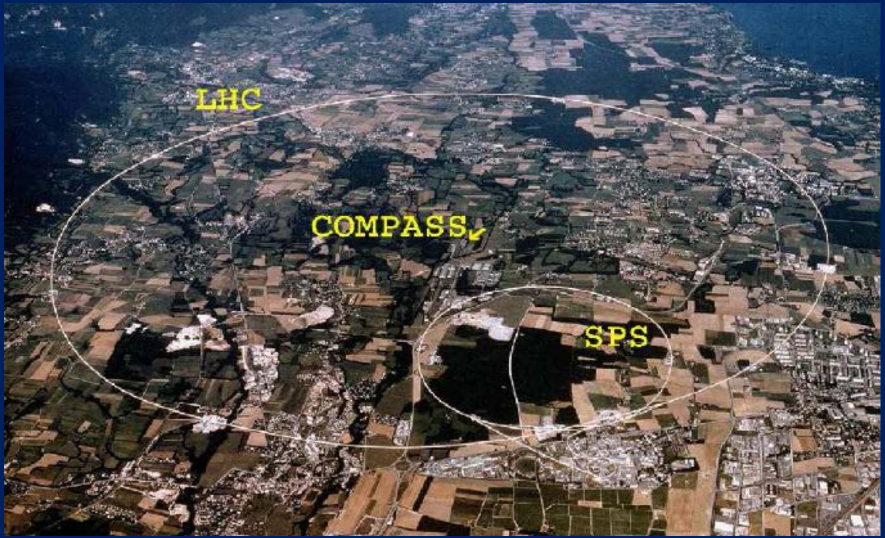
The Relativistic Heavy Ion Collider and Large Hadron Collider: Pushing Forward the Era of Quantitative QCD



Christine A. Aidala

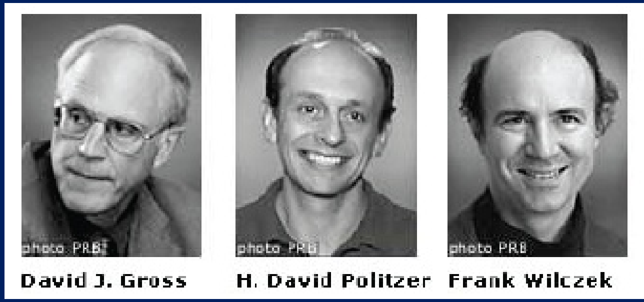
University of Michigan

CIPANP, Vail, CO
May 22, 2015

How do we understand the visible matter in our universe in terms of the quark and gluon degrees of freedom of quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?

QCD: How far have we come?



- Three-decade period after initial birth of QCD dedicated to "discovery and development"

→ Symbolic closure: Nobel prize 2004 - Gross, Politzer, Wilczek for asymptotic freedom

Now early years of second phase: ***quantitative QCD*****!**

Advancing into the era of quantitative QCD: Theory has been forging ahead!

- In perturbative QCD, since 1990s starting to consider detailed internal QCD dynamics that parts with traditional parton model ways of looking at hadrons—and perform phenomenological calculations using these new ideas/tools!

  E.g.:
  - Various *resummation* techniques
  - *Non-linear* evolution at small momentum fractions
  - *Spin-spin* and *spin-momentum* correlations in QCD bound states
  - *Spatial* distributions of partons in hadrons
- Non-perturbative methods:
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.

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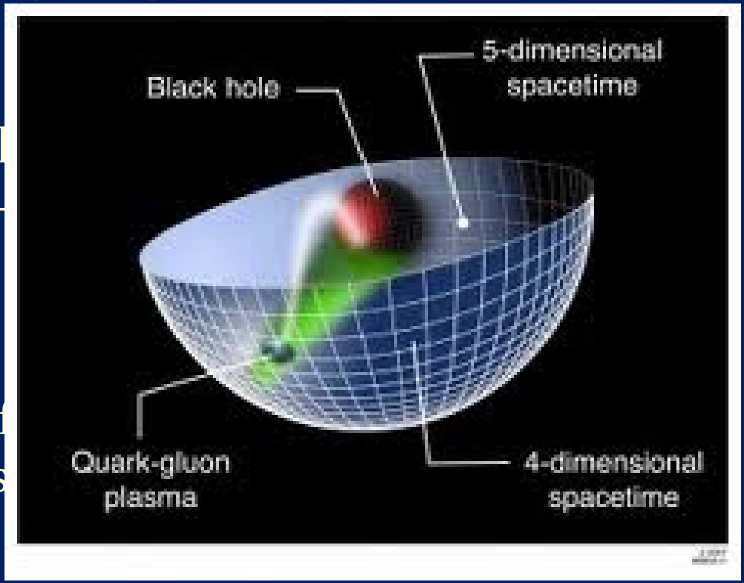

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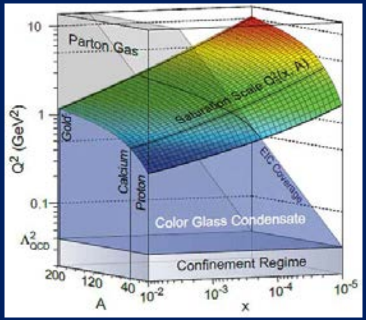
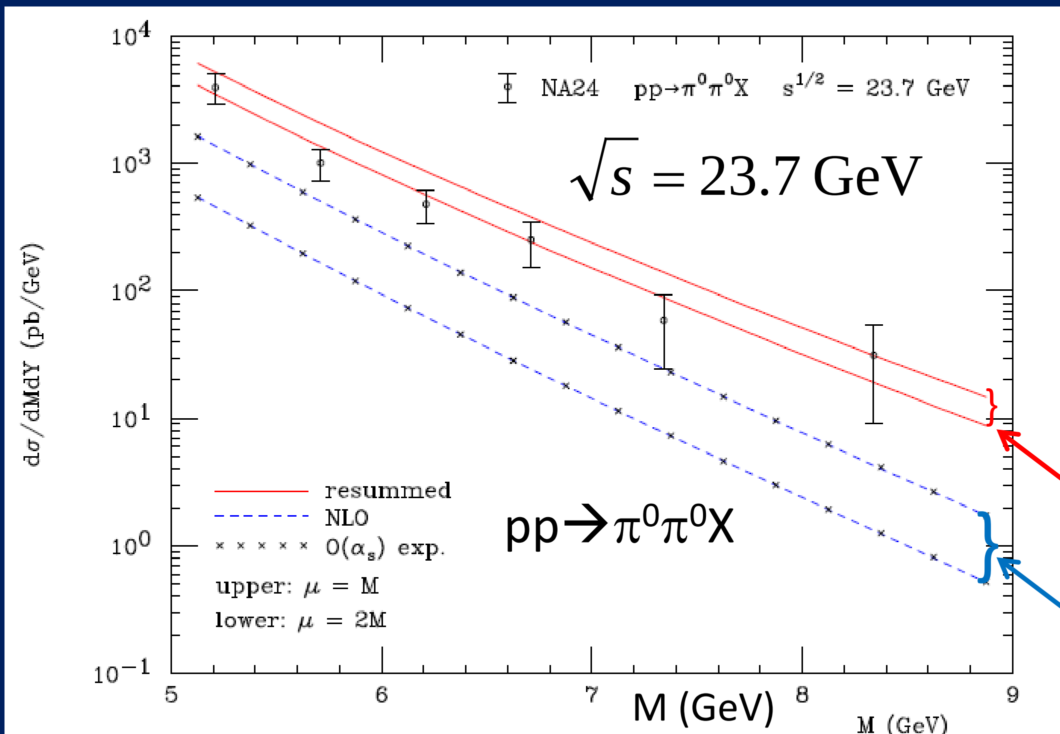
  - Lattice QCD less and less limited by computing resources—since 2010 starting to perform calculations at the physical pion mass (after 36 years!). Plus recent new ideas on how to calculate previously intractable quantities.
  - AdS/CFT “gauge-string duality” an exciting recent development as first fundamentally new handle to try to tackle QCD in decades!

Effective field theories



- QCD exhibits different behavior at different scales—effective field theories are useful approximations within these different regimes
  - Color Glass Condensate – high energies, high densities
  - Soft-Collinear Effective Theory – new insights into performing complicated perturbative calculations very quickly
  - Heavy Quark Effective Theory, Non-Relativistic QCD, . . .
  - Many effective theories for nonperturbative QCD – chiral perturbation theory, . . .

Example: "Threshold resummation" Extending perturbative calculations to lower energies



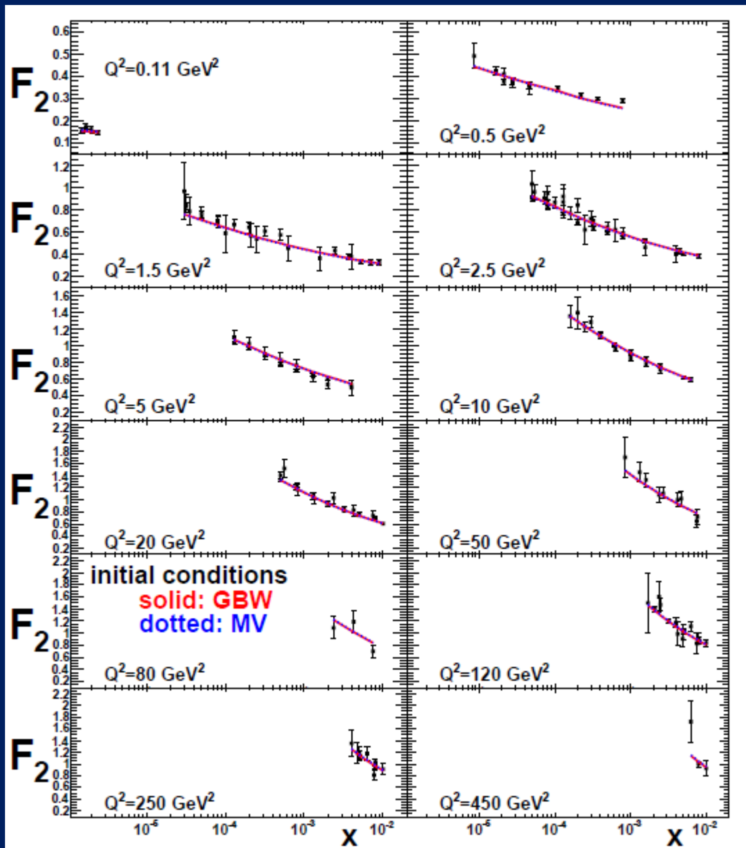
For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

Next-to-leading-order in α_s + resum.

Next-to-leading-order in α_s

Almeida, Sterman, Vogelsang PRD80, 074016 (2009)

Example: Phenomenological applications of a non-linear gluon saturation regime at low x



Fits to proton structure function data at low parton momentum fraction *x*.

Non-linear QCD meets data: A global analysis of lepton-proton scattering with running coupling BK evolution

Phys. Rev. D80, 034031 (2009)

Javier L. Albacete[1], Néstor Armesto[2], José Guilherme Milhano[3] and Carlos A. Salgado[2]

Basic framework for non-linear QCD, in which gluon densities are so high that there's a non-negligible probability for two gluons to combine, developed ~1997-2001. But had to wait until "running coupling BK evolution" figured out in 2007 to compare directly to data!

Talk by Anselm Vossen, today's plenary

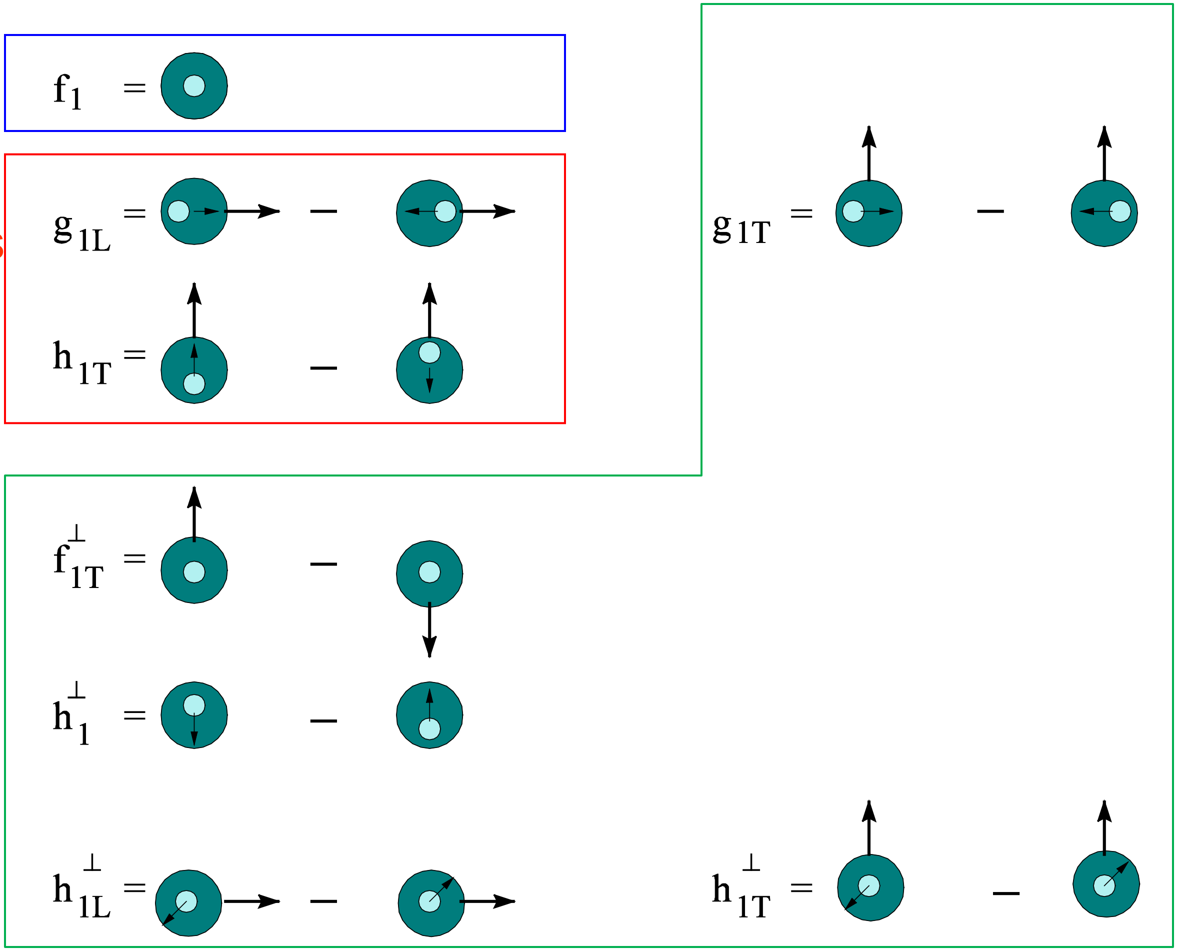
Example: Spin-spin and spin-momentum correlations in QCD bound states

Unpolarized

Spin-spin correlations

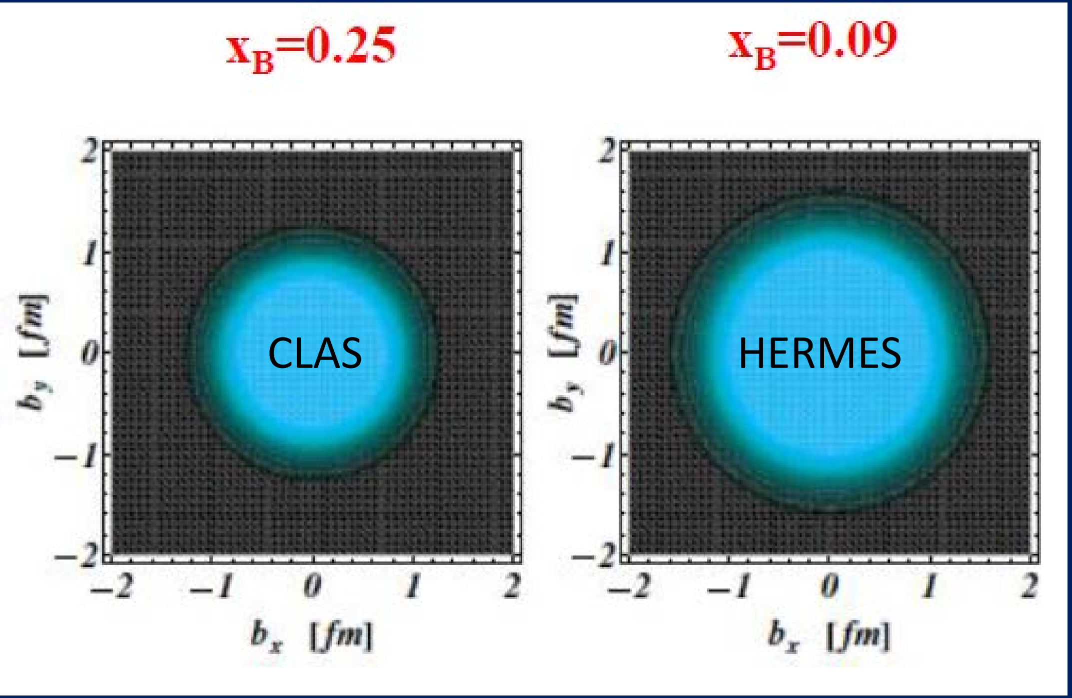
Spin-momentum correlations

$S\bullet(p_1 \times p_2)$



Talk by Nicole D'Hose, today's plenary

Example: Exploring spatial distributions



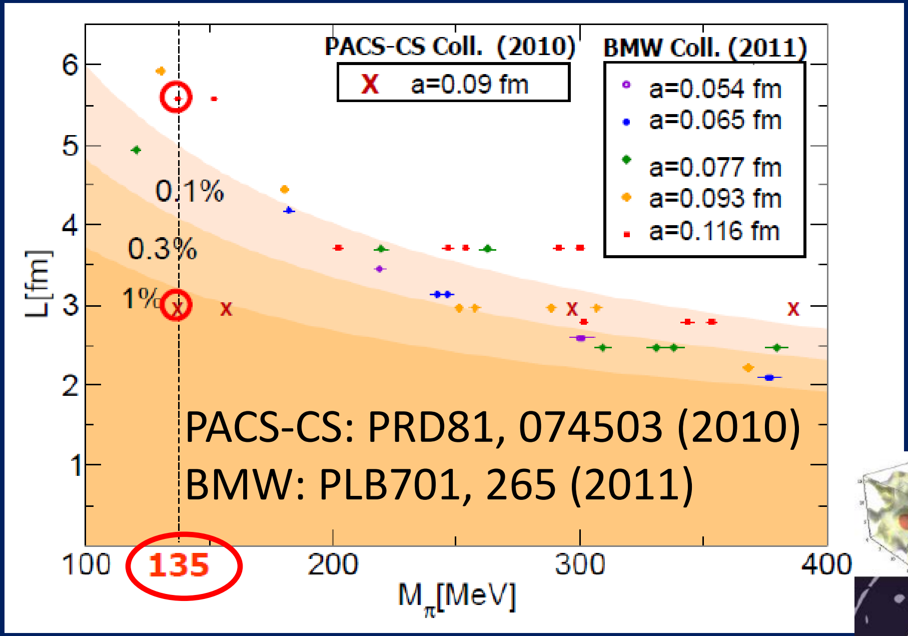
Guidal, Moutarde, Vanderhaeghen, Rept. Prog. Phys. 76 (2013) 066202

