RHIC Physics Program

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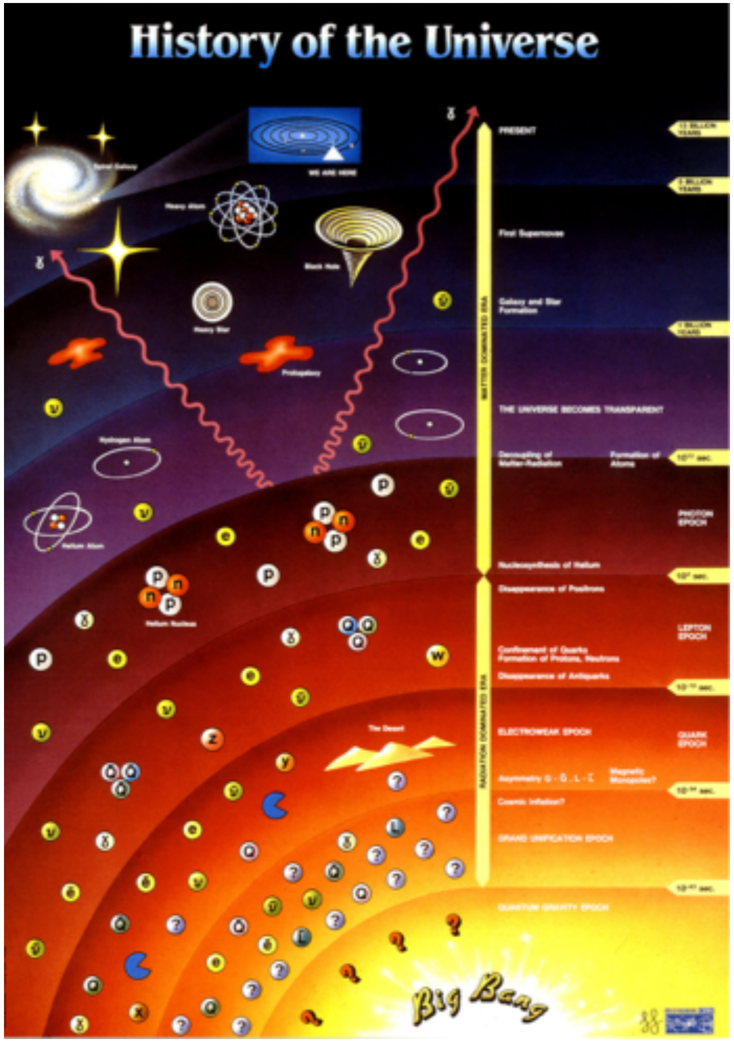
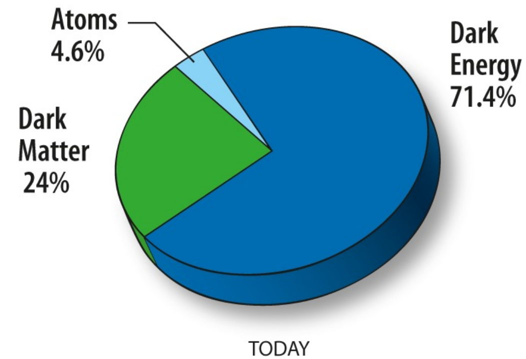
RHIC Retreat, September 16, 2021

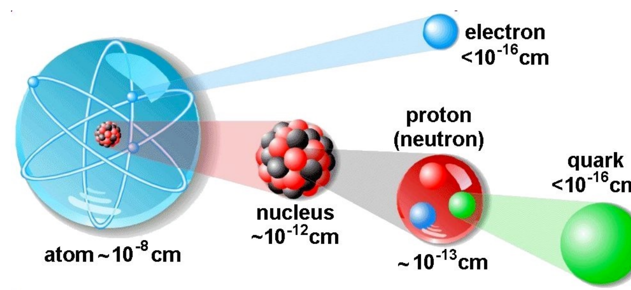
The birth of nucleons and the universe today

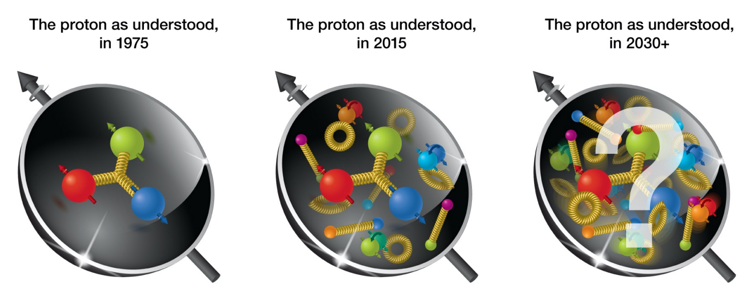


About 1 second after the Big Bang protons and neutrons are formed.



In today's universe, 99% visible matter are protons and neutrons.





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Discoveries of Breit-Wheeler process and vacuum birefringence

PRL127 (2021) 52302

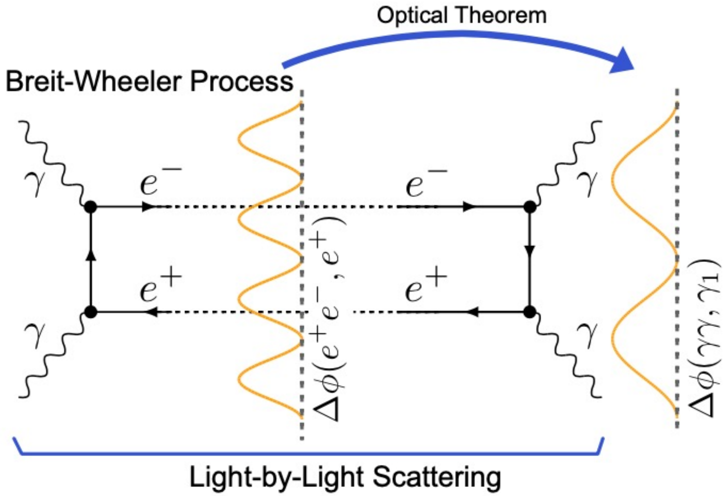
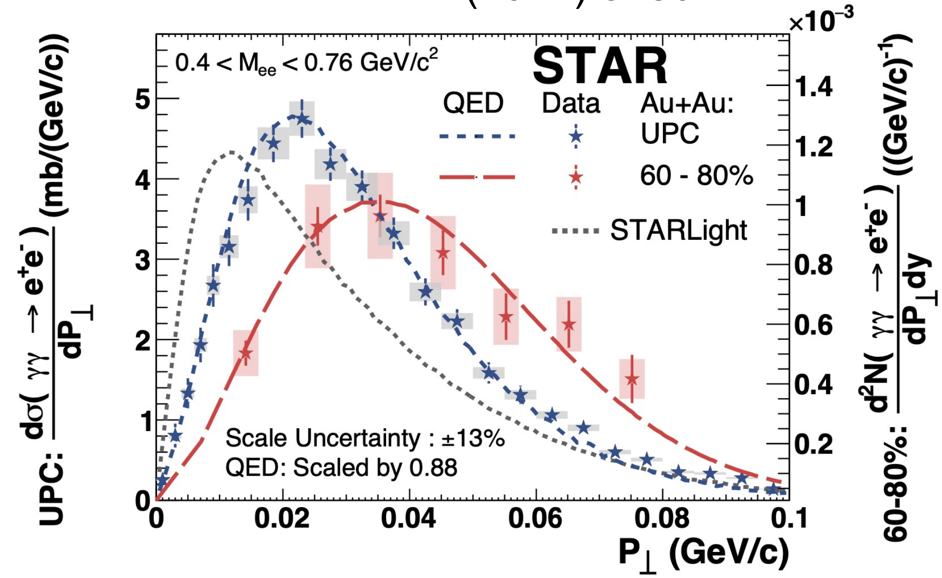
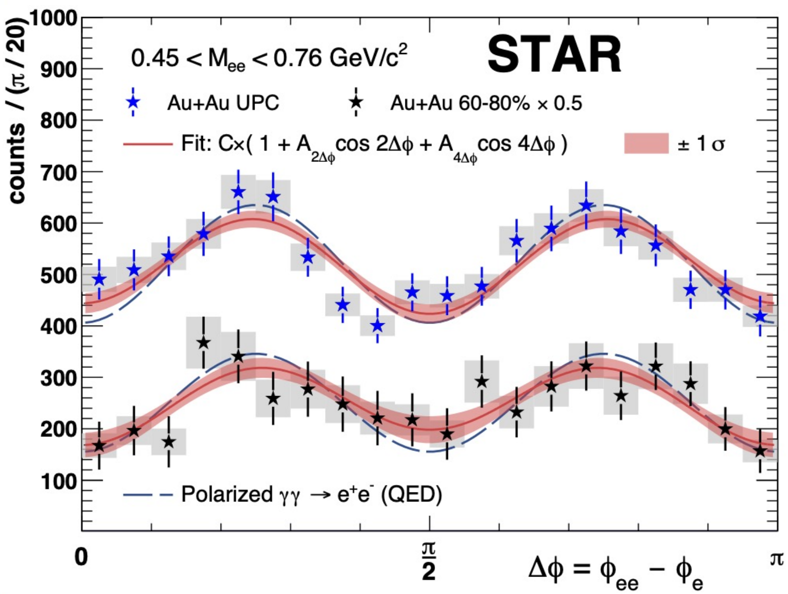


FIG. 1. A Feynman diagram for the exclusive Breit-Wheeler process and the related Light-by-Light scattering process illustrating the unique angular distribution predicted for each process due to the initial photon polarization.





