U.S. DEPARTMENT OF ENERGY

Office of Science

KU

Heavy metal hits the top

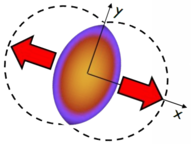
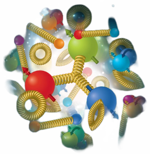
Georgios K Krintiras

The University of Kansas

20th Anniversary

PhD @ UCLouvain/CP3 with Andrea G. (2015–2019)

The three pillars of my work @ CP3

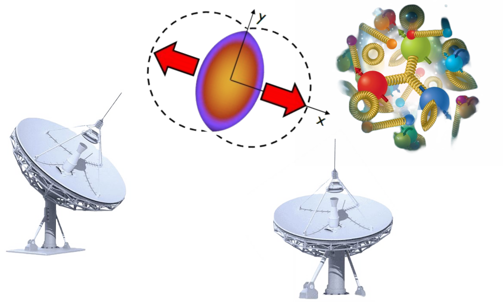




- **Precision**
  - **sustaining new “channels of observation” at LHC** (*)

    → coordinated the luminosity group @ CMS

(*) this is how top quark mass indirectly constrained

The **three pillars** of my work @ CP3



- **Precision**
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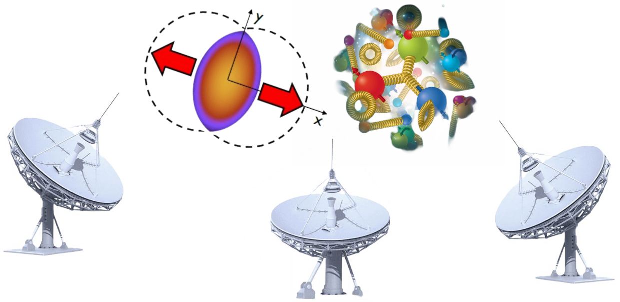
    ⟶ coordinated the luminosity group @ CMS

- **High-density/temperature QCD**
  - **testing the fundamentals of QCD with free partons**

    ⟶ coordinating the heavy ion group @ CMS

The **three pillars** of my work @ CP3



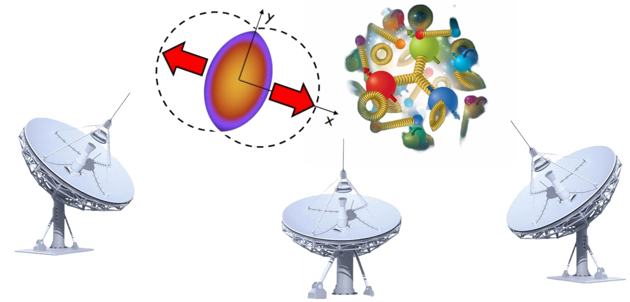
- **Precision**
  - sustaining new “channels of observation” at LHC

    → **coordinated the luminosity group @ CMS**
- **High-density/temperature QCD**
  - testing the fundamentals of QCD with free partons

    → **coordinating the heavy ion group @ CMS**
- **Beyond the Standard Model (BSM) quest**
  - complementing searches with the photonic mode of LHC

    → **coordinated the Forward Physics group @ CMS**

The three pillars of my work @ CP3



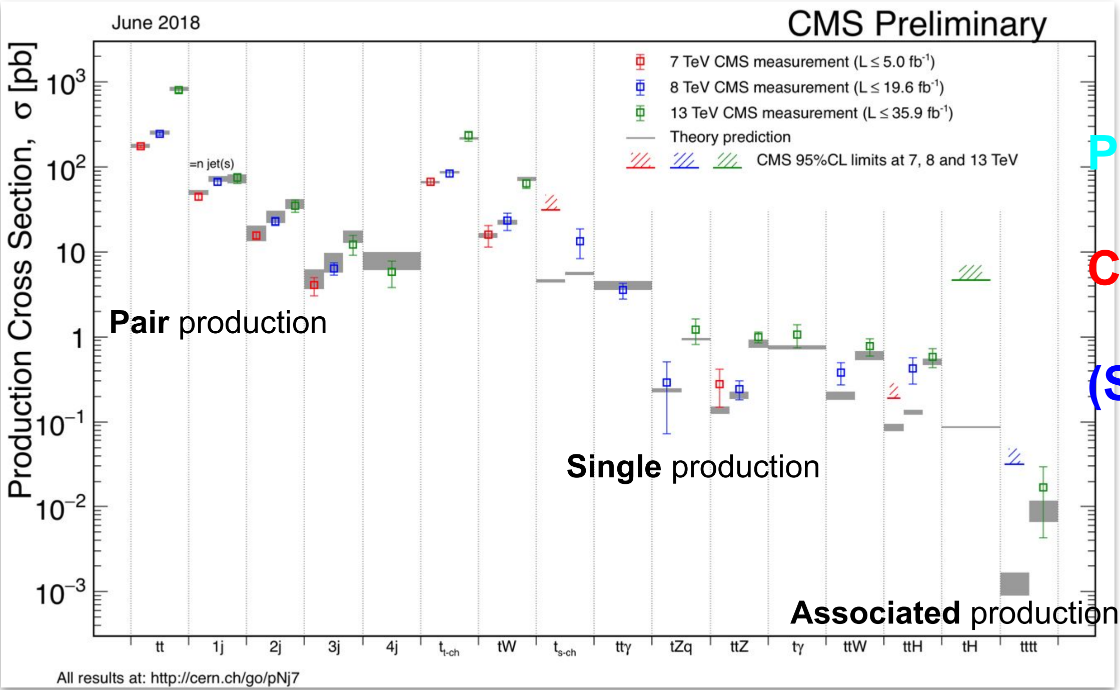
…els of observation" at LHC

…nosity group @ CMS

- …QCD
  - … of QCD with free partons
  - …ion group @ CMS
- …(BSM) quest
  - …with the photonic mode of LHC
  - …d Physics group @ CMS

(the first "Heavy Ions and Hidden Sector" @ CP3)

QCD works spectacularly well (the top quark paradigm)



Phenomenology

Calculable (even on paper)

(Super)computers only

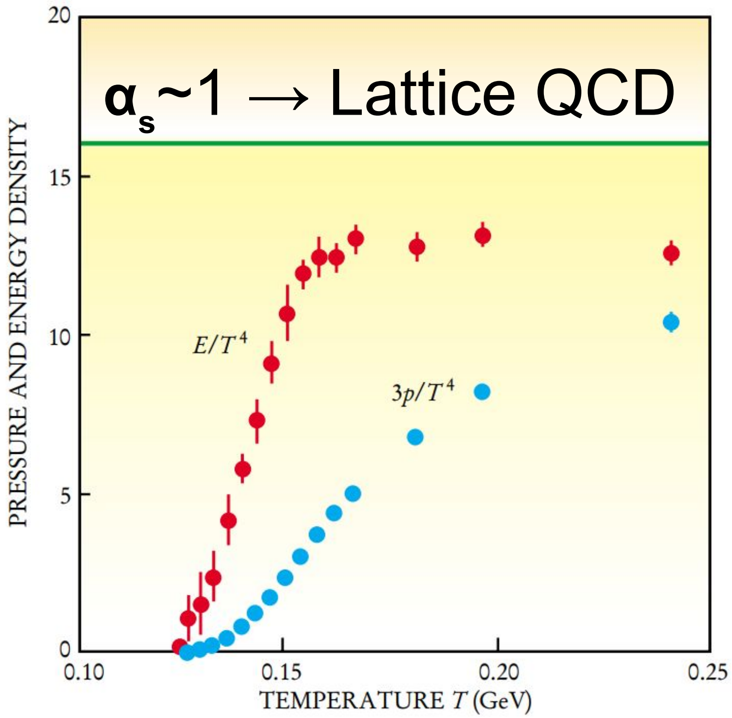
$$\sigma_{h_1 h_2 \to X} = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{h_1/a}(x_1, \mu_F^2)\, f_{h_2/b}(x_2, \mu_F^2) \times \hat{\sigma}_{a,b\to X}\left(x_1, x_2, \alpha_s(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2}\right) \left[+\mathcal{O}\left(\frac{1}{Q^2}\right)\right]$$

PDFs | partonic cross section | power corrections

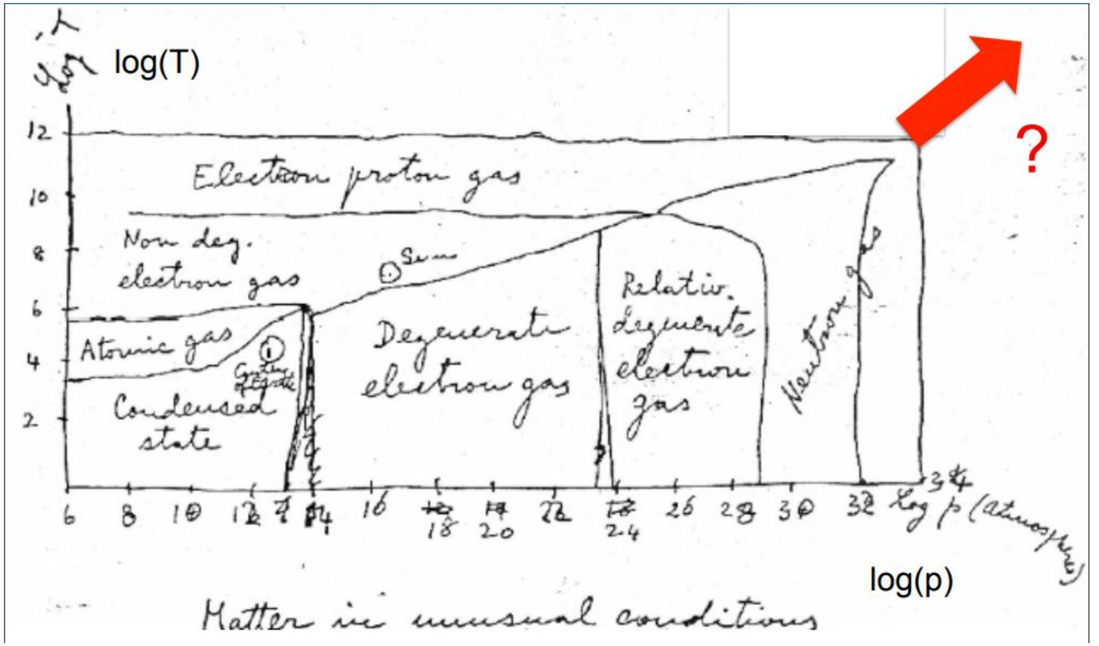
- **Theory & experiment go hand in hand**

(*) provided that the characteristic energy scales are "large enough" → $\alpha_s \ll 1$

How to test QCD as "the strong" interaction?



F. Wilczek, Physics Today 53 (2000) 22

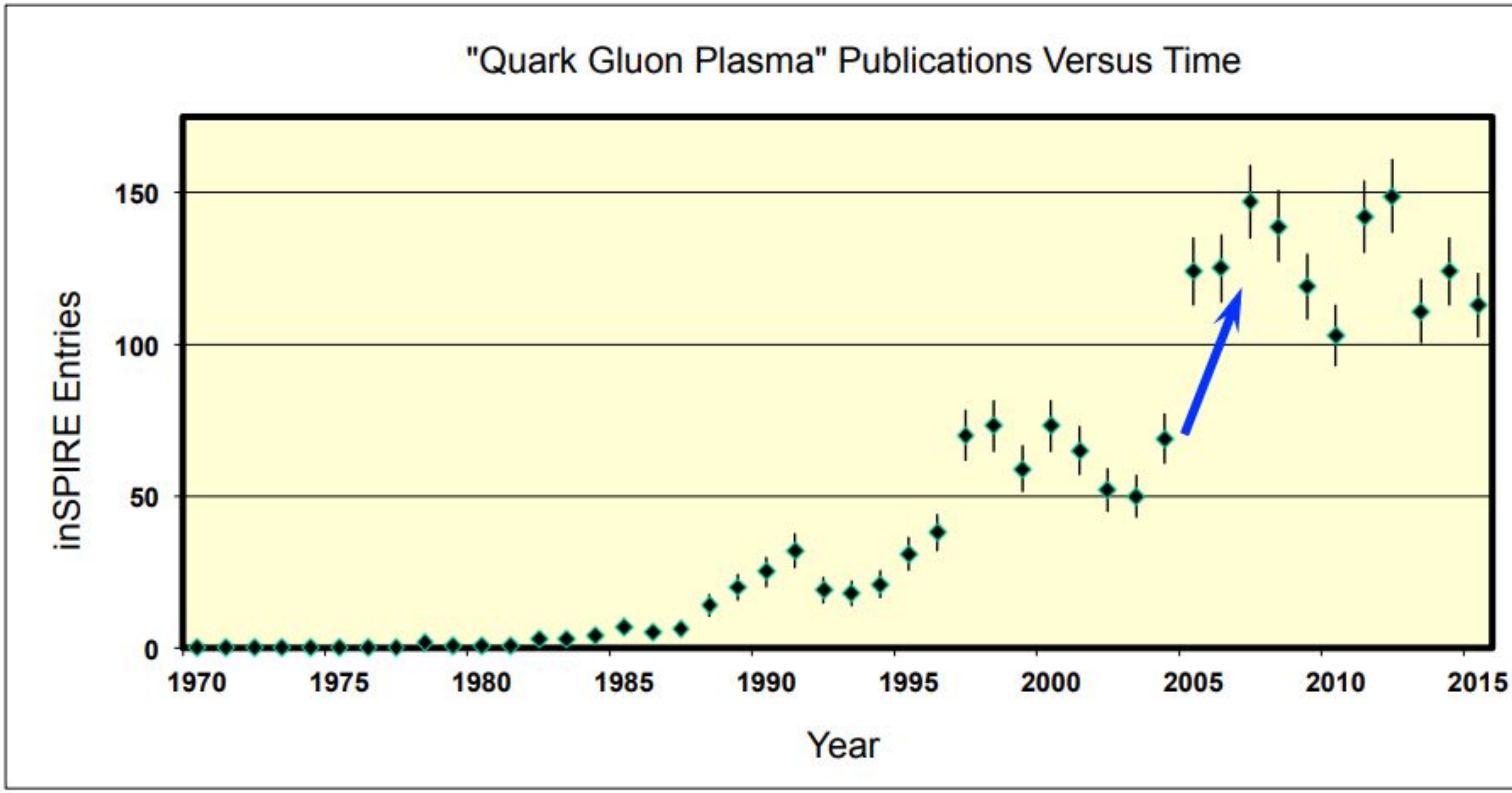


E. Fermi's lectures on statistical physics ~1953

- A phase transition was predicted on the lattice
  - Fermi's initial idea
- Discovery announcements at CERN (2000) and BNL (2005)

How to test QCD is “the strong” interaction?

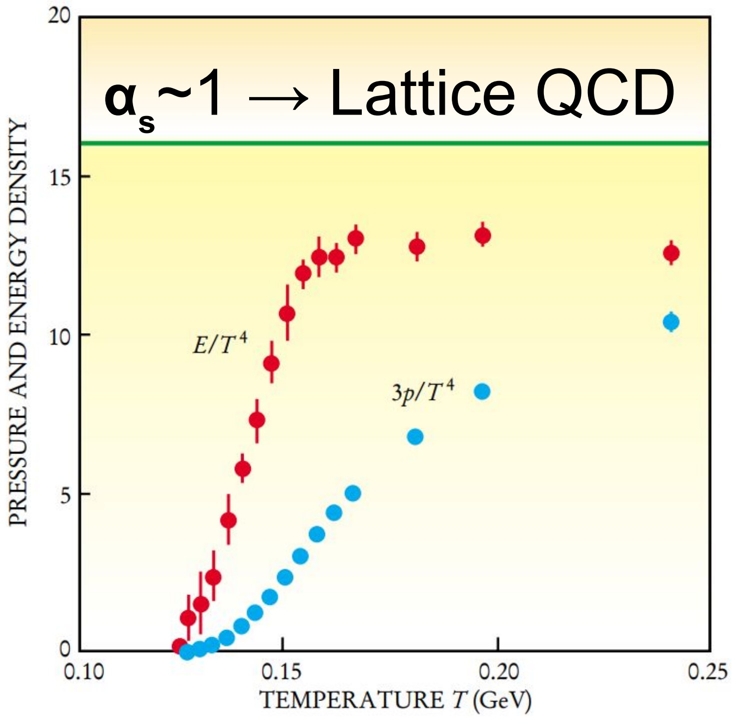
- inSPIRE query for all publications with “QGP” and related words in their title:

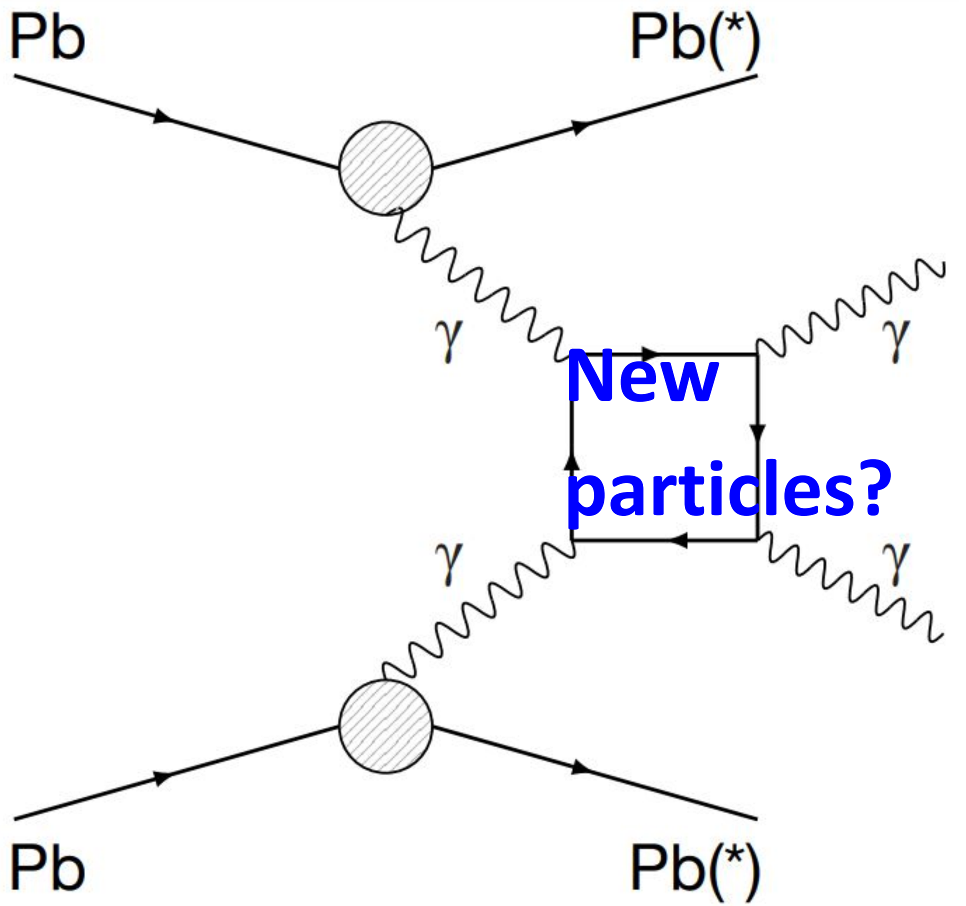


005)

[W.A. Zajc (Anniversary for 30 Years of Heavy Ions)]

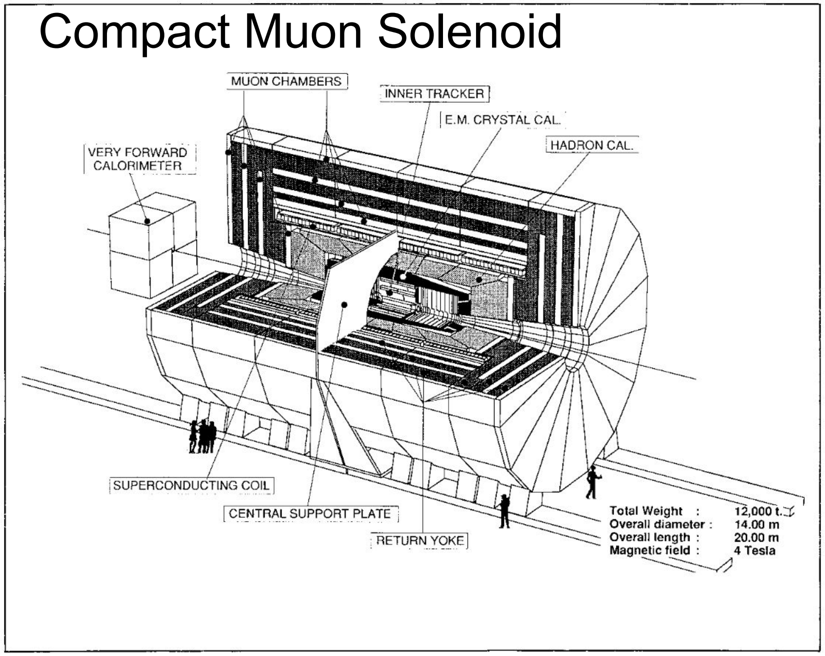
Joining forces to the BSM quest



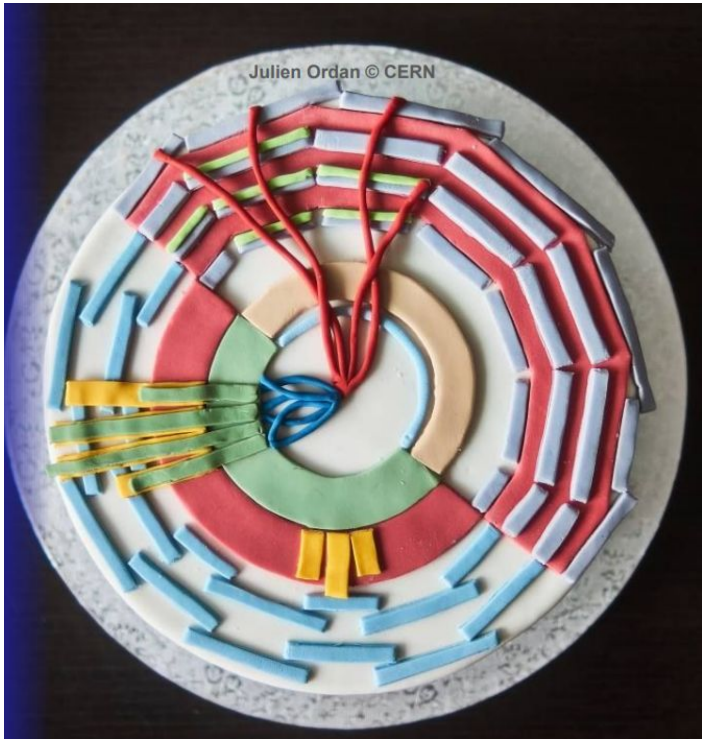


- **A phase transition was predicted on the lattice**
- **Discovery announcements at CERN (2000) and BNL (2005)**
- **We still run a LEP-like configuration @ 160 GeV**

The CMS experiment (1992–)



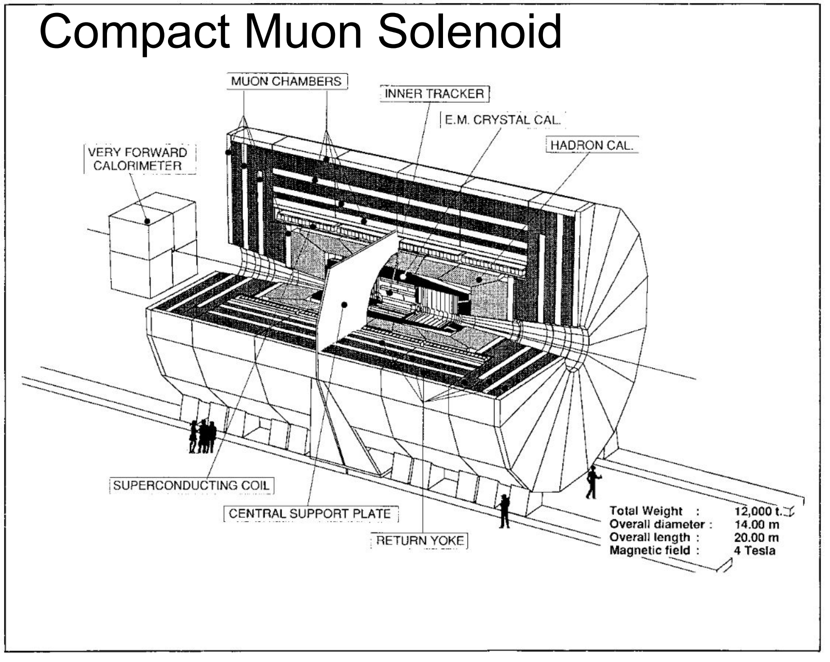
Evian "debut" (**1992**)



ATLAS & CMS turned 30

- **EOI in 1992: LHC to handle protons and lead**
- **CMS capabilities with heavy ions were early recognized**
- **CMS is a thriving community of HEP & NP**

The CMS experiment (1992–)



