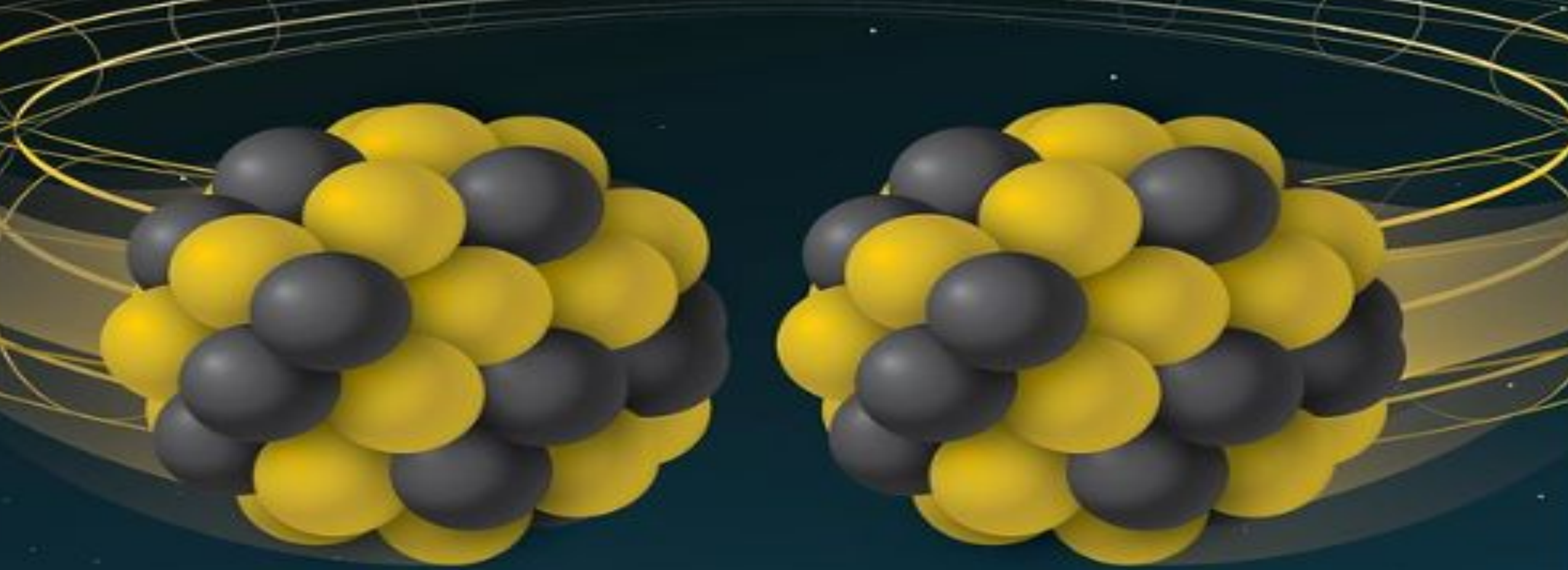


U.S. DEPARTMENT OF ENERGY

Office of Science

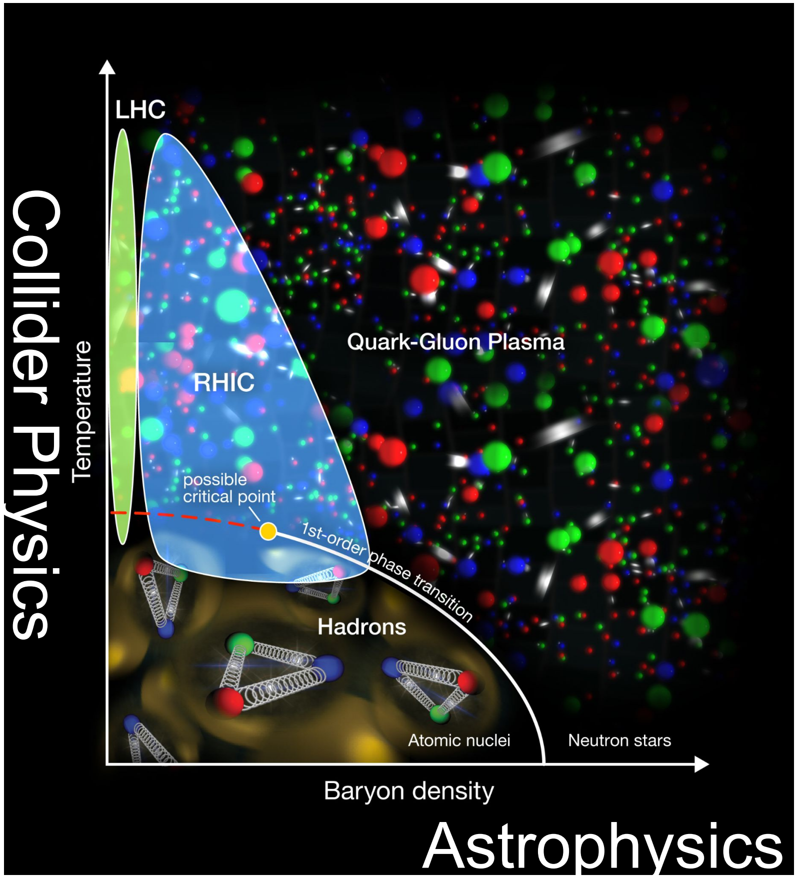
KU

Beyond the Standard Smash: Decoding the QGP at the LHC & beyond

Georgios K Krintiras

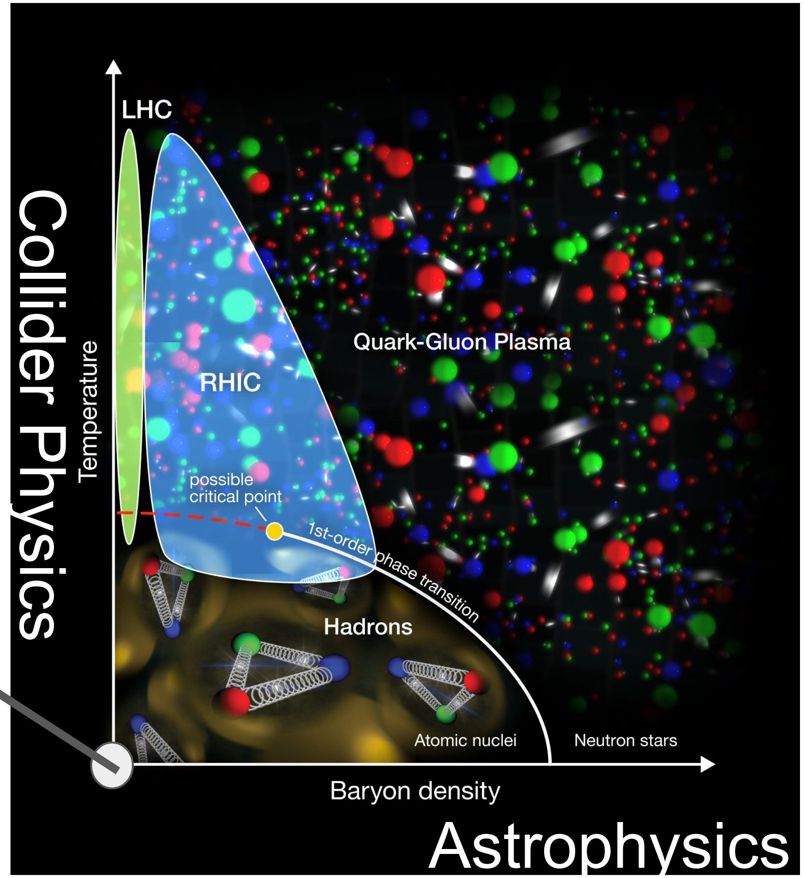
New Trends 2024

QGP: the earliest and simplest form of complex matter



- **The earliest: μs after Big Bang**
- **The simplest: q/g vs organic chemistry ;D**
- **Portal to the understanding of ordinary complex matter?**

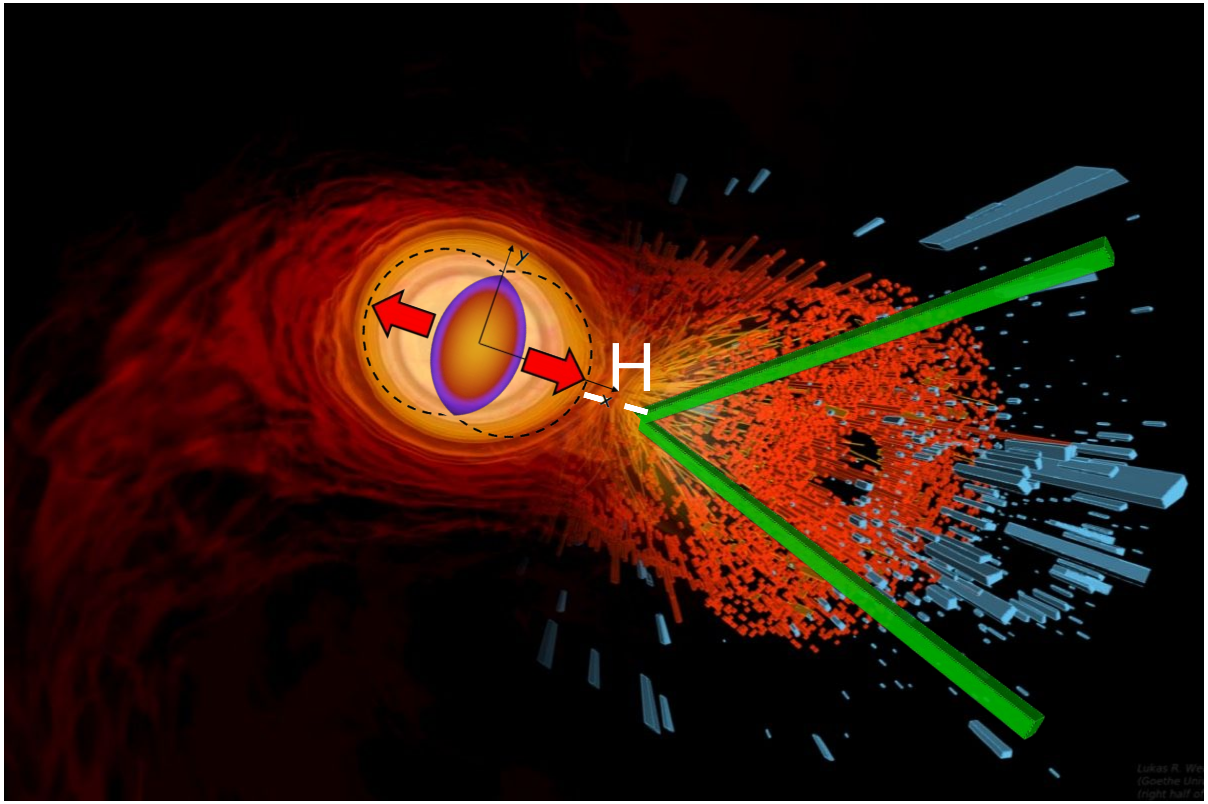
QGP: the **earliest** and **simplest** form of complex matter



$\mu_B \approx 0$

- **The earliest: μs after Big Bang**
- **The simplest: q/g vs organic chemistry ;D**
- **Portal to the understanding of ordinary complex matter?**

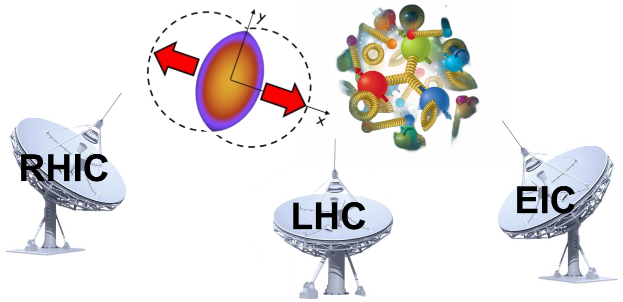
QGP and Higgs boson physics at a crossroads



“Poetic license“

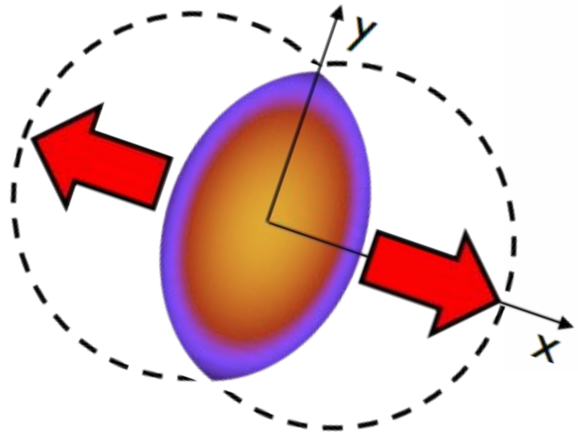
- **We know that they both exist**
- **What are their properties? H properties < 10%, QGP?**
- **Are these unique? *The* or *a* QGP/H?**

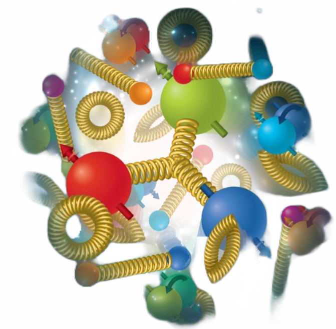
The experimental QCD landscape



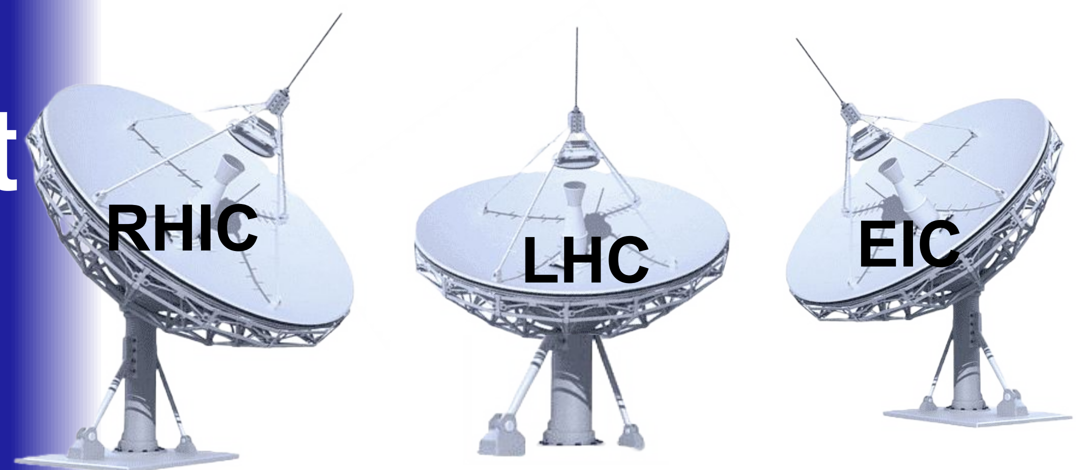
- In the next 2 years
  - RHIC concludes its operation: > 20 /nb of AuAu (*)
  - LHC completes Run 3: > 5 /nb of PbPb(*)
  - Final EIC design and its construction starts
- In the next 10 years
  - Upgraded LHC detectors: > 5 /nb of PbPb(*)
  - EIC starts its operation with 1.5 /fb / month
- Synergy is the key
  - "Cold" & "Hot" QCD ⟶ QCD (Equipment & infrastructure)
  - HEP & NP (R&D, operation & analysis)

(*) only the nucleus-nucleus data sets



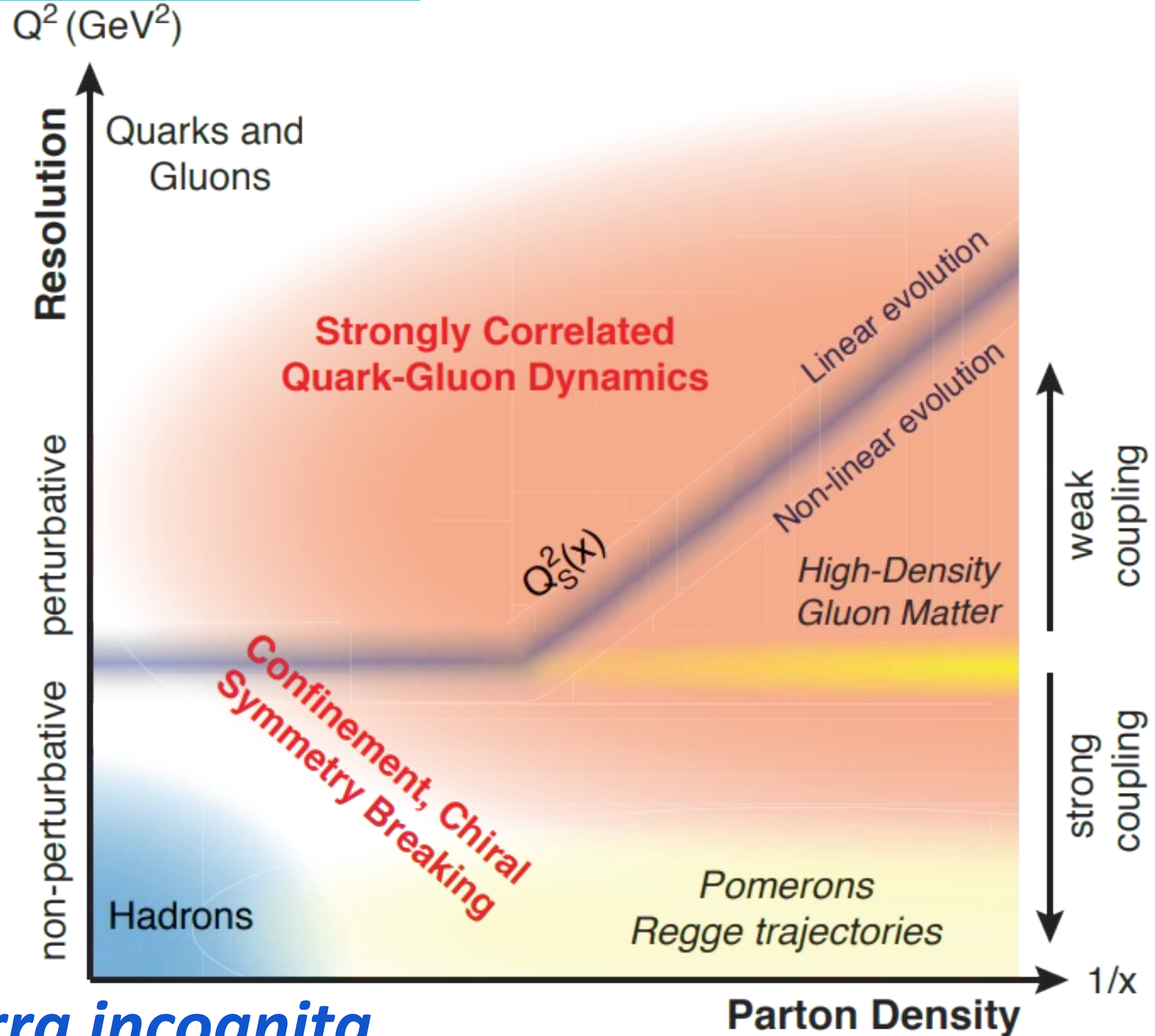


How the fluid behavior emerges at $\mu_B \approx 0$?



The "cold QCD" landscape

arXiv: 1708.01527

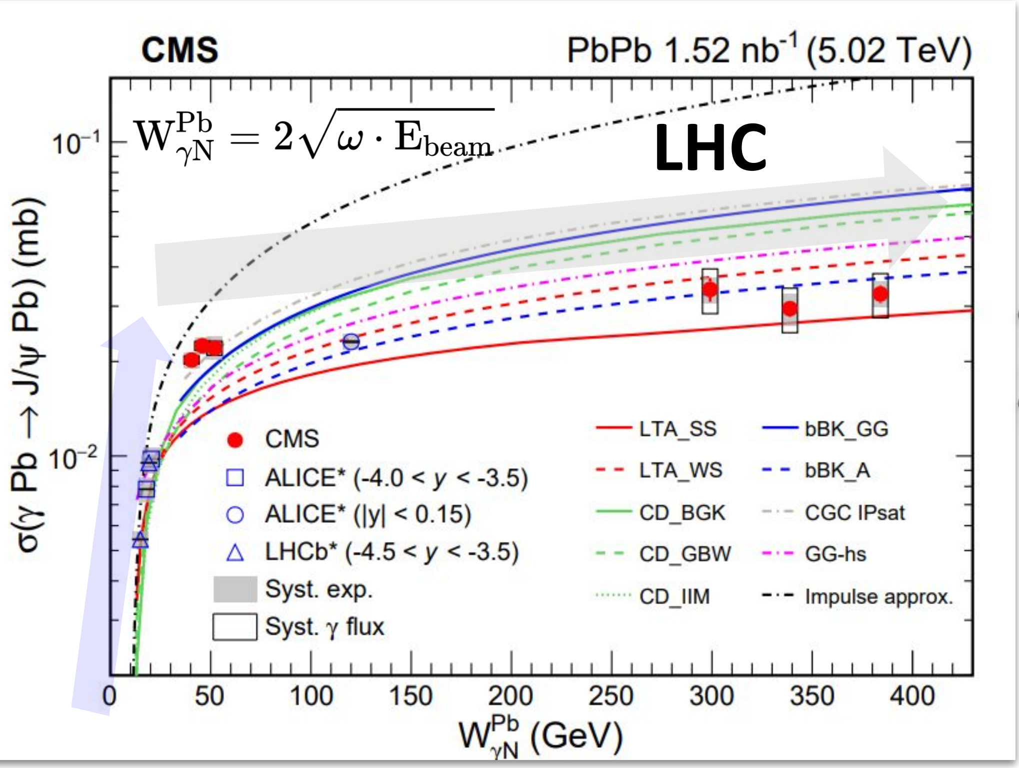


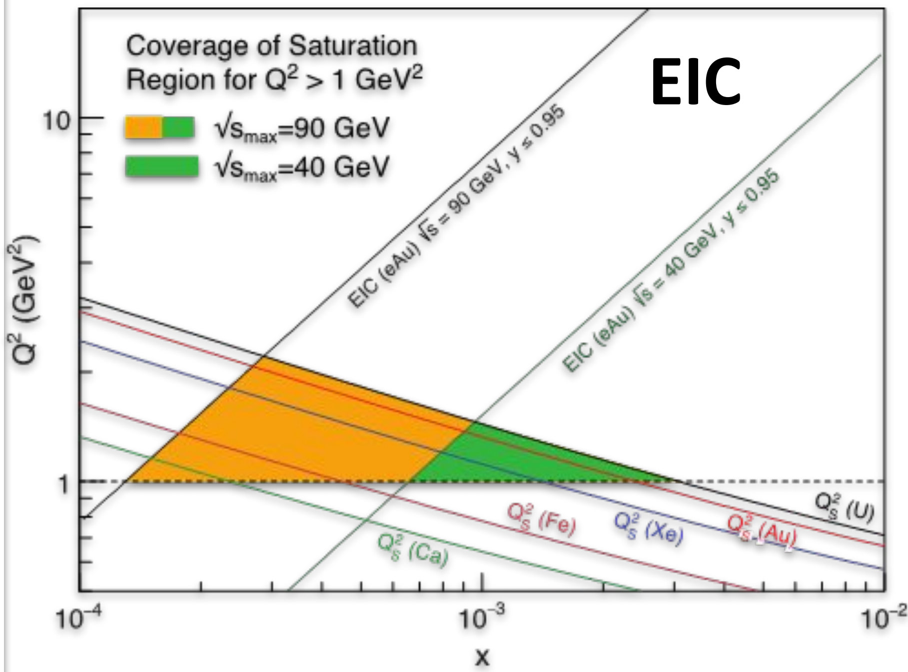
- **Mostly *terra incognita***
- **Hadron properties the result of the confined q/g**
- **A novel regime of QCD may exist: gluons saturate?**

EIC is a gluon factory

arXiv: 2303.16984
arXiv: 2103.05419

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



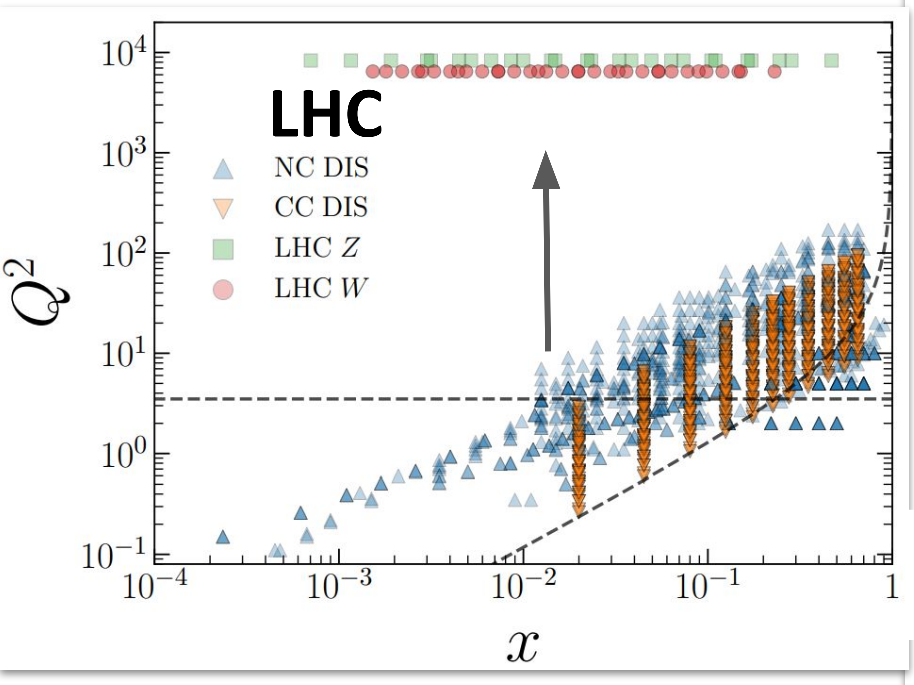


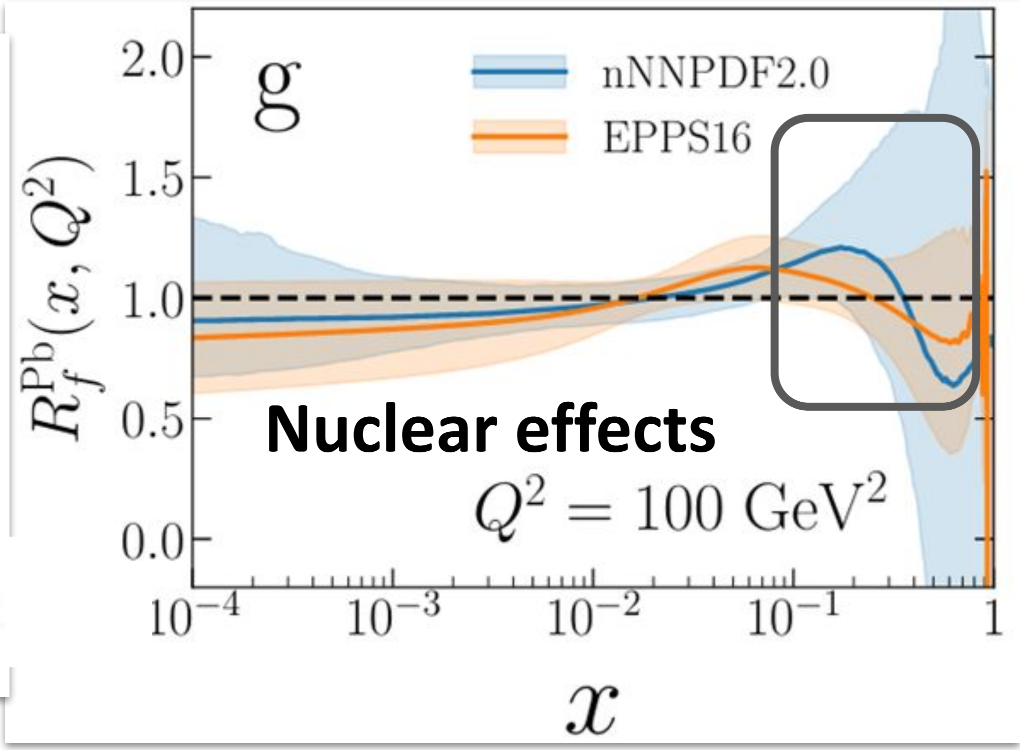
- **We see a milder energy dependence than predicted**
  - gluon saturation? if so, independent of particle species
- **Accessible Q_s values at EIC thanks to ion species and energies**

Explore LHC with more particles; EIC can probe a new state of matter

nPDFs: long way to go

arXiv: 2203.13923
JHEP 09 (2020) 183



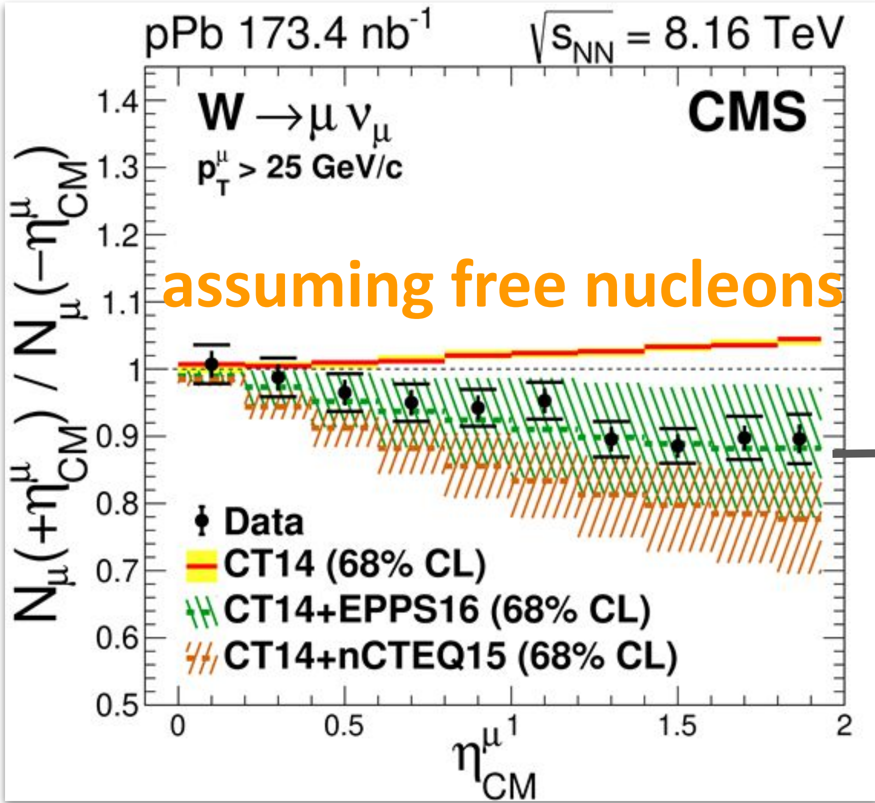


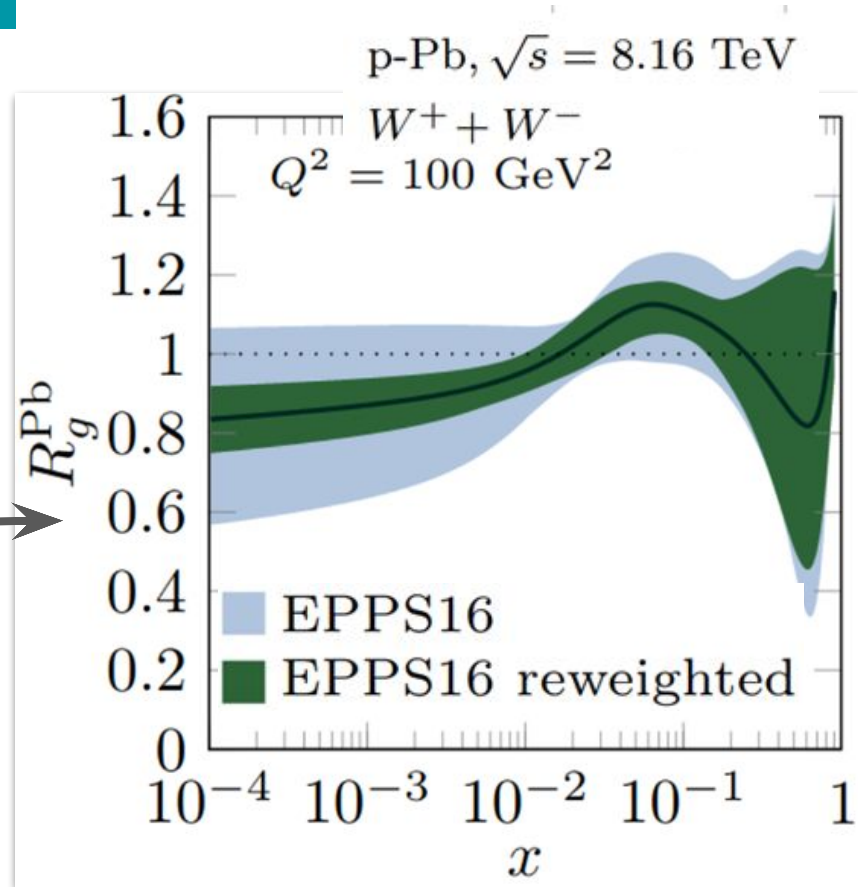
- LHC data gave an increase in kinematic coverage
- The nuclear modification of gluons not well understood
  - available data sets still limited

Can we do better?

