

3D, FUTURE

Contalbrigo Marco
INFN Ferrara

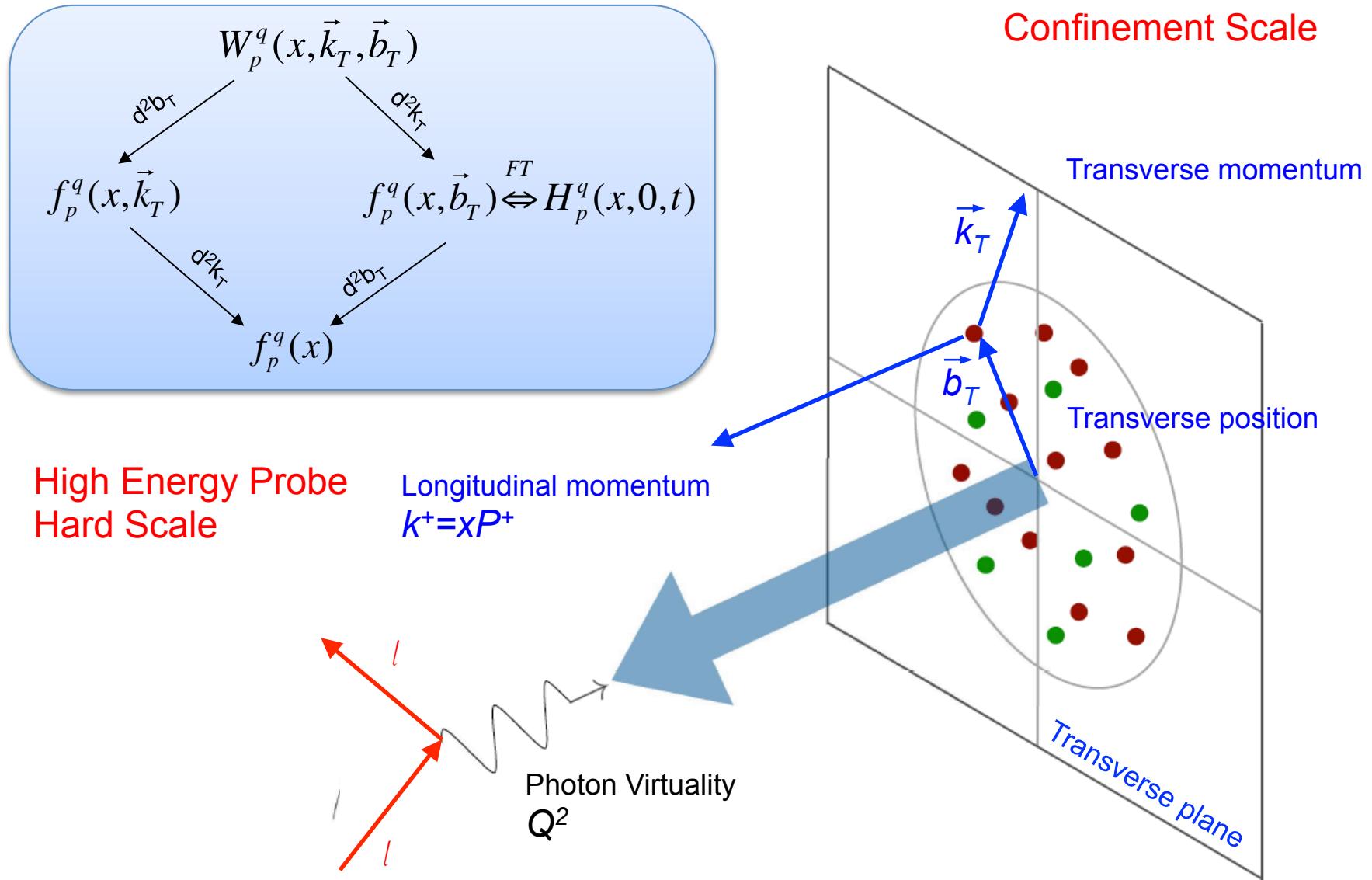
NPQCD 2015
April 22, 2015 Cortona

The QCD View

Non Perturbative Physics

pQCD

The 3D Nucleon Structure



3D Vision

Dynamic Spin

- parton polarization
- orbital motion
- **Form Factors**
- **Anomalous MM**

Parton Correlations

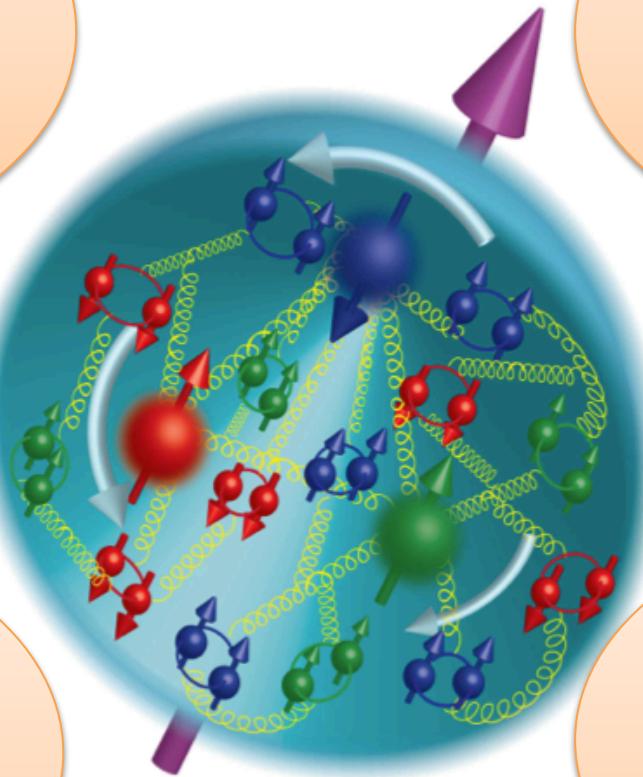
- Short range
- **MPI**

Hadronization

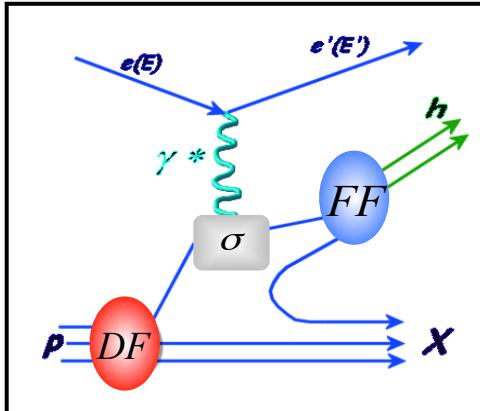
- spin-orbit effects
- parton energy loss
- **Jet quenching**

Color charge density

- nucleon tomography
- **Diffractive physics**
- **Gluon saturation**



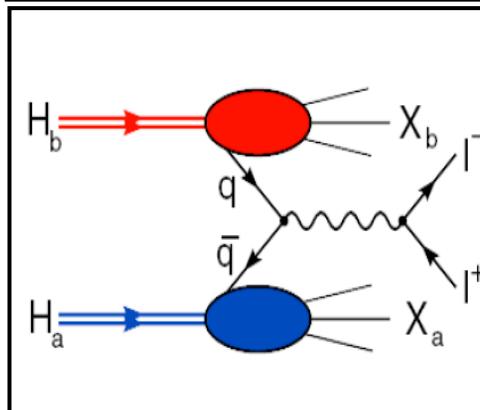
Physics reactions



SIDIS: rich phenomenology, the most explored so far

SIDIS

$$\sigma^{ep \rightarrow ehX} = \sum_q DF \otimes \sigma^{eq \rightarrow eq} \otimes FF$$



e^+e^- : B-factories as powerful fragmentation laboratories

e^+e^-

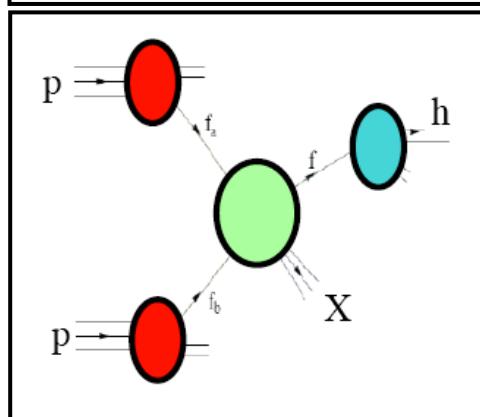
$$\sigma^{ee \rightarrow hhX} = \sum_q \sigma^{qq \rightarrow ee} \otimes FF \otimes FF$$



DY: challenging for experiments (only unpolarized so far)

DY

$$\sigma^{pp \rightarrow eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq \rightarrow ee}$$



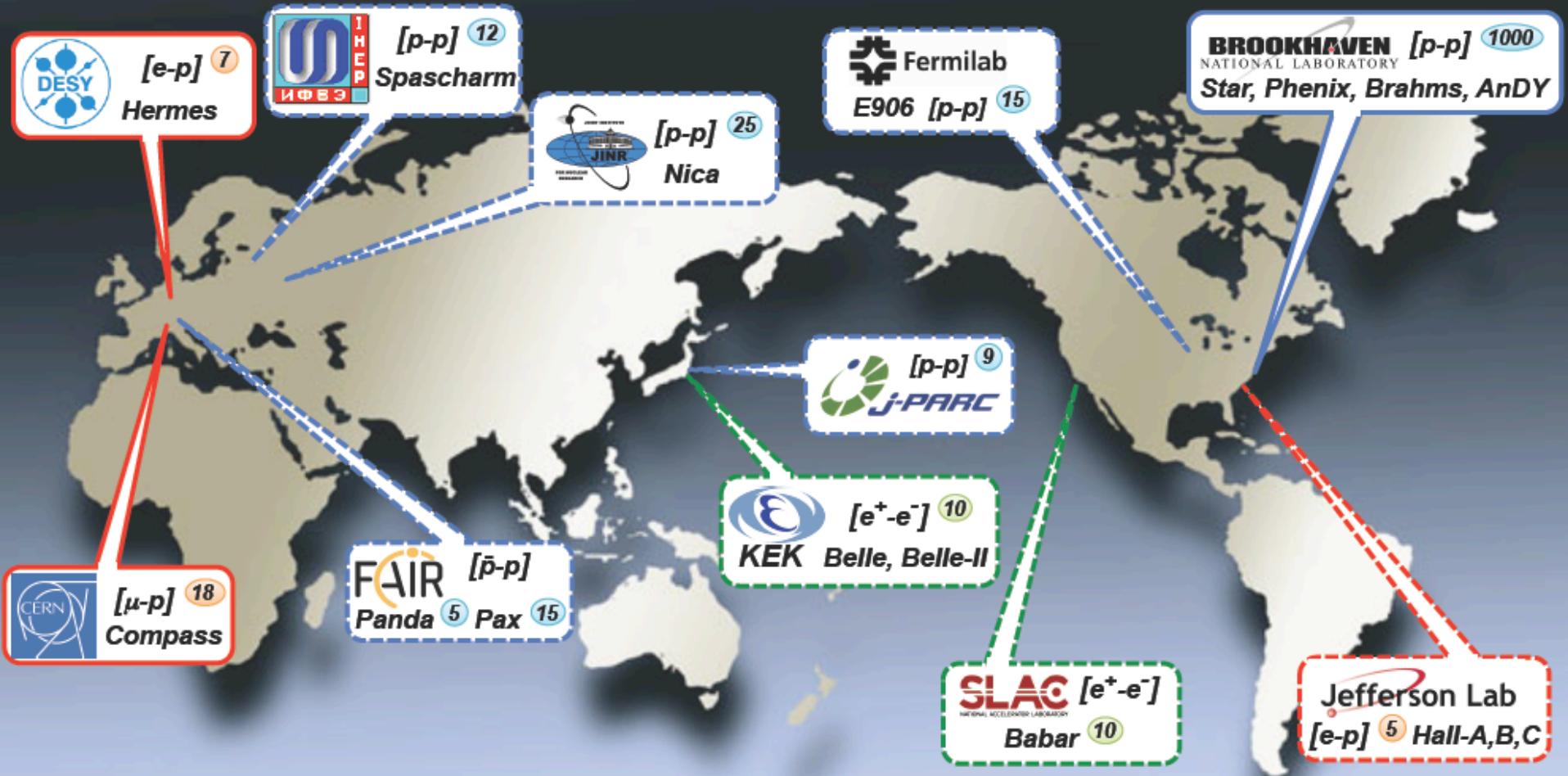
Hadron reactions: challenging for theory (ISI + FSI)

pp

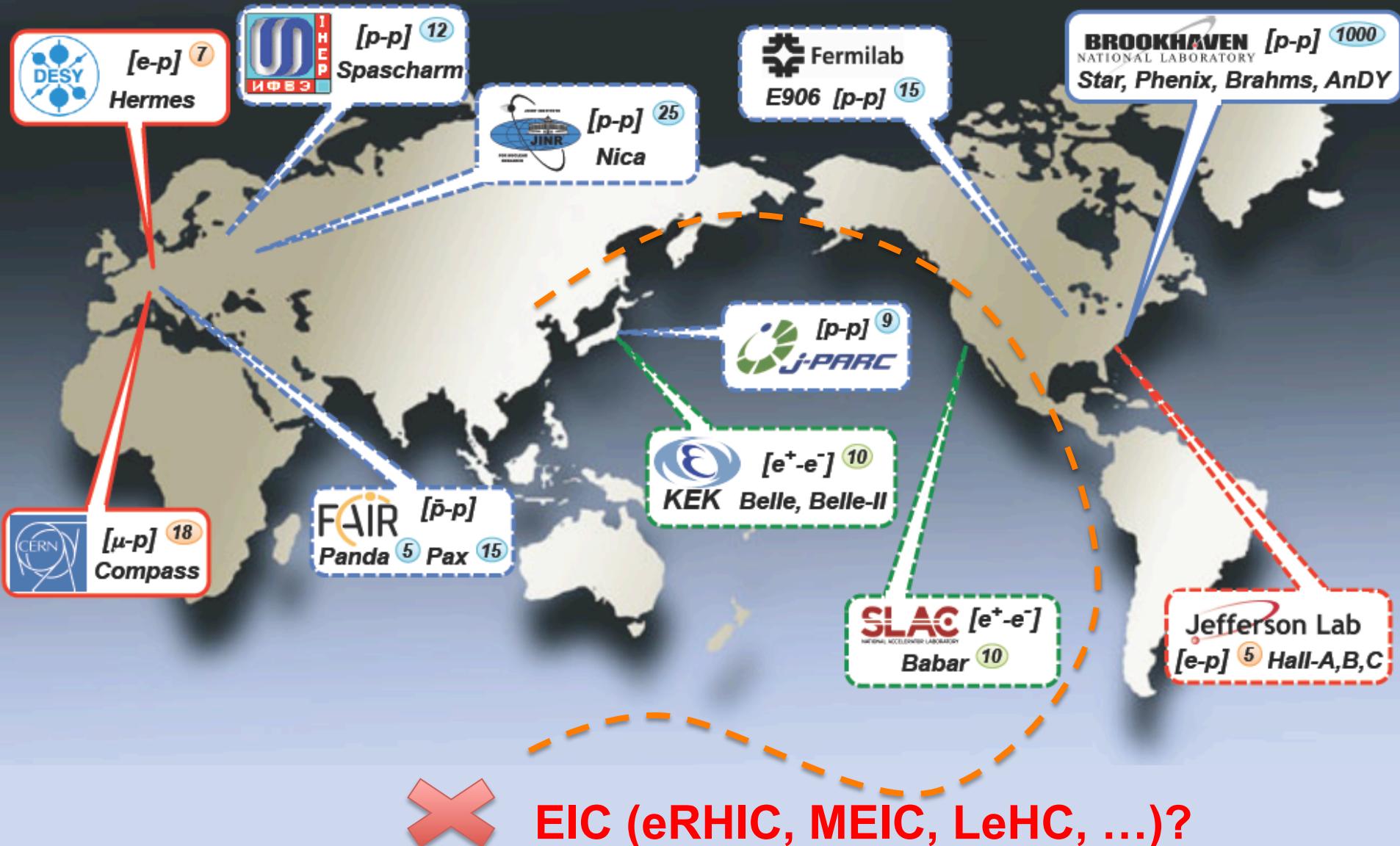
$$\sigma^{pp \rightarrow hX} = \sum_q DF \otimes DF \otimes \sigma^{qq \rightarrow qq} \otimes FF$$



A World-wide Challenge



A World-wide Challenge



Electron Ion Colliders

Past

Possible Future

Europe

US

EIC

China

CEIC

Europe

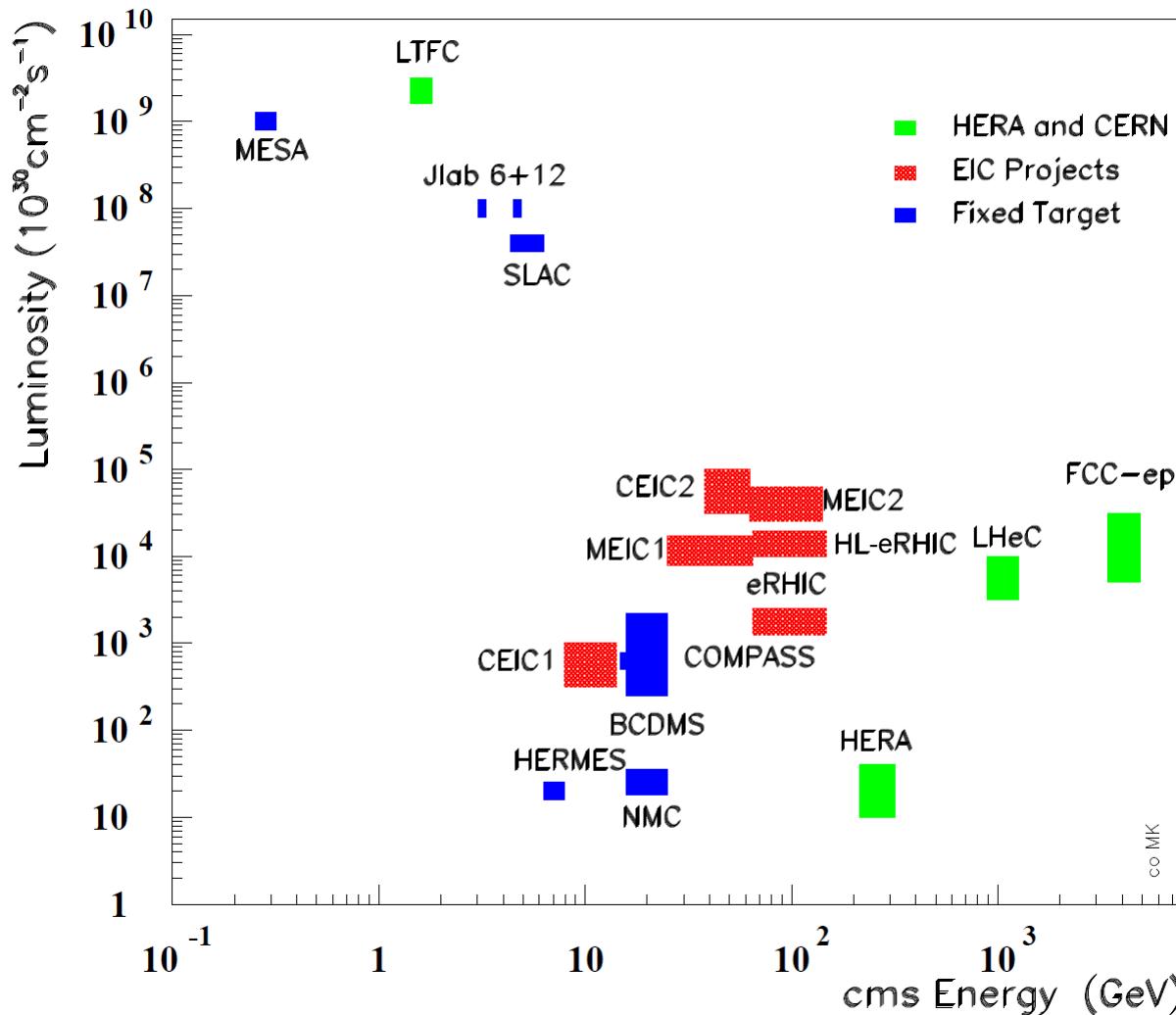
	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	70-150	$12-70 \rightarrow 140$	$12 \rightarrow 65$	14
proton x_{min}	1×10^{-5}	5×10^{-7}	4×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to $\sim^{40}\text{Ca}$
polarization	-	-	p, ^3He	p, d, ^3He (^6Li)	p, d, ^3He	p,d
L [$\text{cm}^{-2} \text{s}^{-1}$]	2×10^{31}	10^{33-34}	$10^{33} \rightarrow 10^{34}$	10^{34-35}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2025	2025	Post-12 GeV	2019 \rightarrow 2030	upgrade to FAIR

