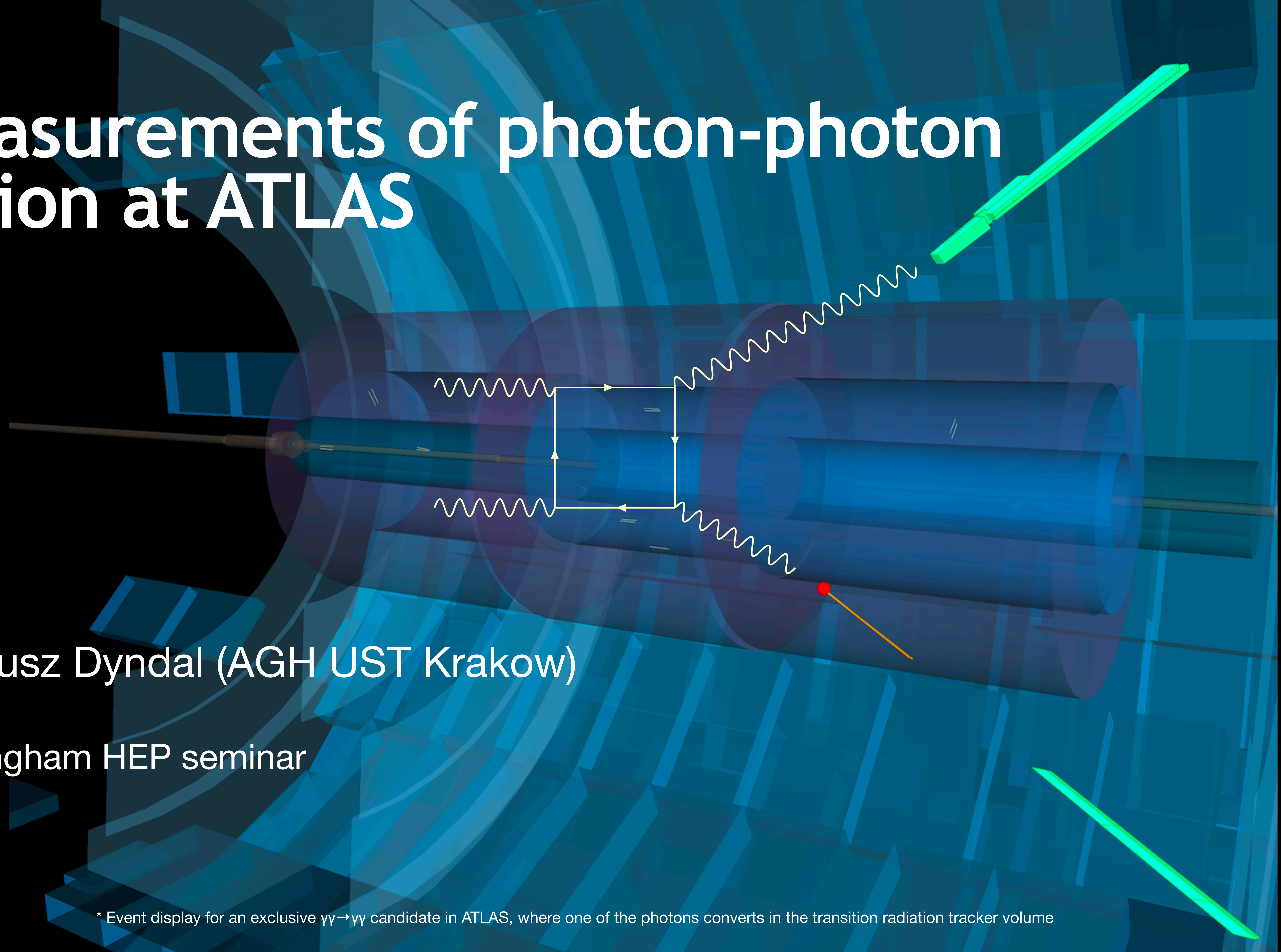
Measurements of photon-photon fusion at ATLAS



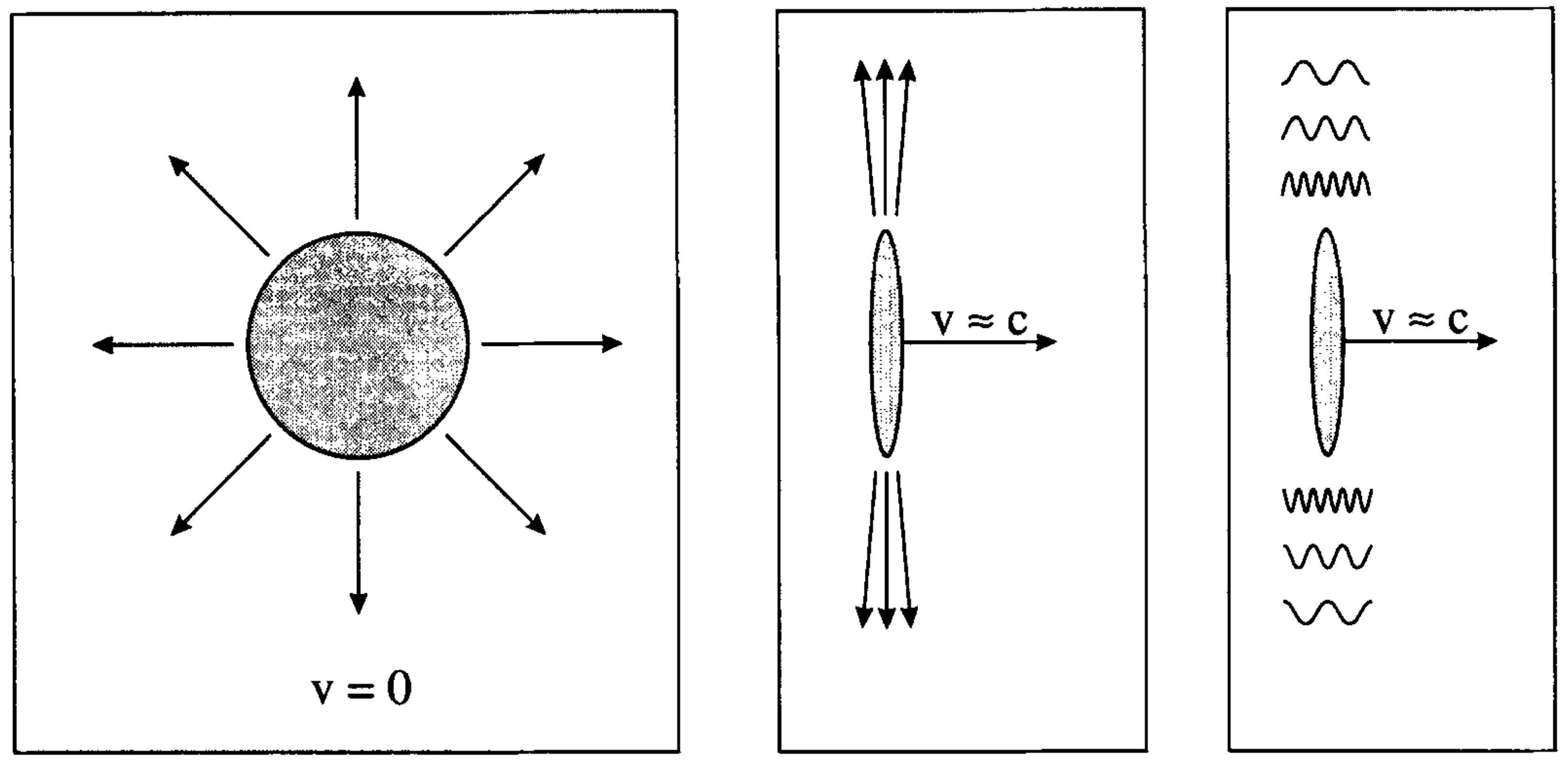
* Event display for an exclusive γγ→γγ candidate in ATLAS, where one of the photons converts in the transition radiation tracker volume

Mateusz Dyndal (AGH UST Krakow)

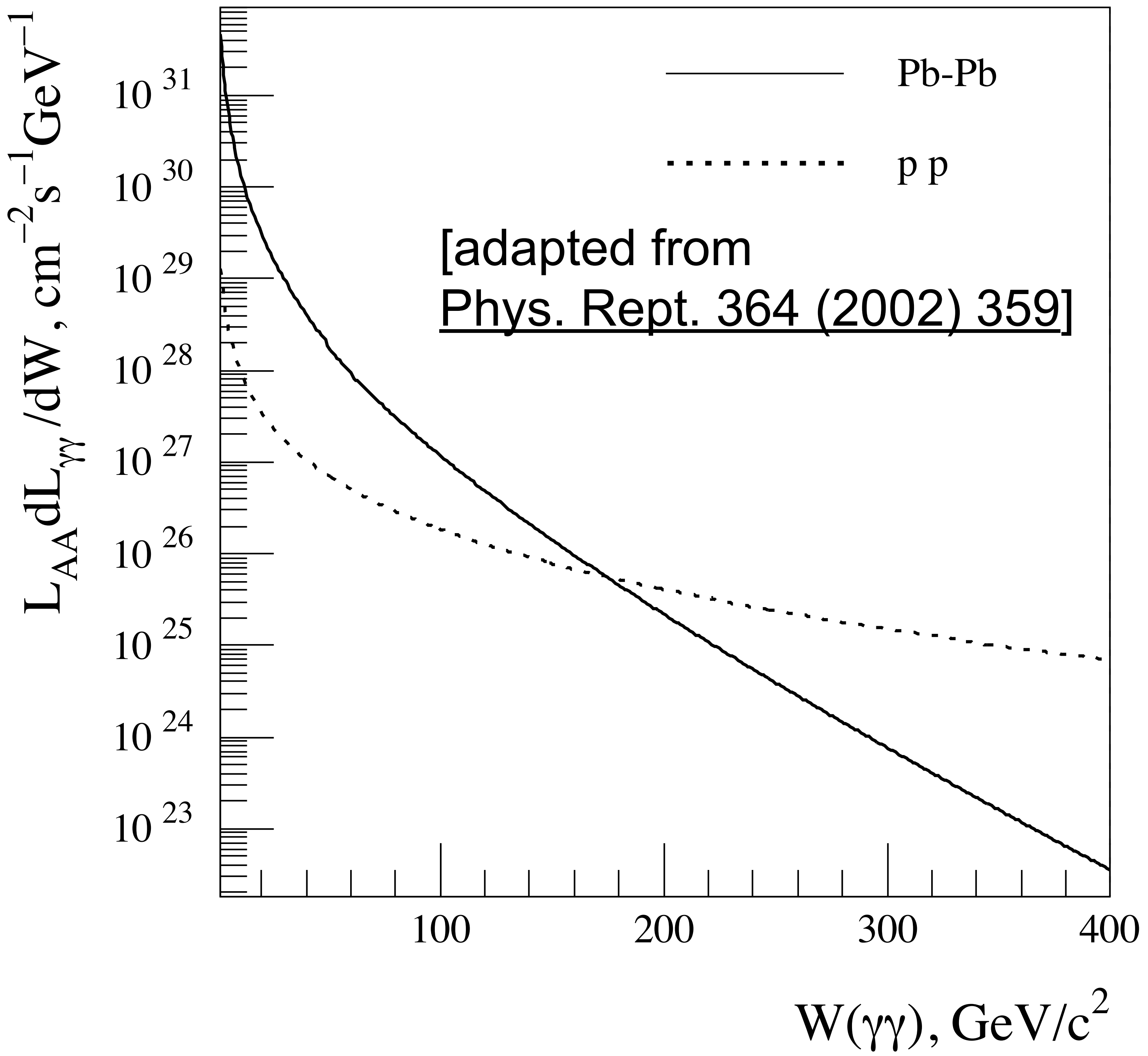
Birmingham HEP seminar

Introduction

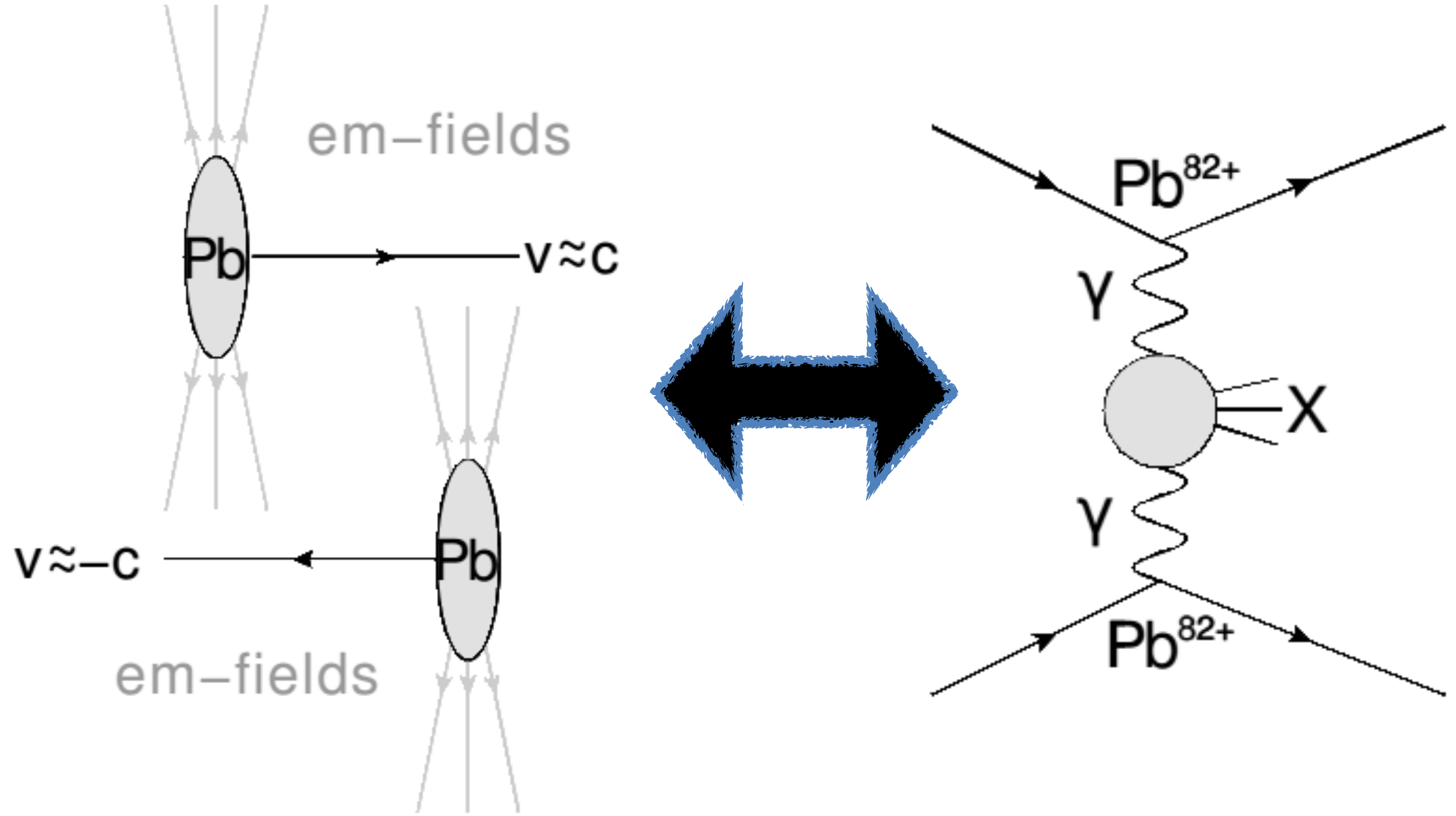
[from Prog. Part. Nucl. Phys. 39 (1997) 503]



- **Boosted charged-particles** are intense source of photons
- **Quasi-real photon flux**
  - $\mathbf{E_{max}}$ ~γ/R **~2 TeV** (protons @LHC)
    ~80 GeV (Pb ions @LHC)



- Clean access to **high-energy electroweak interactions**



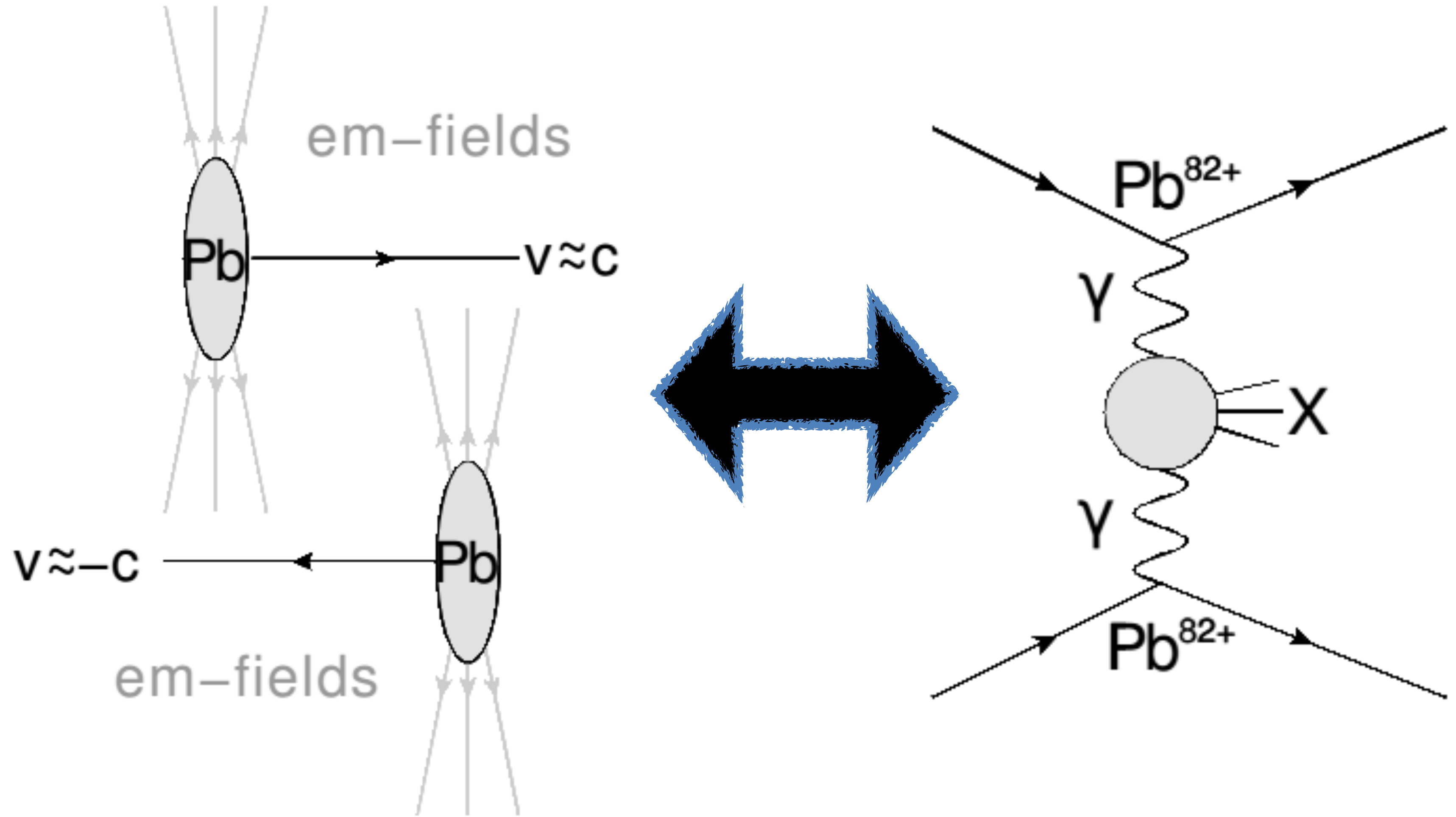
Theoretical calculations (simplified view)

- The cross section for AA (γγ) → AA X process can be calculated using:

(1) Number of equivalent photons (EPA) by integration of relevant EM formfactors:

$$\boxed{\frac{Z^2\alpha_{em}}{\pi^2\omega}\left|\int \mathrm{d}q_\perp q_\perp^2 \frac{F(Q^2)}{Q^2} J_1(bq_\perp)\right|^2}$$

$$Q^2 < 1/R^2$$



(2) EW γγ → X (elementary) cross section:

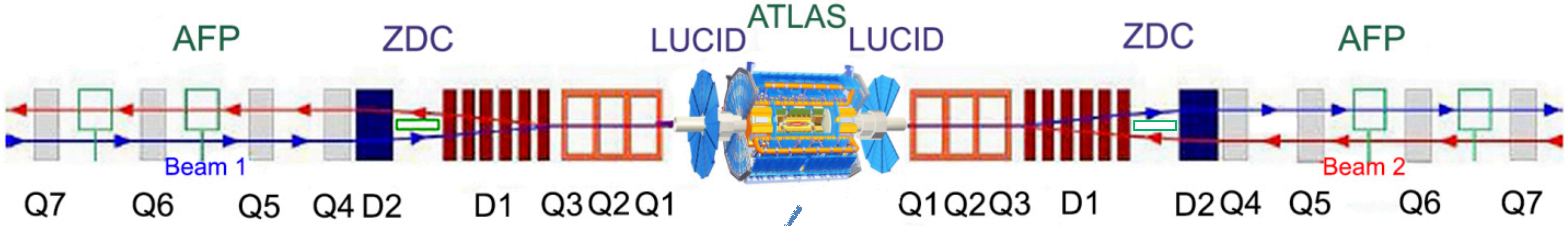
$$\boxed{\sigma^{\mathrm{EPA}}_{A_1A_2(\gamma\gamma)\to A_1A_2X} = \iint \mathrm{d}\omega_1\ \mathrm{d}\omega_2\ n_1(\omega_1)\ n_2(\omega_2)\ \sigma_{\gamma\gamma\to X}(W_{\gamma\gamma})}$$

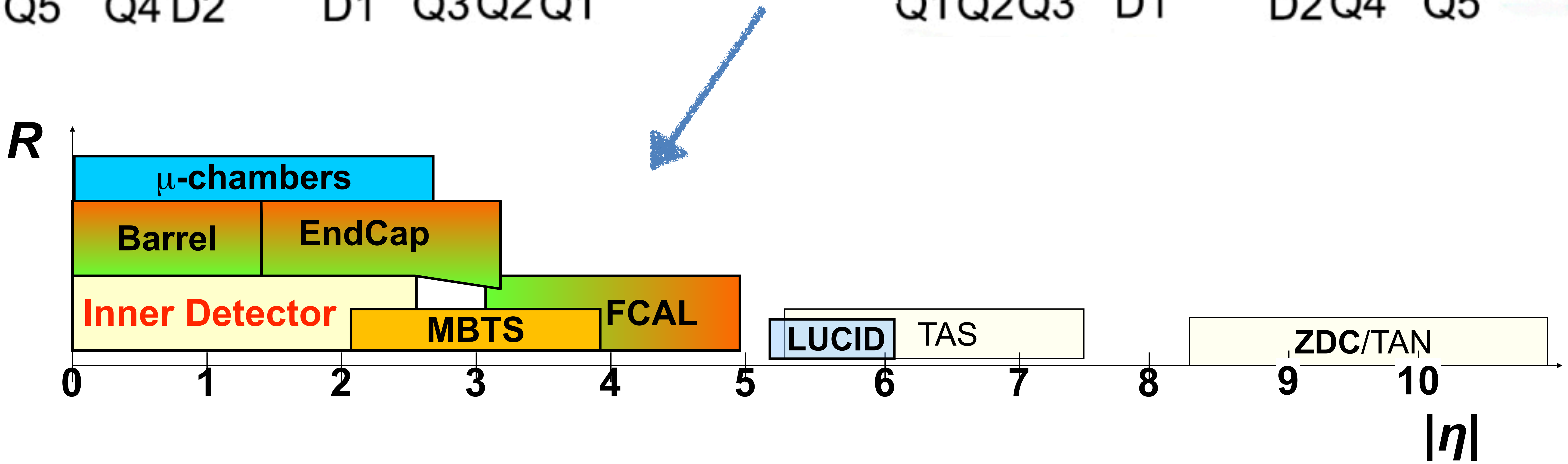
(3) Extra absorptive corrections (when the ions/protons overlap in impact parameter space:

$$\boxed{n_1(\omega_1)\ n_2(\omega_2) \to \int\int n(\vec{b}_1,\omega_1)n(\vec{b}_2,\omega_2)P_{non-inel}(|\vec{b}_1-\vec{b}_2|)d^2\vec{b}_1 d^2\vec{b}_2}$$

Experimental approach

- **Exclusive final states → Exclusivity requirements** are essential
  - Many sub-detectors available in ATLAS
  - Outgoing ions escape into beampipe, protons can be tagged by **AFP** spectrometers
  - Accounting for proton/ion **dissociation** is also important





