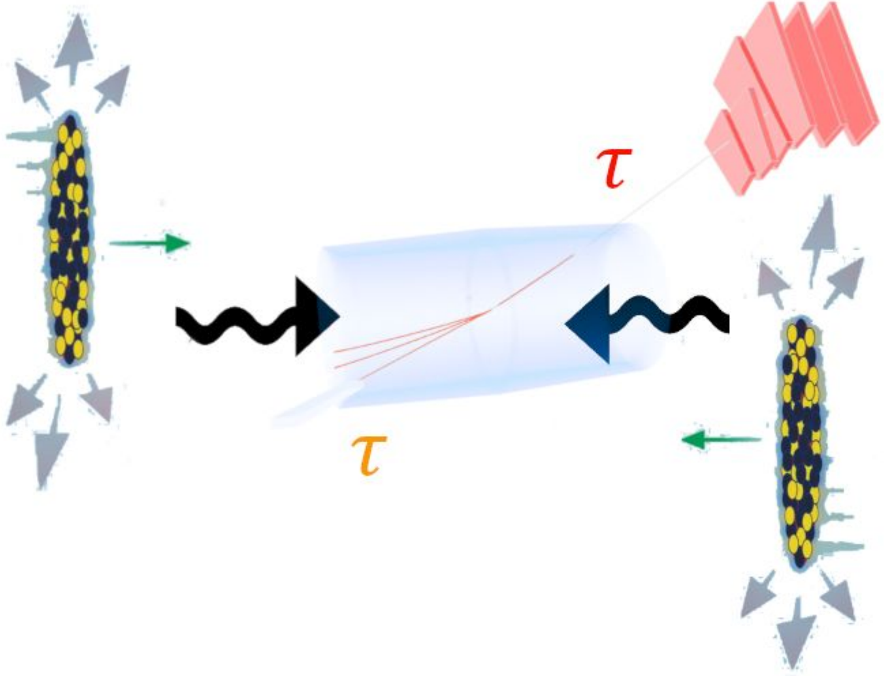


UPC studies, interplay between QCD, QED and BSM searches

GK Krintiras (cern.ch/gkrintir)

U.S. DEPARTMENT OF ENERGY | Office of Science

11 talks in T09+1 Plenary

First dedicated parallel session for UPC in QM series

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

Last workshop

- Run 2 assumptions:

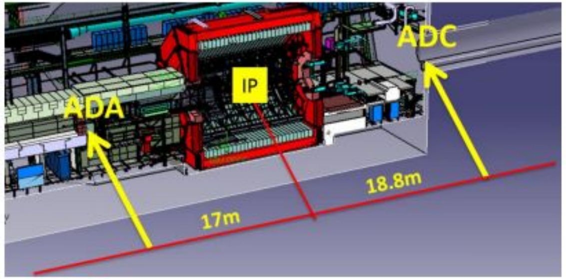
Expectations →

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
- $\gamma\gamma \to \gamma\gamma$: UPC probe to physics beyond SM

← **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

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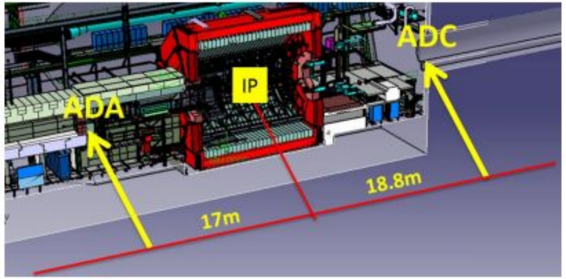
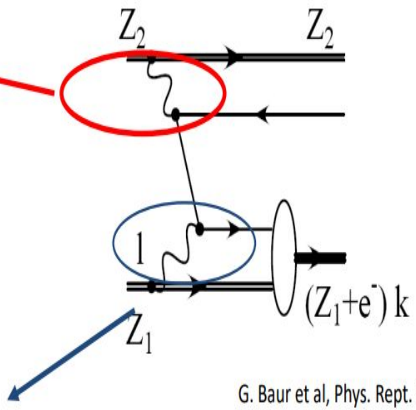


Irony: It's UPC events that limit luminosity production!

Pair production $\propto Z_1^2 Z_2^2$

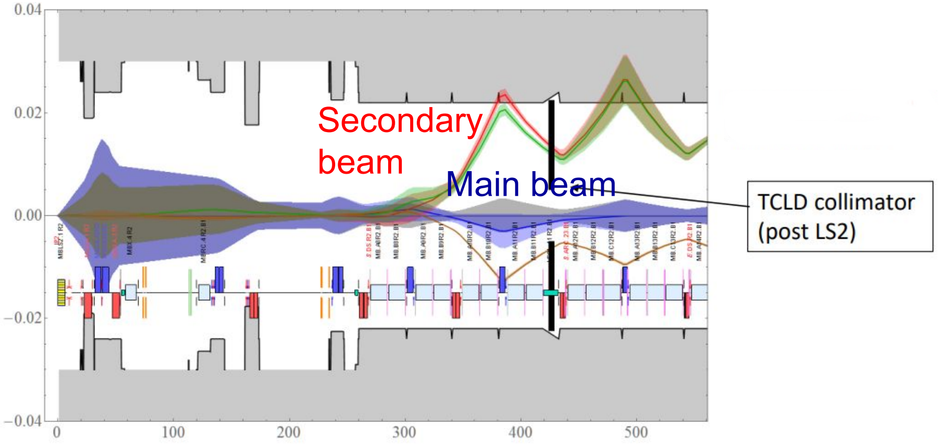


Radial wave function of $1s_{1/2}$ state of hydrogen-like atom in its rest frame

$$R_{10}(r) = \left(\frac{Z_1}{a_0}\right)^{3/2} 2\exp\left(-\frac{Z_1 r}{a_0}\right)$$

$$\Rightarrow \Psi(0) \sim Z_1^{3/2} \Rightarrow |\Psi(0)|^2 \sim Z_1^3$$

G. Baur et al, Phys. Rept. 364 (2002) 359



LHC IP2 (ALICE location)

Total cross-section $\sim Z_2^2 Z_1^5$

$$\text{BFPP: } {}^{208}Pb^{82+} + {}^{208}Pb^{82+} \longrightarrow {}^{208}Pb^{82+} + {}^{208}Pb^{81+} + e^+,$$

Bound-Free Pair Production

$$\approx \begin{cases} 0.2 \text{ b for Cu-Cu RHIC} \\ 114 \text{ b for Au-Au RHIC} \\ 281 \text{ b for Pb-Pb LHC} \end{cases}$$

Prospects for Run 2

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p-Pb	5.1 or 8 TeV	50 nb^{-1}	$\sim$2

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

Done + much more ;D

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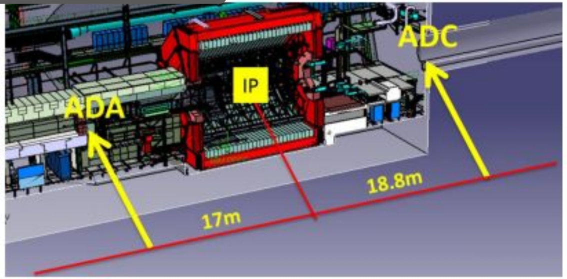
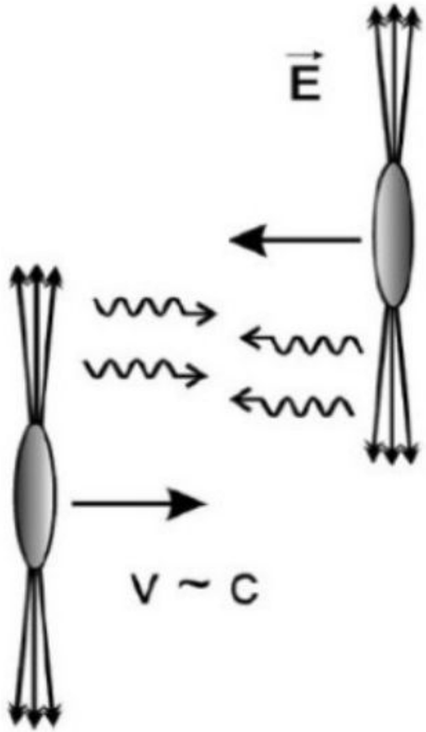


Physics Processes in Ultraperipheral Collisions



Coherent photoproduction: the photon couples to the nucleus as a whole

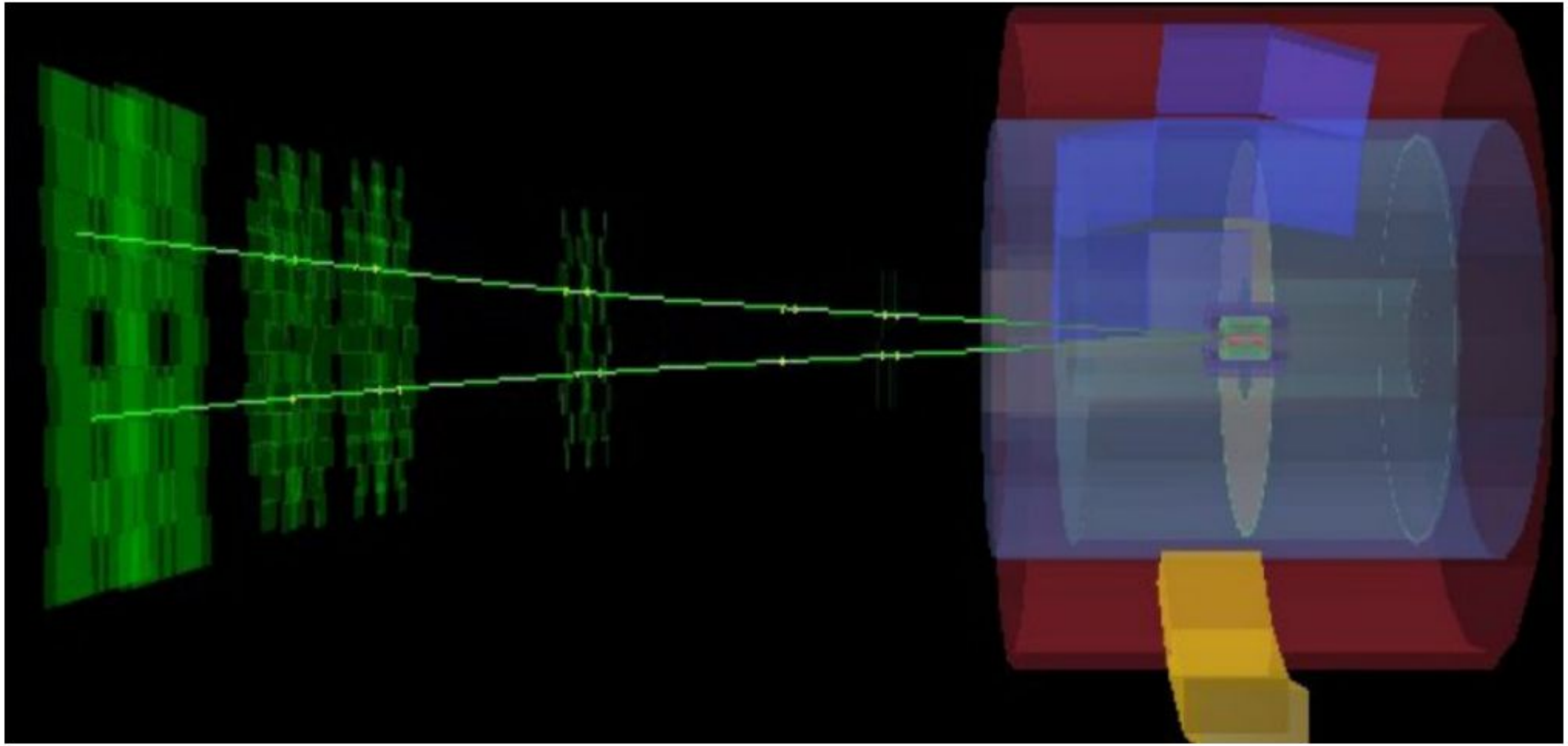
Incoherent photoproduction: the photon couples to the nucleons inside

Photon-photon interaction: photons from the two nuclei can interact with each other producing a lepton pair

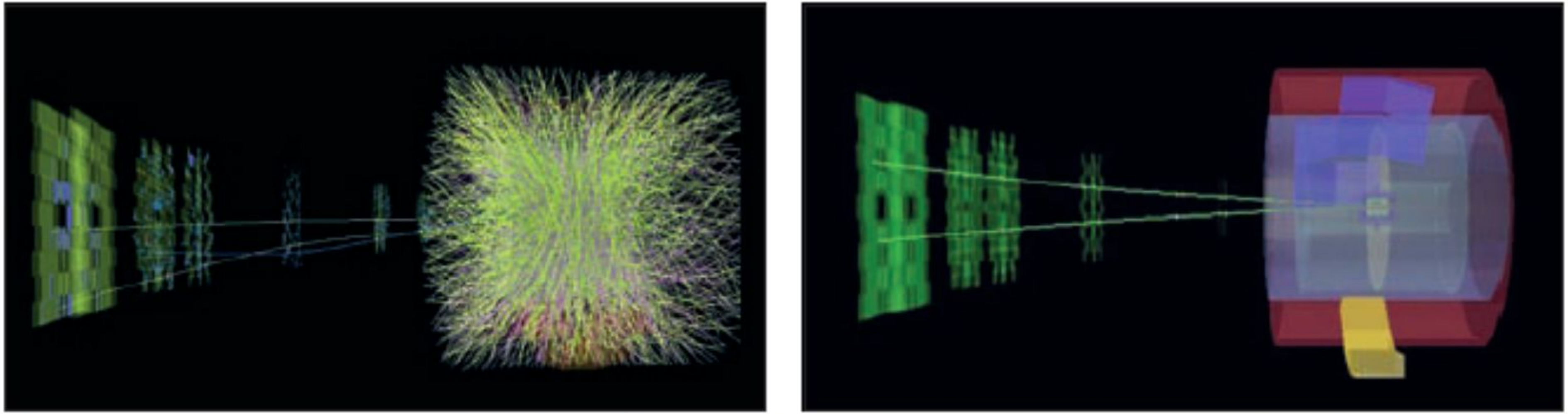
Photonuclear dissociation: neutrons can be ejected from the nucleus by photon induced nuclear break-up

How UPC events typically look like?

Just two muon tracks in an otherwise empty detector



And in comparison with hadronic events?



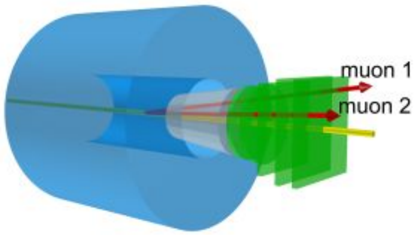
J/ψ candidates in a central PbPb collision (left) and in an ultra-peripheral collision (right).

PbPb produce both the messiest and the cleanest events at the LHC ;D

How we reconstruct leptons from UPC events?

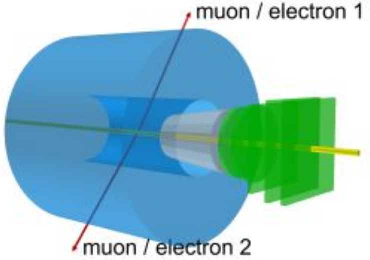
- Analysis criteria: *just two tracks in an otherwise empty detector*
- J/ψ at low-p_T; different laboratory rapidity intervals

|y| for reference



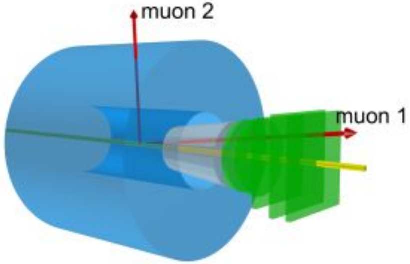
Forward

- Both tracks in muon arm
- J/ψ rapidity $2.5 < |y| < 4.0$
- Pb-Pb and p-Pb



Mid-rapidity

- Both muons or electrons in central barrel
- J/ψ rapidity $|y| < 0.9$
- Pb-Pb and p-Pb



Semi-forward

- One muon in muon arm, one in central barrel
- J/ψ rapidity $1.2 < |y| < 2.7$
- p-Pb

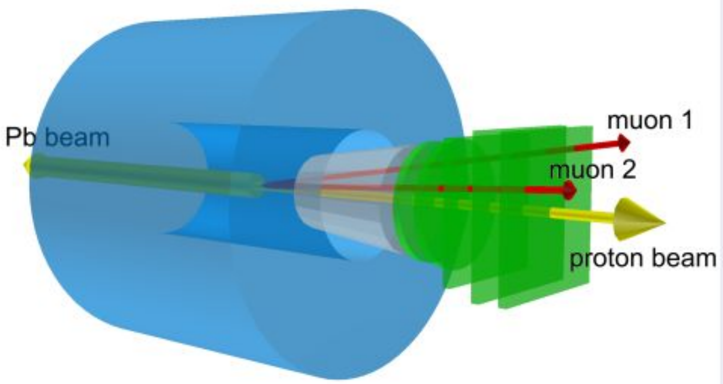
What do we care about |y| at the end?

