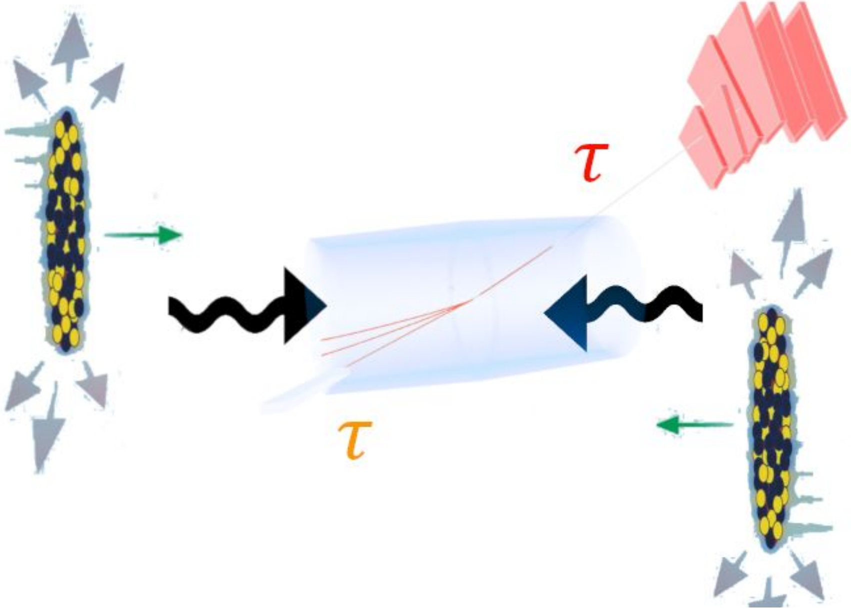


Photon-photon and photon-proton physics in ultraperipheral collisions at CMS

(Using heavy ion collisions as QED & BSM laboratories)

GK Krintiras (cern.ch/gkrintir) on behalf of the CMS Collaboration

Diffraction and Low-*x*, 24–30 Sep 2022

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
ρ_0	$\sim 10^4$	$0.26\ \mu b^{-1}$	stat error $<<$ sys err
J/ψ (mid-rapidity)	~ 500	$23\ \mu b^{-1}$	stat error $<$ sys err
J/ψ (forward)	~ 100	$55\ \mu b^{-1}$	
$\psi(2S)$	~ 50	$23\ \mu b^{-1}$	stat error $>>$ sys err

Workshop in 2014

- Run 2 assumptions:

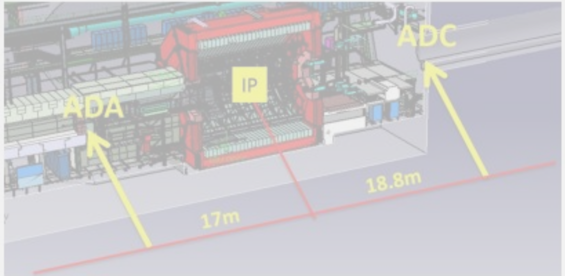
Expectations $\rightarrow$

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

- Precision measurements of J/ψ, study of Υ
- $\gamma\gamma \rightarrow \gamma\gamma$: 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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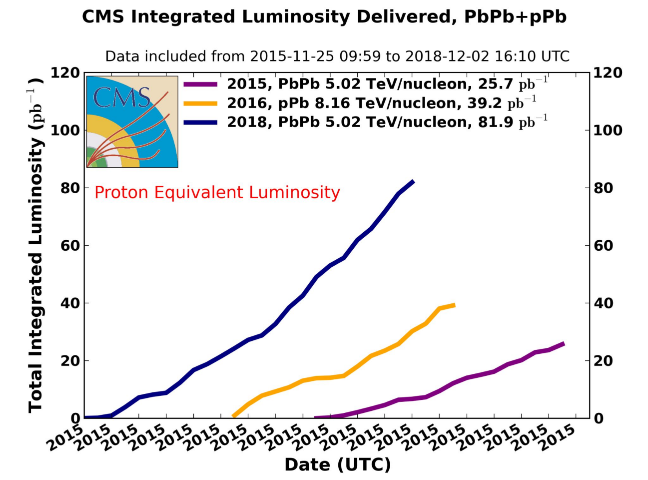
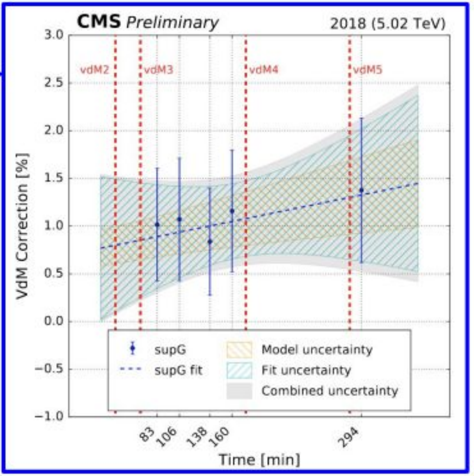
> × 2 at the end

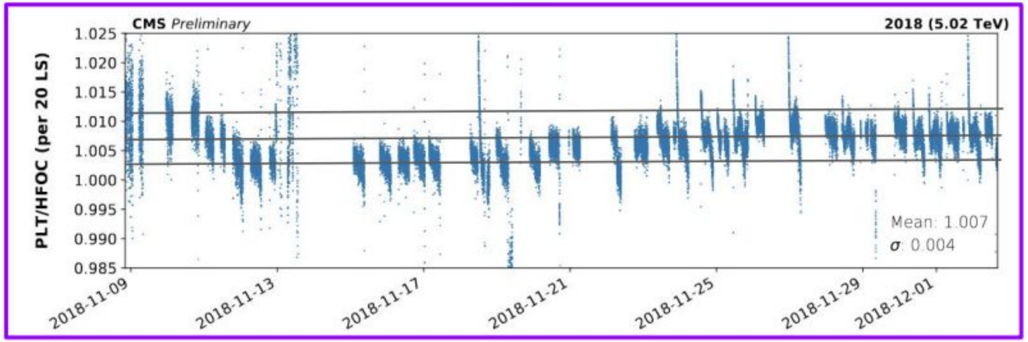


Better & better
(+ Xenon)

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)

