Image credit: Jefferson Lab

Moving from Heavy Ion Collisions to Deep Inelastic Scattering

Olga Evdokimov (University of Illinois at Chicago)

Outline: from HIC to EIC

HIC program and the QGP

- QGP signatures and their evolution
- “Pillar” measurements

HIC topics and direct connections to the EIC Physics

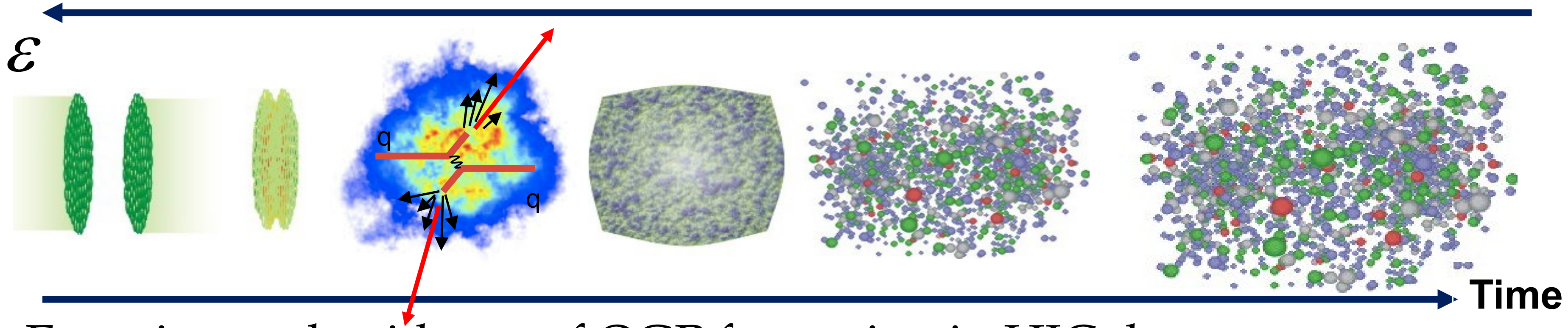
- What we know we don’t know
- Synergies/impact for other fields

From HIC to EIC – detectors

- HIC Detector upgrades and EPIC developments
- Summary

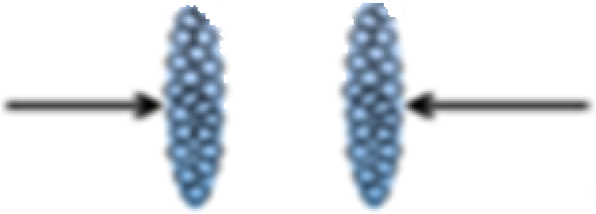
Physics of Heavy Ion Collisions

- 20+ years of QGP exploration on a quest to understand the strong force and confinement by creating a system of deconfined colored quarks and gluons



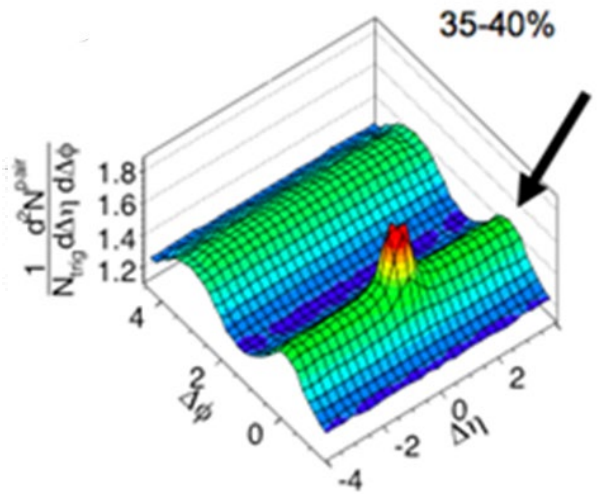
- Experimental evidence of QGP formation in HIC data:
  - Initial medium temperature is well above predicted T_c
  - Its evolution is well-described by near-ideal hydrodynamics
  - The final system appears to be in thermal equilibrium, and is very explosive
  - Medium is strongly interacting and opaque to colored probes
- HIC: era of precision studies of medium properties and collision dynamics requires detailed understanding of nucleons/nuclei

QGP Pillars: Collectivity



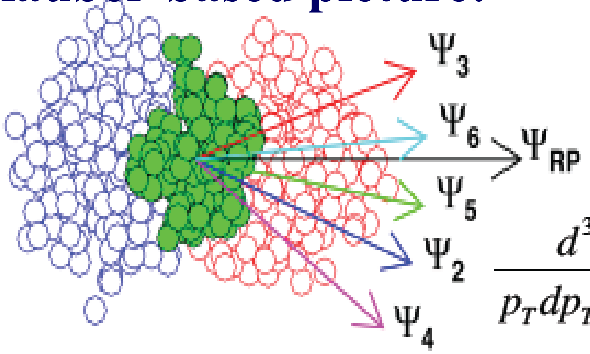
PLB 724 (2013) 213

- Flow correlations are major tool for study of the collective dynamics in of the GQP medium, characterizing how pressure gradients translate initial state fluctuations into final state observables.

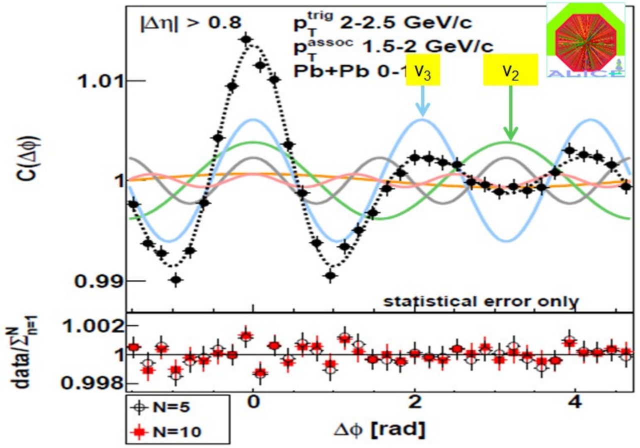


Glauber-based picture:

$$\Psi_m^{pp} = \frac{1}{m}\tan^{-1}\left\{\frac{\sum_{i=1}^{N_{part}} r_i^m \sin(m\phi_i)}{\sum_{i=1}^{N_{part}} r_i^m \cos(m\phi_i)}\right\} - \frac{\pi}{m}$$

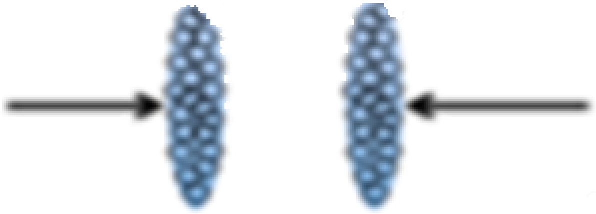


$$\frac{d^3N}{p_T dp_T d\eta d\phi} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T d\eta}\left(1+\sum_{k=1}^{\infty} 2v_{n=km}(p_T,\eta)\cos\left[n(\phi-\Psi_m)\right]\right)$$



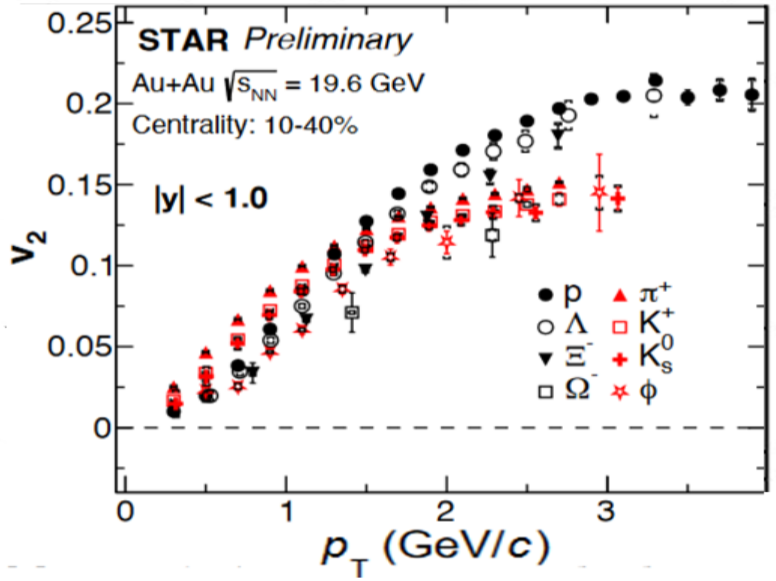
- Early studies have established:
  - Hierarchy of harmonics agrees with theory (hydrodynamics) expectations
  - Estimates of η/s are finite, close to quantum limit

QGP Pillars: Collectivity

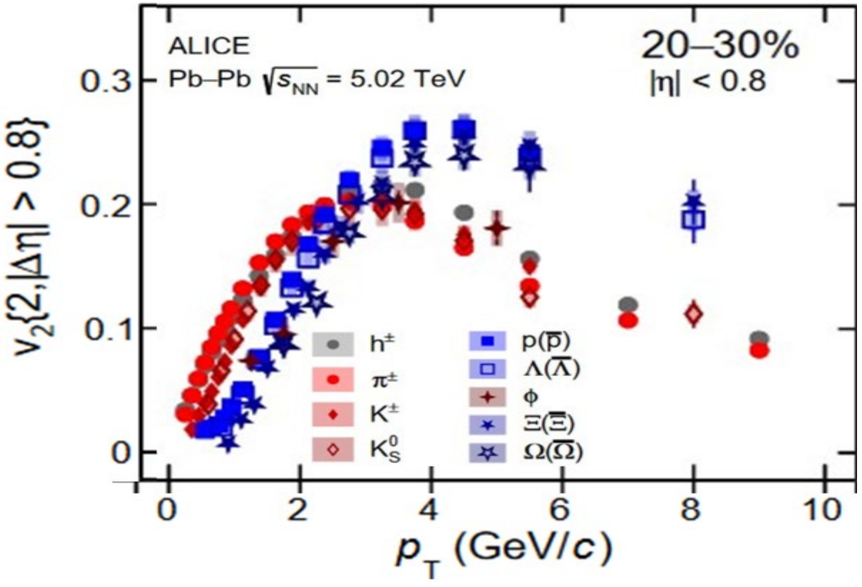


- Anisotropic elliptic flow for identified particle species:

AuAu 19.6 GeV

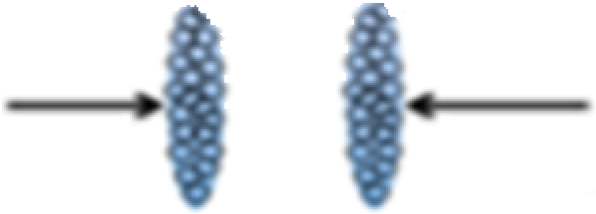


PbPb 5.02 TeV

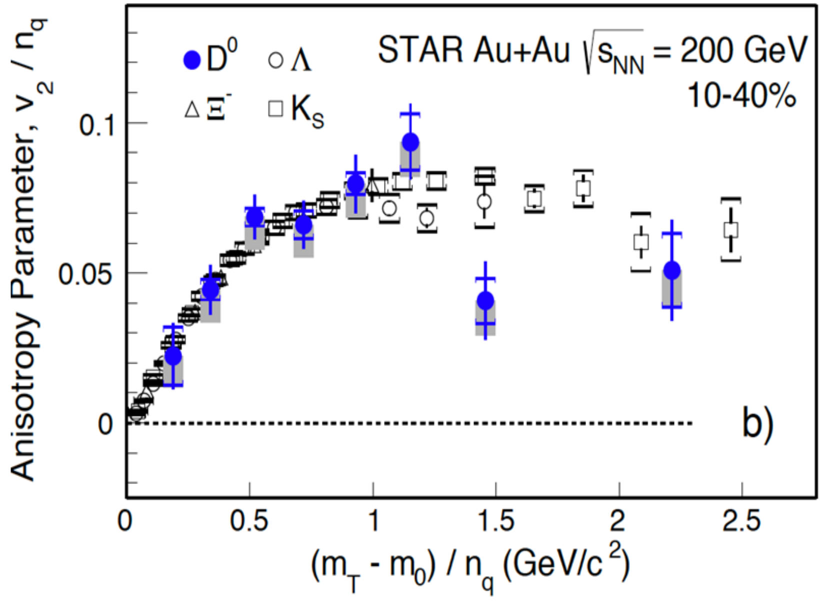


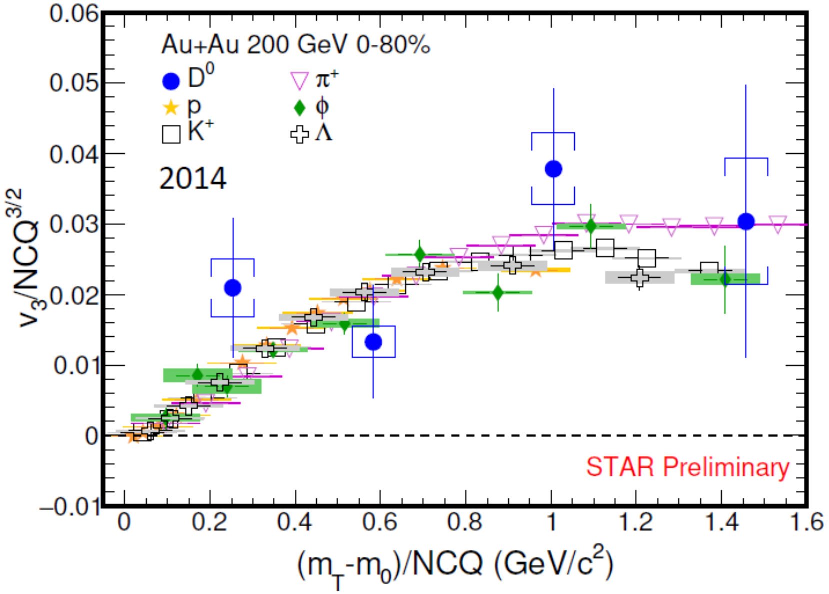
- Common for all energies and systems: mass ordering at low p_T, baryon/meson grouping at intermediate p_T
- Hadronization through recombination/coalescence ↔ partonic origin of the flow

