PHENIX overview

HESZ workshop 2017,
Nagoya, Japan

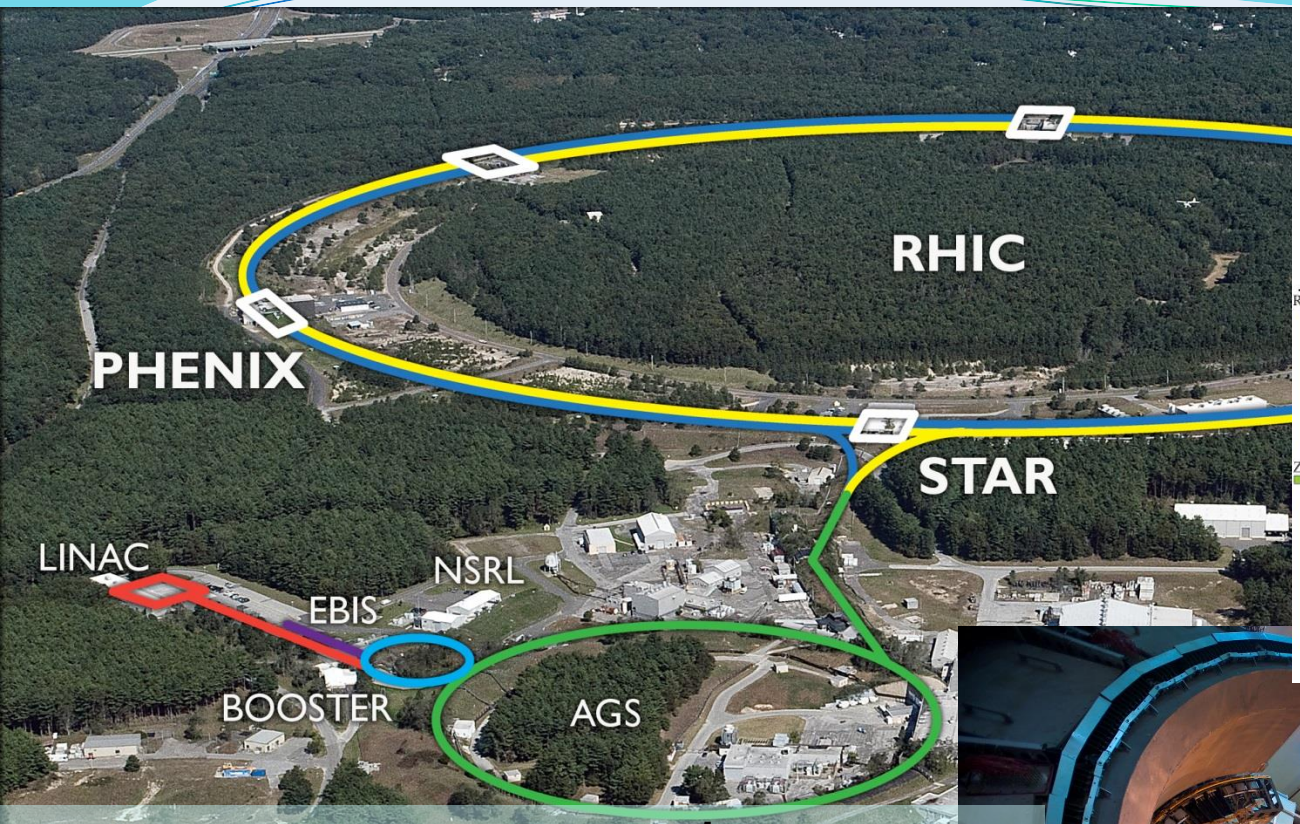
September 28,

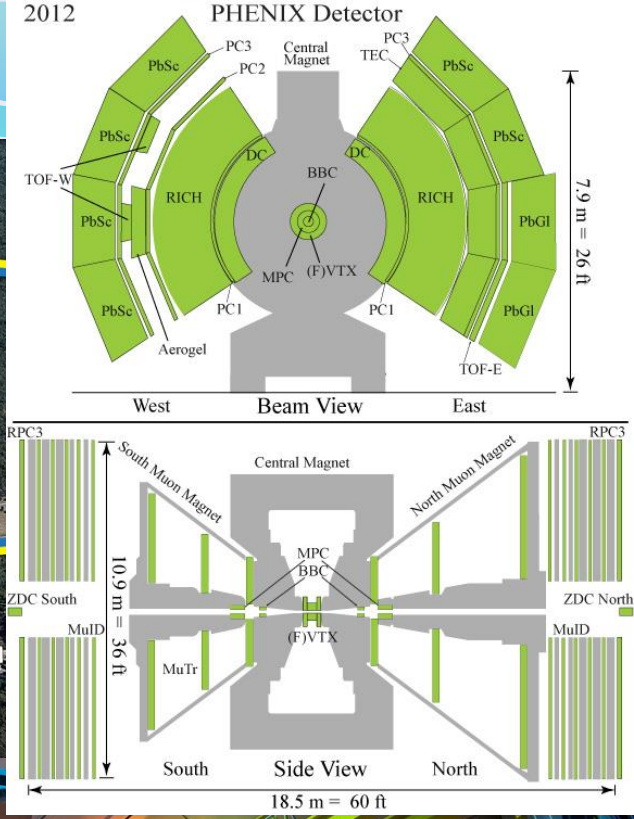
Ralf Seidl(RIKEN)

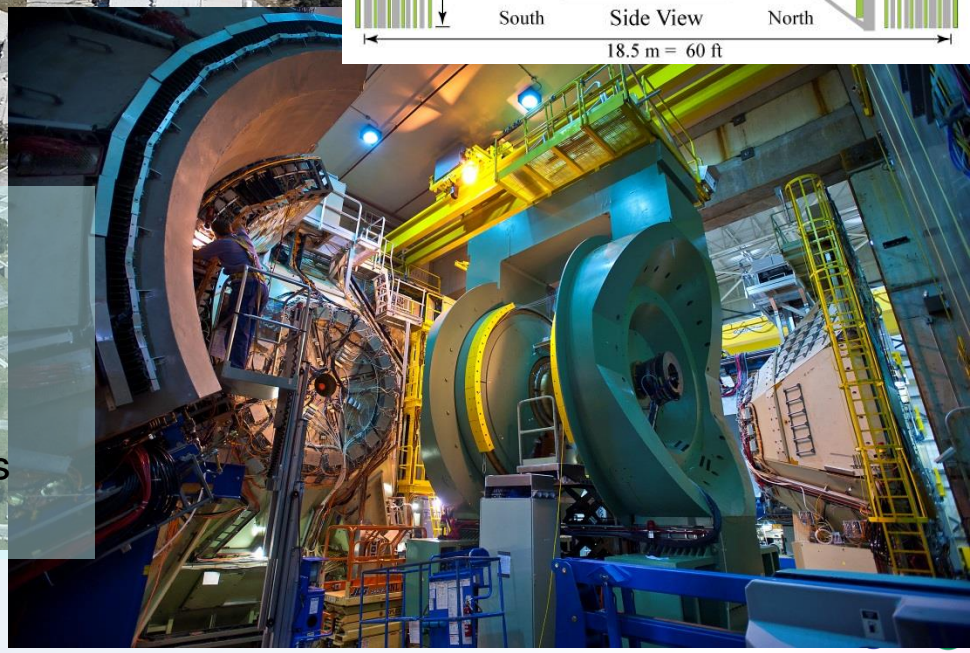
Outline

- Introduction to PHENIX
- Cold nuclear matter effects studied in PHENIX
- (Mostly)Forward spin physics:
  - Discovery of gluon spin contribution
  - Transverse single spin asymmetries
  - Single spin asymmetries in pA
- The Future of RHIC and eRHIC

RHIC and PHENIX



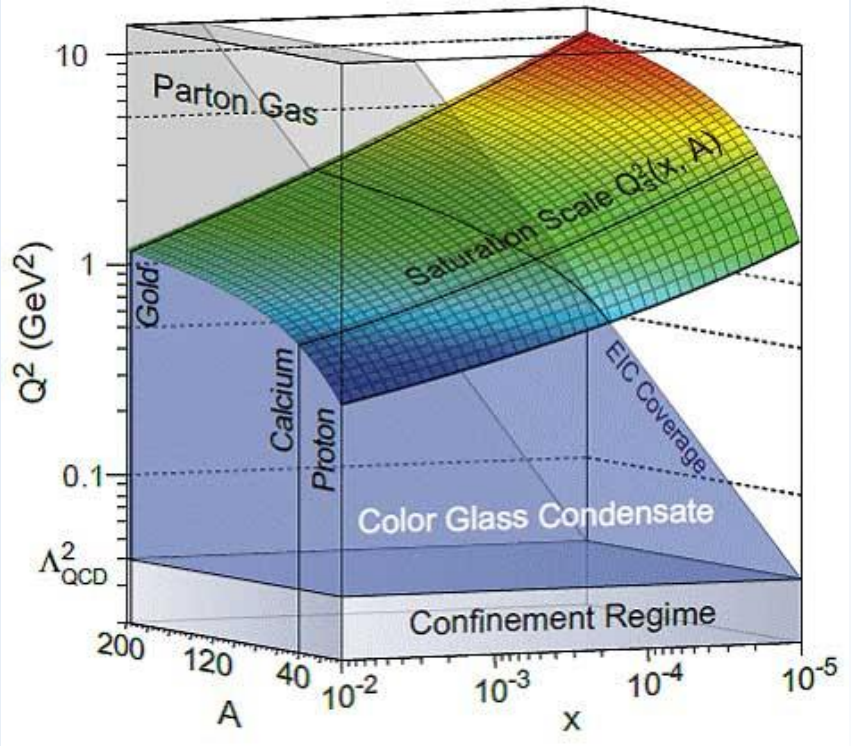




- Polarized proton beams from $\sqrt{s}$ of 62–510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry

Cold nuclear matter effects

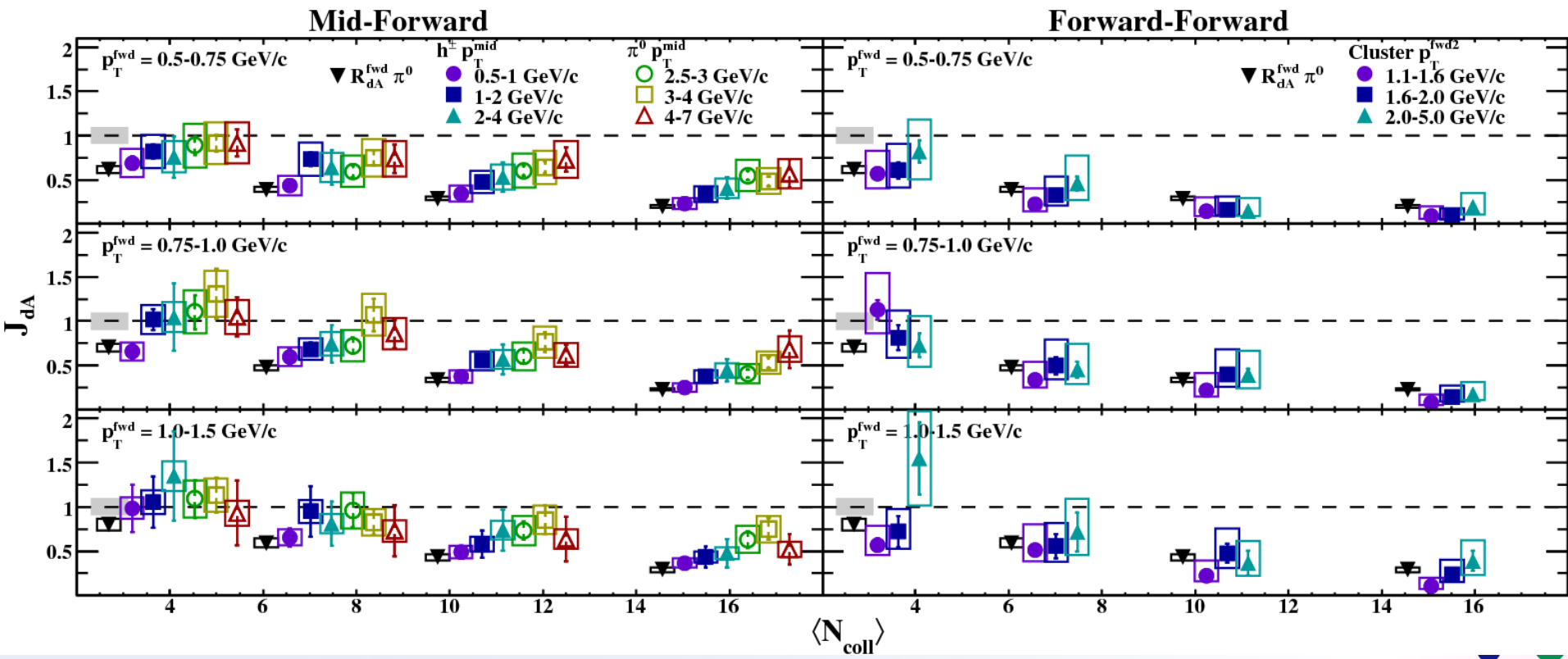
- Main questions:
  - Are there nonlinear effects at low x when gluon densities get too large?
  - Is the saturation scale at x to be reached in p(d)-A collisions and e-A collisions large enough to be perturbative?
  - What are actual smoking guns for such effects?