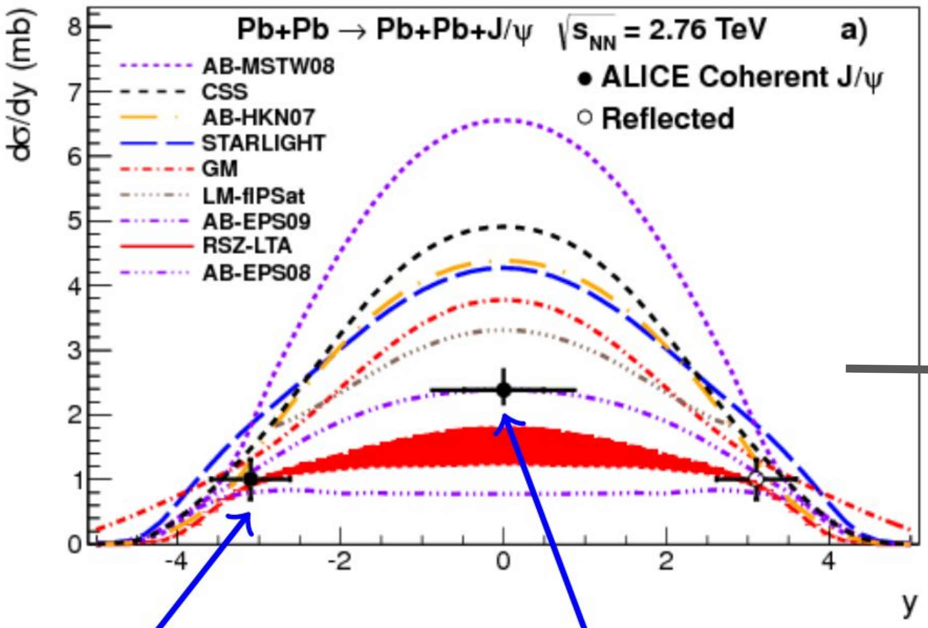
Total uncertainty: 1.5%

PAS-LUM-18-001

150th LHCC Meeting

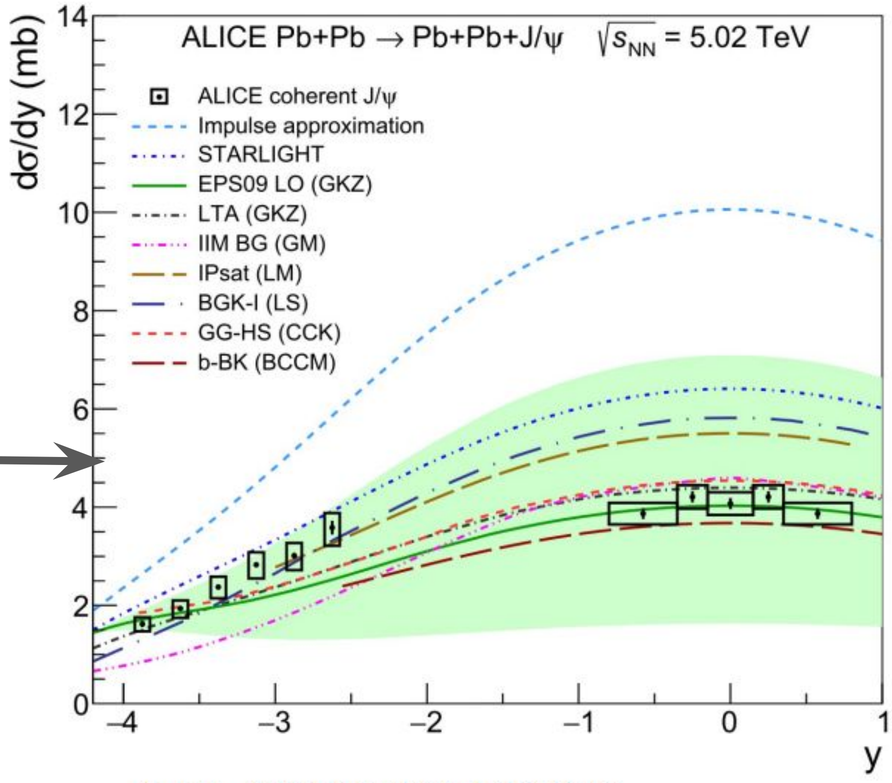
State-of-the-art comparisons

WS in 2014



$x \sim 10^{-2}$ $x \sim 10^{-3}$

Today



ALICE: PLB 798 (2019) 134926

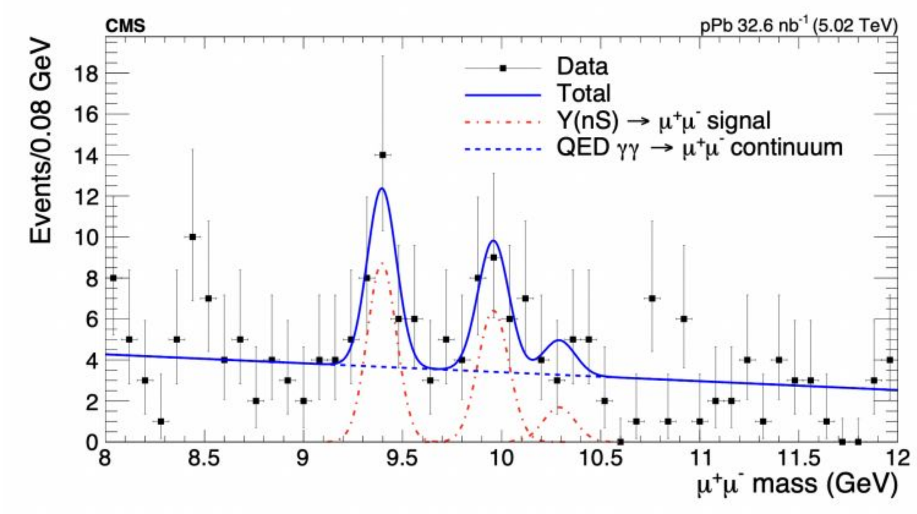
ALICE: EPJC (2021) 81:712

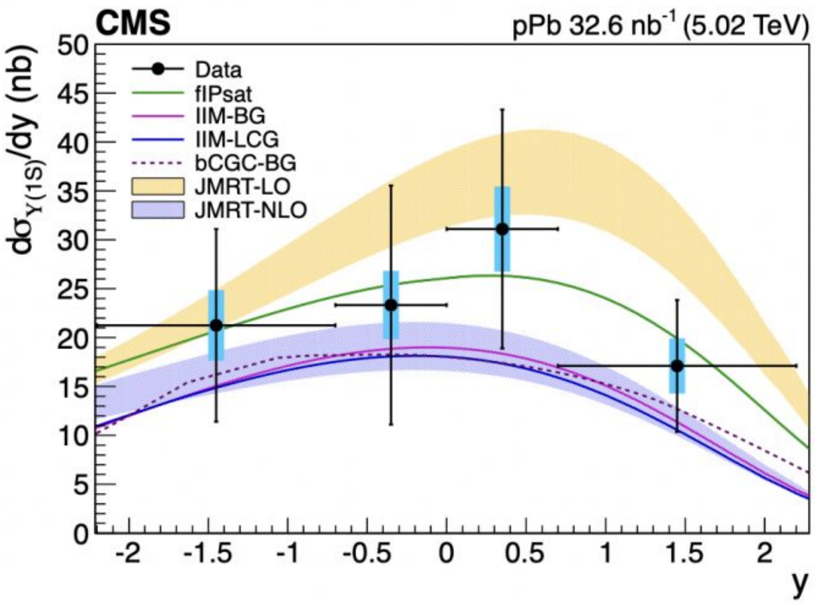
+ LHCb (2206.08221, not shown here)

Upsilon photo-production in UPC p+Pb

CMS, EPJC 79 (2019) 277

- Exclusive Upsilon(nS) measured by CMS in γp collisions

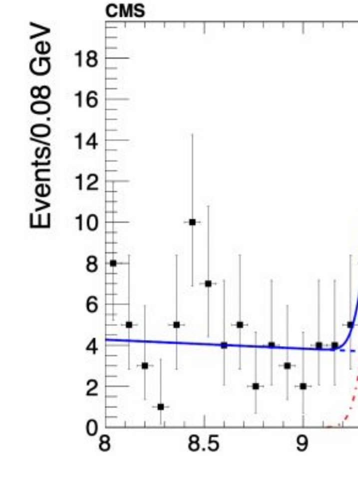


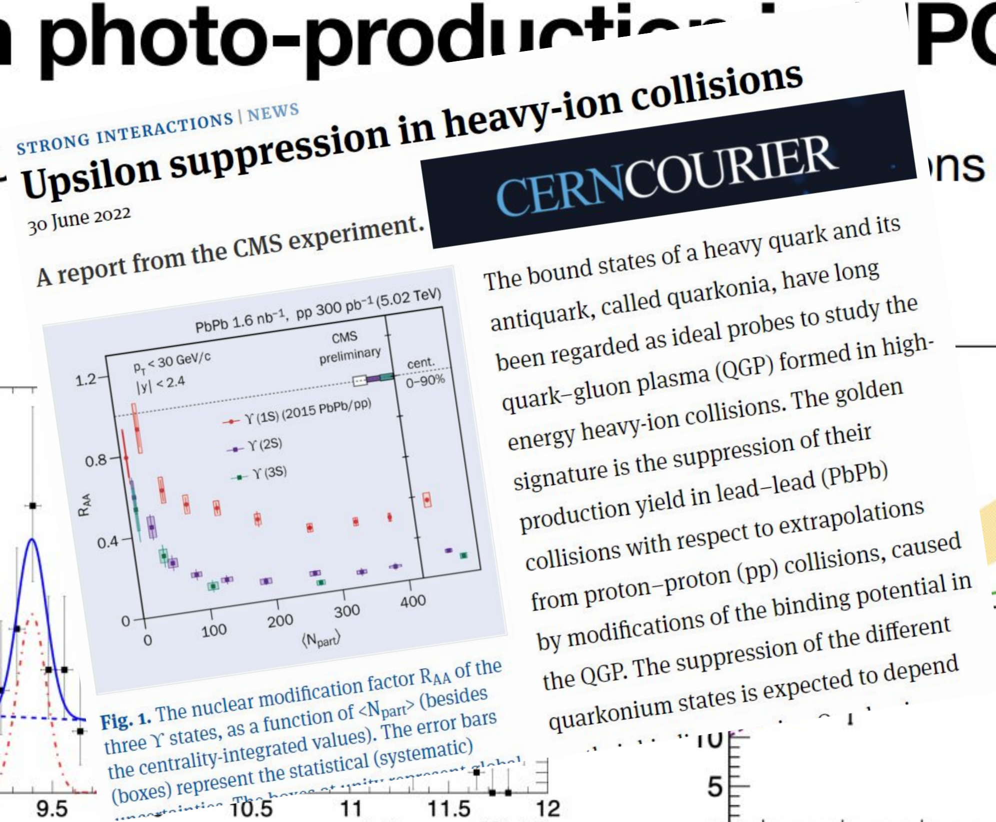


Upsilon photo-produc[...] PC p+Pb

CMS, EPJC 79 (2019) 277

- Exclusive U[...]ns




STRONG INTERACTIONS | NEWS

Upsilon suppression in heavy-ion collisions

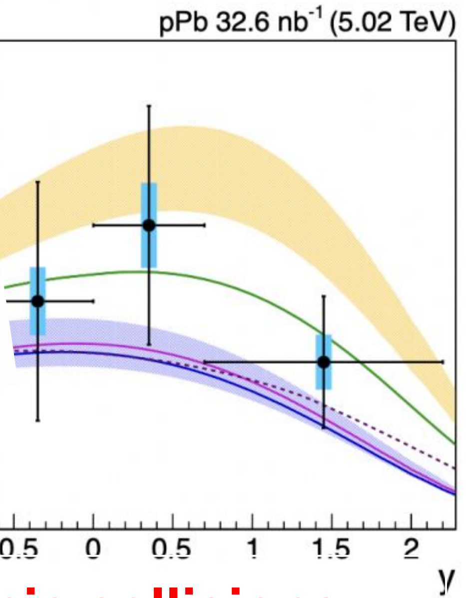
30 June 2022

CERNCOURIER

A report from the CMS experiment.

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

Fig. 1. The nuclear modification factor R_{AA} of the three ϒ states, as a function of <N_{part}> (besides the centrality-integrated values). The error bars (boxes) represent the statistical (systematic) uncertainties.



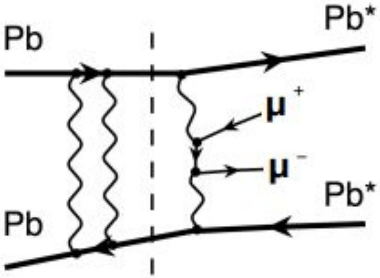
Taking advantage of experience in hadronic collisions

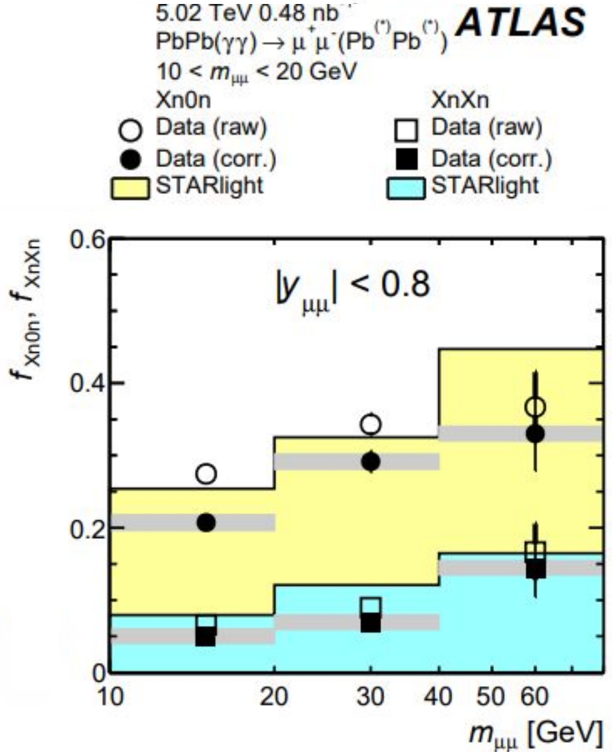
γγ→μμ production in Pb+Pb UPC

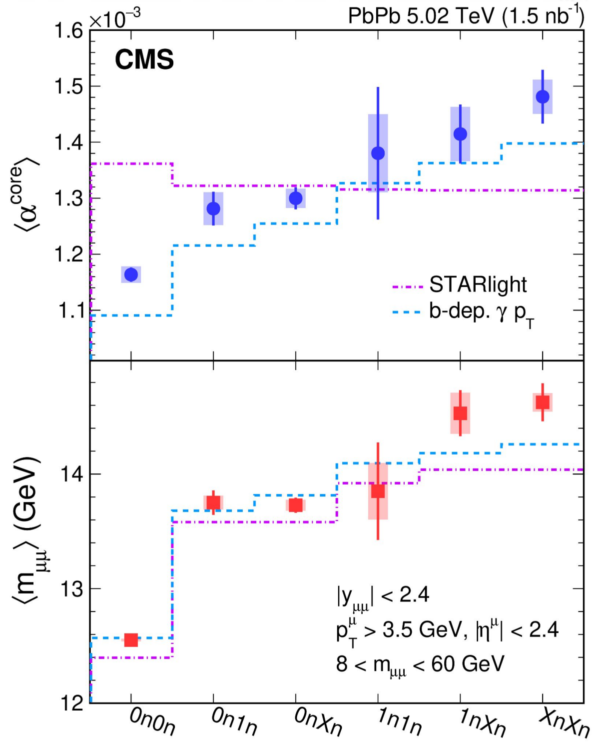
ATLAS, Phys. Rev. C 104 (2021) 024906

CMS, PRL 127, 122001 (2021)

