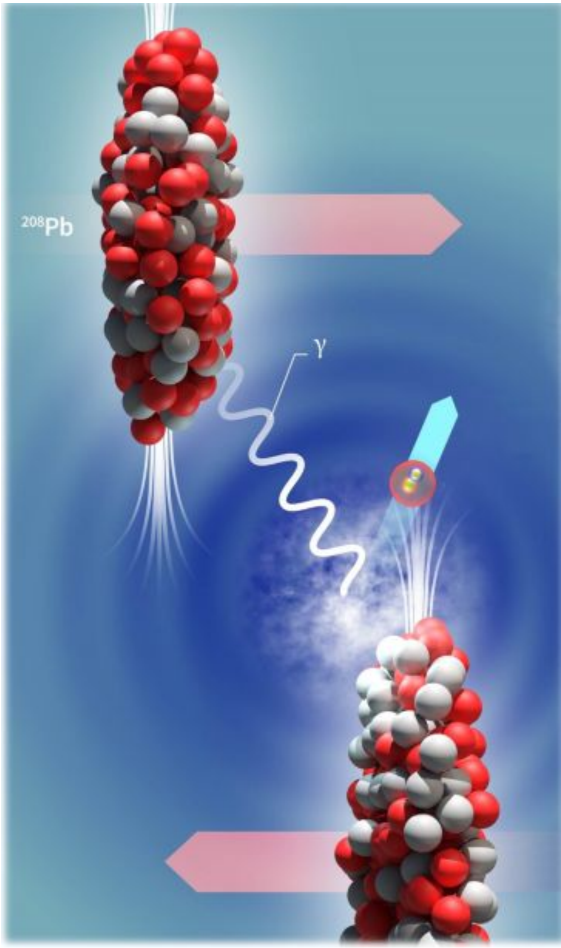
EW precision studies in HI and UPC at LHC



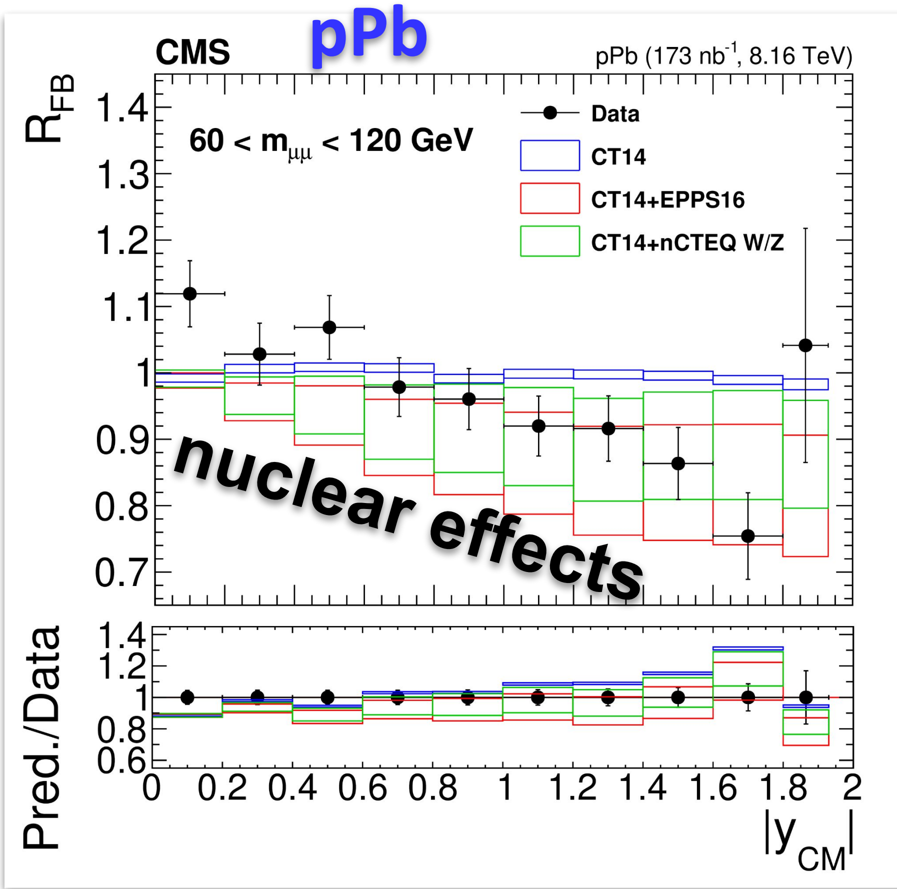
Georgios K Krintiras

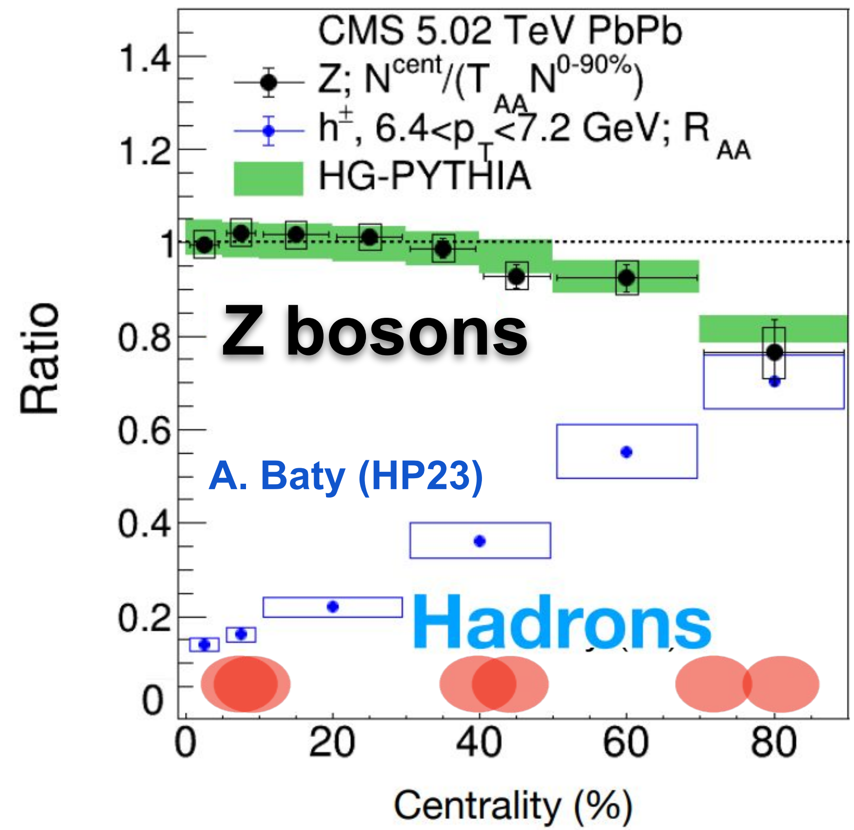
The University of Kansas

Diffraction and gluon saturation at the LHC and the EIC

Probing initial state with EW production

JHEP 05 (2021) 182
PRL 128 (2022) 122301





- Left: Forward-backward σ ratio $R_{FB} \equiv 1$ in the absence of nuclear effects

Probing initial state with EW production

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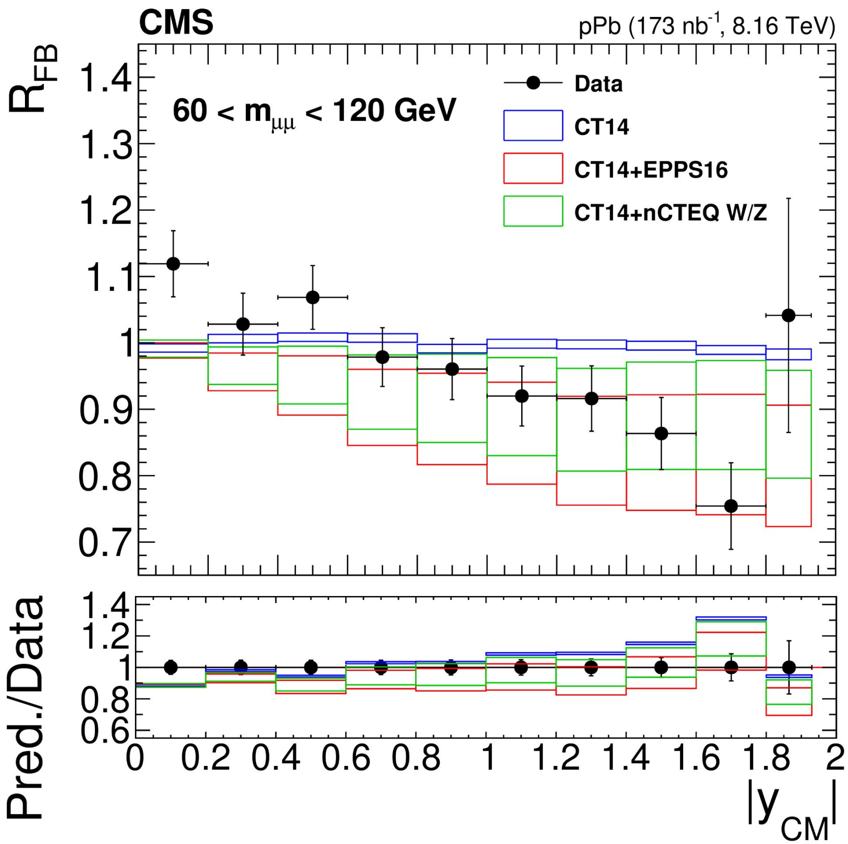
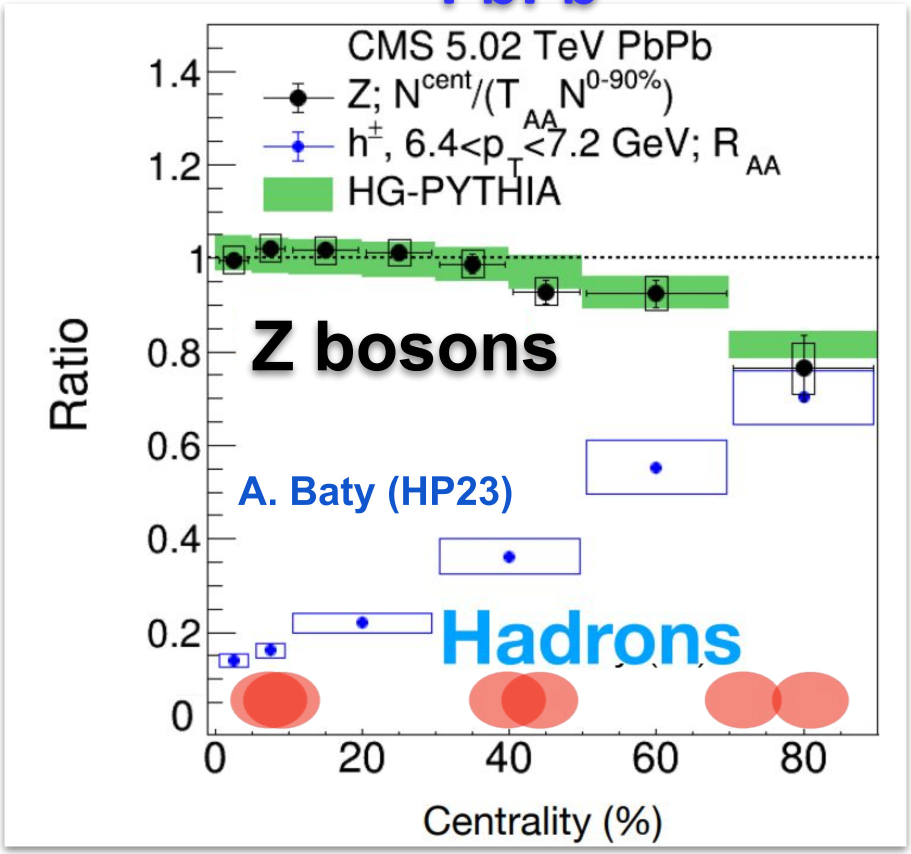


PbPb



- Left: Forward-backward σ ratio $R_{FB} \equiv 1$ in the absence of nuclear effects
- Right: EW bosons in central PbPb unmodified contrary to hadrons (R_{AA}!=1)

Probing initial state with EW production

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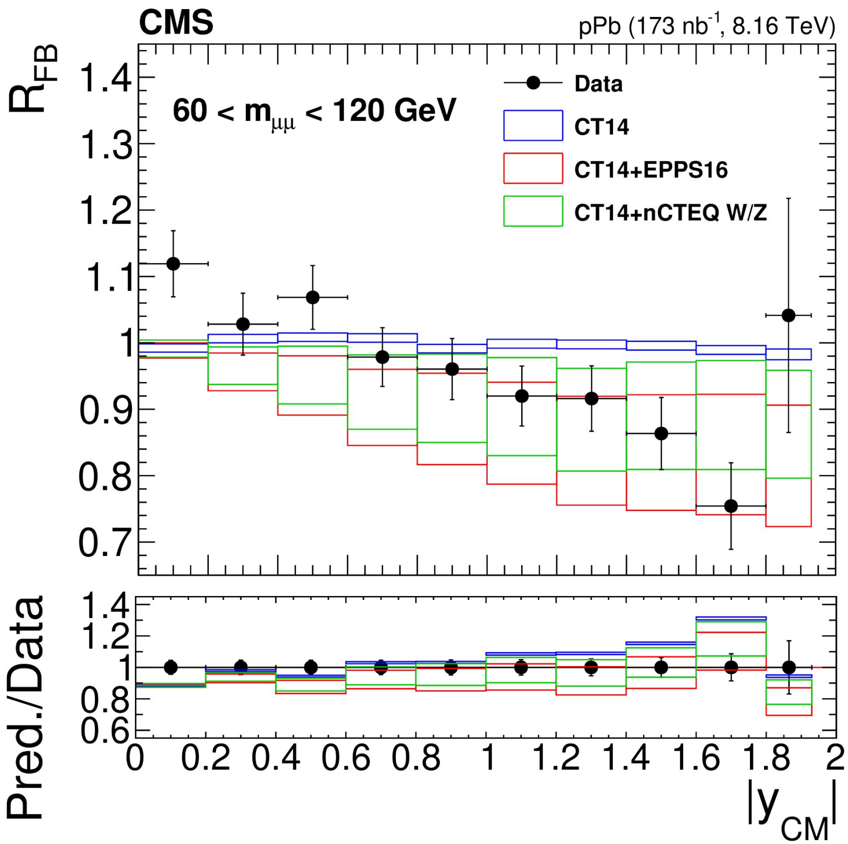
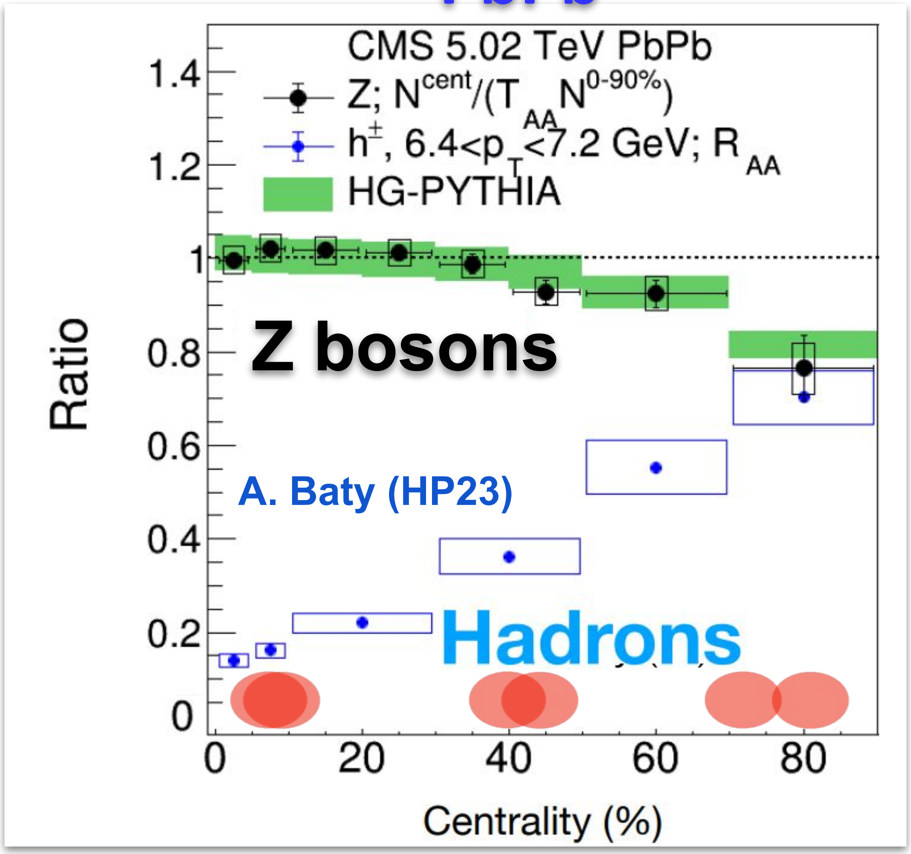


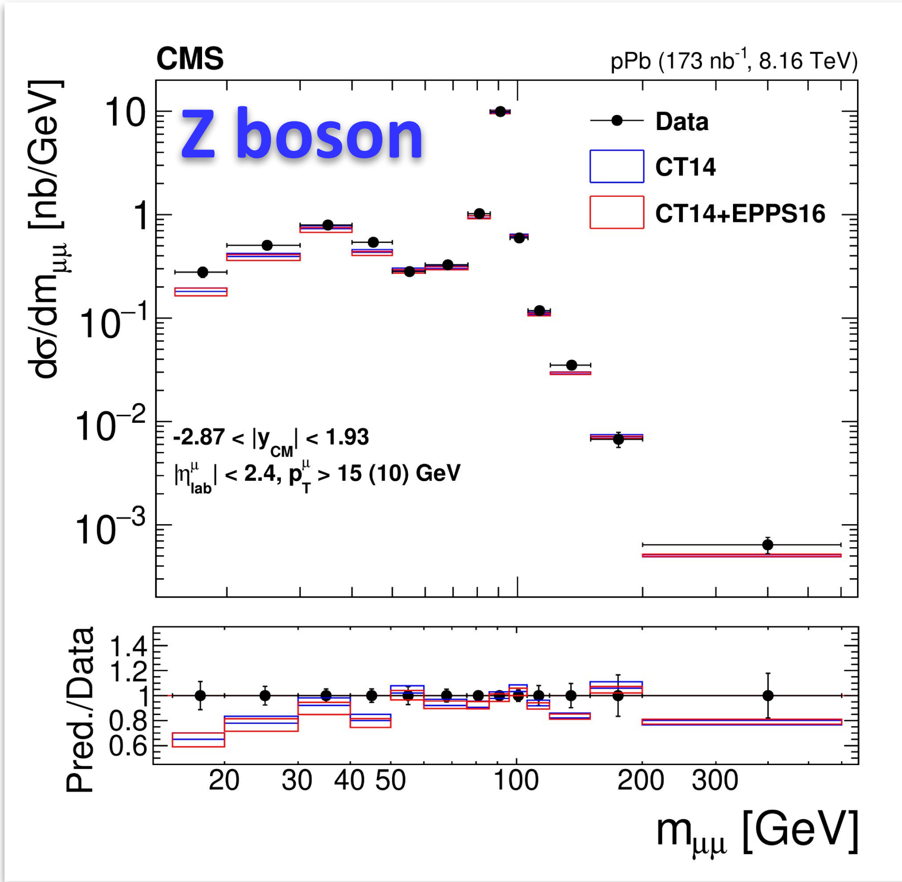
PbPb

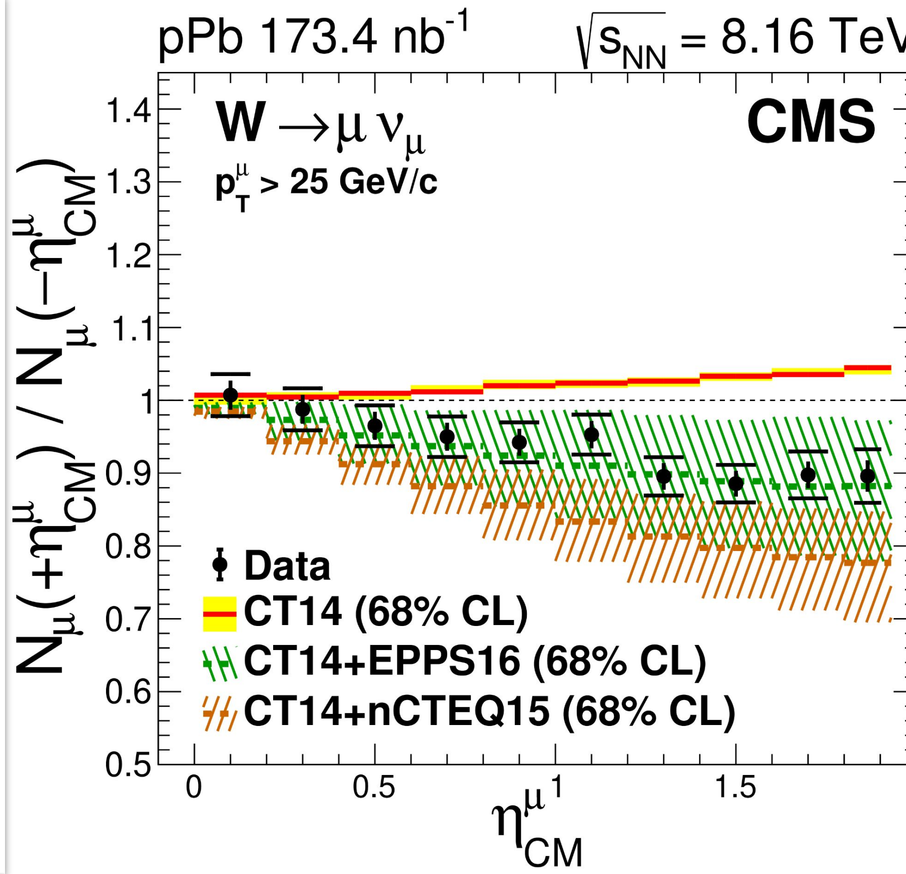


- Left: Forward-backward σ ratio $R_{FB} \equiv 1$ in the absence of nuclear effects
- Right: EW bosons in central PbPb unmodified contrary to hadrons (R_{AA}!=1)
- W bosons, dijets, top quarks sensitive to gluon nPDF at different Bjorken-*x*

