Photon fusion and tau g-2 measurements in ATLAS

New Physical Signals (NePSi)

Physics Department "E. Fermi" of the University of Pisa

Monica Verducci - University of Pisa and INFN

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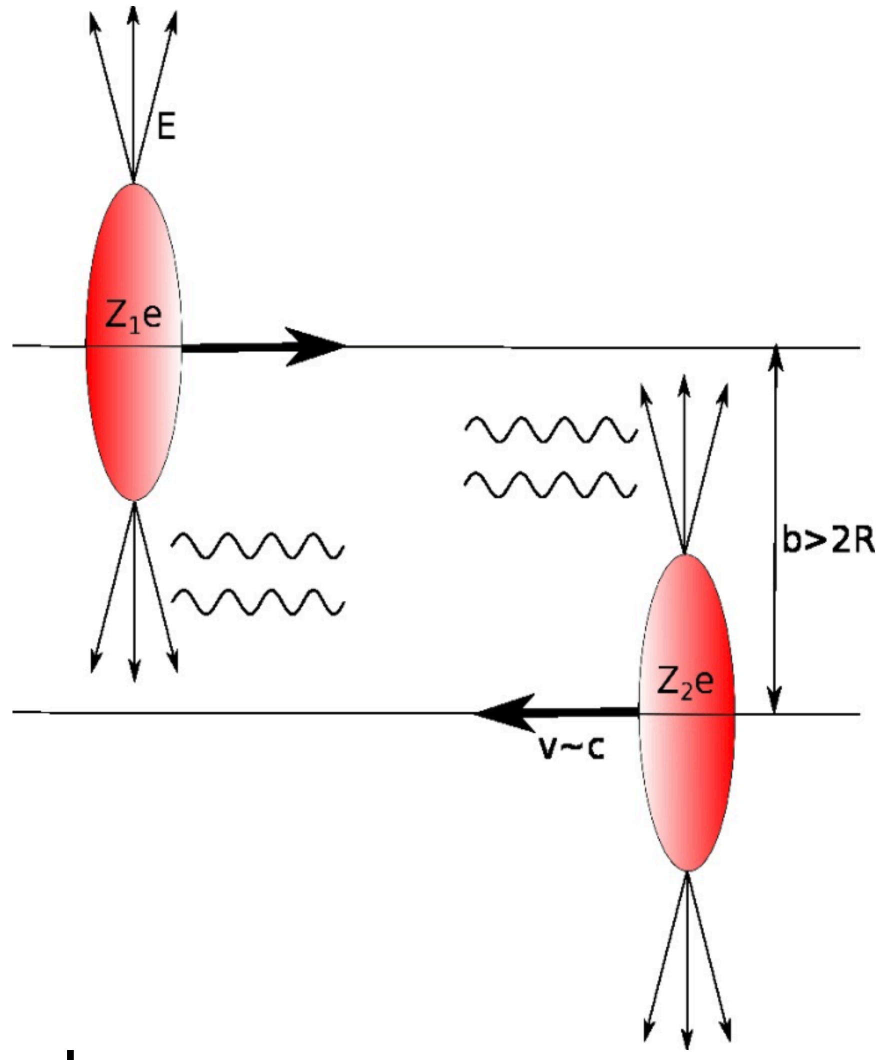
Introduction

- UltraPeripherical Collisions (UPC) of lead-lead (Pb+Pb) at LHC collected 2.2 nb^{-1} integrated luminosity during 2015-2018 data taking
- Extremely interesting for:
  - **Very clean environment** to study quantum electrodynamics (QED): **essentially no pile-up** from hadronic interactions → exclusive selections
    - **low trigger and reco object thresholds**
  - Precision tool to study **photon fluxes** within the Equivalent Photon Approximation (EPA) framework
  - $Z^4(\approx 4.5\text{x}10^7)$ **enhancement of cross sections** in Pb+Pb wrt proton-proton (pp) collisions
  - **Zero Degree Calorimeters (ZDC)** offer control over backgrounds and impact-parameter dependence
  - Tool to search for **beyond Standard Model (BSM) physics**



- The following results from 5.02 TeV UPC Pb+Pb collisions from ATLAS are discussed:
  - $\gamma\gamma \rightarrow \gamma\gamma$ events [JHEP 03 (2021) 243]
    - Light-by-light scattering analysis and axion production limits
  - $\gamma\gamma \rightarrow \tau\tau$ events [arXiv:2204.13478]
    - Analysis description and results on signal strength and a_τ limits
  - $\gamma\gamma \rightarrow \mu\mu$ events [PRC 104 (2021) 024906]
    - Dimuons cross sections
  - $\gamma\gamma \rightarrow ee$ events [ATLAS-CONF-2022-025]
    - Dielectrons cross sections

JHEP 03 (2021) 243

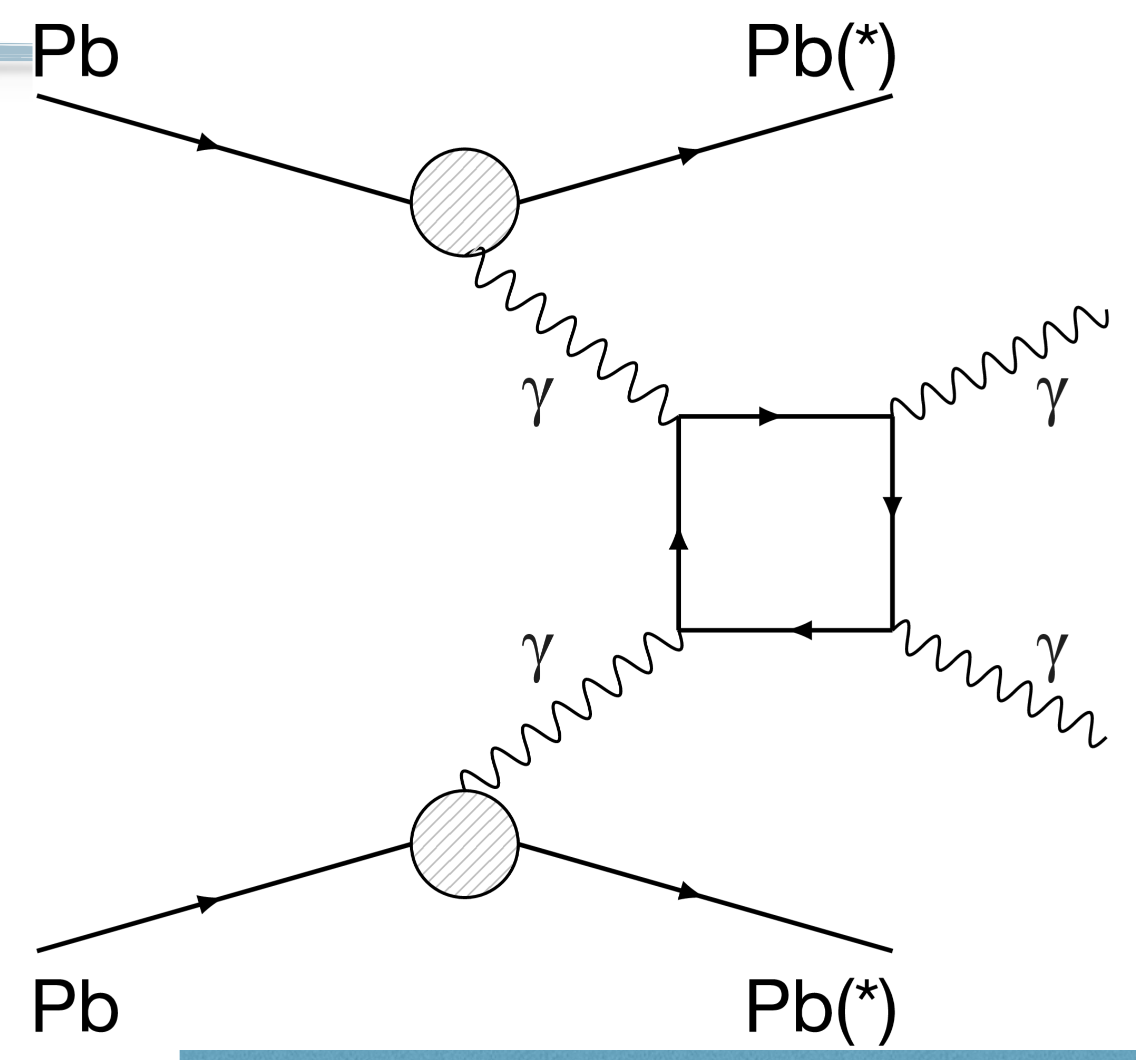
Light-by-Light Scattering and Axion Production

Light-by-Light Scattering

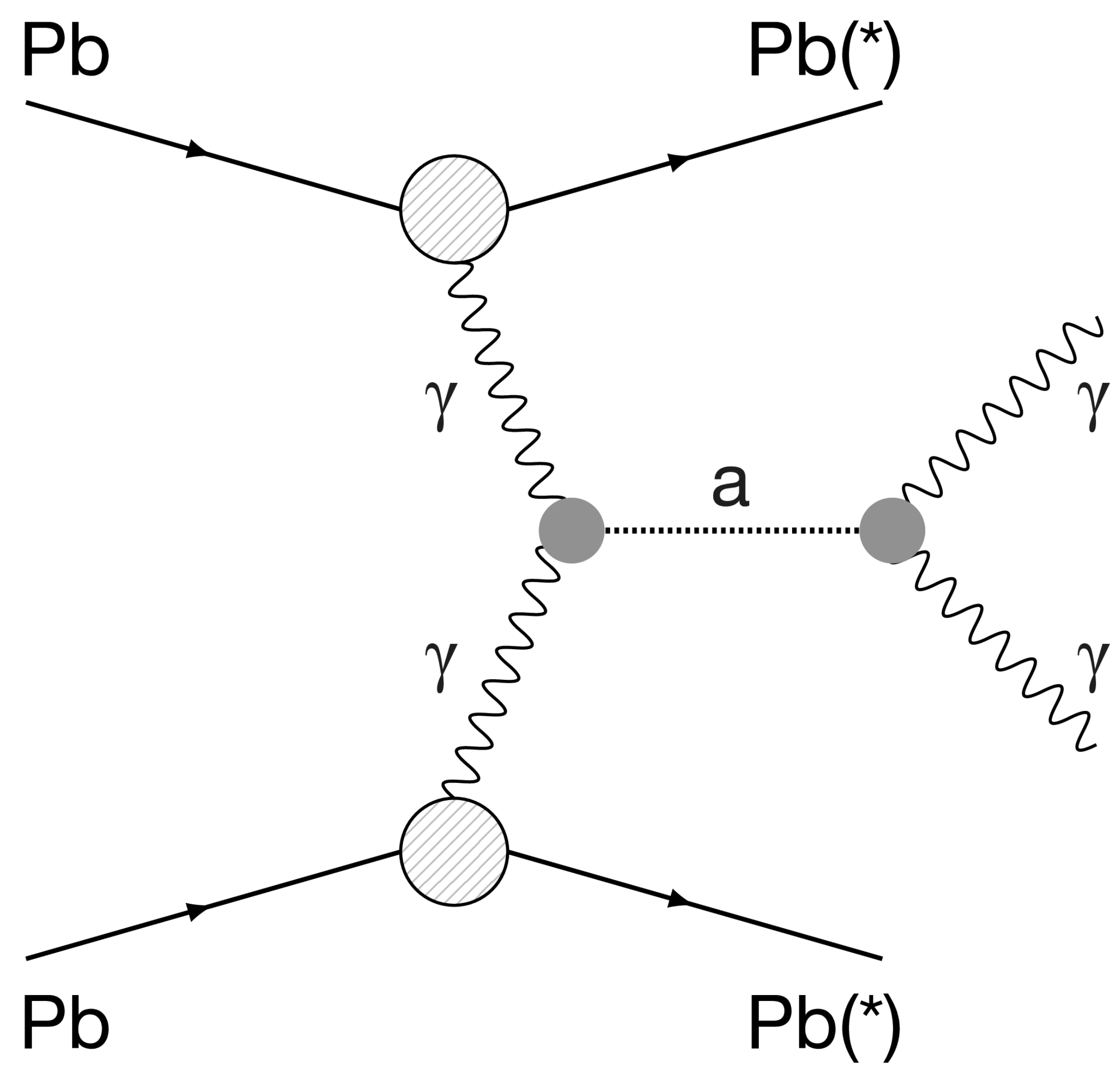
- Light-by-light scattering is a rare fundamental QED process (Observed in a direct way at the LHC for the first time [PRL 123 (2019) 052001]).
- Pb-Pb collisions can be used to set limits on the production of axion-like particles.
  - $Pb + Pb\ (\gamma\gamma) \rightarrow Pb^* + Pb^*\ \gamma\gamma$
- The study uses 2.2 nb^{-1} of integrated luminosity collected in 2015 and 2018 at sqrt(s) = 5.02 TeV resulting in100 event candidates.
- Final-state signature of interest is the **exclusive production of two photons:**
  - two **low-energy photons** with no further activity in the central detector,
  - **no reconstructed charged-particle tracks** originating from the Pb+Pb interaction point are expected. (Due to the absence of tracks, no primary vertex is reconstructed. The photon direction is estimated using the barycentre of the cluster.)

JHEP 03 (2021) 243

SM Light-by-Light Scattering



Axion production



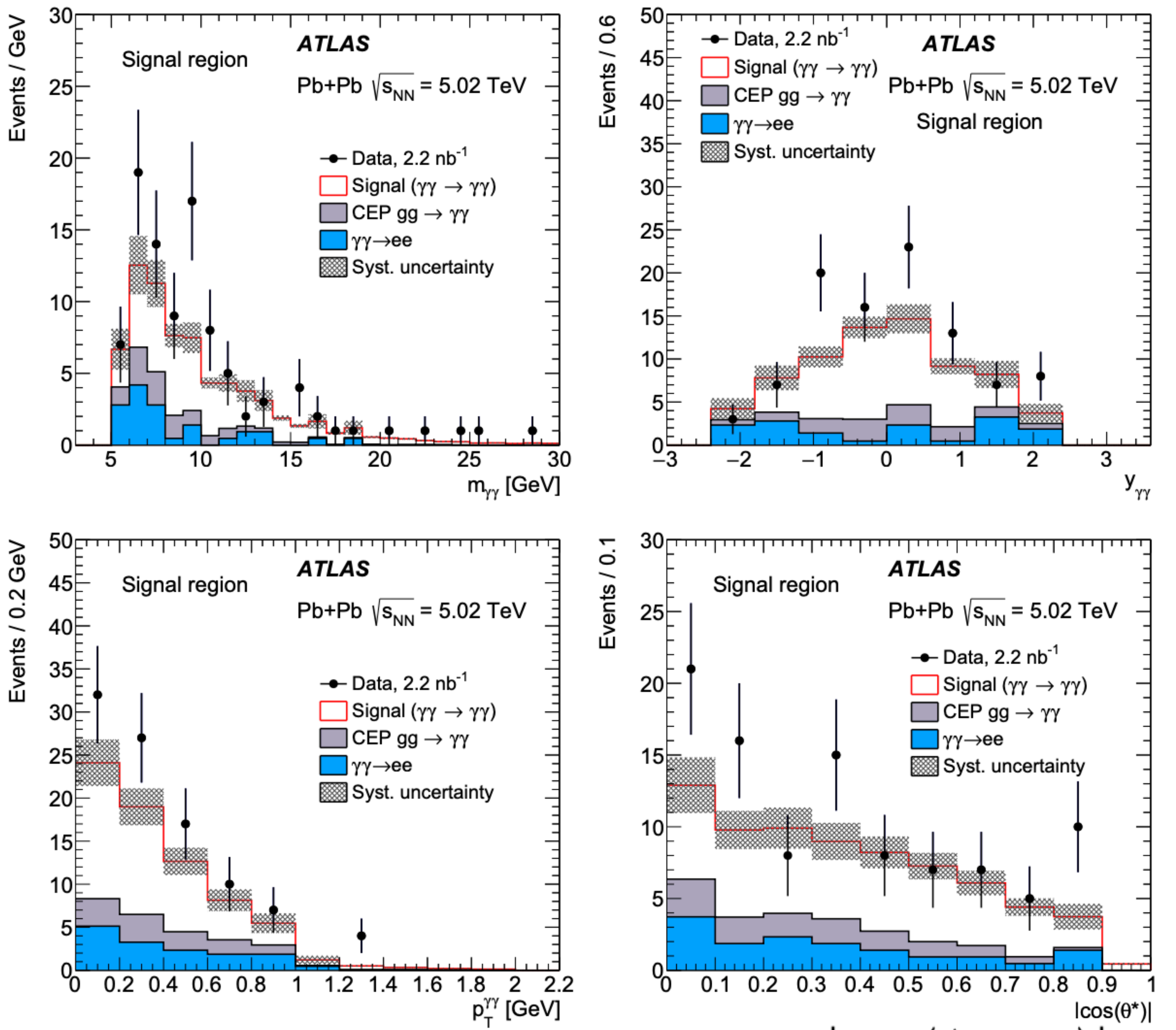
Event Selection $\gamma\gamma \to \gamma\gamma$

JHEP 03 (2021) 243

Look for di-photons final state

- Candidate di-photon events were recorded using a **dedicated trigger for events with moderate activity in the calorimeter** but little additional activity in the entire detector.
  - Photons are reconstructed from Electromagnetic clusters in the calorimeter and tracking information provided by the Inner Detector, which allows the identification of photon conversions
  - SuperChic MC generator

- Variables probing energy and angular correlations of the process
  - Invariant mass of the di-photon system, $m_{\gamma\gamma}$.
  - Average transverse momentum of two photons, $p^{\gamma\gamma}_T$
  - Rapidity of the di-photon system, $y_{\gamma\gamma}$, and angular correlation as cos($\boldsymbol{\theta}$)

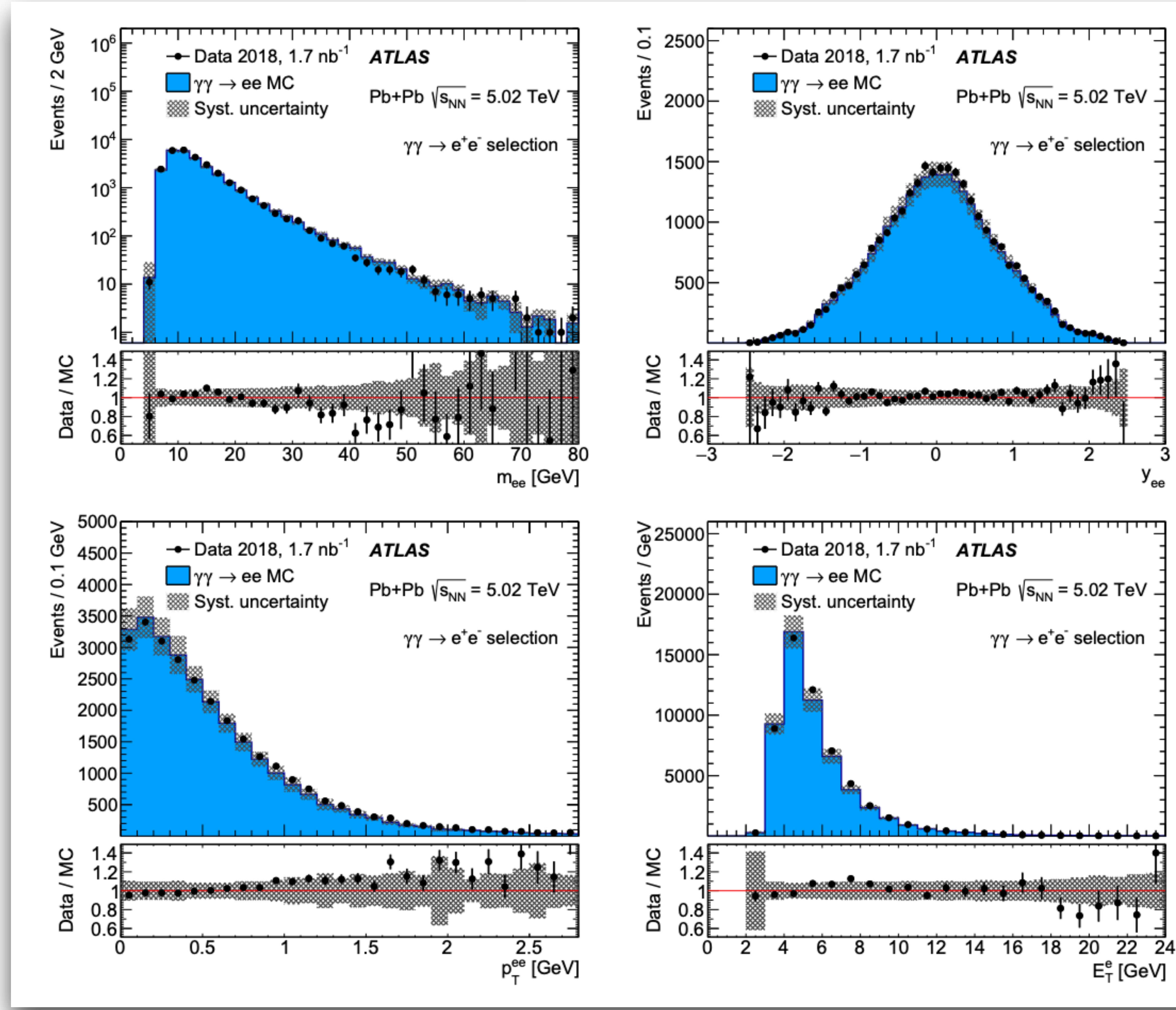


$$|\cos(\theta^*)| = \left|\tanh\left(\frac{\Delta y_{\gamma 1,\gamma 2}}{2}\right)\right|$$