Measuring properties of events with single and mutual EM dissociation
→ indirect probe of PbPb **impact parameter** in γγ interactions







IP-dependent pT of initial photons

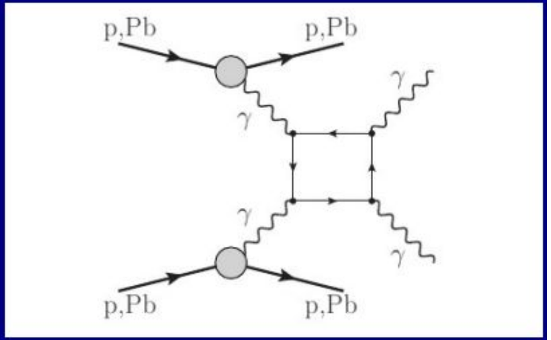
Exclusive $\gamma\gamma$ production

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_{inv} > 5 GeV can be expected in the Atlas/CMS acceptance in a 10 nb^{-1} Pb-Pb run.

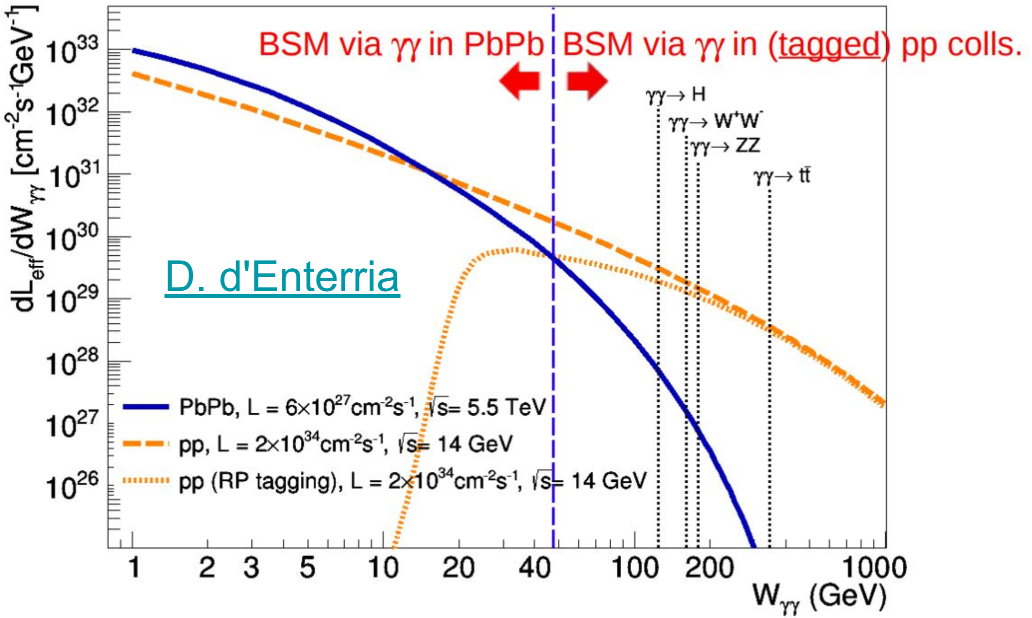
==> Pb-Pb collisions at the LHC might thus provide the first opportunity to study this process!

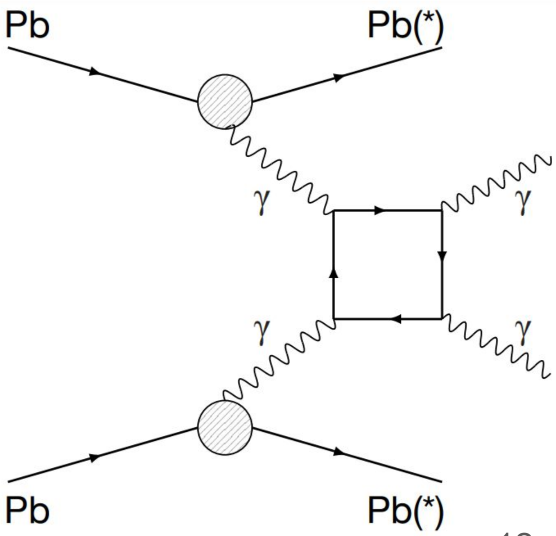


Joakim Nystrand (workshop in 2014)

Two words on **LbyL scattering (with UPC)**

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





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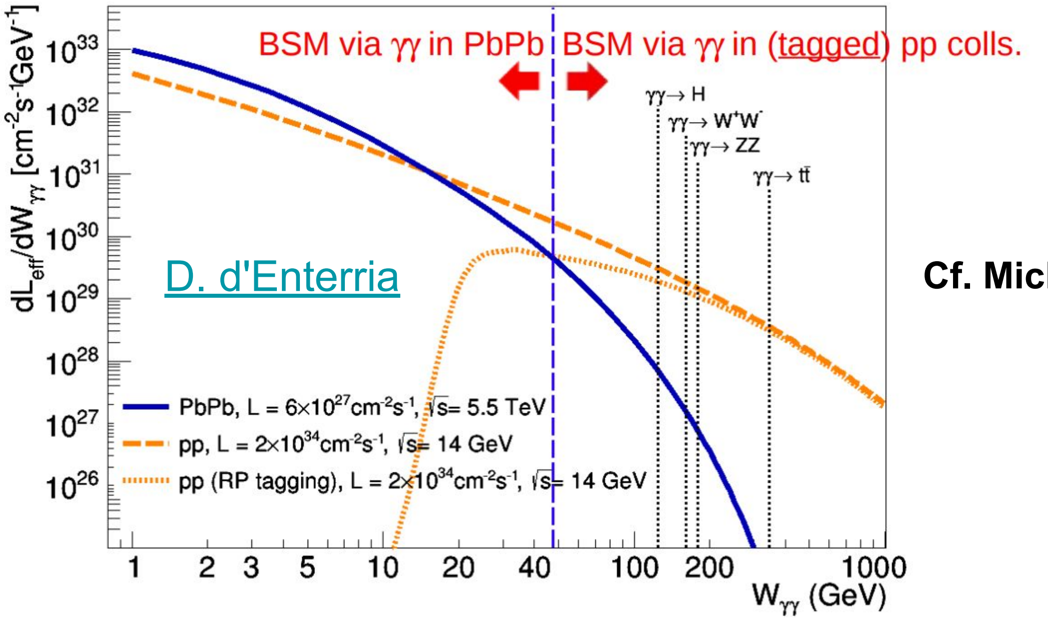
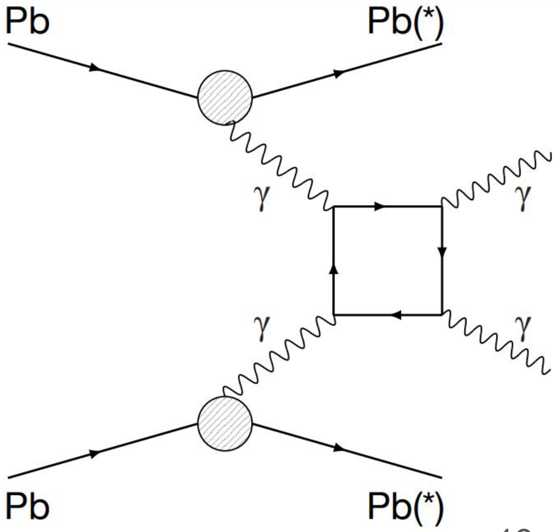


Cf. Michele's talk

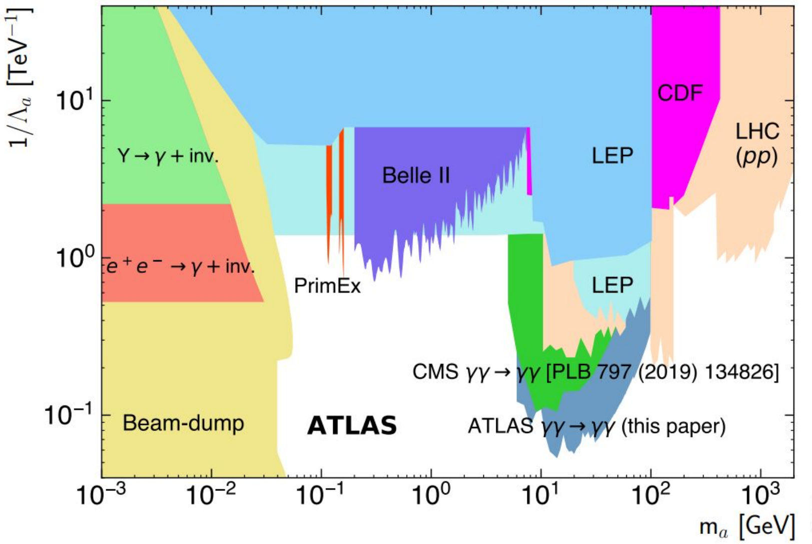


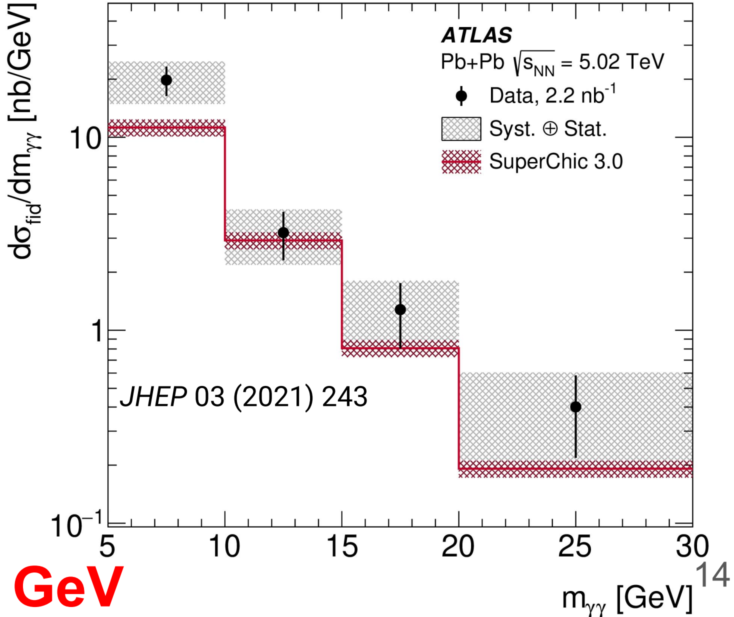
Available LbyL UPC measurements (so far)

- 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

Even differential studies!

