Overview of latest UPC results from CMS (& first glimpse in Run 3)

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on behalf of the CMS Collaboration

Contact:
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UPC 2023: International workshop on the physics of Ultra Peripheral Collisions

THE UNIVERSITY OF KANSAS

U.S. DEPARTMENT OF ENERGY
Office of Science

Outline of UPC Run 2 results

- **Gluon saturation and initial-state effects**
  - **Coherent J/ψ cross session in UPC PbPb, HIN-22-002**
    - comprehensive study vs $W_{\gamma N}$, also in forward neutron multiplicities (A_nA_n)
  - **Azimuthal correlations of exclusive dijets with large Q_T in pPb, HIN-18-011**
    - nontrivial parton distributions inside Pb or simply from ISR/FSR?

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  - **Observation of A_nA_n-dependence of dimuon acoplanarity in UPC PbPb, HIN-19-014**

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  - **Two-particle azimuthal correlations in γp interactions using pPb, HIN-18-008**
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- **QED precision and BSM searches**
  - **Observation of τ lepton pair production in UPC PbPb, HIN-21-009 (editors' suggestion)**
    - pursuing better constraints on τ lepton anomalous magnetic moment than LEP(II)
  - **Evidence for γγ→γγ and searches for axion-like particles in UPC PbPb, FSQ-16-012**
    - first ATLAS+CMS combination (HonexComb group)

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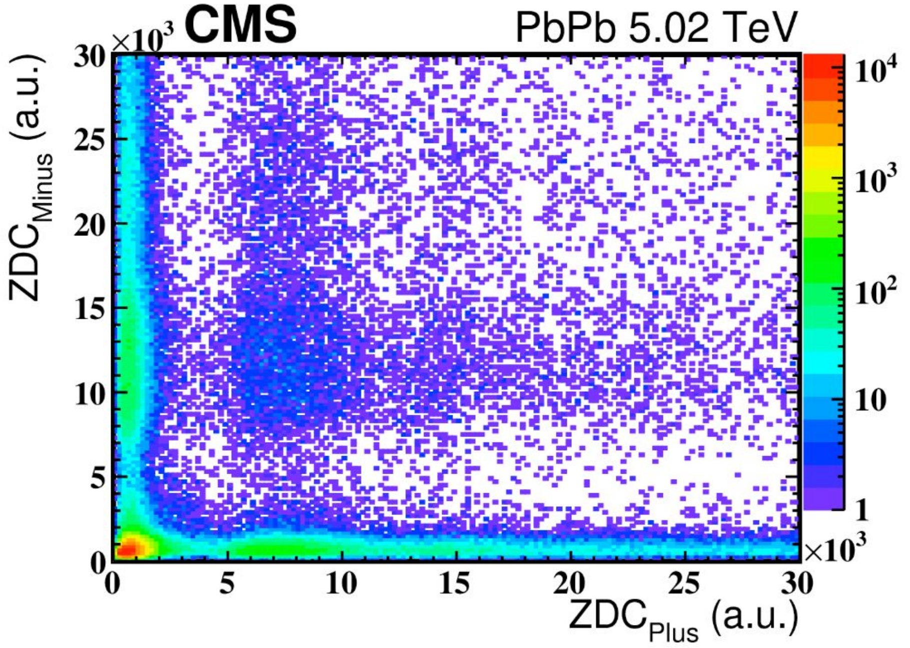
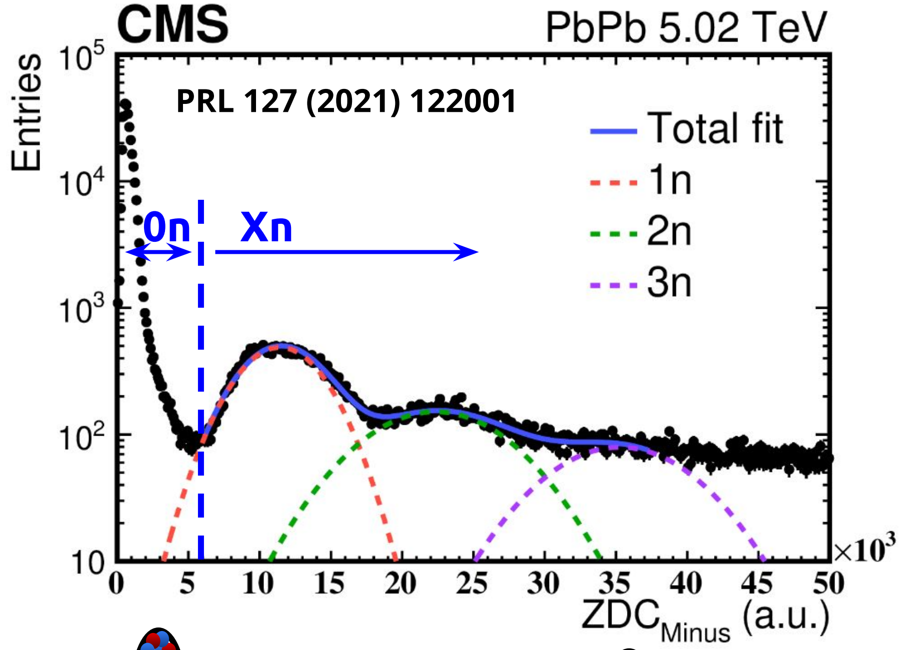
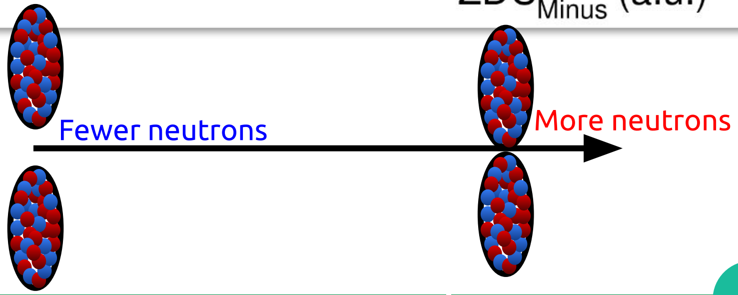
All results published as letters (*) nonexhaustive list (e.g., rapidity gaps, etc)

Event classification in neutron multiplicity classes





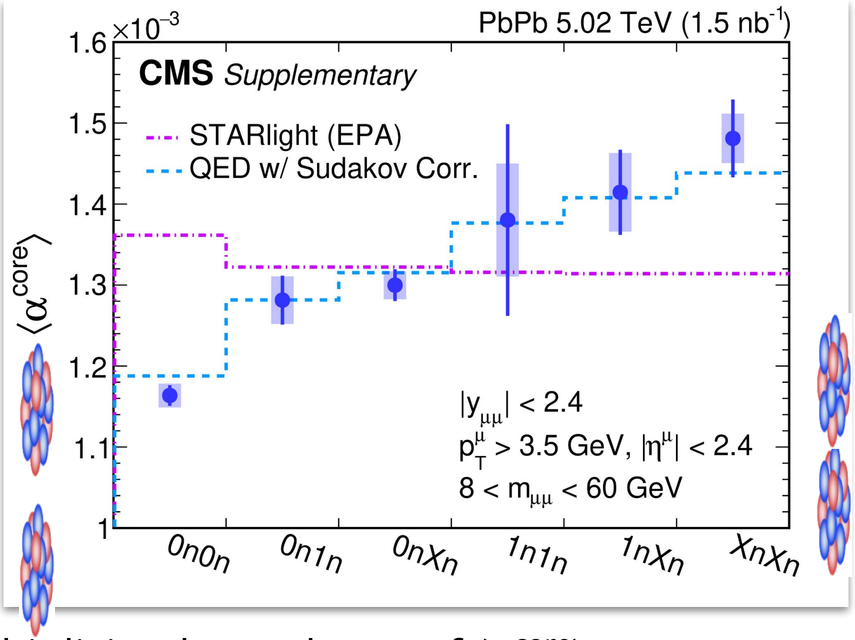
- Multi-Gaussian fits to disentangle # of neutrons:
  - 0n0n, 0nXn, XnXn (X: ≥1)
  - high purity



Method established in HIN-19-014

$\langle\alpha^{core}\rangle$ vs. neutron multiplicity class

HIN-19-014

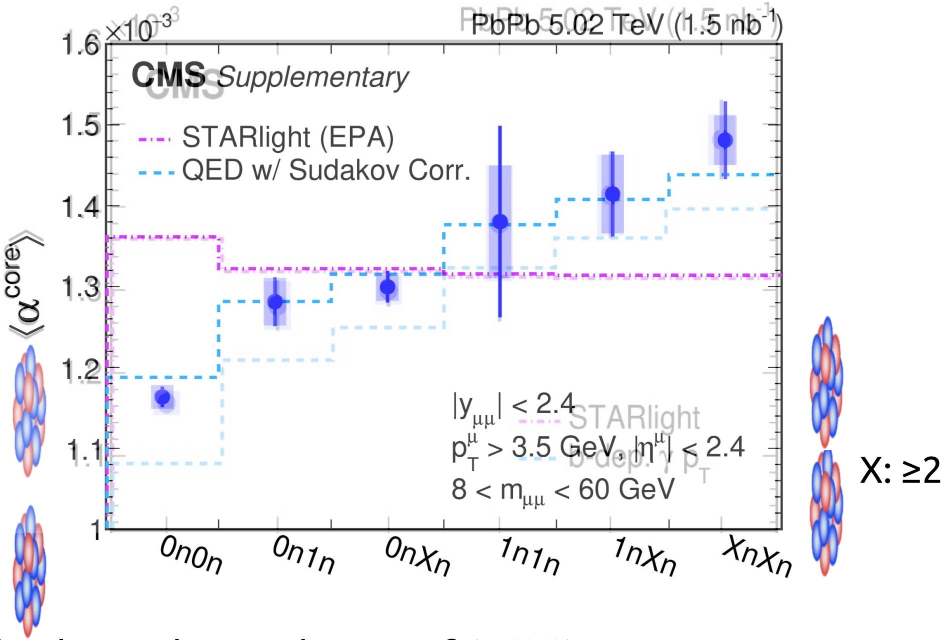


X: ≥2

Strong (5.7 σ) neutron multiplicity dependence of $\langle\alpha^{core}\rangle$

- b dependence of initial photon p_T, not captured by STARLight (recent dev in SuperChic)
- Best described by a QED calculation **with Sudakov effect**

HIN-19-014



Strong (5.7 σ) neutron multiplicity dependence of ⟨α^{core}⟩

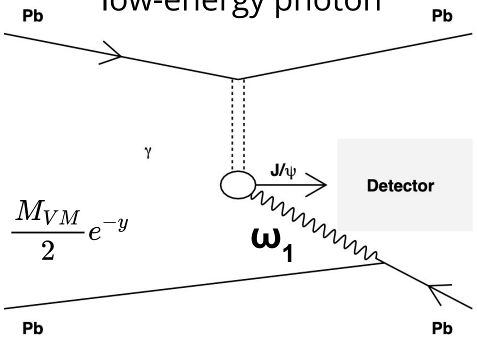
- b dependence of initial photon p_T, not captured by STARLight (recent dev in SuperChic)
- same QED calculation **w/o Sudakov effect → high-precision data**

Search for gluon saturation in heavy nuclei–the challenge

Symmetric system: either ion can serve as the photon source or target nucleus

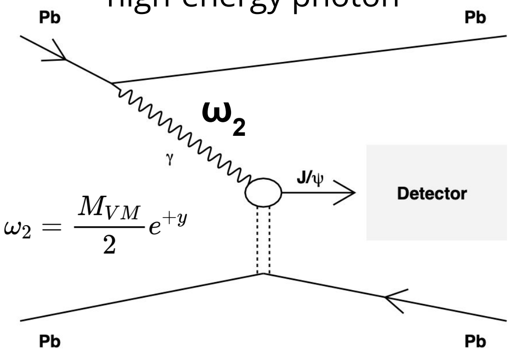
- A two-way ambiguity!

low-energy photon



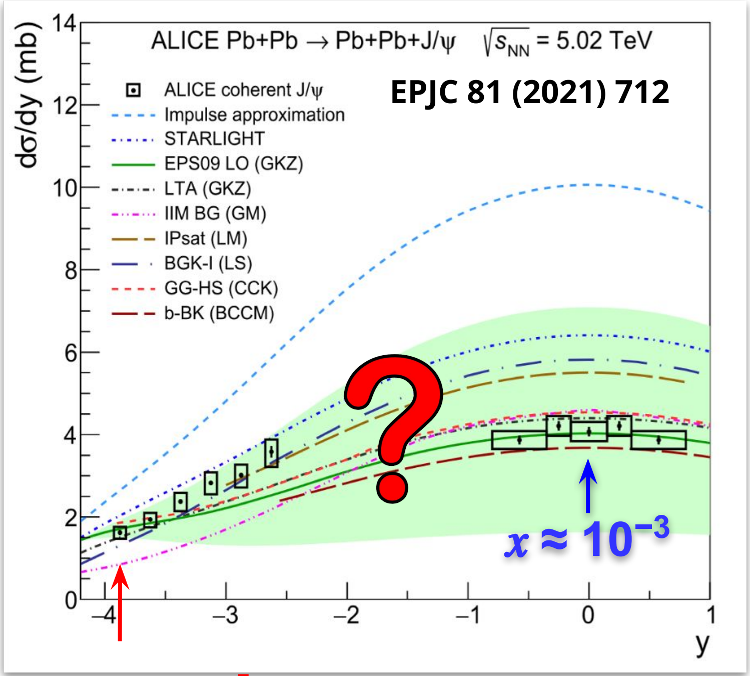
$$\omega_1 = \frac{M_{VM}}{2} e^{-y}$$

high-energy photon



$$\omega_2 = \frac{M_{VM}}{2} e^{+y}$$

$$\frac{d\sigma_{AA \to AA' J/\psi}}{dy} = N_{\gamma/A}(\omega_1) \cdot \sigma_{\gamma A \to J/\psi A'(\omega_1)} + N_{\gamma/A}(w_2) \cdot \sigma_{\gamma A \to J/\psi A'(w_2)}$$



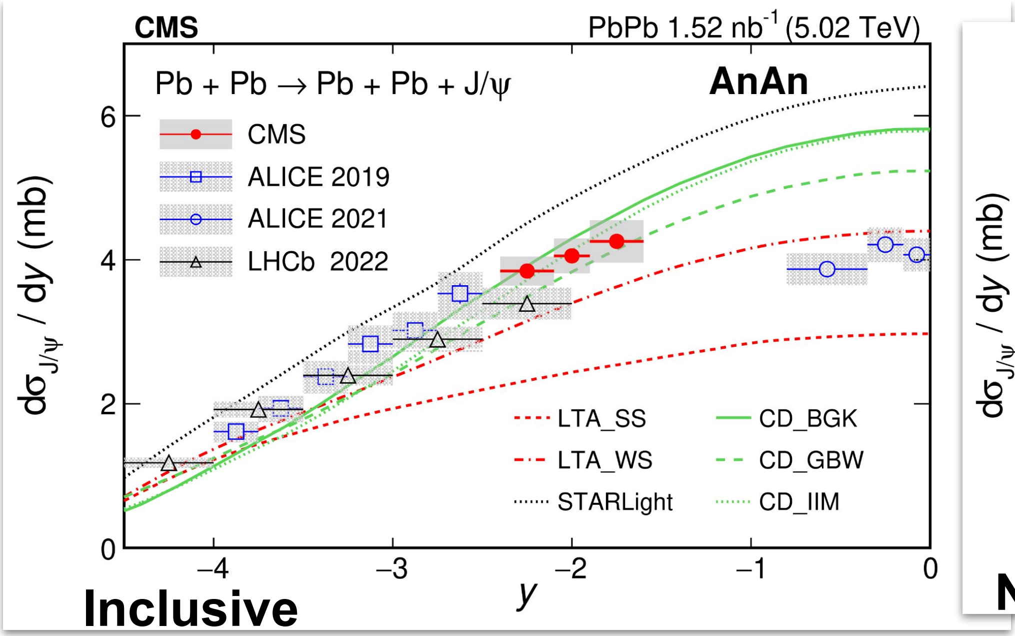
The cross section at a given *y* consists of low- and high-*x* gluon contributions (except for y=0)

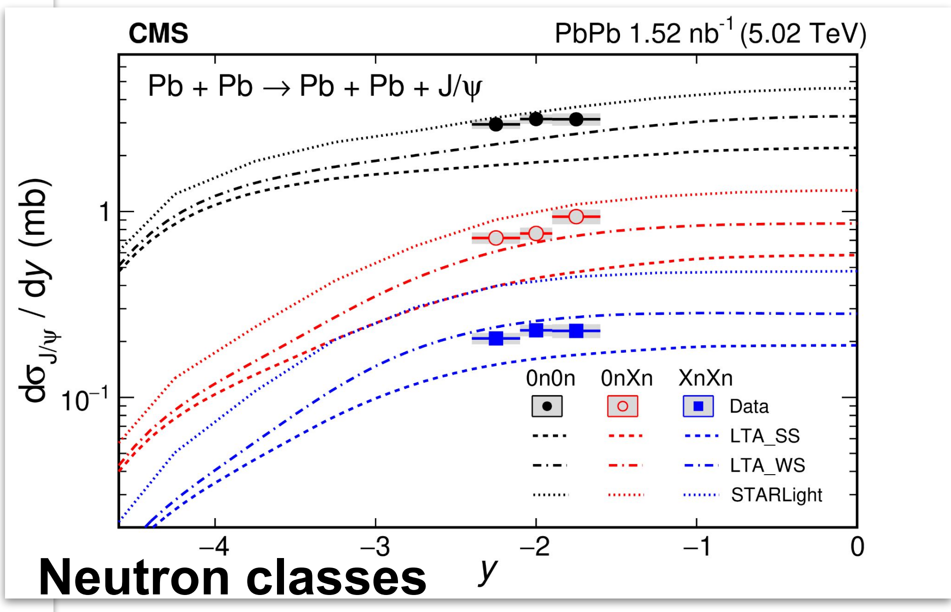
- **No unambiguous access to x ~ 10^{-5}**

$x_1 \approx 10^{-5}$
or $x_2 \approx 10^{-2}$
(~95% high-x)

$$x_{1,2} = \frac{1}{\omega_{1,2}} \cdot \frac{M_{VM}^2}{2\sqrt{s_{\rm NN}}}$$

Search for gluon saturation in heavy nuclei–the answer?





HIN-22-002

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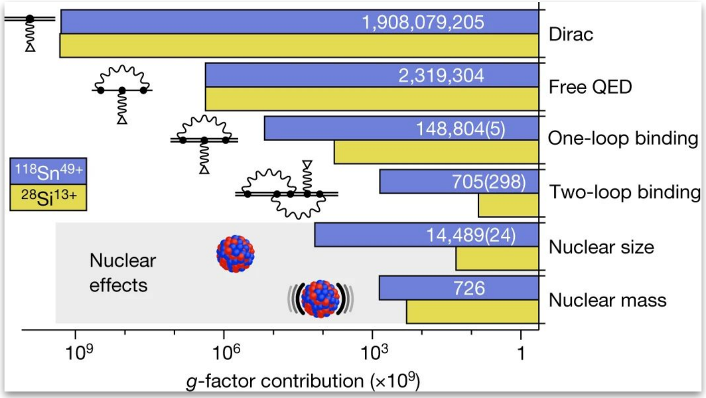
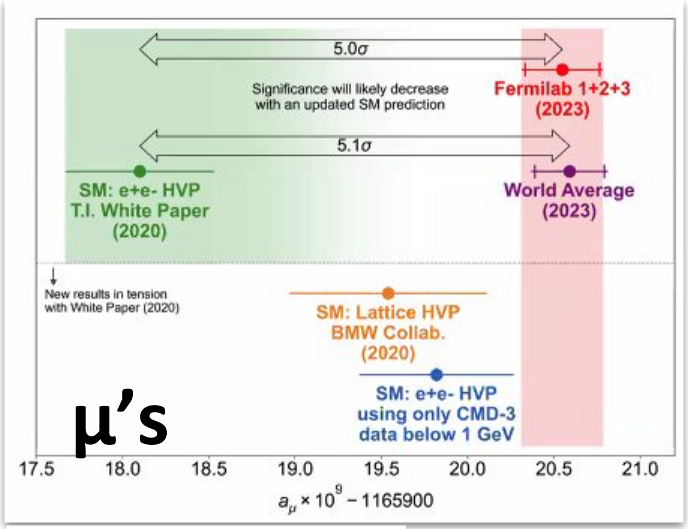
See Luis's talk

The anomalous anomaly for e's & μ's

bound e's



Nature **622** (2023) 53



PRL **26** (2021) 141801, 2308.06230

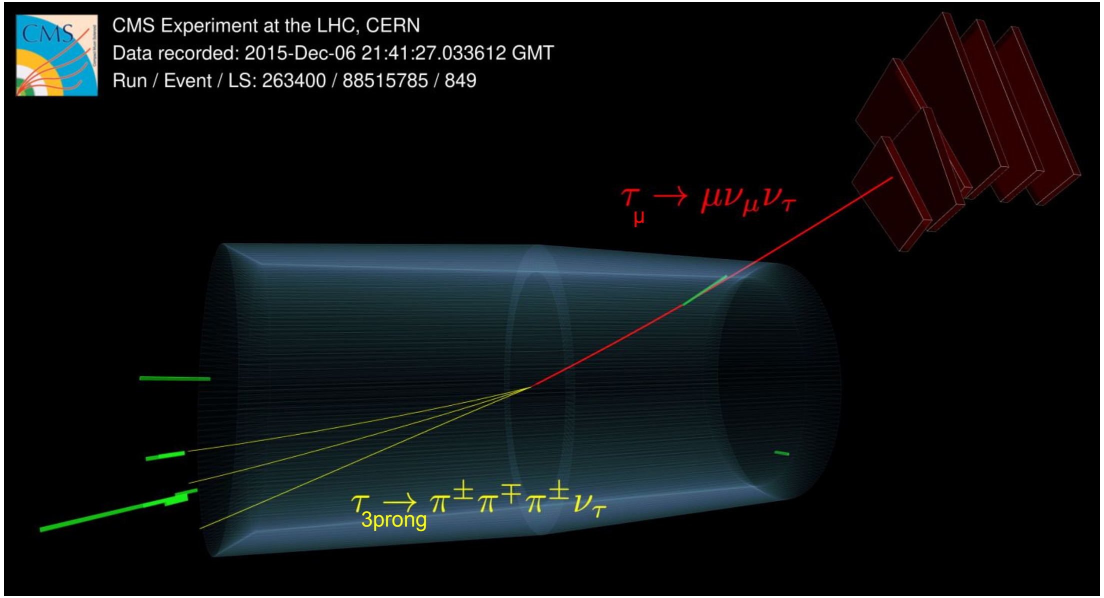
- ALPHATRAP tested **high-field QED** in hydrogen-like heavy nuclei
- FNAL g-2 **reconfirmed** previous discrepancy
  - the exact level depends on theory considerations

Maybe their heavier cousin is more sensitive to new physics?