- Lead-ion is most likely (~95%) the photon source
- Photon-proton CM energy $W^2_{\gamma p} = 2E_p M_{J/\psi} e^{-y}$ is uniquely determined by J/ψ rapidity

(E_p is proton beam energy, $M_{J/\psi}$ is mass of J/ψ and y is rapidity of J/ψ, defined according proton beam direction)

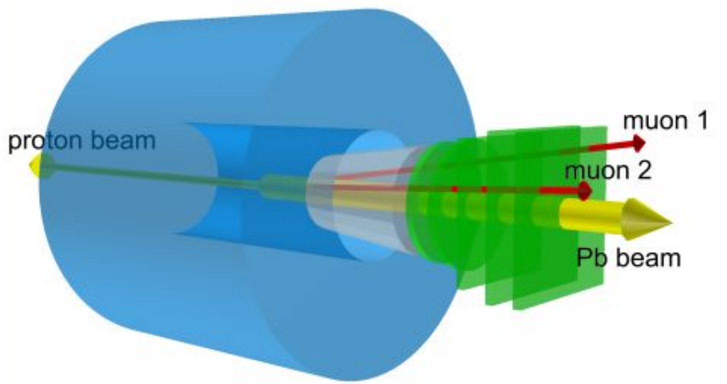
p-Pb: proton beam → muon arm

- Positive (forward) rapidity of J/ψ, lower values of $W_{\gamma p}$



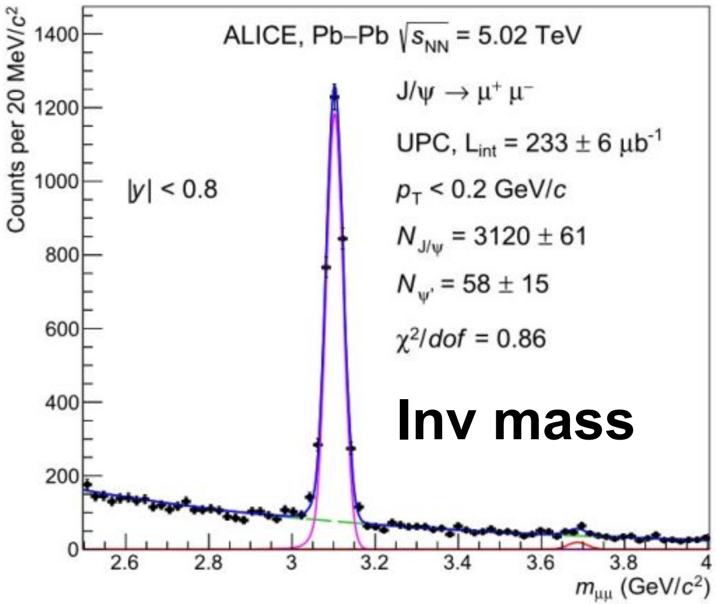
Pb-p: Pb beam → muon arm

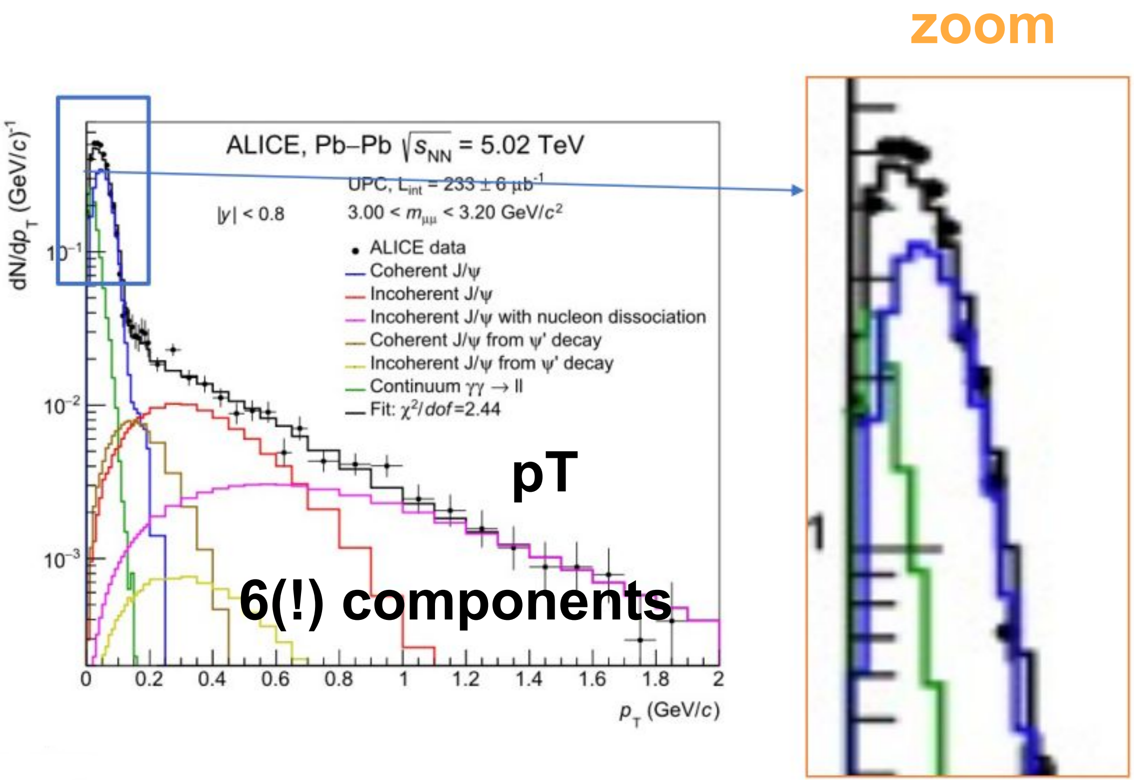
- Negative (backward) rapidity of J/ψ, higher values of $W_{\gamma p}$



We're probing 3 orders of magnitude in Wγp

How are we extracting the signal?

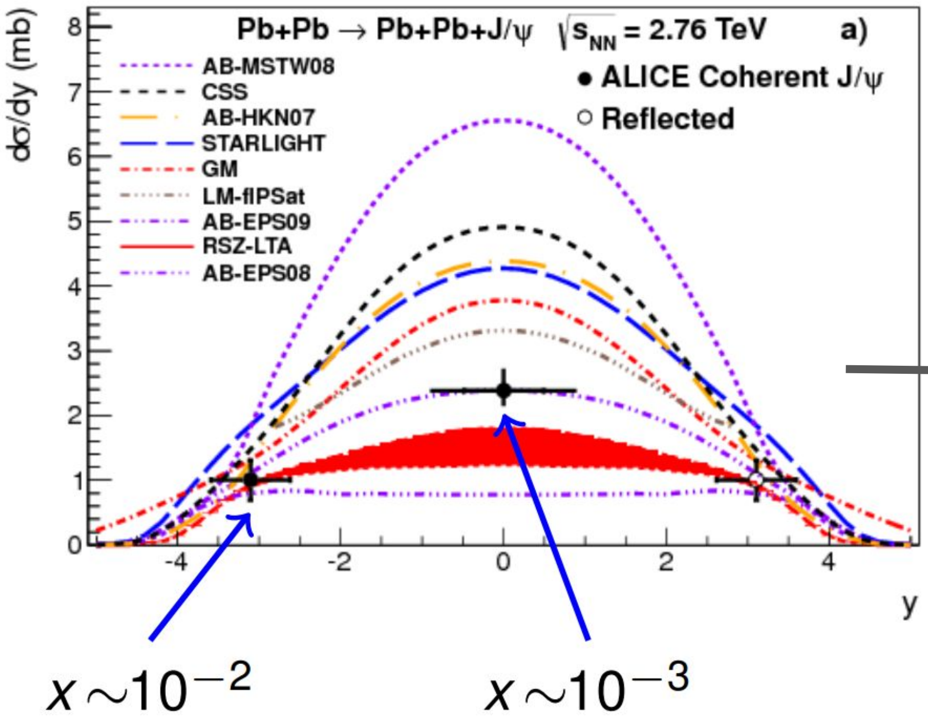


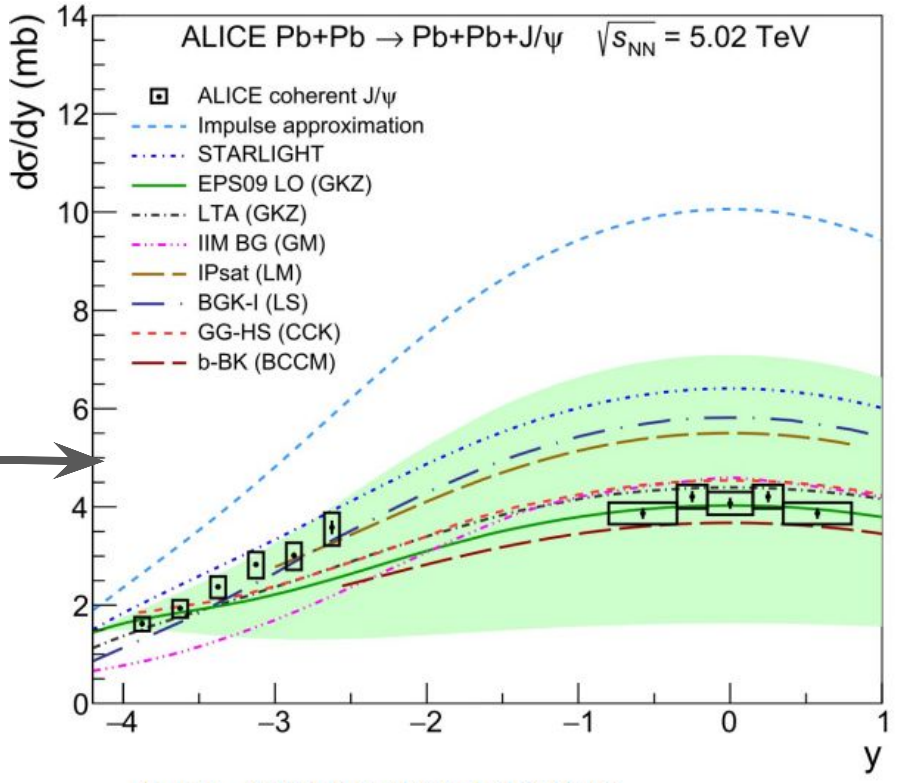


Multi-template fits → high precision reveals mismodelings

State-of-the-art comparisons

Last workshop



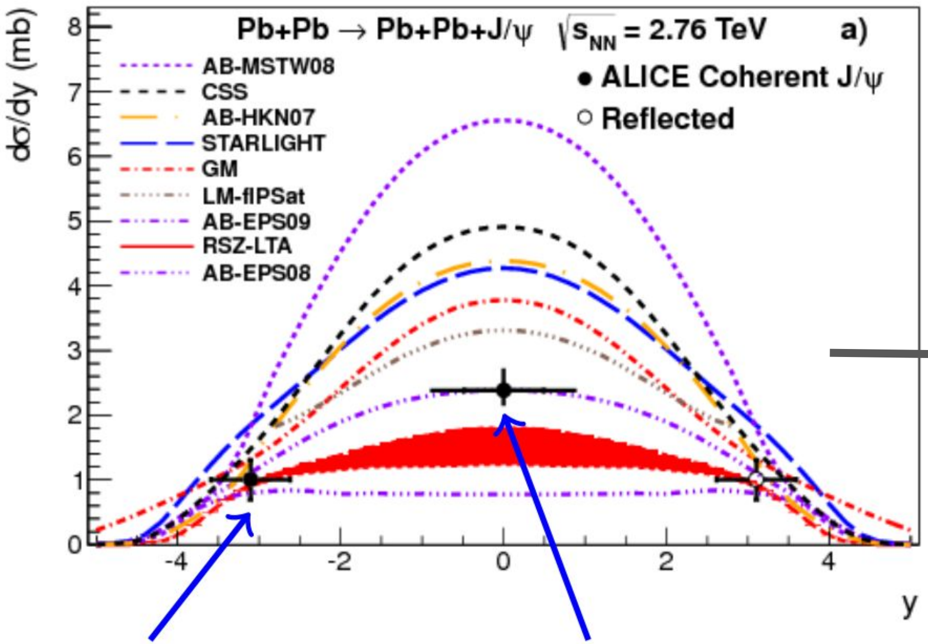


ALICE: PLB 798 (2019) 134926

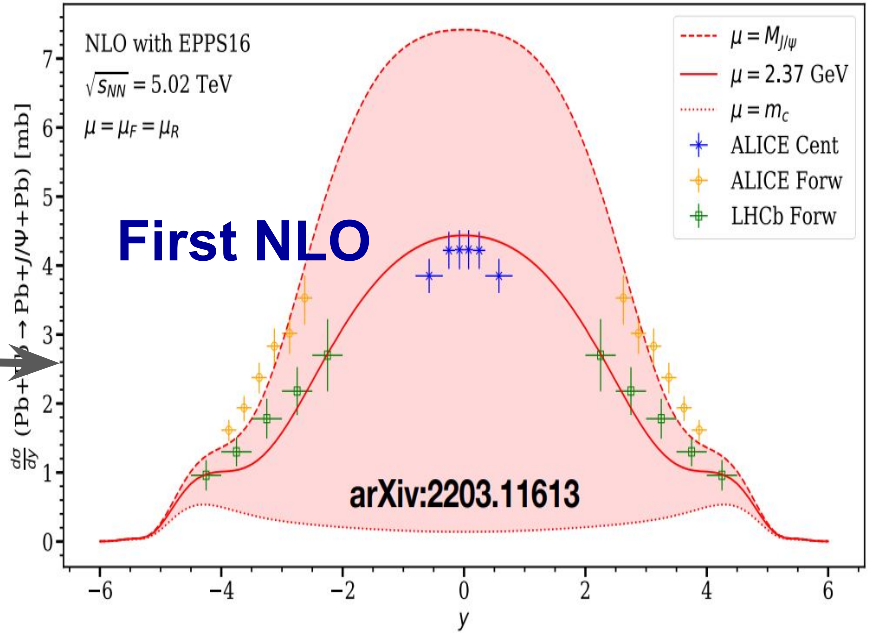
ALICE: EPJC (2021) 81:712

State-of-the-art comparisons

Last workshop

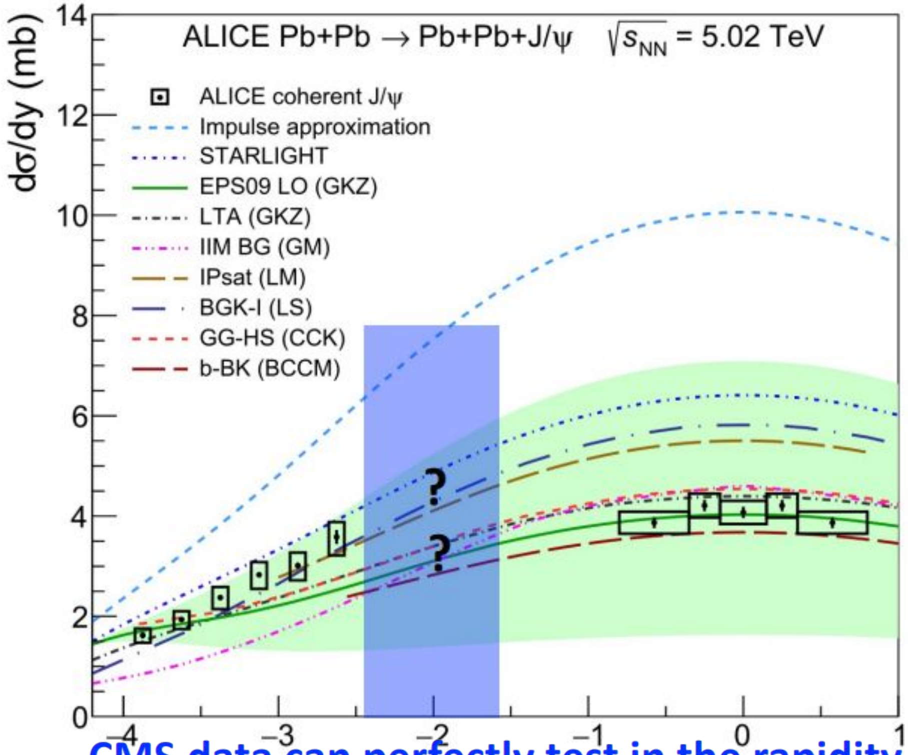


$x \sim 10^{-2}$ $x \sim 10^{-3}$

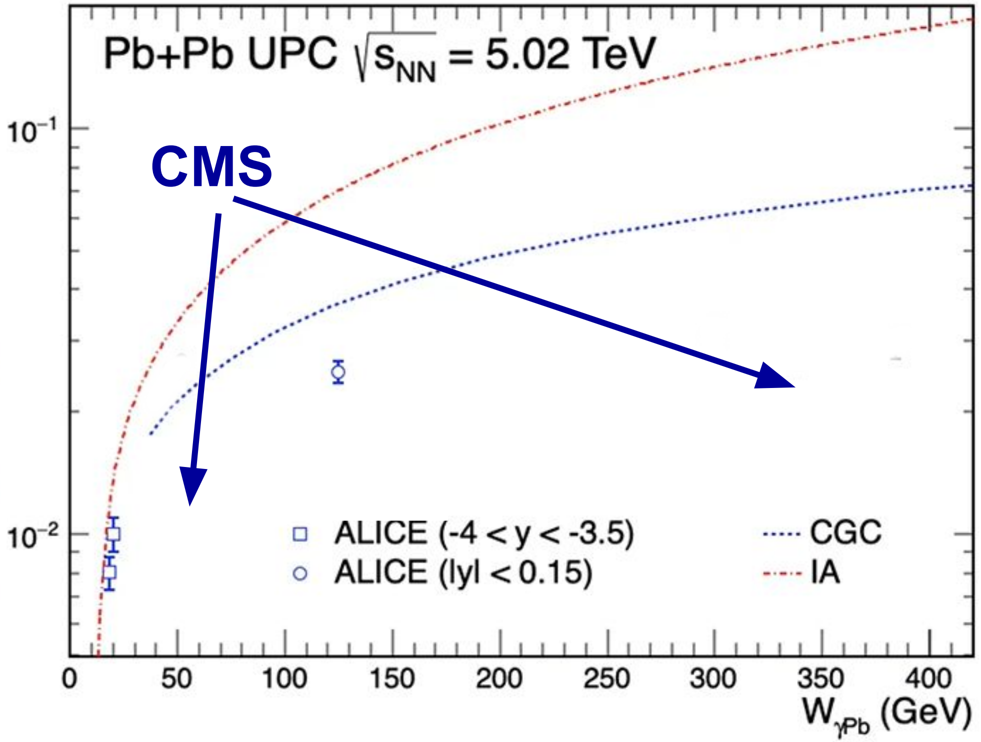


More state-of-the-art comparisons coming..

Hopefully next workshop ;D



CMS data can perfectly test in the rapidity gap region (1.6<|y|<2.4)

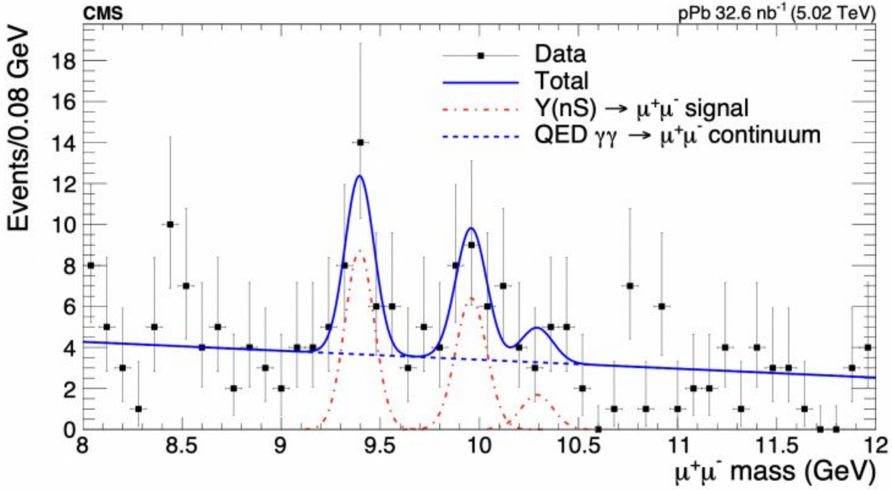


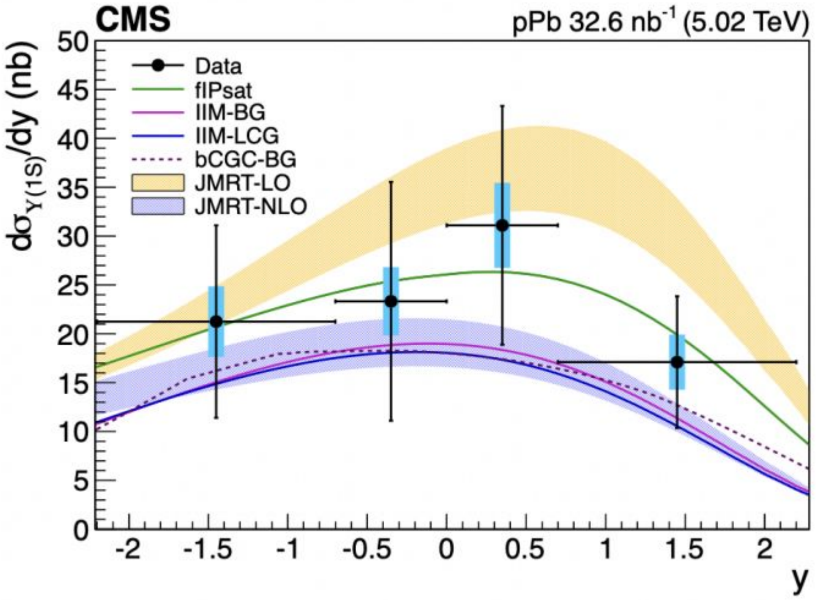
Upsilon photo-production in UPC p+Pb

CMS, EPJC 79 (2019) 277

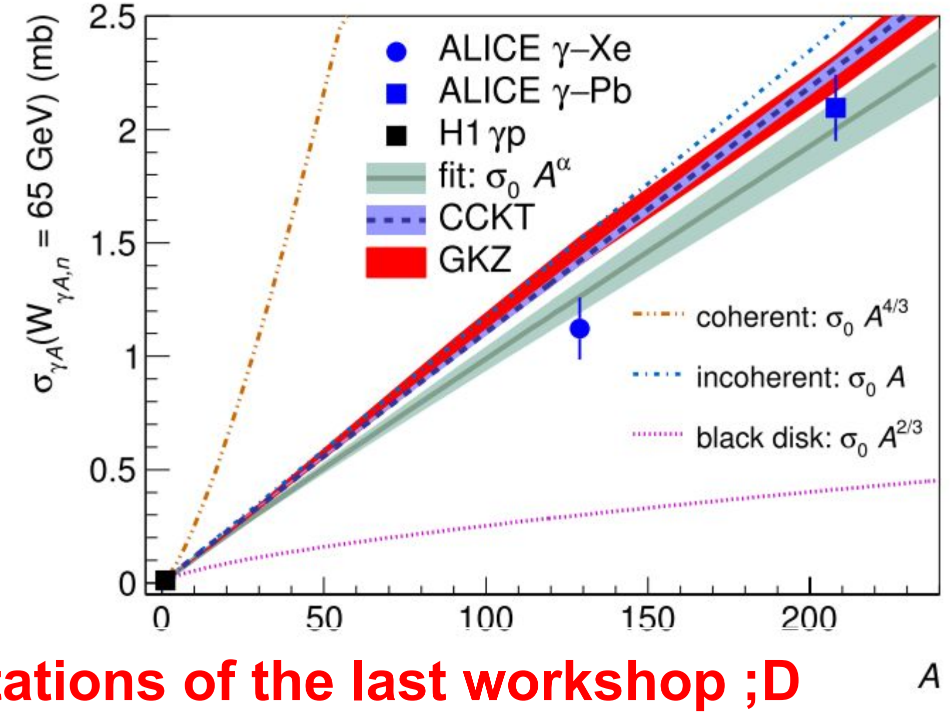
- Exclusive Upsilon(nS) measured by CMS in γp collisions

