PHENIX forward detector upgrades for nucleon structure studies

sPHENIX workfest at RIKEN

July 31st, 2013

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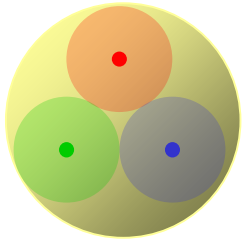
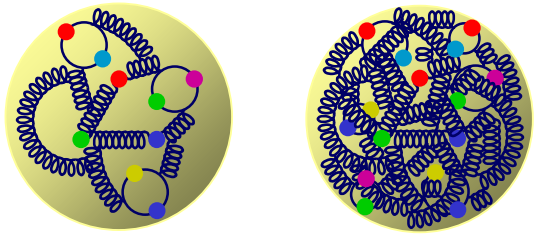
Outline

- Introduction
  - Nucleon (spin) structure
- Forward sPHENIX upgrades
- Design
- Physics
  - 3-dimensional nucleon structure
  - Cold nuclear matter
- Evolution to ePHENIX

Nucleon structure

- Constituent-quark model
  - Quarks with the effective mass (caused by the gluon)
  - Explains the magnetic moment of the nucleons
  - But, the quark spin cannot explain the nucleon spin (“spin puzzle”)
- Quark-gluon model
  - Bare quarks and gluons
  - Initial state of high-energy hadron colliders
- Understanding the differences (or gap) of these models
  - Gluon
  - Chiral symmetry
  - Confinement





Spin puzzle

- Expected to be explained by the quark spin (from the constituent quark model)
- Experiments
  - CERN-EMC experiment (polarized DIS experiment)
    - Quark-spin contribution

      $$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$$

    - Combining with neutron and hyperon decay data
    - Total quark spin constitutes a small fraction of the nucleon spin
    - Integration in x = 0 ~ 1 makes uncertainty
  - SLAC/CERN/DESY/JLAB experiments
    - More data to cover wider x region with more precision
- Based on the quark-gluon model

