GPD sensitivity at the LHC

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University College Dublin

ECT*-APCTP workshop: Exploring resonance structure with transition GPDs

21/8- 25/8 Trento

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Overview

- The LHC and the experiments
- How GPDs can be accessed at hadron collider experiments
  1. DVCS (?)
  2. TCS
  3. DVMP (ρ,J/ψ,Υ production in UPC)
  4. DPE (?)
- Summary

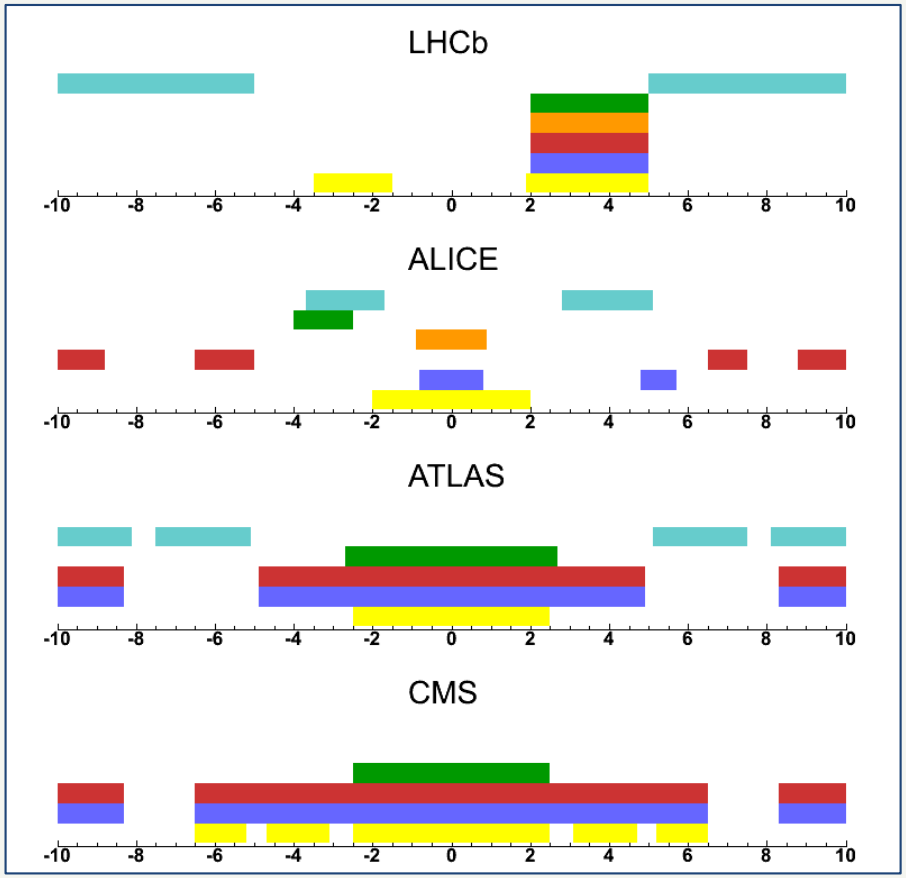
LHC and the detectors

- LHC collides pp, pPb and PbPb
- Also possible is **fixed target** mode of p or Pb on gas

ATLAS, CMS	High Lumi	High pT
ALICE, LHCb	Low Lumi	Low pT

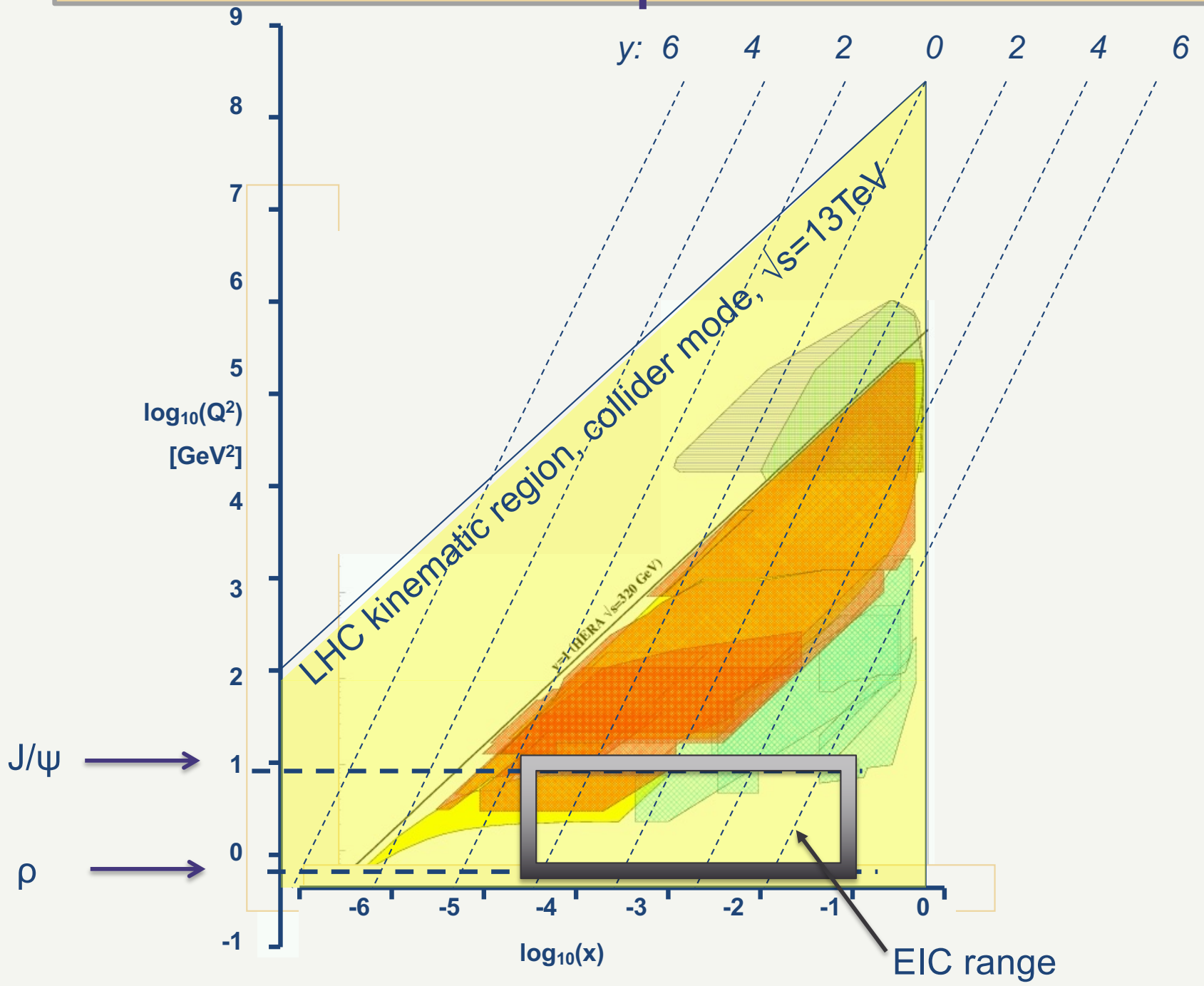
- LHCb: full reconstruction $2<\eta<5$
- ATLAS, CMS, ALICE: $5<\eta<5$

- All have vetos towards beam axis
- ATLAS, CMS, ALICE have ZDCs for neutrons
- ATLAS, CMS(+TOTEM) have roman pots close to beam (but generally do not detect recoil protons for low-mass objects)

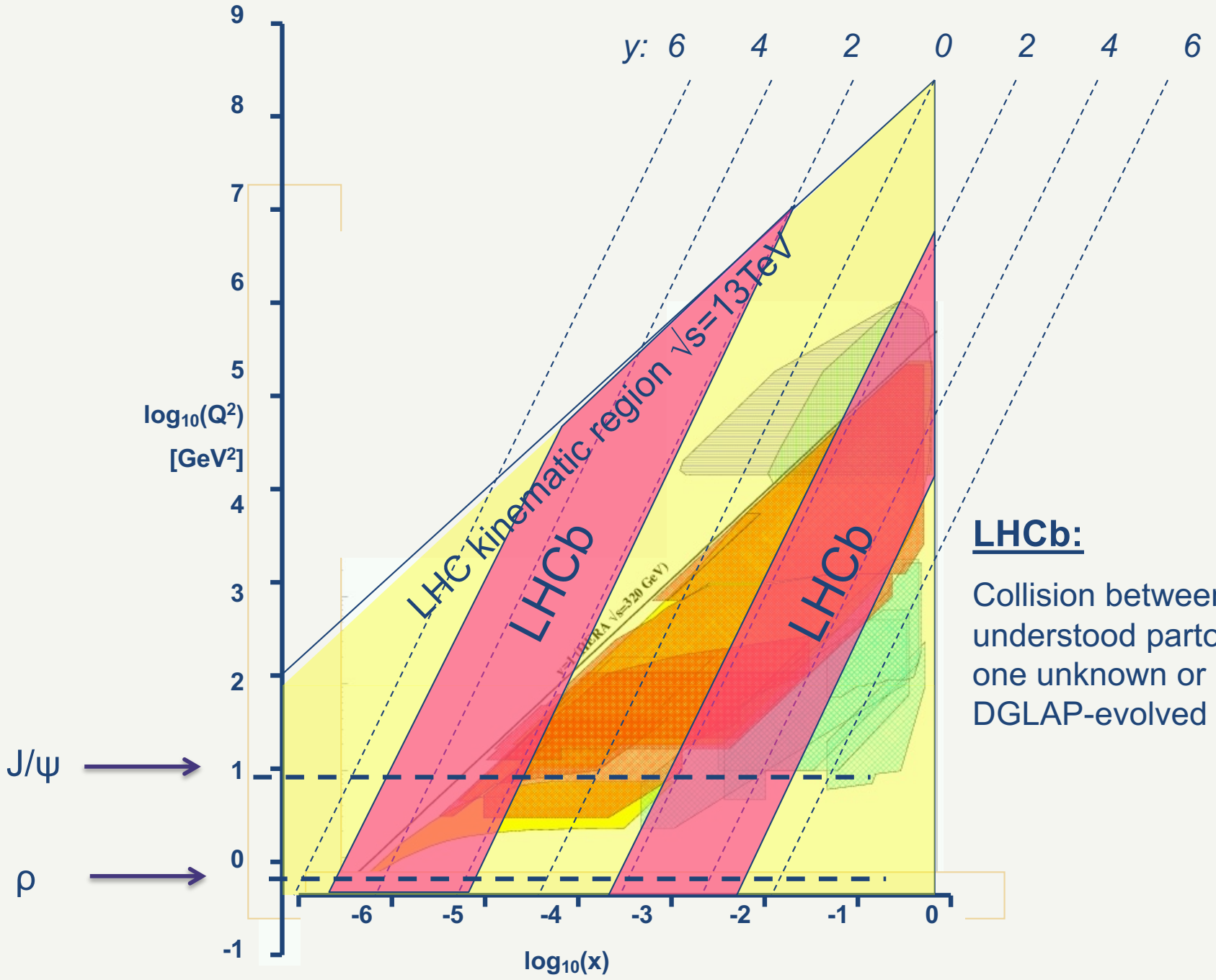


Tracking
ECAL
HCAL
Hadron PID
Muon
Counters

x-Q^2 values probed at LHC



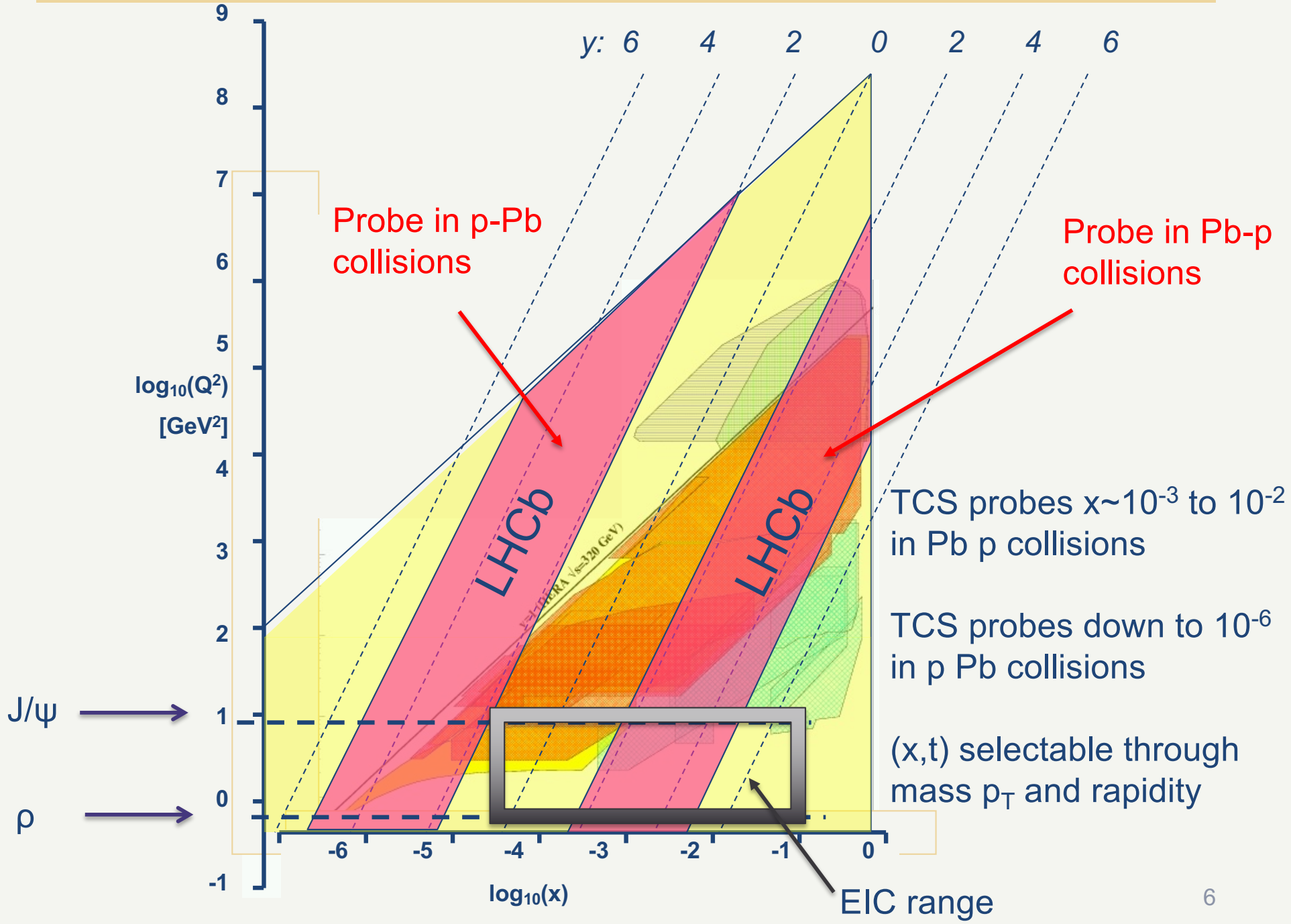
x-Q^2 values probed at LHC



LHCb:

Collision between one well understood parton and one unknown or large DGLAP-evolved parton.

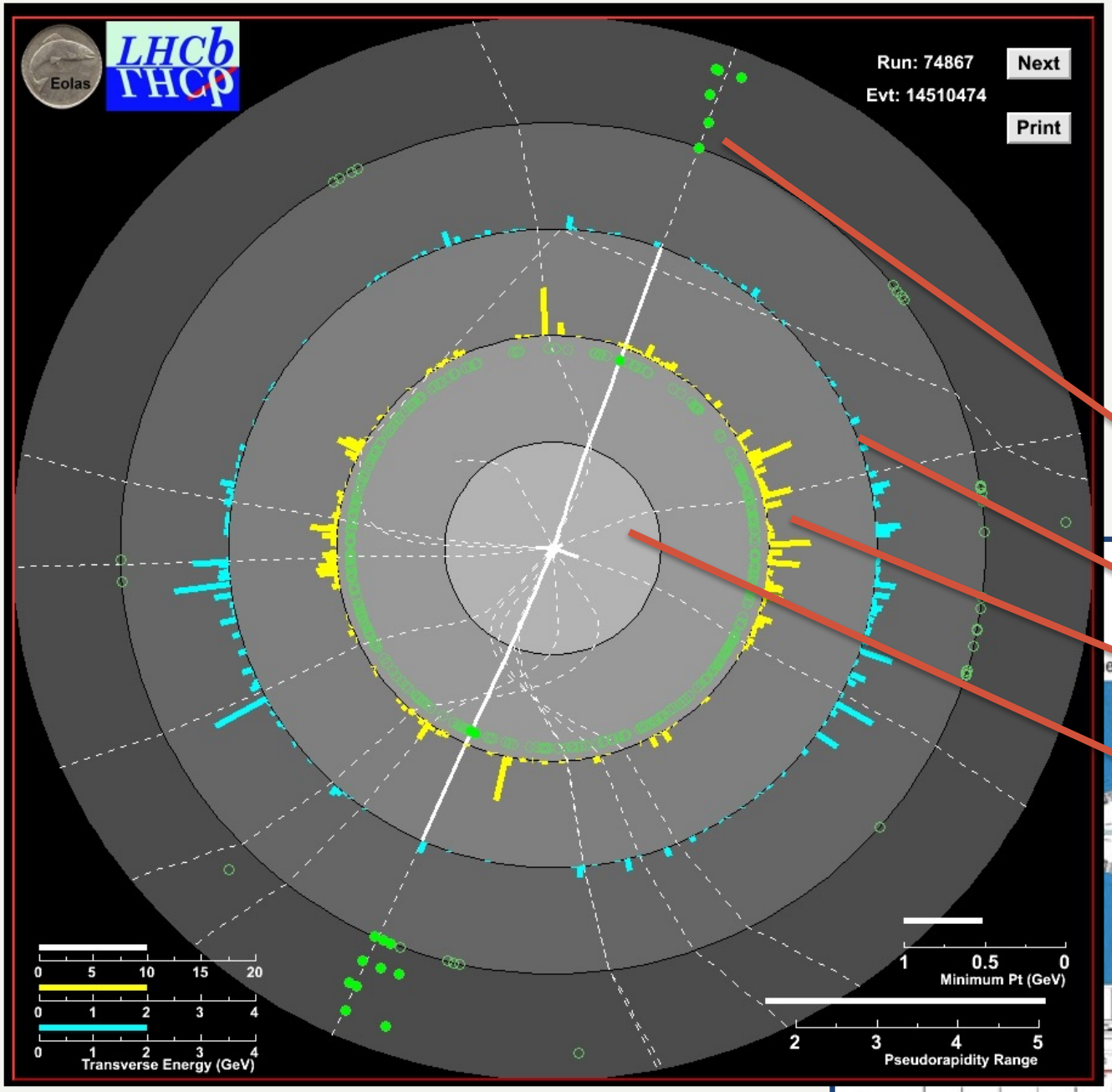
x-Q^2 values probed at LHC



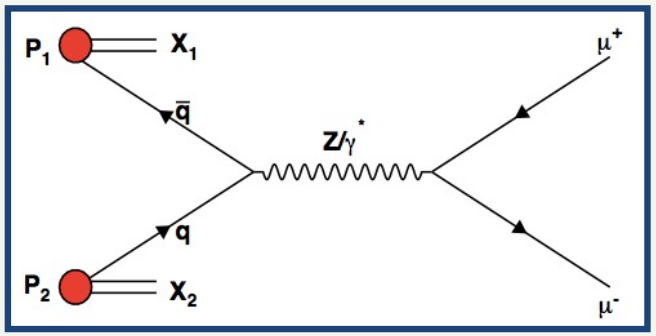
TCS probes $x \sim 10^{-3}$ to 10^{-2} in Pb p collisions