High-Energy Physics

Hadron Physics

CM vs Luminosity Landscape

Lepton–Proton Scattering Facilities



CEIC1 = Chinese version
of Electron-Ion Collider
(“A dilution-free mini-COMPASS”)

MEIC1 = EIC@Jlab

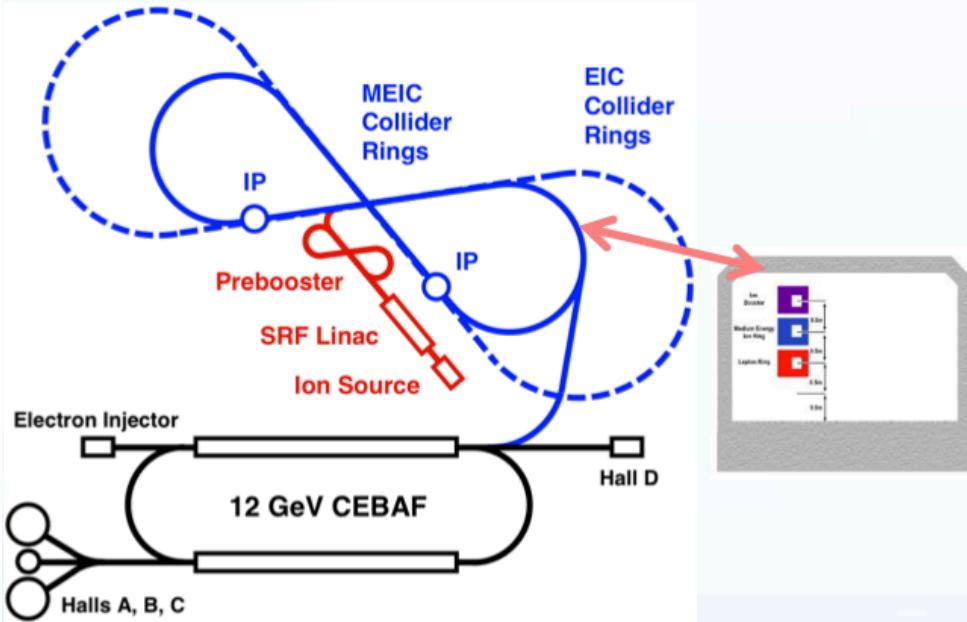
eRHIC = EIC@BNL

LHeC = ep/eA collider
@ CERN

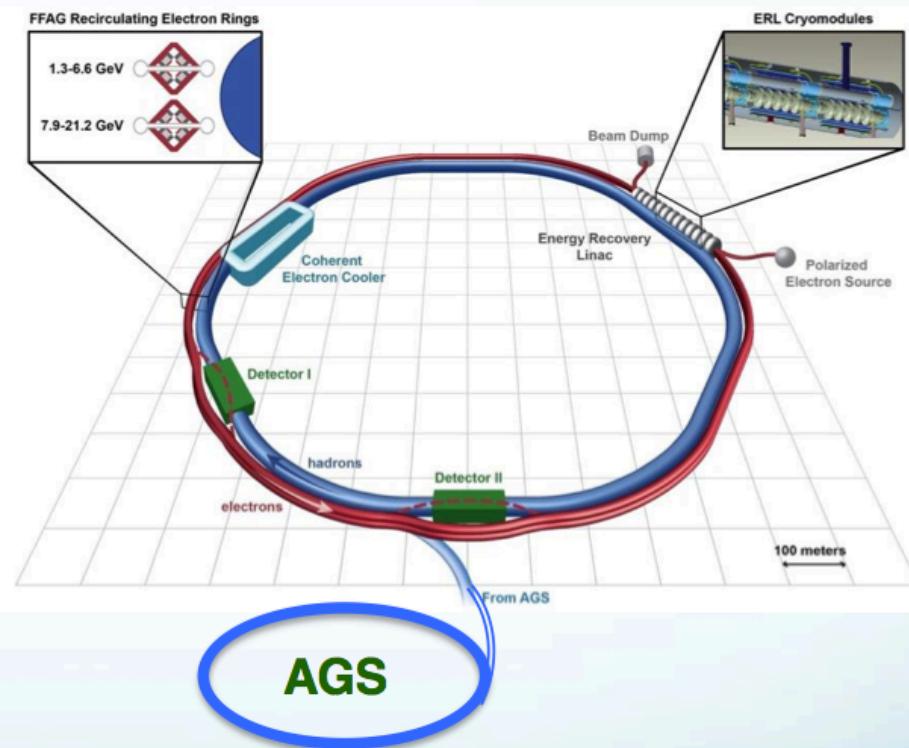
CEIC2
MEIC2
HL-eRHIC
FCC-he

EIC based on the States

MEIC (JLab)



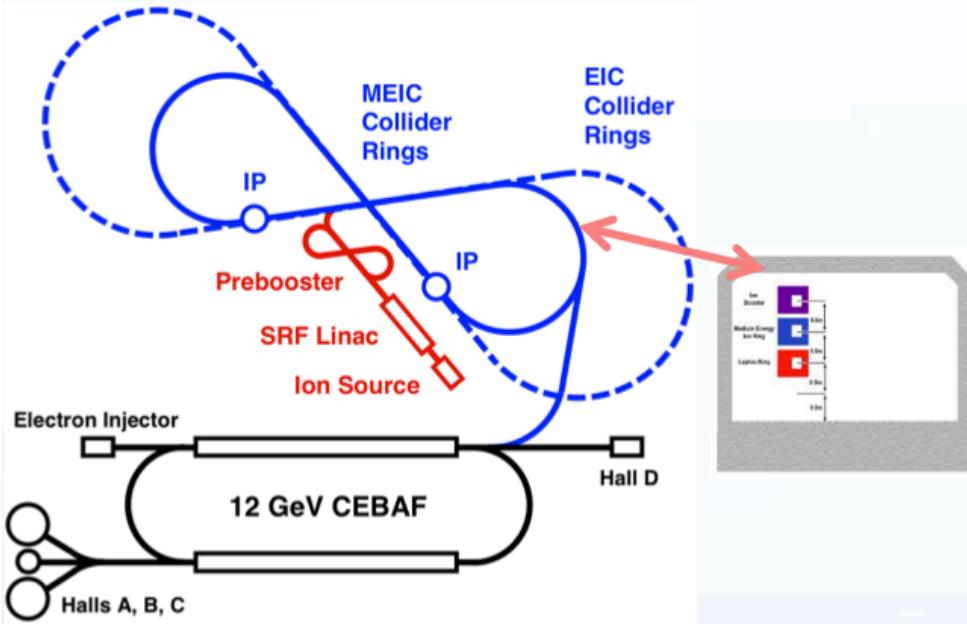
eRHIC (BNL)



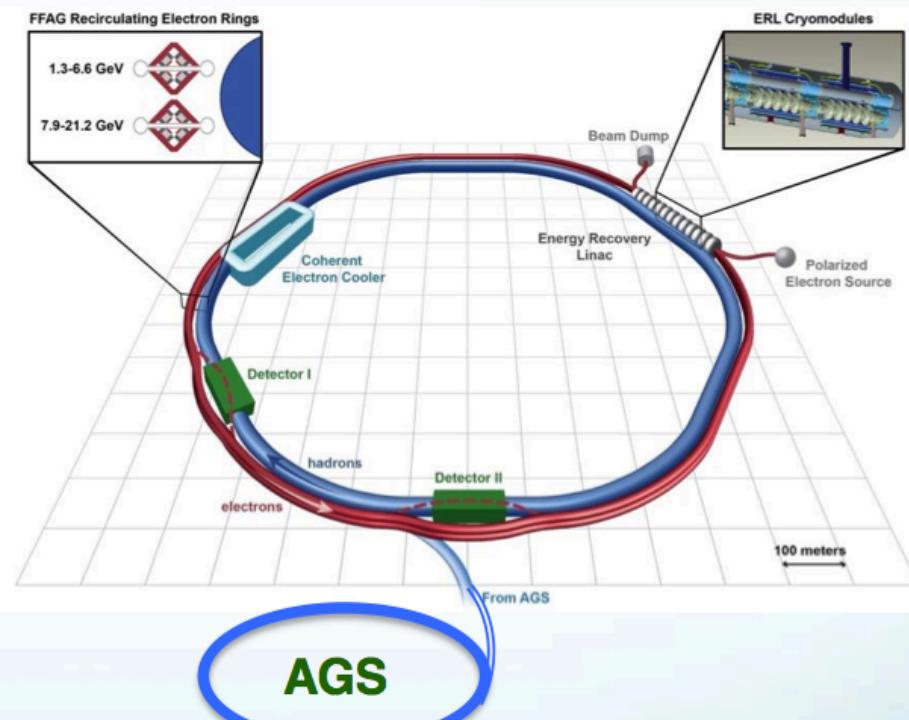
- ✓ First polarized electron-proton/light ions collider
- ✓ First electron nucleus collider
- ✓ Making use of existing facilities
- ✓ Large active community with all needed expertise

EIC based on the States

MEIC (JLab)



eRHIC (BNL)

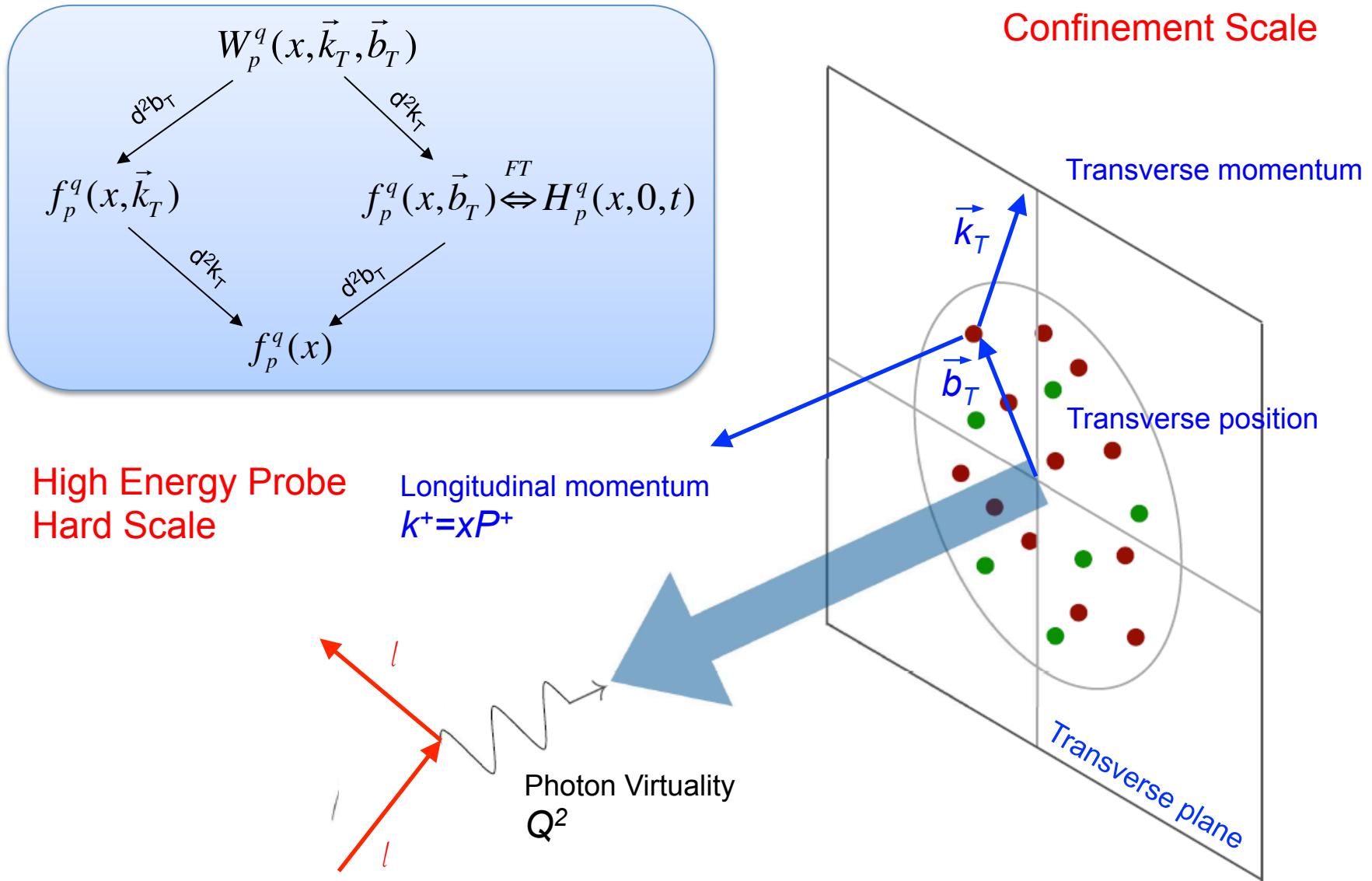


Goals:

- ✓ High polarized (~ 70%) electron and nucleon beams
- ✓ Ion beams from deuteron to lead
- ✓ Variable center-of-mass energy from 20 up to 100 GeV and beyond
- ✓ High collision luminosity 10^{33} - $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

The ultimate facility for 3D nucleon study

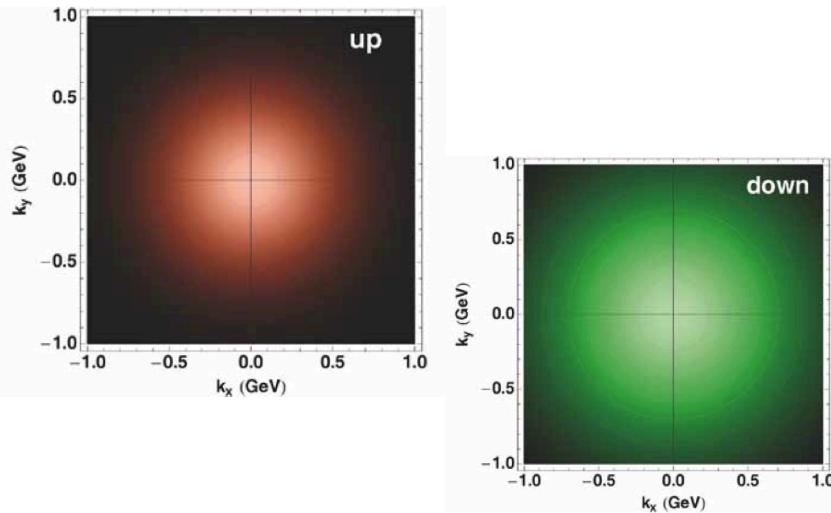
The 3D Nucleon Structure



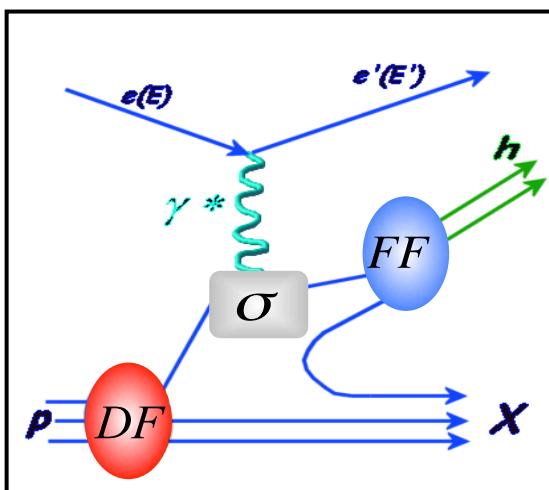
Parton Number Density



Transverse Momentum Dependent Distr.



quark polarisation			
N/q	U	L	T
U	f_1		h_1^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}^\perp	h, h_{1T}^\perp



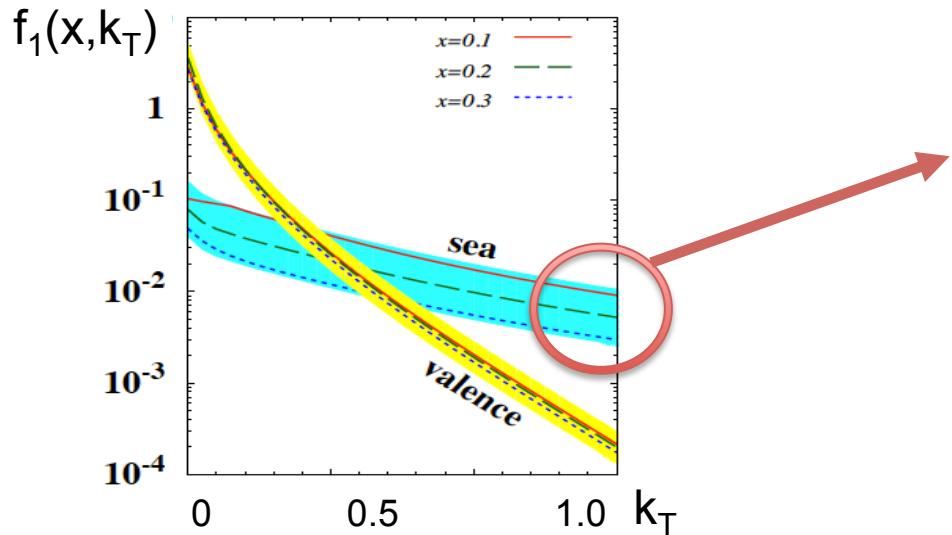
Related to:

- ✓ Low-pT regime:
precise xsec measurements
- ✓ Parton correlations:
short range, MPI
- ✓ Low-x physics:
color glass condensate
- ✓ Hadronization:
parton dynamic in medium

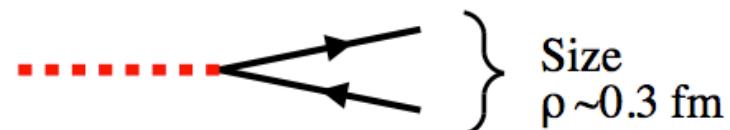
The $P_{h\perp}$ -unintegrated multiplicities

$$\sigma_{UU} \propto f_1(k_T \dots) \otimes D_1(p_T \dots)$$

P. Schweitzer++ [arXiv:1210.1267]



Large tiles extending up to the inverse of the gauge field fluctuation scale $\rho \ll M$

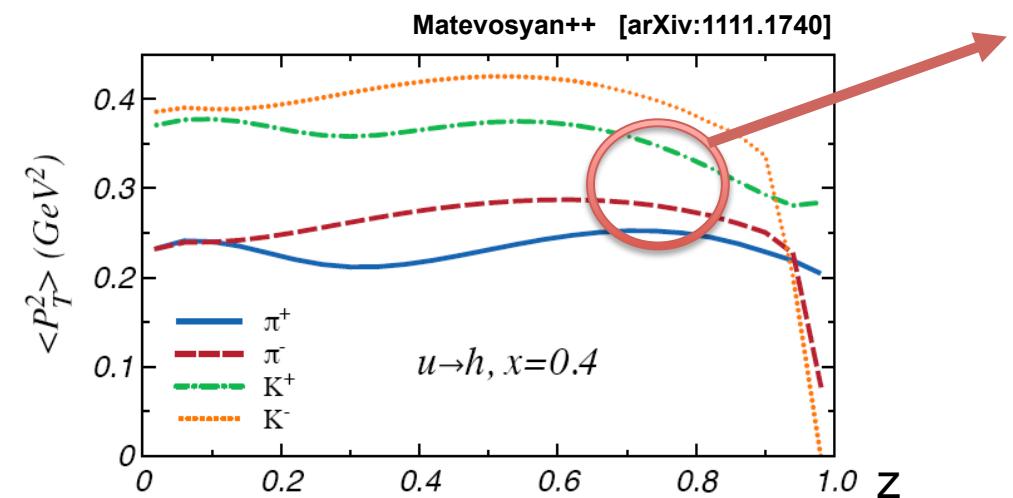


Short range parton correlations may manifest also in pp MPI

Reflect different fragmentation

May be enhanced in medium.

