

# CMS results in photon physics (Using heavy ion collisions as QED & BSM laboratories)

# 1 Plenary + 11 parallel talks

**First(?) dedicated parallel session** for UPC in QM series

Discussing synergies between LHC and Electron Ion Collider

**How we ended up here?**

## Prospects for Run 2

- Vector mesons in Run 1 Pb-Pb@2.76 TeV:

Meson	Yield	$\mathcal{L}_{int}$	Error sources
$\rho_0$	$\sim 10^4$	$0.26 \mu\text{b}^{-1}$	stat error $\ll$ sys err
$J/\psi$ (mid-rapidity)	$\sim 500$	$23 \mu\text{b}^{-1}$	stat error $<$ sys err
$J/\psi$ (forward)	$\sim 100$	$55 \mu\text{b}^{-1}$	
$\psi(2S)$	$\sim 50$	$23 \mu\text{b}^{-1}$	stat error $\gg$ sys err

## Workshop in 2014

- Run 2 assumptions:

## Expectations $\rightarrow$

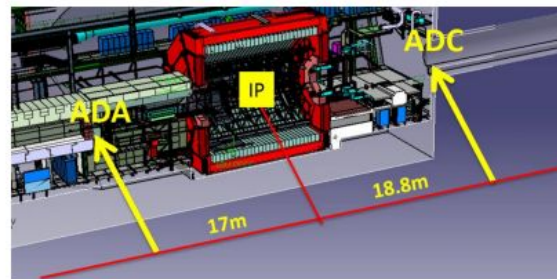
System	$\sqrt{s}$	$\mathcal{L}_{int}$	Increase factor in $\mathcal{L}_{int}$
Pb-Pb	5.1 TeV	$1 \text{ nb}^{-1}$	$\sim 7$
p-Pb	5.1 or 8 TeV	$50 \text{ nb}^{-1}$	$\sim 2$

- Precision measurements of  $J/\psi$ , study of  $\Upsilon$
- $\gamma\gamma \rightarrow \gamma\gamma$ : UPC probe to physics beyond SM

$\leftarrow$  **Wishlist (nonexhaustive)**

- New forward scintillators

- ▶ Two layers each, in coincidence
- ▶ ADA:  $5.5 < \eta < 7.5$
- ▶ ADC:  $-7.5 < \eta < -5.5$
- ▶ Stronger veto to non-UPC events thanks to better coverage compared to existing VZEROS



# Prospects for Run 2

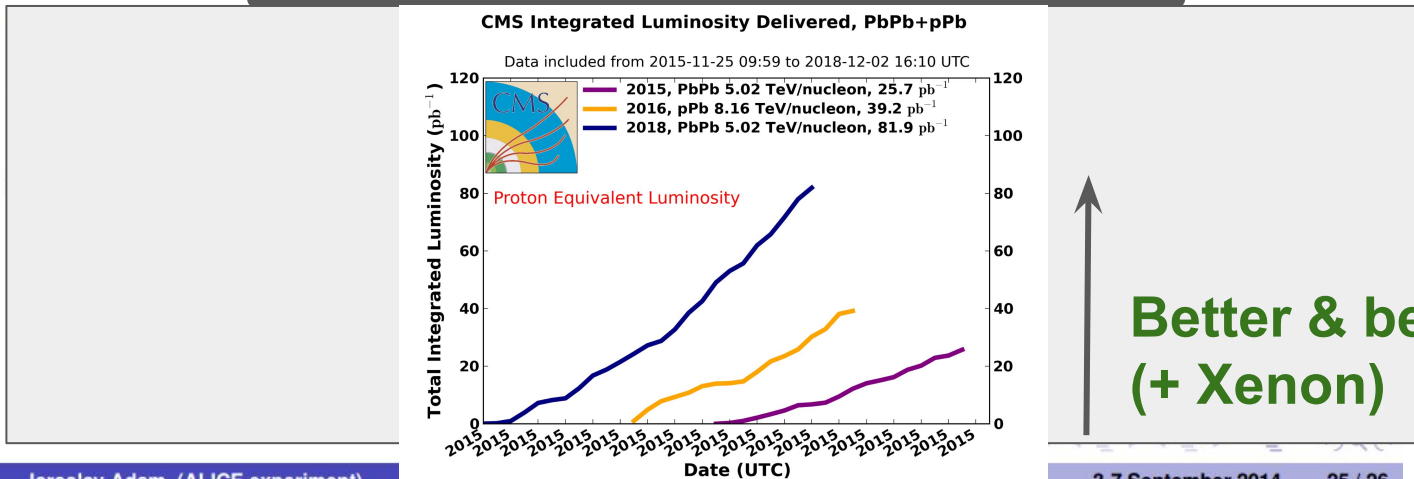
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**>  $\times 2$  at the end**

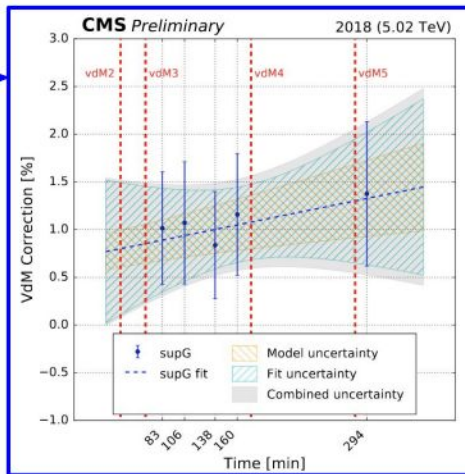




# Luminosity calibration: PbPb @ 5.02 TeV (2018 Nov)



Source	Correction [%]	Uncertainty [%]
Normalization		1.3
Transverse factorizability	+1.0	0.8
Ghost and satellite charge	+3.9	0.5
Length scale calibration	-1.5	0.5
Scan-to-scan variation	—	0.5
Cross-detector consistency	—	0.4
Beam-beam effects	—	0.3
Systematic orbit distortion	—	0.2
Beam current calibration	—	0.2
Noncollision rate	-0.6	0.2
Random orbit distortion	-0.1	0.1
Statistical uncertainty	—	0.1
Integration		0.8
Cross-detector stability	—	0.8
Noncollision rate	—	0.1



**Among most precise PbPb luminosity determinations**

Three systems with independent calibration:

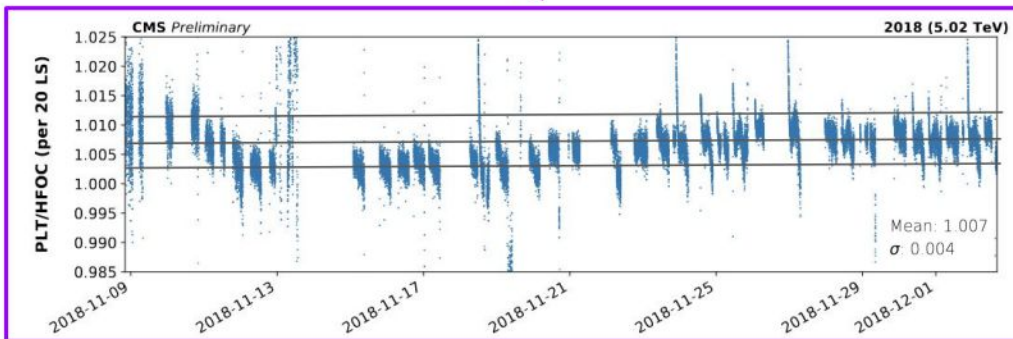
- Fast Beam Conditions Monitor (BCM1F)
- Forward Hadron Calorimeter (HFOC)
- Pixel Luminosity Telescope (PLT)

Stability monitored using emittance scans (short vdM-like scans)

**Total uncertainty: 1.5%**

[PAS-LUM-18-001](#)

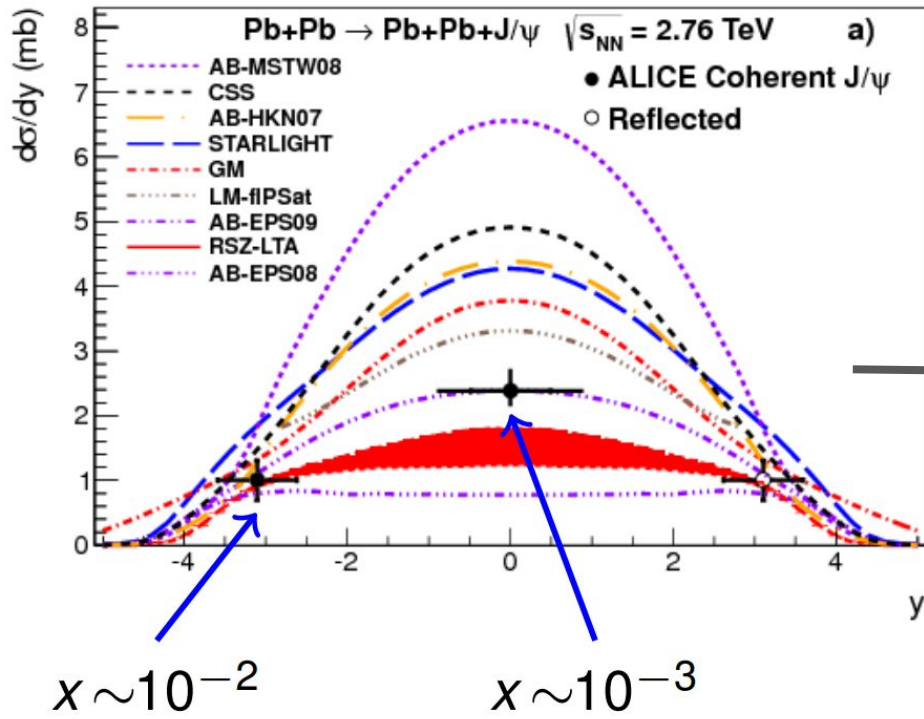
**150th LHCC Meeting**



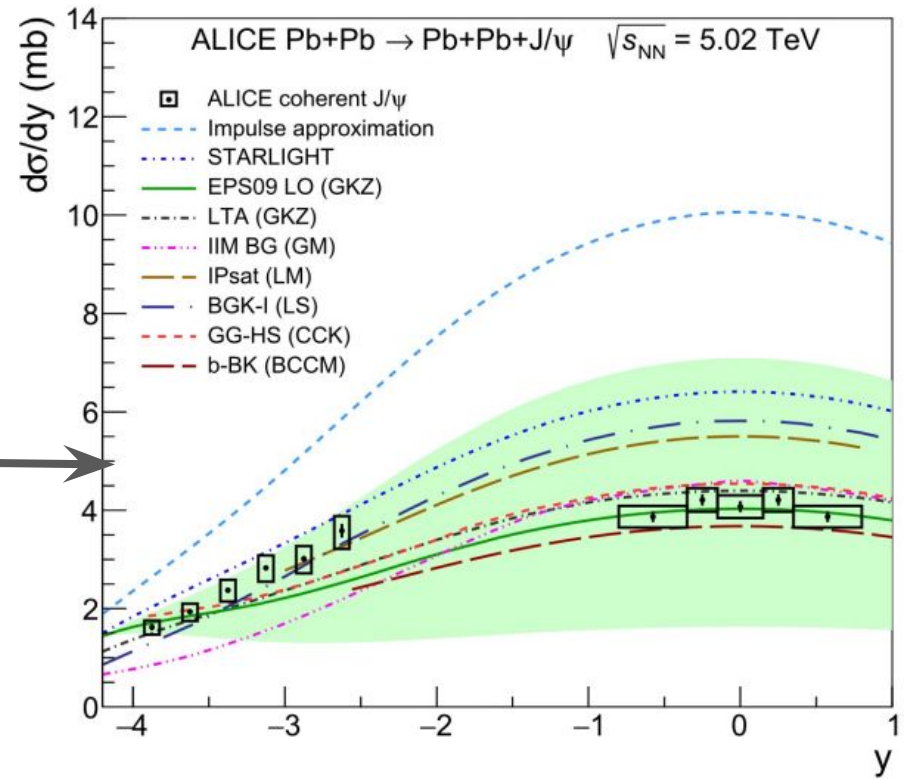


# State-of-the-art comparisons

WS in 2014



Today



ALICE: PLB 798 (2019) 134926

ALICE: EPJC (2021) 81:712

+ LHCb (2206.08221, not shown here)