Existing constraints from JHEP 12 (2017) 044



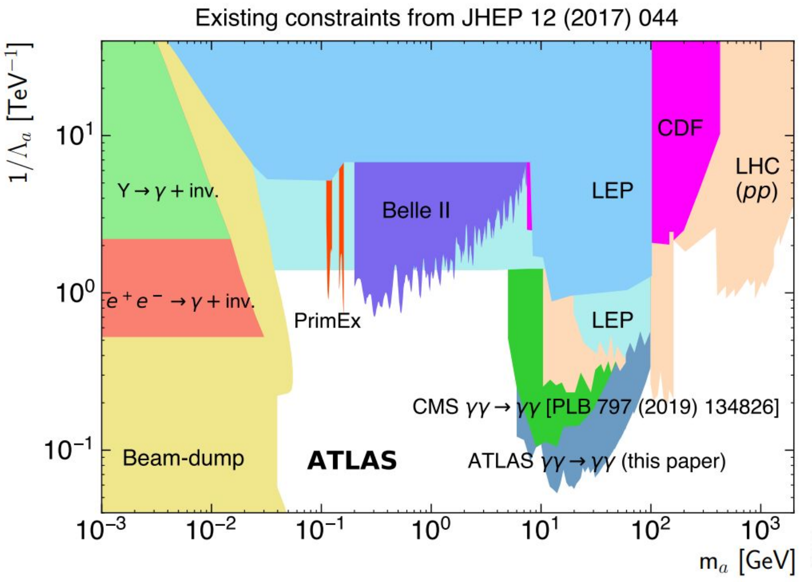


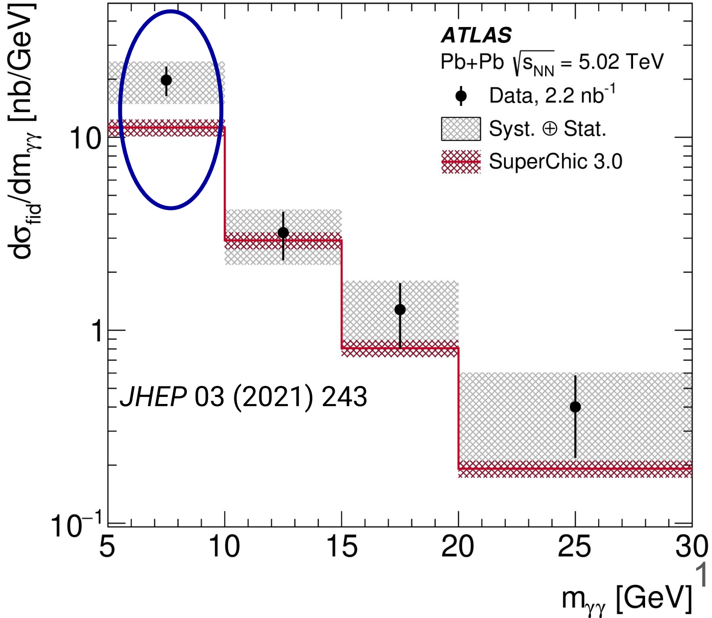
LHC nuclear collisions: best limits in <100 GeV

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?

