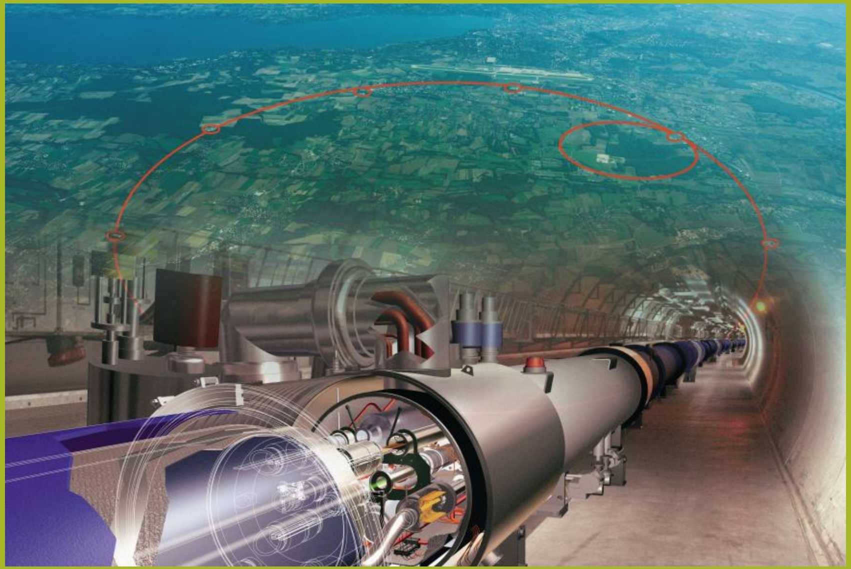
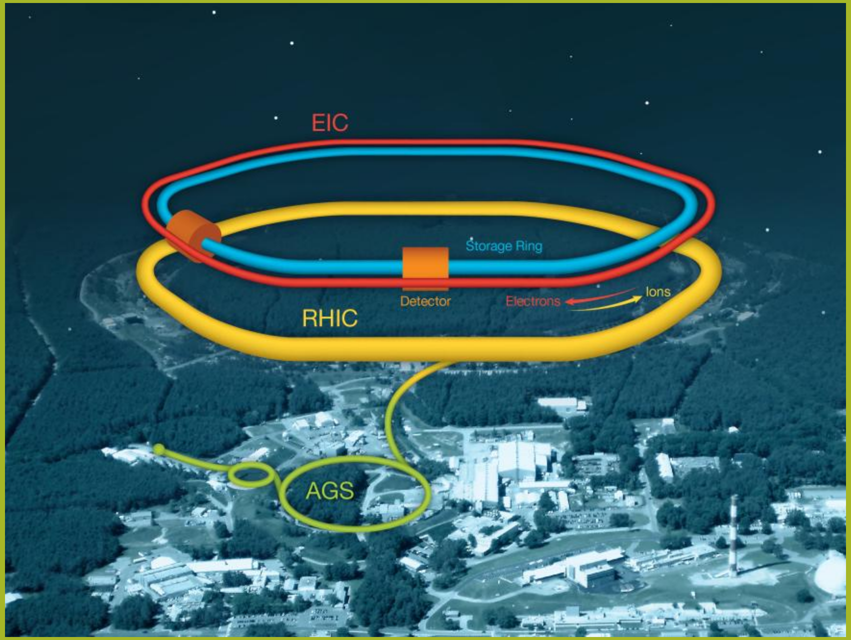


CMS AND EIC SYNERGIES + FEMTOSCOPY

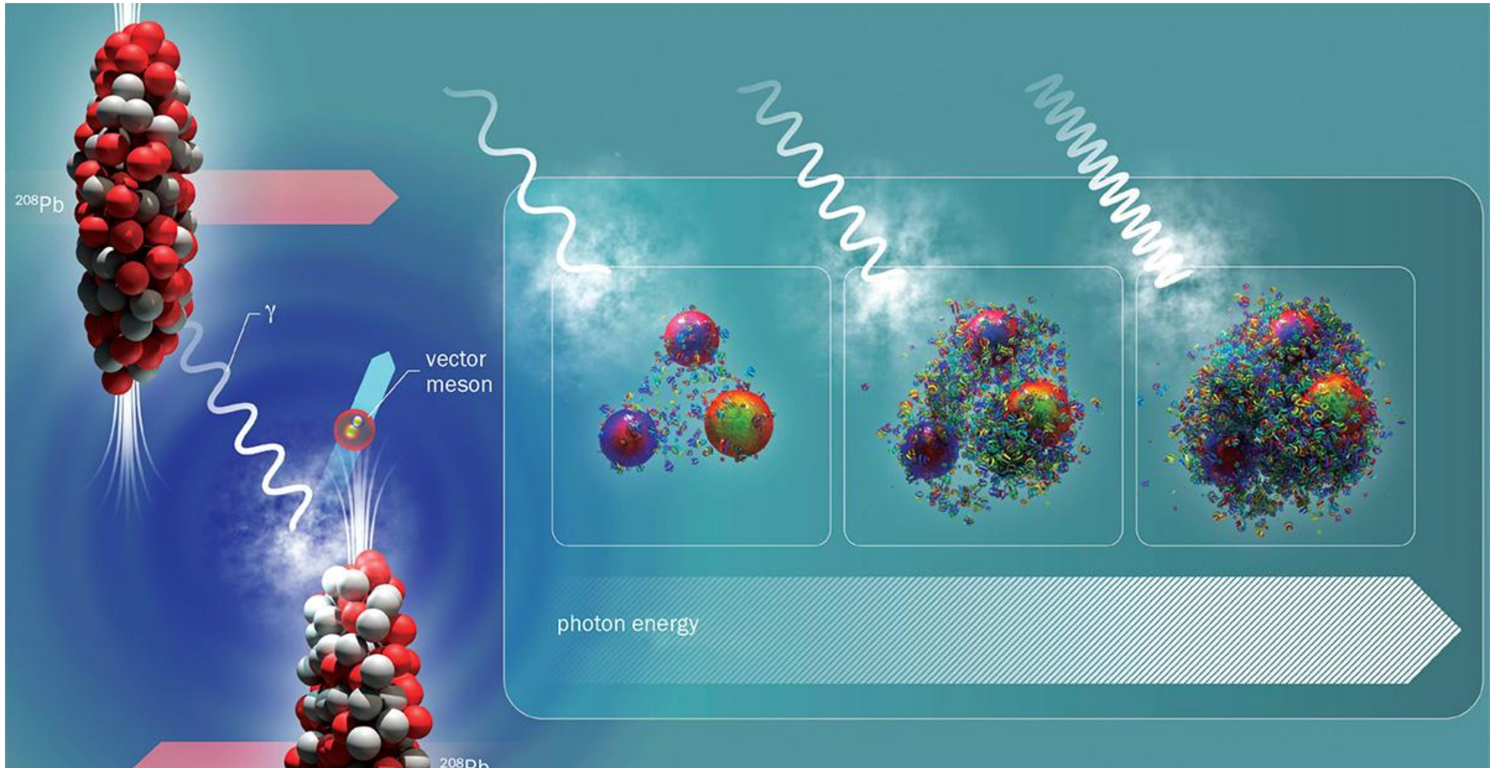
Máté Csanád (for the CMS Collaboration)

ELTE Eötvös Loránd University, Budapest



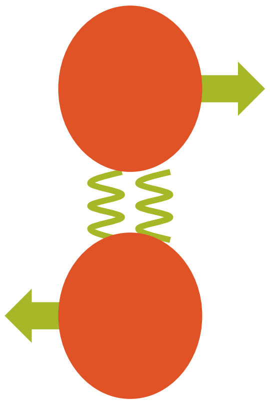
„The other 99%" (© Daniel Takaki, CERN Courier)

- Quarks (current quark masses) contribute to only 1% of the nucleon mass
- Rest comes from gluons and the interaction
- A key challenge: gluon saturation
  - Due to nonlinearity
  - Gluon recombination dominates
  - Saturation scale?
- Point-like probe: EIC
- Until then: photons in UPC!
- Parton distributions important for global fits
- Can be understood in DPS @ LHC

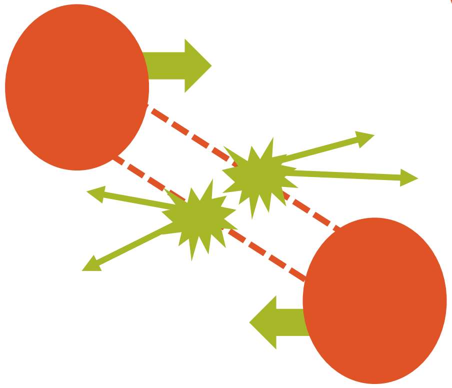


https://cerncourier.com/a/the-other-99/

UPC & DPS: complementary probes of nuclear dynamics



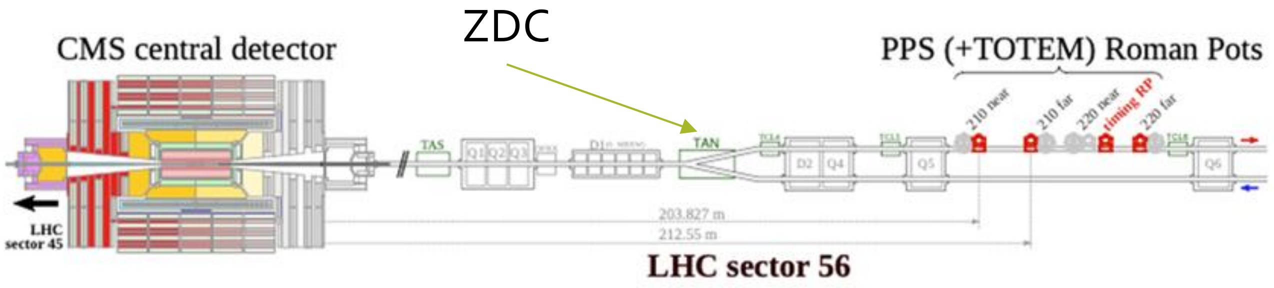
- Ultra-peripheral collisions (UPCs)
  - Use quasi-real photons to probe nuclei at very low x
  - Access gluon densities via exclusive vector mesons, open heavy flavor, etc.
  - Sensitive to coherent vs. incoherent scattering and nuclear shadowing
  - Photon-photon processes in pp complement nuclear UPC programs