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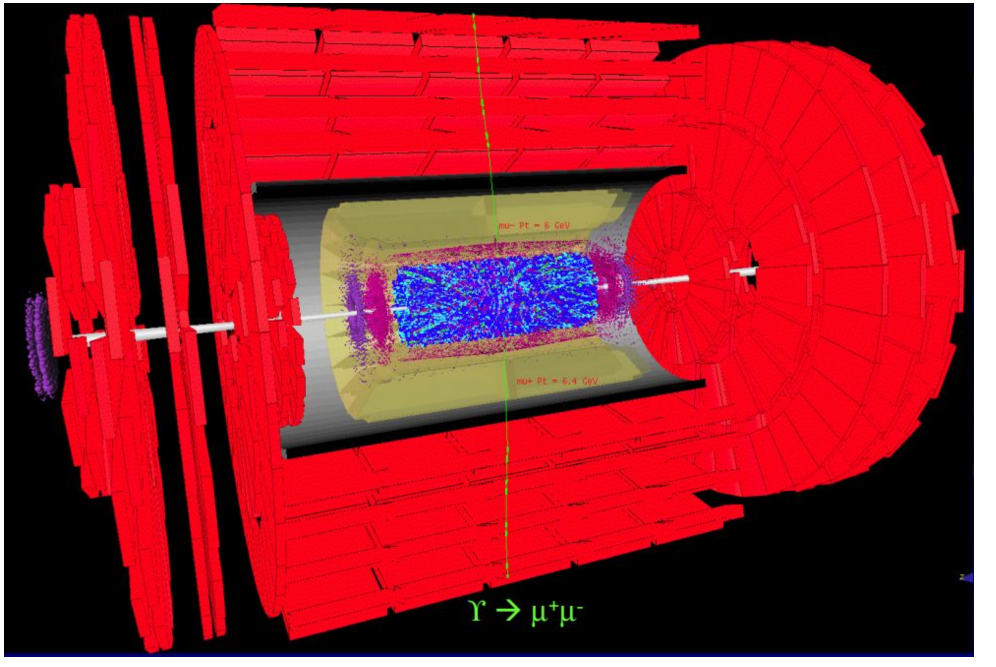
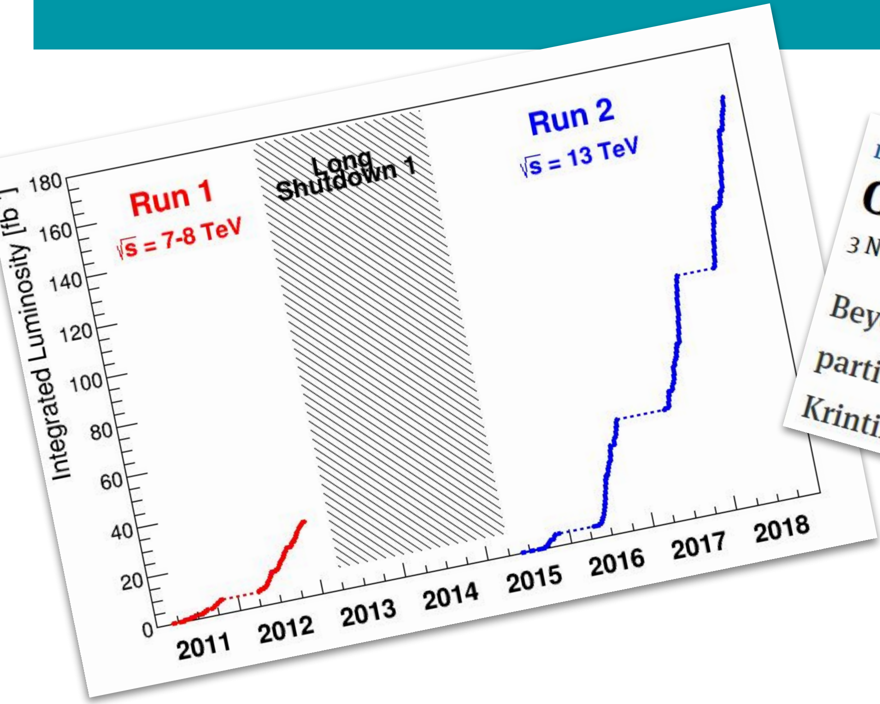


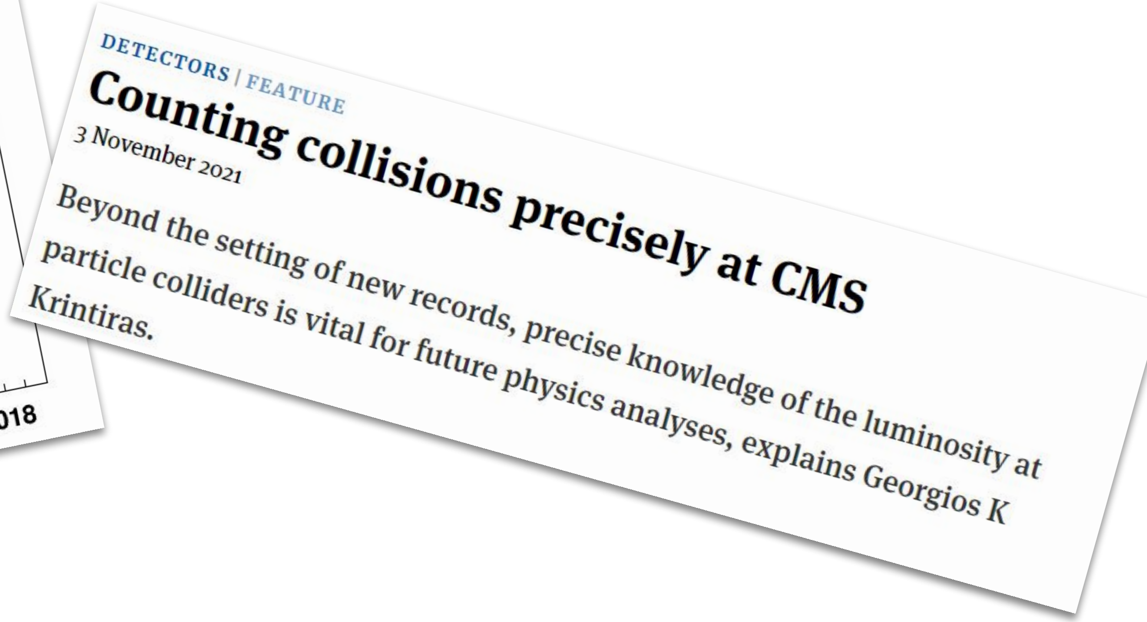
High Density QCD with Heavy Ions in CMS (**2007**)

- **EOI in 1992: LHC to handle protons and lead**
- **CMS capabilities with heavy ions were early recognized**
- **CMS is a thriving community of HEP & NP**
  - we're releasing a detailed review of Run1&2 NP studies

Luminosity: a **prerequisite** for precision

[EPJ C 81 (2021) 800](#)
[CERN Courier](#)




DETECTORS | FEATURE

Counting collisions precisely at CMS

3 November 2021

Beyond the setting of new records, precise knowledge of the luminosity at particle colliders is vital for future physics analyses, explains Georgios K Krintiras.

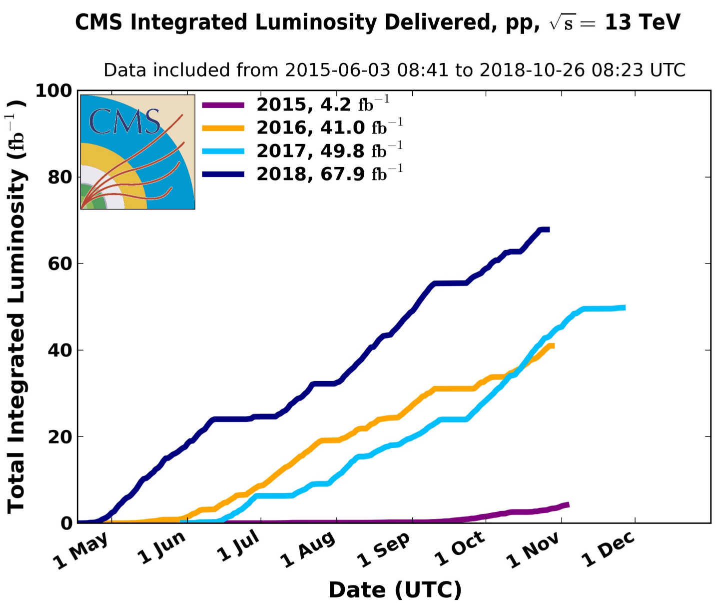
- **LHC comfortably surpassed the target with Run 2 pp data at 13 TeV**
  - This is a collider FOM for delivering statistically significant data samples

- **The precise knowledge of luminosity scale is of equal importance**
  - We measured it with **1%** precision ⟶ CMS publication > 350 citations

Large Hadron Collider

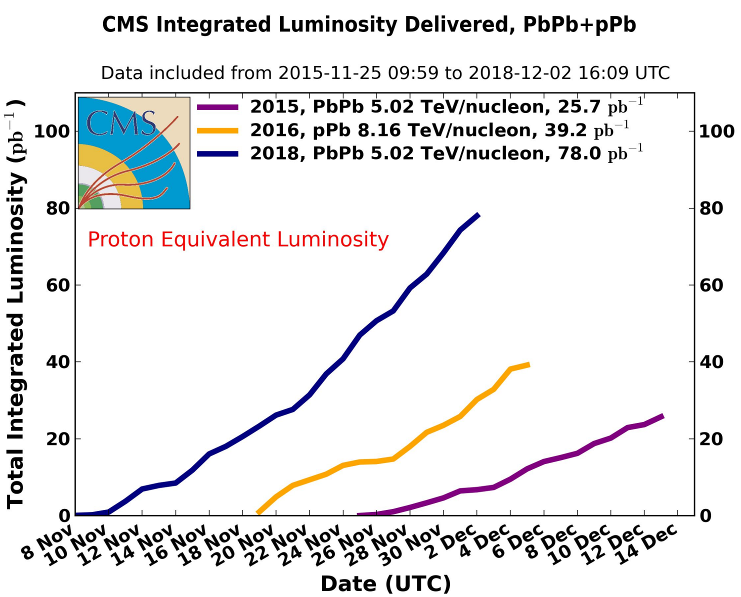
- We have about 2000 times less nuclear (pPb or PbPb) than pp data
- Why?
  - acceleration limitations
  - running time: 4 months vs > 4 years!

proton-proton



We speak of /fb

Nuclear collisions

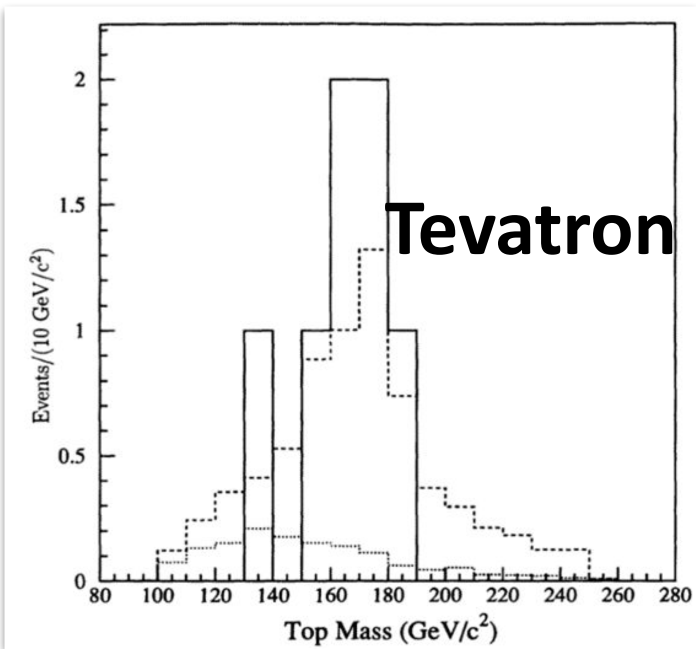


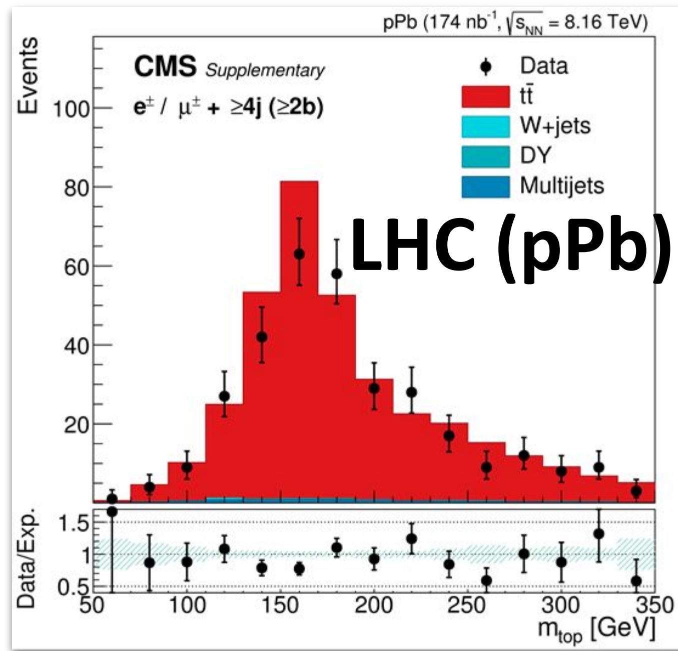
We speak of /pb

Tools so far **"inaccessible"**

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

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





1995 — *Top at Tevatron*
2009 — *Top at LHC (7 TeV)*
2015 — *Top at 13 TeV*
2016 — *Top at 5.02 TeV*
2017 — *Top in pPb*
2020 — *Top in PbPb*

GIZMODO, Dec 2017

Biggest Quark Spotted in Whole New Way

Ryan F. Mandelbaum
12/15/17 6:00pm • Filed to: QUARKS

33.6K 17 8

Image: CMS/CERN

FNRS News , Mar 2018

News

ÉTUDE DES NOYAUX LOURDS

Le Large Hadron Collider (LHC) du CERN produit des collisions entre protons (collisions pp) afin d'étudier les particules élémentaires, telles que le boson de Brout-Englert-Higgs. Moins connue est sa capacité à produire également des collisions impliquant des noyaux atomiques lourds : plomb contre plomb (PbPb) et proton contre plomb (pPb). Le « quark top » est la plus lourde particule élémentaire connue, découverte en 1995 au Tevatron (États-Unis), et scrutée sous tous les angles par de nombreuses études au LHC, jusqu'ici toujours basées sur les données pp. Pour la première fois, la production de quark top a été observée dans les collisions pPb, avec une méthode innovante qui pourrait être appliquée aux prochaines données PbPb. Le but est de mieux comprendre la matière nucléaire en conditions extrêmes, semblables aux premiers instants après le Big Bang.

Physics Review Letters Phys. Rev. Lett. - Observation of top quark production in proton-nucleus collisions

Andrea Giammanco, PhD
Chercheur qualifié F.R.S.-FNRS
Georgios Krintiras, doctorant

Centre for Cosmology, Particle Physics and Phenomenology, UCL

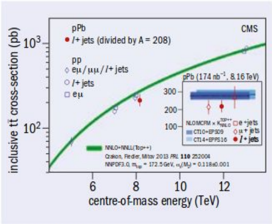
CERN Courier, Nov 2017

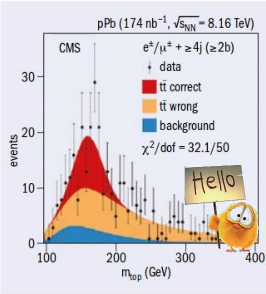
CMS observes top quarks in proton–nucleus collisions

The top quark, the heaviest elementary particle in the Standard Model, has been the subject of numerous detailed studies in proton–antiproton and proton–proton collisions at the Tevatron and LHC since its discovery at Fermilab in 1995. Until recently, however, studies of top-quark production in nuclear collisions remained out of reach due to the small integrated luminosities of the first heavy-ion runs at the LHC and the low nucleon–nucleon (NN) centre-of-mass energies ($\sqrt{s_{NN}}$) available at other colliders such as RHIC in the US.

Proton–lead runs at $\sqrt{s_{NN}} = 8.16$ TeV performed in 2016 at the LHC have allowed the CMS collaboration to perform the first-ever study of top-quark production in nuclear collisions.

Top-quark cross-sections at the LHC can be computed with great accuracy via perturbative quantum chromodynamics (pQCD) methods, thus making this quark a "standard candle" and a tool for further investigations. In proton–nucleus collisions, in particular, the top quark is a novel probe of the nuclear gluon density at high virtualities in the unexplored high Bjorken-x region. In addition, a good understanding of top-quark production in proton–nucleus collisions is crucial for studies of the space–time





(Above) Top-quark pair-production cross-section in pp and pPb collisions as a function of the centre-of-mass energy per nucleon pair. (Right) Invariant mass distribution of the hadronic top-quark candidates in selected events with two b-tagged jets.

science 2.0, Sep 2017

science 2.0 JOIN THE REVOLUTION

Top Quarks Observed In Proton-Nucleus Collisions For The First Time

By Tommaso Dorigo | September 22nd 2017 05:28 AM | Print | E-mail

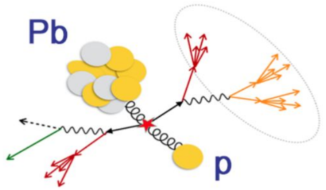
RSS Share / Save Tweet

PRL Synopsis, Dec 2017

Synopsis: Top Quark in Nuclear Collisions

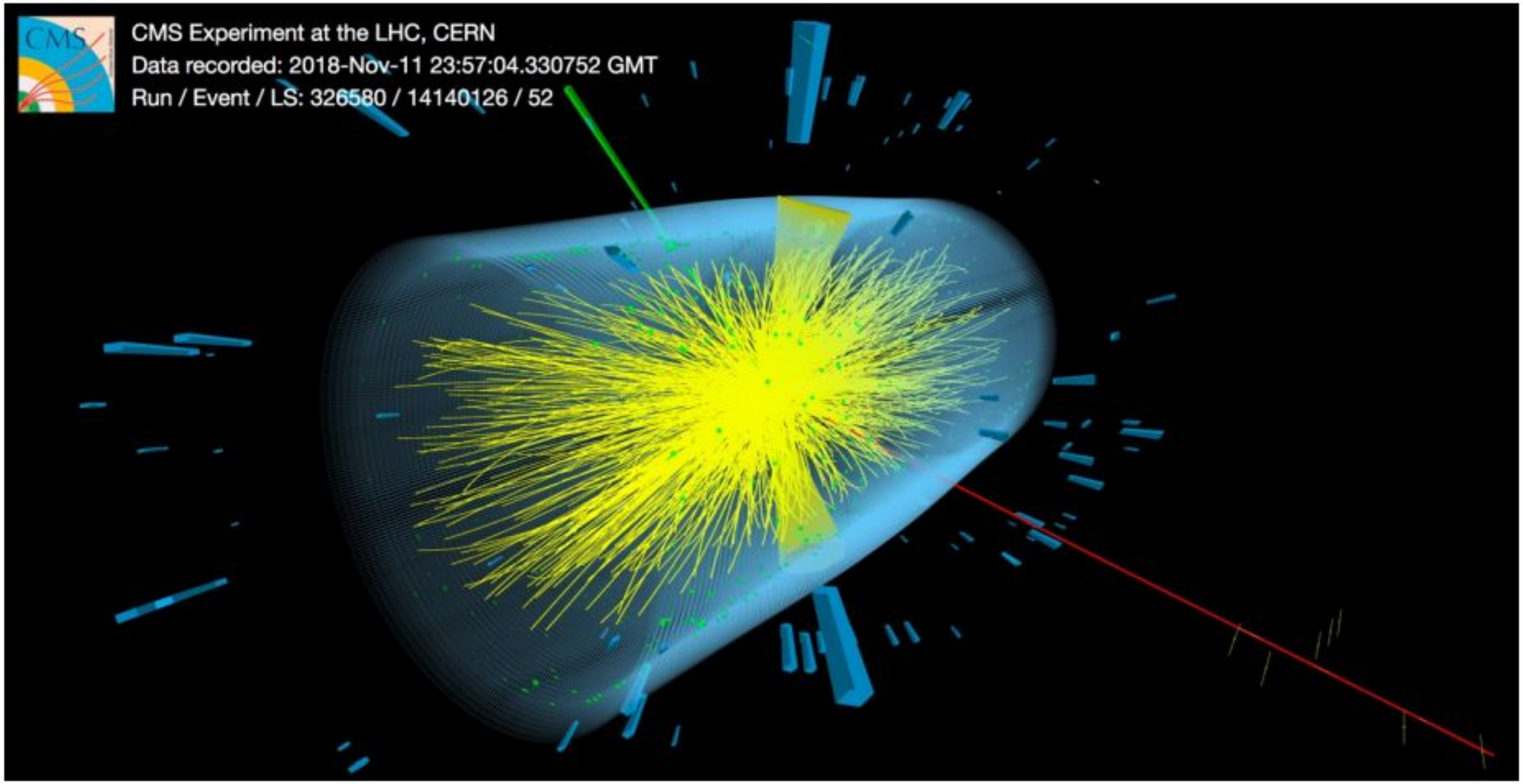
December 14, 2017

The top quark—previously seen in proton collisions—has now been identified in collisions between protons and lead nuclei.



CMS Collaboration/CERN

The road is finally open



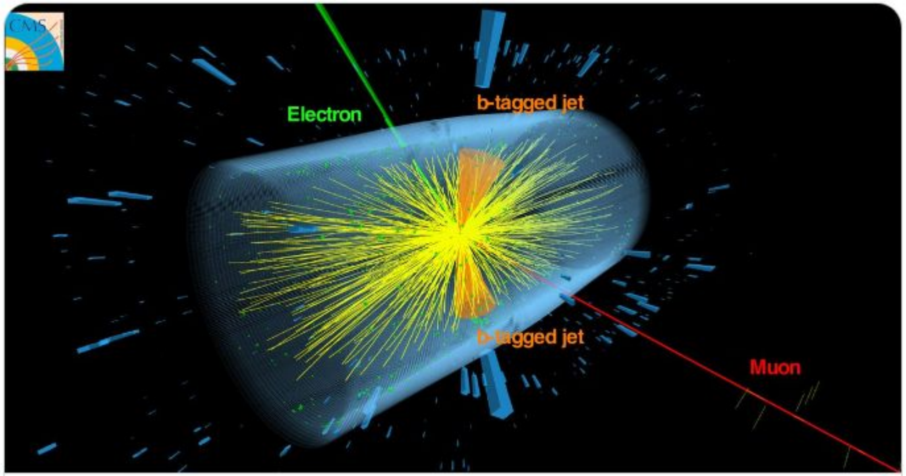
CMS-PHO-EVENTS-2018-010-5 (PbPb 5.02 TeV)

Last slide from my thesis

"Heavy metal hits the top"

CERN @CERN

This result from @CMSExperiment, opens the path to study in a new and unique way the extreme state of matter that is thought to have existed shortly after the #BigBang.



CMS sees evidence of top quarks in collisions between heavy nuclei

The CMS collaboration has seen evidence of top quarks in collisions between heavy nuclei at the Large Hadron Collider (LHC). This isn't the first time this ...

home.cern

CMS Experiment at CERN

October 9 at 9:08 AM ·

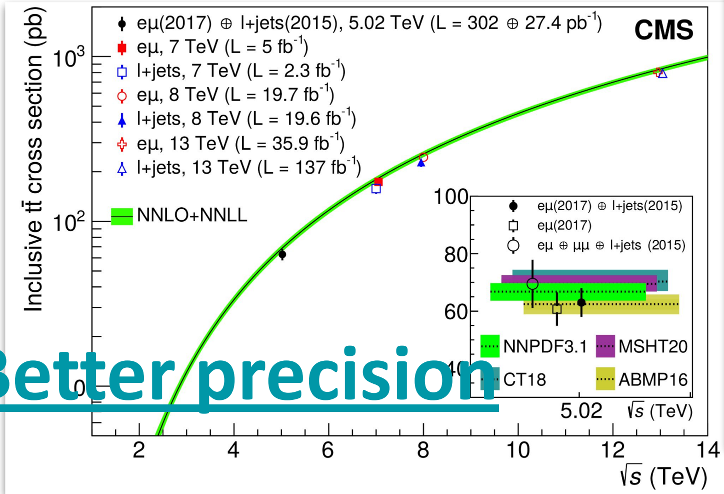
For the first time the CMS Collaboration demonstrates evidence that top quarks are produced in nucleus-nucleus collisions! Read more how the top quark interacts with the heavy metal 🎸💥🎸 of the lead-lead collisions in this CMS physics briefing: ➡️ https://cms.cern/news/heavy-metal-hits-top

Phys Rev Lett **125** (2020) 222001

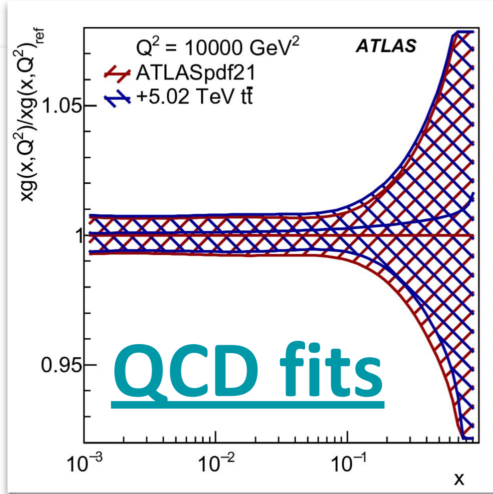
CERN press release

CERN video

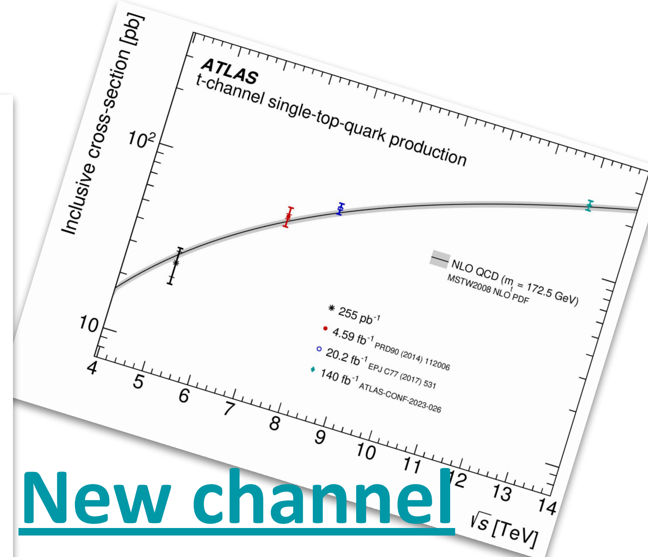
Maybe just a hype?



