Diffractive and photon-induced processes at CMS (focusing on heavy ion data sets)

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on behalf of the CMS Collaboration

Contact:
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XXIX The Cracow Epiphany Conference

Outline of (recent) diffractive & photo-induced results

- **Photon-nucleus energy dependence of coherent J/ψ cross session in UPC PbPb, PAS-HIN-22-002**
  - comprehensive study of the coherent J/ψ photo-production, also in neutron multiplicities
- **Observation of τ lepton pair production in UPC PbPb, HIN-21-009**
  - pursuing better constraints on τ lepton anomalous magnetic moment than LEP(II)
- **Azimuthal correlations of exclusive dijets with large Q_T in pPb, HIN-18-011**
  - nontrivial parton distributions inside Pb or simply from ISR/FSR?
- **Two-particle azimuthal correlations in γp interactions using pPb, HIN-18-008**
  - till what size we have a strongly interacting fluid that responds to the initial geometry?

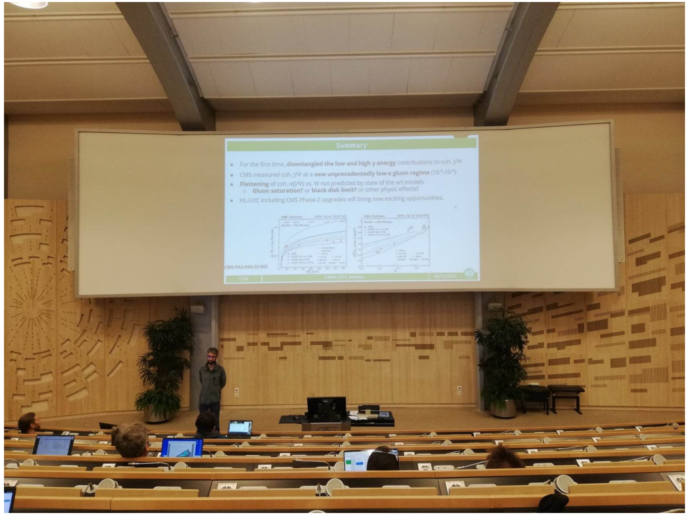
All NEW relative to the last Epiphany version

Recent publicity

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

CERN seminar (André Ståhl, thx for the slides!)

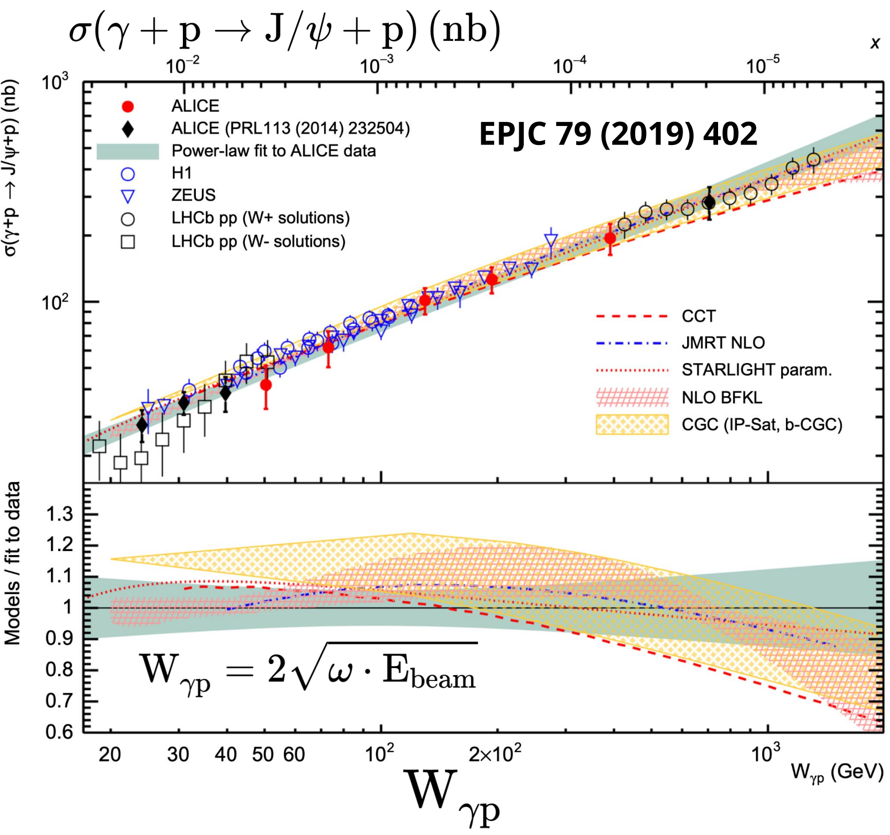
Probing gluon pdf at x->0 with ultraperipheral PbPb collisions at 5.02 TeV in CMS



PRL Editor’s suggestion (to appear), 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)

Search for gluon saturation with γp interactions



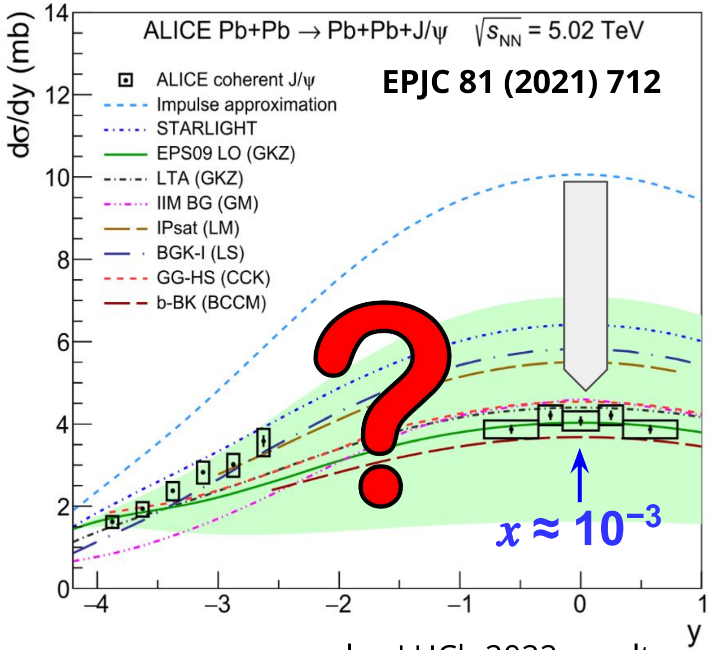
J/ψ photoproduction from **photon-proton** interactions in ep, pPb and pp collisions

- ❖ 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

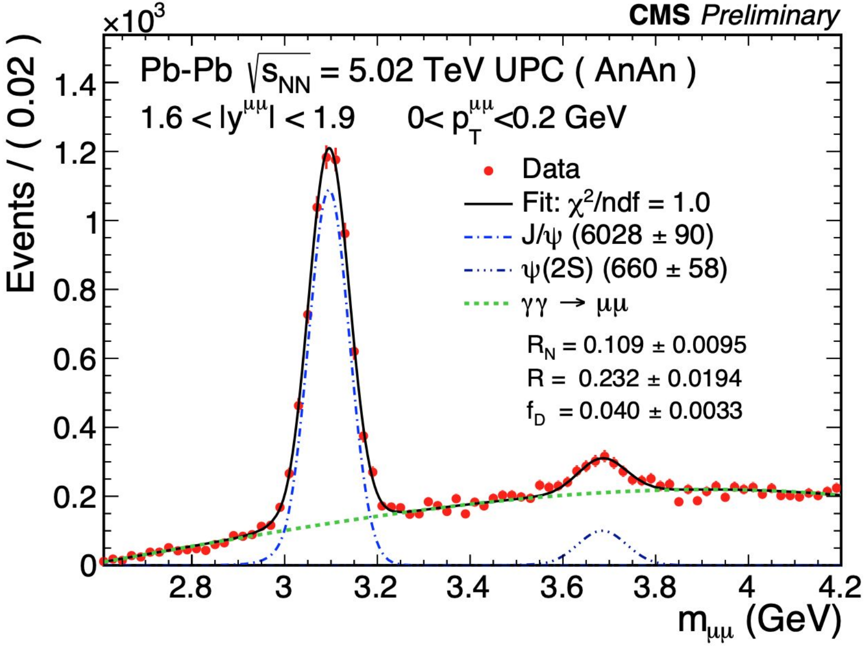
- Coherent Vector Meson production extensively measured at LHC.
- **LO: σ(J/ψ) ∝ [xG(x)]^2 → σ(J/ψ) < I.A.** (no nuclear effects) → evidence for strong nuclear modification in heavy nuclei.
- No theory calculations (e.g., shadowing, saturation) can simultaneously predict mid- and forward rapidity data!?

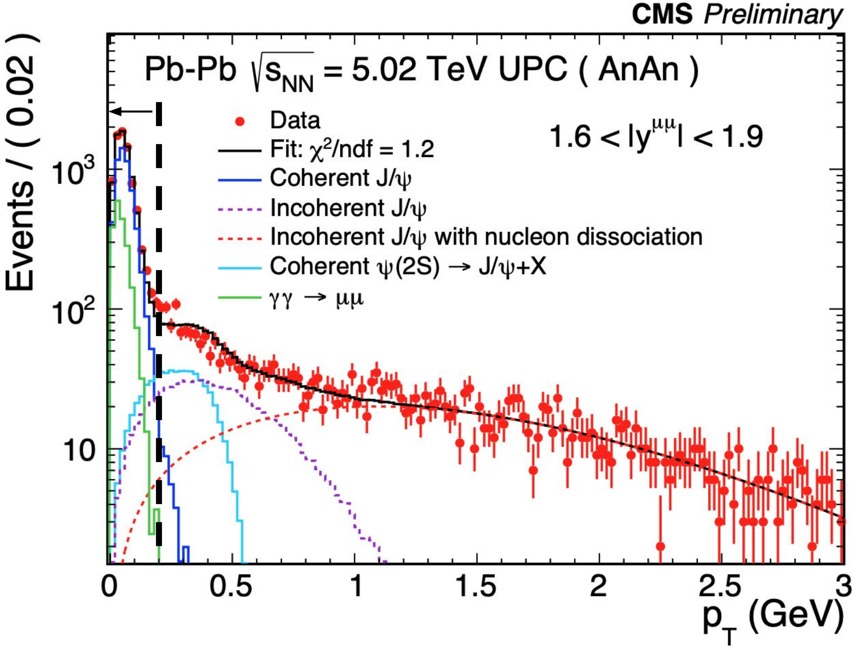


also LHCb 2022 results
arXiv:2206.08221

How robust our signal extraction is?

CMS-PAS-HIN-22-002



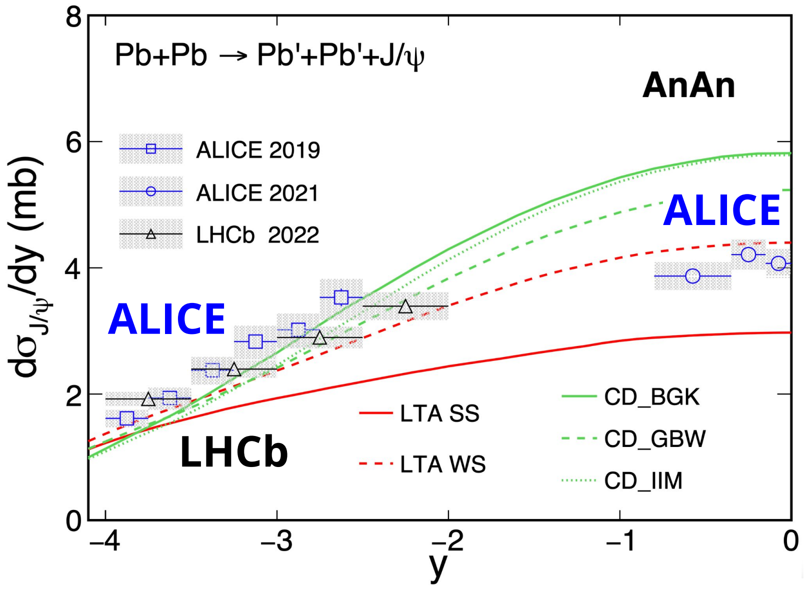


Signal yields are extracted by fitting the mass and transverse momentum spectra.

Clean event sample, well described

Coherent J/ψ in forward and mid-rapidity ranges

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

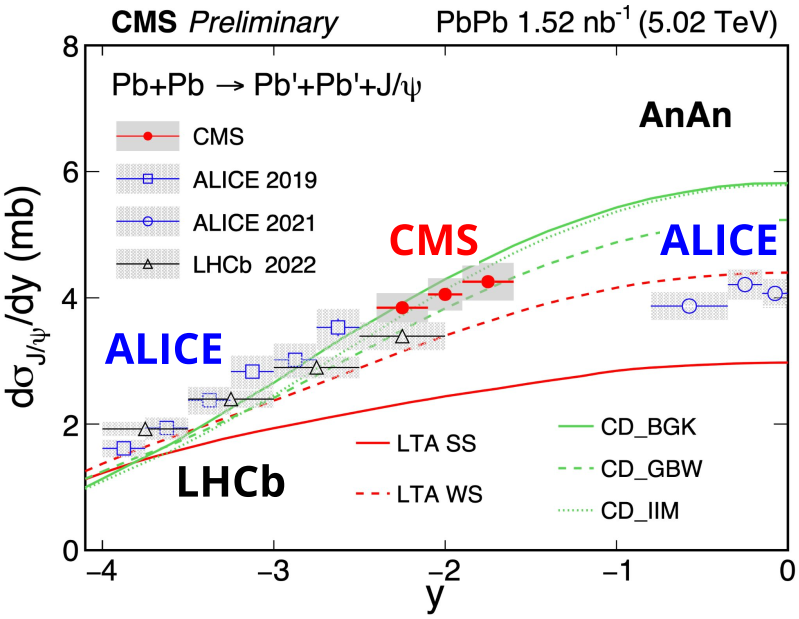


AnAn: No forward neutron selection

- 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.**

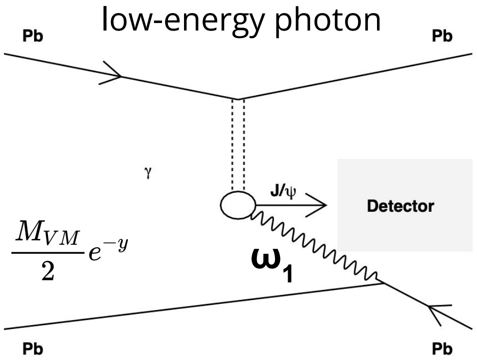
$$\frac{d\sigma^{coh}_{J/\psi}}{dy} = \frac{N(J/\psi)}{(1+f_I+f_D)\cdot\epsilon(J/\psi)\cdot Acc(J/\psi)\cdot BR(J/\psi\rightarrow\mu\mu)\cdot L_{int}\cdot\Delta y}$$

- 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

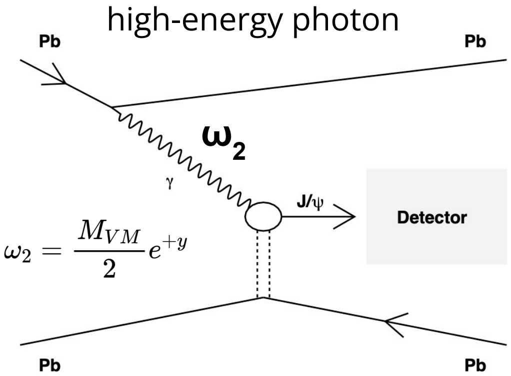
Search for gluon saturation in heavy nuclei–the challenge

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

- A two-way ambiguity!