Spatial charge densities measured via deeply virtual Compton scattering

Initial evidence that quarks carrying larger momentum fractions (25% vs. 9%) in the nucleon are distributed over a smaller volume in space

Plenary talks by Ruth van de Water, Martin Savage

Example: Progress in lattice QCD

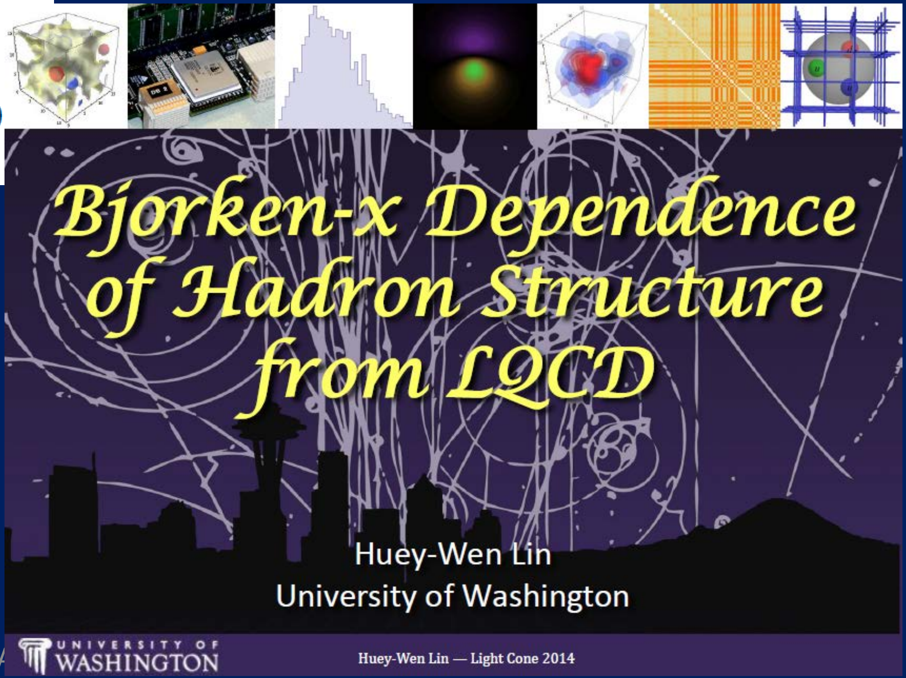


First calculations at physical pion mass 135 MeV

Figure from T. Hatsuda, PANIC 2011

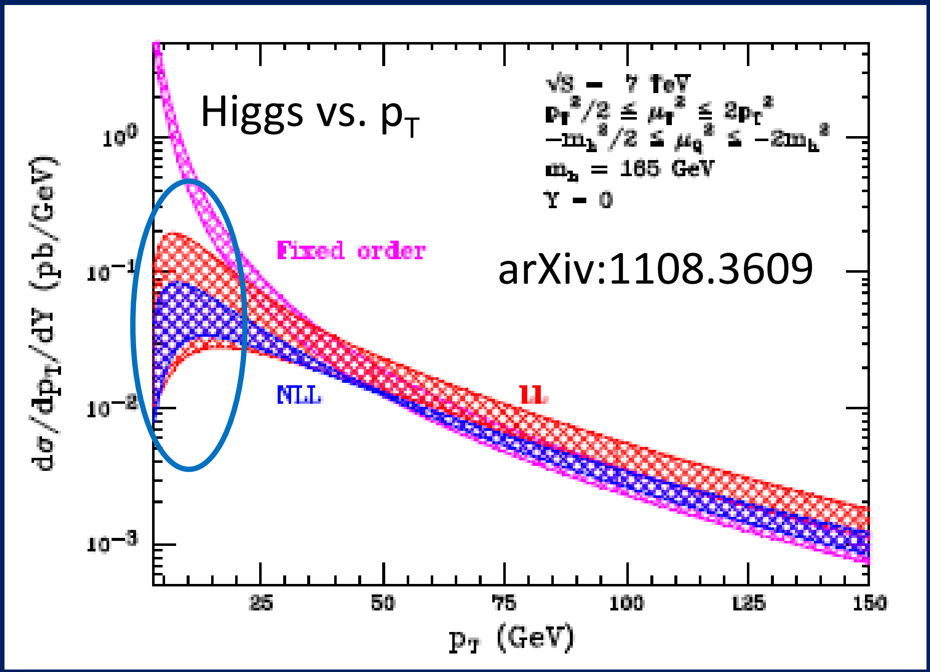
Since 2013, possibility to calculate x dependence of parton distribution functions

Slide from Huey-Wen Lin, Light Cone 2014



Example: Effective field theories

Soft Collinear Effective Theory – p_T distribution for gg→Higgs



TRANSVERSE MOMENTUM DISTRIBUTIONS FROM EFFECTIVE FIELD THEORY

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Frank Petriello
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Department of Physics & Astronomy, Northwestern University
Evanston, IL 60208, USA
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"Modern-day 'testing' of (perturbative) QCD is as much about pushing the boundaries of its applicability as about the verification that QCD is the correct theory of hadronic physics."
– G. Salam, hep-ph/0207147 (DIS2002 proceedings)

Experimental advances

- Ability to systematically vary collision species, energy
- Ability to maintain high-energy polarized proton beams
- High-luminosity facilities enable multidifferential measurements
  - E.g. simultaneously in parton momentum fraction x, rapidity, Q^2, p_T, . . .
- More sophisticated observables
  - E.g. angular distributions, multiparticle final states, various correlations, spin dependence, . . .
  - Often sensitive to parton *dynamics*

→ Demand more of theoretical calculations!

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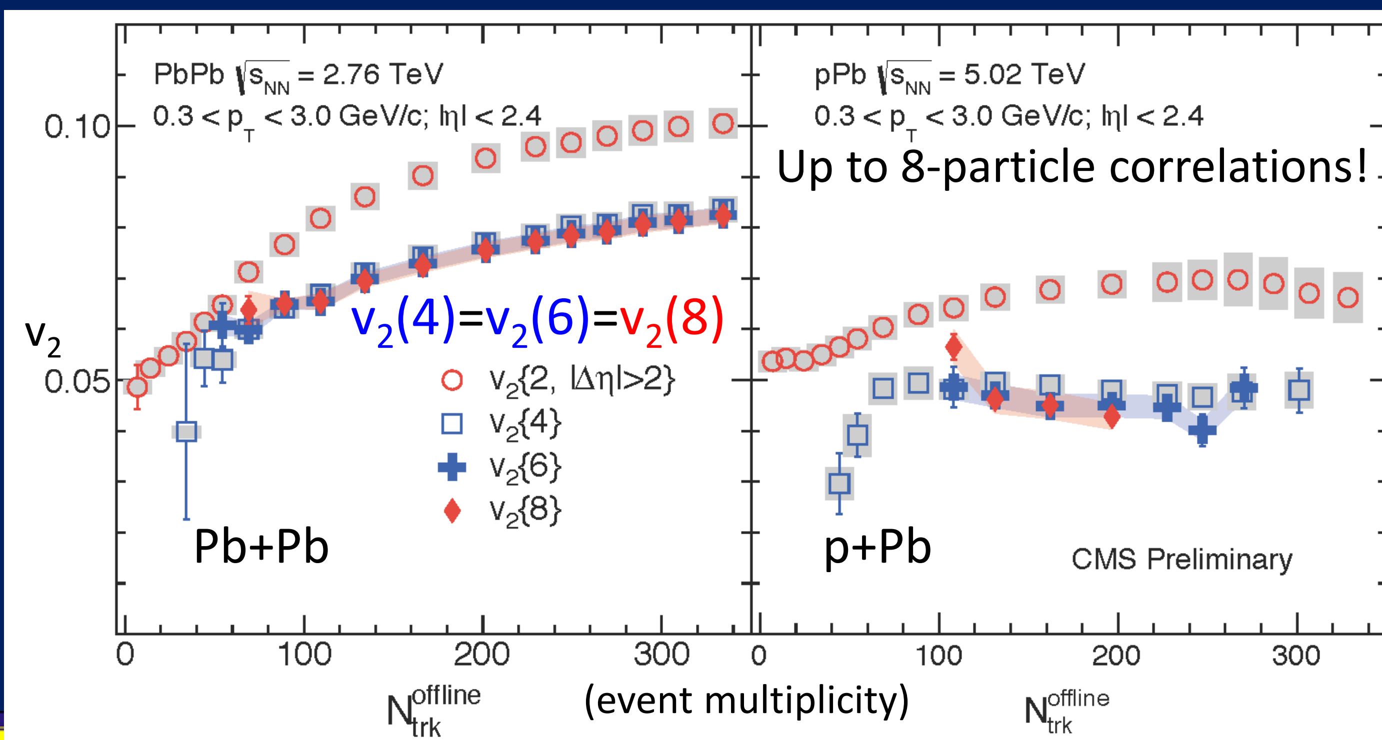


, rapidity, Q^2,

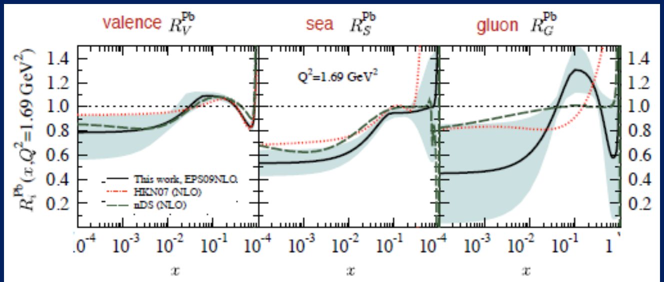
various

The "physics" vs. the "tools"

- "Heavy ion physics"—heavy ions (nuclei) tools to study
  - Hot, dense QCD systems (quark-gluon plasma)
  - QCD phase diagram
  - Low-x physics/gluon saturation
  - Parton energy loss in cold/hot nuclear matter
  - Partonic structure of nuclei
  - Collective phenomena in high-multiplicity partonic/hadronic states
  - …
- Not limited to heavy nuclei as the only relevant tools
  - Light nuclei, collisions of light on heavy nuclei, even p+p!
  - e+p, e+A also useful tools for several of the above

Increasing connections among historically disparate areas of QCD

As we advance, we're building more connections among the various areas of QCD—and to other fields . . .



- Nucleon structure and heavy ion communities
  - Greater focus on initial-state (cold) nuclear effects
  - Parton distribution functions in the proton vs. nuclei
  - Hadronic vs. partonic degrees of freedom
  - RHIC currently running polarized protons on gold! Use polarization to help search for gluon saturation physics
  - Ultraperipheral heavy ion collisions and Generalized Parton Distributions for spatial imaging; impact-parameter-dependent nuclear distributions and collision geometry in heavy ion physics

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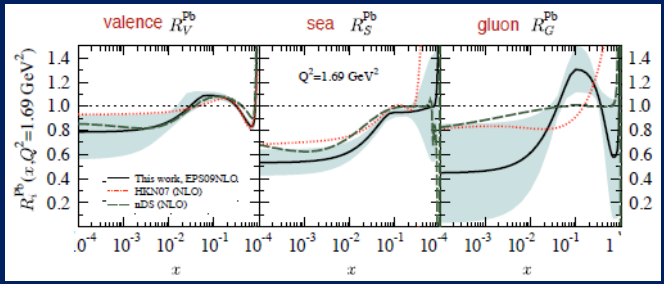

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- Hadron spectroscopy and hadronization (nucleon structure) communities
  - B factories as common facilities
- Heavy ion and hadronization (nucleon structure) communities
  - "String fragmentation" vs. binding of nearby partons in phase space
  - Modified hadronization in hot or cold nuclear matter

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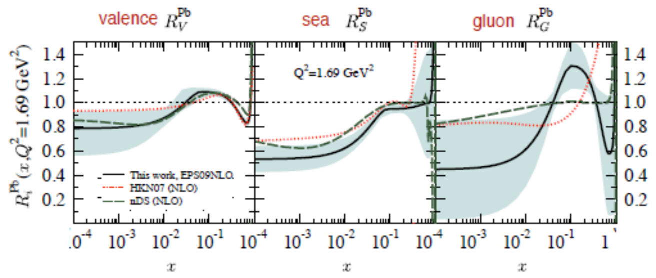

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- Heavy ion and stellar structure communities
  - Quark-gluon plasma and neutron stars: different corners of QCD phase diagram
- Heavy ion and low-energy nuclear reaction, cosmology communities
  - "Little Bang Nucleosynthesis" up to helium-4 (and antihelium-4!) in heavy ion collisions

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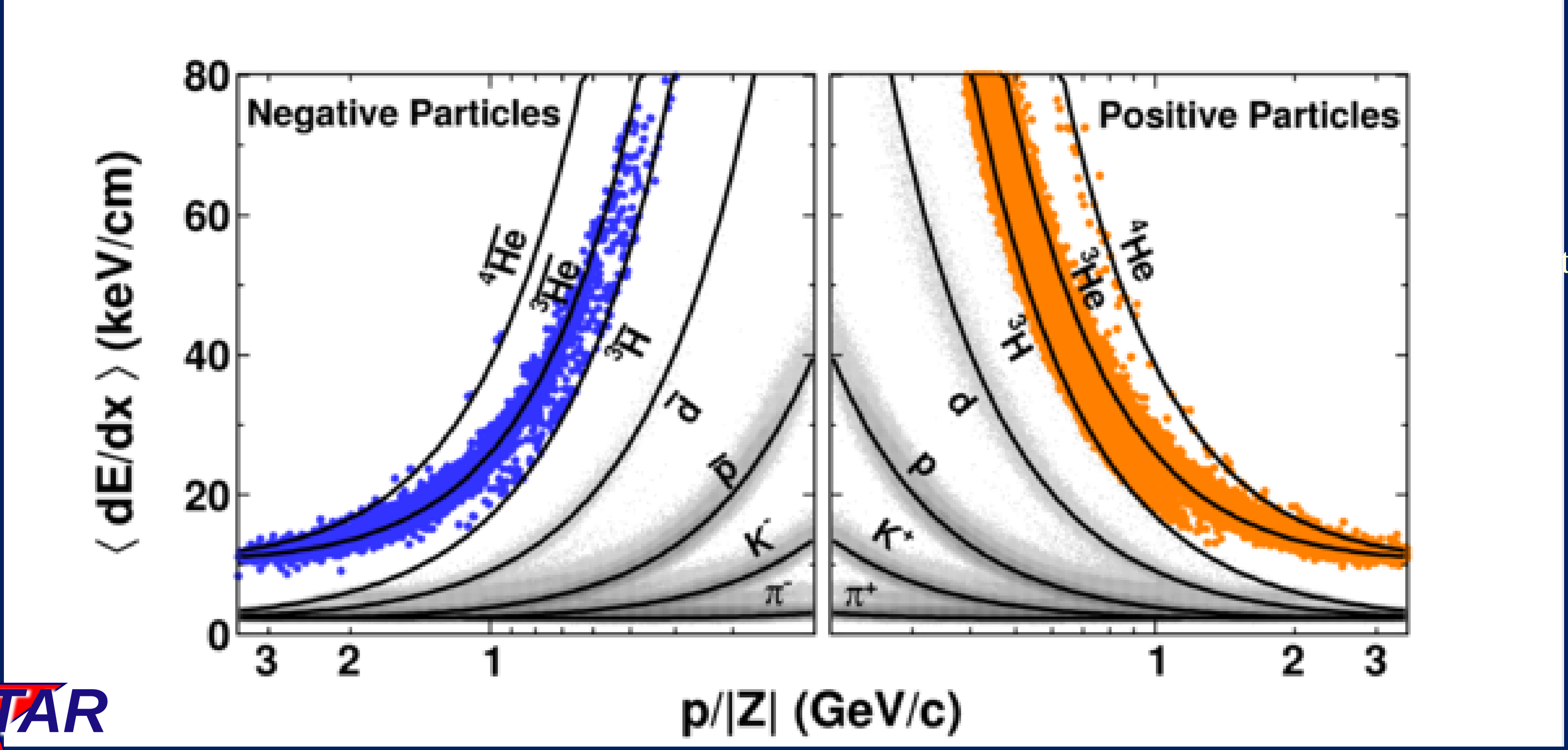
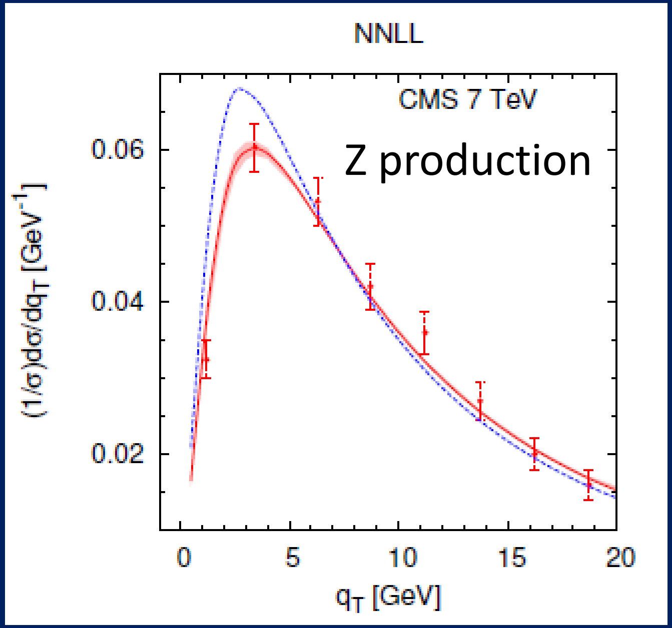


STAR

Nature 473, 353 (2011)

Increasing connections between heavy ion or nucleon structure physics and particle physics

- Low-x/gluon saturation physics
  - Onset expected in higher-energy p+p collisions, lower-energy heavy ion collisions
- Transverse-momentum-dependent parton distribution functions, Q_T resummation, Soft-Collinear Effective Theory
  - Determine transverse momentum distribution for Higgs, Z/W, Drell-Yan at low p_T



D'Alesio, Echevarria, Melis, Scimemi
JHEP 1411 (2014) 098

Need nonperturbative input to describe Z production at low transverse momentum

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Probing Gluonic Spin-Orbit Correlations in Photon Pair Production

Jian-Wei Qiu[1,2], Marc Schlegel[3] and Werner Vogelsang[3]
[1]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA and*
[3]*Institute for Theoretical Physics, Tübingen University, Auf der Morgenstelle 14, D-72076 Tübingen, Germany*
(Dated: July 27, 2011)

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- Collectivity in high-multiplicity systems, regardless of system size
- Searching for dark matter in heavy ion collisions