Parton propagation in cold matter as complementary study to QGP



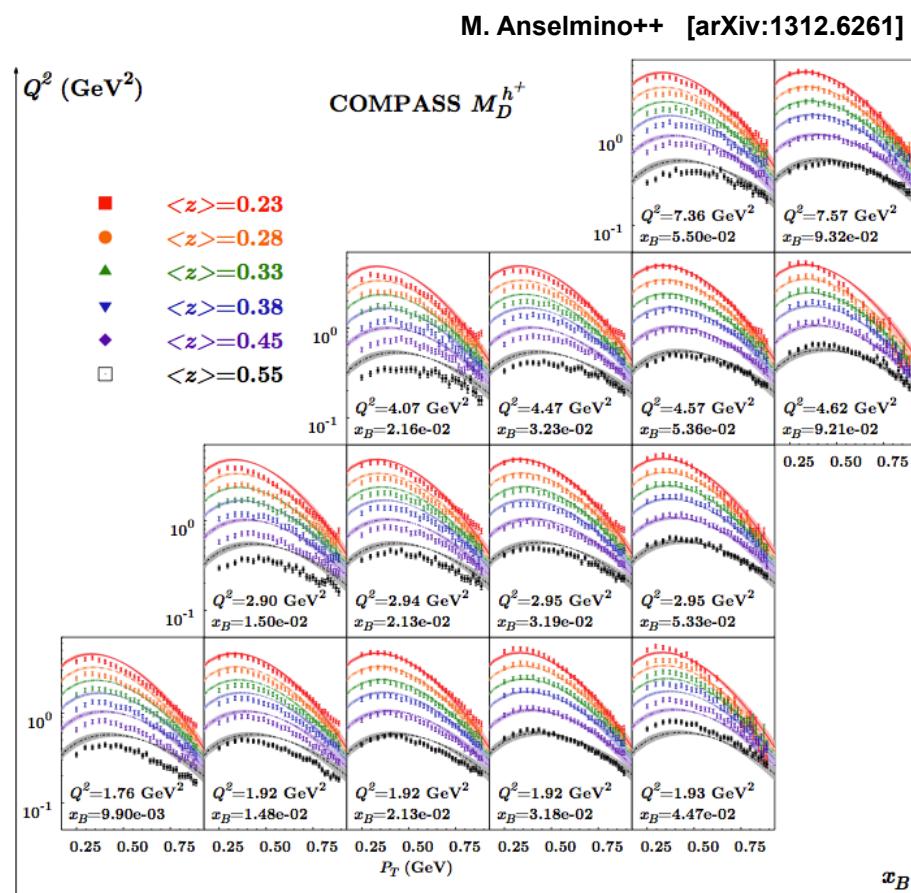
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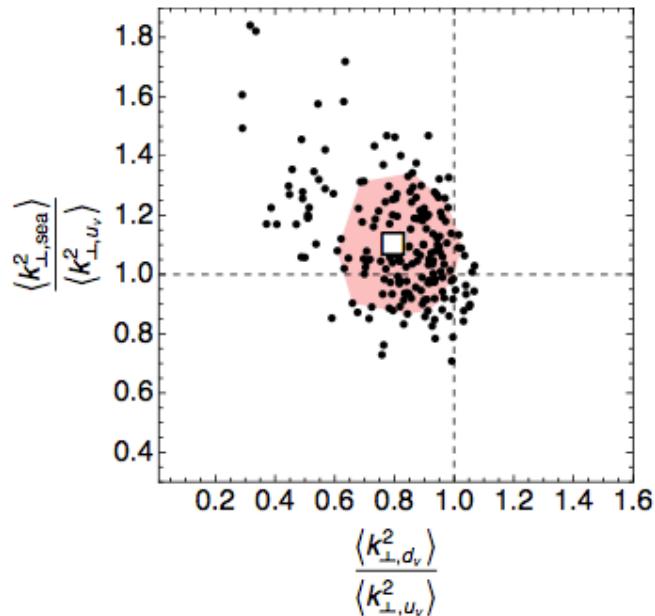
Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T ,

i.e. from gaussian anstaz:

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$



A. Signori++ [arXiv:1309.3507]

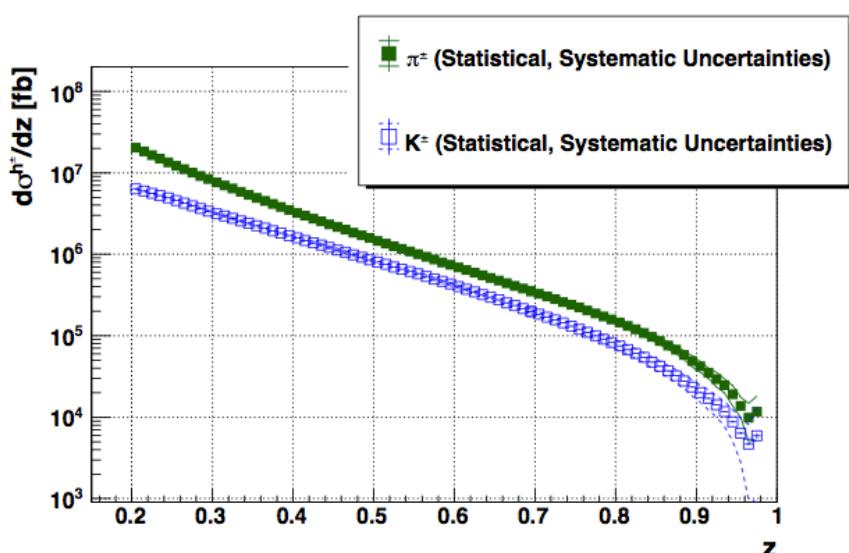


Not yet clear sensitivity on k_T , p_T flavor dependence

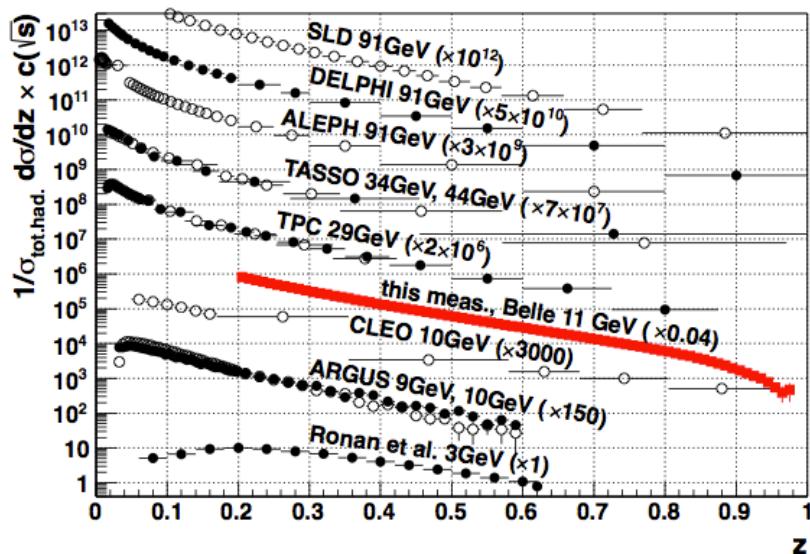
Fragmentation Functions @ B-factories

Belle

[arXiv 1301.6183]

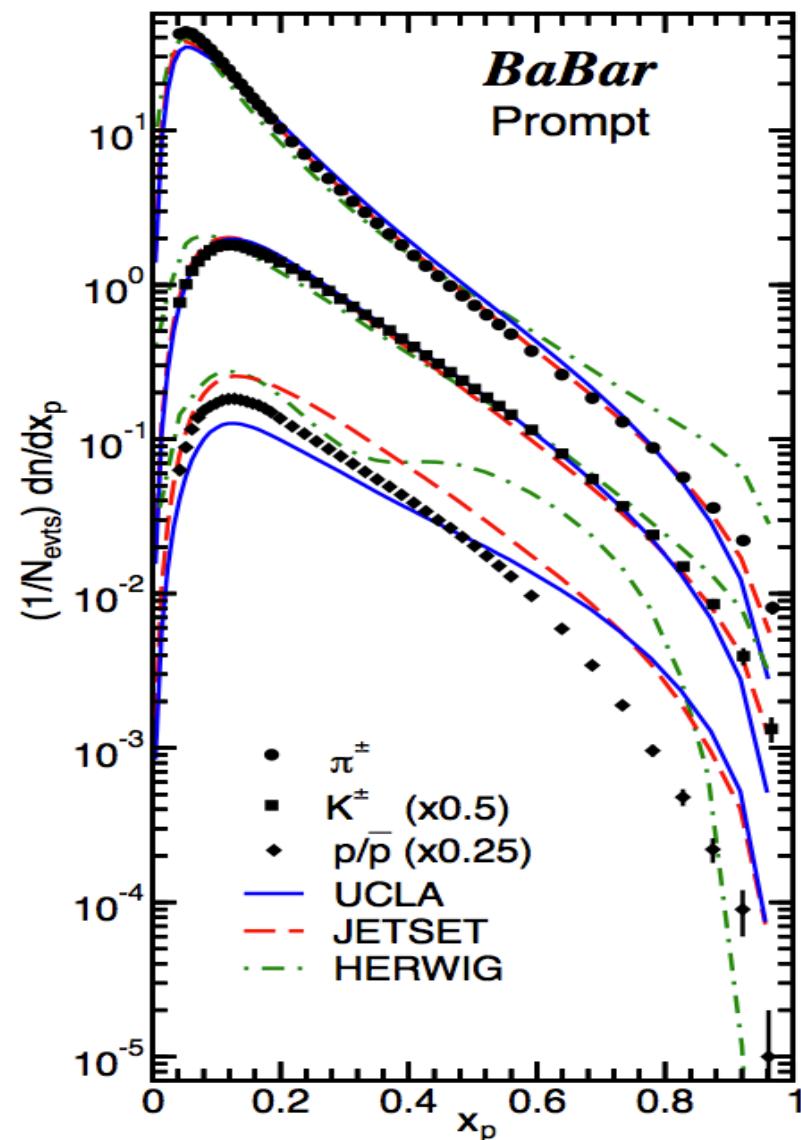


World Data (Sel.) for $e^+e^- \rightarrow \pi^\pm + X$ Production



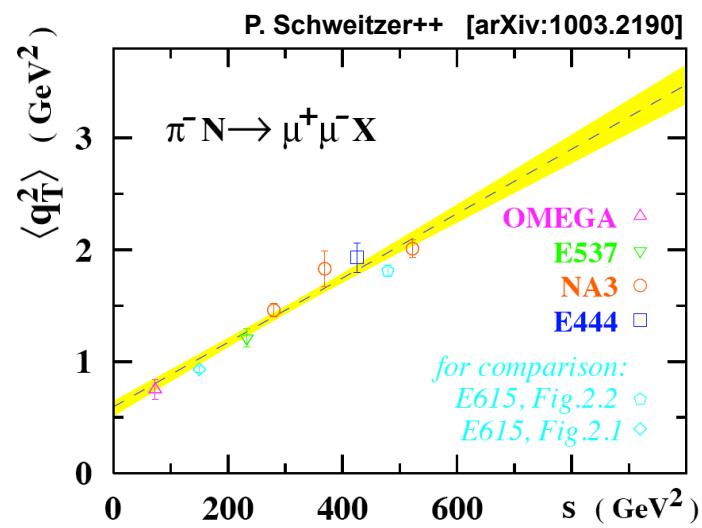
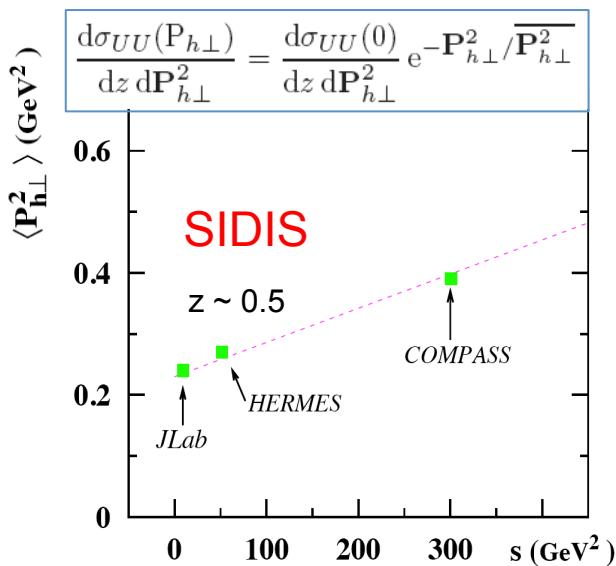
Babar

[arXiv 1306.2895]



TMD Evolution

$f_1 \otimes D_1$



Indication of a k_T and p_T broadening with c.m. energy: TMD evolution

Fixed target SIDIS

$Q^2 \sim \text{few GeV}^2$

TMD Q^2 evolution \neq DGLAP



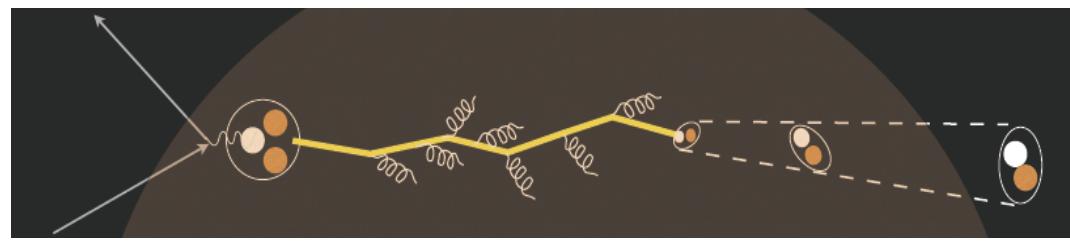
B-factories

$Q^2 \sim 100 \text{ GeV}^2$

Medium modification

In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in SIDIS:

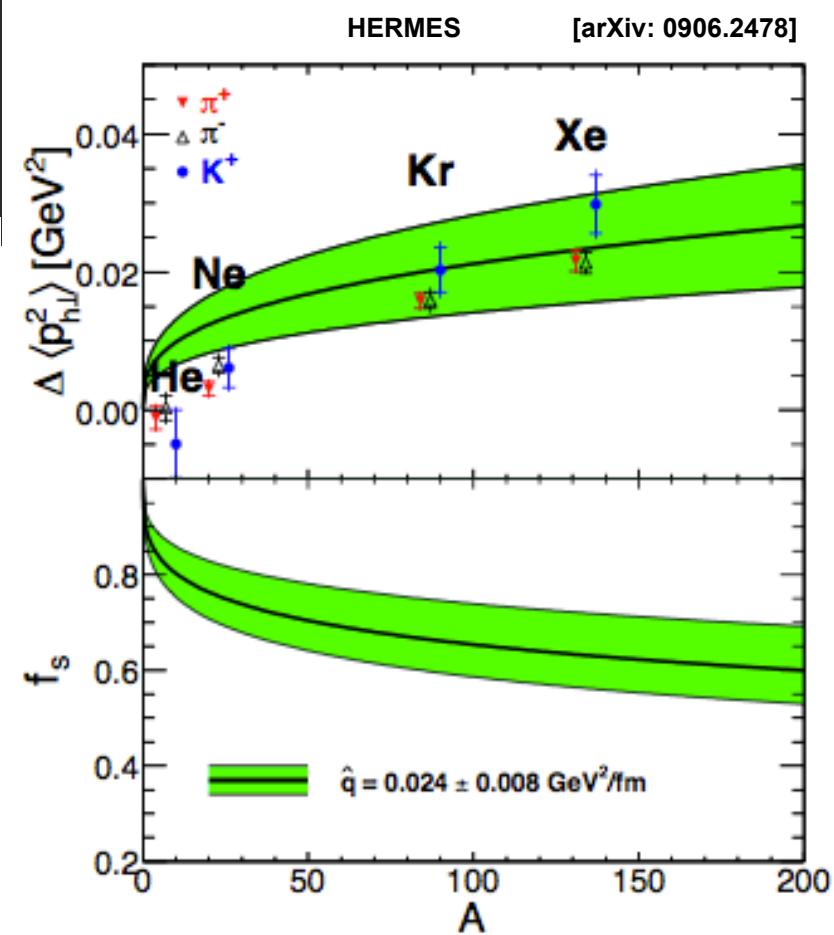
- primordial transverse momentum,
- gluon radiation of the struck quark,
- the formation and soft multiple interactions of the “pre-hadron”
- the interaction of the formed hadrons with the surrounding hadronic medium



N-B Chang ++ [arXiv:1402.3042]

$$\Delta_{2F} = 3 \sqrt{2} \hat{q}_0 r_0 A^{1/3} / 4$$

$$\frac{\langle \cos \phi \rangle_{UU}^{eA}}{\langle \cos \phi \rangle_{UU}^{eN}} \approx \frac{\langle \sin \phi \rangle_{LU}^{eA}}{\langle \sin \phi \rangle_{LU}^{eN}} \approx \frac{\alpha}{\alpha + \Delta_{2F}} = f_s$$

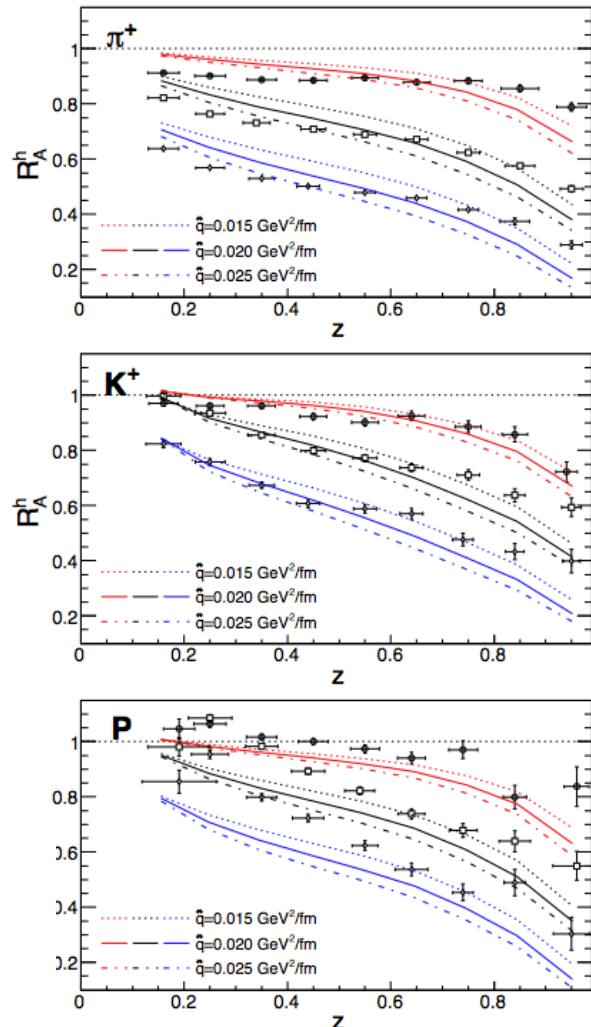


Medium modification

DIS

$$\hat{q}_0 \approx 0.020 \pm 0.005 \text{ GeV}^2/\text{fm}$$

N-B Chang ++ [arXiv:1401.5109]

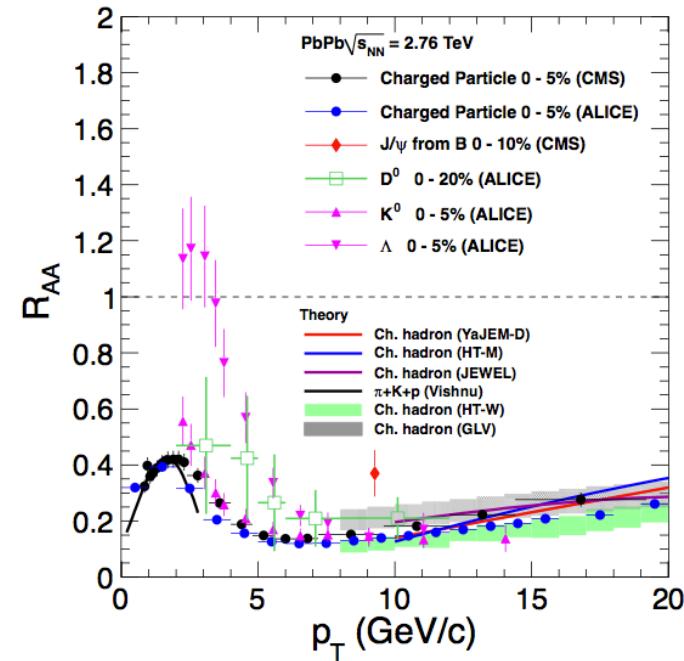


LHC

$$\hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm}$$

Pb+Pb $\sqrt{s} = 2.76 \text{ TeV/n}$

JET Coll. [arXiv:1312.5003]