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

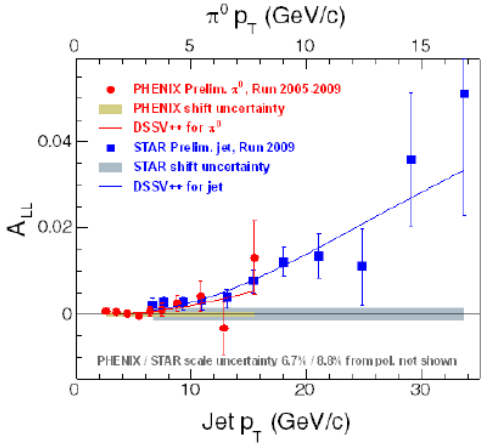
Orbital angular momentum

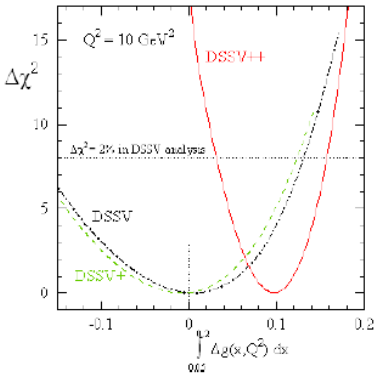
Gluon spin contribution

Quark spin contribution

RHIC spin

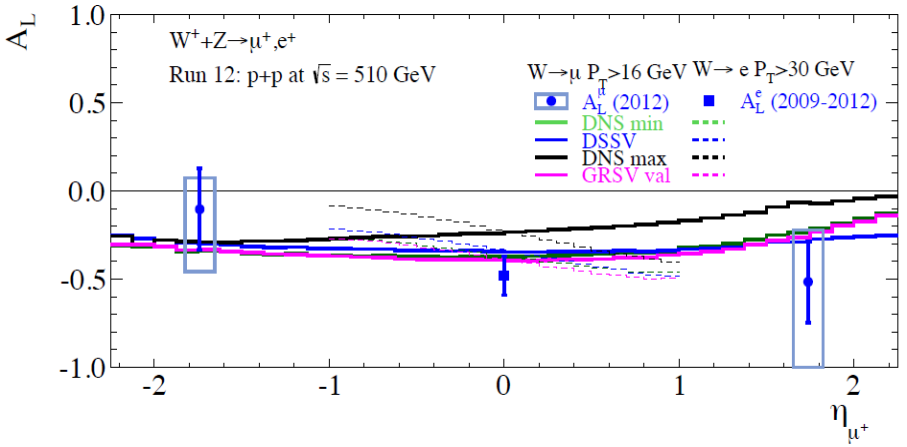
- Gluon polarization

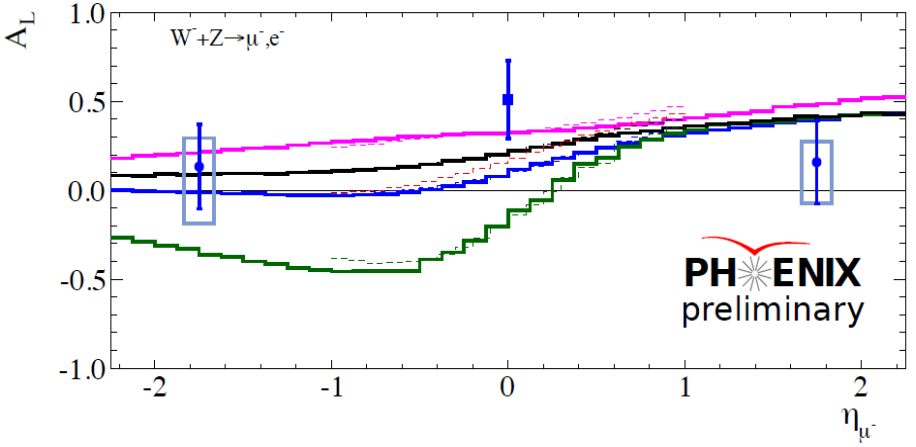




$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

- Sea quark polarization with W measurement

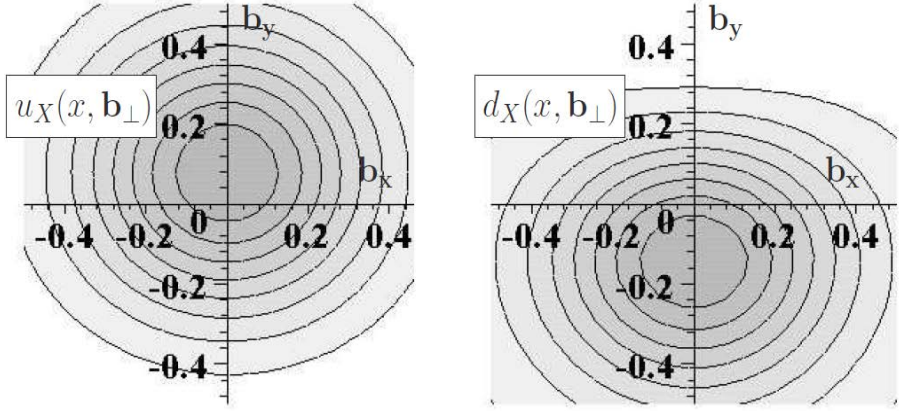




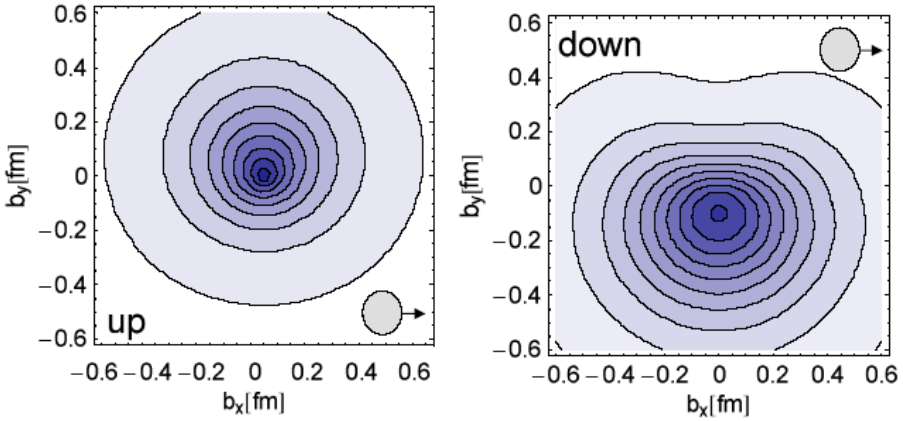
- Next direction: Orbital angular momentum

3-dimensional nucleon structure

- Many-body correlation of partons
  - To describe the orbital motion inside the nucleon
- Parton distribution in transverse direction
  - Extended/generalized picture of the parton distribution
  - Transverse-momentum dependence (TMD)
  - Space distribution (tomography)



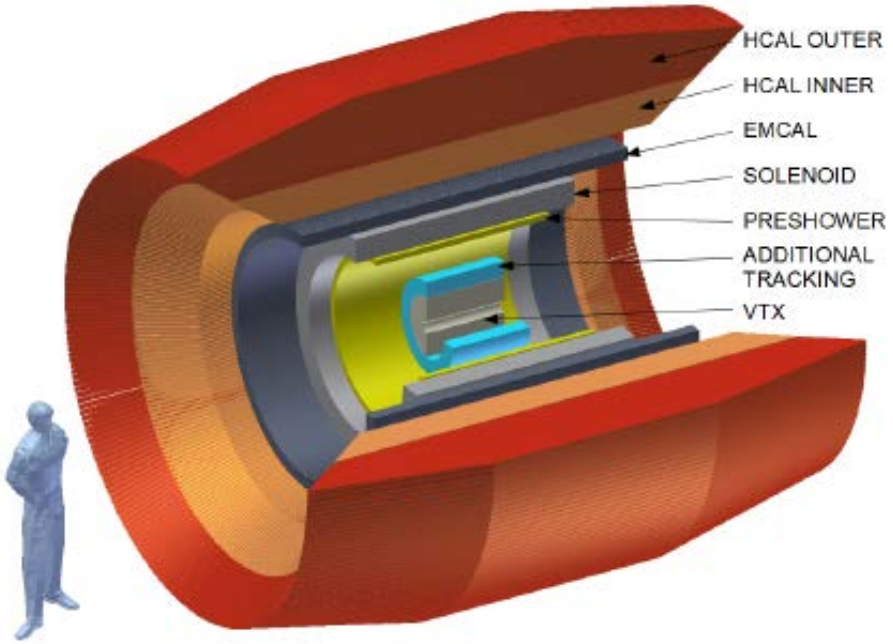
Phenomenological model with GPD data



Lattice QCD calculation

Stages of PHENIX detector upgrades

- Barrel sPHENIX upgrades
  - Compact jet detector at midrapidity with high-rate capability
  - Precision jet / dijet / photon-jet measurement to understand the nature of the strongly coupled QGP
  - Future options to add tracking and preshower for heavy-flavor quarkonia and internal jet structure measurements



Stages of PHENIX detector upgrades

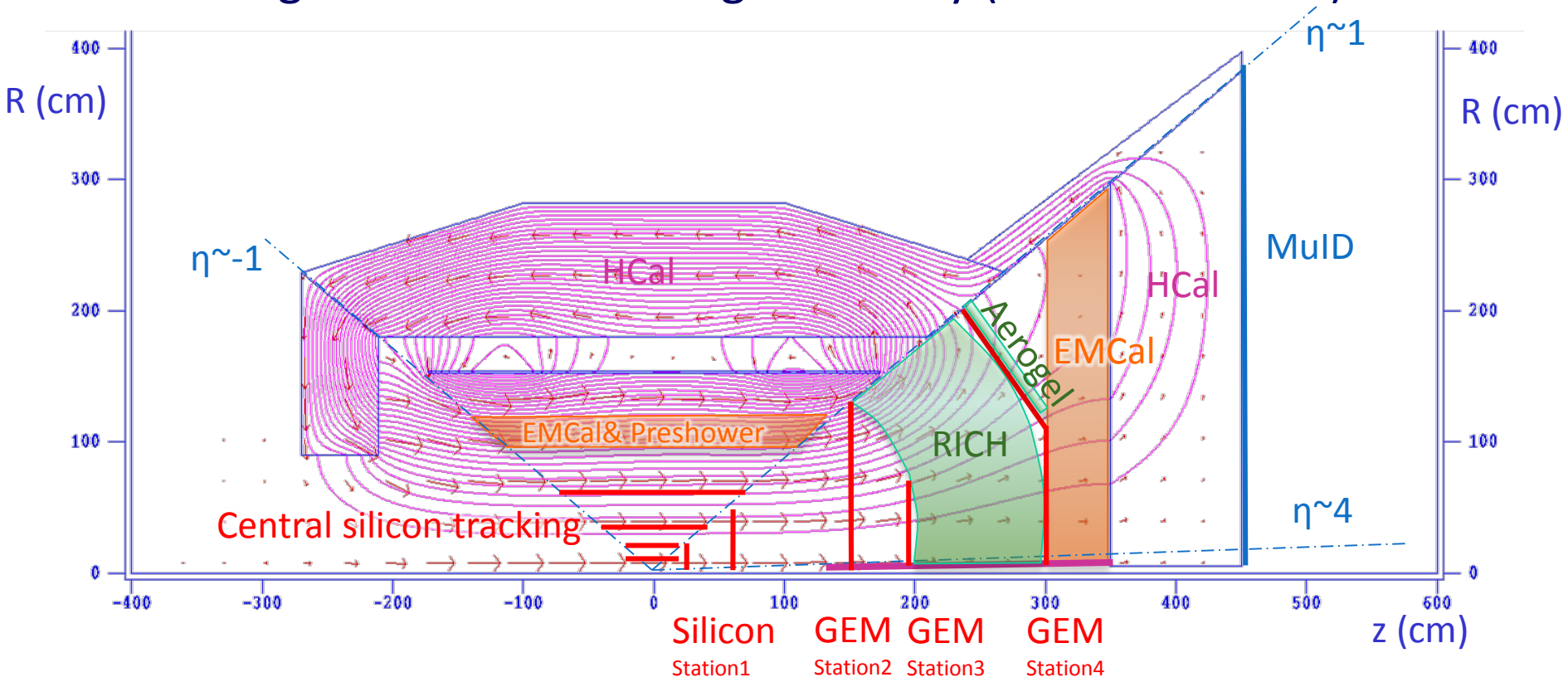
- Forward sPHENIX upgrades
  - Open geometry for wide kinematic coverage of photon / jet / leptons / identified-hadrons
  - Understanding 3-dimensional (TMD) quark-gluon structure of the nucleon and nuclei
  - Measurement of the nuclear gluon distribution and search for gluon saturation at small-x
- Evolution to ePHENIX at eRHIC
  - 3-dimensional space structure (tomography) of the nucleon and nuclei
  - Precision understanding of strongly-coupled QGP by knowing the initial state