Z/γ* & W production in pPb

JHEP 05 (2021) 182
PLB 800 (2020) 135048





- **First Z/γ* study in an extended $m_{\mu\mu}$ range**
  - low $m_{\mu\mu}$ sensitive to NNLO corrections

Z/γ* & W production in pPb

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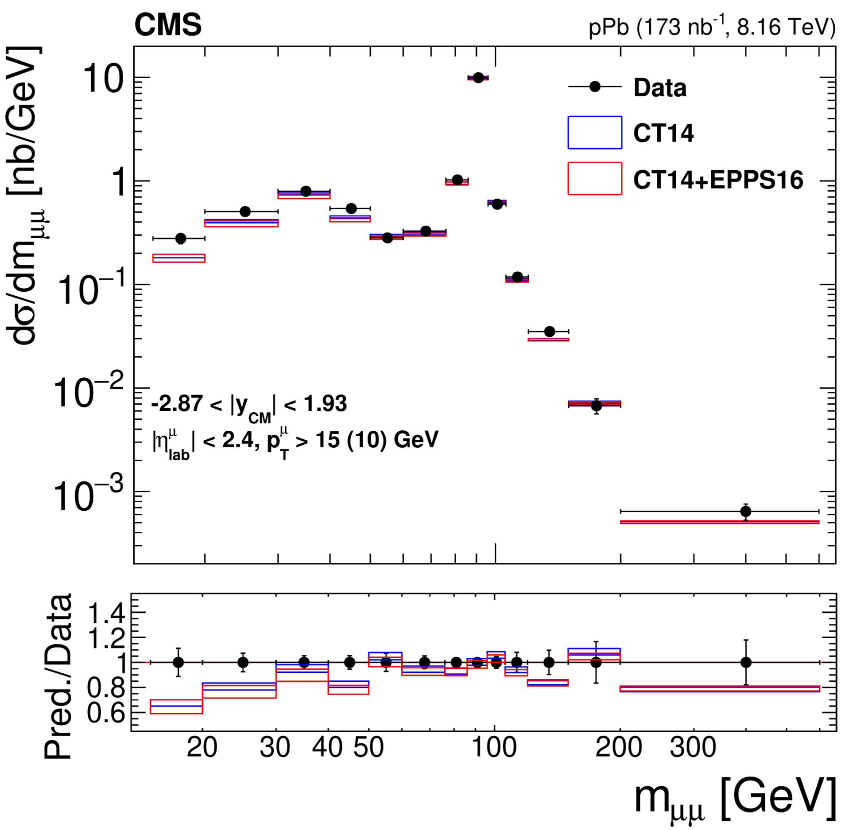
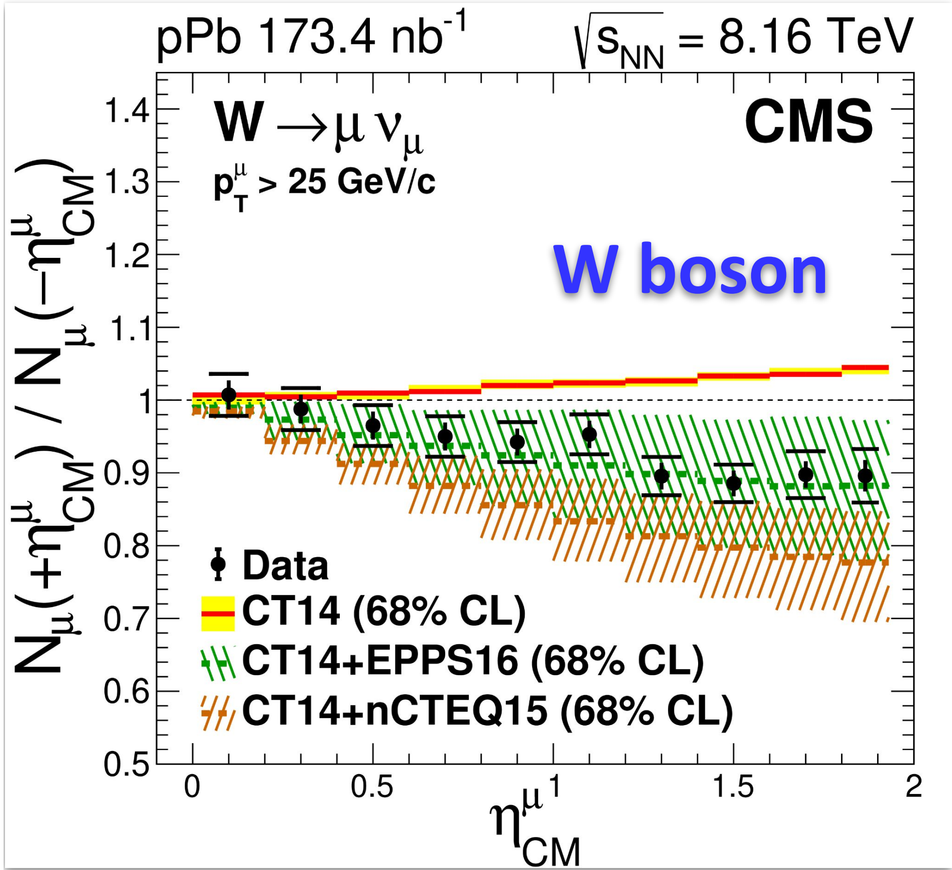
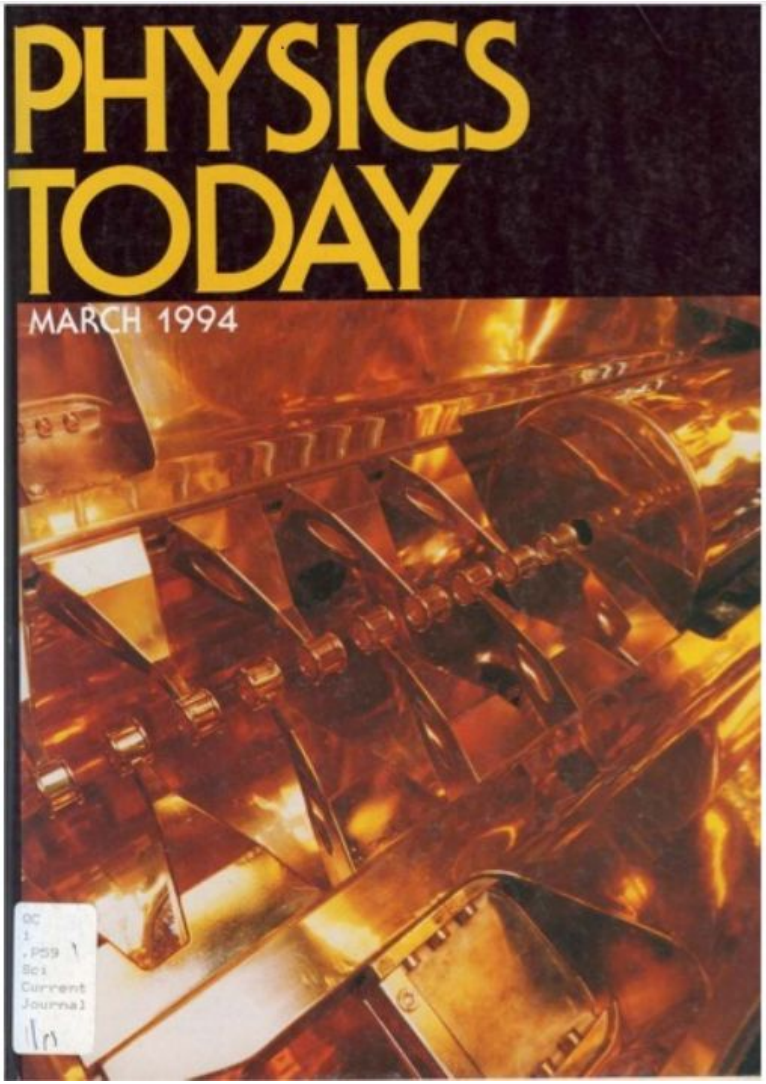




- **First Z/γ* study in an extended $m_{\mu\mu}$ range**
  - low $m_{\mu\mu}$ sensitive to NNLO corrections
- **Observation of nuclear effects in W boson production**
  - included in all recent nPDF fits



RELATIVISTIC HEAVY-ION PHYSICS WITHOUT NUCLEAR CONTACT

The large electromagnetic field generated by a fast heavy nucleus allows investigation of new electromagnetic processes not accessible with real photons.

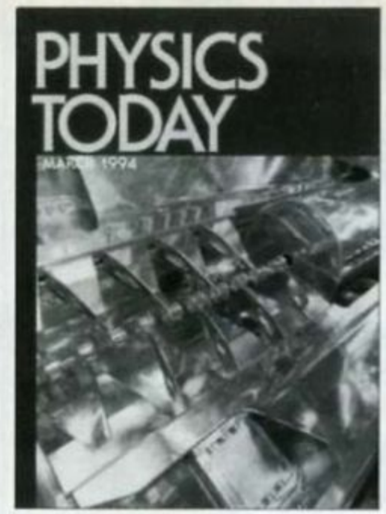
Carlos Bertulani and Gerhard Baur

An increasing number of physicists are investigating nuclear collisions at relativistic energies. (See figure 1.) Accelerators completely devoted to the study of these collisions (such as the Relativistic Heavy Ion Collider at Brookhaven National Laboratory) are under construction. So are hadron colliders (such as the Large Hadron Col-

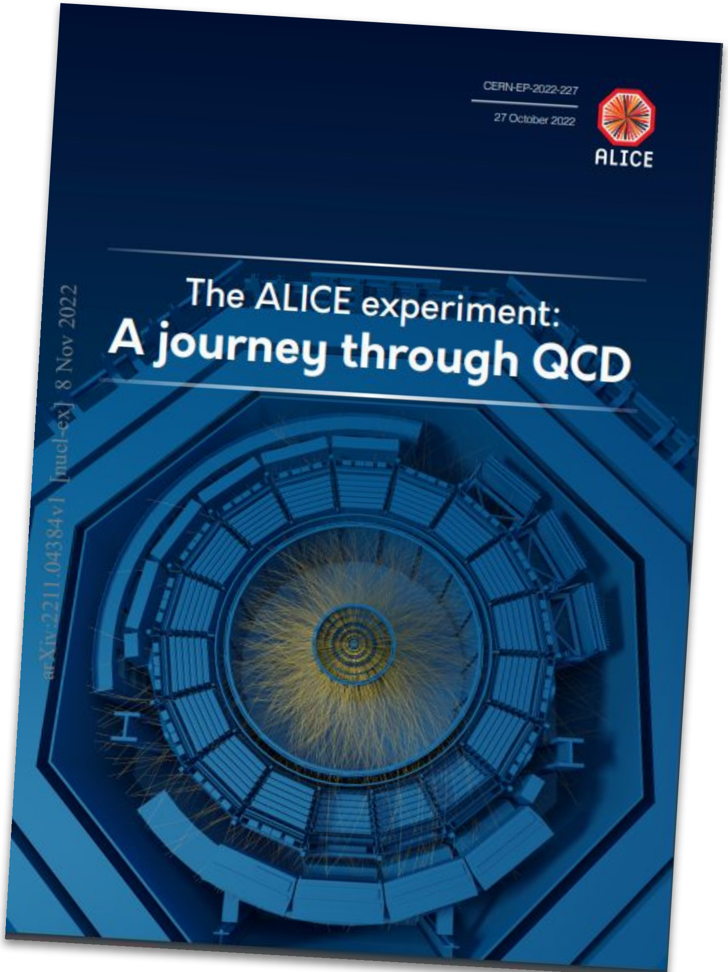
mately by $b/\gamma v$ and that the electric (or magnetic) field during this time interval is very intense: $E \simeq \gamma Ze/b^2$. The factor γ, which is $(1 - v^2/c^2)^{-1/2}$, is very large (on the order of 10^4–10^7) in relativistic heavy-ion colliders.

Theory

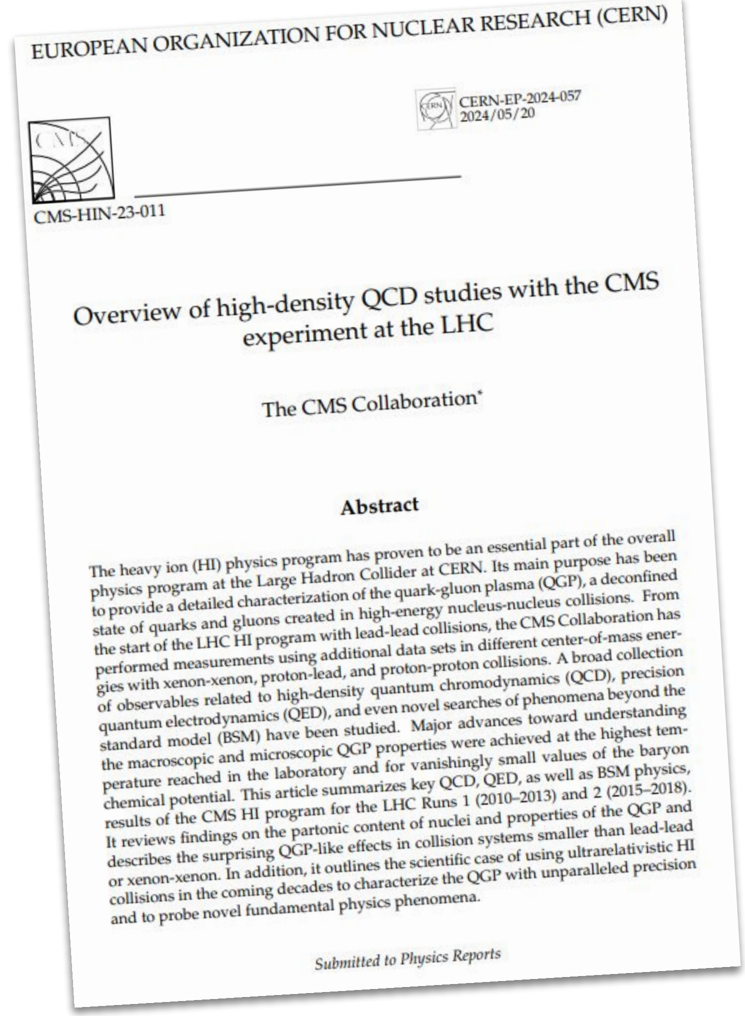
COVER: Inside of a compact high-frequency linear accelerator for heavy ions developed at the Technical University of Munich and at GSI in Darmstadt, Germany. The polished copper structure uses a quadrupole field to focus highly charged ions. Accelerators of this design at GSI and CERN bring ions up to high enough energies that the main accelerators can take them to relativistic energies. In their article on page 22, Carlos Bertulani and Gerhard Baur discuss the physics one can probe by colliding relativistic heavy ions without nuclear contact.



- **A rich physics program, unique on its own**
  - **Seminal results by all 4 major LHC experiments**



237 pages


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-057
2024/05/20

CMS-HIN-23-011

Overview of high-density QCD studies with the CMS experiment at the LHC

The CMS Collaboration*

Abstract

The heavy ion (HI) physics program has proven to be an essential part of the overall physics program at the Large Hadron Collider at CERN. Its main purpose has been to provide a detailed characterization of the quark-gluon plasma (QGP), a deconfined state of quarks and gluons created in high-energy nucleus-nucleus collisions. From the start of the LHC HI program with lead-lead collisions, the CMS Collaboration has performed measurements using additional data sets in different center-of-mass energies with xenon-xenon, proton-lead, and proton-proton collisions. A broad collection of observables related to high-density quantum chromodynamics (QCD), precision quantum electrodynamics (QED), and even novel searches of phenomena beyond the standard model (BSM) have been studied. Major advances toward understanding the macroscopic and microscopic QGP properties were achieved at the highest temperature reached in the laboratory and for vanishingly small values of the baryon chemical potential. This article summarizes key QCD, QED, as well as BSM physics results of the CMS HI program for the LHC Runs 1 (2010–2013) and 2 (2015–2018). It reviews findings on the partonic content of nuclei and properties of the QGP and describes the surprising QGP-like effects in collision systems smaller than lead-lead or xenon-xenon. In addition, it outlines the scientific case of using ultrarelativistic HI collisions in the coming decades to characterize the QGP with unparalleled precision and to probe novel fundamental physics phenomena.

