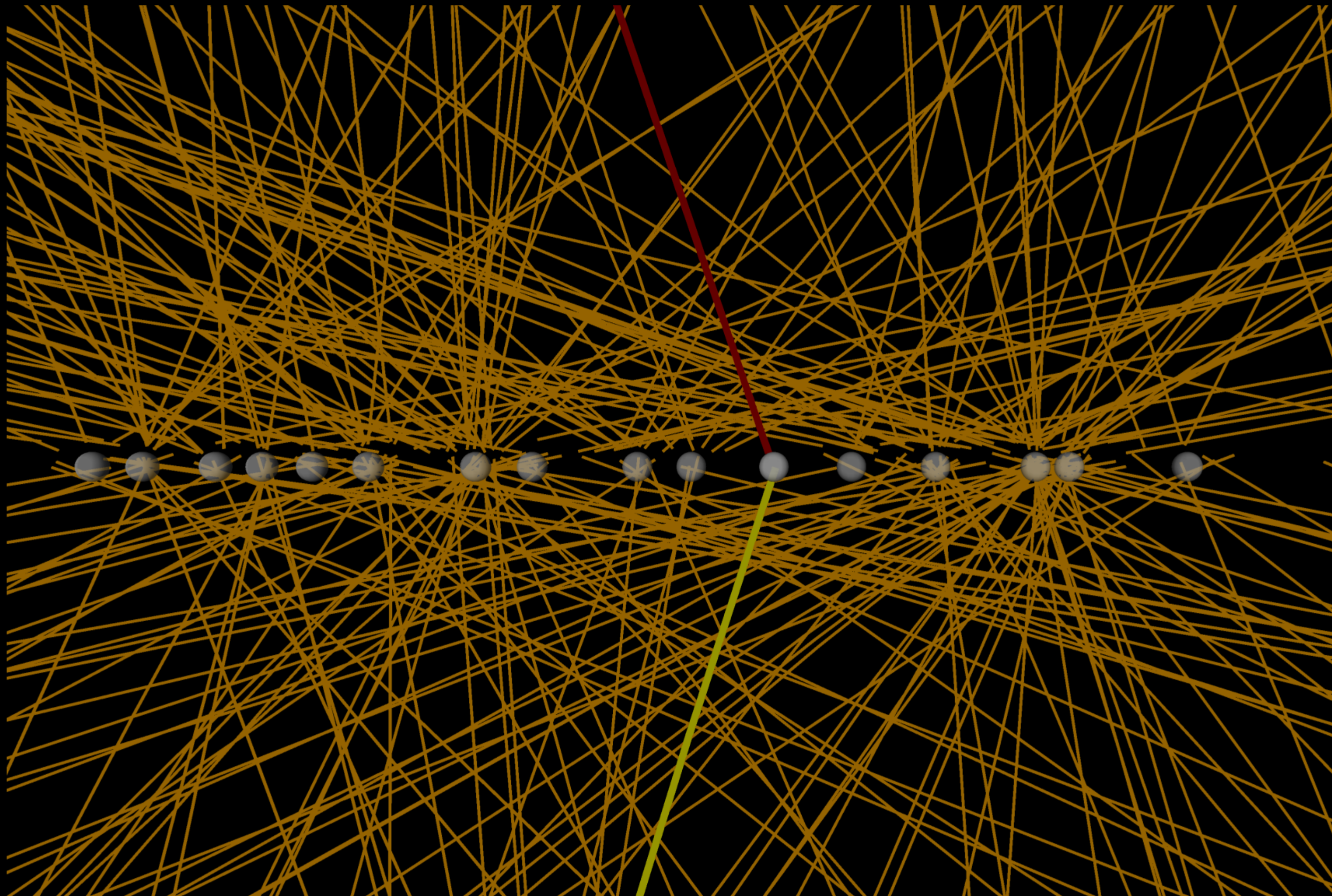
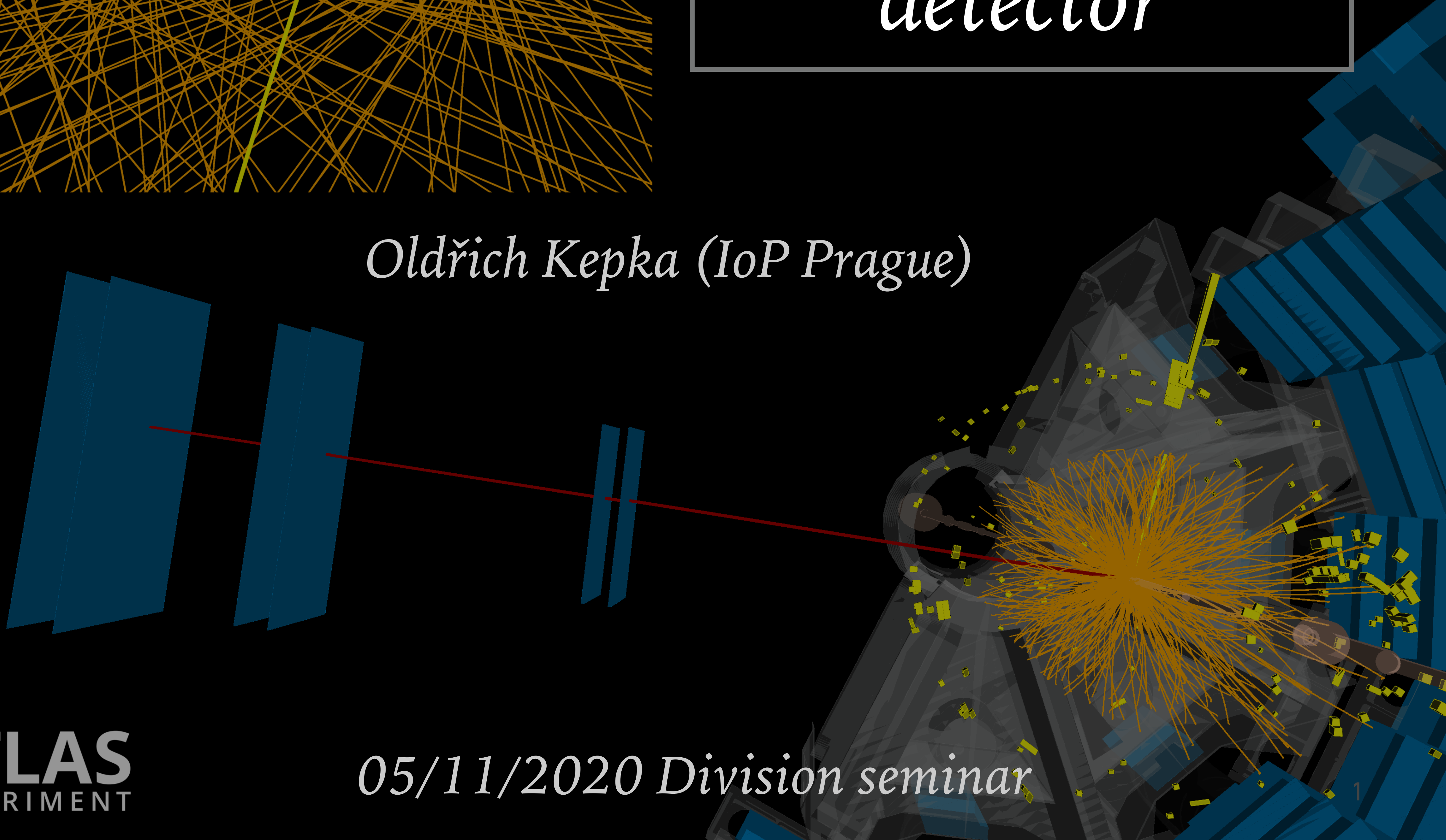


LHC as a photon-photon collider with the ATLAS detector

Oldřich Kepka (IoP Prague)



05/11/2020 Division seminar

Outline

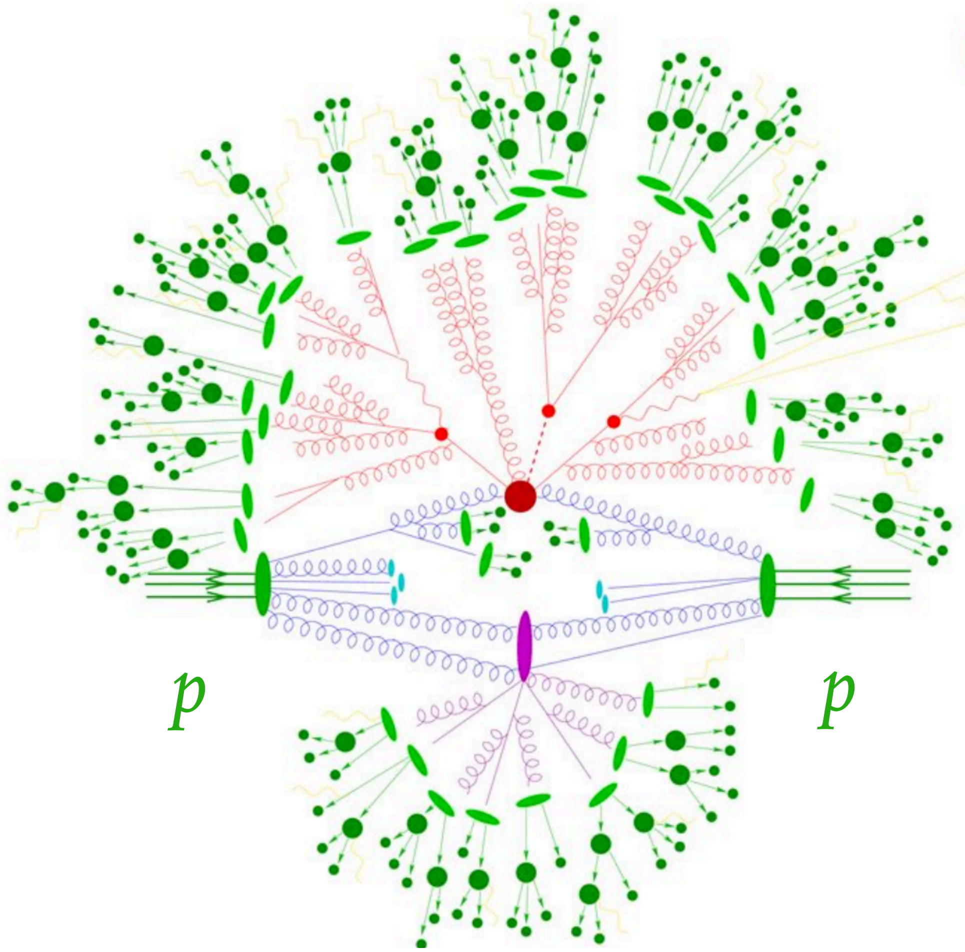
- New ATLAS measurements presented

- Photon-induced measurements in proton-proton at $\sqrt{s} = 13$ TeV
  - $\gamma\gamma \to W^+W^-$ [ATLAS-CONF-2020-038]:
    Observation of photon-induced diboson production, complete Run 2 dataset
  - $\gamma\gamma \to \ell^+\ell^-$ [ATLAS-CONF-2020-041]:
    Measurement of **forward proton scattering** in association with lepton pairs

- Photon-induced measurements in ultra-peripheral lead-lead $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - $\gamma\gamma \to \mu^+\mu^-$ [CERN-EP-2020-138]:
    Differential measurement of exclusive dimuon production with **forward neutron** information
  - $\gamma\gamma \to \gamma\gamma$ [arXiv:2008.05355]:
    Differential measurement of light-by-light scattering and **search for axion-like particles**, complete Run 2 dataset

- Small selection of new ideas

Typical proton-proton collision

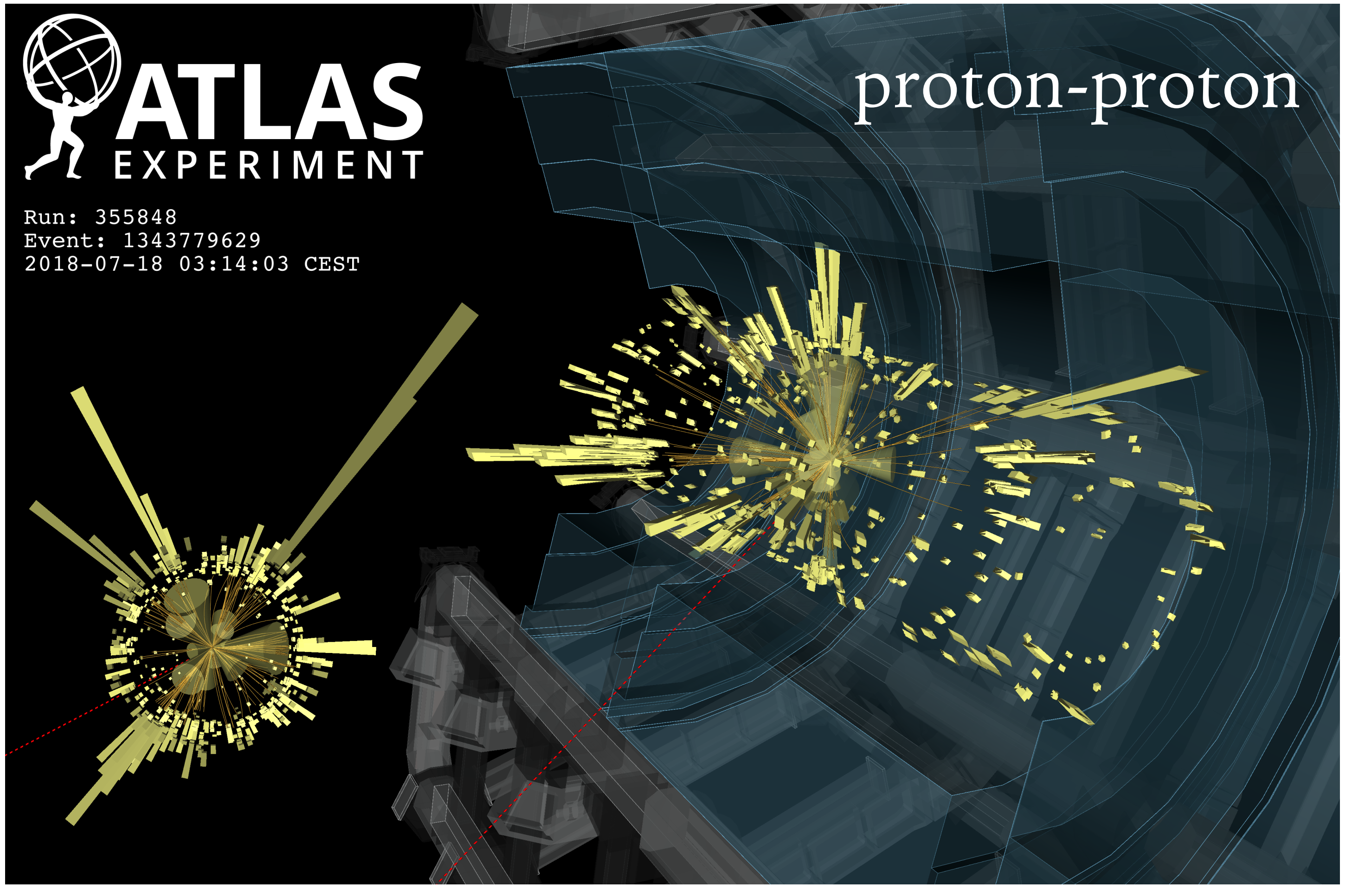


[Sherpa authors]

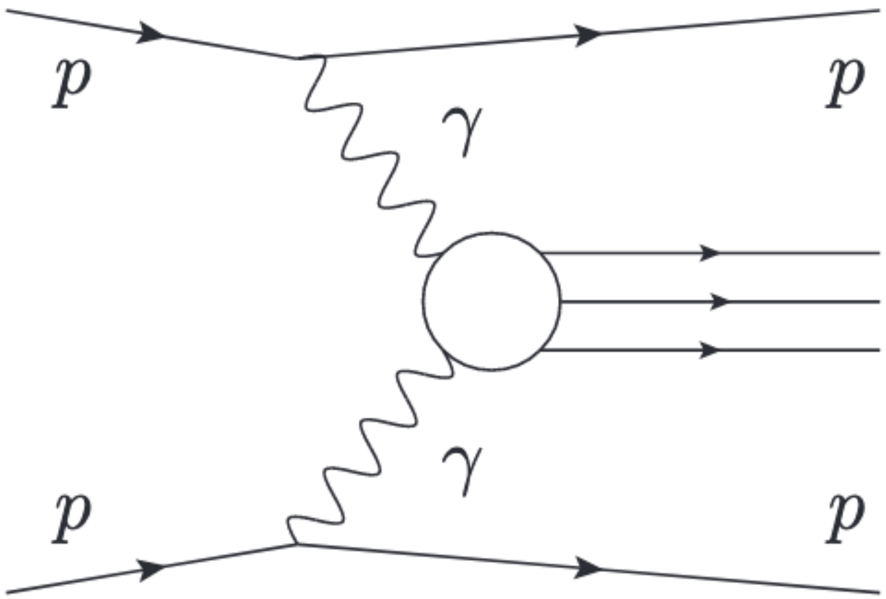
QCD induced interactions are very busy

- Hard scattering initiated by q/g
- Parton shower
- Multi-parton interactions & Underlying event
- Hadronization

Additional activity in PbPb reactions from spectator nucleon-nucleon interactions

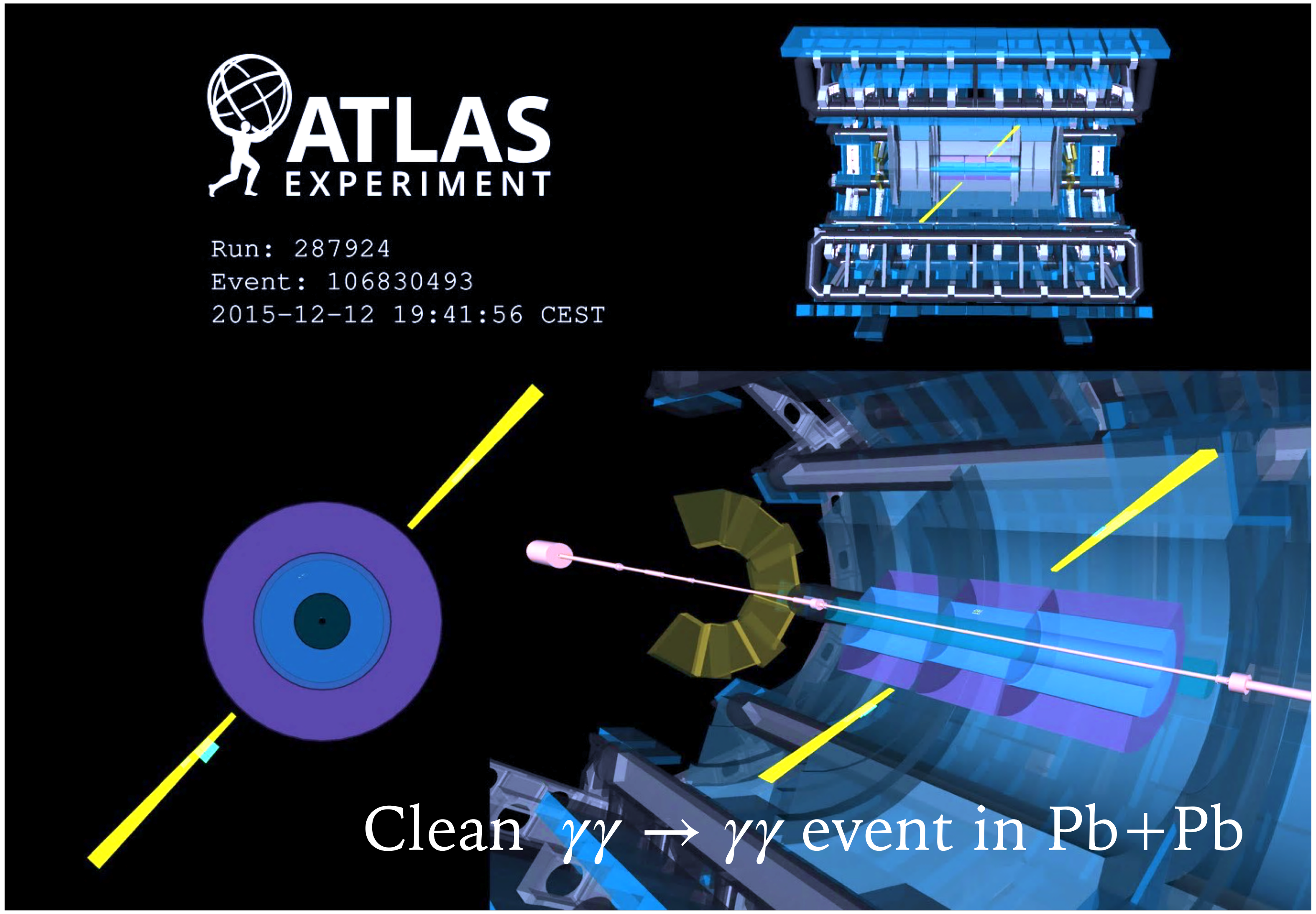


Coherent photon-induced reaction



- Protons (and Pb) beams are source of intense light
- Clean events when both protons emit **coherently** a photon
- Protons stay intact, no other particles produced
- No color flow between protons (small rescattering corrections later)

- Opportunity to measure EW interactions and search for New Physics



Coherent photon-induced reaction

- Photon flux derived from EM form factors of the p/nucleon
- Photons are quasi-real, related to the size R of the p/Pb→ small transverse momentum transfer to the produced system
  - Important experimentally

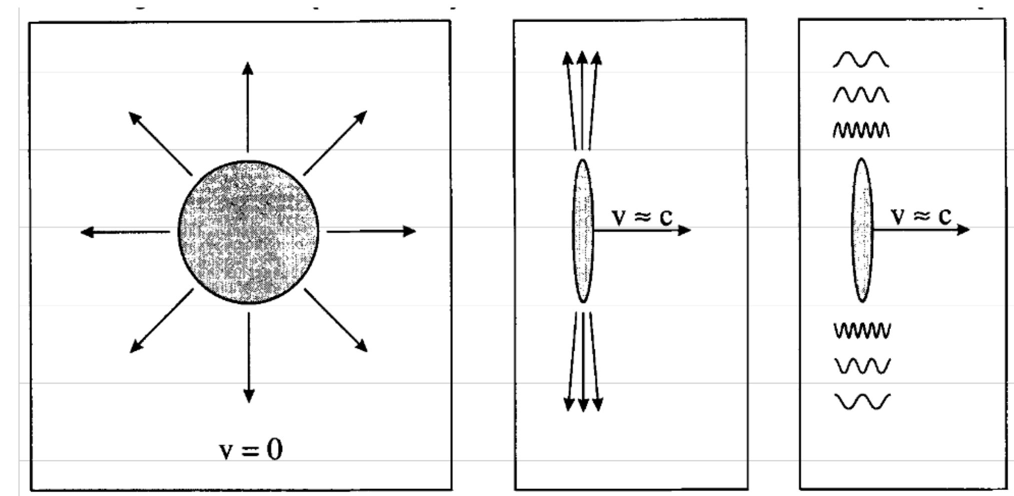
$\boldsymbol{k}_{\perp} \lesssim 1/R$ ~ 0.3 GeV (protons)
~ 0.06 GeV (Pb ions)

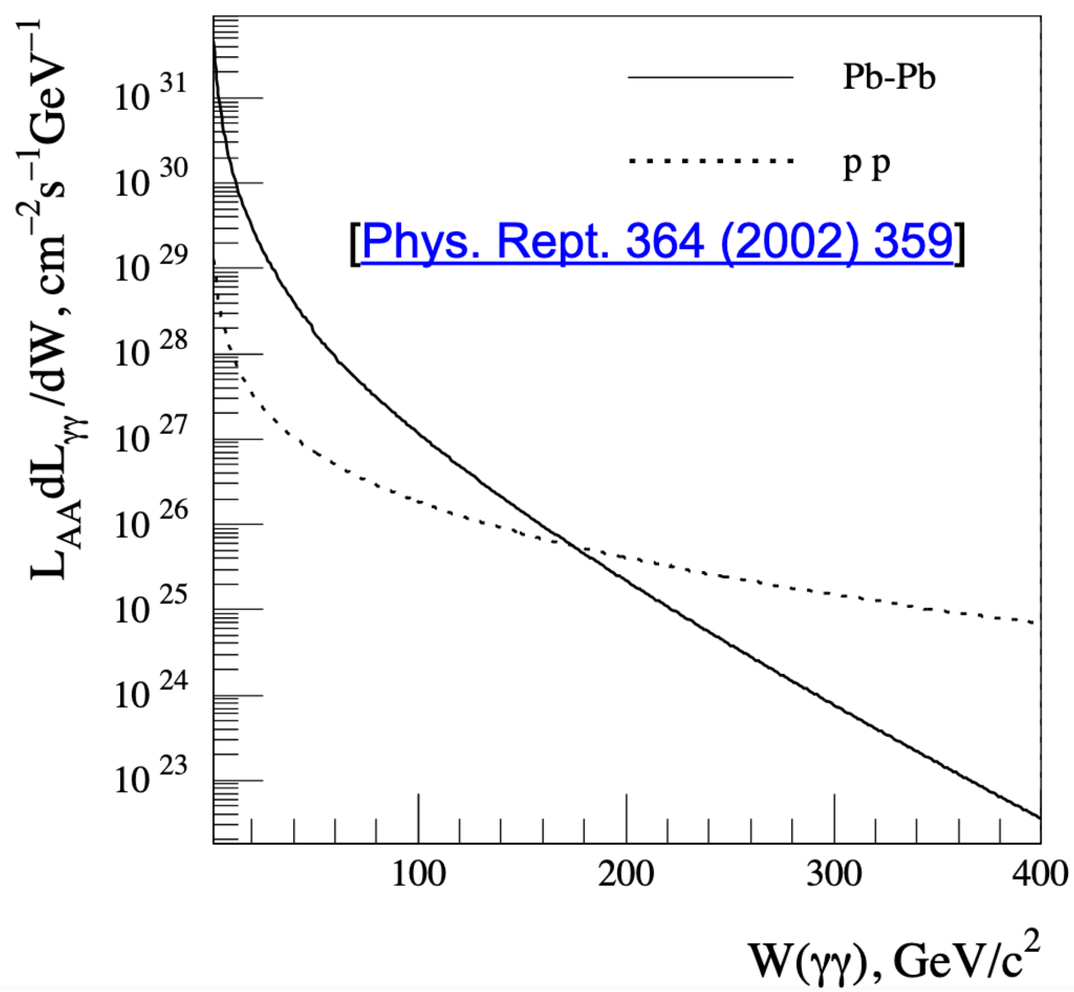
$\boldsymbol{E}_{\max}$ ~ γ/R ~ 2.5 TeV (protons)
~ 80 GeV (Pb ions)

$$\frac{d\sigma}{d\Omega} = \int \frac{d\sigma_{\gamma\gamma\to X}(W)}{d\Omega}\frac{dL_{\gamma\gamma}}{dW}dW$$

- Production enhanced by $Z^4 = 5\mathrm{x}10^7$ in PbPb, Z=82

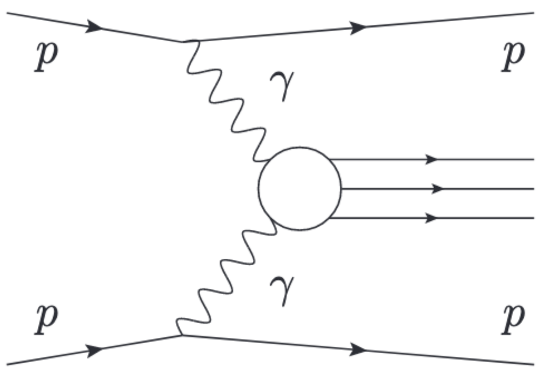
Contracted EM field for fast moving charge



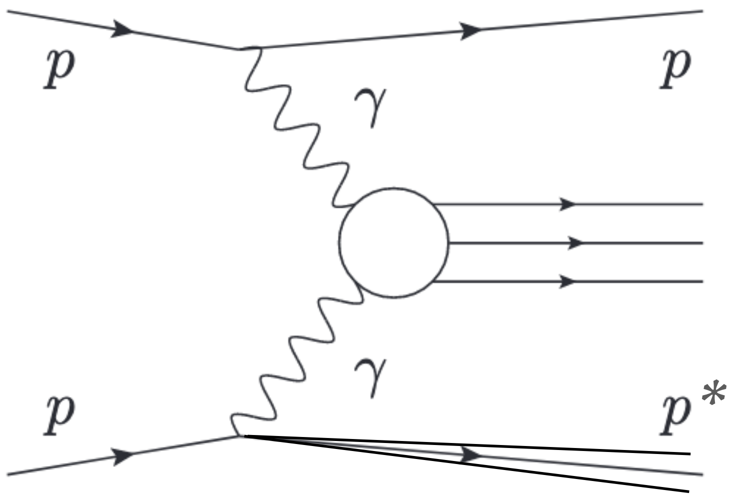


Types of photon-photon induced reactions

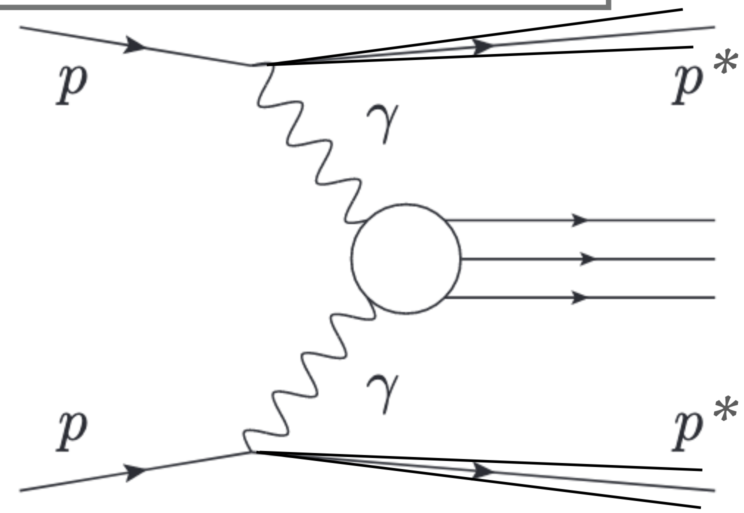
Either or both protons dissociate due to inelastic collision



Coherent
(elastic, exclusive)



Single-dissociative
(semi-exclusive, semi-coherent)



Double-dissociative
(inelastic, incoherent)

Photon in the proton: $f_{\gamma/p}$ = elastic + inelastic contributions

MRST2004, CT14qed ($f_{\gamma/p}$ modelled)

NNPDF23QED, NNPDF30QED ($f_{\gamma/p}$ fitted)

LUXqed17, NNPDF31, MMHT2015qed ($f_{\gamma/p}$ from DIS structure functions, reduced uncertainty, some include elastic)

Dissociative contribution significant in pp

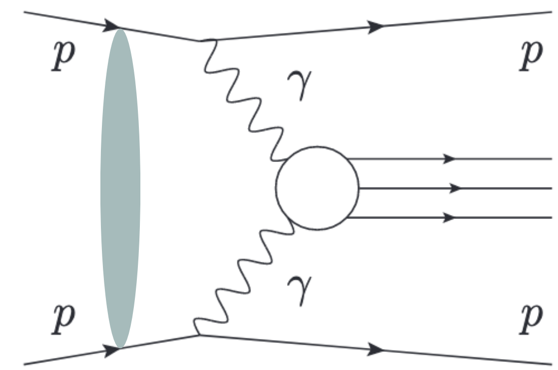
- Larger transverse momentum transferred to X
- Higher particle activity

In Pb+Pb - dissociative contributions small

- Scattering on single nucleon, no *Z* enhancement
- **Forward neutrons** with $E_{beam}/N_{nucleon}$ energy can be detected, ion easily disrupted, binding energy small (~ 10 MeV)

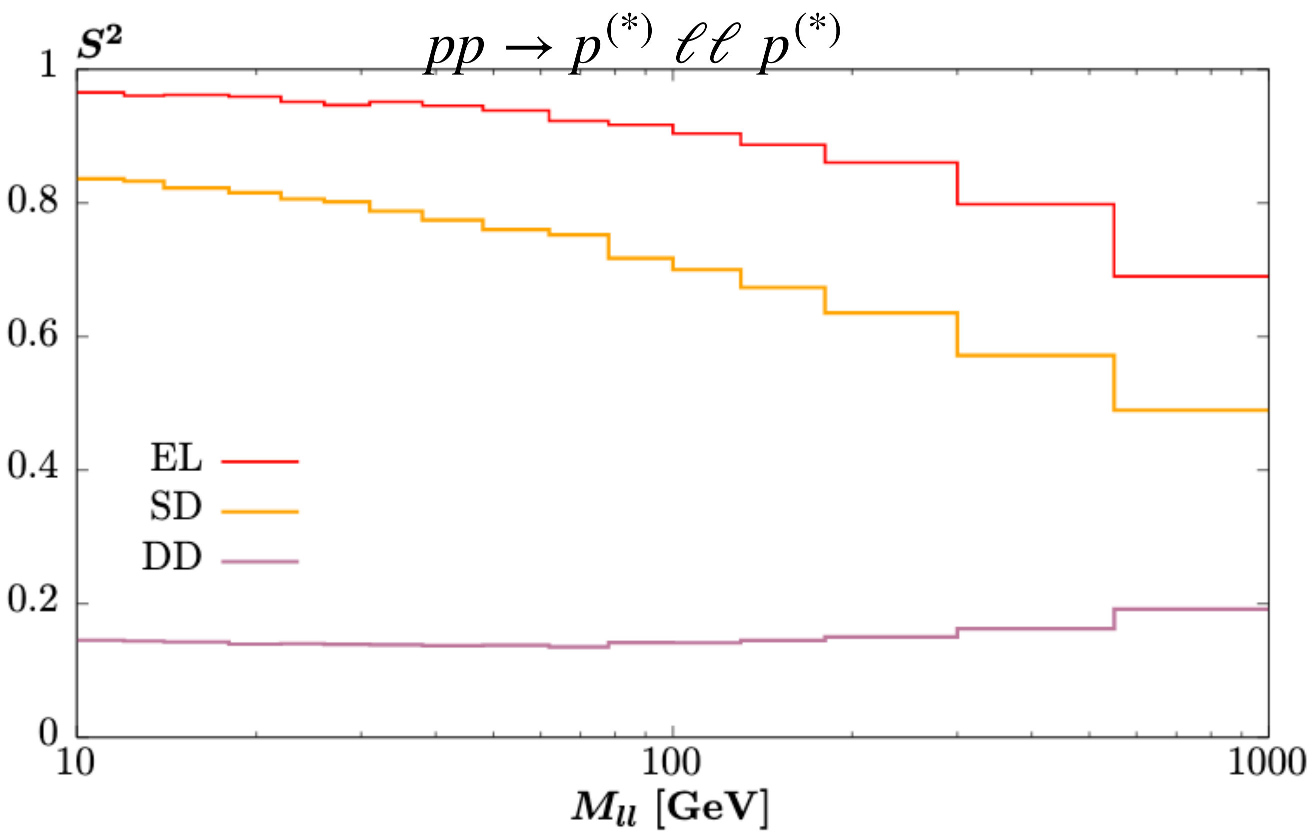
Survival factor

- $\gamma\gamma$ have also underlying
- Require final state with no additional particle production (X + nothing in det.) → accounted for with **survival factor**
- Only allow those rescattering, which do not break the proton Harland-Lang [arXiv:1601.03772], Dyndal [arXiv:1410.2983]



Prb. that there is no inelastic scattering, proton opacity Ω extracted from pp elastic scattering

$$\langle S^2_{\rm eik}\rangle = \frac{\int d^2\mathbf{b}_{1t}\, d^2\mathbf{b}_{2t}\, |T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2 \exp(-\Omega(s,b_t))}{\int d^2\,\mathbf{b}_{1t} d^2\mathbf{b}_{2t}\, |T(s,\mathbf{b}_{1t},\mathbf{b}_{2t})|^2}$$

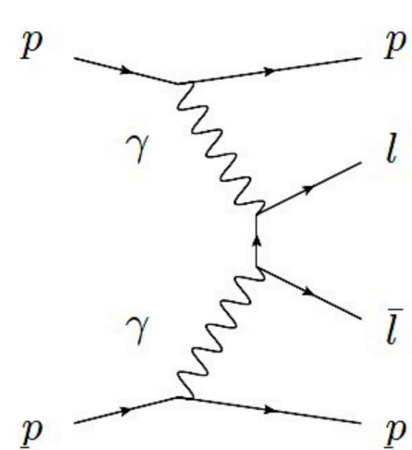


Harland-Lang [arXiv:2007.12704]

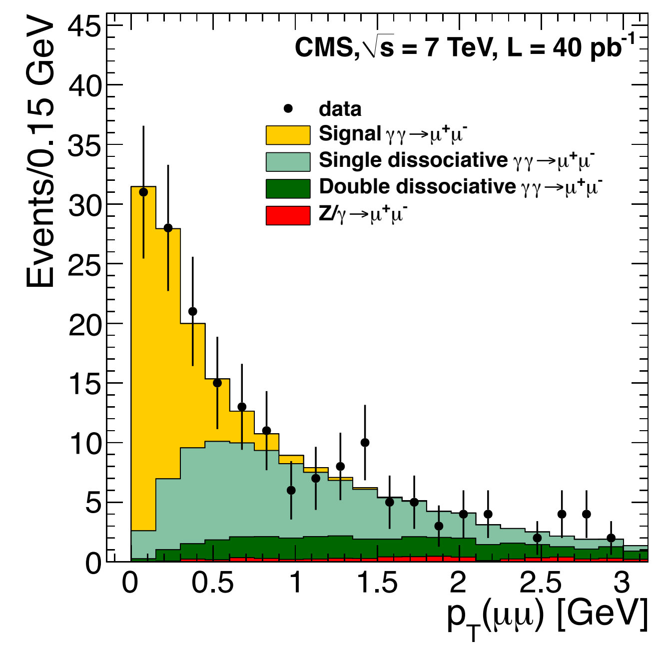
- In general, lack of implementation of survival prb in MC generators
- NEW: implemented for $\gamma\gamma \to ll$ for elastic & inelastic in SuperChic 4.0
- SD/DD occur at smaller impact parameter → smaller S^2

Standard Candle $\gamma\gamma \rightarrow ll$ in pp

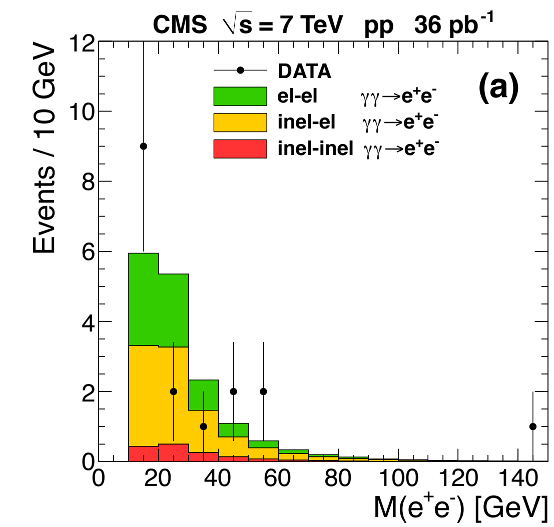
- **From handful of dilepton events in Run 1**
  - Veto additional energy in the whole detector (tracker, el/had calorimeters, …)
  - Low pileup



JHEP 01 (2012) 052

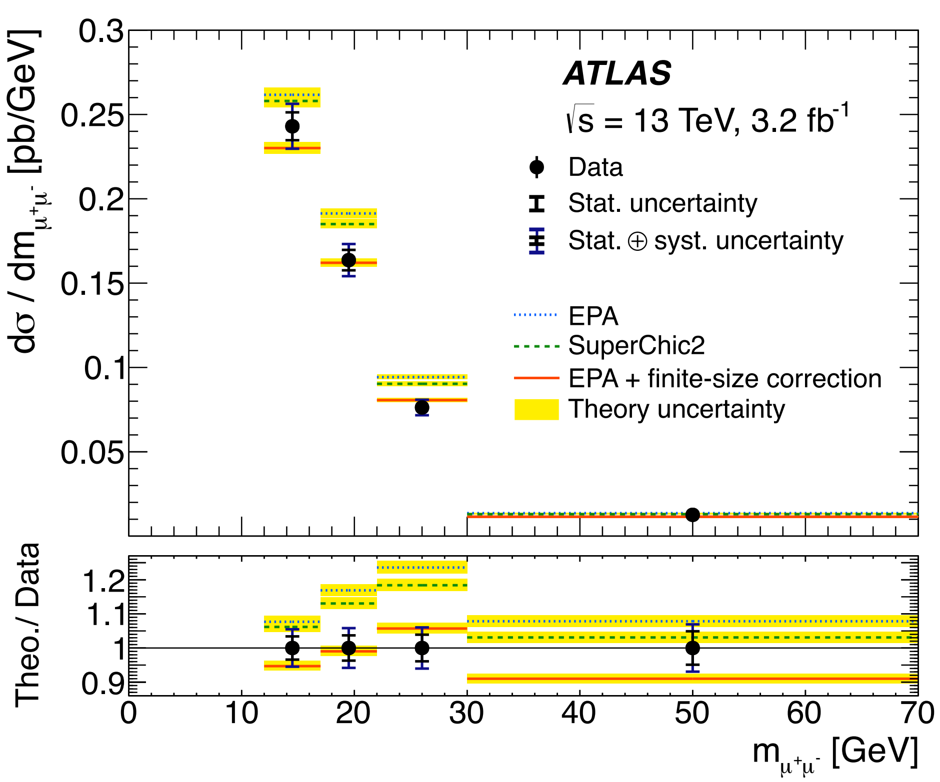


JHEP 11 (2012) 080



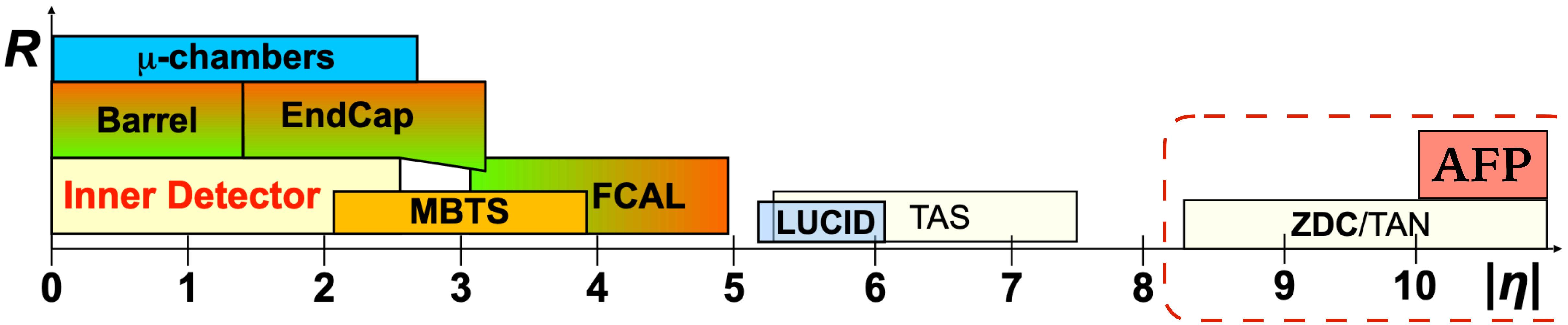
See also ALICE: EPJ C 73 (2013) 2617

PLB 777 (2018) 303 PLB 749 (2015) 242



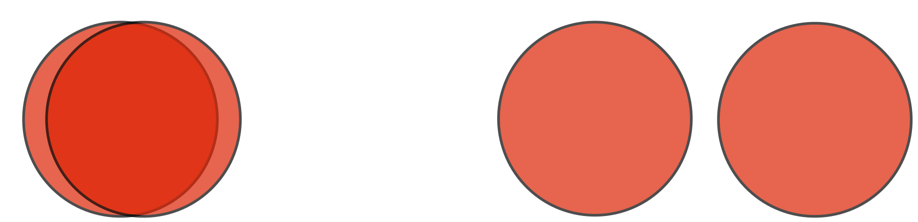
- **To thousands of events with 2015 dataset**
- Extract signal using track-based selection in high-pileup
- Survival probability models tested using differential distribution
- Potential for improvement by including full Run2