Dijet suppression in dAu vs pp collisions

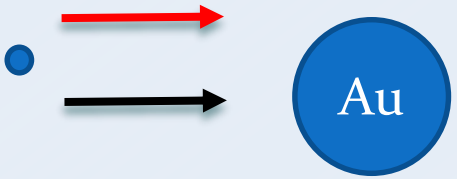
- Suppression increasing with increasing N_{coll}
- Decreasing with increasing momentum (related to increasing x)

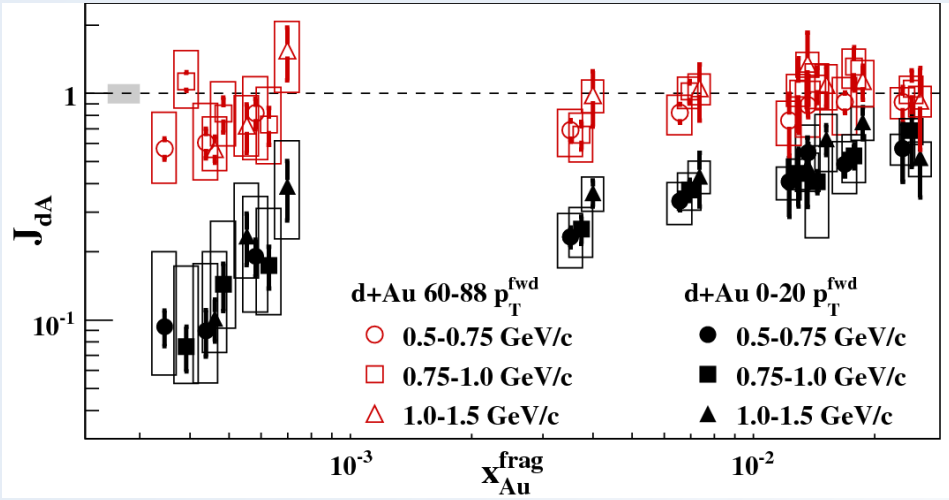
Phys.Rev.Lett. 107 (2011) 172301



Indications of CNM effects at low x

- Peripheral collisions: little to no di-jet suppression
- Central collisions: Strong suppression at lowest x visible



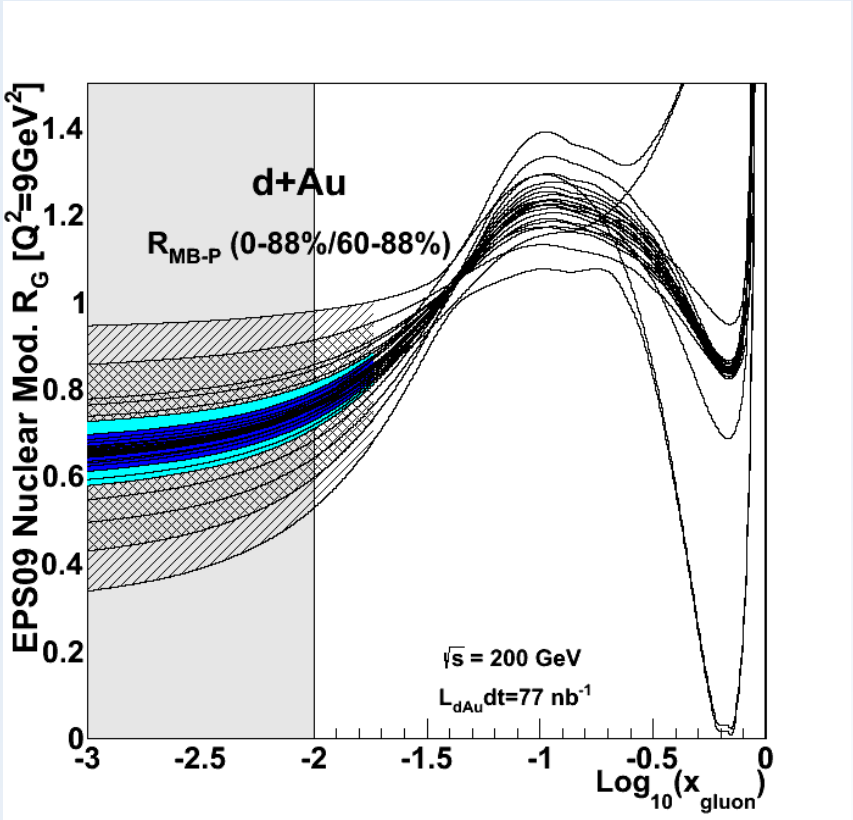


$$x_{Au}^{frag} = \left(\langle P_{T1} \rangle e^{-\langle \eta_1 \rangle} + \langle P_{T2} \rangle e^{-\langle \eta_2 \rangle} \right) / \sqrt{s_{NN}}$$

$$x_{Au}^{frag} < x_{Au}$$

2016 MPC-EX data analysis ongoing

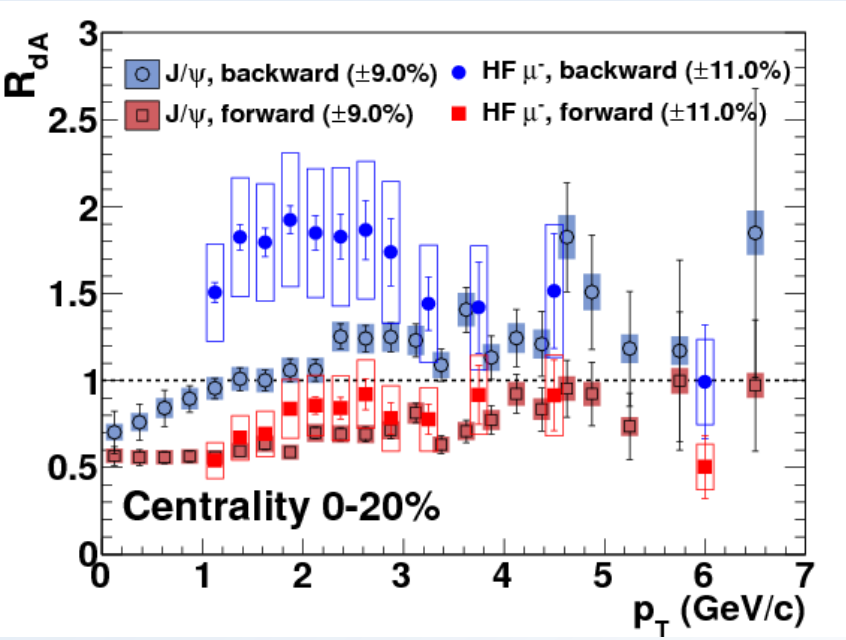
- Successful dAu@200 GeV data taking in 2016 with MPC-EX for di-pion measurements with high statistics will access nuclear gluon PDF for $x_g < 10^{-2}$



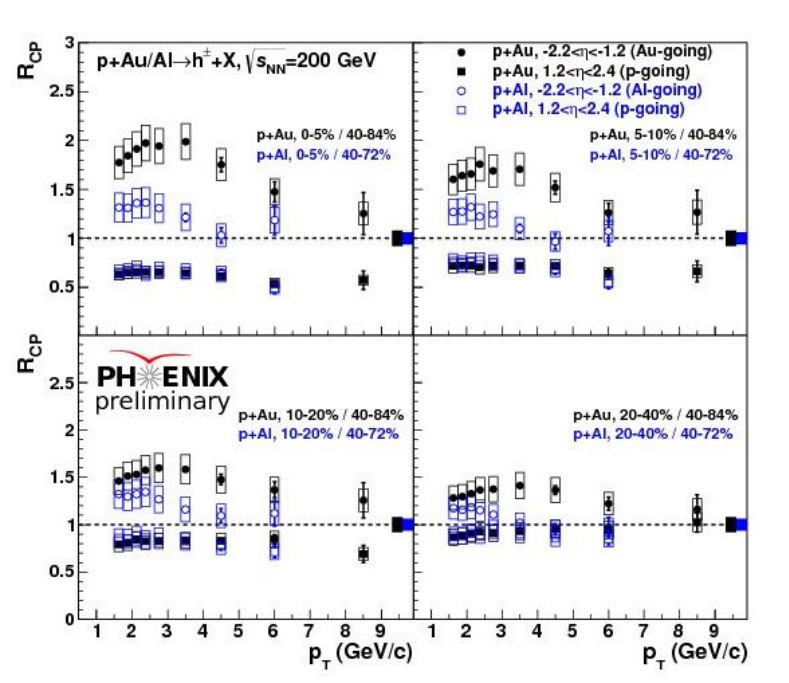
CNM effects at moderately forward rapidities

- J/Psi and open heavy flavor production at rapidities $1.4<|\eta|<2.0$ in dAu collisions extracted
- For lower-x_{Au} (d-forward) suppression up to 50% seen in both particle types
- Higher xAu show pronounced enhancement in HF muons at lower pT but not for J/Psi

Phys.Rev.Lett. 112 (2014), 252301

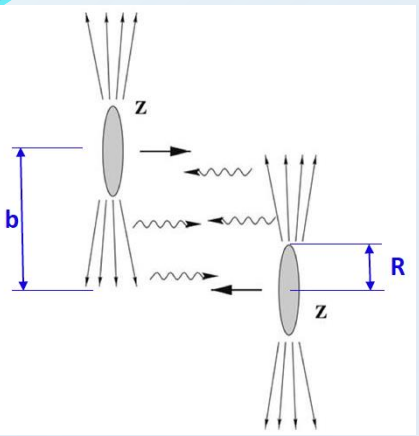


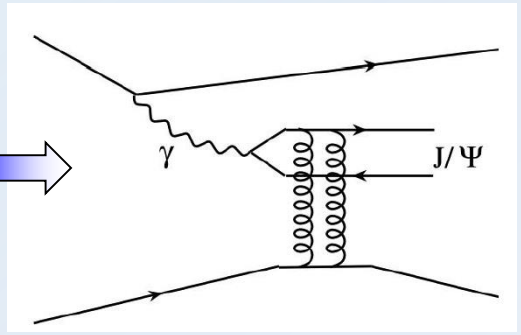
R_{CP} in pA for charged hadrons

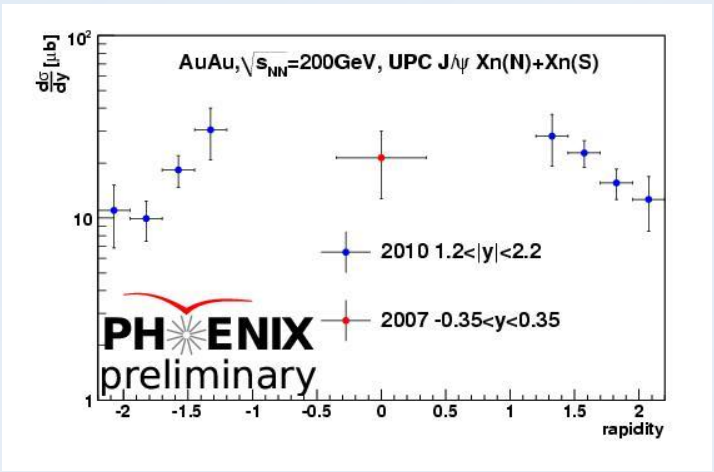


- Similar suppression seen for charged hadrons in pA collisions in p going direction
- Similar enhancement seen in A going direction
- Effects strongest for central collisons, much smaller for peripheral collisions
- pAl and pAu suppression consistent within uncertainties but enhancement different