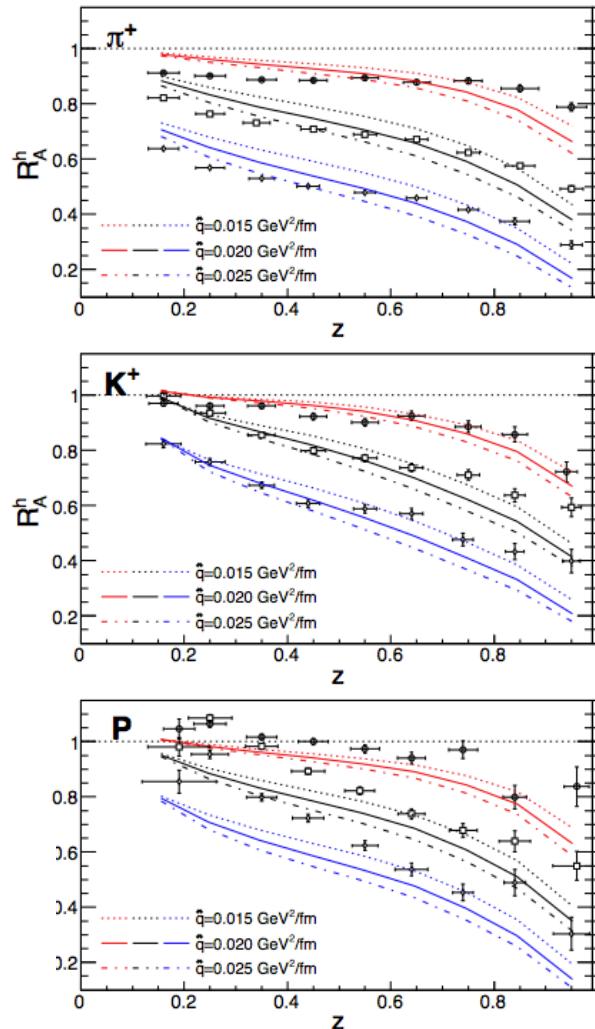


Medium modification

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N-B Chang ++ [arXiv:1401.5109]

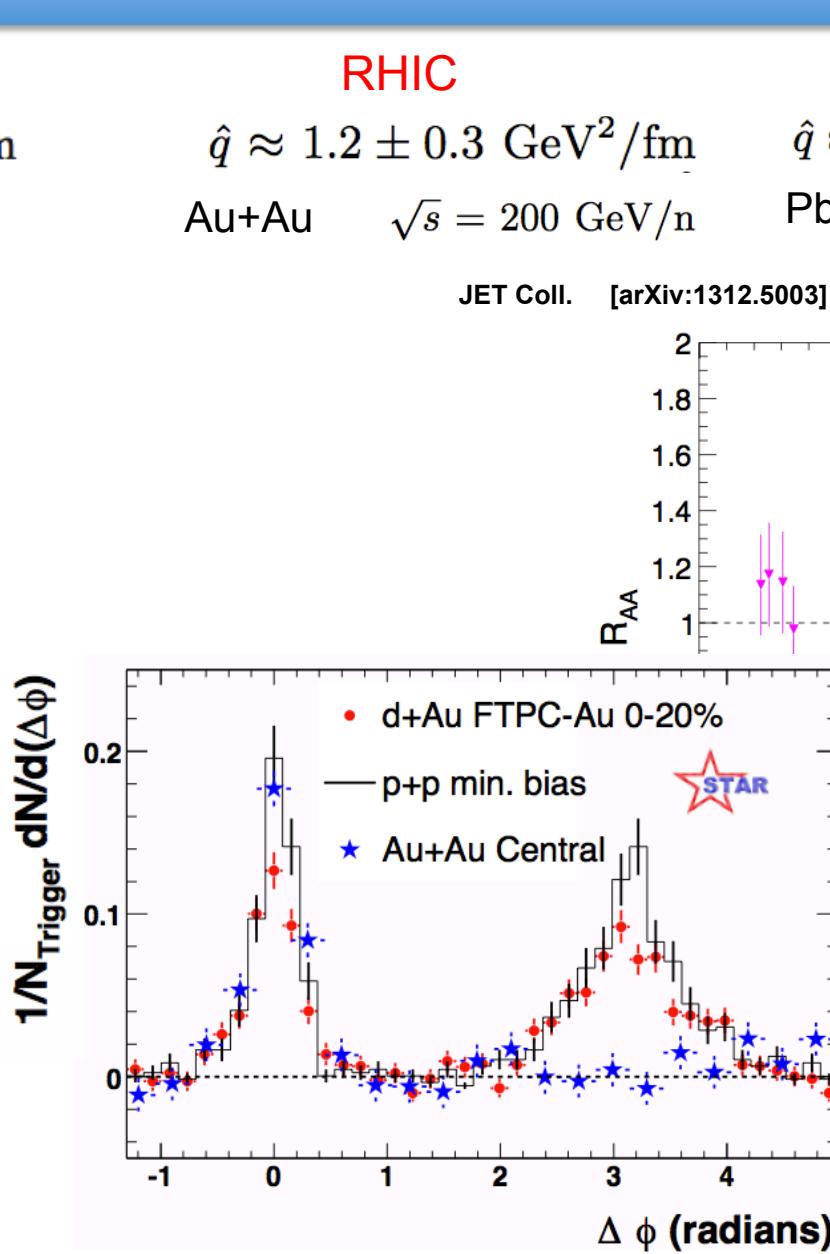


RHIC

$$\hat{q} \approx 1.2 \pm 0.3 \text{ GeV}^2/\text{fm}$$

Au+Au $\sqrt{s} = 200 \text{ GeV/n}$

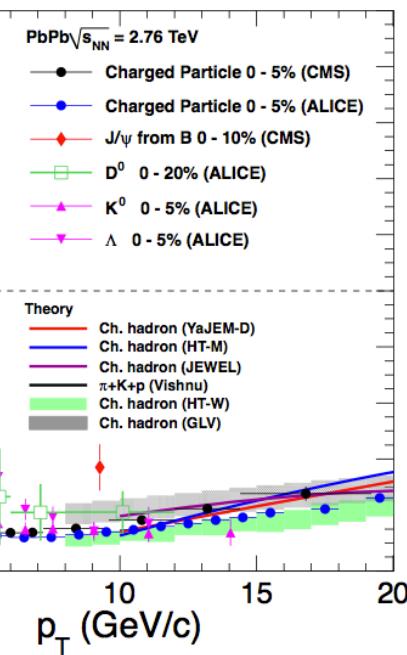
JET Coll. [arXiv:1312.5003]



LHC

$$\hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm}$$

Pb+Pb $\sqrt{s} = 2.76 \text{ TeV/n}$



Medium modification @ EIC

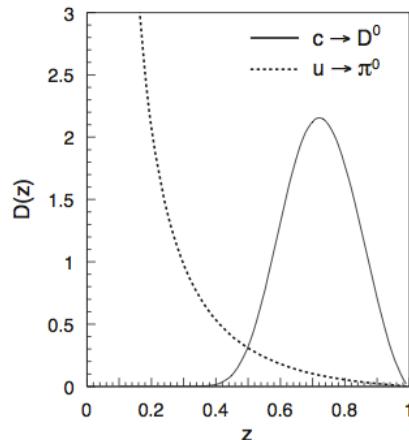
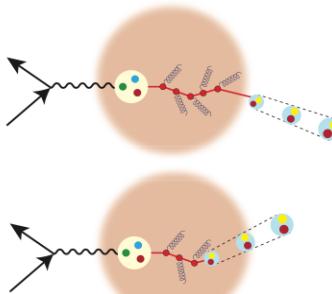
Unprecedented precision over a wide Q^2, ν range

Light vs heavy quarks

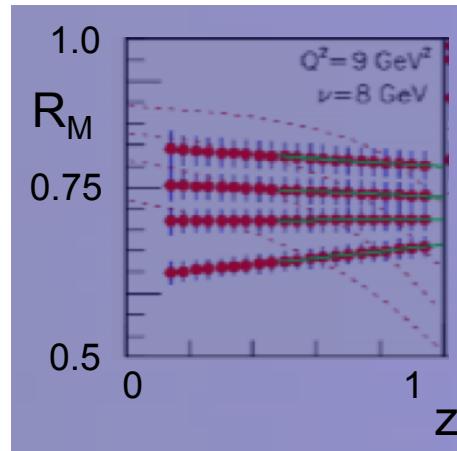
D^0 enhancement due to the different FFs

Slope sensitive to the transport parameter

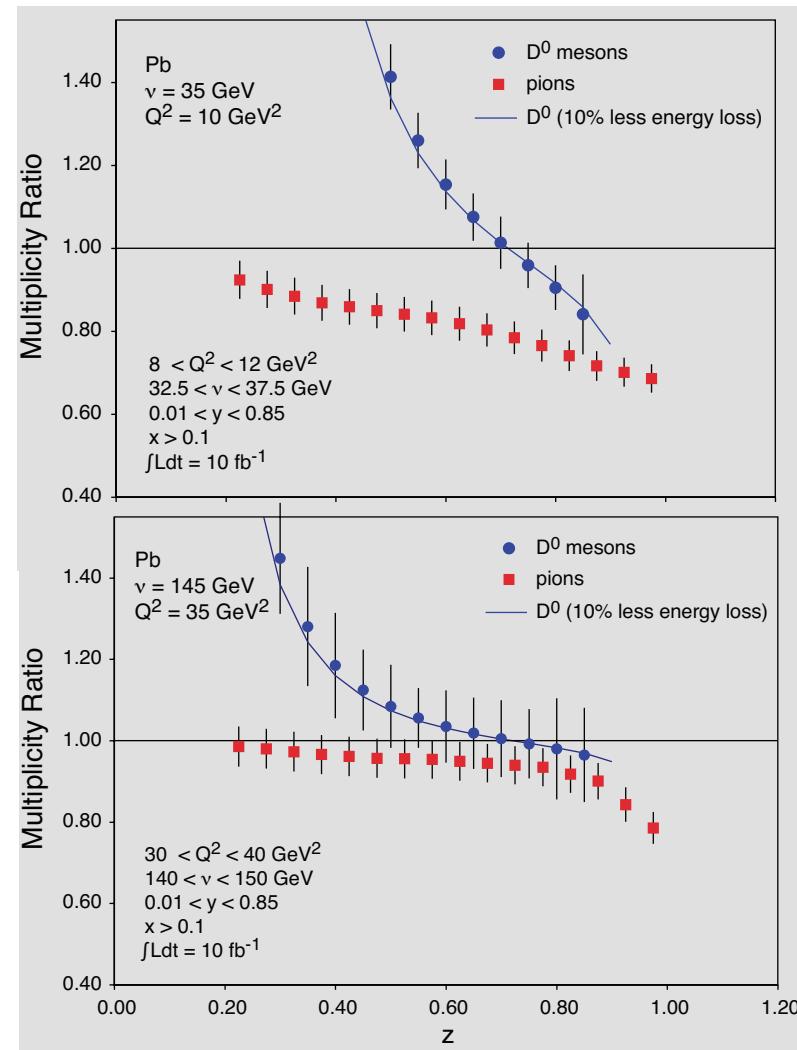
Shape sensitive to ν



Comparable precision
but much limited range
@ JLab12:

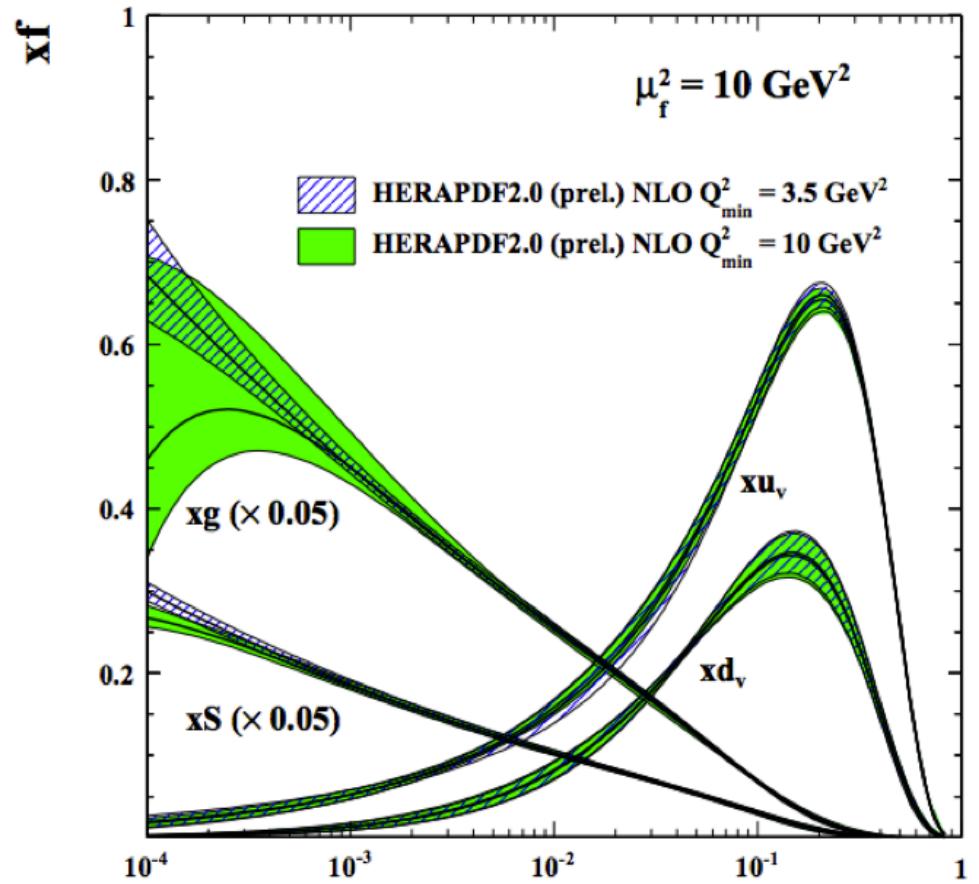


A. Accardi et al. [arXiv 1212.1701]



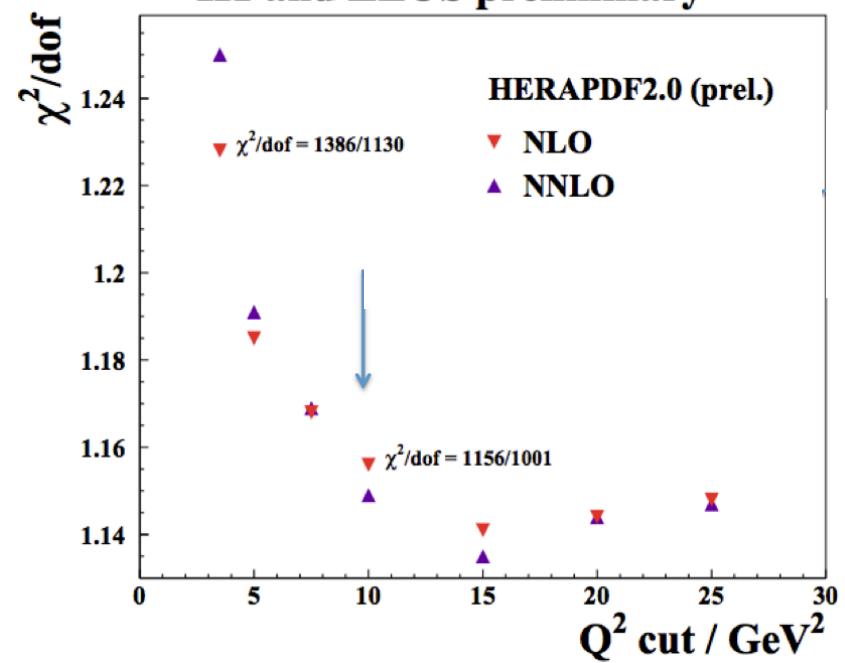
Low-x Physics

H1 and ZEUS preliminary



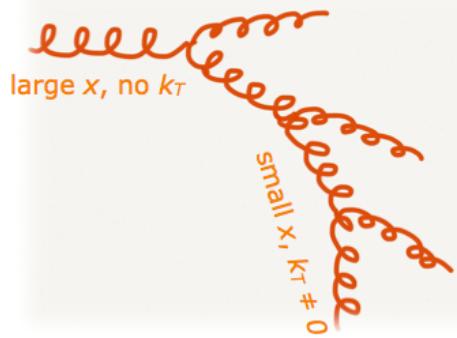
[V. Radescu @ DIS14]

H1 and ZEUS preliminary



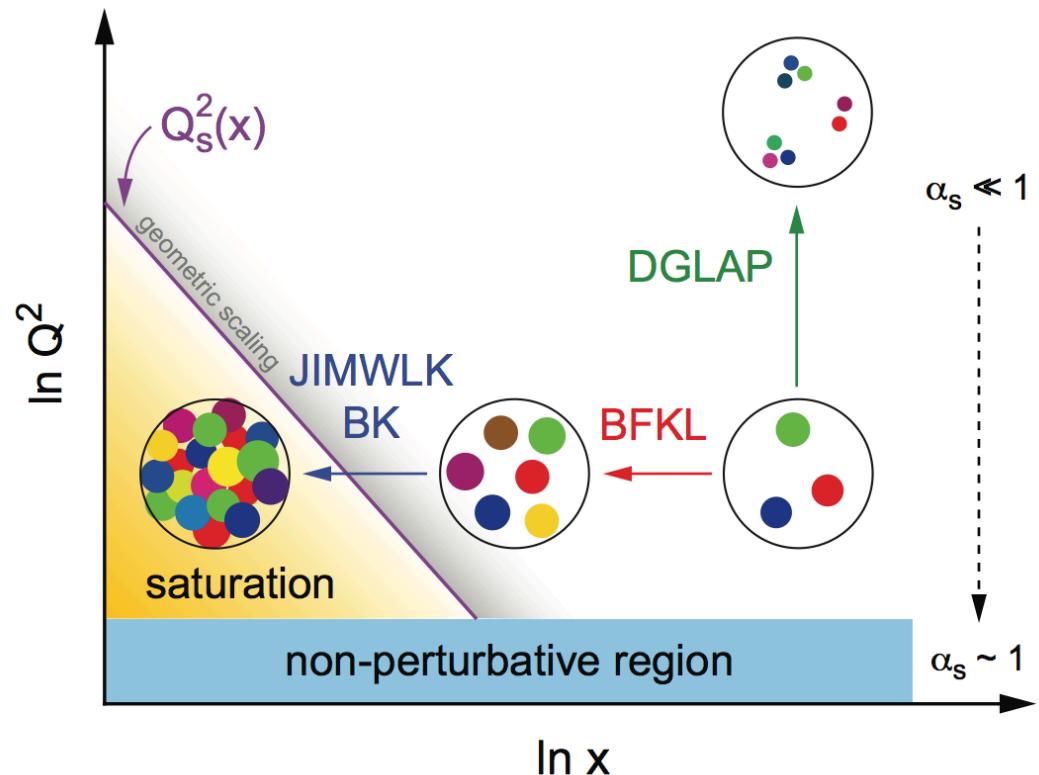
Interplay of the data cut at low Q^2 and impact on gluon at low x

QCD Phase Diagram



x low, Q^2 not too high:

- ▶ **partonic k_T** may become important!
 - are (perturbative) parton showers enough to describe this?
 - or does one need something more? k_T -dependent parton densities?