Techniques to detect $\gamma\gamma$ interactions in ATLAS



- **Large pp** dataset with **pileup**
- Signal isolated from QCD background by requiring **0 additional tracks found around hard vertex region** using Inner Detector
- Unique opportunity to **tag the outgoing protons in AFP** forward detector in ATLAS

- **No pileup** in PbPb
- Reject activity in all detectors: ID, Calo, MBTS, Forward detectors
- **ZDC to identify / reject background**
- Dedicated triggers to select 'silent' ultra-peripheral collisions (UPC)

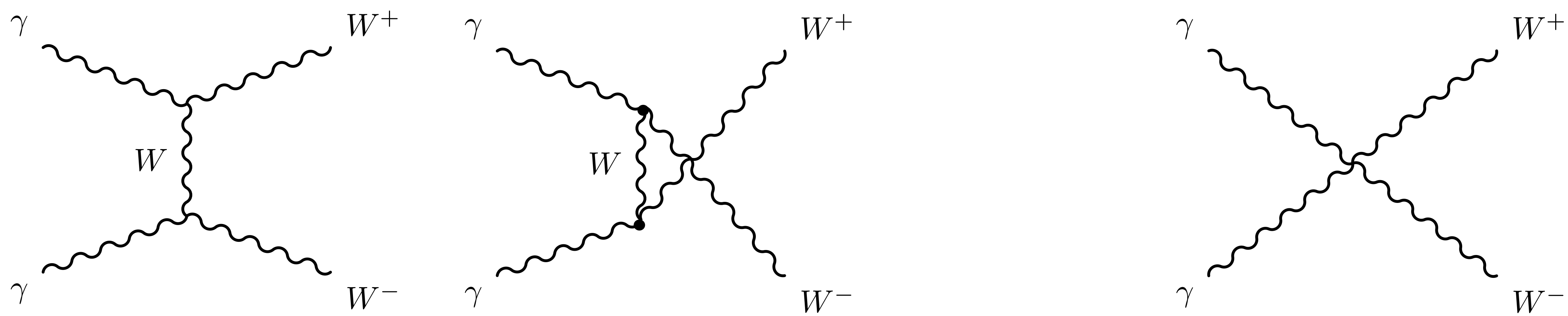


Central collisions UPC

Observation of photon-induced $\gamma\gamma \rightarrow W^+W^-$ production in pp collisions at $\sqrt{s}$ =13 TeV using the ATLAS detector [ATLAS-CONF-2020-038]

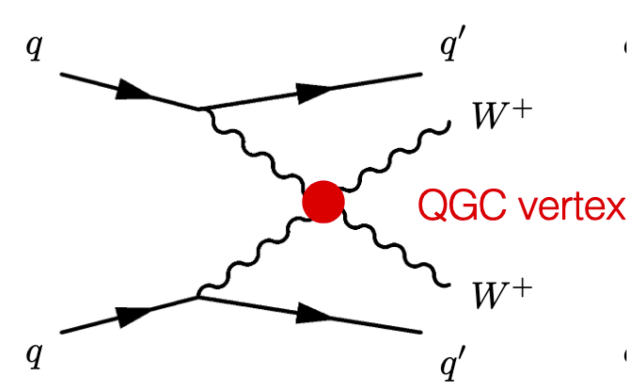
$\gamma\gamma \to W^+W^-$: Motivation

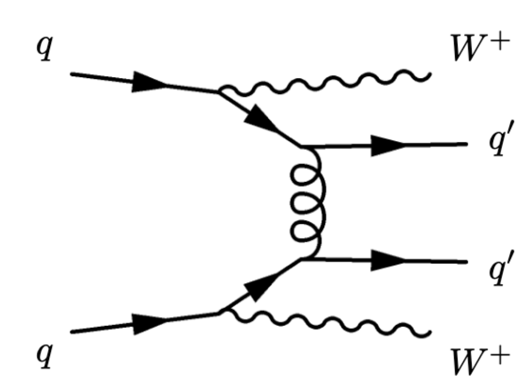
- Excellent laboratory to test EW sector of SM
  - Direct access to **triple** γW^+W^- and **quartic** $\gamma\gamma W^+W^-$ interactions, $\mathrm{O}(\alpha_{\mathrm{EM}}^2)$ process
  - No coupling to Z or H at LO



- Tree-level unitarity required for SM to be renormalizable theory
- Amplitude of individual diagrams grows with CME (longitudinal polarizations of W)
- Both linear and quadratic divergence cancelled in the sum.

- Clear interpretation - only EW fields interacting at LO
  - Compare with e.g. same-sign WW which includes strong production





$\gamma\gamma \to W^+W^-$: Analysis overview

- Cross section measurement using leptonic decays of W: 139 fb^{-1}, full Run 2 dataset
- Previous measurements at 7/8 TeV
  - ATLAS/CMS 3σ evidence [arXiv:1607.03745], [arXiv:1604.04464]
- Only central detector, no proton tagging
- **Dissociative production is part of signal**

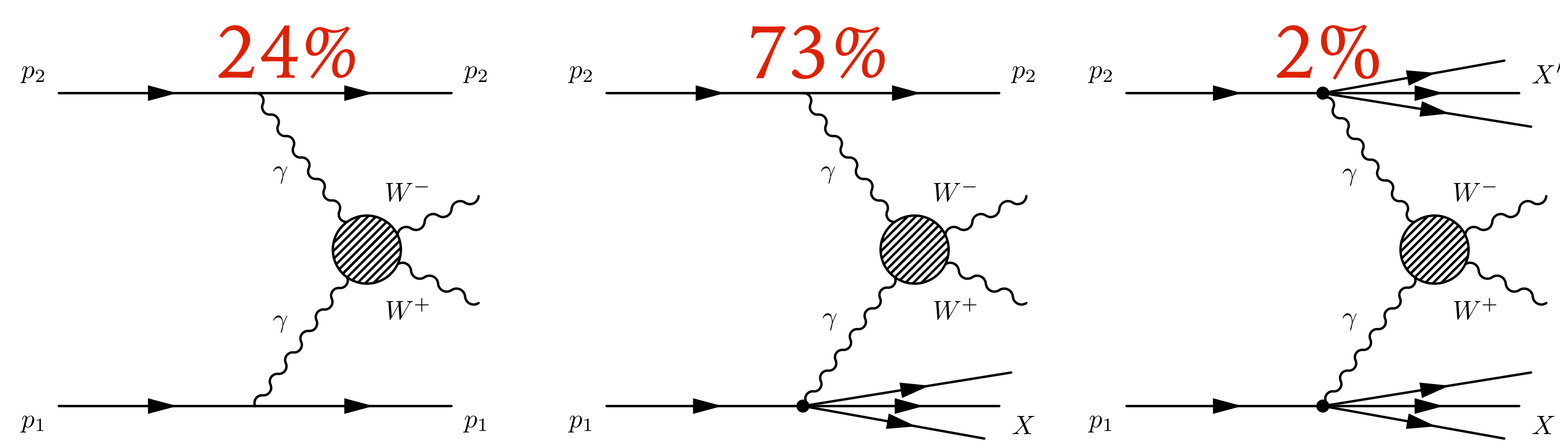
Exactly **one electron and muon** with opposite charge

$p_{\mathrm{T}}^{\mathrm{lep}} > 27,\ 20\ \mathrm{GeV}$

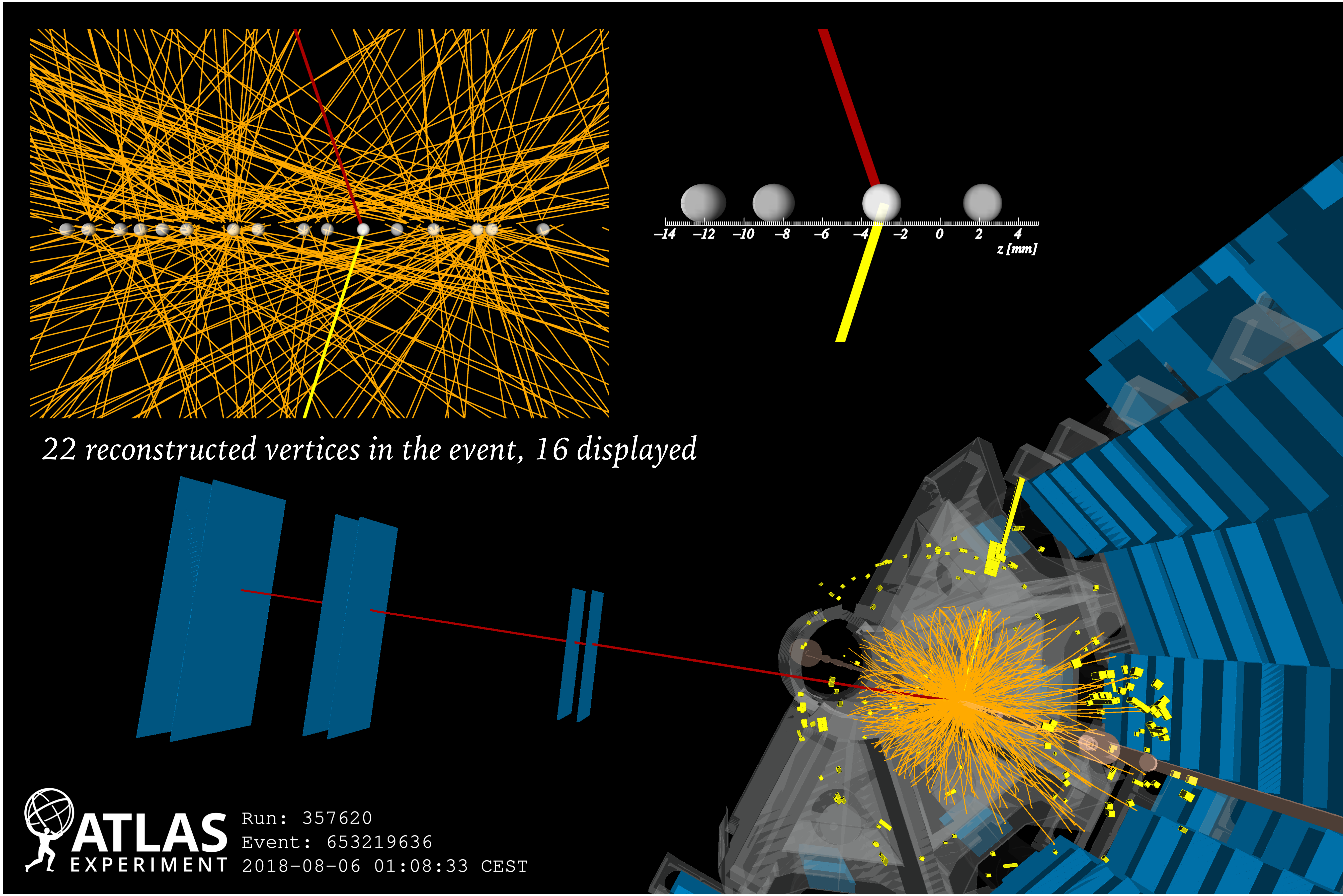
$p_{\mathrm{T}}(e\mu) > 30\ \mathrm{GeV}, m_{e\mu} > 20\ \mathrm{GeV}$

No track associated with the hard scatter vertex

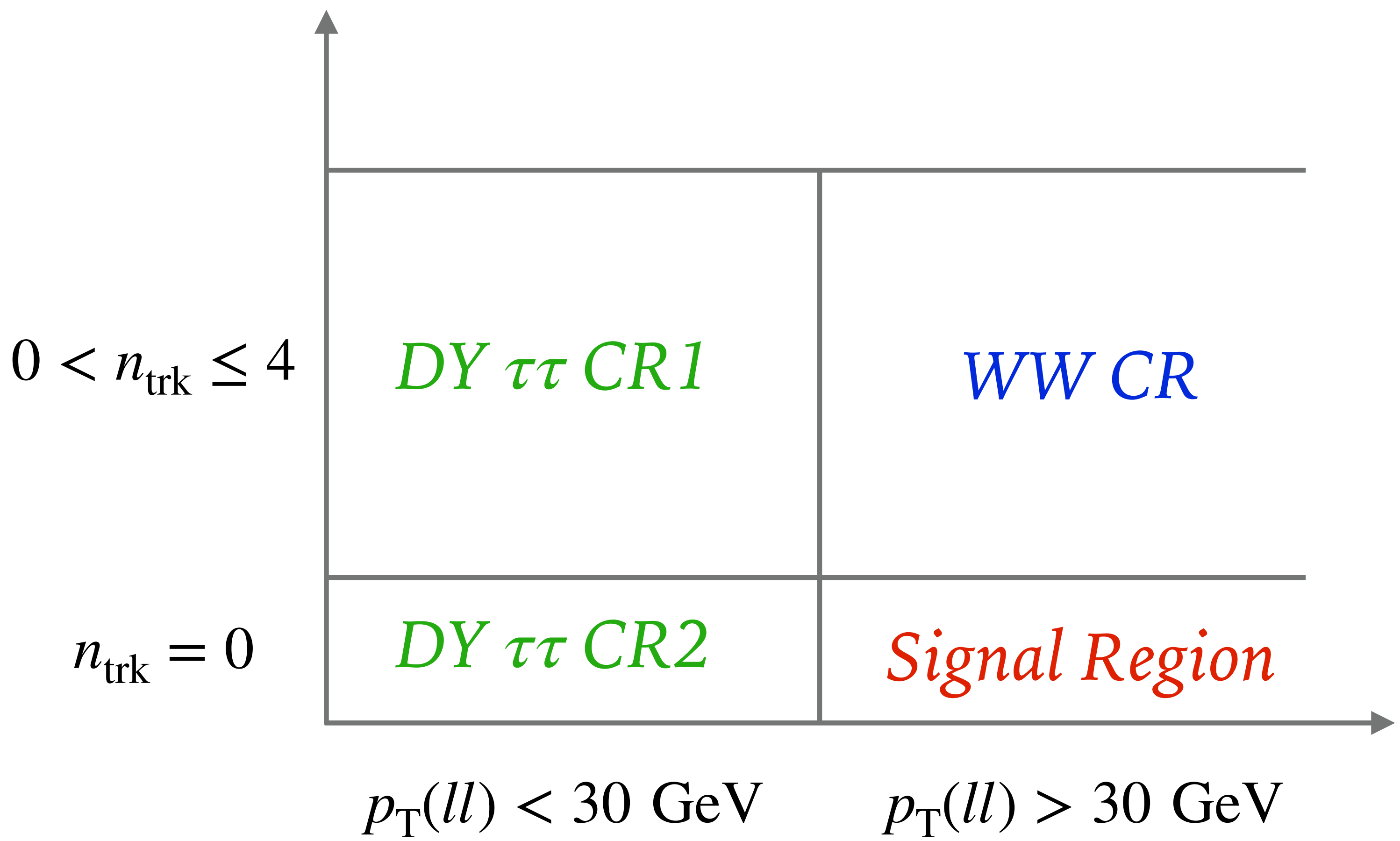
- Signal modelling
  - Elastic: Herwig7
  - Dissociative productions: MG5_aMC@NLO+Pythia8
  - No soft survival accounted for LO only



- Main backgrounds:
  - pp → WW and pp → Z → $\tau\tau$ events with 0 tracks: Powheg+Pythia8/Herwig7, Sherpa

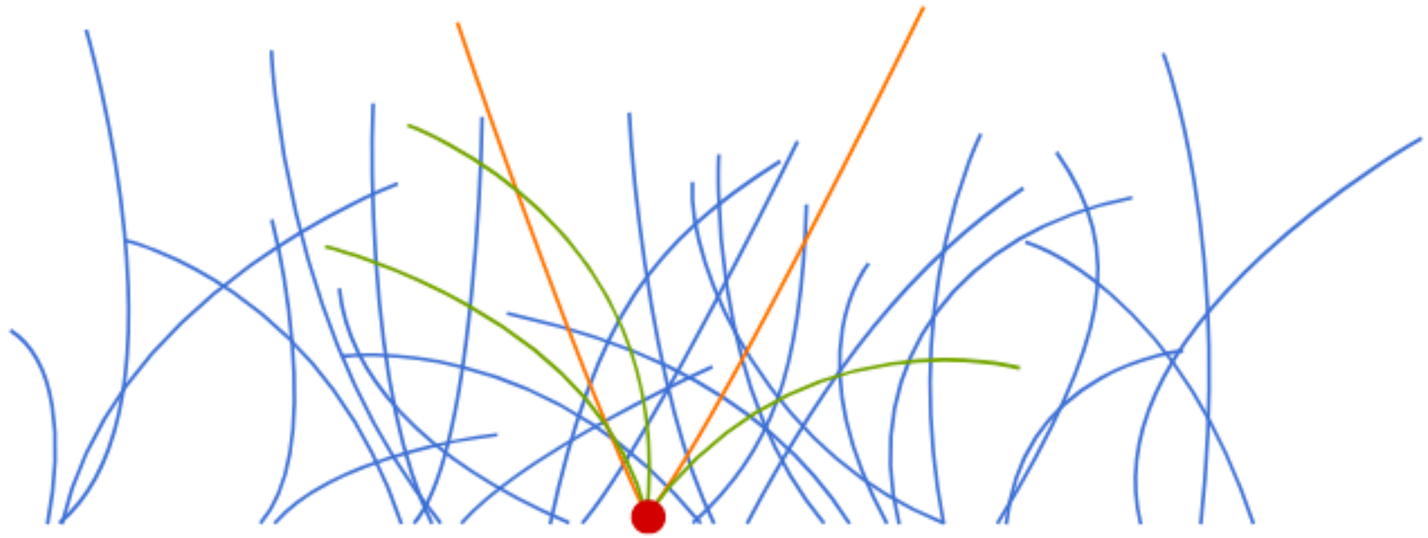

–14 –12 –10 –8 –6 –4 –2 0 2 4
z [mm]
22 reconstructed vertices in the event, 16 displayed
ATLAS
EXPERIMENT
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Analysis strategy



- Analysis relies on precise modelling of low number of tracks in signal & background processes

Experimental technique



Experimental techniques

- Harsh LHC environment
- Typical selected event has primary interaction vertex, and leptons from hard interaction, particles from underlying event and pileup

Dedicated algorithms or data driven corrections

- Special vertex reconstruction
- Underlying event correction for background
- Pileup density and track multiplicity correction
- Modelling correction for signal (account for dissociation and survival factor)

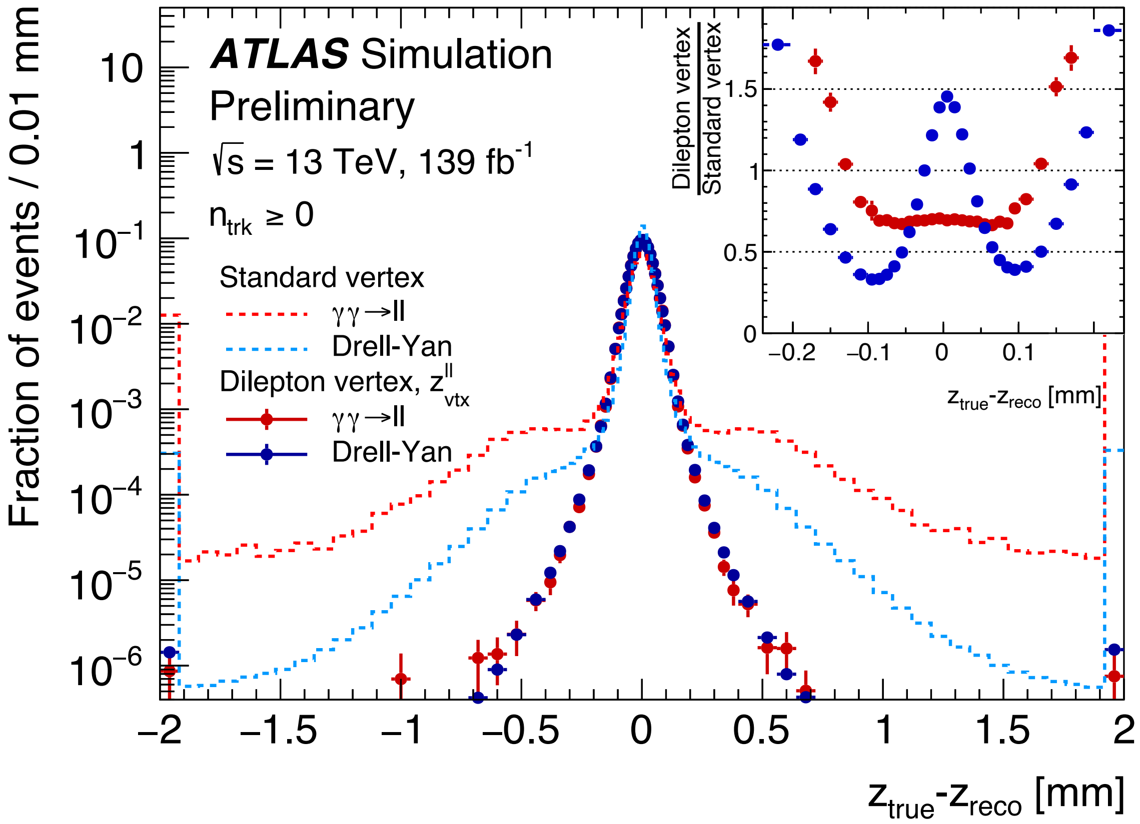
Building on previous ATLAS exclusive measurements [arXiv:1708.04053], [arXiv:1708.04053]

Vertex reconstruction and track selection

- **Lepton tracks used to define interaction vertex**

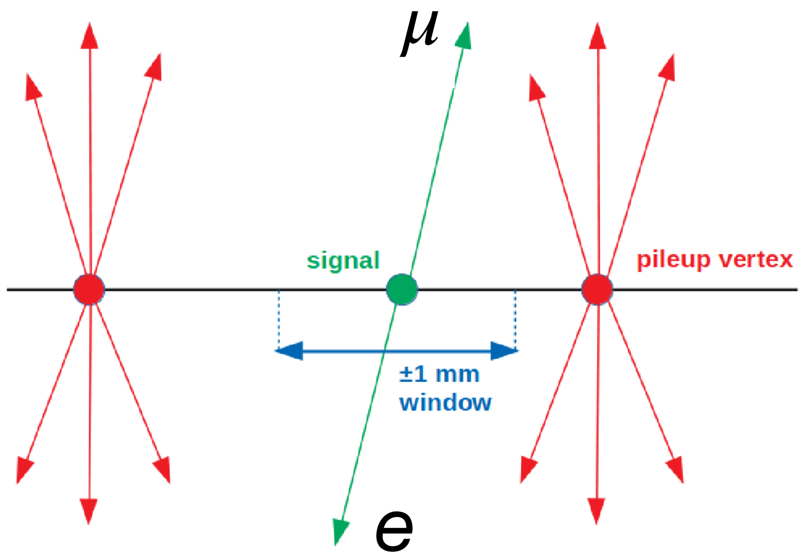
$$z_{\rm vtx}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

- $\sin^{-1}\theta_\ell$ parameterises the uncertainty of the measured z_ℓ position
- Position not biased by nearby pileup tracks
- Advantage compared to ATLAS standard vertex (selected with max sum p_T^2)



- **Track counting in 2 mm window**
  - $p_T > 500$ MeV, $|\eta| < 2.5$
  - Not associated to any lepton
  - Transverse and longitudinal impact parameters $|d_0|, |z_0| < 1\,\mathrm{mm}$

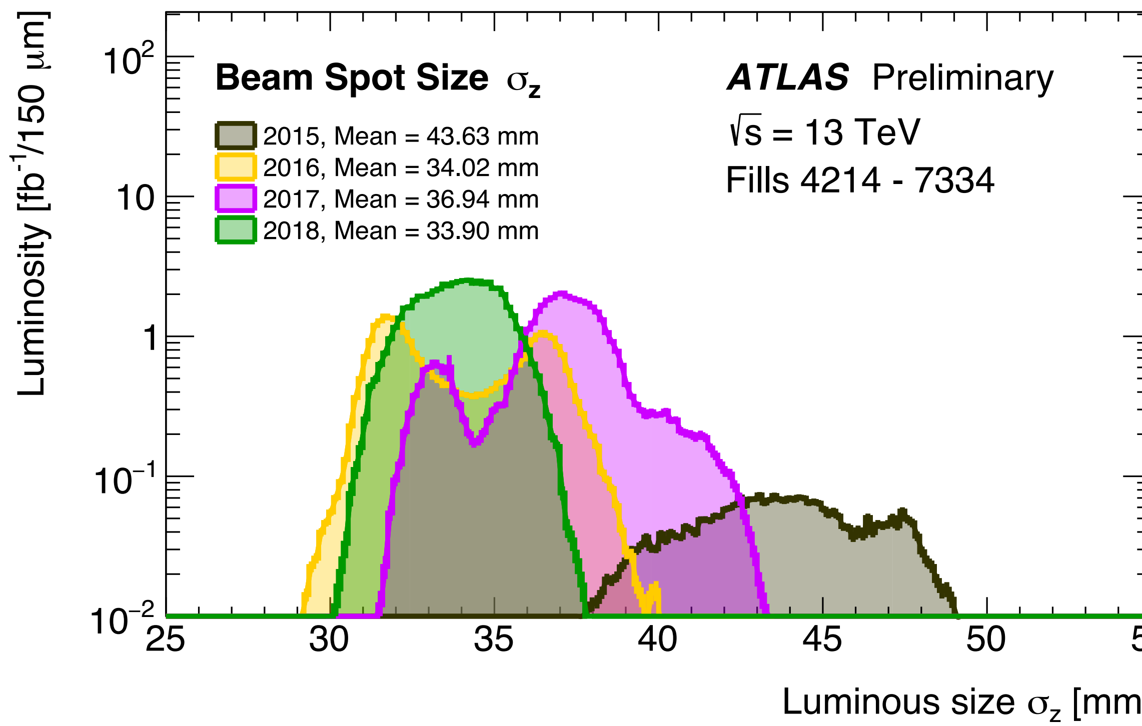
$$n_{\rm trk} = n_{\rm trk}^{\rm UE} + n_{\rm trk}^{\rm PU} + \varepsilon(\text{fakes}, \ldots)$$



Pileup and beamspot

Issue: longitudinal size of luminous region time dependent and smaller than in MC

- $\sigma^{\text{BS}}_{\text{Data}} = 36\text{ mm}, \sigma^{\text{BS}}_{\text{MC}} = 42\text{ mm}$
- Exclusive selection more efficient in MC due to smaller pileup track density

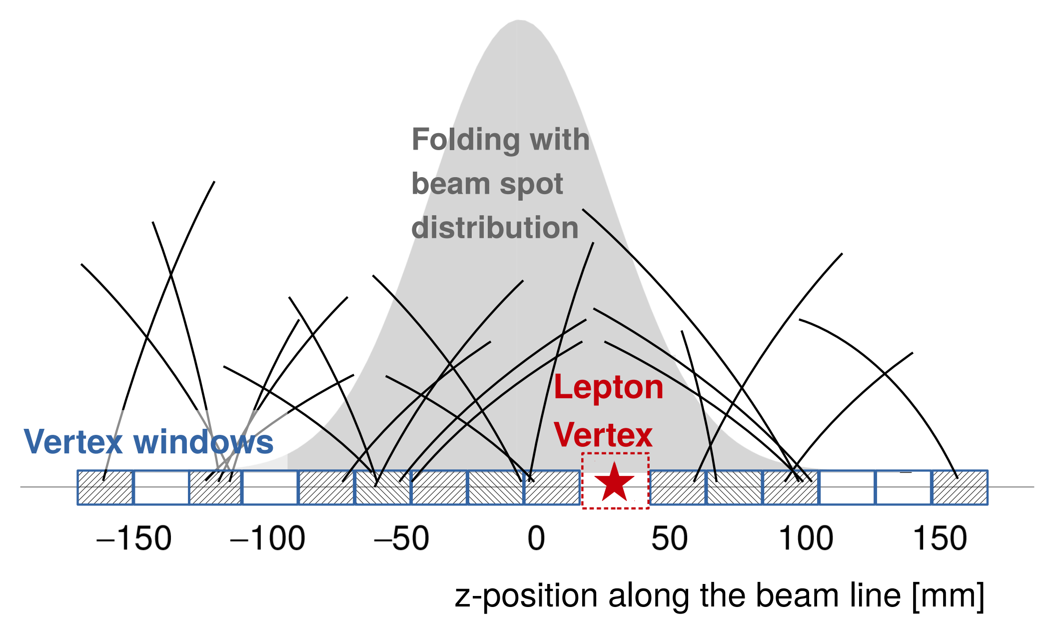


Beamspot size correction

- Corrected by scaling z_0 impact parameter of pileup tracks with $\sigma^{\text{BS}}_{\text{Data}}/\sigma^{\text{BS}}_{\text{MC}}$
- Signal processed matching the BS size in data

Validation

- Pileup modelling as a function of z validated using "tail positions" in Drell-Yan events
- Tracks counted in 2 mm windows, well separated from lepton vertex $|z^{\ell\ell}_{\text{vtx}} - z_{\text{trk}}| > 10\text{ cm}$
- Data/MC differences applied as additional correction



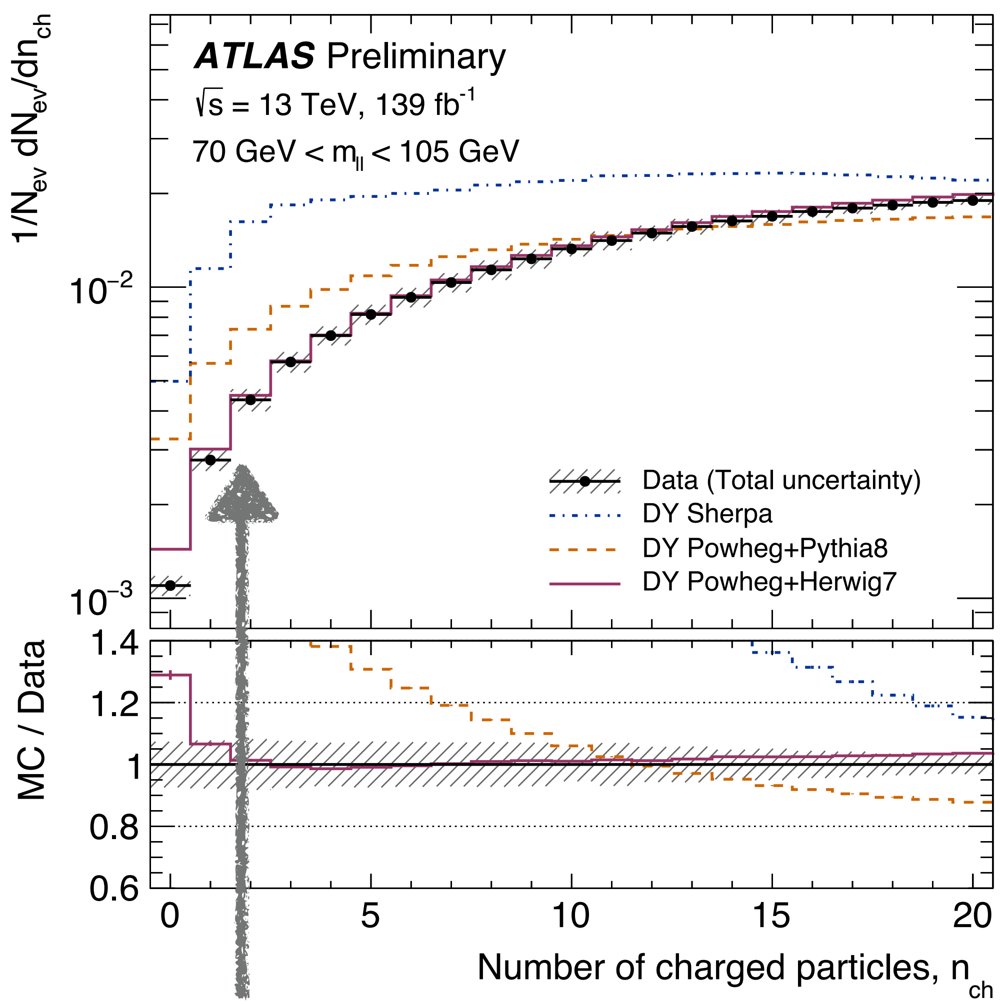
Background and pileup modelling

ATLAS-CONF-2020-038

- V and VV have similar colour structure → therefore similar UE → correct VV mismodelling using Drell-Yan measurement
- Applied a function of $p_T(V)$ and $p_T(VV)$ to qq induced WW, WZ, ZZ and Drell-Yan

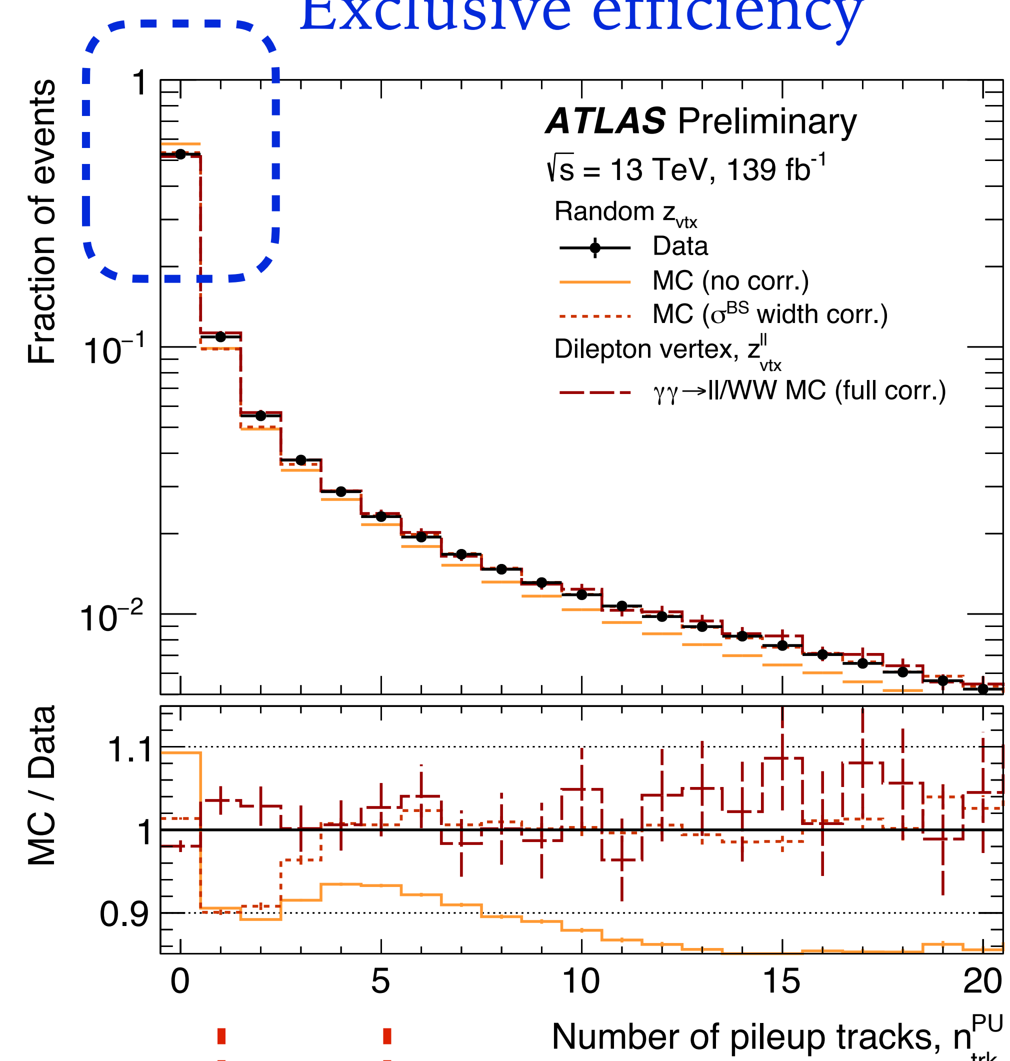
- Fully data-driven method to estimate probability for number of pileup tracks in 2mm selection window around leptons
- **52.6% average Run 2 exclusive efficiency,** $\langle \mu \rangle = 33.7$

$70 < m_{ll} < 105$ GeV



Herwig7 well performing

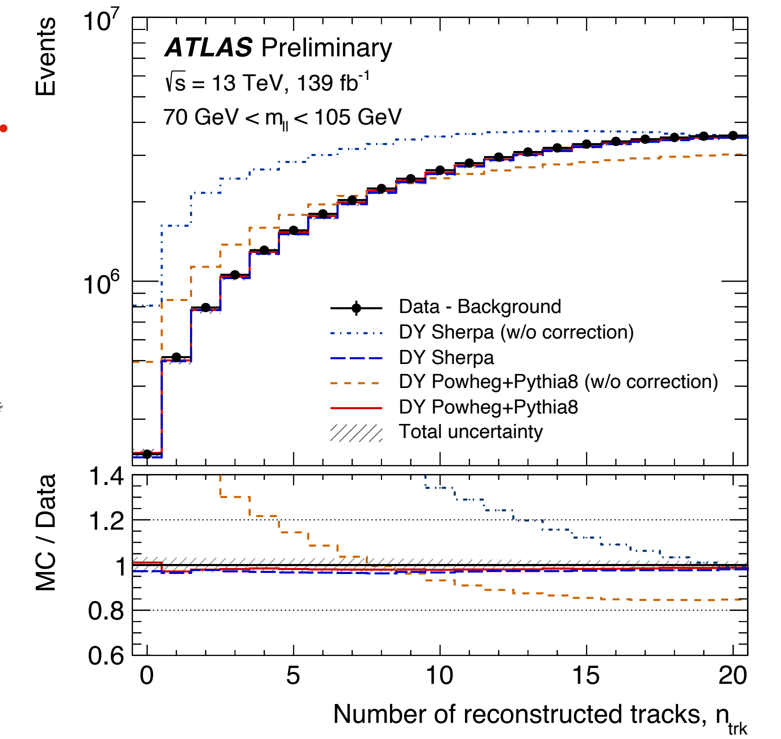
Exclusive efficiency



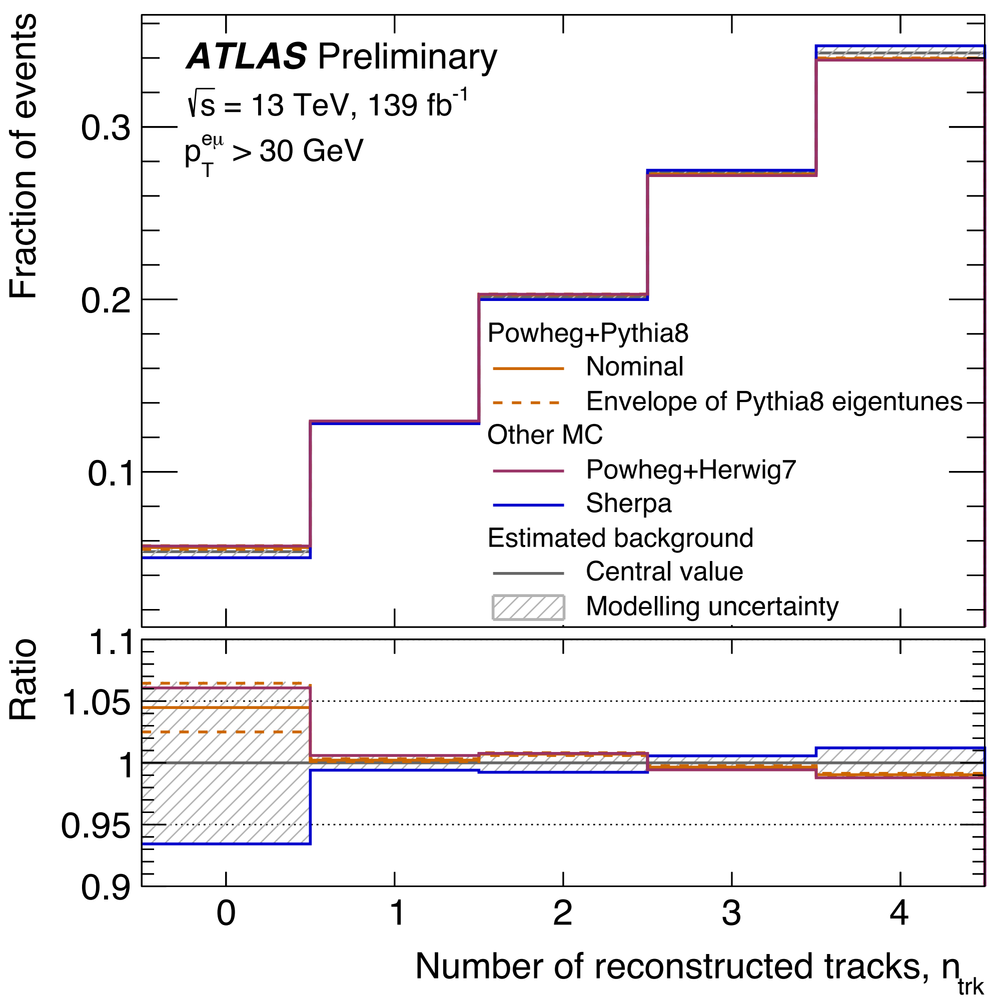
SR | CR

Application of UE correction

- Excellent modelling of DY using $p_T(Z)$ dependent correction for both Powheg and Sherpa