Submitted to Physics Reports

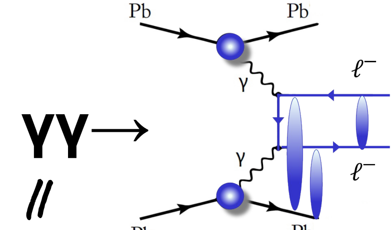
154 pages

- **A rich physics program, unique on its own**
  - **Seminal results by all 4 major LHC experiments**
- **Featured in the high-density QCD reviews by ALICE and CMS**

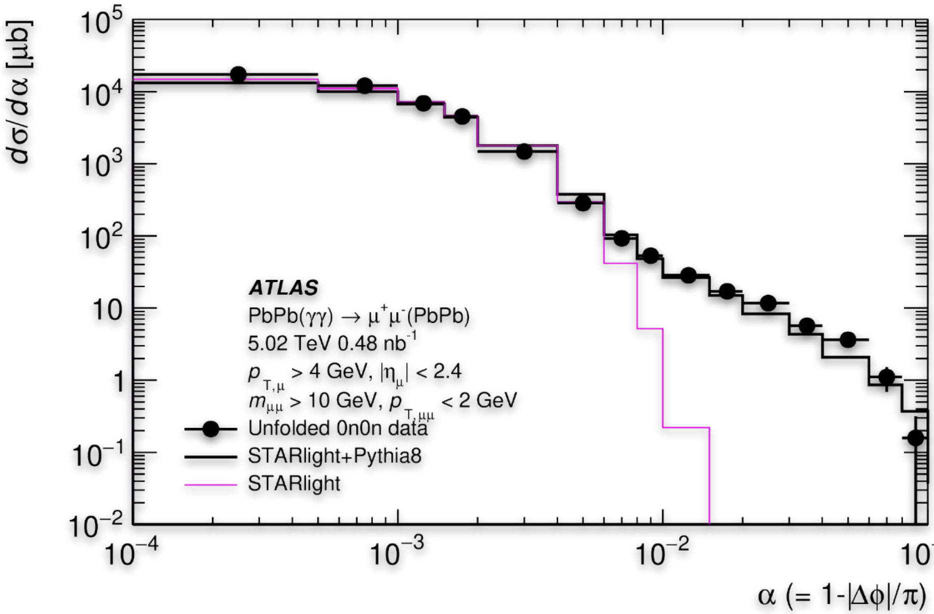
Focus of this talk

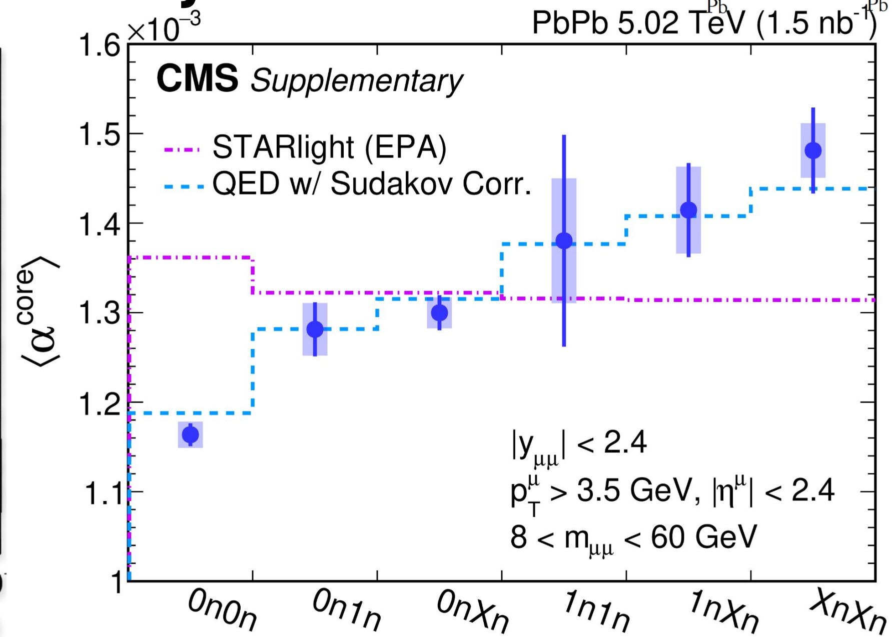
Free lepton pair production

[PRC **104** (2021) 024906](#)
[PRL **127** (2021) 122001](#)



Accoplanarity



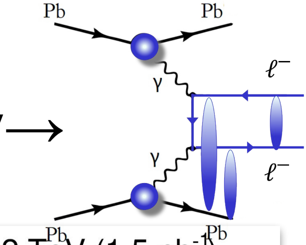


- **"Standard candle" to unveil NLO QED emissions and calibrate γ fluxes**
  - precision goal: to model these effects at **1% level** (stat unc is negligible)
    - another method to calibrate luminosity (considered as ["golden channel"](#))

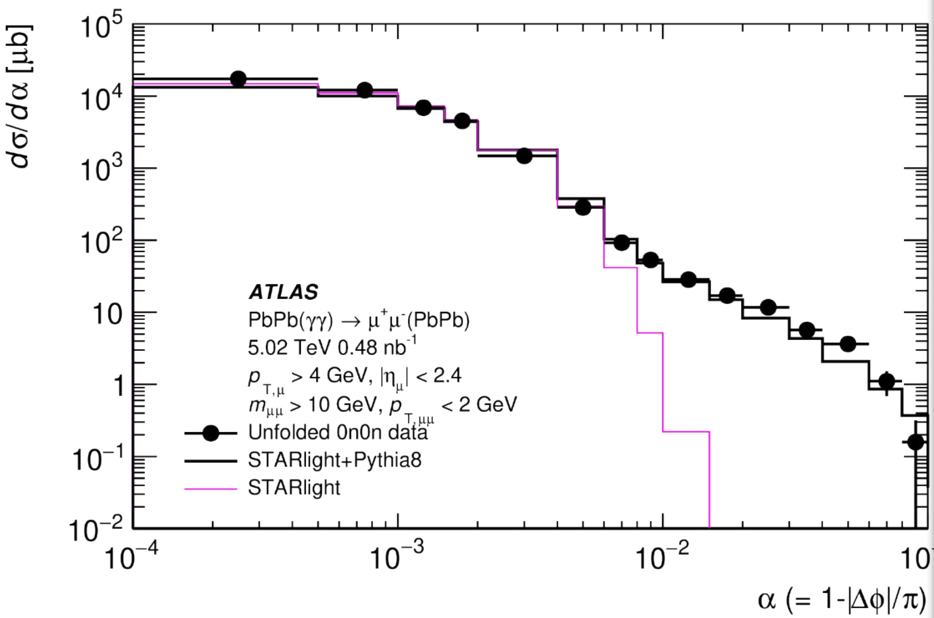
Free lepton pair production

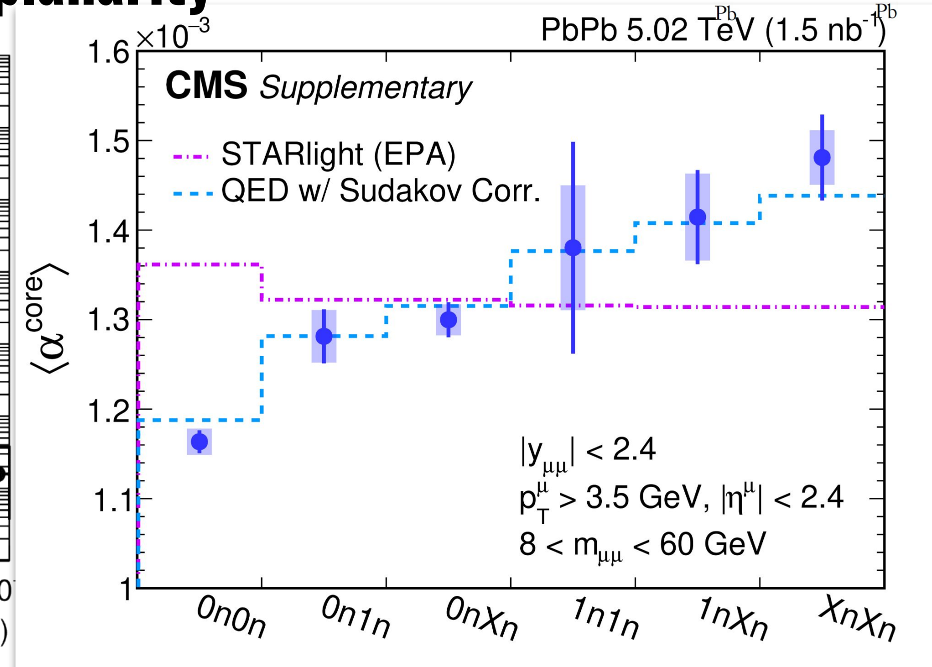
PRC **104** (2021) 024906
PRL **127** (2021) 122001

γγ→ //



Accoplanarity

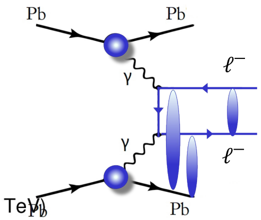


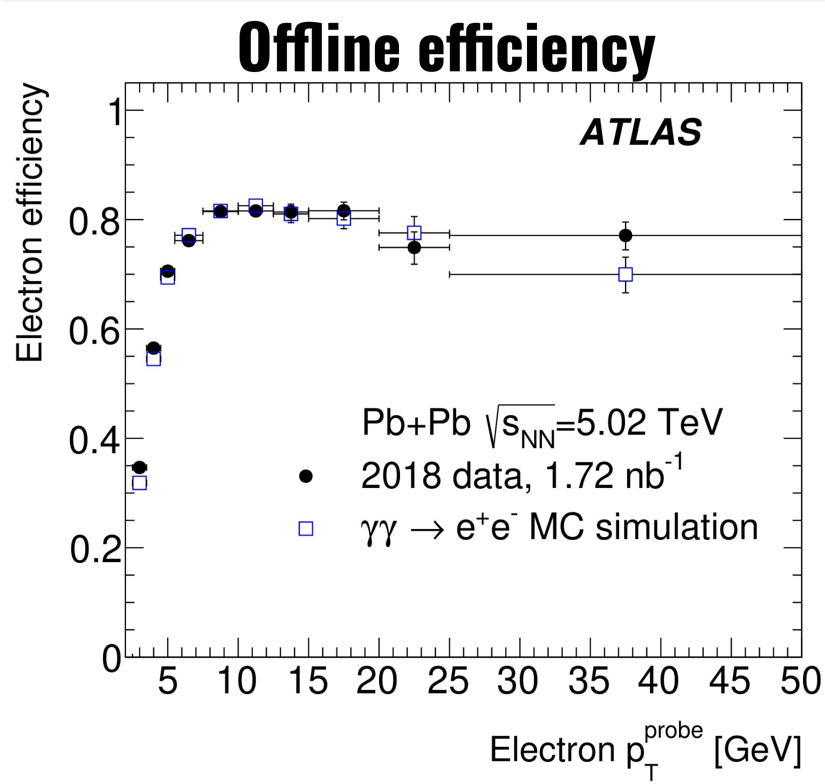


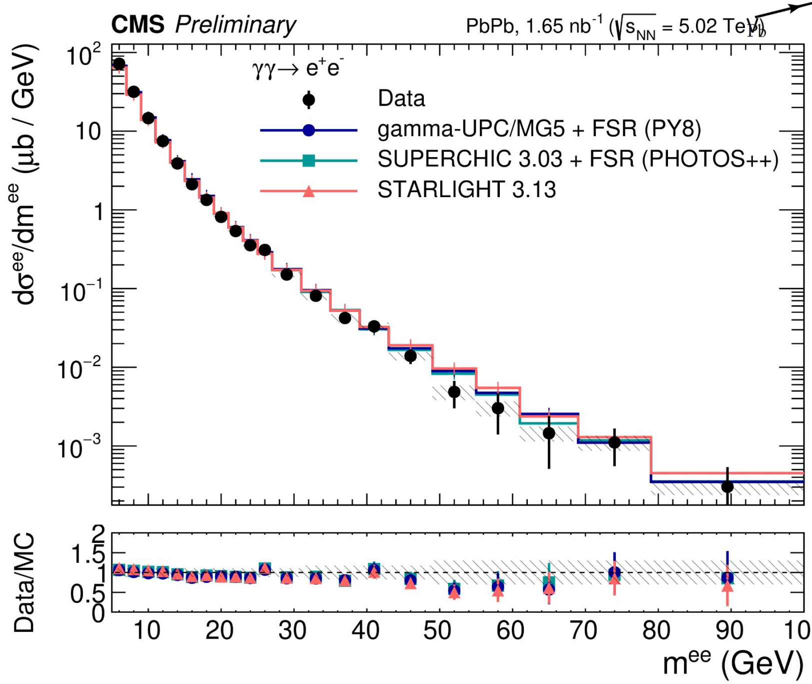
- **“Standard candle” to unveil NLO QED emissions and calibrate γ fluxes**
  - precision goal: to model these effects at **1% level** (stat unc is negligible)
    - another method to calibrate luminosity (considered as “golden channel”)
- **Studies of correlation with forward neutron emissions**
  - γγ interactions occur in conjunction with ion excitation denoted as AnAn
    - AnAn-dependent production → reflects the **initial γ energy distribution**

γγ→ ll differential production

[JHEP **06** (2023) 182](#)
[CMS-PAS-HIN-21-015](#)



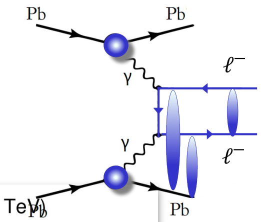




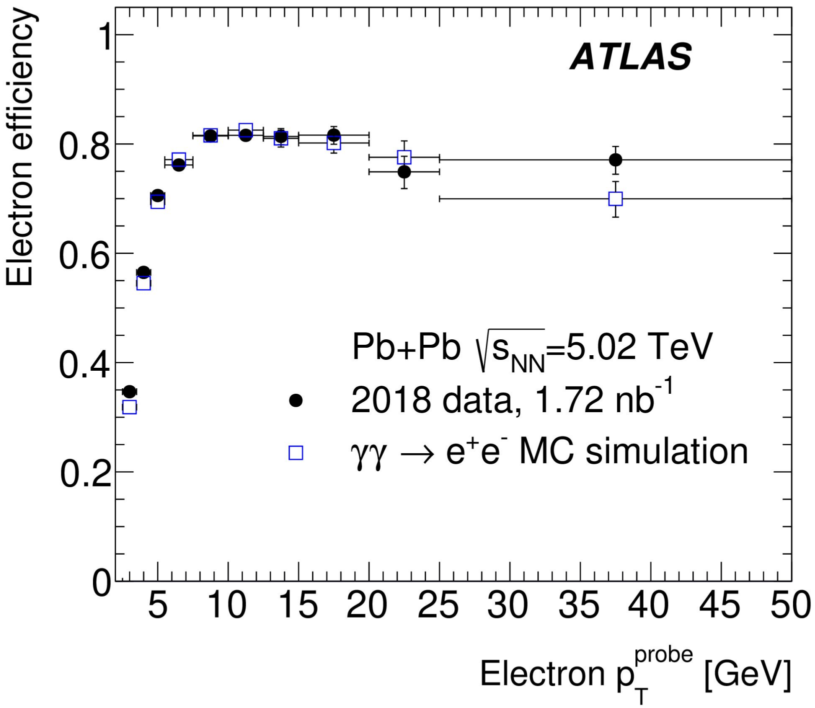
- **ATLAS/CMS optimize their low-E_T reconstruction to maximize statistics**
  - signal dominantly in the E_T<10 GeV region ⟶ default reco has to be **tuned**

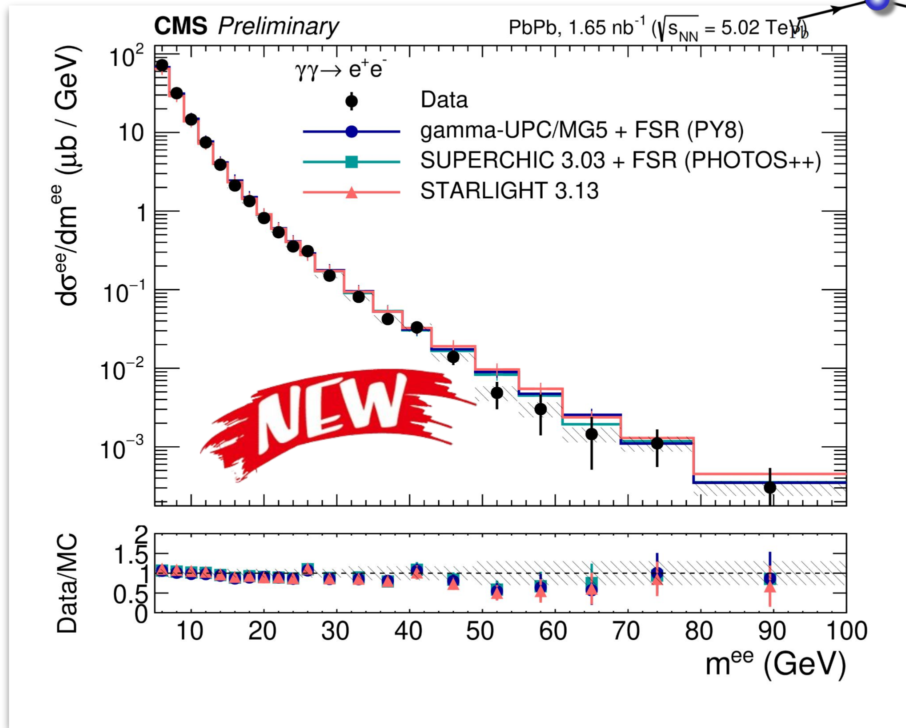
γγ→ ℓℓ differential production

[JHEP **06** (2023) 182](#)
[CMS-PAS-HIN-21-015](#)



e^+e^- inv mass



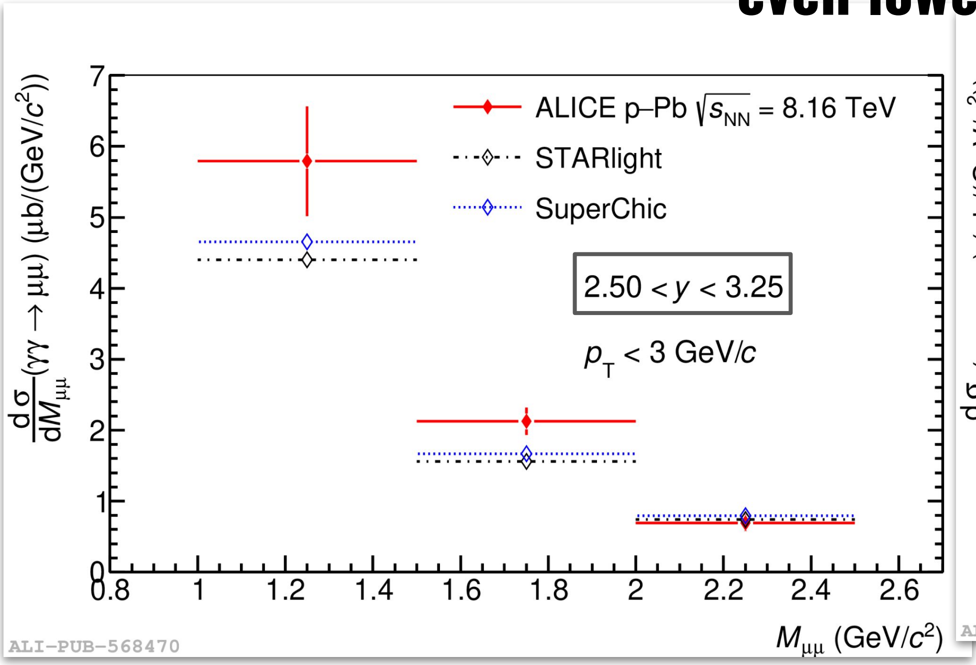


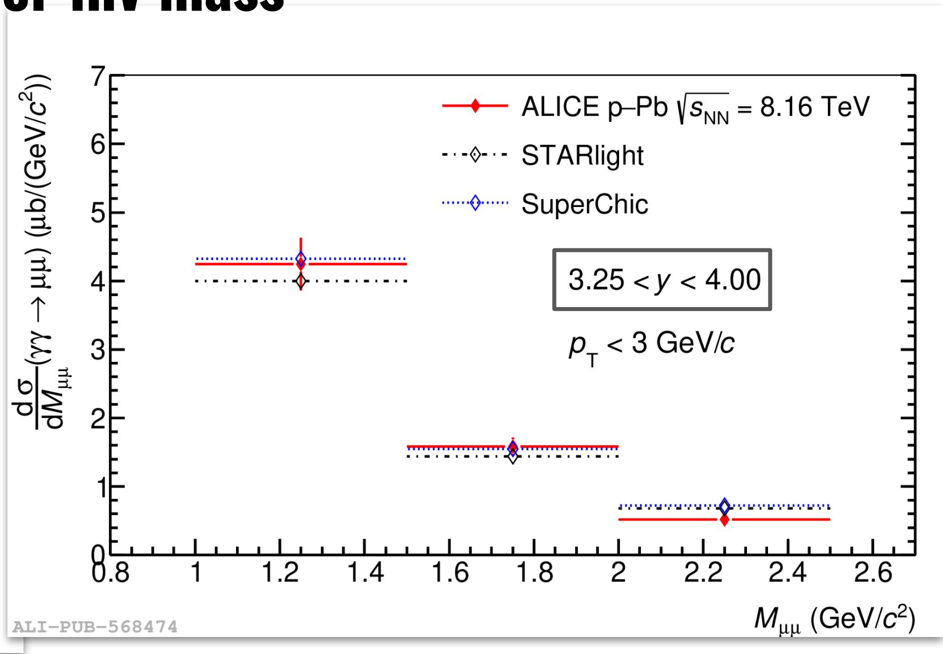
- **ATLAS/CMS optimize their low-E_T reconstruction to maximize statistics**
  - signal dominantly in the E_T<10 GeV region ⟶ default reco has to be **tuned**
- **Combined with increased luminosity ⟶ detailed differential studies**
  - probing **two orders** of magnitude in inv mass (5–100 GeV)
    - NLO QED predictions in better agreement with data