Outline

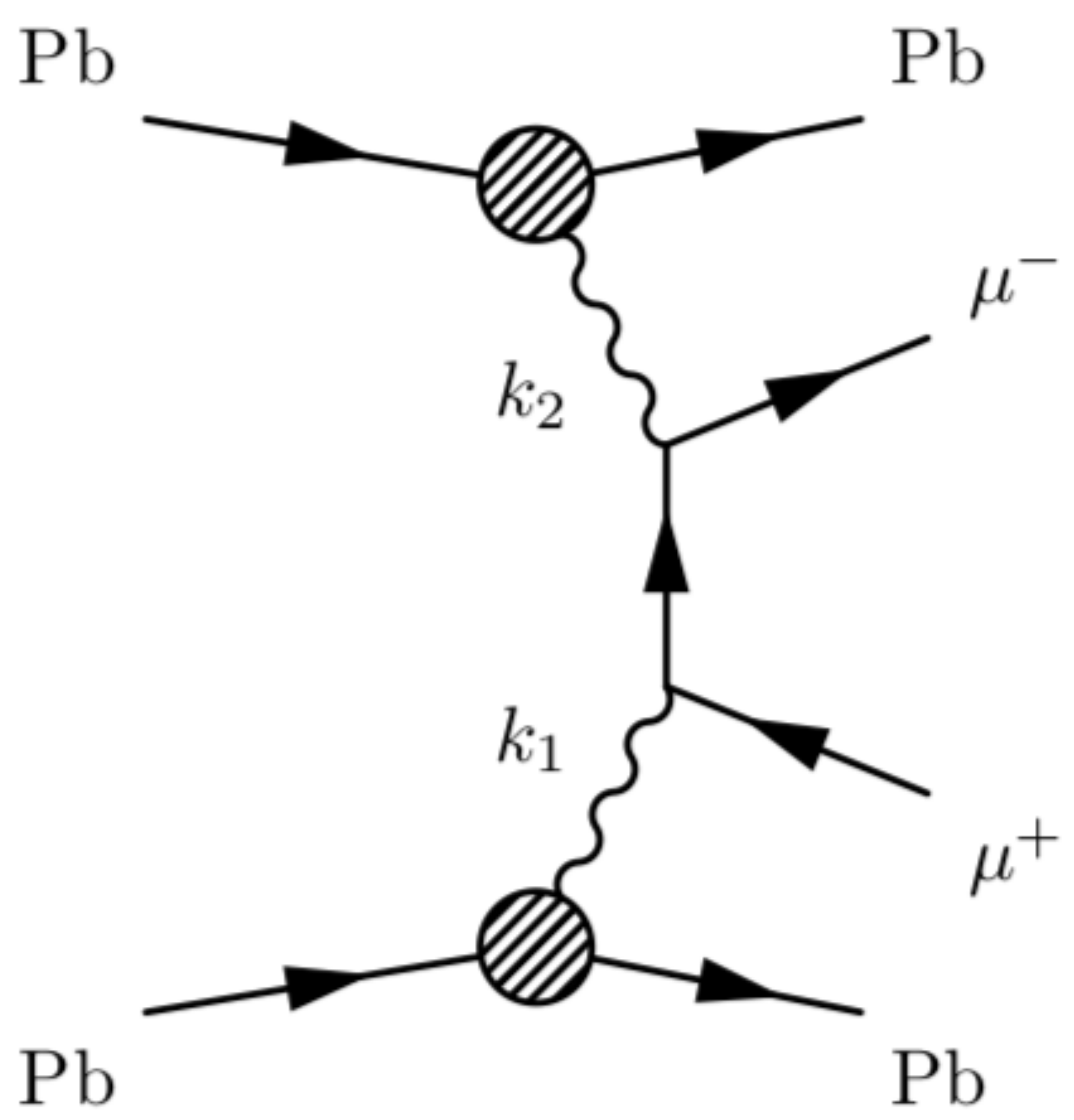
- A set of **new** ATLAS measurements will be covered in this talk:
  - *Exclusive **dimuon** production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ATLAS* [arXiv:2011.12211]
  - *Measurement of **light-by-light scattering** and search for **axion-like particles** with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector* [JHEP 03 (2021) 243]

Pb+Pb data
$\sqrt{s_{NN}} = 5.02$ TeV

  - *Observation and measurement of **forward proton** scattering in association with **lepton pairs** produced via the photon fusion mechanism at ATLAS* [Phys. Rev. Lett. 125 (2020) 261801]
  - *Observation of **photon-induced WW** production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector* [Phys. Lett. B 816 (2021) 136190]

pp data
$\sqrt{s} = 13$ TeV

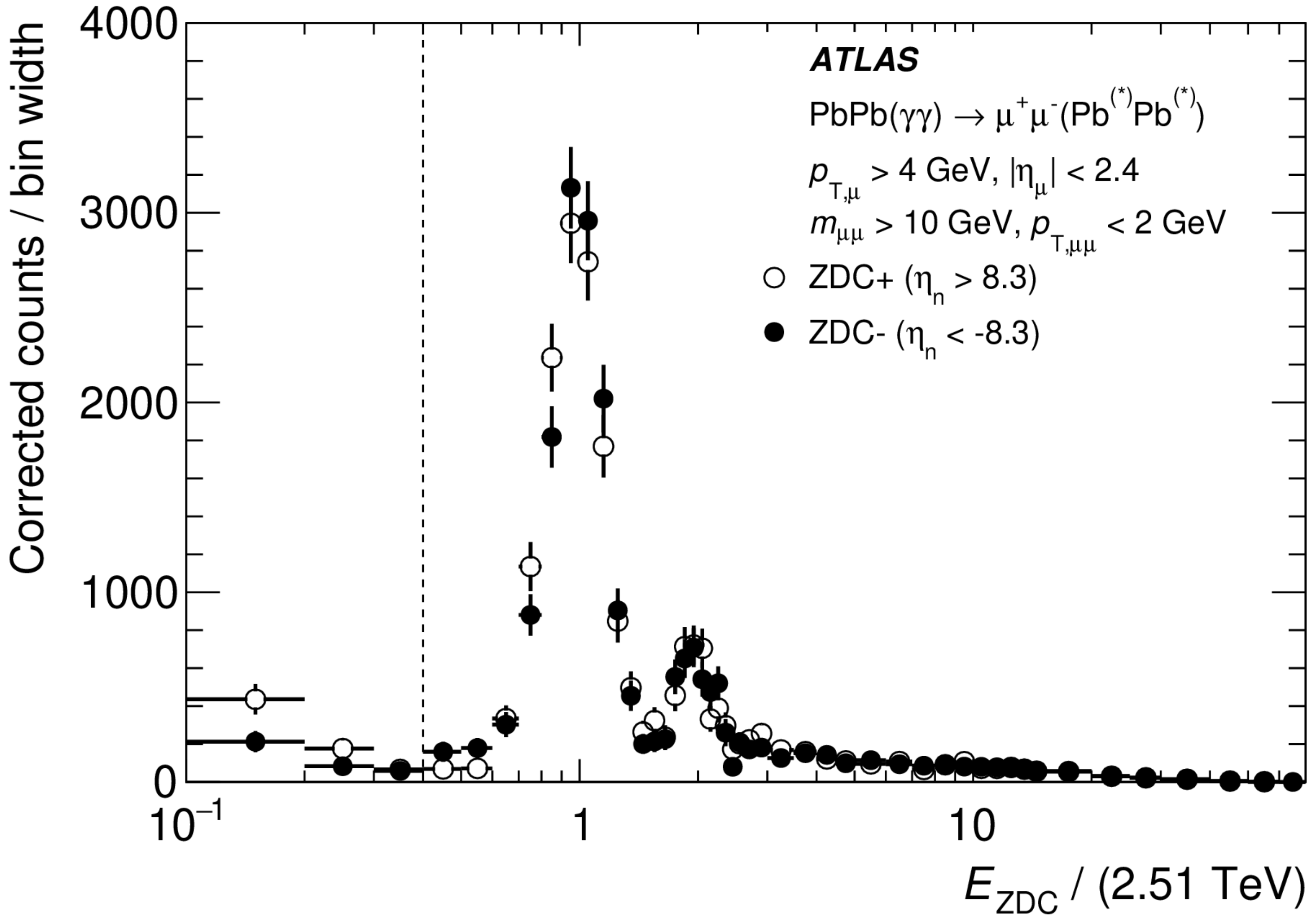
(I) Exclusive dimuons in PbPb



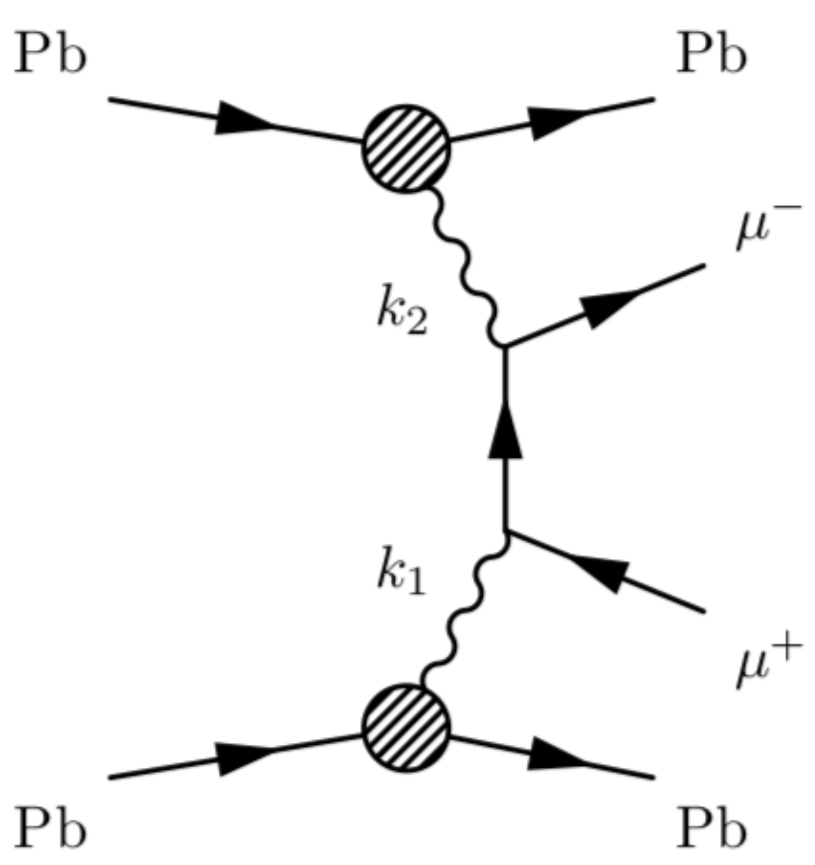
Exclusive dimuons in PbPb

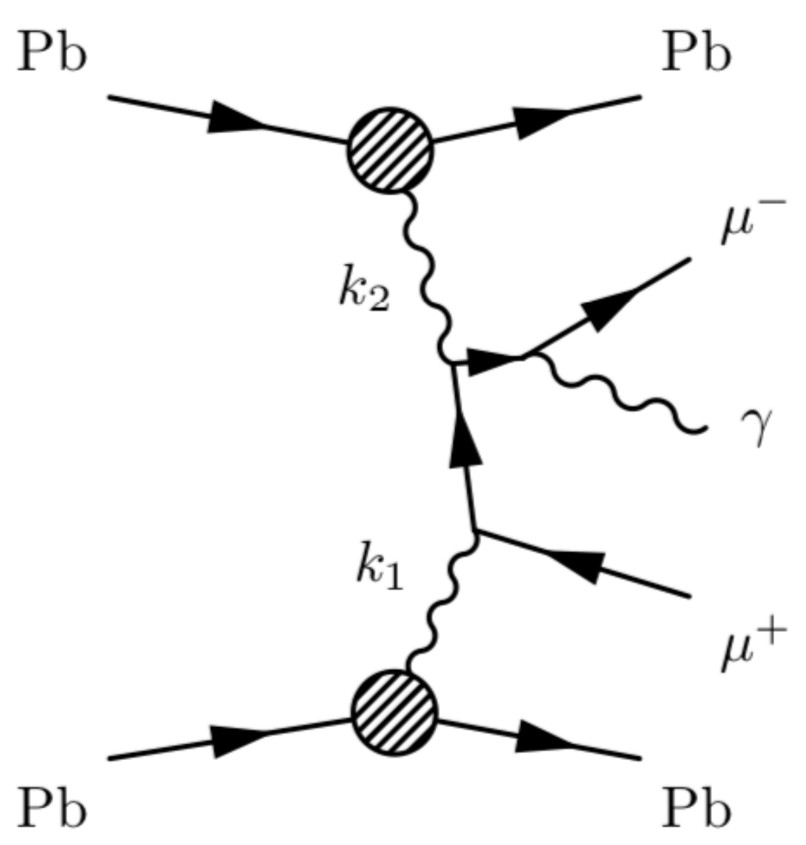
arXiv:2011.12211

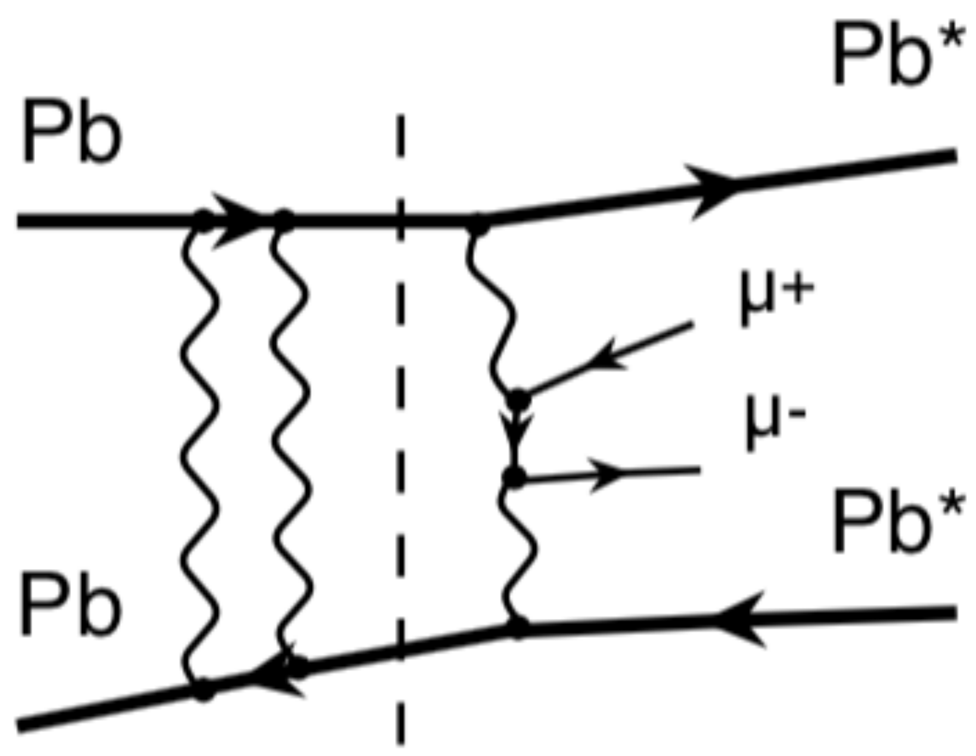
- ‘Standard candle’ process
  - Good sensitivity for Pb EM formfactors → **photon fluxes**
  - Sensitivity to probe **higher-order corrections** (FSR, extra ion-ion “Coulomb” exchanges)

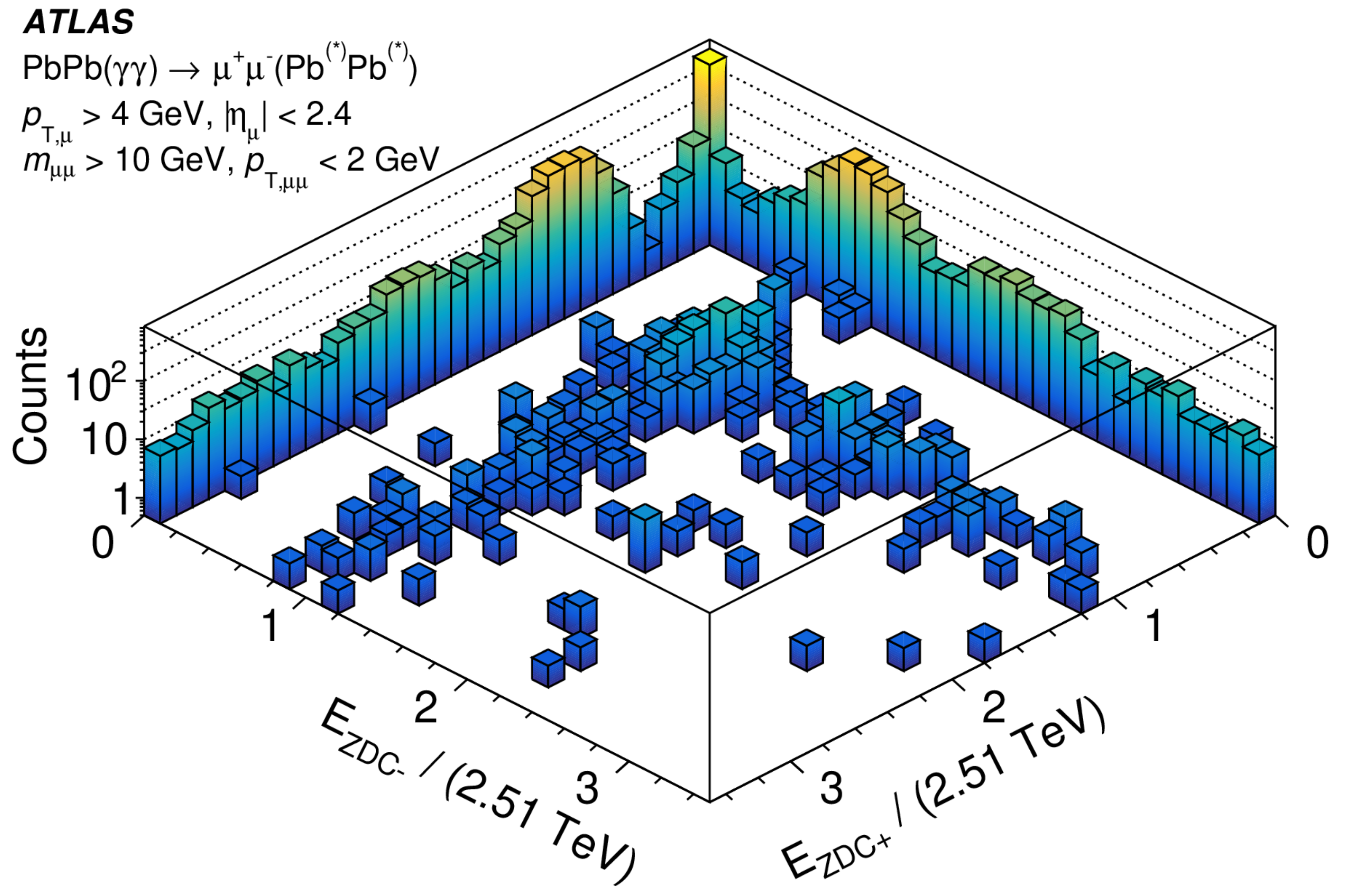


- Events categorised wrt **ZDC** neutron activity (0n0n, 0nXn, XnXn)