From qq→Z to qq→WW



- **$0 < n_{trk} \leq 4$**: very good agreement for WW using $p_T(WW)$ dependent correction for all generators / tune variations
- **Extrapolation to SR**: expected WW yield taken as midpoint between predictions

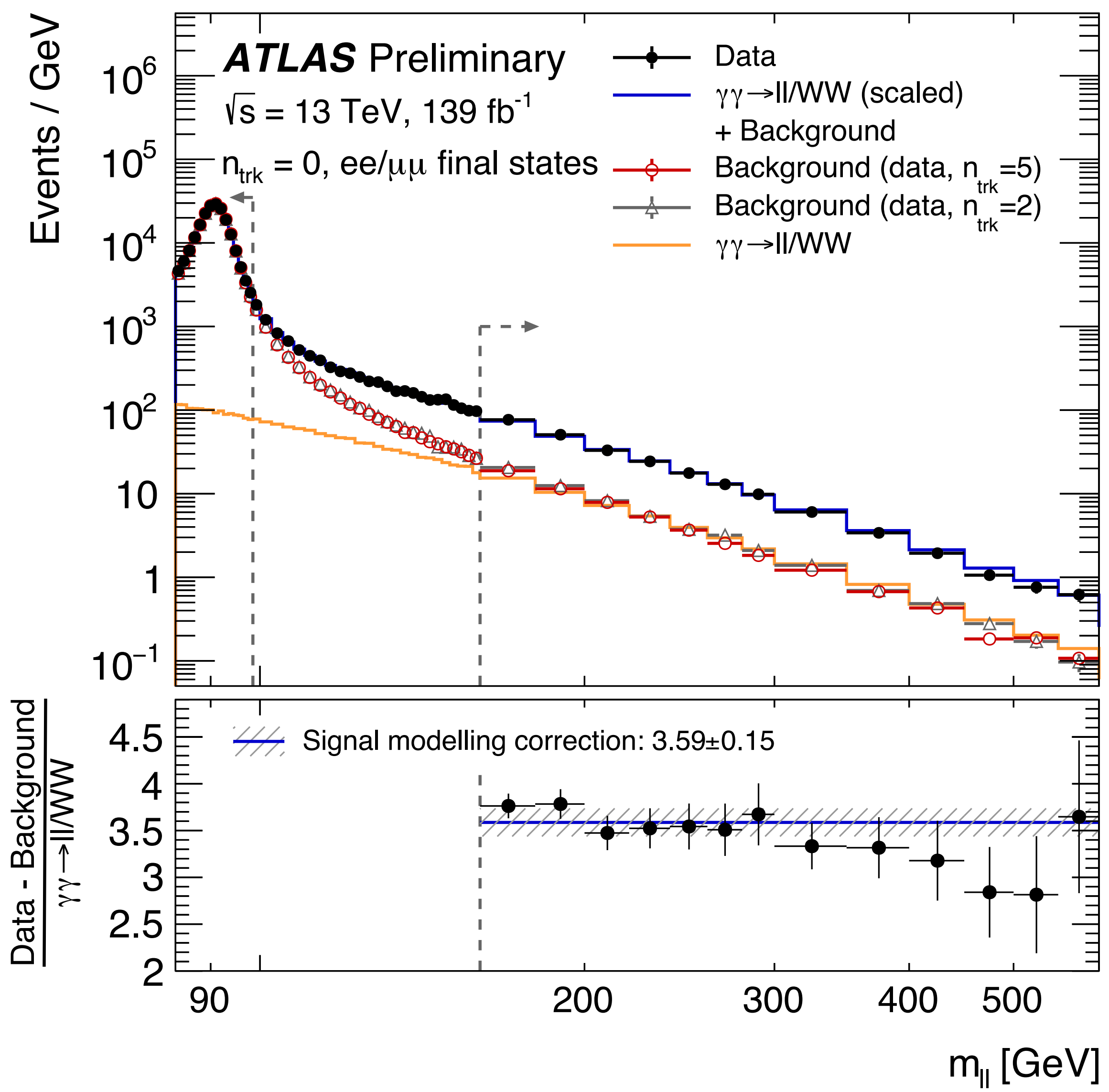
  Powheg+Pythia8 and UE eigentune variations
  Powheg+Herwig7
  Sherpa

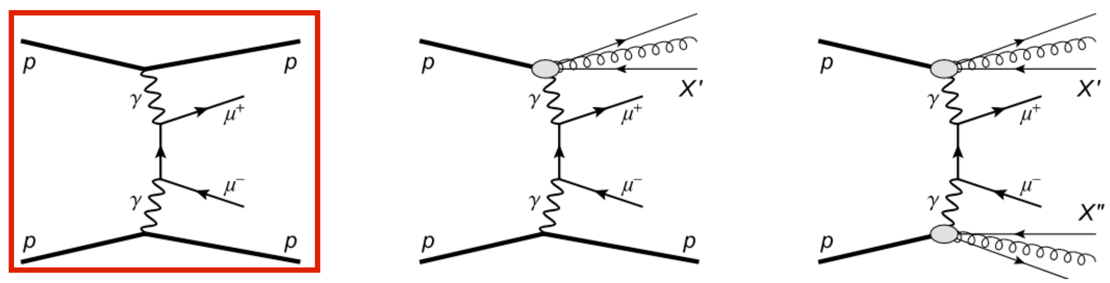
- Maximum deviation taken as uncertainty

Signal modelling

ATLAS-CONF-2020-038

- **Dissociative production is part of signal**
- MC with complete modelling of $\gamma\gamma \to W^+W^-$ not available (in the future in Superchic)
  - MG5-Pythia8 interface issues for single-diss sample (FSR emitted from intact p)
  - No survival effects for dissociate contributions
- **Use data m_{ll}>160 GeV n_{trk}=0 to estimate missing components and scale elastic WW**

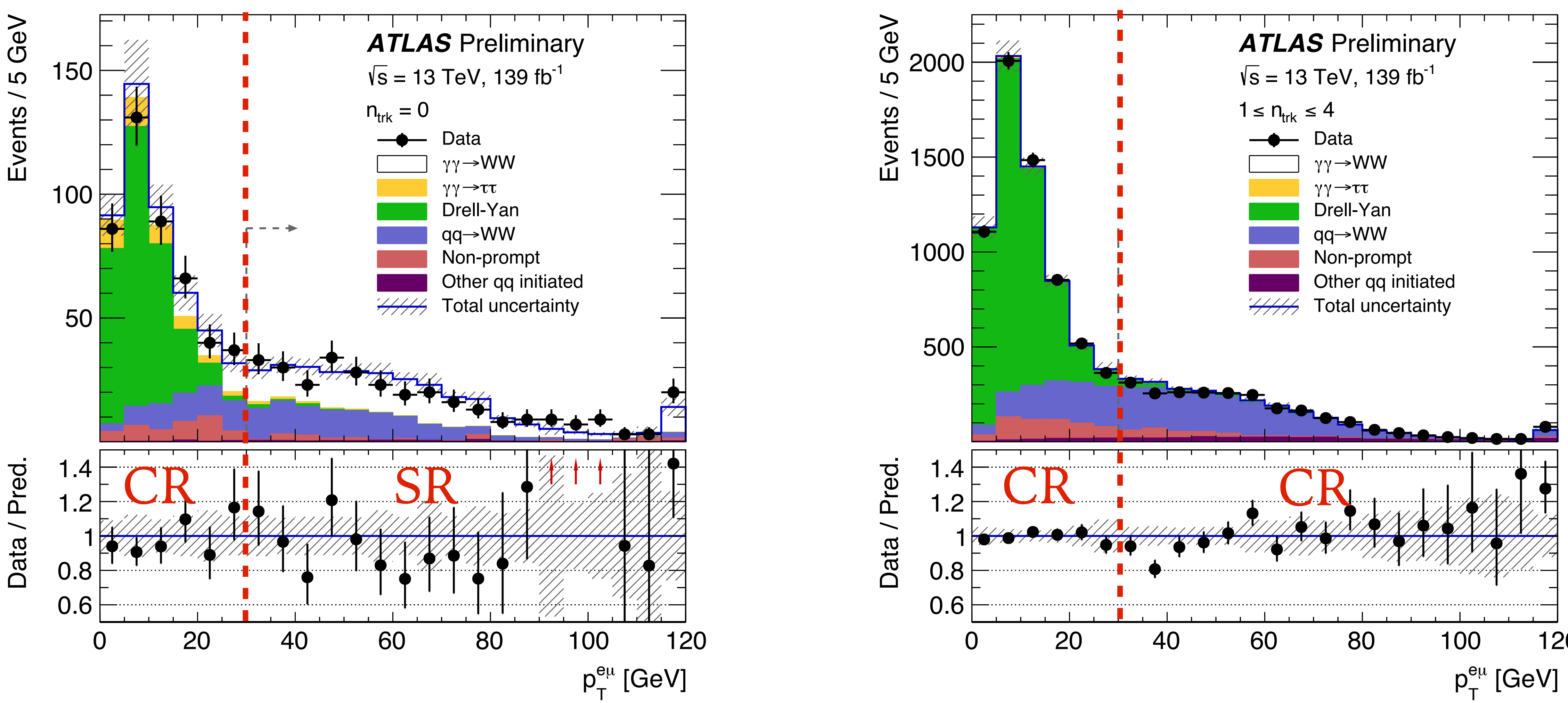




- $$\mathrm{SF} = \frac{N_{\mathrm{data}} - N_{\mathrm{DY}}}{N^{\mathrm{MC,Elastic}}_{\gamma\gamma\to ll}} = 3.59 \pm 0.15\ (\mathrm{stat+syst})$$
- DY background from data, selected with $n_{\mathrm{trk}} = 2$ and $n_{\mathrm{trk}} = 5$, normalized in Z peak

Signal and control regions

- Signal extracted in a profile likelihood fit
  - four bins with $p_T(ll) < 30$ GeV or $p_T(ll) > 30$ GeV, and $1 \leq n_{\text{trk}} \leq 4$ or $n_{\text{trk}} = 0$
  - one bin for signal modelling correction (m(ll)>160GeV)
  - four free parameters:
    normalizations of $\gamma\gamma \to WW$, $\gamma\gamma \to ll$, Drell-Yan and *WW*

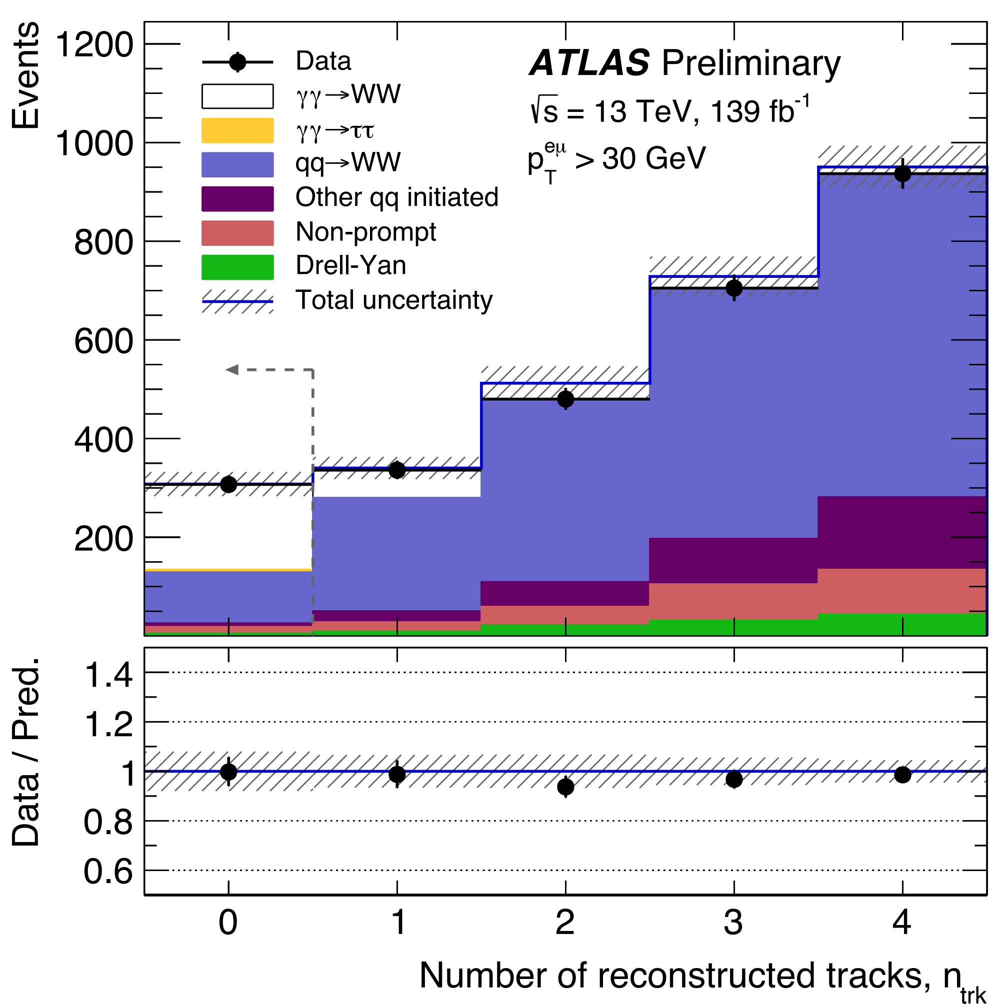


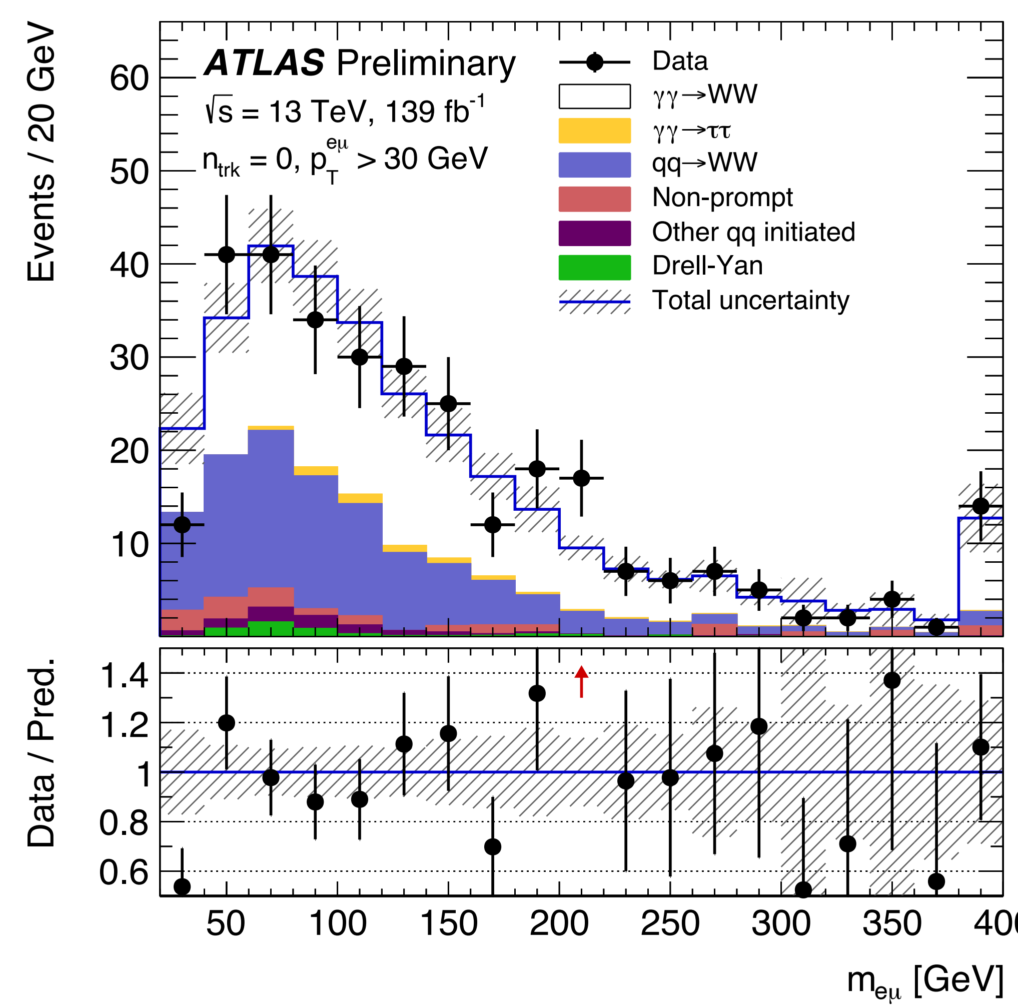
Results

- 307 observed, 132 background events expected
- Signal normalization $\mu_{\gamma\gamma\to WW}$ is expressed relative to scaled predictions using high-mass $\gamma\gamma \to ll$

$$\beta_{WW} = 1.21^{+0.19}_{-0.23}$$
$$\beta_{DY} = 1.16^{+0.10}_{-0.12}$$
$$\beta_{\gamma\gamma\to ll} = 3.59 \pm 0.15$$
$$\mu_{\gamma\gamma\to WW} = 1.33 \pm 0.14\ (\text{stat.})^{+0.22}_{-0.17}\ (\text{syst.})$$

- Background only hypothesis rejected with 8.4σ (6.7σ expected)





Fiducial cross section

- Measured fiducial cross-section

$$\sigma_{\text{fid}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}$$

- Dominant systematic uncertainties
  - WW modelling in the SR
  - Signal modelling scale factor: evaluated as a change of the SF over $160 < m_{ll} < 400$ GeV
  - Statistical uncertainty on the background (includes CR for misidentified leptons)

Source	Impact [%]
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	1.5
Background, statistical	6.7
Modelling	
Pileup modelling uncertainties	1.1
Underlying event modelling uncertainties	1.4
Signal modelling uncertainties	2.1
WW modelling uncertainties	4.0
Other background uncertainties	1.7
Luminosity	1.7
Total	8.9

- Theoretical prediction MG5+Pythia8 (MMHT): $\sigma_{\text{MG5}} = 4.3 \pm 1 \text{ (scale)} \pm 0.12 \text{ (PDF) fb}$
  - No soft rescattering effects in WW available
    MG5-Pythia8 interface issues for single-diss sample

- Data-normalized prediction (scaled by 3.59): $\sigma_{\text{MC,Elastic}} \times 3.59 = 2.34 \pm 0.27 \text{ fb}$
  - Requires data input and is only valid in the $m_{\gamma\gamma}$ mass range investigated, unsuitable for generalised theory reinterpretations

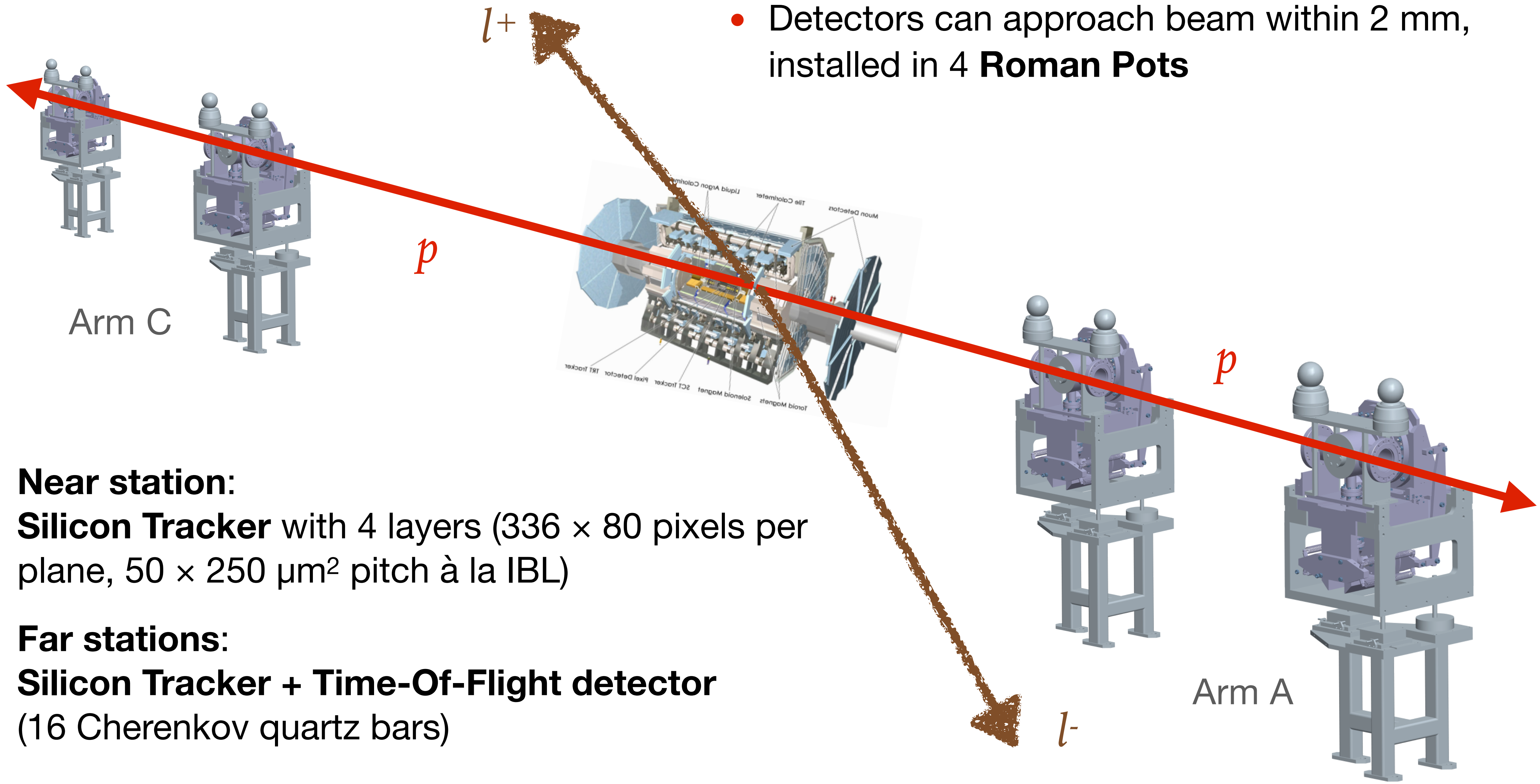
- Small tension observed, modelling of diboson system would profit from improvements
- Outlook: differential distribution and BSM interpretations

Observation and measurement of **forward proton scattering** in association with lepton pairs produced via the photon fusion mechanism at ATLAS [ATLAS-CONF-2020-041]

ATLAS Forward Proton (AFP) Detector

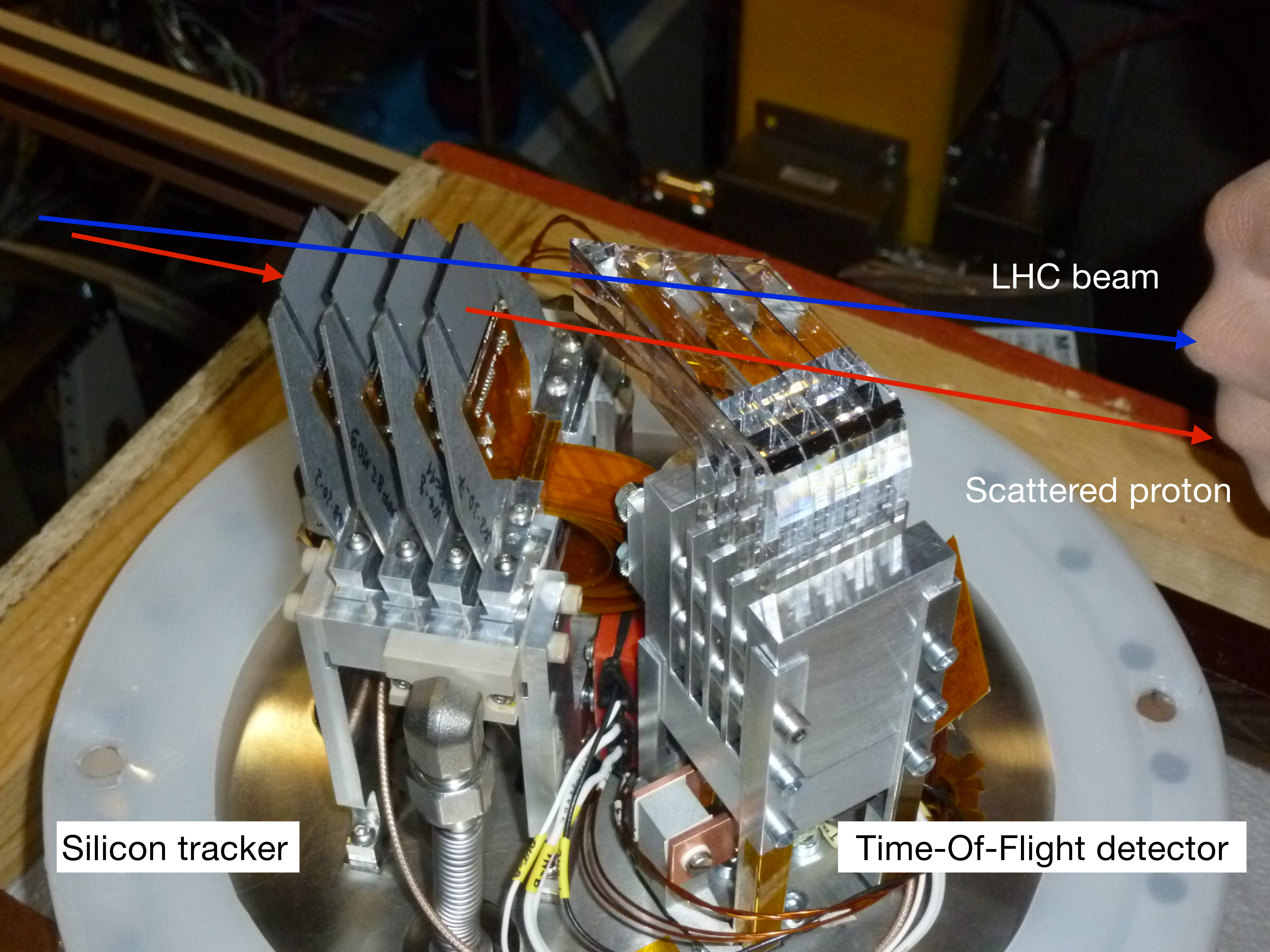
- Directly measure intact protons 220 m from the ATLAS interaction point
  - Open new physics program of diffractive & photon collisions
- Both A and C arms installed in 2017 for standard high-luminosity LHC data-taking

- Detectors can approach beam within 2 mm, installed in 4 **Roman Pots**



Near station:
Silicon Tracker with 4 layers (336 × 80 pixels per plane, 50 × 250 μm² pitch à la IBL)

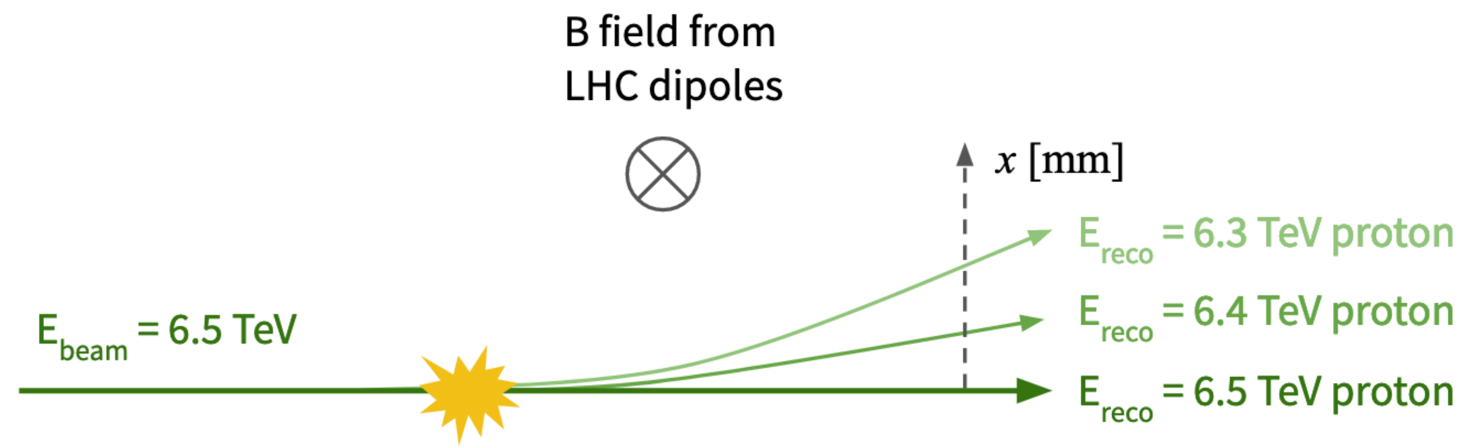
Far stations:
Silicon Tracker + Time-Of-Flight detector
(16 Cherenkov quartz bars)


LHC beam
Scattered proton
Silicon tracker
Time-Of-Flight detector

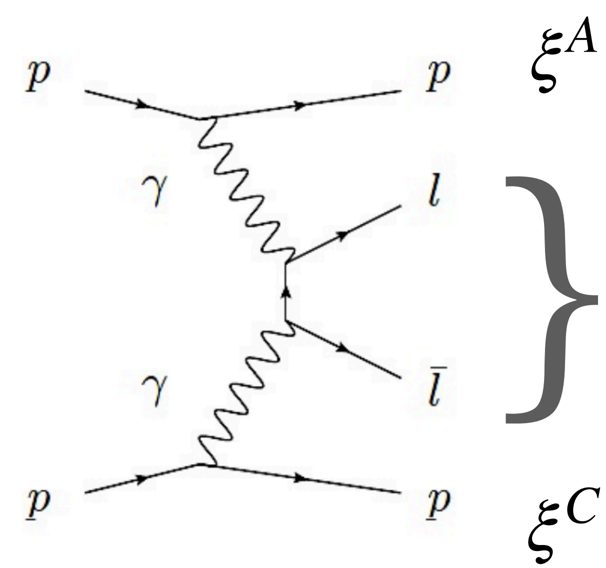
TeV Spectrometer

- Infer energy lost by proton
from displacement from the beam

$$\xi = 1 - E_{\text{reco}}/E_{\text{beam}}$$



- Typical acceptance depends on details of the LHC optics and approach to the beam
  - ATLAS: $0.02 < \xi < 0.1$
  - CMS: $0.03 < \xi < 0.15$



$$\xi_{ll}^{A,C} = (m_{ll}/\sqrt{s})e^{\pm y_{ll}}$$

- **Calculate** expected proton energy loss from dilepton system
- **Match** with the measurement in AFP/PPS
- Selection allows efficient background suppression

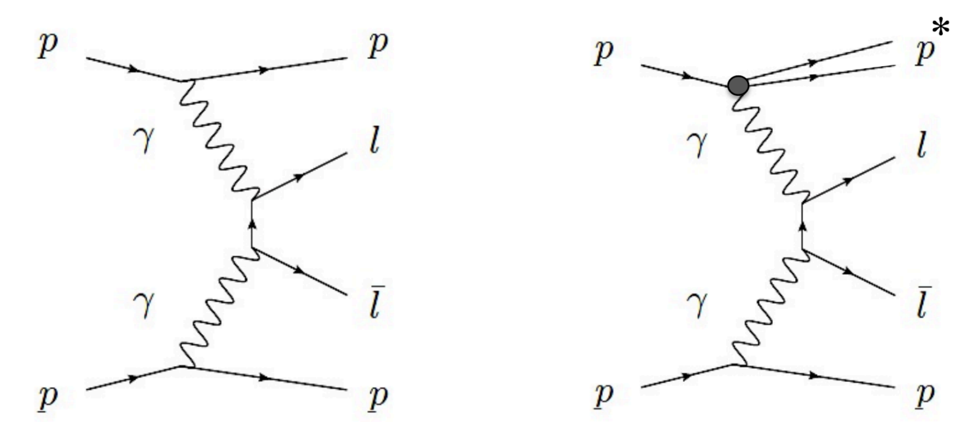
$$|\xi_{\ell\ell} - \xi_{\text{AFP}}| < \sigma(\xi_{\ell\ell}) + \sigma(\xi_{\text{AFP}})$$

- Forward taggers at LHC can double-tag central masses $M_X = \sqrt{s\xi_A\xi_C}$,
$300 - 500\,\text{GeV} < M_X < 1.1 - 1.5\,\text{TeV}$

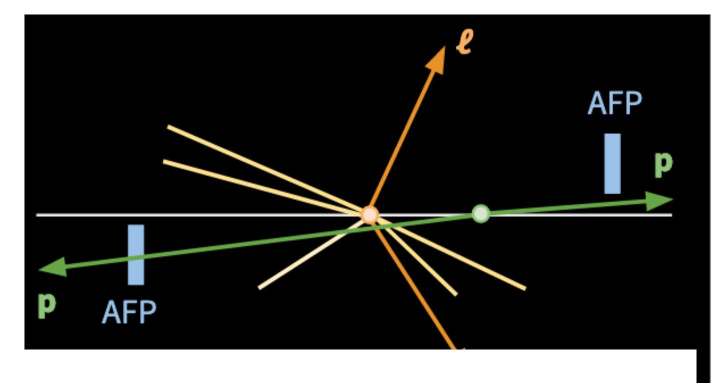
Analysis overview $\gamma\gamma \to l^+l^- + \text{AFP}$

arXiv:2009.14537

- At least 1 proton tag
- Kinematic match $|\xi_{\ell\ell} - \xi_{\text{AFP}}| < 0.005$
- No charged track in addition to leptons

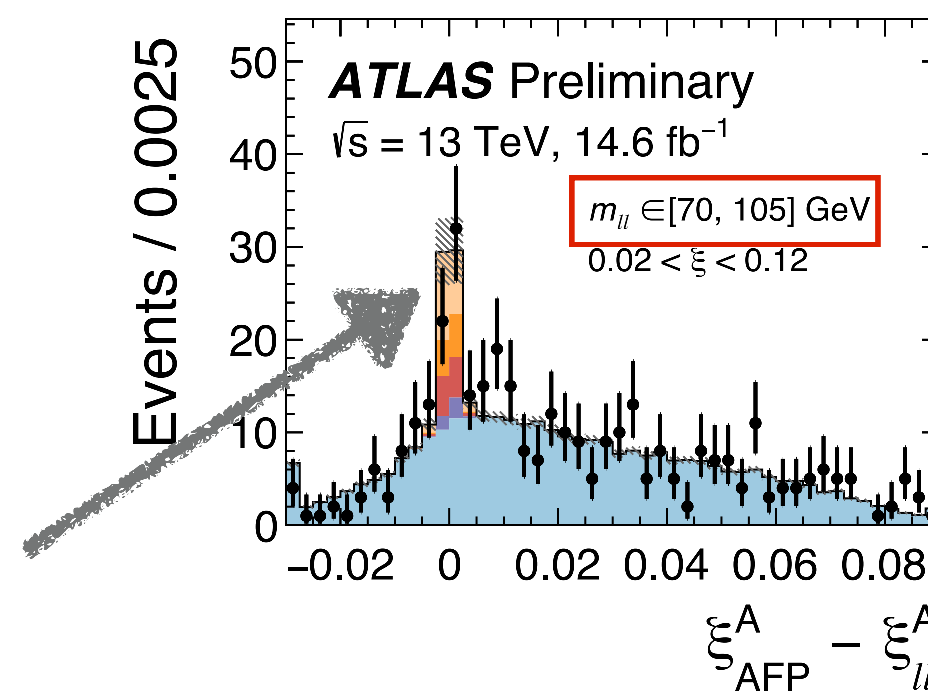


- **Initial observation at CMS+CT-PPS with 2016 data** with 50 events, ee/μμ combined, 9.4fb^{-1} , JHEP 07 (2018) 153 (see backup)



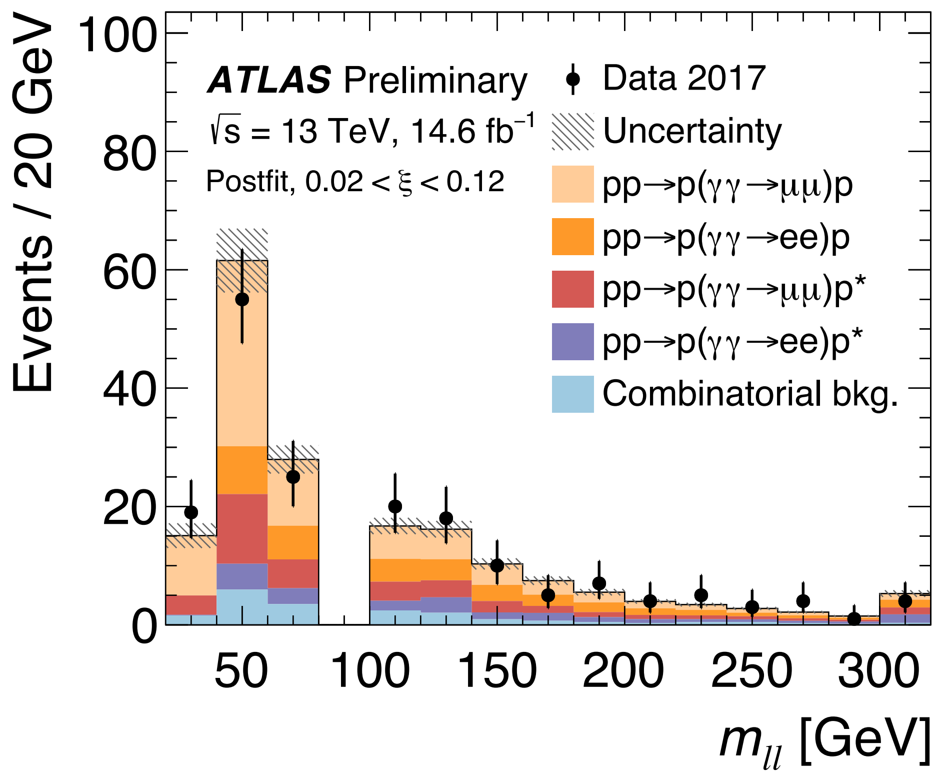
- Signal = elastic + single-dissociation
- Background dominated by Drell-Yan + random protons from pileup
  - Robust data-driven estimate for combinatoric background
  - Mixing events + side-band fit to $|\xi_{ll} - \xi_{\text{AFP}}| > 0.005$
  - Cross-check in $70 < m_{ll} < 105$ GeV region

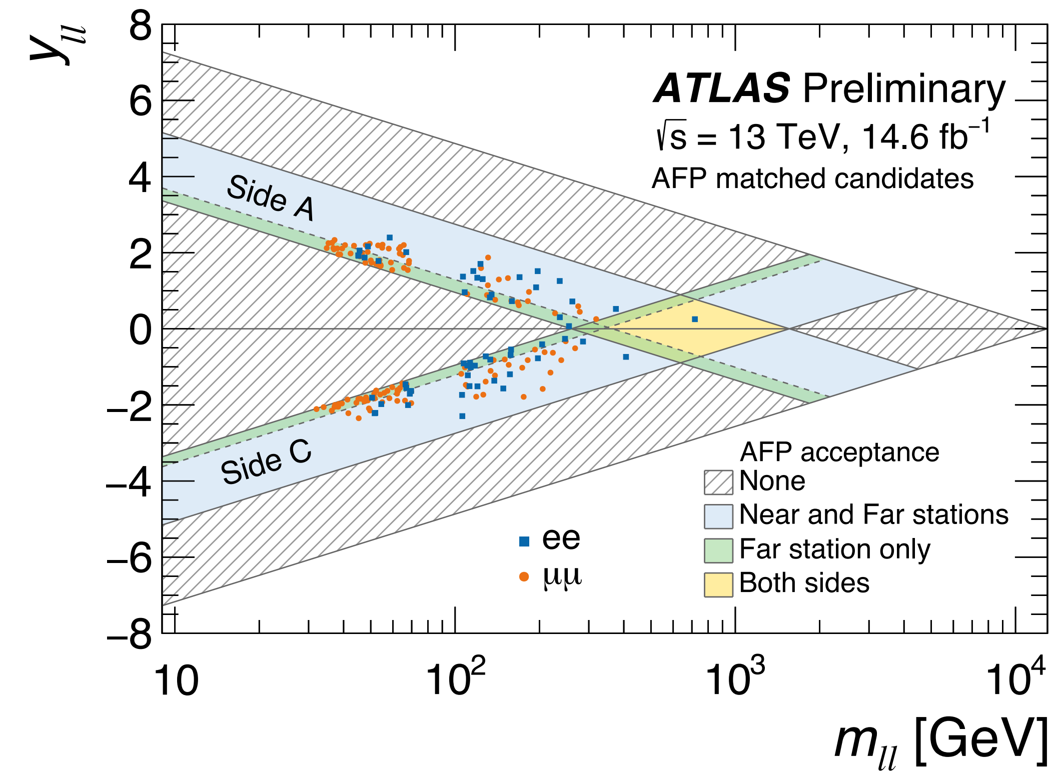
S/B discrimination even under Z peak thanks to AFP!