UPC J/Psi production

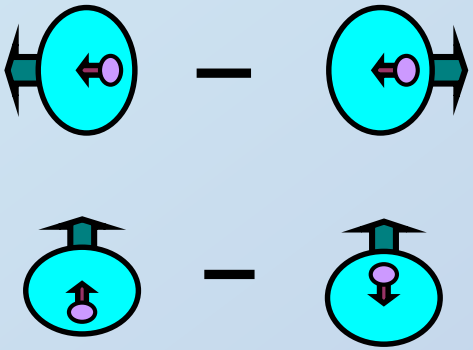






- At impact parameter larger than nucleii sizes use virtual photon fields for DIS-like diffractive measurements
- Especially VMs have same Quantum numbers as photons and their mass can provide the scale
- Experimentally triggered by no activity in main collision triggers but various neutrons in ZDCs

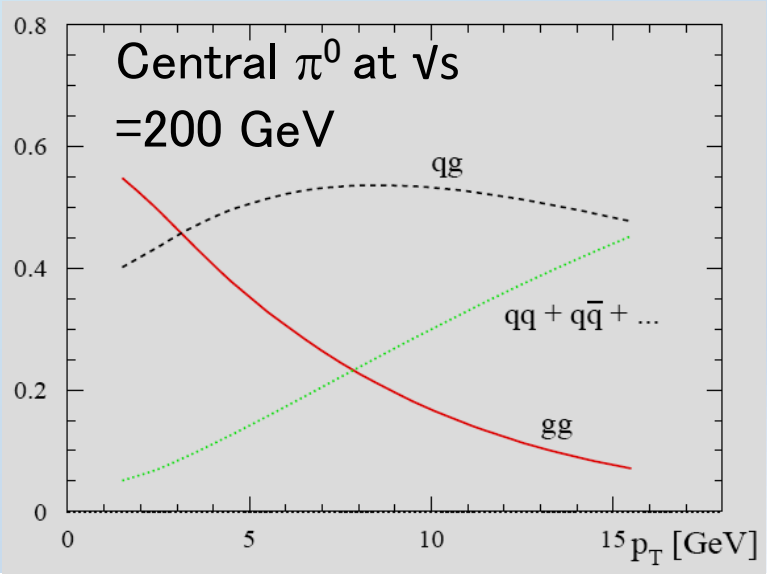
Spin Physics

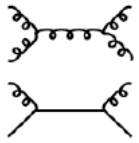
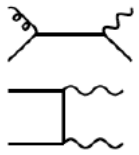
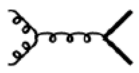


Gluon polarization

- Barely access via DIS data through DGLAP evolution (no large Q^2 lever arm)
- Some access in SIDIS through high Pt hadrons and charmed mesons
- Polarized pp collisions at LO in α_S sensitive to gluons

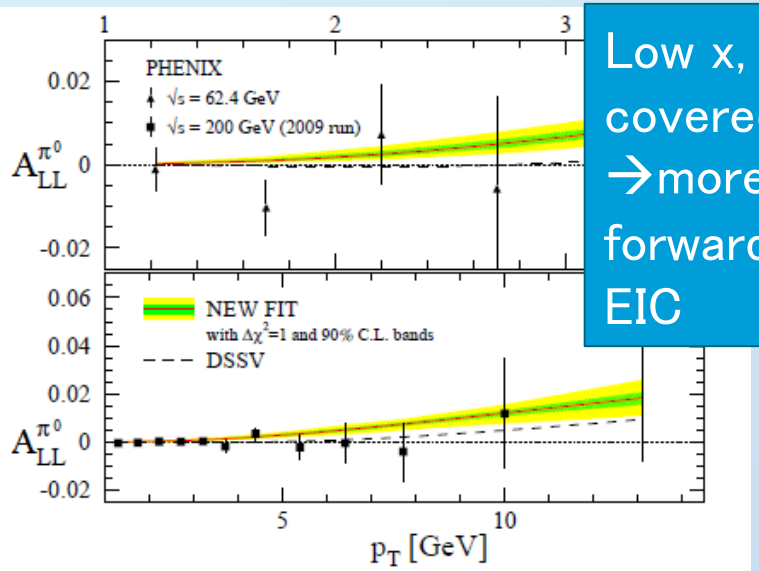
➔long. double spin asymmetries A_{LL} access Δg



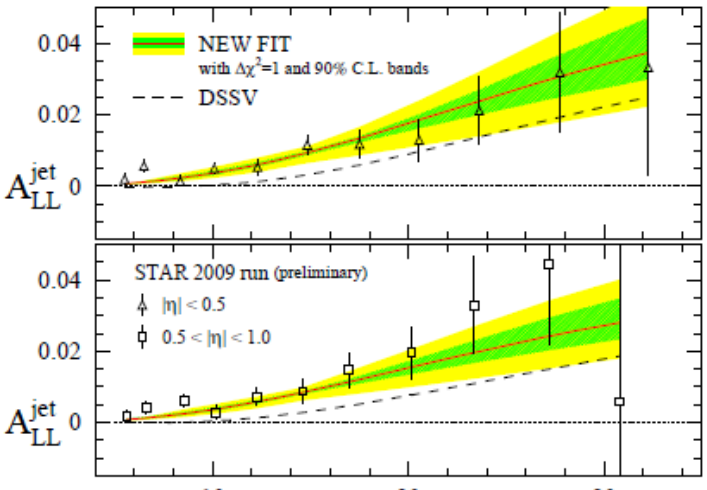
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet} + X$	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$	Δg Δg	
$\vec{p}\vec{p} \to \gamma\gamma + X$	$\vec{q}\vec{\bar{q}} \to \gamma\gamma$	$\Delta q, \Delta\bar{q}$	
$\vec{p}\vec{p} \to DX, BX$	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg	

First nonzero gluon spin indication

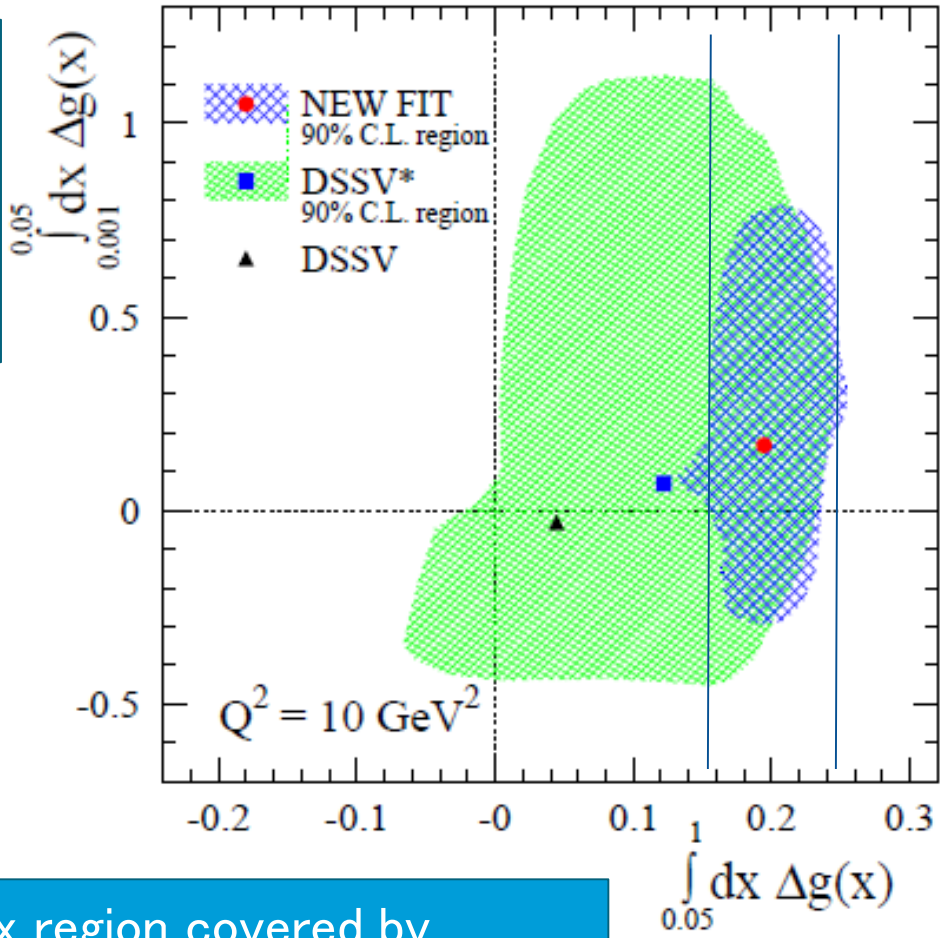
- DSSV:Phys.Rev.Lett. 113 (2014) 012001



Low x, not covered so far →more forward pp, EIC



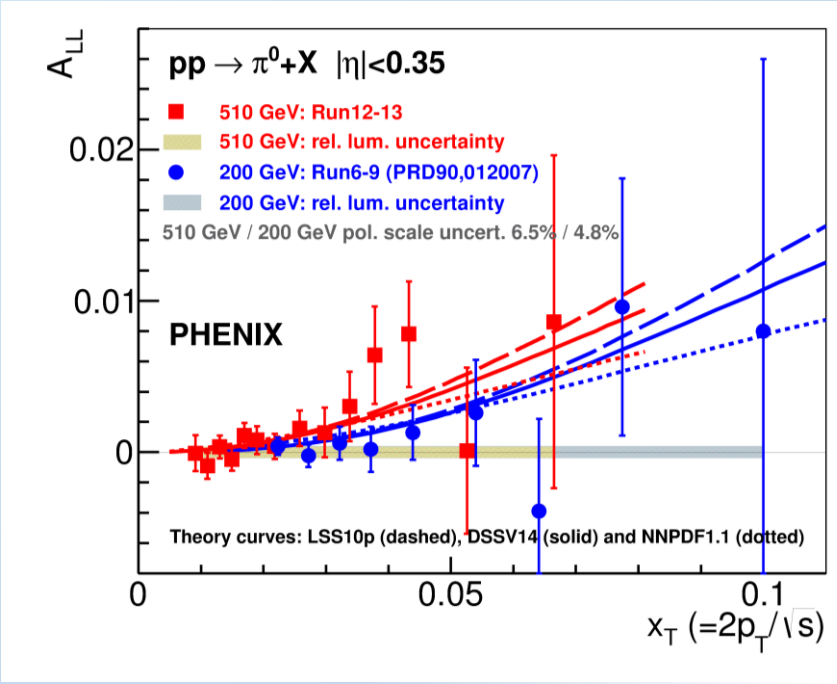
Also confirmed by NNPDFpol fit



x region covered by 200GeV RHIC and DIS results

Gluon spin: To higher energies

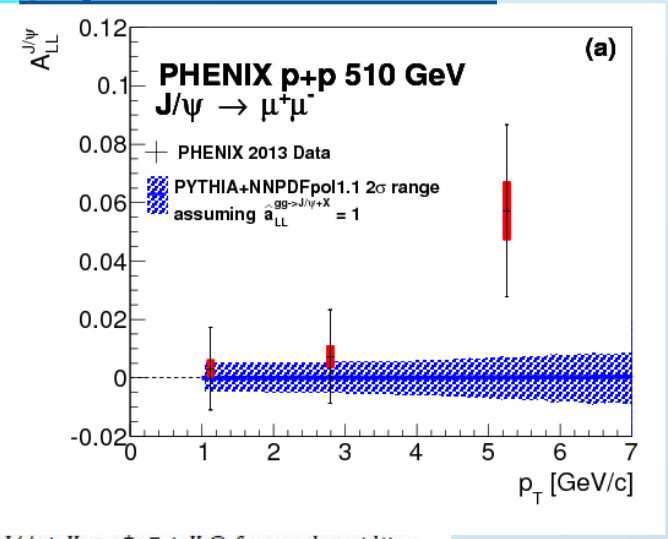
- Nonzero gluon polarization established with RHIC √s = 200 GeV data
- RHIC 510 GeV data (>2011) now confirms it in workhorse (jet, pion) measurements
- Extend access to lower x by higher energy (now~ 10^{-2})