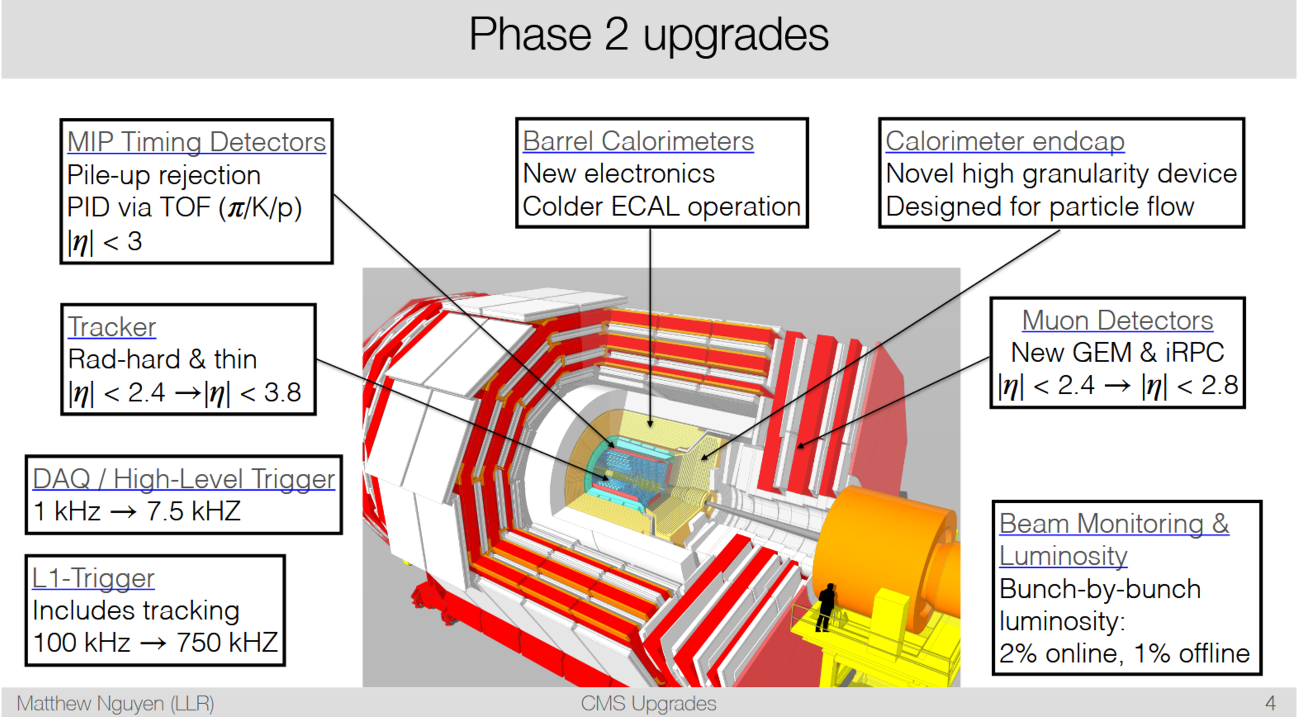


- Double parton scattering (DPS)
  - Two hard interactions in the same pp (or pA) collision.
  - Sensitive to multi-parton correlations, parton densities
  - Same-sign WW, Z+jets, 4-jet final states:
    constrain multiparton interactions (MPI), parton overlap
- Synergy with the EIC physics program
  - UPCs: clean photon–nucleus probe ⟶ gluon imaging at low x
  - DPS: pp/pA multiparton structure ⟶ transverse correlations & effective overlap area
  - Together: constrain longitudinal (x) & transverse, spatial parton distributions ⟶ input for EIC global fits

CMS capabilities in EIC physics

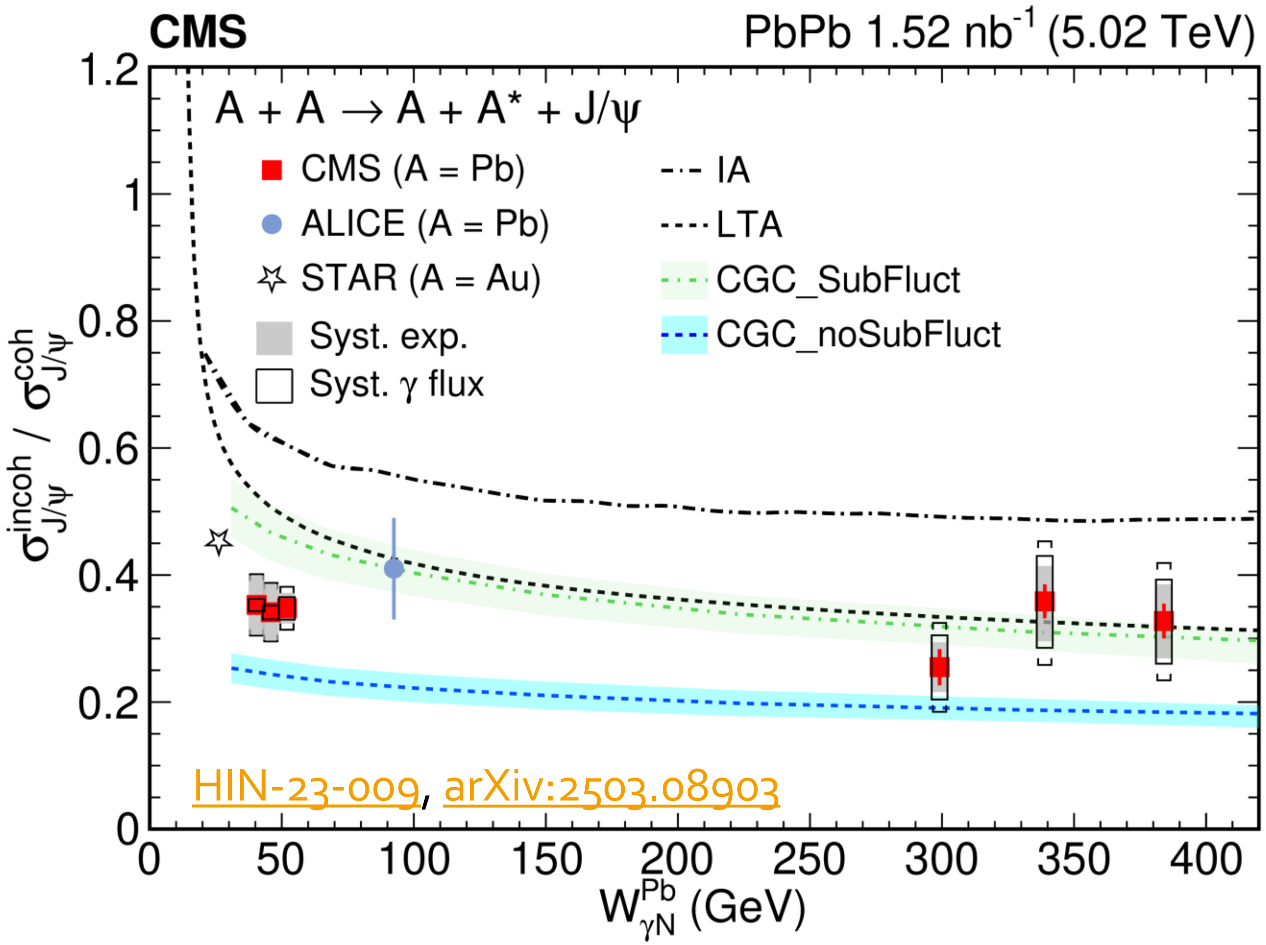
- Basic acceptance: $|\eta| < 2.5$ & full azimuth
- Many additional forward capabilities
  - ZDCs for neutrons (& photons): important in UPCs (e.g. #n tagging)
  - PPS Roman Pots for near-beam protons: important for central exclusive production, also photon and Pomeron processes
- Many upgrades for HL LHC
  - Increased coverage in η
  - Increased rates
  - New capabilities, such as TOF PID
- Many more details in the talk of Matthew Nguyen (Tue morning)





Small-x evolution: incoherent J/ψ in UPC

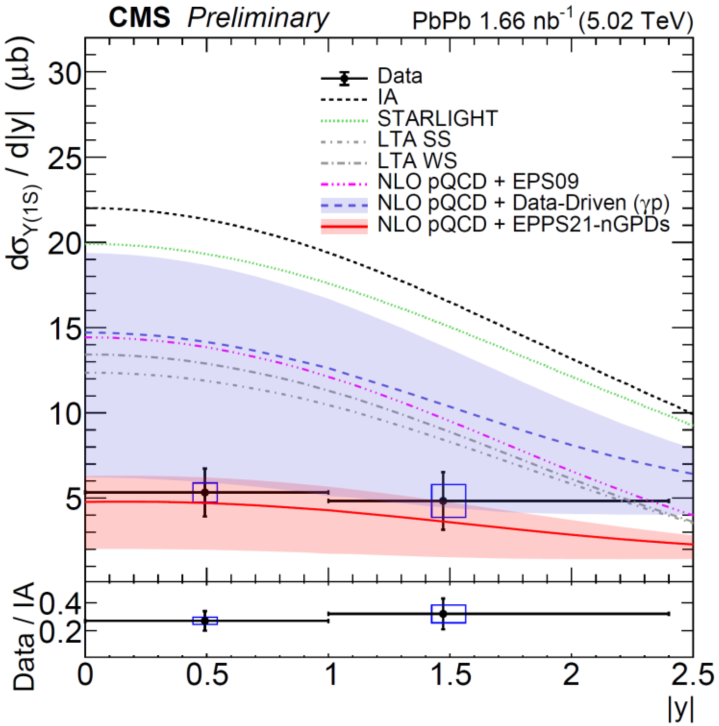
- First energy-dependent measurement of incoherent J/ψ photoproduction
  - Covering γN center of mass energy range $W_{\gamma N} \approx 40 - 400$ GeV
- Significant nuclear suppression
  - Incoherent cross section significantly below predictions without nuclear effects (Impulse Approximation)
  - Strong shadowing or saturation
- Stable incoherent-to-coherent ratio
  - Remains roughly constant across explored $W_{\gamma N}$ range
  - At odds with expectations
- Models challenged