$\gamma\gamma \rightarrow l^+l^-$ measurement in ATLAS

arXiv:2009.14537





- First **fiducial cross section measurement** with a proton tag at the LHC
- Mostly single tag events, with 30 < m_{ll} < 630 GeV, substantial contribution above the EW scale
  - No double-tagged event matching leptons seen yet
- Constrain modelling of survival effects/photon fluxes

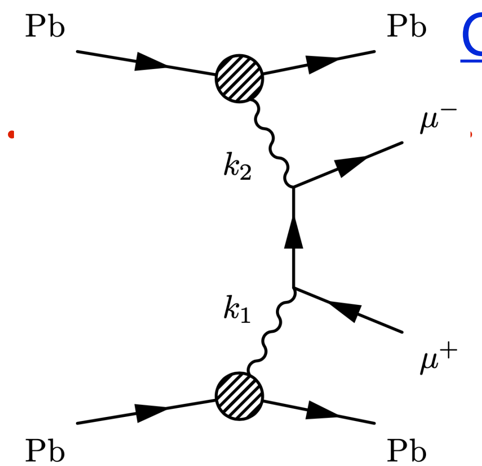
$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [31,30]	10.9 ± 0.8	9.4 ± 0.7
SuperChic 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

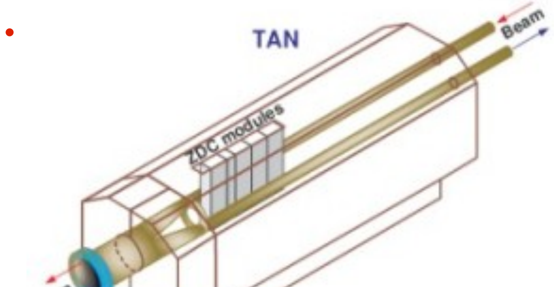
Exclusive dimuon production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ATLAS [CERN-EP-2020-138]

Exclusive dimuons in UPC Pb+Pb

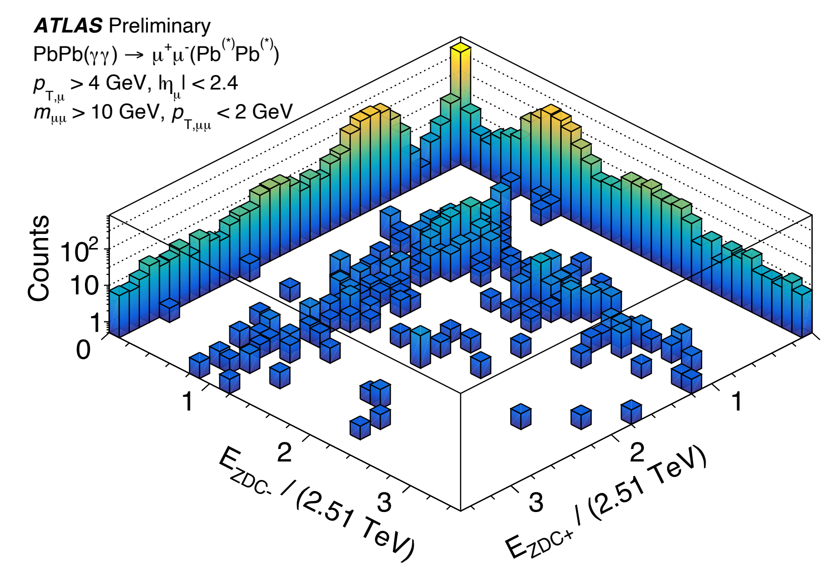
- Sensitive to higher order effects (FSR photons, Coulomb)
- Categorize events with **0n0n, Xn0n, XnXn**
  - Categories defined by cutting on the ZDC energy
- Signal and background modelling
  - Signal: Starlight+Pythia8 (LO+ FSR)
  - Semi-coherent: LPair (pp)
- Signal extraction obtained fitting acoplanarity distribution

CERN-EP-2020-138

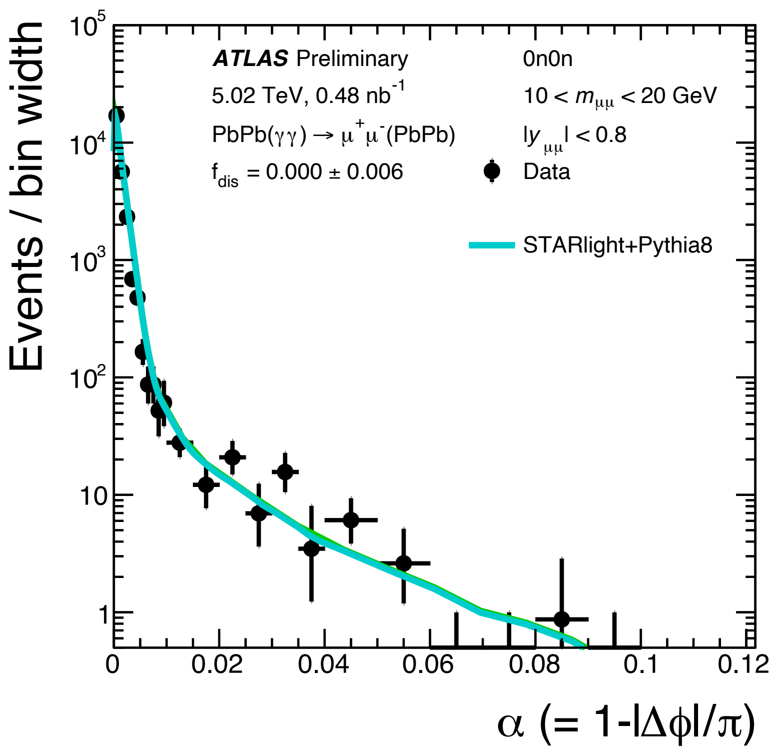




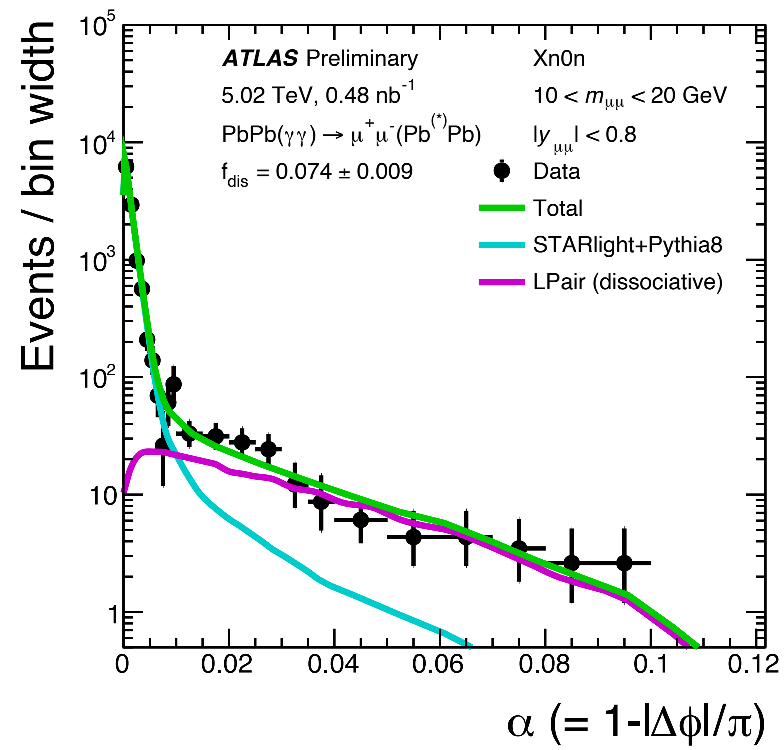
ZDC



0n0n



Xn0n

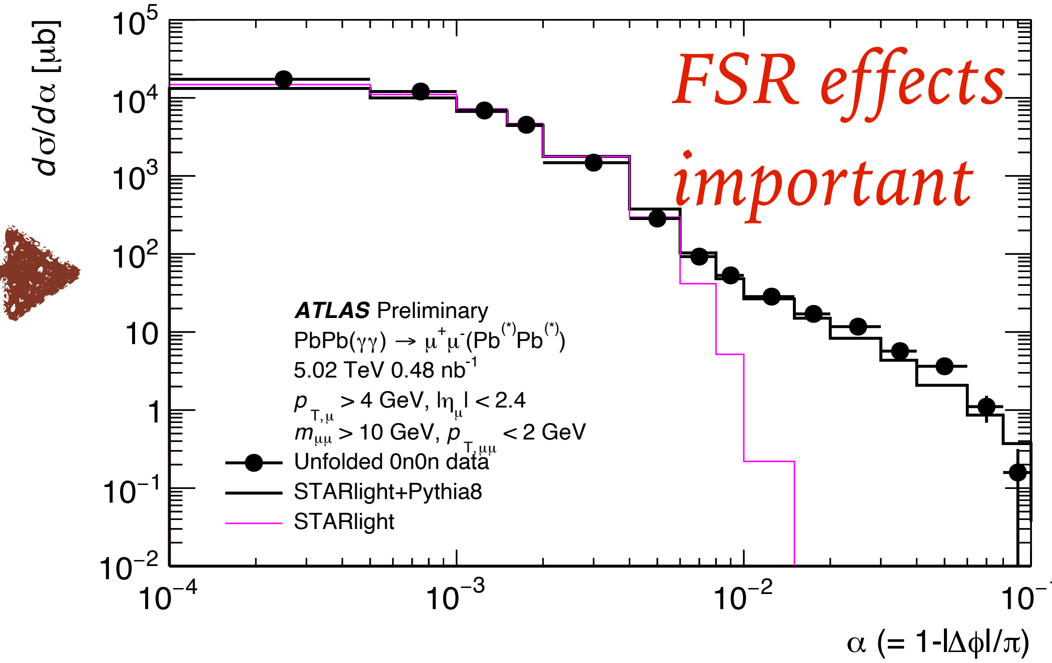


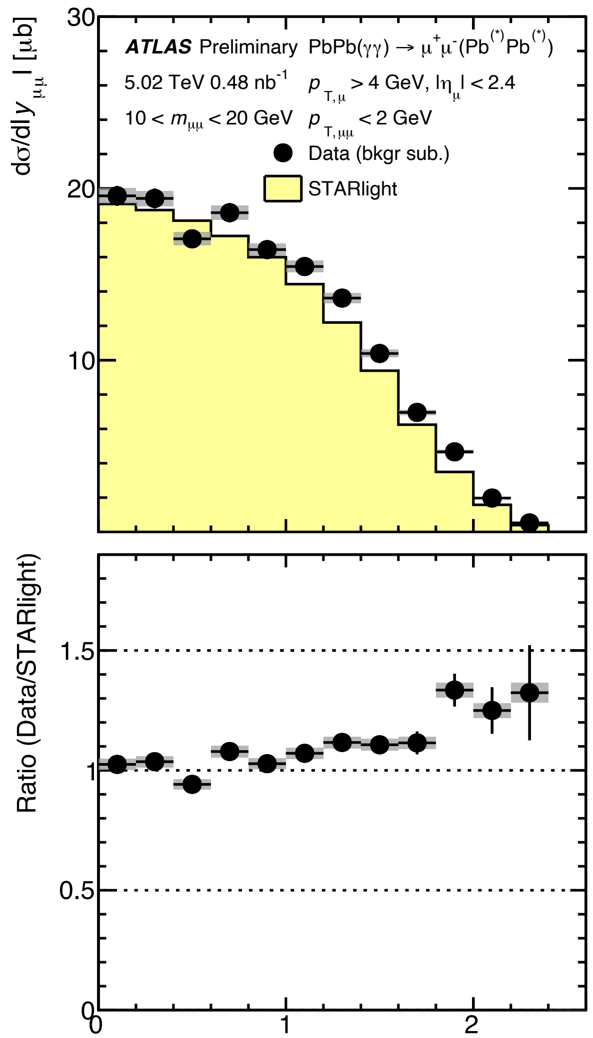
- **ZDC selections have strong effect on acoplanarity**
- LPair provides satisfactory description of dissociative background

Cross section measurement

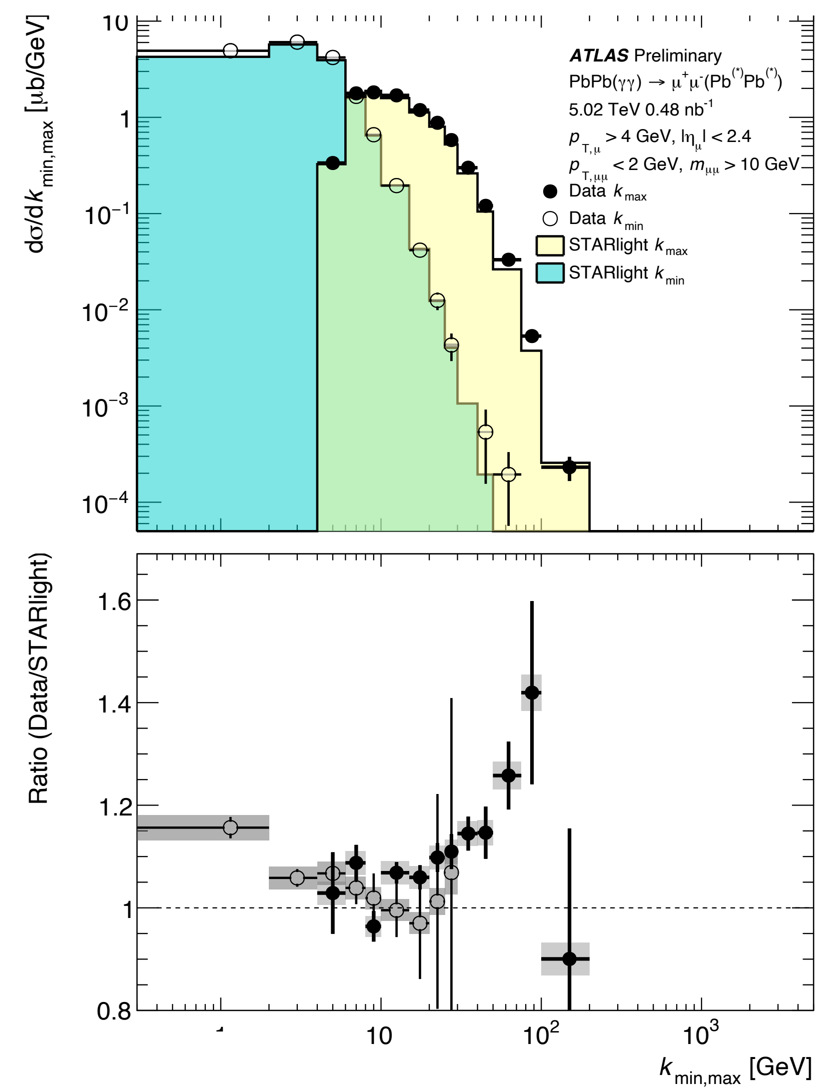
[CERN-EP-2020-138]

- Fiducial measurement as a function of
  - $m_{\mu\mu}$, $|y_{\mu\mu}|$, $\cos(\theta^*_{\mu\mu})$, Acoplanarity
- Some disagreement seen at small and high rapidity
- Interpreted as discrepancy at low and high photon energies





$$k_{\text{min,max}} = (1/2)\; m_{\mu\mu} e^{\mp y_{\mu\mu}}$$



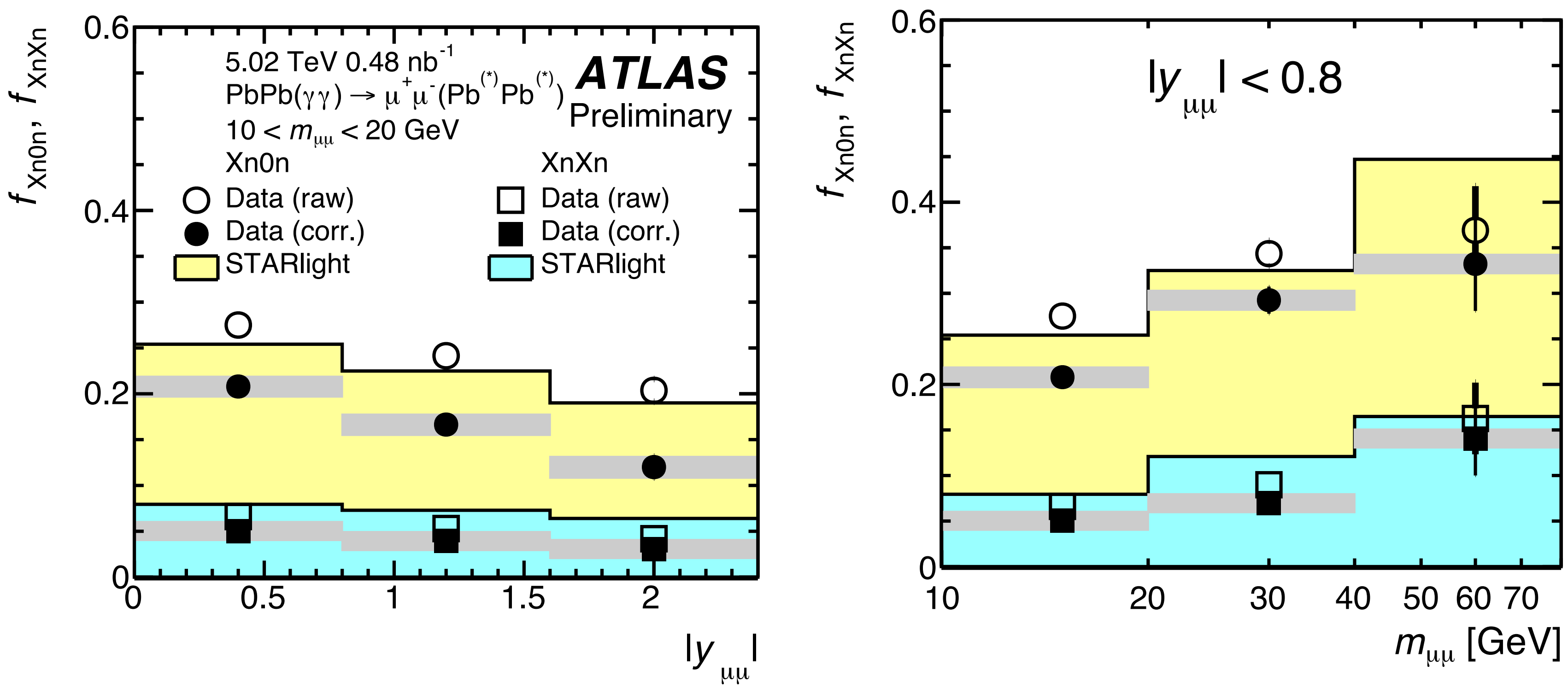
Integration limits ensuring that produced particles do not break the nucleus. Might be too strict for lepton pairs that weakly interact with nuclei.

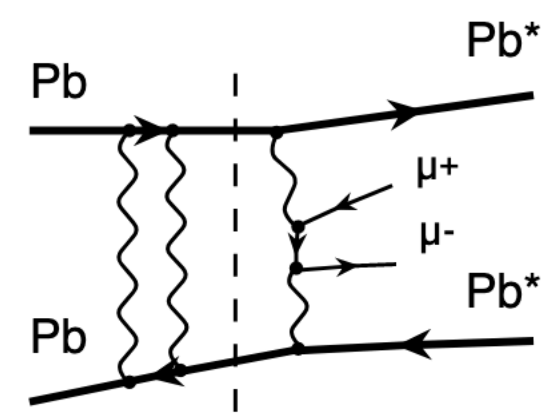
$$\frac{d^2N_{\gamma\gamma}}{dk_1 dk_2} \propto \int_{b_1>R_A} d^2b_1 \int_{b_2>R_A} d^2b_2\; n(k_1,b_1)\; n(k_2,b_2)\; P(b)$$

$\gamma\gamma \rightarrow \mu^+\mu^-$ in Pb+Pb: forward neutrons

CERN-EP-2020-138

- Measured fraction with different activity (0nXn, XnXn)
  - Impact parameter dependence of the photon fluxes
  - Sensitive to additional EM interactions between ions leading to Pb dissociation and forward neutrons
  - Correction for 'EM pileup' - other UPC PbPb interaction can produce neutrons (low pileup, but large electromagnetic dissociation cross section)
- Forward neutrons more likely to be produced in simulation

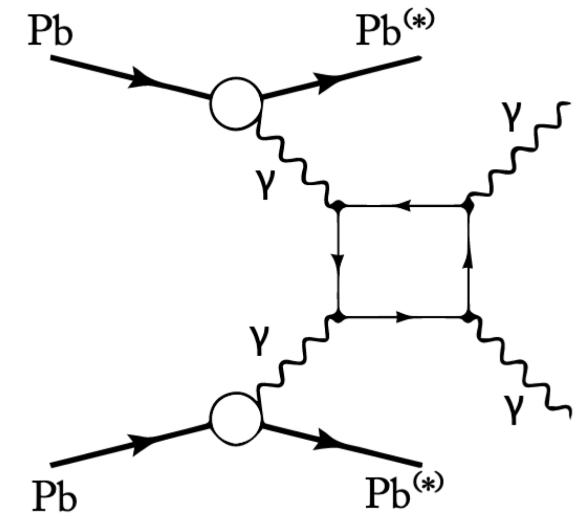




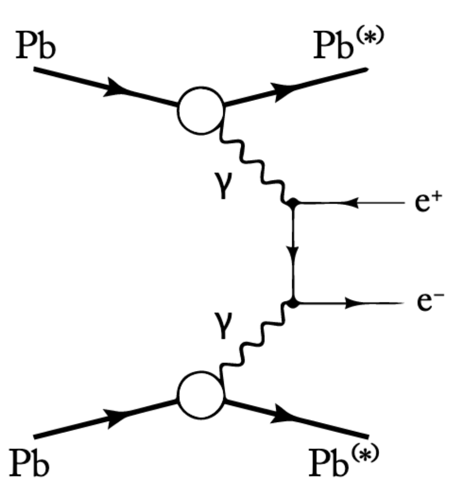
Measurement of **light-by-light scattering** and **search for axion-like particles** with 2.2 nb−1 of Pb+Pb data with the ATLAS detector [arXiv:2008.05355]

Light-by-Light Scattering in PbPb

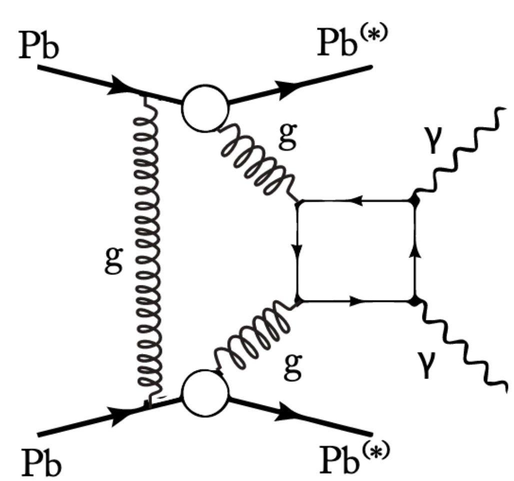
- Detector selection at the limit of ATLAS capabilities
  - Very low E_T photons, **E_T>2.5 GeV**
  - Track veto (**p_T > 100 MeV**) + pixel track veto (**p_T>50 MeV**) in the vicinity of the reconstructed electrons



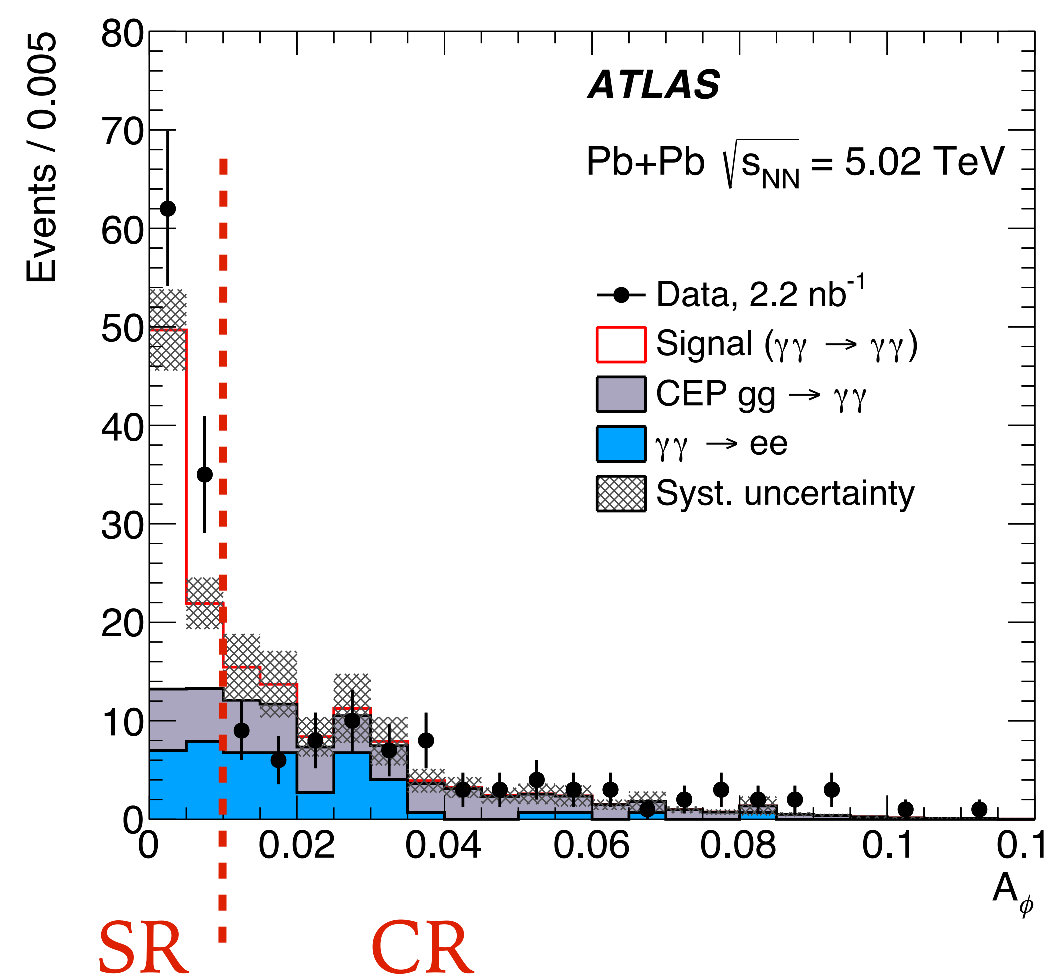
- Dedicated selections at trigger level
  - L1: Minimal energy in the calorimeters
  - HLT: Limited number of hits in Pixel, Veto in MBTS/FCal detectors
- Previous measurements
  - 2018 data: ATLAS (8.2 σ observation) PRL 123 (2019) 134826
  - 2015 data: ATLAS/CMS (~4 evidence)
    Nat. Phys. 13 (2017) 852, PLB 797 (2019) 134826
- Main backgrounds
  - $\gamma\gamma \rightarrow e^+e^-$ with 2 fake photons, CEP $gg \rightarrow \gamma\gamma$
  - Estimated using data driven methods

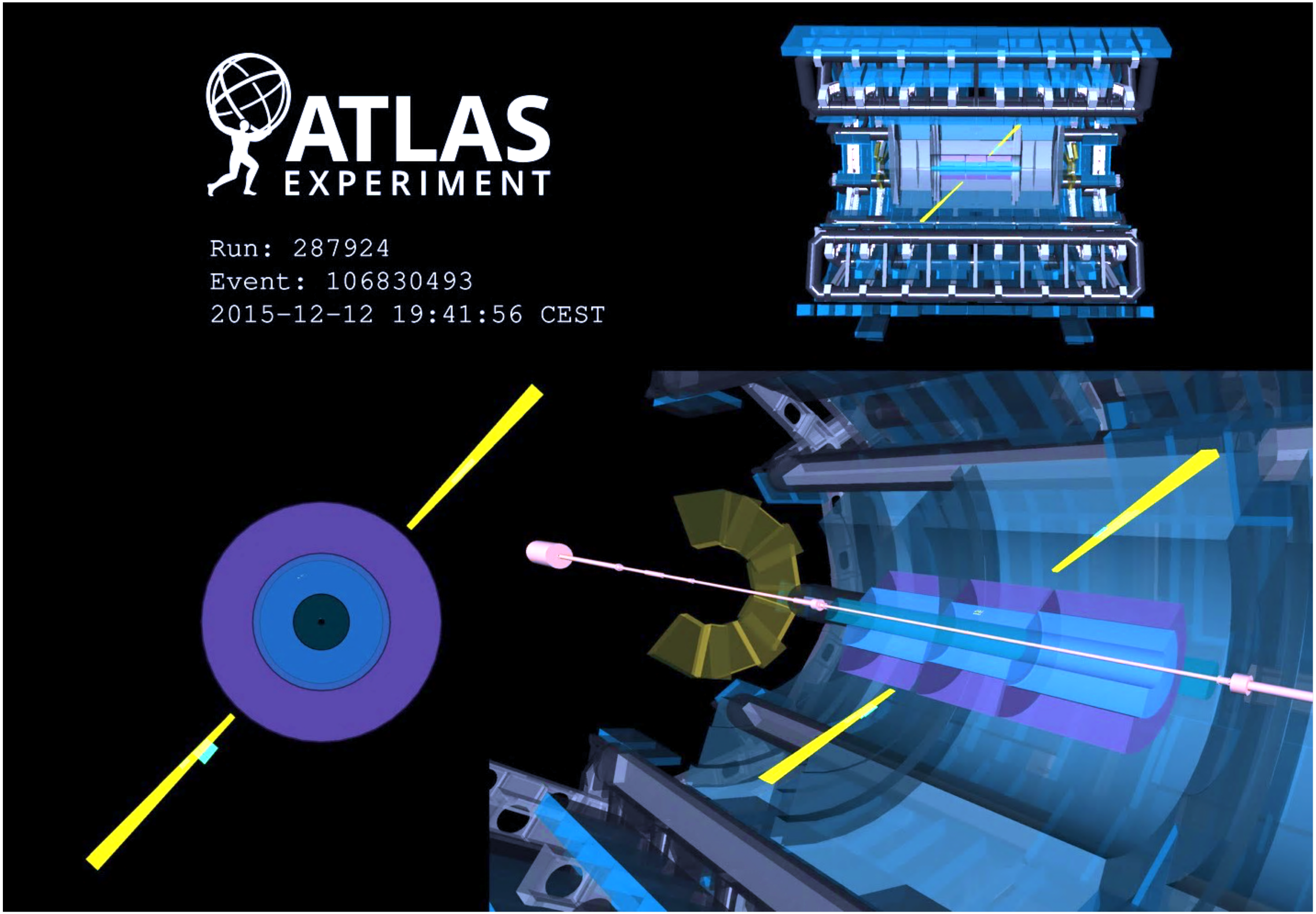


QED $\gamma\gamma \rightarrow e^+e^-$

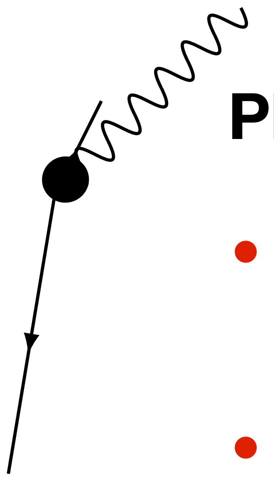


CEP $gg \rightarrow \gamma\gamma$



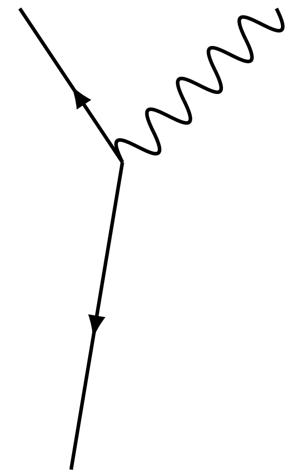

ATLAS
EXPERIMENT
Run: 287924
Event: 106830493
2015-12-12 19:41:56 CEST

Photon efficiency and ID performance



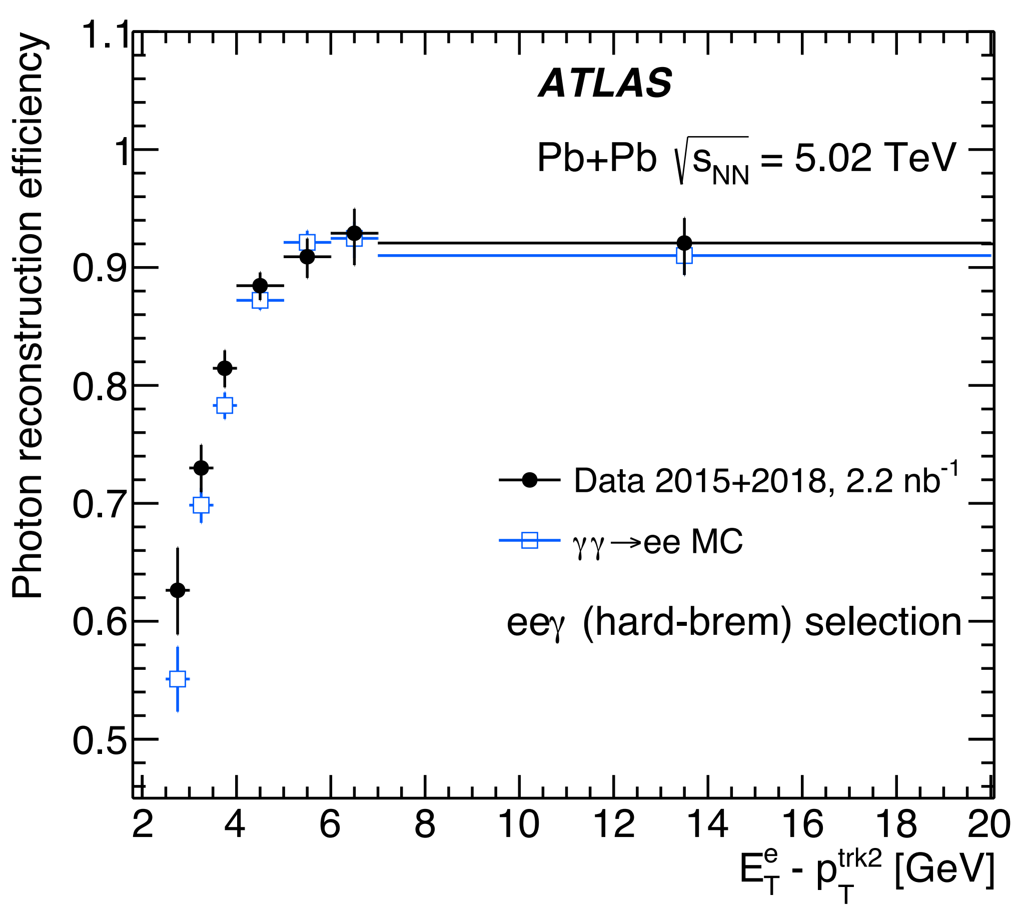
Photon efficiency

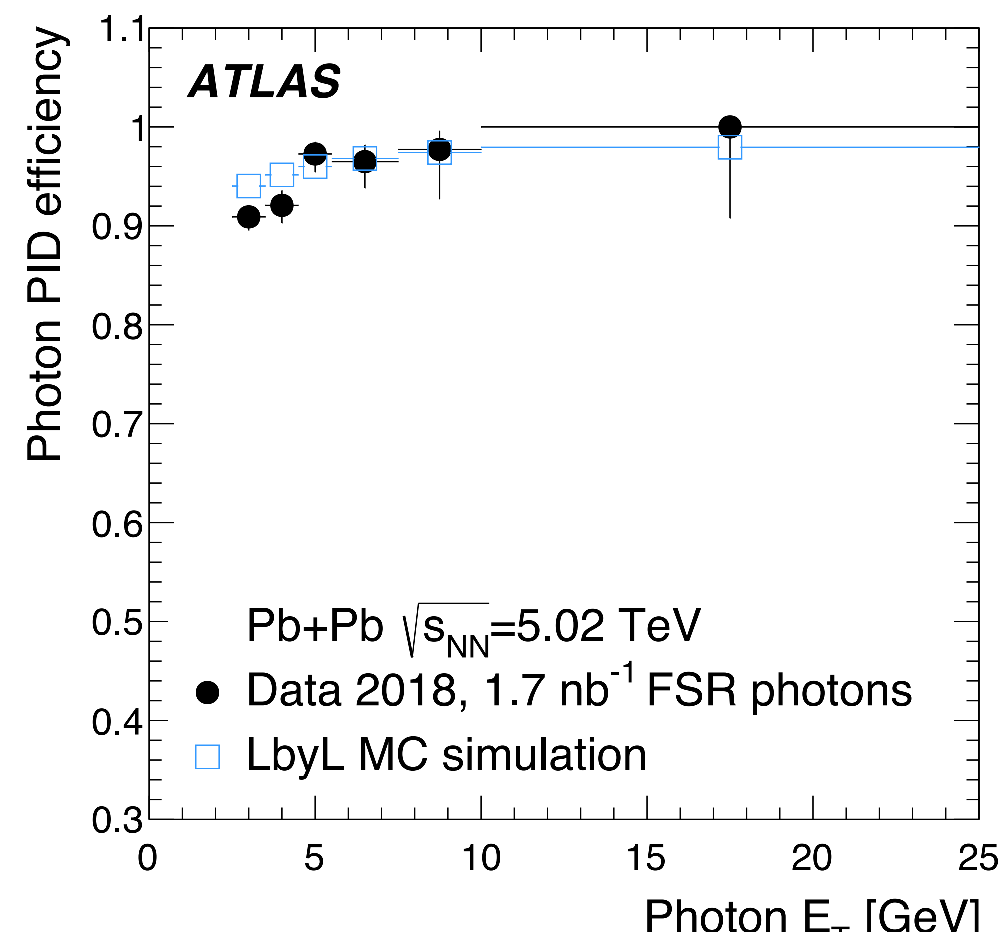
- $\gamma\gamma \rightarrow e^+e^-\gamma$ with bremsstrahlung due interaction with ID material
- 1 (tag) electron reconstructed
- 2 pixel tracks, one low-p_T



Photon identification

- $\gamma\gamma \rightarrow l^+l^-\gamma$ with hard FSR photons
- Verify photon shower shapes and efficiency for good photon to pass photon identification