γγ→ ℓℓ differential production in pPb

PRD **108** (2023) 112004

even lower inv mass

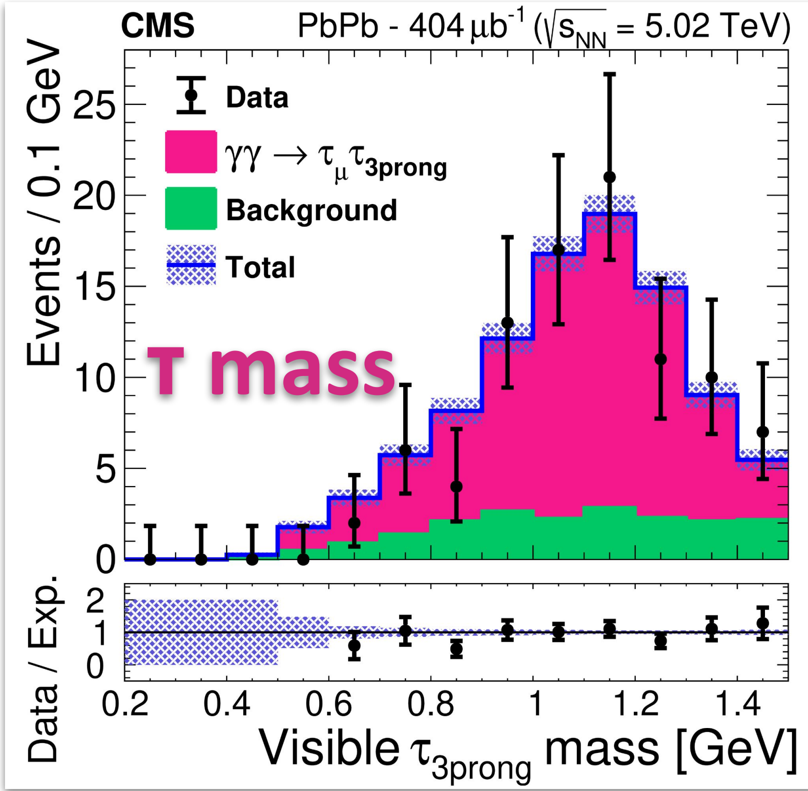


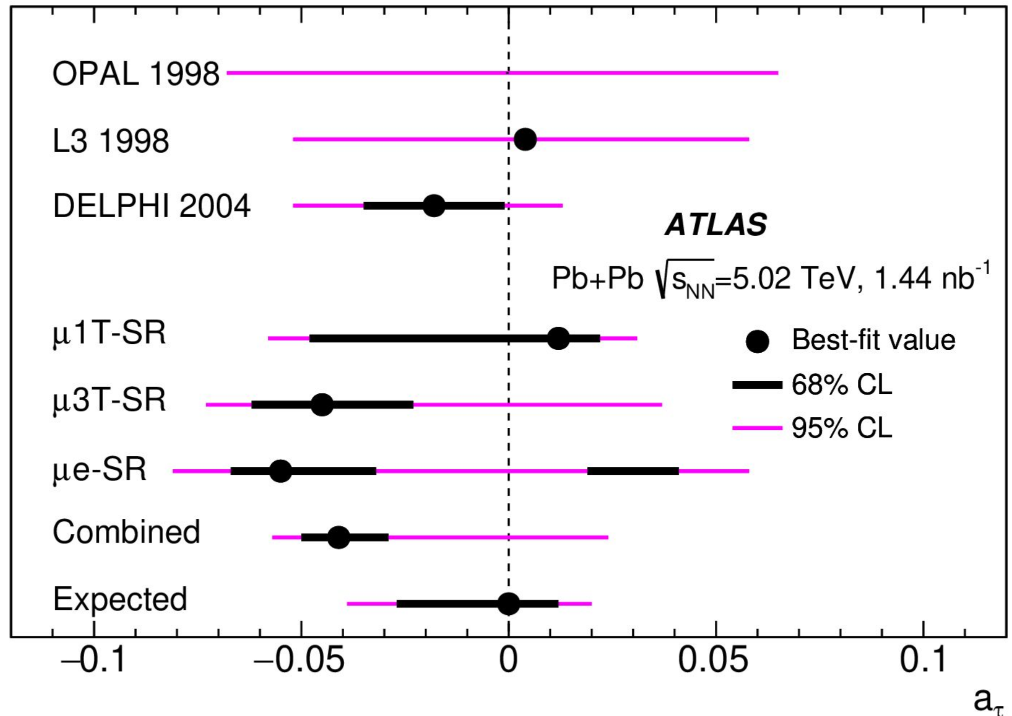


- **ALICE extends the inv mass reach**
  - consistent picture with UPC pPb: LO QED predictions up to 3σ away from data
    - the measurement will profit from more pPb data (foreseen for Run 4..)
    - dedicated workshop at CERN in July; everyone is kindly invited :)

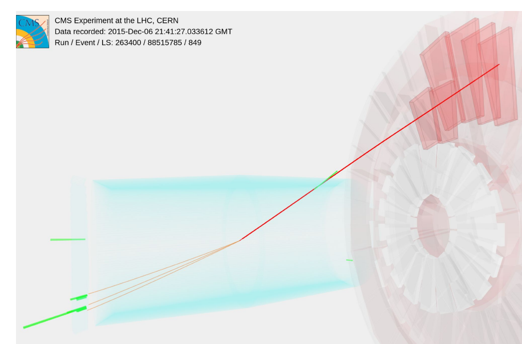
τ lepton pair production in UPC PbPb

PRL **131** (2023) 151802
PRL **131** (2023) 151803





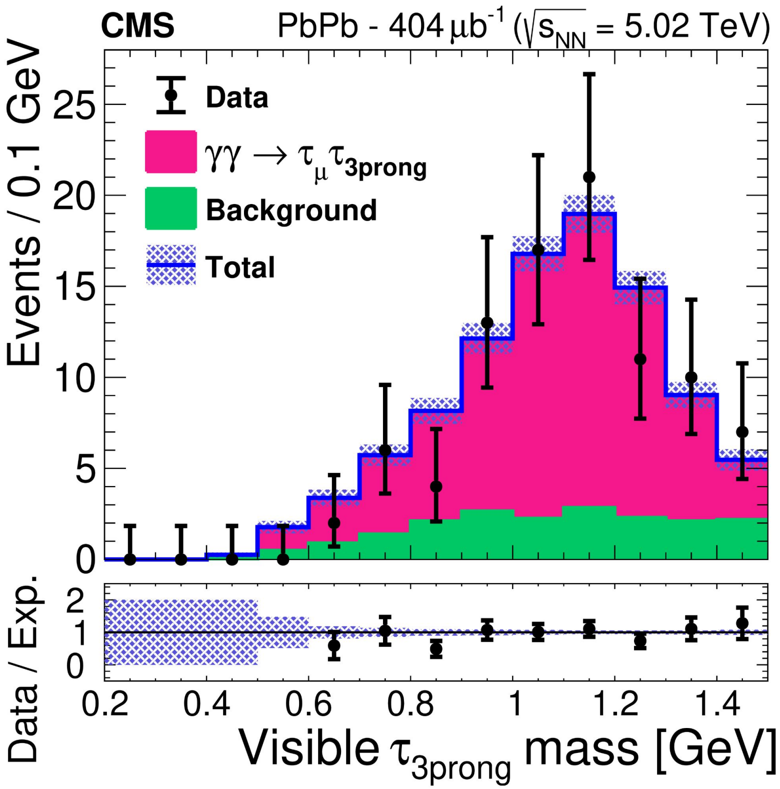
- **Observation of $\gamma\gamma \rightarrow \tau^+\tau^-$ at LHC**
  - ATLAS: full Run 2, multiple final states
  - CMS: part of Run 2, with a single but clean state
  - Pheno projections for ALICE/LHCb here

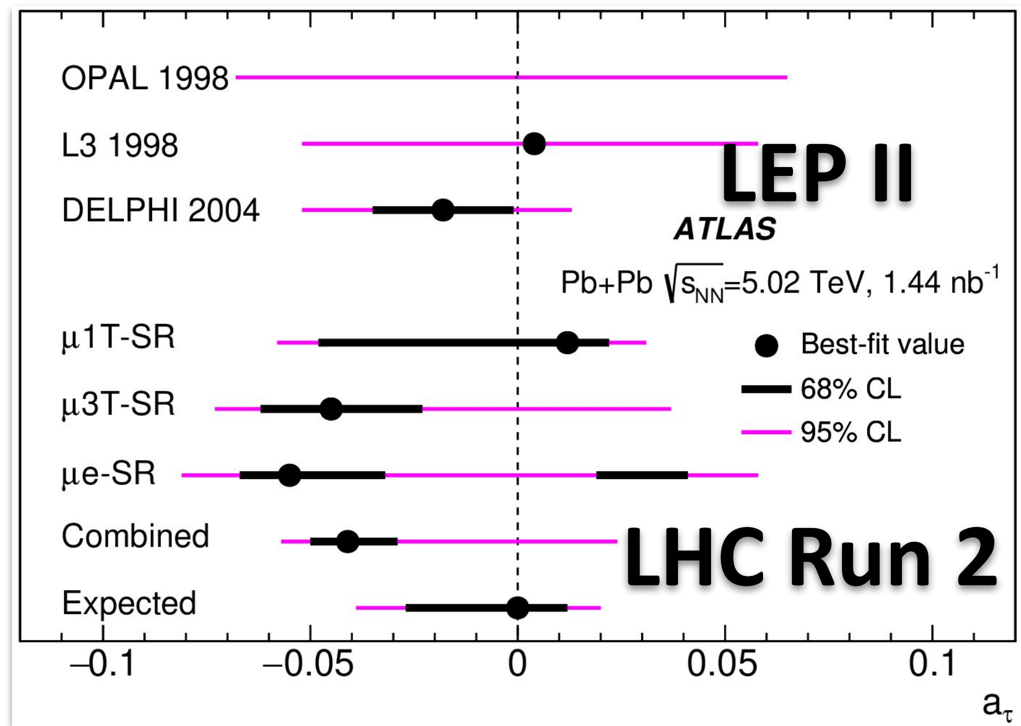


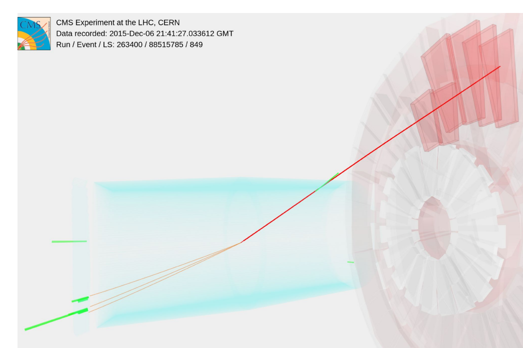
τ lepton pair production in UPC PbPb

PRL **131** (2023) 151802
PRL **131** (2023) 151803

g_τ-2







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  - ATLAS: full Run 2, multiple final states
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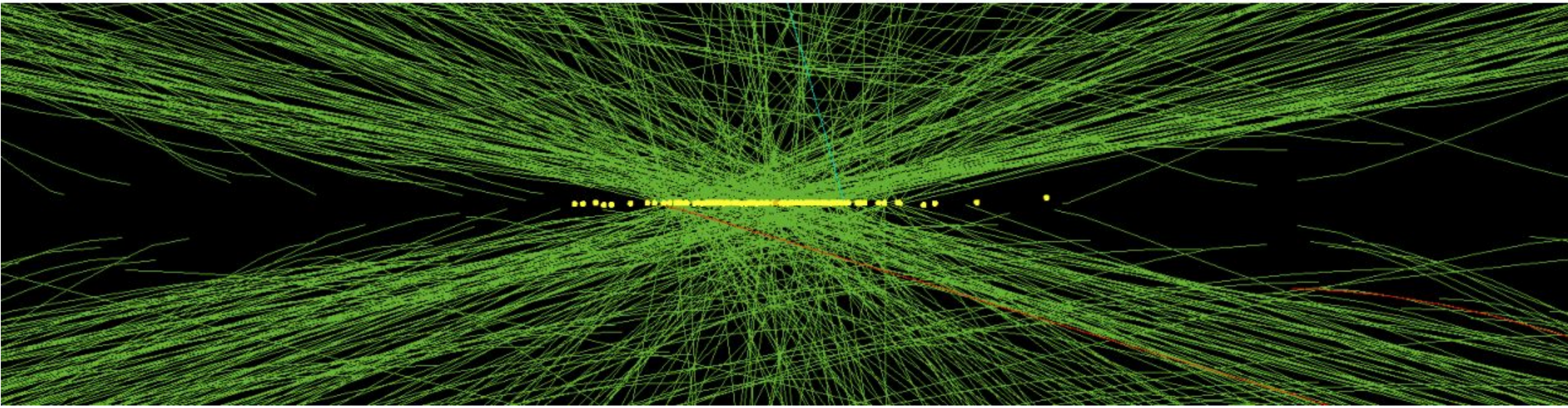
  - Pheno projections for ALICE/LHCb here
- **Model-dependent constraints on a_τ obtained**
  - competing with LEP II limits; complementary to the pp search by CMS

Counting tracks

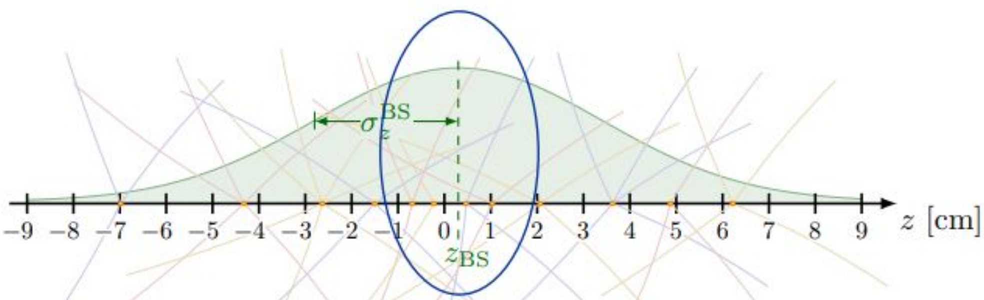
- Photon-induced processes are exceptionally clean…
- … but proton-proton collisions are incredibly busy
  - Average of > 30 pileup interactions in 2018

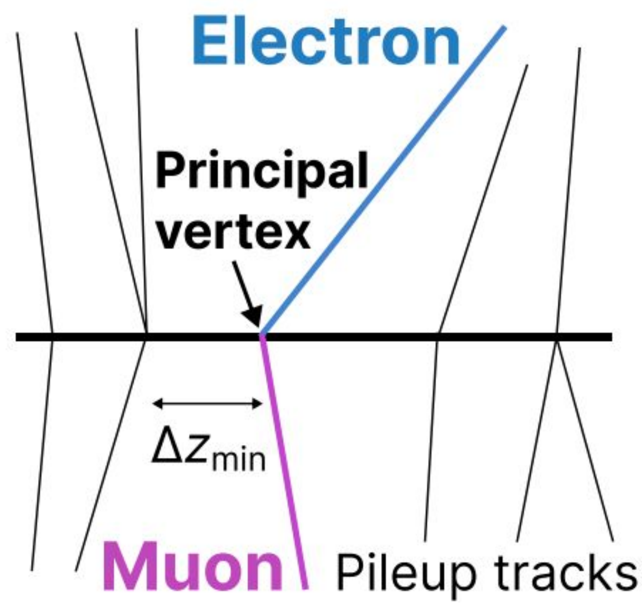


Counting tracks

- Define **z position of di-tau vertex** as average z position of selected tau leptons
- Define $\mathbf{N_{tracks}}$ as the number of tracks
  - with $p_T > 0.5$ GeV and $|\eta| < 2.5$
  - within a window of **0.1 cm** around the di-tau vertex
  - Excluding tracks from tau leptons

Extraordinary tracking capabilities of the CMS detector!