QGP Pillars: Collectivity

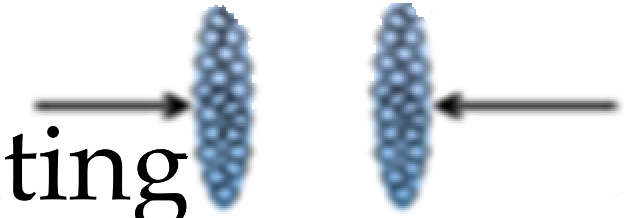


- Constituent quark scaling was observed for the flow harmonics through intermediate transverse momenta, first for light-flavor hadrons, then for strange and charm hadrons





- Common NCQ trend for v_2 and v_3 for light, and strange hadrons – evidence for thermalized partonic medium; hadronization by coalescence
- D^0 mesons – significant v_2 and v_3, common scaling trends – charm collectivity and possibly thermalization

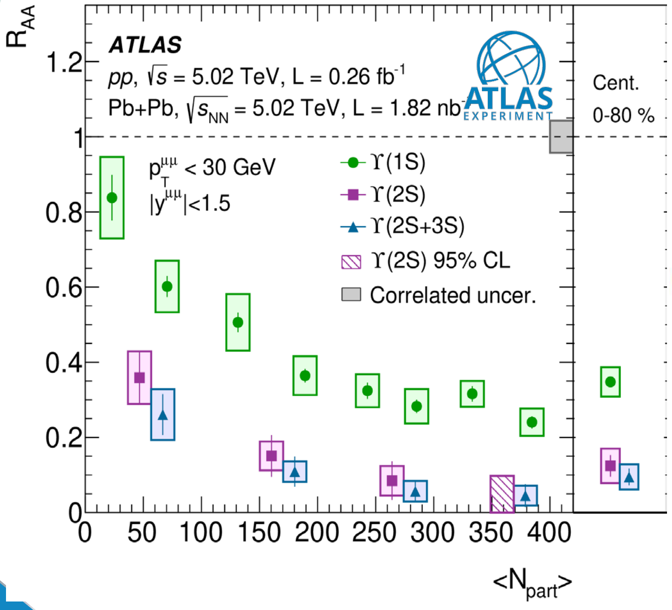


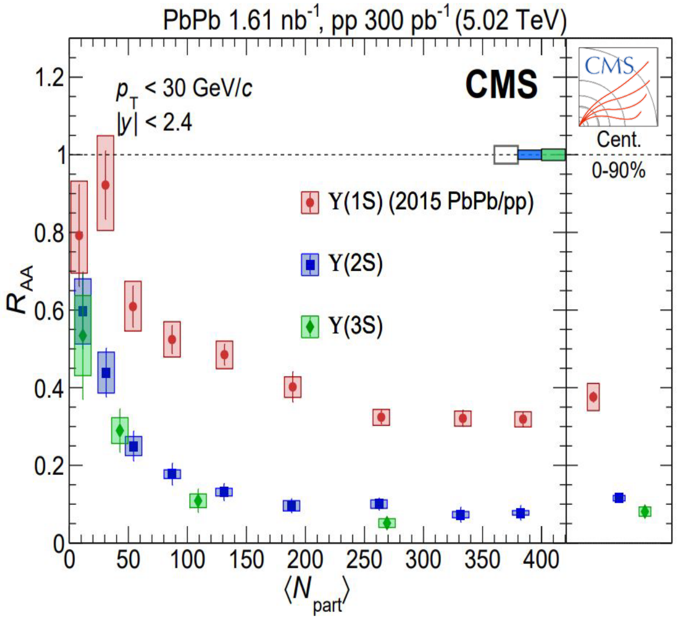
QGP Pillars: Quarkonia Melting

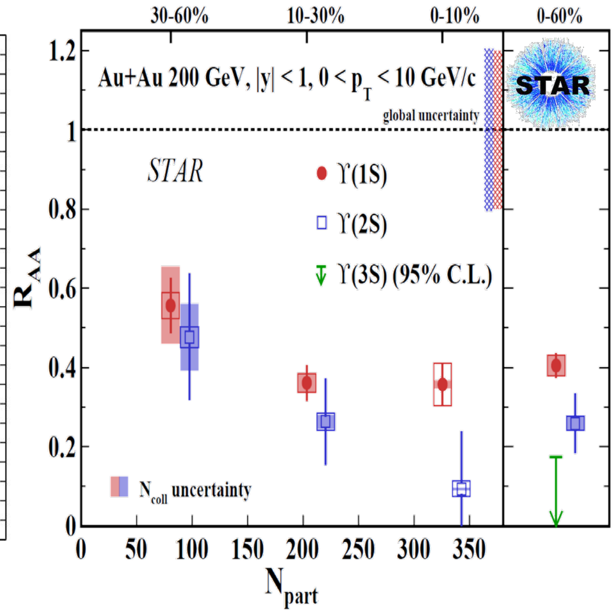
QGP is hot!

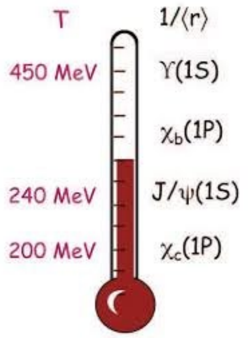
- Heavy quarks are another established QGP probe: produced predominantly by initial hard process (mc, mb ≫ ΛQCD) then interact with the QGP medium

$$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{binary}\rangle_{AA}}{\text{Yield}_{pp}}$$





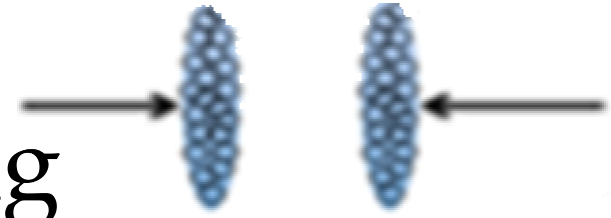




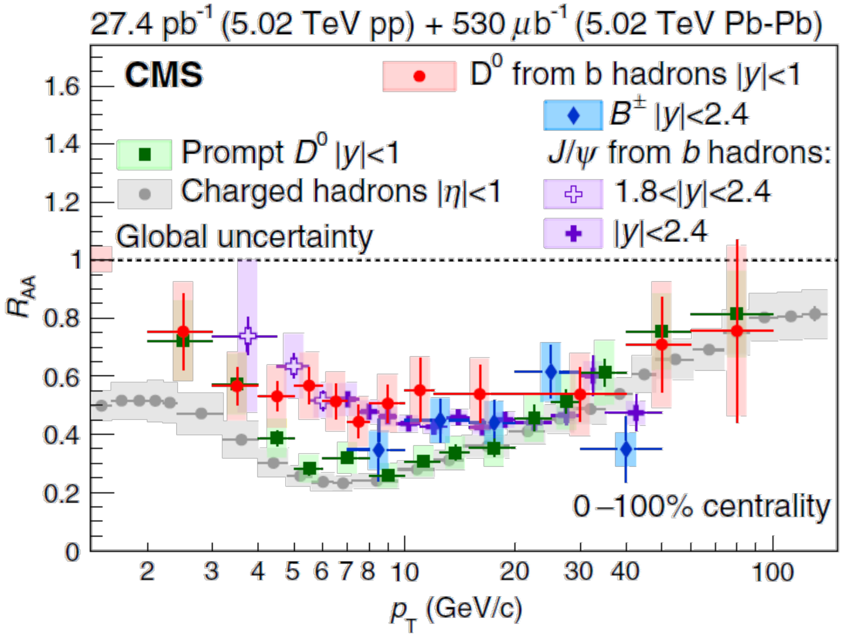
- Sequential "melting" is established by the hierarchy of Upsilon states suppression

Binding energy range probes medium temperature and its centrality dependence

QGP Pillars: Jet Quenching



- The beginning of the jet-quenching era: comparing particle production rates at high p_T provides (indirect) information on the fate of the jets in QGP



- Nuclear modification:

prompt- and non-prompt D^0, non-prompt J/ψ, $B^{\pm}$

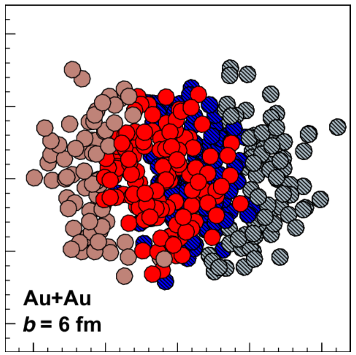
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{< N_{bin} > d^2N^{pp}/dp_T d\eta}$$

- Mid-p_T : flavor dependence of E-loss

$R_{AA}(b) > R_{AA}(c) \sim R_{AA}(\text{light flavors})$

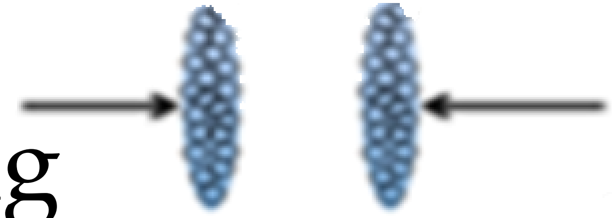
- High p_T : radiative E-loss dominates

$R_{AA}(b) \sim R_{AA}(c) \sim R_{AA}(\text{light flavors})$

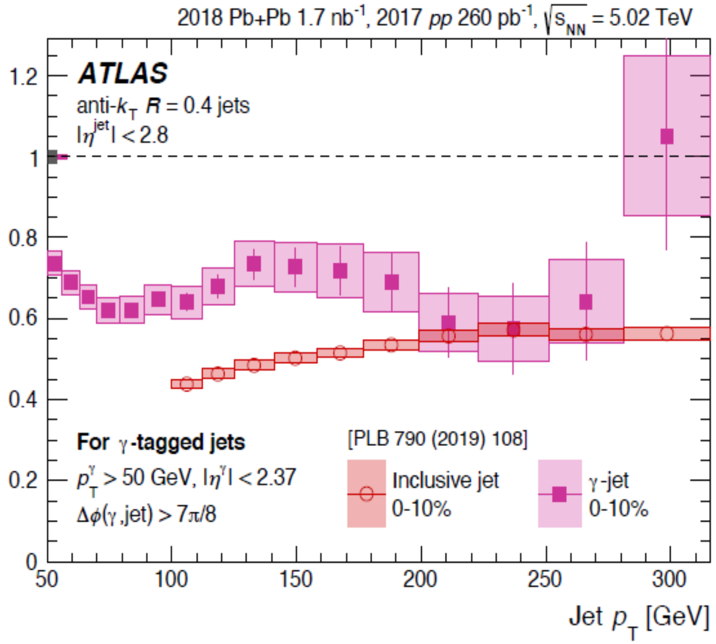


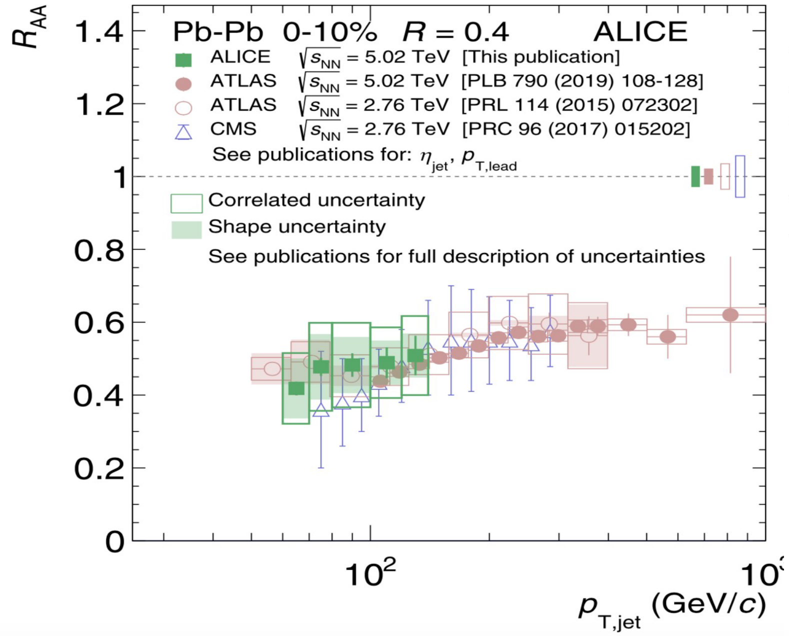
- Number of binary collisions $< N_{bin} >$ is extracted from Glauber calculations and are verified by colorless probes.