Tools for precise nPDF extraction

PLB 800 (2020) 135048





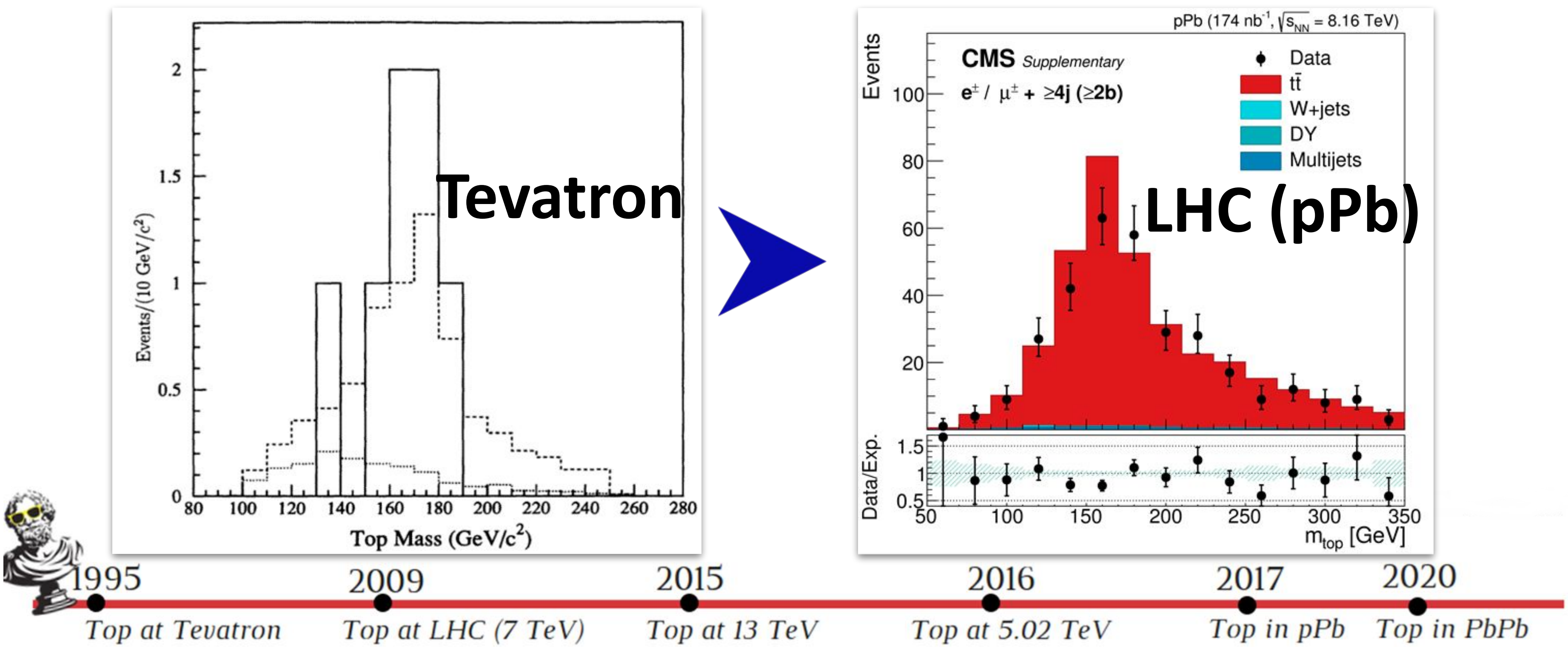
- **LHC data reduced the gluon nPDF uncertainty**
- **The large-*x* (> 0.1) region is not affected though**
  - **only dijets and top quarks probe this *x* region**

LHC data unique chance to pin down nPDF uncertainties

Tools for “**inaccessible**” nPDFs

PRL 119 (2017) 242001 (**editor’s suggestion**)
PRL 73 (1994) 225 (PRL Retrospective)

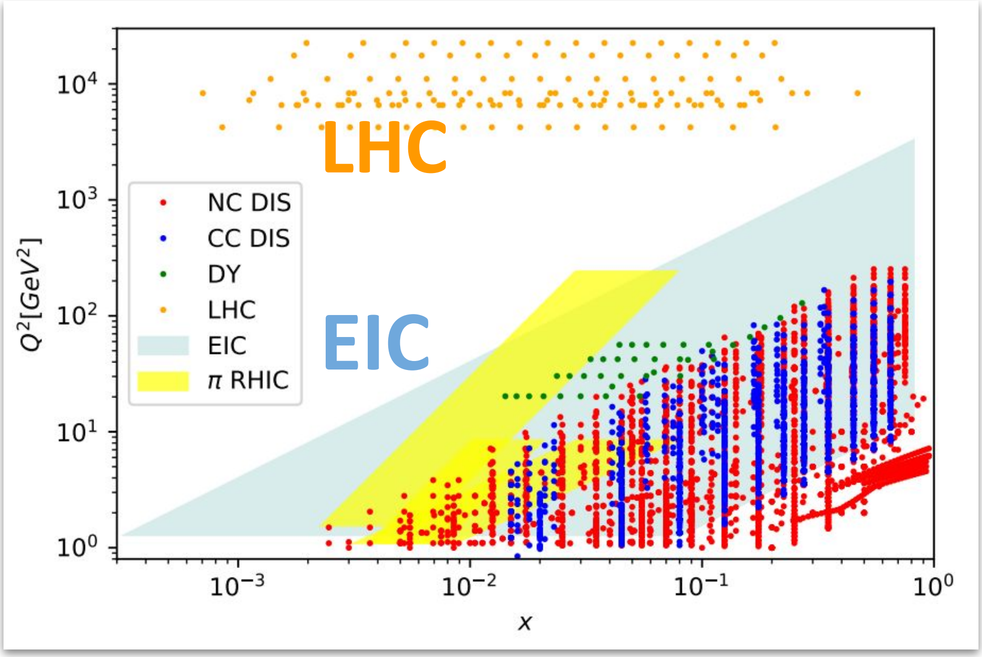
- **Top quark observed at Tevatron**
  - **further studied in pp collisions at LHC**
- **Established a top quark program in the nuclear environment**
  - **going from baseline (“reference” pp) → pPb → PbPb data**

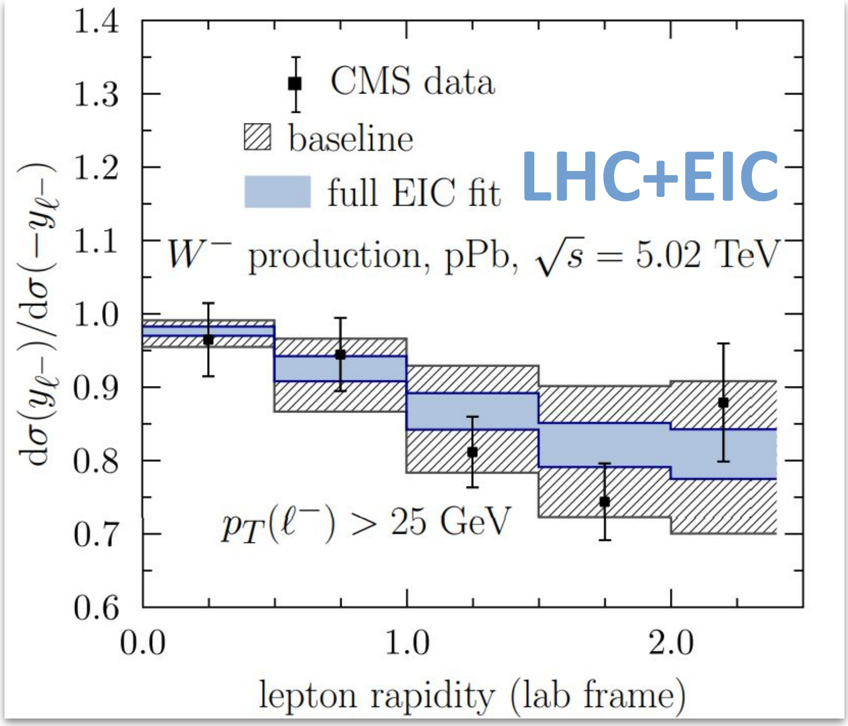


Top quarks can constrain gluons in so far inaccessible regions

Are nPDFs global or not?

arXiv: 2103.05419
PRD 96 (2017) 114005



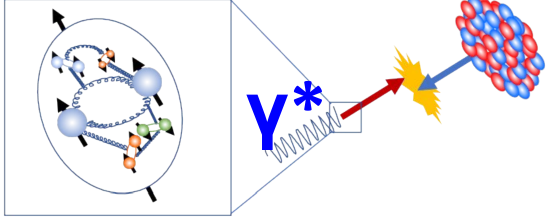


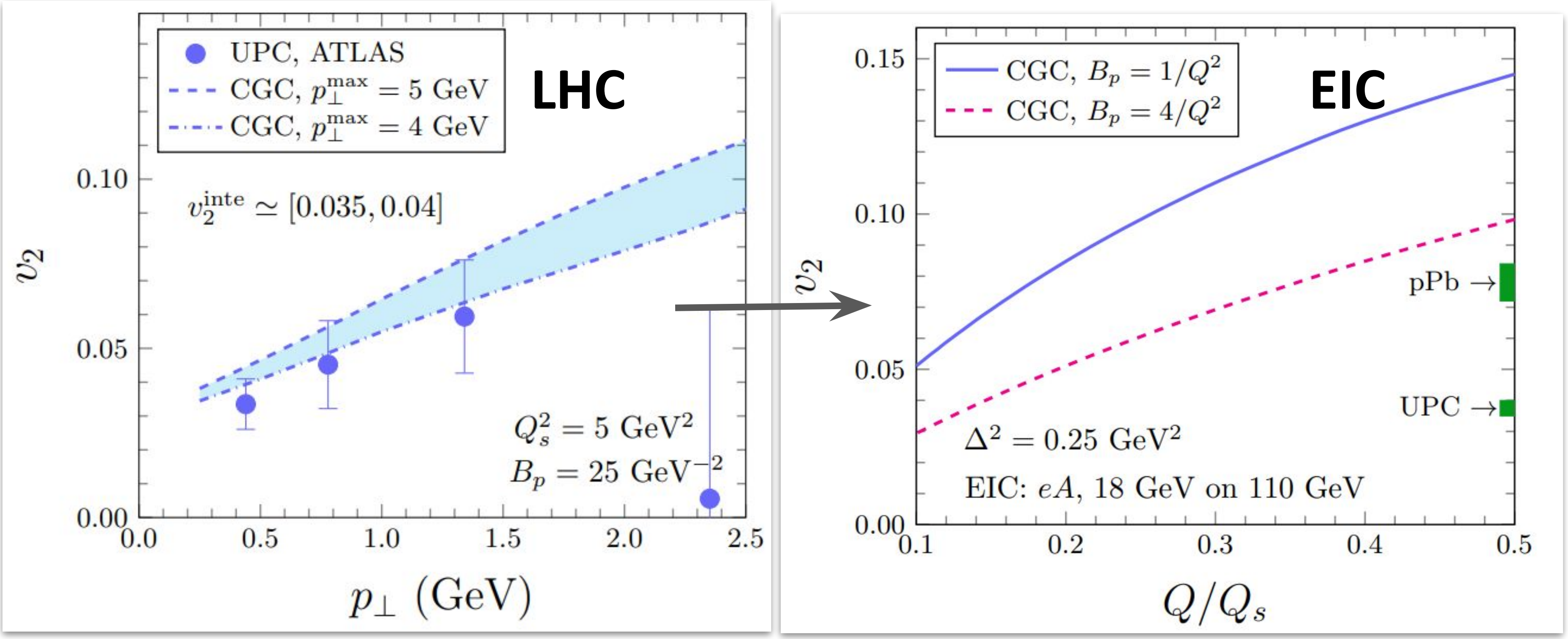
- **EIC will also offer a huge increase in kinematic+*A* coverage**
- **We'll answer whether nPDFs are universal or not**
- **nPDFs are only the "LO" of a tomography/spatial imaging**

EIC provides key constraints on nPDFs and at different Q^2

What's the **small size** QGP limit?

[PRD 103 (2021) 054017]

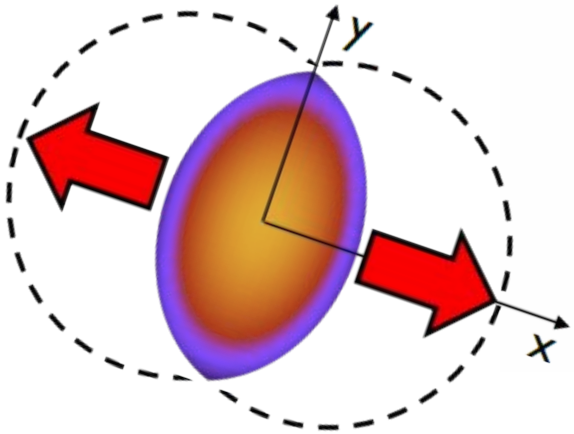


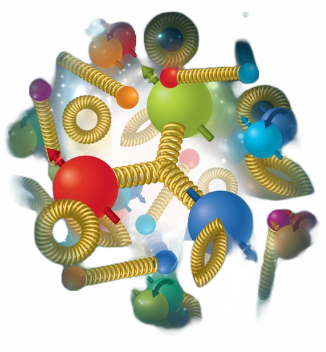


- **Gluon saturation models describe LHC anisotropy (υ_2) data**
  - but equally well with hydro models ⟶ an open question
- **These models predict sizeable υ_2 values at EIC**

LHC with more data; EIC unprecedented opportunity to study the origin of υ_2

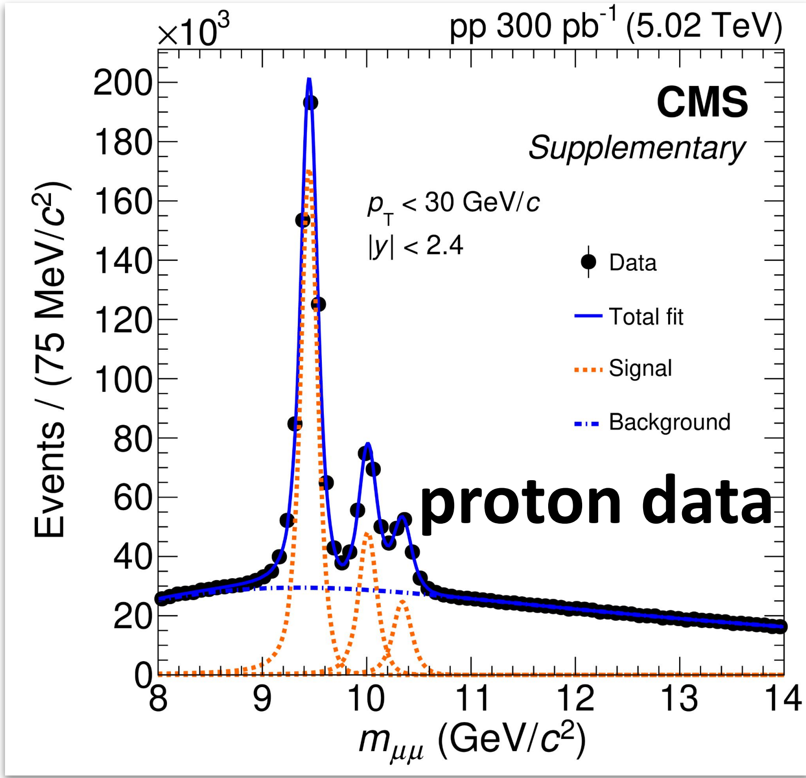
How can we quantify the QGP & nuclear medium properties?

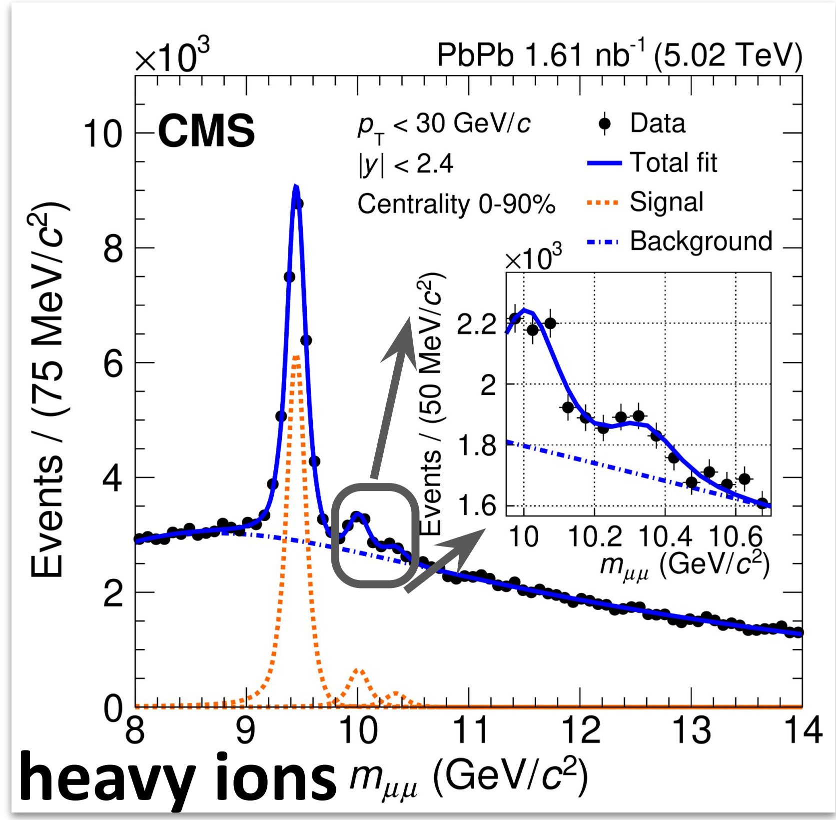




How we know of “medium modifications”?

PRL **133** (2024) 022302

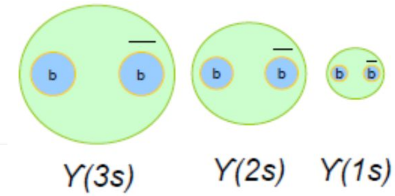


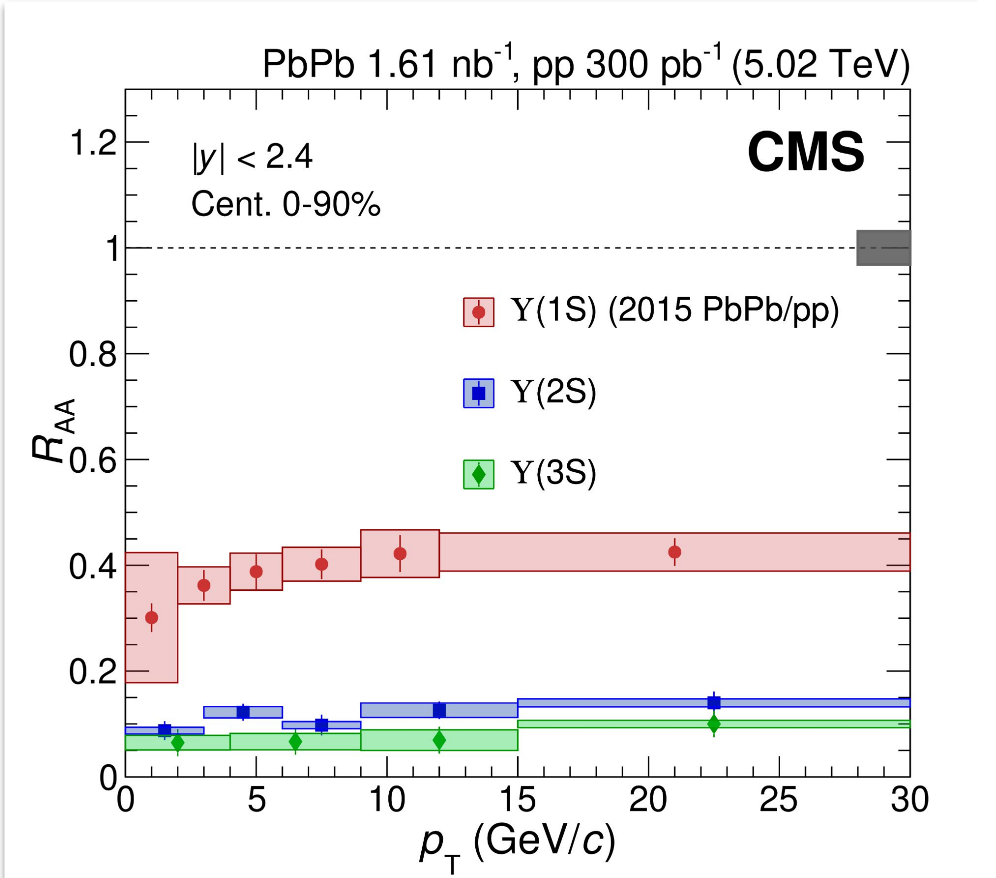


- **We form ratios (R_{AA}) between proton and heavy ion data sets**
- **A long hunt came to an end: entire Υ “family” observed in PbPb**
  - the heaviest states that survived QGP (with some fatalities ;)

What's special with Υ's?

arXiv: 2303.17026
arXiv:2205.03042
PRL 130 (2023) 112301



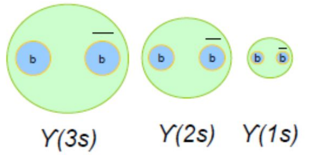


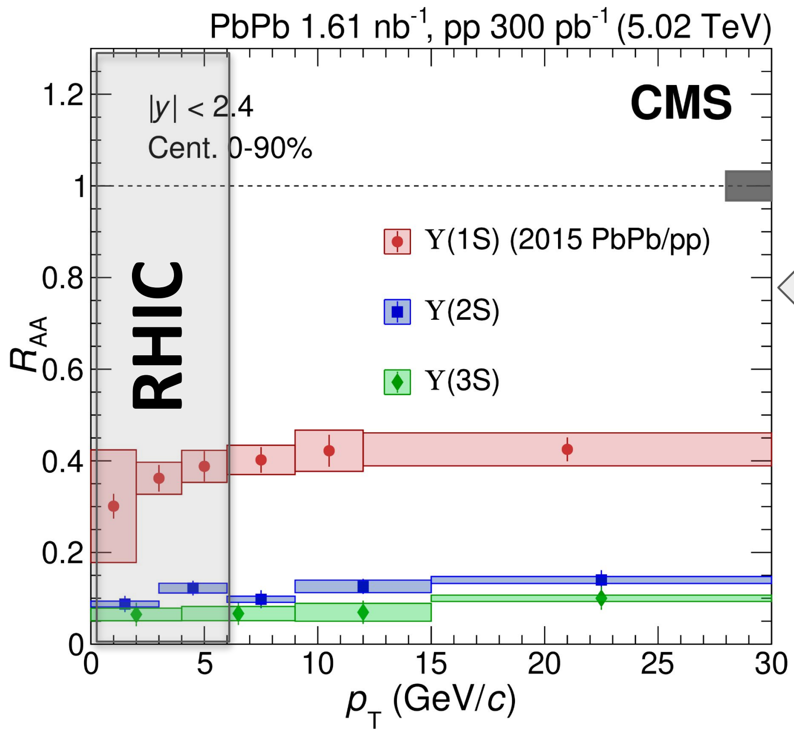
- **A long hunt came to an end: entire Υ "family" observed in PbPb**
  - indication of hierarchical modification $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
    - Υ(2S)+Υ(3S) reproduced by ATLAS and STAR

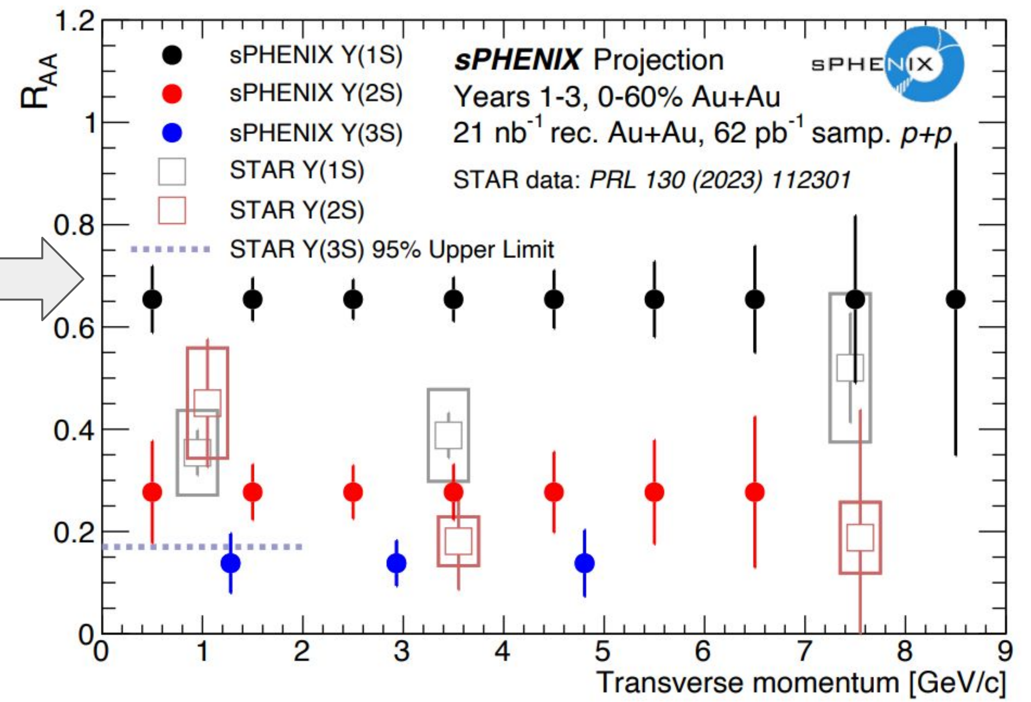
Can we gain insights from LHC and RHIC?

Υ(ns) suppression in LHC and RHIC

arXiv: 2303.17026
PRL 130 (2023) 112301
sPHENIX BUP





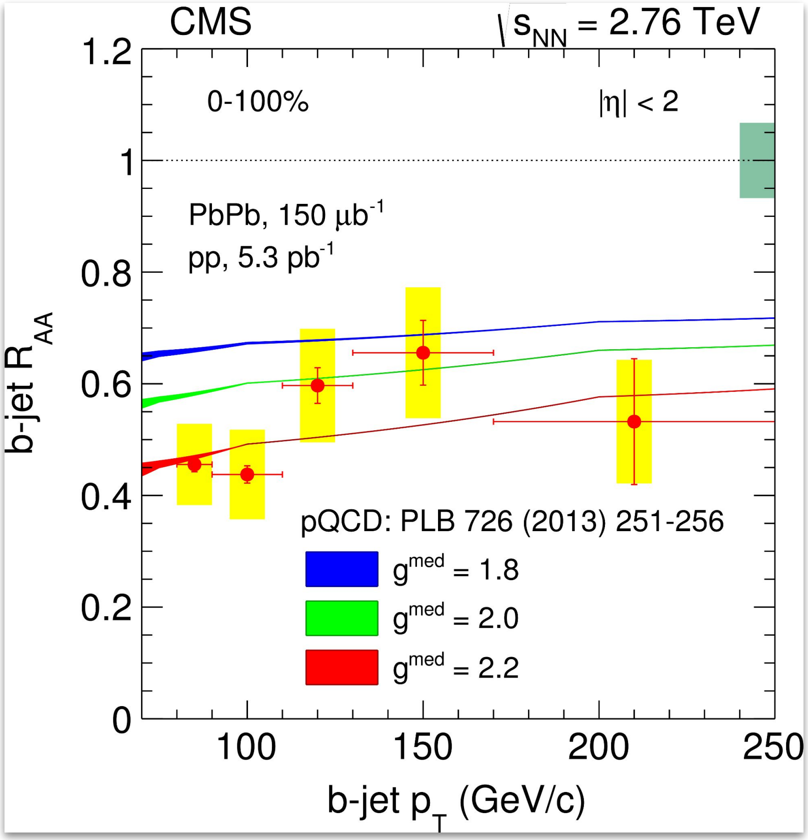


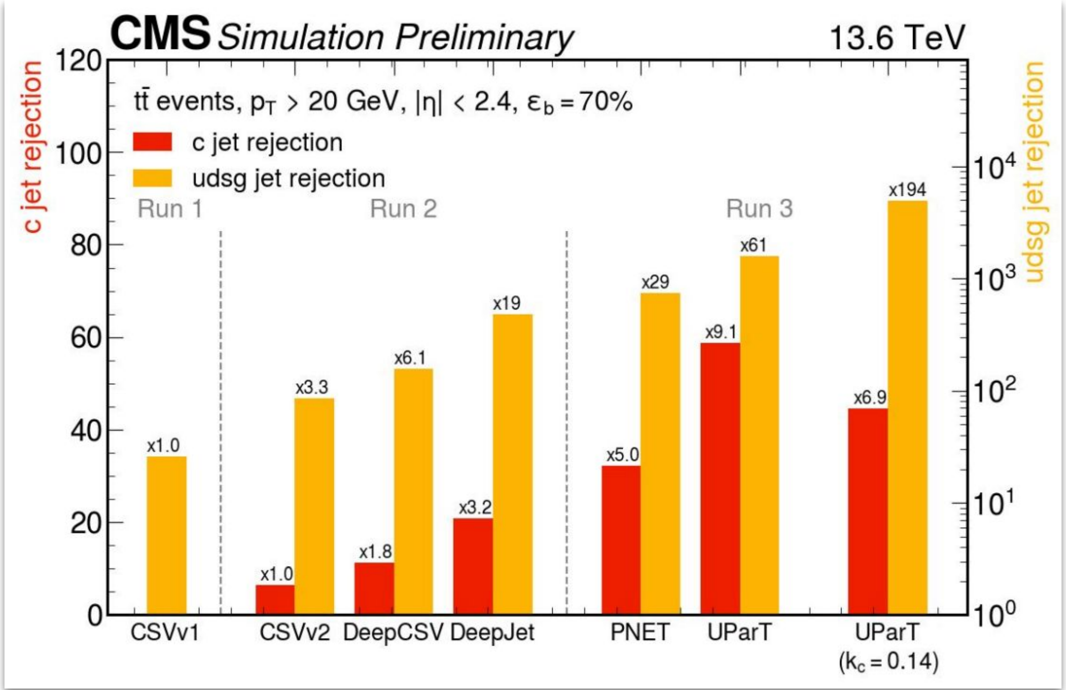
- **Strong complementarity between LHC and RHIC**
  - Υ's will set constraints on transport, hadronization, etc models

LHC+RHIC: does the resolving power of QGP depend on its temperature?

Can we see **single b quarks?**

PRL 113 (2014) 132301
JINST 13 (2018) P05011





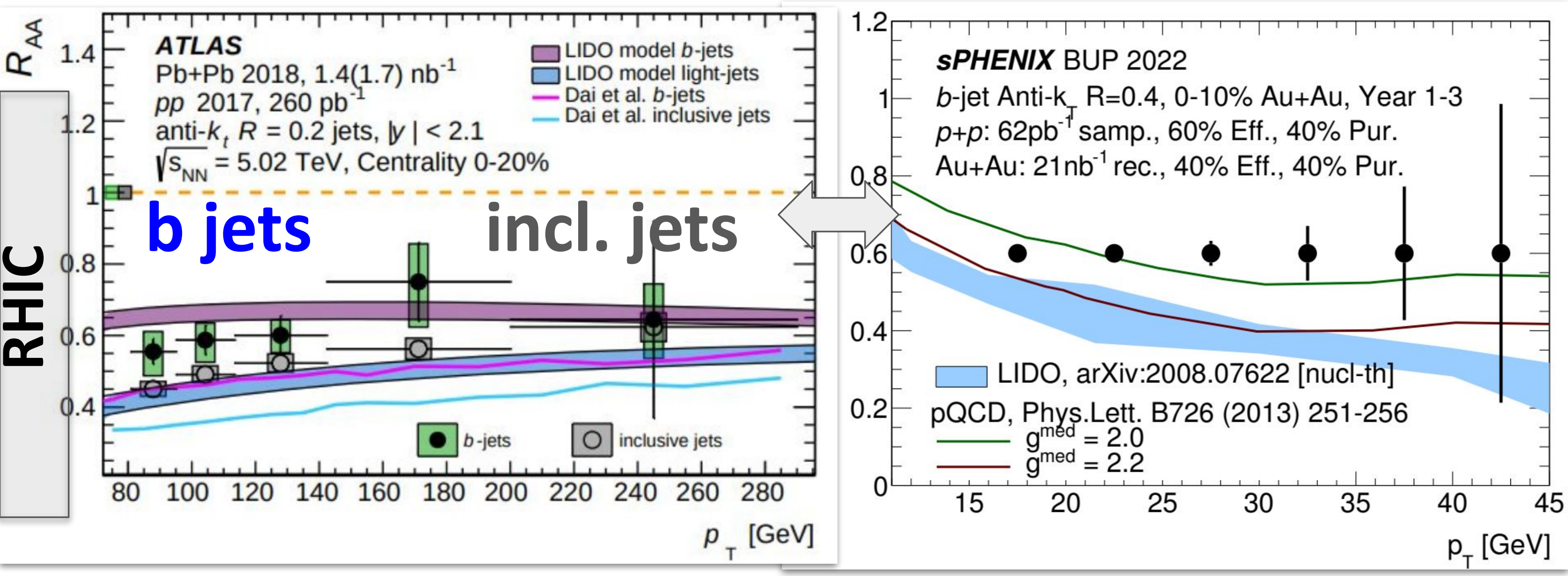
- **Since early LHC data taking we know b jets are heavily modified**
  - more data not always enough

    → performed methodology advancements

But what's the main motivation behind b jets?

How **mass & charge** affects en. loss?

