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Ultraperipheral heavy-ion collisions

Valerie Lang
On behalf of the large LHC experiments

LHCP Conference, Boston, US
4 June 2024

Foto von David Trinks auf Unsplash

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Or: News from nearly empty detectors?

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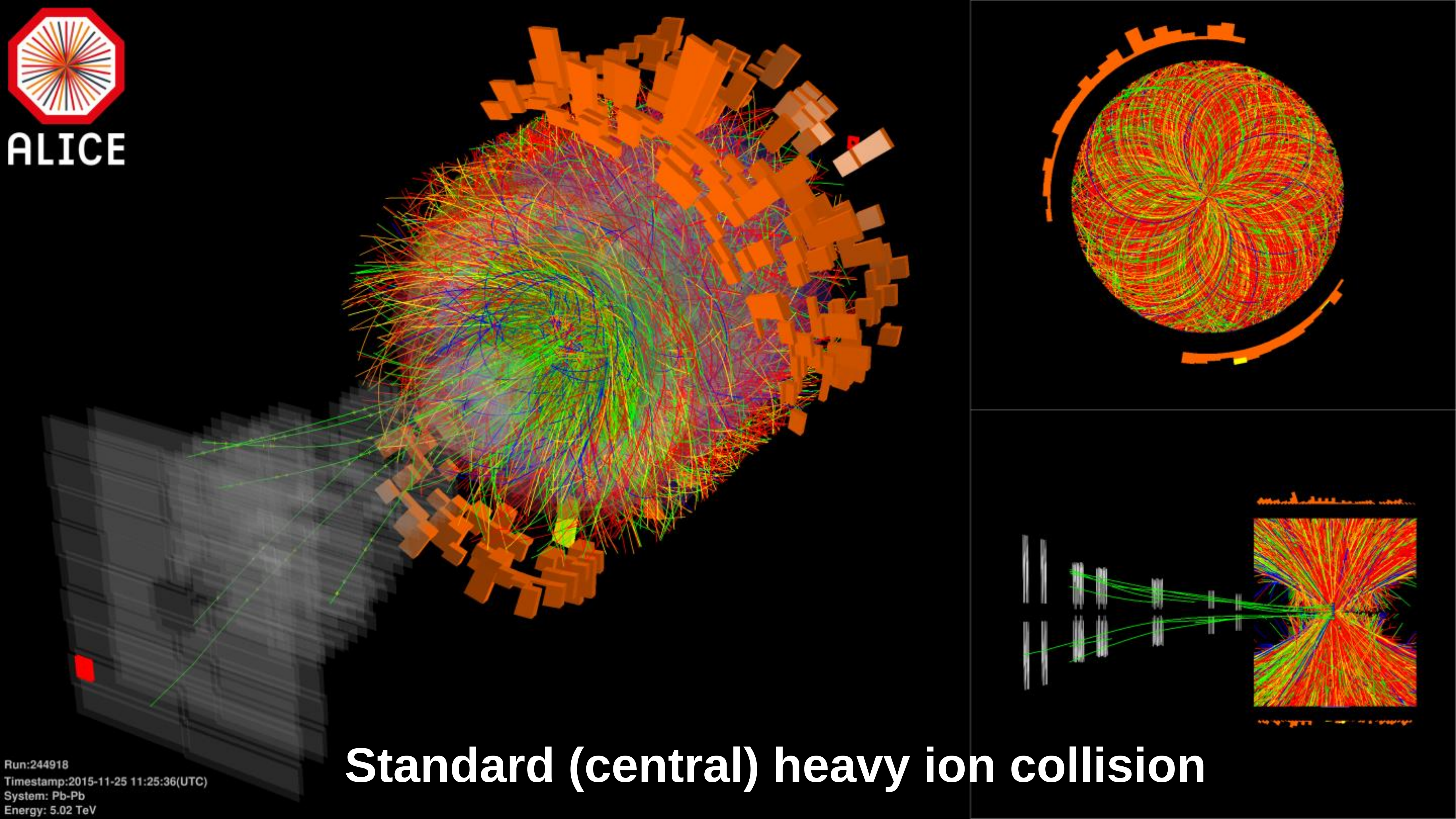
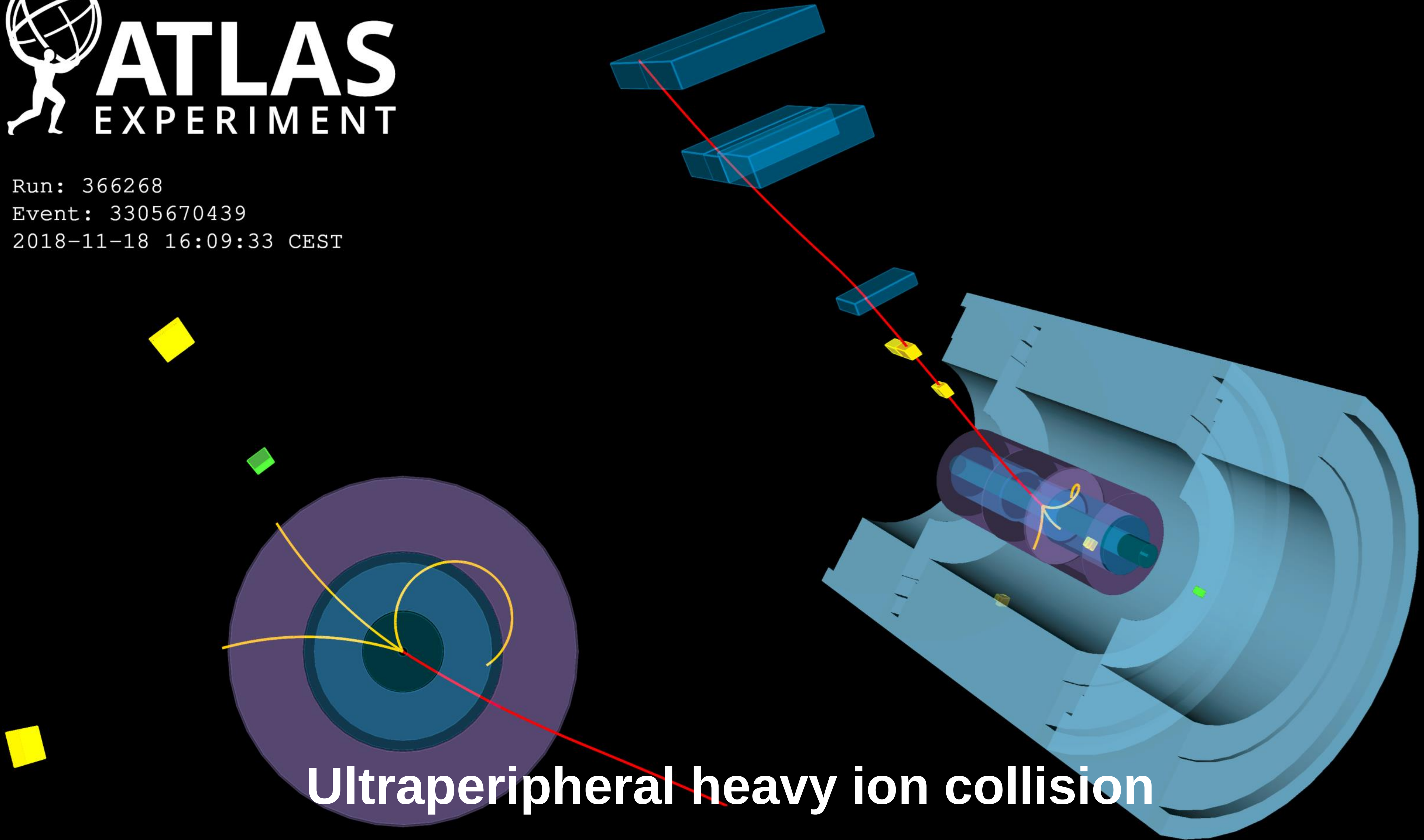
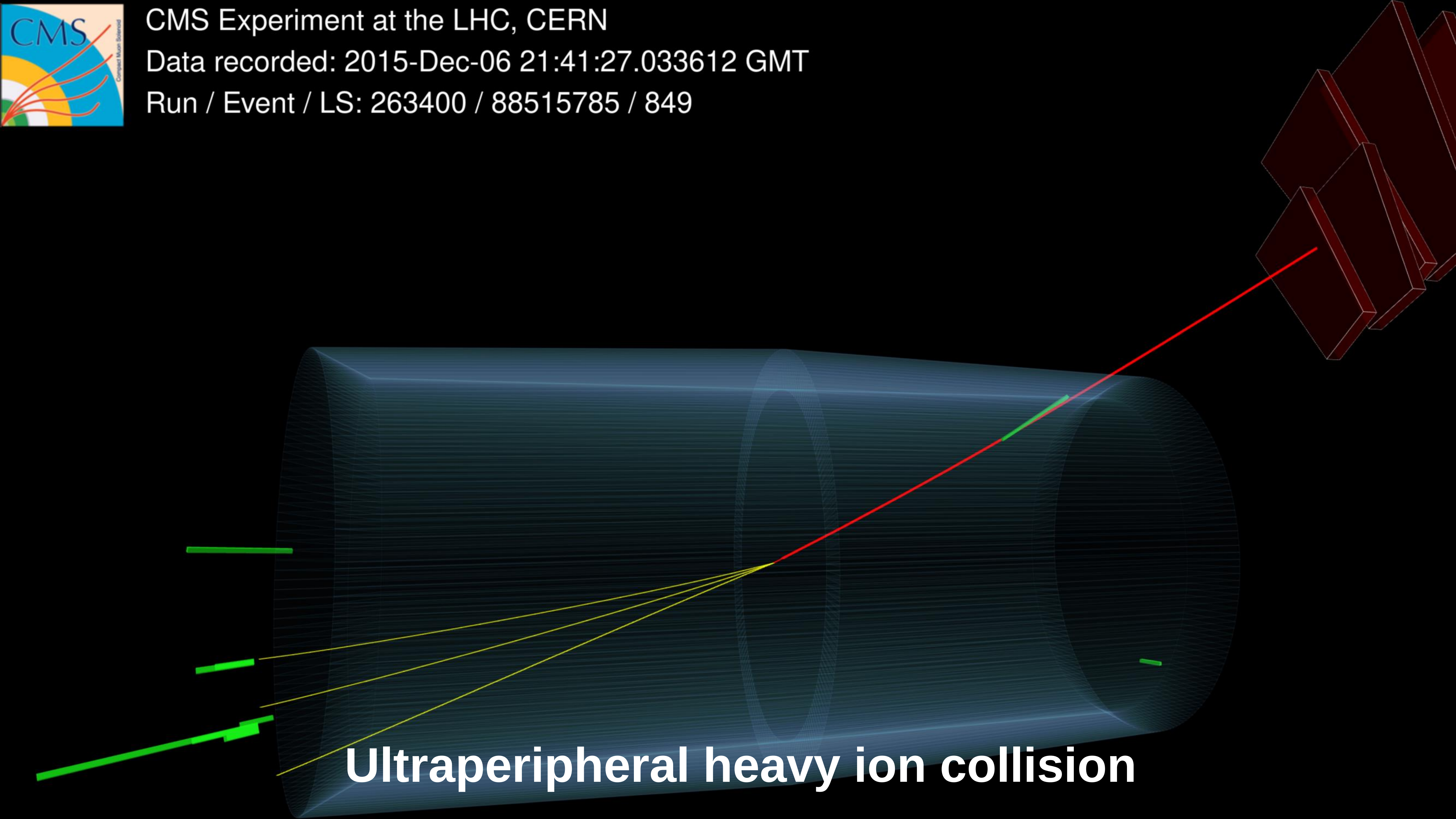


Standard (central) heavy ion collision



Ultraperipheral heavy ion collision



Ultraperipheral heavy ion collision

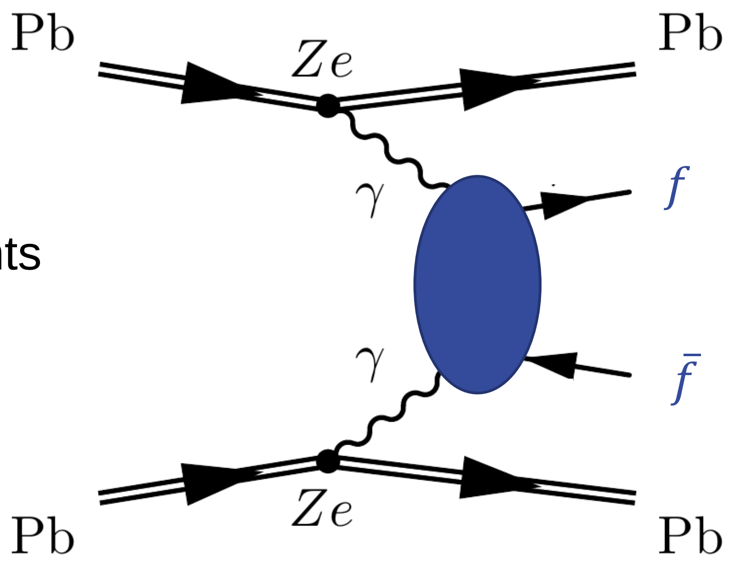
Features of ultraperipheral collisions

Interaction of Pb-nuclei via electromagnetic fields for impact parameters $b > 2R_{Pb}$

- Production of new particles from interaction of photons
  - Cross section enhanced by $Z^4 = 4.5 \cdot 10^7$ w.r.t. proton-proton

  → Large Hadron Collider (LHC) acts as photon collider!

- Also interaction of photon with nucleus possible → Photonuclear events
- Study various categories of produced particles and their properties
  - Di-lepton production: e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$
  - Charged hadron production: Pions, strange mesons, charm mesons, jets, etc.
  - Light-by-light scattering



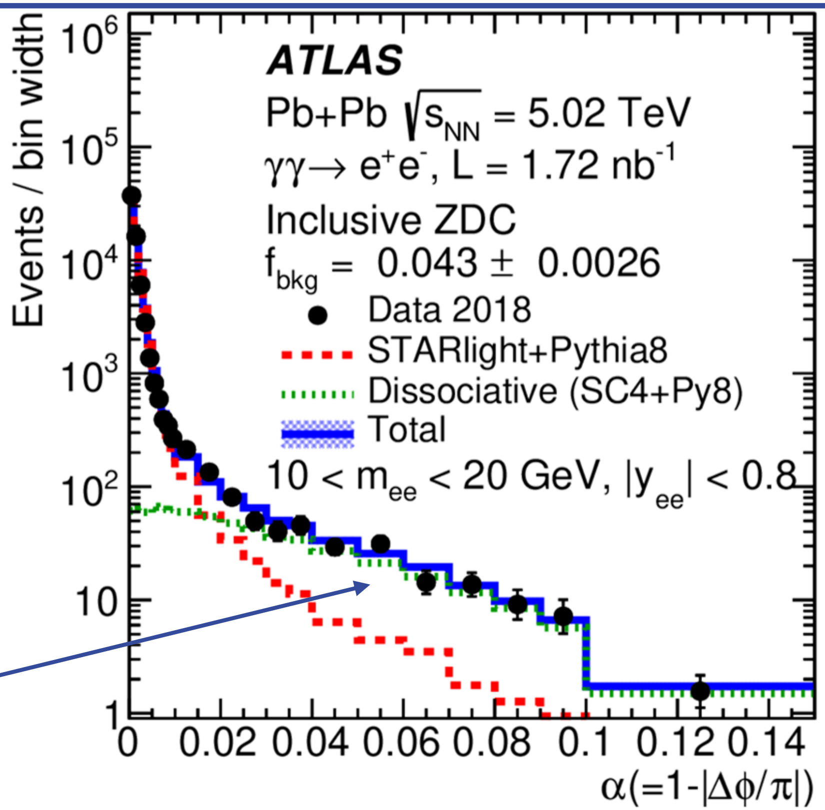
→ Disclaimer: Only show (personal) selection of results from ultraperipheral collisions
→ Consider as a teaser → Feel free to dive in deeper into many interesting results

Understanding the photon flux

ATLAS 5.02 TeV, 1.72 nb^{-1}
JHEP 06 (2023) 182

Investigate production of e^+e^- pairs

- Equivalent photon approximation (EPA):
  - Total cross section = convolution of photon flux with elementary production cross-section
- Break-up of Pb-nuclei possible → Electromagnetic dissociation
  - Induced by additional photon exchanges → Higher likelihood for smaller impact parameters → More forward neutrons
  - Suppress or enhance through selections in very-forward calorimeters (ZDC)
- In addition: Backgrounds:
  Υ and $\tau^+\tau^-$ production and single-dissociative process
  - Dissociation of emitting nucleus, if origin of the photons from substructure of nucleon (proton, neutron) → Largest background → Determined from fit to acoplanarity:



$$\alpha = 1 - |\Delta\phi|/\pi \begin{cases} \to 0 \text{ → Back-to-back configuration} \\ \to 1 \text{ → Collinear configuration} \end{cases}$$