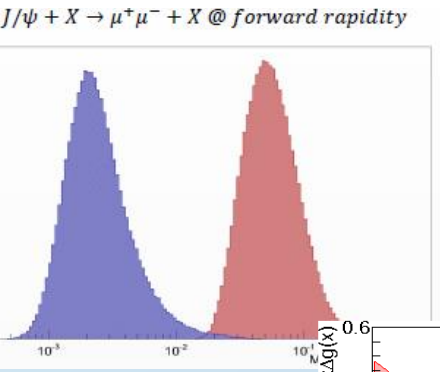


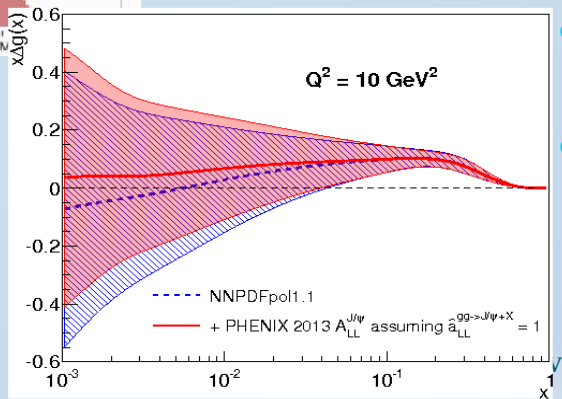
PHENIX result:
RIKEN press release
BNL and DOE research highlights
DOE labs 2016 research highlights report

…and lower x (i.e. forward)

Phys.Rev. D94 (2016)

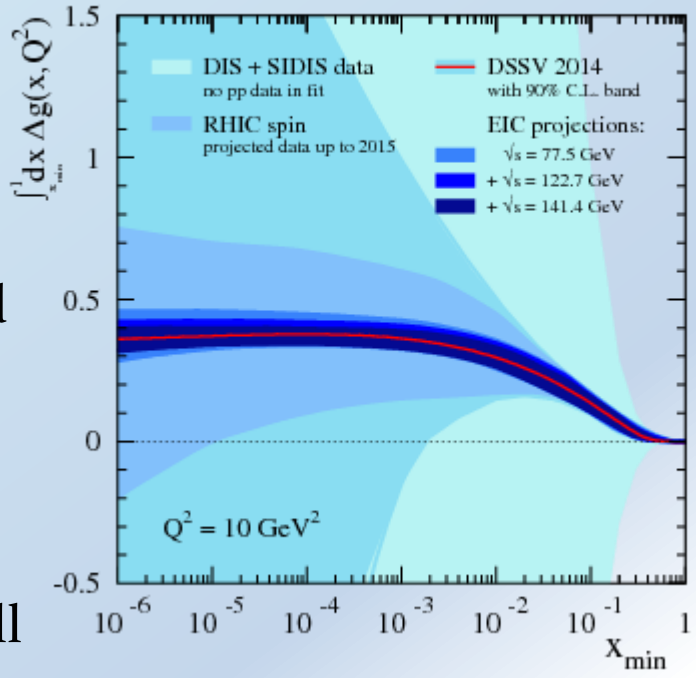






- PHENIX forward J/ψ measurements reach close to $x\sim10^{-3}$
- Including feed-down almost entirely produced from gg
- Due lack of knowing production mechanism interpretation still difficult

RPD 92 (2015) 094030



- Other forward π^0 measurements ongoing to get better precision down to $x\sim10^{-3}$
- Eventually EIC to pin down integrals, strangeness and need for OAM

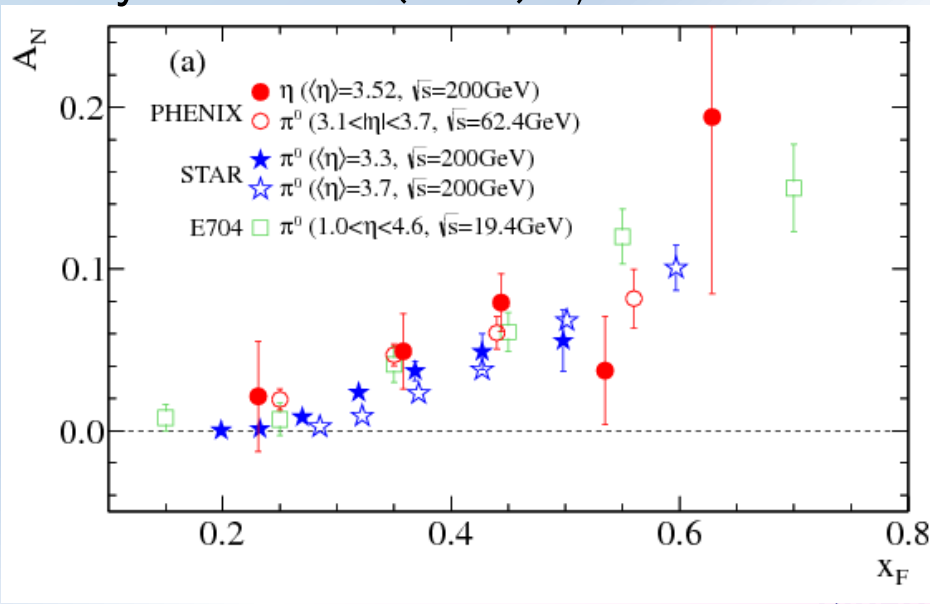
RIKEN

Inclusive single hadron left-right asymmetries in pp collisions

- Both initial state and final state effects contribute
  - Only one scale → need to be described by collinear higher twist functions
  - Initial state higher twist effect related to kt moment of Sivers TMD
  - Final state effect related to transversity and kt moments of Collins fragmentation function
  - Some indications for potentially other origins

- Explicit hadron-in-jet and DY asymmetries directly related to TMDs
- Also study A dependence in pA collisions

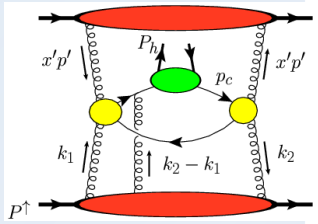
Phys.Rev. D90 (2014) 7, 072008
Phys.Rev. D90 (2014) 1, 012006

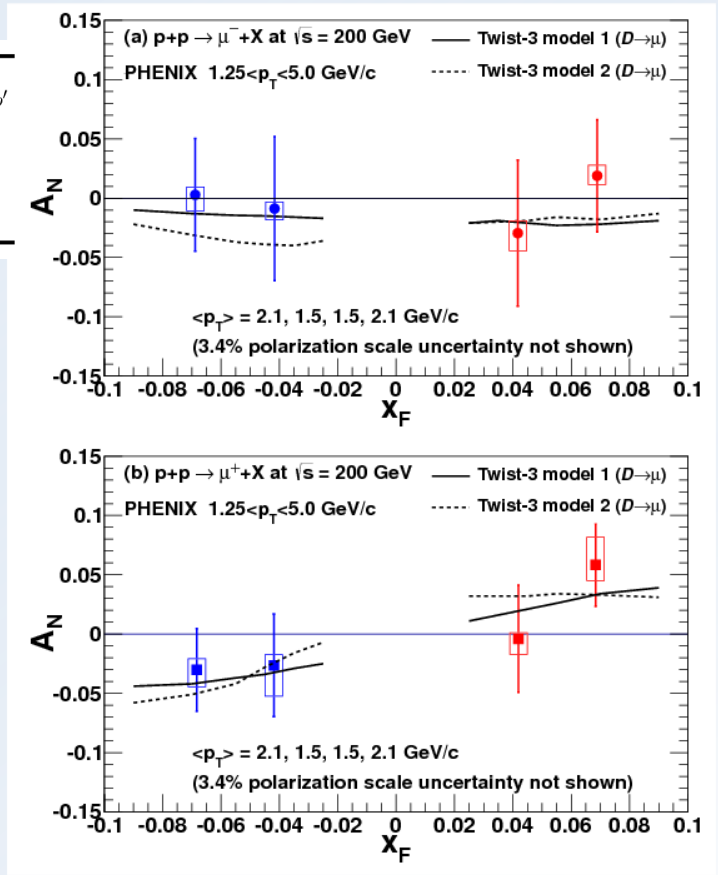


Heavy flavor asymmetries

Phys.Rev. D95 (2017) 112001

- Heavy flavor asymmetries most sensitive to Twist-3 counterpart of Gluon Sivers and tri-gluon correlator,
- no final state effects expected due to heavy quark mass
- Both contributions poorly known