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

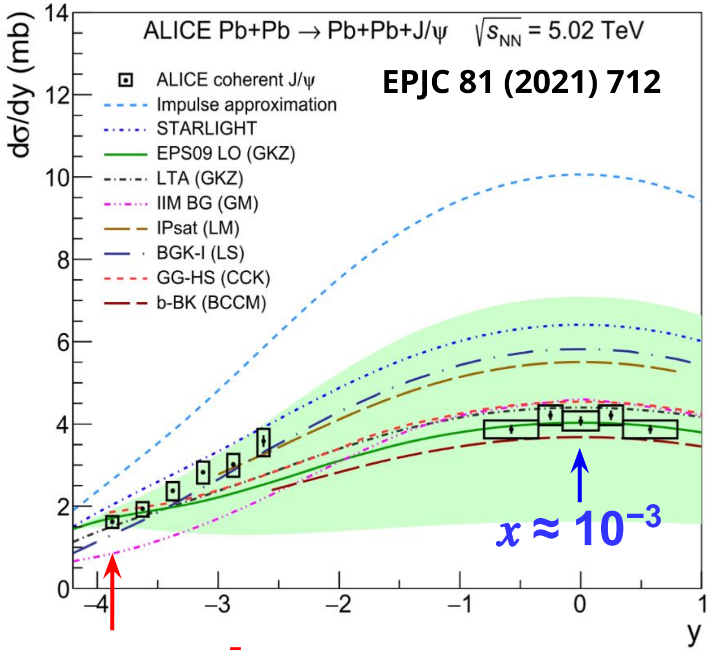


$\omega_2 = \frac{M_{VM}}{2} e^{+y}$

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

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}**

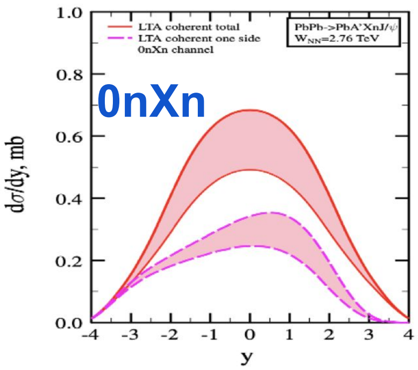


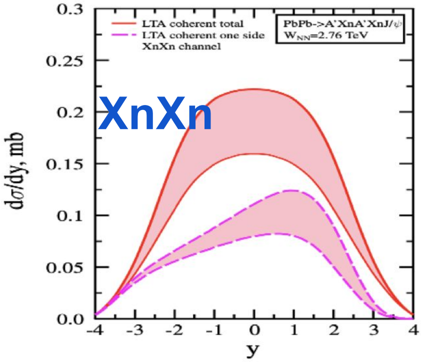
$x_1 \approx 10^{-5}$ or $x_2 \approx 10^{-2}$ (~95% high-x)

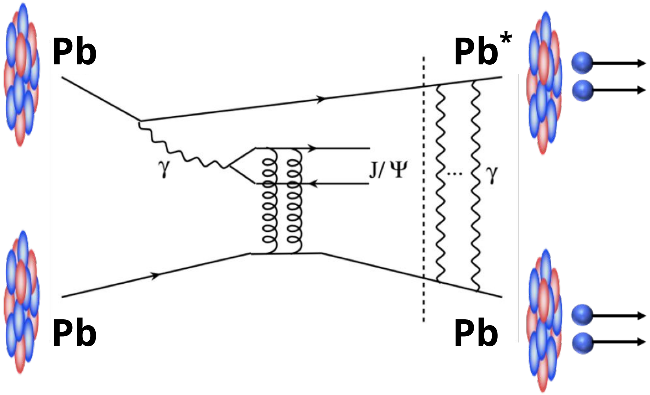
$x_{1,2} = \frac{1}{\omega_{1,2}} \cdot \frac{M_{VM}^2}{2\sqrt{s_{NN}}}$

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**

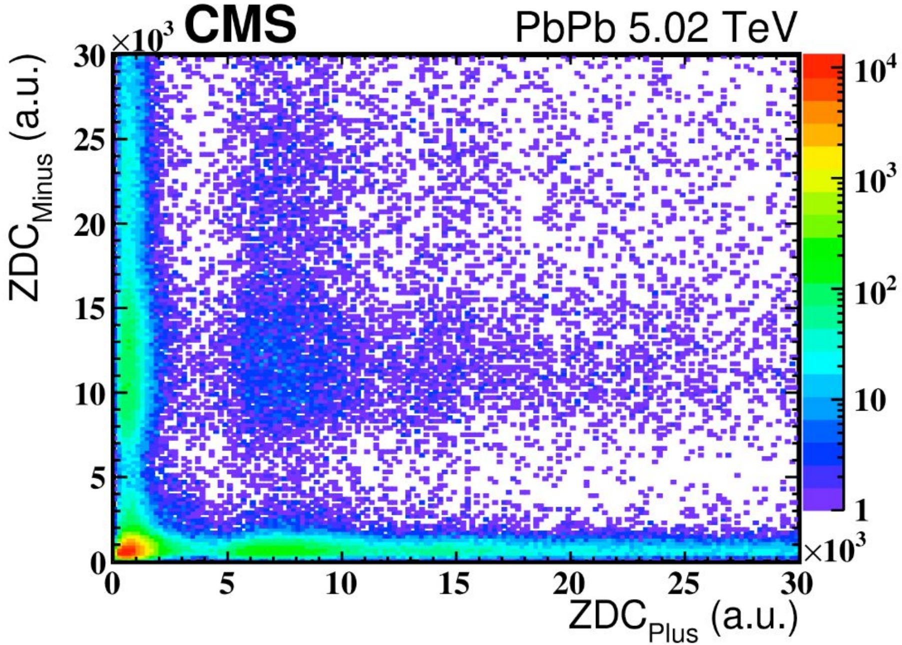
$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

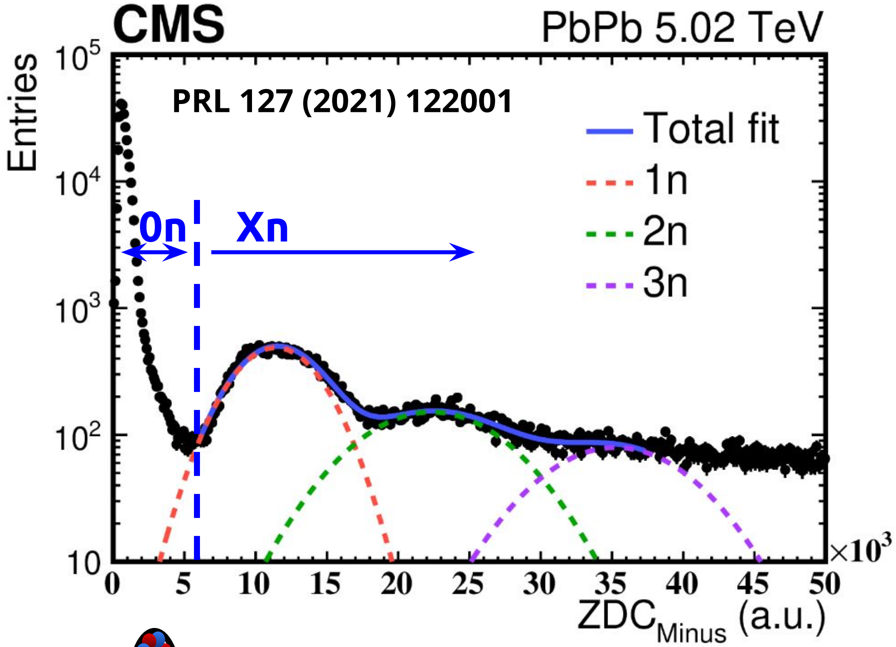
$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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

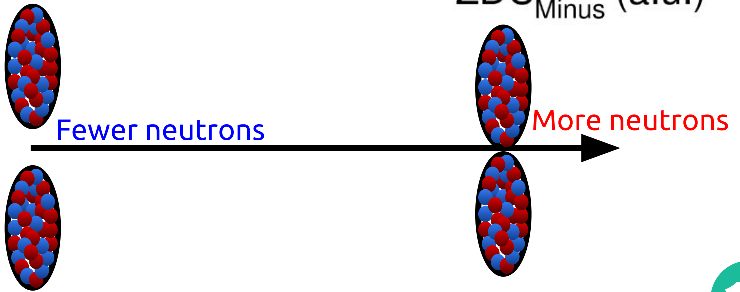
Entering a new regime of small x ~ 10^{-4}-10^{-5} in nuclei w/o the need to increase the energy!

Event classification in neutron multiplicity classes





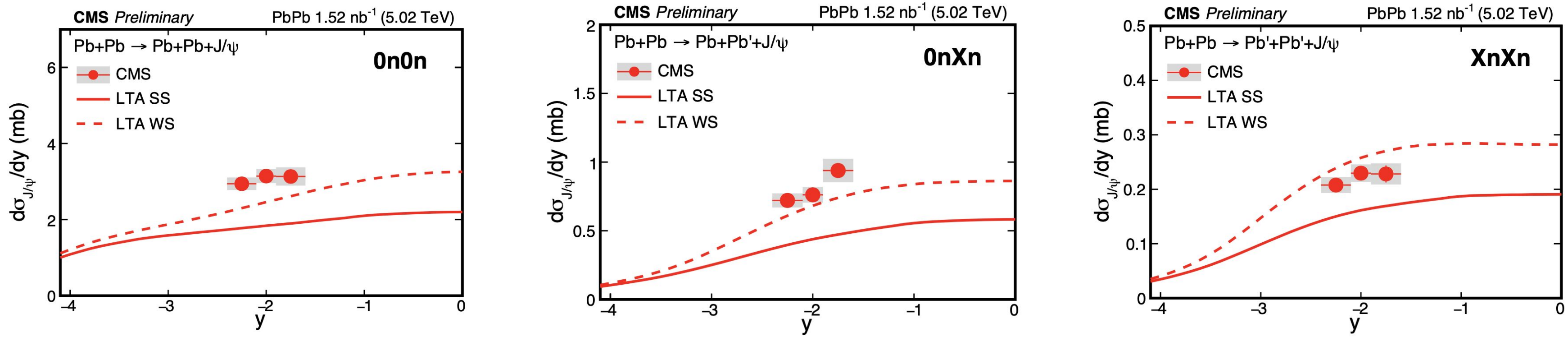
- Multi-Gaussian fits to disentangle # of neutrons:
  - 0n0n, 0nXn, XnXn (X: ≥1)
  - high purity



Method established in HIN-19-014

Coherent J/ψ in 0n0n, 0nXn, XnXn

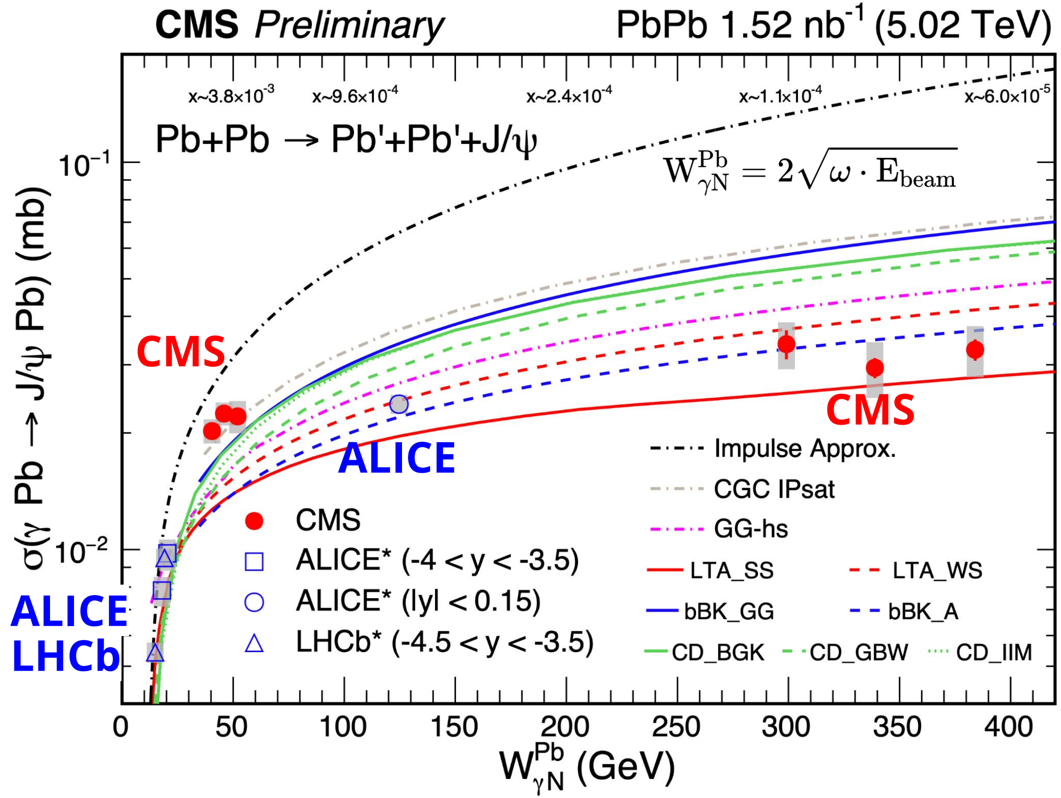
CMS-PAS-HIN-22-002



- 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:

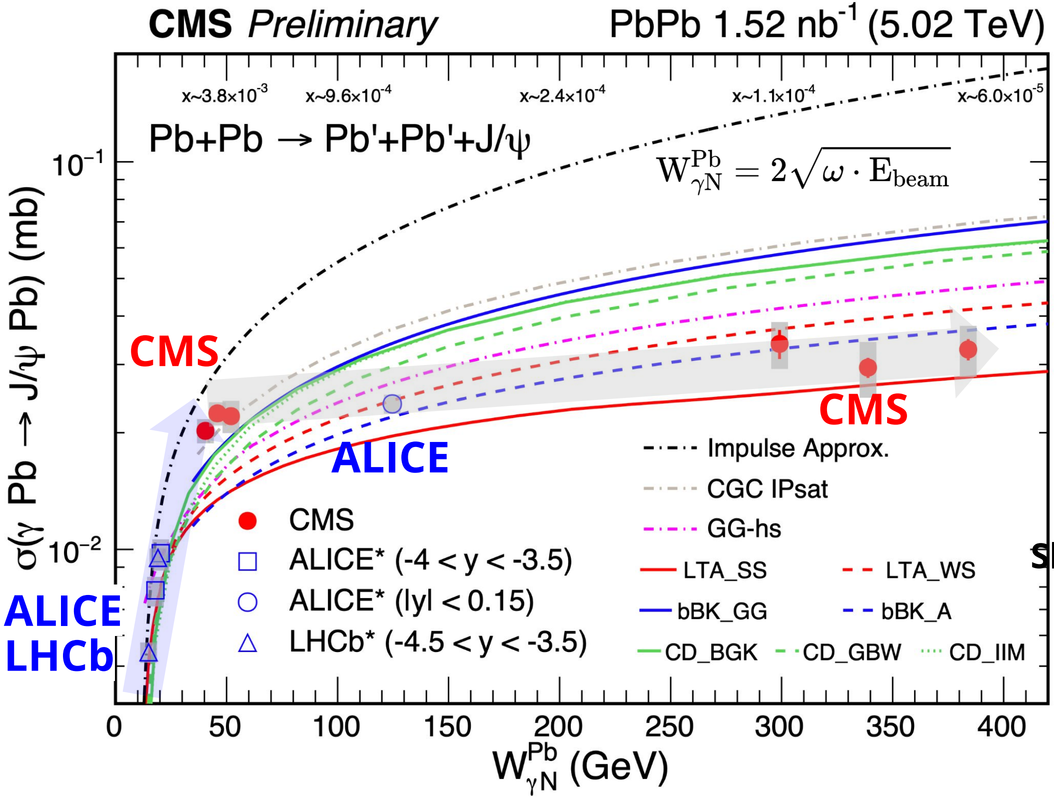
- Data close to IA at low W.
- Data lower than IA at W~125 GeV.