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**

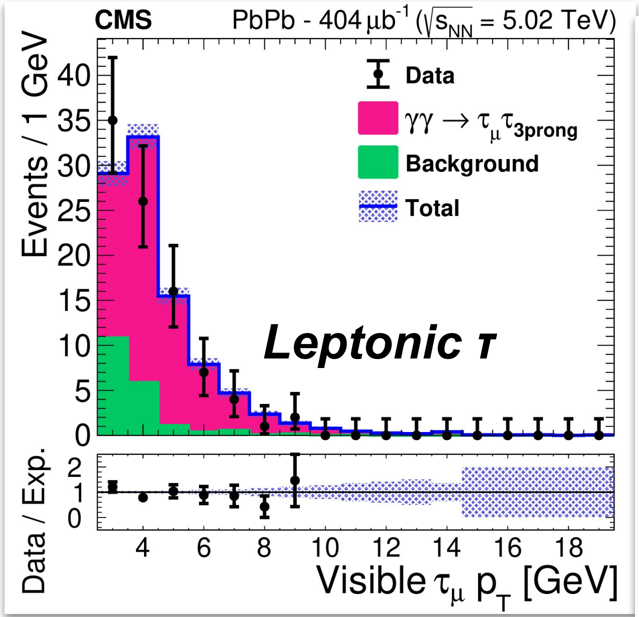


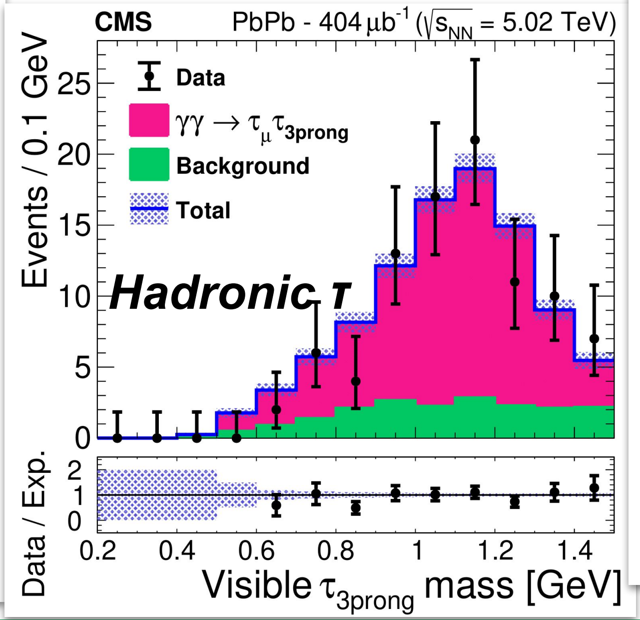
Data-to-exp comparison: control plots in the signal region

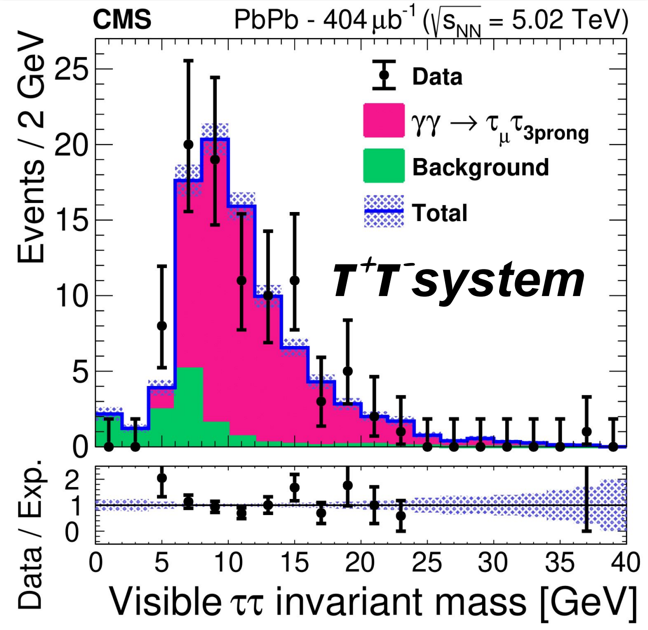
- Very good **agreement** between data & expectations
  - signal MC (aMC@NLO) is scaled to the **integrated luminosity**
  - we're in an almost **bkg-free** phase space region(!)
  - **unambiguous reconstruction** of the $\tau^+\tau^-$ system

HIN-21-009

See [Matthew's talk]



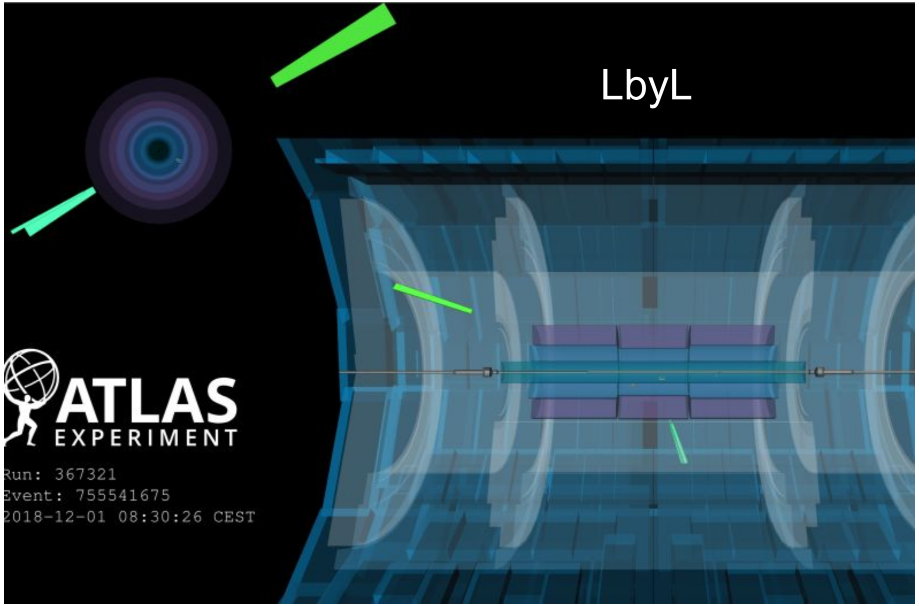


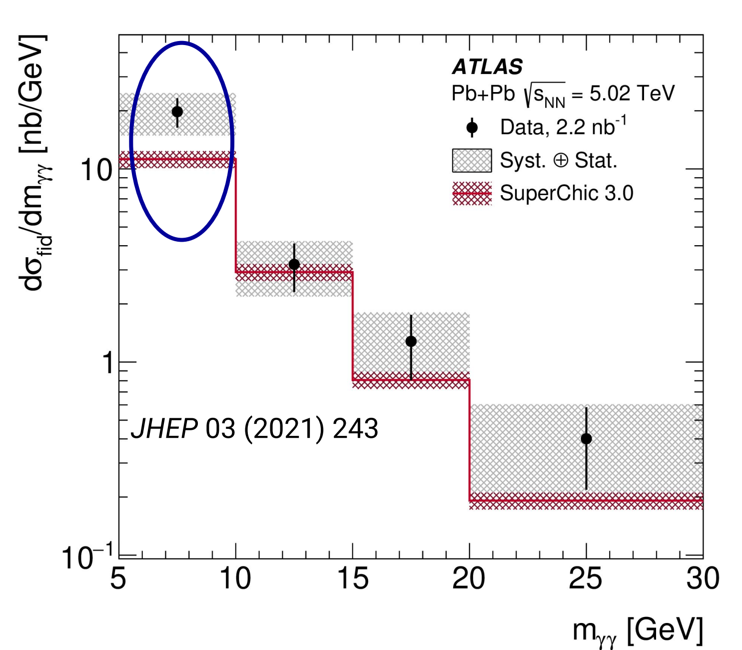


Available LbyL UPC measurements (so far)

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

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

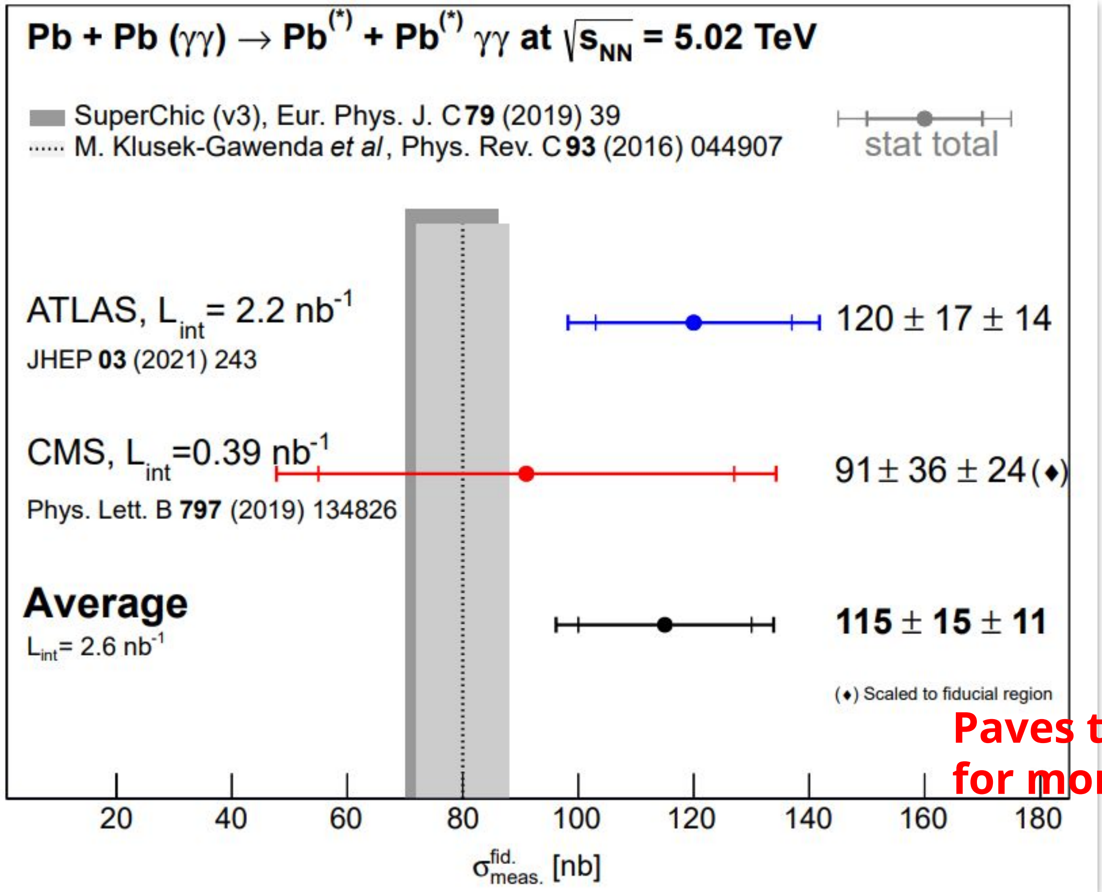




Averaged result and **comparison to theory**

GKK *et al* arXiv:2204.02845 (presented in QM22)

- The data-to-theory discrepancy is at **~2σ level**

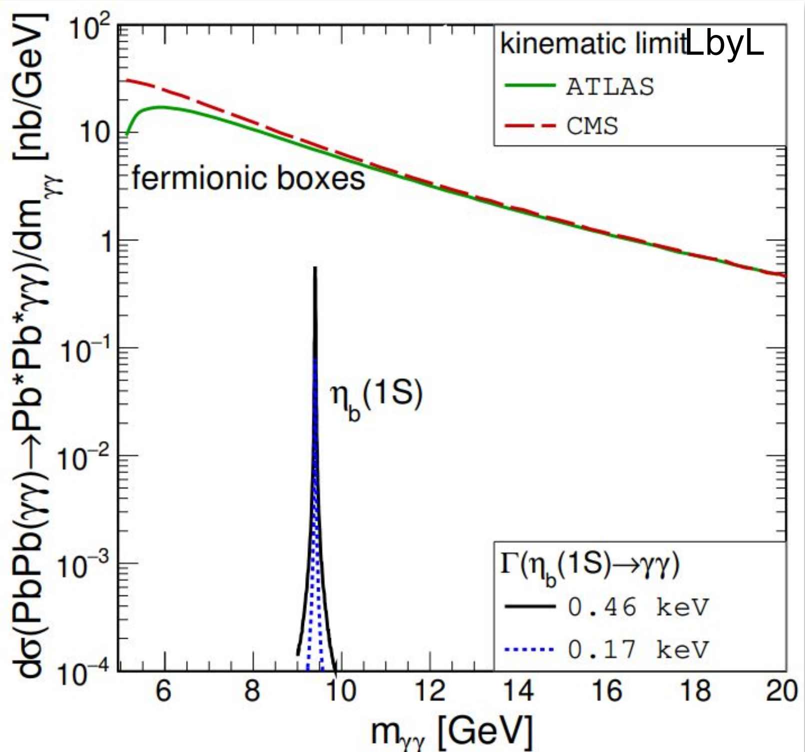


Paves the way for more combinations!

Trying to explain **the excess**

GKK *et al* arXiv:2204.02845 (presented in QM22)

- We calculated the inclusive σ for the **photoproduction of $\eta_b(1S)$**
  - $\sigma = (0.19-1.41)\ 10^{-2}$ nb (range reflects max. and min. of γγ decay rates)
- this contribution **isn't significant**
- alternative efforts exist, e.g., γγ decay of the recently discovered X(6900) exotic meson



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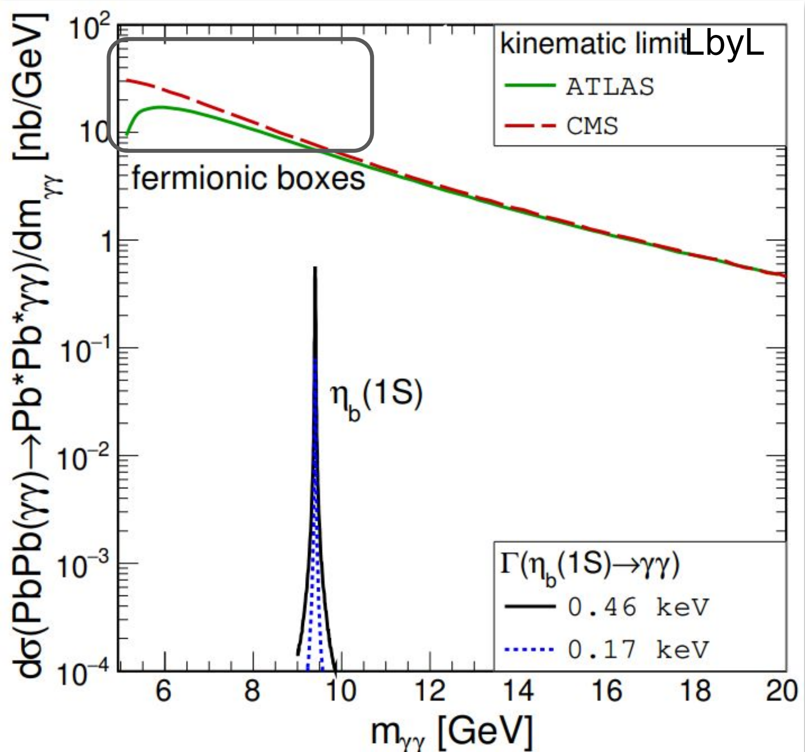
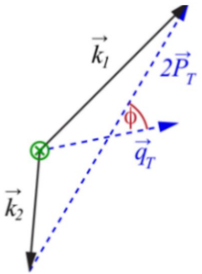


Exclusive dijets with large momentum transfer in γPb collisions

- Good agreement between data and MC.
  - Photon flux in RAPGAP correctly reproduces UPC γPb data
- The measurement is performed in $Q_T < 25$ GeV
  - large momentum transfer but "back-to-back" regime, i.e., $P_T > Q_T$



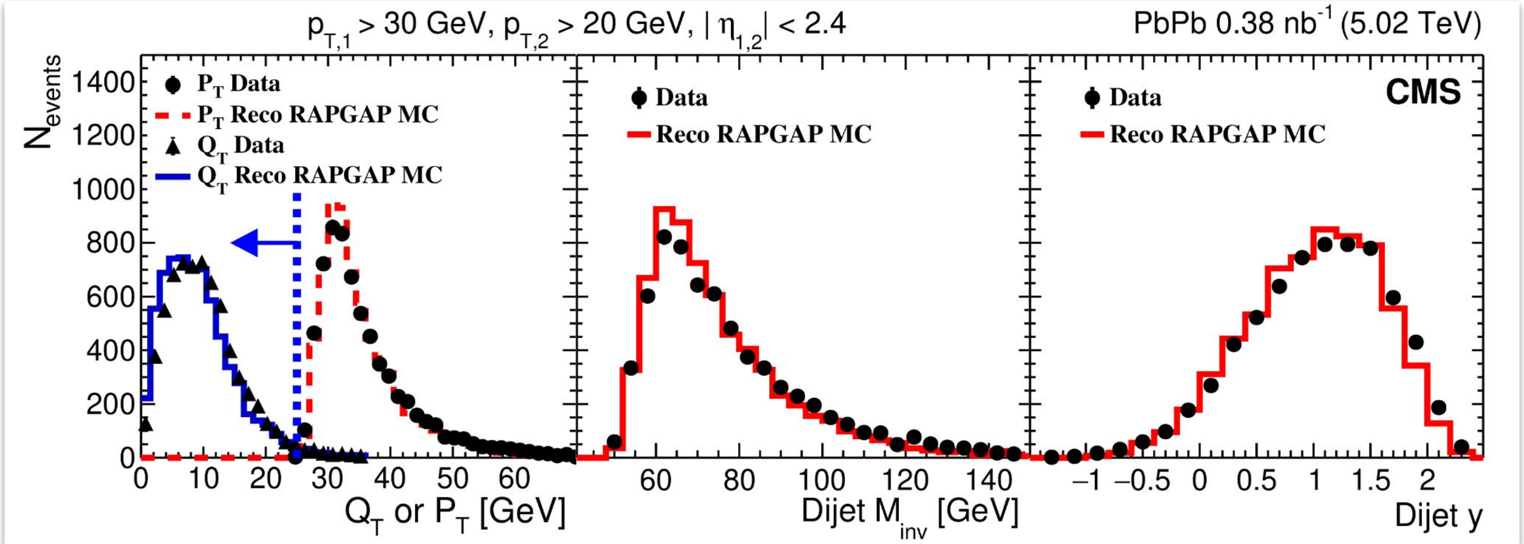
Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k}_1 + \vec{k}_2$$

Vector difference of 2 jets

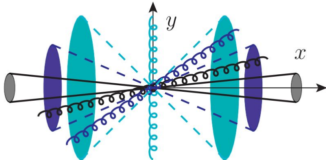
$$\vec{P}_T = \frac{1}{2}(\vec{k}_1 - \vec{k}_2)$$

HIN-18-011



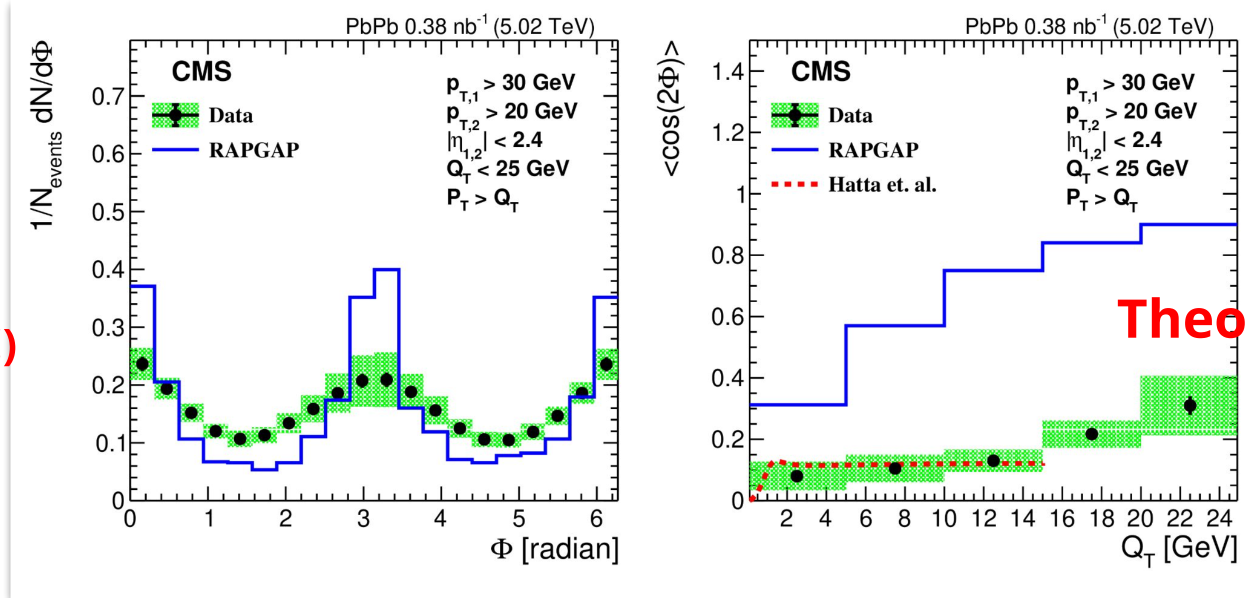
Angular correlations in exclusive dijets

- $\Phi \equiv$ correlation between $\mathbf{P_T}$ and $\mathbf{Q_T}$
- Similar trend between data and RAPGAP, with prediction slightly above (below) the data
- <cos(2Φ)> reaches a constant value ~0.4 at $Q_T > 5$ GeV
  - prediction including final-state interactions better describes data
  - recent finding: **initial** soft gluon emissions also gives sizeable <cos(2Φ)>



2106.05307

HIN-18-011
(unfolded data!)

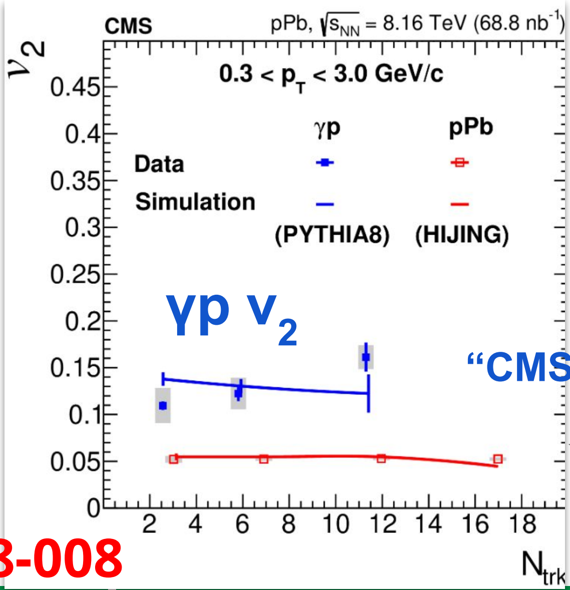


Theo dev needed

Collectivity in γp vs γPb collisions

- v_2 in γp > than min-bias events
  - no "non-flow" subtraction: challenging in low N_{trk}
  - PYTHIA8 describes v_2 → jet-like correlations dominate(?)
- v_2 in γPb < than pPb and pp at similar multiplicity
  - Done with "non-flow" subtraction

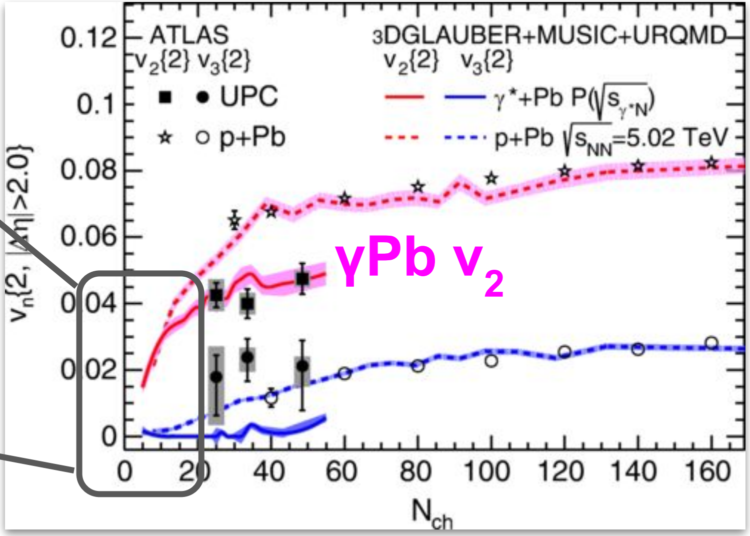
Interesting to bridge the two systems



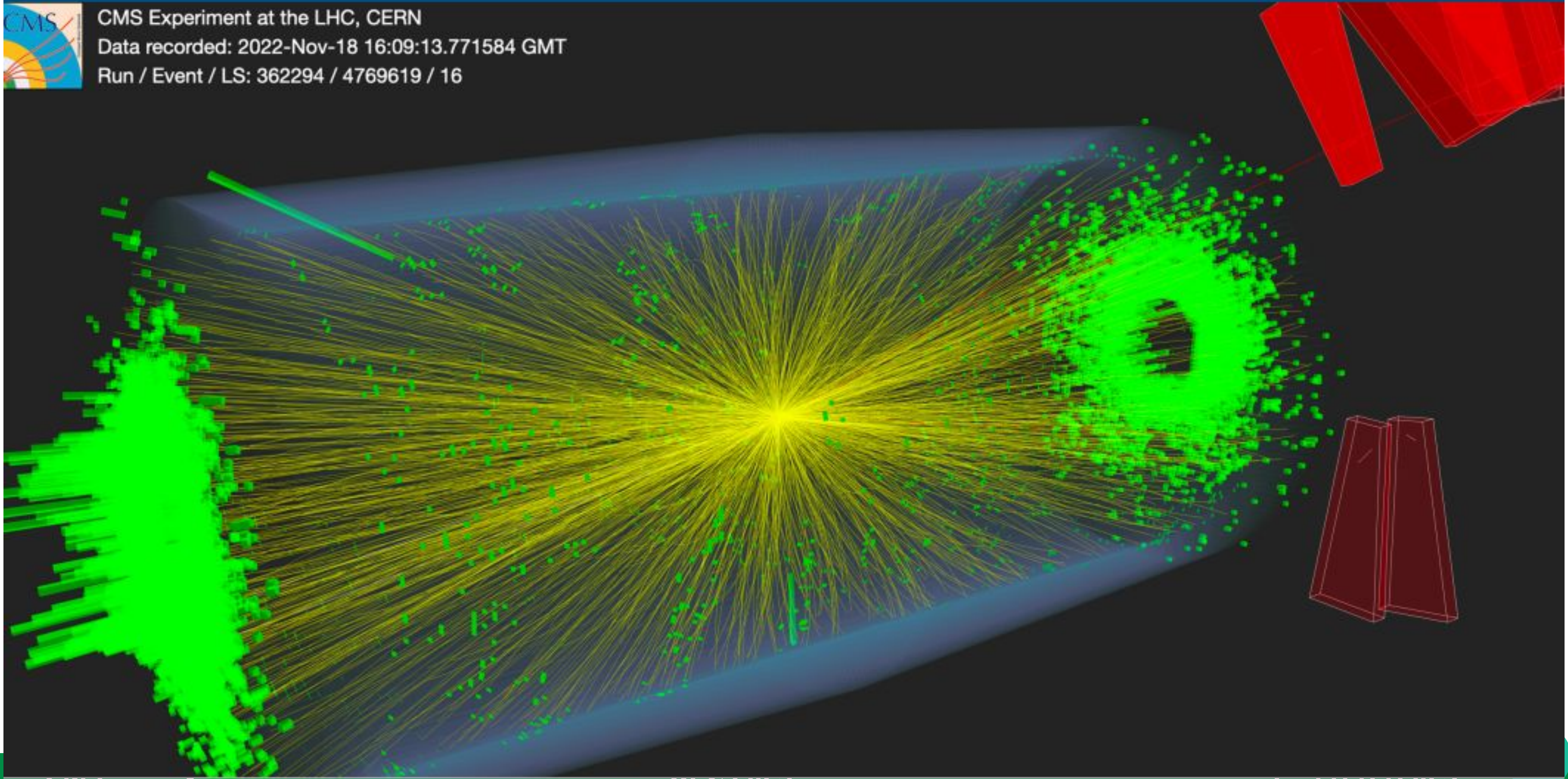
HIN-18-008

"CMS region"

Zhao *et al* 2203.06094



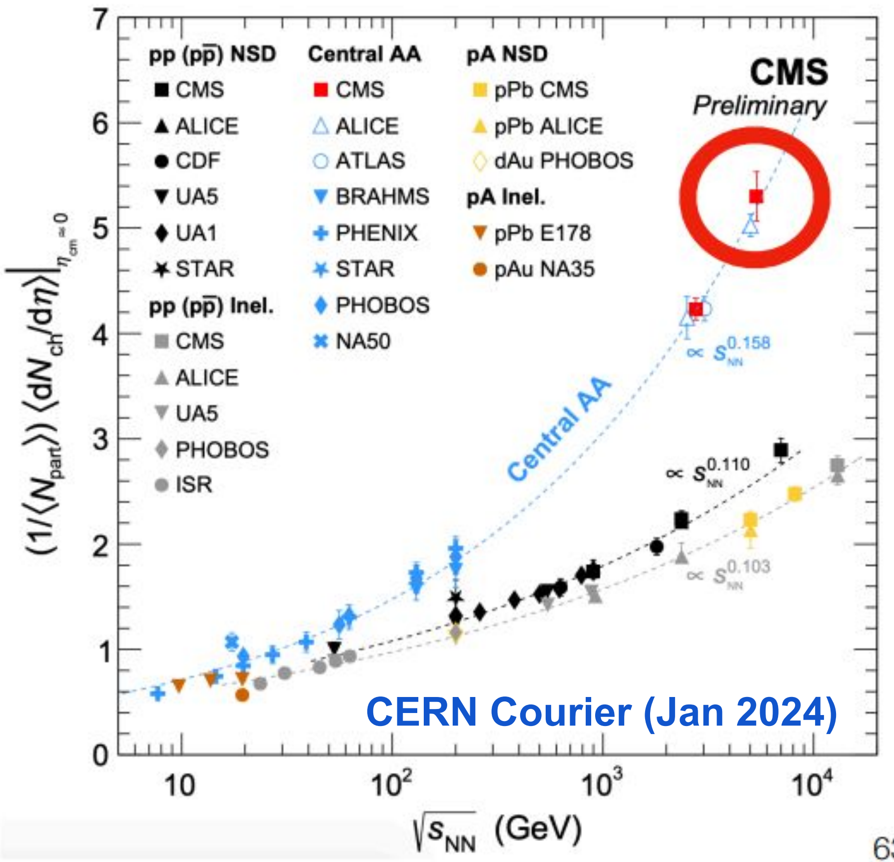
5.36 TeV PbPb Collisions!