Better precision

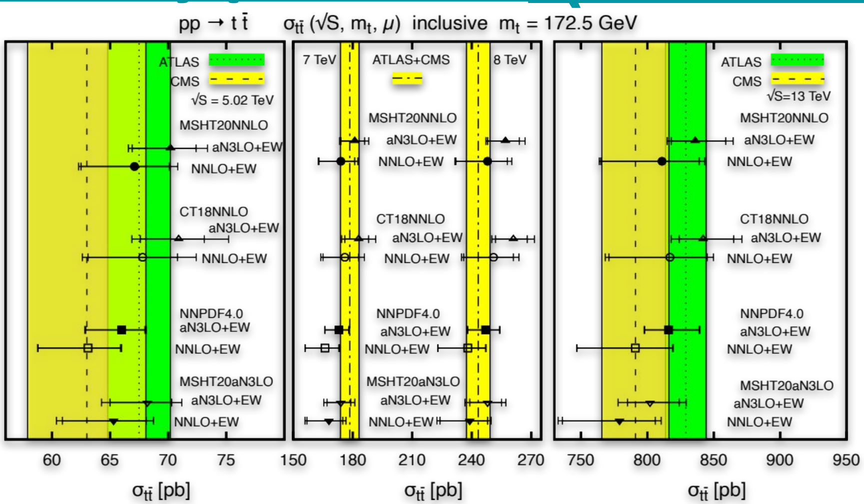


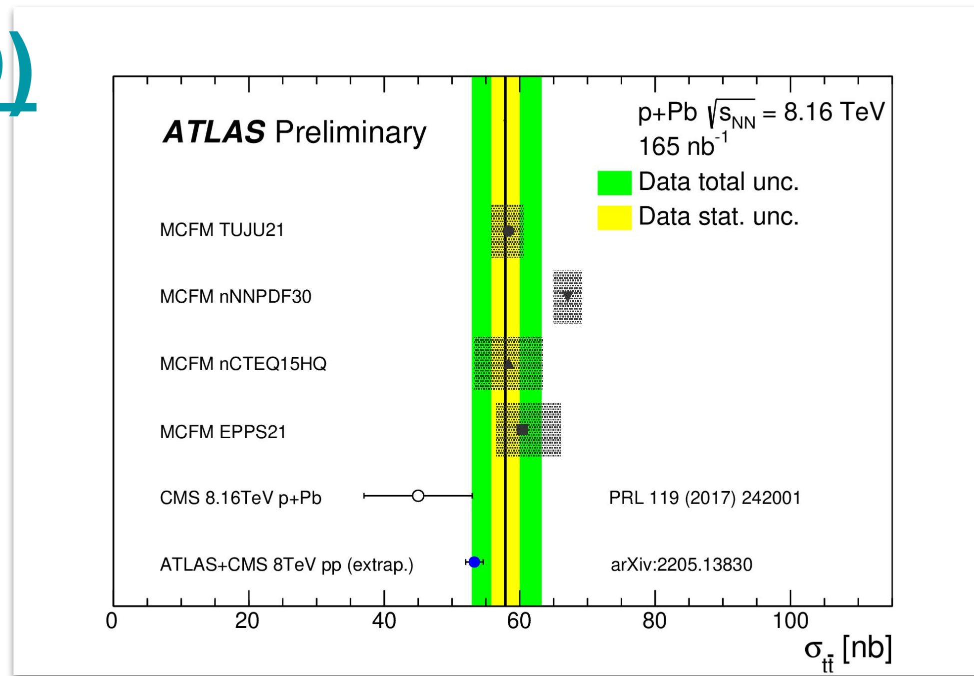
QCD fits



New channel

Theory precision (aN3LO)





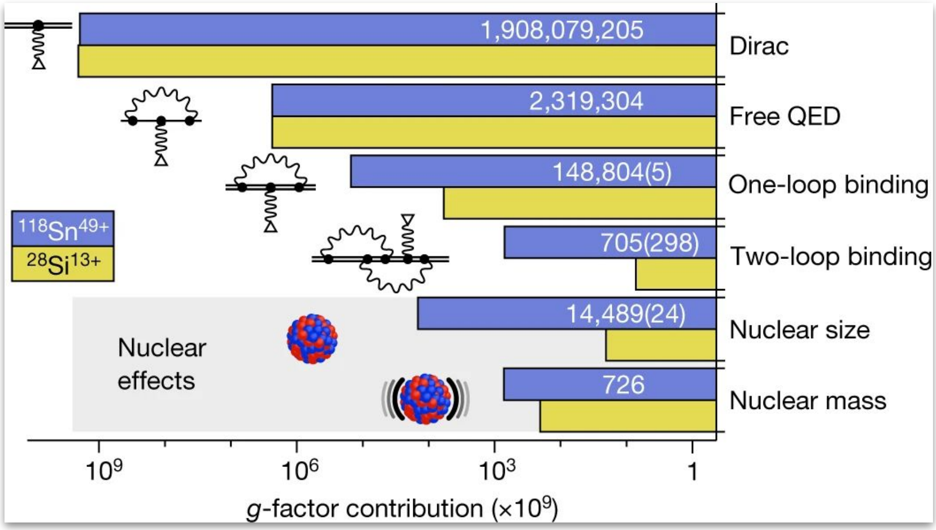
A series of followup results

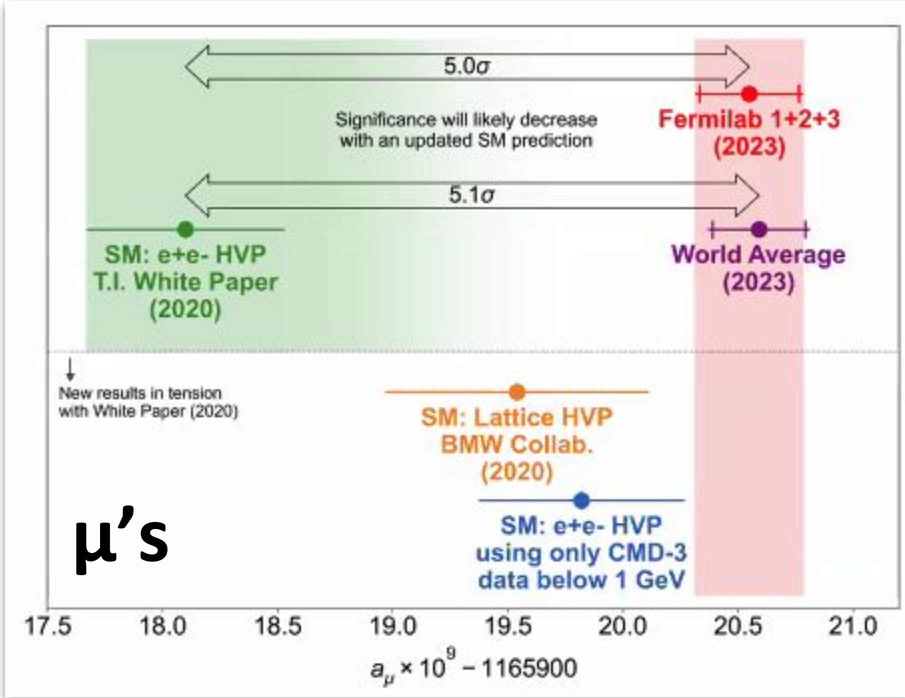
Re-observation (Oct 2023)

The anomalous anomaly for e's & μ's

[Nature **622** (2023) 53](#)
[PRL **26** (2021) 141801](#), [2308.06230](#)

bound e's

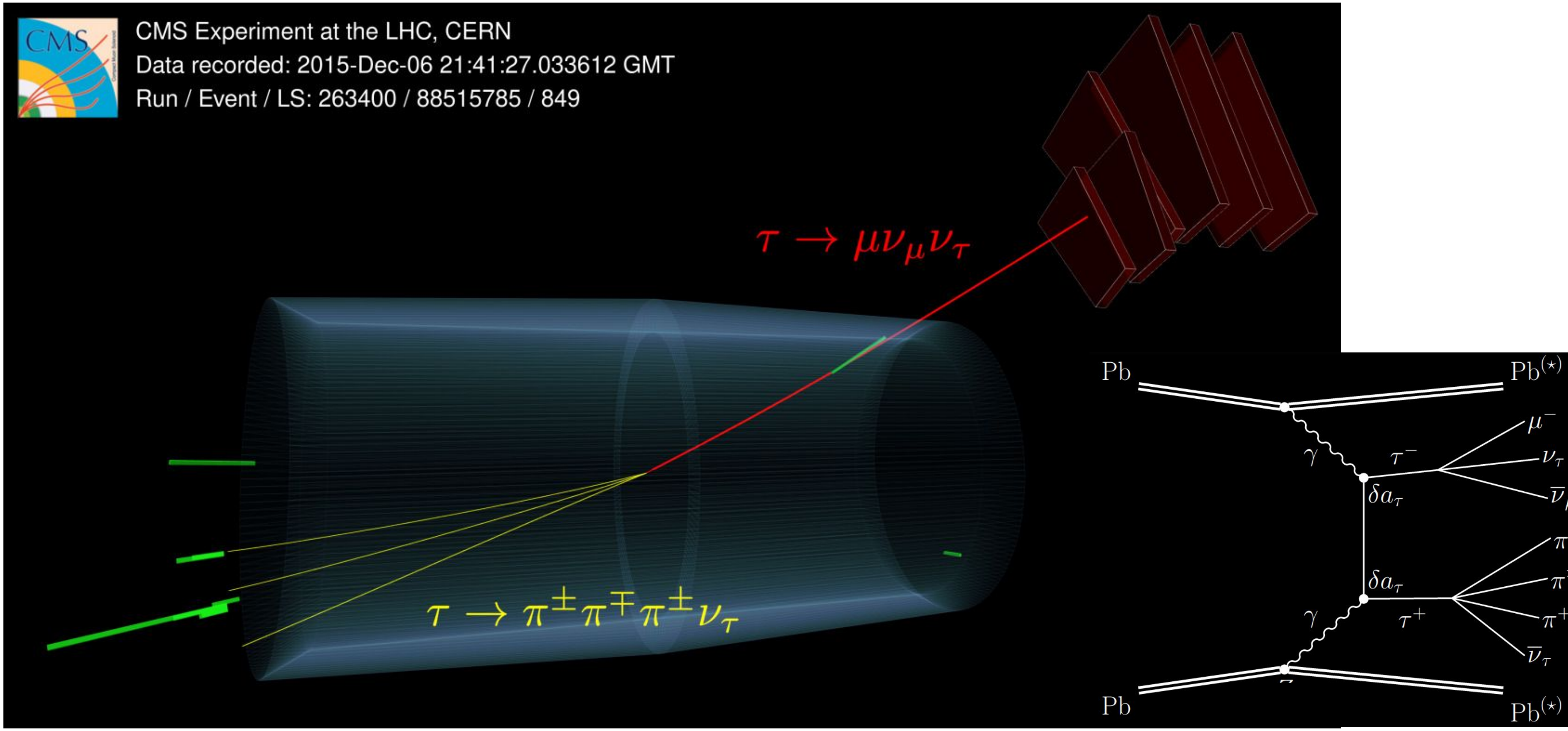




- **ALPHATRAP tested high-field QED in hydrogen-like heavy nuclei**
- **FNAL g-2 reconfirmed previous discrepancy**
    - the exact level depends on theory considerations

Maybe their heavier cousin is more sensitive to new physics?

τ's in ultraperipheal ion-ion collisions

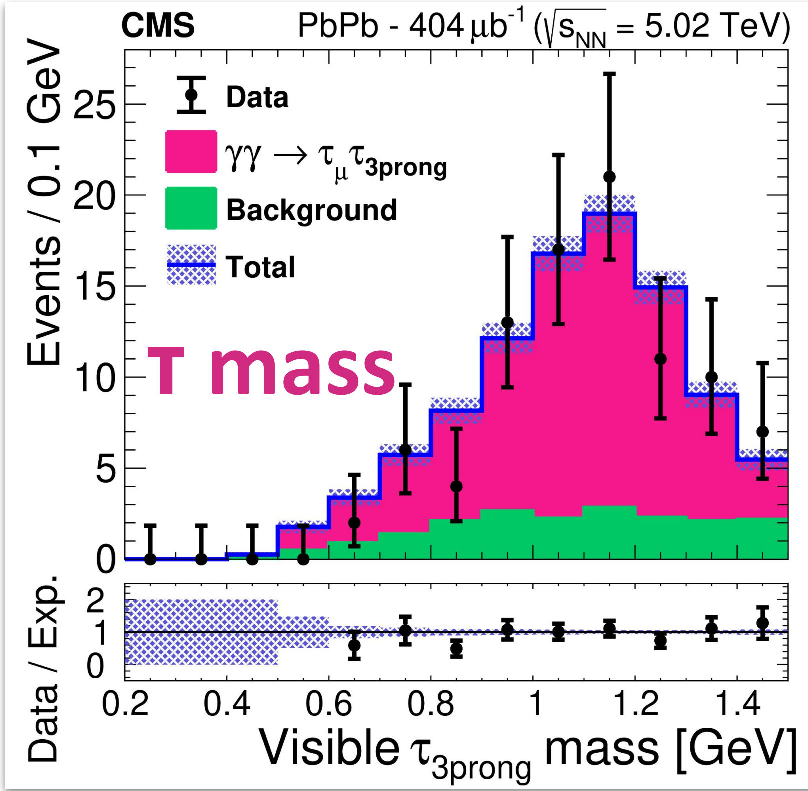


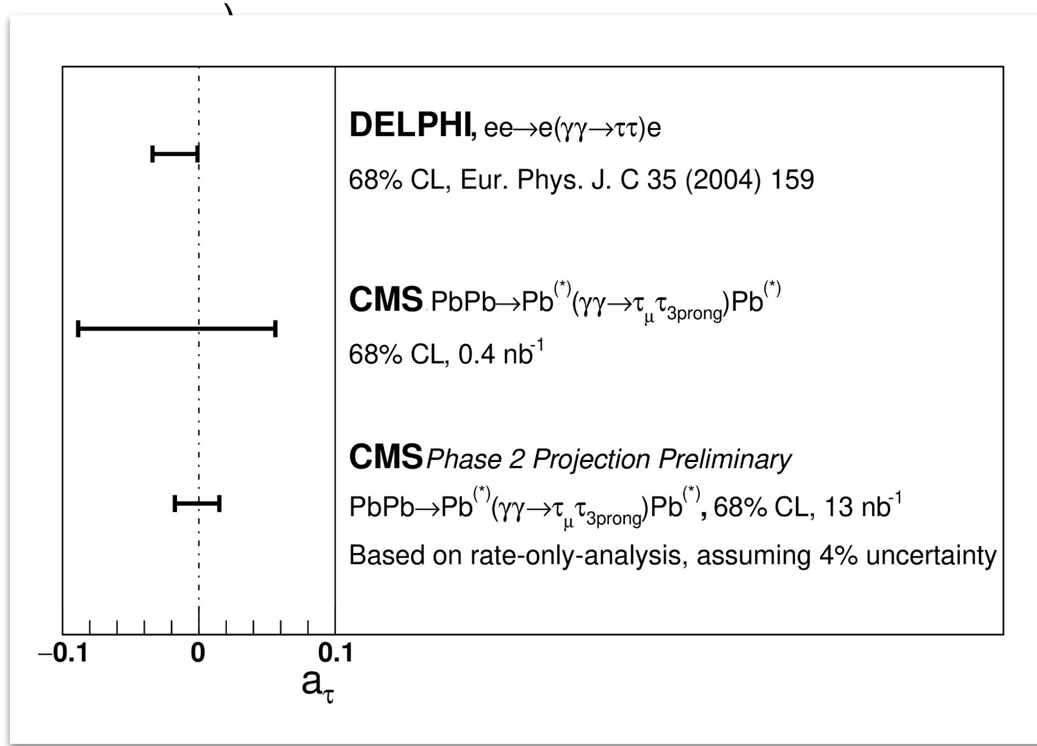
- **Exceptionally clean events**
  - price to pay: ion-ion luminosity is low @ LHC
- **This process can be studied in pp too (more complex but doable)**

A dedicated physics program @ LHC to improved constraints on a_τ

The anomalous anomaly for τ's

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

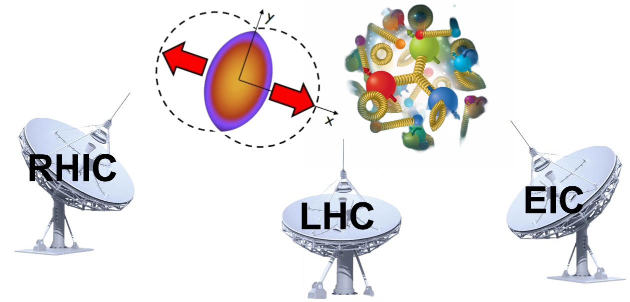




- **We observed $\gamma\gamma \rightarrow \tau^+\tau^-$ at LHC**
  - obtained only with a single final state
- **First constraints on a_τ obtained at LHC**

ATLAS+CMS: improvements on a_τ with more data and final states

The experimental QCD landscape



- Synergy is the key
  - “Cold” & “Hot” QCD ⟶ QCD (Equipment & infrastructure)
  - CMS shows the way: HEP & NP (R&D, operation, analysis)
- In the next 5 years
  - RHIC concludes its operation: > 20 /nb of AuAu
  - LHC completes Run 3: > 5 /nb of PbPb
  - Final EIC design (we’re missing 2nd det ;) and construction
- In the next 10 years
  - Upgraded LHC detectors: > 5 /nb of PbPb
  - EIC starts its operation with 1.5 /fb / month

Hopefully in the next birthday occasion we’ll be discussing them ;D

Thank you

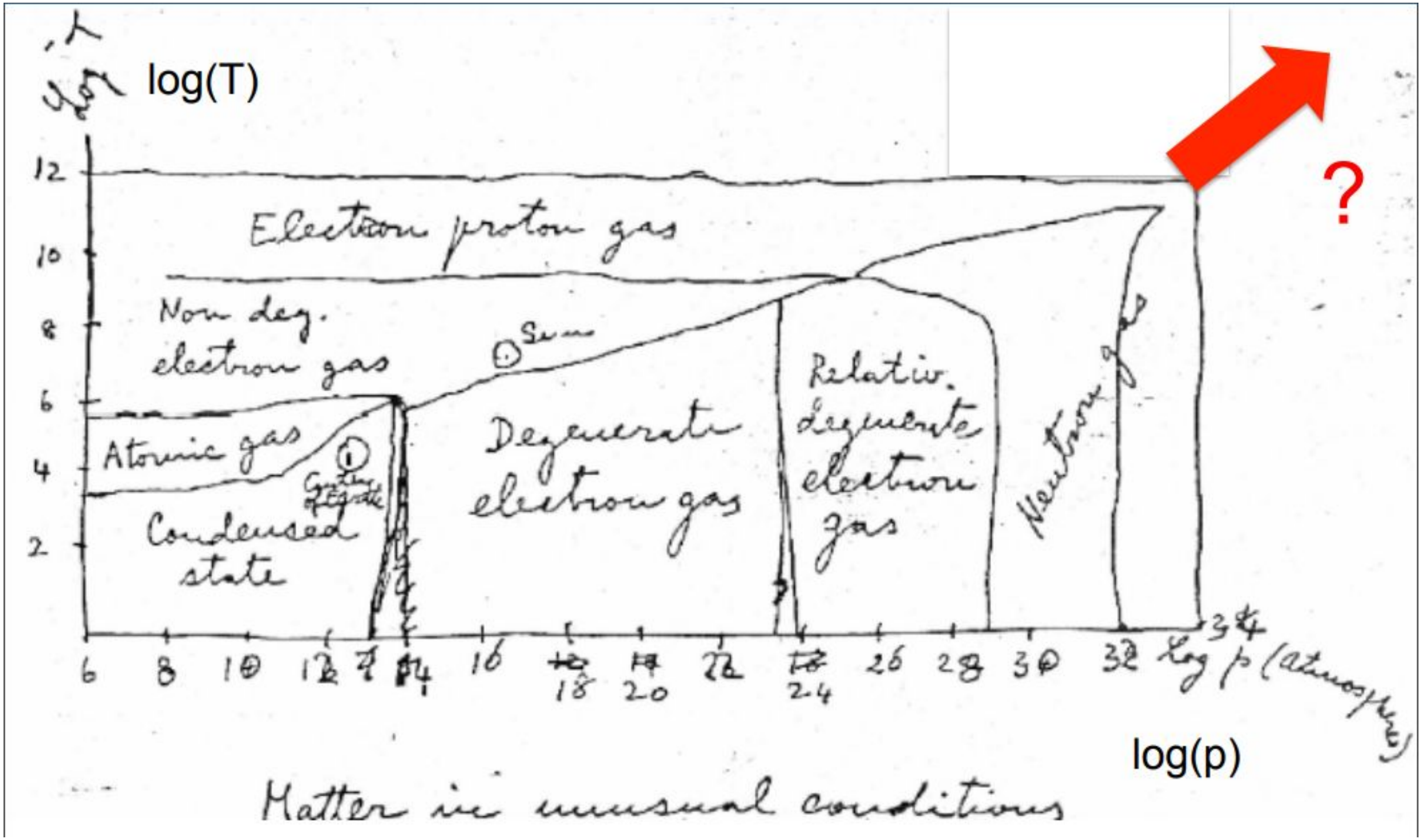
for a tremendous suppor

&

Happy Birthday 20th

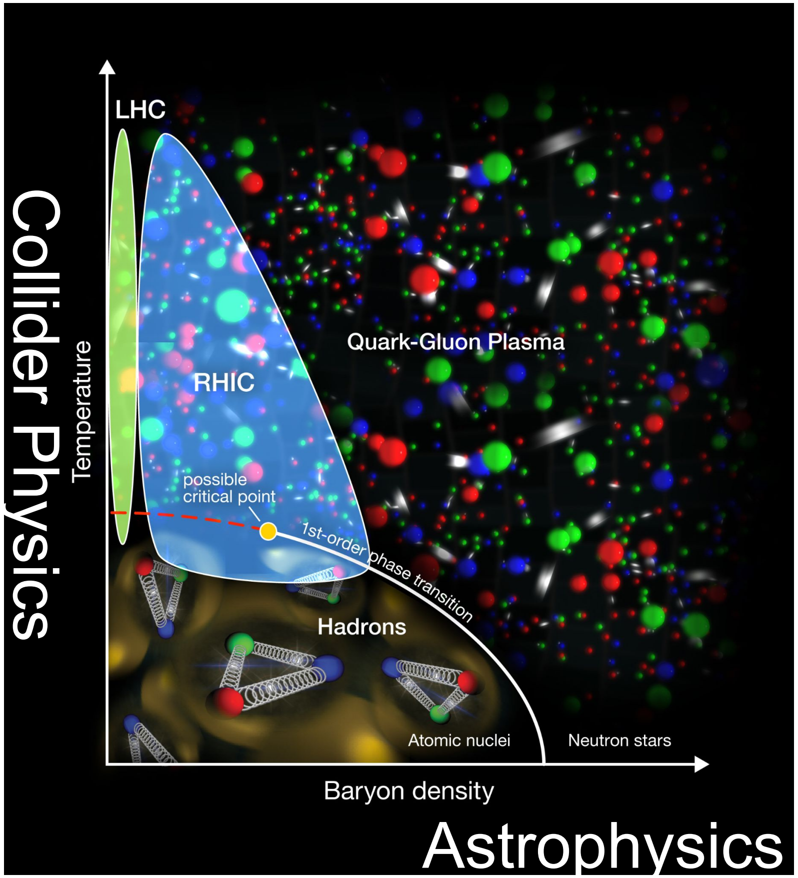
slides

Enrico Fermi's lectures on statistical physics ~1953



Something that molecularly is the same can still behave in **a dramatically different way**

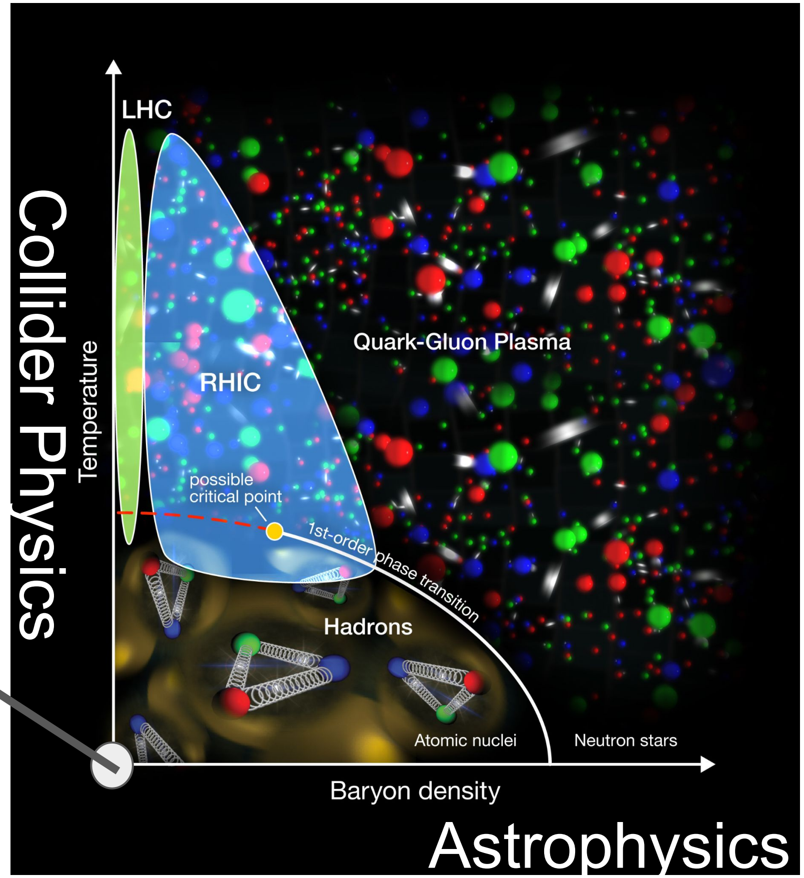
QGP: the earliest and simplest form of complex matter



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

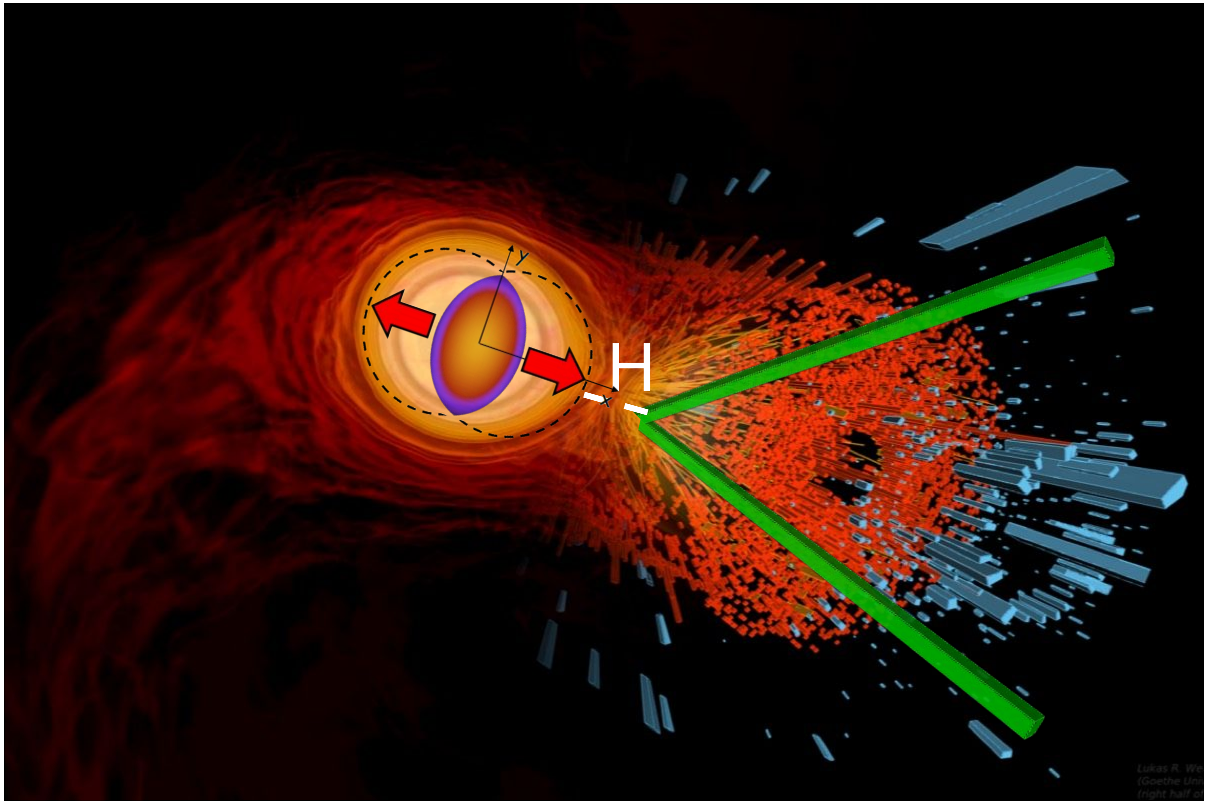
QGP: the earliest and simplest form of complex matter