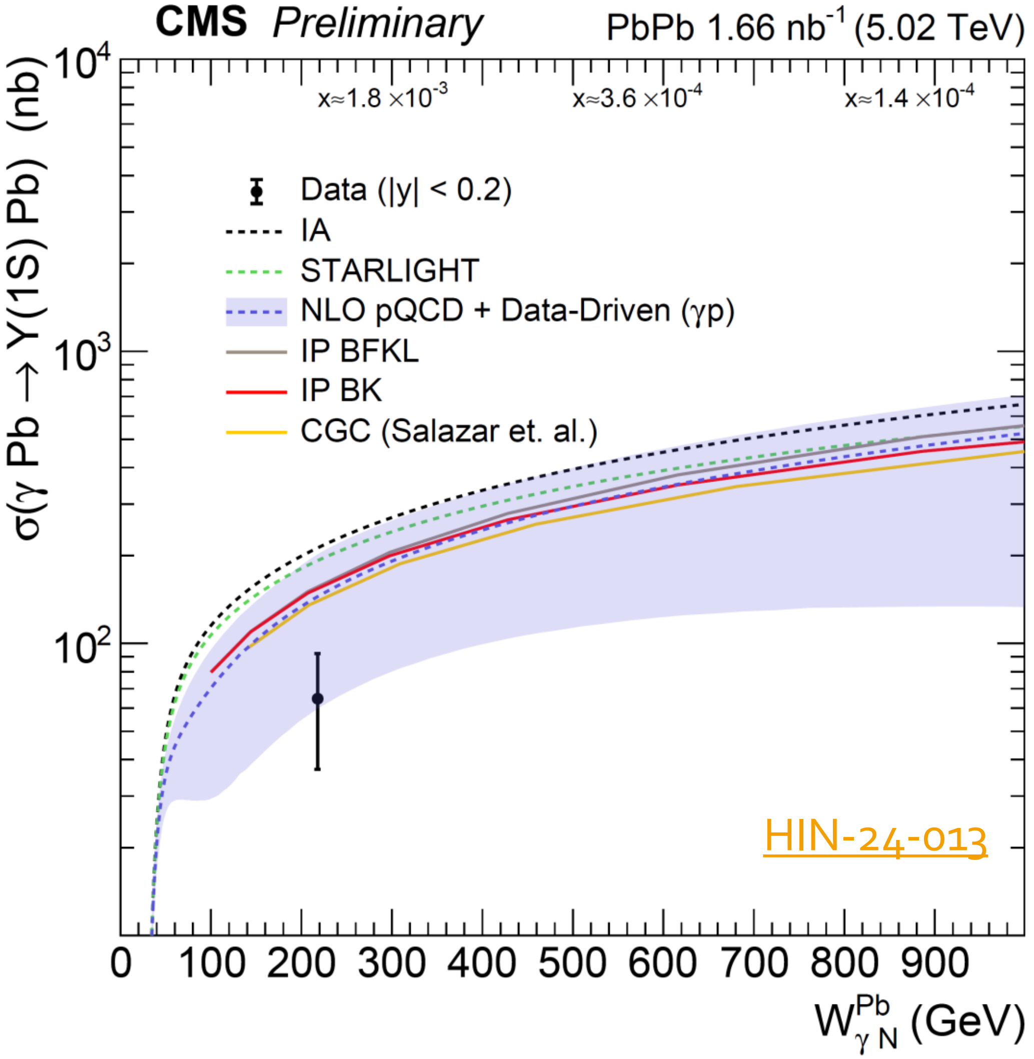


HIN-23-009, arXiv:2503.08903

Coherent Υ(1S) photoproduction in UPC

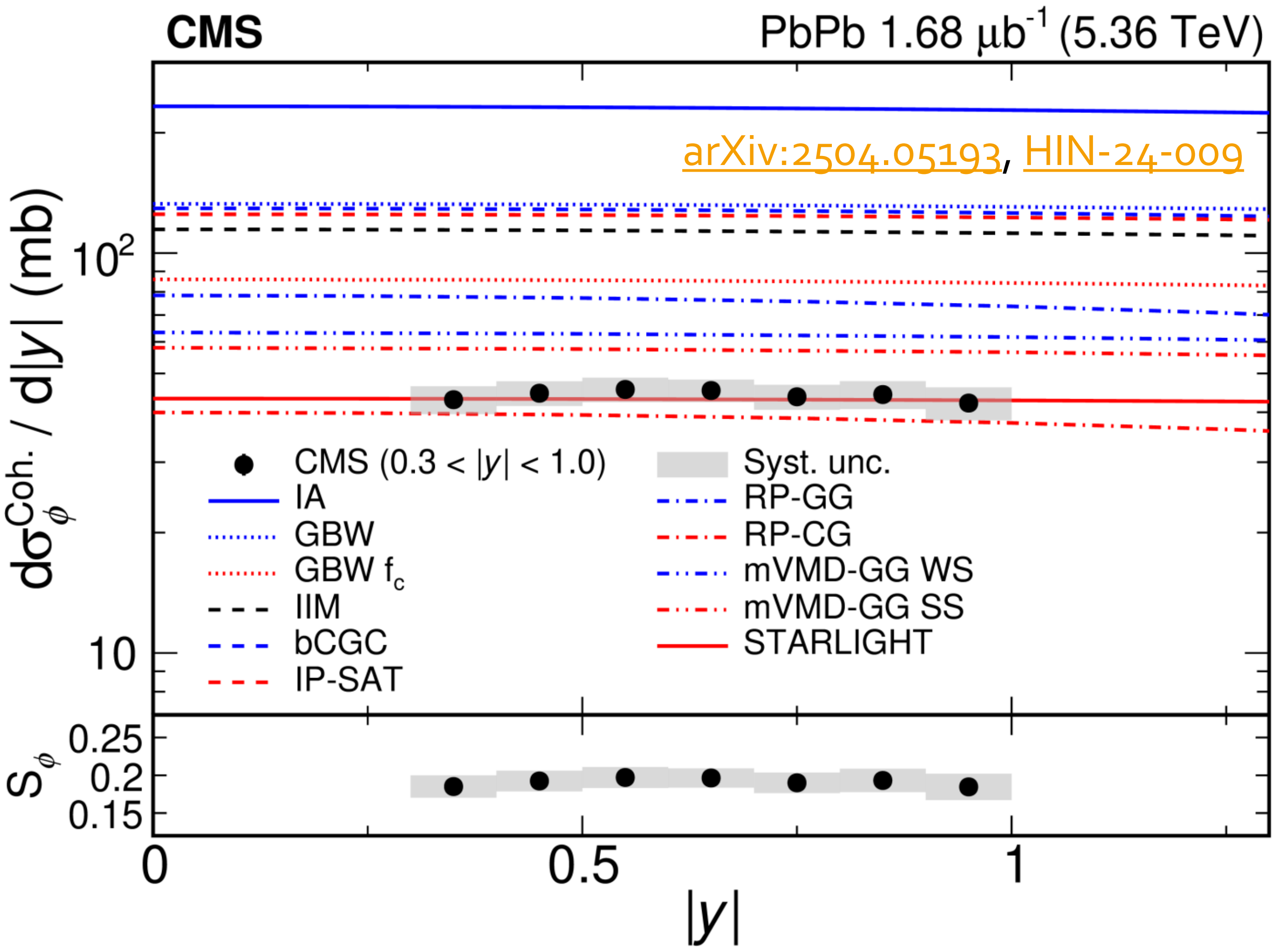
- First coherent Υ(1S) measurement in UPC
- Significant suppression $W_{\gamma N} \approx 200$ GeV & $|y| < 0.2$
- Data notably lower than rescaled $p\gamma$ expectations
- Models overpredict results
  - Except collinear fact. framework (nGPD)
- Gluon suppression: $R_g = 0.53 \pm 0.11$
  - Indicates ~50% reduction compared to calculations wo/ nuclear effects





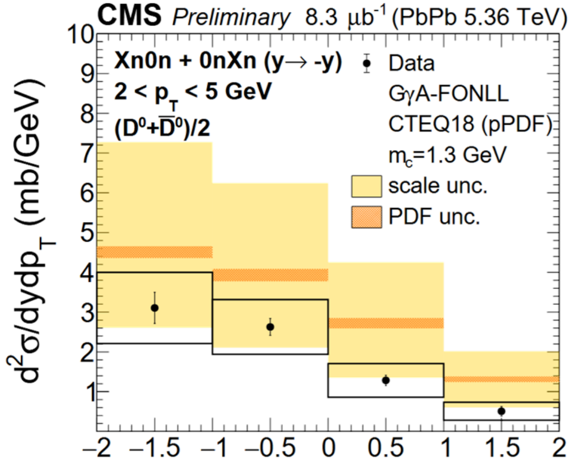
Coherent ϕ(1020) photoproduction in UPC

- First observation via $\phi \to K^+K^-$
- Flat differential cross section across $|y| = 0.3 - 1.0$ $(x \sim 10^{-4})$
- Strongly suppressed (~20%) compared to impulse-approximation prediction
  - Free nucleon picture incompatible with observations
- Models with nuclear shadowing match overall trend
- Saturation approaches vary in accuracy

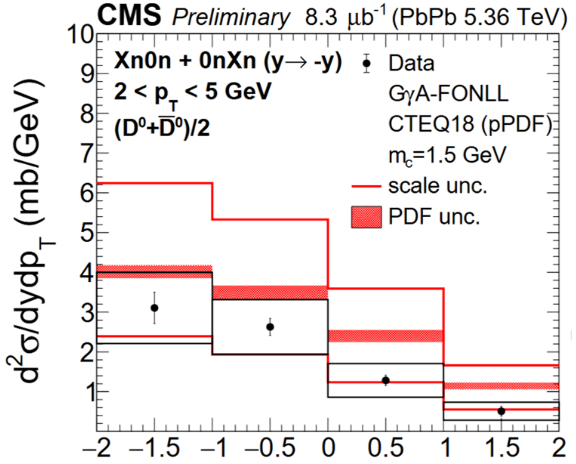


Constraining low-x gluon densities via open charm

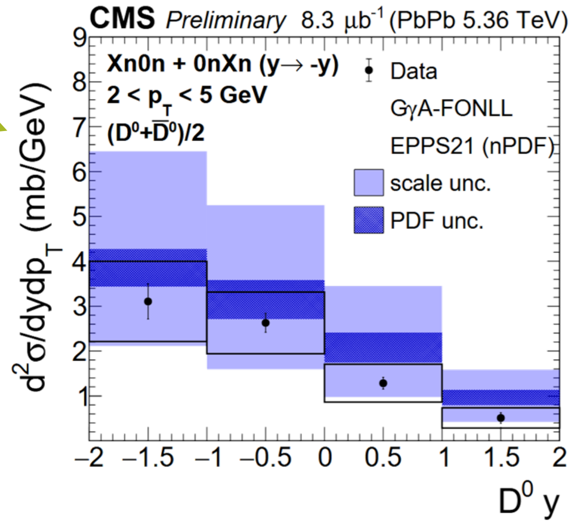
- First low-p_T (2–5 GeV) D^0 photoproduction measurement in UPC, $y \in [-2, +2]$
- Strong sensitivity to low-x ($\sim 10^{-3}$) gluon dynamics: shadowing and saturation
- Measured cross section below CTEQ18 FONLL baseline
  - Utilizing proton PDF
- Aligns with EPPS21/nNNPDF3.0 + FONLL
  - Incorporating nuclear effects (nPDF)
- Tightens constraints on low-x nuclear gluon PDFs in a less explored regime (Q^2 of a few GeV²)