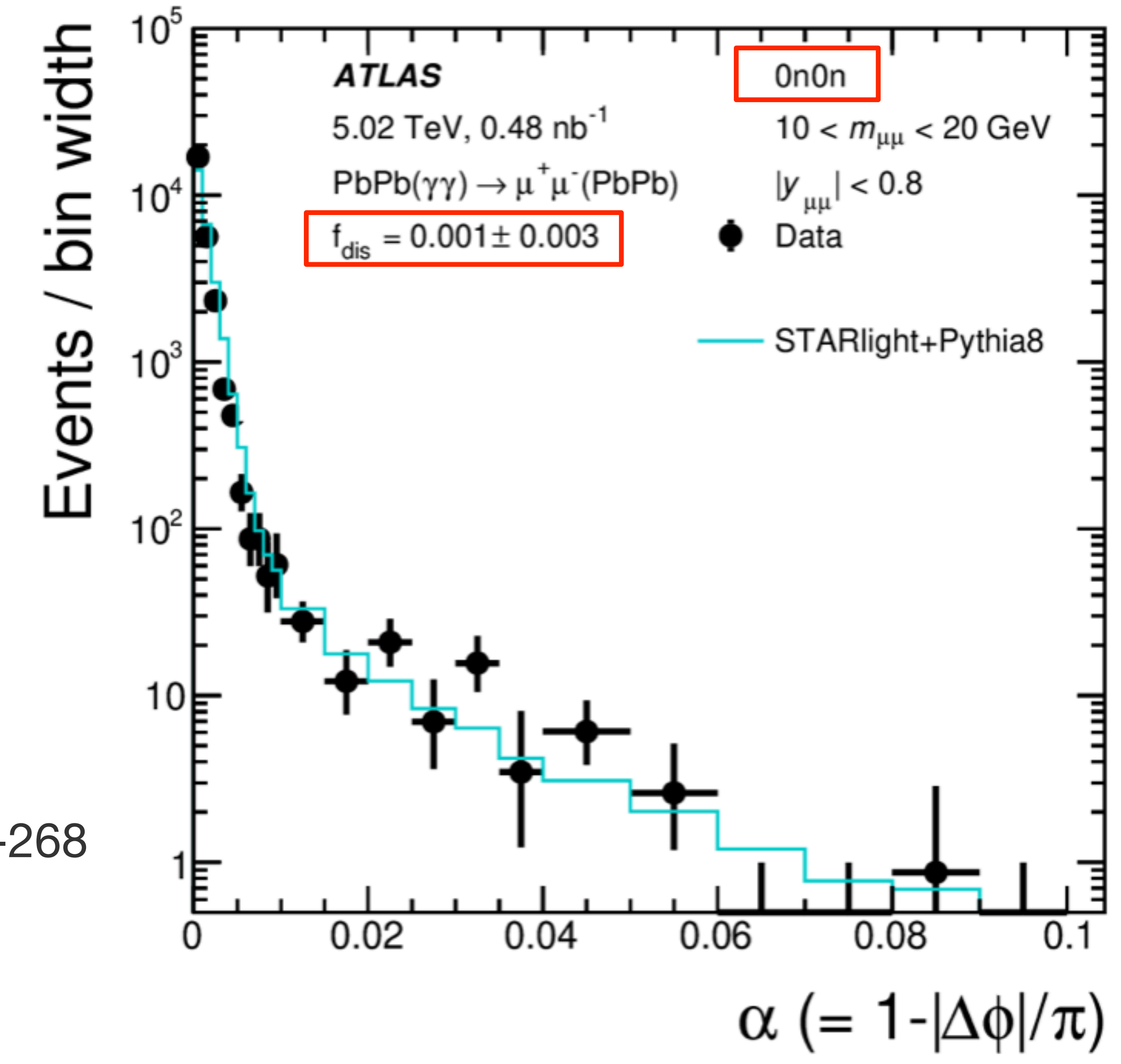


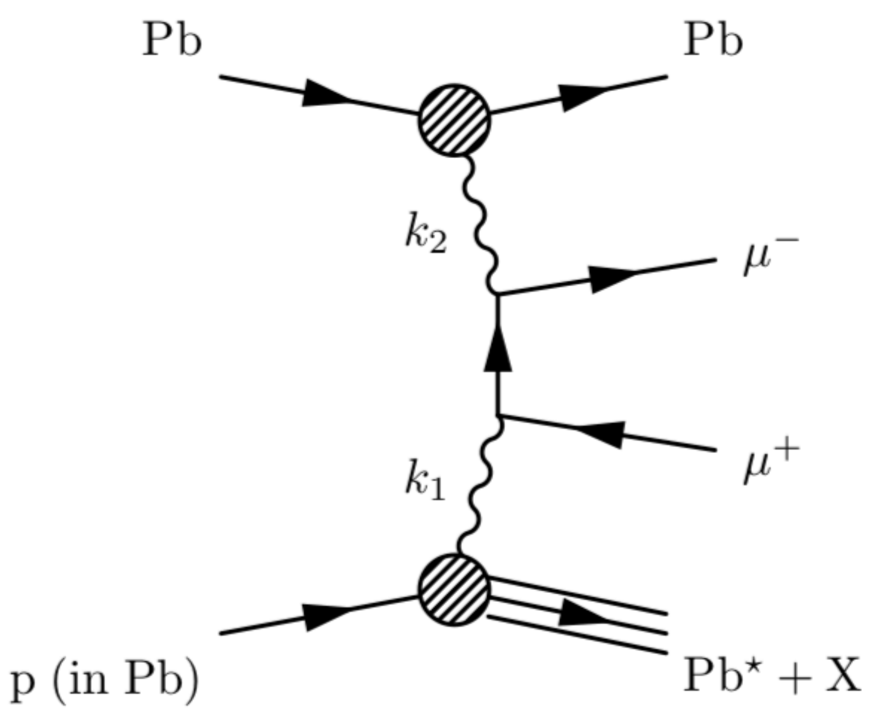


Exclusive dimuons in PbPb

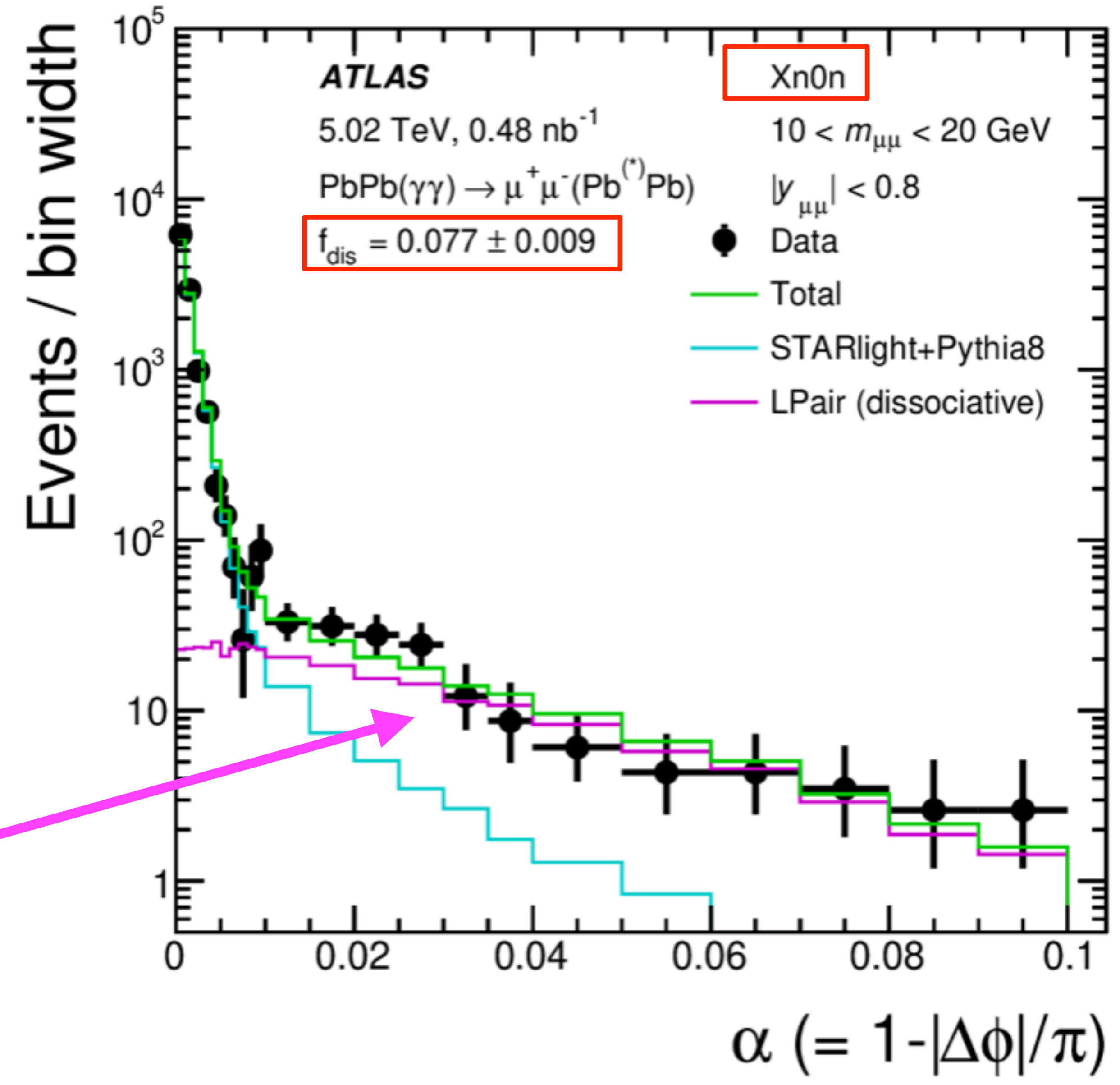
arXiv:2011.12211

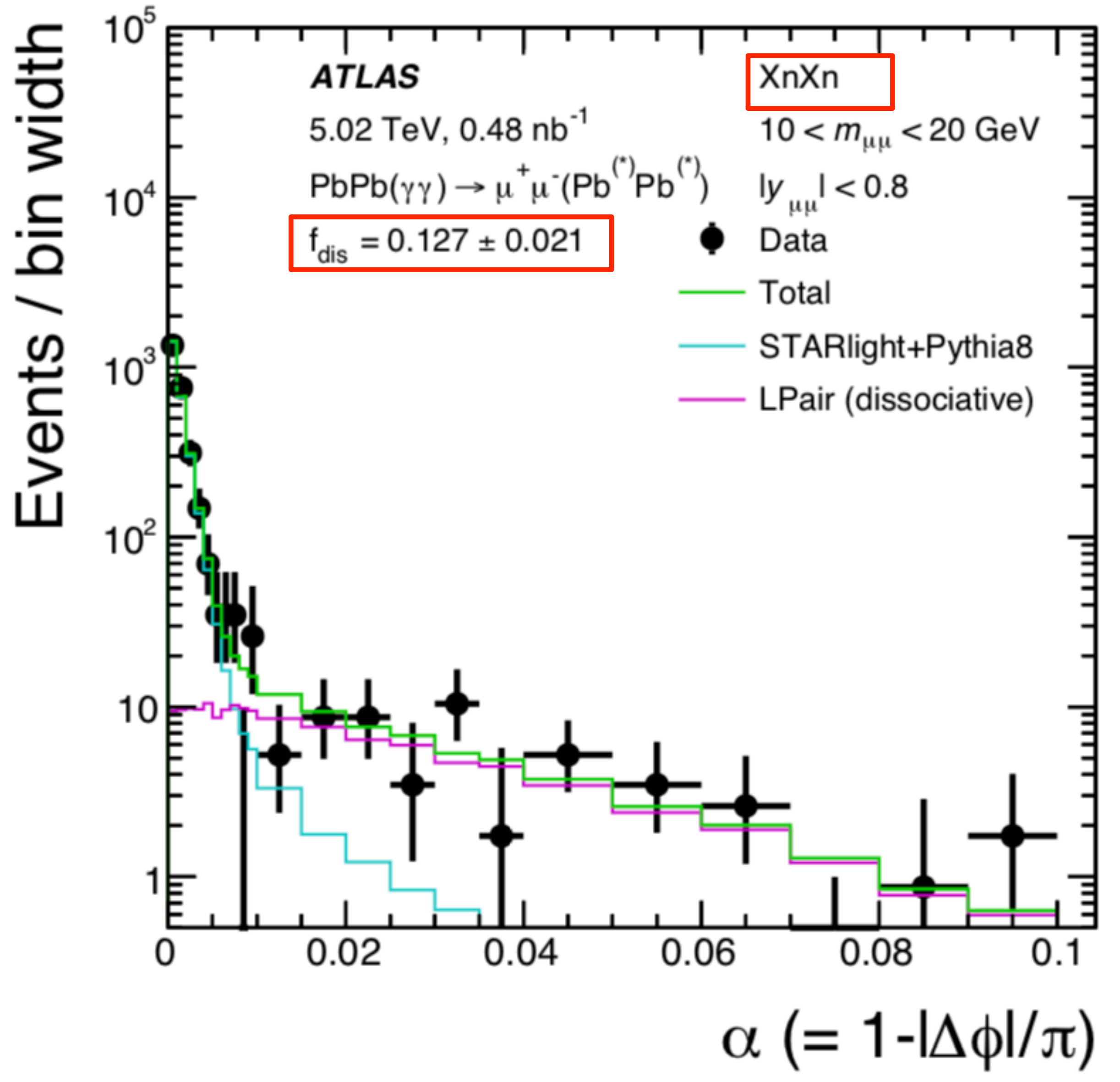
- Event selection
  - ==2 muons with $p_T > 4$ GeV, |eta|<2.4
  - no other charged-particle track activity
- Signal and background modelling
  - Signal: STARlight+Pythia8 (LO+FSR) *STARlight: Klein et al. Comput.Phys.Commun.* 212 (2017) 258-268
  - Semi-coherent background ($\gamma^*\gamma\to\mu\mu$): LPair 4.0 (pp), fit to dimuon acoplanarity





semi-coherent bkg

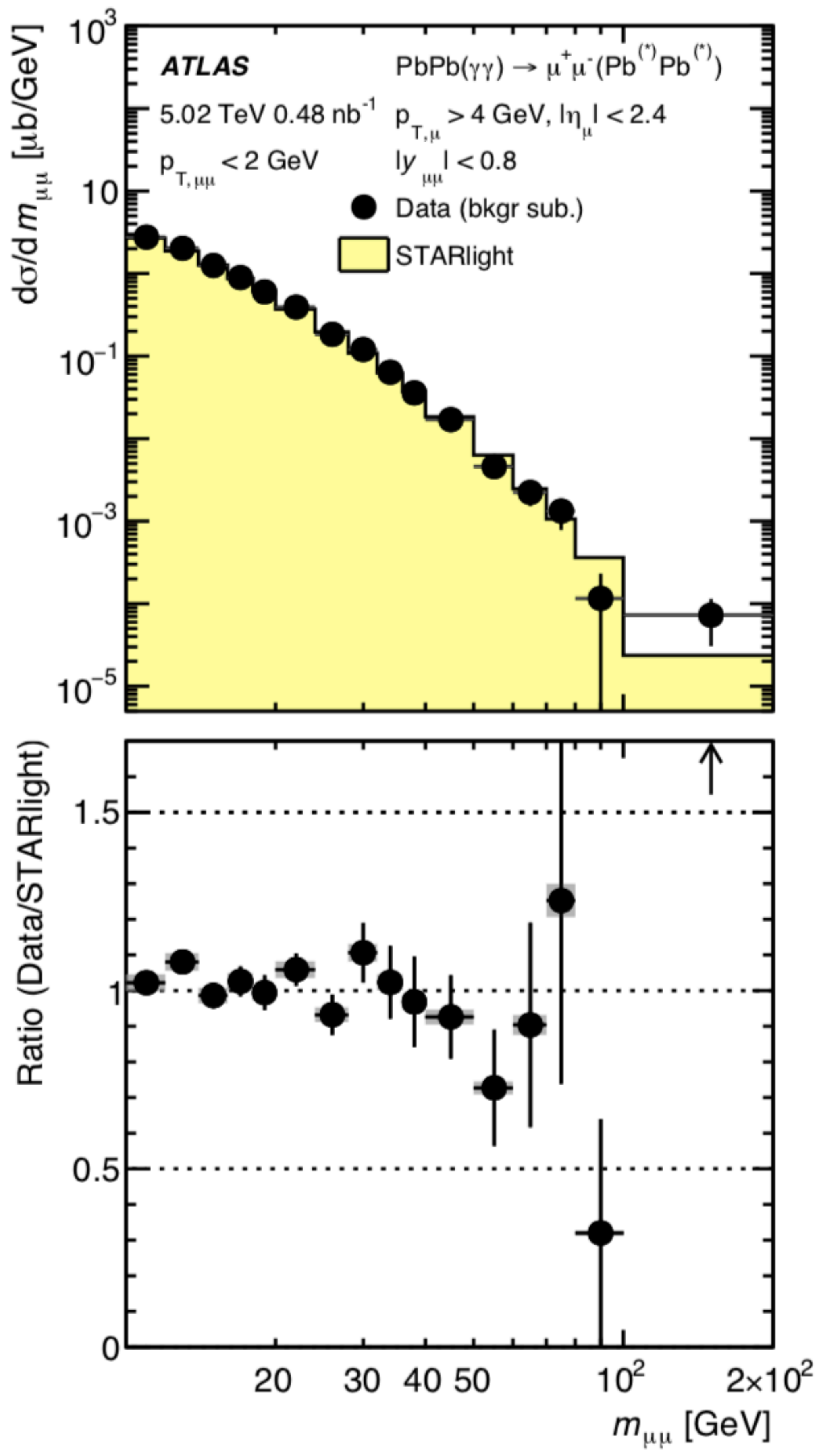


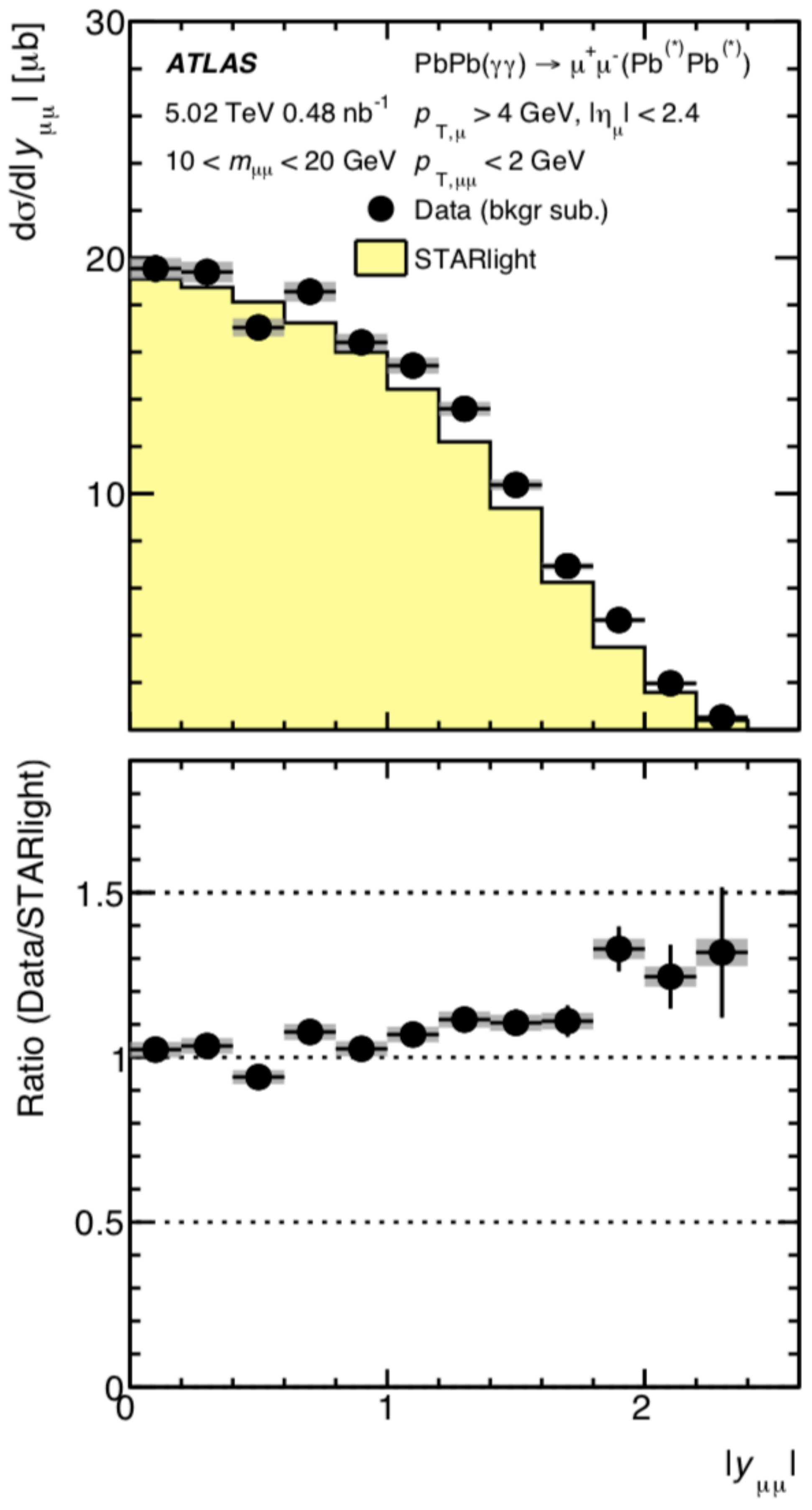


Exclusive dimuons in PbPb

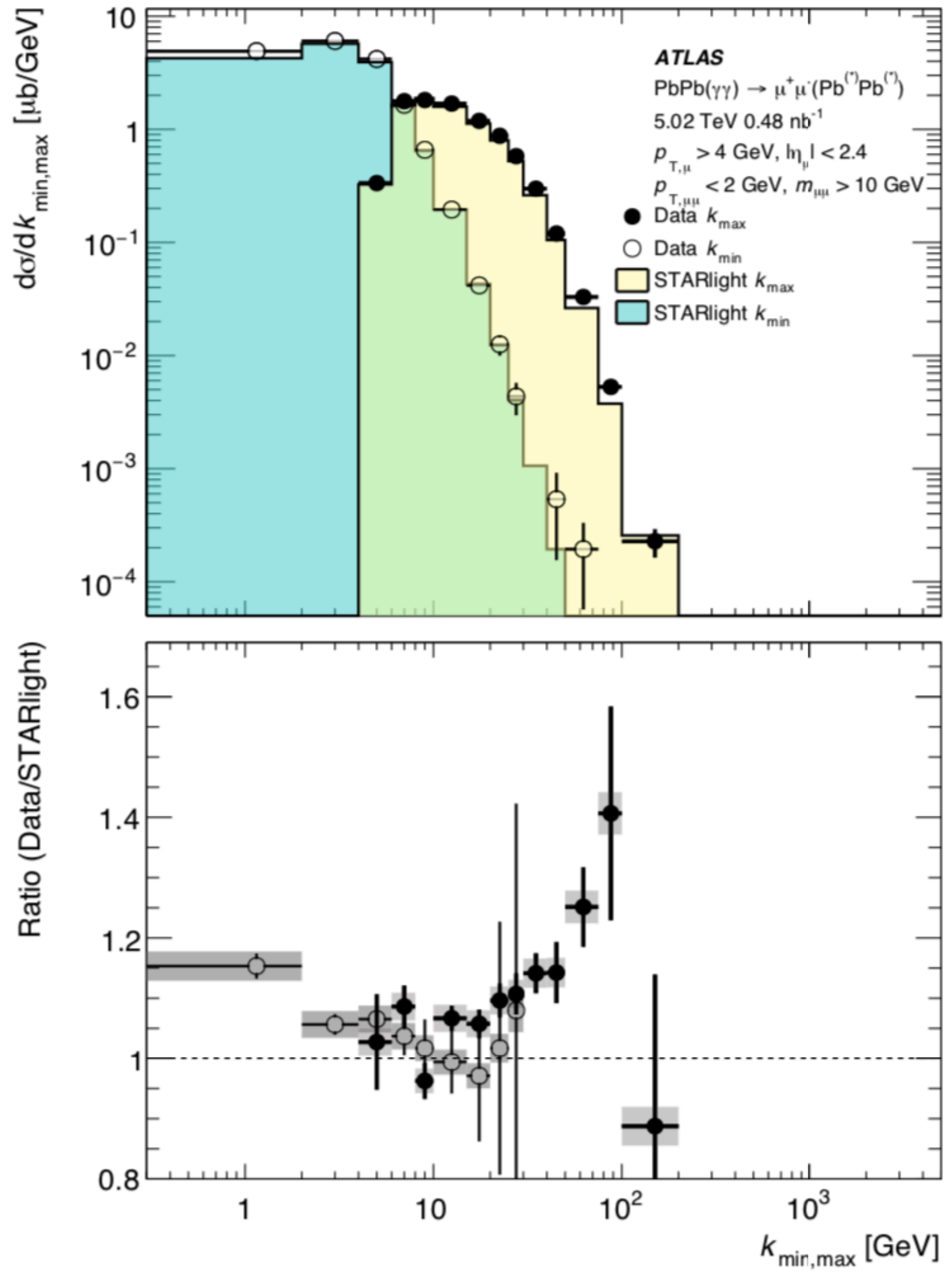
arXiv:2011.12211

- **Differential** cross sections as function of $\mathbf{m_{\mu\mu}}$, $\mathbf{|y_{\mu\mu}|}$, **cos(θ*)**
  - In reasonable agreement with STARlight
  - Some disagreement seen mainly at large $|y_{\mu\mu}|$ →Translated into disagreement at low and high photon energies





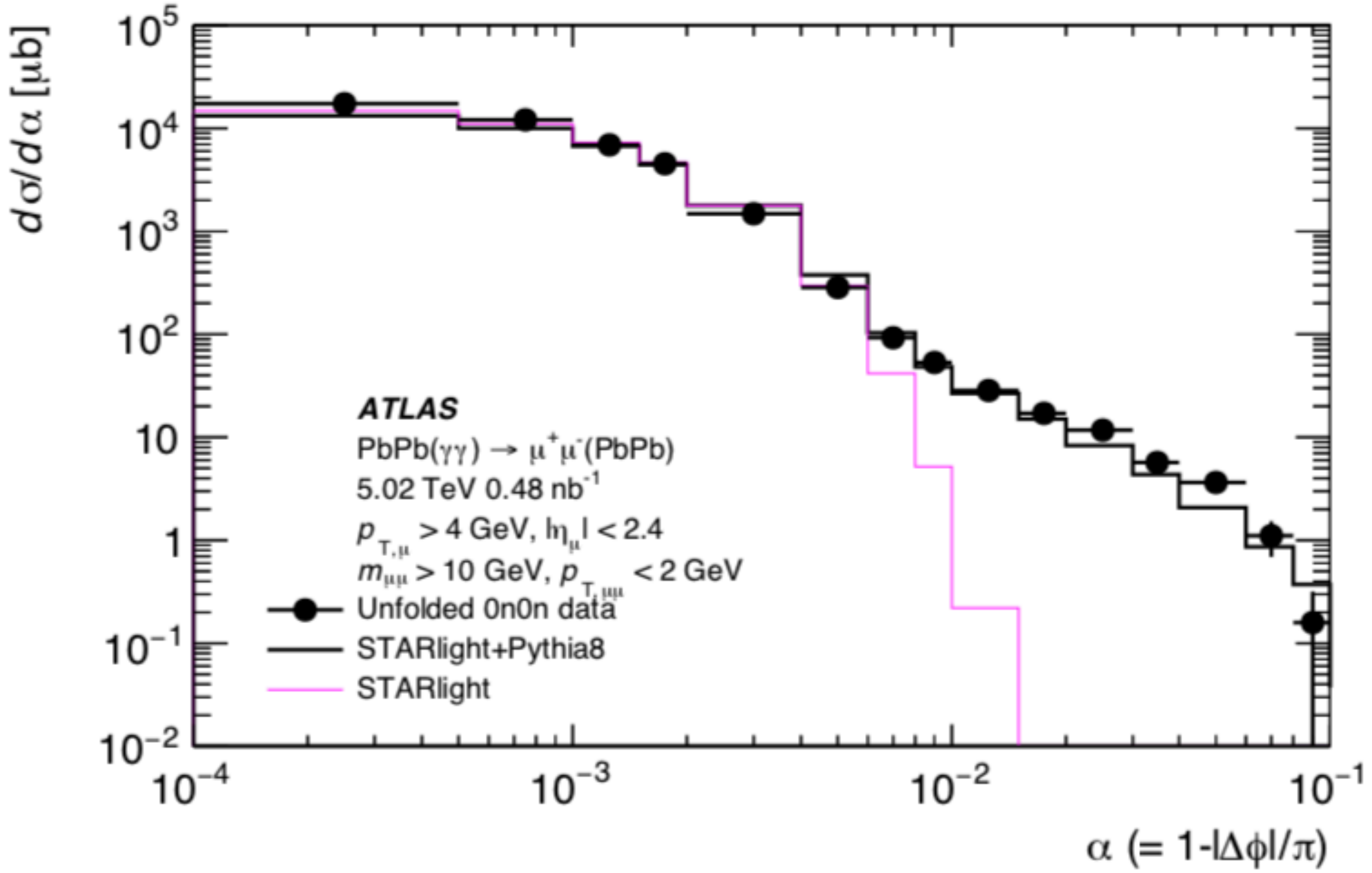
$$k_1, k_2 = (1/2)m_{\mu\mu}\exp(\pm y_{\mu\mu})$$



Exclusive dimuons in PbPb

arXiv:2011.12211

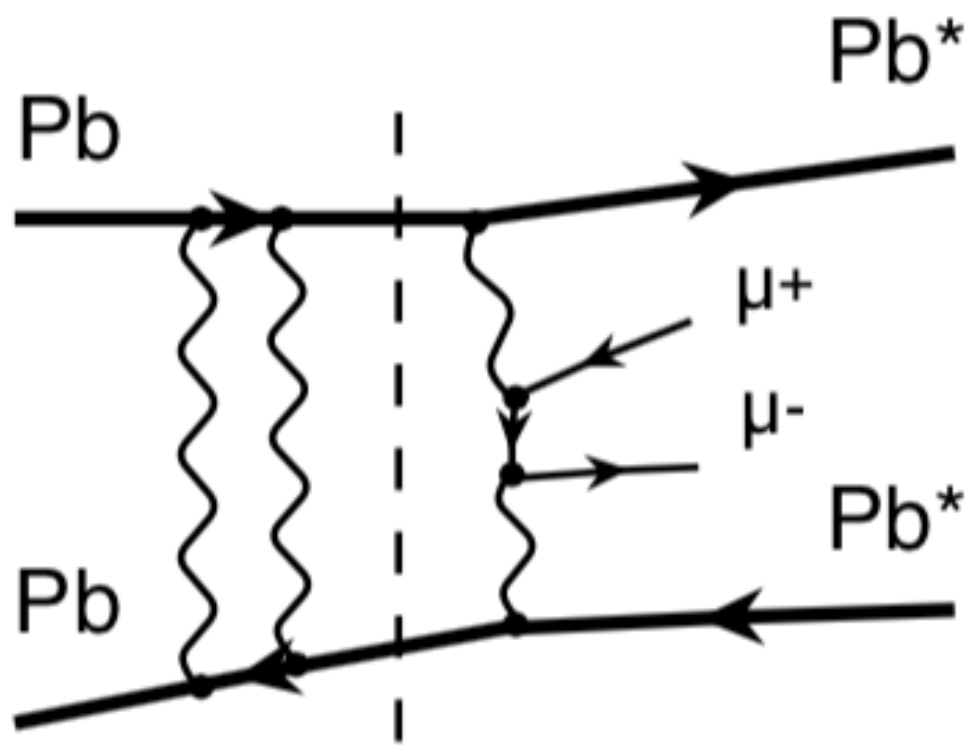
- **Differential** cross sections as function of **dimuon acoplanarity (0n0n)**
  - Benchmark scenario to test FSR corrections
  - Fair FSR modeling by STARlight+Pythia8