New data from CMS:

- Rapid increase at W<40 GeV.

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

CMS-PAS-HIN-22-002



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:

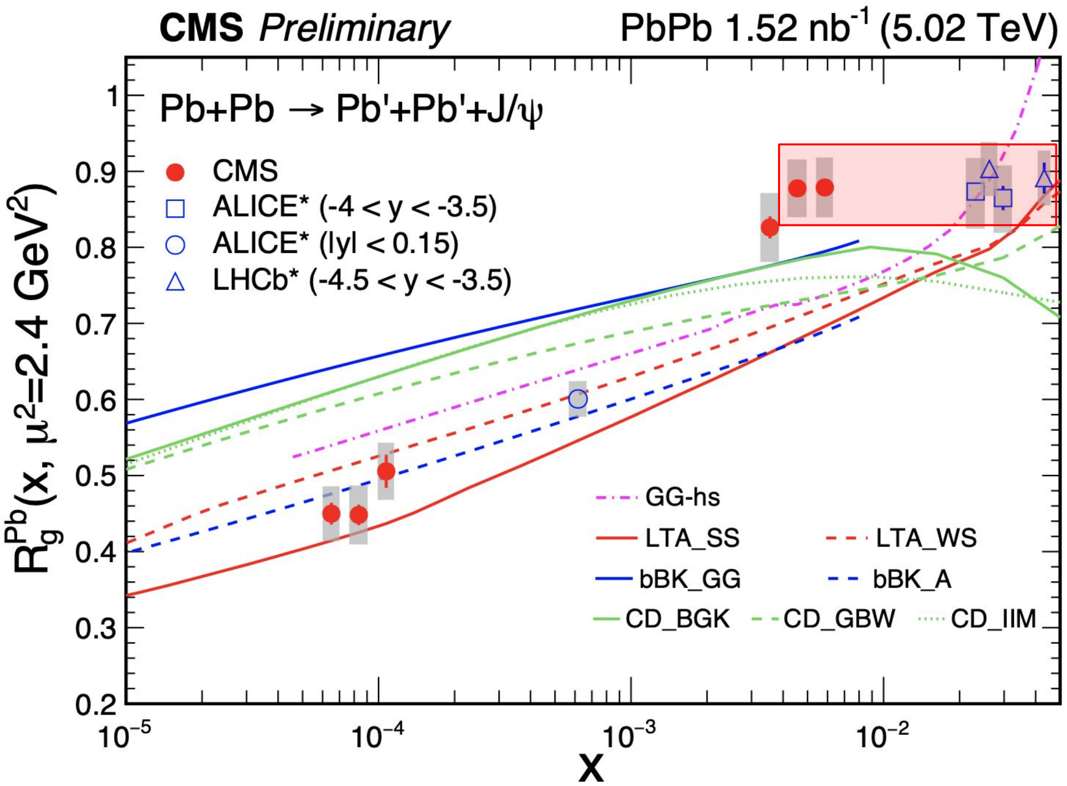
- Rapid increase at W<40 GeV.
- A nearly flat trend for W>40 GeV.

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



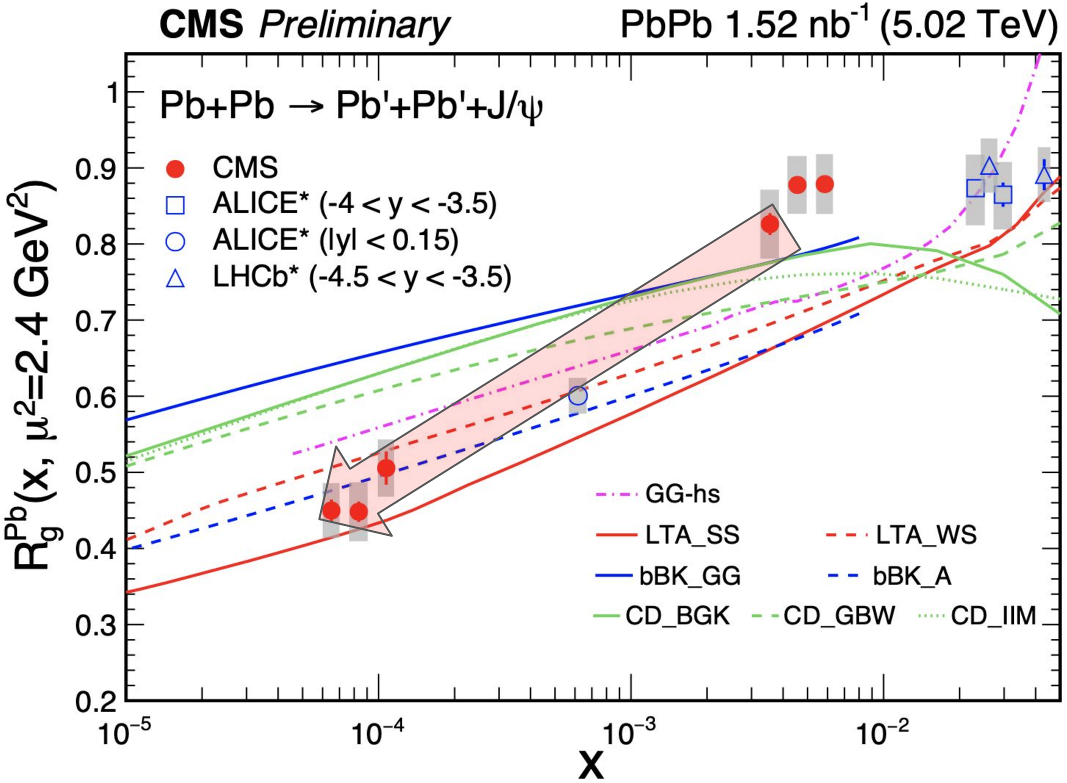
$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}} \right)^{1/2}$$

Impulse approx. (IA) neglects all nuclear effects.

- Rg represents nuclear gluon suppression factor at LO.
- x~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.

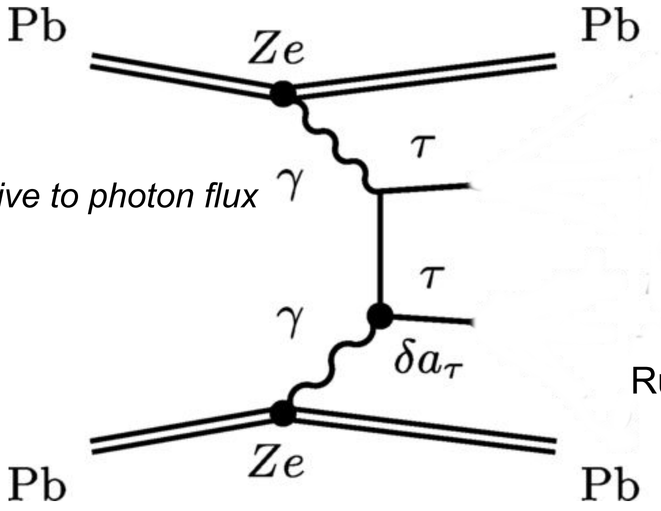
- Rg represents nuclear gluon suppression factor at LO.
- x~10^{-3} - 10^{-2}: flat trend.
- Quickly decrease towards lower x region.

Beyond models' expectations

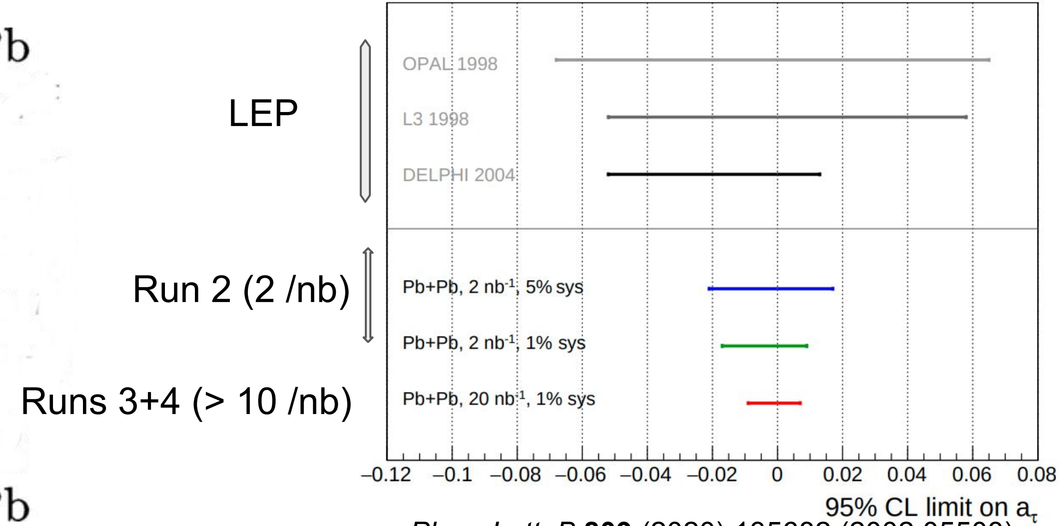
Overview of the $\gamma\gamma \to \tau\tau$ process

- **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)



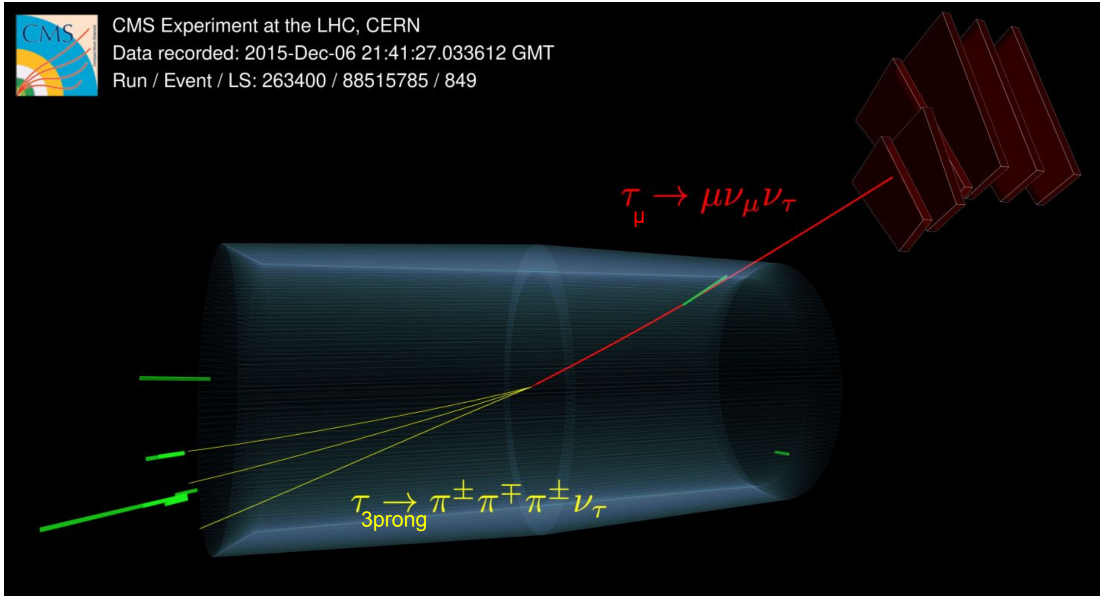
Phys. Lett .B **809** (2020) 135682 (2002.05503)

Phys. Rev. D **102** (2020) 113008 (1908.05180)

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**

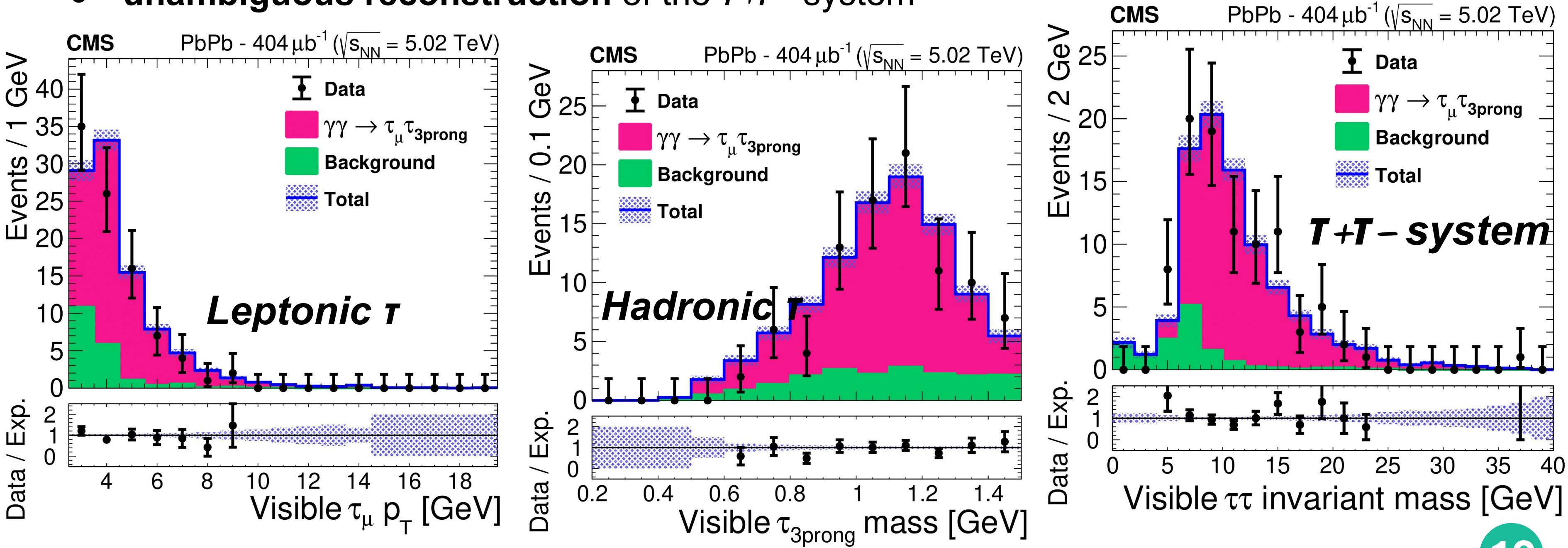
→ All channels needed for **ultimate precision**