Forward sPHENIX design

- Compatible design for eRHIC
  - Constraint from IR design
    - focusing and bending magnets for the electron-ion collision
    - 4.5 m from IP available in z direction
  - Hermeticity for exclusive measurements
- Magnet discussion
  - Piston
  - Dipole
  - Toroid
  - Solenoid extension
- Detector configuration
  - Charged-particle tracking (e.g. GEM)
  - Particle identification (e.g. RICH)
  - EM and hadron calorimeters
  - Vertex detector? (silicon or GEM?)
  - (Roman pot detector for exclusive measurements at eRHIC)
- More discussion by Joe Seele this afternoon

Forward sPHENIX design

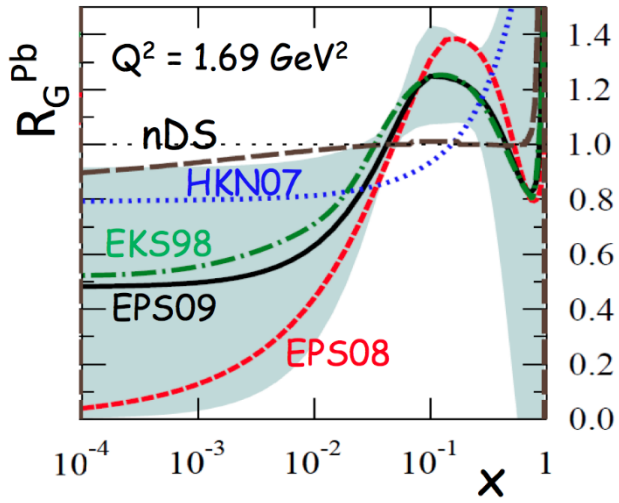
- Forward field shaper
  - Passive piston
  - Total flux much enough?
  - High resolution tracking necessary (silicon detector)

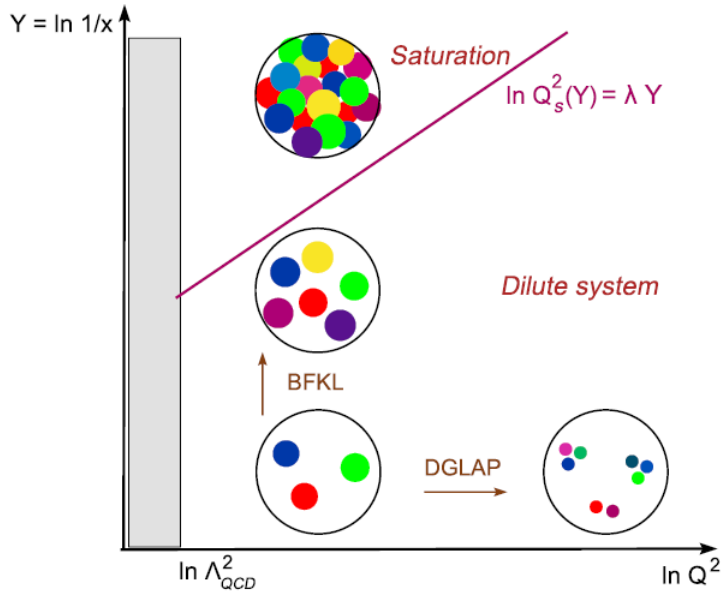


From Jin Huang

Cold Nuclear Matter (CNM) physics

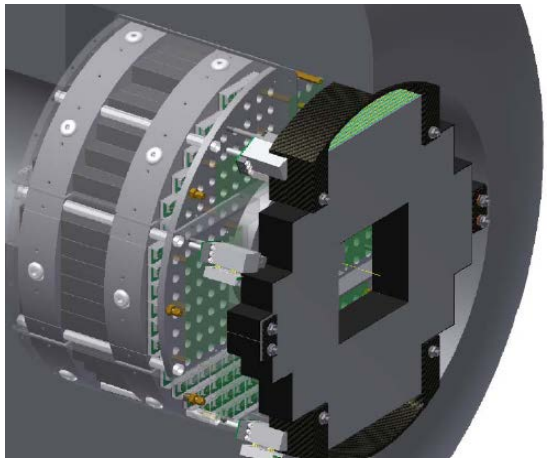
- Measurement of the nuclear gluon distribution $G_A(x)$
  - To know initial state of heavy-ion collisions
  - precision understanding of strongly-coupled QGP
- Search for gluon saturation, or suppression of $G_A(x)$ at small-x and verify CGC (color glass condensation) framework
  - CGC: effective field theory to describe the saturated gluon
- Energy loss of partons in CNM and its relation to p_T broadening
- Hadronization mechanism and time scales





CNM physics at PHENIX

- Current measurements
  - J/ψ and hadron-hadron correlations over a broad range of rapidity
    - Sensitive to extended range of x
  - Open heavy-flavor and a first look at Drell-Yan
    - With FVTX installed in 2012
    - Comparison data to J/ψ
- MPC + MPC-EX upgrade (2014 –)
  - More details by John Lajoie this afternoon
  - Electromagnetic calorimeter + preshower
  - $3.1 < \eta < 3.8$ in the muon piston
  - Prompt-photon



CNM physics at forward sPHENIX

- Quarkonia
- Vertex-tagged open heavy-flavor
- Inclusive hadrons
- Fully-reconstructed jets
- jet-jet correlations
- Drell-Yan
  - Much more extended kinematic reach
  - Smaller statistical and systematic uncertainties
  - Different energies and nuclear species

Transverse-spin physics

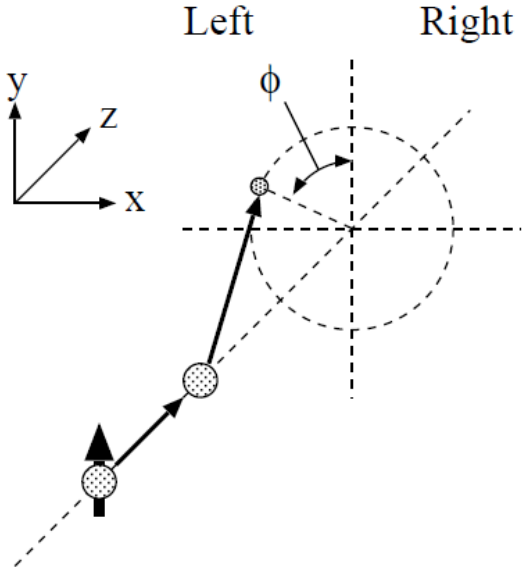
- Single transverse-spin asymmetry

$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

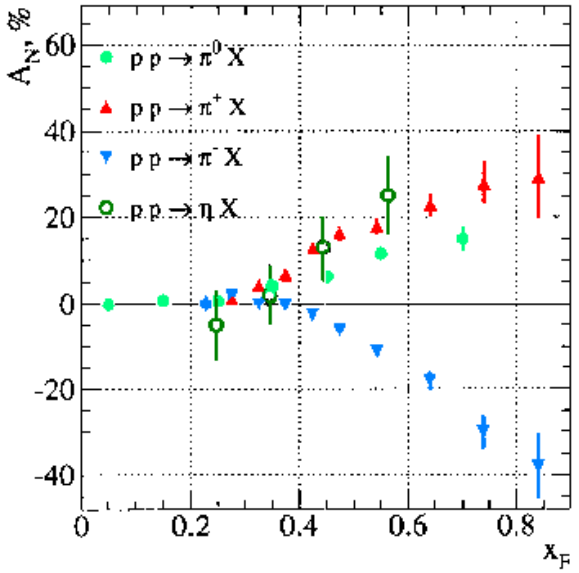
  - Expected to be small in hard scattering at high energies

$$A_N \approx \frac{m_q \alpha_S}{p_T} \approx 0.001$$

Kane, Pumplin, Repko
PRL 41 1689 (1978)