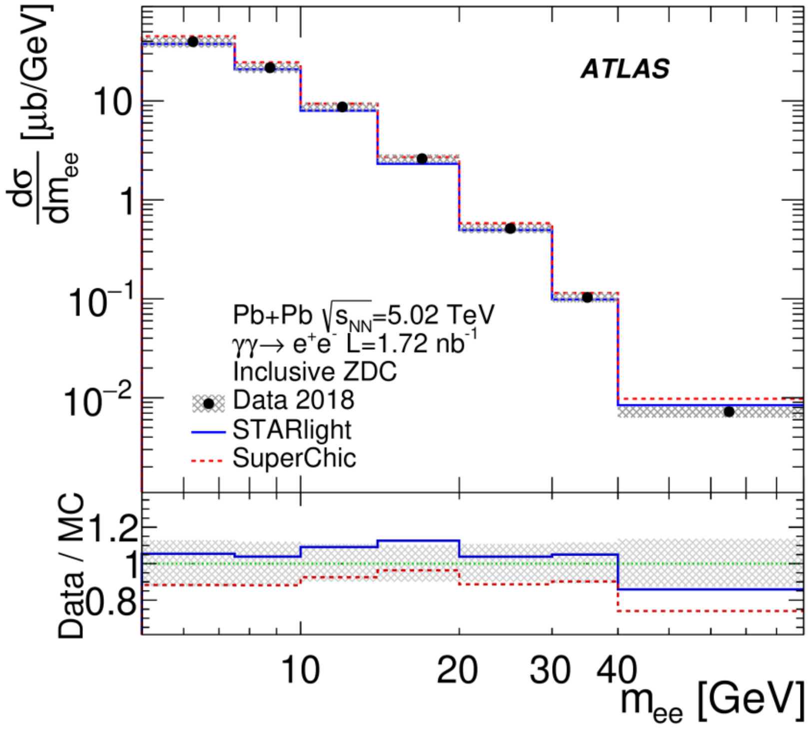
Understanding the photon flux

ATLAS 5.02 TeV, 1.72 nb^{-1}
JHEP 06 (2023) 182

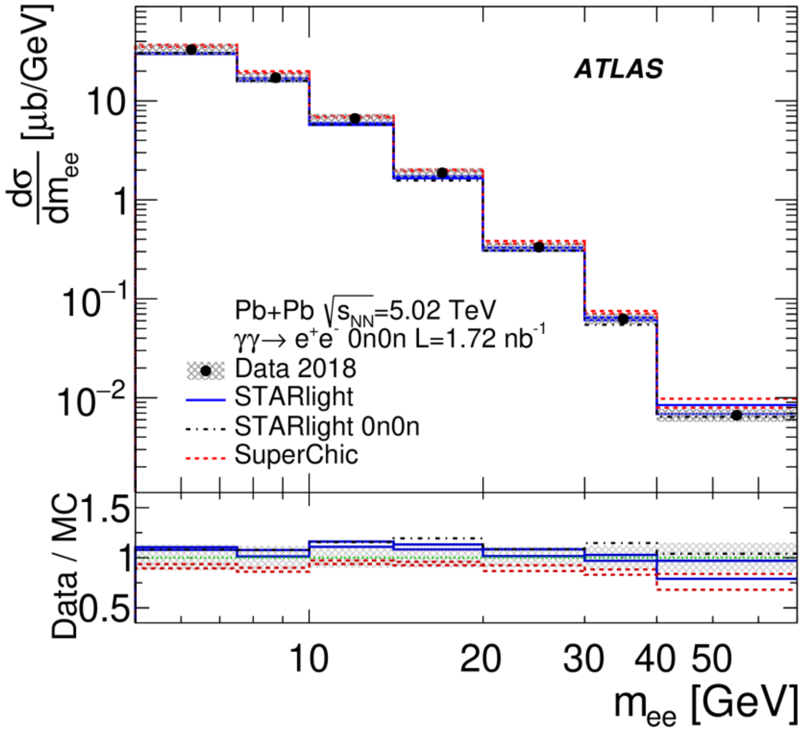
Investigate production of e^+e^- pairs

- Measurement of differential cross sections, e.g. as function of invariant mass m_{ee}

Inclusive



Zero neutrons on either side in ZDC: 0n0n



→ Comparison to two generators with different photon flux modelling: STARlight and SuperChic

→ STARlight: Photon flux from point-like sources, restricting impact parameter $b > R_{Pb}$

→ SuperChic: Photon flux from nuclear form factor, impact parameters down to $b = 0$

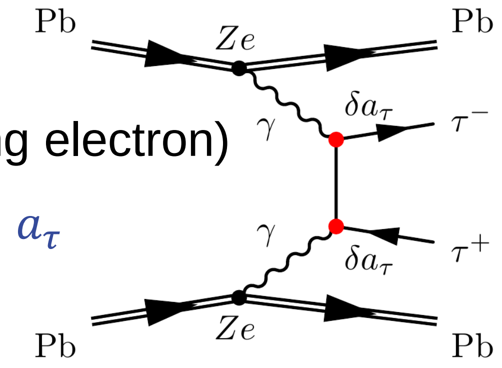
→ Similar shapes as in data, but slight (different) offsets

Study τ-lepton properties

CMS 5.02 TeV, 0.40 nb^{-1}
PRL 131 (2023) 151803

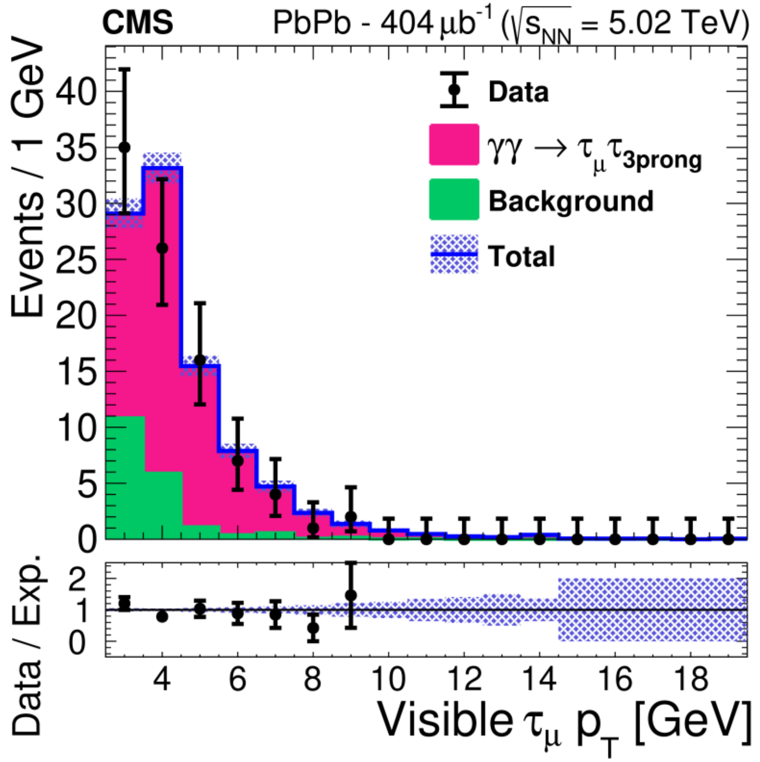
ATLAS 5.02 TeV, 1.55 nb^{-1}
PRL 131 (2023) 151802

Investigate production of $\tau^+\tau^-$ pairs

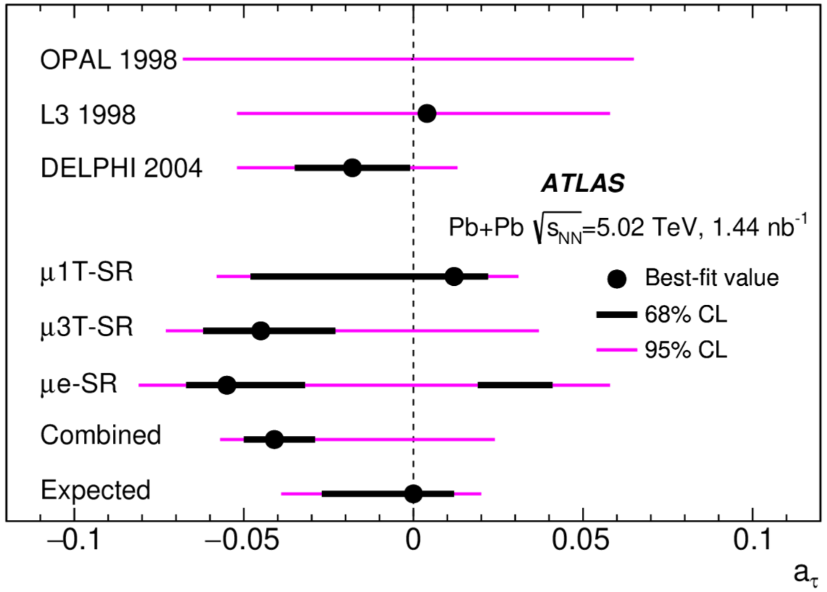


- Select events w/ one τ-lepton decay involving muon, the other hadronically (or involving electron)

$\gamma\gamma \rightarrow \tau\tau$ clearly observed



Extract anomalous magnetic moment of τ-lepton: a_τ



→ Use fit to decay muon p_T distribution (ATLAS)
→ Use cross-section dependence on a_τ (CMS)

Study τ-lepton properties

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PRL 131 (2023) 151803

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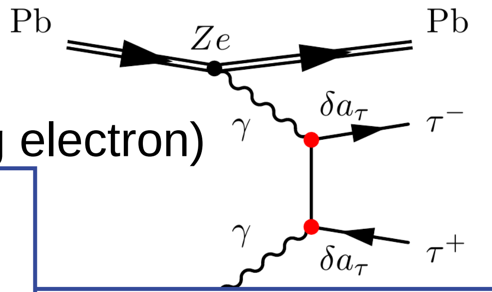

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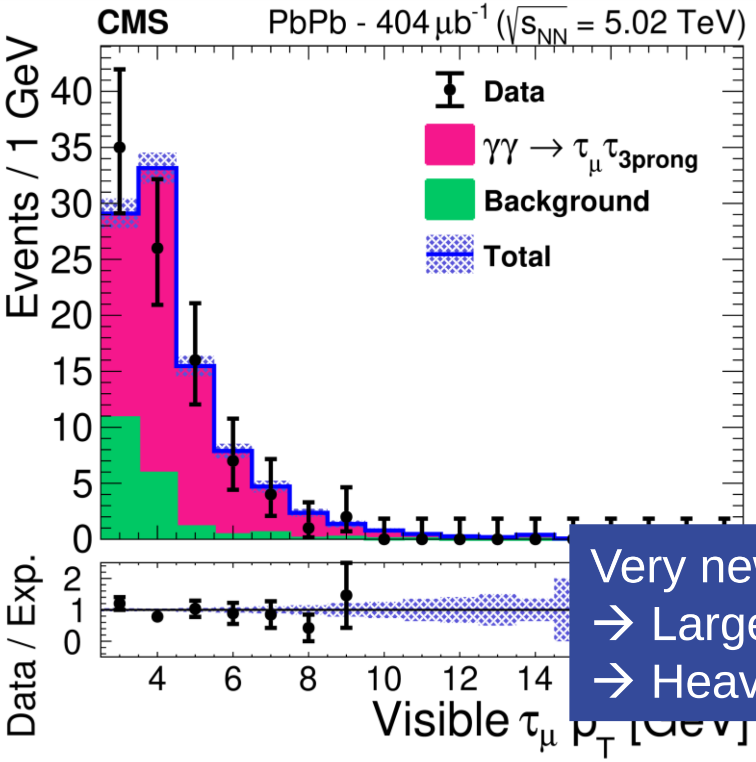
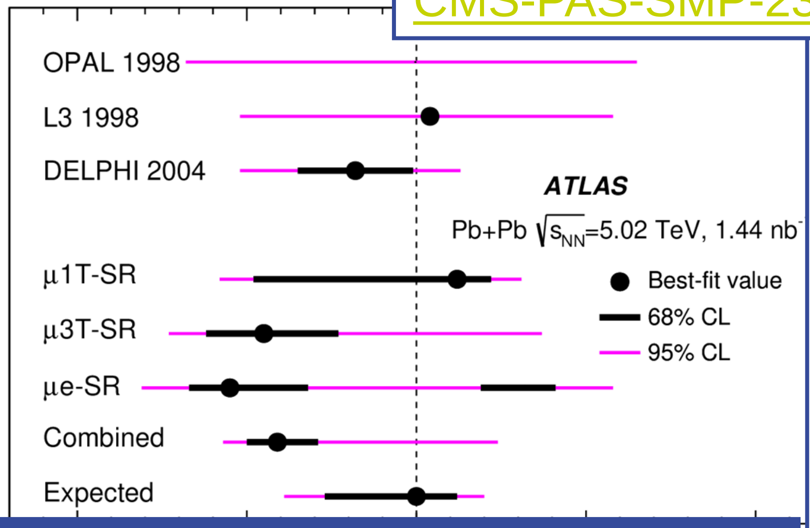
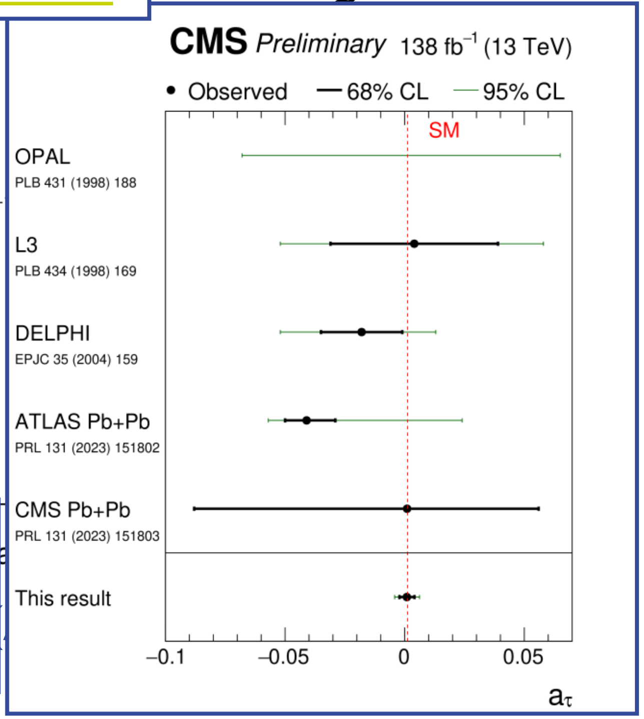


Extract anomalous magne



CMS 13 TeV, 138 fb^{-1}
CMS-PAS-SMP-23-005



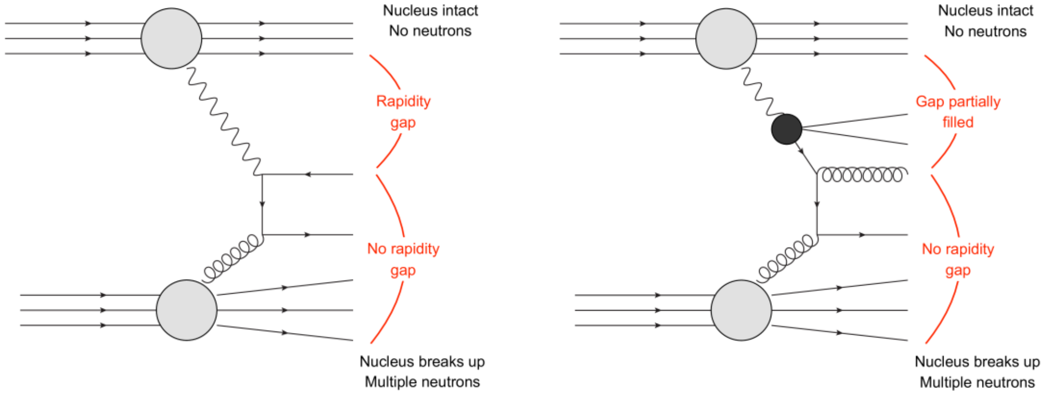
Very new: $\gamma\gamma \to \tau\tau$ in pp collisions!
→ Larger statistics beats lower cross sections
→ Heavy ion UPC measurements need to catch up

Investigate photon interactions with nucleus

ATLAS 5.02 TeV, 1.73 nb^{-1} ATLAS-CONF-2023-059

Charged hadron production in direct and resolved photonuclear interactions

- Direct interaction of photon with parton in nucleus, or fluctuation of photon to vector-meson (VM), e.g. ρ



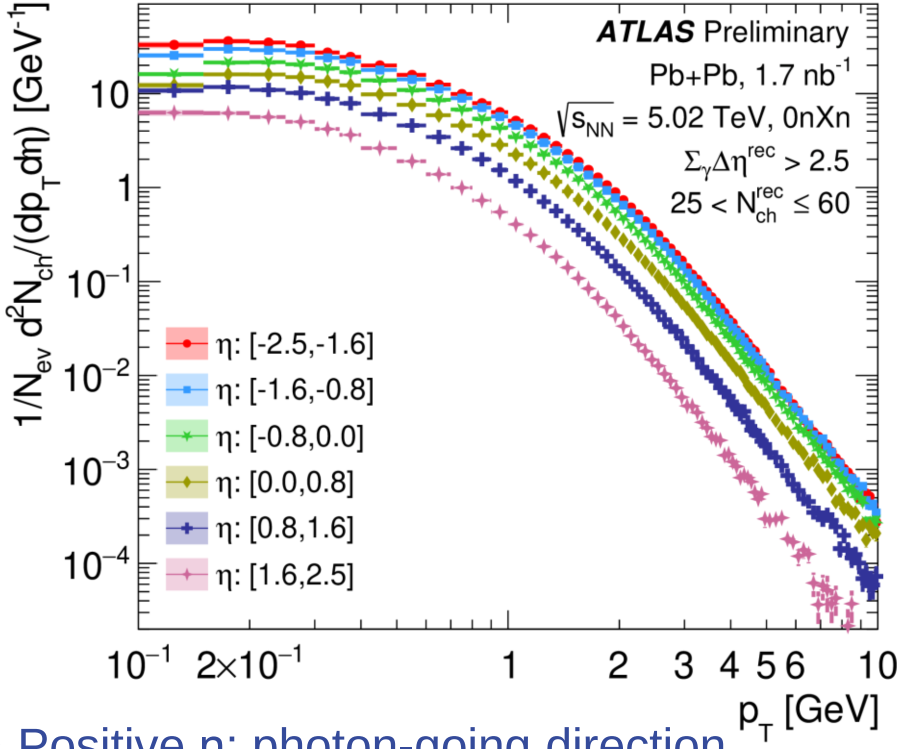
- Determine charged particle yield

$$Y(\eta, p_{\mathrm{T}}) = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}N^2_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}$$