BFKL must be the correct theory of low-x QCD

It naturally incorporates k_T -unintegrated PDFs

Mechelen at DIS2014: no clear evidence of BFKL in experimental data

Gluon TMDs

F. Hautmann and H. Jung [arXiv 1312.7875]

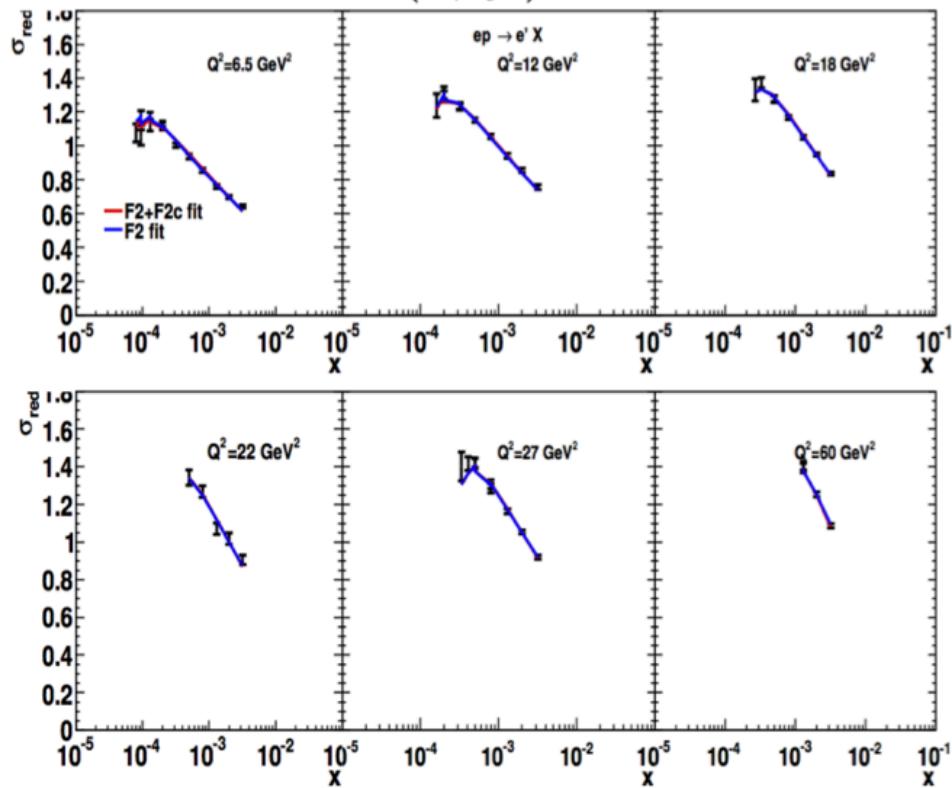
Starting distribution for gluons at q_0

$$x\mathcal{A}_0(x, k_\perp) = Nx^{-B} \cdot (1-x)^C (1-Dx + E\sqrt{x}) \exp[-k_t^2/\sigma^2]$$

CCFM (BFKL like) evolution + Herafitter package

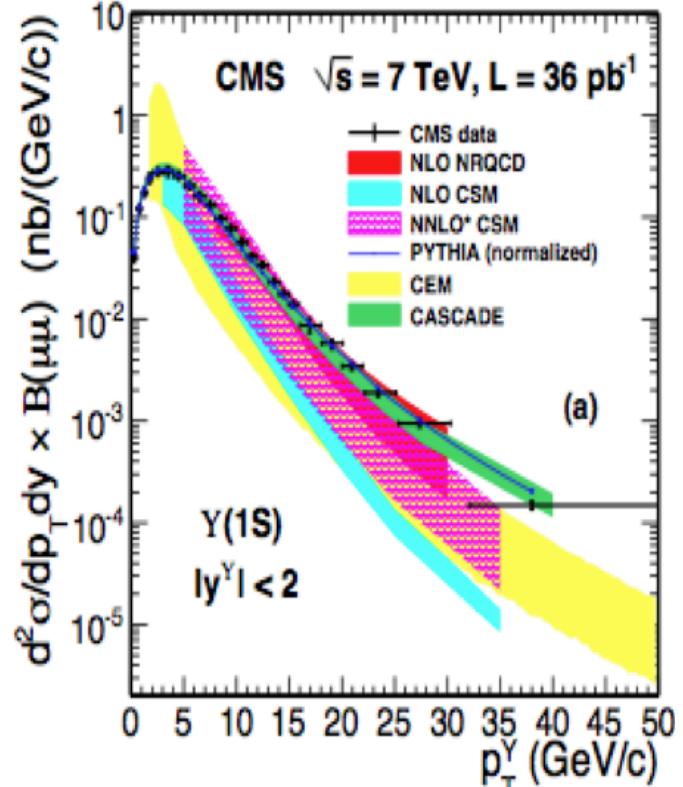
$$\sigma^2 = q_0^2 / 2$$

$F_2(x, Q^2)$



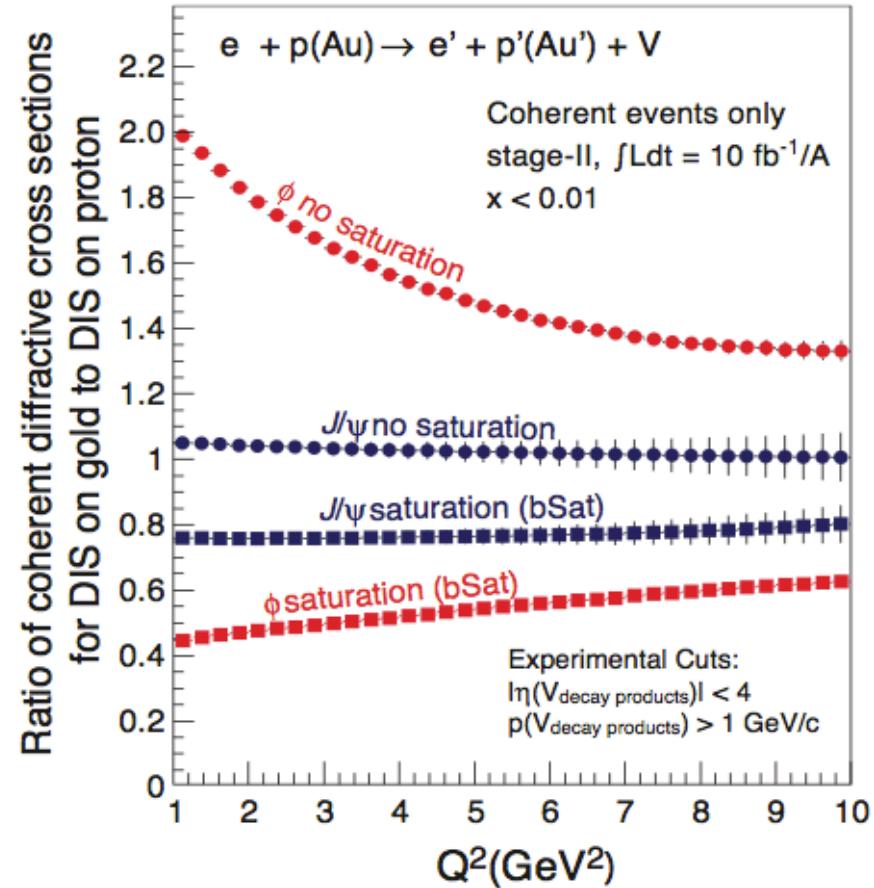
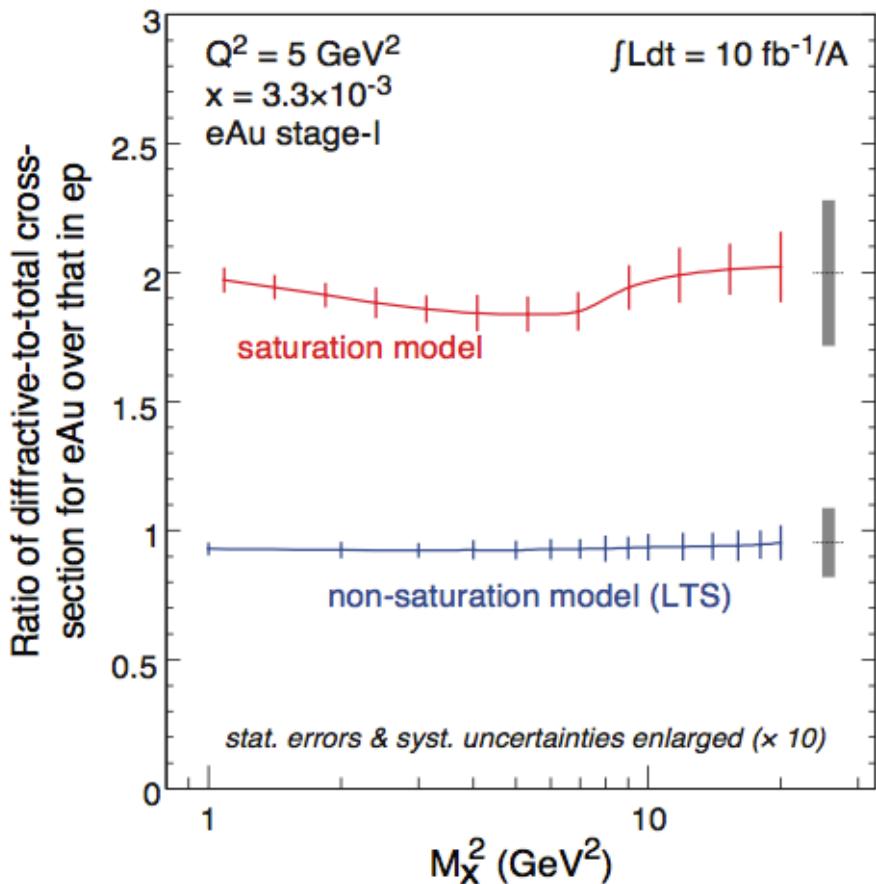
$g^* g^* \rightarrow \Upsilon g$

CMS [arXiv:1303.5900]



Gluon Saturation @ EIC

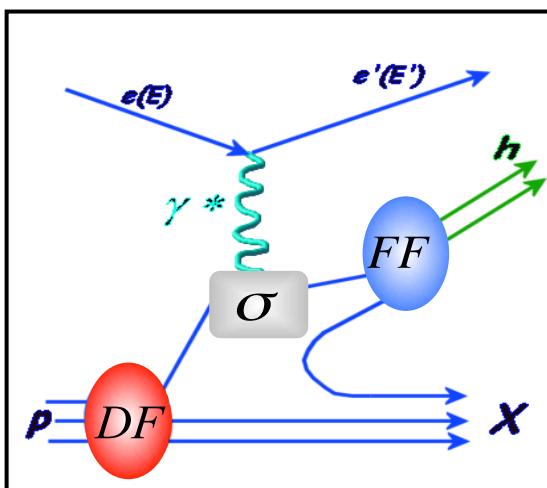
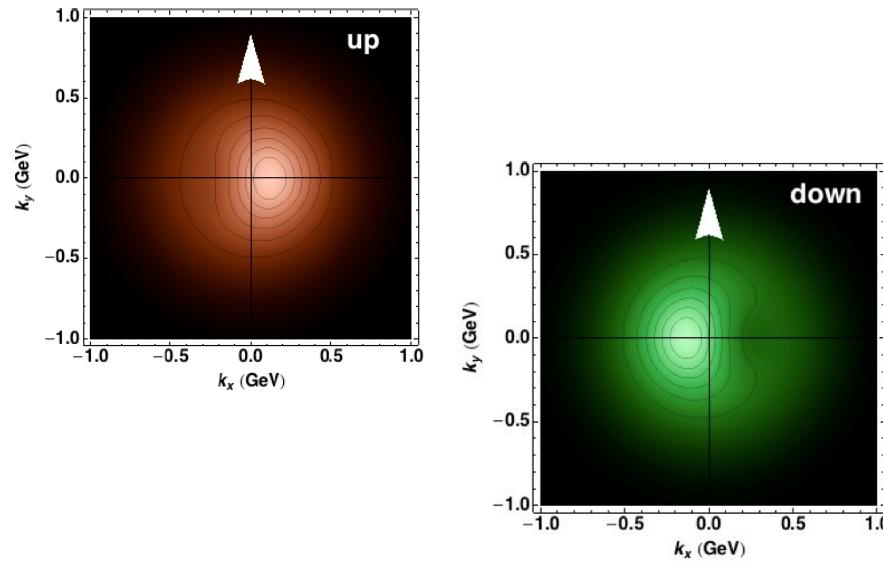
Ions effectively enhance gluon density contribution when
coherent length $\sim 1/x$ is larger than nucleus diameter $\sim A^{1/3}$



Spin-Orbit Effects



Transverse Momentum Dependent Distr.



		quark polarisation		
		U	L	T
nucleon polarisation	U	f_1		h_1^\perp
	L		g_1	h_{1L}^\perp
	T	f_{1T}^\perp	g_{1T}^\perp	h, h_{1T}^\perp

Off-diagonal elements:

Interference between wave functions with different angular momenta: testing QCD at the amplitude level

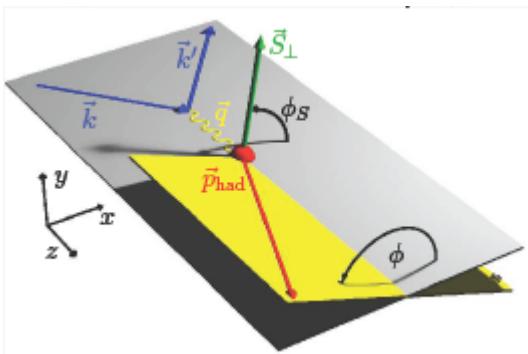
T-odd elements:

- Sign change between DY and SIDIS
Generalized universality of TMDs

Related to:

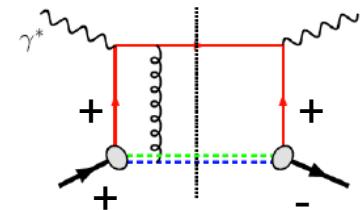
- ✓ Parton Spin-Orbit effects: may explain pp SSA & DY Lam-Tung
- ✓ Parton Orbital motion

Sivers Signals



SIDIS:
 $e p \rightarrow e' h X$

$$\sigma_{UT}^{\sin(\phi - \phi_S)} \propto f_{1T}^\perp \otimes D_1$$

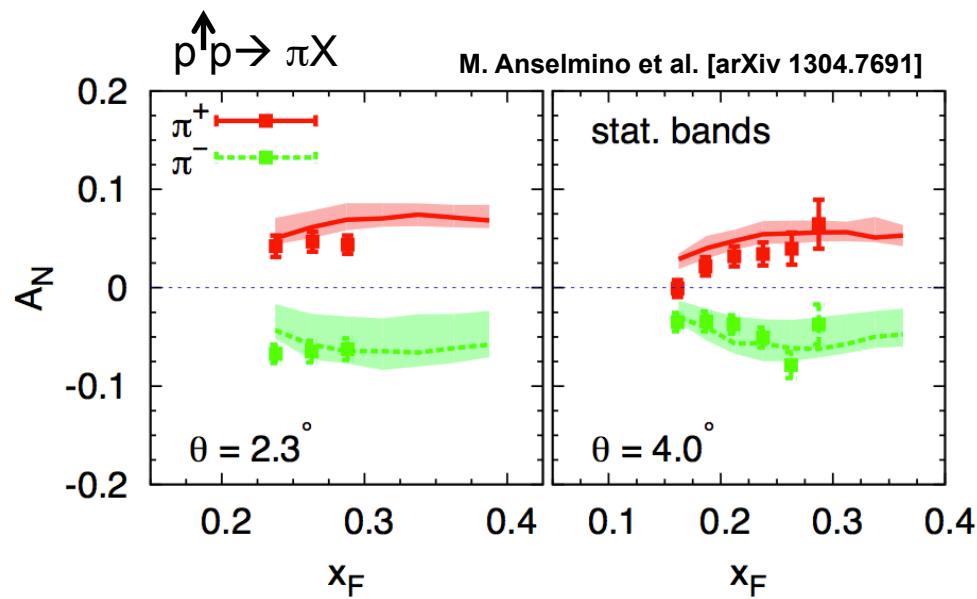
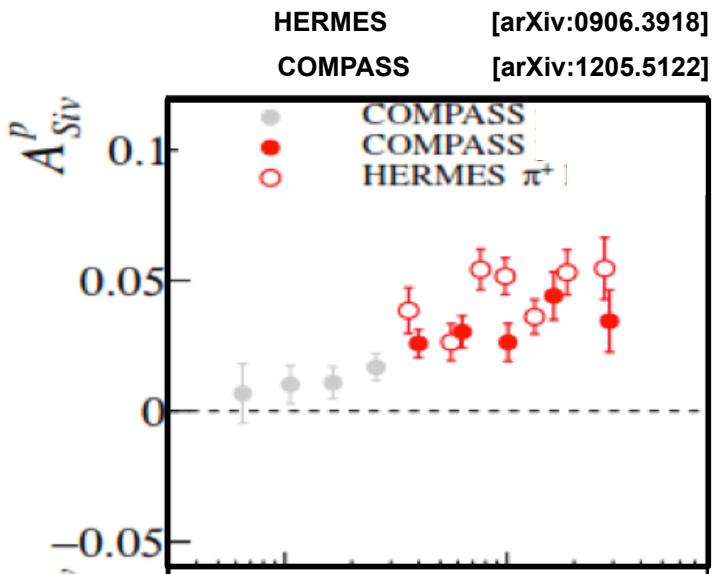


Interference between proton wave function components with different orbital angular momentum

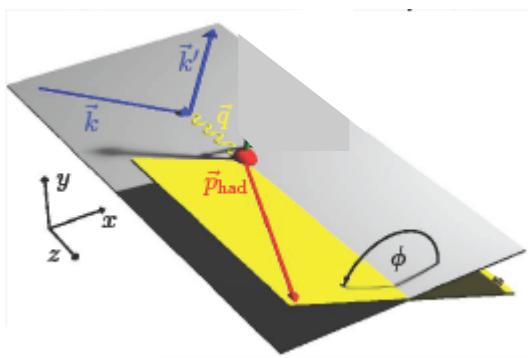
**Sivers from
polarized SIDIS**



**May generate the mysterious
hadronic SSA**

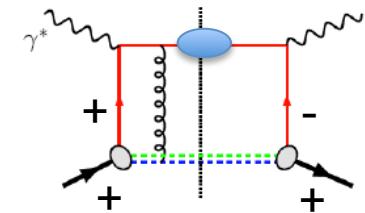


Boer-Mulders Signals



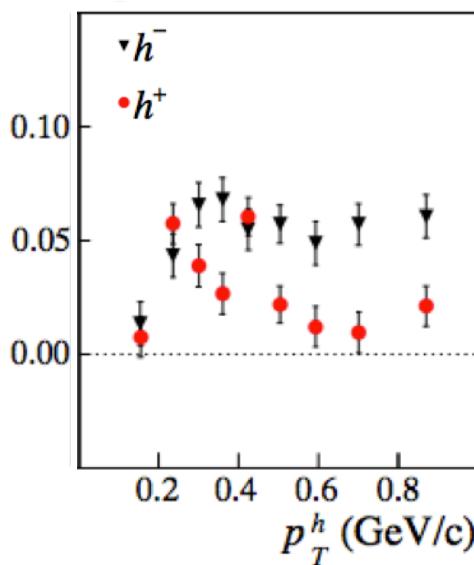
SIDIS:
 $e p \rightarrow e' h X$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp$$

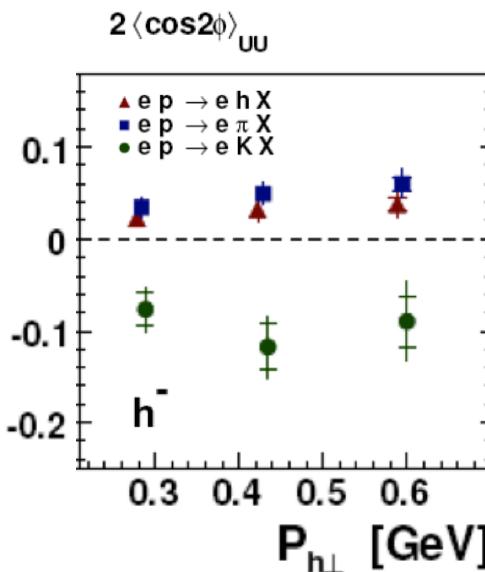


Interference between proton wave function components with different orbital angular momentum

$$A_{\cos 2\phi_h}^{UU}$$



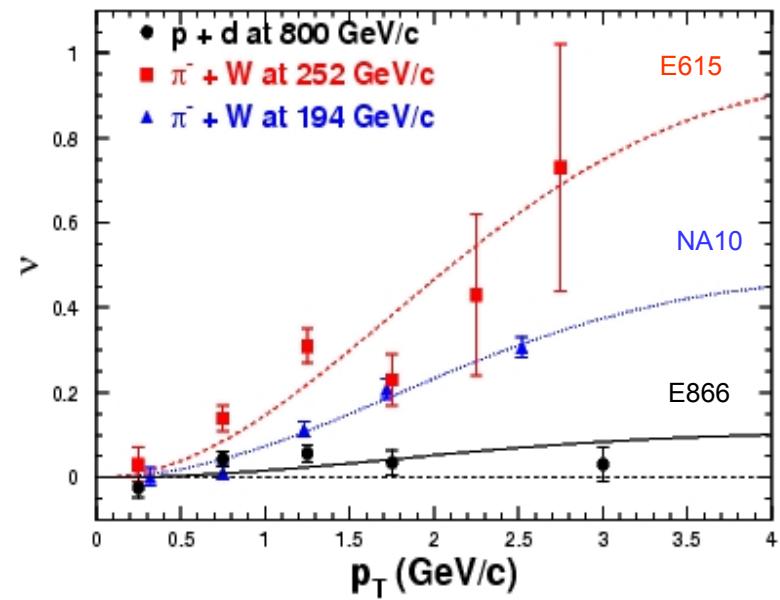
Unpol. SIDIS



COMPASS [arXiv:1401.6284]

HERMES [arXiv:1204.4161]