Observation of Breit-Wheeler process with all possible kinematic distributions (yields, M_{ee}, p_T, angle)

Dielectron p_T spectrum: broadened from large to small impact parameters

Observation of vacuum birefringence: 6.7σ in Ultra-peripheral collisions

Collisions of Light Produce Matter/Antimatter from Pure Energy: https://www.bnl.gov/newsroom/news.php?a=119023

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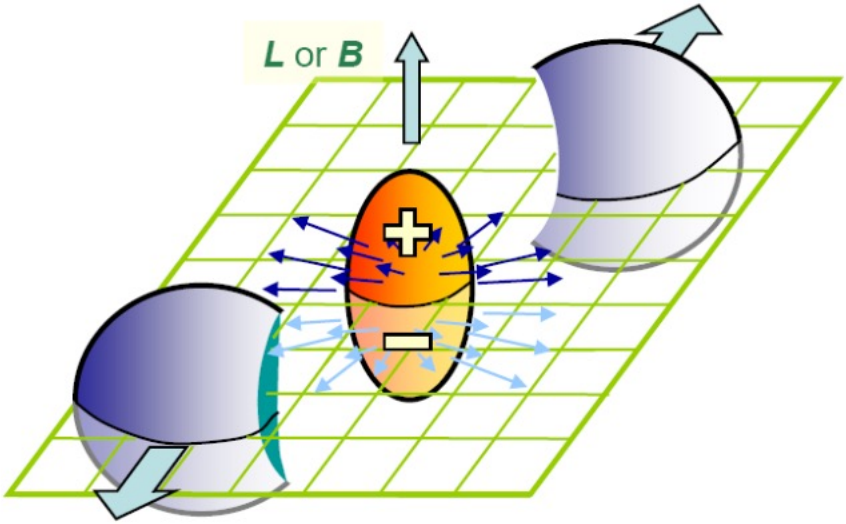
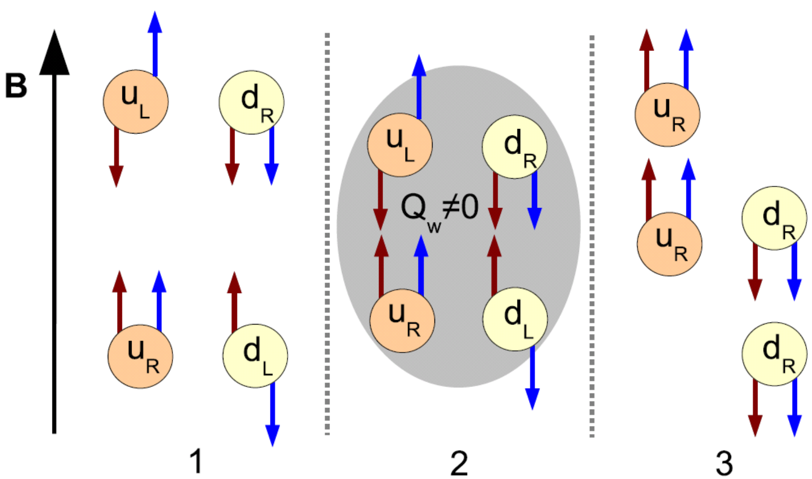
The search for Chiral Magnetic Effect (CME)



Non head-on heavy ion collisions generate large magnetic field (peaked at 10^{15} T)

In QGP, massless quark interactions with gluon-field topological charge lead to chiral imbalance (non-zero μ_A)

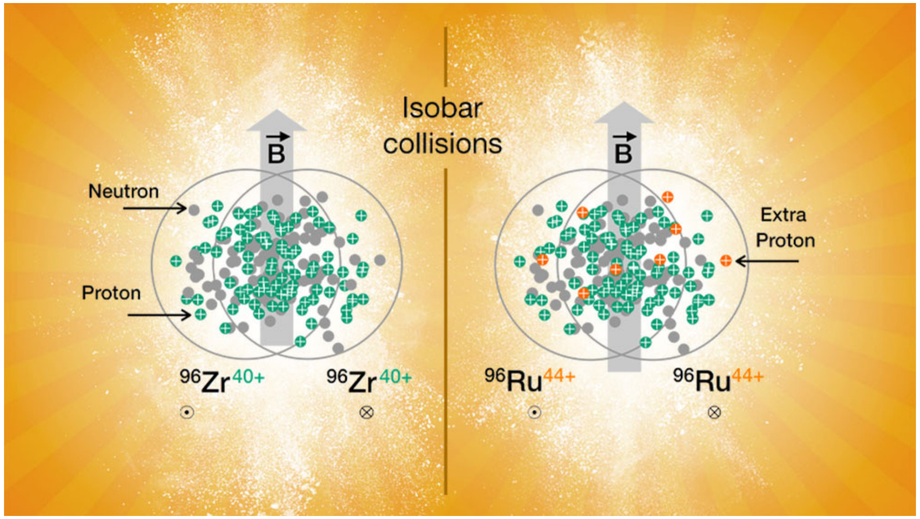


charge separation caused by anomaly induced chiral imbalance and large magnetic field

$$\vec{J}_V = \frac{eN_C}{2\pi^2}\mu_A\vec{B}$$

D. Kharzeev

Isobar blind analysis: search for Chiral Magnetic Effect



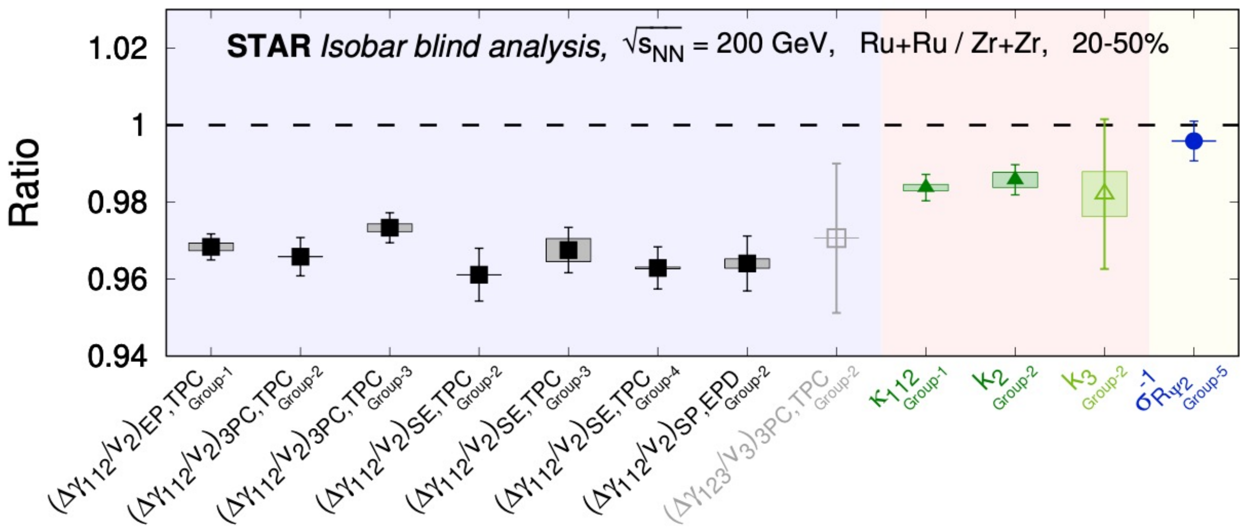
https://www.bnl.gov/newsroom/news.php?a=119062

arXiv: https://arxiv.org/abs/2109.00131

Isobar idea: change signal while keeping background fixed

Blind analyses of CME studies of Run-18 isobar data recommended by the 2017 BNL NPP Physics Advisory Committee and implemented at STAR

Large collective efforts from STAR collaboration



Pre-defined CME signatures: All ratios > 1

Not seen

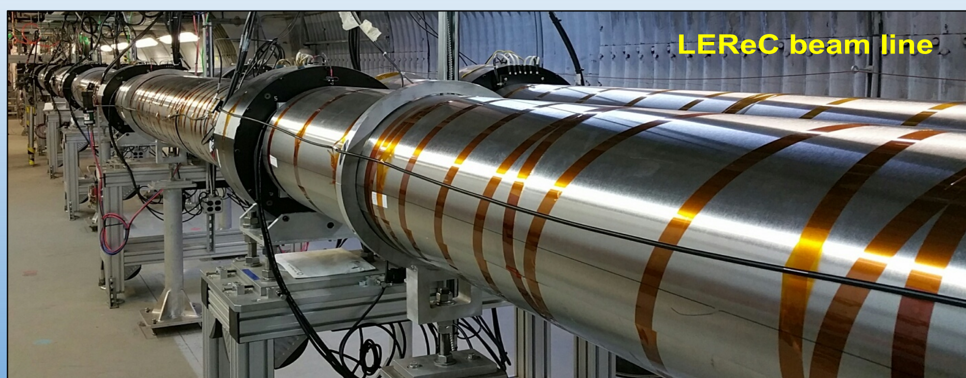
A precision down to 0.4% is achieved, as anticipated, in the relative magnitudes of the pertinent observables between the two isobar systems