Cécile Caillol, LPCC seminar, March 12th

Method also described in 2403.06336 (L. Beresford *et al*)

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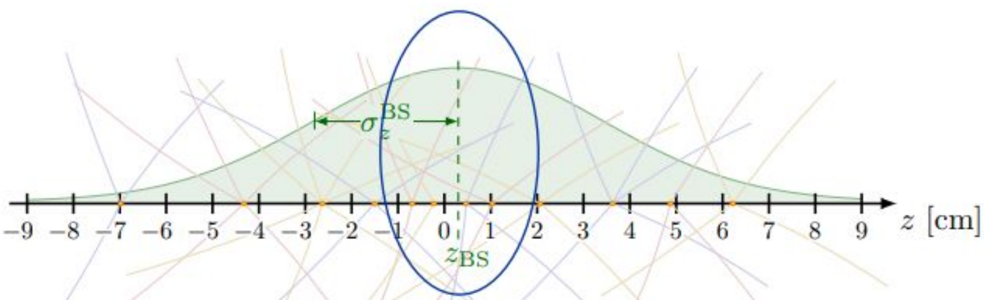
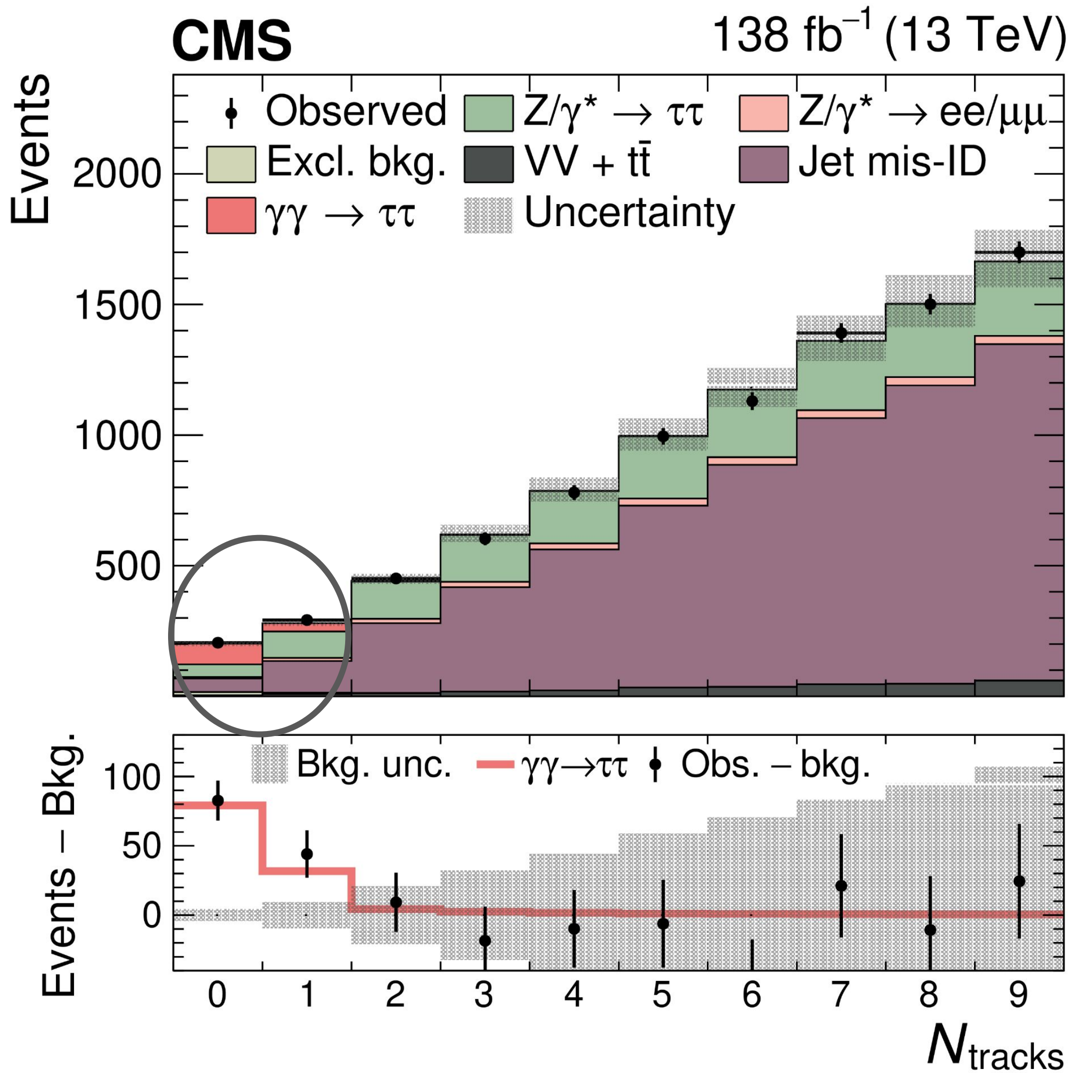


- About 30% of the windows at the center of the beamspot do not contain any pileup track

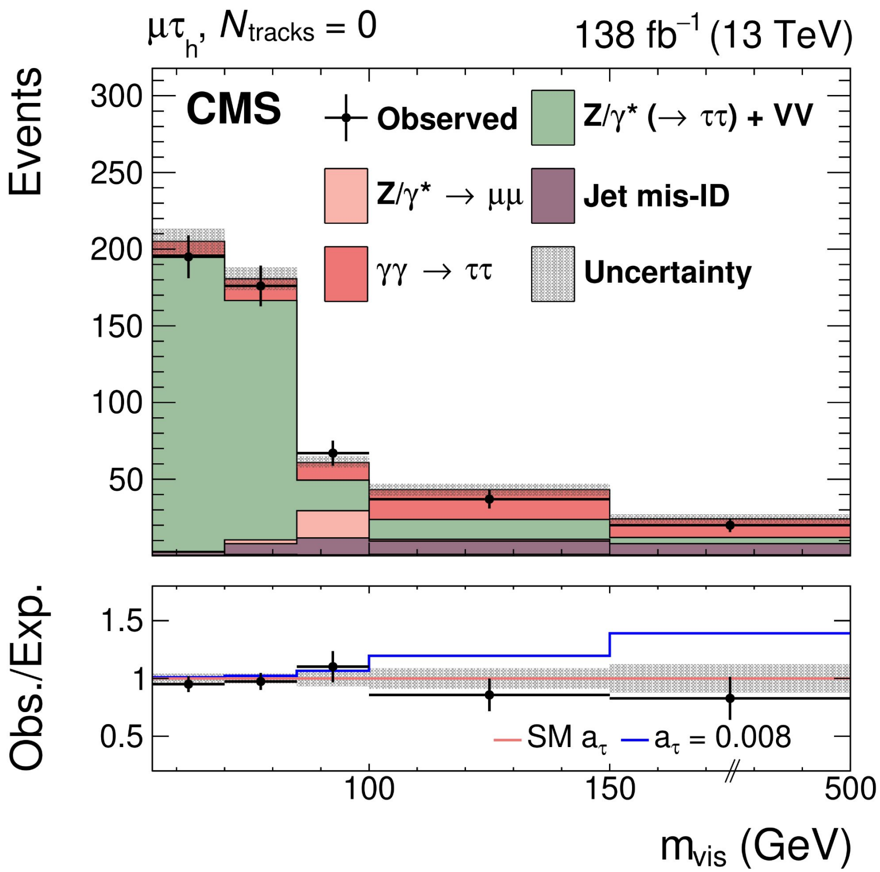
Cécile Caillol, LPCC seminar, March 12th

Method also described in 2403.06336 (L. Beresford *et al*)



- Postfit N_{tracks} distribution for m_{vis} > 100 GeV
  - **We can model well the N_{tracks} distribution for backgrounds**
  - **The signal is seen as an excess of events at very low N_{tracks}**

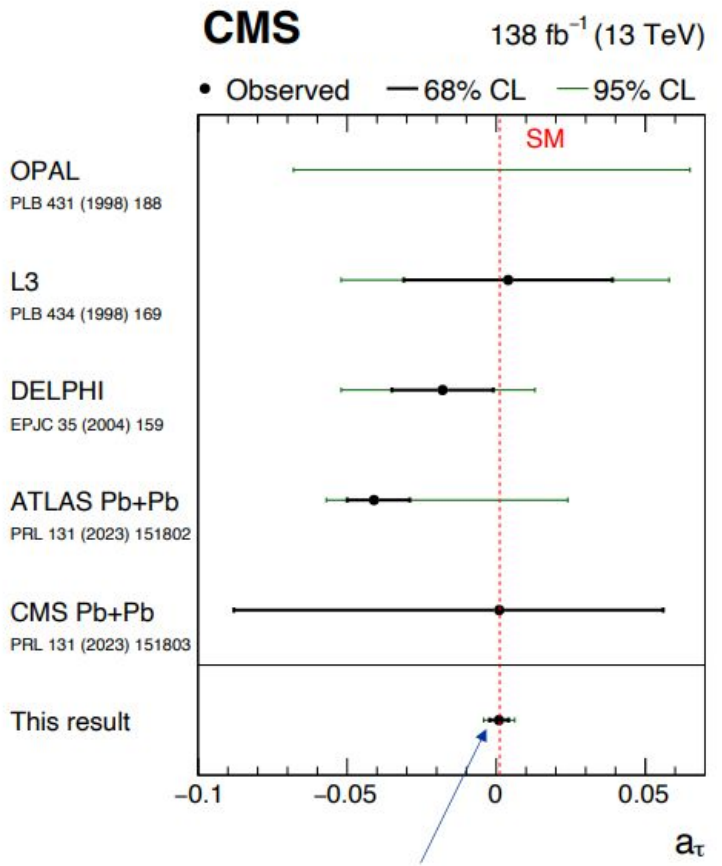
How it translates in this analysis



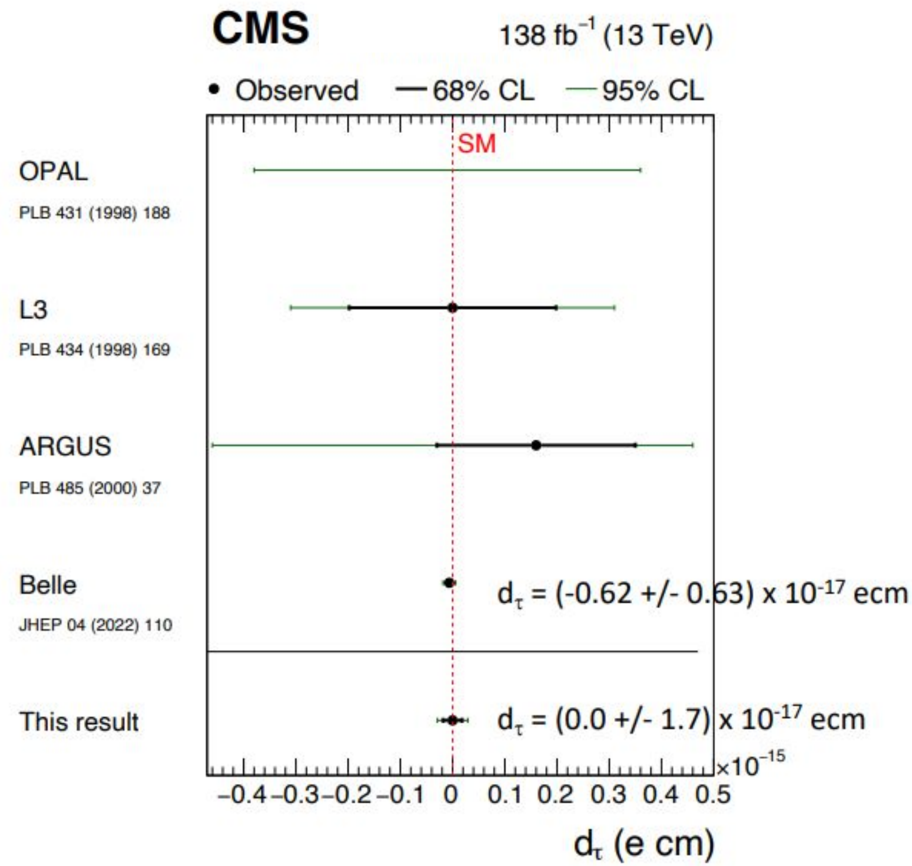
- Changing a_τ from its SM value modifies the $\gamma\gamma \rightarrow \tau\tau$ prediction
- Differences between SM and BSM a_τ scenarios increase with m_{vis}
- a_τ can be constrained from the same m_{vis} distributions used to observe $\gamma\gamma \rightarrow \tau\tau$
- m_{vis} < 500 GeV to remain far from new physics scale and preserve validity of EFT interpretation

45

Comparing to previous results



Large improvement over LEP and LHC Pb-Pb



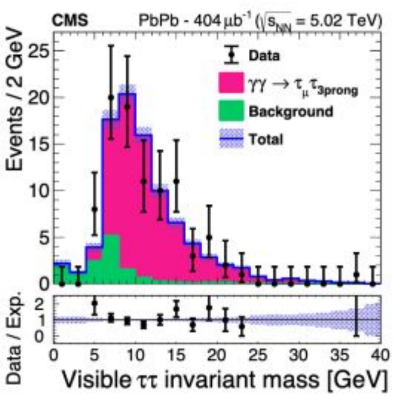
Approaching Belle precision

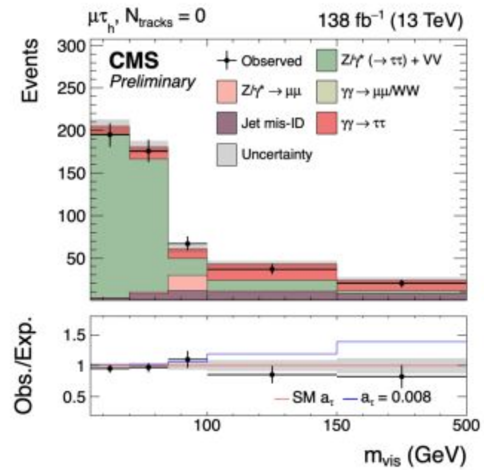
48

Cécile Caillol, LPCC seminar, March 12th

The precision journey has just started…

- Heavy ion runs
- pp runs with track counting
- pp runs with proton tagging





PPS approved for Run-4

$m_{\tau\tau}$

50 GeV

350 GeV

2 TeV

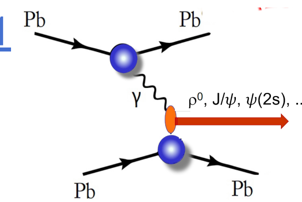
The majority of CMS data has not been collected yet. Exciting complementary approaches for upcoming Runs!

50

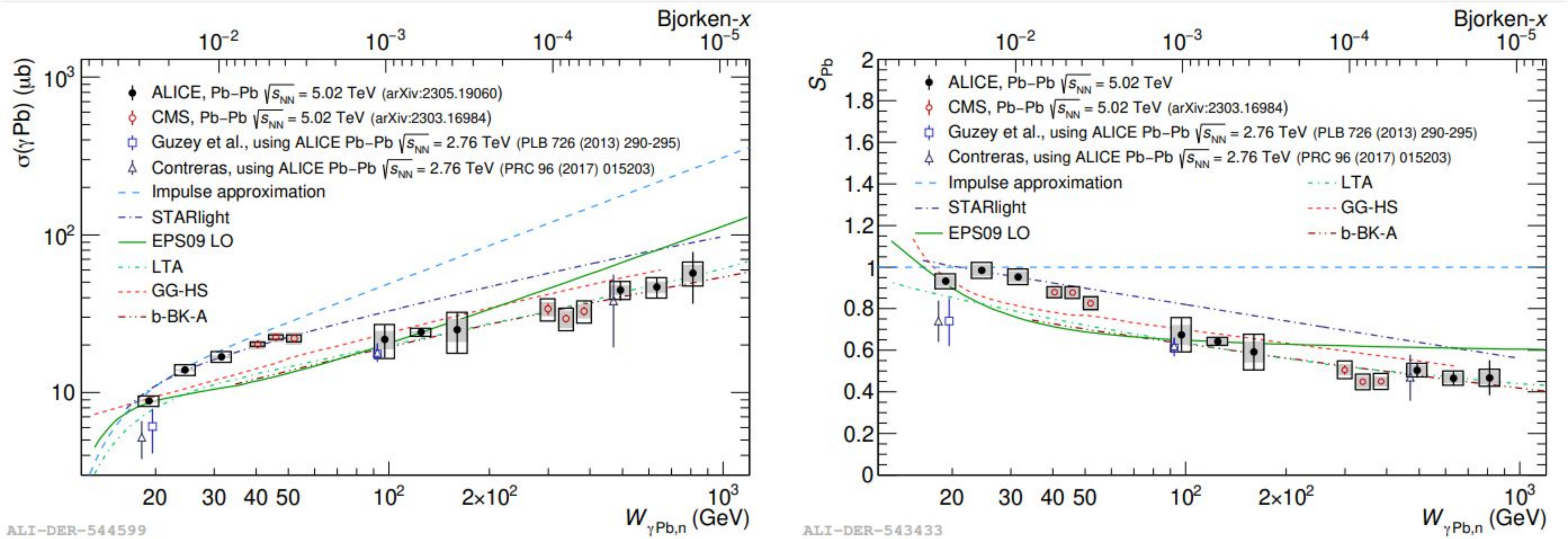
Cécile Caillol, LPCC seminar, March 12th

Coherent J/ψ production in UPC PbPb

PRL **131** (2023) 262301
JHEP **10** (2023) 119



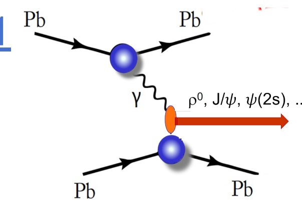
Cross section



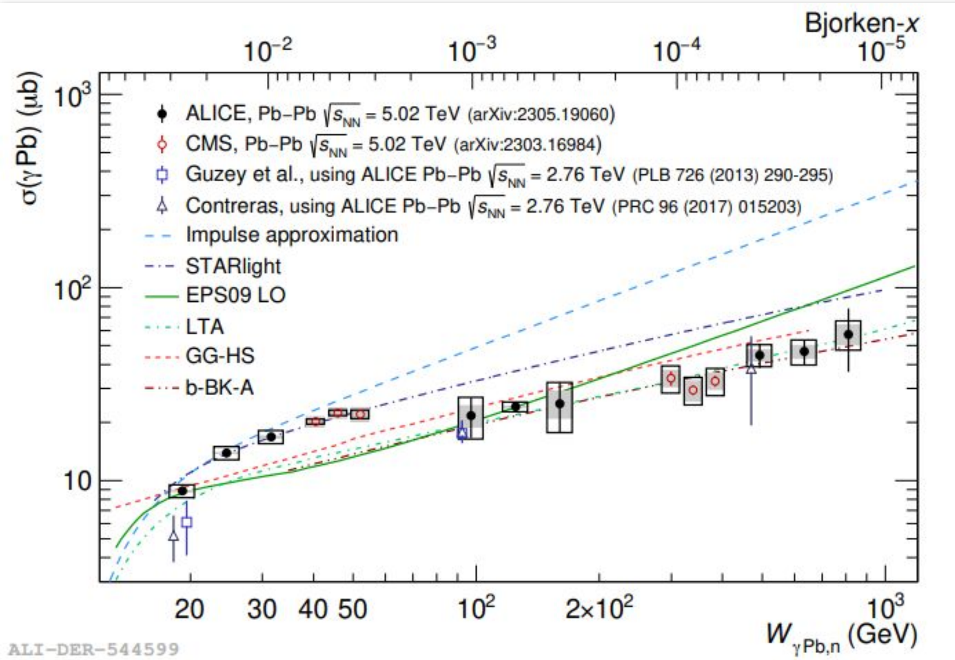
- **Using ZDCs, higher energy photons are extracted w/o increasing √s**
  - experimental uncertainty **correlated** across or $W_{\gamma N}^{Pb}$
    - models cannot predict σ(J/ψ) vs. $W_{\gamma N}^{Pb}$ evolution

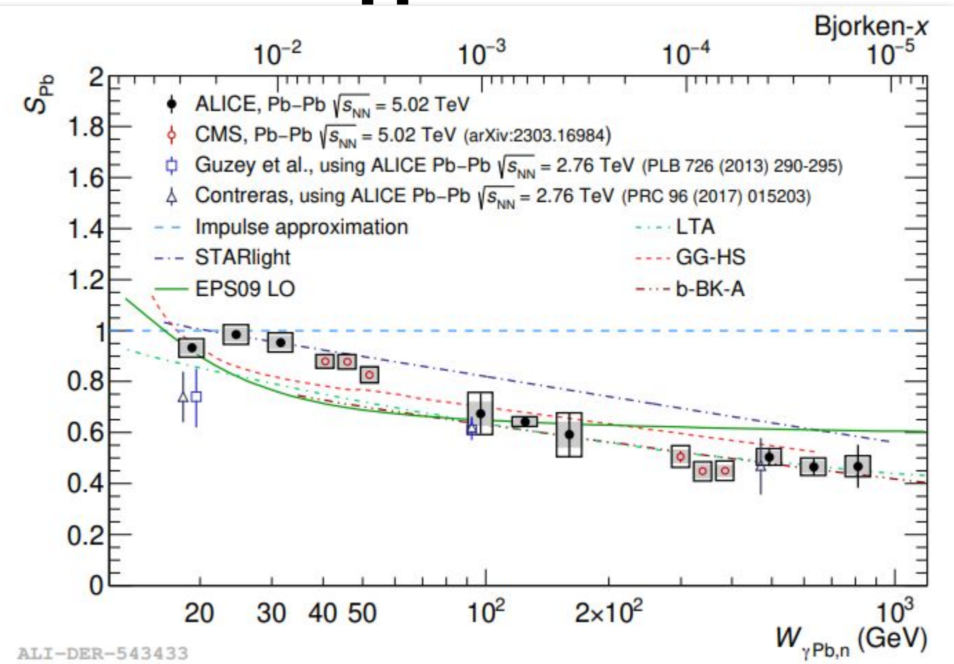
Coherent J/ψ production in UPC PbPb

[PRL **131** (2023) 262301](#)
[JHEP **10** (2023) 119](#)