First CMS Run 3 result - $dN_{ch}/d\eta$

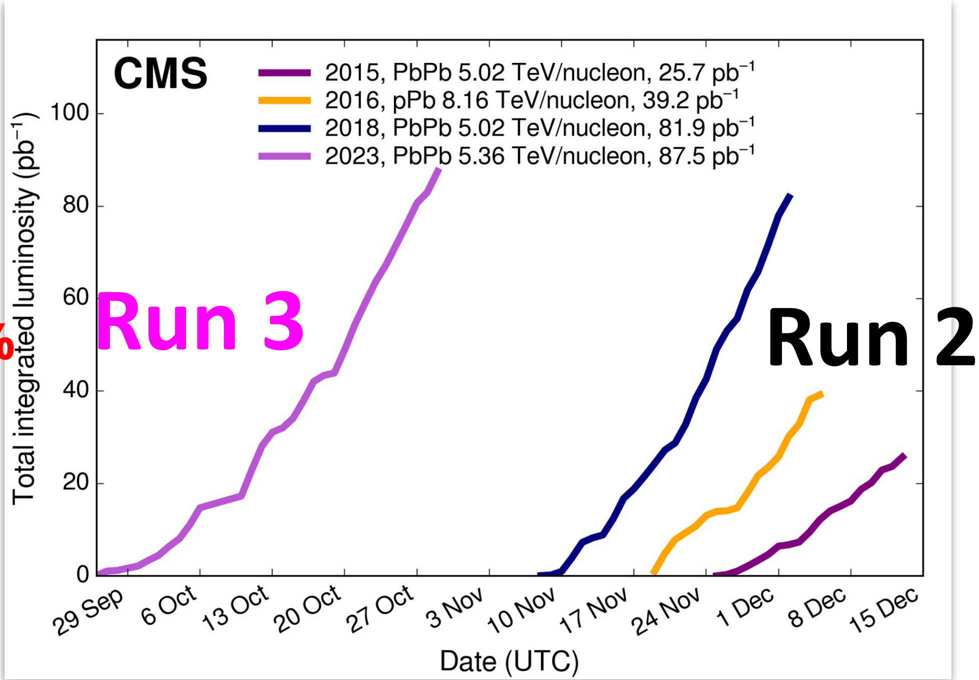
- **5.36 TeV data from 2022 test run**
- **Challenging for MC generators to predict both magnitude and shape of $dN_{ch}/d\eta$**
- **$\sqrt{s_{NN}}$ dependence consistent with power law calculated using lower energies**

PAS-HIN-23-007



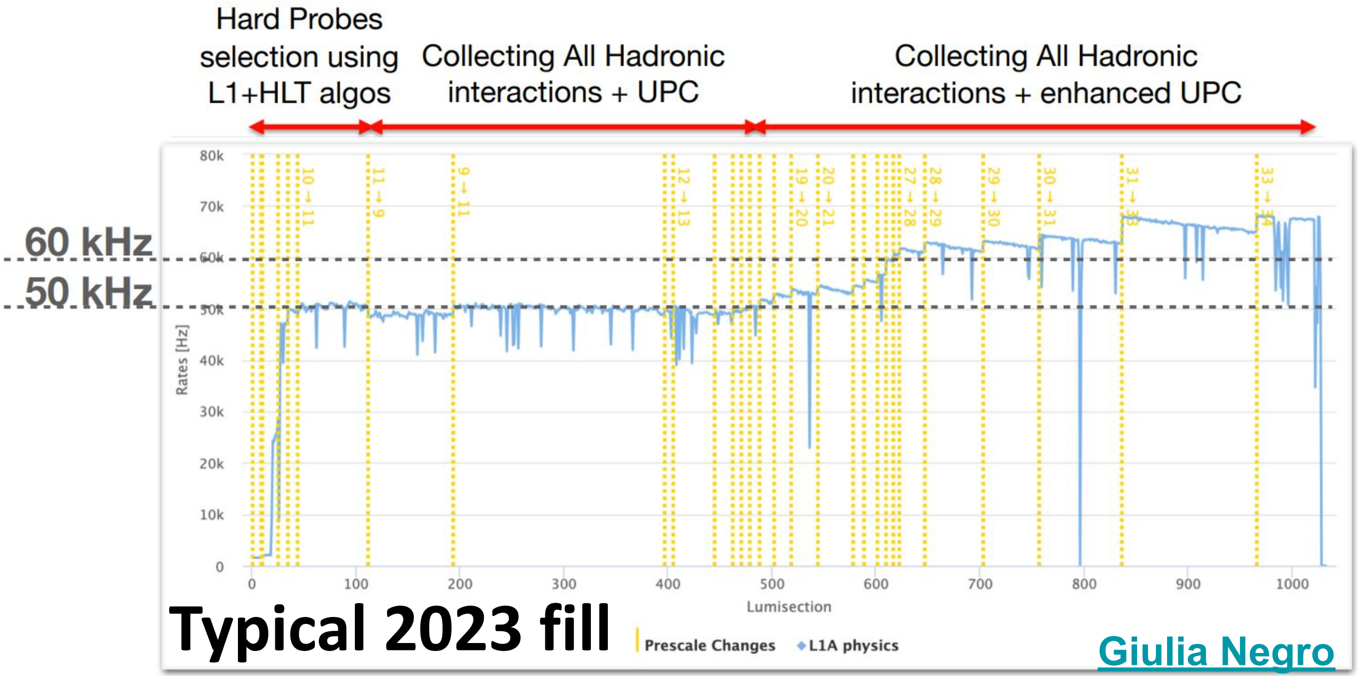
Grand summary so far..

CMS recorded >90%



- Despite decreased LHC availability, PbPb lumi in Run 3 already ~ Run 2
- Relied on many new concepts → lessons learned (see Roderik's talk at 156th LHCC)
  → ***Ongoing studies to improve understanding and define mitigation measures***

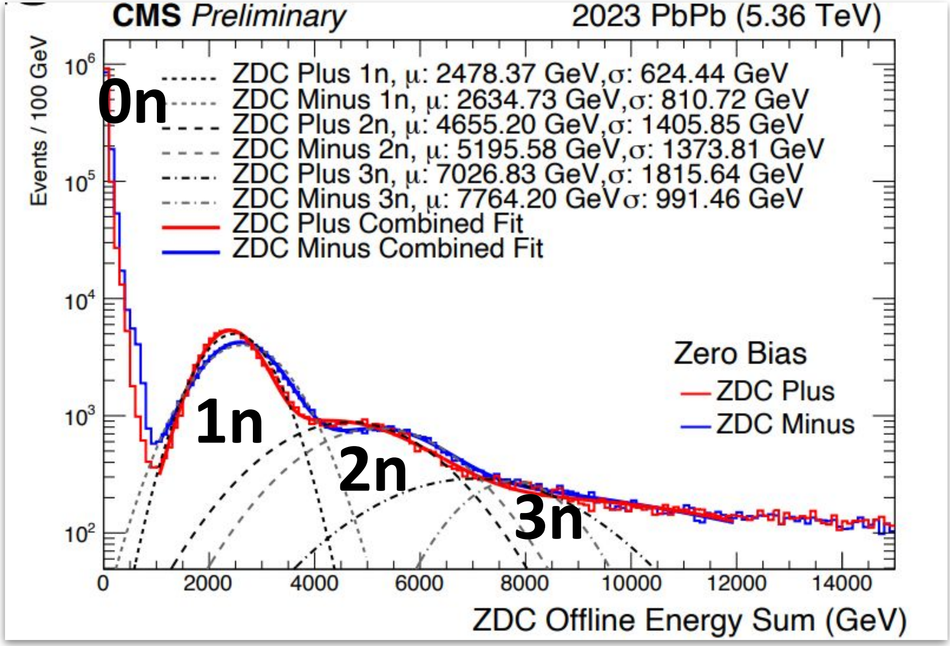
Heavy ion data-taking strategy in 2023



- **Record** L1 rate > 50 kHz (vs 35 kHz in 2018) with less than 8% deadtime
  - up to 50 kHz at the beginning of the fill (**large amount of MB**)
  - > 60 kHz at the end of the fill recording **increased amount of UPC**
  - other physics triggers too (high-p_T jets, leptons, etc)

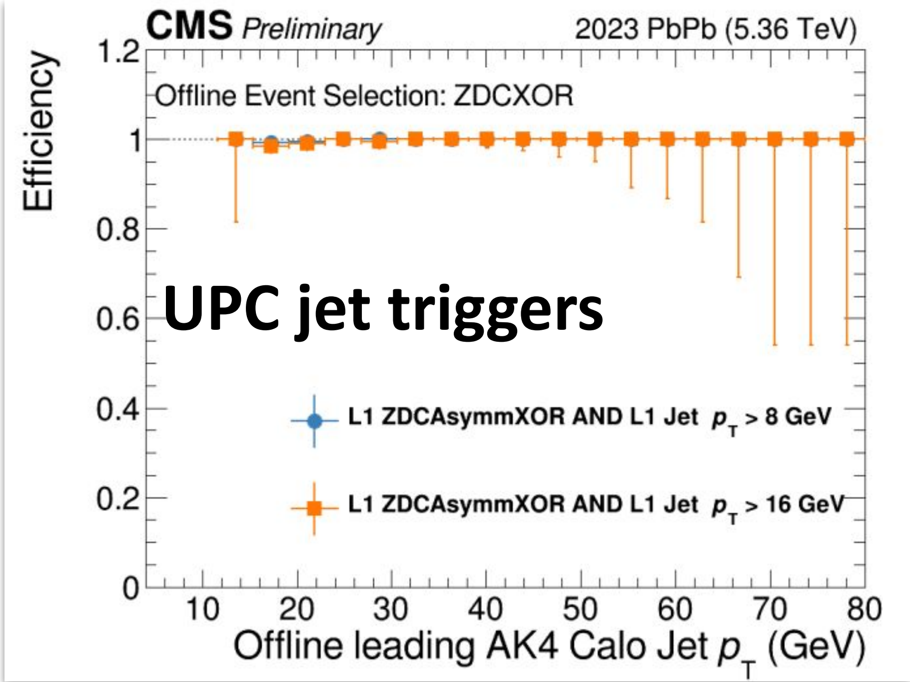
ZDC Offline Energy Sums

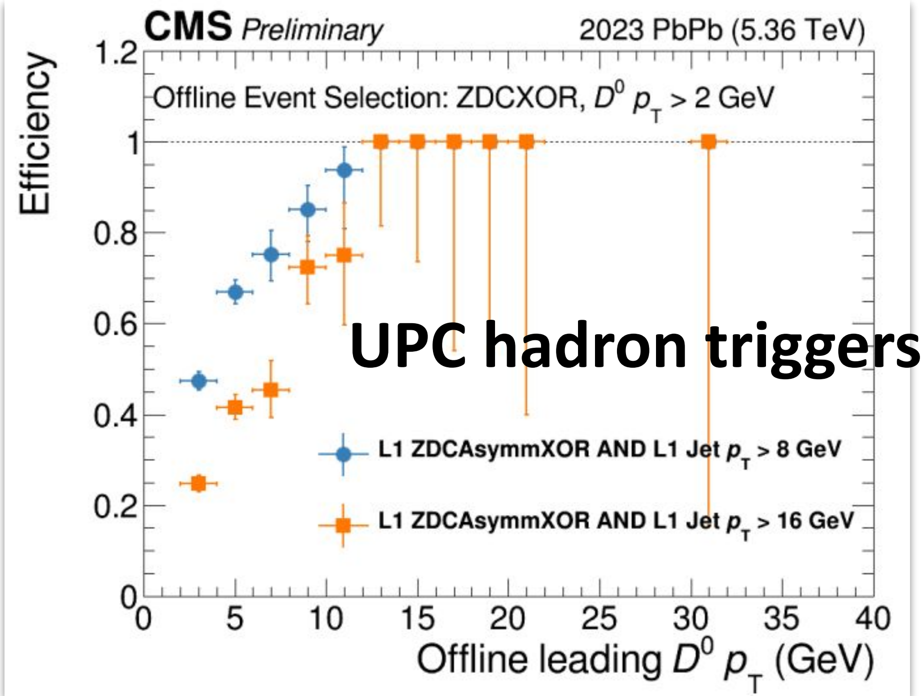
DP-2023-X



- **Excellent** ZDC performance
  - neutron peaks are clearly seen
  - ZDC+ has slightly better resolution
  - ZDC included as **part of the trigger** for the first time

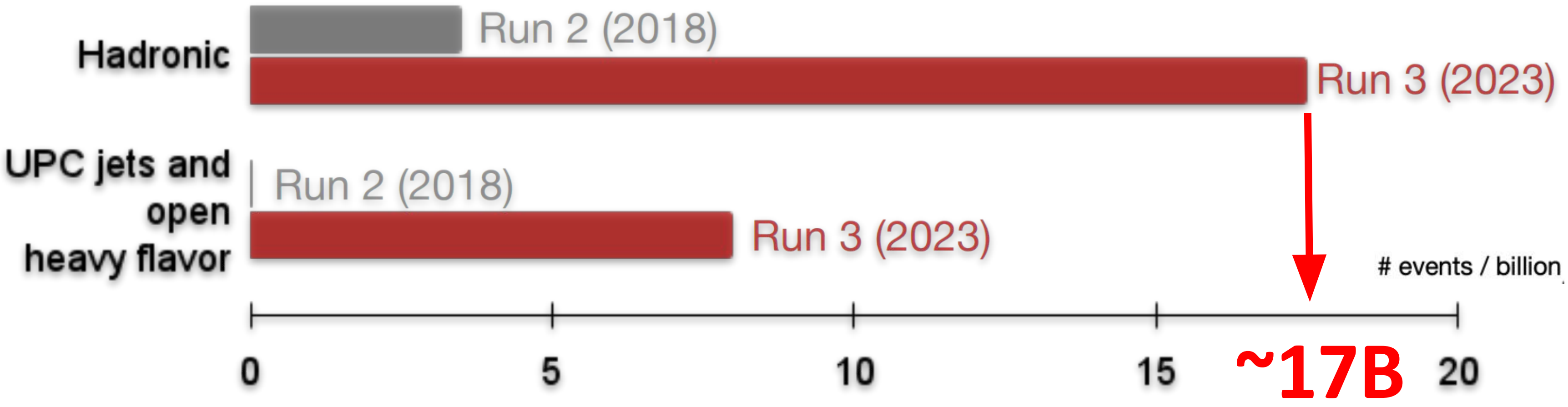
New jet and hadron triggers for photo-nuclear events DP-2023-X





- **UPC jet and heavy flavor** data sample
  - jet pT > 16 GeV was run **unprescaled** over the entire data-taking period
  - access of HF hadrons down to p_T **of 2.5 GeV**

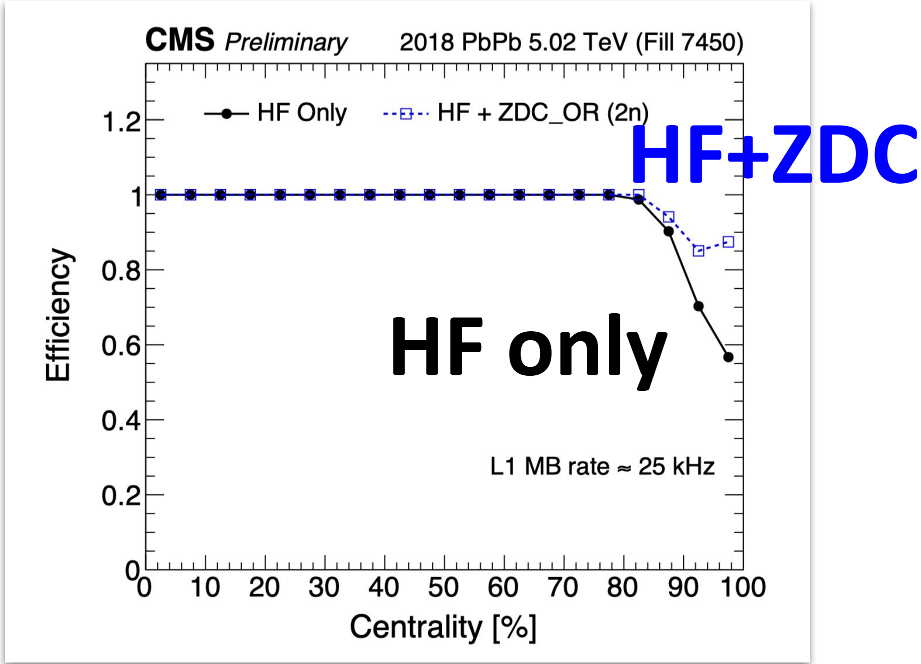
Similar lumi, but huge improvements in Run 3 PbPb DP-2023-X

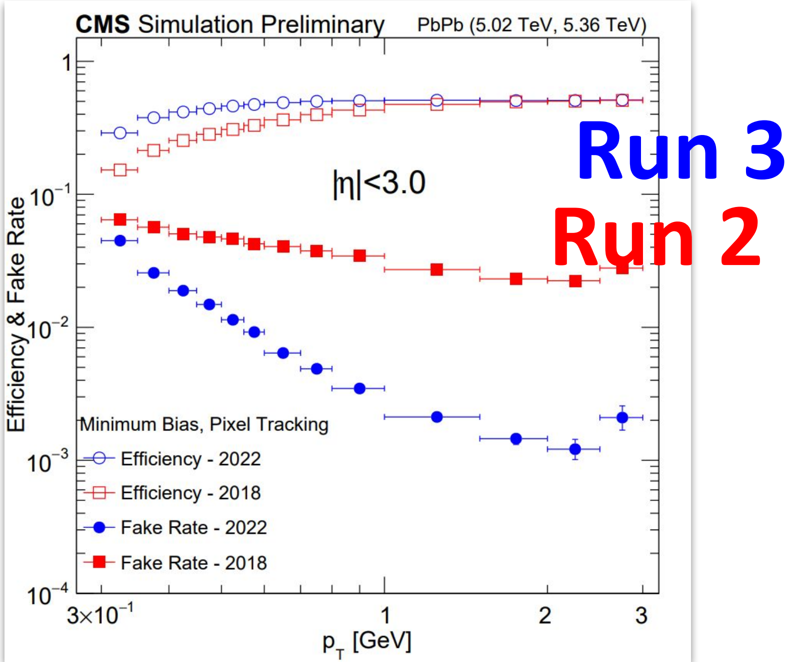


- **>3 times** the MB events from 2018: compressed event size, apart from the increased rate
- **Unprecedented sample** of UPC jet and heavy flavor events
  → ***in 2018 we relied on zero-bias trigger meaning we went from millions to billions***

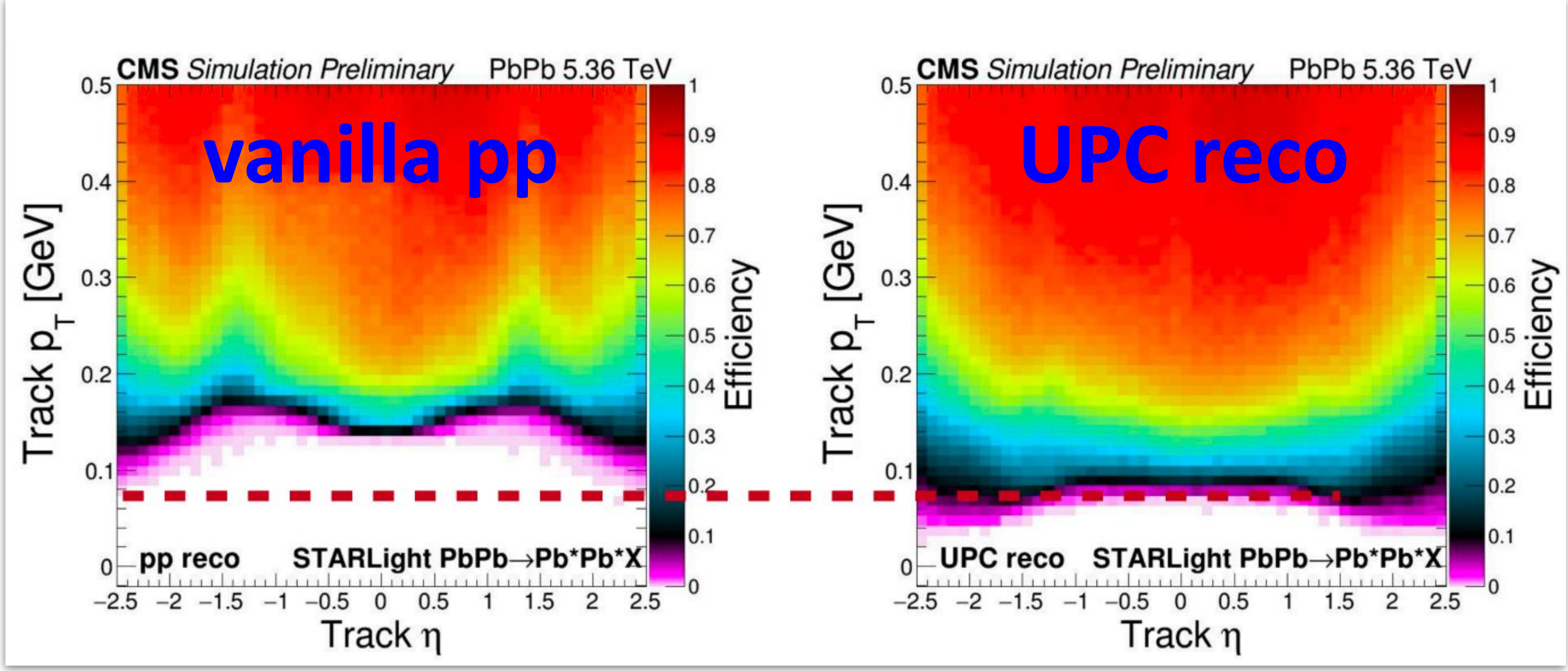
Additional improvements in Run 3 PbPb

DP-2023-011





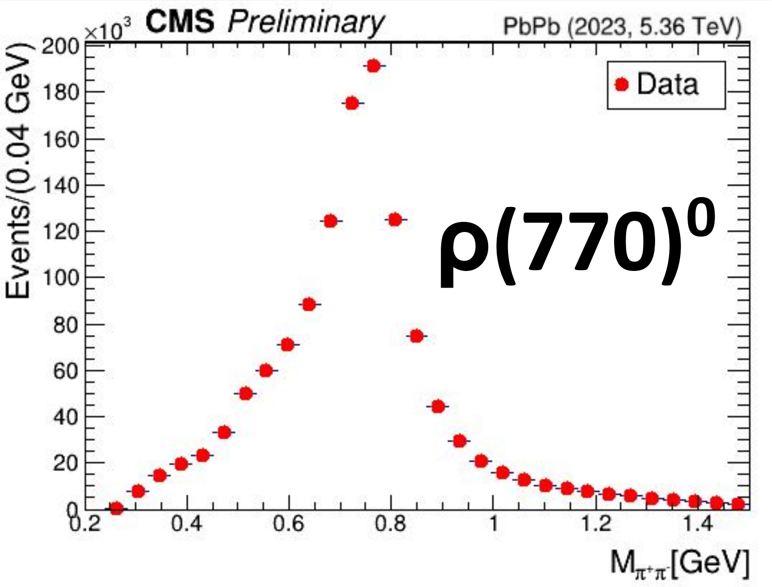
- Increased MB trigger efficiency in **peripheral events** with ZDC inclusion
- better low-pT tracking thanks to innermost pixel layer consideration
  → ***increased efficiency and reduced fake rate***

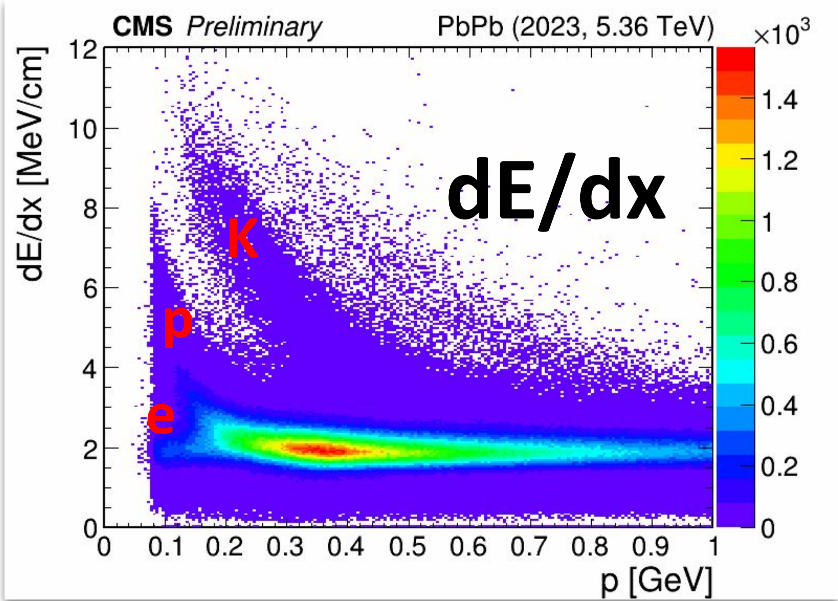


- **Dedicated UPC setup** to further improve low-p_T reconstruction capabilities
→ ***tracks down to p_T of 50 MeV***