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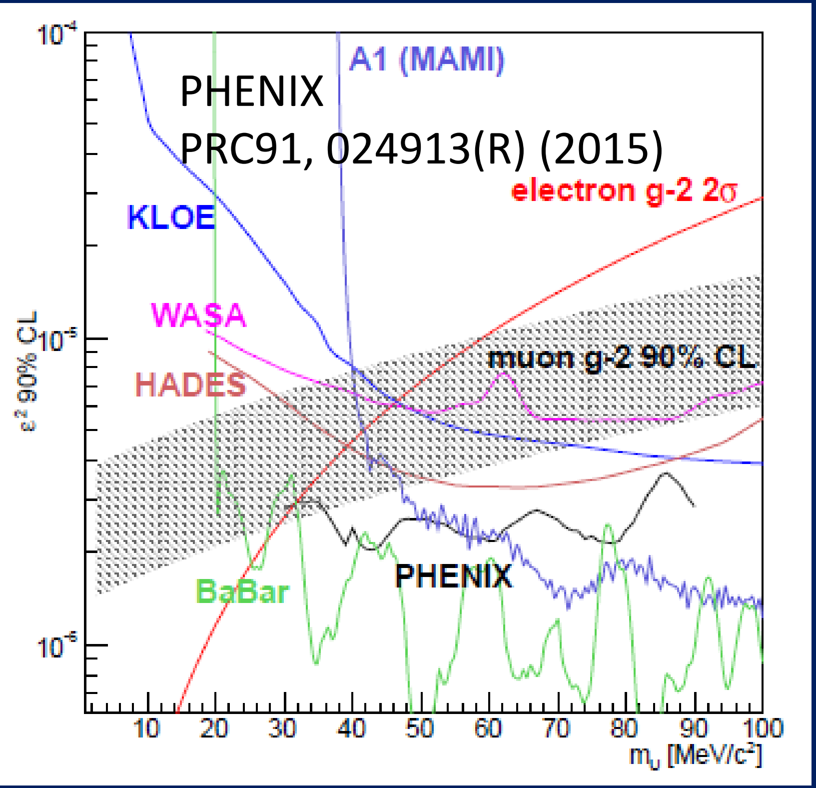
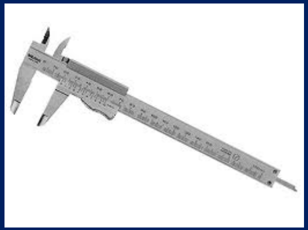
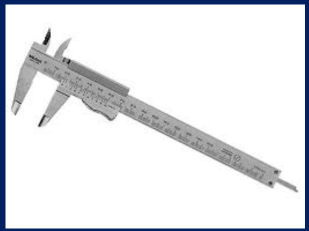




Overlapping tools and techniques

- HEP, nucleon structure, and heavy ion communities sharing an increasing number of tools/techniques
  - Jets—to study parton energy loss in quark-gluon plasma, in-medium modification of fragmentation functions, gluon spin contribution to spin of proton, . . .



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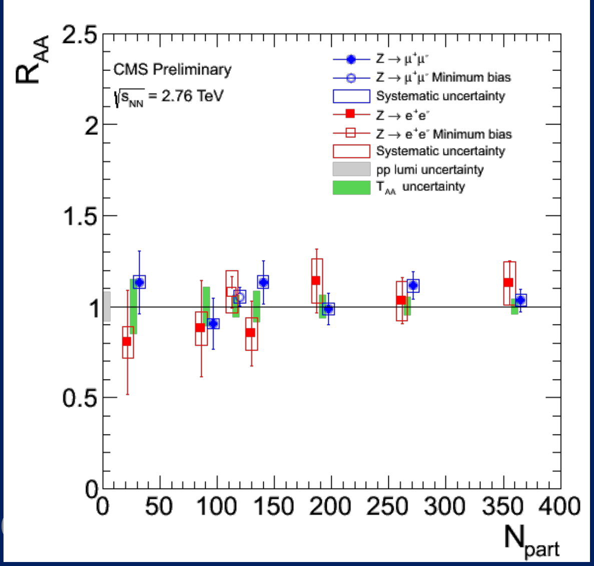
Ratio of Z production in Pb+Pb to scaled p+p
→ No modification



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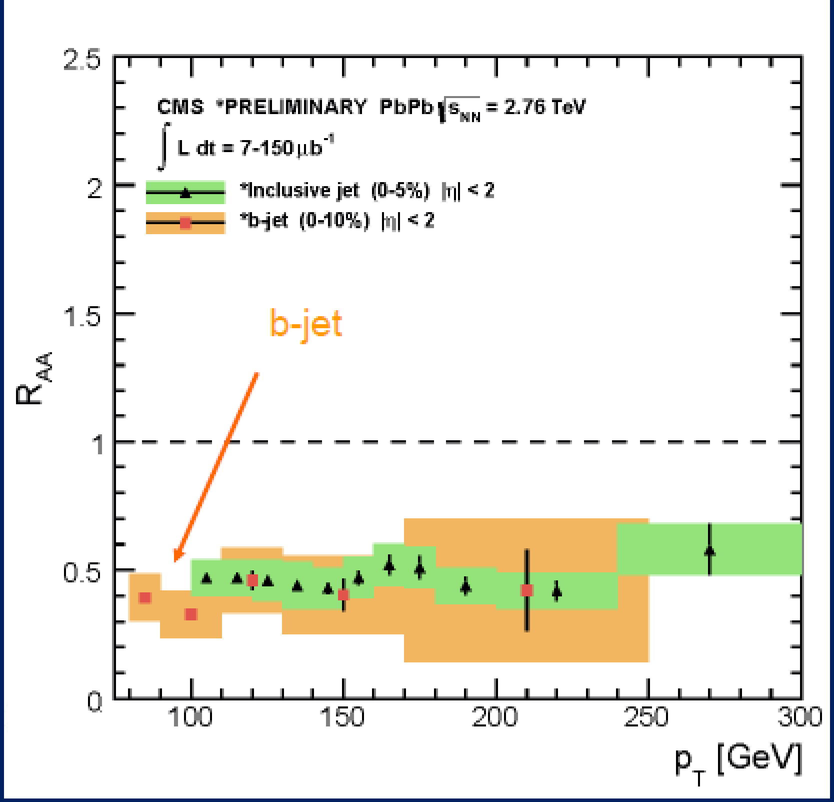
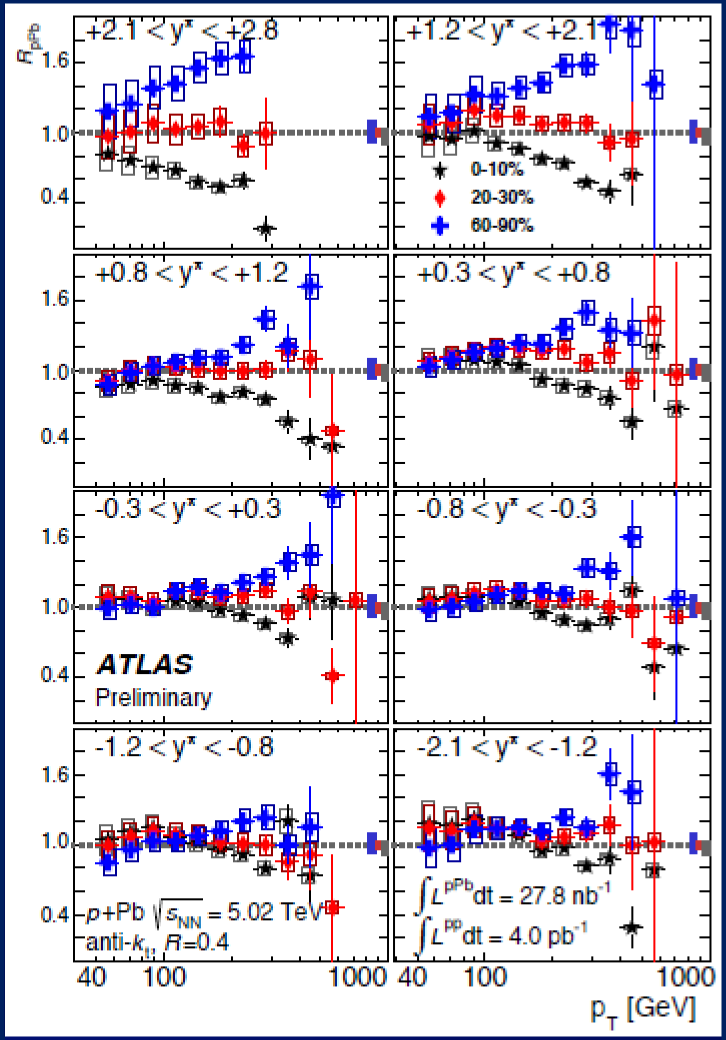
  - Bose-Einstein interferometry (Hanbury-Brown – Twiss)—to study properties and spatial extent of sources emitting radiation and particles—astronomy, heavy ions, e^+e^-, e+p, p+pbar, p+p

Heavy ion jet measurements



b-tagged jet suppression in Pb+Pb similar to inclusive jet suppression at high jet p_T



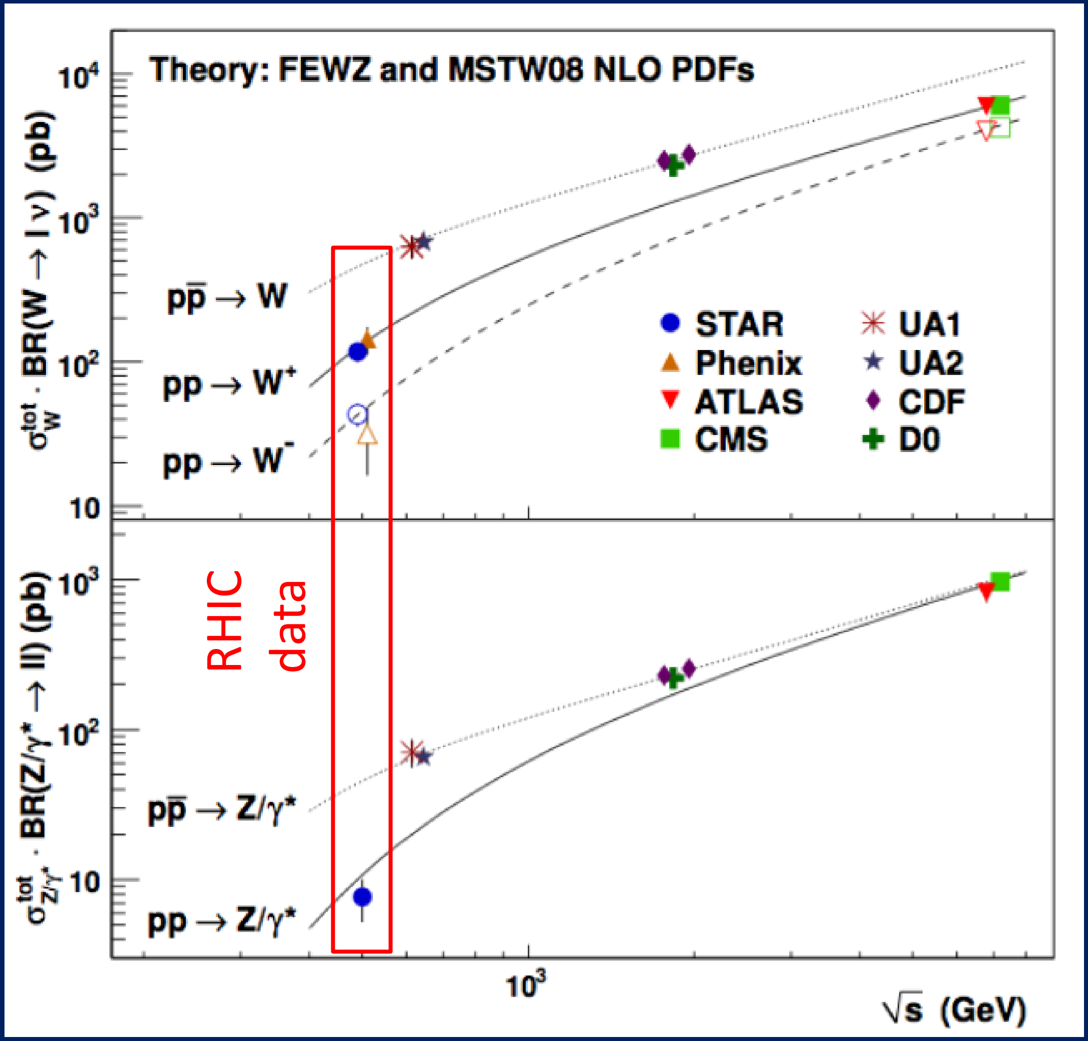
Food for thought for theorists . . .

Strong dependence of jet production in p+Pb as function of jet p_T, rapidity, centrality

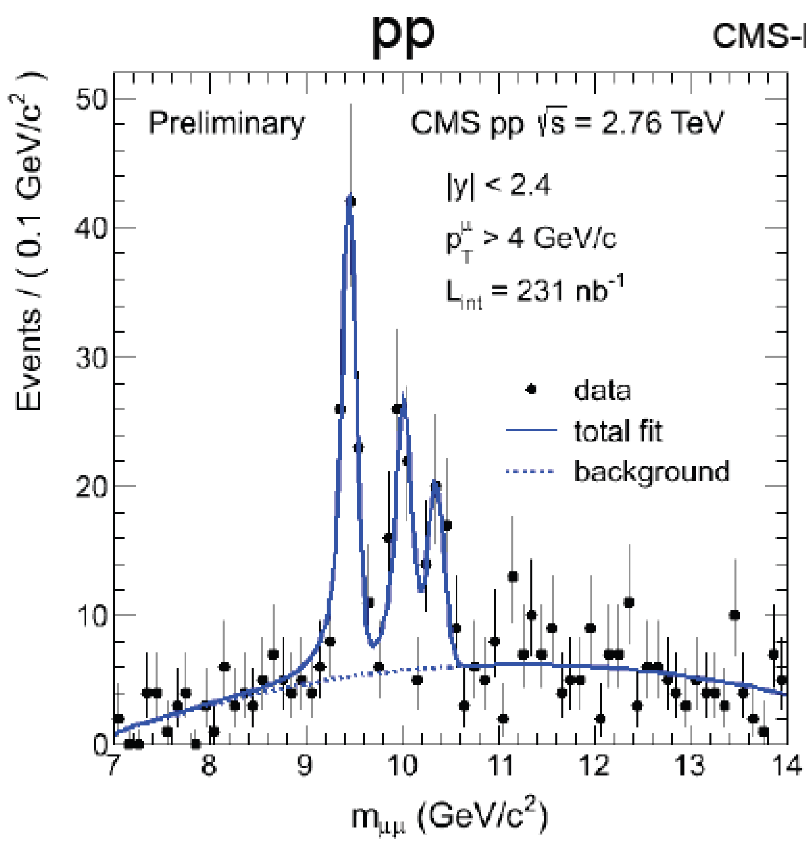
World W cross section measurements

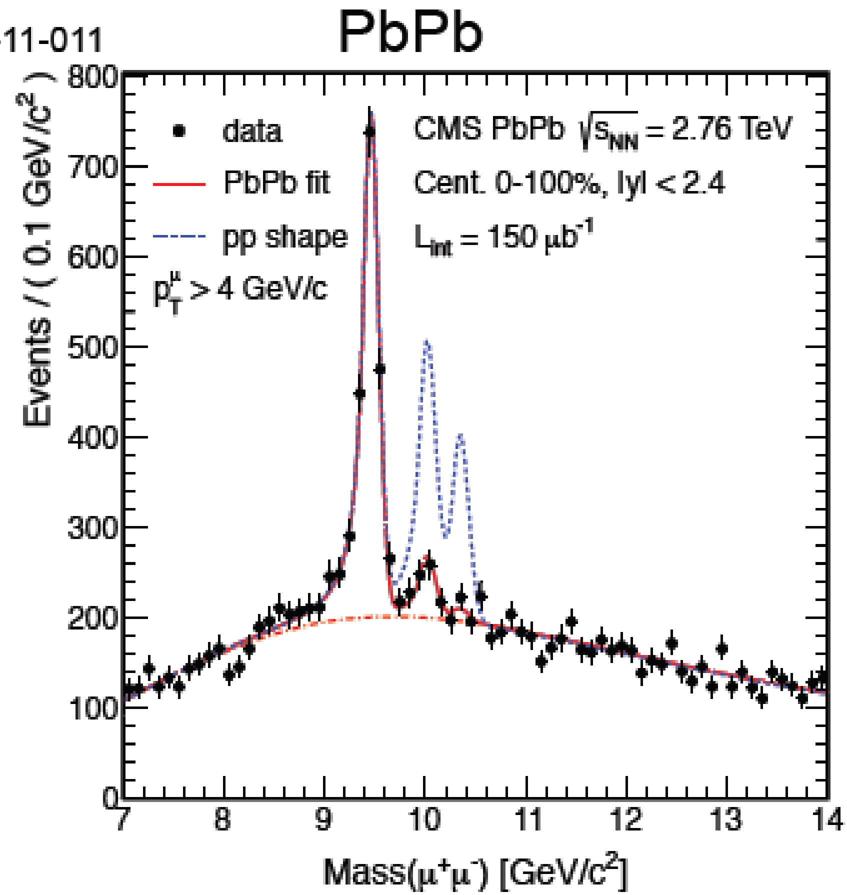
First-ever p+p → W+X cross section submitted for publication—by PHENIX! (PHENIX arXiv:1009.0505; ATLAS arXiv:1010.2130)

Previous W measurements in hadronic collisions from antiproton-proton collisions



Bottomonium in heavy ion collisions





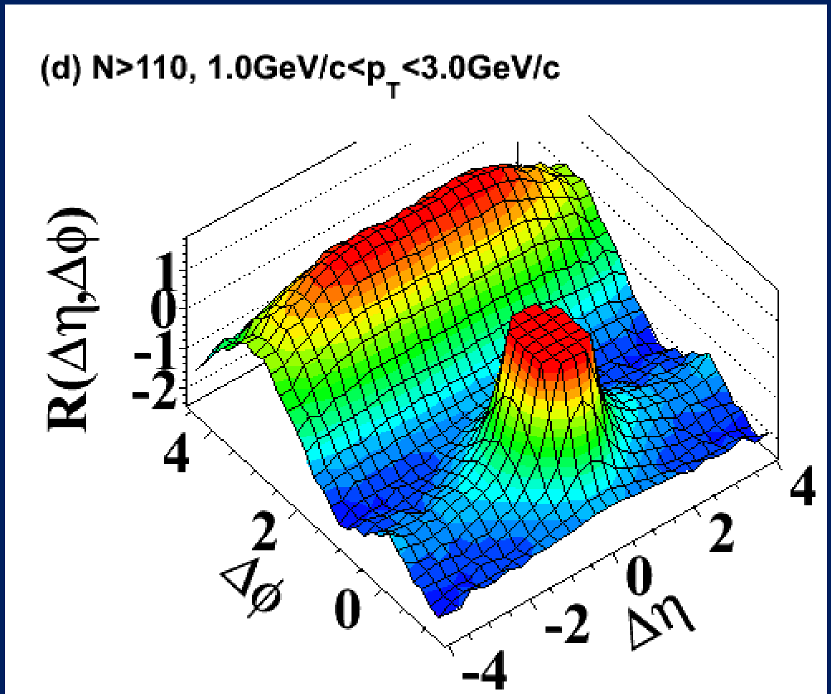
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

See talk by Rosi Reed, Sunday plenary, for more on heavy ion physics . . .

