eRHIC

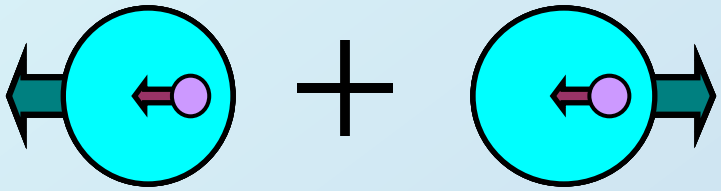
第3回高エネルギーQCD・核子構造勉強会,
京都大学
2014年8月18日

Ralf Seidl
(RIKEN)

Outline

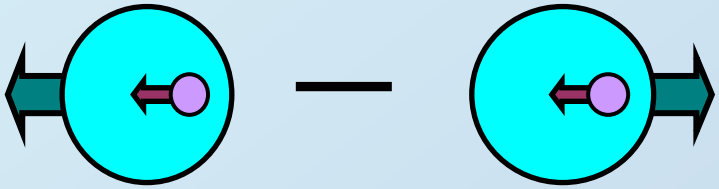
- Spin structure of the nucleon
  - Helicity distributions and spin sum rule
  - (Transverse spin and) GPDs
- Current knowledge from
  - (SI)DIS
  - RHIC
- eRHIC
  - Physics goals
  - Accelerator design
  - IR design
  - Detector concepts
- Outlook

Quark distributions



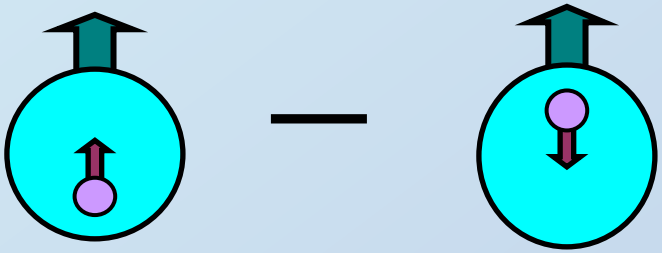
Unpolarized distribution function q(x)

Sum of quarks with parallel and antiparallel helicity relative to proton helicity
(well known from Collider DIS experiments,hadron colliders)



Helicity distribution function Δq(x)

Difference of quarks with parallel and antiparallel helicity relative to longitudinally polarized proton
(known from fixed target (SI)DIS experiments)



Transversity distribution function δq(x)

Difference of quarks with parallel and antiparallel spin relative to transversely polarized proton
(little known from fixed target (SI)DIS experiments)

The Spin sum rule

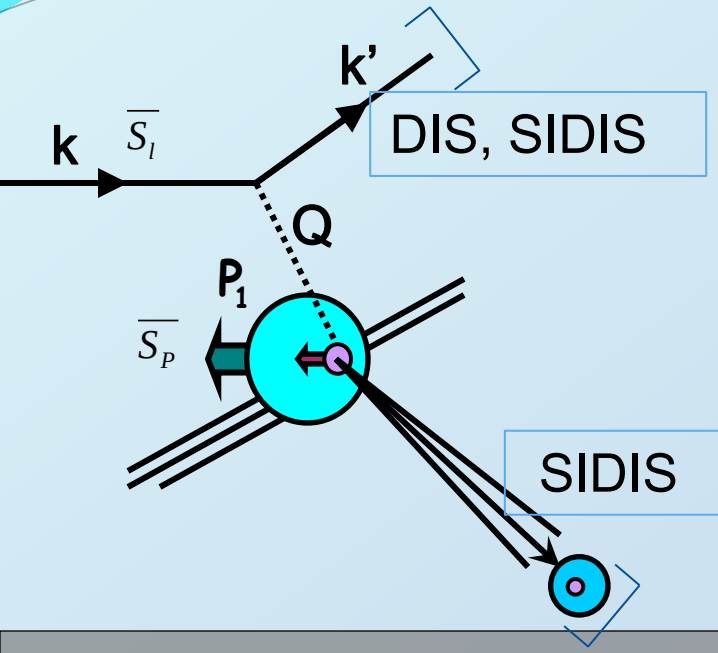
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Jaffe, Manohar

$$\Delta\Sigma = \int dx \left[(\Delta u(x) + \Delta\overline{u}(x)) + (\Delta d(x) + \Delta\overline{d}(x)) + (\Delta s(x) + \Delta\overline{s}(x))\right]$$

- Other decompositions exist (see previous talk)
- $\Delta\Sigma$ and ΔG can be accessed in longitudinally polarized (SI)DIS and pp collisions
- more on orbital angular momentum later

(SI)DIS Kinematics



$$\frac{d\sigma}{dQ^2} = f_q(x_1) \otimes \tilde{\sigma} \otimes D^h(z)$$

Quark distribution functions: quark q in nucleon

Fragmentation functions functions: quark q →hadron h

$$\begin{aligned} Q^2 &= -q^2 \\ &= -(k-k')^2 \end{aligned}$$
- Squared Momentum transfer of photon/Z

$$x_B = \frac{Q^2}{2Pq}$$
- Bjorken scaling variable, at high Q^2 momentum fraction of quark

$$k^+ = xP^+$$

$$y = \frac{qP}{kP}$$
- Inelasticity (sometimes called depolarization factor)

$$W^2 = (P+q)^2$$
- Mass of hadronic final state

$$P_h^- = zk^-$$
- Fractional hadron momentum

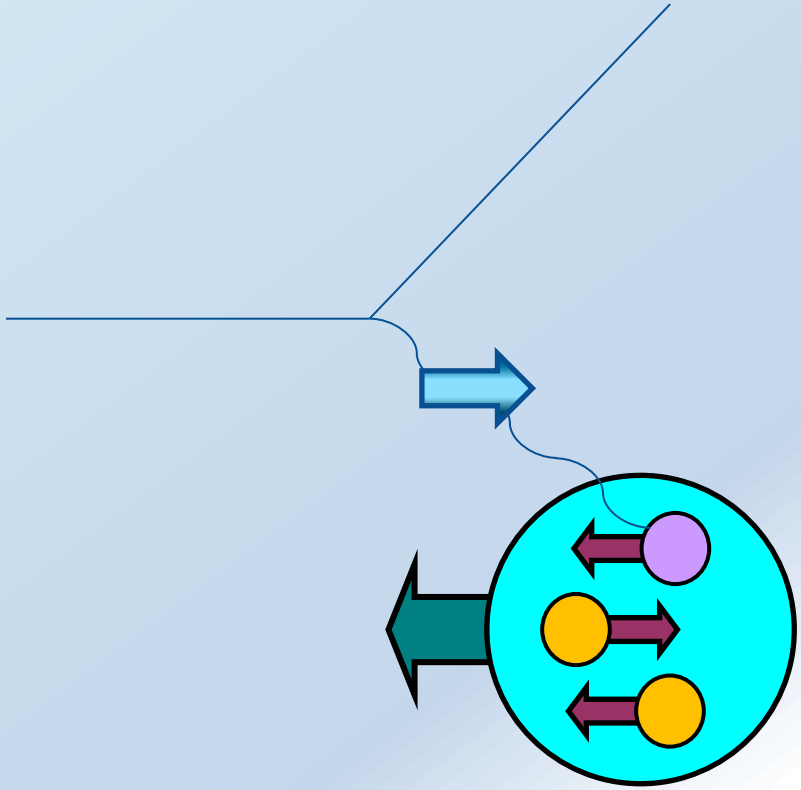
•Hard scales: $Q^2 >> 1$ GeV^2 otherwise photoproduction

RIKEN

Deep Inelastic Scattering: ep → e'X ...and spin crisis

$$A_1(x) = \frac{\sum_q e_q^2 \Delta q(x)}{\sum_q e_q^2 q(x)}$$

- Initially naïve expectation of: ½ = ½ + ½ - ½ (100% of nucleon spin from quark spin)
- Relativistic effects → ~70% (consistent with old SLAC data)
- but lower x data(EMC showed only 14% carried by quark spins
- Nowadays ~30% from quarks



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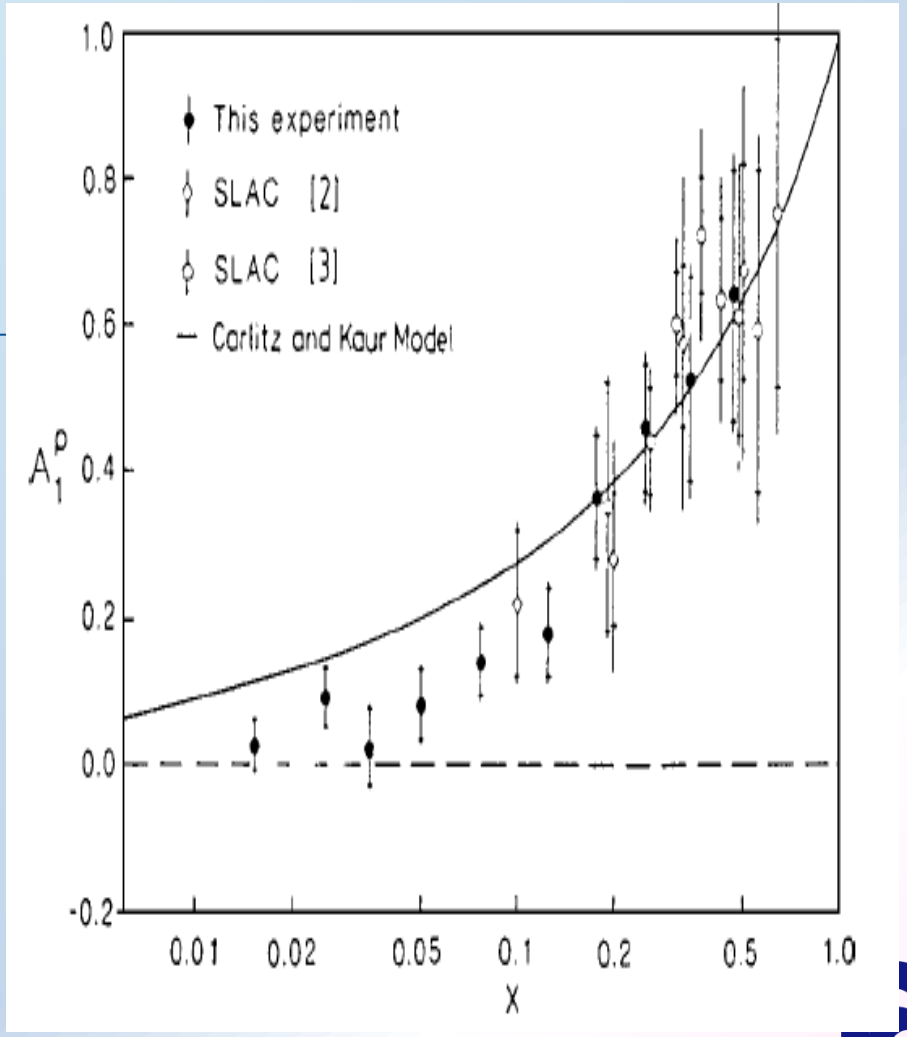

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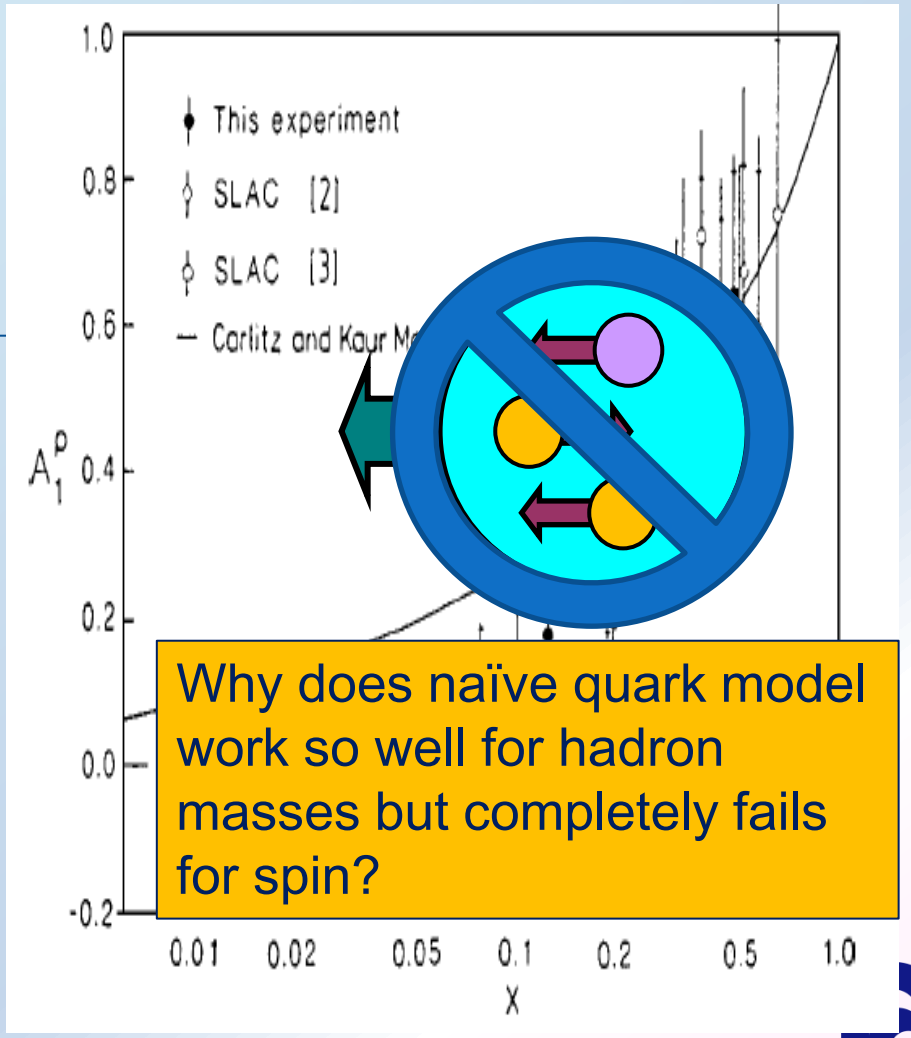
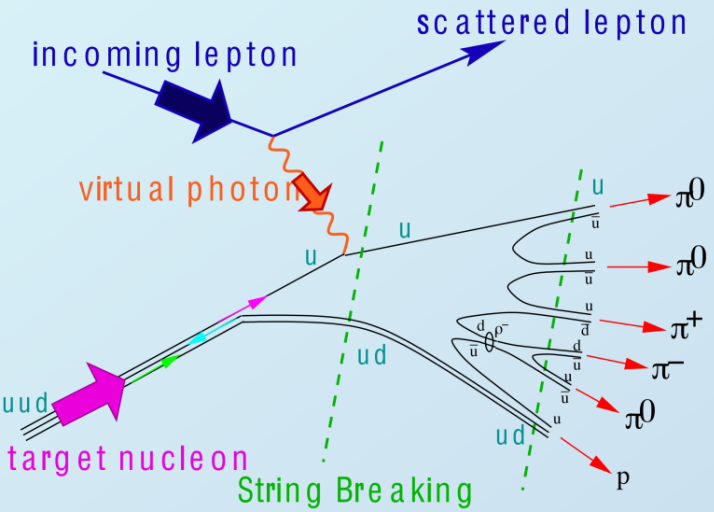
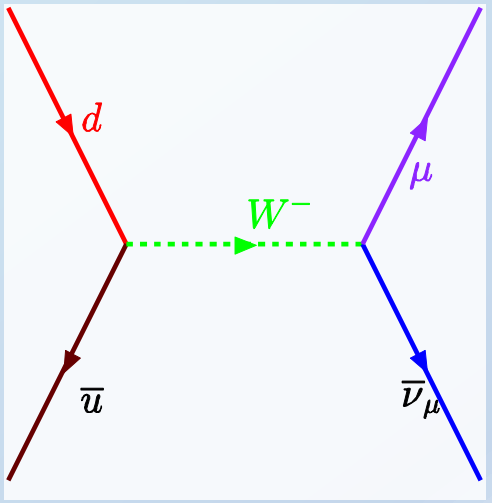


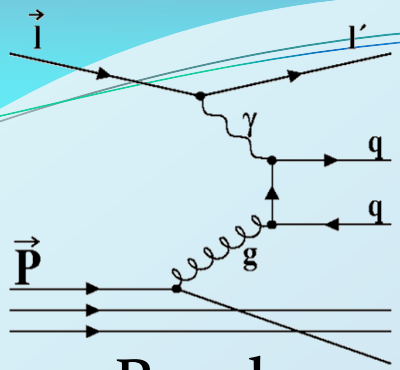
Flavor information via SIDIS and W production in pp





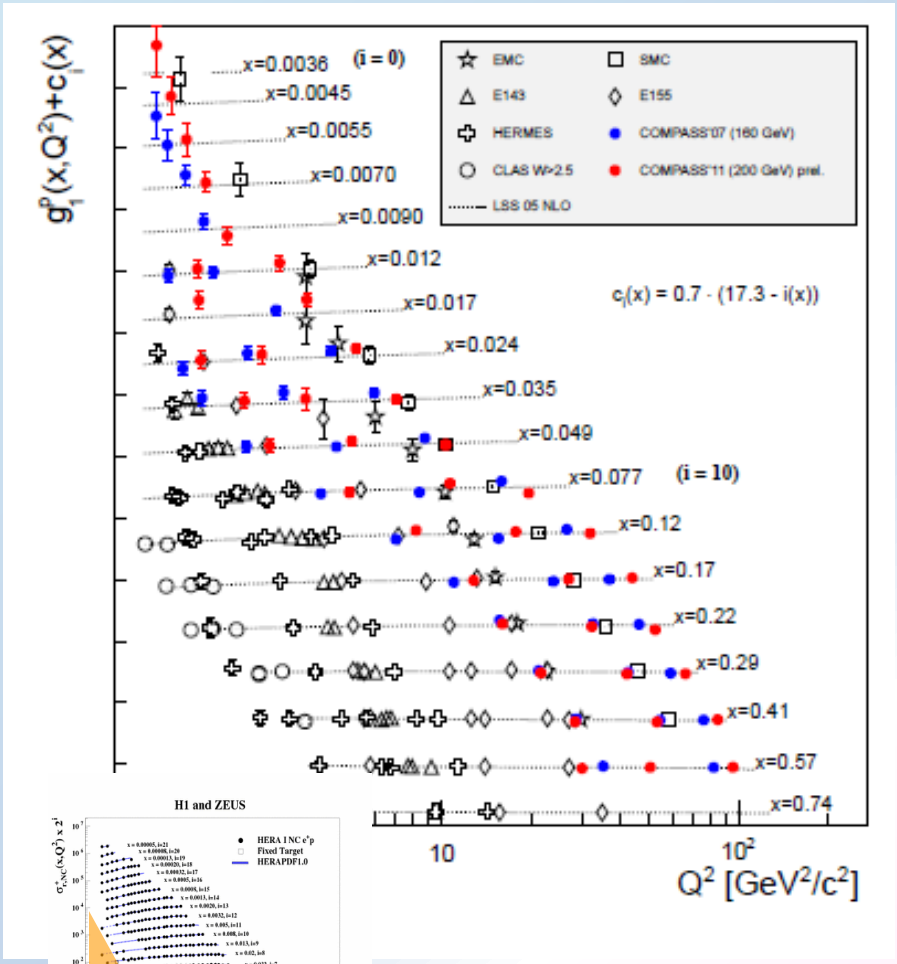
- Semi-inclusive DIS: detect at least one final state hadron
- Hadron type relates to initial parton via fragmentation functions

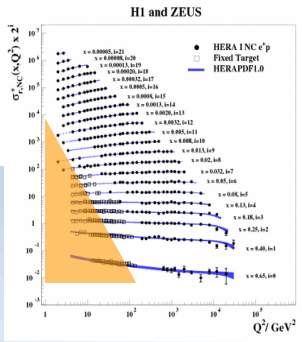
- W production in pp collisions selects participating quark and antiquark flavors and its helicity

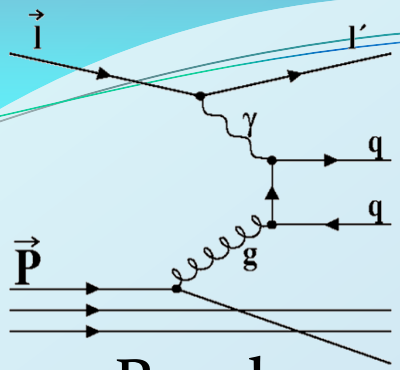


Gluon polarization

- Barely access via DIS data through DGLAP evolution (no high Q^2 data)
- Some access in SIDIS through high Pt hadrons and charmed mesons







Gluon polarization

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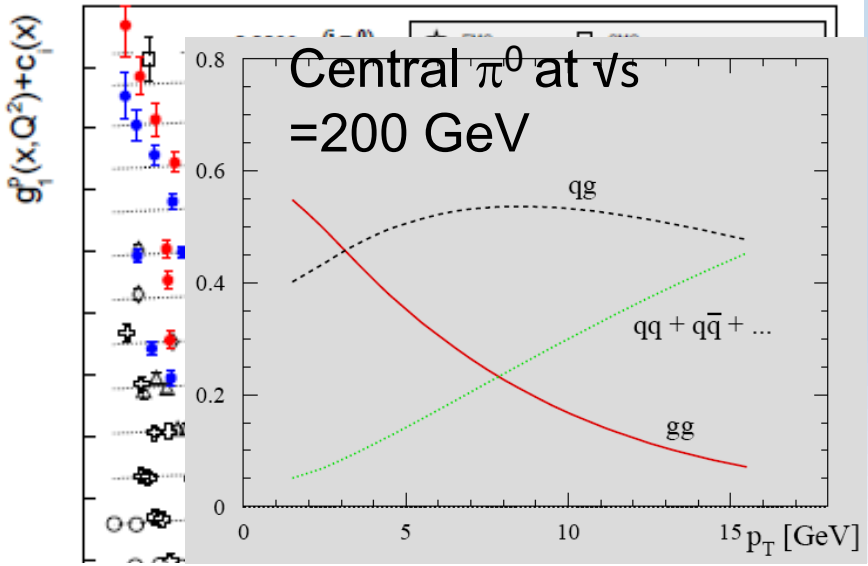
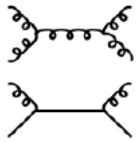
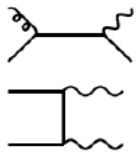
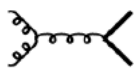
- Some access in SIDIS through high Pt hadrons and charmed mesons
- Polarized pp collisions at LO in α_S sensitive to gluons

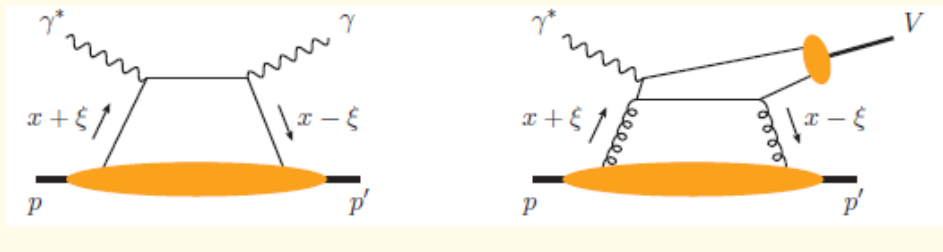


Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)
$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \text{jet}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

Orbital angular momentum (OAM)

- Some indications for its existence from magnetic moments of p and n, nonzeroness of Sivers function
- Ji sum rule allows access to J_q via exclusive reactions:

$$J^q = \frac{1}{2}\int dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$



- GPDs related to regular pdfs and form factors:

  $H \rightarrow$ q, $\tilde{H} \rightarrow \Delta$q for $\xi \rightarrow$ 0

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1^p(t)\,, \qquad \sum_q e_q \int dx\, E^q(x,\xi,t) = F_2^p(t)$$

