Observation of $\gamma\gamma \rightarrow \tau\tau$ in ultraperipheral lead-lead collisions and constraints on τ g-2

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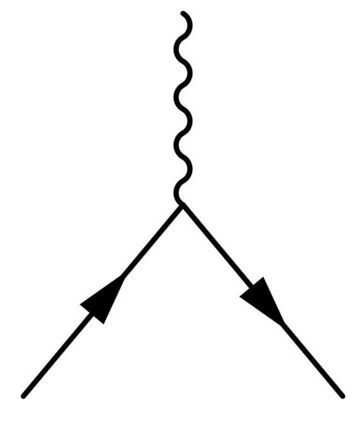
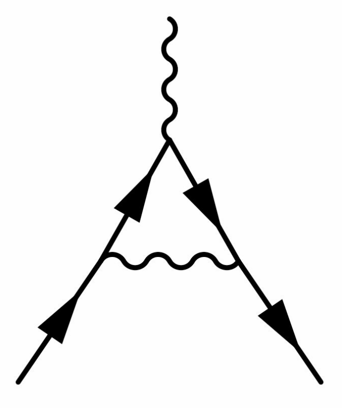
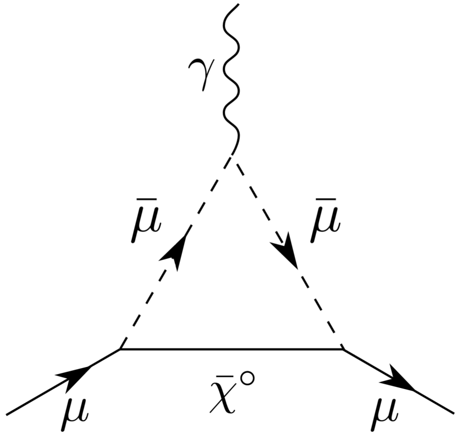
Motivation and how to measure τ g-2

Motivation for measuring τ g-2

Magnetic moment of a particle: $\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{S}$

$g_\ell =$  +  + 

2
Dirac 1928

α / π
Schwinger 1948

Possible new physics

Anomalous magnetic moment: $a_l \equiv \frac{g_l - 2}{2}$

Muon g-2: +4.2σ tension with the SM

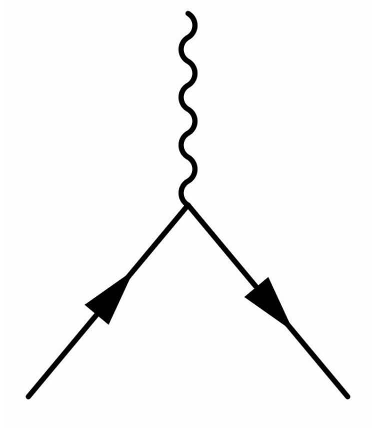
Electron g-2: -2.5σ tension with the SM, Science 360, 191 (2018)

Phys. Rev. Lett. **126**, 141801

Motivation for measuring τ g-2

Magnetic moment of a particle: $\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{S}$

$g_\ell =$



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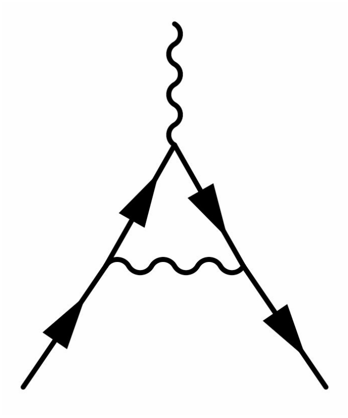

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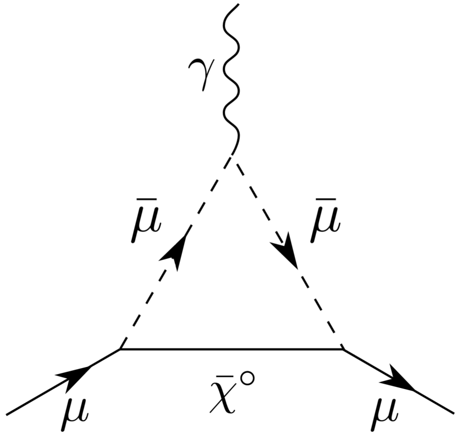


2

Dirac 1928

$\boldsymbol{\alpha / \pi}$

Schwinger 1948

Possible new physics

Tau is 280× more sensitive to SUSY than muon

$$\delta a_\ell \sim m_\ell^2 / M_{\mathrm{SUSY}}^2$$

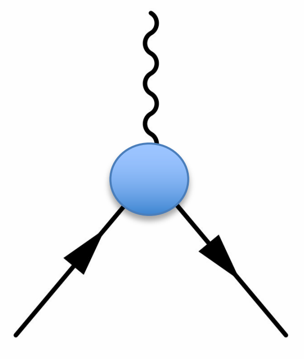
Martin, Wells, Phys. Rev. D64 (2001) 035003

$$m_\tau^2 / m_\mu^2 \sim 280$$

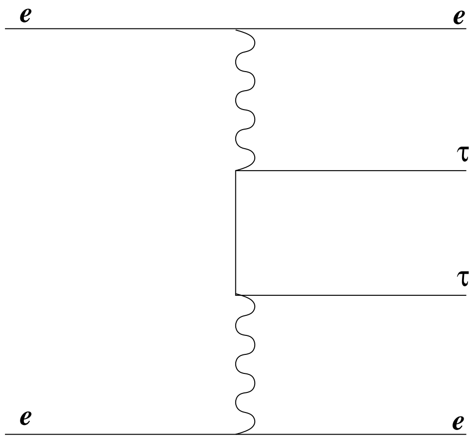
How to measure τ g-2 at collider

Measure the process with τ-γ-τ vertex to get a_τ :

$$a_\tau \equiv \frac{g_\tau - 2}{2}$$



Before LHC, the most precise measurement of a_τ is from LEP



Experimental measurement: $a_\tau = -0.018 \pm 0.017,$

DELPHI, Eur. Phys. J. C35: 159-170, 2004

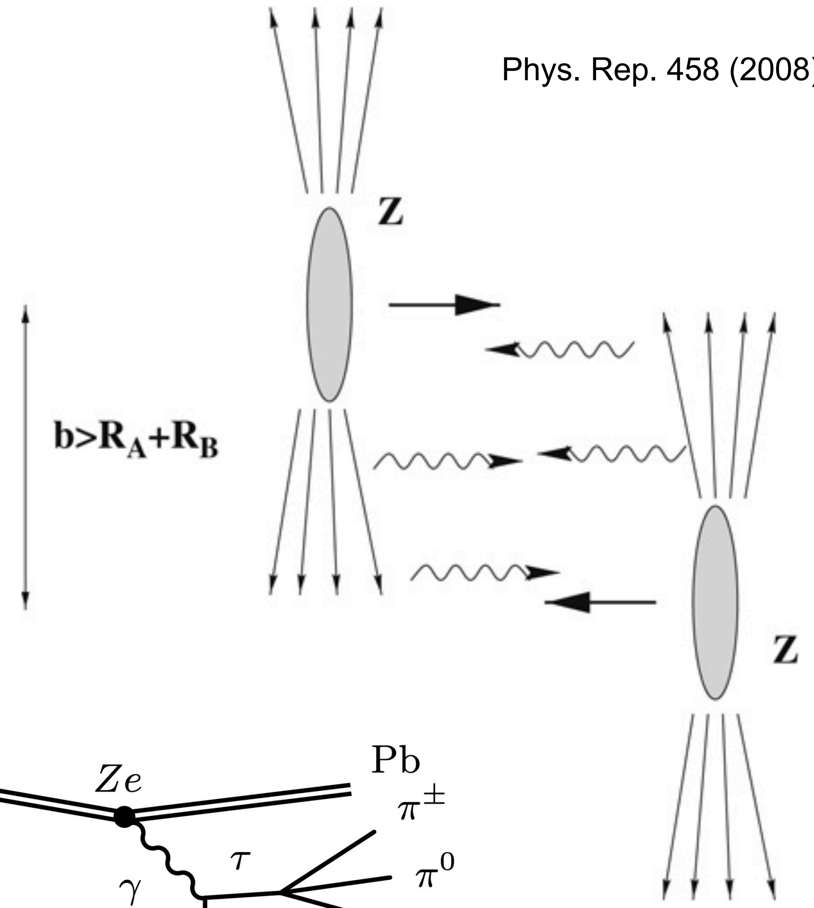
SM prediction : $a_{\tau,\,\mathrm{SM}}^{\mathrm{pred}} = 0.001\,177\,21\,(5)$

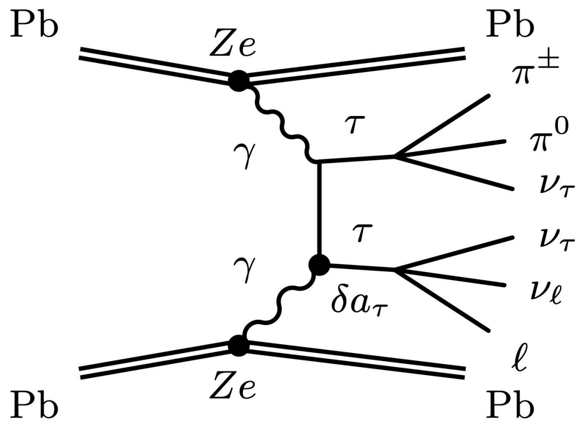
Eidelman, Passera, Mod. Phys. A22:159-179, 2007

Ultraperipheral Collisions

- 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 ultraperipheral collisions (UPC)
- UPC of lead-lead could be used as a low-energy photon-photon collider
- Measure the process of γγ→ττ in ultraperipheral lead-lead collisions
- Cross section enhanced by Z^4 ~ 4.5x10^7 with Z_{Pb} = 82

Phys. Rep. 458 (2008) 1





Extracting a_τ

The amplitude of $\gamma\gamma \to \ell^+\ell^-$:

PLB 809 (2020) 135682

$$\mathcal{M} = (-i)\,\epsilon_{1\mu}\epsilon_{2\nu}\,\bar{u}(p_3) \times \Bigg(i\Gamma^{(\gamma\ell\ell)\,\mu}(p_3, p_t)\frac{i(\not{p}_t + m_\ell)}{t - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell\ell)\,\nu}(p_{t'} - p_4) + i\Gamma^{(\gamma\ell\ell)\,\nu}(p_3, p_u)\frac{i(\not{p}_u + m_\ell)}{u - m_\ell^2 + i\epsilon} i\Gamma^{(\gamma\ell\ell)\,\mu}(p_{u'} - p_4)\Bigg) v(p_4)\,.$$

$$q = p' - p.$$

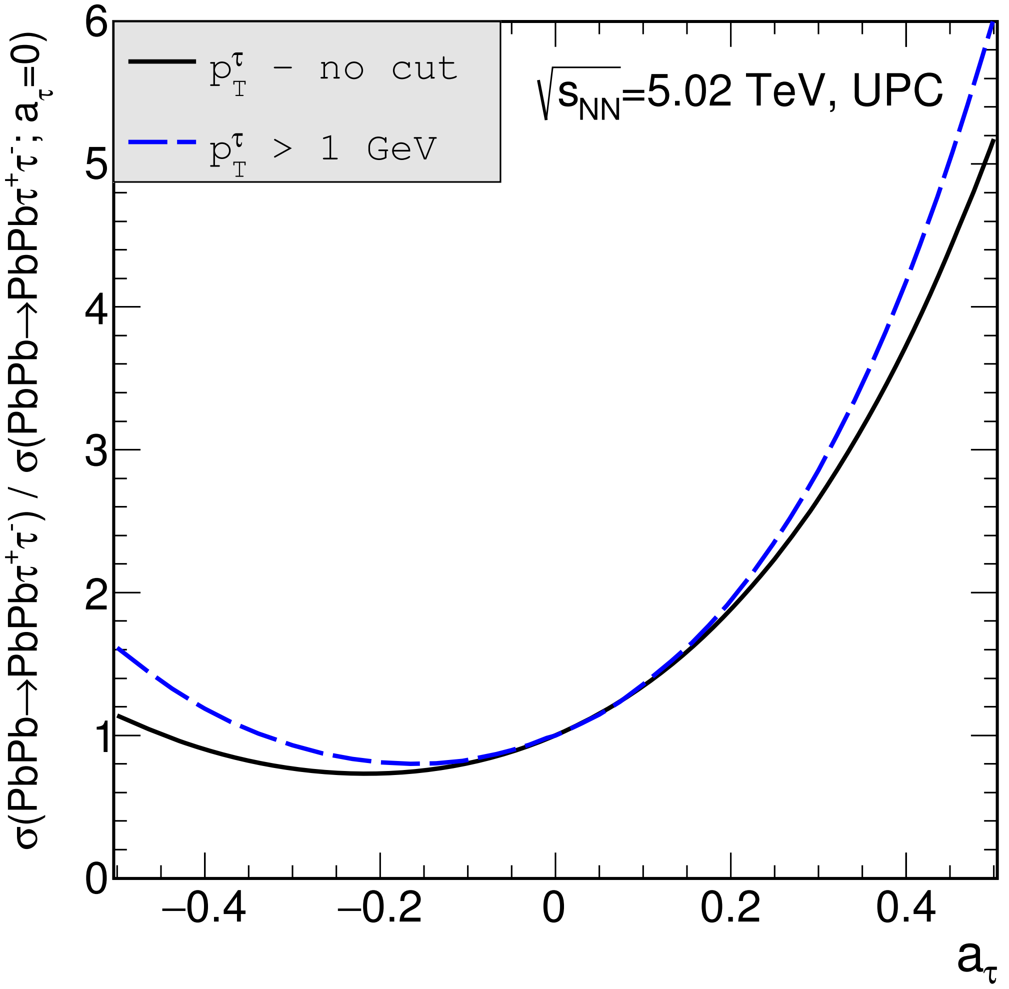
$$i\Gamma_\mu^{(\gamma\ell\ell)}(p', p) = -ie\left[\gamma_\mu F_1(q^2) + \frac{i}{2m_\ell}\sigma_{\mu\nu}q^\nu F_2(q^2) + \frac{1}{2m_\ell}\gamma^5\sigma_{\mu\nu}q^\nu F_3(q^2)\right],$$