Background for $\gamma\gamma \rightarrow \gamma\gamma$

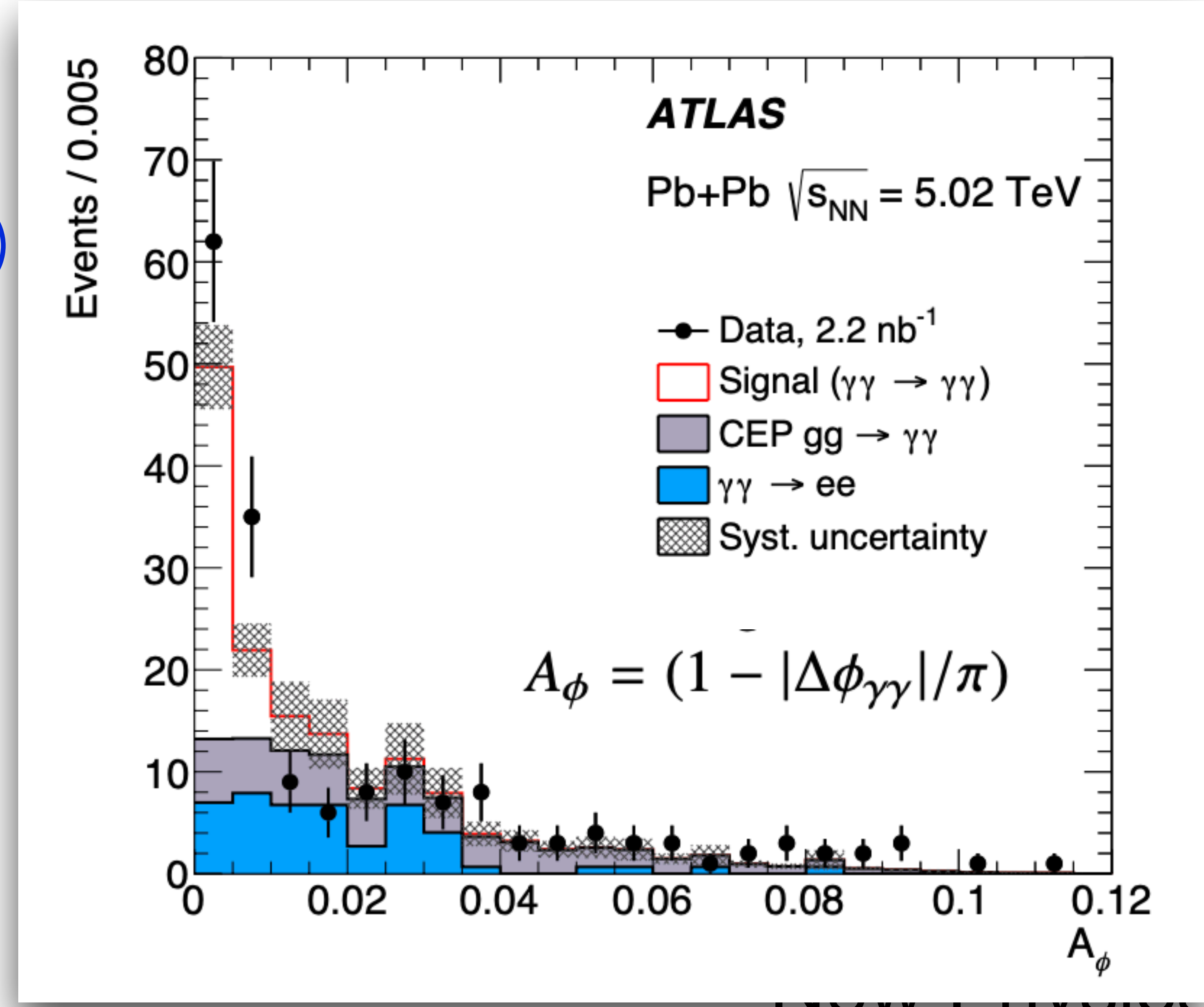
[JHEP 03 (2021) 243]

$\gamma\gamma \rightarrow e+\ e-$



Backgrounds:

- $\gamma\gamma \rightarrow e+\ e-$
  - electron-to-photon misidentification can occur when the electron track is not reconstructed or electron emits a hard bremsstrahlung photon -> data driven estimation
    - Process modelled with the STARlight v2.0 MC generator
- **$gg \rightarrow \gamma\gamma$ Central exclusive di-photon production.** MC generator SuperChic v3.0
- Minor contributions:
  - $e\gamma\gamma \rightarrow e+e-\gamma\gamma$
  - $\gamma\gamma \rightarrow q\bar{q}$ (Herwig)



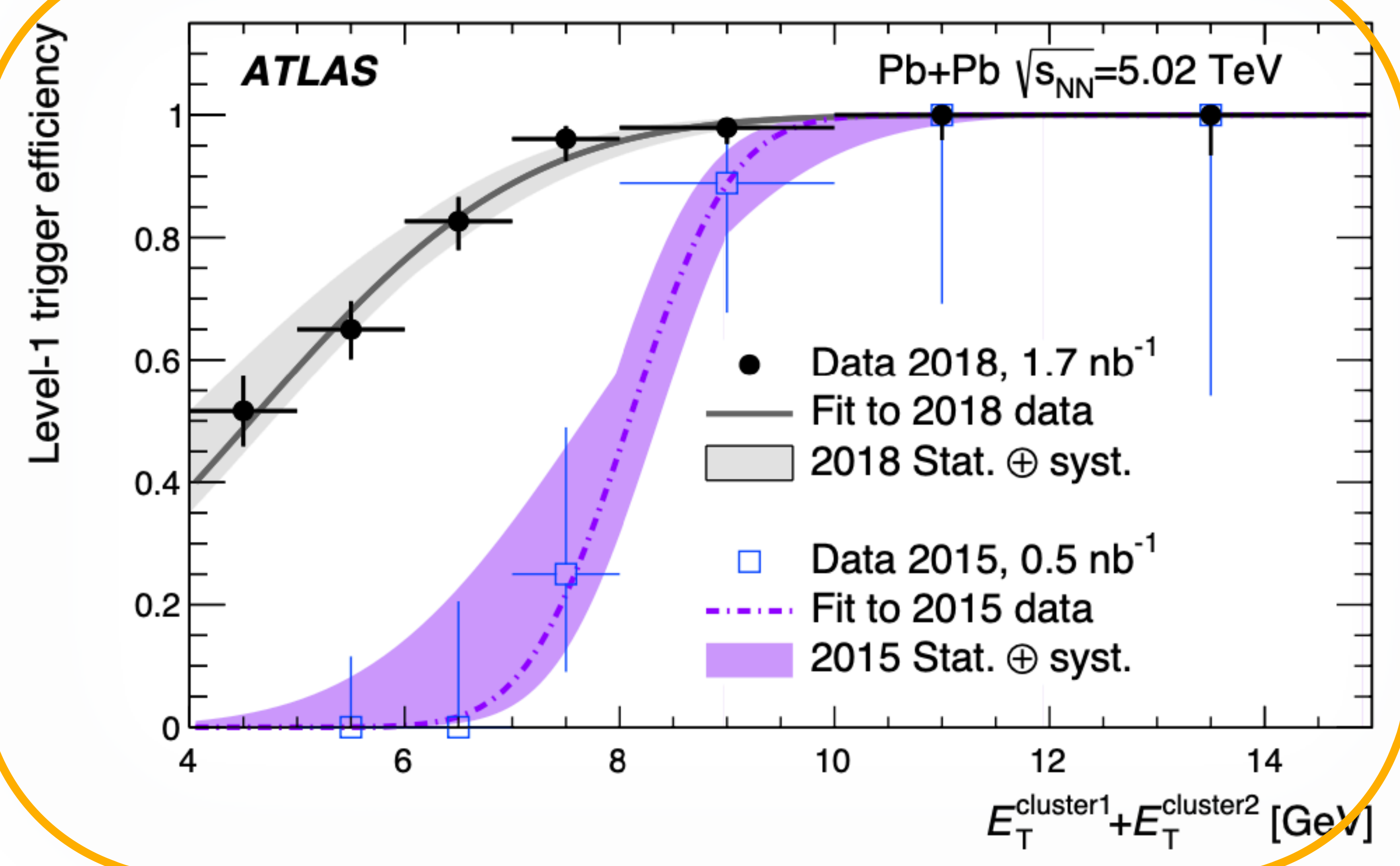
Systematic Uncertainty

JHEP 03 (2021) 243

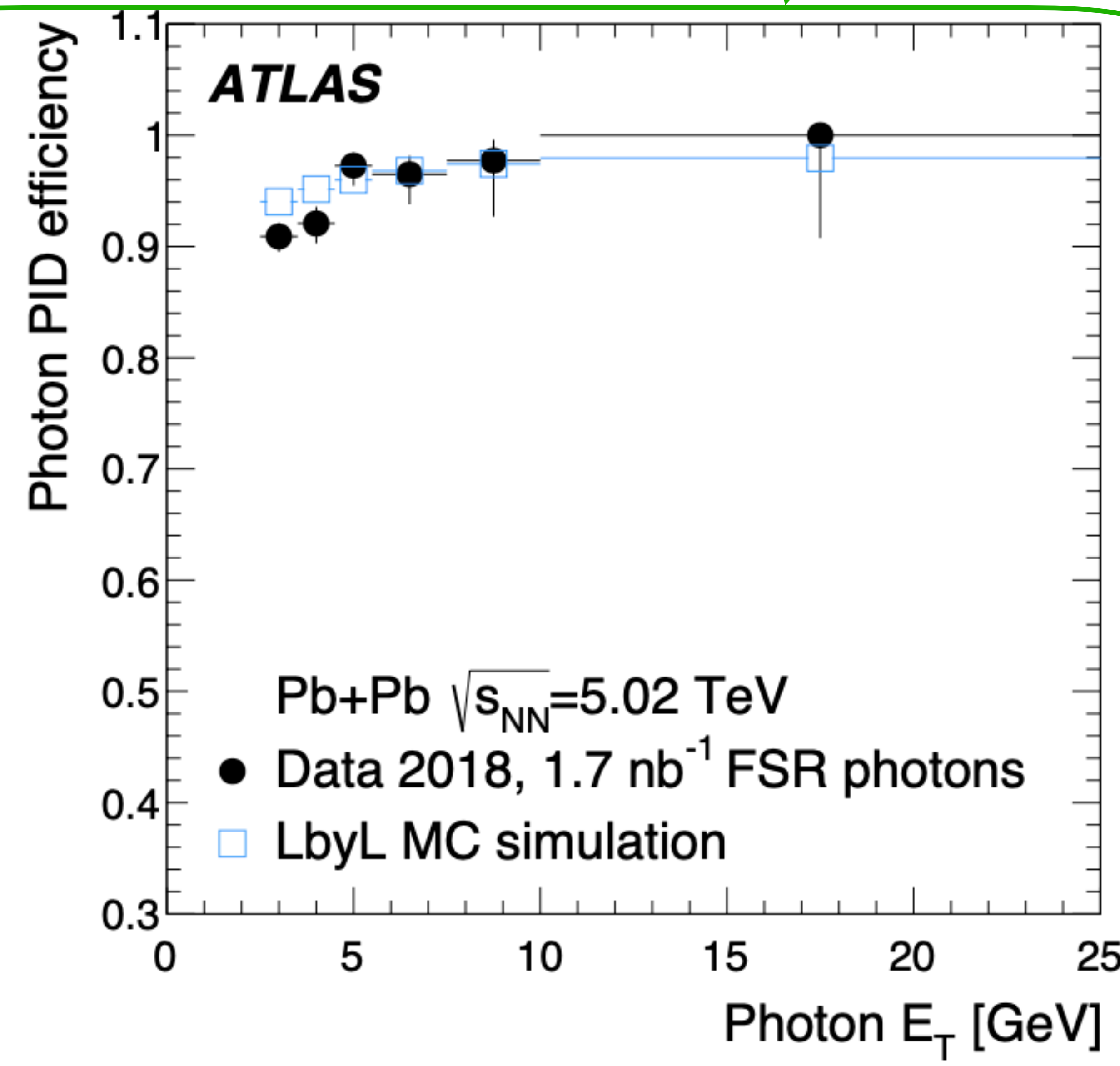
Impact of experimental effects on the measurement: resolutions, calibration

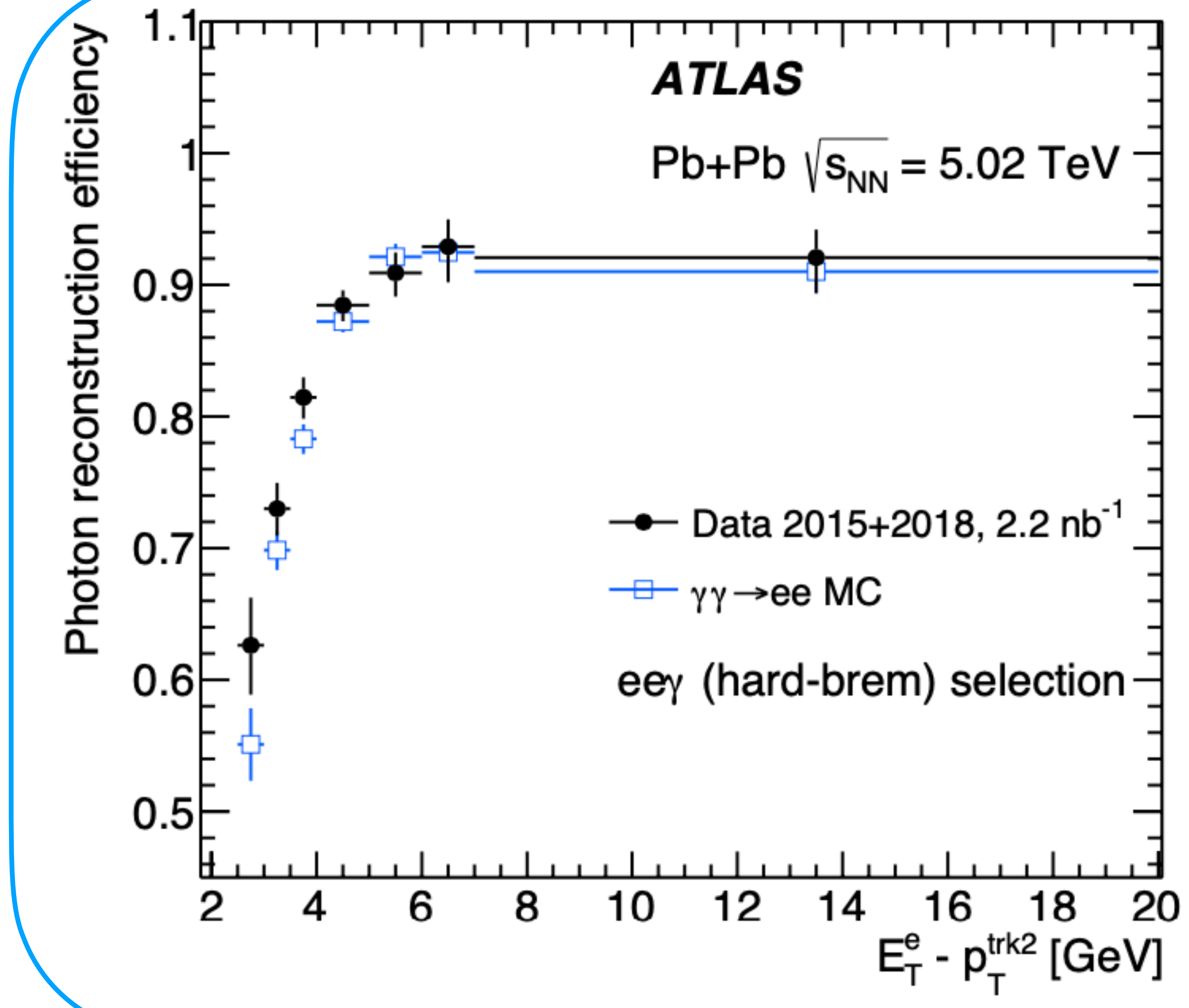
MC Theory Model

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%



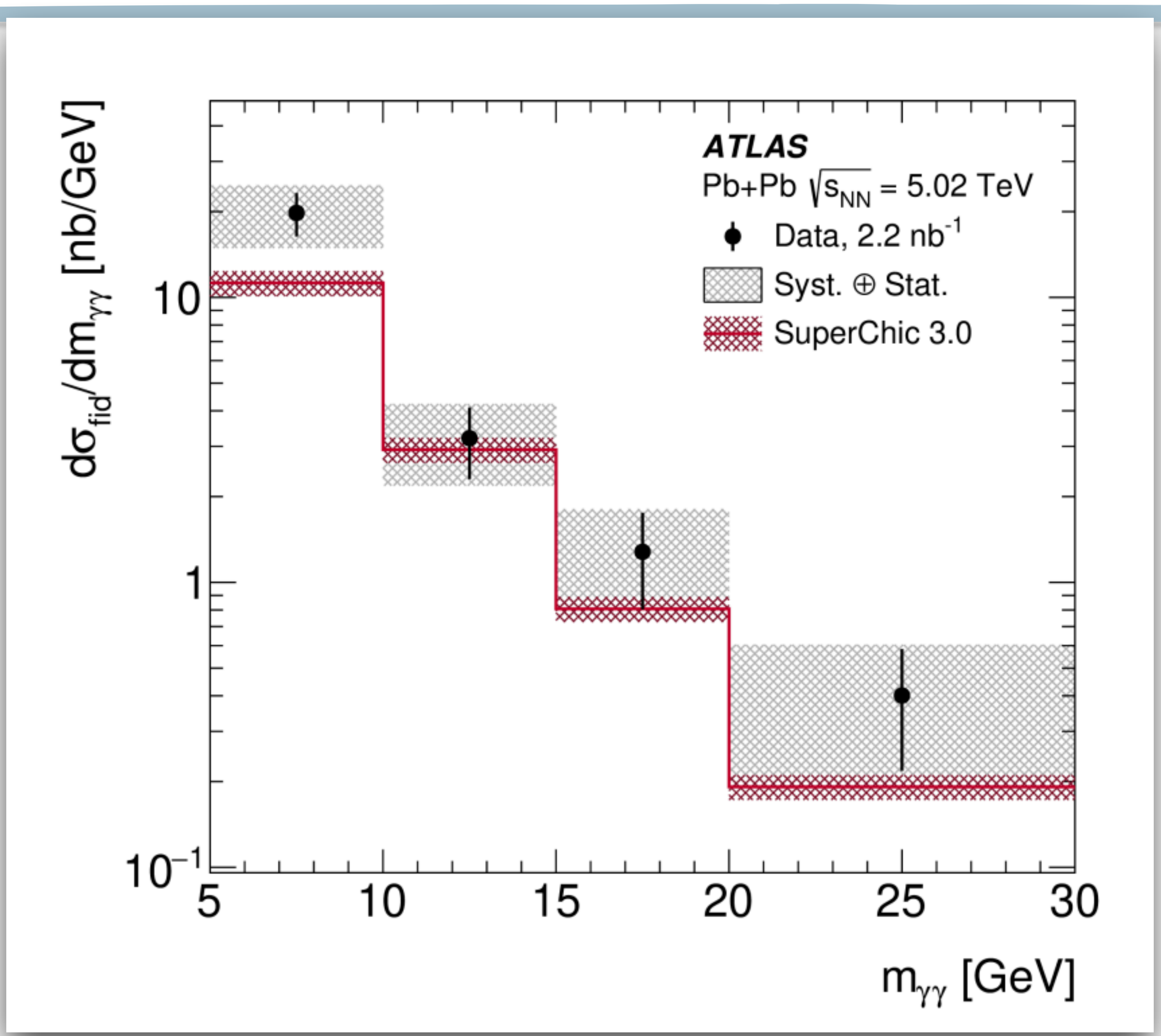
The trigger efficiency is parameterised using an error function fit that is used to reweight the MC simulation.

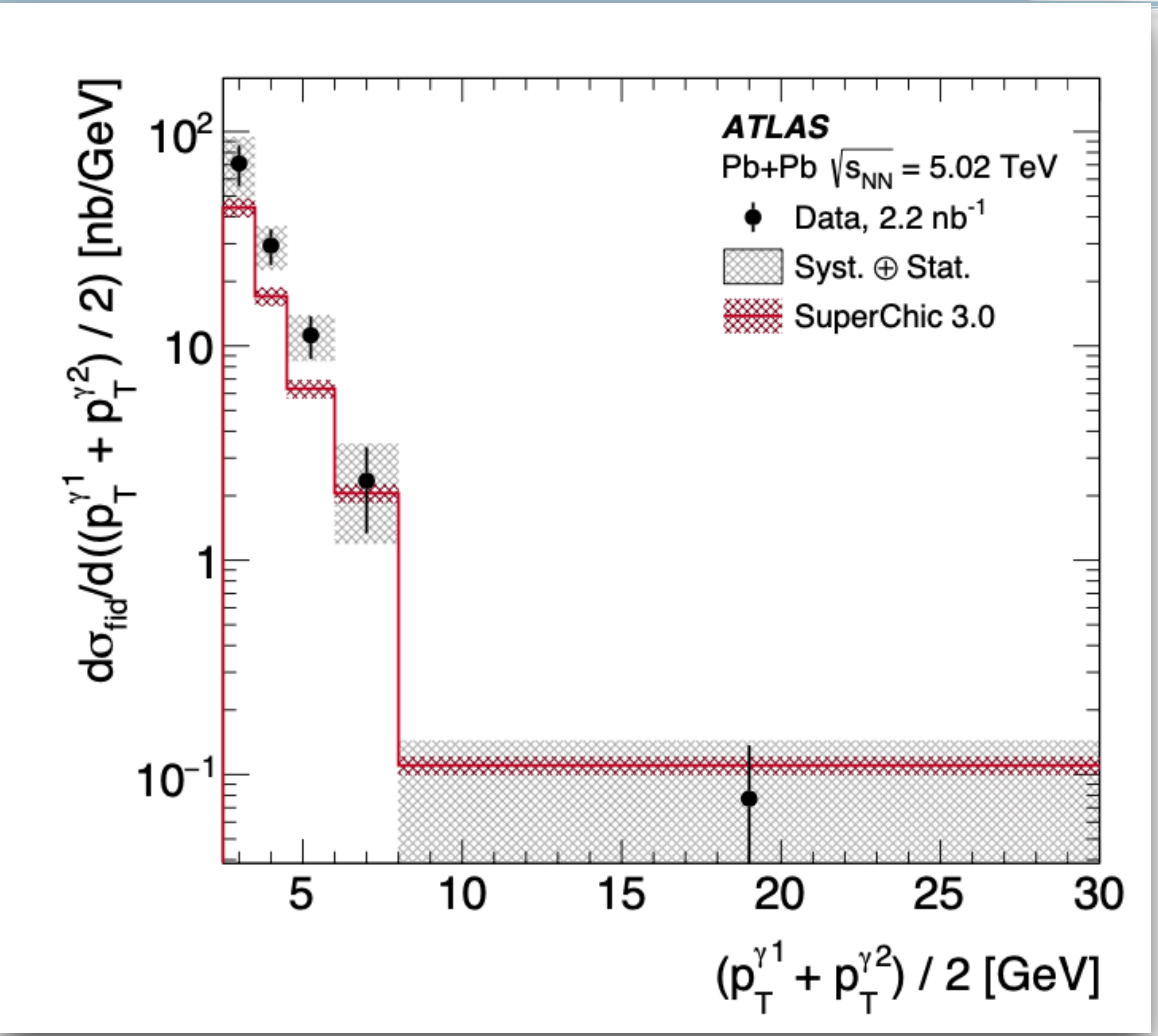




Light-by-light scattering: Cross Section

JHEP 03 (2021) 243





The measured integrated fiducial cross section is σ_{fid} = 120 ± 17 (stat.) ± 13 (syst.) ± 4 (lumi.) nb
The data-to-theory ratio is of the order of 1.50

- **Cross sections measured** in the fiducial region defined by:
  $E_T^\gamma > 2.5\text{GeV},\ m_{\gamma\gamma} > 5\text{GeV},\ |\eta^\gamma| < 2.4,\ p_T^{\gamma\gamma} < 1\text{GeV}$
- Differential Cross section in $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $|cos\theta^*|$, $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$
  - **Good agreement in shape, differences in the normalisation**
- Theory predictions from [PRC 93 (2016) 044907] and [EPJ C 79 (2019) 39] about 50% below data

Look for Axion Production

[JHEP 03 (2021) 243]

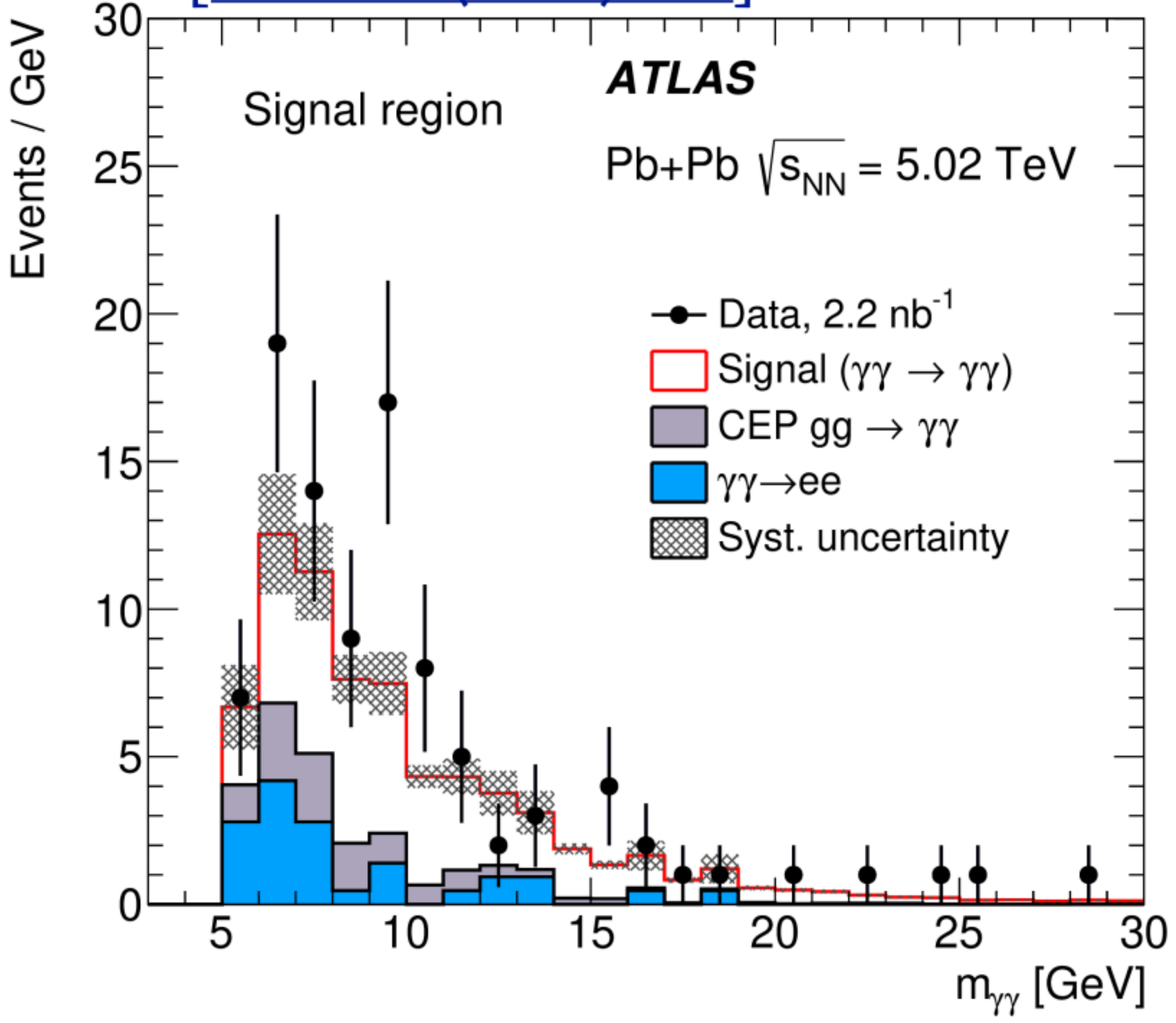
Resonance peak in the invariant mass spectrum.