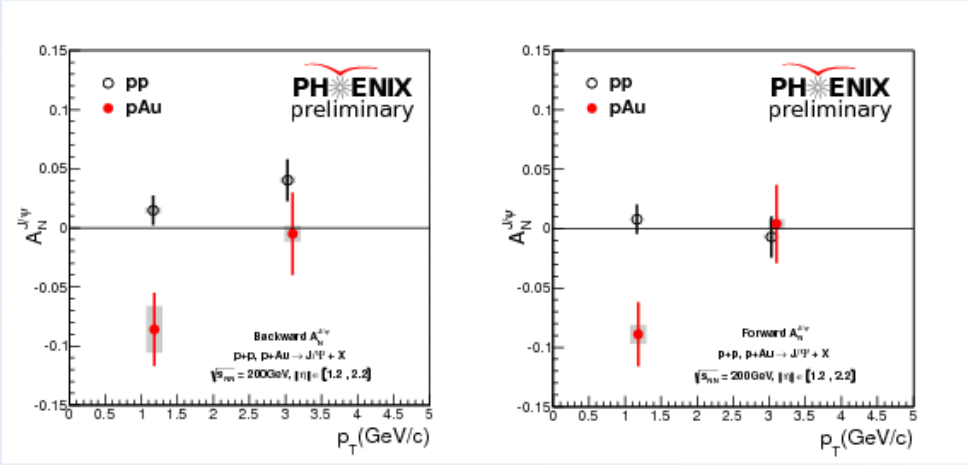


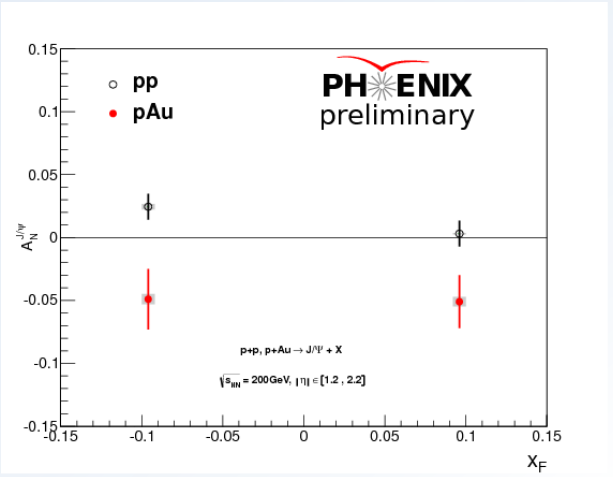


Model calculations from: Koike et.al. Phys.Rev. D84 (2011) 014026

J/Psi A_Ns

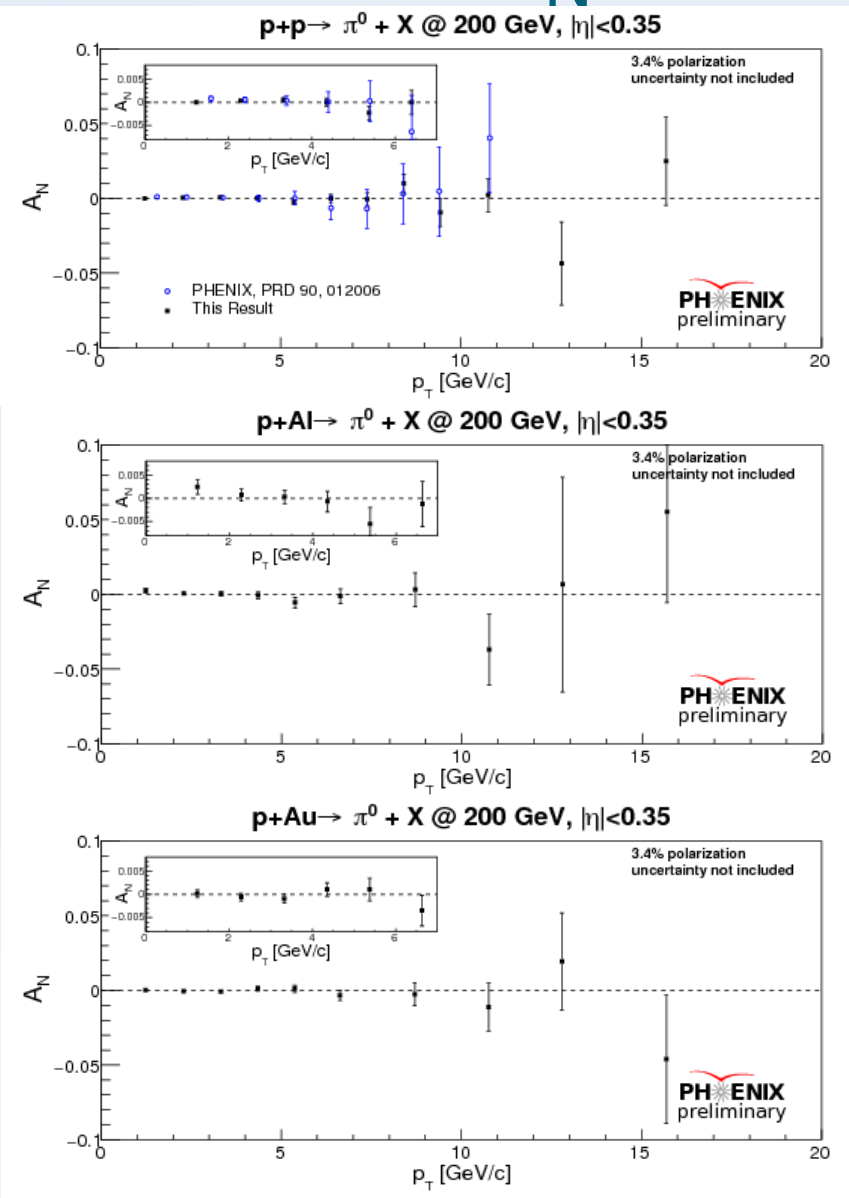
- Surprising nonzero J/Psi A_Ns seen in pAu collisions while pp Asymmetries are mostly consistent with zero
- Nonzero effect only visible at the lowest available Pt
- Diffractive effects as cause not very likely due to coincidence with hard collision trigger
- pAl data is being analyzed





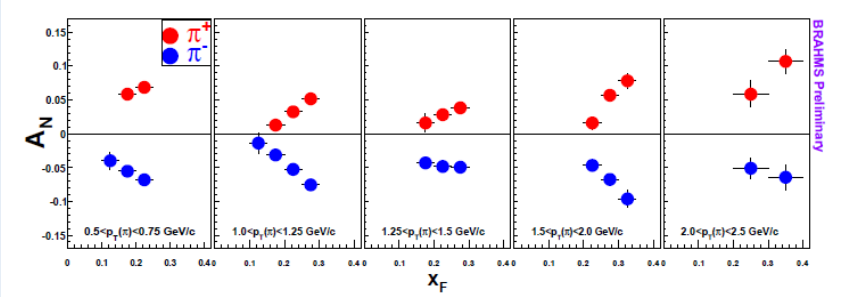
A dependence of central π^0 A_Ns

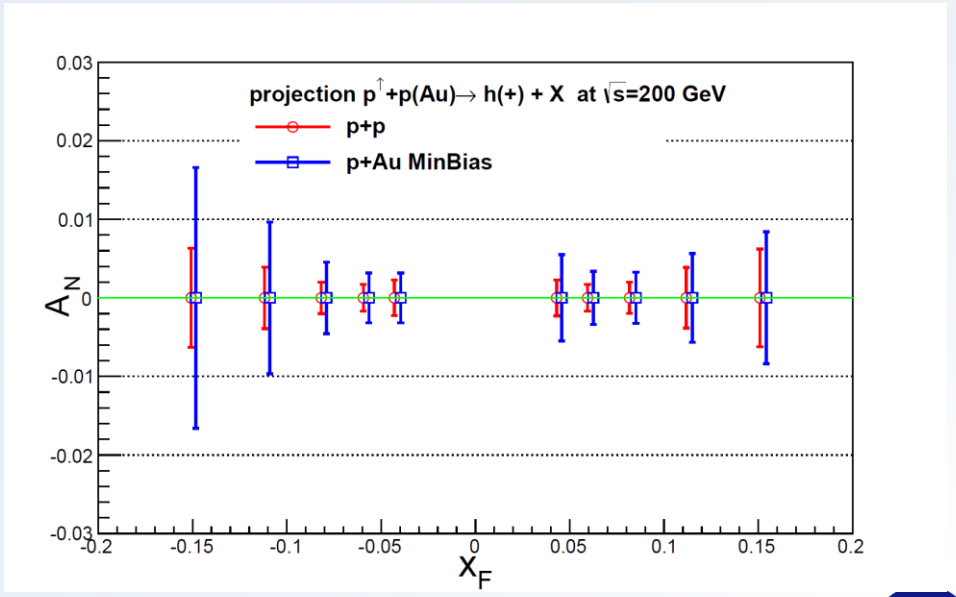
- Central rapidity A_Ns mostly sensitive to Gluon Sivers Twist-3 counter-part
- pp results consistent with zero at even higher precision
- No surprises in A dependence



A dependence of charged hadron A_Ns

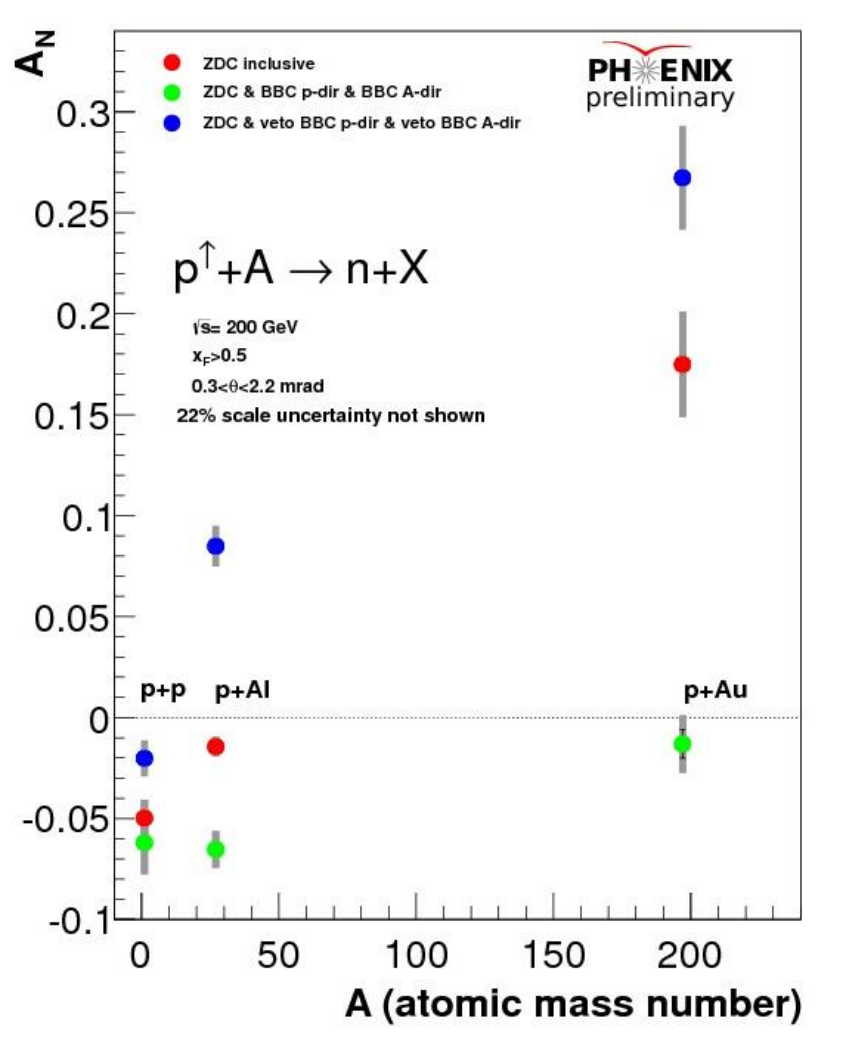
- Clear nonzero charged pion, kaon and proton asymmetries seen by Brahms at x_f>0.1
- PHENIX can cover charged hadrons in the muon arms at overlapping x_f
- Hadron composition mostly understood
- Asymmetries from 2015 pp and pAu data expected soon





Forward neutron asymmetries

arXiv:1703.10941

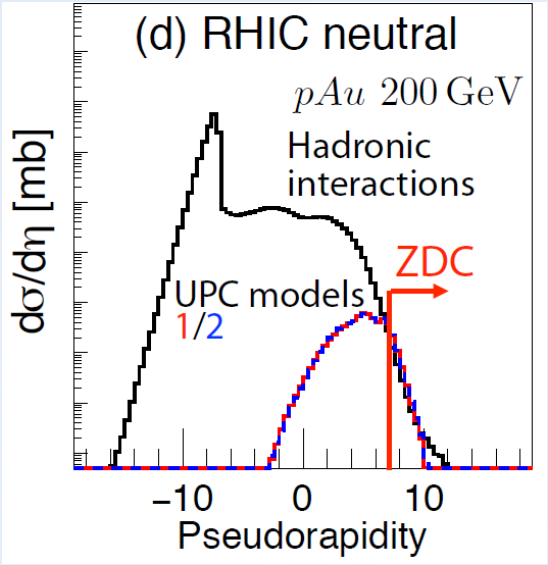


- Unexpectedly large A dependence in neutron asymmetries
- Sign change seen
- Possibility of ultra-peripheral collisions (UPC) effect, enhanced by Z^2 for nucleii
- (anti-)Correlations with main Collision detector system enhance/reduce UPC contribution

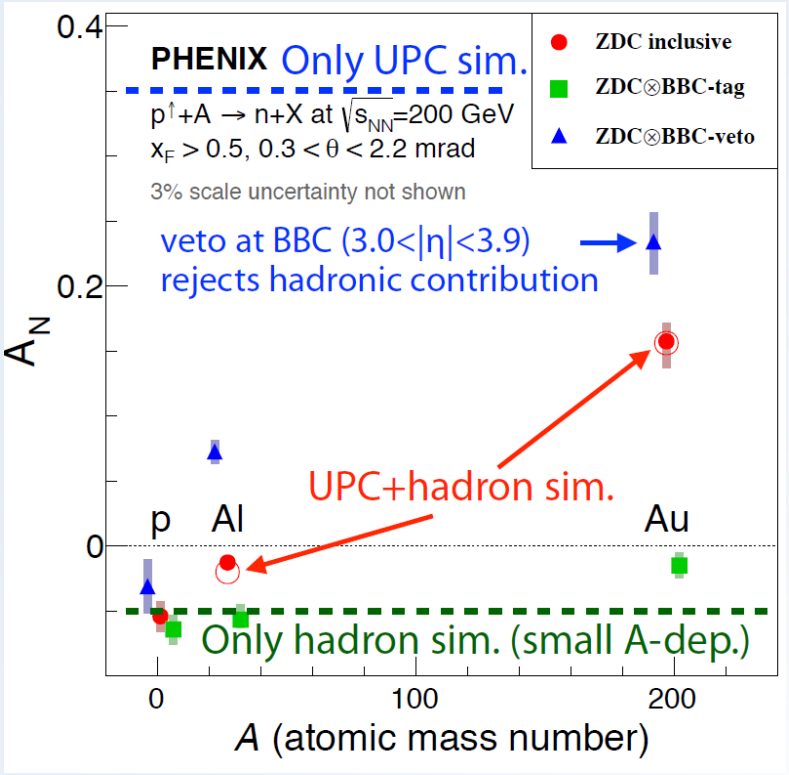
UPC explanation of neutron ANs

- From MAID simulations UPC cross section in ZDCs is indeed substantial in pAu collisions