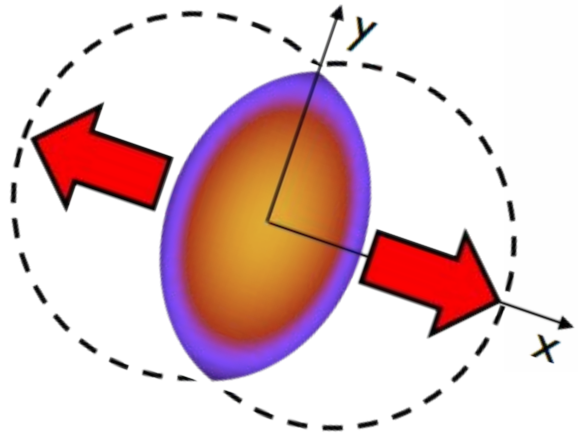
arXiv: 2204.13530
sPHENIX BUP

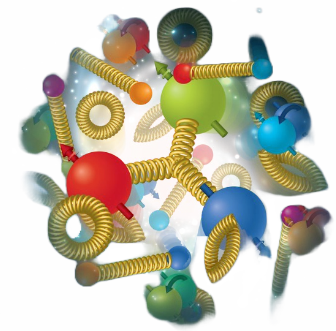


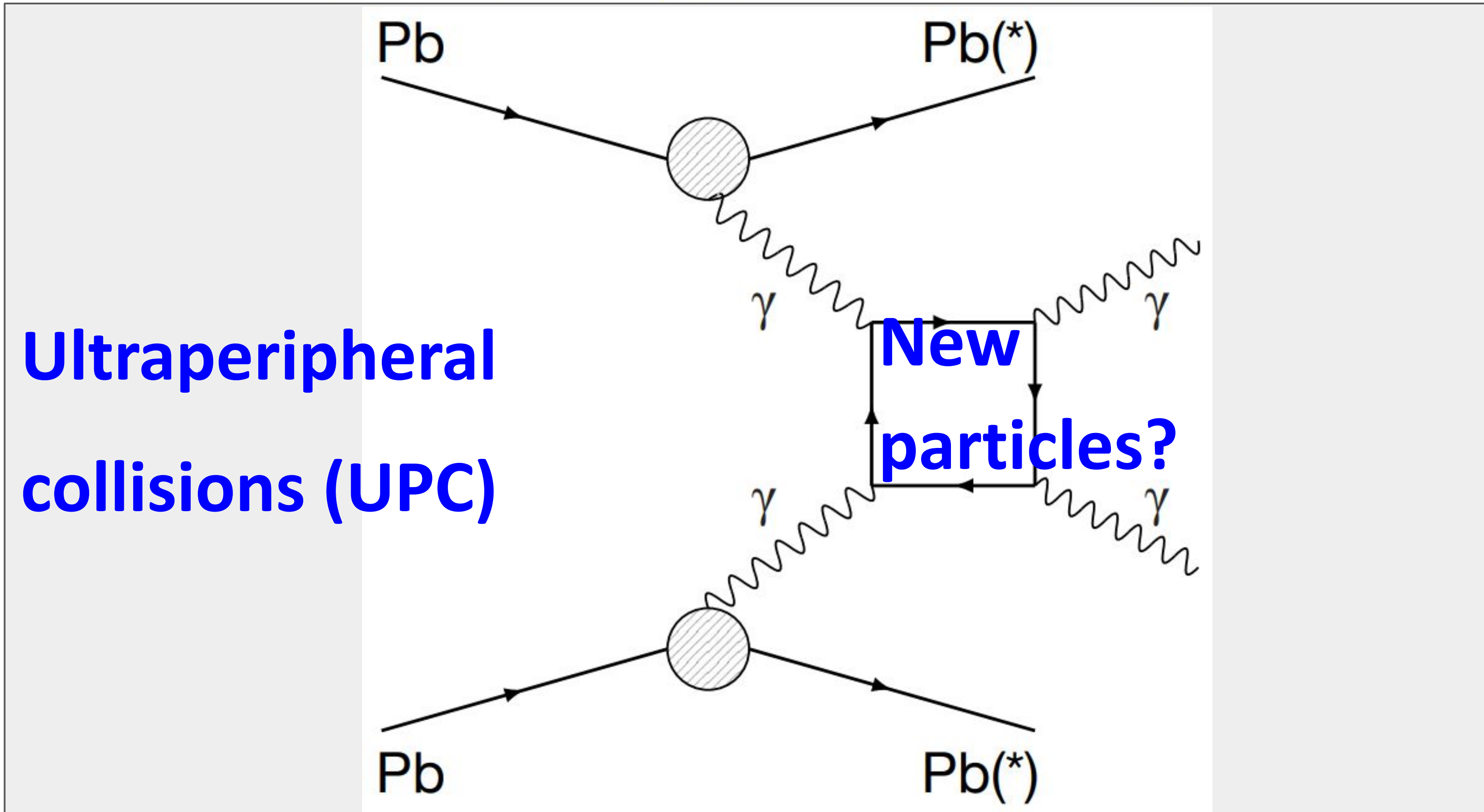
- **b quark mass ≫ light quarks, QCD charge is well controlled**
  - role for mass and colour-charge effects in partonic energy loss

b jets @ LHC+RHIC: open up a new dimension of QGP en. loss studies

Can we fully exploit/diversify the broad reach of NP?







G. Graziani slide 3

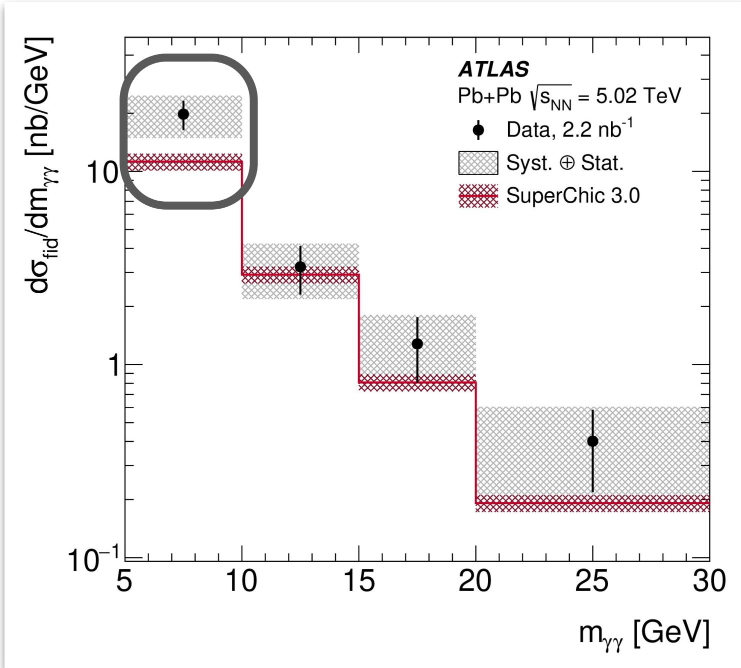
Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

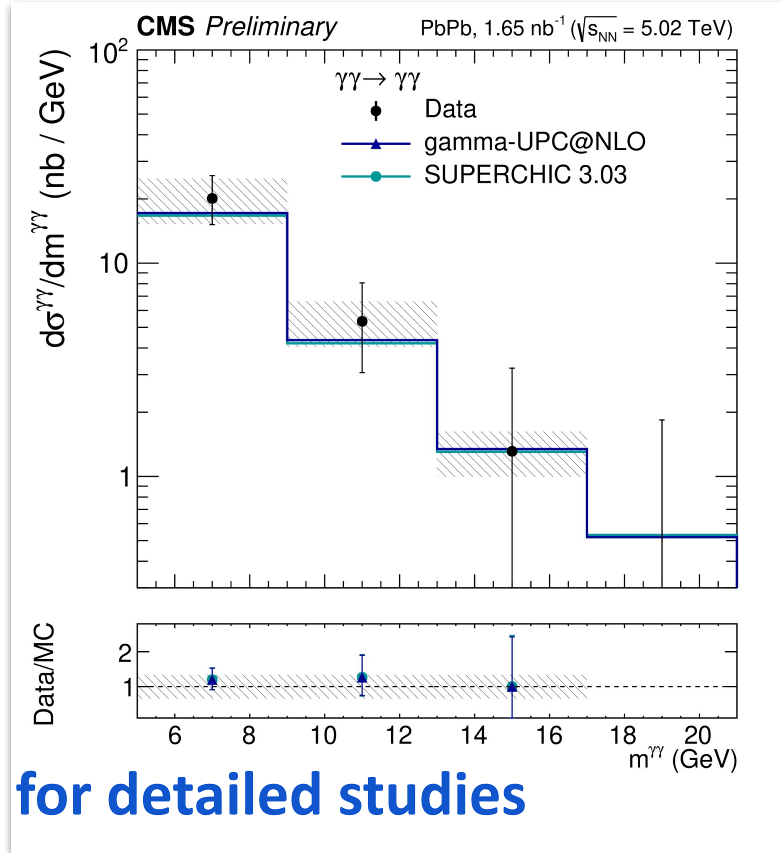
ATLAS Collaboration

Nature Physics **13**, 852–858 (2017) | Cite this article

LbyL production in UPC AA

Nature Phys. 13 (2017) 852
Krintiras *et al*, arXiv: 2204.02845
CMS-PAS-HIN-21-015



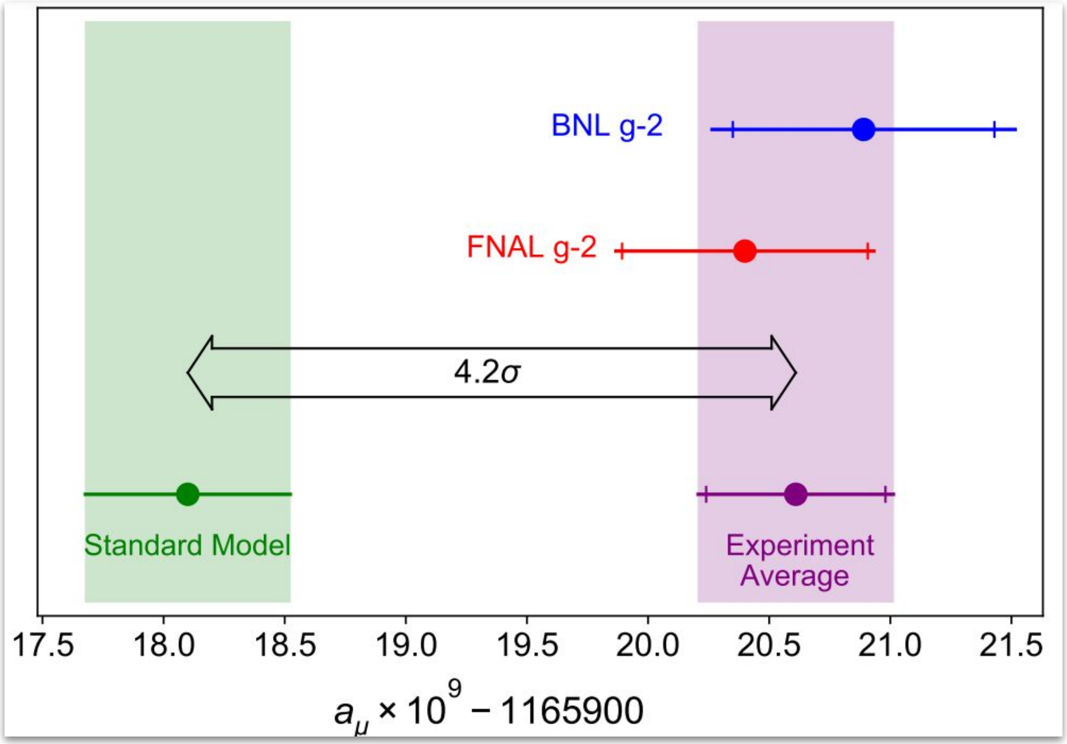


- **Event statistics already allow for detailed studies**
  - low-mass excess triggered already dedicated efforts
    - optimized the low-energy photon reconstruction
    - performed the first combination with NP data at LHC
- **NP naturally complements BSM efforts**

LHC+RHIC data: a great boost to our search for new physics

The anomalous anomaly for μ's

PRL 26 (2021) 141801

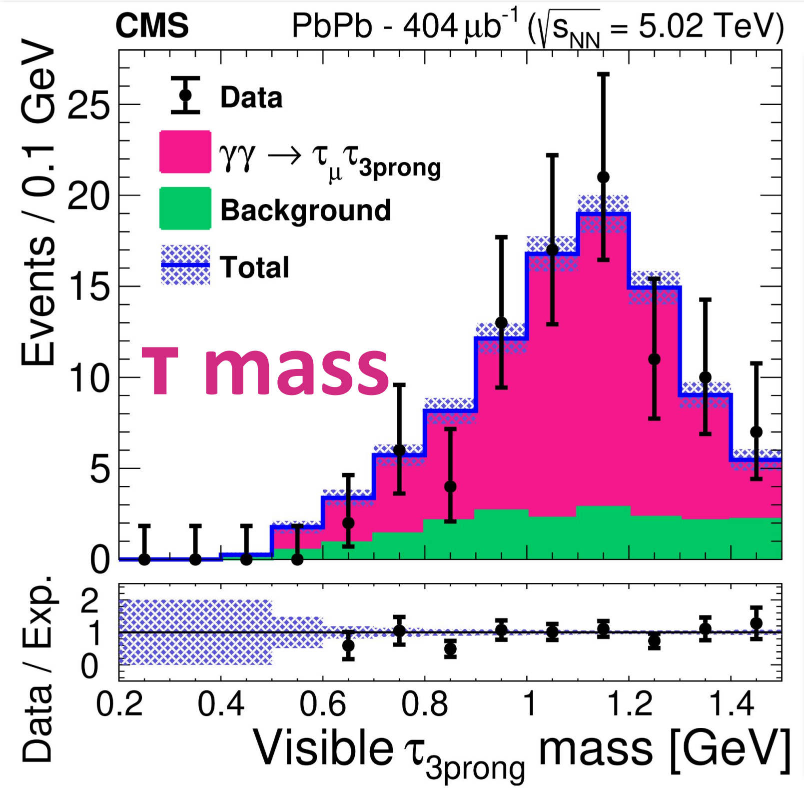


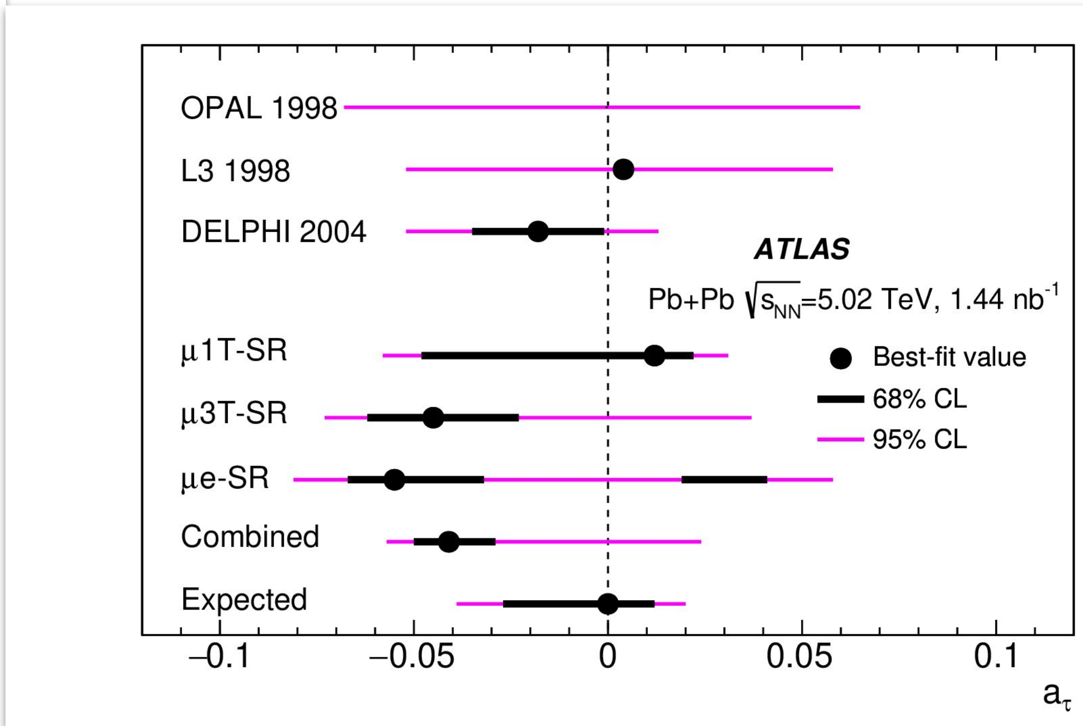
- **FNAL g-2 experiment confirmed previous discrepancy**
  - the exact level depends on theory considerations

Maybe it's heavier cousin is more sensitive to new physics?

The anomalous anomaly for τ's

arXiv:2204.13478
arXiv:2206.05192
(PRL, **editor's suggestion**)



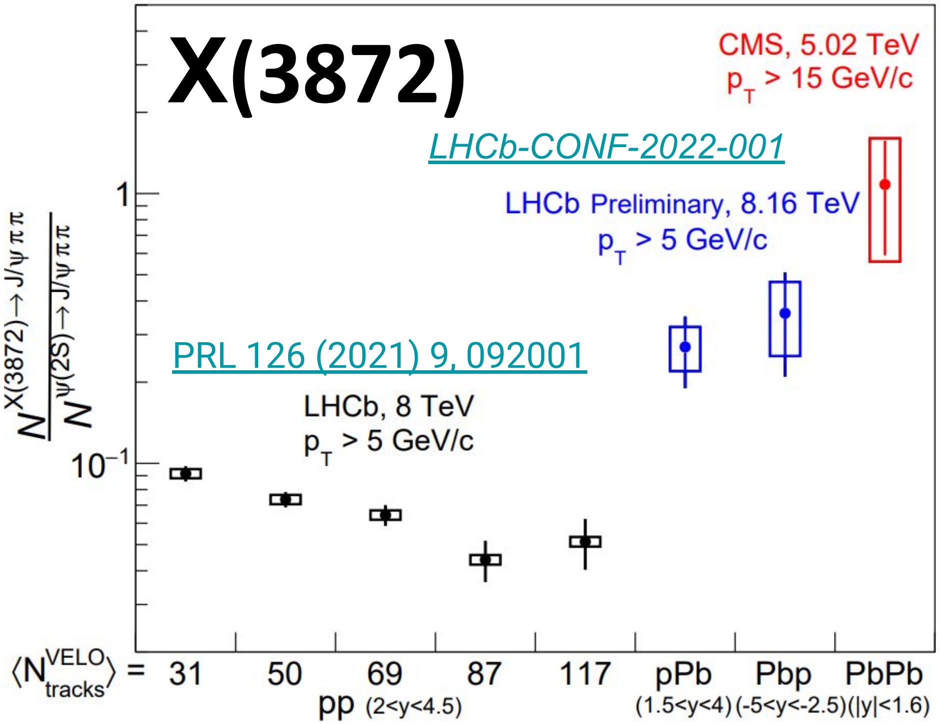


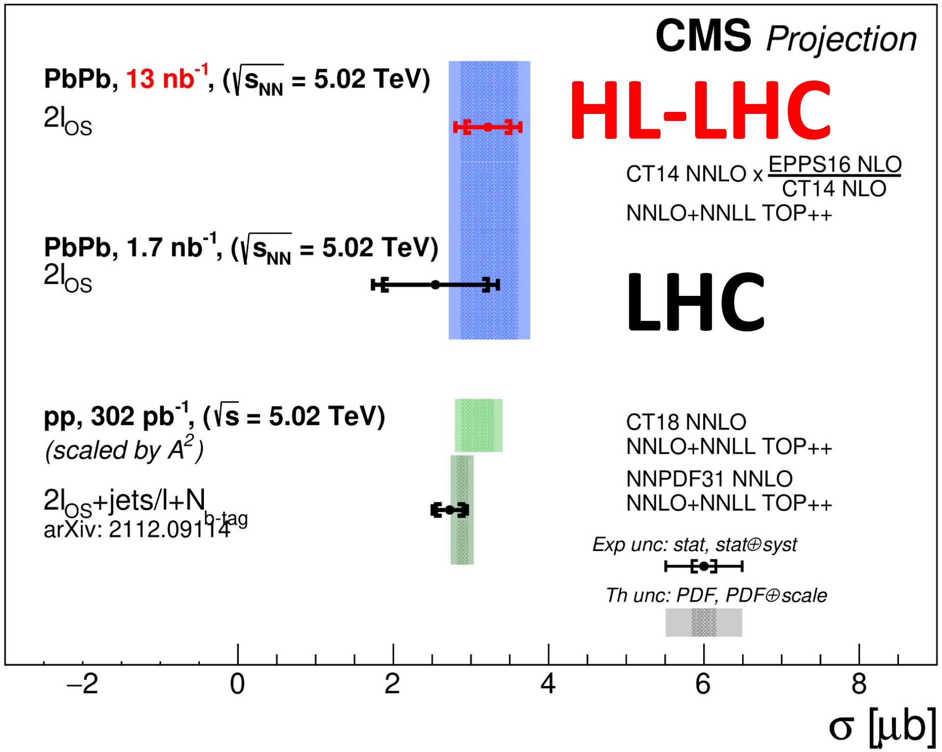
- **observed $\gamma\gamma \to \tau^+\tau^-$ for the first time at LHC**
  - using multiple clean final states
- **First constraints on a_τ obtained at LHC**

LHC+RHIC: improvements on a_τ with more data and final states

Exotic hadrons and top quarks in AA

PRL 128 (2022) 032001
PRL 125 (2020) 222001





- **NP can revolutionize exotic hadron spectroscopy**
  - quark configurations for many exotics remain elusive
- **Use top quark production as a new tool**
  - reducing nPDF uncertainty; the most primordial b jets

Mapping the QCD uncharted territory–All campaigns

- How the fluid behavior at $\mu_B \approx 0$ emerges?
  - constraining the initial state
  - non-linear color fields and gluon saturation
  - small-size limit of QGP
- How can we quantify the QGP properties?
  - integrate soft with heavy and hard probes
  - going in shorter scales and examine T behavior
  - particle propagation and nuclear transport properties
- Can we fully exploit/diversify the broad reach of NP?
  - revolutionary studies beyond the QGP and even QCD

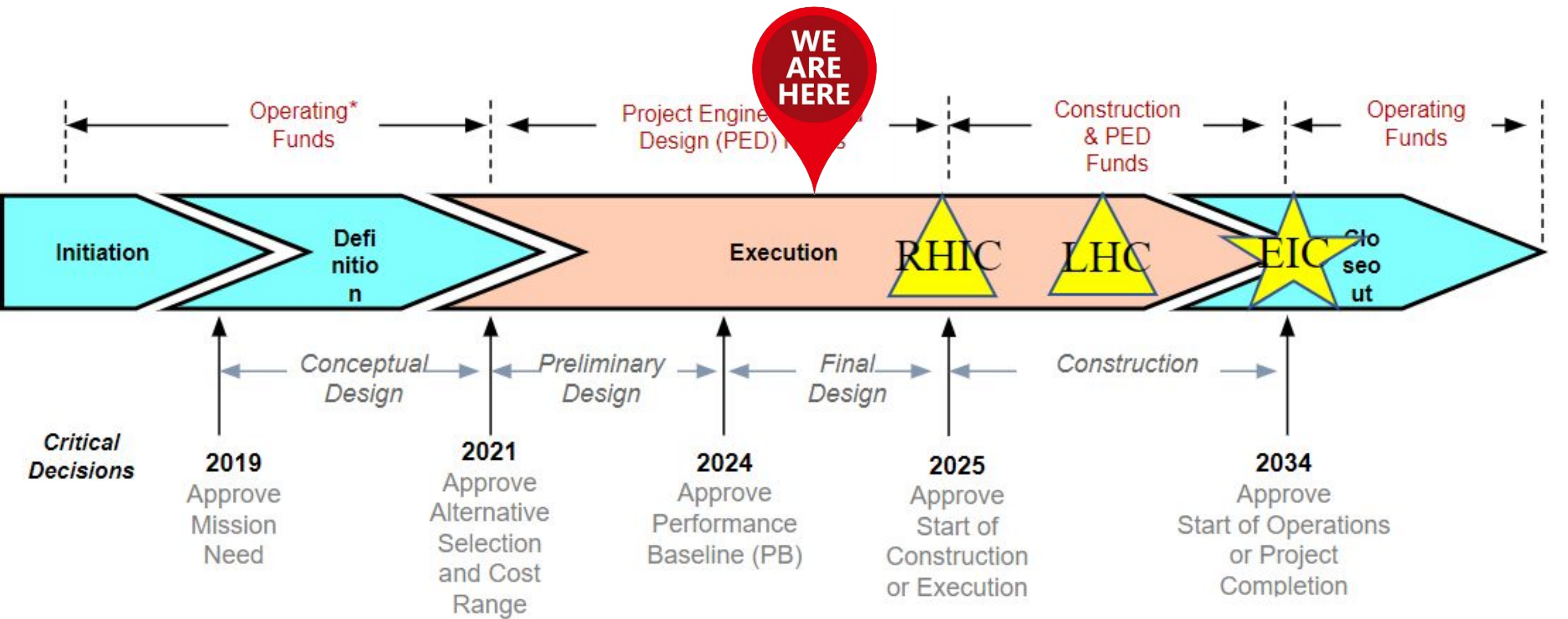
Putting all together

- **Diverse NP program at 3 facilities (a dream for an EC ;)**
  - **last two decades of work on QGP (+ from HEP)**

    → paves the way for its detailed characterization

    → a basis to build upon EIC

    → nucleus + QGP: a common laboratory for QCD

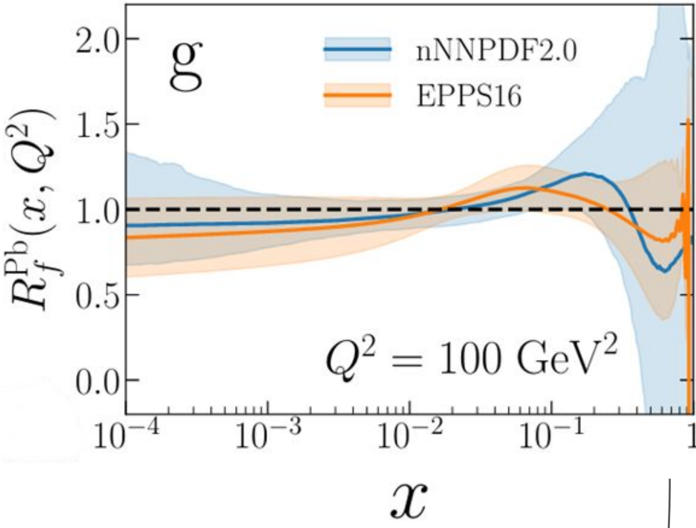


S slides

nPDFs from several groups but long way to go

2203.13923

Nuclear (most recent) PDFs	nCTEQ15	EPPS16	nNNPDF2.0 (1.0)	TUJU19
Perturbative order	NLO	NLO	NLO, NNLO	NLO, NNLO
Heavy quark scheme	ACOT	S-ACOT	FONLL	ZM-VFN
Value of $\alpha_s(m_Z)$	0.118	0.118	0.118	0.118
Input scale Q_0	1.30 GeV	1.30 GeV	1.00 GeV	1.69 GeV
Data points	708	1811	1467 (451)	2336
Fixed Target DIS	✓	✓	✓ (w/o ν-DIS)	✓
Fixed Target DY	✓	✓		
LHC DY and W		✓	✓ (✗)	
Jet and had. prod.	(π^0 only)	(π^0, LHC dijet)		
Independent PDFs	6	6	3	6
Parametrisation	simple pol.	simple pol.	neural network	simple pol.
Free parameters	16	20	256 (178)	16
Statistical treatment	Hessian	Hessian	Monte Carlo	Hessian
Tolerance	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$



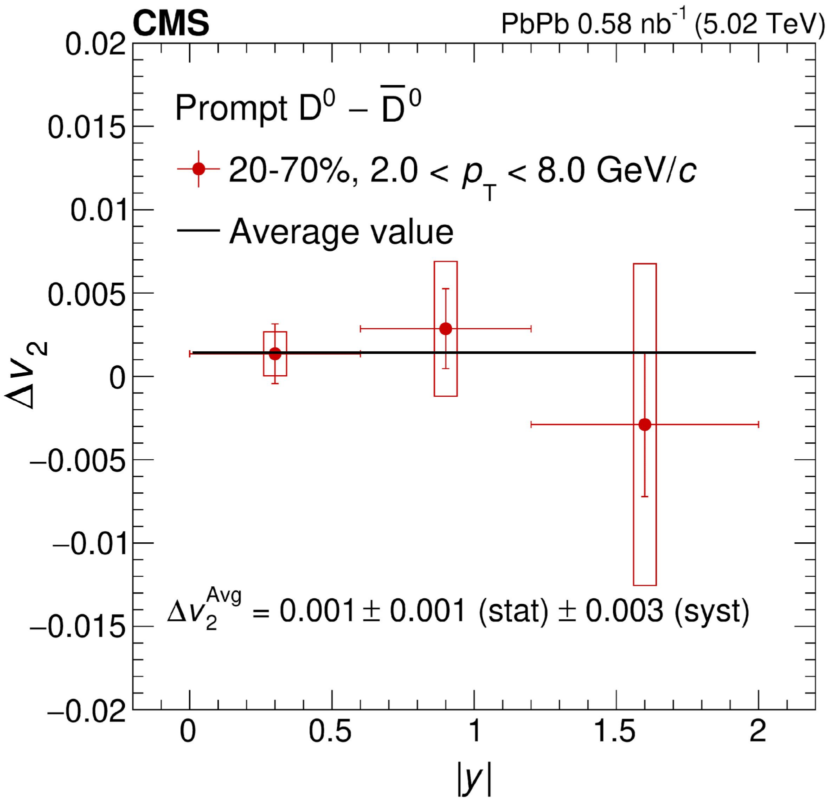
- **Features of the current fits**
  - **Less available sets compared to proton PDFs**
  - **Different sets, theoretical assumptions, and methodological settings**
- **The nuclear modification of the gluon distribution not well understood**

Prompt D^0 - $\bar{D}^0$ production and v_2 fluctuations

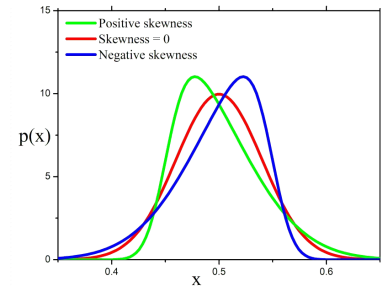
CMS FINAL HP23

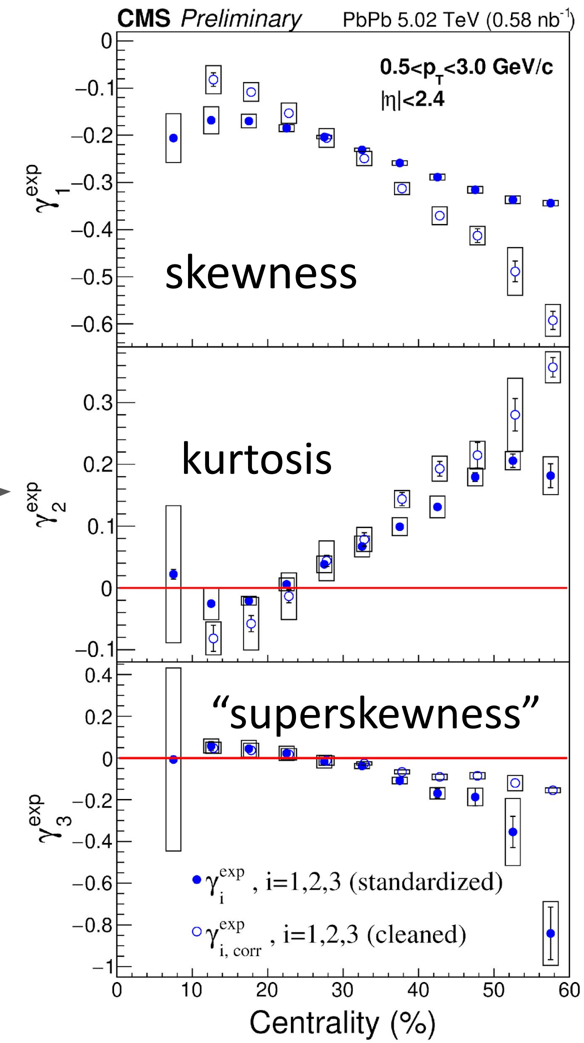
CMS NEW RESULT HP23

PLB 816 (2021) 136253
CMS-PAS-HIN-21-010



Fluctuations



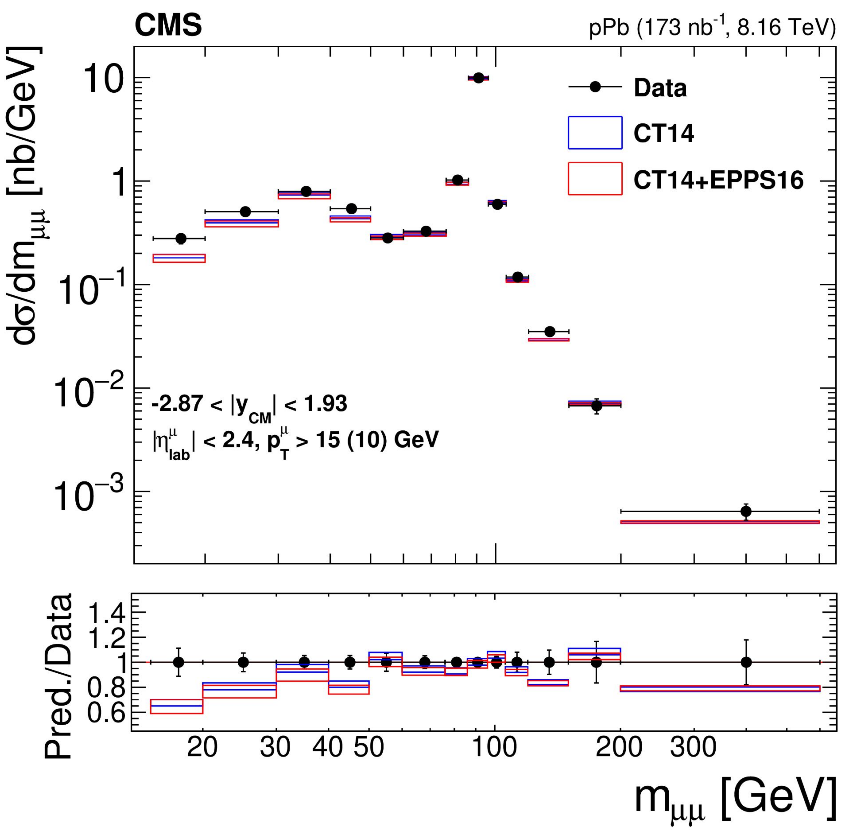


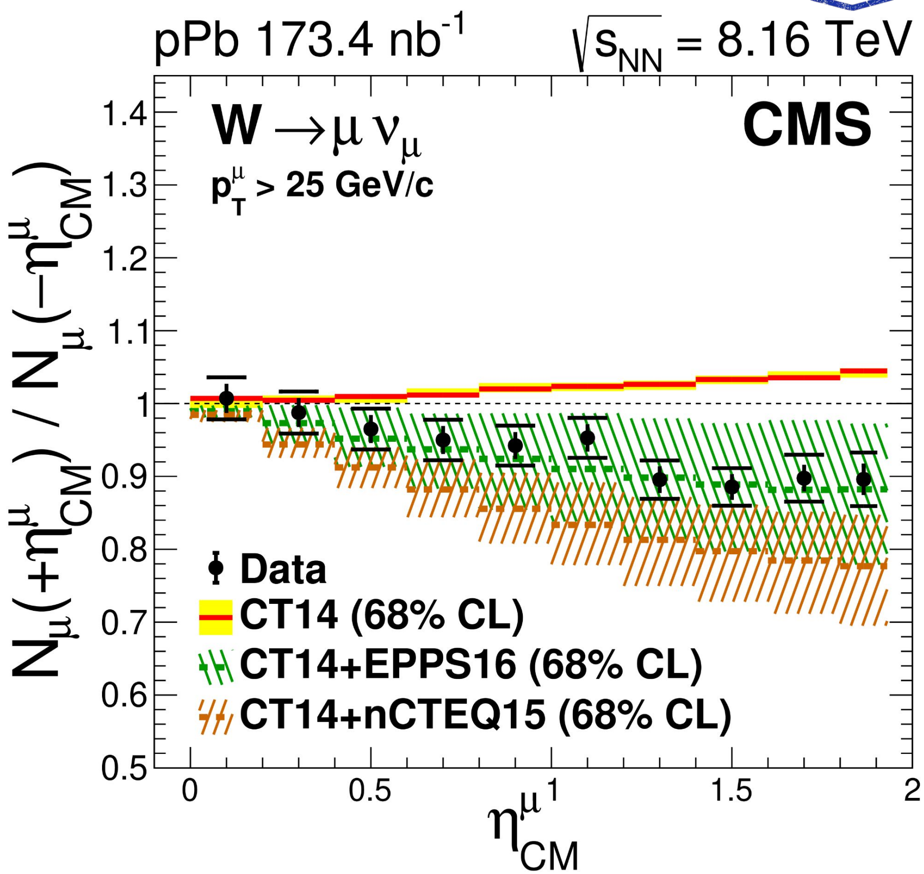
- **First y-dependent Δv_2 measurement for D^0**
  - searching for strong initial Coulomb field
- **Fine splitting up to $v_2\{10\}$(!)**
  - higher order moments (γ_{1-3}) in initial state revealed