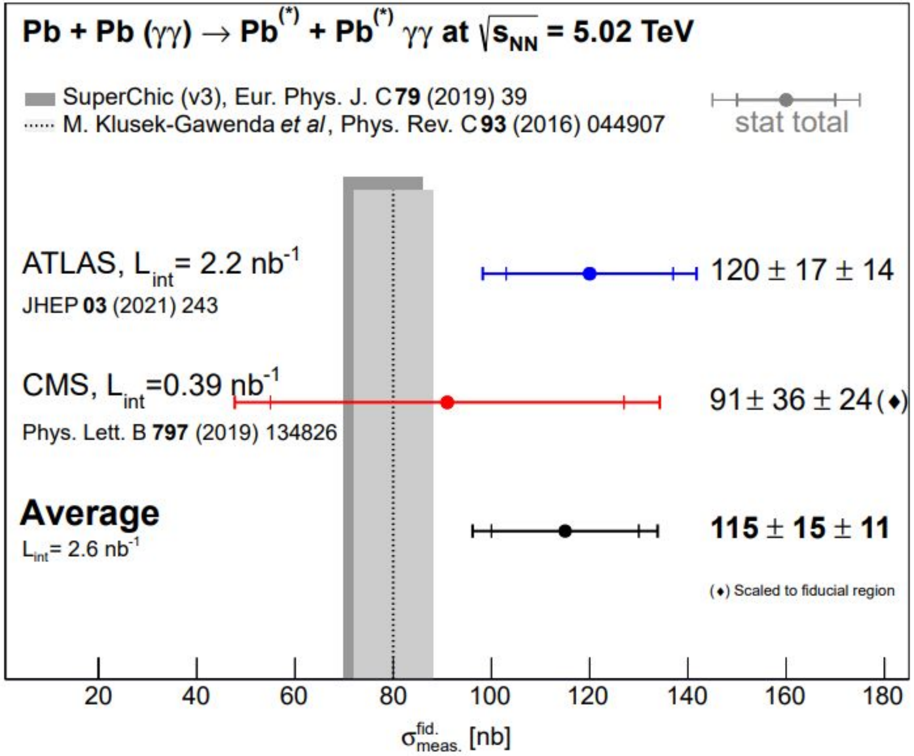




Measurement of light-by-light scattering

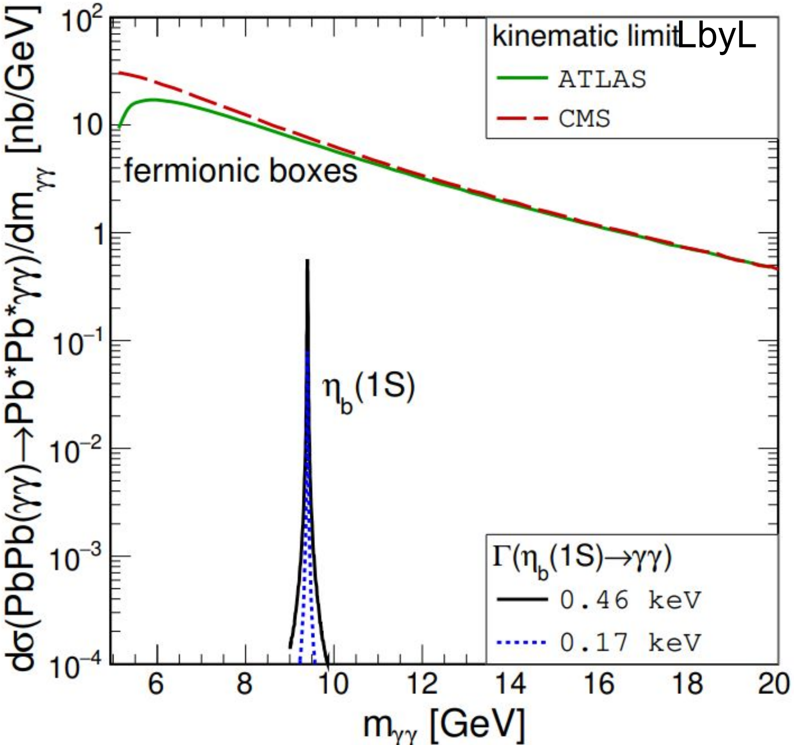
Krintiras et al., arXiv:2204.02845

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



Trying to explain **the excess**

- We calculated the inclusive σ for the **photoproduction of η_b(1S)** Krintiras et al., arXiv:2204.02845
  - $\sigma = (0.19-1.41)\ 10^{-2}$ 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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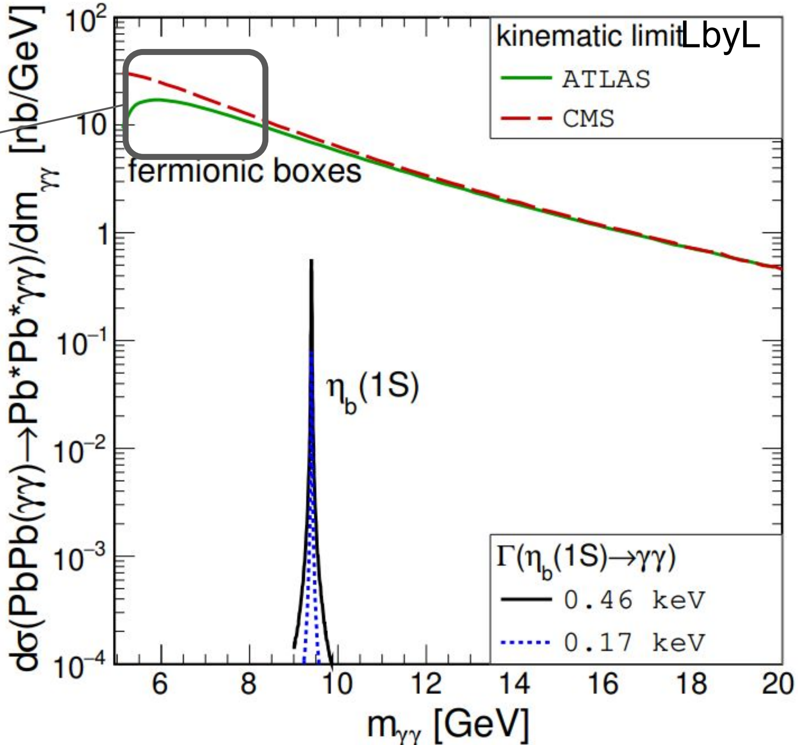
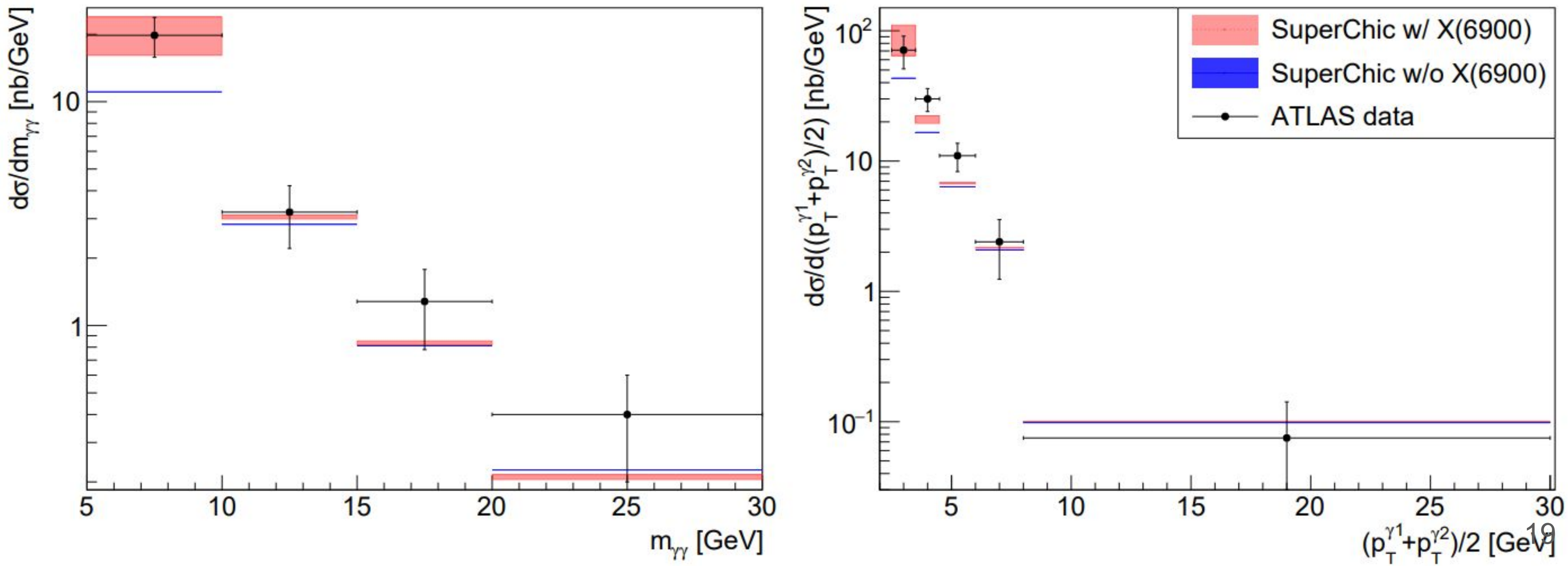
Lower trigger cut



Trying to explain **the excess**

- The recently observed **tetraquark state X(6900)**, in principle, could account for the excess
- Further measurements of the LbL scattering in the **5 to 10 GeV mass range crucial**

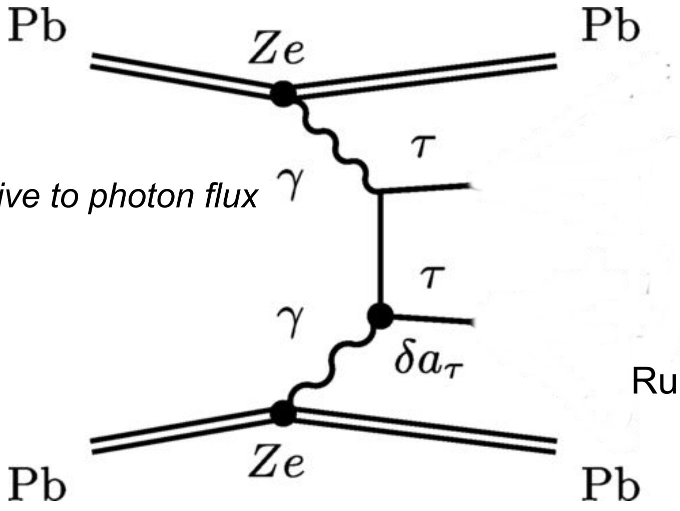
Biloshytskyi *et al* 2207.13623.



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

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

Sensitive to photon flux

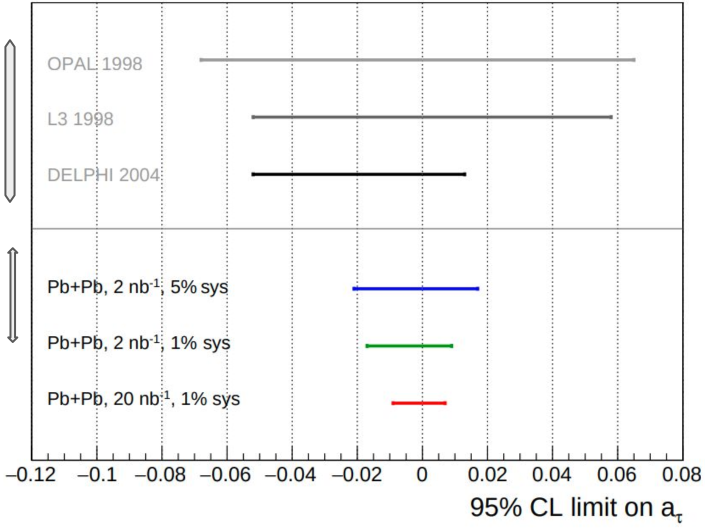


τ lepton photoproduction in ultraperipheral collisions (UPC)

LEP

Run 2 (2 /nb)

Runs 3+4 (> 10 /nb)



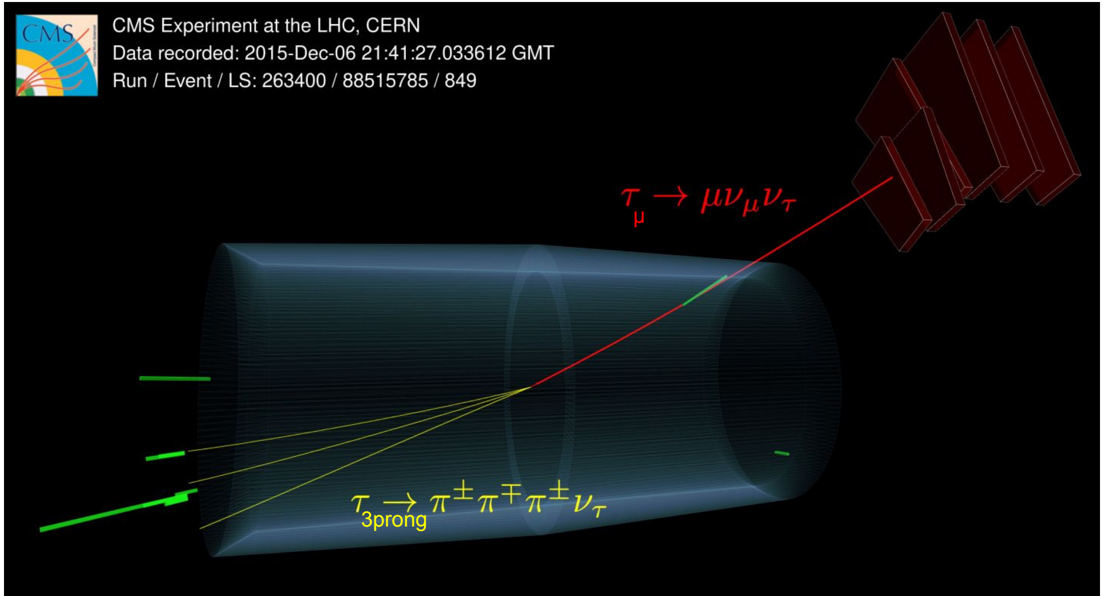
Phys. Lett .B **809** (2020) 135682 (2002.05503)
Phys. Rev. D **102** (2020) 113008 (1908.05180)

τ's are **multifaceted**

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

→ All channels needed for **ultimate precision**

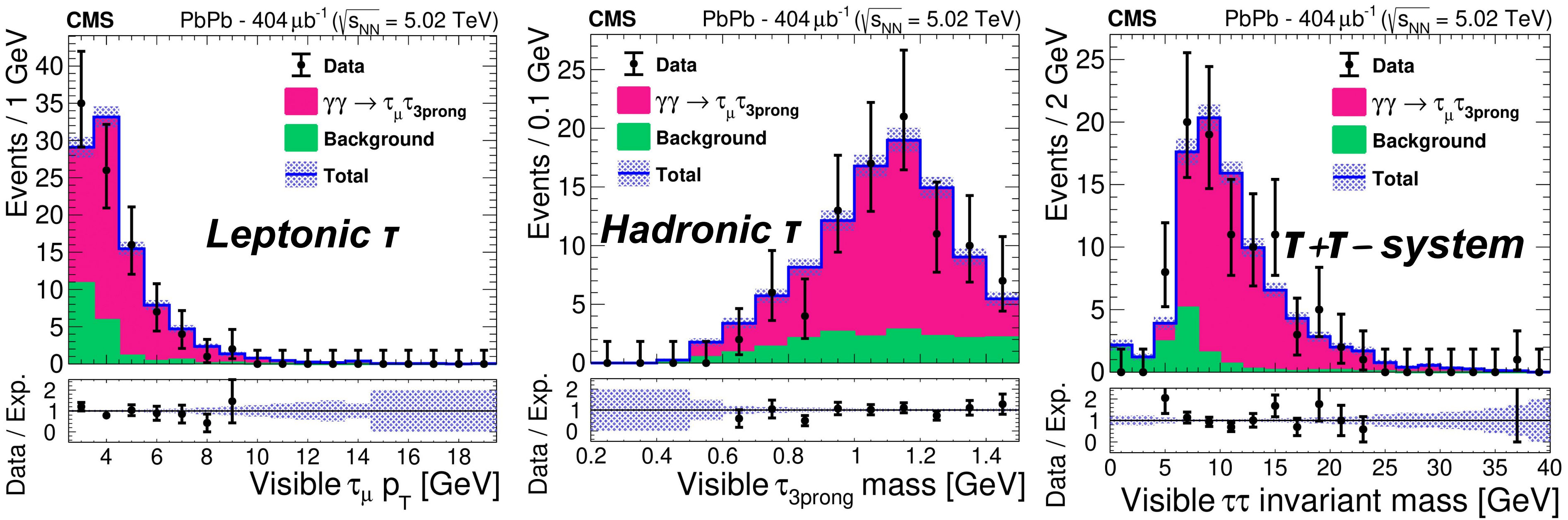
CMS-PHO-EVENTS-2022-003-2



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

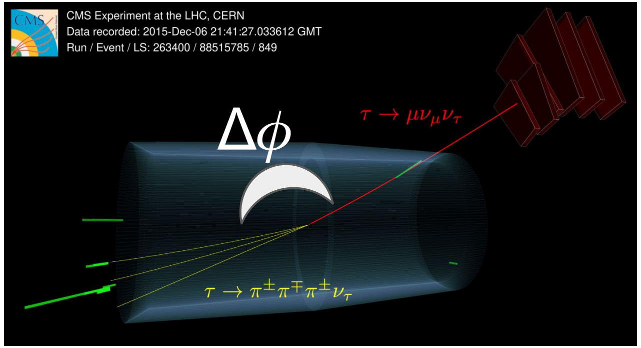
- Very good **agreement** between data & expectations
  - signal MC is scaled to the **integrated luminosity**
  - we're in an almost **bkg-free** phase space region(!)
  - **unambiguous reconstruction** of the $\tau^+\tau^-$ system