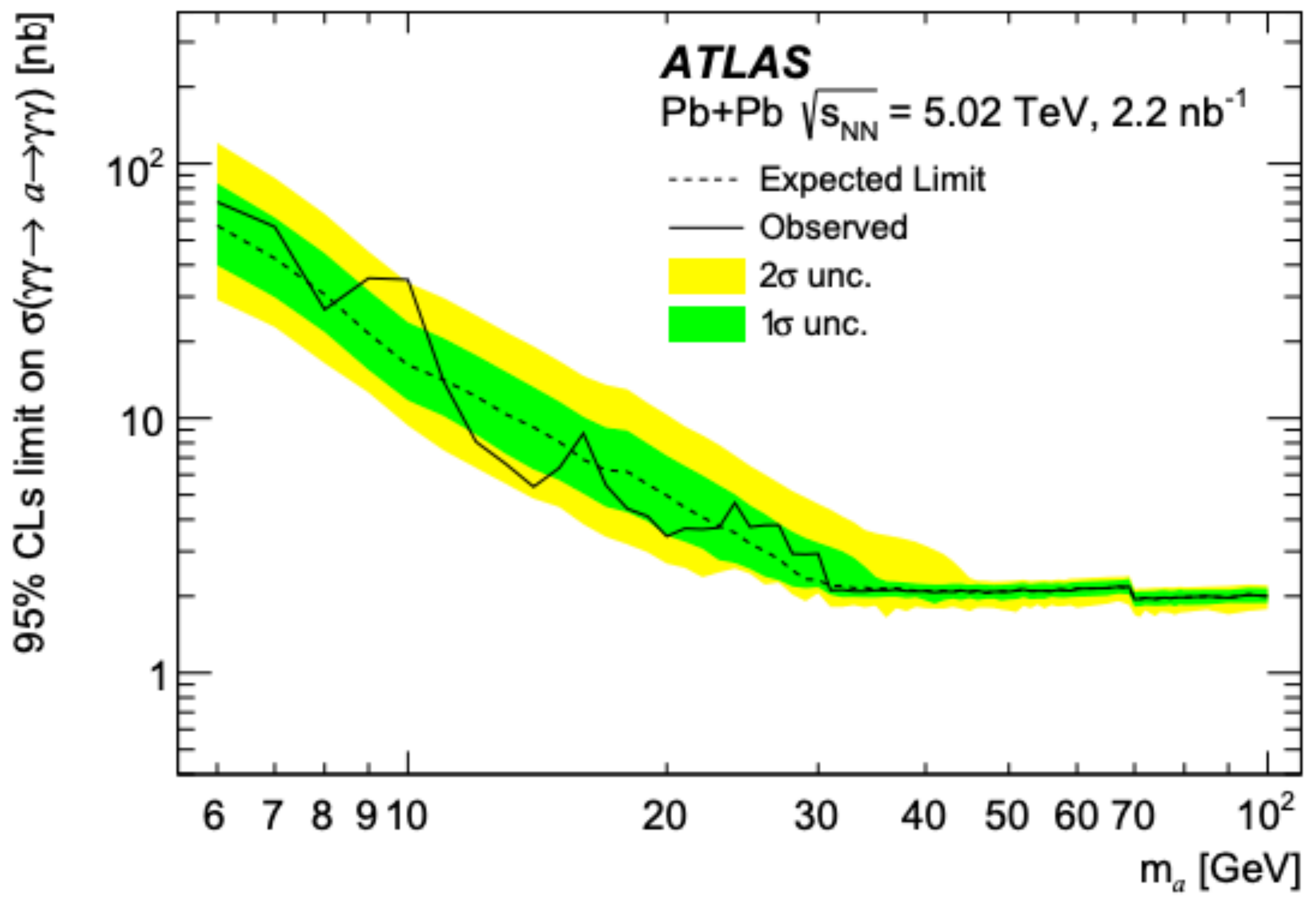
Search for ALP in range of $6 < m_{\gamma\gamma} < 100$ GeV using a cut-and-count method

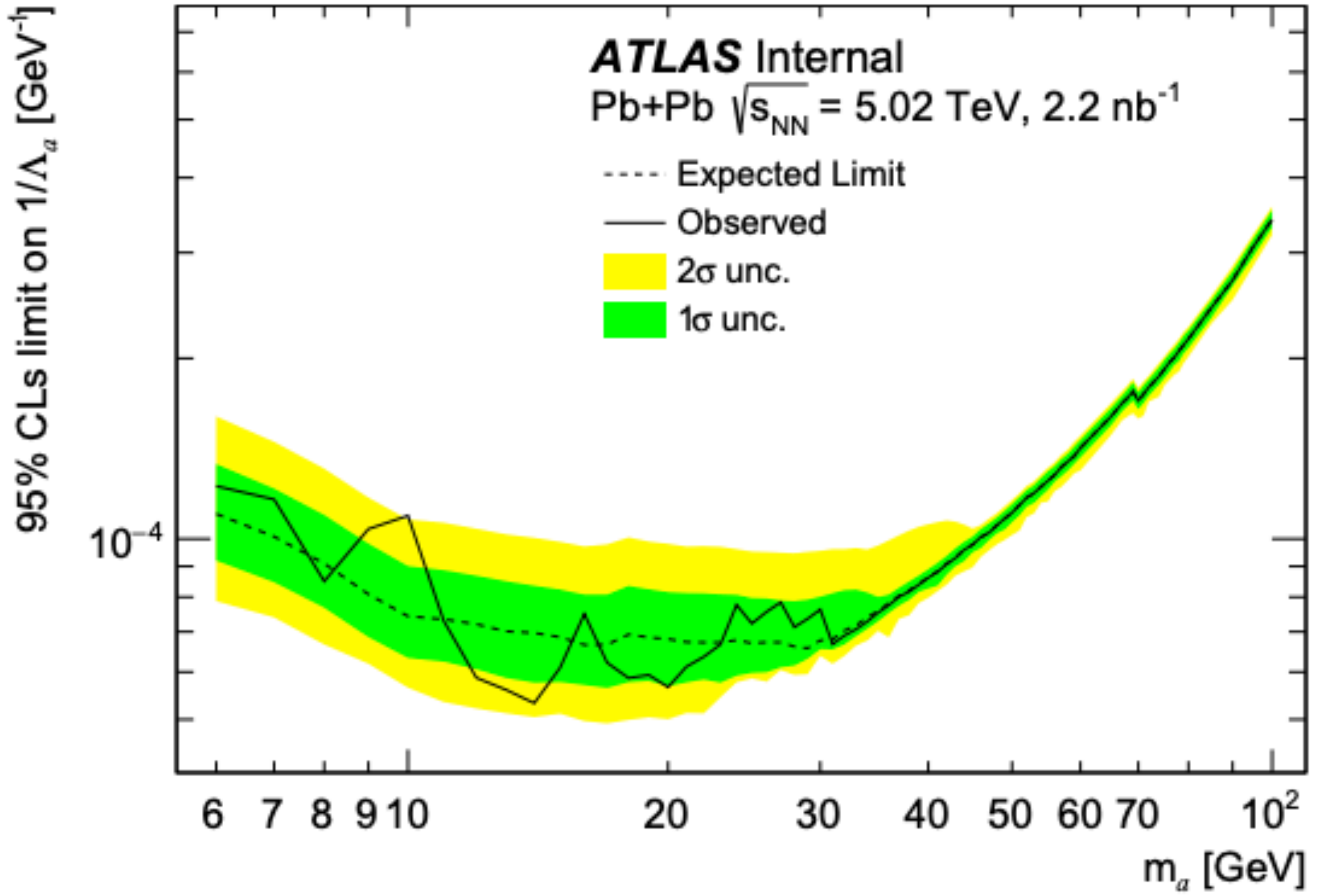
Signal: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$, BR($a \rightarrow \gamma\gamma$)=100%, STARlight MC

- The signal contribution is fitted individually for every bin using a maximum-likelihood fit in the di-photon invariant mass.
  - no significant deviation from the background-only hypothesis is observed, upper limit on the ALP signal strength is set.

[JHEP 03 (2021) 243]







Results

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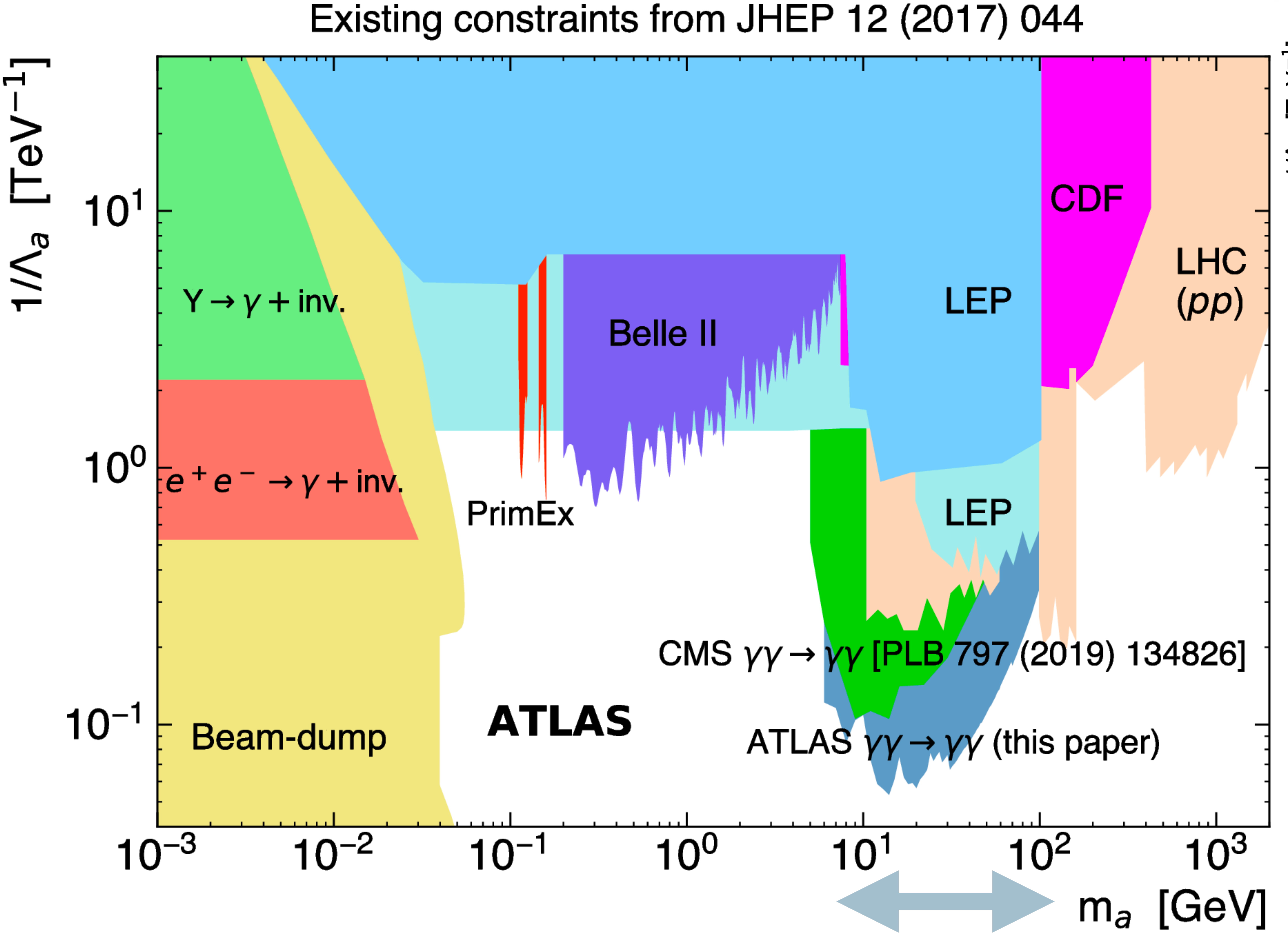
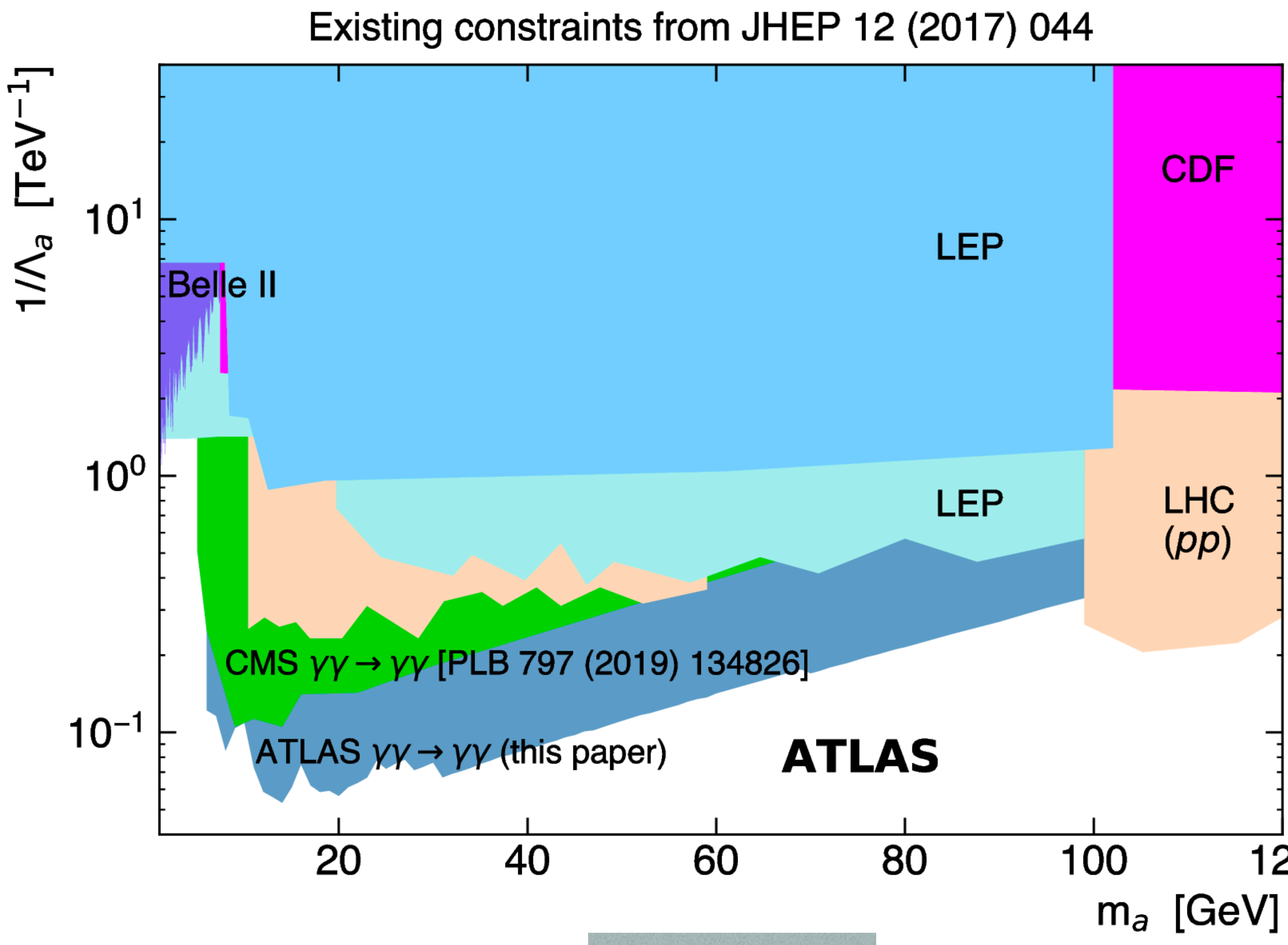
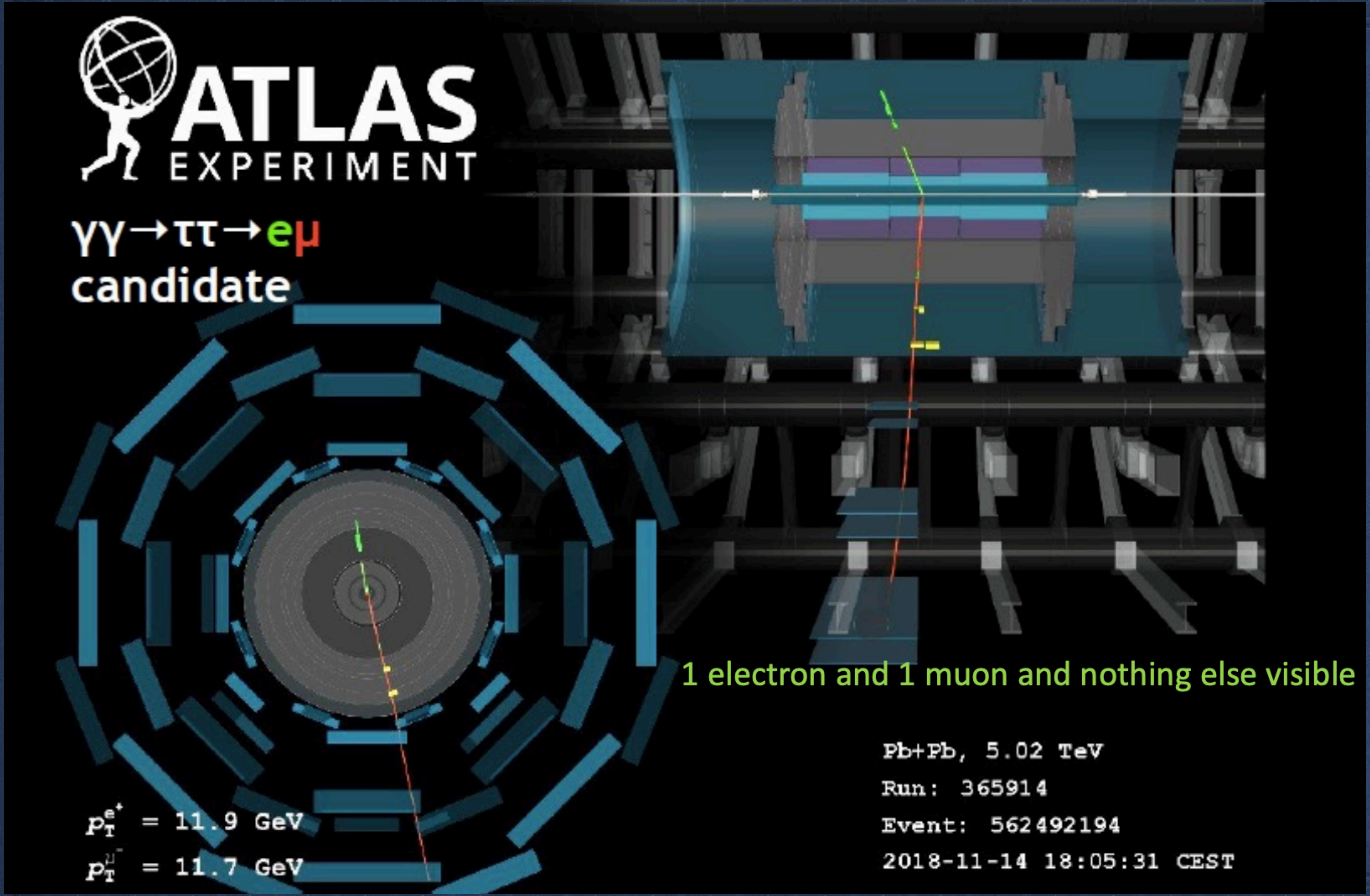




ZOOM

Largest deviation of 2.1σ at $m_{\gamma\gamma}$ ~10 GeV

The most stringent limit established for ALP masses between 6-100 GeV!