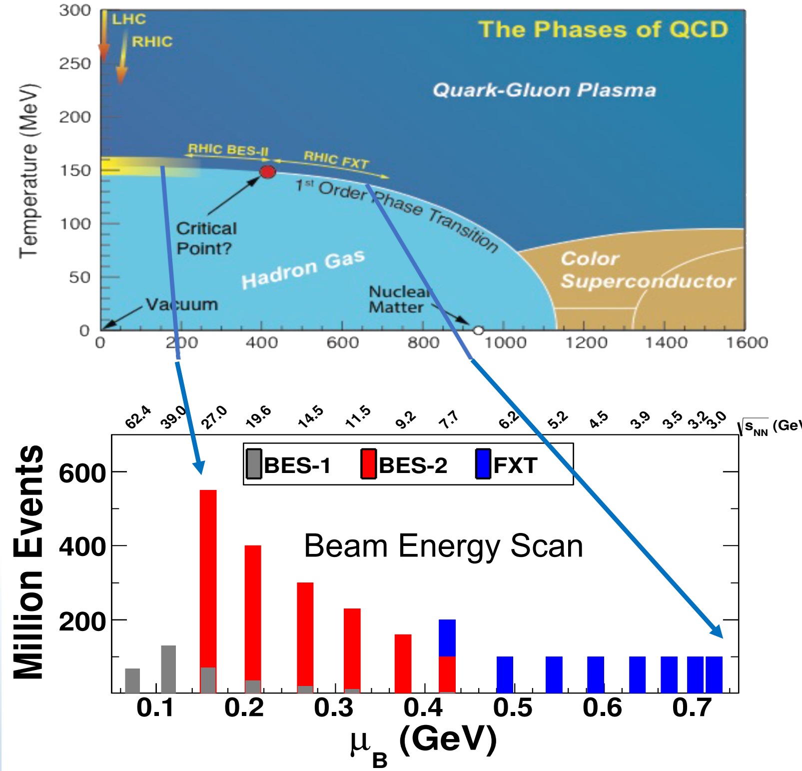
No CME signature that satisfies the pre-defined criteria observed
The observed multiplicity difference between the isobars requires future CME analyses to better understand the baselines in order to best utilize the precision demonstrated in this analysis

After over a decade of discovery science – RHIC in the 2015 NSAC Long Range Plan

"There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC."**

LEReC = Low Energy RHIC electron Cooling
First-ever electron cooling with bunched beams
Test case for electron cooling at EIC





Beam Energy Scan

- What is the phase boundary of ordinary nuclear matter?
- Is there a critical point in the QCD phase diagram? If so, where?
  - 3-years run program, 13 energies
  - 7 energies new (fixed target)
  - >10-fold statistics for all energies
  - **Completed in July 2021**

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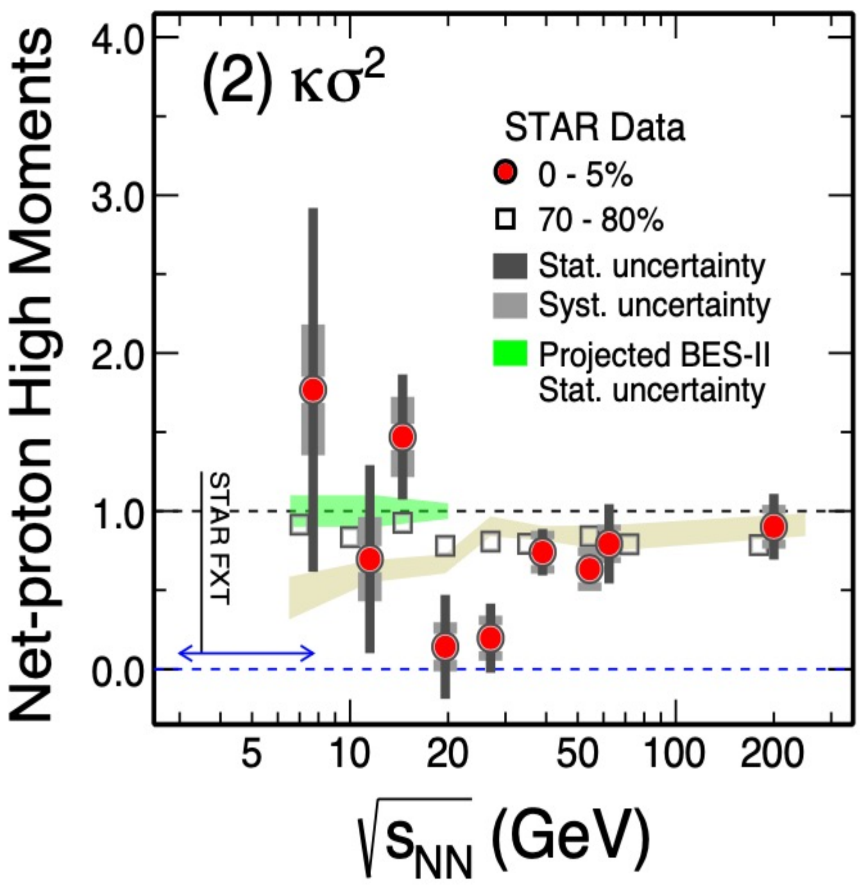
STAR: Critical Point Search

Phys. Rev. Lett. **126** (2021) 92301



- Non-monotonic variation of moments of net-baryon number distribution
  - Related to correlation length and susceptibilities of the system, suggested as a signature of a critical point
- Final BES-I based result

kurtosis × variance of the net-proton number: non-monotonic variation as a function of collision energy observed (3.1σ)

Acknowledgement:
the STAR Collaboration

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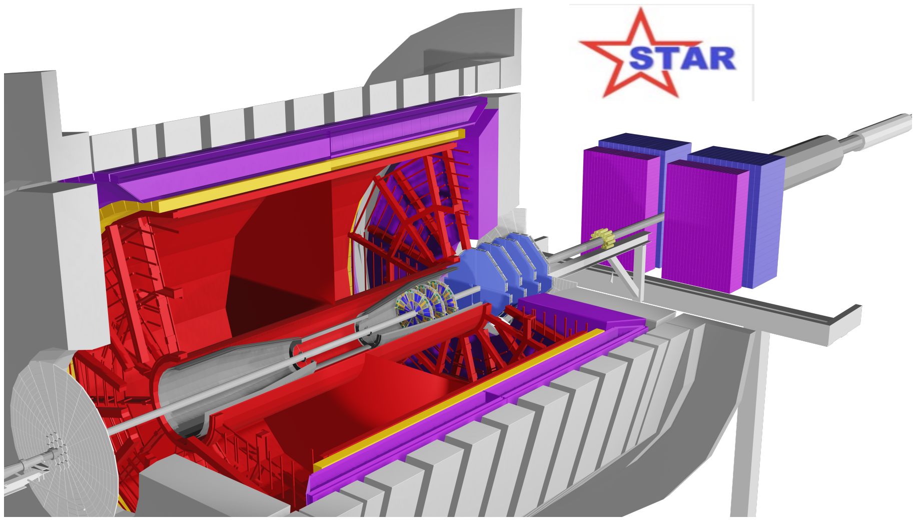
Completing the RHIC Mission: STAR Forward Upgrade

- New STAR forward detector upgrade probes universality of 3-D parton dynamics
- Important for EIC physics program



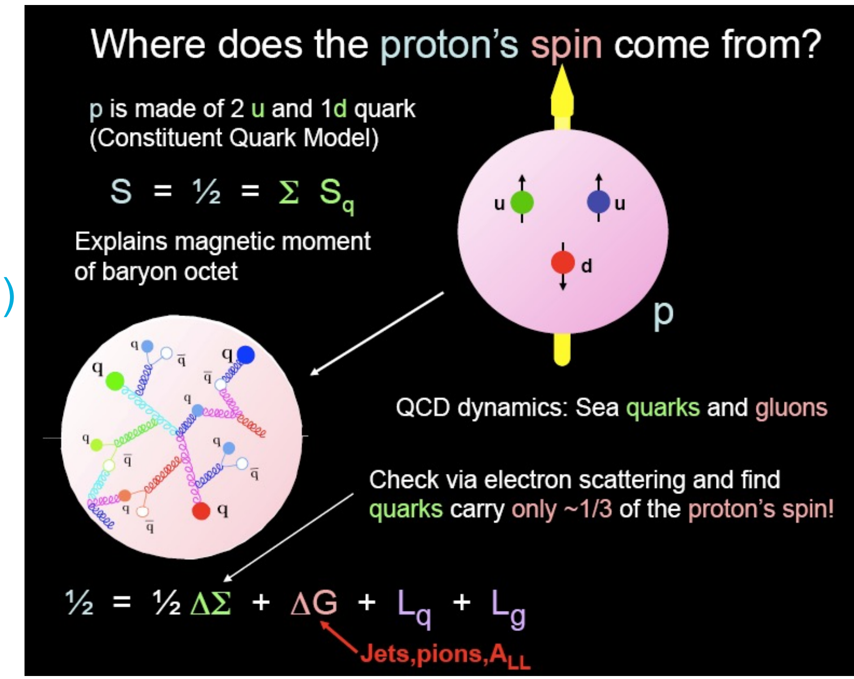
RHIC data taking scheduled for 2022

$\sqrt{s}$: 510 GeV transverse p+p spin run enhanced by forward upgrades of STAR

Spin and Proton Spin

- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - 1980s: "Proton spin crisis"
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: "New breakthrough in spin physics"?