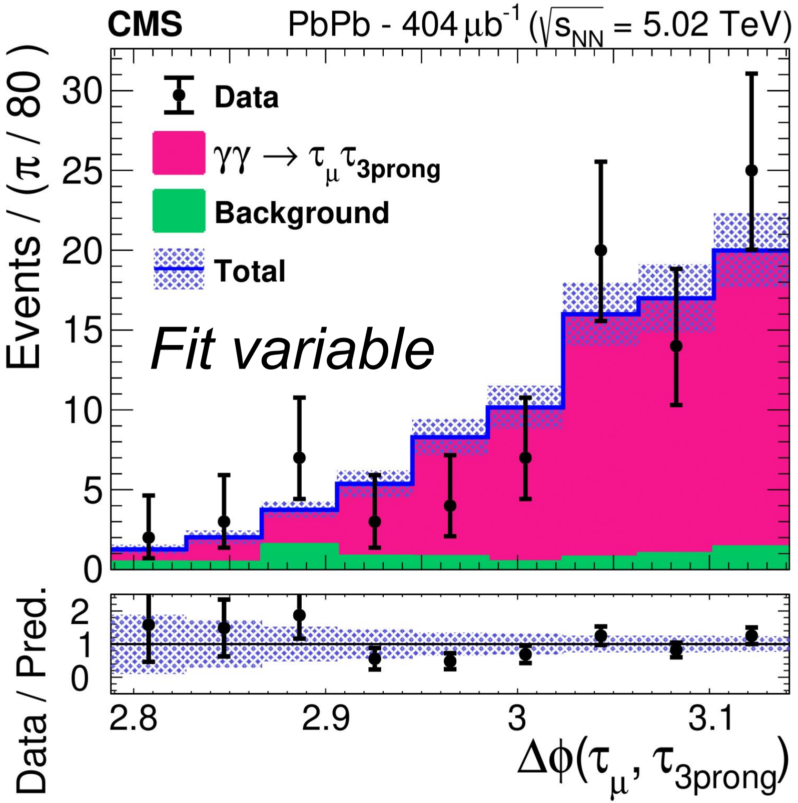
2206.05192 (submitted to PRL)



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 ± 12
- Observed significance is **more than 5σ**
  - **taking into account** systematic uncertainties
    - affecting the rate with log-normal priors
    - affecting the shape with Gaussian prior

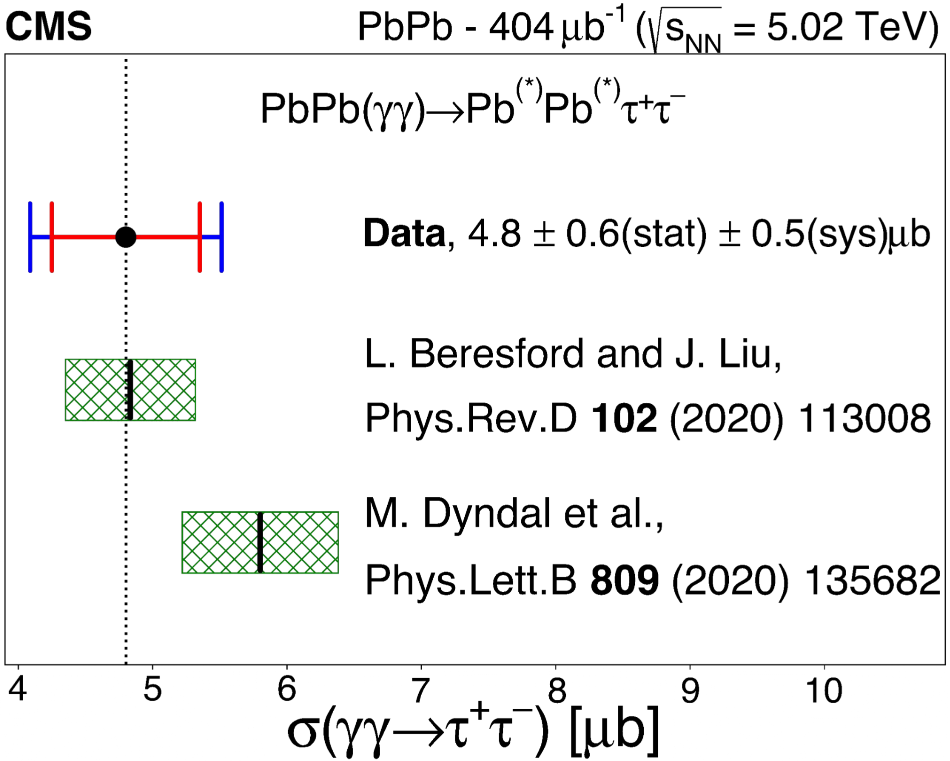




Cross section **measurement**

- Extra ingredients needed
  - **L** = 404 $/\mu b$
  - $B\tau_{\mu}$ = 17.39%
  - $B\tau_{3\,prong}$ =14.55%
  - **efficiency** (ϵ) from MC = 78.5%

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



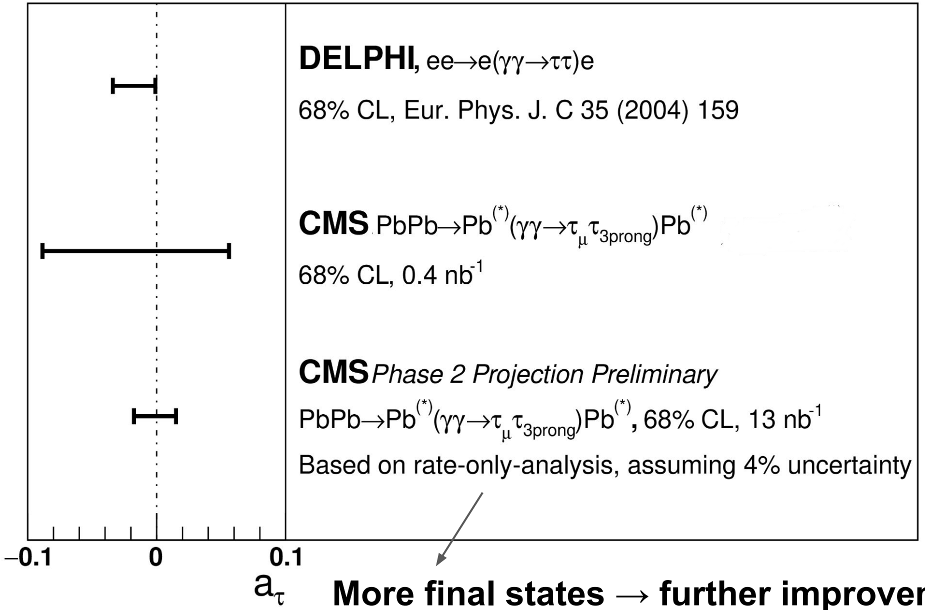
$$\sigma_{fiducial} = 4.8 \pm 0.6(stat) \pm 0.5(sys)\ \mu b$$

Constraints on a_T and **expected performance** at HL-LHC

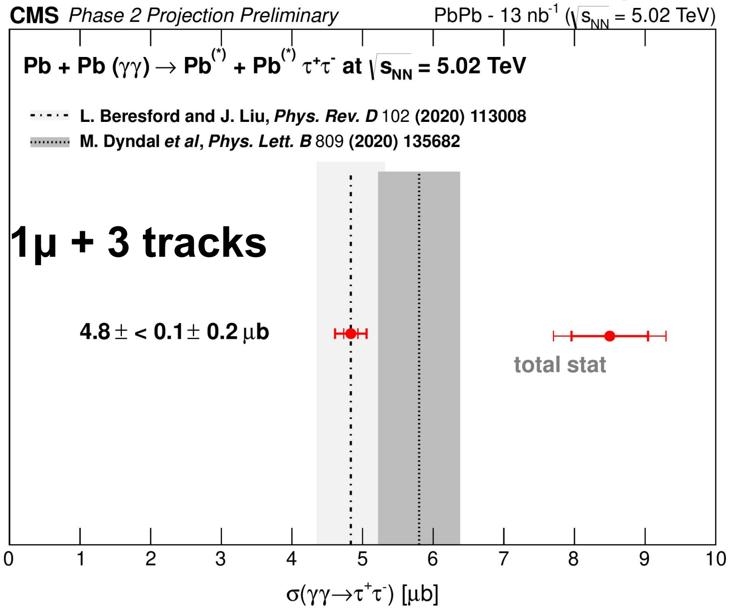
- Using the theo calculation of $\sigma(\gamma\gamma\rightarrow\tau\tau)$ as a function of a_T –scale only
  - **model-dependent measurements** at LHC can be obtained