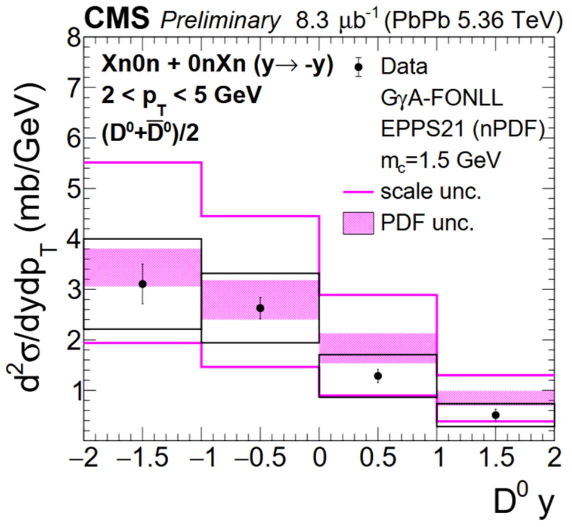


HIN-25-002



HIN-25-002





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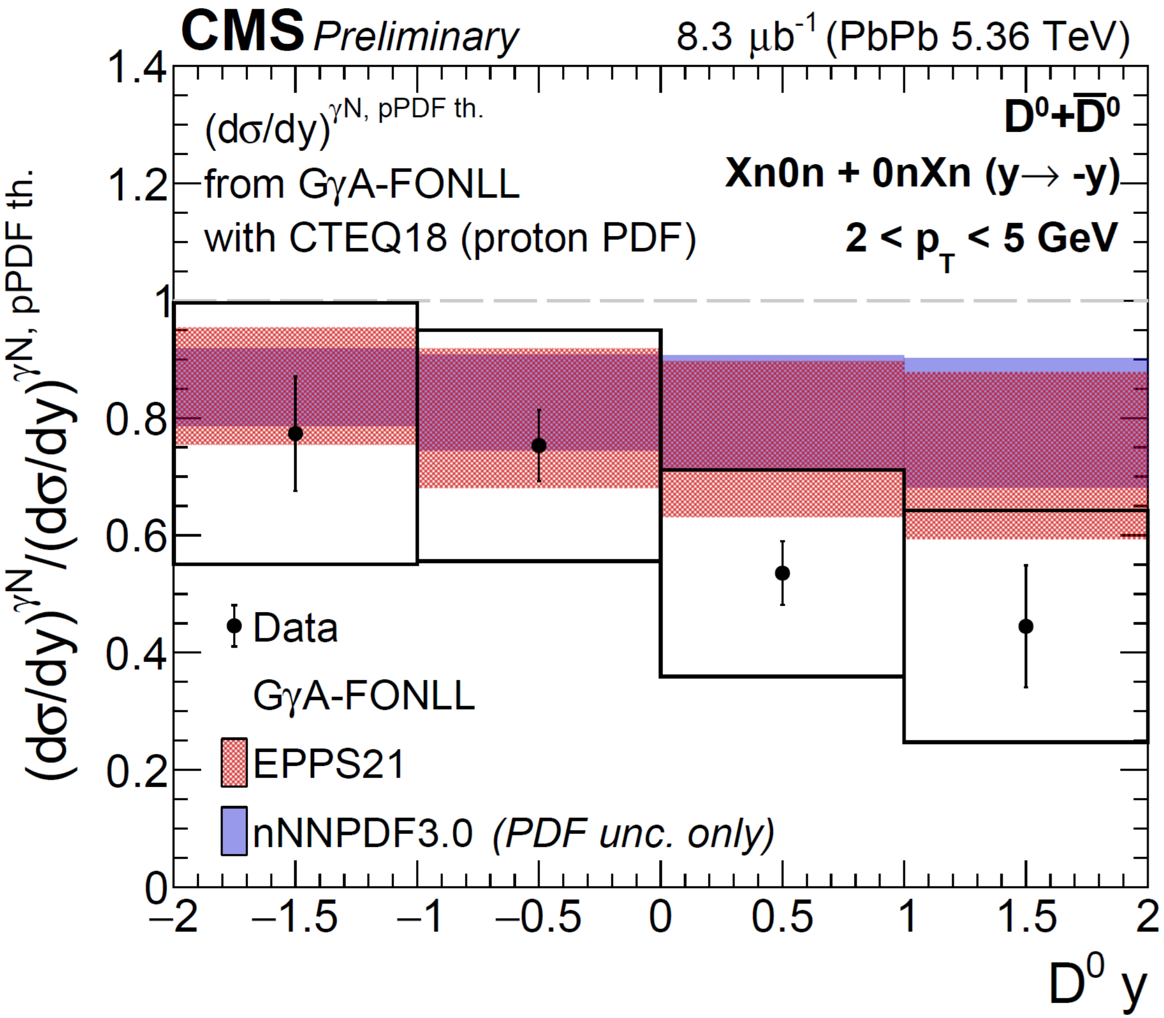
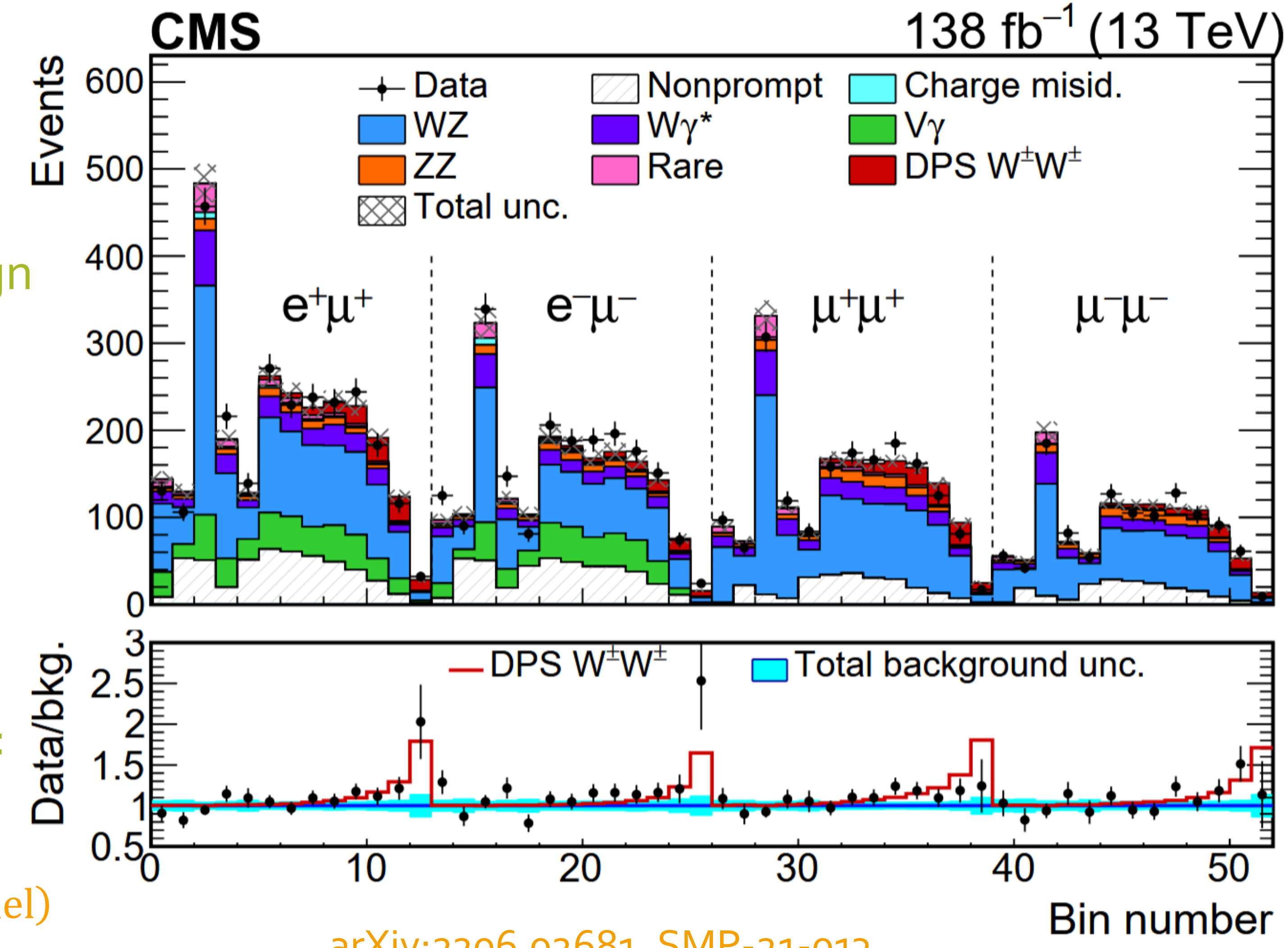
HIN-25-002



DPS-induced WW production in pp

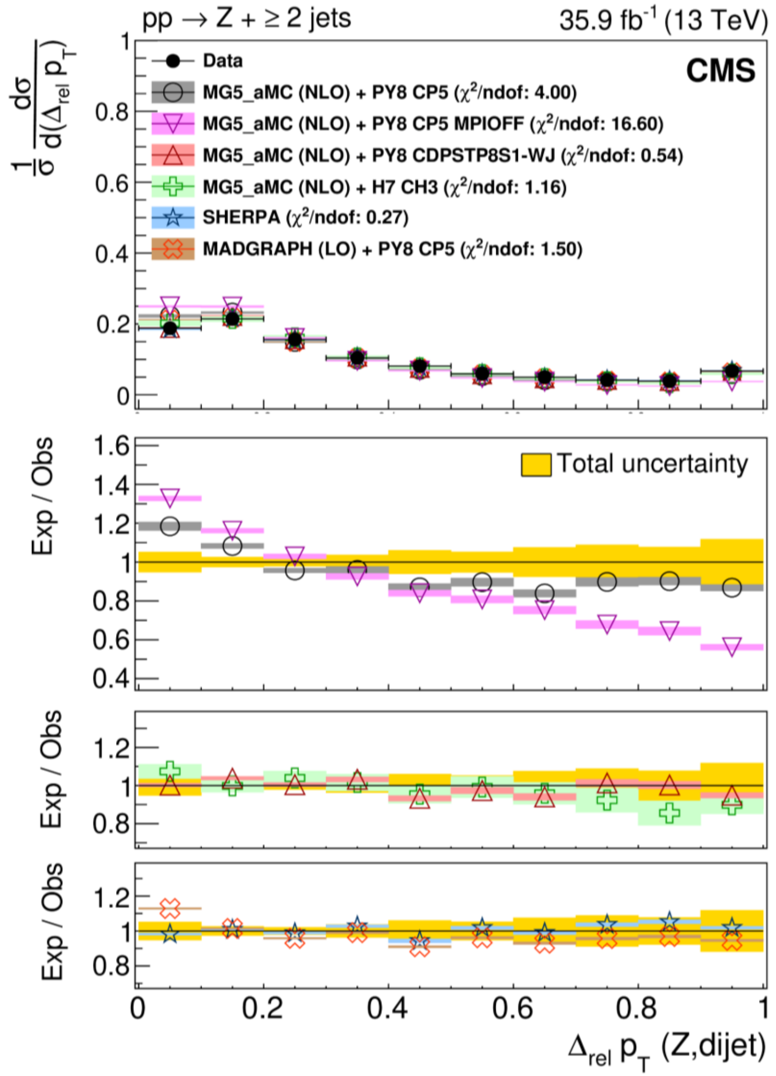
- DPS offers constraints on parton spatial/correlation structures
  - key to multi-parton dynamics
- First 6.2σ observation of DPS same-sign $W^{\pm}W^{\pm}$ production
- BDT discriminants trained to measure signal
- Distribution shown in 4 categories:
  - Largest bin: most signal-like
- Cross section ($\sigma_{\mathrm{DPS}}^{\mathrm{W^{\pm}W^{\pm}}}$ in fb) measured:
  - $80.7 \pm 11.2(\mathrm{stat})\ {}^{+9.5}_{-8.6}(\mathrm{syst}) \pm 12.1(\mathrm{model})$
  - Fiducial cross section: $6.28 \pm 0.81(\mathrm{stat}) \pm 0.69(\mathrm{syst}) \pm 0.37(\mathrm{model})$



