Dilepton and diphoton production and BSM searches with UPC photon fusion processes in Pb+Pb collisions with the ATLAS detector

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On behalf of the ATLAS Collaboration

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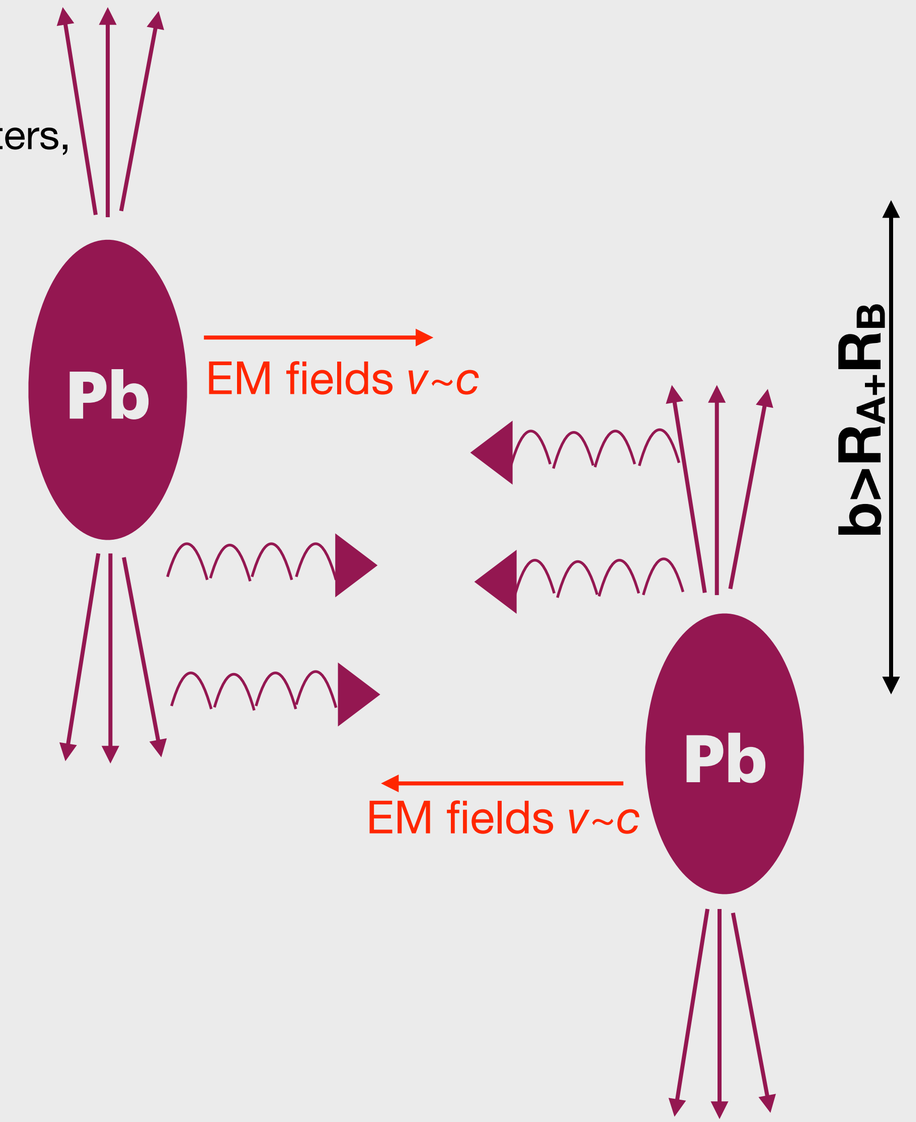
Ultra-peripheral collisions

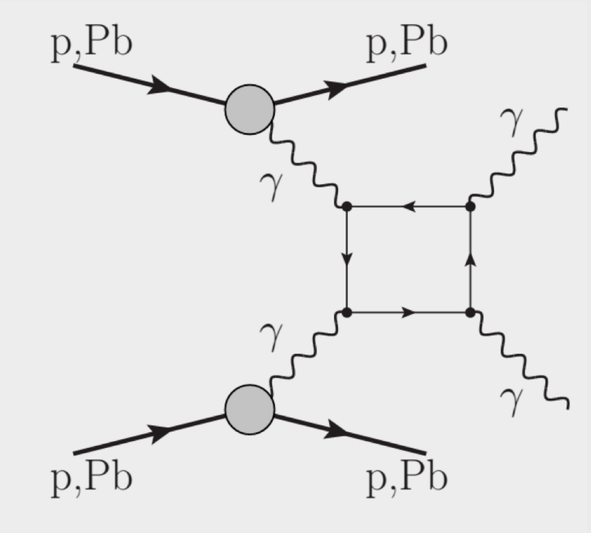
- Electromagnetic (EM) interactions become dominant at large impact parameters, $b>2R_A$, where R_A is the ion radius. Such collisions are usually referred to as **ultra-peripheral collisions (UPC) .**
  - **Electromagnetic (EM)** fields associated with relativistic ions treated as fluxes of photons.
  - Described in a Equivalent Photon Aproximation (EPA) framework.
  - Equivalent photon flux scales with Z^2.
  - Pb+Pb collisions at LHC are a **superb source** of high energy **photons.**
  - Excellent tool to study rare processes and to search for **beyond Standard Model (BSM) physics.**
- **Advantages of UPC over the proton-proton (pp) collisions:**
  - Z^4 enhancement of cross sections in Pb+Pb wrt pp system**.**
  - Very low hadronic pileup - exclusivity selections.
  - Low p_T thresholds in trigger and offline reconstruction.

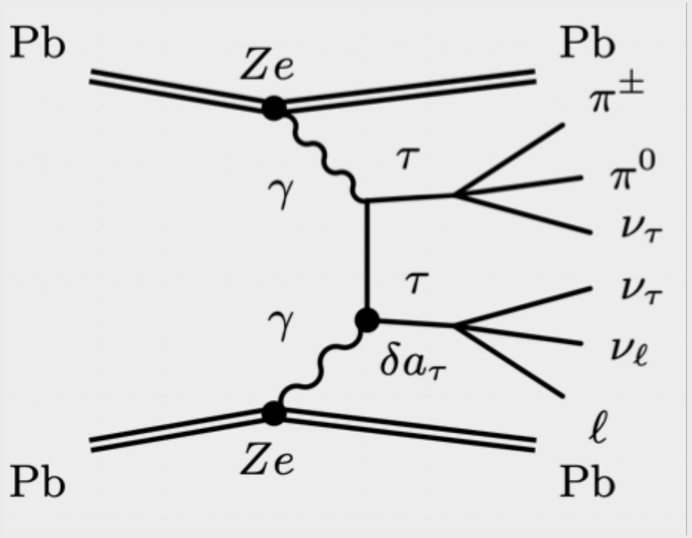


Motivation

This talk will cover these new measurements of dilepton production performed by ATLAS Collaboration **in UPC PbPb at 5.02 TeV** :

- **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]
  - New particles can enter the loop.
  - Light-by-light (LbyL) cross-sections can be modified by various BSM phenomena (Born-Infeld extensions of QED, space-time non-commutativity in QED, extra spatial dimensions, ...)
- **Exclusive ditau production and measurement of the τ-lepton anomalous magnetic moment:** [arXiv:2204.13478], accepted by PRL.
  - Constraints on τ-lepton anomalous magnetic moment
  - Its value is sensitive to many BSM models (lepton compositeness, supersymmetry (δa_τ m_τ^2/M_S^2, TeV-scale leptoquarks, ...) .

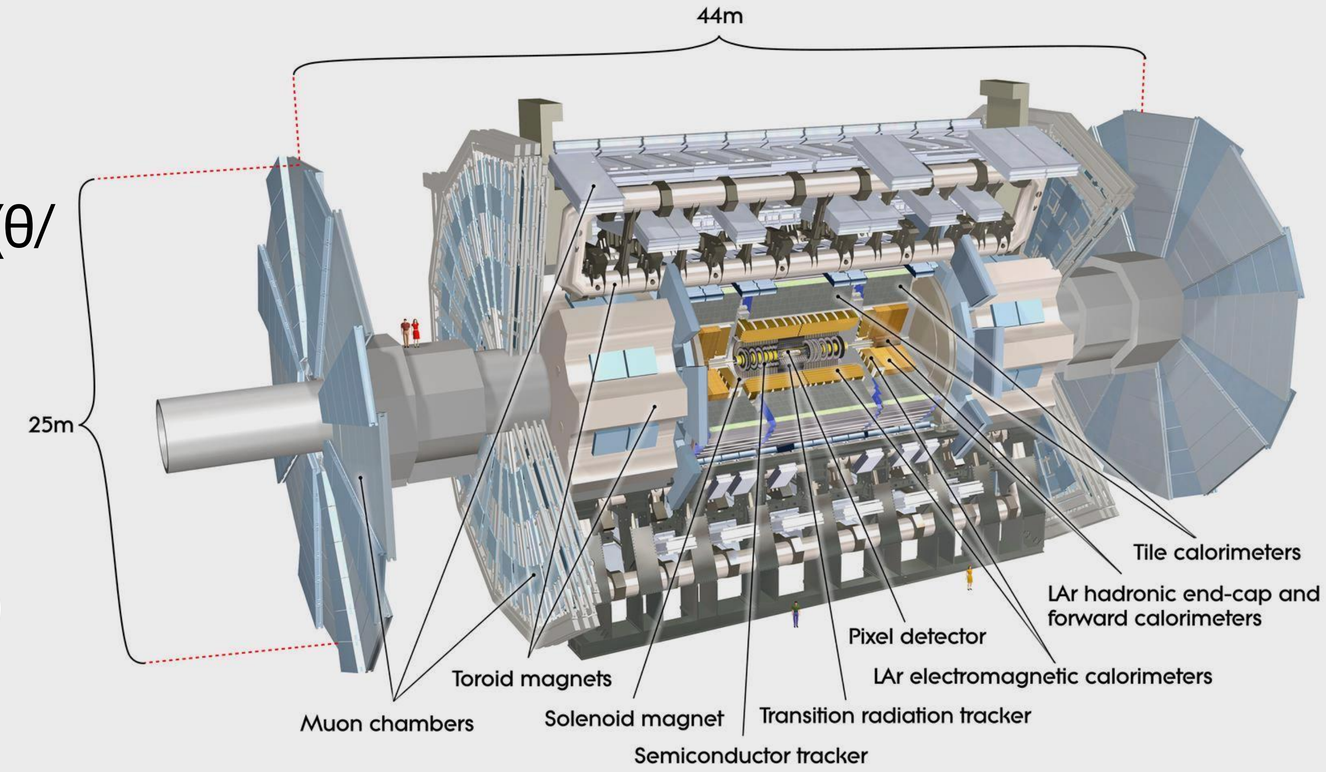


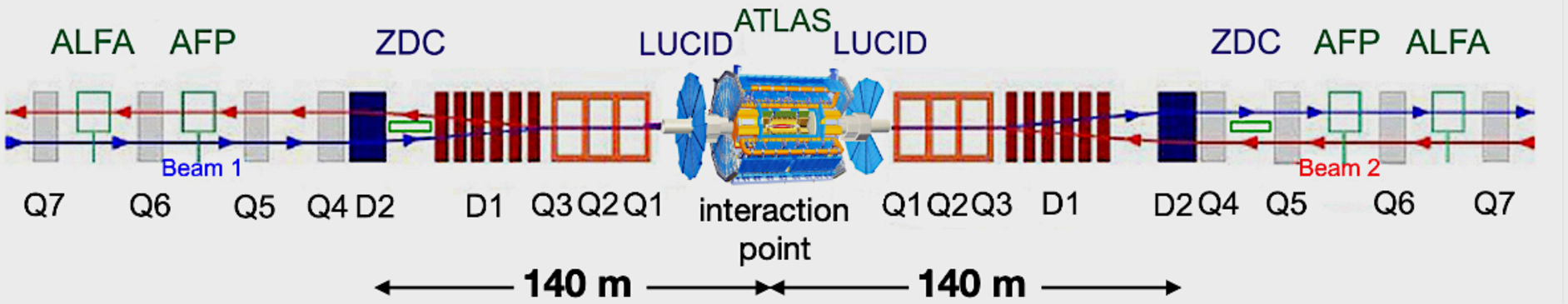


ATLAS detector

Large general-purpose detector with almost 4π coverage :

- Inner detector $|\eta|<2.5$ ($\eta = -\ln(\tan(\theta/2))$)
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- **Zero-Degree-Calorimeters (ZDC)** capture neutral particles with $|\eta|>8.3$