Z/γ* & W production in pPb

[JHEP 05 (2021) 182](#)
[PLB 800 (2020) 135048](#)

CMS FINAL HP23





- **First Z/γ* study in an extended $m_{\mu\mu}$ range**
  - low $m_{\mu\mu}$ sensitive to NNLO corrections
  - on-shell production less well described: statistical fluctuations(?)
- **Observation of nuclear effects in W boson production**
  - included in all recent nPDF fits

Key characteristics of the nPDF global fits

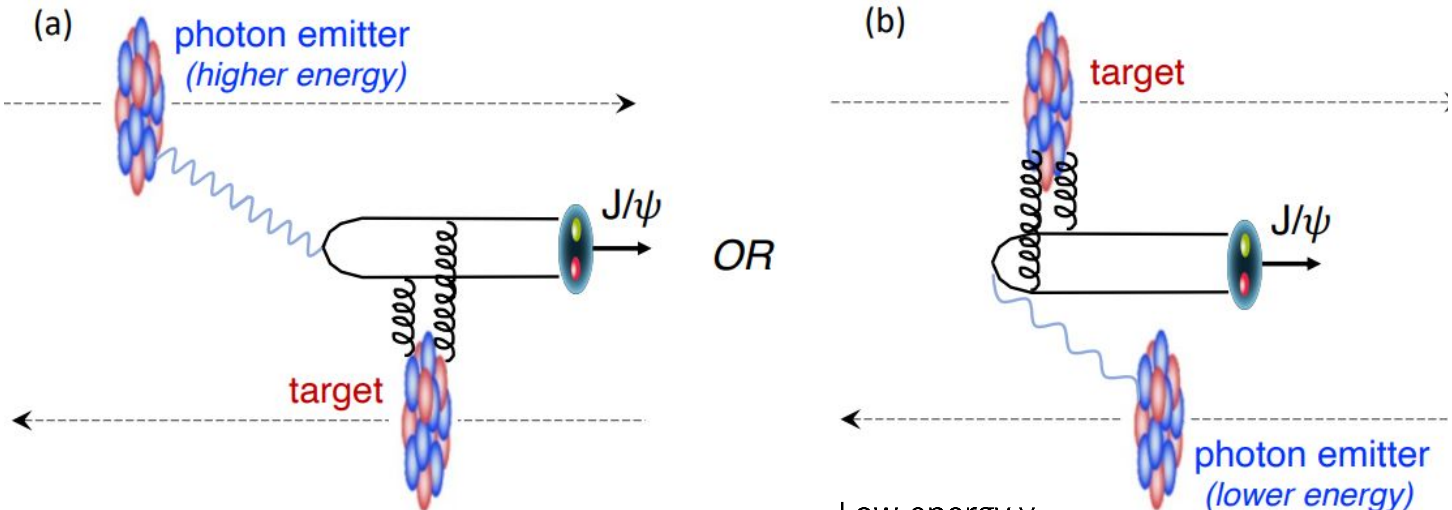
	KSASG20	nCTEQ15WZSIH	TUJU21	EPPS21	nNNPDF3.0
Order in α_s	NLO & NNLO	NLO	NLO & NNLO	NLO	NLO
lA NC DIS	✓	✓	✓	✓	✓
νA CC DIS	✓		✓	✓	✓
pA DY	✓	✓		✓	✓
πA DY				✓	
RHIC dAu π^0,$\pi^\pm$		✓		✓	
LHC pPb π^0,$\pi^\pm$,$K^\pm$		✓			
LHC pPb dijets				✓	✓
LHC pPb D^0				✓	✓ reweight
LHC pPb W,Z		✓	✓	✓	✓
LHC pPb γ					✓
Q, W cut in DIS	1.3, 0.0 GeV	2.0, 3.5 GeV	1.87, 3.5 GeV	1.3, 1.8 GeV	1.87, 3.5 GeV
p_{T} cut in D^0,h-prod.	N/A	3.0 GeV	N/A	3.0 GeV	0.0 GeV
Data points	4353	948	2410	2077	2188
Free parameters	9	19	16	24	256
Error analysis	Hessian	Hessian	Hessian	Hessian	Monte Carlo
Free-proton PDFs	CT18	~CTEQ6M	own fit	CT18A	~NNPDF4.0
Free-proton corr.	no	no	no	yes	yes
HQ treatment	FONLL	S-ACOT	FONLL	S-ACOT	FONLL
Indep. flavours	3	5	4	6	6
Reference	PRD 104, 034010	PRD 104, 094005	arXiv:2112.11904	arXiv:2112.12462	arXiv:2201.12363

P. Paakkinen (DIS22)

How to unambiguously access low-x gluons?

The theo. solution

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



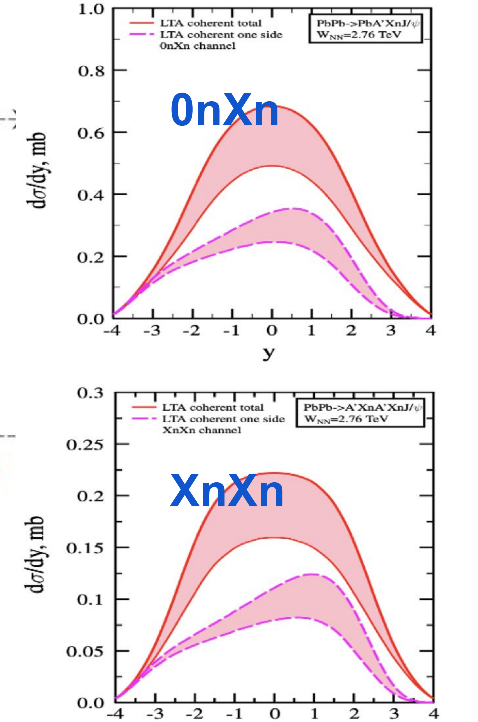
High-energy γ

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

The issue

Low-energy γ

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



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

The exp. solution

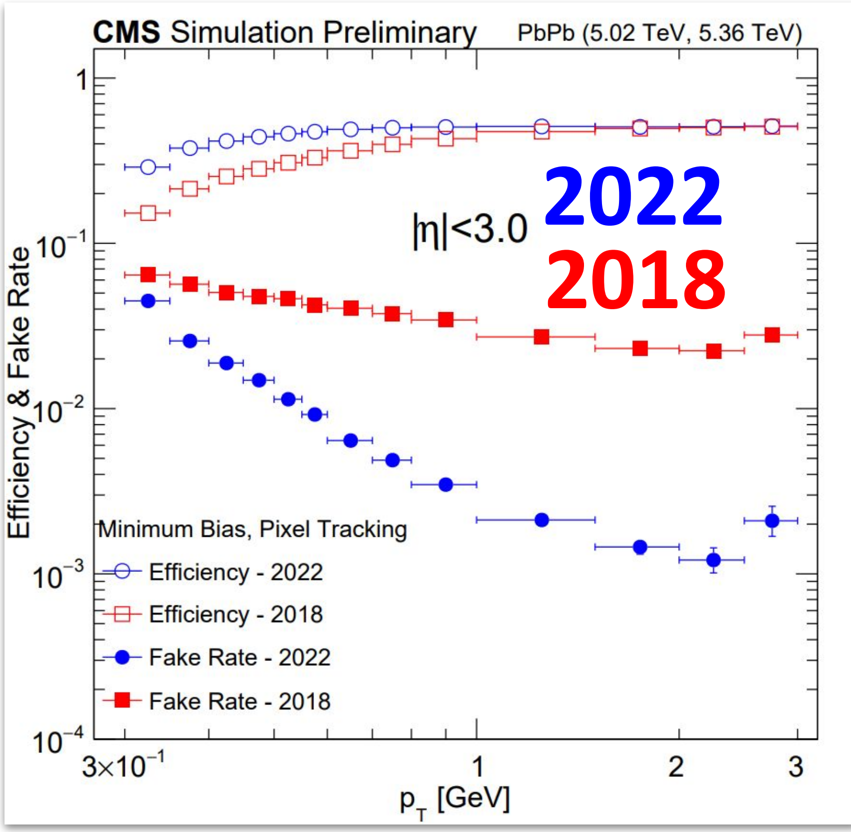
$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = N^{0nXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{0nXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

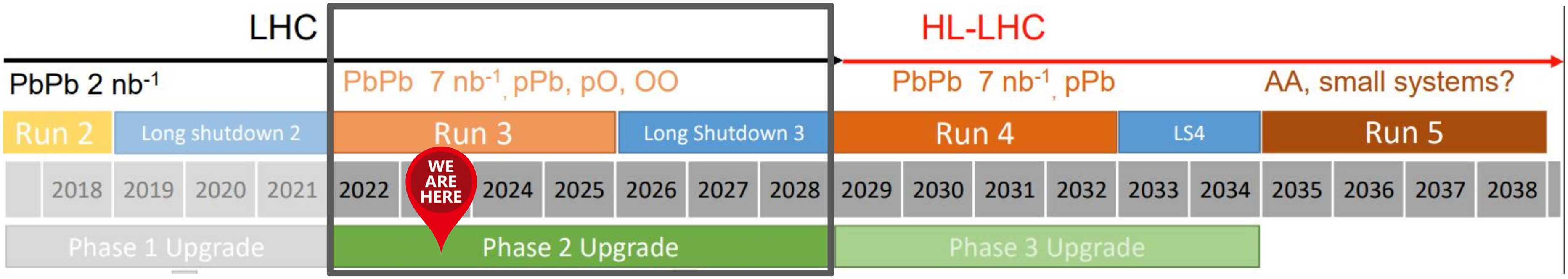
$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = N^{XnXn}_{\gamma/A}(\omega_1)\cdot\sigma_{\gamma A\to J/\psi A'(\omega_1)} + N^{XnXn}_{\gamma/A}(w_2)\cdot\sigma_{\gamma A\to J/\psi A'(w_2)}$$

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

LHC Run 3, ...

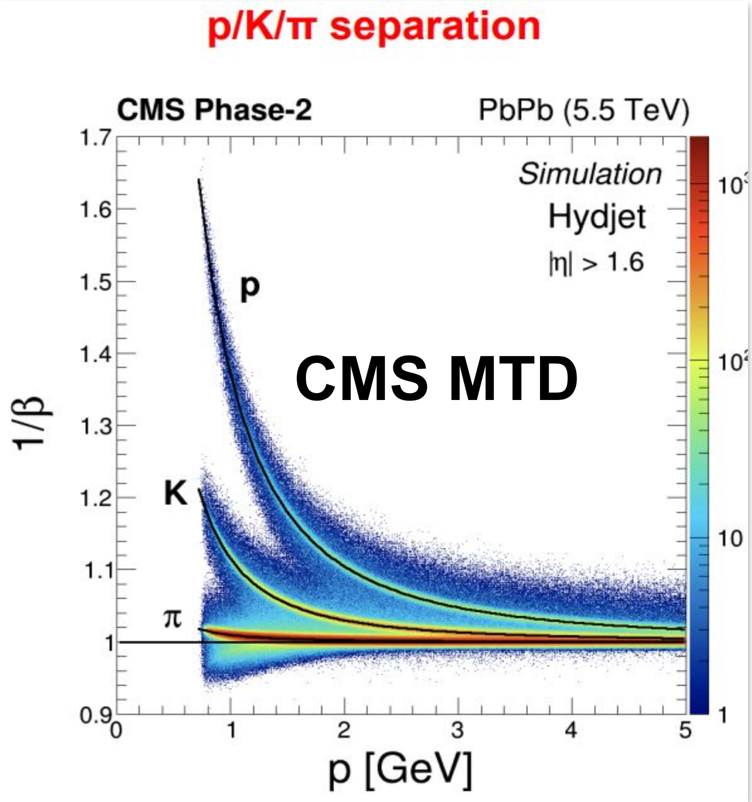
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- ALICE & LHCb/SMOG2

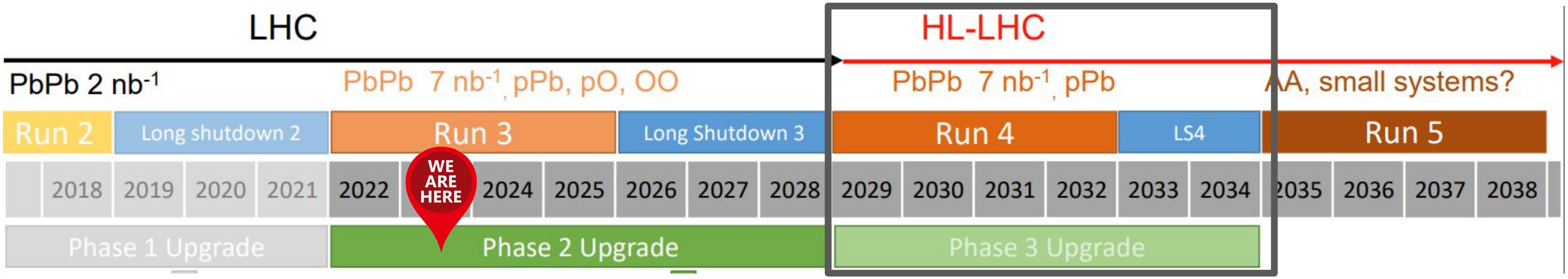




LHC Runs 3, 4, ...

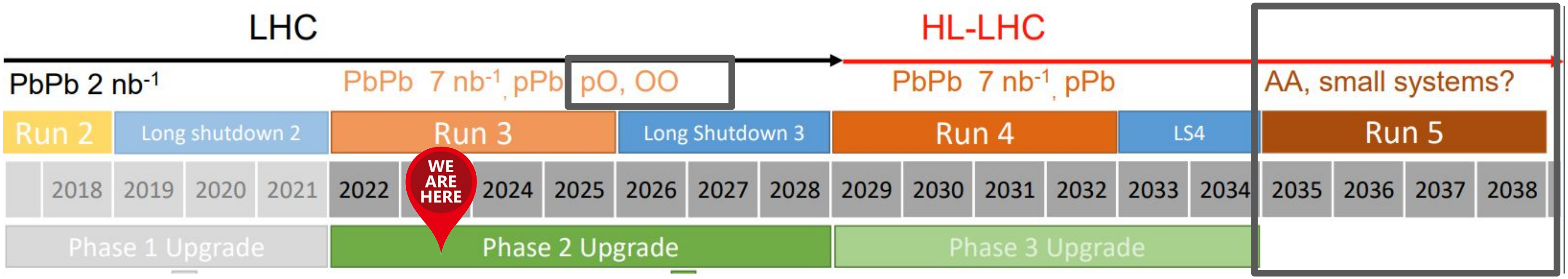
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- Upgraded detectors in Run 4
  - 3x increase in DAQ rate
  - PID and 4D tracking
  - ↑ tracking and muon coverage
  - high-granularity Hcal
  - radiation-hard ZDCs





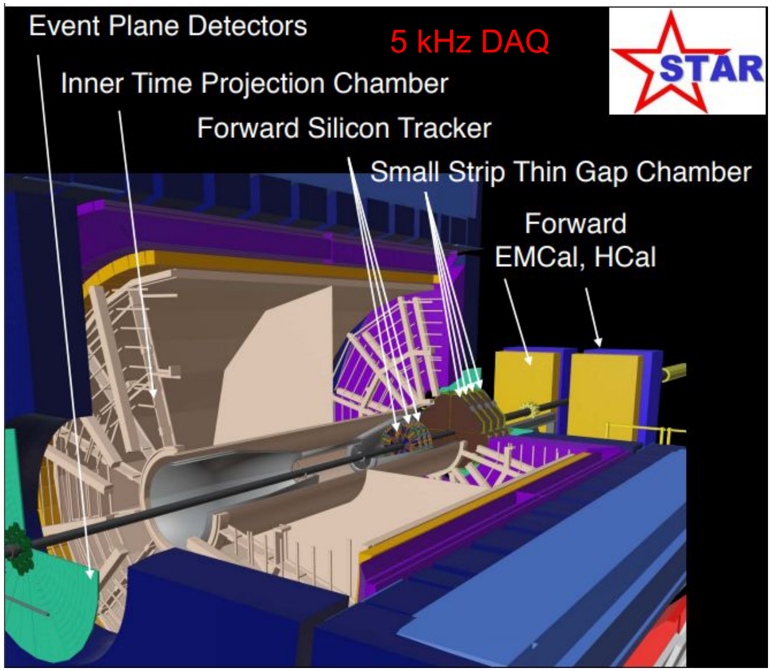
LHC Runs 3, 4 & beyond

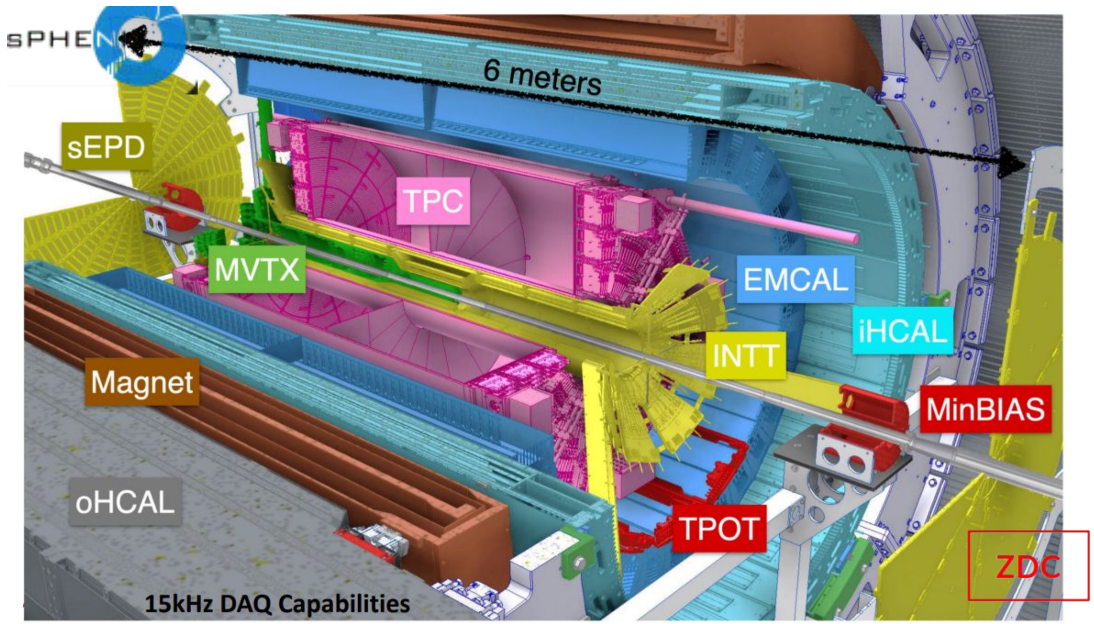
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- Upgraded detectors in Run 4
- Run 5 unique chance to enrich the NP program
  - dedicated taskforce for lighter ions
  - benchmark performance with O in 2024



RHIC Run Plan 2023–2025

- Upgraded detectors, major ones in sPHENIX
  - extended coverage → closing the gap with the LHC
- Realization of the 2015 NSAC Long Range Plan
  - Study the microstructure of the QGP
  - Precision jet and heavy flavor measurements

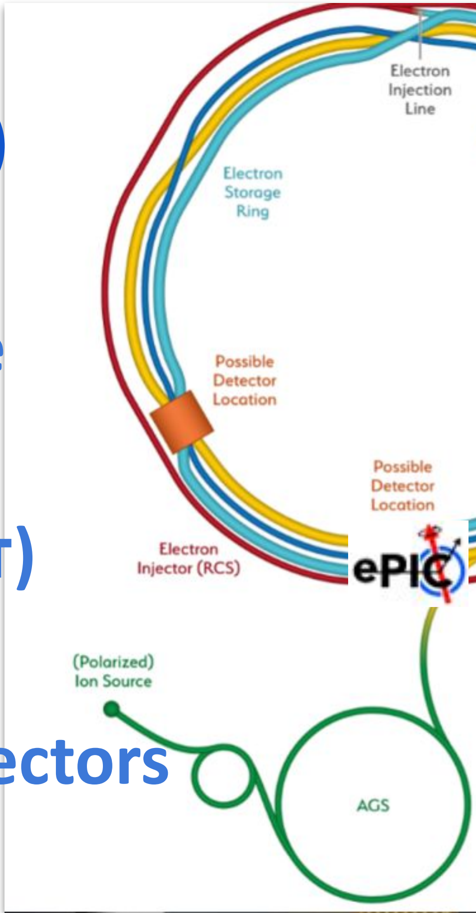




EIC: the nuclear HERA

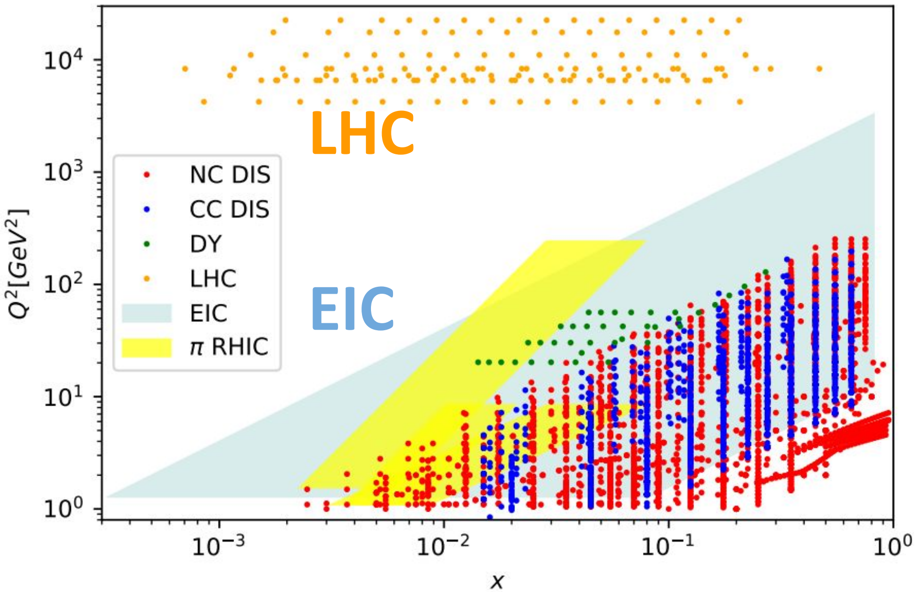
A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

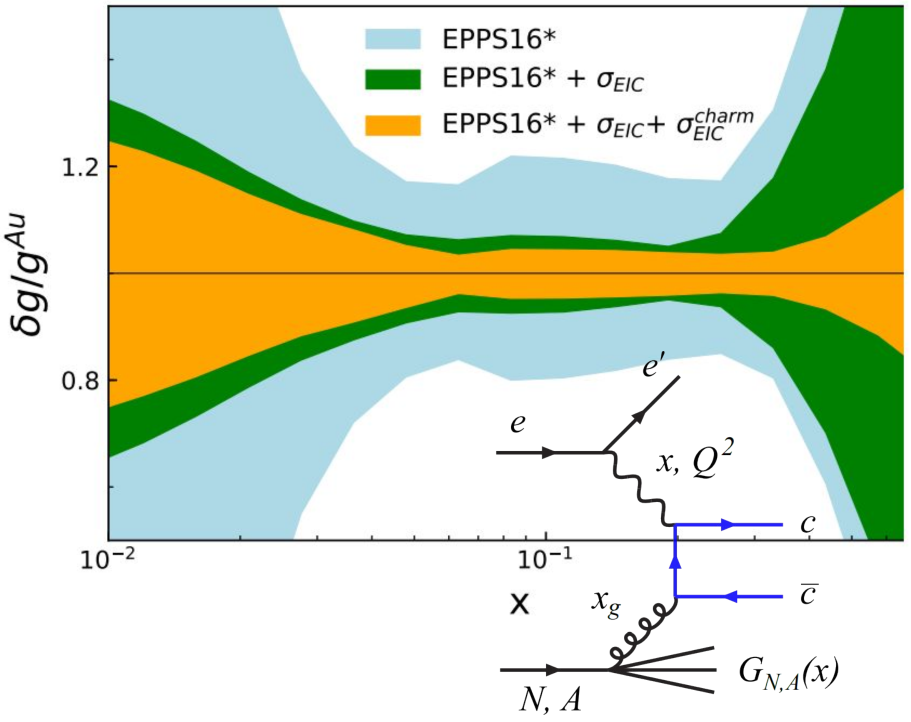
- Only new collider in foreseeable future
  - frontier of Accelerator S&T
- ePIC Collaboration formed (IR6)
- General purpose detector
  - -4<η<4 & fwd/bkw coverage
    - low-mass tracking
  - PID capabilities (π, K, p, e/π)
  - hermetic ECAL & HCAL
  - tagging p/n⟶ beamline detectors
  - High control of systematics
    - luminometry, e & h polarimetry
- Integration into IR6 is critical



E_e: 5 ... 18 GeV
E_p: 41 ... 275 GeV
E_{ion}: 41 ... 110 GeV/n
Ions: from p to U
Pol (e,p,He, etc): >70%
Lum: up to 10^{34} cm^{-2} s^{-1}

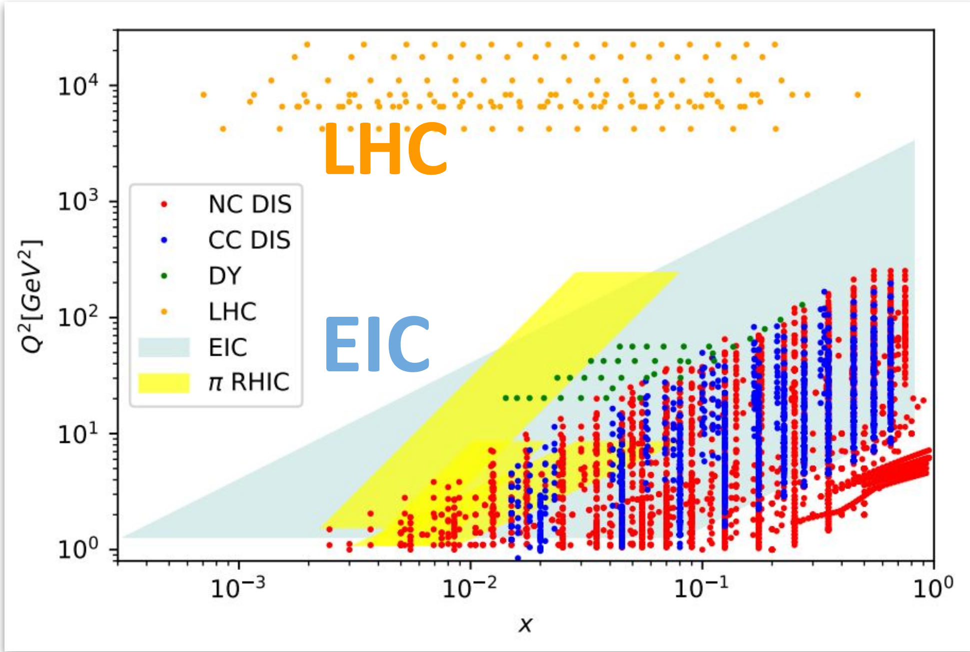
HF is key for nPDFs with ever-increasing precision

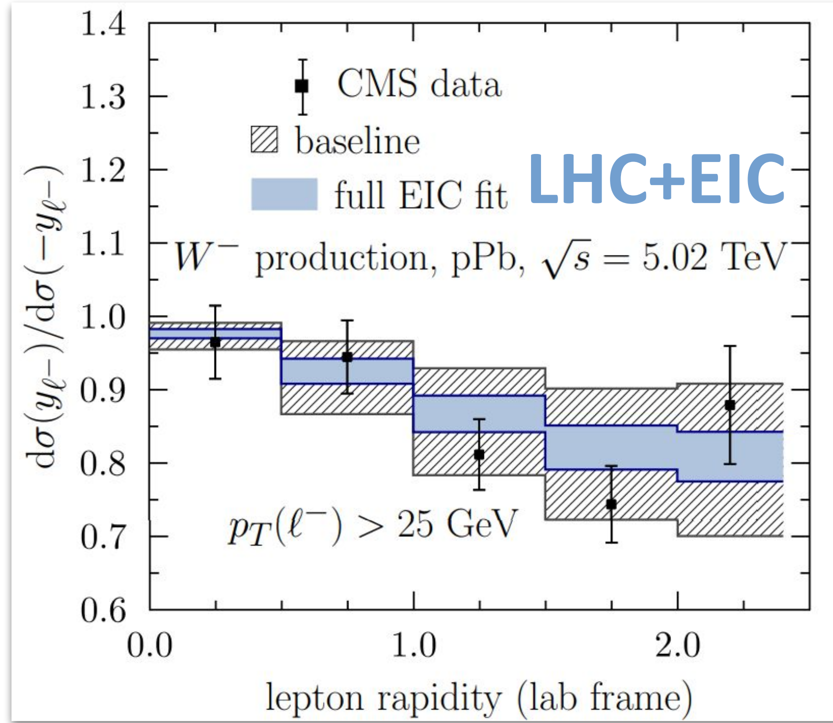




- **Inclusive DIS σ at most a few % ⟶ EIC key constraints on nPDFs**
- **Further constraints for gluons from HF, complementary to inclusive DIS**
  - **specially at high *x* (∝ m^2)**
  - **HF mass schemes tested and the intrinsic HF in the nPDFs**

Are nPDFs global or not?