Nuclear suppression

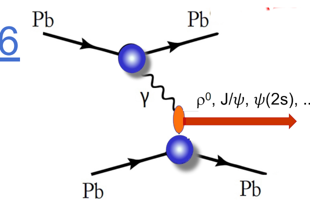




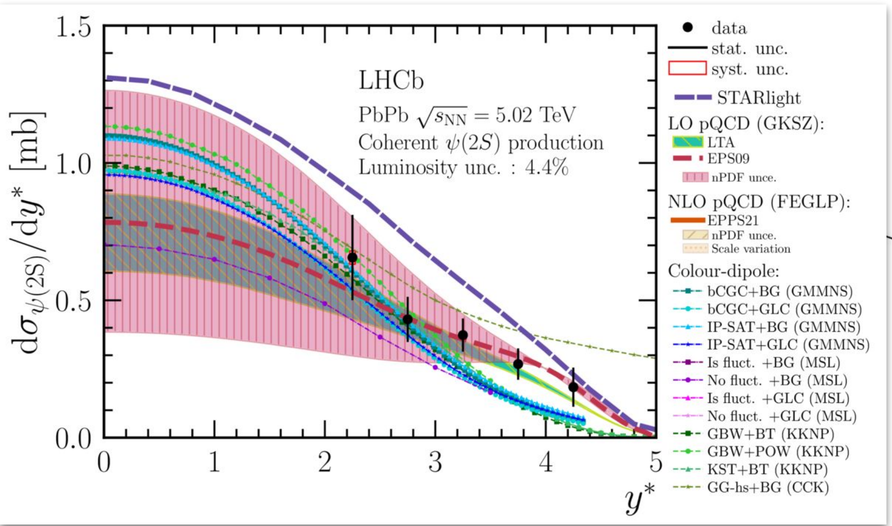
- **Using ZDCs, higher energy photons are extracted w/o increasing √s**
  - experimental uncertainty **correlated** across or $W_{\gamma N}^{Pb}$
    - models cannot predict σ(J/ψ) vs. $W_{\gamma N}^{Pb}$ evolution
- **An unprecedentedly low-*x* gluon regime is probed (10^{-4}–10^{-5})**
  - LHC data seem to **consistently point** to a common *x* evolution

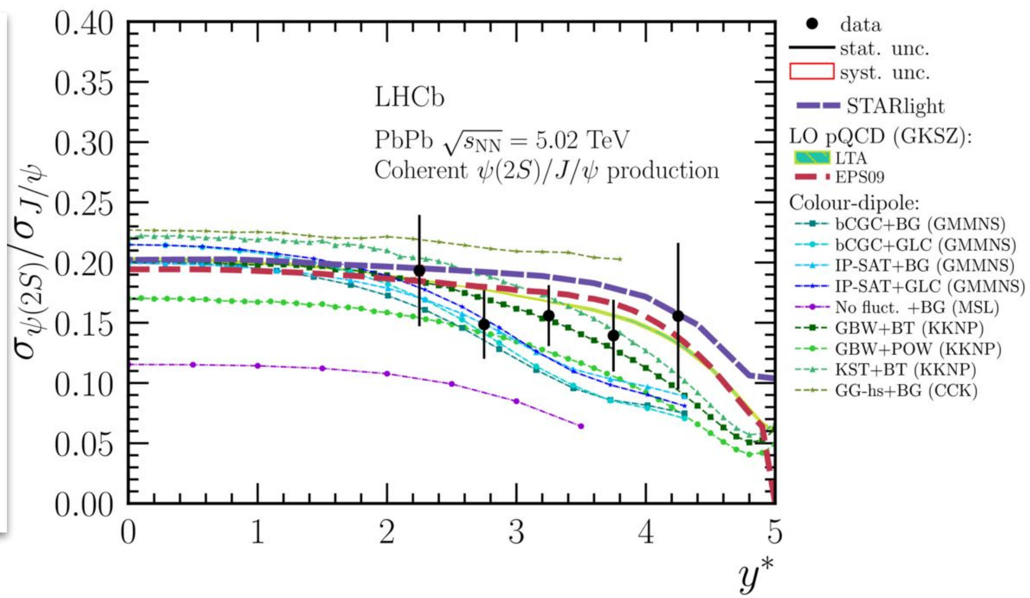
Coherent ψ(2S) production in UPC PbPb

[JHEP **06** (2023) 146](#)



ψ(2S) cross section

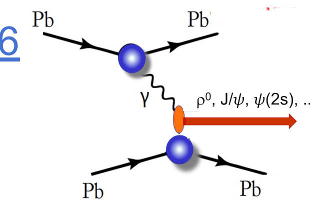




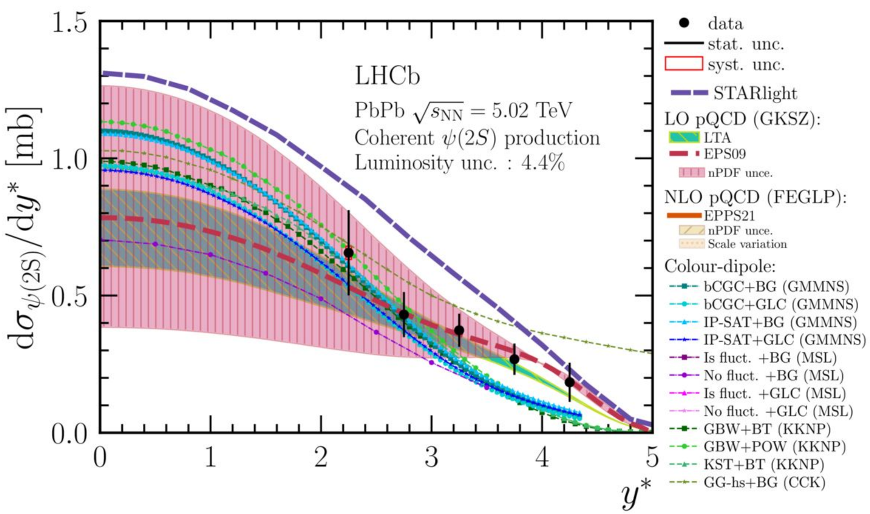
- **The first ψ(2S) photo-induced measurement in the forward region**
  - data unc << than QCD scale and nPDF unc
    - can **constrain** higher order QCD effects and less precise nPDFs at high y
    - bump in 3<y<4 reproduced by QCD calculations

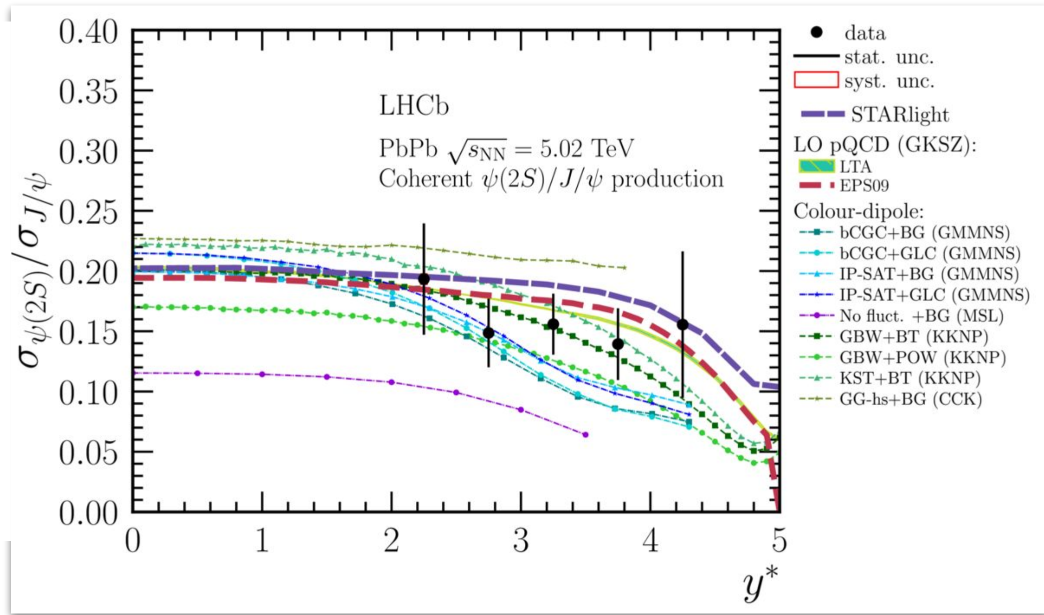
Coherent ψ(2S) production in UPC PbPb

JHEP **06** (2023) 146



ψ(2S) / J/ψ ratio





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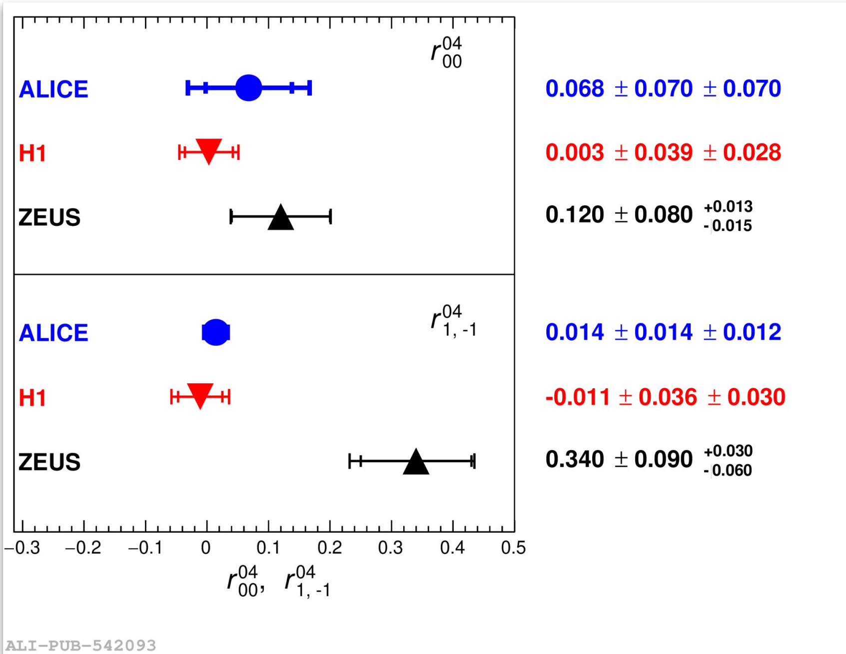
  - data unc << than QCD scale and nPDF unc
    - can **constrain** higher order QCD effects and less precise nPDFs at high y
    - bump in 3<y<4 reproduced by QCD calculations
- **Systematic uncertainties largely cancel in the ratio with J/ψ**
  - beneficial for dipole scattering models (relying on meson wave function)

Polarization and incoherent J/ψ

[arXiv: 2304.10928](https://arxiv.org/abs/2304.10928)
PRL **132** (2024) 162302

Spin density elements



- **J/ψ's are indeed transversely polarized → carrying photons polarization**
  - helped clarifying a standing discrepancy between H1 and ZEUS at HERA
    - harder selection in ZEUS → photons more virtual so partially longitudinally polarized

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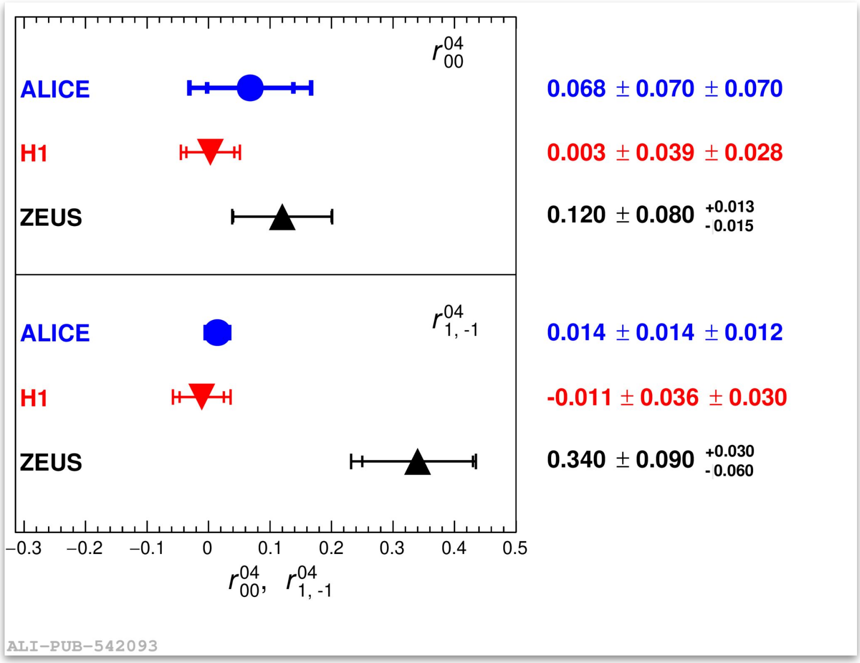
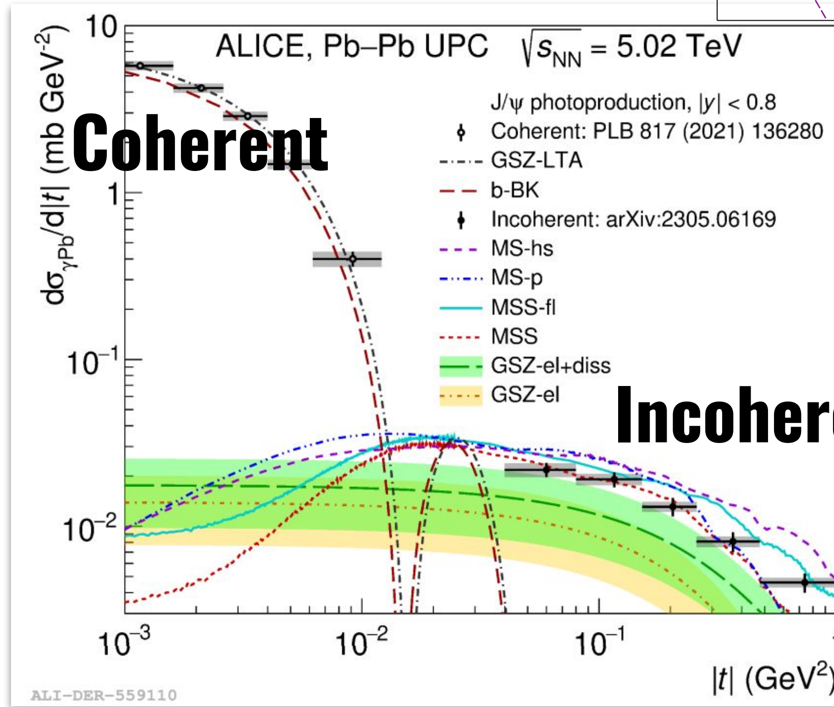
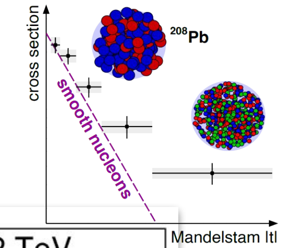






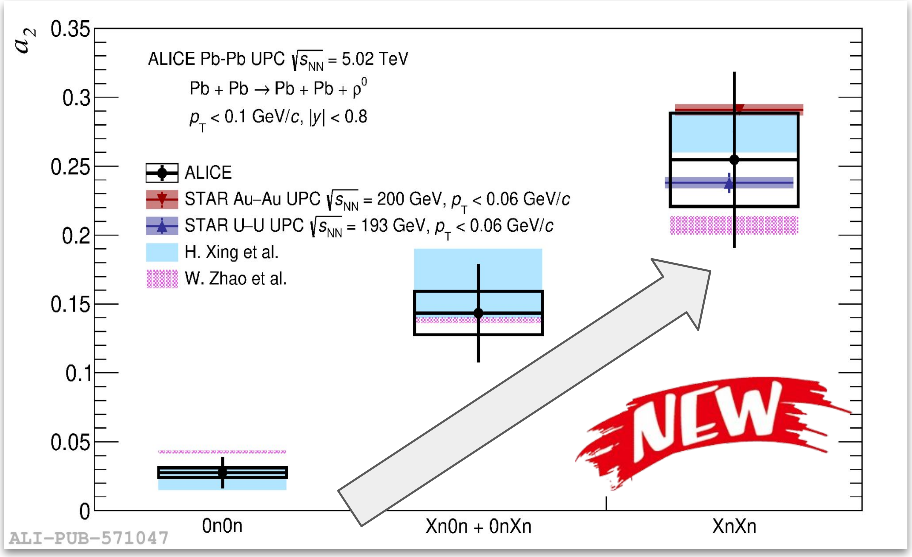
- **J/ψ's are indeed transversely polarized → carrying photons polarization**
  - helped clarifying a standing discrepancy between H1 and ZEUS at HERA
    - harder selection in ZEUS → photons more virtual so partially longitudinally polarized

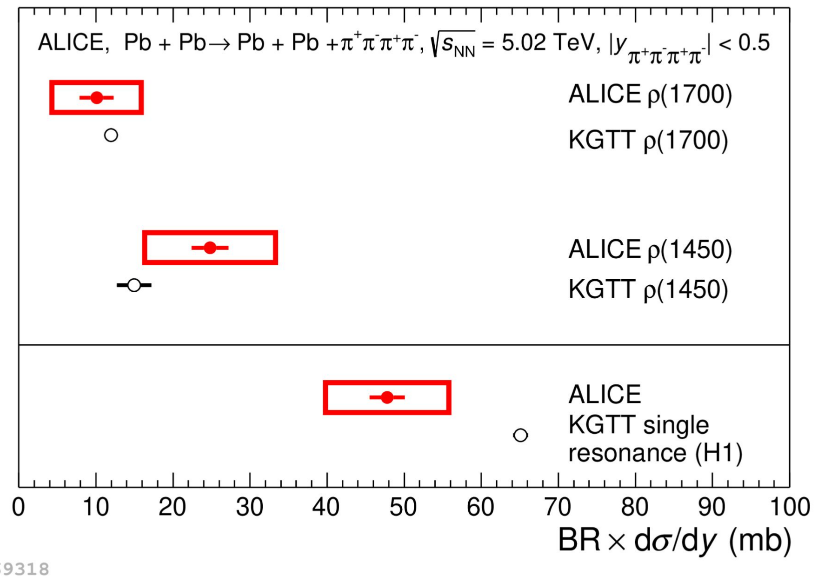
- **Three orders of magnitude in |t| with a HERA-like accuracy**
  - Large-|t| (i.e., incoherent) production sensitive to **sub-nucleon fluctuations**

ρ^0 and 4π production in UPC PbPb

arXiv: 2405.14525
arXiv: 2404.07542

Angular modulation





- **The amplitude of this modulation increases from large to small IPs**
  - here the angle is between the sum and the difference of the two pions p_T
    - manifestation of **quantum interference**: which nuclei emitted the photon?
    - interference effects are also studied in **$K^{\pm}K^{-}$ photoproduction**

ρ^0 and 4π production in UPC PbPb

[arXiv: 2405.14525](#)
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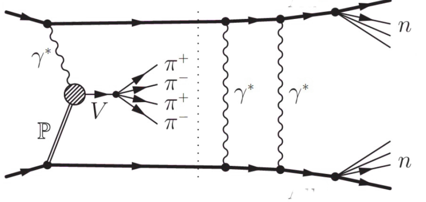