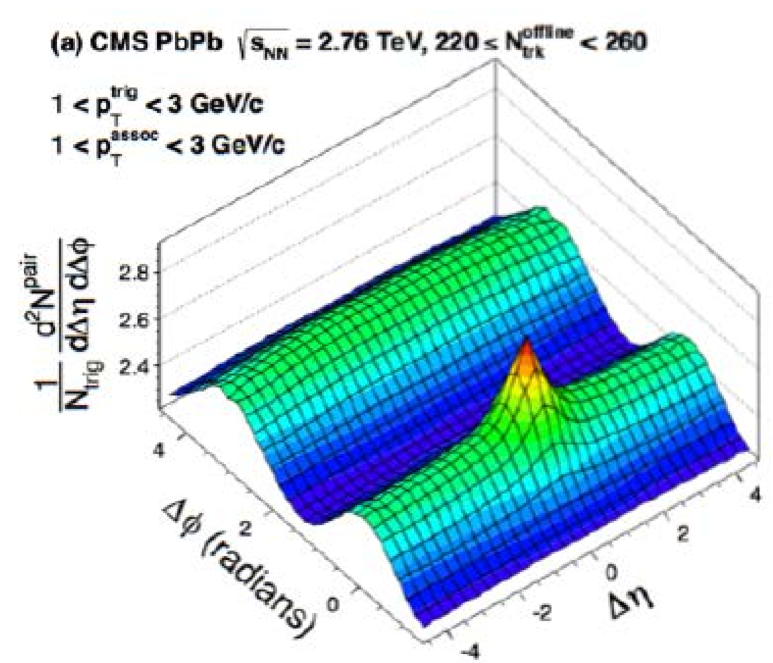
Surprising collectivity in high-multiplicity systems, regardless of size



CMS JHEP 09 (2010), 091

Long-range correlations in high-multiplicity p+p at 7 TeV

Surprising collectivity in high-multiplicity systems, regardless of size

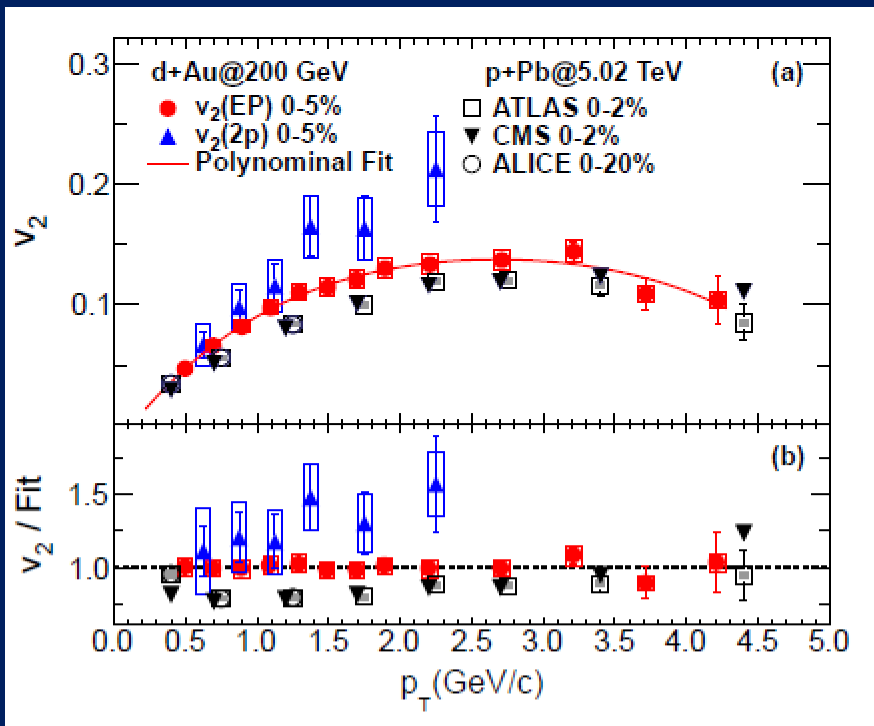


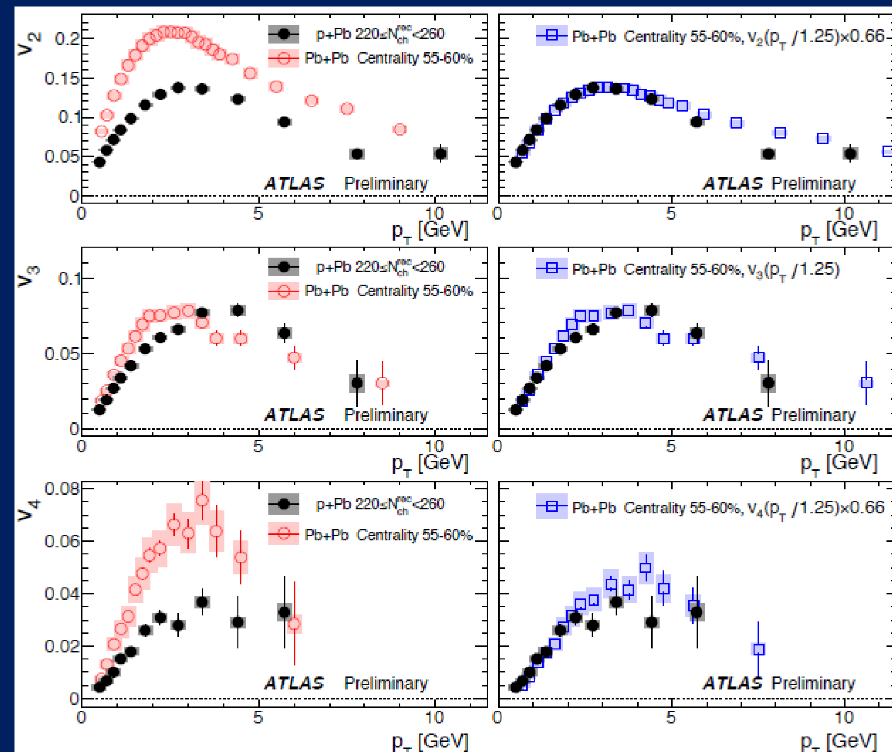
CMS, PLB 718 (2013) 795

And in Pb+Pb at 2.76 TeV and high-multiplicity p+Pb at 5.02 TeV.
In Pb+Pb (and RHIC Au+Au) understood to be due to hydrodynamic flow of equilibrated quark-gluon plasma. What's going on in high-multiplicity p+p, p+Pb, d+Au?

Collectivity in high-multiplicity systems: Fourier amplitudes

PHENIX: PRL 114, 192301 (2015)



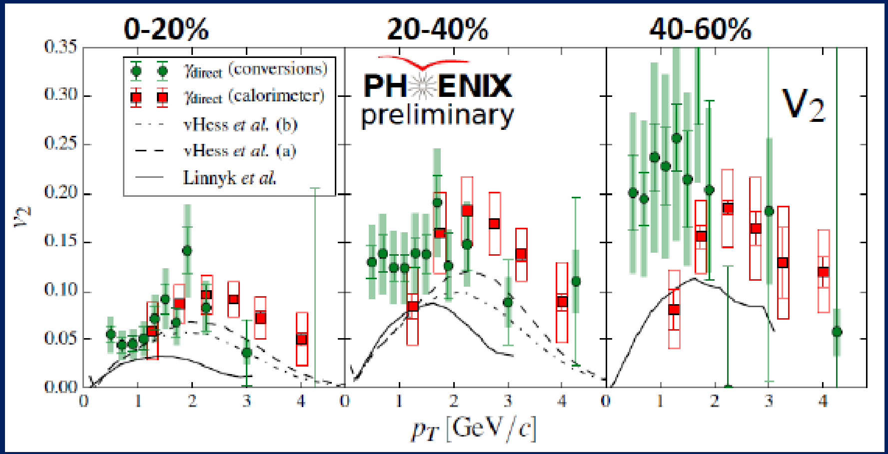


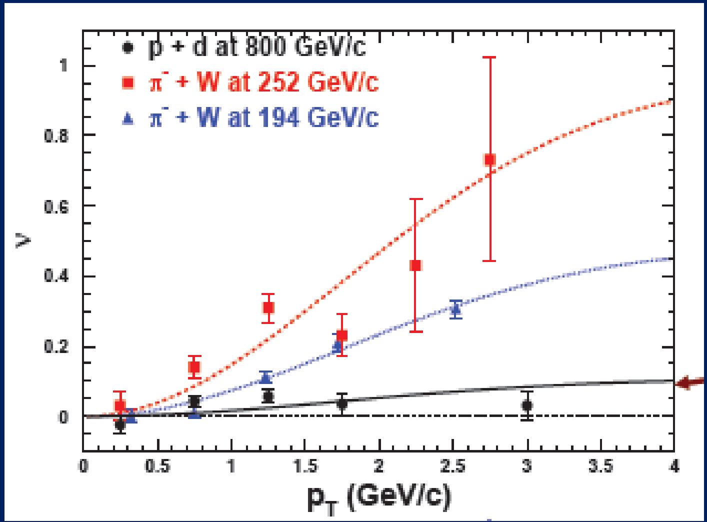
Large cos 2ϕ modulation in d+Au at 200 GeV, p+Pb at 5.02 TeV

Higher Fourier harmonics also large in high-multiplicity p+Pb. Empirical scaling shows similarity between p+Pb and Pb+Pb.

How many ways can a cos 2ϕ modulation be generated in hadronic collisions??

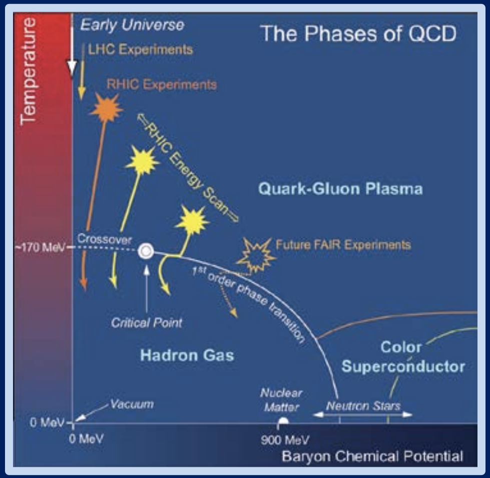
- Large modulation in direct photon production in 200 GeV Au+Au collisions
  - Not well understood
- *Huge* modulation in pion-induced Drell-Yan!
  - Understood as due to spin-momentum correlations of partons inside (unpolarized) hadrons



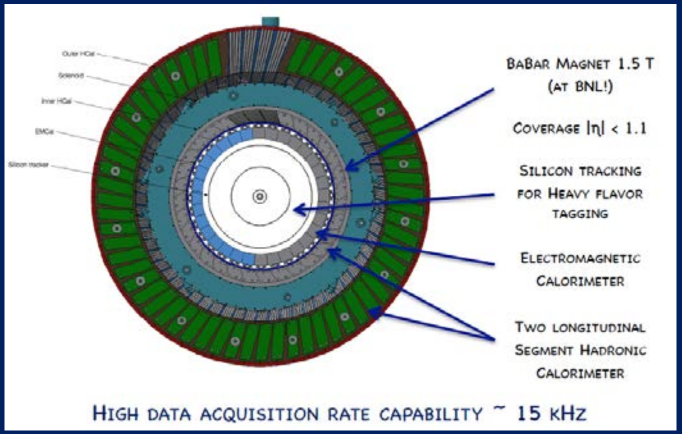


E866, PRL 99, 082301 (2007)
E615, PRD39, 92 (1989)
NA10, ZPC31, 513 (1986)

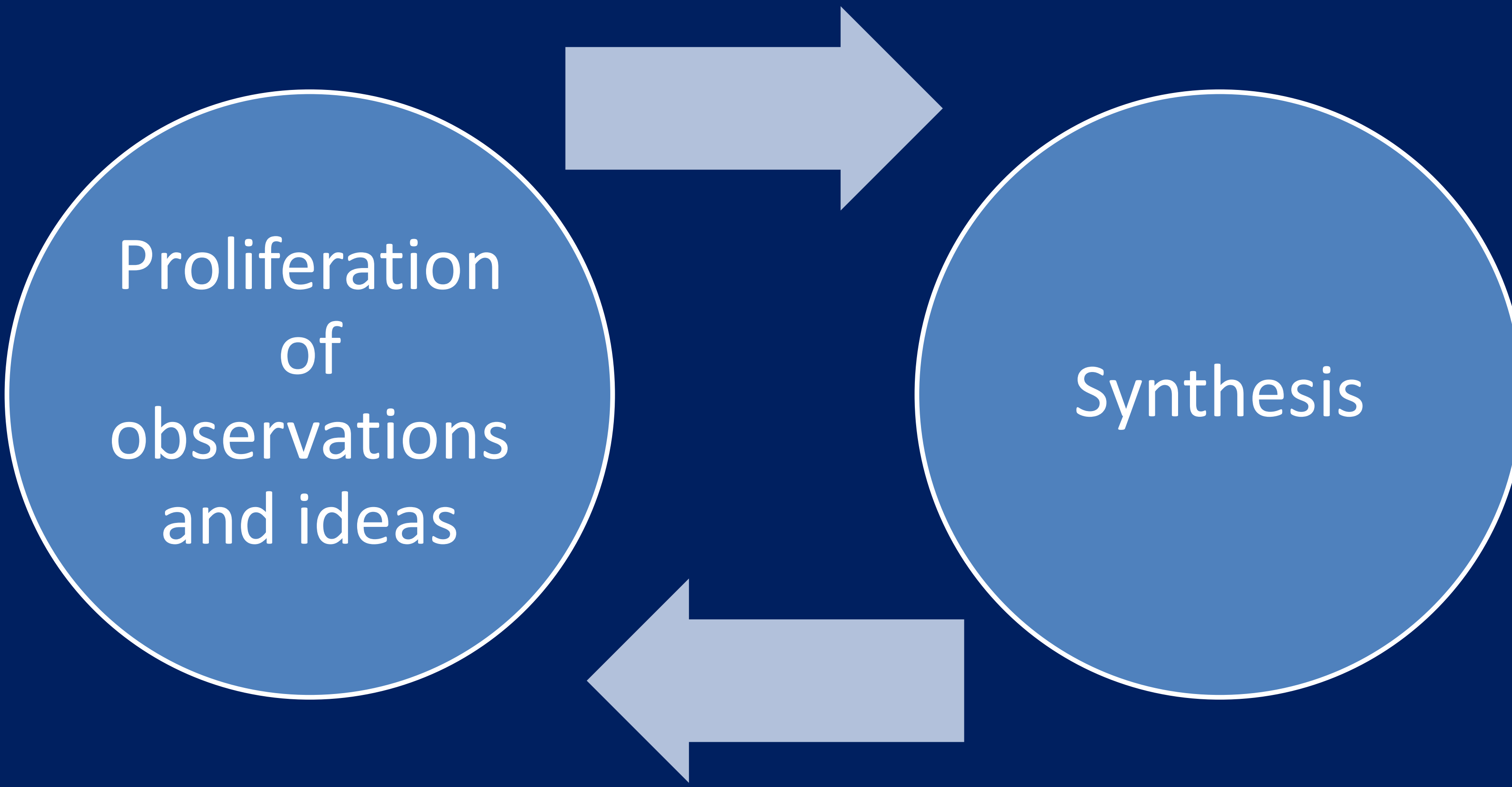
Coming up at RHIC



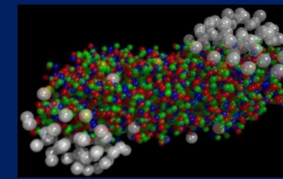
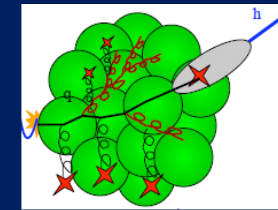
- RHIC Beam Energy Scan II
  - Search for QCD critical end point (Talk by Mike Lisa, Saturday parallel)
- sPHENIX
  - Proposed new detector at RHIC focused on jets, jet correlations, upsilons (Talk by Ali Hanks, Sunday parallel)
- Many more results from recent data sets: ^{3}He+Au, Cu+Au, U+U, $p^{\uparrow}$+Au, $p^{\uparrow}+p^{\uparrow}$, . . .



A cyclical process



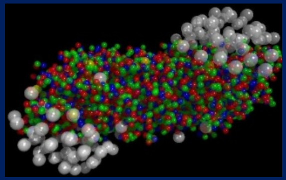
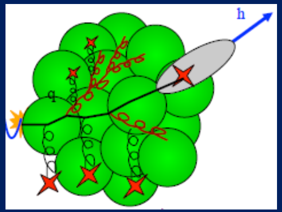

Summary

- Disparate subfields within QCD and within particle and nuclear physics have been starting to converge over last ~15 years
  - Increasingly quantitative treatment and understanding within the various subfields/regimes
    → QCD maturing!
- RHIC and LHC nuclear collision and p+p programs major drivers in this convergence
  - Along with complementary work at lepton-hadron and e^+e^- facilities

Summary

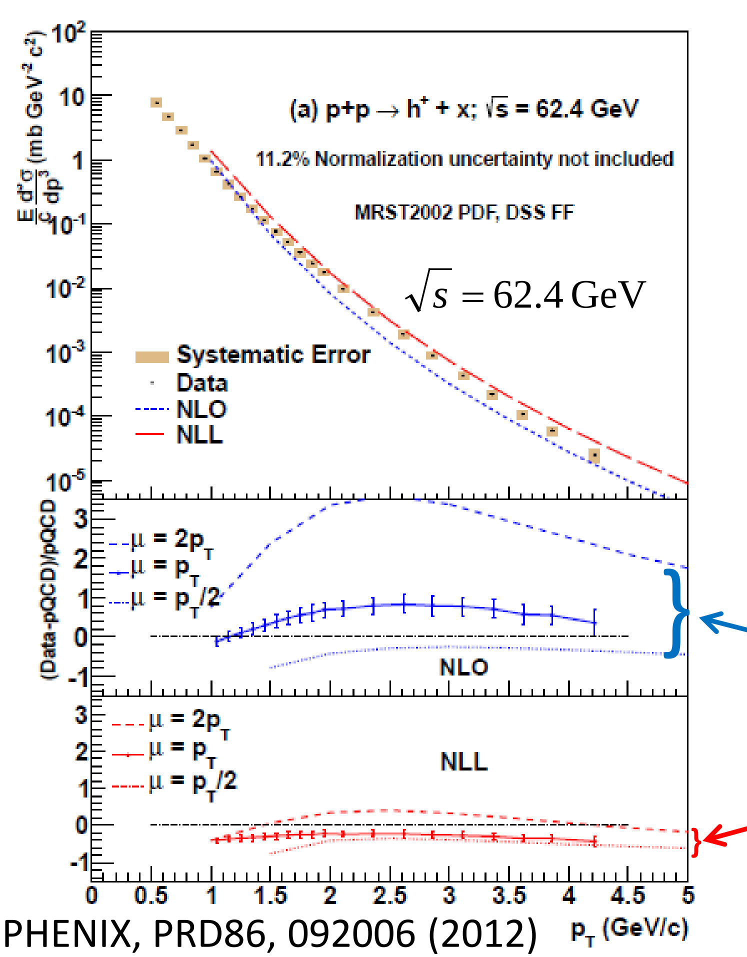
 

- Disparate subfields within QCD and within particle and nuclear physics have been starting to converge over last ~15 years
  - Increasingly quantitative treatment and understanding within the various subfields/regimes
    → QCD maturing!
- RHIC and LHC nuclear collision and p+p programs major drivers in this convergence
  - Along with complementary work at lepton-hadron and e^+e^- facilities

Taking small, initial steps along the path toward "grand unification" of QCD across different scales, from partons to neutron stars . . .