In the $q^2 \to 0$ limit: $F_1(0) = 1$, $F_2(0) = a_\ell$ and $F_3(0) = \mathrm{d}_\ell 2m_\ell/e$

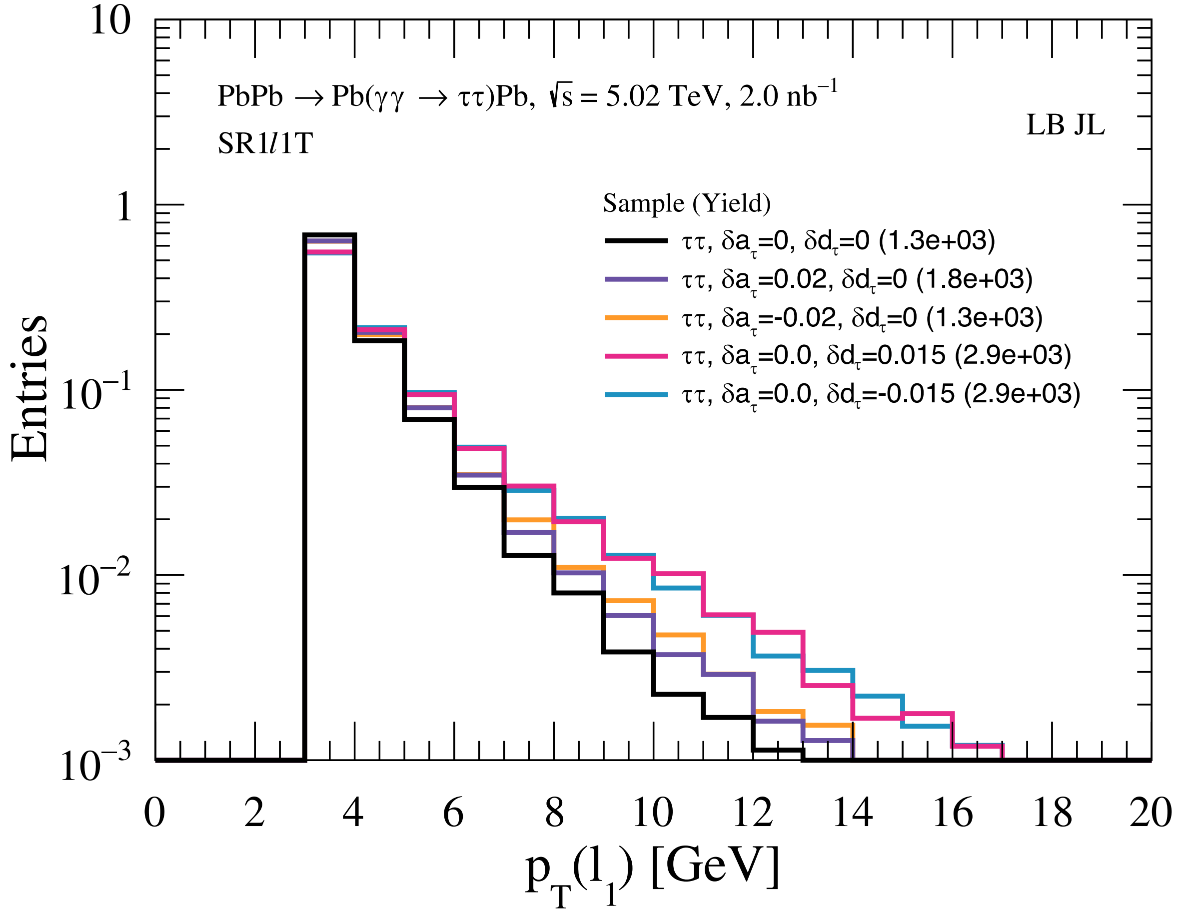
The photons from the ultraperipheral collisions (UPC) have small virtualities. They are almost on-shell photons and are in the $q^2 \to 0$ limit

Extracting a_τ

PLB 809 (2020) 135682



PRD 102, 113008 (2020)



Detectors

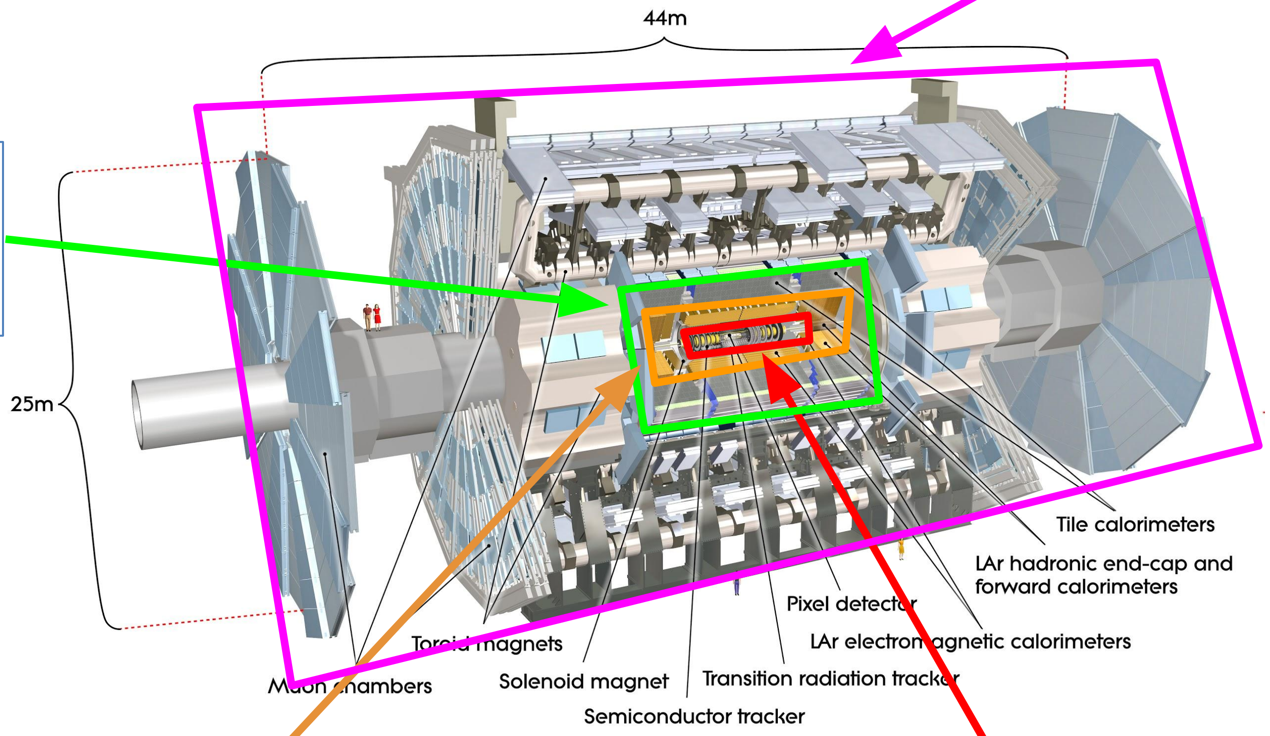
ATLAS Detector

ATLAS Collaboration：~3000

Muon spectrometer（|η|<2.7）

Weight: 7000 tons
Length: 44 meters
Height: 25 meters

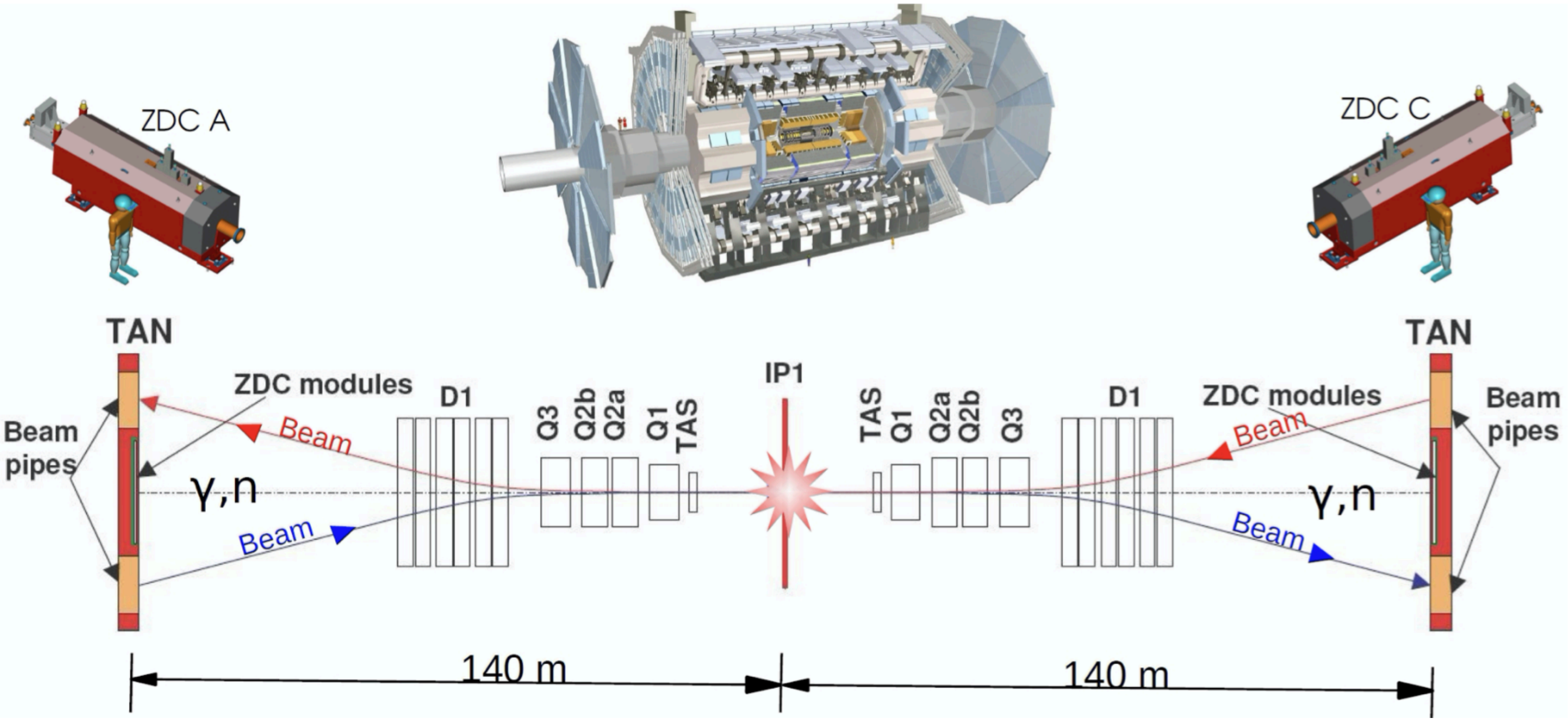
Hadronic Calorimeter（|η|<4.9）
Scintillator/Steel