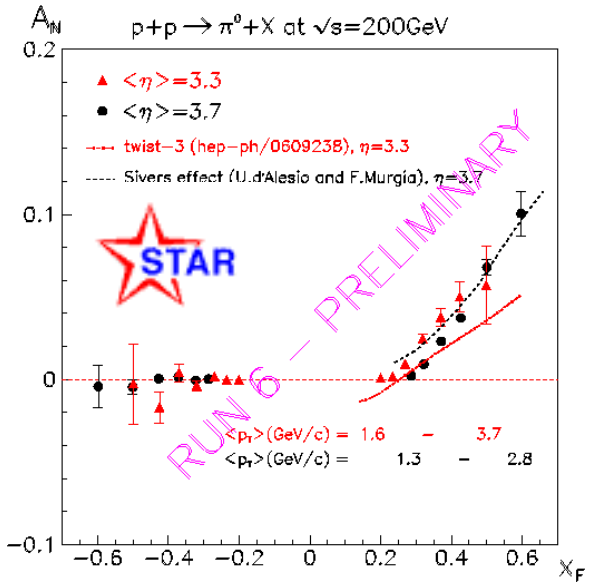


- FNAL-E704
  - Unexpected large asymmetry found in the forward-rapidity region
  - Development of many models based on perturbative QCD

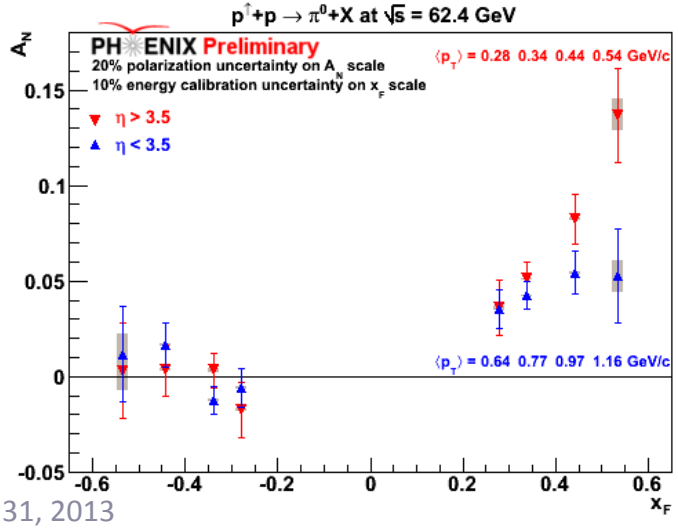


Transverse spin asymmetries at RHIC

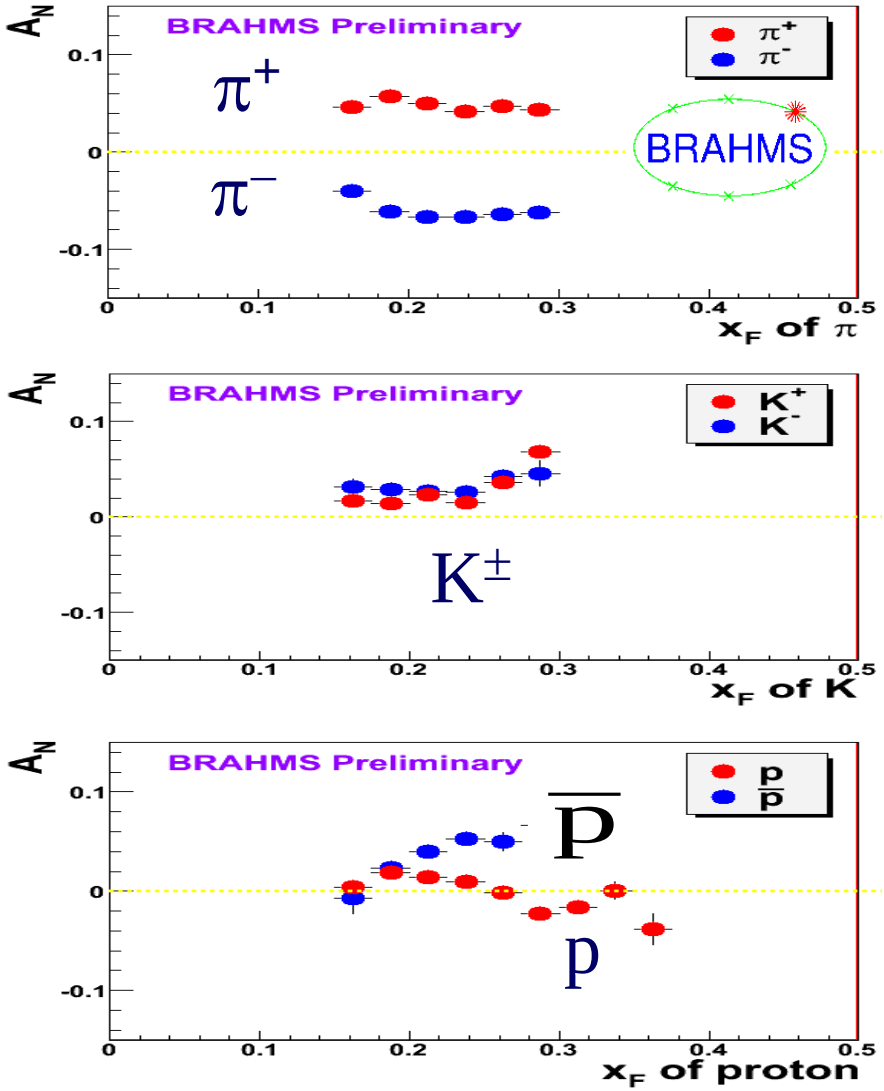
Forward rapidity π^0 at STAR at $\sqrt{s}$ = 200 GeV



Forward rapidity π^0 at PHENIX at $\sqrt{s}$ = 62.4 GeV



Forward identified particles at BRAHMS



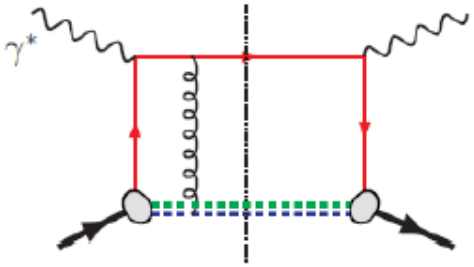
TMD and higher twist

- At small p_T
  - Described by the TMD (Transverse Momentum Dependent) factorization framework
  - Sivers mechanism
    - Correlation between the transverse spin of the nucleon and intrinsic p_T of partons in the initial state
  - Collins mechanism
    - Correlation between the transverse spin of the parton and p_T of hadrons in the final state
- At large p_T
  - Described by the collinear factorization framework
  - Higher twist effect
    - Spin-dependent p_T components generated through quark-gluon and multi-gluon correlations
- At intermediate p_T
  - Identity of the Sivers mechanism and the higher twist effect