arXiv:2206.02681, SMP-21-013

DPS with Z+jet events

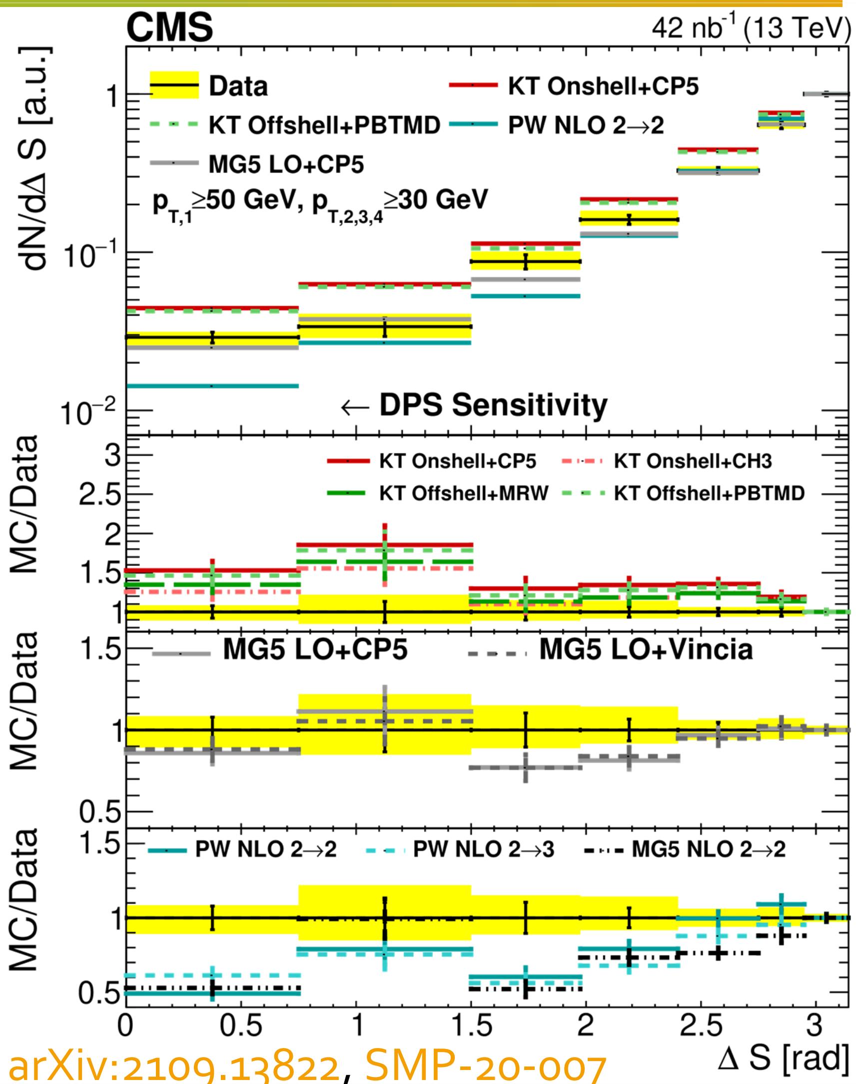
- Complements the WW DPS observation by probing DPS/MPI in a clean Z+jets final state
- Method: Unfolded differential and area-normalized shapes for DPS-sensitive observables ($\Delta\phi, \Delta p_T^{\text{rel}}$)
- Data compared to several models (MADGRAPH, SHERPA)
  - MPI-OFF clearly fails (shape/tails)
  - Standard tunes show tensions
  - The DPS-specific tune (CDPSTP8S1-WJ) best reproduces shape across observables
  - Strong sensitivity of Z+jets to DPS/MPI modelling.
- Provides constraints for MPI/DPS tunes at 13 TeV
- Useful input for DPS modelling in generators and for backgrounds in precision/BSM analyses



SMP-20-009, arXiv:2105.14511

DPS in four-jet events

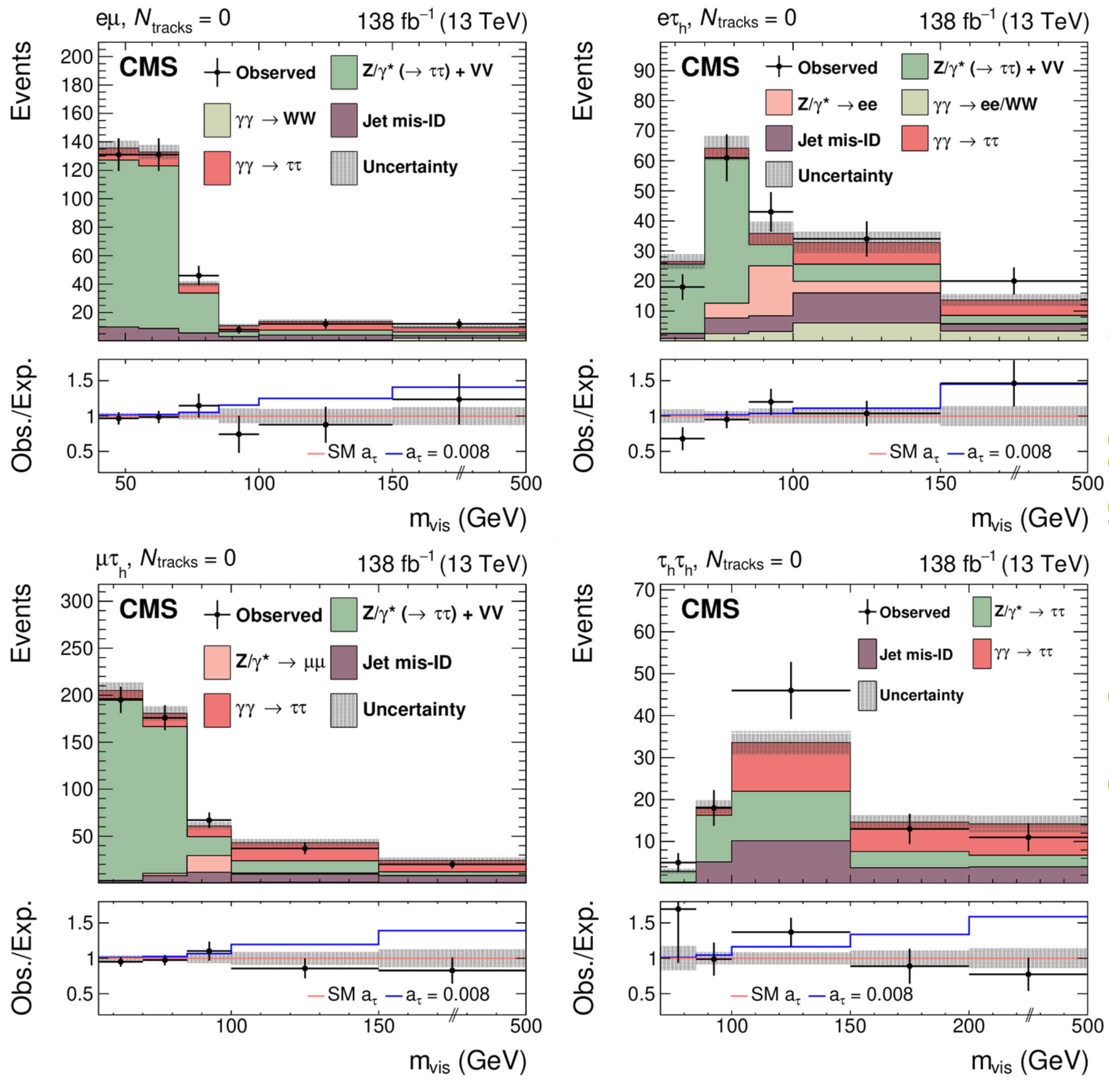
- Measured inclusive four-jet production (down to 20 GeV)
- Angular variables ($\Delta p, \Delta S, \Delta\phi, \Delta Y$) to disentangle DPS & SPS
  - ΔS: azimuthal angle between soft and hard jet pairs
  - Extracted DPS fraction by template fit
  - Focusing on ΔS as robust variable against parton-shower effects
- Derived effective cross section, compared to previous results
  - Sensitivity to SPS model assumptions
- Angular difference distributions are key discriminants
  - Deviations from SPS tunes indicate DPS components
- Impact: improves modeling of multiple parton scatterings
- Valuable input for future LHC/EIC synergy studies.



arXiv:2109.13822, SMP-20-007

Exclusive photon fusion to tau pairs in pp

- Like UPC in PbPb, photon fusion exploits quasi-real γ
  - Complements UPC programs to precision EW tests
- First observation of $\gamma\gamma \rightarrow \tau\tau$ fusion, 5.3σ significance
- Event signature: τ + τ (leptonic & hadronic decays)
  - Minimal additional tracks near the τ+τ vertex,
  - Low azimuthal acoplanarity
  - Ensures clean QED-dominated topology
- Consistent with QED predictions: $\sigma_{\text{fid}}^{\text{obs}} = 12.4^{+3.8}_{-3.1}$ fb
- Limits on anomalous τ moments:
  - Magnetic dipole moment: $a_\tau = 0.0009^{+0.0032}_{-0.0021}$
  - Electric dipole moment: $|d_\tau| < 2.9 \cdot 10^{-17} e\text{cm}$
  - Consistent with the Standard Model
  - Most stringent constraints to date