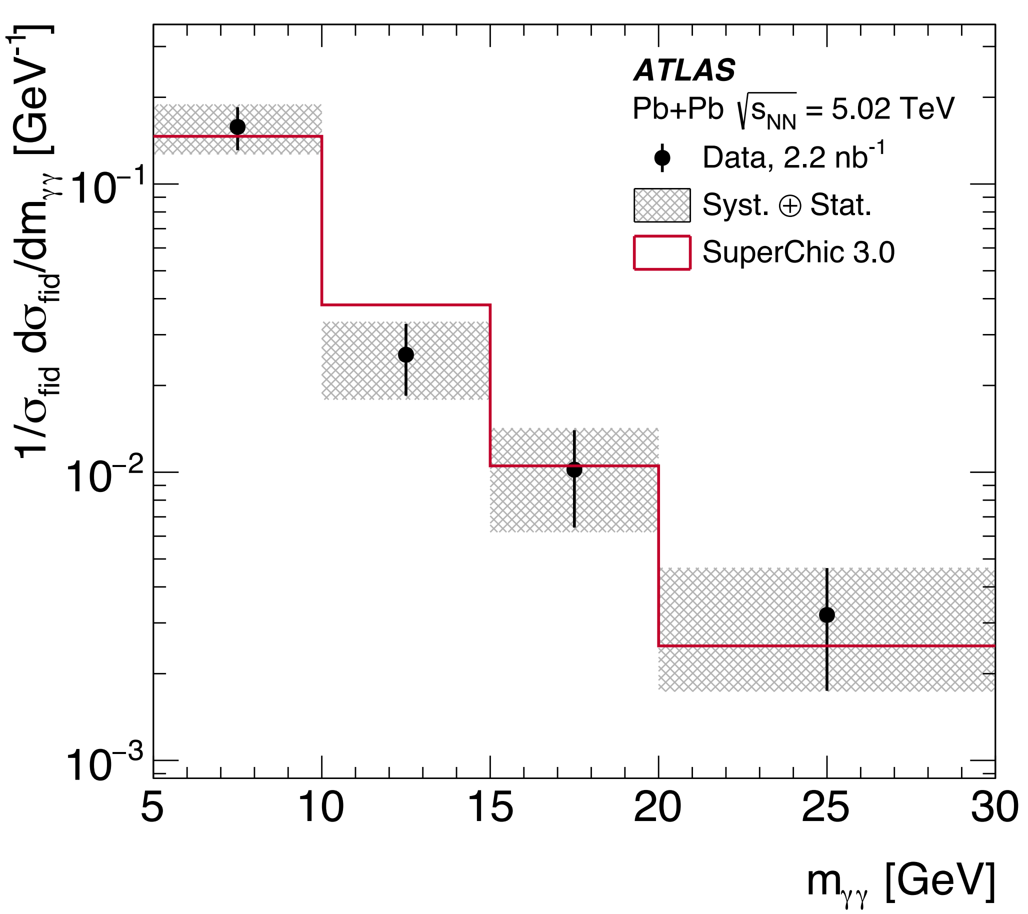


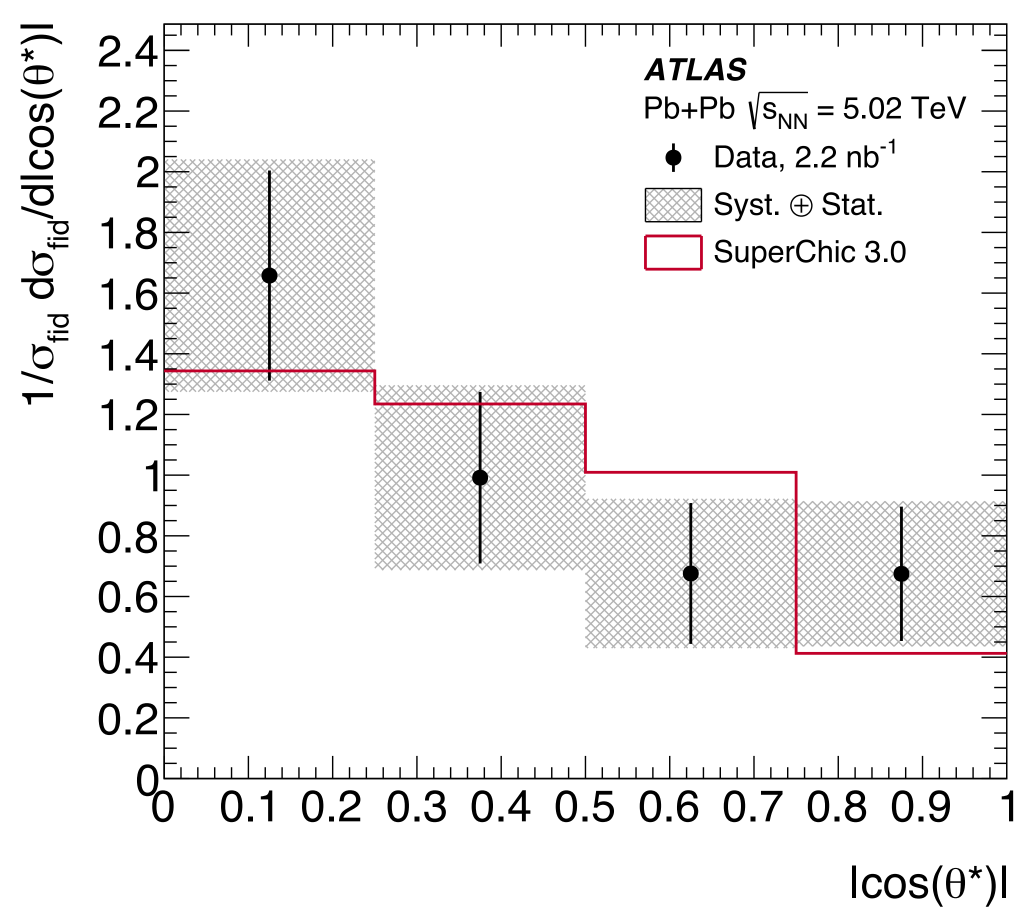


- Differences between data and MC accounted for using scale factors

2015+2018 PbPb data

- 97 events observed, 45 signal + 27 expected
- Measured cross section: $\sigma_{\text{fid}} = 120 \pm 17\ (\text{stat.}) \pm 14\ (\text{syst.}) \pm 4\ (\text{lumi.})\ \text{nb}$
  - Measurement statistically limited. Dominant sources of uncertainty: trigger efficiency, photon reconstruction eff, $\gamma\gamma \to e^+e^-$ background estimate (statistics in CR)
- Predictions: $\sigma_{\text{theory}} = 80 \pm 8\ \text{nb},\ 78 \pm 8\ \text{nb}$ (SuperChic 3.0, PRC 93 (2016) 044907)
- Distributions unfolded to particle level $(m_{\gamma\gamma},\ |y_{\gamma\gamma}|,\ (p_T^{\gamma 1} + p_T^{\gamma 2})/2,\ |\cos(\theta^*)|)$
- Cross section 1.7σ higher than predictions, shapes modeled well

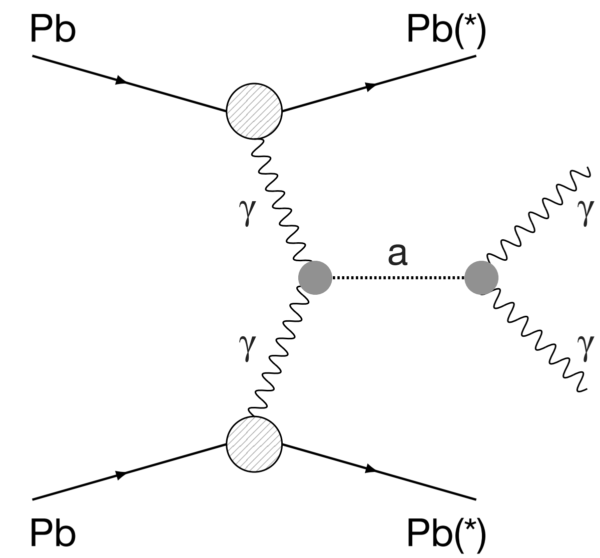


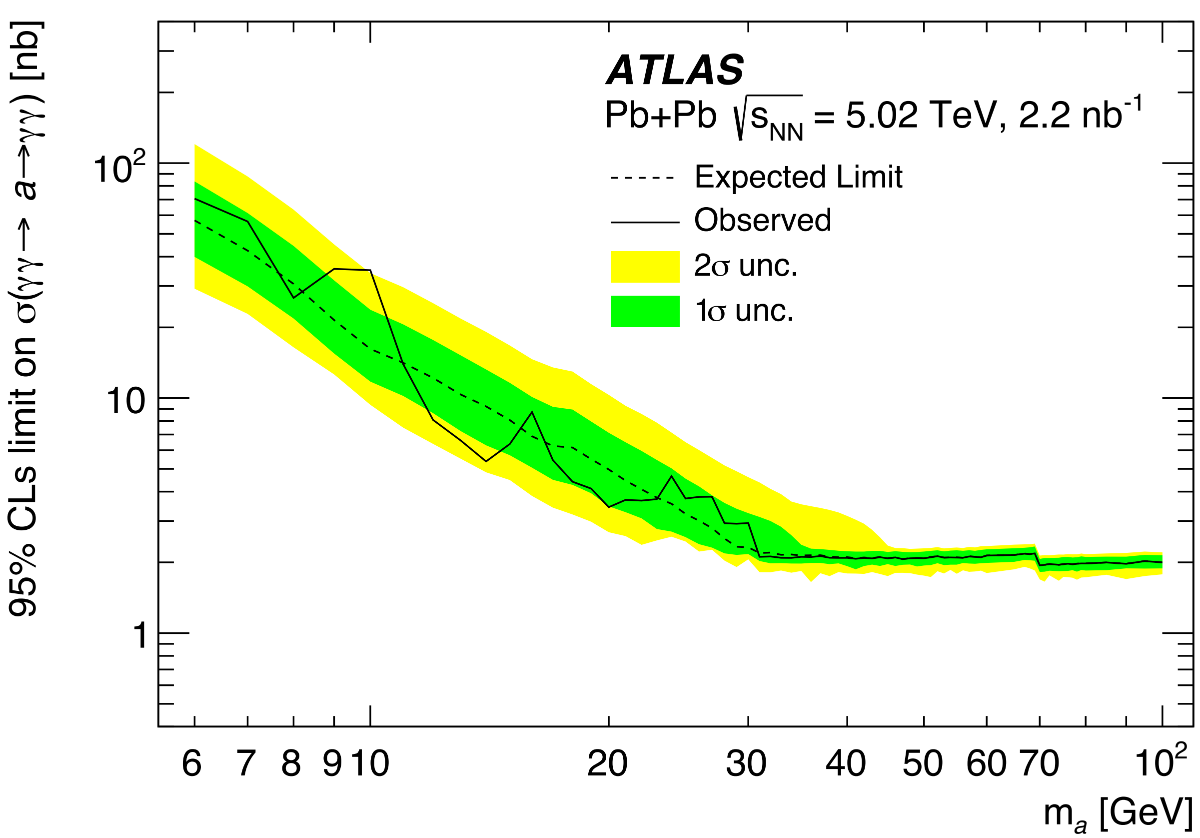


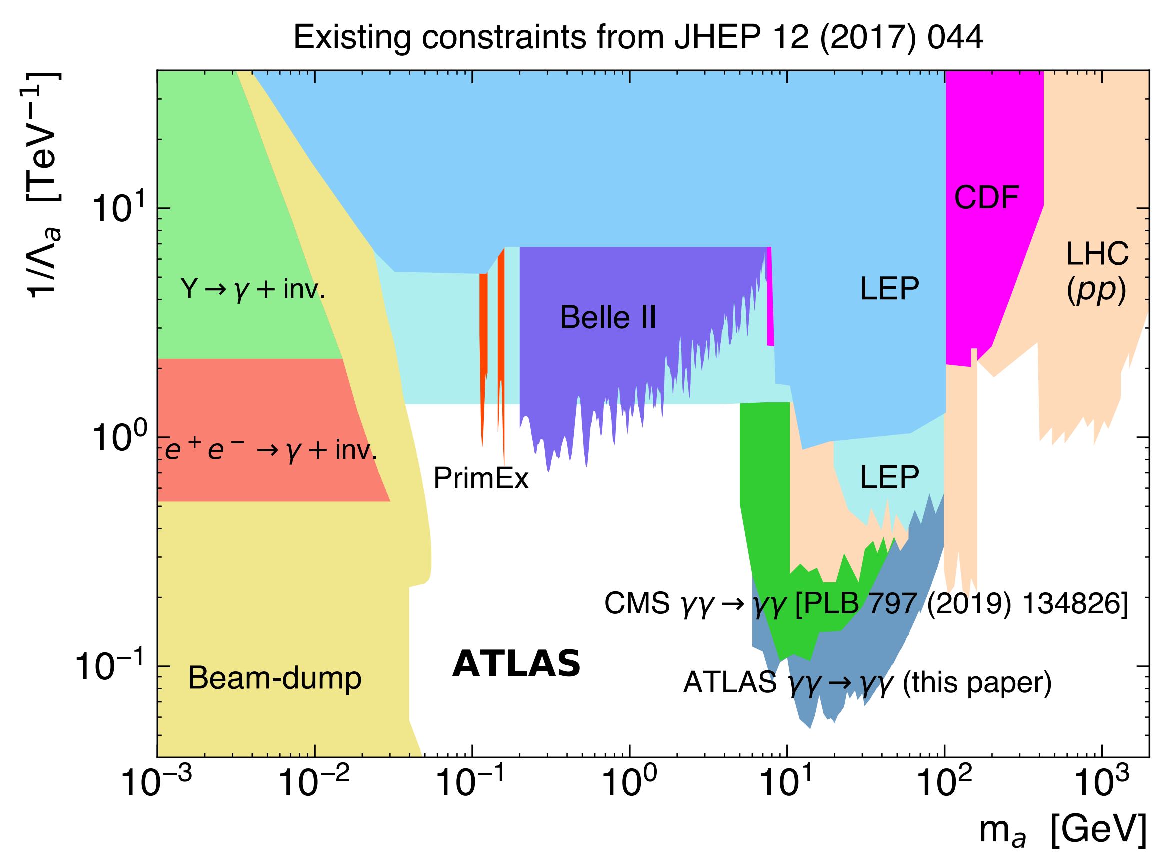
Search for Axion-Like-Particles

arXiv:2008.05355

- Search for (pseudo) scalar $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ resonance
  - Proposed as a solution to strong CP problem
  - Background includes SM LbyL, CEP $\gamma\gamma$ and ee
- Limits on $\sigma_{\gamma\gamma \rightarrow a \rightarrow \gamma\gamma}$ extracted
  - Cast into limits on $a\gamma\gamma$ coupling ($1/\Lambda_a$) assuming BR($a \rightarrow \gamma\gamma$)=1
  - Most stringent ALP limits for medium masses

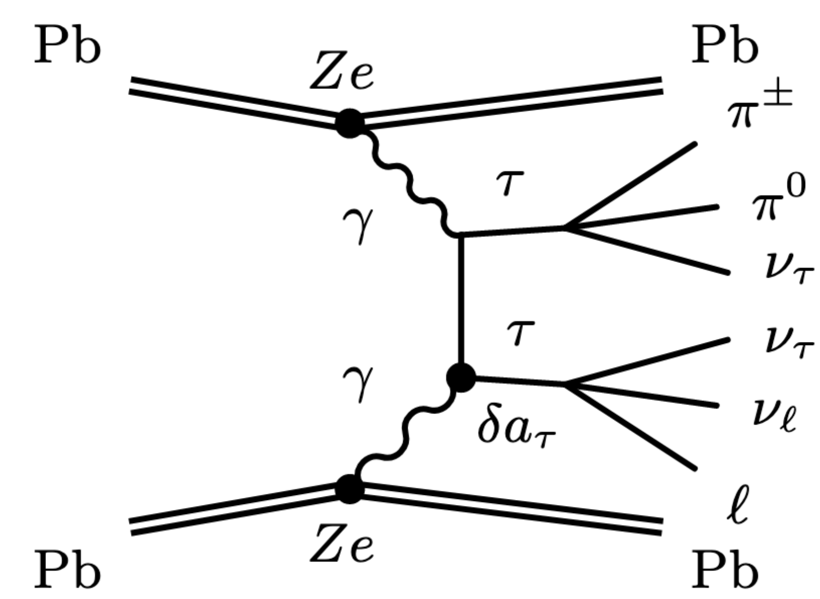




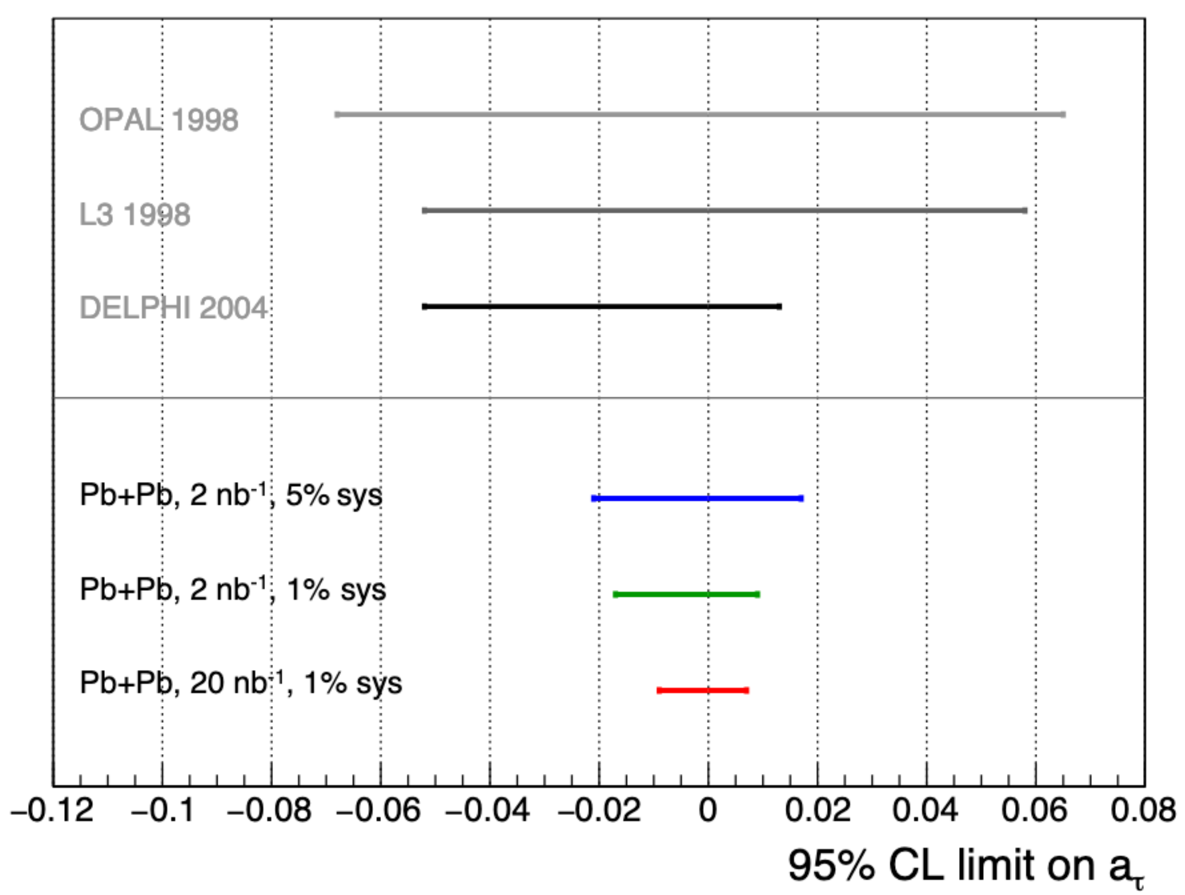


Constrain Tau g-2 in PbPb

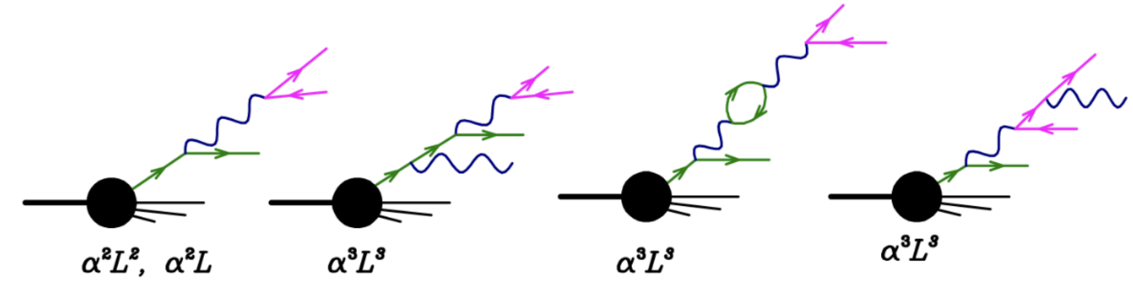
- Tau anomalous magnetic moment
  - Poorly constrained experimentally
  - BSM g-2 modifies the tau-photon coupling
  - Can be $(\mathbf{m_\tau/m_\mu})^2$ ~ 280x more sensitive to BSM than $\mathbf{a_\mu}$
- 10^6 **$\gamma\gamma \to \tau+\tau-$** produced with Run 2 PbPb dataset
- 2-3x better precision for a_τ than PDG today



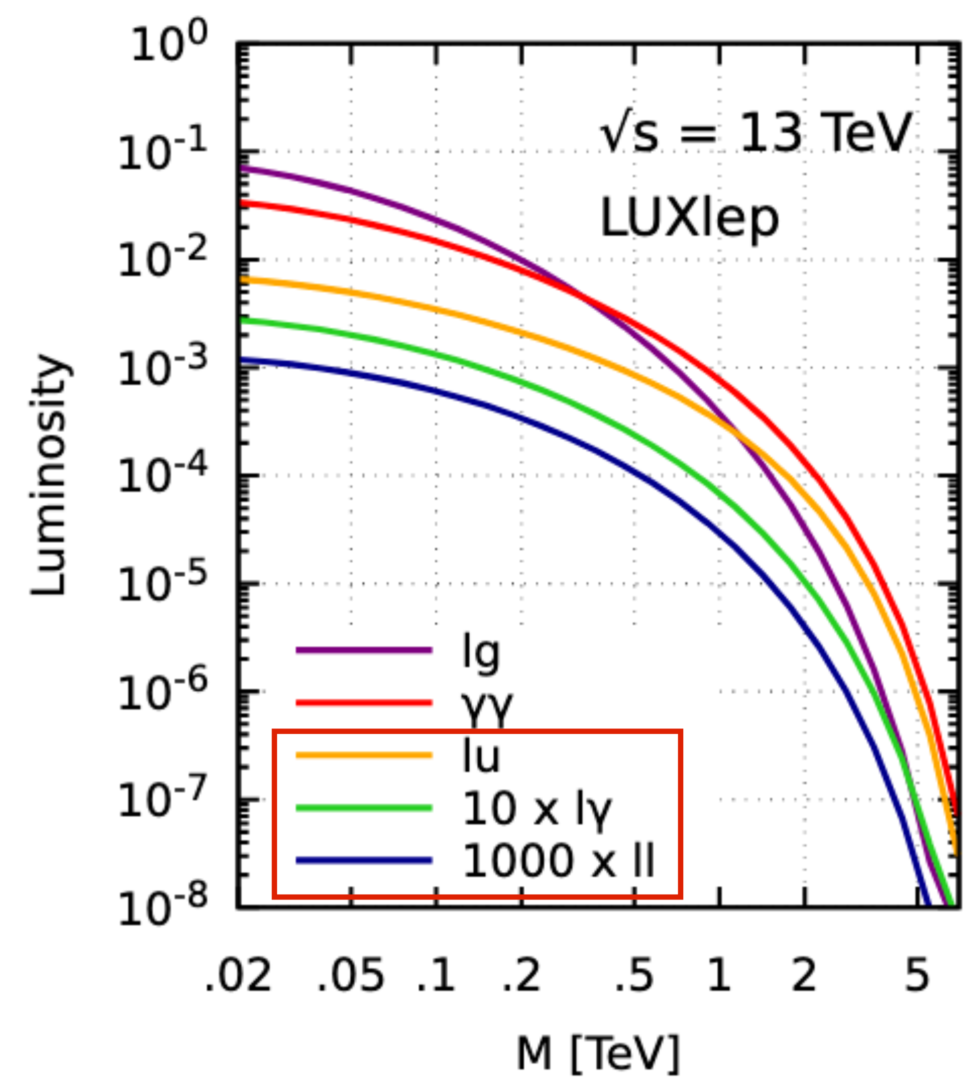
Dyndal et al [2002.05503]
See also Beresford, Liu [1908.05180]

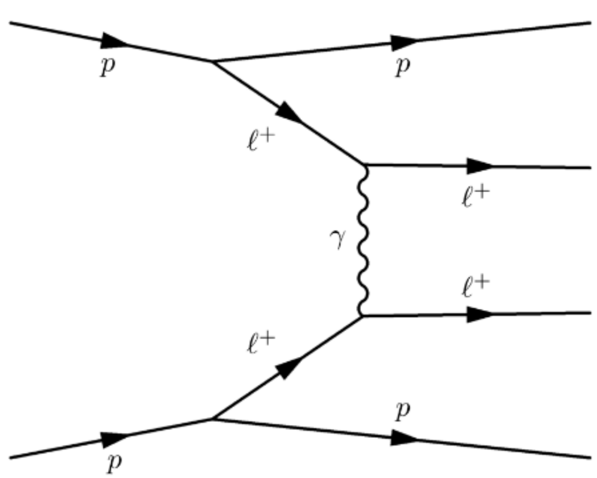


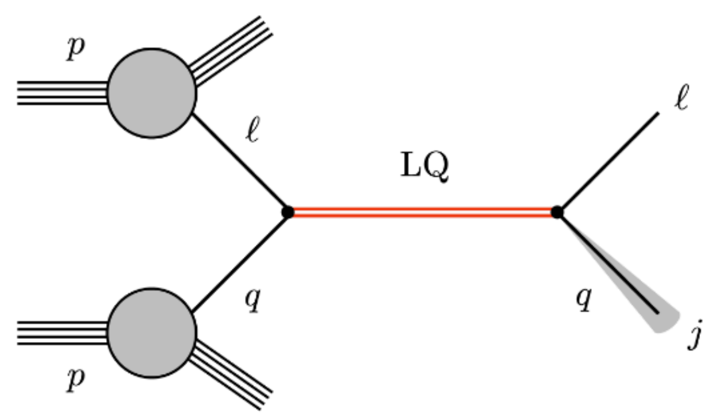
The LHC as a lepton collider



- Proton not only source photons, but also leptons!
- LUX approach applied to calculate the **lepton PDF**
- Much suppressed with respect to the QCD induced processes
- Opens some rare lepton-initiated processes and BSM productions at the LHC







	$e^+\mu^-$	$e^+\tau^-$	$\mu^+\tau^-$	e^+e^+	$\mu^+\mu^+$	$\tau^+\tau^+$
$\sigma_{13\,\mathrm{TeV}}$ [fb]	$0.29^{+0.13}_{-0.10}$	$0.18^{+0.11}_{-0.08}$	$0.16^{+0.10}_{-0.07}$	$0.24^{+0.10}_{-0.08}$	$0.19^{+0.09}_{-0.07}$	$0.08^{+0.06}_{-0.04}$
$\sigma_{27\,\mathrm{TeV}}$ [fb]	$0.53^{+0.25}_{-0.18}$	$0.34^{+0.21}_{-0.15}$	$0.30^{+0.19}_{-0.14}$	$0.440^{+0.19}_{-0.14}$	$0.34^{+0.16}_{-0.12}$	$0.14^{+0.12}_{-0.07}$

L. Buonocore, P. Nason, F. Tramontano & G. Zanderighi: JHEP 08 (2020) 019

Summary

- **Photon-induced events are excellent laboratory to test EW physics**

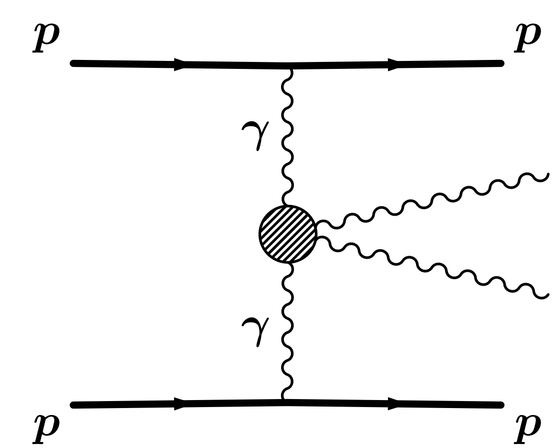
- Several new EW measurements using full Run2 in pp and PbPb
- **Proton tagging** can be used to enhance S/B or look for BSM signatures (110 fb^{-1} data available to be analyzed with CMS+PPS, 14.6 fb-1 with ATLAS+AFP)
- Mainly WW and $\gamma\gamma$, measurements can easily be extended to other FS (ZZ, WZ …)

- **PbPb UPC collisions** are significant part of the program. Look for signatures that are unreachable in high-pileup pp environment.

Thanks for your attention!

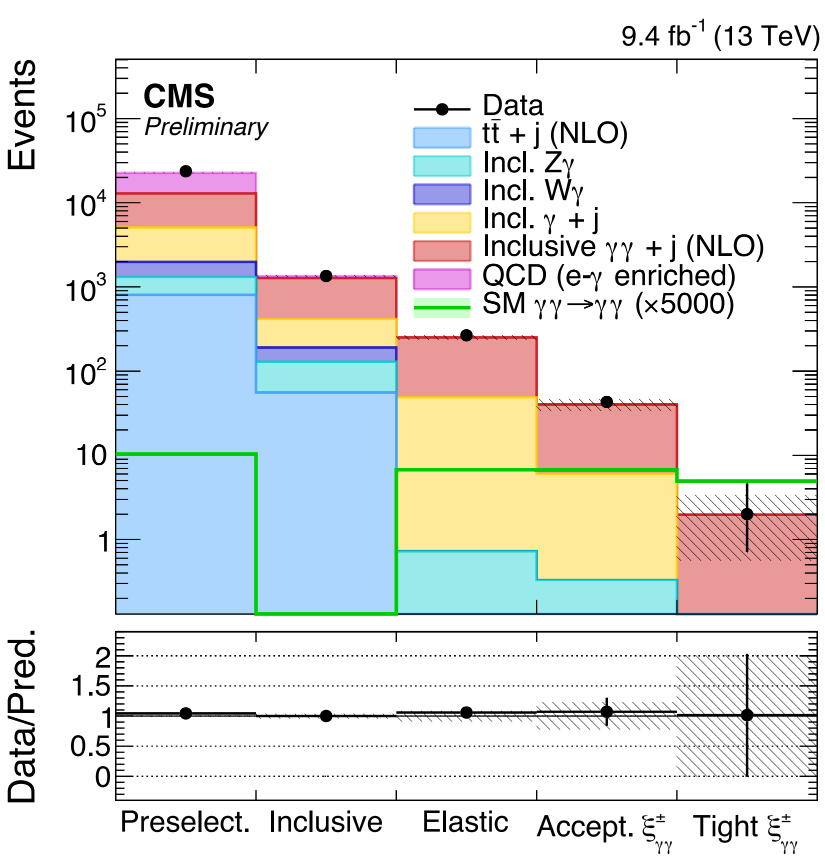
LbyL with tagged protons in CMS

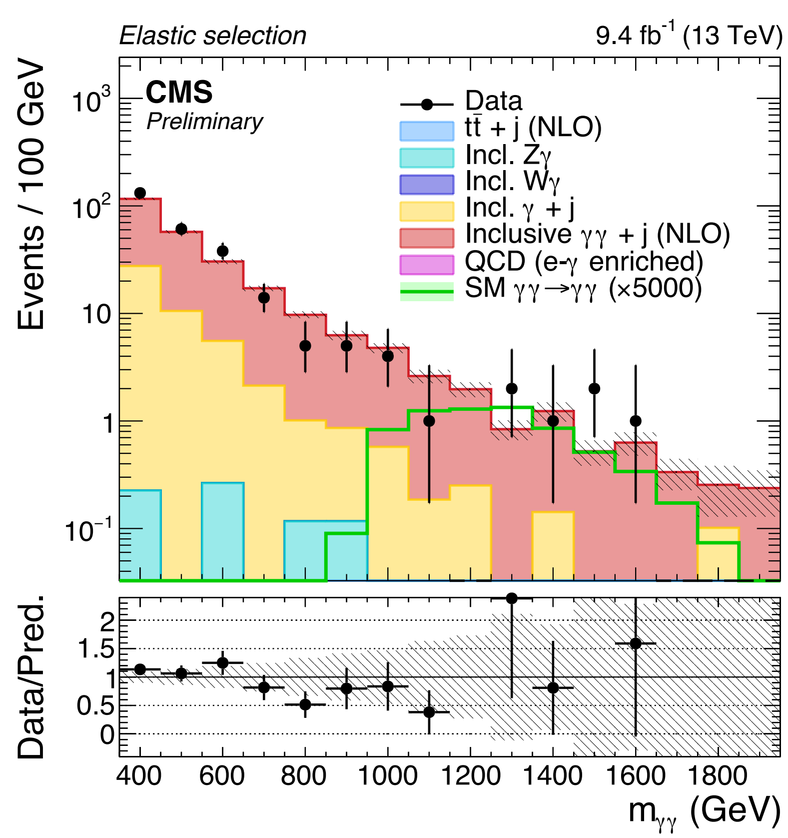
EXO-18-014, TOTEM 2020-003



- Goal: Search for anomalous 4-photon couplings at high mass $m_{\gamma\gamma}$>350 GeV
- Data collected in 2016, 9.6fb-1, will be extended to total of 110 fb^{-1} of Run2
- Extension of SM dim-8 charge-parity conserving operators

$$L_8^{\gamma\gamma\gamma\gamma} = \zeta_1 F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2 F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu}$$





- No events observed when mass/rapidity matched between di-photons and forward protons
- Limits on anomalous couplings

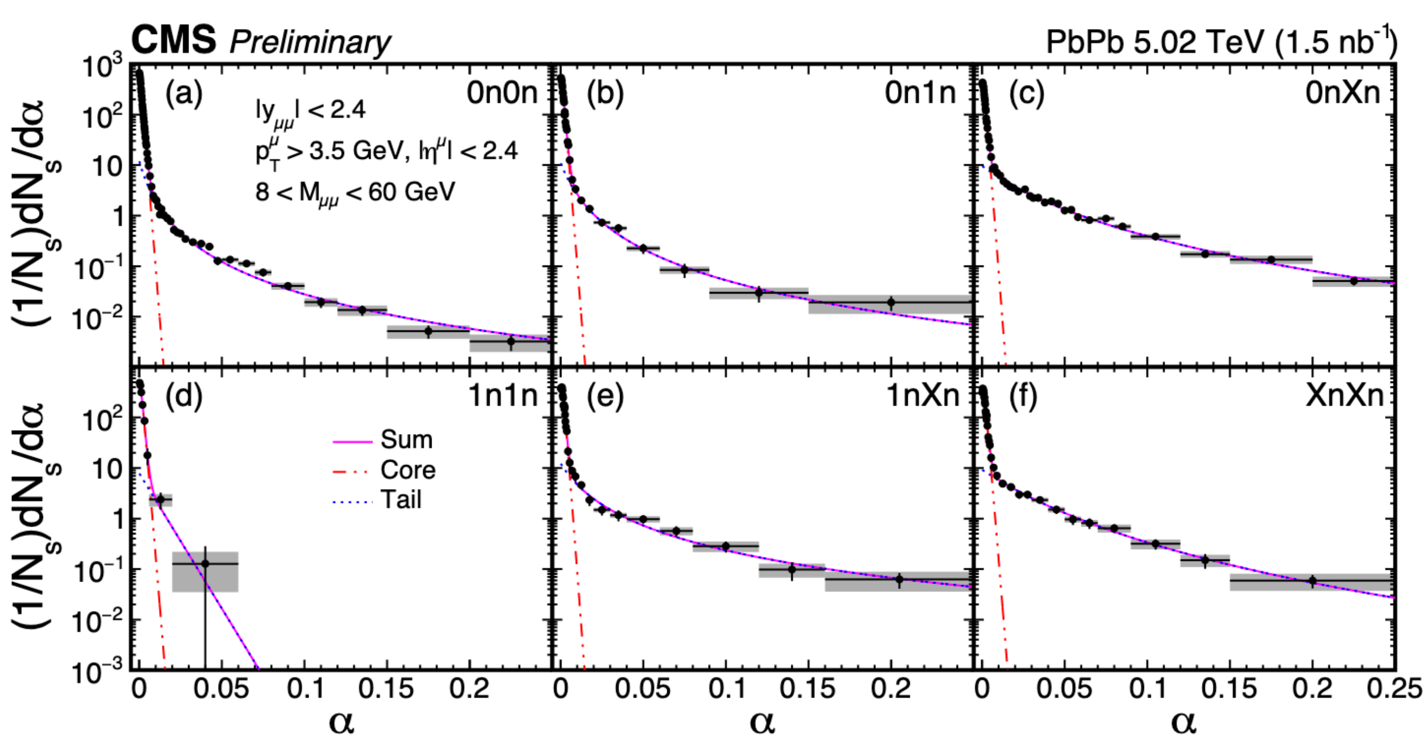
$$|\zeta_1| < 3.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_2 = 0)$$
$$|\zeta_2| < 7.7 \times 10^{-13}\ \mathrm{GeV}^{-4} \quad (\zeta_1 = 0)$$

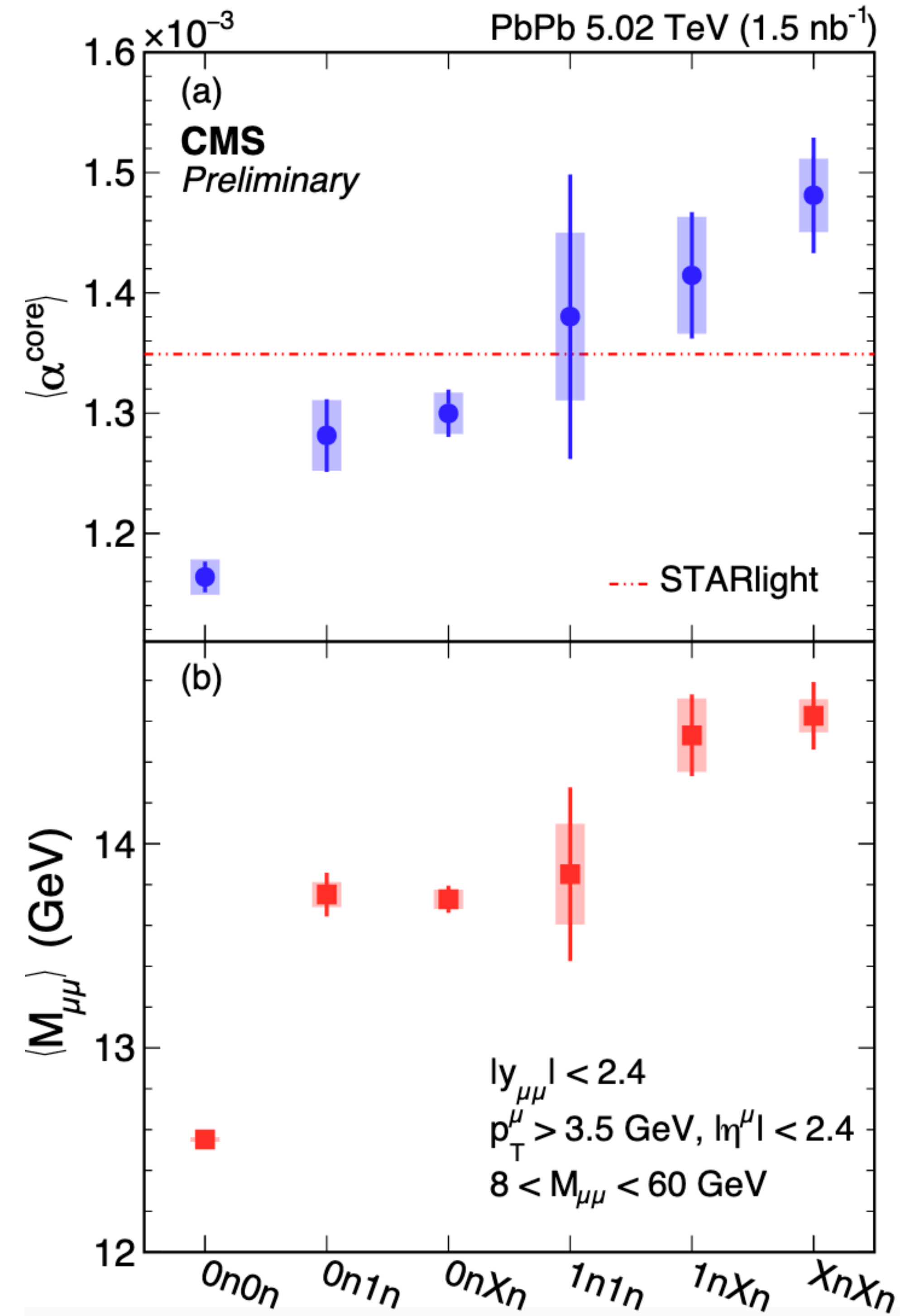
266 events with elastic selection $1 - |\Delta\phi|/\pi < 0.005$

Exclusive dimuons in UPC Pb+Pb in CMS

CMS HIN-19-014

- Determine neutron multiplicity from ZDC
- Strategy: agnostic to signal and background modelling
- Fit core and tail in acoplanarity distribution
- Strong dimuon acoplanarity and mass observed as function of forward neutron multiplicity
- Demonstrates impact parameter dependence of p_T and E of the photon fluxes





Photon PDFs and interface to generators

- PDF sets using modern LuxPDF approach
- Elastic, inelastic, and combined versions

LUXqed17_plus_PDF4LHC15_nnlo_100
NNPDF31_nlo_as_0118_luxqed
NNPDF31_nnlo_as_0118_luxqed
MMHT2015qed_nnlo_total
MMHT2015qed_nnlo_inelastic
MMHT2015qed_nnlo_elastic

- The use of these PDFs in generators would benefit from improvements
  - Modules responsible for showering should not touch the 'elastic' proton

- **Example**: single dissociative production in MG5_aMC@NLO+Pythia8
  - Too much radiation despite setting appropriate parameters (BeamRemnants:unresolvedHadron)
  - Pythia8 runs FSR on the intact proton (hadronization behaves correctly)
  - Charged particle spectra re-weighted to LPair to make of the SD sample
- LPair can only $\gamma\gamma \to e^+e^-, \mu^+\mu^-$ and uses obsoleted Suri-Yennie photon structure functions obtained at small Q^2
- Superchic 4.0+Pythia8: $\gamma\gamma \to l^+l^-$ production for EL/SD/DD. WW in the future.