TMD non-universality

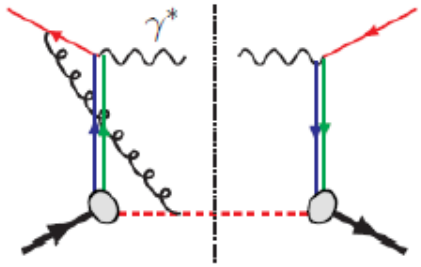
- Opposite-sign contribution to the transverse-spin asymmetries in the semi-inclusive DIS process and the Drell-Yan process
- Fundamental QCD prediction based on gauge invariance
- Verification is an important milestone for the field of hadron physics
- Competitive program in fixed target experiments and in collider experiments

SIDIS



attractive

Drell-Yan



repulsive

$$f^{Sivers}(x,k_T)|_{SIDIS} = -f^{Sivers}(x,k_T)|_{DY}$$

TMD evolution

- Recent theoretical progress in the derivation of the evolution equation for TMD parton distribution and fragmentation functions
- Comparison of the asymmetries at fixed-target energies and collider energies for test of the TMD evolution
- QCD analysis of TMD observables to be possible

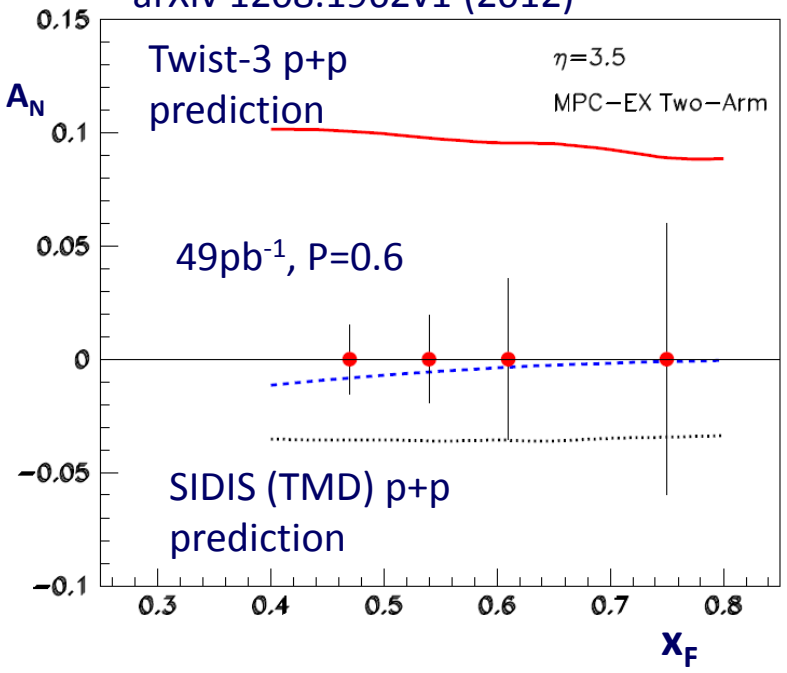
Collins effect and transversity

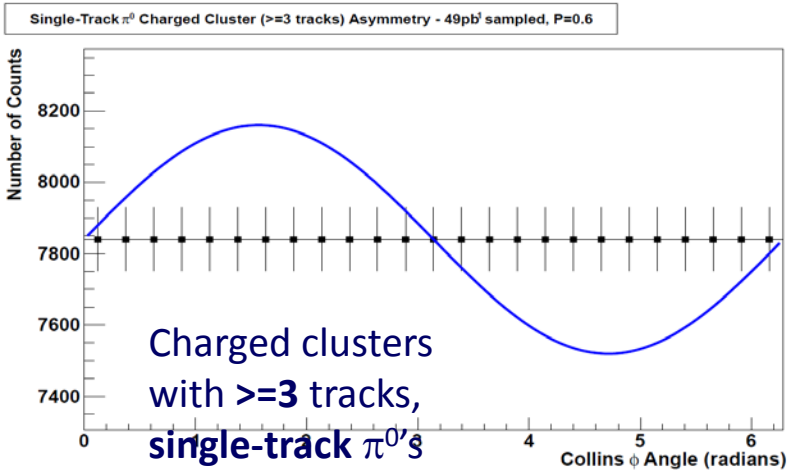
- Azimuthal anisotropy in the distribution of hadrons in final-state jets
- Transversity measurement with single identified hadrons (Collins fragmentation function) or with identified hadron pairs (interference fragmentation function)
  - Determination of the tensor charge of the nucleon
  - Test of the Lattice QCD prediction

Transverse spin asymmetries at PHENIX

- MPC-EX (2014 –)
- Prompt photon asymmetry
  - To distinguish the Sivers effect and the hither-twist effect
- Collins asymmetry in jets
  - π^0 correlations with jet-like clusters

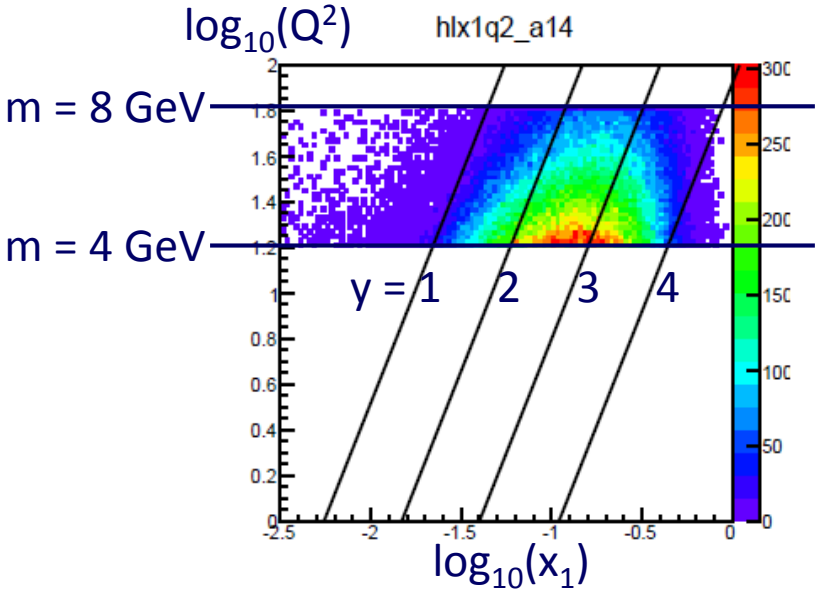
Phys Rev. D 83 094001 (2011)
arXiv 1208.1962v1 (2012)