➢1980s: "Proton spin crisis" (original EMC result from CERN)



Topological insulator, quantum computer, QIS

Nature:http://www.nature.com/milestones/milespin/index.html

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Impressive experimental progress in QCD spin physics in the last 30+ years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C

- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab

- **Polarized pp collisions**
  - BNL: PHENIX & STAR
  - FNAL: POL. DY

- **e+e- collisions**
  - KEK: Belle
  - BaBar
  - BESIII

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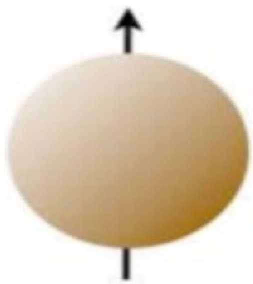
Adapted from Z. Meziani's

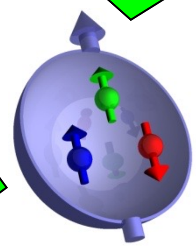
The incomplete nucleon: spin puzzle

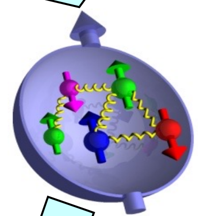
Jaffe-Manohar, 90
Ji, 96

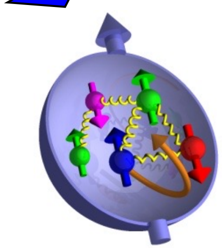


Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$







Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

~40% (RHIC Spin data)
At $Q^2 = 10\ GeV^2$

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

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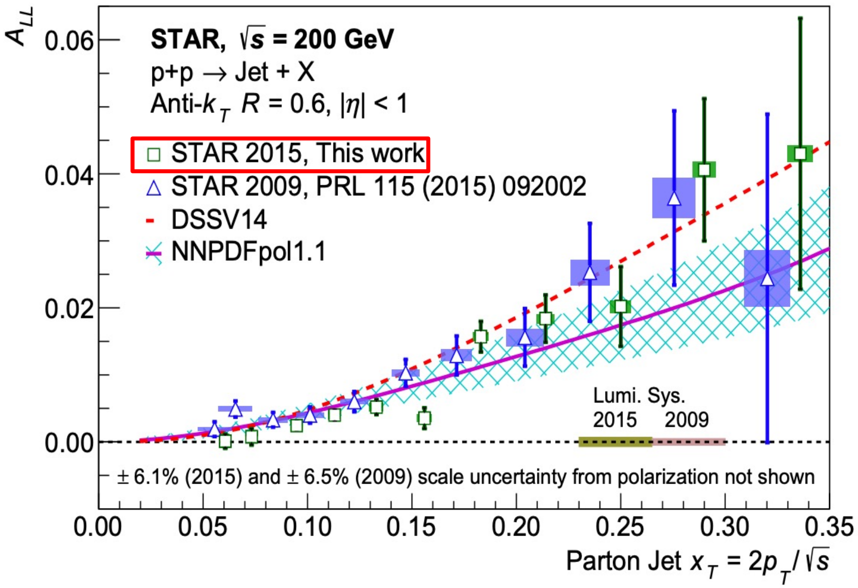
Helicity PDFs: ΔG

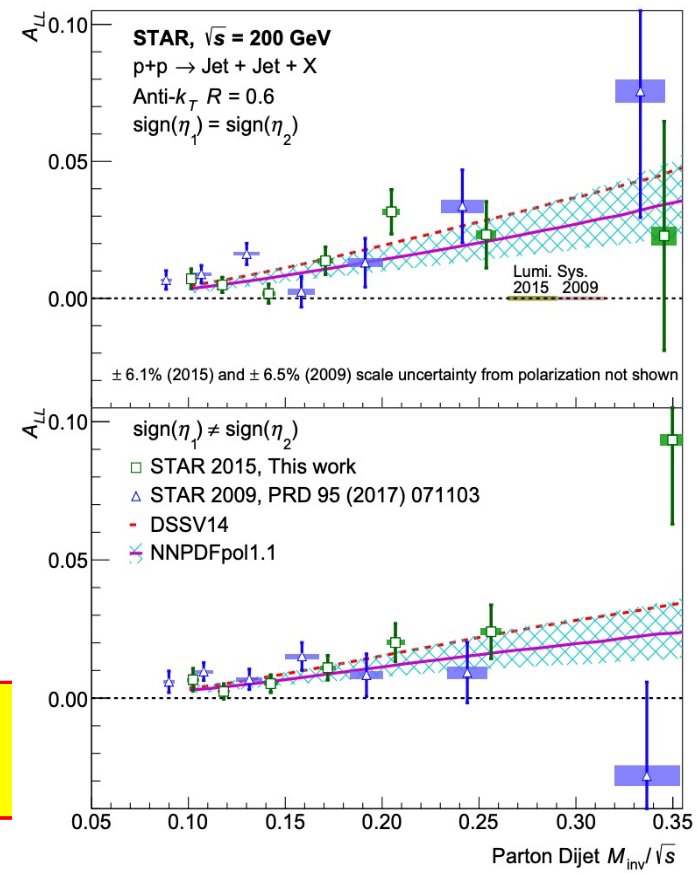
PRD 103 (2021) L091103



Newly published results:

- Largest 200 GeV longitudinally polarized pp dataset (2015); improved both statistical and systematic uncertainties
- Include jet and di-jet A_{LL} : constrain gluon polarization for x_T > 0.05

Di-jets: Much narrower ranges of initial state partonic momentum fraction tested; different topologies enhance sensitivity of the data to selected x



This result will reduce the uncertainty of gluon polarization for x_T > 0.05 if included in global fits

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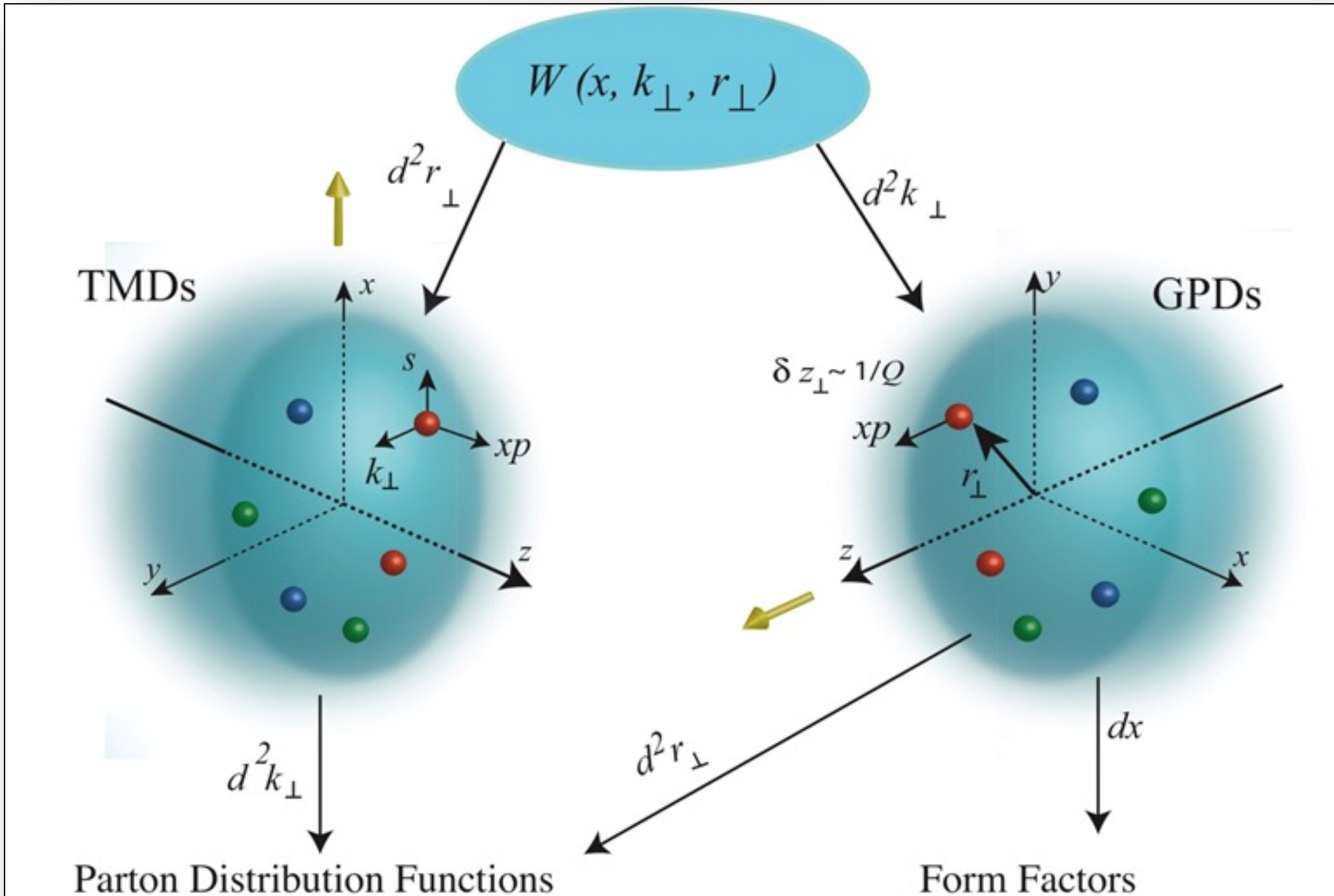
Nucleon Structure from 1D to 3D – orbital motion

5-D Wigner distribution



X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)

Generalized parton distribution (GPD)

Transverse momentum dependent parton distribution (TMD)

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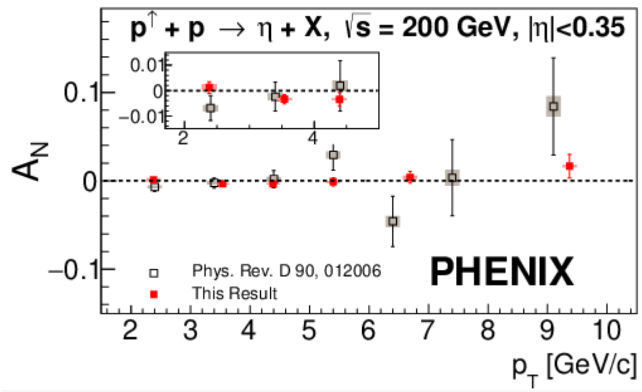
Image from J. Dudek et al., EPJA 48,187 (2012)

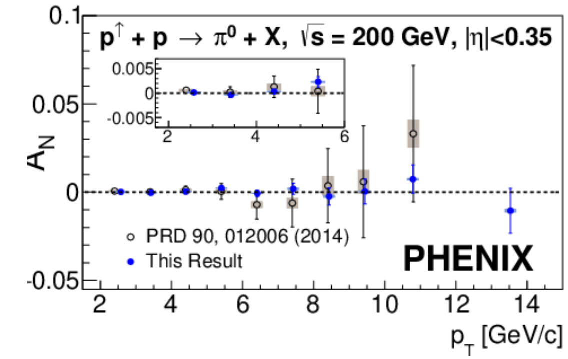
Spin highlights from PHENIX

Central arm A_N

[PRD 103 (2021), 052009](PRD 103 (2021), 052009)

