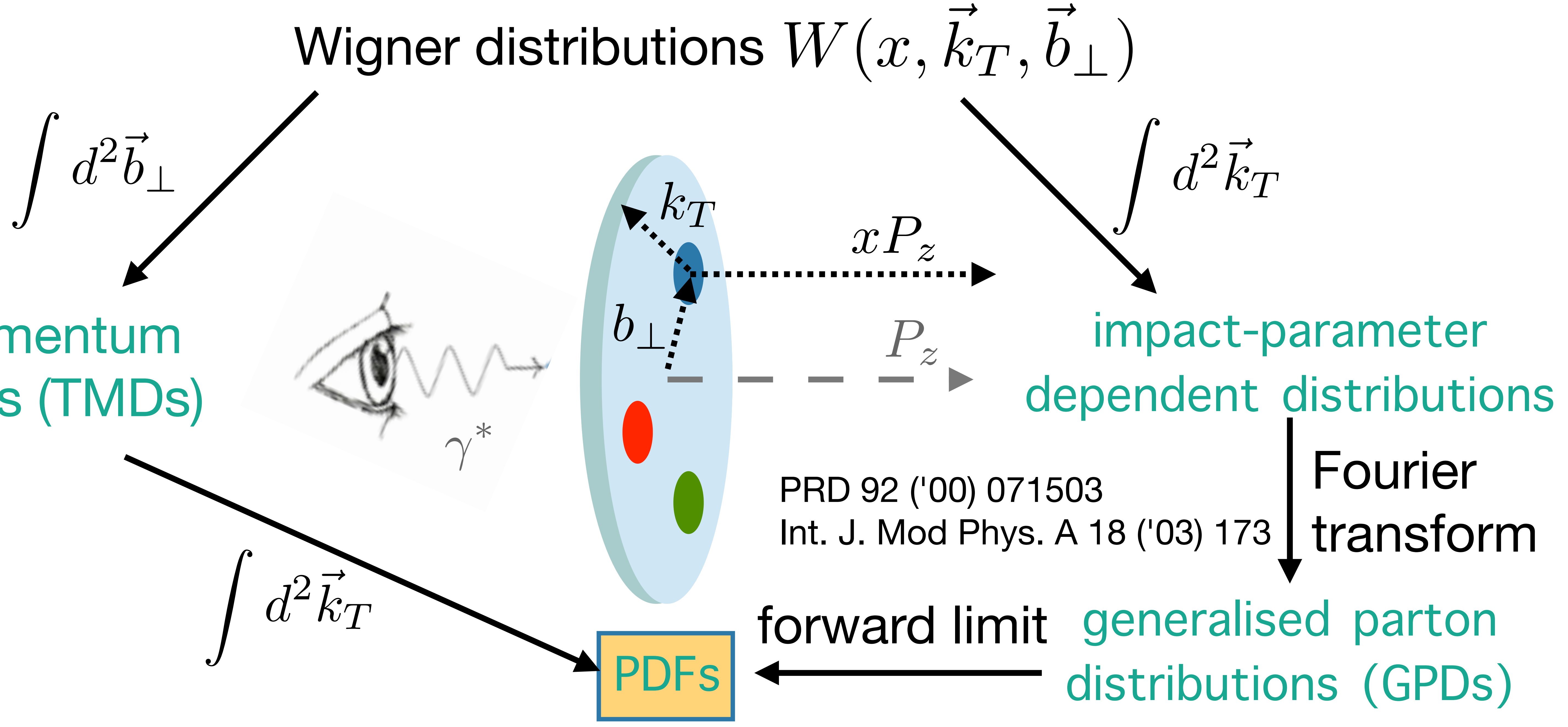

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