$\mu_B \approx 0$



- **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

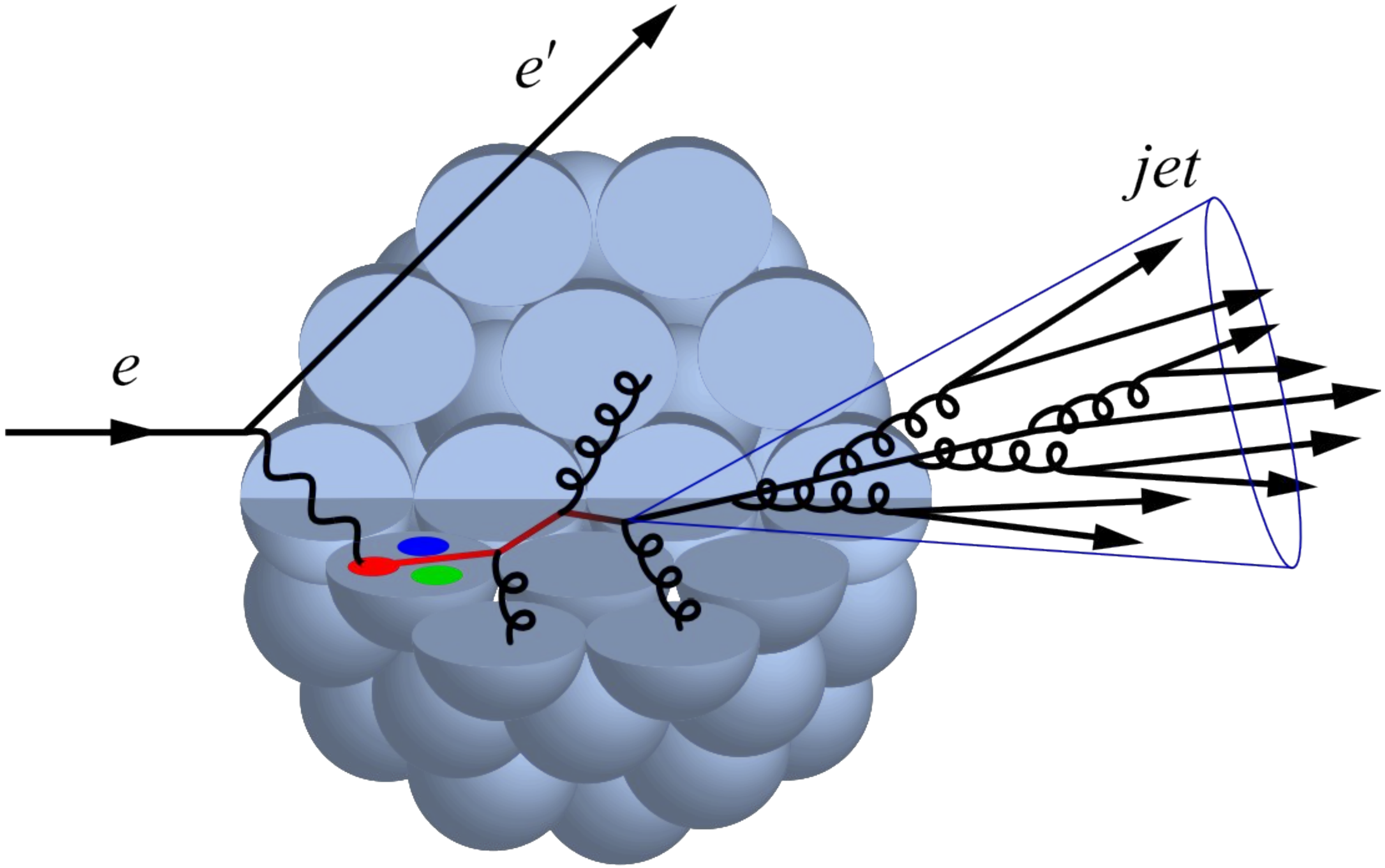


"Poetic license"

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

Nucleus: a new laboratory

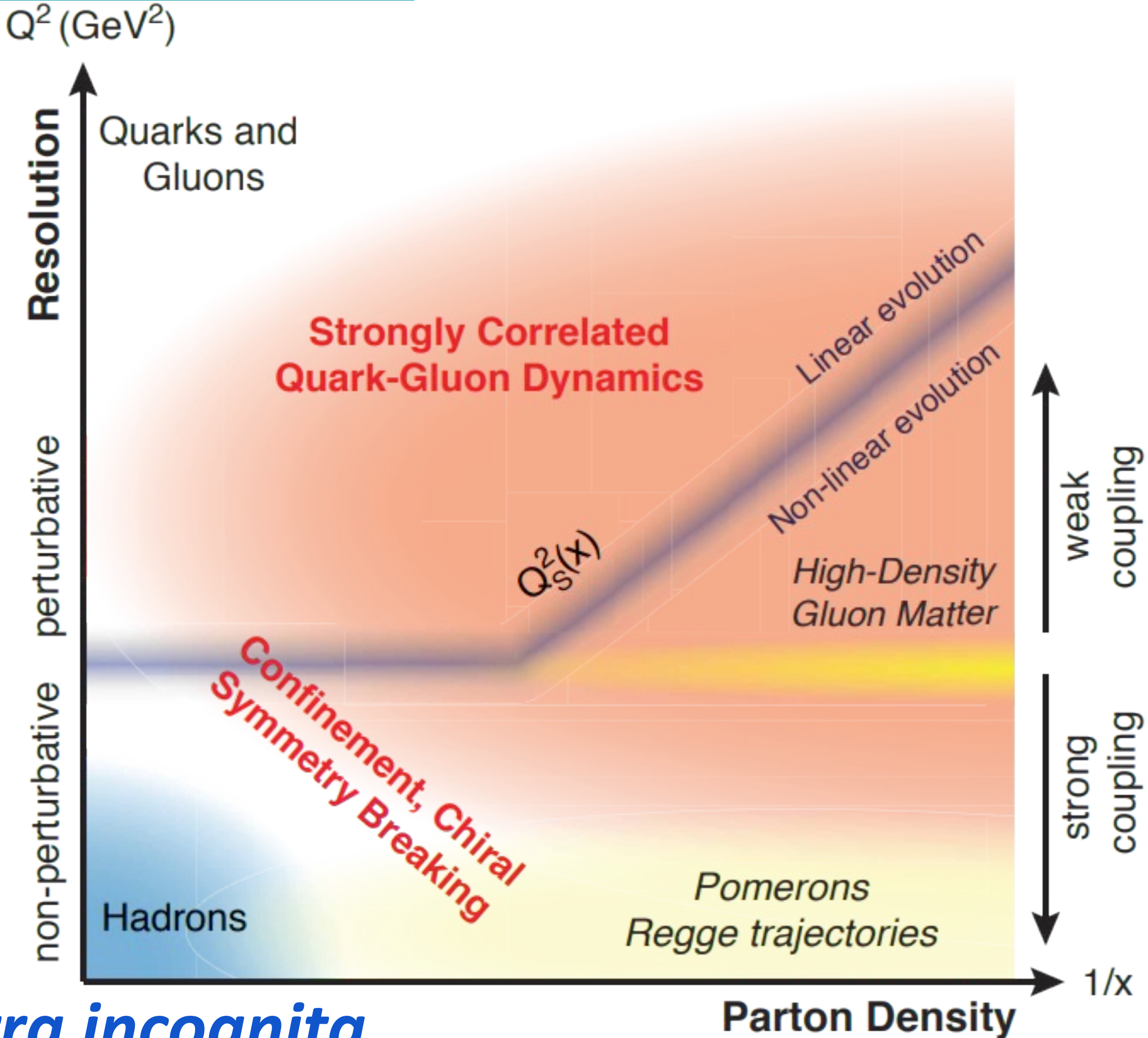
arXiv: 1708.01527



- Efforts focused on how q/g propagate in QGP ("en. loss")
- How q/g transport inside the nuclear medium?
- A novel application of QCD developments

The "cold QCD" landscape

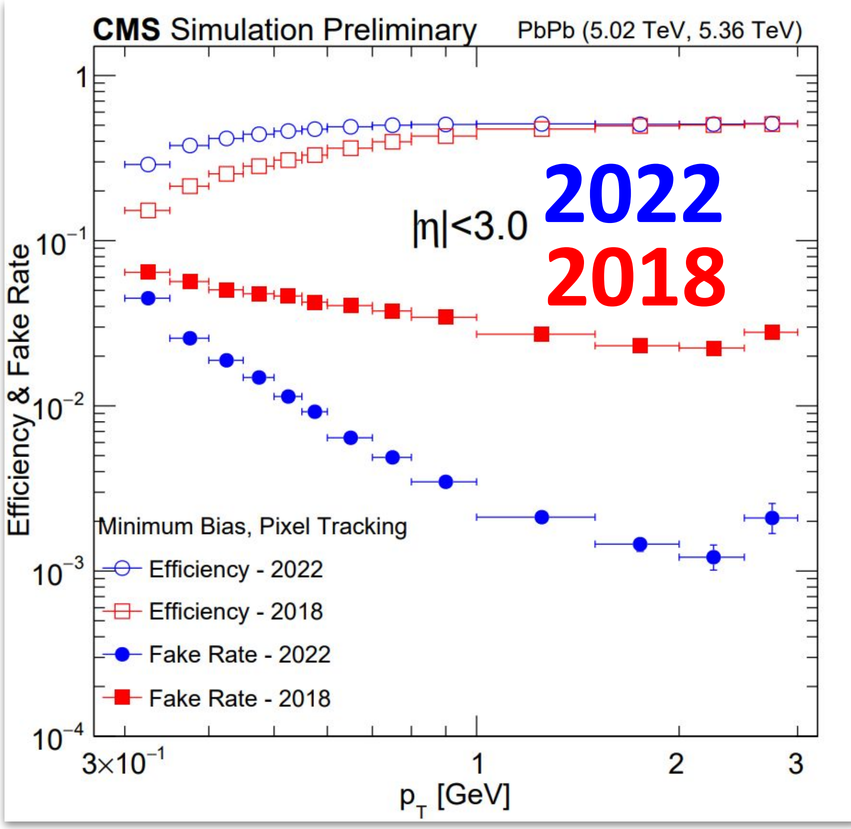
arXiv: 1708.01527

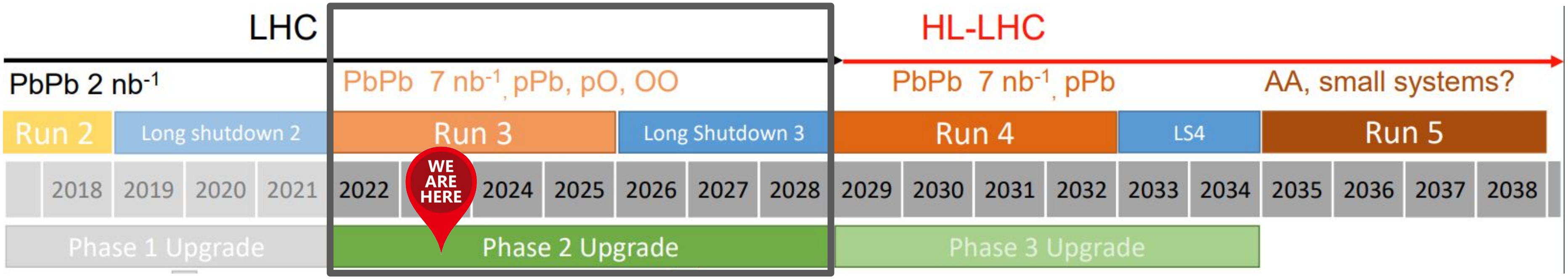


- Mostly *terra incognita*
- Hadron properties the result of the confined q/g
- A novel regime of QCD may exist: gluons saturate?

LHC Run 3, ...

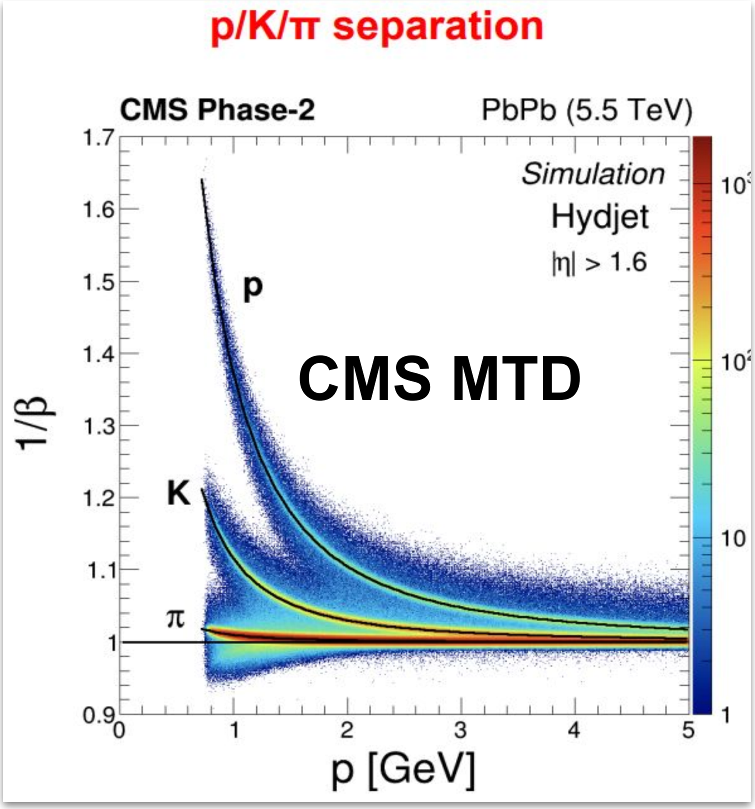
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- ALICE & LHCb/SMOG2

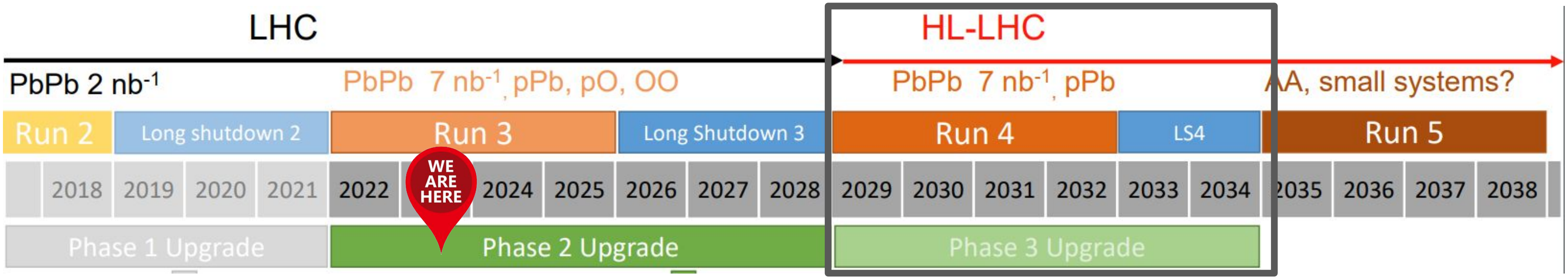




LHC Runs 3, 4, …

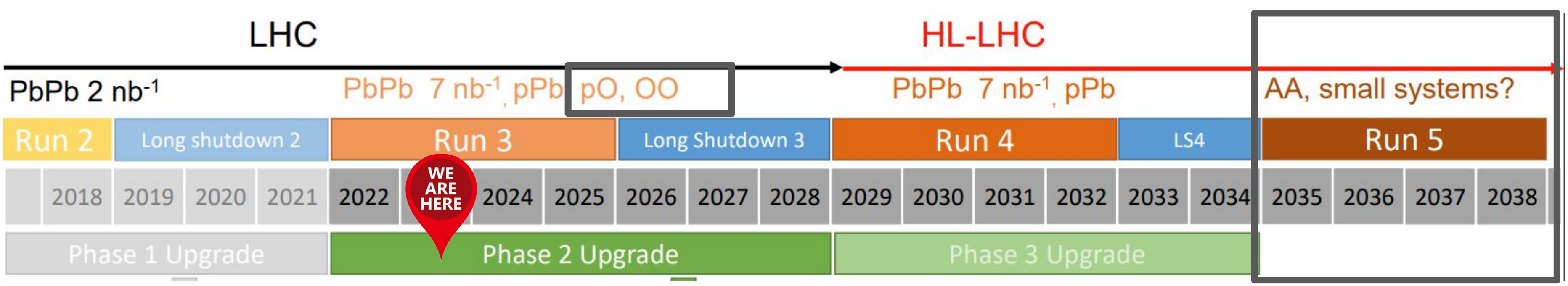
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- Upgraded detectors in Run 4
  - 3x increase in DAQ rate
  - PID and 4D tracking
  - ↑ tracking and muon coverage
  - high-granularity Hcal
  - radiation-hard ZDCs





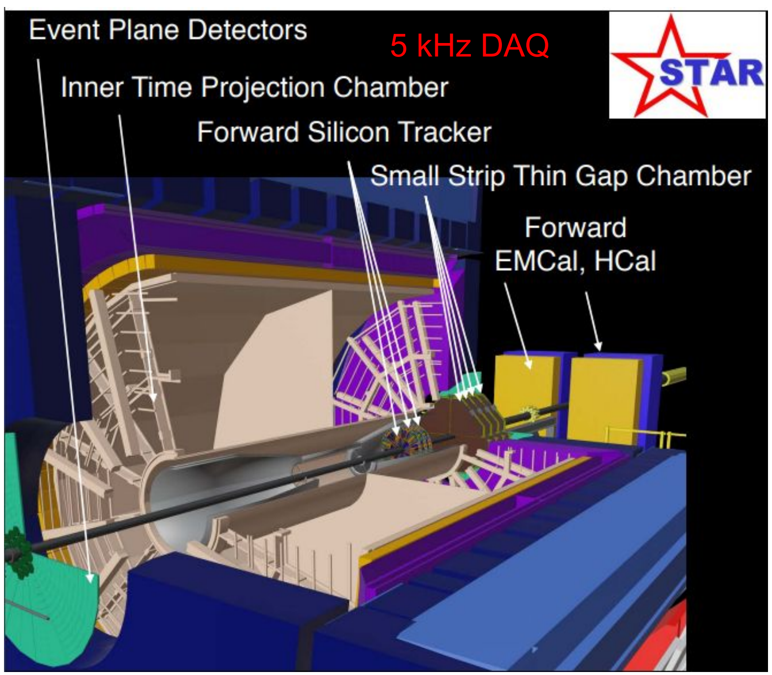
LHC Runs 3, 4 & beyond

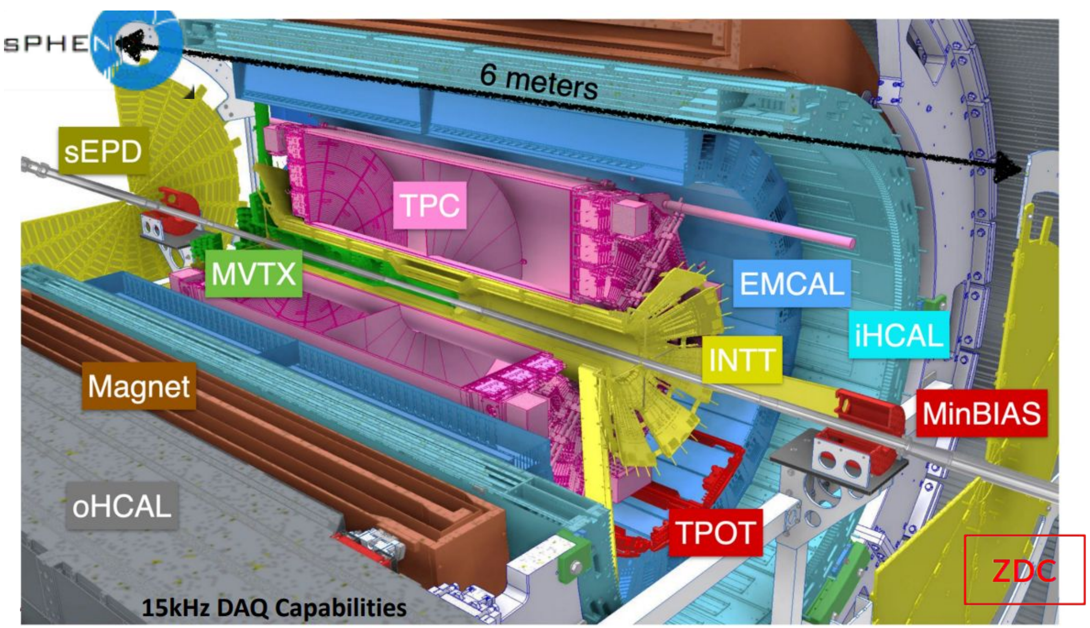
- Improvements relative to Run 2 for CMS
  - 3x increase in DAQ rate
  - 4 layer pixel in our software
- Upgraded detectors in Run 4
- Run 5 unique chance to enrich the NP program
  - dedicated taskforce for lighter ions
  - benchmark performance with O in 2024



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

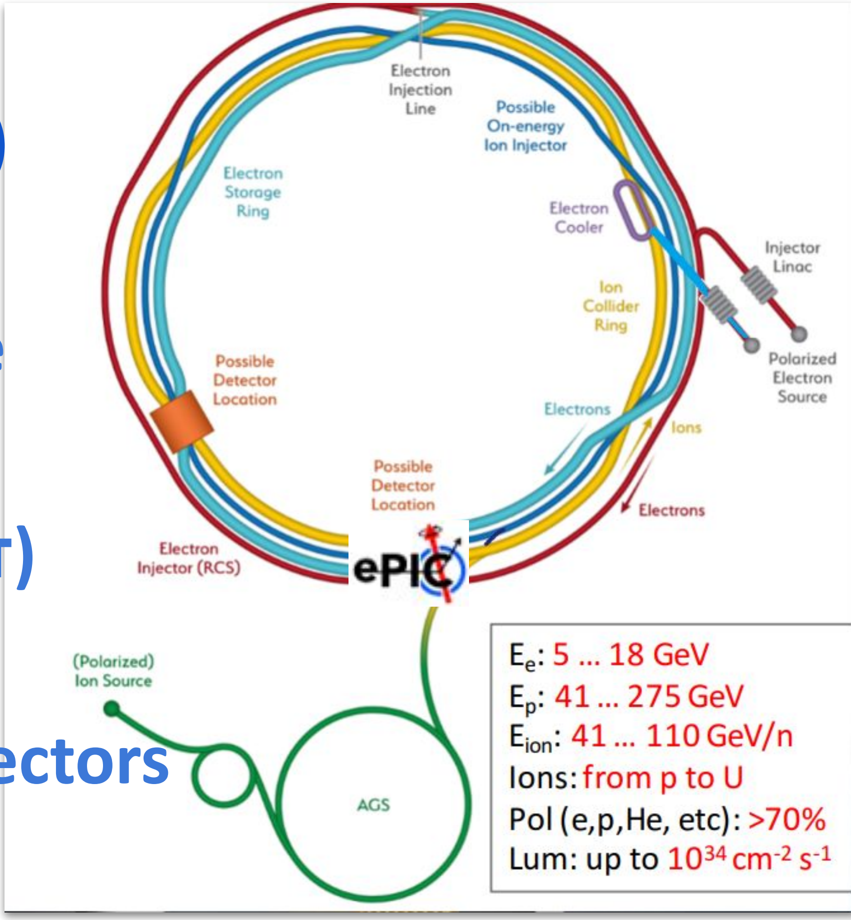




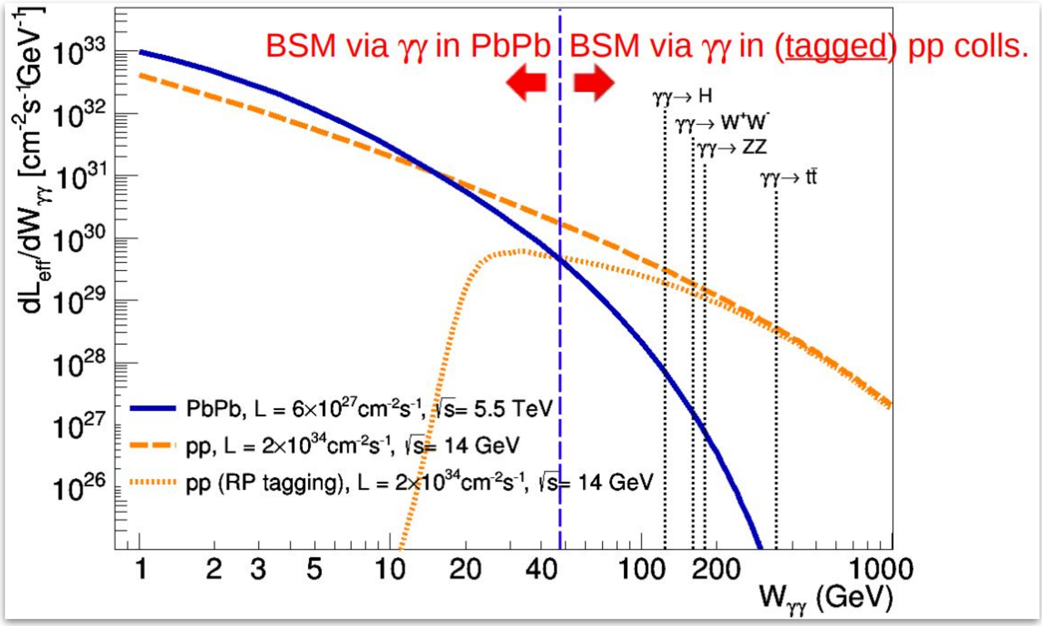
EIC: the nuclear HERA

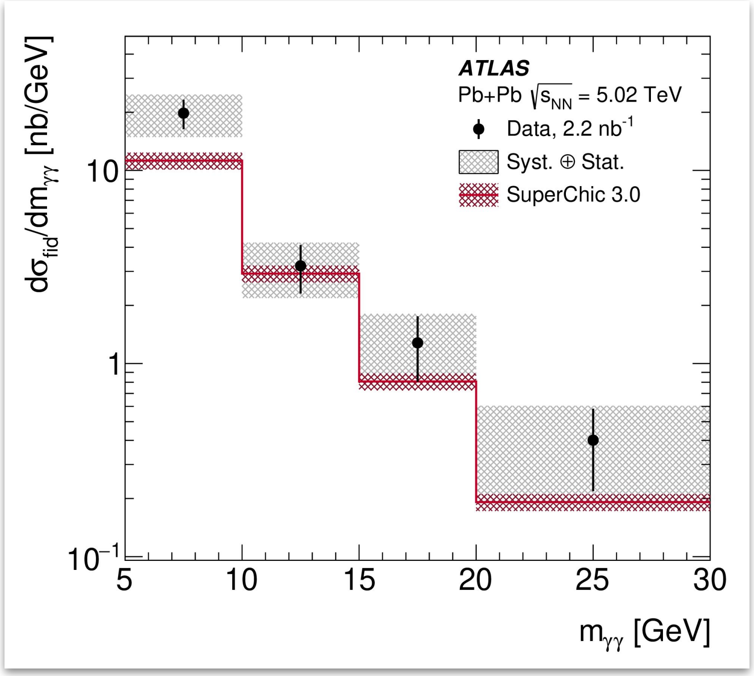
A high luminosity ($10^{33} - 10^{34}$ cm^{-2}s^{-1}) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