- Substantial updates for π^0 and η single spin asymmetries at central rapidity

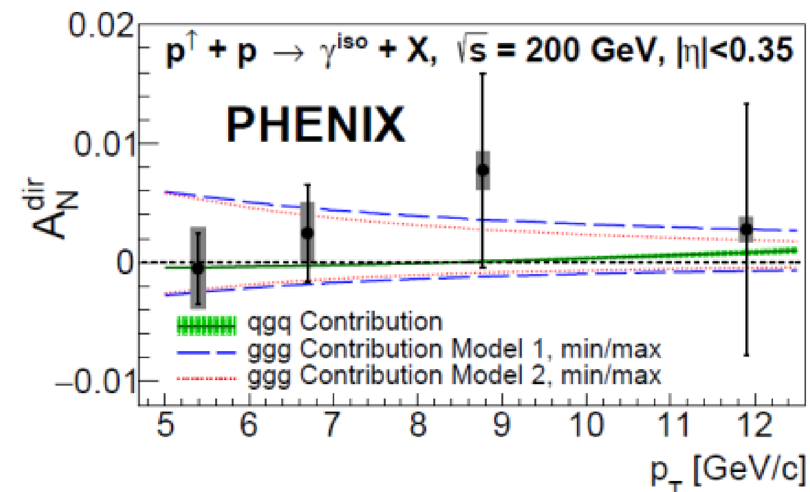


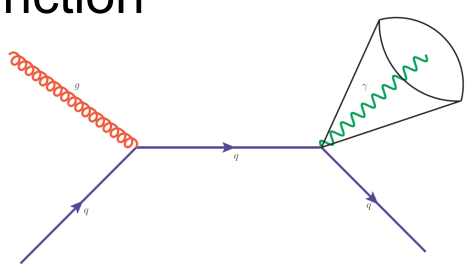


- First direct photon A_N extracted at RHIC

2102.13585, to appear in PRL

- Mostly sensitive to initial state effects (no fragmentation) → quark-gluon and gluon-gluon correlation functions
- Power to constrain gluon-gluon correlation function as well





Acknowledgement:
the PHENIX Collaboration

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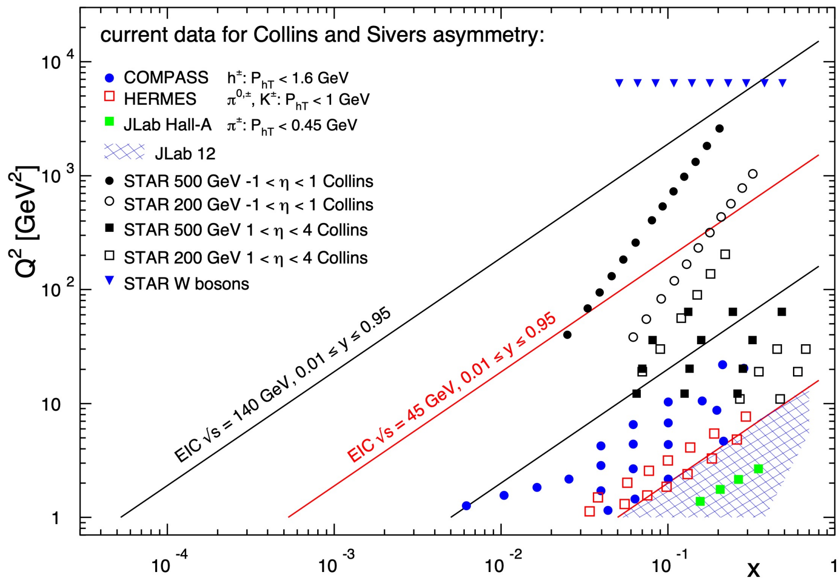
BUR for Run-22

$\sqrt{s}$ (GeV)	Species	Polarization	Run Time	Sampled Luminosity	Priority
510	p+p	Transverse	16 weeks	400 pb^{-1}	1

Kinematic coverage for Collins and Sivers Asymmetry
STAR covers 0.005<x<0.5



p+p 510 GeV up to η~4.2
probe down to x~2 × 10^{-3} (gluons)
and up to x~0.5 (valence quarks)

Forward upgrades will be ready for Run-22
First p+p run with BES-II upgrade detectors

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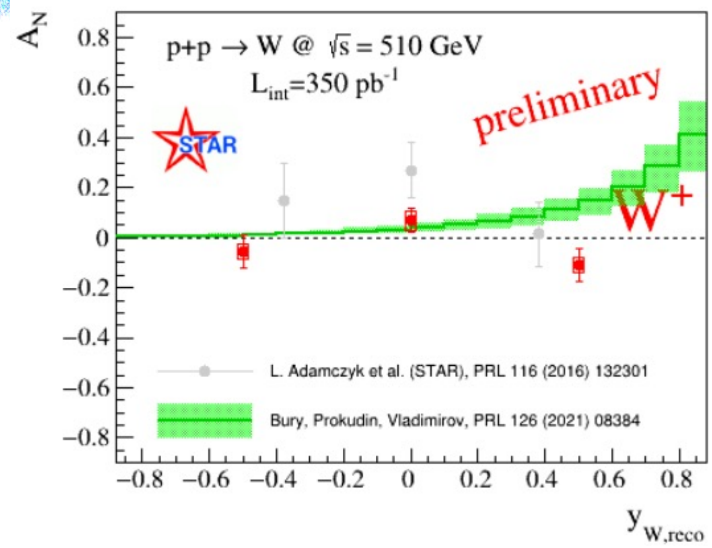
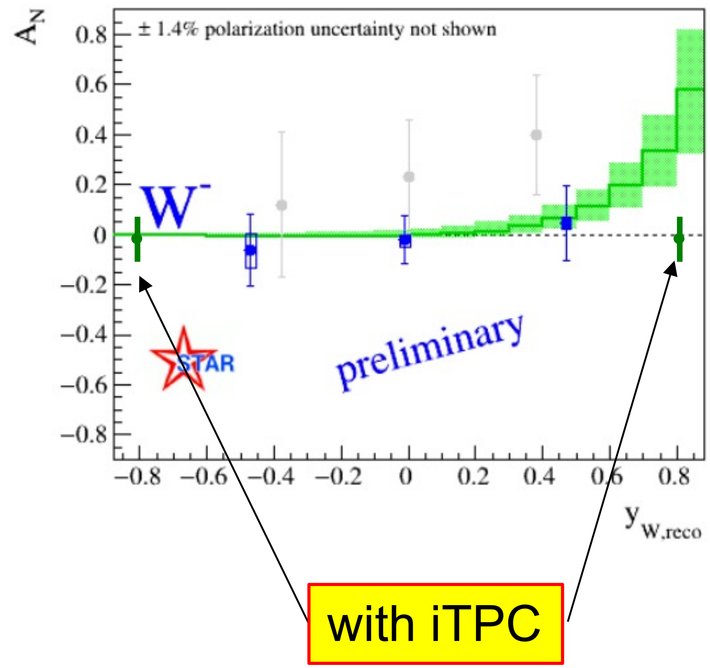
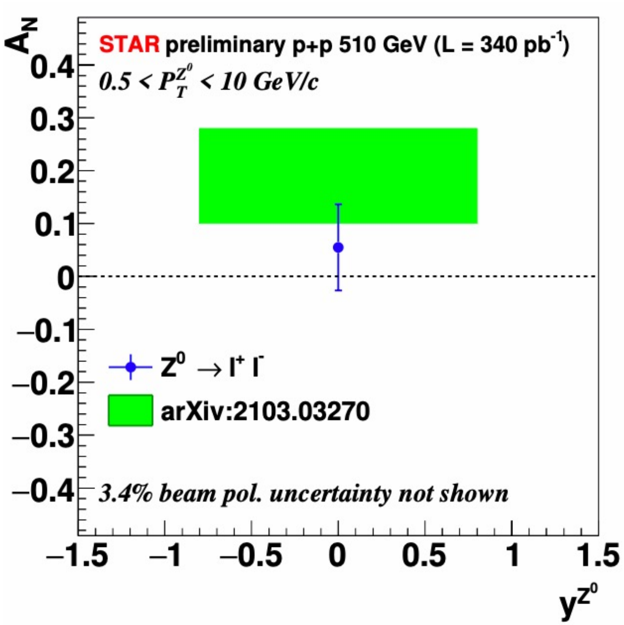
Sivers effect