Mitsuka: Eur.Phys.J. C75 (2015) 614



Mitsuka: Phys.Rev. C95 (2017) 044908

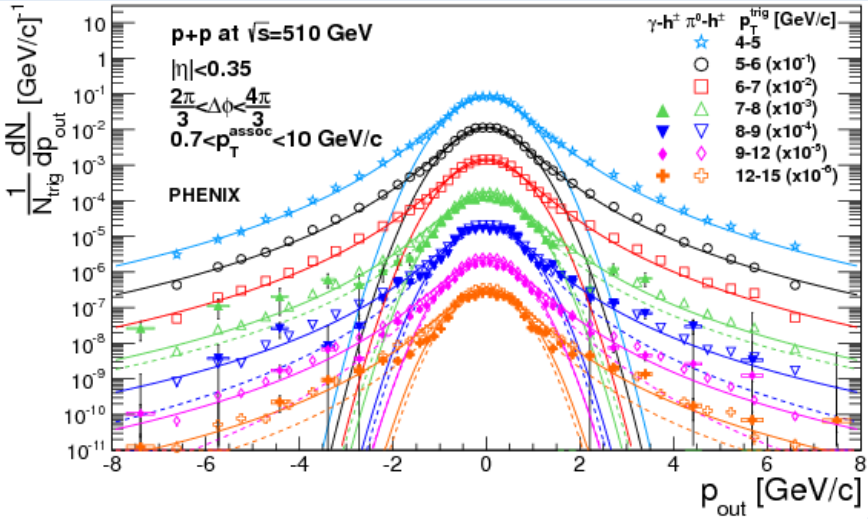


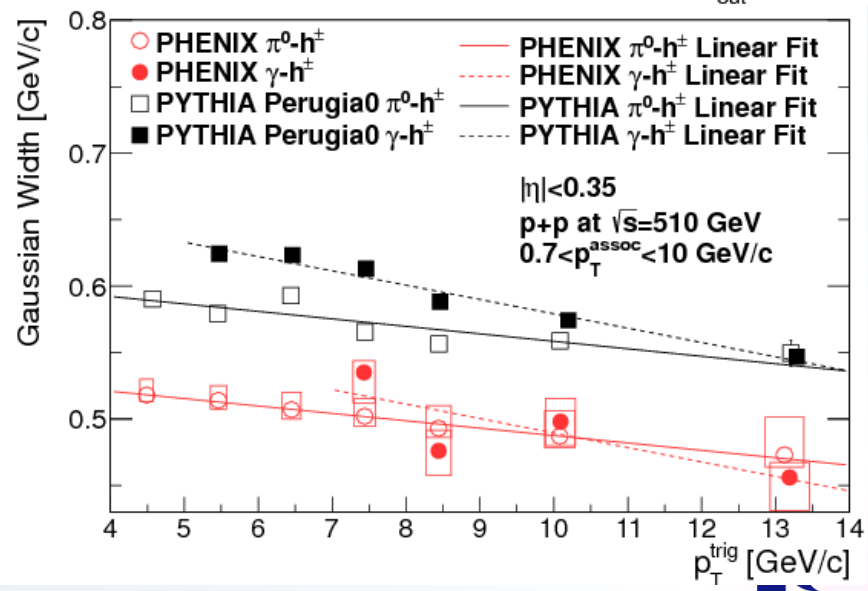
- More details to follow with explicit Pt dependent Asymmetry analysis (ongoing)

Di-hadron and h-γ correlations

Phys.Rev. D95 (2017) 072002

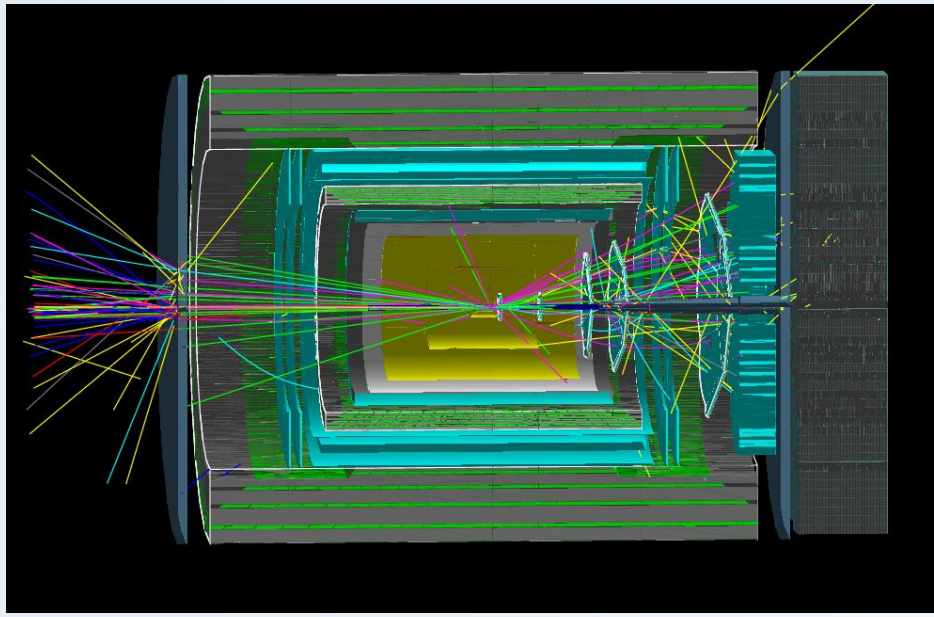
- Look at angular correlation between nearly back-to-back particles
- Widths of Gaussian components seem to be decreasing with trigger particle momentum while increase is expected
- Pythia qualitatively describes this effect





RHIC future (for spin and CNM physics)

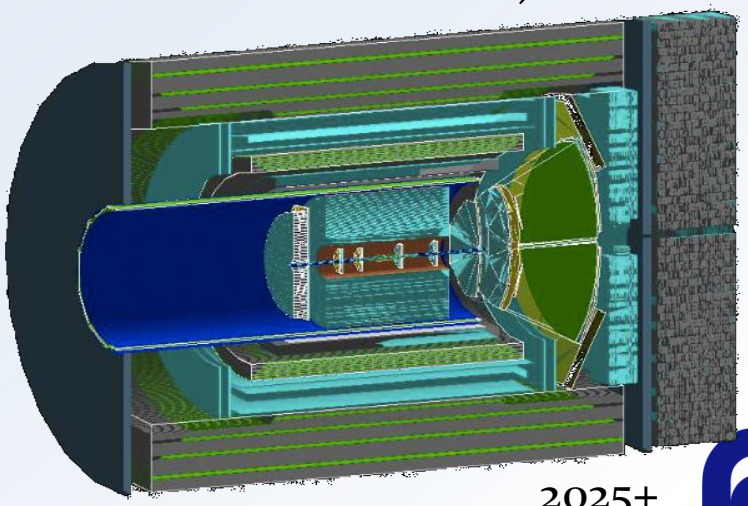
- Currently 510 GeV run ongoing in STAR for Sivers function mesurements in Ws, Z and DY
- sPHENIX detector (-1.1<η<1.1):
  - 1.4T Babar magnet
  - Central TPC + MAPS vertex tracker
  - EM+HCAL
  - CDo in Fall 2016
- For spin and CNM interest in Forward rapidites:
  - origin of large asymmetries,
  - high/low x reach
- fsPHENIX (2<η<4):
  - Reused PHENIX EMCal
  - New HCAL (joint development for STAR/fsPHENIX/EIC led by UCLA)
  - Tracking (GEMs or sTGCs)



- Most detectors directly useable for eRHIC
- Main Goals:
  - jet transverse asymmetries (flavor enhanced or Collins),
  - DY/photons in pA for nuclear /gluon PDFs
  - Hadronization in medium

eRHIC

- 2015 NSAC long range plan highest priority new facility: electron Ion Collider (EIC)
- Currently National Academy of Science review ongoing
- DOE CD process starting soon
- 2 potential realizations:
  - JLAB (CEBAF+new pol. ion accelerator – concentration on first high intensity, lower CMS energy)
  - eRHIC (RHIC + new pol electron beam – concentration on first high CMS energy, initially lower intensity)
  - ePHENIX (fsPHENIX + electron side+PID)

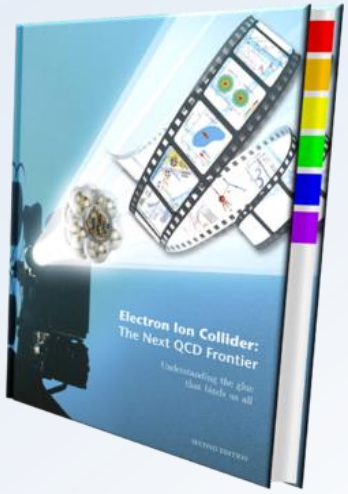


2025+

Summary

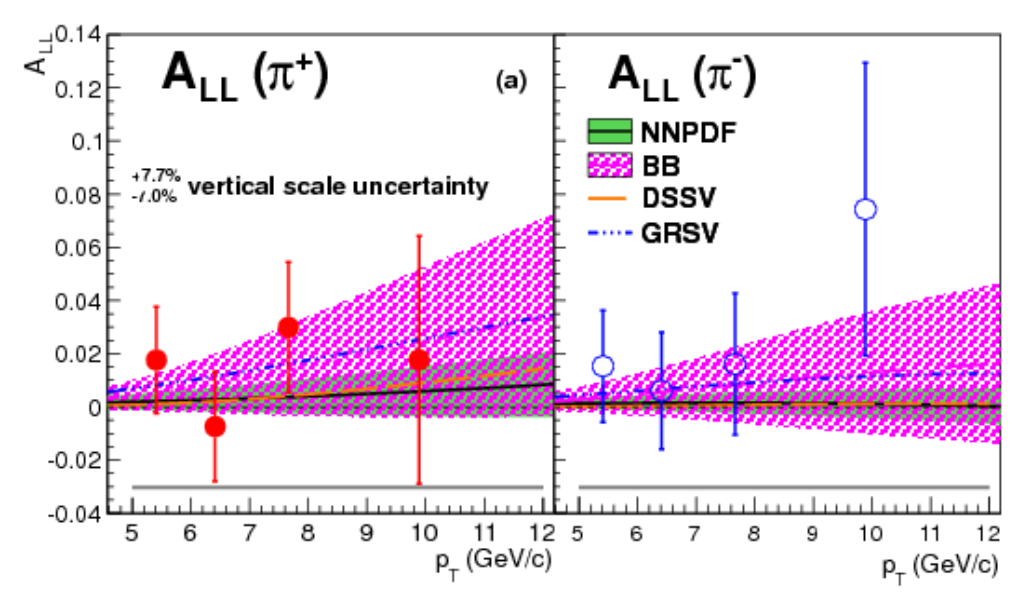
- Indication of CNM effects seen in PHENIX, more to come soon
- Gluon spin contribution confirmed at higher collision energies, started accessing lower x
- New information towards understanding transverse asymmetries in hadron collisions, but also new puzzles (such as A dependence)