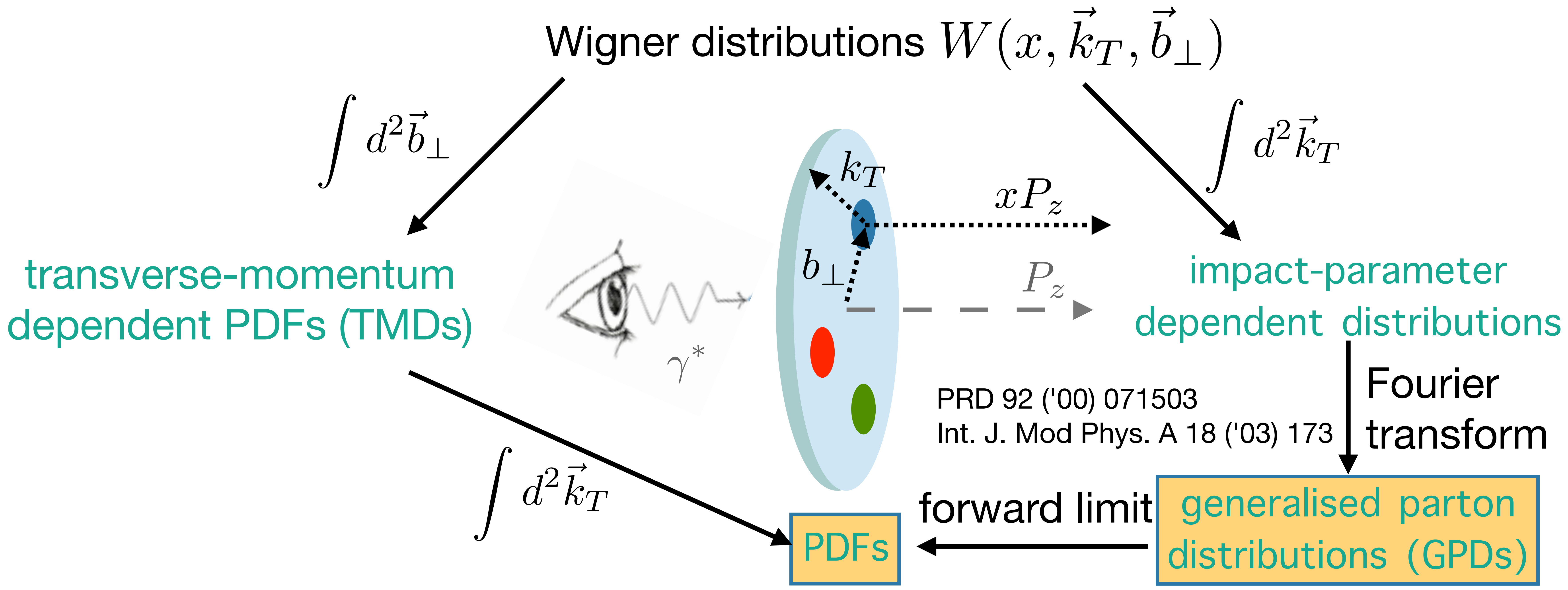

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