Run-22 will reduce red and blue uncertainties by 1.5

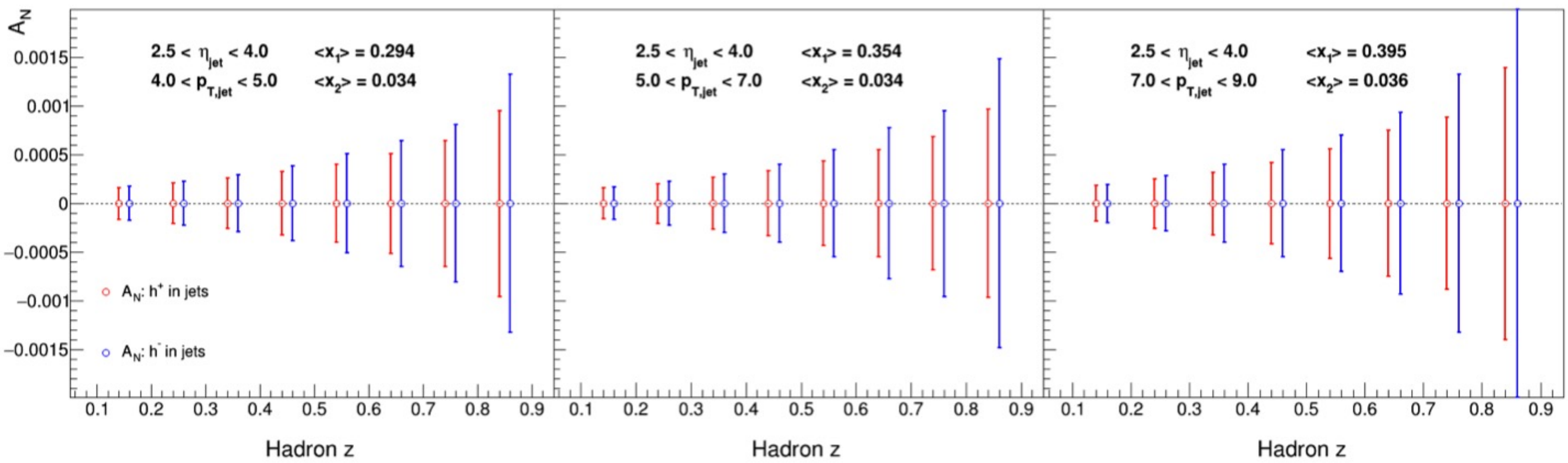
W/Z A_N provides important input for

- Confirmation of Sivers effect sign change
- Magnitude of TMD evolution

Collins effect at large x

forward upgrade

h^- in jets at forward rapidity



Extending Collins asymmetry measurements to the forward direction allows access to transversity at x>0.3.

- Transversity at 0.3<x<0.5, never explored by SIDIS

Perform high precision "Collins-like" asymmetry measurement to access the distribution of linear polarized gluon down to x~0.005.

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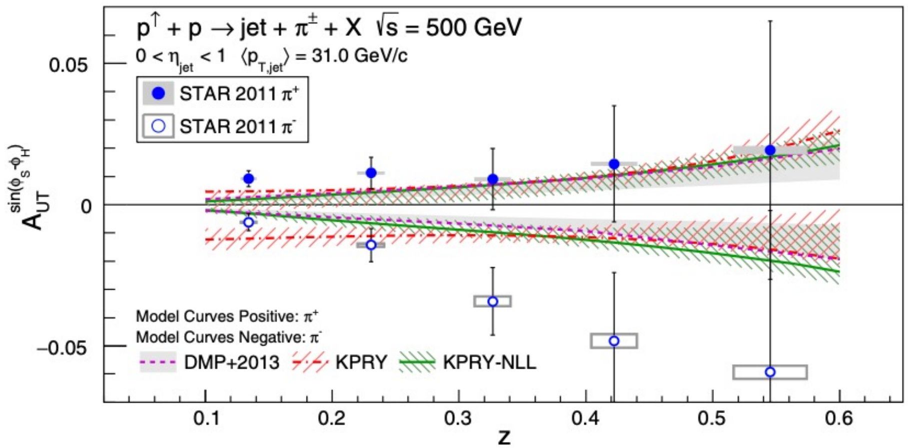
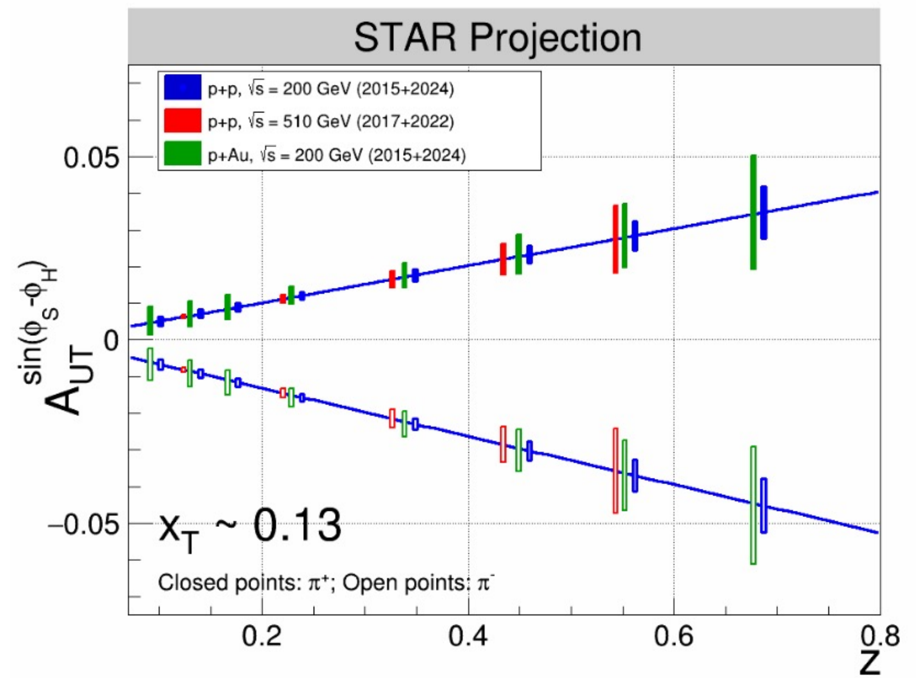
Collins asymmetry: $\pi^{\pm}$ in jets at mid-rapidity

improved PID, extended η coverage by iTPC





Multi-differential (p_T, η, z, j_T, Q^2) precise Collins asymmetry measurements at mid-rapidity will probe TMD factorization, universality, and evolution.

- Similar x coverage but much larger Q^2 compared to SIDIS measurements

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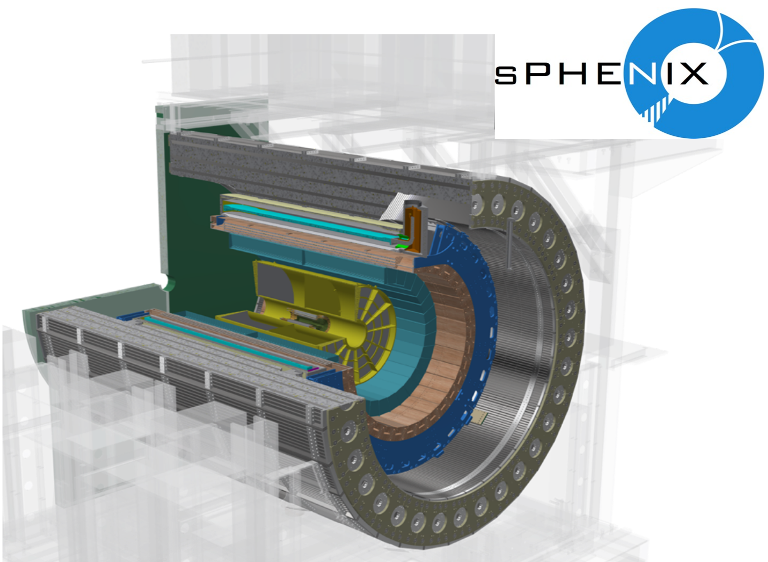
Completing the RHIC Mission: sPHENIX

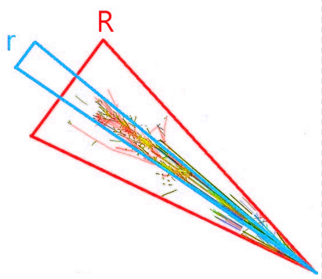
- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma on different length scales
  - Where and how does plasma transitions from (quasi)particles to structureless "perfect" fluid?
- State-of-the-art collider detector using technology developed for LHC by ONP and OHEP



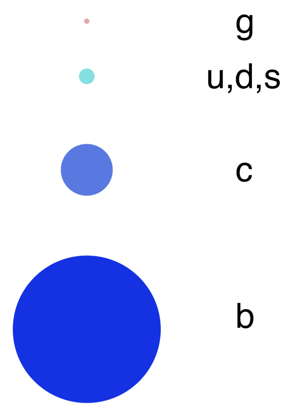
sPHENIX upgrade will fully utilize the enhanced (50 times design) luminosity of RHIC

sPHENIX Science

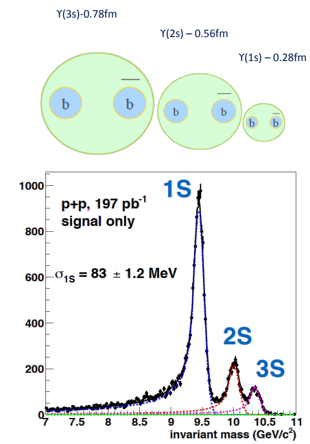
Jet cor. & substructure
Vary momentum/angular size of probe



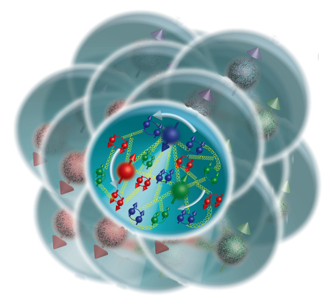
Parton energy loss
Vary mass/momentum of probe



Upsilon spectroscopy
Vary size of the probe



Cold QCD
Vary temperature of QCD matter



Mission: **Study QCD phenomena discovered at RHIC** with unprecedented precision

- Focus on **hard probes** (jets and heavy flavor)
- Kinematic reach and capabilities to allow **direct comparison with LHC**
- Affirmed by **Hot QCD white paper → LRP → sPHENIX CD-0 → ECFA → PAC**
- more than **100 (!) PRL/PLB** from RHIC, LHC on these topics since LRP (2015)

4

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sPHENIX run schedule

Each of run period has distinct, critical role for sPHENIX science mission

- 2023 - **commissioning** of detector, RHIC and data operations with Au+Au
- 2024 - **high statistics p+p** reference and **p+Au** cold QCD data
- 2025 - **high statistics Au+Au** data
- This is the **minimal "safe" schedule**
  - ensure safe combined operation of detector and collider
  - provide development time for calibration and reconstruction to ensure successful completion of science mission before transition to EIC
- For successful completion of sPHENIX science mission, **each of these runs needs to be successful**