arXiv:2204.13478

g-2
Anomalous
Magnetic Moment

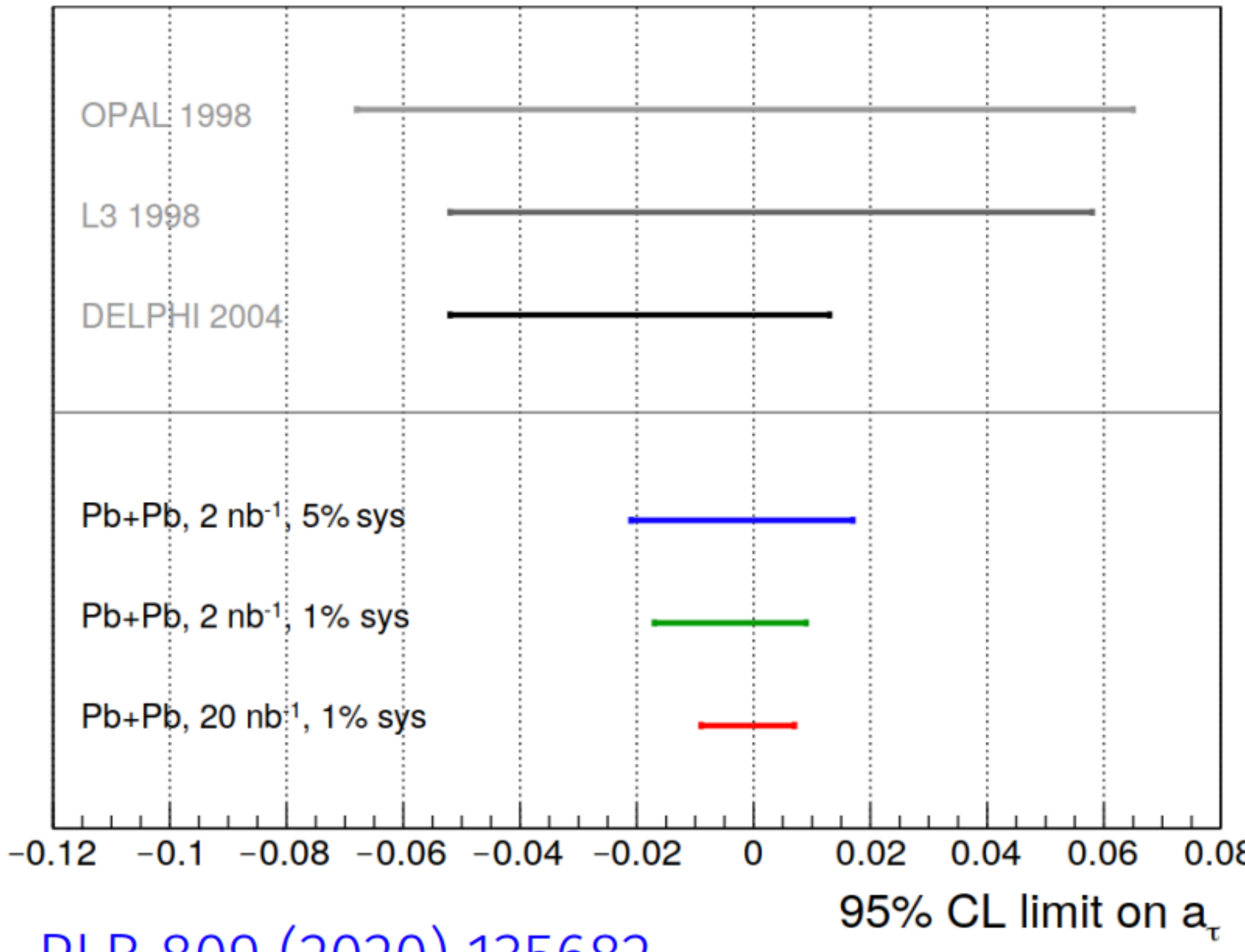
Current status of a_τ measurement

arXiv:2204.13478

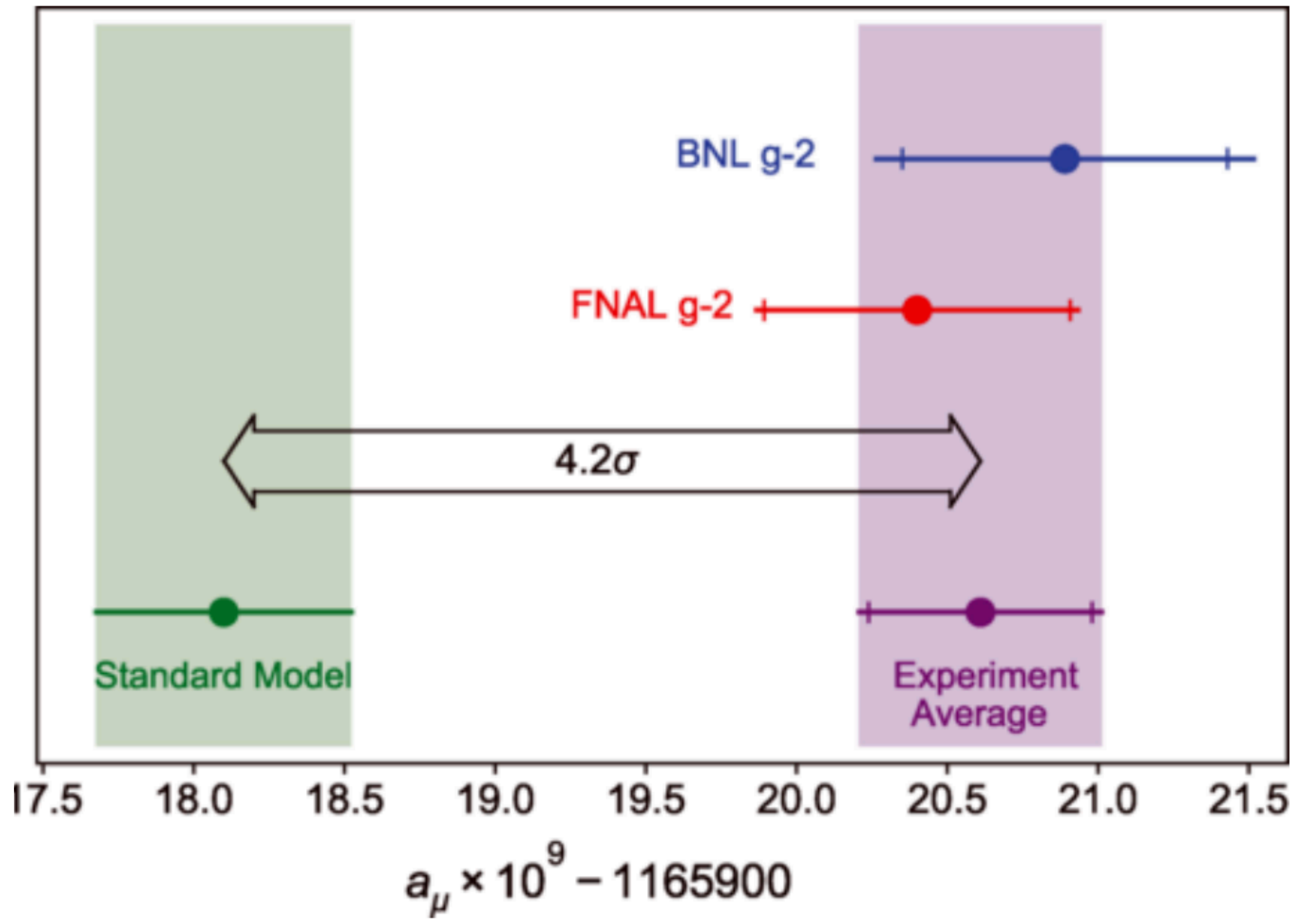
- **Anomalous magnetic moment:**

$$a_\tau = \frac{(g-2)_l}{2}$$

  - **Standard Model prediction (Mod. Phys. Lett. A 22 (2007) 159):**
    - $a_\tau = 0.00117721 \pm 0.00000005$
  - **Best experimental limits on a_τ set by DELPHI at LEP (EPJ C 35 (2004) 159):**
    - $-0.052 < a_\tau < 0.013$ (95% CL)
- Relevant for precision measurement of QED, electroweak, and QCD
- **Many BSM models predict modifications of a_τ:**
  - lepton compositeness where corrections are of O(m_{lepton}/ $m_{constituent}$)
  - SUSY models O($\delta a_\tau \sim m^2_\tau / M^2_S$)
    - a_τ can be $m^2_\tau / m^2_\mu \approx 280$ times more sensitive to BSM than a_μ

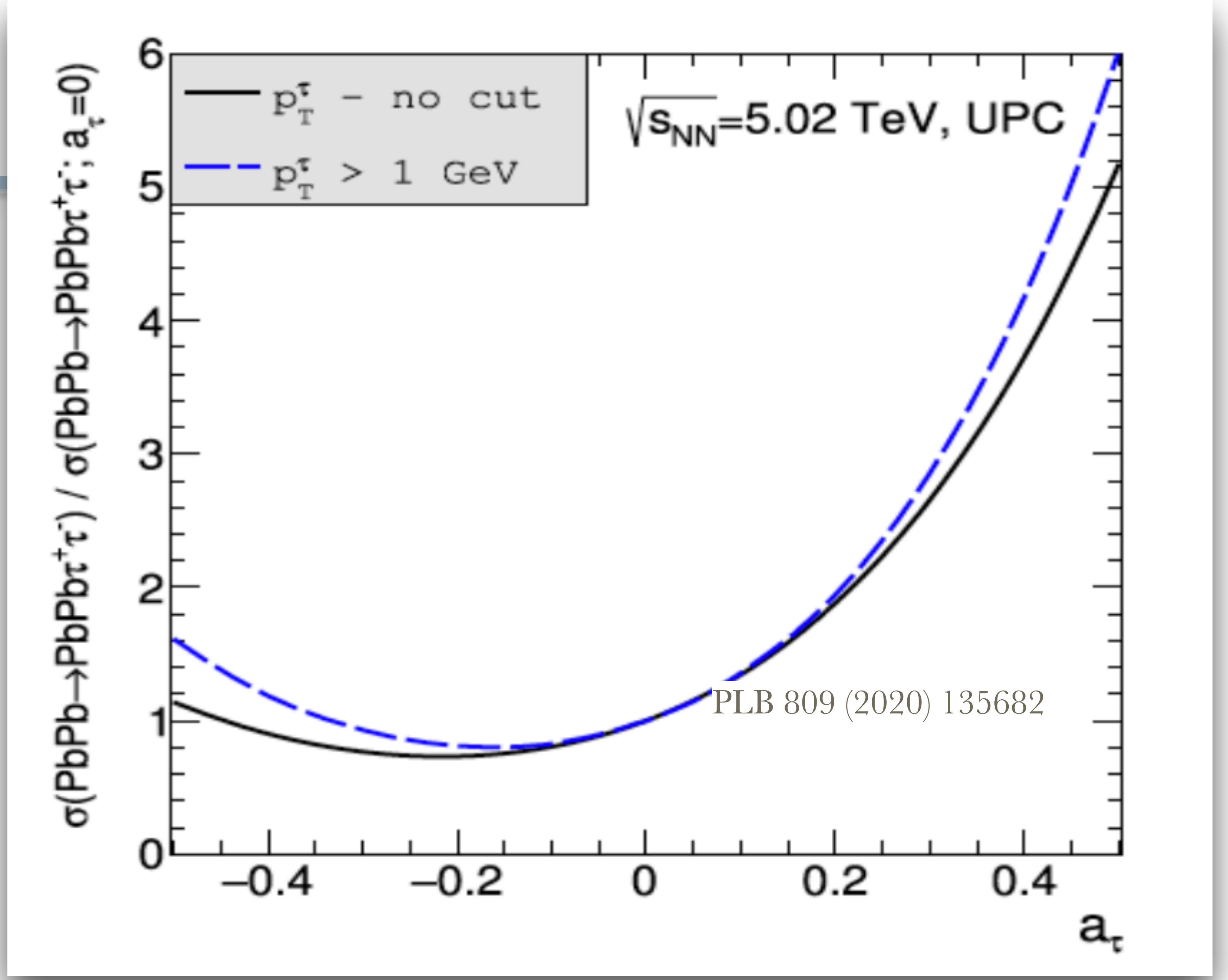


PLB 809 (2020) 135682

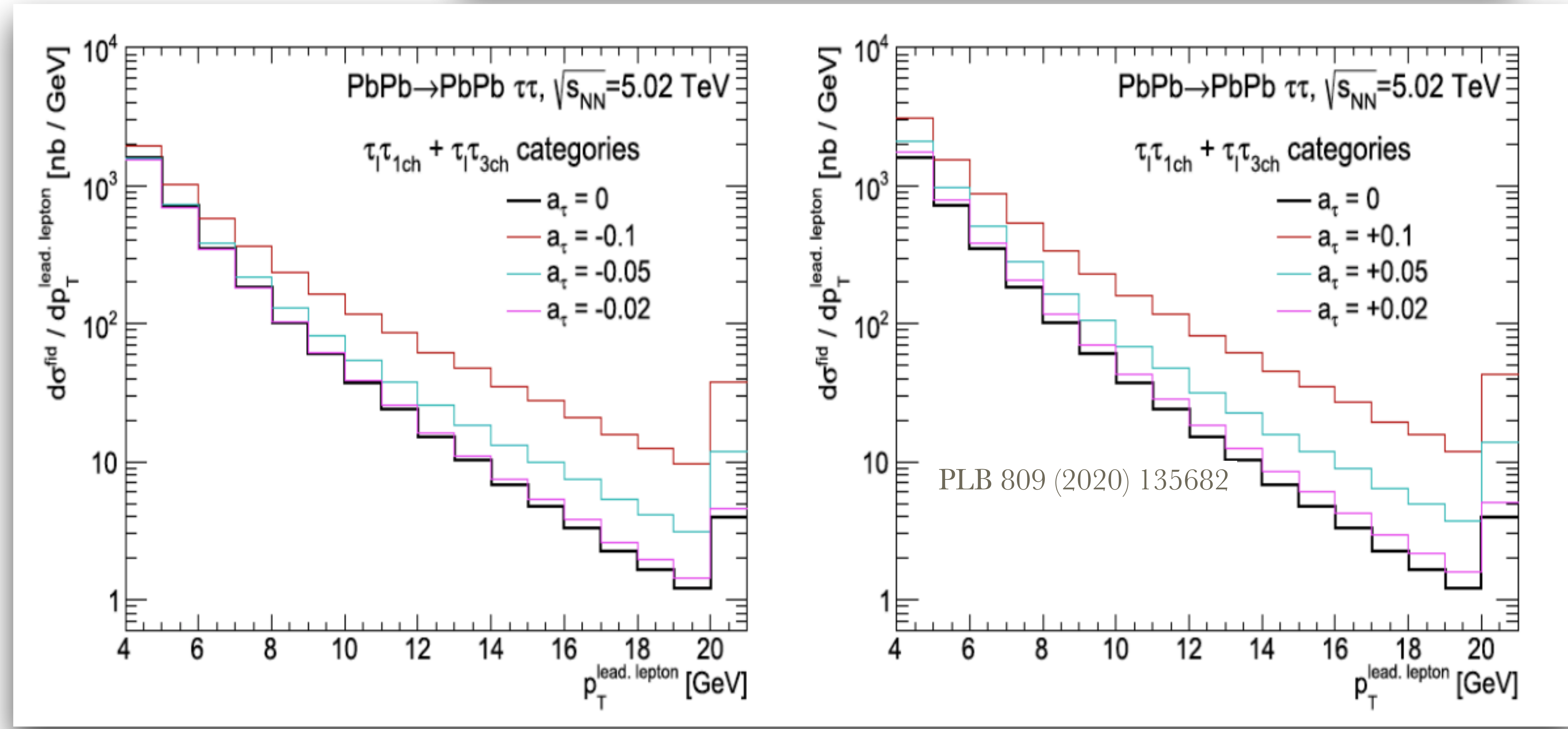


PhysRevLett.126.141801

Measuring a_τ with ATLAS



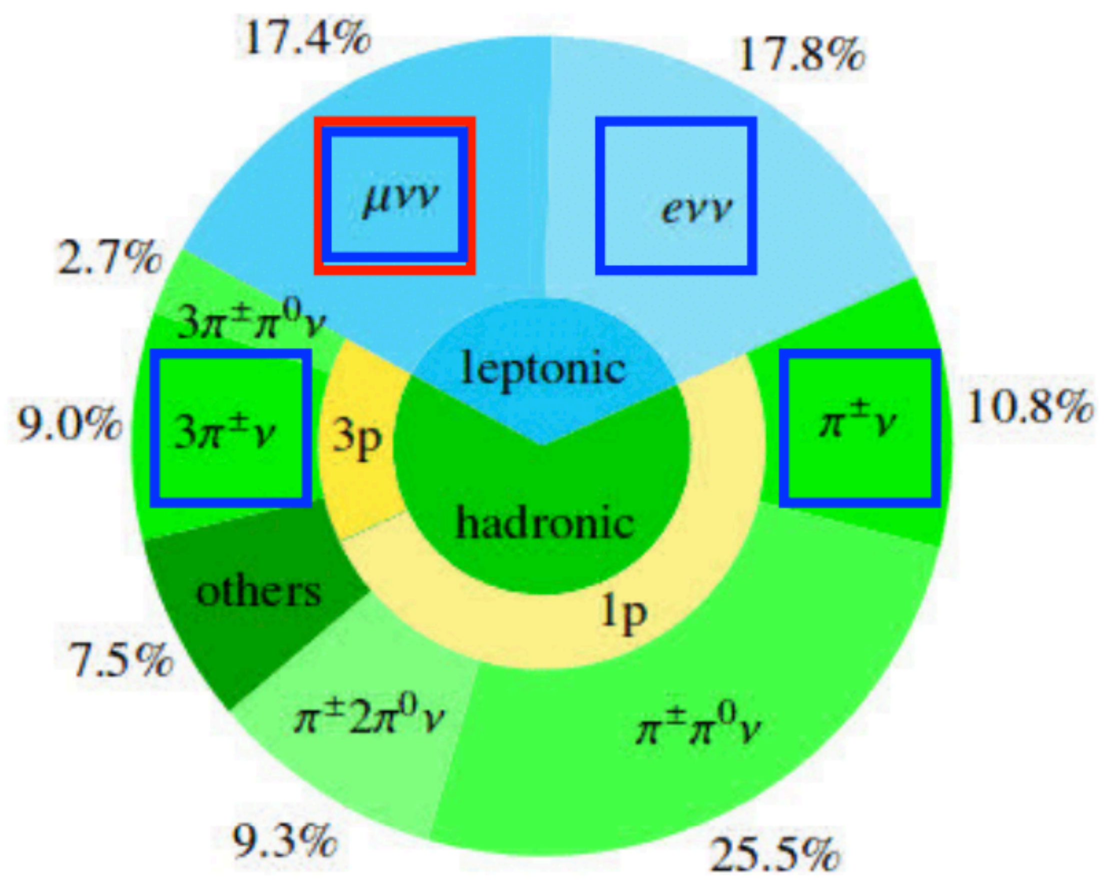
- **Analysis idea from:**
  - L. Beresford, J. Liu, PRD 102 (2020) 113008
  - M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek, PLB 809 (2020) 135682
- Constraints on a_τ from total $\gamma\gamma \to \tau\tau$ cross-section / yield and differential distributions (e.g. leading lepton p_T)
  - MC generators: Starlight + Tauola (tau-decays) + Pythia8
- Main Background
  - $\gamma\gamma \to ll$ (Starlight with Pythia8 (QED FSR)
  - $\gamma\gamma \to qq$ (Starlight with Pythia8 (QED FSR)
  - **photo-nuclear events**

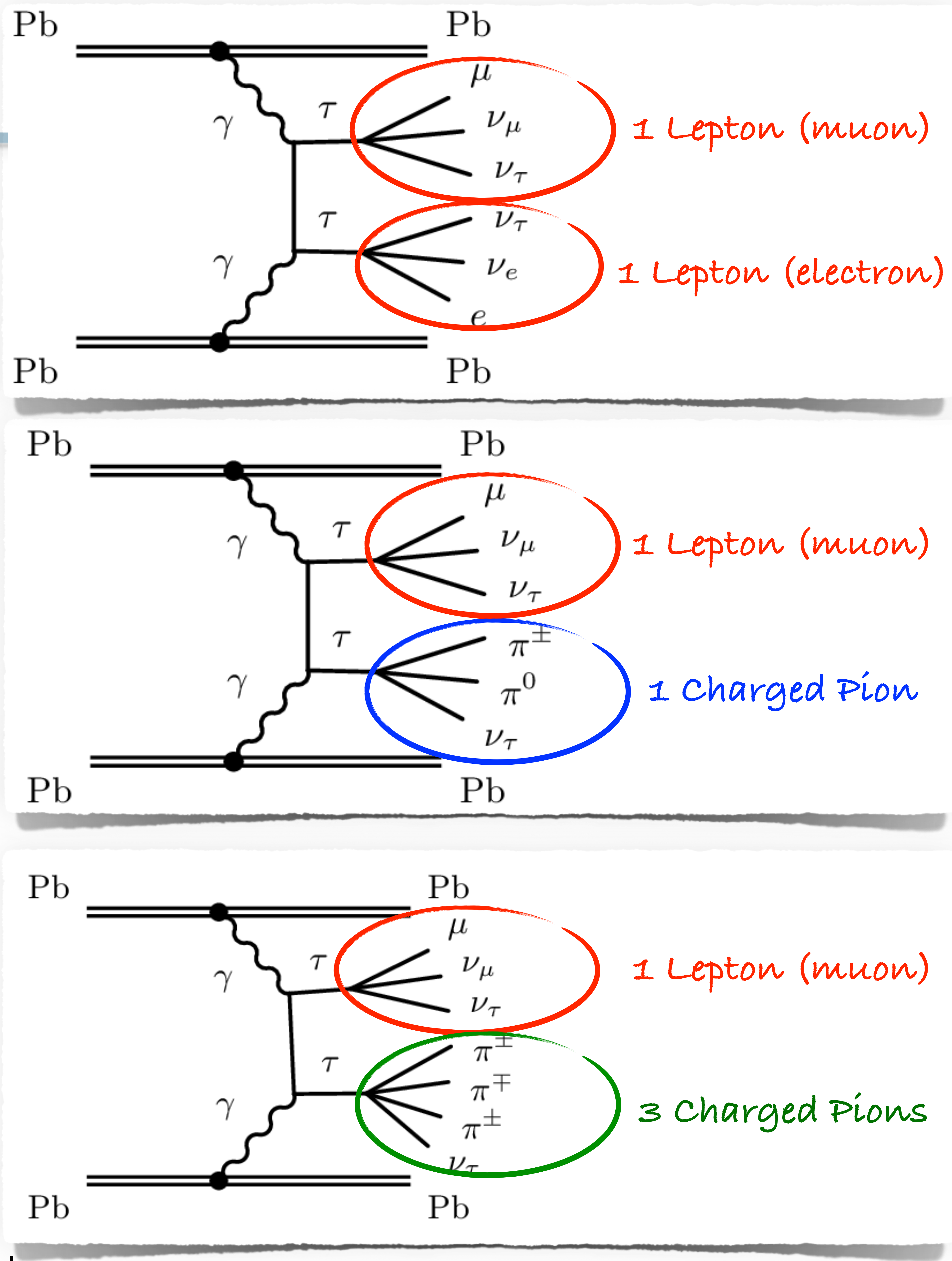


Event Topology

arXiv:2204.13478

- Each tau can decay in hadrons or in leptons with different branching ratios (BRs).
  - 1 Lepton
    - $\tau^{\pm} \rightarrow \nu_{\tau} + l^{\pm} + \nu_{l} \ (l = e, \mu)$
    - BR = 35%
  - 1 Charged Pion
    - $\tau^{\pm} \rightarrow \nu_{\tau} + \pi^{\pm} + n\pi^{0}$
    - BR = 45.6%
  - 3 Charged Pions
    - $\tau^{\pm} \rightarrow \nu_{\tau} + \pi^{\pm} + \pi^{\mp} + \pi^{\pm} + n\pi^{0}$
    - BR = 19.4%





- ATLAS selects events where one tau decays in 1muon (which drives the trigger selection) and the other tau can decay both in 1 electron or in 1 charged pion or in 3 charged pions.