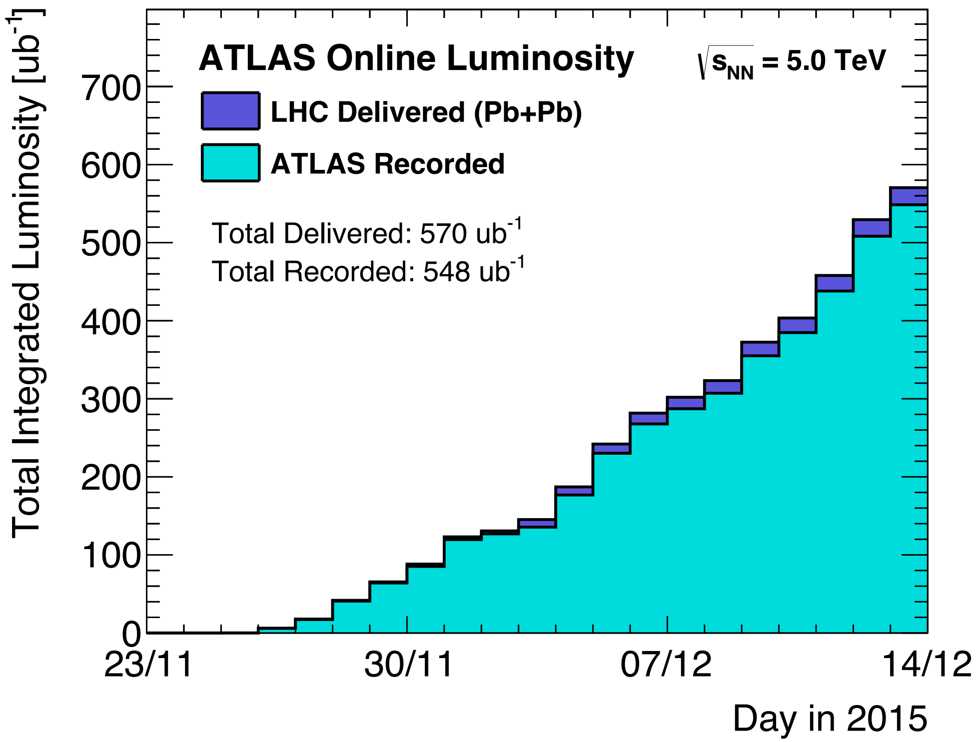
EM Calorimeter（|η|<3.2）
LAr/Pb

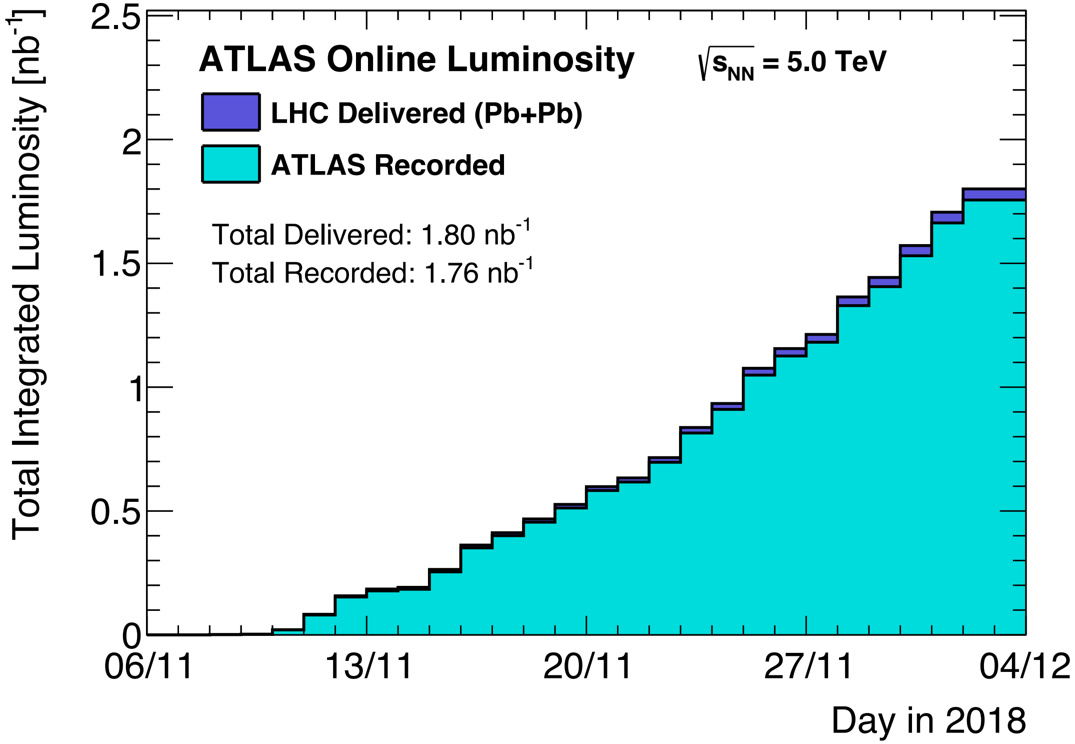
Inner Tracker（|η|<2.5）
2T Solenoid
Pixels, SCT and TRT

Zero Degree Calorimeter (ZDC)



PbPb data taking during LHC Run 2



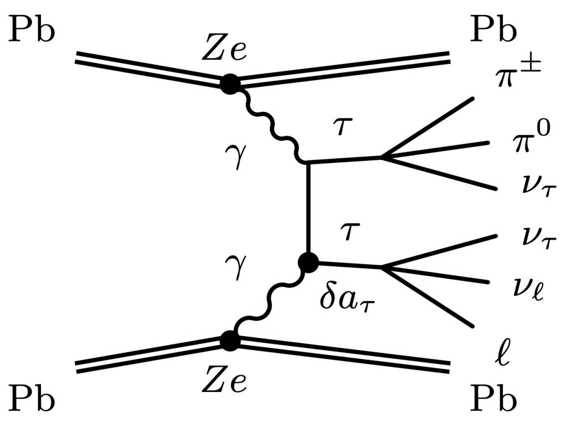


2015: 0.5 nb^{-1} used in physics

2018: 1.7 nb^{-1} used in physics

Analysis strategy

Decay mode		Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$	} ~ 35%		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$			17.4
$\tau^- \to h^- \nu_\tau$	} ~ 50%		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$		$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$		$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	} ~ 15%	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$			4.8
Other modes with hadrons			3.2
All modes containing hadrons			64.8



- Use 1.44 nb^{-1} ultraperipheral lead-lead collisions data collected in 2018
- Target the $\gamma\gamma \to \tau\tau$ events with one leptonic decay (as trigger) and one hadronic
- The p_T of τ in this analysis is low ($p_T^{vis} < 10$ GeV for most of τ)
- Use one track or three tracks to tag hadronic τ
- Fit to the lepton (e/μ) p_T to exact a_τ

Event selections

Trigger: $p_{\mathrm{T}}^{\mu} > 4$ GeV, MET < 50 GeV; $\sum E_{\mathrm{T}}^{\mathrm{FCAL}} < 3$ GeV on any side of FCal $(3.2 < |\eta| < 4.9)$

Offline event selections:

- Muon, $p_{\mathrm{T}}^{\mu} > 4$ GeV
- Electron, $p_{\mathrm{T}}^{e} > 4$ GeV
- Track, $p_{\mathrm{T}}^{\mathrm{trk}} > 100$ MeV

Event categorization

- Muon+1track
- Muon+3track
- Muon+electron

Data: 0n0n ZDC selection to suppress photonuclear/hadronic backgrounds

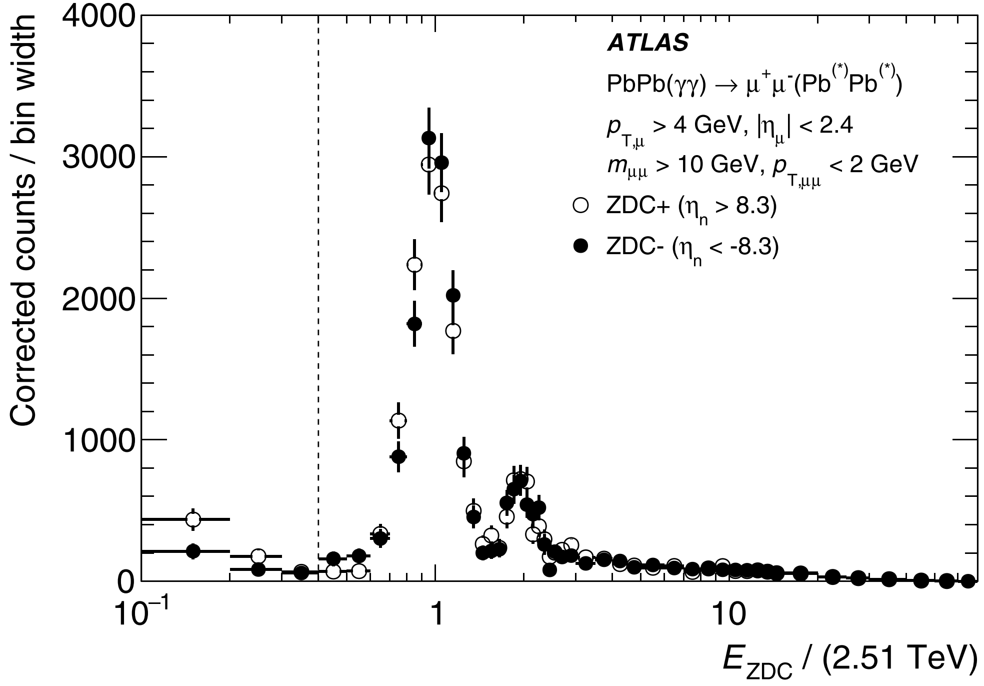
Simulation reweighted from 0n0n+0nXn+XnXn to 0n0n with data-driven weights

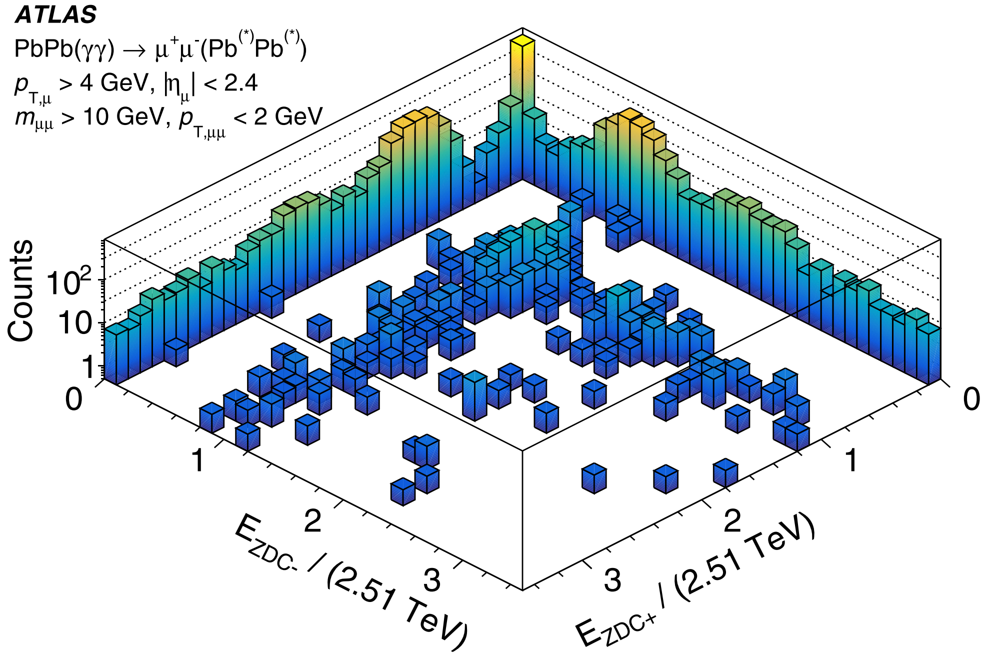
Veto additional clusters and tracks

$p_{\mathrm{T}}^{\mathrm{cluster}} > 1$ GeV $(|\eta| < 2.5)$;
$p_{\mathrm{T}}^{\mathrm{cluster}} > 100$ MeV $(2.5 < |\eta| < 4.5)$;

ZDC selections

PRC 104, 024906 (2021)



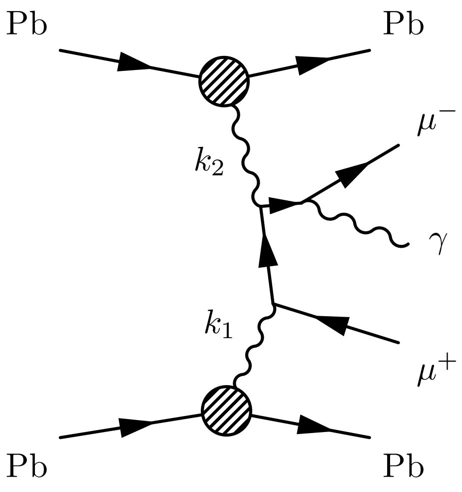


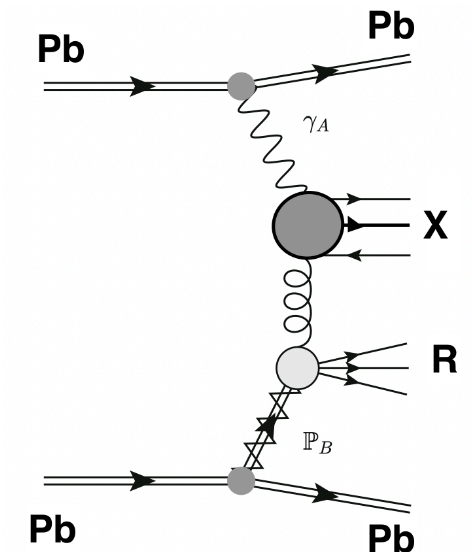
Distribution of ZDC energies in events selected in the fiducial region, normalized by the beam energy per-nucleon of 2.51 TeV

Signal and backgrounds

- Monte Carlo simulations:
  - Signal $\gamma\gamma \rightarrow \tau\tau$: Starlight+Tauola (Pythia8+Photos for QED FSR)
  - Background $\gamma\gamma \rightarrow \mu\mu$: Starlight+Pythia8
  - Background $\gamma\gamma \rightarrow \mu\mu(\gamma)$: Madgraph5 (reweighted to Pb+Pb photon flux)
  - All samples reweighted to photon flux from SuperChic3
- Data-driven estimation of diffractive photonuclear events