May explain the Lam-Tung
relation violation in Drell-Yan



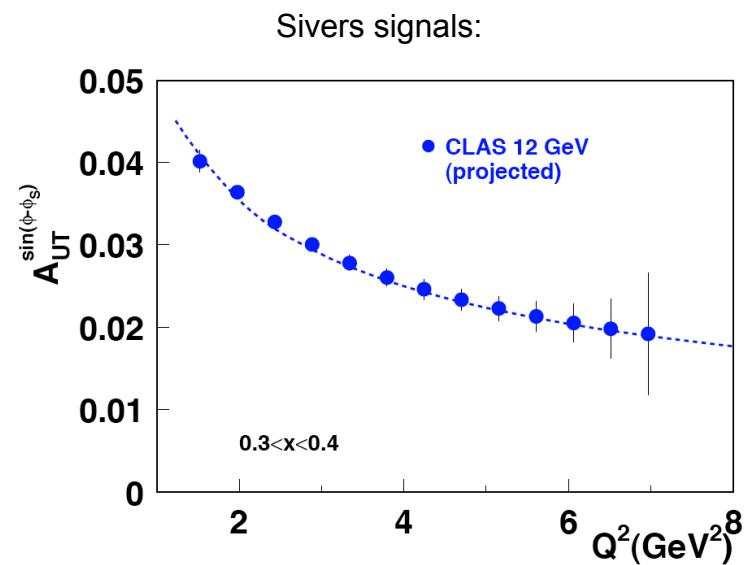
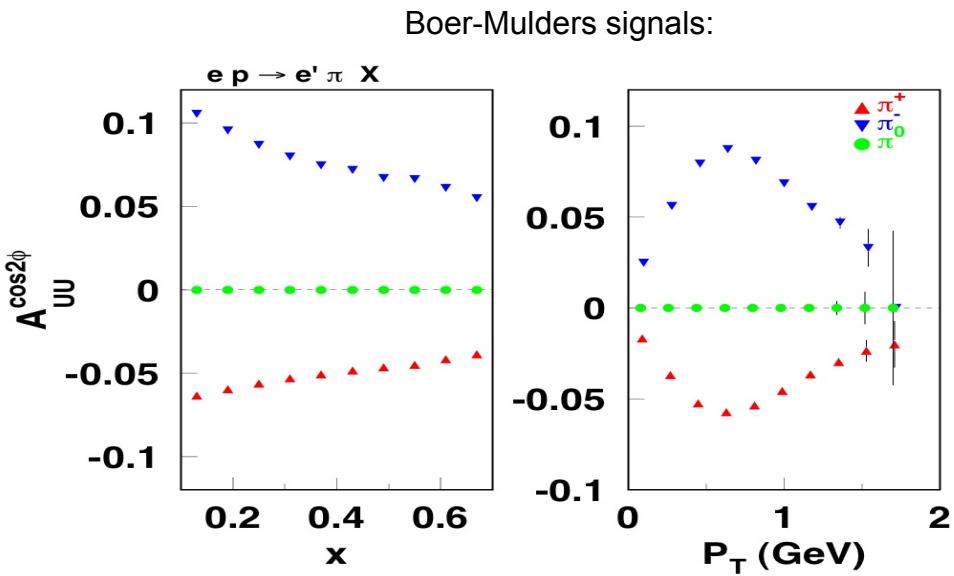
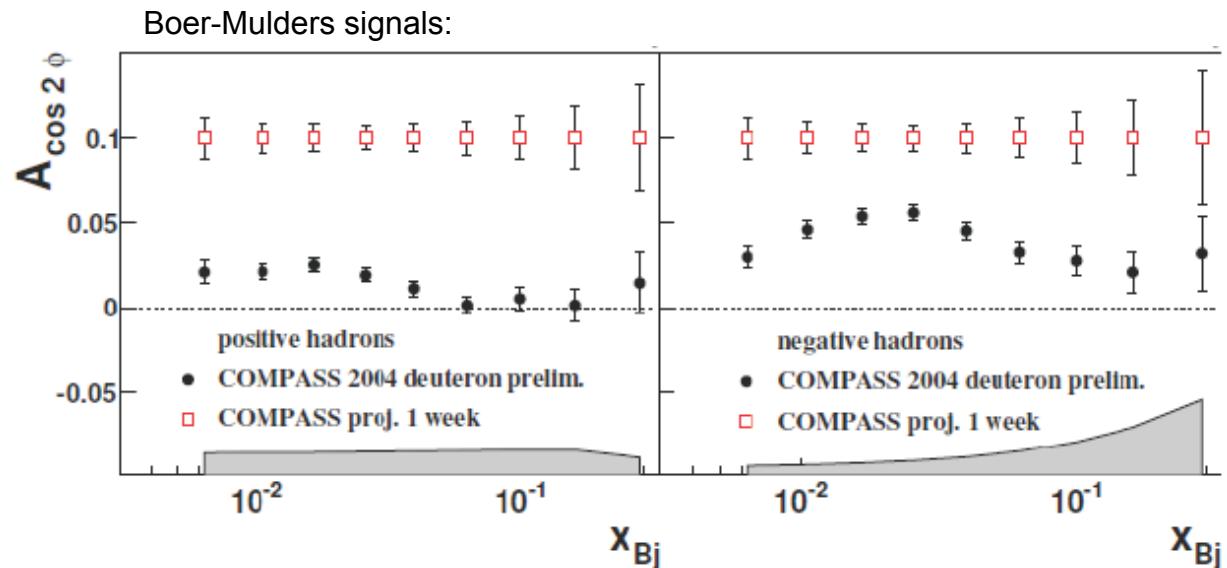
SIDIS News in 2016+

COMPASS-II:

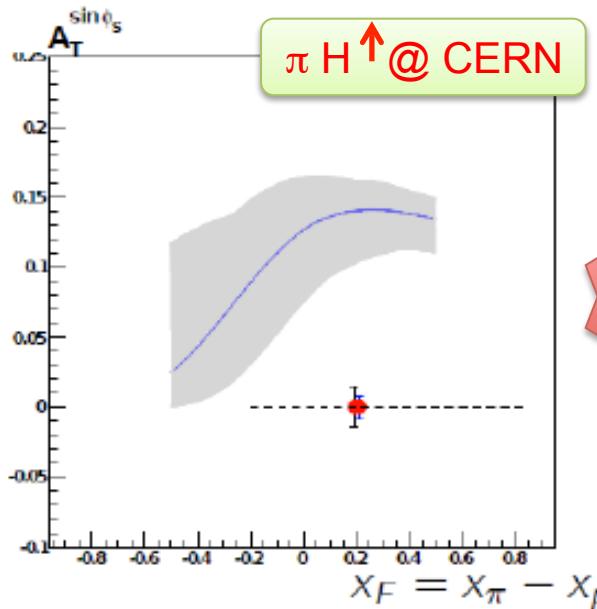
LH₂ target
160 GeV/c muons
 $\text{L} \sim 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

JLAB12:

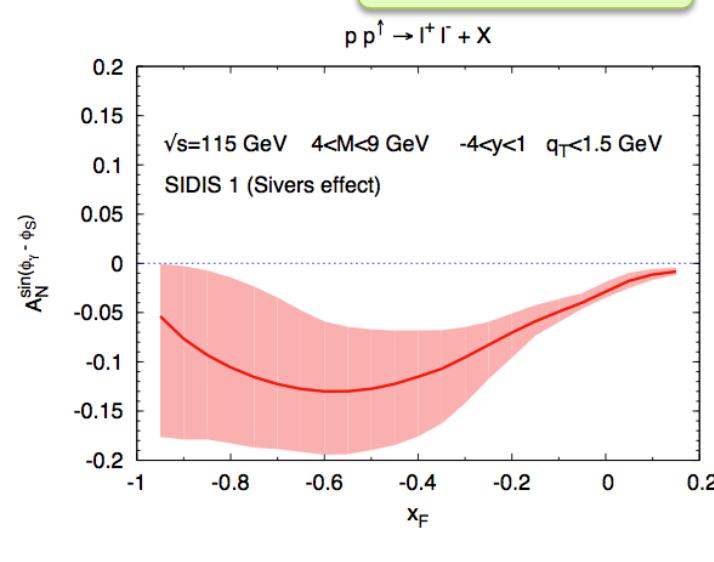
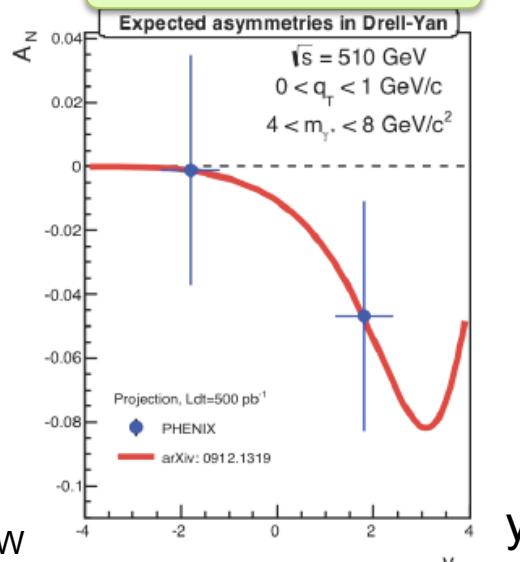
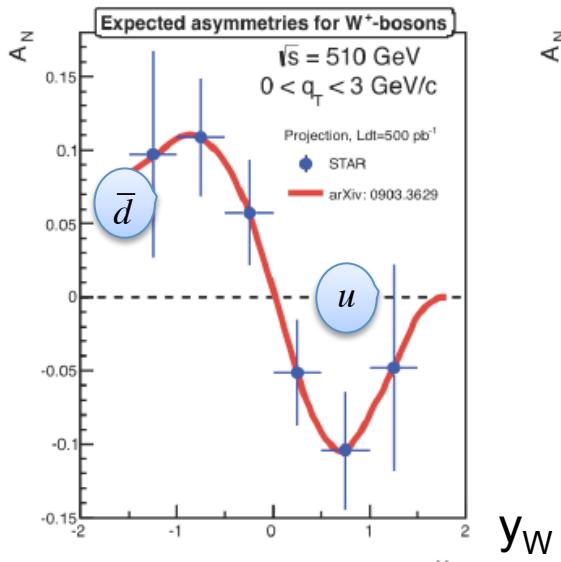
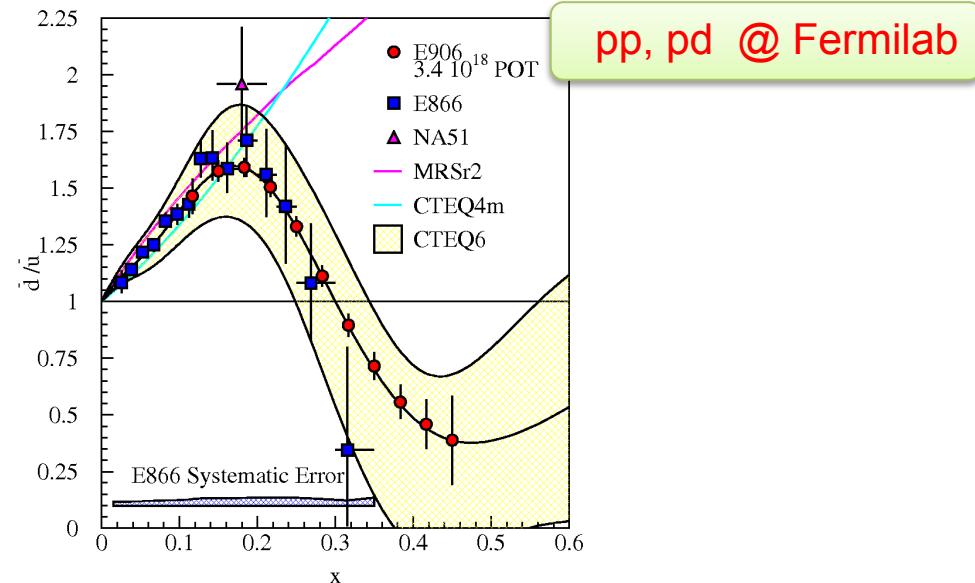
LH₂, HD-ice, NH₃ target
12 GeV/c electrons
 $\text{L} \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$



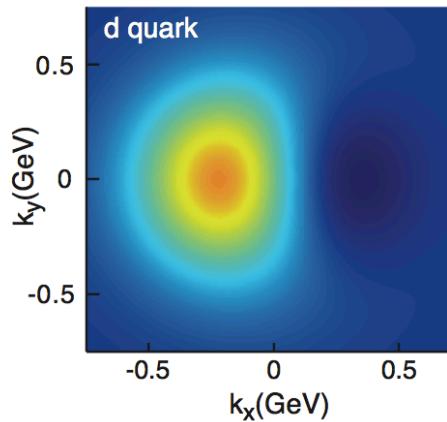
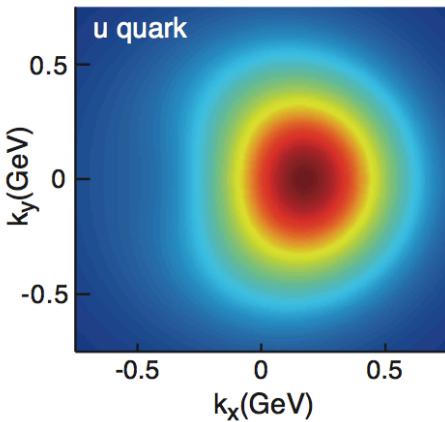
The Drell-Yan Landscape 2015+



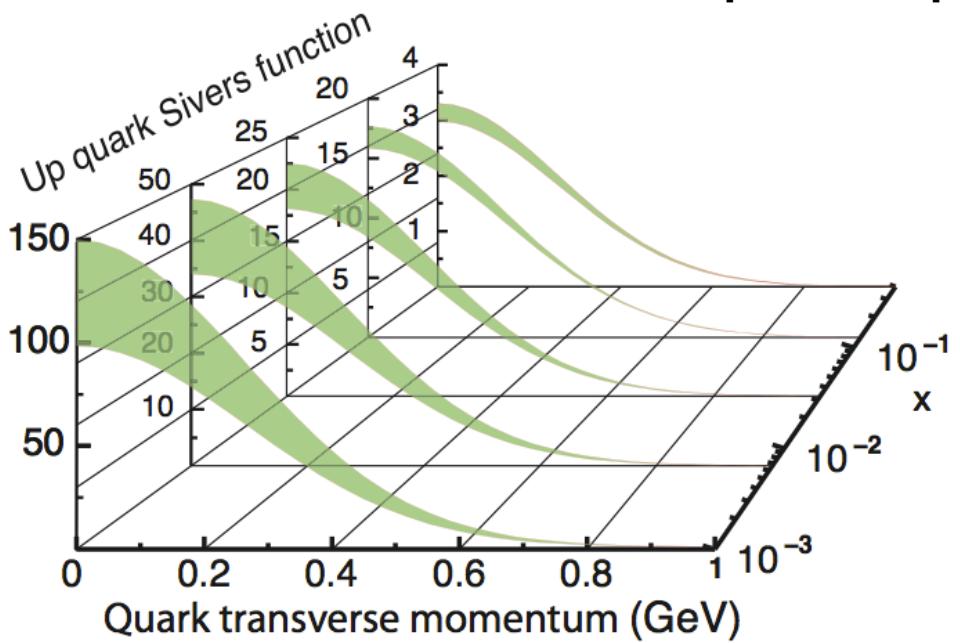
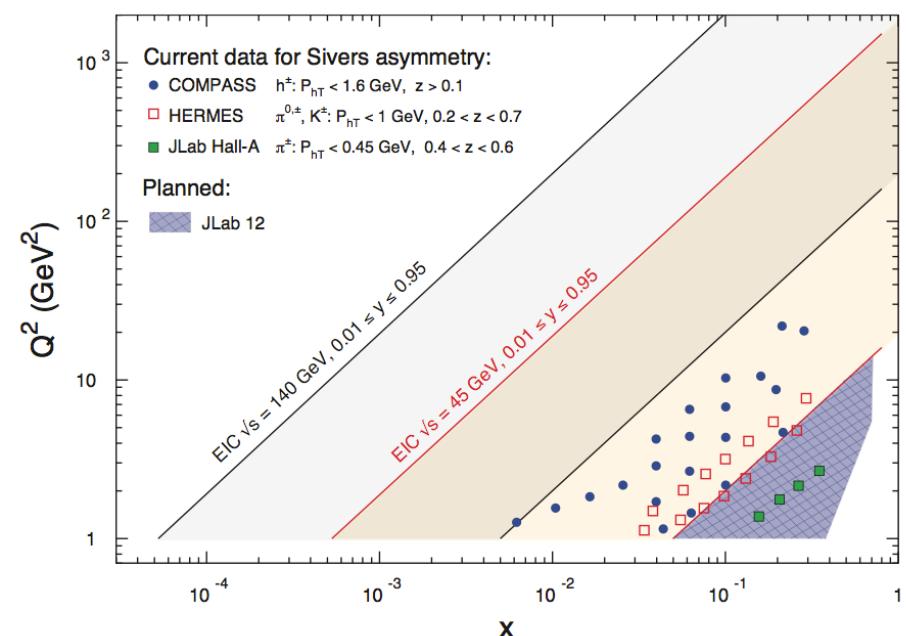
TMD SIGN CHANGE ?



Sivers @ EIC



A. Accardi et al. [arXiv 1212.1701]

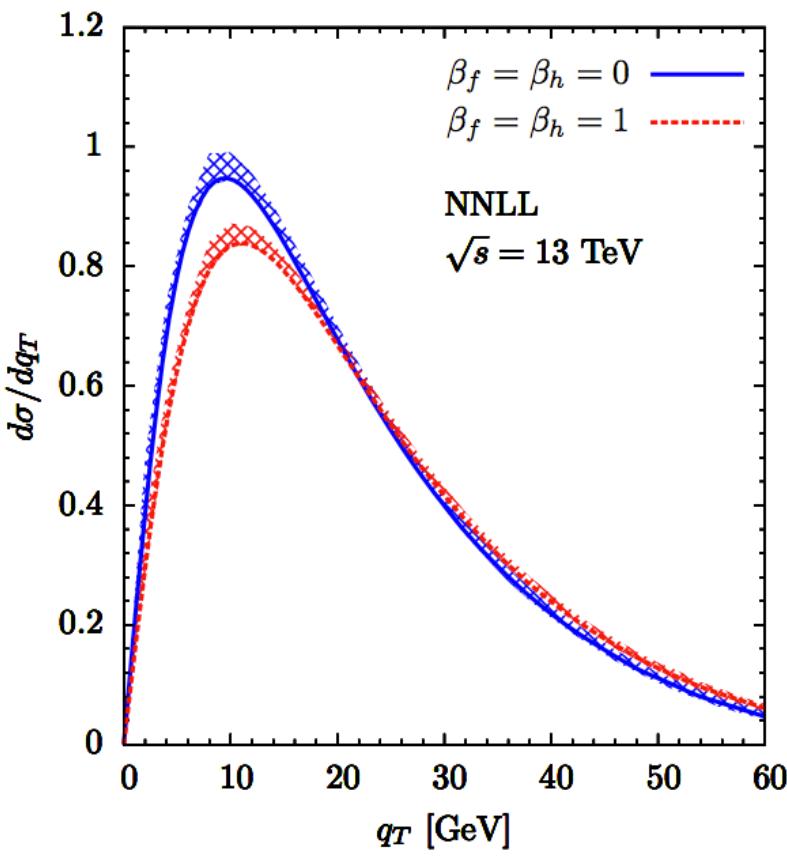


Gluon Linear Polarization @ LHC

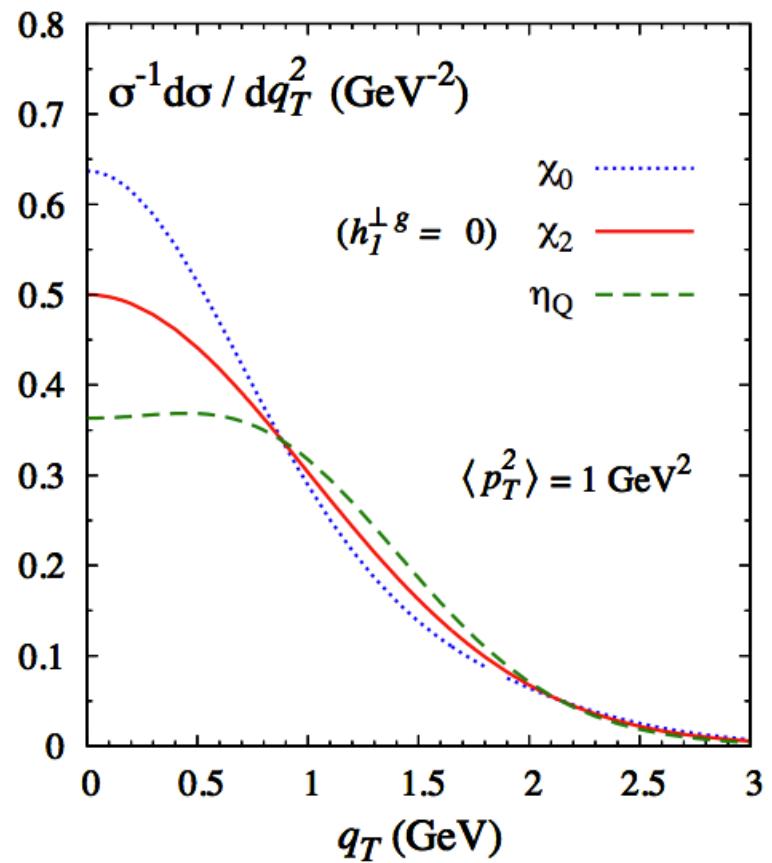
$$\frac{1}{\sigma} \frac{d\sigma}{dq_T^2} = [1 \pm R(q_T)] \frac{1}{2\langle p_T^2 \rangle} e^{-q_T^2/2\langle p_T^2 \rangle}$$

$$R(q_T^2) \equiv \frac{\mathcal{C} [w h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C} [f_1^g f_1^g]}$$