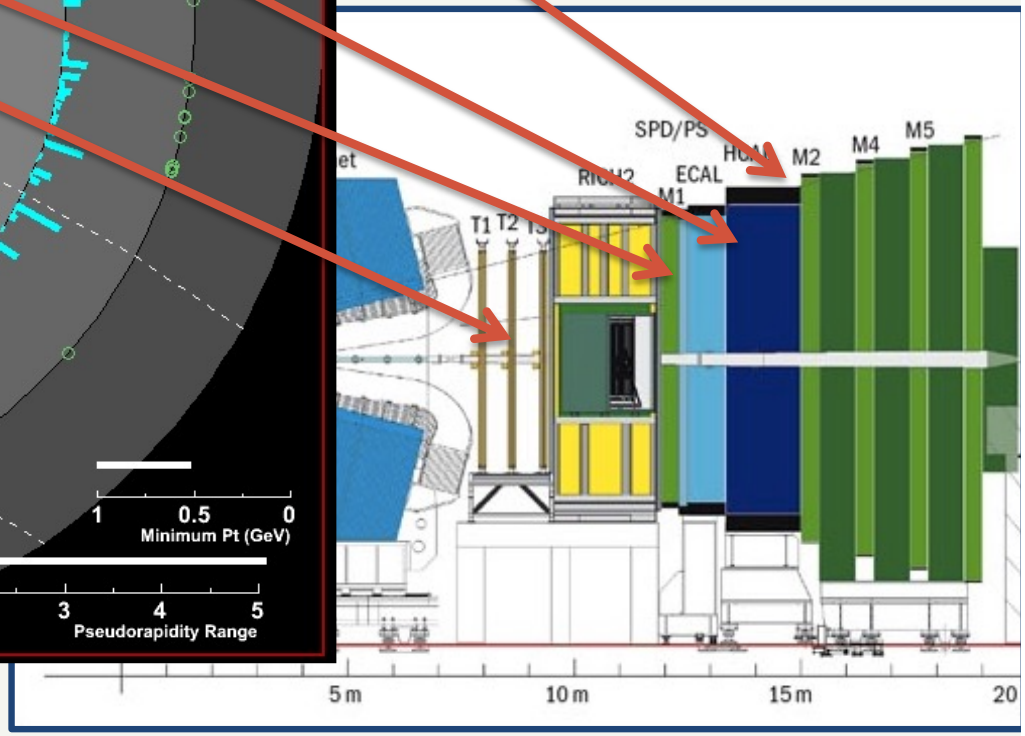
TCS probes down to 10^{-6} in p Pb collisions

(x,t) selectable through mass p_T and rapidity

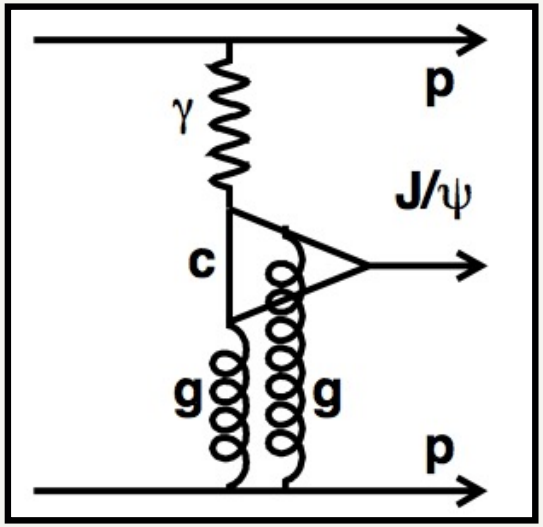


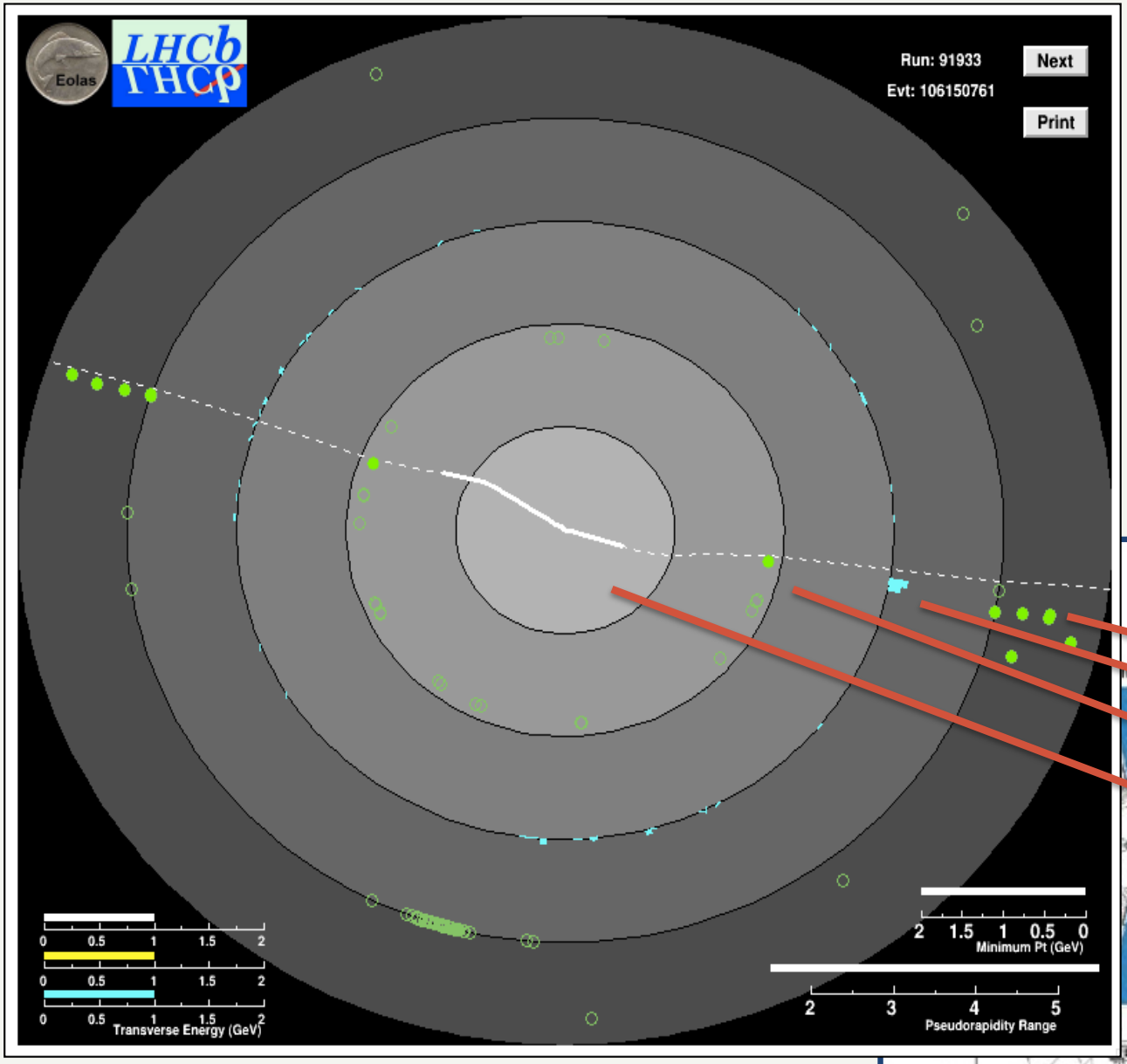
Inclusive pp->ZX

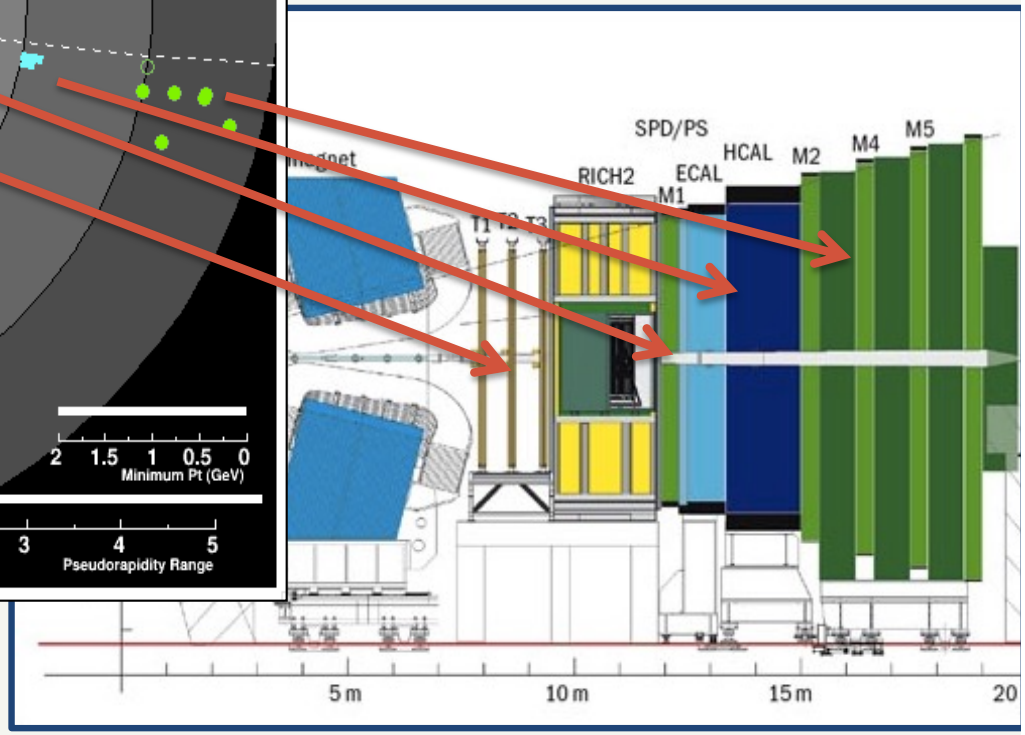




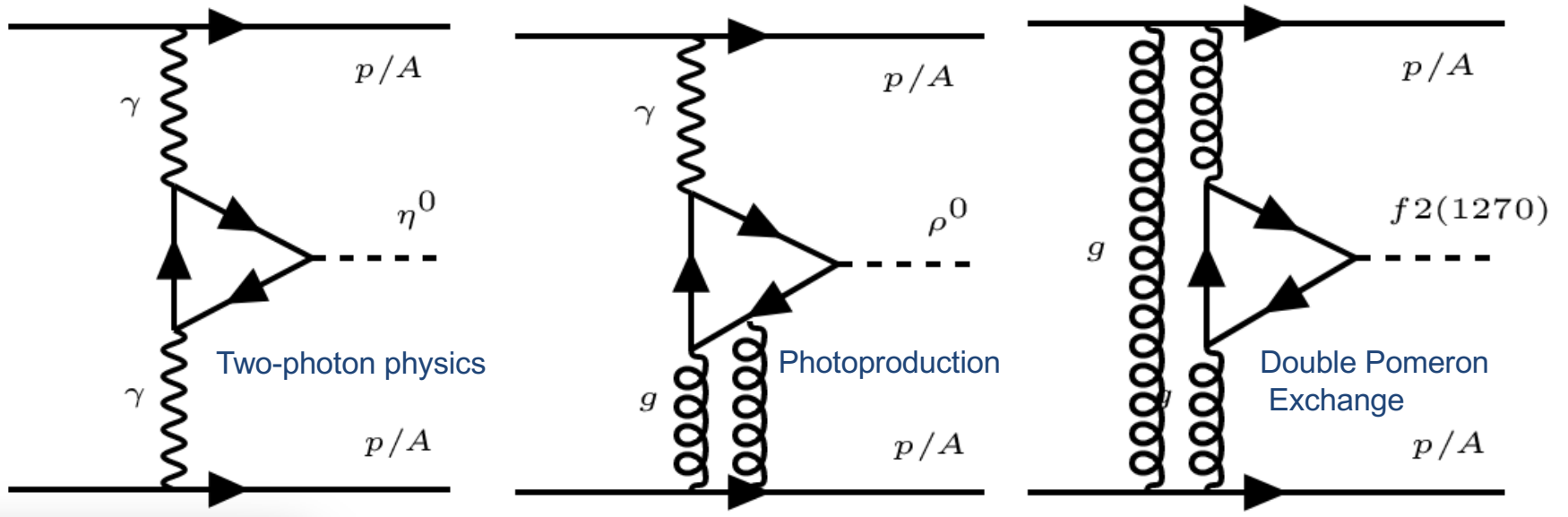
UPC

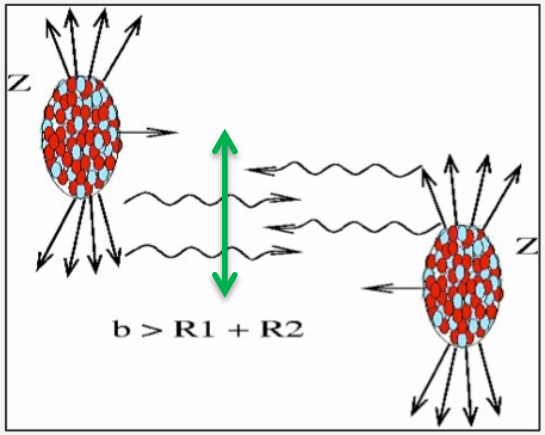

γ
p
J/ψ
c
g
g
p


LHCb
Eolas
Run: 91933
Evt: 106150761
Next
Print
0 0.5 1 1.5 2
0 0.5 1 1.5 2
0 0.5 1 1.5 2
Transverse Energy (GeV)
2 1.5 1 0.5 0
Minimum Pt (GeV)
2 3 4 5
Pseudorapidity Range


SPD/PS
HCAL
M2
M4
M5
RICH2
ECAL
M1
5 m
10 m
15 m

Colourless propagators





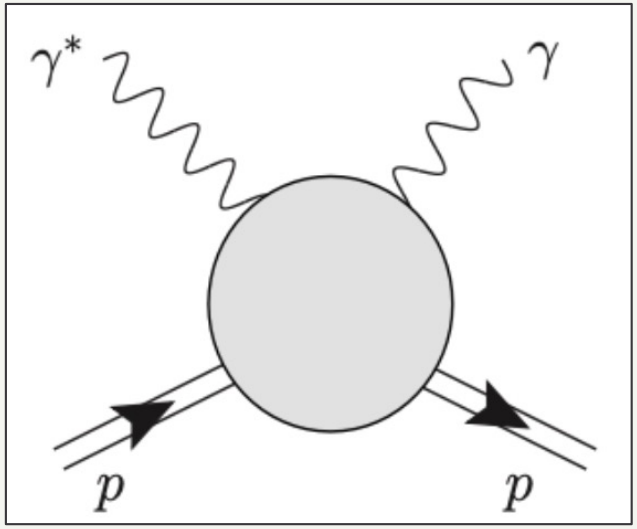
Generally, to ensure no (colourful) QCD interaction, $d>R_1+R_2$ (1.5 - 6 fm).

1. DVCS

DVCS

Workhorse for current GPD extractions (through CFF)

- Boer, Guidal, JPG 42 no. 3, 034023 (2015)
- Shiells, Guo, Ji, JHEP 08 048 (2022)
- Kumericki, Liuti, Moutarde, Eur. Phys. J. A 52, no. 6, 157 (2016)
- Dupré, Guidal, Vanderhaeghen, PRD 95 no.1, 011501 (2017)
- Moutarde, Sznajder, Wagner, EPJC 78 11, 890 (2018)
- Moutarde, Sznajder, Wagner, EPJC 79 7, 614 (2019)
- Dutrieux et al., Eur.Phys.J.A 57 8, 250 (2021)



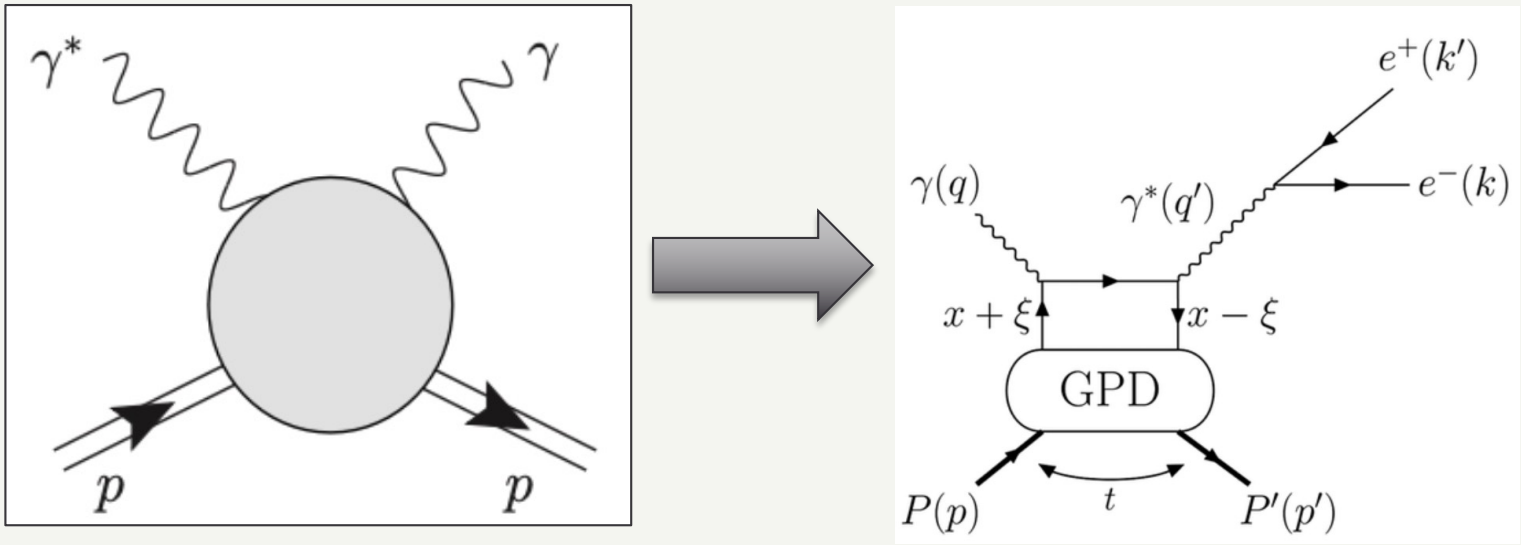
Data: Hermes, H1, Zeus, CLAS, Hall A, COMPASS

γ^* originates from **lepton**

Can this come from **hadron** (LHC) ?