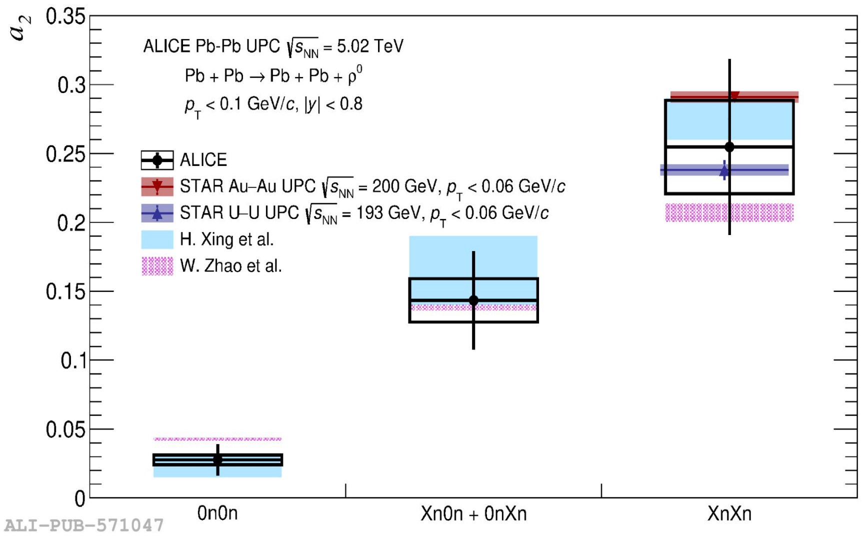

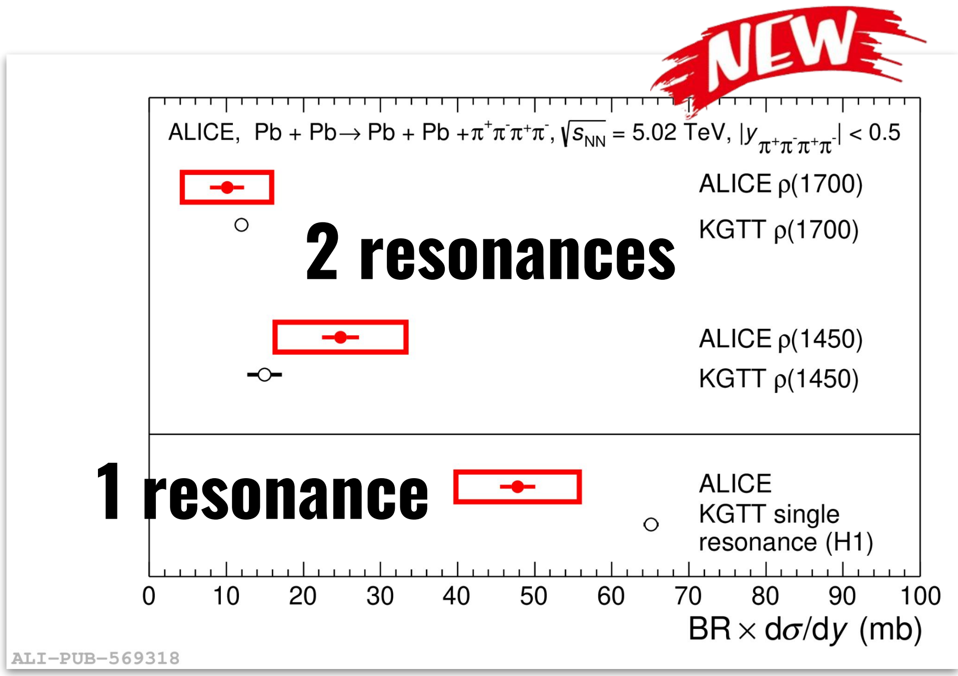

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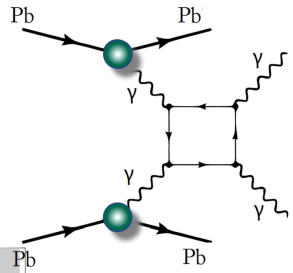
  - here the angle is between the sum and the difference of the two pions p_T
    - manifestation of **quantum interference**: which nuclei emitted the photon?
    - interference effects are also studied in [**$K^{\pm}K^{\mp}$ photoproduction**](#)
- **First measurement of 4π production to search for ρ resonances**
  - data favor the **two-resonance scenario** with ρ(1450) and ρ(1700)
  - ρ / ρ^0 production ratio **lower than at RHIC**: Reggeon exchange contributions?

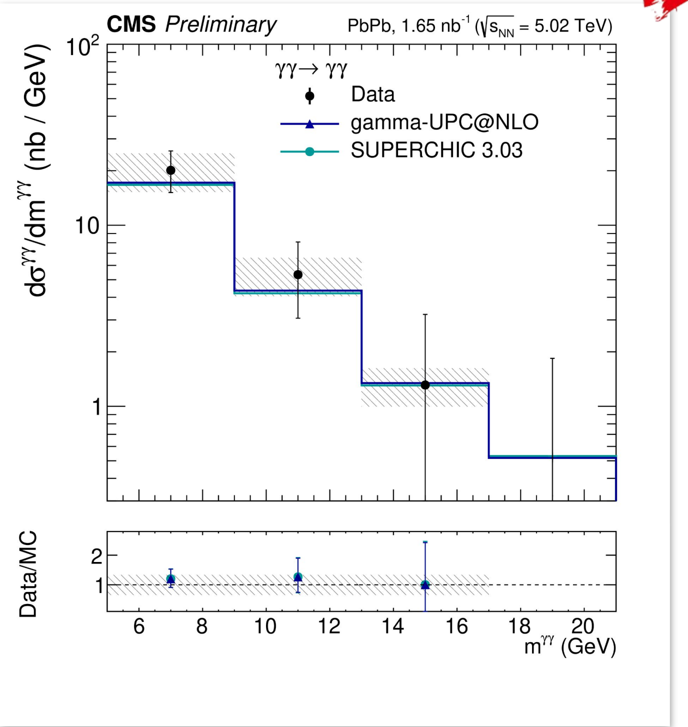
γγ→γγ production in UPC PbPb

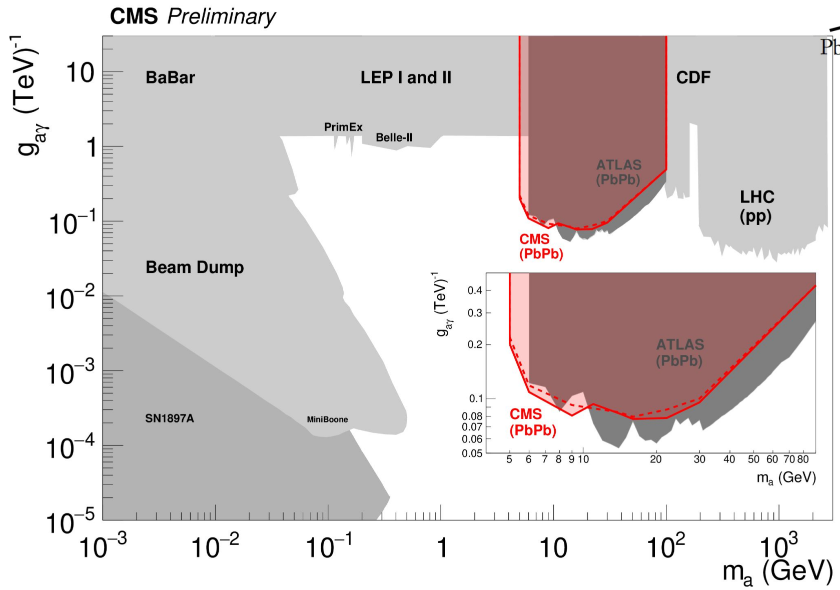
[JHEP 03 (2021) 243](#)
[CMS-PAS-HIN-21-015](#)



Inv mass

NEW



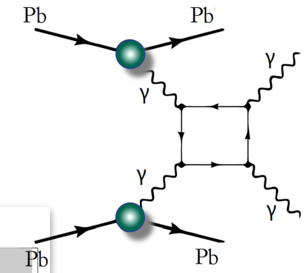


- **After its first evidence in 2015, observation in 2019**
  - extensive studies since then by ATLAS and CMS
    - 2σ excess seen in ATLAS **not reproduced** by CMS (yet stricter event selection)

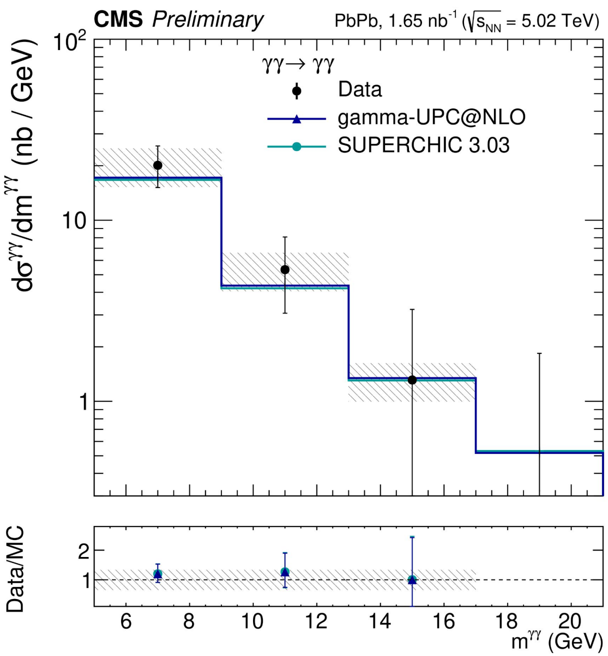
$\gamma\gamma\to\gamma\gamma$ production in UPC PbPb

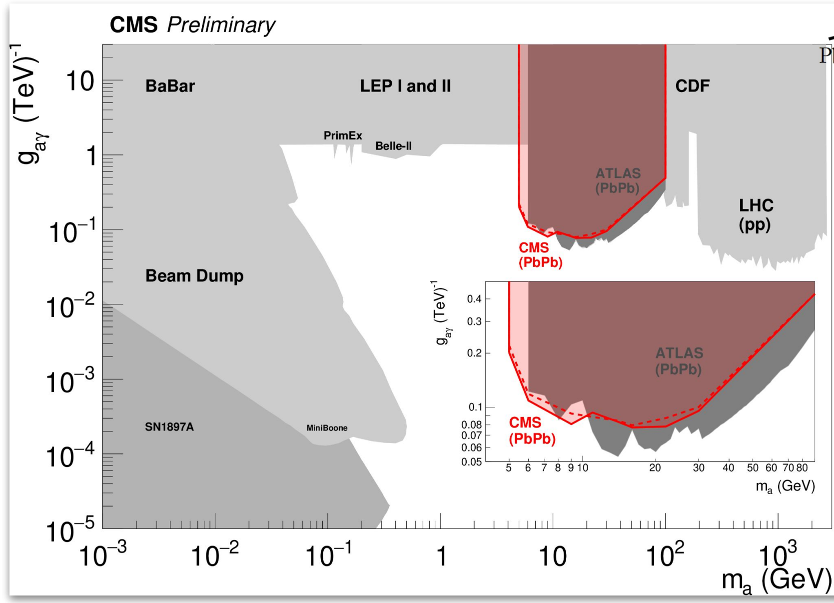
JHEP 03 (2021) 243
CMS-PAS-HIN-21-015

NEW



Limits on ALPs

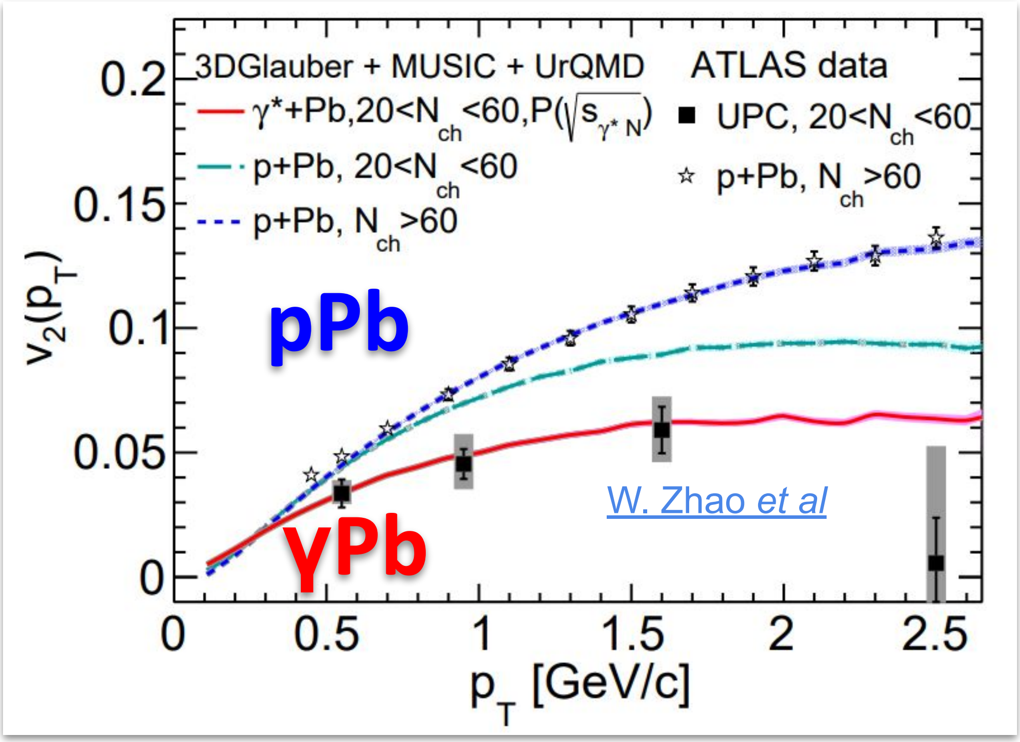


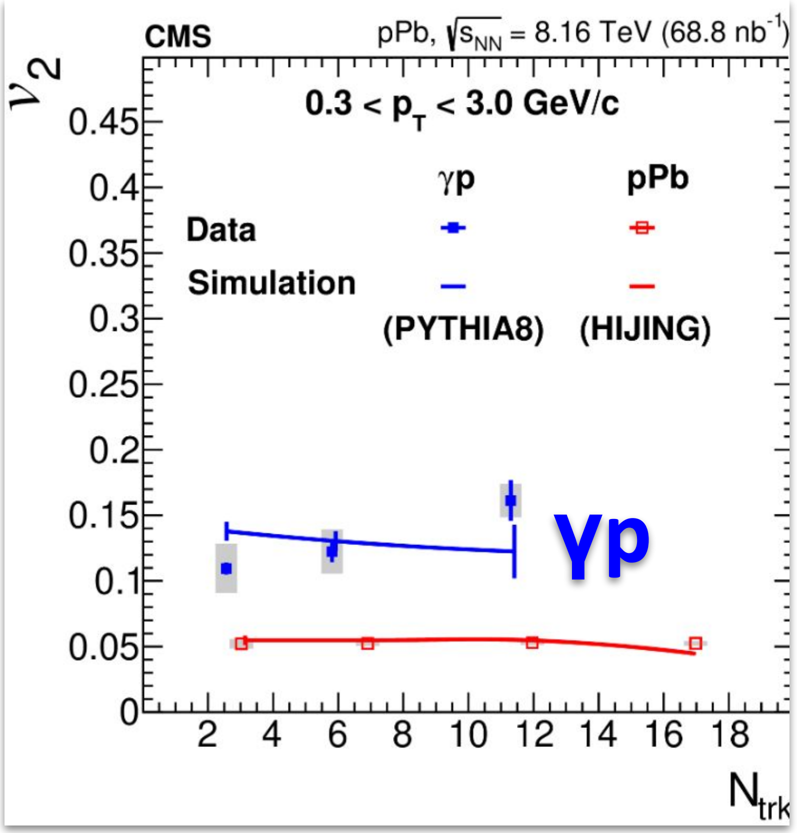


- **After its first evidence in 2015, observation in 2019**
  - extensive studies since then by ATLAS and CMS
    - 2σ excess seen in ATLAS **not reproduced** by CMS (yet stricter event selection)
- **Limits are set on axion-like particle (ALP) resonant production**
  - UPC PbPb uniquely cover the **1–100 GeV** mass range
  - ATLAS (CMS) better limits at high (lower) mass due to event count (trigger)

Angular correlations in γPb and γp

Phys. Rev. C **104** (2021) 014903
PLB 844 (2023) 137905

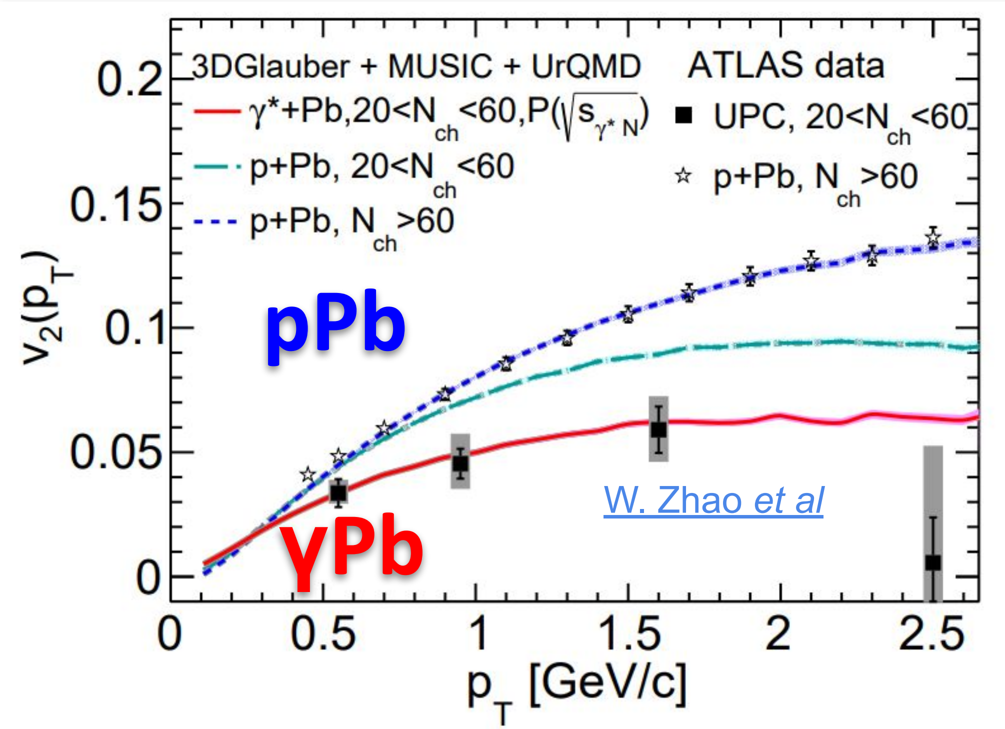


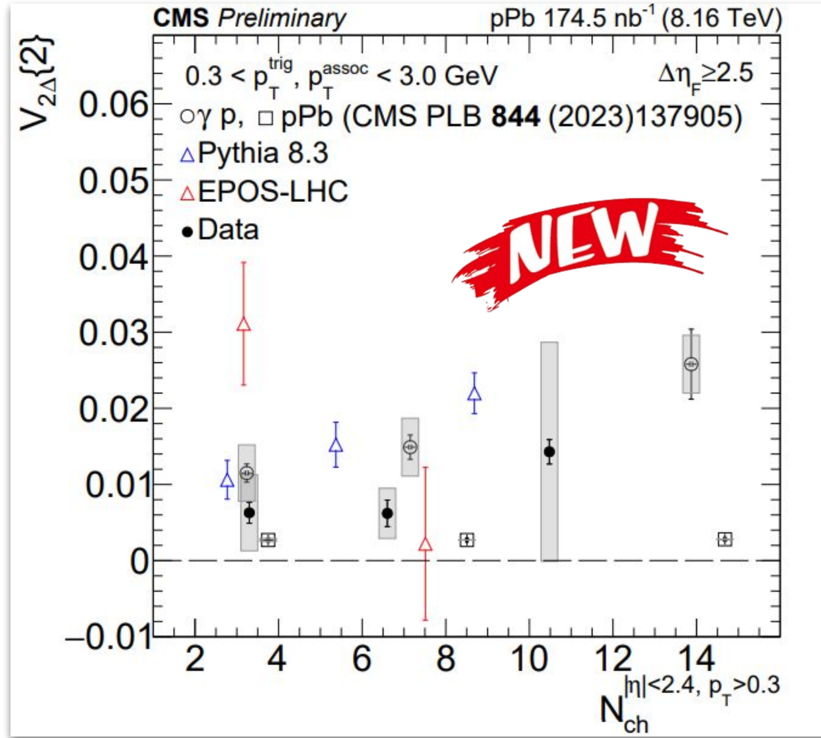


- **Bridging large with exceedingly small systems (UPC PbPb)**
  - hierarchy of flow in **pPb** vs γPb reproduced by (3+1)D dynamical simulations
- **Challenging to go smaller in N_{trk}: tiny flow signal competes to nonflow**
  - PYTHIA8 describes v_2 **in γp** → jet-like correlations still dominate