Higgs @ LHC



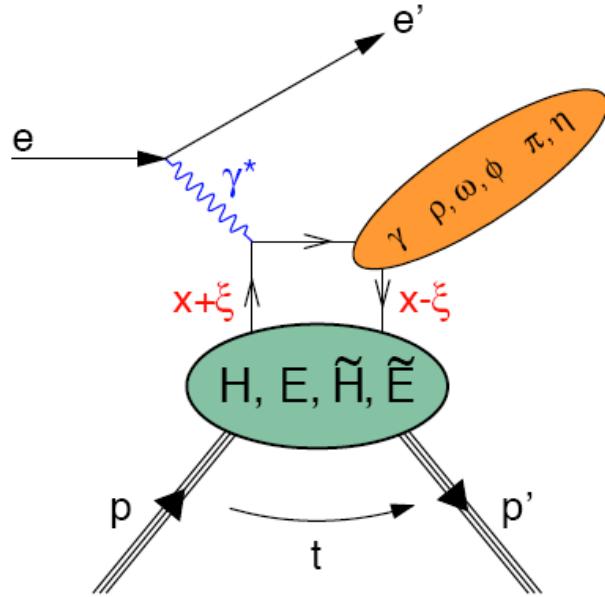
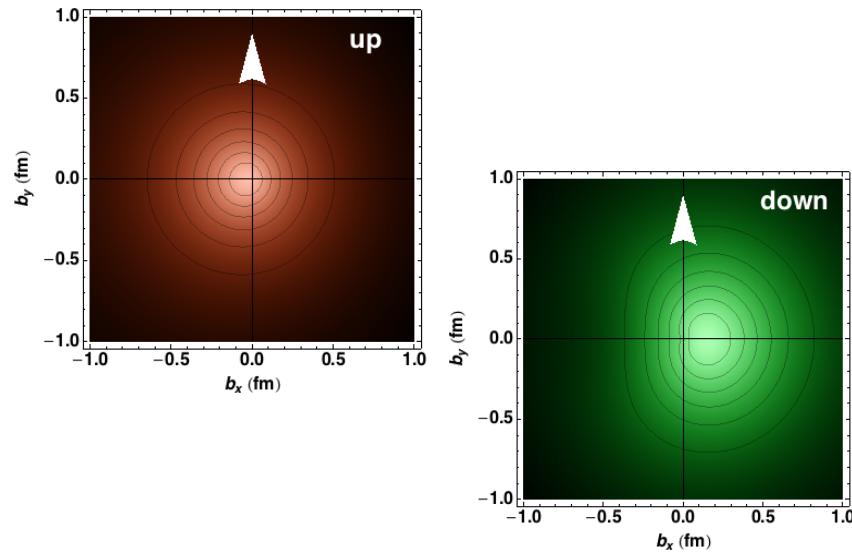
Quarkonium @ AFTER



Orbital Motion



Generalized Parton Distributions



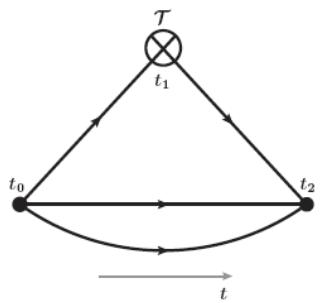
		quark polarisation		
N/q	U	L	T	
U	H			ϵ_T
L		\tilde{H}	E	
T	E	E	H_T, \tilde{H}_T	

Related to:

- ✓ Nucleon form factors
- ✓ Impact parameter:
nucleon tomography, gluon radius
- ✓ Parton Orbital motion:
may solve the proton spin puzzle

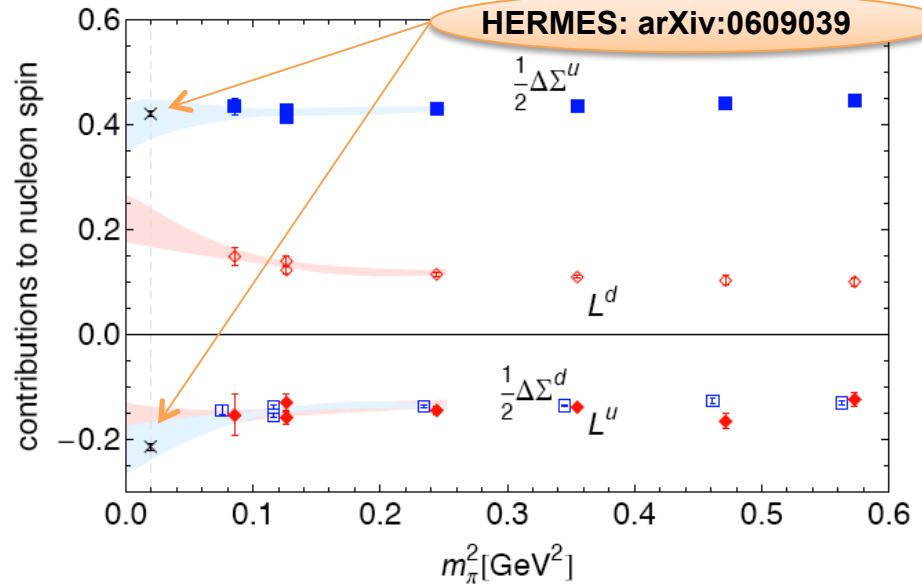
$$\begin{aligned}
 J_q &= \frac{1}{2} \Delta \Sigma + L_q \\
 &= \lim_{t \rightarrow 0} \int_{-1}^1 dx \ x \left[H(x, \xi, t) + E(x, \xi, t) \right]
 \end{aligned}$$

Spin Budget from Lattice

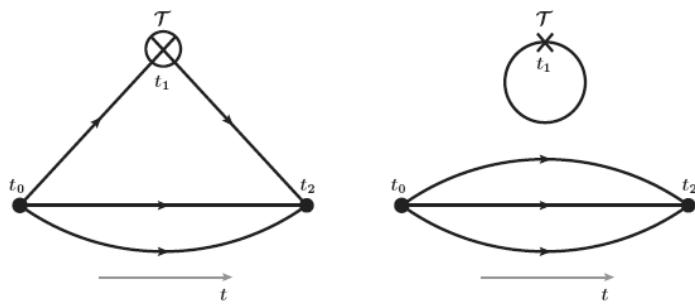


$$L^u + L^d \sim 0$$

With connected diagrams

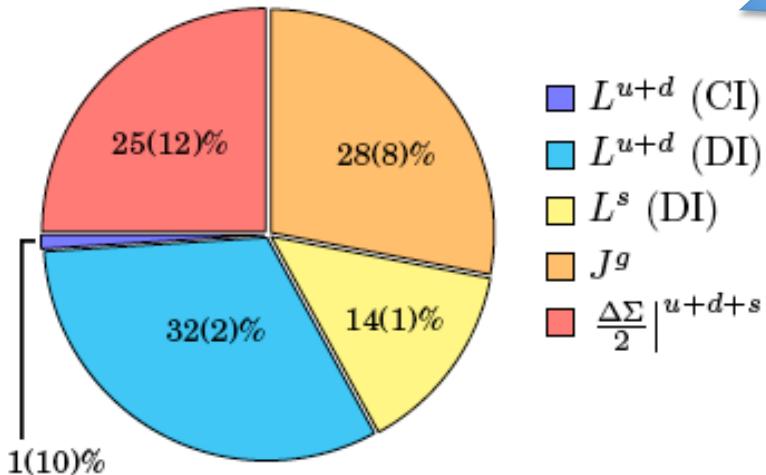


Spin Budget from Lattice



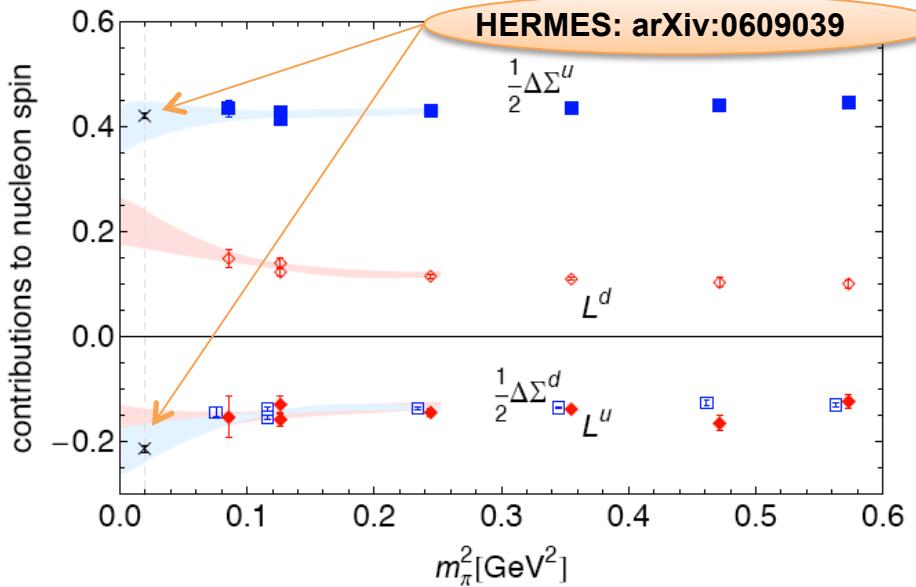
With (dis)connected diagrams

Liu ++, arXiv:1203.6388

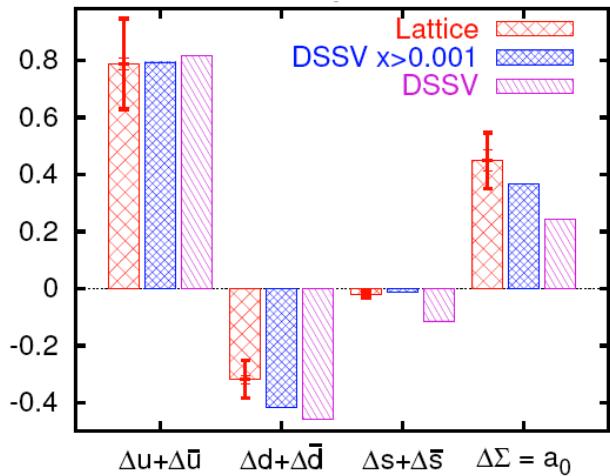


$$\Delta s (\text{DI}) = -0.12(1)$$

L_q mainly from sea and up to 50 % of the proton spin



$$\begin{aligned} \Delta \Sigma &= \Delta u + \Delta d + \Delta s &= & 0.45(4)(9) \\ \Delta s &= & -0.020(10)(4) \end{aligned}$$

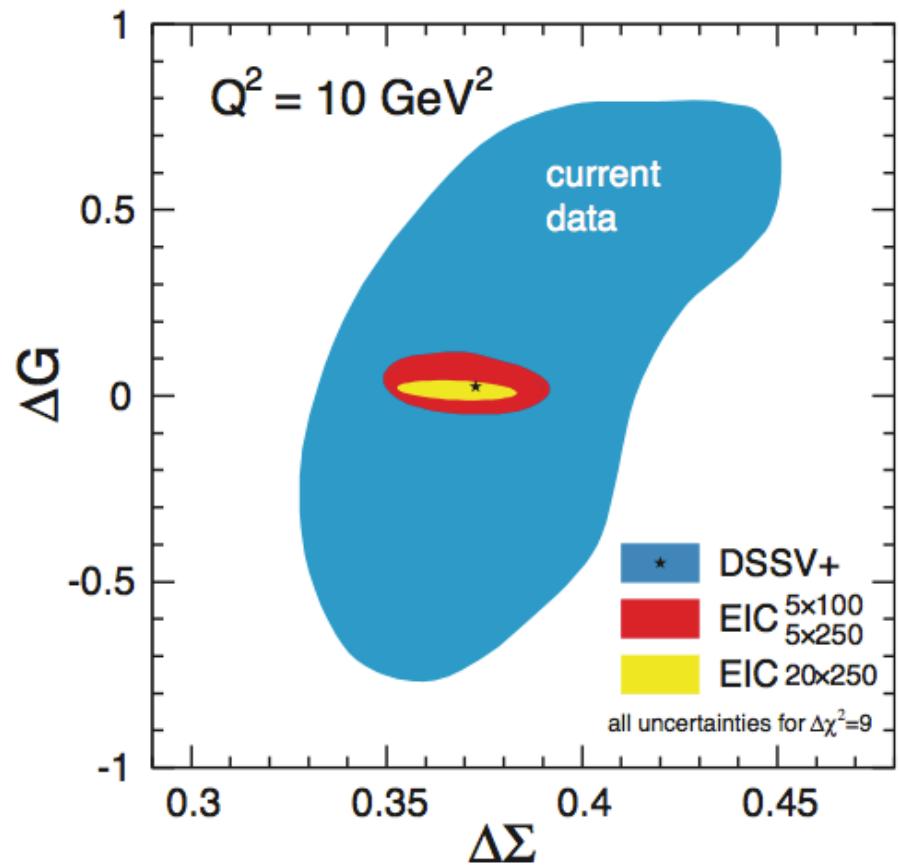
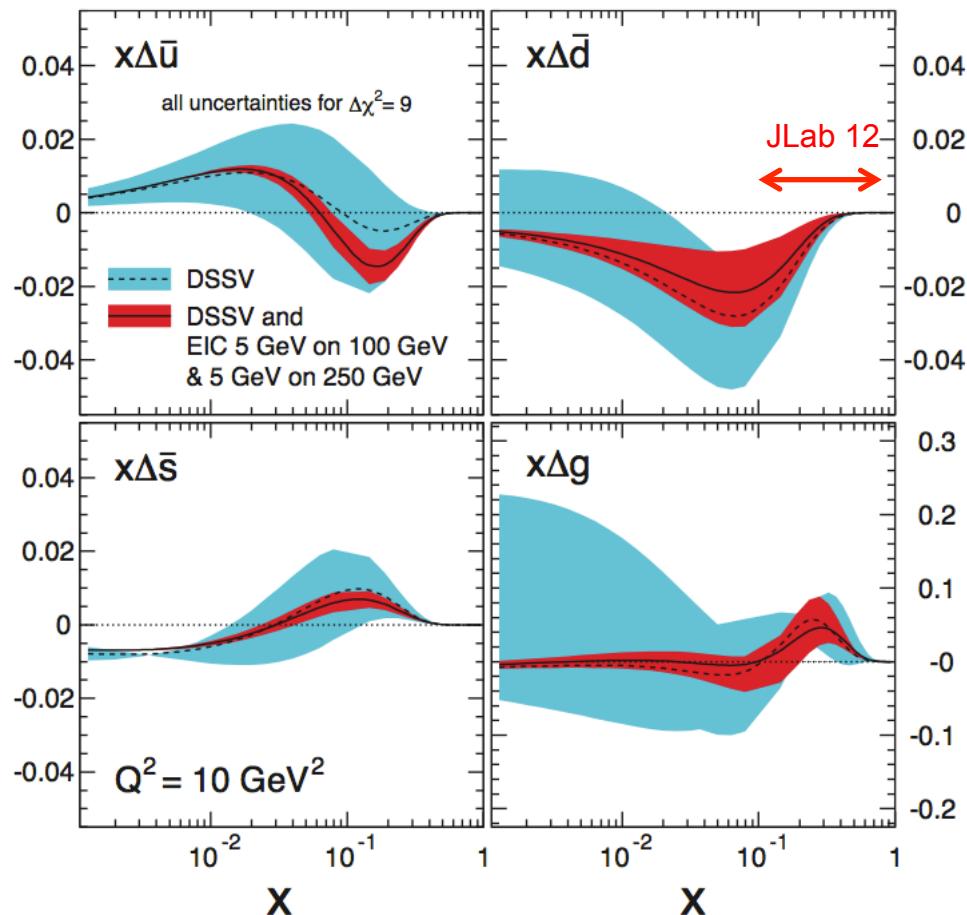


Parton Helicity @ EIC

Proton Spin Decomposition:

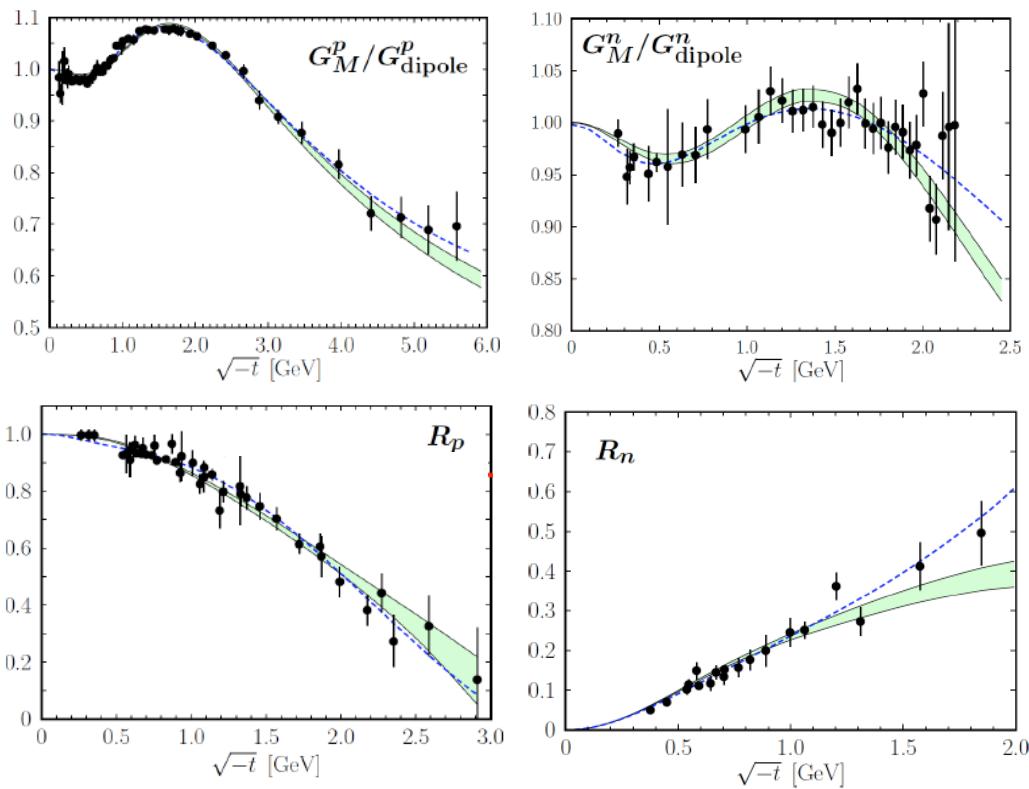
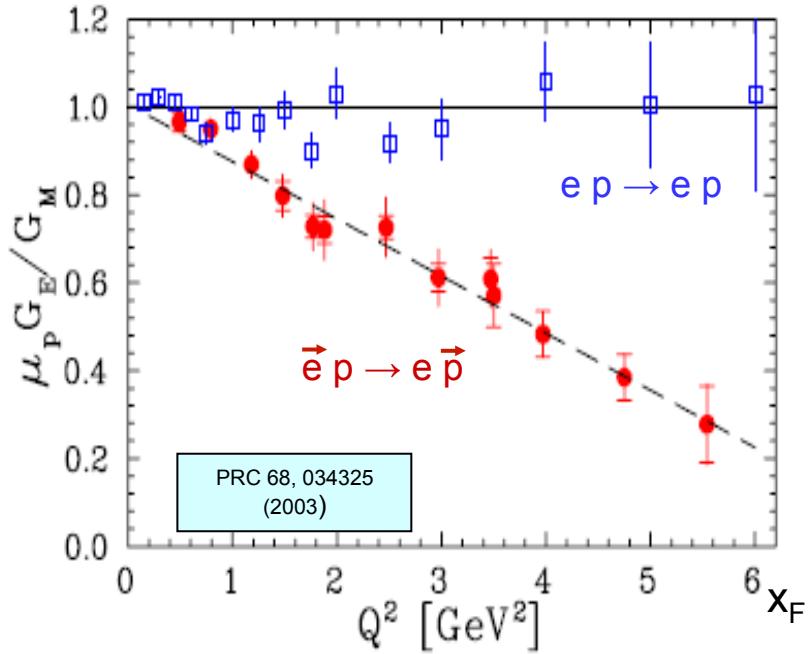
$$\frac{1}{2} = \frac{1}{2} \sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