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

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

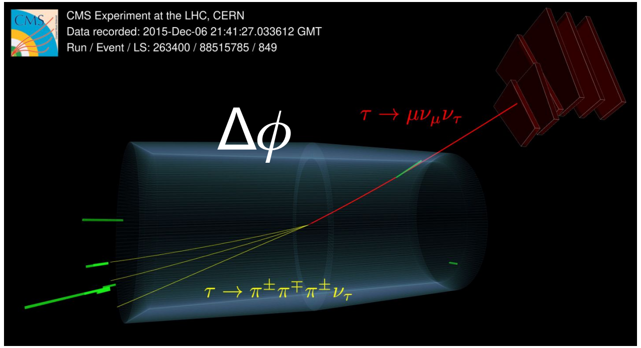
HIN-21-009

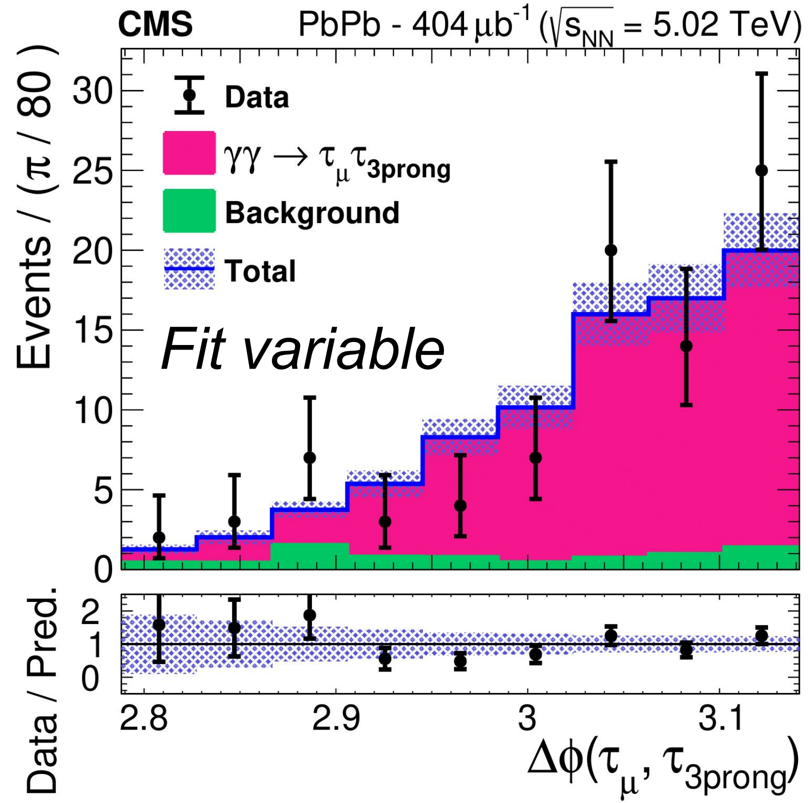


Signal yield estimation

HIN-21-009

- 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 5*σ***
  - **taking into account** systematic uncertainties
    - affecting the rate with log-normal priors
    - affecting the shape with Gaussian prior

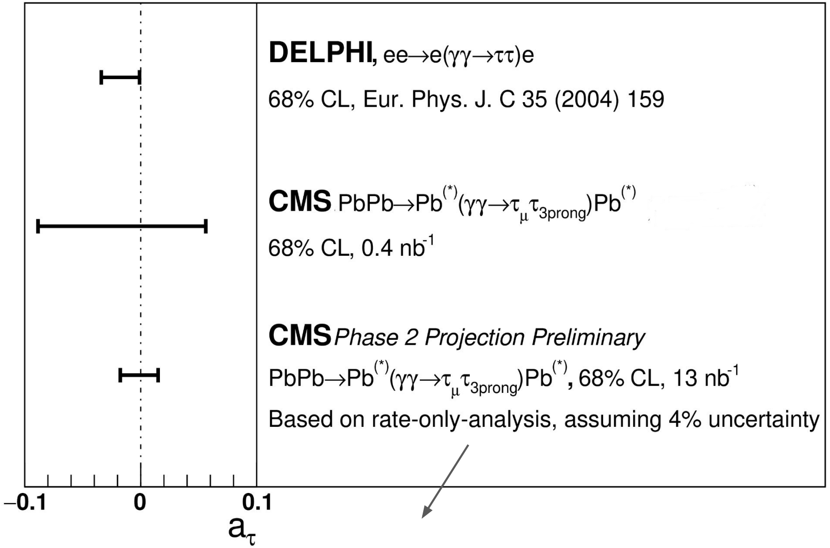




Constraints on a_τ, performance at HL-LHC, a_τ from ATLAS

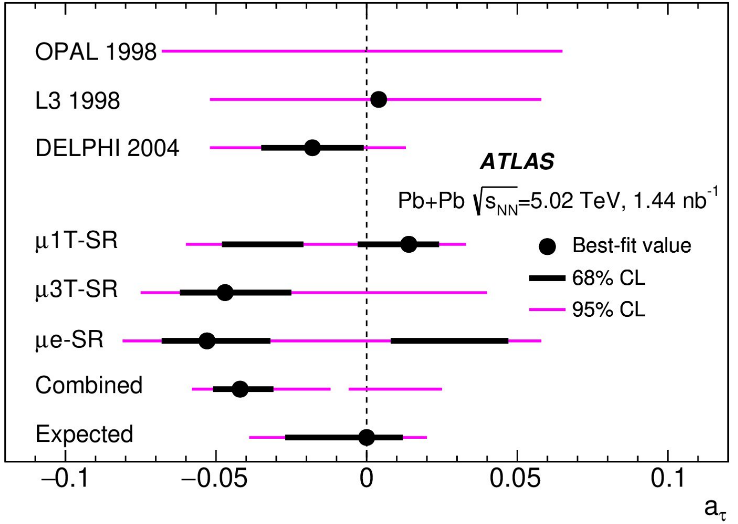
- Using the theo calculation of $\sigma(\gamma\gamma\to\tau\tau)$ as a function of a_τ –scale only
  - **model-dependent measurements** at LHC can be obtained

- We expect a total uncertainty well below the current theory uncertainty
  - projected limit at HL-LHC **competing with** LEP



More final states → further improvements

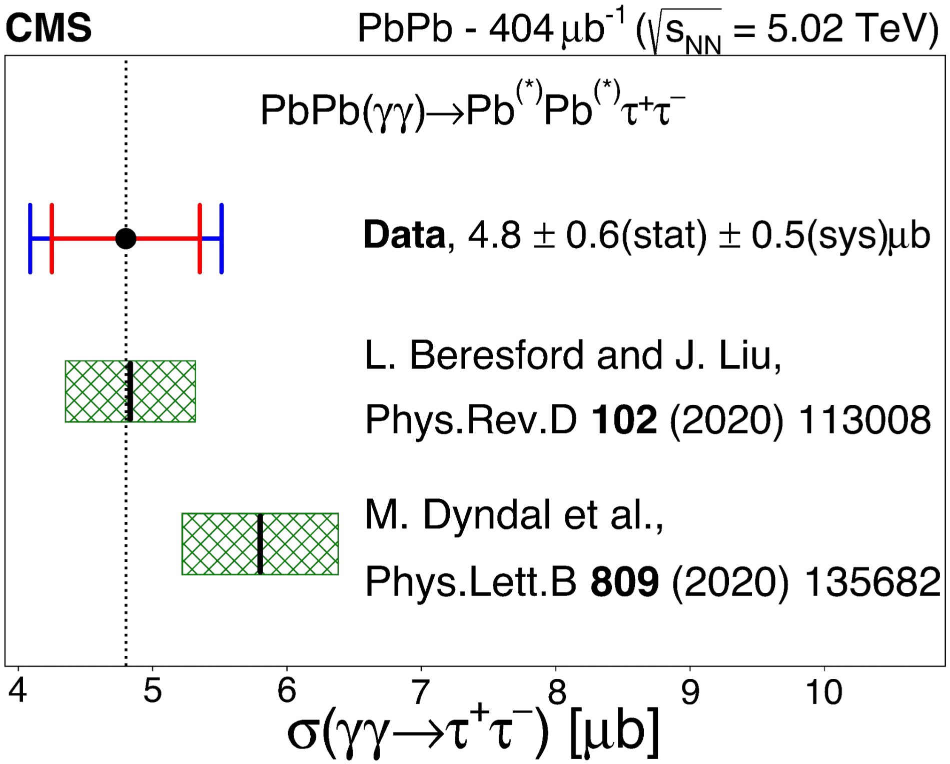
Sensitivity from shape analysis+final states



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%

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

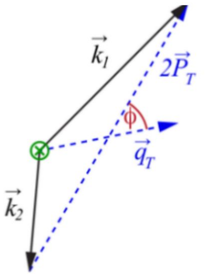


HIN-21-009

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

Exclusive dijets with large Q_T in pPb

- 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., $P_T > Q_T$



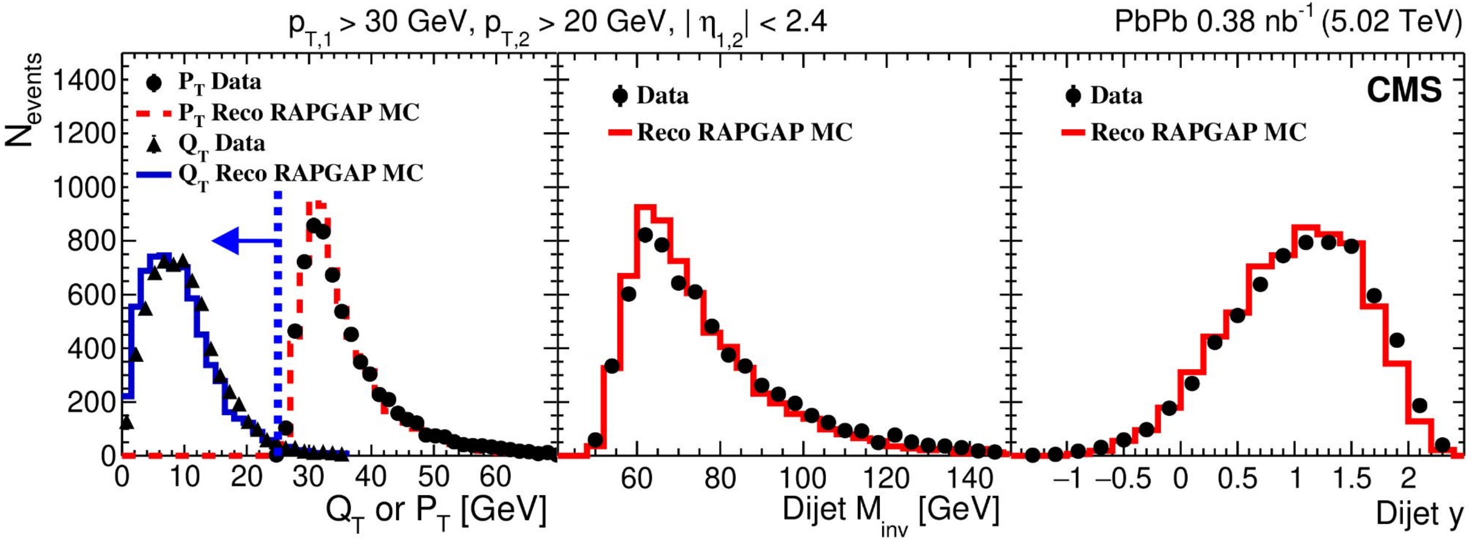
Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k_1} + \vec{k_2}$$

Vector difference of 2 jets

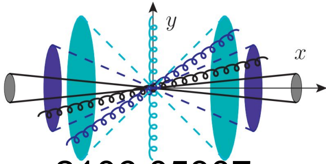
$$\vec{P}_T = \frac{1}{2}(\vec{k_1} - \vec{k_2})$$

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)>



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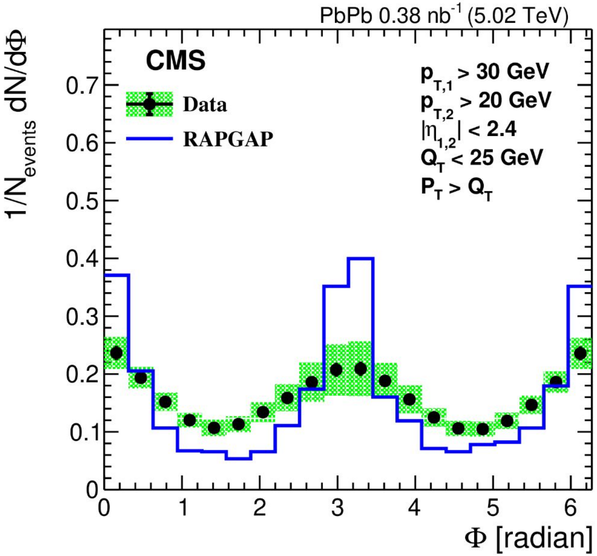
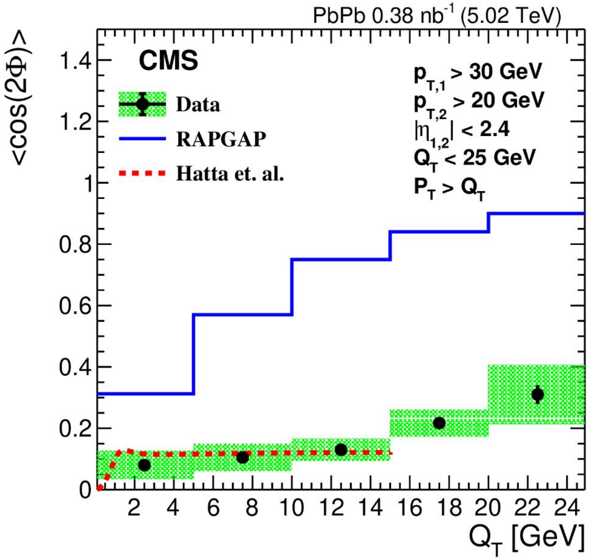
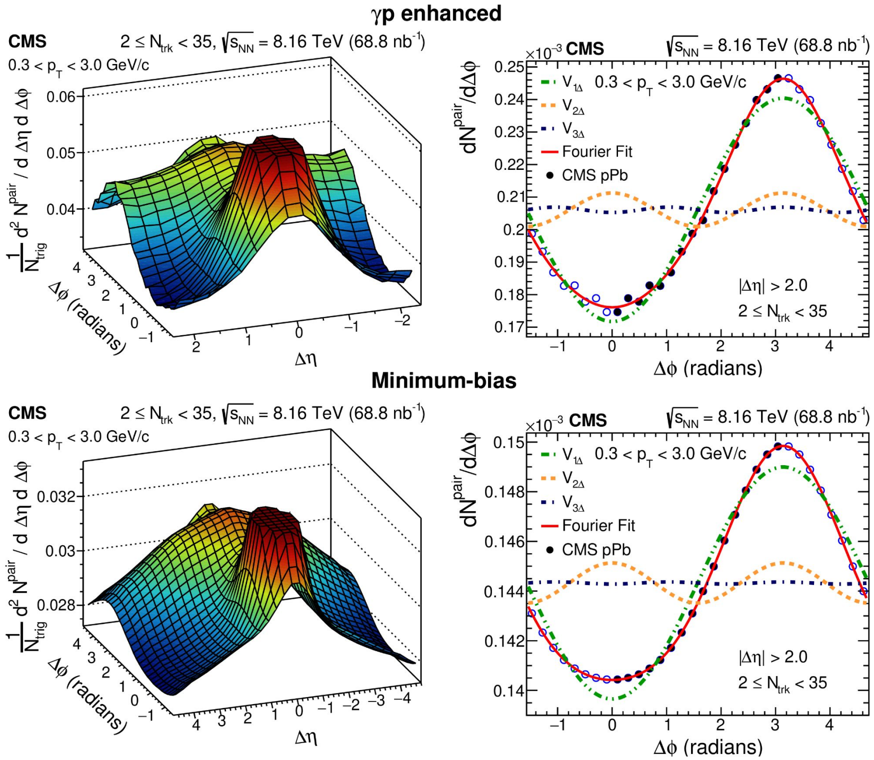
HIN-18-011

Unfolded





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.