Angular correlations in γPb and γp

Phys. Rev. C **104** (2021) 014903
PLB 844 (2023) 137905
CMS-PAS-HIN-22-004





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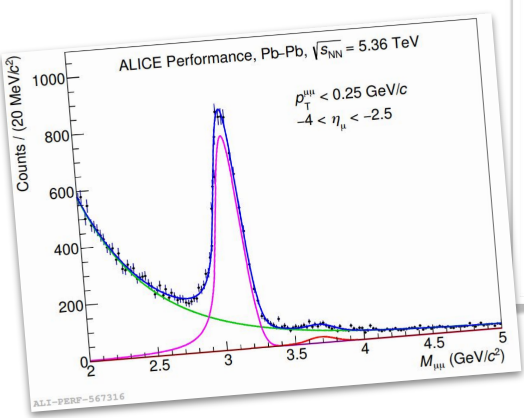
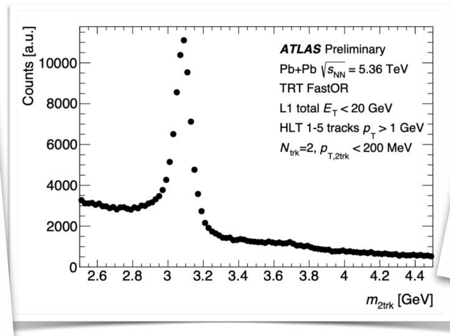
  - hierarchy of flow in **pPb** vs γPb reproduced by (3+1)D dynamical simulations
- **Challenging to go smaller in N_{trk}: tiny flow signal competes to nonflow**
  - PYTHIA8 describes v_2 **in γp** → jet-like correlations still dominate
  - same for events with **large rapidity gaps**

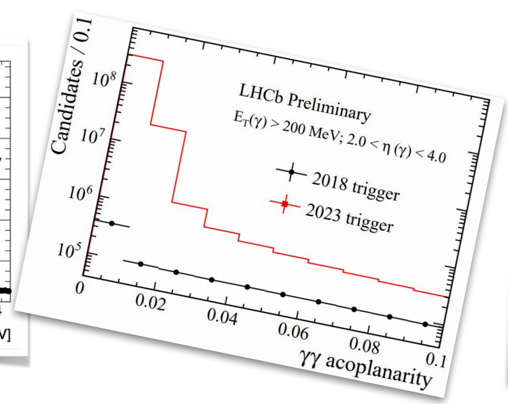
Bright future ahead

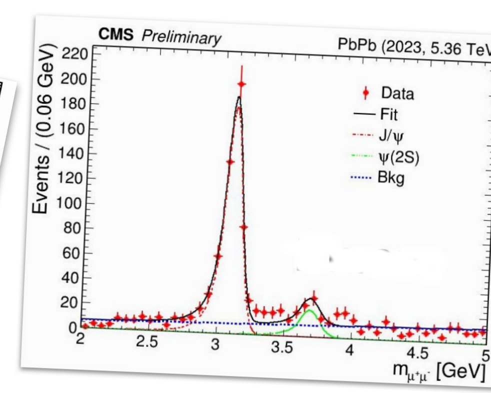
- Exciting time for UPCs in Runs 3 and 4 (order of magnitude increase in lumi)
- Experiments collected Run 3 PbPb data with major improvements to Run 2
    - pPb only in Run 4
- Precision measurements, low-mass/exotic resonances as well as new physics!
- Strangeness, open charm, heavy quarkonia (Υ) in UPCs
- New physics searches: ALPs, g_τ-2, ..
- Yet nonexhaustive list: jet production, particle collectivity, ..
- Most welcome to join the effort!

UPC performance in Run 3









slides

Key characteristics of the nPDF global fits

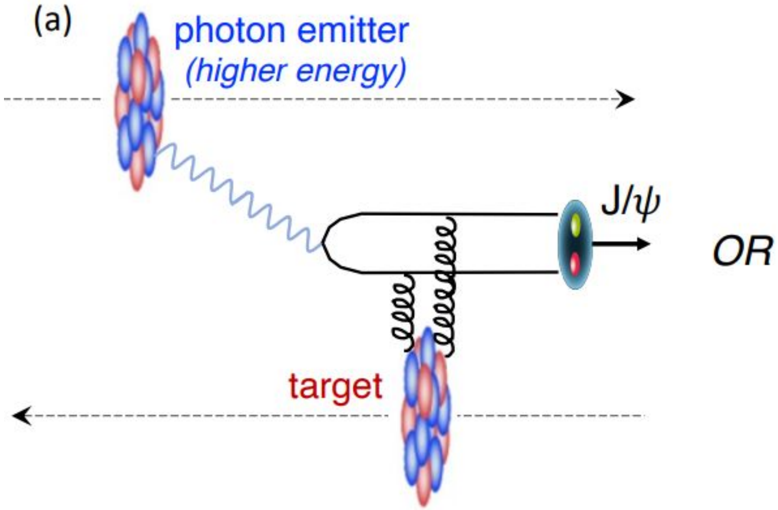
	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D^0				✓	✓ reweight
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_T cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	948	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	∼CTEQ6M	own fit	CT18A	∼NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	arXiv:2112.12462	arXiv:2201.12363

P. Paakkinen (DIS22)

How to unambiguously access **low-x gluons?**

The theo. solution

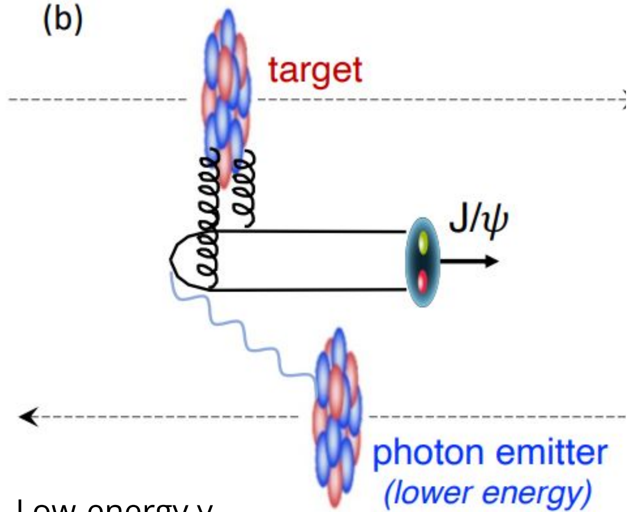
Guzey et al., **EPJC 74 (2014) 2942**



High-energy γ

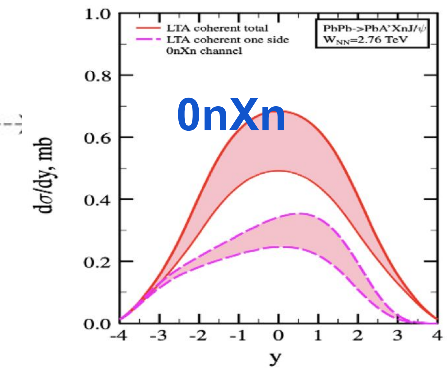
$$w_2 = \frac{M_{VM}}{2} e^{+y}$$

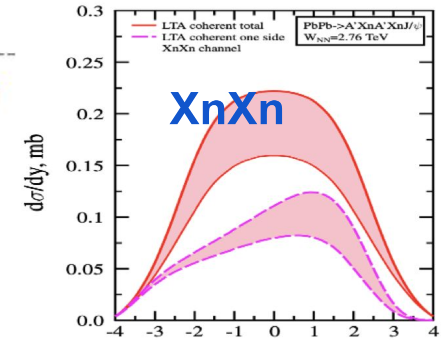
The issue



Low-energy γ

$$w_1 = \frac{M_{VM}}{2} e^{-y}$$





The exp. solution

What is measured | **Photon flux from theory** | **What we want to extract**

$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

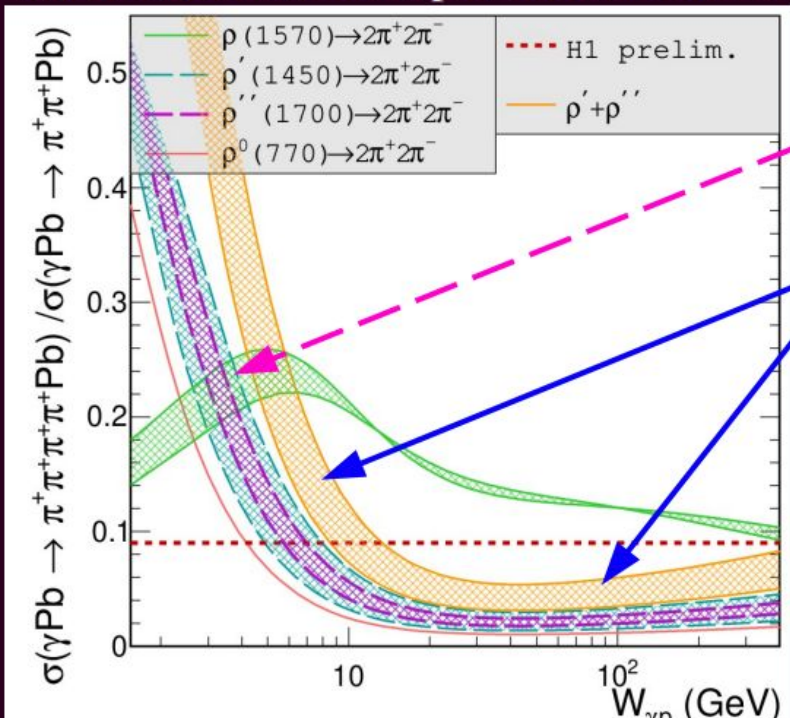
$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

Entering a new regime of small x ~ 10^{-4}-10^{-5} in nuclei w/o the need to increase the energy!

Cross section ratio

$$(\rho \rightarrow \pi^+\pi^-\pi^+\pi^-)/(\rho^0 \rightarrow \pi^+\pi^-)$$

Theory calculation from
M. Klusek and D. Tapia Takaki Acta Phys. Polon. B 51 (2020) 6, 1393



Rapid reduction of Reggeon exchange for excited ρ at low center-of-mass energies.

		$\sqrt{s_{NN}}$	Ratio
STAR	Au–Au	200 GeV	(13.4 ± 0.8 ± 4.4) %
ALICE	Pb–Pb	5.02 TeV	(7.3 ± 0.4 ± 1.2) %

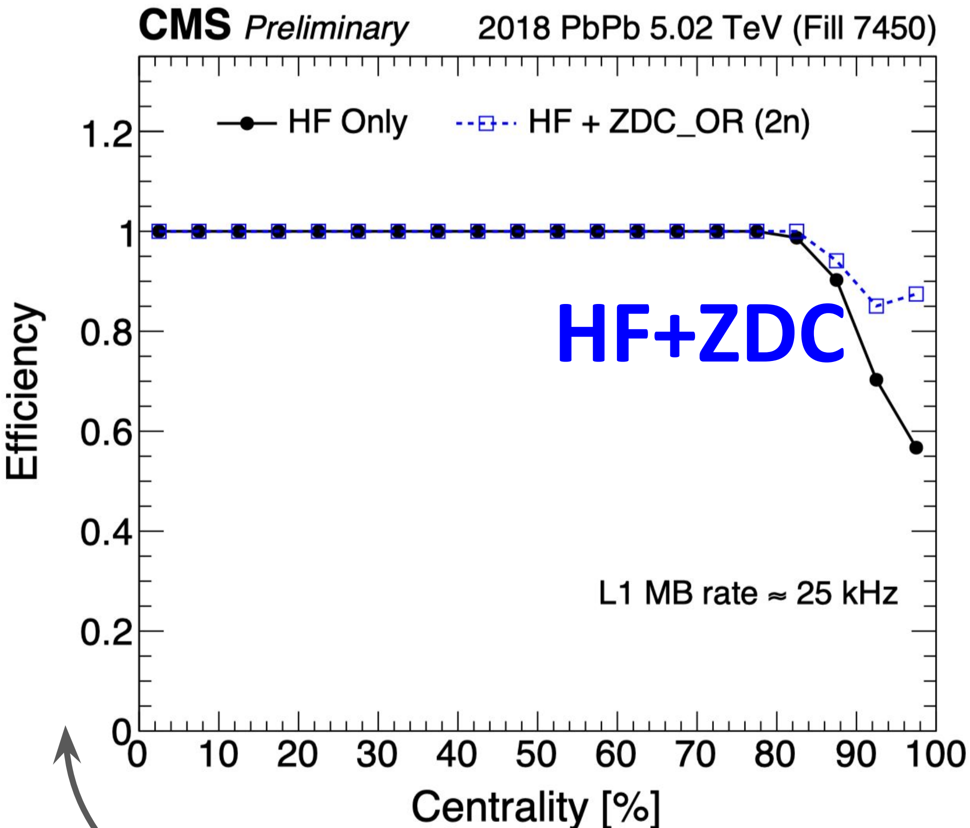
STAR Collaboration performed the measurement for the events with mutual nuclear excitation.

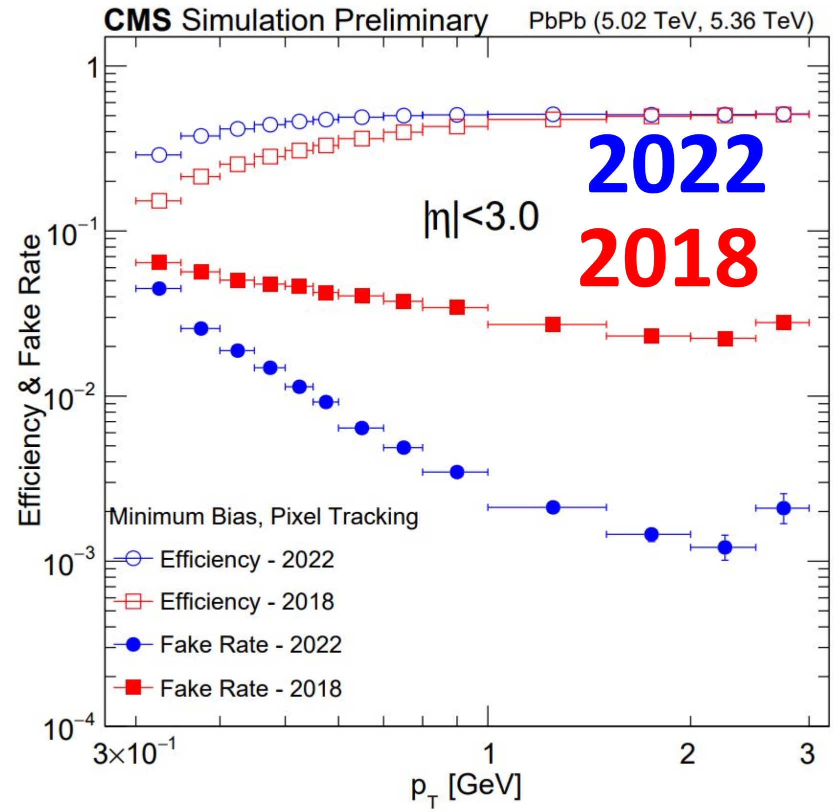
Theoretical calculation is performed as a function of $W_{\gamma p}$, so no direct comparison is possible, but a qualitative agreement is observed.

Sasha Bylinkin (DIS24)

Improvements in Run 3 PbPb

CMS-DP-2023-011





- **Improvements expected already in Run 3, e.g.,**
  - online: increased MB trigger efficiency in peripheral events with ZDC inclusion
  - offline: better low-p_T tracking thanks to innermost pixel layer consideration
- **Overall CMS will record 25 kHz of MB PbPb events**
  - representing an increase of 80x to 2015 and 3x to 2018

CMS Phase 2 Upgrades (HI related)

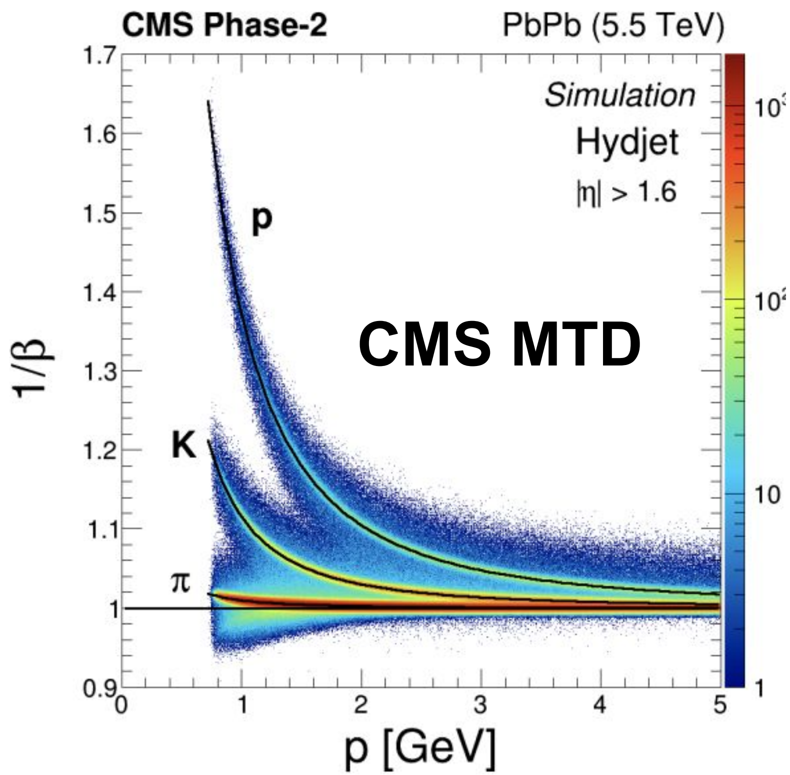
CMS-DP-2021-037

Phase 2 Upgrade

CMS Phase 2 for Run 4

- Tracker $|\eta|<4$
- Muon ID up to $|\eta|<2.8$
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing
  - **p/K/π PID** (CMS MTD)
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

p/K/π separation



- **Main batch of CMS Upgrades in Run 4**
  - Among others, unique hermetic particle identification coverage by CMS MTD
- **Physics requests documented in past years over a diverse set of reports**
  - WG5 HL-LHC, ATLAS+CMS Snowmass'22, QCD Town Meeting WP, CMS HIN