In general, No, since $Q^2 < (\hbar c/d)^2$

2. TCS

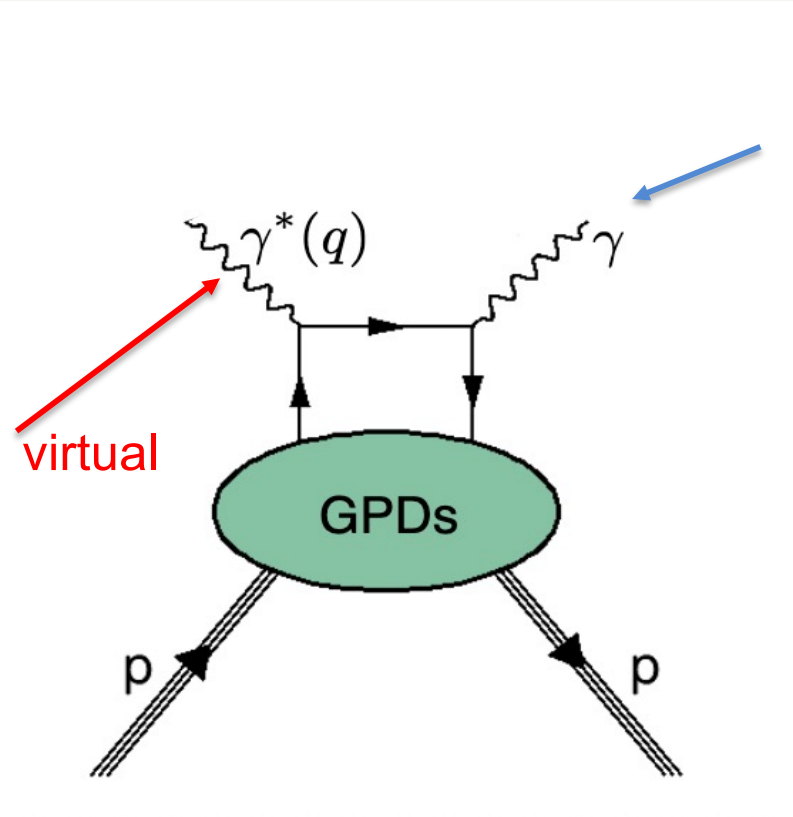


DVCS-TCS

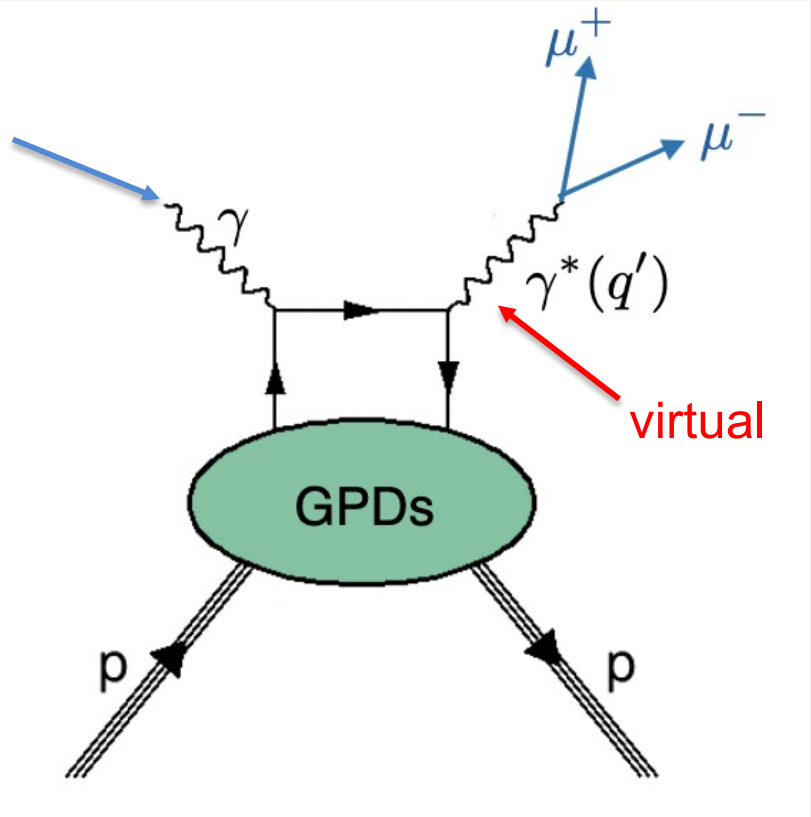
Phys.Rev.D 79 (2009) 014010

Can one measure timelike Compton scattering at LHC ?

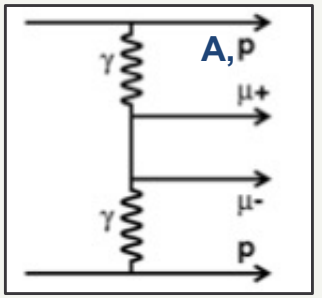
B. Pire[1] and L. Szymanowski and J. Wagner[2]



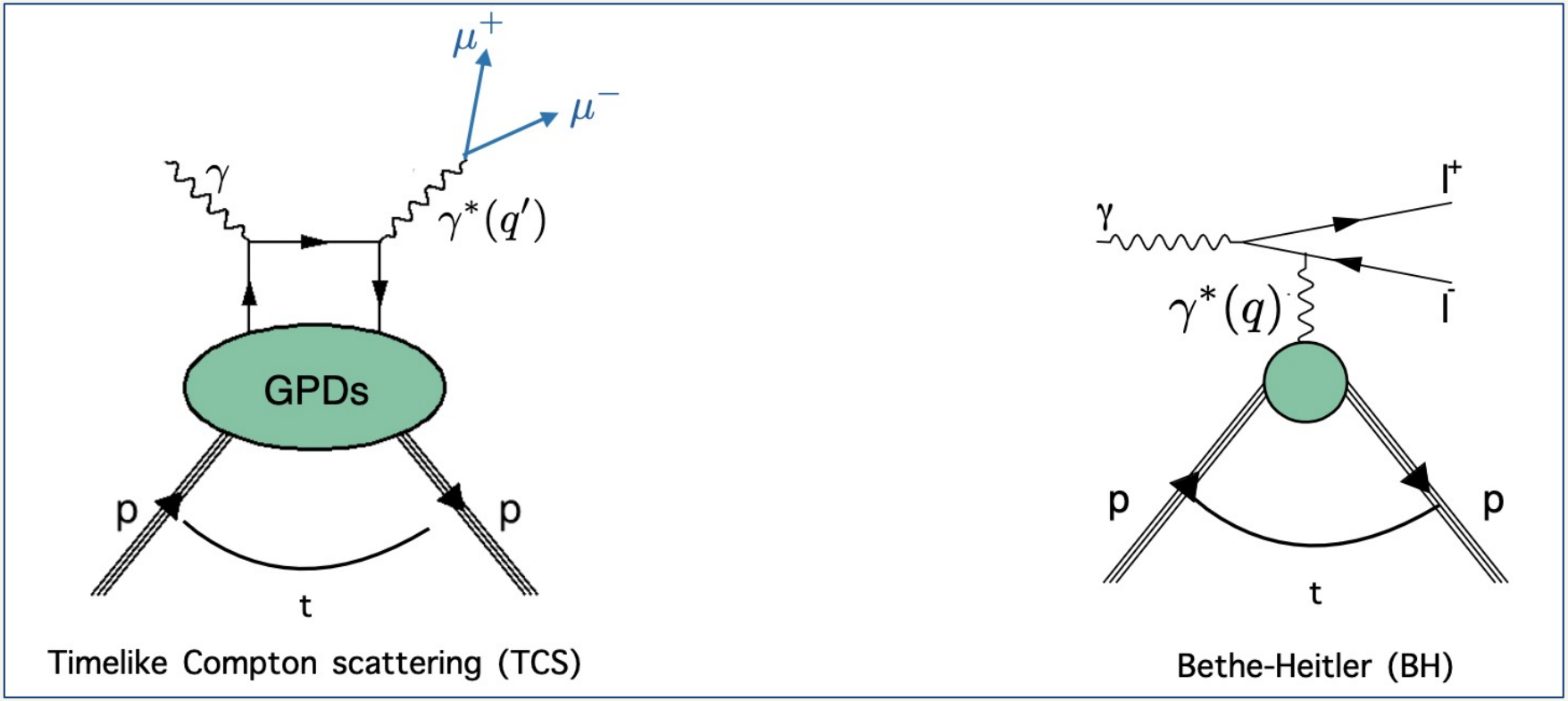
real



Final state of two leptons and nothing else.
Q^2 given by mass of dilepton system
t given by p_T^2 of dilepton system

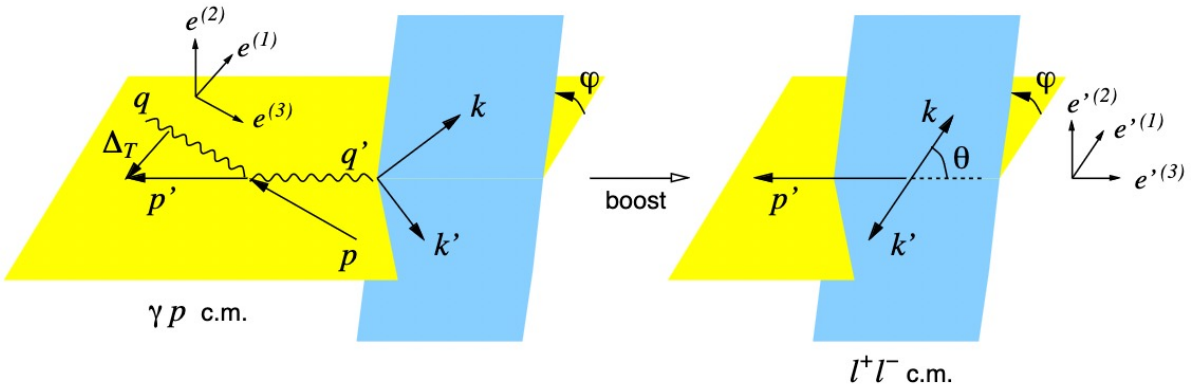


Complication from Bethe-Heitler



$$\sigma = |T_{BH}|^2 + |T_{TCS}|^2 + \underbrace{T_{TCS}T_{BH}^* + T_{TCS}^* T_{BH}}_{\text{Interference term}}$$

Use background to amplify signal



Bethe Heitler

$$\frac{d\sigma_{\ell\ell}^{\gamma h\,\mathrm{BH}}}{dQ^2\; dq_T^2\, d\cos\theta\, d\phi}(y_{\mathrm{cms}}^{\ell\ell}) \approx J\frac{\alpha_{em}^3}{2\pi s_{\gamma h}^2}\,\frac{1}{-t}\,\frac{1+\cos^2\theta}{\sin^2\theta}$$

$$\times\left[\left(F_1^2(t)-\frac{t}{4M_N^2}F_2^2(t)\right)\frac{2(s_{\gamma h}-M_N^2)^2}{Q^4}\,\frac{q_T^2}{-t}+(F_1(t)+F_2(t))^2\right]\Bigg|_{t=t(y_{\mathrm{cms}}^{\ell\ell},q_T^2,Q,\epsilon)}$$

Interference Bethe Heitler and Timelike Compton scattering

$$\frac{d\sigma_{\ell\ell}^{\gamma h\,\mathrm{INT}}}{dQ^2\, dt\, d\cos\theta\, d\phi} \approx -\frac{\alpha_{em}^3}{4\pi s_{\gamma h}^2}\,\frac{\sqrt{t_0-t}}{-tQ}\,\frac{\sqrt{1-\eta^2}}{\eta}\left(\cos\phi\,\frac{1+\cos^2\theta}{\sin\theta}\right)$$

$$\times\,\mathrm{Re}\left[F_1(t)\mathcal{H}(\eta,t)-\eta(F_1(t)+F_2(t))\,\tilde{\mathcal{H}}(\eta,t)-\frac{t}{4M^2}F_2(t)\,\mathcal{E}(\eta,t)\right]$$

$$+\cos(2\phi)\ \text{and}\ \cos(3\phi)\ \text{contributions}$$

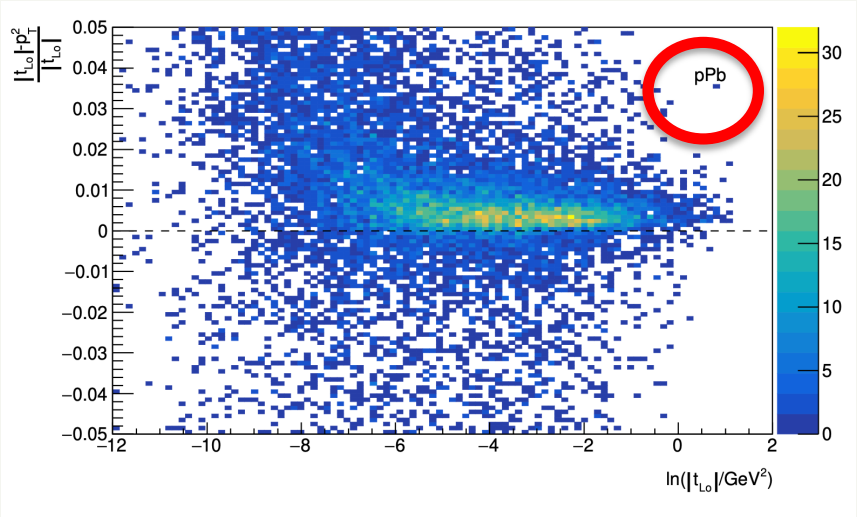
TCS<<BH

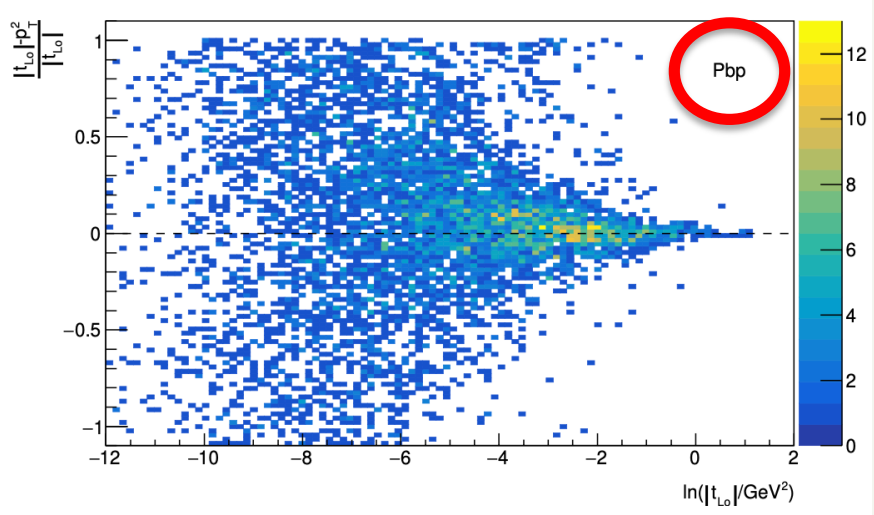
TCS accesible via interference. $|T_{TCS}|^2$ has no ϕ dependence.

First efforts towards measurement

(Charlotte!)

Fractional difference between true t and reconstructed p_T^2

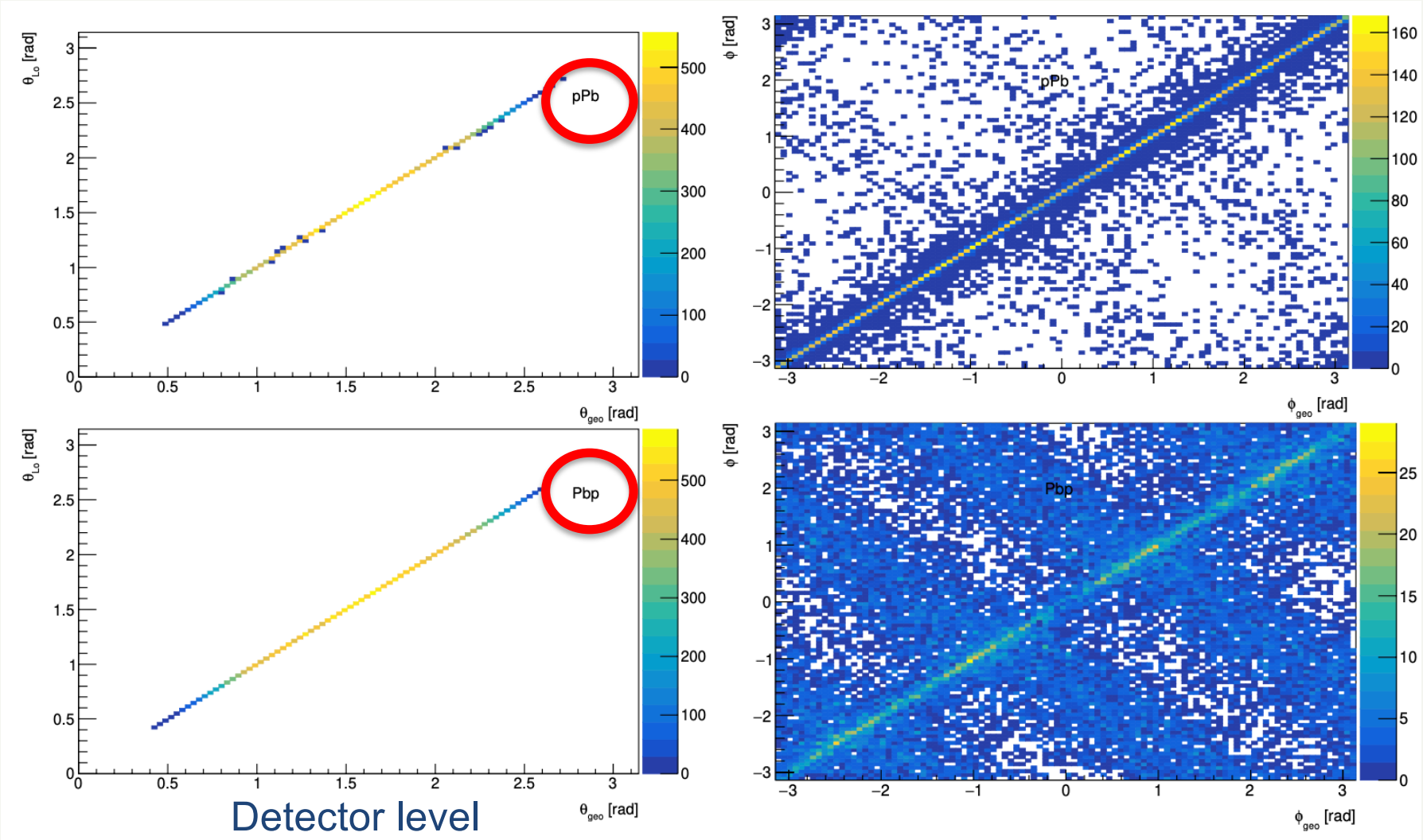




log(t)

First efforts towards measurement

Generator level

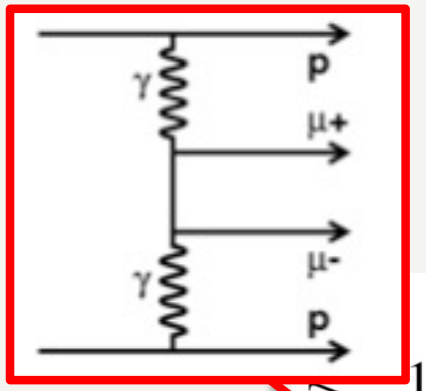


Detector level

Relevant kinematics can be reconstructed albeit with some geometric effects

And the data exists.....