Validation of tracking and dE/dx prospects in Run 3 PbPb

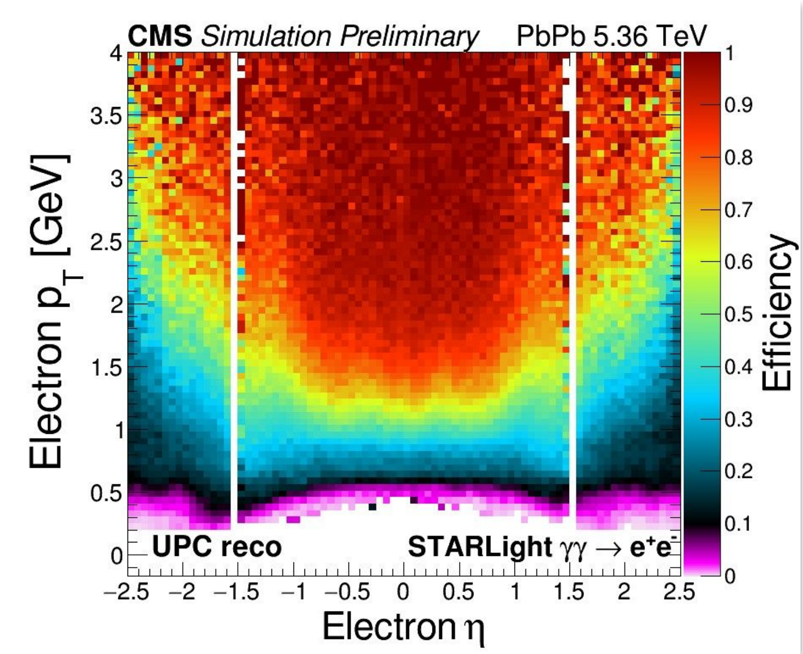
DP-2023-X

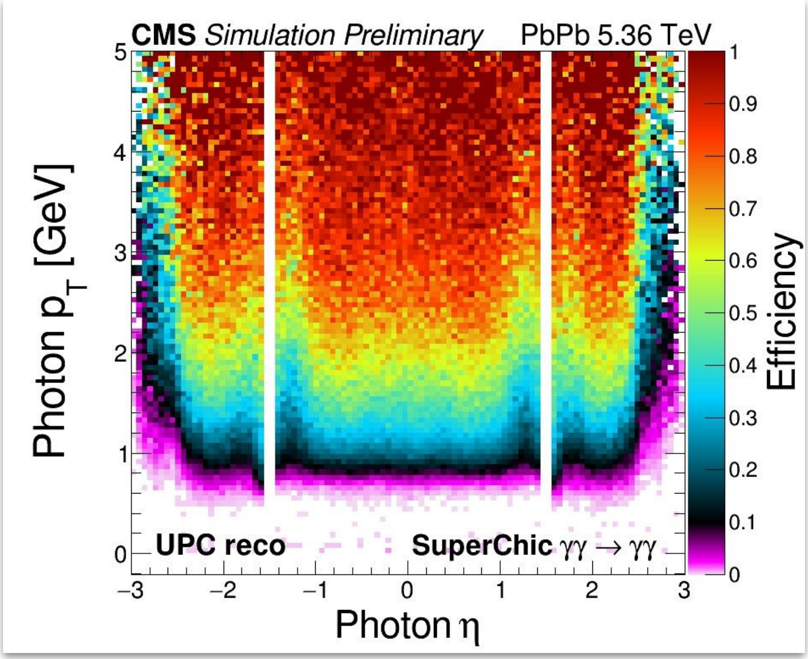




- Excellent resolution for **low-mass resonances**
- Good **PID discrimination** using dE/dx
  → ***better control of background***

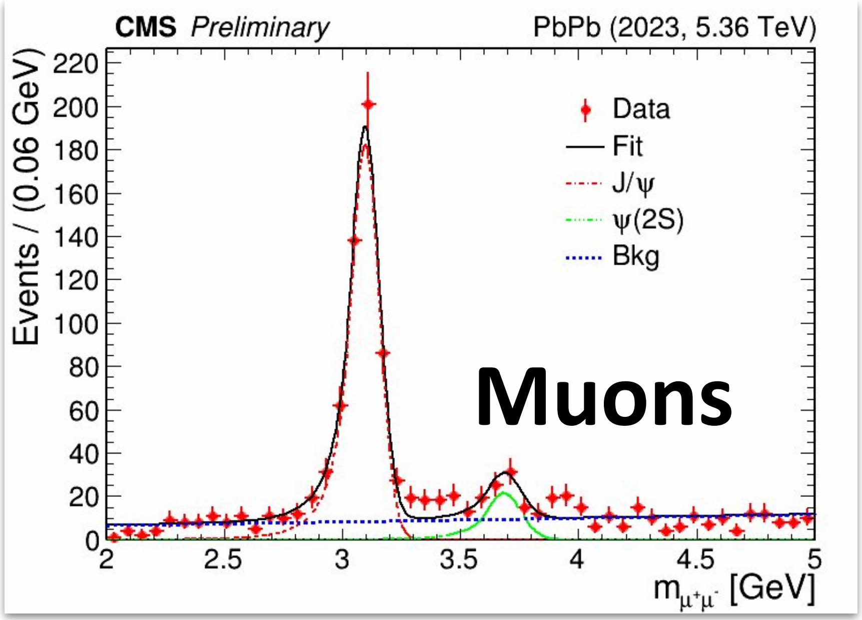
Testing the limits of low p_T EGM reconstruction in Run 3 PbPb DP-2023-X

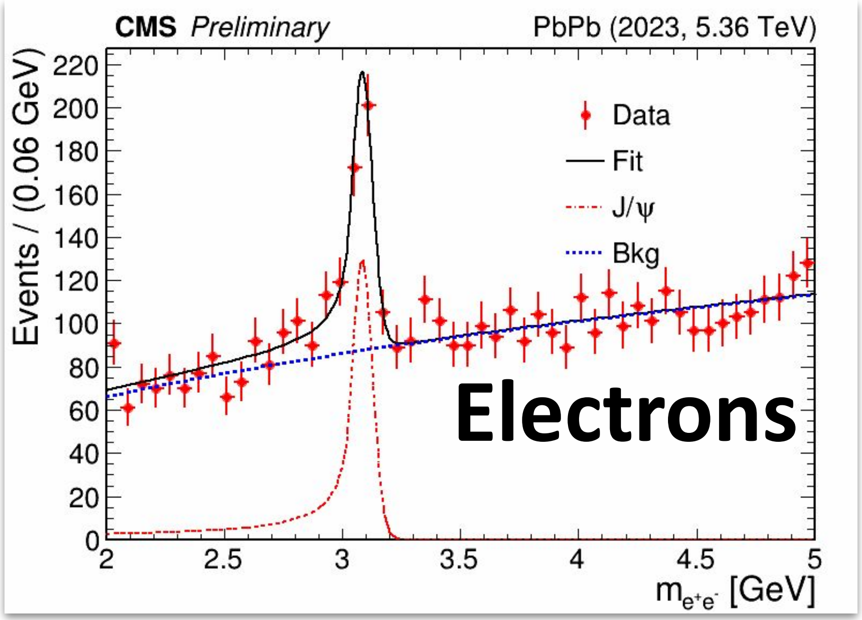




- **Dedicated UPC setup** to access low-p_T electrons (new) and photons (like in Run 2) → ***electromagnetic (EGM) objects down to p_T of 0.5–1 GeV***

Validation of low p_T lepton reconstruction in Run 3 PbPb DP-2023-X



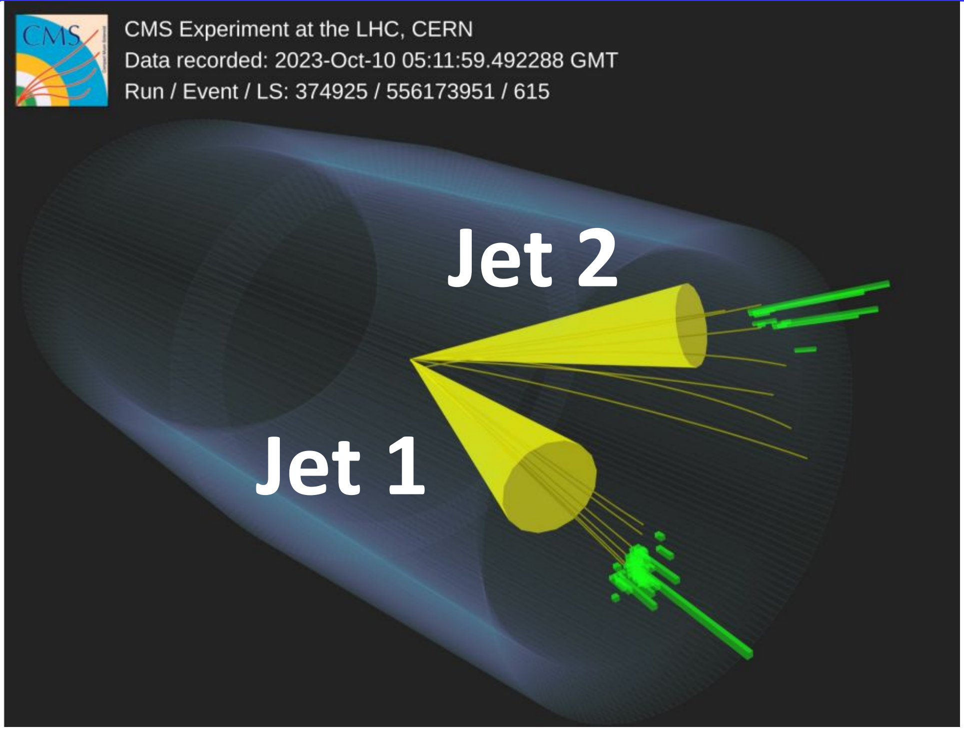


- Excellent resolution for **intermediate-mass resonances**
  → ***ψ(2S) peak already evident despite a small fraction of data is shown***

Outlook

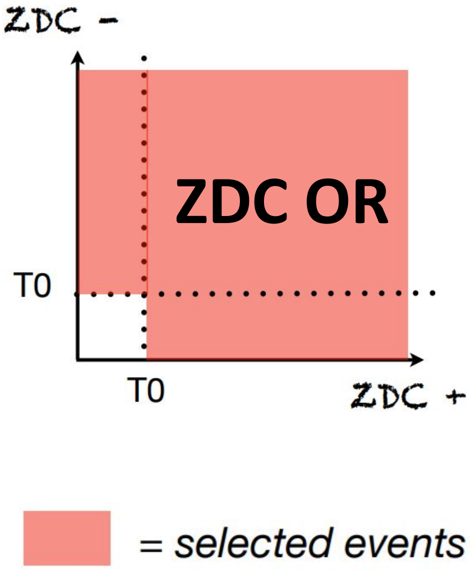
- Rich set of UPC results with the Run 2 CMS data set
  - more questions than answers…
- CMS has invested heavily (also) in the PbPb Run 3
  - as of now **O(10B) UPC** events recorded
  - further offline optimization in the (very) low-p_T realm

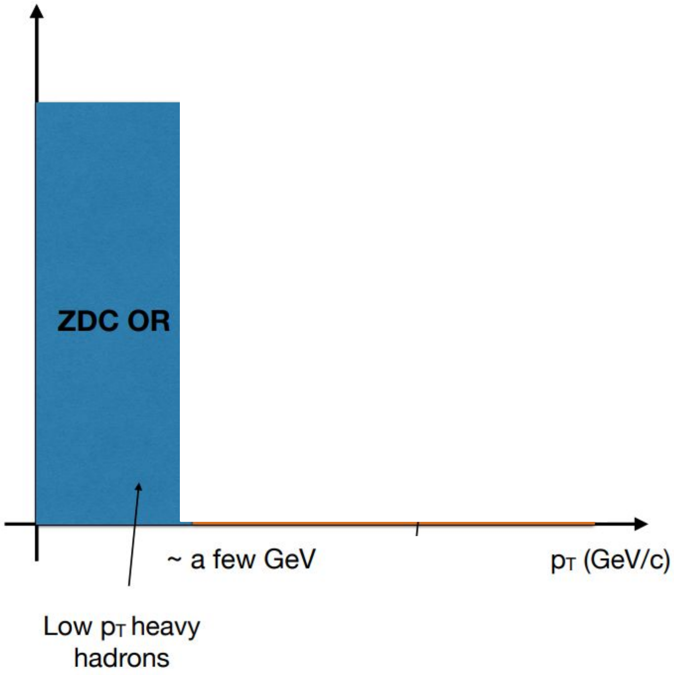
Thank you for your attention!



EXTRA SLIDES

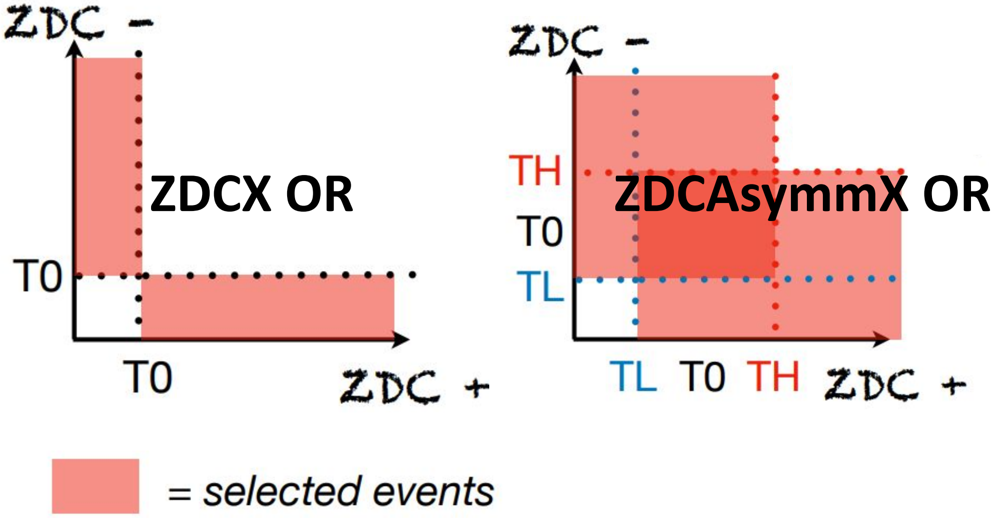
New hadron triggers for photo-nuclear events

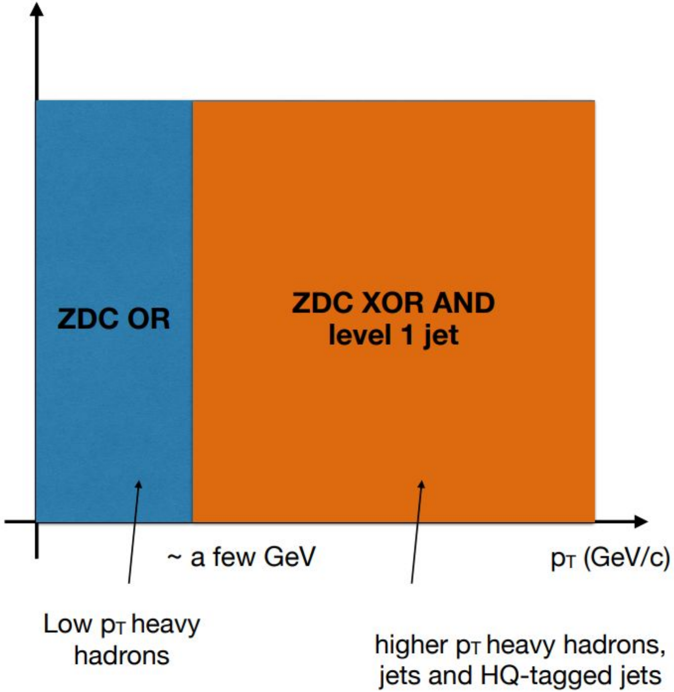




- ZDC trigger strategy
  - **For low p_T**: at least 1 broken nucleus ("ZDC OR") - **no p_T requirement** on central system

New jet triggers for photo-nuclear events



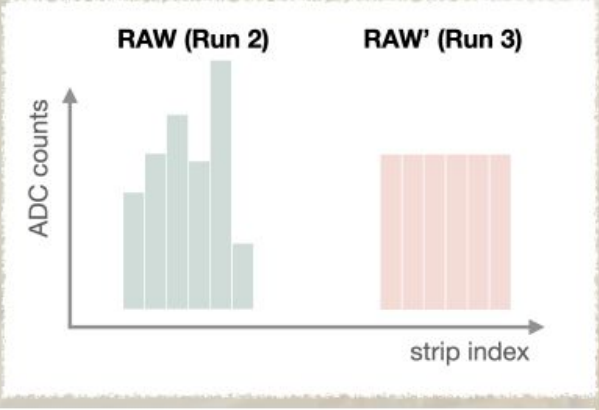


- ZDC trigger strategy
  - For low p_T: at least 1 broken nucleus ("ZDC OR") - no p_T requirement on central system
  - **For high p_T**: one nucleus remains intact ("ZDCXOR") & **asymmetric** ZDCXOR **for jets**
    - 1 ZDC > a low threshold (TL), and the other ZDC < a high threshold (TH)

Approximated SST clusters — “ RAW’ ”

LHCC poster

- PbPb Run2 at 5.02 TeV (2015-2018): SST info is stored as per-strip ADC counts in raw data
- PbPb Run3 at 5.36 TeV (from 2023): new **RAW’** data format is deployed
  - Implemented in the High Level Trigger
  - Rectangular cluster-amplitude approximation, in place of the original per-strip-ADC-count data format:
    - Barycenter: amplitude-weighted strip-index center (10% strip’s width precision)
    - Size: the length of the cluster’s strip sequence (exact info from original cluster)
    - Average charge: average amplitude of the strip sequence (integer precision)
      *Total charge has the precision of (cluster’s size) * (integer precision)*
    - Booleans for the strips’ amplitude saturation and the cluster shape peak filter
  - A list of modules associated to Front End Driver in error state is stored on the event basis



SST cluster format	RAW		RAW’	
Stored content	Strip index	ADC counts (8-bit int)	Approximated cluster properties	

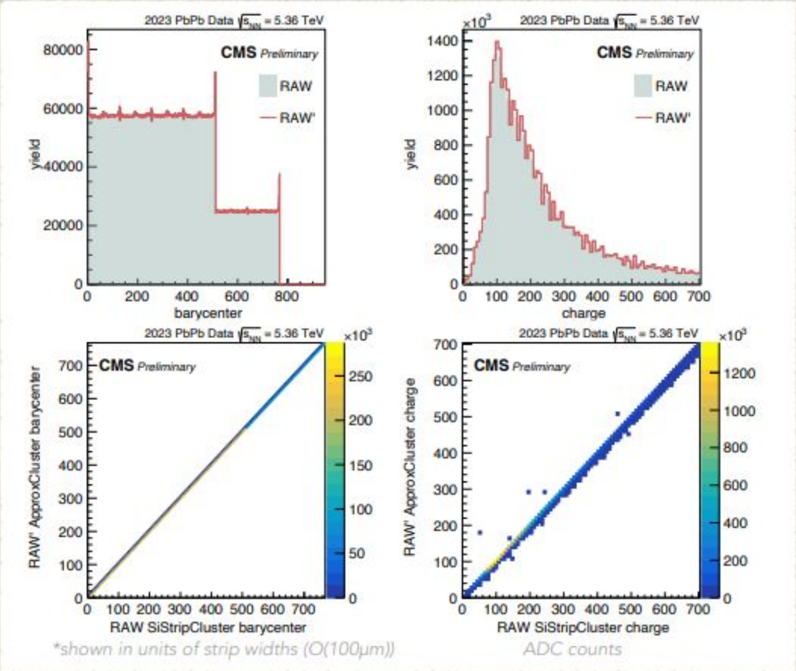
Example stored tracker data	First strip 123 (16-bit int)	75	• Barycenter = 125.5 (10-bit int) (We store 10x barycenter as int)
			• Size = 6 (6-bit int)
			• Average charge = 100 (8-bit int)
			• Cluster shape: (1-bit Boolean)
			  • Saturated strip
			  • Peak filter
				[Event-basis] FED modules & readout error info

	124 (derived by first strip & ADC list)	103		
	125	127		
	126	94		
	127	161		
	128	42		
Example total bits per cluster	16 + 8*6 = 64 bits		10 + 6 + 8 + 1*2 = 26 bits + smaller FED error contribution	

An example and sketch of RAW & RAW’ SST cluster data format

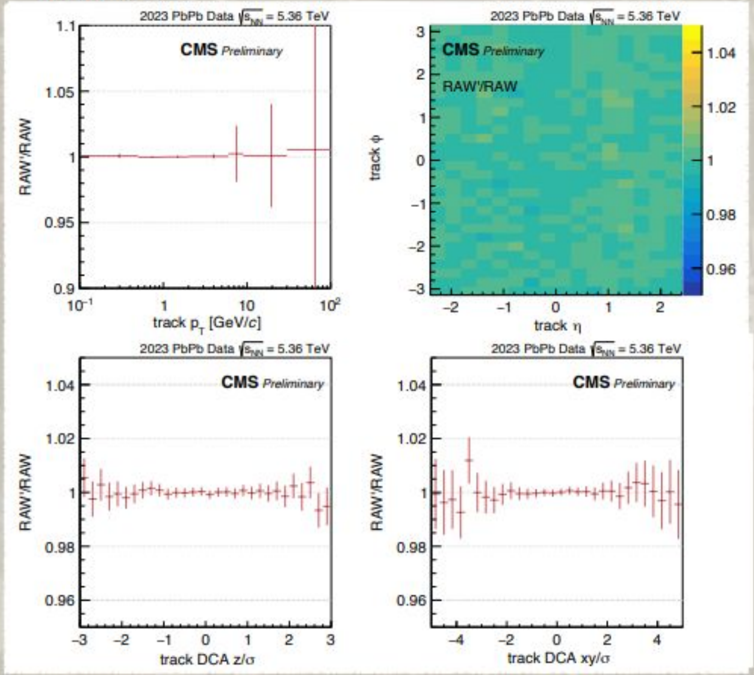
SST cluster property validations LHCC poster *Performance check on tracks*

- Good agreement on cluster barycenter & charge btw original RAW v.s. RAW′ data format!



- Preserving barycenter accuracy within a deviation of 10% the strip's width
- Outliers in the cluster charge scatter plot are impacts from noisy and dead SST channels

- An agreement better than 2% btw RAW & RAW′ is achieved!



** The uncertainties shown in the plots are statistical errors*

** Analysis-level track selections are applied*

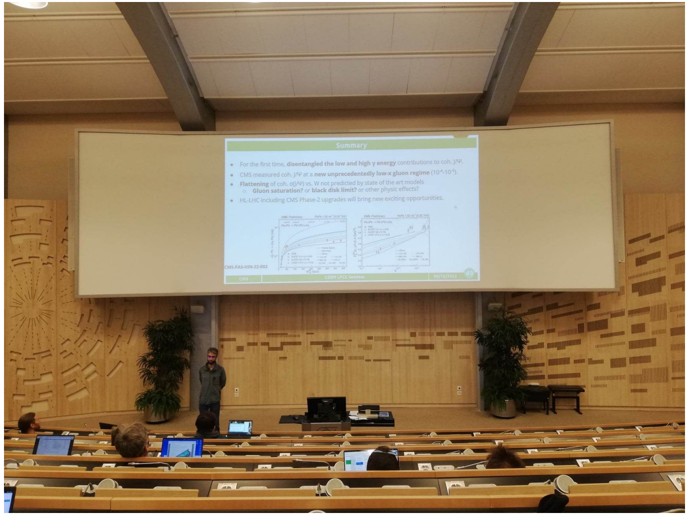
Some relevant publicity

- **Photon-nucleus energy dependence of coherent J/ψ cross session in UPC PbPb, HIN-22-002**
  - comprehensive study of the coherent J/ψ photo-production, also in neutron multiplicities

CERN seminar (CMS Collaboration)

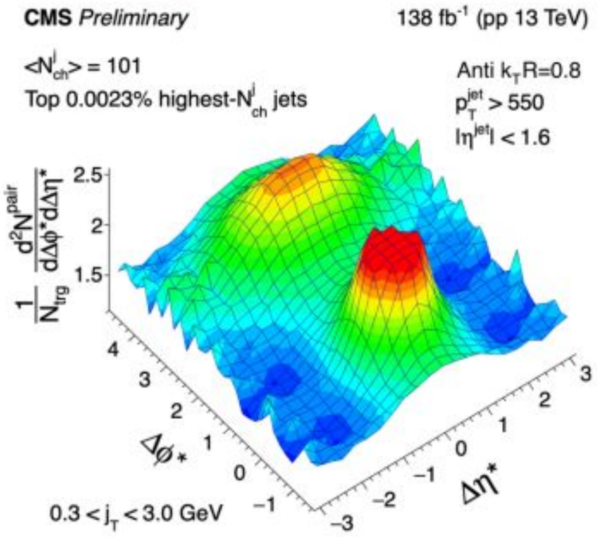
Probing gluon pdf at x->0 with ultraperipheral PbPb collisions at 5.02 TeV in CMS

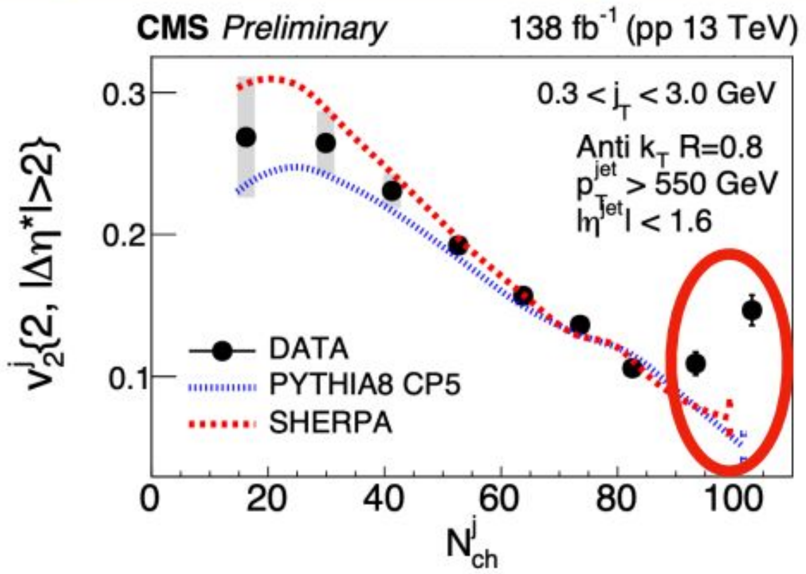
PRL Editor’s suggestion, Summary



- **Observation of τ lepton pair production in UPC PbPb, HIN-21-009**
  - pursuing better constraints on τ lepton anomalous magnetic moment than LEP(II)