# A novel solution: Neutron tagging

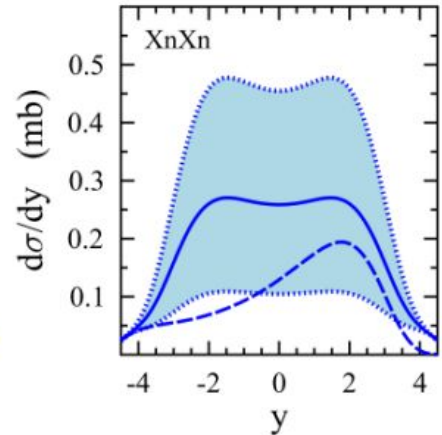
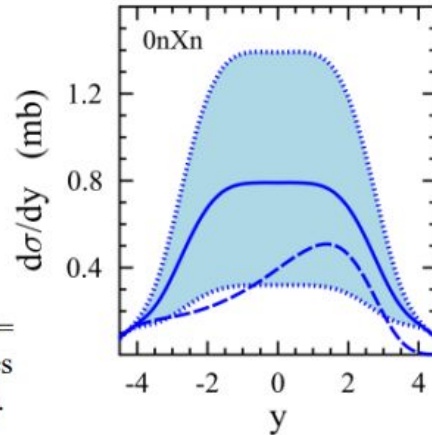
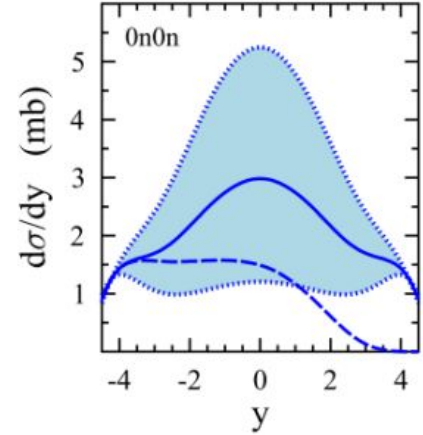
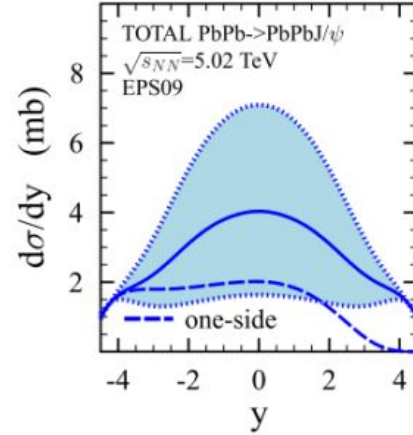
- Proposed by V. Guzey, M. Strikman, and M. Zhalov  
<https://arxiv.org/abs/1312.6486>
- High photon flux  $\rightarrow$  Additional ion excitation  $\rightarrow$  Emitting Neutrons
  - 0n0n: **No** neutron on both ZDC
  - 0nXn: At least **one** neutron on **one** ZDC
  - XnXn: At least **one** neutron on **both** ZDC

More on  
Jesus talk

$$y = \ln\left(\frac{2\omega}{M_{J/\psi}}\right)$$

Cross section as a function of the  $J/\psi$  rapidity  $y$  at  $\sqrt{s_{NN}} = 5.02$  TeV: areas show the uncertainties. The dashed curves labeled “one side” show the contribution of the first term.

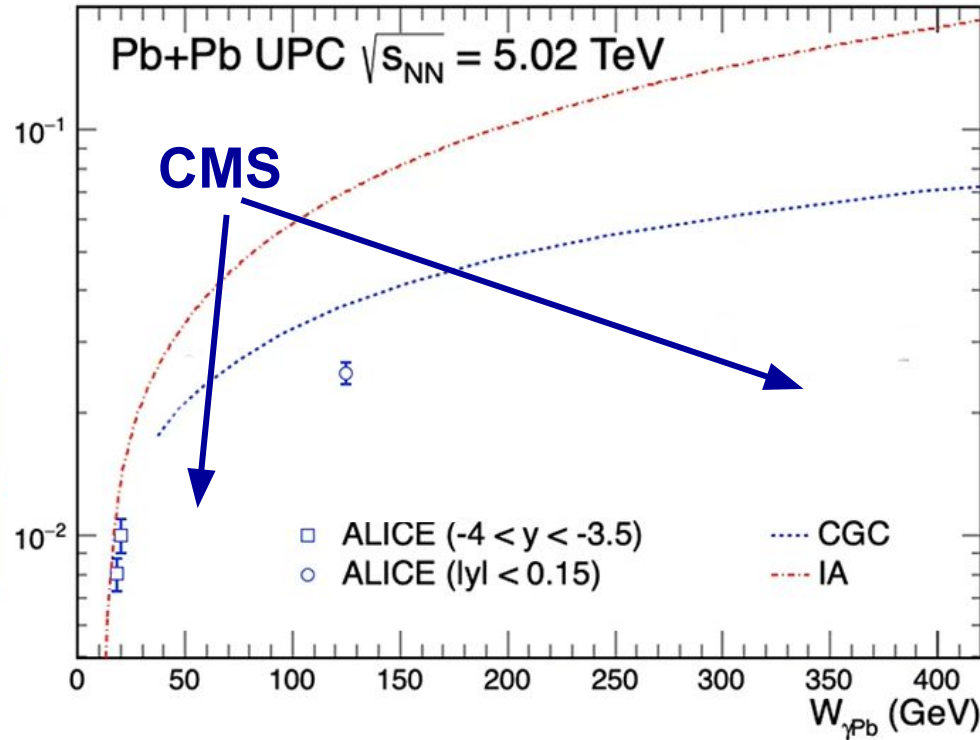
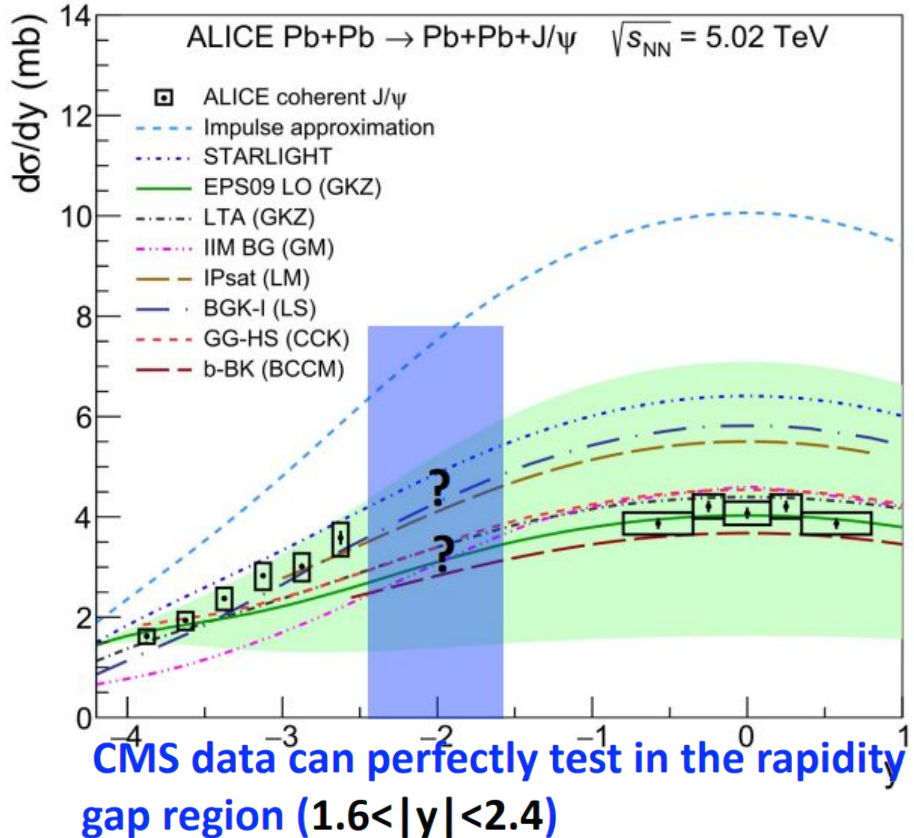
<https://journals.aps.org/prc/abstract/10.1103/PhysRevC.93.055206>





# More state-of-the-art comparisons coming..

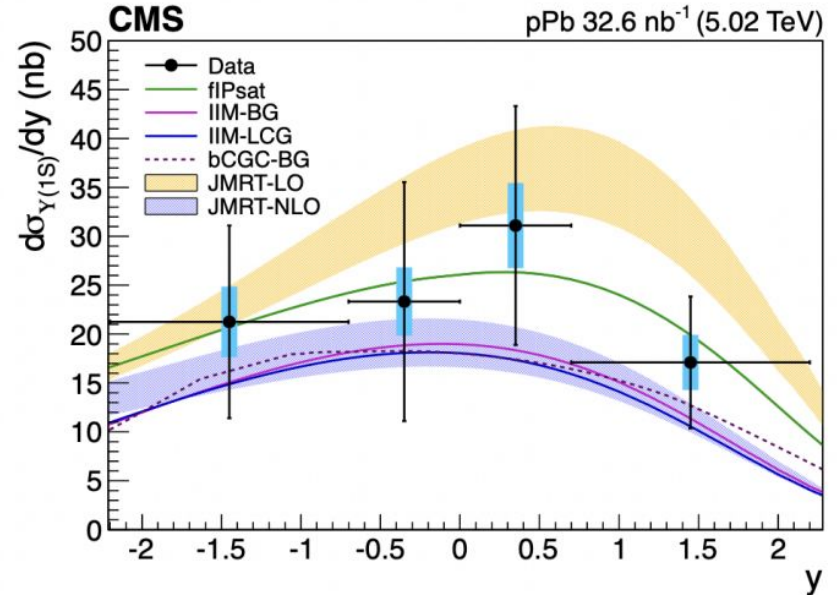
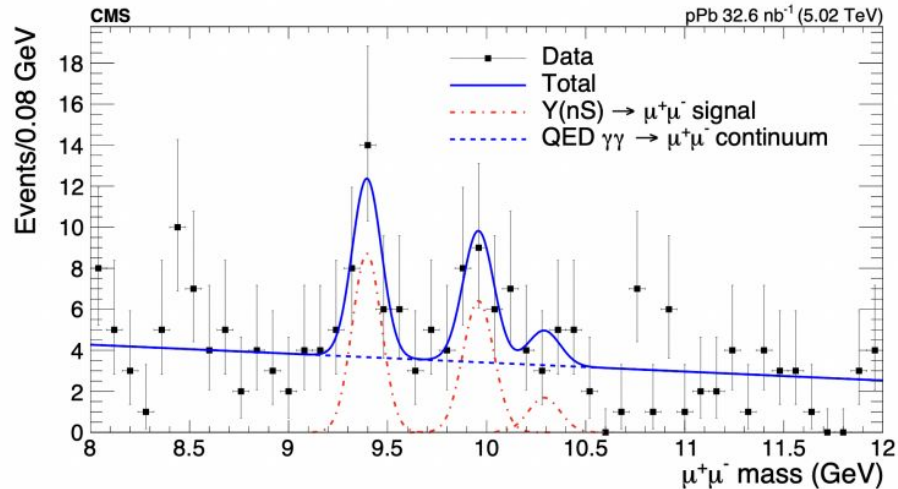
Hopefully in some next workshop ;D



# Upsilon photo-production in UPC p+Pb

CMS, EPJC 79 (2019) 277

- Exclusive Upsilon(nS) measured by CMS in  $\gamma p$  collisions



# Upsilon photo-production in PC p+Pb

CMS, EPJC 79 (2019) 277

- Exclusive  $\Upsilon$  production in heavy-ion collisions

STRONG INTERACTIONS | NEWS

30 June 2022

A report from the CMS experiment.