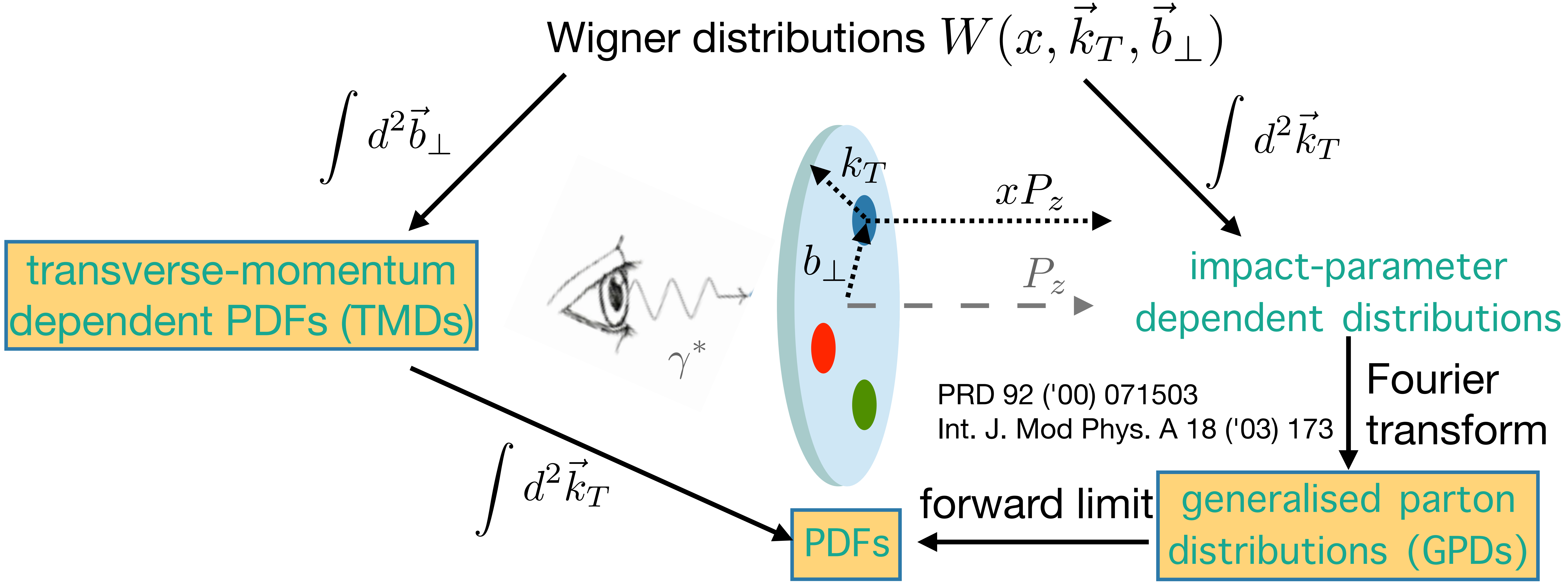

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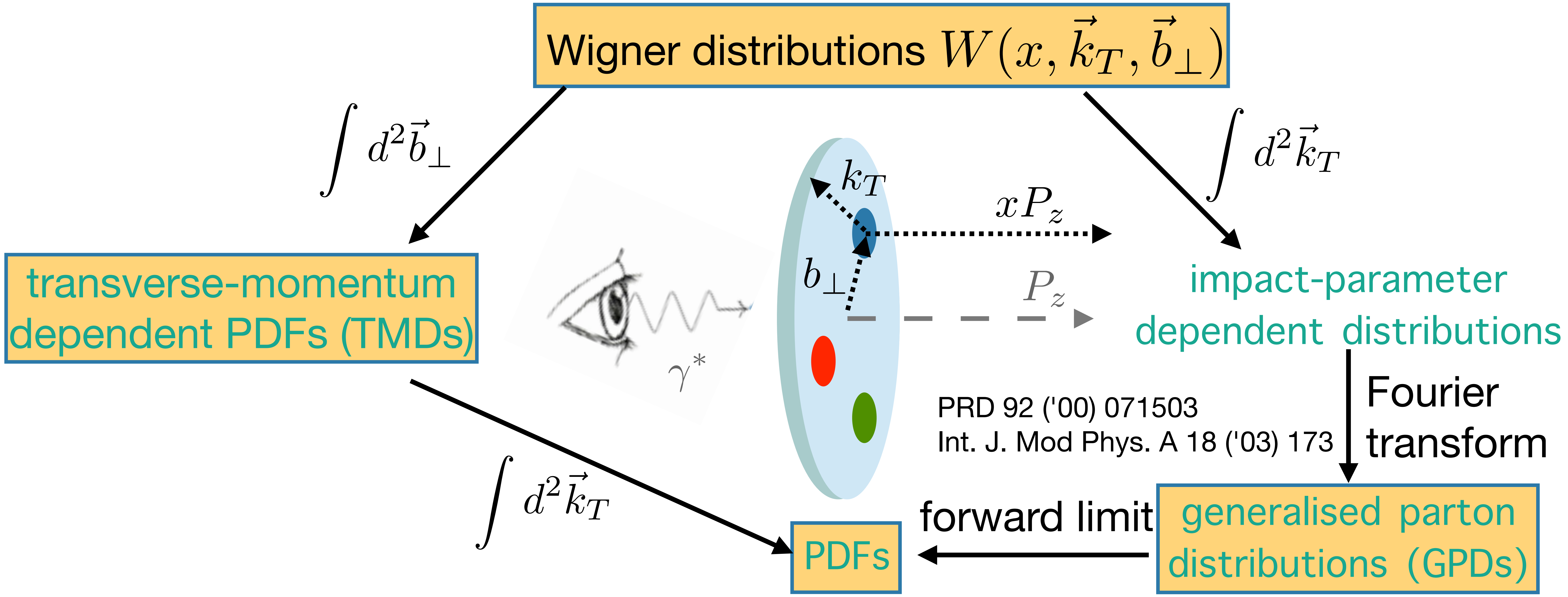