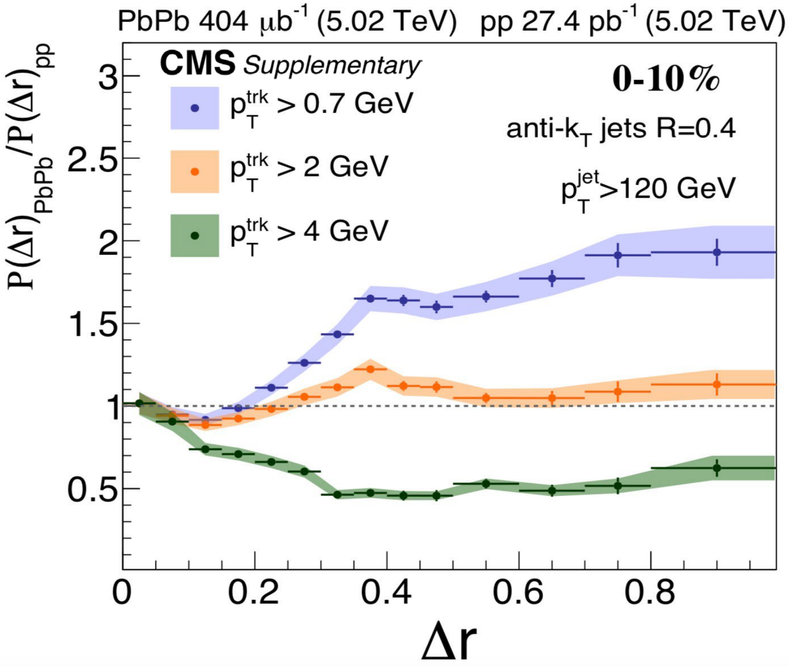
QGP Pillars: Jet Quenching



- Detailed measurements of jet R_{AA} – shape/level depends on steepness of the spectra:



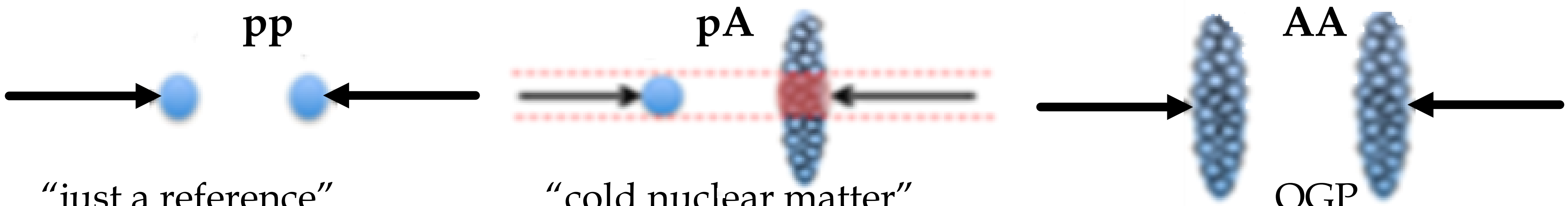




- Jet quenching is more than nuclear modification: rich set of energy balance (γ-jet, Z-jet) and jet substructure observable map out details of parton-medium interactions and partonic energy loss in the hot nuclear medium.

How does this connect to DIS?

- Heavy Ion physicists do more than colliding two heavy ions
- System size for control over initial and final state effects



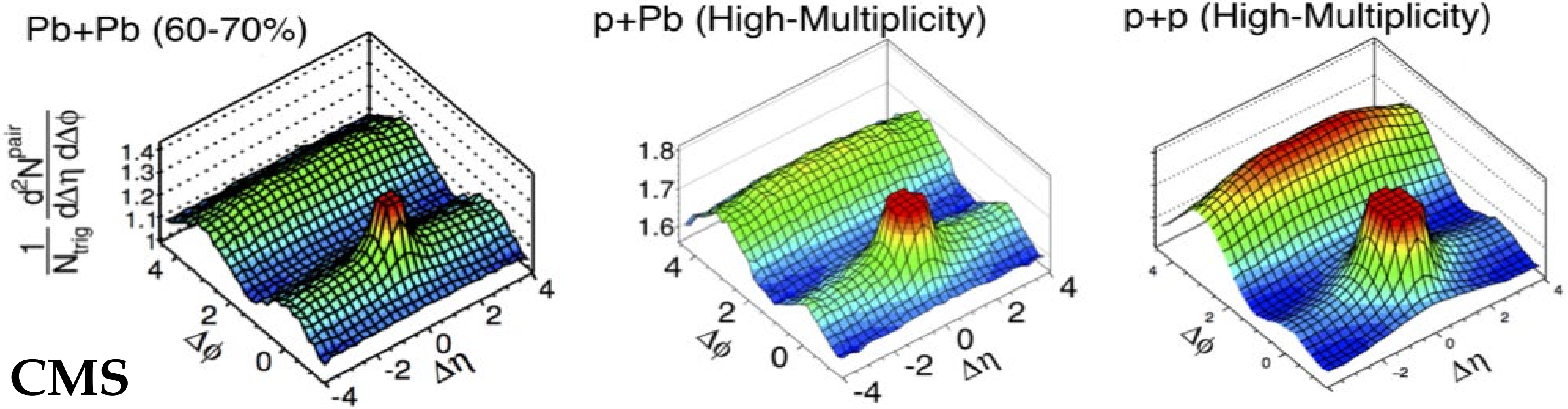
"just a reference"
for hard processes/
vacuum fragmentation

"cold nuclear matter"
initial state effects
(e.g., shadowing, anti-shadowing,…)

with centrality "dial"
final state effects

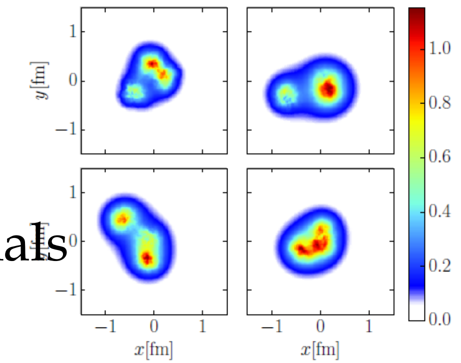
Now: changing paradigm of the old division, blurring the edges of applicability of initial/final state language; interesting new phenomena across the board.

Collective Phenomena in Small Systems



CMS

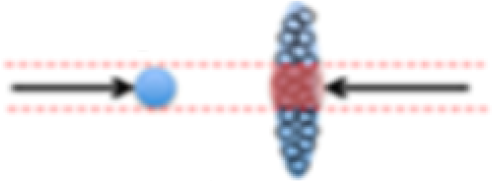
PRD 94(2016)034042



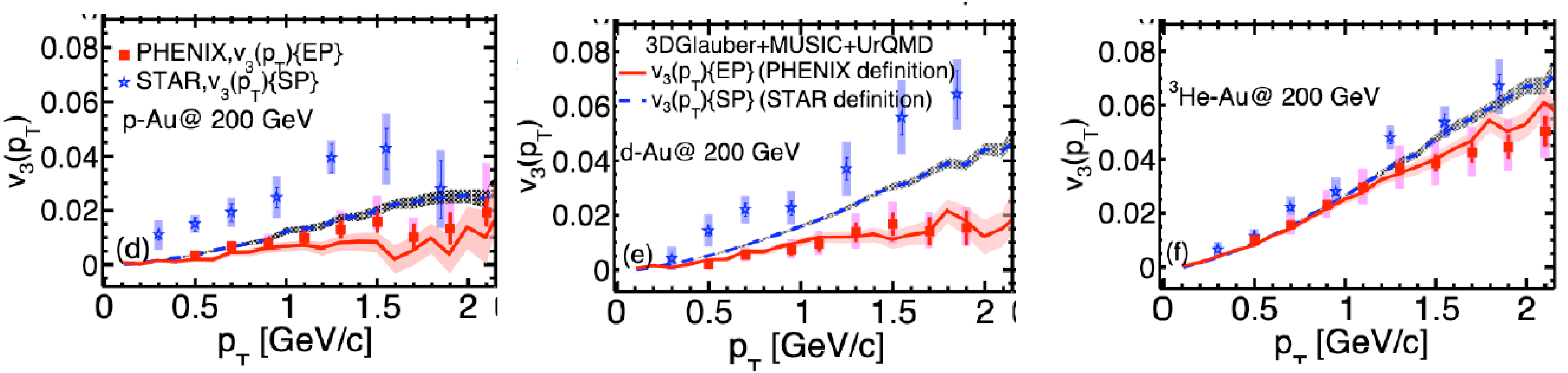
proton density
$x \sim 10^{-3}$

- Long range correlations: everywhere! AA collisions, pA, high multiplicity pp
  - NOT reproduced in any established MC generators
- Understanding of proton structure is critical for reproducing the signals
- Impacts: HIN (QGP formation in small systems, initial state,…)

Collective Phenomena in Small Systems

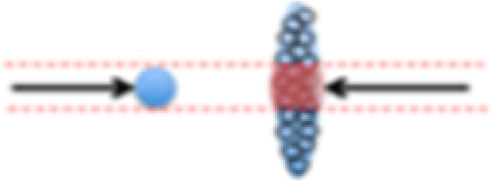


- Discovery of collective effects in small systems:
  - CMS: high multiplicity pp @ 7 TeV and pPb @ 5 TeV
  - PHENIX: pAu, dAu, ^{3}HeAu @ 200GeV

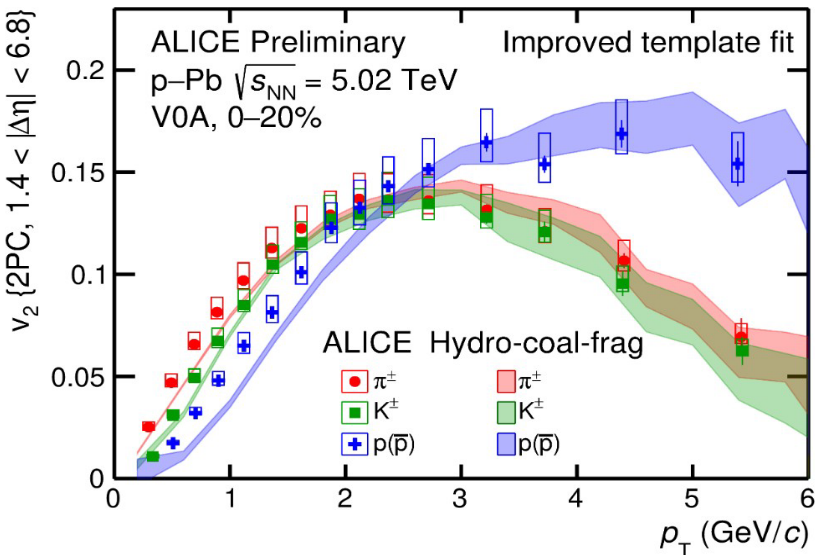


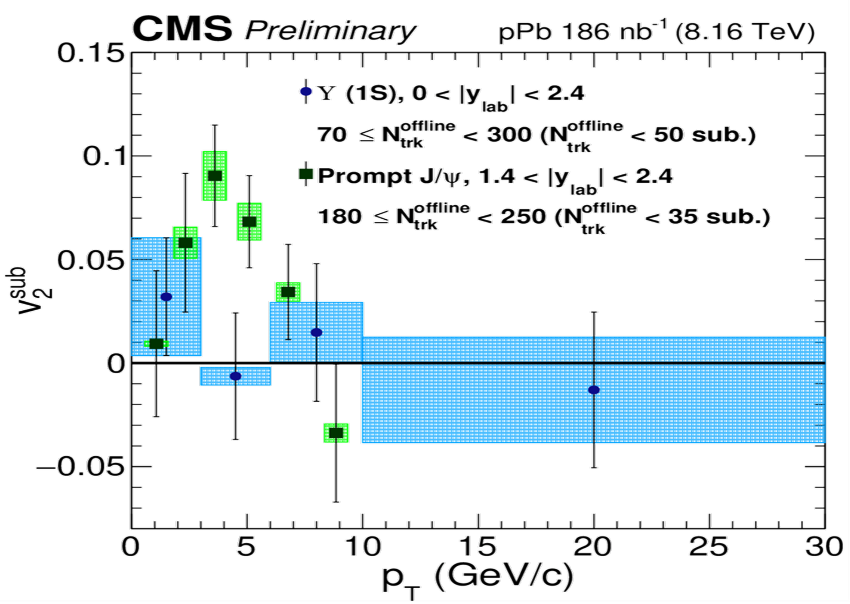
- Results are found consistent with 3+1D hydrodynamic modeling of a "small droplet of QGP"
- Can the system that small reach an equilibrium?
- Is this a manifestation of initial state phenomena? CGC?

Collective Phenomena in Small Systems



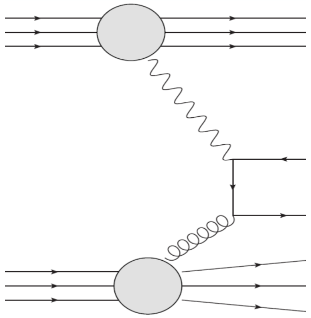
- Similar flow strength at similar event multiplicity
- NCQ scaling trends for light, strange and charm hadrons!