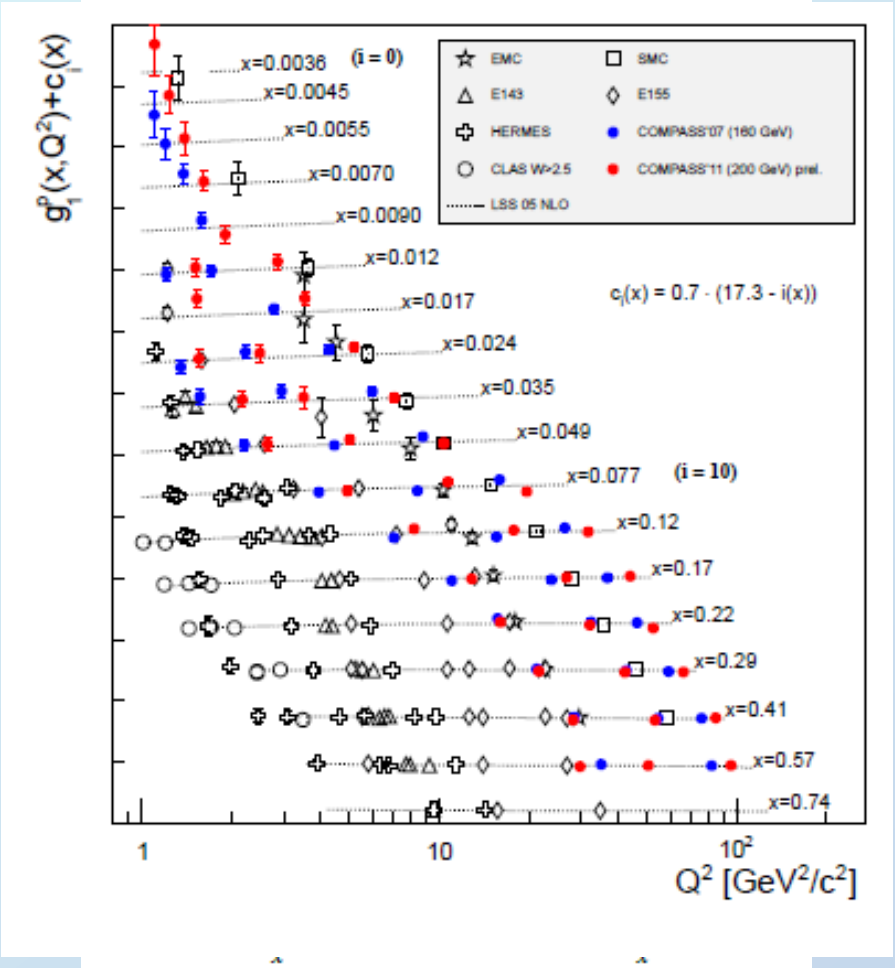
- Any access to gluon OAM only via Twist 3

t =(p' – p)^2 →FT of impact parameter → spatial structure

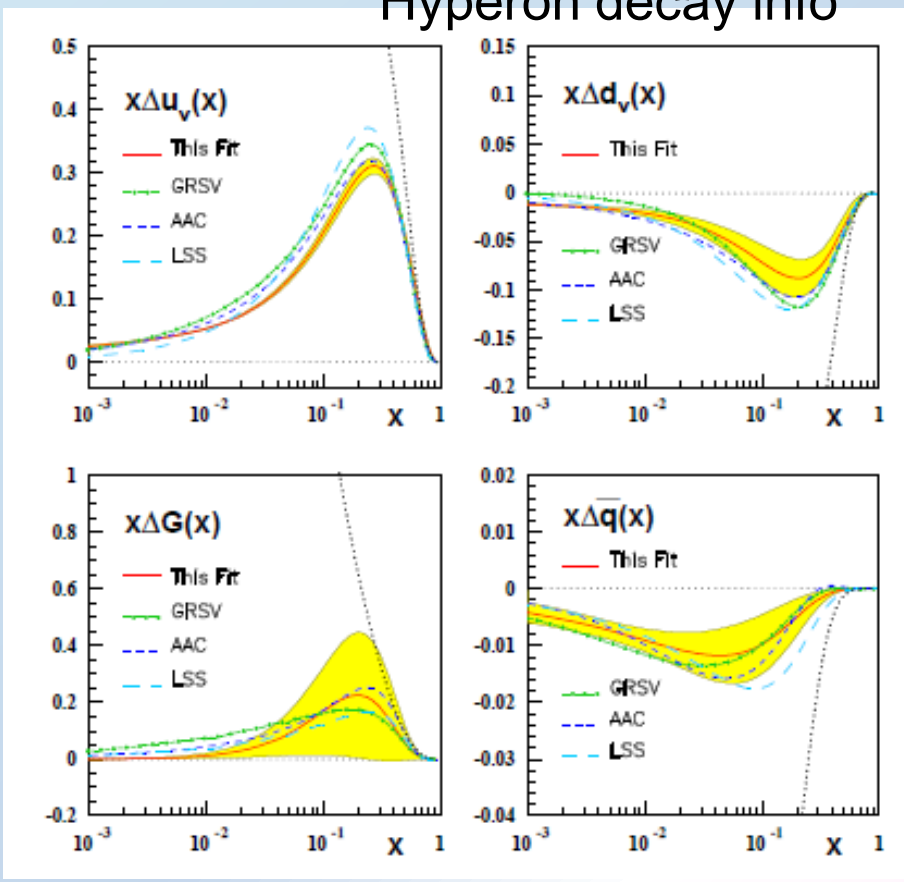
Current status

Current highlights: Quark helicities via inclusiv DIS fits

+ β decay and Hyperon decay info

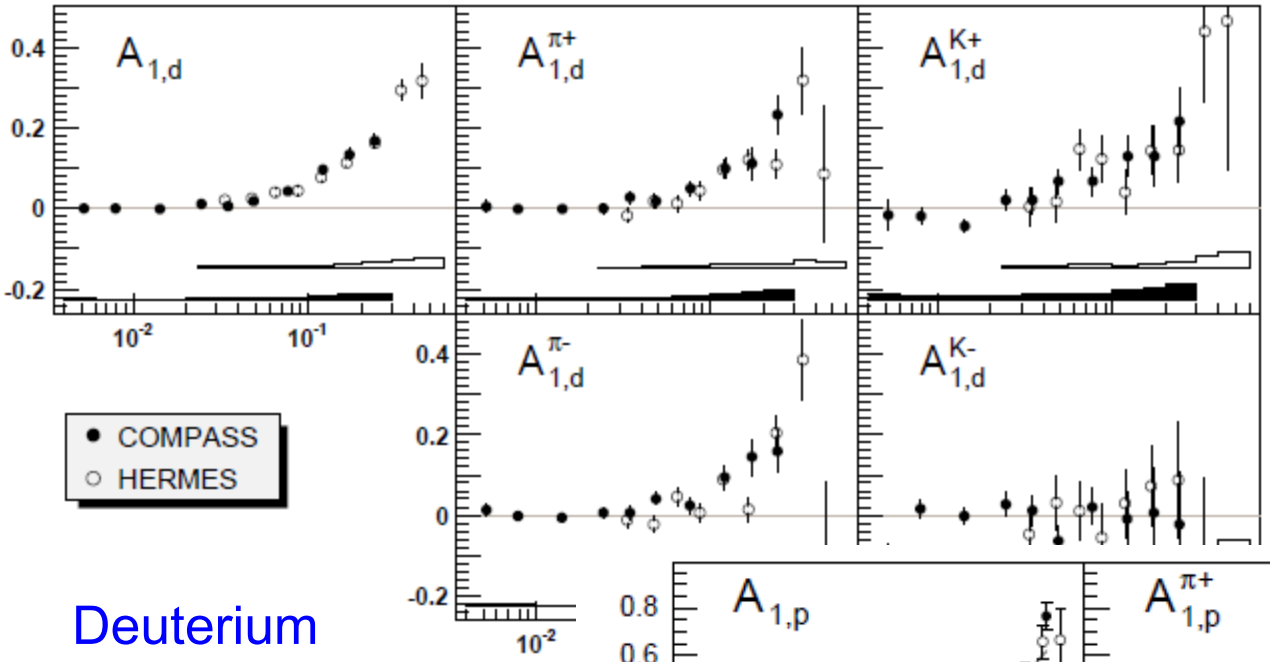


Jimenez et al, Phys.Rev. D89 (2014) 034025



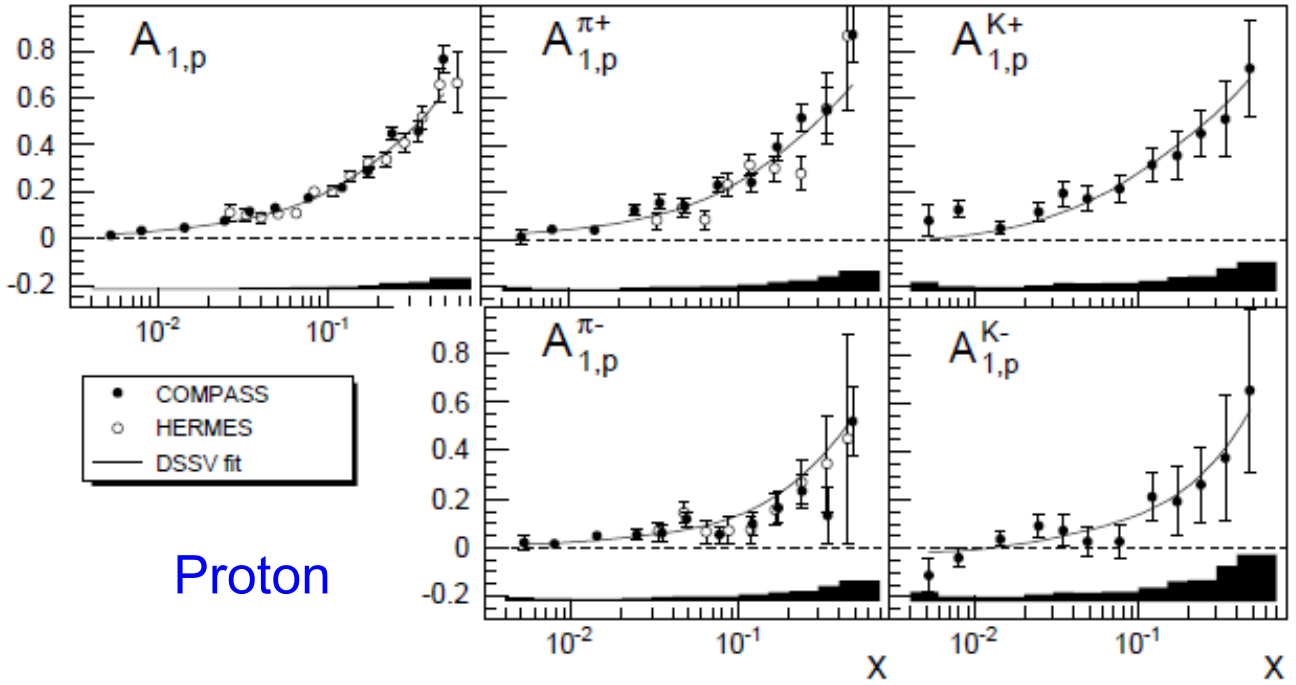
Bluemlein Boettcher 2010: Nucl.Phys. B841 (2010) 205-230

Current highlights: sea quark helicities



Deuterium

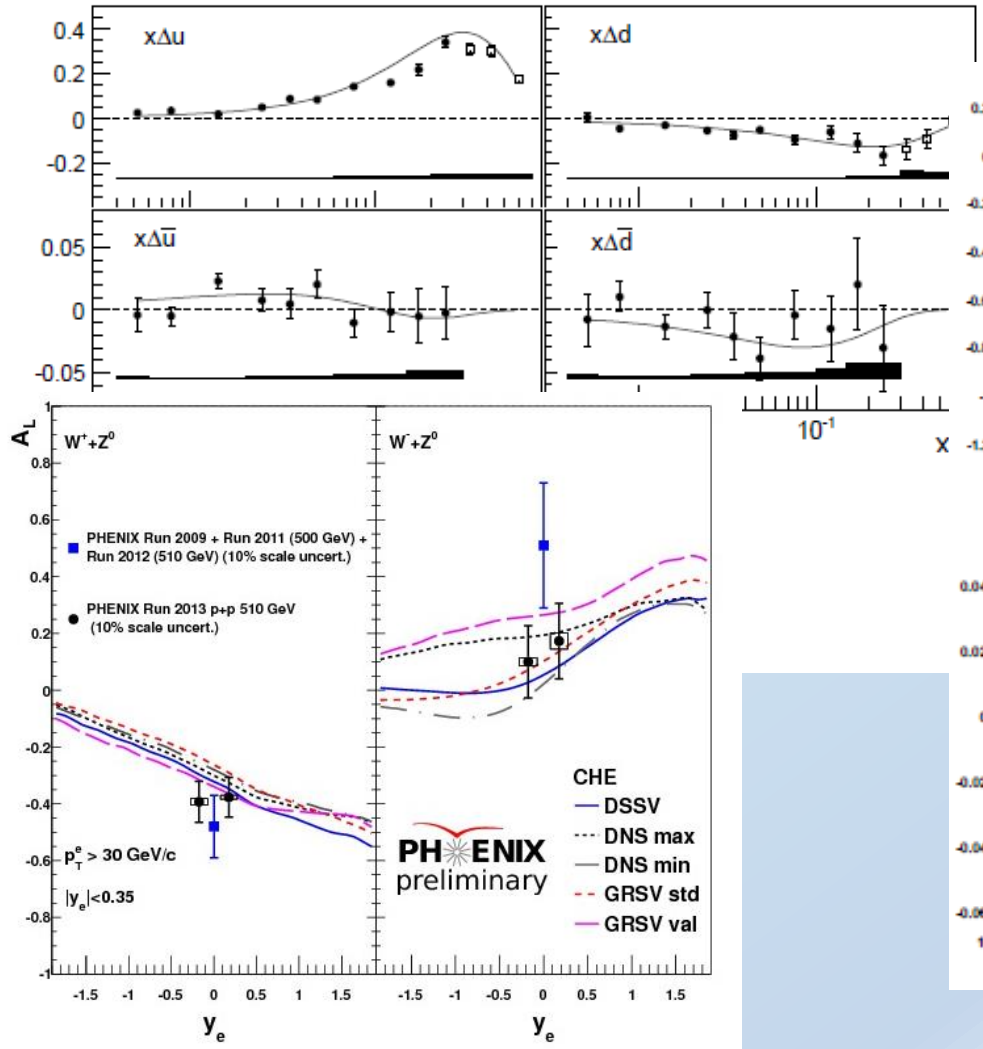
Phys.Lett. B680 (2009) 217-224



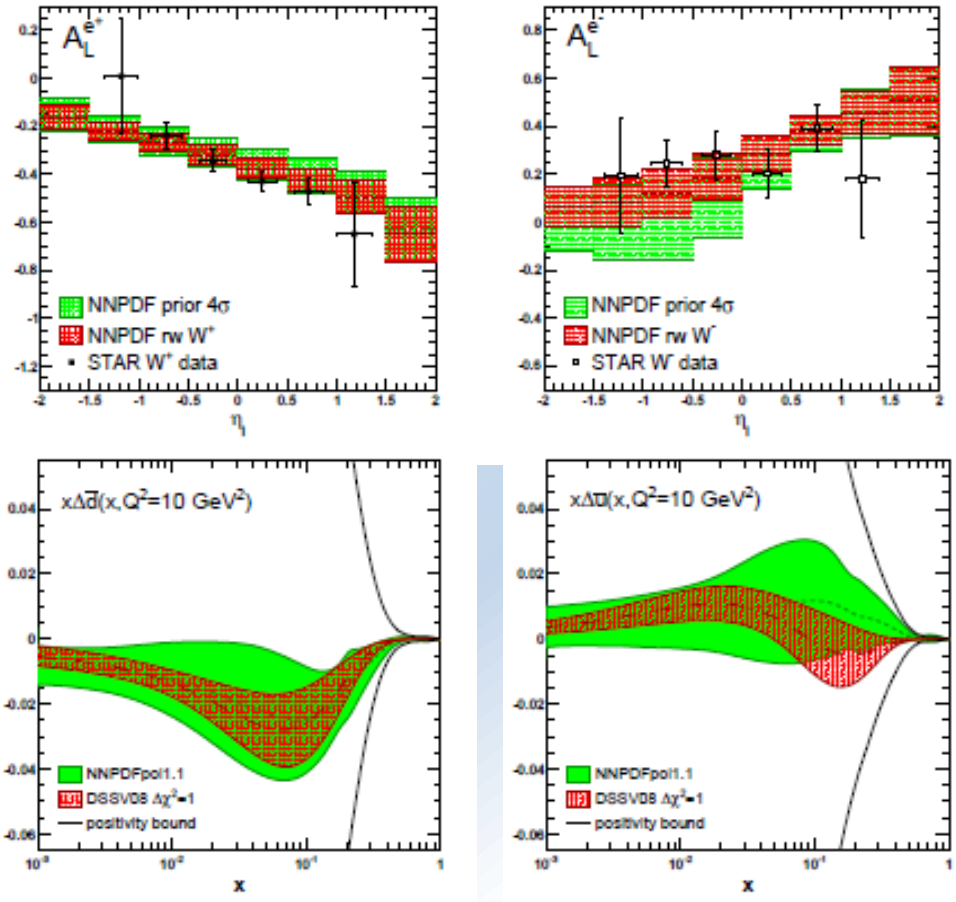
Proton

Phys.Lett. B690 (2010) 466-472

Current highlights: sea quark helicities



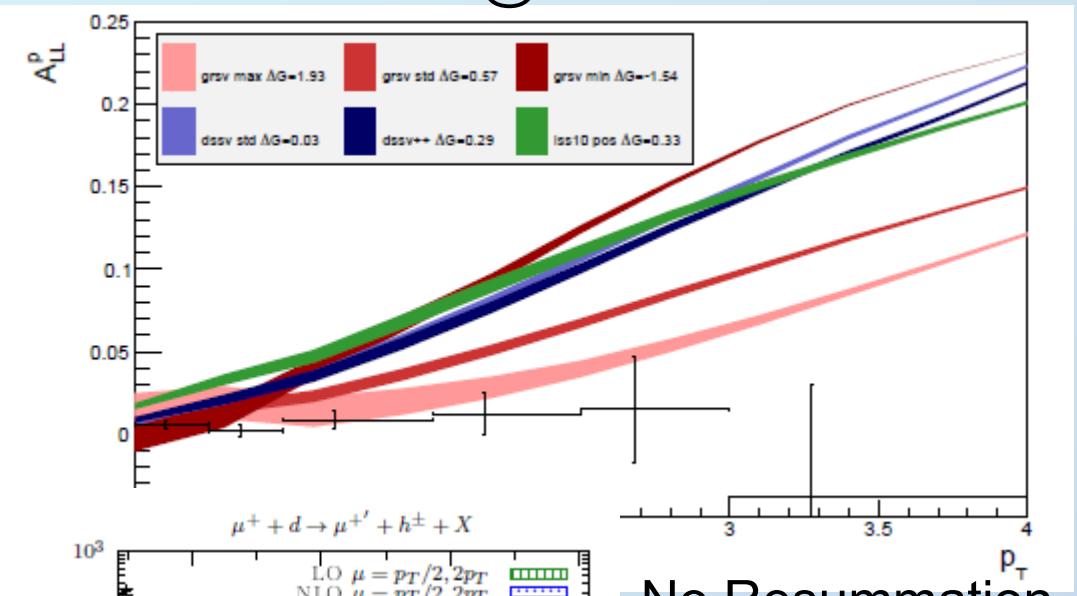
STAR: arXiv:1404.6880

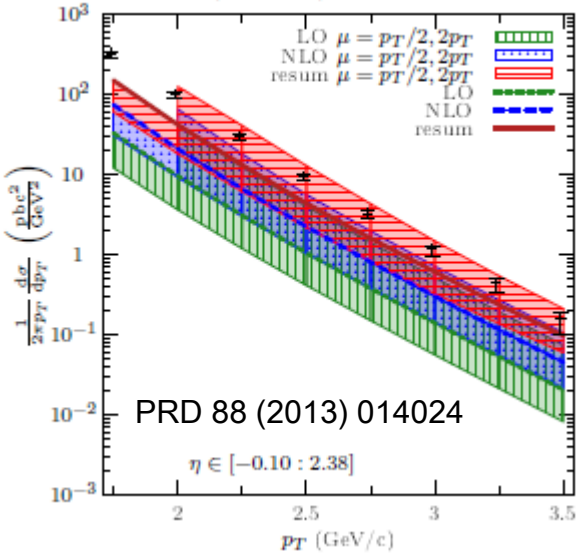


NNPDFpol1.1: E. Nocera et al.. Jun 20, 2014.
e-Print: arXiv:1406.5539

Current highlights: gluon helicities

Levillain@DIS2014

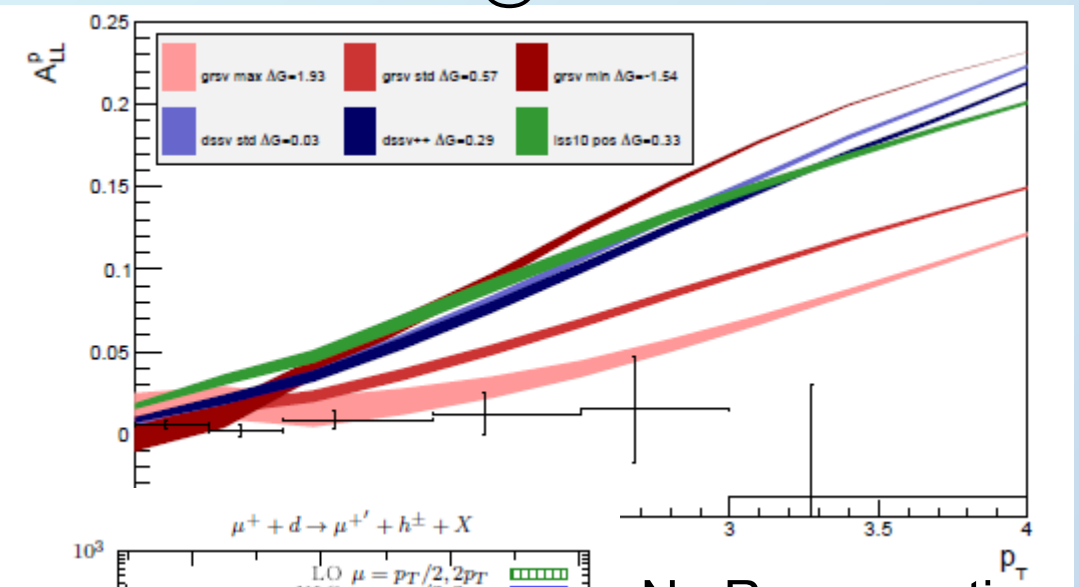


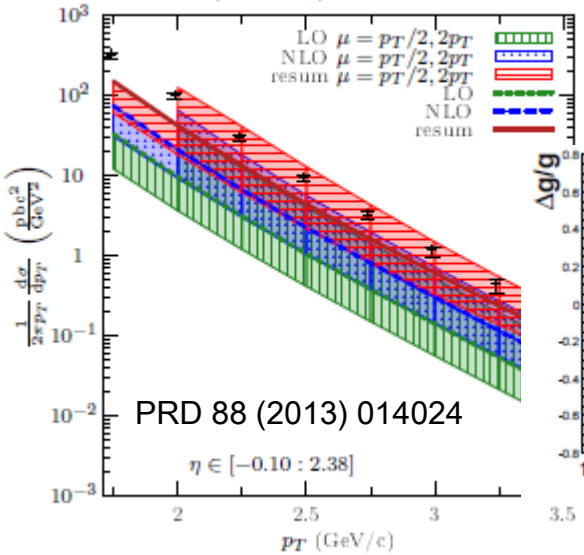


No Resummation taken into account

Current highlights: gluon helicities

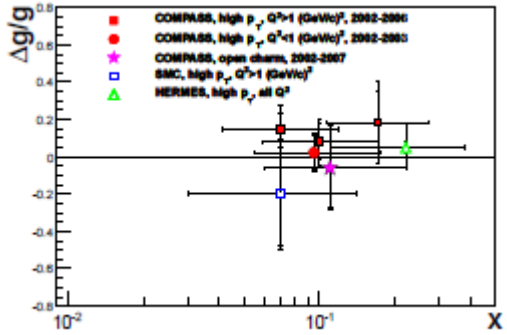
Levillain@DIS2014

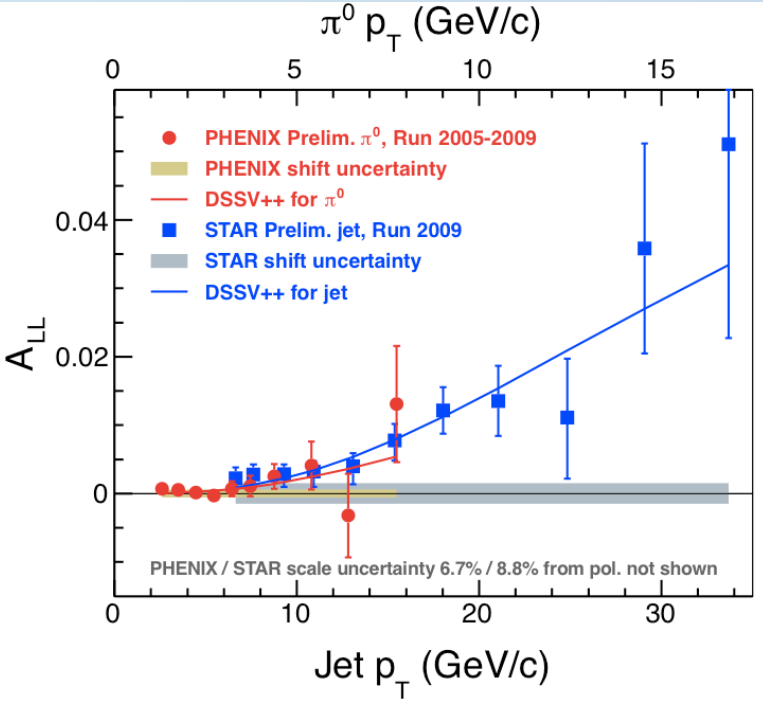




PRD 88 (2013) 014024

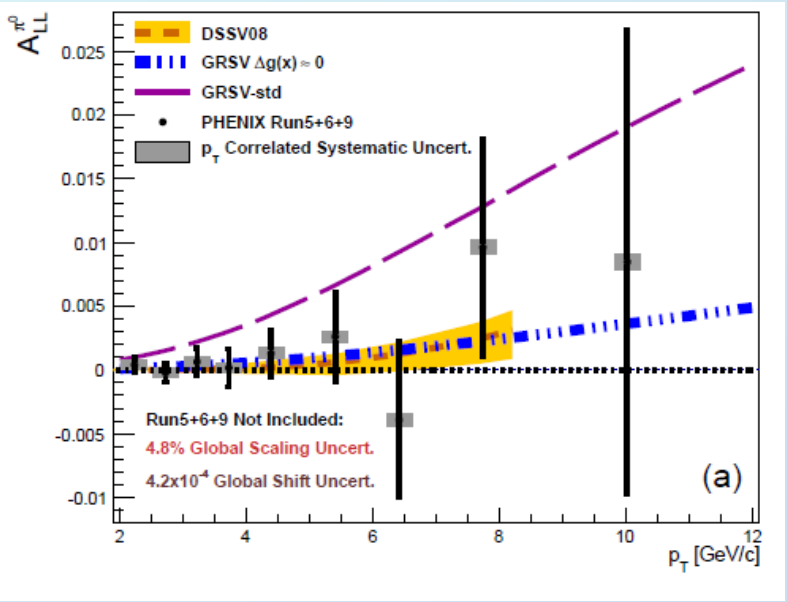
No Resummation taken into account





- PHENIX: Phys.Rev. D90 (2014) 012007
- STAR: arXiv:1405.5134
- DSSV:Phys.Rev.Lett. 113 (2014) 012001