- More to come in the future:
  - RHIC (CNM 2017-23 plan)
- EIC



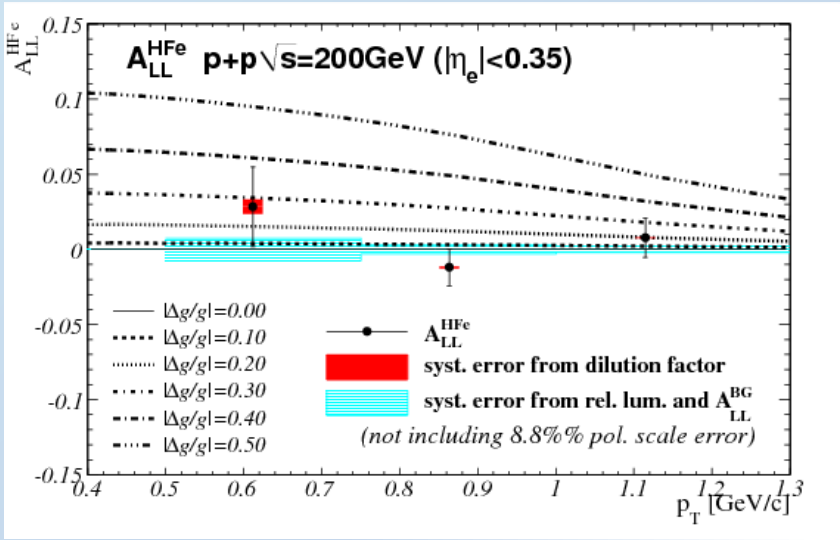
Other 200 GeV results not yet used in global fit

Phys.Rev. D91 (2015) 3, 032001



- Charged pions as potential direct indicator for sign of Δg via pion A_{LL} ordering
- 500 GeV analysis ongoing
- Reduced statistics compared to π^0 due to triggering
- Also central η

Phys.Rev. D87 (2013) 012011



- Single electrons at central rapidity from heavy flavor production directly sensitive to gluon helicity
- Large scale given by the HF quark masses

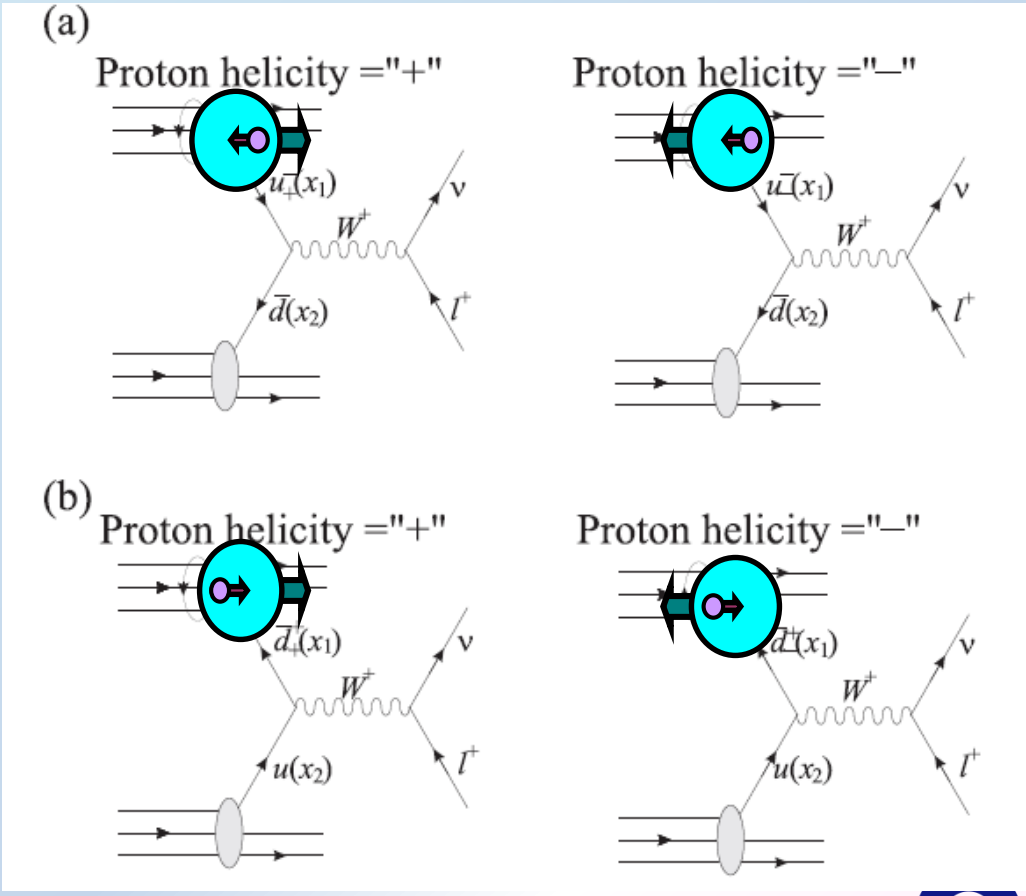
Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:

➔Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

➔Difference of the cross sections gives quark helicities $\Delta q(x)$

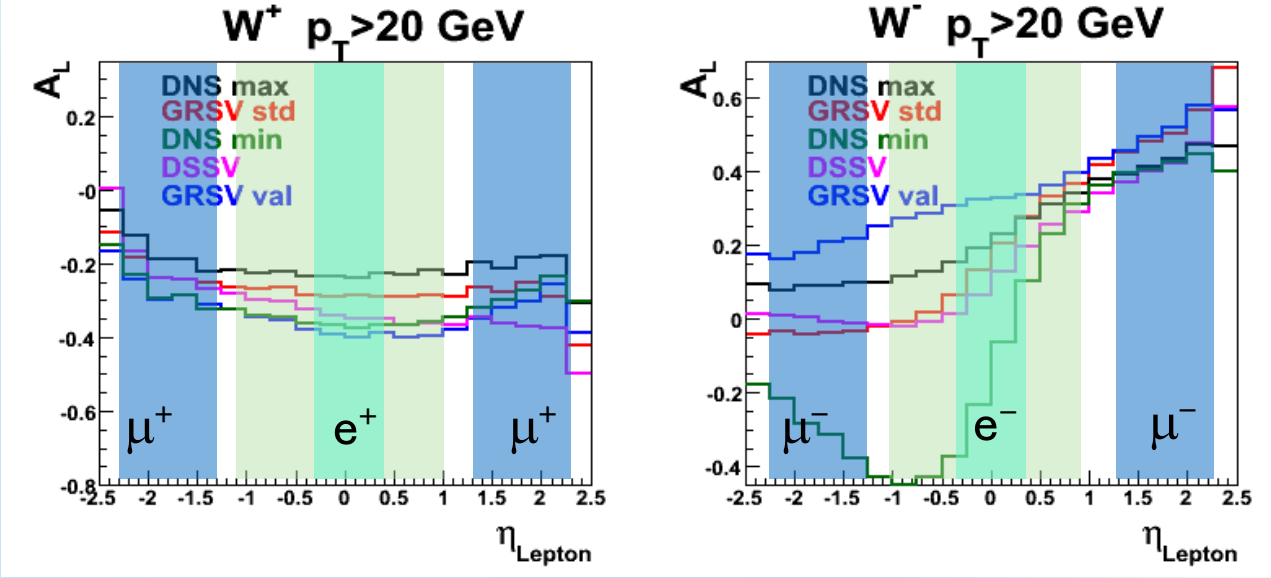
- No Fragmentation function required
- Very high scale defined by W mass



Bourrely , Soffer
Nucl.Phys. B423 (1994) 329–348

Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics



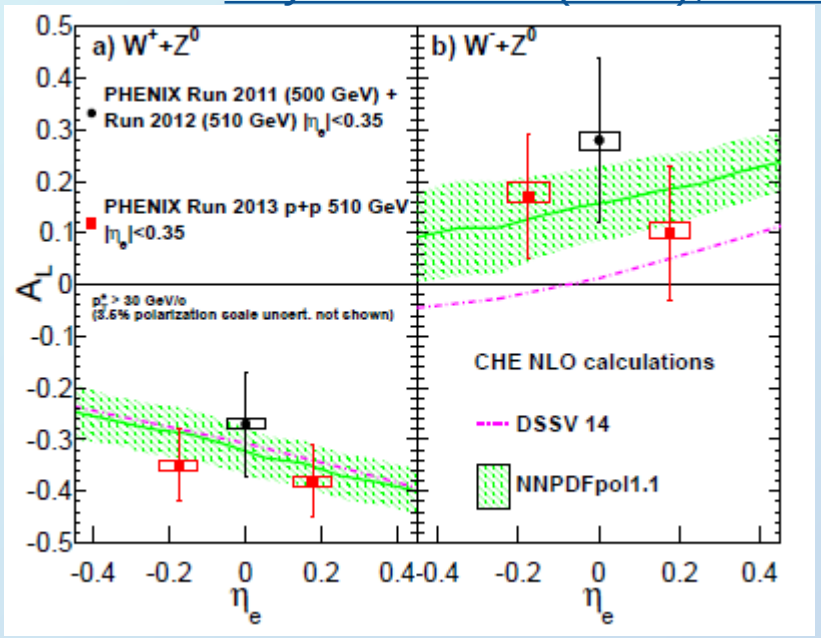
$$A_L^{W^+} \approx \frac{-\Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2}{u(x_1)\bar{d}(x_2)(1-\cos\theta)^2 + \bar{d}(x_1)u(x_2)(1+\cos\theta)^2}$$

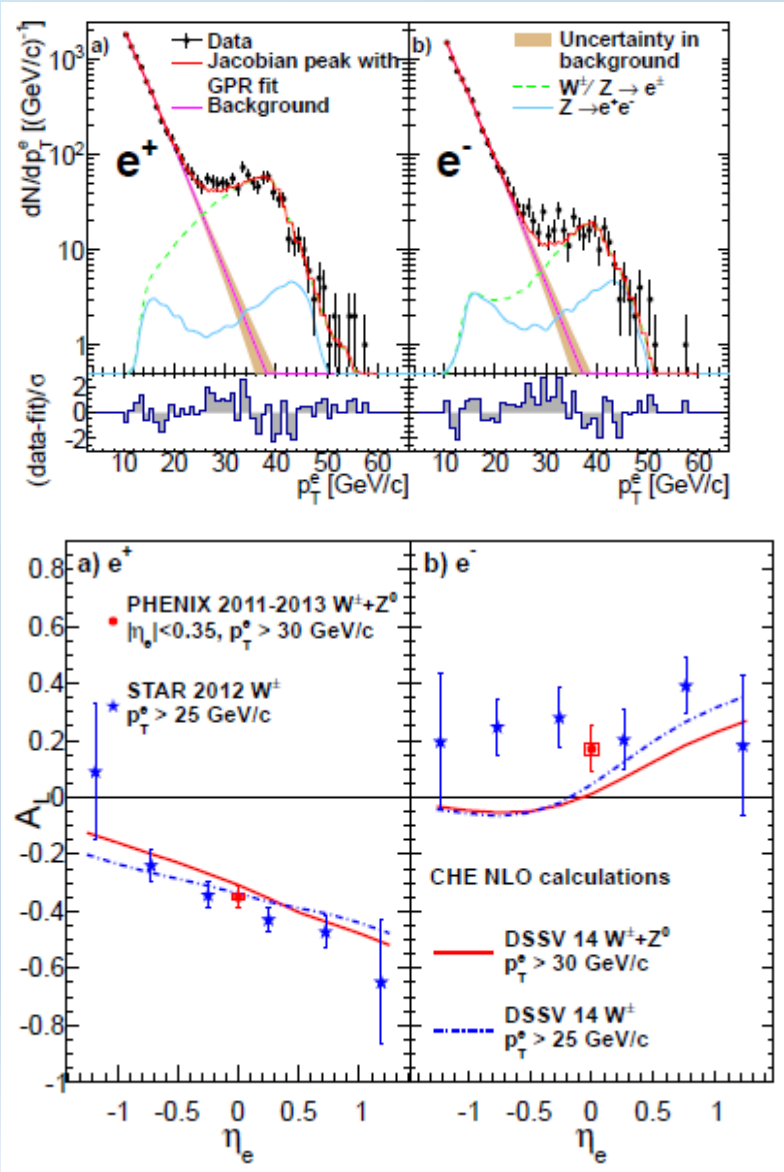
$$A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2}{d(x_1)\bar{u}(x_2)(1+\cos\theta)^2 + \bar{u}(x_1)d(x_2)(1-\cos\theta)^2}$$