$\gamma\gamma \to ll$ tagged photon-induced events in CMS

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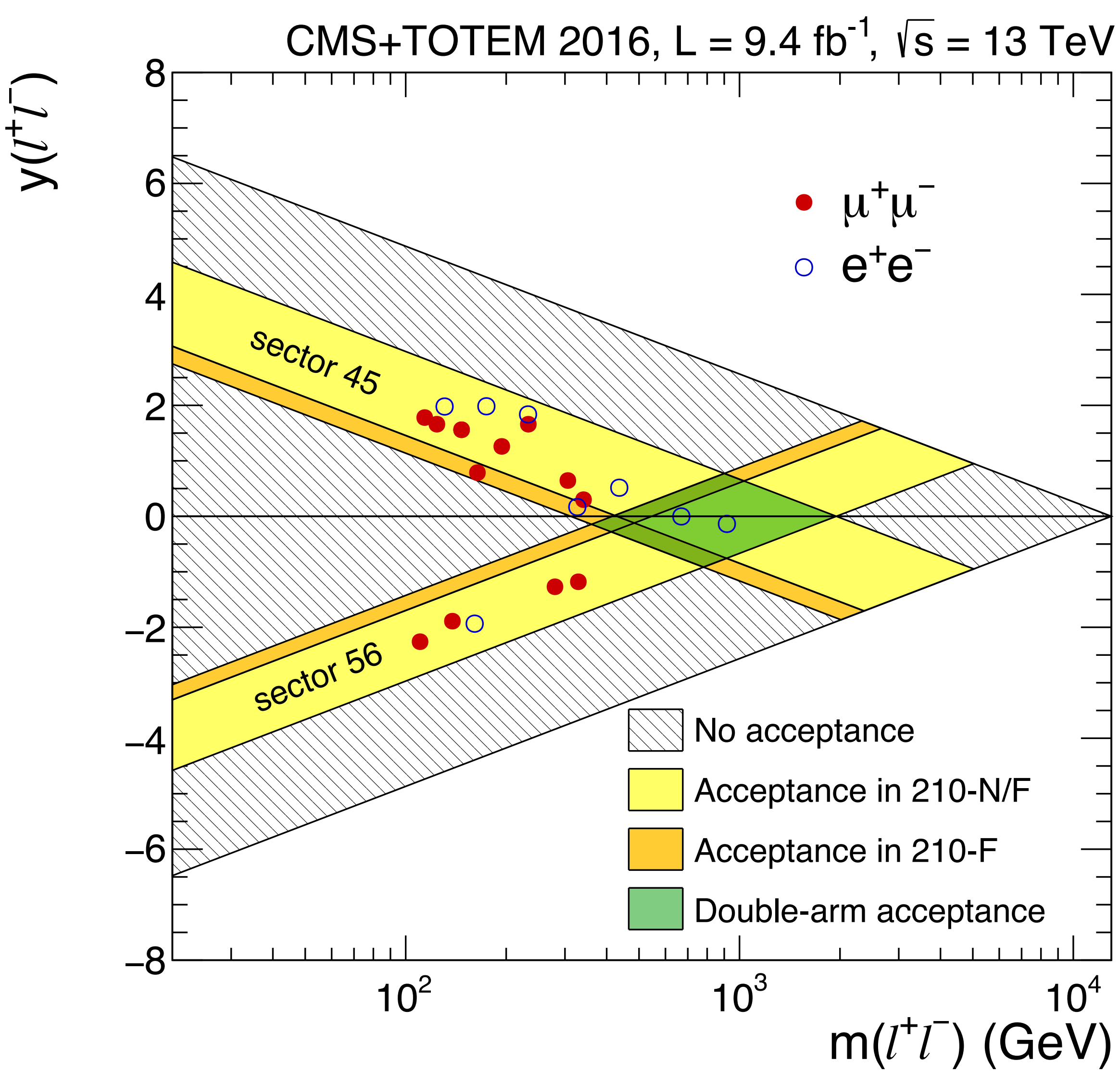
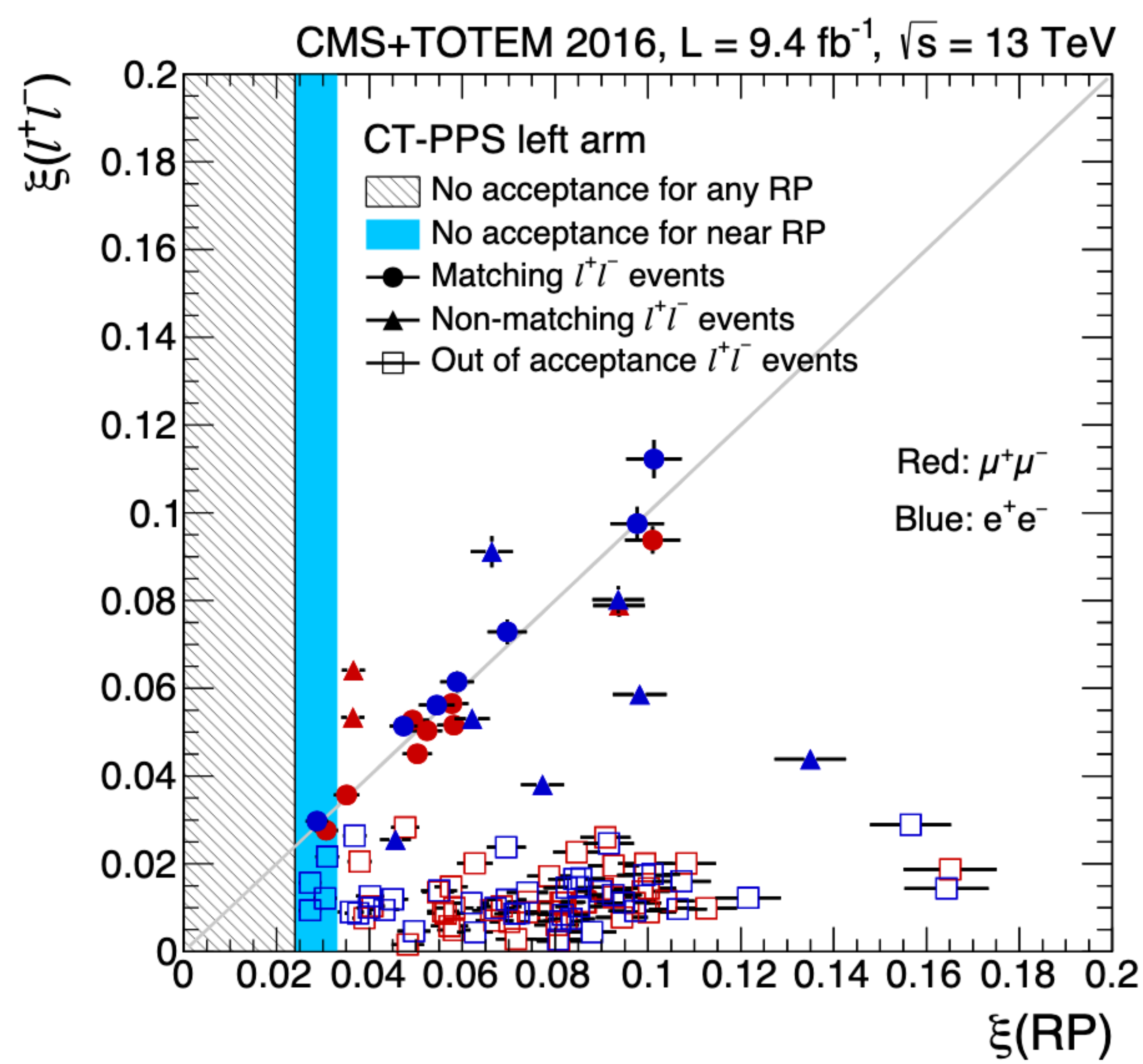
- Only 1 proton tag required to increase acceptance
- No charged particle tracks in additional to the leptons
- Acoplanarity and $p_T(ll)$ selections

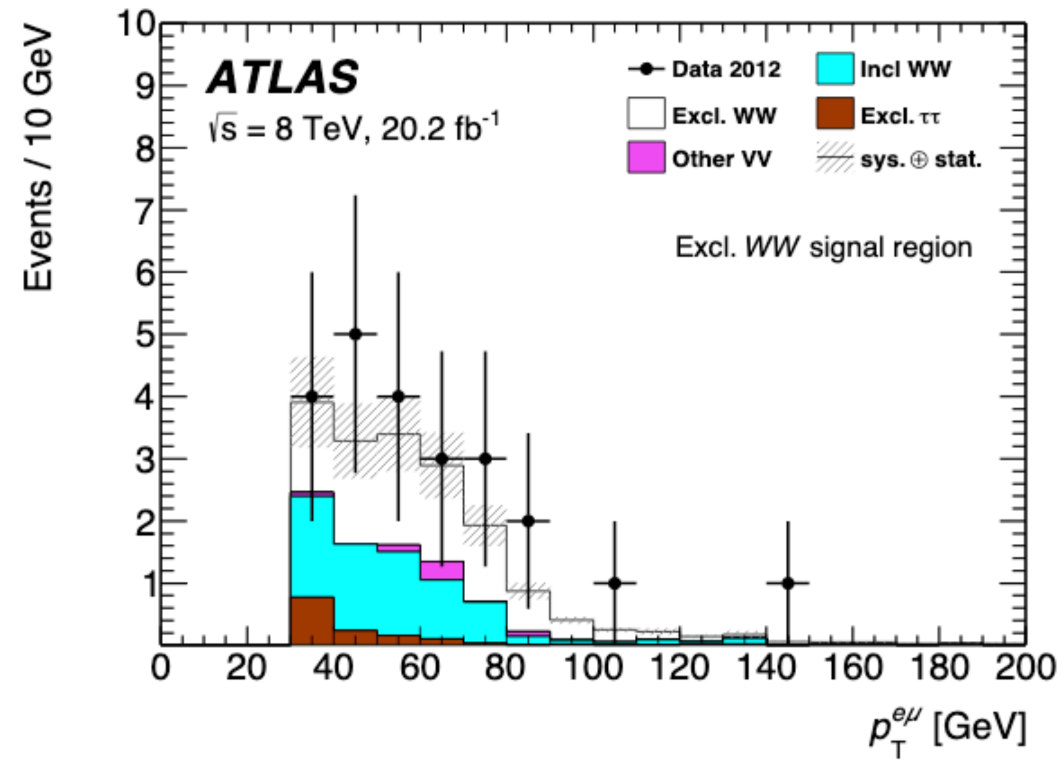
- 17 $\mu^+\mu^-$ and 23 e^+e^- events with a kinematic match between leptons and th
- First observation of proton-tagged γγ collisions at the electroweak scale when ee/mm combined

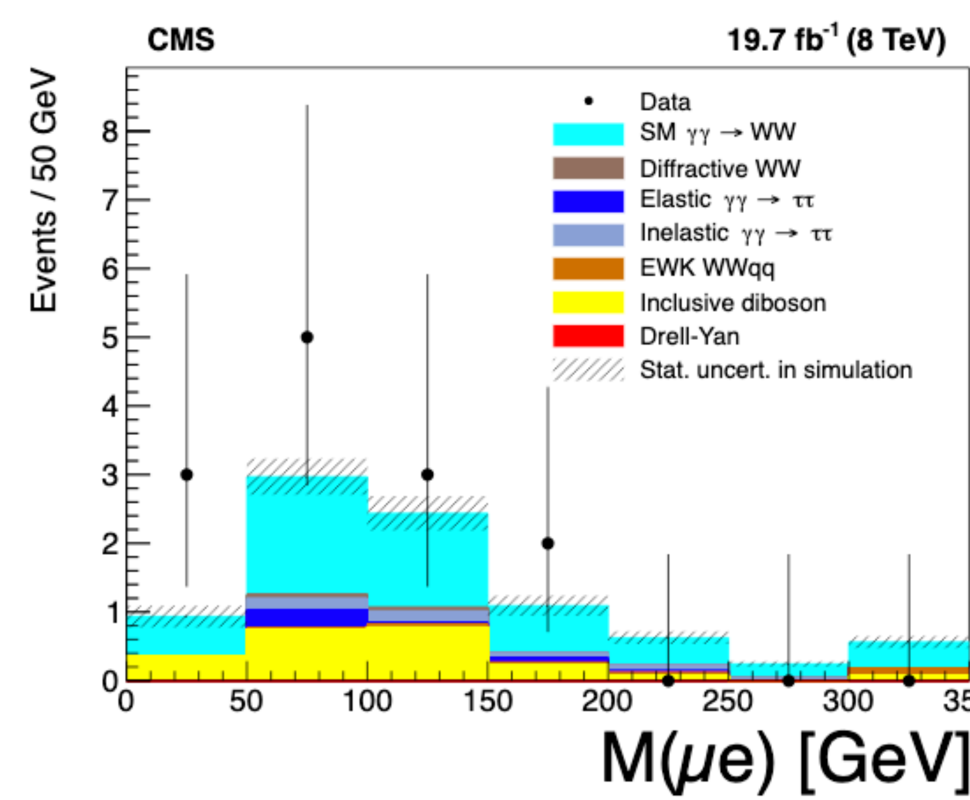




$\gamma\gamma \to$ WW: Previous measurements

- 3σ evidence with Run 1 data by ATLAS/CMS
- ATLAS 8 TeV measurement arXiv:1607.03745
  - 23 observed events, 8.3±2.6 expected background events
- CMS 7+8 TeV measurement arXiv:1604.04464
  - 13 observed events with 3.9±0.6 expected at 8 TeV
- Similar sensitivity between ATLAS/CMS on anomalous quartic coupling
- At the time, up to factor ~10 better sensitivity than inclusive WWγ measurements

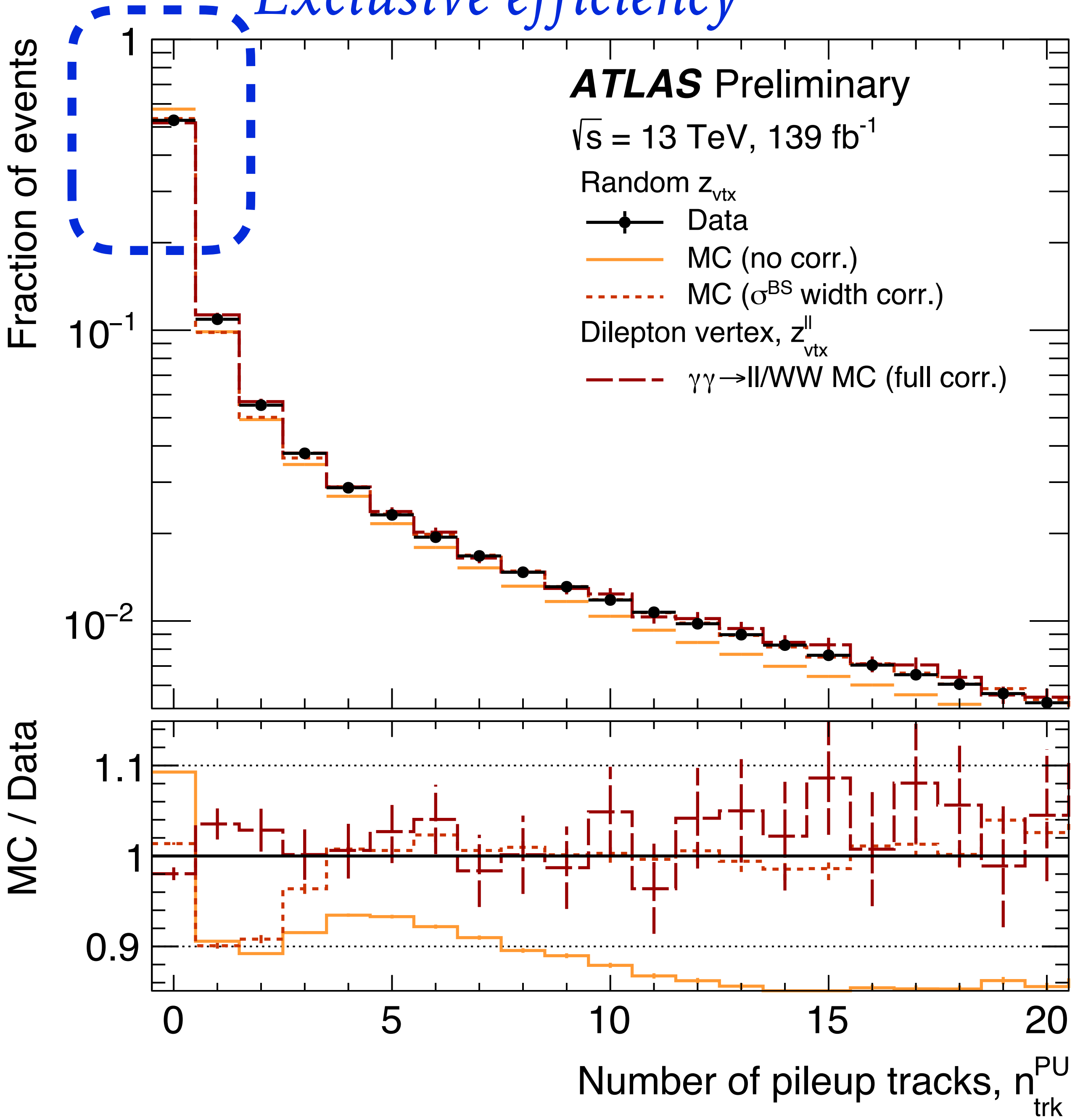


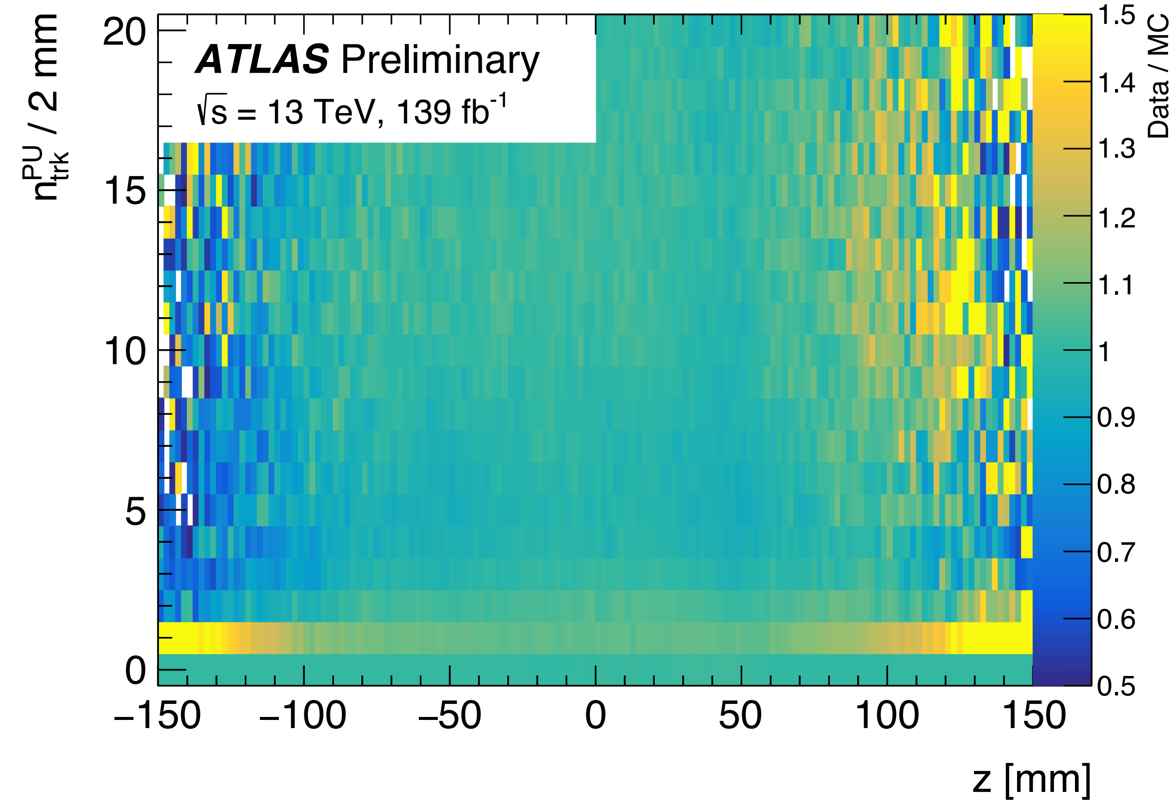


Pileup correction

- Pileup correction applied as a function of $z_{vtx}^{\ell\ell}$ and number of pileup tracks

Exclusive efficiency





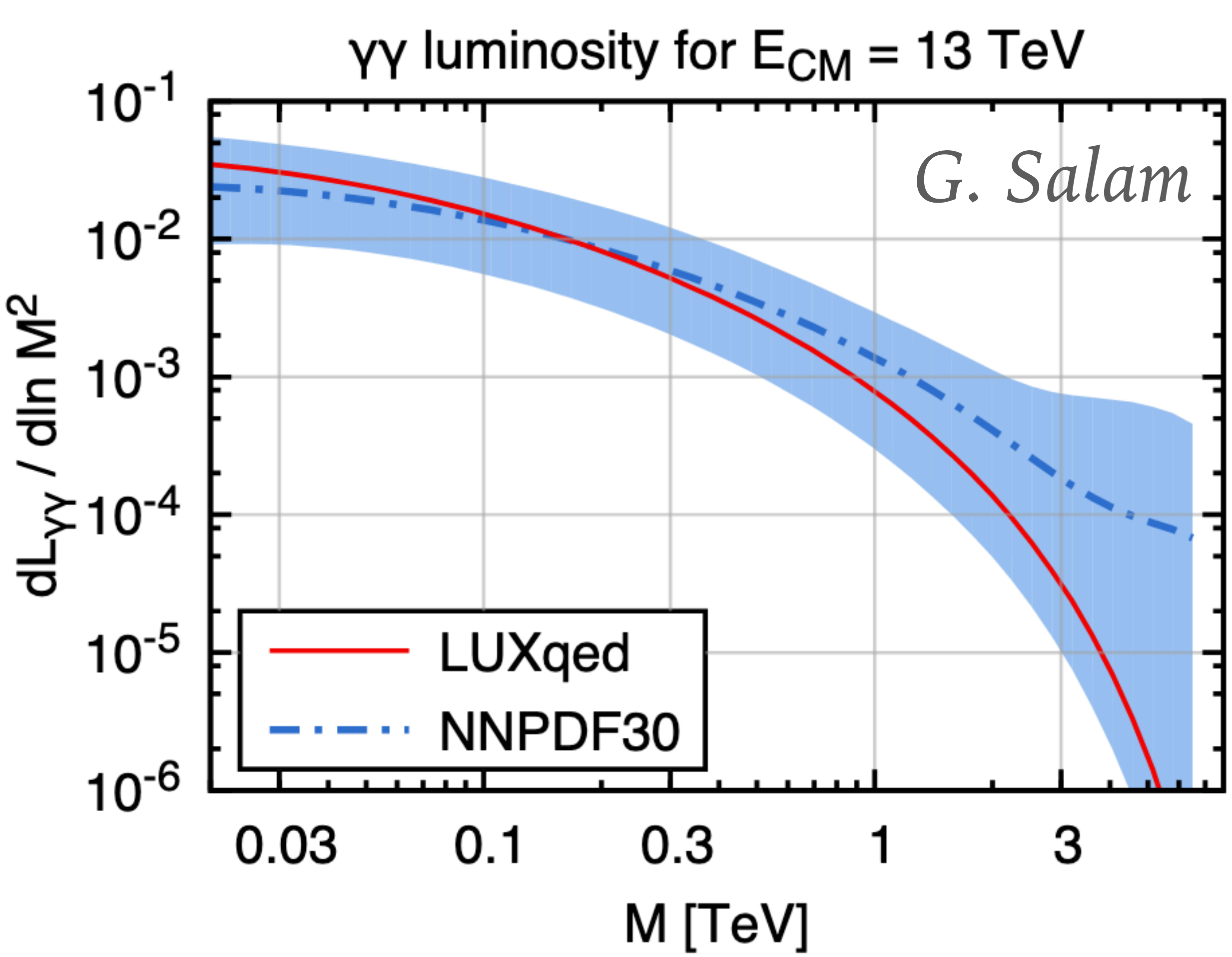
- Excellent modelling of the expected number tracks around lepton vertex after trk z0 scaling and pile-up correction
- Obtained by folding in the beam spot distribution
- n_{trk}^{PU}=0 → signal selection efficiency due to track selection

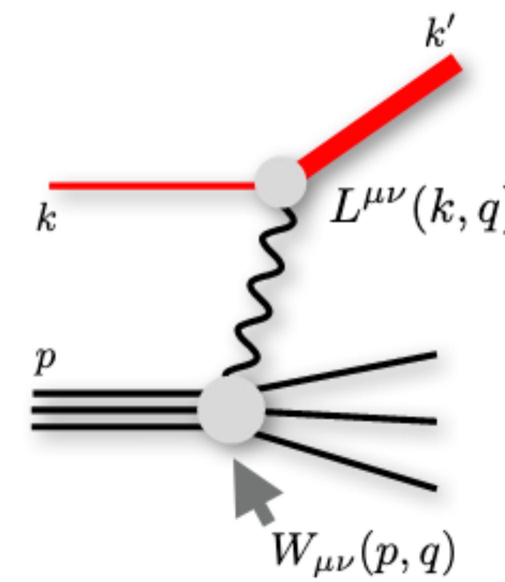
How bright is the proton?

- Approaches to inelastic part in the past (list not exhaustive)
  - Photon is modelled, radiated from constituent quarks q→q**γ**: MRST2004, CT14qed
  - Photon PDF is constrained by pp→l^+l^-: NNPDF23QED, NNPDF30QED
- Large uncertainties (~100%), impact on precision physics (W/Z fusion, WH production)

LuxQED advancement [arXiv:1607.04266]

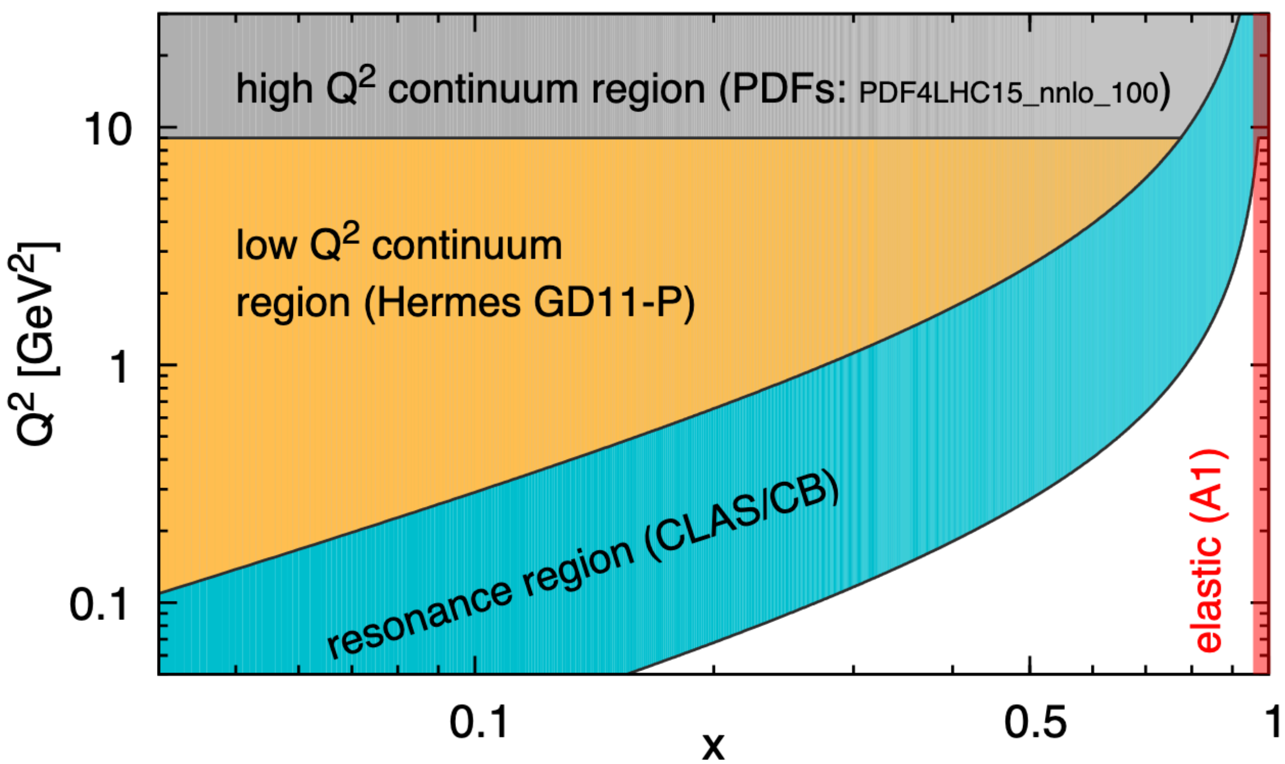
- $f_{\gamma/p}$ computed from the structure functions of DIS
- Viewed as lepton scattering on a photon inside proton
- Uncertainties at 1% level



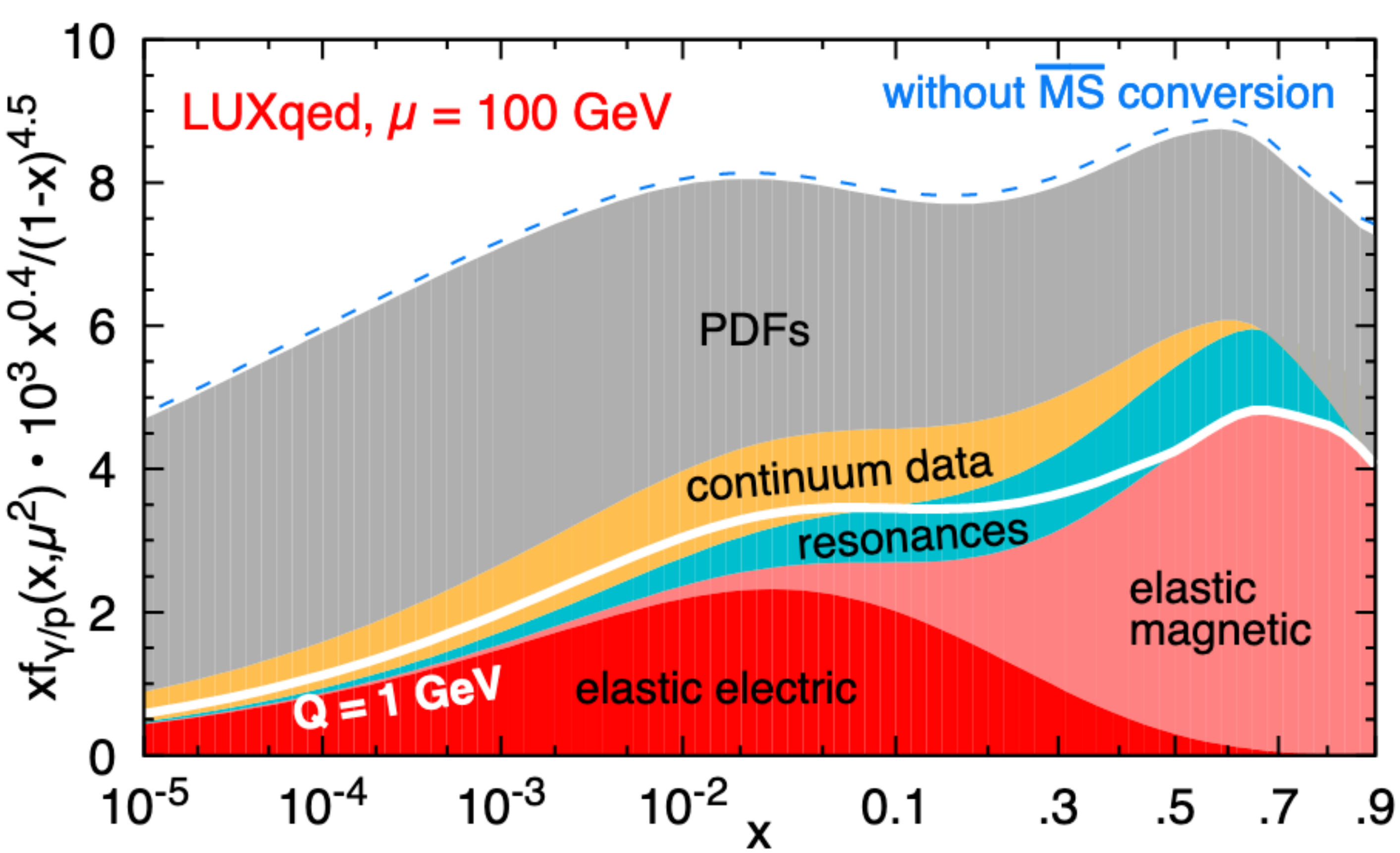


$$x f_{\gamma/p}(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)} \int_x^1 \frac{dz}{z} \left\{ \int_{\frac{x^2 m_p^2}{1-z}}^{\frac{\mu^2}{1-z}} \frac{dQ^2}{Q^2}\alpha^2(Q^2) \left[\left(z p_{\gamma q}(z) + \frac{2x^2 m_p^2}{Q^2}\right) F_2(x/z,Q^2) - z^2 F_L\left(\frac{x}{z},Q^2\right)\right] - \alpha^2(\mu^2) z^2 F_2\left(\frac{x}{z},\mu^2\right)\right\}$$

Photon PDF composition



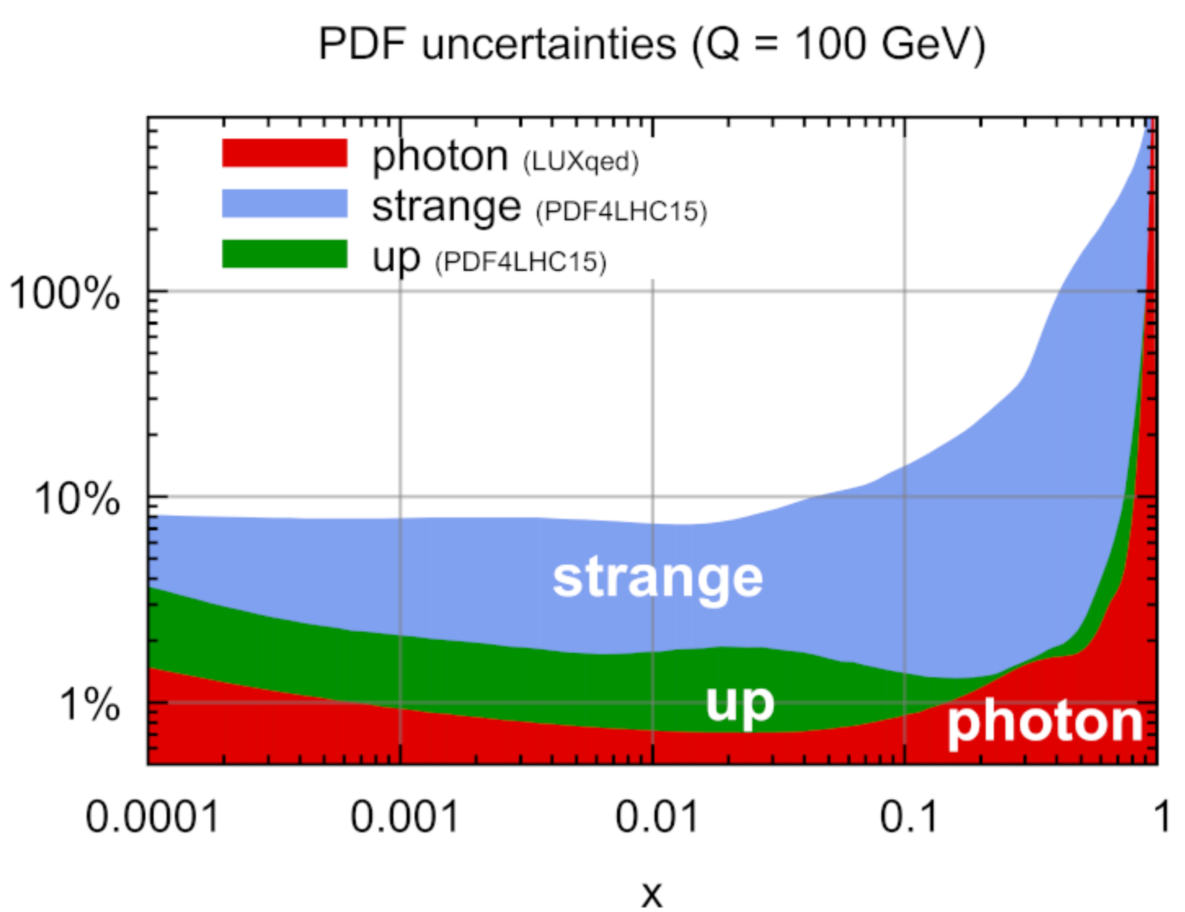
Input data sources in x and Q^2 plane

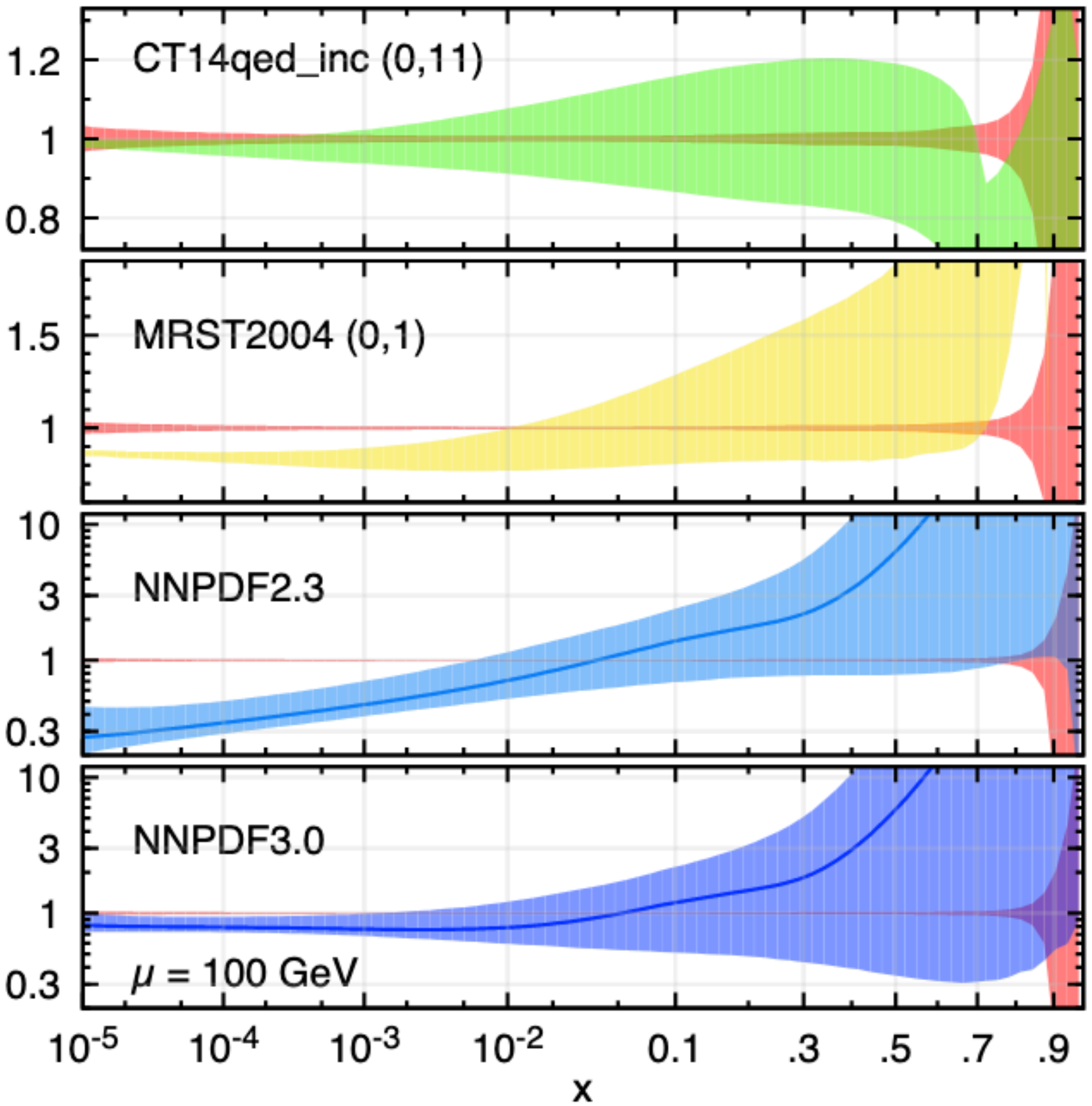


Photon PDF composition μ = 100 GeV scaled by $1000x^{0.4}/(1-x)^{4.5}$

Photon PDF uncertainties

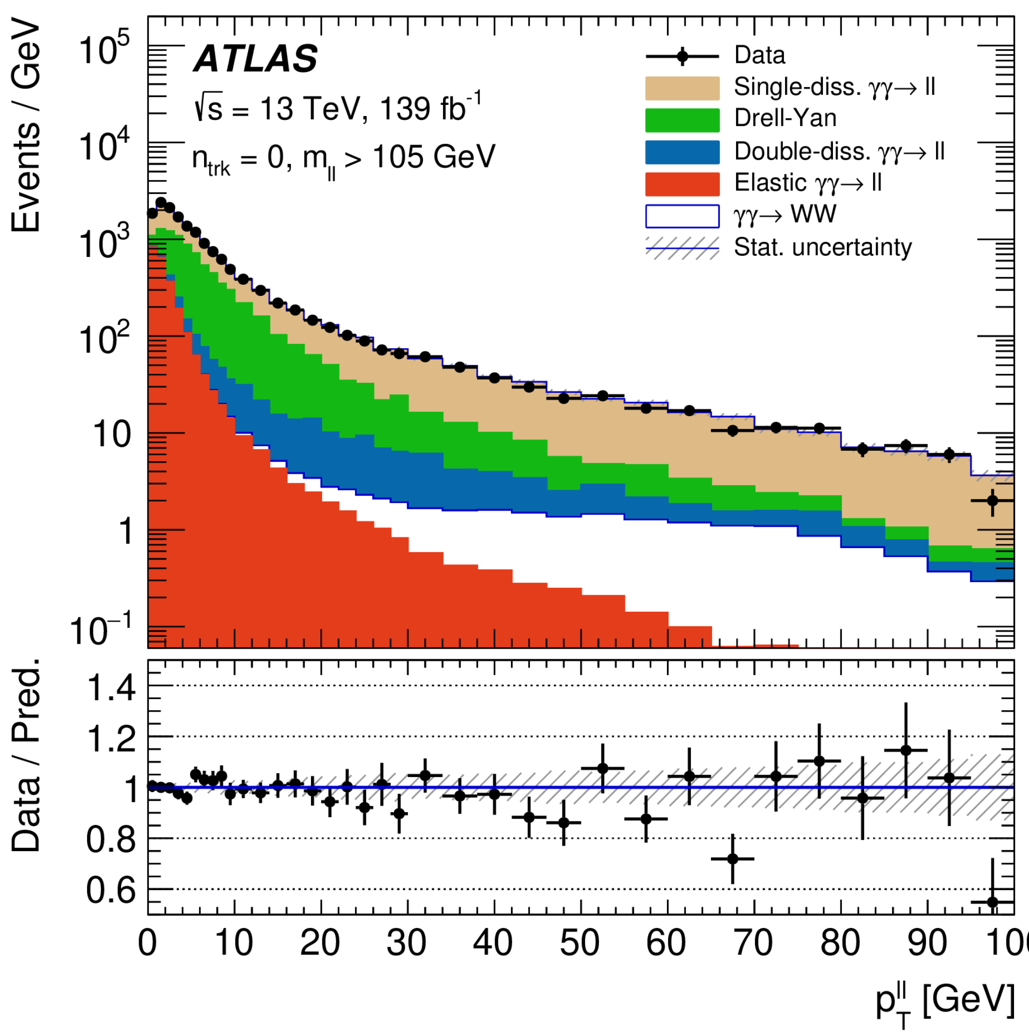
[arXiv:1607.04266]