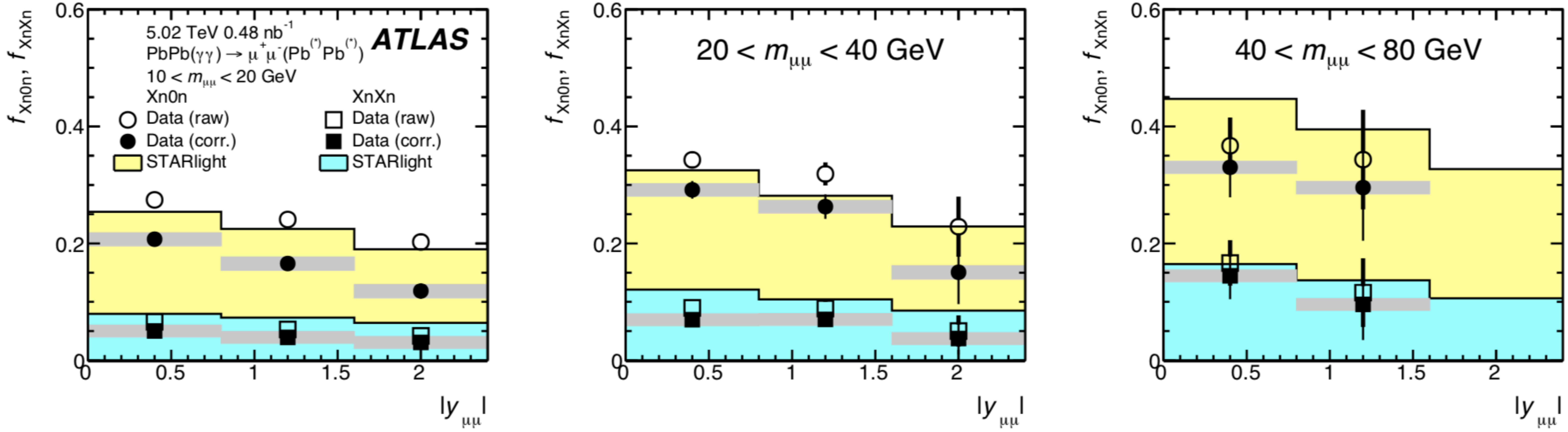


Exclusive dimuons in PbPb

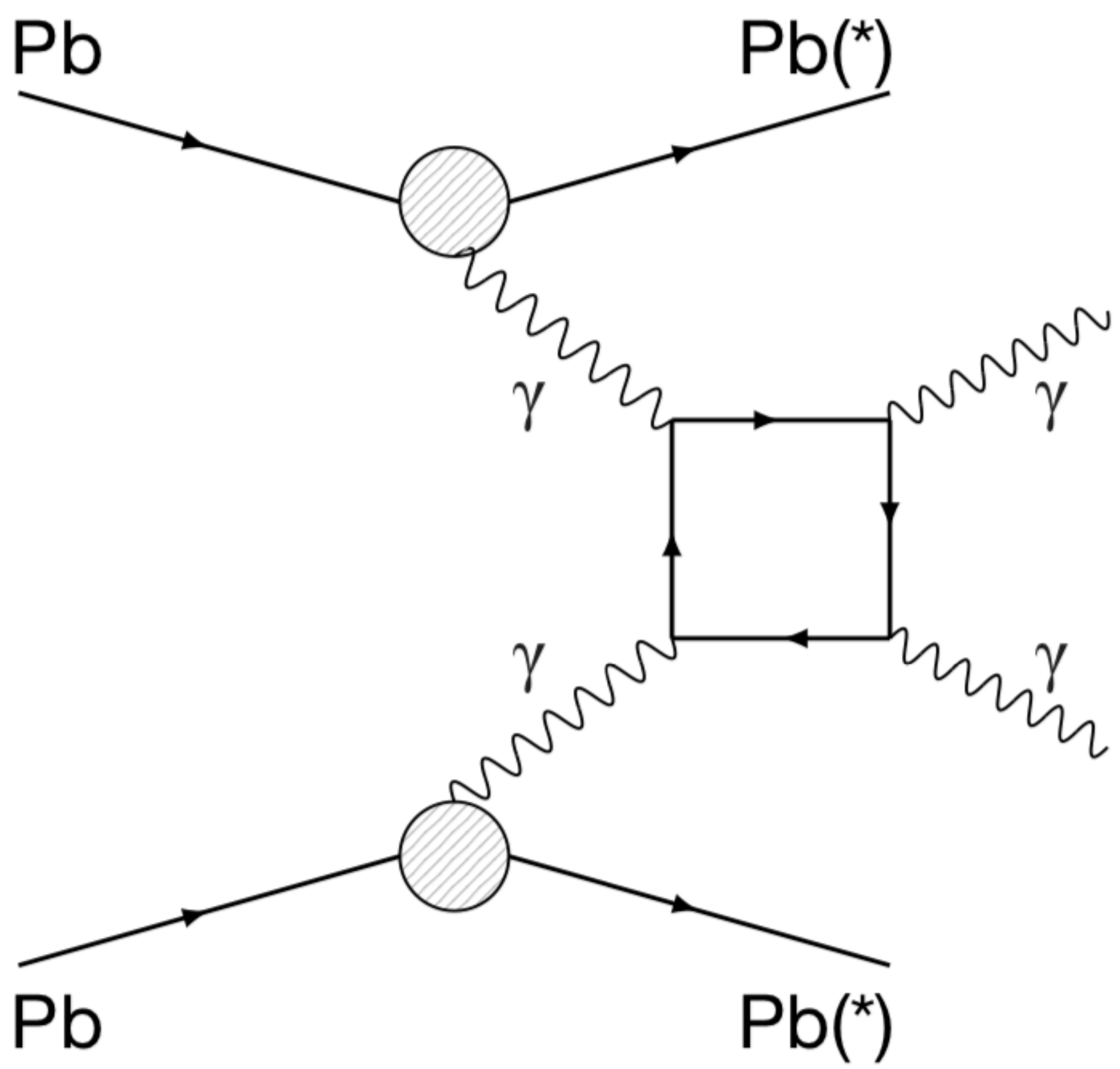
arXiv:2011.12211

- Event **fractions** with activity in **ZDC** are also measured differentially
  - Sensitive to extra Coulomb interactions between Pb ions
    → indirect probe of impact parameter in UPC
  - Measurement needs correction for “EM pileup” contribution
  - Observing less fragmentation in data vs STARlight





(II) Light-by-light scattering and search for Axion-like particles in PbPb



LbyL scattering in PbPb

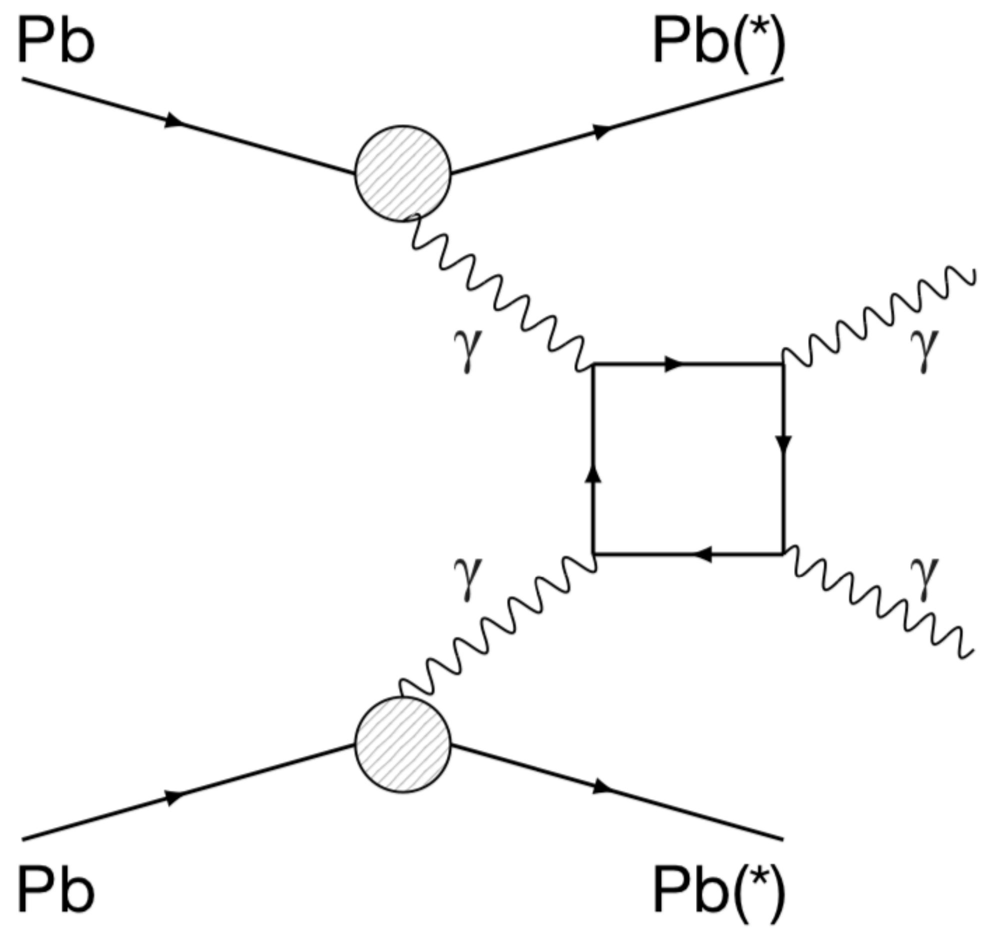
Original idea:
PRL 111 (2013) 080405

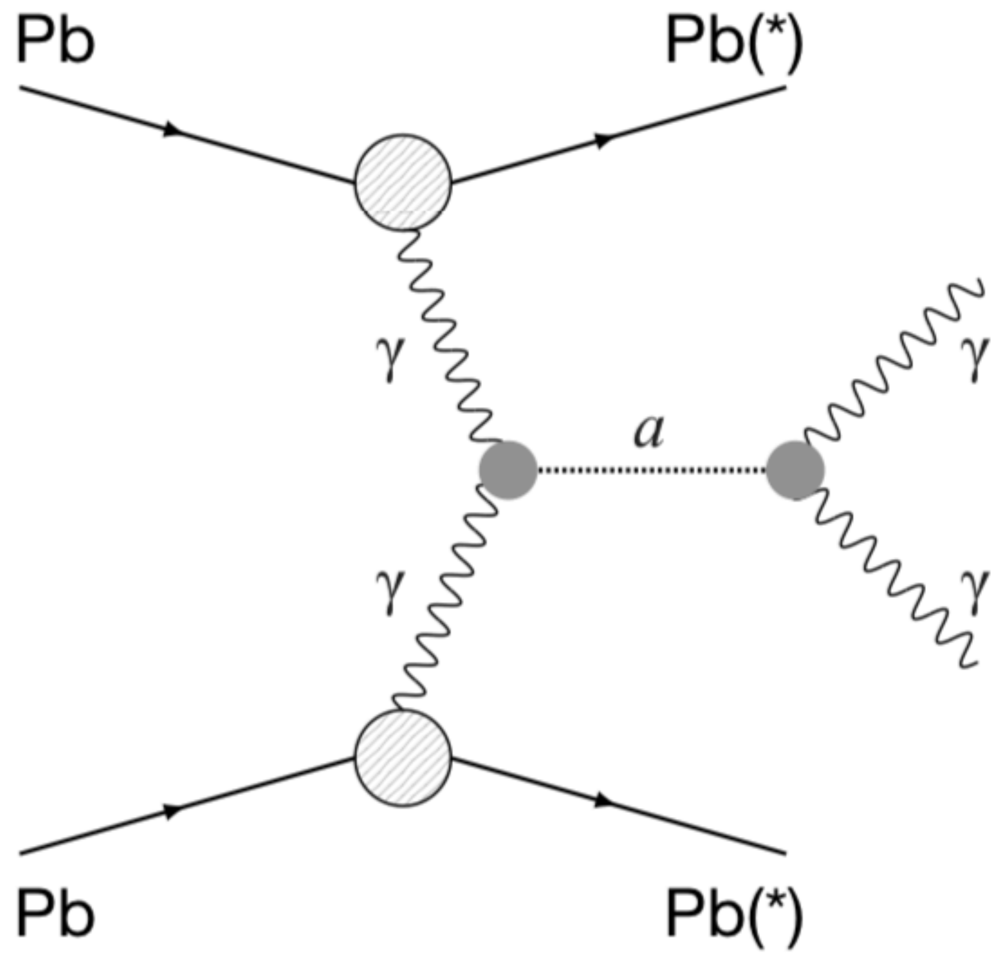
- Rare $O(\alpha_{EM}^4)$ process
  - Sensitive to BSM physics

ATLAS, Nature Phys. 13 (2017) 852
CMS, PLB 797 (2019) 134826
ATLAS, PRL 123 (2019) 052001

- Previous LHC measurements:
  - 2015 data: ATLAS & CMS (~4σ evidence)
  - 2018 data: ATLAS (8.2σ observation)

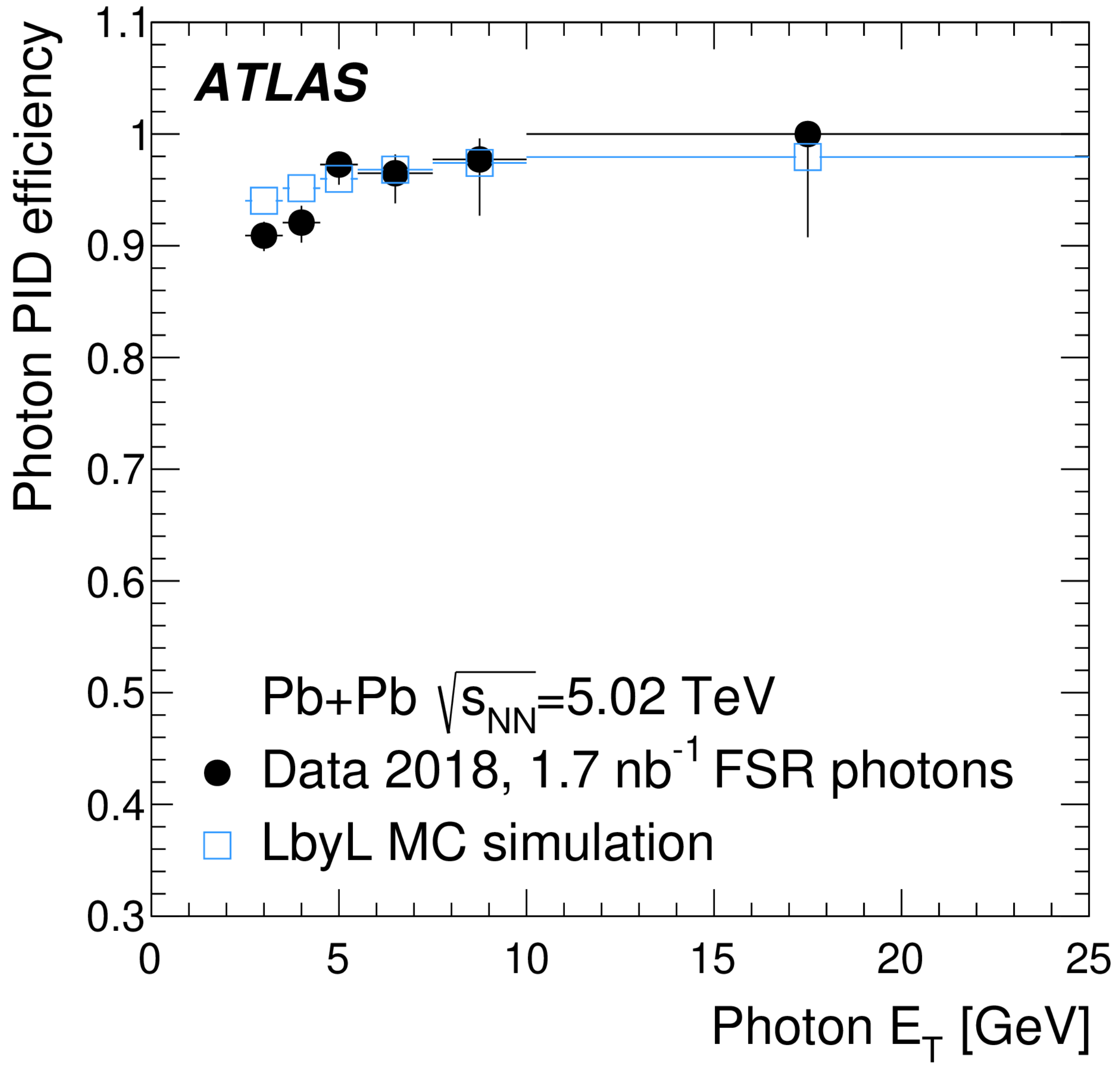
- **The new analysis covers**:
  - Exploration of full Run-2 Pb+Pb dataset
  - Differential cross-section measurement
  - Search for axion-like particles

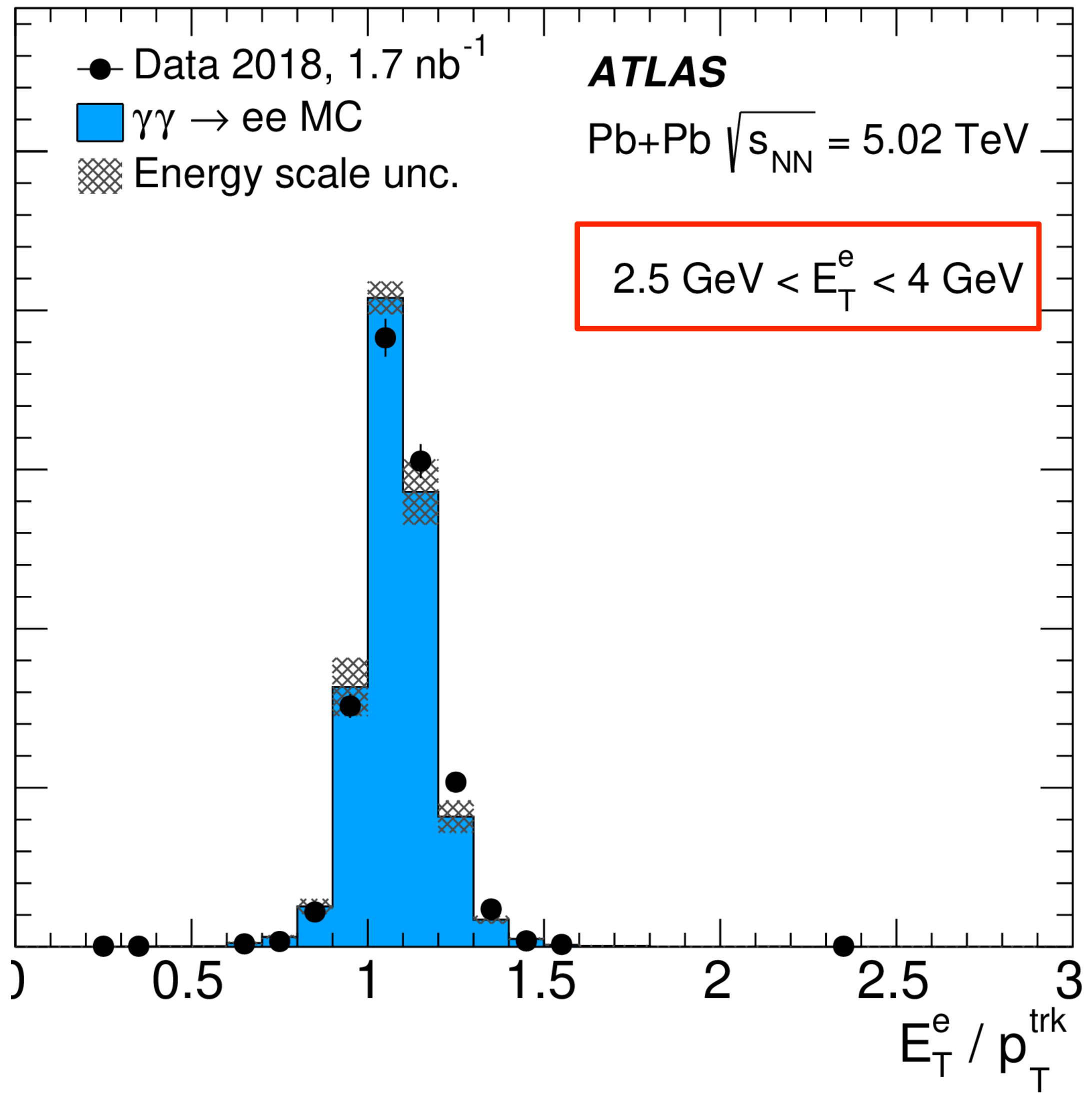




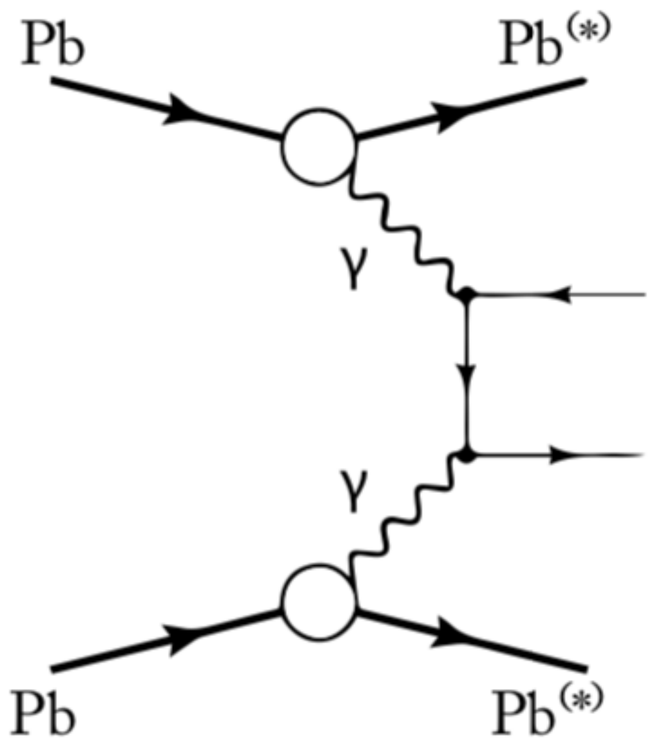
LbyL scattering in PbPb

- Detectors are pushed to the limits
  - Very low E_T photons (E_T >2.5 GeV)
  - Track veto (p_T >100 MeV) + pixel track veto (p_T >50 MeV)

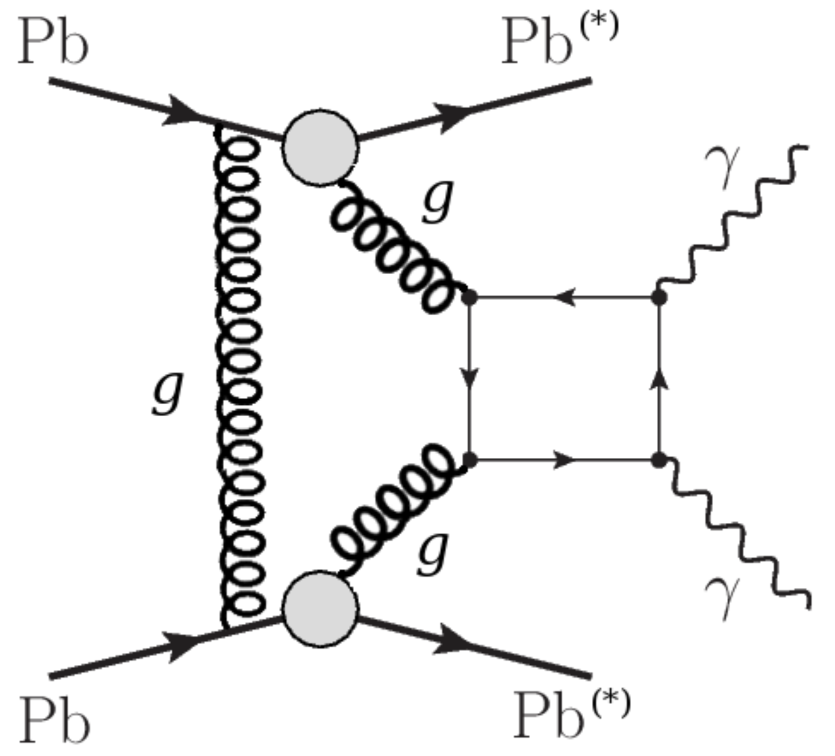




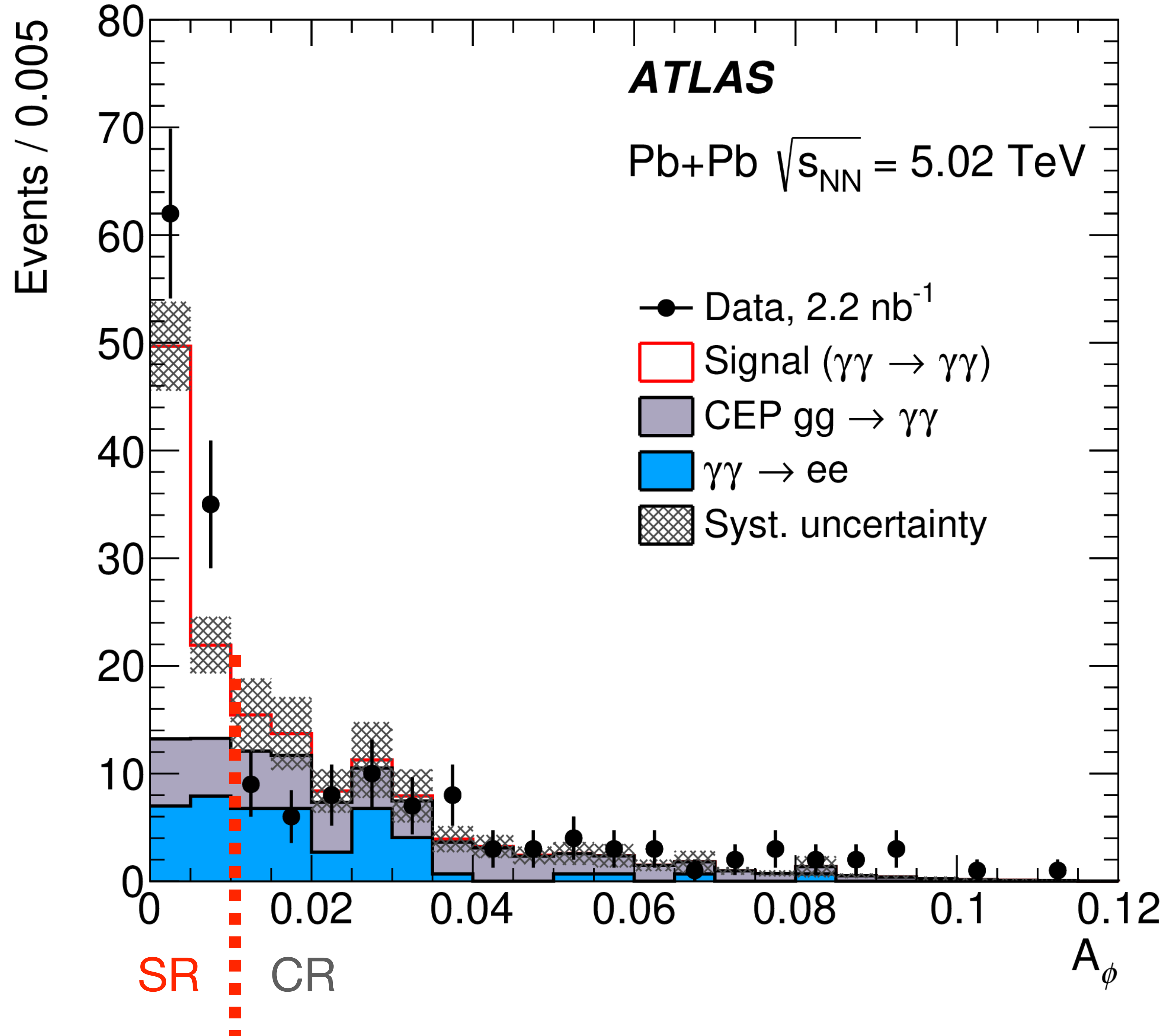
- Backgrounds
  - Dominated by misid γγ→ee and CEP γγ production
  - Estimated using data-driven methods