Final 2009 RHIC ALL results



- +various other published results such as charged pion ALLs, η ALL, HF electron ALL

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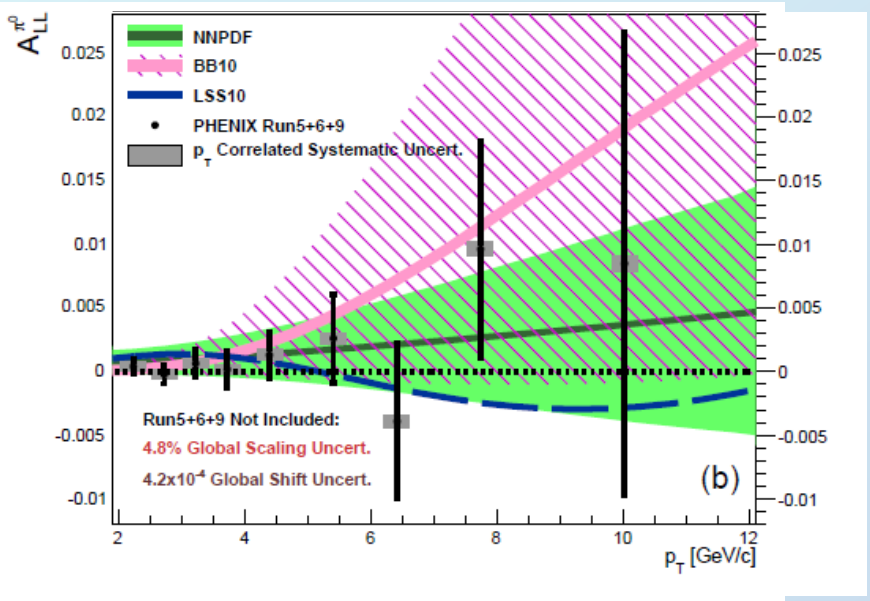

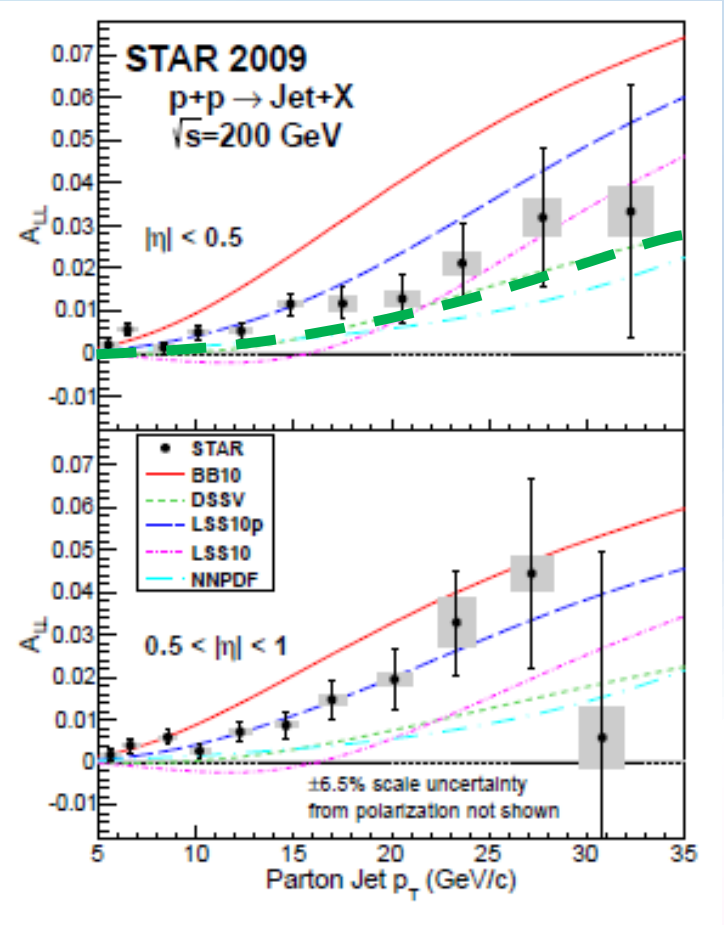

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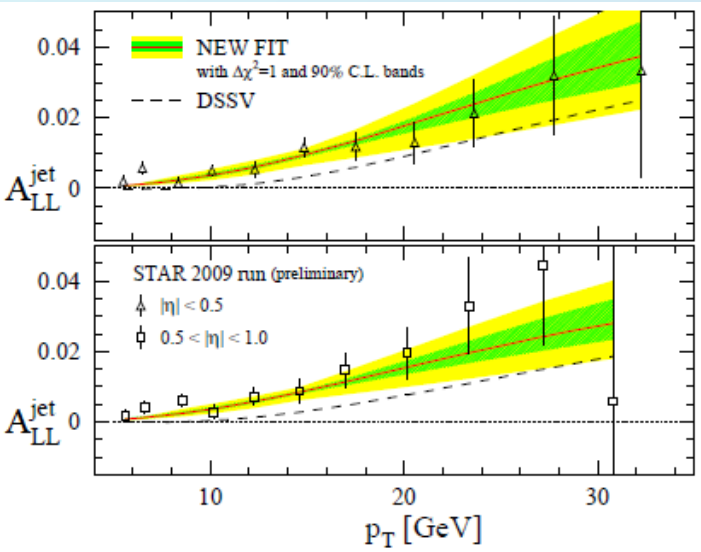
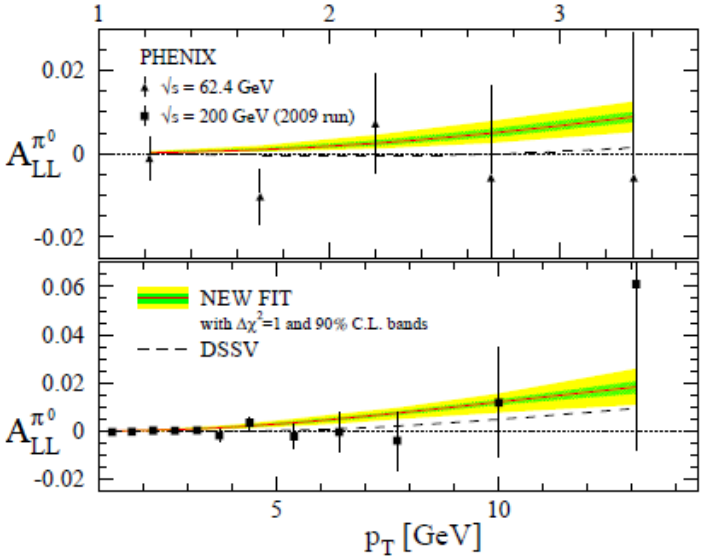
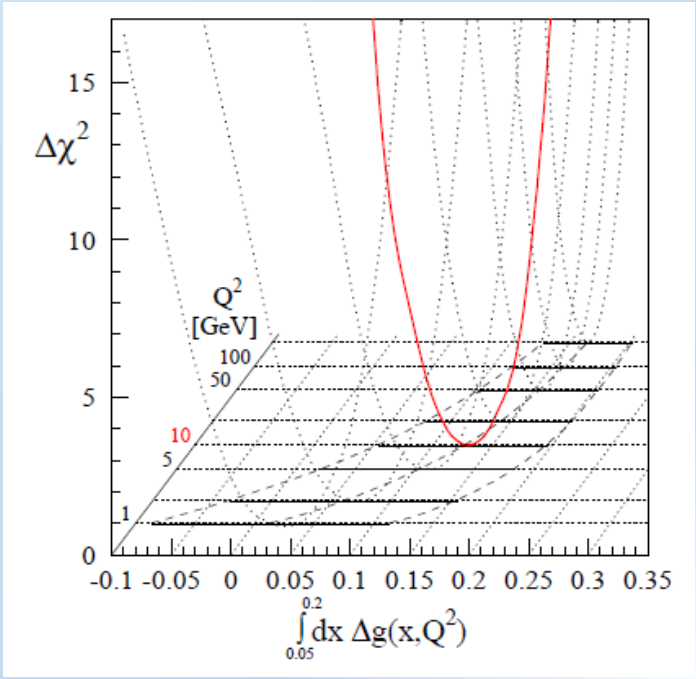
DSSV++





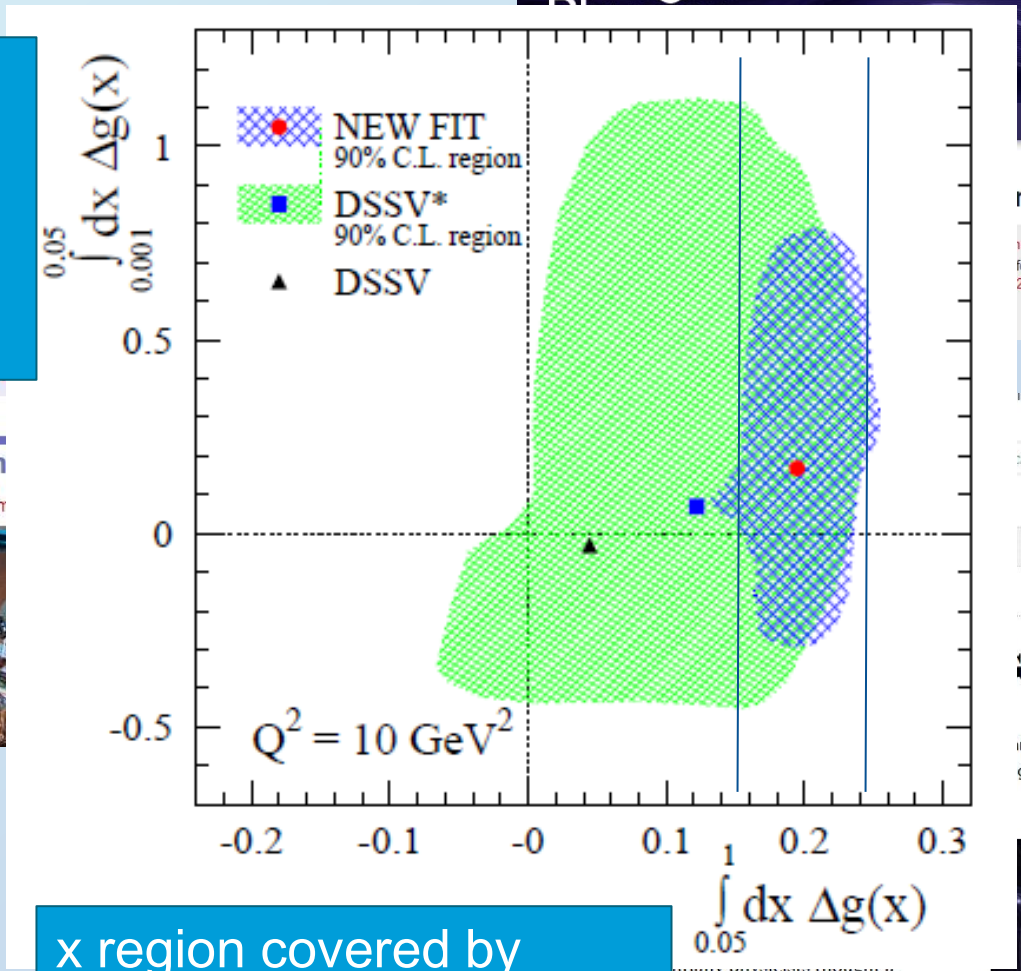


- Pions at slightly smaller x
- and smaller Pt → Δg smaller due to evolution

- DSSV:Phys.Rev.Lett. 113 (2014) 012001 (but still using preliminary data!)

Press interest

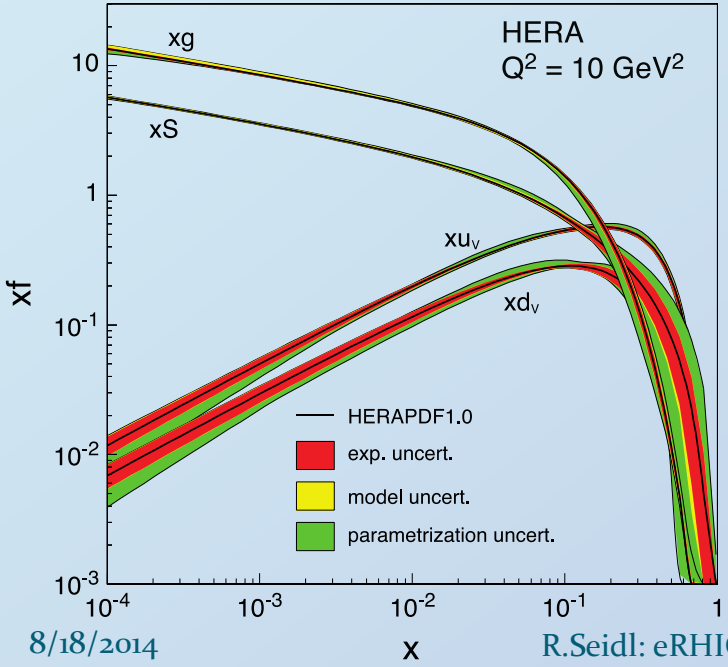
Low x, not covered so far →more forward pp, EIC

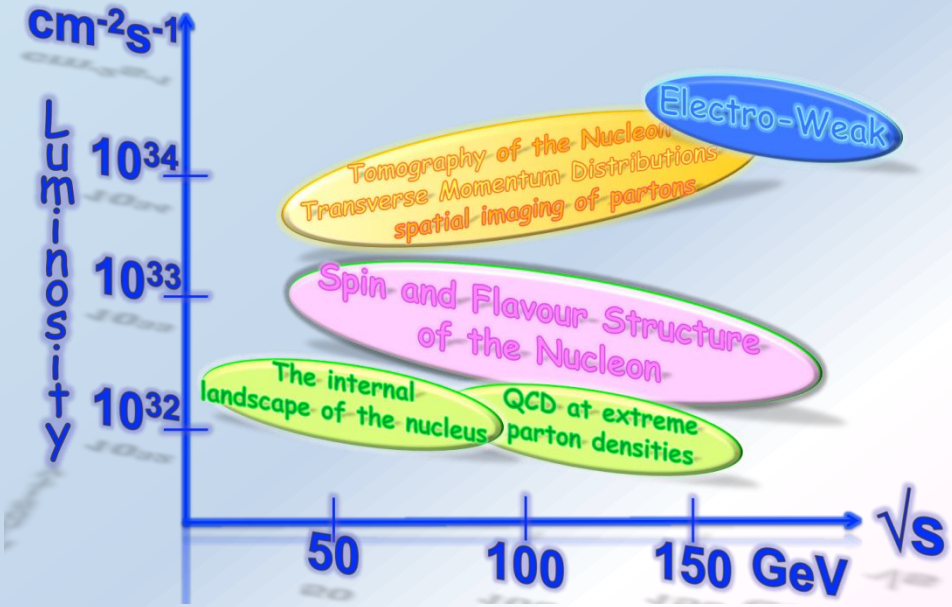


x region covered by current RHIC and DIS results

Electron Ion Collider

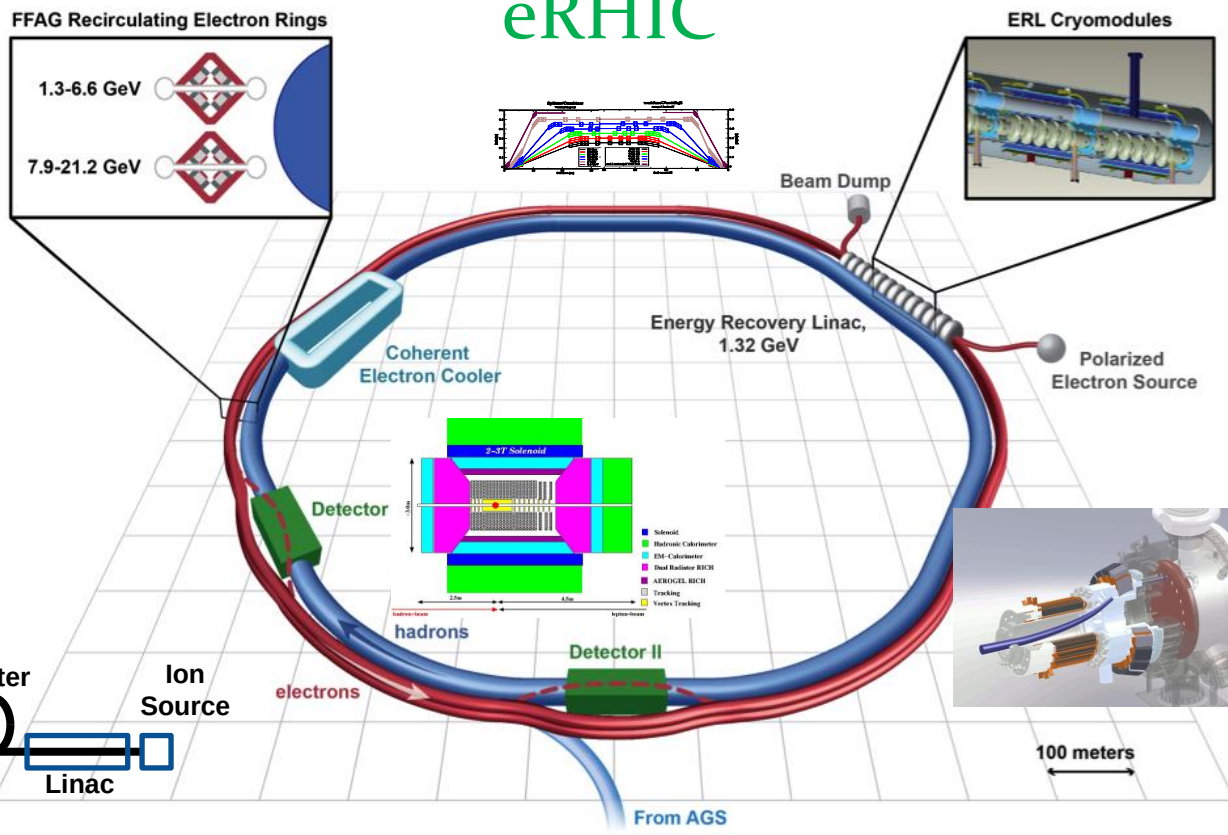
Many slides taken from: EIC INT paper, white paper and presentations by V. Litvinenko, E. Aschenauer and others



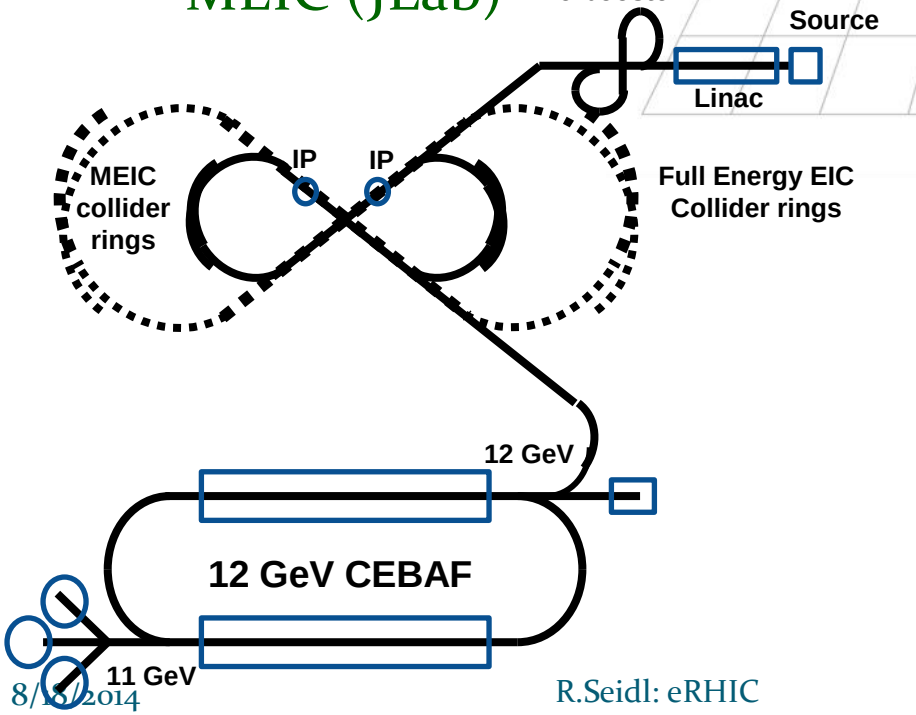


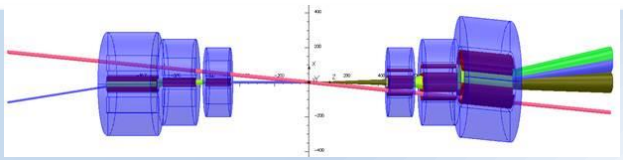
US EIC proposals

eRHIC



MEIC (JLab)