$\gamma\gamma \rightarrow \mu\mu(\gamma)$ events



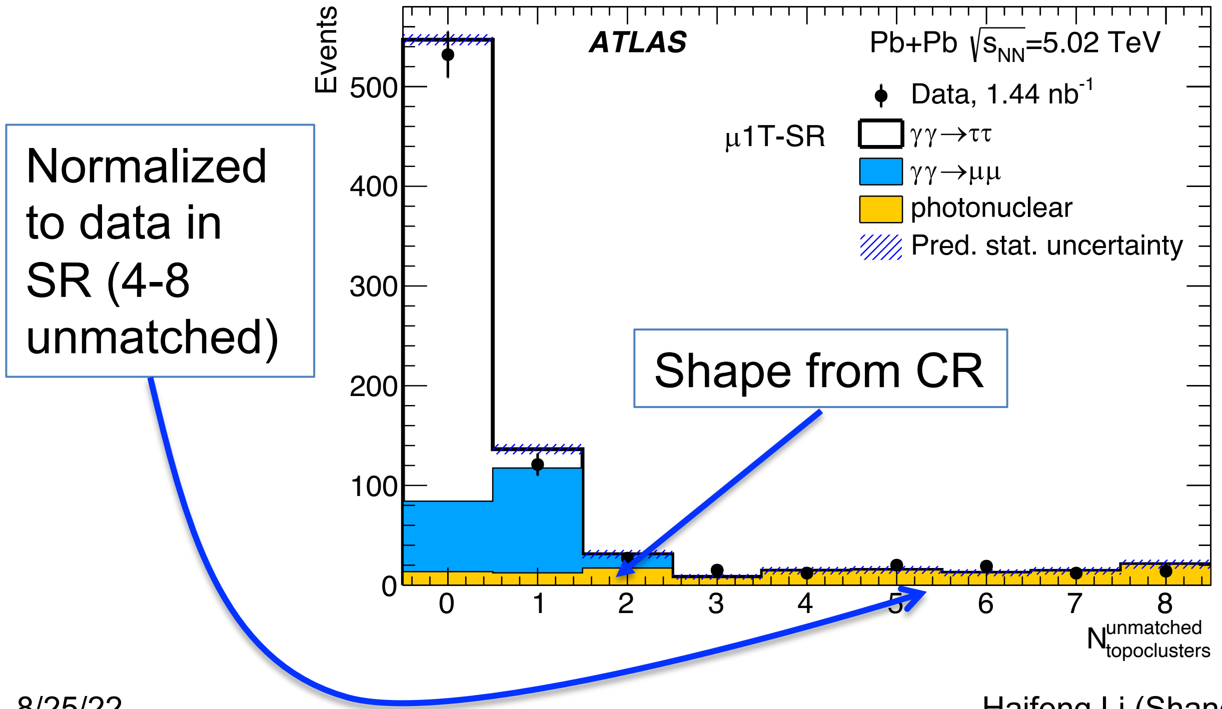


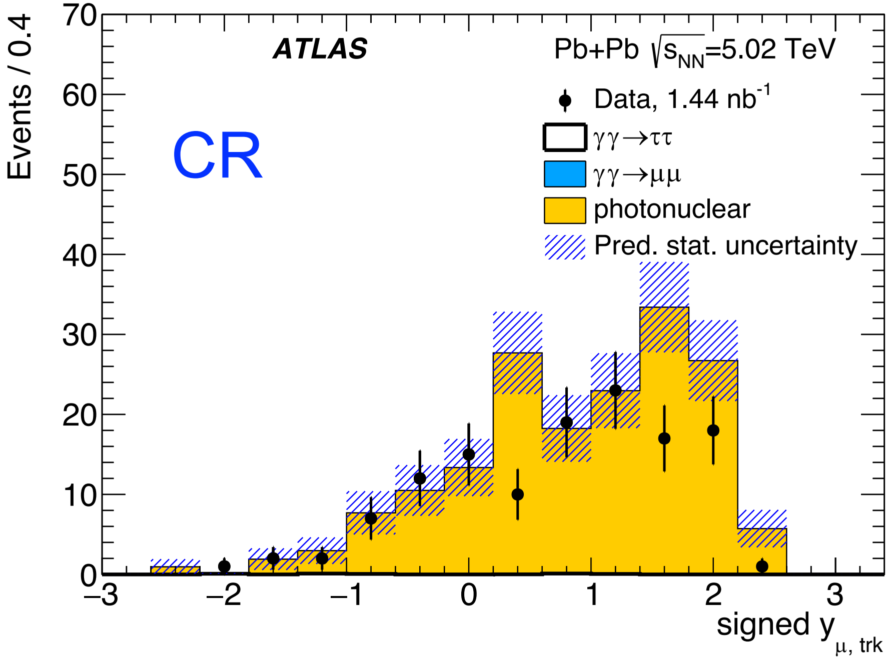
Diffractive photonuclear process

Photonuclear background

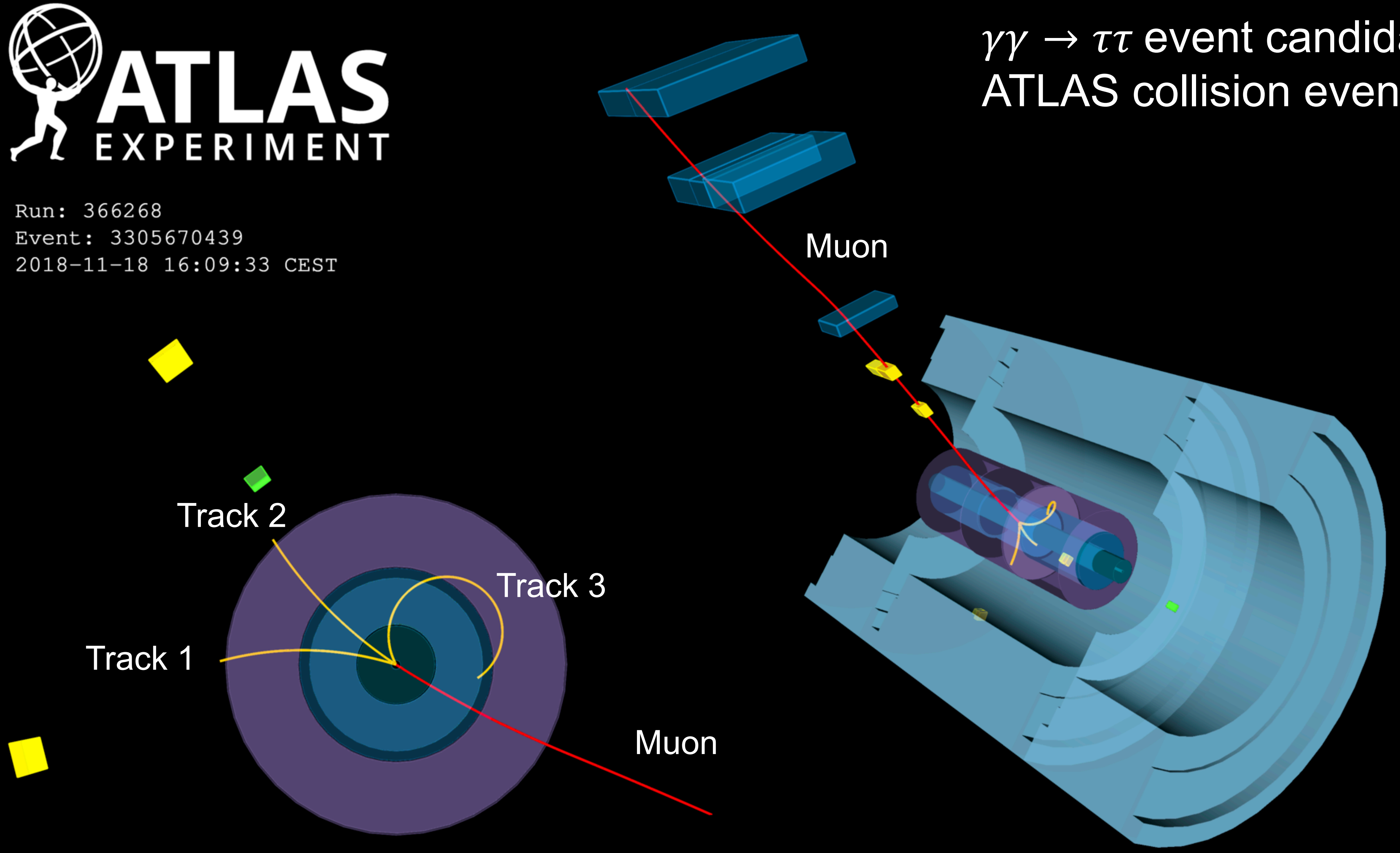
- Data-driven estimation of diffractive photonuclear events in μ+1track SR and μ +3track SR
- Templates built from control regions similar to SRs, but requiring an additional track with pT < 500 MeV and allowing 0nXn ZDC events
- Normalization: relax cluster veto. Use region with 4-8 unmatched clusters

arXiv:2204.13478



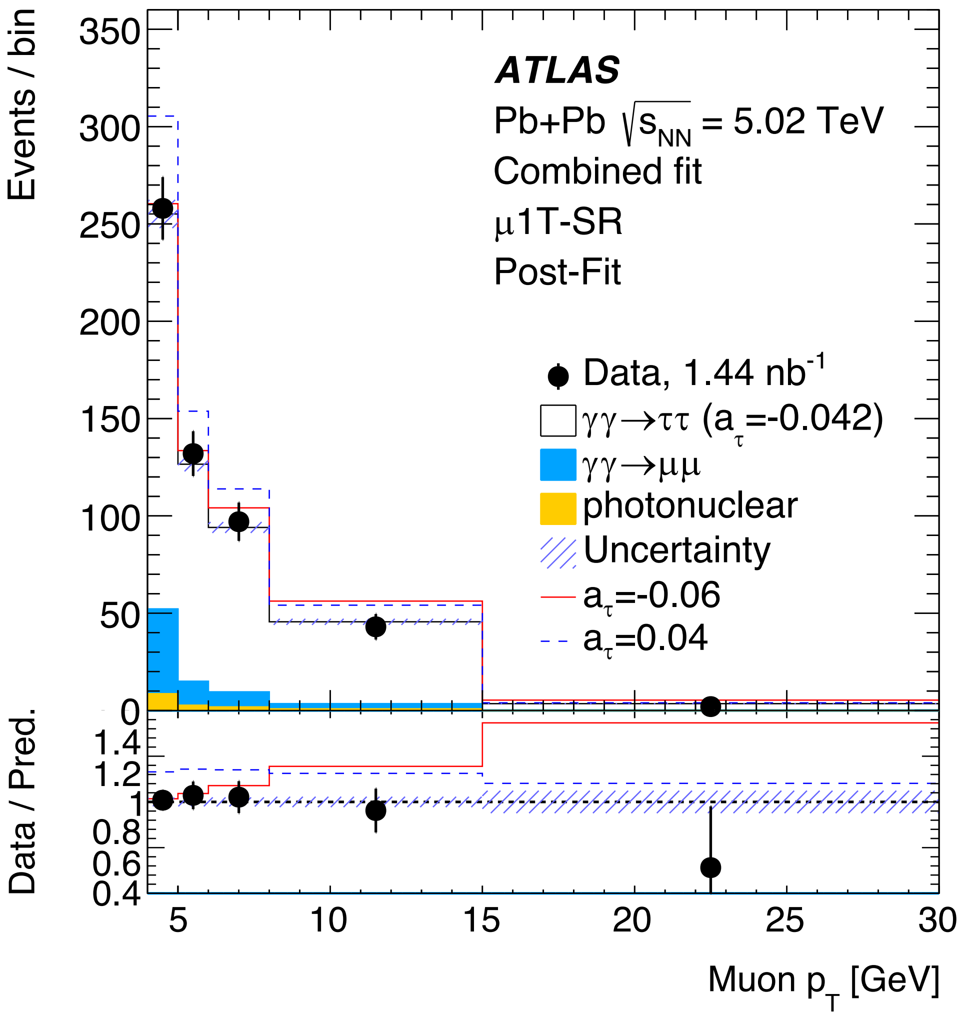


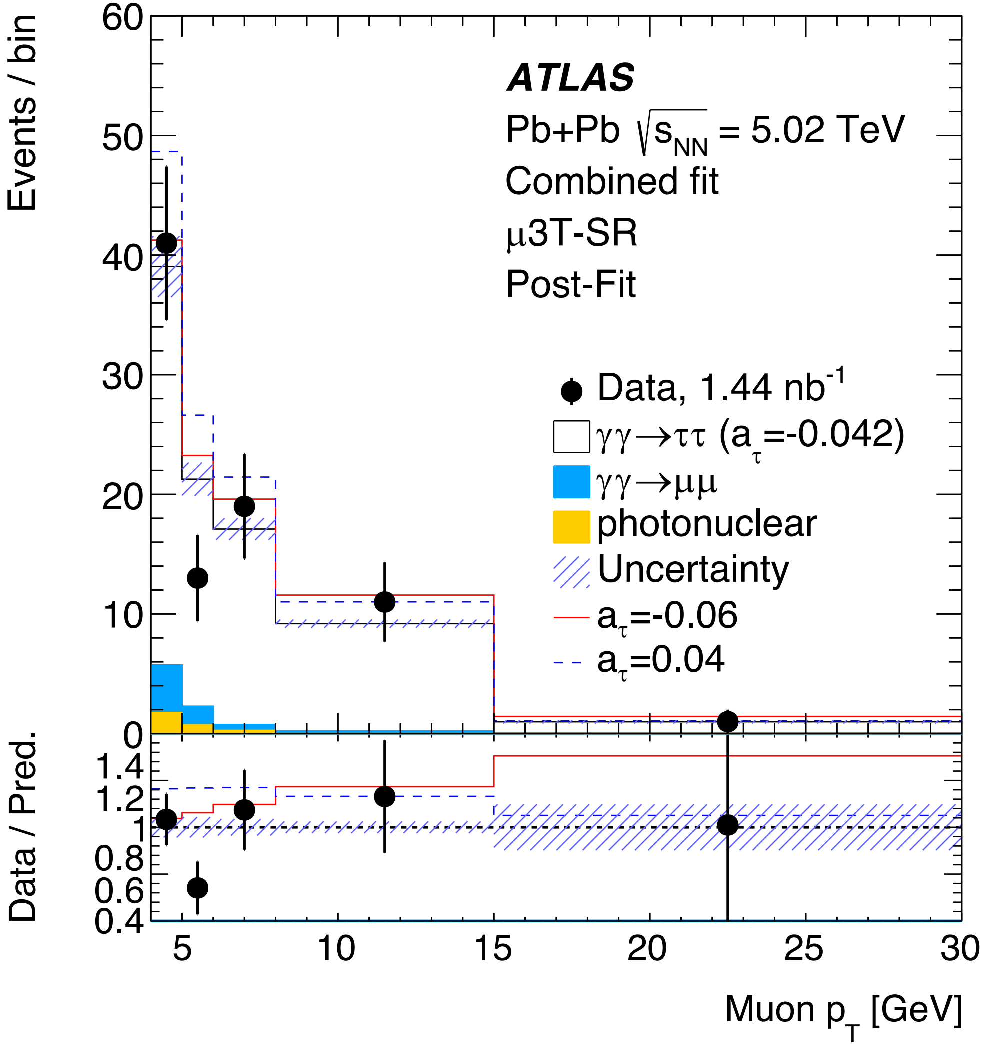
$\gamma\gamma \rightarrow \tau\tau$ event candidate
ATLAS collision event