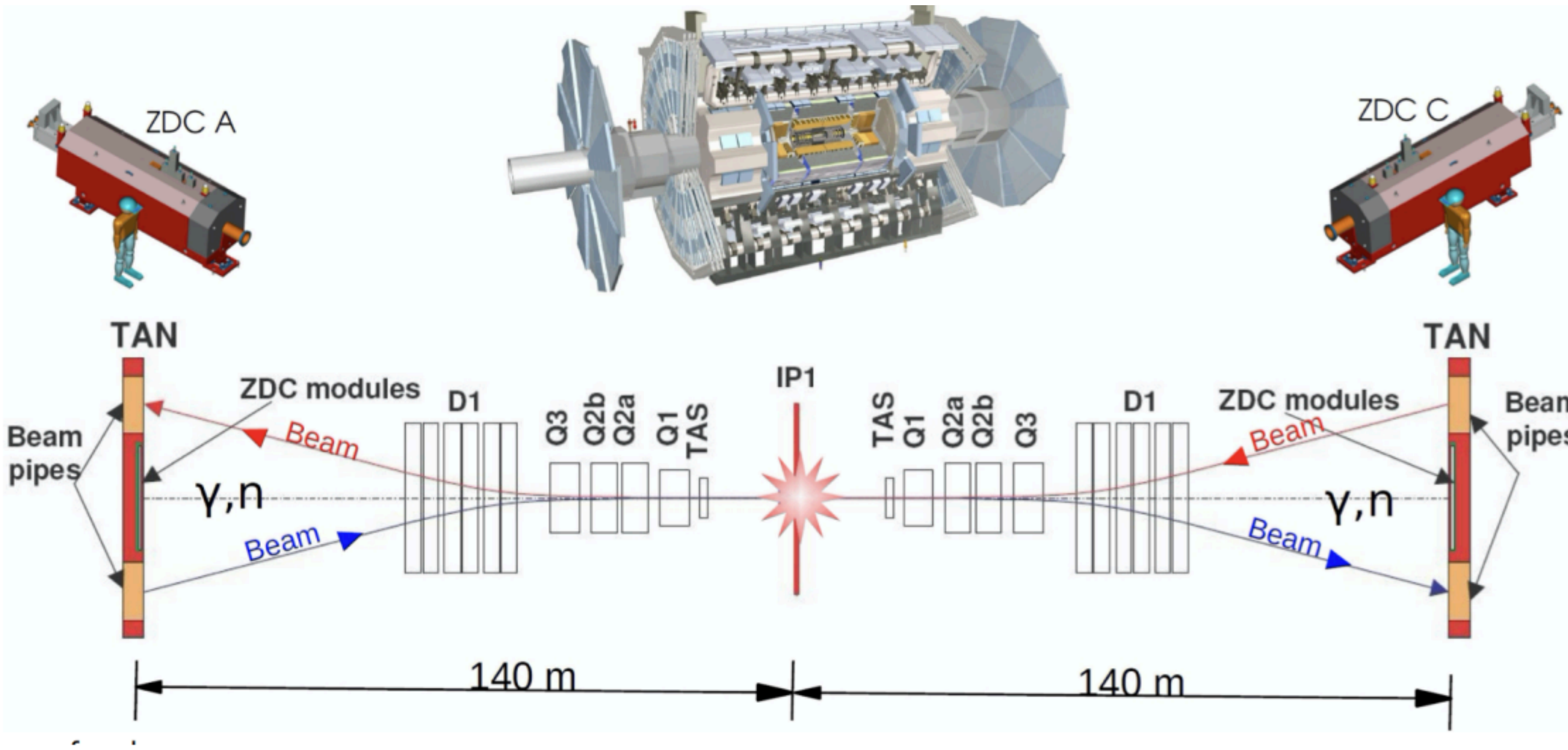
Analysis Strategy

arXiv:2204.13478

Muon to trigger the event: high efficiency

Vetoing Forward activity to separate UPCs from inelastic Pb+Pb collisions

Zero Degree Calorimeter η>8.3



Analysis Strategy:

- 3 periods of heavy ion collisions during Run2
- Ultraperipheral Collisions (UPC) of PbPb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - Order of 1.44 nb^{-1} data sample
  - Elastic & diffractive
  - Small energy deposit in the forward detector system

- Categorise di-tau events in three Signal Regions (SRs):
  - **SR1M1T**: 1 muon + 1 track (pion)
  - **SR1M3T**: 1 muon + 3 tracks (3pions)
  - **SR1M1E**: 1 muon + 1 electron
- **Control region 2MCR:** Events with 2 muons with invariant mass above 11 GeV to suppress quarkonia states and no additional tracks

- Experimental challenges:
  - UPC selection
  - tau-identification
  - neutrinos in the final state
  - muon misidentified as a pion and the emission of a FS photon can mimic the topology muon-pion

Event Selection

arXiv:2204.13478

ATLAS

Event Preselection

- **Trigger:** HLT_mu4 + FCal-based forward gap + total E_T at L1 < 50 GeV
- E_{ZDC} <1TeV: reduce neutral particles in the forward region helps to separate UPCs from inelastic Pb+Pb collisions. Reduce photo-nuclear background

Region Selection

- Exclusivity selections: no tracks except signal leptons/tracks - no clusters unmatched to signal leptons/tracks
- Cuts on system p_T help to suppress $\gamma\gamma \to \mu\mu$ background in 1M1T SR

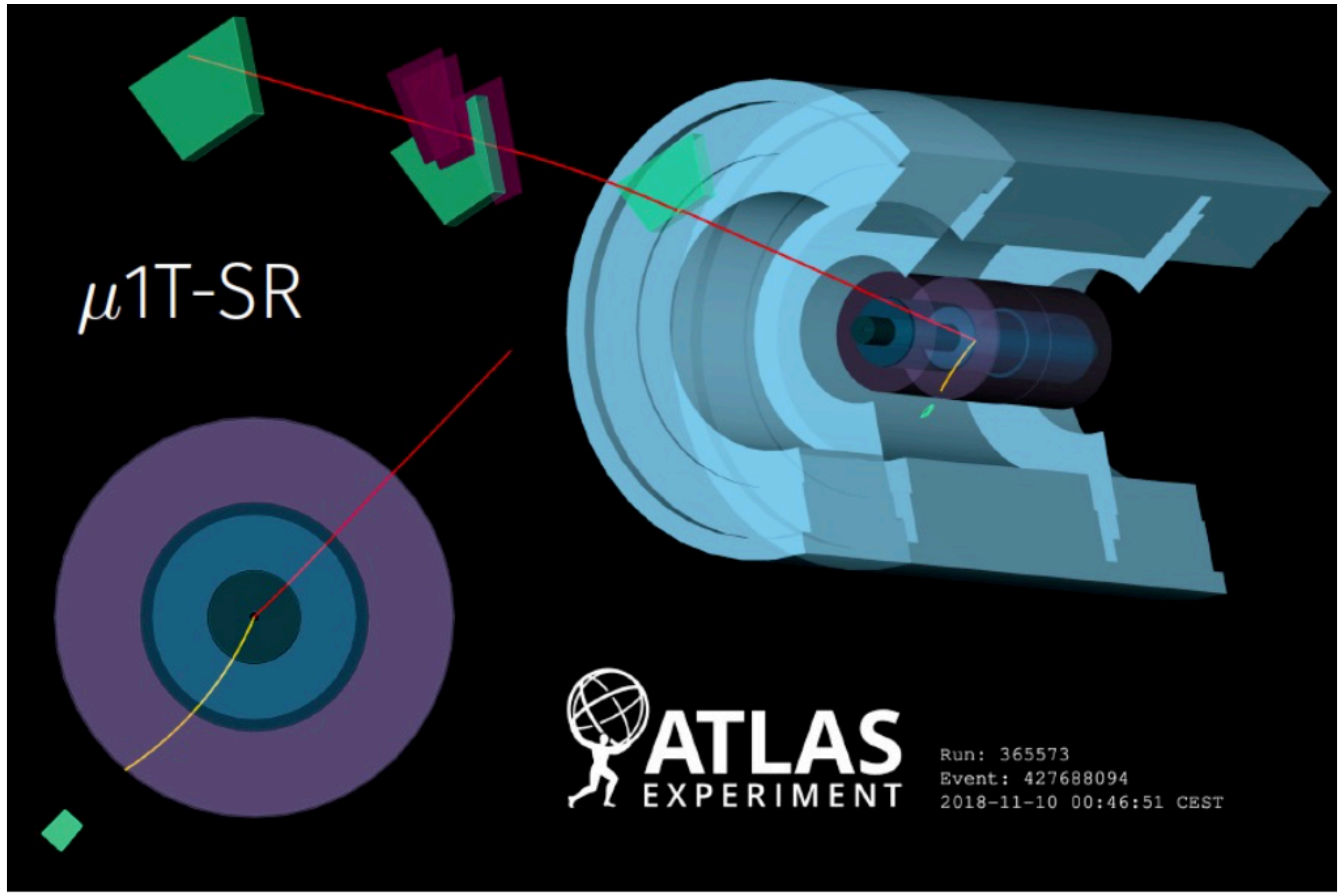
Region	Data	Signal $\gamma\gamma \to \tau\tau$	Background $\gamma\gamma \to \mu\mu(\gamma)$	Background $\gamma\gamma \to ee$	Background $\gamma\gamma \to$ jet	Background photonuclear
1M1T SR	532.0	497.1	70.2	0.0	0.1	13.5
1M3R SR	85.0	90.2	6.7	0.0	0.3	2.8
1M1E SR	39.0	35.2	2.8	0.0	0.0	0.0

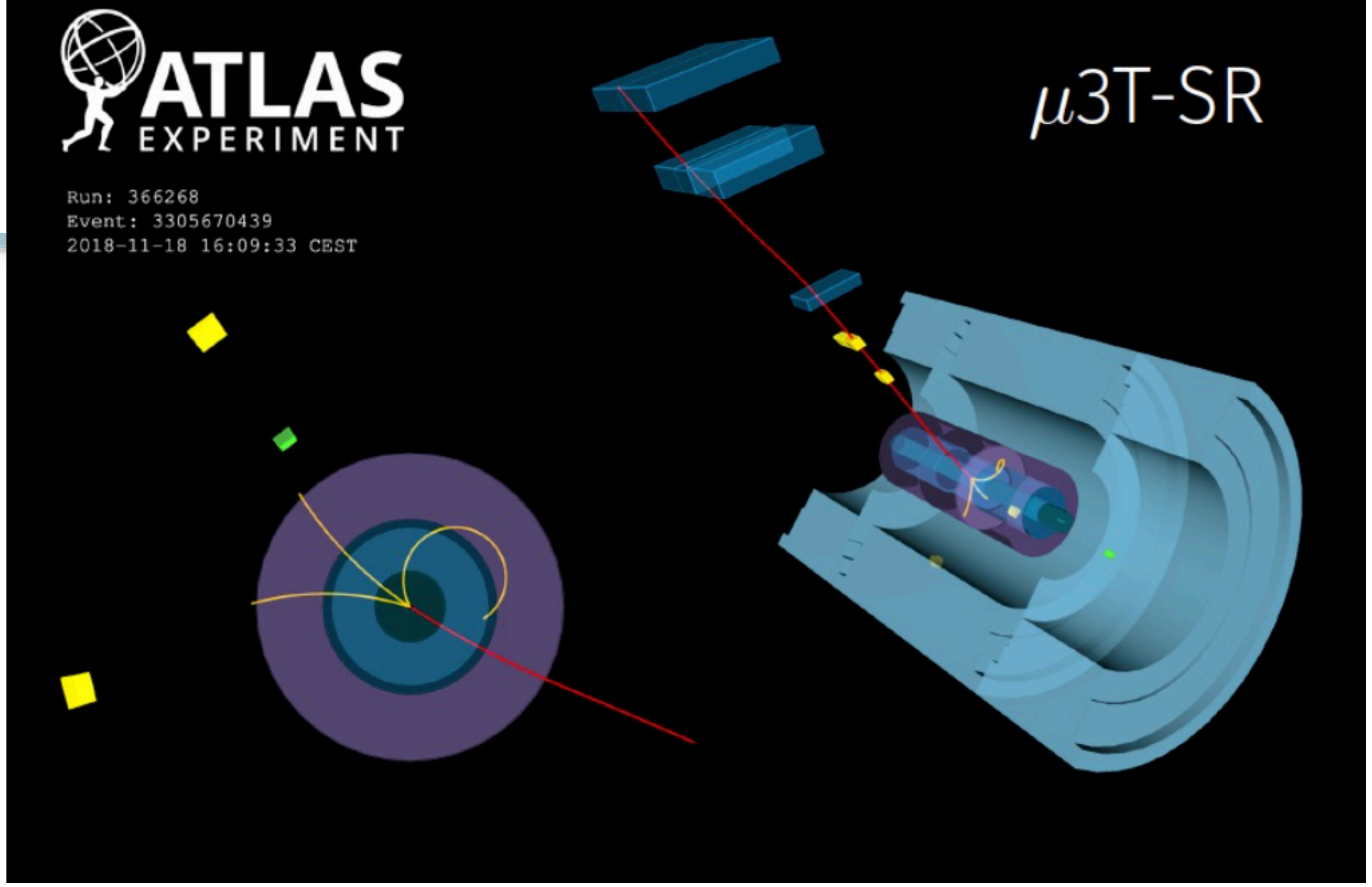
Observable	Preselection			
GRL	Pass			
$E_{ZDC}^{A,C}$	< 1 TeV			
Trigger	HLT_mu4_hi_upc_FgapAC3_L1MU4_VTE50 fired			
Region	1M1T SR	1M3T SR	1M1E SR	2M CR
$N_\mu^{baseline}$	= 1	= 1	—	—
N_μ^{sig}	= 1	= 1	= 1	2
N_e^{sig}	= 0	= 0	= 1	—
$N_{trk}\,\Delta R > 0.1$ from μ^{sig}	= 1	= 3	—	—
$N_{trk}\,\Delta R > 0.1$ from ℓ^{sig}	—	—	= 0	= 0
Unmatched clusters	= 0	= 0	—	—
$\sum$ charge	= 0	= 0	= 0	—
$p_T^{(\mu,trk)}$	> 1 GeV	—	—	—
$p_T^{(\mu,trk,\gamma)}$	> 1 GeV	—	—	—
$p_T^{(\mu,trk,cluster)}$	> 1 GeV	—	—	—
m_{trks}	—	< 1.7 GeV	—	—
$A_\phi^{\mu,trk(s)}$ (*)	< 0.4	< 0.2	—	—
$m_{\mu\mu}$	—	—	—	> 11 GeV

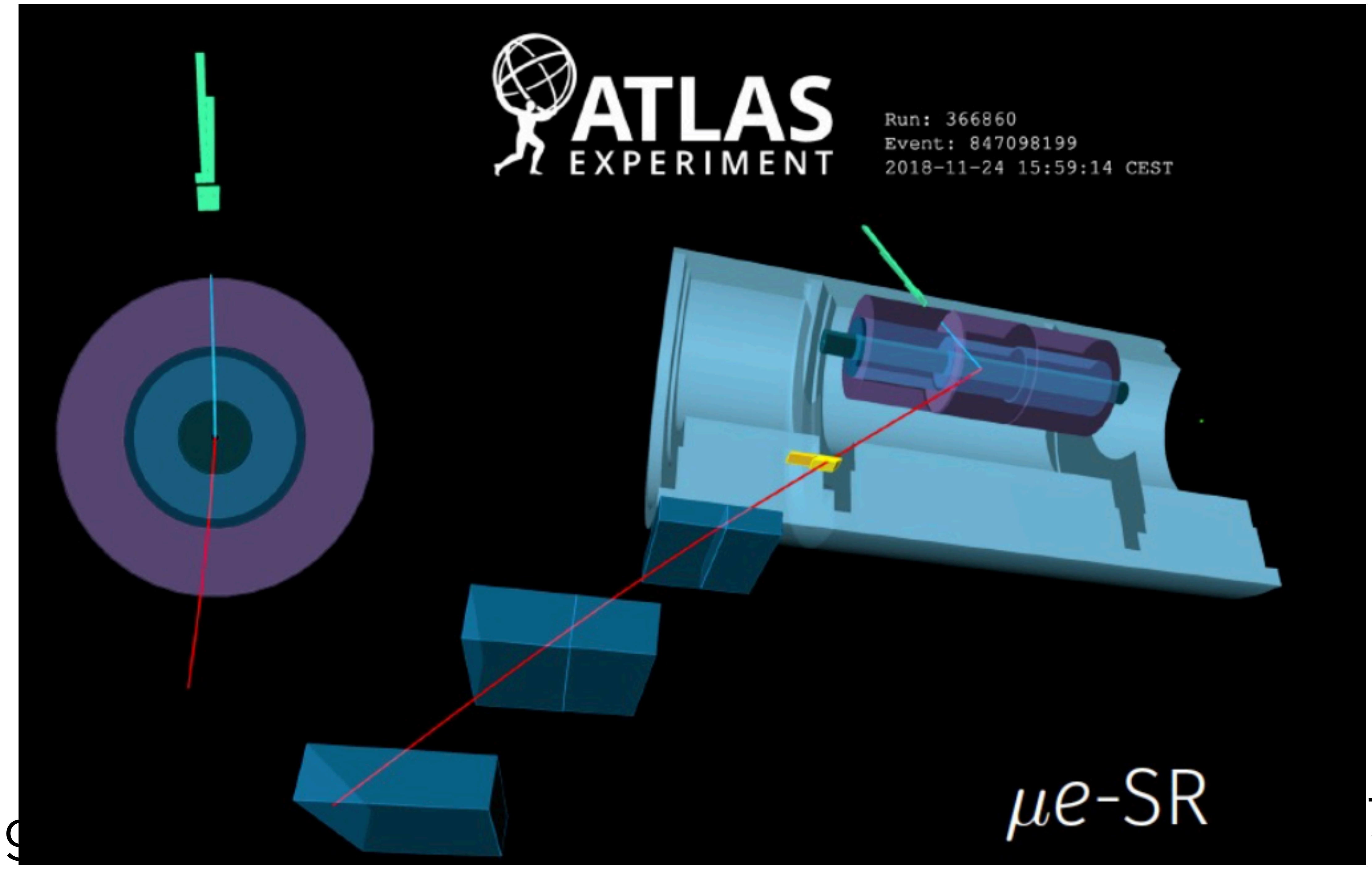
1Muon+ 1Track | 1Muon+ 3Tracks | 1Muon+ 1Electron

(*) $A_\phi^{\mu,trk(s)} \equiv 1 - |\Delta\phi_{\mu,trk(s)}|/\pi$

Signal Candidates







Muon
Electron
Tracks

arXiv:2204.13478

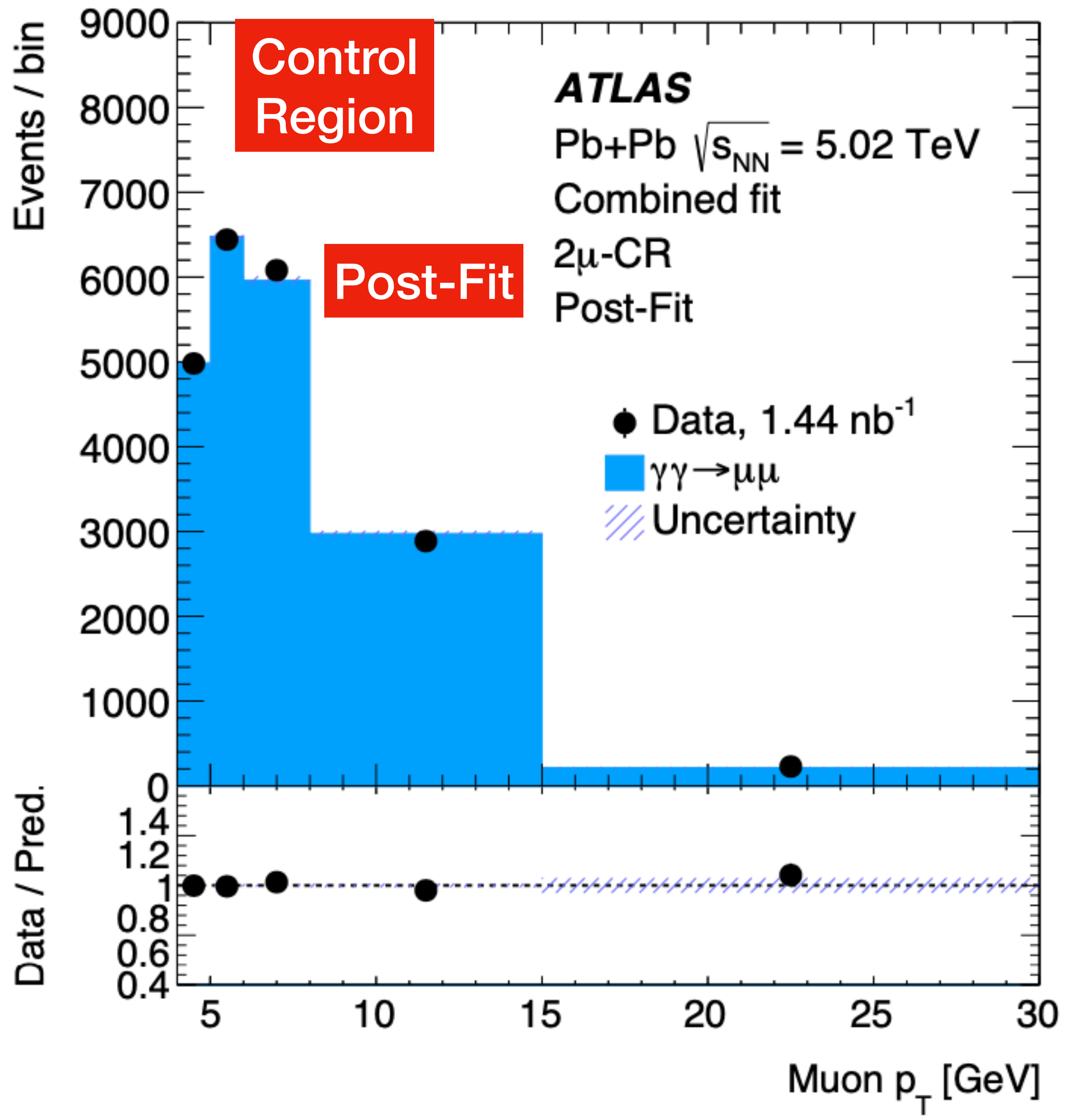
Fitting the data

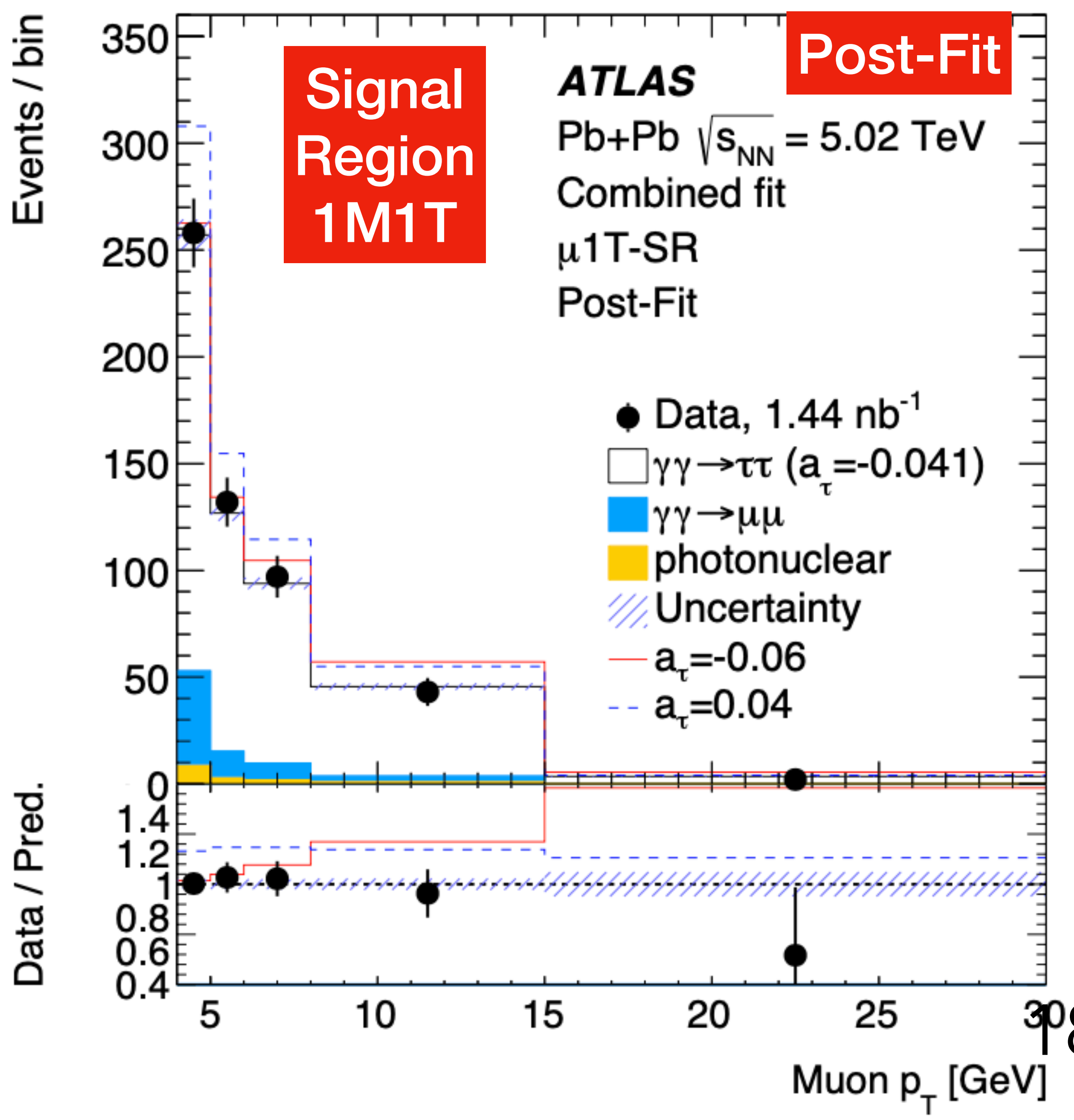
arXiv:2204.13478

Profile likelihood fit to the **muon p_T distribution in the three Signal Regions (SRs) and 1 Control Region (2MCR) used to extract $\gamma\gamma \rightarrow \tau\tau$ signal strength: $\mu_{\tau\tau}$ and a_τ**