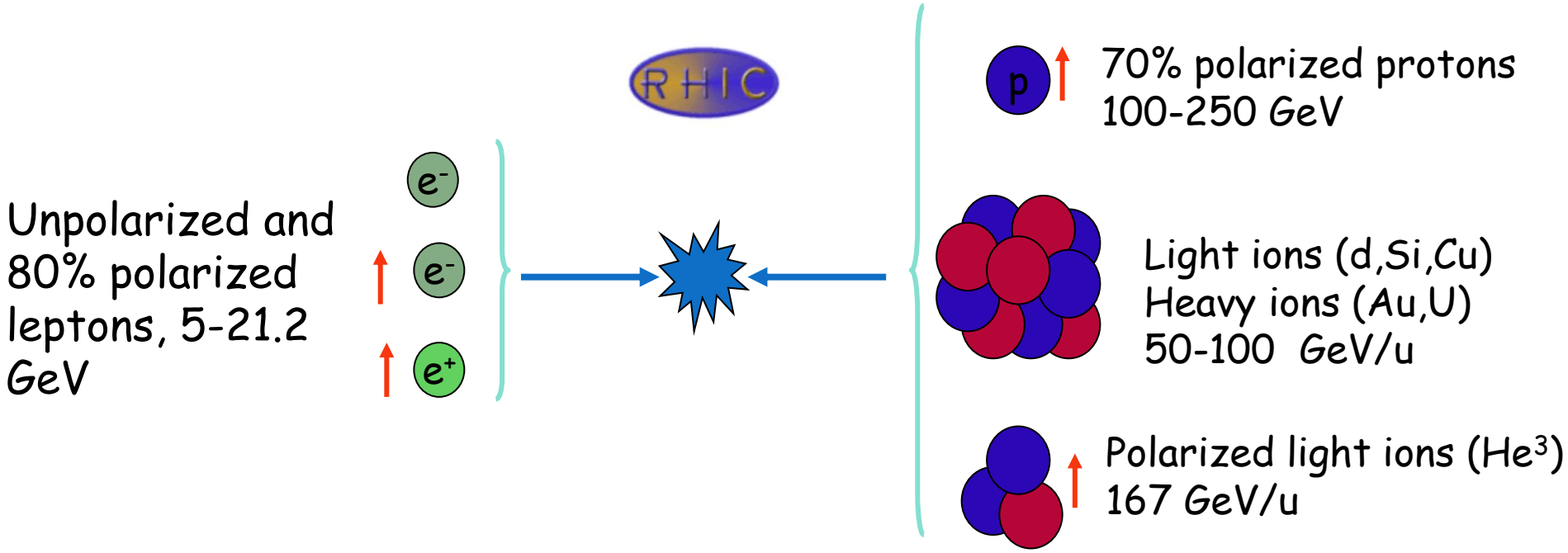




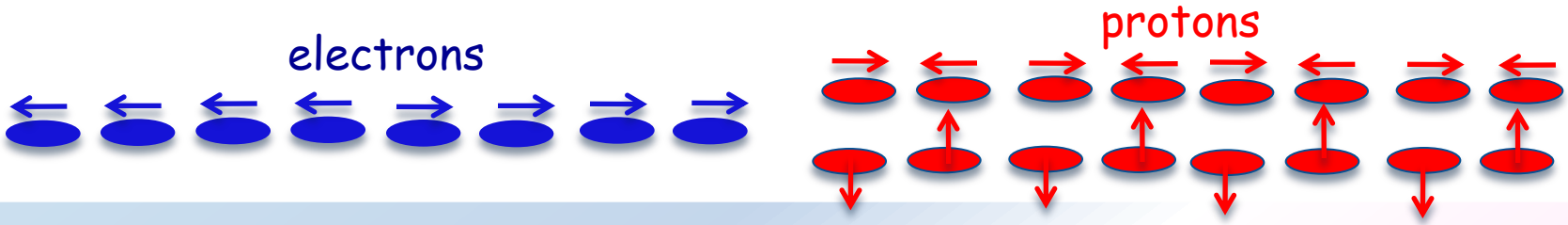
- Today:

  concentrate on eRHIC

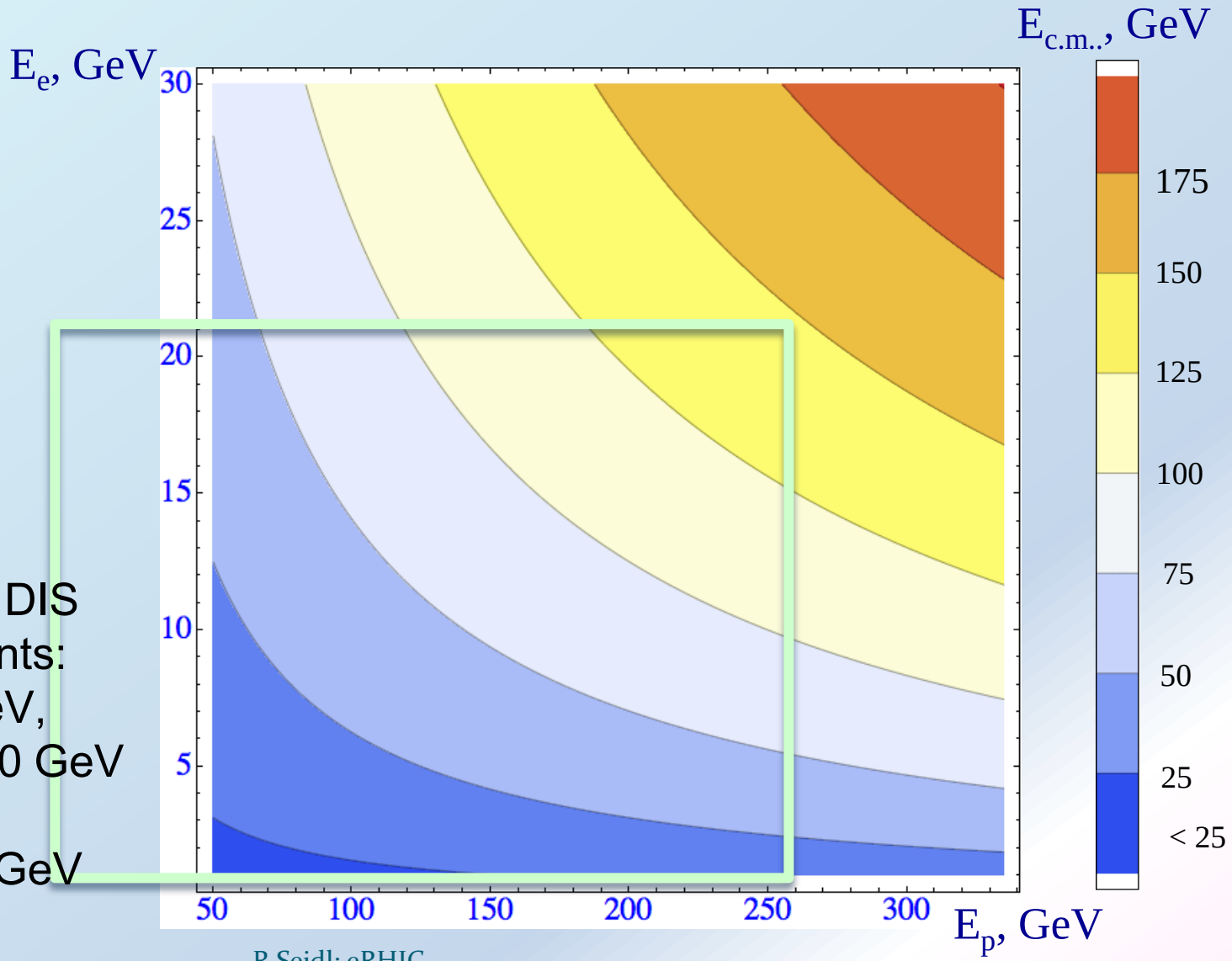
Add electron accelerator to the existing $2B RHIC



Center of mass energy range: 30-145 GeV
Any polarization direction in lepton-hadrons collisions



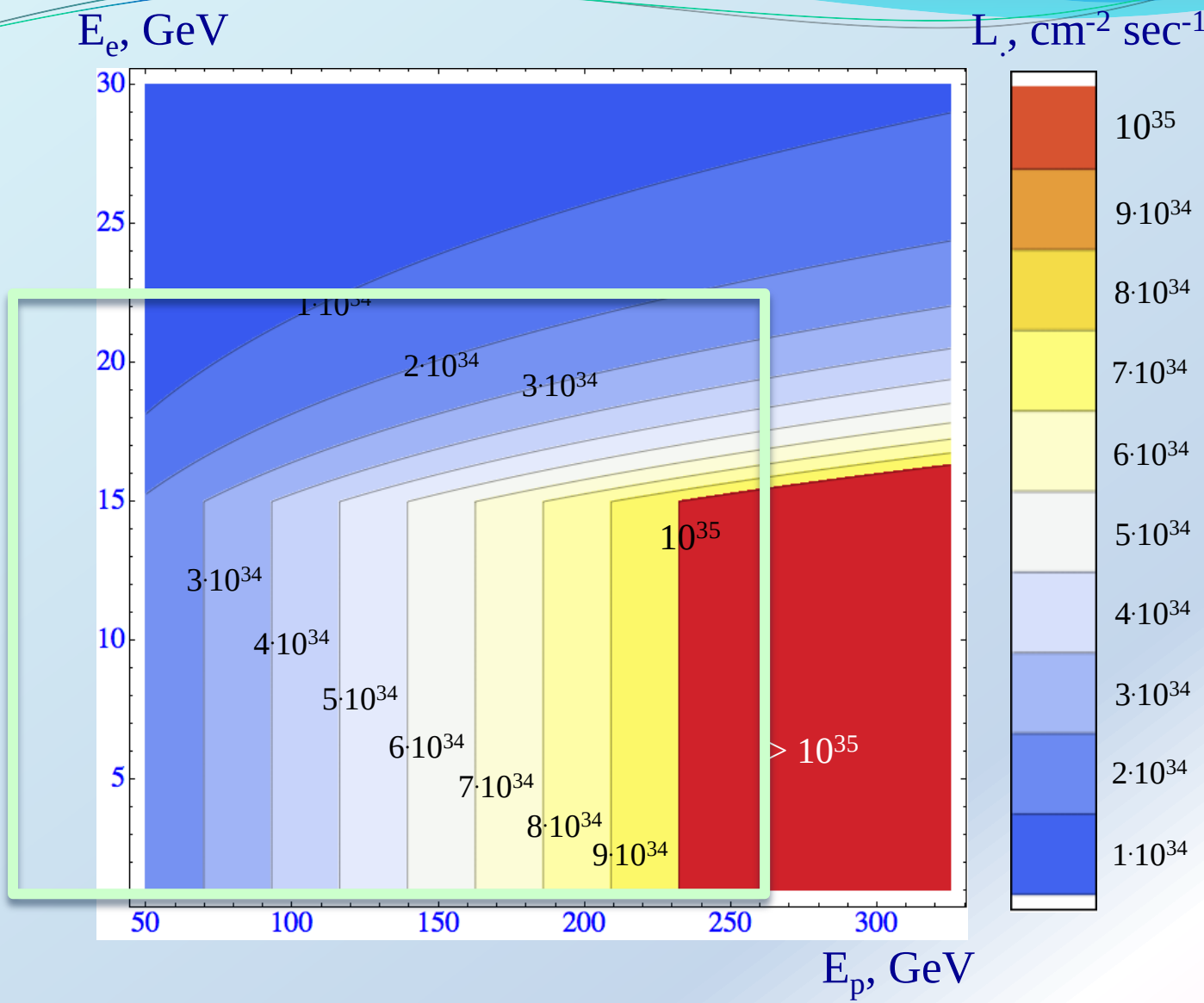
Center of mass energy



Current polarized DIS experiments:
E_p = 1 GeV,
E_e = 5-200 GeV

E_{cm} < 20 GeV

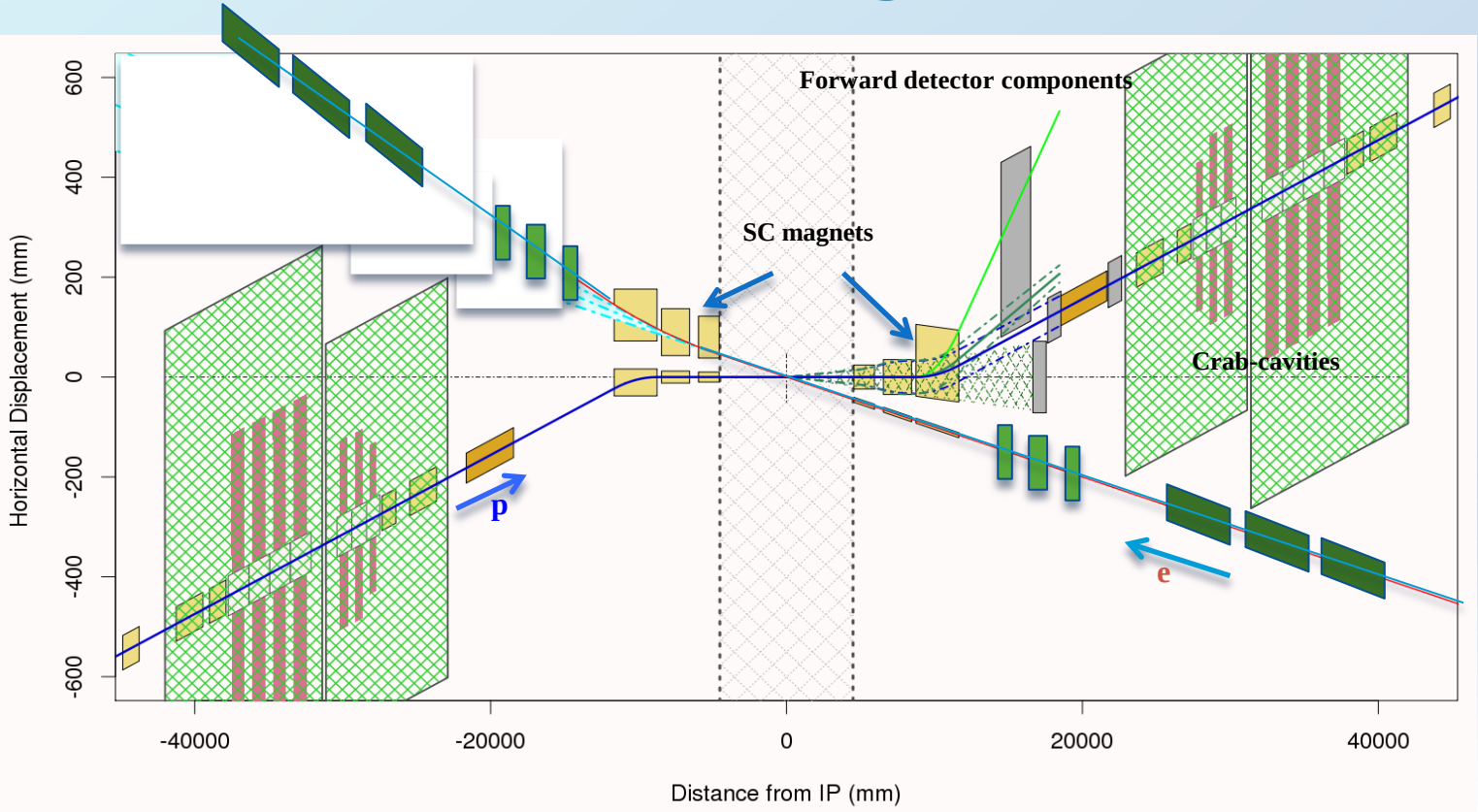
Ultimate eRHIC luminosity as function of beam energies



The box shows eRHIC reach in energy with current FFAG arc design from day one

RIKEN

IR design



- Try to remove most synchrotron radiation in the IR region by little bending (far away) before collision and crossing angle of 10mrad

EIC key mesurements (Helicity)

Deliverables	Observables	What we learn	Requirements
polarized gluon distribution Δg	scaling violations in inclusive DIS	gluon contribution to proton spin	coverage down to $x \simeq 10^{-4}$; $\mathcal{L}$ of about 10 fb^{-1}
polarized quark and antiquark densities	semi-incl. DIS for pions and kaons	quark contr. to proton spin; asym. like $\Delta\bar{u} - \Delta\bar{d}$; Δs	similar to DIS; good particle ID
novel electroweak spin structure functions	inclusive DIS at high Q^2	flavor separation at medium x and large Q^2	$\sqrt{s} \geq 100$ GeV; $\mathcal{L} \geq 10$ fb^{-1} positrons; polarized d or ^{3}He beam

EIC key mesurements (Helicity)

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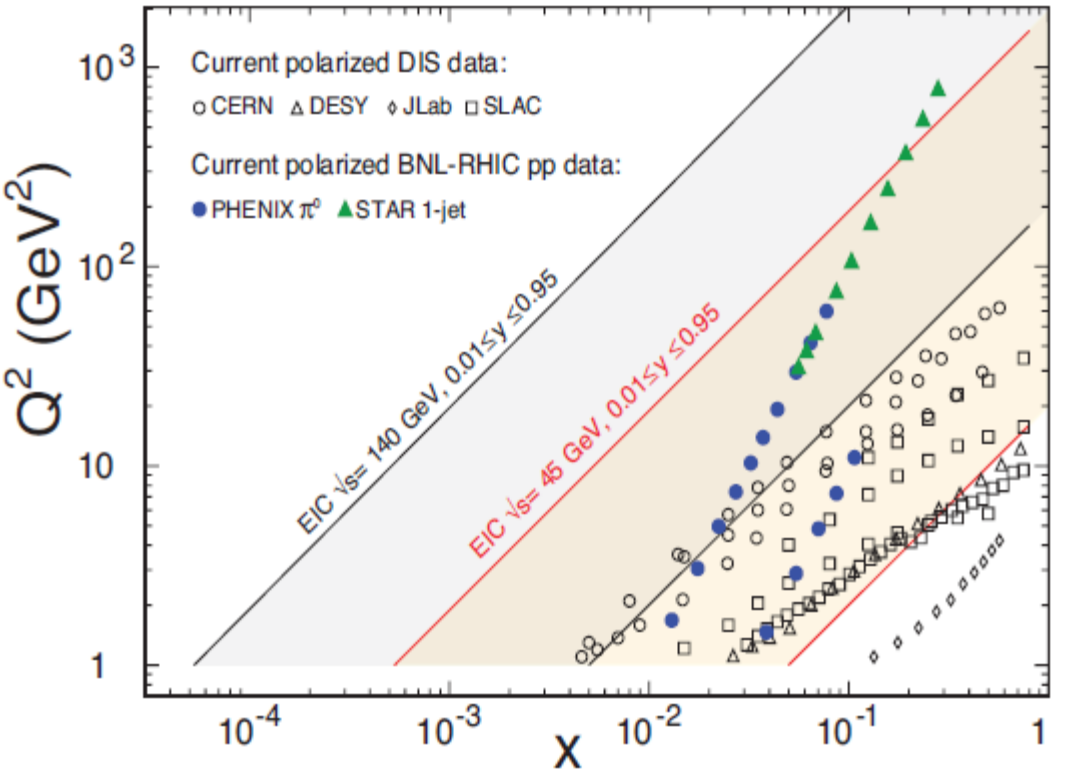
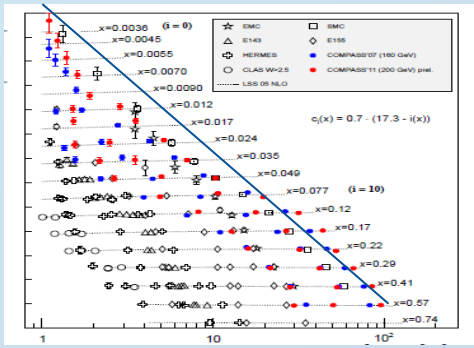
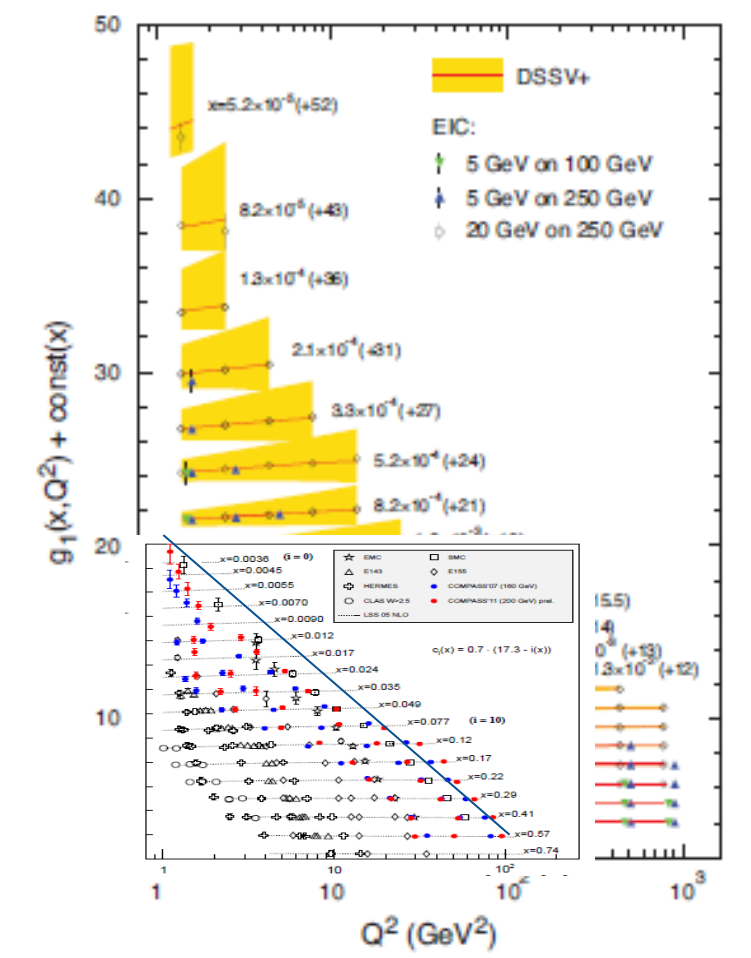


Inclusive DIS



- Several orders of magnitude of Q^2 at same x allows to determine gluon helicity via DGLAP evolution
- Inclusive DIS is certainly not statistics limited
- Main systematics expected from y reconstruction

Inclusive DIS



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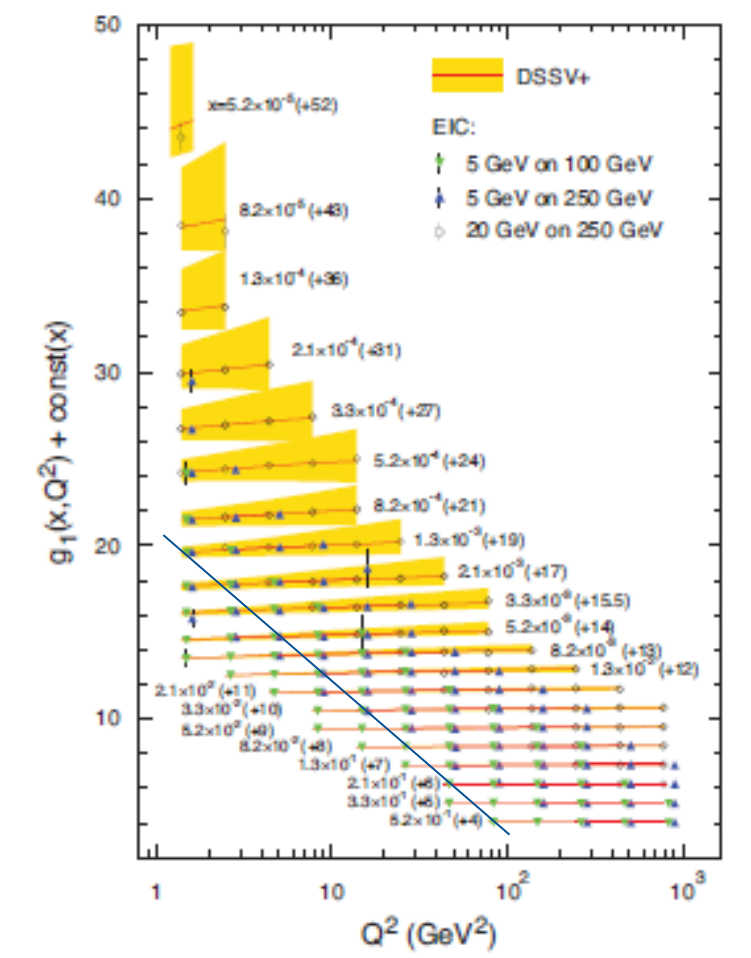