- Only new collider in foreseeable future
  - frontier of Accelerator S&T
- ePIC Collaboration formed (IR6)
- General purpose detector
  - $-4<\eta<4$ & 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



LbyL production in UPC AA

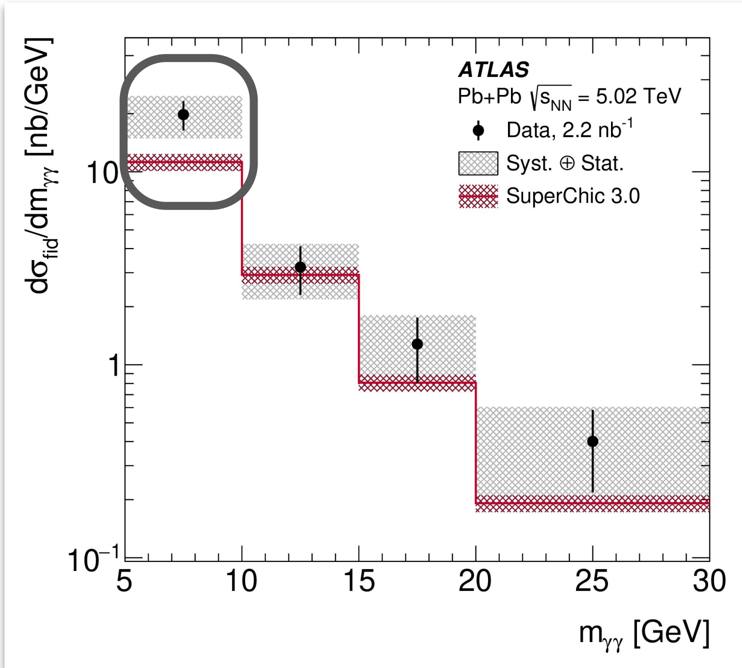


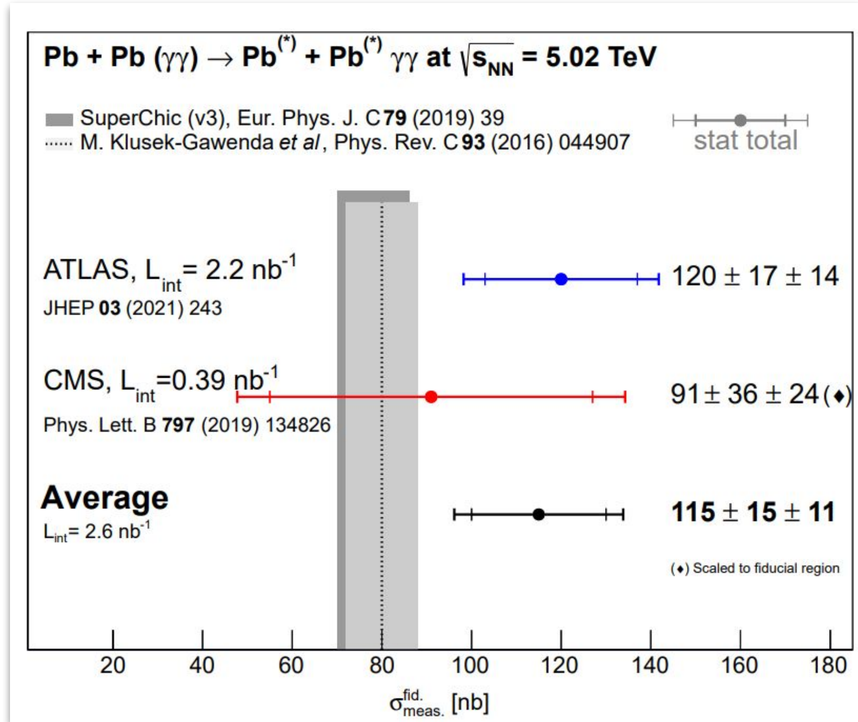


- **Z^4 enhancement: γγ luminosities ≫ pp ones at low $W_{\gamma\gamma}$**
  - NP naturally complements BSM efforts
    - concerted effort with large AA samples at RHIC+LHC
- **Event statistics already allow for differential studies**
  - low-$\mathbf{m}_{\gamma\gamma}$ excess triggered already dedicated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

LbyL production in UPC AA

Nature Phys. 13 (2017) 852
Krintiras *et al*, arXiv: 2204.02845
JINST 16 (2021) P05014



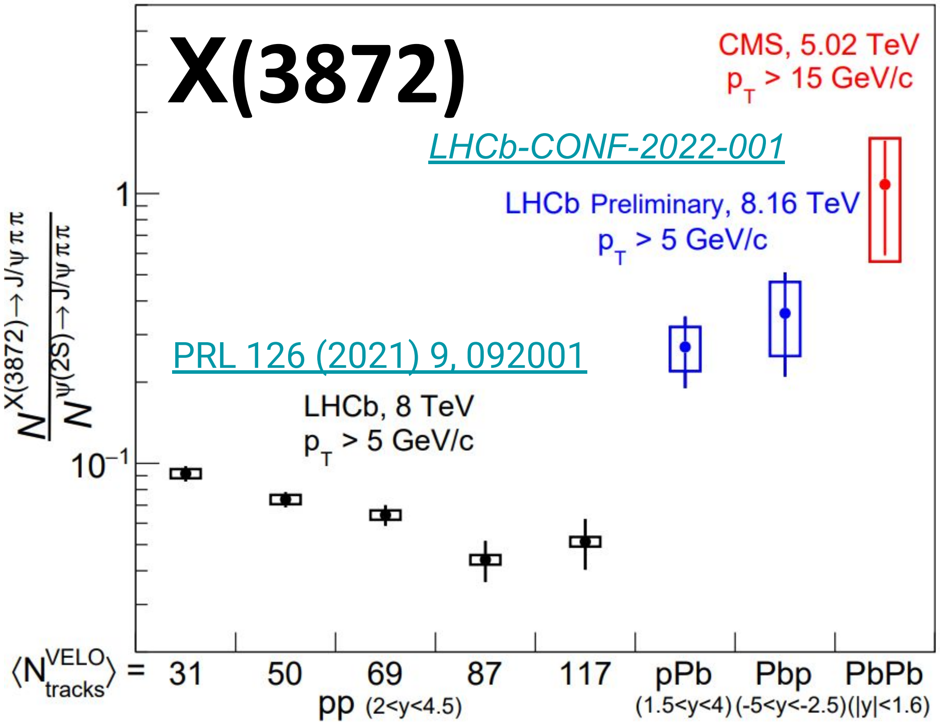


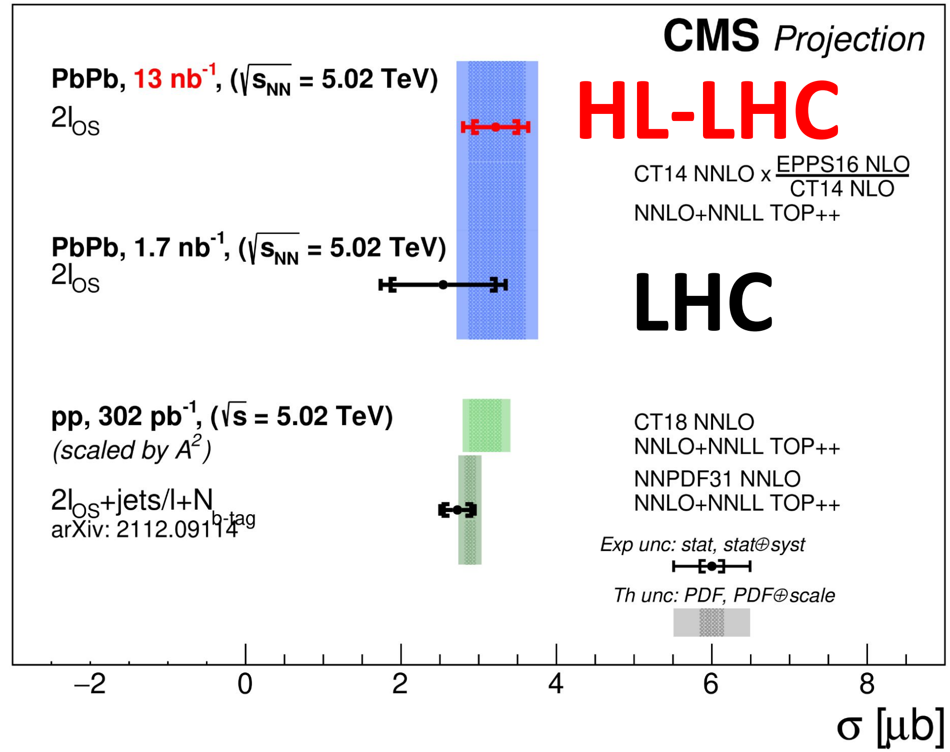
- **Event statistics already allow for detailed studies**
  - low-mass excess triggered already dedicated efforts
    - optimized the low-energy photon reconstruction
    - I performed the first combination with NP data at LHC
- **NP naturally complements BSM efforts**

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

Exotic hadrons and top quarks in AA

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

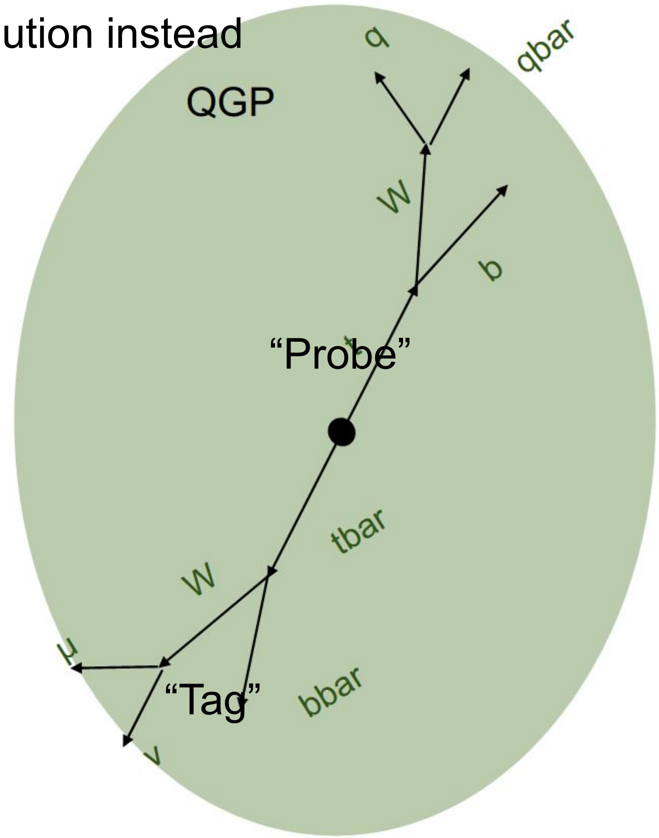


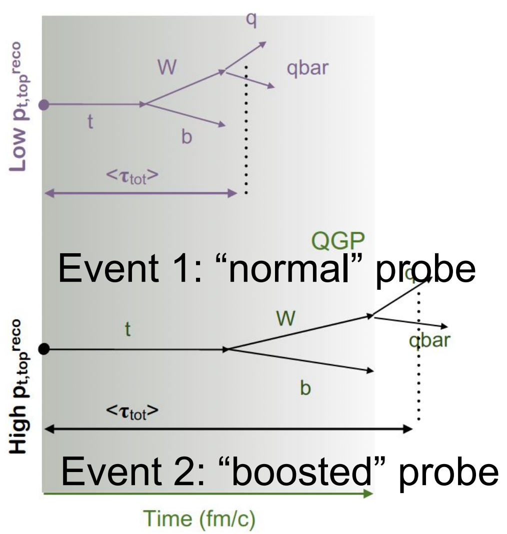


- **NP can revolutionize exotic hadron spectroscopy**
  - quark configurations for many exotics remain elusive
- **Use top quark production as a new tool**
  - reducing nPDF uncertainty; the most primordial b jets

Probing the “final state”: the yoctosec QGP lifetime

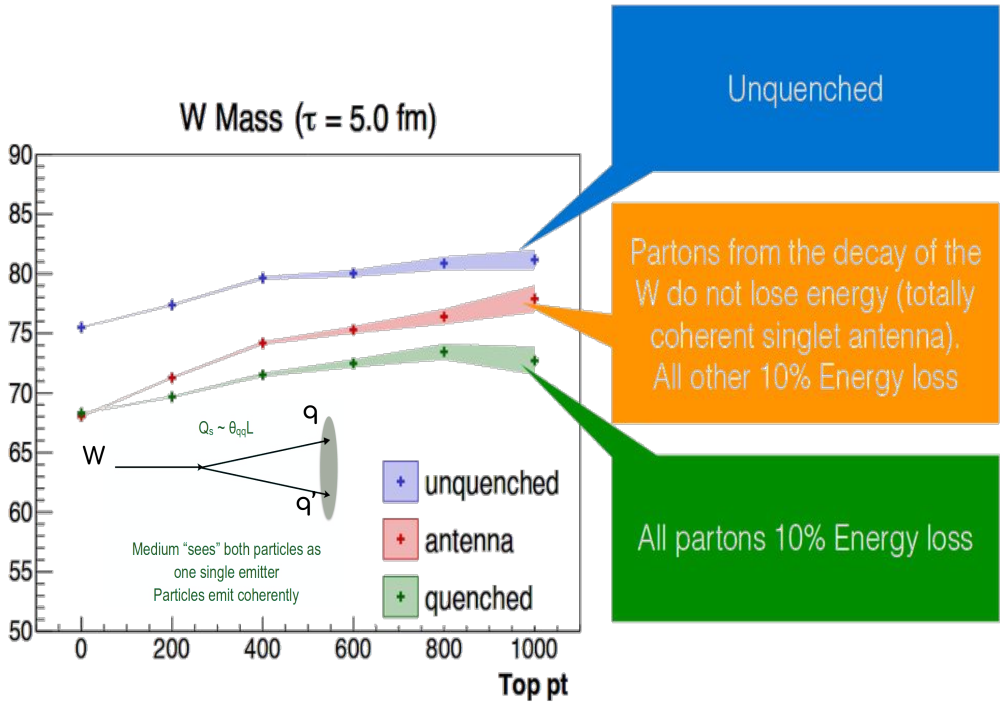
- Probes for jet quenching, e.g., dijets, Z/γ+jet, are produced **simultaneously** with the collision
- Top decay products have the potential to **resolve** the QGP evolution instead
- Leptonic & hadronic branches as “tag” & “probe”
- qq’ start interacting with the medium at **later** times
- top p_T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

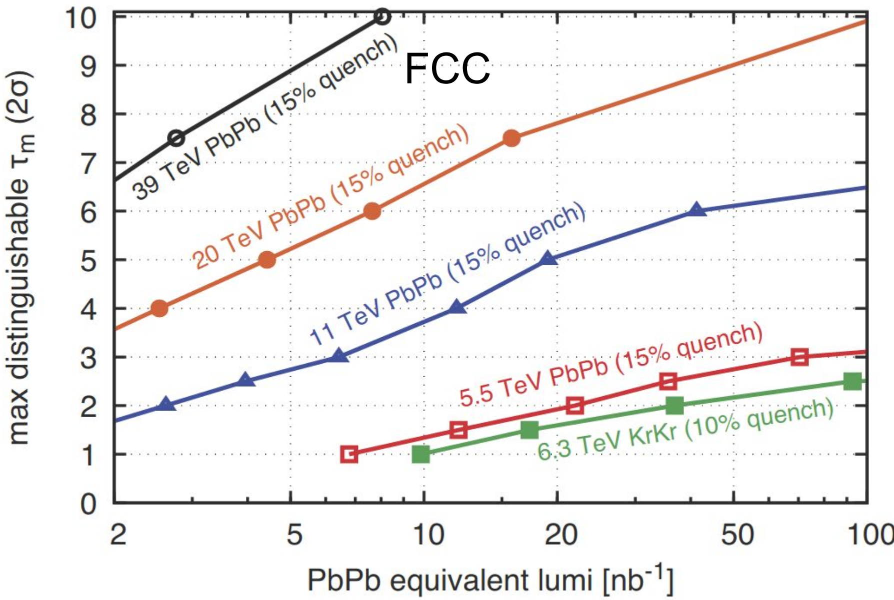




W mass vs top p_T and QGP lifetime reach

- 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)



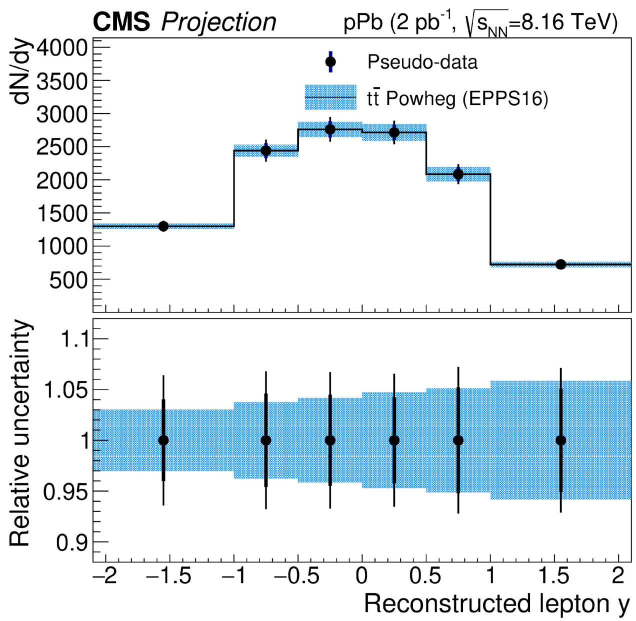


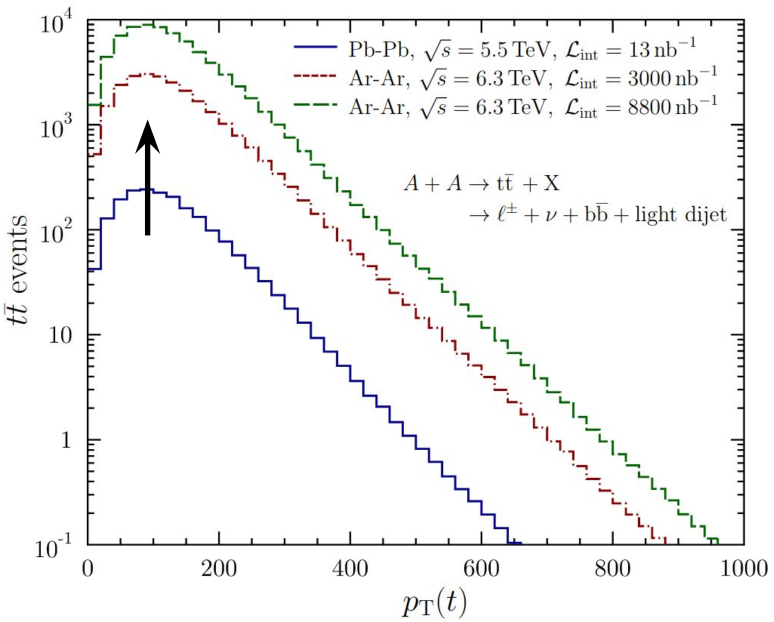
HL-LHC

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

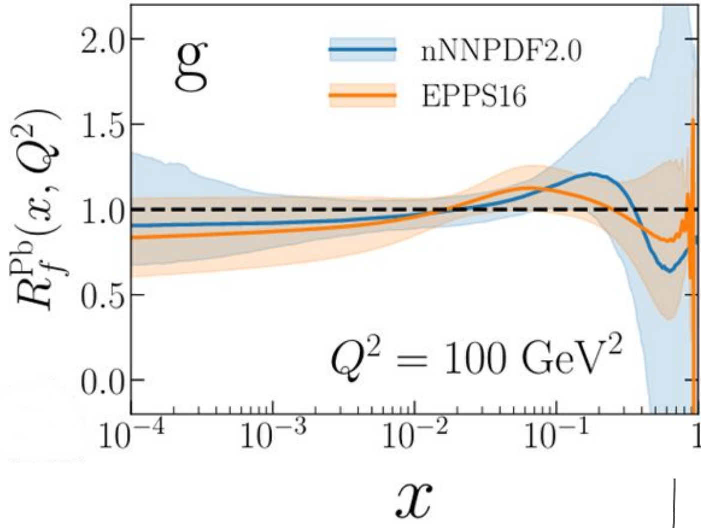




nPDFs from several groups but long way to go

2203.13923

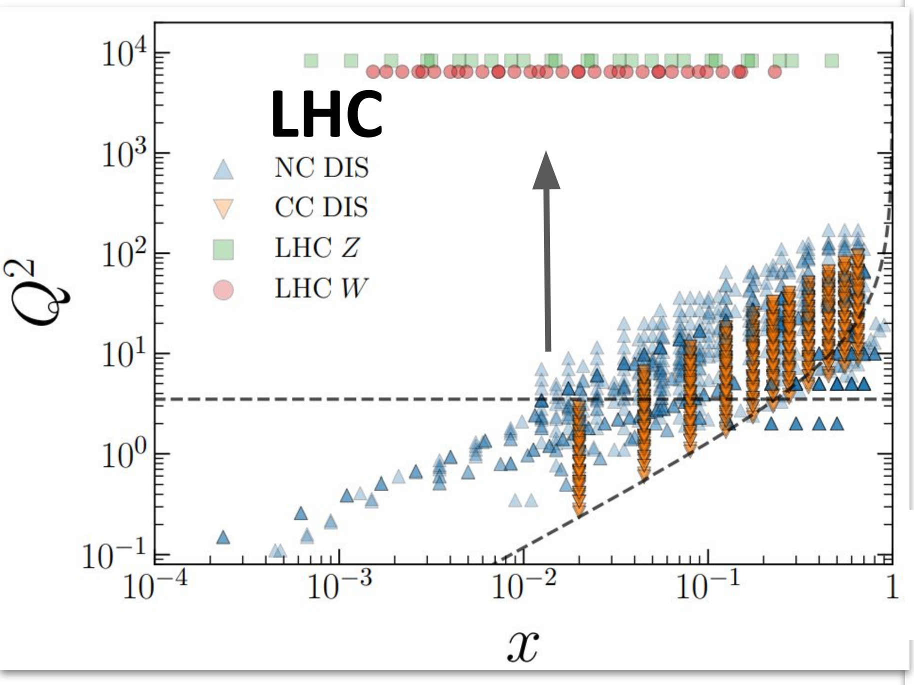
Nuclear (most recent) PDFs	nCTEQ15	EPPS16	nNNPDF2.0 (1.0)	TUJU19
Perturbative order	NLO	NLO	NLO, NNLO	NLO, NNLO
Heavy quark scheme	ACOT	S-ACOT	FONLL	ZM-VFN
Value of $\alpha_s(m_Z)$	0.118	0.118	0.118	0.118
Input scale Q_0	1.30 GeV	1.30 GeV	1.00 GeV	1.69 GeV
Data points	708	1811	1467 (451)	2336
Fixed Target 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	$\Delta\chi^2 = 35$	$\Delta\chi^2 = 52$	—	$\Delta\chi^2 = 50$