Light-by-light scattering

Light-by-light scattering

- **Light-by-light (LbyL)** scattering is a **very rare** QED process.
- Several LbyL measurements performed with the LHC Pb+Pb UPC data:

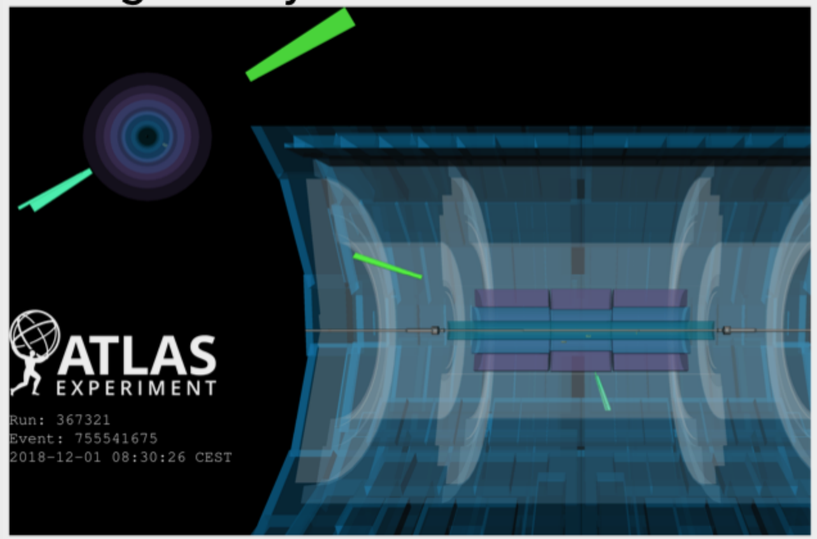
  ATLAS: 2015: [Nature Physics 13 (2017) 852], 2018: [PRL 123 (2019) 052001]

  2015+2018: [JHEP 03 (2021) 243]

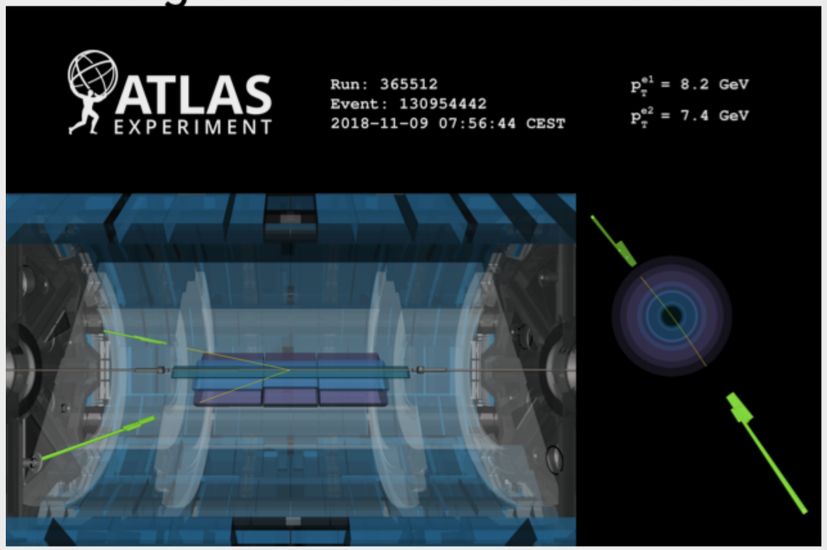
  CMS: 2015: [PLB 797 (2019) 134826]

- Exclusivity requirements:
  - **Two photons** (each with $E_T > 2.5$ GeV, $|\eta| < 2.37$) with no activity observed in the detector
  - Invariant diphoton mass $m_{\gamma\gamma} > 5$ GeV, low diphoton $P_T^{\gamma\gamma} < 1$ GeV, low diphoton acoplanarity: $A_\phi = 1 - |\Delta\phi|/\pi < 0.01$.
  - Veto on any extra low-p_T tracks
- **Background: $\gamma\gamma \to e^+e^-$, central exclusive production of $gg \to \gamma\gamma$.**

Signal: LbyL event candidate



Background: e^+e^- event candidate



Light-by-light scattering: cross sections

[JHEP 03 (2021) 243]

- **Cross-section is** measured in a fiducial phase space, defined by the requirements reflecting event selection.

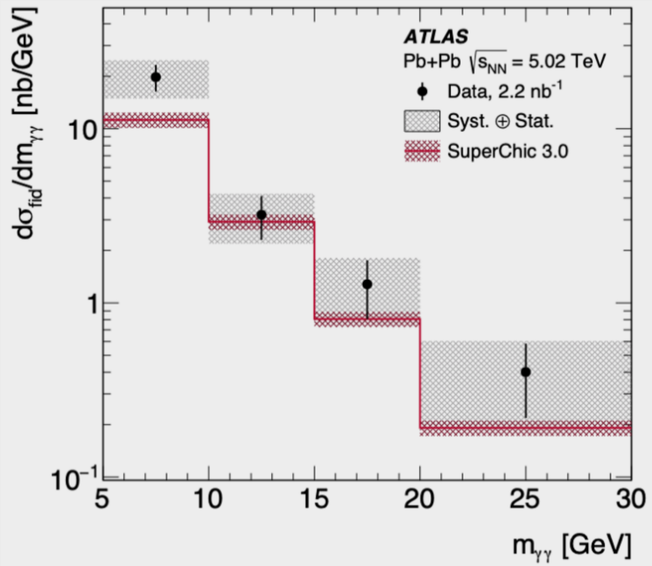
Measured fiducial cross section:

$\sigma_{\text{fid}} = 120 \pm 17\,(\text{stat.}) \pm 13\,(\text{syst.}) \pm 4\,(\text{lumi.})\ \text{nb}$

Theory predictions:

$\sigma_{\text{fid}}^{\text{theory1}} = 78 \pm 8$ nb (SuperChic 3 MC)

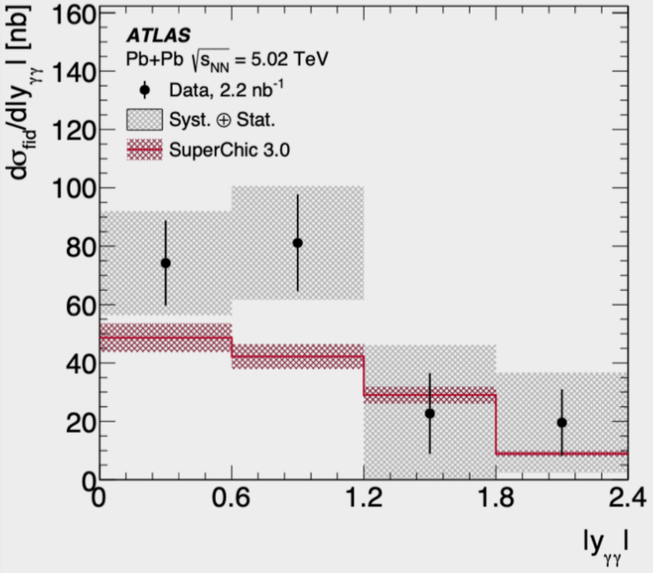
$\sigma_{\text{fid}}^{\text{theory2}} = 80 \pm 8$ nb (Phys. Rev. C 93 (2016) 044907)



- Differential fiducial cross-sections measured in diphoton:

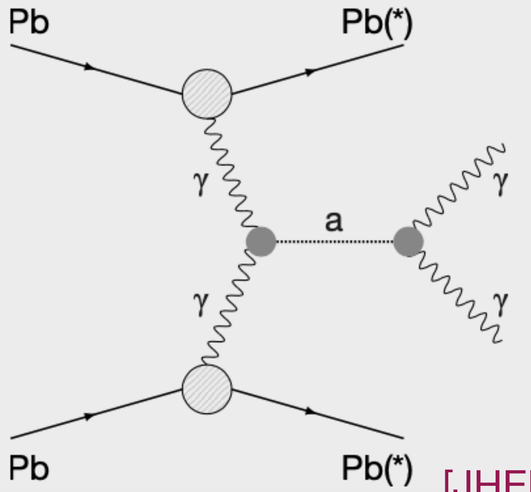
  $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, average P_T^{γ} and $|\cos\theta^*|$.

- The unfolded differential fiducial cross-sections are compared with the predictions from SuperChic v3.0.
  - **Good agreement in shape**, differences in the normalization.

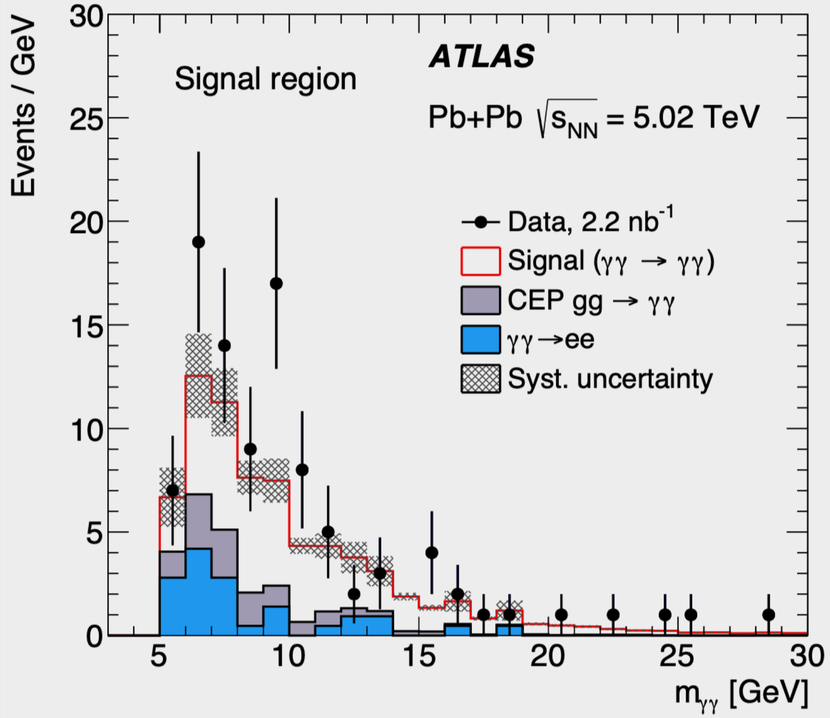


Search for ALP production

- **LbyL scattering** can be used to search for processes beyond the Standard Model, **such as axion-like particles (ALP)**.
- ALP are **hypothetical**, (pseudo-)scalar particles that appear in many theories with a spontaneously broken global symmetry.
- ALPs may have identical signature as **SM LbyL scattering**: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$.
- **ALP production** would lead to an **excess** of scattering events with diphoton mass equal to the mass of a.
- The search performed using m$\gamma\gamma$ distribution