Last workshop wishlist





ALICE: coherent ρ^0 in Pb+Pb & Xe+Xe



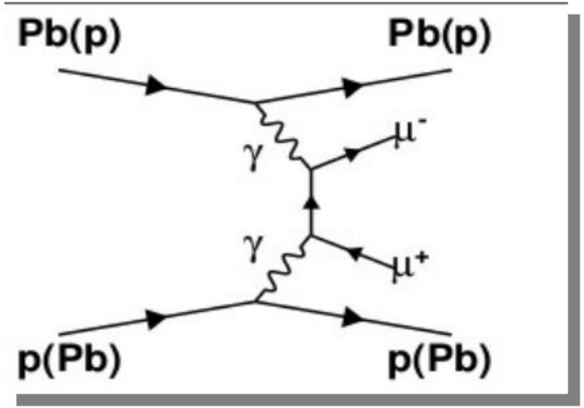
Beyond expectations of the last workshop ;D

A-dependence provides insight into shadowing on nuclei.
Huge deviation from coherent production, interpreted as "incoherent+enormous shadowing"

Study of $\gamma\gamma$-interactions in pPb

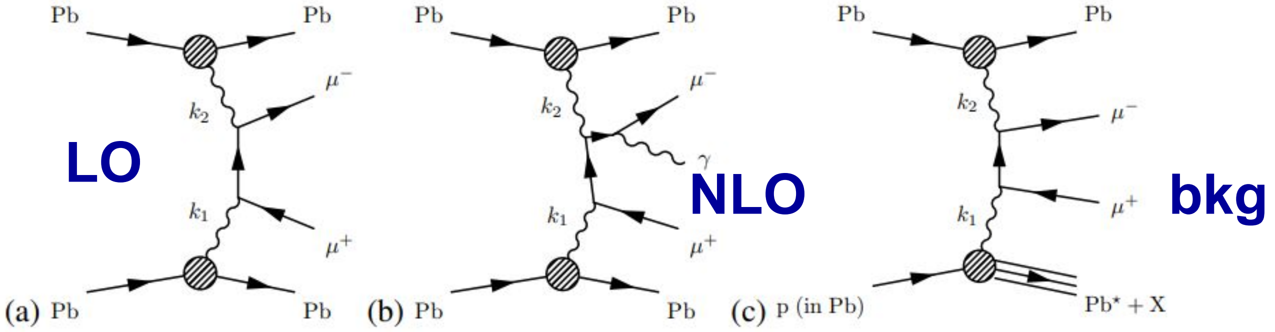
- Theoretically clean, pure QED process: $\gamma\gamma \rightarrow \mu^+\mu^-$
- Luminosity candle
- Scan a wide range of invariant masses

Last workshop



[CMS public twiki: CMSExclusiveGGMMHighmass]

Exclusive dilepton processes & dissociation



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

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

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

Exclusive LHC physics with heavy ions: SuperChic 3

L. A. Harland-Lang[1,a], V. A. Khoze[2,3], M. G. Ryskin[3]

[1] Clarendon Laboratory, Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Parks Road, Oxford OX1 3PU, UK
[2] Institute for Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK
[3] 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[a,*], Evgeny Kryshen[a], Paul Bühler[b], Roman Lavicka[b]

[a] *Petersburg Nuclear Physics Institute named by B.P.Konstantinov of National Research Center «Kurchatov Institute», 1 mkr. Orlova roshcha, 188300 Gatchina, Russia*
[b] *Stefan Meyer Institute for Subatomic Physics, Kegelgasse 27, 1030 Vienna, Austria*

ELSEVIER

Computer Physics Communications
Volume 253, August 2020, 107181

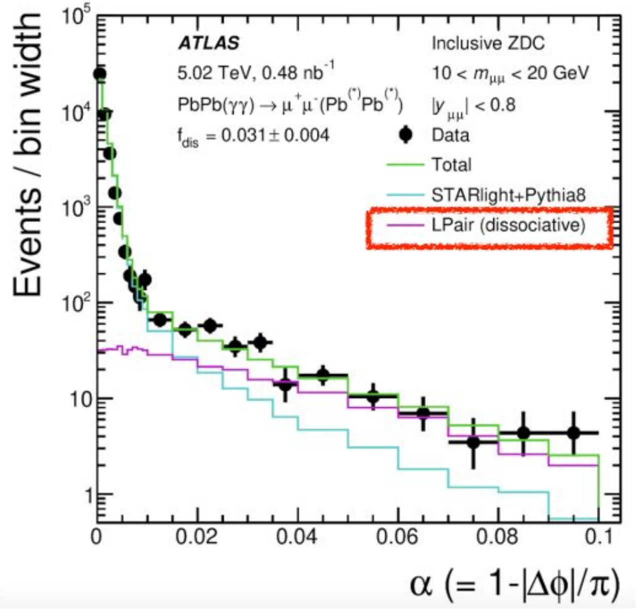
A generator of forward neutrons for ultra-peripheral collisions: $\mathbf{n_0^On}$ ☆, ☆☆

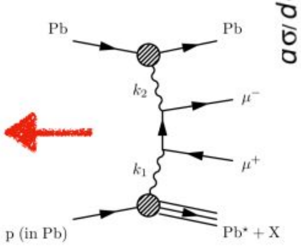
M. Broz[a], J.G. Contreras[a], J.D. Tapia Takaki[b]

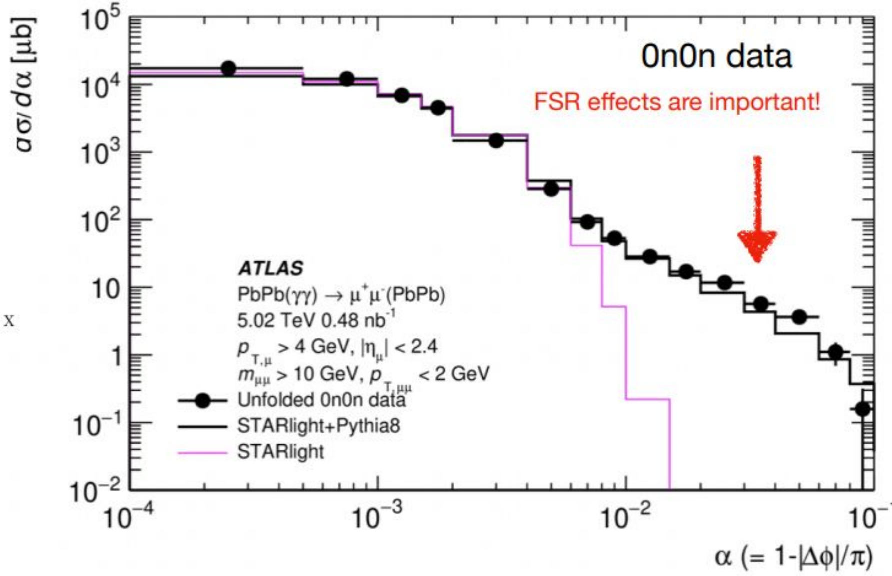
γγ→μμ production in Pb+Pb UPC

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

- Abundant rate → precision test of QED and initial photon flux modeling
- Comprehensive measurement of cross sections in dimuon mass, rapidity, cos(theta), acoplanarity



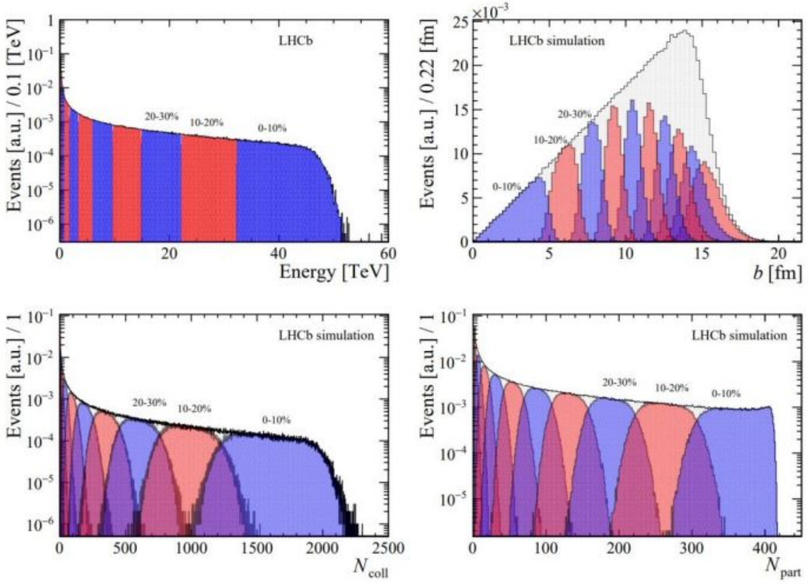




Intermezzo: Centrality in AA & fixed target collisions

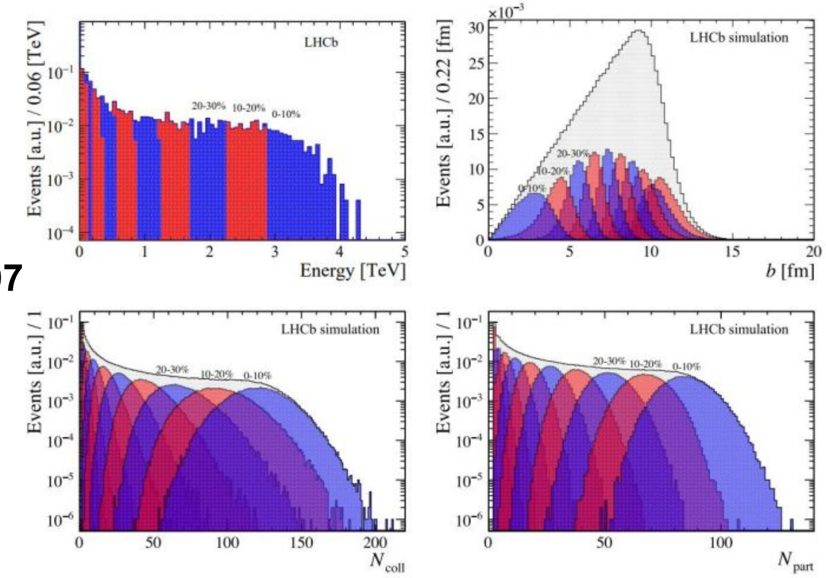
- Classified the data into geometric quantities from **Glauber MC**
  - using deposits in the **electromagnetic calorimeter** to map the real data

PbPb collisions at 5 TeV



2111.01607

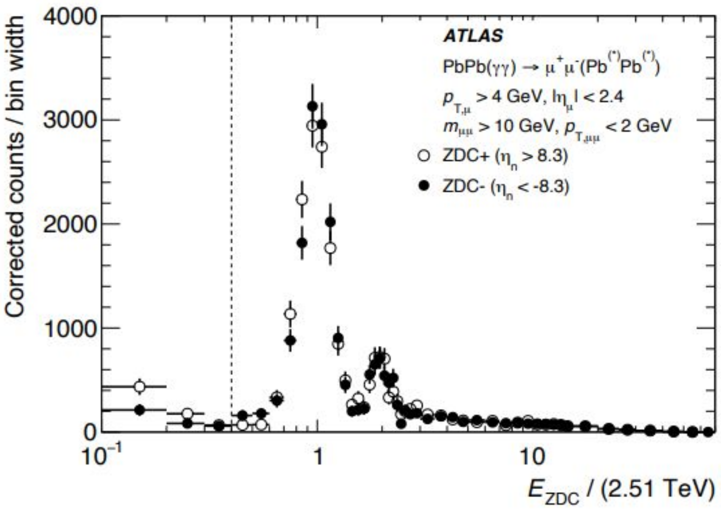
PbNe collisions at 68.5 GeV

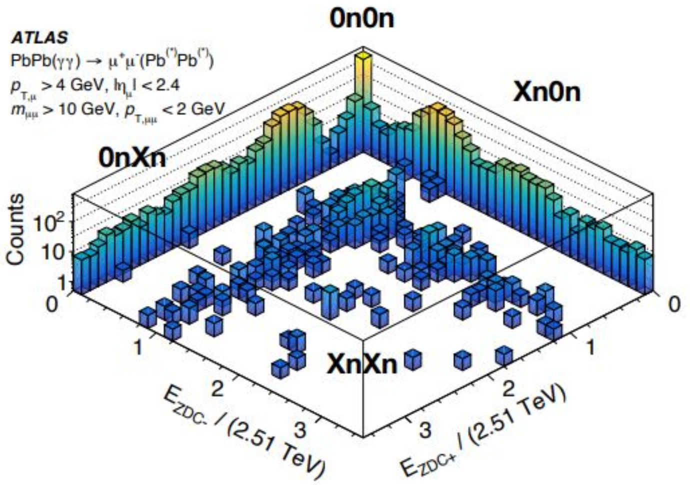


*But UPC events are empty: how do we know **how far** nuclei are at the end?*

Phys. Rev. C 104, 024906 (2021)

ZDC selections in exclusive $\gamma\gamma \to \mu\mu$





ZDCs can easily distinguish 0n from 1n, 2n or more neutrons

We can then classify events by their neutron topology:

- **0n0n** - no neutrons on either side
- **Xn0n/0nXn** - neutrons on one side
- **XnXn** - neutrons on both sides

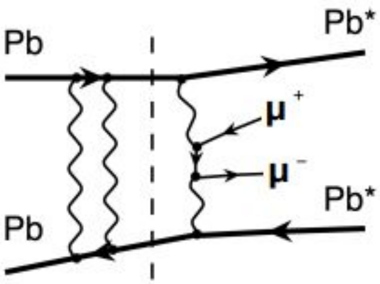
Experimental handle on impact parameter

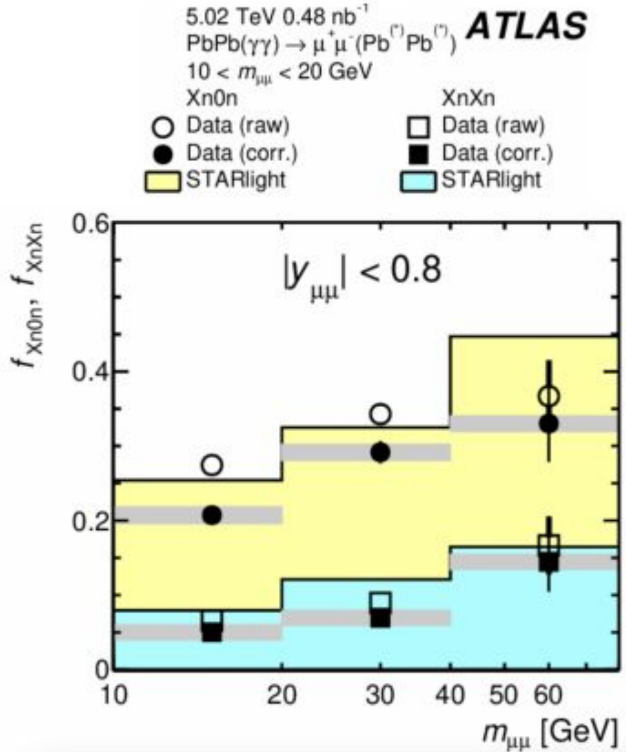
γγ→μμ production in Pb+Pb UPC

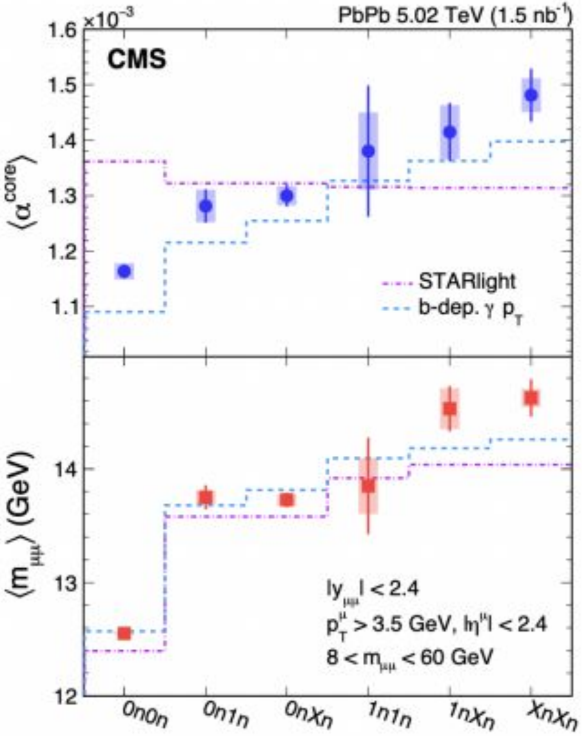
ATLAS, Phys. Rev. C 104 (2021) 024906

CMS, PRL 127, 122001 (2021)

- Measuring properties of events with singe and mutual EM dissociation
  → indirect probe of Pb+Pb impact parameter in γγ interactions

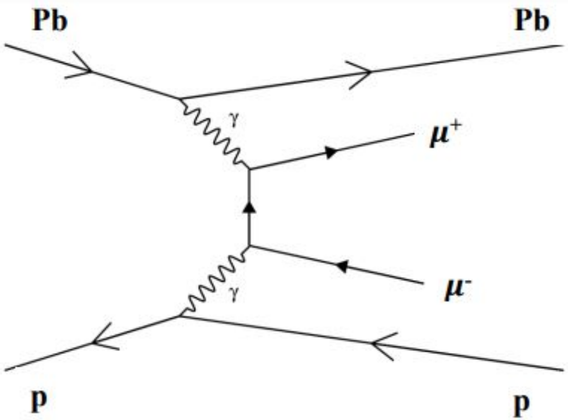






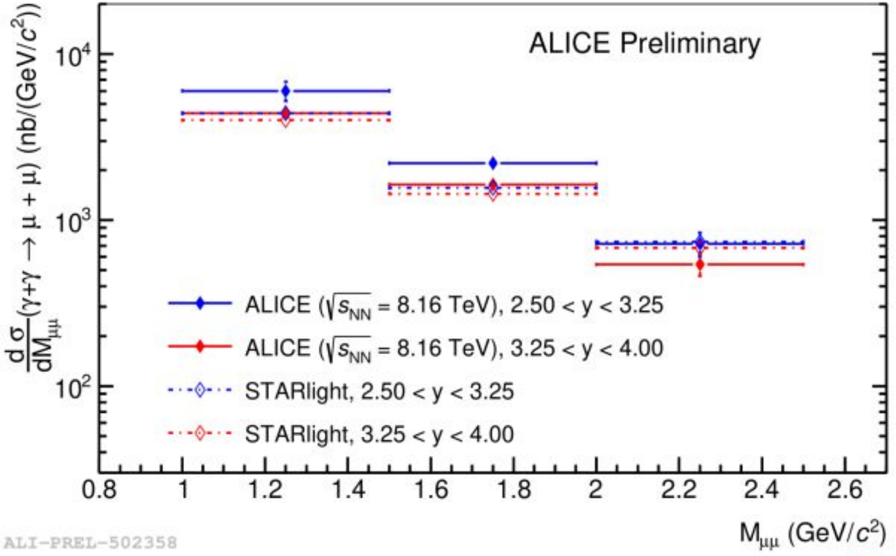
$\gamma\gamma \rightarrow \mu\mu$ cross section