γγ→ee



CEP γγ

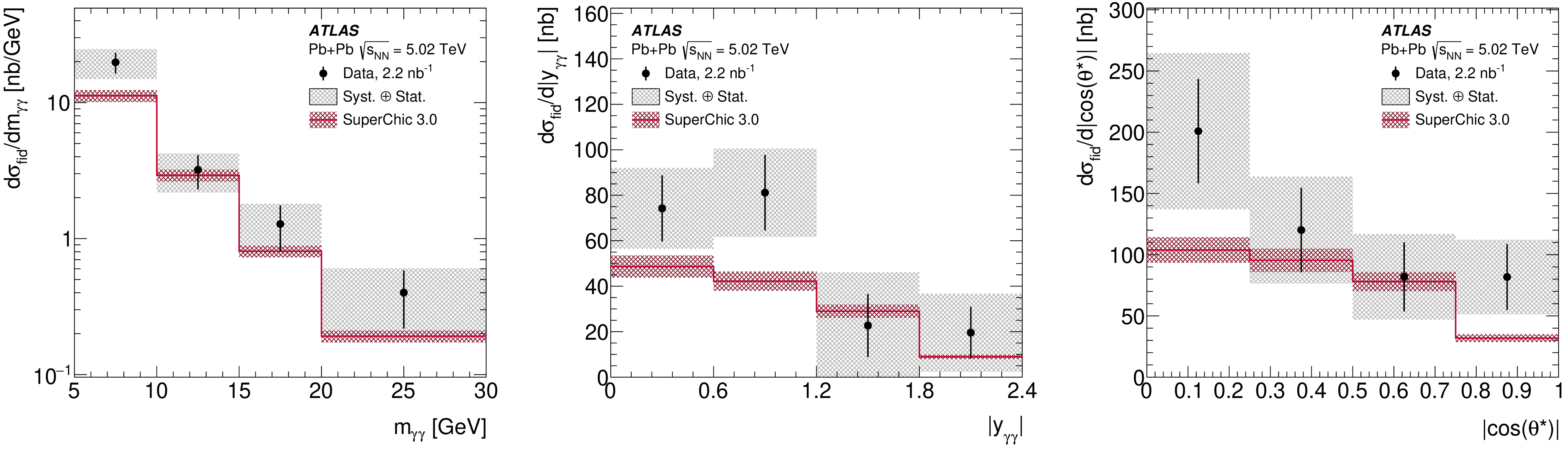


JHEP 03 (2021) 243

LbyL scattering in PbPb

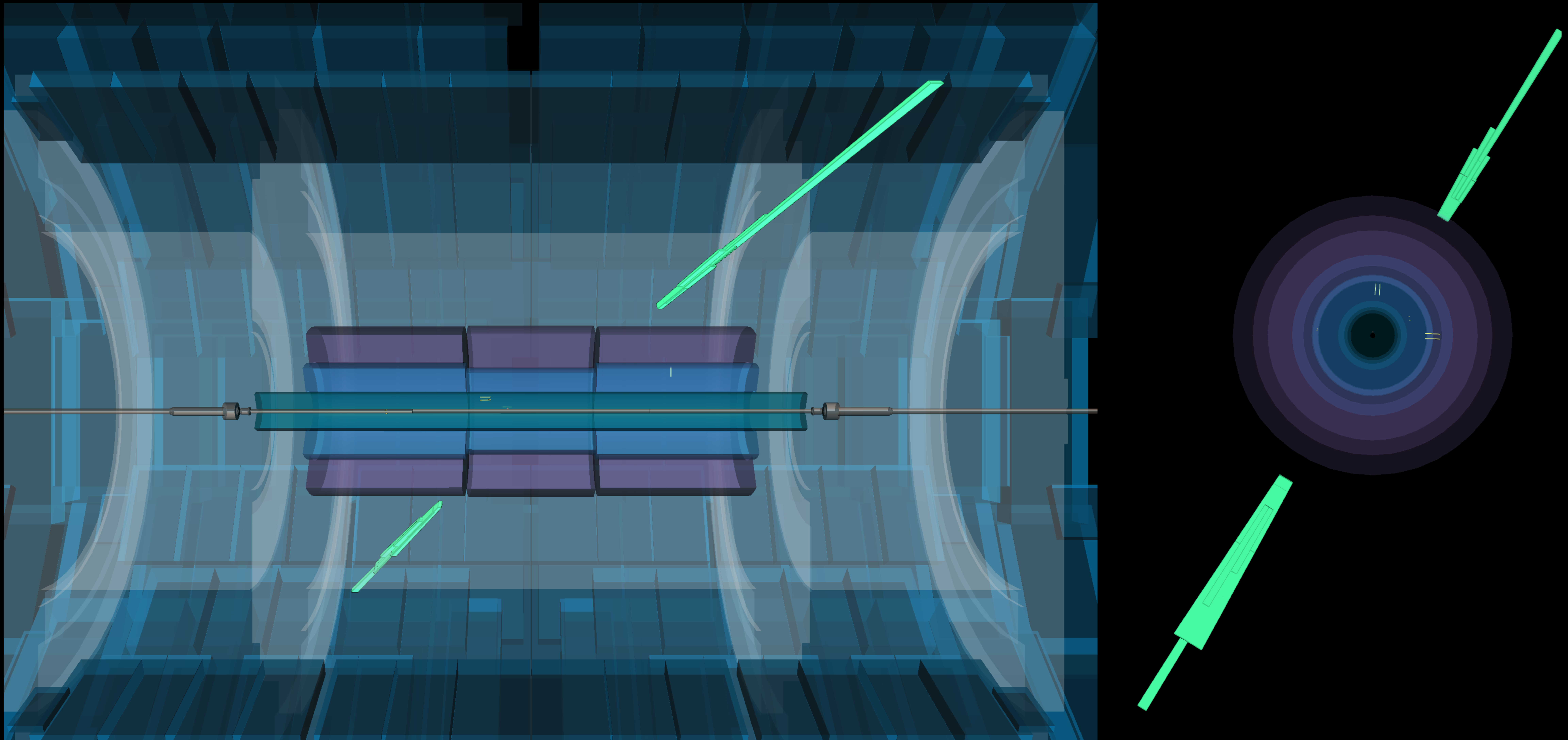
JHEP 03 (2021) 243

- Cross section measurements
  - Fiducial and differential (**$m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $|\cos(\theta^*)|$, average p_T^γ**) cross sections, comparison with **SuperChic 3 MC** [Harland-Lang et al. EPJC 79 (2019) 1, 39]
  - Integrated fiducial cross section about 1.7σ higher than the predictions [Klusek-Gawenda et al. PRC 93 (2016) 044907, Harland-Lang et al. EPJC 79 (2019) 39]



ATLAS EXPERIMENT

Run: 366994
Event: 453765663
2018-11-26 18:32:03 CEST

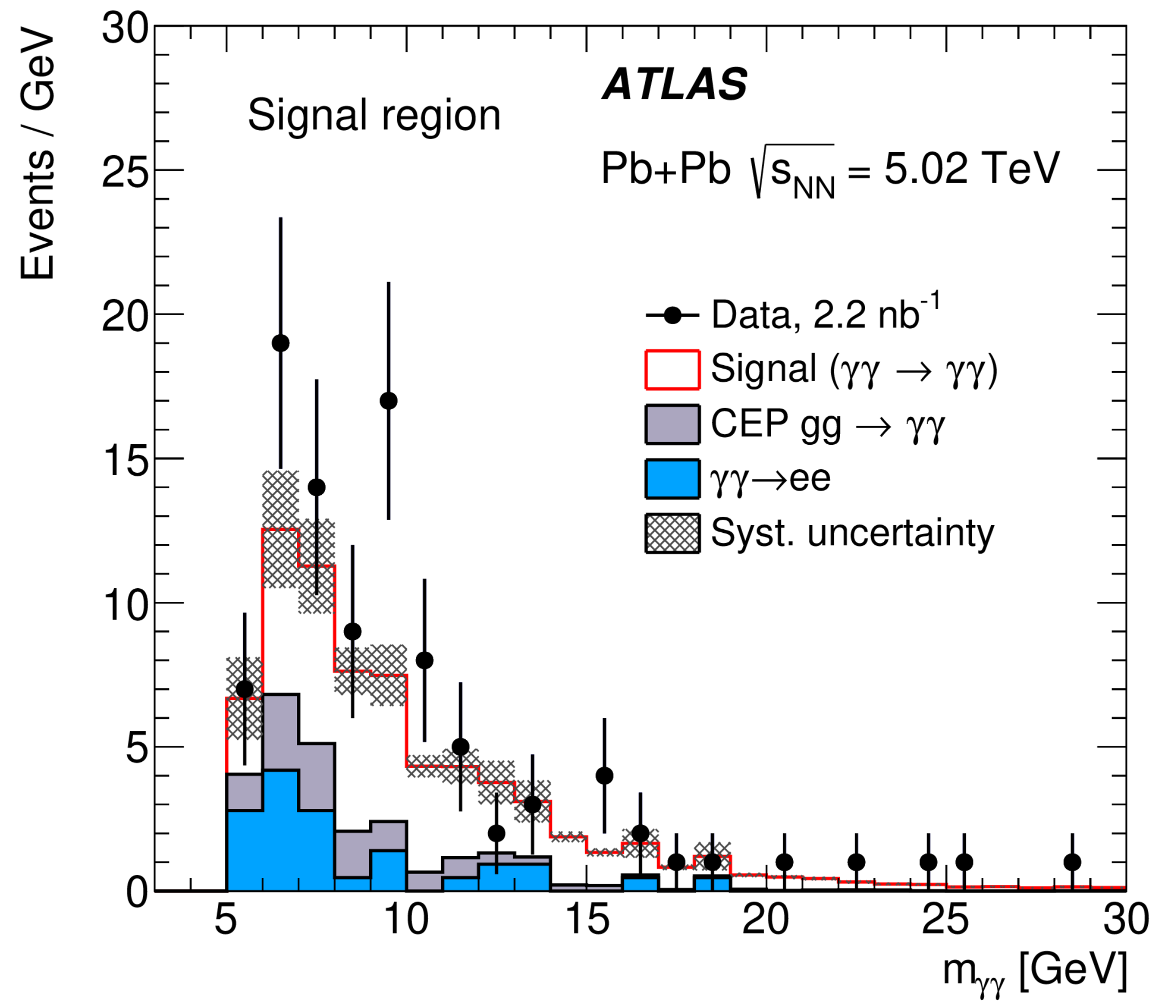


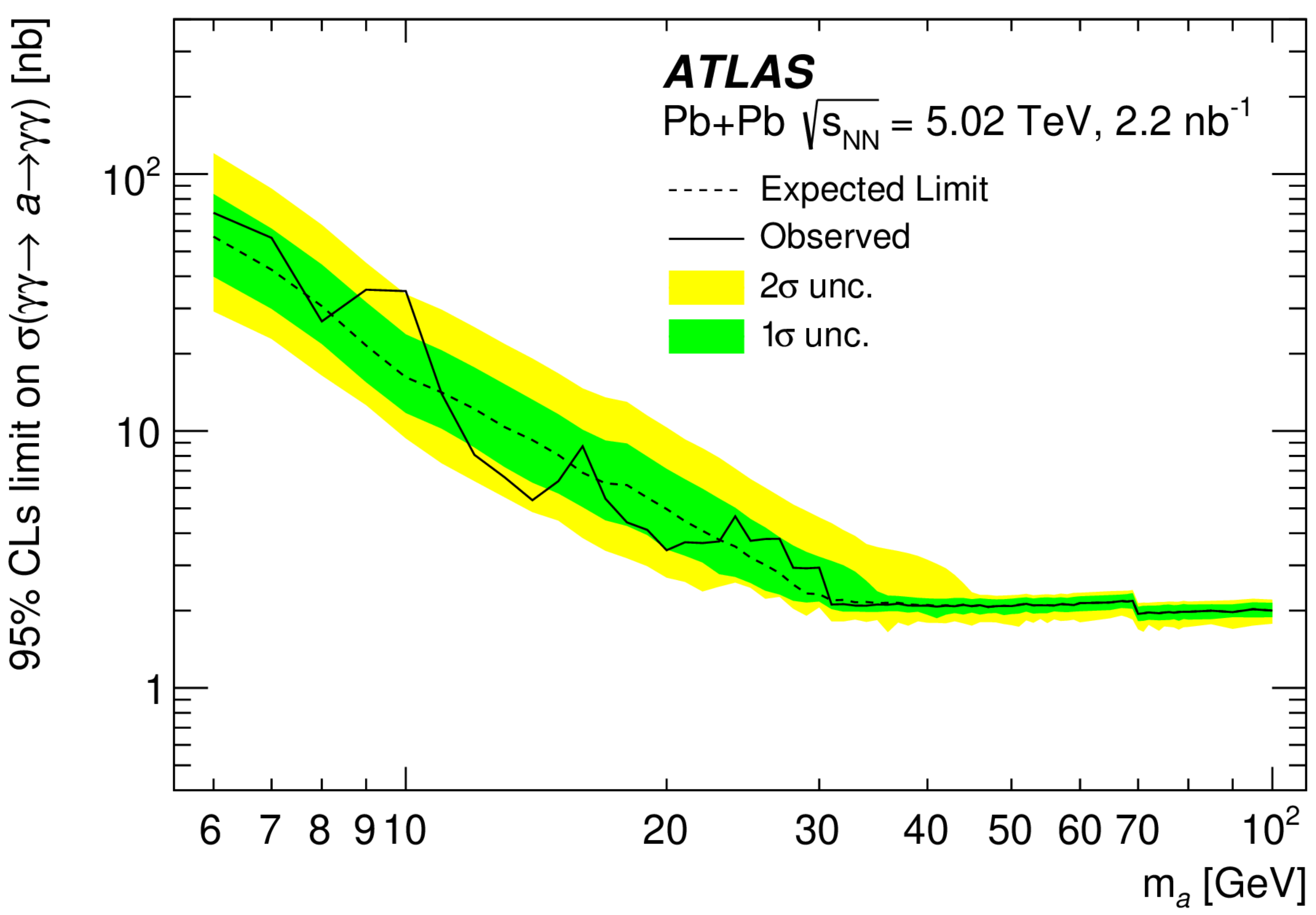
Search for Axion-like particles (ALPs)

JHEP 03 (2021) 243

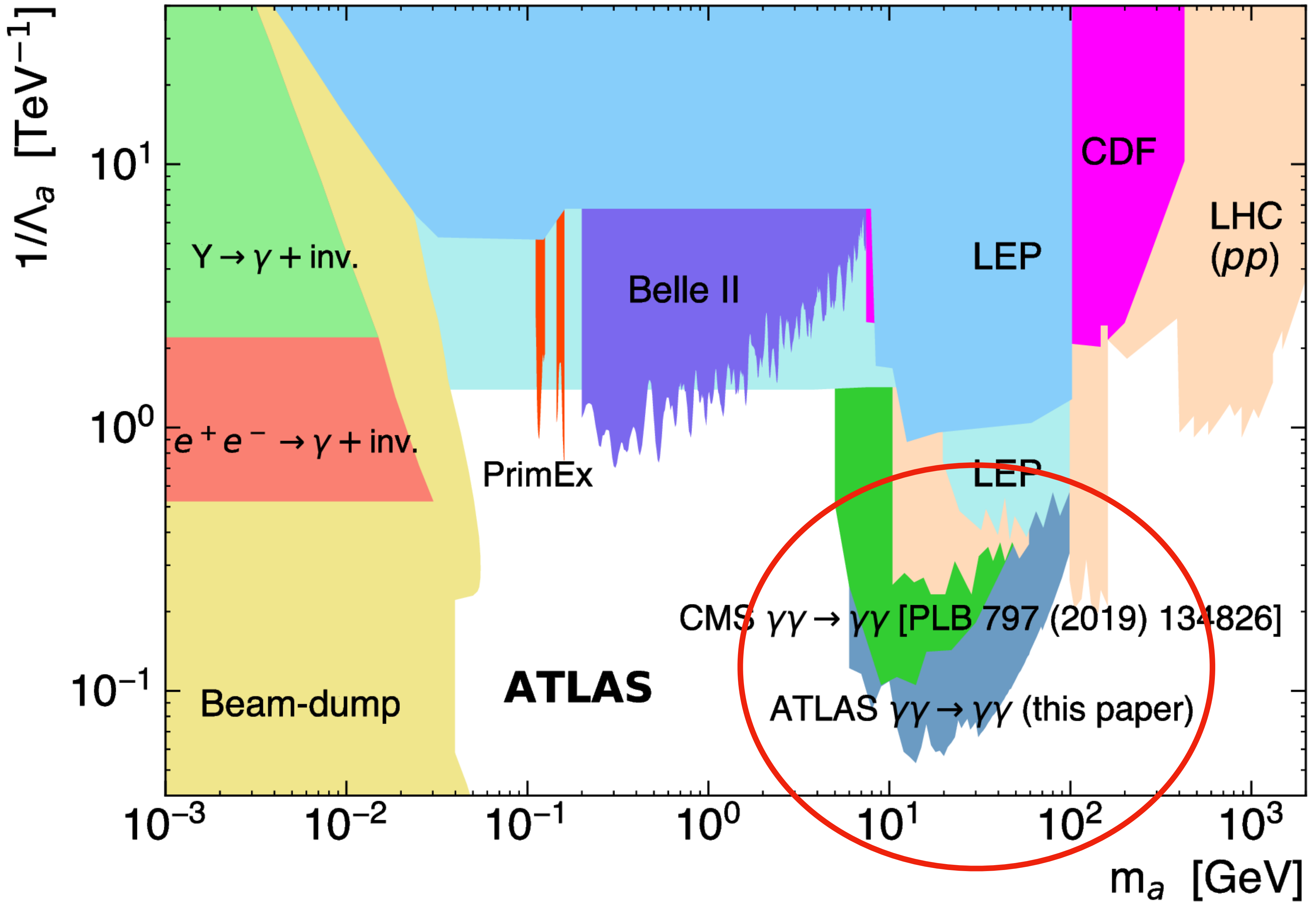
- Idea: search for new **$\gamma\gamma \to a \to \gamma\gamma$** resonances
  - Background includes SM LbyL, CEP $\gamma\gamma$ and ee
  - ALP signal generated with STARlight MC for various m_a

- No significant deviation from SM predictions observed
  → limits on $\sigma_{\gamma\gamma\to a\to\gamma\gamma}$ are extracted
  - Limits on σ are cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$)
  - **Most stringent ALP constraints (6< m_a <100 GeV) to date**

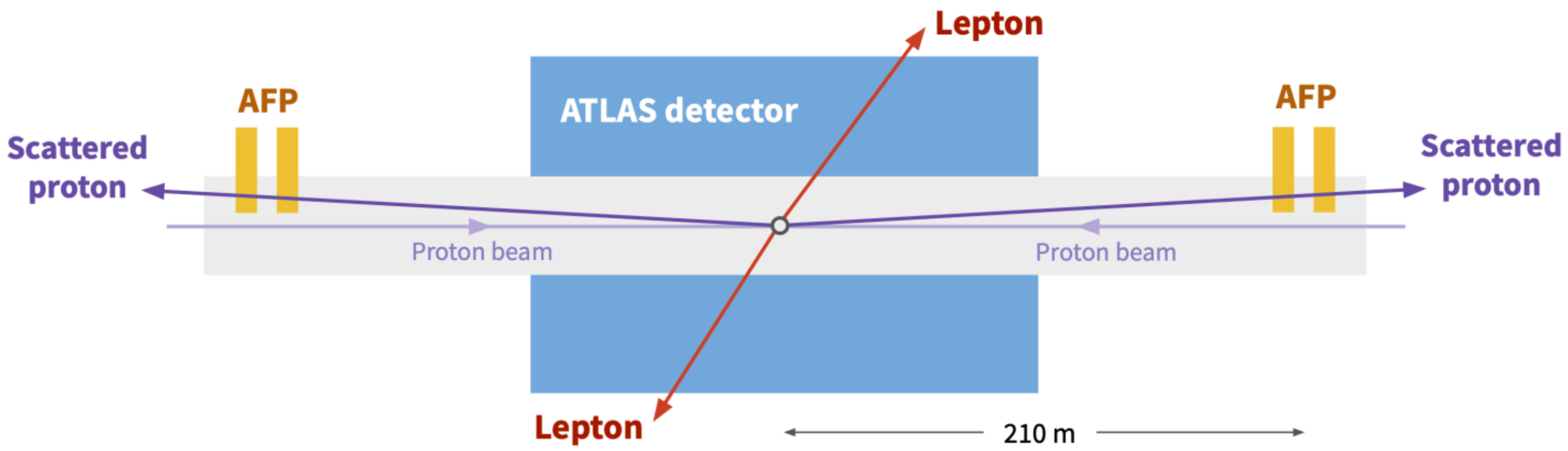




Existing constraints from JHEP 12 (2017) 044

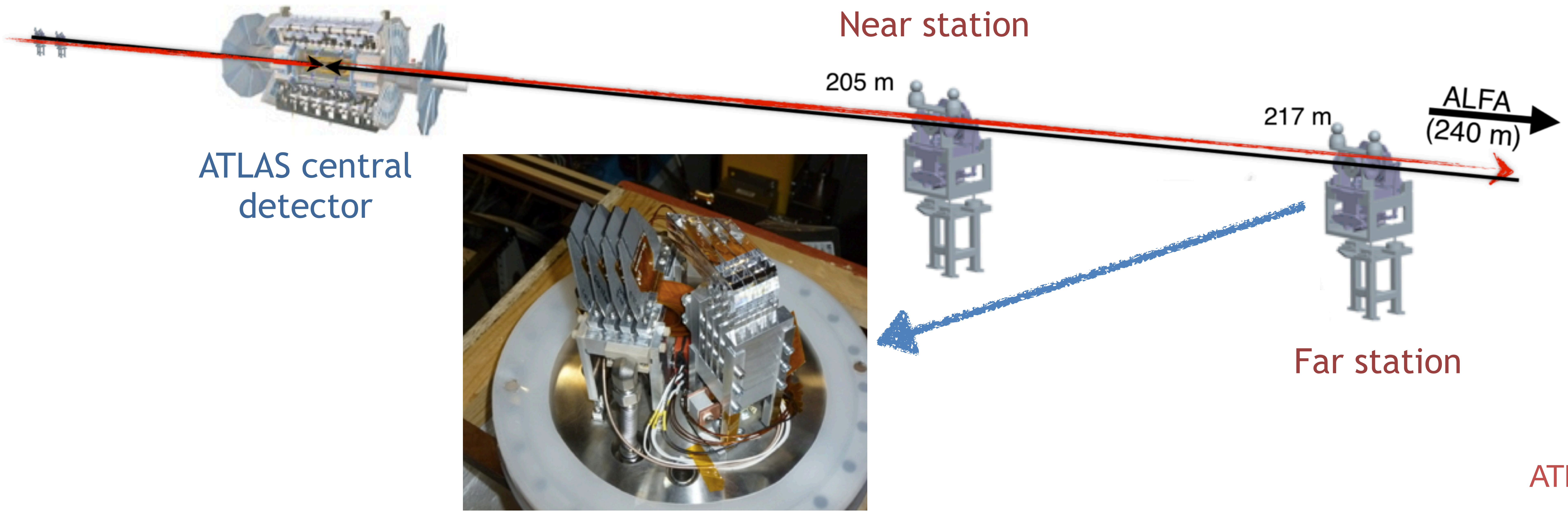


(III) Exclusive dileptons with AFP proton tag



The ATLAS Forward Proton (AFP) detectors

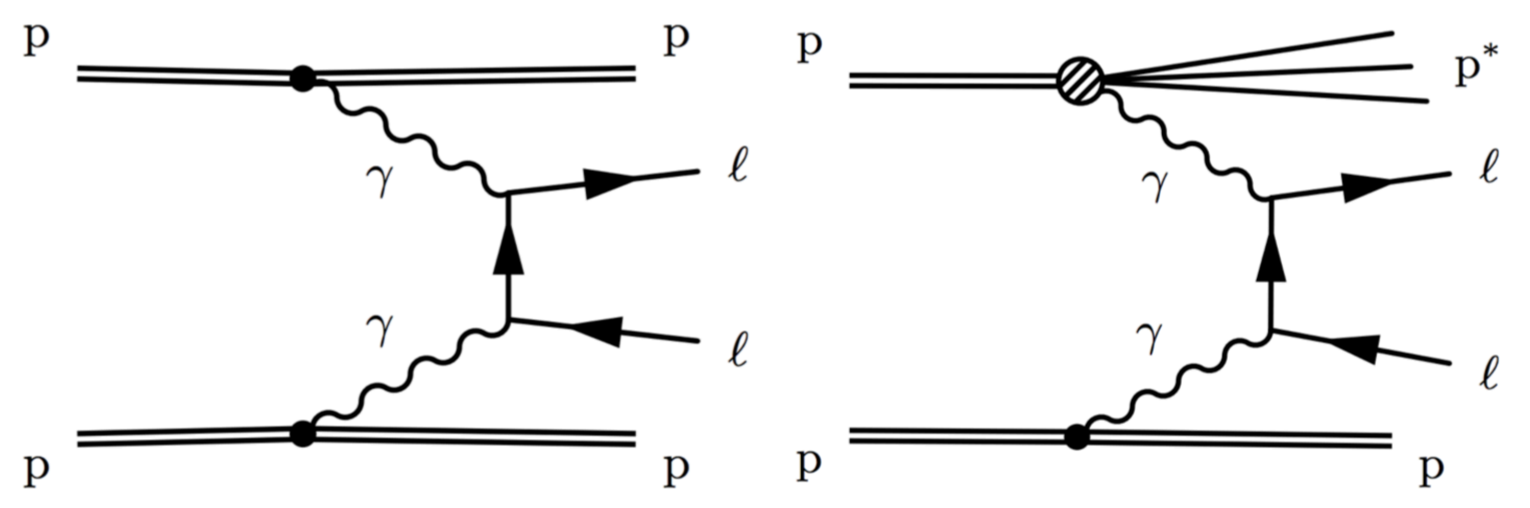
- Detectors are housed in **4 Roman Pots** (two in each side: ±205 m and ±217 m from ATLAS IP)
- **Near station: Silicon Tracker with 4 planes** (336 × 80 pixels per plane, 50 × 250 μm^2 pitch)
- **Far station: Silicon Tracker + Time-Of-Flight detector** (16 Cherenkov Quartz bars)
- **Full AFP** installation successful in **April 2017 ->** Participation in most LHC fills in 2017