Number of charged particles

Number of selected events

  - While selecting 0nXn topology in ZDC



→ Positive η: photon-going direction
→ Negative η: Pb-going direction

Investigate photon interactions with nucleus

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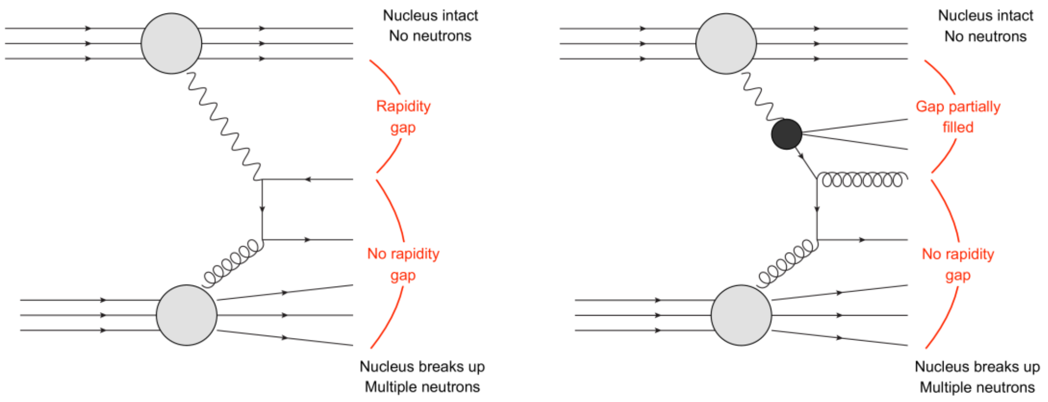


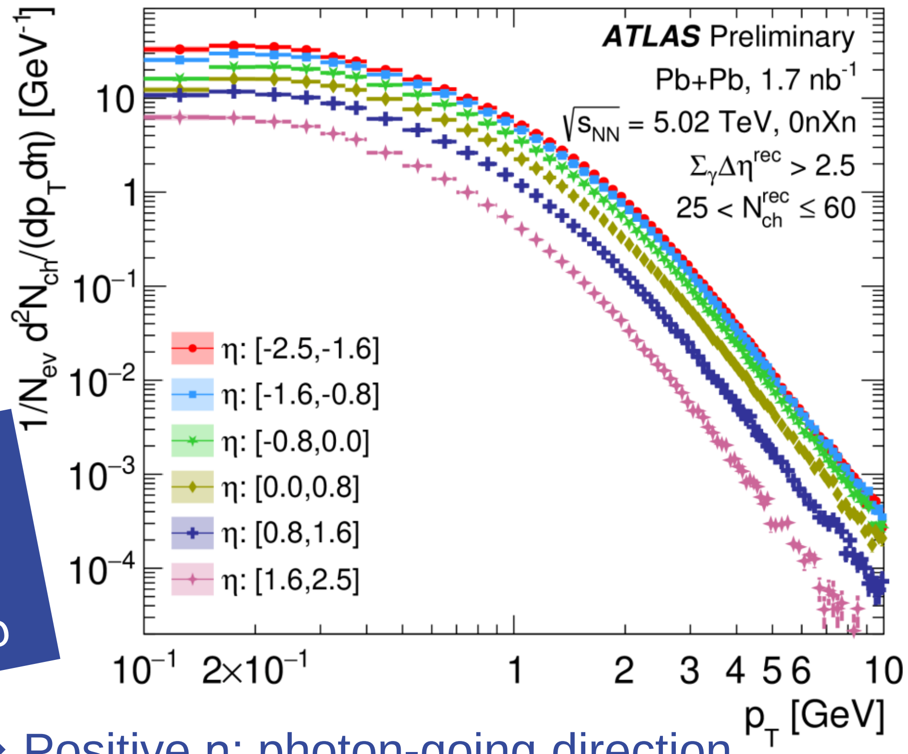
- Determine charged particle yield

$Y(\eta, p$ [illegible]

Number of selected even[illegible]

- While selecting [illegible] topology in ZDC

→ Less charged particles in photon-going direction, more in Pb-going direction
→ Consistent with lower photon energy compared to per-nucleon energy of Pb



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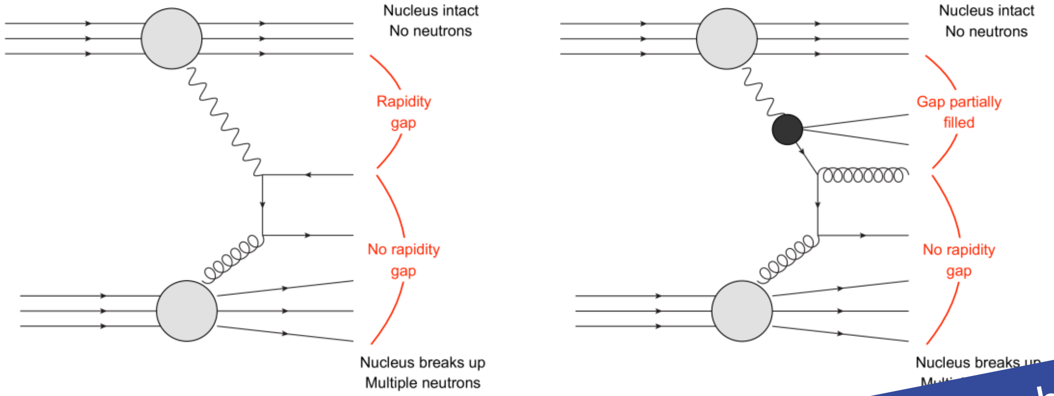
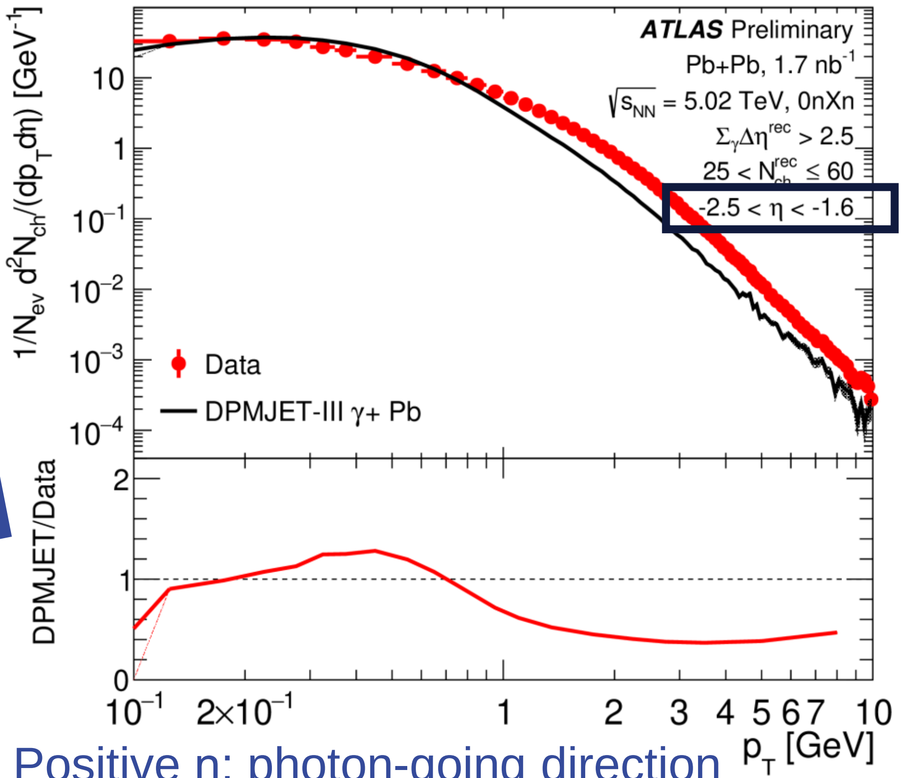




- Determine charged particle yiel...

...rticles

Nu...
sel...ted events

- While selecting 0nXn topology in ZDC

→ Comparison to MC generator in separate-η bins
→ Important to improve simulation to understand potential collective flow effects

→ Positive η: photon-going direction
→ Negative η: Pb-going direction

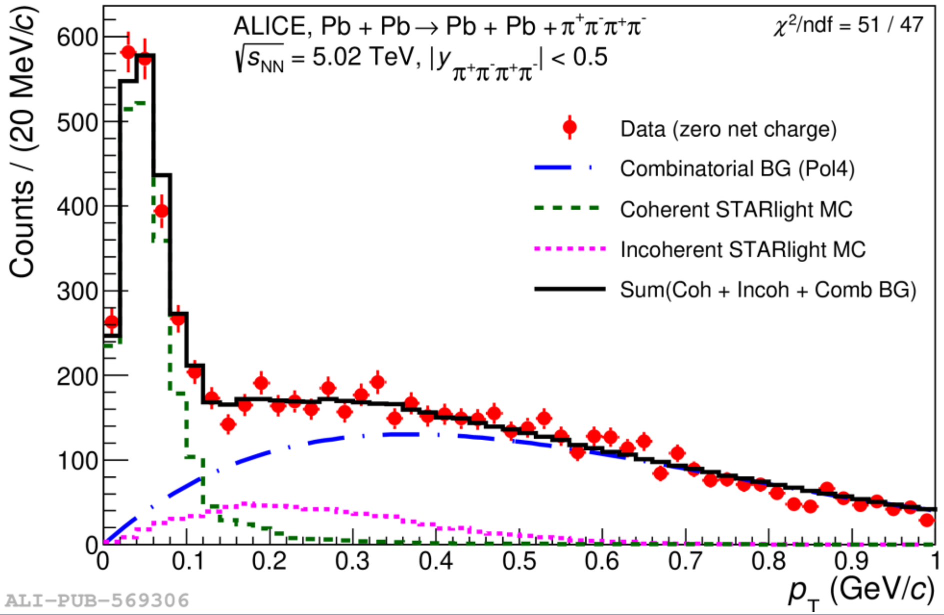
Exclusive four pion production

ALICE 5.02 TeV,
0.62 nb^{-1}
arXiv:2404.07542

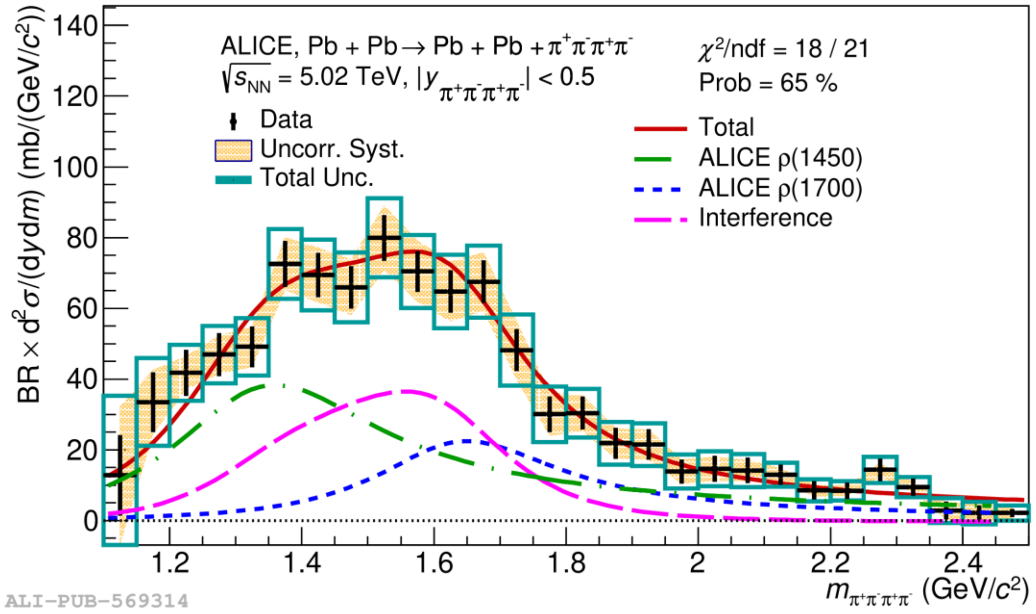
Elastic scattering of a photon-generated VM of the target nucleus (coherently)

- Coherent scattering usually leaves the nucleus intact → Dominated by ρ-meson photoproduction
  - Experimental hints for excited ρ-resonance with decay to $\pi^+\pi^-\pi^+\pi^-$ → Which resonance?
- Select events with 4 tracks, and veto activity in scintiallator-based forward detectors V0 and AD

Estimation of combinatorial background



Fit with interfering resonances with mixing angle



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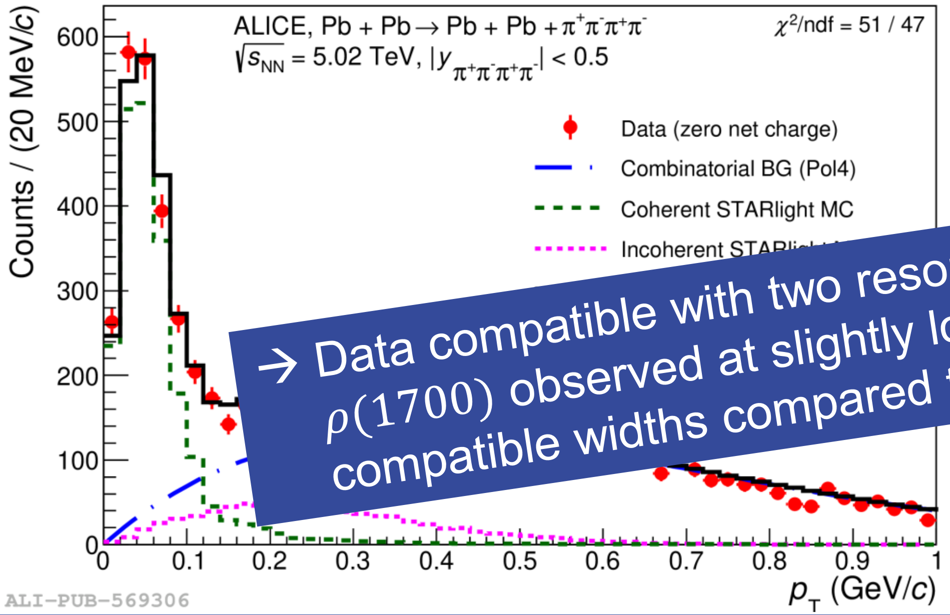

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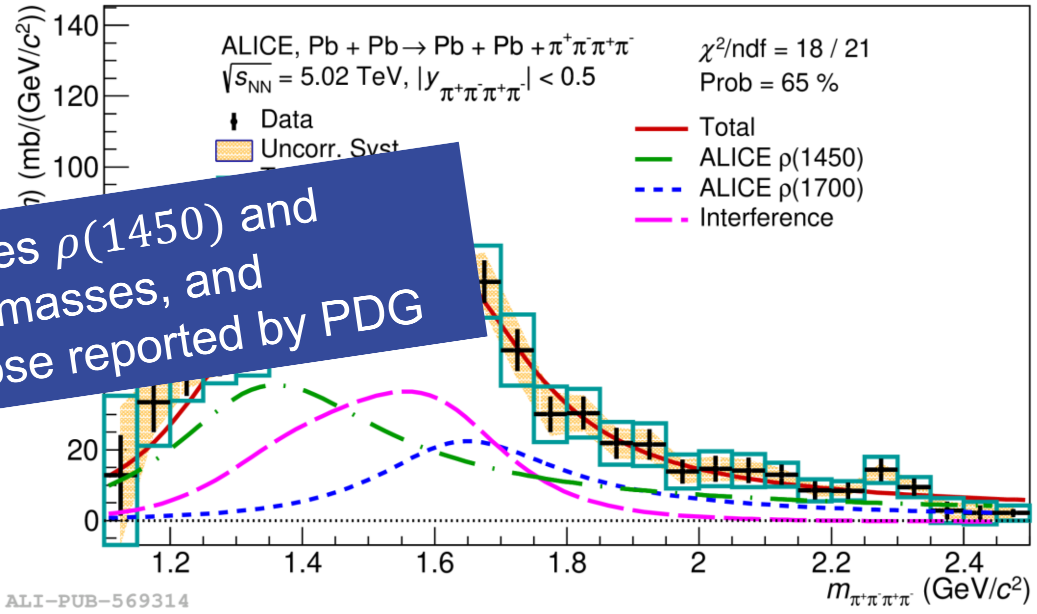
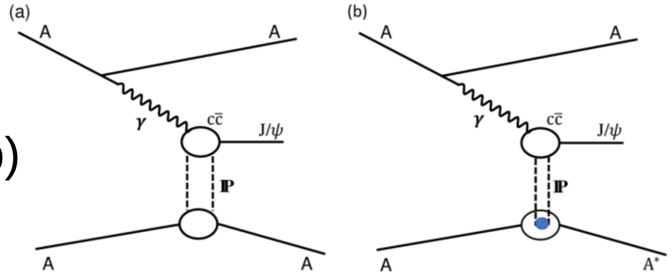