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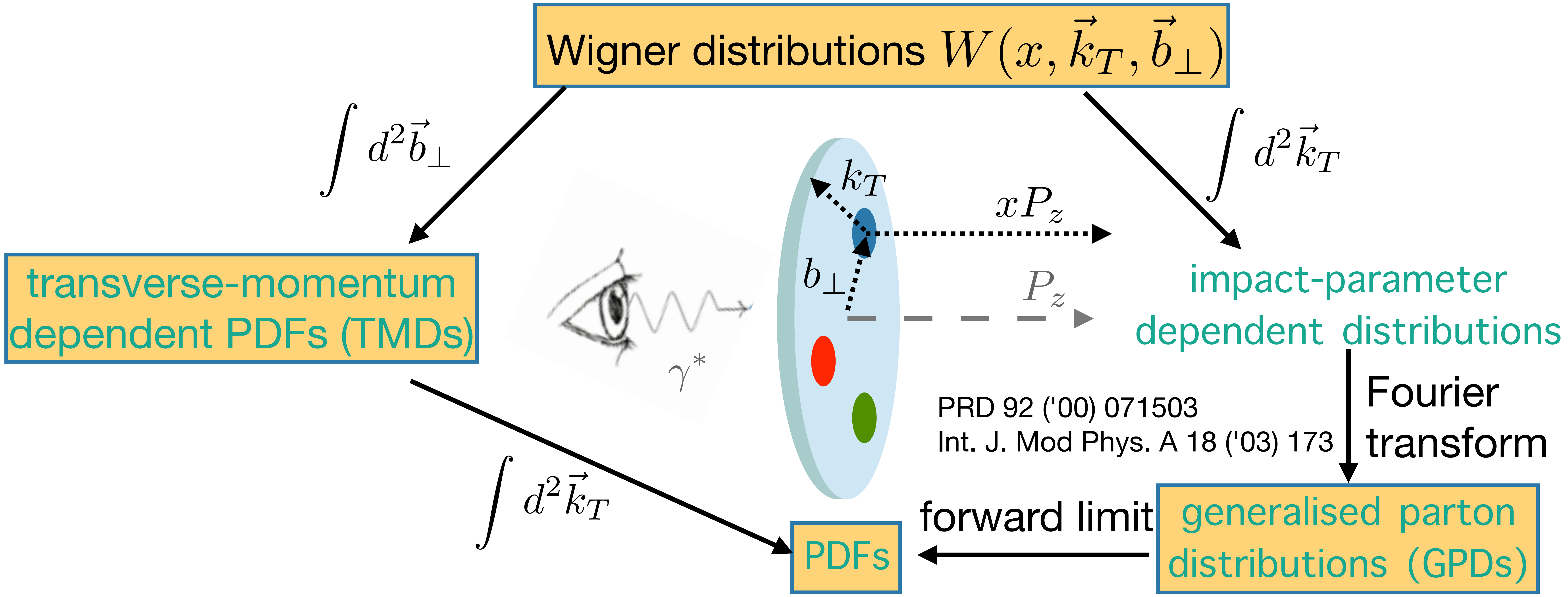