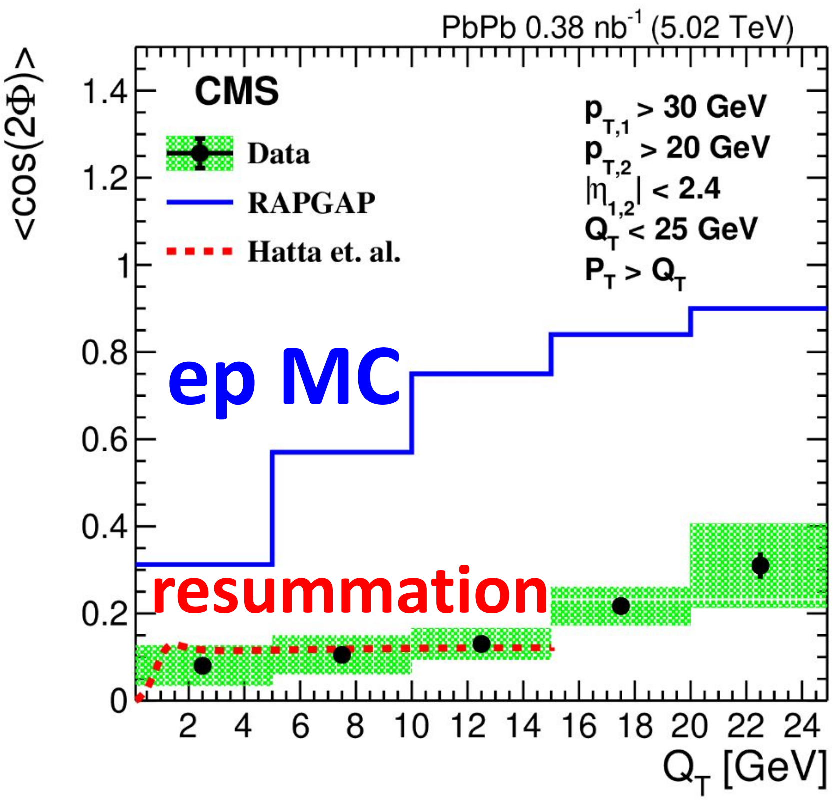


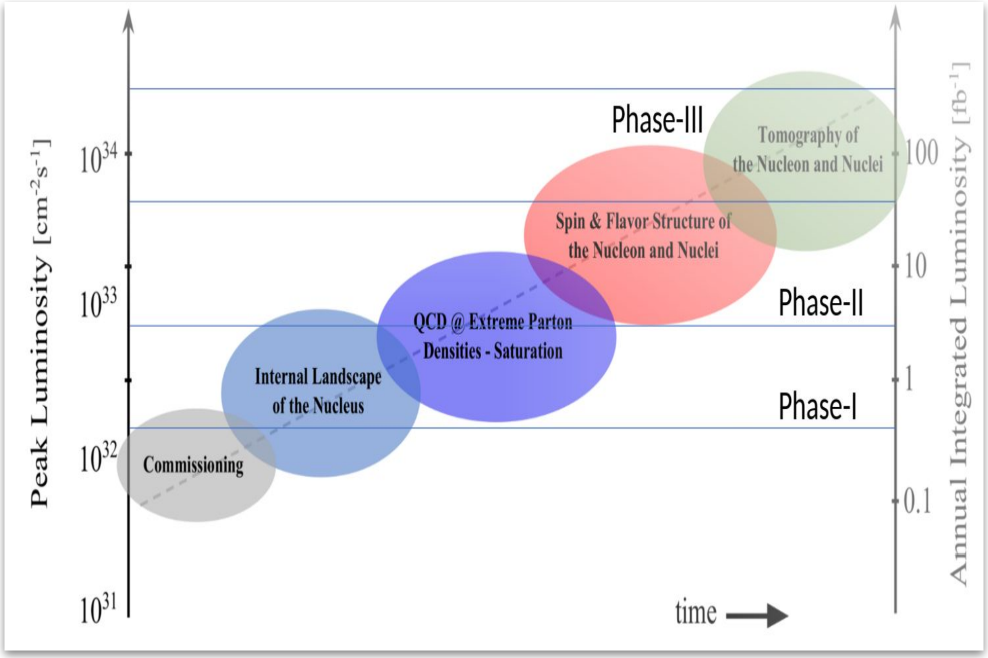


- A-dependence of nPDFs? Single global fit with whole set of available nuclei
- Is DGLAP valid across Q^2? True if constraints at low & high Q^2 consistent
- Combined determination of p, d, & nPDFs within an integrated global fit

Still this would be the first step for a long journey

arXiv:2205.00045
(accepted by PRL)

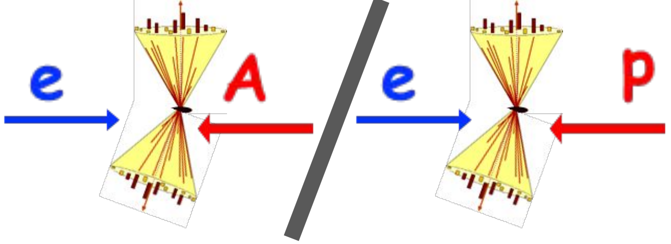


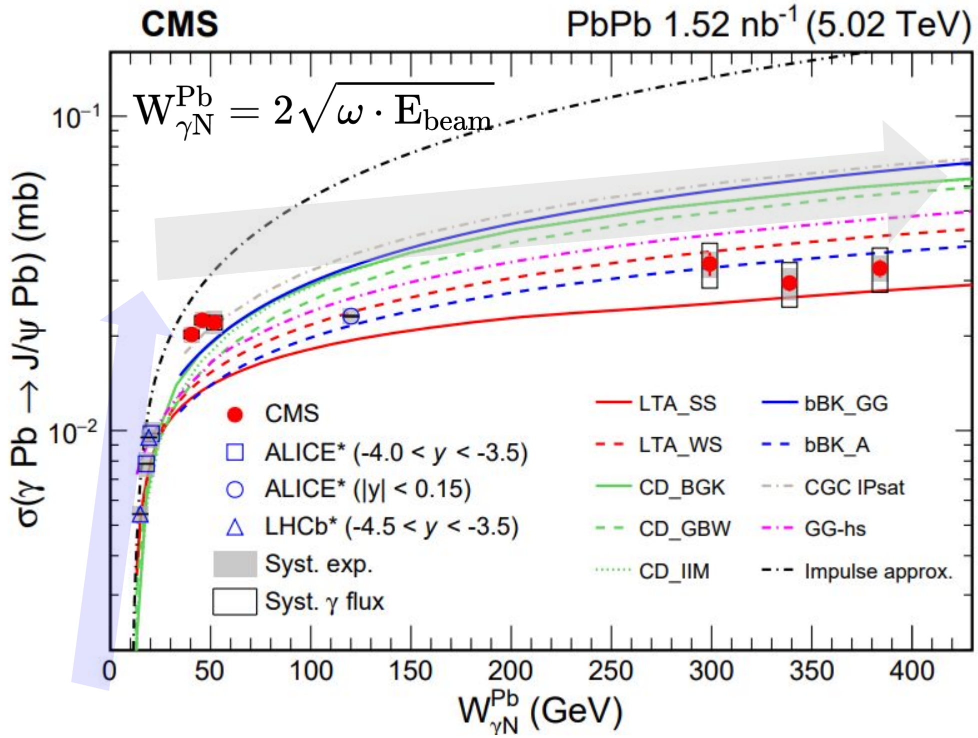


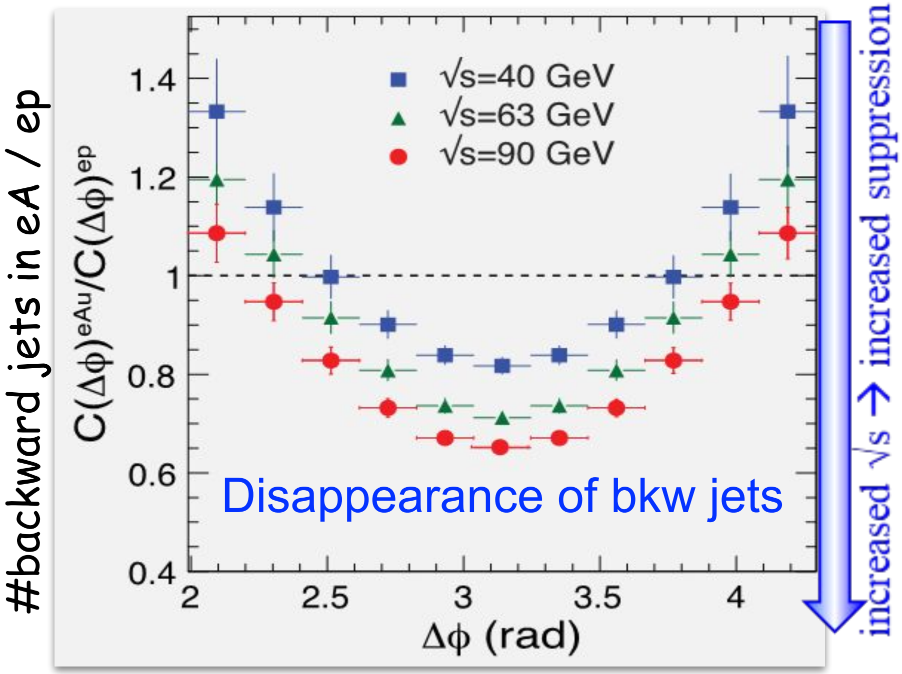
- **<cos(2Φ)> for exclusive dijets not well described by MC tuned in ep**
  - sensitive to primordial asymmetry due to the linearly polarized gluons
- **nPDFs are only the "LO" of a 4+1D tomography/spatial imaging**
  - inclusive DIS ⟶ semi-inclusive DIS ⟶ exclusive processes

EIC is a gluon factory

HIN-22-002
(to appear)



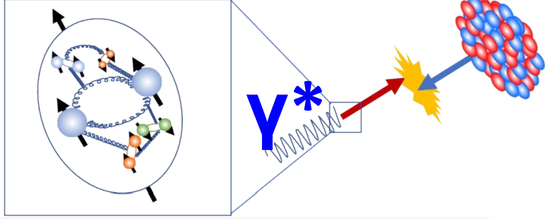


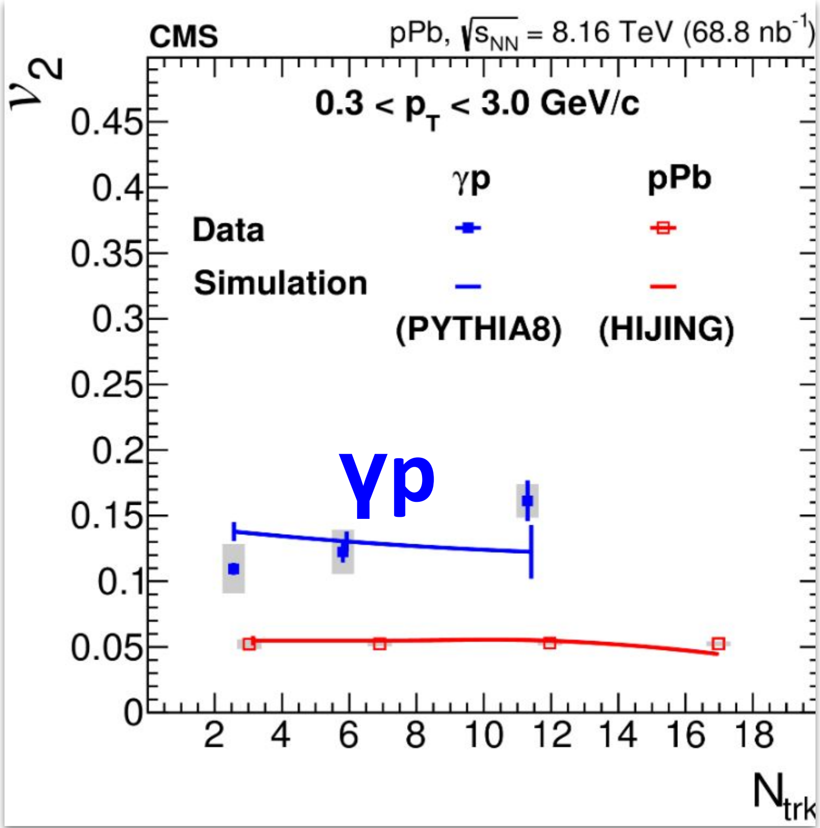


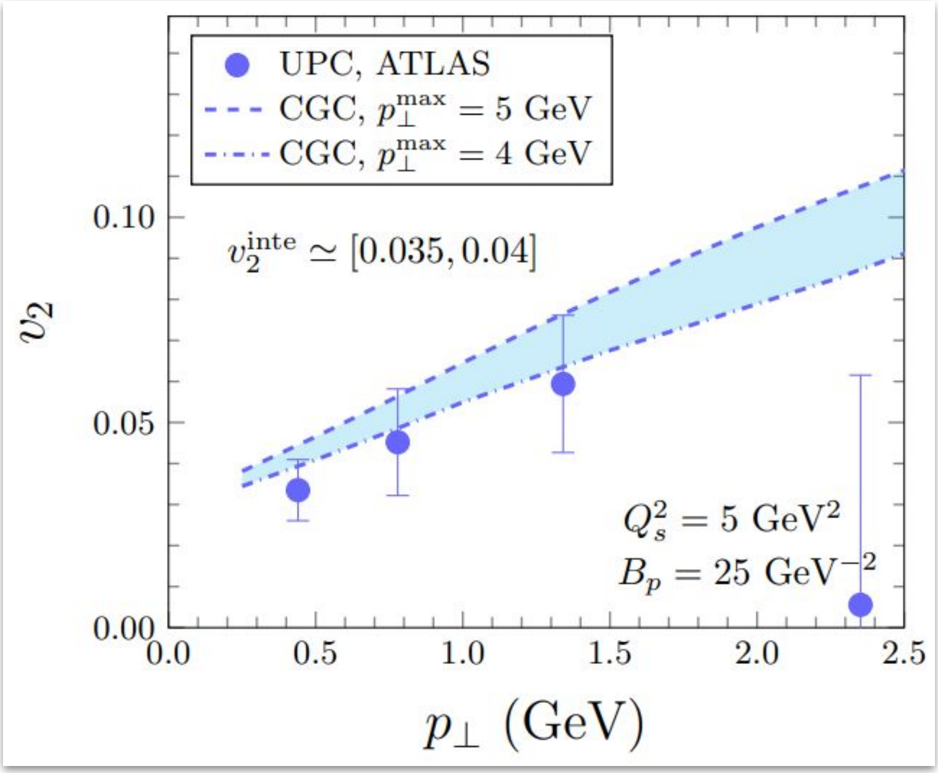
- **ALICE and CMS dissentagled low- and high-γ energy contributions**
  - experimental uncertainty **correlated** across or $W_{\gamma N}^{Pb}$
    - flattening of coherent σ(J/ψ) vs. $W_{\gamma N}^{Pb}$ not predicted by models
- **Nonlinear QCD regime reached at lower √s in nuclei than in proton?**
  - EIC can map the transition to a nonlinear QCD evolution of Qs with *x*
    - EIC can discover a new state of matter, e.g., counting # jets in ep/eA

What's the small size QGP limit?

arXiv:2204.13486
arXiv:2008.03569







- **Bridging large with exceedingly small systems**
  - PYTHIA8 describes v_2 in γp collisions ⟶ jet-like correlations still dominate
- **A simplified CGC model can describe the γ*Pb UPC data**
  - contribution from final-state effects is yet an open question

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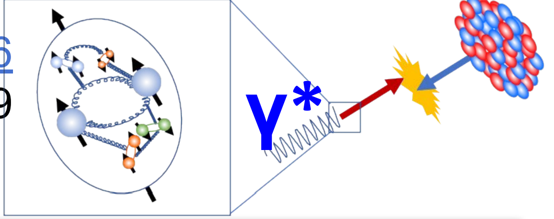
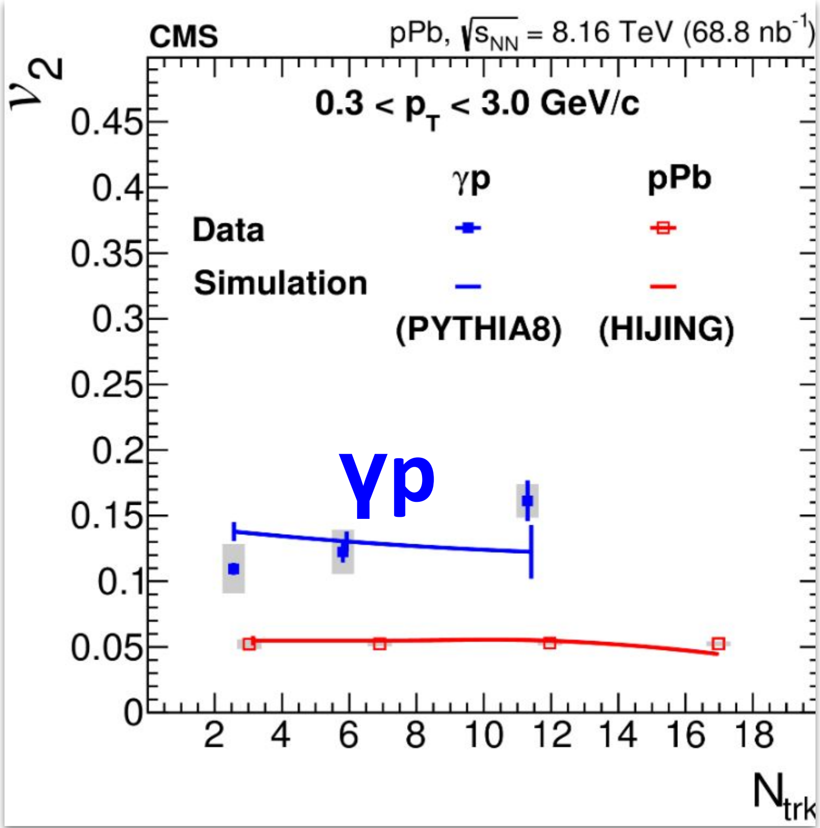
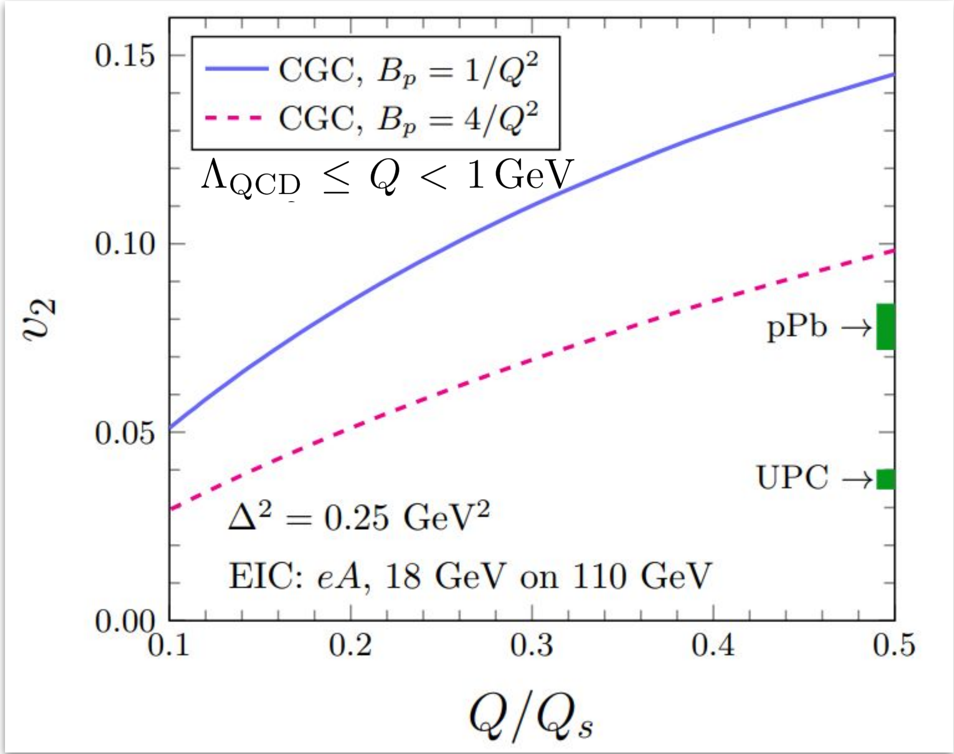






- **Bridging large with exceedingly small systems**
  - PYTHIA8 describes v_2 in γp collisions ⟶ jet-like correlations still dominate
- **A simplified CGC model can describe the γ*Pb UPC data**
  - contribution from final-state effects is yet an open question
  - EIC an unprecedented opportunity to study v_2 vs system size (Q^2)

HF transport models: ingredients

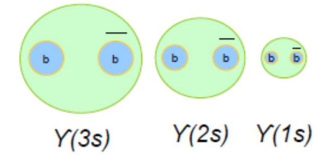
	Collisional en. loss	Radiative en. loss	Coalescence	Hydro	nPDF
TAMU	✅	❌	✅	✅	✅
LIDO	✅	✅	✅	✅	✅
PHSD	✅	❌	✅	✅	✅
DAB-MOD	✅	✅	✅	✅	❌
Catania	✅	❌	✅	✅	✅
MC@sHQ+EPOS	✅	✅	✅	✅	✅
LBT	✅	✅	✅	✅	✅
POWLANG+HTL	✅	❌	✅	✅	✅
LGR	✅	✅	✅	✅	✅

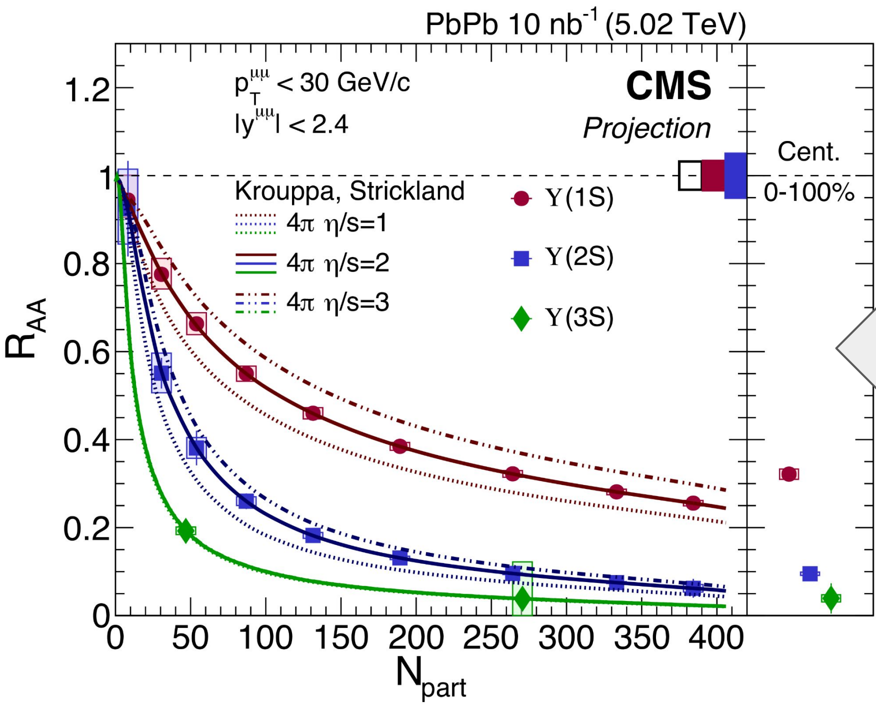
But more importantly: different **implementations** and **input parameters**.

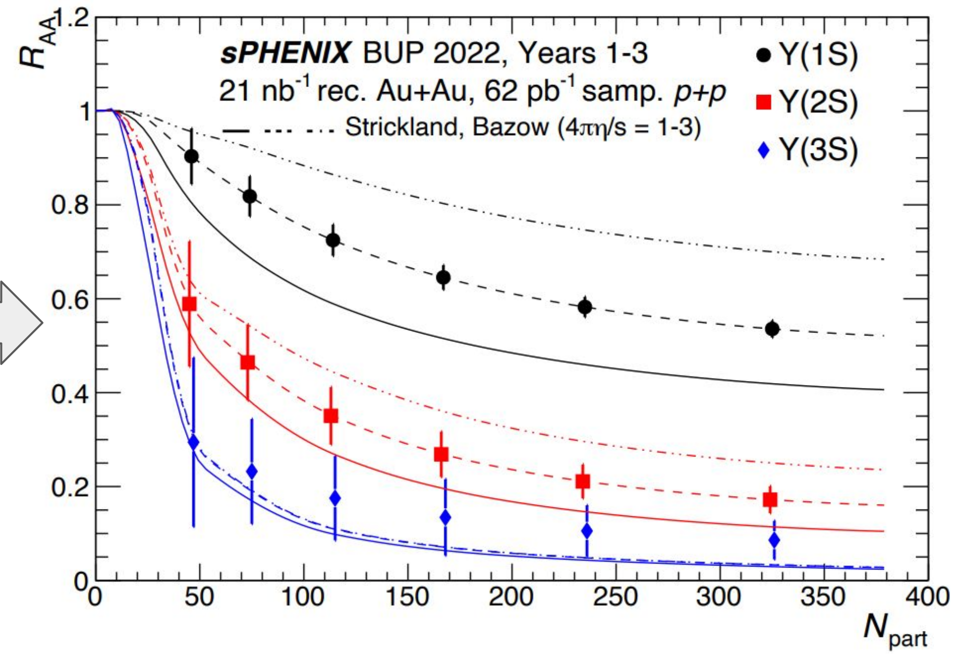
Input from
QM22 conference (Luuk Vermunt)

Υ(ns) suppression in LHC and RHIC

HIN-21-007 (to appear)
PLB 835 (2022) 137397



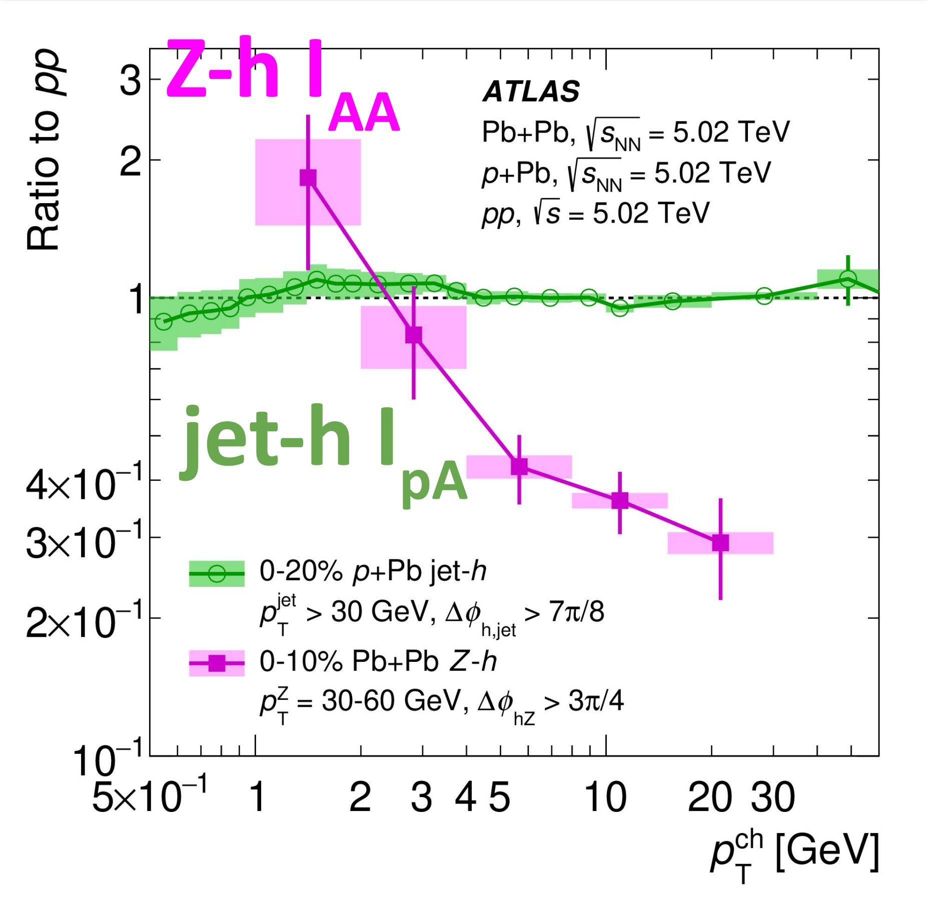


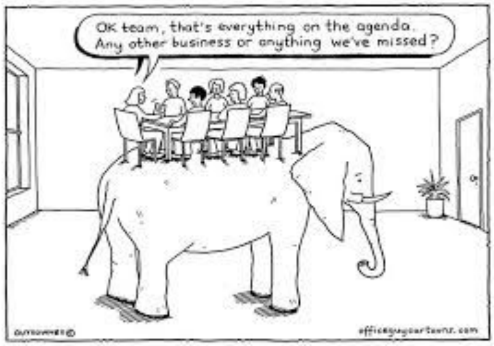


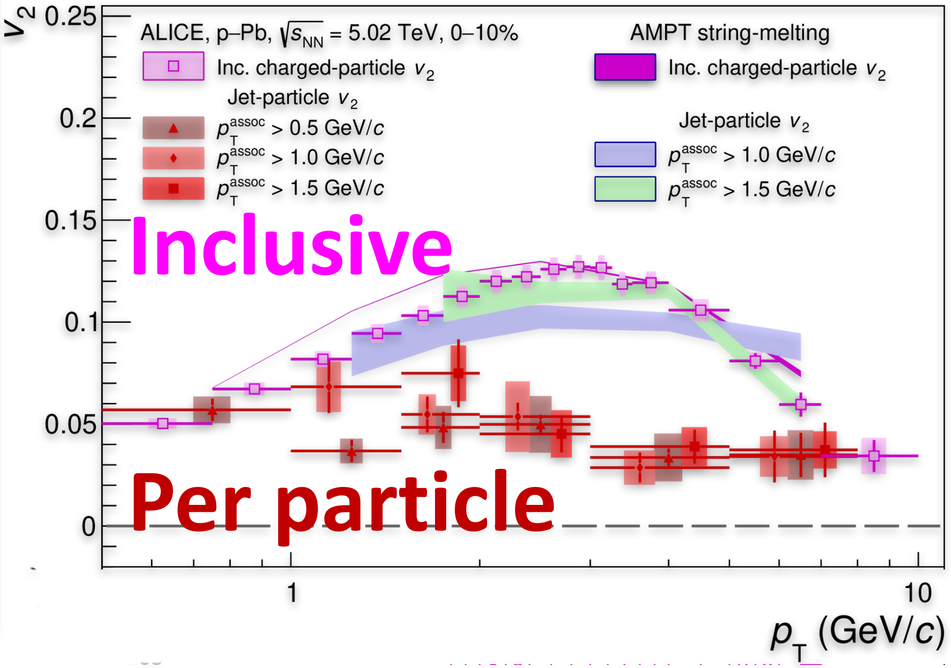
- **Observation of Υ(3S) also in PbPb**
  - indication of sequential suppression up to Υ(3S), ATLAS and STAR Υ(2S)+Υ(2S)
  - strong challenge for models to reproduce Υ(3S) $R_{AA}>0$
- **Strong complementarity between LHC and RHIC**
  - Excited states will set constraints on transport, hadronization, etc models

En.loss in smaller systems?

arXiv:2206.01138
arXiv:2212.12609





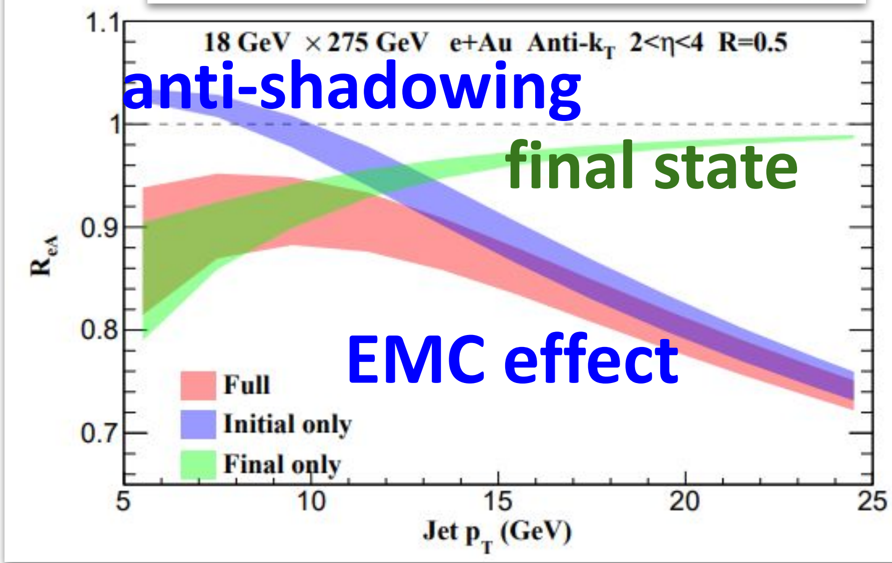


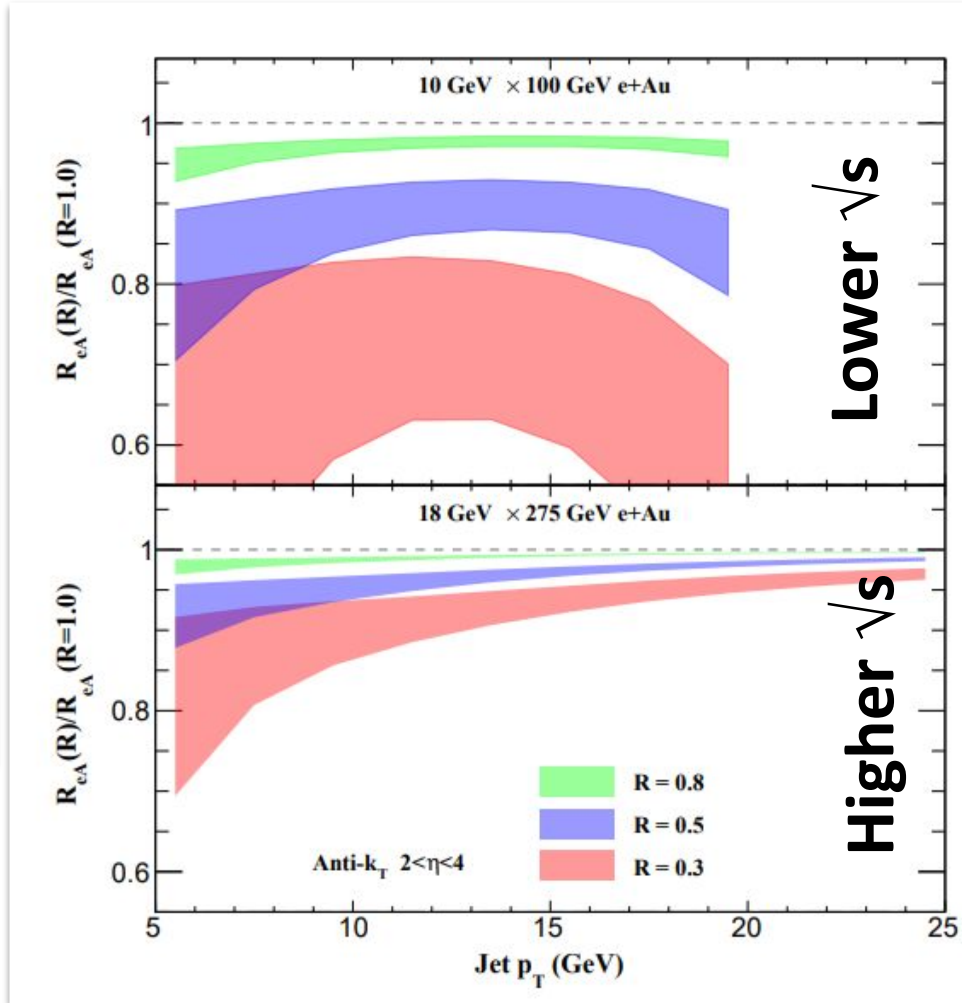
- $v_2>0$ in pA up to high p_T but, e.g., no modifications of hadron yields
  - new technique for jet particle v_2 consistent with transport model whose $R_{pA}=1$
  - opportunities with OO data at RHIC and LHC