→ Data compatible with two resonances $\rho(1450)$ and $\rho(1700)$ observed at slightly lower masses, and compatible widths compared to those reported by PDG

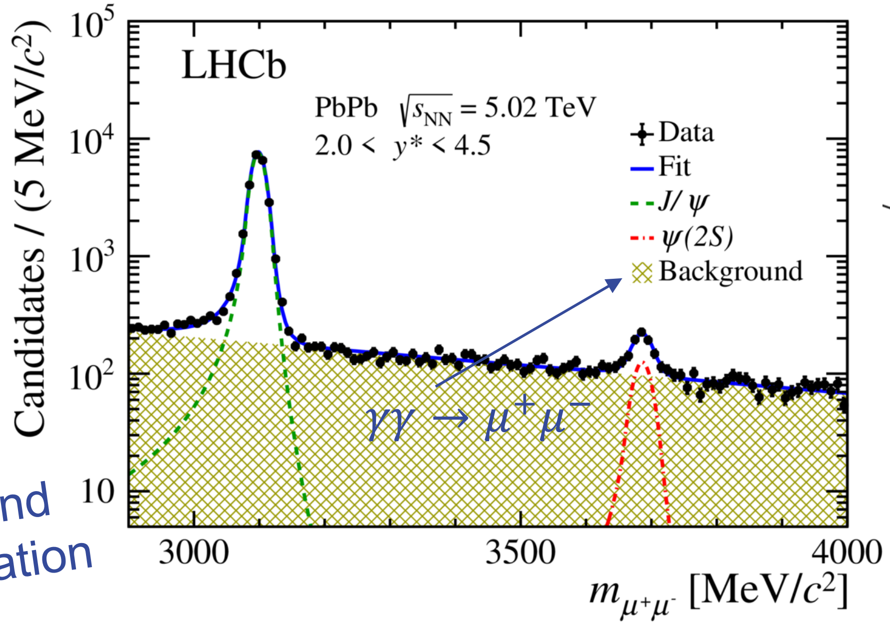
Characteristics of heavy VM production

LHCb 5.02 TeV, 0.23 nb^{-1} JHEP 06 (2023) 146

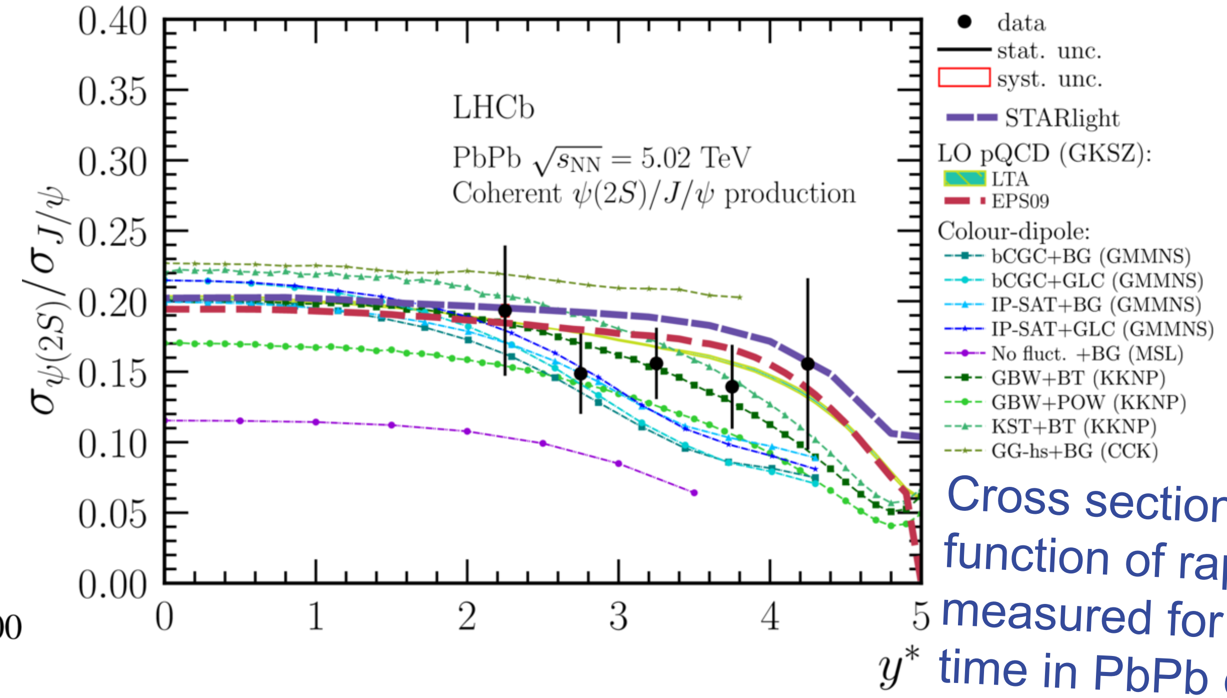
Coherent (a) vs. incoherent (b) production of $c\bar{c}$ mesons



- Pomeron (≥ 2 gluons) exchange w/ full nucleus (a) or particular nucleon only (b)
- Selection through decays $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$
  - Enhance coherent production and UPC through forward activity suppression in scintillating-pad (SPD) and forward shower counters (HeRSCheL)



Background determination



Cross section ratio as function of rapidity measured for the first time in PbPb collisions

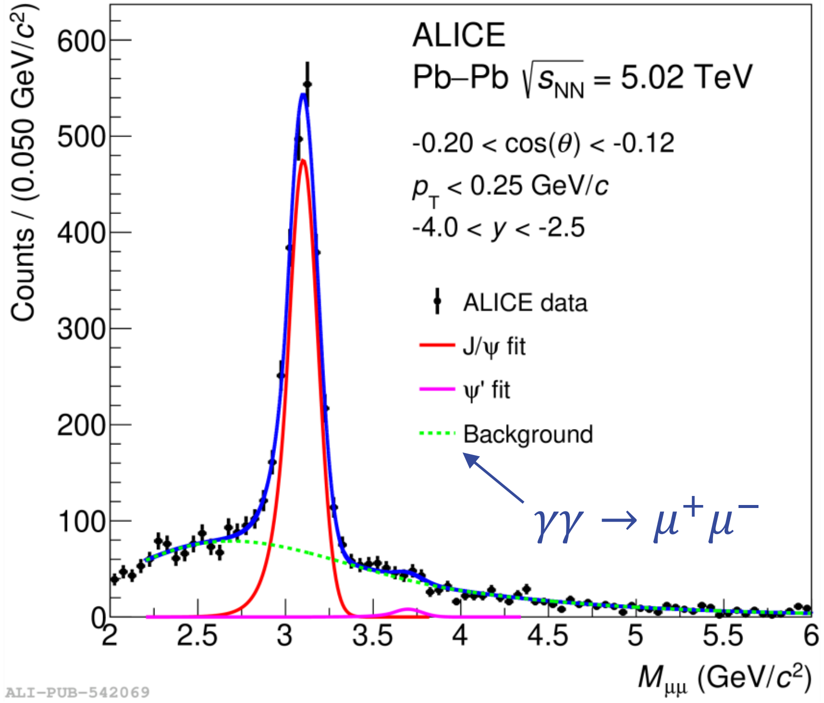
Characteristics of J/ψ production

ALICE 5.02 TeV,
0.75 nb^{-1}
arXiv:2304.10928

Coherent production enhanced through suppression of forward activity in V0 & AD

- J/ψ reconstruction via muonic decays: 2 opposite sign muons in muon-spectrometer range ($-4.0 < \eta < -2.5$)
  - Helicity frame: z-axis in flight direction of J/ψ, y-axis perpendicular to plane by collision axis & J/ψ direction

Extraction of signal yield in bins of $\cos(\theta)$ and φ



→ Fitting angular distribution of decay muons from J/ψ signal using 3 polarisation parameters with properties:

→ $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0,0,0)$ → Isotropic

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1,0,0)$ → Transversely polarized

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0)$ → Longitudinally polarized

λ_θ	λ_φ	$\lambda_{\theta\varphi}$
$0.75 \pm 0.25 \pm 0.24$	$0.03 \pm 0.03 \pm 0.02$	$0.10 \pm 0.05 \pm 0.06$

→ Consistent with transversely polarized J/ψ mesons from coherent production

→ Consistent with s-channel helicity conservation

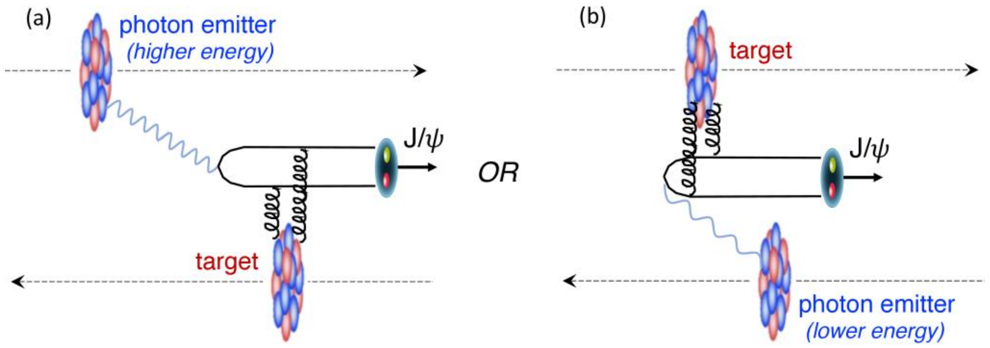
J/ψ‘s as probe of the nucleus

ALICE 5.02 TeV, 0.23-0.53 nb^{-1} JHEP 10 (2023) 119

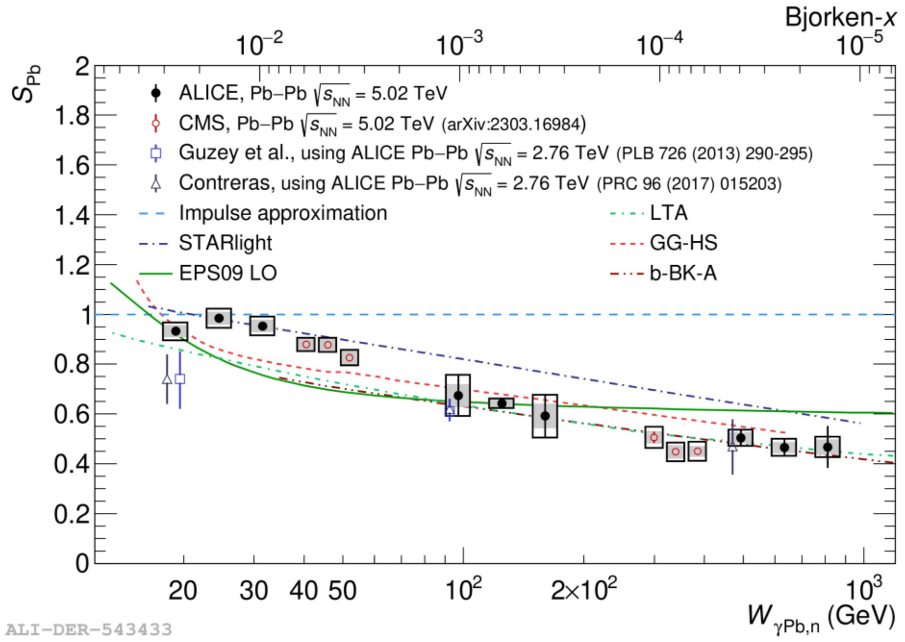
CMS 5.02 TeV, 1.52 nb^{-1} PRL 131 (2023) 262301

Coherent production proportional to square of gluon density functions (at LO)

- Resolve ambiguity betw. photon emitter and target nucleus through electromagnetic dissociation (EMD) of ion



→ Determine nuclear suppression factor: $R_g^{Pb} = \sqrt{\sigma_{meas}/\sigma_{IA}}$ (IA = impulse approximation, i.e. scaled from proton interactions + nuclear form factor)



- Neutron emission from EMD detected in ZDC/ZN: Categorize as 0n0n, 0nXn and XnXn

- Relation between rapidity and gluon momentum fraction

$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \cdot e^{\pm y}$$

→ Resolve ambiguity between $\pm y$ through simultaneous extraction from 3 neutron categories

J/ψ‘s as probe of the nucleus

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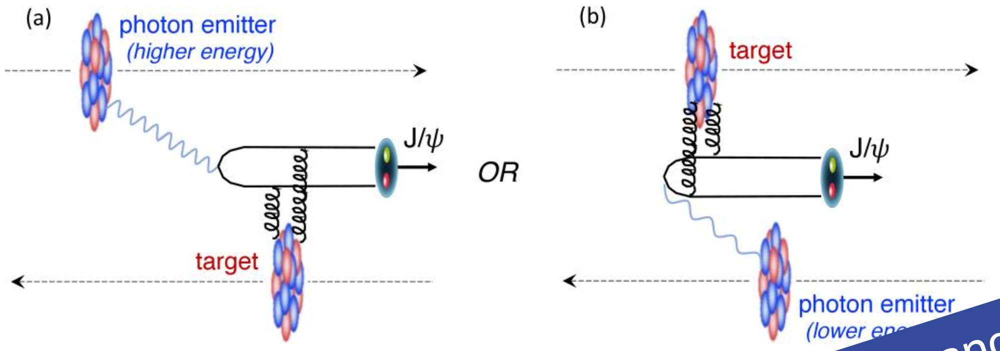

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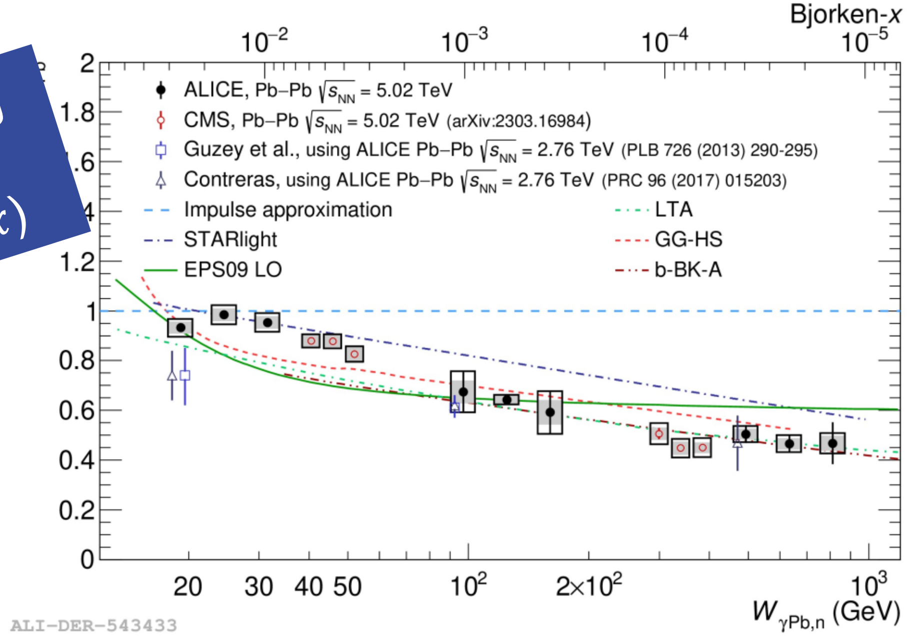
  Categorize as 0n0n, 0
- Relation betwee ... omentum fraction

$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} \cdot e^{\pm y}$$

...esolve ambiguity between $\pm y$ through simultaneous extraction from 3 neutron categories

→ Both, gluon saturation (red) and shadowing (green) models provide reasonable description of data at high energies (low x)