- CR used to constrain a set of systematic uncertainties (systematic uncertainties are largely correlated between muon and tau channels)
- Weights from PLB 809 (2020) 135682 used to build templates for different a_τ values from signal MC:
  - 3D weights in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$
  - a_τ values: ±0.01, ±0.02, ±0.03, ±0.04, ±0.05, ±0.06, ±0.1 (assuming a SM τ = 0)
- **Morphing between a_τ templates uses linear interpolation**

- Main Systematic uncertainties:
  - muon/electron and track reconstruction efficiency, muon trigger efficiency
  - cluster reconstruction efficiency and calibration
  - photonuclear background template and photon flux modelling
  - Tau decay modelling

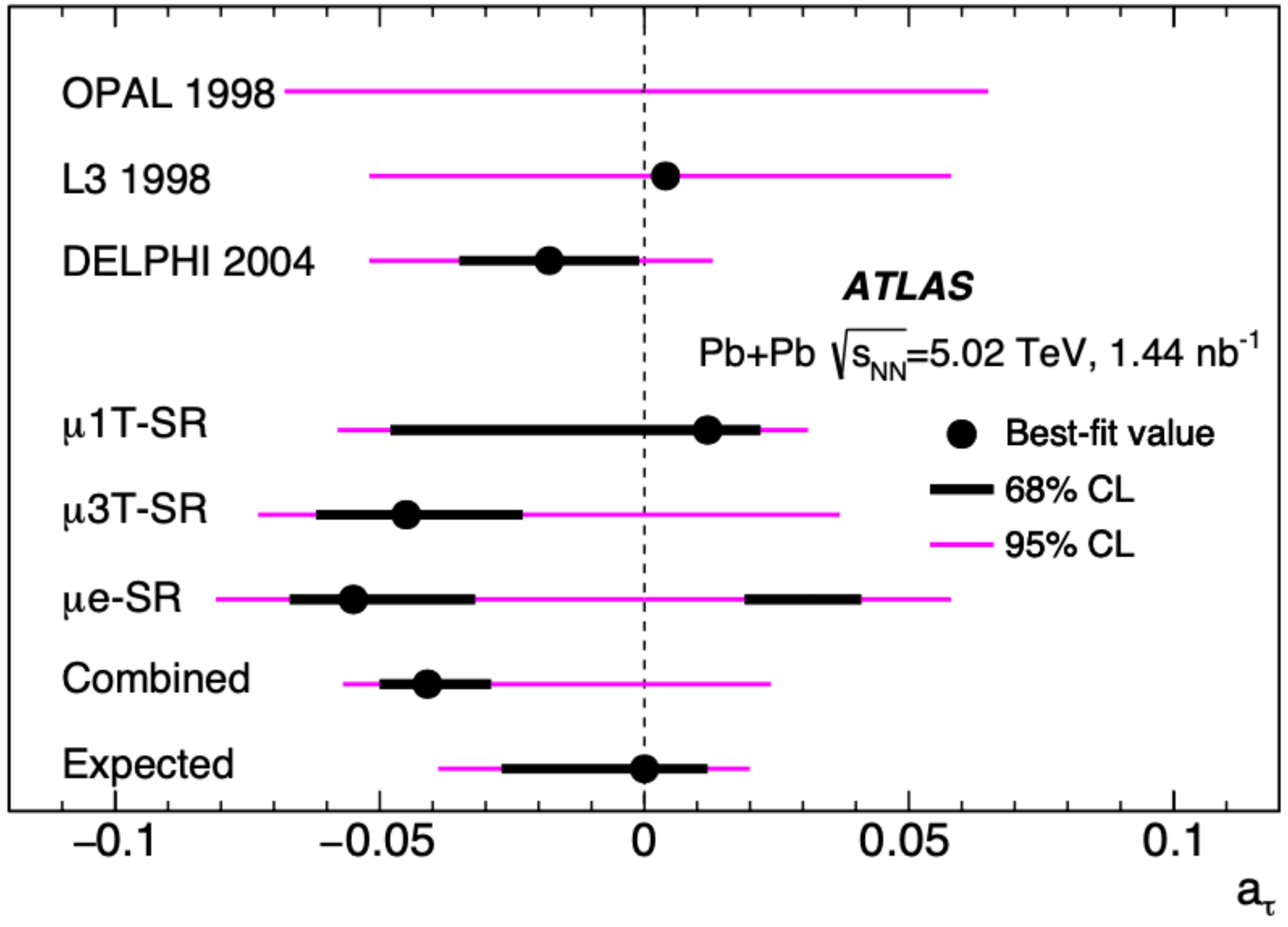


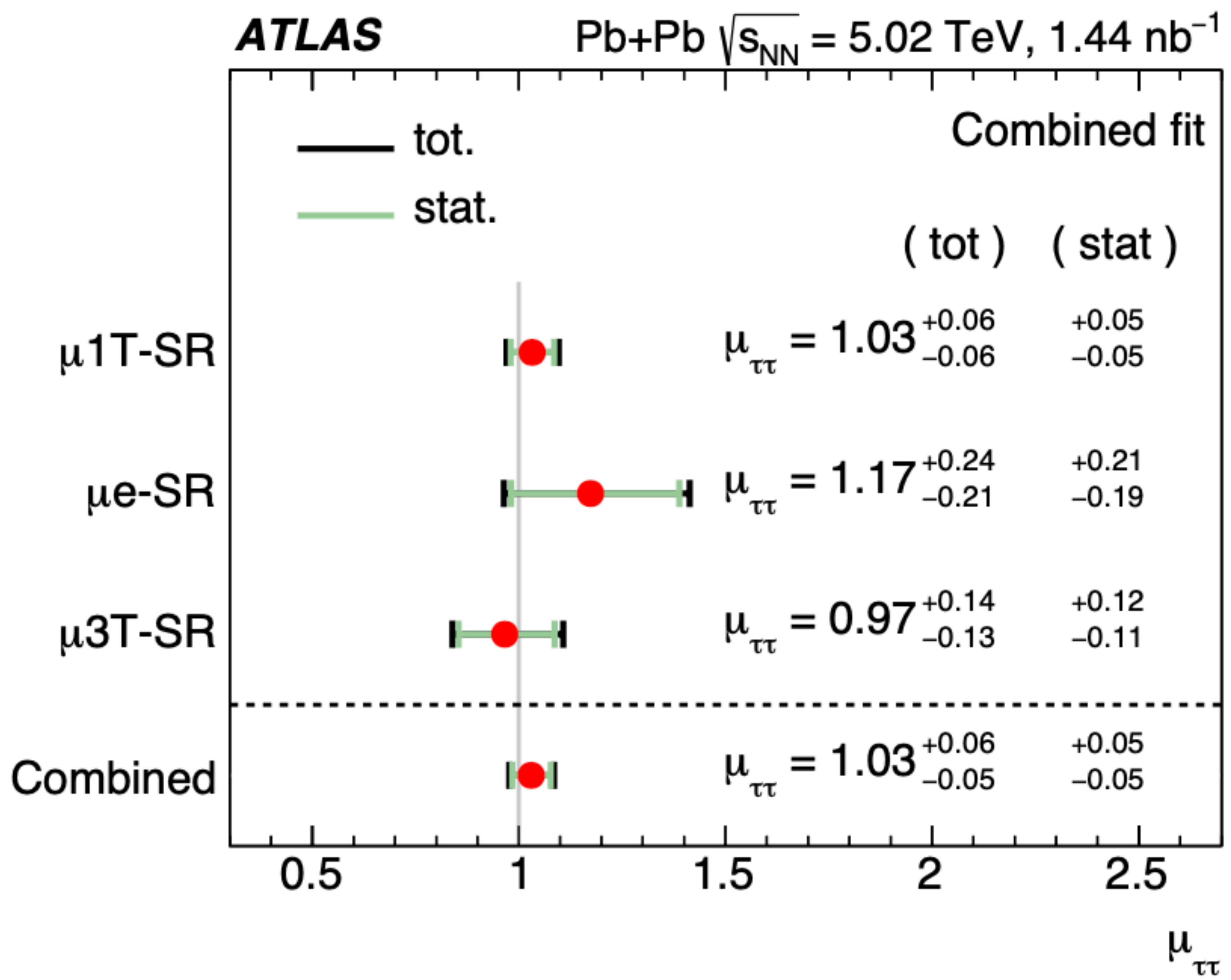


Results

arXiv:2204.13478

- Separate fit setup used to extract the $\gamma\gamma \rightarrow \tau\tau$ signal strength ($\mu_{\tau\tau}$) under the assumption of $a_\tau = 0$.
  - **$-0.057 < a_\tau < 0.024$ @ 95% CL**
  - Profile-likelihood fit with as $\mu_{\tau\tau}$ is the only free parameter and approximately 80 nuisance gave: $\mu_{\tau\tau} = 1.03^{+0.06}_{-0.05}$

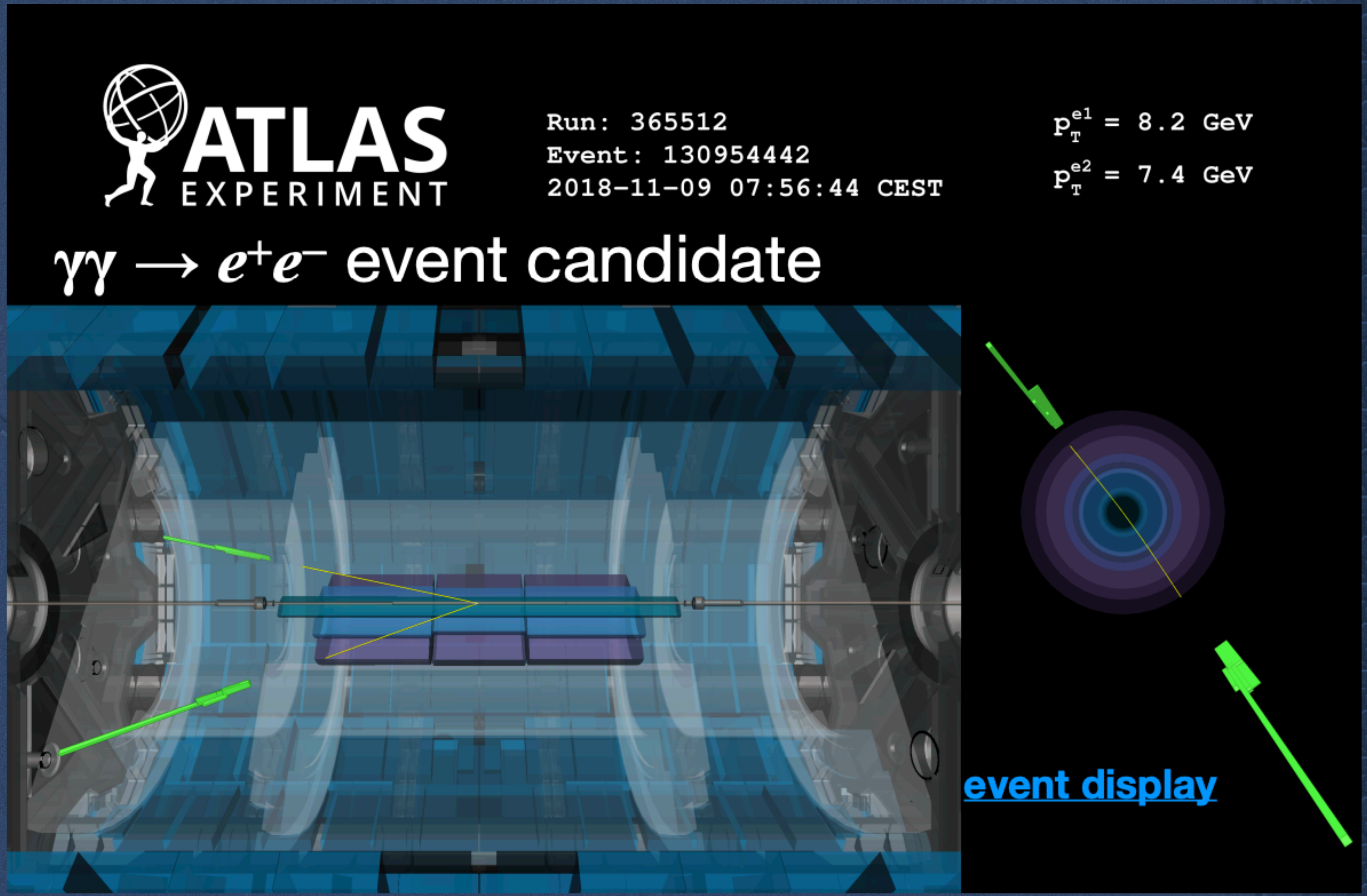




[PRC 104 (2021) 024906]

[ATLAS-CONF-2022-025]

Exclusive di-muons and di-electrons production



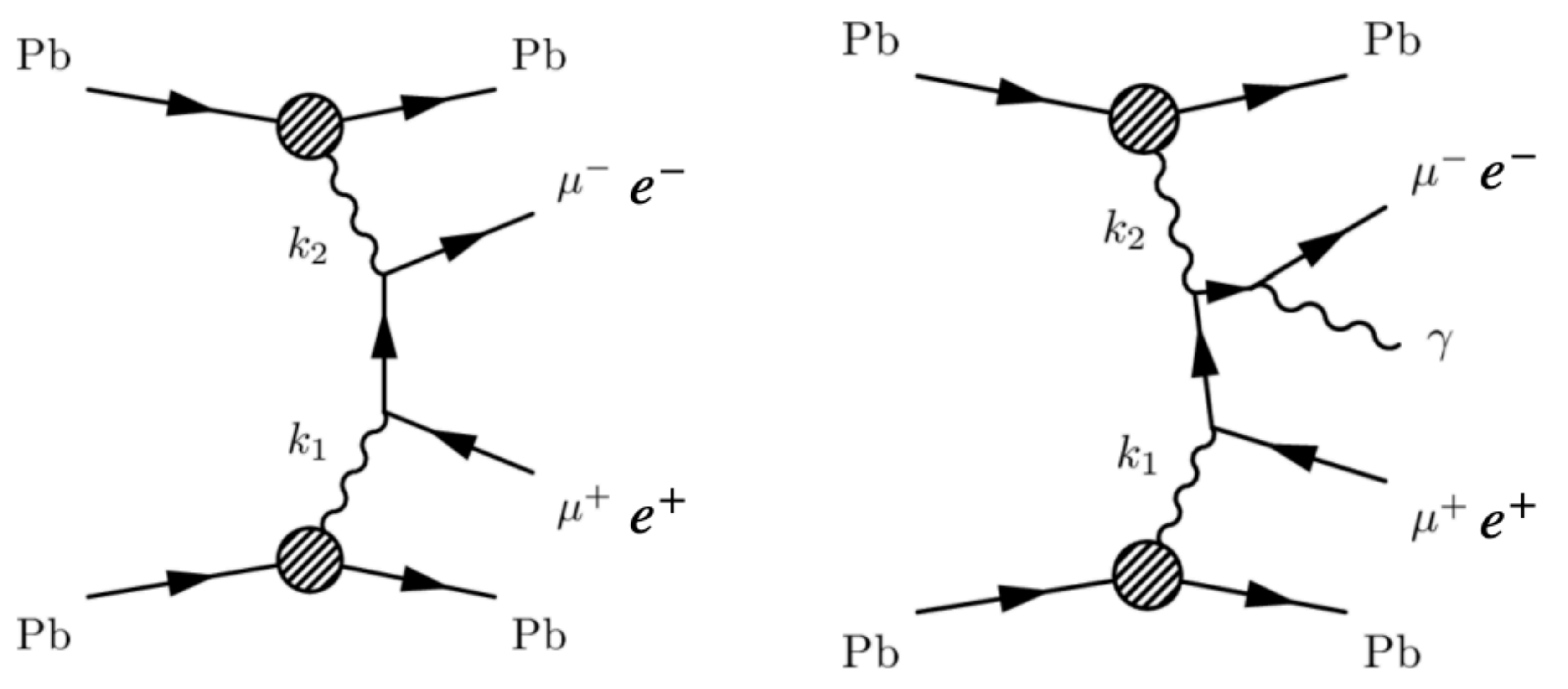
Exclusive dimuons and dielectrons Productions

[PRC 104 (2021) 024906]
[ATLAS-CONF-2022-025]

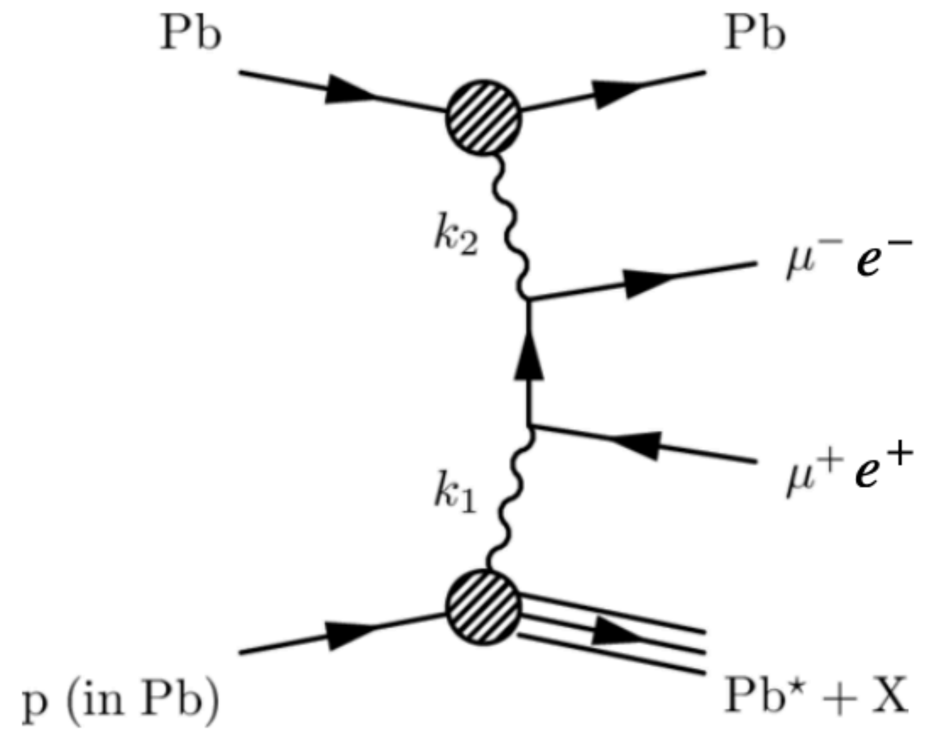
- **Measurements of the cross section** for the exclusive $\gamma\gamma \rightarrow \mu\mu$ and $\gamma\gamma \rightarrow ee$ productions. Studies on the dependance of angular distribution from the **ZDC identification.**

	$\gamma\gamma \rightarrow \mu\mu$	$\gamma\gamma \rightarrow ee$
Data	2015	2018
Integrated Luminosity	0.48 nb^{-1}	1.72 nb^{-1}
Fiducial Cuts	$p_T^\mu > 4$ GeV $\lvert\eta^\mu\rvert < 2.5$ $m_{\mu\mu} > 10$ GeV $p_T^{ll} < 2.0$ GeV	$p_T^e > 2.5$ GeV $\lvert\eta^e\rvert < 2.5$ $m_{ee} > 5$ GeV $p_T^{ll} < 2.0$ GeV
Number of events	12k	30k
Background	Dissociative LPair 3%	Dissociative SuperChic 4%