Jets at EIC

arXiv:2103.05419
arXiv:2108.07809

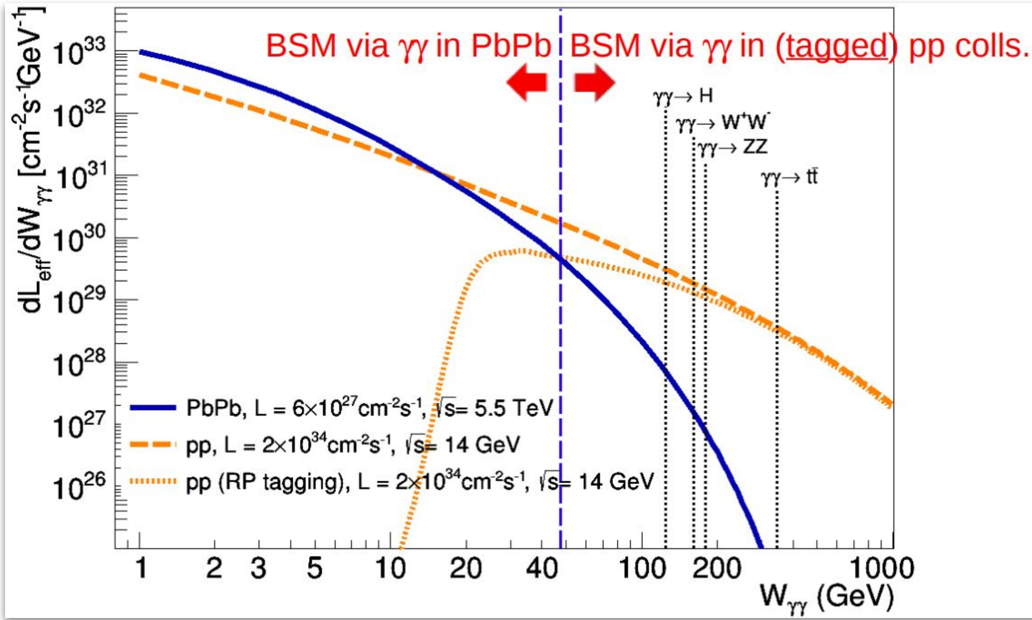
$$R_{eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T|_{e+p}}$$

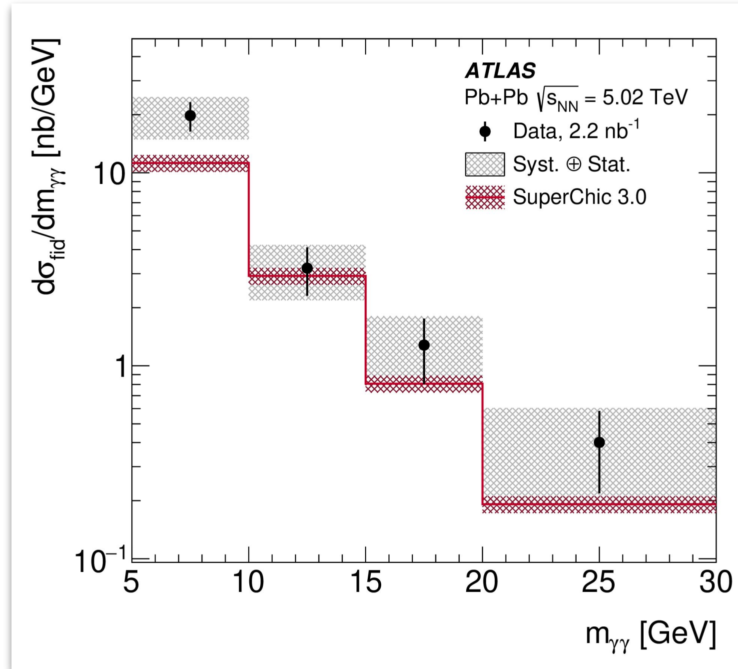




- **Large uncertainty in nuclear transport**
  - R_{eA} probes interactions inside nuclei and nPDFs at moderate and large *x*
  - $R_{eA}(R)/R_{eA}(R=1)$ eliminates initial-state effect; extra insights from varying √s (steeper p_T)

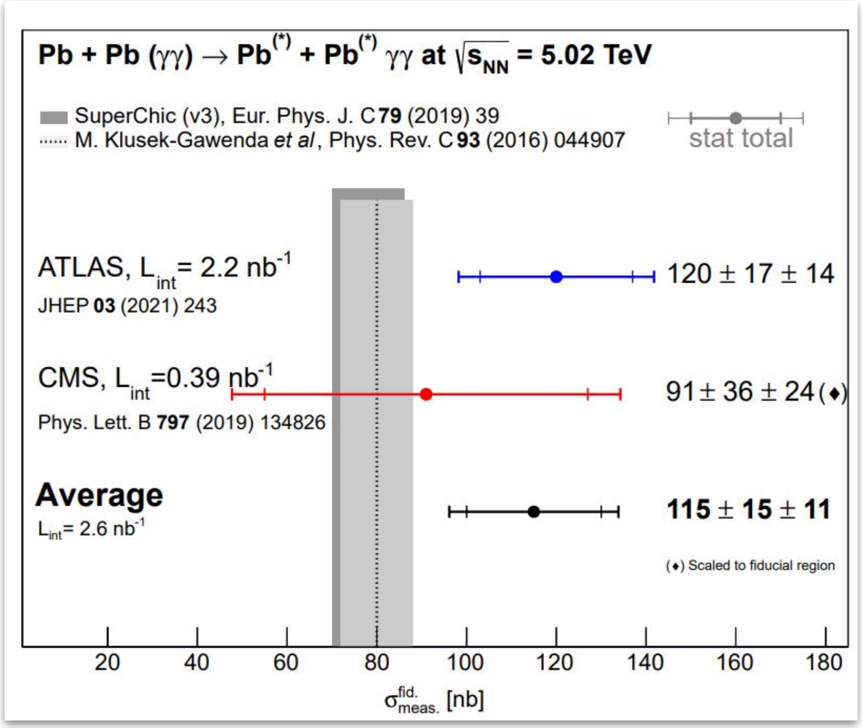
LbyL production in UPC AA

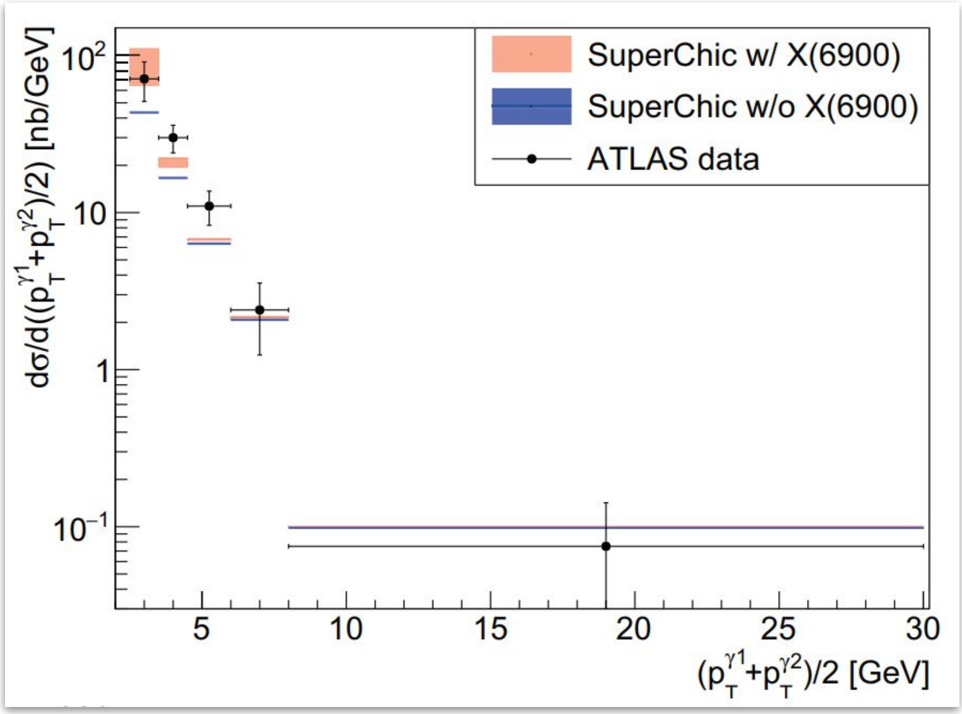


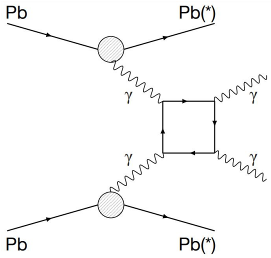


- **Z^4 enhancement: γγ luminosities ≫ pp ones at low $W_{\gamma\gamma}$**
  - NP naturally complements BSM efforts
    - concerted effort with large AA samples at RHIC+LHC
- **Event statistics already allow for differential studies**
  - low-$\mathbf{m}_{\gamma\gamma}$ excess triggered already dedicated efforts

LbyL production in UPC AA





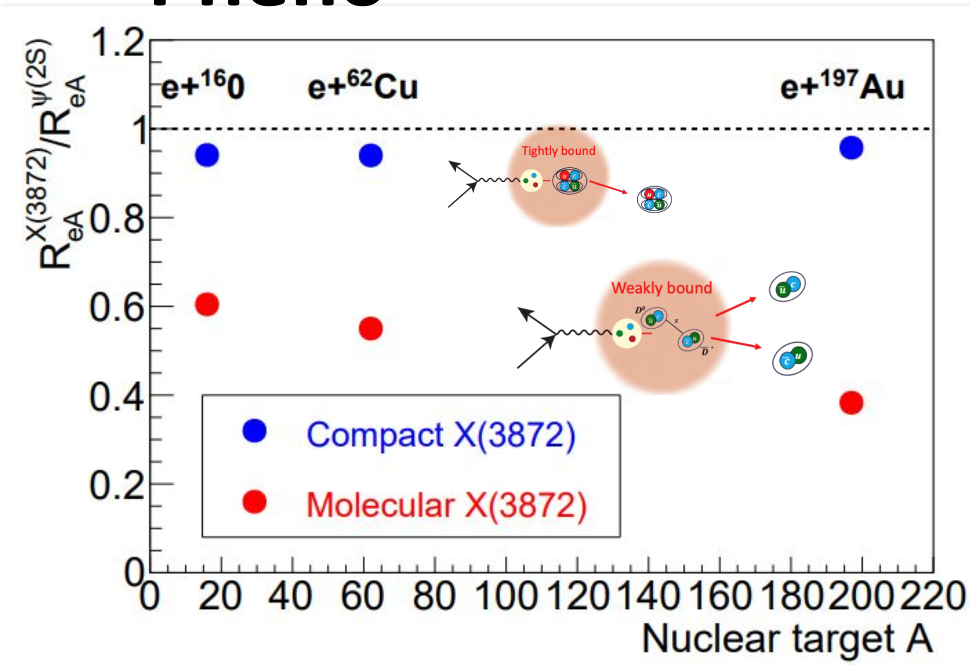


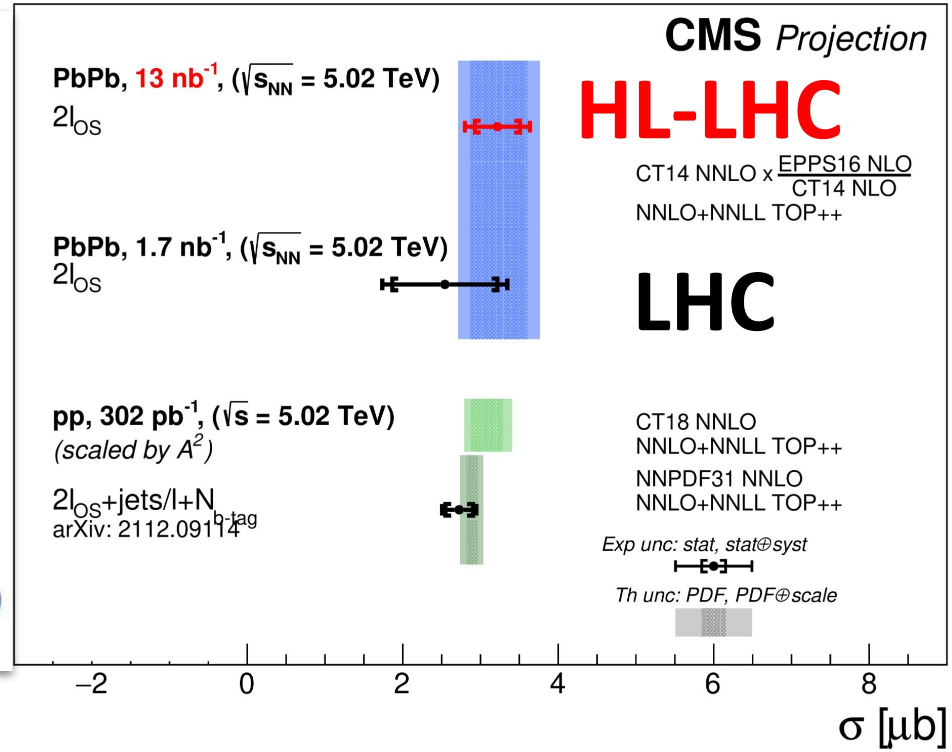
- **Z^4 enhancement: γγ luminosities ≫ pp ones at low $W_{\gamma\gamma}$**
  - NP naturally complements BSM efforts
- **Event statistics already allow for differential studies**
  - low-$m_{\gamma\gamma}$ excess triggered already dedicated efforts
    - the first combination with NP data at LHC
    - application from exotic hadron spectroscopy

Exotic hadrons and top quarks in AA

arXiv: 2103.05419
PRL 125 (2020) 222001

Pheno

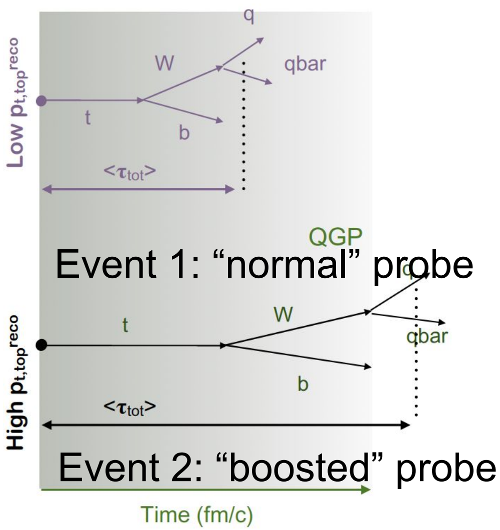


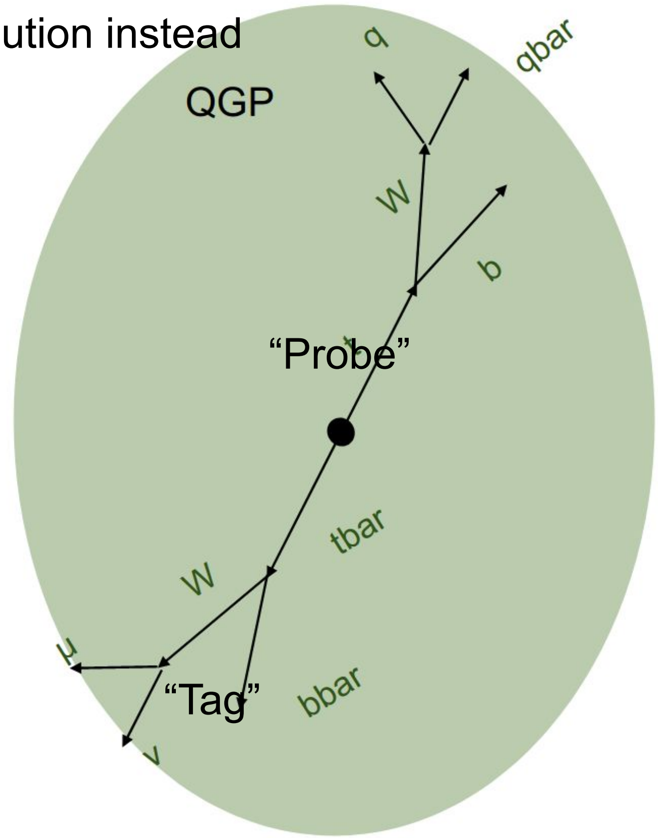


- **NP can revolutionize exotic hadron spectroscopy (EIC too)**
  - quark configurations for many exotics remain elusive
- **Use top quark production as a new tool**
  - reducing nPDF uncertainty; the most primordial b jets

Probing the "final state": the yoctosec QGP lifetime

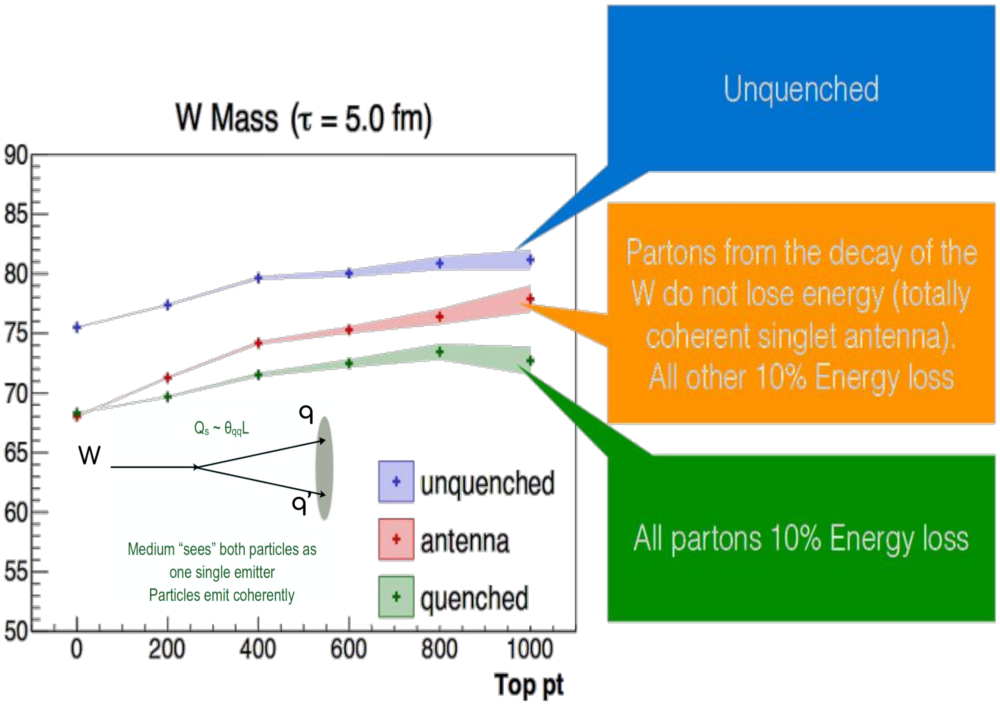
- Probes for jet quenching, e.g., dijets, Z/γ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead
- Leptonic & hadronic branches as "tag" & "probe"
- qq' start interacting with the medium at **later** times
- top p_T acts as the "trigger" on the onset of the interaction

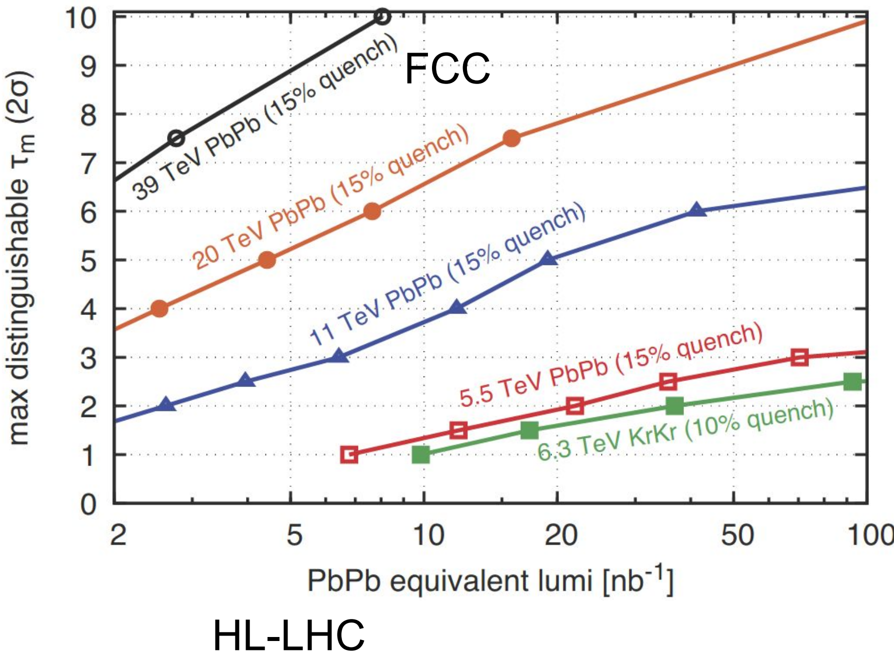




W mass vs top p_T and QGP lifetime reach

- What would be the observable to measure the amount of energy loss?
- By reconstructing **W mass vs top p_T** we can trace the quenching time dependence
- At HL-LHC, possible to distinguish low-duration scenarios (inclusively)
- At FCC, possible to assess the QGP density evolution (i.e., ‘triggering on’ top p_T)

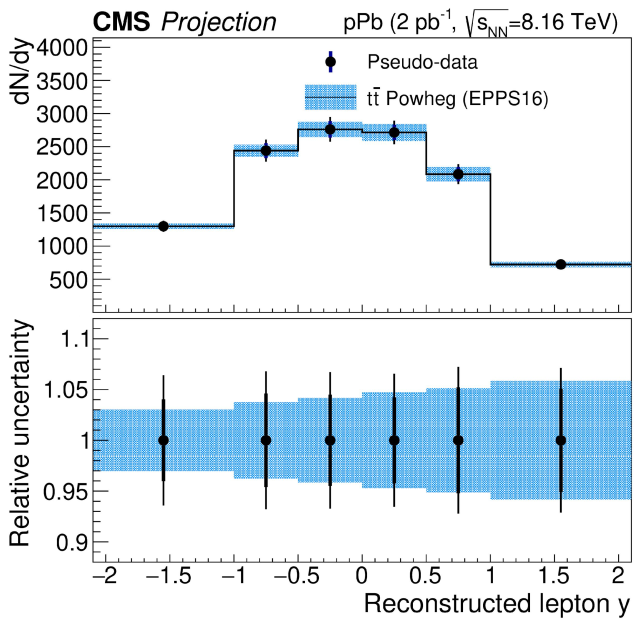


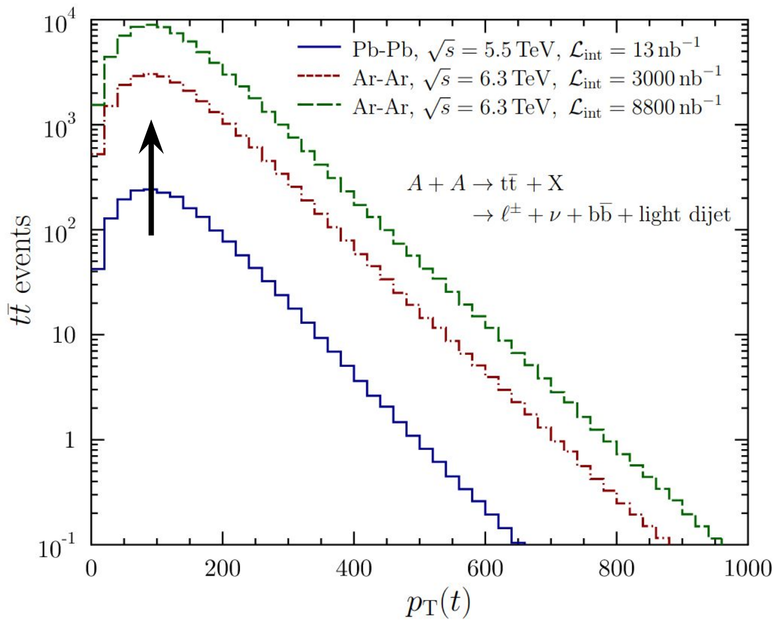


Phys. Rev. Lett. **120** (2018) 232301

Prospects for top quark production at pA HL-LHC

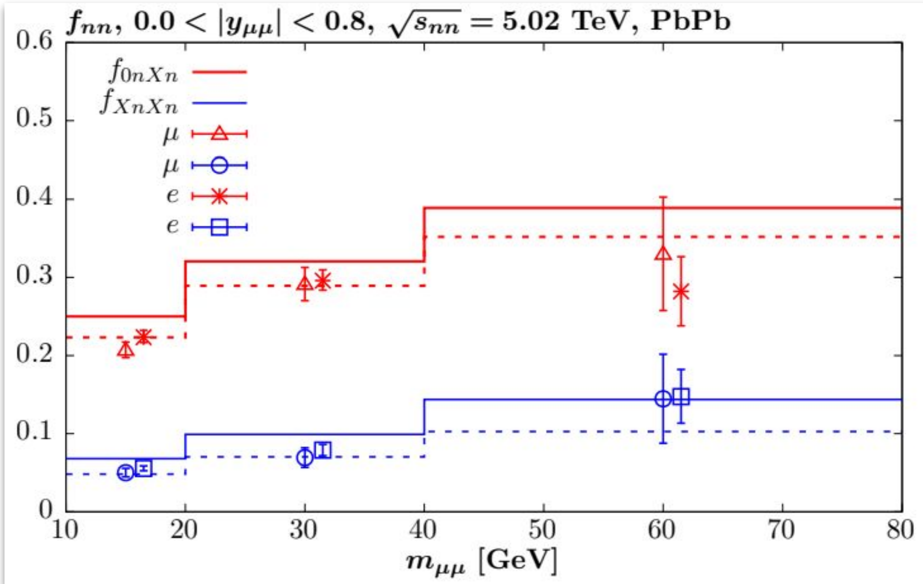
- The y of the decay leptons sensitive probe of the nuclear gluon density
- **comparable** experimental and nPDF uncertainty with the pPb data set in Runs 3–4
- depending on the expected systematic error and bin-by-bin correlations
- to showcase **another potential**: In a pAr mode, the higher √s + lumonsity → increased tt̄ yield



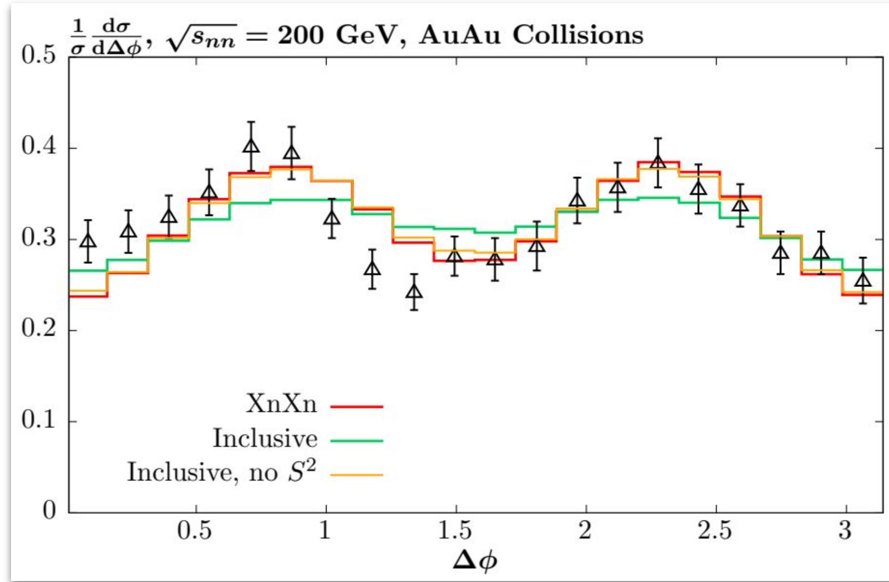


It's an excess, bkg, mismodeling?

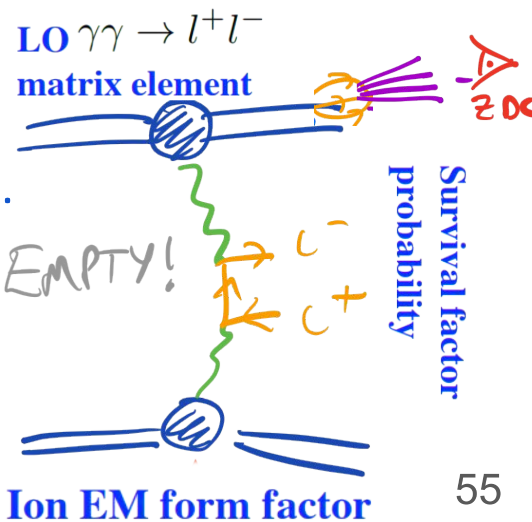
LHC



RHIC

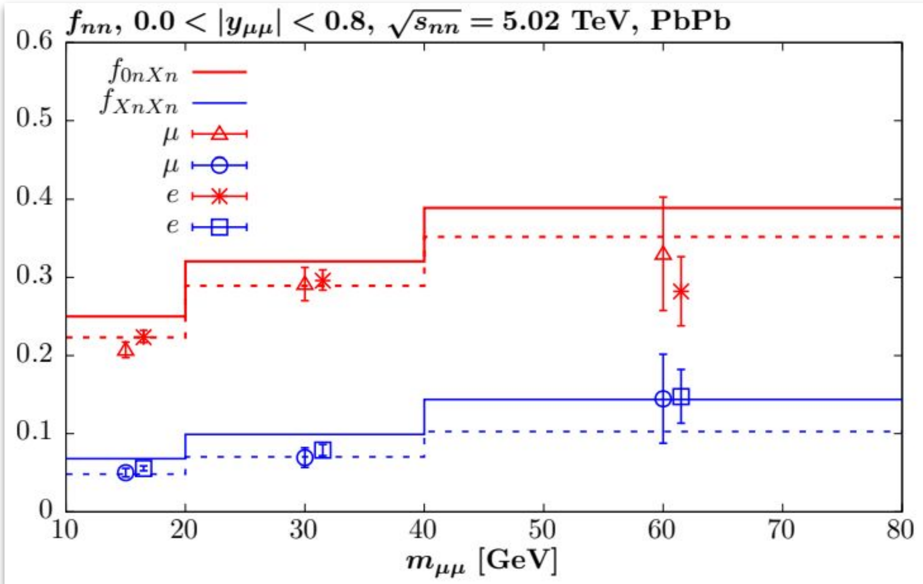


- **Key ingredients so far missing from UPC modeling**
  - Ion EM form factor, survival factor probability, mutual diss.
  - next to LO effects (FSR, multiscattering, ..)

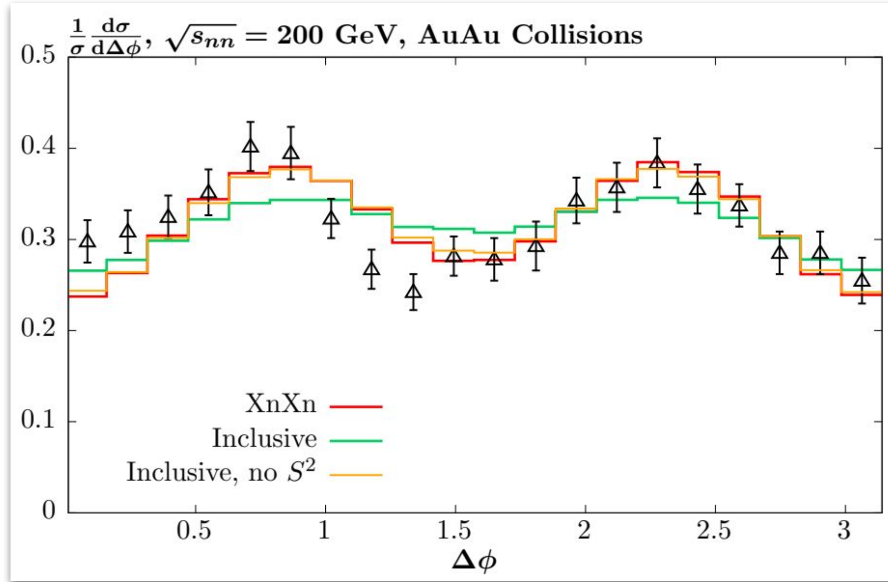


It's an excess, bkg, mismodeling?