- 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

ATLAS+CMS **Snowmass22 WhitePaper**



More final states → 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

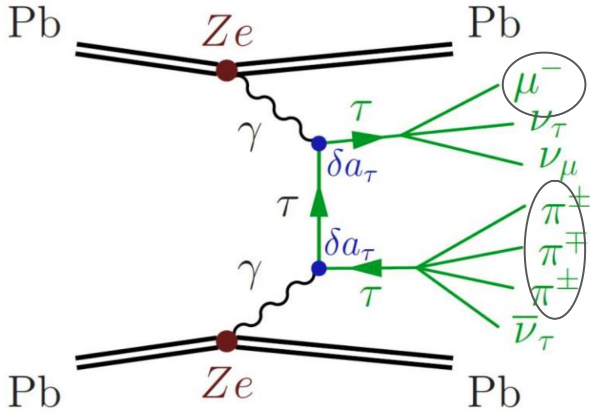
- Ample room for **cross-experiment collaboration**
  - existing measurements can be used for further **combinations** of HIC data at LHC

slides

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 mb) → O(1 M) with 2 /nb
  - **we expected <100** 1μ+3 tracks events **within** acceptance

- τ lepton reco **challenging** at low-p_T (<20 GeV)
  - till recently **no** measurement in nuclear collisions
    - indirect presence via Z/γ* in top quark events



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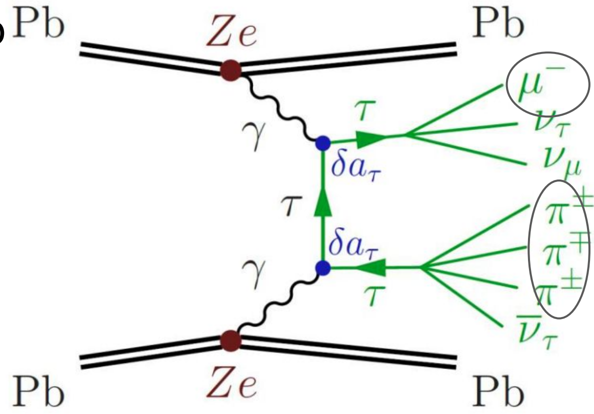

- τ lepton reco **challenging** at low-p_T (<20 GeV)
  - till recently **no** measurement in nuclear collisions
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- Take advantage of **UPC** events and τ lepton **unique** decay signatures
  - low track multiplicity (N_{ch}), UPC triggers, and "exclusivity" requirements
    - **single lepton** triggers
    - **no activity** in forward hadron (HF) calorimeters above noise threshold

- Aim **to establish** $\gamma\gamma \to \tau\tau$ at LHC as **the first** crucial step during a dedicated physics program
  - using **PbPb** collisions in 2015 (~0.5 /nb)
  - followed by the **inclusion** of 2018 (~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 & + >=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_{ch}=3
  - other N_{ch} and HF activity regions used in **bkg estimation**
- MC simulation for **signal and validation** (main bkg, efficiency)

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

→ **Low-p_T** muons

Overview of **uncertainties**

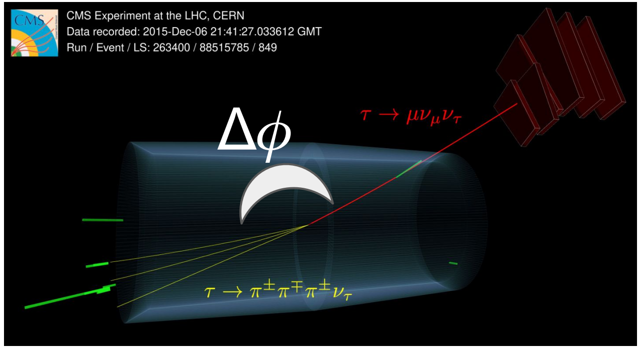
- **Statistically dominated** (13%)
- Systematic wise (9.7%) the **dominant sources** are related to
  - muons (trigger efficiency)
  - pion efficiency
  - luminosity

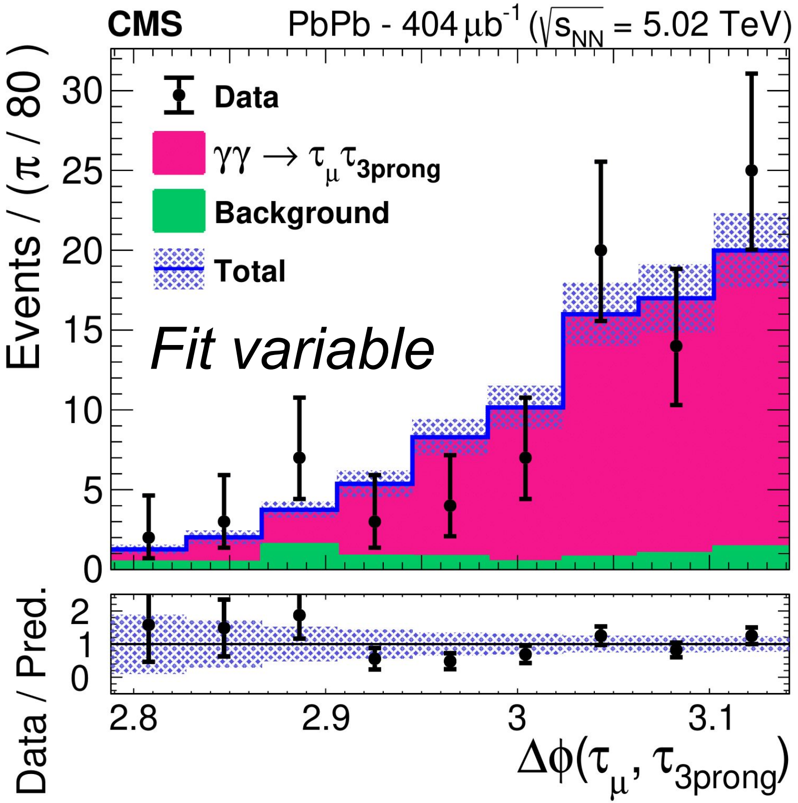
- Total uncertainty comparable to the current theory uncertainty
  - difficult to **discriminate** between existing models
  - **model-dependent** limits on anomalous moments can be set

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
τ lepton branching fraction	0.6
Effect of n_{ch} on background shape	0.2
Total (systematic)	9.7

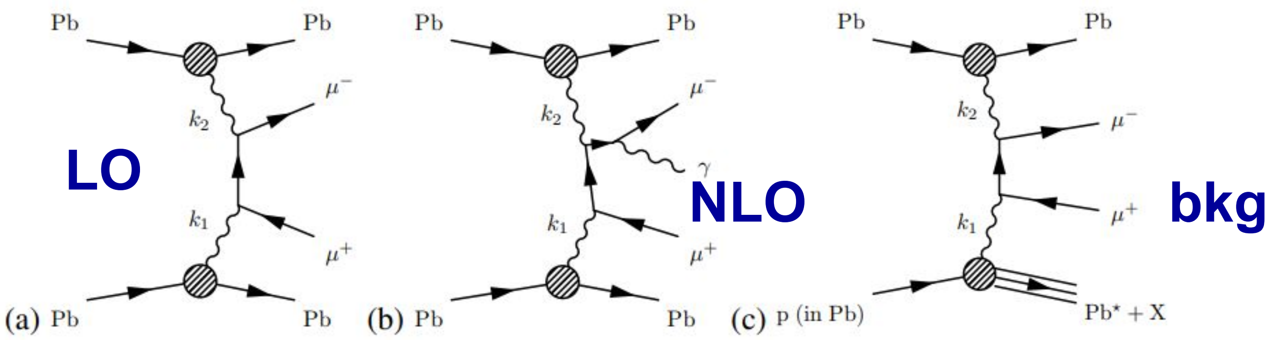
Signal yield estimation

- 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 ± 12
- Observed significance is **more than 5σ**
  - **taking into account** systematic uncertainties
    - affecting the rate with log-normal priors
    - affecting the shape with Gaussian prior





Exclusive dilepton processes & dissociation



$PbPb(\gamma\gamma) \rightarrow \mu^+\mu^-(Pb^{(\star)}Pb^{(\star)})$ is the primary signal Breit-Wheeler process cross section implemented in STARlight, SuperChic, etc.
$PbPb(\gamma\gamma) \rightarrow \mu^+\mu^-\gamma(Pb^{(\star)}Pb^{(\star)})$ 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
$Pb + N/Pb(\gamma\gamma) \rightarrow \mu^+\mu^-X(Pb^\star Pb^{(\star)})$ is dissociative background (non-EPA) process, including nuclear breakup as well, modeled using LPair (μμ) 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 yy->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**

Eur. Phys. J. C (2019) 79:39
https://doi.org/10.1140/epjc/s10052-018-6530-5
THE EUROPEAN PHYSICAL JOURNAL C
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Regular Article - Theoretical Physics

Exclusive LHC physics with heavy ions: SuperChic 3

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

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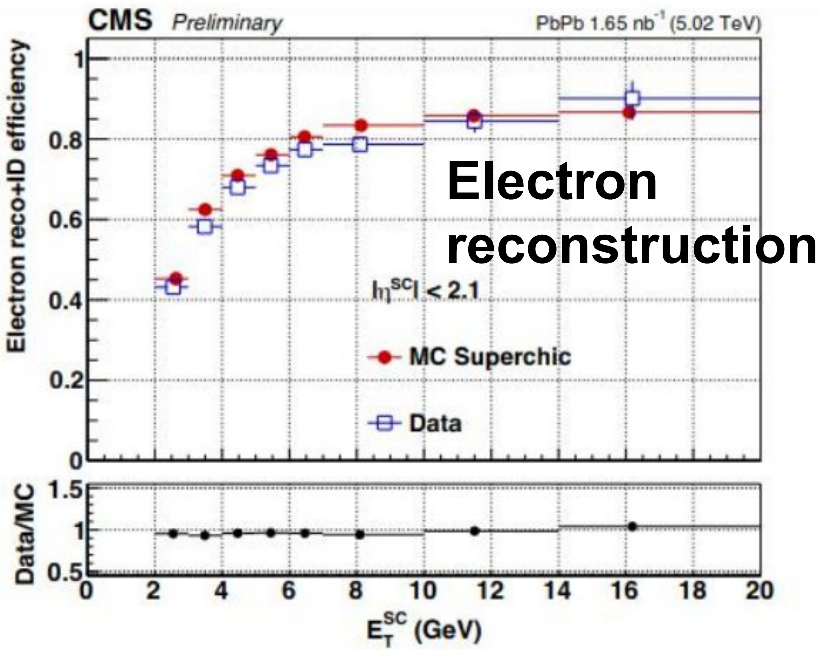
Computer Physics Communications
Volume 253, August 2020, 107181

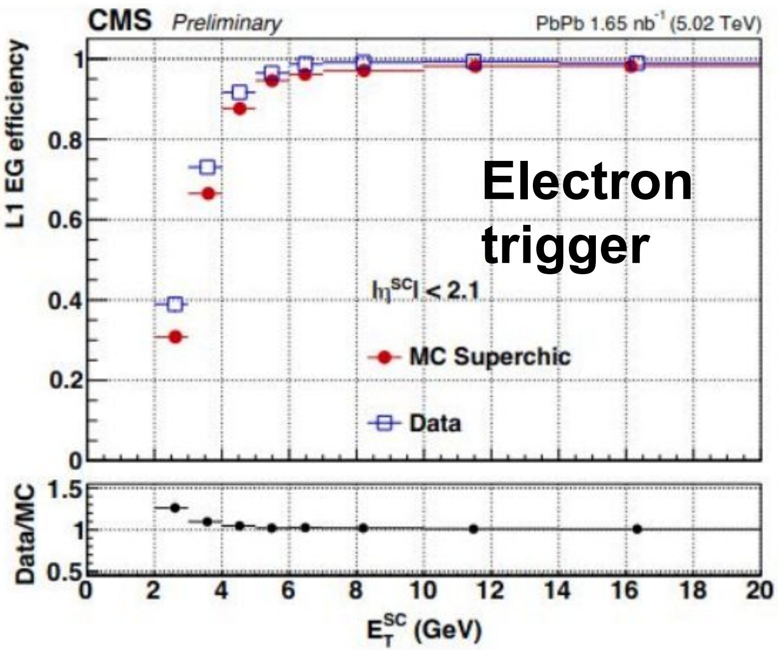
A generator of forward neutrons for ultra-peripheral collisions: n_0^0n ☆, ☆☆

M. Broz, J.G. Contreras, J.D. Tapia Takaki

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.