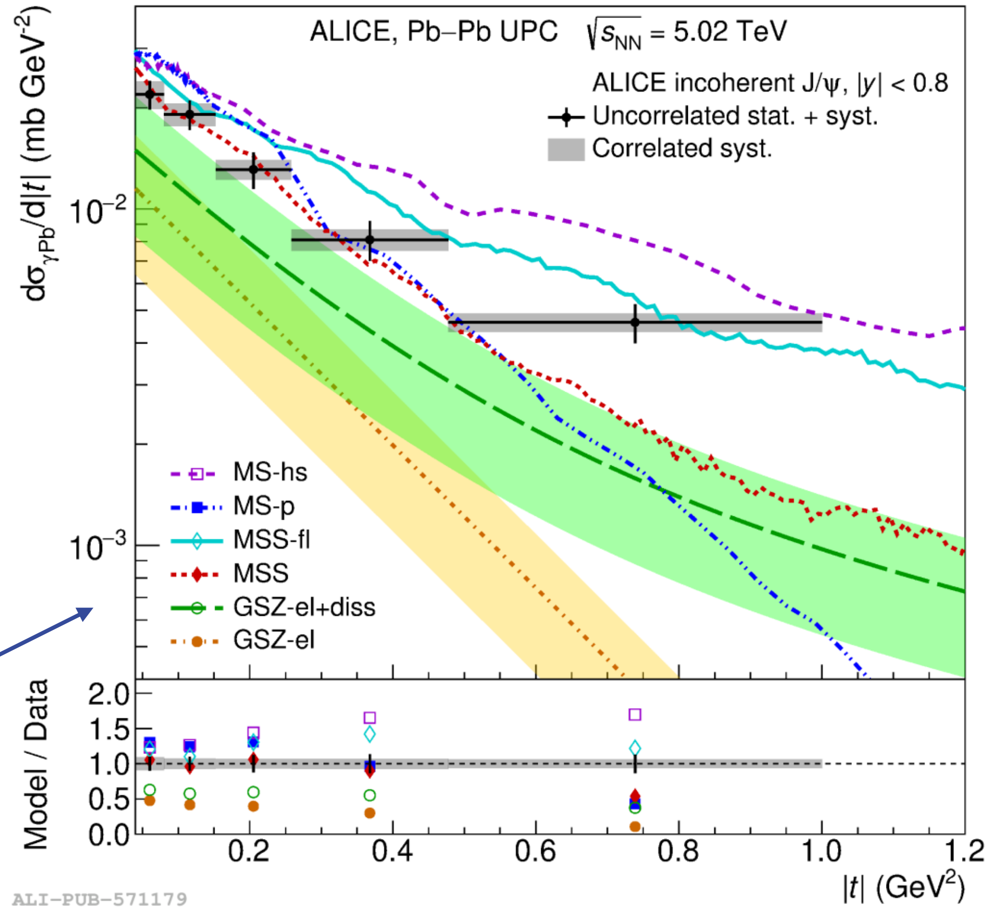
J/ψ's as probe of the nucleus

ALICE 5.02 TeV, 0.23 nb^{-1} PRL 132, 162302 (2024)

Incoherent production: Sensitive to variance of spatial gluon distribution

- Variance related to quantum fluctuations of subnucleon degrees of freedom
  - Small variance at small momentum fractions x = possible sign of gluon saturation
- Contribution of incoherent J/ψ production grows with larger momentum transfers $|t|$
  → Measurement of cross section as function of $|t|$
  - Use J/ψ transverse momentum as proxy: $|t| \approx p_T^2$
    → Veto any other activity through V0 and AD dectors

→ No prediction simultaneously describes absolute normalization and $|t|$ depedence
→ Models including quantum fluctuations (purple, light-blue, green) provide better description of $|t|$ depedence

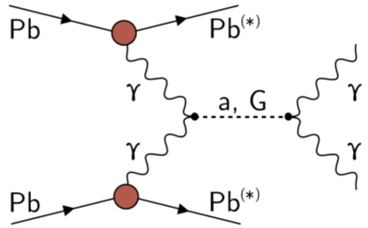


A light to new physics?

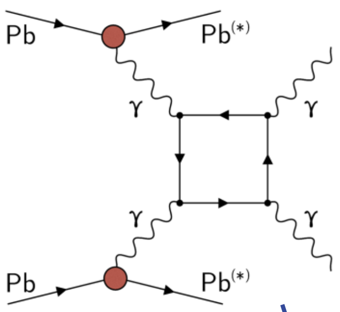
CMS 5.02 TeV, 1.65 nb^{-1} — CMS-PAS-HIN-21-015

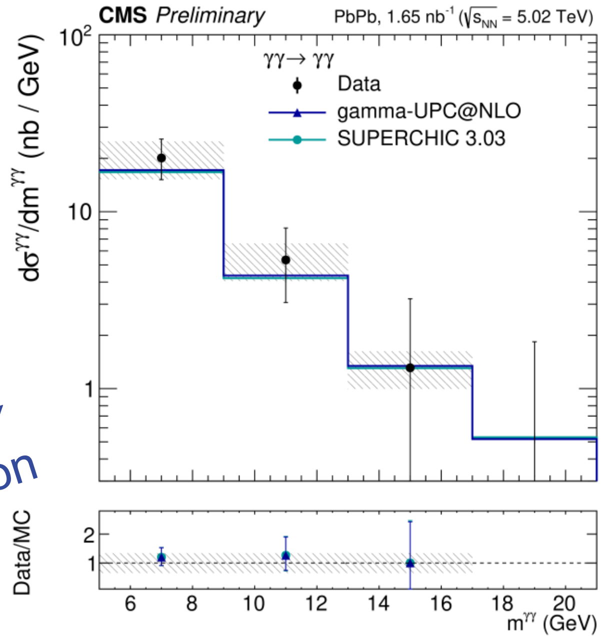
ATLAS 5.02 TeV, 2.2 nb^{-1} — JHEP 03 (2021) 243

Scattering of photons to photons through loop or axion-like mediator



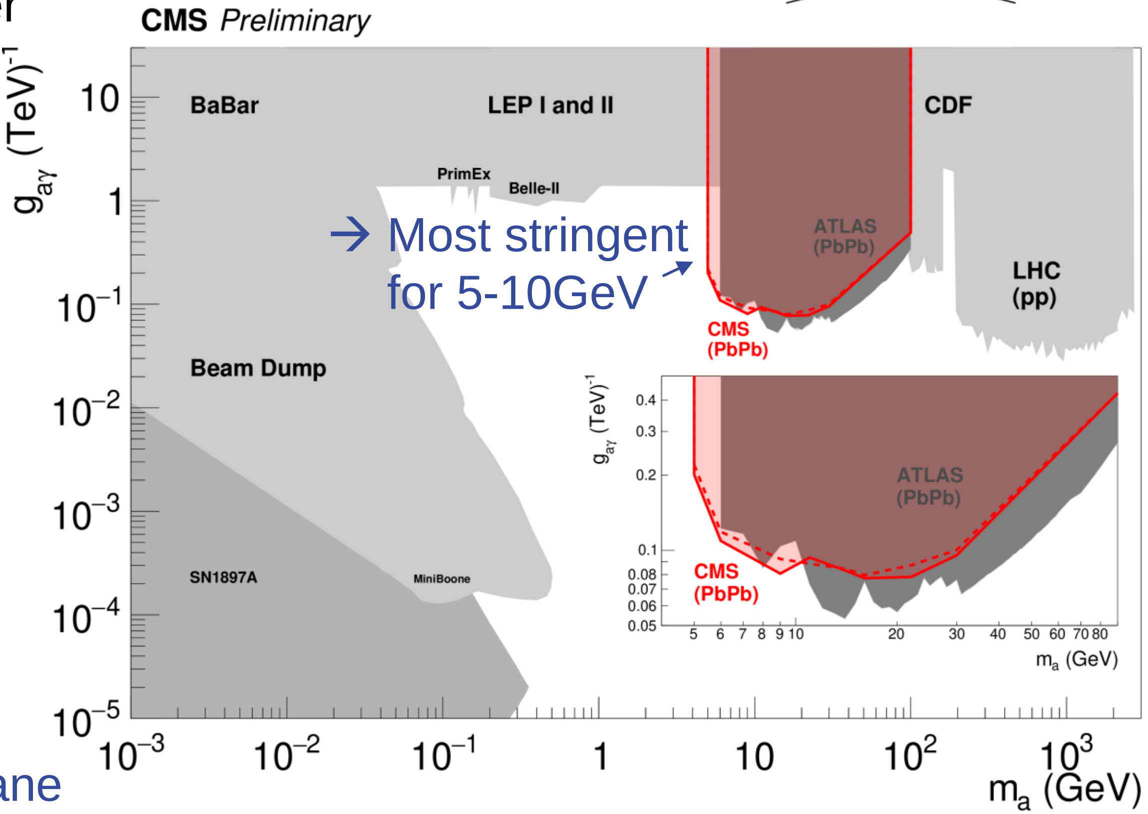
- Large photon-photon luminosities in UPC PbPb collisions provide access to rare processes
  - Selection of two photons → Suppression of any other neutral or charged particles, less than 3 neutrons in both ZDCs





→ Determine differential cross section for $\gamma\gamma \rightarrow \gamma\gamma$

→ Consistent with prediction



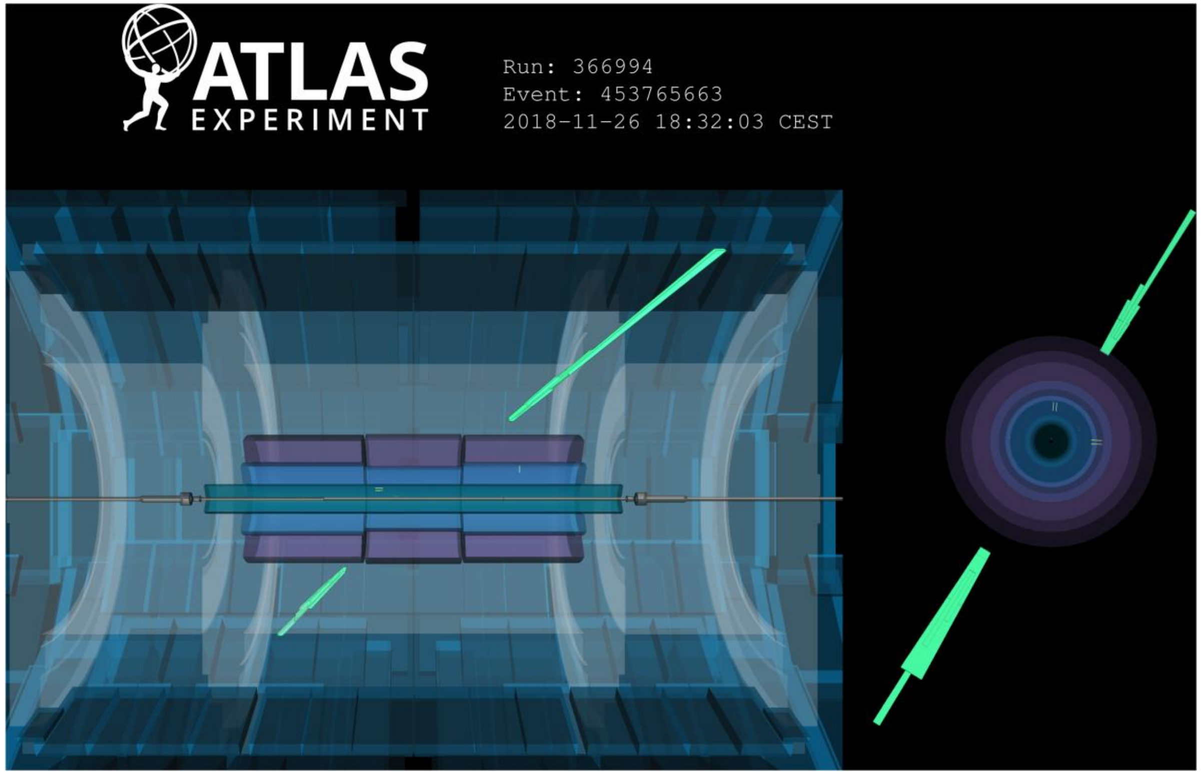
→ Most stringent for 5-10GeV

→ Extract limits in mass-coupling plane

Summary

Ultraperipheral (UPC) heavy ion collions → Provide unique physics potential

- LHC as photon-photon and photon-nucleus collider
- Photon-induced di-lepton production
  - Study photon flux, properties of τ-lepton
- Photonuclear interactions
  - Charged hadron production as probe to potential collective flow effects
  - Light or heavy vector-meson production to study resonances, helicity conservation, nuclear gluon densities, incl. gluon saturation
- Rare processes through charge-enhanced cross sections with Pb ions
  - Probe photophilic interaction of axion-like particles



→ Proof of extraordinary experimental versatility of LHC experiments!

→ Lots of trigger improvements in Run 3 → Let‘s stay curious!

Thank you for your attention.

Backup

Additional interesting publications

New measurements that did not make it into the talk anymore (non-complete list):

- ALICE: Impact parameter dependence in coherent ρ^0 production: https://arxiv.org/abs/2405.14525
- ALICE: Photoproduction of K^+K^- pairs: Phys. Rev. Lett. 132 (2024) 222303

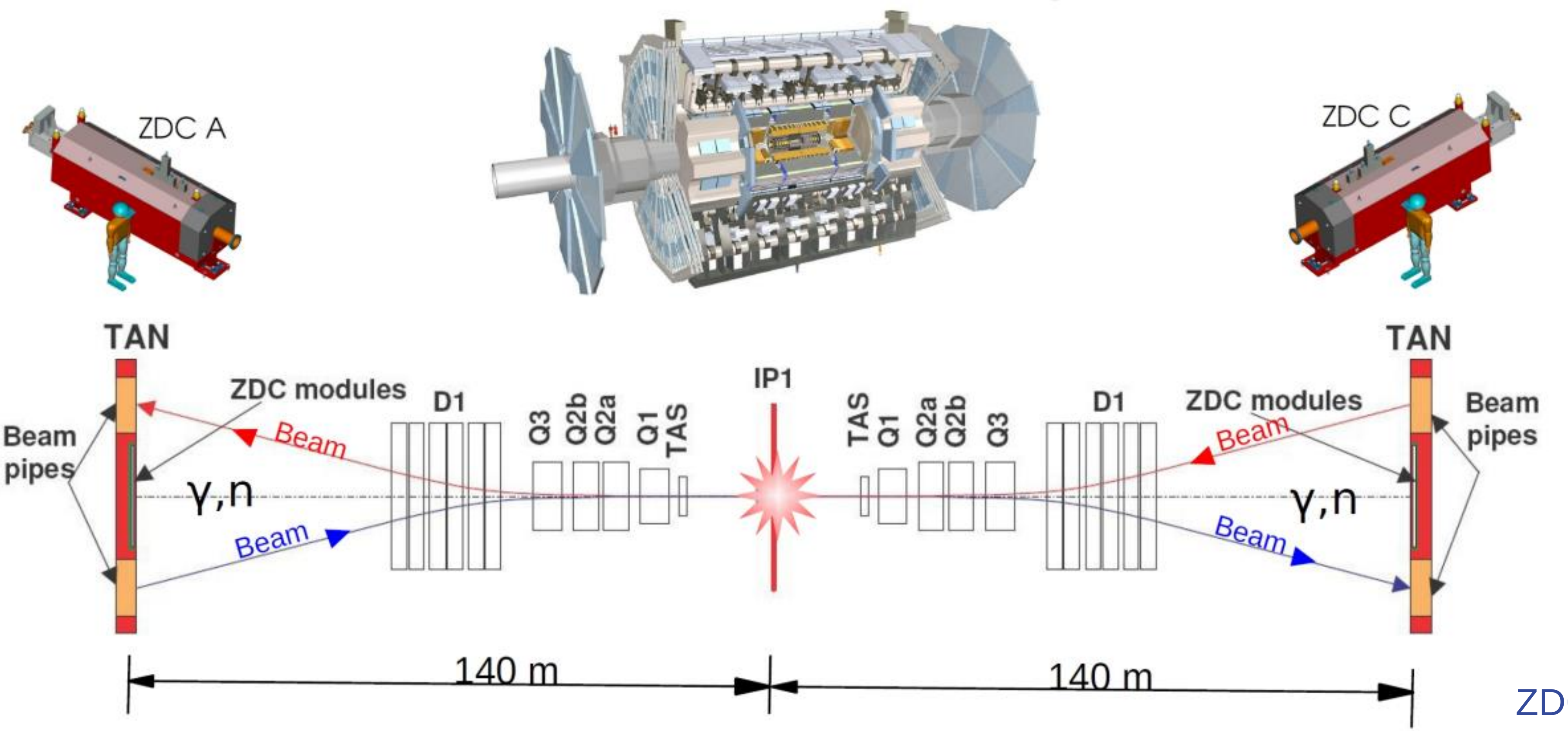
Earlier measurements on some of the topics included in my talk (non-complete):

- ATLAS: Exclusive dimuon production: Phys. Rev. C 104 (2021) 024906
- ATLAS: Charged particle multiplicities and two-particle correlations: Phys. Rev. C. 104 (2021) 014903
- ALICE: Coherent J/ψ and ψ' at midrapidities: EPJC **81** (2021) 712
- ALICE: Coherent J/ψ production at forward rapidities: Phys. Lett. B798 (2019) 134926

Interesting further reading:

- K. J. Eskola et al.: J/ψ photoproduction at NLO: Phys. Rev. C 106 (2022) 035202, Phys. Rev. C 107 (2023) 044912