Extra

Example: “Threshold resummation” Extending perturbative calculations to lower energies



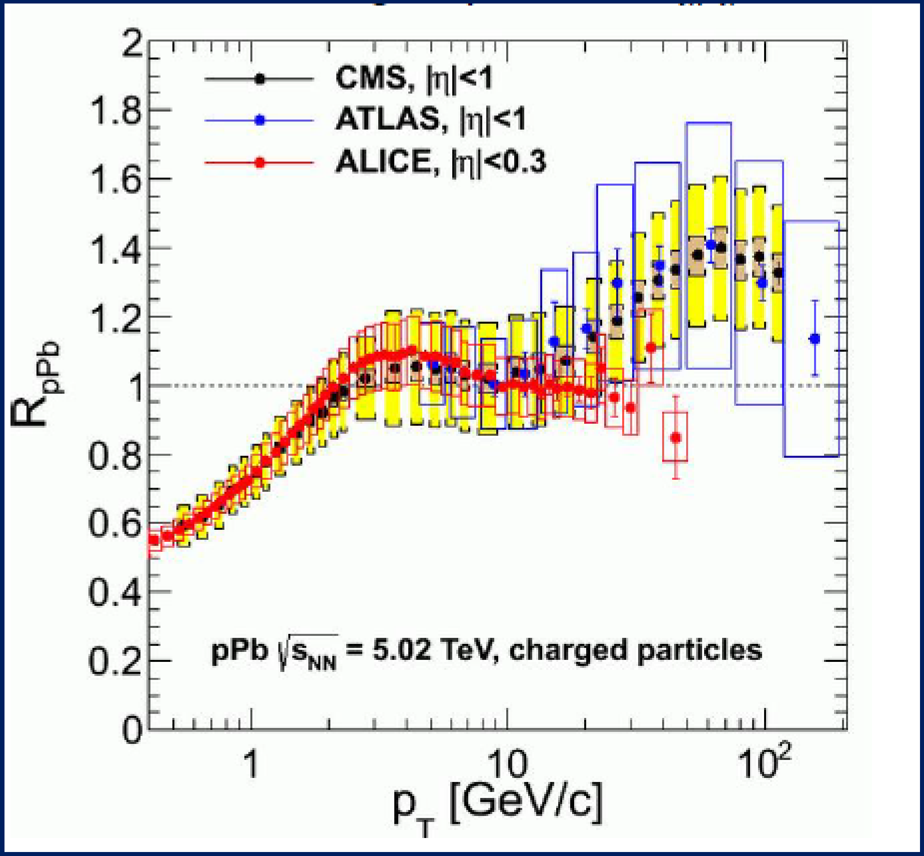
PHENIX, PRD86, 092006 (2012)

For observables with two different scales, sum logs of their ratio to all orders in the strong coupling constant

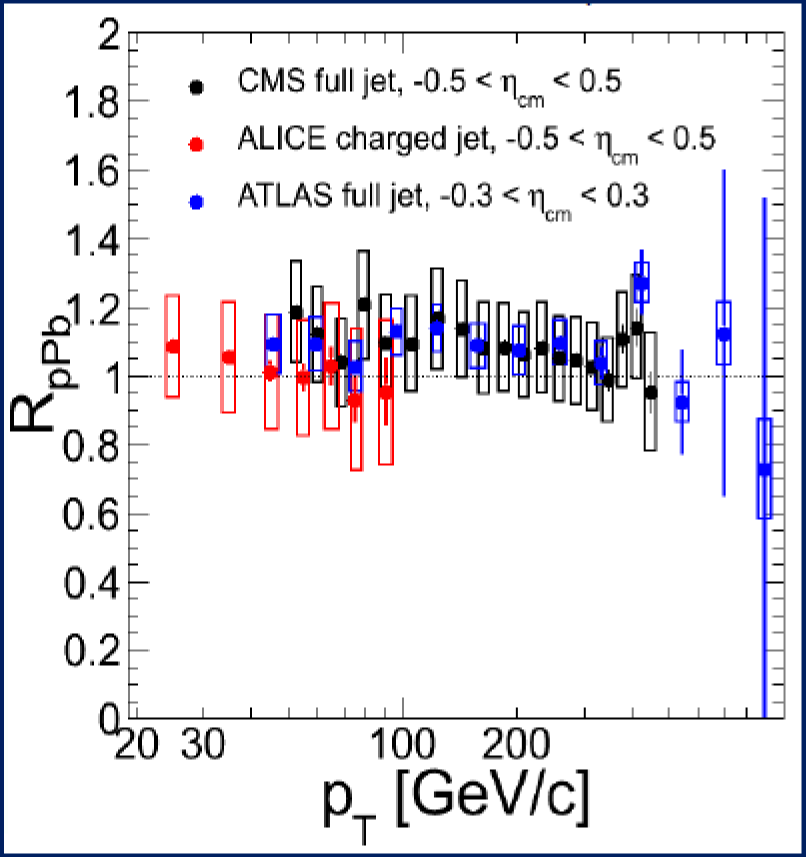
Relative difference between data and next-to-leading-order in α_s

Improvement in absolute agreement and theoretical uncertainty with next-to-leading-order in α_s + resum.

p+Pb excess of charged particles $p_T > 30$ GeV

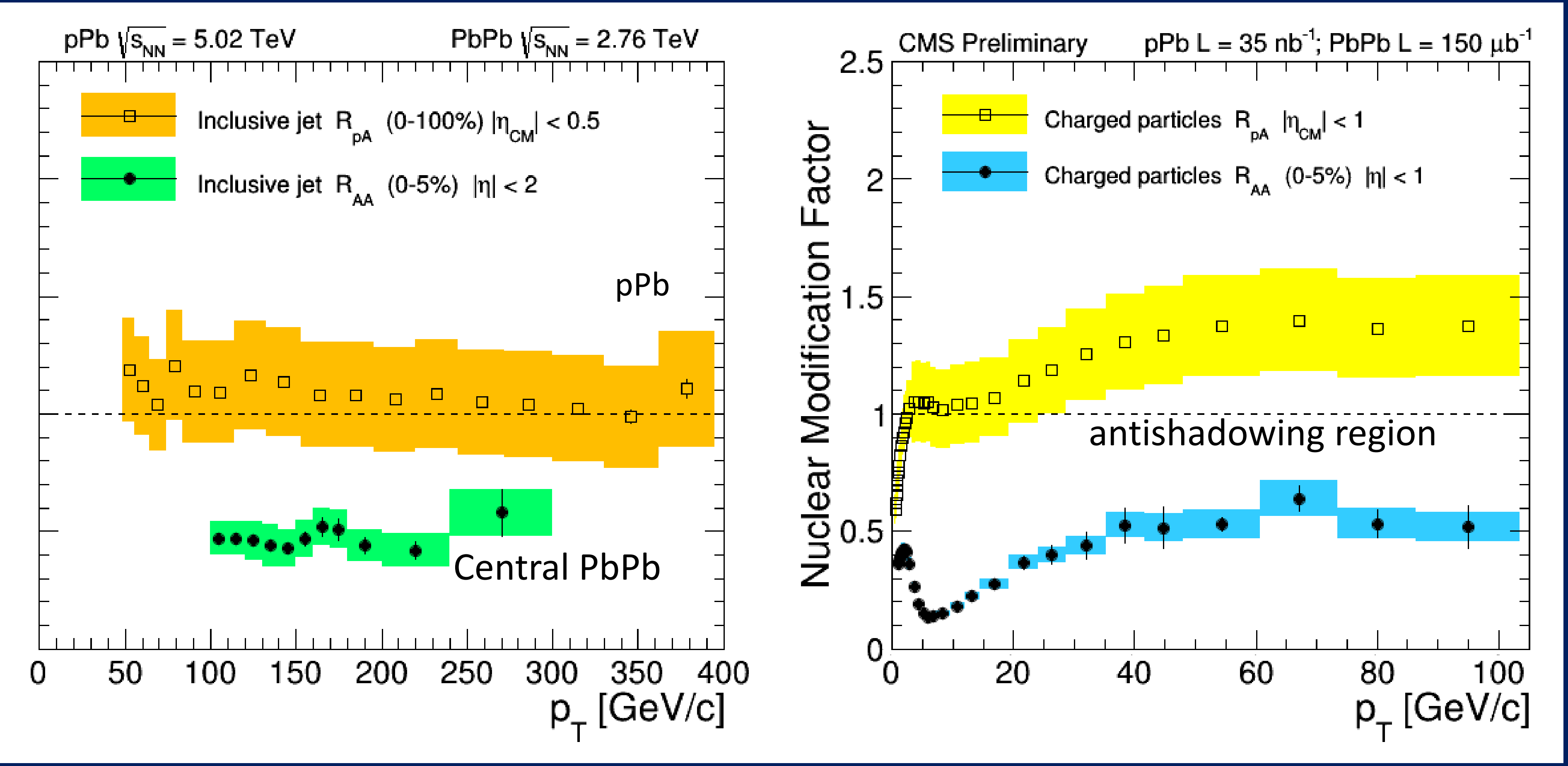


Seen by CMS, ATLAS, but not ALICE



But full jets show little or no enhancement

R_{pA} & R_{AA} for jets and tracks

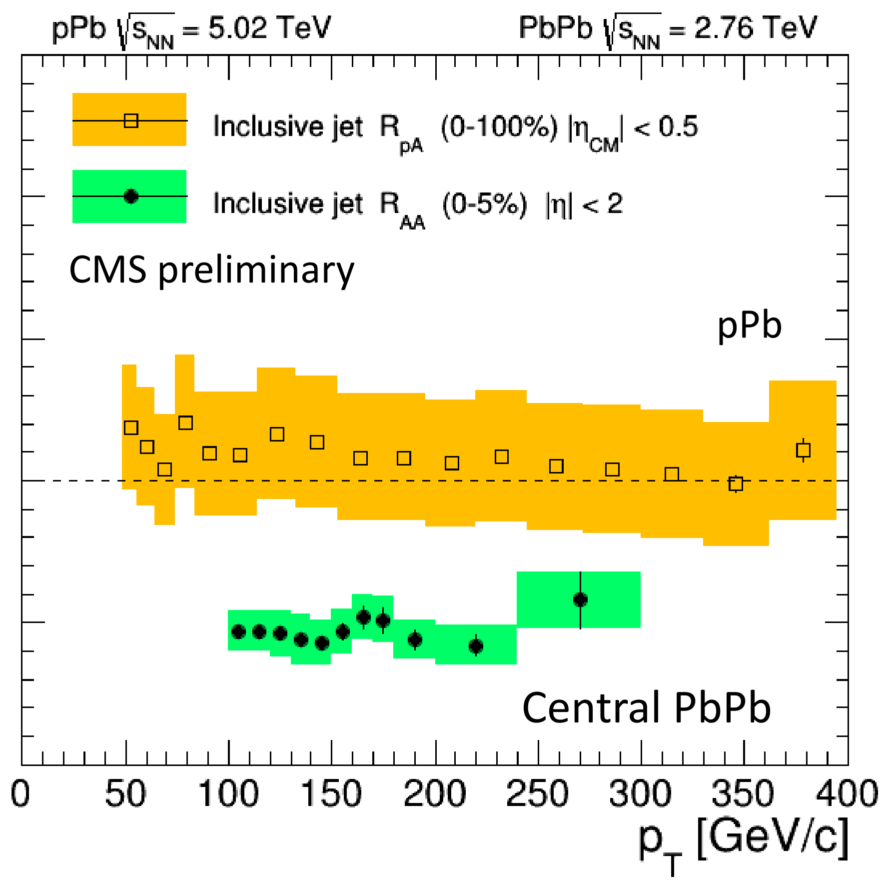


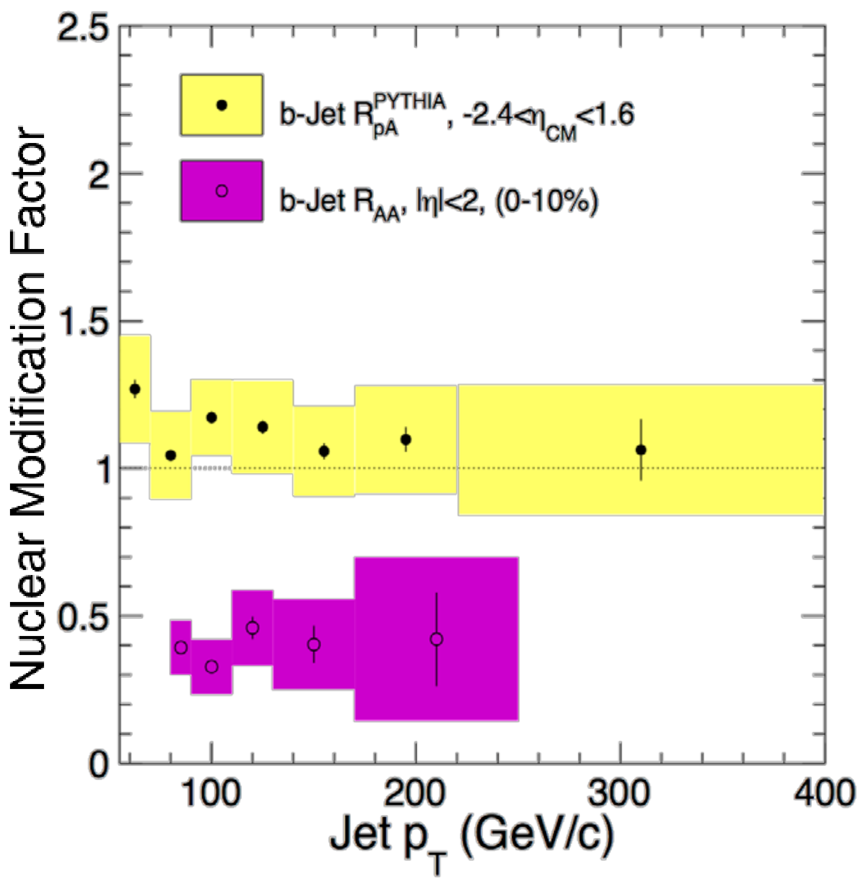
Enhancement observed at high p_T

Too large to be due to antishadowing?

Other nuclear effect?

R_{pA} & R_{AA} for jets and b-tagged jets

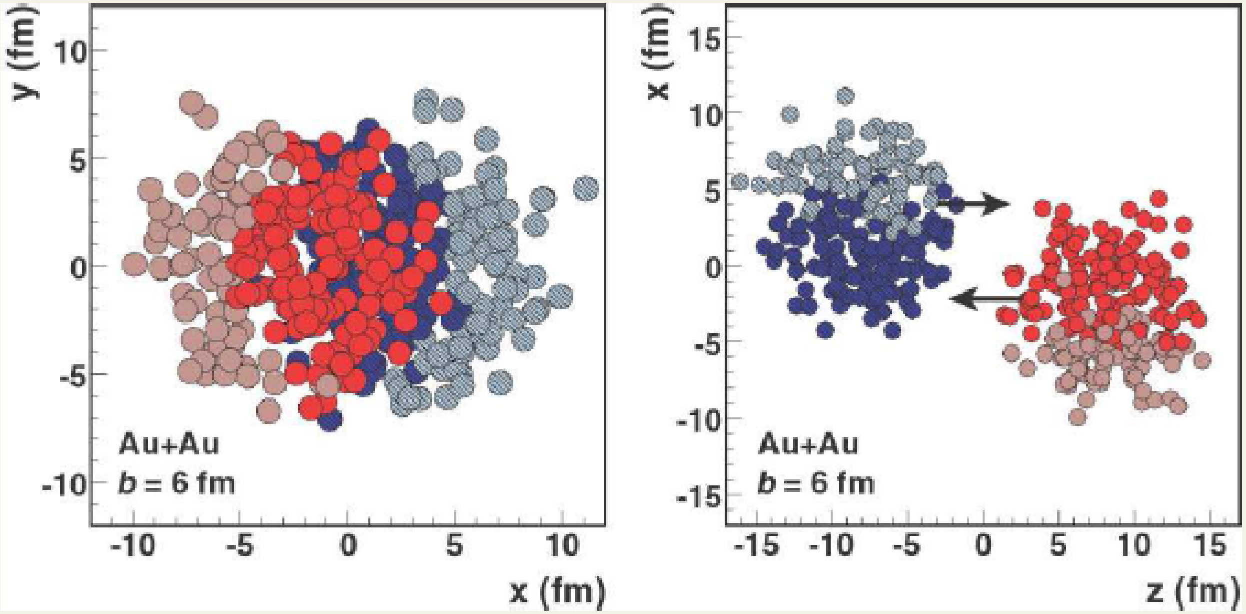




- Jets coming from b (secondary vertex)
  - as suppressed as incl. jets ($R_{AA} \approx 0.5$)
  - not suppressed in pPb ($R_{pA} \approx 1$)