arXiv:2406.03975, /SMP-23-005

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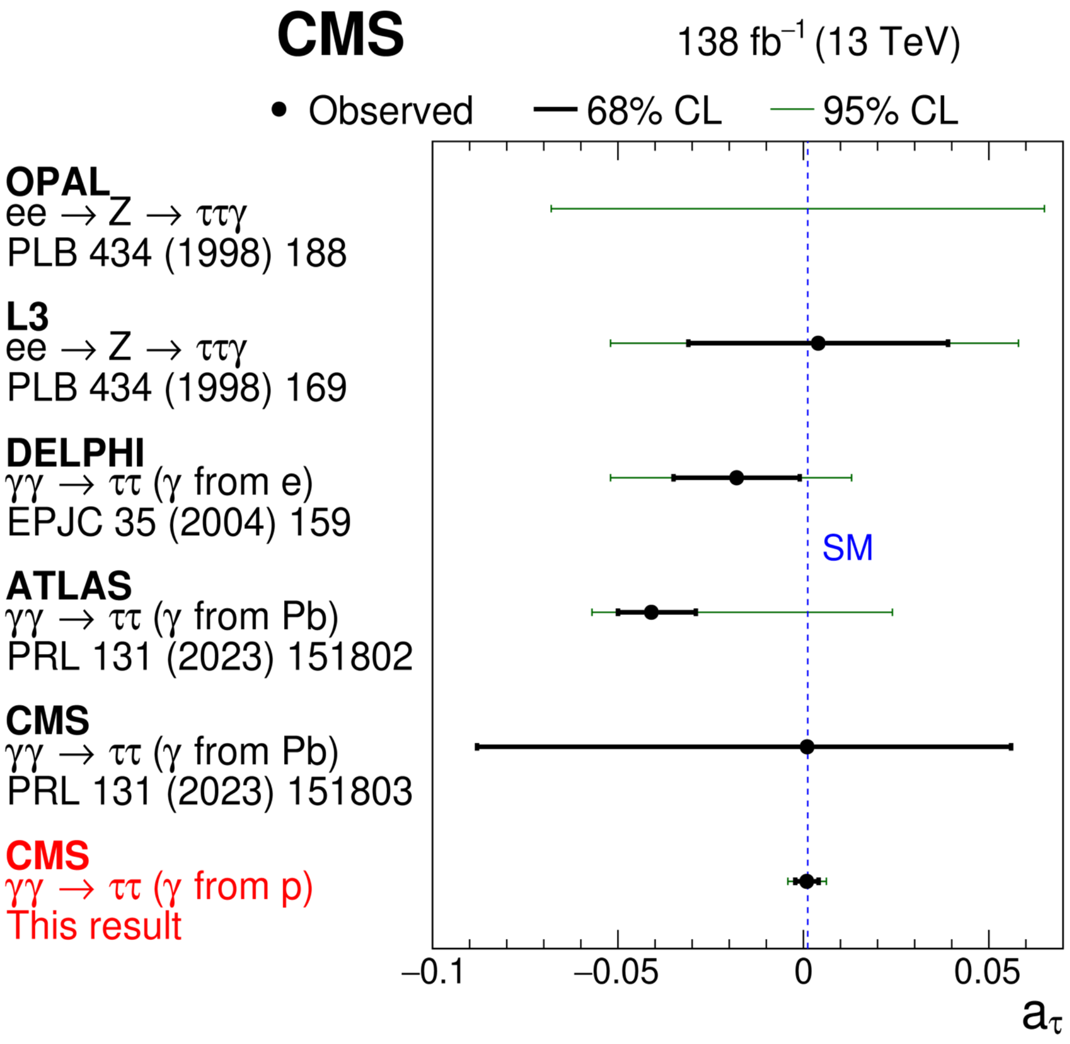
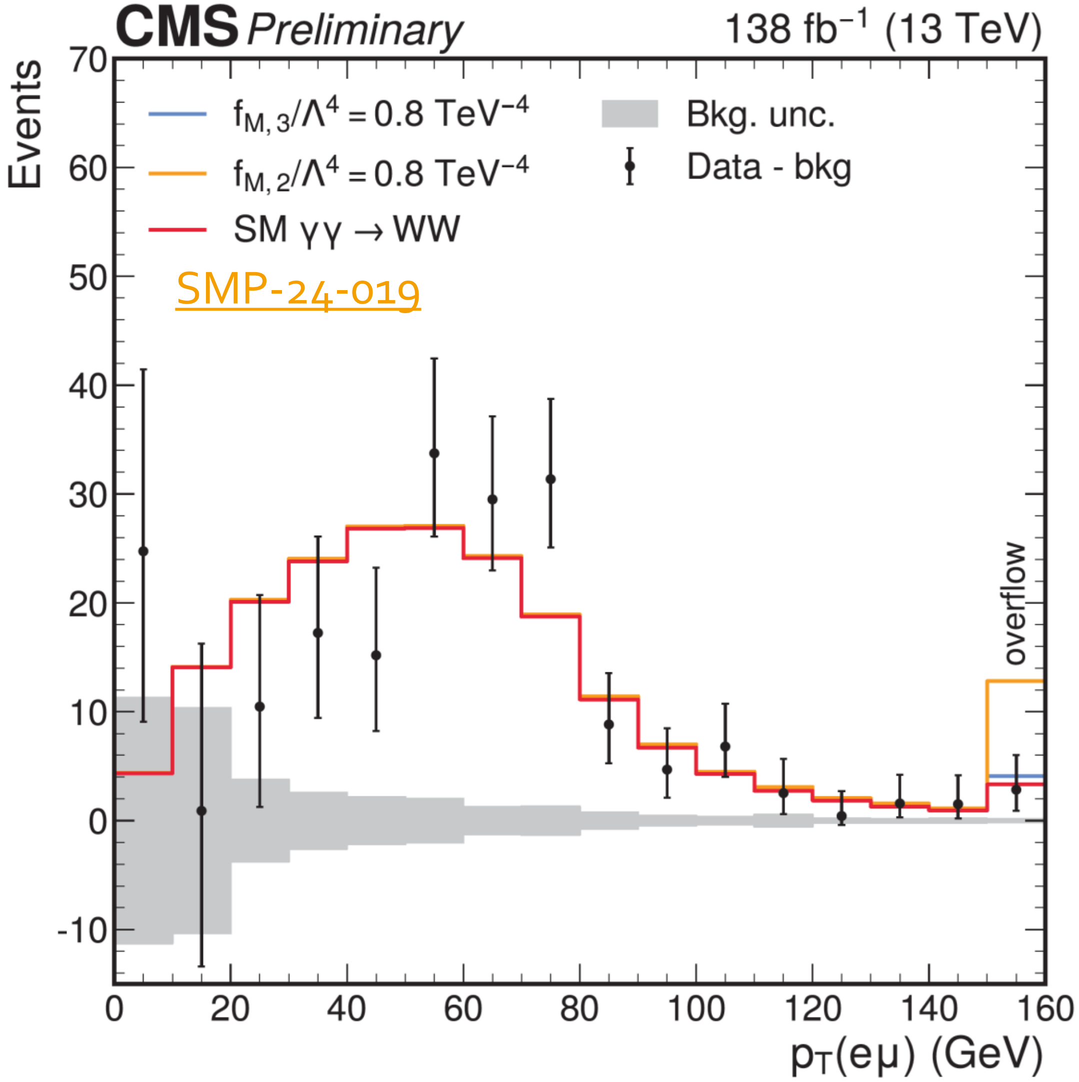


arXiv:2406.03975, /SMP-23-005

Exclusive photon fusion to WW pairs in pp

- Photon fusion: pp analogue of UPC photon physics
  - Relevant for EIC photon-induced studies
- Observation of exclusive γγ ⟶ WW ⟶ eμνν
  - e + μ signature: suppress Drell-Yan processes
  - Improves background for exclusive environment
  - Still ~10% branching fraction
- Measured cross sections:
  - $\sigma_{\text{tot}} = 659^{+82}_{-78}$ fb, $\sigma_{\text{fid}} = 4.1 \pm 0.1$ fb
- Key variable (p_T vector sum) clearly separates photon-fusion signal
- Sensitive test of gauge couplings (γWW, γγWW)
  - Sets limits on BSM (dimension-8 EFT) operators



AND NOW FOR SOMETHING COMPLETELY DIFFERENT…

HBT or femtoscopy in high energy physics

- R. Hanbury Brown, R. Q. Twiss - observing Sirius with radio telescopes
  - Intensity correlations vs detector distance ⇒ angular size of point-like star
- Goldhaber et al: applicable in high energy physics
  - Understanding: Glauber, Fano, Baym, … (PRL10, 84; Rev. Mod. Phys. 78 1267, …)
- Momentum correlation $C(q)$ related to source $S(r)$

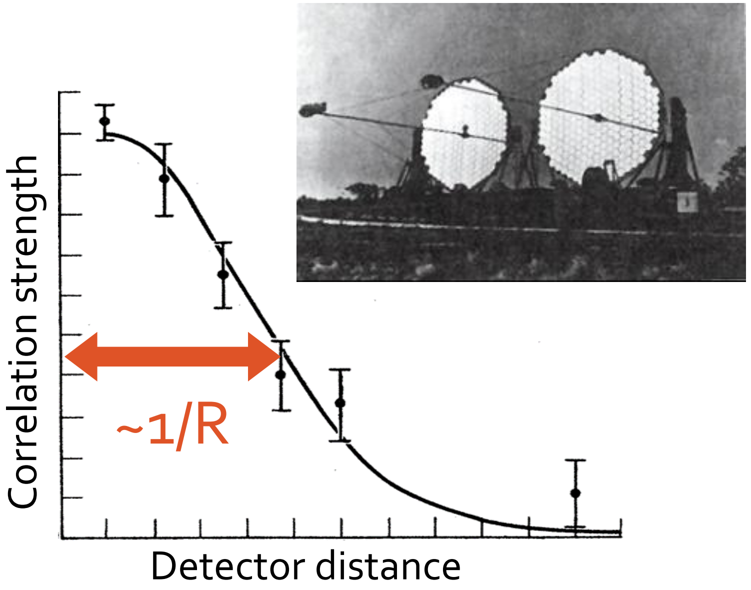
$$C(q) \cong 1 + \left|\int S(r) e^{iqr} dr\right|^2$$

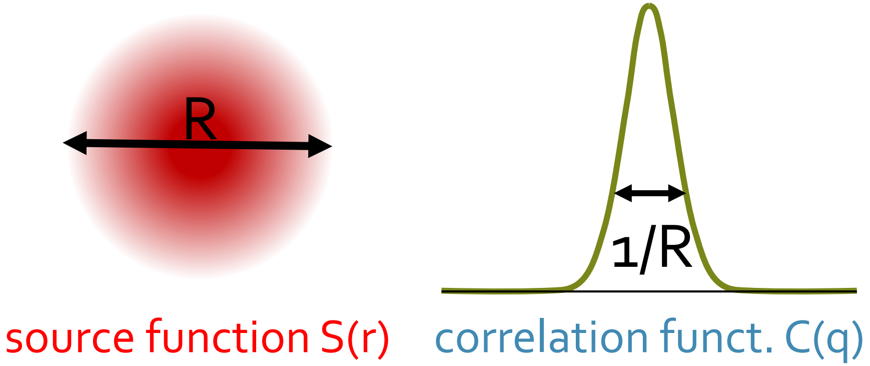
(under some assumptions)