18

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Run plan for 28 week scenario

Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

Unchanged compared to 2020 BUP

- **Focus on core science** mission
- **Minimization of risk** guides ramp-up, commissioning and running conditions
- **Maximize science output** for investment
  - MIE, 1008 upgrade, research effort, RHIC ops, US HI research workforce

19

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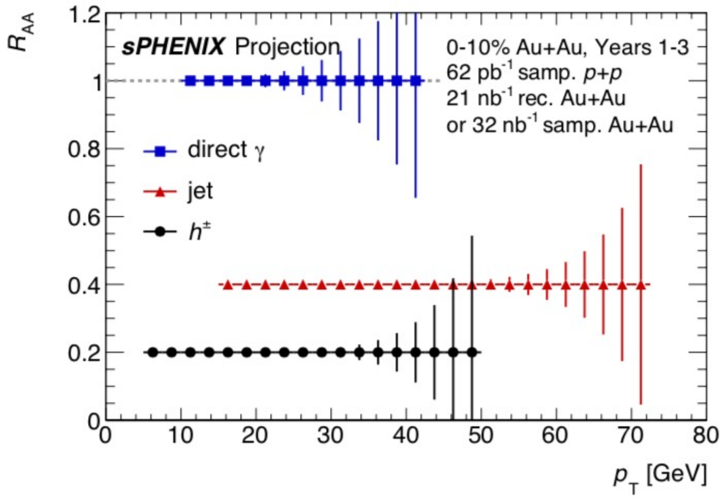
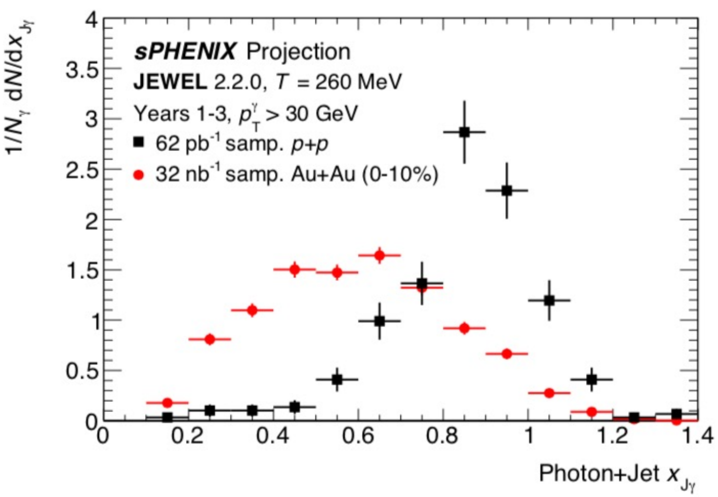
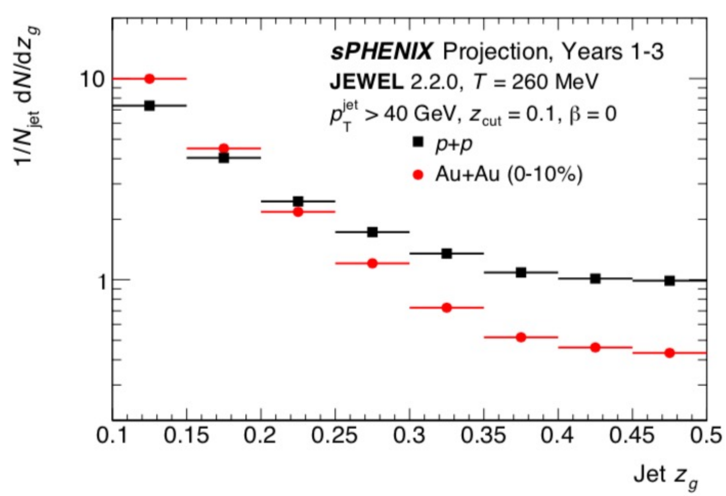
Promises and Deliverables: Jets and Photons

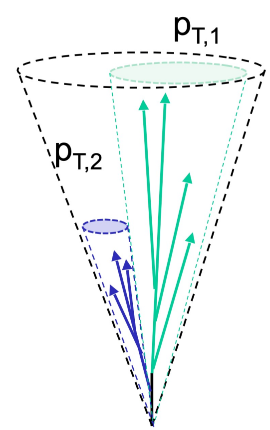


High statistics jets, photons, hadrons
No trigger bias in AuAu, no bias on the physics

Enables precision differential measurements







J. Nagle@PAC2020

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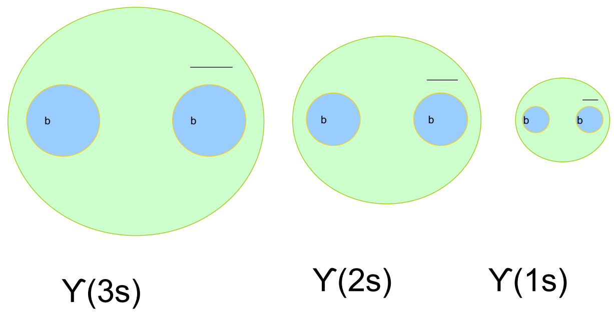
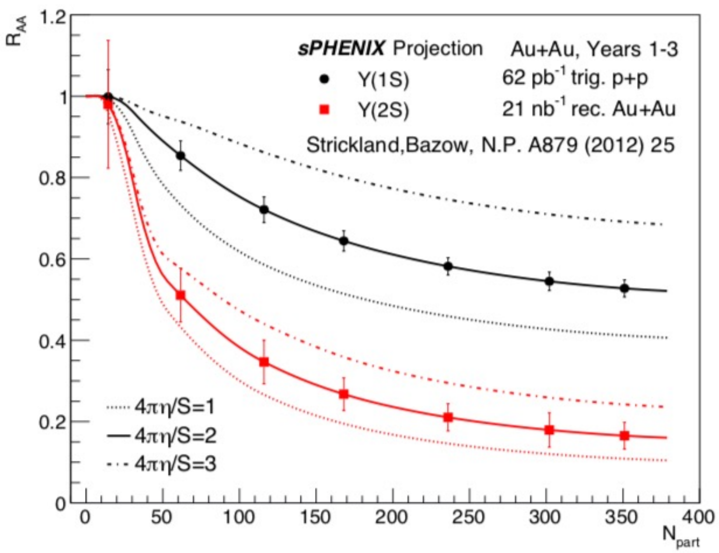
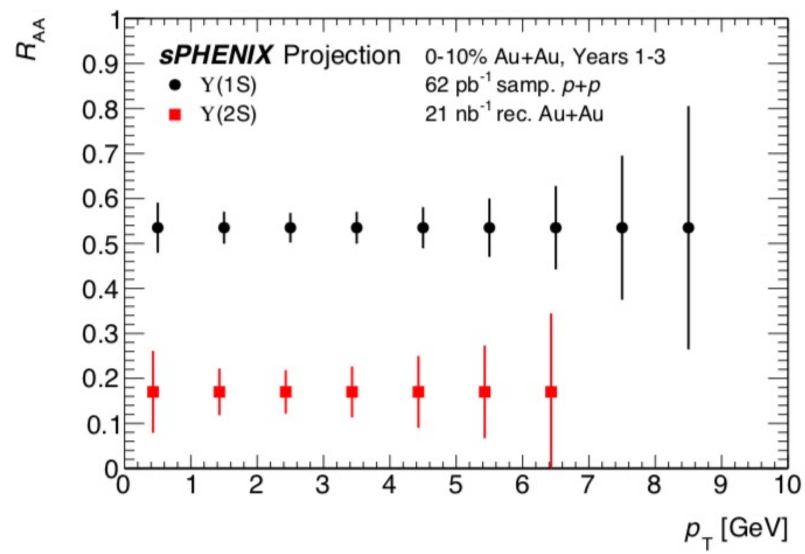
Promises and Deliverables: Closed Heavy Flavor