Initial density distribution

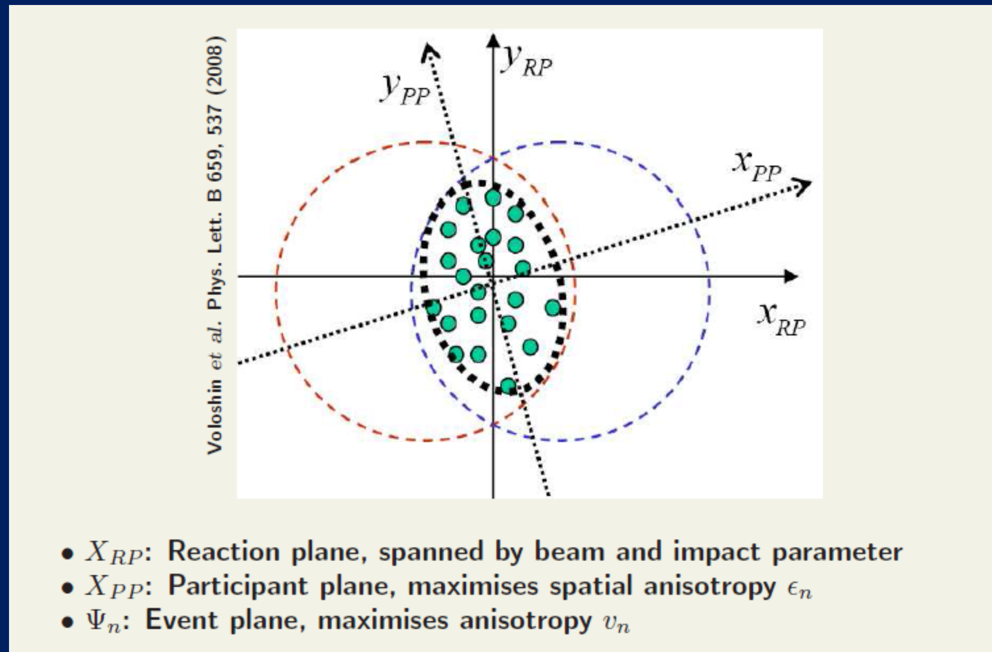
- Nuclear geometry implies that density varies event-by-event

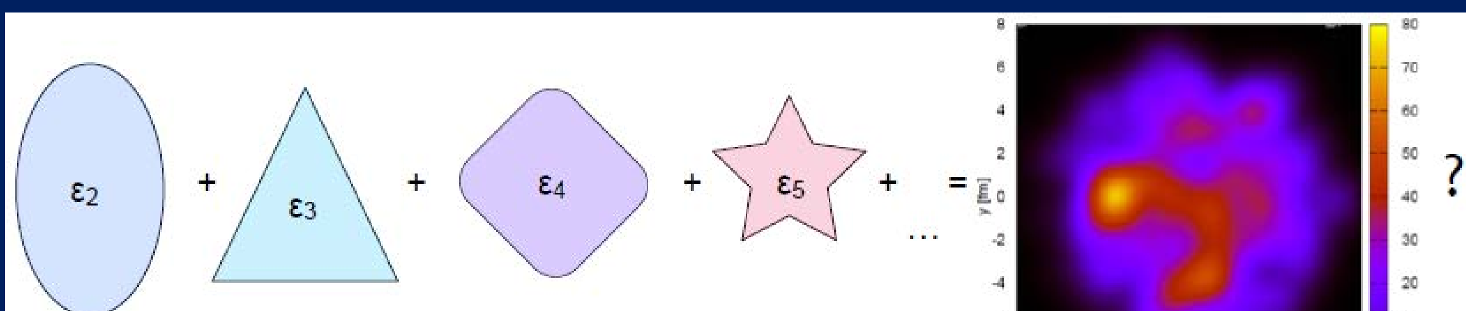


Miller *et al.*, Ann.Rev.Nucl.Part.Sci. 57, 205 (2007)

- evaluate average initial state, and evolve it or
- evolve many initial state ⇒ event-by-event hydro

Fourier analysis of initial condition profile



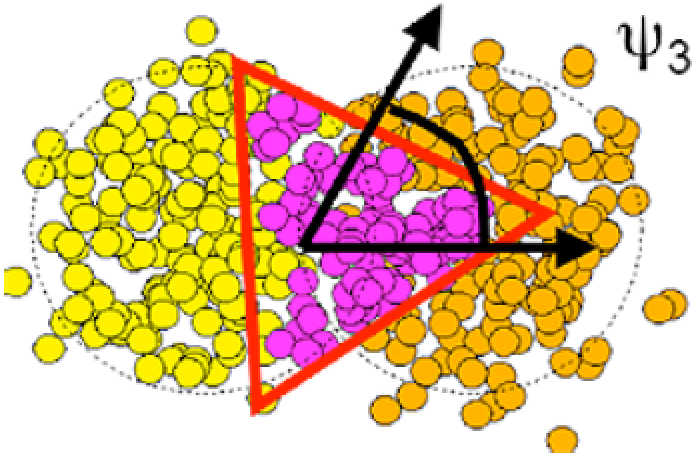


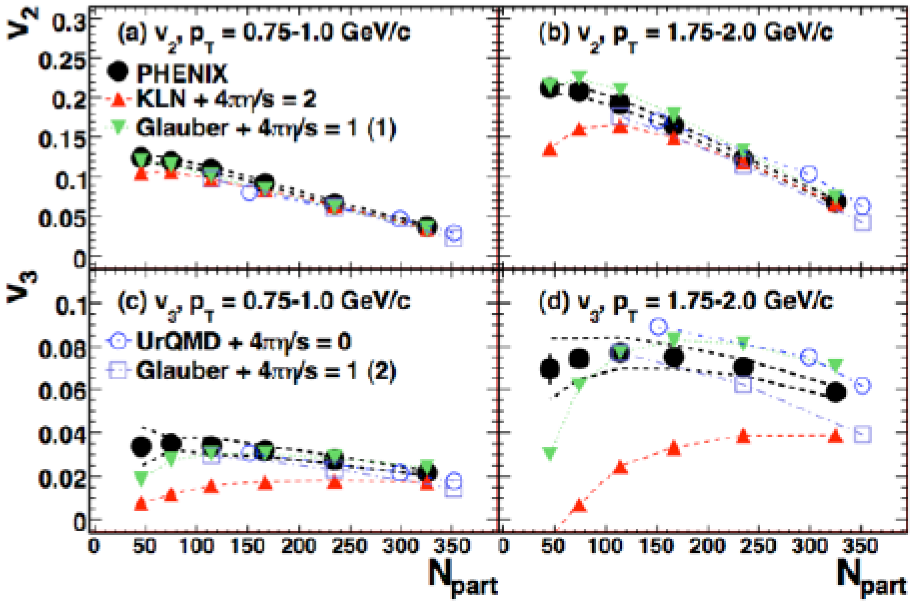
Hannah Petersen, Quark Matter 2014

Triangular Flow

Initial State Fluctuations

Third Harmonic Coefficient

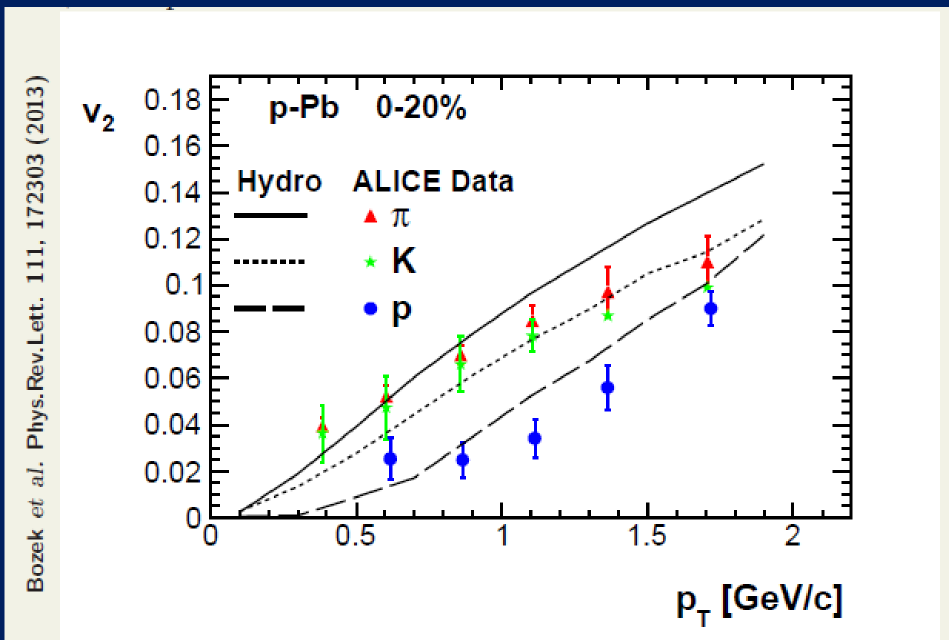


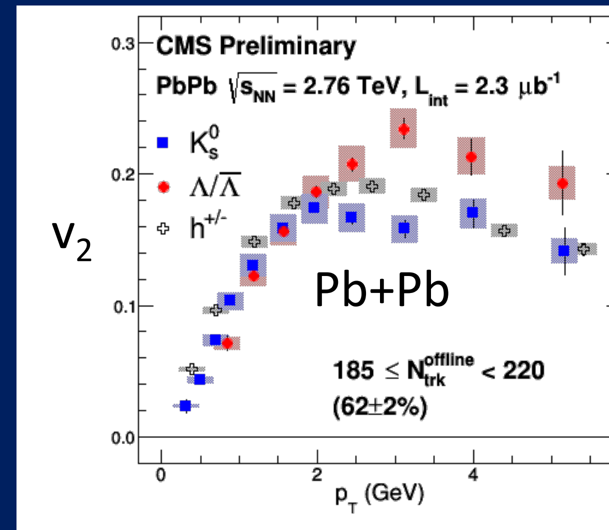


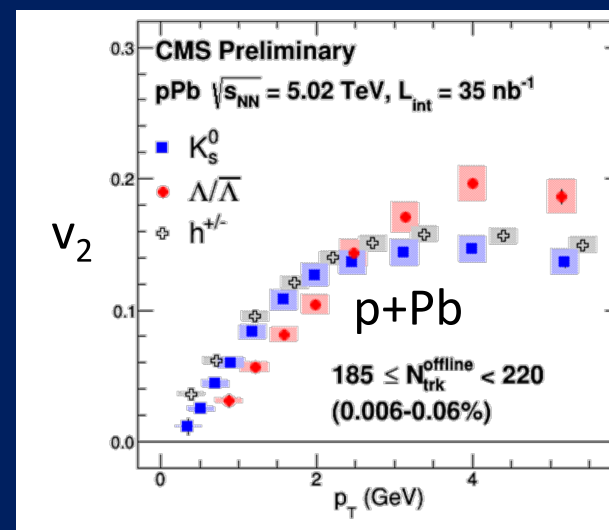
- Fluctuations introduce **higher order flow coefficients** that have been observed at the RHIC and LHC experiments (first results at QM 2011)
- Many more detailed measurements and calculations since then

B. Alver and G. Roland, PRC 2010; NEXspheRIO, PRL 103,242301, 2009; P. Sorensen, JPG, 37, 094011,2010 … and many more, results taken from PHENIX in Phys.Rev.Lett. 107 (2011) 252301

v_2 in p+Pb even exhibits mass ordering expected from hydrodynamical flow





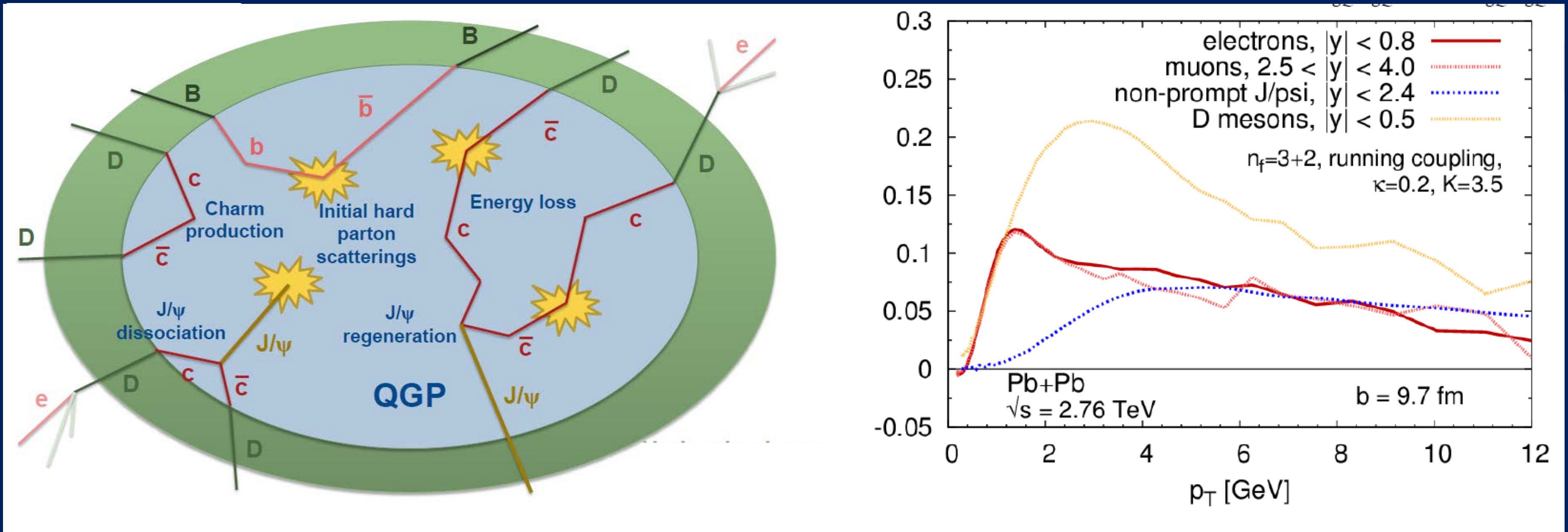


Heavy flavor v_2

(E. Scomparin, QM2014)

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium → $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium → Transported through the full system evolution

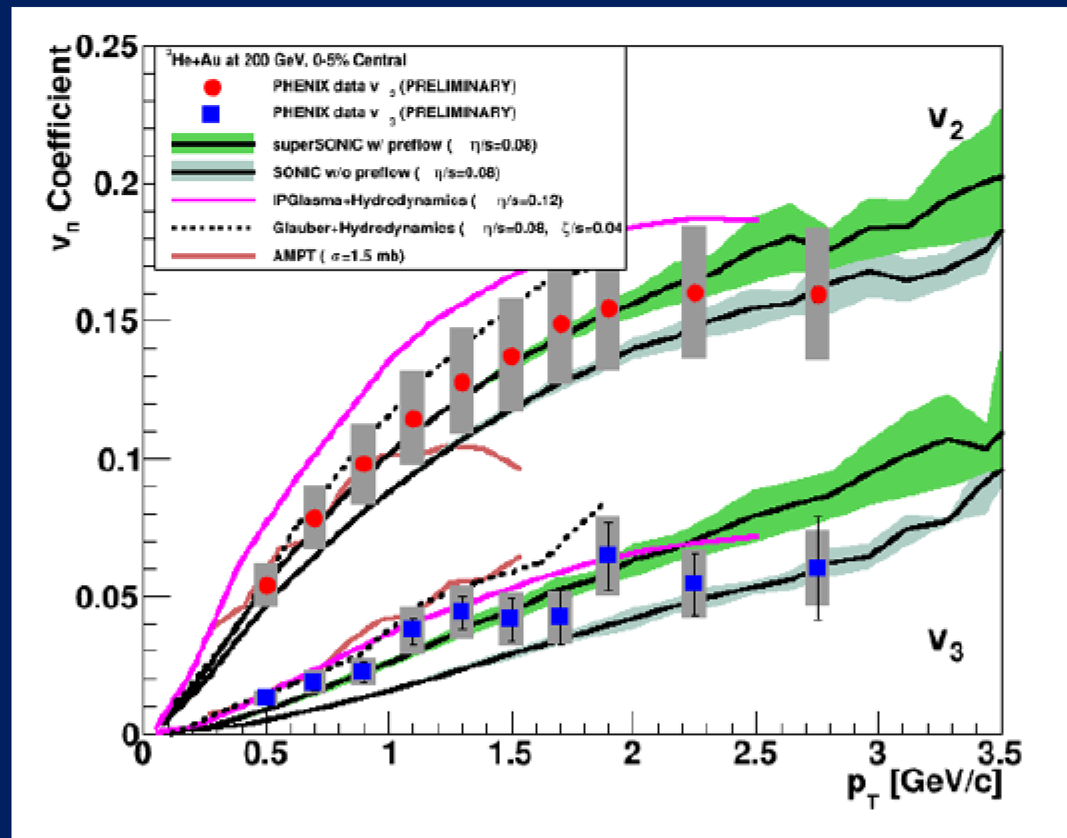
J. Uphoff et al., PLB 717 (2012), 430



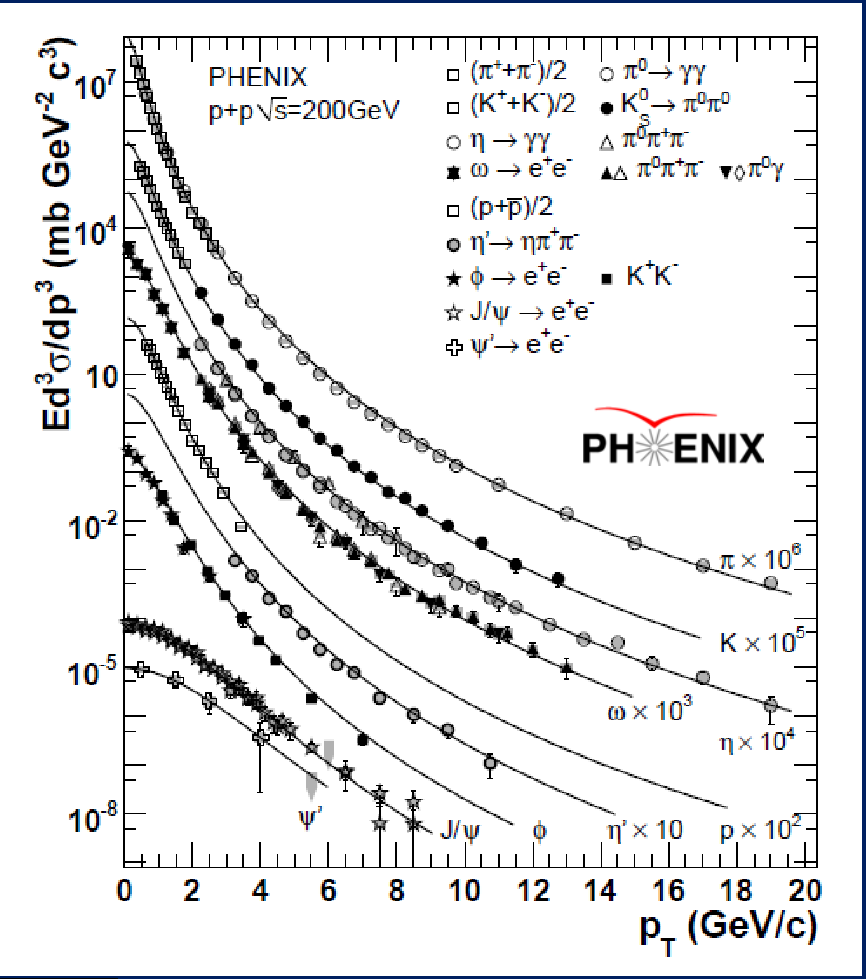
Can the unprecedented abundance of heavy quarks produced at the LHC bring to a (final ?) clarification of the picture ?

2nd and 3rd Fourier coefficients in ^{3}He+Au collisions

RHIC ran with ^{3}He+Au to test geometry effects. Large 3rd Fourier coefficient as expected from triangular initial shape of ^{3}He.