- $\gamma\gamma \rightarrow \mu\mu$ cross section in the **low mass** region!
- STARlight:
  - LO QED without final-state radiation or other NLO effects
  - No interactions within the radius of the targets



NEW

→ **Slight excess in data**
agreement within 3 sigma



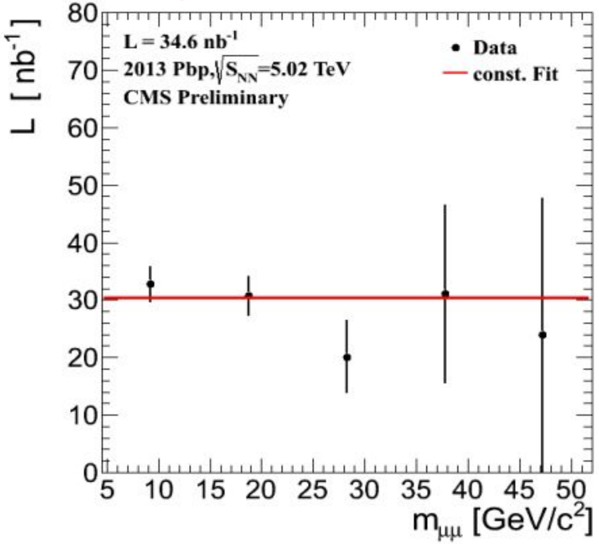
- Can be used to improve current models
  - **Fix background** for VM or jet **photoproduction**
  - Improve predictions for **light-by-light scattering**

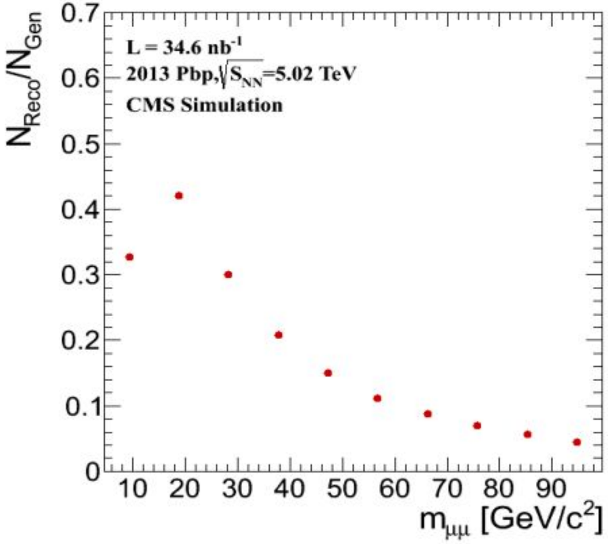
Study of γγ-interactions in pPb: luminosity cross-check

Karlsruhe Institute of Technology

$$\mathcal{L}(\gamma\gamma \to \mu\mu) = \frac{N^{\mu\mu}_{Data}}{\epsilon^{\mu\mu} \times \sigma_{\gamma\gamma\to\mu\mu}} = (30.4 \pm 2.2(stat.) \pm 3.9(syst.))\, nb^{-1}$$

Worth following up from the last workshop



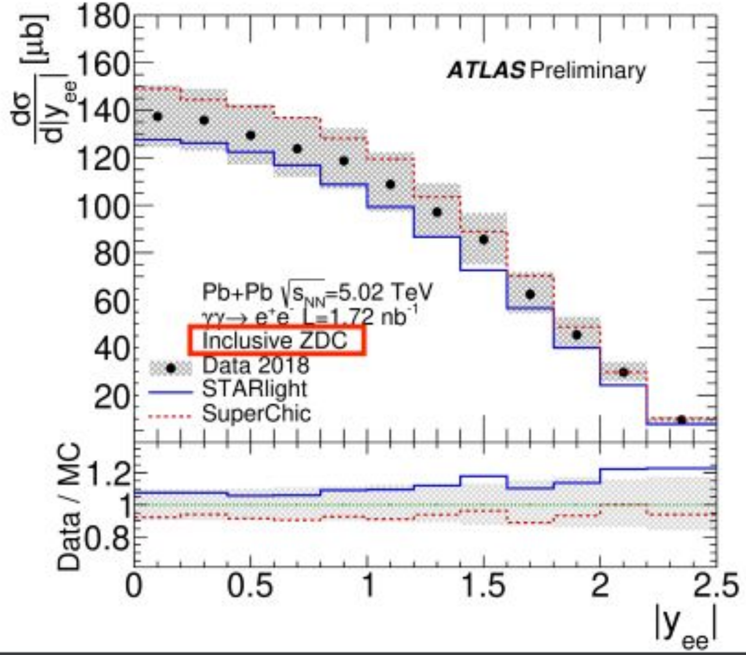


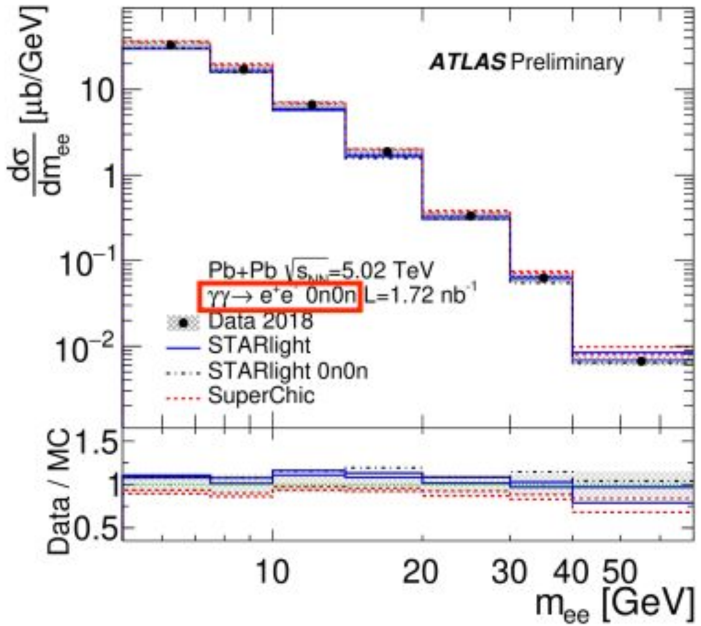
γγ→ee production in Pb+Pb UPC

ATLAS-CONF-2022-025

- Similar techniques as in ATLAS μμ UPC measurement but notable advances
  - Higher statistics from 2018 data
  - Extended fiducial region

New high-mass channel: dielectrons





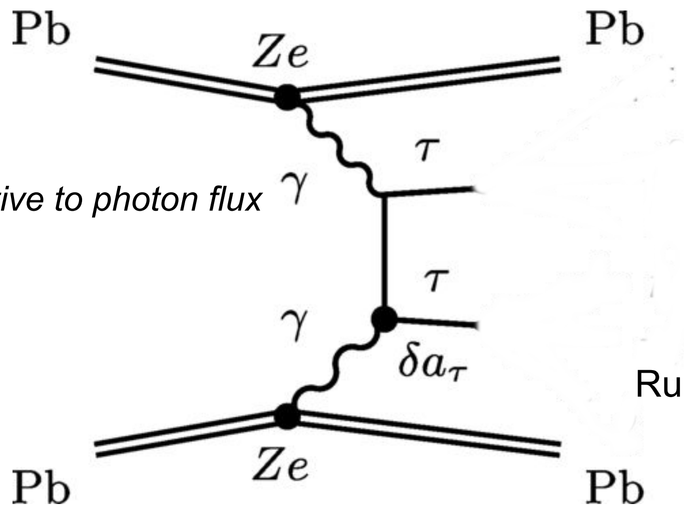
Overview of the $\gamma\gamma \to \tau\tau$ process

- **Promising candidate** for the a_τ = $(g_\tau-2)/2$ determination
  - "using a large heavy ion collider" for g_τ-2 suggested since 90s
  - cross section in UPC receives a **Z^4 enhancement** relative to pp

New channel for BSM: ditaus

- 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

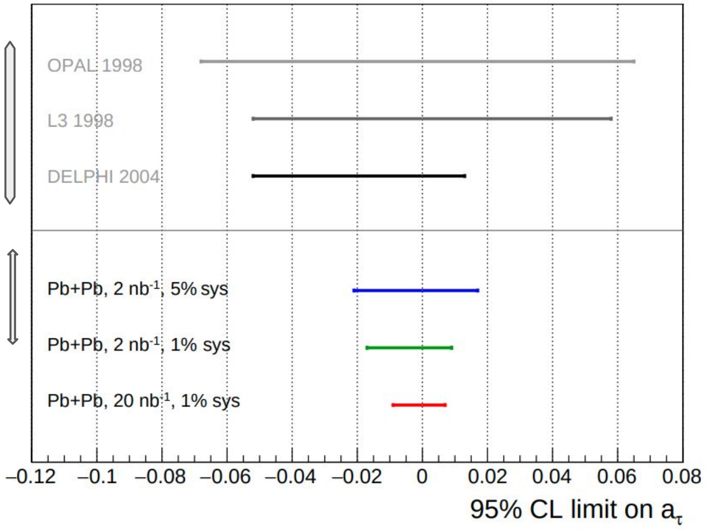


τ lepton photoproduction in ultraperipheral collisions (UPC)

LEP

Run 2 (2 /nb)

Runs 3+4 (> 10 /nb)

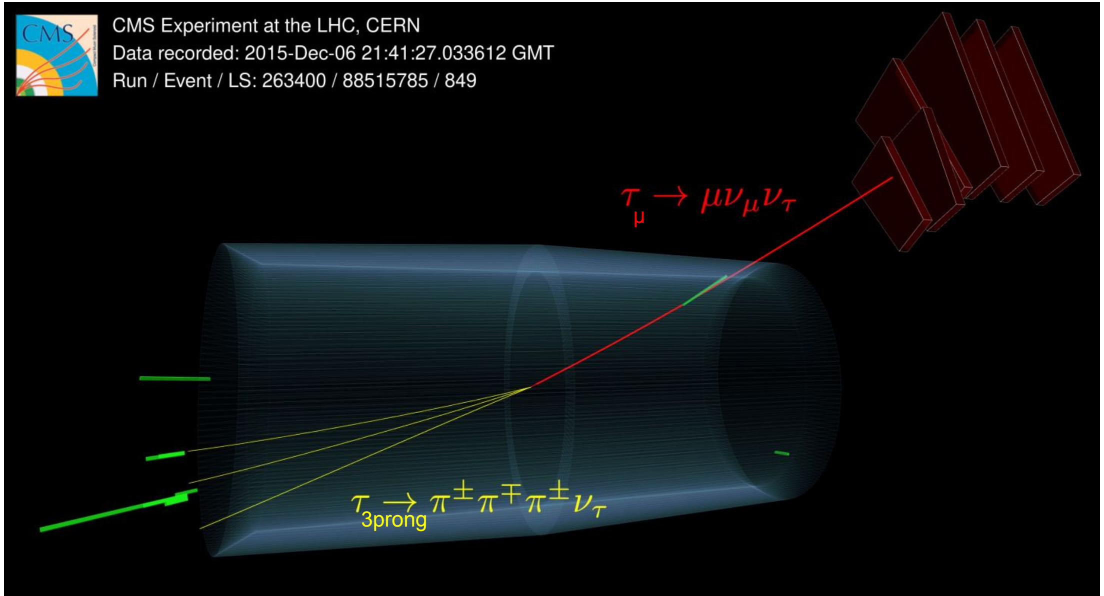


Phys. Lett .B **809** (2020) 135682 (2002.05503)
Phys. Rev. D **102** (2020) 113008 (1908.05180)

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**

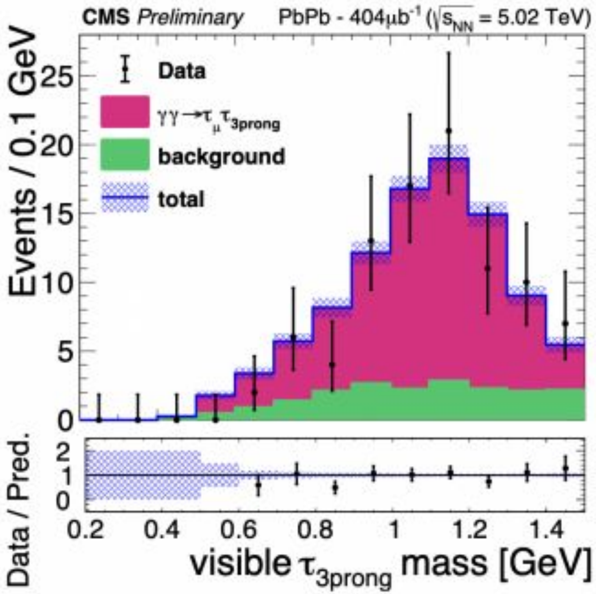
→ All channels needed for **ultimate precision**

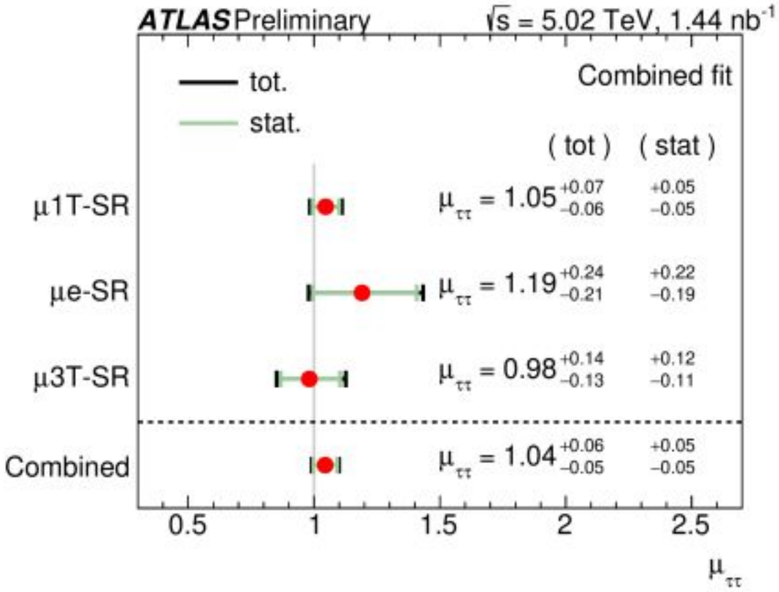


$\gamma\gamma \to \tau\,\tau$ production in Pb+Pb UPC

ATLAS: CERN-EP-2022-079
CMS: CMS-PAS-HIN-21-009

- $\gamma\gamma \to \tau\,\tau$ production observed for the first time in hadron collisions
  - Targeting mu+3prong decays (CMS) or mu+3prong, mu+1prong and mu+e (ATLAS)
  - CMS: fiducial cross section measured with 16% rel. precision (2015 data)
  - ATLAS: signal strength measured with **5%** rel. precision (2018 data)



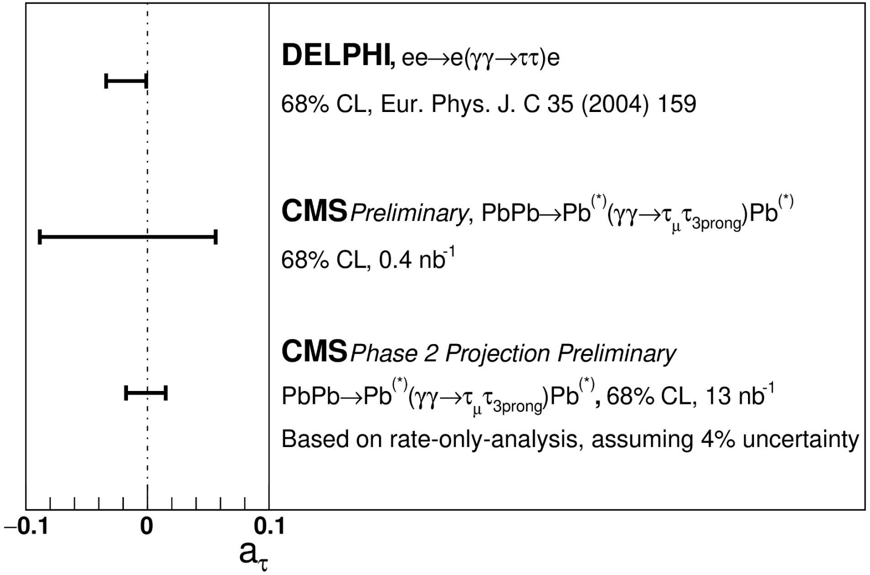


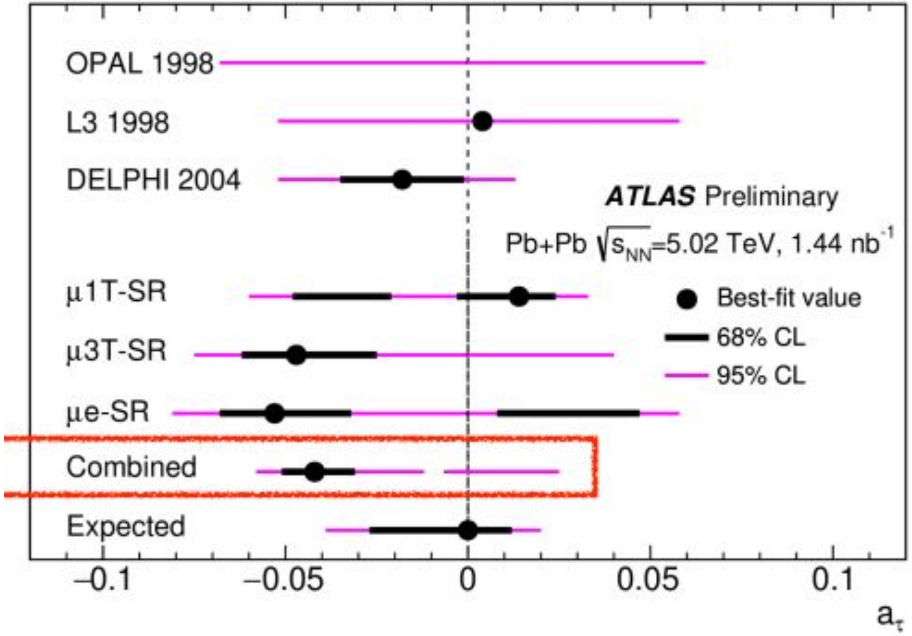
Constraints on tau anomalous magnetic moment

ATLAS: CERN-EP-2022-079

CMS: CMS-PAS-HIN-21-009

- Both ATLAS and CMS provide their first constraints on a_{tau}
- ATLAS precision (stat.-dominated) competitive with DELPHI@LEP (PDG) limits
  - Excellent prospects for LHC Run 3 & beyond





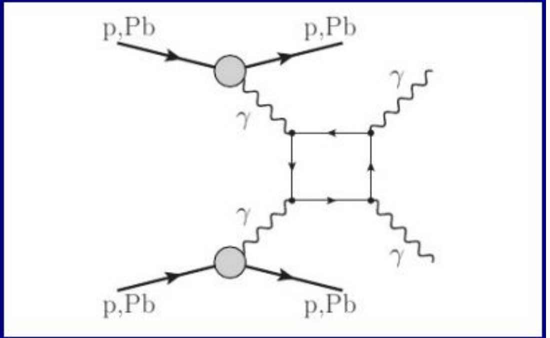
Exclusive $\gamma\gamma$ production

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.