and a possible path to new physics

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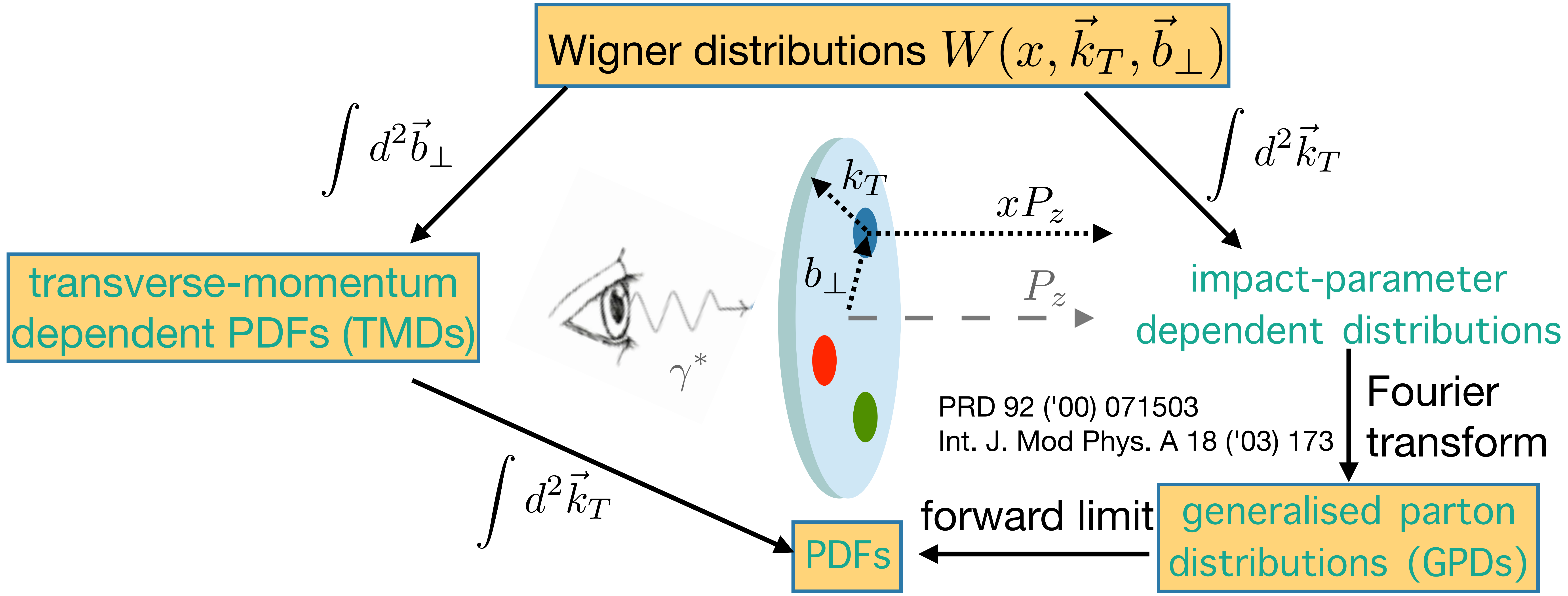
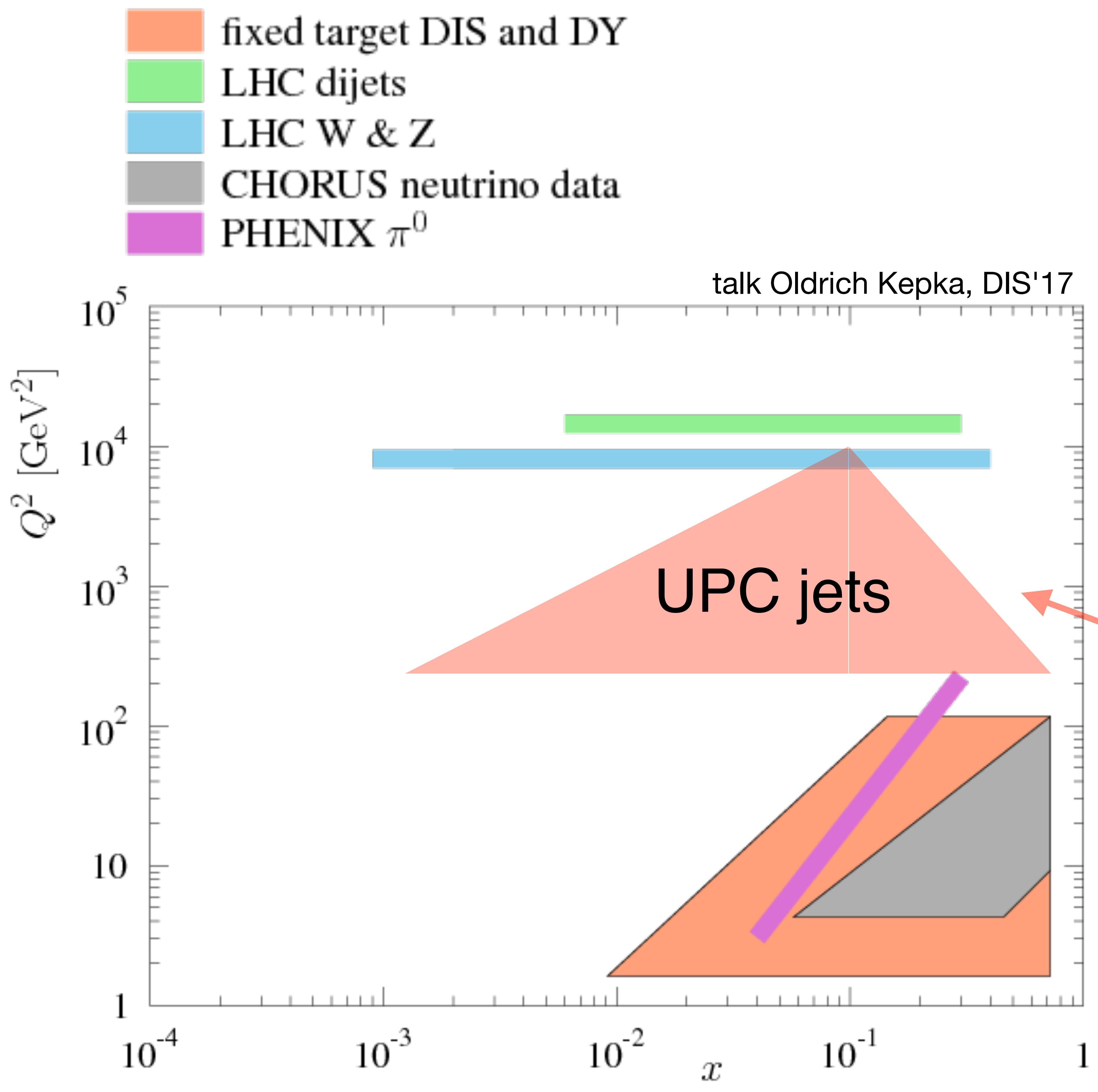


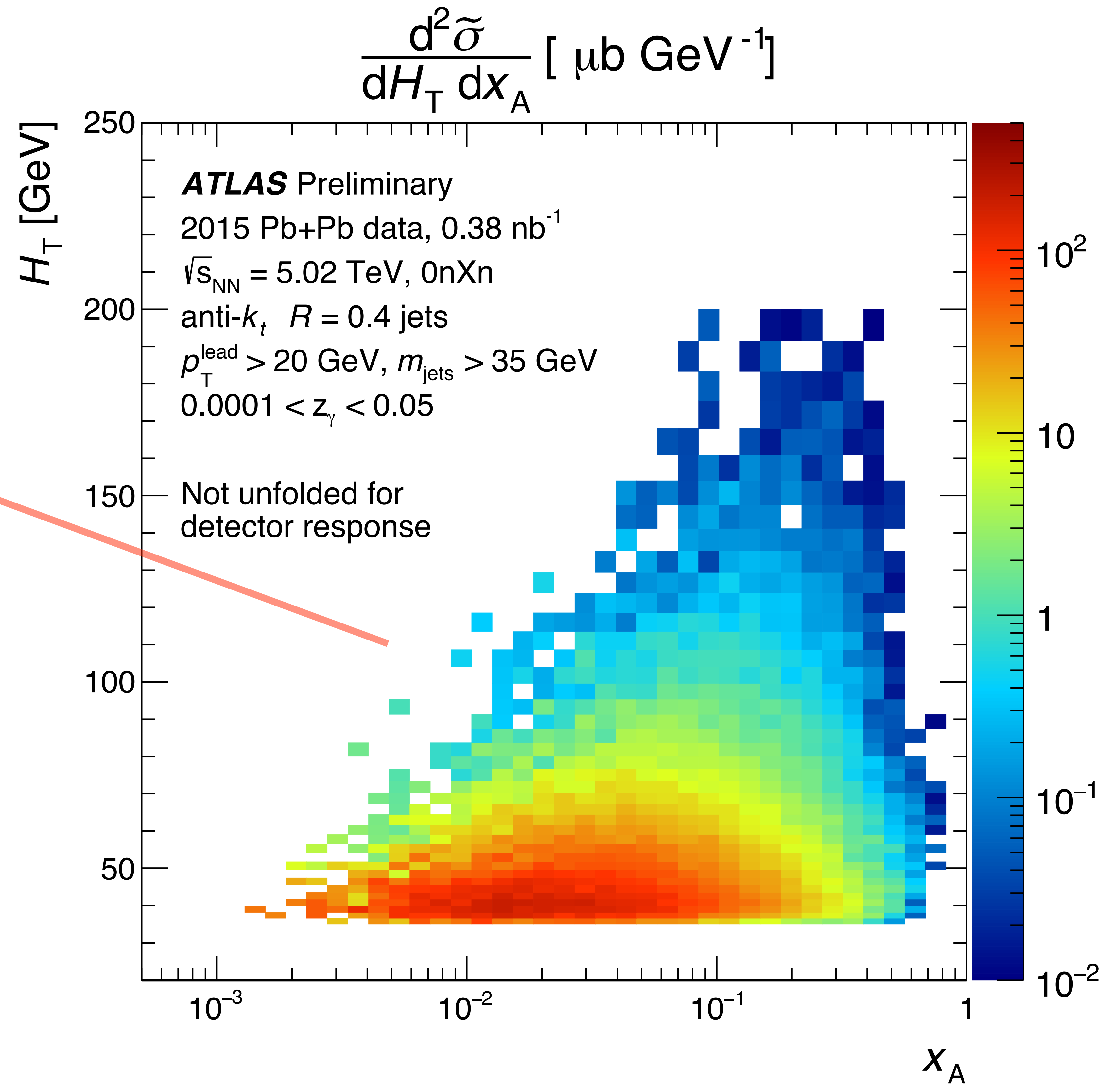
and a possible path to new physics

Beautiful physics programme to look forward to :)!