In-jet v_2 with respect to the jet axis



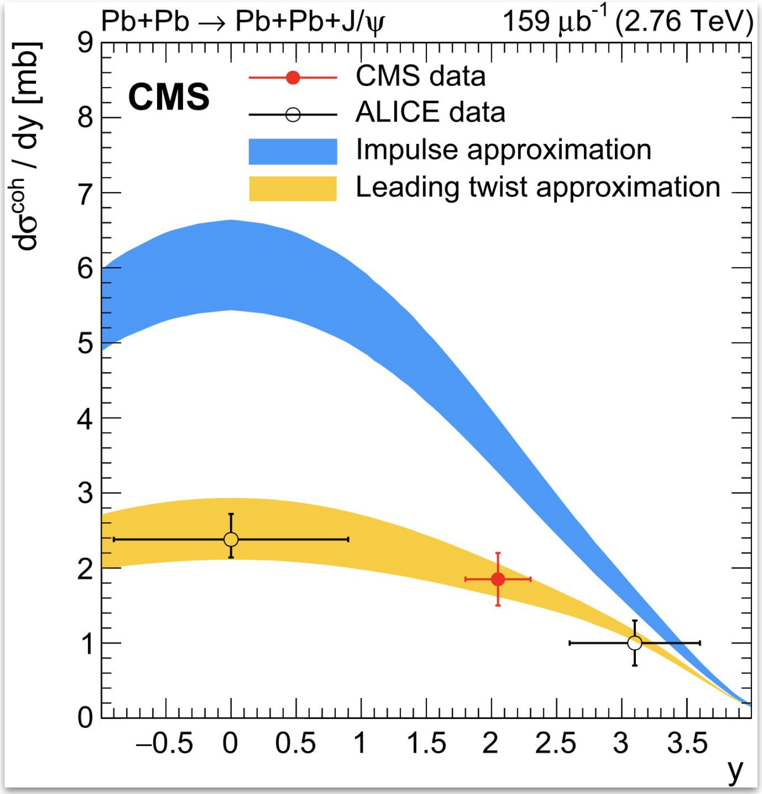


- *In rotated reference frame,* **calculate two particle correlation using jet constituents**
- **v_2 well described by MC for N_{ch}^{jet}<80**
- **Upward trend seen for N_{ch}^{jet}>80**
  - **Potential sign of collectivity in jets?**

CMS PAS HIN-23-013

Coherent J/ψ in Run 1

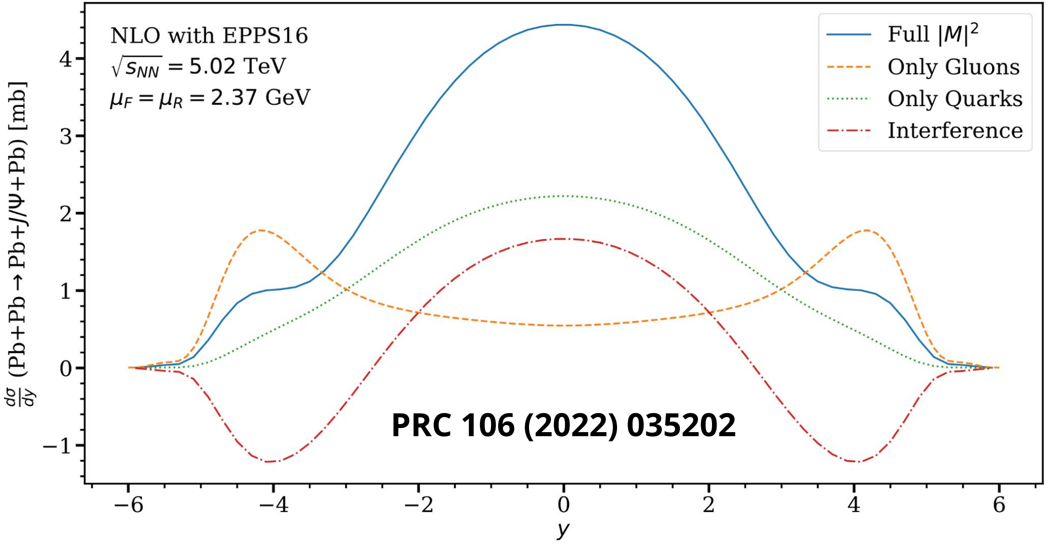
PLB 772 (2017) 489



- Run 1 data from CMS and ALICE well consistent with LTA model calculations
- **Large uncertainties and wide y bins**

First NLO calculations on exclusive J/ψ production

- First NLO pQCD calculations published recently (Eskola et al).
- Quark contributions at NLO + strong cancellations between LO and NLO gluons → ***dominance of quark contribution at central rapidities.***

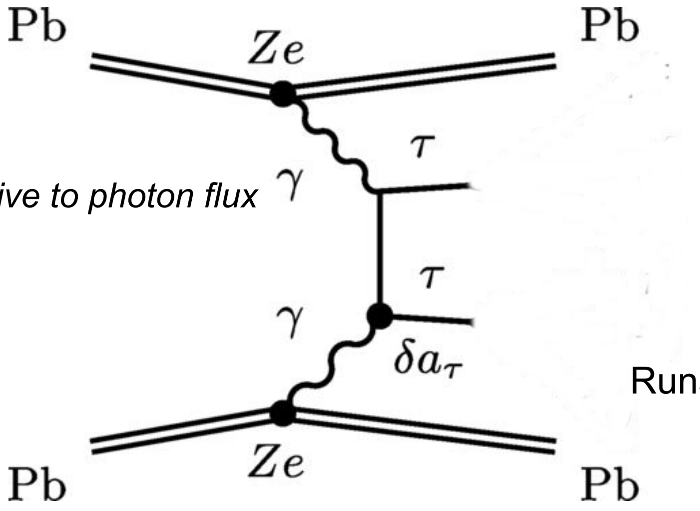


- Needs careful attention when interpreting the data.
- "σ ∝ (gluon PDF)^2" not true at NLO.
- Large scale dependency.

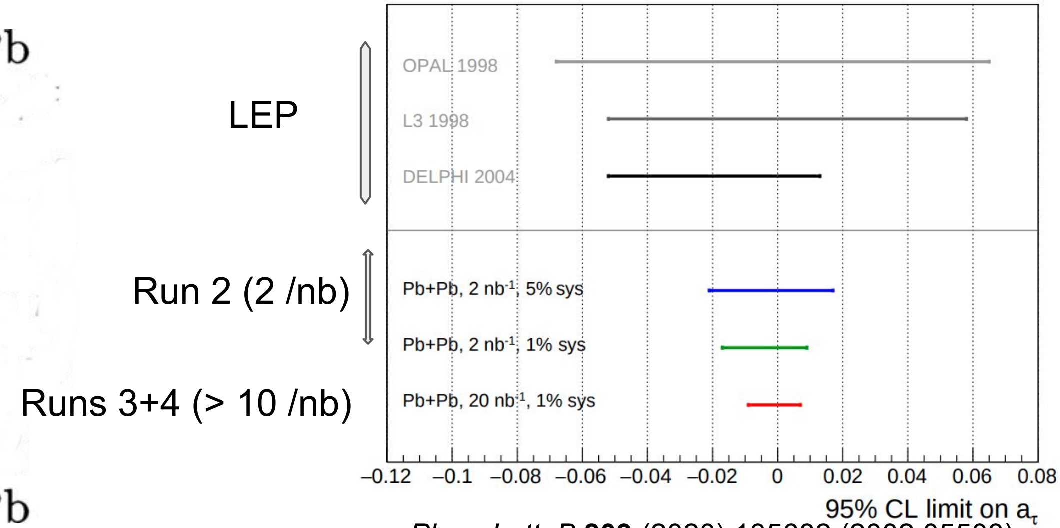
Overview of the $\gamma\gamma \to \tau^+\tau^-$ process

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

Sensitive to photon flux



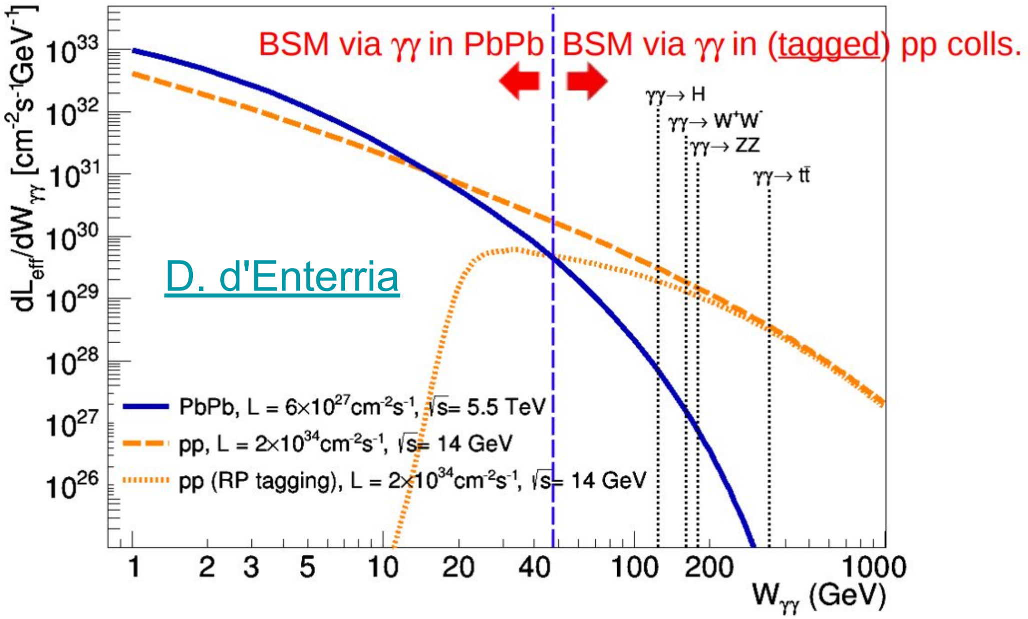
τ lepton photoproduction in ultraperipheral collisions (UPC)

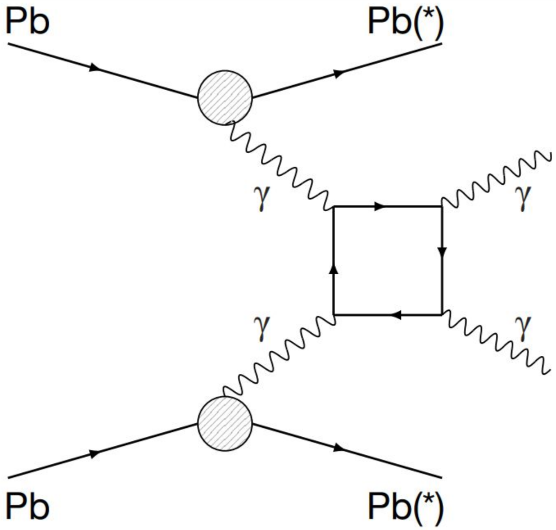


Phys. Lett .B **809** (2020) 135682 (2002.05503)
Phys. Rev. D **102** (2020) 113008 (1908.05180)

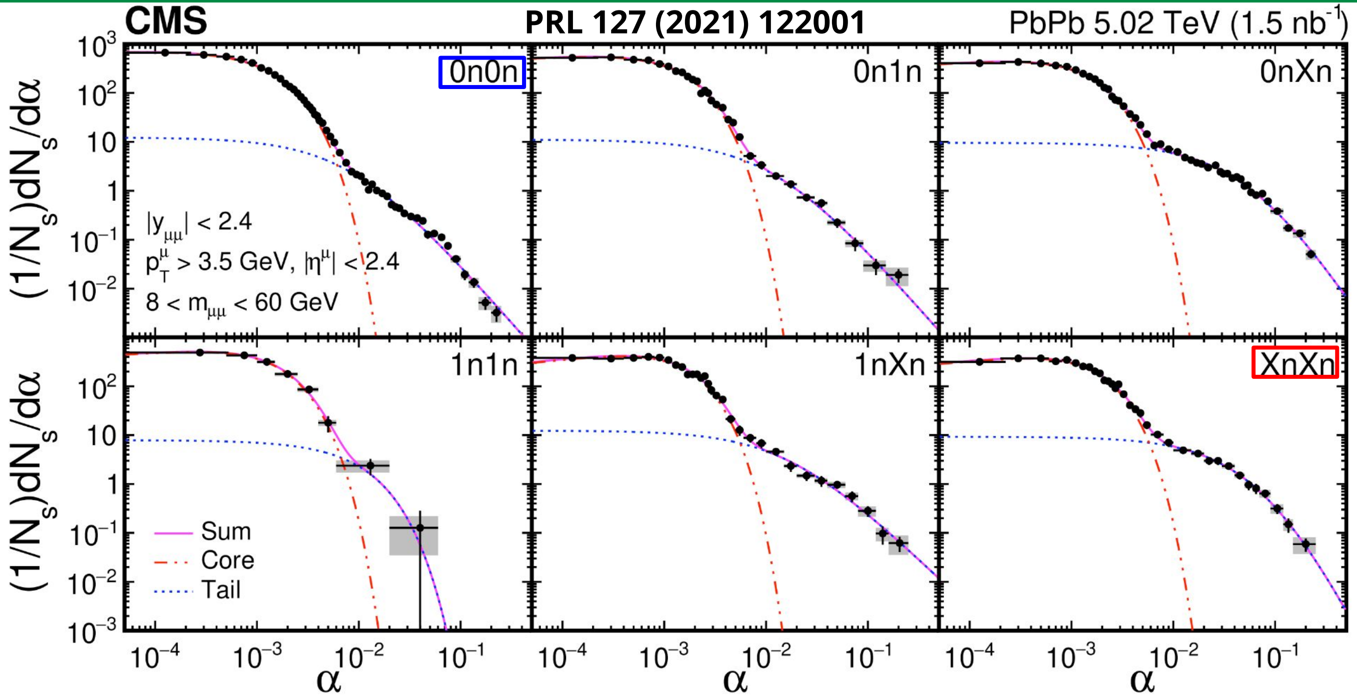
LbyL scattering (with UPC)

- 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



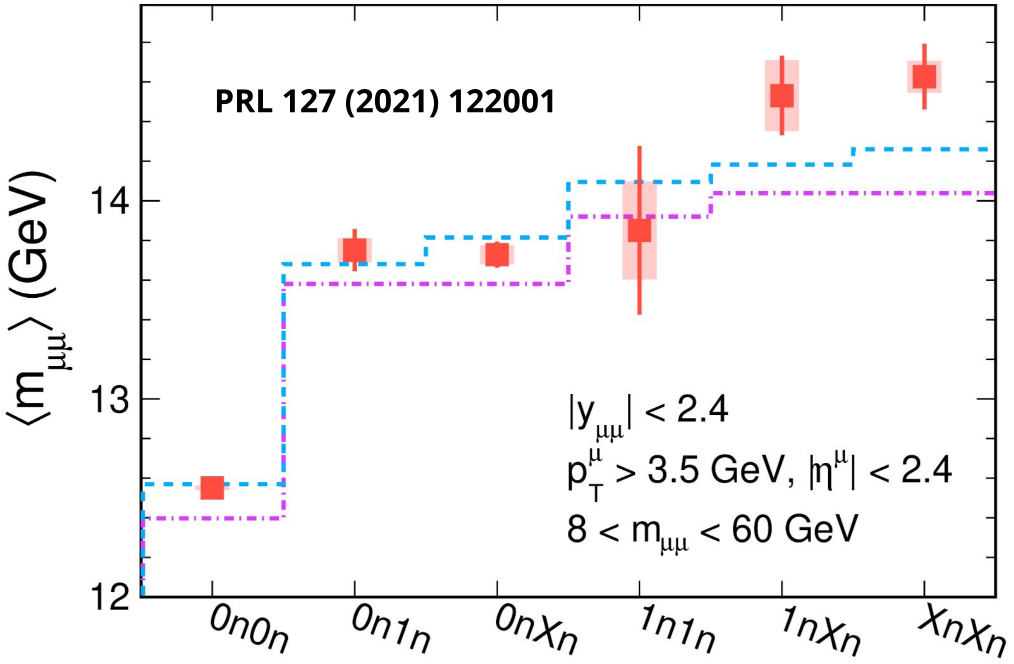


α spectrum vs. neutron multiplicity



- **0n0n (fewer neutrons)** → **XnXn (more neutrons)**
  - Tail contribution becomes larger.
  - Seems has depletion in the very small α.

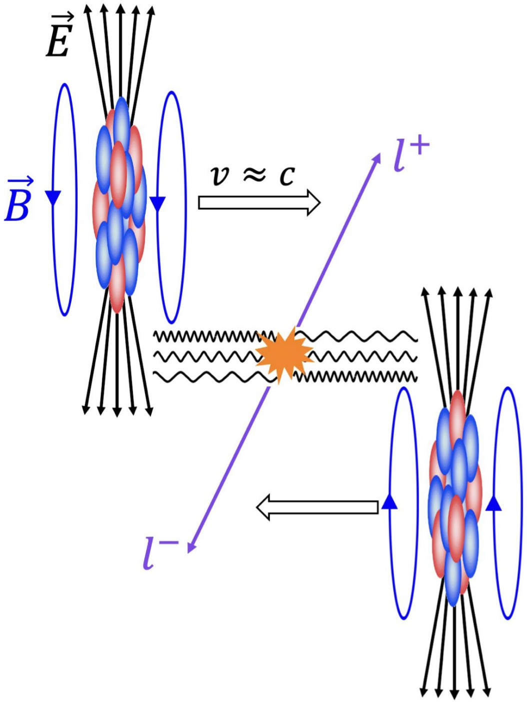
⟨$m^{\mu\mu}$⟩ vs. neutron multiplicity



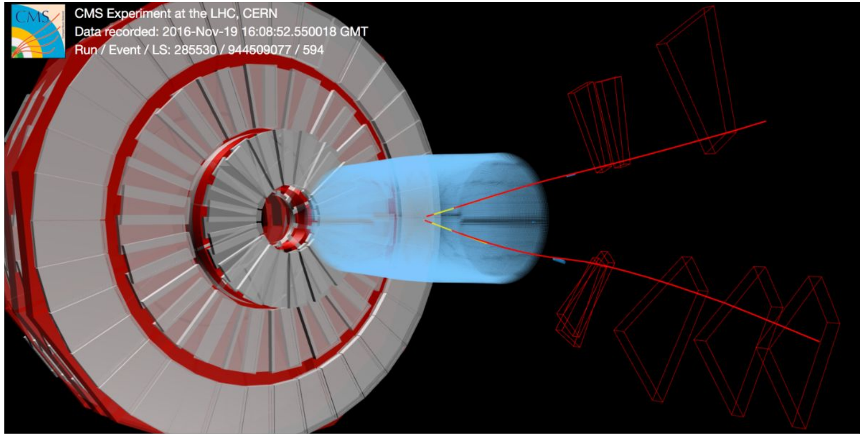
- Strong neutron multiplicity dependence of ⟨$m_{\mu\mu}$⟩
  - Deviation from constant >> 5σ
  - b dependence of initial photon energy.

Ultra-peripheral nuclear collisions

When two ions "miss" each other, no QGP is created but,



- Strong EM fields generated by relativistic ions ($B \sim 10^{16}$ T).
- Lorentz contracted EM fields → flux of quasi-real γ ($Q^2 < \hbar^2/R^2$). The photon flux ∝ Z^2.
- Photon kinematics: $p_T < \hbar/R_A \sim 30$ MeV ($E_{max} \sim 80$ GeV) at LHC.

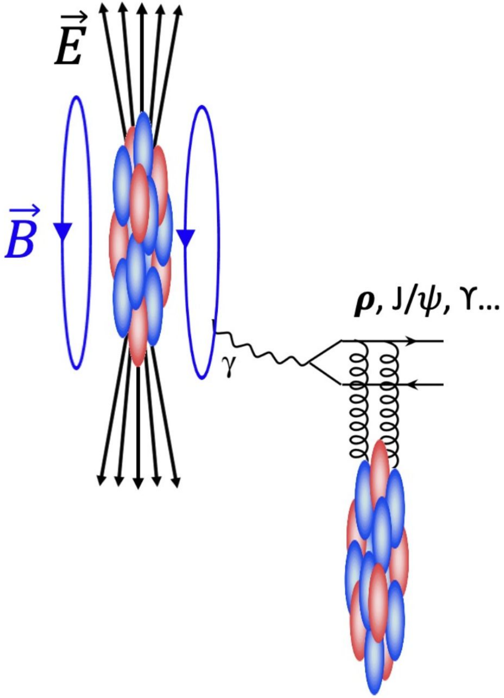


- light-light and light-Nucleus collider
- BSM searches (ALP, g_τ-2).

Vector meson photoproduction

Directly probes gluonic structure of nucleus and nucleon.

At LO in pQCD, cross section ~ photon flux ⊗ $[xG(x)]^2$ (gluon PDFs)



Coherent production:

- Photon ($\hbar/k_L$ > 2R) couples coherently to whole nucleus.
- Vector Meson (VM) $\langle p_T \rangle$ ~ 50 MeV.
- Target nucleus usually remains intact.

Incoherent production:

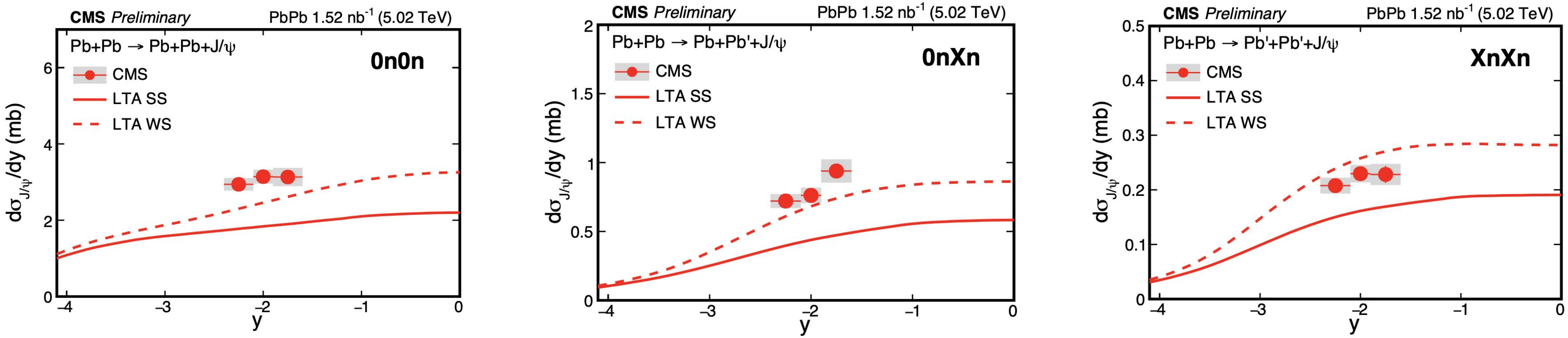
- Photon couples to part of nucleus.
- VM $\langle p_T \rangle$ ~ 500 MeV.
- Target nucleus usually breaks.

Final state kinematics directly map to:

- Photon energy: $\omega = \frac{M_{VM}}{2} e^{\pm y}$
- ***Bjorken-x*** of gluons: $x = \frac{M_{VM}}{\sqrt{s_{\mathrm{NN}}}} e^{\mp y}$

Coherent J/Ψ in 0n0n, 0nXn, XnXn help to disentangle

CMS-PAS-HIN-22-002



$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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

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

⇒

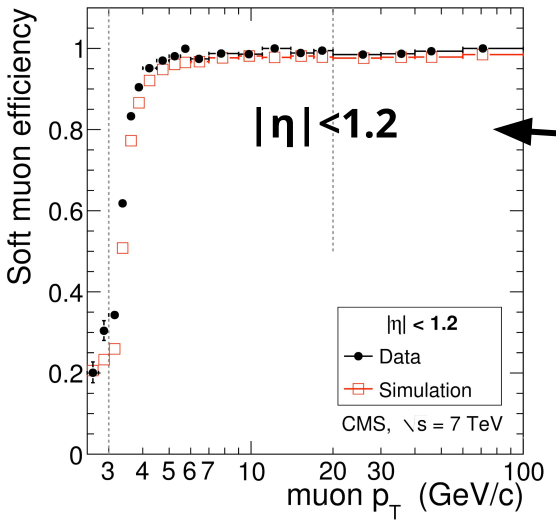
$\sigma_{\gamma A\to J/\psi A'}(w_1)$ → Low-energy γ: $w_1 = \frac{M_{VM}}{2}e^{-y}$

$\sigma_{\gamma A\to J/\psi A'}(w_2)$ → High-energy γ: $w_2 = \frac{M_{VM}}{2}e^{+y}$

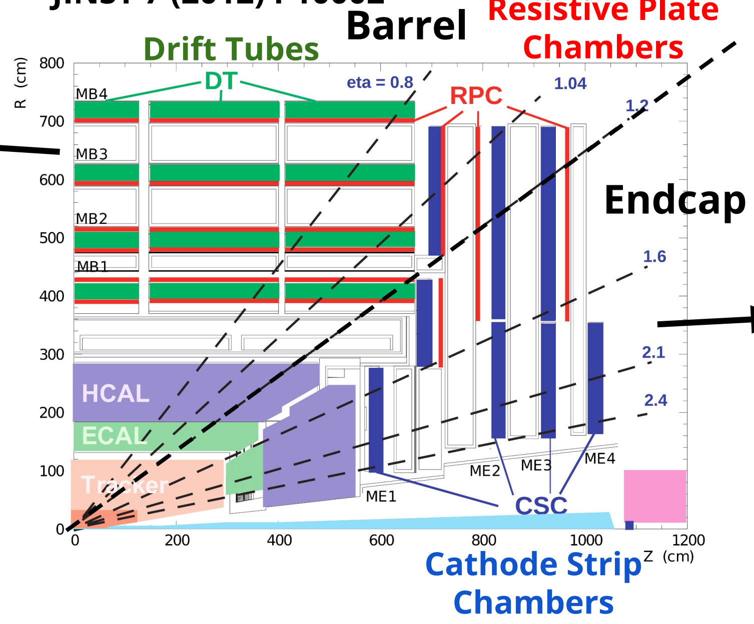
- Disentangle the low- and high- energy photon-nucleus contributions of a single γ+Pb.