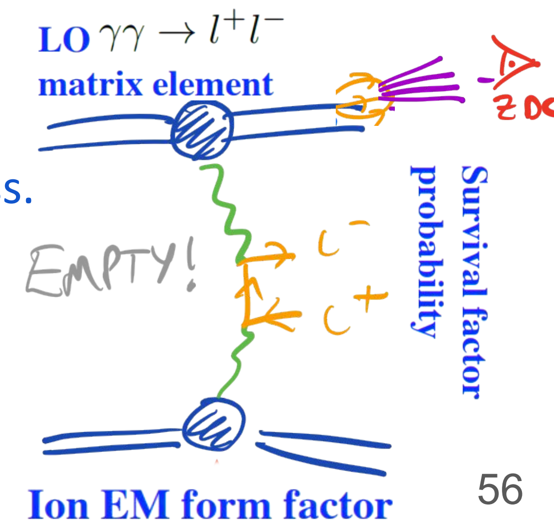
LHC



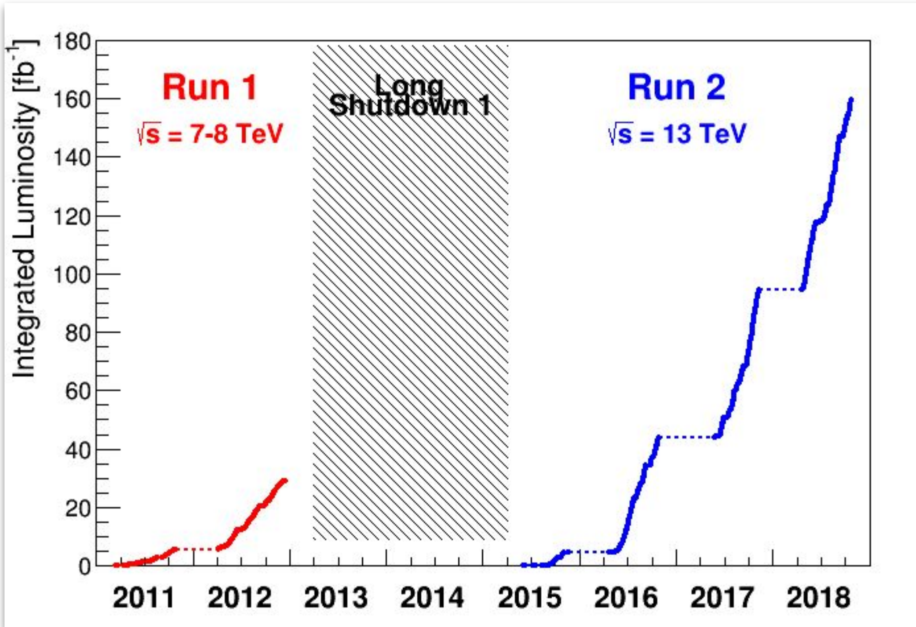
RHIC

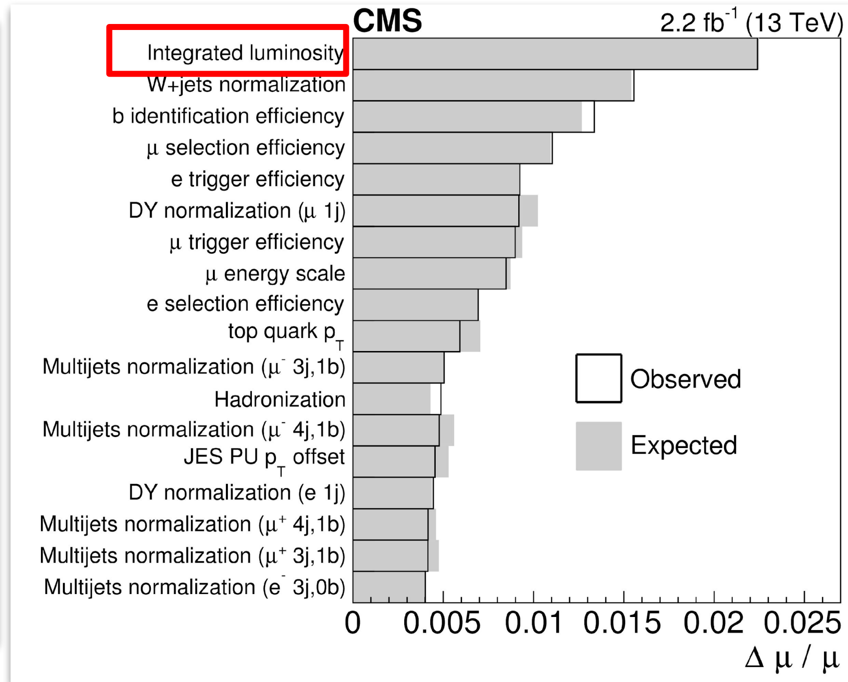


- **Key ingredients so far missing from UPC modeling**
  - Ion EM form factor, survival factor probability, mutual diss.
  - next to LO effects (FSR, multiscattering, ..)
- **Data/MC comparison encouraging**
  - applicable to other final states?
  - essential for precision QED program



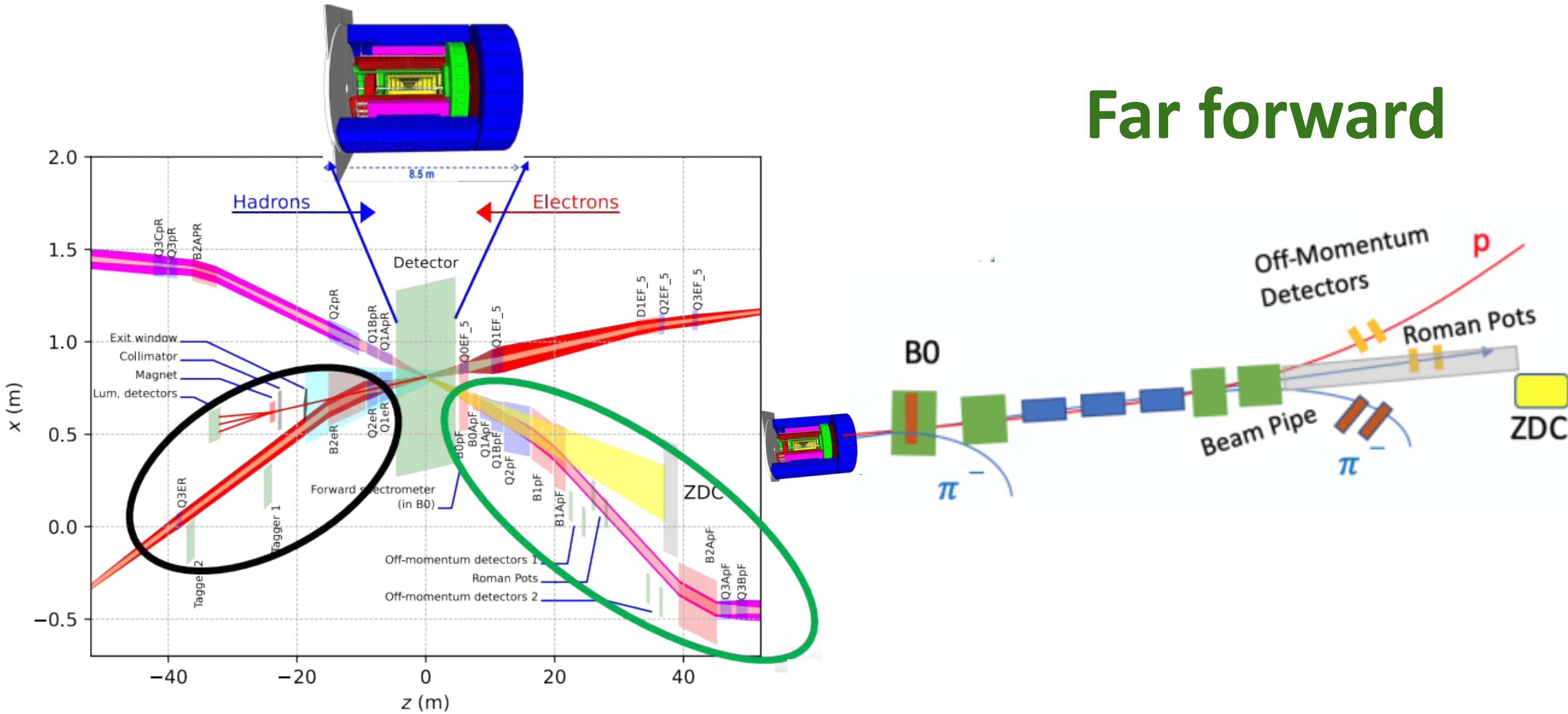
Luminosity: a **blessing** and a **curse**





- **LHC comfortably surpassed the target with Run 2 pp data at 13 TeV**
  - This is a collider FOM for delivering statistically significant data samples
- **The precise knowledge of luminosity scale is of equal importance**
  - for accelerator performance and physics measurements
  - This is therefore a synergy between accelerator+experiments
    - we can measure it with **0.8–1.5%**, depending on the system
    - CMS the only LHC experiment independently verified it with $Z \rightarrow \mu^+\mu^-$

EIC far-fwd & far-bkw regions

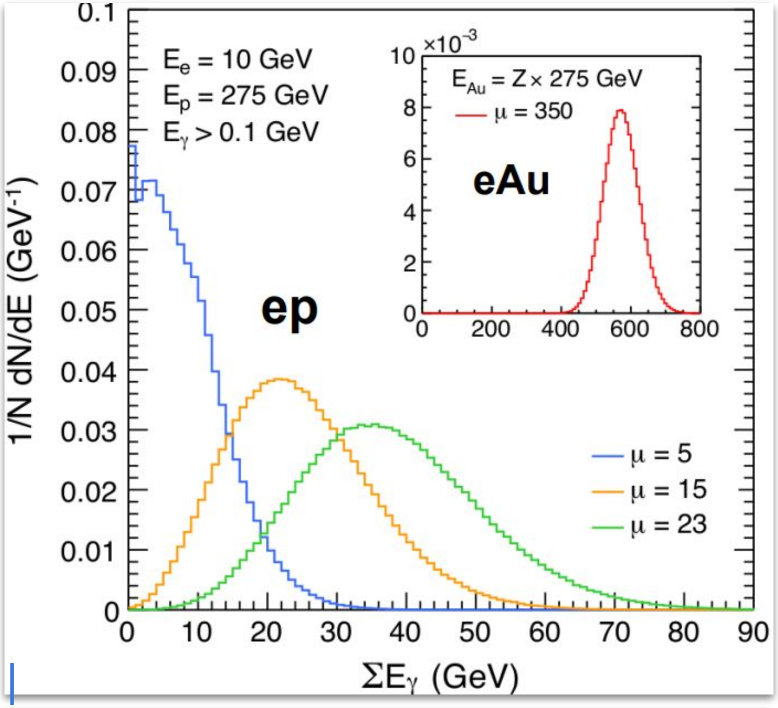


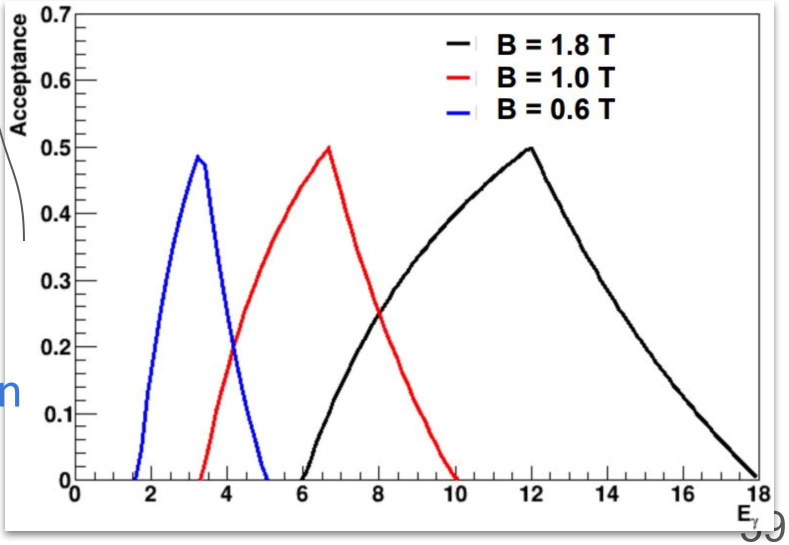
- **Apart from central detector, dedicated systems into the beamline**
  - Complicated layout + limited space ⟶ integration a challenge
- **At hadron- (far-forward) and electron-going (far-backward) directions**
  - systems crucial for delivery of full EIC physics program
    - Large acceptance for diffraction, proton tagging, and neutrons from breakup
    - High control of systematics: luminometry, electron & hadron polarimetry

Road to luminosity precision

- **Direct γ measurement @ 0°**
  - simple concept
  - straightforward γ acceptance
  - in primary sync. rad. fan
  - 'fuzzy' cutoff @ $E_\gamma \to 0$
  - pileup: many γ's per bunch ×ing
- **Pair spec. + tracking measurement**
  - outside primary sync. rad. fan
  - natural low-E_γ cutoff
  - rate adjustable: converter, geometry, dipole |B|
  - Successfully implemented by ZEUS @ HERA
  - complex implementation → ML assistance?
  - γ acceptance requires accurate simulation
- **Two approaches complement each other**
  - Coincidence in pair spec.?
    - conversion probability, verify simulation
  - Shower in γ-calorimeter?
    - calibrate Ecal

low-Q^2 taggers

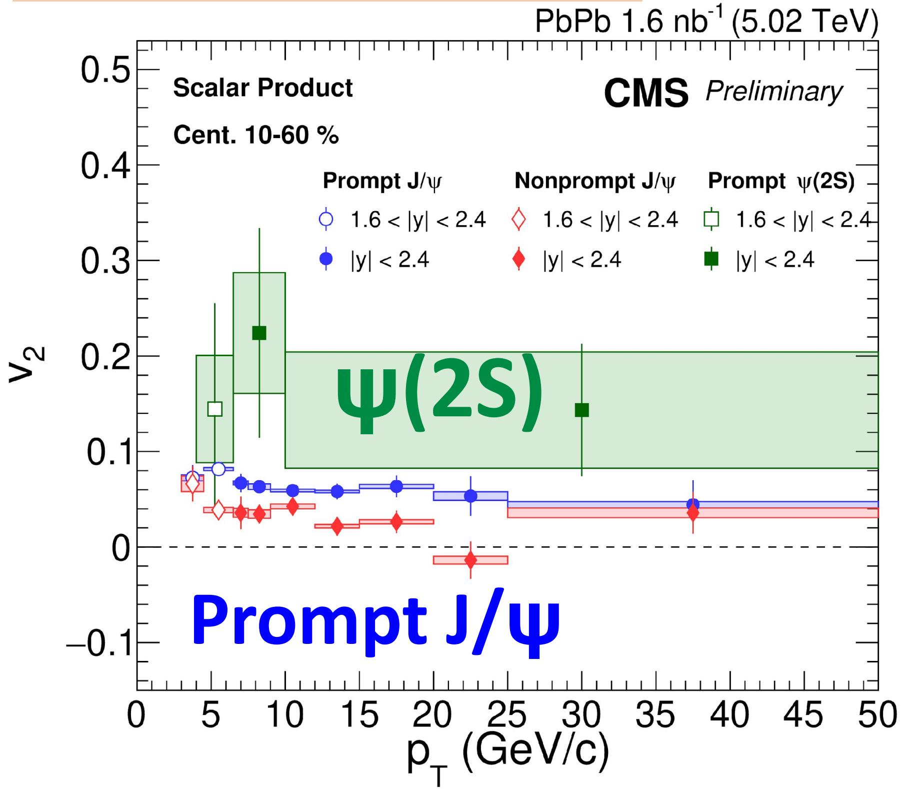


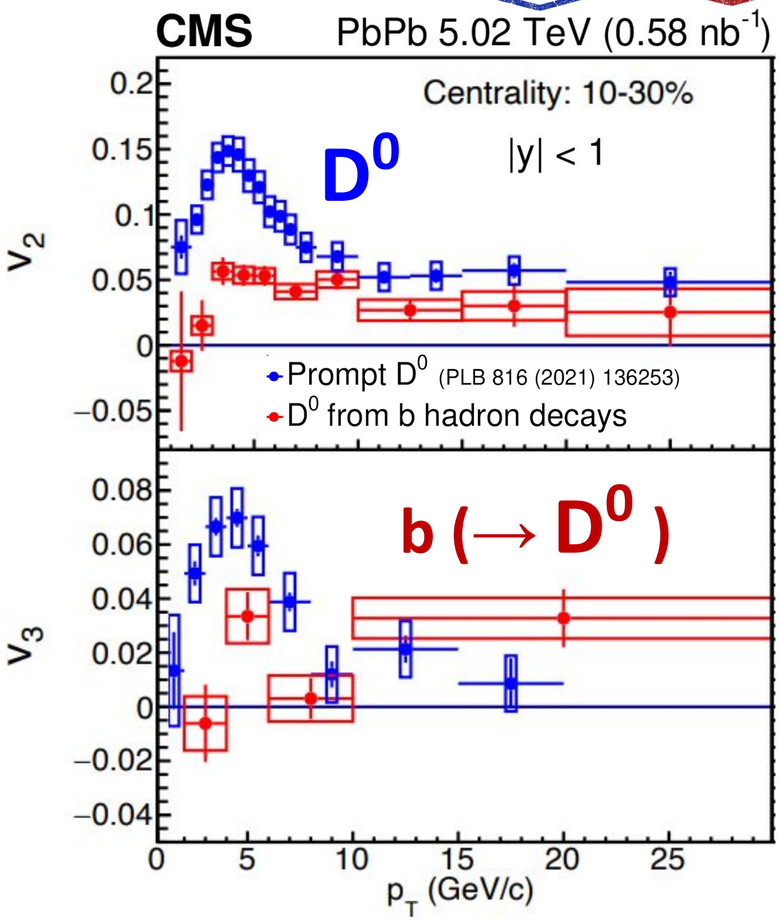


Heavy flavor flow in PbPb

G. Oh: Tue 11.50 am
M. Stojanovic: Wed 2.00 pm

CMS-PAS-HIN-21-008
arXiv:2212.01636





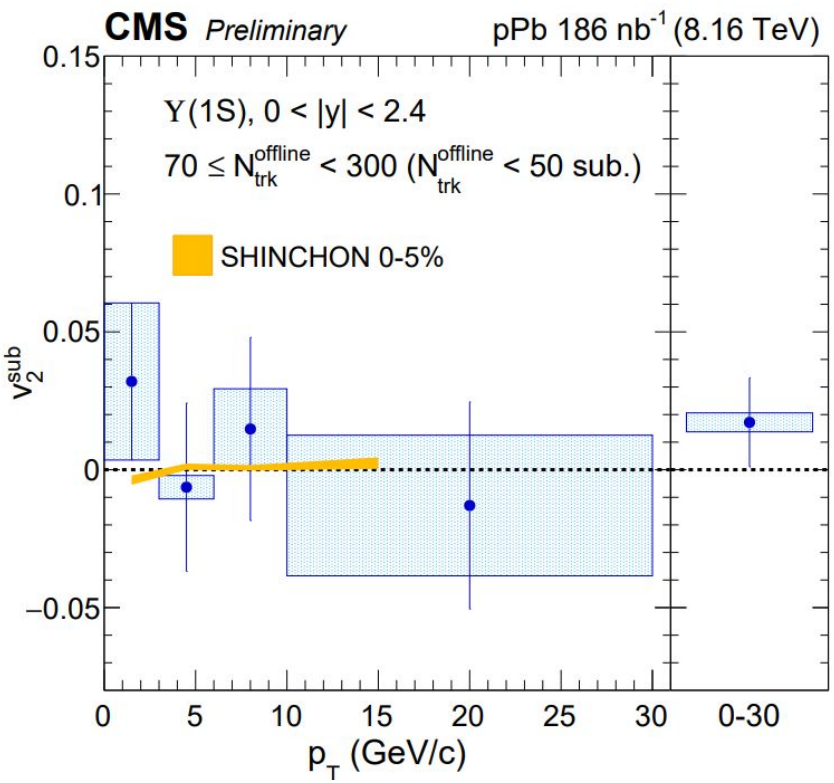
- **First v_2 for b (→ D^0); b quark and D^0 meson p_T well correlated**
  - **charm** > b (→ **D^0**) v_2, whereas Υ(1S), Υ(2S) v_2≈0
  - evidence for b (→ **D^0**) v_3 >0 at intermediate p_T

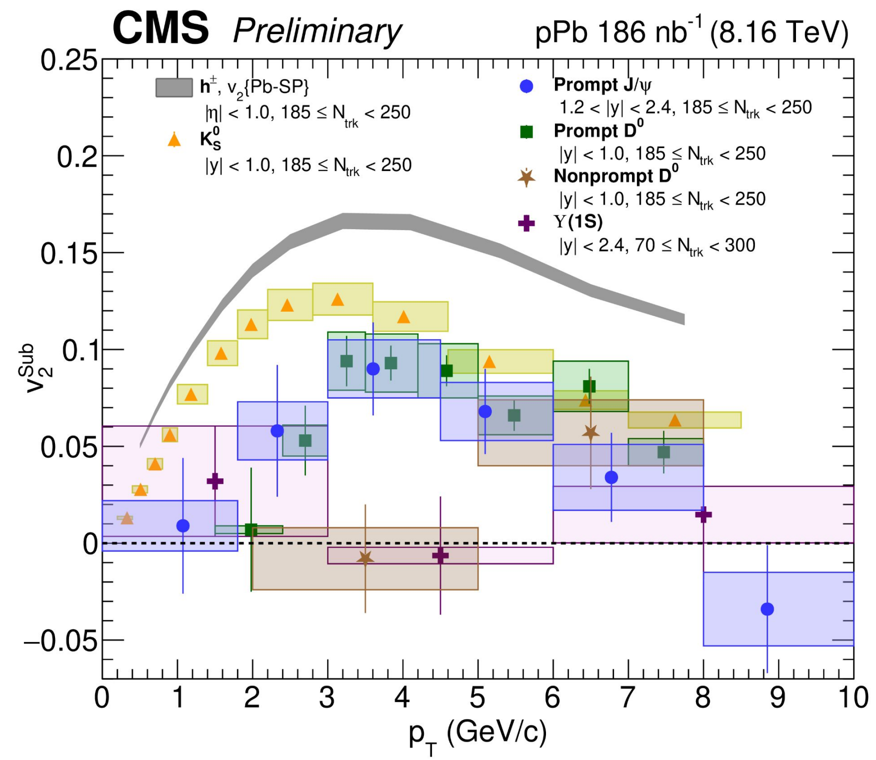
Heavy flavor flow in high-multiplicity pPb

CMS-PAS-HIN-21-001

CMS NEW RESULT HP23

K. Lee: Tue 11.30 am





- **First v_2 measurement for Υ(1S)**
  - v_2≈0 up to 30 GeV(!), similar to a model with final-state interactions only
- **Bridging HF flow measurements in large & small systems**
  - clear **mass hierarchy**: heavier particles flow less
  - open question: do open/closed b hadrons flow in pPb?

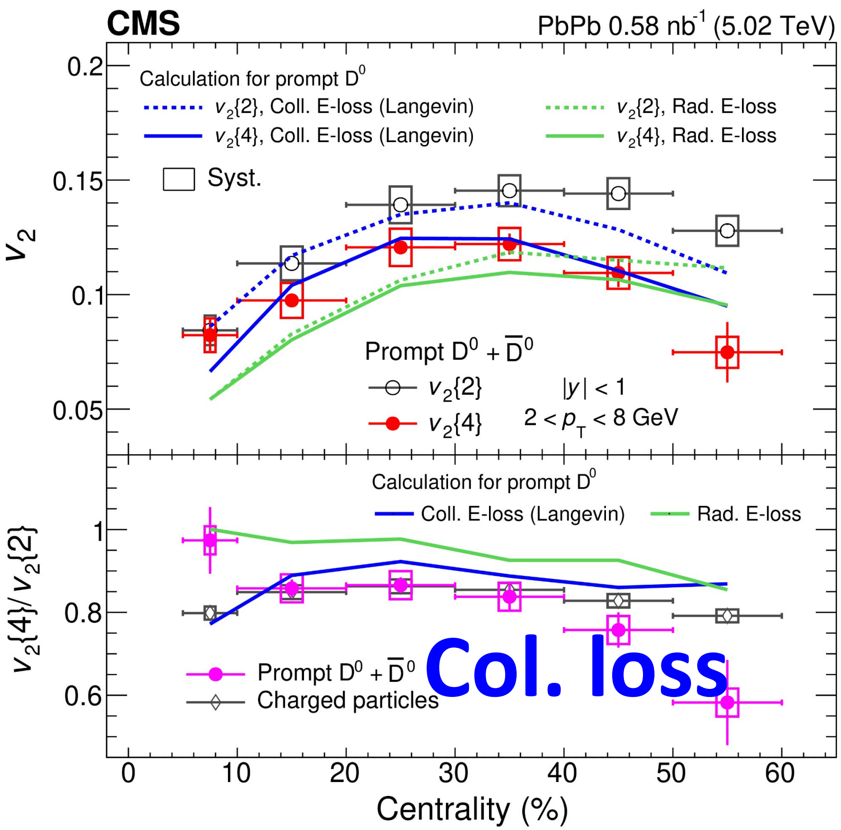
Charm quark energy loss in PbPb

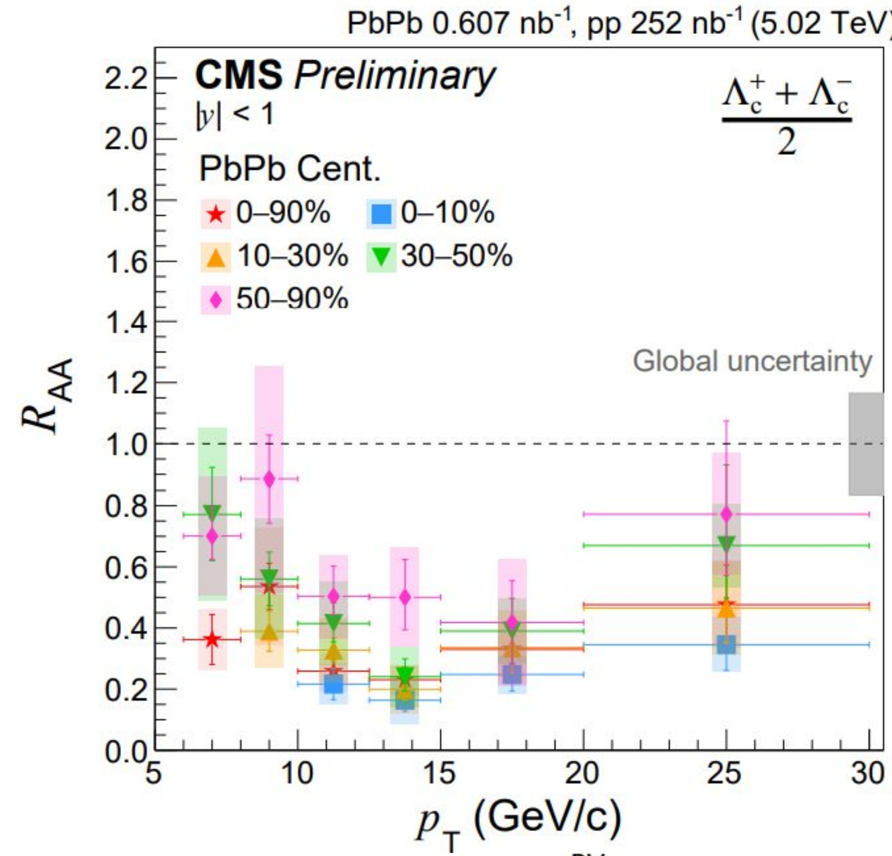
S. Chandra, M. Stojanovic: Poster
M. Stojanovic, Wed 2.00 pm

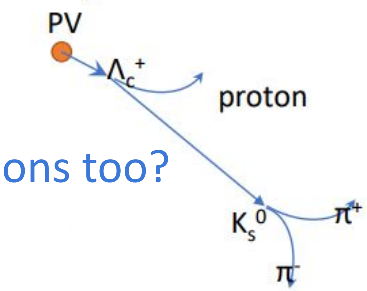
PRL 129 (2022) 022001
CMS-PAS-HIN-21-004

CMS FINAL HP23

CMS NEW RESULT HP23





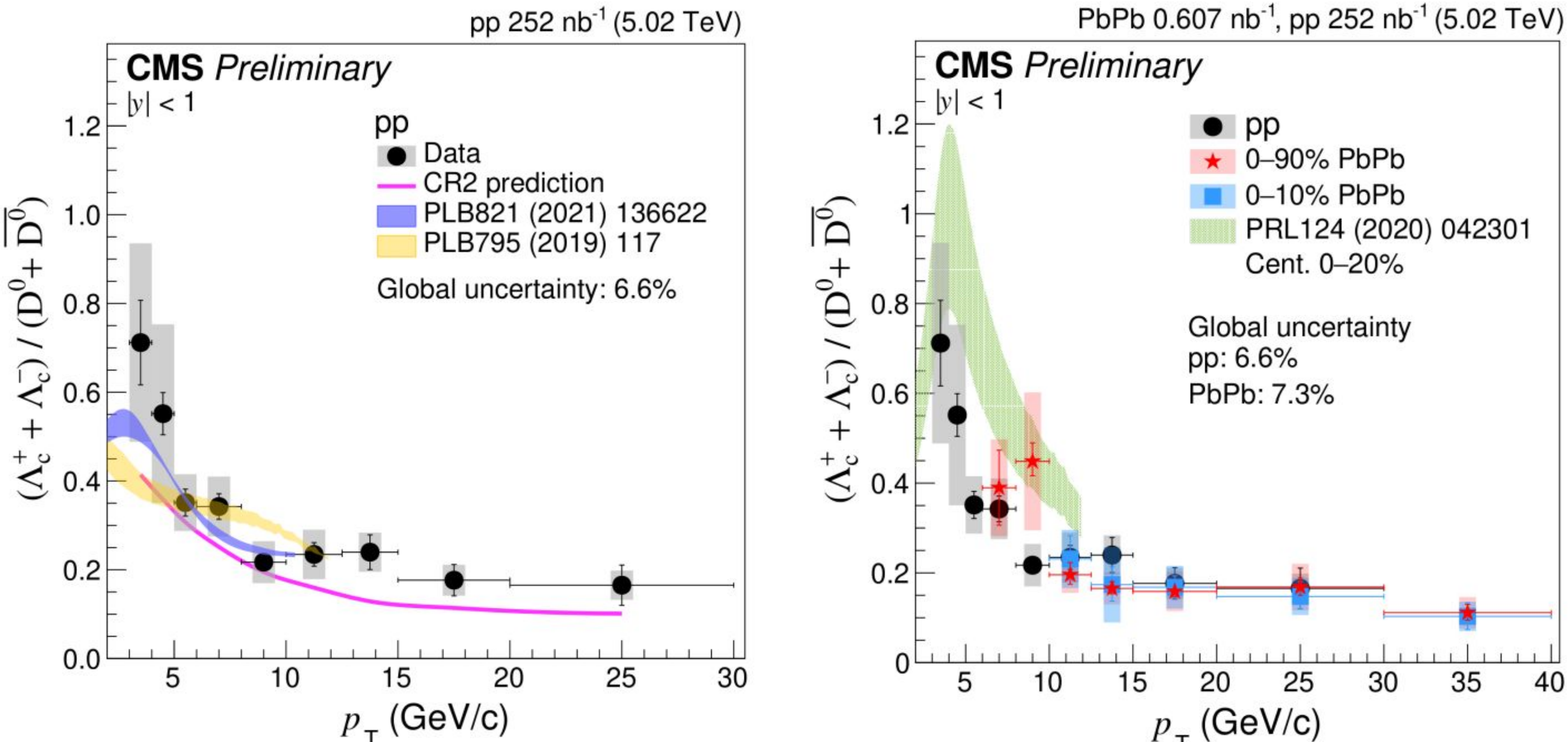


- **First high-precision $v_2\{4\}/v_2\{2\}$(!)**
  - compare D^0 to **light** flavor → v_2 fluctuations due to en. loss fluctuations too?
- **HF en. loss measurement with Λ_c^+ R_{AA}**
  - Large suppression but with min R_{AA} at ≈ 14 GeV contrary to other HF measurements

Charm quark hadronization in pp and PbPb

CMS-PAS-HIN-21-004

Y. Zhang: Tue 5.30 pm
S. Chandra, M. Stojanovic: Poster

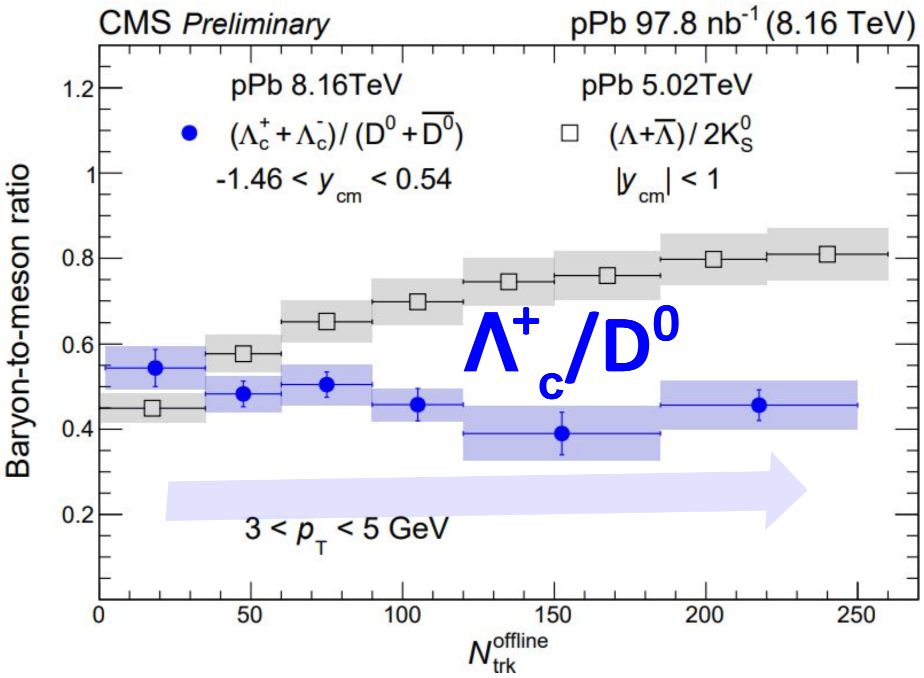


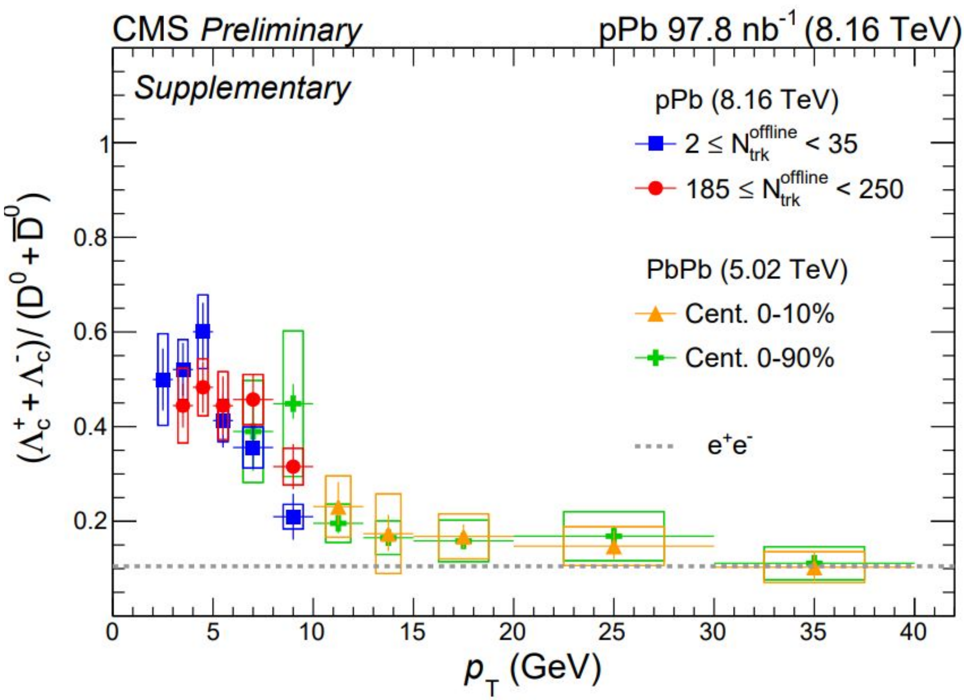
- **PYTHIA8+CR describes Λ_c^+/D^0 at p_T <10 GeV in pp, similar to models**
  - containing decays of excited c baryons; involving coalescence and fragmentation
- **Extending the p_T (<40 GeV) and centrality (0–90%) reach in PbPb**
  - Λ_c^+/D^0 in pp and PbPb consistent → no significant contribution from coalescence