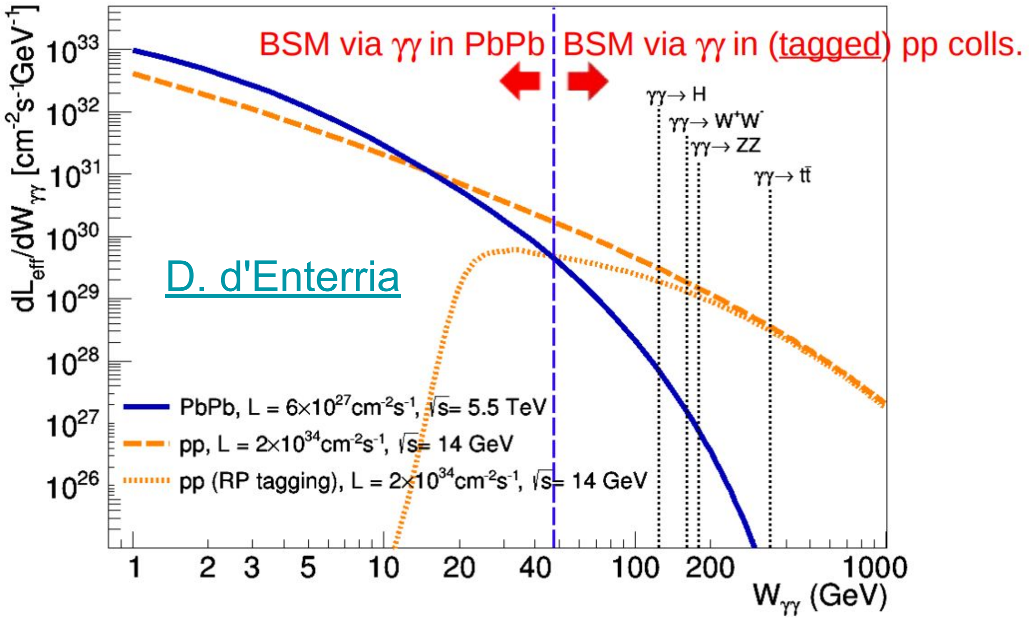
==> Pb-Pb collisions at the LHC might thus provide the first opportunity to study this process!



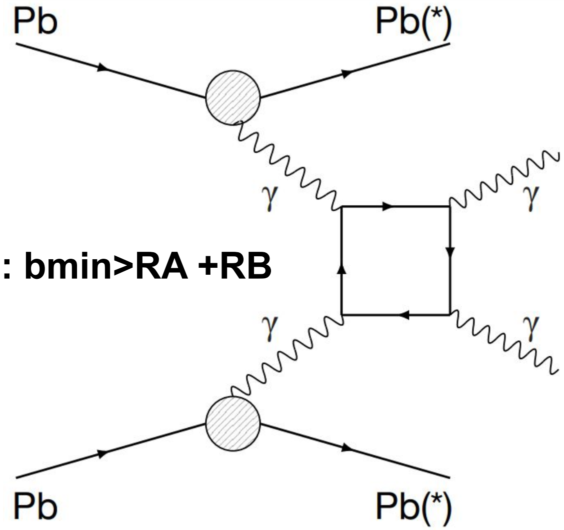
Joakim Nystrand (last workshop)

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 Z^4 **~10^7** factor in PbPb, γγ luminosities >> pp ones at low Wγγ

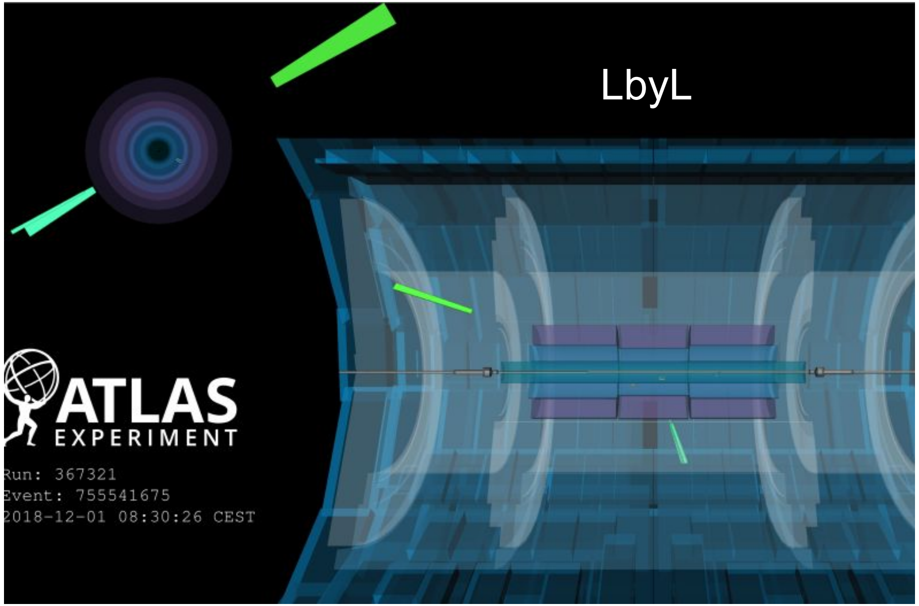


UPC: bmin>RA +RB

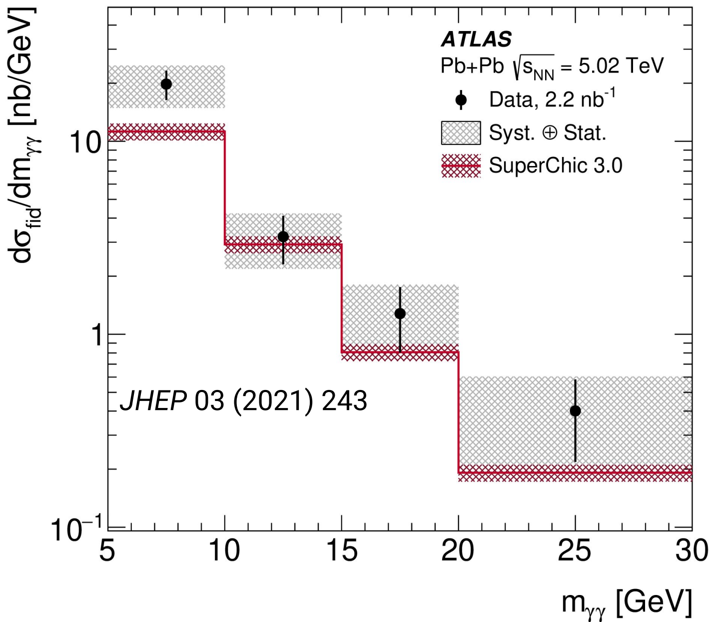


Available LbyL UPC measurements (so far)

- 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



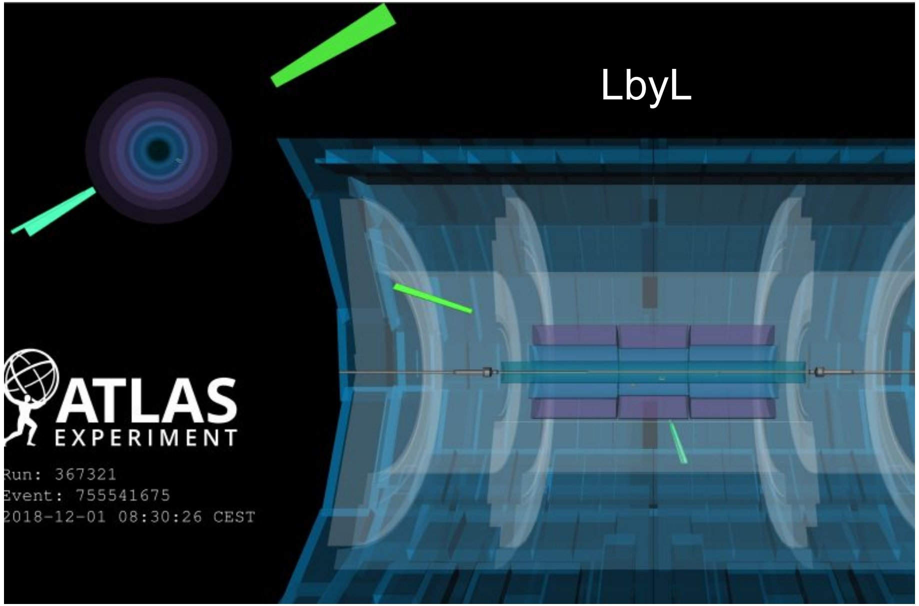
Even differential studies!

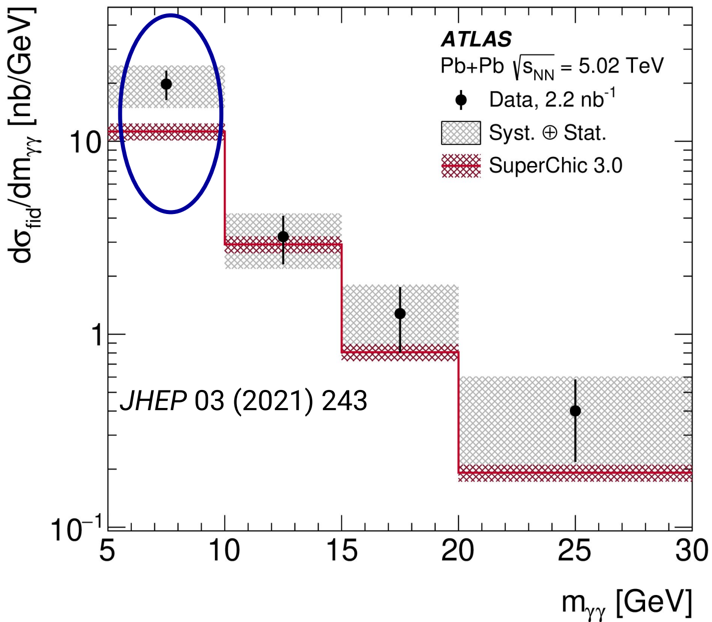


Goals of this analysis

- 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?

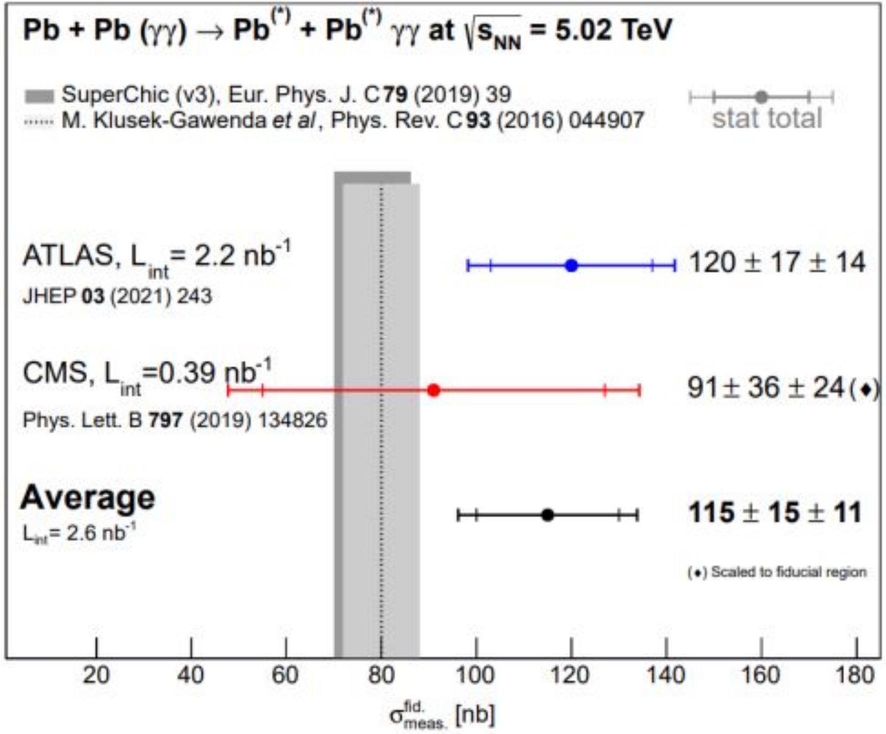




Measurement of light-by-light scattering

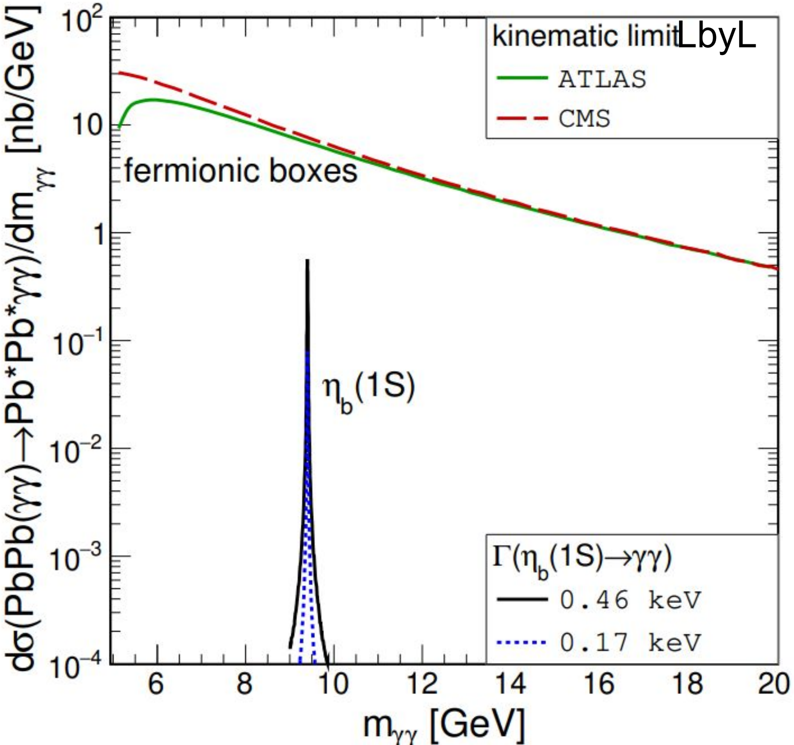
Krintiras et al., arXiv:2204.02845

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

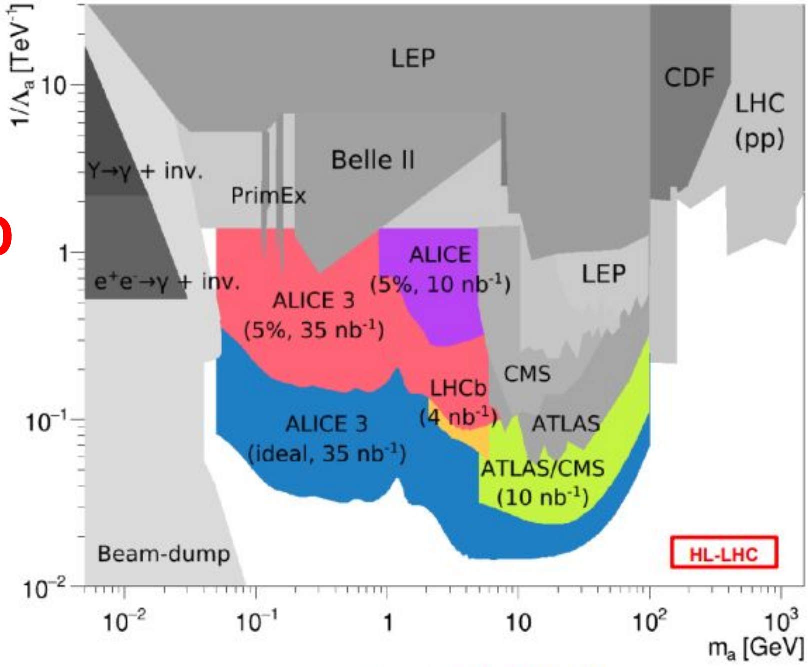


Trying to explain **the excess**

- We calculated the inclusive σ for the **photoproduction of η_b(1S)**
  - σ = (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**



HI and NP: ALP Search



In some future v. of the workshop ;D

arXiv:2203.05939

- ALP and Monopole searches: rely on the large EM field in heavy ion collisions.
- New performance compilation from arXiv:2203.13199
- ALICE 3 + CMS will push the ALP limit well below 1/TeV between 50 MeV and 100 GeV
  - Interesting because ALPs found in this range could potentially explain muon anomalous magnetic moment puzzle

CMS

Outlook

KIT
Karlsruhe Institute of Technology

- Several very encouraging results on ultra-peripheral collisions in CMS
  - Exclusive J/ψ in PbPb
  - Photoproduction of muon pairs up to high invariant masses in pPb
- Besides hot topics for the era of high energy/luminosity
  - Light-light scattering and Higgs production...
- … measuring UPC ψ(2S), Υ in PbPb should become definitely feasible
- More specific proposals are being drafted for the LPCC Forward Physics Working Group Yellow Report → **WG5 YR/Swnowmass22**

We did pretty well with ~⅙ of the data ;D

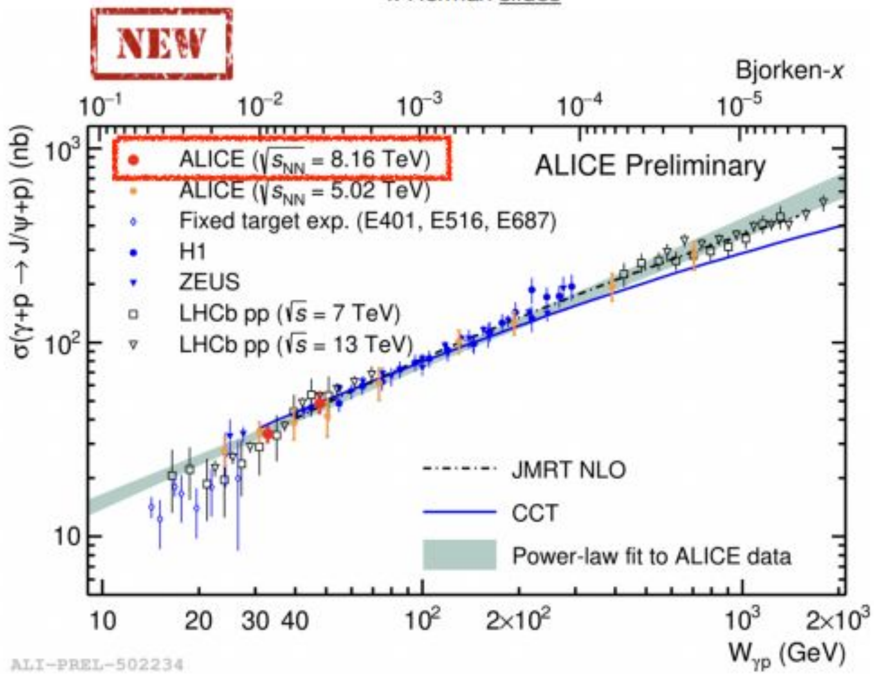
Backup

J/ψ photo-production in UPC

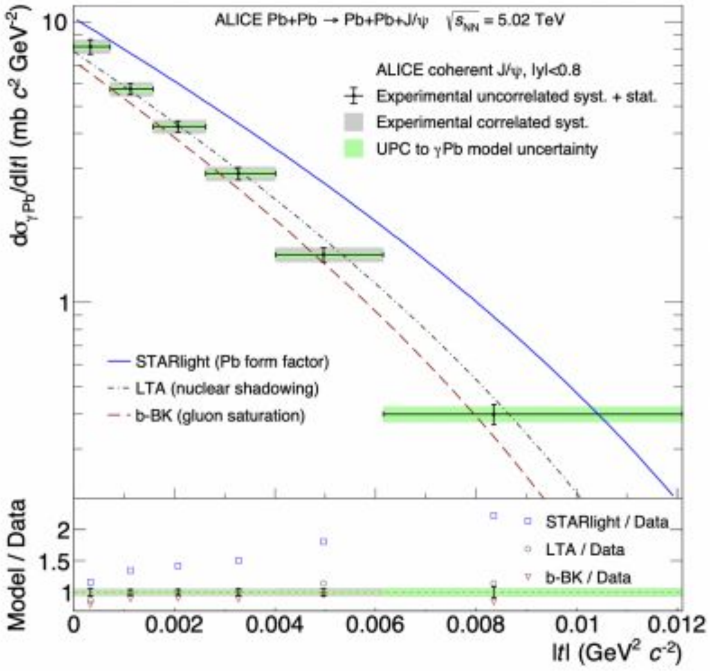
- New ALICE measurements in p+Pb and Pb+Pb