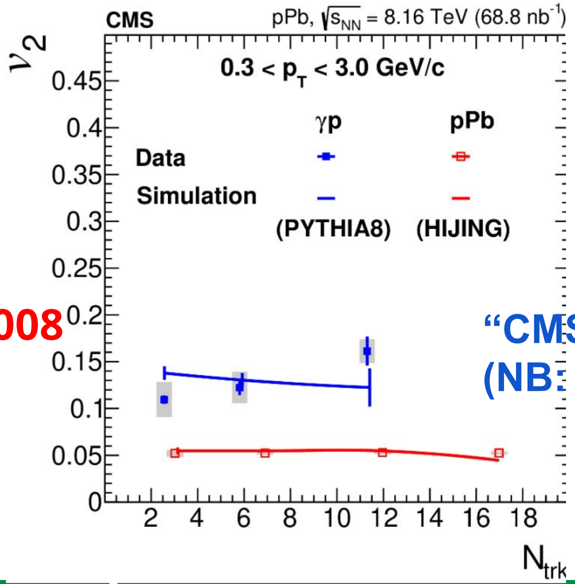
Collectivity in γp vs γPb collisions

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

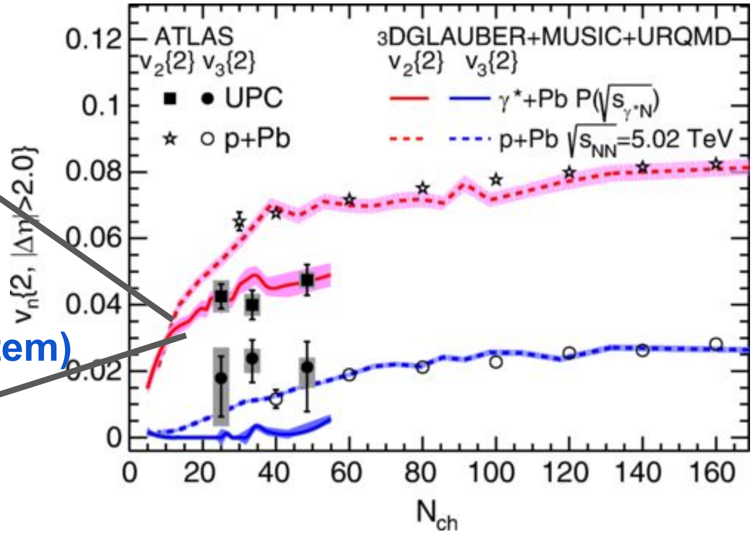
Interesting to bridge the two systems

2203.06094

HIN-18-008



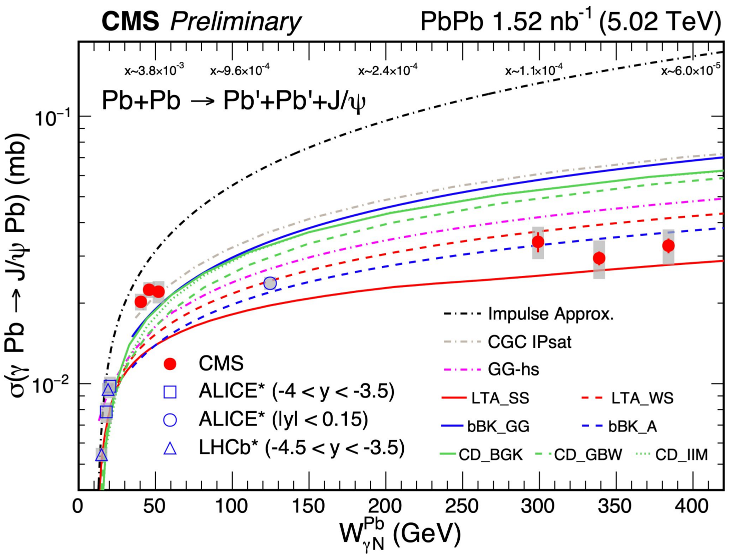
"CMS region"
(NB: different system)



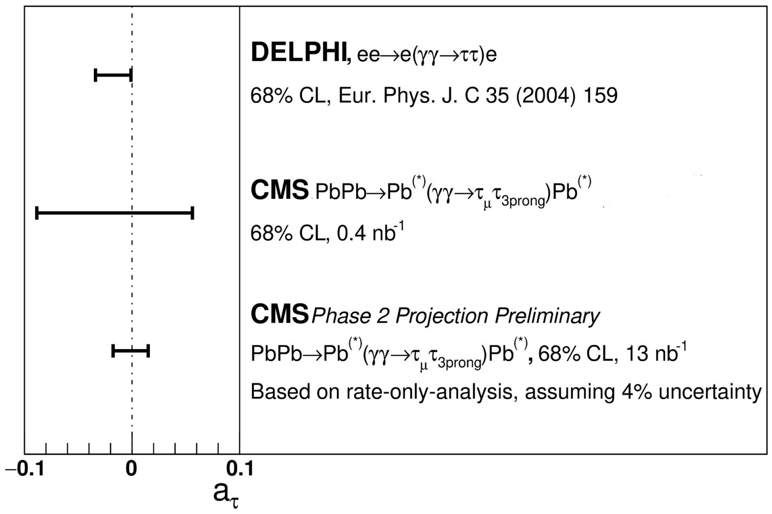
Outlook

- 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
- τ+τ- observation paves the way for **precise at a_τ (HL-)LHC**

PAS-HIN-22-002



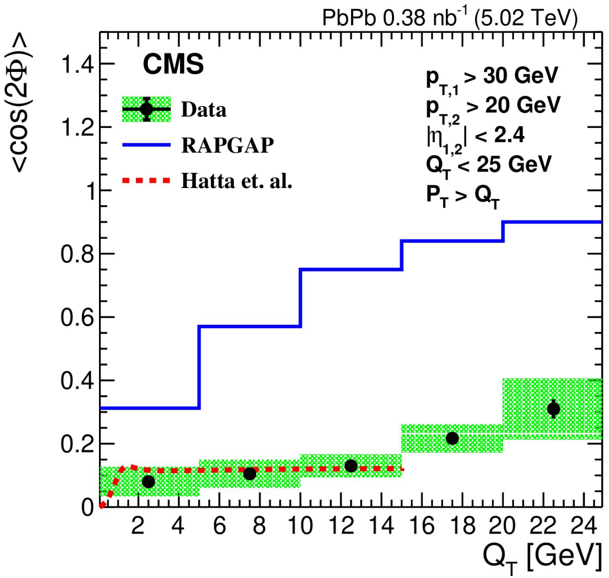
HIN-21-009



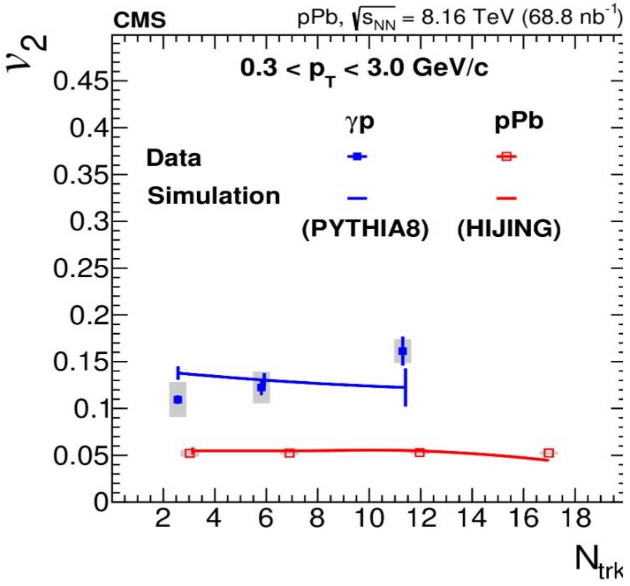
Outlook

- Exclusive dijets in UPC pPb at **large Q_T to be understood**
  - also link to the linearly polarized gluon distribution faces **challenge from ISR**
- Common framework to understand **collectivity in γp vs γPb collisions**

HIN-18-011



HIN-18-008

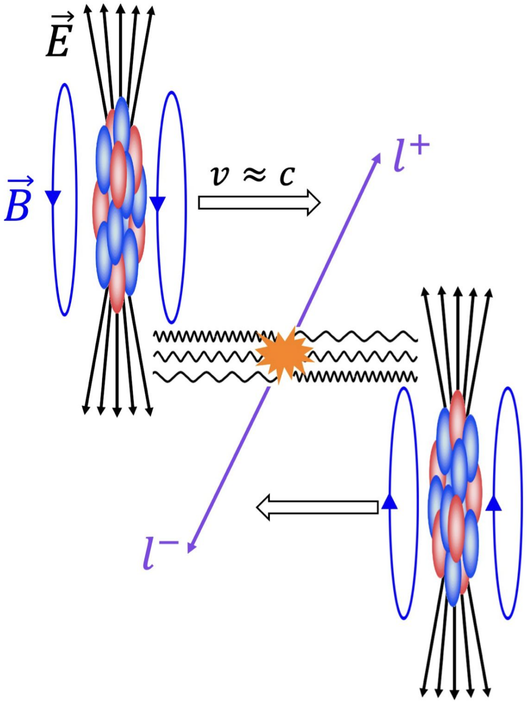


Thank you for your attention!

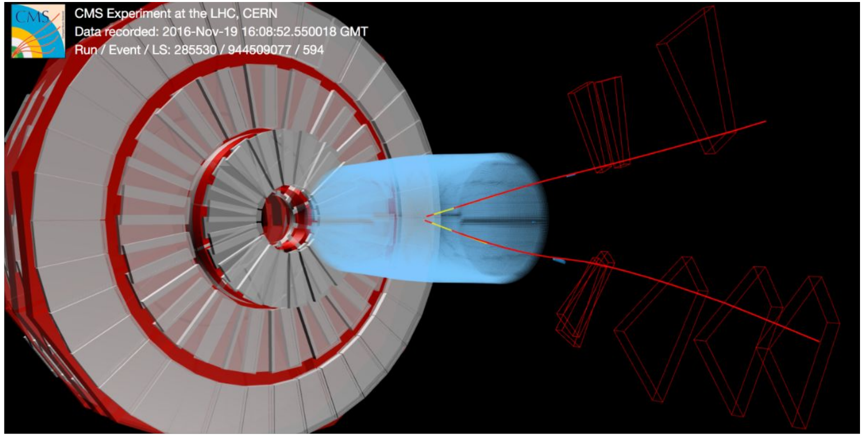
EXTRA SLIDES

Ultra-peripheral nuclear collisions

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



- Strong EM fields generated by relativistic ions (B ~ 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: $p_T < \hbar/R_A$ ~ 30 MeV (E_{max} ~ 80 GeV) at LHC.

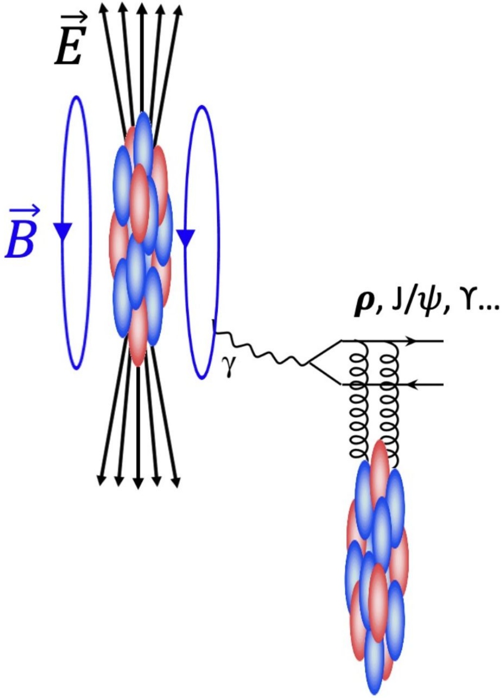


- light-light and light-Nucleus collider
- BSM searches (ALP, g_τ-2).

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

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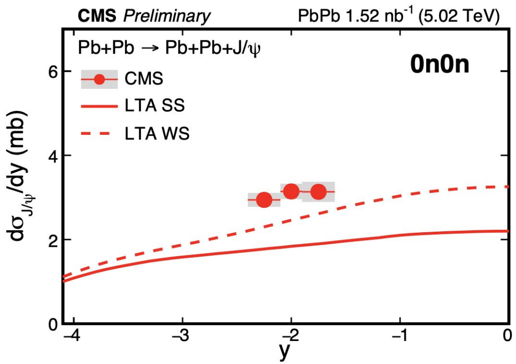
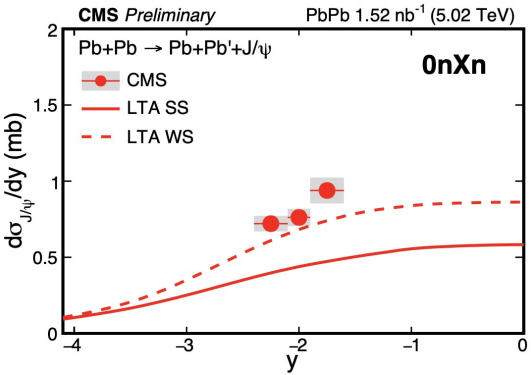
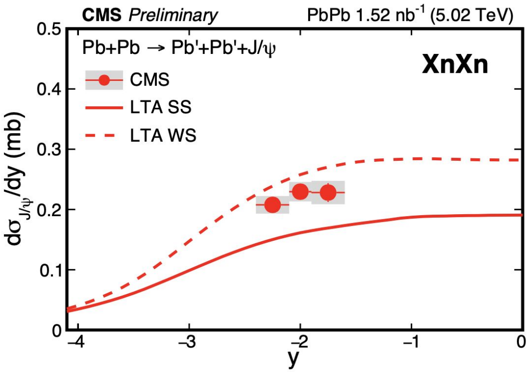






$$\frac{d\sigma^{0n0n}_{AA\to AA'J/\psi}}{dy} = N^{0n0n}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0n0n}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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

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

⇒

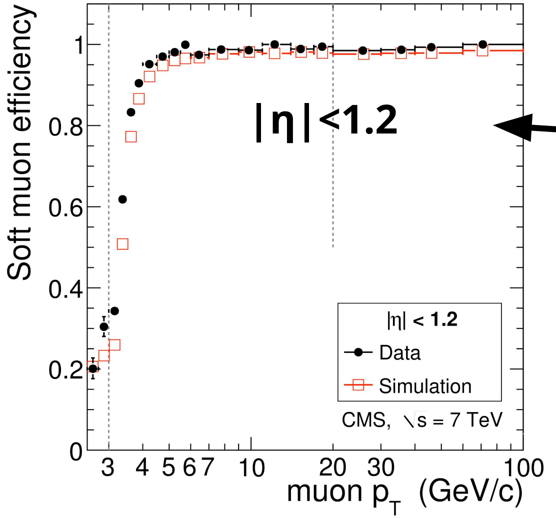
$\sigma_{\gamma A\to J/\psi A'}(w_1)$ → Low-energy γ: $w_1 = \frac{M_{VM}}{2}e^{-y}$

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

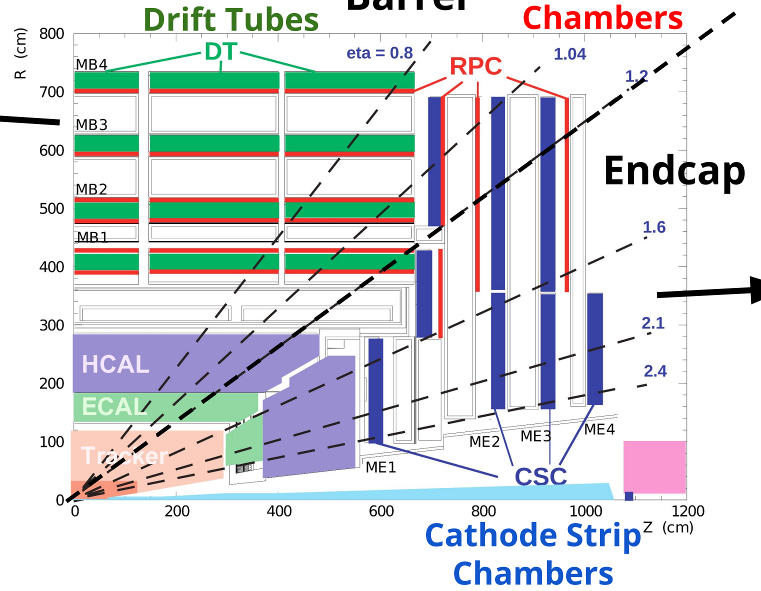
- Disentangle the low- and high- energy photon-nucleus contributions of a single γ+Pb.