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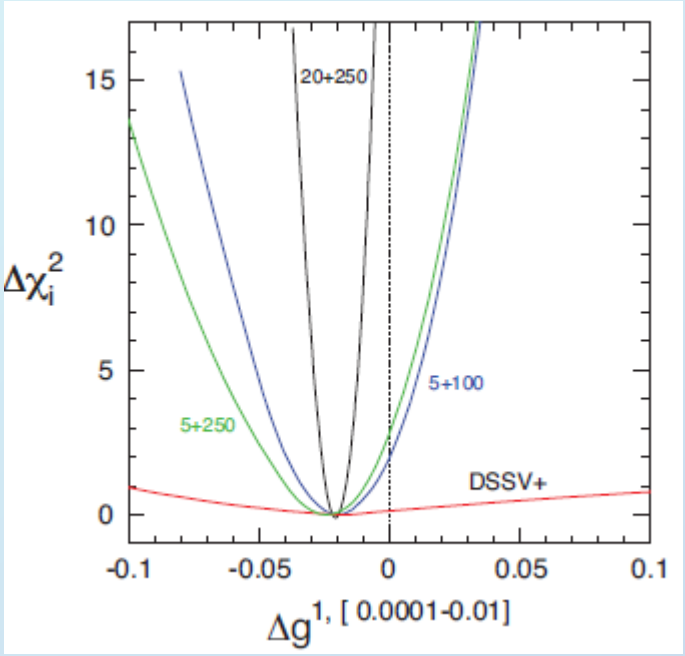
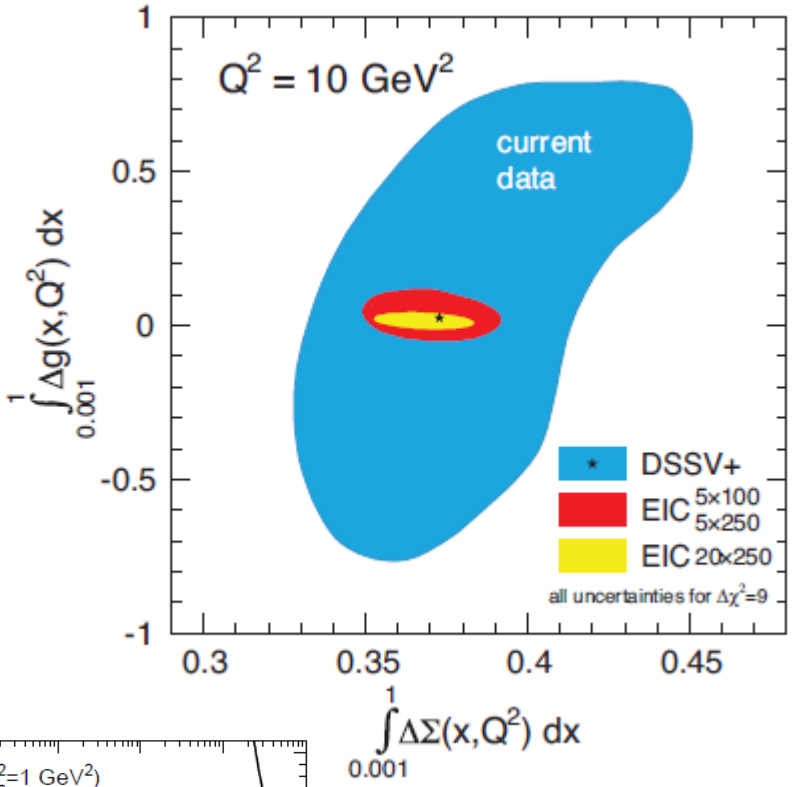
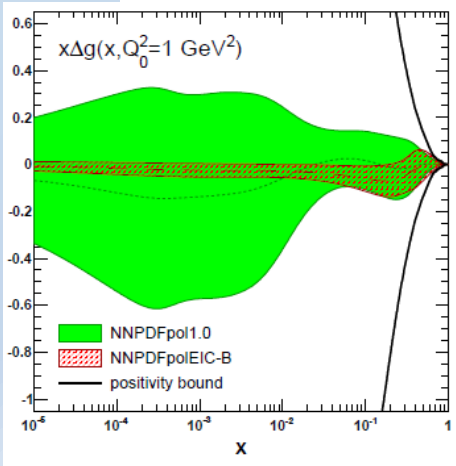
Gluon polarization

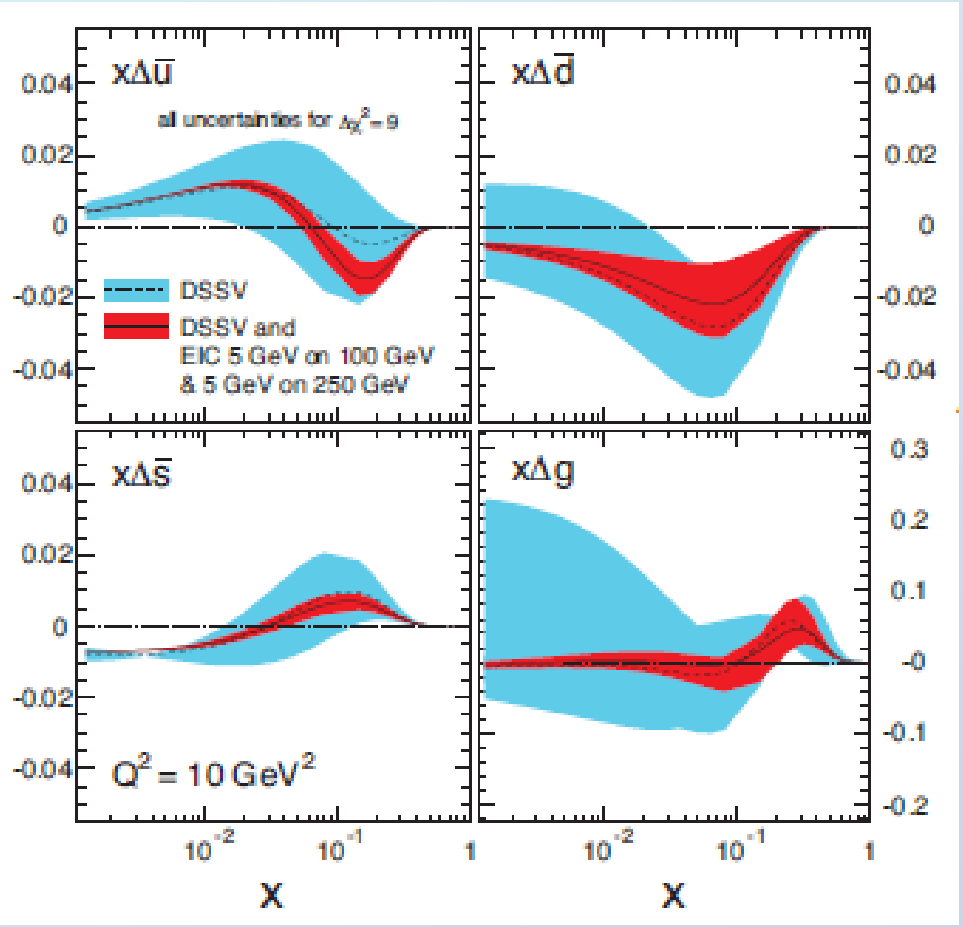




- 1 year of EIC running will pin down gluon polarization

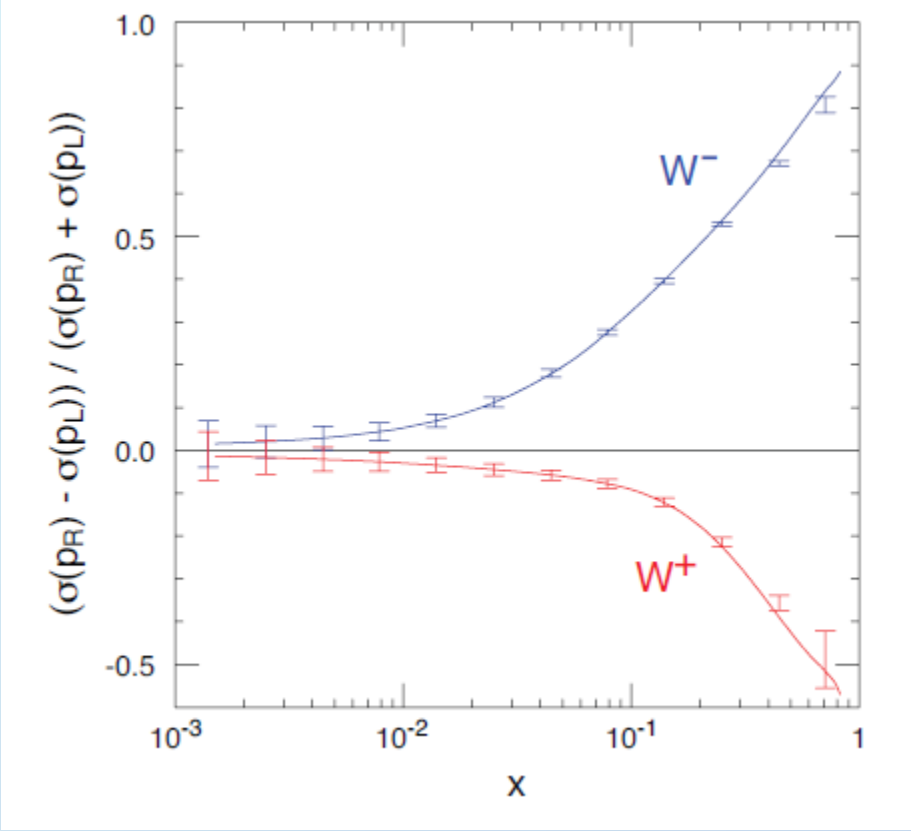


Sea quarks



- Answer questions whether light quark sea is really symmetric or not
- Resolve strange helicity puzzle (or shoot down $SU(3)_f$ applicability from hyperon decays)

CC DIS

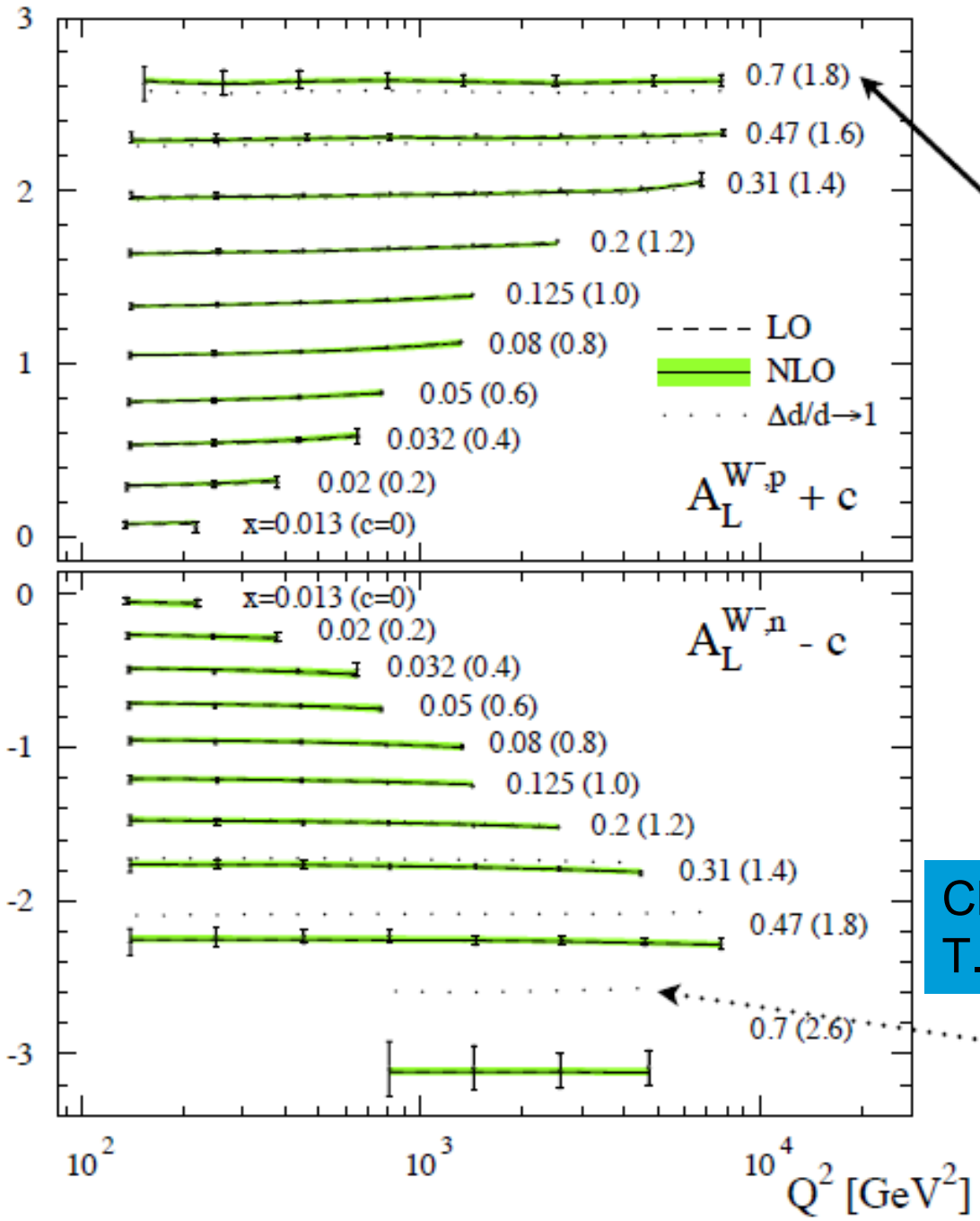


$$g_1^{W^-}(x,Q^2) = \left[\Delta u + \Delta\bar{d} + \Delta c + \Delta\bar{s}\right](x,Q^2)\,,$$
$$g_5^{W^-}(x,Q^2) = \left[-\Delta u + \Delta\bar{d} - \Delta c + \Delta\bar{s}\right](x,Q^2)\,,$$

- Gain even more flavor sensitivity with the weak interaction:

$$e\,\vec{p} \rightarrow \nu_e X$$

A_L^W results

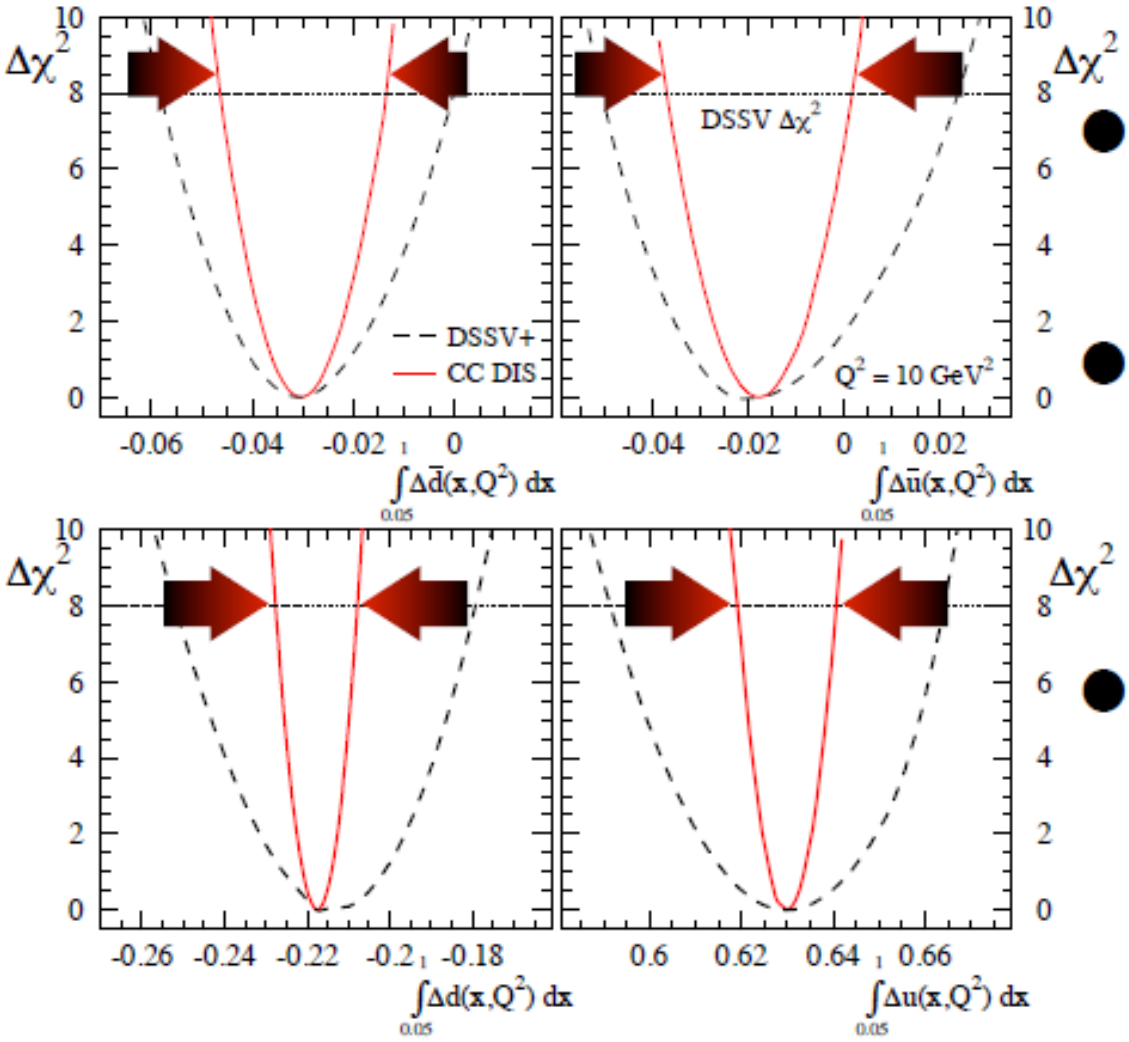


- Large A_L^W at large x ~80%
- NLO effects small
- $\sigma(A_L^W)/A_L^W$ small
  - <~5% for **p**
  - <~8% for **n**

Charged current DIS at an EIC; T. Burton at DIS2014

- Sensitive to "helicity retention"

Impact on global analyses



- Constrain **u**, **d** & **anti-q** helicities
- Flavour constraint independent of **fragmentation**
- Important cross check on **SIDIS**
  - low Q^2, higher twist effects

Charged current DIS at an EIC;
T. Burton at DIS2014

Sivers function and 3D momentum structure

Deliverables	Observables	What we learn	Stage I	Stage II
Sivers & unpolarized TMD quarks and gluon	SIDIS with Transverse polarization; di-hadron (di-jet)	Quantum Interference & Spin-Orbital correlations	3D Imaging of quarks valence+sea	3D Imaging of quarks & gluon; Q^2 (P_{hT}) range QCD dynamics
Chiral-odd functions: Transversity; Boer-Mulders	SIDIS with Transverse polarization	3rd basic quark PDF; novel hadronization effects	valence+sea quarks	Q^2 (P_{hT}) range for detailed QCD dynamics

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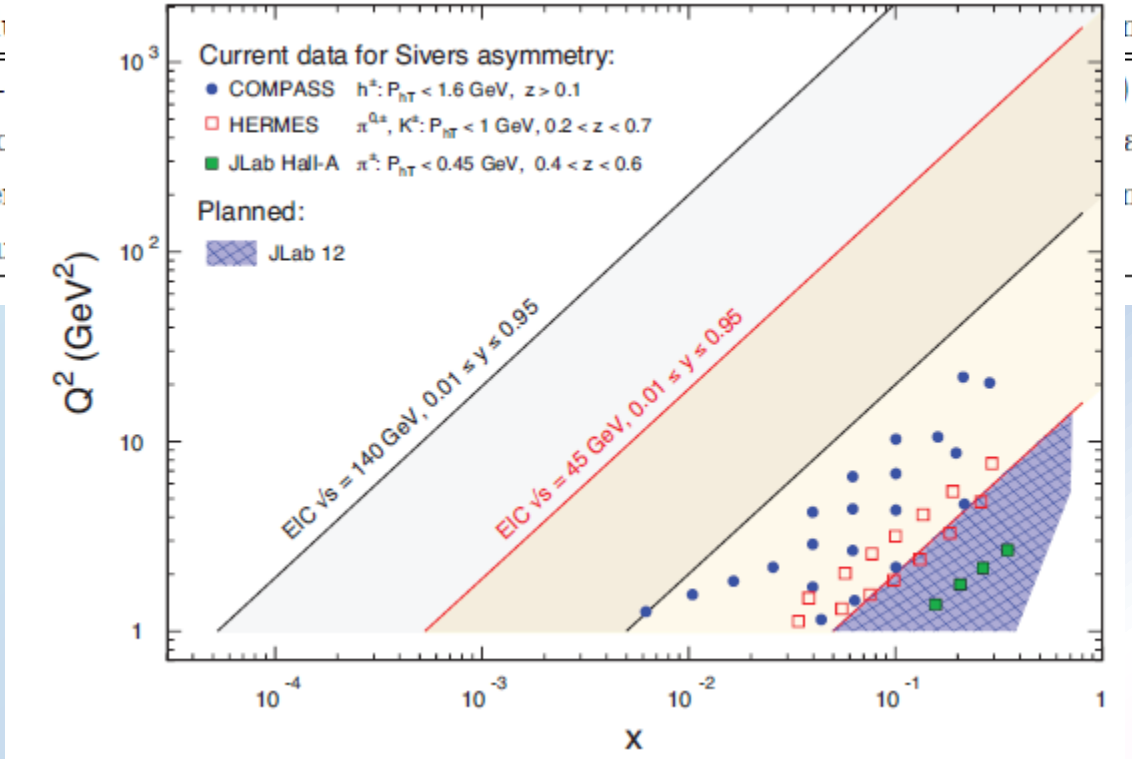
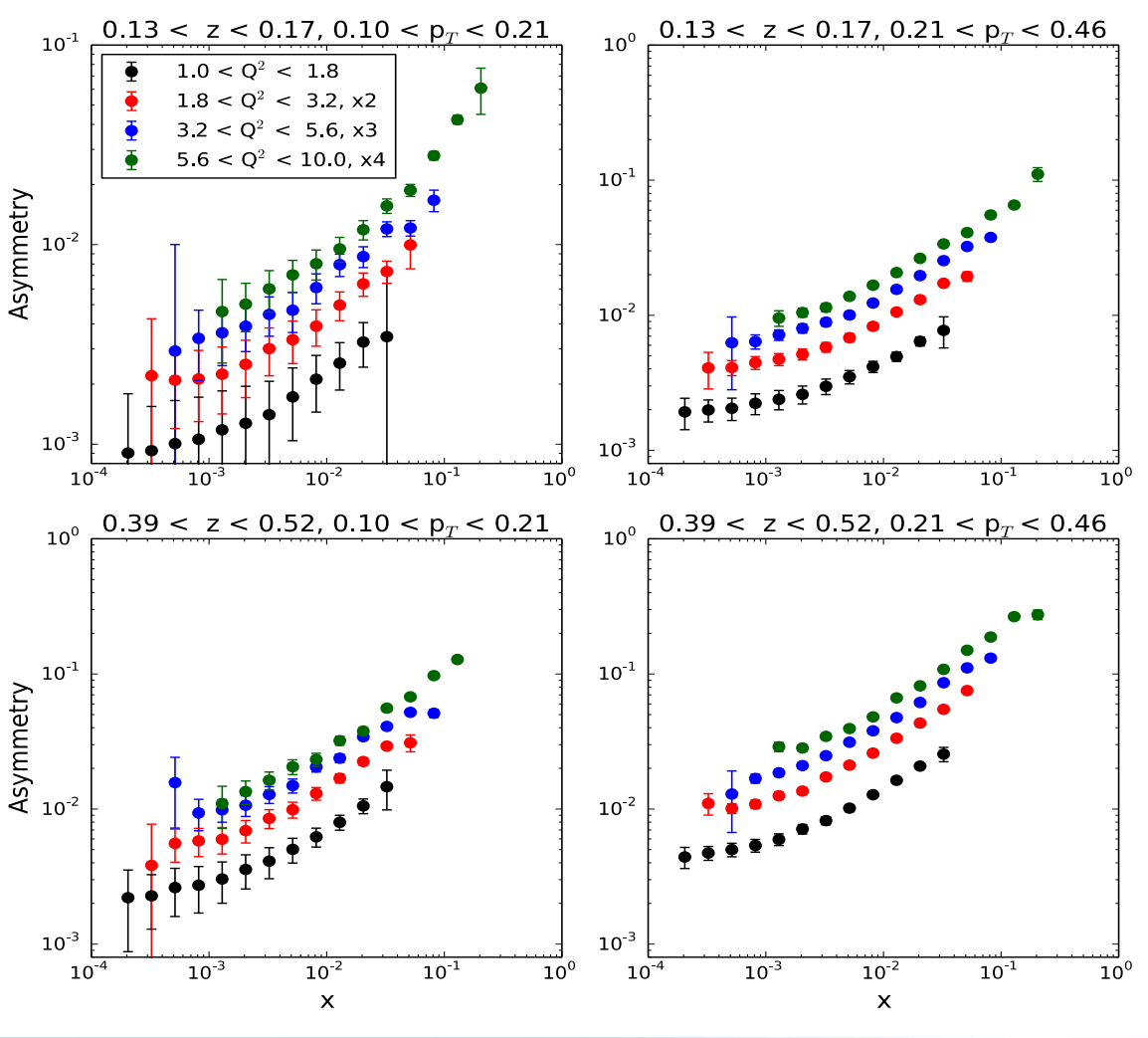
Chiral- functic Transve Boer-Mu				range ailed namics