Central W+Z→e asymmetries

STAR: Phys.Rev.Lett. 113 (2014) 072301

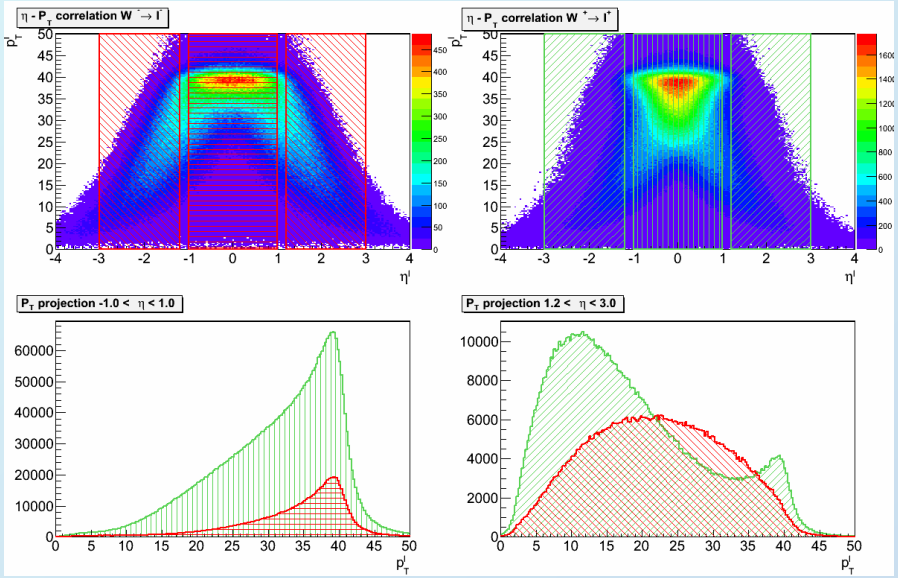
PHENIX: Phys.Rev. D93 (2016), 051103





- Leptonic W decays very clearly visible via Jacobian peak
- Large asymmetries found, consistent between experiments
- e^- significantly above latest global fit

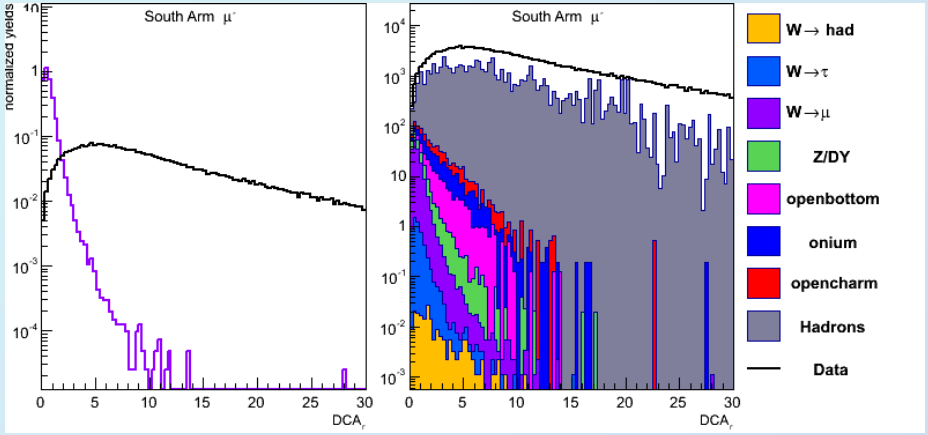
Forward W+Z → μ asymmetries



- At forward rapidities no Gaussian peak to identify W decay muons
- Lower P_T hadrons as fake high P_T "muons"
- Successfully performed unbinned max likelihood analysis to identify signal

- Asymmetries as expected
- Still working on improving the uncertainties

Forward W+Z →μ asymmetries



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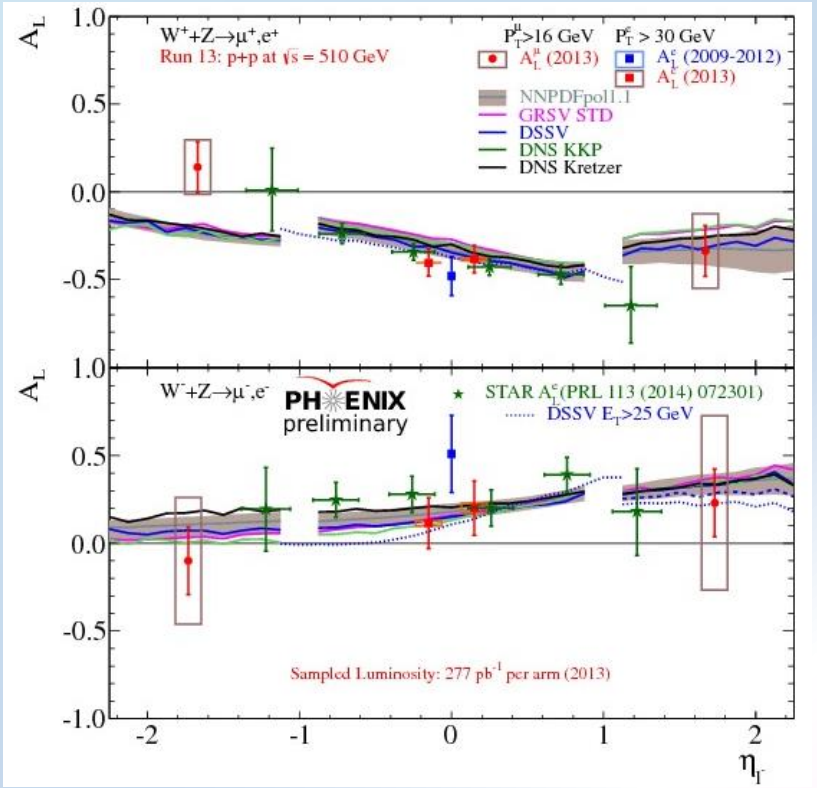

- Asymmetries as expected
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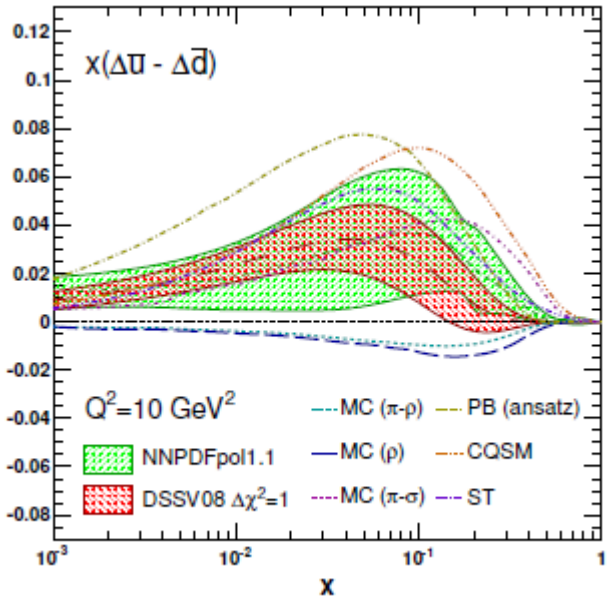
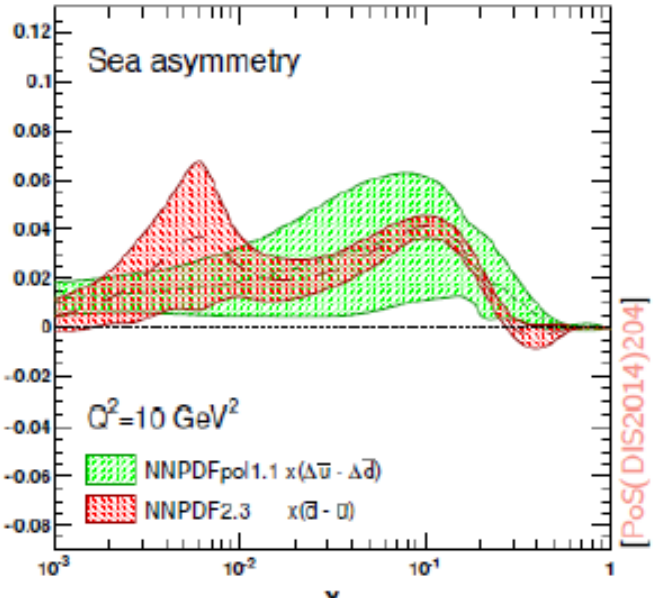
Sea quark helicites

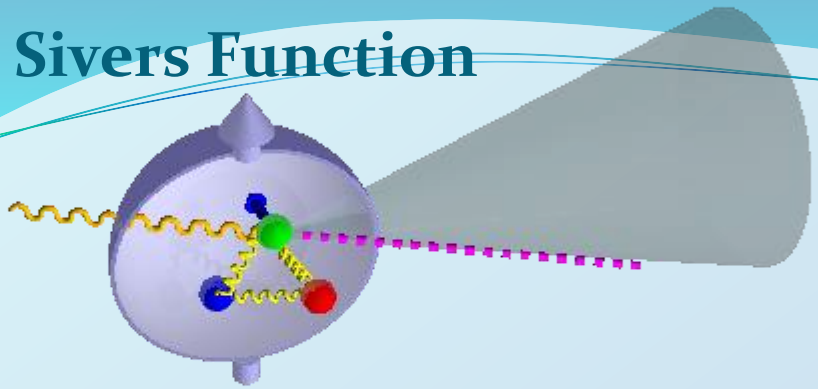
NNPDFpol1.1:
arXiv:1406.7122

- STAR 2012 data at boundary of DSSV uncertainty bands
- Reweighted NNPDFpol1.1 shows substantial polarized light sea asymmetry
- opposite sign to most cloud models
- All central PHENIX data published,
- 2013 STAR data and forward PHENIX data pending

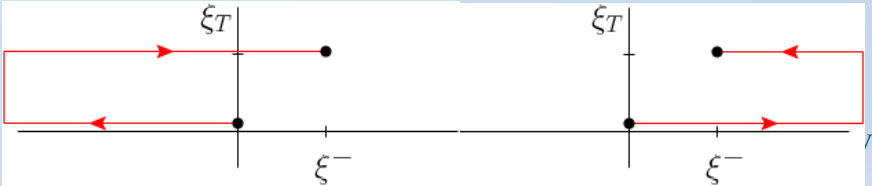




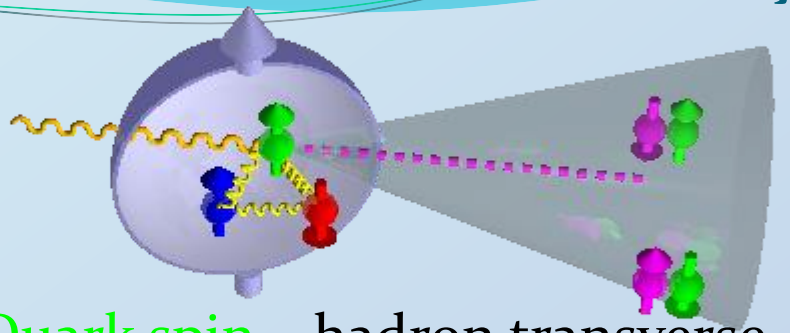
Sivers Function



- Proton–spin – quark orbit (k_T) correlation
- Suggested in ’93 – dead due to time reversal
- Brodsky-Hwang-Schmid ‘02 model example of Sivers function using gauge links
- Belitsky-Yuan ‘02 → gauge links generally needed
- Collins → function can exist, but modified universality (the SIGN change)



Collins Function (x Transversity)



- Quark spin – hadron transverse momentum correlation (in fragmentation)
- Analyzer for quark transversity → access to tensor charge (Lattice, BSM?)
- A polarized (ie signed) fragmentation function
- Transverse momentum conservation requires some compensation (Terayev-Schaefer)

Figs from Buffing et al. : PRD 86 (2012) 074030