Muon reconstruction

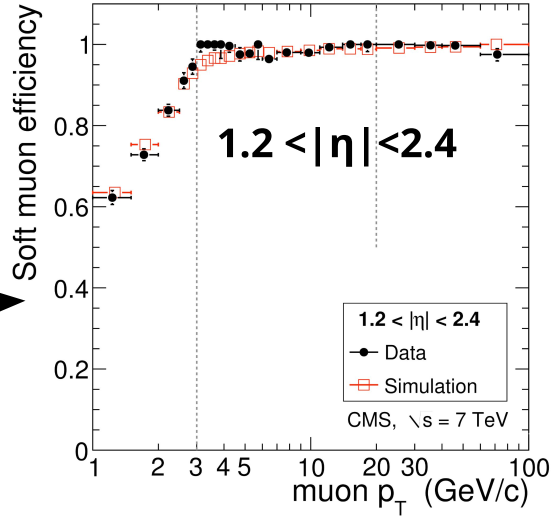
Muon efficiency



JINST 7 (2012) P10002

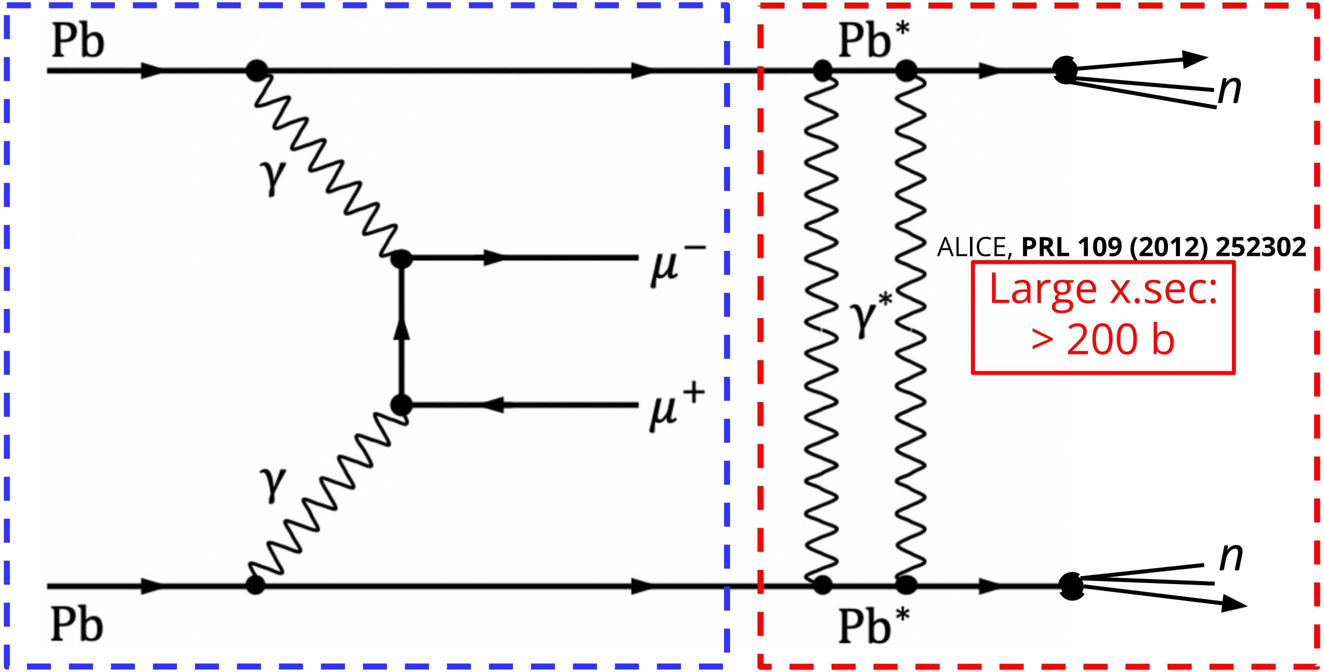


Muon efficiency



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

EM dissociative pileup correction



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

different collisions

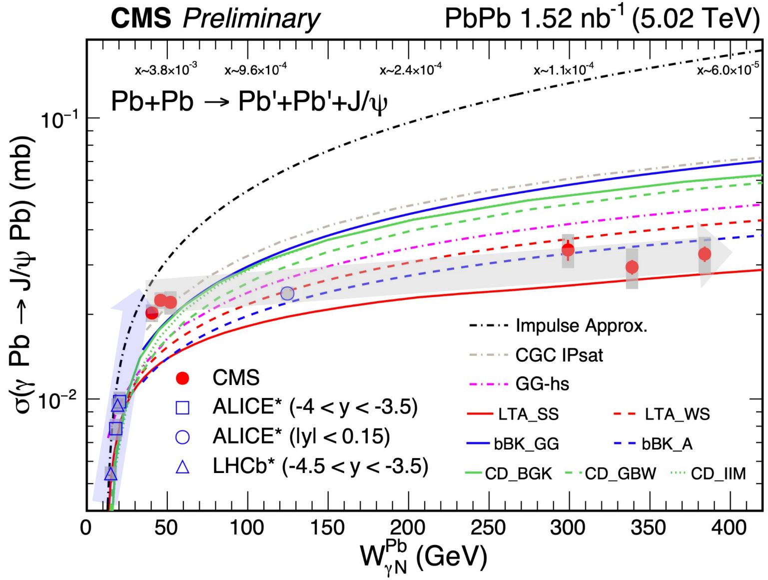
EM dissociation **without** any $\gamma\gamma \rightarrow \mu^+\mu^-$

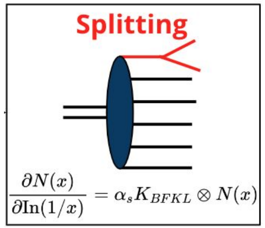
$\gamma\gamma \rightarrow \mu^+\mu^-$ with neutron multiplicity migration

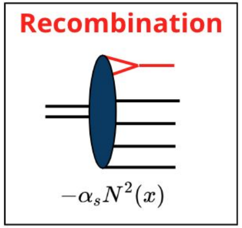
Impact of dissociative PU corrected by measuring neutron multiplicity in events without any activity in CMS tracker.

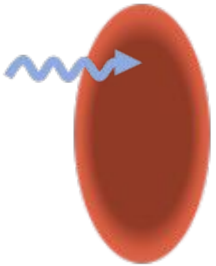
What physics behind?

CMS-PAS-HIN-22-002









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

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

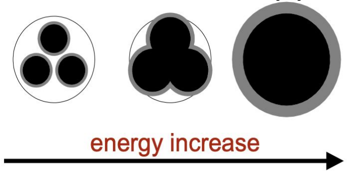
OR

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

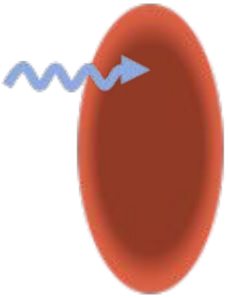
Another novel regime of QCD: Black Disk Limit

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

Inner structure disappears



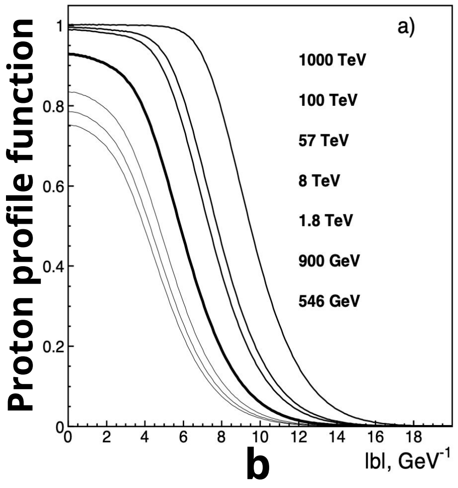
In the *strong absorption scenario*, the interaction probability may reach the unitarity limit. The nucleus target becomes totally absorptive to incoming photons.



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

“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

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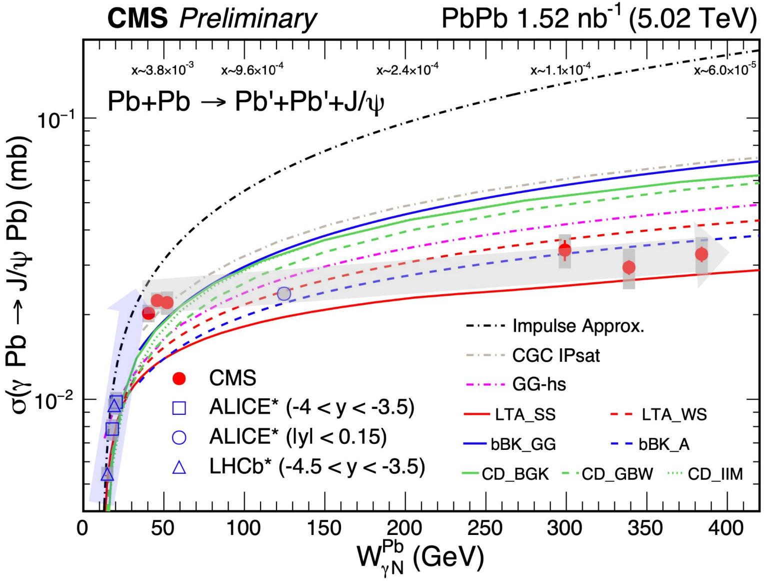
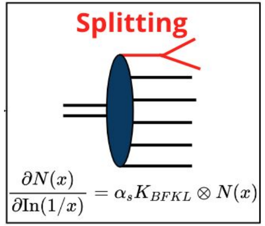
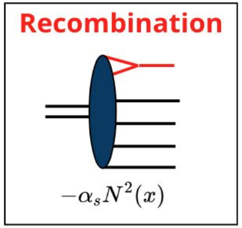
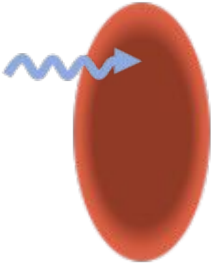






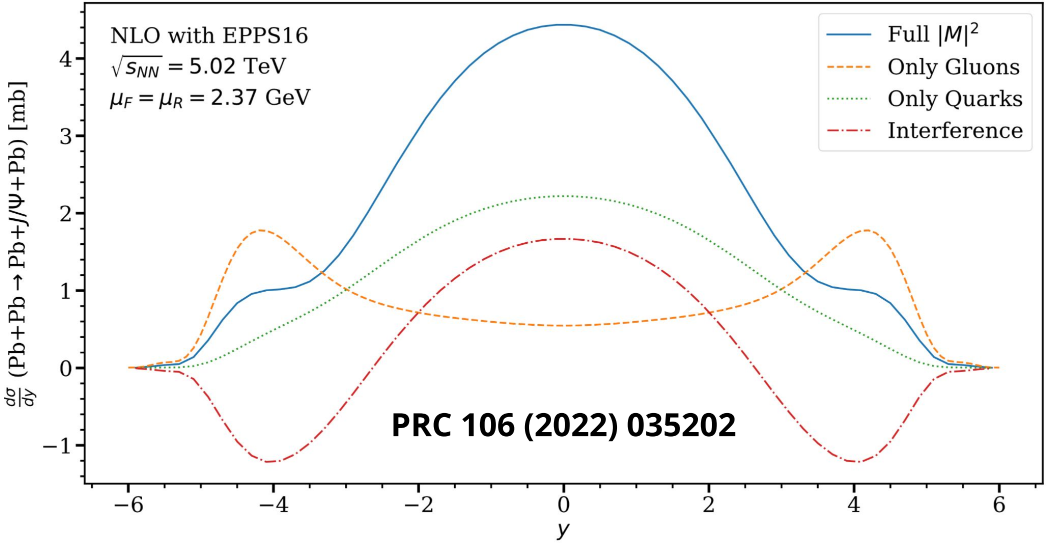


$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

- 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.