Upsilon QGP "thermometer" measurements

Precision 1s, 2s and 3s (depends on the level of suppression) in pp, pAu, AuAu





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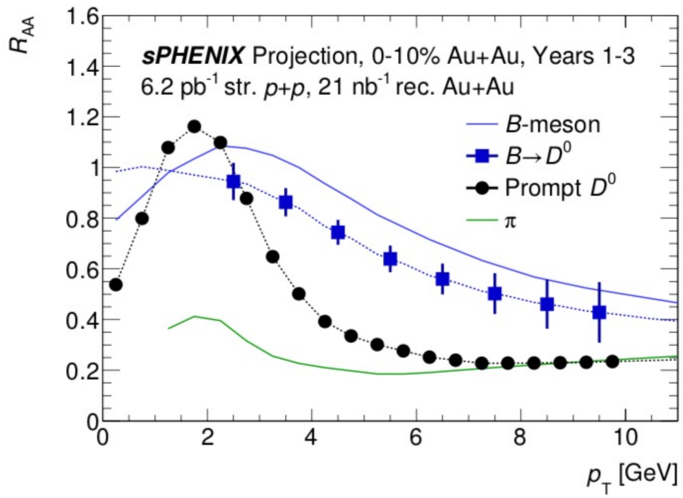
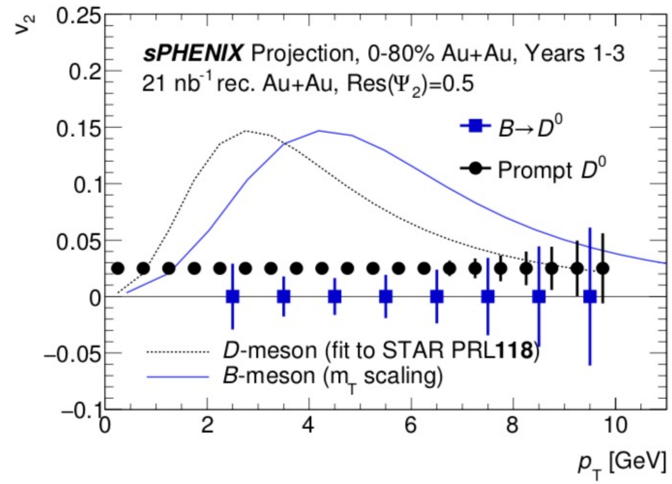
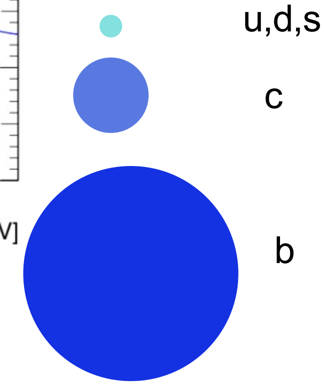
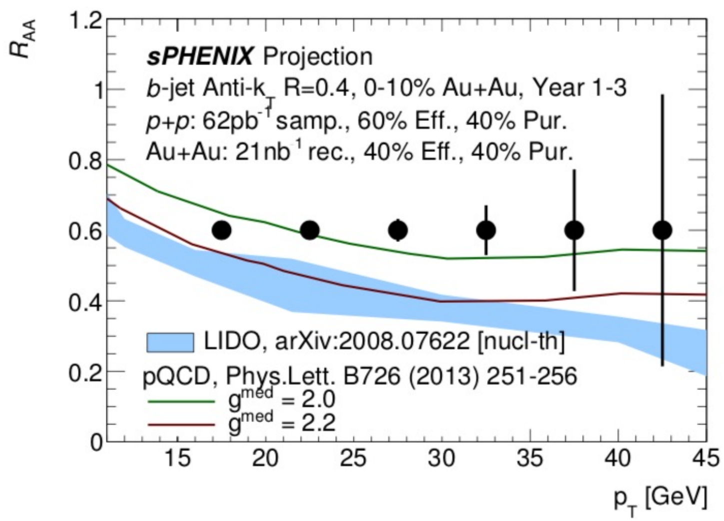
Promises and Deliverables: Open Heavy Flavor



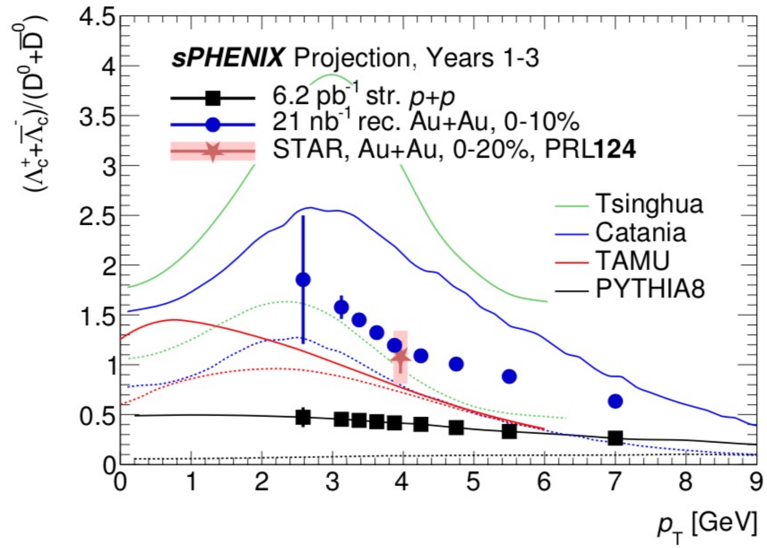


Precision charm and bottom measures in medium





Tagged-bottom jets!



Precision Charm Hadron-Chemistry in Au+Au and p+p

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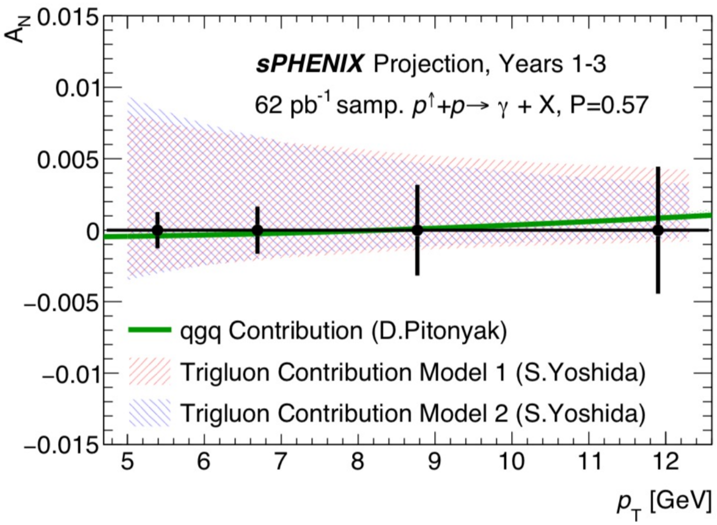
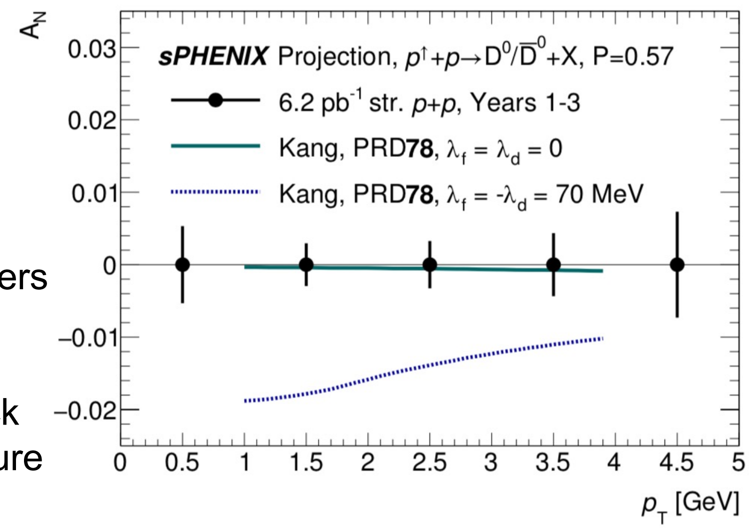
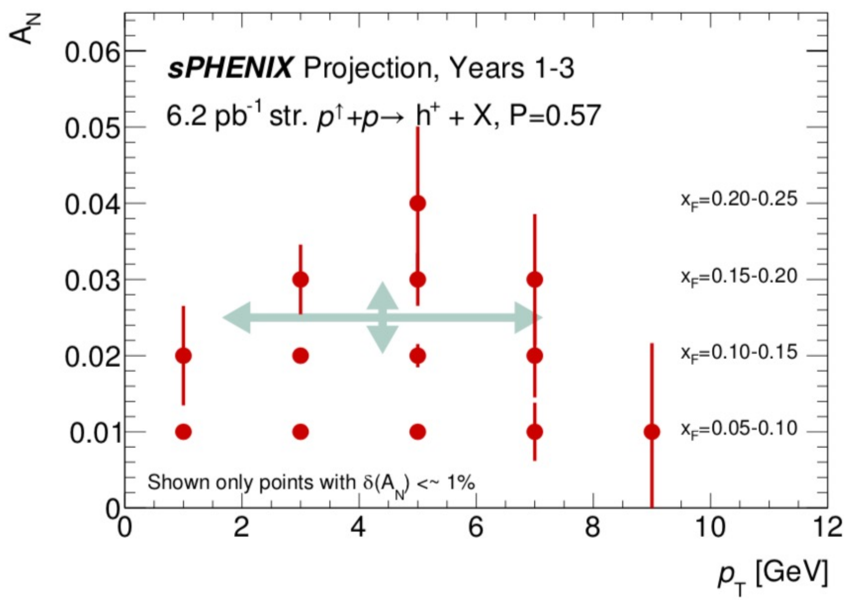
Transverse polarized pp and pAu



Probes the gluon dynamics within the nucleon through the collinear tri-gluon correlation function

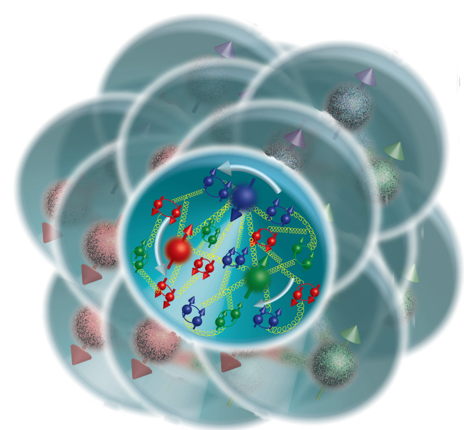
- Connect with Sivers function (TMD)
- Poorly known
- Universality check with HF A_N at future EIC





Nuclear dependence of spin asymmetries

- Provides crucial information on the nature of TSSA
- Nuclear effect studies with spin probes



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PAC 2021 Recommendations

- The PAC strongly endorses the STAR Run 22 BUR. C-AD is strongly encouraged to optimize RHIC operations to fulfill the goals of both CeC and STAR.
- Run 23-25: The top overall priority in planning for these three runs is to commission the sPHENIX detector and to achieve its scientific program
  - The PAC strongly supports focusing in Run 23 on sPHENIX commissioning using 200 GeV Au+Au collisions. This is the highest priority and must come first. This should be followed by continued running of 200 GeV Au+Au collisions to begin the sPHENIX scientific program.
  - The highest priority for Run 24 is a pp run of sufficient duration to provide the reference data needed to achieve the science goals, including the precision goals, that motivate the sPHENIX program.
  - Completion of the proposed 200 GeV Au+Au data set is the highest priority for Run 25