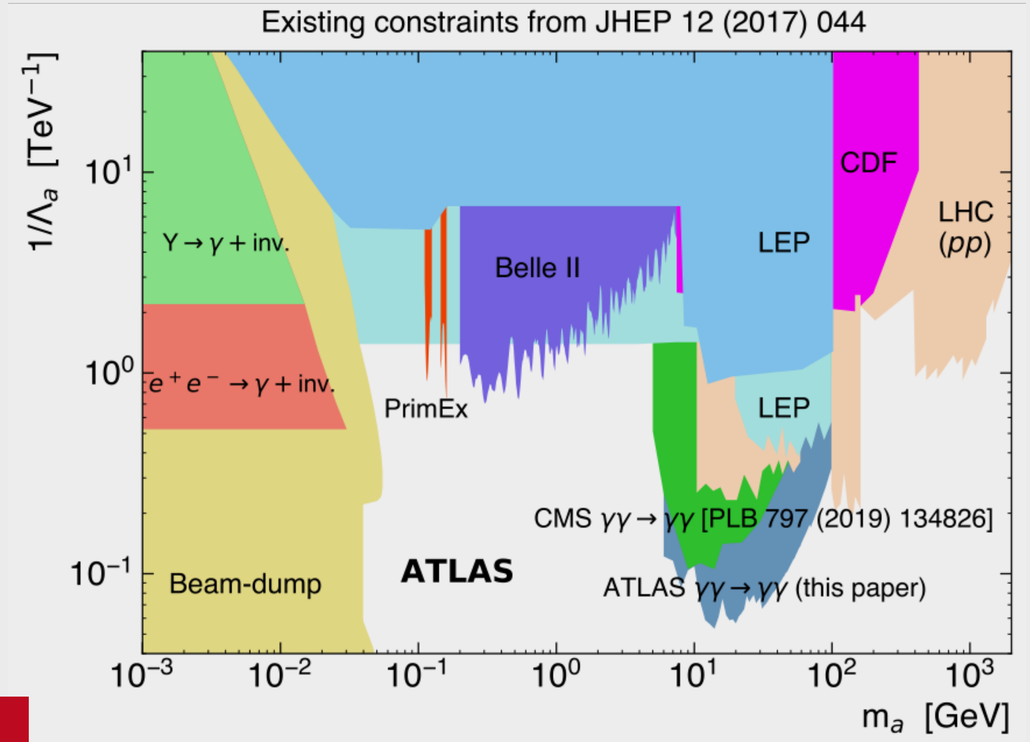


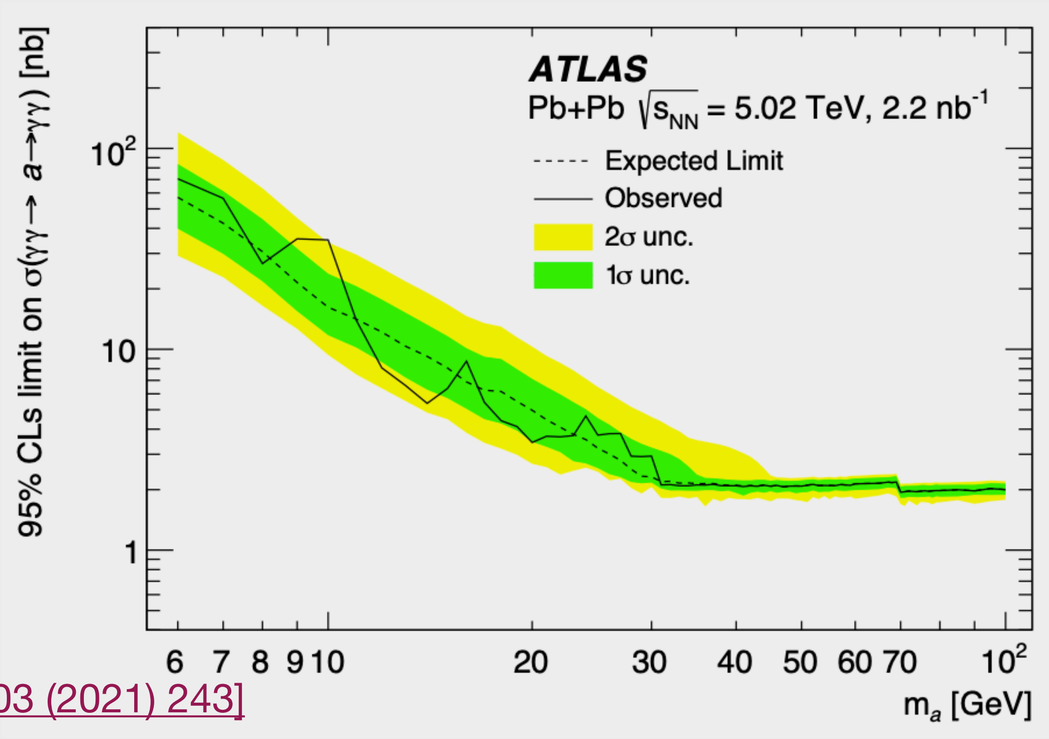
[JHEP 03 (2021) 243]



Search for ALP production

- ALP contribution fitted individually for every mass bin using **a maximum-likelihood fit**.
- **No significant deviation** from the background-only hypothesis observed.
- The upper limit on the ALP **cross-section** and ALP c**oupling 1/Λa** at 95% confidence level is **established** .
- The obtained exclusion limits are **the strongest so far in the mass range** of 6 < ma < 100 GeV .





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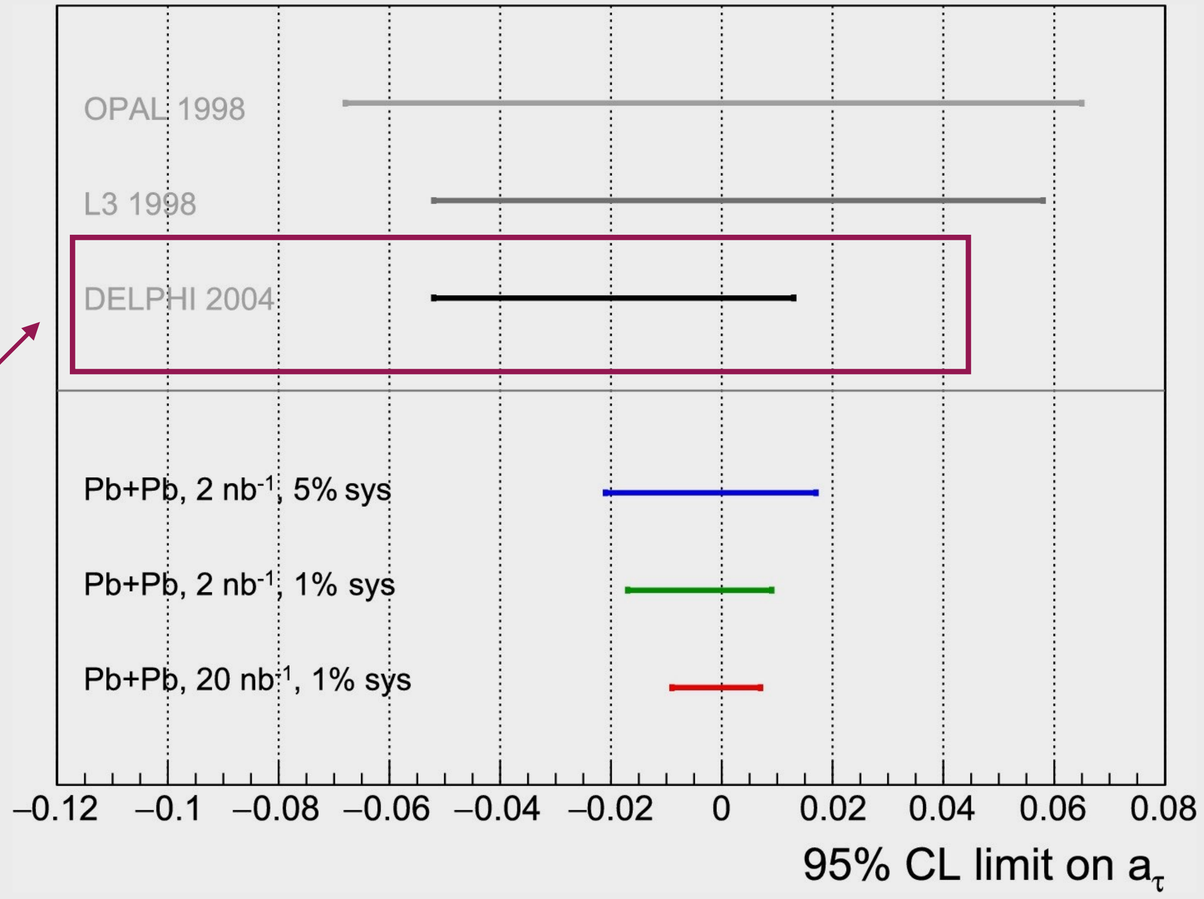
Ditaus

a_τ - measurement strategy

- Magnetic moment of the particle and its spin are related by g-factor: **μ**=g q/2m **S**.
- Dirac's equation predicts $\mathbf{g = 2}$ for charged leptons, higher-order corrections result in $\mathbf{g \neq 2}$.
- These discrepancies are measured with lepton anomalous magnetic moments
  $a_l = (g-2)_l/2$.
- Currently the best constraints for aτ are from **DELPHI** experiment: **-0.052 < a_τ < 0.013** (95% CL), EPJC 35 (2004) 159
- Measurement of a_τ in HI UPC collisions proposed

in several publications:

- *F. del Águila, F. Cornet, J.I. Illana,*
  PLB 271 (1991) 256 L. Beresford, J. Liu, PRD 102 (2020) 113008
- *M. Dyndal, M. Schott, M. Klusek-Gawenda,*
  A. Szczurek, PLB 809 (2020) 135682



Ditau event selection

- **Signal τ-leptons** are **low-energetic**, typically with **p_T < 10 GeV**.
- Events classified based on the charged **τ-lepton decay products**.
- **Three signal categories:** μ + 1 track, μ + 3 tracks, and μ + e.
- Single muon trigger used to record signal events with muon p_T > 4 GeV**.**

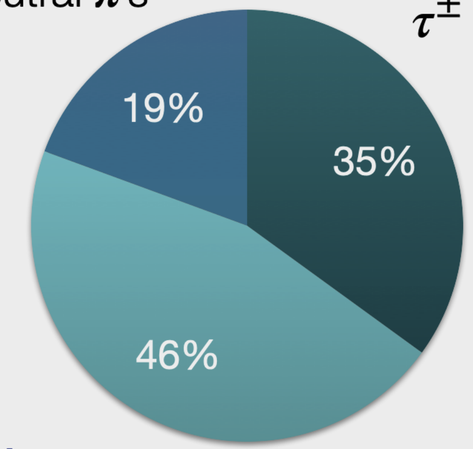
3 prong

$\tau^{\pm} \rightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

+ ≥ 0 neutral π's

Leptonic

$\tau^{\pm} \rightarrow l^{\pm}\nu_{l}\nu_{\tau}$



1 prong

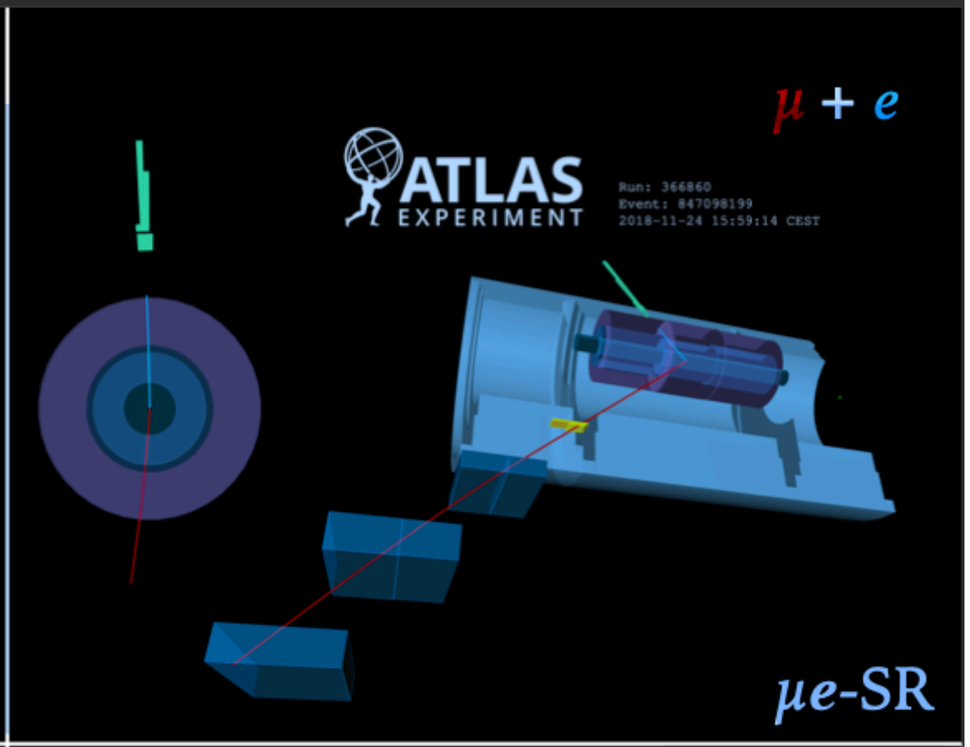
$\tau^{\pm} \rightarrow \pi^{\pm}\nu_{\tau}$