CERN COURIER

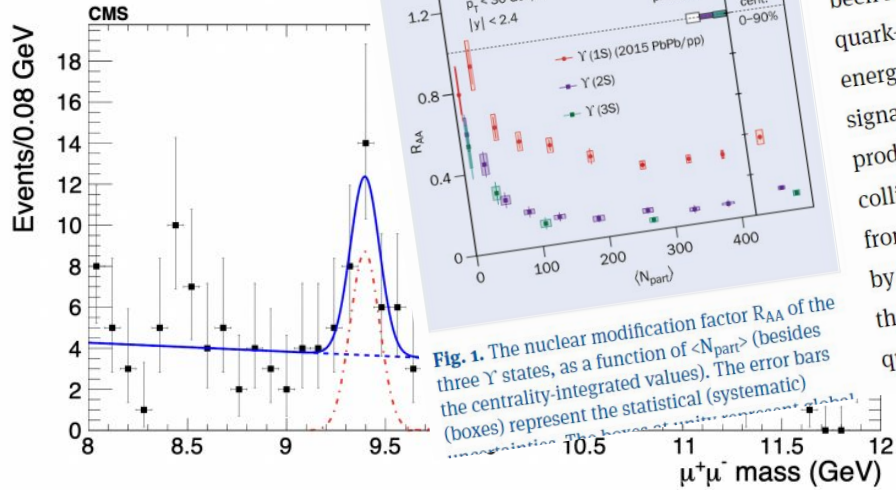
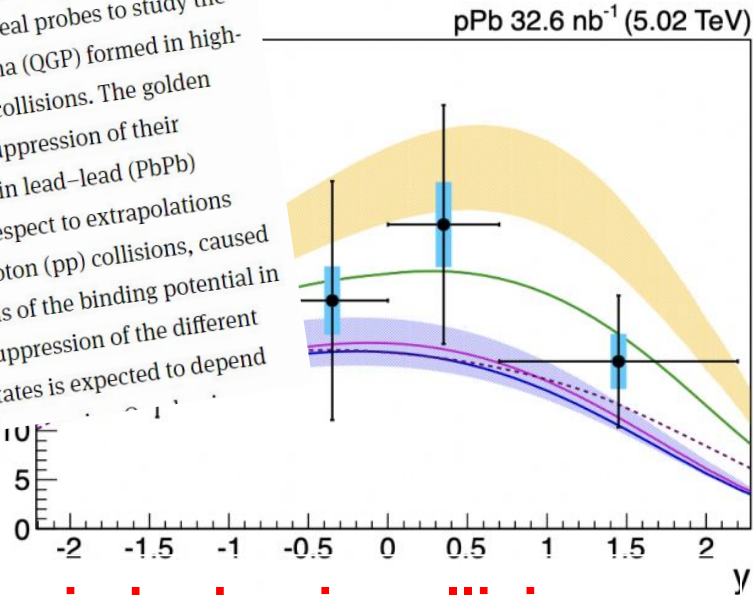


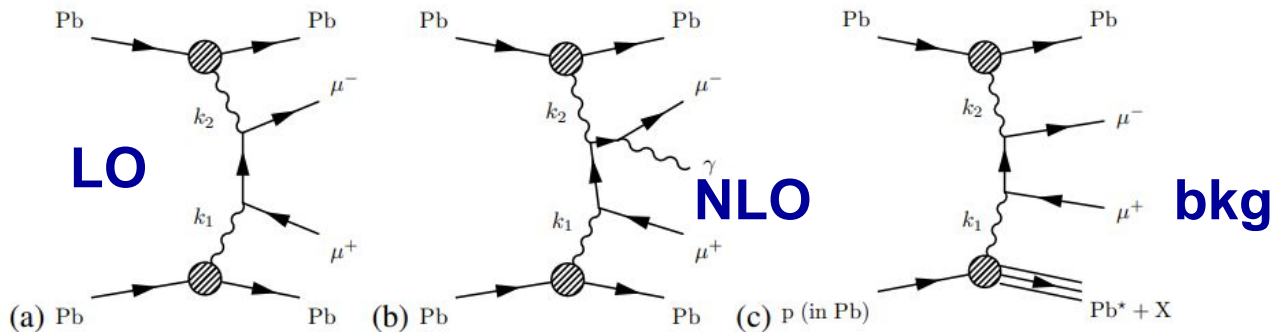
Fig. 1. The nuclear modification factor  $R_{AA}$  of the three  $\Upsilon$  states, as a function of  $\langle N_{part} \rangle$  (besides the centrality-integrated values). The error bars (boxes) represent the statistical (systematic)

The bound states of a heavy quark and its antiquark, called quarkonia, have long been regarded as ideal probes to study the quark-gluon plasma (QGP) formed in high-energy heavy-ion collisions. The golden signature is the suppression of their production yield in lead-lead (PbPb) collisions with respect to extrapolations from proton-proton (pp) collisions, caused by modifications of the binding potential in the QGP. The suppression of the different quarkonium states is expected to depend



Taking advantage of experience in hadronic collisions

# Exclusive dilepton processes & dissociation



$\text{PbPb}(\gamma\gamma) \rightarrow \mu^+\mu^-(\text{Pb}^{(*)}\text{Pb}^{(*)})$  is the primary signal Breit-Wheeler process cross section implemented in STARlight, SuperChic, etc.

$\text{PbPb}(\gamma\gamma) \rightarrow \mu^+\mu^-\gamma(\text{Pb}^{(*)}\text{Pb}^{(*)})$  is a higher order final state, also signal. Not in any existing MC, but now being addressed in calculations, and can be added to final states (e.g. from STARlight) using Pythia8 as afterburner

$\text{Pb} + \text{N/Pb}(\gamma\gamma) \rightarrow \mu^+\mu^-X(\text{Pb}^{(*)}\text{Pb}^{(*)})$  is dissociative background (non-EPA) process, including nuclear breakup as well, modeled using LPair ( $\mu\mu$ ) or SuperChic ( $ee$ )



# Progress in MC generators

Harland-Lang et al., EPJC 79 (2019) 1, 39  
EPJC 80 (2020) 10, 925

Burmasov et al., arXiv:2111.11383 [hep-ph]

Broz et al., Comput.Phys.Commun. 253 (2020) 107181

- **SuperChic 3+** → [v4](#)
  - Simulates variety of QCD-induced and photon-induced exclusive reactions
  - Also handles loop-induced processes (LbyL) and variety of BSM models (ALPs, monopoles, etc.)
  - refined treatment of the photon flux and nuclear overlap
  - Polarization effects taken into account

- **UPCgen**

- Focus on  $\gamma\gamma \rightarrow ll$  production
- refined treatment of photon fluxes
- photon polarization effects included
- Can set arbitrary values of the lepton anomalous magnetic moment (useful in the studies of tau  $g-2$ )

- **Noon**

- Generates extra neutrons from EM dissociation in UPC
- Can be interfaced to other MC generators

- **gamma-UPC MG5 2207.03012**

More on  
Jesus's  
& Lucian's  
talks

Eur. Phys. J. C (2019) 79:39  
<https://doi.org/10.1140/epjc/s10052-018-6530-5>

THE EUROPEAN  
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

**Exclusive LHC physics with heavy ions: SuperChic 3**

L. A. Harland-Lang<sup>1,a</sup>, V. A. Khoze<sup>2,3</sup>, M. G. Ryskin<sup>3</sup>

<sup>1</sup> Clarendon Laboratory, Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK  
<sup>2</sup> Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK  
<sup>3</sup> Petersburg Nuclear Physics Institute, NRC Kurchatov Institute, Gatchina, St. Petersburg 188300, Russia

Upcgen: a Monte Carlo simulation program for dilepton pair production in ultra-peripheral collisions of heavy ions

Nazar Burmasov<sup>a,\*</sup>, Evgeny Kryshen<sup>a</sup>, Paul Bühler<sup>b</sup>, Roman Lavicka<sup>b</sup>

<sup>a</sup>Petersburg Nuclear Physics Institute named by B.P.Konstantinov of National Research Center «Kurchatov Institute», 1 mkr. Orlova voshcha, 188300 Gatchina, Russia  
<sup>b</sup>Stefan Meyer Institute for Subatomic Physics, Kegelgasse 27, 1030 Vienna, Austria

ELSEVIER

Computer Physics Communications  
Volume 253, August 2020, 107181

A generator of forward neutrons for ultra-peripheral collisions:  $n_0^n$  ☆, ☆☆

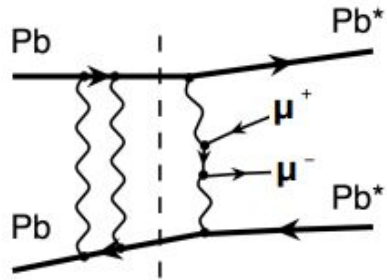
M. Broz<sup>a</sup>, J.G. Contreras<sup>a</sup>, J.D. Tapia Takaki<sup>b</sup>



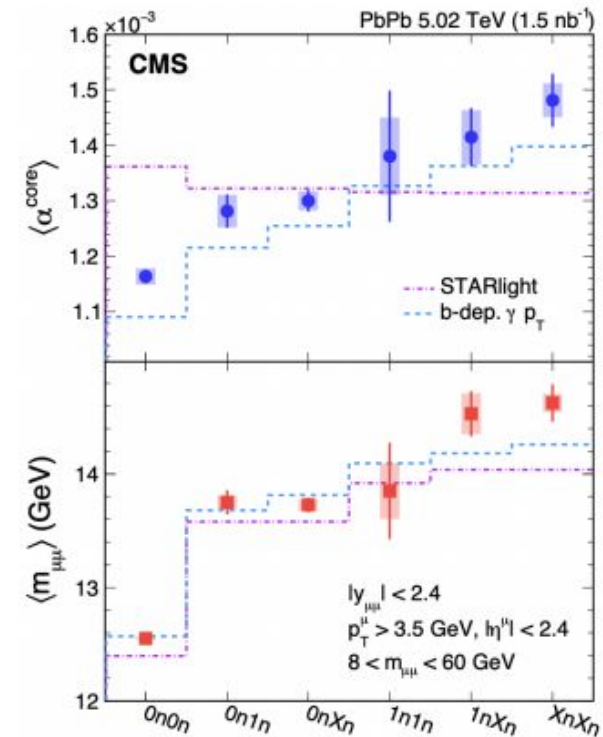
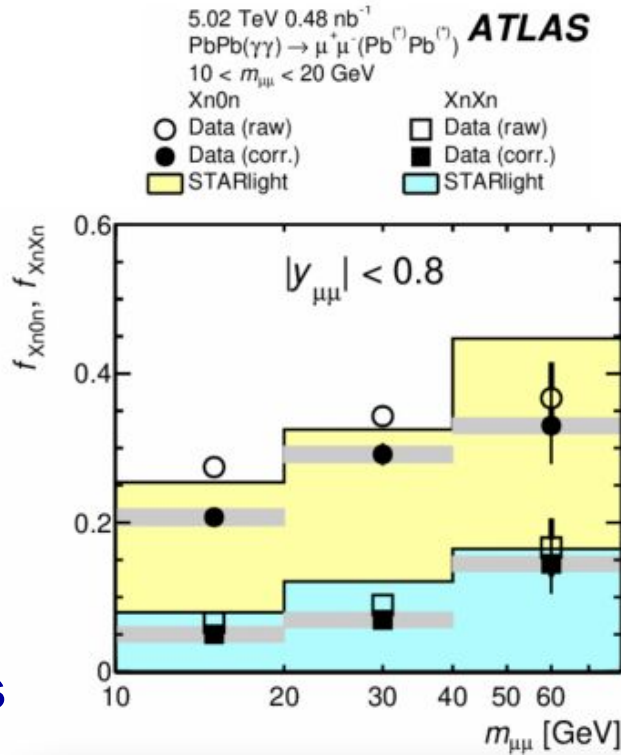
# $\gamma\gamma \rightarrow \mu\mu$ production in Pb+Pb UPC

- Measuring properties of events with single and mutual EM dissociation  
 → indirect probe of Pb+Pb impact parameter in  $\gamma\gamma$  interactions

More on  
Jakub's  
talk



IP-dependent  $p_T$   
of initial photons



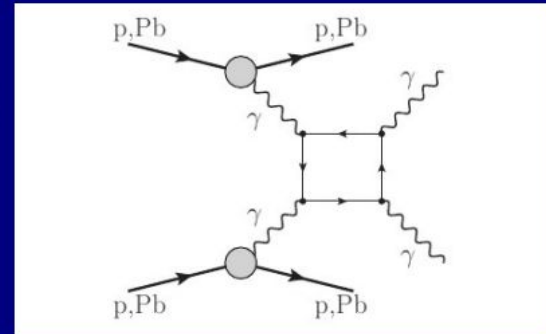
## Exclusive $\gamma\gamma$ production

Light-by-light scattering,  $\gamma\gamma \rightarrow \gamma\gamma$ , has so far not been directly observed.