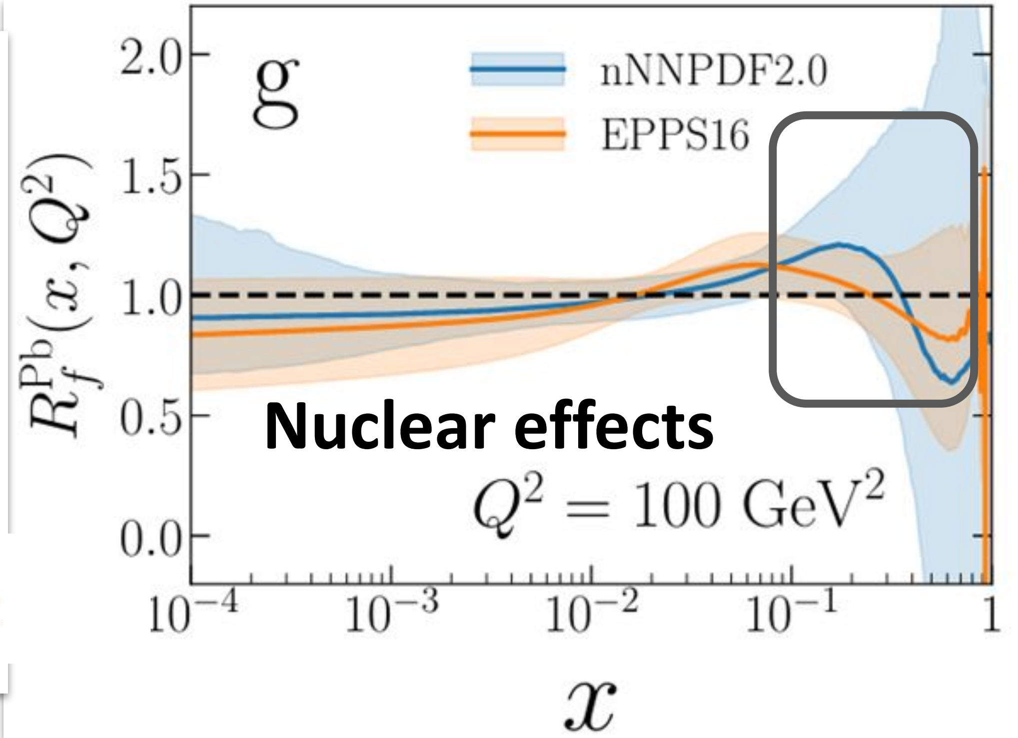


- **Features of the current fits**
  - **Less available sets compared to proton PDFs**
  - **Different sets, theoretical assumptions, and methodological settings**
- **The nuclear modification of the gluon distribution not well understood**

nPDFs: long way to go

arXiv: 2203.13923
JHEP 09 (2020) 183



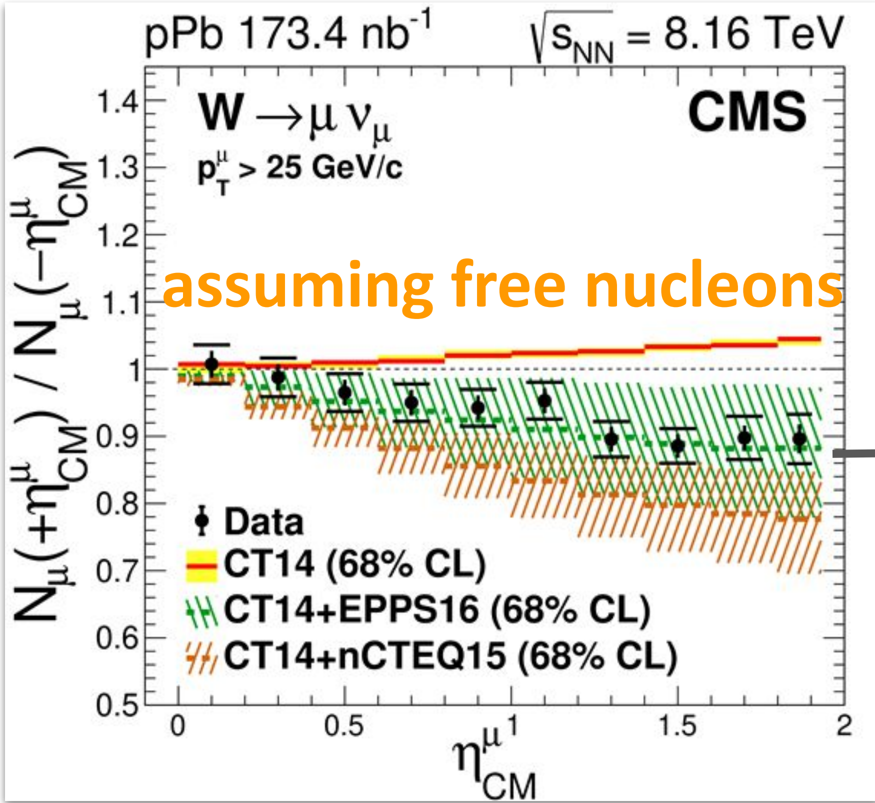


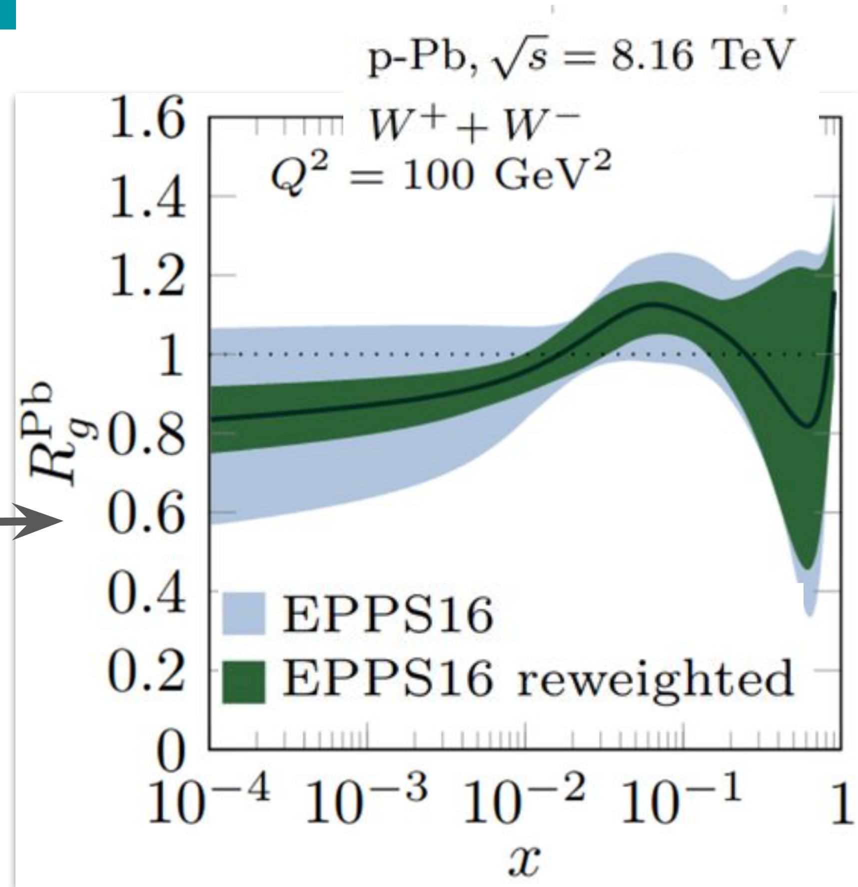
- LHC data gave an increase in kinematic coverage
- The nuclear modification of gluons not well understood
  - available data sets still limited

Can we do better?

Tools for **precise** nPDF extraction

PLB 800 (2020) 135048



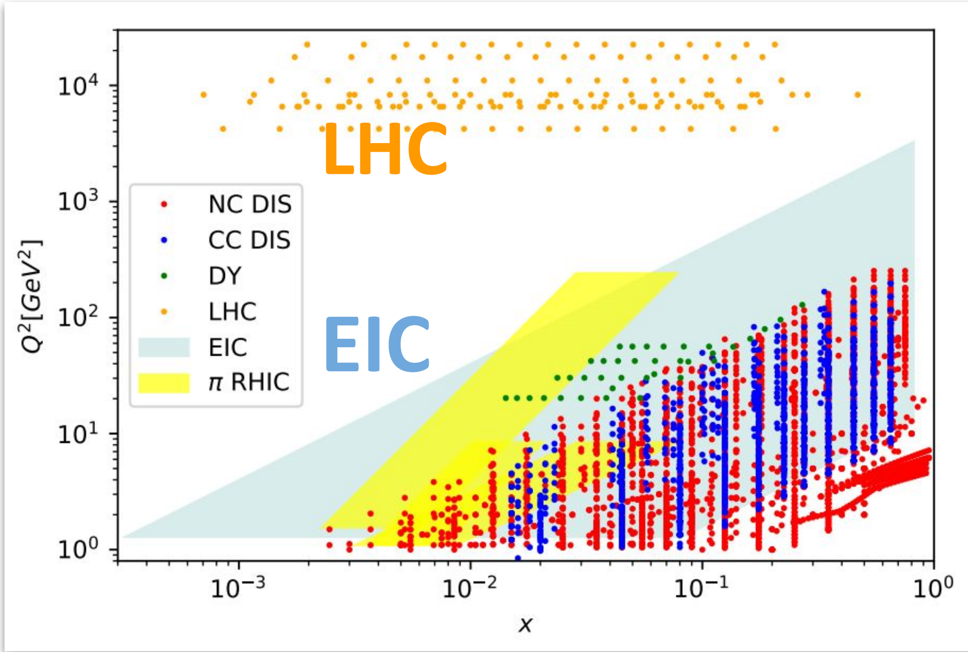


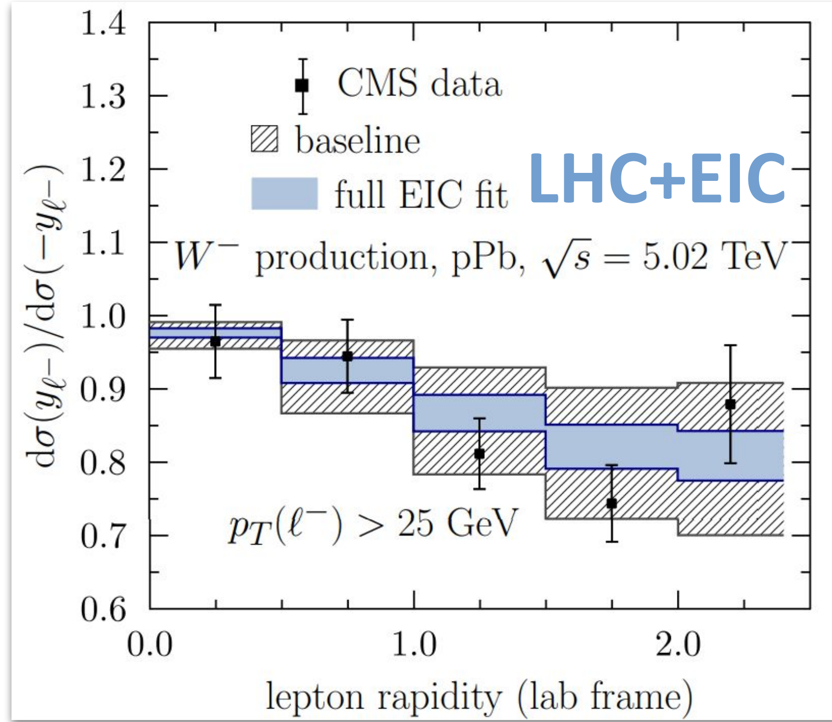
- **LHC data reduced the gluon nPDF uncertainty**
- **The large-*x* (> 0.1) region is not affected though**
  - **only dijets and top quarks probe this *x* region**

LHC data unique chance to pin down nPDF uncertainties

Are nPDFs global or not?

arXiv: 2103.05419
PRD 96 (2017) 114005



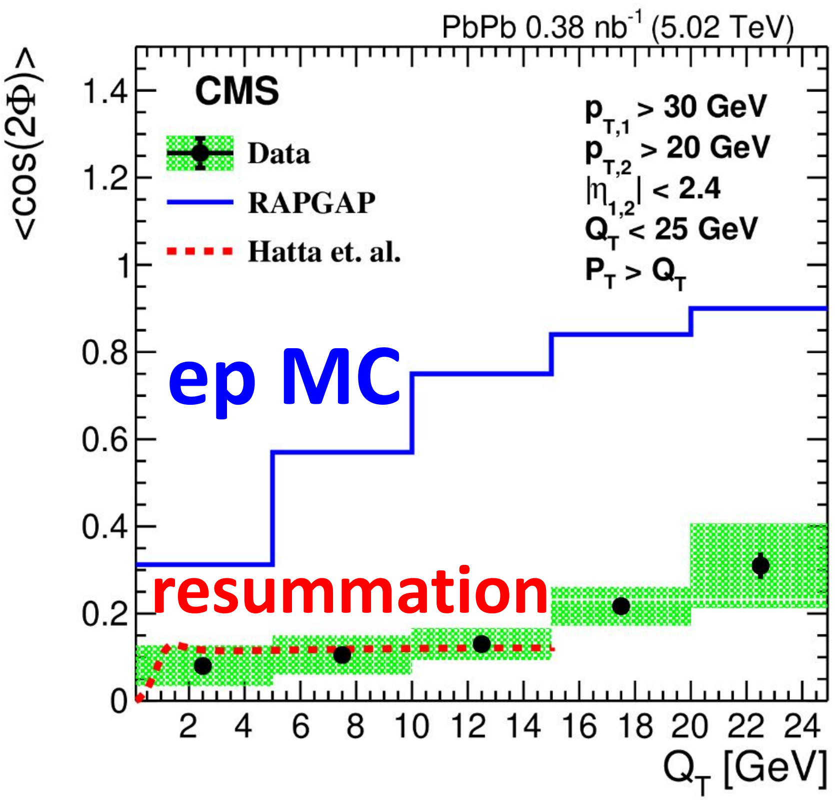


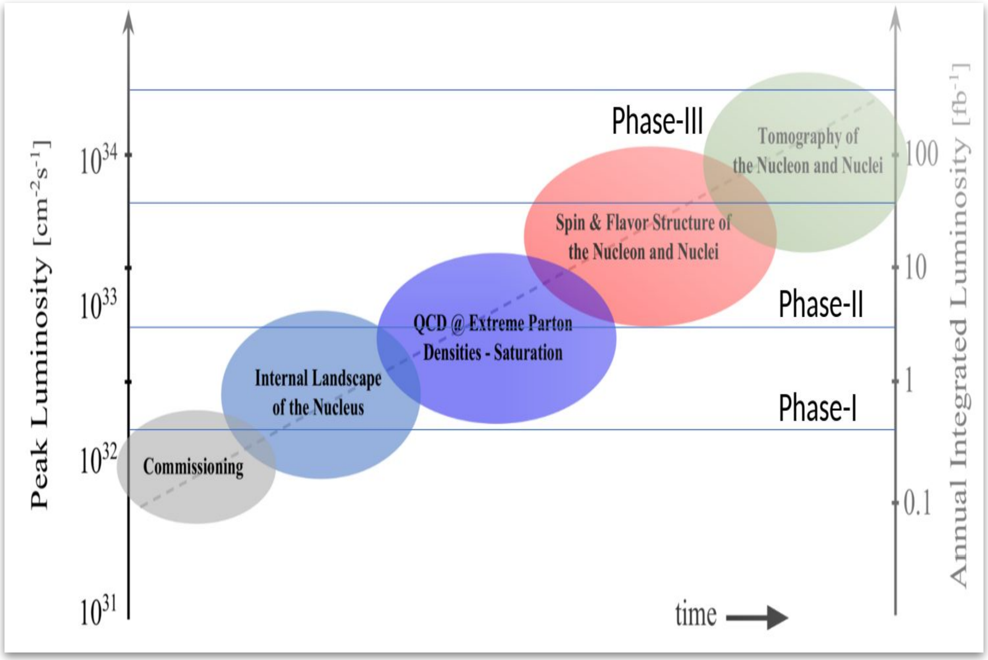
- EIC will also offer a huge increase in kinematic+*A* coverage
- We'll answer whether nPDFs are universal or not
- nPDFs are only the "LO" of a tomography/spatial imaging

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

Still this would be the first step for a long journey

arXiv:2205.00045 (accepted by PRL)



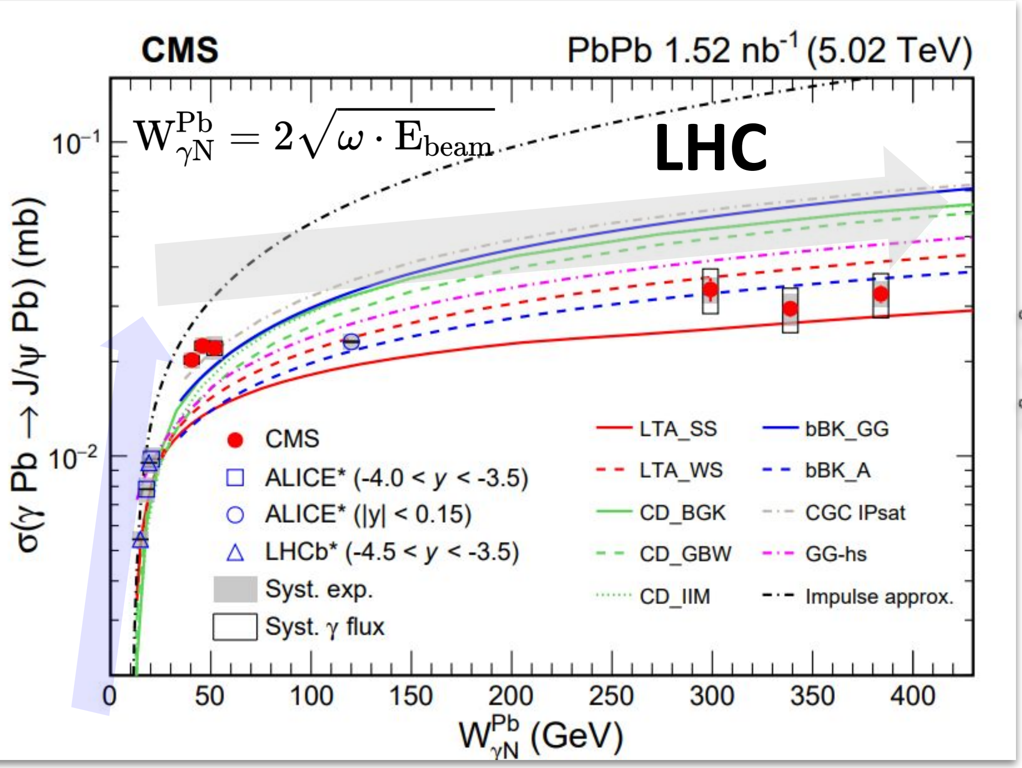


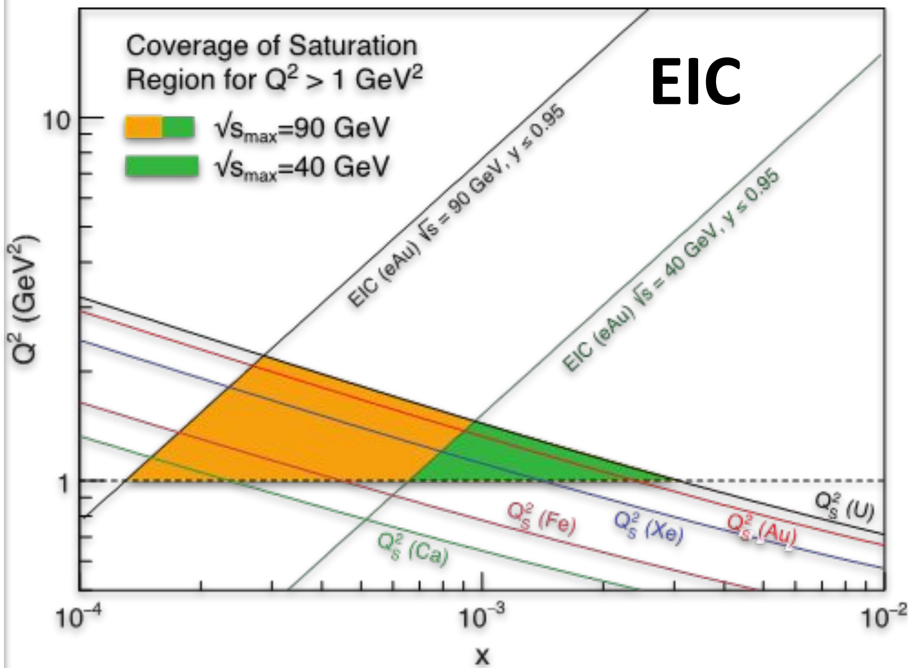
- **<cos(2Φ)> for exclusive dijets not well described by MC tuned in ep**
  - sensitive to primordial asymmetry due to the linearly polarized gluons
- **nPDFs are only the "LO" of a 4+1D tomography/spatial imaging**
  - inclusive DIS ⟶ semi-inclusive DIS ⟶ exclusive processes

EIC is a gluon factory

arXiv: 2303.16984
arXiv: 2103.05419

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



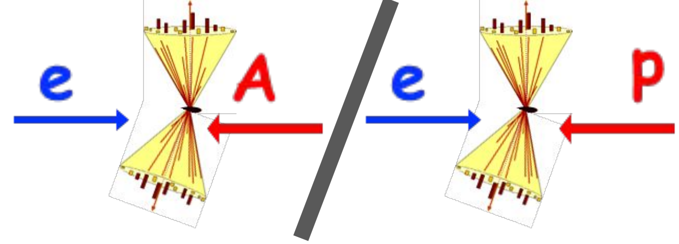


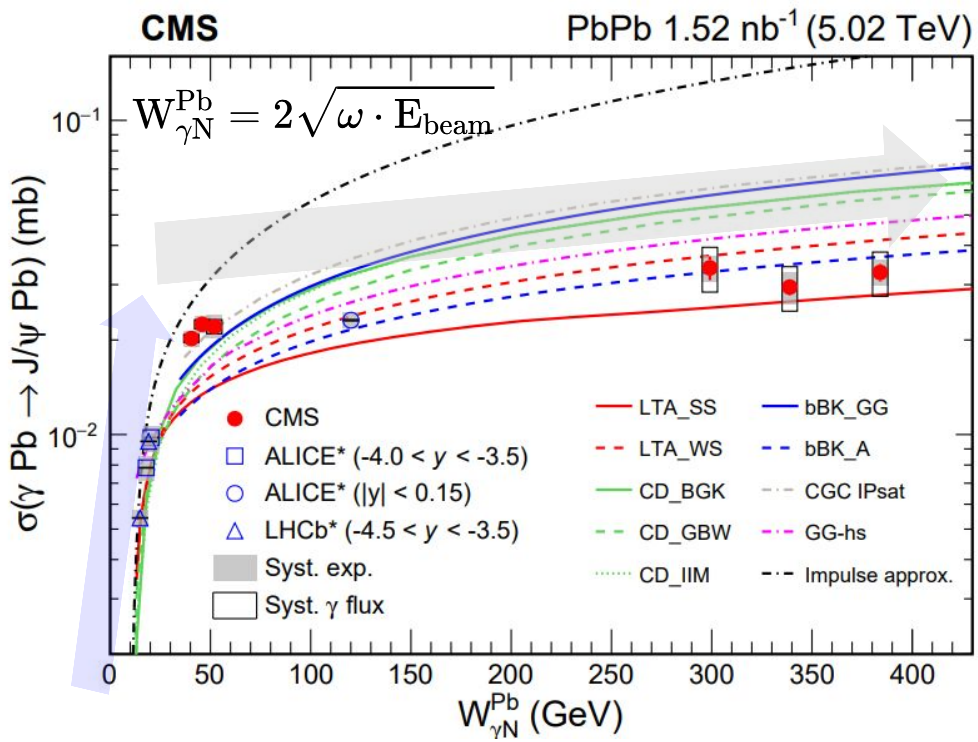
- **We see a milder energy dependence than predicted**
  - gluon saturation? if so, independent of particle species
- **Accessible Q_s values at EIC thanks to ion species and energies**

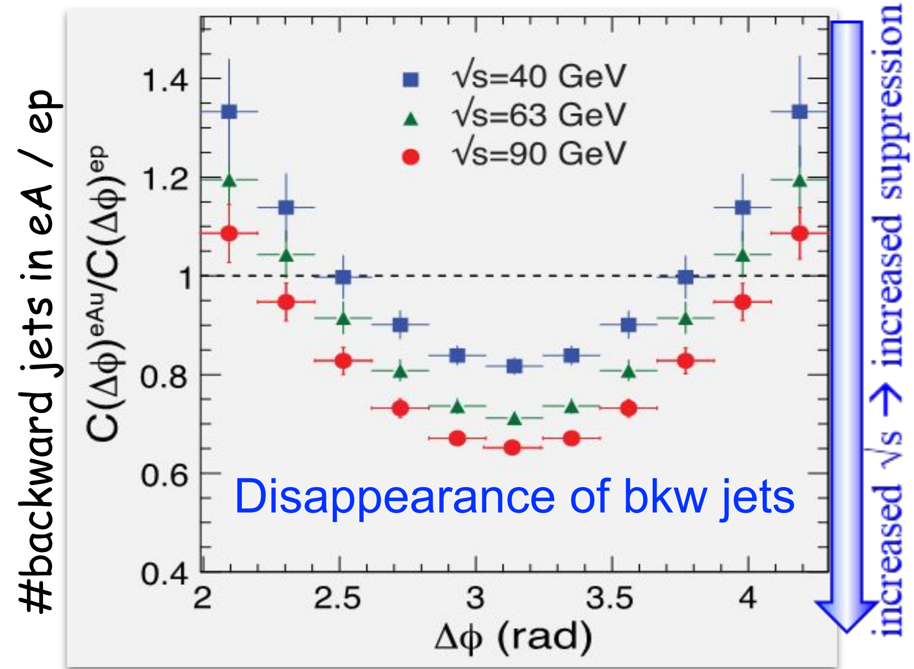
Explore LHC with more particles; EIC can discover a new state of matter

EIC is a **gluon factory**

HIN-22-002
(to appear)



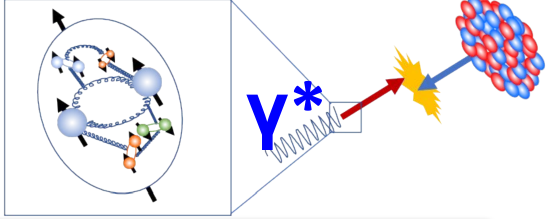


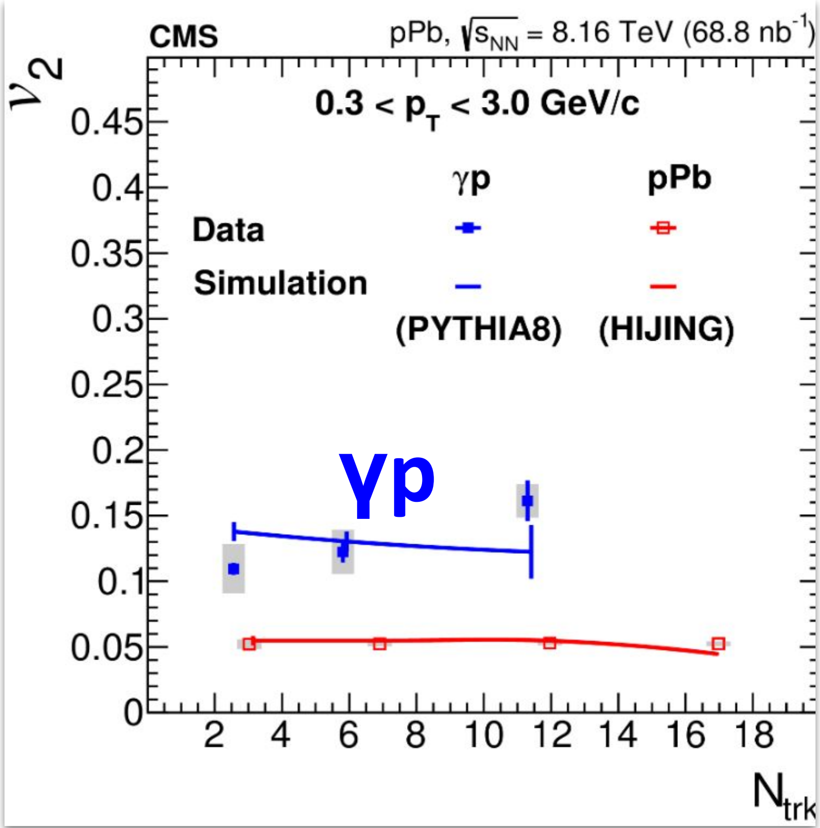


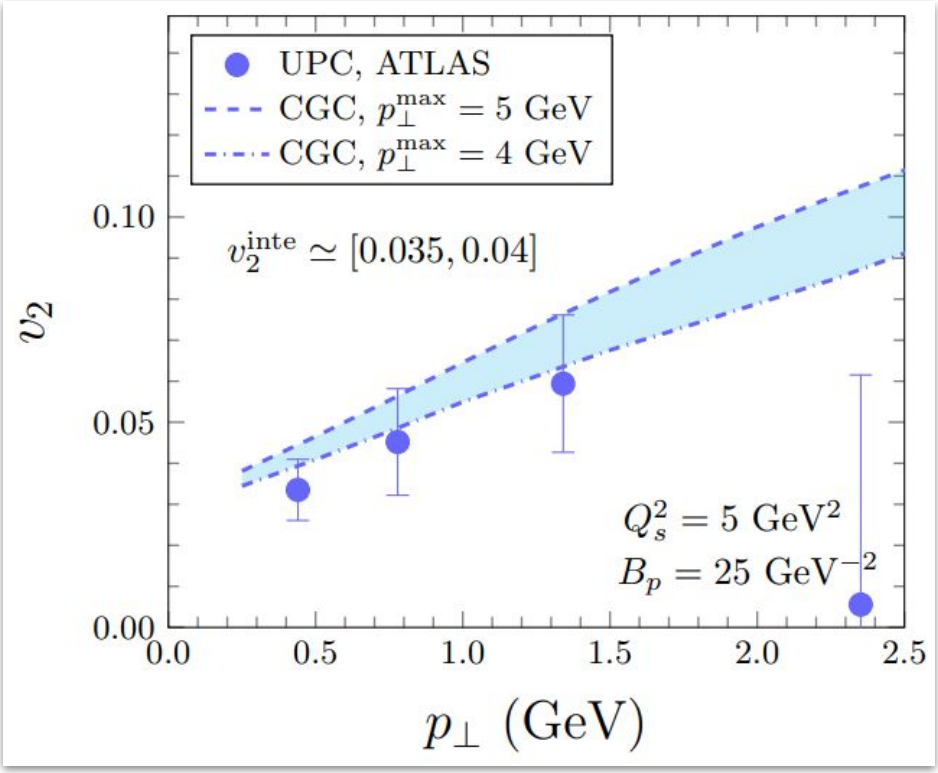
- **ALICE and CMS dissentagled low- and high-γ energy contributions**
  - experimental uncertainty **correlated** across or $W_{\gamma N}^{Pb}$
    - flattening of coherent σ(J/ψ) vs. $W_{\gamma N}^{Pb}$ not predicted by models
- **Nonlinear QCD regime reached at lower √s in nuclei than in proton?**
  - 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