Charm quark hadronization in pPb and PbPb

CMS-PAS-HIN-21-016
CMS-PAS-HIN-21-004

Y. Zhang: Tue 5.30 pm
S. Chandra, M. Stojanovic: Poster





- **First measurement of Λ_c^+/D^0 vs N_{trk}**
  - different trend compared to **strange sector**, i.e., small dependence
- **Extending the system (pPb 8 TeV), p_T (<40 GeV), and centrality (0–90%)**
  - Λ_c^+/D^0 in pPb and MB PbPb consistent at intermediate p_T
  - at high p_T MB and central PbPb approach the ratio from e^+e^- → no coalescence

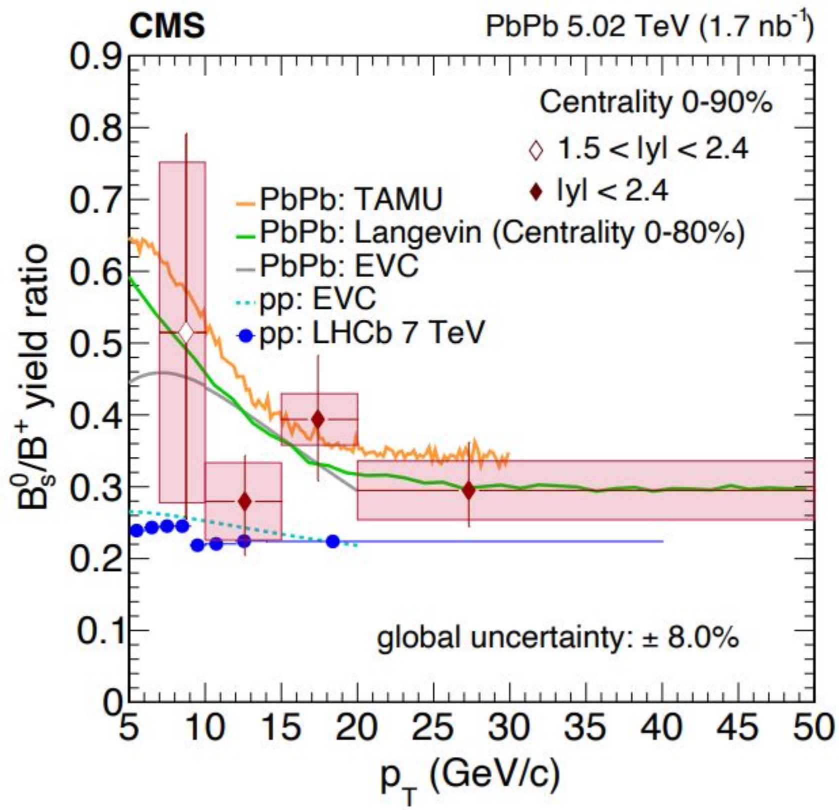
Beauty hadronization in PbPb

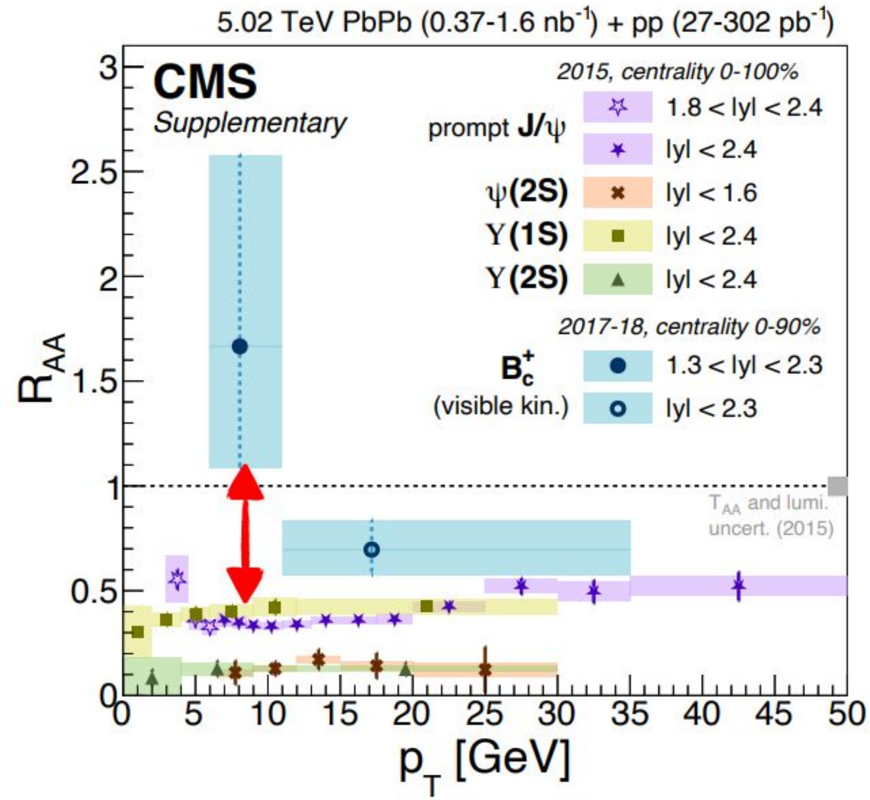
Tzu-An Sheng: Thu 10.20 am

PLB 829 (2022) 137062
PRL 128 (2022) 252301

CMS FINAL HP23

CMS NEW RESULT HP23





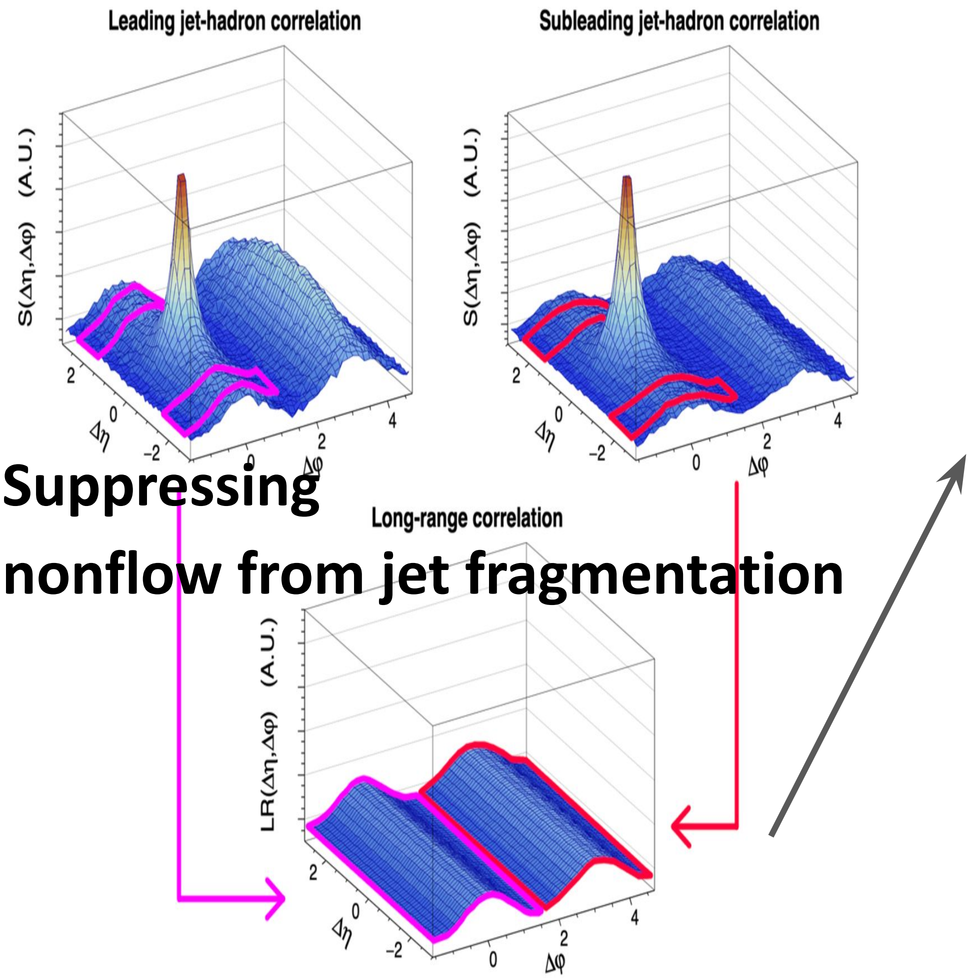
- **Observation** of B_s^0
  - indication of enhanced B_s^0/B^+ in PbPb to **pp** at low p_T
  - similar to models with recombination or coalescence
- **Observation** of B_c^+
  - flavor-dependent R_{AA}: at low/medium p_T: recombination of c and b

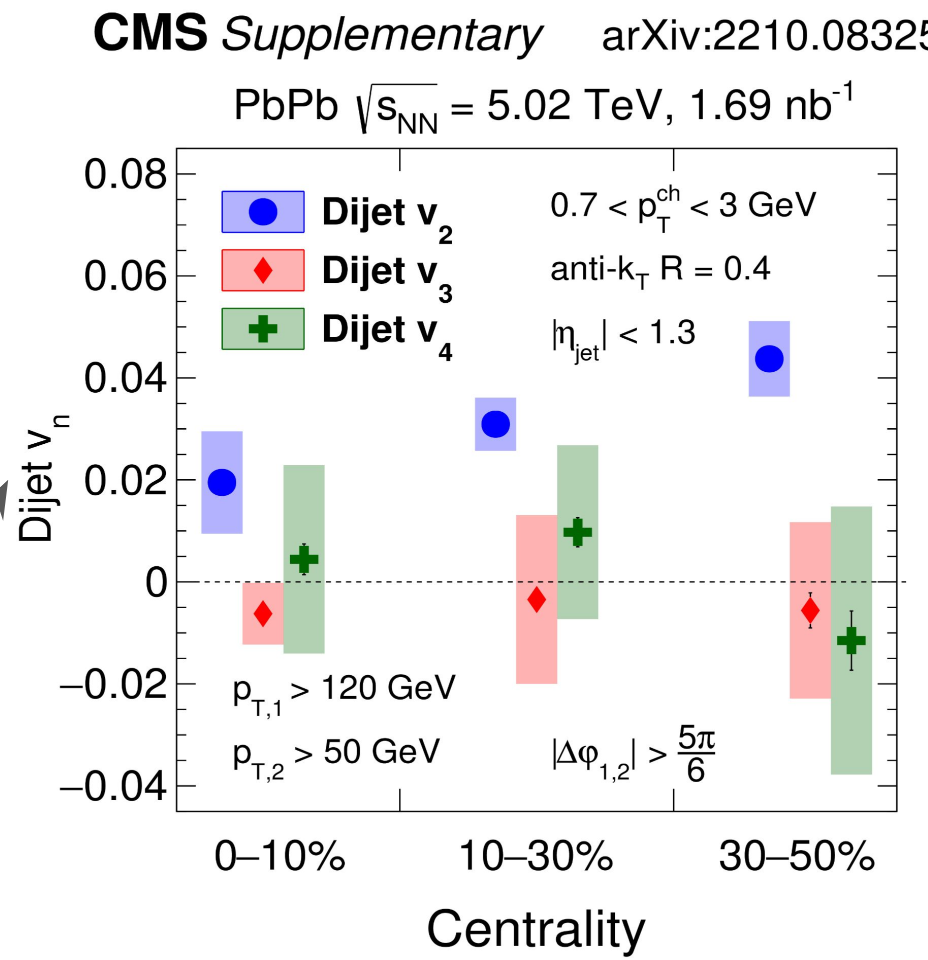
Dijet vn in PbPb

arXiv:2210.08325
(accepted by JHEP)

CMS FINAL HP23 · CMS NEW RESULT HP23

Suppressing nonflow from jet fragmentation





- **Path-length dependent energy loss & its fluctuations**
  - dijet $\mathbf{v_2}$>0 with expected centrality dependence; consistent with high-p_T hadron v_2
  - dijet $\mathbf{v_3}$,$\mathbf{v_4}$≈0 → not yet(?) sensitive to initial-state/en. loss fluctuations

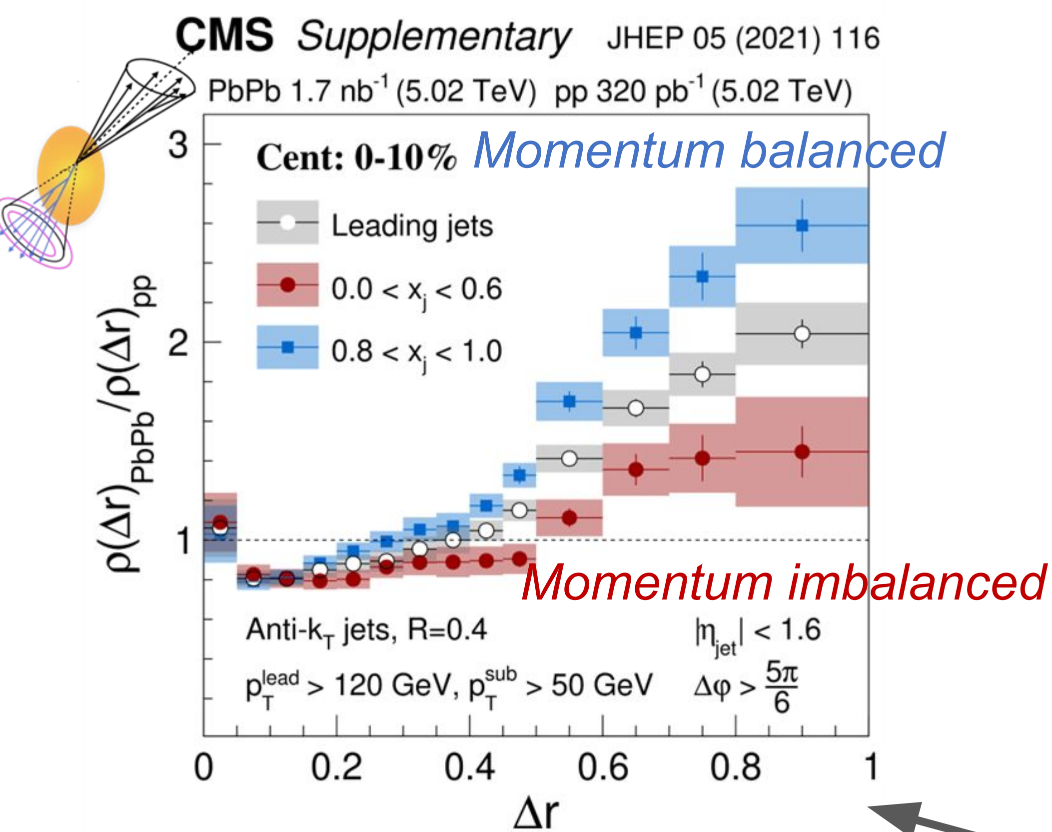
How energy loss is distributed?

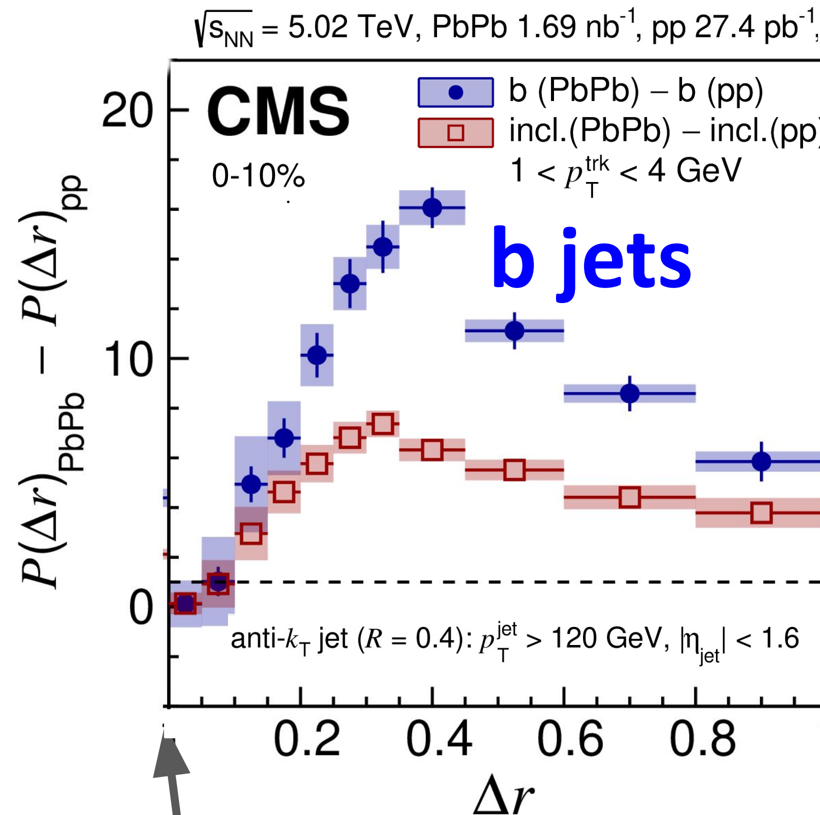
L. Kalipoliti: Wed 12.10 pm

JHEP 05 (2021) 116
arXiv:2210.08547
(accepted by PLB)

CMS FINAL HP23

CMS NEW RESULT HP23

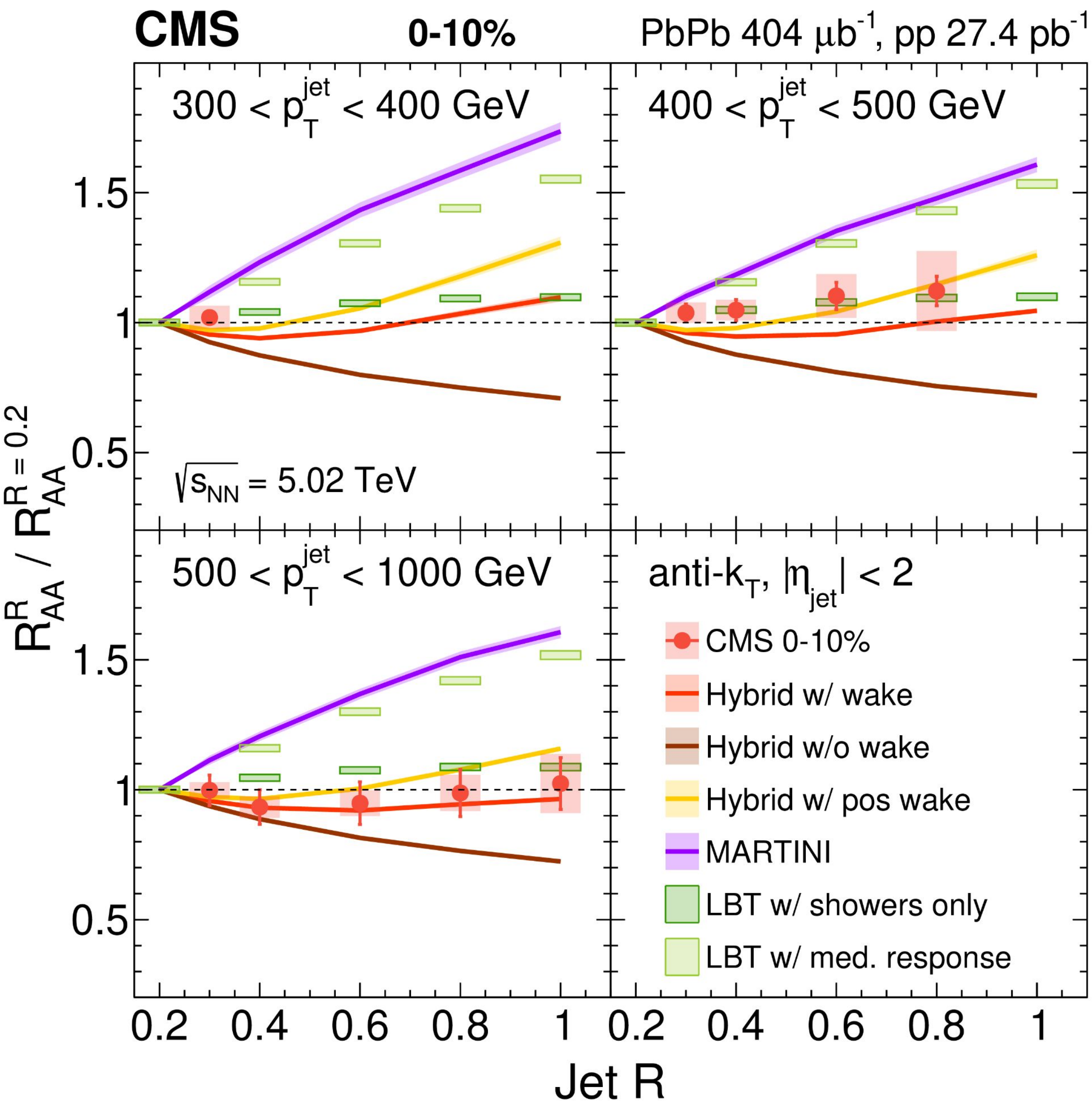




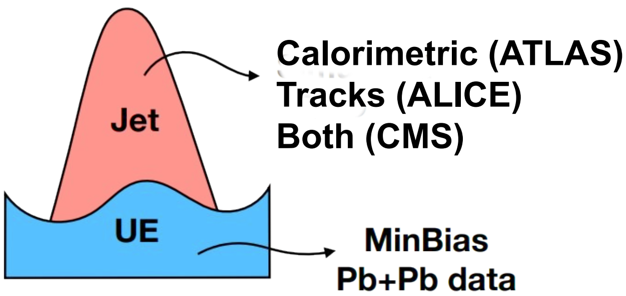
- **Jet shape: radial profile of particles in dijets, b jets**
  - in-medium path length for leading jets is larger when $x_J \approx 1$ (vice versa for subleading)
  - for b jets
    - small-Δr depletion: sensitive to dead-cone effect
    - large-Δr enhancement: enhanced medium response to b quarks

Jet quenching depends on jet radius?

JHEP 05 (2021) 284

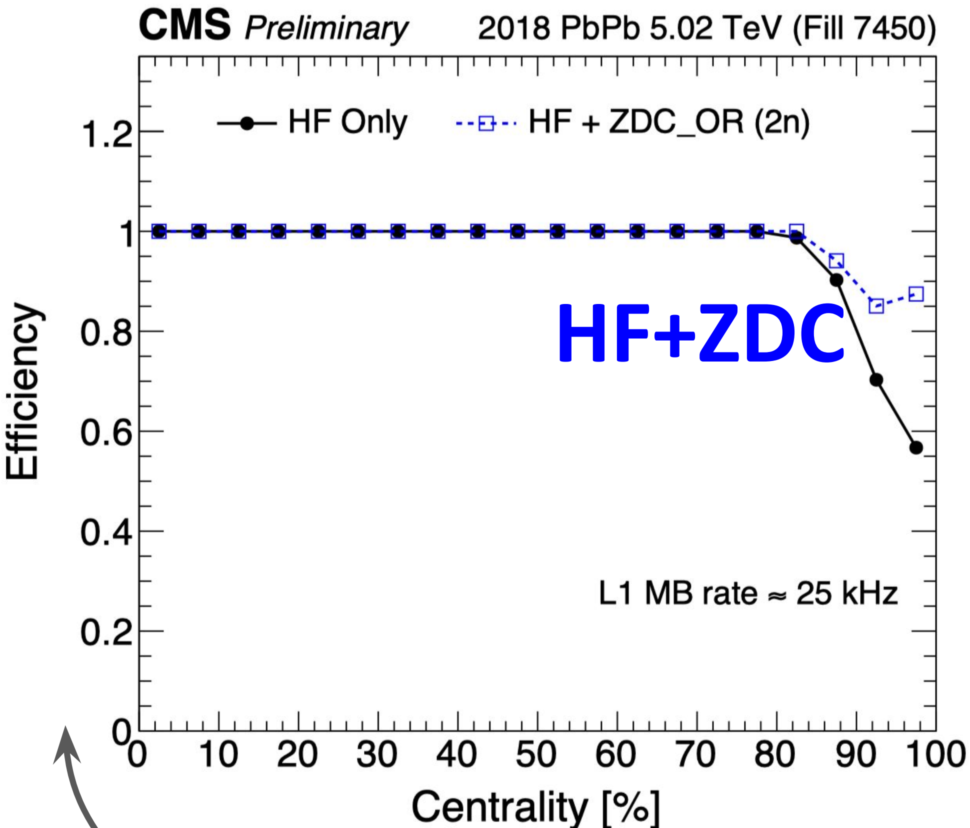


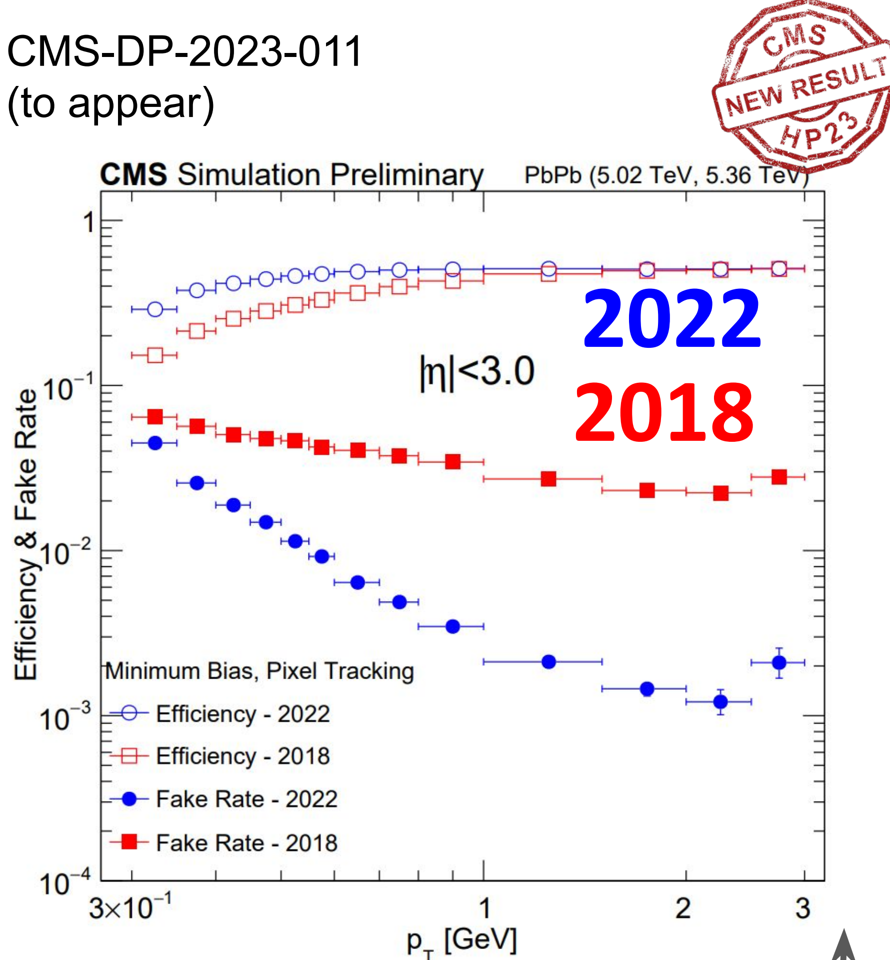
- Larger jet R → wider area to recover lost energy
  - but **R-independent** suppression seen
- Cross experiment effort
  - Different jet collections and UE treatment



Improvements in Run 3 PbPb

CMS-DP-2023-011
(to appear)





- **Improvements expected already in Run 3, e.g.,**
  - online: increased MB trigger efficiency in peripheral events with ZDC inclusion
  - offline: better low-p_T tracking thanks to innermost pixel layer consideration
- **Overall CMS will record 25 kHz of MB PbPb events**
  - representing an increase of 80x to 2015 and 3x to 2018

CMS Phase 2 Upgrades (HI related)

CMS-DP-2021-037

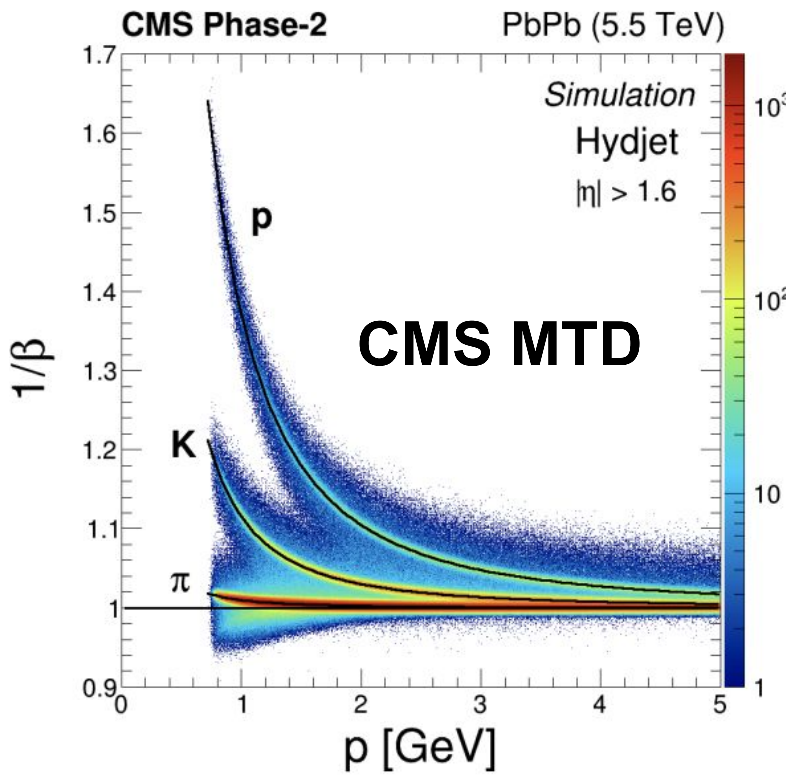
Yen-Jie Lee: Tue 2.00 pm

Phase 2 Upgrade

CMS Phase 2 for Run 4

- Tracker |η|<4
- Muon ID up to |η|<2.8
- High Granularity Calorimeter
- MIP timing detector
  - 4D vertexing
  - **p/K/π PID (CMS MTD)**
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

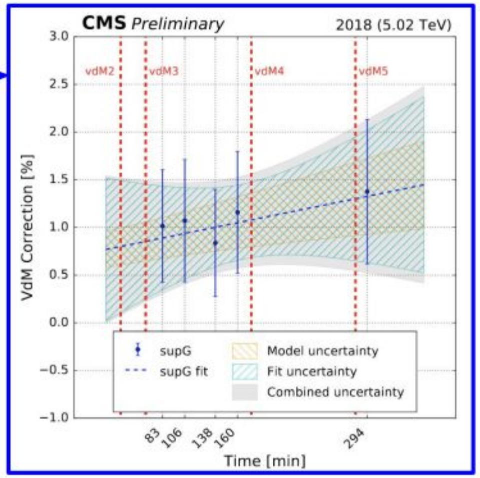
p/K/π separation

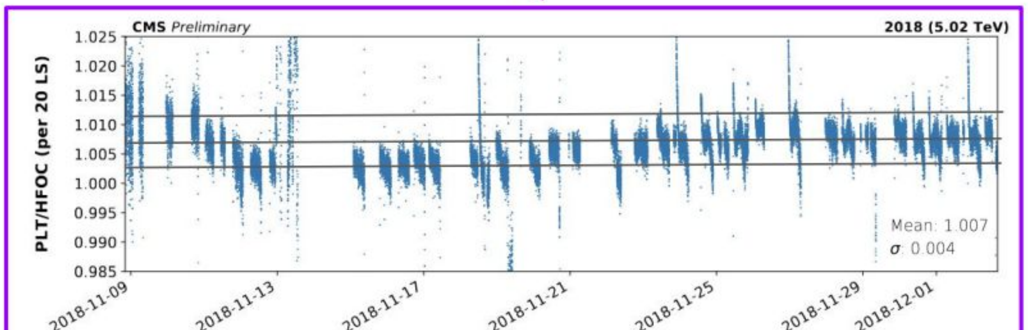


- **Main batch of CMS Upgrades in Run 4**
  - Among others, unique hermetic particle identification coverage by CMS MTD
- **Physics requests documented in past years over a diverse set of reports**
  - WG5 HL-LHC, ATLAS+CMS Snowmass'22, QCD Town Meeting WP, CMS HIN

Luminosity calibration: PbPb @ 5.02 TeV (2018 Nov)

Source	Correction [%]	Uncertainty [%]
Normalization		1.3
Transverse factorizability	+1.0	0.8
Ghost and satellite charge	+3.9	0.5
Length scale calibration	−1.5	0.5
Scan-to-scan variation	—	0.5
Cross-detector consistency	—	0.4
Beam-beam effects	—	0.3
Systematic orbit distortion	—	0.2
Beam current calibration	—	0.2
Noncollision rate	−0.6	0.2
Random orbit distortion	−0.1	0.1
Statistical uncertainty	—	0.1
Integration		0.8
Cross-detector stability	—	0.8
Noncollision rate	—	0.1





Among most precise PbPb luminosity determinations

Three systems with independent calibration:

- Fast Beam Conditions Monitor (BCM1F)
- Forward Hadron Calorimeter (HFOC)
- Pixel Luminosity Telescope (PLT)

Stability monitored using emittance scans (short vdM-like scans)

Total uncertainty: 1.5%

PAS-LUM-18-001

150th LHCC Meeting