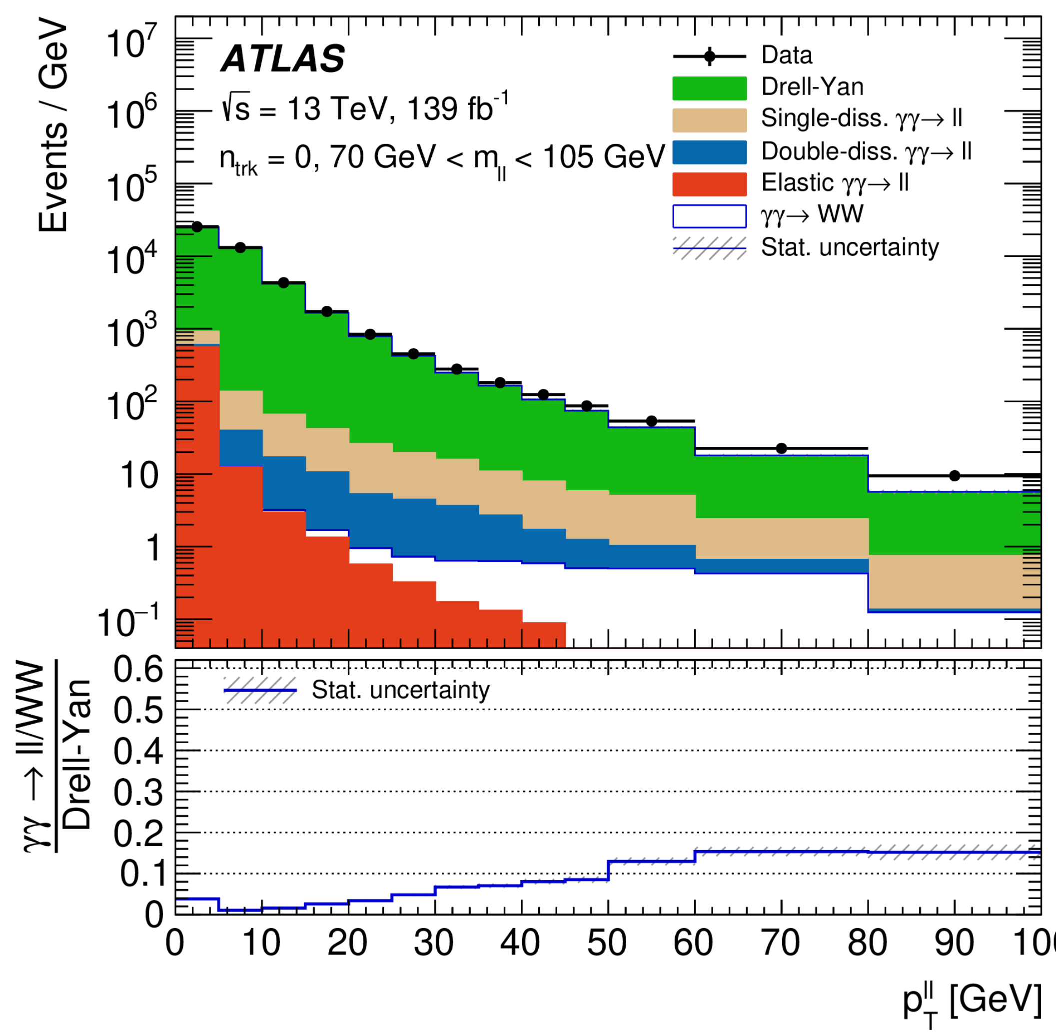


Photon-induced process templates

70 < m_{ll} < 105 GeV

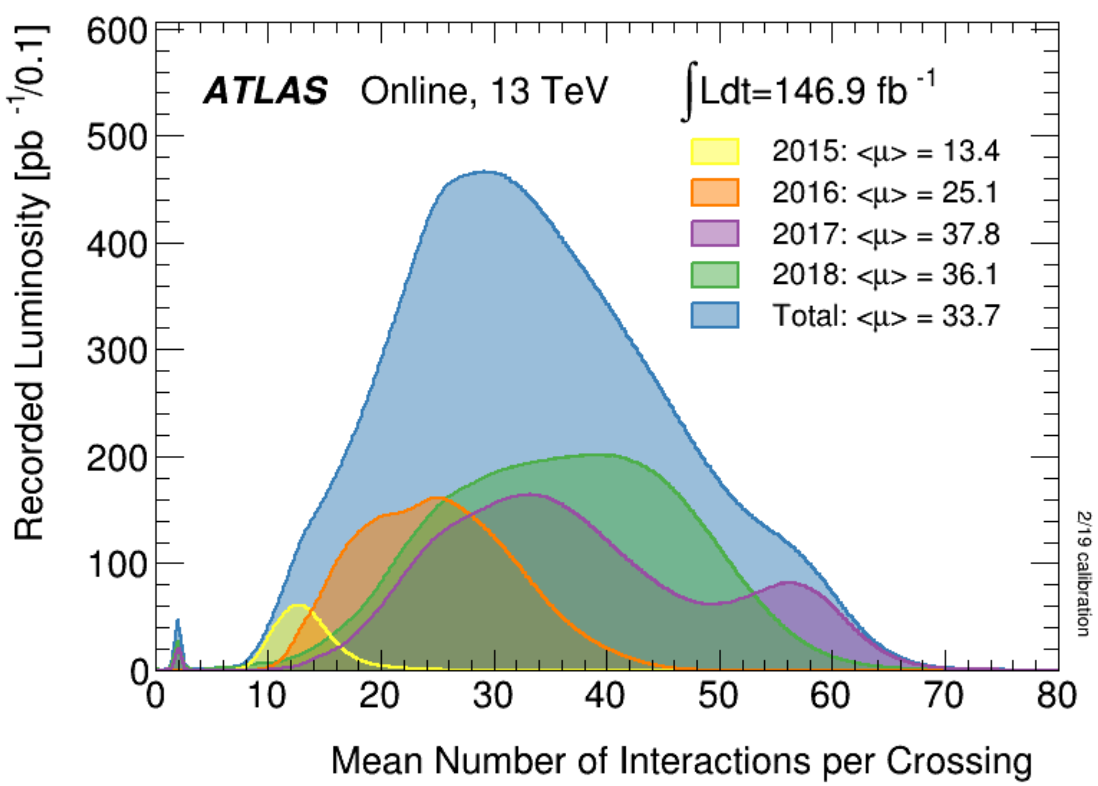


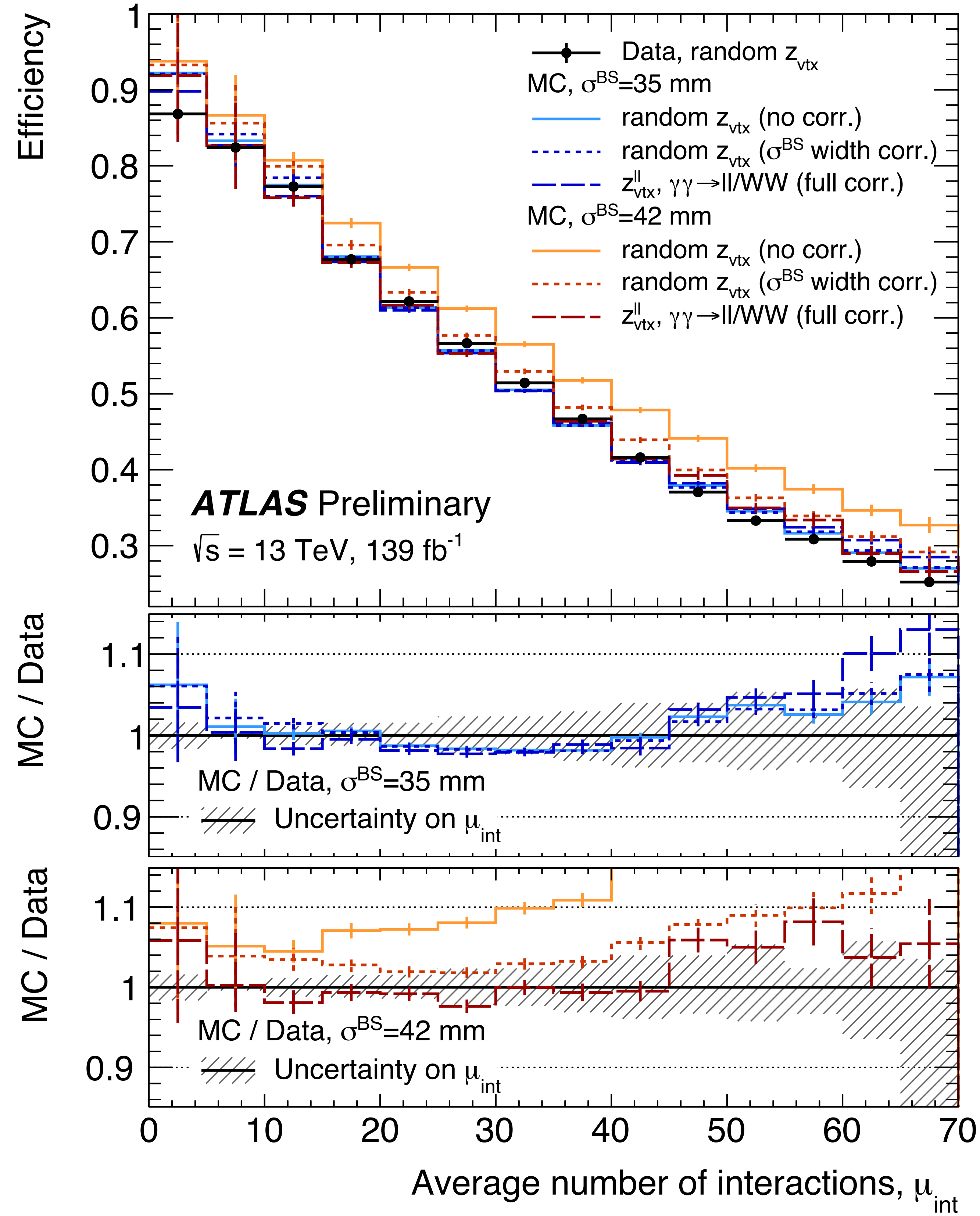
m_{ll} > 105 GeV



$\gamma\gamma \rightarrow$ WW: Exclusive efficiency

- Run 2 average exclusive efficiency (n_{trk}=0 selection): 52.6 %
- Strong dependence on μ - number of *pp* interactions per crossing
- Modelled within 2% across the full μ range





$\gamma\gamma \to$ WW yields

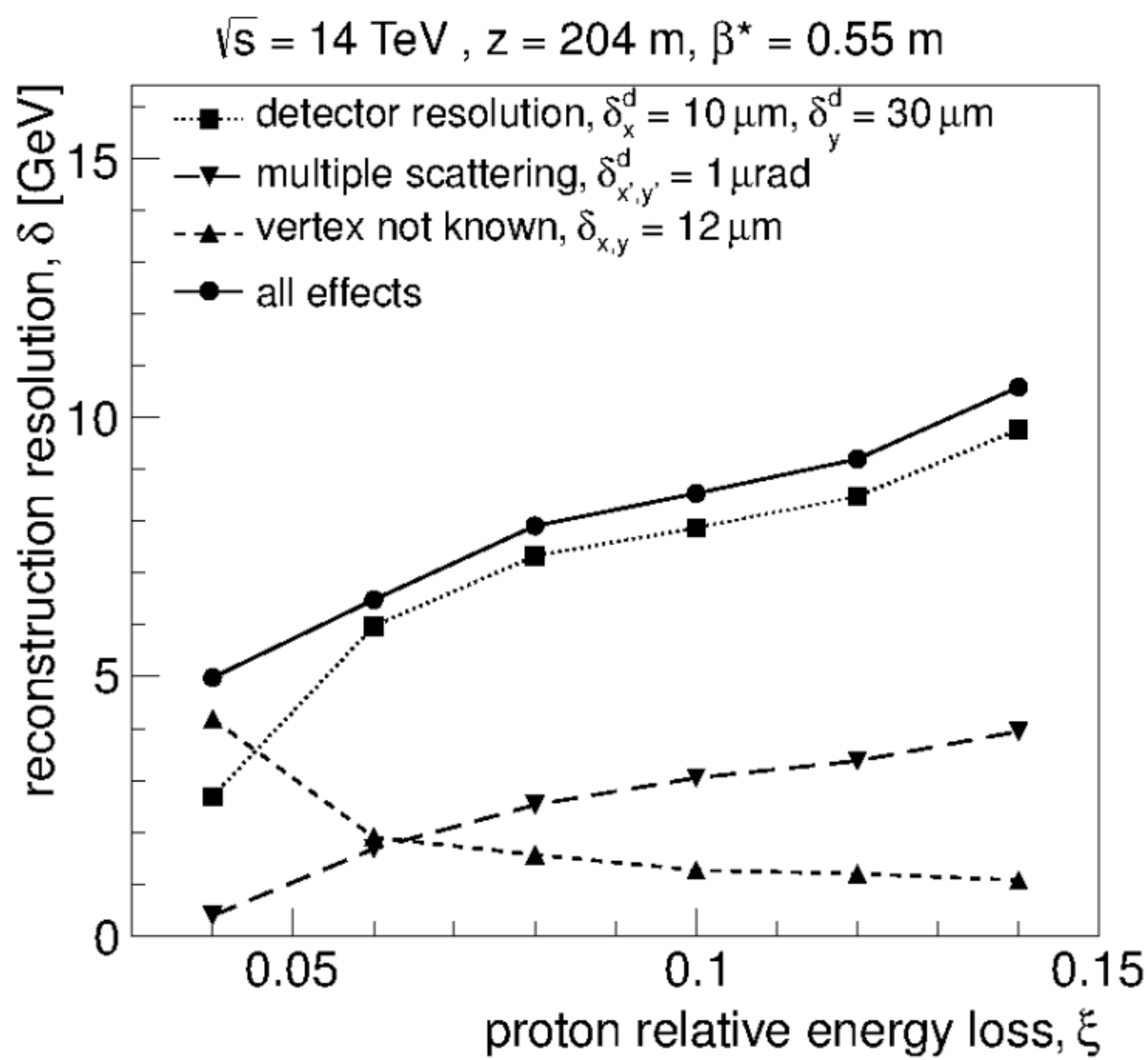
- 307 candidate observed, 132 background events expected
- Signal normalization is expressed relative to scaled predictions using high-mass $\gamma\gamma \to ll$

$$\beta_{WW} = 1.21^{+0.19}_{-0.23}$$
$$\beta_{DY} = 1.16^{+0.10}_{-0.12}$$
$$\beta_{\gamma\gamma\to ll} = 3.59 \pm 0.15$$
$$\mu_{\gamma\gamma\to WW} = 1.33 \pm 0.14\ (\text{stat.})^{+0.22}_{-0.17}\ (\text{syst.})$$

	Signal region		Control regions	
n_{trk}	$n_{\text{trk}} = 0$		$1 \leq n_{\text{trk}} \leq 4$	
$p_{\text{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell-Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other qq initiated	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

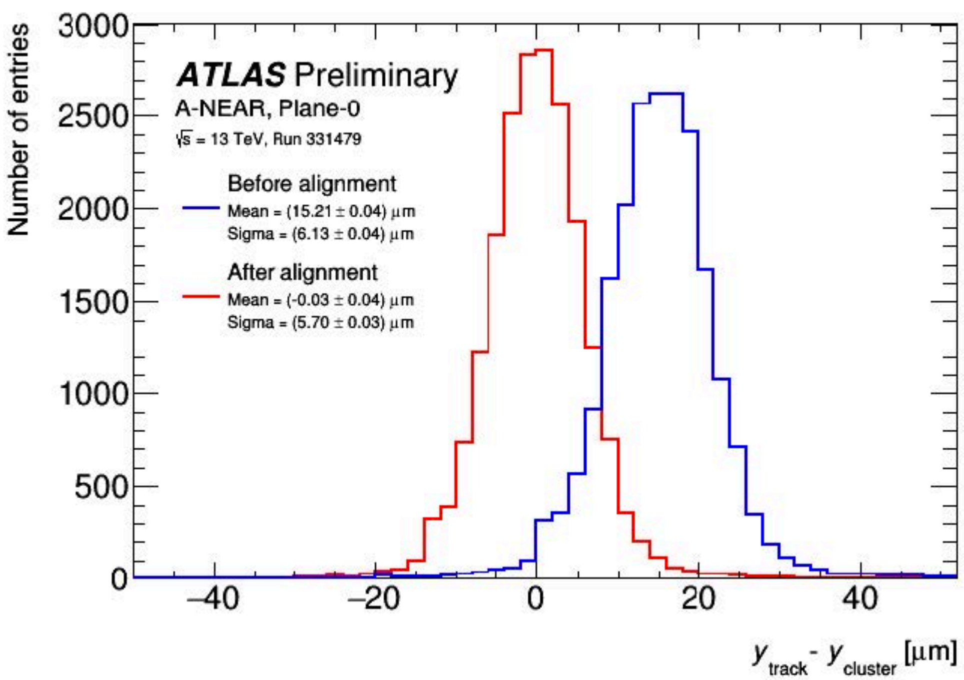
AFP momentum reconstruction

- Different contributions deteriorating the momentum resolution of the proton.

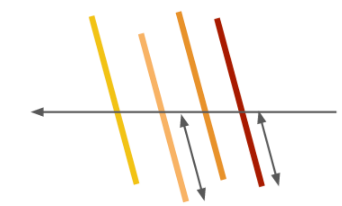


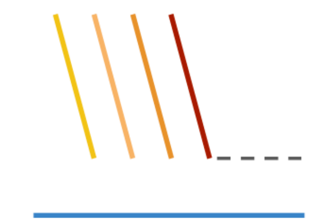
From ISRN High Energy Physics (2012) 491460; ATLAS-TDR-024

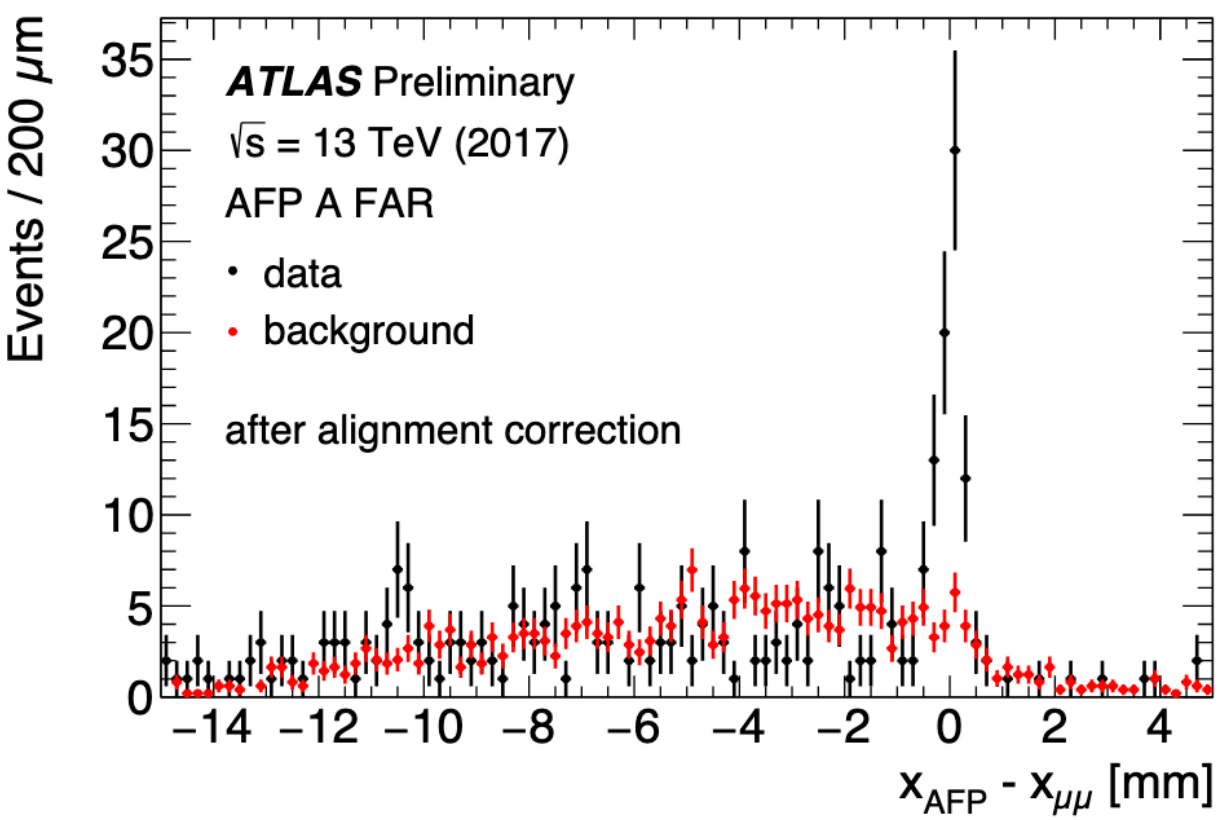
AFP Alignment

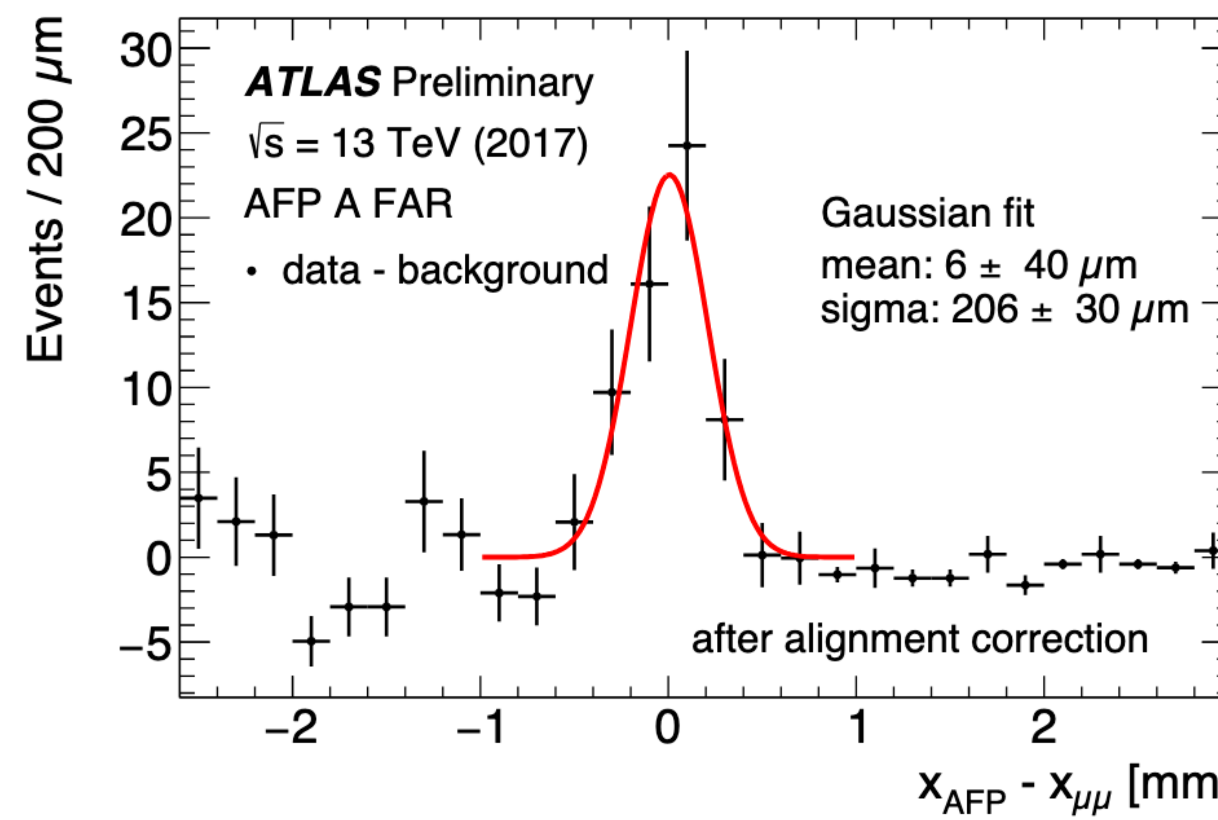


- **Inter-plane alignment** - minimize pixel-cluster residuals from the track, precision several μm
- **Global position** using beam based alignment - approach collimated beam to scape beam envelope, precision $\sim 300\mu m$
- Validated using $\xi_{ll} - \xi_{\mathrm{AFP}}$ correlation
- **ξ** resolution ~10% (optics), 25% at small **ξ** (alignment)





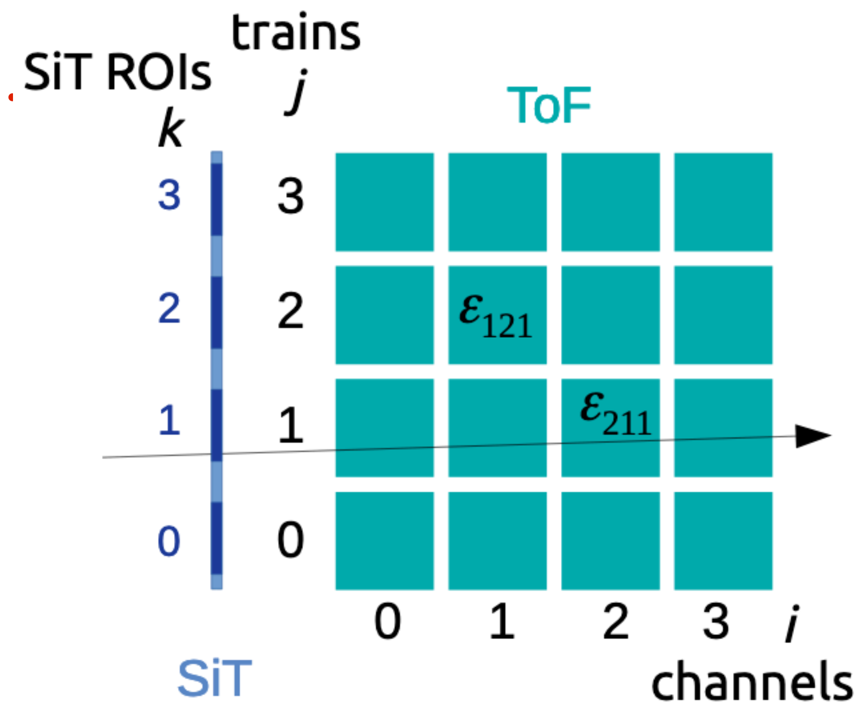


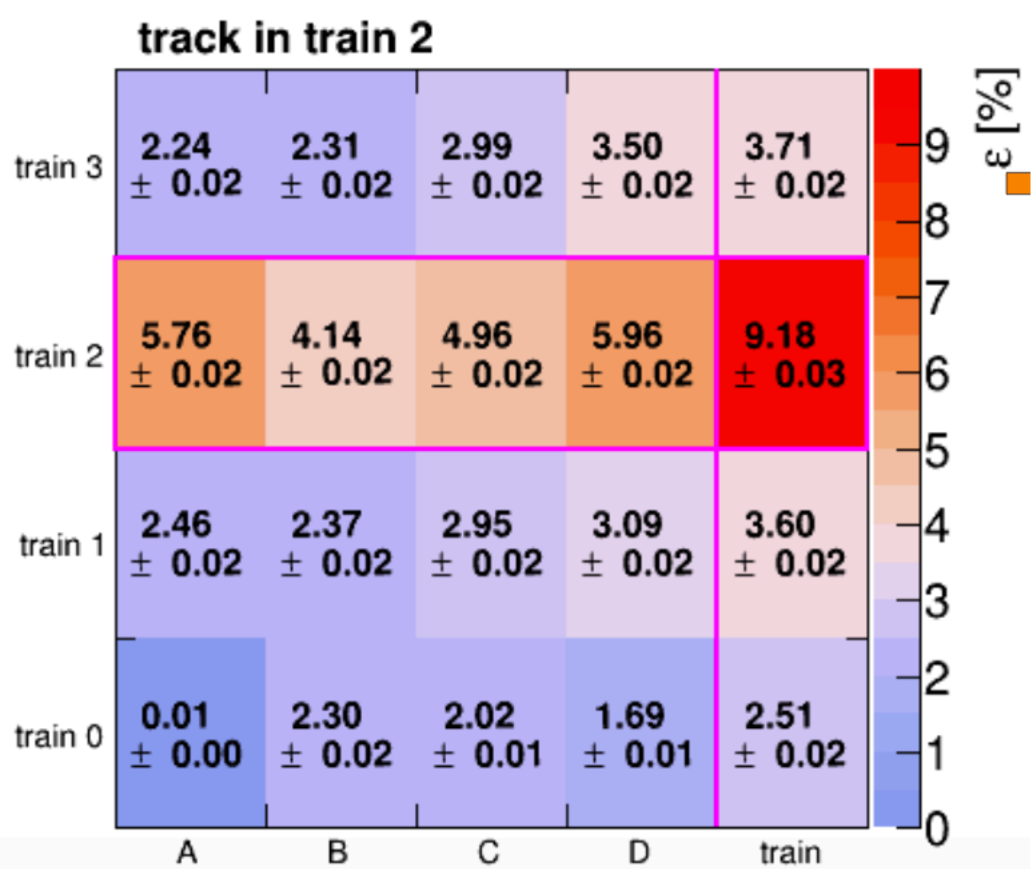


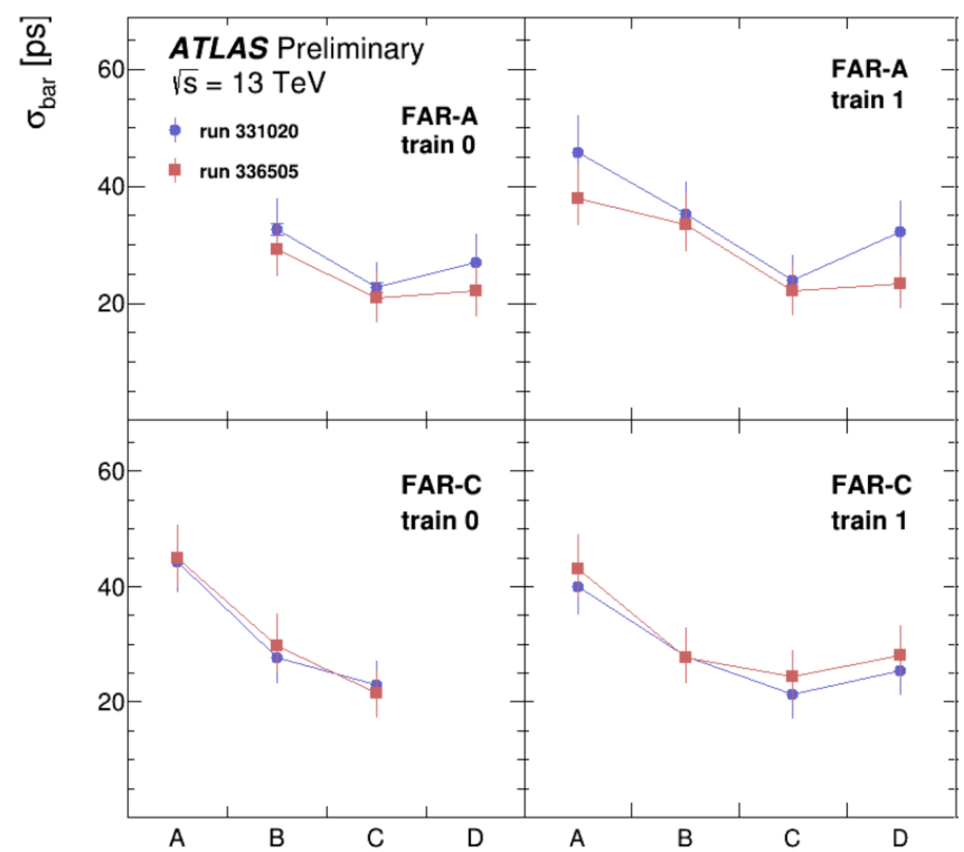
- see [Jesse Liu ICHEP talk] for details

AFP ToF Detector

- Analyzed 2017 data
- 20-30 ps achieved timing resolution, 40-50 ps in the first channel (no enrichment from the previous bars)
- Efficiency limited (few %) in 2017 due due to PMT deterioration with radiation

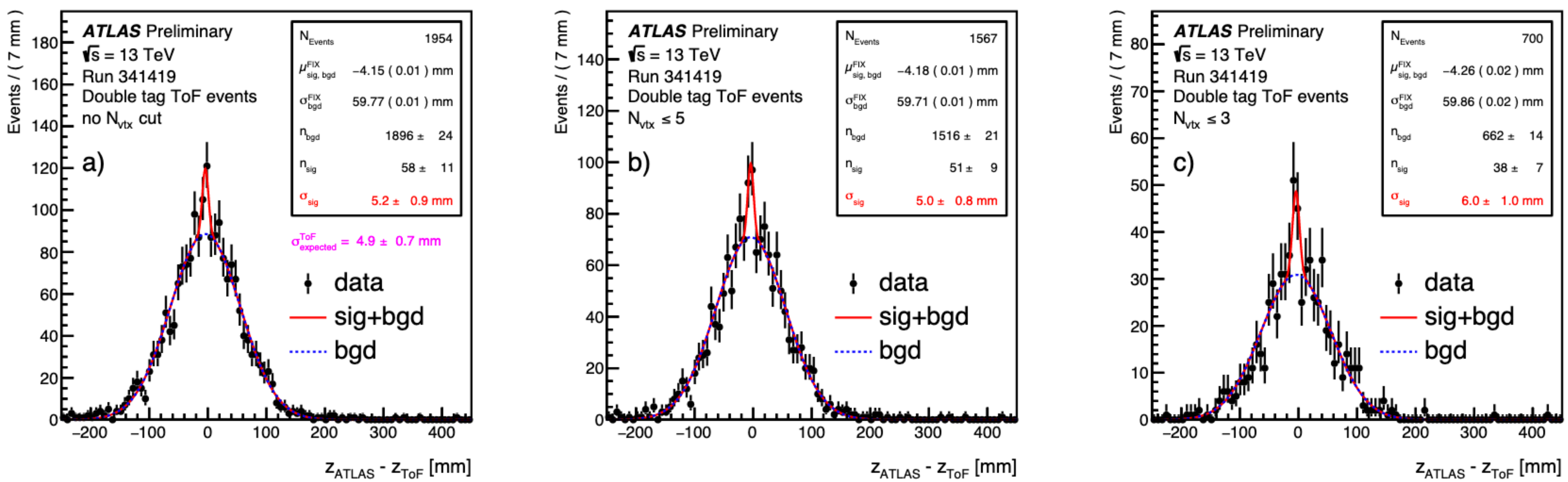




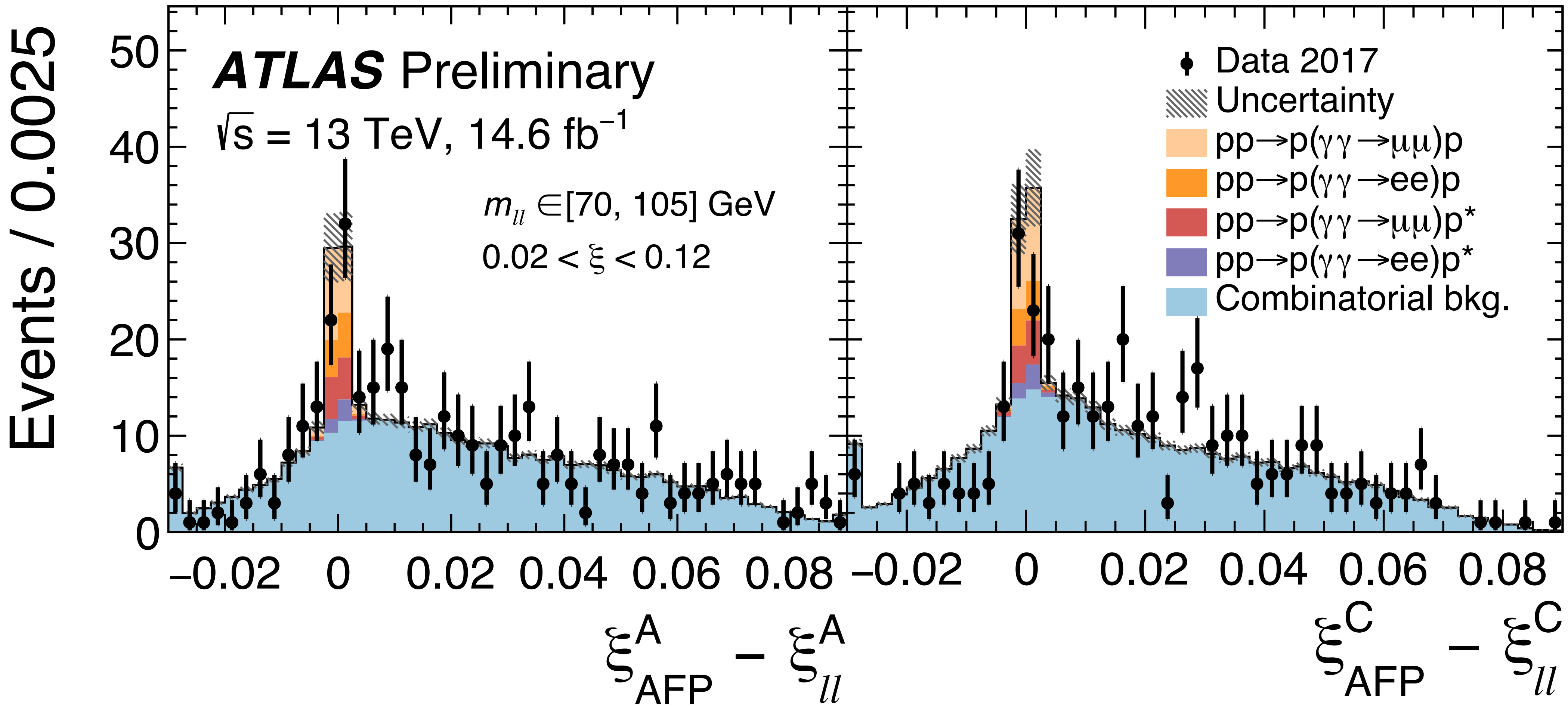


AFP: reconstructed interaction vertex from ToF

- Difference between reconstructed interaction vertex from ToF

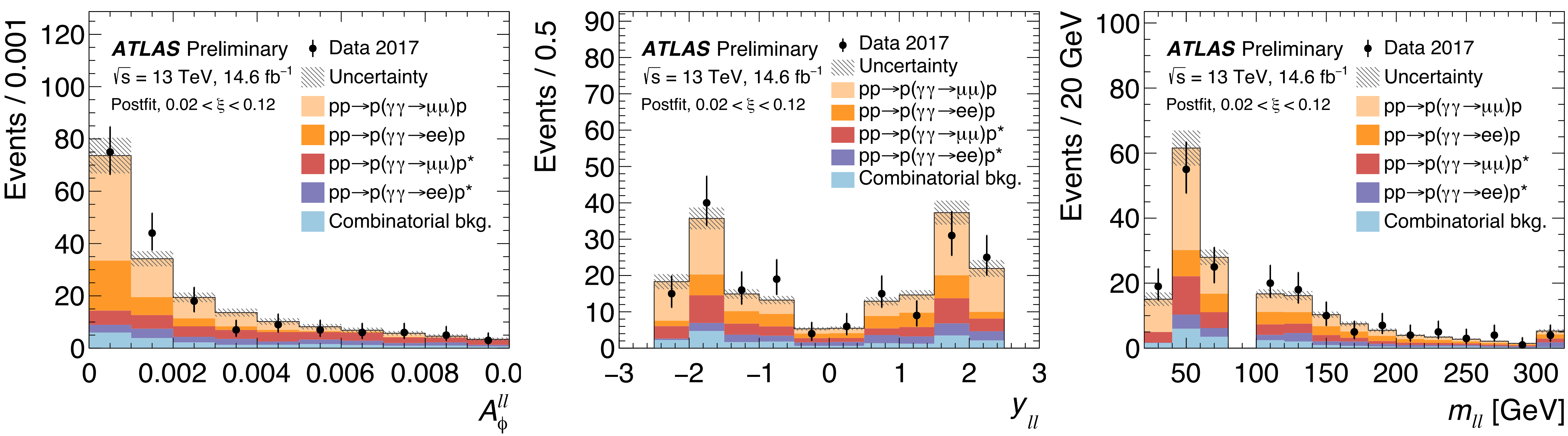


AFP $\gamma\gamma \rightarrow$ ll: background control region



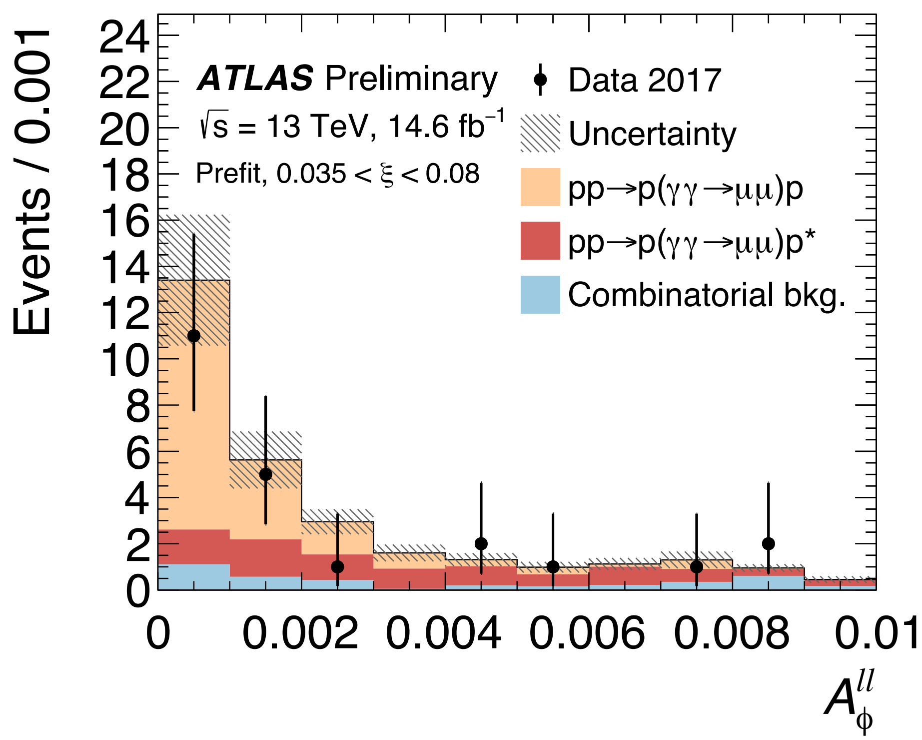
AFP $\gamma\gamma \rightarrow$ ll: control distributions