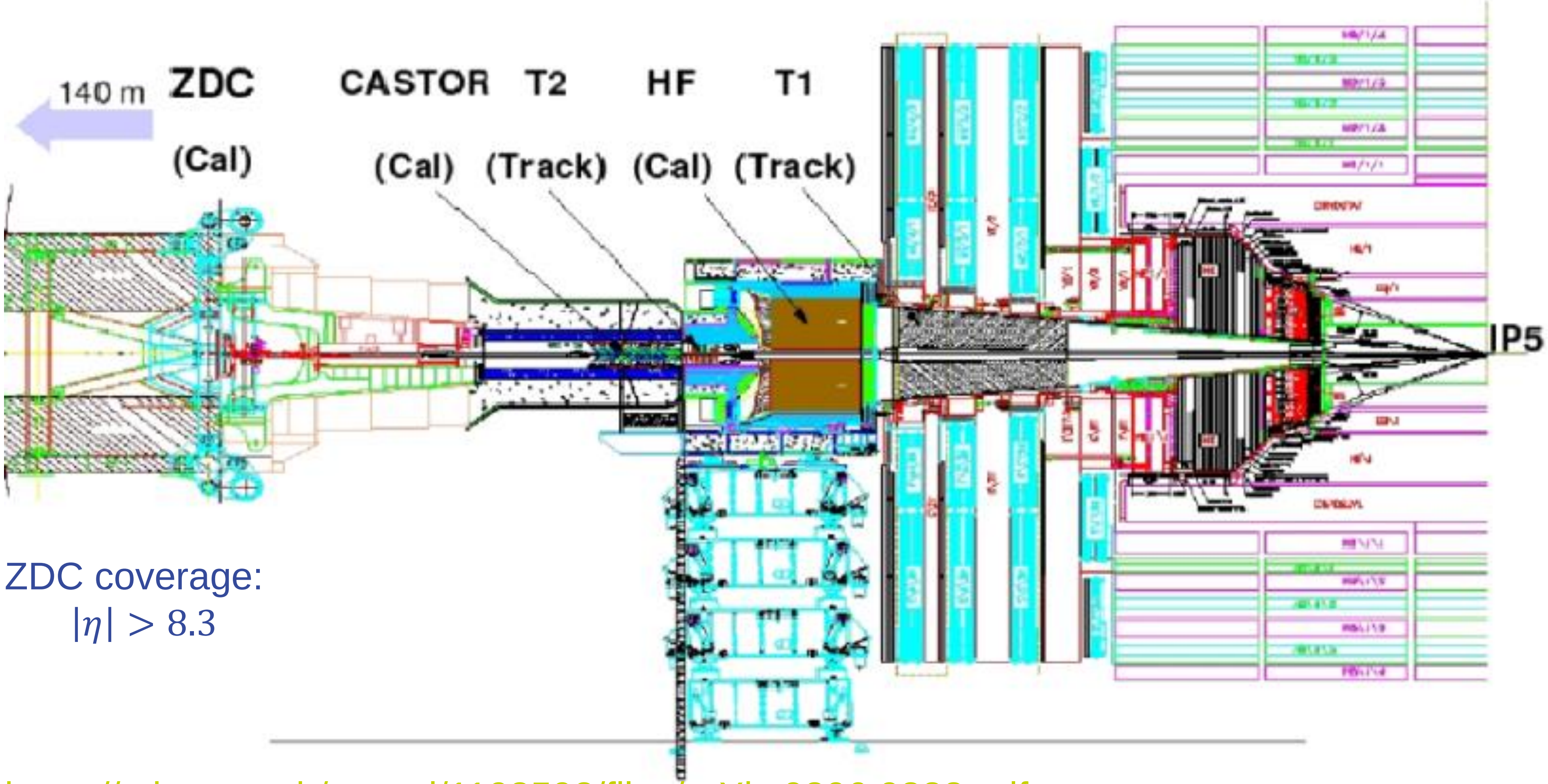
ATLAS including ZDC



ZDC coverage:
$|\eta| > 8.3$

https://cds.cern.ch/record/1628749/files/ATL-FWD-PROC-2013-001.pdf

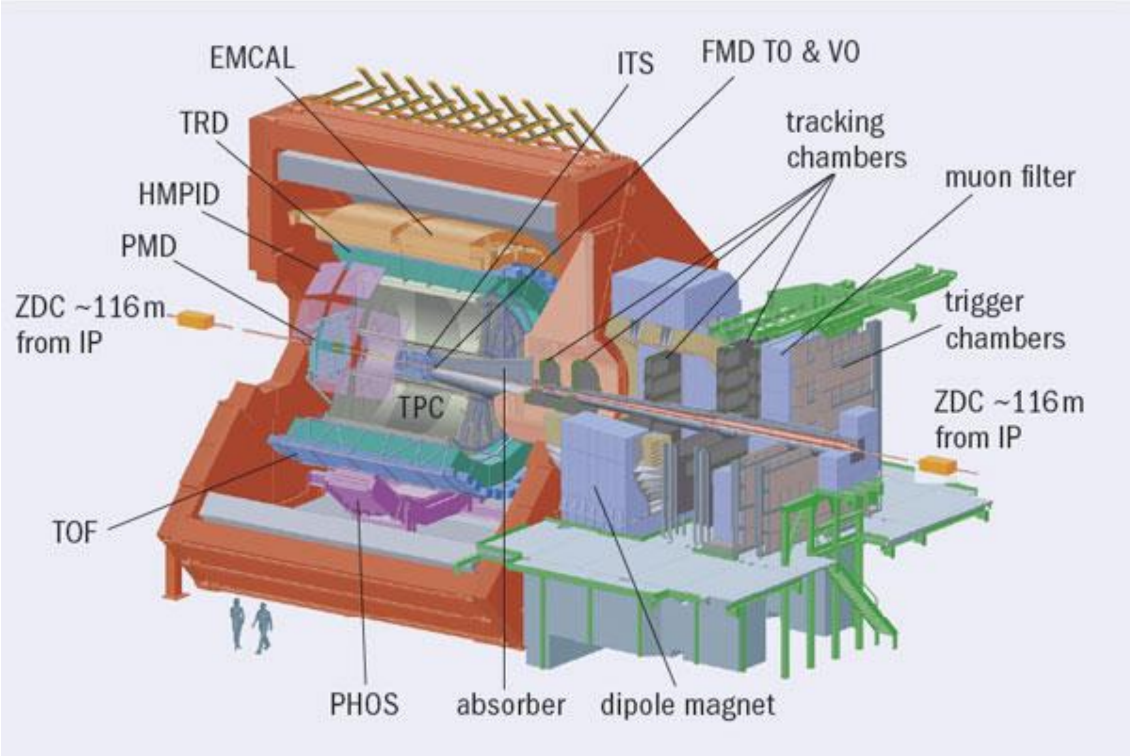
CMS including ZDC



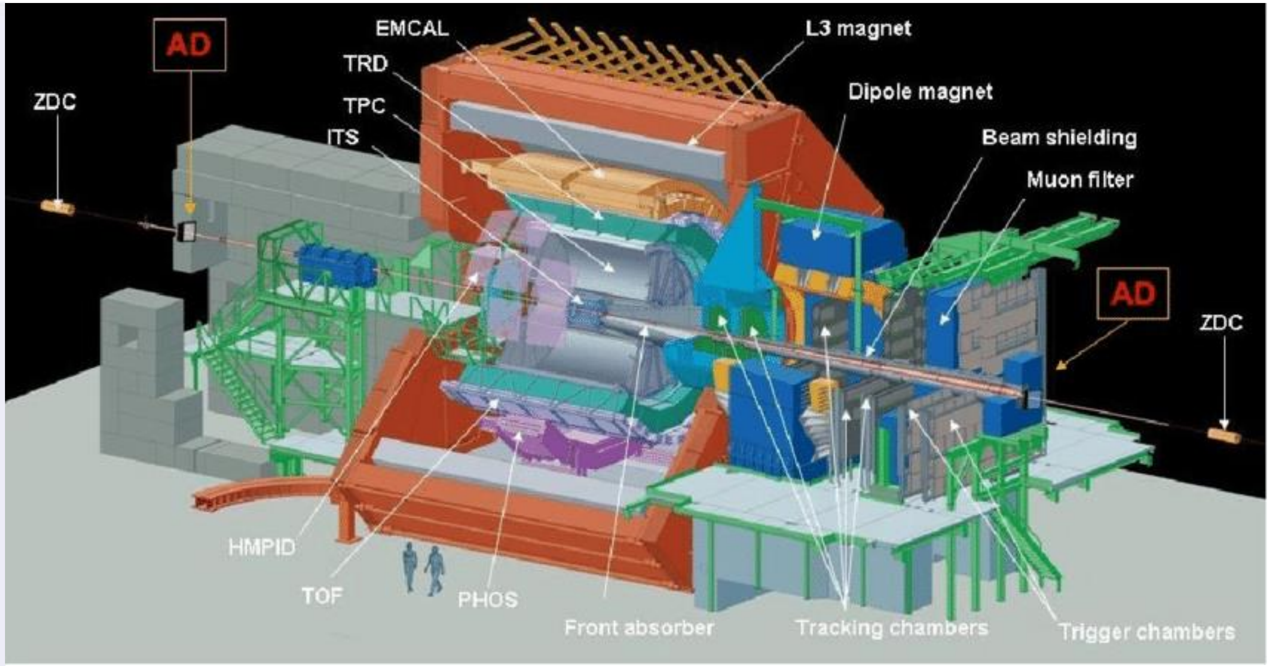
ZDC coverage:
$|\eta| > 8.3$

https://cds.cern.ch/record/1108592/files/arXiv:0806.0883.pdf

ALICE with forward detectors



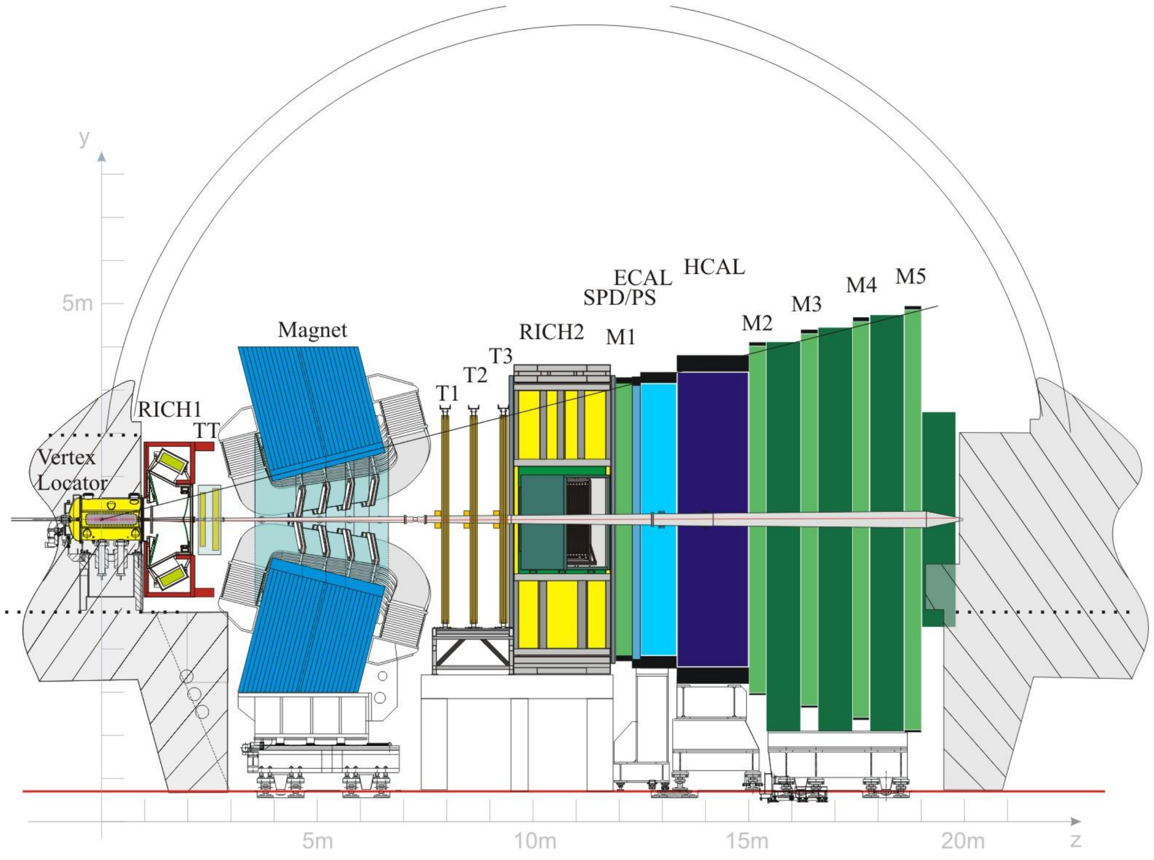
https://cerncourier.com/a/alice-the-heavy-ion-challenge/



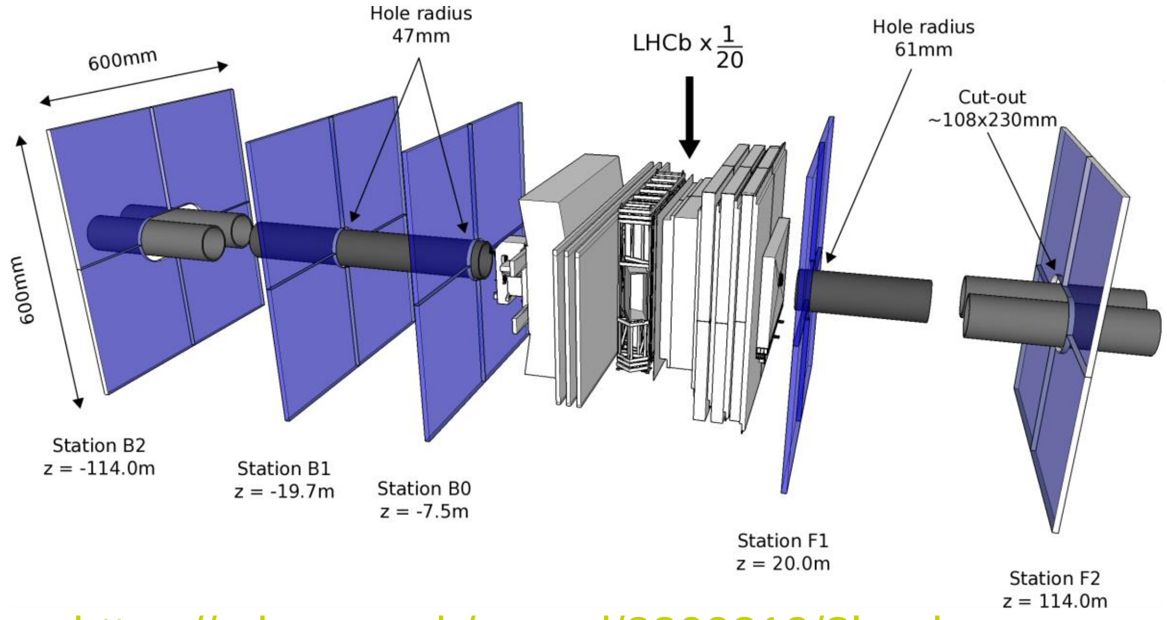
https://iopscience.iop.org/article/10.1088/1742-6596/624/1/012008

V0 coverage: $-3.7 < |\eta| < -1.7,\ 2.8 < |\eta| < 5.1$
AD (ALICE Diffractive) coverage: $-6.9 < |\eta| < -4.9,\ 4.7 < |\eta| < 6.3$

LHCb with forward detectors



https://lhcb.web.cern.ch/lhcb_page/infrastructure/lhcb-geom/



https://cds.cern.ch/record/2300319/?ln=de

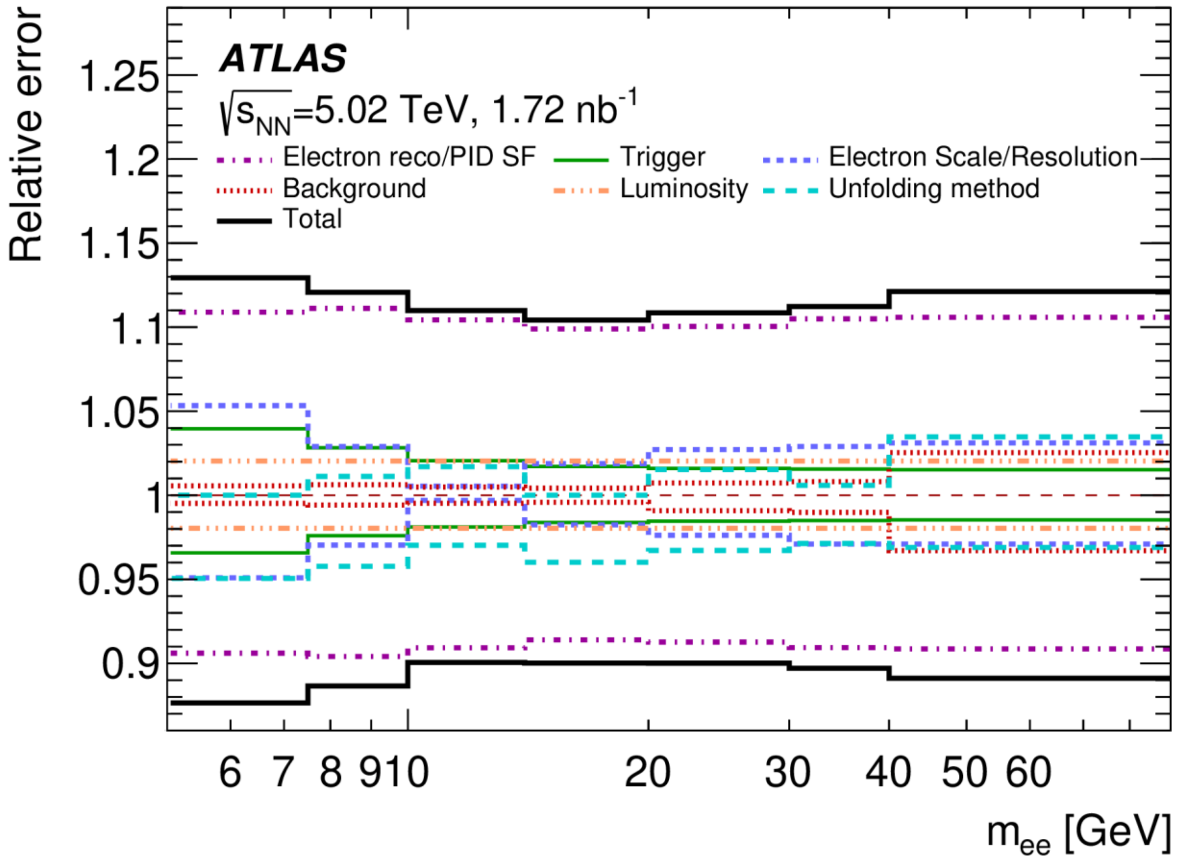
LHCb coverage: $2 < |\eta| < 5$
HeRSCheL coverage: $5 \lesssim |\eta| \lesssim 10$