- Can be expressed with distance distribution $D(r)$:

$$C(q) \cong 1 + \int D(r) e^{iqr} dr$$

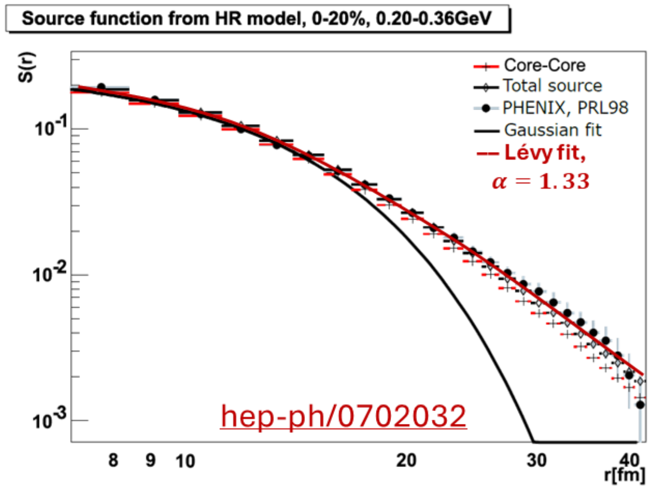
- Neglected: pair reconstruction, final state interactions, multi-particle correlations, coherence, …
- What is the source shape? Can be explored via femtoscopy

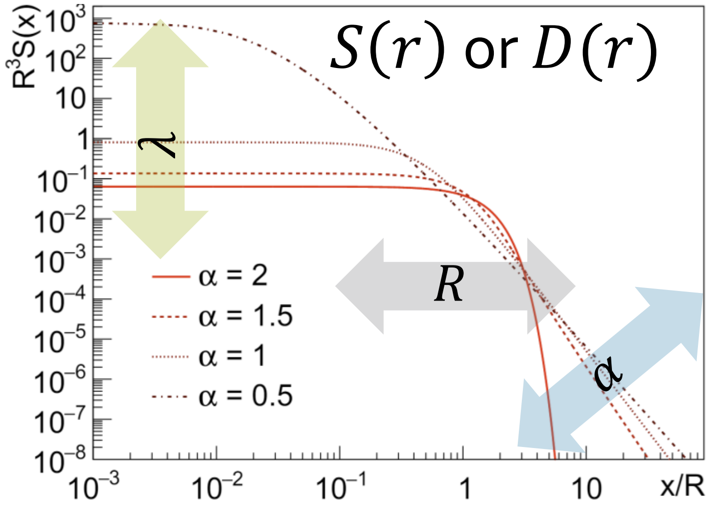


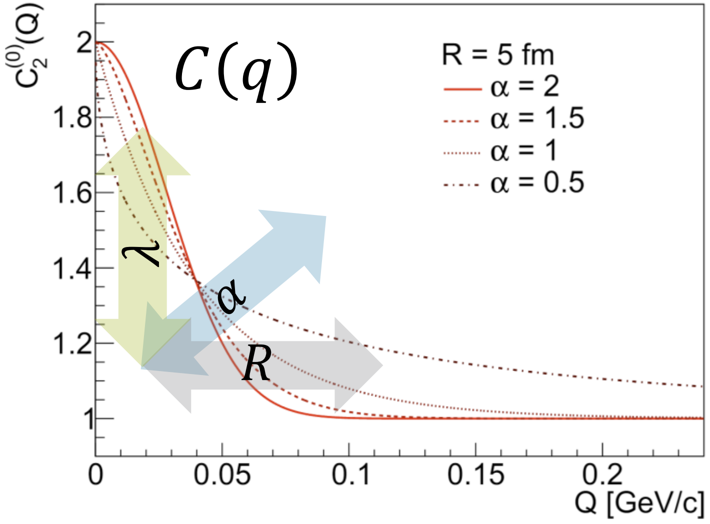


Lévy distributions in heavy-ion physics

- Central limit theorem, diffusion, and thermodynamics lead to Gaussians
- Measurements suggest phenomena beyond Gaussian distribution
- Lévy-stable distribution (symmetric):
  $$\mathcal{L}(\alpha,R;r)=\frac{1}{2\pi}\int d^3q e^{iqr}e^{-\frac{1}{2}|qR|^{\alpha}}$$
  - From generalized central limit theorem
  - Power-law tail $\sim r^{-1-\alpha}$ if $\alpha < 2$
  - Special cases: α = 2 Gaussian, α = 1 Cauchy
- Shape of the correlation functions with Lévy source: $C_2(q) = 1 + \lambda \cdot e^{-|qR|^{\alpha}}$
  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67-78
- **Parameters: strength λ, scale R, shape α** →
- Lévy source seen & exponent measured from SPS through RHIC to LHC
  NA61 [EPJC83(2023)919], PHENIX [PRC97(2018)064911 & PRC110(2024)064909], CMS [PRC109(2024)024914]

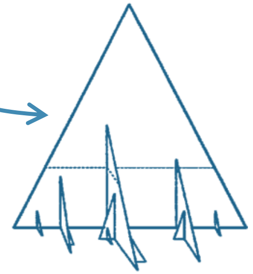


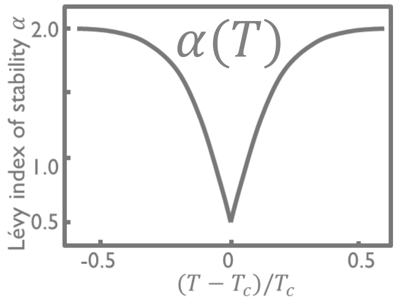




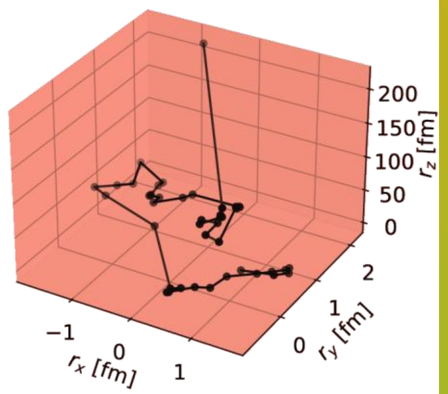
Why do Lévy shapes appear, why is it important?

- A more comprehensive list of possible reasons:
  - Jet fragmentation (Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36 (2005) 329-337)
    - See also Caucal, Mehtar-Tani, JHEP 09 (2022) 023
    - Important in e^+e^-, see L3 Collaboration, Eur.Phys.J.C 71 (2011) 164
  - Critical phenomena (Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) 525-532)
    - Role in the few GeV region? Affected by finite size effects?
  - Directional or event averaging (Cimerman et al., Phys.Part.Nucl. 51 (2020) 282)
    - Ruled out by event-by-event and 3D analyses
  - Lévy walk (BJP37(2007); PRB103(2021), Entropy24(2022); PLB847(2023); Comm.Phys.8(2025)55)
    - Only plausible explanation (so far) at high energies and large systems



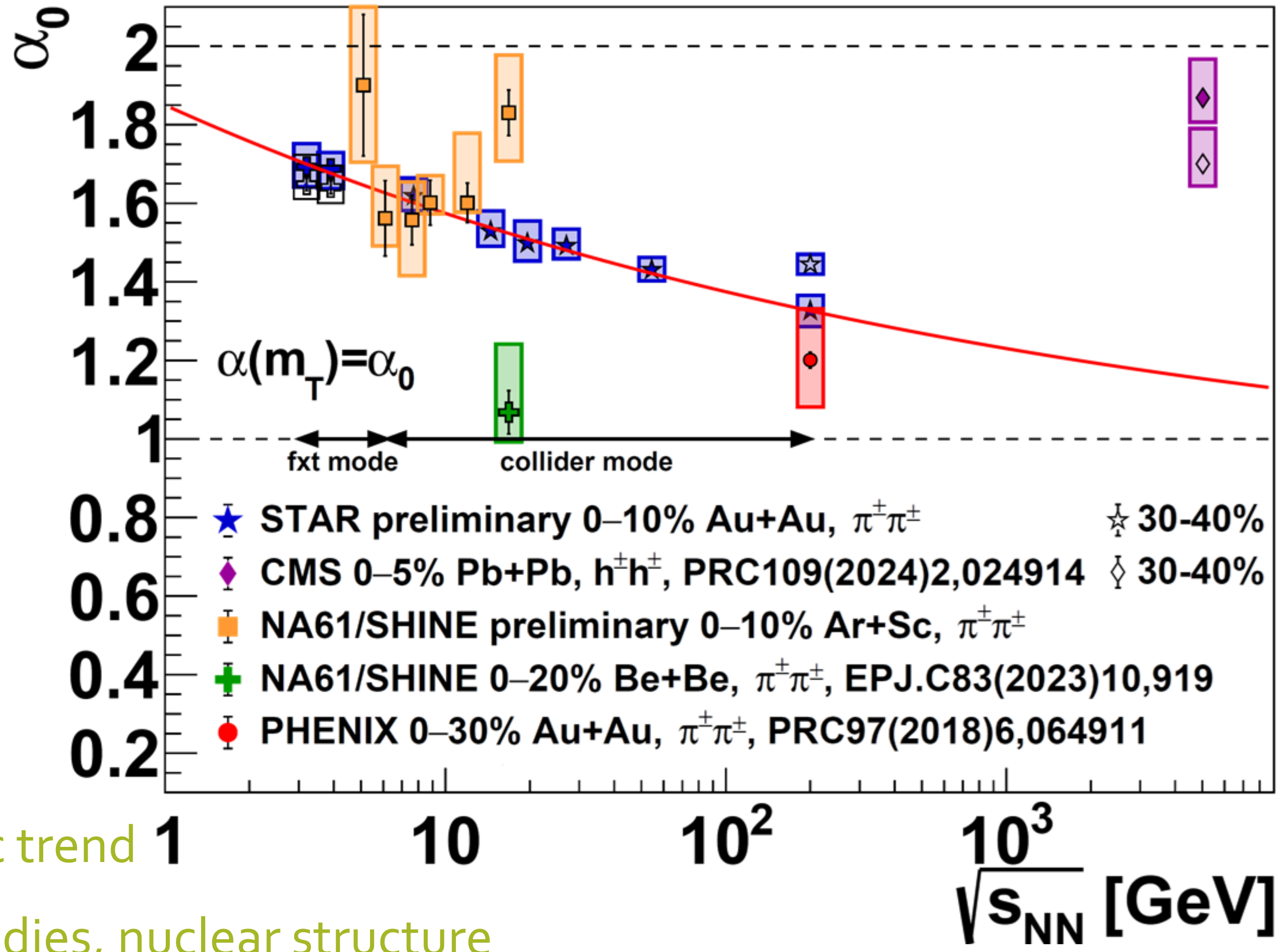


- Importance of utilizing Lévy sources in heavy-ion physics
  - Measuring α and R: quark-hadron transition, critical point, etc.
  - Measuring λ: In-medium mass modification, coherent pion production