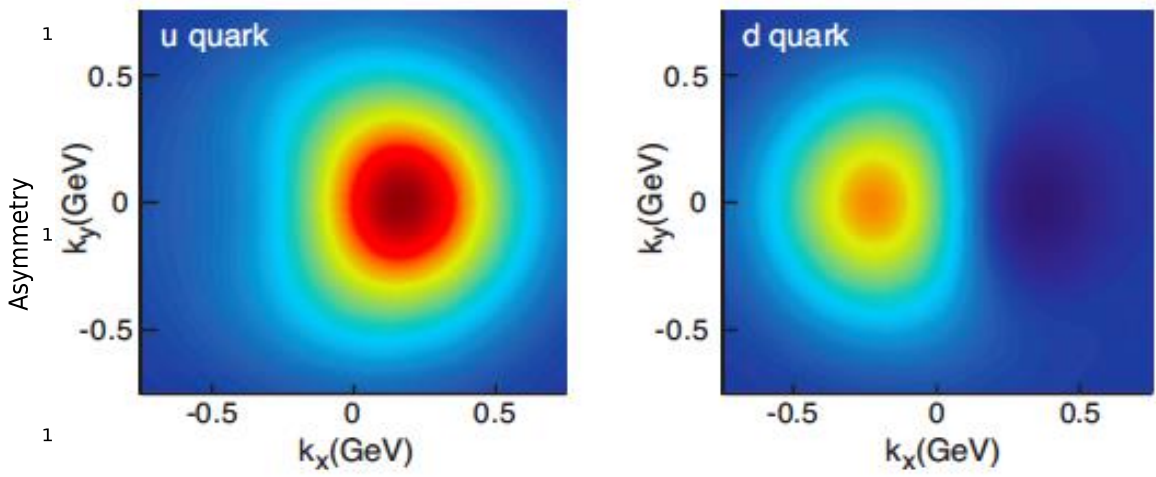
Sivers sensitivites

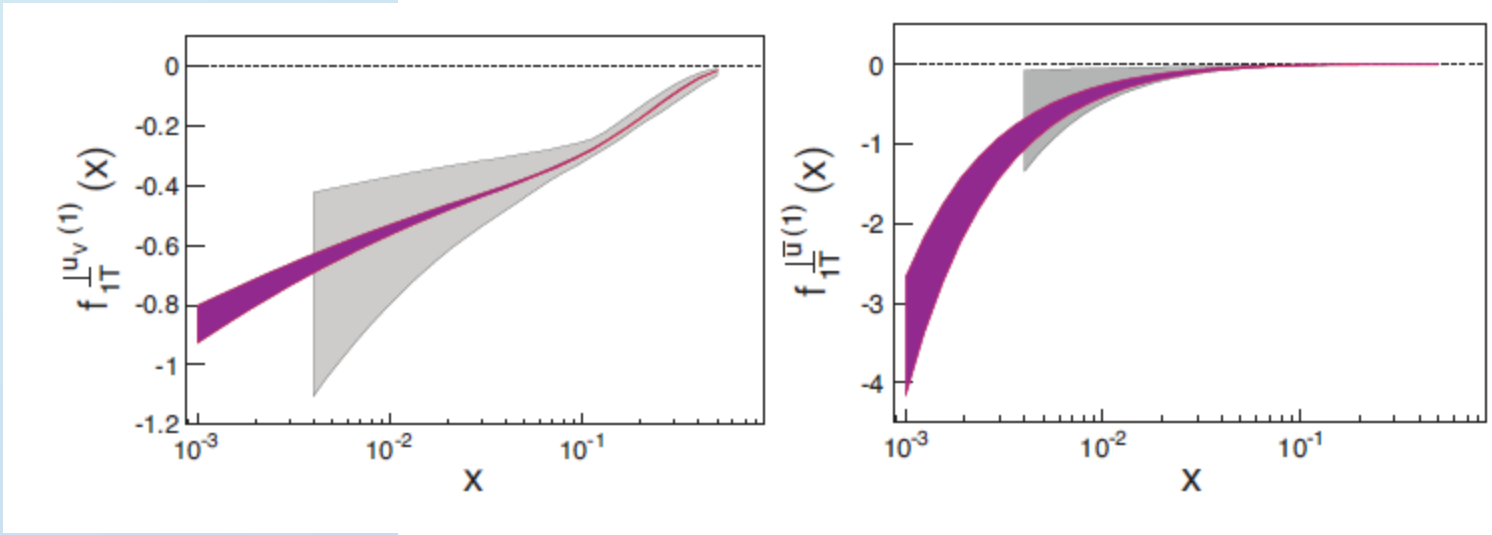


Also ideas on how to access gluon Sivers via D meson production

Similar reach for Transversity → Tensor charges of the nucleon for various Quark flavors and comparison to Lattice calculations

Sivers sensitivites





Also ideas on how to access gluon Sivers via D meson production

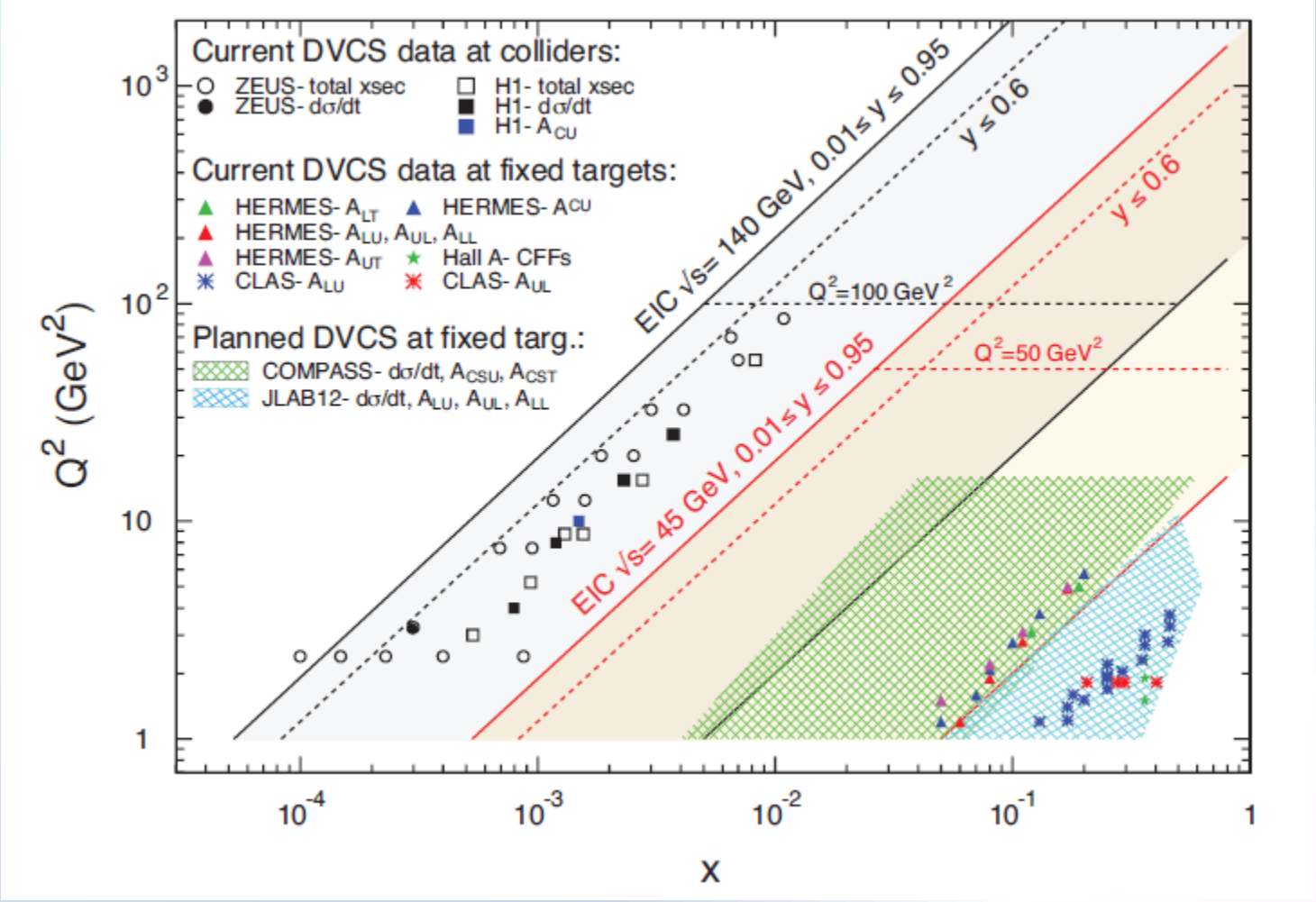
Similar reach for Transversity → Tensor charges of the nucleon for various Quark flavors and comparison to Lattice calculations

3 dimensional spatial structure

Deliverables	Observables	What we learn	Requirements
GPDs of sea quarks and gluons	DVCS and $J/\Psi, \rho^0, \phi$ production cross-section and polarization asymmetries	transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations	$\int dt\, L \sim 10$ to $100\,\mathrm{fb}^{-1}$; leading proton detection; polarized e^- and p beams; wide range of x and Q^2; range of beam energies; e^+ beam valuable for DVCS
GPDs of valence and sea quarks	electro-production of π^+, K and ρ^+, K^*	dependence on quark flavor and polarization	

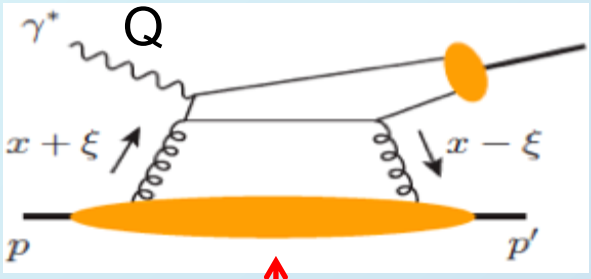
Table 2.3: Key measurements for imaging partons in the transverse plane. With energies in stage I, one can in particular investigate the transition from the valence to the sea quark regime and measure the processes in the lower block, whereas stage II provides access to a wide region dominated by sea quarks and gluons.

DVCS reach


Current DVCS data at colliders:
ZEUS- total xsec
ZEUS- dσ/dt
H1- total xsec
H1- dσ/dt
H1- A_CU
Current DVCS data at fixed targets:
HERMES- A_LT
HERMES- A^CU
HERMES- A_LU, A_UL, A_LL
HERMES- A_UT
Hall A- CFFs
CLAS- A_LU
CLAS- A_UL
Planned DVCS at fixed targ.:
COMPASS- dσ/dt, A_CSU, A_CST
JLAB12- dσ/dt, A_LU, A_UL, A_LL
EIC √s= 140 GeV, 0.01≤ y ≤ 0.95
y ≤ 0.6
Q²=100 GeV²
EIC √s= 45 GeV, 0.01≤ y ≤ 0.95
y ≤ 0.6
Q²=50 GeV²
Q² (GeV²)
10³
10²
10
1
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
x

Spatial imaging of gluon density

- Exclusive vector meson production:



J/Ψ, Φ, …

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

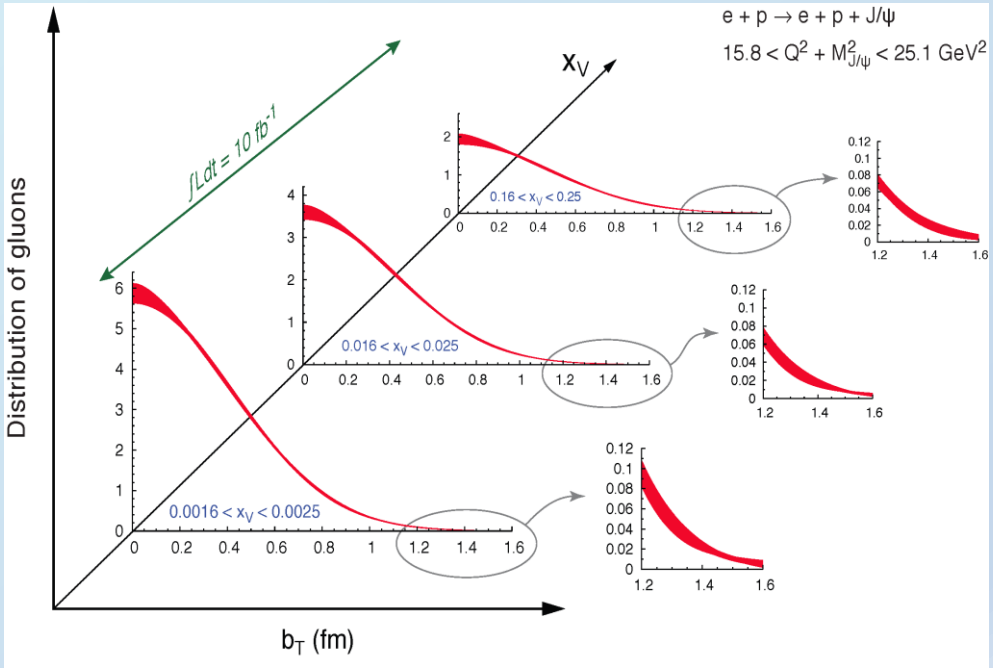
↑ t-dep

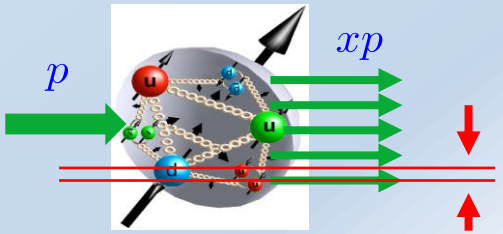
✧ Fourier transform of the t-dep

➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$

- Gluon imaging from simulation:





$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

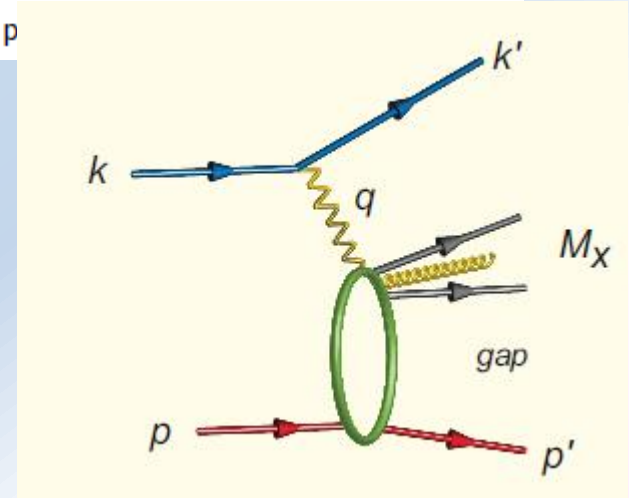
Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region

Nucleii at high gluon densities and hadronization

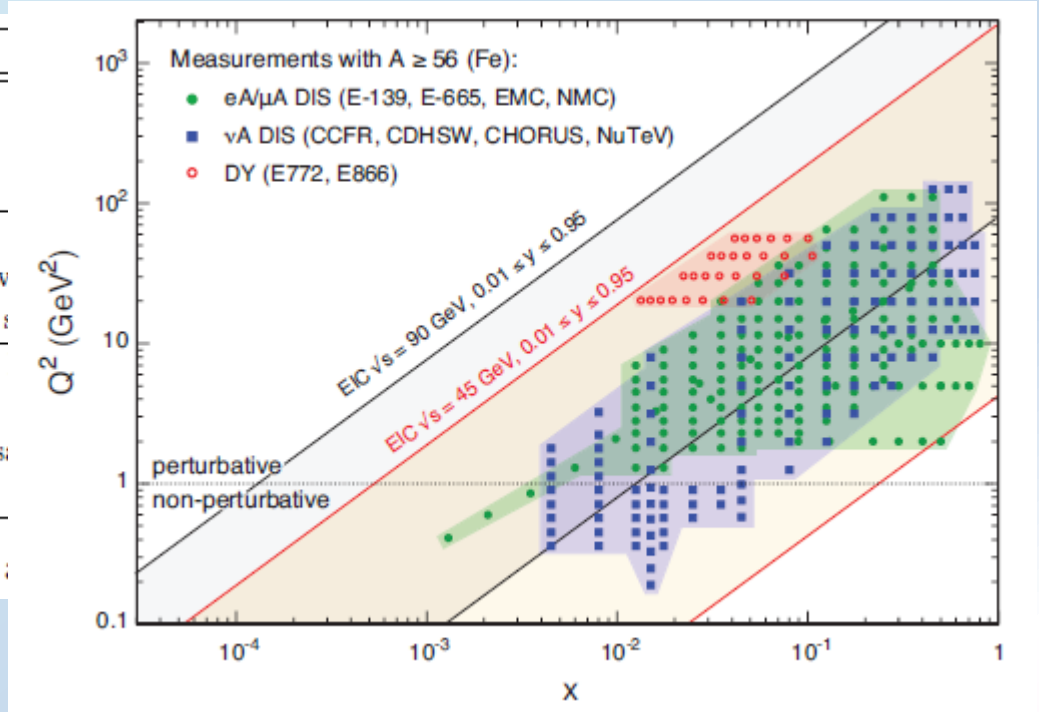
Deliverables	Observables	What we learn	Stage-I	Stage-II
Integrated gluon momentum distributions $G_A(x,Q^2)$	$F_{2,L}$	Nuclear wave function; saturation	Gluons at $10^{-3} \lesssim x \lesssim 1$	Exploration of the saturation regime
k_T-dependent gluons $f(x,k_T)$; gluon correlations	Di-hadron correlations	Non-linear QCD evolution/universality; saturation scale Q_s	Onset of saturation; Q_s measurement	Non-linear small-x evolution
Spatial gluon distributions $f(x,b_T)$; gluon correlations	Diffractive dissociation $\sigma_{\rm diff}/\sigma_{\rm tot}$ vector mesons & DVCS $d\sigma/dt$, $d\sigma/dQ^2$	Non-linear small-x evolution; saturation dynamics; black disk limit	saturation vs. non-saturation models	Spatial gluon distribution; Q_s vs centrality

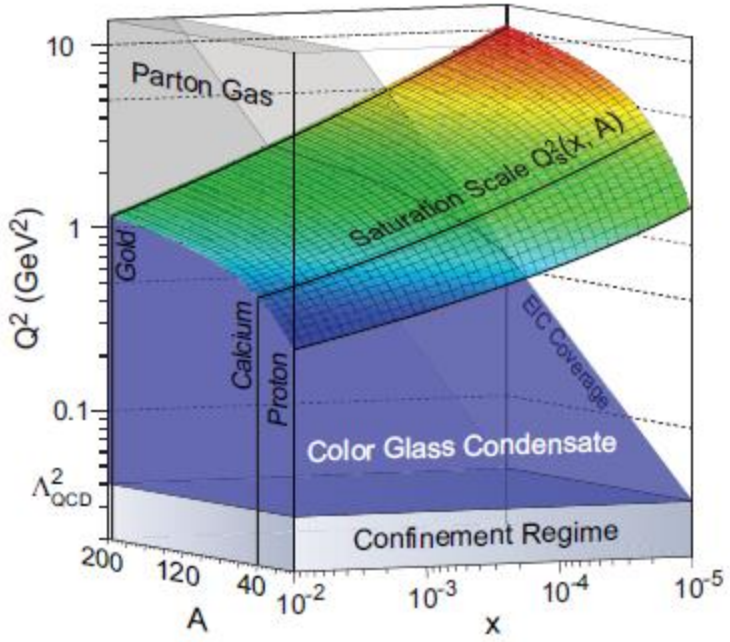
Table 3.1: Key measurements in e+A collisions at an EIC addressing the p

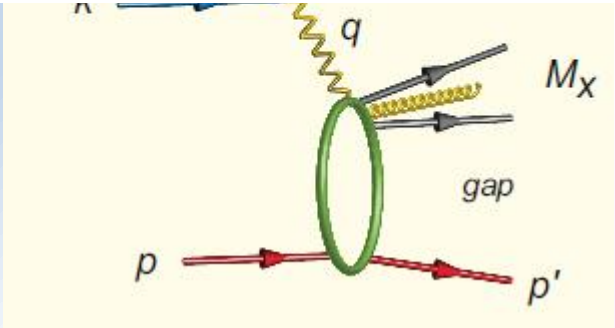


Nucleii at high gluon densities and hadronization

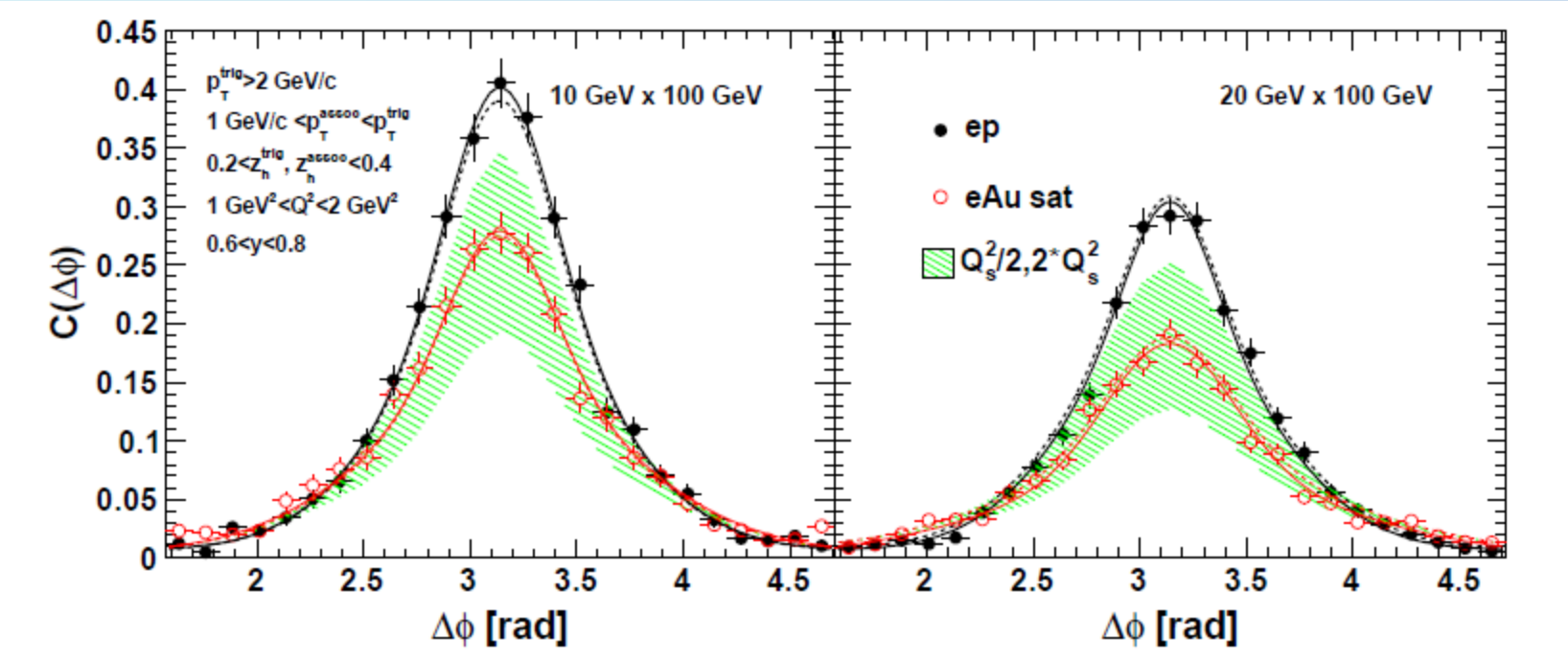
Deliverables	Observables
Integrated gluon momentum distributions $G_A(x, Q^2)$	$F_{2,L}$
k_T-dependent gluons $f(x, k_T)$; gluon correlations	Di-hadron correlations