Post-fit distributions

arXiv:2204.13478





Post-fit distributions

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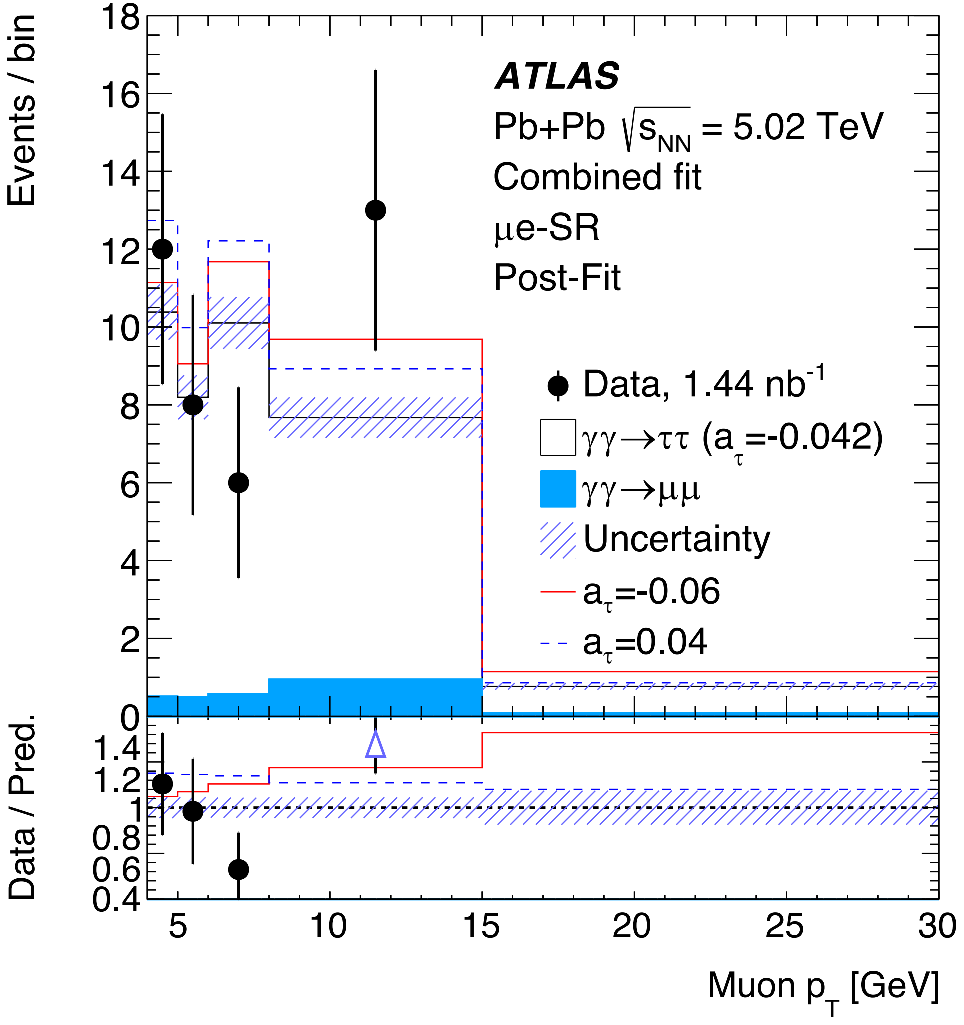
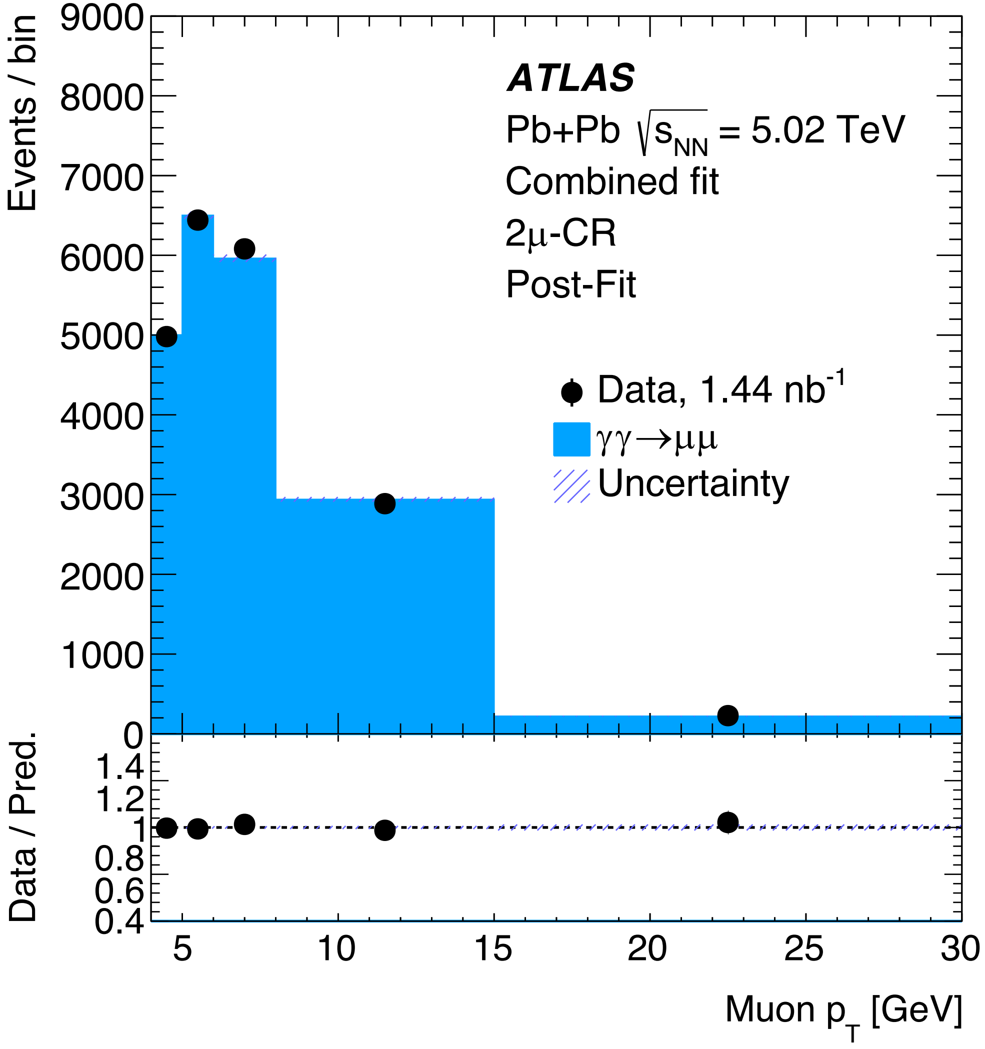
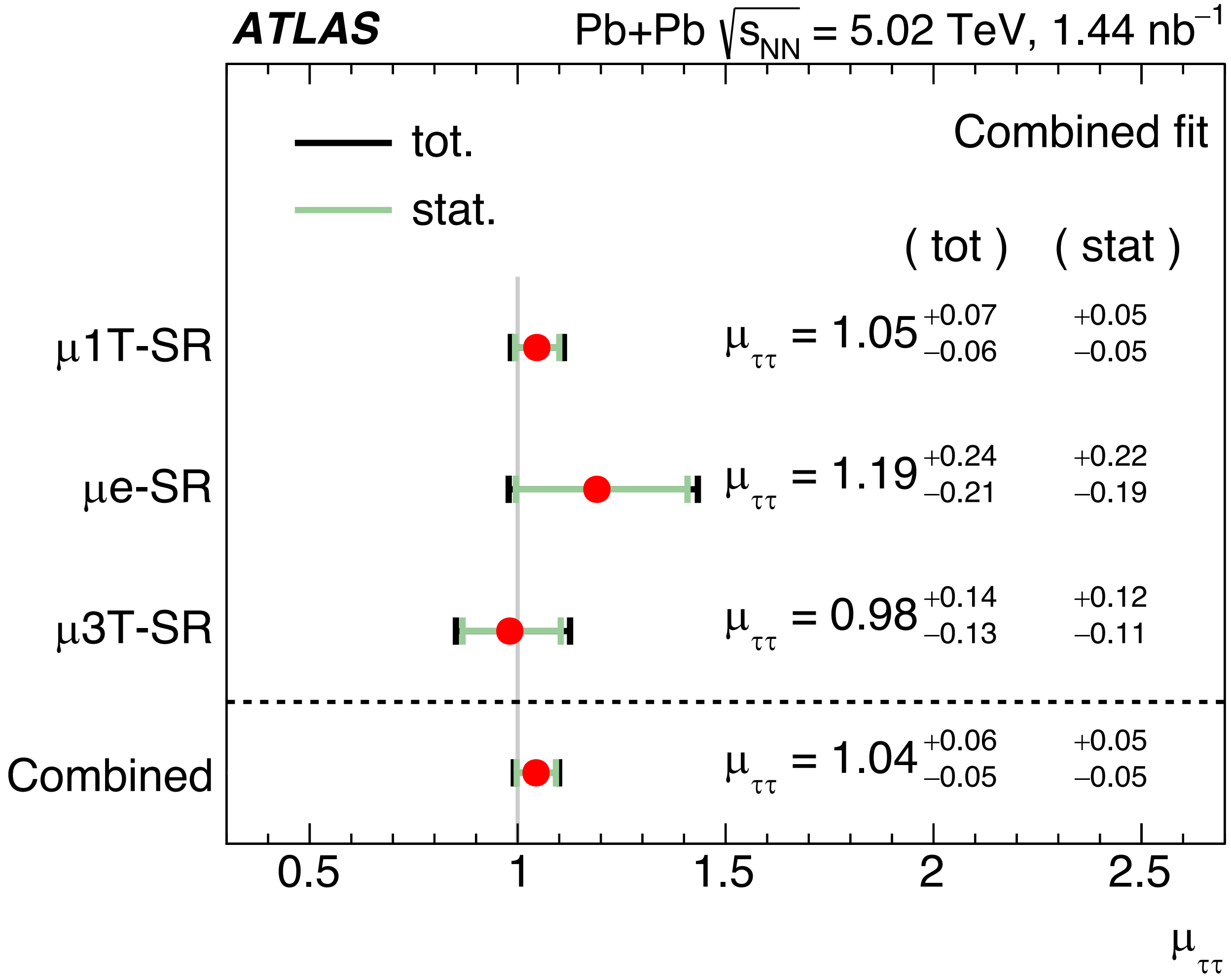




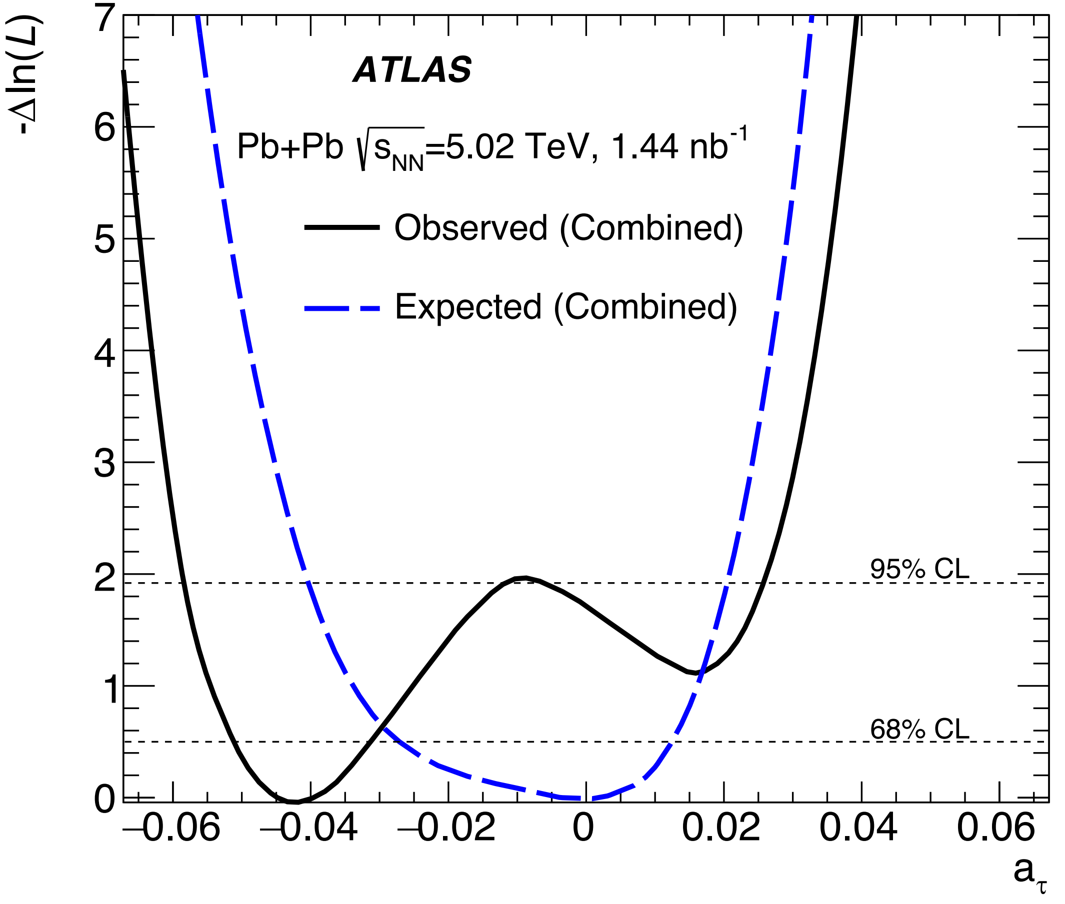
Results: $\gamma\gamma \rightarrow \tau\tau$ signal strength