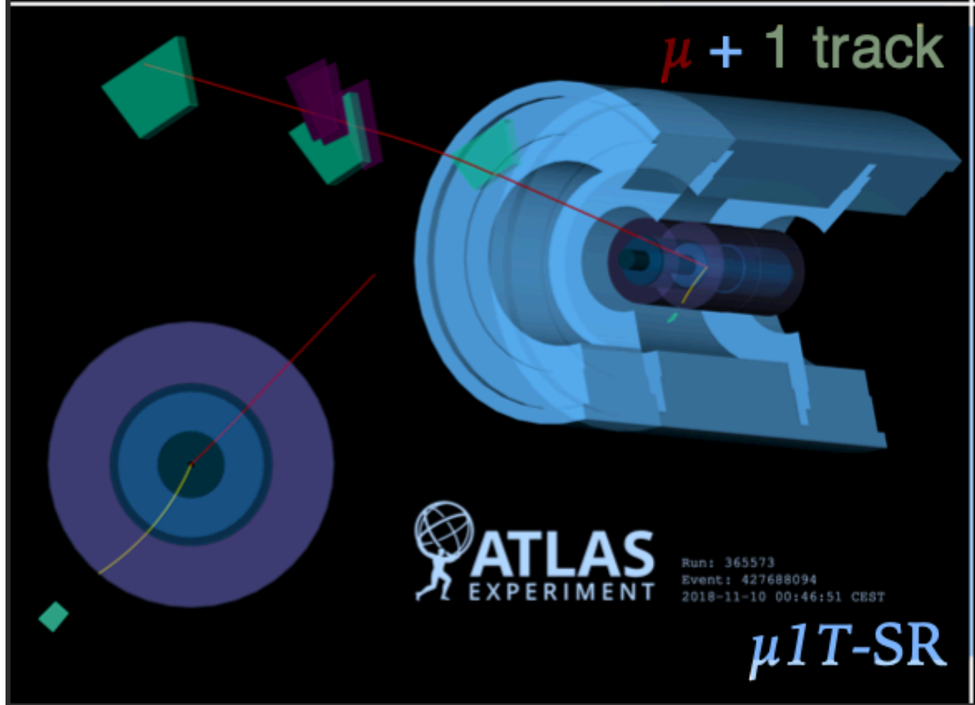
+ ≥ 0 neutral π's

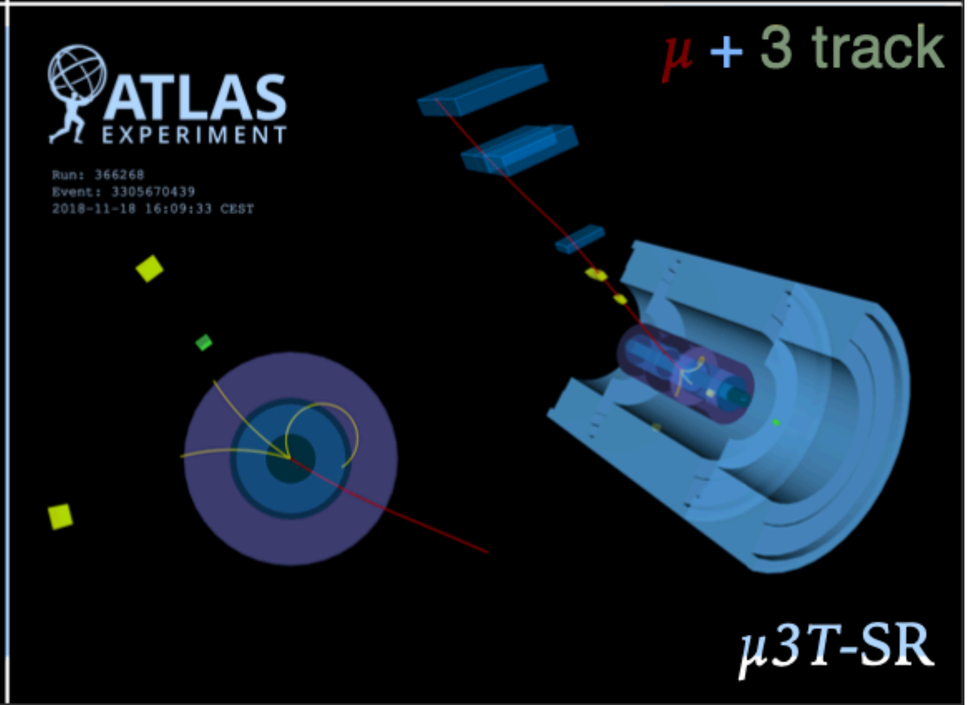
- **Exclusivity requirements**:
  - Veto on forward neutron activity (using 0n0n configuration based on ZDC signal).
  - For μ + 1 track and μ + 3 tracks signal regions: veto on additional low-p_T tracks and low p_T clusters.
- **Main background contributions** are from dimuon production and diffractive photo-nuclear interactions.

→ $\tau\tau$ event candidate

Signal Regions (SRs)

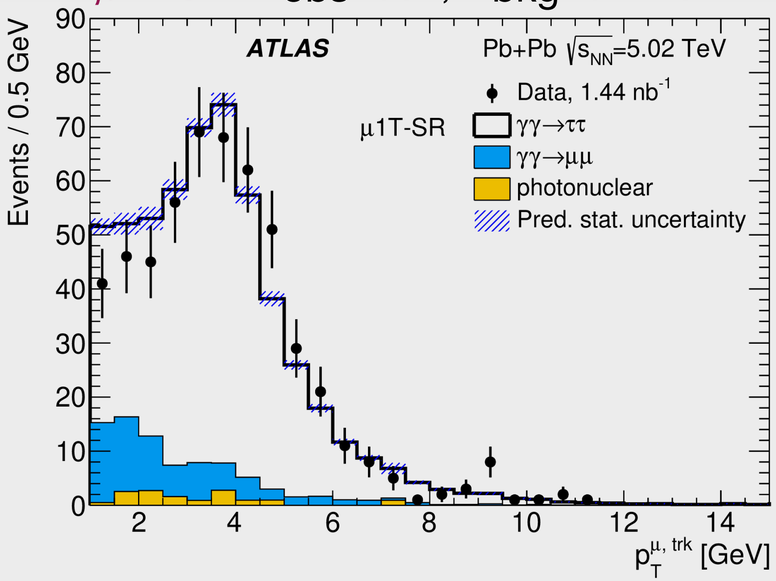




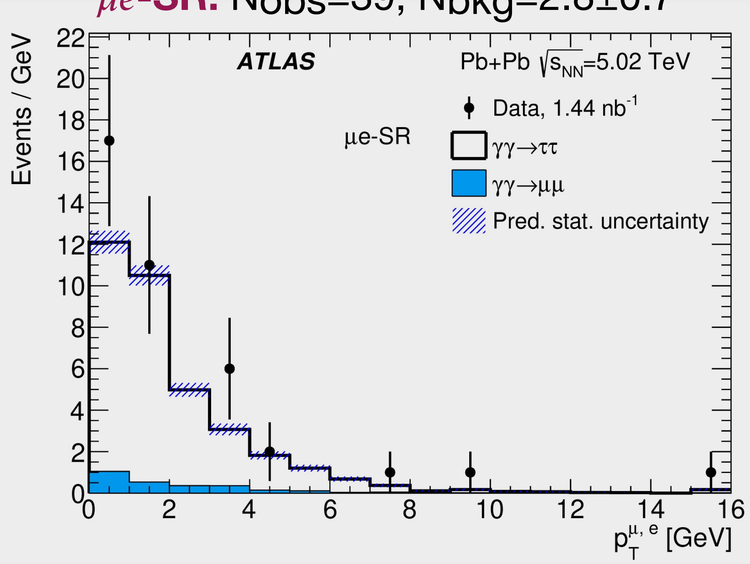


Signal region distributions

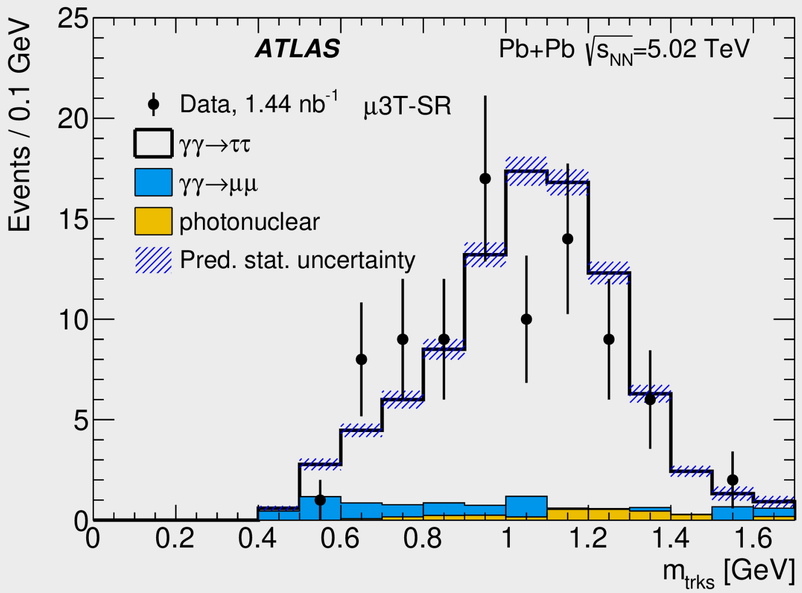
μ**1T-SR**: Nobs=532, Nbkg=84±19



μe**-SR:** Nobs=39, Nbkg=2.8±0.7



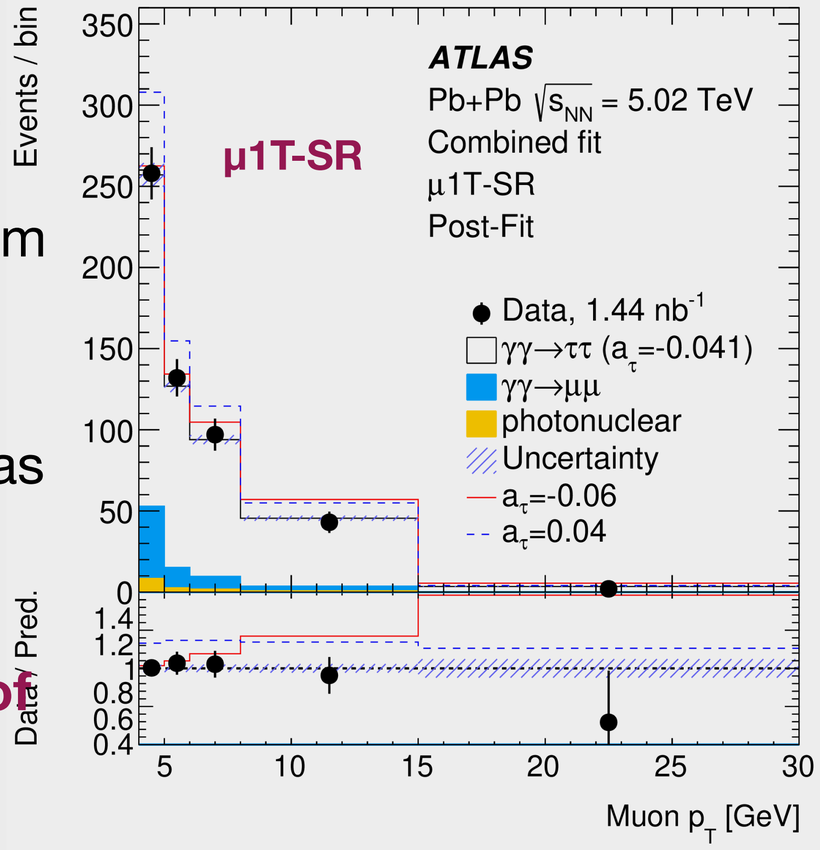
μ**3T-SR**: Nobs=85, Nbkg=9±3 **arXiv:2204.13478**

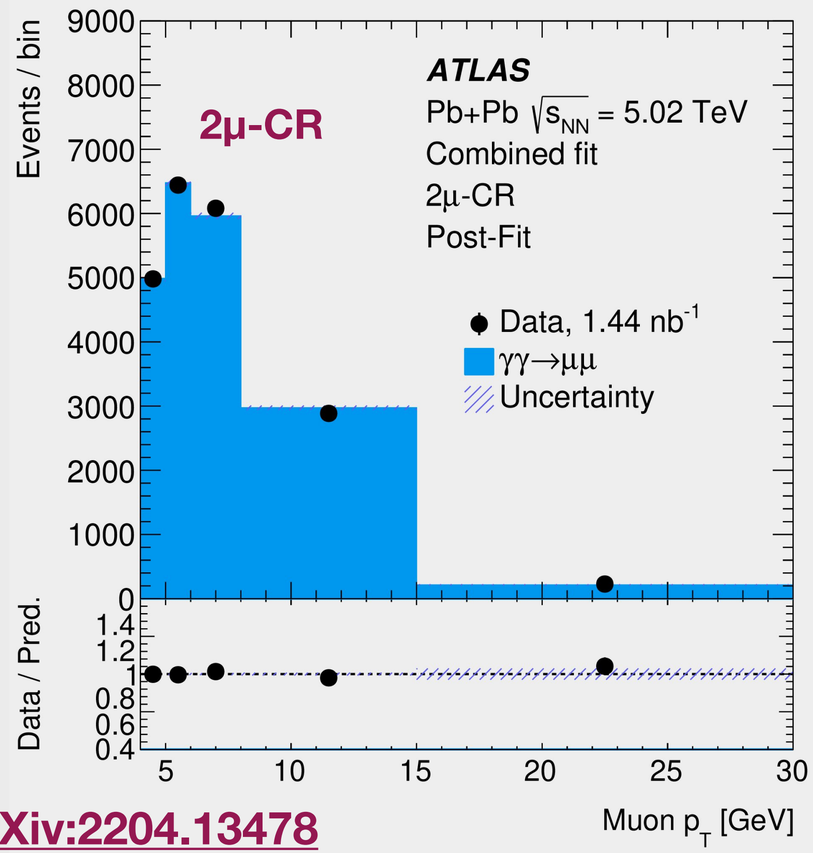


- Good agreement of pre-fit predictions with data.
- Total of about 650 events across all SRs.
- Small background contributions