The reaction is of fundamental interest as deviations from SM prediction may be caused by anomalous gauge couplings, SUSY particle contributions in the loop etc.

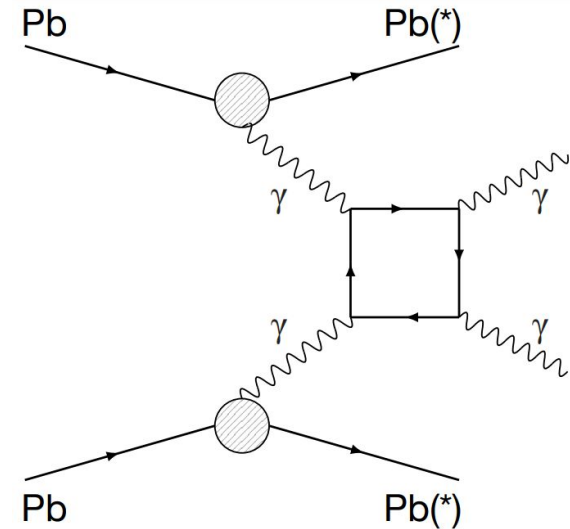
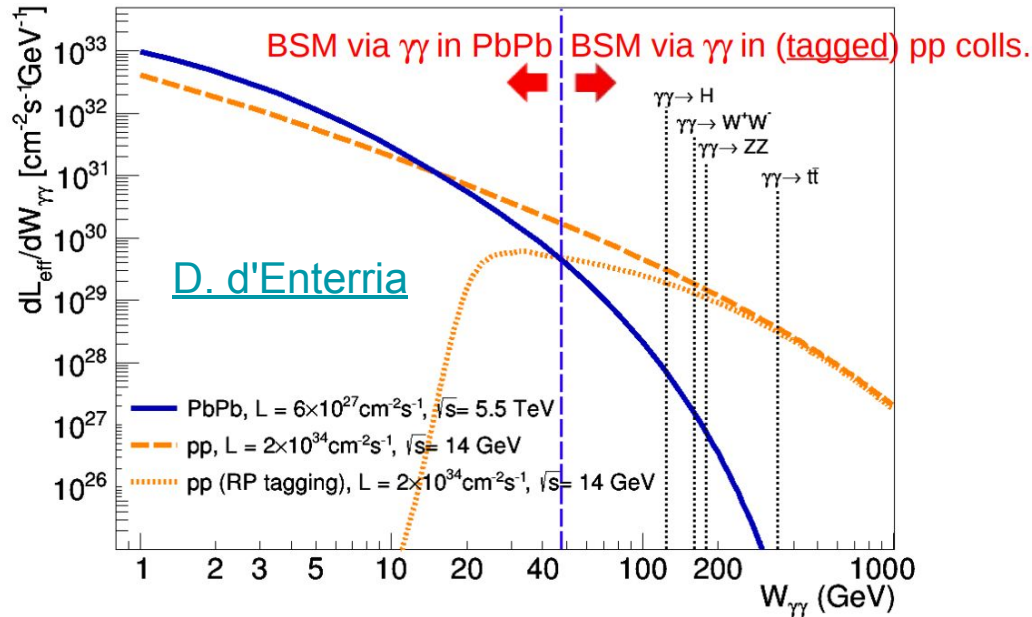
According to the recent paper (d'Enterria, Silveira PRL 111 (2013) 080405),  $\approx 200$  signal events with  $m_{\text{inv}} > 5$  GeV can be expected in the ATLAS/CMS acceptance in a  $10 \text{ nb}^{-1}$  Pb-Pb run.

**==> Pb-Pb collisions at the LHC might thus provide the first opportunity to study this process!**



# Two words on $L_{\gamma\gamma}$ scattering (with UPC)

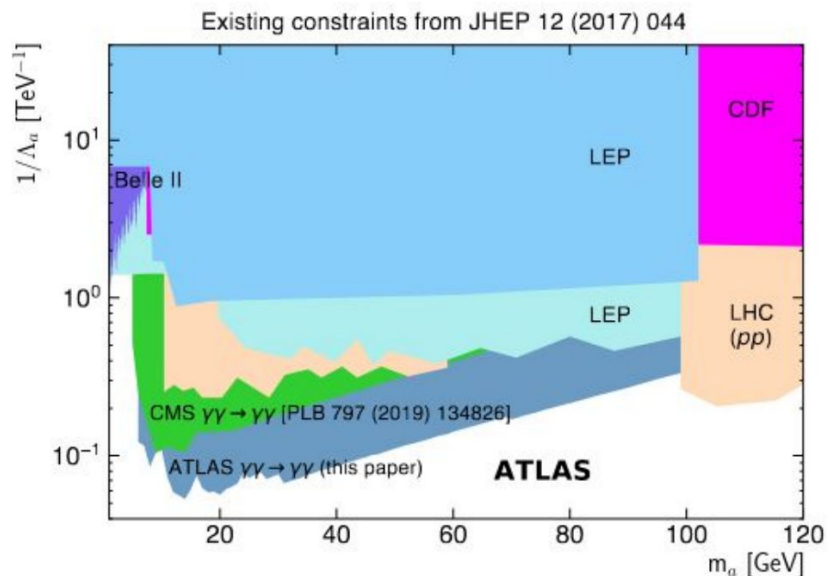
- BSM at high masses: Increase  $\sqrt{s}$
- BSM at low couplings: Increase  $\mathcal{L}$ 
  - plus **taking advantage of** reduced pileup, kin. thresholds, and clean final states
- Thanks to the  $Z^4$  factor,  $\gamma\gamma$  luminosities (in PbPb)  $\gg$  pp ones at low  $W_{\gamma\gamma}$



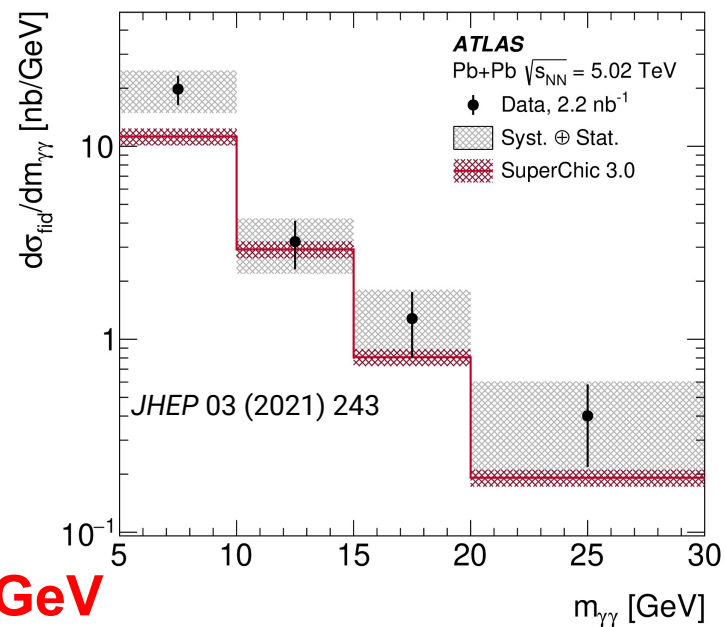
# Available LbyL UPC measurements (so far)

- ATLAS
  - 2015 data, 0.48/nb, *Nature Phys.* 13 (2017) 9, 852-858
  - 2018 data, 1.73/nb, *Phys.Rev.Lett.* 123 (2019) 052001
  - **2015+18 data**, 2.2/nb, *JHEP* 03 (2021) 243
- CMS
  - **2015 data**, 0.39/nb, *Phys.Lett.B* 797 (2019) 134826

More on  
Jakub's  
talk



Even differential studies!

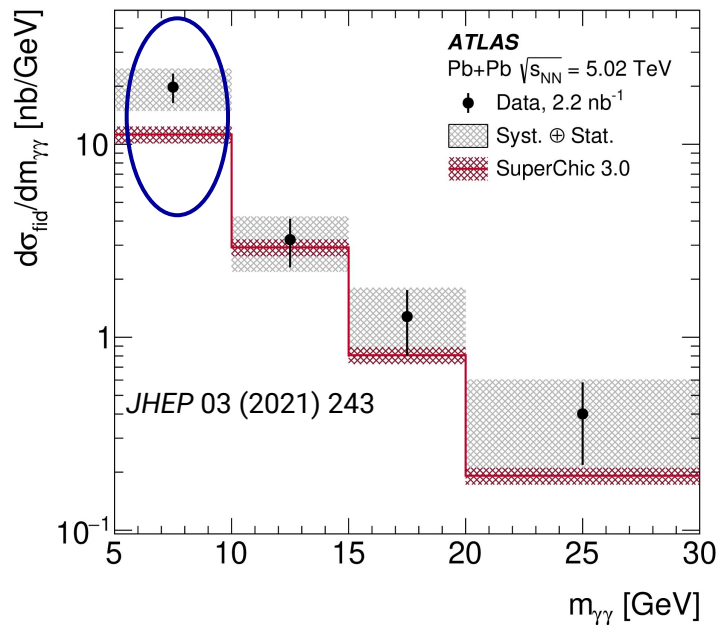
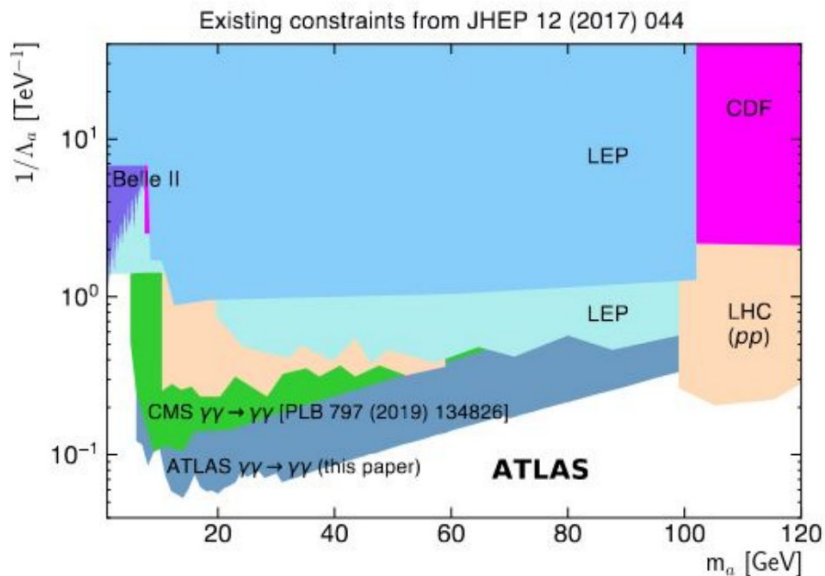