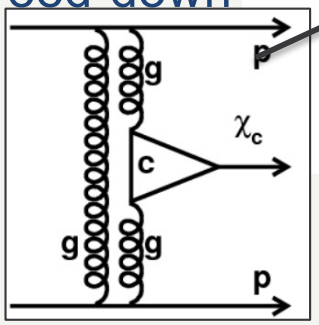
Dimuons in pp collisions

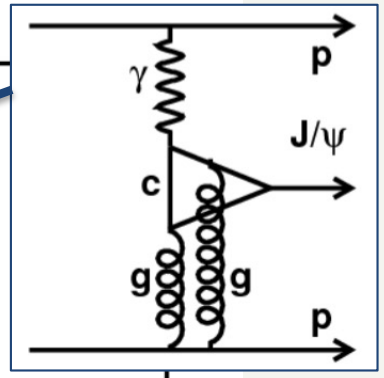


$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV

(electrons down to ~200MeV)

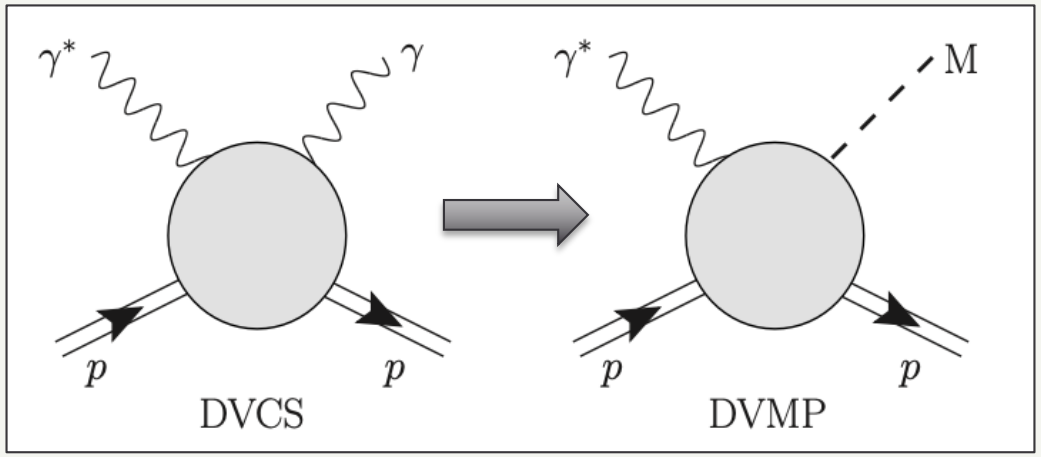
Feed-down



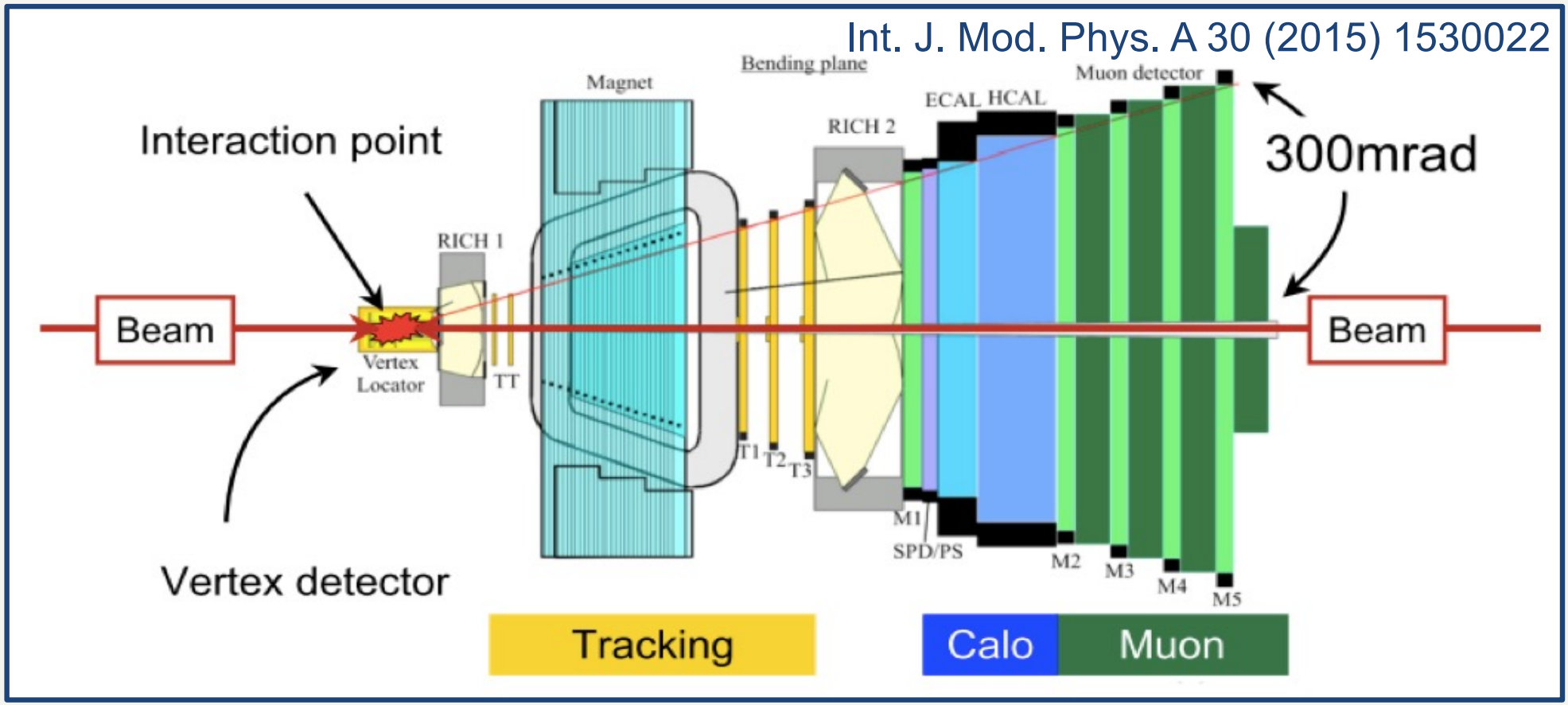


Two muons and nothing else in the LHCb detector

3. DVMP



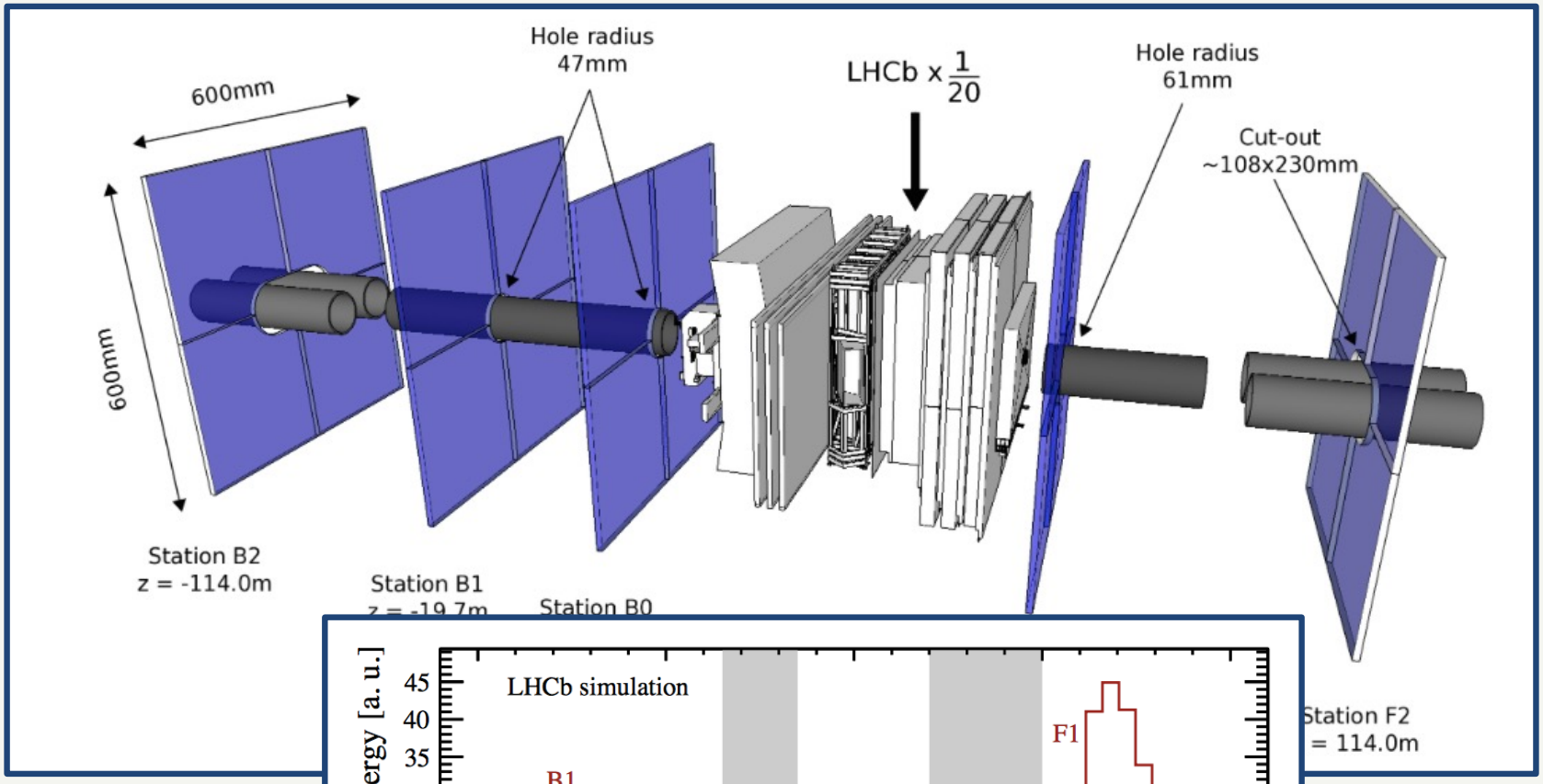
The LHCb detector



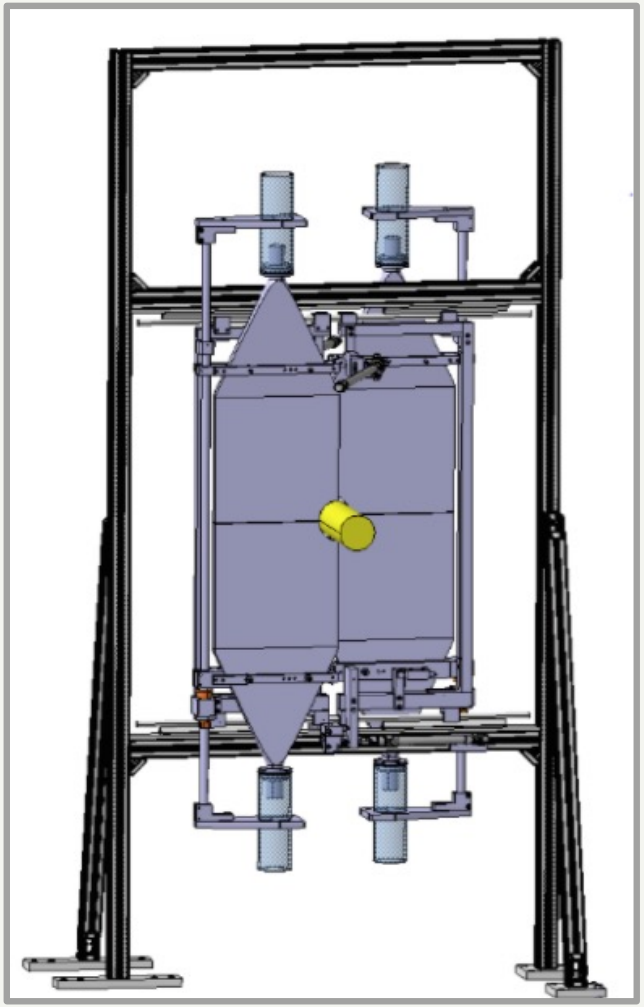
Fully instrumented: $2 < \eta < 5$

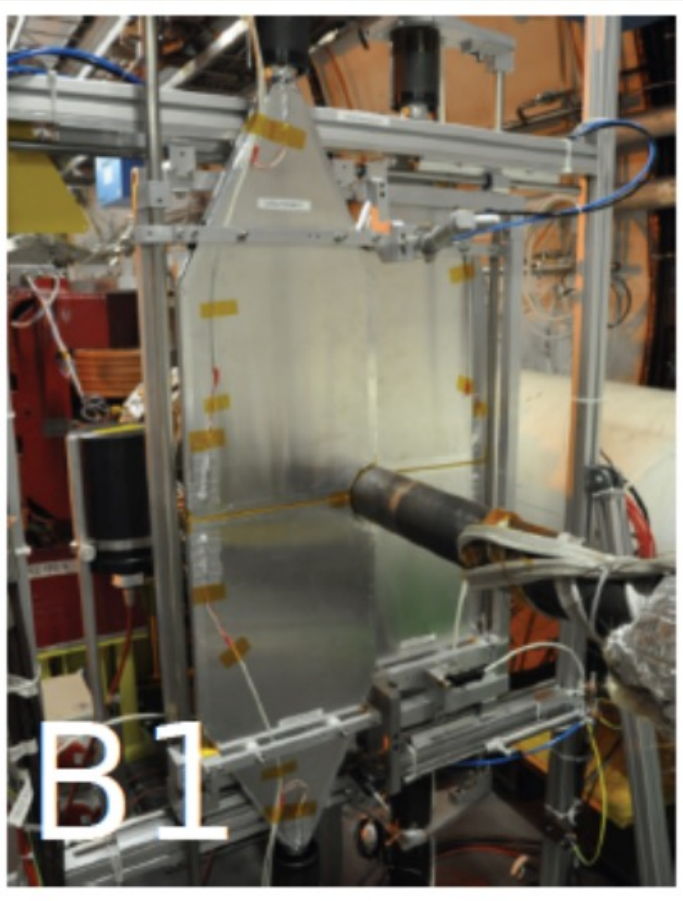
Veto region (Run 2): $-10<\eta<-5$, $5<\eta<10$