Observation of exclusive ditau production

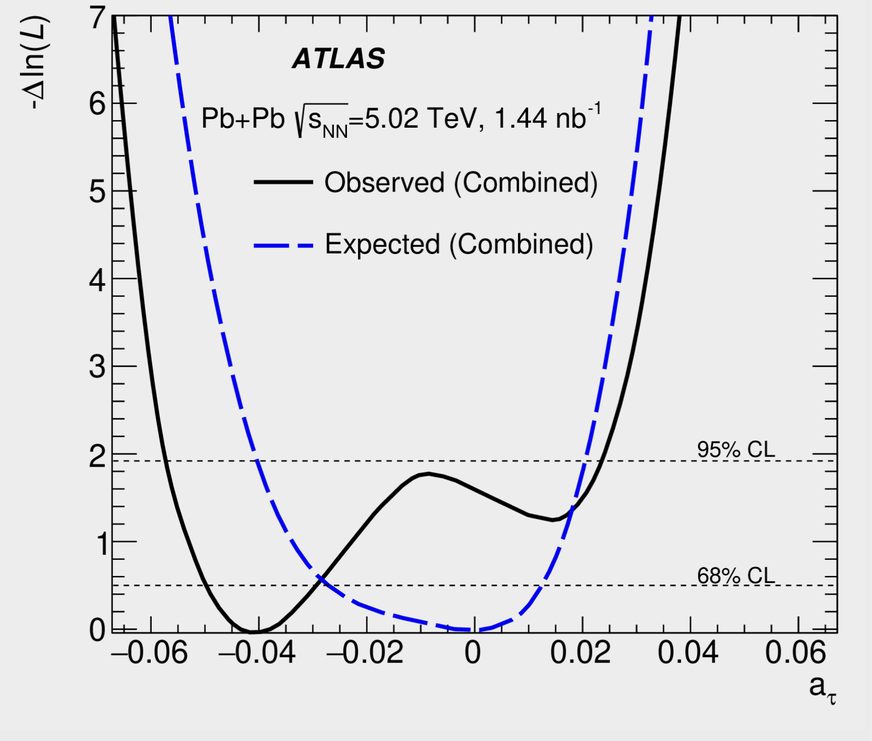
- a_τ **value is extracted**: Using a profile likelihood fit using **the muon p_T** distribution.
- **Simultaneous fit** combining all signal regions and **dimuon control region**:
  - Dimuon **control region** ($\gamma\gamma \to \mu\mu$ events) used to **reduce systematic uncertainty** from the photon flux.
- Build templates for different a_τ values by reweighting signal MC using weights from [**PLB 809 (2020) 135682**]
- Calculations are based on the same parameterization as was used in previous LEP measurements.
- **Clear observation (» 5σ) of $\gamma\gamma \to \tau\tau$ process**.

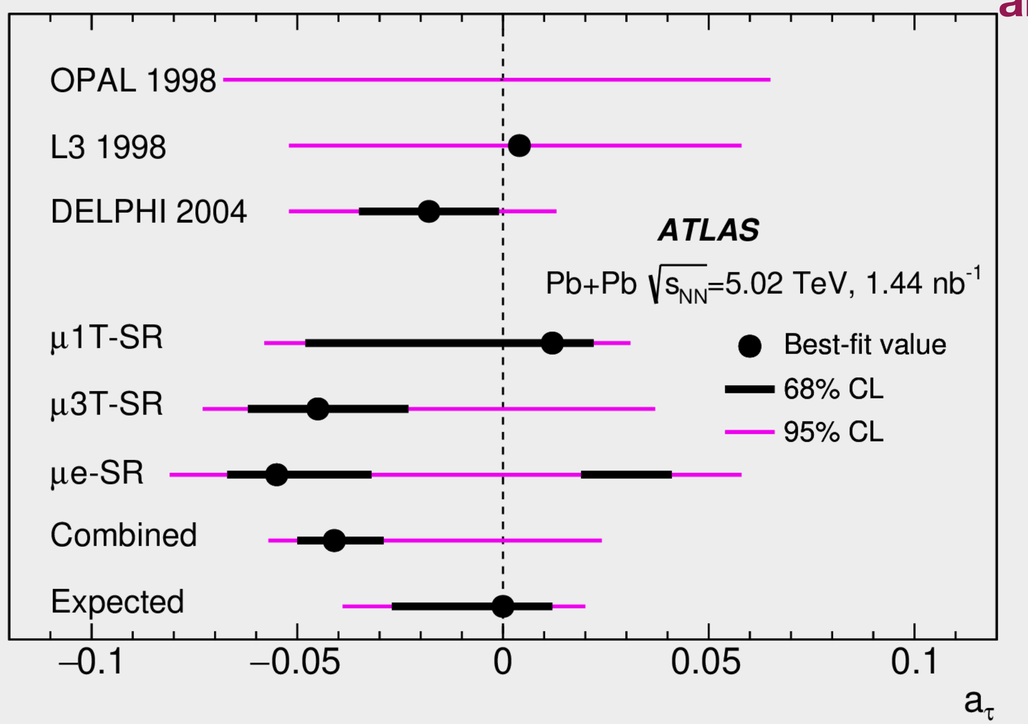




arXiv:2204.13478

Results: a_τ





arXiv:2204.13478

- The best fit value is a_τ = **-0.041** with corresponding **95% CL** interval being **(-0.057, 0.024)**
- Constraints on a_τ have similar precision as those observed by **DELPHI** [EPJC 35 (2004) 159]
- Statistical uncertainties dominant → expected to improve with **Run-3 data** .
- Leading systematic uncertainties: trigger efficiency, τ decay modeling.

Summary

- UPCs can be used to probe rare SM processes and search for BSM phenomena.
- ATLAS provides a final measurement of exclusive ditau production in Pb+Pb UPC at the LHC **with above 5σ significance**.
- The measurement of the τ**-lepton anomalous magnetic moment** is competitive with previous best limit from the LEP era.
- **Light-by-light scattering** well established by ATLAS experiment at the LHC.
- The **LbyL ATLAS** result set the most stringent limits to date on **ALP production** for masses in the range **6-100 GeV**.
  - Excellent prospects for new searches with **Run-3 and Run-4 data**

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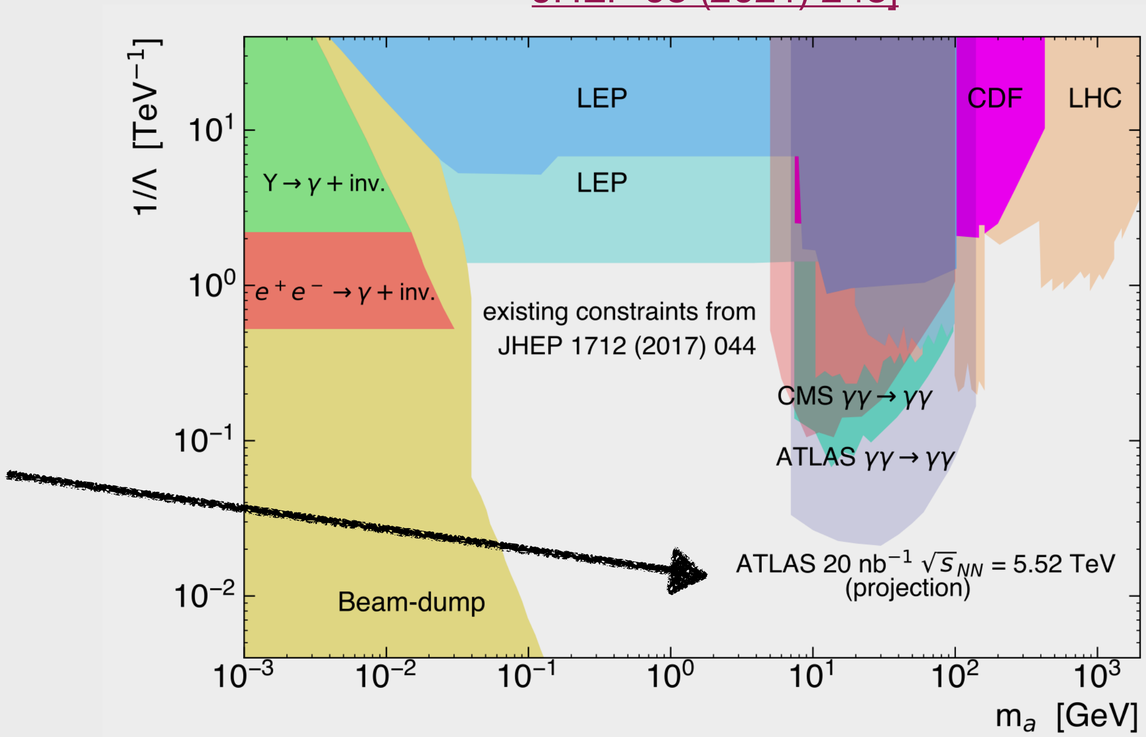
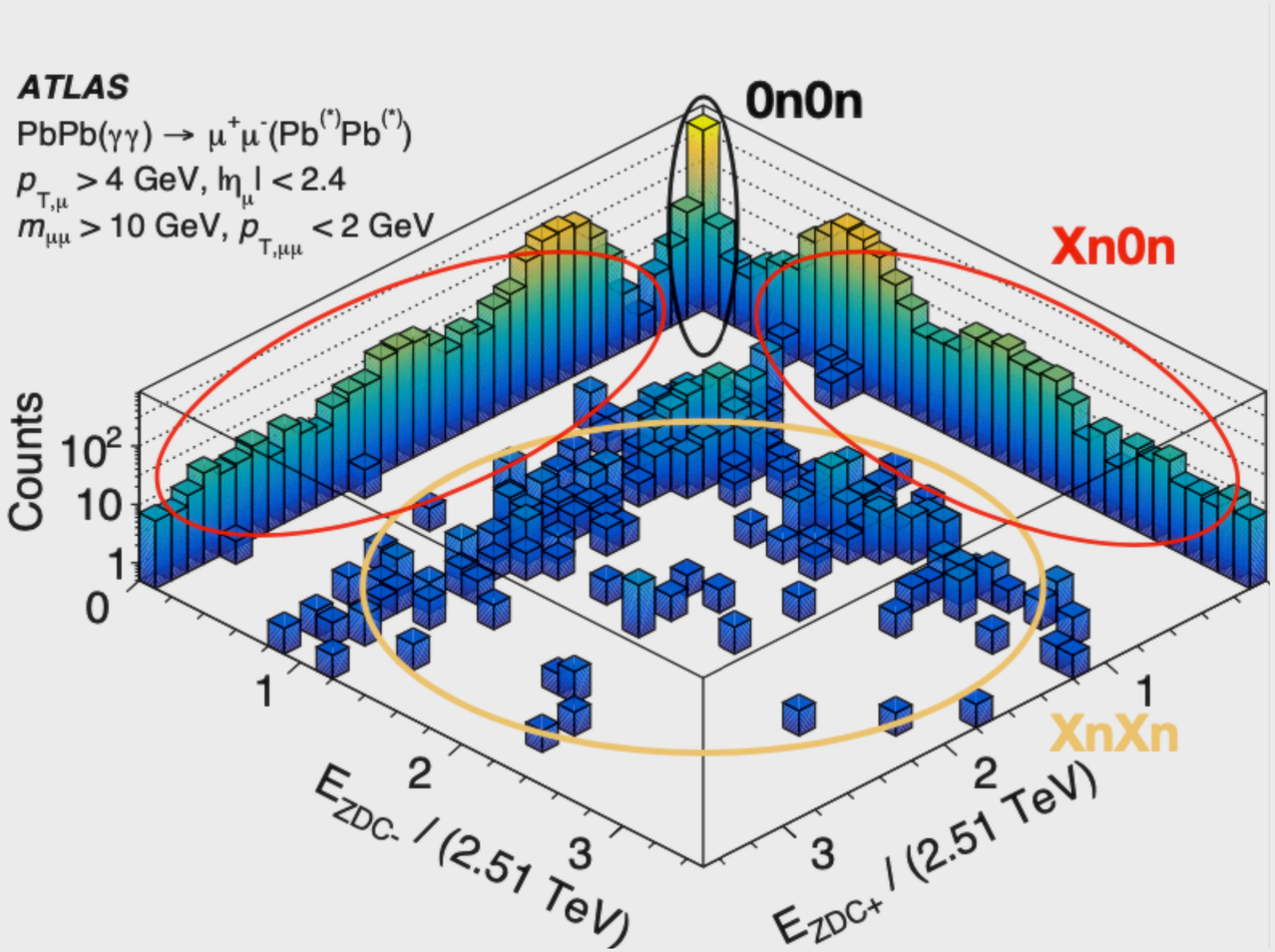


Backup

ZDC selection

PRC 104, 024906 (2021)

- Different processes present **different activity in the forward region**:
  - Exclusive dilepton production - ions **remain intact**
  - Background events with nuclear breakup
- **Three different classes** are defined based on the signal in the ZDC: **0n0n**, **Xn0n** and **XnXn.**
- **The association** between given **ZDC signal** and given process is **nontrivial:**
  - Migrations due to ion excitation and presence of EM pile-up.