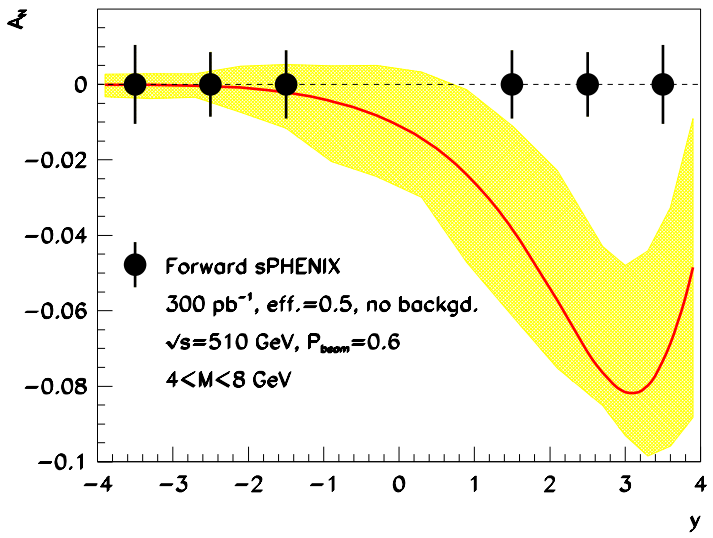




Transverse spin asymmetries at forward sPHENIX

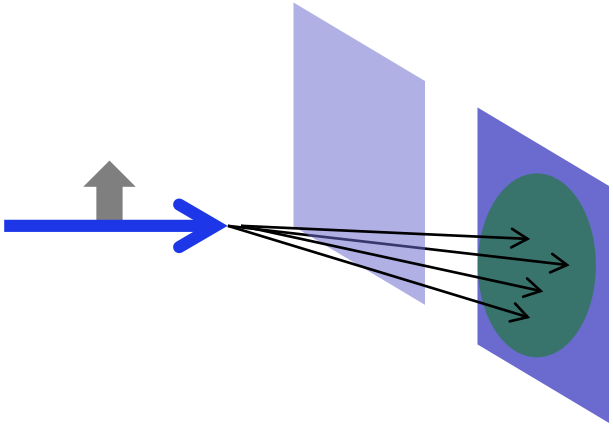
- Sivers effect in Drell-Yan process
  - $\sqrt{s}$ = 500 GeV
  - $1 < \eta < 4$
  - 4 GeV < mass < 8 GeV
    - cover the valence-quark region around $x_{Bj} = 0.2$
    - comparison with SIDIS measurements
    - large asymmetry
    - $3 < \eta < 4$ is important to explore higher x_{Bj} region

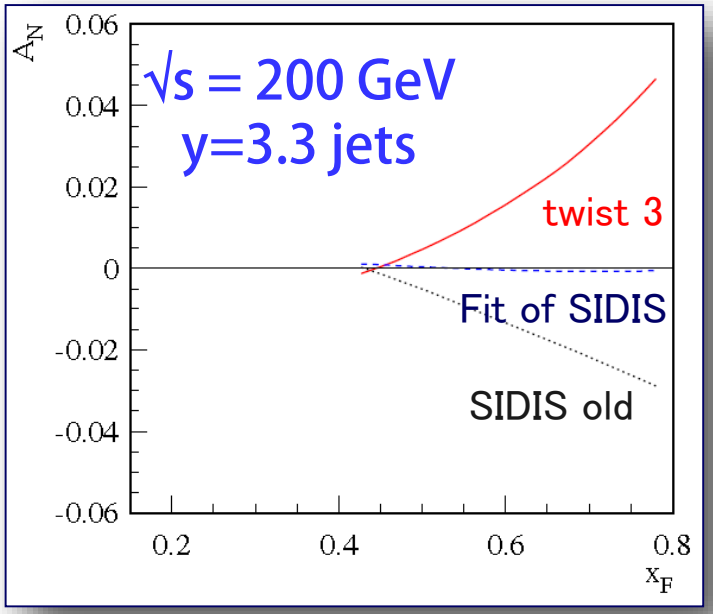




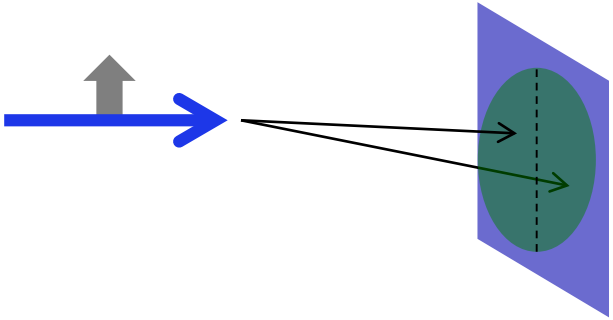
Transverse spin asymmetries at forward sPHENIX

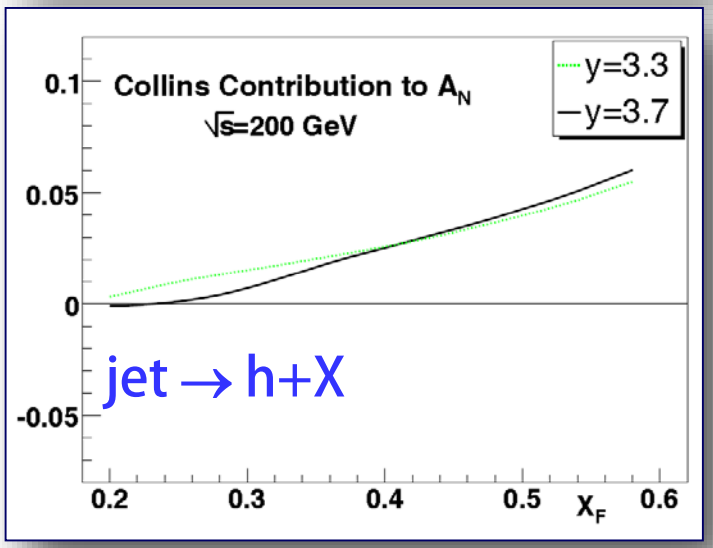
- Jet asymmetry measurement
  - Sivers or higher-twist effect





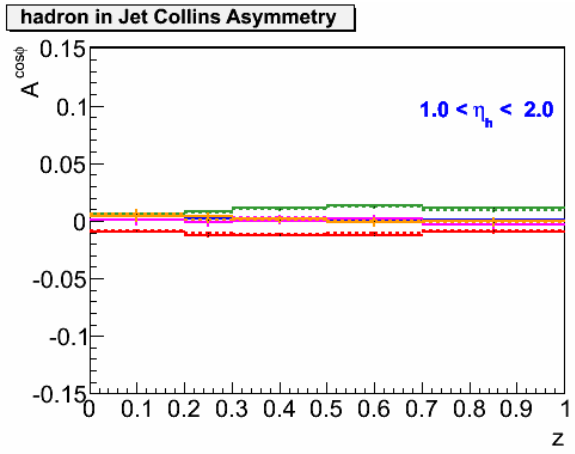
- Asymmetry inside the jet
  - Collins function
  - Interference fragmentation function