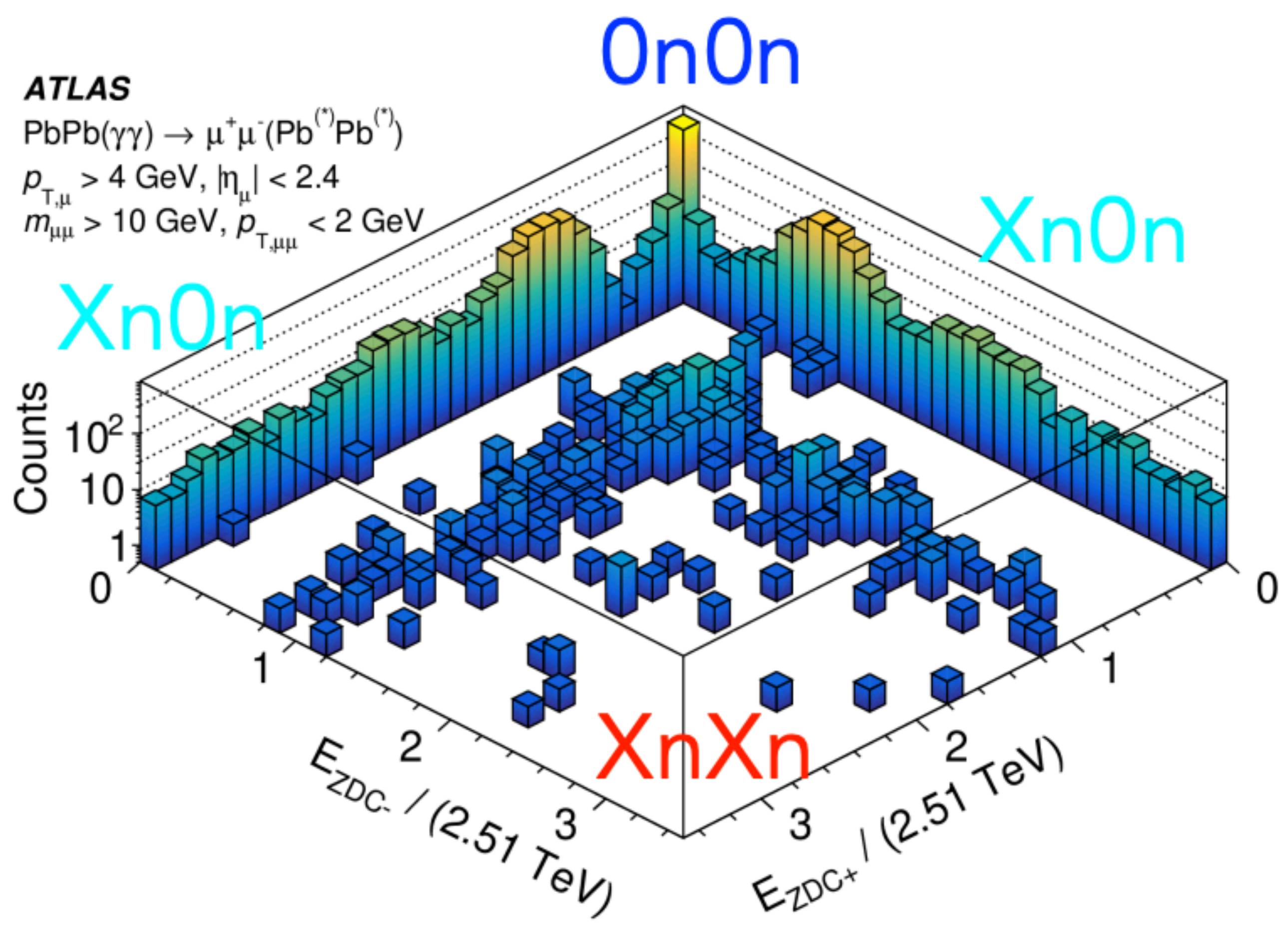
Signal

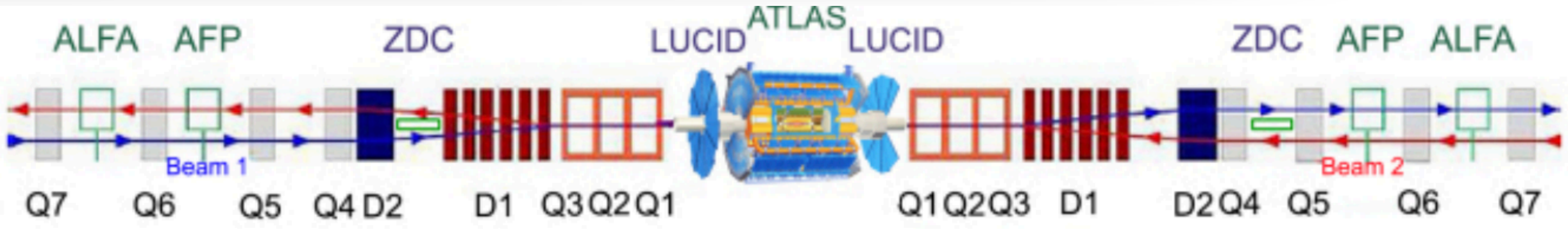


Background

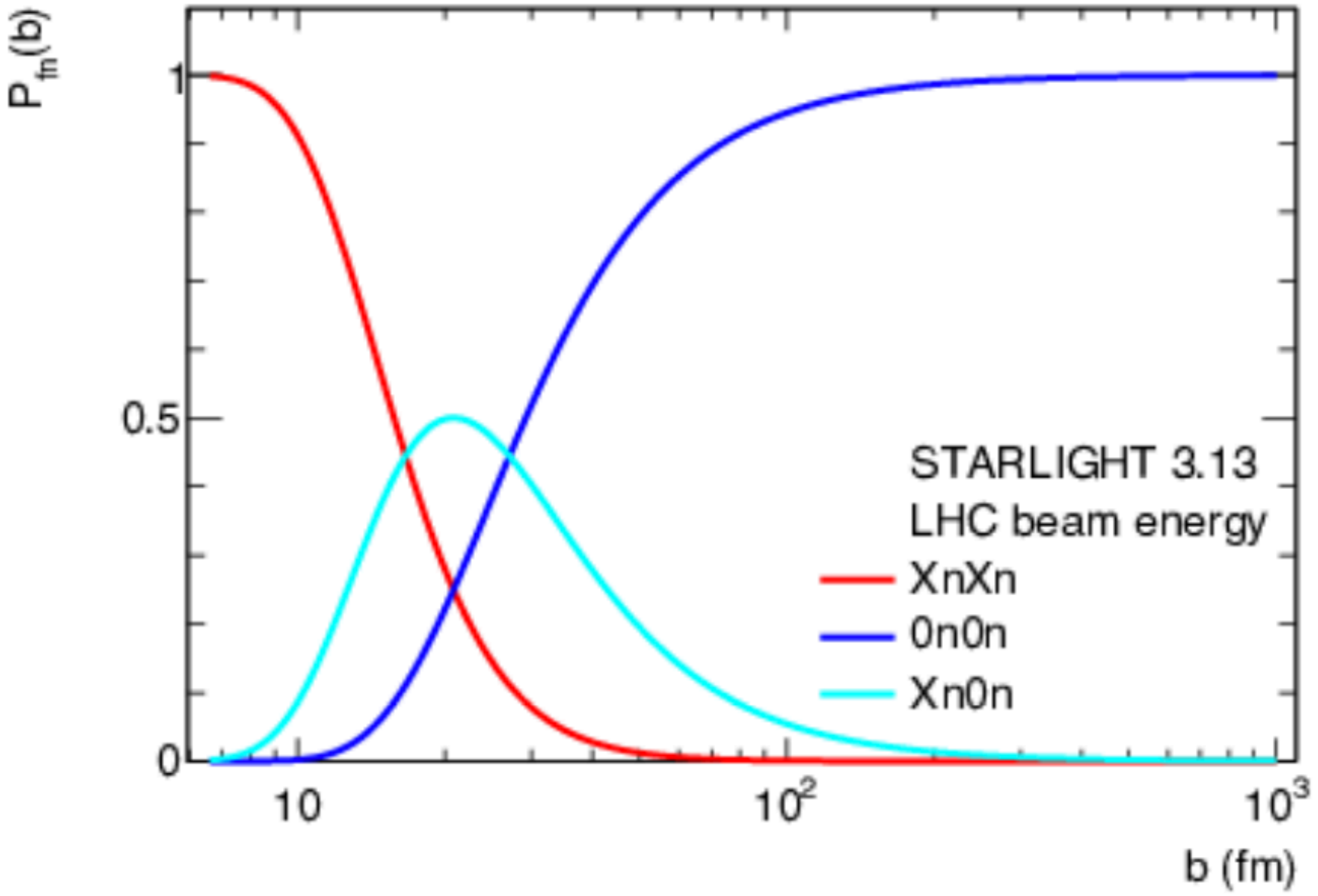


Dependency on ZDC Activity





[Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354]



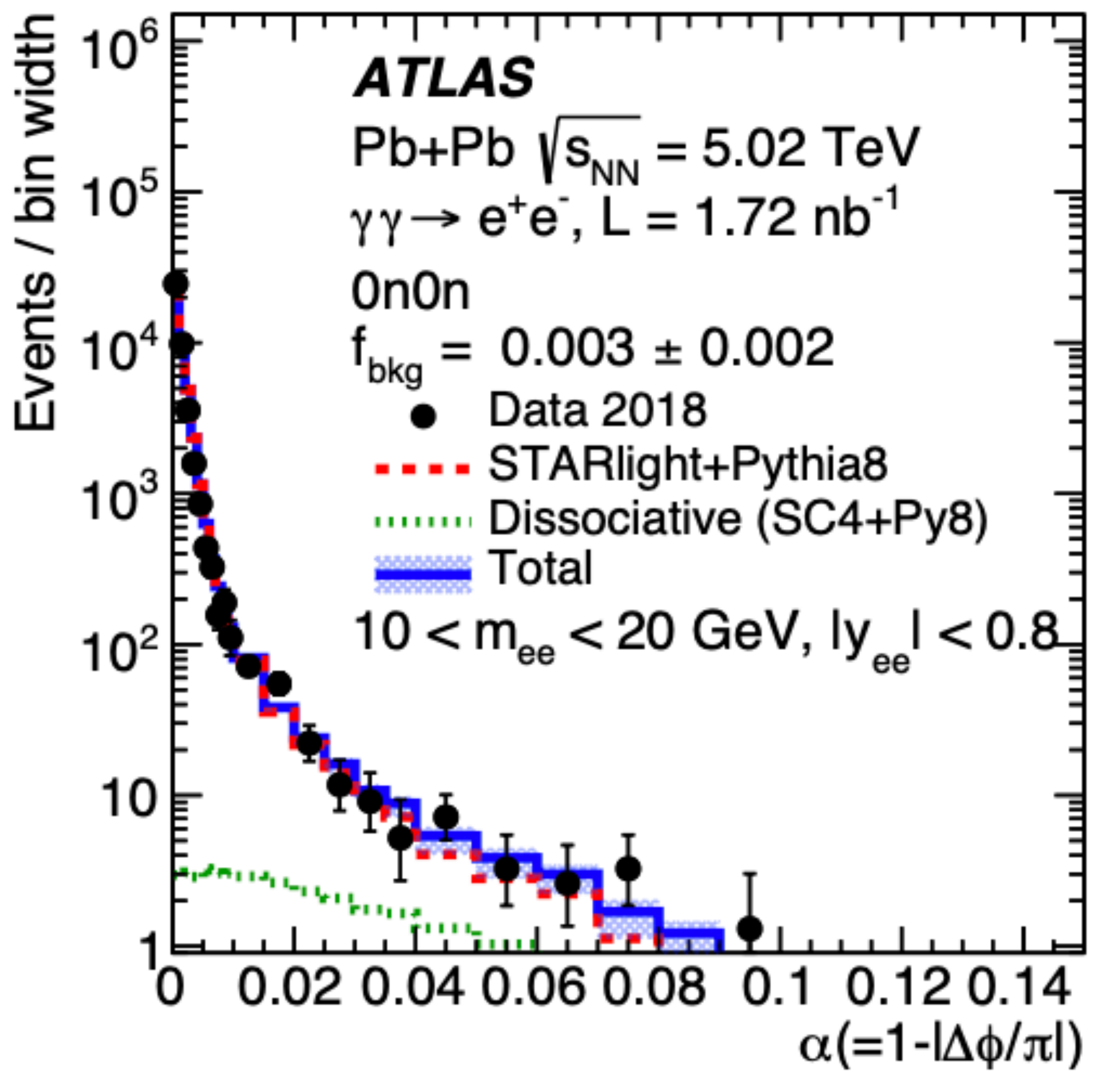
ZDC are 140 m away from the IP (η>8.3)

- Detect neutral particles (e.g. neutrons, photons)
- Inclusive sample $\gamma\gamma \rightarrow ll$ of can be divided into three categories
  - **0n0n: no activity in neither ZDC arm**
  - **Xn0n: activity in one ZDC arm**
  - **XnXn: activity in both ZDC arms**
- Fractions of events falling to each category f0n0n, fXn0n, fXnXn are measured
  - After subtracting backgrounds and accounting for electromagnetic pileup
- **Each category probes different impact parameters (b)**

[ATLAS-CONF-2022-025]

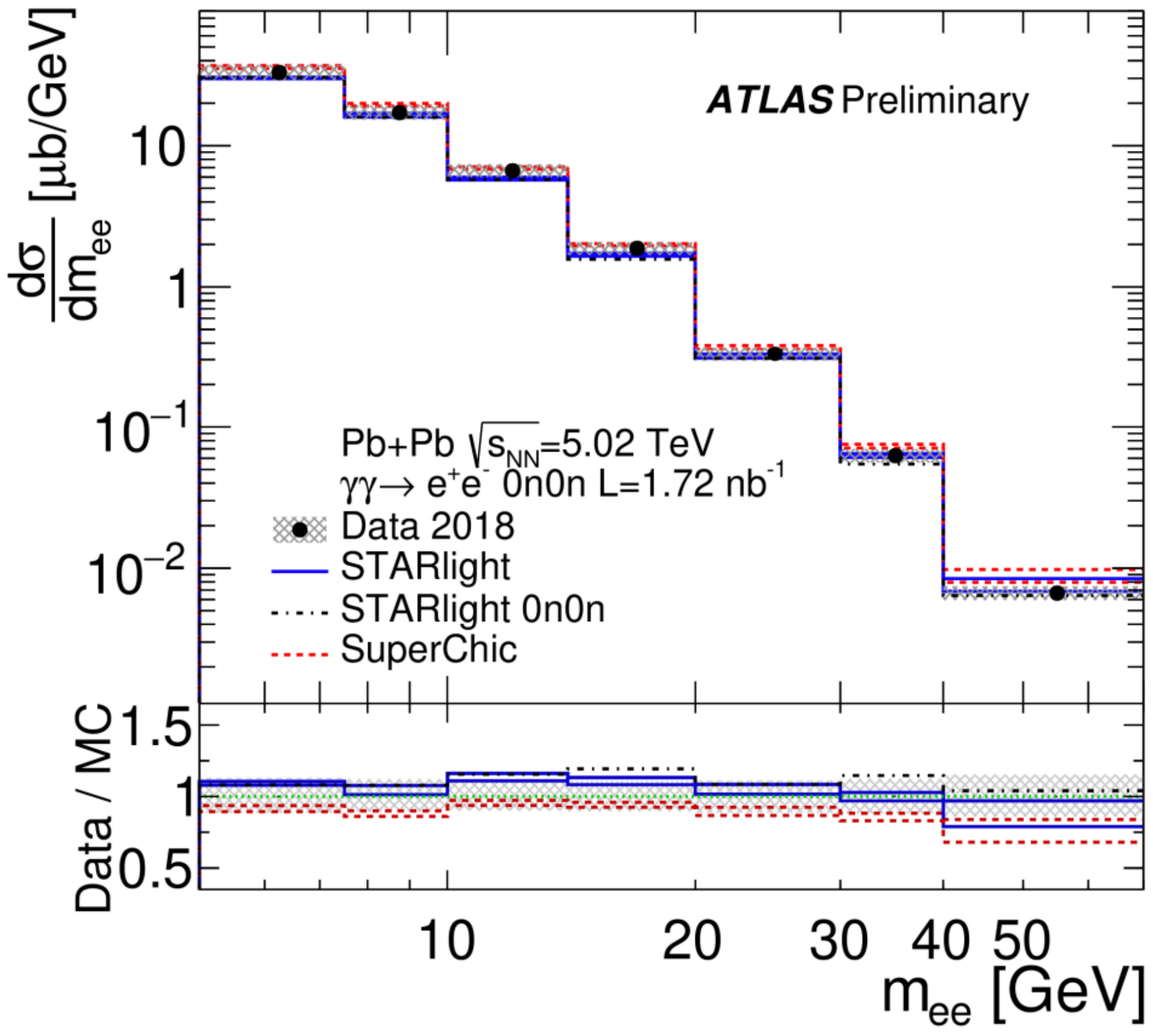
Dielectrons Cross Section

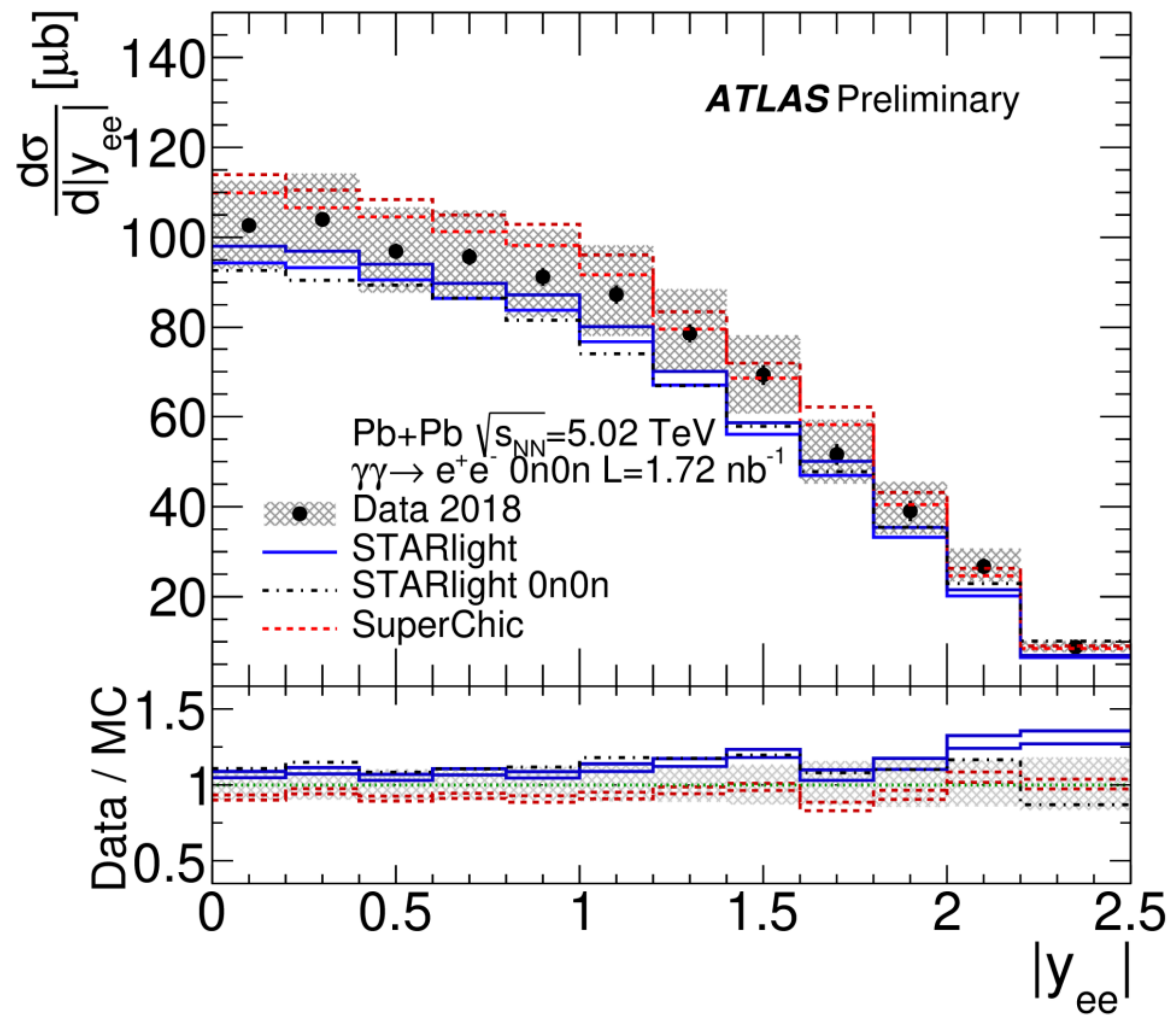
- Differential Cross section in m_{ee} , $|y_{ee}|$, $|cos\theta^*|$, $< p_T^e >$
  - STARlight provides predictions for neutron production (black dotted line)
  - Use measured 0n0n fractions with uncertainties to correct both STARlight and SuperChic predictions



General conclusions similar to the inclusive ZDC case

- STARlight 3.13 (SuperChic 3.05) systematically lower (higher) than data
- SuperChic is better in description of shapes