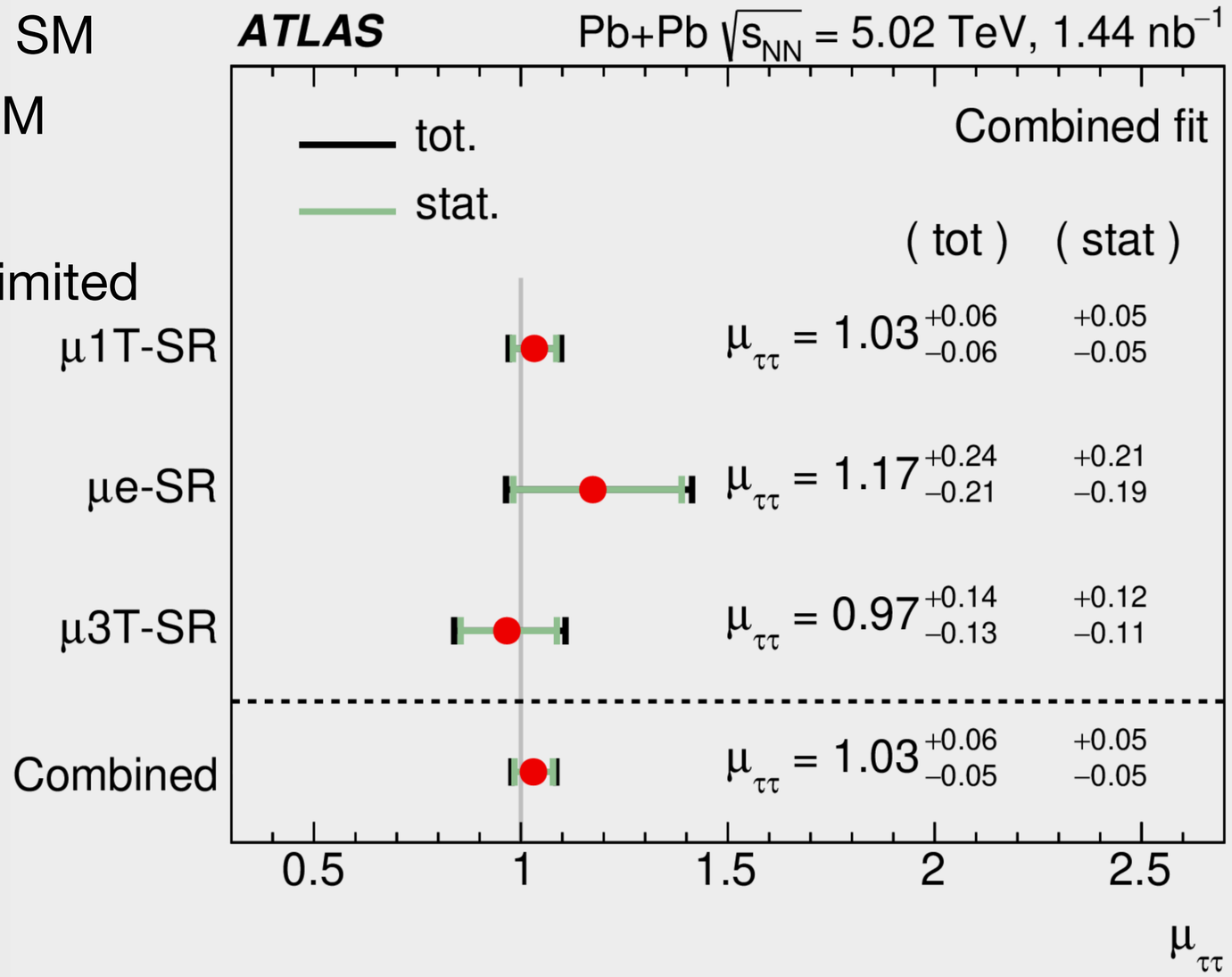
SR MC cutflow

Requirement	Number of $\gamma\gamma \to \tau\tau$ events
Common selection	
$\sigma \times \mathcal{L}$	352611
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	28399
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}} \times w_{\text{SF}}$	35383
Pass trigger	1840
$E_{\text{ZDC}}^{A,C} < 1$ TeV	1114
μ1T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1023
$N_{\mu}^{\text{signal}} = 1$	900
$N_e = 0$	867
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1$) $= 1$	575
Zero unmatched clusters	552
$\sum$ charge $= 0$	546
$p_{\text{T}}^{\mu,\text{trk}} > 1$ GeV	503
$p_{\text{T}}^{\mu,\text{trk},\gamma} > 1$ GeV	482
$p_{\text{T}}^{\mu,\text{trk,clust}} > 1$ GeV	462
$A_{\phi}^{\mu,\text{trk}} < 0.4$	459

μ3T-SR	
$N_{\mu}^{\text{preselected}} = 1$	1023
$N_{\mu}^{\text{signal}} = 1$	900
$N_e = 0$	867
N_{trk} (with $\Delta R_{\mu,\text{trk}} > 0.1$) $= 3$	88.1
Zero unmatched clusters	85.2
$\sum$ charge $= 0$	84.1
$m_{\text{trks}} < 1.7$ GeV	83.4
$A_{\phi}^{\mu,\text{trks}} < 0.2$	83.3
μe-SR	
$N_{\mu}^{\text{signal}} = 1$	958
$N_e = 1$	33.9
N_{trk} (with $\Delta R_{\mu/e,\text{trk}} > 0.1$) $= 0$	32.6
$\sum$ charge $= 0$	32.5

Results: Signal strength

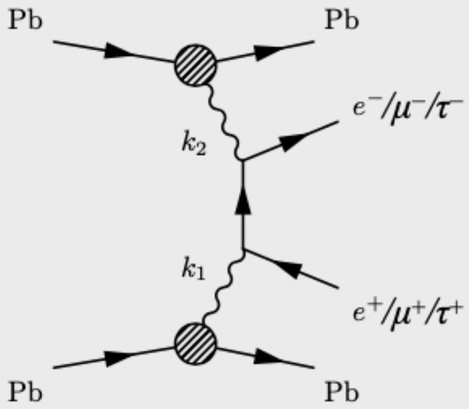
- Fit of $\gamma\gamma \to \tau\tau$ signal strength assuming SM value for aτ : $\mu\tau\tau$ = observed yield / SM expectation
- Combined fit reaches 5% precision, limited by statistical uncertainties.



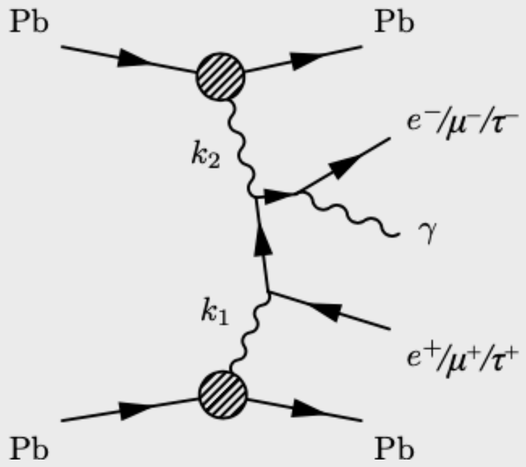
Background sources

Various background sources are considered for $\mu\mu/ee$:

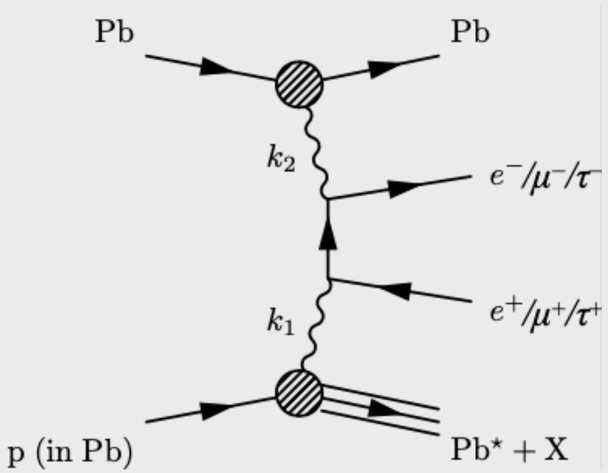
- **Upsilon (nS)** production: STARlight+Pythia8 MC samples (only in dielectron measurement).
- **Exclusive ditau production** : STARlight+Pythia8 MC samples (only in dielectron measurement).
- **Dissociative production of $\ell^+\ell^-$ pairs:** Data-driven method (LPair / SuperChic4 + Pythia8 in pp collisions).



Signal (LO)



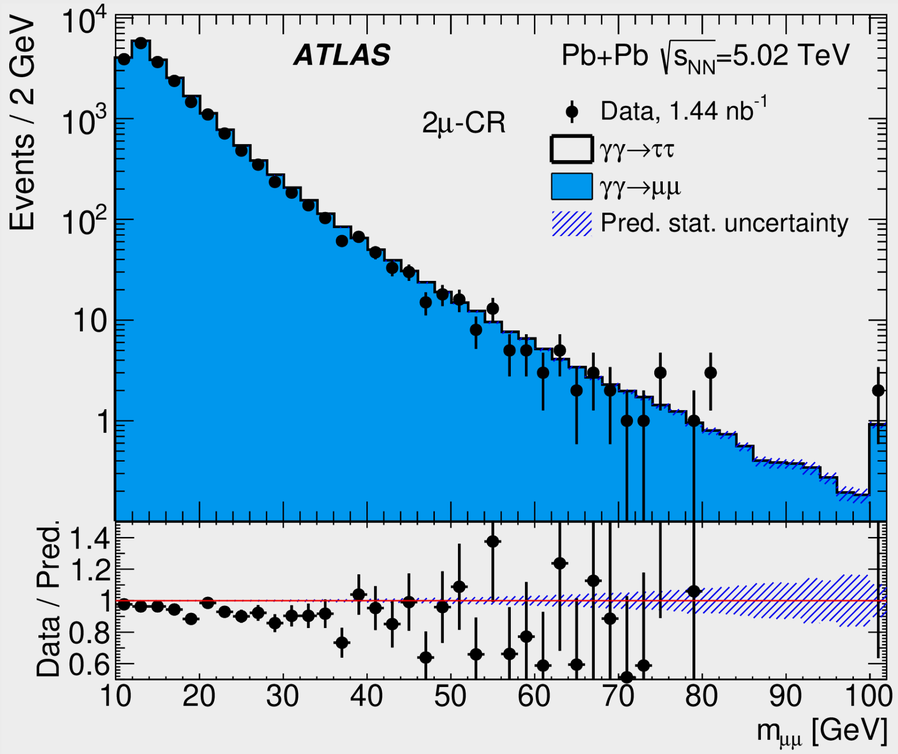
Signal (FSR)