ATLAS-TDR-024

Exclusive dileptons with AFP proton tag

- Goal: observe (γγ→l+l-) + **p** and measure cross-section
  - Exclusive and S-diss are treated as signal
- Dataset: 14.6 fb^{-1} of 13 TeV pp data

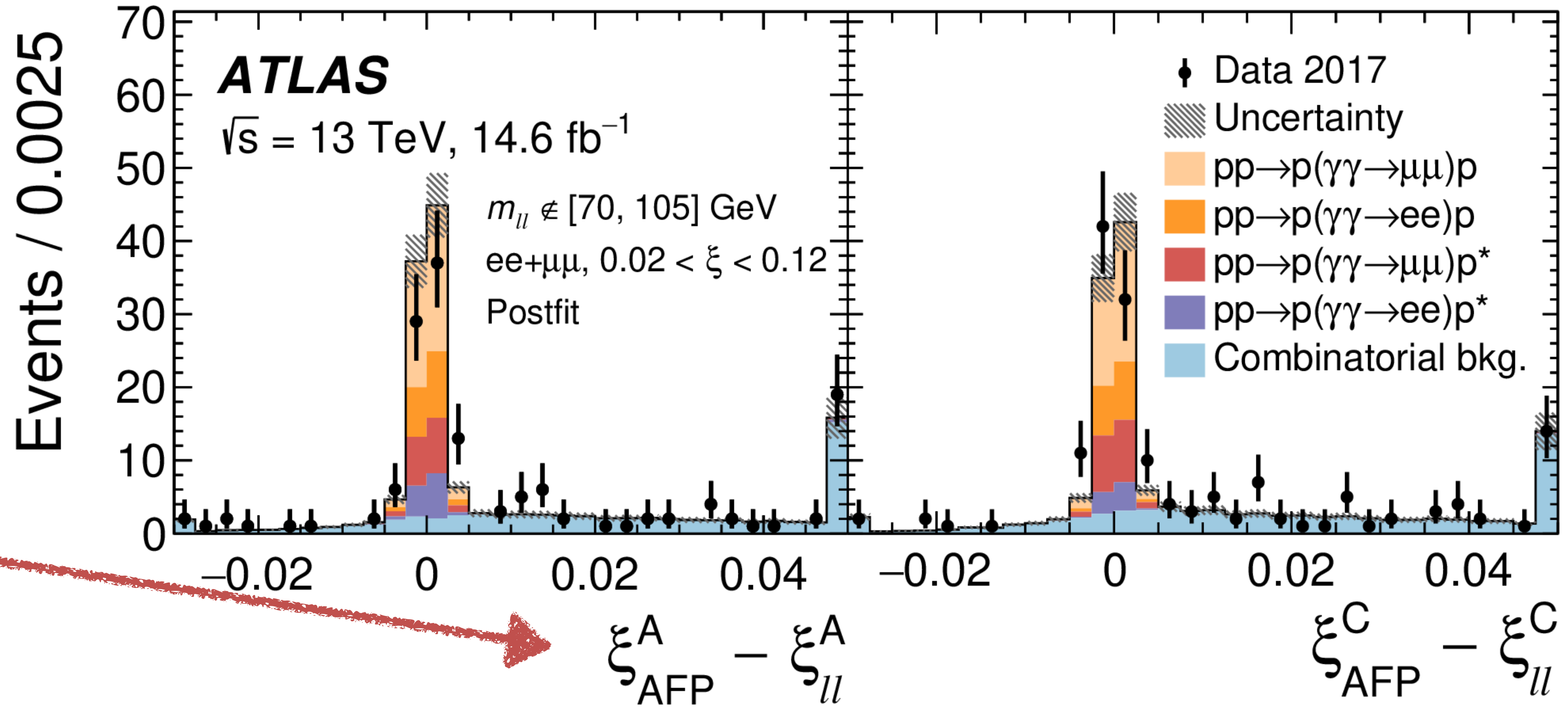


Exclusive

Single-dissociative (S-diss)

- Pioneering performance work is performed to understand new AFP detector
  - Proton reconstruction: proton transport function based on MAD-X simulation
  - Reconstruction efficiencies: T&P method between Near and Far stations
  - Detector alignment: BLMs + in-situ corrections based on selected dimuon events

PRL 125 (2020) 261801

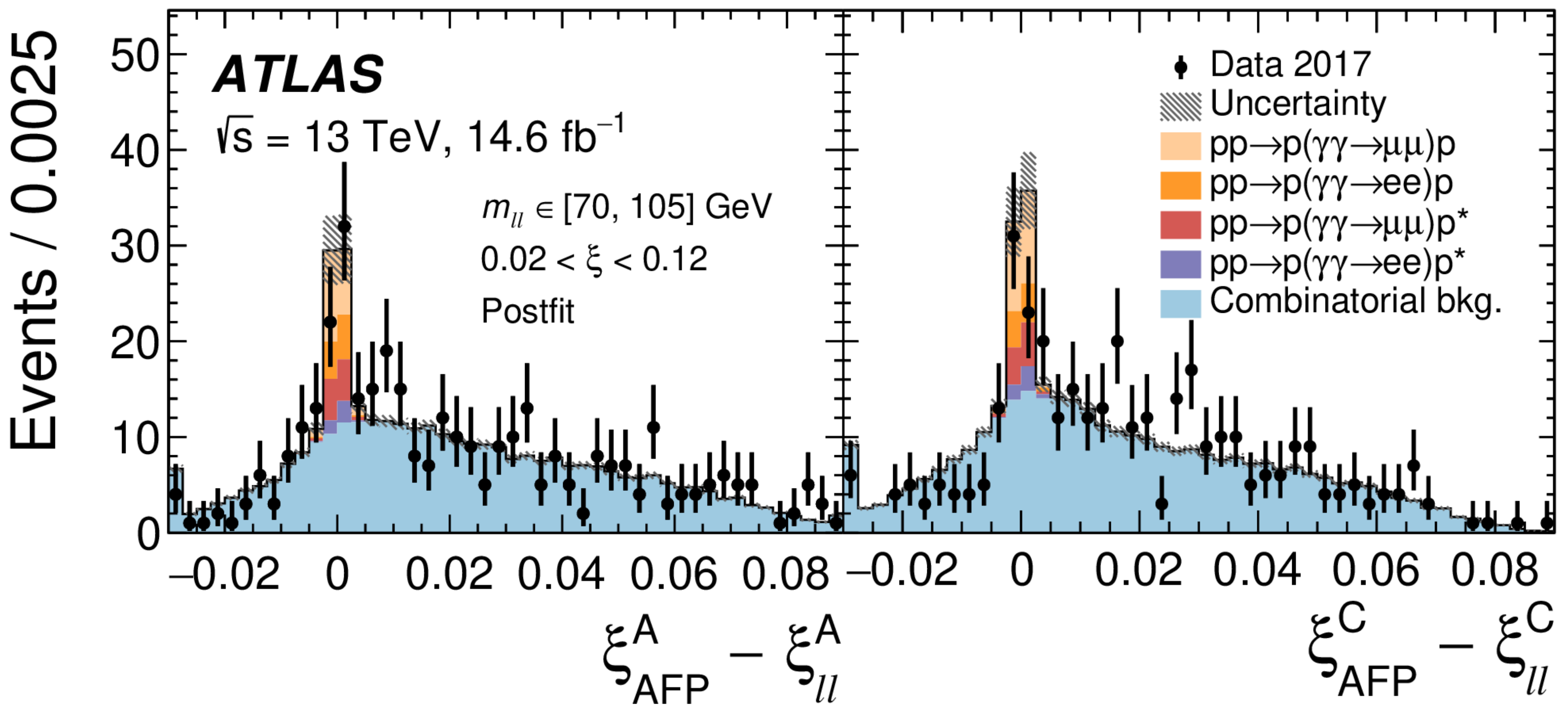


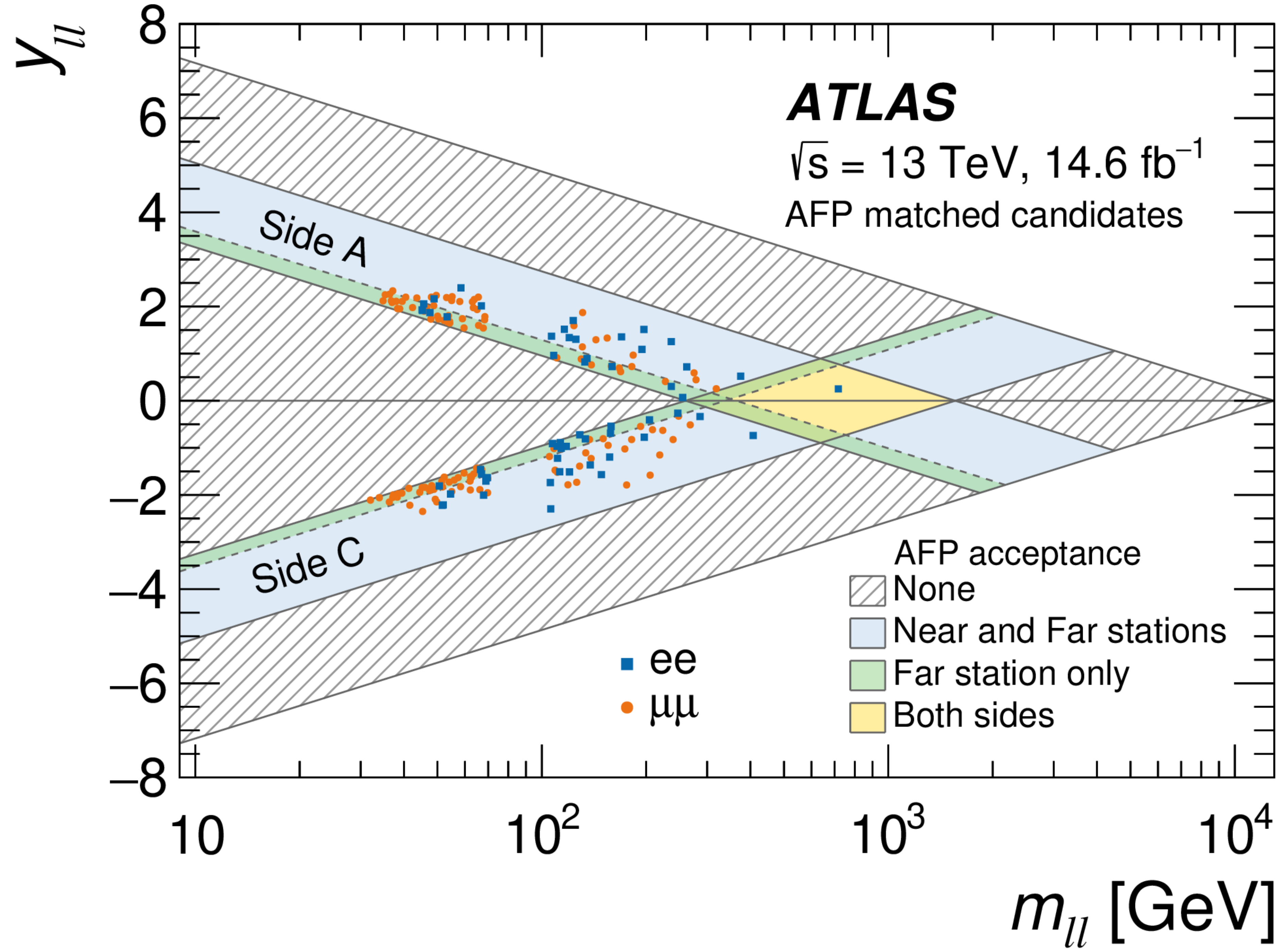
$$\xi^{\pm}_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{\ell\ell}}$$
$$\xi_{AFP} = 1 - E_p/E_{beam}$$

key observables!

Exclusive dileptons with AFP proton tag

- Background
  - Dominated by Drell-Yan (DY) +pileup proton **combinatorics**
  - Fully data-driven method is used (event mixing + sideband fit in $|\xi_{AFP}-\xi_{ll}|>0.005$)
  - Validated in $70< m_{ll} <105$ GeV region
- Signal events required to pass $\boldsymbol{|\xi_{AFP}-\xi_{ll}|<0.005}$
  - Kinematic matching
  - Cleans events from inclusive background





PRL 125 (2020) 261801

PRL 125 (2020) 261801

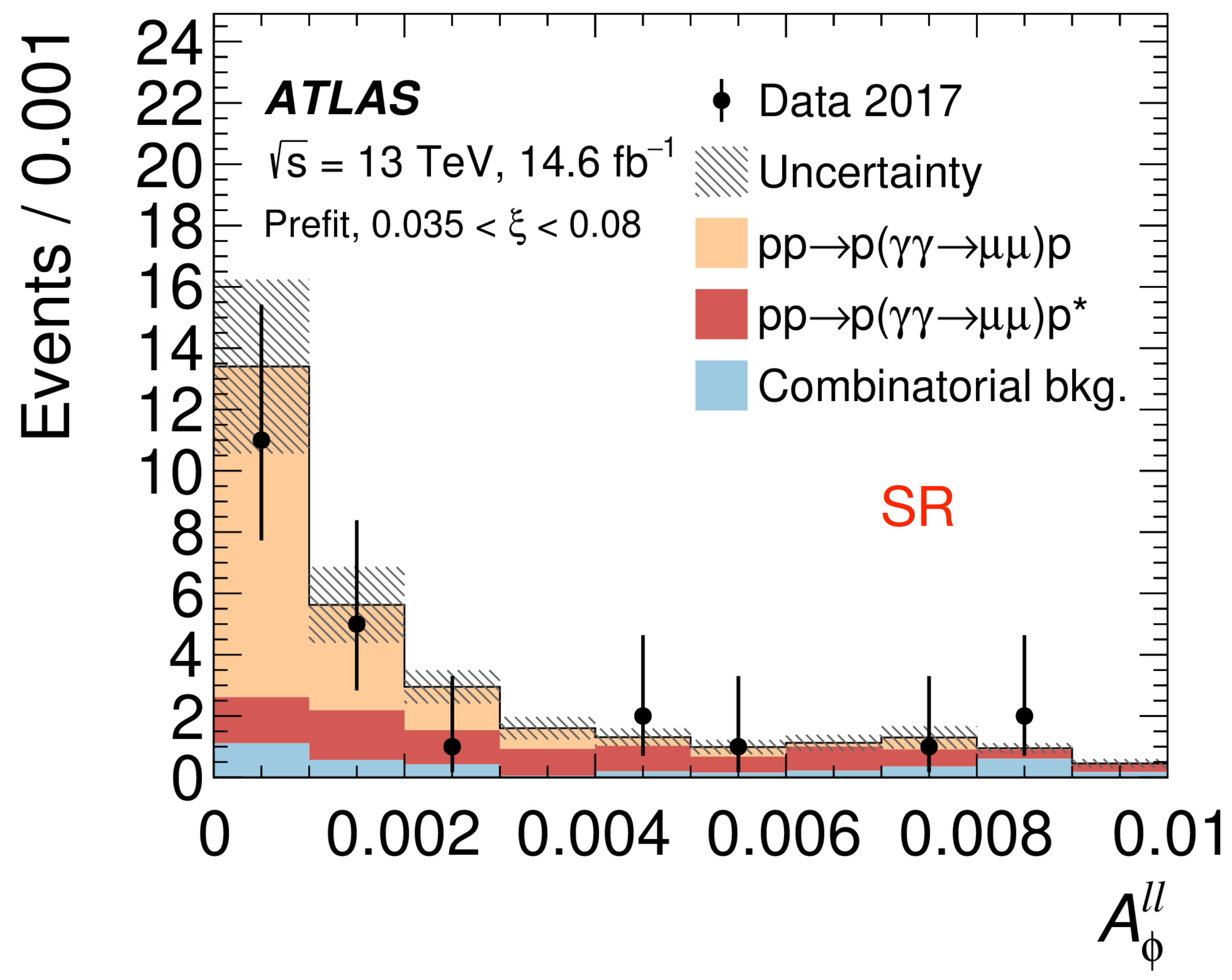
Exclusive dileptons with AFP proton tag

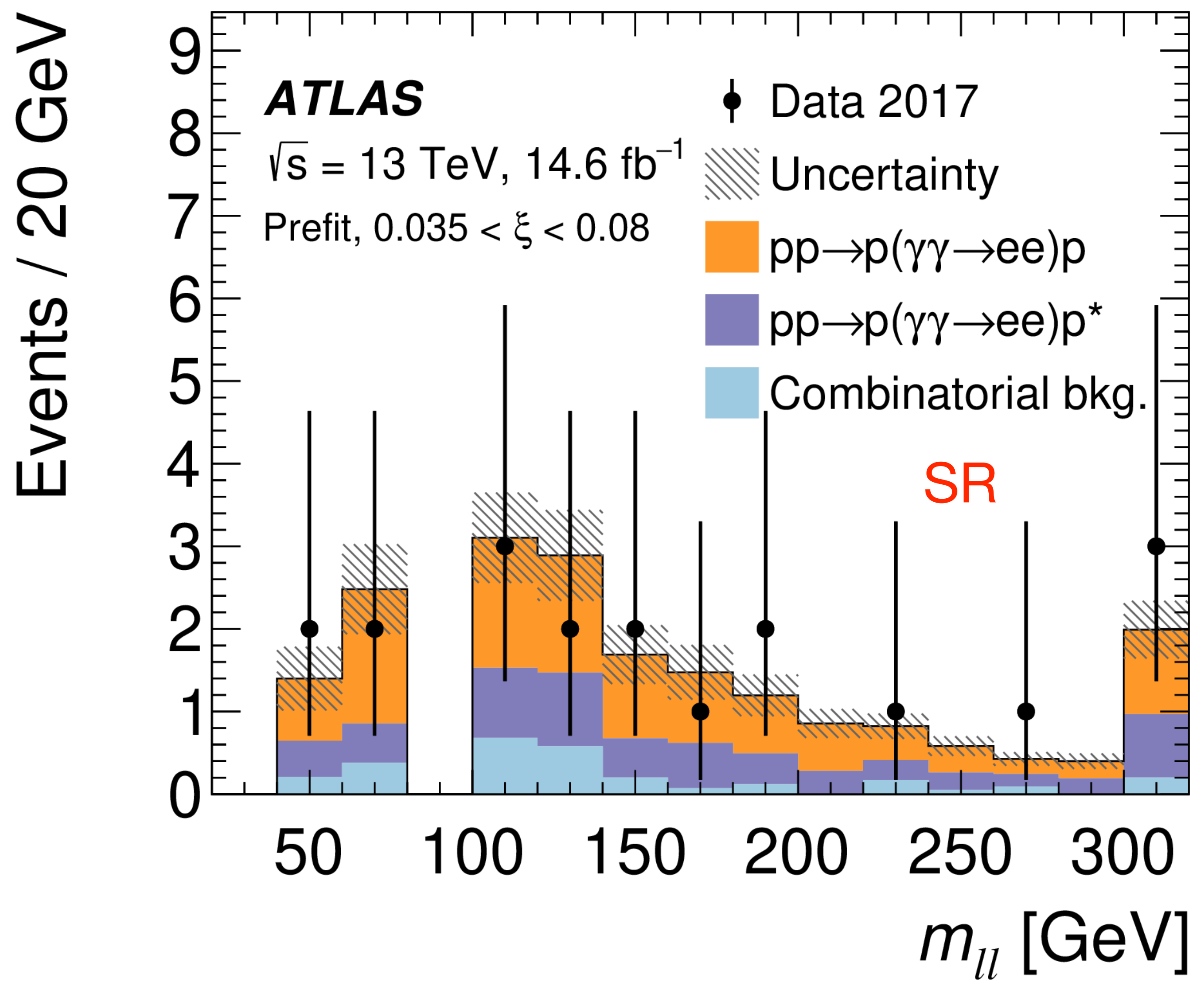
- Fiducial cross-sections measured in the region ξ ∈ [0.035,0.08]
  - Event kinematics in SR in agreement with expectations