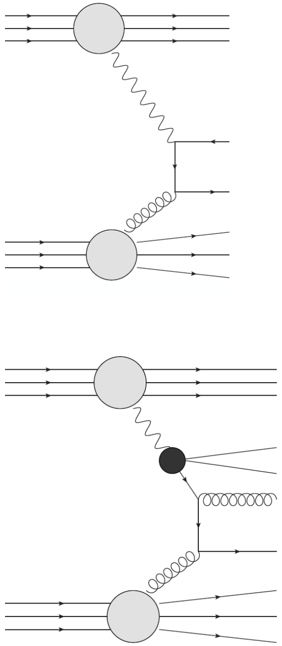


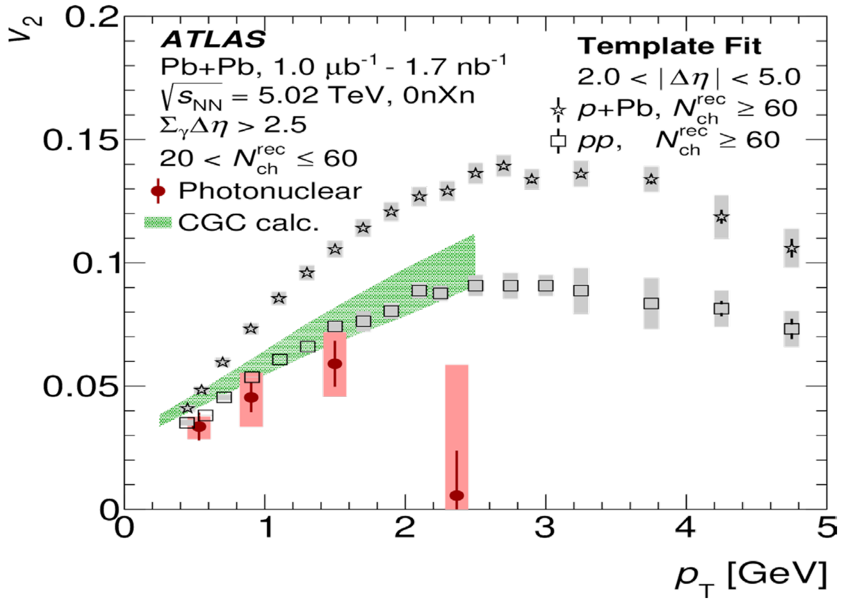
- **Small systems:** mass ordering at low p_T
  - Baryon/meson grouping at mid-p_T
- **Small systems:** prompt J/ψ: still flows!
  - Υ(1S) – no significant v_2 even in high multiplicity events (but none was seen even in PbPb)

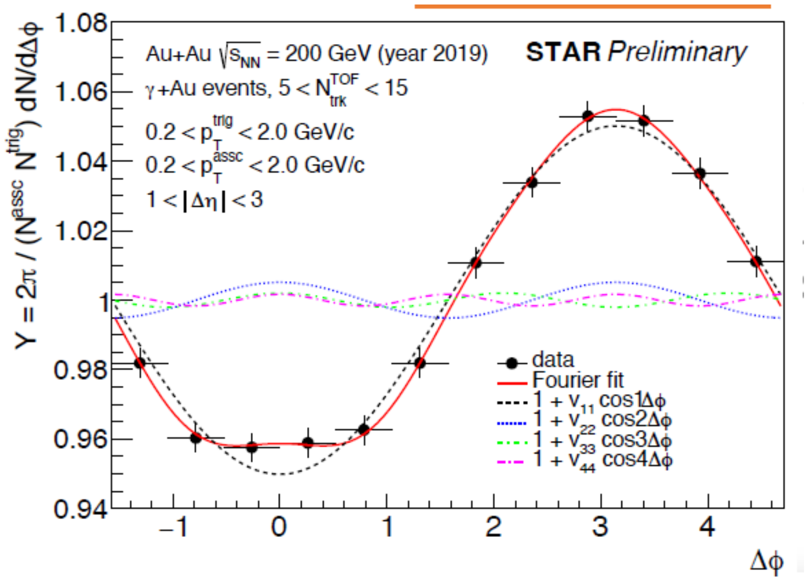
Collective Phenomena in Small Systems



- Anisotropies in ever-smaller systems

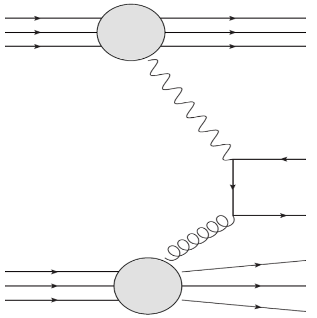






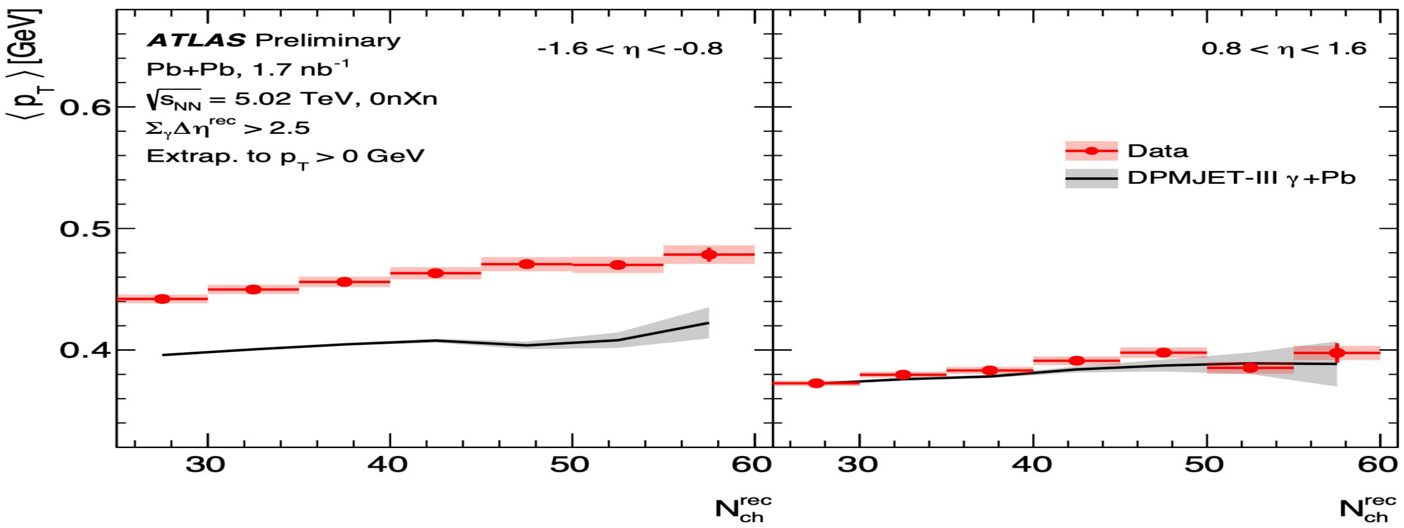
- ATLAS: non-zero v_2 in γPb collisions
- Consequence of **ρ**Pb interactions? CGC?

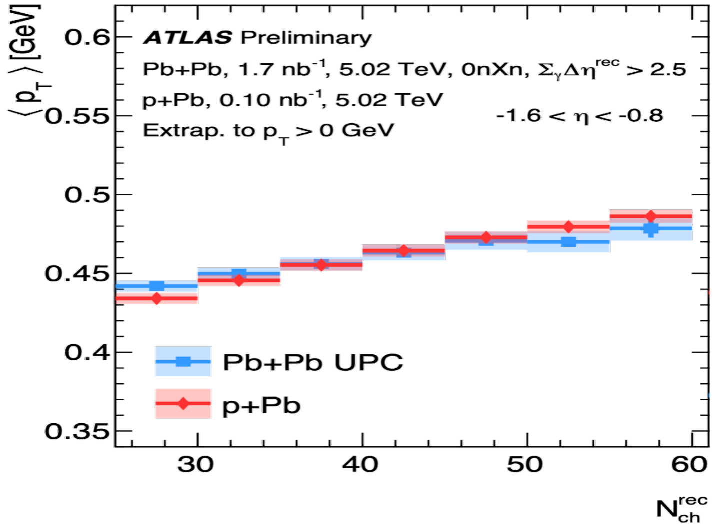
- STAR: correlations from γAu collisions
- Needs careful handling of non-flow



Collective Phenomena in Small Systems

- Collective expansion → build up of radial flow
- New ATLAS UPC data from 5.02 TeV Pb+Pb events: $\langle p_T \rangle$ increase in backward pseudorapidity region

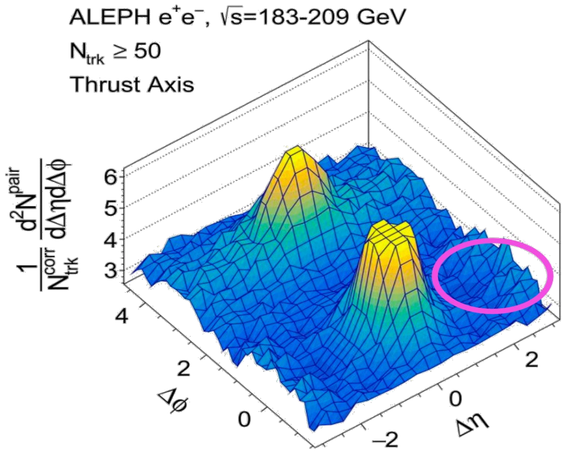


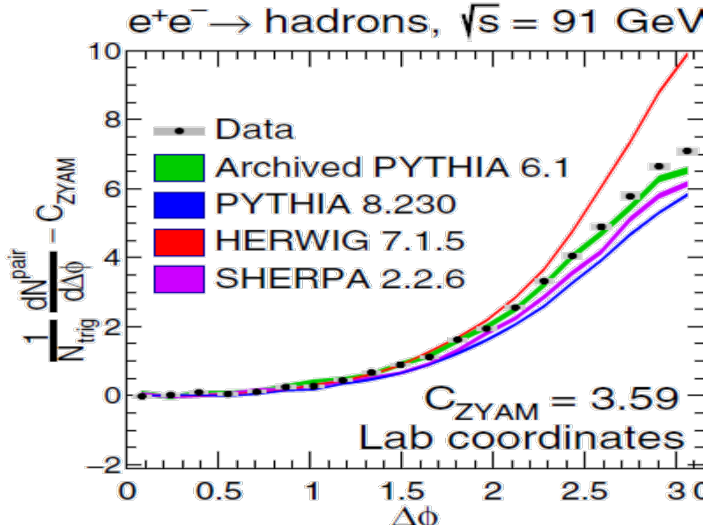


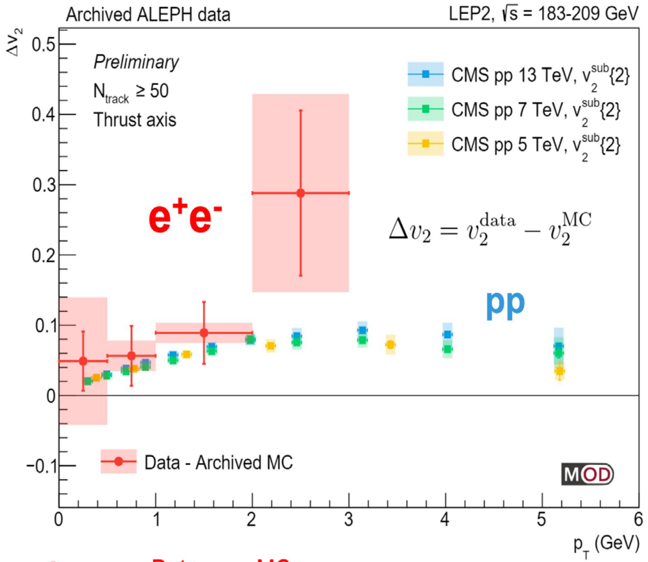
- Mean-p_T trend vs multiplicity in backward region is not captured well by DPMJET
- UPC $\langle p_T \rangle$ in backward match pPb measurements for the same multiplicities
- The larger $\langle p_T \rangle$ at backward vs. forward rapidity in UPC events -- radial flow?

What's too small for collective phenomena?

- ZEUS *ep* JHEP04(2020)070
  - No ridges at high multiplicity, described by MC
- ALEPH: minimum bias e^+e^- PRL123(2020)212002
  - No ridges, described by MC





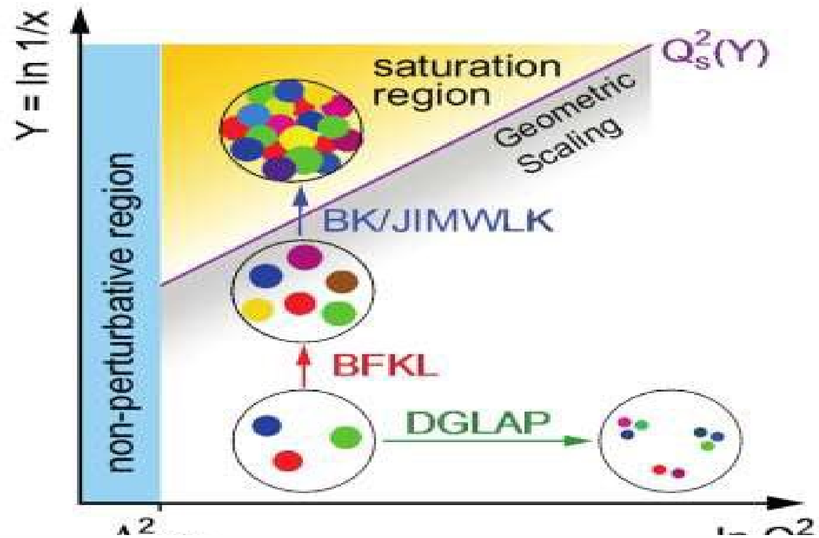


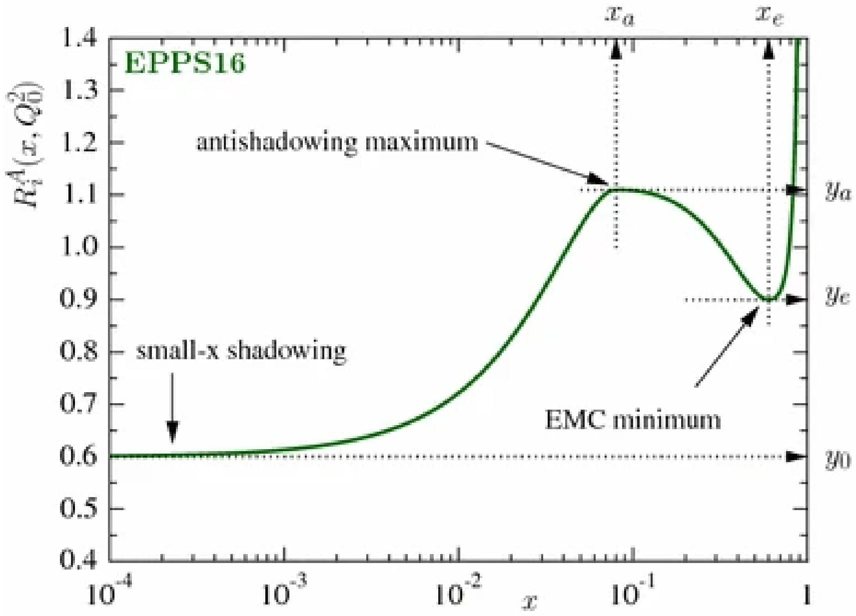
- ALEPH: high-multiplicity e^+e^- enriched with $e^+e^- \to W^+W^-$ (a two-string system)
  - Ridge structure similar to that of high multiplicity pp events!

- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

pA to eA: Initial State

- Nature of initial state?
  - High density of low-x gluons
  - QGP droplet?
  - Saturated CGC state?
- Nuclear Parton Distribution Functions:
  - PDF for bound nucleons are different than that of a free proton
  - Nuclear modification R_g^{Pb}: ratio of distributions in Pb and in p
  - Shadowing, Anti-shadowing, EMC effects
  - Large theory uncertainties
- Energy Loss
  - Initial vs. Final state

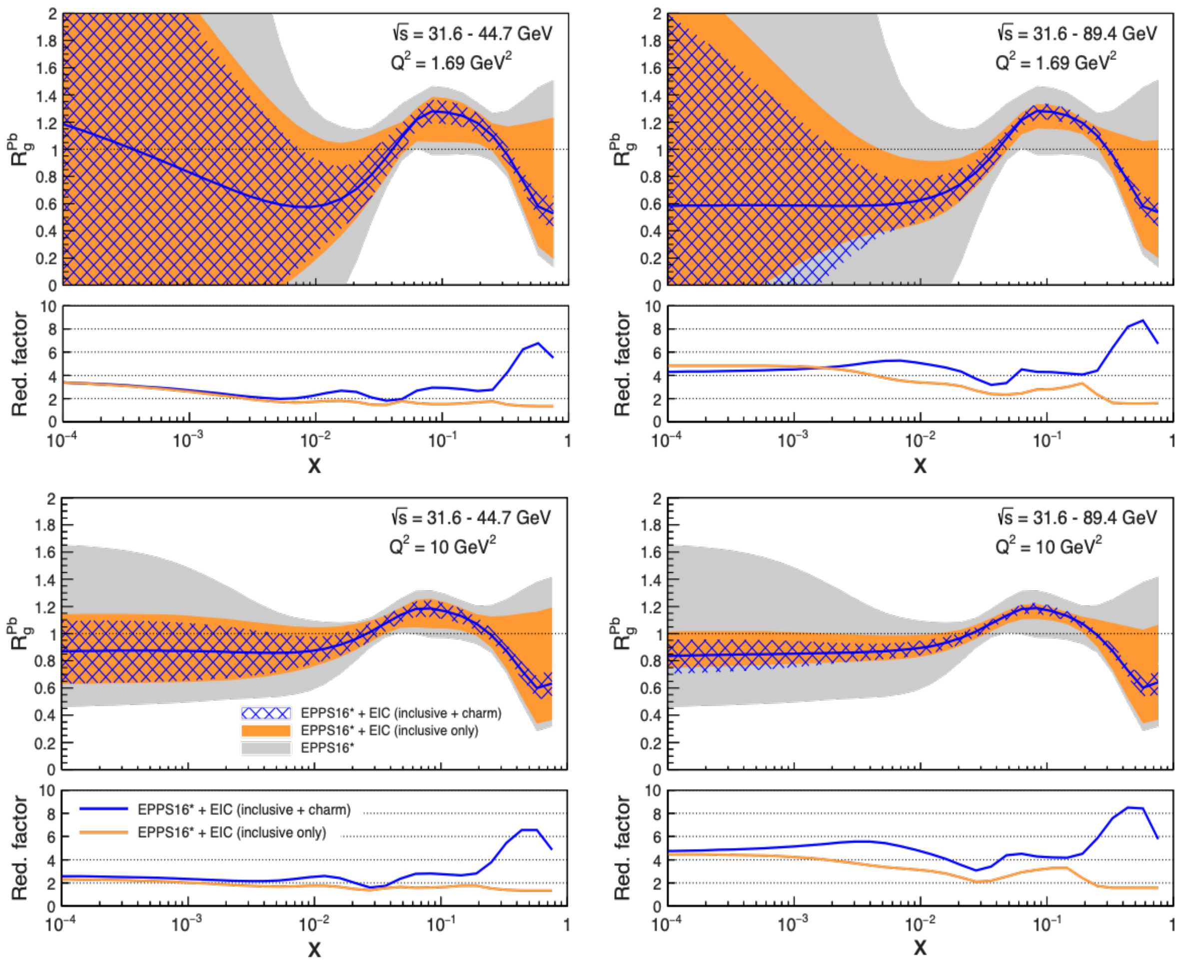




pA to eA: Nuclear PDF effects

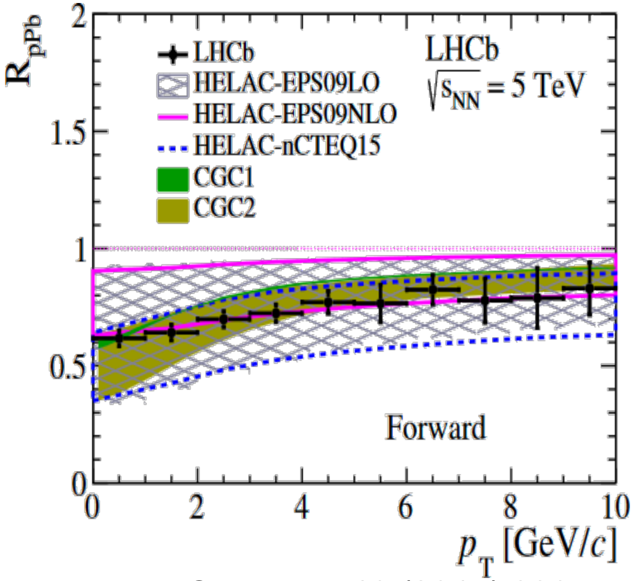
- Projected precision of EIC measurements allows for substantial reduction of nPDF uncertainties
- Will have no potential complications of disentangling initial and final state effects
- Impacts: HIN (initial state; jet quenching baseline, low-x regime relevant for gluon saturation,…)
- In the meantime: RHIC and LHC pA data!

arXiv:1708.01527

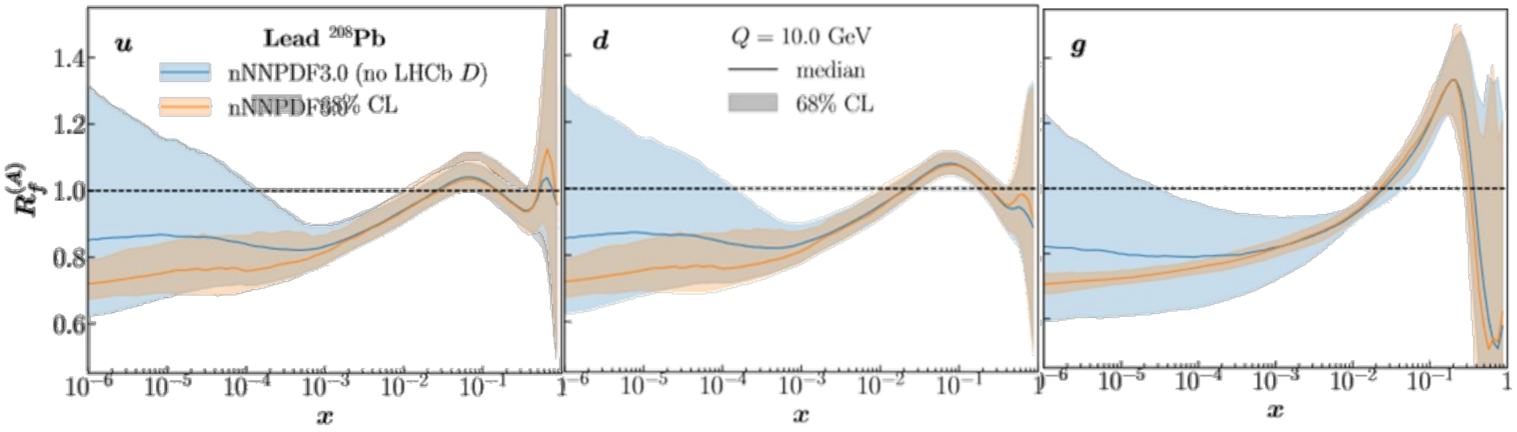


Understanding Initial State

- Modifications parton densities modified in nuclei with respect to free nucleon PDF are particularly poorly constrained in the low-x region (“shadowing”) by previous data



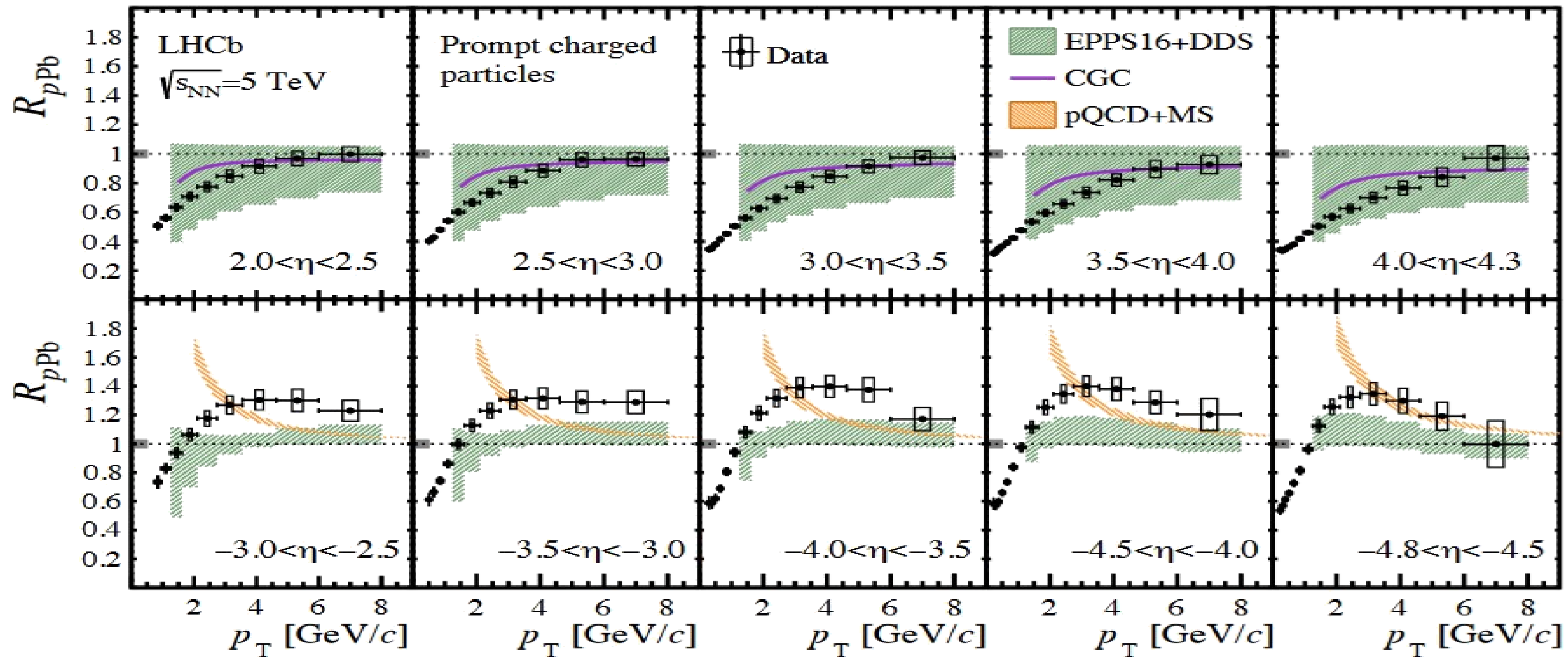
LHCb, JHEP 10 (2017) 090



- EPPS16 vs. EPPS 21:CMS dijet and LHCb forward prompt D^0 R_{pA} – major reduction of nPDF uncertainties down to $x{\sim}10^{-6}$

Understanding Initial State

- New measurements for nuclear modification with charged hadrons in pPb

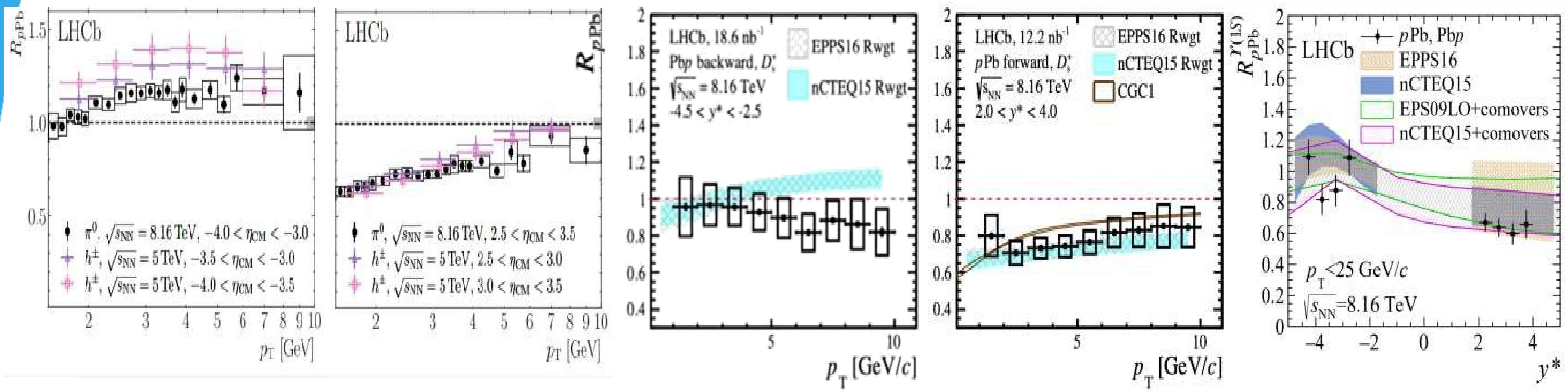


LHCb PRL 128 (2022)142004

- Suppression at forward rapidities (captured by several models)
- Enhancement at backward rapidities presents difficulty for the models
- No simultaneous description of RHIC and LHC