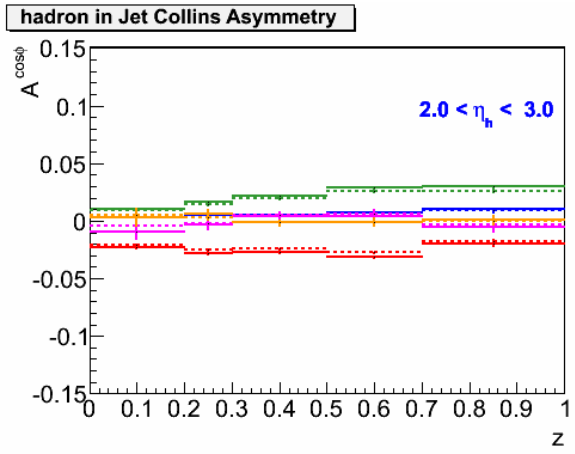


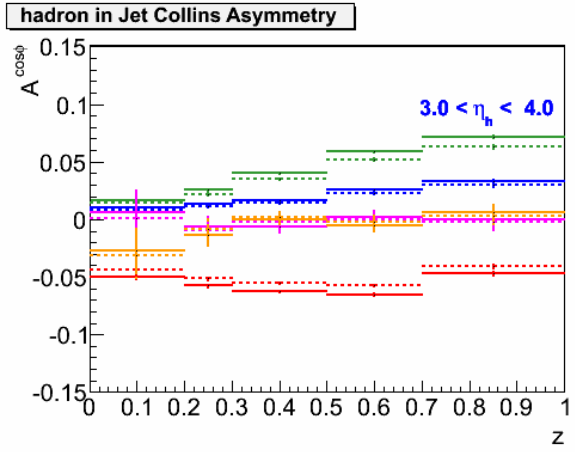


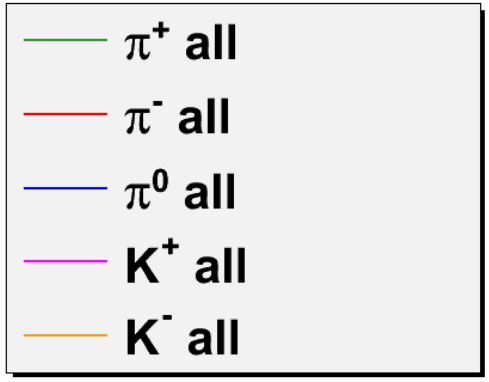
Transverse spin asymmetries at forward sPHENIX

- Collins asymmetry inside the jet
  - TppMC simulation
    - Collins/Sivers functions from Torino
    - Transversity from Soffer bound
    - $p_T > 1$ GeV/c
  - From Ralf Seidl









Transverse spin asymmetries at forward sPHENIX

- Polarized-proton nuclei collision for saturation study
  - Link between CNM and spin physics
  - Transverse single-spin asymmetries in polarized p+A collisions are sensitive to the saturation scale in the nucleus

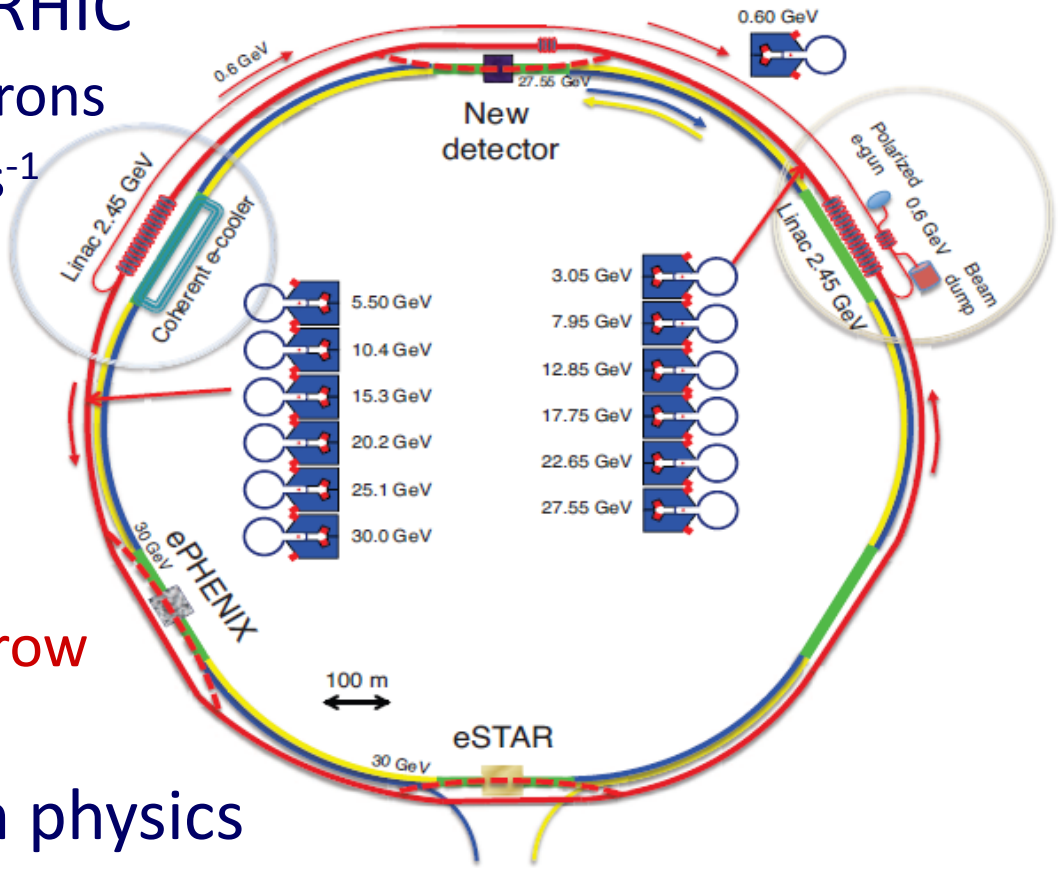
$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h<<Q_s^2}{\approx} \frac{Q_{s,p}^2}{Q_{s,A}^2} f(p_T^h)$$

$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h>>Q_s^2}{\approx} 1$$

Z.-B.Kan and F.Yuan
PRD84, 034019 (2011).

Evolution to ePHENIX

- Stage-1 detector of eRHIC
  - 5 GeV – 10 GeV electrons
  - Luminosity 10^{33} $cm^{-2}s^{-1}$

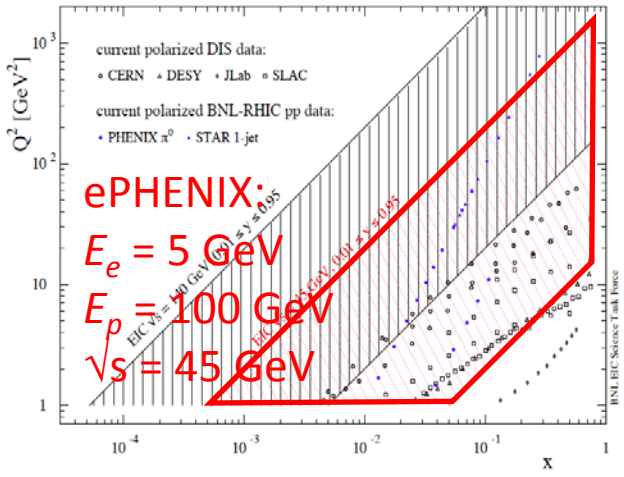


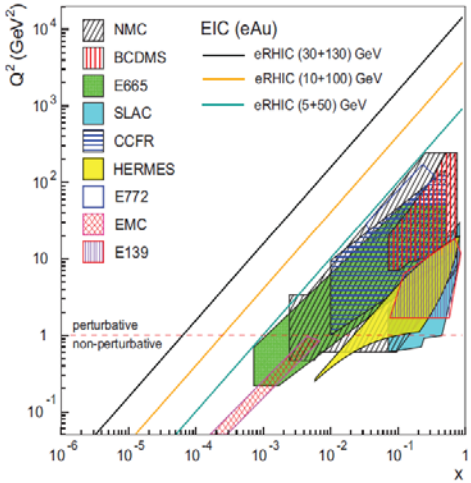
More details on eRHIC given by Abhay Deshpande tomorrow