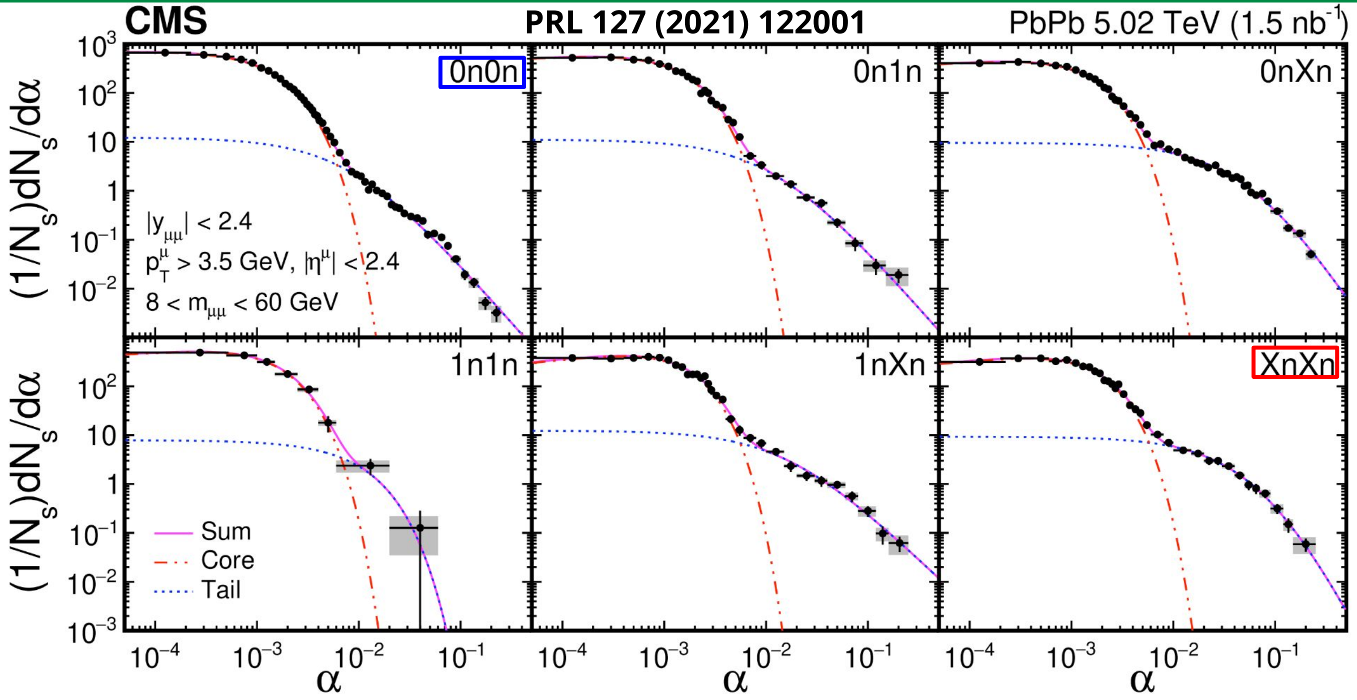
First NLO calculations on exclusive J/Ψ production

- 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.***



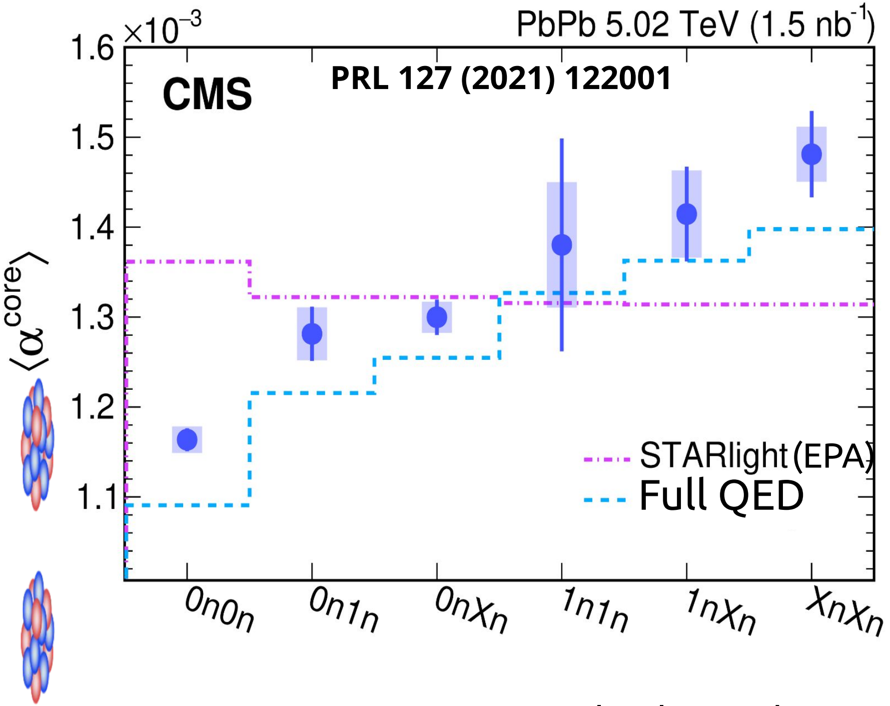
- Needs careful attention when interpreting the data.
- "σ ∝ (gluon PDF)^2" not true at NLO.

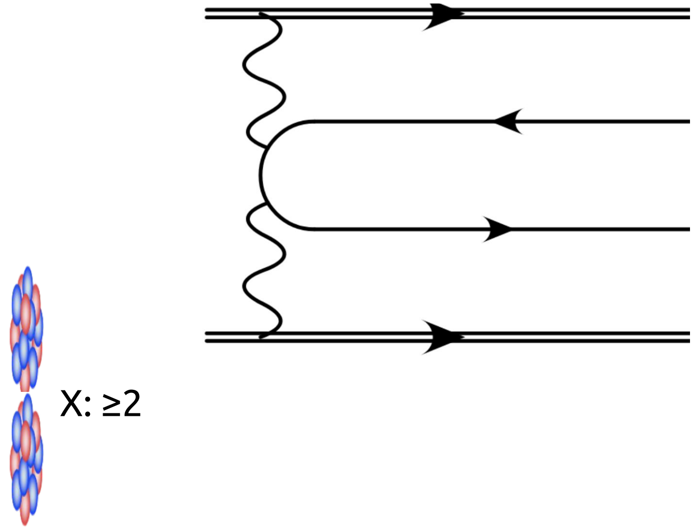
α spectrum vs. neutron multiplicity



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

⟨α^{core}⟩ vs. neutron multiplicity class

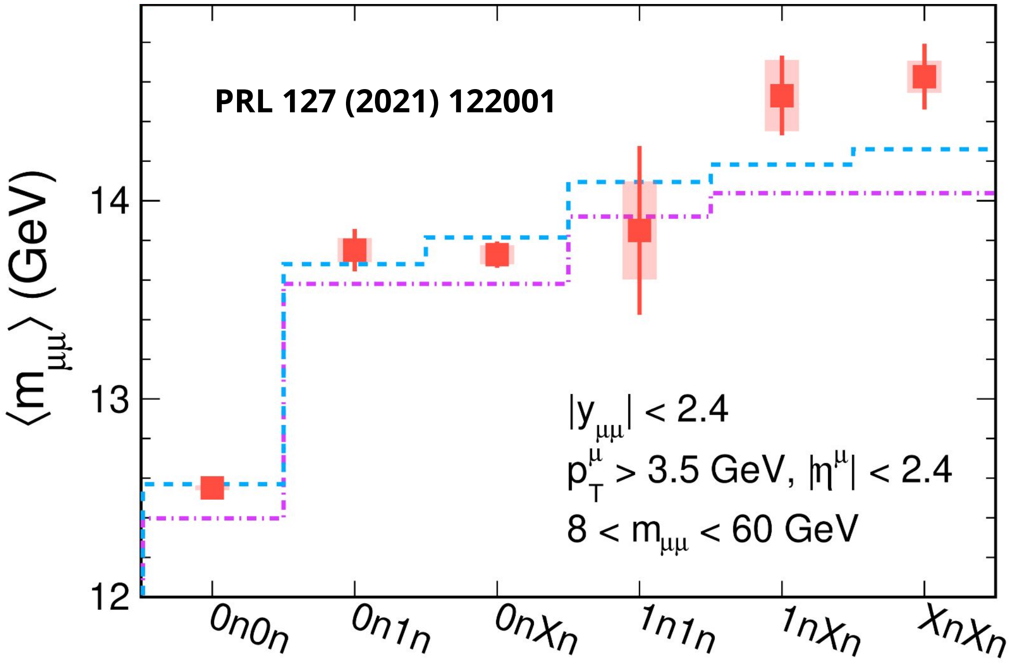




Strong (5.7 σ) neutron multiplicity dependence of ⟨α^{core}⟩ ∝ $\gamma\, p_T$

- b dependence of initial photon p_T, not captured by STARLight
- **Described by a leading order QED calculation with b dependence.**

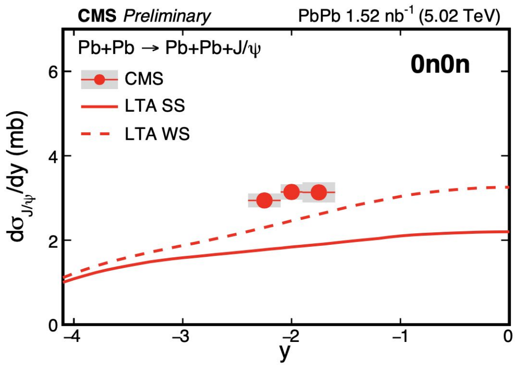
$\langle m^{\mu\mu} \rangle$ vs. neutron multiplicity

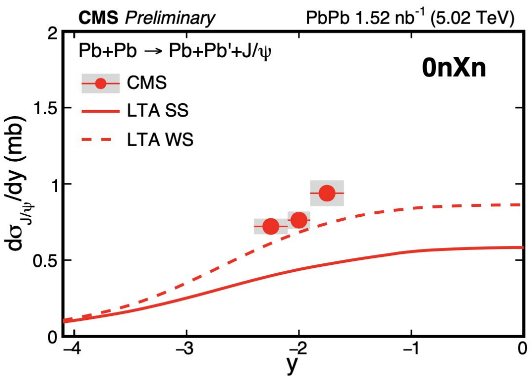


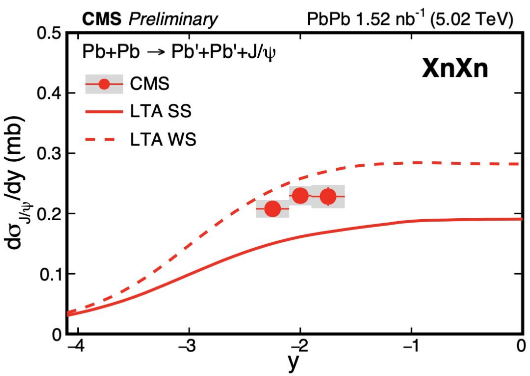
- Strong neutron multiplicity dependence of $\langle m_{\mu\mu} \rangle$
  - Deviation from constant >> 5σ
  - b dependence of initial photon energy.