LHC nuclear collisions: best limits in <100 GeV

# Goals of this analysis

- ATLAS
  - 2015 data, 0.48/nb, *Nature Phys.* 13 (2017) 9, 852-858
  - 2018 data, 1.73/nb, *Phys.Rev.Lett.* 123 (2019) 052001
  - 2015+18 data, 2.2/nb, *JHEP* 03 (2021) 243
- CMS
  - 2015 data, 0.39/nb, *Phys.Lett.B* 797 (2019) 134826

1. How an **averaged value** compared to theory?
2. Could some **SM bkg** explain the excess?

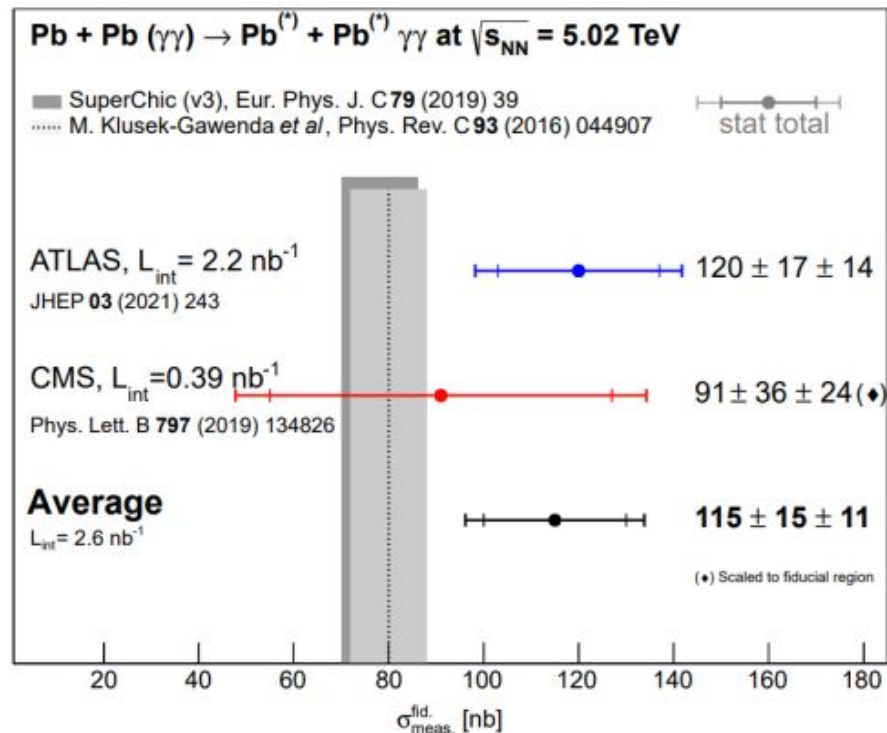




# Measurement of light-by-light scattering

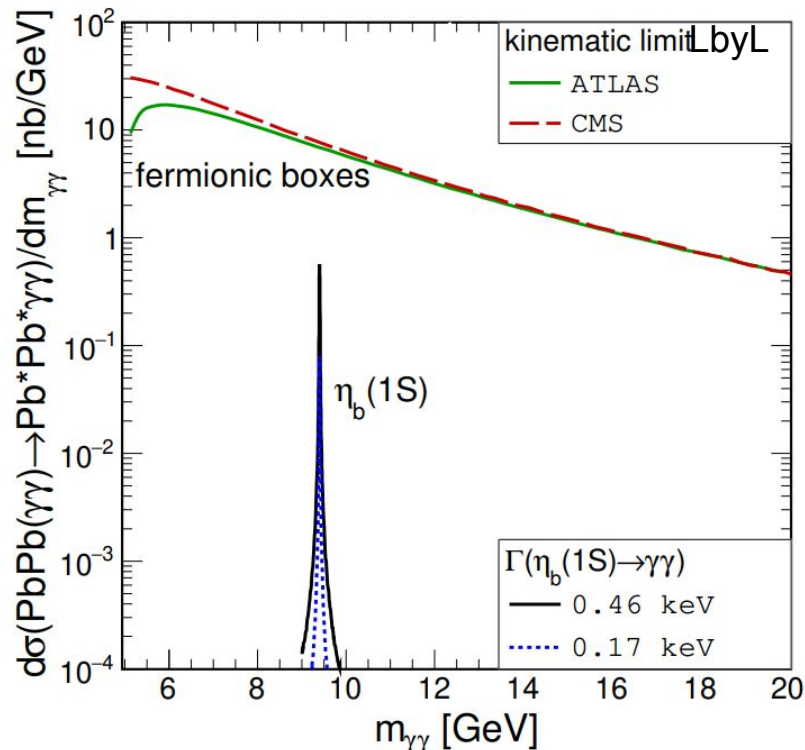
Krintiras et al., arXiv:2204.02845

- Combining ATLAS+CMS measurements in a “common” fiducial phase-space



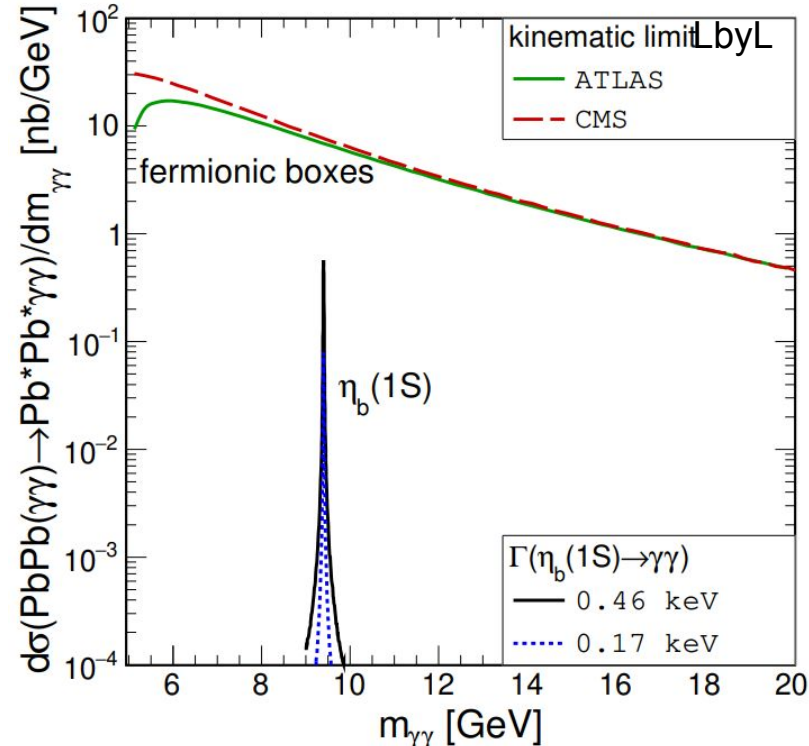
# Trying to explain **the excess**

- We calculated the inclusive  $\sigma$  for the **photoproduction of  $\eta_b(1S)$** 
  - $\sigma = (0.19-1.41) 10^{-2}$  nb
  - range reflects max. and min. of two-photon decay rates, i.e., 0.46 and 0.17 keV
- this contribution **isn't significant**



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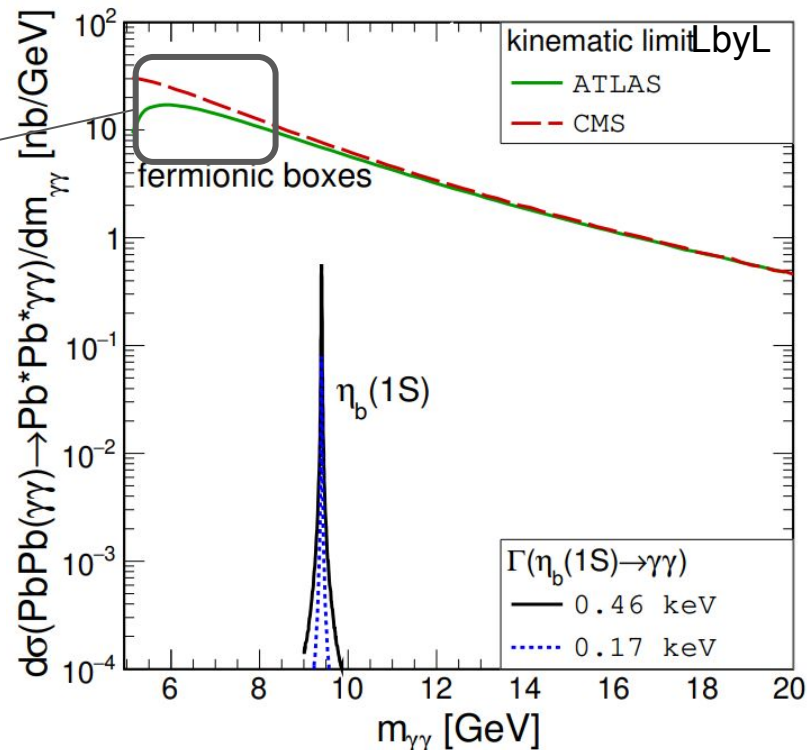


**2207.13623**  
**More on**  
**Lucian's(?)**  
**talk**

# Trying to explain the excess

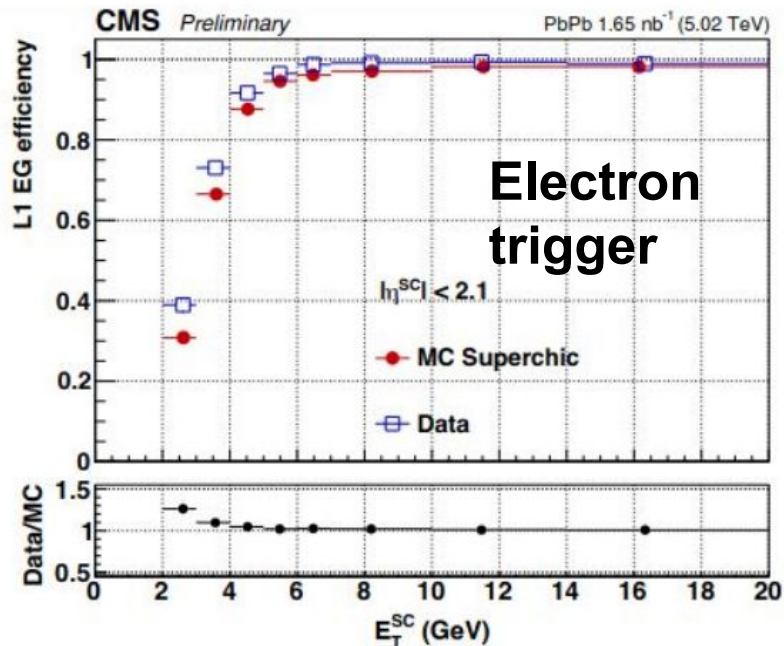
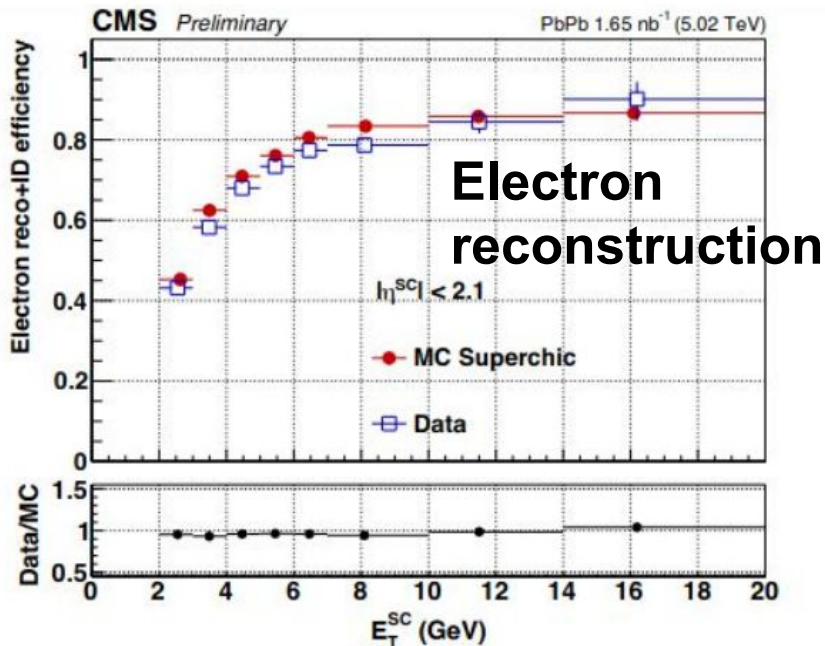
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Lower trigger cut