Lévy exponent in AA from 3.2 GeV to 5 TeV

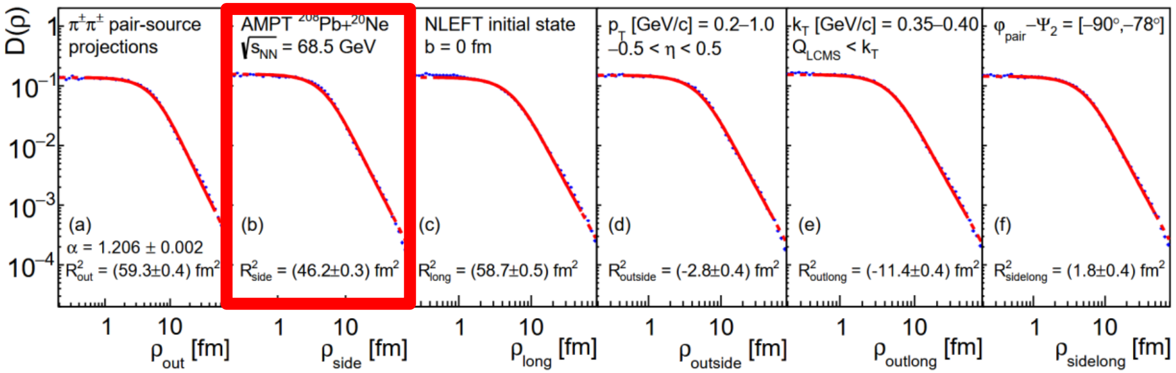
- Non-gaussian values ($\alpha \ll 2$)
- 200 GeV centrality dependence: smaller α for central collisions
- Same with energy: increasing density → decreased α:
  more time for Lévy walk?
- RHIC trend described by power-law:
  $\alpha_0 \approx 0.85 + \sqrt{s_{NN}}^{-0.14}$
- CMS result at 5 TeV: off the RHIC trend
  - Opposite centrality dependence: smaller α for peripheral collisions
- SPS: interesting, almost non-monotonic trend
- EIC synergy: jet fragmentation, QCD studies, nuclear structure

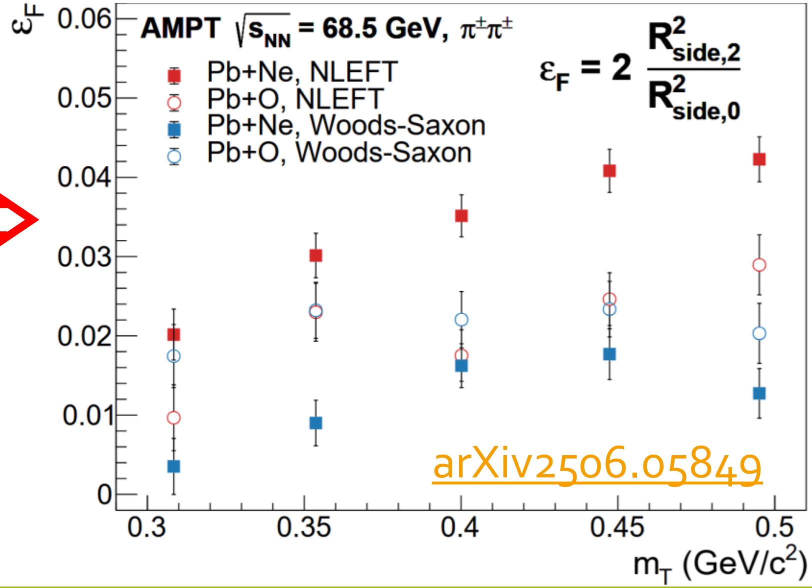


Nuclear structure with Lévy femtoscopy

- 3D analysis of the source: 6 directions,
  - In several bins of pair p_T and ϕ
  - Simultaneous fit of all projections
- Azimuthal anisotropy revealed in angular oscillation of the source radii
- Important observable: $\epsilon_F = 2\frac{R^2_{side,2}}{R^2_{side,0}}$
  - Captures amplitude of ϕ-oscillation in „side" direction (0,1,0)
  - Sensitive to final state spatial eccentricity
  - Complements flow studies
  - Helps disentangle spatial and velocity-space anisotropies
- Sensitive to nuclear structure as well!
- Details: D. Kincses, arXiv:2506.05849

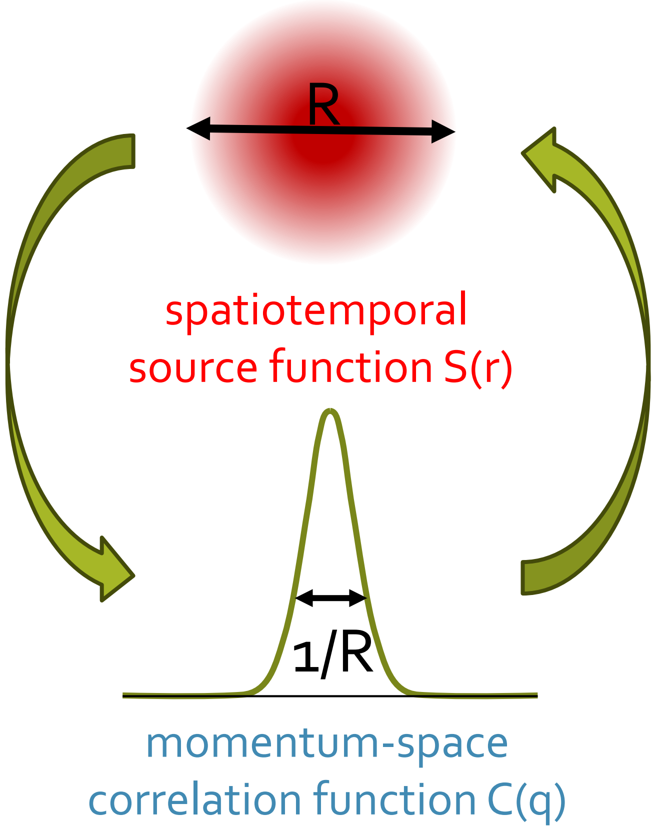
(1,0,0), (0,1,0), (0,0,1), (1,1,0), (1,0,1), (0,1,1)





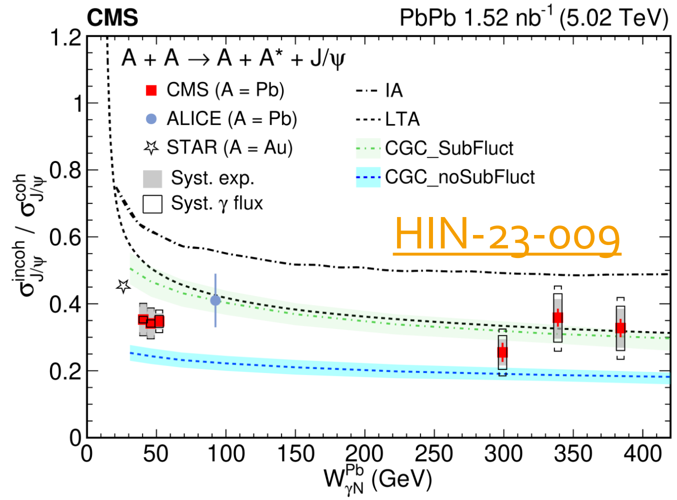
Femtoscopy at the EiC

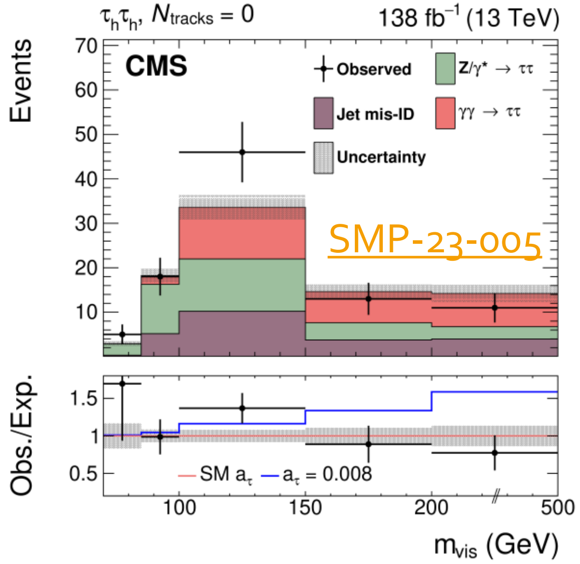
- Provides a "femtoscope" for hadronization
  - mapping emission radii & formation times as functions of Q^2, z, p_T
  - spatiotemporal image of hadron creation under controlled hard scales
- Real-space probe of cold-nuclear and small-x physics
  - How saturation or shadowing modify the space-time pattern of particle production
  - Complementary to momentum-space observables (TMD, GPD)
- New channels and constraints for nonperturbative QCD
  - Clean EIC environment enables tests of color neutralization, string breaking, final-state interactions
- Initial state correlations
  - Bose enhancement of gluons, different signatures as compared to HBT w.r.t. kinematic domains
  - Altinoluk, Armesto, Eur.Phys.J.A 56 (2020) 8, 215



Summary

- Ultra-peripheral collisions: small-x evolution and gluon densities
  - Incoherent J/ψ, coherent Υ(1S) & ϕ(1020) photoproduction in UPC
  - D^0 photoproduction in UPC
- Exclusive photon fusion to ττ and WW pairs in pp
  - Precision EW and BSC tests
- Double parton scattering: transverse distributions
  - WW production in pp, Z+jet events , four-jet events
- Femtoscopy with Lévy sources
  - Source shape in small systems determined by jet fragmentation, Lévy walk
  - Complements flow measurements
  - Sensitive to nuclear structure
  - Sensitive to initial state via gluon Bose enhancement





Thank you for your attention

… and if you are interested in similar topics:

https://zimanyischool.kfki.hu/25/

https://wpcf2026.elte.hu/

WPCF 2026

Workshop on Particle Correlations and Femtoscopy
May 18-22, 2026, Budapest, Hungary

Special Issue

"10th Anniversary of Universe: Studying the Strongly Interacting Matter in Nuclear Reactions from Intermediate to Ultra-Relativistic Energies"

Short information for the Special Issue

In ultra-relativistic heavy-ion collisions, a strongly interacting Quark Gluon Plasma (sQGP) is created, resembling the matter of the early Universe. Experiments at LHC and RHIC explore its transition to hadronic matter, while FAIR and related facilities probe possible first-order phase transitions and the elusive Critical Endpoint (CEP). The RHIC Beam Energy Scan and CERN SPS programs, together with precision studies at the LHC, have advanced our understanding of the QCD phase diagram.

At lower energies (FAIR, FRIB, RIKEN, GANIL), dense nuclear matter can be produced, enabling studies of neutron star properties under laboratory conditions. These results link to astrophysical observations of neutron star radii, masses, gravitational waves, and neutrino emissions from supernovae. Accurate knowledge of the nuclear Equation of State across densities is crucial for interpreting such phenomena.

This Special Issue aims to connect insights from different energy regimes, commemorate the QGP discovery, and highlight its significance across nuclear physics, particle physics, and astrophysics.

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