The LHCb detector

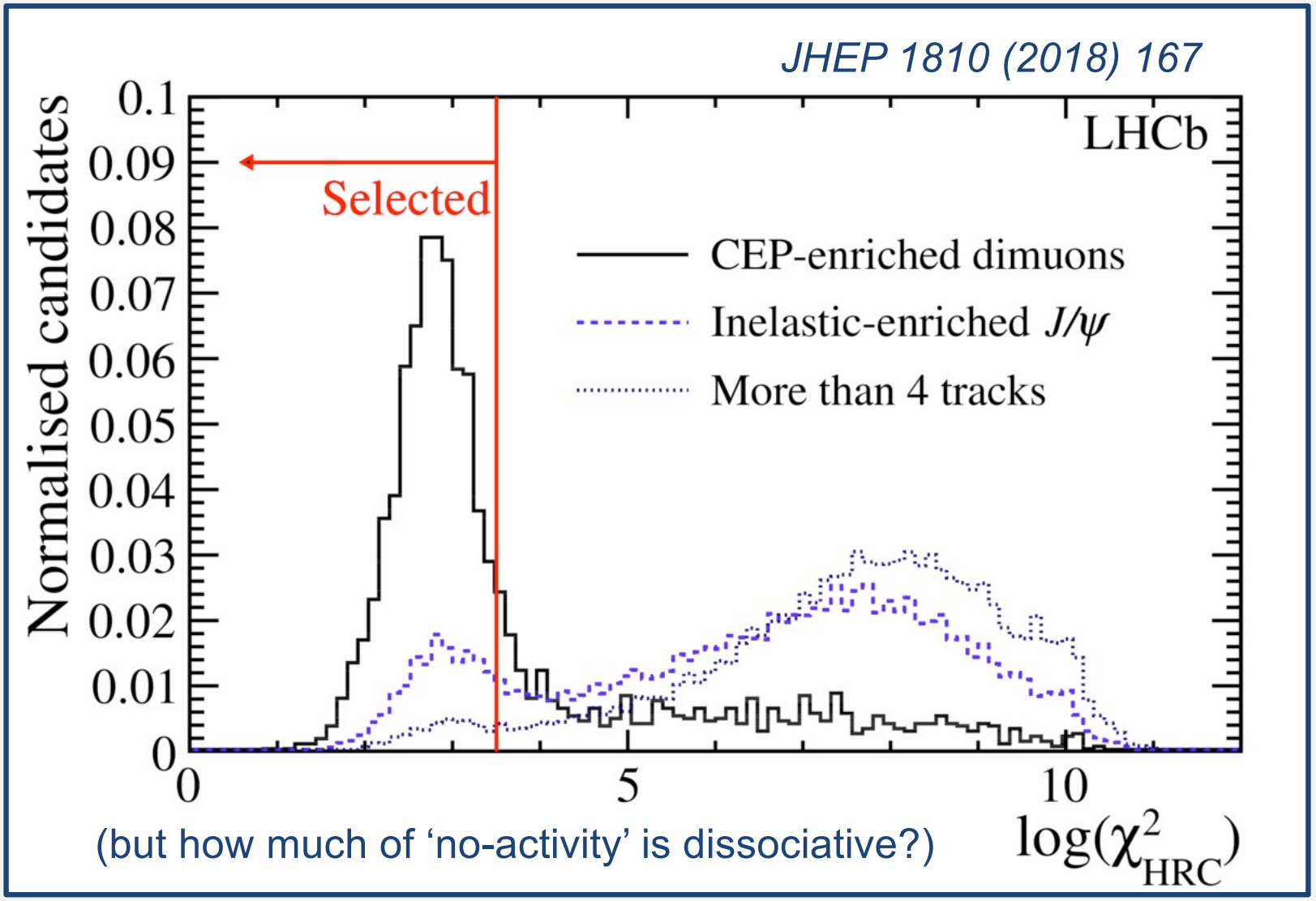


The LHCb detector

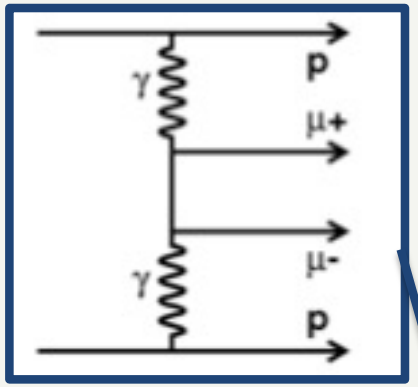




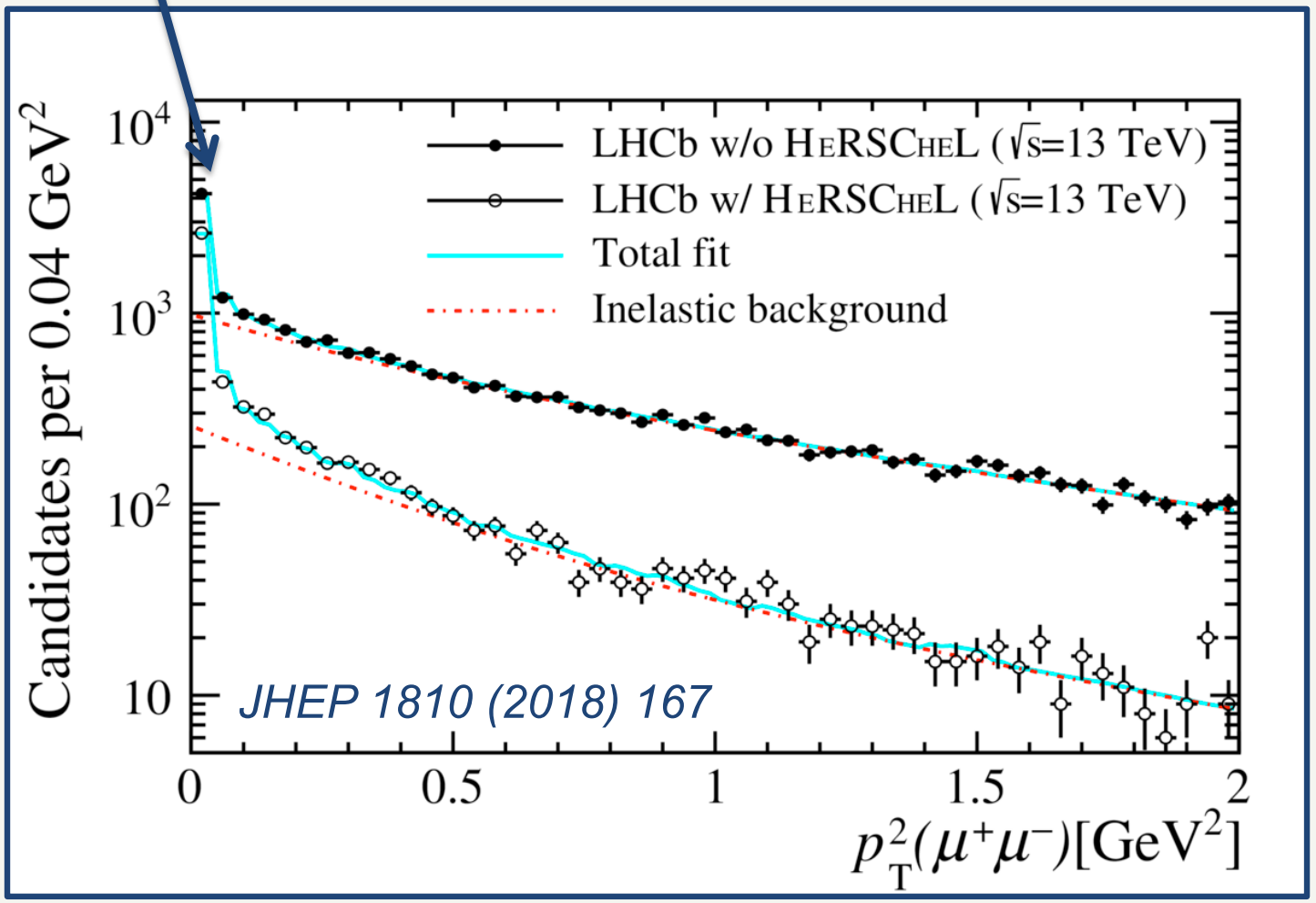
Discrimination power of Herschel



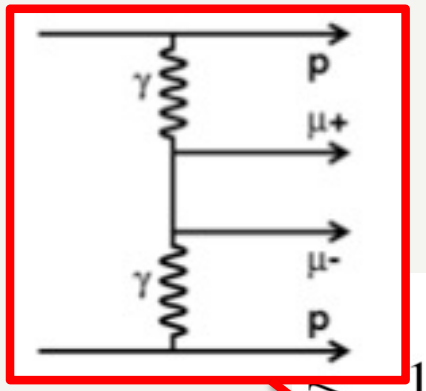
(but how much of 'no-activity' is dissociative?)



Dimuon continuum



Dimuons in pp collisions



$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV

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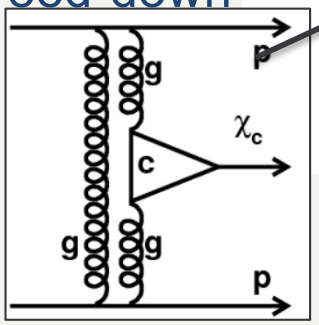
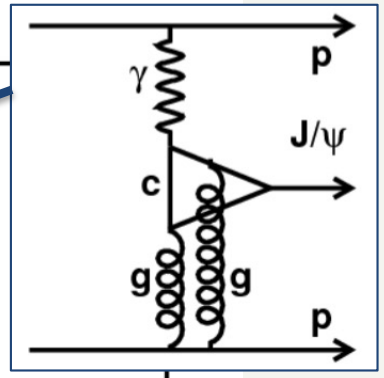
Feed-down





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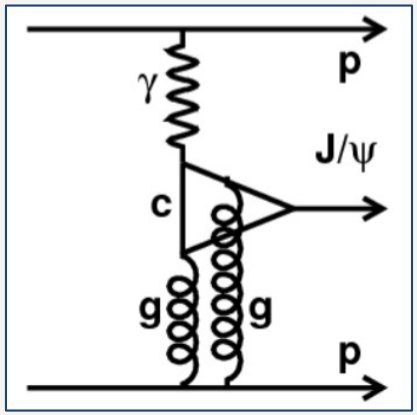
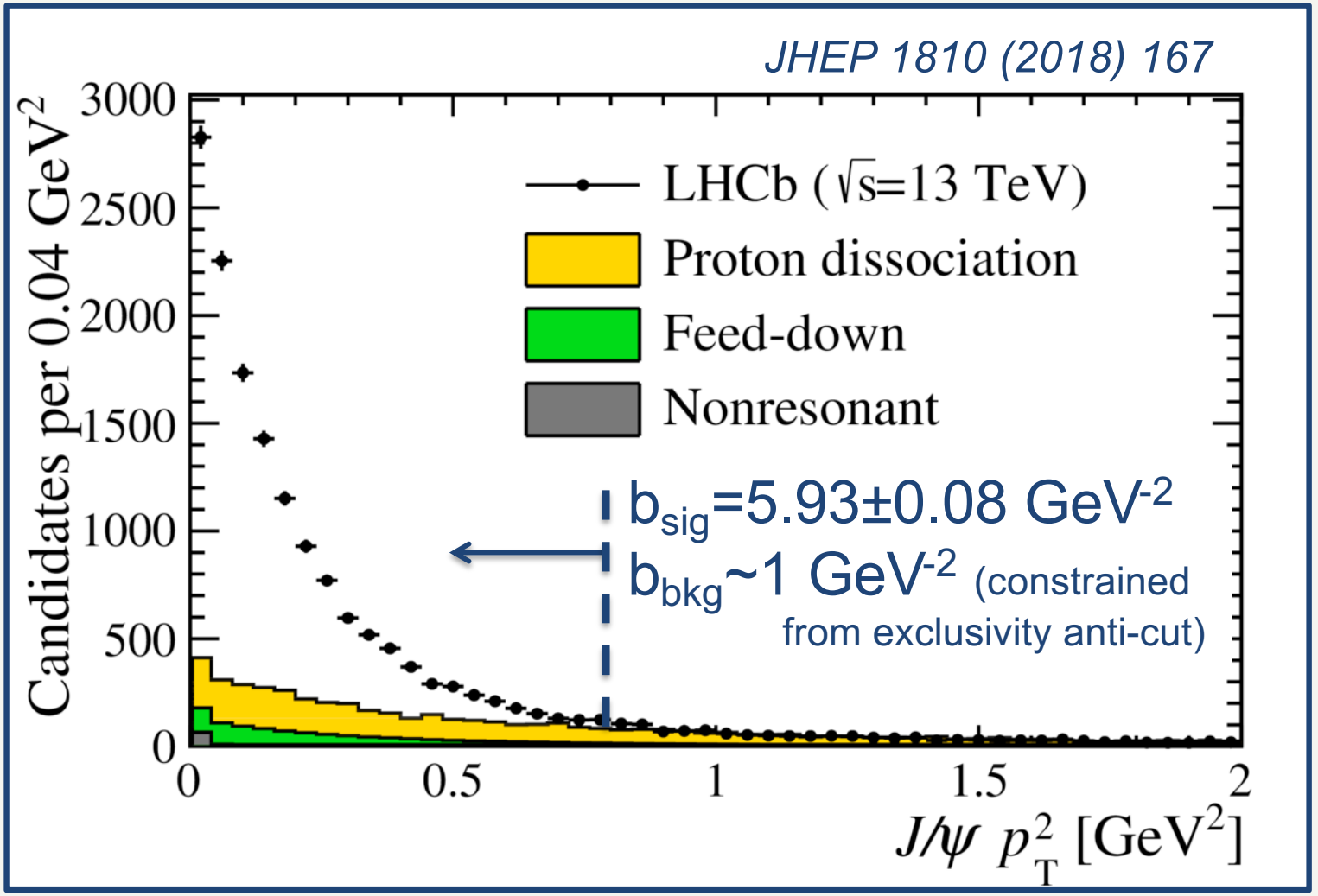


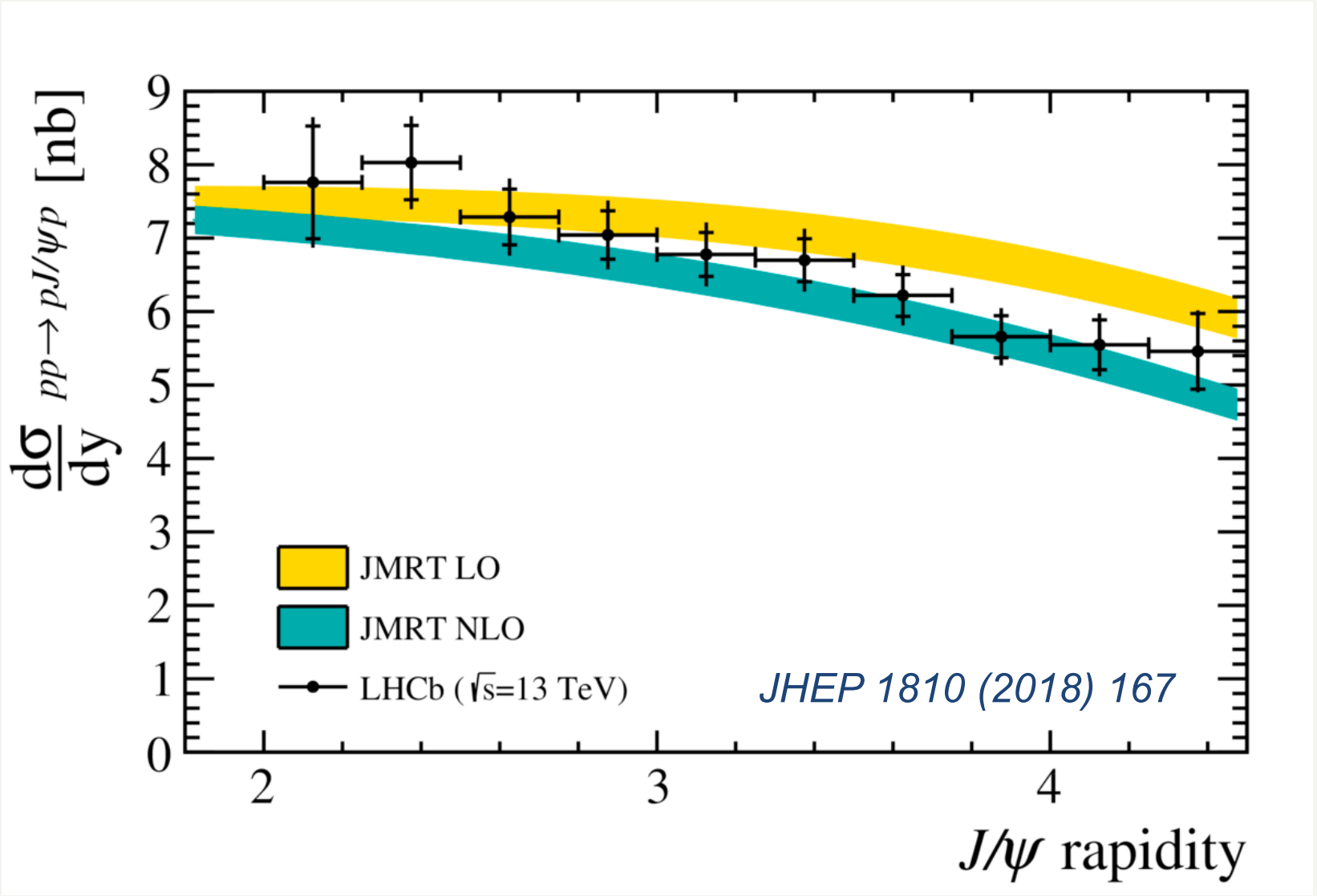
Purity for CEP of J/ψ

Assume Signal and Background

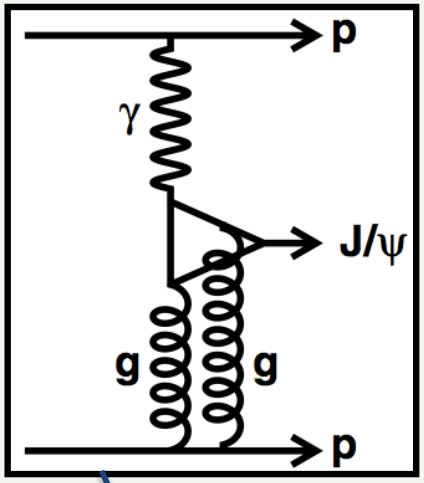
$$\frac{d\sigma}{dt} \sim e^{bt}$$

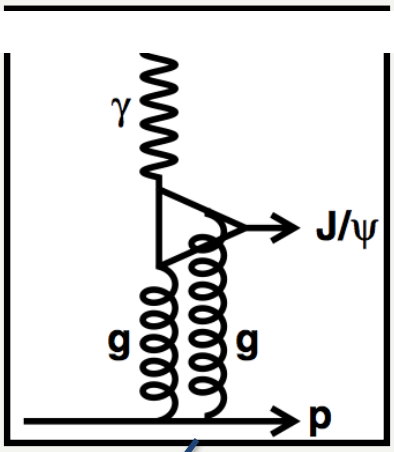


Differential cross-section pp➔pJ/ψp



Convert to photo-production cross-section





LHCb measures

Photon Flux

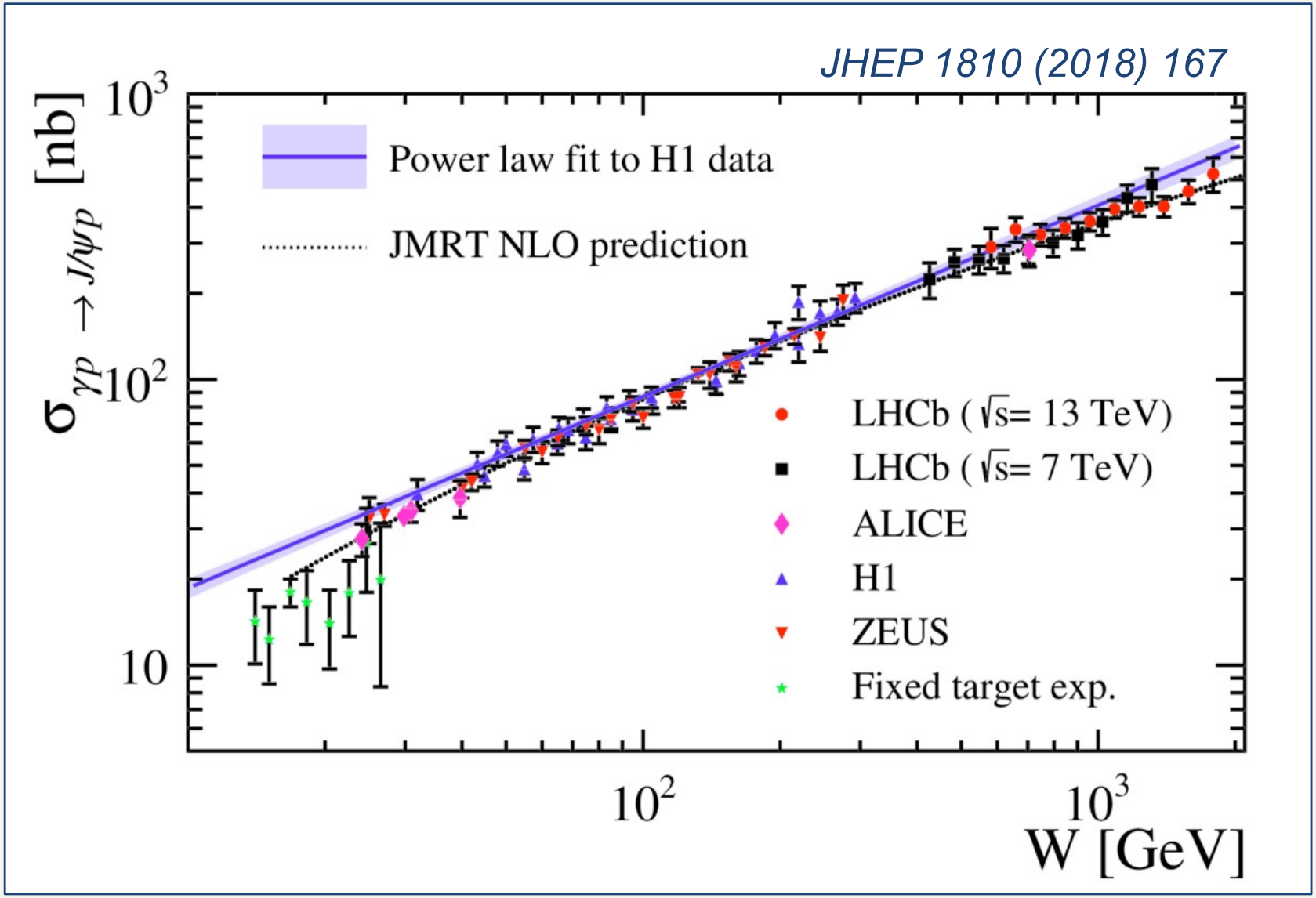
HERA measured

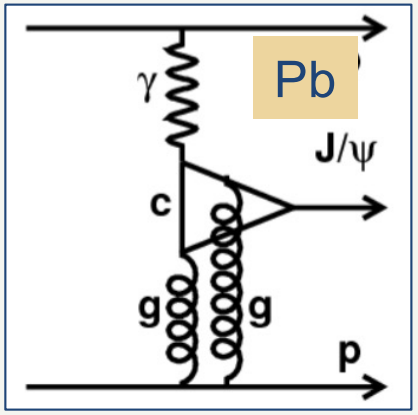
$$\frac{d\sigma}{dy}_{pp\to pJ/\psi p} = r_+ k_+ \frac{dn}{dk_+}\sigma_{\gamma p\to J/\psi p}(W_+) + r_- k_- \frac{dn}{dk_-}\sigma_{\gamma p\to J/\psi p}(W_-)$$

Gap Survival

HERA measured power-law: $\sigma_{\gamma p\to J/\psi p}(W) = 81(W/90\,\mathrm{GeV})^{0.67}\,\mathrm{nb}$