# Electron and L1 EM cluster efficiency for 2018 PbPb

CMS DP -2022/006

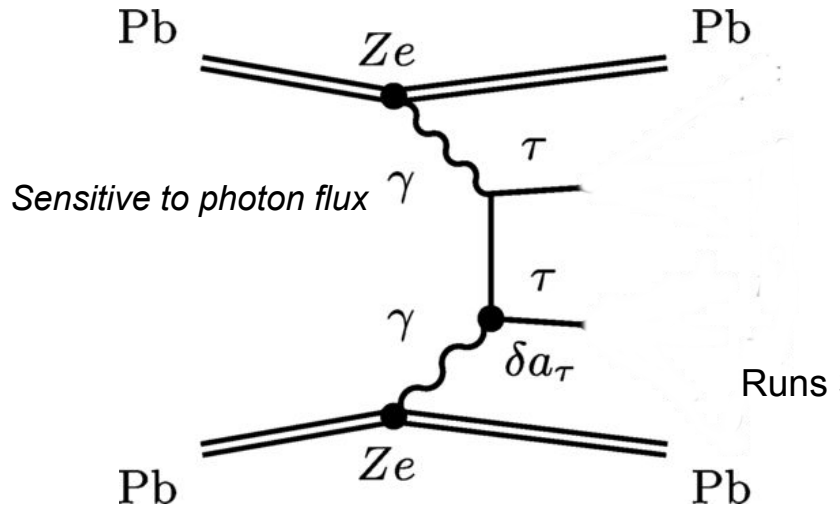


Comparison of electron reconstruction+identification (left) and Level-1 electromagnetic cluster (right) efficiencies for data (blue) and Superchic [3] simulation (red) as a function of supercluster  $E_T$  for  $|\eta| < 2.1$  derived in 2018 PbPb ultraperipheral collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The efficiencies are estimated using the tag and probe technique.



# Overview of the $\gamma\gamma \rightarrow \tau\tau$ process

- **Promising candidate** for the  $a_\tau = (g_\tau - 2)/2$  determination
  - “using a large heavy ion collider” for  $g_\tau - 2$  suggested since **90s**
  - cross section in UPC receives a  **$Z^4$  enhancement** relative to pp
- LHC could **improve** the sensitivity on  $a_\tau$  relative to LEP
  - **probe** the anomalous  $\tau$  lepton **electric moment** too like **BELLE**

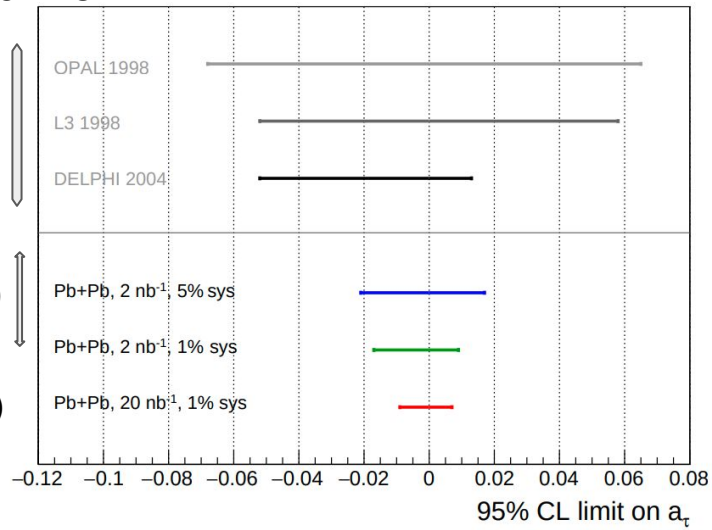


$\tau$  lepton photoproduction in ultraperipheral collisions (UPC)

LEP

Run 2 (2 /nb)

Runs 3+4 (> 10 /nb)



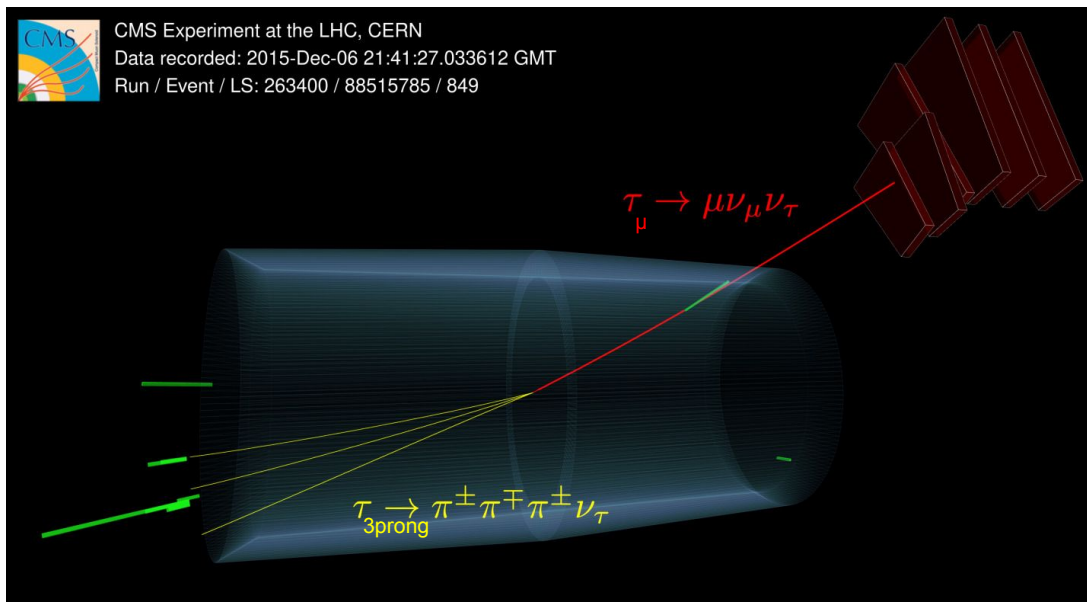
*Phys. Lett. B* **809** (2020) 135682 (2002.05503)

*Phys. Rev. D* **102** (2020) 113008 (1908.05180)

# $\tau$ 's are multifaceted

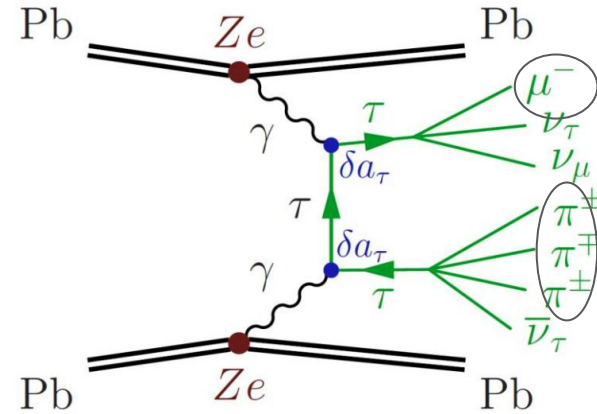
- $\tau\tau$  signal regions can be then defined based on the lepton and/or hadron **multiplicity**
    - dilepton: the lowest reco efficiency
    - $1\ell + 1$  track: main bkg due to  $\mu\mu$ ,  $ee$
    - **$1\ell + 3$  tracks**: clean with high enough yield
- All channels needed for ultimate precision

CMS-PHO-EVENTS-2022-003-2



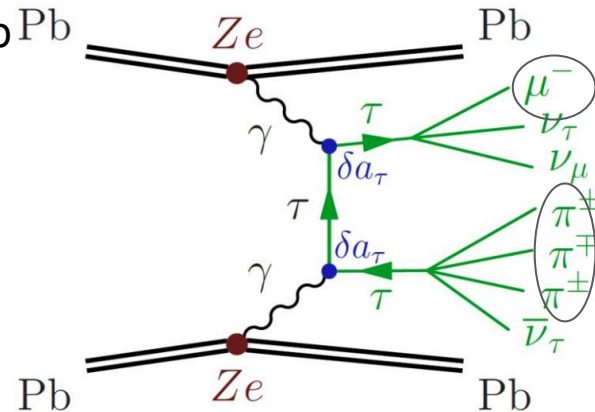
# How to observe the $\gamma\gamma \rightarrow \tau\tau$ process at LHC

- The total  $\gamma\gamma \rightarrow \tau\tau$  cross section is of  $O(1 \text{ mb}) \rightarrow O(1 \text{ M})$  with 2 /nb
  - **we expected <100** 1 $\mu$ +3 tracks events **within** acceptance
- $\tau$  lepton reco **challenging** at low- $p_T$  (<20 GeV)
  - till recently **no** measurement in nuclear collisions
    - indirect presence via  $Z/\gamma^*$  in top quark [events](#)



# How to observe the $\gamma\gamma \rightarrow \tau\tau$ process at LHC

- The total  $\gamma\gamma \rightarrow \tau\tau$  cross section is of  $O(1 \text{ mb}) \rightarrow O(1 \text{ M})$  with  $2/nb \text{ PbPb}$ 
  - **we expected <100**  $1\mu+3$  tracks events **within** acceptance
- $\tau$  lepton reco **challenging** at low- $p_T$  ( $<20 \text{ GeV}$ )
  - till recently **no** measurement in nuclear collisions
    - indirect presence via  $Z/\gamma^*$  in top quark [events](#)
- Take advantage of **UPC** events and  $\tau$  lepton **unique** decay signatures
  - low track multiplicity ( $N_{\text{ch}}$ ), UPC triggers, and “exclusivity” requirements
    - **single lepton** triggers
    - **no activity** in forward hadron (HF) calorimeters above noise threshold
- Aim to **establish**  $\gamma\gamma \rightarrow \tau\tau$  at LHC as **the first** crucial step during a dedicated physics program
  - using **PbPb** collisions in 2015 ( $\sim 0.5 /nb$ )
  - followed by the **inclusion** of 2018 ( $\sim 1.5 /nb$ )
  - Runs 3+4 **projection** in the realm of the joint ATLAS+CMS [Snowmass22](#) effort



# Our event **selection** and MC **simulation**

- **Trigger:** 1 muon & +  $\geq 1$  track in the pixel detector + no HF activity on either side
- **Optimized offline** event selection (cf Table)
- Our **signal region** is 1 muon &  $N_{\text{ch}}=3$ 
  - other  $N_{\text{ch}}$  and HF activity regions used in **bkg estimation**
- MC simulation for **signal and validation** (main bkg, efficiency)