Eventually even more global global fits of fragmentation functions?

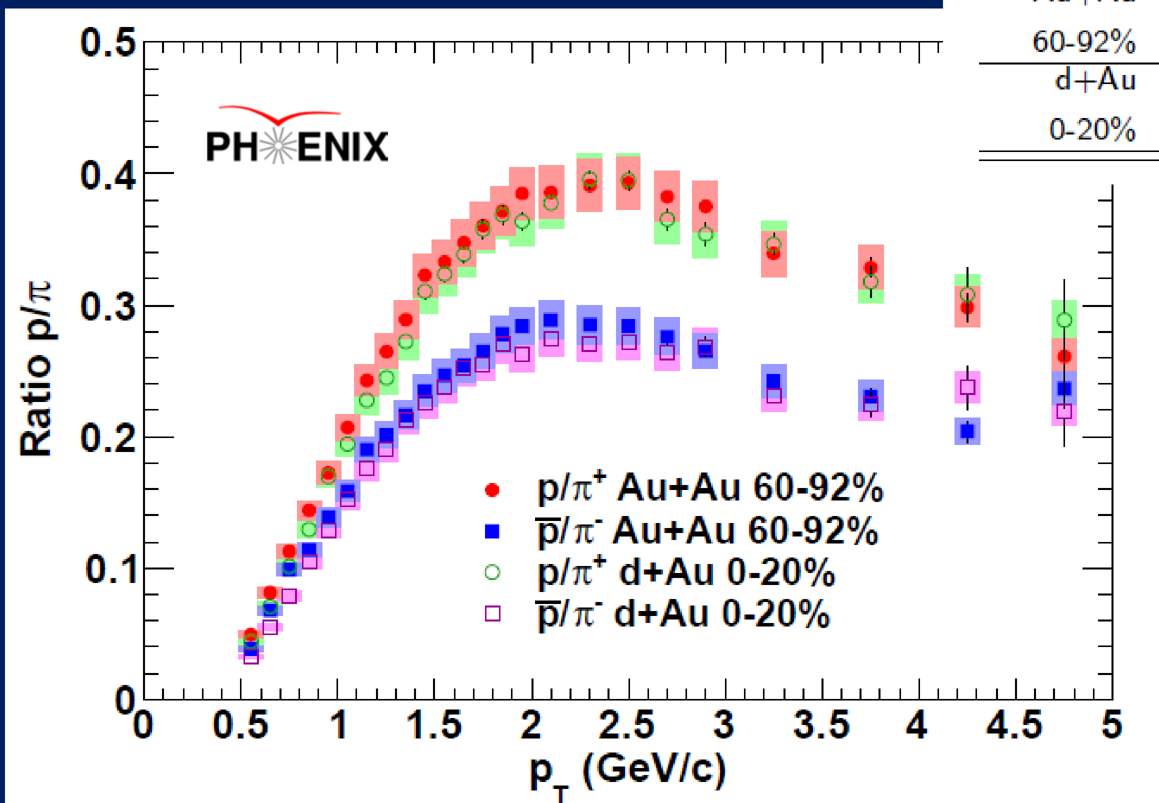


PRD83, 052004 (2011)

- Perform fragmentation function parameterizations for even more particles simultaneously?
  - Will constrain relative normalizations well
- Ultimate goal: Measure jet and all particles within it!
- Fit pdfs and FFs simultaneously . . .

Comparing proton/pion ratio in central d+Au with peripheral Au+Au

Centrality	$\langle N_{coll} \rangle$	$\langle N_{part} \rangle$
Au+Au		
60-92%	14.8 ± 3.0	14.7 ± 2.9
d+Au		
0-20%	15.1 ± 1.0	15.3 ± 0.8



PRC88, 024906 (2013)

Both shape and magnitude identical!

Suggests common mechanism(s) for baryon production in the two systems—partons nearby in phase space bind?

Jet Fragmentation at LHC

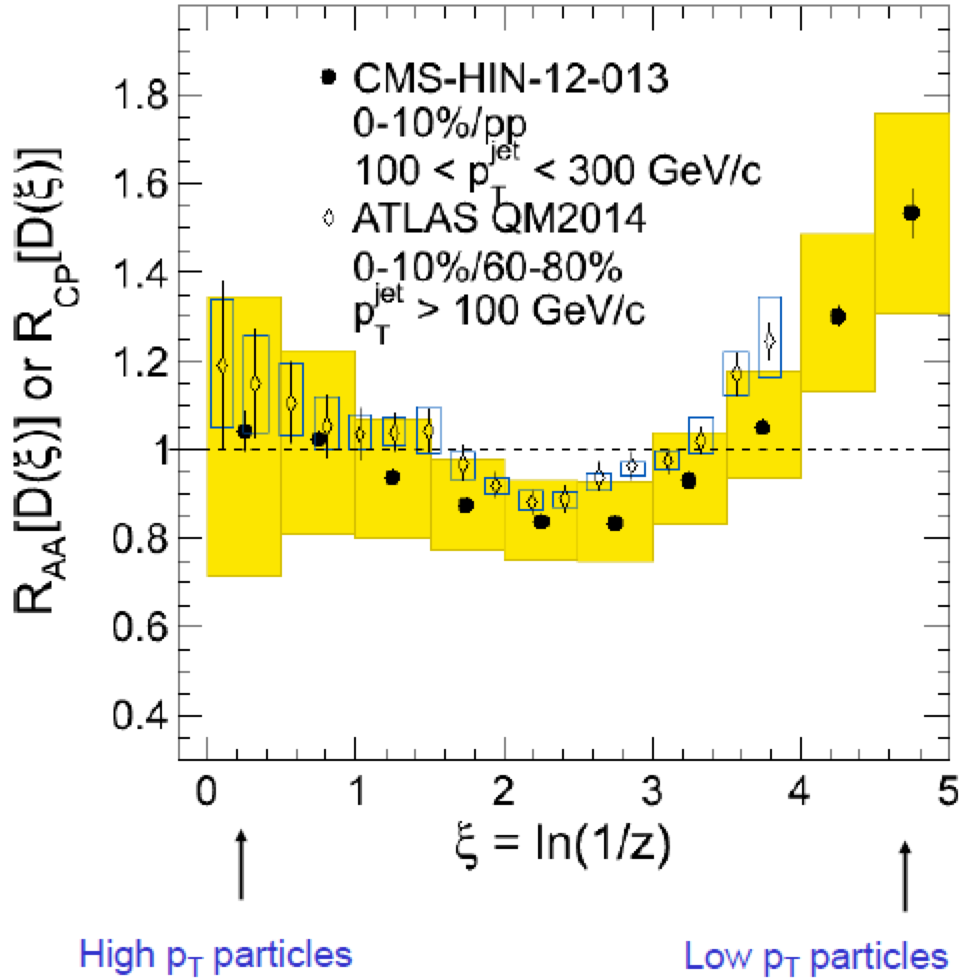
Using **Jet Energy** as a reference

CMS FF R_{AA} compared to ATLAS FF R_{CP}

$Z = p_T^{Trk} / p_T^{Jet}$

Qualitative consistent results between CMS and ATLAS

ATLAS update: indication of enhancement of low ξ (high z) particles in the jet cone



Martin Spousta (ATLAS 5/20)

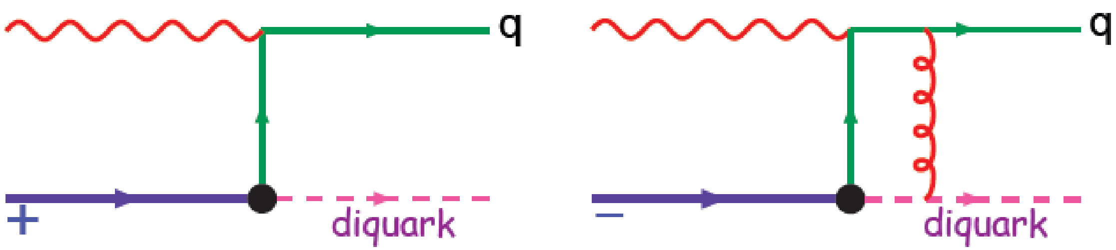
Gauge links have physical consequences

We have ignored here the subtleties needed to make this a gauge invariant definition: an appropriate path ordered exponential of the gluon field is needed [18].

Collins, 1993

gauge links have physical consequences;
quark models for non vanishing Sivers function,

SIDIS final state interactions



Brodsky, Hwang, Schmidt, PL B530 (2002) 99 - Collins, PL B536 (2002) 43

An earlier proof that the Sivers asymmetry vanishes because of time-reversal invariance is invalidated by the path-ordered exponential of the gluon field in the operator definition of parton densities. Instead, the time-reversal argument shows that the Sivers asymmetry is reversed in sign in hadron-induced hard processes (e.g., Drell-Yan), thereby violating naive universality of parton densities. Previous phenomenology with time-reversal-odd parton densities is therefore validated.

$$[f_{1T}^{q\perp}]_{\mathrm{SIDIS}} = -[f_{1T}^{q\perp}]_{\mathrm{DY}}$$

From M. Anselmino, Transversity 2014

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

Wikipedia:

“The Aharonov–Bohm effect is important conceptually because it bears on three issues apparent in the recasting of (Maxwell's) classical electromagnetic theory as a gauge theory, which before the advent of quantum mechanics could be argued to be a mathematical reformulation with no physical consequences. The Aharonov–Bohm thought experiments and their experimental realization imply that the issues were not just philosophical.

The three issues are:

- whether potentials are "physical" or just a convenient tool for calculating force fields;
- whether action principles are fundamental;
- the principle of locality.”

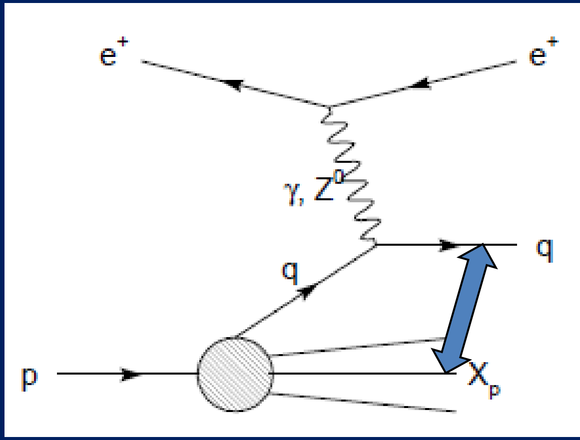
Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm (1959)

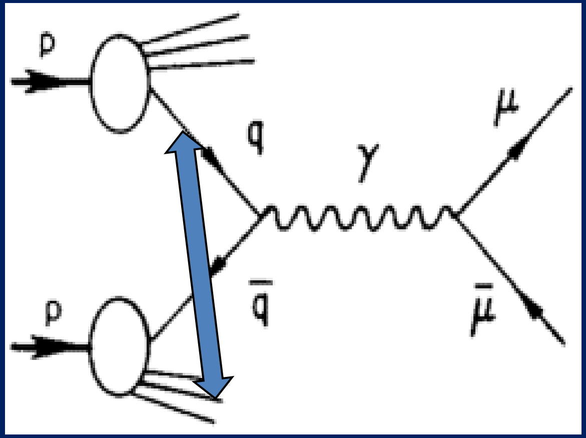
Physics Today, September 2009 :
The Aharonov–Bohm effects: Variations on a subtle theme,
by Herman Batelaan and Akira Tonomura.

"Aharonov stresses that the arguments that led to the prediction of the various electromagnetic AB effects apply equally well to any other gauge-invariant quantum theory. In the standard model of particle physics, the strong and weak nuclear interactions are also described by gauge-invariant theories. So one may expect that particle-physics experimenters will be looking for new AB effects in new domains."

Physical consequences of a gauge-invariant quantum theory: Aharonov-Bohm effect in QCD!!

Deep-inelastic lepton-nucleon scattering: Attractive final-state interactions	Quark-antiquark annihilation to leptons: Repulsive initial-state interactions

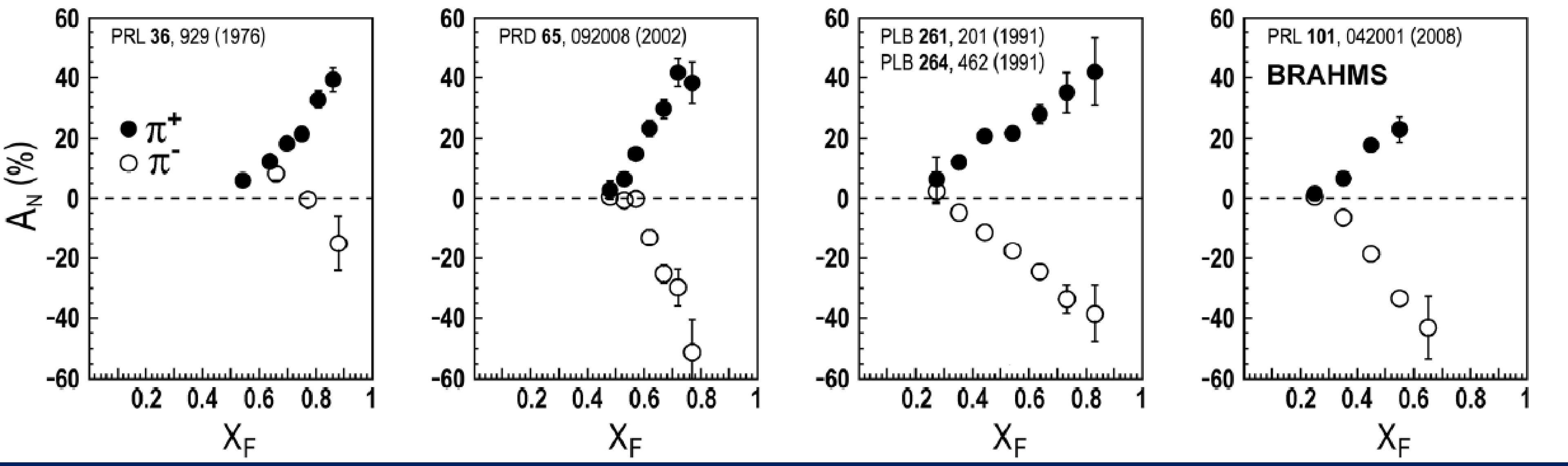




As a result: $$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

See e.g. Pijlman, hep-ph/0604226 or Sivers, arXiv:1109.2521

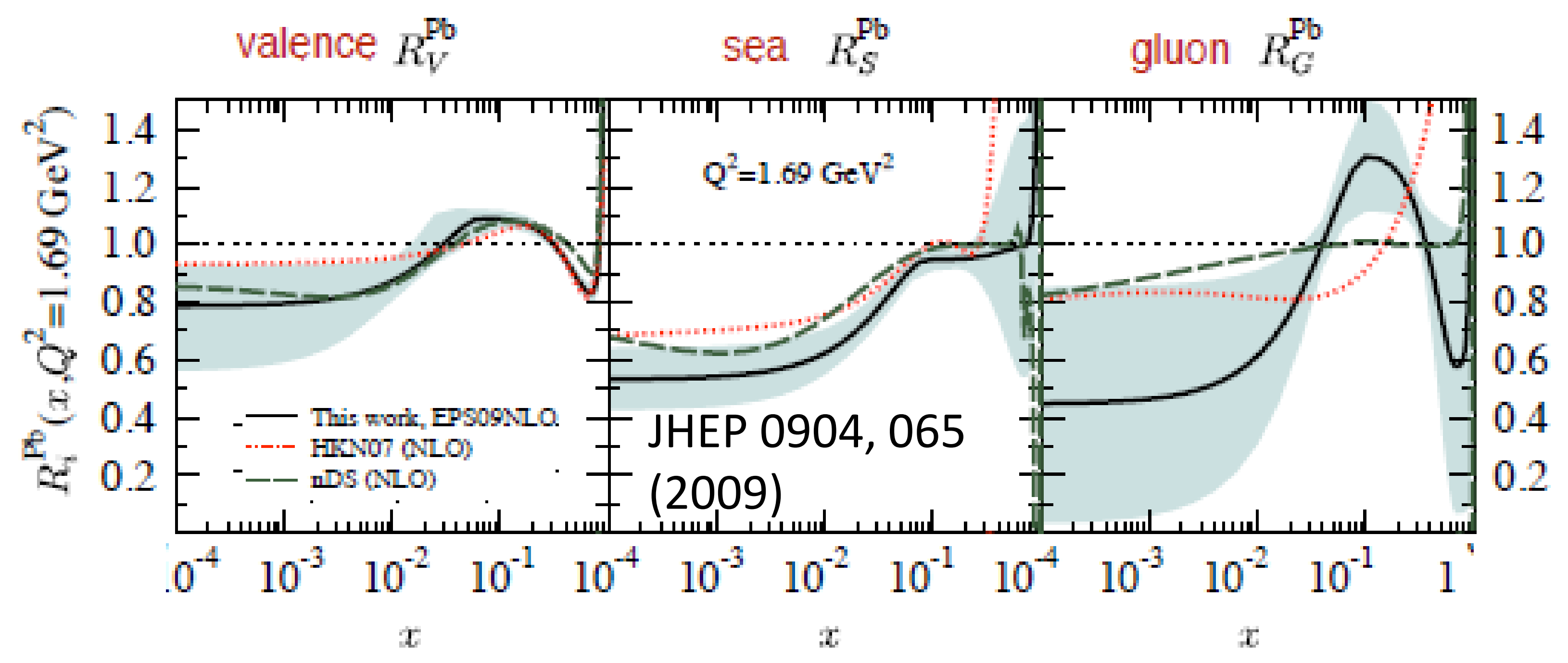
Multiparton correlations



- Similar effects across energies → Continuum between non-perturbative/non-partonic and perturbative/partonic descriptions of this non-perturbative structure??
- Extend our ideas about (single-parton) pdfs to correlation functions that can't be associated with a single parton . . .

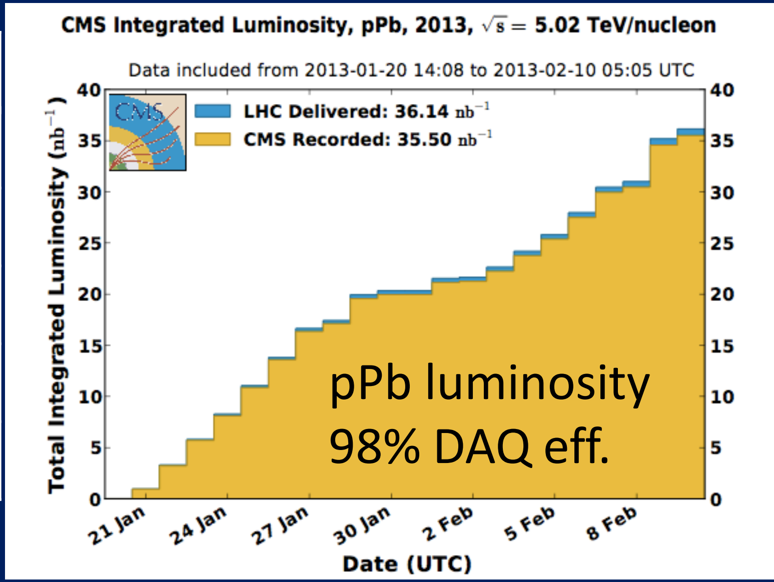
Recent renaissance in nuclear pdfs

- Renaissance in nuclear pdfs
  - EPS09 464 citations!