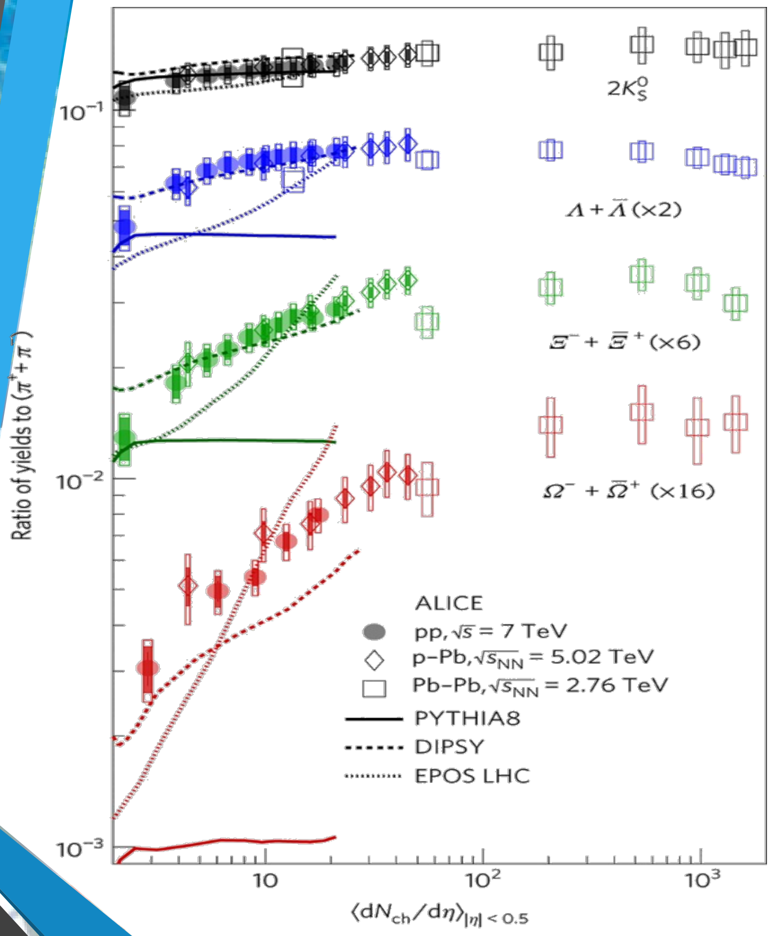
Understanding Initial State

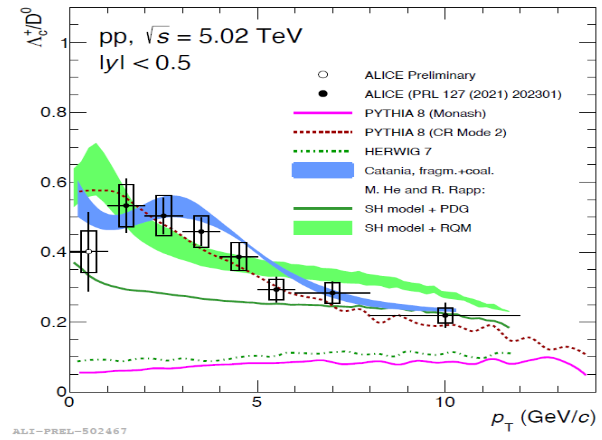
- Identified light and heavy hadron measurements from pPb collisions

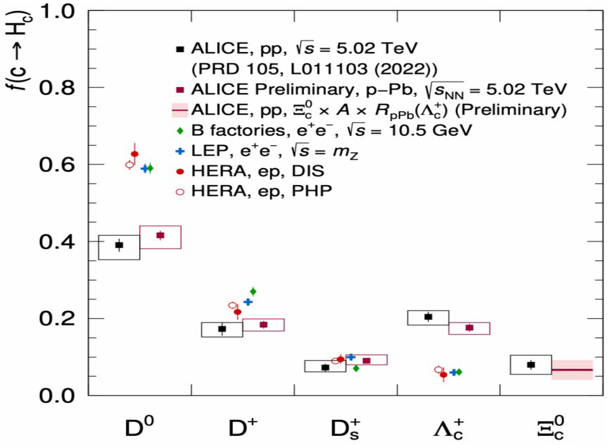


- Forward – suppression, backward – enhancement ?
- Generally, (forward) data are consistent with the nPDFs set with gluon shadowing. Co-mover absorption? Need better precision theory.

Understanding (aspects of) Hadronization



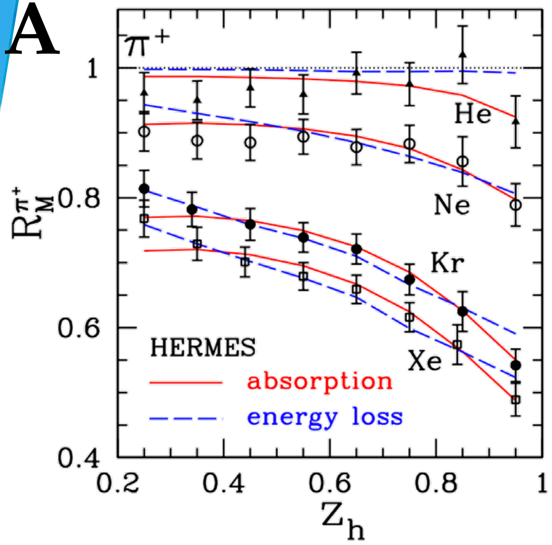


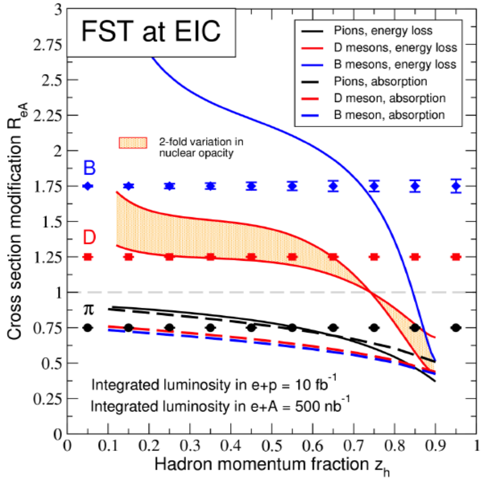


- Strangeness and baryon-to-meson enhancements, once envisioned as QGP signatures are seen in small systems at RHIC and LHC
- Strangeness:
  - multiplicity dependent enhancements in pp collisions of similar levels as pA and peripheral AA
- Charm sector:
  - $\Lambda c/D^0$: enhancements over $e{+}e-$ for pp and AA
  - Charm-fragmentation fractions appear non universal
- Impacts: HIN, HEP, Hadronic physics (understanding of hadronization)

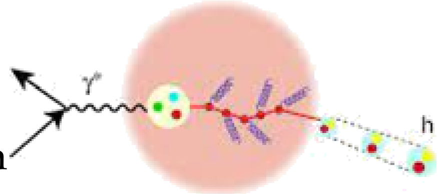
Understanding (aspects of) Hadronization

eA

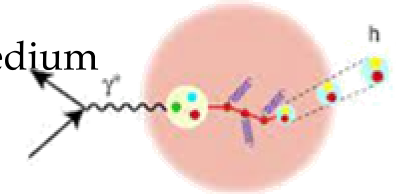




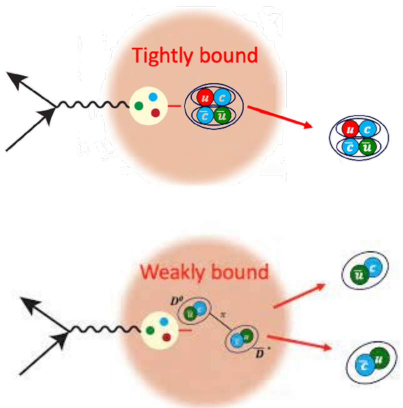
- Energy loss
  - hadronization outside the medium
  - gluon radiation off struck quark



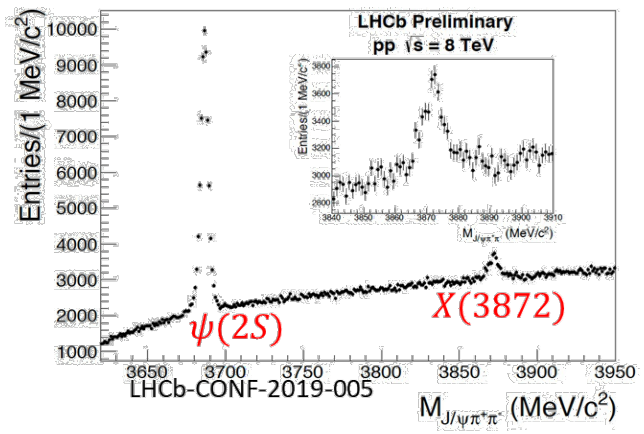
- Prehadron absorption
  - color neutralization inside the medium
  - prehadron-nucleon scatterings



- Exotic hadron structure:
- Example: X(3872) – compact tetraquark vs. hadronic molecule?



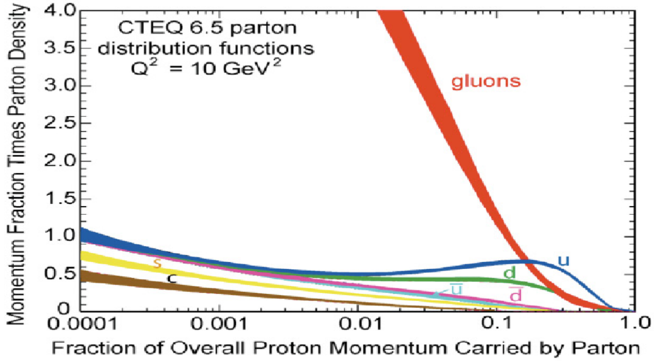
$\psi(2S)$ and exotic X(3872) via $J/\psi\pi\pi$



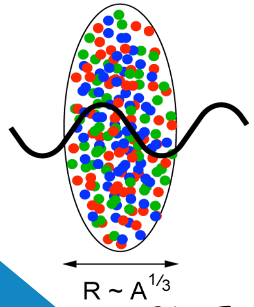
Matt Durham EIC @ Snowmass

- Impacts: Differentiating between E-loss absorption models; CNM transport properties; Hadron structure

EIC eA: Gluon Saturation



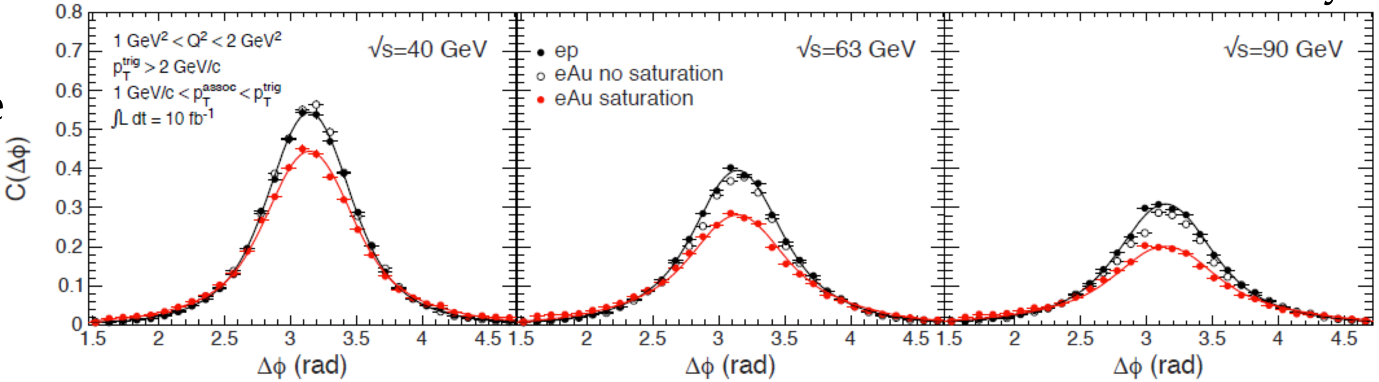
- Could the gluon density G(x, Q²) continuously grow?
- New idea: Non-Linear Evolution
  - Recombination compensates gluon splitting
  - New evolution equations
  - Saturation of gluon densities characterized by scale $Q_s(x)$
- Saturation → Color-Glass-Condensate
- Experimentally, nucleus serves as Q_s amplifier



$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$

- Di-hadron correlations are sensitive to the transverse momentum dependence of the gluon distribution and gluon correlations

2→2 vs. 2→many

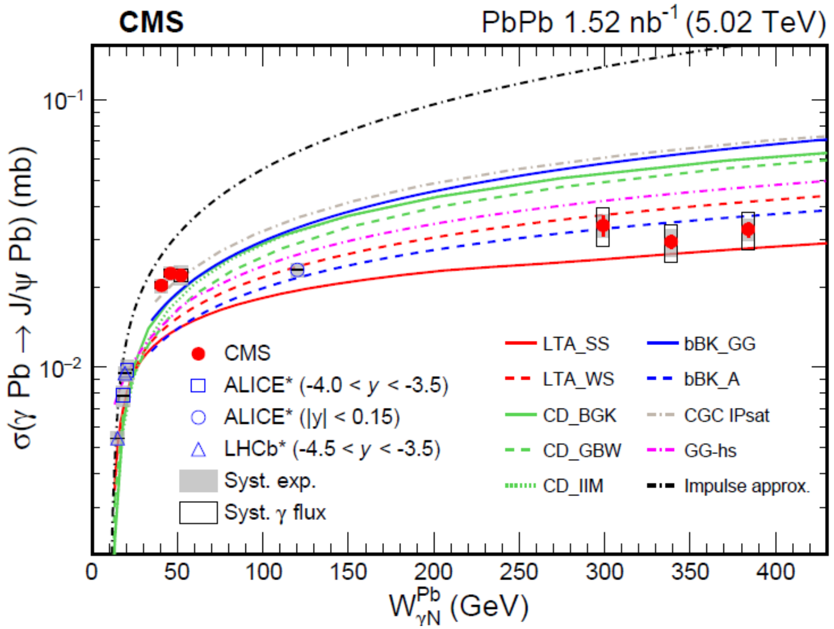


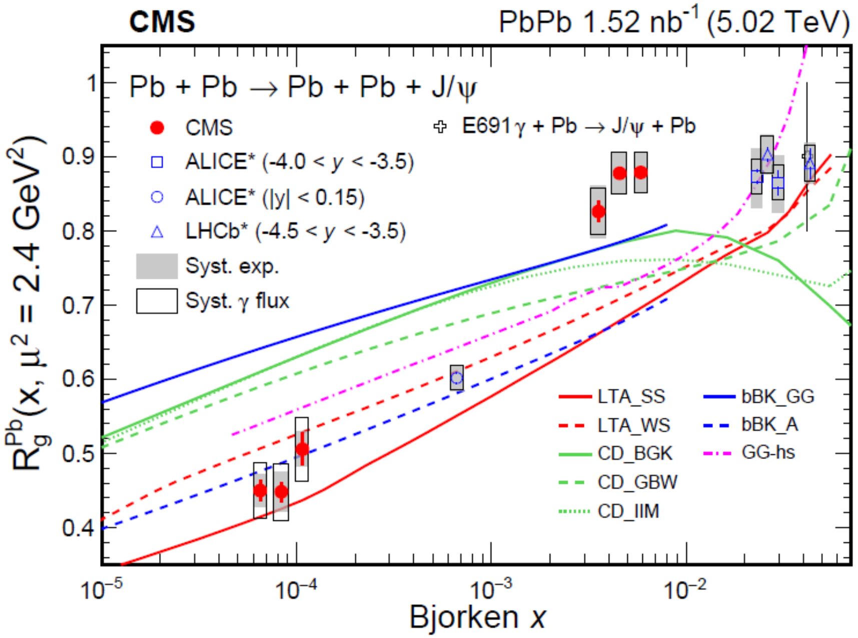
- EIC allows to study the evolution of Q_s with x
- Impacts: HIN (initial state), CGC discovery?,…

UPC in HIC, Saturation?