Di-hadron correlations to cleanly probe saturation



Probing Gluon Saturation through Dihadron Correlations at an Electron-Ion Collider ,L. Zheng et al, **Phys.Rev. D89 (2014) 074037**

Exclusive vector meson production

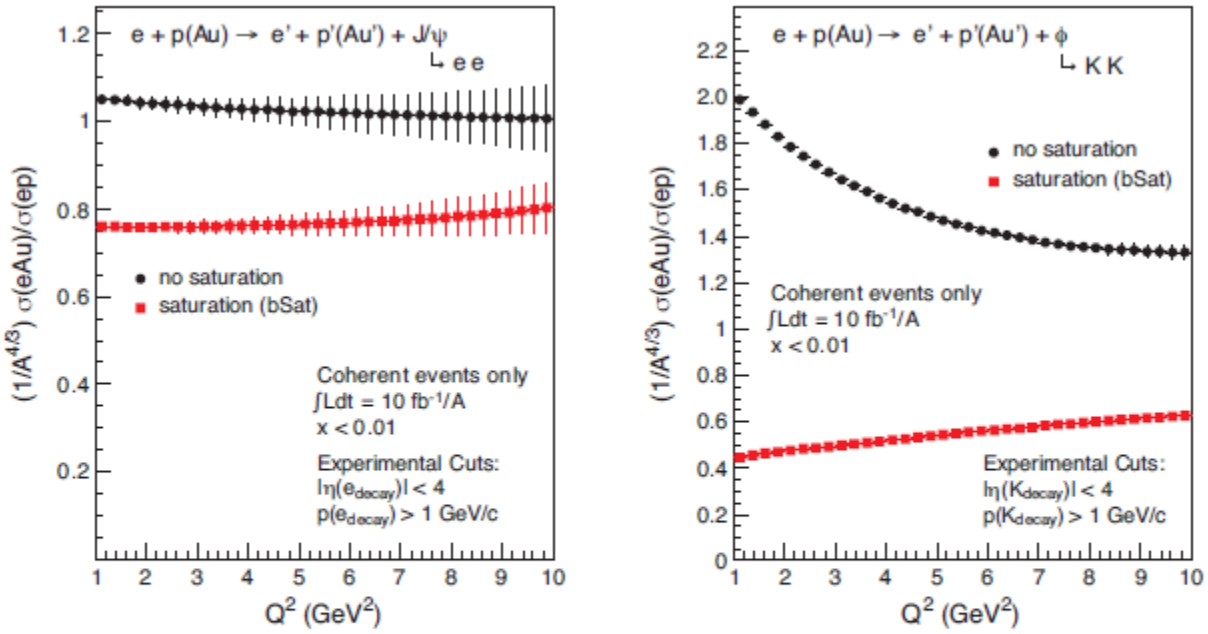
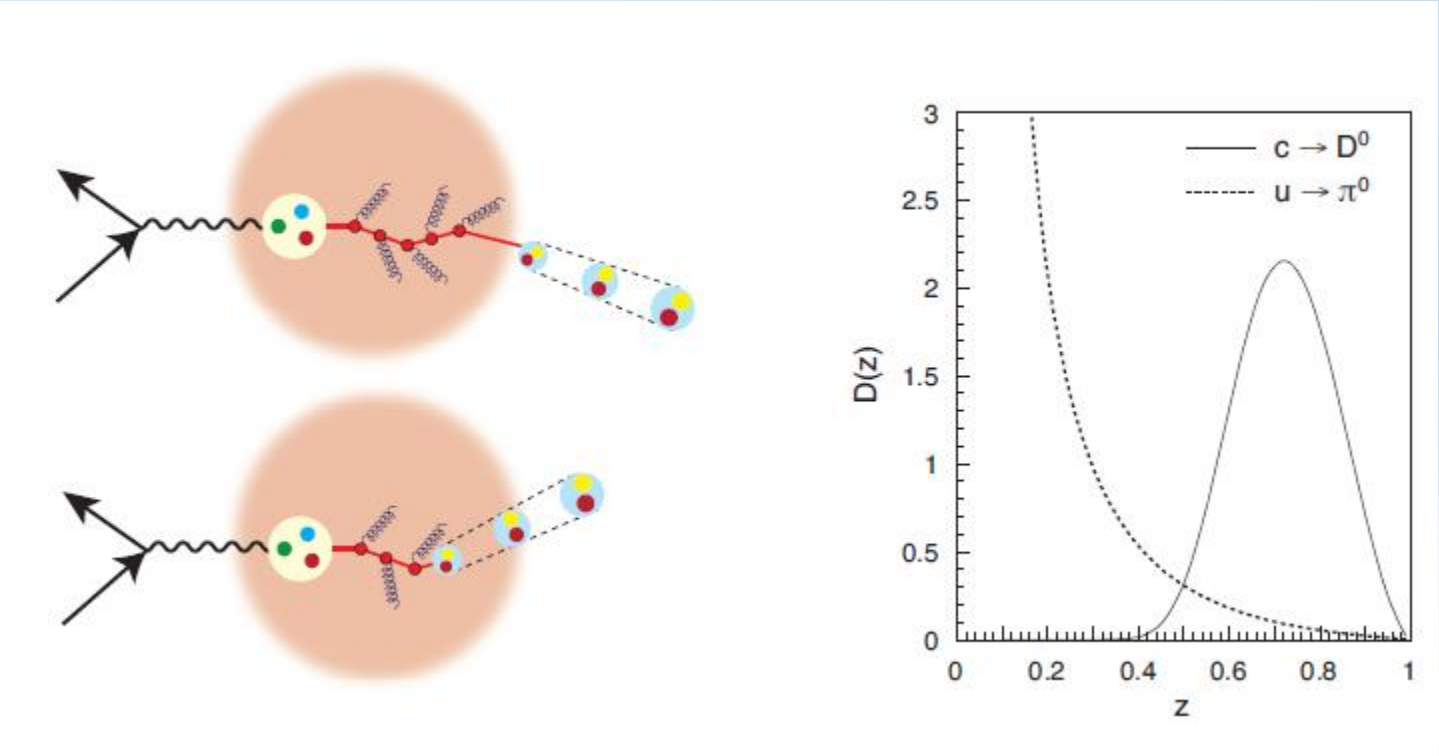
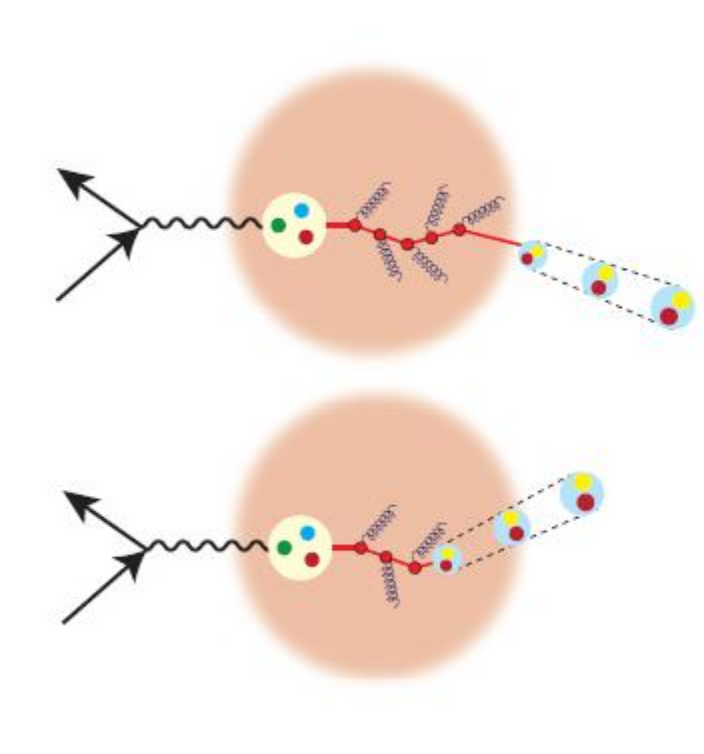


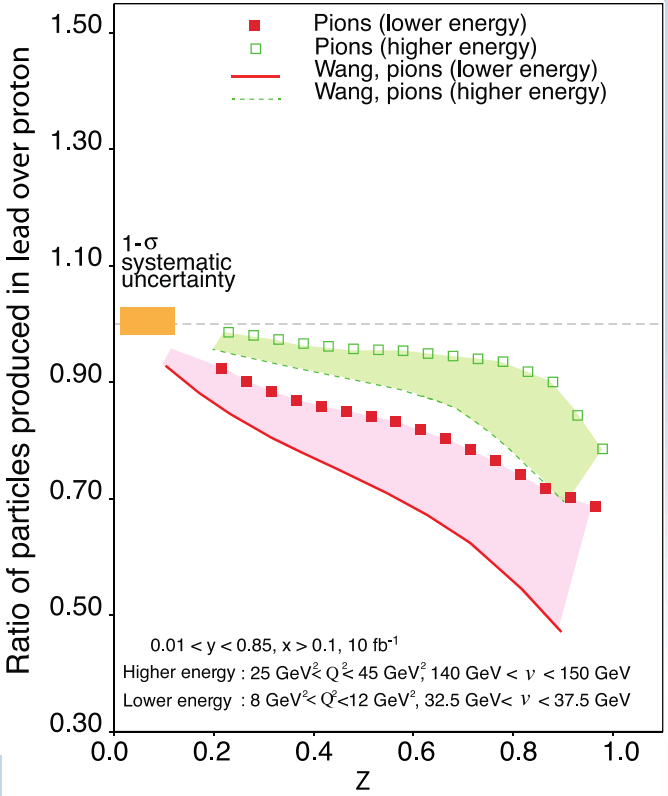
Figure 3.19: Ratios of the cross-sections for exclusive J/ψ (left panel) and ϕ (right panel) meson production in coherent diffractive e+A and e+p collisions as a function of Q^2. Prediction for saturation and non-saturation models are presented. The ratios are scaled by $1/\mathrm{A}^{4/3}$.

Fragmentation in the nucleus

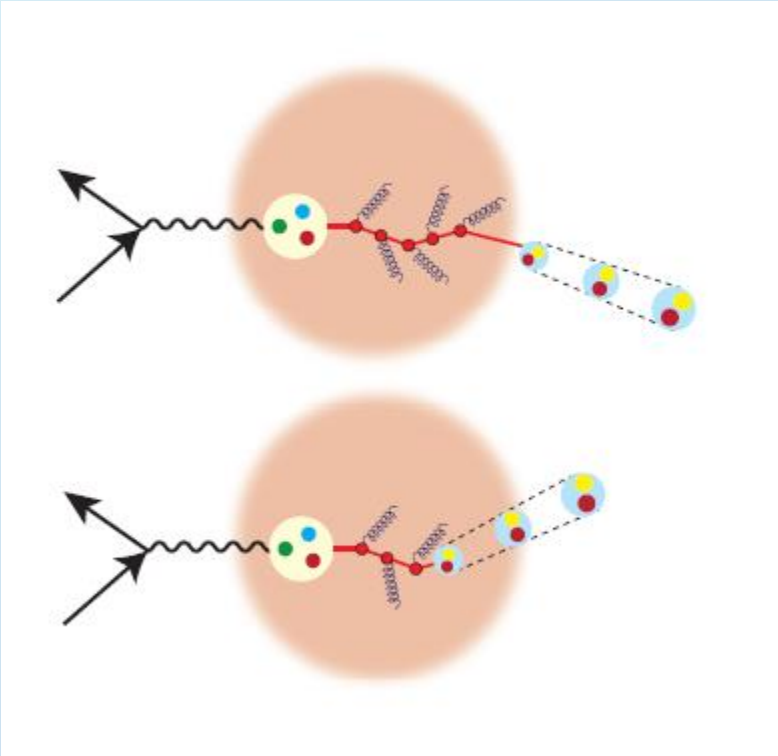


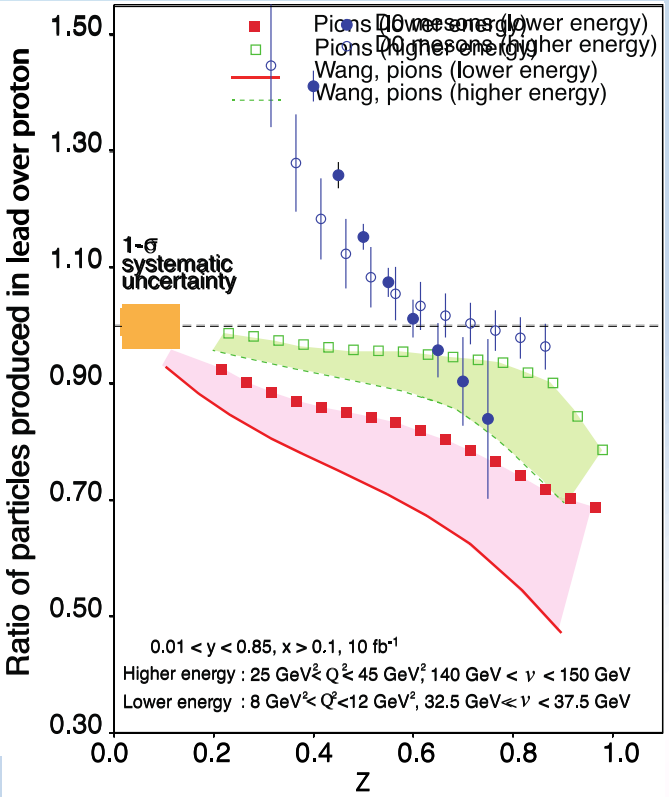
Fragmentation in the nucleus





Fragmentation in the nucleus



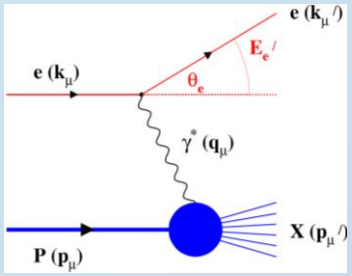


Detector considerations

What is Needed to Realize this Program

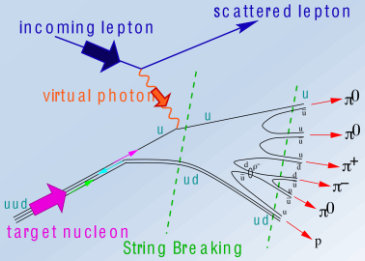
Inclusive Reactions in ep/eA:

- Physics: Structure Fcts.: g_1, F_2, F_L
- Very good electron id → identify scattered lepton
- Momentum/energy and angular resolution of e' critical
- scattered lepton → kinematics of event (x,Q^2)



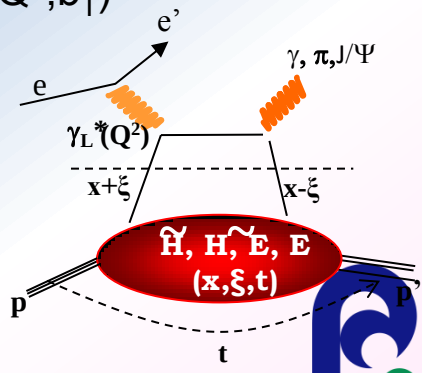
Semi-inclusive Reactions in ep/eA:

- Physics: TMDs, Helicity PDFs, FF → flavor separation, dihadron-corr.,…
  → Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^{\pm}$,$K^{\pm}$,$p^{\pm}$ separation over a wide range in $-3<\eta<3$
  → excellent p resolution at forward rapidities
- TMDs: full Φ-coverage around γ*, wide p_t coverage
- Excellent vertex resolution → Charm, Bottom separation

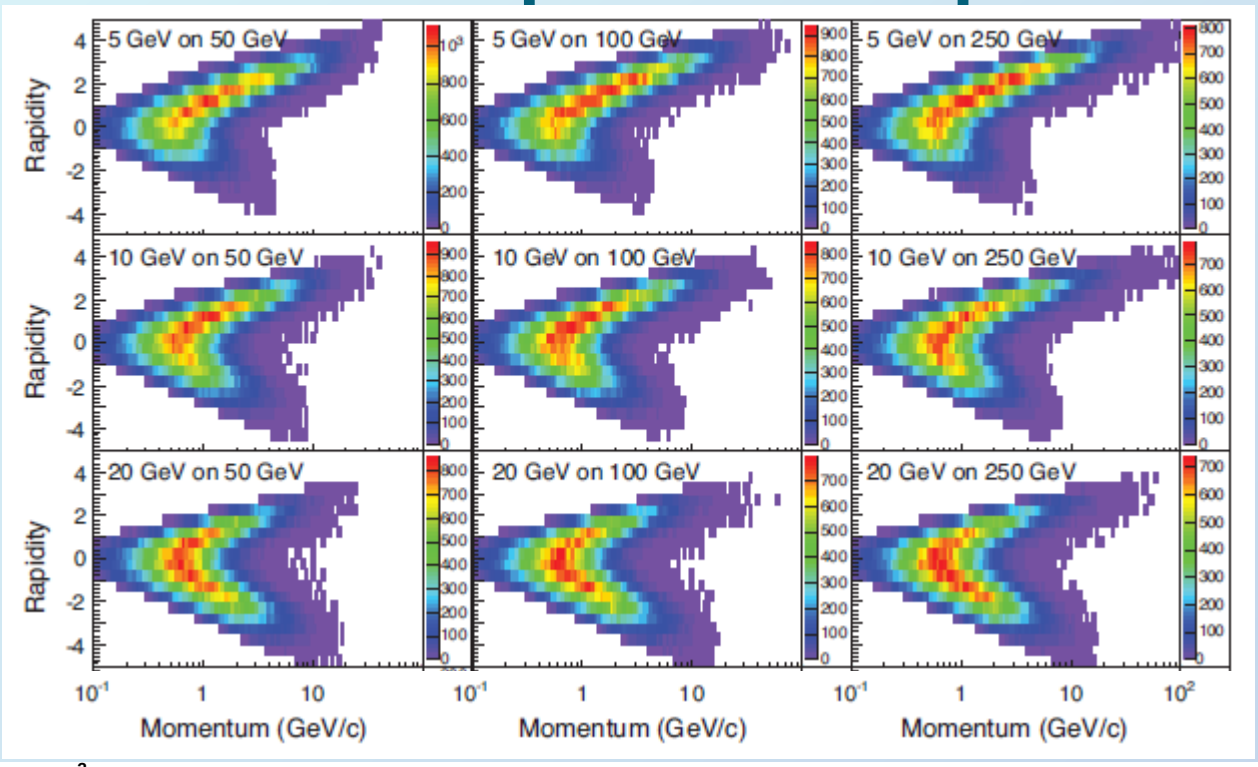


Exclusive Reactions in ep/eA:

- Physics: DVCS, excl. VM/PS prod. → GPDs, parton imaging in b_T; $g(x,Q^2,b_T)$
- Exclusivity → large rapidity coverage → rapidity gap events
  ↘ reconstruction of all particles in event
- high resolution, wide coverage in t → b_t → Roman pots
- eA: veto nucleus breakup, determine impact parameter of collision
  → acceptance for neutrons in ZDCs

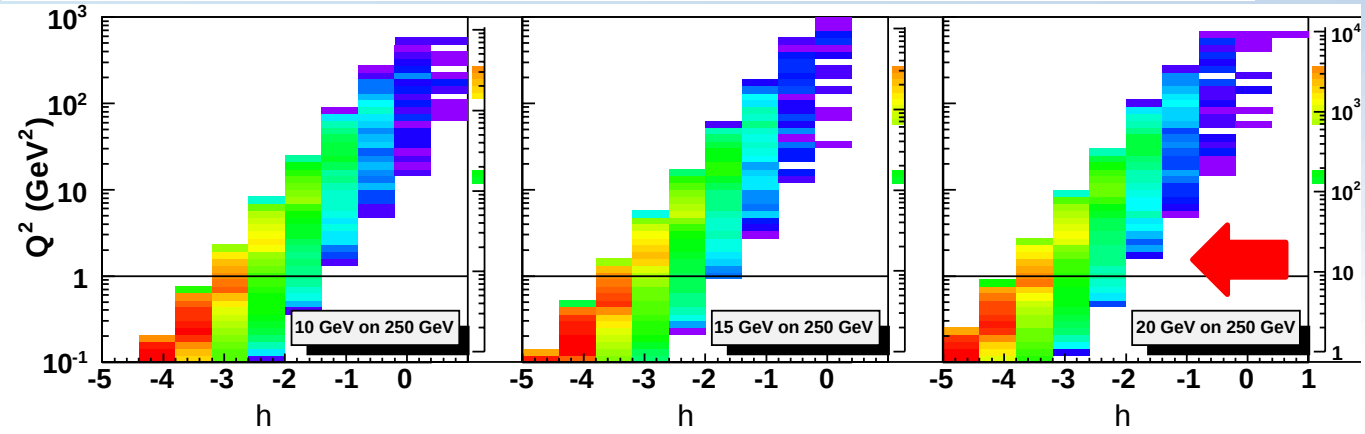


Lepton requirements



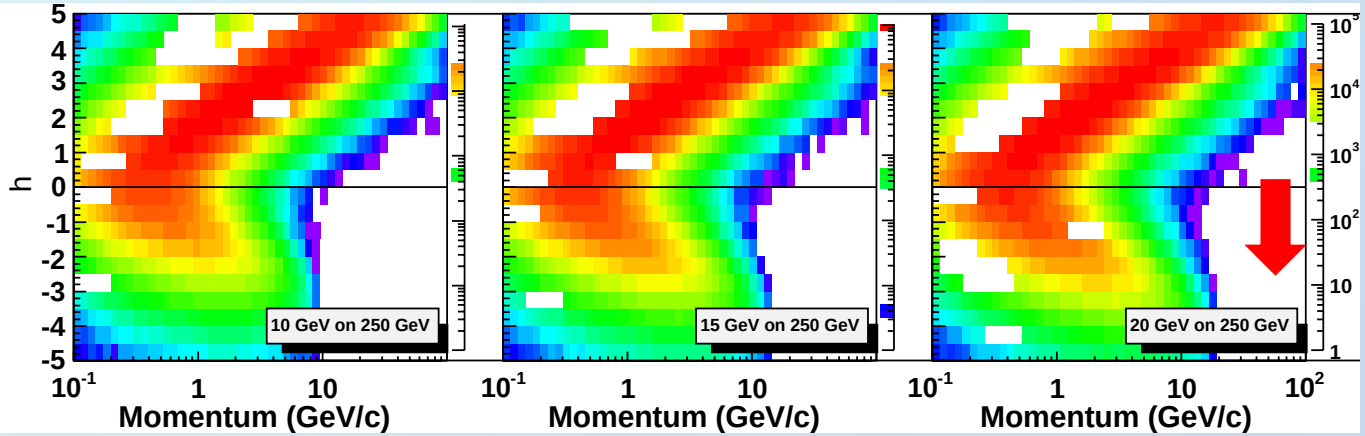
DIS Cuts:
Q^2>1 GeV,
0.01<y<0.95

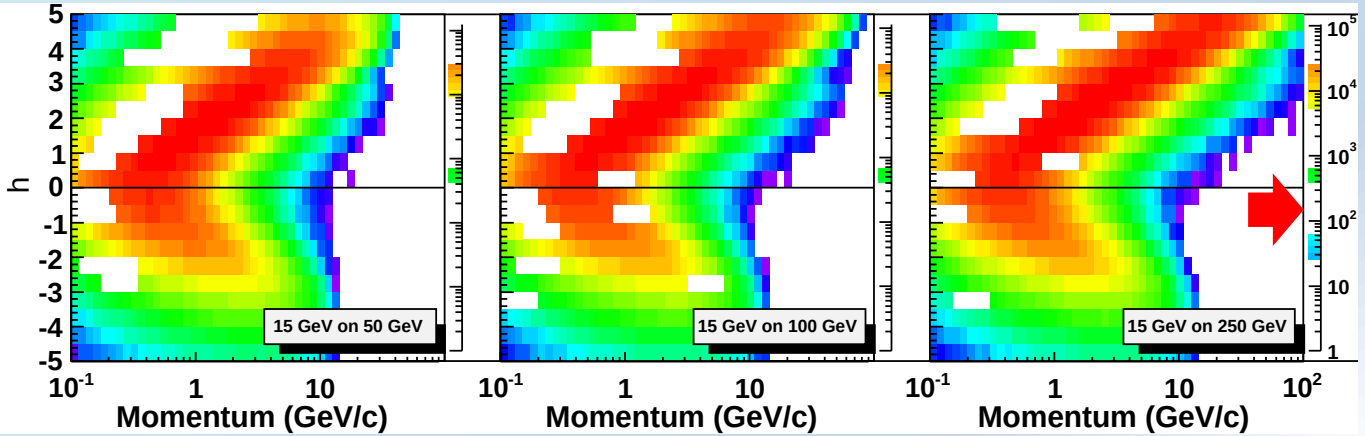
- Rapidity for scattered electron detection >-4 for DIS events,
- >-6 for low Q^2 detection