Muon reconstruction

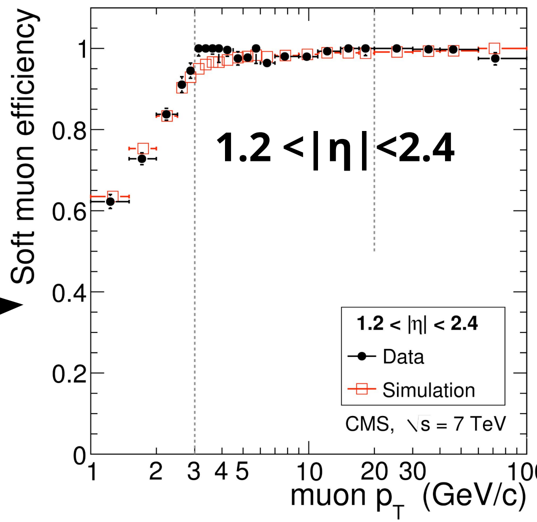
Muon efficiency



JINST 7 (2012) P10002

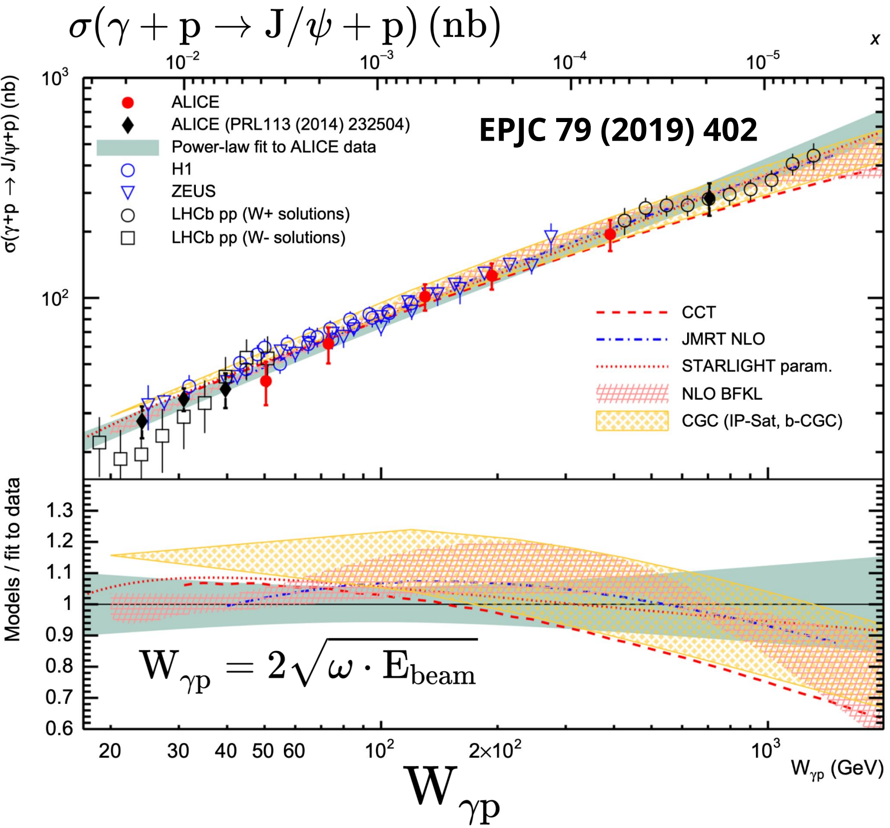


Muon efficiency



- Tracker and muon detectors used to reconstruct/identify muons.
- CMS able to reconstruct muons down to muon p_T~ 1 GeV in forward region.

Search for gluon saturation with γp interactions



J/ψ photoproduction from **photon-proton** interactions in ep, pPb and pp collisions

- ❖ Data follow a power-law trend, consistent with expectation from the rapidly increasing gluon density in a proton.

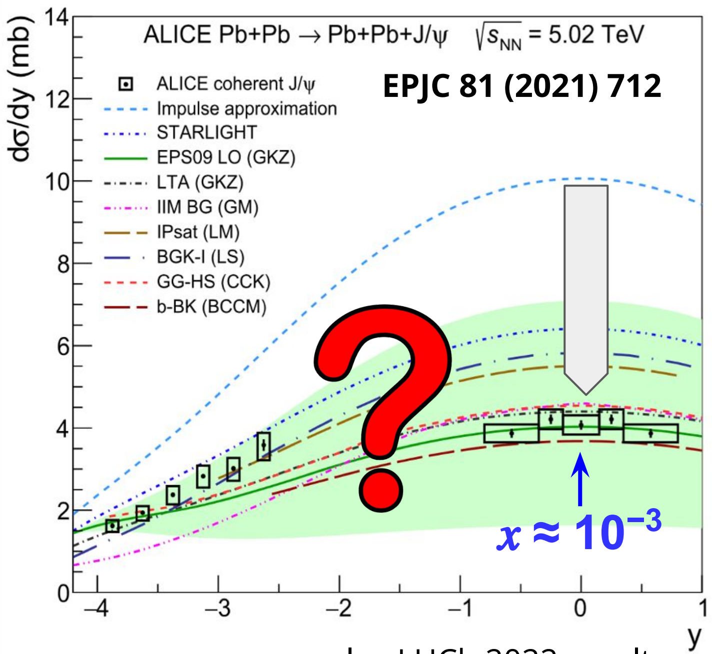
No clear indication of gluon saturation down to x ~ 10^{-5} in a free nucleon.

Search for gluon saturation with heavy nuclei

- Coherent Vector Meson production extensively measured at LHC.

- **LO: σ(J/ψ) ∝ $[xG(x)]^2$ → σ(J/ψ) < I.A.** (no nuclear effects) → evidence for strong nuclear modification in heavy nuclei.

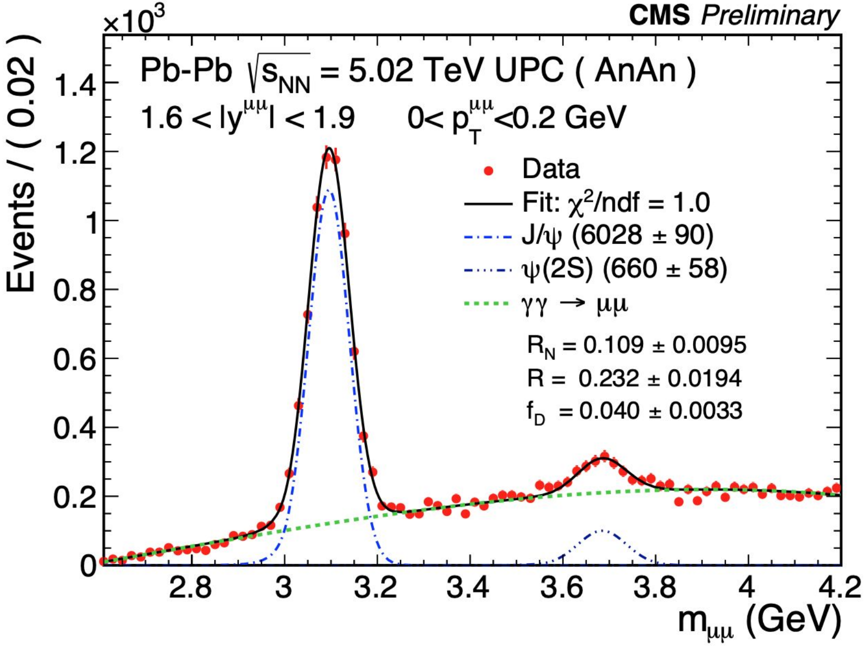
- No theory calculations (e.g., shadowing, saturation) can simultaneously predict mid- and forward rapidity data!?

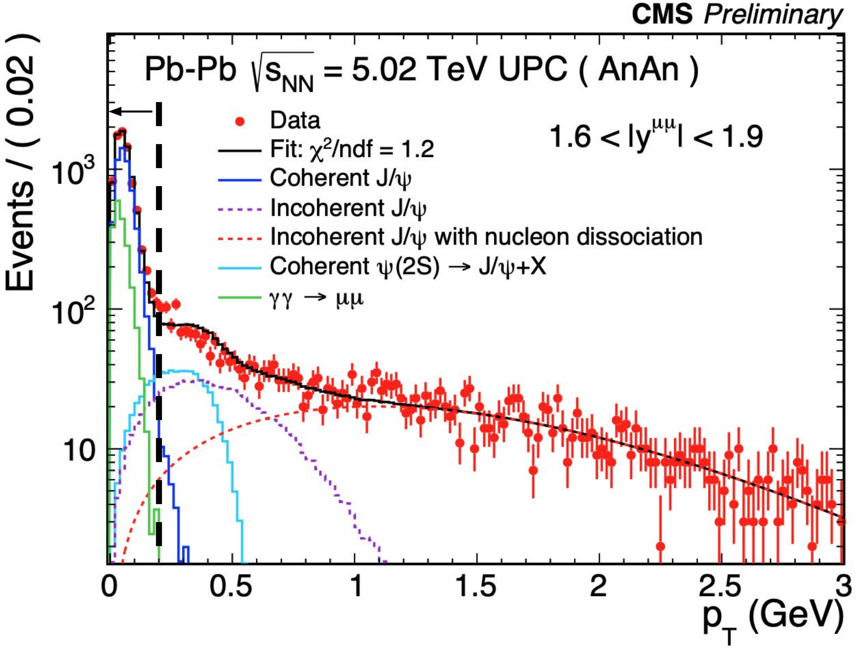


also LHCb 2022 results
arXiv:2206.08221

How robust our signal extraction is?

CMS-PAS-HIN-22-002



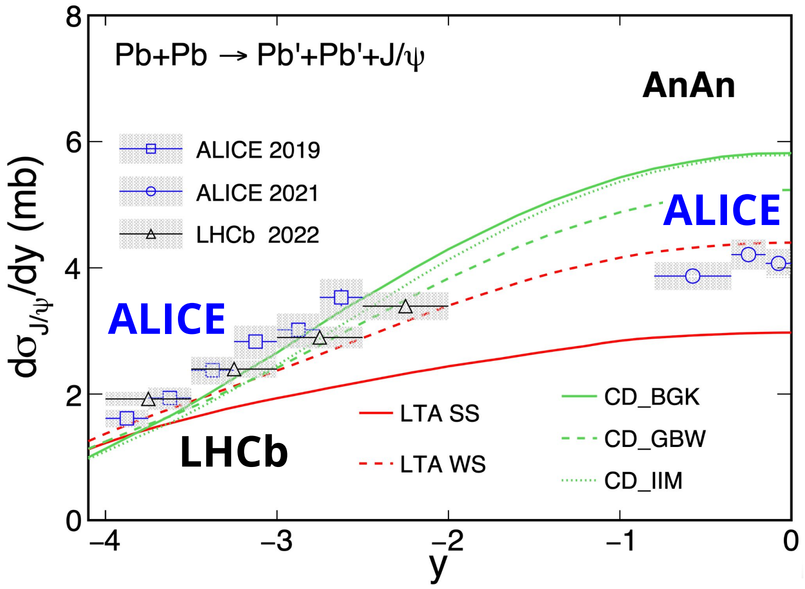


Signal yields are extracted by fitting the mass and transverse momentum spectra.

Clean event sample, well described

Coherent J/ψ in forward and mid-rapidity ranges

ALICE, **EPJC 81 (2021) 712**
LHCb, **arXiv:2206.08221**

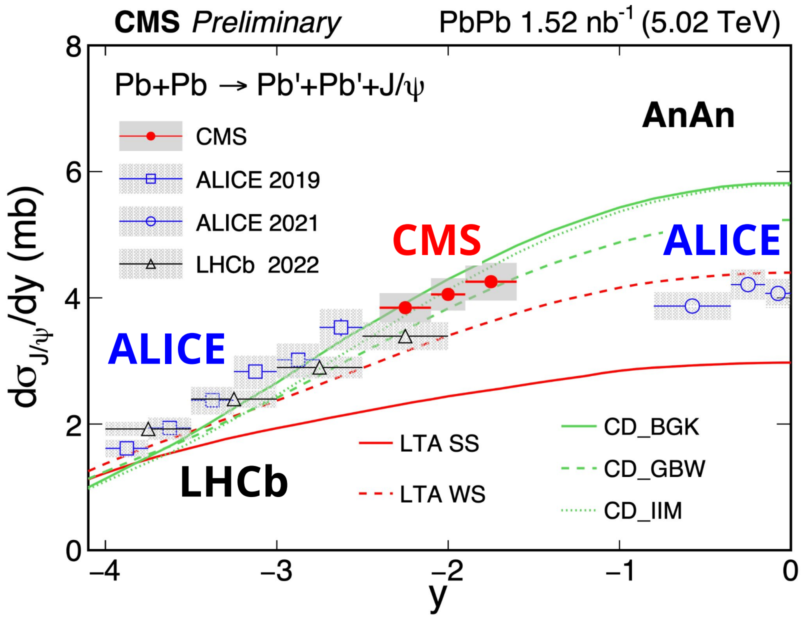


AnAn: No forward neutron selection

- A tension between ALICE forward and mid rapidity data?

Coherent J/ψ in extended rapidity range

CMS-PAS-HIN-22-002



(*) measured in |y| but placed in y<0 for illustration

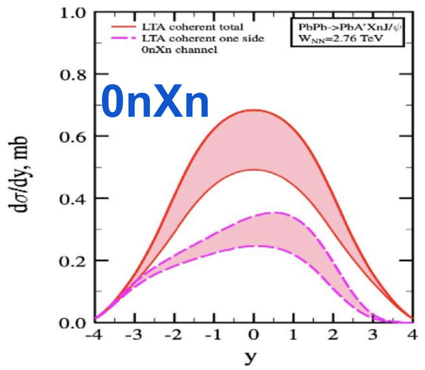
- A tension between ALICE forward and mid rapidity data?
- **CMS data cover a unique rapidity region.**

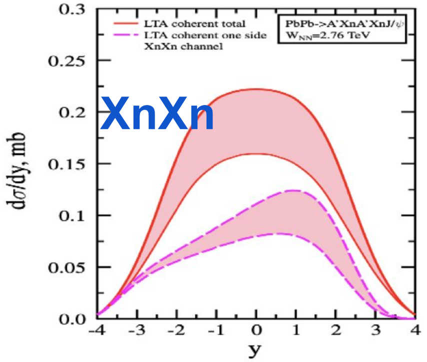
$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{N(J/\psi)}{(1+f_I+f_D)\cdot\epsilon(J/\psi)\cdot Acc(J/\psi)\cdot BR(J/\psi\to\mu\mu)\cdot L_{int}\cdot\Delta y}$$

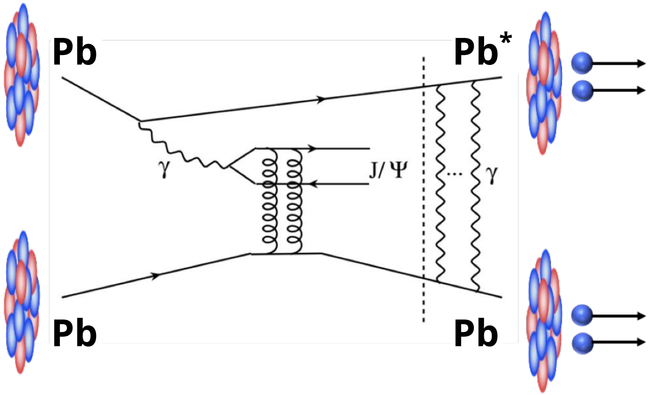
- Extracted from the fits
  - incoherent (f_I) and feed-down (f_D) fractions
- Calculated in-situ
  - efficiency (ε) and acceptance (Acc)
- Estimated from calibration methods
  - integrated luminosity L_{int} (PAS-LUM-18-001)
- Given as external input
  - the BR

A solution to the two-way ambiguity puzzle

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







Low-energy γ

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

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

High-energy γ

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

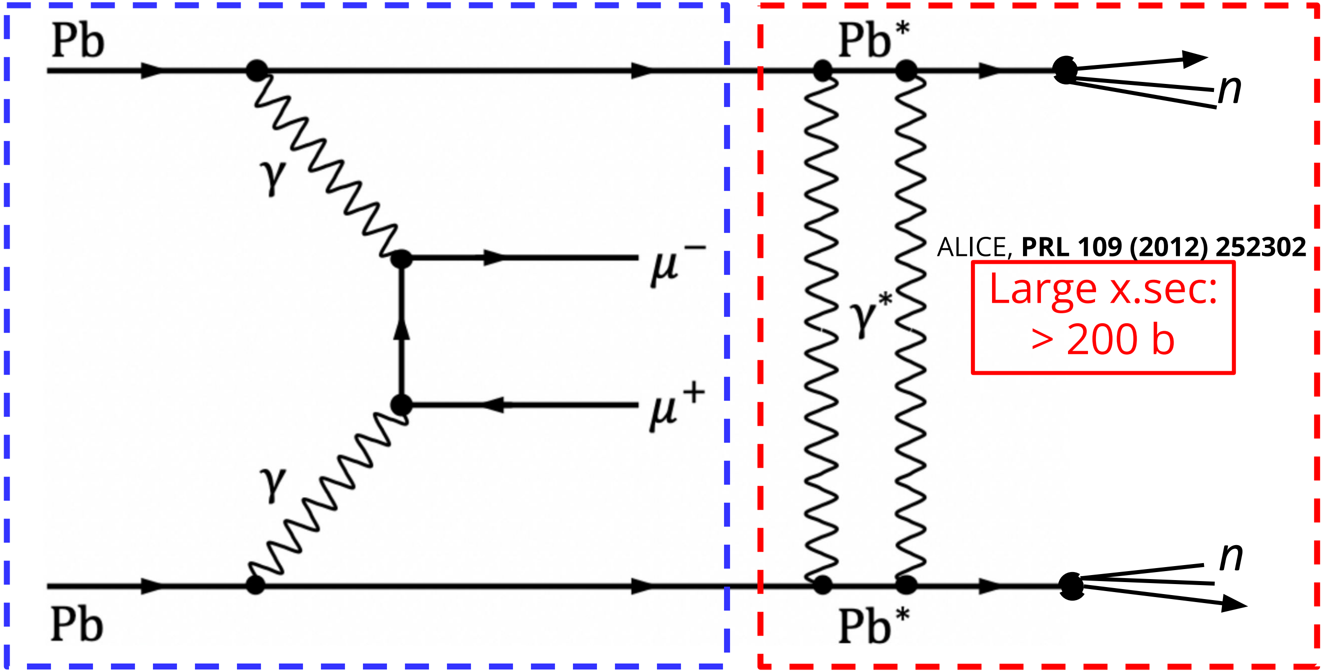
$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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

→ Solve for $\sigma_{\gamma A\to J/\psi A'(\omega_1)}$ and $\sigma_{\gamma A\to J/\psi A'(w_2)}$

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

EM dissociative pileup correction



Impact of dissociative PU corrected by measuring neutron multiplicity in events without any activity in CMS tracker.

$\gamma\gamma\to\mu^+\mu^-$ **with/without neutron emitting**

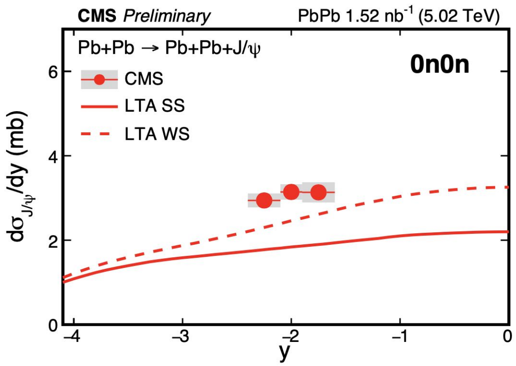
different collisions

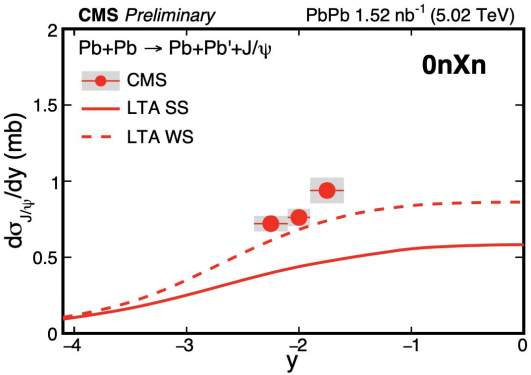
EM dissociation **without** any $\gamma\gamma\to\mu^+\mu^-$

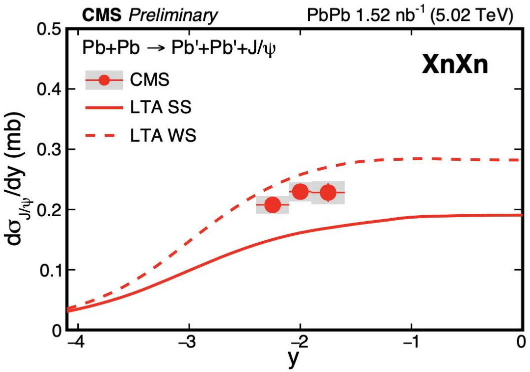
$\gamma\gamma\to\mu^+\mu^-$ with neutron multiplicity migration

Coherent J/ψ in 0n0n, 0nXn, XnXn

CMS-PAS-HIN-22-002



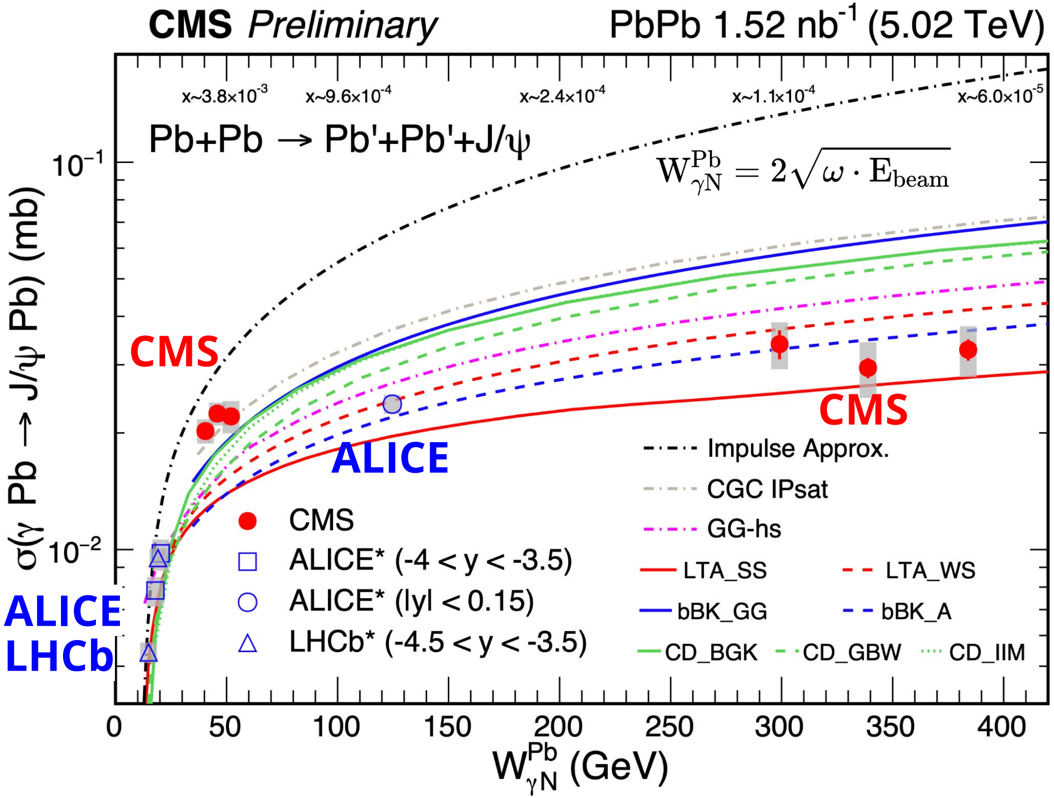




- Data in 0n0n and 0nXn are higher than Leading Twist Approximation (LTA) prediction.
- Data in XnXn stay in between LTA weak suppression (WS) and strong suppression (SS) assumptions.
- Competing experimental (up to ~8%) and theory (up to ~9%) systematic uncertainty
  - experimental related to fit extraction
    - subdominant efficiency, luminosity, exclusivity, and neutron bin migrations
  - theory related to photon flux estimation

Coherent J/ψ cross section of single γ+Pb vs. W

CMS-PAS-HIN-22-002



ALICE, LHCb vs. IA:

- Data close to IA at low W.
- Data lower than IA at W~125 GeV.

New data from CMS:

- Rapid increase at W<40 GeV.

Coherent J/ψ cross section of single γ+Pb vs. W

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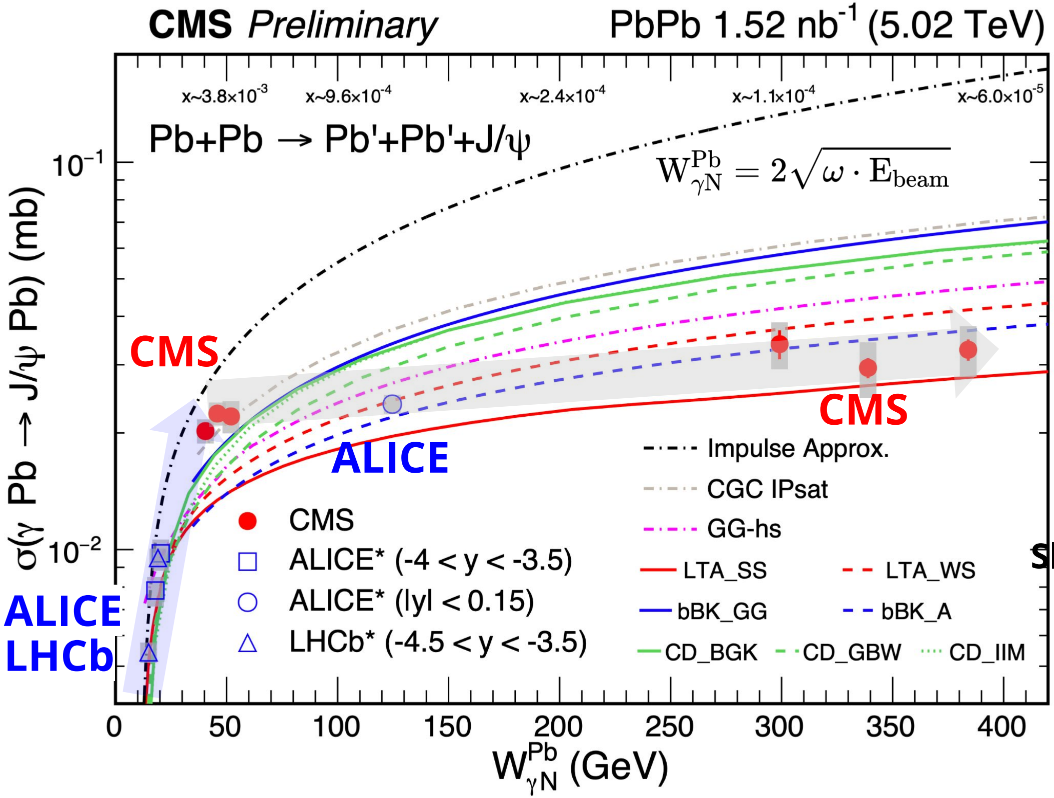


Experimental uncertainty highly correlated across W

ALICE, LHCb vs. IA:

- Data close to IA at low W.
- Data lower than IA at W~125 GeV.