\+ Coherent ϱ 0 cross section in XeXe
\+ Dissociative J/ψ cross section

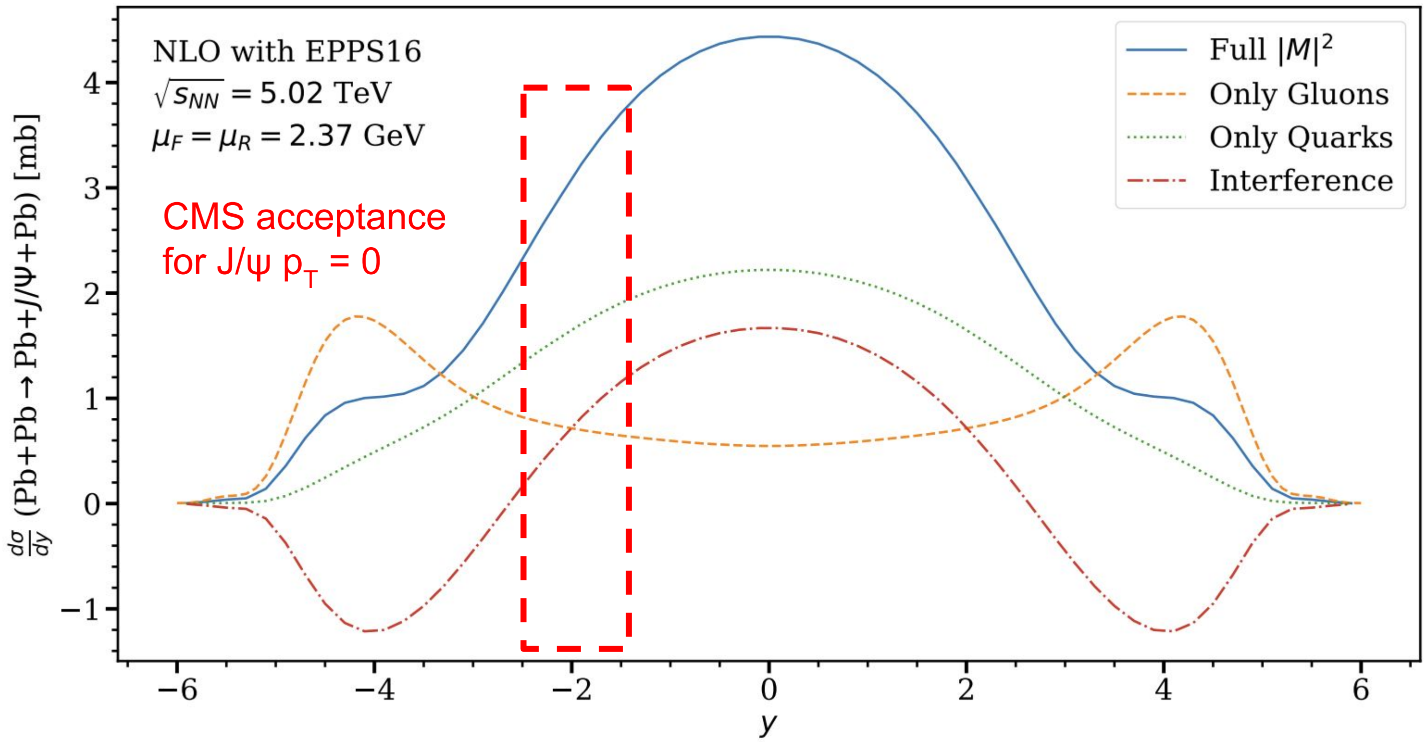
T. Herman slides



ALICE: PLB 817 (2021) 136280



Sensitivity to the quark contribution [arXiv:2203.11613]



- Now, at $y = 0$ *quark* contribution dominates. Different from LO! Reason: LO and NLO gluon amplitudes cancel.

X(6900) → J/ψ J/ψ kinematics [PRD 104 (2021) 114029]

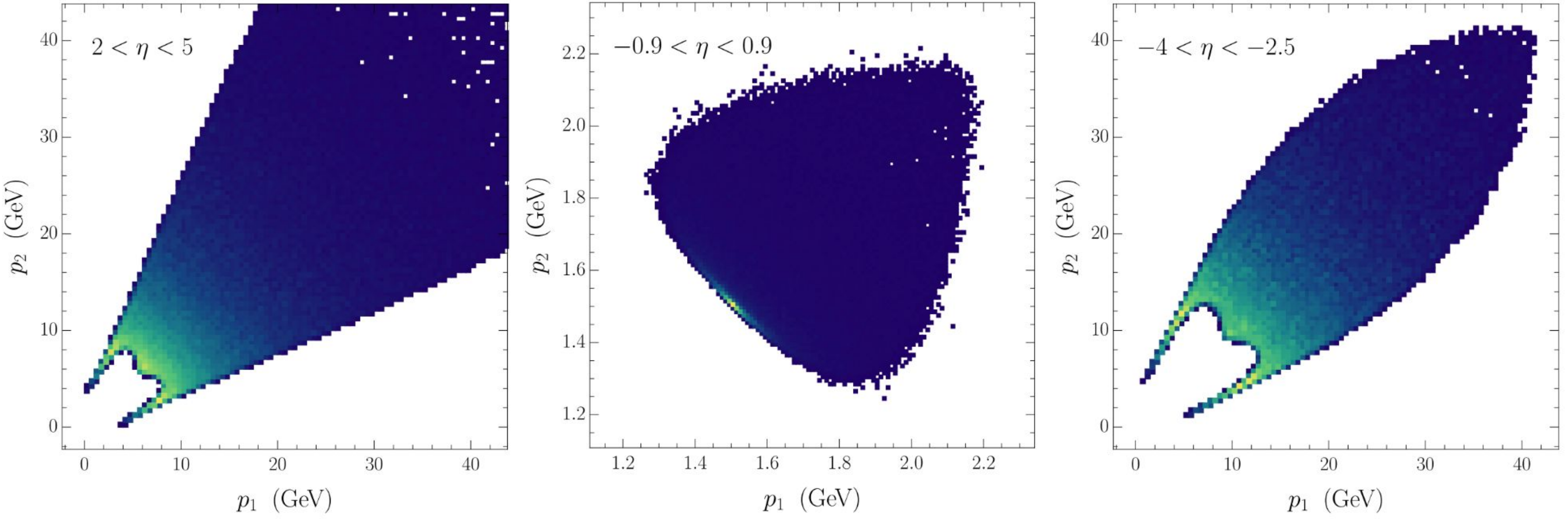
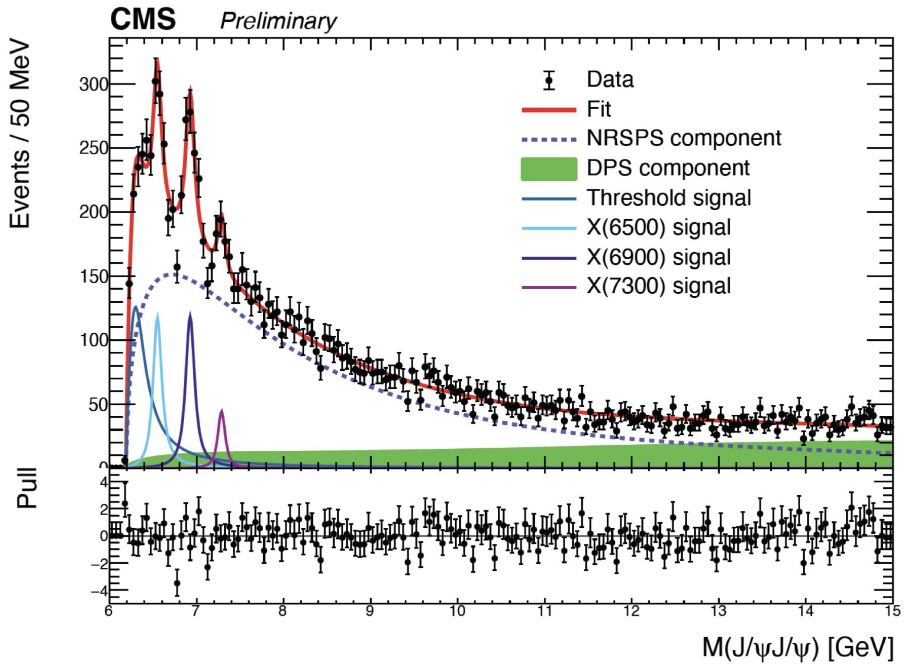
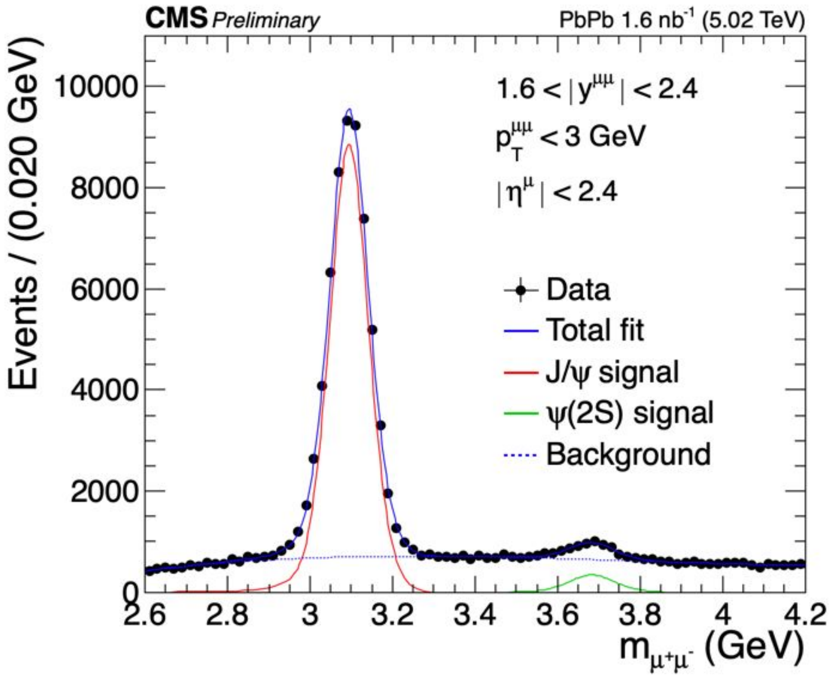


FIG. 2. Momentum distributions of the two J/ψ's produced by the decay of the $X(6900)$, for the pseudorapidity cuts corresponding to the LHCb detector (left), the ALICE electron detector (center) and the ALICE muon detector (right). While for the ALICE electron detector the two decay products are rather soft, the forward detectors should collect energetic ones. The pseudorapidity cuts have efficiencies of 21%, 8%, and 10%, respectively.

Search for X(6900) → J/ψ J/ψ in CMS



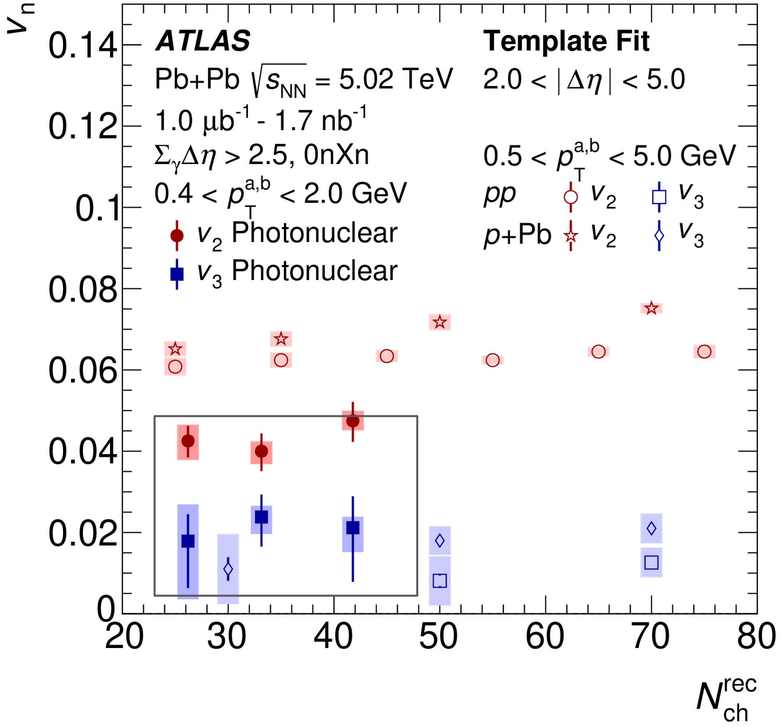


Resonant structures observed in BPH-21-003!!!
Analysis of the full Run 2 data (135 fb^{-1})

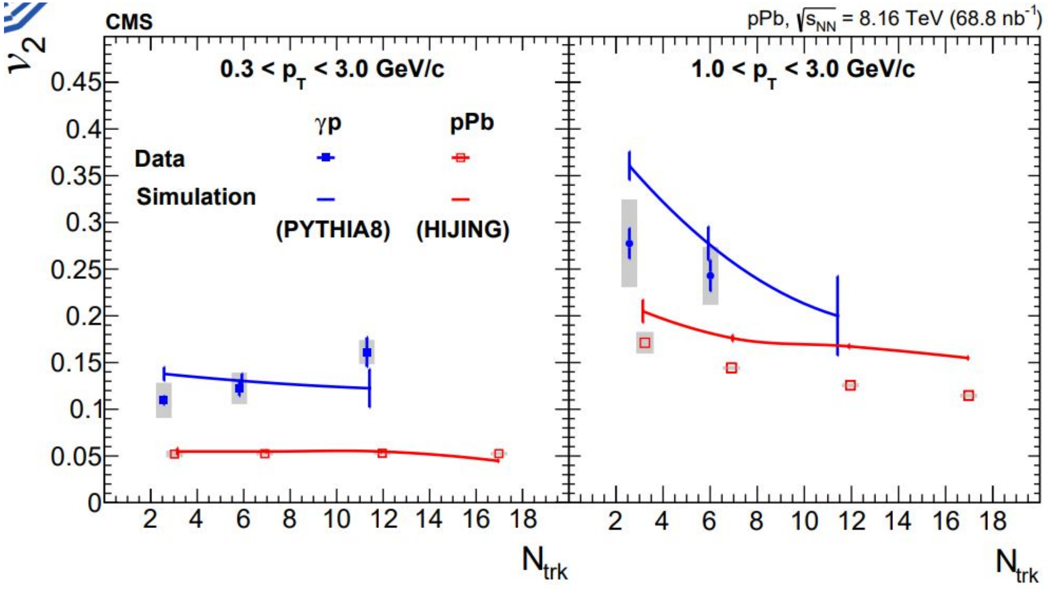
Large sample of low-p_T J/ψ in 2018 PbPb data. Better S/B and larger cross section ideal for tetraquark hunting in UPCs!!!

vn in the smallest collision systems

Phys. Rev. C. 104 (2021) 014903



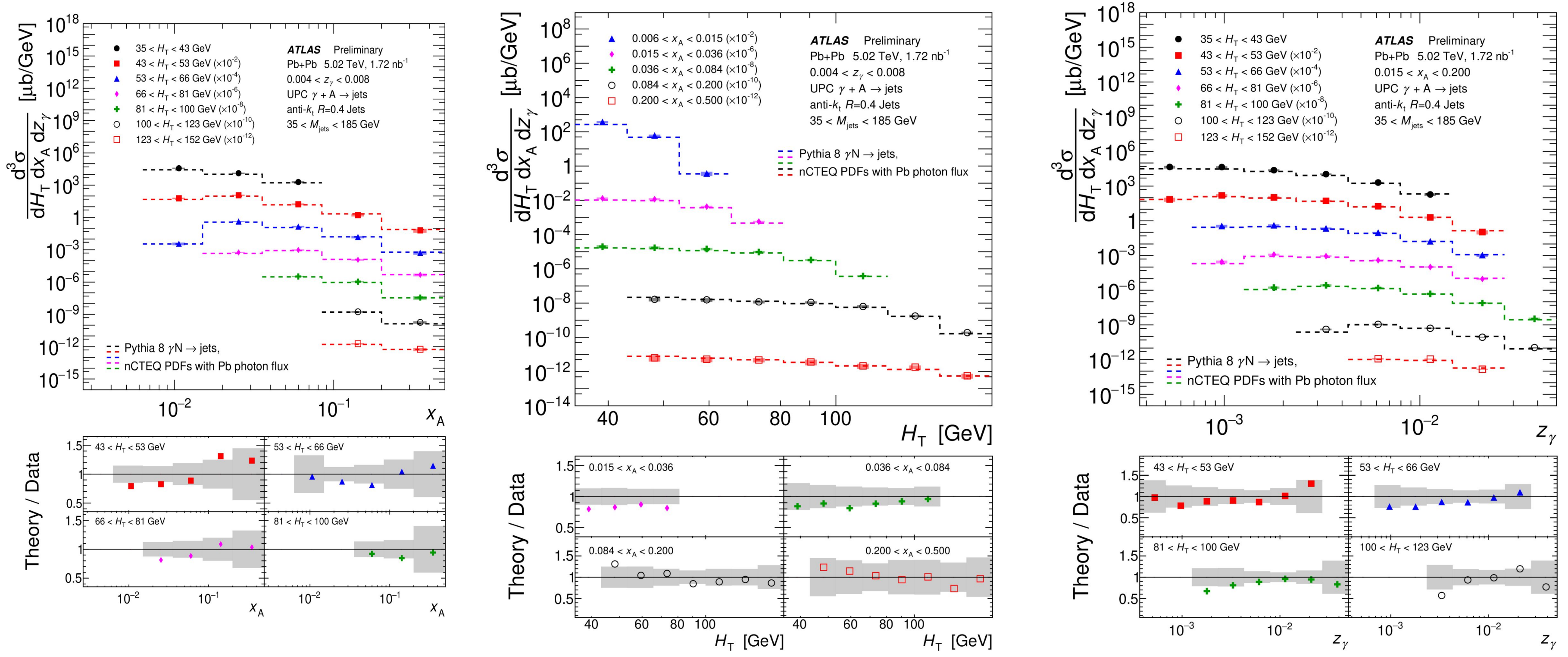
CMS-HIN-18-008



Can we go a bit higher in Nch? Can we reproduce with pQCD models ATLAS results?