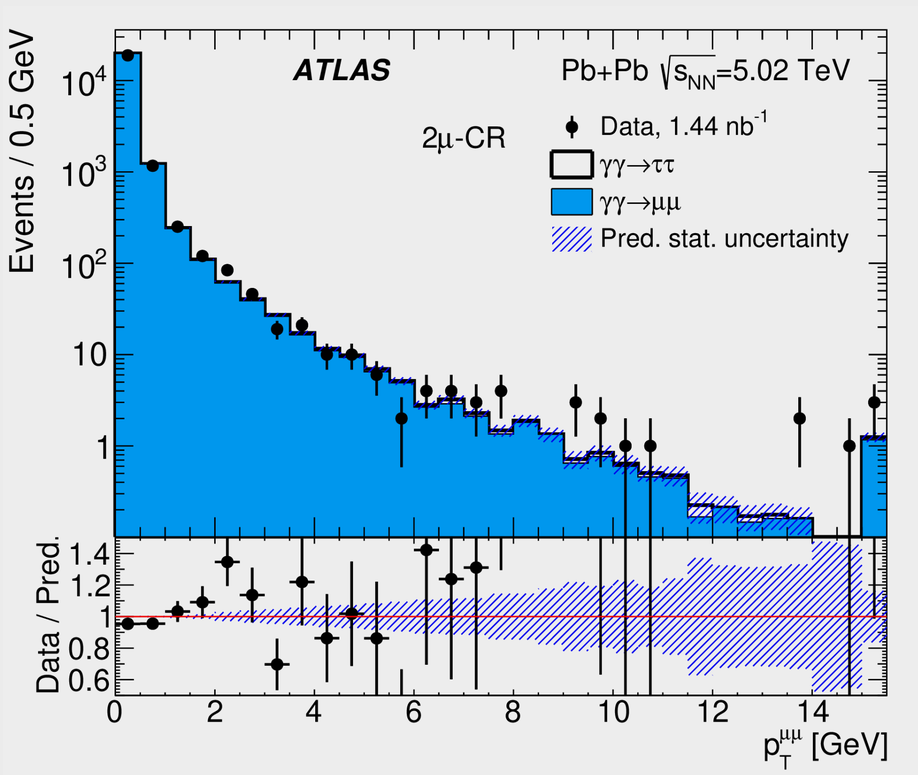


Dissociative background

Background processes: $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production

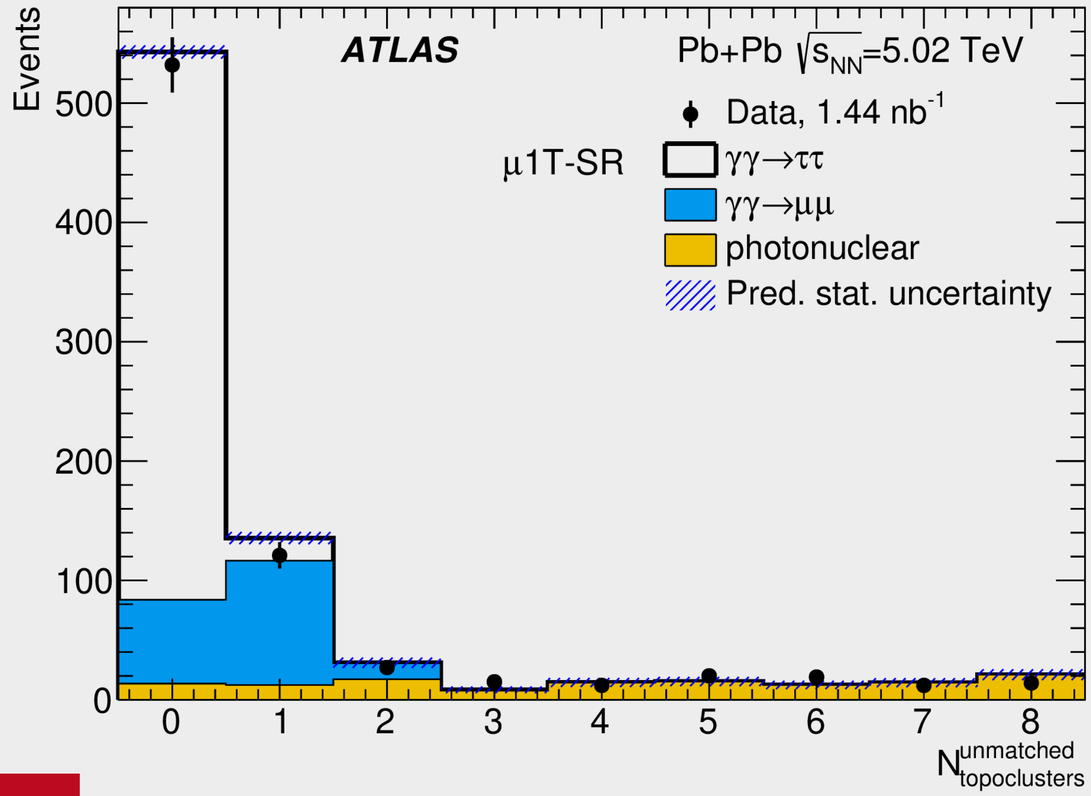
- **Background from** $\gamma\gamma \rightarrow \mu\mu(\gamma)$ production estimated using MC simulation**.**
- Validation of modeling performed in dimuon control region **(2μ-CR)**.
- Normalization off by +6% with SuperChic3 photon flux (Starlight: -13%).
- Good description of FSR emissions seen in $p_T^{\mu\mu}$ distribution tail.

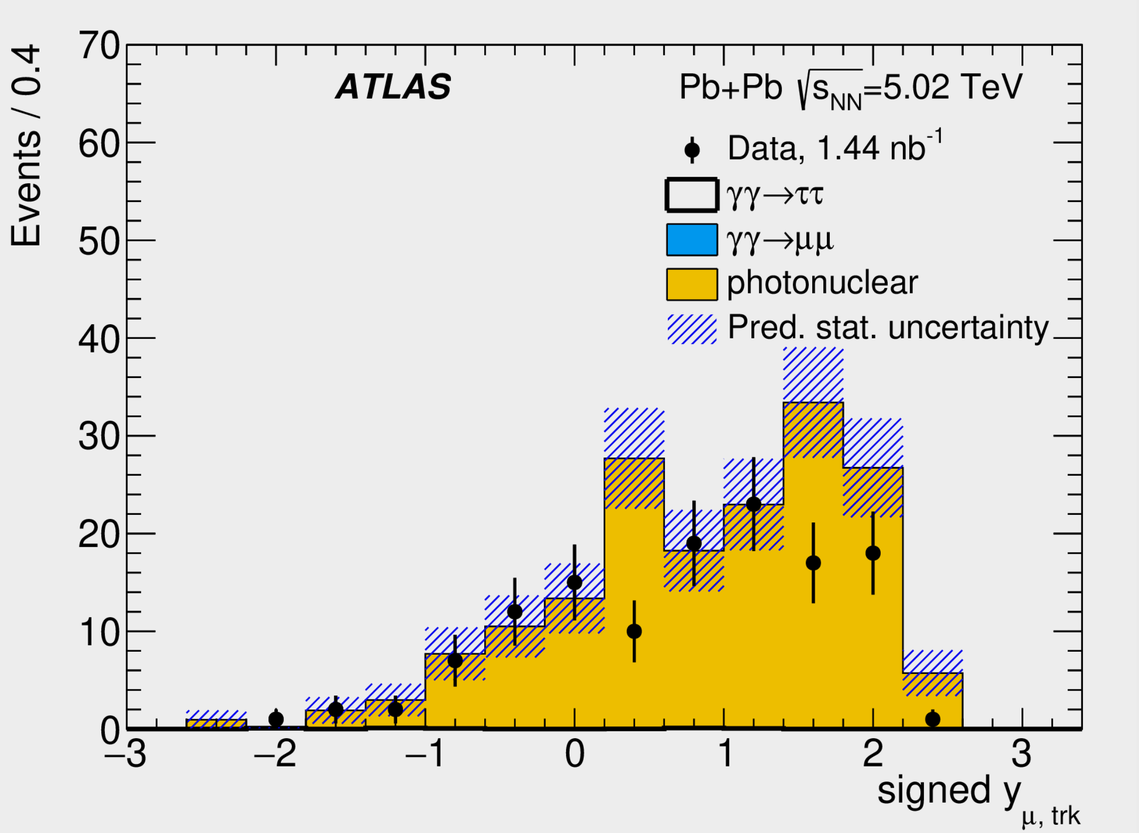




Background processes: diffractive photo nuclear events

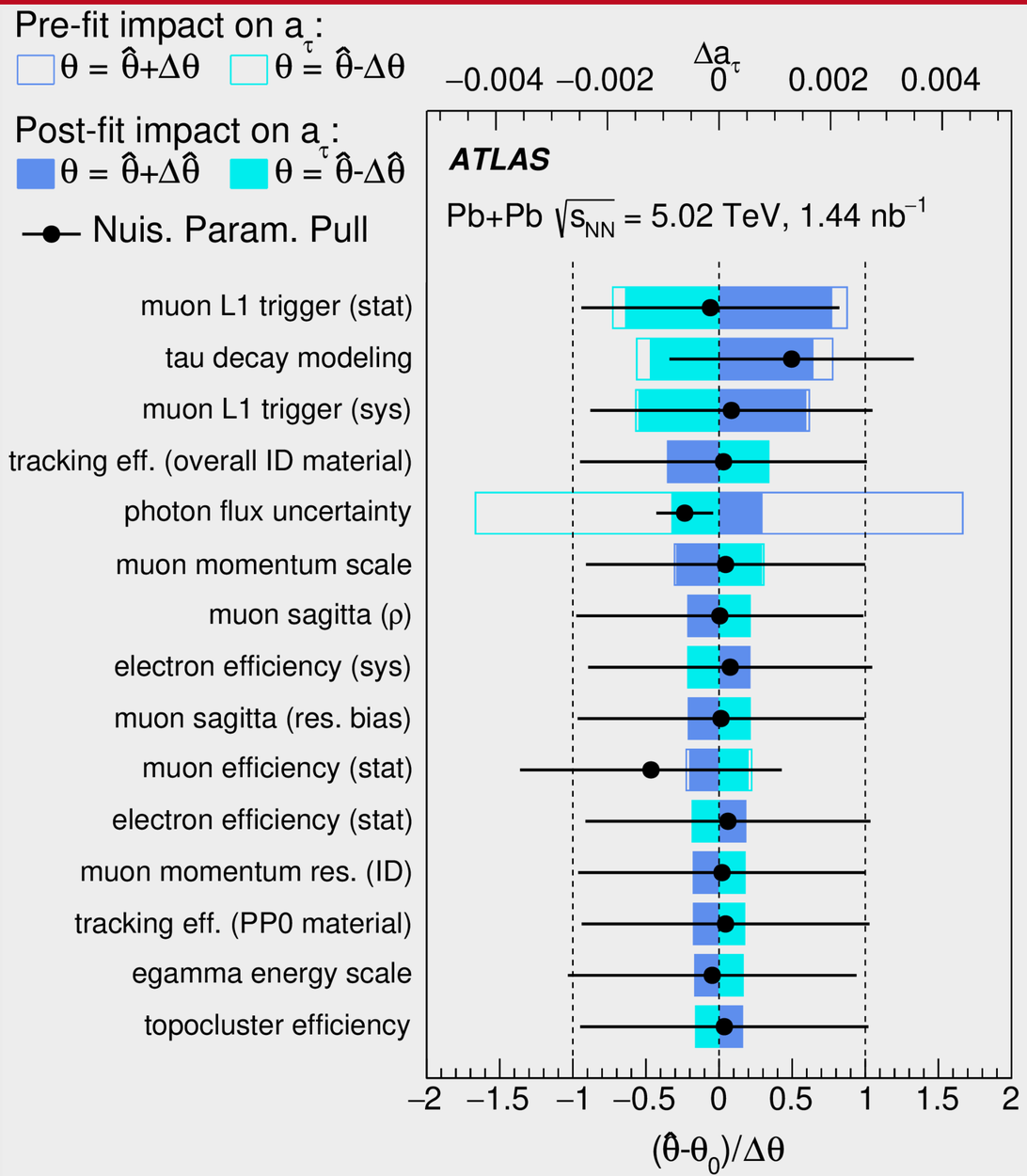
- Data-driven estimation of diffractive photonuclear events in μ1T-SR and μ3T-SR.
- Templates built from control regions similar to SRs, but requiring an additional track with $p_T < 0.5$ GeV and allowing 0nXn ZDC events.
- Normalization: relax cluster veto → use region with 4-8 unmatched clusters.