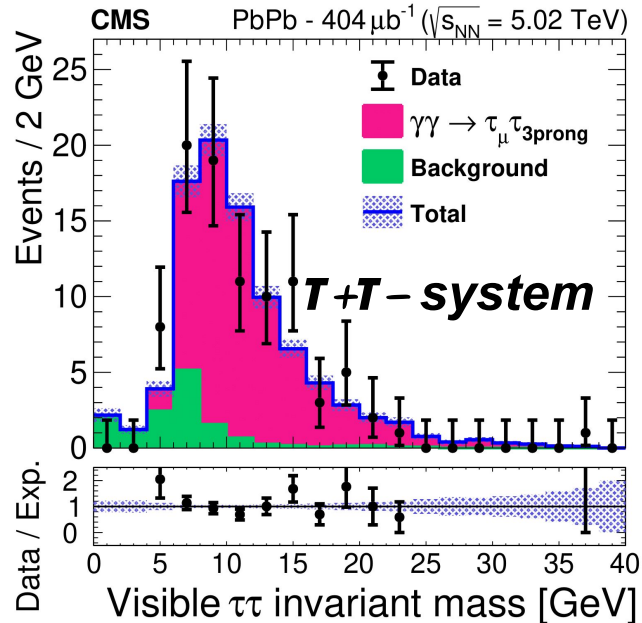
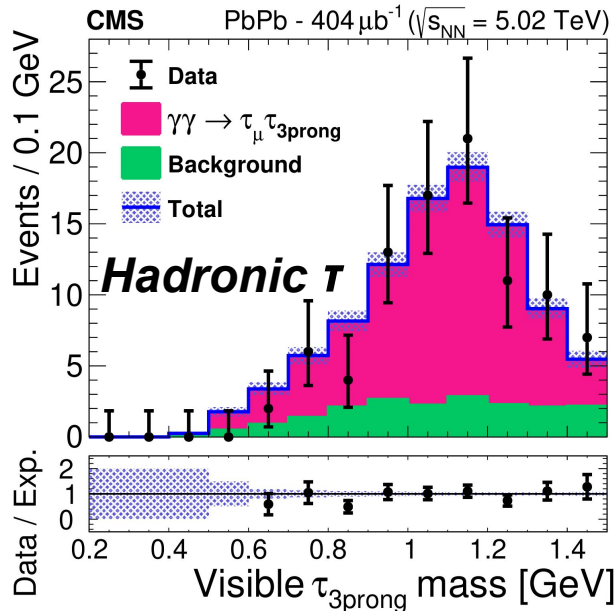
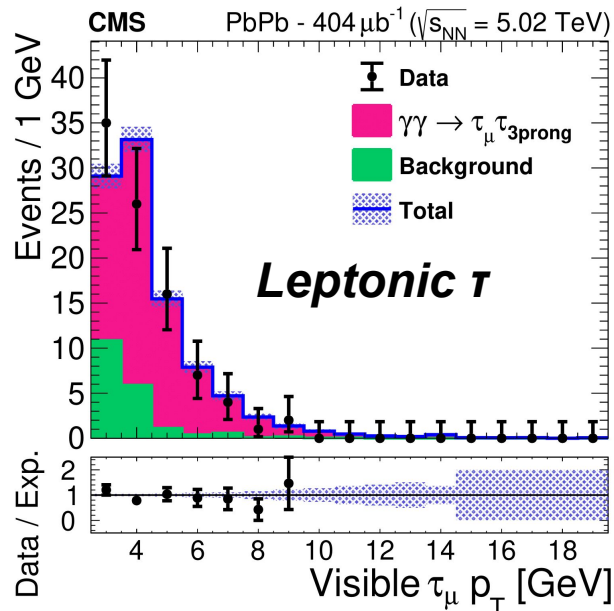
Object	Criteria
$\mu$	$p_T > 3.5 \text{ GeV}$ for $ \eta  < 1.2$ $p_T > 2.5 \text{ GeV}$ for $1.2 <  \eta  < 2.4$
$\pi^\pm$	$p_T > 0.5 \text{ GeV}$ for leading $\pi^\pm$ $p_T > 0.3 \text{ GeV}$ for (sub-)sub-leading $\pi^\pm$ $ \eta  < 2.5$
$\tau_{3\text{prong}}$	$p_T^{\text{vis}} > 0.2 \text{ GeV}$ $0.2 \text{ GeV} < m_{\pi\pi\pi} < 1.5 \text{ GeV}$

→ **Low- $p_T$  muons**

# Data-to-exp comparison: control plots in the signal region

- Very good **agreement** between data & expectations
  - signal MC is scaled to the **integrated luminosity**
  - we're in an almost **bkg-free** phase space region(!)
- **unambiguous reconstruction** of the  $T+T-$  system

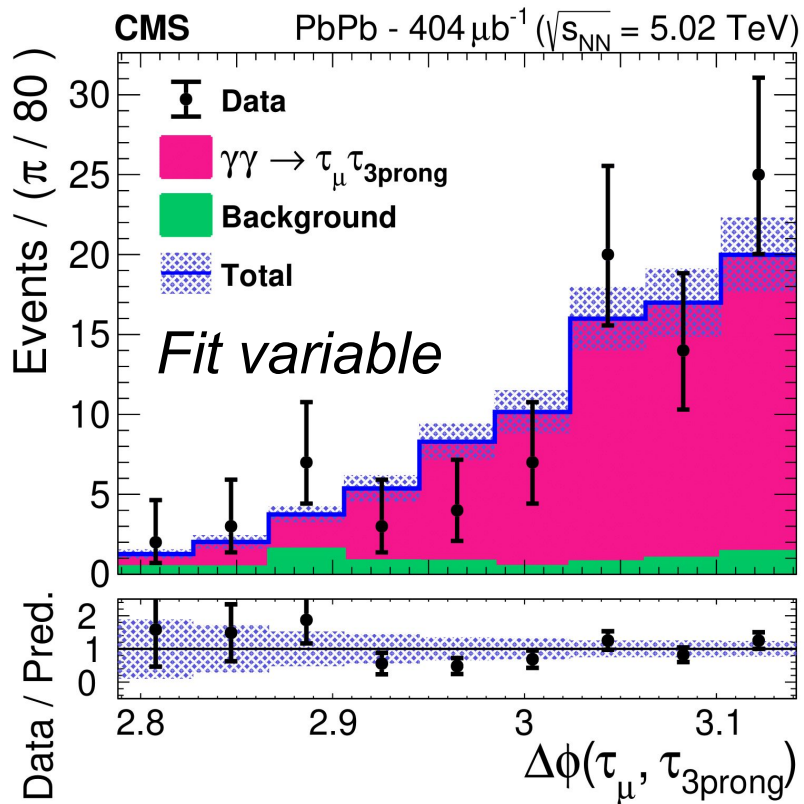
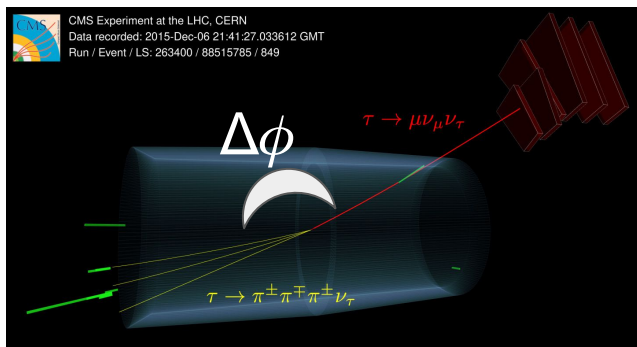
**2206.05192**  
**(submitted to PRL)**





# Signal yield estimation

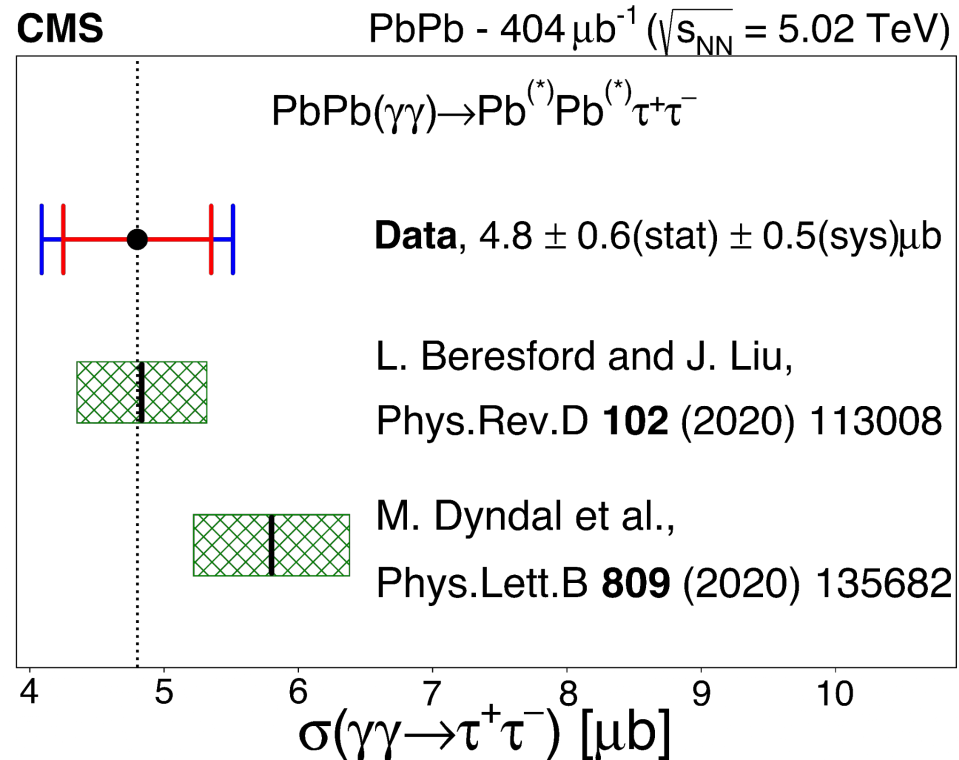
- Binned likelihood fit to a discriminating variable
- **Angular separation** ( $\Delta\phi$ ) between leptonic and hadronic candidates
  - MC signal (peaky) and bkg template (flat) from data
- Number of observed post-fit **signal events**:  $77 \pm 12$
- Observed significance is **more than  $5\sigma$** 
  - **taking into account** systematic uncertainties
    - affecting the rate with log-normal priors
    - affecting the shape with Gaussian prior



# Cross section measurement

- Extra ingredients needed
  - $L = 404 \mu b$
  - $B_{\tau_{\mu}} = 17.39\%$
  - $B_{\tau_{3\text{prong}}} = 14.55\%$
  - **efficiency** ( $\epsilon$ ) from MC = 78.5%

$$\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = N_{\text{sig}} / (2\epsilon \mathcal{L}_{\text{int}} B_{\tau_{\mu}} B_{\tau_{3\text{prong}}})$$



$$\sigma_{\text{fiducial}} = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{sys}) \mu b$$