Photoproduction cross-section



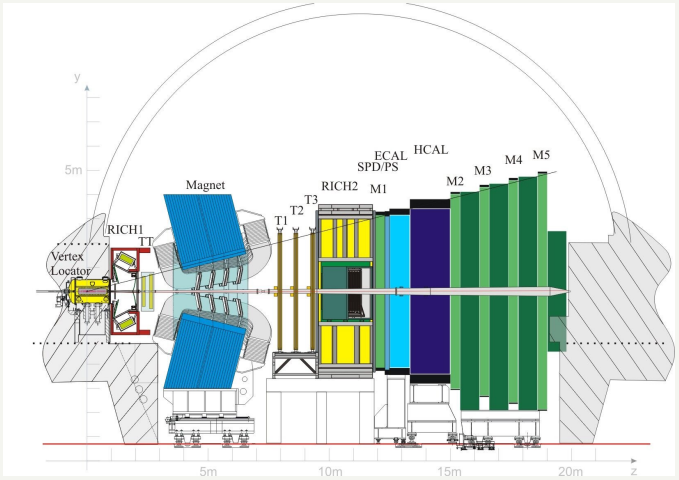


Which projectile produced the photon?

pomeron

Photon

pPb collisions



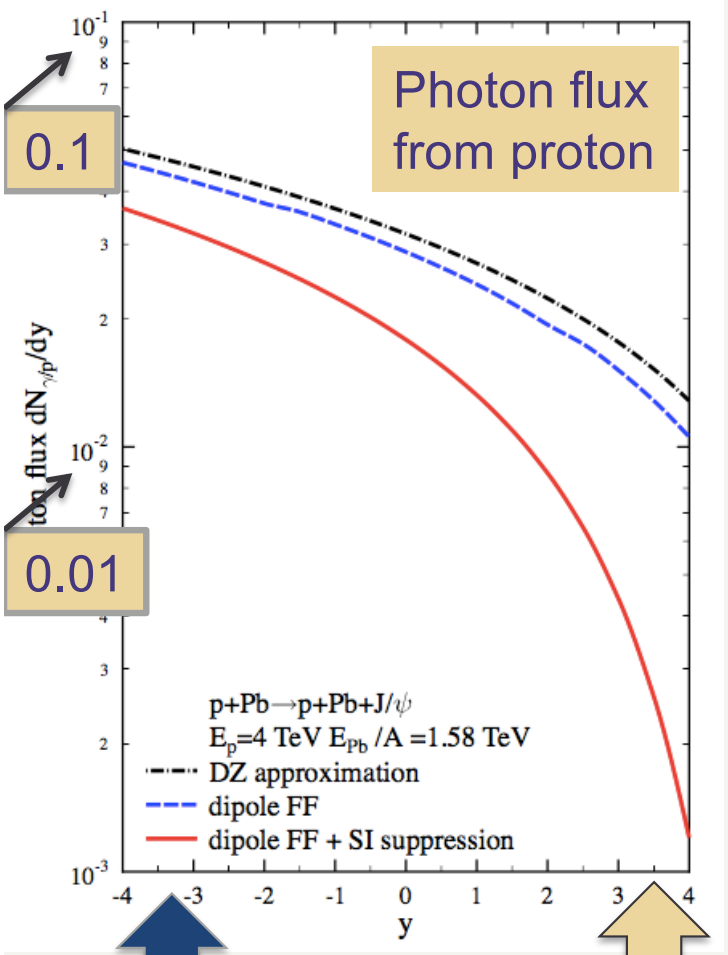
Photon

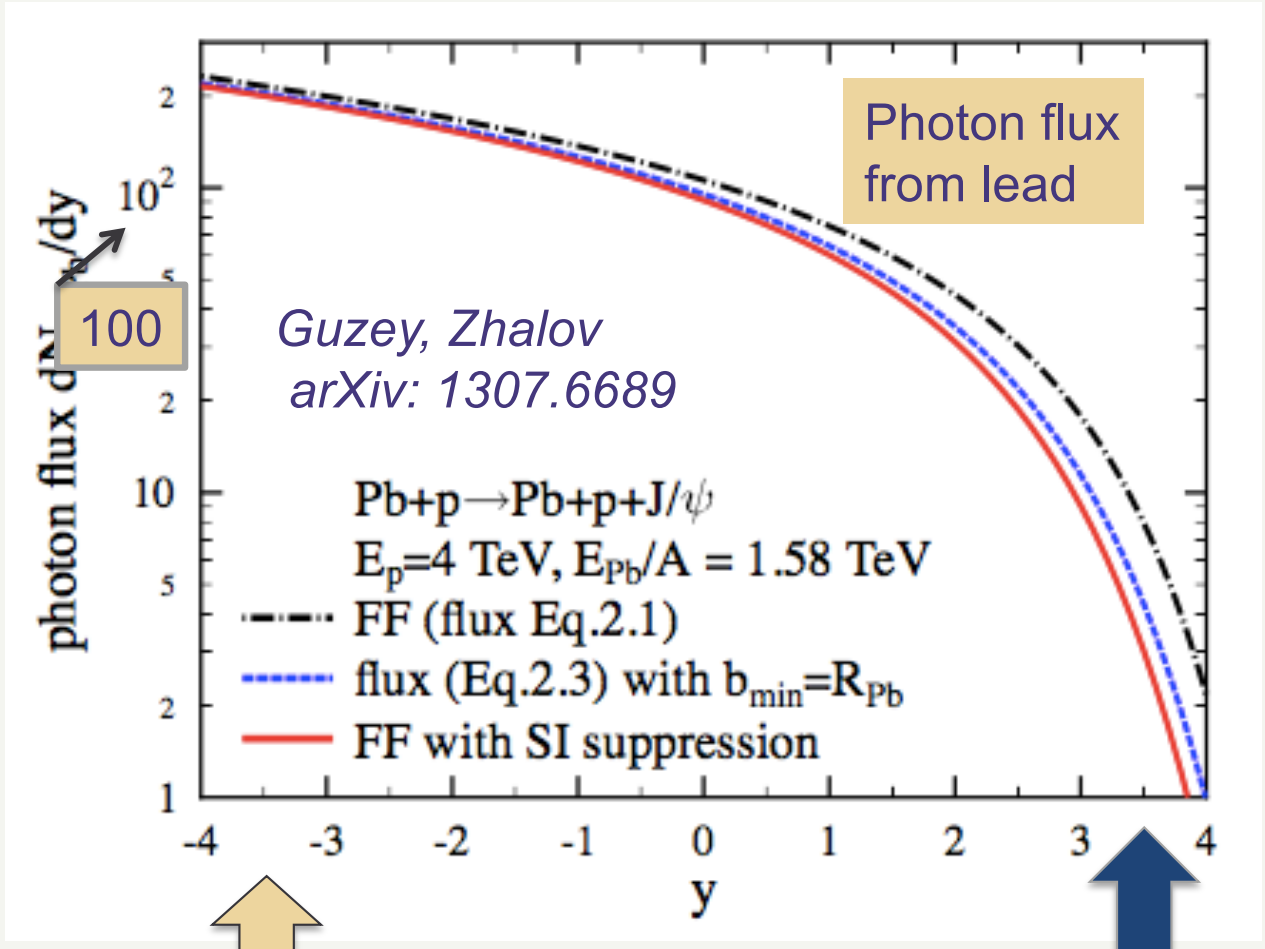
pomeron

Pbp collisions

Which projectile produced the photon?

At y~0, photon comes from lead (Z^2 enhancement)



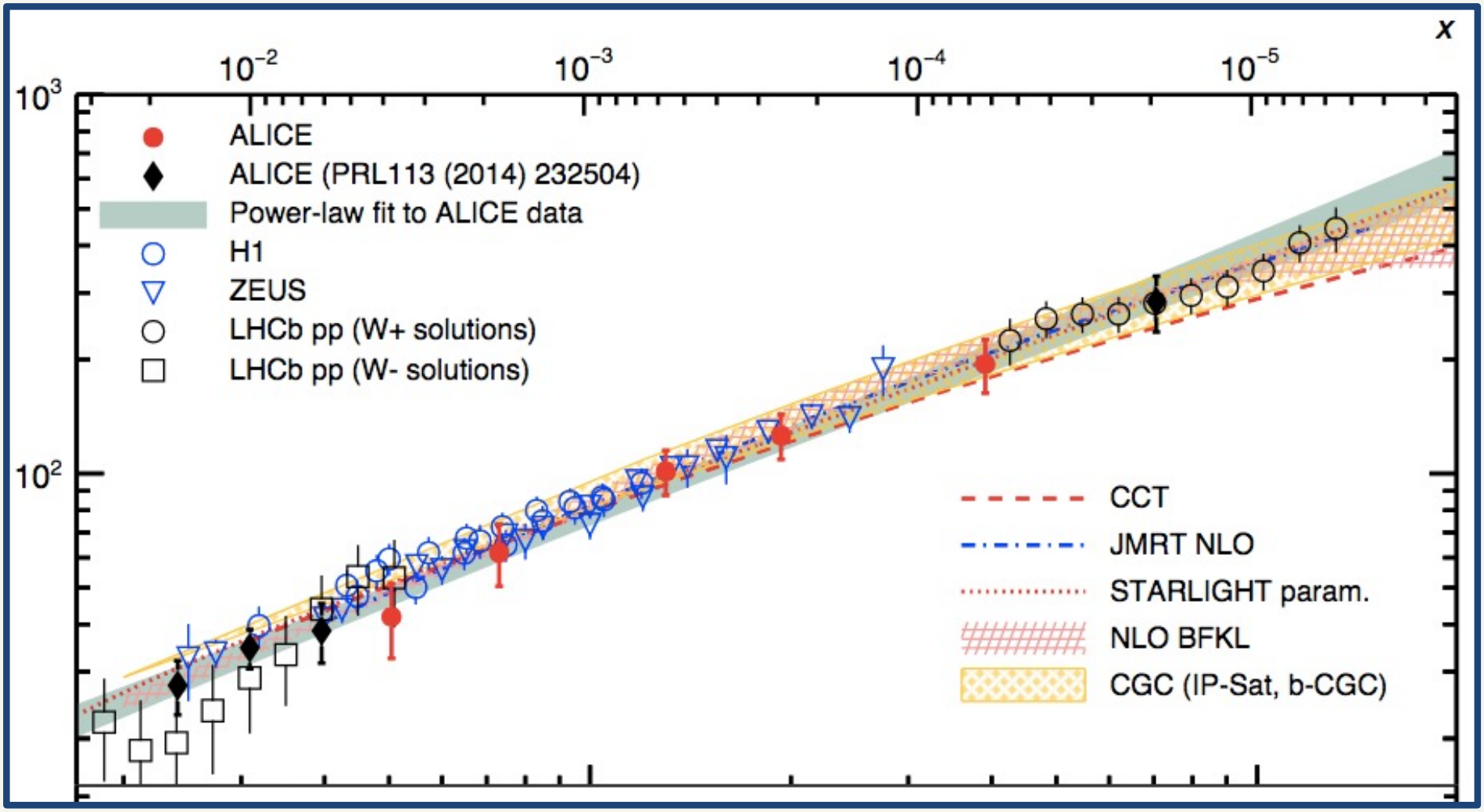


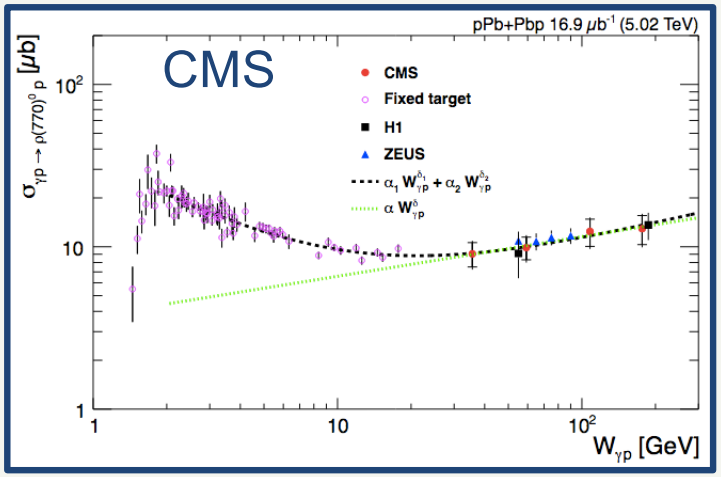
For LHCb, In pPb collisions, photon comes from lead

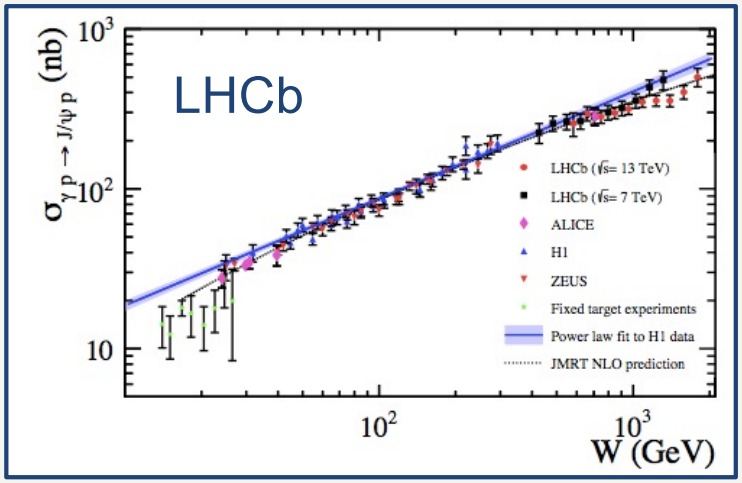
For Pbp collisions, ~1% comes from p

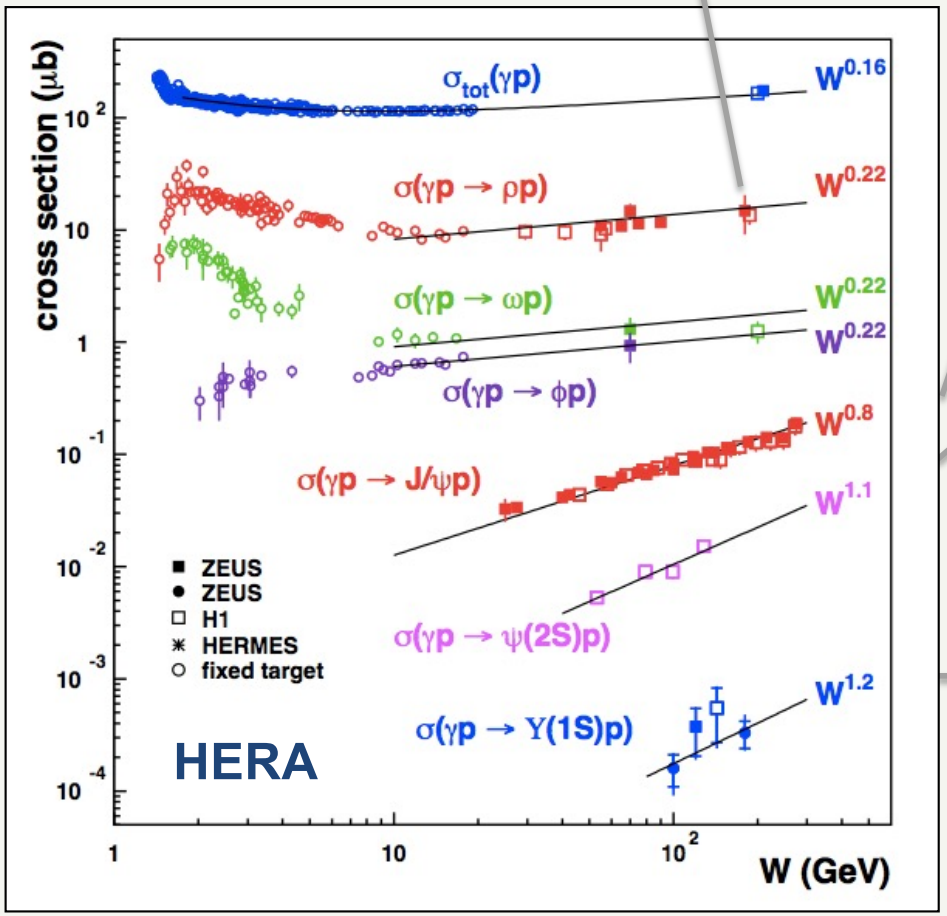
J/ψ production in pPb and Pbp

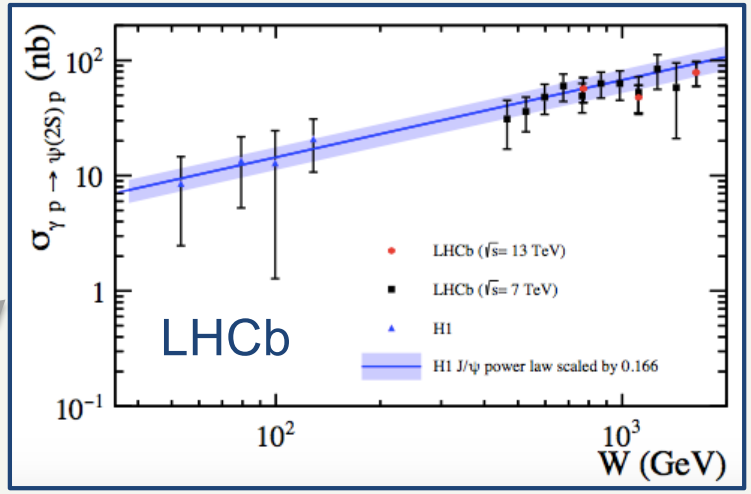
Eur.Phys.J. C79 (2019) no.5, 402

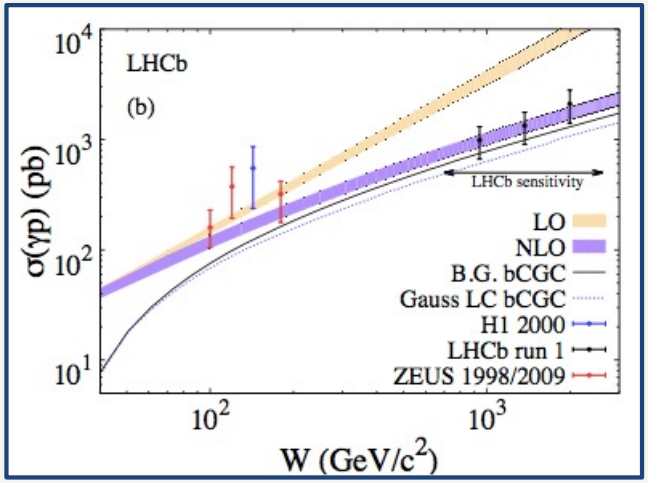



CMS
pPb+Pbp 16.9 μb⁻¹ (5.02 TeV)
CMS
Fixed target
H1
ZEUS
W_γp [GeV]

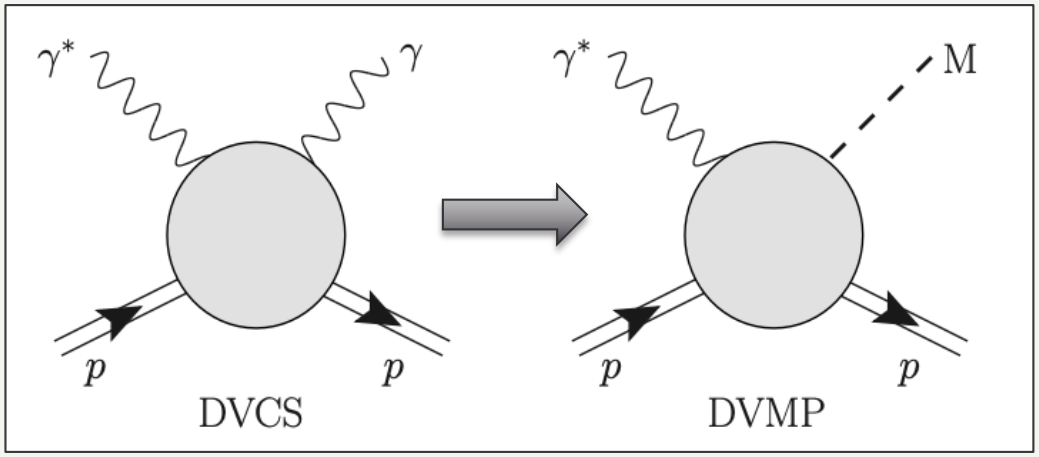

LHCb
LHCb (√s= 13 TeV)
LHCb (√s= 7 TeV)
ALICE
H1
ZEUS
Fixed target experiments
Power law fit to H1 data
JMRT NLO prediction
W (GeV)


cross section (μb)
σ_tot(γp)
W^0.16
σ(γp → ρp)
W^0.22
σ(γp → ωp)
W^0.22
W^0.22
σ(γp → φp)
W^0.8
σ(γp → J/ψp)
W^1.1
σ(γp → ψ(2S)p)
W^1.2
σ(γp → Υ(1S)p)
ZEUS
ZEUS
H1
HERMES
fixed target
HERA
W (GeV)


LHCb
LHCb (√s= 13 TeV)
LHCb (√s= 7 TeV)
H1
H1 J/ψ power law scaled by 0.166
W (GeV)

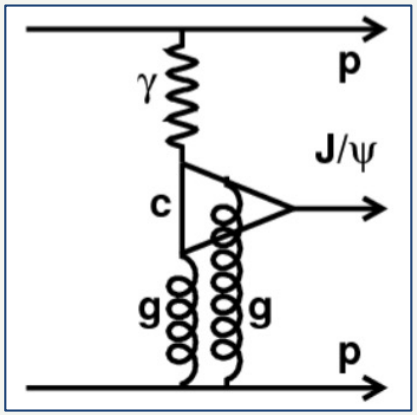

LHCb
(b)
LHCb sensitivity
LO
NLO
B.G. bCGC
Gauss LC bCGC
H1 2000
LHCb run 1
ZEUS 1998/2009
W (GeV/c²)

Question to theorists/global fitters



- Do we have LHC predictions for σ_{VM}(GPD)?
  - LHC data has not yet been used to constrain GPDs

- Quite some work has been done recently on σ_{VM}(PDF)....