- Coherent J/ψ photoproduction in UPC is used to probe small-x gluonic structure of Pb

PRL 131 (2023) 262301

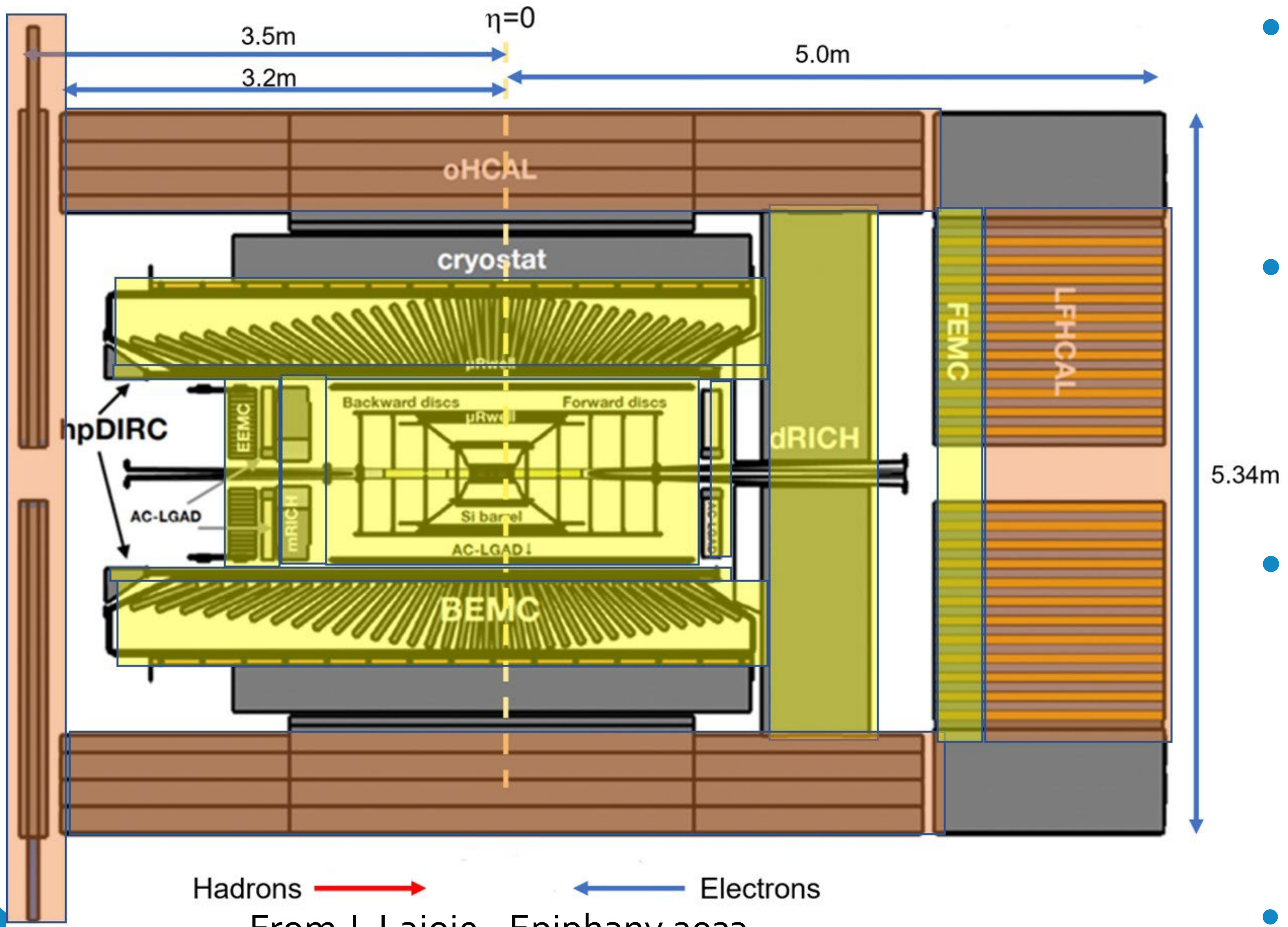




- Rapid growth of cross-section at low $W_{\gamma N}^{Pb}$, then plateau in a new regime of small-x ($\sim 6 \times 10^{-5}$) gluons probed in the nucleus
  - Black-disc strong absorption limit or Gluon saturation?

The trend of the nuclear gluon suppression factor R_{Pb}^{g} is not fully captured by models

Preparing for Future DIS collisions

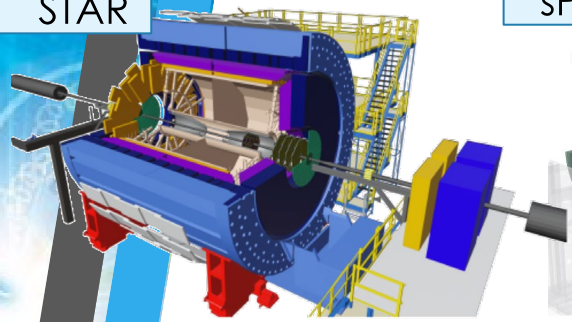


From J. Lajoie - Epiphany 2023

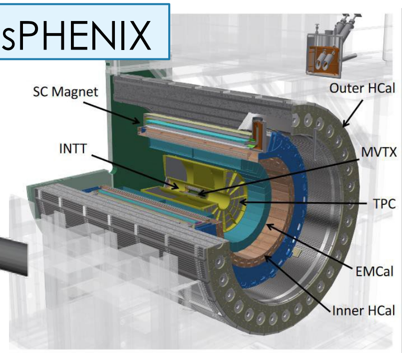
- Tracking:
  - New 1.7T solenoid
  - Si MAPS Tracker
  - MPGDs (mRWELL/mMegas)
- PID:
  - hpDIRC
  - mRICH/pfRICH
  - dRICH
  - AC-LGAD (~30ps TOF)
- Calorimetry:
  - SciGlass/Imaging Barrel EMCal
  - PbWO4 EMCal (backward)
  - Finely segmented EMCal +HCal (forward)
  - Outer HCal (sPHENIX re-use)
  - Backwards HCal (tail-catcher)
- (And a suit of far froward/backward detectors)

… meanwhile, taking HIC data

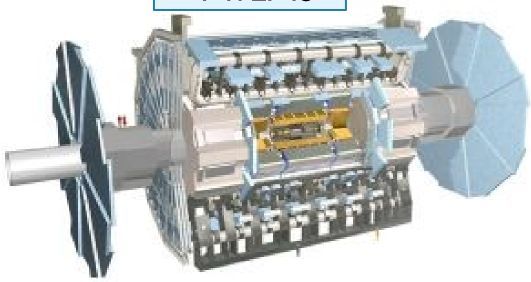
STAR



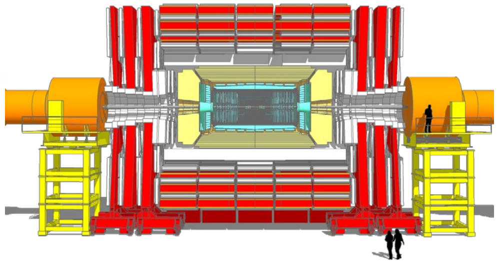
sPHENIX



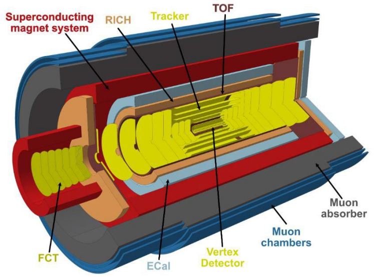
ATLAS



CMS



ALICE (3)



Forward upgrades

Brand new!
quarkonia, jets, b-tag

LS2 Upgrades
muon detectors, Lar, TDAQ,…

LS2 Upgrades
Pixel, Hcal, EMCal,…

LS2 Upgrades
TPC, Si tracker
ALICE3 proposal

RHIC

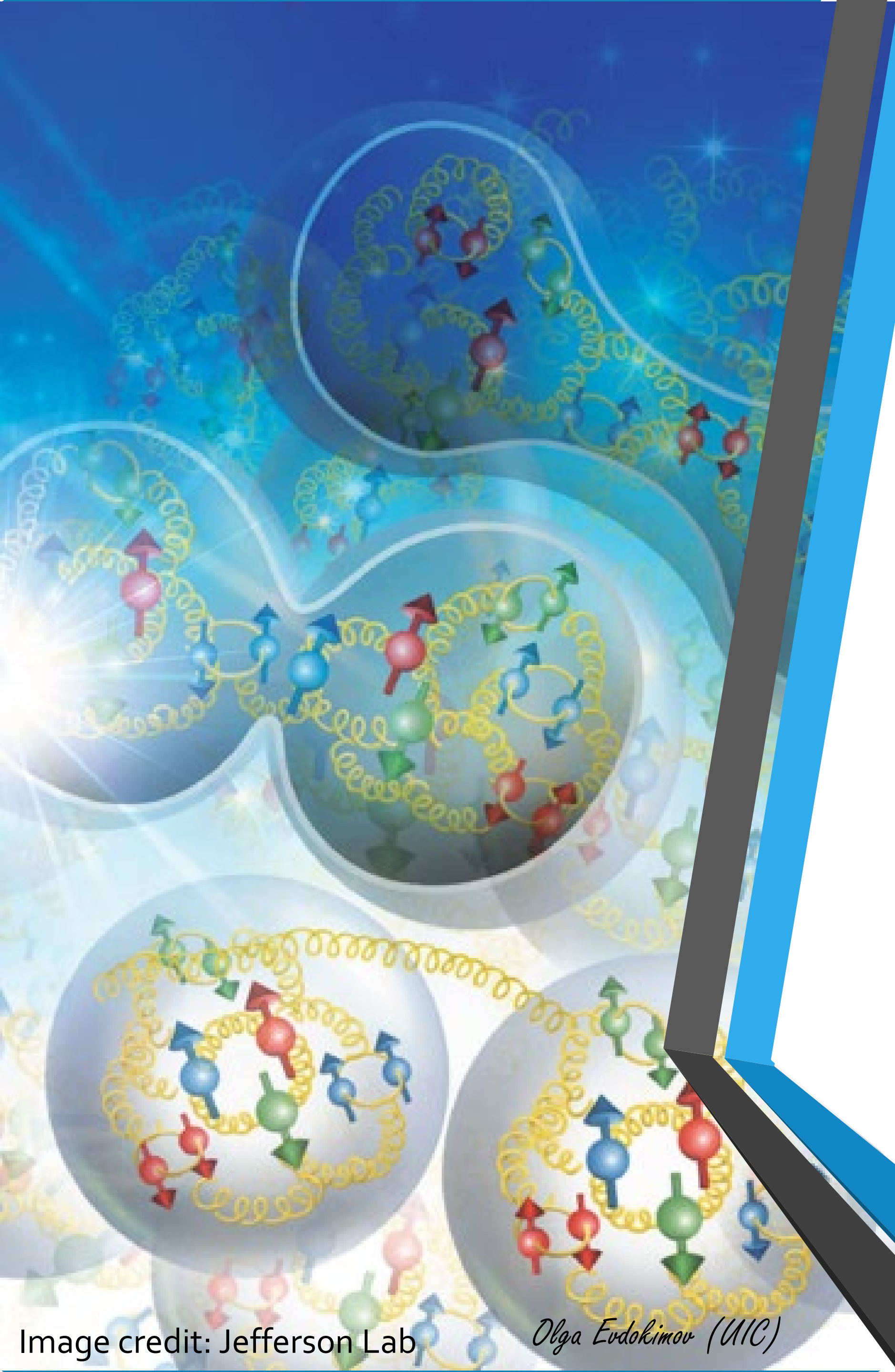
- Remaining experimental operations in 2024-25
- 200 GeV pp, pAu, AuAu collisions
- Data taking by upgraded STAR and sPHENIX
- Program completion in 2025

LHC

- Runs 3 & 4 with upgraded detectors
- High luminosity LHC era
- Precision QGP studies
- LHCb: SMOG upgrade for fixed-target mode

Summary

- 20+ years of QGP exploration advanced our understanding of the strong force and confinement and raised many questions, many with deep connections to the DIS research domain.
- HIC experiments are in the era of precision studies and provided many new constraints on nuclear properties and their sub-nucleonic degrees of freedom.
- While EIC, the new collider facility that will enable tackling profound open questions with broad implications for many subfields, is underway, the HIC community continues to provide new experimental input to help shape QCD explorations at EIC.
- Strong synergy in physics interests and detector R&D exists between the HIN and DIS communities; bringing these communities together is critical to the EIC's success.