- Results are compared to several theory predictions

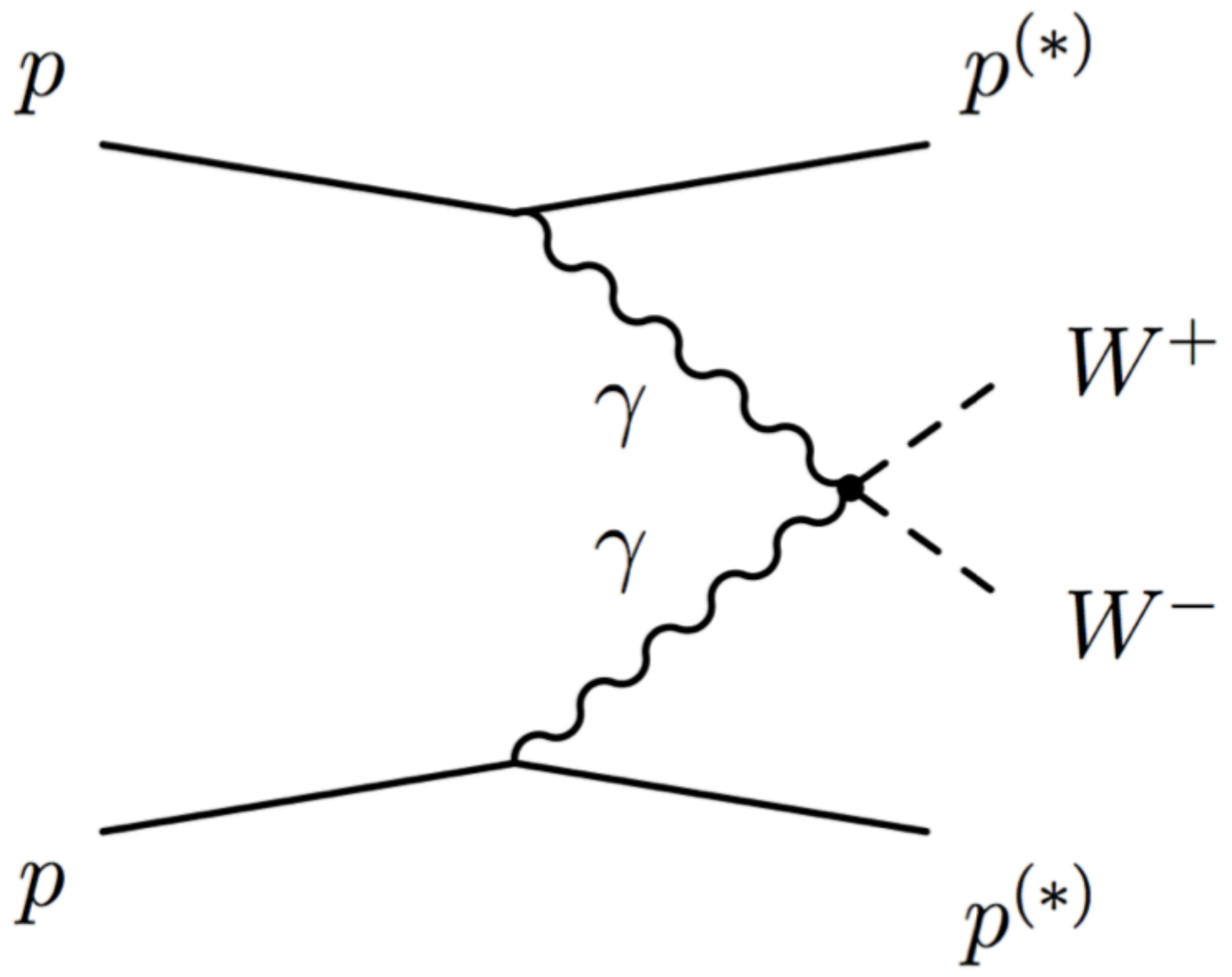
	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
HERWIG+LPAIR	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [31,30]		
HERWIG+LPAIR	10.9 ± 0.8	9.2 ± 0.7
SUPERCHIC 4 [Harland-Lang et al. EPJC 80 (2020) 10, 925]		
Exclusive + single-dissociative	12.2 ± 0.9	10.4 ± 0.7

slightly different phase-space between ee and μμ



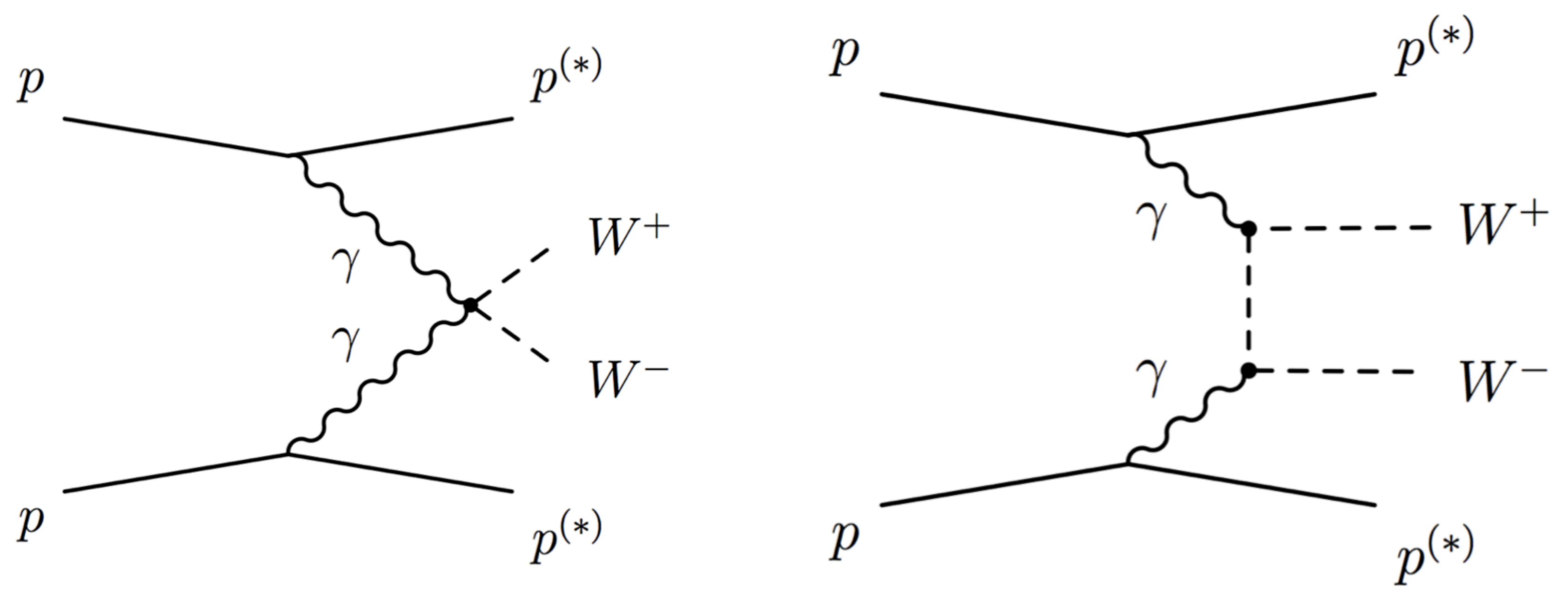


(IV) $\gamma\gamma \to WW$ scattering in pp

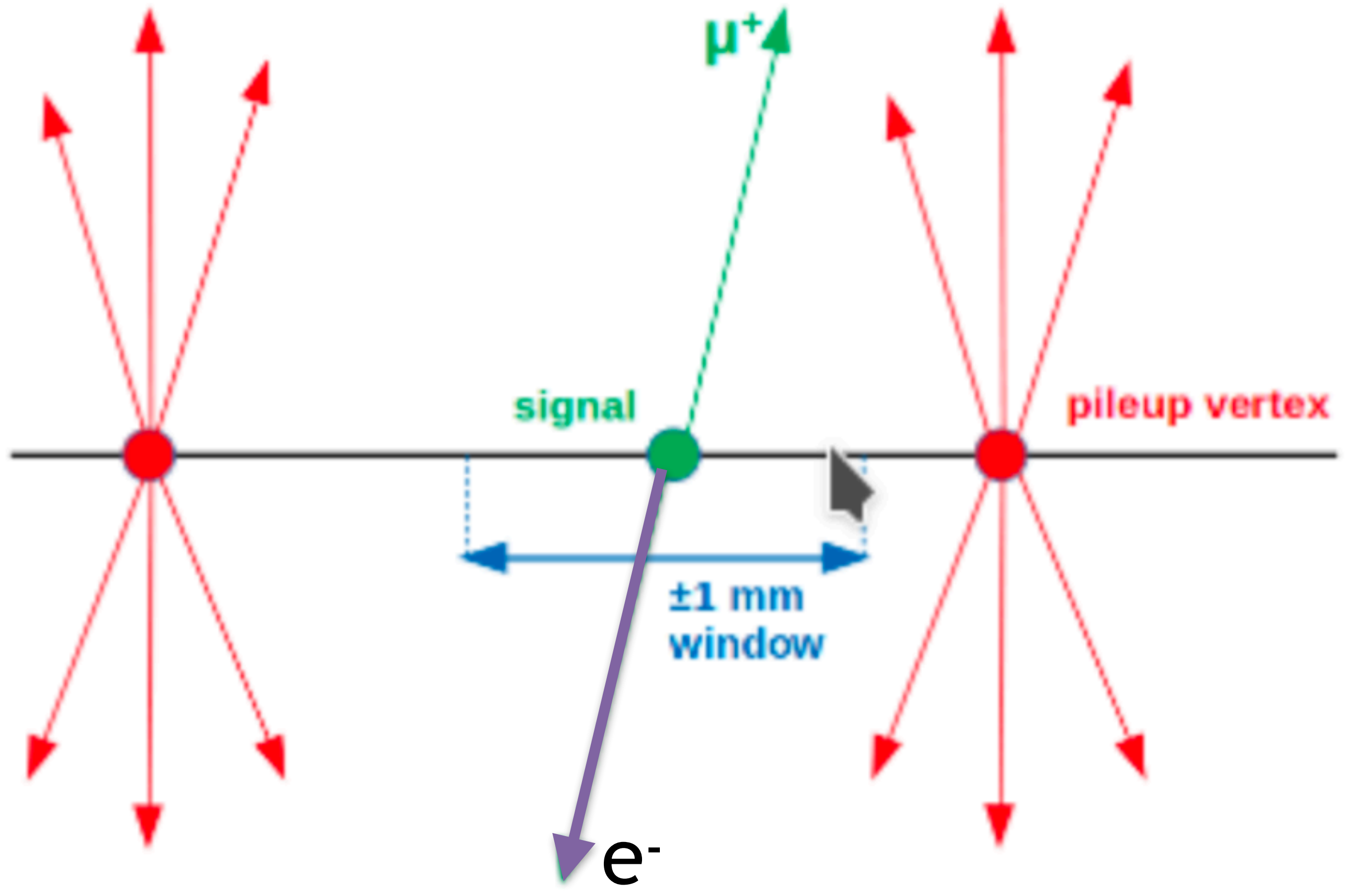


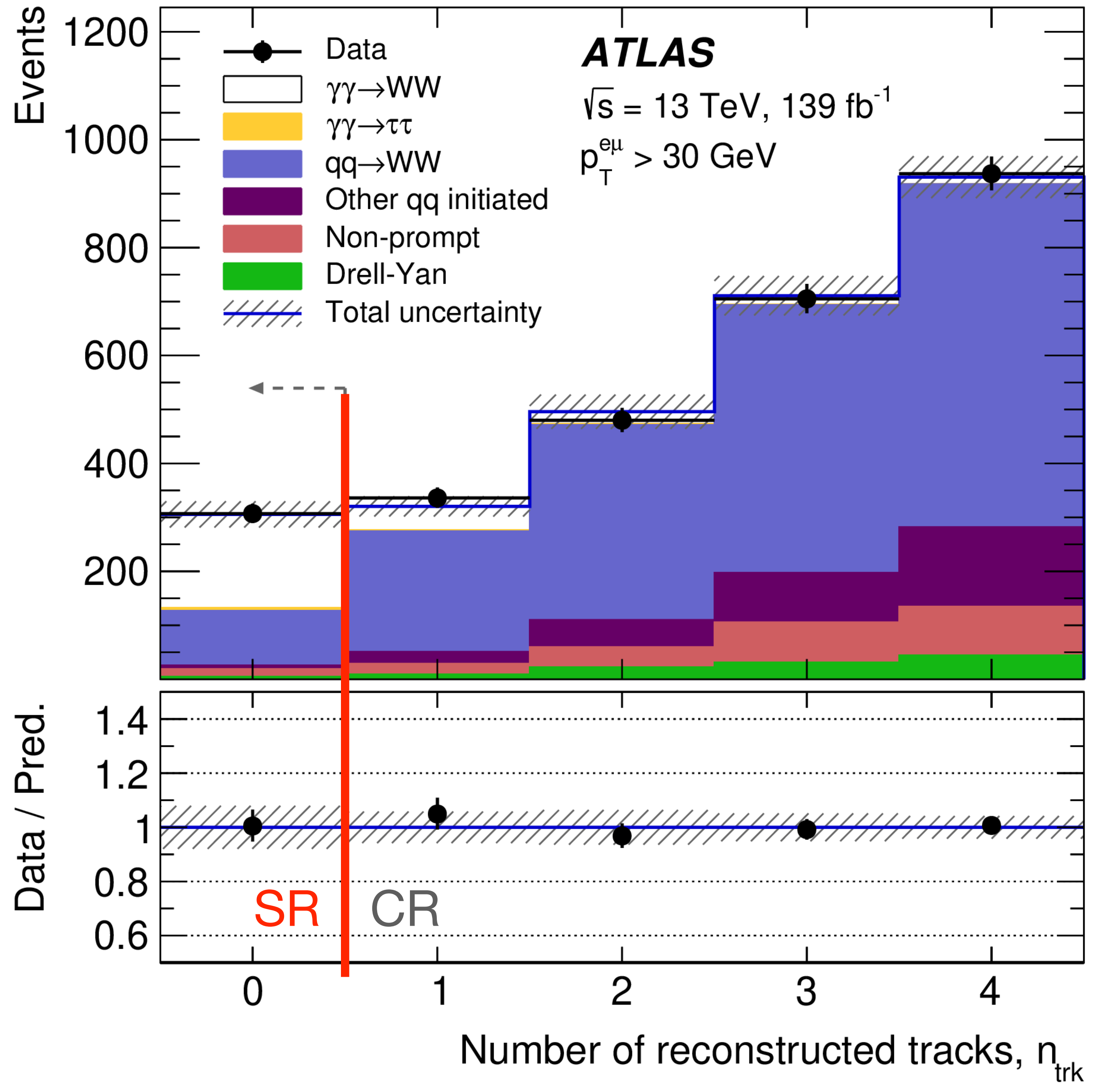
γγ→WW scattering in pp

PLB 816 (2021) 136190



- Rare electroweak process that probes SM **γγWW** vertex
- **New measurement** exploits full Run-2 pp dataset
  - Follow-up of Run-1 "evidence" measurements:
    ATLAS: PRD 94 (2016) 032011, CMS: JHEP 1608 (2016) 119
  - Tag **$e^{\pm}\mu^{\mp}$ pairs** with $p_T^{e\mu}$ > 30 GeV ($p_T^{e\mu}$ as a MET proxy)
  - Key signature: No tracks near dilepton vertex (note no AFP tag is used)
- Main background: QCD-induced WW
- Main challenge:
  Physics modelling of events with small particle activity (UE, pileup, …)

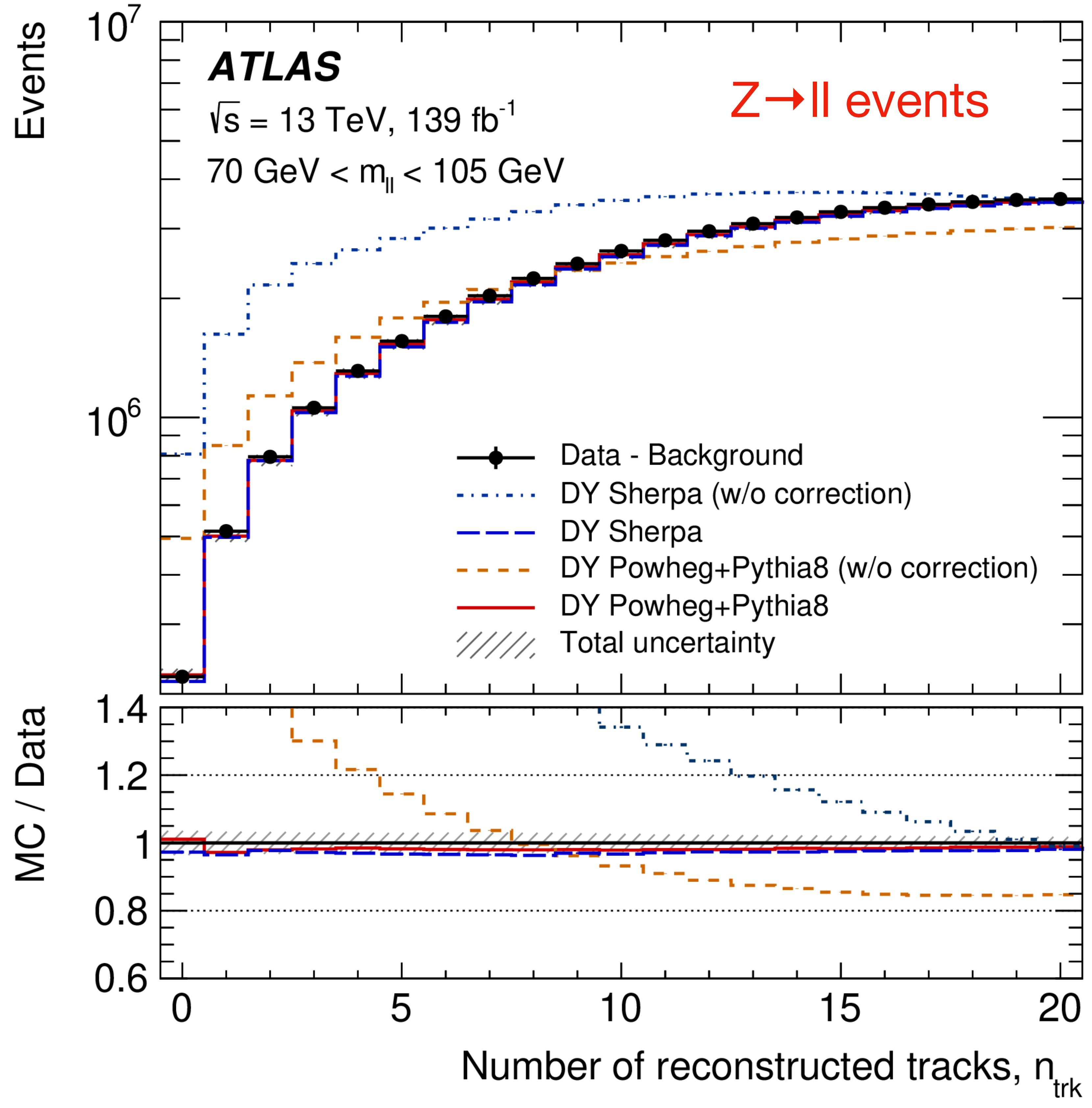


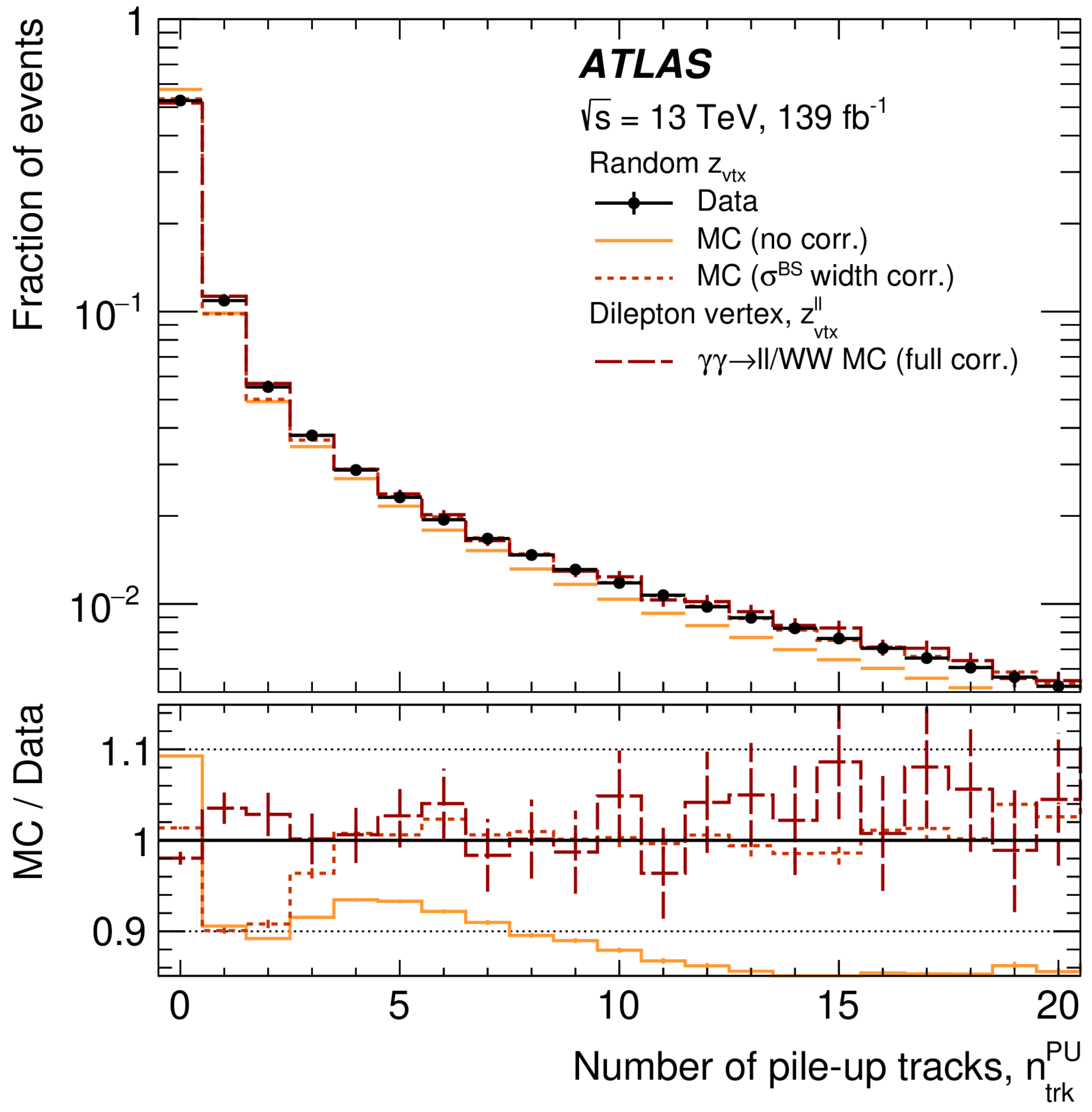


γγ→WW scattering in pp

PLB 816 (2021) 136190

- Charged-particle multiplicity (N_{ch}) modelling corrections
  - Underlying event correction: reweight inclusive WW and DY ττ backgrounds such that N_{ch} spectrum matches data (weights derived in Z-peak region)
  - Pileup correction: correct for PU tracks randomly associated with the interaction vertex (data-driven technique is employed)