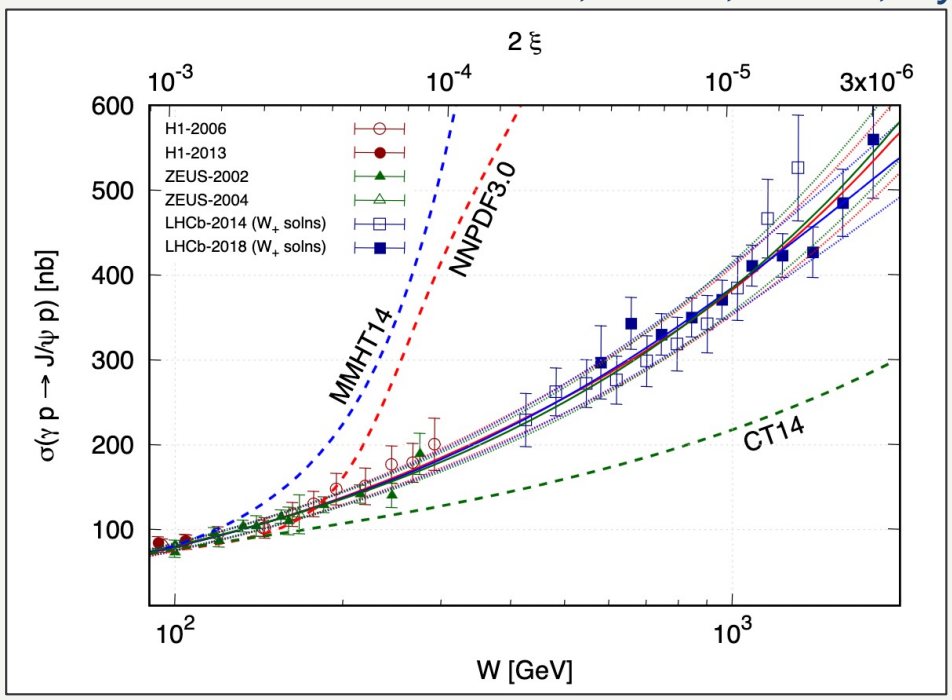


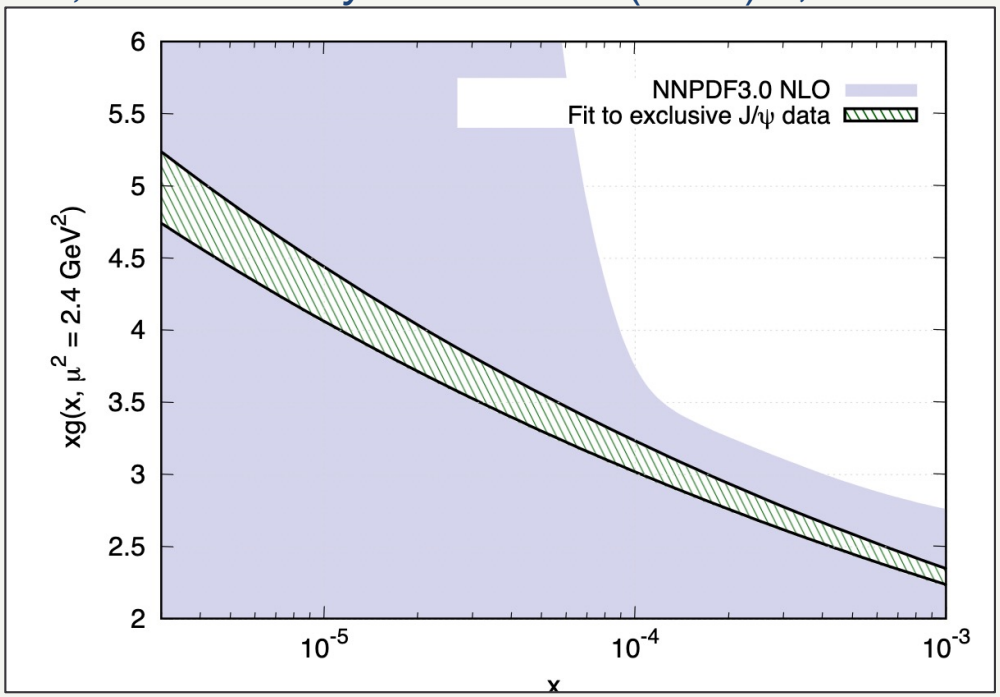
Implications: gluon PDF

Ryskin, Z. Phys. C 57 (1993) 89

$$\left.\frac{\mathrm{d}\sigma}{\mathrm{d}t}\left(\gamma^* p \to J/\psi\, p\right)\right|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha}\left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} x g(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_{J/\psi}^2}\right)$$

Flett, Martin, Ryskin, Teubner. Phys.Rev.D 102 (2020) 114021
Flett, Jones, Martin, Ryskin, Teubner. Phys.Rev.D 101 (2020) 9, 094011





makes use of Shuvaev transform to relate GPDs and PDFs

$$H_q(X,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s}{y(s)\sqrt{1-y(s)x'}}\right]\frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{q(x')}{|x'|}\right),$$

$$H_g(X,\xi) = \int_{-1}^{1} \mathrm{d}x' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{\mathrm{d}s\ (X+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right]\frac{\mathrm{d}}{\mathrm{d}x'}\left(\frac{g(x')}{|x'|}\right),$$

where the transform kernel,

$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

GPD v PDF: it matters

Dutrieux, Winn, Bertone, Phys.Rev.D 107 (2023) 11, 114019

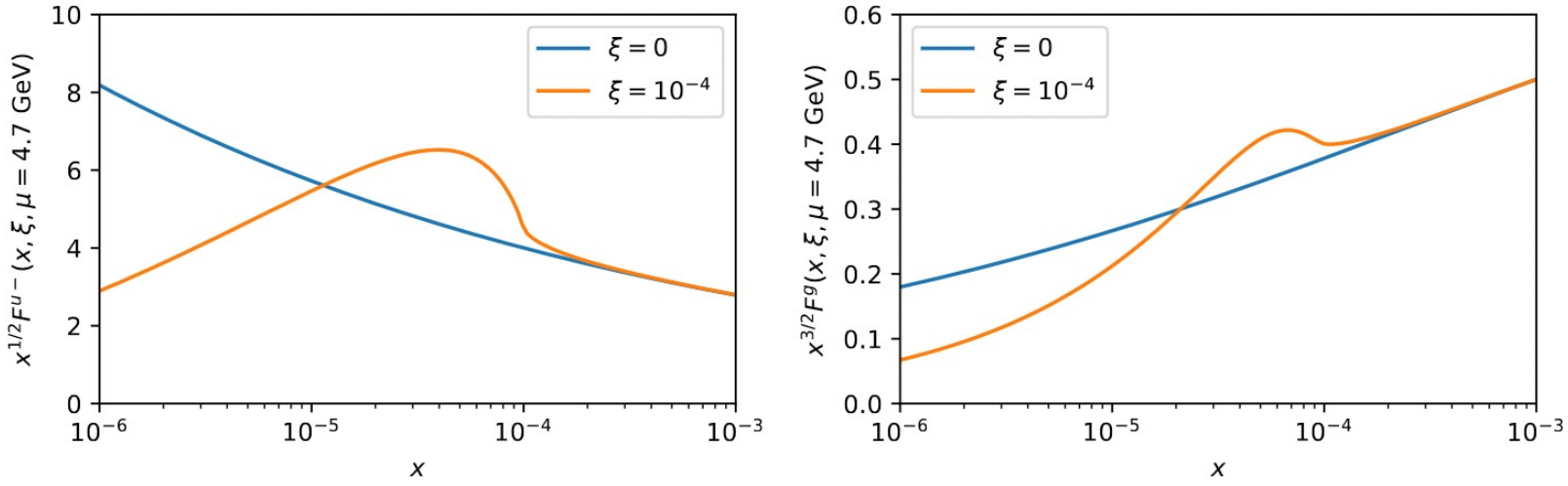
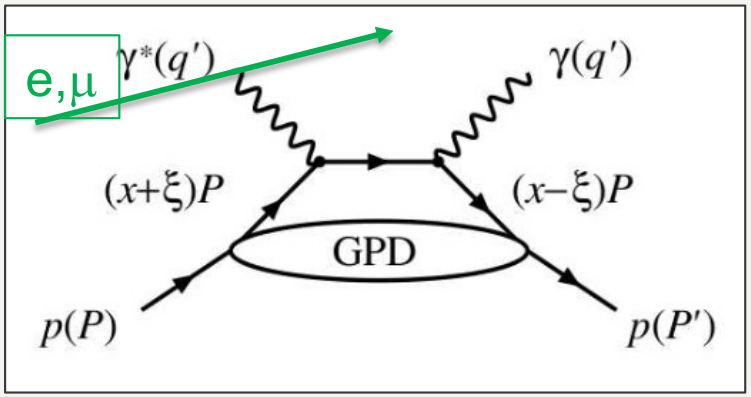


Figure 2: Evolution of the MMHT2014 LO PDF [44] from $\mu_0 = 1$ GeV to 4.7 GeV using the DGLAP evolution (blue curve) and the GPD evolution at $\xi = 10^{-4}$ (orange curve). On the left, we show the non-singlet u PDF defined by $u^-(x) = u(x) - \bar{u}(x)$. On the right, the gluon PDF. The difference between the two curves becomes sizeable for $x \lesssim 3\xi$.

(1. DVCS)

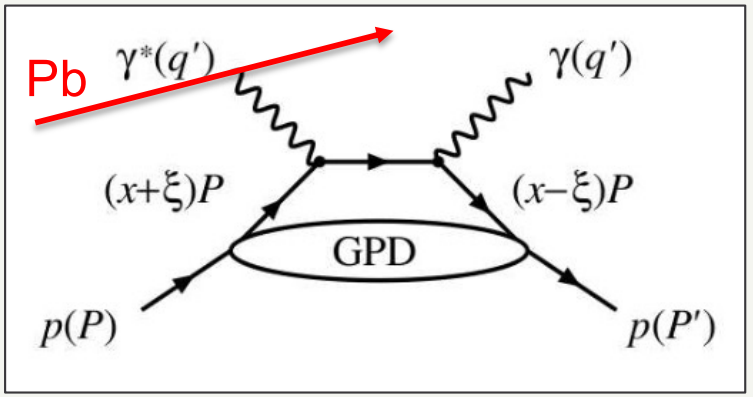
DVCS @ LHC?



Workhorse for current GPD extractions

Data: Hermes, H1, Zeus, CLAS, Hall A, COMPASS, where γ^* originates from **lepton**

DVCS @ LHC?



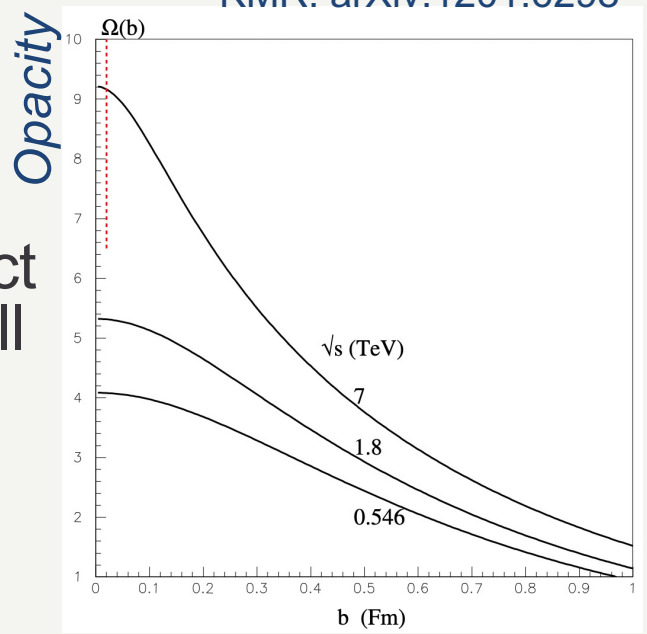
Workhorse for current GPD extractions

Data: Hermes, H1, Zeus, CLAS, Hall A, COMPASS, where γ^* originates from **lepton**

Can this come from **hadron** (LHC) ?

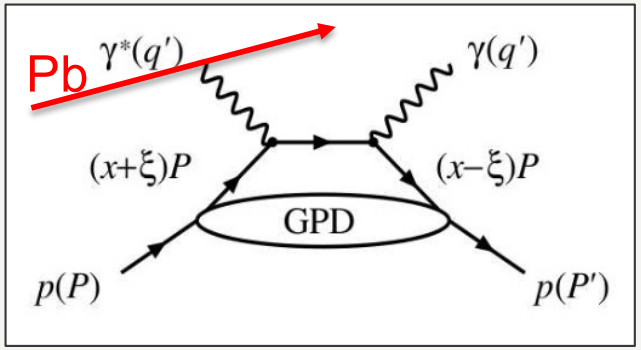
- Yes, but for large Q^2 γ^* we have small impact parameter and hadronic QCD interaction will usually be superimposed
- Low multiplicity when hadrons remain intact
  - **Ultraperipheral collisions (UPC)**
  - Projectiles separated $d>R_1+R_2$
  - Large impact parameters => small Q^2 γ^*. [$Q^2<(\hbar c/d)^2$]

KMR: arXiv:1201.6298



Impact parameter

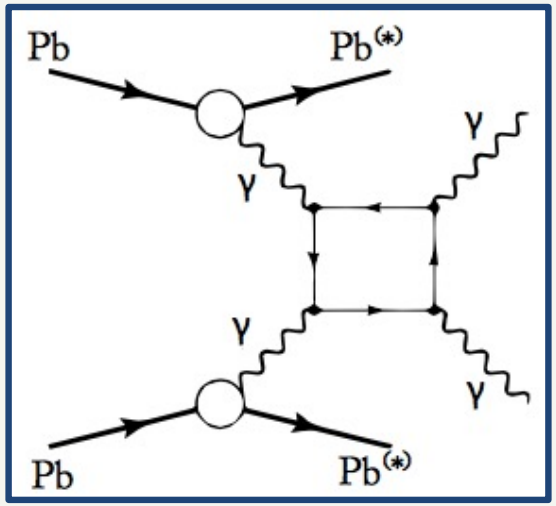
DVCS @ LHC?



- Use pPb collisions to enhance photon flux (factor 82^2)
- Signal is single photon and no other activity
  - Most γ^* quasi-real so γ down beam line
  - For higher Q^2, QCD interaction usually superimposed (but not always)
  - Machine backgrounds / beam gas / acceptance make reliable identification of single photon difficult
- Look difficult but maybe not impossible.
- No full study. For discussion?