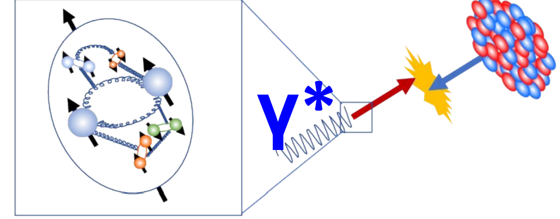


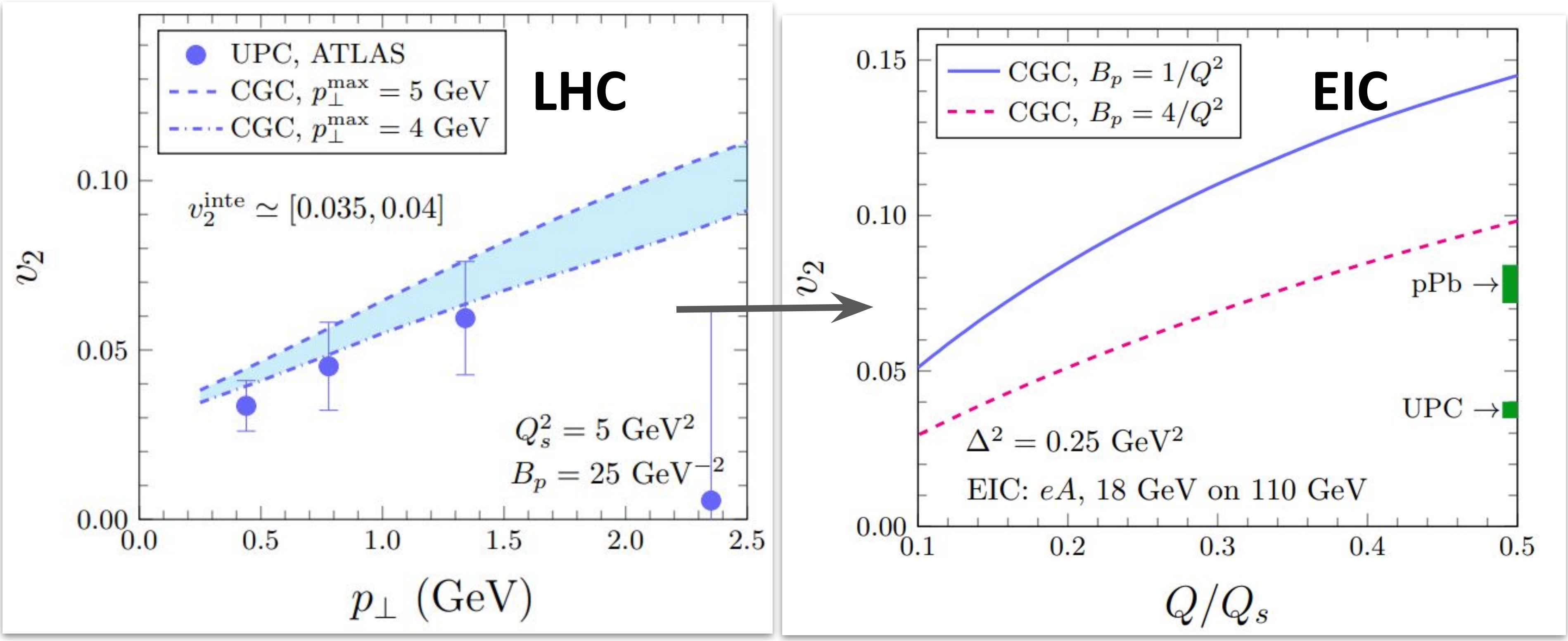


- **Bridging large with exceedingly small systems**
  - PYTHIA8 describes v_2 in γp collisions ⟶ jet-like correlations still dominate
- **A simplified CGC model can describe the γ*Pb UPC data**
  - contribution from final-state effects is yet an open question

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

PRD 103 (2021) 054017



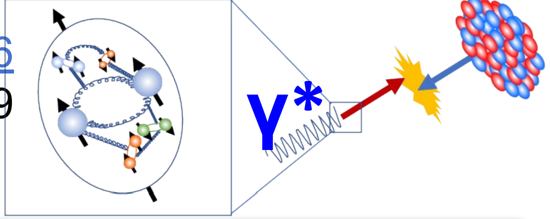


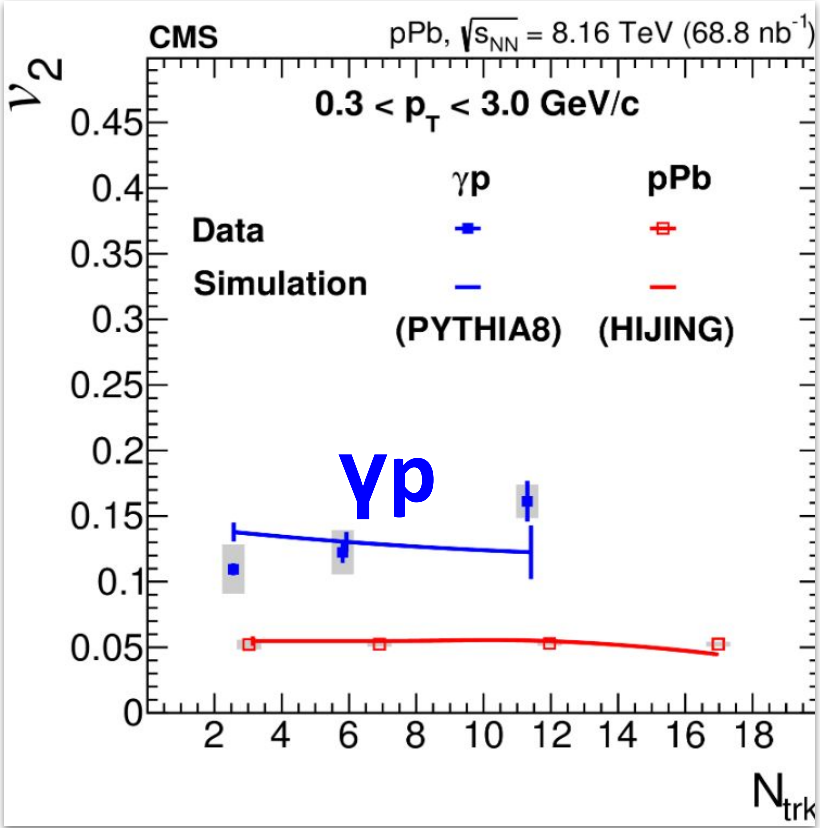
- **Gluon saturation models describe LHC anisotropy (υ_2) data**
  - but equally well with orthogonal models ⟶ an open question
- **These models predict sizeable υ_2 values at EIC**

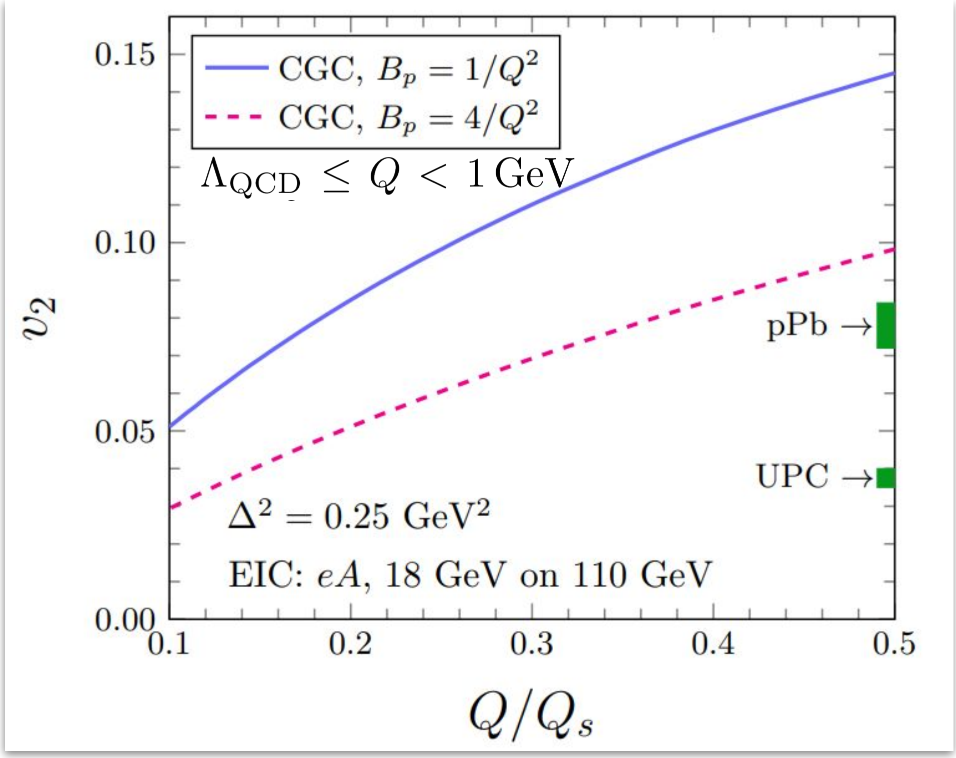
LHC with more data; EIC unprecedented opportunity to study the origin of υ_2

What's the small size QGP limit?

arXiv:2204.13486
arXiv:2008.03569



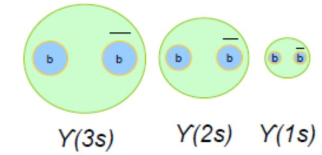


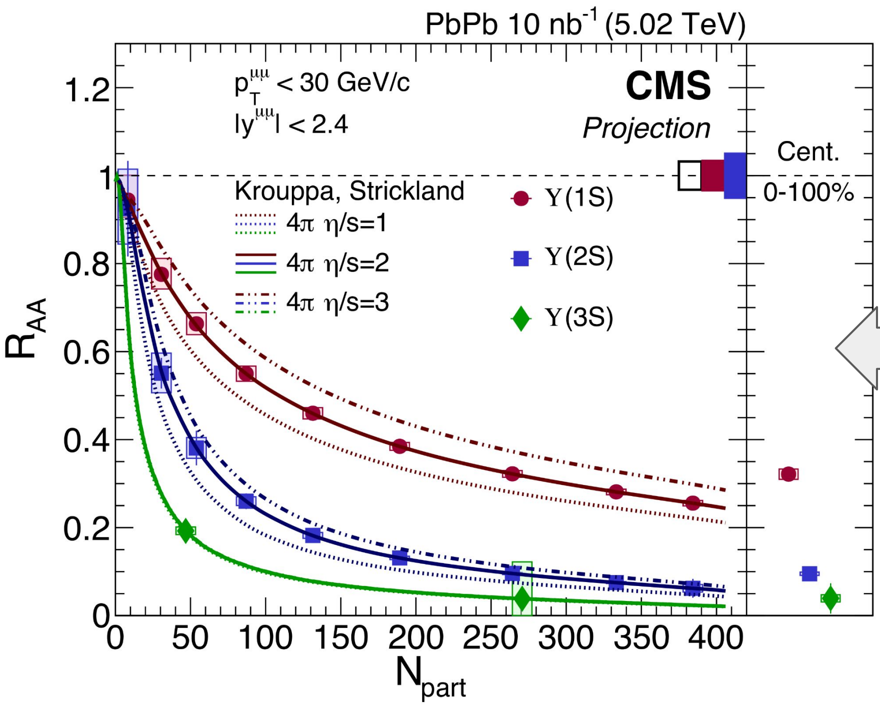


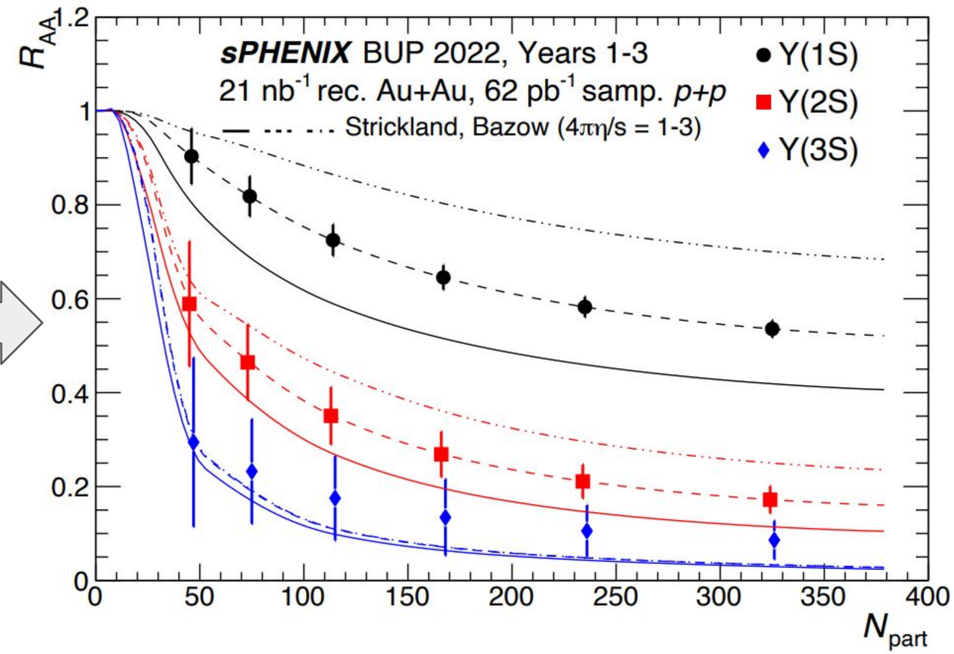
- **Bridging large with exceedingly small systems**
  - PYTHIA8 describes v_2 in γp collisions ⟶ jet-like correlations still dominate
- **A simplified CGC model can describe the γ*Pb UPC data**
  - contribution from final-state effects is yet an open question
  - EIC an unprecedented opportunity to study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

Υ(ns) suppression in LHC and RHIC

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





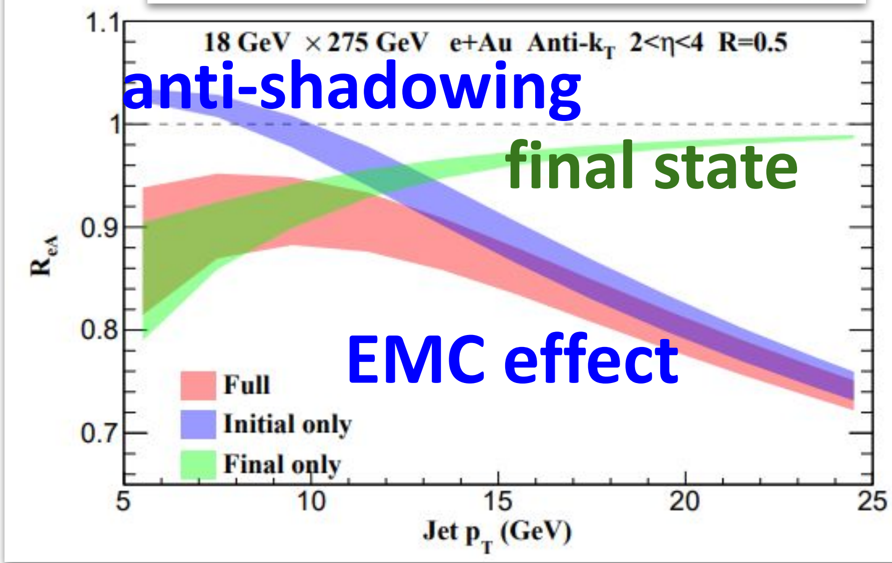


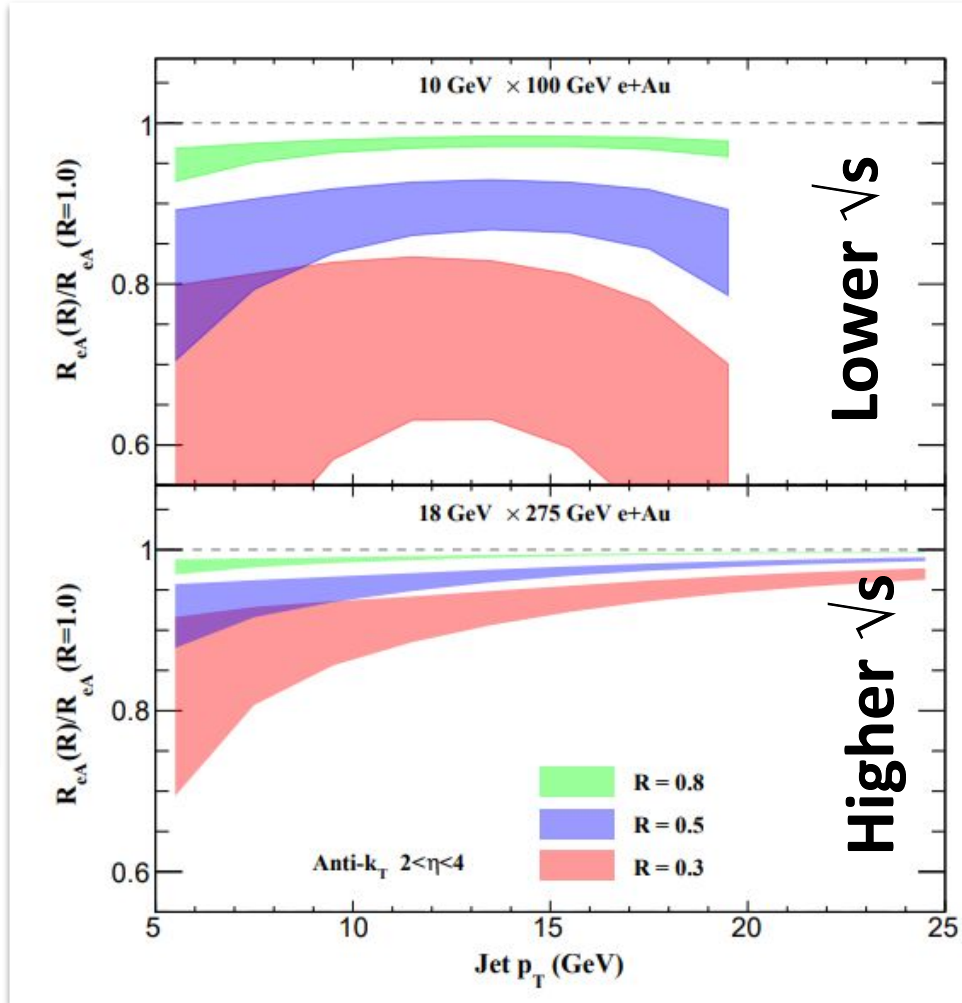
- **Observation of Υ(3S) also in PbPb**
  - indication of sequential suppression up to Υ(3S), ATLAS and STAR Υ(2S)+Υ(2S)
  - strong challenge for models to reproduce Υ(3S) R_{AA}>0
- **Strong complementarity between LHC and RHIC**
  - Excited states will set constraints on transport, hadronization, etc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

Jets at EIC

arXiv:2103.05419
arXiv:2108.07809

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

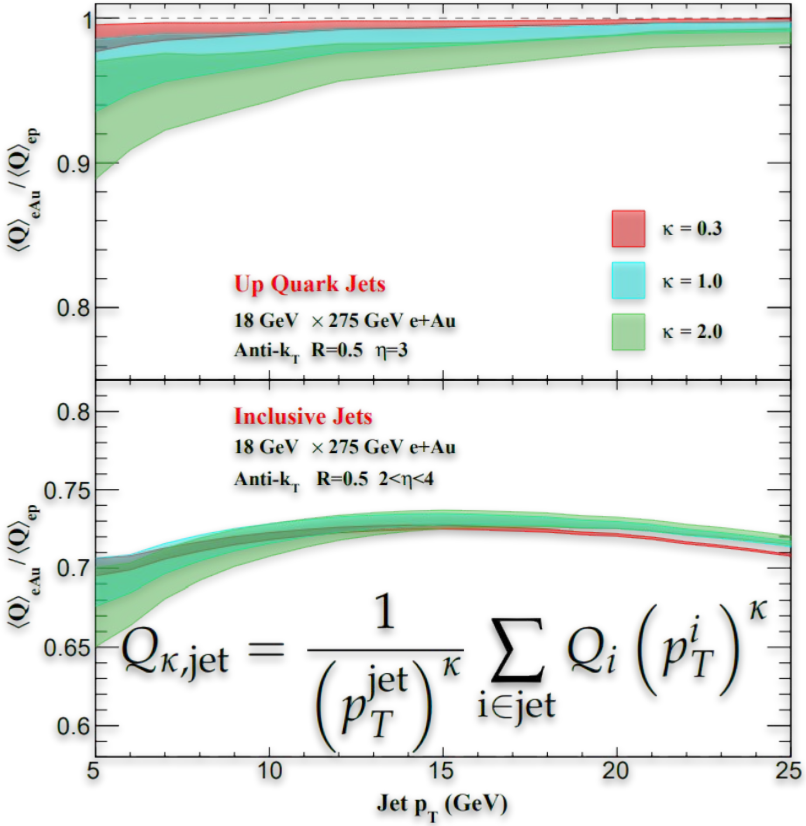


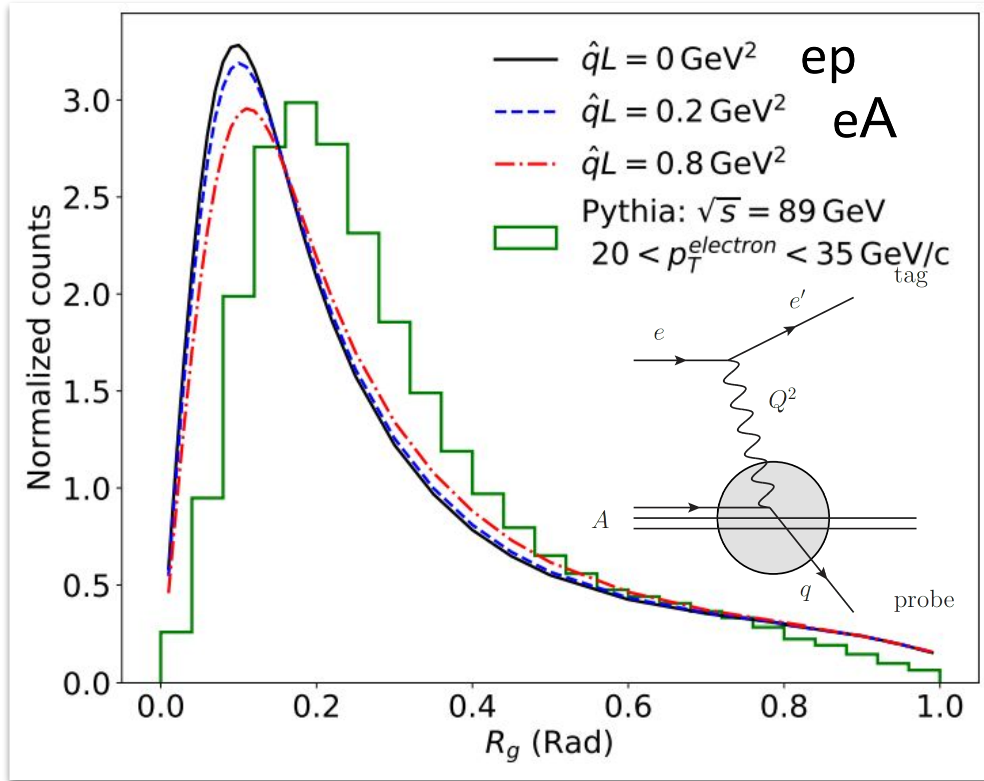


- **Large uncertainty in nuclear transport**
  - R_{eA} probes interactions inside nuclei and nPDFs at moderate and large *x*
  - $R_{eA}(R)/R_{eA}(R=1)$ eliminates initial-state effect; extra insights from varying √s (steeper p_T)

Jets at EIC

arXiv:2103.05419
arXiv:1912.05931

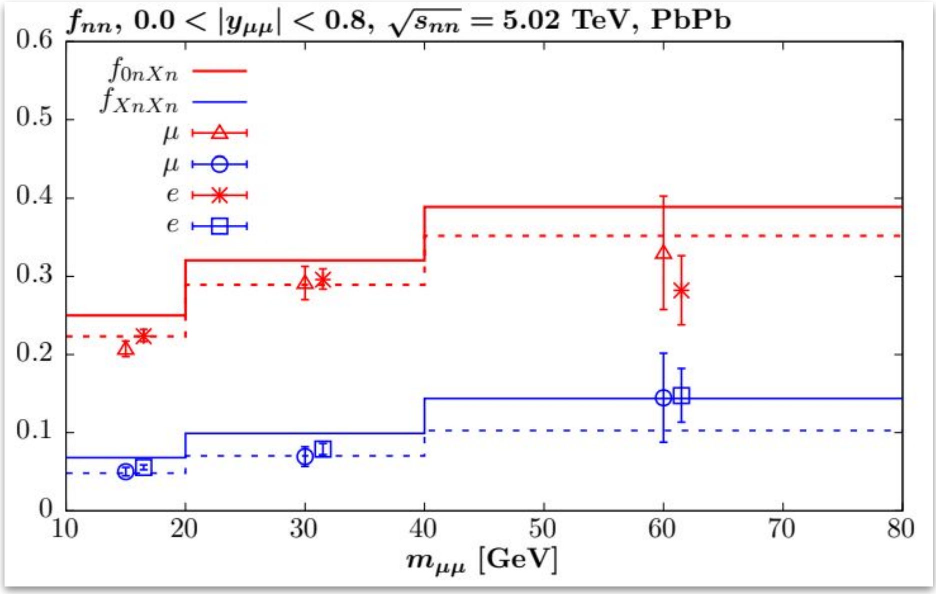




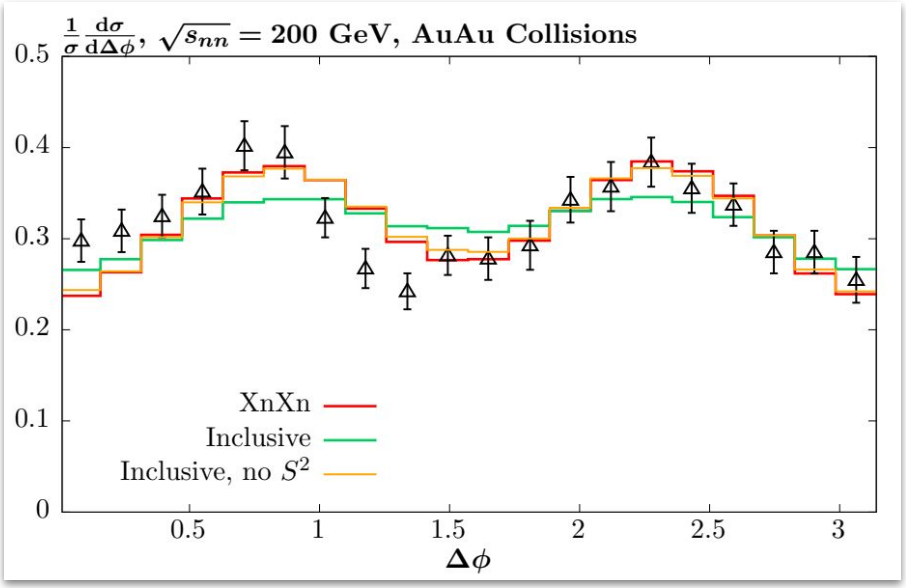
- **"Jet charge" strongly correlated with the parton's electric charge**
  - with flavor separation (Olga's group at LHC): final-state interaction with varying k
  - inclusive jets: constrain isospin effects and the up/down quark nPDFs
- **Jet substructure of DIS jets: wealth of new opportunities**
  - independent constraints on the parton transport coefficient in nuclei

It's an excess, bkg, mismodeling?