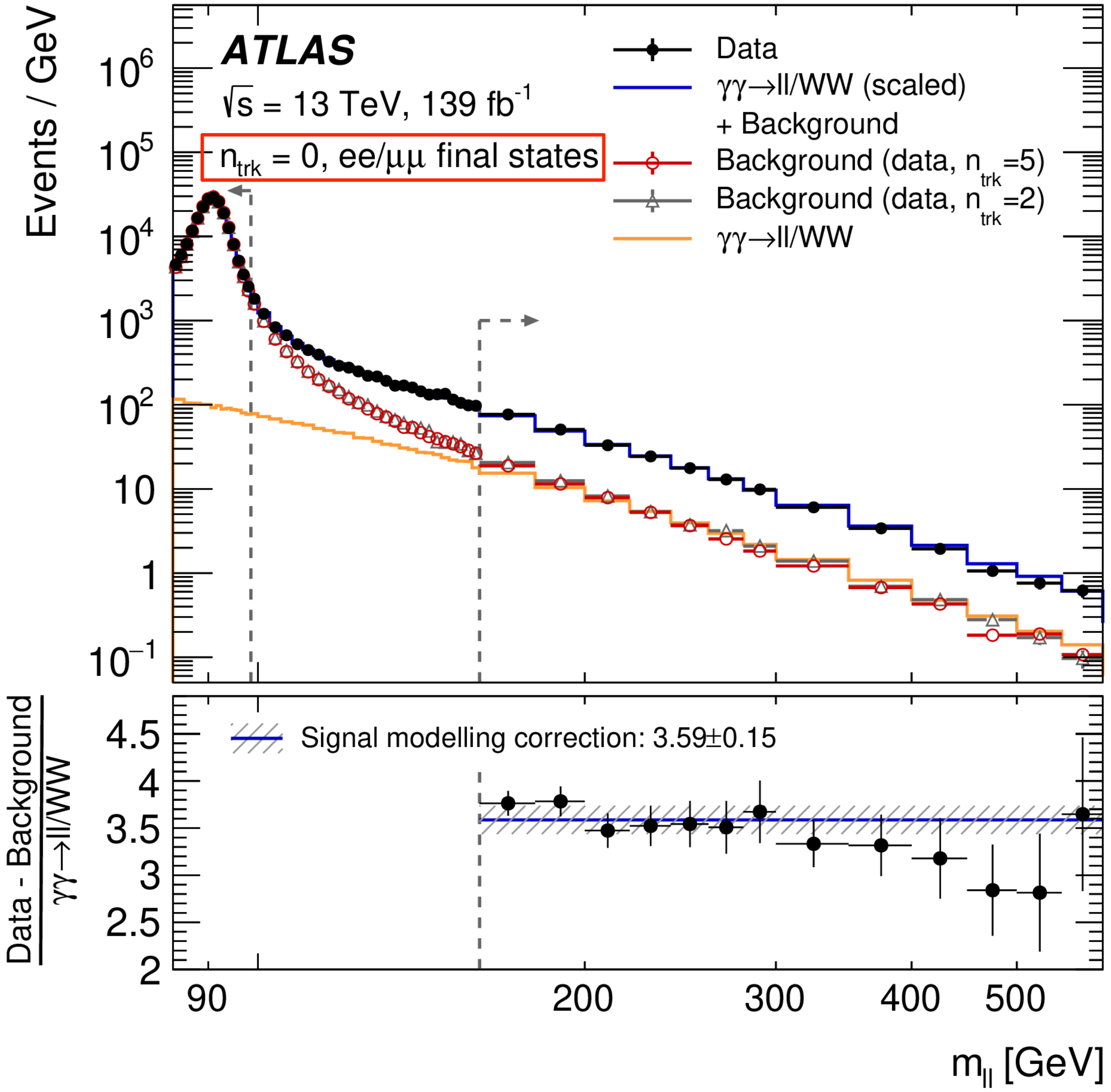




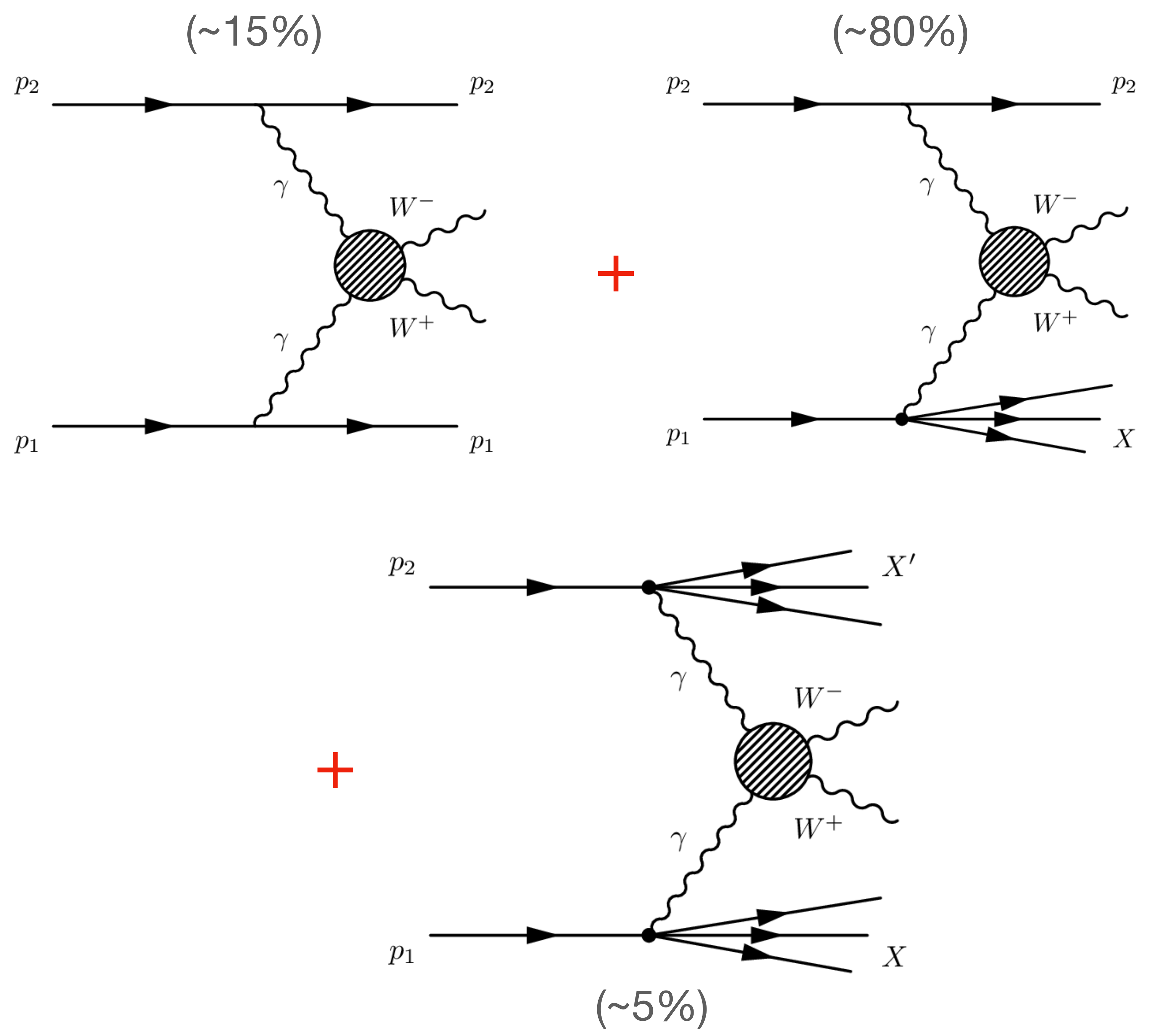
γγ→WW scattering in pp

PLB 816 (2021) 136190

- Dedicated signal corrections
  - Exclusive efficiency (N_{trk} = 0) in MC signal corrected using data-driven measurement
  - Baseline signal MC includes only fully elastic contribution
    → N_{trk} = 0 events corrected with **dissociative SF (3.59±0.15)** using γγ→l+l- events for $m_{ll} > 2m_W$



Signal =



γγ→WW scattering in pp

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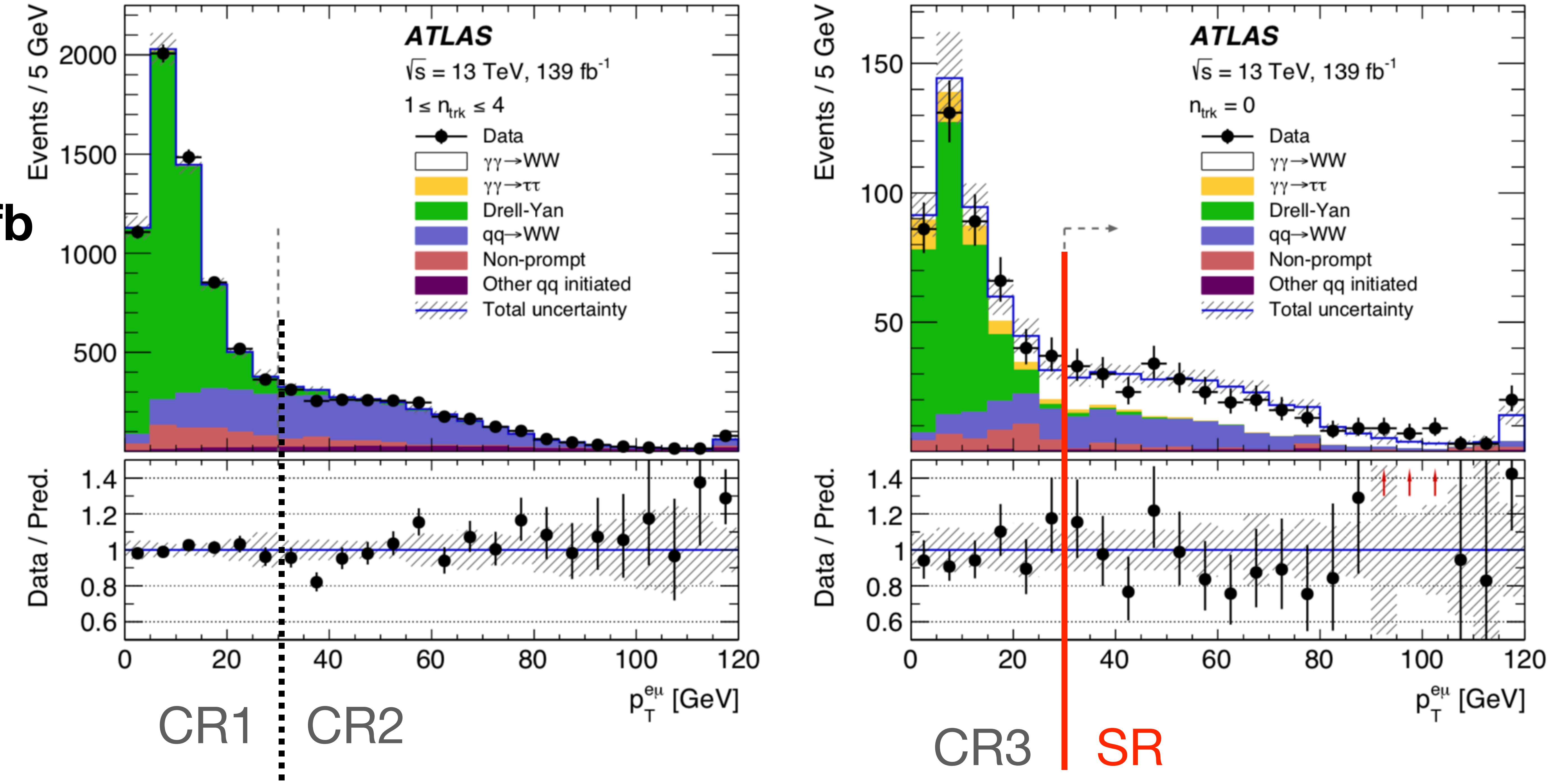
- Simultaneous fit performed to yields in **SR** and **3 CRs**
  - CRs used to constrain inclusive WW and DY ττ

- 307 events observed in SR (132 background events expected)
  - **γγ→WW observed with a significance of 8.4σ** (6.7σ expected)

- Measured fiducial cross-section:
  3.13 ±0.31 (stat.) ±0.28 (syst.) fb

- Theory predictions:
  - Herwig7 (elastic) scaled by 3.59 = **2.34 ±0.27 fb**
  - (MG5+Pythia8 based) lie in the range of **2.8** and **3.5 fb**
    - Depending on the choice of soft survival model

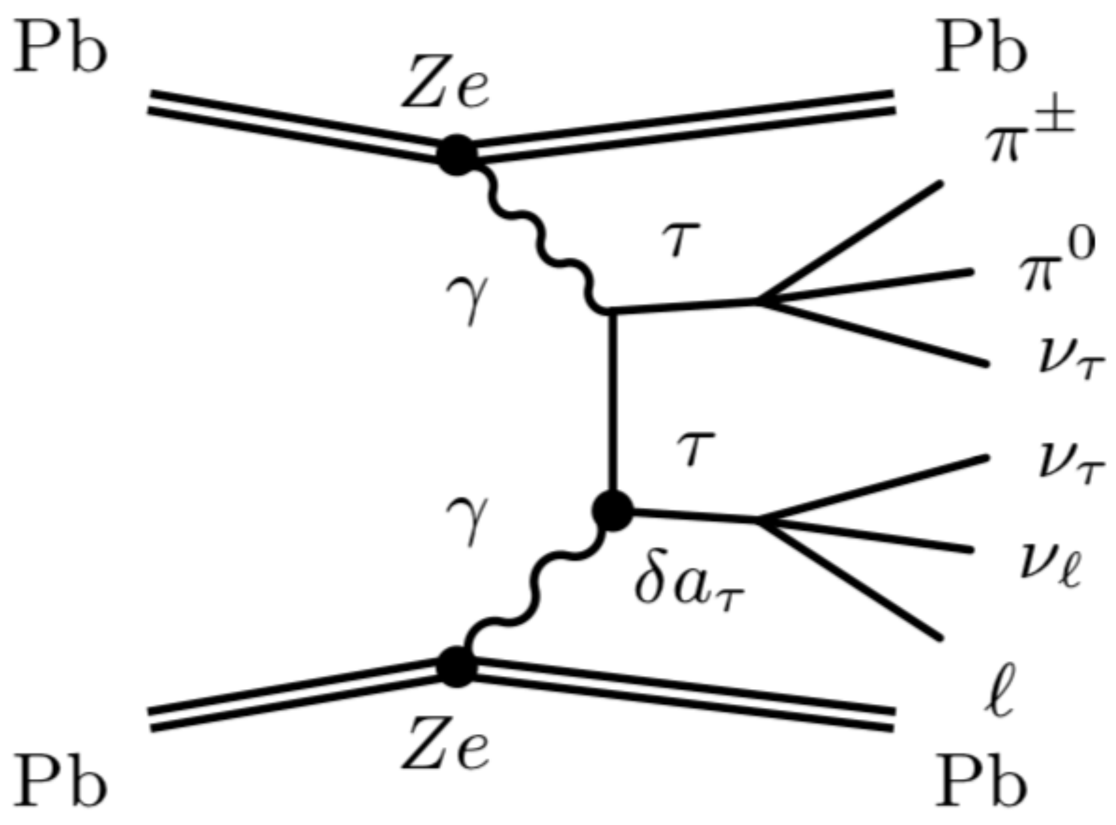


−14 −12 −10 −8 −6 −4 −2 0 2 4
z [mm]

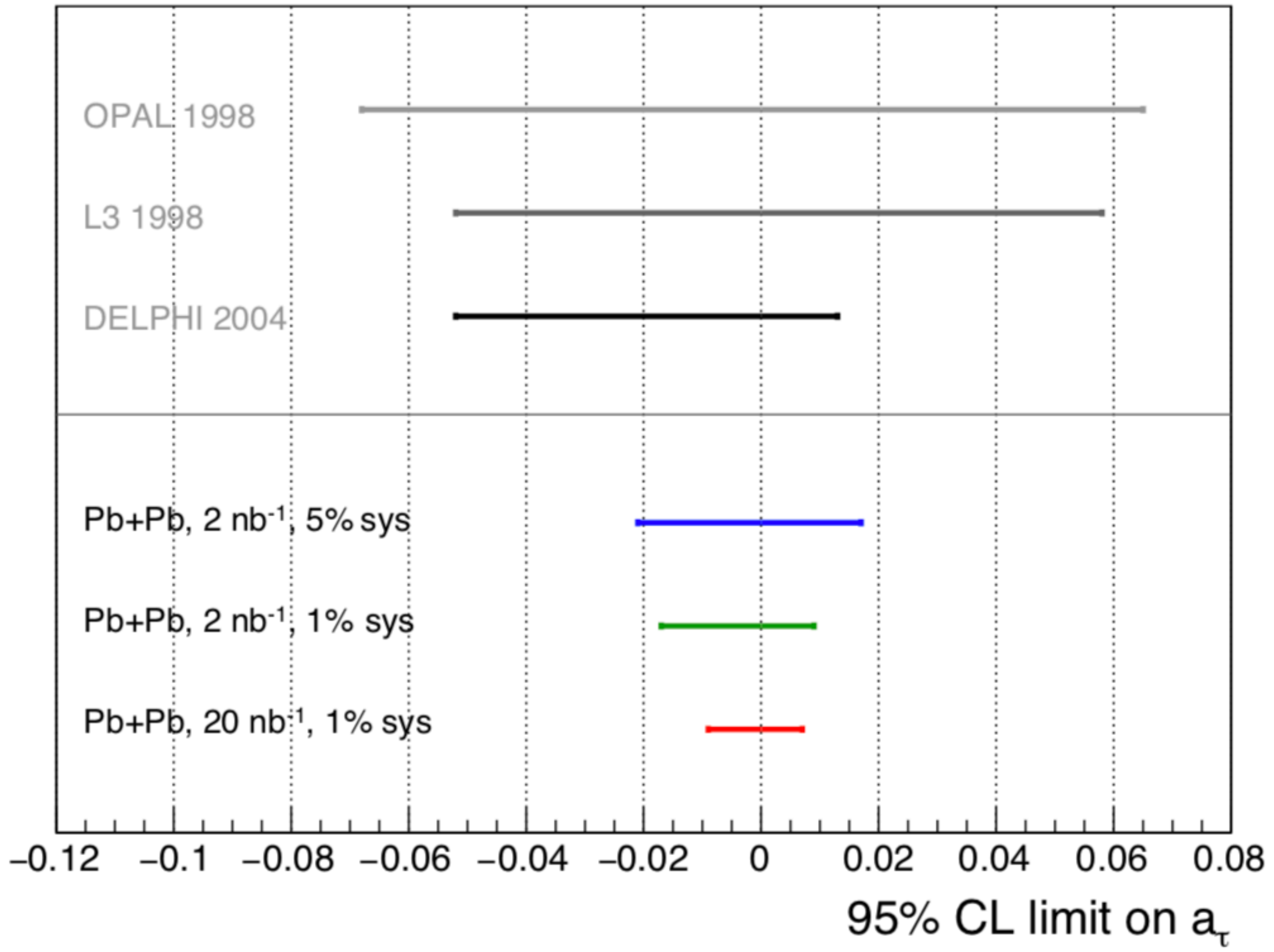
(V) Prospects for new measurements and some open questions

Prospects for new measurements (a biased example)

- Tau anomalous magnetic moment (tau g-2)
- Poorly constrained experimentally so far
  - Can be sensitive to BSM effects
- Large rate of $\gamma\gamma \to \tau^+\tau^-$ events in PbPb UPC
  - lepton + X channels to allow easy triggering and reconstruction
  - Ratio to ee/mumu process to cancel systematics
- Prospect studies: can improve LEP a_τ precision by **~x2** with existing ATLAS data



$a_\tau = (g_\tau - 2)/2$

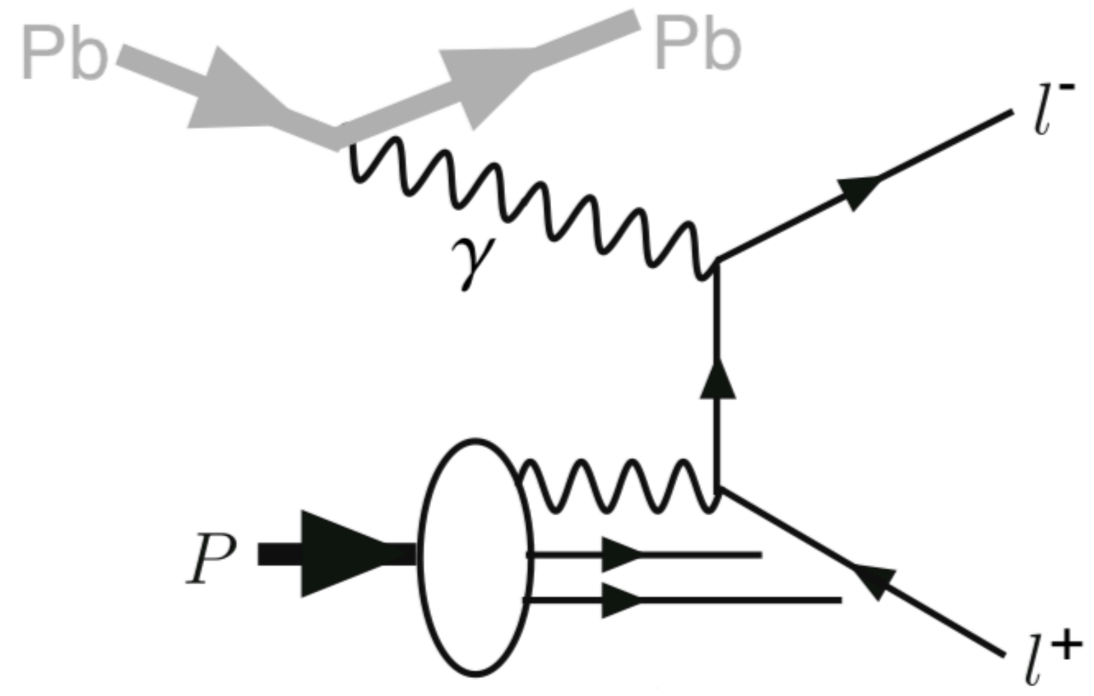


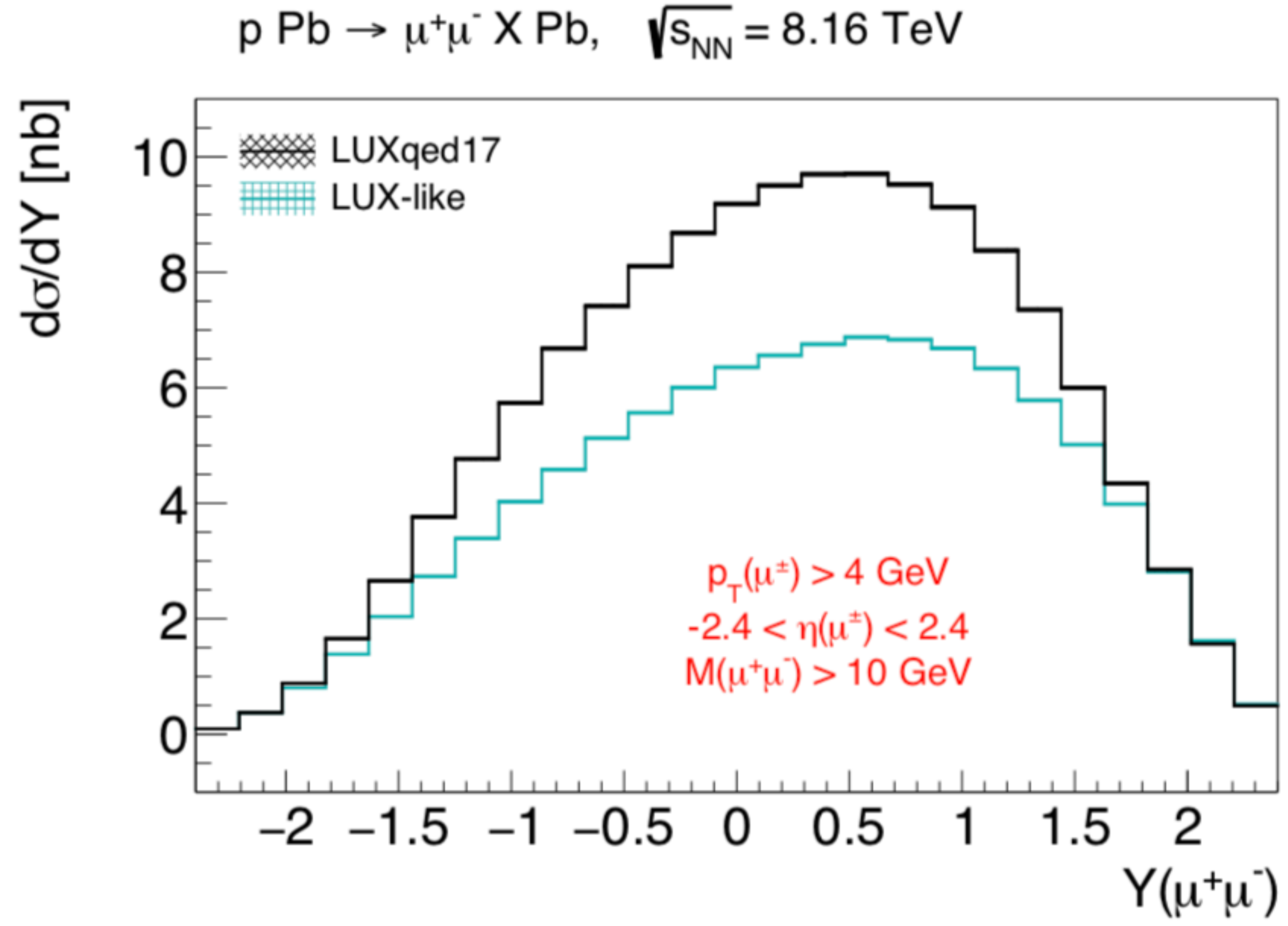
MD, Klusek-Gawenda, Schott, Szczurek
PLB 809 (2020) 135682

Beresford, Liu **PRD 102 (2020) 113008**

Prospects for new measurements (a biased example)

- $\gamma\gamma \to l+l-$ in pPb can be used to probe photon-PDF
  - Necessary ingredient in precision EW physics
- Clean background-free environment
  - Relies on ZDC veto to suppress inclusive production
- Important to probe transverse momentum distribution of photons in the proton
  - Up to 30% difference between collinear LUXqed PDF and equivalent calculations with photon qT (see also Harland-Lang *JHEP* 03 (2020) 128)
- Expecting ~3000 inelastic events per lepton channel for existing 2016 pPb dataset @ 8.16 TeV
  - This data can be also used to validate/tune UE/PS for photon-induced proton dissociation





[MD, Glazov, Luszczak, Sadykov, [PRD 99 (2019) 114008](PRD 99 (2019) 114008)]

Some open questions

- Despite being "pure" EWK processes, there are some open questions regarding photon-photon fusion processes at the LHC:

- Agreement of Pb+Pb dimuon data with STARlight
    - Points to (mis)modeling of initial photon fluxes?
    - Individual impact parameter cuts in STARlight - unphysical?

$$\frac{\mathcal{L}_{\gamma\gamma}}{dWdy} = \mathcal{L}_{AA}\frac{W}{2}\int_{b_1>R_A} d^2b_1 \int_{b_2>R_A} d^2b_2 n(k_1,b_1)n(k_2,b_2)$$

- Strong-field QED effects in Pb+Pb? lepton-ion Coulomb corrections, …
    - Note $Z\alpha \sim 0.6$ for Pb ion…
    - Can be a large effect (-20% for lepton pairs - arXiv:2103.04605)

- FSR modeling in two-photon reactions: Pythia8 does general QED shower, but no guarantee to work when p_T(gamma) > p_T(l)
    - Need for dedicated calculations (NLO vs QED shower, matching, …)

- Modeling of photon-induced dissociation in pp:
    - Good progress in MC generators (use of structure functions, survival factors etc.), but a dedicated UE/PS modeling studies are likely needed

Summary

- Rich physics program of **two-photon interactions** at the LHC
    - At the ‘boundary’ of **electroweak**, **forward** and **heavy-ion** physics
    - Measurements utilise both **pp** and **Pb+Pb** dataset

- Diverse set of measurements performed with ATLAS, including:
    - **Precision** (differential) cross section measurements
    - Non-standard **BSM** searches
    - First proton-tagged photon collisions observed with new **AFP** detector
    - **Observation** of new SM processes ($\gamma\gamma \rightarrow WW$ scattering)

    - This is clearly way beyond “simple **QED** testing”
    - Excellent groundwork for future, more detailed studies → stay tuned!

Backup

LbyL scattering in PbPb

Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%

$\gamma\gamma \to WW$ measurement in pp

Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

Exclusive dileptons with AFP proton tag

Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	$< 1\%$
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon scale and resolution	3%
Muon trigger, isolation, reconstruction efficiencies	1%
Electron trigger, isolation, reconstruction efficiencies	1%
Electron scale and resolution	1%
Background modeling	2%
Luminosity	2%