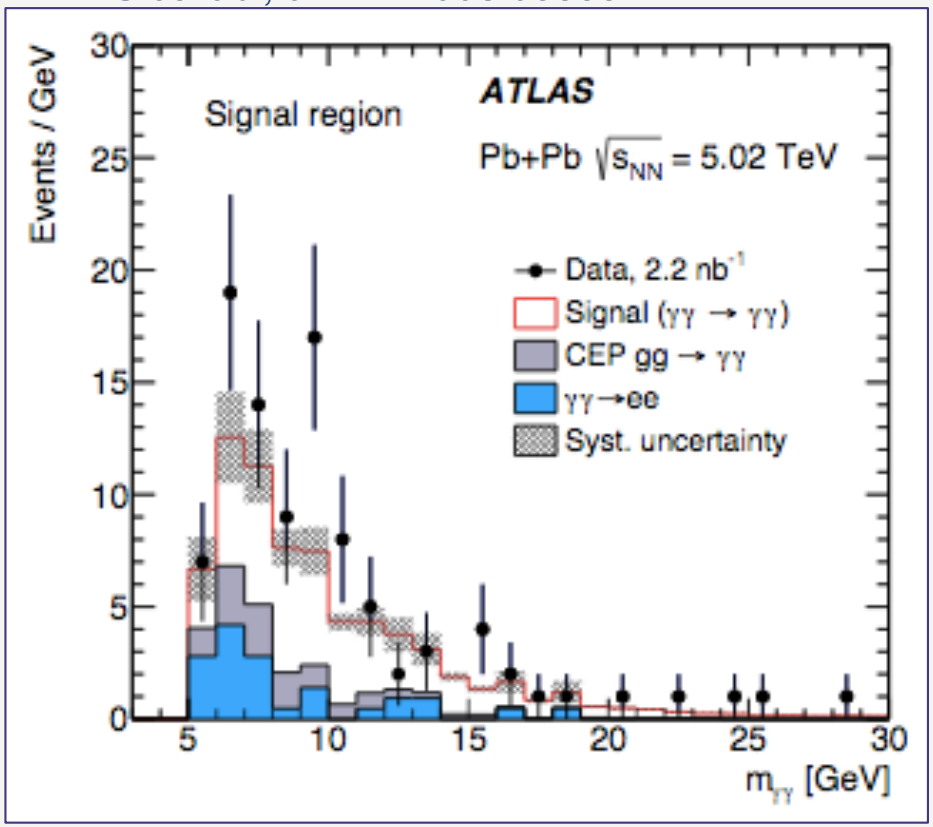
Light-by-light scattering

Forbidden in classical EM
Text-book illustration of QM

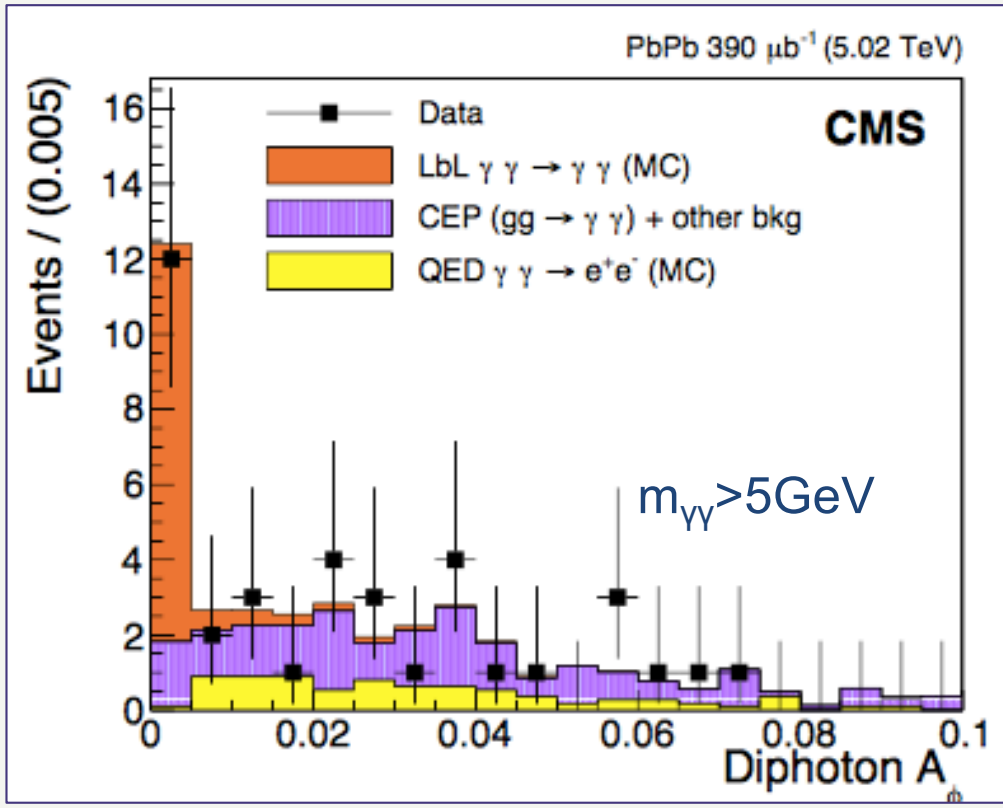


ATLAS collab., Nature Physics 13 (2017) 852

ATLAS collab., arXiv: 2008.05355

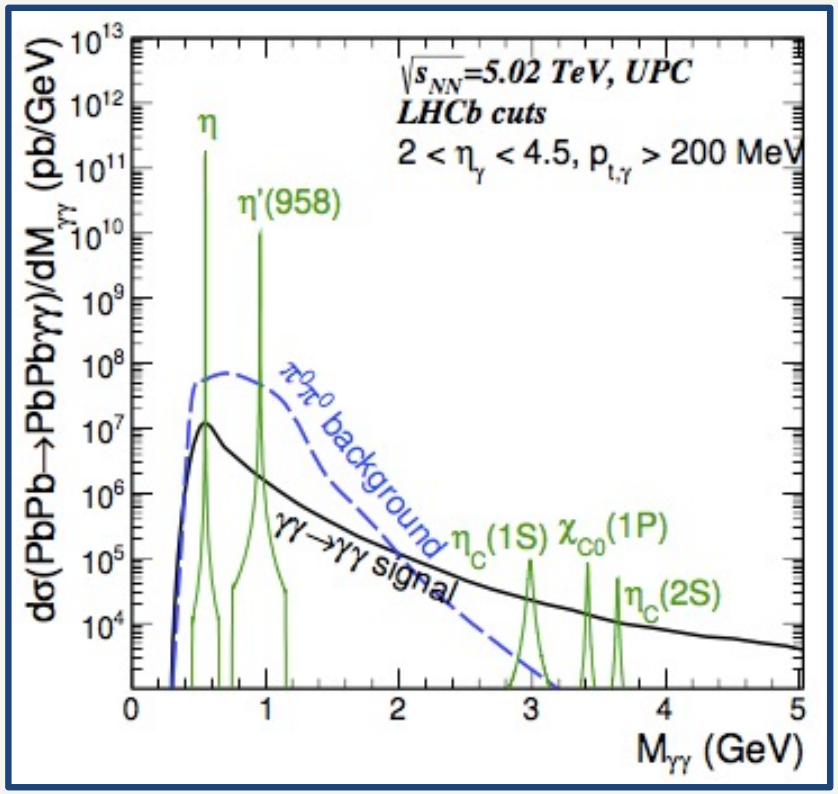


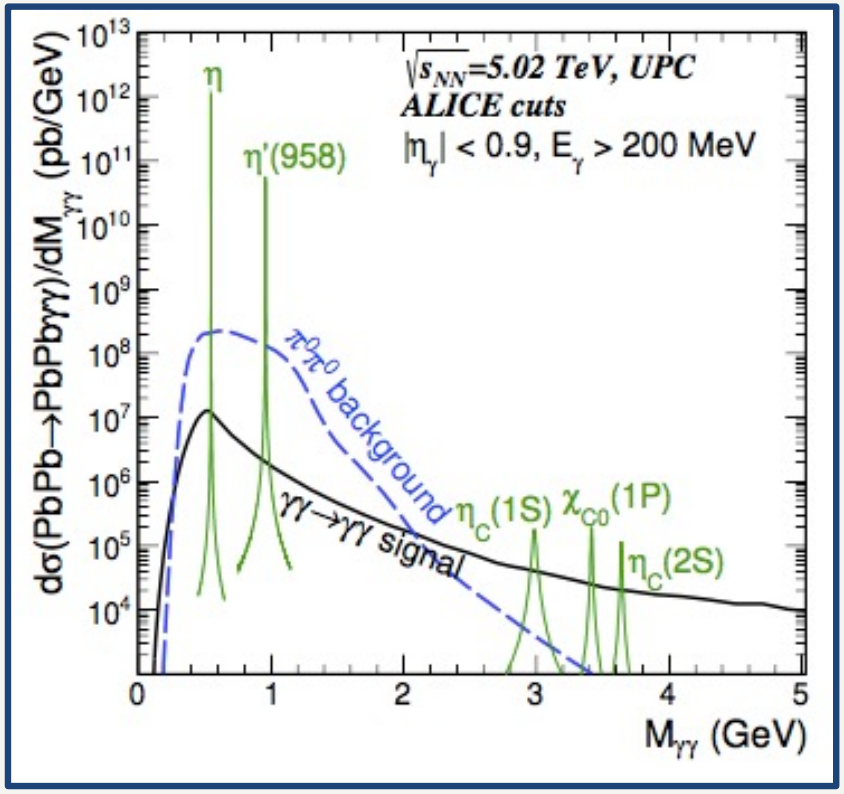
CMS. collab., Phys.Lett.B 797 (2019) 134826



Light-by-light scattering

M. Klusek-Gawenda, R. McNulty, R. Schicker, A. Szczurek, Phys.Rev. D99 (2019) no.9, 093013

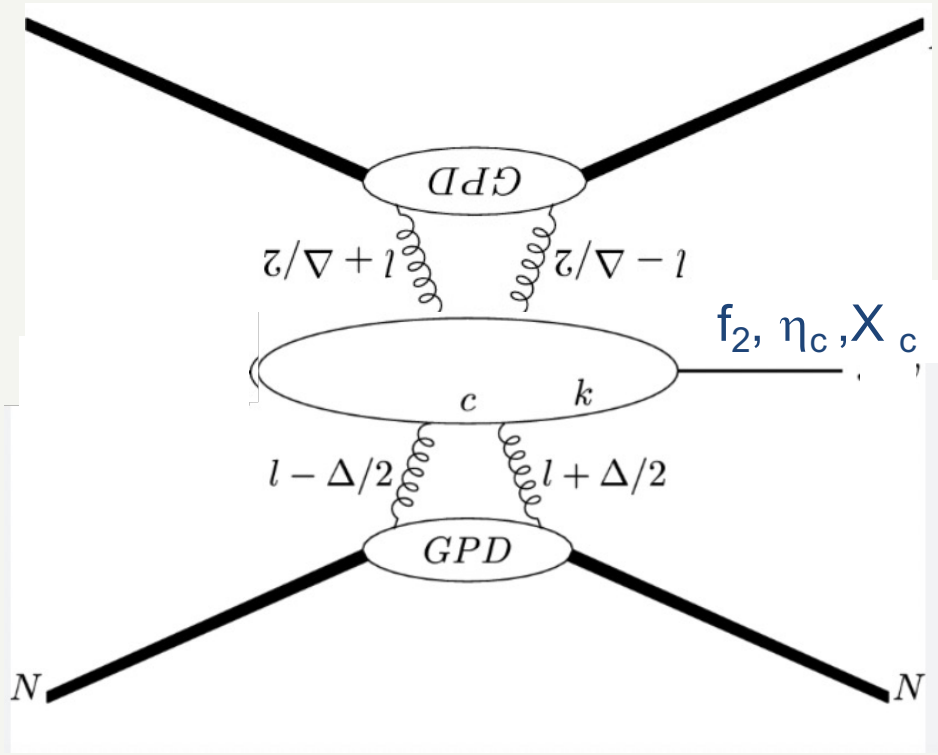




LHCb and ALICE have potential to observe this at low mass.
Important in searches for new particle decaying to photons

4. DPE

Double pomeron exchange



Plenty of data from LHC

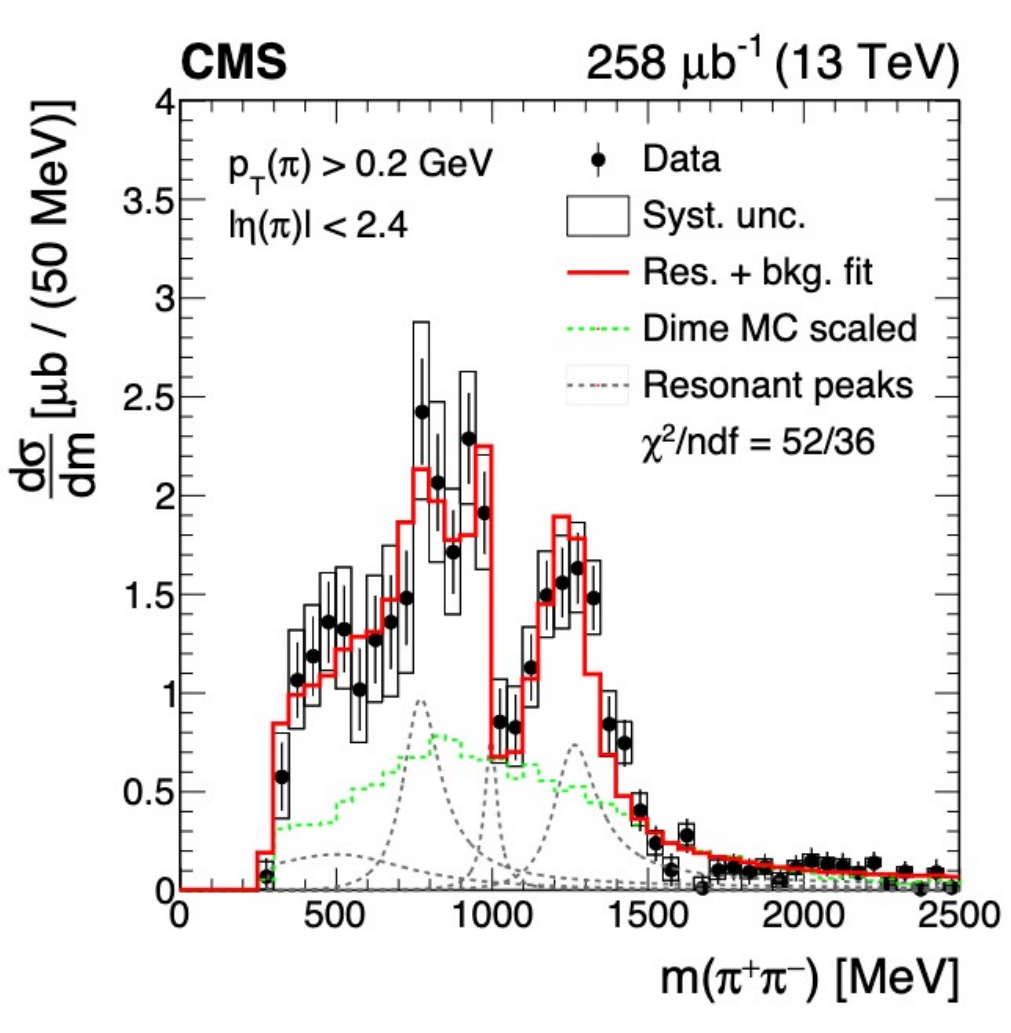
In principle this is two GPDs?

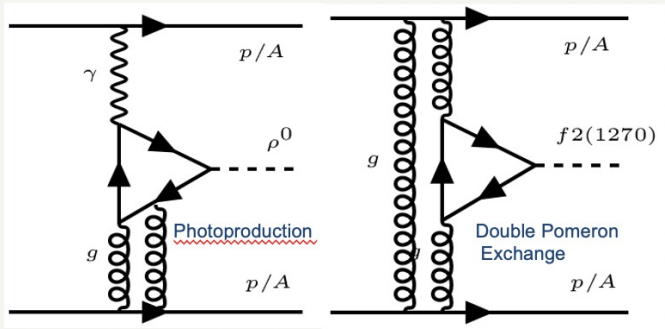
Should be some sensitivity by measuring this?

Problem of measuring kinematic variables?

Double pomeron exchange

CMS, *Eur.Phys.J.C* 80 (2020) 8, 718

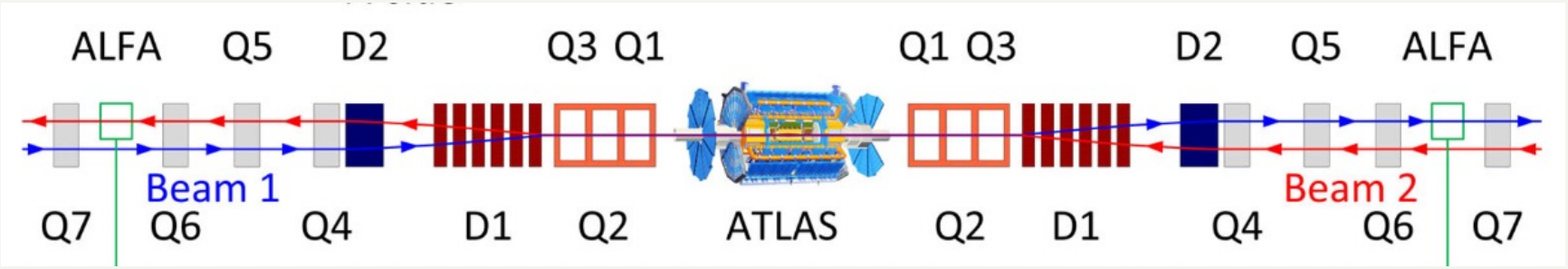




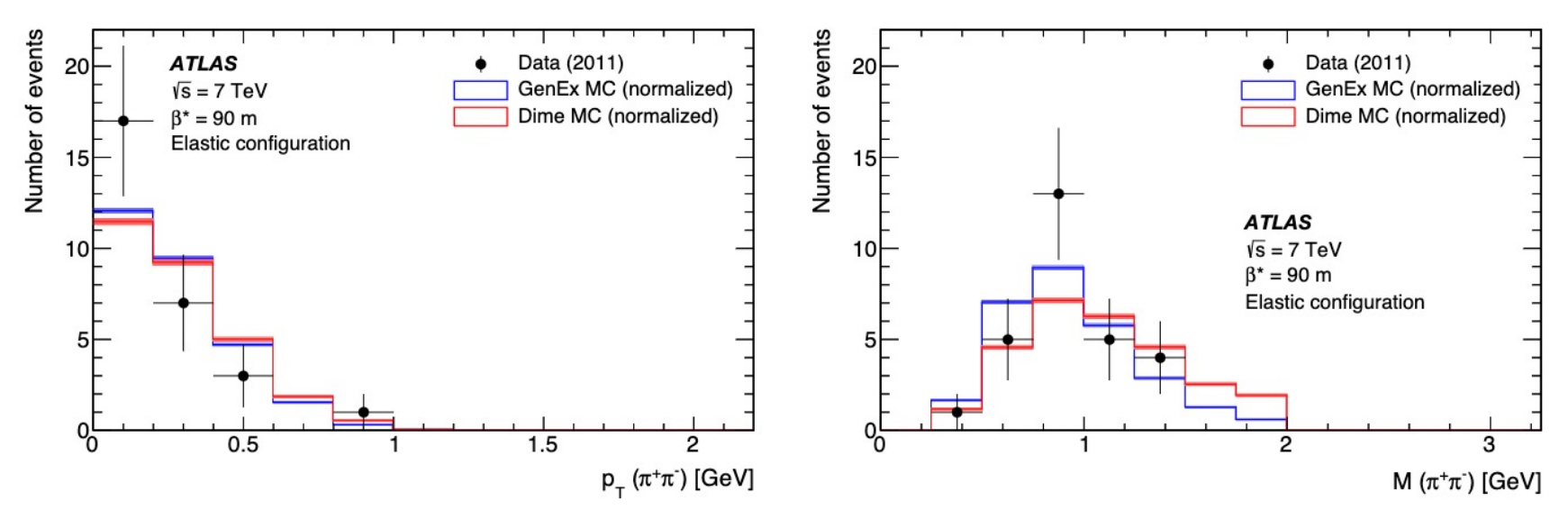
Example of dipion spectrum and for comparison with what Stefan showed this morning

Maybe reconstruct outgoing proton

ATLAS: EPJ C 83 (2023) 627



Special high β^*=90 m runs creates optics that allow deflected proton to be measured. Independent measurements of p_T of protons that balance p_T of pions.



(Limited data for the moment due to low-lumi running)

Summary: topics for discussion

	+	-	
DVCS	Direct measurement of CFF	Clean single photon detection difficult. σ too low?	Experimentally probably impossible
TCS	Clean 'easy' measurement	Indirect GPD constraint Interference from Bethe-Heitler	No experimental measurements yet
DVMP	Measurements have been performed	Even more indirect constraint	Theory predictions?
DPE	Measurements have been performed	Little sensitivity to GPD?	Theoretically probably insensitive

Complementary x-Q^2 to EIC