Measurement of photo-nuclear dijet production in PbPb

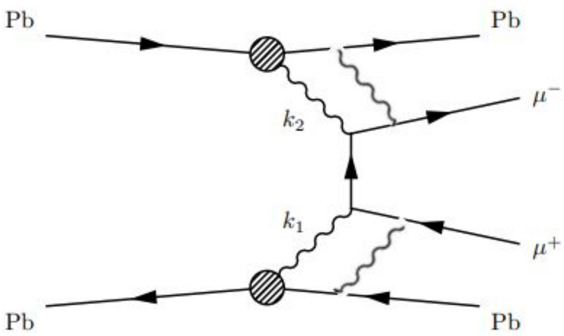
ATLAS-CONF-2022-021



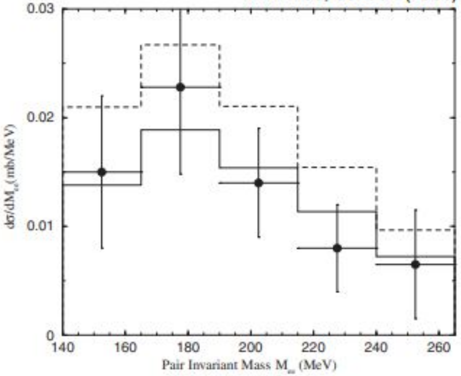
Followup from 2018: **Triple-differential** cross-sections extracted (xA, zy, HT)

Comparison to Pythia 8 + nPDFs → Potential to constrain nPDFs

Higher order contributions

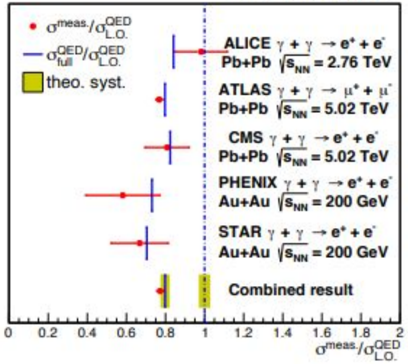


PRL 100, 062302 (2008)



<u>Baltz, 2008</u>
~20% reduction in cross sections at low e+e- masses

JHEP 08 (2021) 083



<u>Tang & Zha, 2021</u>
large reductions in all kinematic regions going from LO to HO

HO Coulomb corrections not included in either STARlight or SuperChic:
These corrections qualitatively <u>lower</u> the cross sections,
perhaps up to 20% (e.g. Tang & Zha) compensating for the increase!

However, some disagreement between groups on just how much:
some authors predict impact on muons should be negligible.

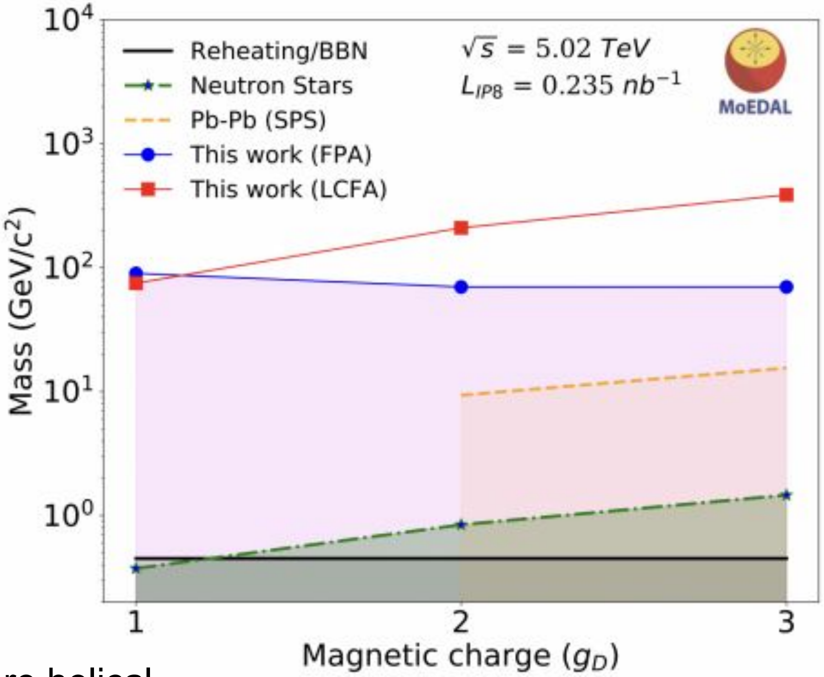
May be important for correct fluxes: **watch this space**!

Magnetic monopoles via the Schwinger production

MoEDAL, Nature 602 (2022) 7895, 63-67

- Recent MoEDAL search
  - Exposure of Monopole Trapping Detector in 0.235 nb^{-1} of Pb+Pb in 2018
  - Limits on monopoles of charge **1 – 3 g_D** and masses up to **75 GeV**

- First direct search sensitive to monopoles that are not point-like, based on non-perturbative calculation of monopole production cross section



PF algo basic assumption is that particle trajectories are helical

1812.07688 ⟶

Magnetic monopoles would manifest as parabolic → development needed though quite interesting

Signal / control regions

μ1T-SR
- exactly 1 muon
- no electrons
- exactly 1 track
- net charge = 0
- $p_T^{\mu+\text{trk}} > 1$ GeV
- $p_T^{\mu+\text{trk}+\gamma} > 1$ GeV
- $p_T^{\mu+\text{trk}+\text{clus}} > 1$ GeV
- $A_\phi^{\mu,\,\text{trk}} < 0.4$

Most sensitive

μ3T-SR
- exactly 1 muon
- no electrons
- exactly 3 tracks
- net charge = 0
- $m_{\text{trks}} < 1.7$ GeV
- $A_\phi^{\mu,\,\text{trks}} < 0.2$

μe-SR
- exactly 1 muon
- exactly 1 electron
- net charge = 0

Cleanest

2μ-CR
- exactly 2 muons
- $m_{\mu\mu} > 11$ GeV

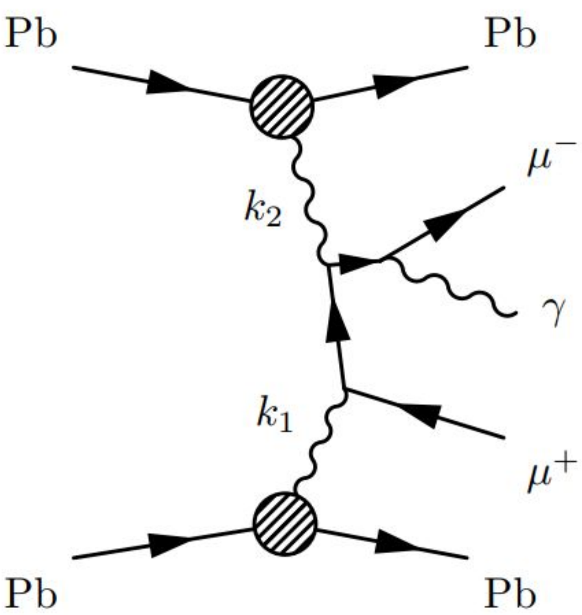
Bkg region in the combined fit

Muons: $p_T^\mu > 4$ GeV
Electrons: $p_T^e > 4$ GeV
Tracks: $p_T^{\text{trk}} > 100$ MeV
Clusters: $p_T^{\text{clus}} > 1$ GeV ($|\eta| < 2.5$),
$p_T^{\text{clus}} > 100$ MeV ($2.5 < |\eta| < 4.5$)

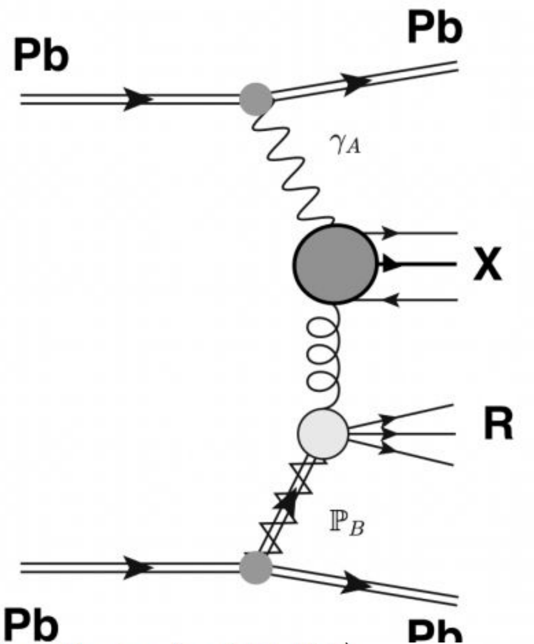
- Trigger requirements:
  - $p_T^\mu > 4$ GeV   CMS: no p_T cut at trigger level!
  - total E_T in calorimeter below 50 GeV
  - E_T in forward calorimeters below 3 GeV (rapidity gaps)
- Data only: 0n0n ZDC selection (simulation reweighted: 0n0n+0nXn+XnXn $\to$ 0n0n)
- Exclusivity: veto additional clusters (μ1T-SR and μ3T-SR only) and tracks

Background processes

$\gamma\gamma \to \mu\mu(\gamma)$ production

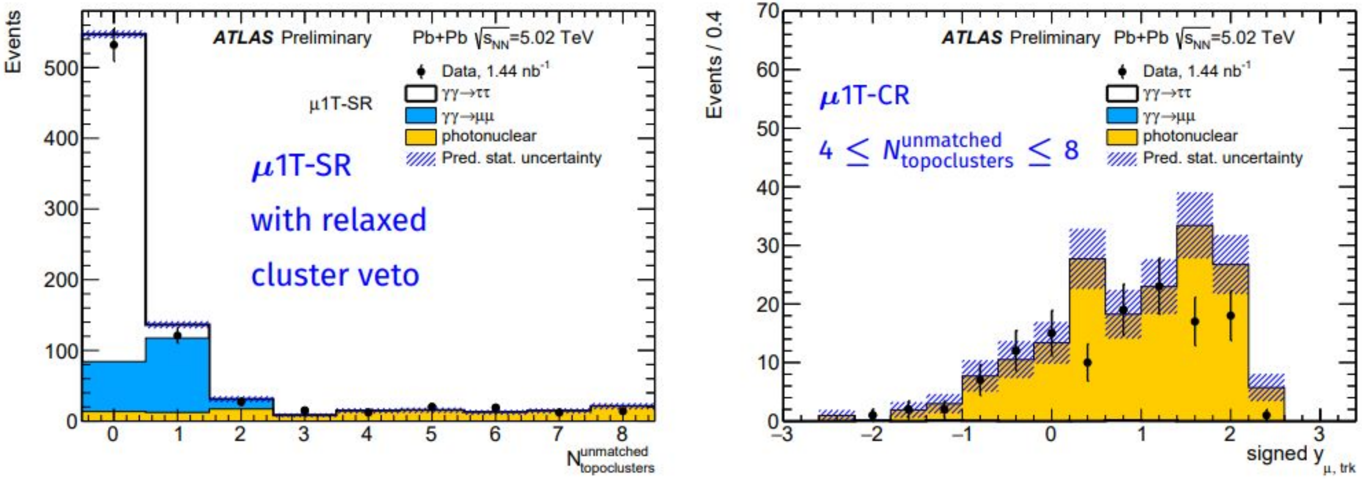


diffractive photonuclear events

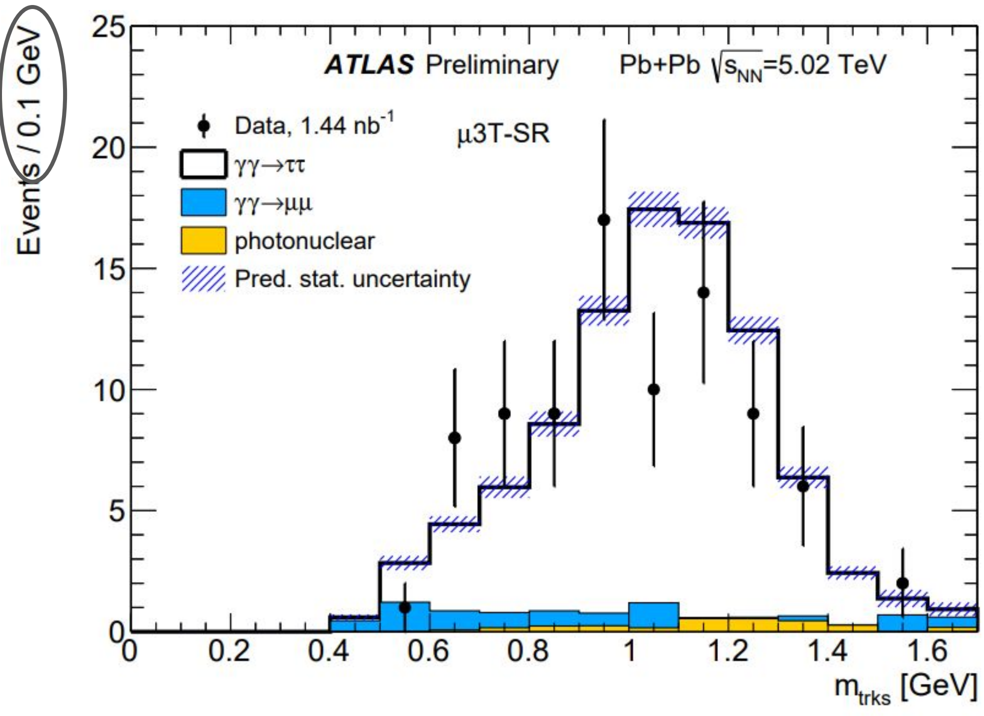


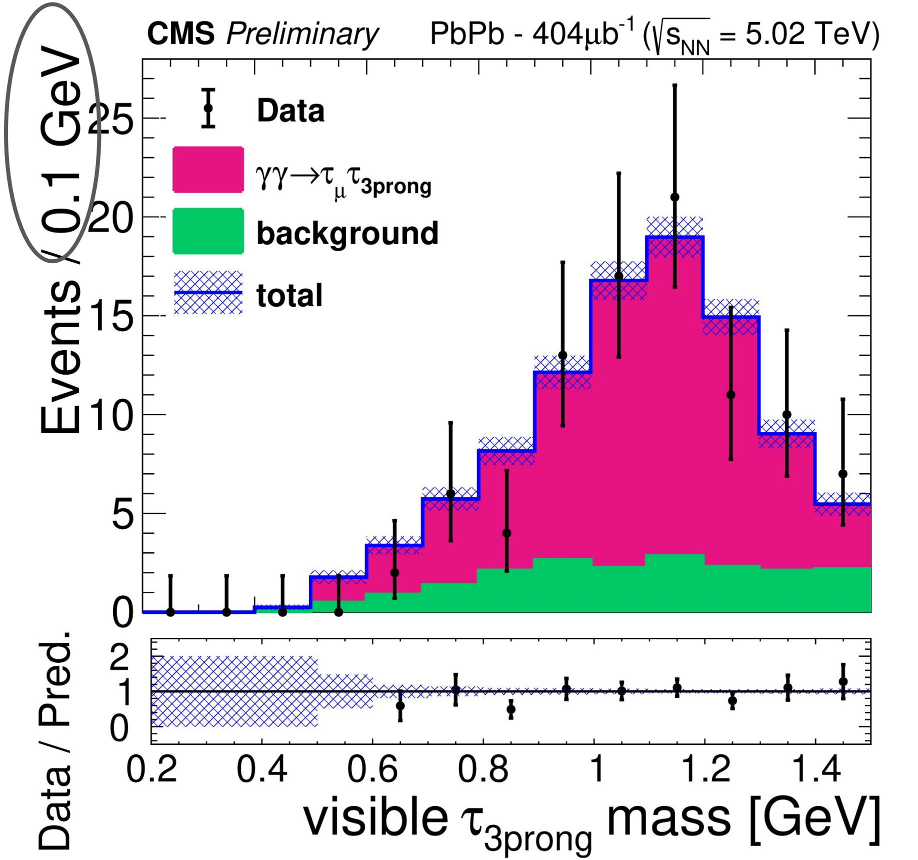
- $\gamma\gamma \to \tau\tau$ signal: Starlight+Tauola (Pythia8+Photos for QED FSR)
- $\gamma\gamma \to \mu\mu$ background: Starlight+Pythia8
- $\gamma\gamma \to \mu\mu\gamma$ background: Madgraph5 (reweighted to Pb+Pb photon flux)
- all samples reweighted to photon flux from SuperChic3

Backgrounds: diffractive photonuclear events



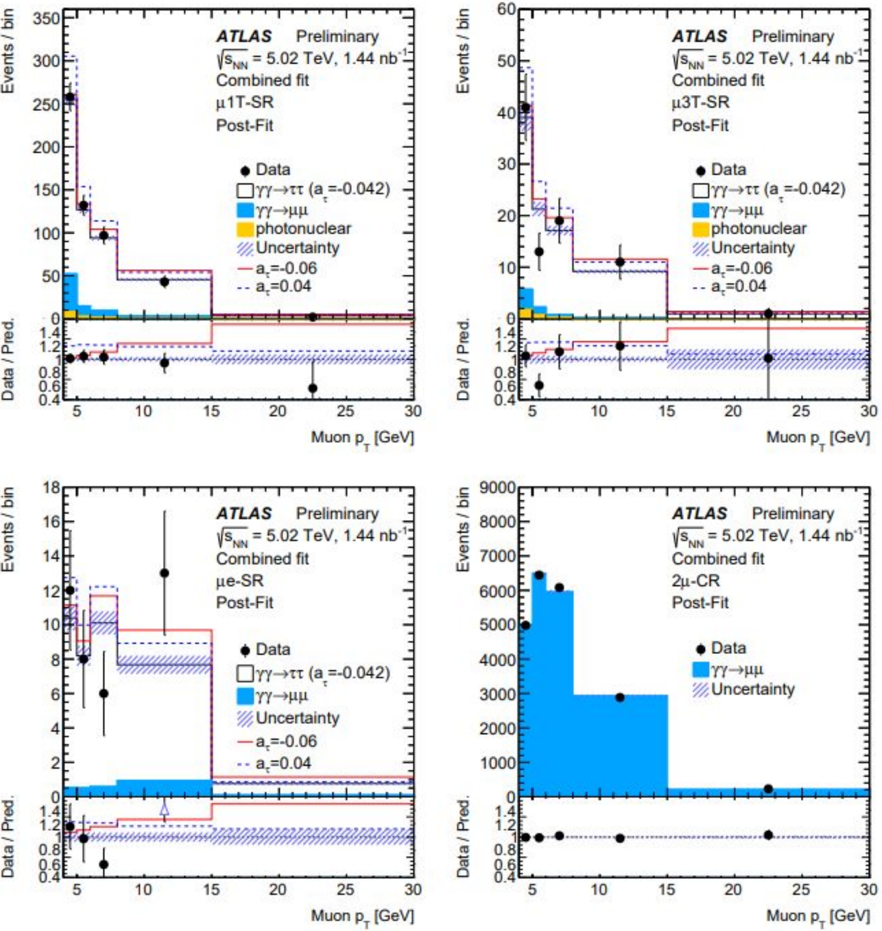
- Data-driven estimation of diffractive photonuclear events in μ1T-SR and μ3T-SR
- Templates built from control regions similar to SRs, but requiring an additional track with $p_T < 500$ MeV and allowing 0nXn ZDC events
- Normalisation: relax cluster veto $\to$ use region with 4-8 unmatched clusters
- Kinematic distributions in this region well described by the CR templates





Despite ×4 data set, **comparable stats and S/B** → much better reco/algo, ZDC cuts?
Important to highlight in the paper maybe

Post-fit p_T^μ distributions

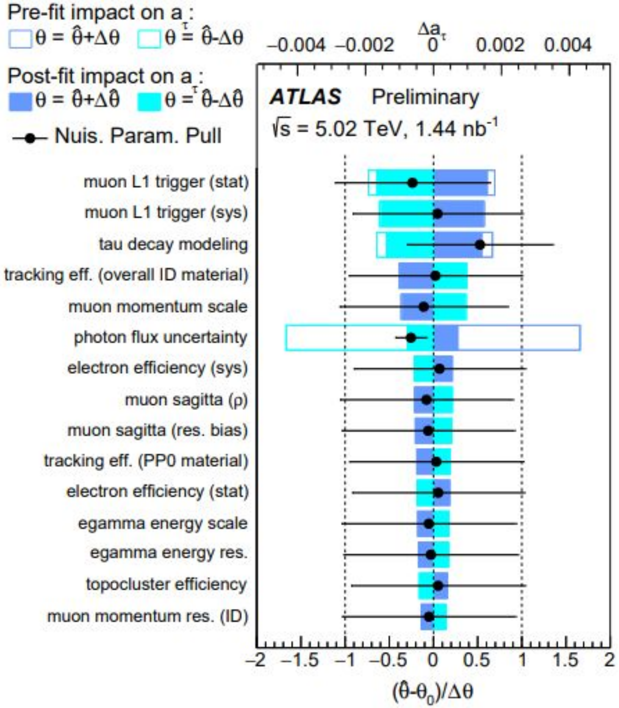


- Post-fit distributions of p_T^μ in the SRs and 2μ-CR
- Results of combined fit using all regions
- Clear observation ($\gg 5\sigma$) of $\gamma\gamma \to \tau\tau$ process
- Photon flux modelling well constrained with high-precision and high-purity 2μ-CR