Understanding the photon flux

ATLAS 5.02 TeV, 1.72nb^{-1}
JHEP 06 (2023) 182

Investigate production of e^+e^- pairs

- Systematic uncertainties



Study τ-lepton properties

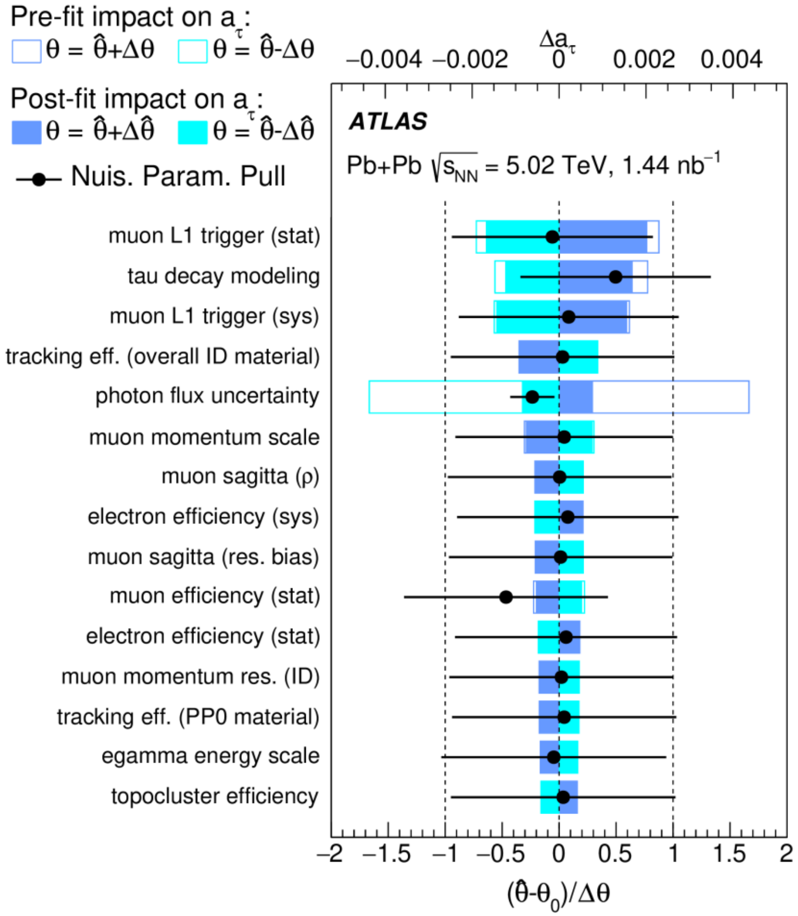
ATLAS 5.02 TeV, 1.55 nb^{-1}
Phys. Rev. Lett. 131 (2023) 151802

Investigate production of $\tau^+\tau^-$ pairs – in heavy ion collisions

- For signal strength of $\gamma\gamma \rightarrow \tau\tau$

Uncertainty	Impact on $\mu_{\tau\tau}$ [%]
muon Level-1 trigger (sys)	1.0
τ decay modeling	1.0
tracking eff. (overall ID material)	0.9
muon Level-1 trigger (stat)	0.7
topocluster reco. eff.	0.6
muon reco. eff. (stat)	0.6
tracking eff. (PP0 material)	0.6
topocluster energy calib.	0.5
muon reco. eff. (sys)	0.5
photonuclear template var. (μ1T-SR)	0.5
Total systematic	2.6

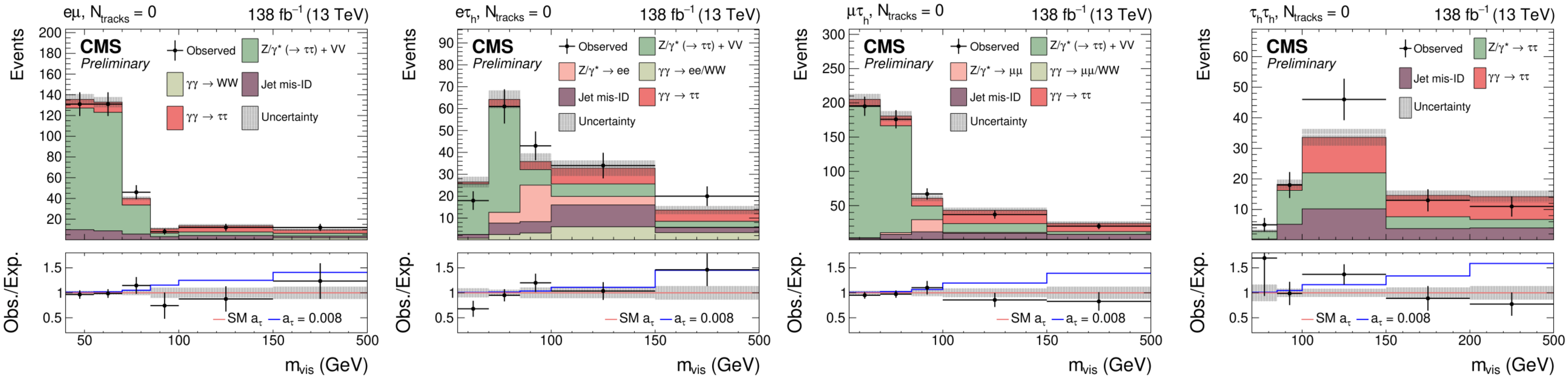
For a_τ



Study τ-lepton properties

CMS 13 TeV, 138 fb^{-1}
CMS-PAS-SMP-23-005

Investigate production of $\tau^+\tau^-$ pairs – in pp collisions



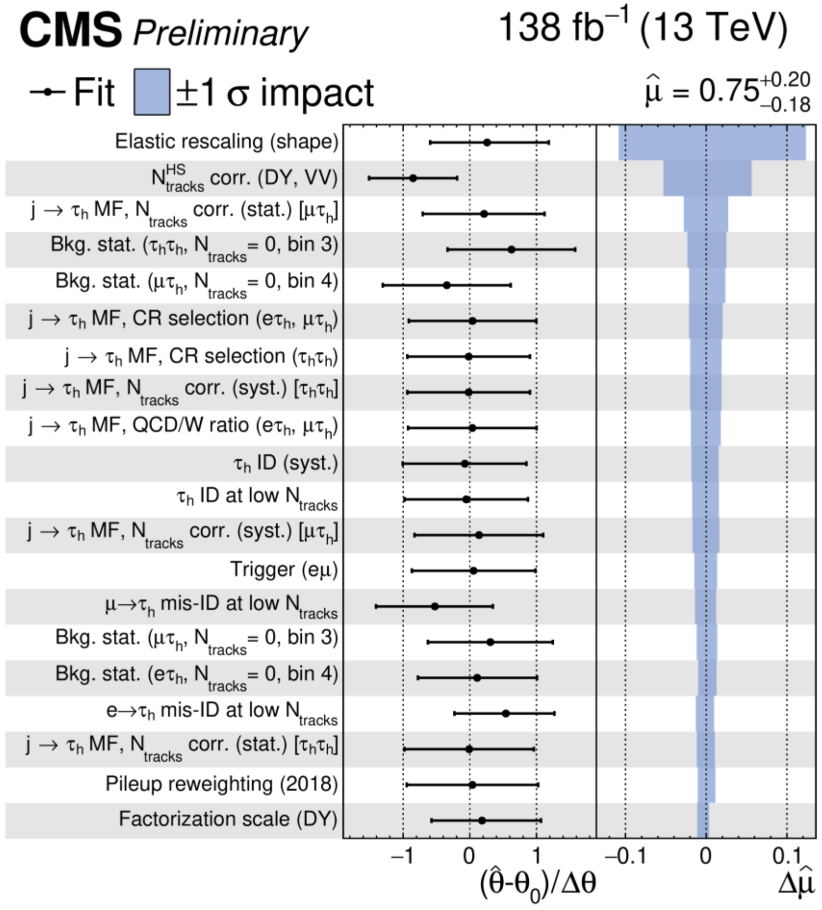
The observed (expected) significance is 5.3 (6.5) s.d. for the exclusive $\gamma\gamma \to \tau\tau$ process. This constitutes the first observation of this process in pp collisions. The corresponding significances per final state are 2.3, 3.0, 2.1, and 3.4 (3.2, 2.1, 3.9, and 3.9) s.d. in the eμ, eτ_h, $\mu\tau_h$, and $\tau_h\tau_h$ final states, respectively. The most sensitive channel in terms of expected significance is $\mu\tau_h$

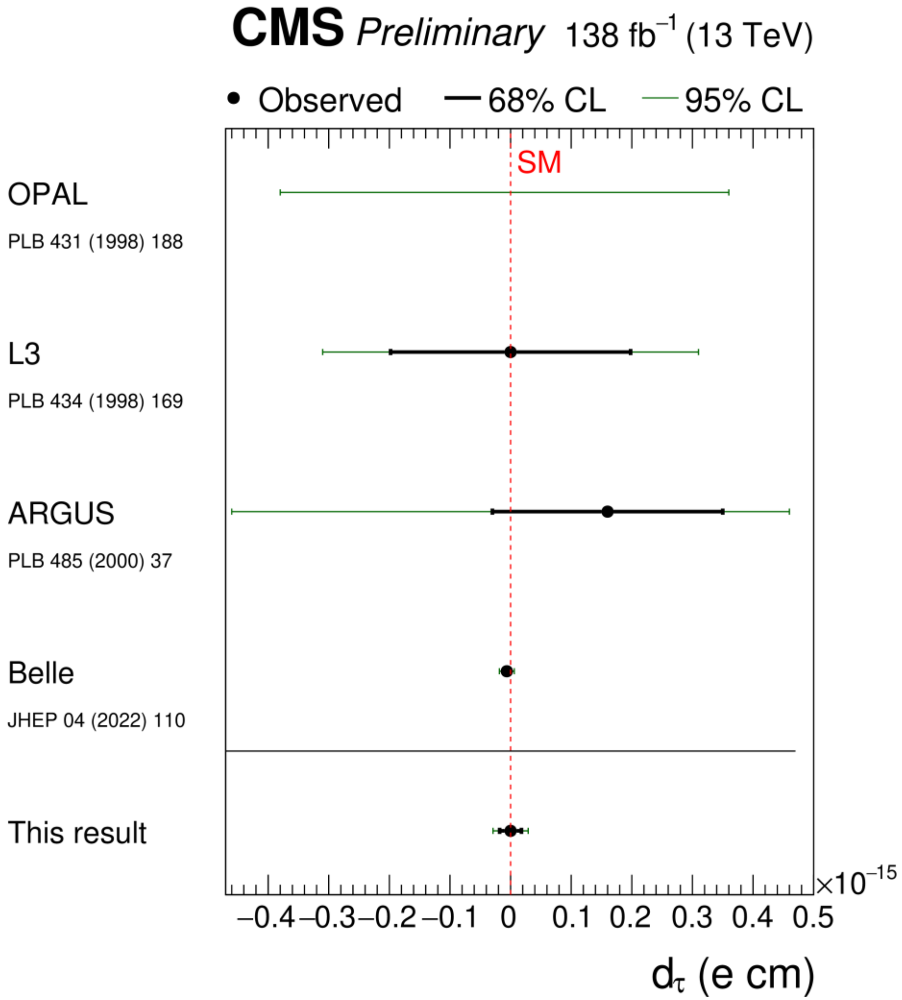
Study τ-lepton properties

CMS 13 TeV, 138 fb^{-1}
CMS-PAS-SMP-23-005

Investigate production of $\tau^+\tau^-$ pairs – in pp collisions

→ For the fit of the signal strength of $\gamma\gamma \rightarrow \tau\tau$:

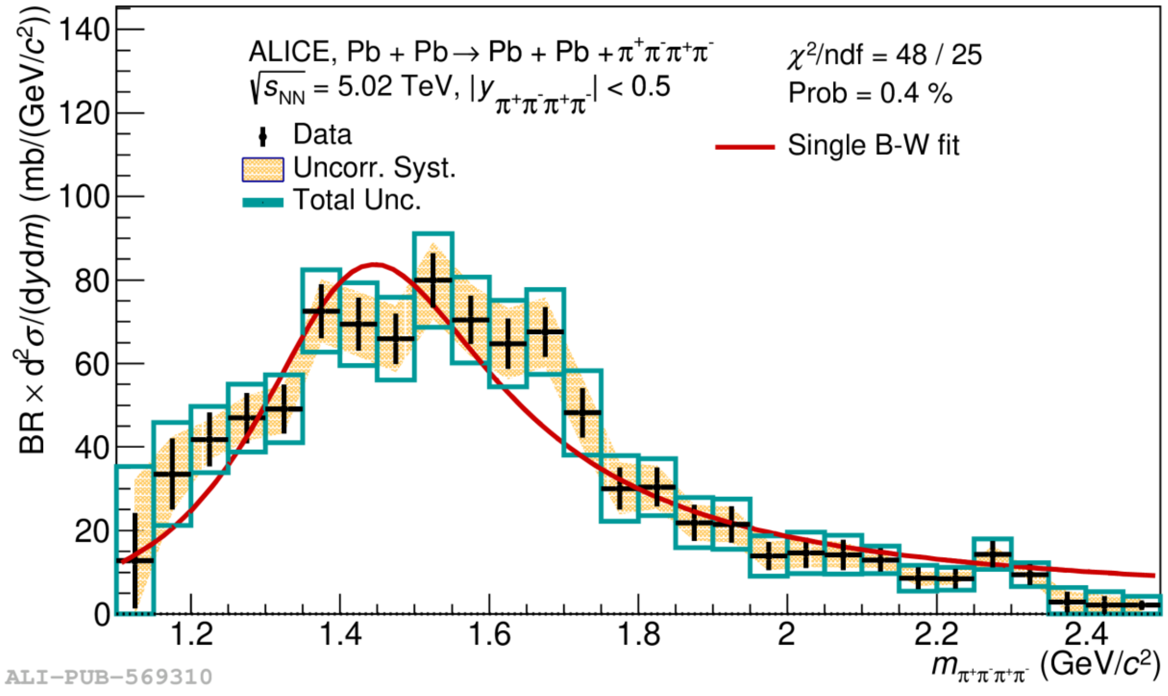




Exclusive four pion production

ALICE 5.02 TeV, 0.62 nb^{-1}
arXiv:2404.07542

Singe resonance fit



→ Bad chi2/ndf → not a good fit to the data

Systematic uncertainties

Source	Uncertainty (%)
Background subtraction	1.5
Angular distribution	6.5
Total uncorrelated	6.7
Angular distribution	12.0
Signal extraction	1.7
Track selection	1.5
Track matching	4.0
Incoherent contribution	1.5
Trigger efficiency	1.0
Pileup	3.8
Luminosity	2.6
Total correlated	13.7

→ Azimuthal angular distribution betw. 2 positive pions reweighted to match flat (isotropic) distribution
→ Propagated to re-calculate $A \times \varepsilon$ corrections

Characteristics of heavy VM production

LHCb 5.02 TeV, 0.23 nb^{-1} JHEP 06 (2023) 146

Systematic uncertainties

Source	Relative uncertainty [%]	
	$\sigma^{coh}_{J/\psi}$	$\sigma^{coh}_{\psi(2S)}$
Tracking efficiency	0.5–2.0	0.5–2.0
PID efficiency	0.9–1.6	0.9–1.6
Trigger efficiency	2.7–3.7	2.1–2.5
HeRSCheL efficiency	1.4	1.4
Background estimation	1.2	1.2
Momentum resolution	0.9–34	1.3–27
Branching fraction	0.6	2.1
Luminosity	4.4	4.4

→ Largest momentum resolution uncertainties from p_T^* interval: 140-160MeV with very small event yields

Interval [MeV/c]	$d^2\sigma^{coh}_{J/\psi}/dp^*_T dy^*$ [mb/(GeV/c)]	Uncertainties [mb/(GeV/c)]			
		Stat.	Syst.	Lumi.	Total
$0 < p^*_T < 20$	13.391	0.352	0.908	0.587	1.138
$20 < p^*_T < 40$	33.940	0.556	2.007	1.489	2.560
$40 < p^*_T < 60$	35.077	0.495	1.462	1.538	2.179
$60 < p^*_T < 80$	22.645	0.381	0.492	0.993	1.172
$80 < p^*_T < 100$	9.945	0.249	0.472	0.436	0.689
$100 < p^*_T < 120$	2.028	0.128	0.311	0.089	0.347
$120 < p^*_T < 140$	0.432	0.083	0.138	0.019	0.163
$140 < p^*_T < 160$	0.781	0.103	0.273	0.034	0.293
$160 < p^*_T < 180$	0.986	0.118	0.213	0.043	0.247
$180 < p^*_T < 200$	0.464	0.102	0.080	0.020	0.131
$0 < p^*_T < 200$	11.904	0.103	0.233	0.522	0.581

Interval [MeV/c]	$d^2\sigma^{coh}_{\psi(2S)}/dp^*_T dy^*$ [mb/(GeV/c)]	Uncertainties [mb/(GeV/c)]			
		Stat.	Syst.	Lumi.	Total
$0 < p^*_T < 30$	2.073	0.942	0.141	0.091	0.957
$30 < p^*_T < 70$	5.447	0.775	0.254	0.239	0.850
$70 < p^*_T < 90$	3.476	0.535	0.110	0.152	0.567
$90 < p^*_T < 110$	1.136	0.337	0.108	0.050	0.357
$110 < p^*_T < 150$	0.000	0.093	0.000	0.000	0.093
$150 < p^*_T < 200$	0.025	0.051	0.006	0.001	0.051
$0 < p^*_T < 200$	1.833	0.160	0.052	0.080	0.187

→ Starred notation indicates definition in nucleus-nucleus centre-of-mass frame

→ Account for the non-zero crossing angle between two Pb beams in lab frame

Characteristics of J/ψ production

ALICE 5.02 TeV,
0.75 nb^{-1}
arXiv:2304.10928

Systematic uncertainties

Systematics	λ_θ	λ_φ	$\lambda_{\theta\varphi}$
$\cos\theta$ range	0.142	0.002	0.056
signal extraction	0.026	0.002	0.008
unfolding	0.019	0.004	0.004
response matrix	0.009	0.008	0.004
single muon p_T threshold	0.196	0.022	0.019
Total	0.244	0.023	0.060

Table 1: Summary of the systematic uncertainty contributions, presented as absolute values. The $\cos\theta$ range systematic uncertainty refers to the fitted range variation, the signal extraction to the choice of the description of the J/ψ, the unfolding systematic uncertainty is due to the choice of the number of iterations, the response matrix refers to the input distribution in generating the matrix, and the trigger systematic uncertainty is associated to the single muon p_T selection used for the trigger efficiency calculation.