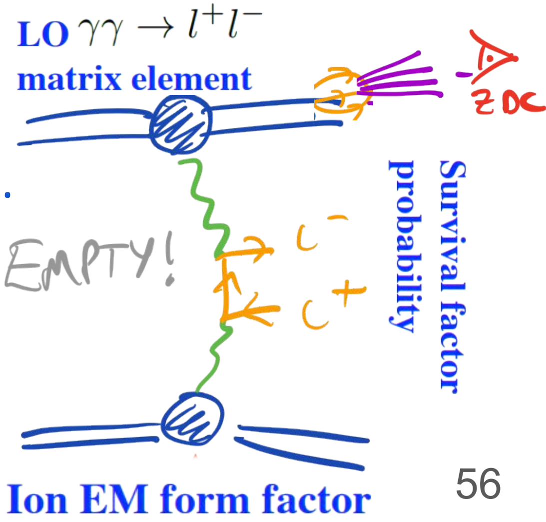
LHC



RHIC

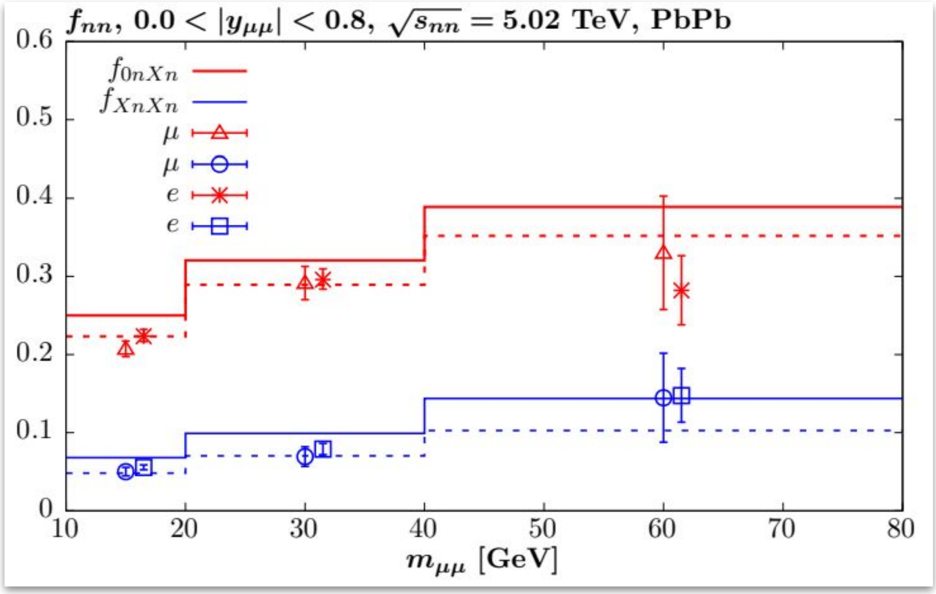


- **Key ingredients so far missing from UPC modeling**
  - Ion EM form factor, survival factor probability, mutual diss.
  - next to LO effects (FSR, multiscattering, ..)

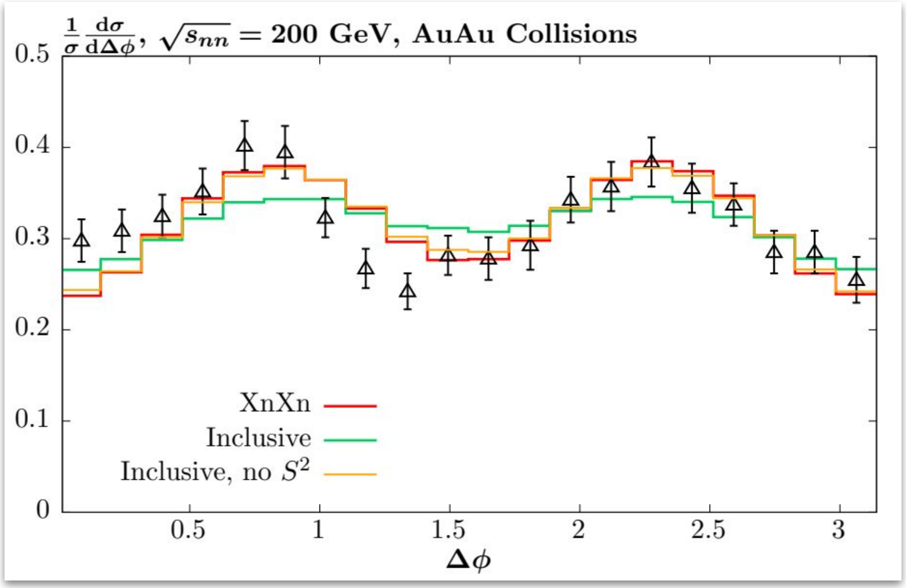


It's an excess, bkg, mismodeling?

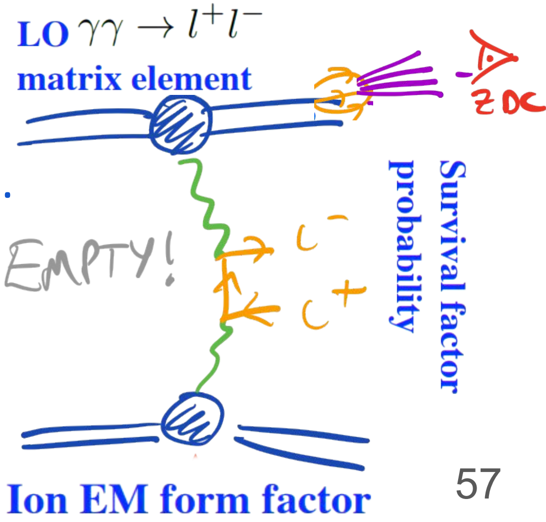
LHC



RHIC

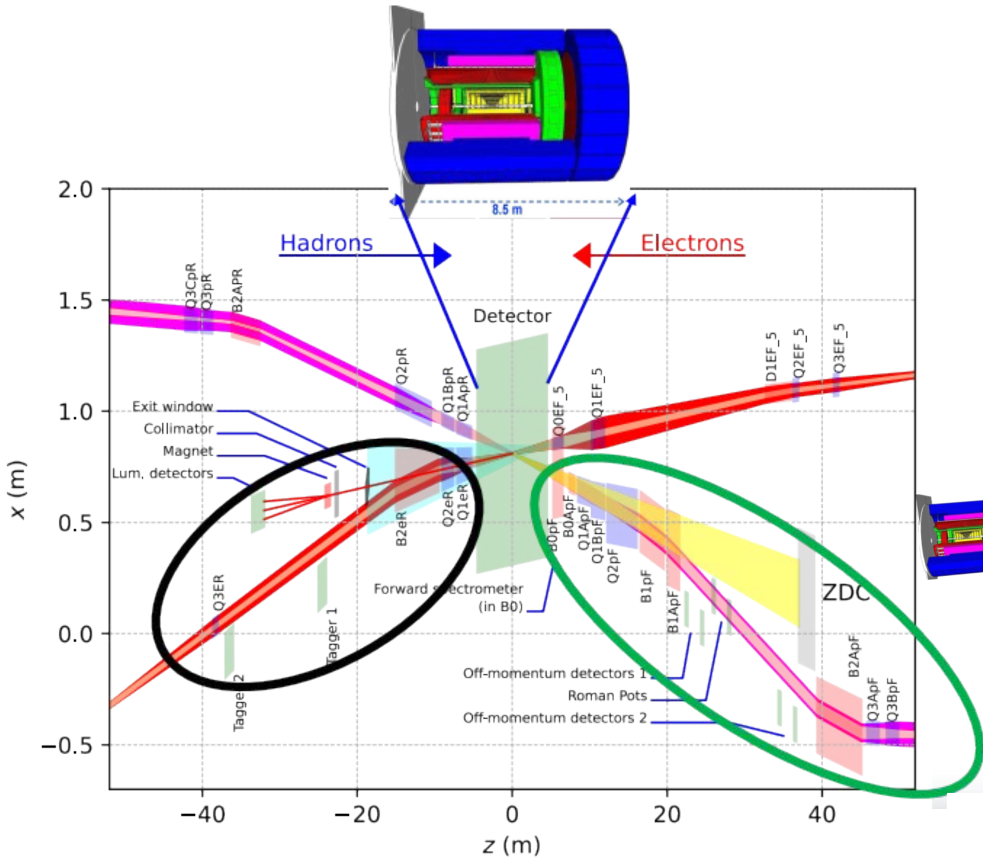


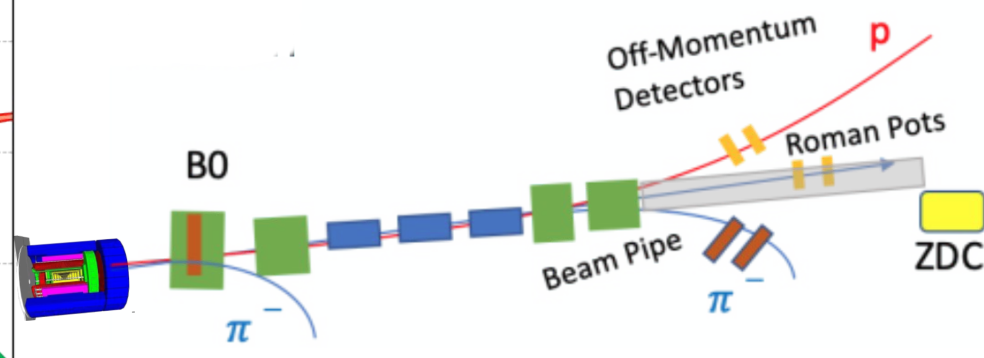
- **Key ingredients so far missing from UPC modeling**
  - Ion EM form factor, survival factor probability, mutual diss.
  - next to LO effects (FSR, multiscattering, ..)
- **Data/MC comparison encouraging**
  - applicable to other final states?
  - essential for precision QED program



EIC far-fwd & far-bkw regions

Far forward



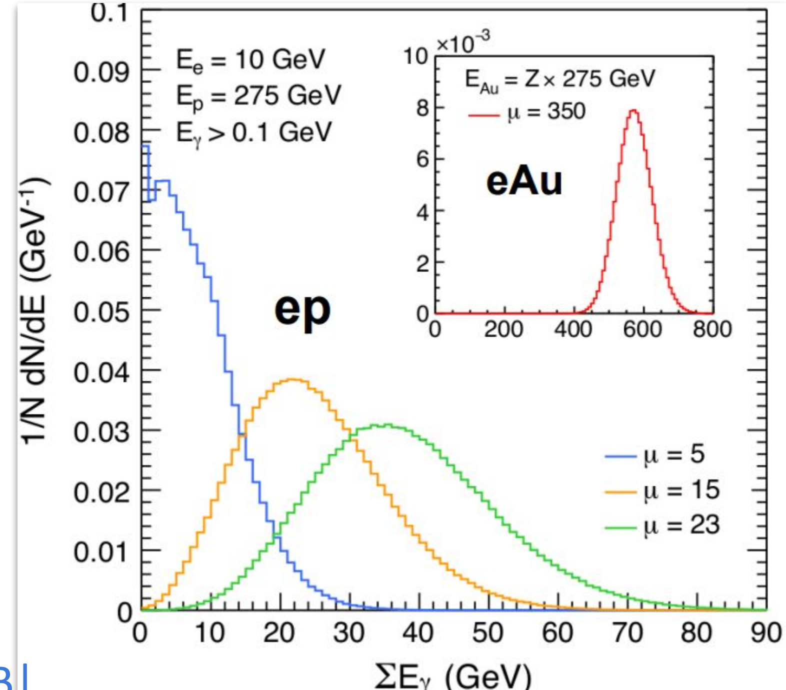


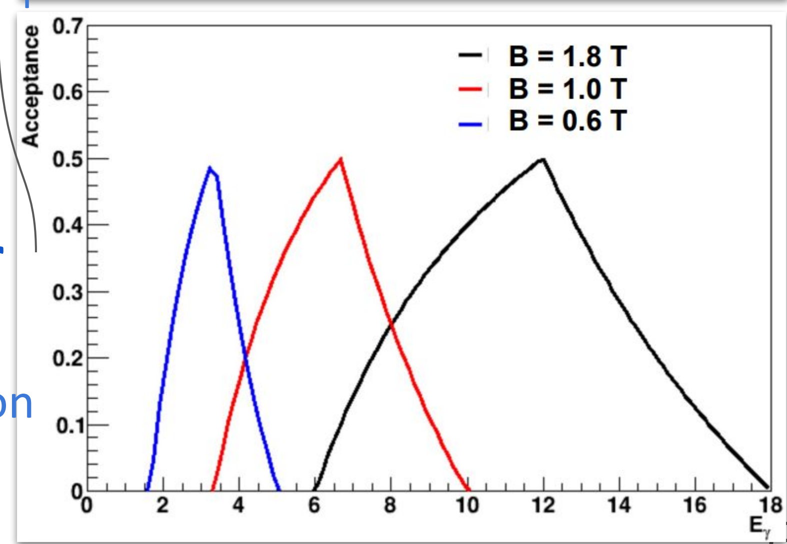
- **Apart from central detector, dedicated systems into the beamline**
  - Complicated layout + limited space ⟶ integration a challenge
- **At hadron- (far-forward) and electron-going (far-backward) directions**
  - systems crucial for delivery of full EIC physics program
    - Large acceptance for diffraction, 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





CMS Phase 2 Upgrades (HI related)

CMS-DP-2021-037

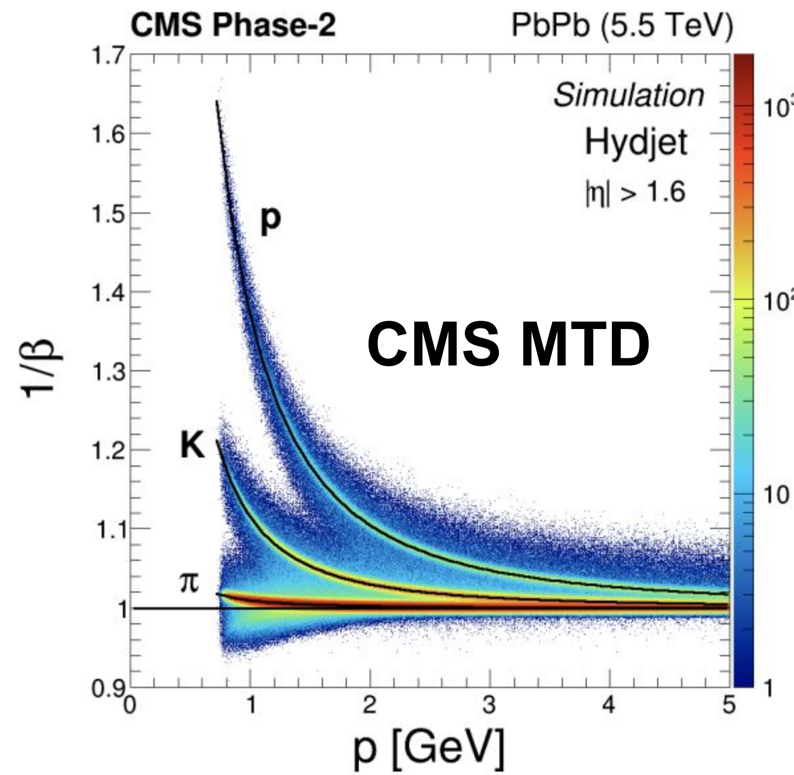
Yen-Jie Lee: Tue 2.00 pm

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

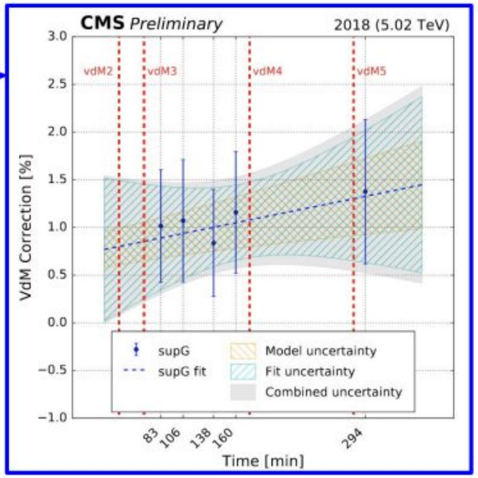
p/K/π separation

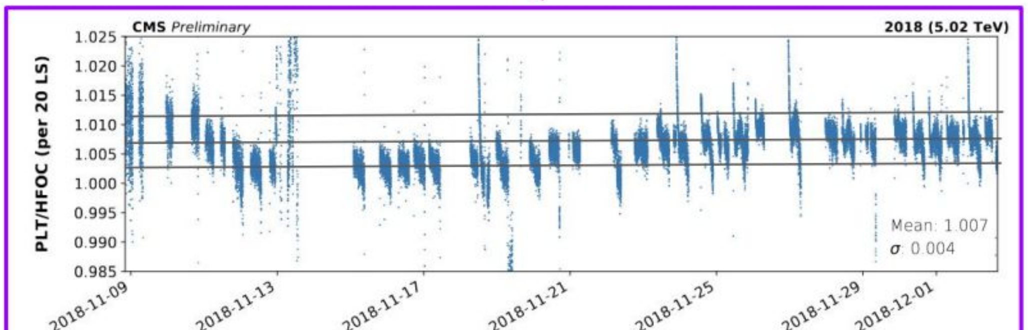


- **Main batch of CMS Upgrades in Run 4**
  - Among others, unique hermetic particle identification coverage by CMS MTD
- **Physics requests documented in past years over a diverse set of reports**
  - WG5 HL-LHC, ATLAS+CMS Snowmass’22, QCD Town Meeting WP, CMS HIN

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)

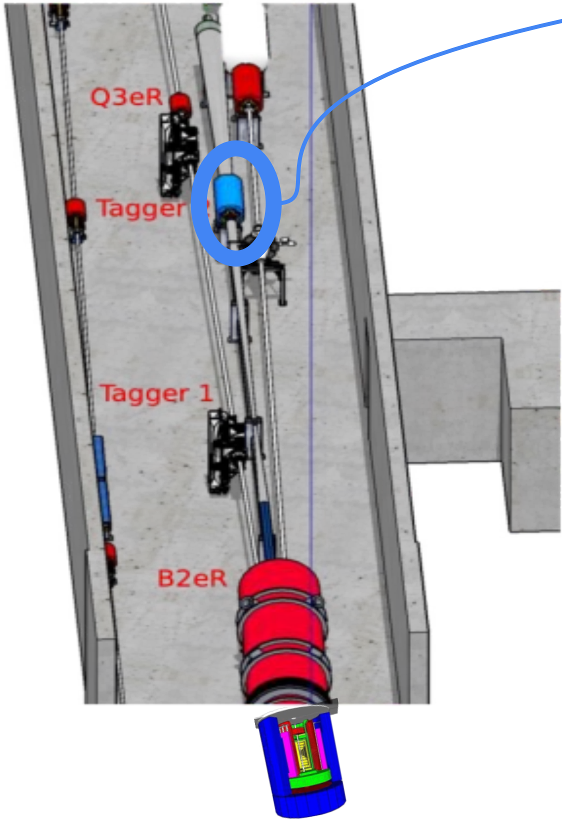
Stability monitored using emittance scans (short vdM-like scans)

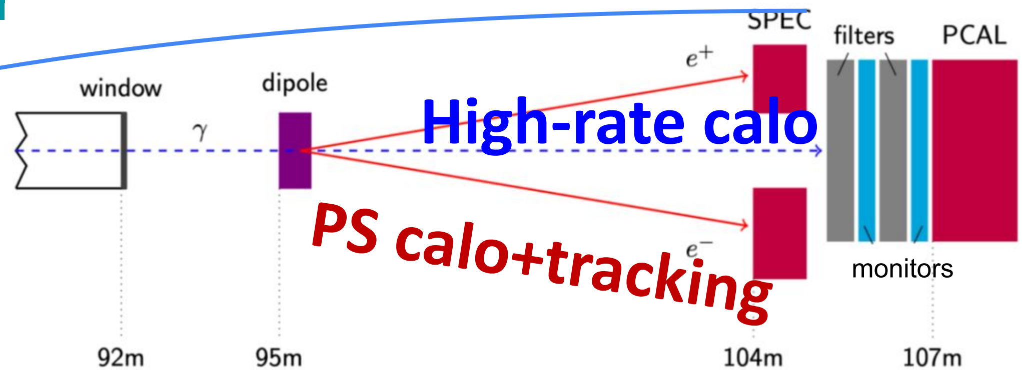
Total uncertainty: 1.5%

PAS-LUM-18-001

150th LHCC Meeting

EIC luminosity monitors

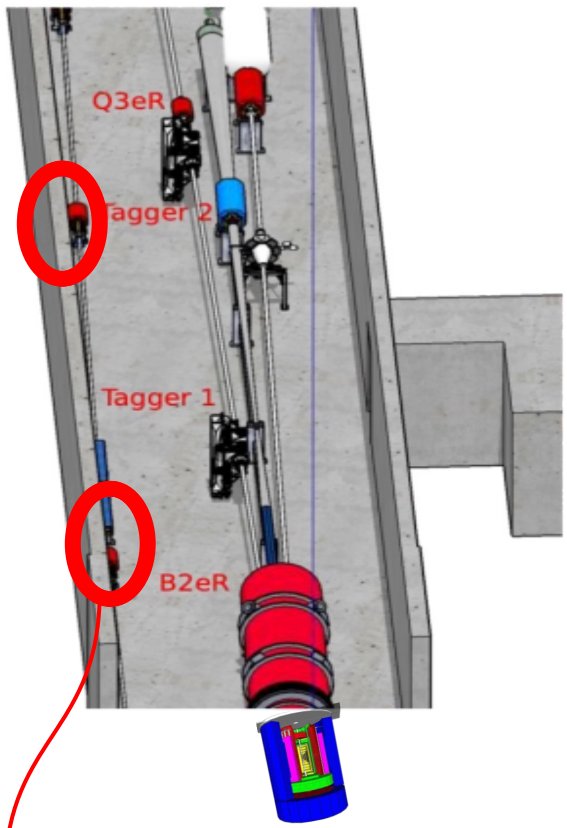


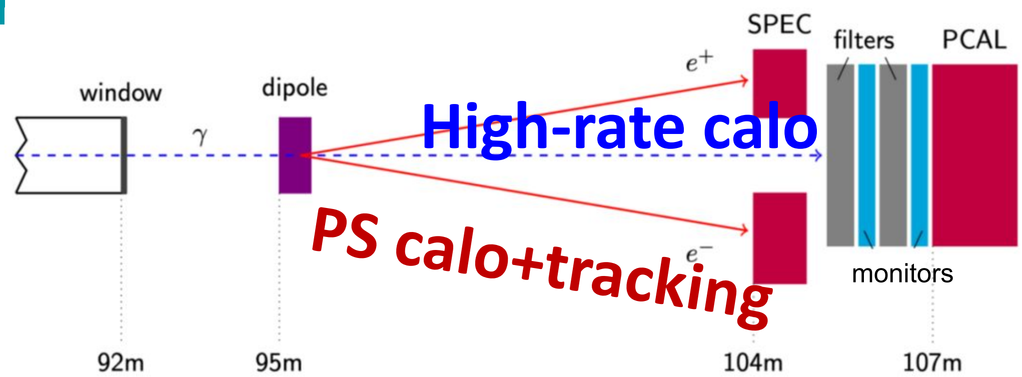


- **Luminosity systems with challenging target**
  - δL/L ~ 1% or rel. determination > 10^{-4} precision
- **Based on bremsstrahlung from ep(A) ⟶ ep(A)γ**
  - Bethe-Heitler σ known with ~0.5%
  - for 18x275 GeV: σ~275 mb ($\sigma_{eA} \propto Z^2$)
- **Two systems with different technologies**
  - orthogonal systematics

Previous experiments managed at ~2%; can we do better?

EIC luminosity monitors





- **Luminosity systems with challenging target**
  - $\delta L/L \sim 1\%$ or rel. determination > 10^{-4} precision
- **Based on bremsstrahlung from ep(A) ⟶ ep(A)γ**
  - Bethe-Heitler σ known with ~0.5%
  - for 18x275 GeV: σ~275 mb ($\sigma_{eA} \propto Z^2$)
- **Two systems with different technologies**
  - orthogonal systematics

- **Clean photoproduction in low-Q^2 taggers**
  - e's from bremsstrahlung will hit them
    - $E_\gamma = E_{beam} - E_e$ ⟶ calibration
    - necessary to reconstruct photoproduced VMs
  - PbWO4 ECal and AC-LGAD trackers

Synergies