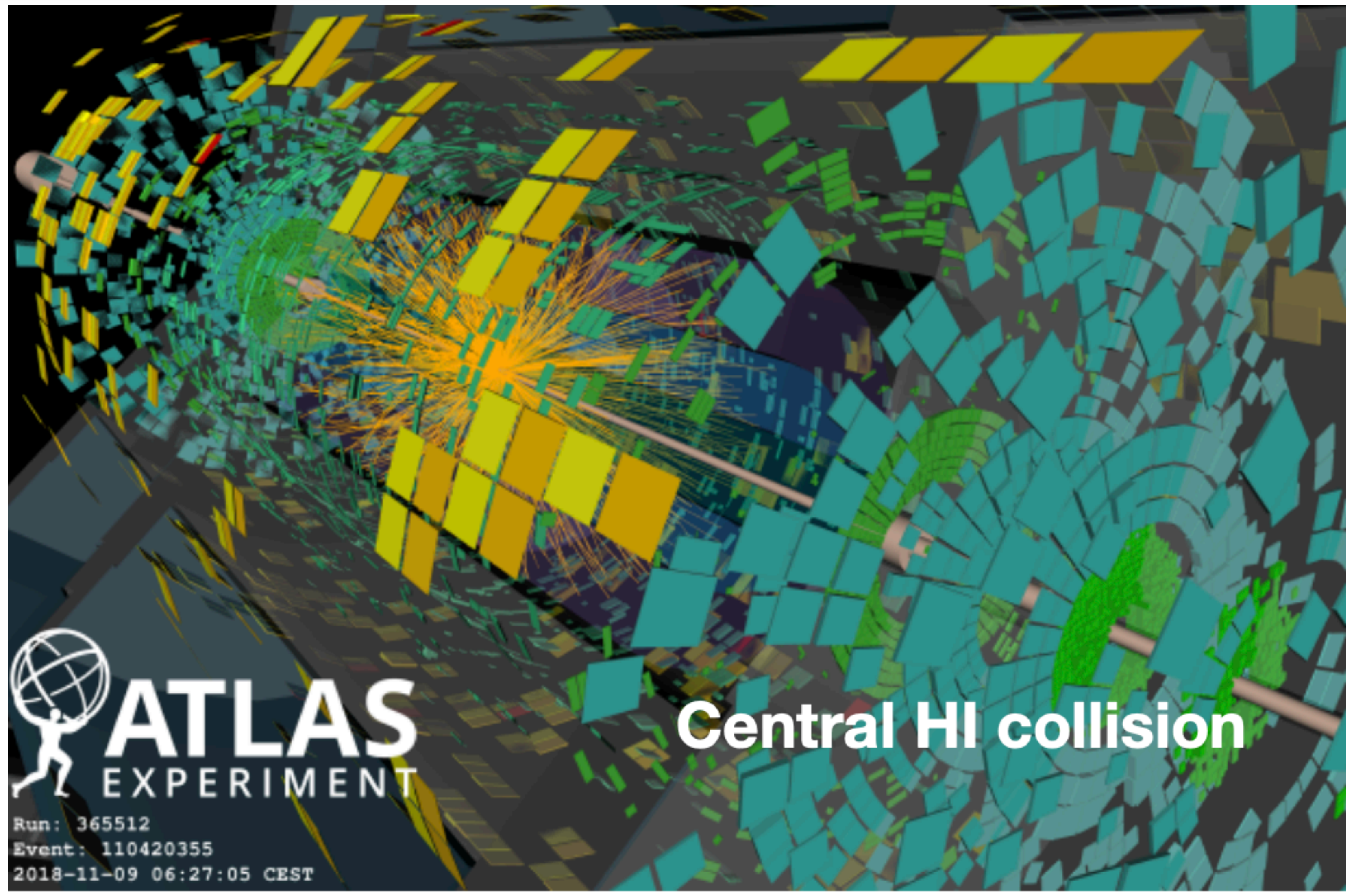
Dimuons Cross Section

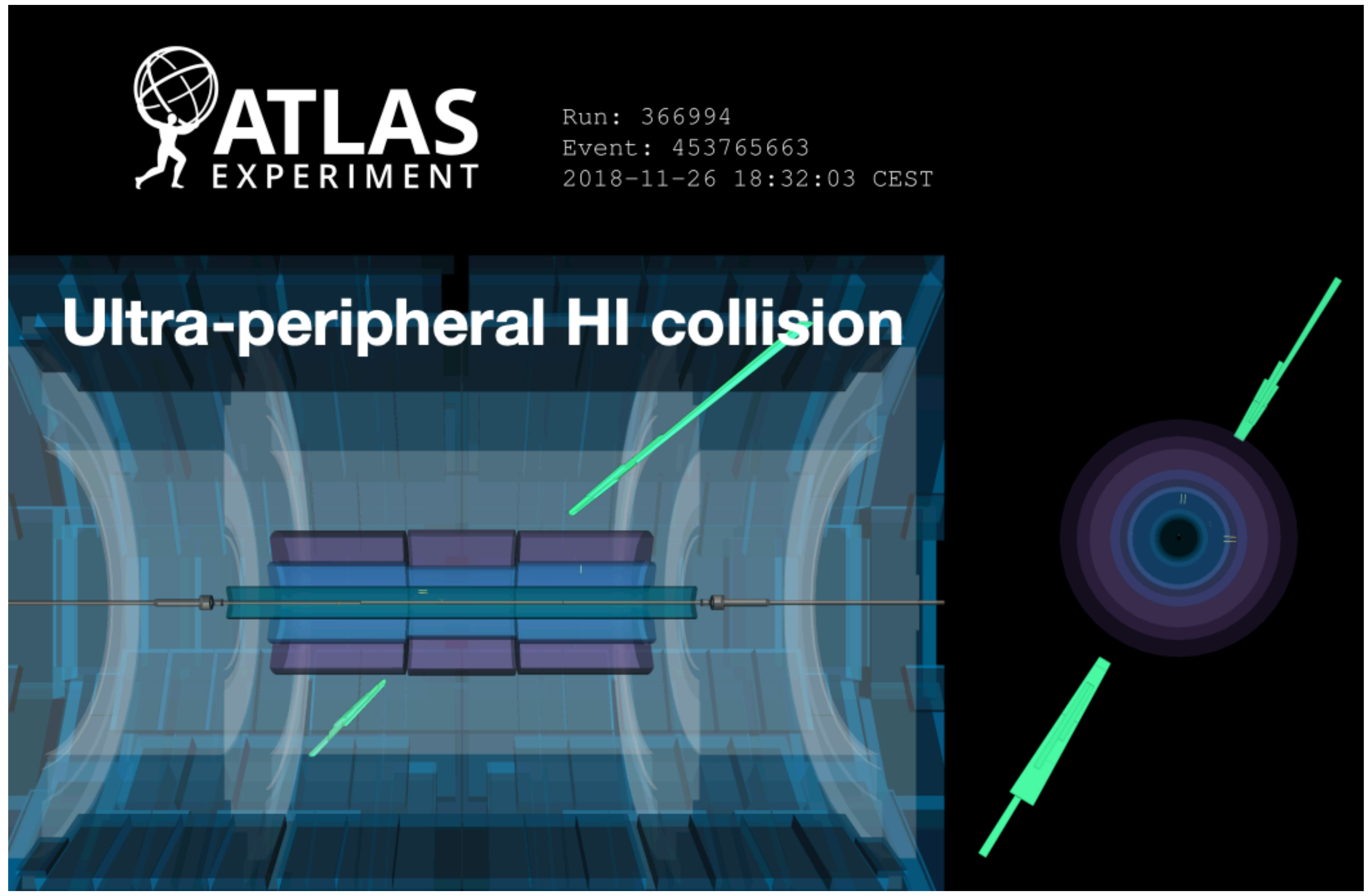
[PRC 104 (2021) 024906]

- Differential Cross section in $m_{\mu\mu}$, $|y_{\mu\mu}|$, $|cos\theta^*|$, $< p_T^\mu >$
  - Good agreement with STARlight
  - but systematic excess of the data at higher rapidity

Conclusions

- **ATLAS measures light-by-light cross section** from the full Run 2 Pb+Pb data
  - Input to the **first combination of ATLAS+CMS data at the LHC** [arXiv:2204.02845]
  - UPC Pb+Pb proves to provide constraints for BSM physics
    - Most stringent limits on ALP production!
- **ATLAS shows a first measurement of exclusive ditau production** in UPC Pb+Pb collisions at the LHC with above significance
  - **Data is used to constrain $\mu_{\tau\tau}$ and a_{τ} at the LHC**
- **ATLAS provides precision results on dimuons and dielettrons cross sections** with UPC Pb+Pb collisions recorded in Run 2
  - Measured cross sections reveal systematic differences with STARlight and SuperChic calculations
  - **ZDC uses to constraint background and impact-parameter dependence studies**
- LHC Run 3 started!
  - Expect to largely improved physics results with increased luminosity after Run 3

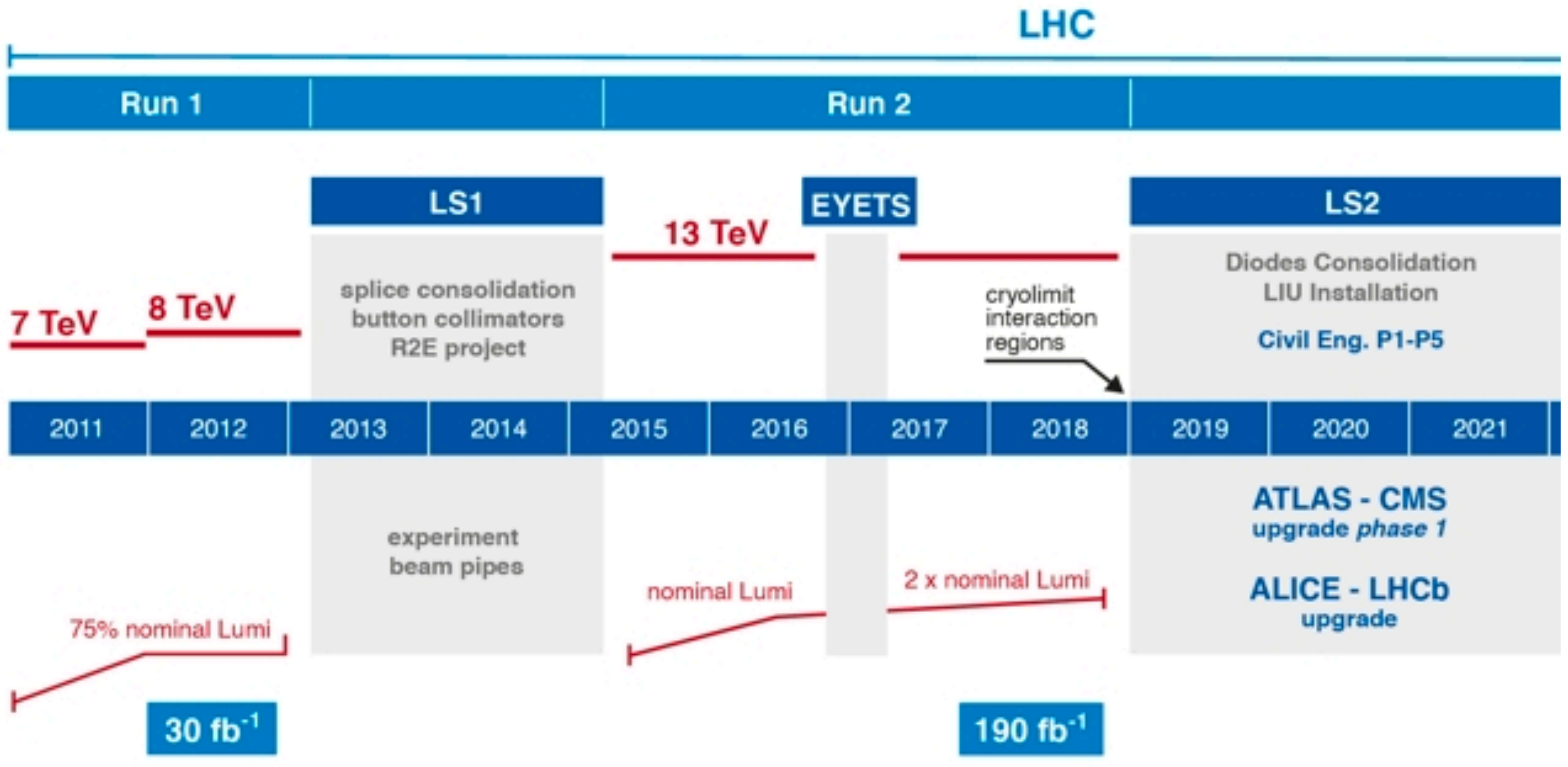


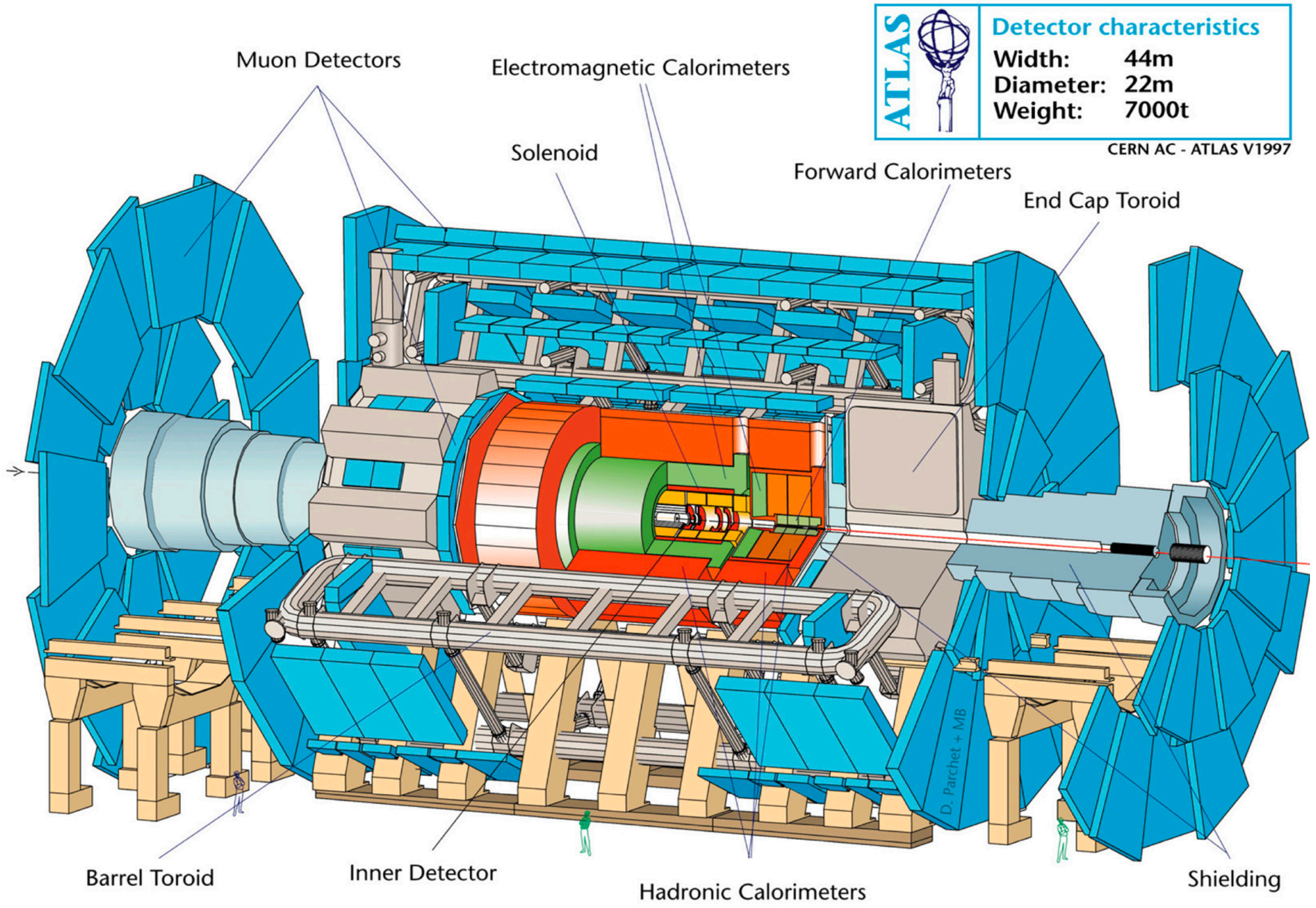


Back-up

Physics in ATLAS

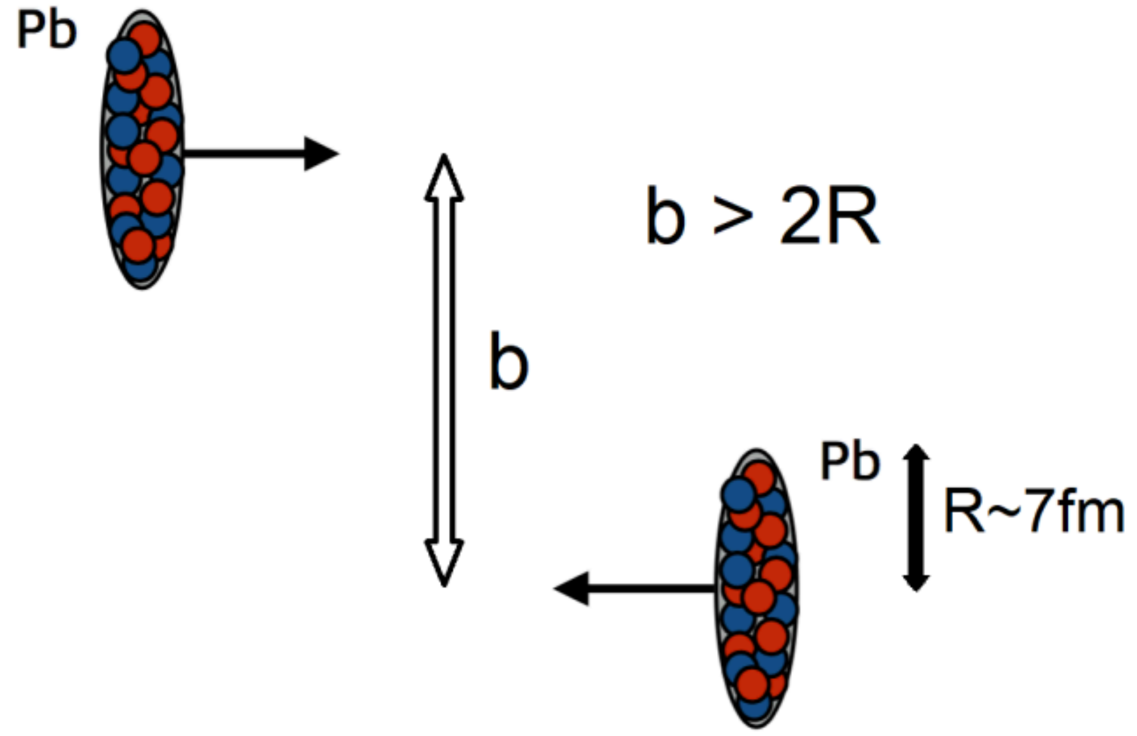
ATLAS @ Full Run2 recorded 139 fb^{-1} (year 2015-2018)
ATLAS @ 2015-2016 about 36 fb^{-1}



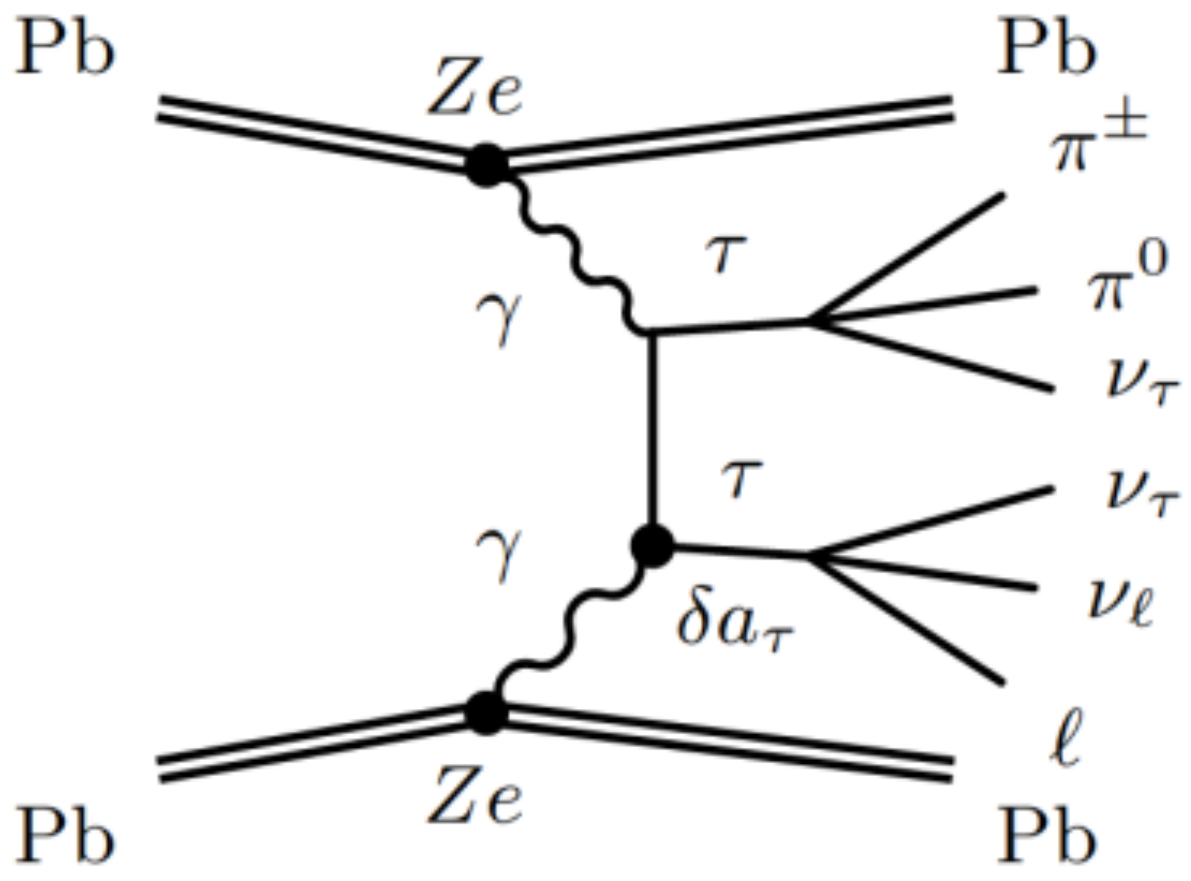


Constraining a_τ with ATLAS

ATLAS analysis aims to improve existing constraints on $a_\tau = (g-2)/2$ by using $\gamma\gamma \rightarrow \tau\tau$ events produced in ultraperipheral Pb+Pb collisions.



- The calculation of the process Pb+Pb→Pb+Pb+$\tau^+\tau^-$ requires the convolution of the two-photons luminosity with the elementary $\gamma\gamma \rightarrow \tau\tau$ cross section
  - δa_τ modifies the $\gamma \rightarrow \tau\tau$ coupling

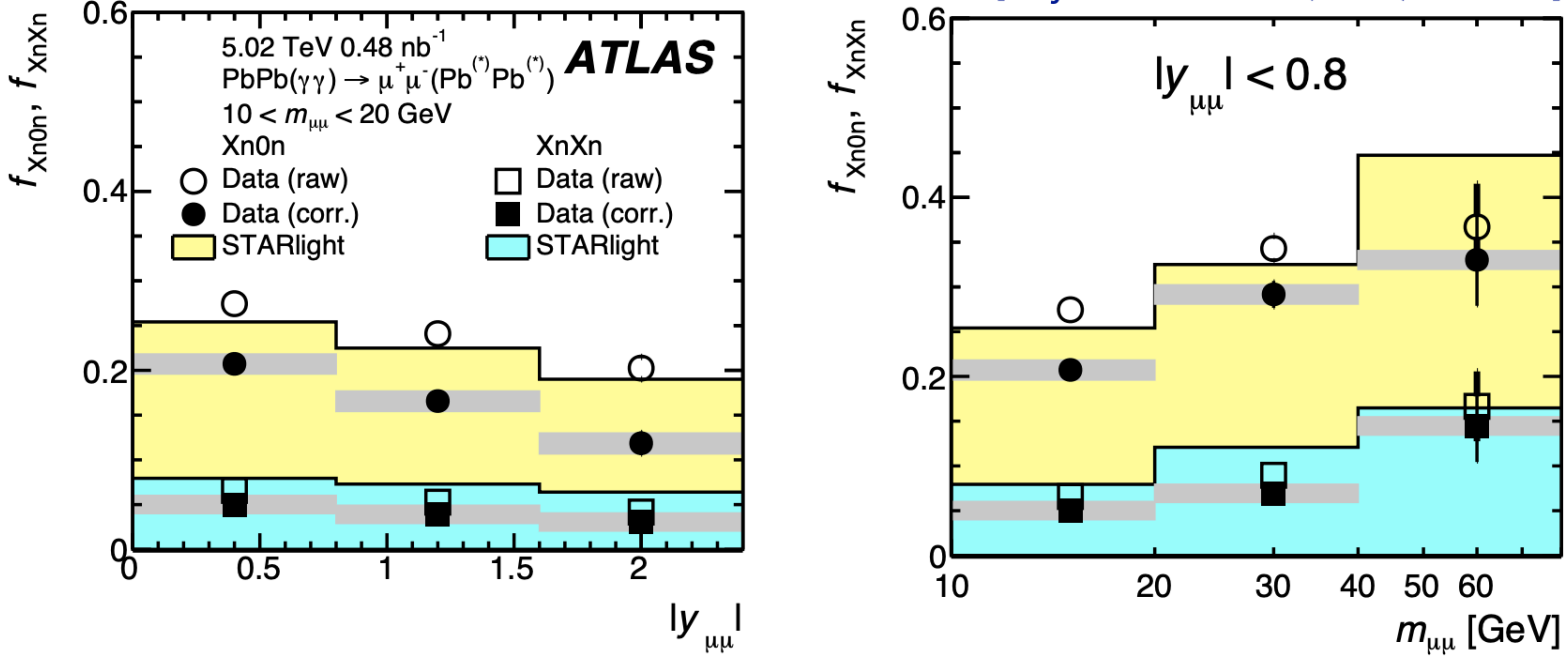


$Z = 82$

$Z^4 \approx 4.5 \cdot 10^7$

Exclusive dimuons: forward activity

[Phys. Rev. C 104 (2021) 024906]



Raw and corrected fractions of events in Xn0n and XnXn categories

- Corrected fractions are lower after accounting for electromagnetic pileup
- fXn0n, fXnXn decrease with $|y_{\mu\mu}|$ and increase with $m_{\mu\mu}$
- STARlight describes the shapes well but overestimates the value

Glauber Model

The collisions of two nucleus/ion is described as a sequence of **independent binary nucleon-nucleon collisions.** The nucleons travel on straight-line trajectories, and the **inelastic nucleon-nucleon cross section is assumed to be independent of the number of collisions** a nucleon underwent before.

The impact parameter b is monotonically related to particle multiplicity, both at midrapidity and forward rapidity:

- **for large b events ("peripheral"):**
  - low multiplicity at midrapidity and a **large number of spectator nucleons at beam rapidity**,
- **for small b events ("central")**
  - large multiplicity at midrapidity and a **small number of spectator nucleons at beam rapidity**

Annu. Rev. Nucl. Part. Sci. 2007. 57:205–43