New data from CMS:

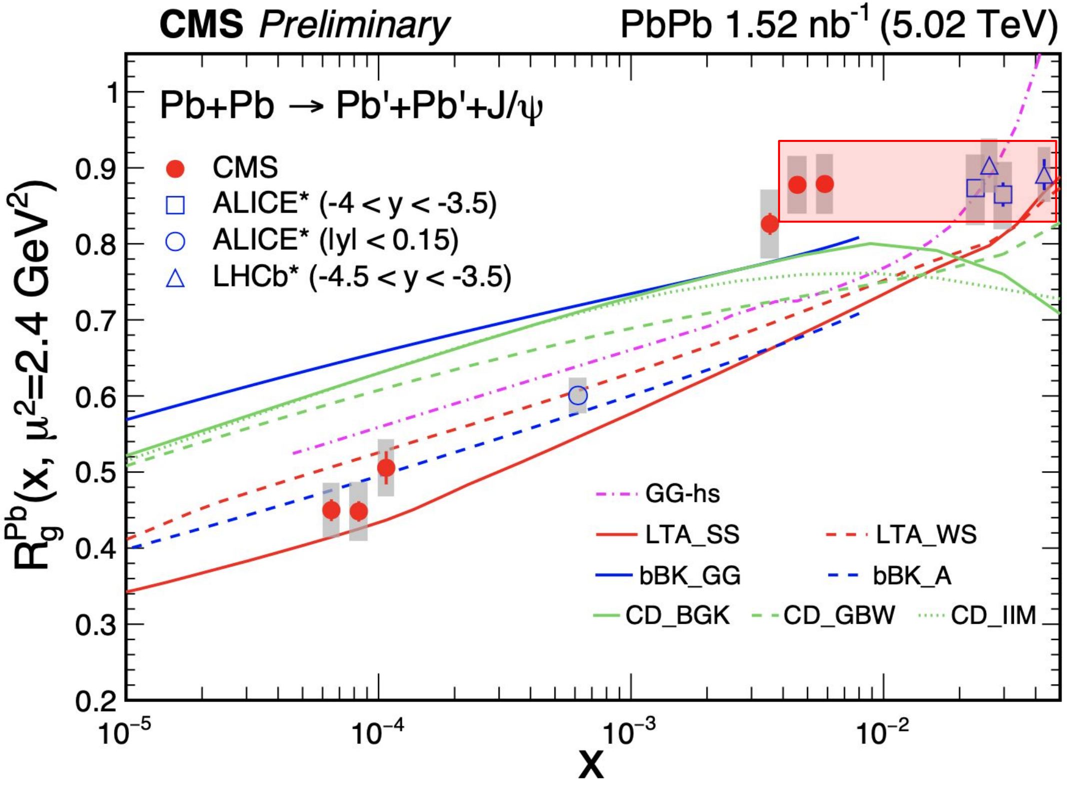
- Rapid increase at W<40 GeV.
- A nearly flat trend for W>40 GeV.

Slope = 2.98 ± 0.42 (stat.) ±1.06 (syst.)×10^{-5} mb/GeV

No models can describe the entire data distribution.

Nuclear gluon suppression factor

CMS-PAS-HIN-22-002



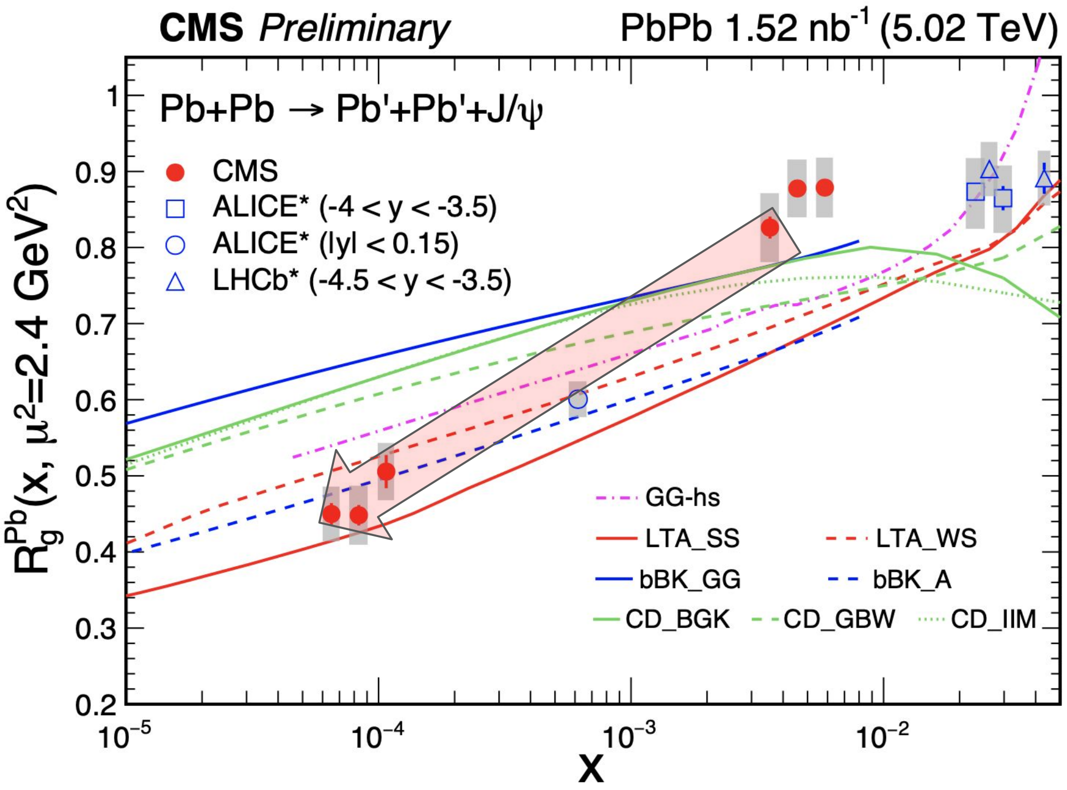
$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}} \right)^{1/2}$$

Impulse approx. (IA) neglects all nuclear effects.

- Rg represents nuclear gluon suppression factor at LO.
- $x \sim 10^{-3}$ - 10^{-2}: flat trend.

Nuclear gluon suppression factor

CMS-PAS-HIN-22-002



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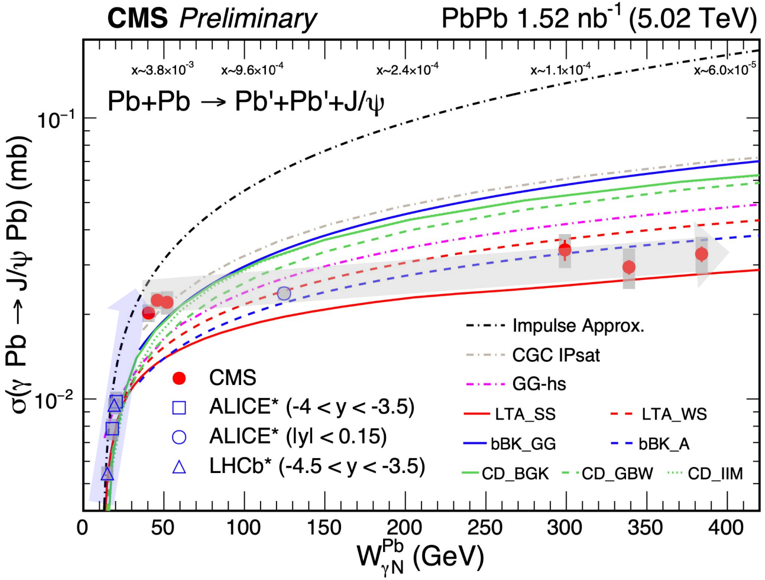
Impulse approx. (IA) neglects all nuclear effects.

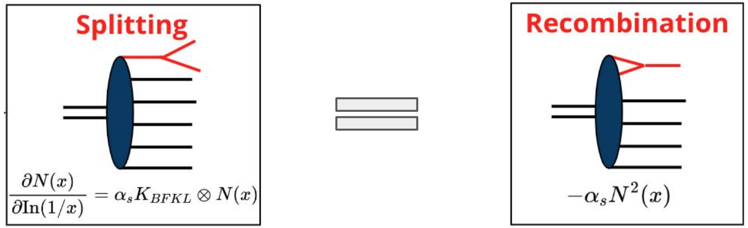
- Rg represents nuclear gluon suppression factor at LO.
- $x \sim 10^{-3}$ - 10^{-2}: flat trend.
- Quickly decrease towards lower x region.

Beyond models' expectations

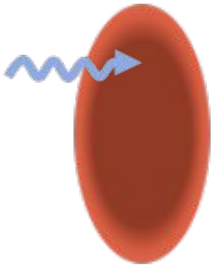
What physics behind?

CMS-PAS-HIN-22-002





$$\frac{\partial N(x)}{\partial \ln(1/x)} = \alpha_s K_{BFKL} \otimes N(x) \quad = \quad -\alpha_s N^2(x)$$



$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

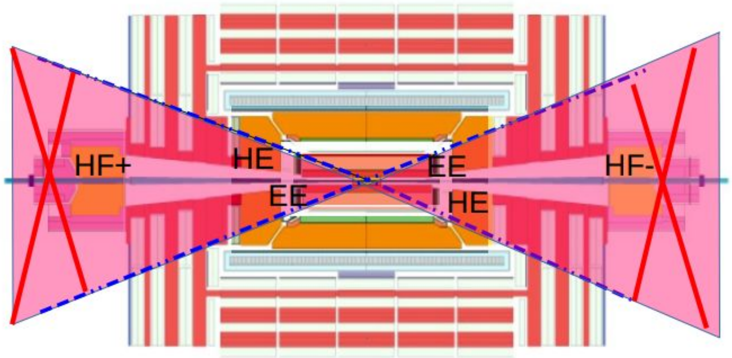
- σ stops rapid rising trend → splitting and recombination of gluons become equal
  - **Clear evidence for gluon saturation!!?**

OR

- Nucleus target becomes totally absorptive to incoming photons → **Black Disk Limit!!?**
  - **Nucleus becomes a black disk, internal structure is invisible.**

Exclusive dijets in UPC PbPb @5 TeV

- Analysis selections (part I):
  - At least one track in the central tracker
  - Particle flow jets using the anti-k_t algorithm with R=0.4
  - Only two jets $|\eta_{lab}| < 2.4$, $p_{T,1} > 30$ GeV, $p_{T,2} > 20$ GeV
  - Veto activity in the forward region ($2.8 < |\eta| < 5.2$): HF, HE and EE calorimeters



RAPGAP MC extensively exploited for **ep** collisions at HERA
is used for modelling exclusive dijet photoproduction via photon-gluon fusion

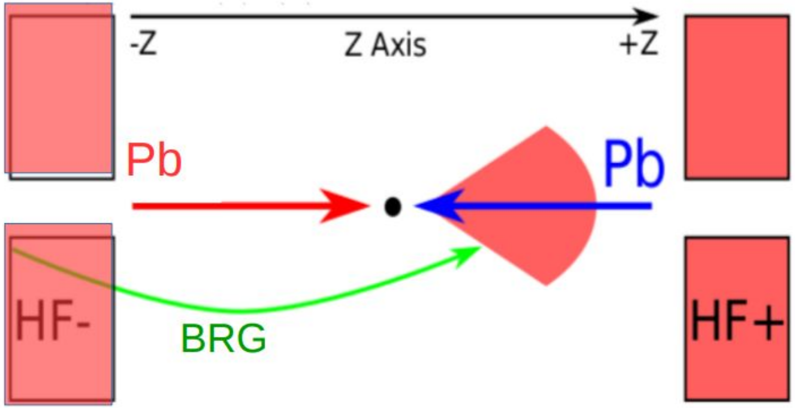
3

Exclusive dijets in UPC PbPb @5 TeV

γ + Pb → jet + jet + Pb events are asymmetric in rapidity.

Rapidity Gap Selection: No track with $p_T > 0.2$ GeV, $|\eta| < 2.5$

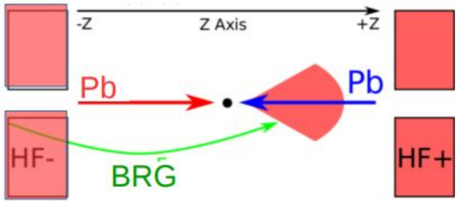
Two separate data sets are defined:
one of them has BRG > FRG, and the other FRG > BRG



Samples are merged by changing the rapidity sign of the jets in the FRG > BRG dataset.

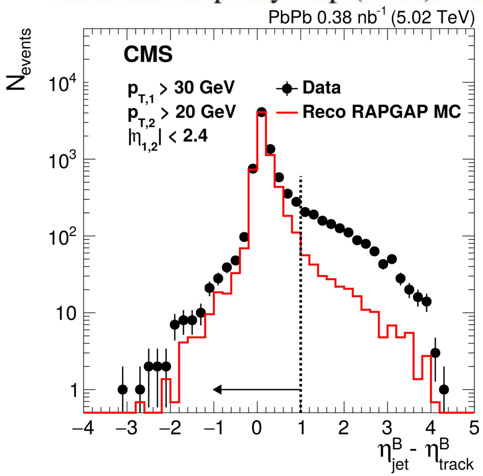
4

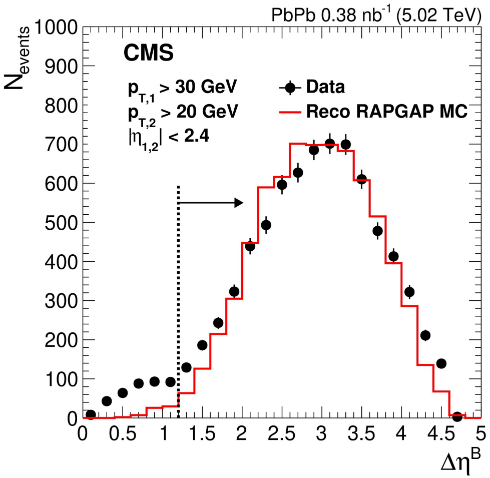
Exclusive dijets in UPC PbPb @5 TeV



No tracker activity far from the jets to reject non-exclusive and two-photon processes.

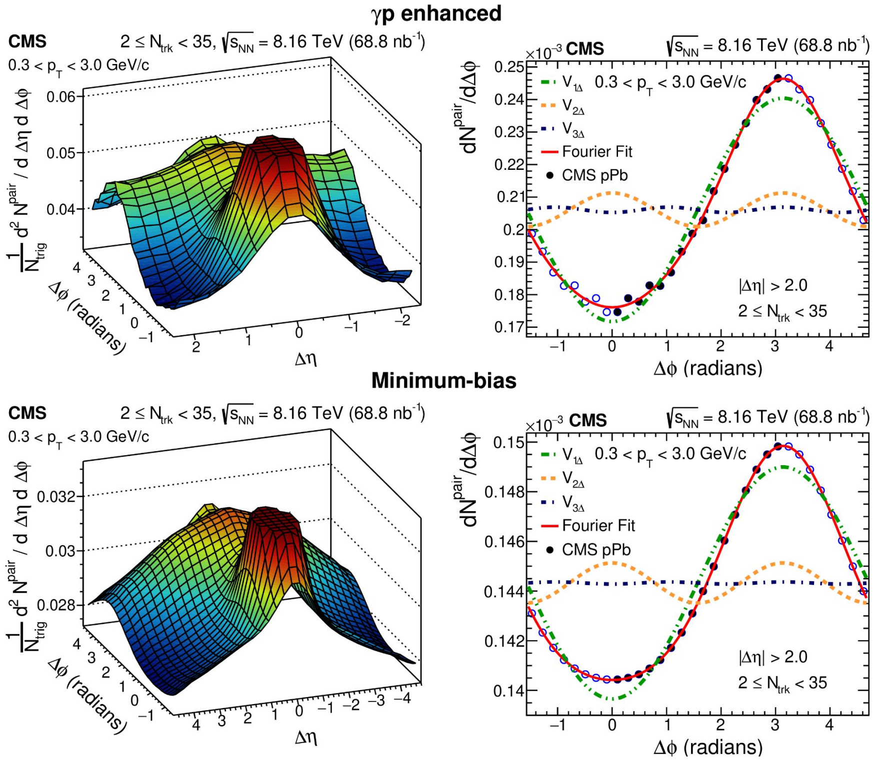
- $\max[\eta_{jet} - \eta_{track}] < 1$
- Backward Rapidity Gap (BRG) > 1.2





5

Two-particle (2PC) azimuthal correlations in γp interactions using pPb

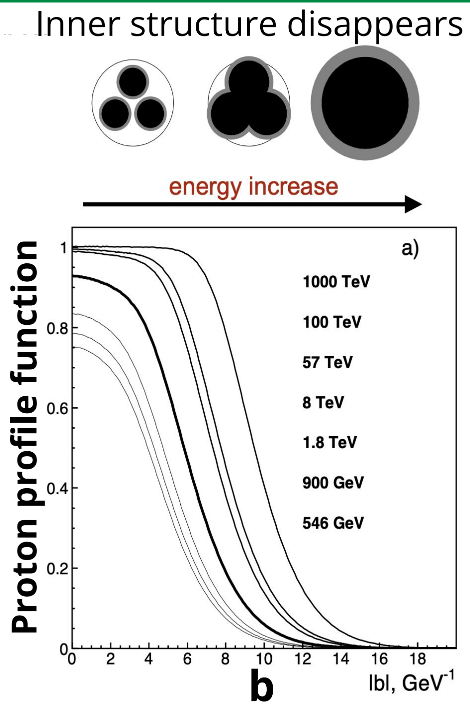


HIN-18-008

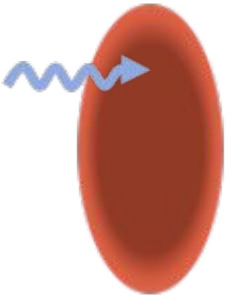
- Select enriched sample of γp events in UPC pPb collisions.
- Require no neutron on Pb-going size ZDC, as well as a large region with no detector activity on Pb going side.
- Plots show 2D and 1D 2PCs in γp events and min-bias pPb events.
- Stronger away-side correlation observed in γp events compared to min-bias pPb.

Another novel regime of QCD: Black Disk Limit

L. Frankfurt, V. Guzey, M. McDermott, M. Strikman **PRL 87 (2001)192301**
L. Frankfurt, M. Strikman, M. Zhalov, **PLB 537 (2002) 51**



In the *strong absorption scenario*, the interaction probability may reach the unitarity limit. The nucleus target becomes totally absorptive to incoming photons.



$$\hat{\sigma}^{\rm inel}_{\rm PQCD} \leq \hat{\sigma}_{\rm black} = \pi R^2_{\rm target}$$

“Black Disk Limit (BDL)”

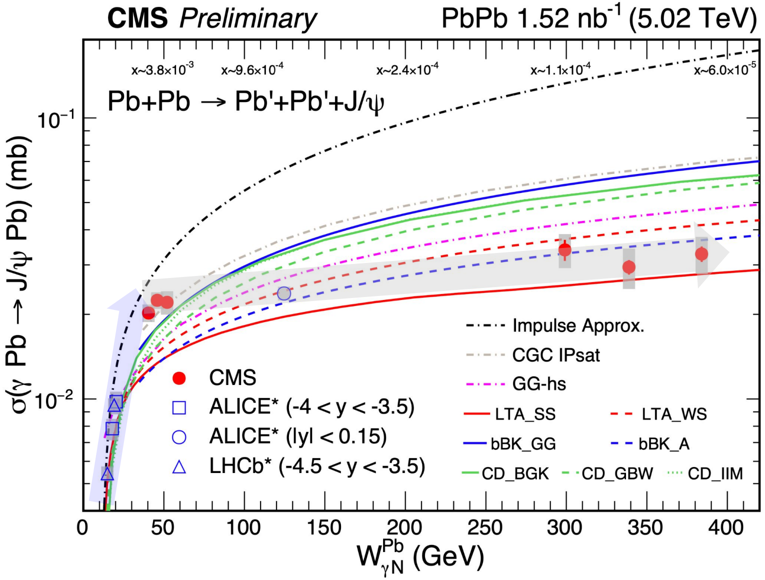
- opposite to the “color transparency”

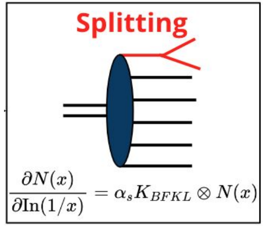
The BDL represents a novel regime at small x when the LO QCD and the notion of the parton distributions becomes inapplicable for describing hard processes .

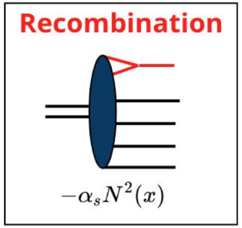
- **New theoretical tools are needed in this regime!**

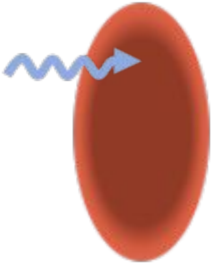
The slowly increasing trend at high W

CMS-PAS-HIN-22-002







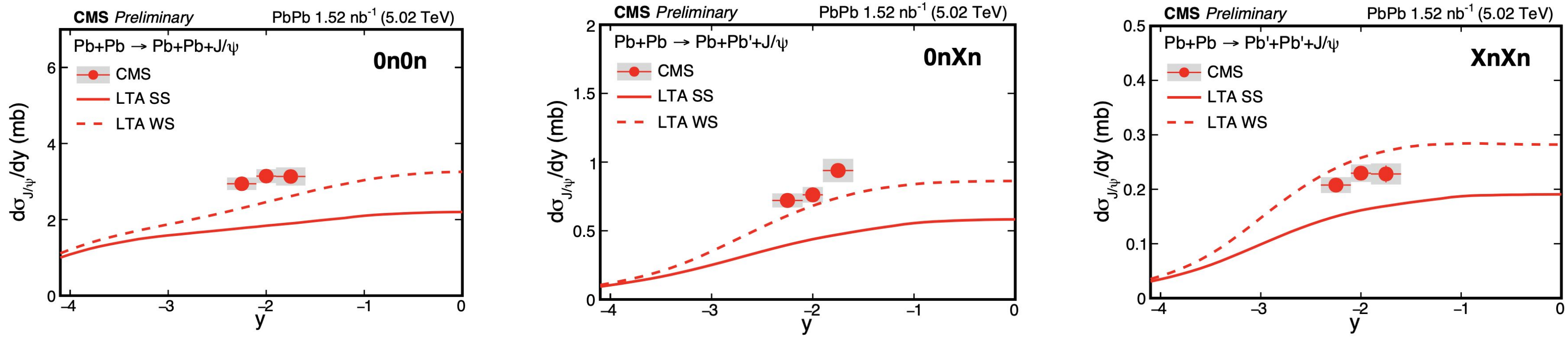


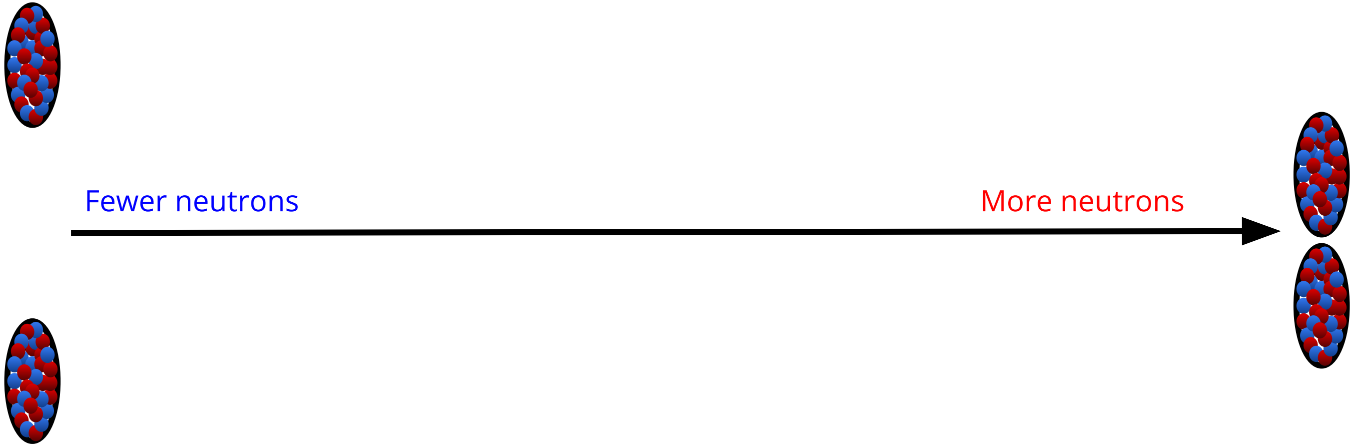
$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

- Periphery of nucleus may not be fully saturated or fully black at W~40 GeV, but gradually turn to saturated or fully black with further increasing of the probing energy.