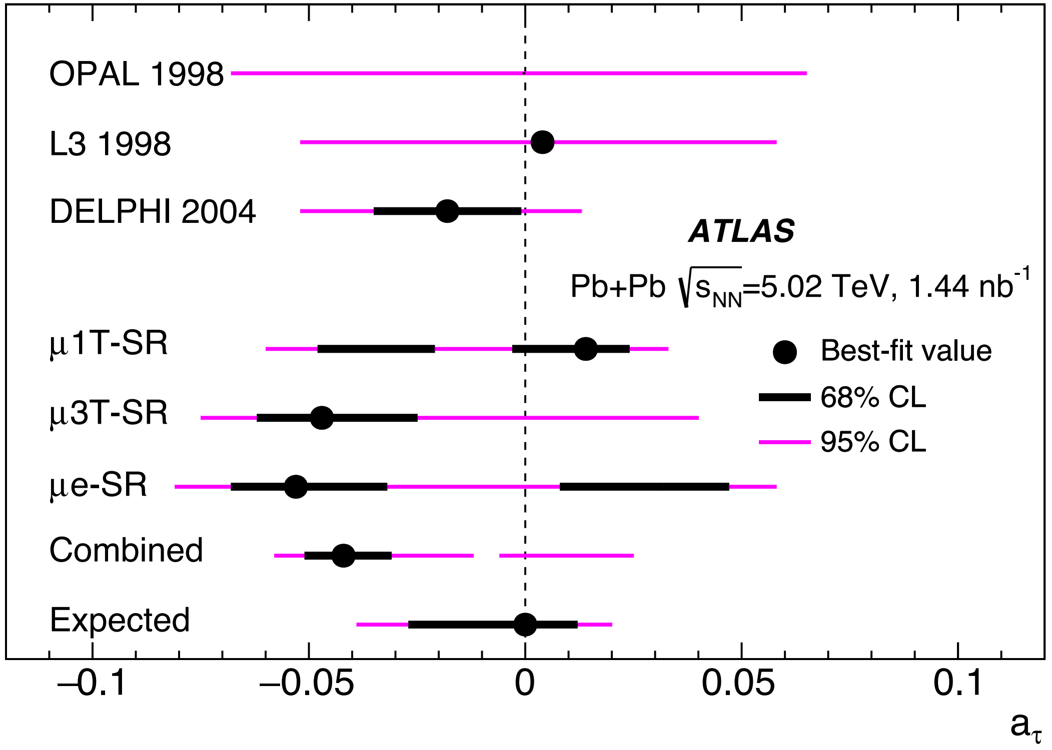
arXiv:2204.13478



Results: a_τ

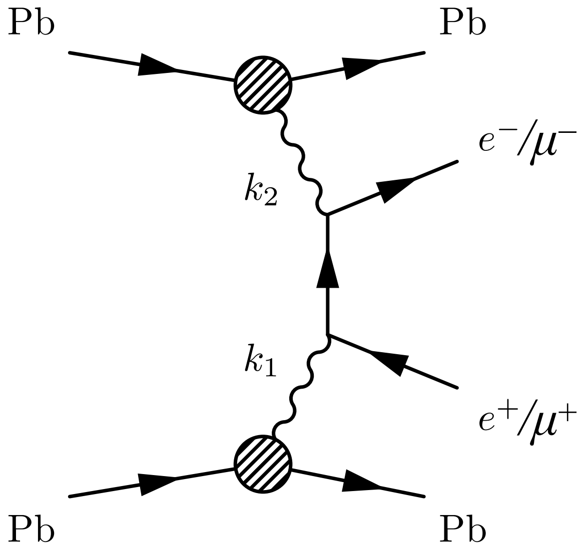
arXiv:2204.13478



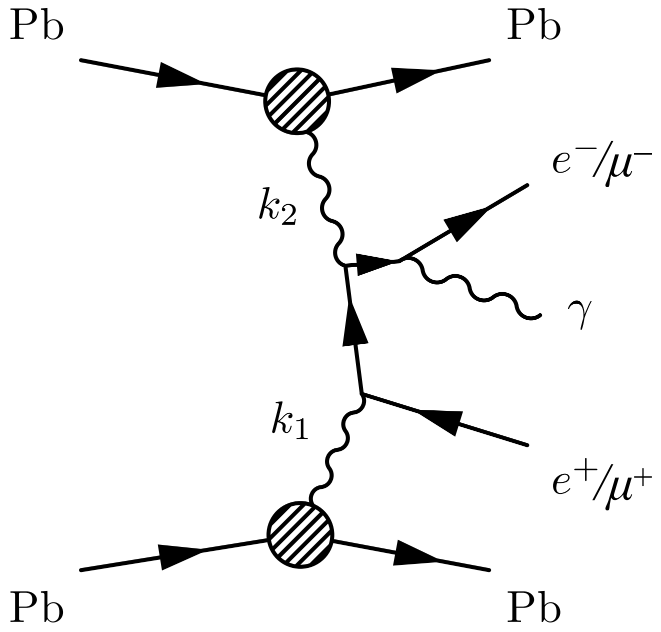


$\gamma\gamma \to \mu\mu/ee$

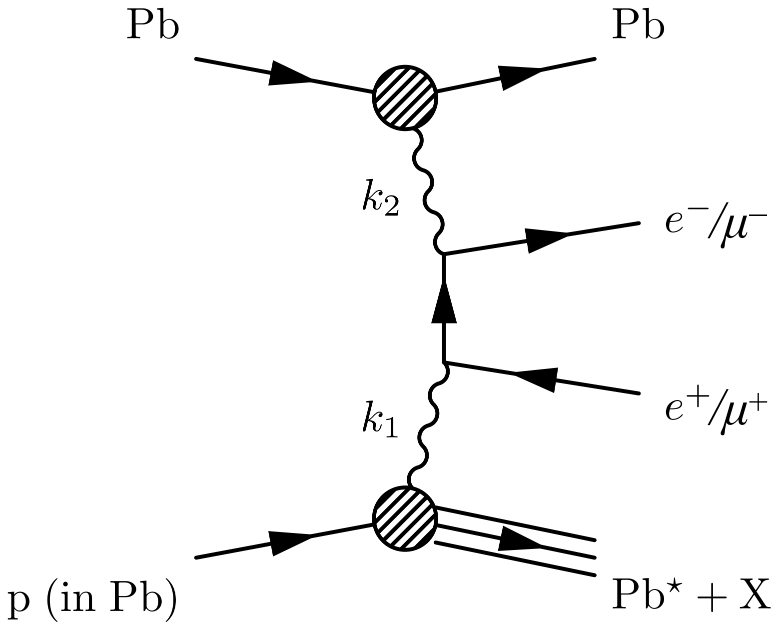
Signal and backgrounds for γγ→μμ/ee



Signal



Signal with FSR



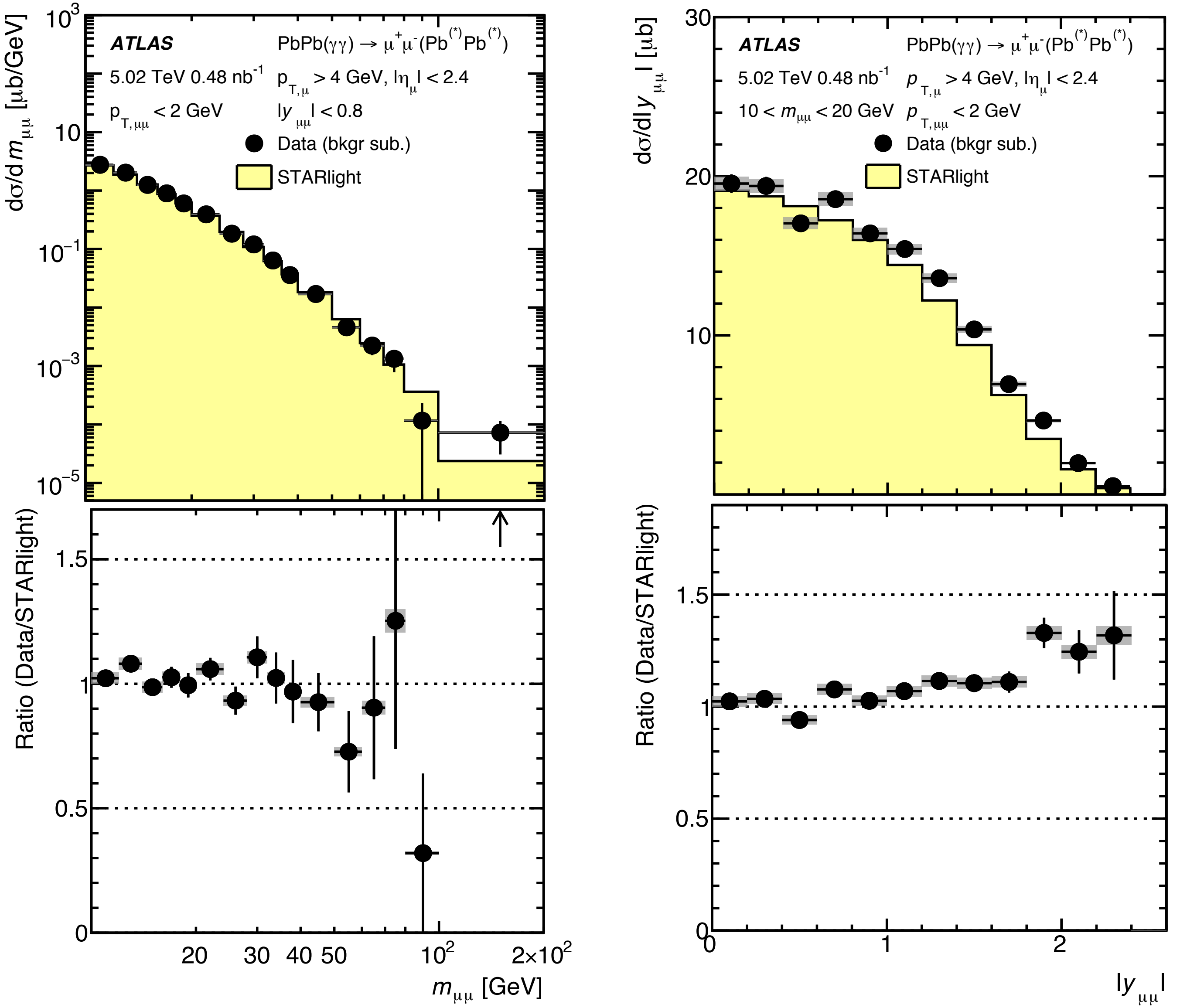
Dissociative backgrounds

- Dissociative backgrounds: estimated with data-driven method.
- Templates taken from LPair (μμ), SuperChic4+Pythia8 (ee)