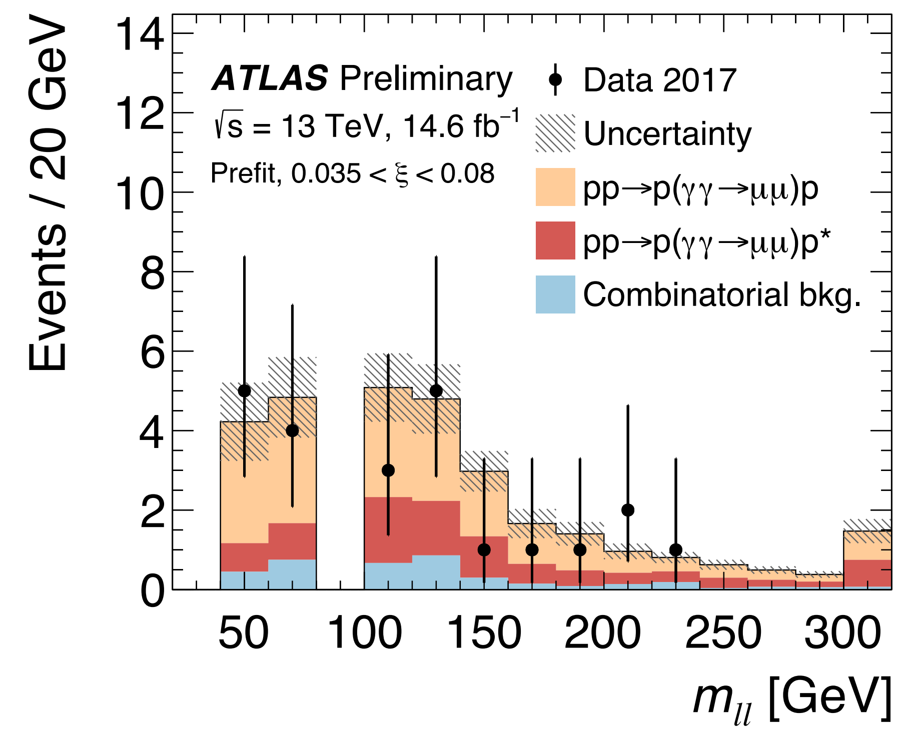
- Shapes of distributions modelled well by Herwig7+LPair
- Postfit distribtion of AFP single tag events



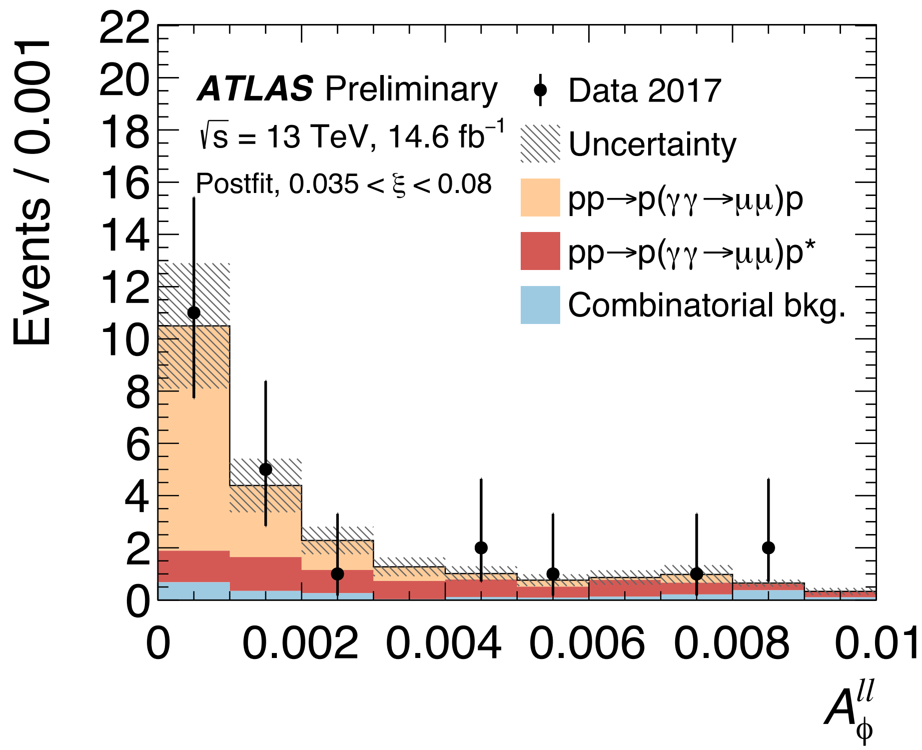
AFP $\gamma\gamma \rightarrow$ ll: Measurement prefit and postfit distributions

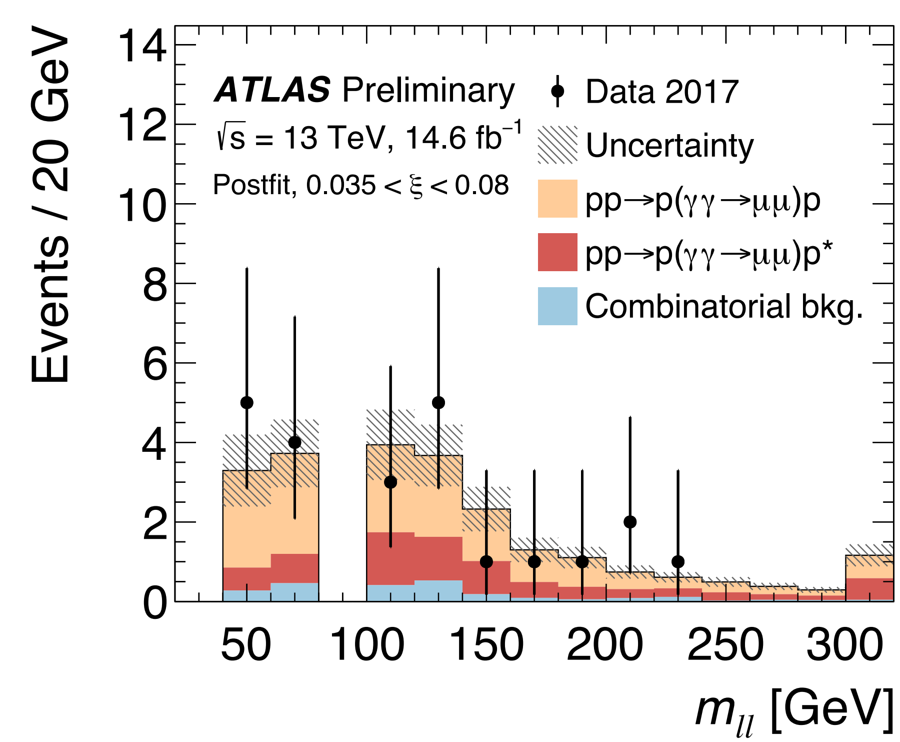
Prefit





Postfit





AFP $\gamma\gamma \rightarrow ll$: Systematic uncertainties

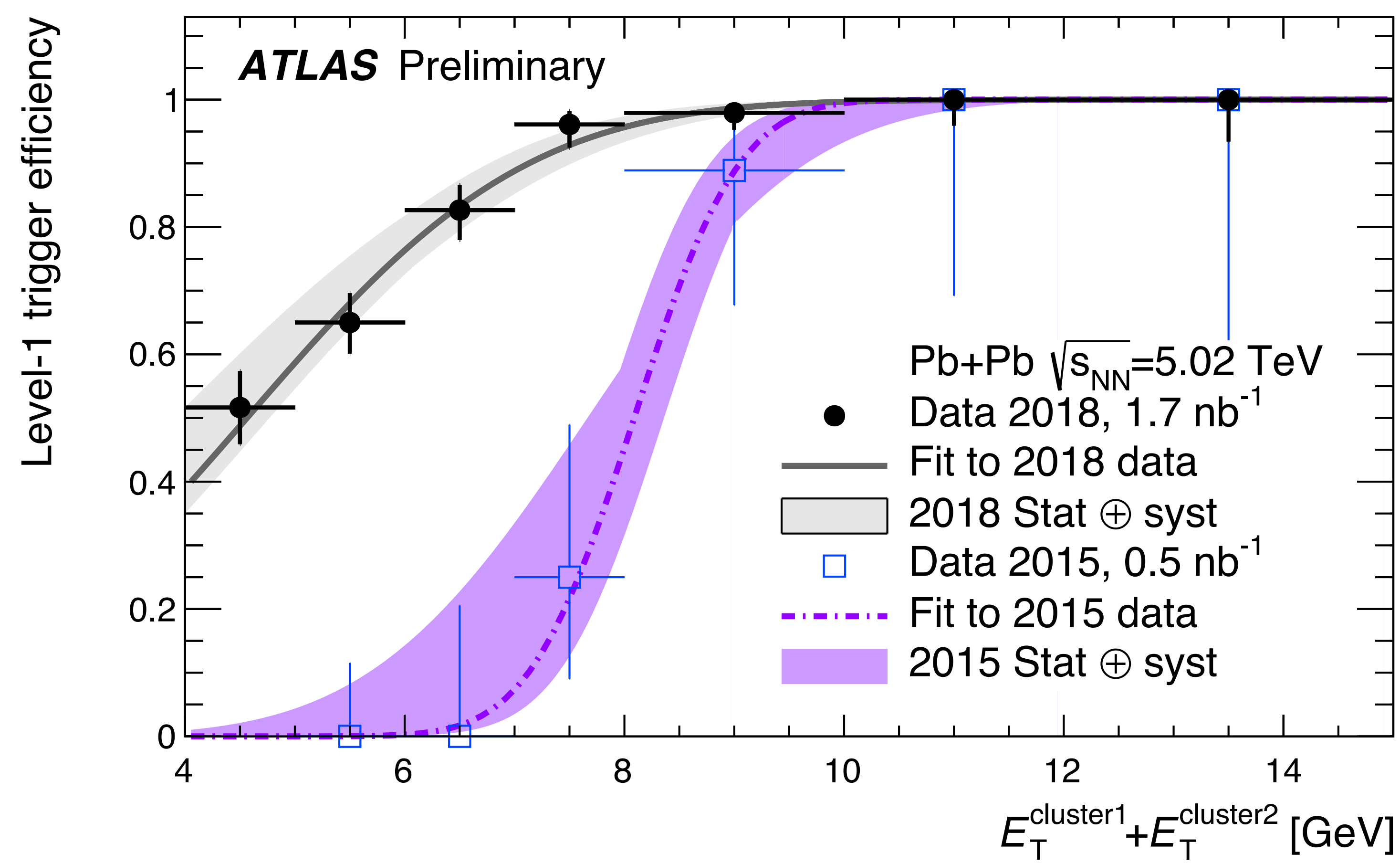
Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	$< 1\%$
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon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

LbyL Trigger Efficiency

- 2015:
  - L1: E_T registered in the calorimeter between 5–200 GeV
  - HLT: MBTS veto if > 1 hit in MBTS, <10 hits in Pixel
- 2018:
  - L1: (1) >=1 EM cluster with E_T > 1 GeV & E_T registered in the calorimeter between 4–200 GeV, or (2) >=2 EM clusters with E_T > 1 GeV & E_T registered in the calorimeter below 50 GeV
  - HLT: E_T in FCal < 3 GeV, <15 hits in Pixel

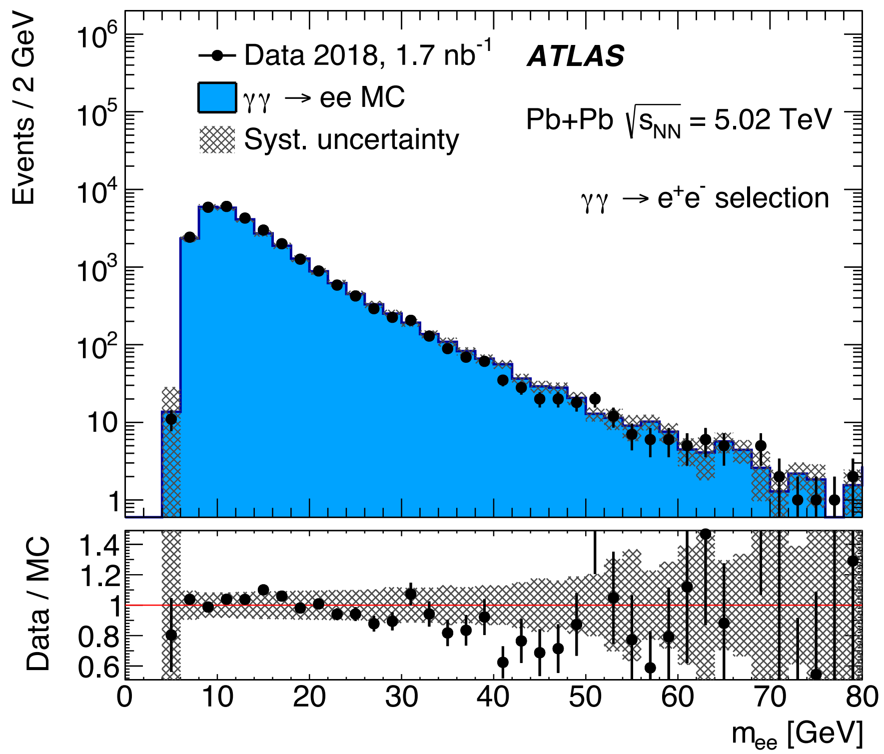
- Supporting triggers:
  Signal in one or both ZDC sides, total E_T in the calorimeter < 50 GeV

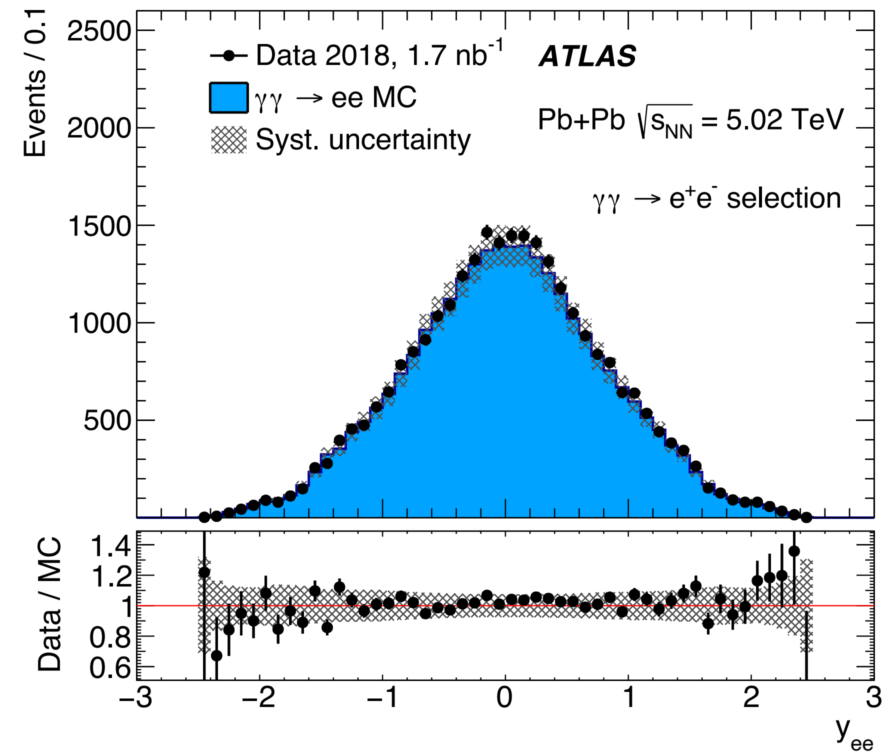
- Measured using $\gamma\gamma \rightarrow e^+e^-$

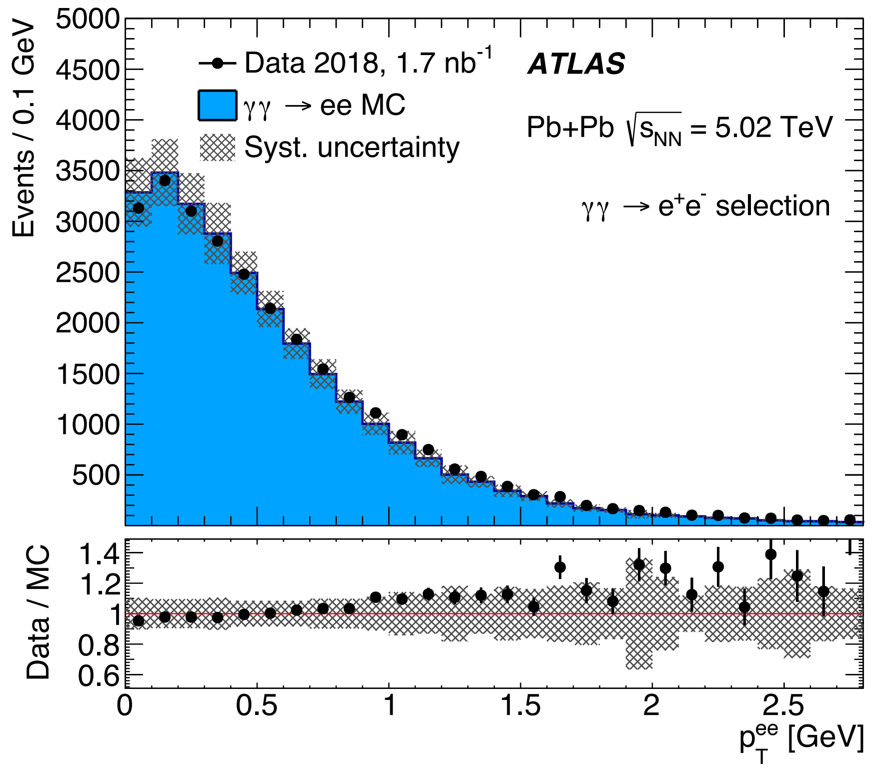


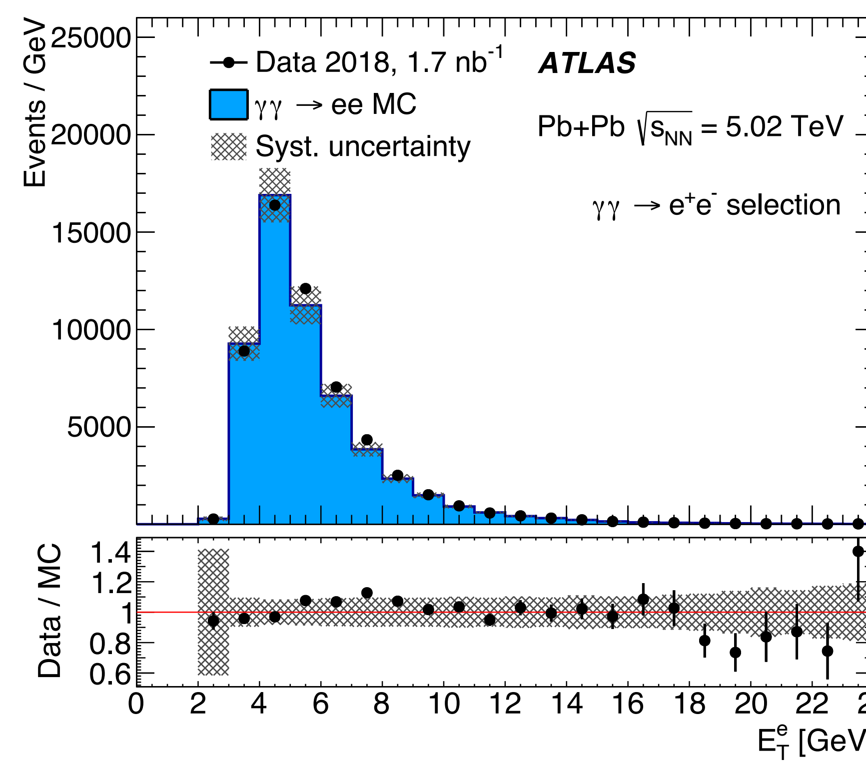
Control distributions

- Good modelling of the background $\gamma\gamma \to e^+e^-$

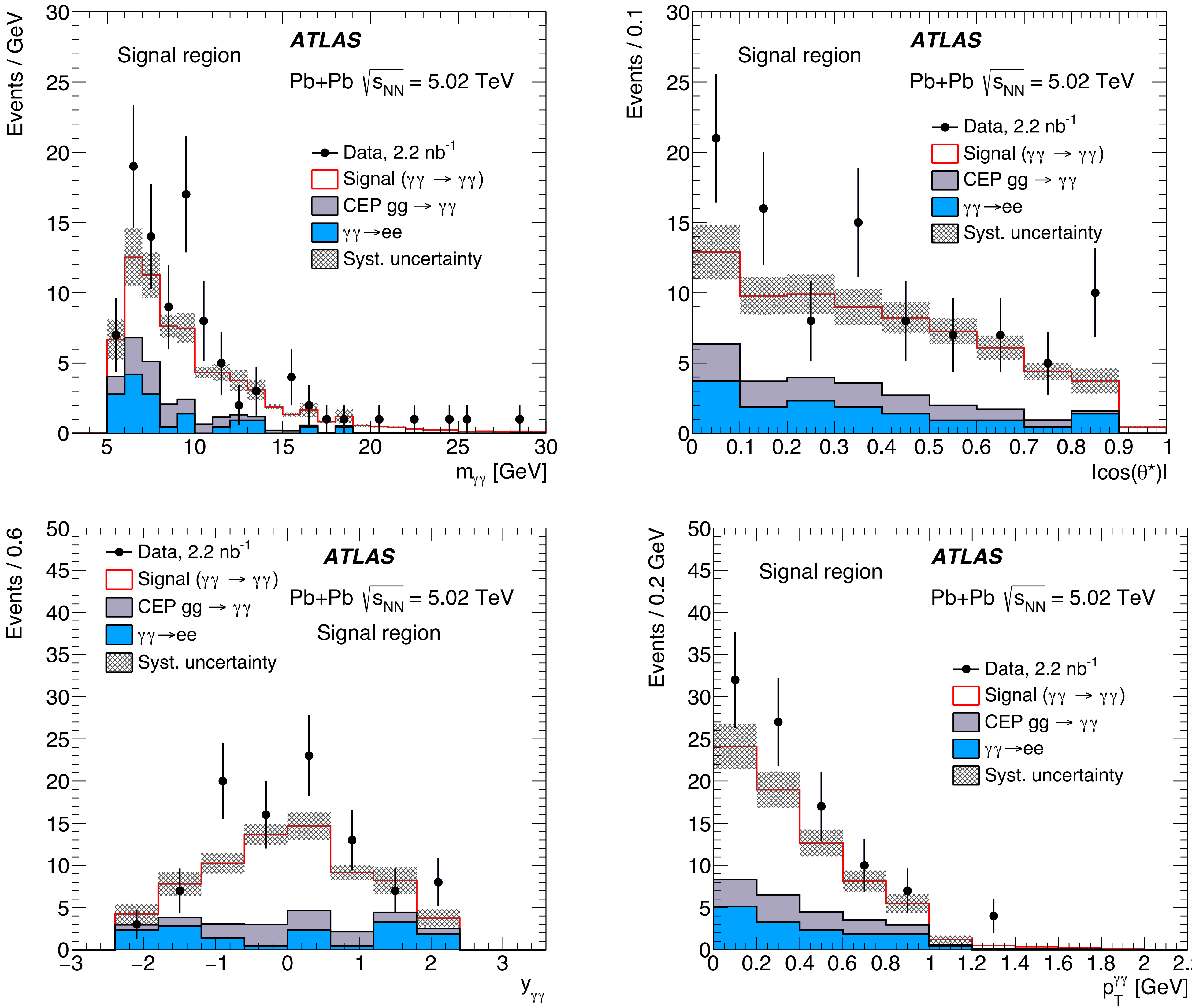




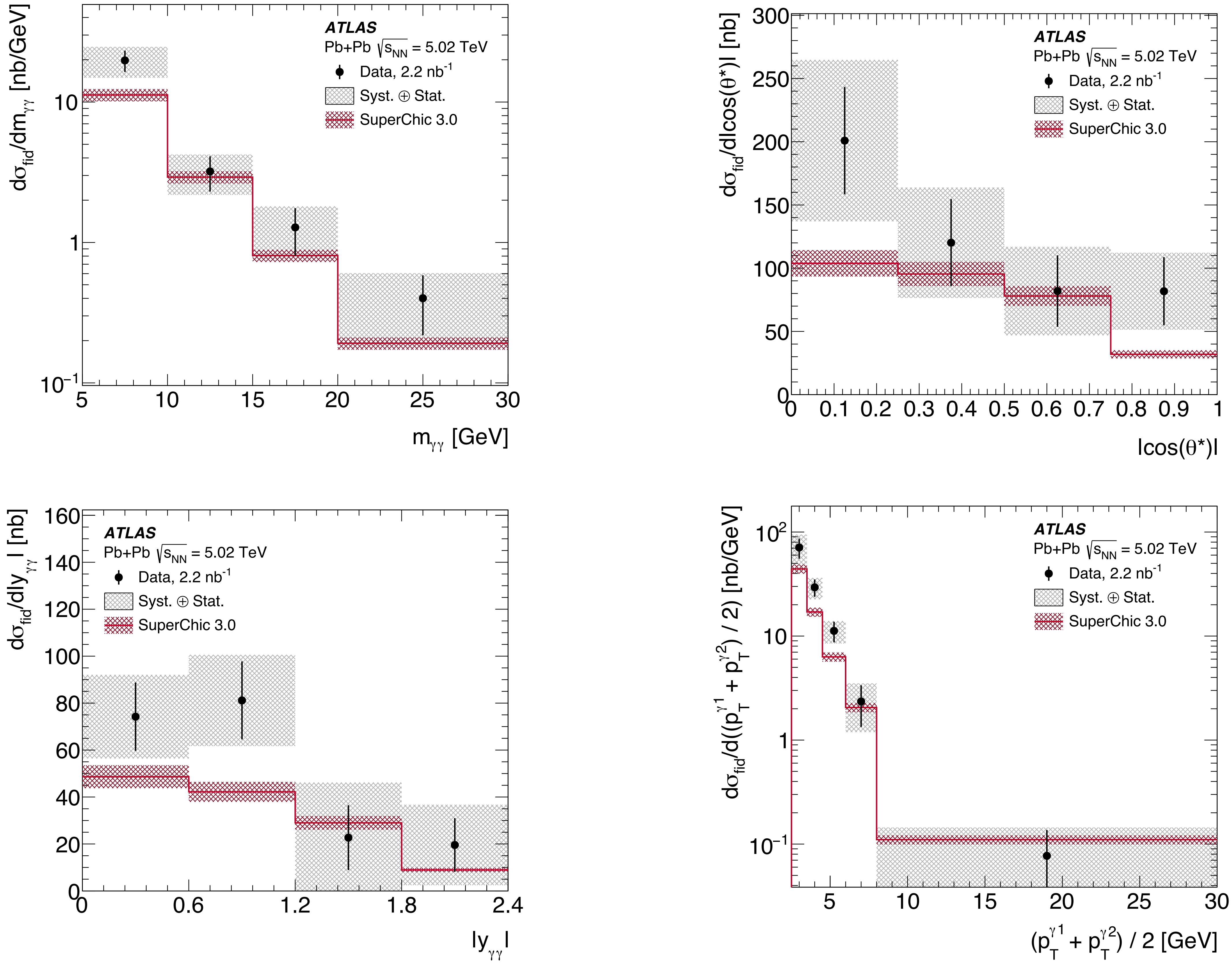




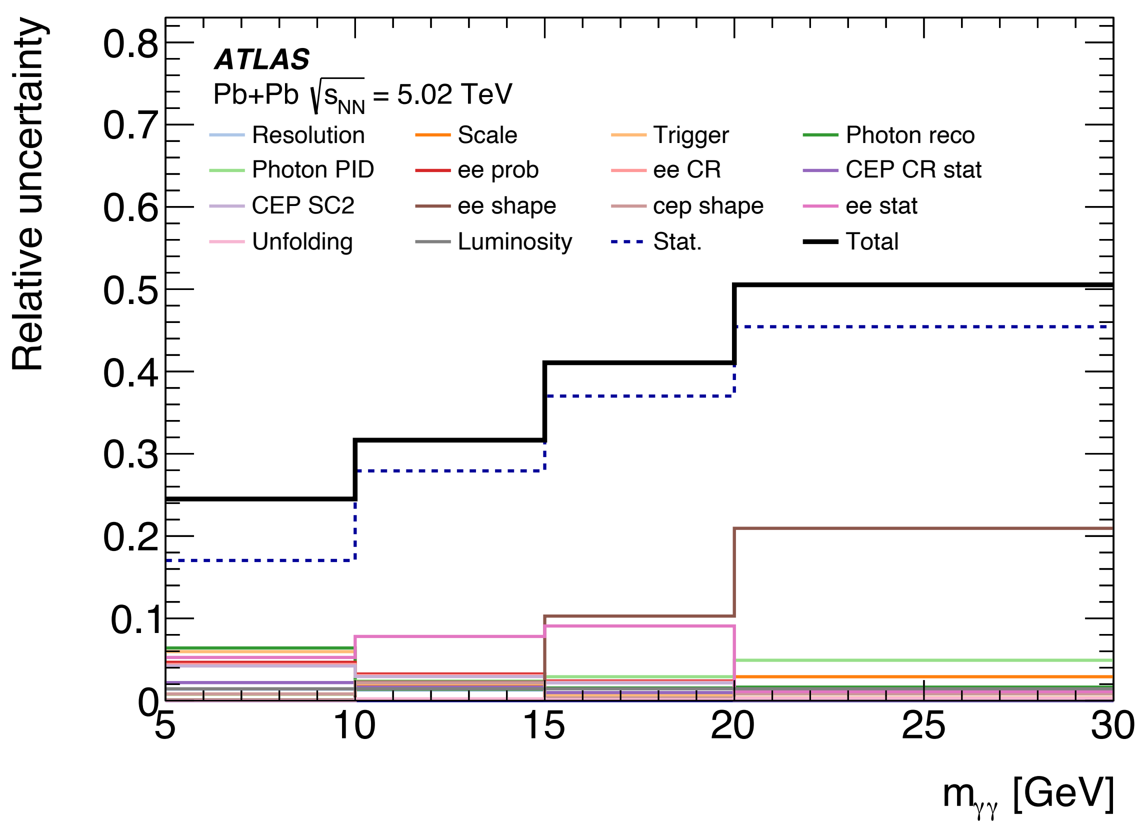
LByL: signal region

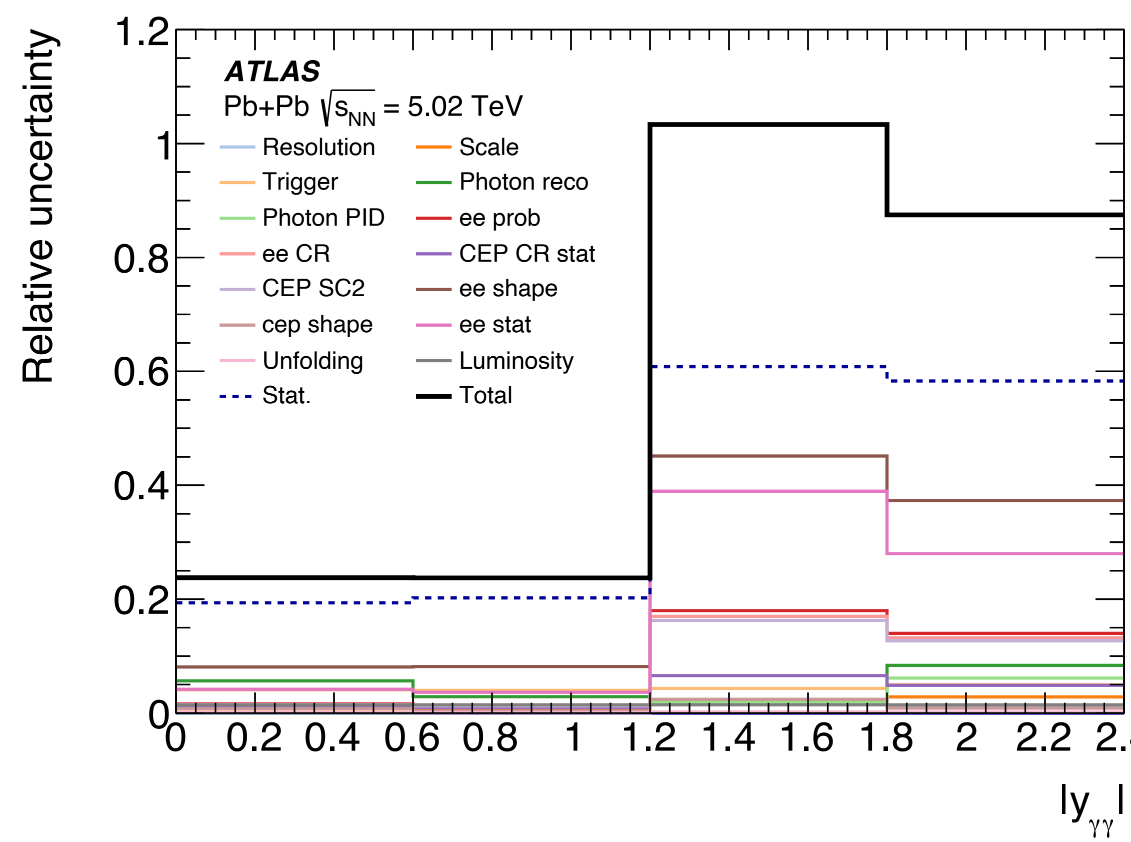


LByL: differential cross sections



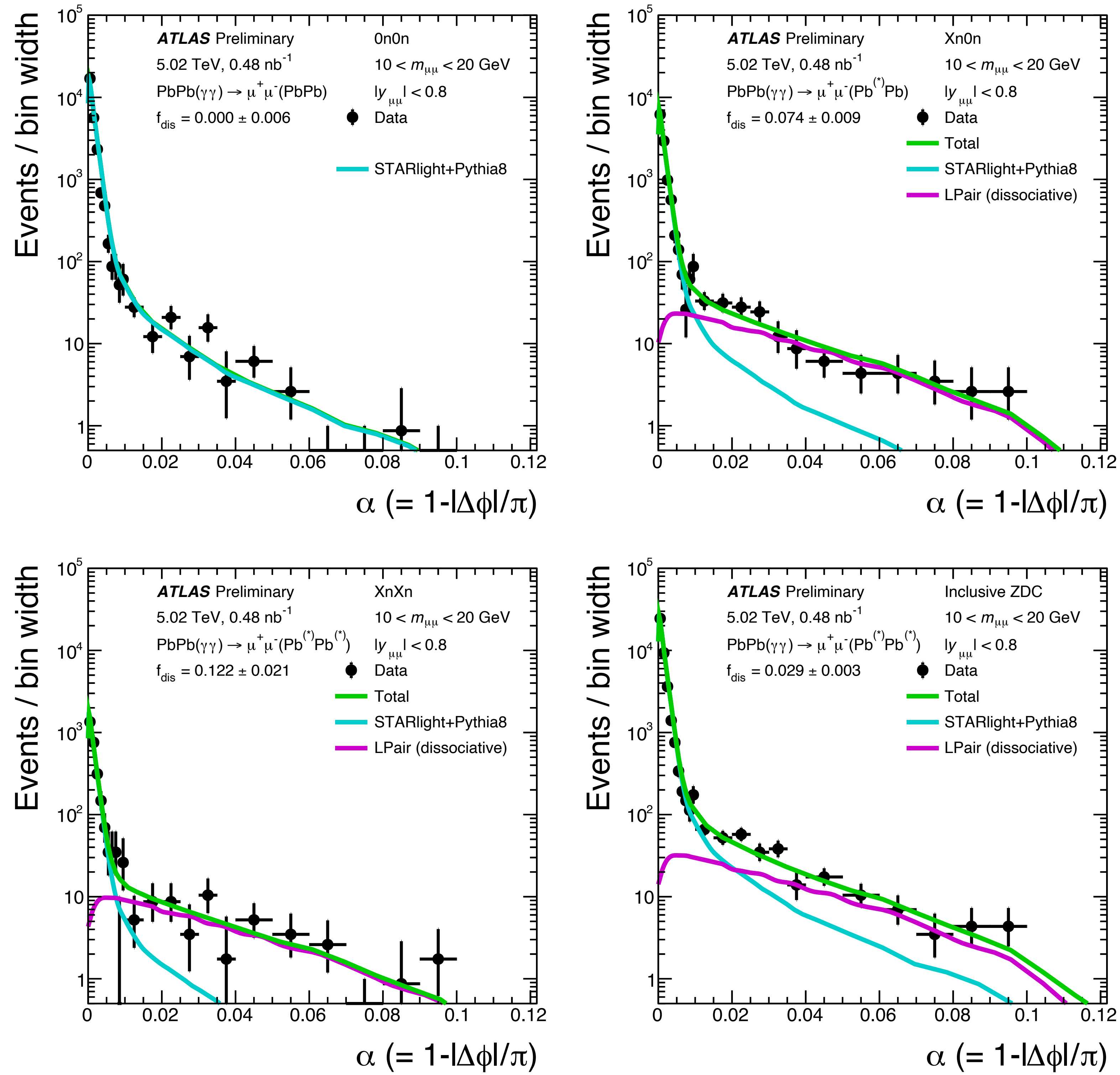
LByL: systematic uncertainties



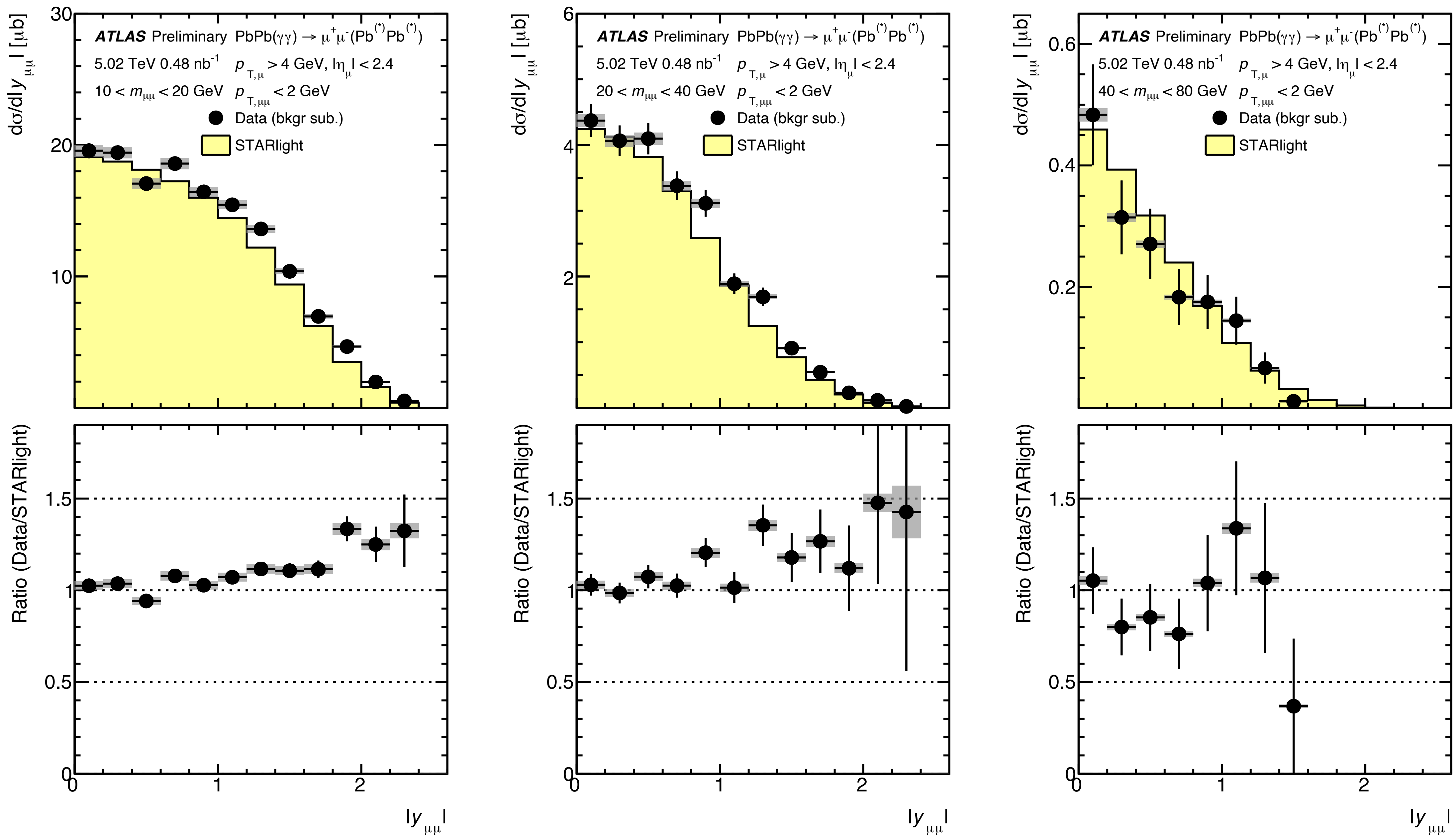


Exclusive dimuons in UPC Pb+Pb

- ZDC selections have strong effect on acoplanarity
- LPair provides satisfactory description of dissociative background



dimuons in UPC Pb+Pb: Results



Fraction of events with Xn0n, XnXn activites

- Measured fraction with different activity (0nXn, XnXn)