- Build templates for different a_τ values by reweighting signal MC using weights from PLB 809 (2020) 135682:
  - a_τ values: 0, ±0.01, ±0.02, ±0.03, ±0.04, ±0.05, ±0.06, ±0.1
  - 3D weights in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$

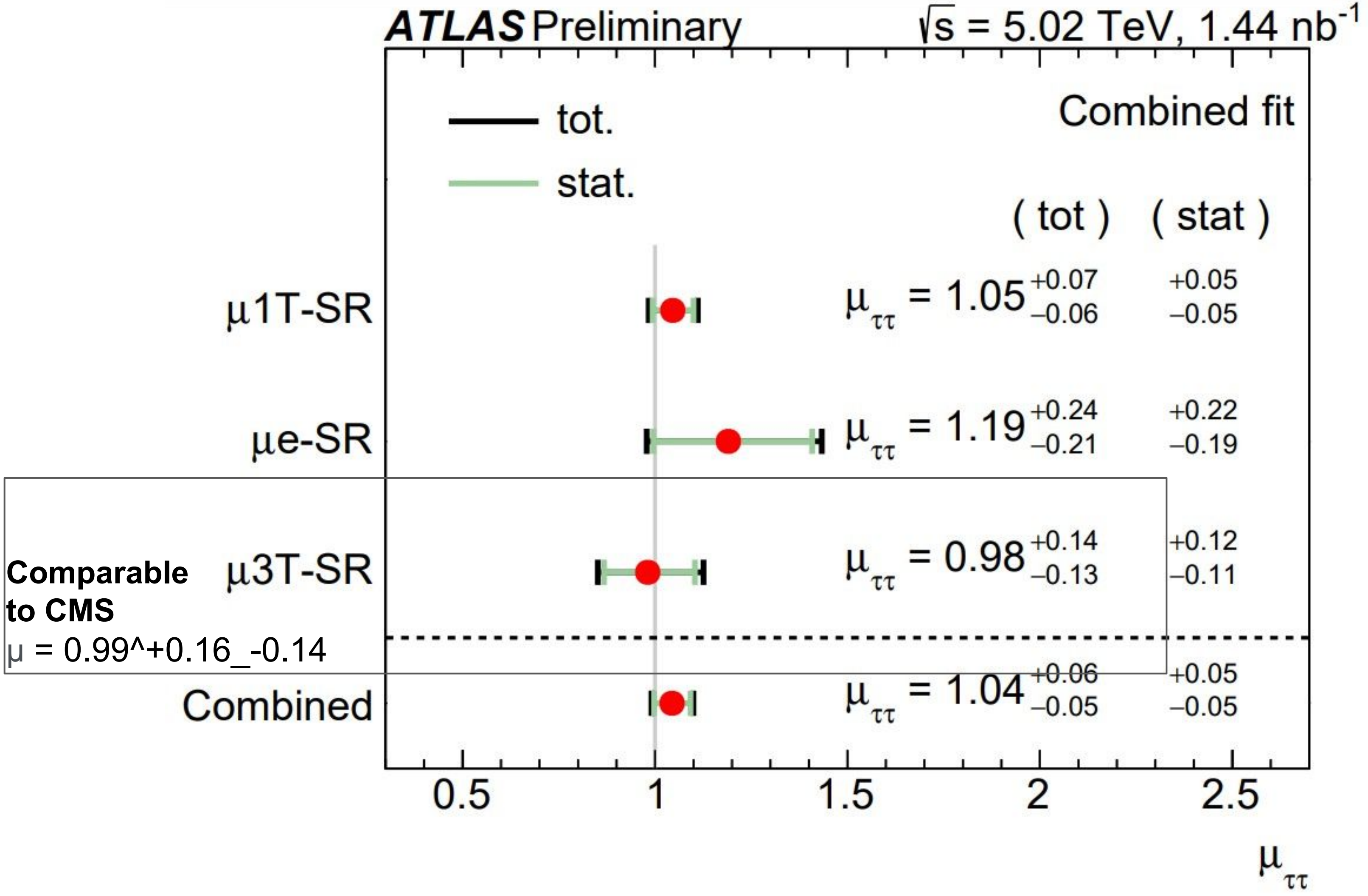
Systematic uncertainties in a_τ

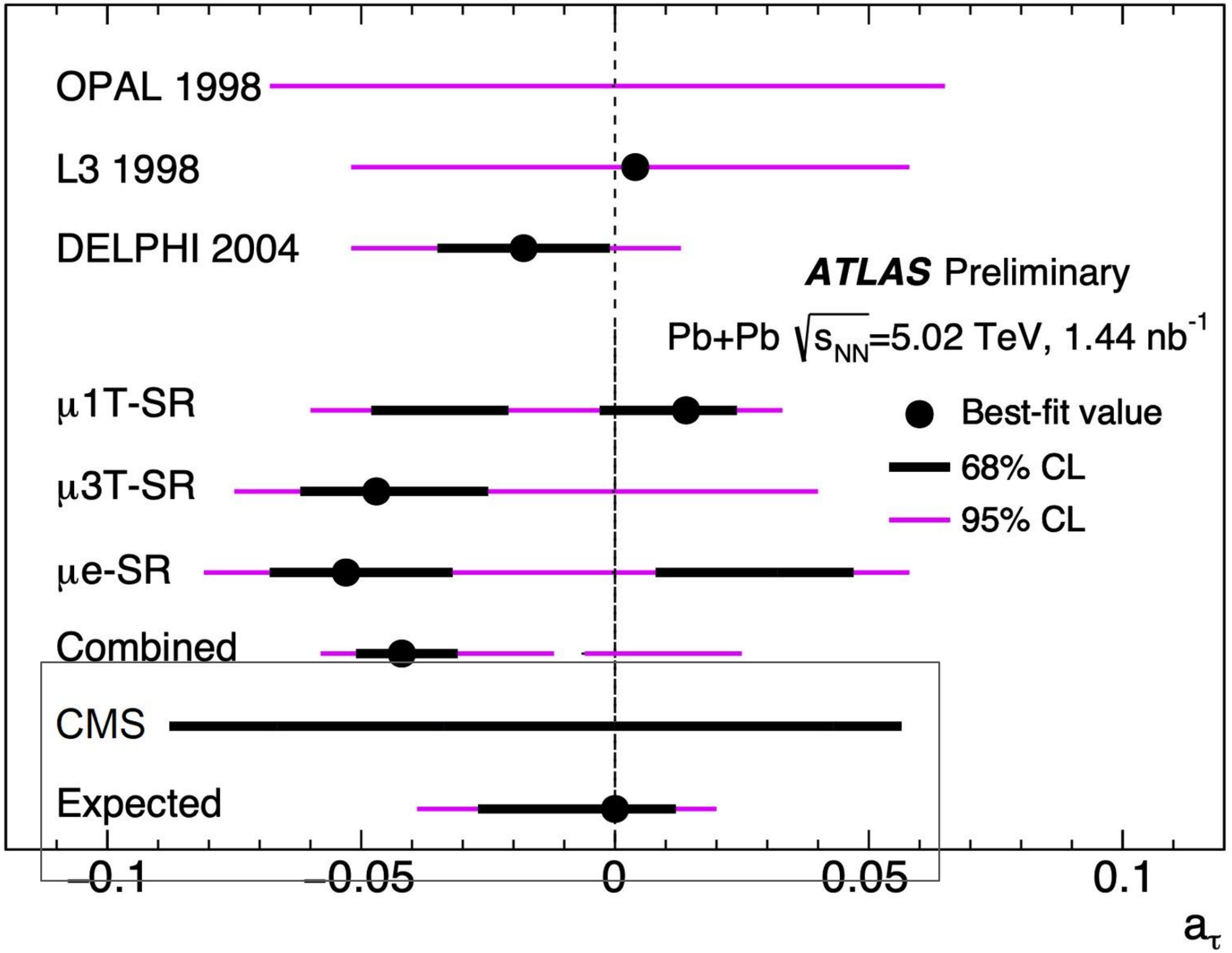
- Detector-related:
  - **muon trigger efficiency**
  - muon/electron reconstruction/identification efficiency and calibration
  - track reconstruction efficiency
  - cluster reconstruction efficiency and calibration
- Background:
  - photonuclear background template variation
- Theory:
  - **photon flux modelling (SuperChic3 vs. Starlight)**
  - **τ decay modelling (Tauola vs. Pythia8)**
  - 0n0n ZDC reweighting variation



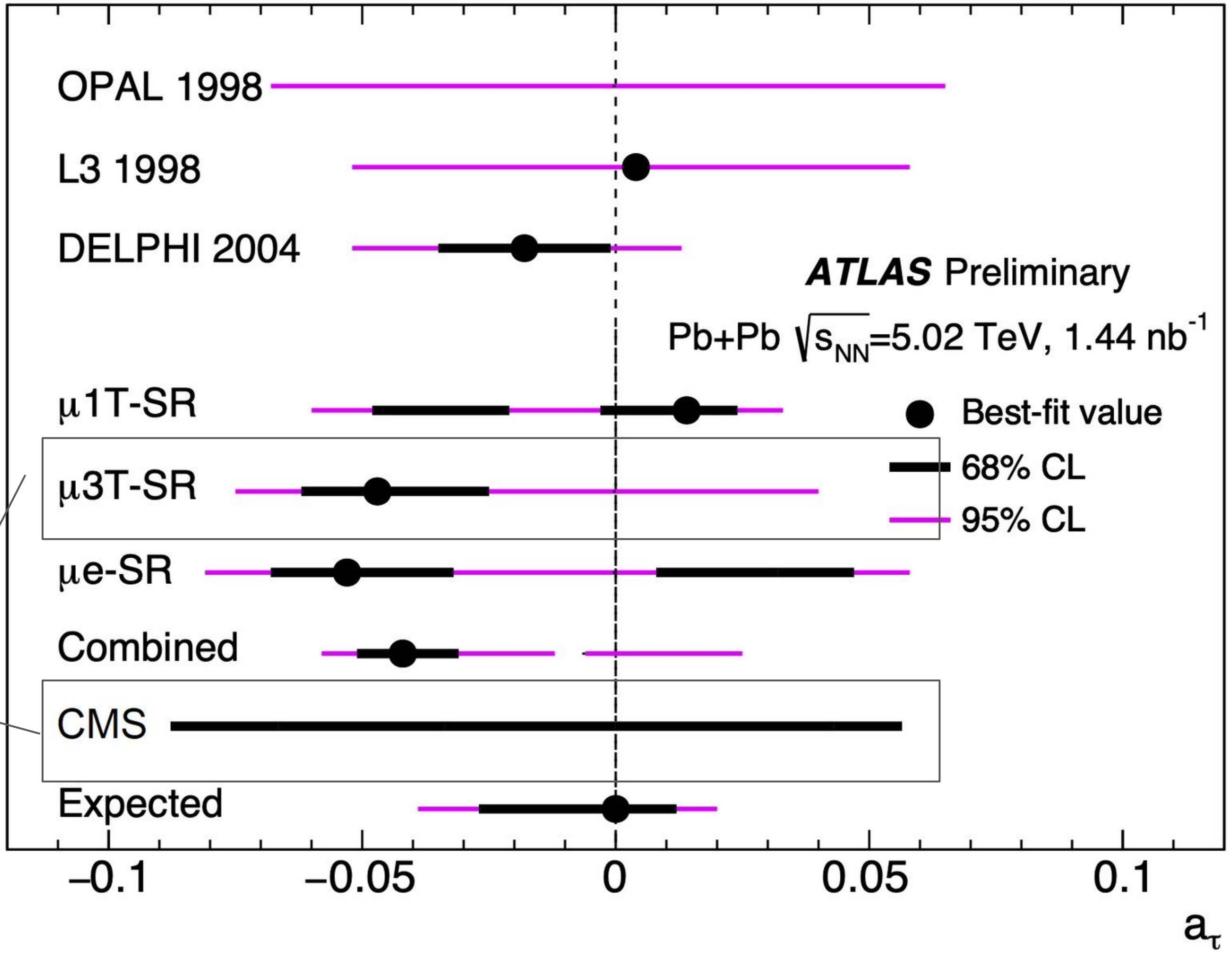
Mariola said not necessarily reflecting photon fluxes

CMS isn't using Tauola anymore


ATLAS Preliminary
√s = 5.02 TeV, 1.44 nb^-1
tot.
stat.
Combined fit
(tot) (stat)
μ1T-SR
μ_ττ = 1.05 +0.07 −0.06 +0.05 −0.05
μe-SR
μ_ττ = 1.19 +0.24 −0.21 +0.22 −0.19
μ3T-SR
μ_ττ = 0.98 +0.14 −0.13 +0.12 −0.11
Combined
μ_ττ = 1.04 +0.06 −0.05 +0.05 −0.05
0.5
1
1.5
2
2.5
μ_ττ
Comparable to CMS
μ = 0.99^+0.16_-0.14

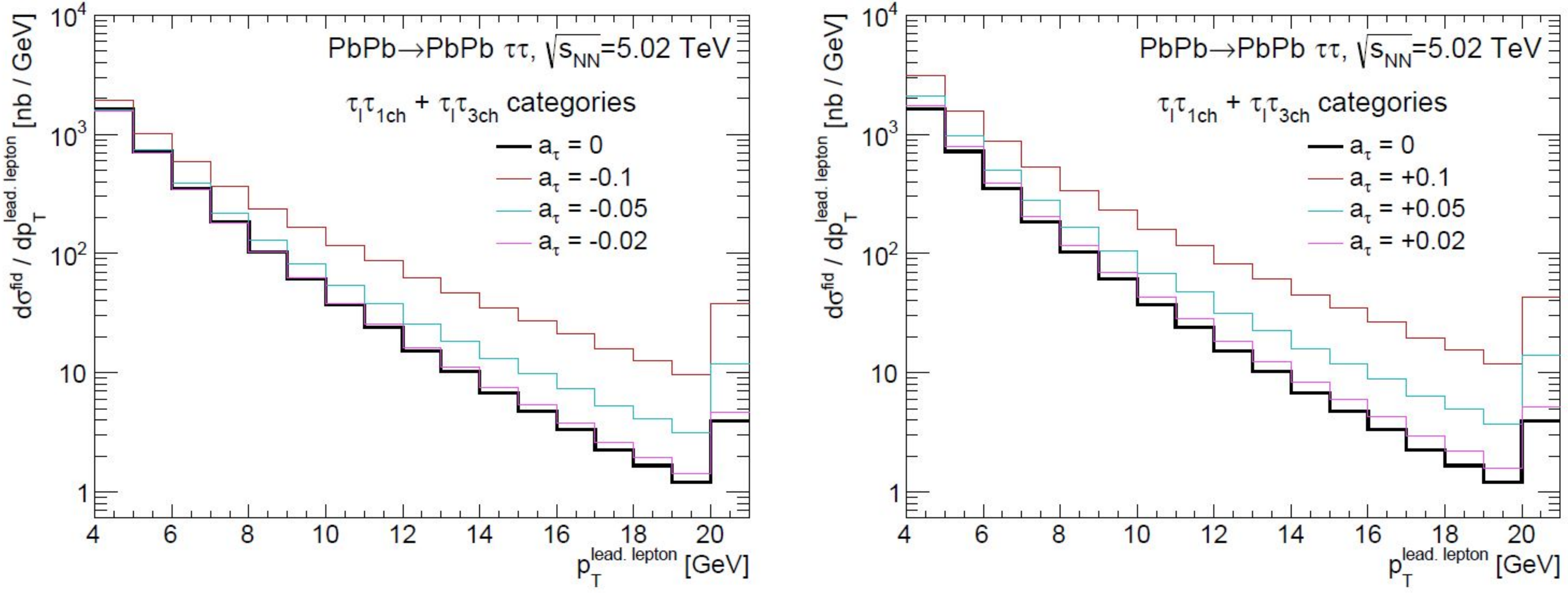


~3 improvement from m1T-SR

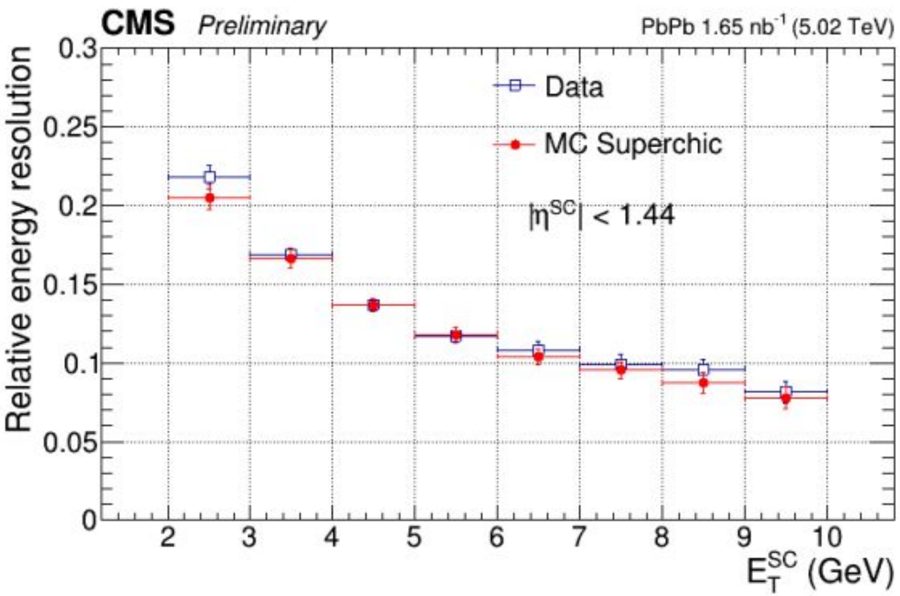


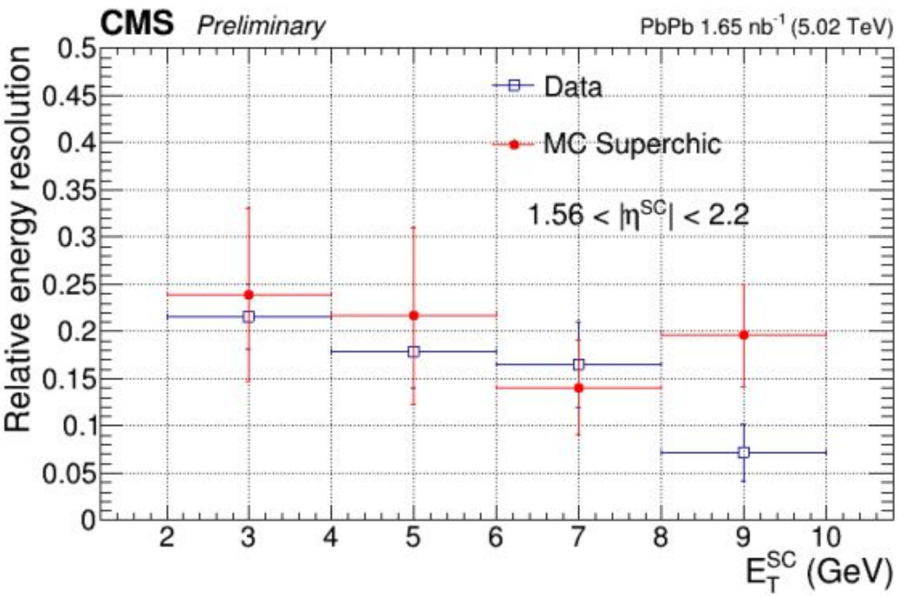
Despite mu's similar improvement from shape analysis(?)

Sensitivity to a_tau (Dyndal)



energy resolution in barrel and endcap region





HINEGammaDPForQM22