J/ψ's as probe of the nucleus

ALICE 5.02 TeV, 0.23-0.53 nb^{-1} JHEP 10 (2023) 119

Systematic uncertainties

- Study of energy dependence

Source	Type	$\|y\| < 0.2$ 0n0n	$\|y\| < 0.2$ 0nXn+Xn0n	$\|y\| < 0.2$ XnXn	$0.2 < \|y\| < 0.8$ 0n0n	$0.2 < \|y\| < 0.8$ 0nXn+Xn0n	$0.2 < \|y\| < 0.8$ XnXn
Signal extraction	U	1.5	1.5	1.5	1.5	1.5	1.5
Incoherent fraction	U	0.1	1.5	1.3	0.1	1.5	1.3
Coherent shape	C	0.1	0.8	0.6	0.1	0.8	0.6
Feed-down	C	0.6	0.6	0.6	0.6	0.6	0.6
Branching ratio	C	0.5	0.5	0.5	0.5	0.5	0.5
Luminosity	C	2.5	2.5	2.5	2.5	2.5	2.5
Trigger live time	C	1.5	1.5	1.5	1.5	1.5	1.5
ITS-TPC matching	C	2.8	2.8	2.8	2.8	2.8	2.8
TOF trigger	C	0.7	0.7	0.7	0.7	0.7	0.7
SPD trigger	C	1	1	1	1	1	1
ϵ_{pu}	C	3	3	3	3	3	3
ϵ_{emd}	C	0	3.2	3.5	0	3.2	3.5
Migrations	A	−3.9	3.4	0.9	−3.6	3.1	1.1

Table 1. Summary of the systematic uncertainties, given in percent, related to the measurements performed with the central barrel detectors. The minus sign in the entry for migrations in the 0n0n class signifies that this uncertainty is anti-correlated with those from migrations in the 0nXn+Xn0n and XnXn classes. The second column identifies the type of uncertainty (U=uncorrelated, C=correlated, A=anticorrelated) as used in eq. (6.1).

Source	Type	$2.5 < \|y\| < 3.0$ 0n0n	$2.5 < \|y\| < 3.0$ Xn0n	$2.5 < \|y\| < 3.0$ XnXn	$3.0 < \|y\| < 3.5$ 0n0n	$3.0 < \|y\| < 3.5$ Xn0n	$3.0 < \|y\| < 3.5$ XnXn	$3.5 < \|y\| < 4.0$ 0n0n	$3.5 < \|y\| < 4.0$ Xn0n	$3.5 < \|y\| < 4.0$ XnXn
Signal extraction	U	0.2	1.3	0.8	0.1	0.6	0.7	0.5	0.5	0.9
Incoherent fraction	U	0.4	0.6	1.6	0.4	0.9	3.3	0.4	0.5	2.2
Coherent shape	C	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Feed-down	C	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Branching ratio	C	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Luminosity	C	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Tracking	C	3	3	3	3	3	3	3	3	3
Trigger	C	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
Matching	C	1	1	1	1	1	1	1	1	1
ϵ_{pu}	C	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
ϵ_{emd}	C	0	1.1	6	0	1.1	6	0	1.1	6
Migrations	A	−0.3	3.8	3.3	−0.2	3.6	3.6	−0.2	3.3	3.6

Table 2. Summary of the systematic uncertainties, given in percent, related to the measurements performed with the muon spectrometer. The minus sign in the entry for migrations in the 0n0n class signifies that this uncertainty is anti-correlated with those from migrations in the 0nXn+Xn0n and XnXn classes. The second column identifies the type of uncertainty (U=uncorrelated, C=correlated, A=anticorrelated) as used in eq. (6.1).

J/ψ‘s as probe of the nucleus

ALICE 5.02 TeV, 0.23 nb^{-1}
Phys. Rev. Lett. 132, 162302 (2024)

Systematic uncertainties for incoherent production

TABLE II. Summary of the identified systematic uncertainties to the cross section. The numbers in parentheses denote a range of values in the different $|t|$ intervals. Except for the first two uncertainties, all others are correlated in $|t|$.

Source	Uncertainty (%)
Signal extraction	(1.0,2.9)
Selection on $|z_{\mathrm{vtx}}|$	(0.0,2.9)
f_{C}	(0.0,0.4)
f_{D}	(0.2,6.5)
Integrated luminosity	2.9
Veto inefficiency due to pileup	3.0
Veto inefficiency due to dissociation	3.8
ITS-TPC tracking	2.8
Trigger efficiency	1.3
Branching ratio	0.6
Photon flux	2.0

A light to new physics?

CMS 5.02 TeV, 1.65 nb^{-1}
CMS-PAS-HIN-21-015

Light-by-light cross section determination: Background estimation and systematic uncertainties

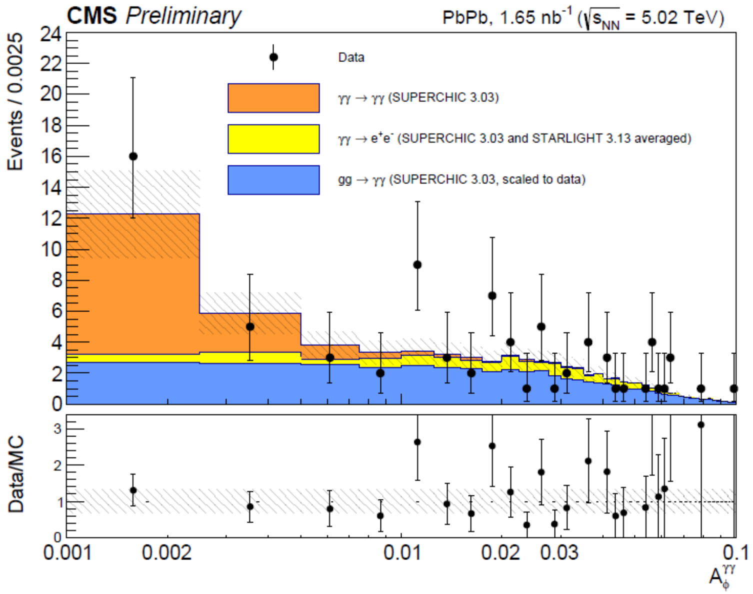


Figure 5: Diphoton acoplanarity distribution over $A_\phi^{\gamma\gamma}$ = 0–0.1 in events passing the fiducial criteria of Table 1 (except the $A_\phi^{\gamma\gamma} < 0.01$ one) measured in data (black dots) compared with the predictions for the LbL signal (orange histogram), the B–W process (yellow histogram), and the CEP (blue histogram, normalised to data as explained in the text) backgrounds. Error bars on the data points show statistical uncertainties, and dashed bands on the stacked histograms (and at unity in the data/MC ratio) represent systematic uncertainties.

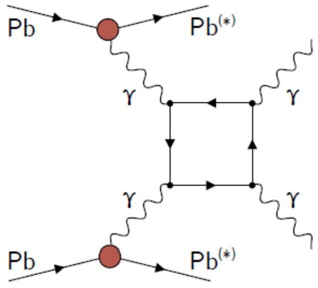
Table 7: Summary of relative systematic uncertainties in the measurement of the LbL scattering cross section.

Background normalisation	15%
Background shape	14%
Exclusive diphoton efficiencies	12.5%
Luminosity	1.5%
Total (statistical/nonstatistical)	24% (15%/19%)

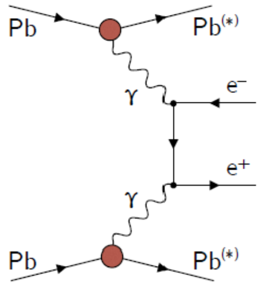
→ CEP MC scaled to data in region $A_\phi^{\gamma\gamma} > 0.015$

→ Extrapolated to signal region $A_\phi^{\gamma\gamma} > 0.01$

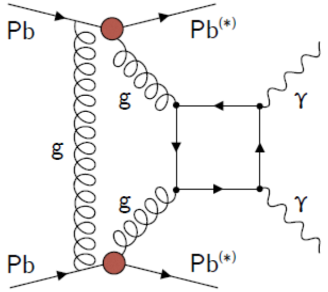
Signal process



Breit-Wheeler $\gamma\gamma \to e^+ e^-$



Central exclusive diphoton production (CEP) $gg \to \gamma\gamma$



A light to new physics?

ATLAS 5.02 TeV, 2.2 nb^{-1}
JHEP 03 (2021) 243

Light-by-light cross section determination: Background estimation and systematic uncertainties

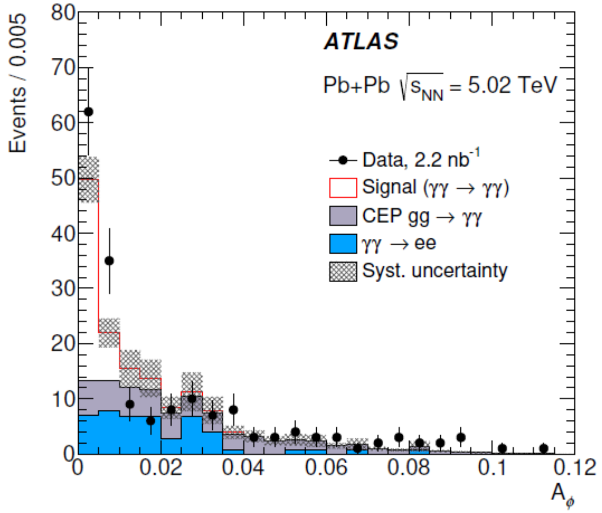


Figure 6. The diphoton acoplanarity distribution for events satisfying the signal region selection, but before applying the $A_\phi < 0.01$ requirement. Data are shown as points with statistical error bars, while the histograms represent the expected signal and background levels. The CEP $gg \to \gamma\gamma$ background is normalised in the $A_\phi > 0.01$ control region. The signal prediction is normalised to the same integrated luminosity as the data. The shaded band represents the uncertainties in signal and background predictions, excluding the uncertainty in the luminosity.

$$\sigma_{\text{fid}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C \times \int L dt}$$

Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%

Table 1. The detector correction factor, C, and its uncertainties for the integrated fiducial cross-section measurement. The second row lists the numerical value of C together with the total uncertainty. The total uncertainty on C is a quadratic sum of systematic and statistical components.

→ Uncertainty in background estimation gives 6% uncertainty in integrated fiducial cross section

γγ→μμ with non-UPC configuration

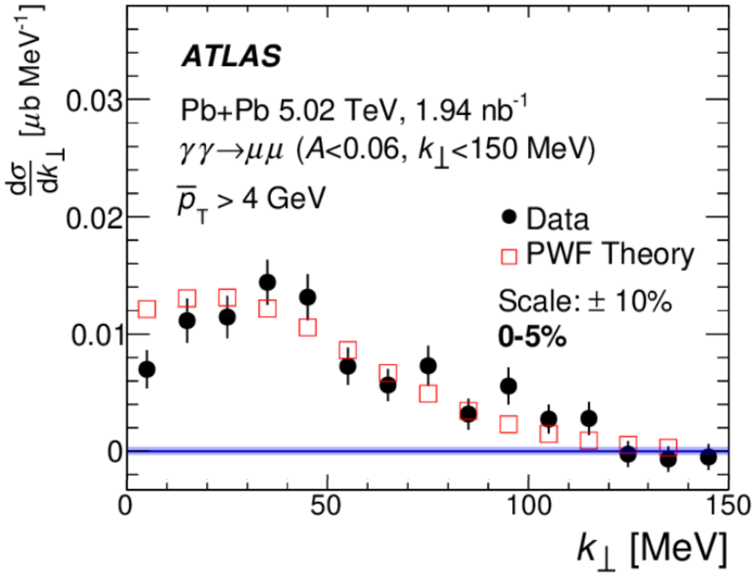
ATLAS 5.02 TeV, 1.94 nb^{-1}
Phys. Rev. C 107 (2023) 054907

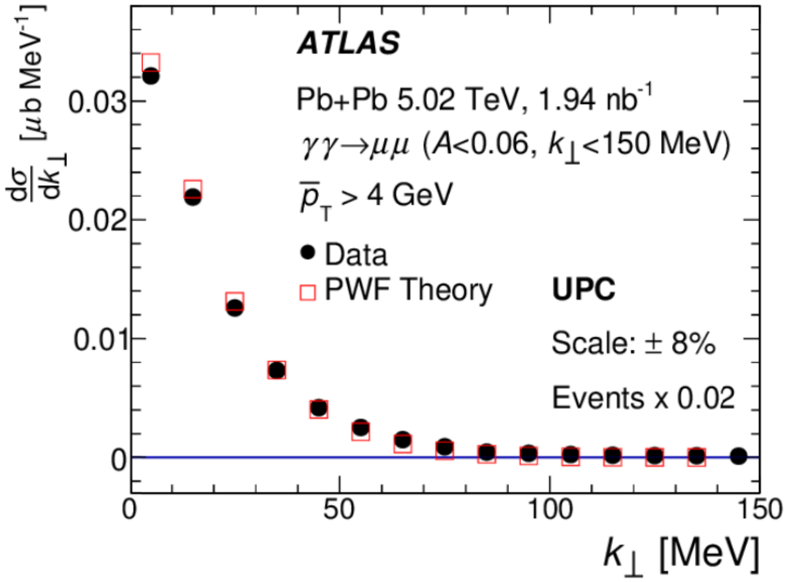
Muon pairs as electromagnetic probes of the quark-gluon plasma

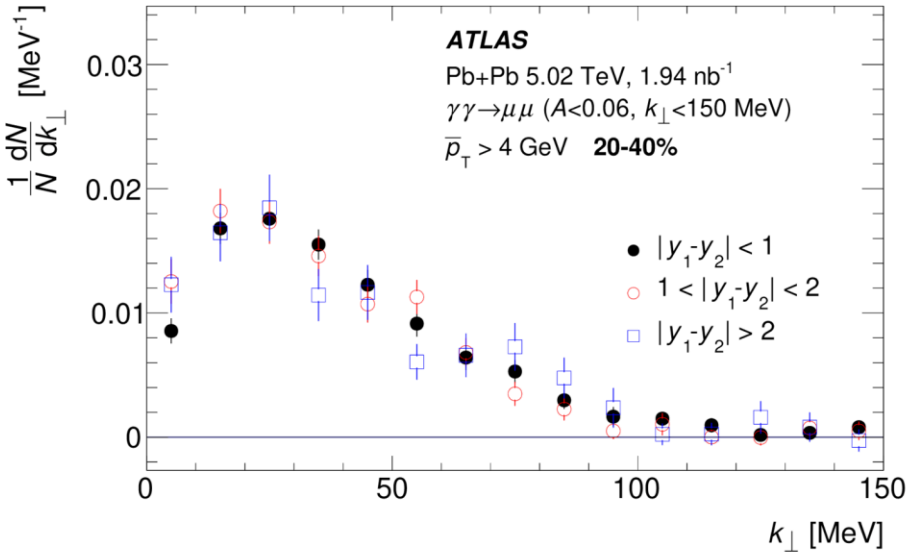
- Consider transverse momentum scale: $k_\perp = 1/2(p_{T1}+p_{T2})(\pi - |\phi_1 - \phi_2|)$
  - $k_\perp \approx 0$, if leptons are back-to-back in ϕ
  - $k_\perp \approx$ factor*average p_T, where factor is larger if leptons are more aligned in ϕ

→ Dependence on collision centrality

→ Influence of magnetic field effects?







→ More central collisions have on average broader $k_\perp$-distribution, but not an effect from magnetic fields