Theory **predictions**

- **LbyL** cross sections calculated based on **SuperChic v3** [16] and **M. Klusek-Gawenda *et al*** [17]
  - for **three** phase space regions, reflecting experiments' **fiducial regions**
    - based on **single-/pair- photon kinematics**
  - **good agreement** between the two predictions found
  - **lower** value in comparison to the one in *Phys.Lett.B* 797 (2019) 134826
    - the assigned theory unc (10%) **comparable** to the difference

arXiv:2204.02845

$\sqrt{s_{NN}}$	Process	Accuracy	$\sigma^{\text{fid.}}_{\text{theo.}}$ [nb]	Phase space region
5.02 TeV	$\text{Pb}+\text{Pb}\,(\gamma\gamma) \rightarrow \text{Pb}^{(*)}+\text{Pb}^{(*)}\,\gamma\gamma$	LO	101 ± 10 [16]	$E_T > 2.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	103 ± 10 [17]	$E_T > 2.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	$77 \pm 8^{\dagger}$ [16]	$E_T > 2.5$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	80 ± 8 [17]	$E_T > 2.5$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 5$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	50 ± 5 [16]	$E_T > 3.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 6$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$
		LO	51 ± 5 [17]	$E_T > 3.0$ GeV, $\lvert\eta\rvert < 2.4$, $m_{\gamma\gamma} > 6$ GeV, $p_T^{\gamma\gamma} < 1$ GeV, $A_\phi < 0.01$

→ **used as extrapolation correction**

Extrapolation correction

- Fiducial-region definition **differs** between input measurements in **single-photon E_T**
  - ATLAS: > 2.**5** GeV
  - CMS: > 2.**0** GeV

- We need to “scale down” the CMS result by **76%**
  - using the predictions from SuperChic (highlighted in the previous table)
  - we found the pair photon p_T<1 GeV to have **no significant effect** (same for the accoplanarity)
    - for future reference

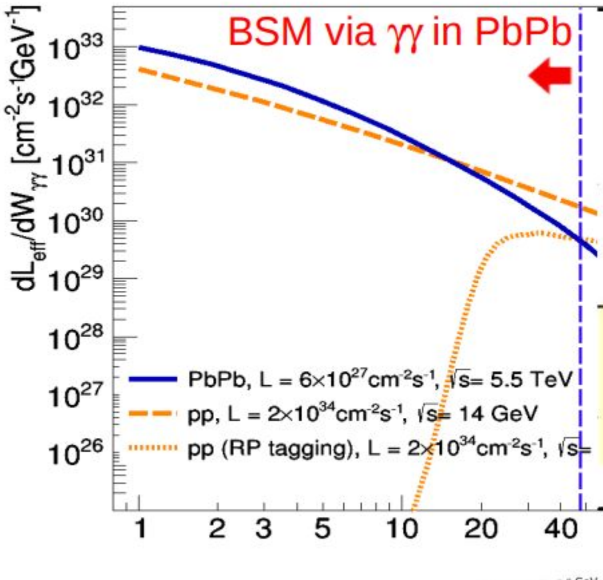
arXiv:2204.02845

		ATLAS		CMS	
$\sqrt{s_{NN}}$	Year (Lumi. [nb^{-1}])	$\sigma^{fid.}_{raw}$ [nb]	$\sigma^{fid.}_{cor.}$ [nb]	$\sigma^{fid.}_{raw}$ [nb]	$\sigma^{fid.}_{cor.}$ [nb]
5.02 TeV	2015 (0.39–0.48)	70 ± 29 [11]	108 ± 45	120 ± 55 [12]	91 ± 42†
	2018 (1.73)	78 ± 15 [15]	120 ± 23	—	—
	2015+2018 (2.2)	120 ± 22 [10]	120 ± 22†	—	—

(boxed) → **used in the average**

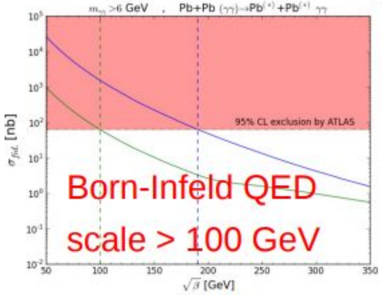
Summary: BSM searches via UPC PbPb@LHC

- Competitive mass range for BSM in UPCs PbPb: $m_{\gamma\gamma\to X}$=0.5–45 GeV



$\gamma\gamma \to \tilde{f}\bar{\tilde{f}},\ \tilde{\chi}_i^+\tilde{\chi}_i^-$	pairs of sfermions, charginos	NO
$\gamma\gamma \to \tilde{g}\tilde{g}$	pairs of gluinos	NO
$\gamma\gamma \to M^+M^-$	pairs of monopoles	YES
$\gamma\gamma \to H^+H^-$	pairs of charged-Higgs	NO
$\gamma\gamma \to W^+W^-$	anom. W inter., extra dimensions	NO
$\gamma\gamma \to 4W/(Z)$	WW scatt., quartic anom. W,Z	NO
$\gamma\gamma \to t\bar{t}$	anomalous top quark interactions	NO
$\gamma\gamma \to \gamma\gamma$	Born-Infeld QED, non-conmutat. theories)	YES
$\gamma\gamma \to \phi$	Scalars (axions, radions, ...)	YES
$\gamma\gamma \to G$	Tensors (gravitons,...)	YES
$\gamma\gamma \to S[\tilde{t}\bar{\tilde{t}}]$	-onia (monopolium, $\tilde{t}\bar{\tilde{t}}$ stoponium)	YES
$\gamma\gamma \to H, A \to bb$	MSSM heavy Higgs, interm. $\tan\beta$	NO

- First BSM limits set:



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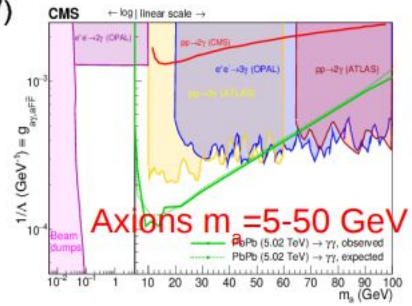
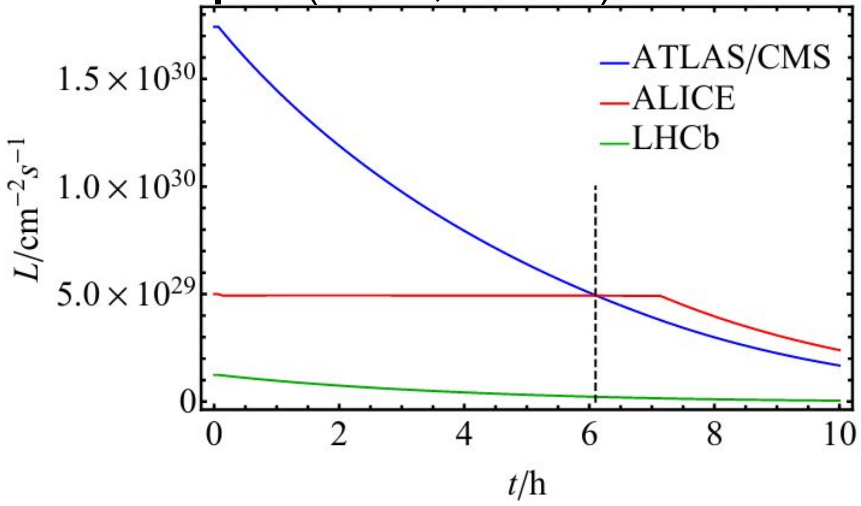
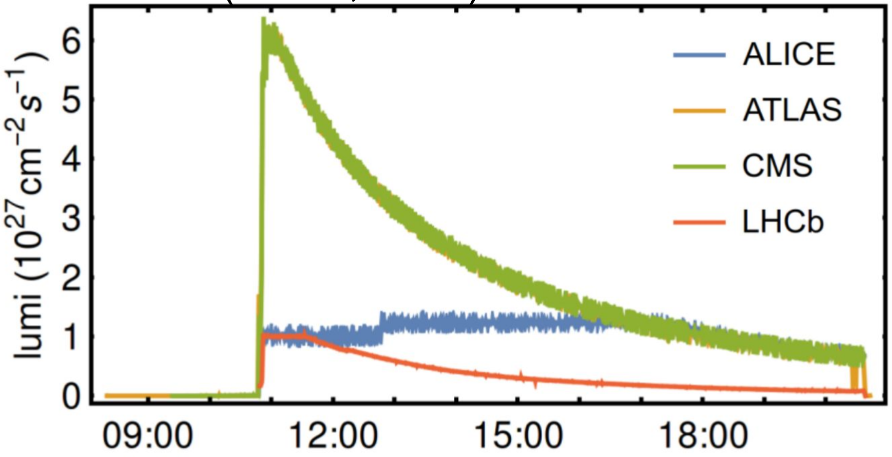


Heavy ion collisions (HIC) at LHC

pPb (Run 2, 200 /nb)



PbPb (Run 2, 2 /nb)



- 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