EIC measurement at high- Q^2 and low- x → Precise helicity flavor decomposition



GPDs from FFs

$$R^p = G_E^p / (G_M^p / \mu_p)$$



- obtain at $\mu = 2$ GeV

$$J_v^u = 0.230^{+0.009}_{-0.024}$$

$$J_v^d = -0.004^{+0.010}_{-0.016}$$

Diehl et al. arXiv: 1302.4604

- within errors consistent with determination from Sivers distrib. and model for chromodynamic lensing:

$$J_v^u = 0.214^{+0.009}_{-0.013}$$

$$J_v^d = -0.029^{+0.021}_{-0.008}$$

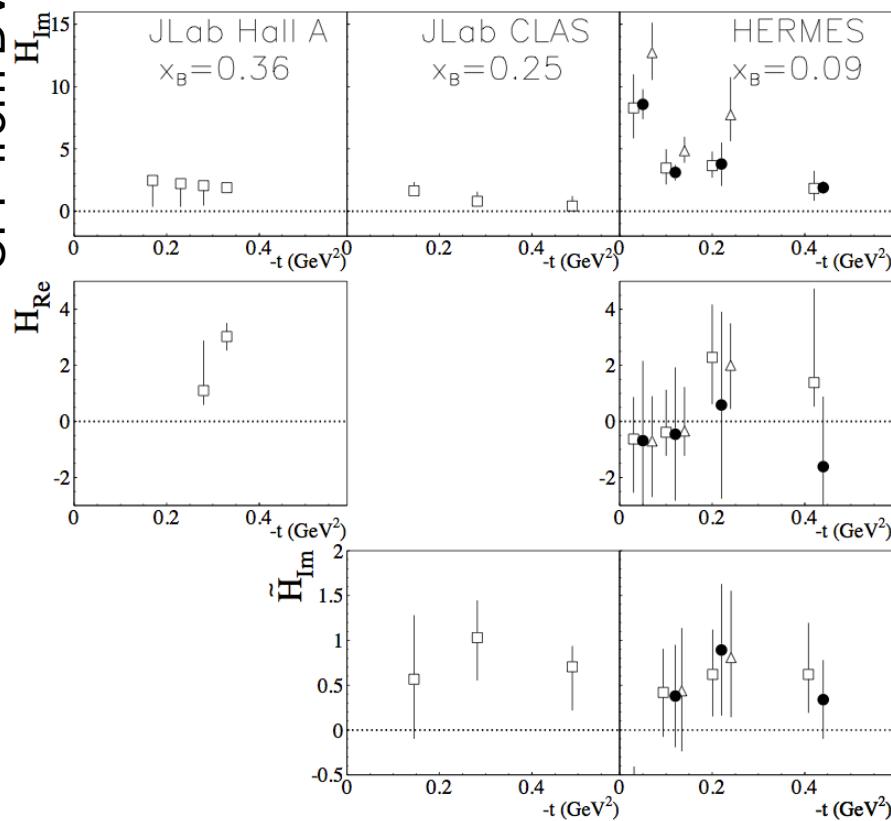
Bacchetta et al. arXiv: 1107.5755

GPDs from DVCS

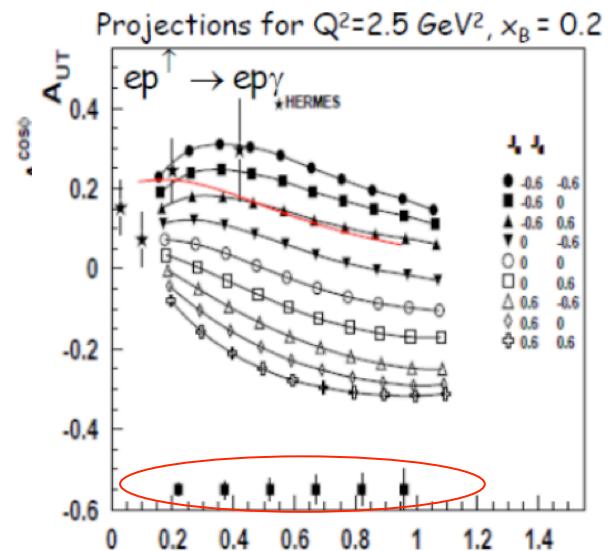
$$J_q = \frac{1}{2} \Delta \Sigma + L_q = \lim_{t \rightarrow 0} \int_{-1}^1 dx \ x \left[H(x, \xi, t) + E(x, \xi, t) \right]$$

CFF from DVCS

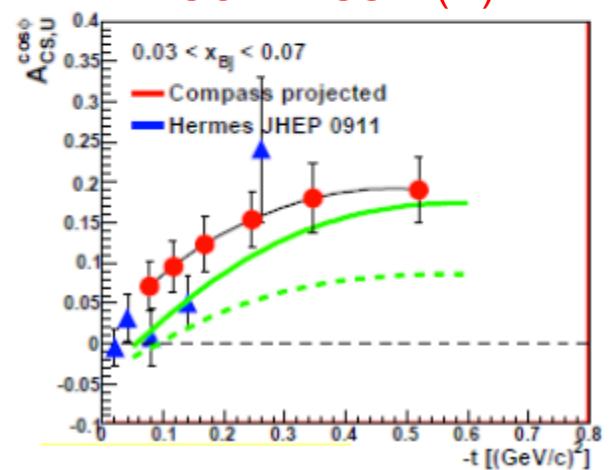
Present



JLab12 (H & E):

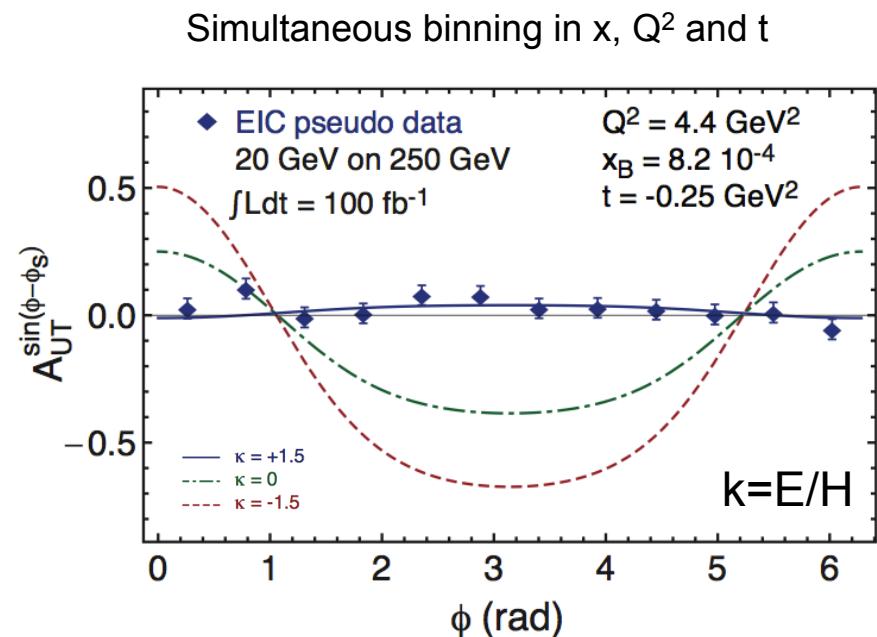
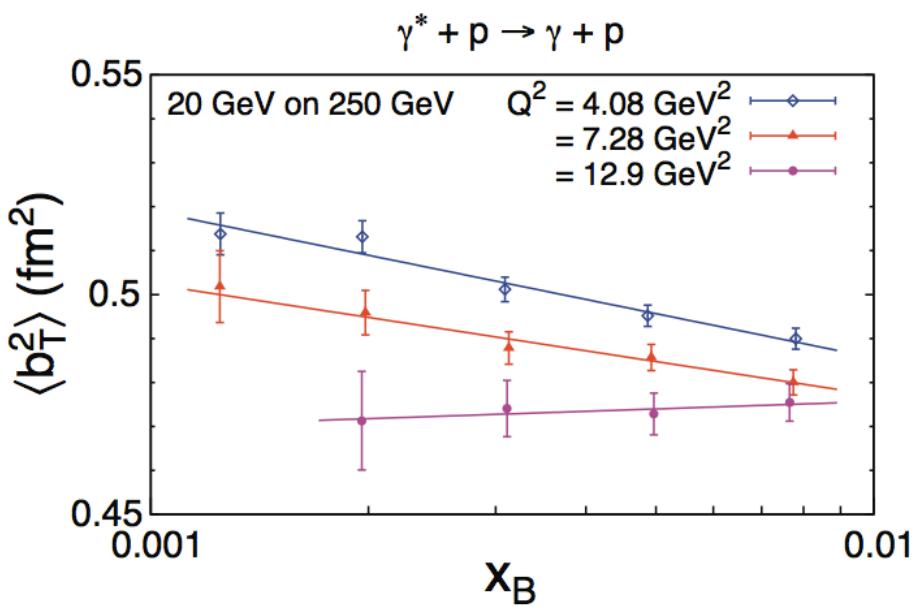
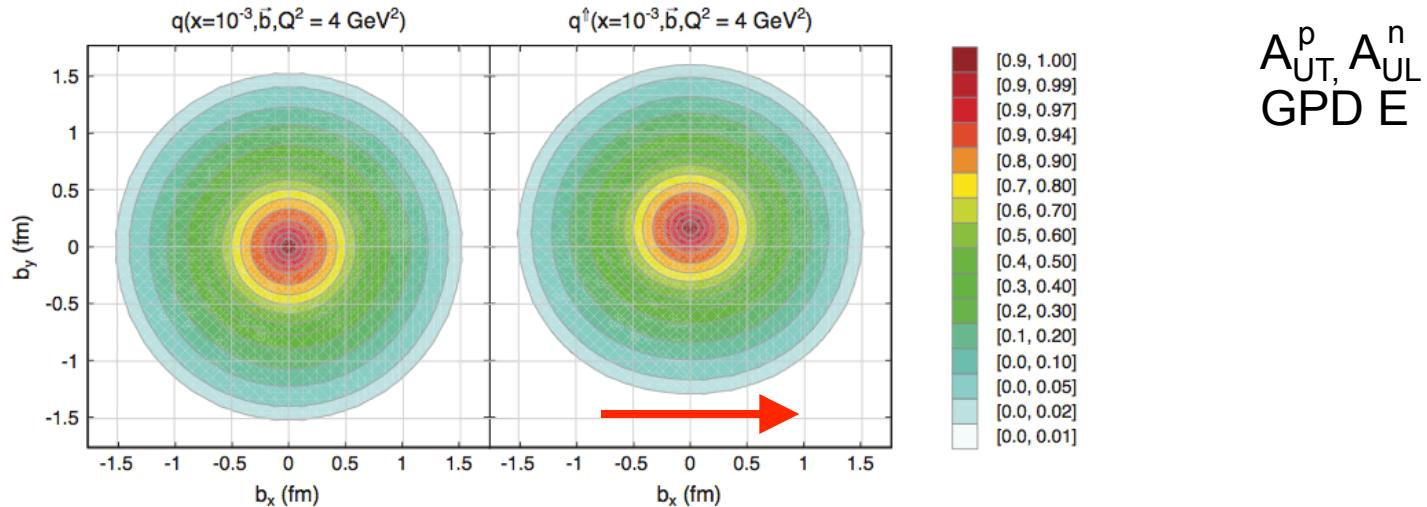


COMPASS-II (H):

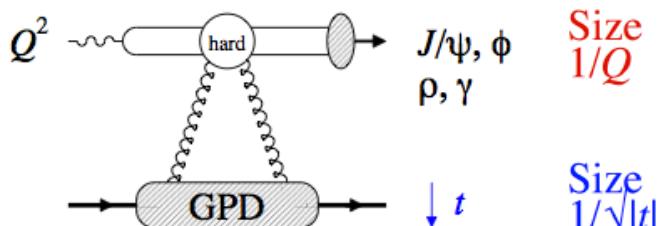


Parton Spatial Distribution@ EIC

X-sec
GPD H

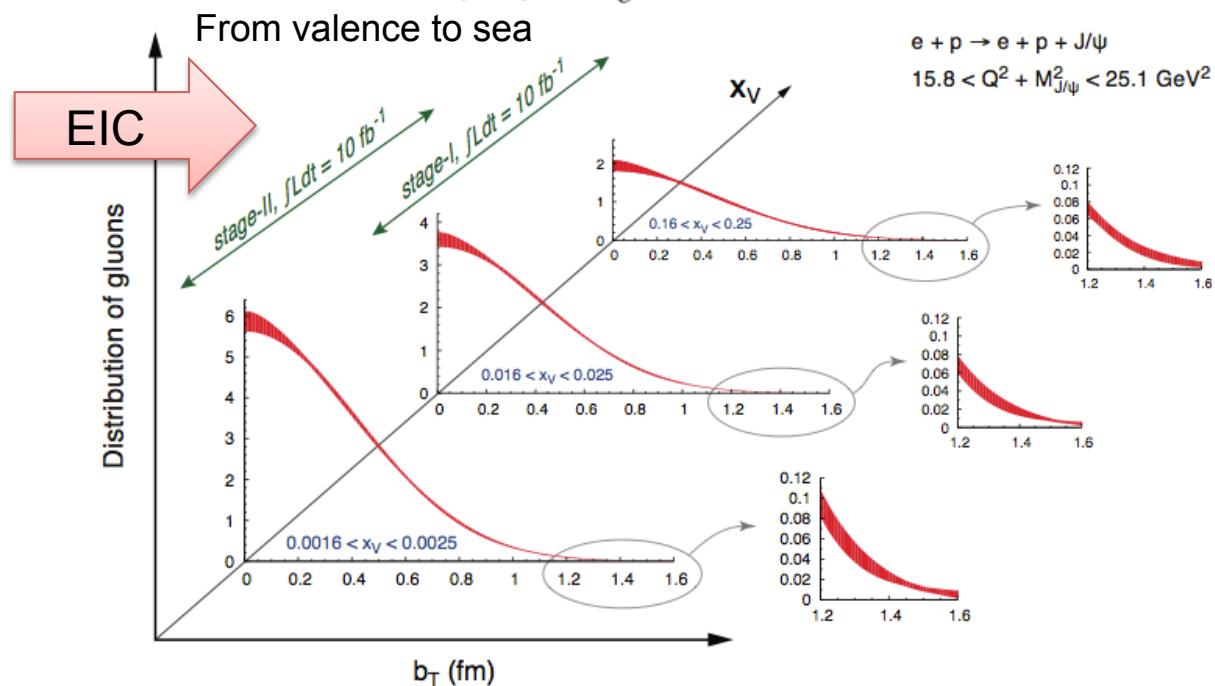
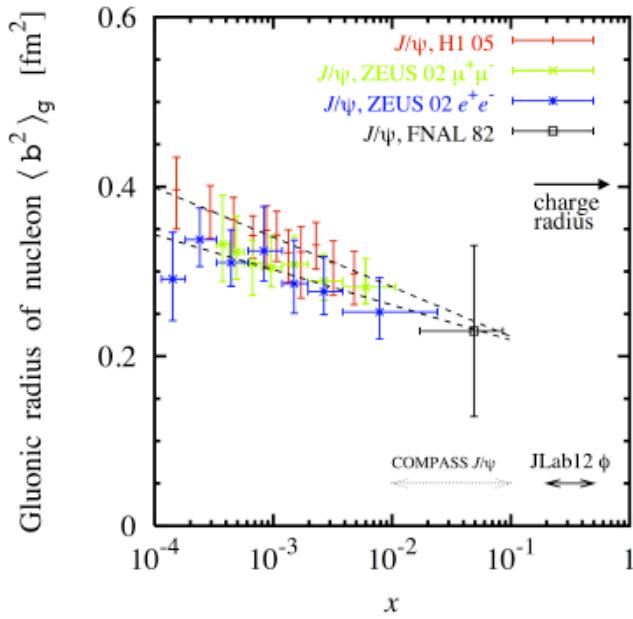
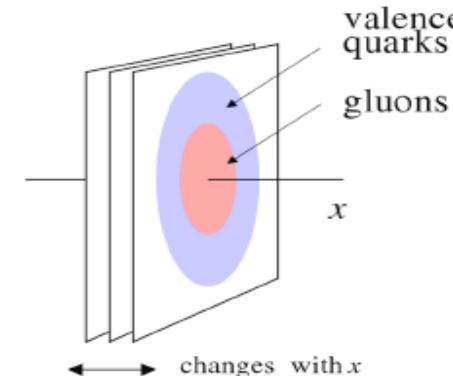


Gluonic Radius @ EIC



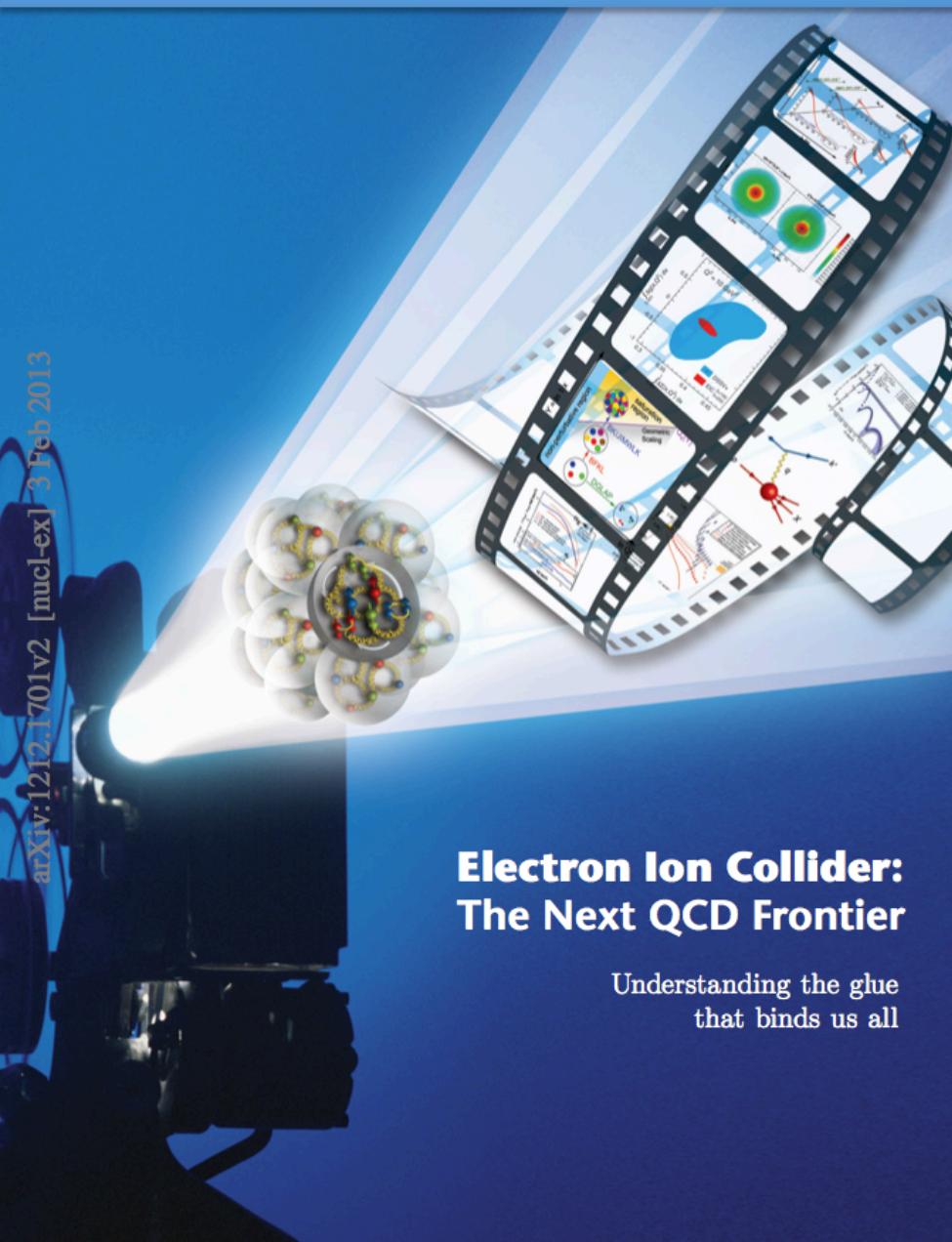
Dominance of small-size configurations
at $Q^2 \sim$ few GeV^2

From t slope of $d\sigma/dt$ ($e p \rightarrow e p J/\psi$)
→ average impact parameter



The Next QCD Frontier

arXiv:1212.1701v2 [nucl-ex] 3 Feb 2013



Electron Ion Collider: The Next QCD Frontier

Understanding the glue
that binds us all

3D nucleon:
an endeavor on NPQCD dynamics
with many
connections with other QCD topics

EIC is a unique opportunity
for a comprehensive study
and possible breakthroughs

A strong effort is ongoing to make it
a reality by a motivated
and experienced community
all over the world

This projects deserve the strongest
support as we may all benefit !!