Hadron kinematics

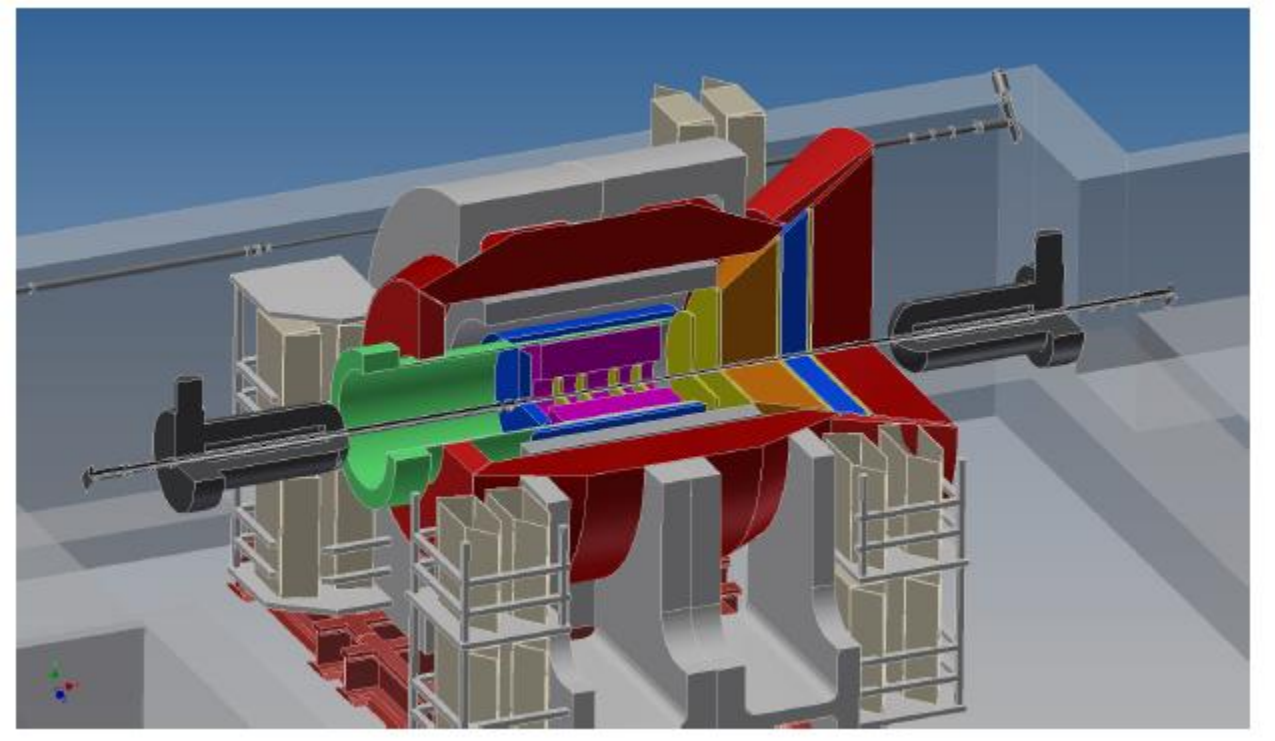
Cuts: Q^2>1 GeV, 0.01<y<0.95, z>0.1

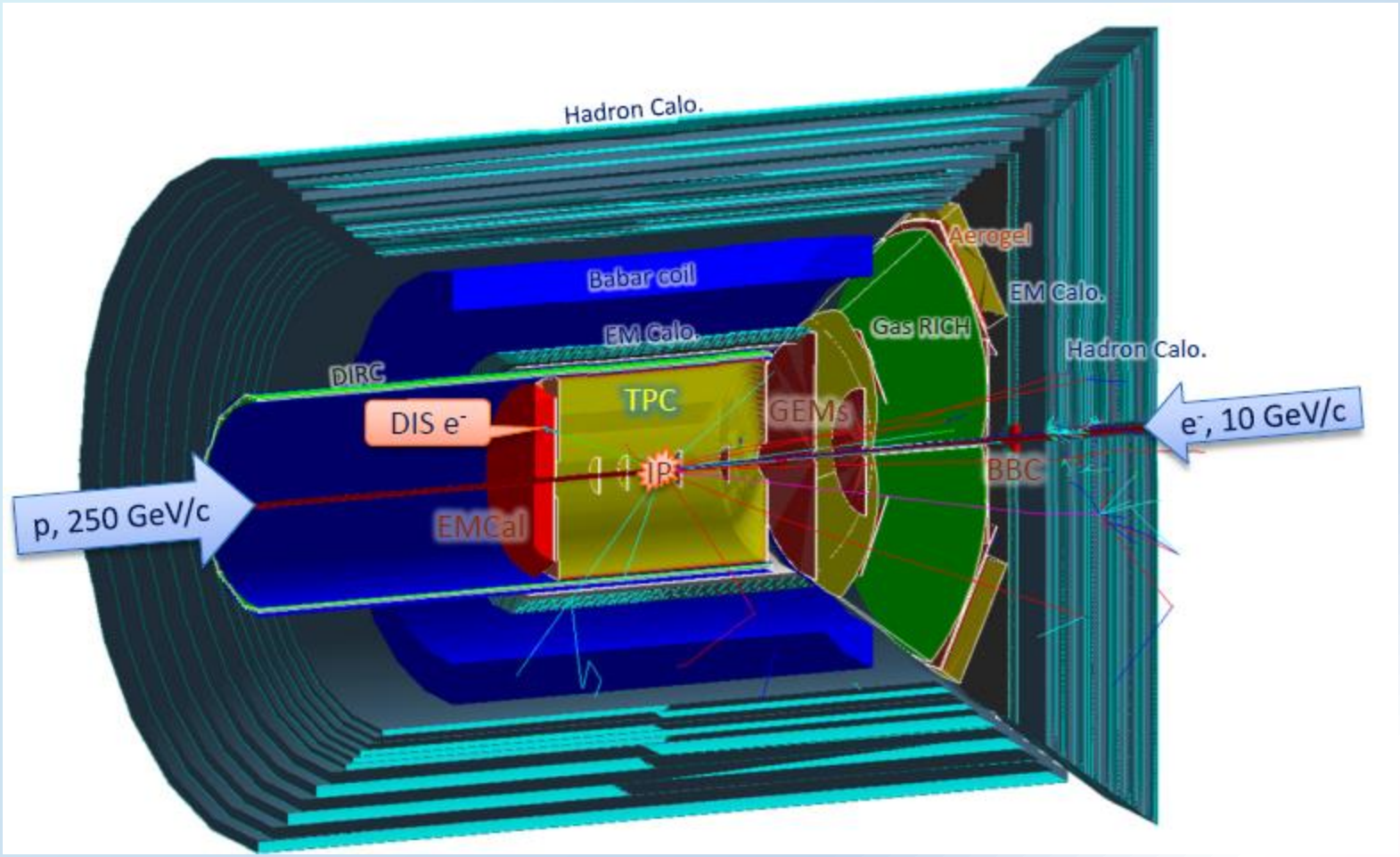




- Hadrons from -2 to +5 (+diffractive more forward)
- Central/Backwards momenta < 10 GeV
- Forward momenta up to 100 GeV → Inportant for forward PID

sPHENIX based eRHIC detector




Hadron Calo.
Babar coil
EM Calo.
DIRC
DIS e⁻
TPC
GEMs
IP
EMCal
Aerogel
EM Calo.
Gas RICH
Hadron Calo.
BBC
e⁻, 10 GeV/c
p, 250 GeV/c

Hadron going, high energy PID

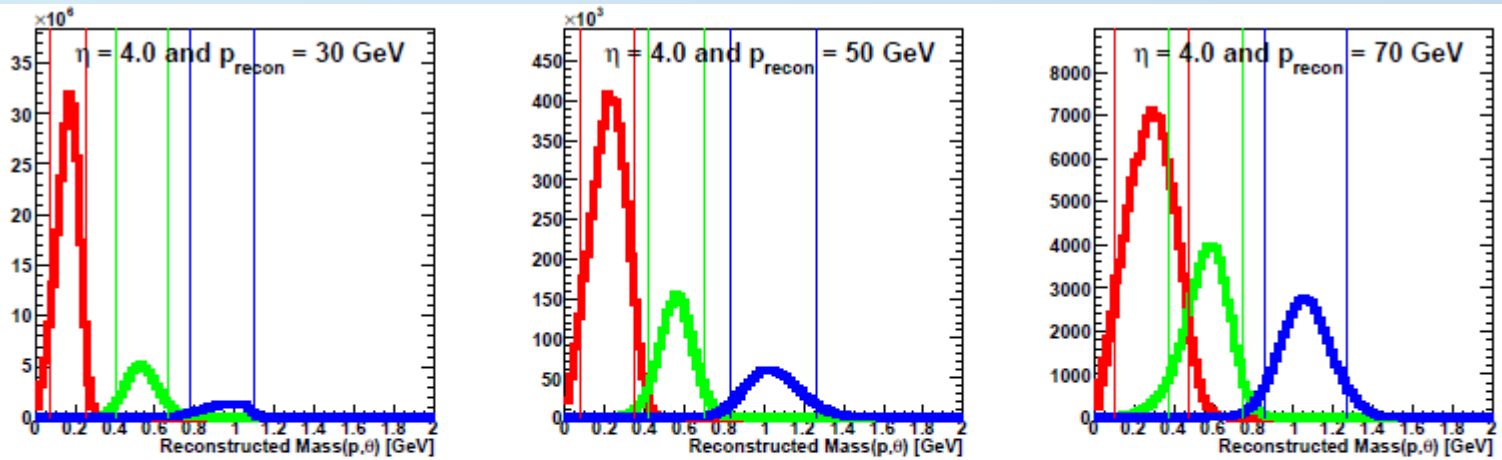
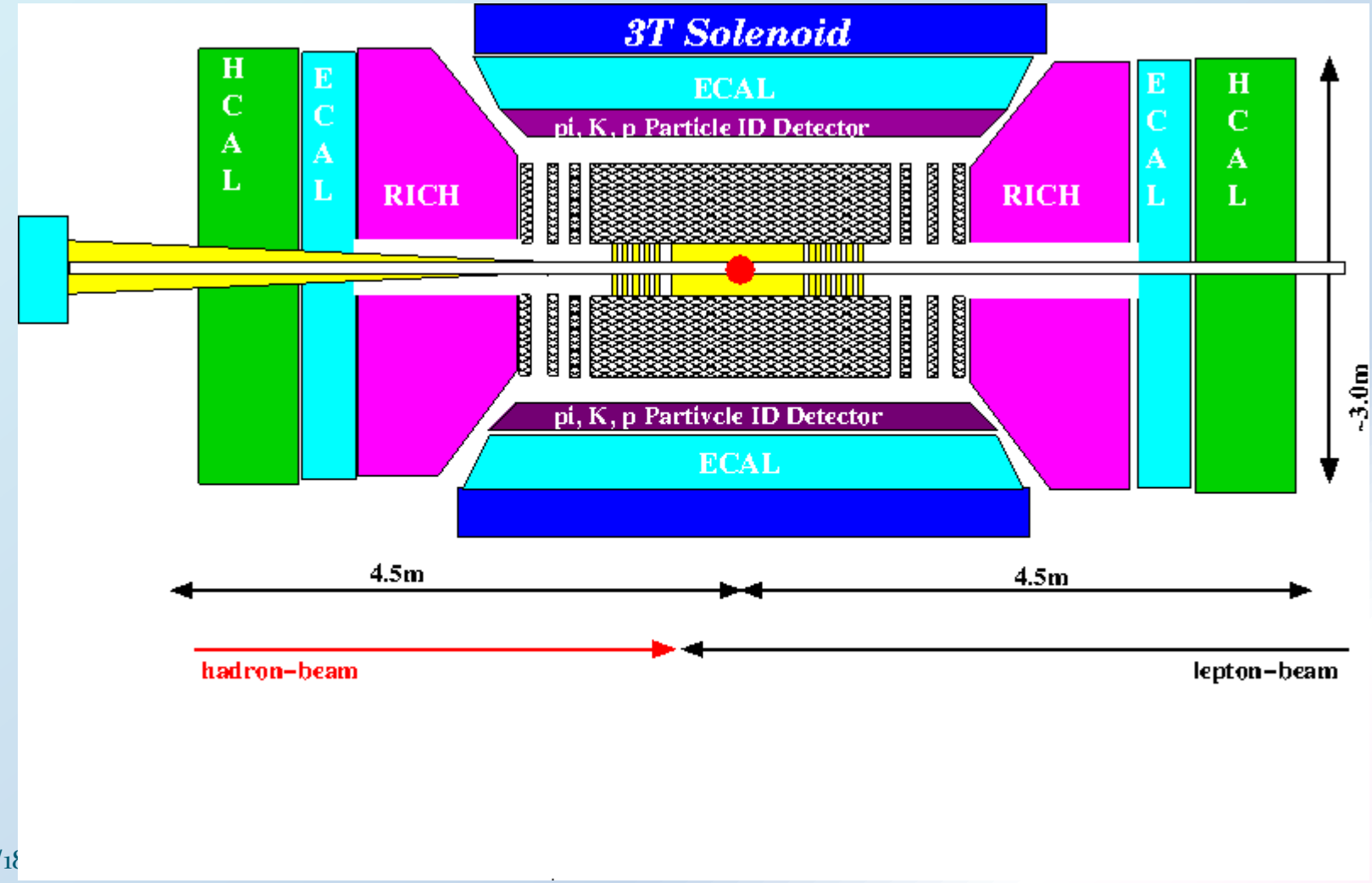


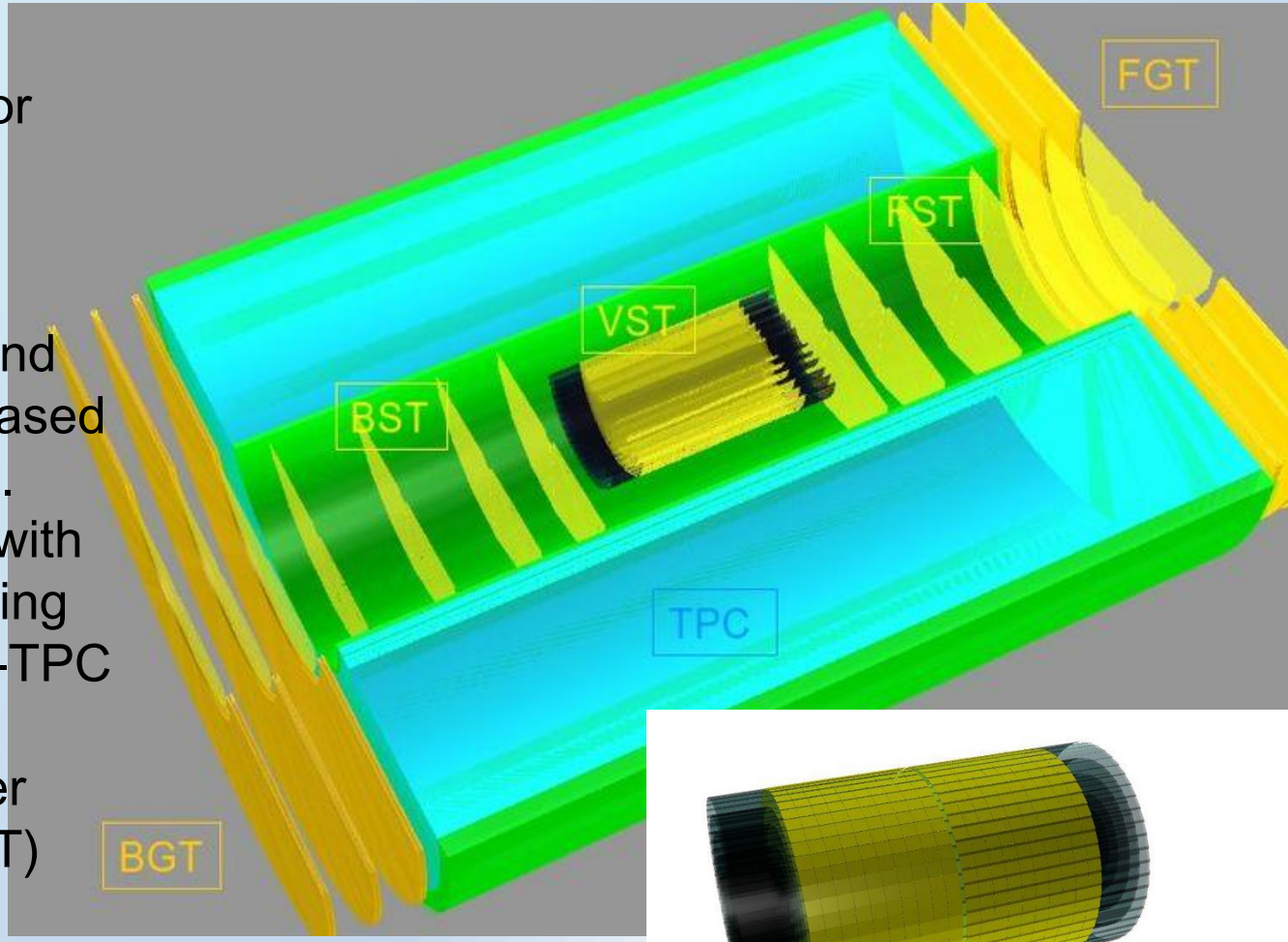
Figure 3.9: Reconstructed mass distribution via m(p,θ_{Crk}) at $\eta = 4$ for reconstructed momenta 30 GeV/c (left), 50 GeV/c (middle) and 70 GeV/c (right), for pions (red), kaons (green) and protons (blue), with the parent momentum and particle abundances from the PYTHIA generator. Vertical lines indicate the symmetric mass cuts corresponding to 90% efficiency. Note that particle true momentum is on the average smaller than reconstructed momentum, see Figure 3.10.

Dedicated eRHIC detector



Dedicated detector inner

- Barrel micro-vertex tracking (VST)detector based on MAPS-technology.
- Forward / Backward vertex tracker (FST and BST)detector disks based on MAPS-technology.
- Barrel-Tracker: TPC with GEM read-out, following the design of the ILC-TPC
- Forward / Backward: possible GEM Tracker planes (FGT and BGT)



Various Detector R&D projects ongoing

- Ultrafast (10ps) time-of-flight as a way to have thin pion, kaon and proton PID from mid to high rapidities (RD2013-5)
- Very high momentum RICH using specially coated mirrors and CsI coated GEMs as readout + tracking (RD2011-6)
- DIRCs for PID (RD2011-3)
- Various GEM based tracking studies (RD 2012-3)
- High precision polarimeters for an EIC
- Magnetic Field Cloaking Device (RD2013-2)
- Calorimetry

Summary

- The knowledge of the nucleon as the simplest bound state of QCD (and visible matter) still needs to be improved to understand QCD and be able to use it similar to how QED is used now in many different fields

- Reasonable understanding of valence quark and gluon helicities at intermediate x
- Gluon dominated lower x is not known at all
- 3D picture in momentum and position space
- High gluon densities and saturation

eRHIC Schedule

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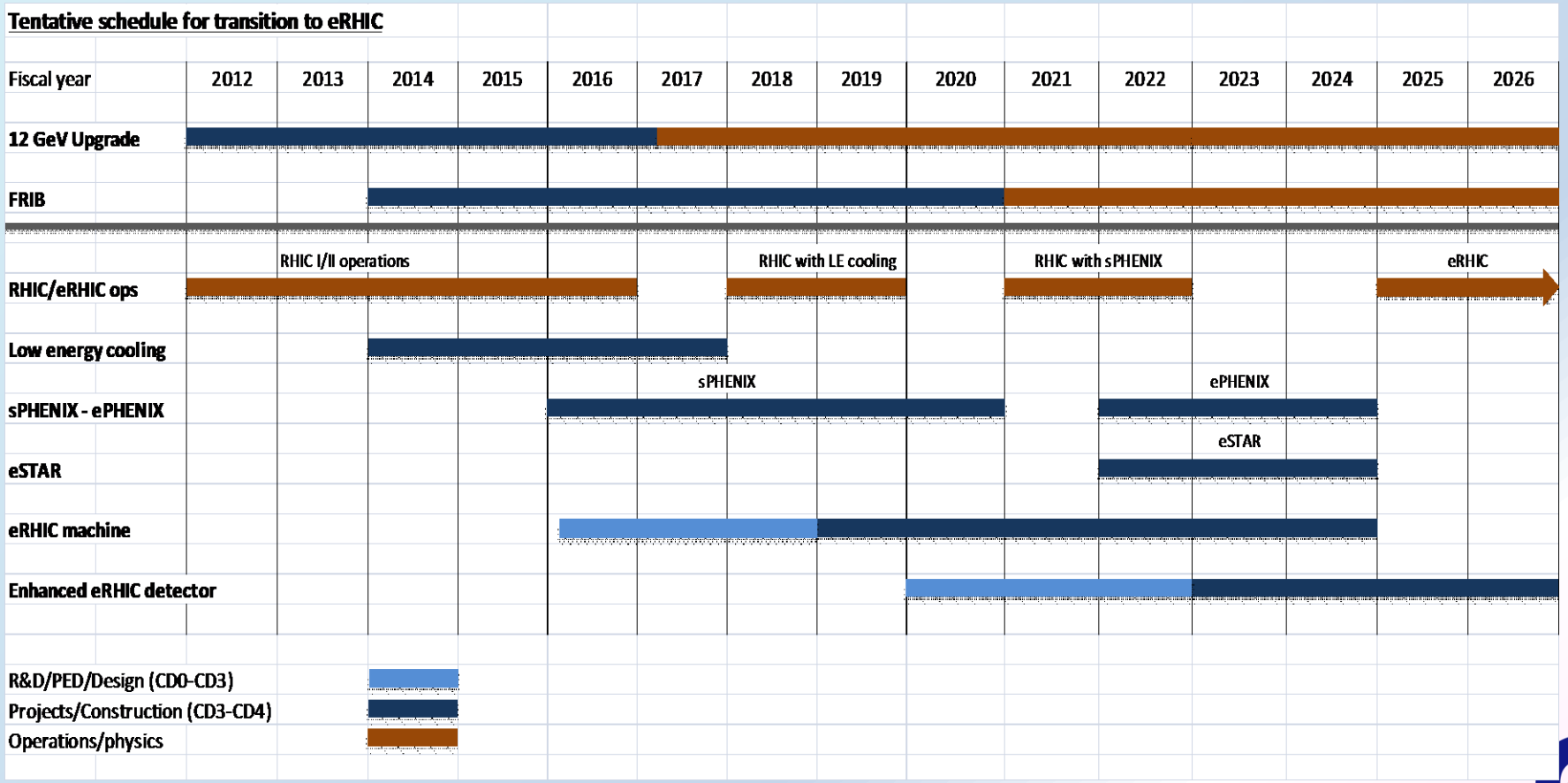

Main EIC references

- Long 2011 INT writeup: Gluons and the quark sea at high energies: Distributions, polarization, tomography
  Daniel Boer *et al.*. Aug 2011. 547 pp., e-Print: **arXiv:1108.1713**

- EIC White paper: Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all
  A. Accardi *et al.*. Dec 2012. 146 pp., e-Print: **arXiv:1212.1701**

- PHENIX based Detector concept: Concept for an Electron Ion Collider (EIC) detector built around the BaBar solenoid
  PHENIX Collaboration (A. Adare *et al.*). Feb 5, 2014. 59 pp. e-Print: **arXiv:1402.1209**

- eRHIC CDR: **eRHIC Design Study An Electron-Ion Collider at BNL** E.C. Aschenauer *et al.*