γγ→μμ Results

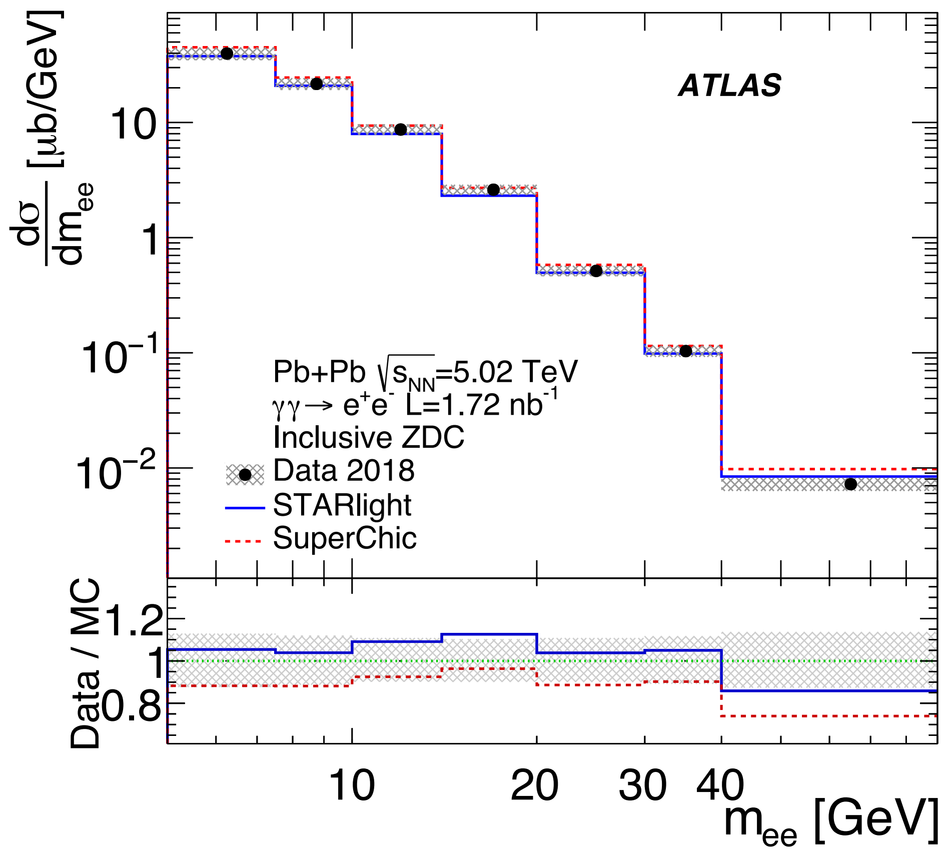
Phys. Rev. C 104 (2021) 024906

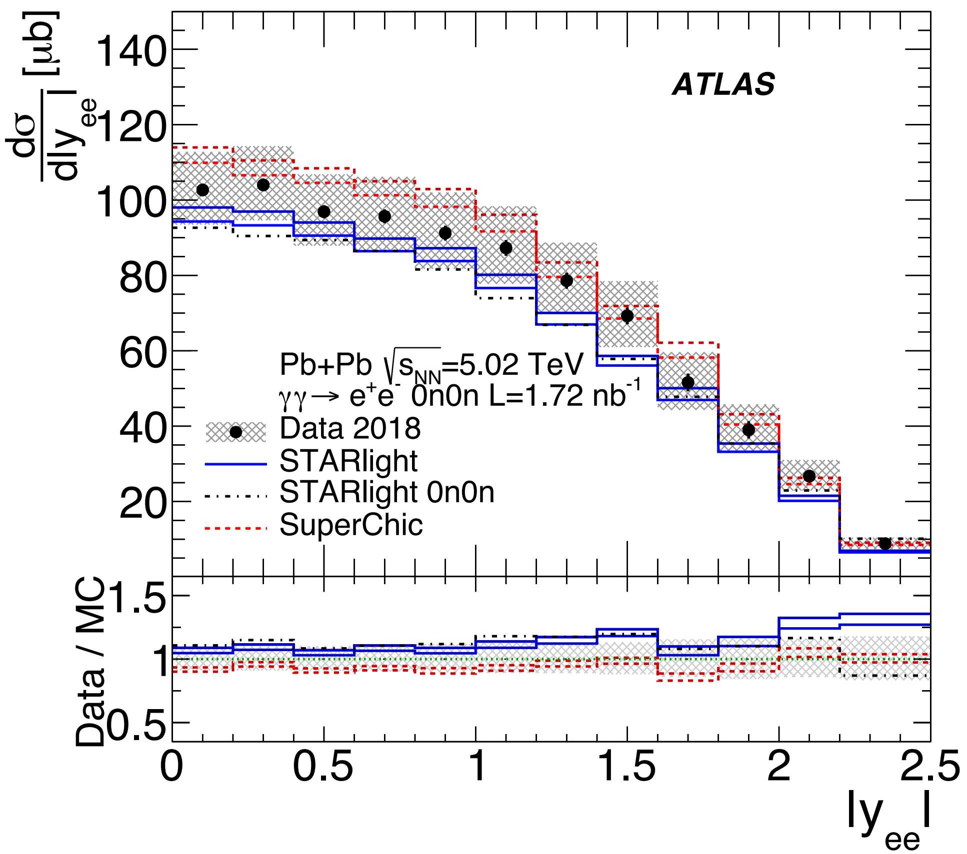
- The cross-sections are measured as a function of m$\mu\mu$ and |y$\mu\mu$|
- Data is compared with STARlight
- MC simulation of γγ → μ+μ- process w/o FSR



γγ→ee Results

arXiv:2207.12781





- Differential cross sections measured in m_{ee}, $|y_{ee}|$, $<p_T^e>$, $|\cos\theta*|$
- STARlight 3.13 (SuperChic 3.05) is systematically lower (higher) than data

$$\gamma\gamma \to \gamma\gamma$$

γγ→ γγ

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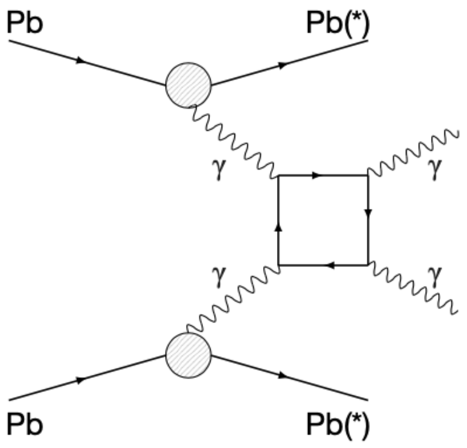

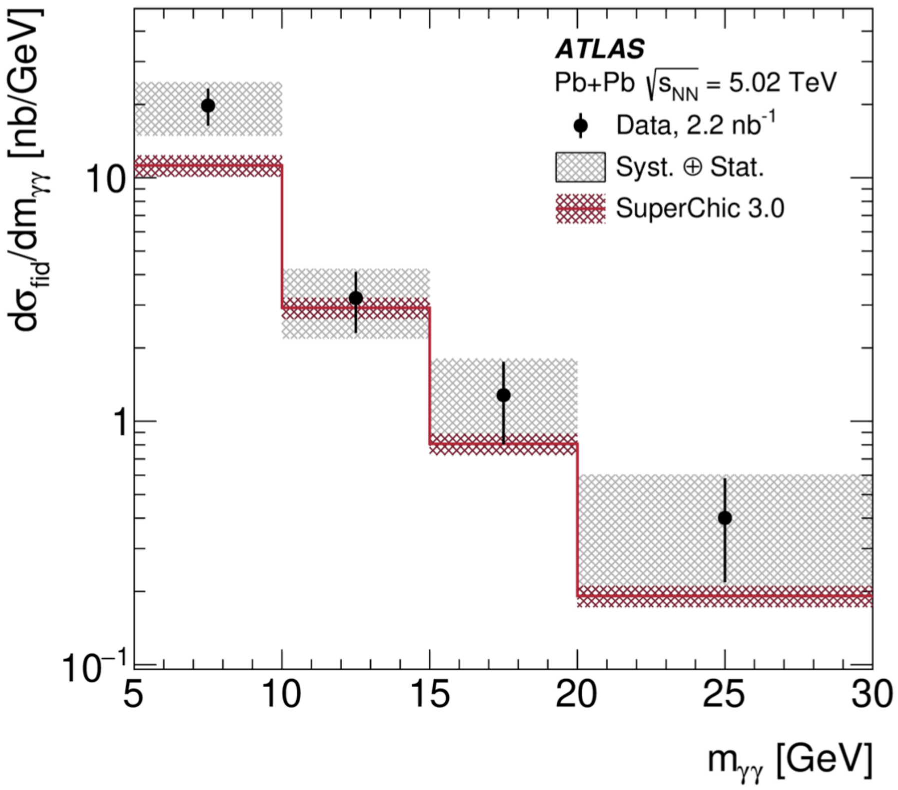

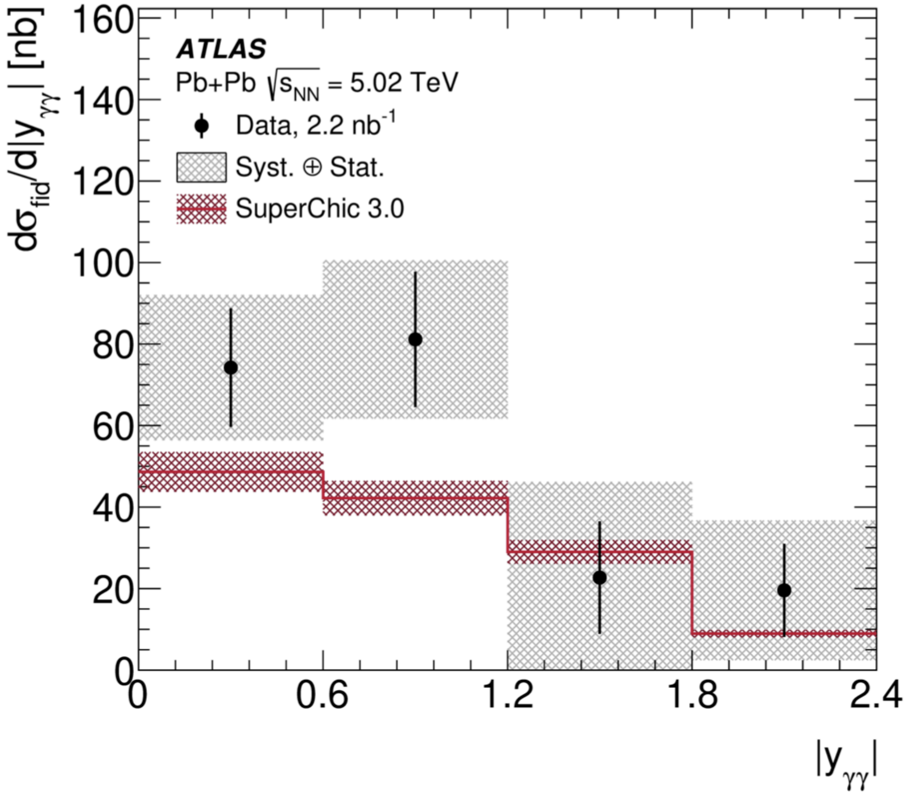

Fiducial cross sections are measured in E^{γ}_{T}> 2.5 GeV, $m_{\gamma\gamma}$ > 5 GeV, $|\eta_{\gamma}|$ < 2.4, $p_{T}^{\gamma\gamma}$ < 1 GeV

γγ→ γγ: search for axion-like particles

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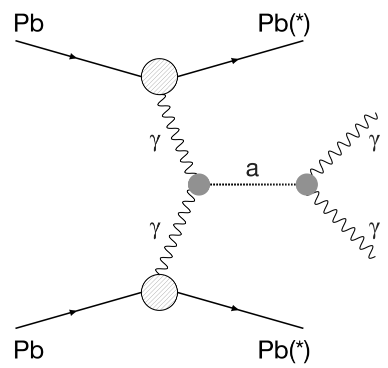
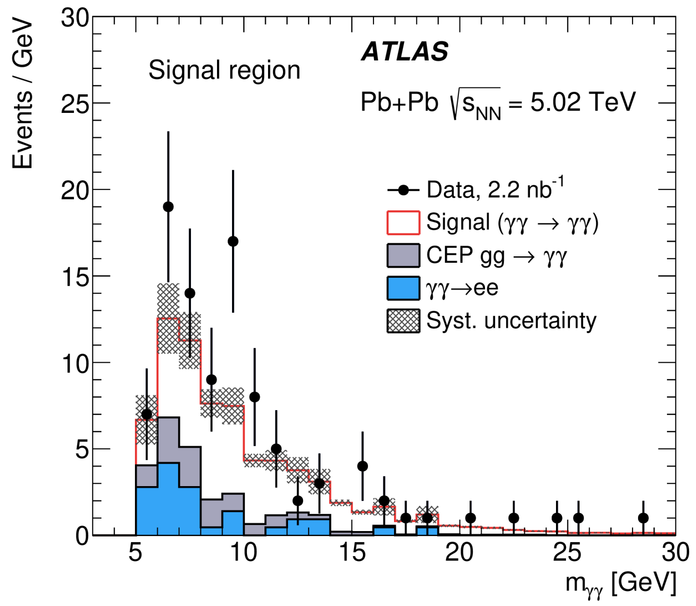
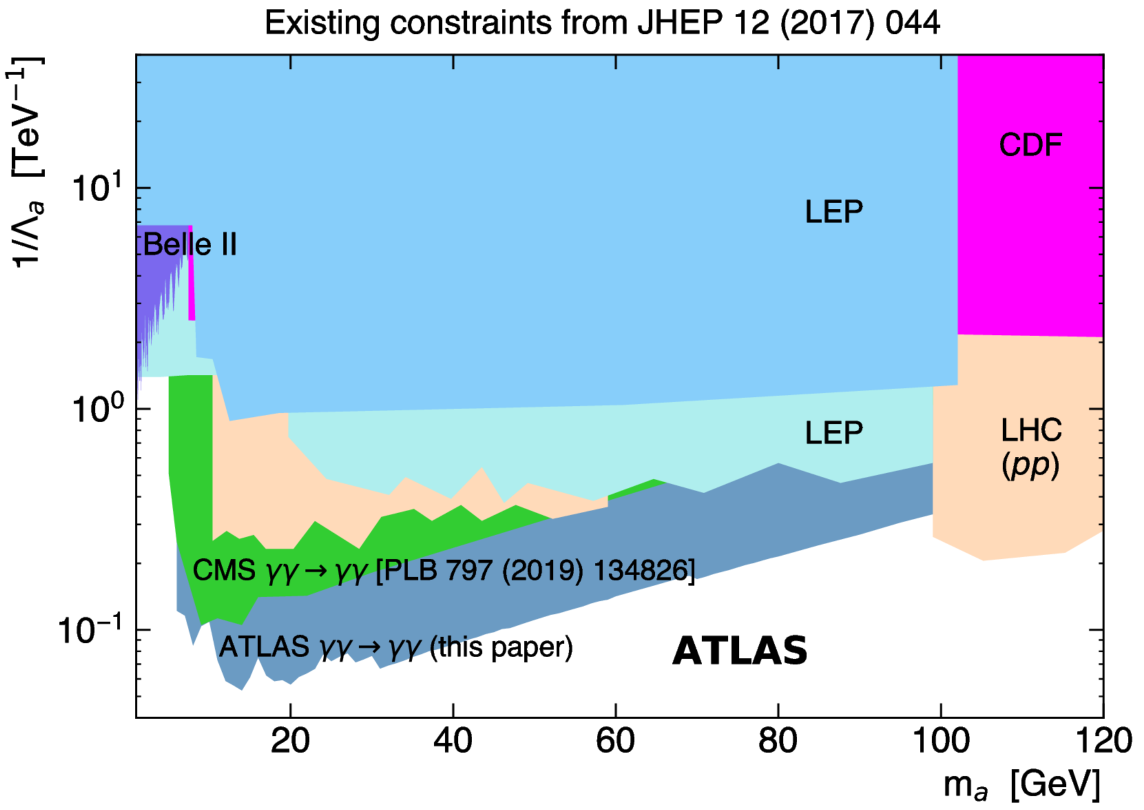
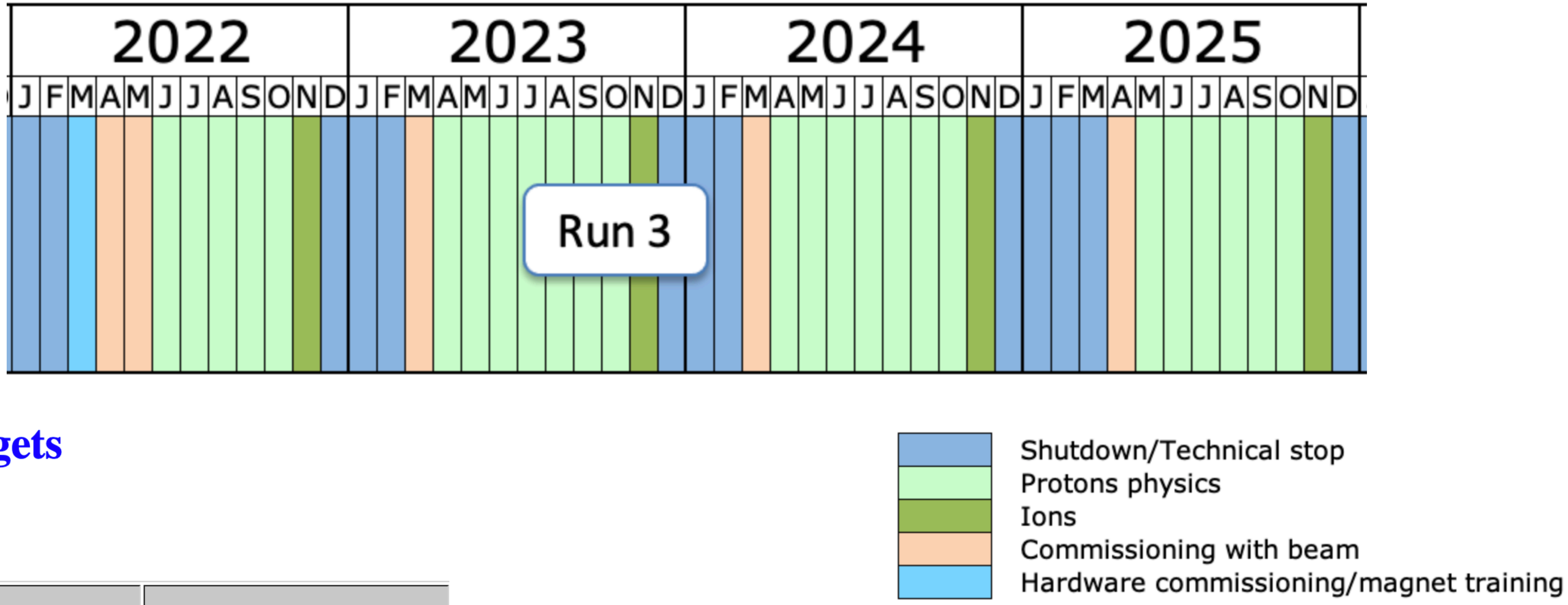