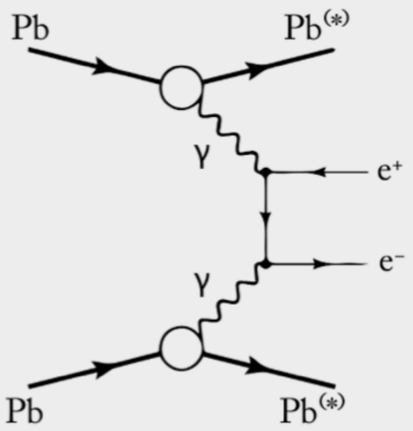
Systematic uncertainties in a_τ

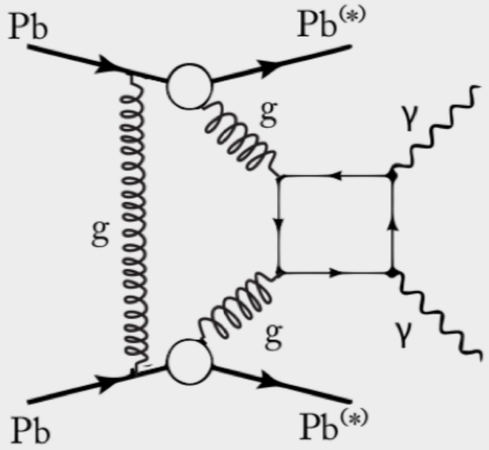
- Detector related :
  - Muon trigger efficiency
  - Muon/electron reconstruction/ID efficiency and calibration
  - Track reconstruction efficiency
  - Cluster reconstruction efficiency and calibration
- Background:
  - Photonuclear background template variation .
- Theory:
  - Photon flux modeling (SuperChic3 vs. Starlight).
  - τ decay modelling (Tauola vs. Pythia8).
  - 0n0n ZDC reweighing variation .

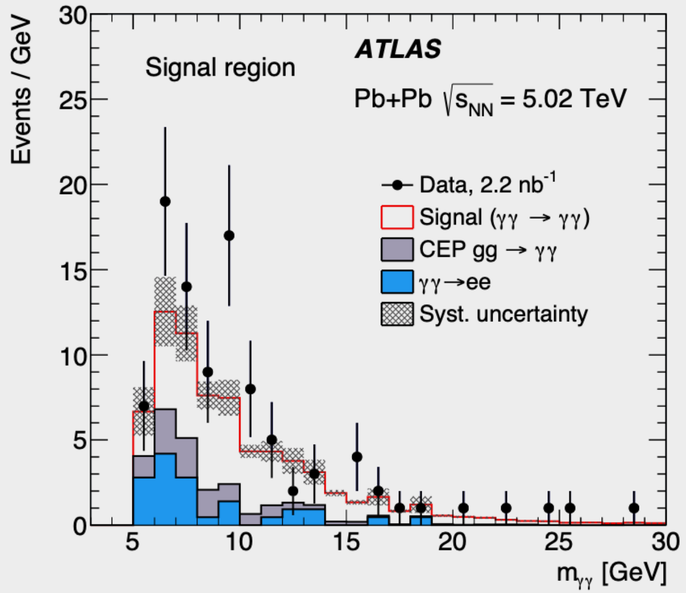


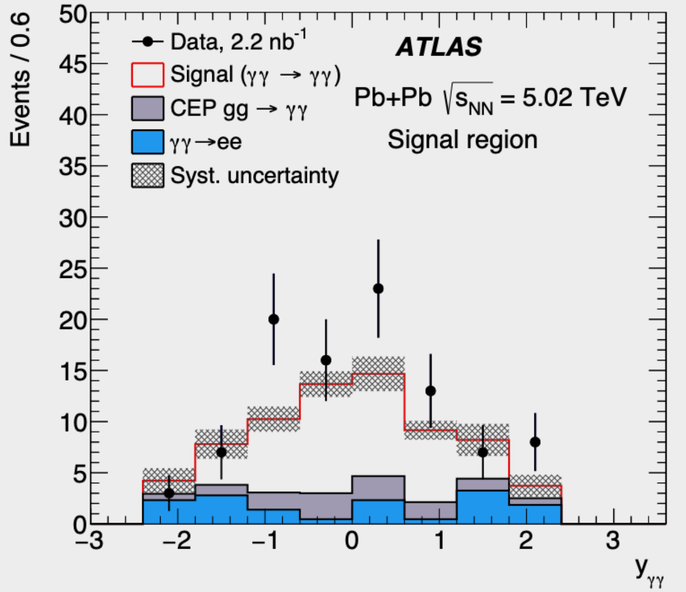
LbyL Background

- Various background sources considered, the largest contribution from: :
  - Exclusive dielectron production $\gamma\gamma \rightarrow e^+e^-$
  - Central exclusive production (CEP) $gg \rightarrow \gamma\gamma$
- **Main background** sources are estimated using data-driven techniques
- Shapes of the distributions are in good agreement but data excess visible in both distributions.



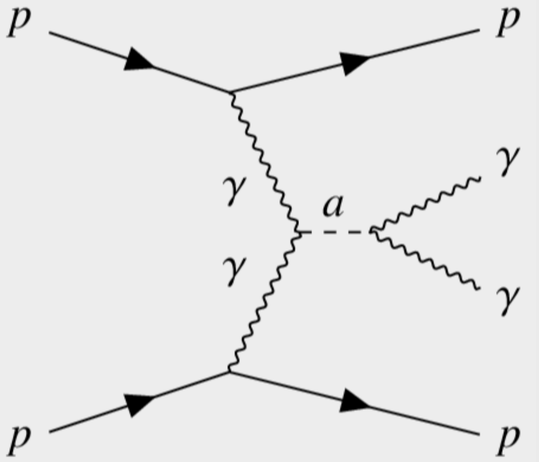






Search for ALP production with ATLAS AFP

- A search for ALP carried out by ATLAS using pp collisions in the diphoton mass range $m_{\gamma\gamma}$ = [150,1600] GeV.
- Exploit events with centrally produced photon pairs tagged by forward scattered protons
- Exploit events with centrally produced photon pairs tagged by forward scattered protons
- No signal is observed:
  - Data consistent with a combinatorial SM background
- Upper limit on the ALP coupling constant to two photons set in the range 0.04-0.09 TeV^{-1} at 95% confidence level



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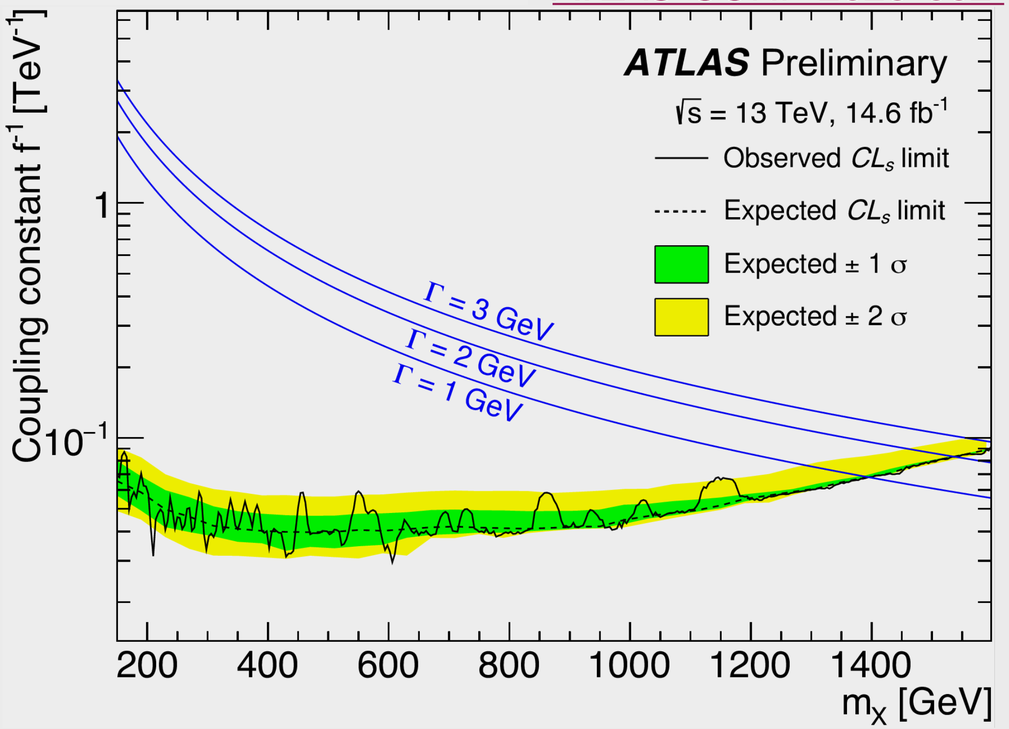
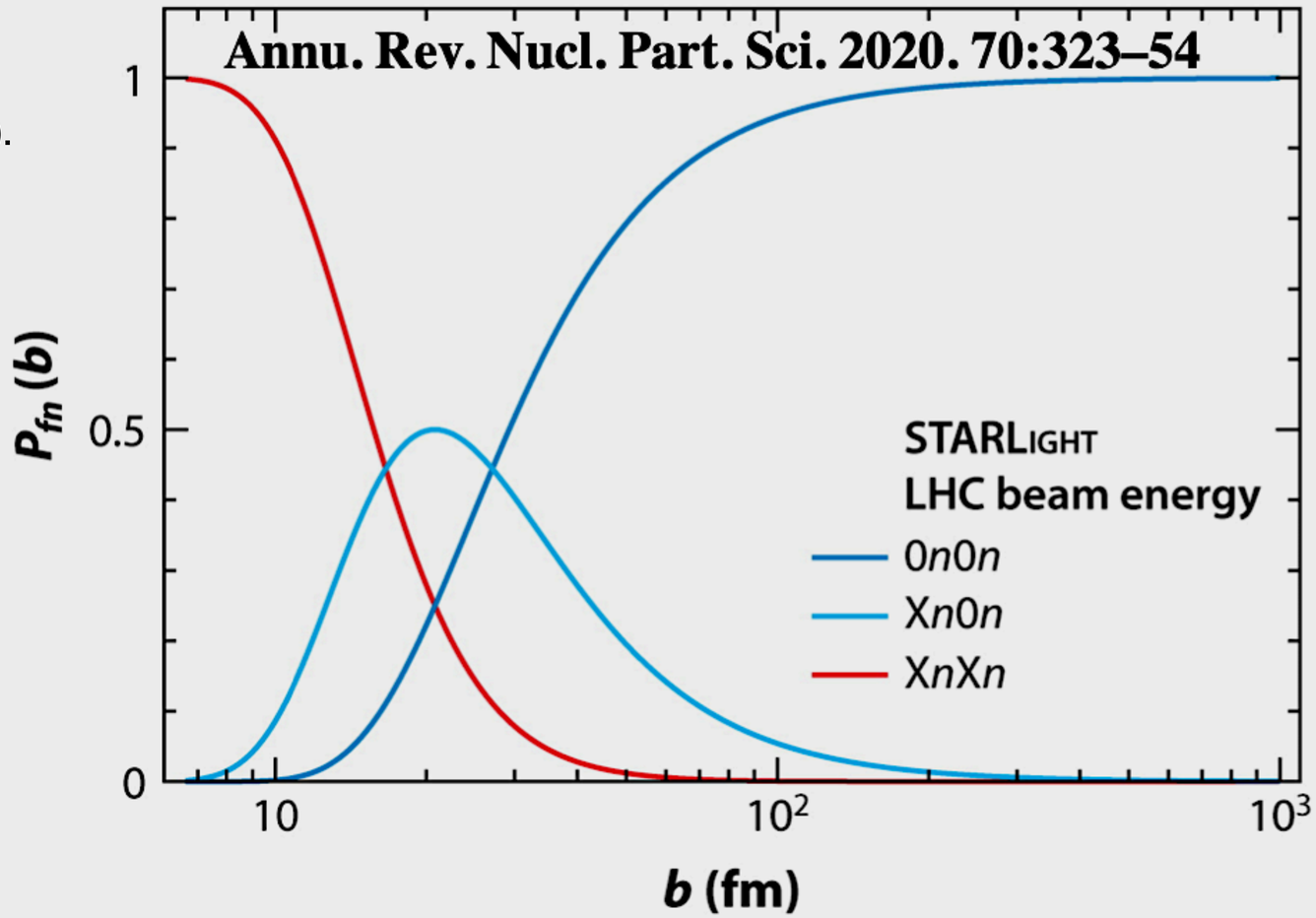


ZDC fractions

- The probability of producing a given ZDC category depends on the value of the impact parameter, b (based on the Coulomb excitation probabilities ~ $1/b^{2)}$.

- With different selections on the ZDC topology, we probe different ranges of dilepton mass and impact parameters, as photon fluxes vary with b.



fXn0n and fXnXn fractions - dimuons

The corrected f_{Xn0n} and f_{XnXn} fractions are compared with the **STARlight predictions**.

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