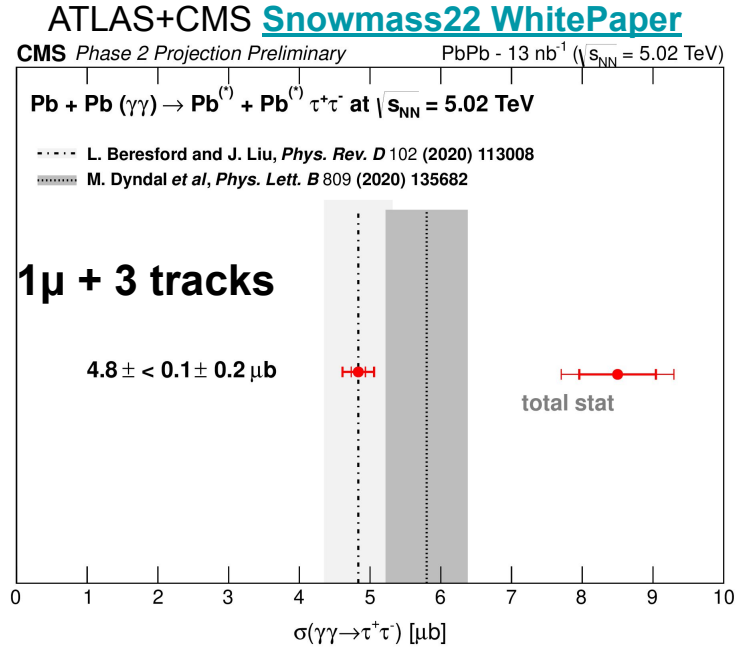
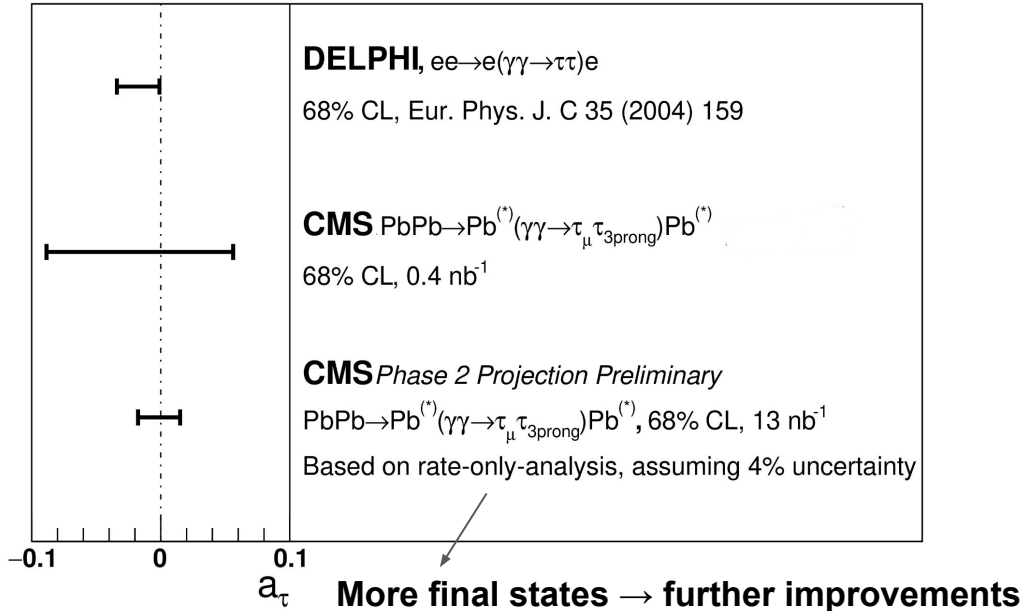
# Overview of uncertainties

- **Statistically dominated** (13%)
- Systematic wise (9.7%) the **dominant sources** are related to
  - muons (trigger efficiency)
  - pion efficiency
  - luminosity
- Total uncertainty comparable to the current theory uncertainty
  - difficult to **discriminate** between existing models
  - **model-dependent** limits on anomalous moments can be set

Source	Uncertainty (%)
Muon efficiency	6.7
Integrated luminosity measurement	5
Pion efficiency	3.6
Simulation sample size (bin-by-bin)	3.0
Simulation sample size (efficiency)	1.1
HF scale effect on background shape	0.9
$\tau$ lepton branching fraction	0.6
Effect of $n_{\text{ch}}$ on background shape	0.2
Total (systematic)	9.7

# Constraints on $a_\tau$ and expected performance at HL-LHC

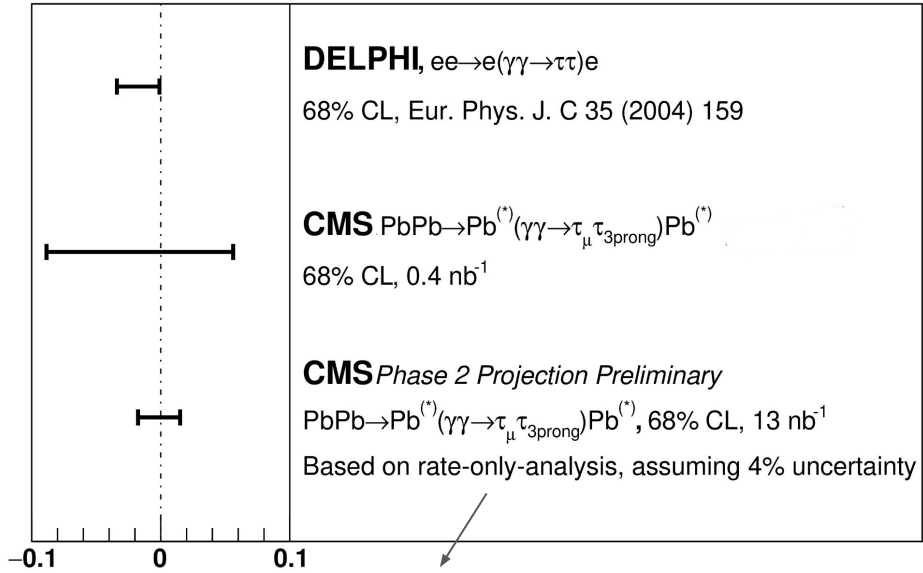
- Using the [theo calculation](#) of  $\sigma(\gamma\gamma \rightarrow \tau\tau)$  as a function of  $a_\tau$ -scale only
  - model-dependent measurements** at LHC can be obtained
- We expect a total uncertainty well below the current theory uncertainty
  - we can discriminate** between existing models
  - projected limit at HL-LHC **competing with LEP**



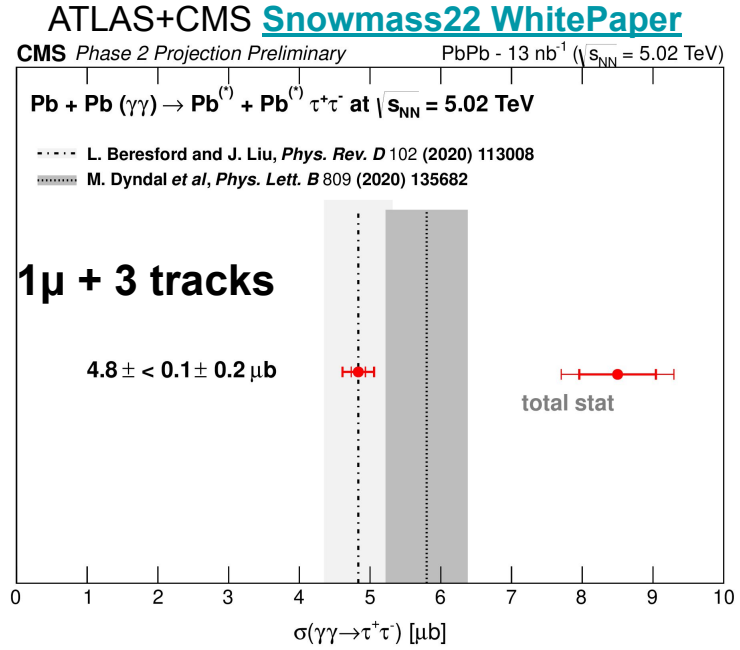
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**More on  
Jakub's  
& Lydia's  
talks**



$a_\tau$  **More final states  $\rightarrow$  further improvements**



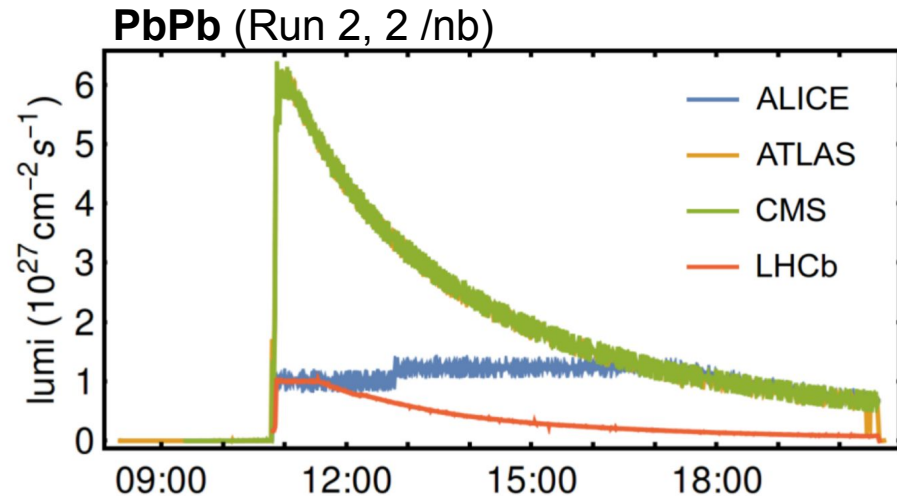
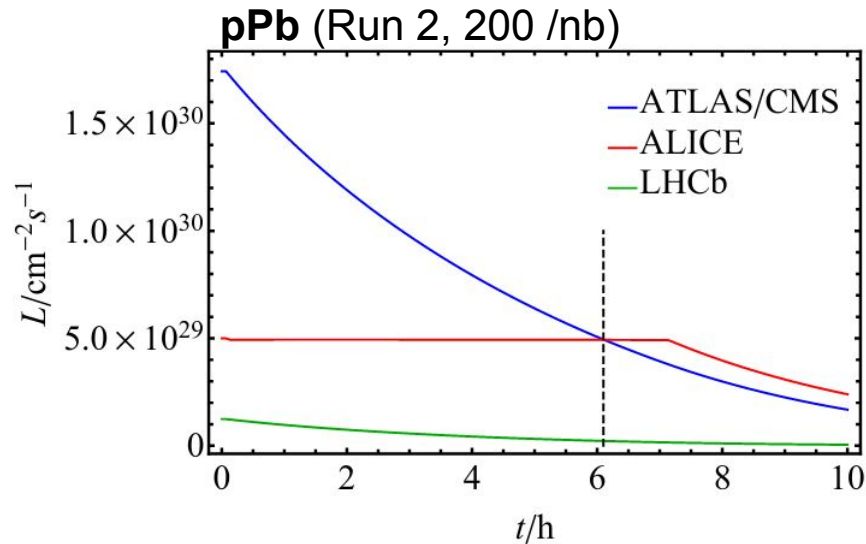


# Outlook

- LHC heavy ion collision (HIC) data are a **gamechanger**
  - accelerator performance well **surpassed** any initial expectations
  - exploiting HIC is a **unique and complementary means** to **search for BSM phenomena**
    - but also to **improve** existing modeling
- A **dedicated physics program** for studying photon-photon physics with HIC in CMS
  - I focused on QED but **extra results**, e.g., on **correlations** and **exclusive dijet production**
  - **further improvements** with inclusion of more data, final states, & improved techniques
    - HL-LHC **baseline projection** done for the expected limits on  $a_T$
- Ample room for **cross-experiment collaboration**
  - existing measurements can be used for further **combinations** of HIC data at LHC



# Heavy ion collisions (HIC) at LHC



- LHC collided **more** types of beam, than originally foreseen, with **better** than expected performance
  - In practice, we've come close to the “**HL-LHC**” **performance** with pPb and PbPb collisions
- Opens up **further opportunities** for **probes** not accessible so far due to lower luminosity and/or energy
  - **two** one-month runs would be needed to reach the Runs 3+4 target of **1200 /nb in pPb**
  - **five** one-month runs would be needed to reach the Runs 3+4 target of **13 /nb in PbPb**
  - **all 4** experiments participate
    - makes luminosity sharing far **more challenging** than high-pileup pp running
    - **complementary** phase space regions, cross checks