Coherent Jpsi in 0n0n, 0nXn, XnXn

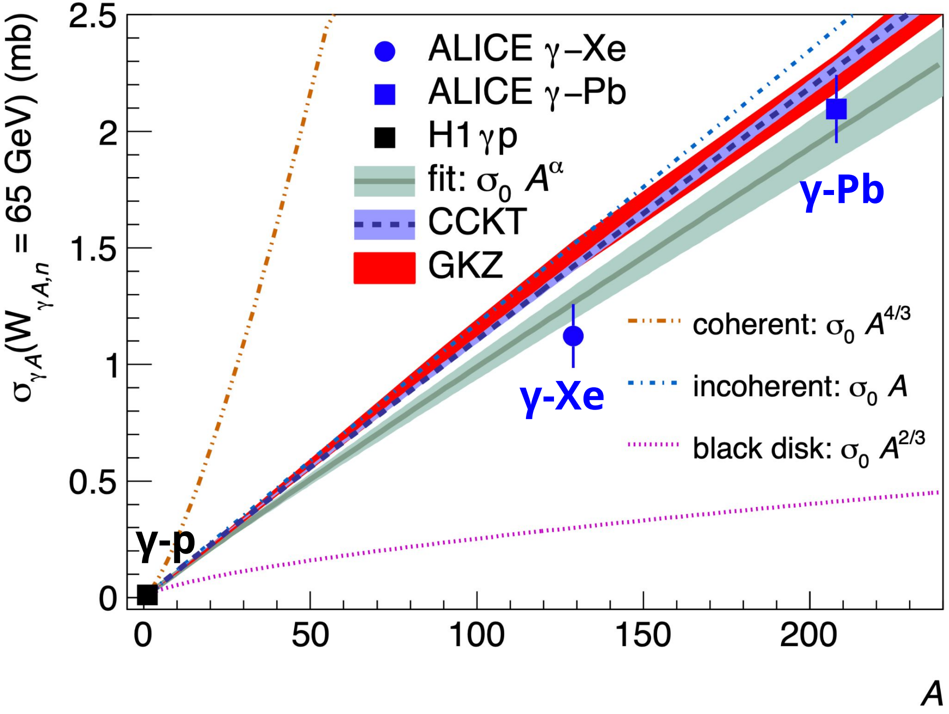
CMS-PAS-HIN-22-002





ALICE UPC ρ vs system size

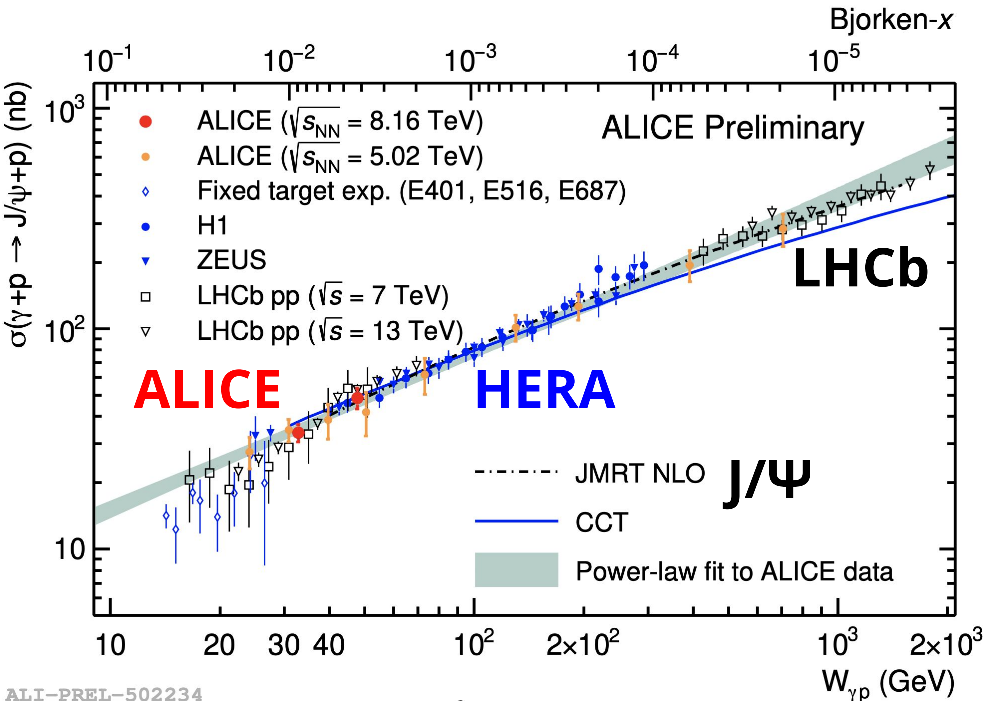
ALICE, **PLB 820 (2021) 136481**

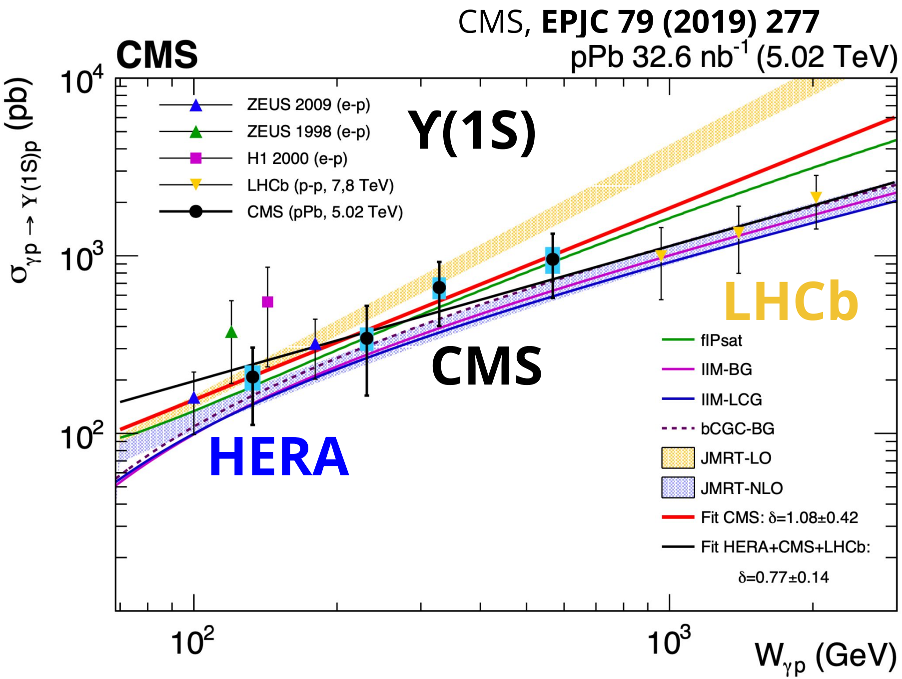


If J/Ψ-nucleus approaches BDL, why ρ-Nucleus does not?

- With A decrease, it is harder to reach BDL → the direct $A^{2/3}$ cannot scale to small A.
- Relation of dipole size vs. M in seen by nucleus is different to what seen by nucleon?

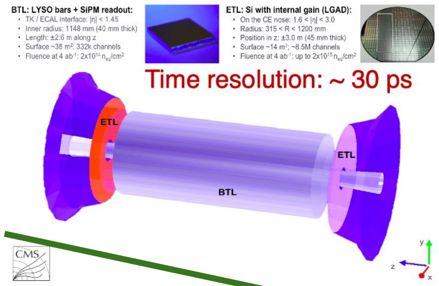
Quarkonium photoproduction in γ-p



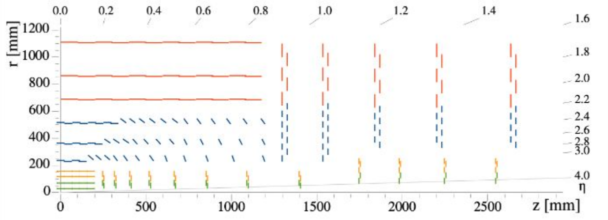


Future opportunities

MIP Timing Detector for PID

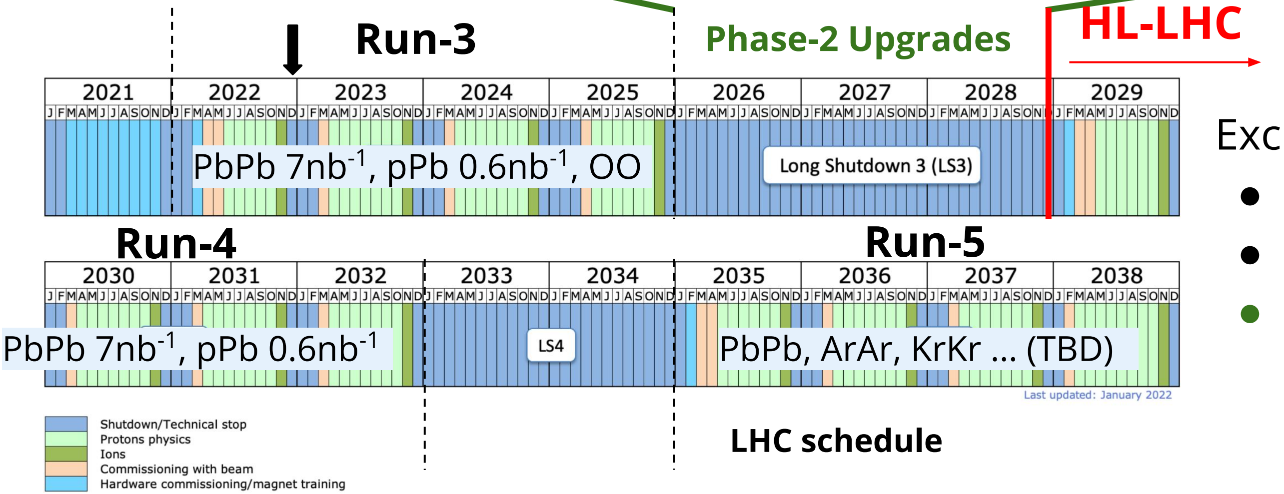


Tracker with |η|<4 and better resolution, lighter materials



- Muon systems with |η|<2.8
- Trigger and DAQ rate: ~10x

……

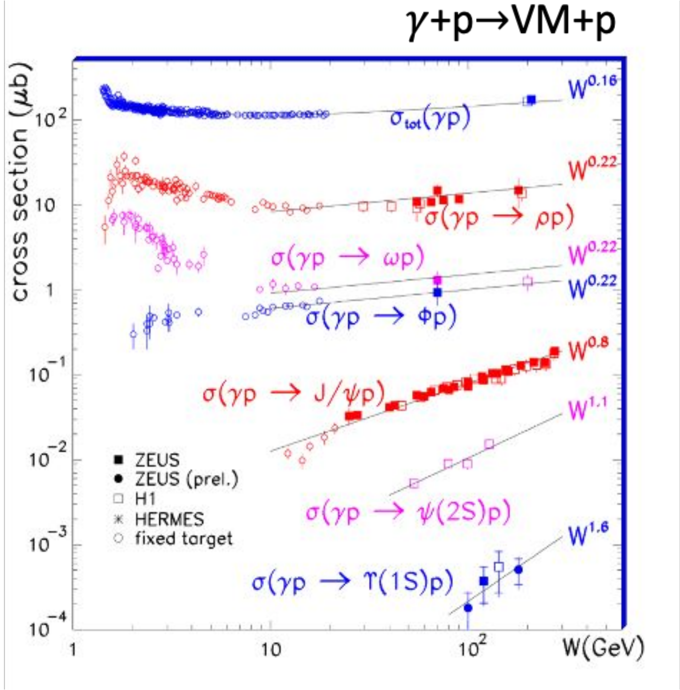


LHC schedule

Exciting opportunities ahead by:

- Higher luminosities.
- A variety of ion species.
- Upgrades enabled by new technologies!

Future opportunities



Various vector meson species in **γPb** as a function of a broad W range with neutron tagging

➢ e.g., control of dipole sizes and hard scales.

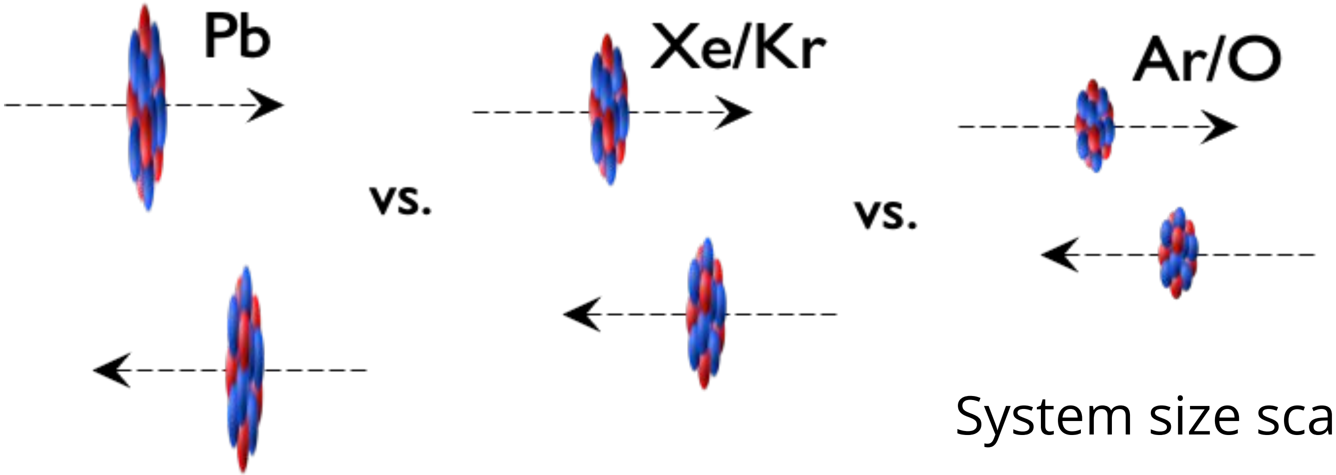
CERN yellow report, **arXiv:1812.06772**

Condition	Tot.	Central 1 Narrow	Central 2 Wide	Forward 1 Narrow	Forward 2 Wide
Rapidity	-	$\lvert y\rvert < 0.9$	$\lvert y\rvert < 2.4$	$2.5 < y < 4.0$	$2 < y < 5$
$e/\pi/\mu$ pseudorapidity	-	$\lvert \eta\rvert < 0.9$	$\lvert \eta\rvert < 2.4$	$2.5 < \eta < 4.0$	$2 < \eta < 5$

PbPb L_{int} = 13 nb^{-1}

Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$Y(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Future opportunities



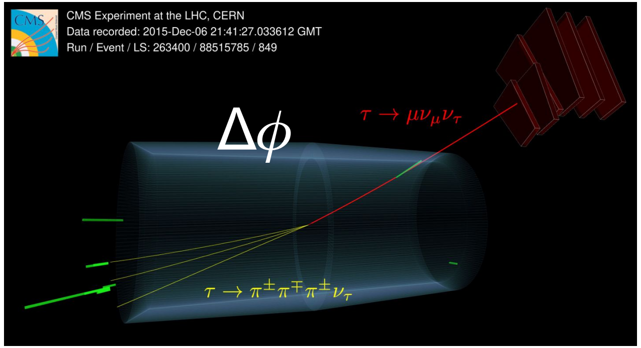
System size scan

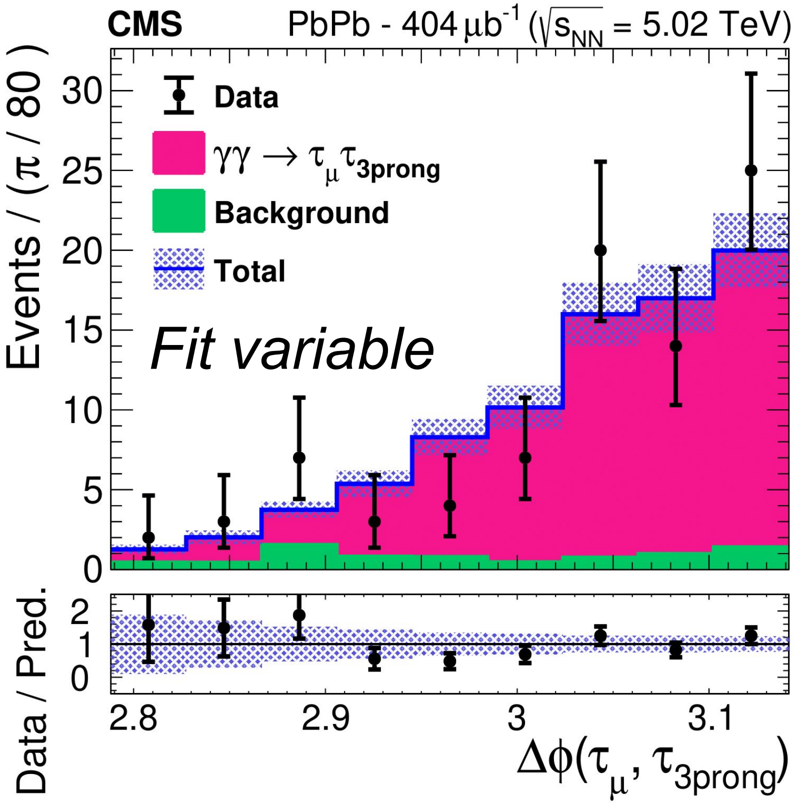
- Variation of saturation scales in search for gluon saturation.
- When approaching the BDL:
  - Coh. cross section scales with $A^{2/3}$
  - Incoh. cross section strongly suppressed, internal substructure becomes invisible

Signal yield estimation

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

HIN-21-009





Cross section measurement

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

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

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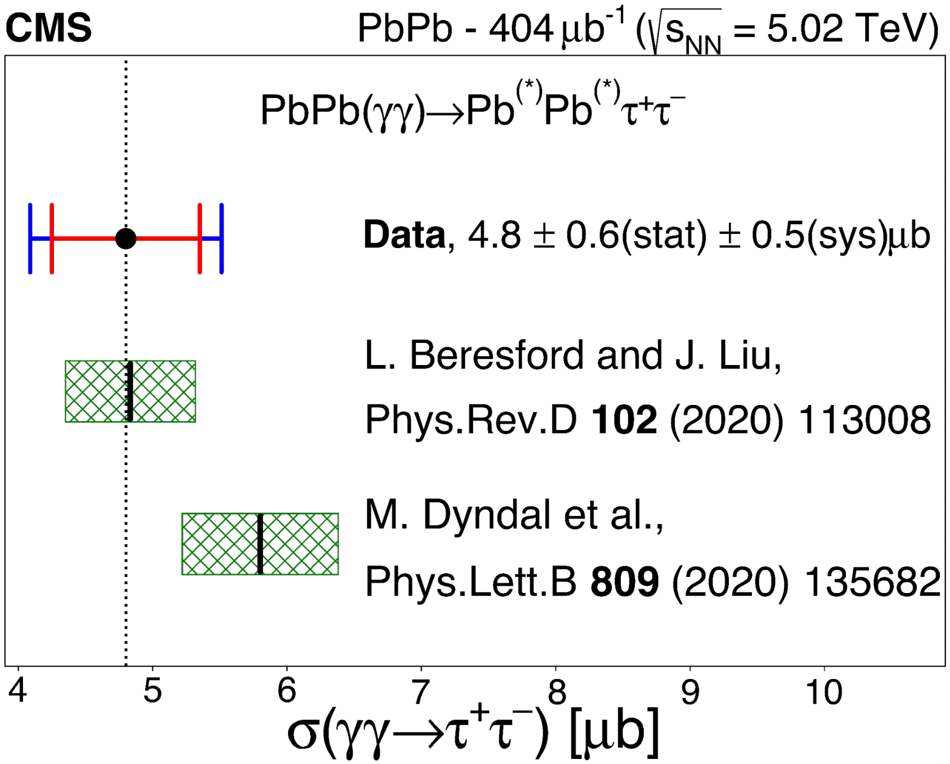
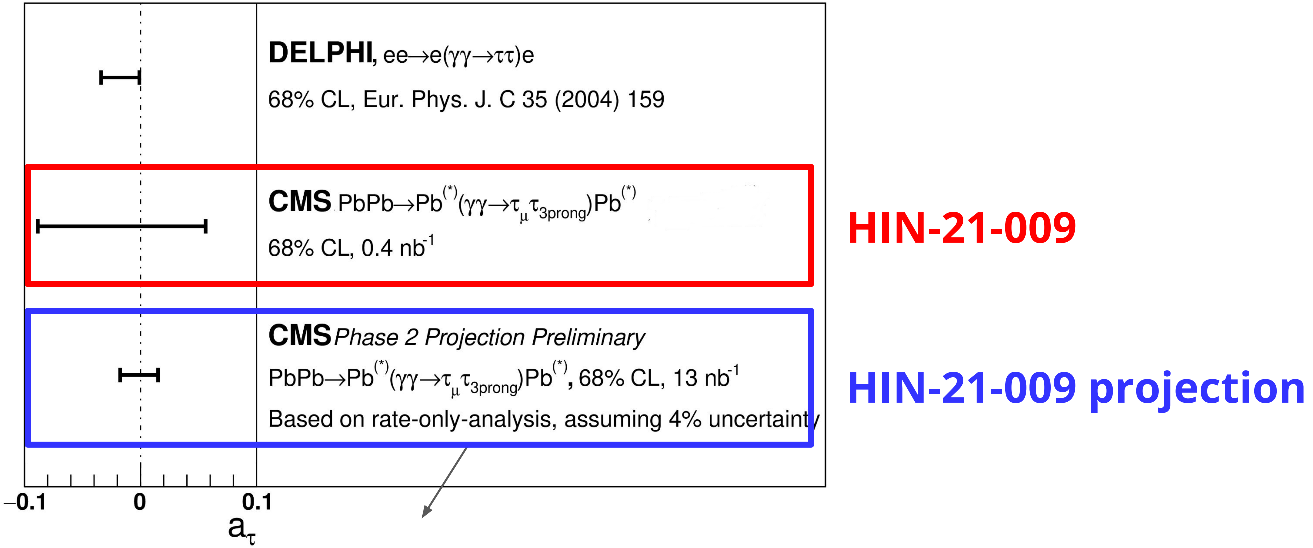


$$\sigma_{fiducial} = 4.8 \pm 0.6(stat) \pm 0.5(sys)\ \mu b$$

Constraints on a_τ, performance at HL-LHC, a_τ from ATLAS

- Using the theo calculation of $\sigma(\gamma\gamma\rightarrow\tau\tau)$ as a function of a_τ –scale only
  - **model-dependent measurements** at LHC can be obtained
- We expect a total uncertainty well below the current theory uncertainty
  - projected limit at HL-LHC **competing with** LEP



More final states → further improvements

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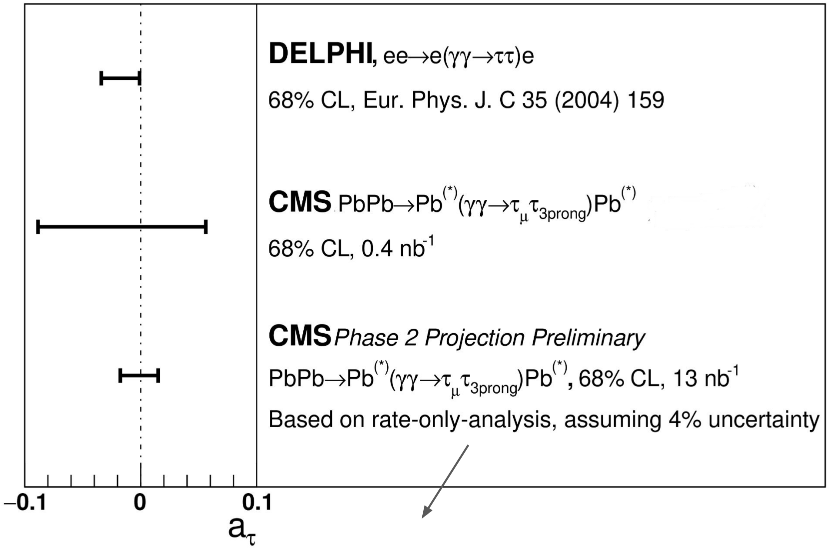
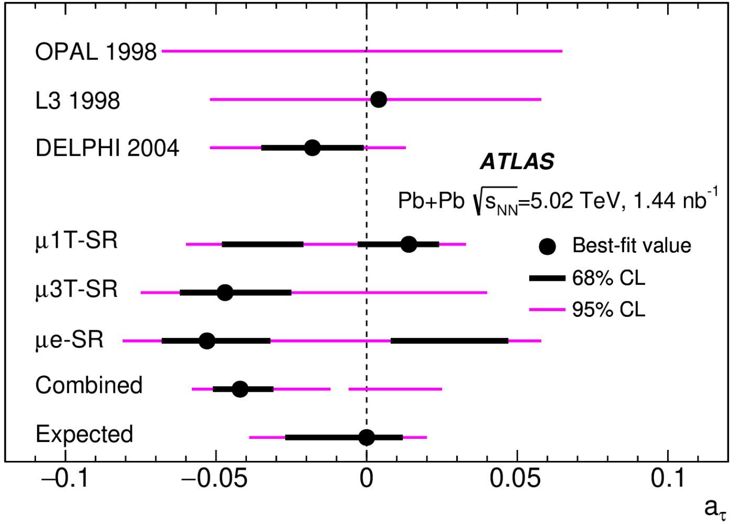


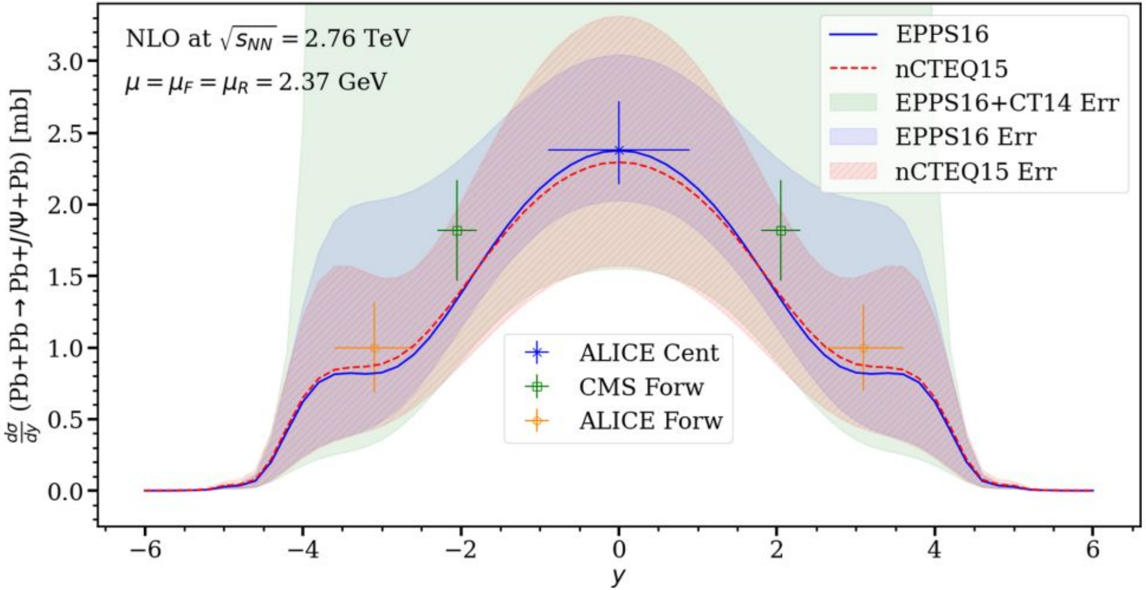
More final states → further improvements

Sensitivity from shape analysis+final states



Nuclear PDFs uncertainty in exclusive J/Ψ production

- EPPS16 larger unc in fwd region (more freedom in the gluon PDF shape than nCTEQ)
- Rapid gluon increase at low-x dictates the upper boundaries of the large unc
  → ***reduced scale sensitivity and stronger dependence on the gluon PDFs for Υ's?***



Outlook

- For the first time, **disentangled the low and high γ energy** contributions to coh. J/ψ
  - a new region from W=40 to 400 GeV to be studied/understood
  - interesting recent theo dev that the small-x **quark** PDFs dominate exclusive J/ψ at y !~0
- τ+τ- observation paves the way for **precise at a_τ (HL-)LHC→ cross exp combinations**

HIN-21-009