Overview of five HI-oriented runs

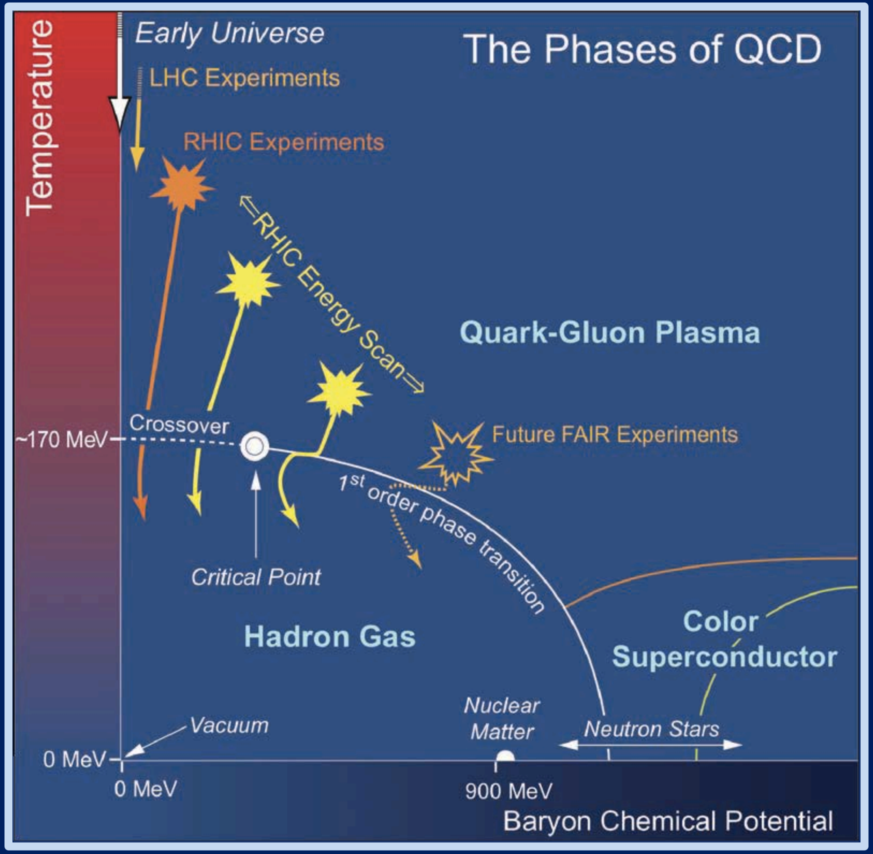
Period	Species	Energy	Lumi
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Feb. 2013	p+p	2.76 TeV	5.4 pb^{-1}



- Same N_{coll} scaled luminosities for pp, pPb, PbPb
  - (as many Z's and W's, modulo the √s dependence)

Beam Energy Scan-I at RHIC

Nu Xu, Quark Matter 2014



Study QCD Phase Structure
- Onset of sQGP
- Phase boundary and critical point
- Chrial symmetry restoration

Observables:

1st order phase transition

(1) Azimuthally sensitive HBT

(2) Directed flow v_1

Partonic vs. hadronic dof

(3) R_{AA}: Nucl. Mod. Fact.

(4) Charge separation

(5) v_2 - NCQ scaling

Critical point, correl. length

(6) Fluctuations

Chiral symmetry restoration

(7) Di-lepton production

BES-I: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39 GeV

BES-II will focus on $\sqrt{s_{NN}}$ < 20 GeV

Dark photon search at PHENIX

- π^0, $\eta \rightarrow e^+e^-\gamma$ (Dalitz decays) in d+Au, p+p collisions
- Search for possible π^0, $\eta \rightarrow \gamma U$, $U \rightarrow e^+e^-$ by looking at invariant mass of e^+e^- pairs 30-90 MeV

PRC91, 024913(R) (2015)

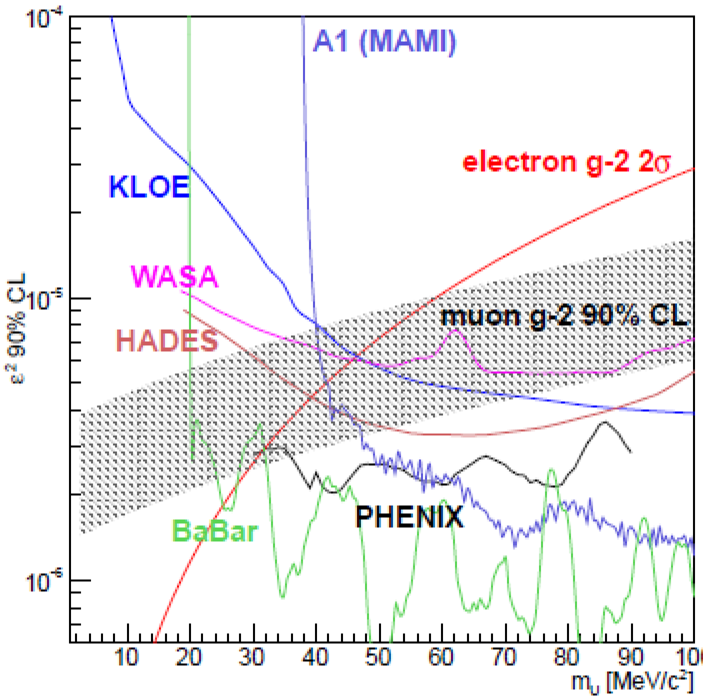


FIG. 4. (Color online) A compilation of the limits on the U-γ mixing parameter, showing the PHENIX results. Also shown are the limits at 90% CL from WASA [29], HADES [30], KLOE [31], A1(MAMI) [32], and BaBar [33] experiments and the band indicating the range of mass and coupling parameters favored by the $(g-2)_\mu$ anomaly at 90% CL. Also shown is the 2σ upper limit obtained from $(g-2)_e$ [34].

Data set – 1st period of LHC running completed

System	$\sqrt{s_{NN}}$ (TeV)	Year	Data analyzed
pp	7	2010	5 nb^{-1}
pp	2.76	2011	1.1 nb^{-1}
Pb-Pb	2.76	2010	2.12 μb^{-1}
Pb-Pb	2.76	2011	28 μb^{-1} central 6 μb^{-1} semi-peripheral
p-Pb	5.02	2013	48.6 μb^{-1}

LHC: Tentative Schedule

2010/11: **long run** with **pp** collisions at **7 TeV**

1 month of **Pb+Pb** collisions each year

2012: **long run** with **pp** at **8 TeV**

2012/13: **p+Pb control measurement**

2013/14: Machine consolidation and training

2015/16/17: **pp, p-Pb** and **Pb+Pb** at **13(14) TeV**

2018: long shutdown, luminosity + detector upgrades

2019: **pp, p-Pb,** and **Pb+Pb(50 kHz)** at **HL-LHC**

Quarkonia – where are we ?

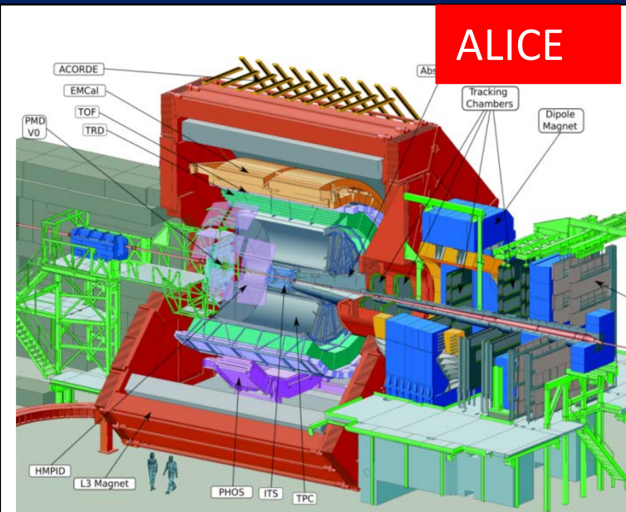
- Two main mechanisms at play
  1) Suppression in a deconfined medium
  2) Re-generation (for charmonium only!) at high $\sqrt{s}$

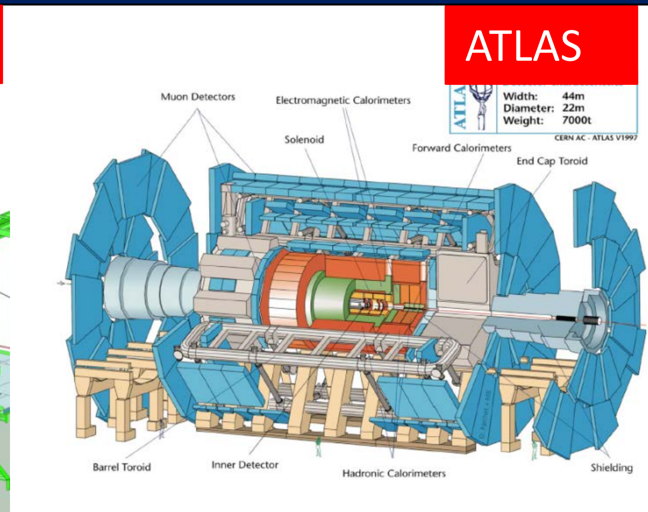
  can qualitatively explain the main features of the results

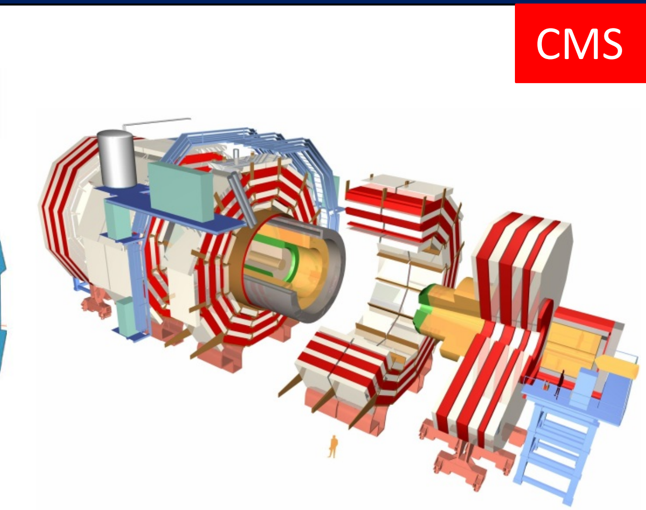
E. Scomparin, QM 2014

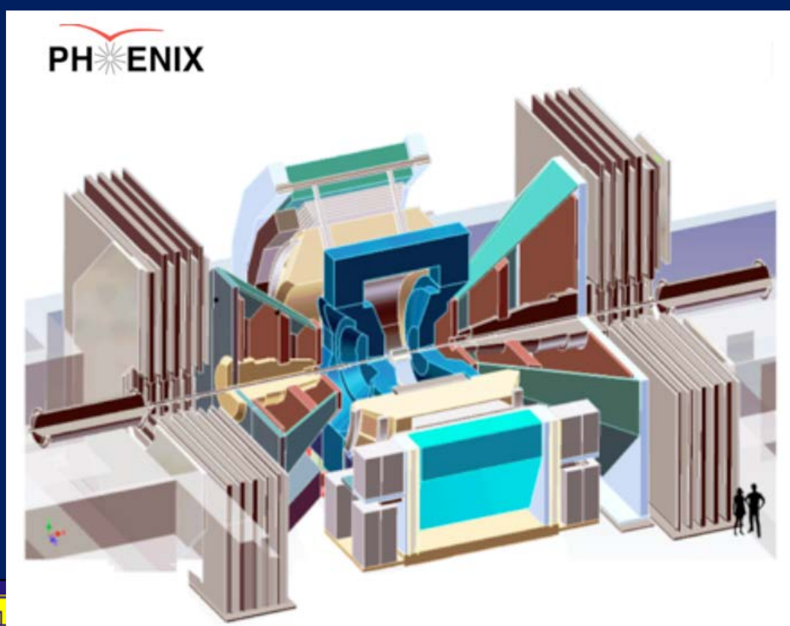
- ALICE is fully exploiting the physics potential in the charmonium sector (optimal coverage at low p_T and reaching 8-10 GeV/c)
  - R_{AA} → weak centrality dependence at all *y,* larger than at RHIC
  - Less suppression at low p_T with respect to high p_T
  - CNM effects non-negligible but cannot explain Pb-Pb observations

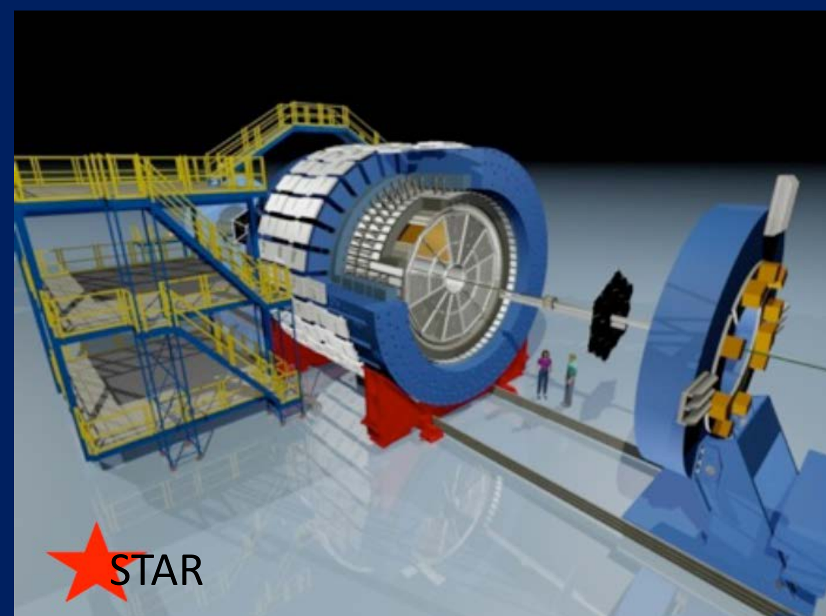
- CMS is fully exploiting the physics potential in the bottomonium sector (excellent resolution, all p_T coverage)
  - Clear ordering of the suppression of the three Υ states with their binding energy → as expected from sequential melting
  - $\Upsilon(1S)$ suppression consistent with excited state suppression (50% feed-down)


ALICE
ACORDE
EMCal
TOF
TRD
PMD
V0
Tracking Chambers
Dipole Magnet
HMPID
L3 Magnet
PHOS
ITS
TPC

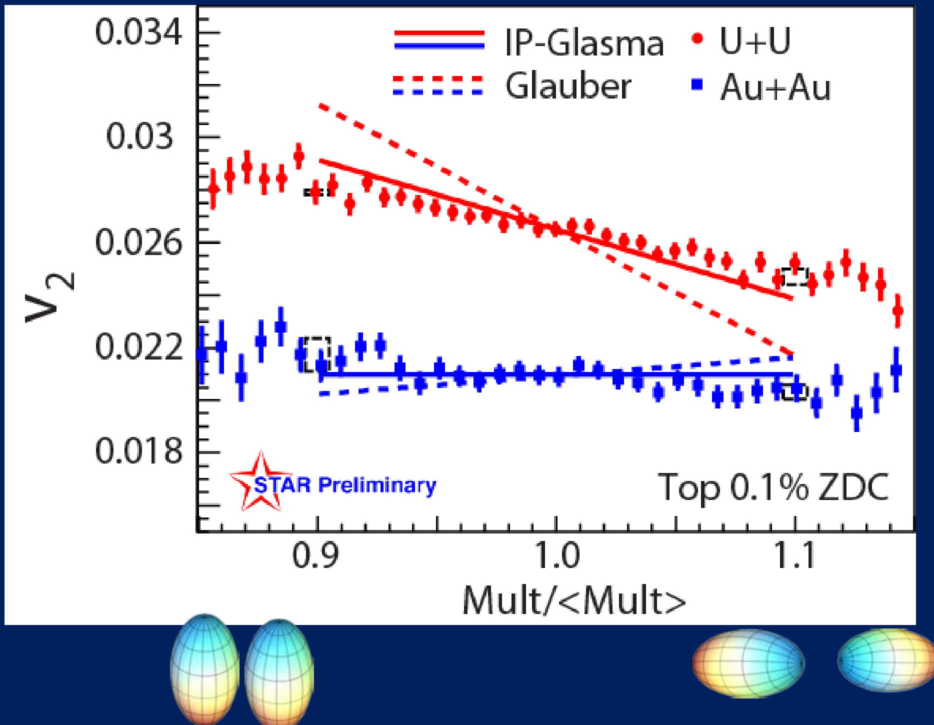

ATLAS
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

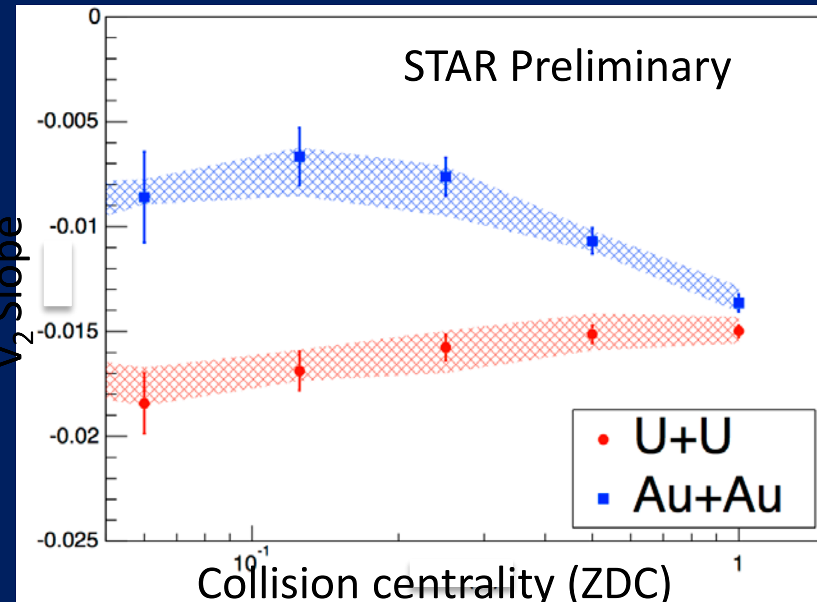

CMS


PHENIX


STAR

193 GeV U+U collisions





1) RHIC delivered the U+U collisions in order to study geometry effects. Model expectation: 20% increase in energy density in very central collisions
2) Tip-tip and body-body enhanced samples selected via ZDC-mult cut
3) IP-Glasma model consistent with the observation: implying CGC type of initial condition at RHIC

- Bjoern Schenke, et al. arXiv:1403.2232

- Maciej Rybczyński, et. al. PRC87,044908(13)

Nu Xu, Quark Matter 2014