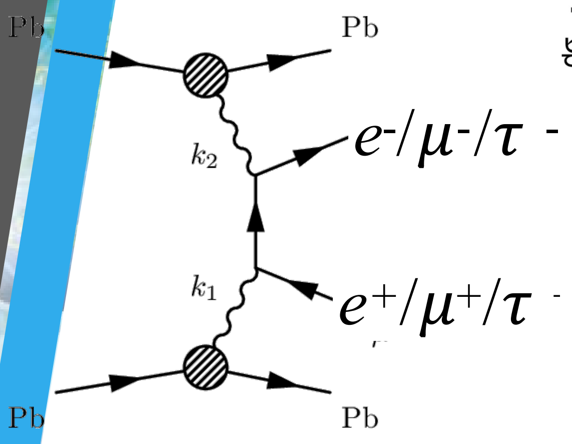


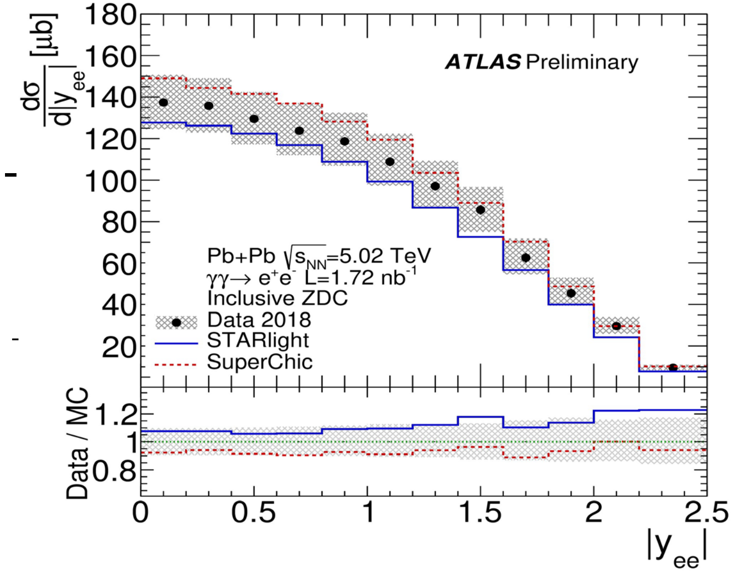
Thank you!

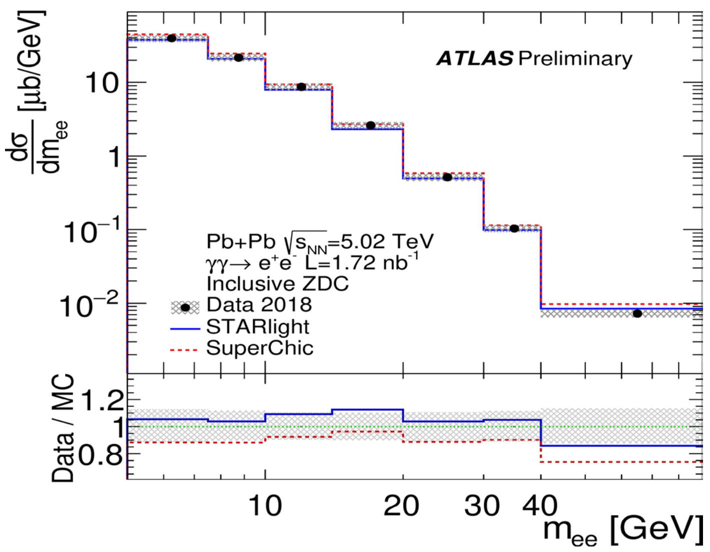
The UIC Group's work is supported by DOE-NP

UPC dilepton production: $\gamma\gamma \rightarrow ee$

ATLAS-CONF-2022-025







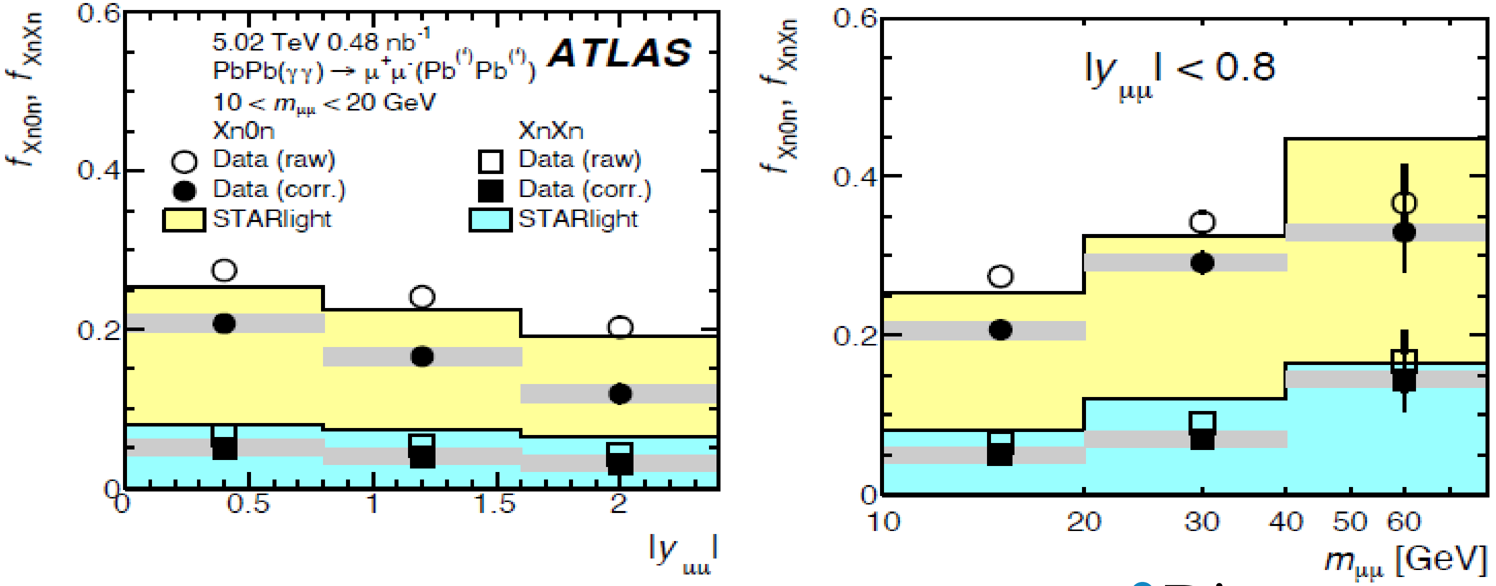
cross sections in inclusive and 0n0n ZDC events

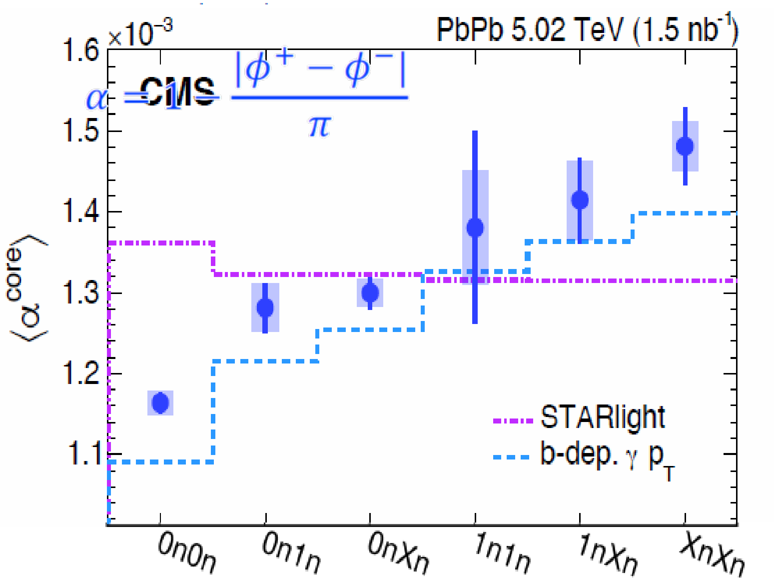
- UPC dilepton production is one of the fundamental processes in $\gamma\gamma$ interaction
- Exclusive $\gamma\gamma \rightarrow ee$ benchmark process for other γ induced processes
- Provides new constraints on photon fluxes from nuclei

UPC dilepton production: $\gamma\gamma \rightarrow \mu\mu$

CMS PRL 127 (2021) 122001

ATLAS PRC 104 (2021) 024906

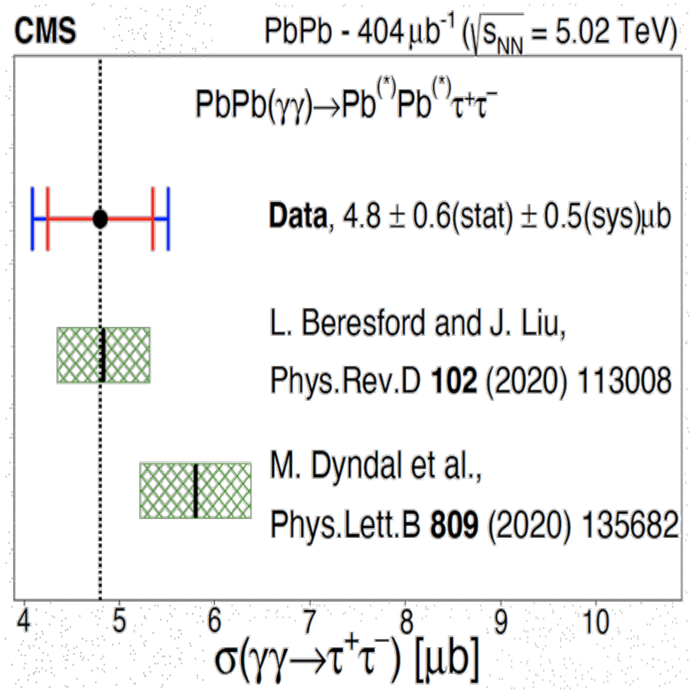


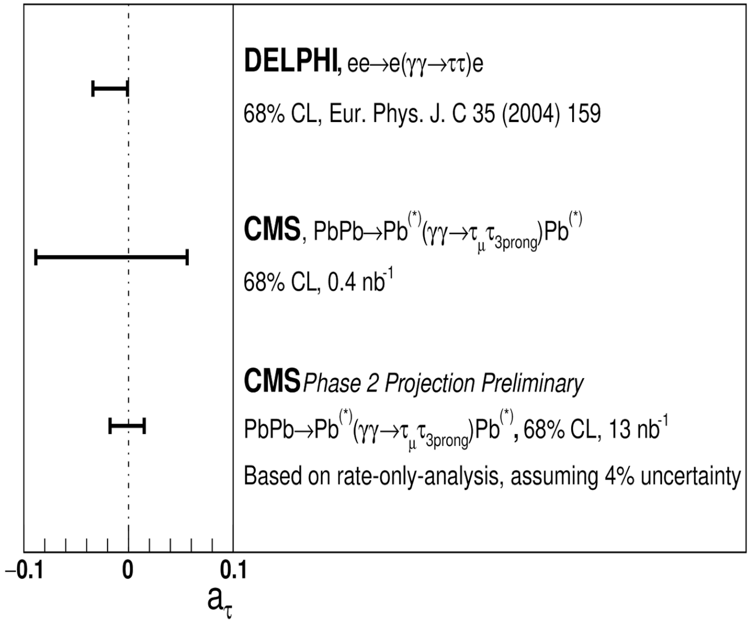


- Forward neutron multiplicity dependence of dimuon distributions:
  - Events with neutrons have a harder $m_{\mu\mu}$ spectrum and narrower $y_{\mu\mu}$
- Dimuon acoplanarity:
  - Clear impact parameter dependence
  - QED calculations need b-dependence of initial photon p_T

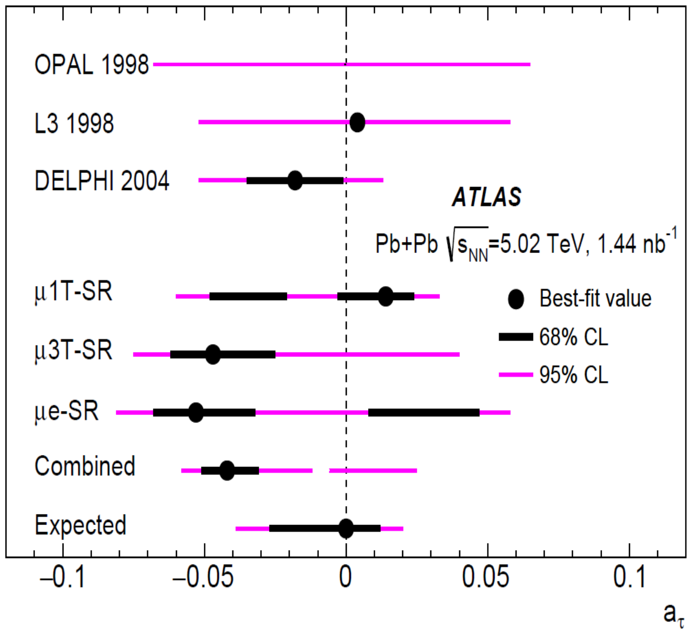
UPC dilepton production: $\gamma\gamma \rightarrow \tau\tau$

CMS arXiv:2206.05192





ATLAS arXiv:2204.13478



- Observation of $\gamma\gamma \rightarrow \tau\tau$ by both CMS and ATLAS in UPC heavy ion collisions
- Constrains the anomalous magnetic moment $a_\tau = \frac{(g-2)_\tau}{2}$ for the first time at the LHC