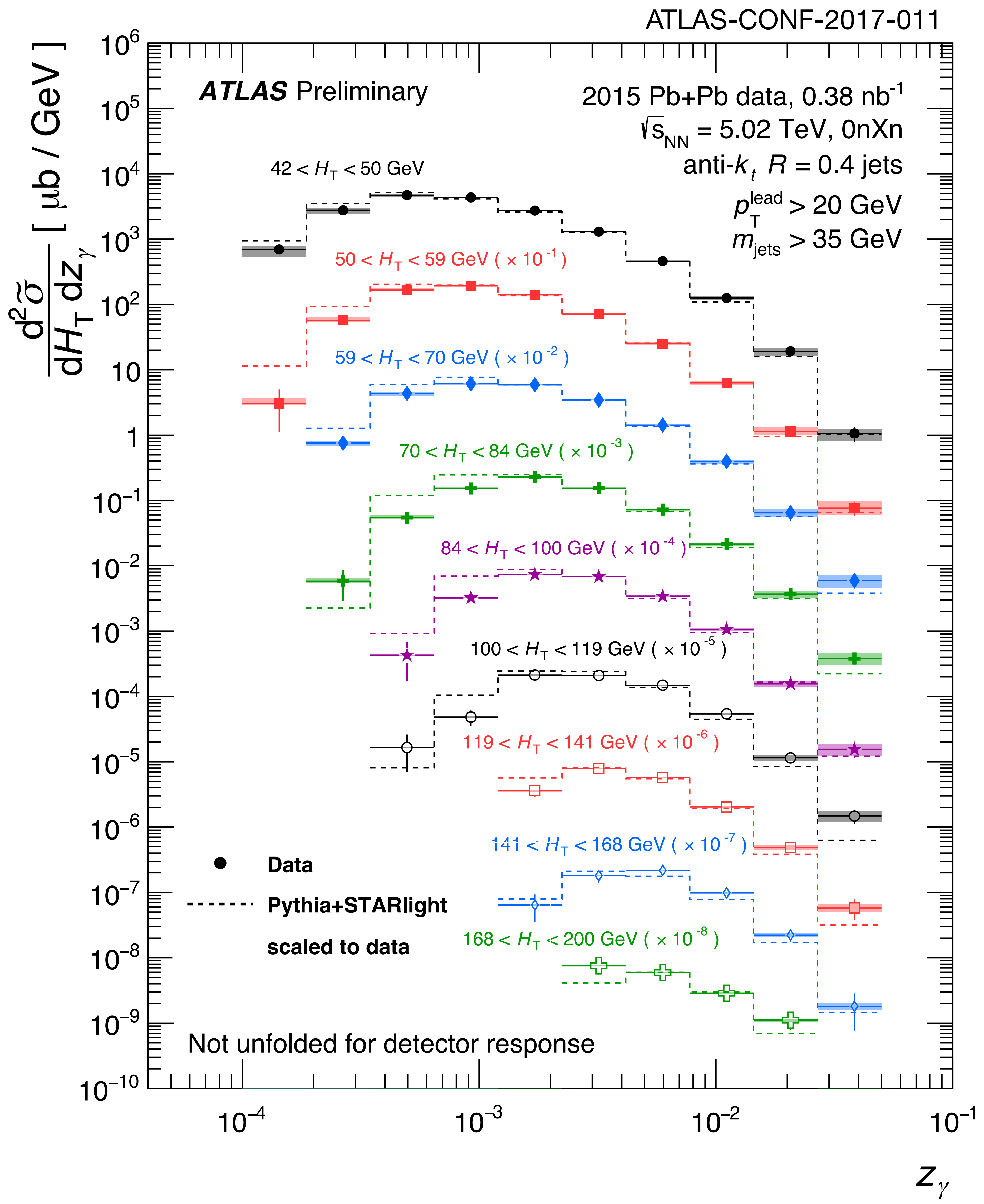
Back up

ATLAS measurement dijets





ATLAS measurement: results



$$y_J = \frac{1}{2}\ln\left(\frac{\sum_{\text{jet}} E_{\text{jet}} + \sum_{\text{jet}} p_{z,\text{jet}}}{\sum_{\text{jet}} E_{\text{jet}} - \sum_{\text{jet}} p_{z,\text{jet}}}\right)$$

$$x_A = \frac{M_J}{\sqrt{s}} e^{-y_J}$$

$$z_\gamma = \frac{M_J}{\sqrt{s}} e^{+y_J}$$