- CNM physics and spin physics
  - 3-dimensional space structure of nucleon and nuclei
  - Precision understanding of strongly-coupled QGP by knowing the initial state

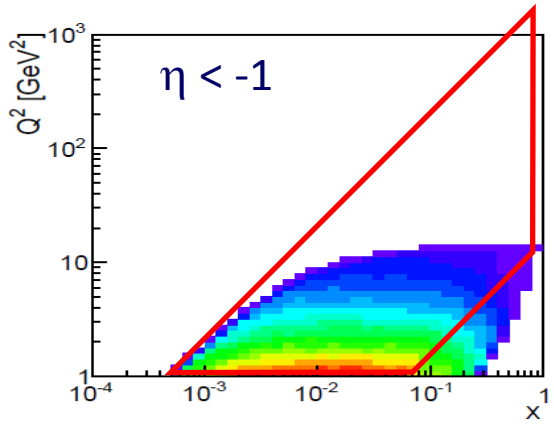
Evolution to ePHENIX

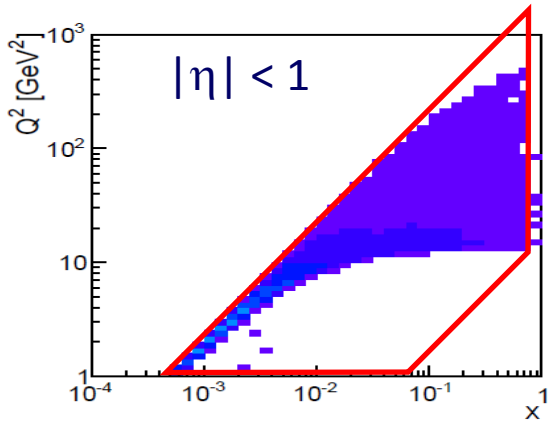
- Inclusive DIS
  - Gluon and sea-quark helicity distributions





  - Scattered electron detection at backward rapidity and midrapidity





Evolution to ePHENIX

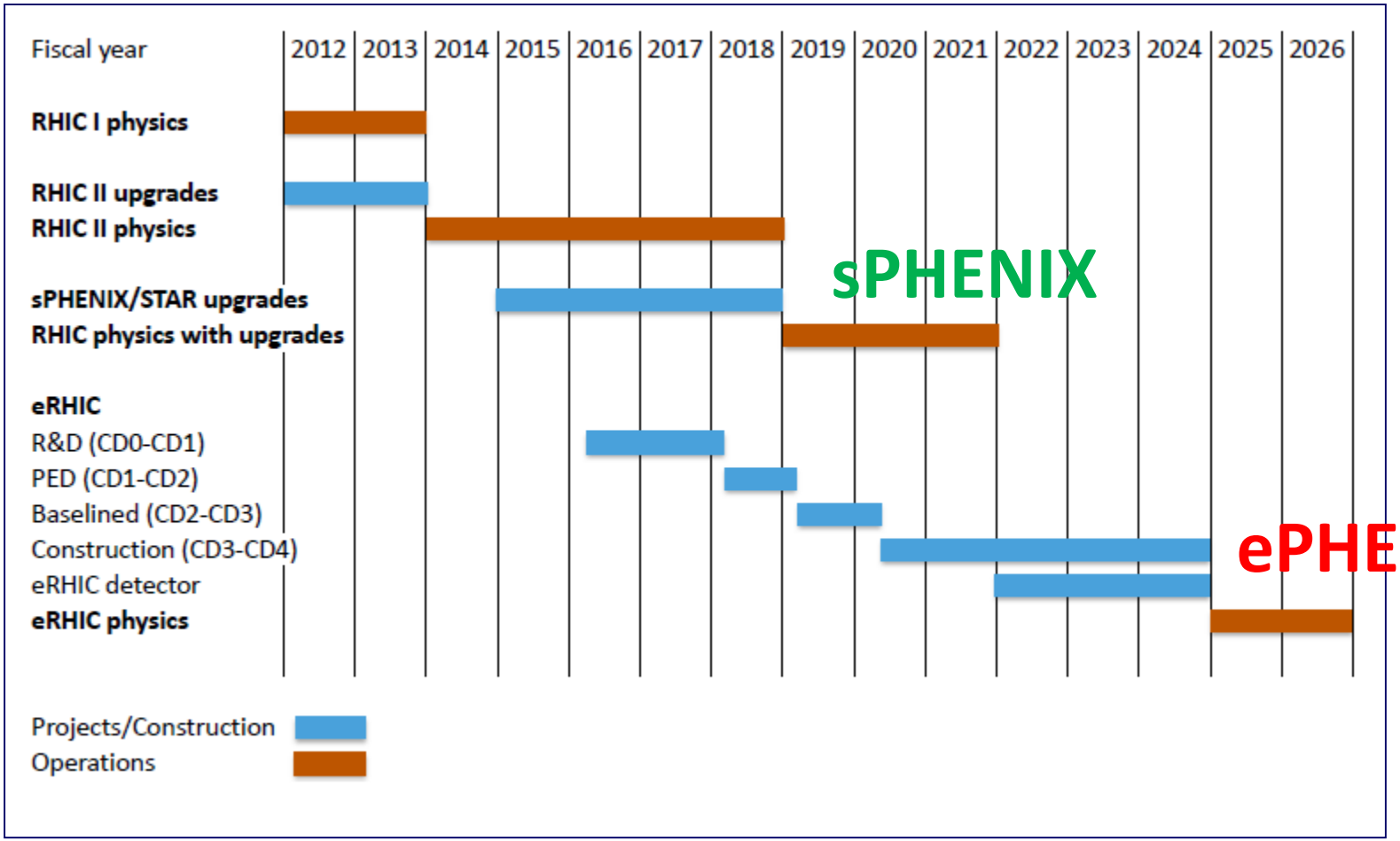
- Semi-inclusive DIS
  - Quark and gluon TMD measurements
  - Tag pions and kaons
  - Extract Δs
- Exclusive and diffractive channels
  - DVCS (Deeply Virtual Compton Scattering) and HEMP (Hard Exclusive Meson Production)
    - With a limited luminosity at stage-1 eRHIC
- More discussion to be performed in the ePHENIX LoI session (by Kieran/Jin/Itaru) Friday morning

Requirements for the detector design

- Sivers effect in Drell-Yan process
  - Open heavy-flavor background
    - Vertex detector
  - Light-hadron background
    - For e^+e^- measurement
      - Calorimeter and tracking
      - Additional e/π separation
    - For $\mu^+\mu^-$ measurement?
- Jet asymmetry measurements
  - Calorimeter and tracking
  - Particle-ID
- ePHENIX
  - Scattered electron detection
    - Backward rapidity and midrapidity
  - Particle-ID
    - Midrapidity and forward rapidity
  - Roman-pot detector to tag scattered proton

Timeline

- Forward sPHENIX
  - RHIC physics (polarized p+p / p+A / d+A) not on the table



Summary

- The forward sPHENIX upgrades will give us great opportunities for studying the nucleon spin structure and cold nuclear matter
  - Sivers asymmetry in Drell-Yan process
  - Jet asymmetry measurements
  - Search for gluon saturation
- Detector design and studies are ongoing with physics requirements
  - Detector configuration
  - Magnet discussion
  - Evolution to ePHENIX
- It is important to perform physics not only at eRHIC but also at RHIC with polarized p+p / p+A / d+A