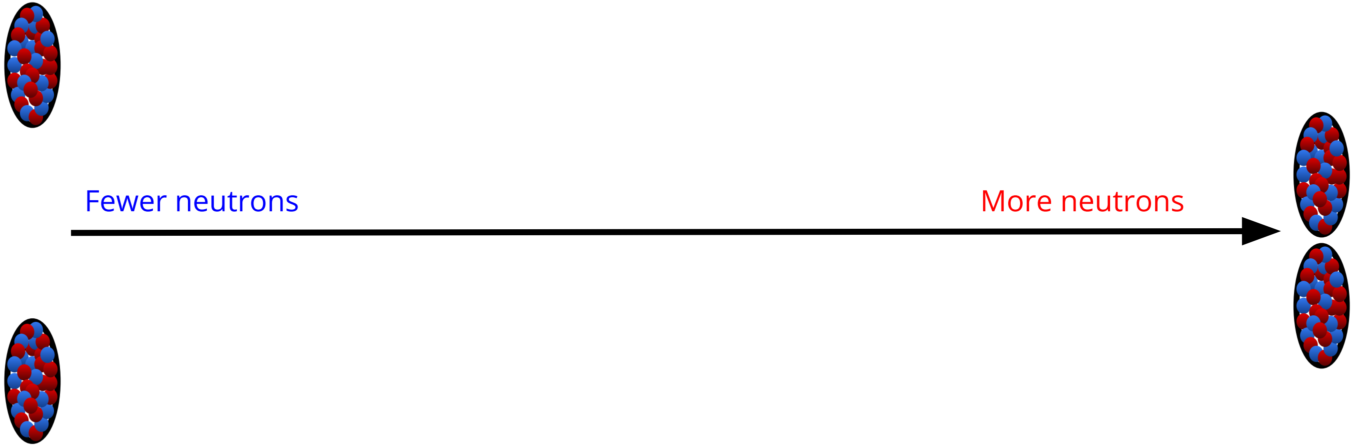
Coherent Jpsi in 0n0n, 0nXn, XnXn

CMS-PAS-HIN-22-002

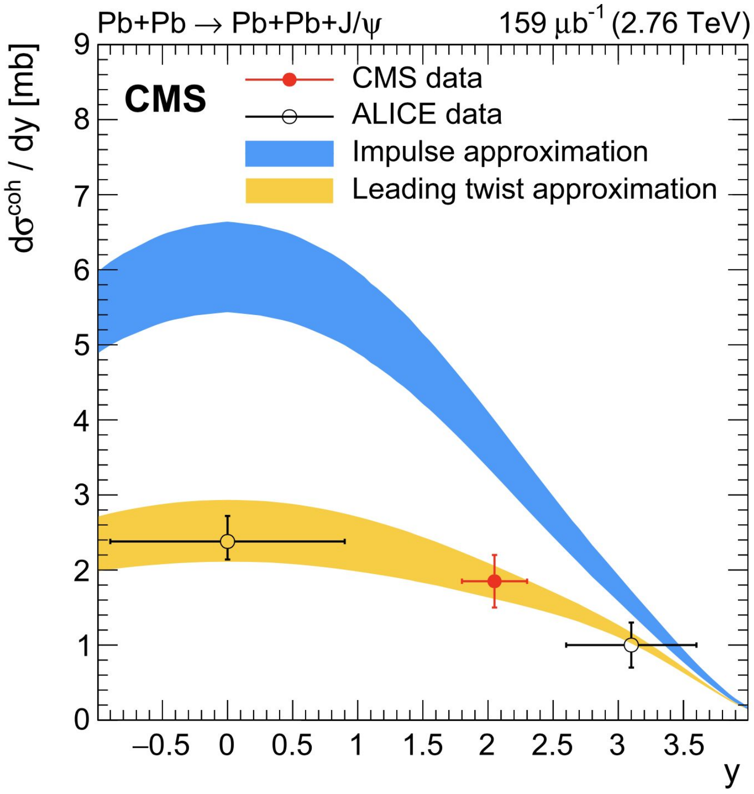








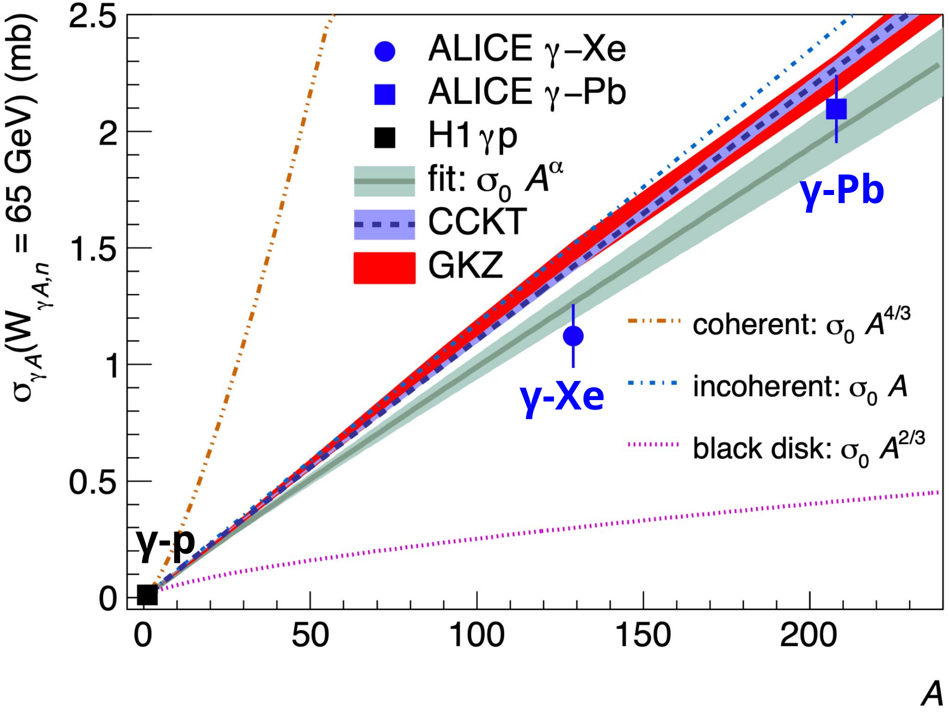
PLB 772 (2017) 489



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

ALICE UPC ρ vs system size

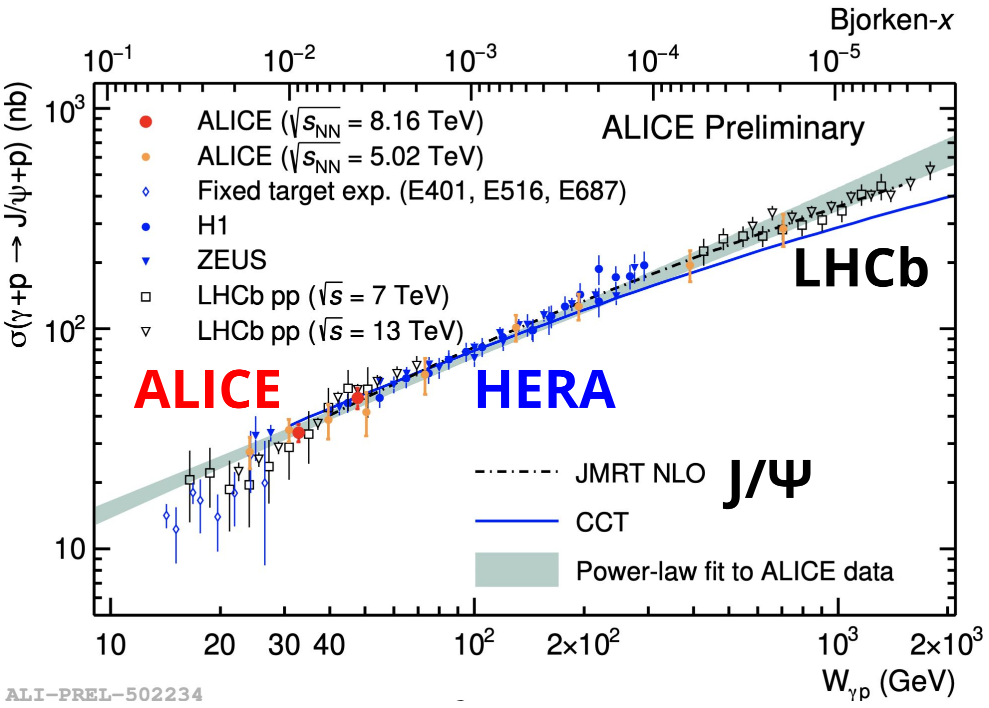
ALICE, **PLB 820 (2021) 136481**

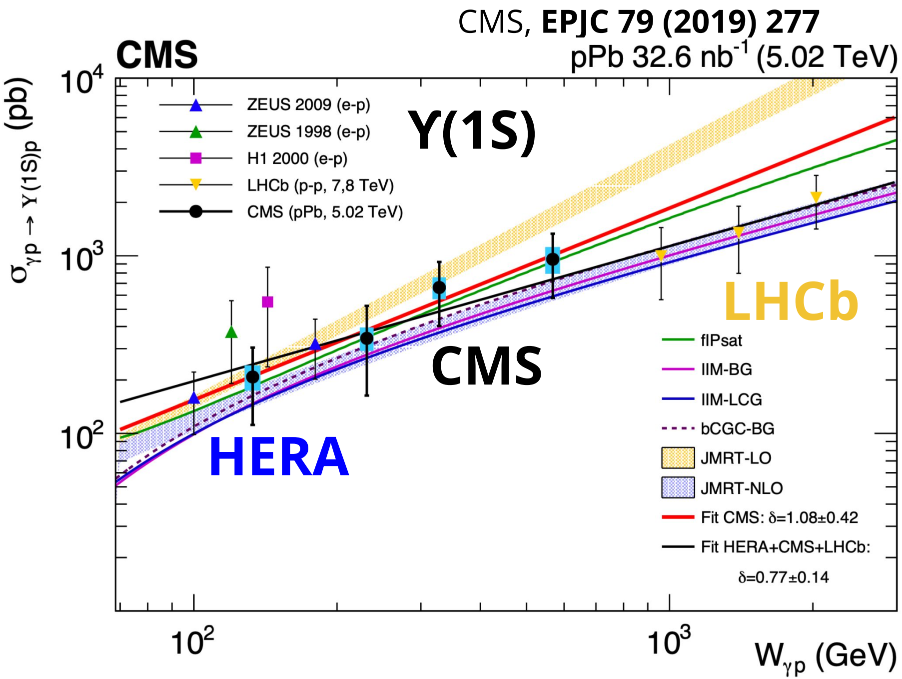


If J/Ψ-nucleus approaches BDL, why ρ-Nucleus does not?

- 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?

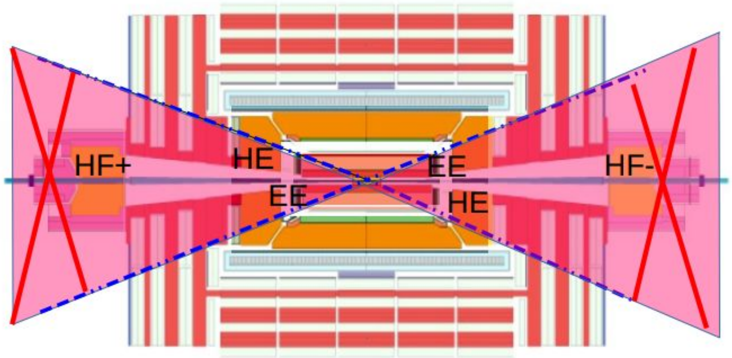
Quarkonium photoproduction in γ-p





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

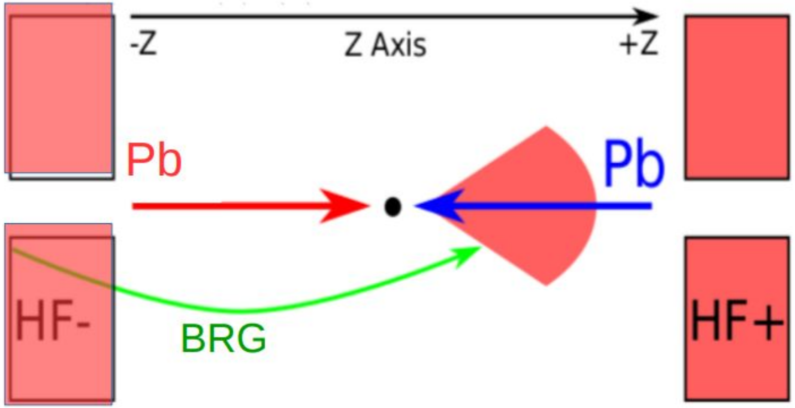
3

Exclusive dijets in UPC PbPb @5 TeV

γ + Pb $\rightarrow$ jet + jet + Pb events are asymmetric in rapidity.

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

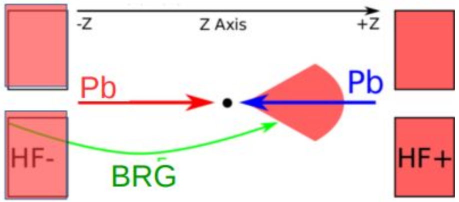
Two separate data sets are defined:
one of them has BRG > FRG, and the other FRG > BRG



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

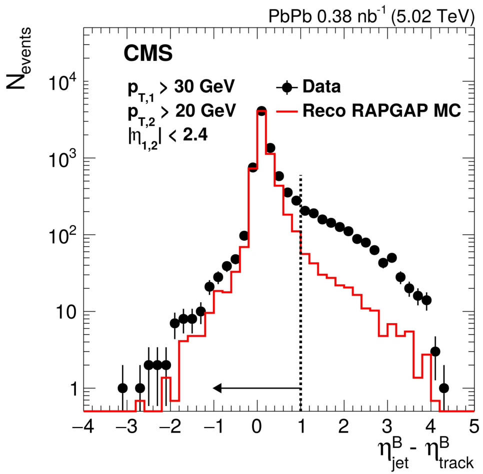
4

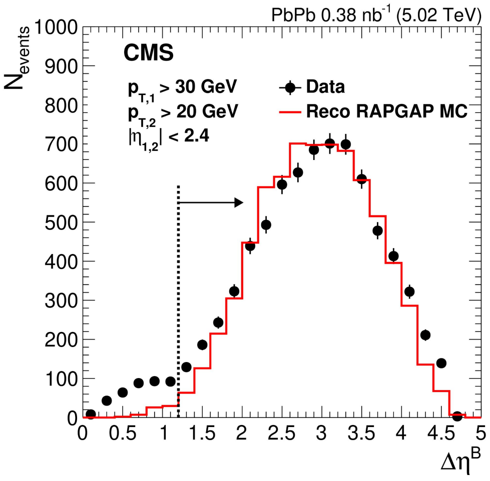
Exclusive dijets in UPC PbPb @5 TeV



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

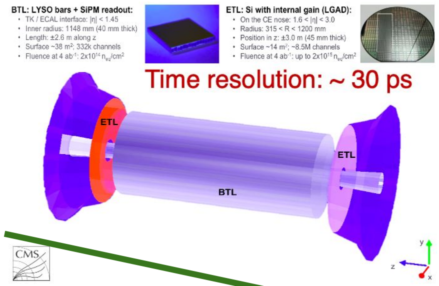




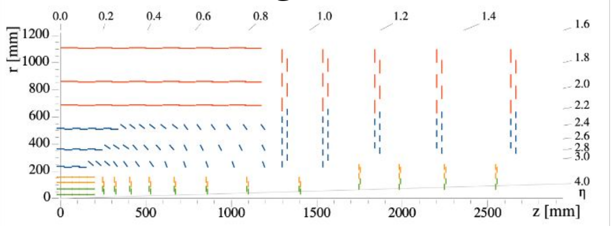
5

Future opportunities

MIP Timing Detector for PID

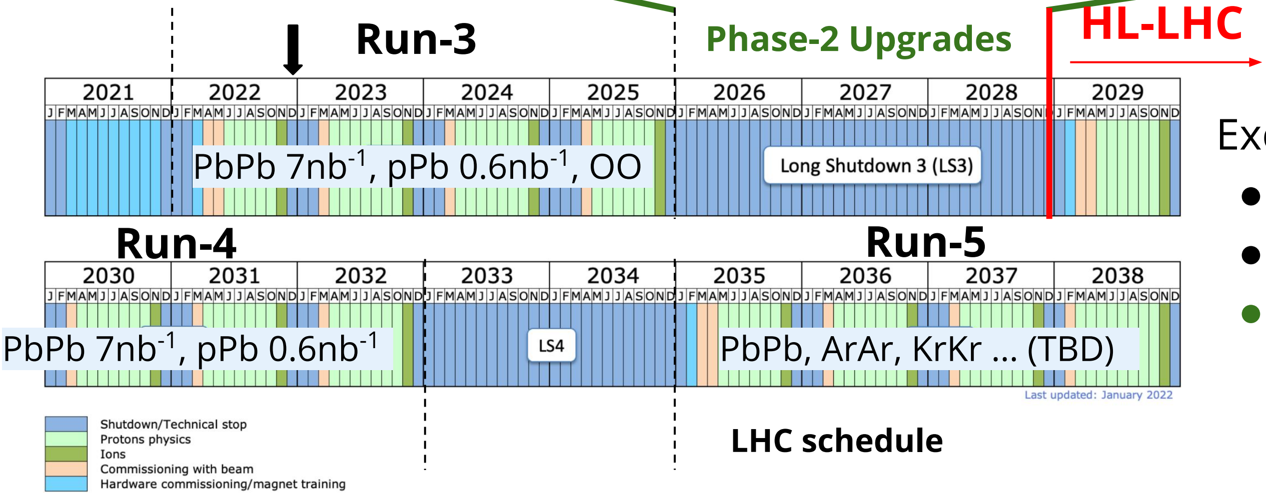


Tracker with |η|<4 and better resolution, lighter materials



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

……

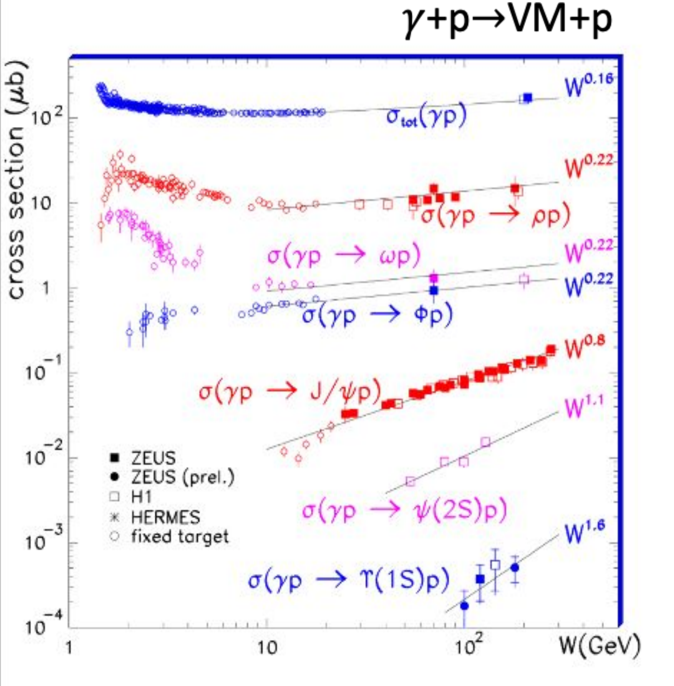


LHC schedule

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

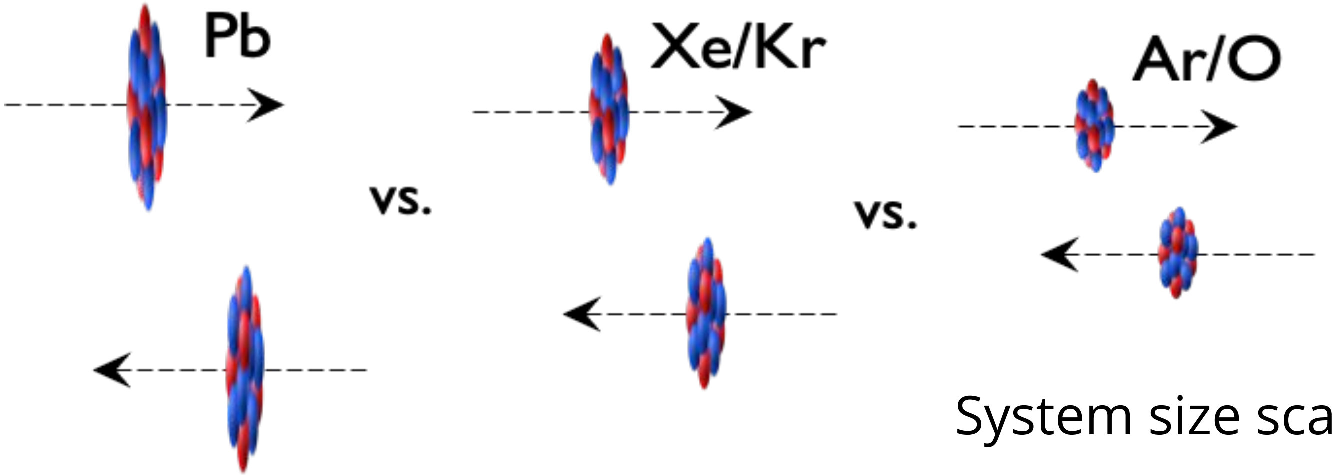
➢ e.g., control of dipole sizes and hard scales.

CERN yellow report, **arXiv:1812.06772**

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

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