The most stringent limit established for ALP masses between 6-100 GeV

LHC Run 3 for PbPb



Run 3 luminosity targets

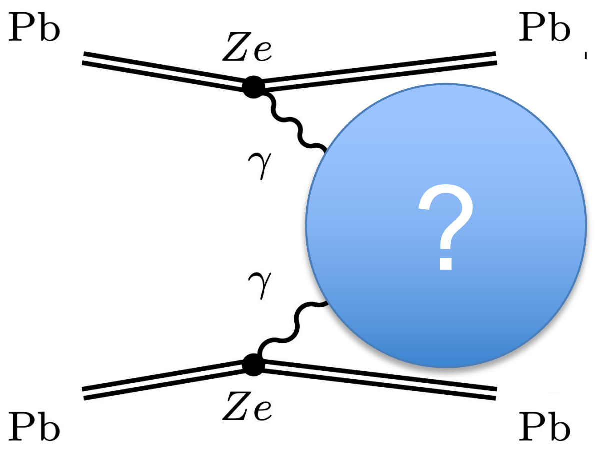
Indicative!

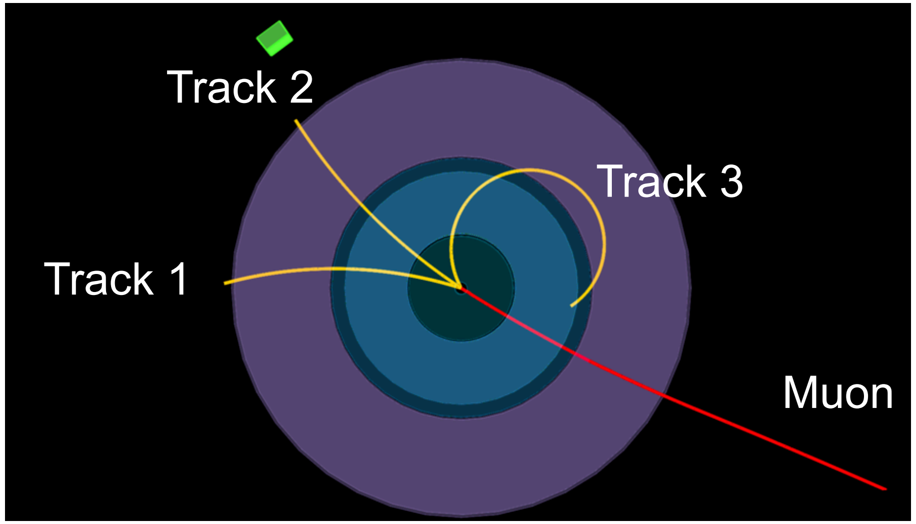
Mode	GPDs
p-p	250/fb
Pb-Pb	7/nb (13/nb by LS4)
p-Pb	0.5/pb (~1/pb by LS4)
O-O	0.5/nb
p-O	LHCf 1.5/nb

Expect to have 7 nb^{-1} for LHC Run 3 for PbPb data

Summary

- Observation of $\gamma\gamma \rightarrow \tau\tau$ in ultraperipheral lead-lead collisions from ATLAS, arXiv:2204.13478, accepted by PRL
- Set constraints on the τ anomalous magnetic moment
- UPC events are very clean and ideal for precision studies. Opening physics opportunities for QED studies at hadron collider
- Constraints on a_τ are competitive with LEP results. Will be improved with more data





- $\gamma\gamma \rightarrow ee$: arXiv:2207.12781, submitted to JHEP
- $\gamma\gamma \rightarrow \mu\mu$: Phys. Rev. C 104 (2021) 024906
- $\gamma\gamma \rightarrow \tau\tau$: arXiv:2204.13478, accepted by PRL
- $\gamma\gamma \rightarrow \gamma\gamma$: JHEP 03 (2021) 243

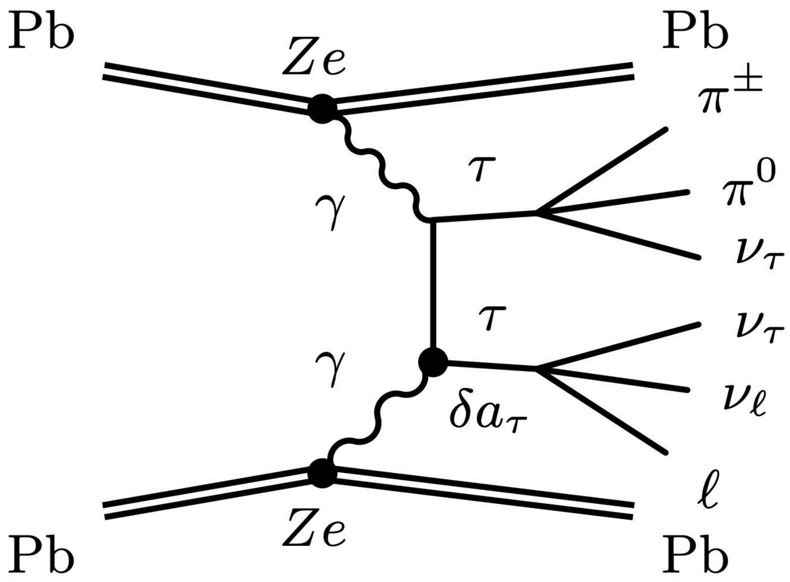
Backup

Measure τ g-2 at hadron collider

Proposed by Jesse Liu and Lydia Beresford Phys. Rev. D 102, 113008 (2020)

First proposed by: F. del Aguila, F. Cornet, and J. I. Illana, Phys. Lett. B 271, 256 (1991)

Measure the process of $\gamma\gamma \rightarrow \tau\tau$ in ultraperipheral lead-lead collisions



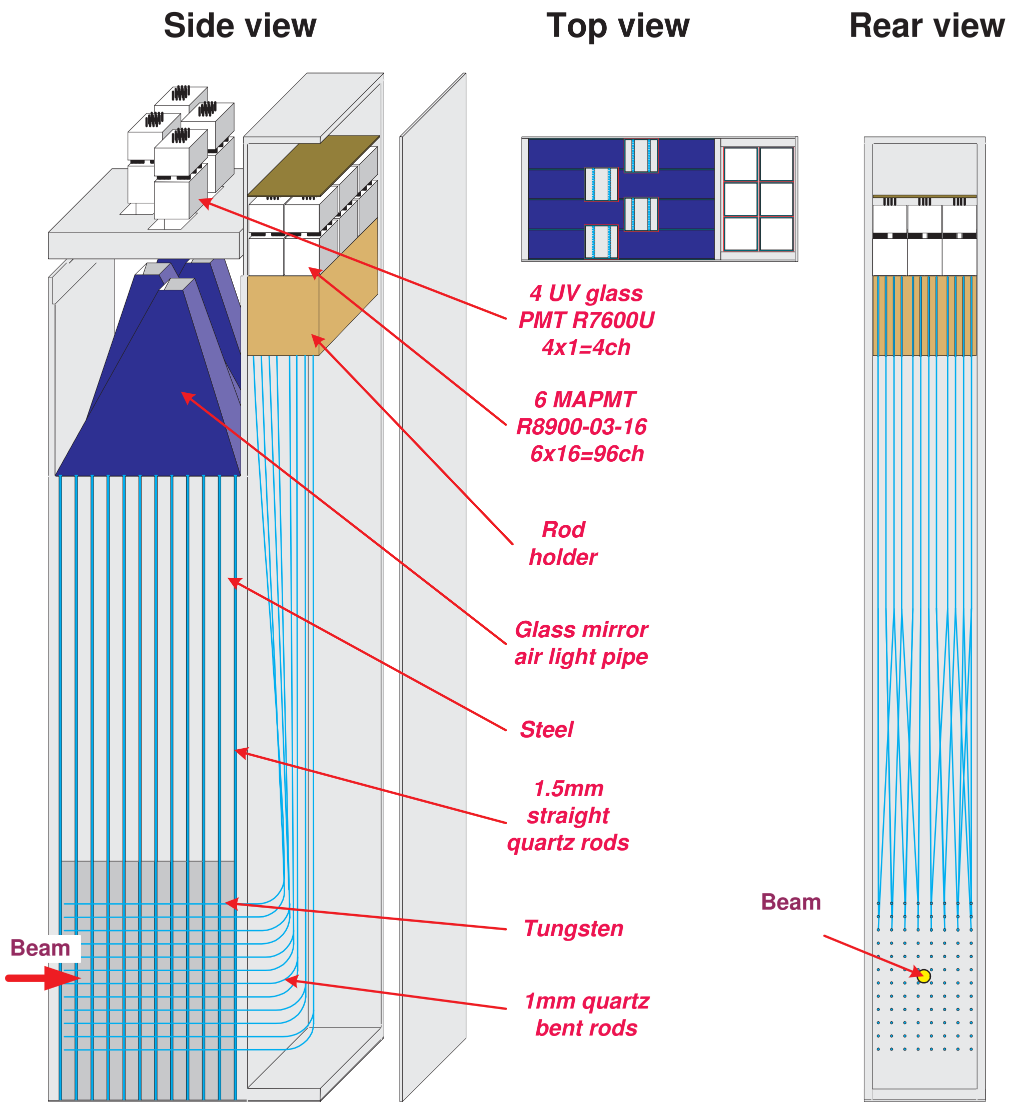
Cross section parameterization is also studied:

M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek, PLB 809 (2020) 135682

Zero Degree Calorimeter Module

LHCC/2007-001

- Beam impinges on tungsten plates at bottom of module, and showers.
- Quartz rods pick up Cerenkov light from the shower and pipe it to multi-anode phototube at top of module.
- Phototubes measure light from strips through four air light pipe funnels.



ZDC fractions

Observed fractions

Corrected fractions

$$\begin{bmatrix} f'_{0n0n} \\ f'_{\mathrm{X}n0n} \\ f'_{\mathrm{X}n\mathrm{X}n} \end{bmatrix} = \begin{bmatrix} (1-p_{\mathrm{S}})(1-p_{\mathrm{S}})(1-p_{\mathrm{M}}) & 0 & 0 \\ 2p_{\mathrm{S}}(1-p_{\mathrm{S}}-p_{\mathrm{M}}+p_{\mathrm{M}}p_{\mathrm{S}}/2) & (1-p_{\mathrm{S}})(1-p_{\mathrm{M}}) & 0 \\ p_{\mathrm{M}}+p_{\mathrm{S}}^2 & p_{\mathrm{M}}+p_{\mathrm{S}}-p_{\mathrm{M}}p_{\mathrm{S}} & 1 \end{bmatrix} \begin{bmatrix} f_{0n0n} \\ f_{\mathrm{X}n0n} \\ f_{\mathrm{X}n\mathrm{X}n}. \end{bmatrix}$$

- p_{S}: probability of single disassociation
- p_{M}: probability of mutual disassociation

EM pileup

Systematics