Theoretical Opportunities at the EIC

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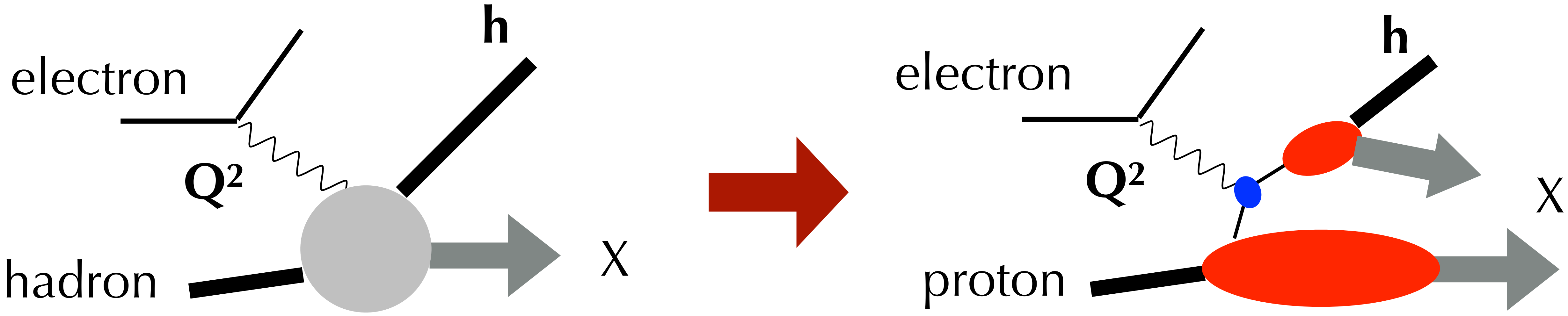
Pavia

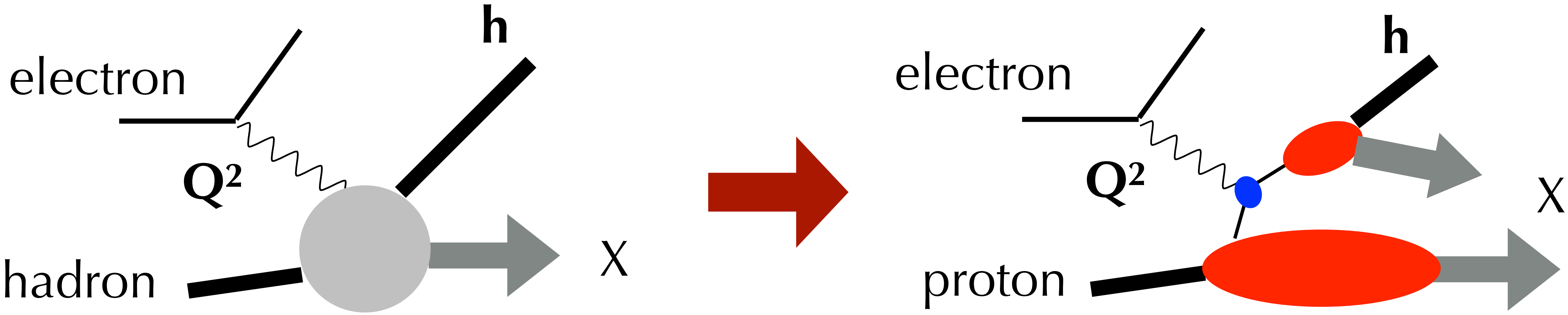
Theoretical tools : Non perturbative Maps



Factorization Theorem

- ● hard cross section, **perturbatively** calculable
- ● **non perturbative MAPS** of - dynamics of colored partons inside colorless hadrons
  - fragmentation of colored partons in colorless hadrons

Theoretical tools : Non perturbative Maps



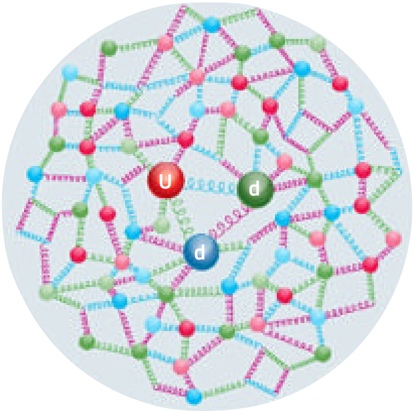
Factorization Theorem

● hard cross section, **perturbatively** calculable

● **non perturbative MAPS** of - dynamics of colored partons inside colorless hadrons
- fragmentation of colored partons in colorless hadrons

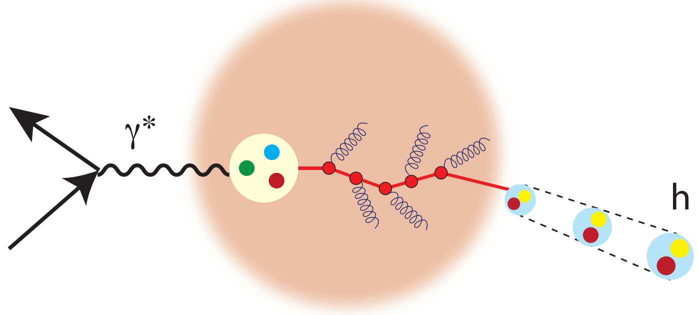
extract more precise MAPS → **understand how confinement comes about**

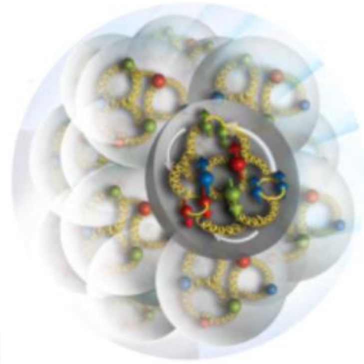
The EIC physics case : The key questions



1) How are **partons** with their spins **distributed in space and momentum** inside the **Nucleon**, such that its **properties** emerge from their interactions?

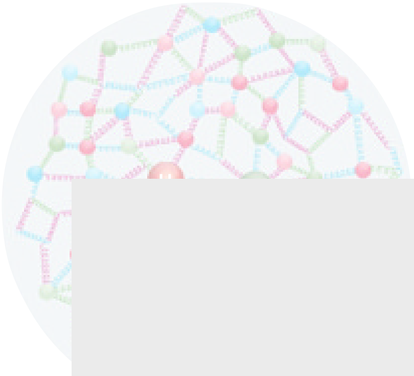
2) How do **colored partons propagate** and interact with nuclear medium such that eventually **colorless hadrons emerge** ?





3) Does **gluon density saturate** at high energy, giving rise to a **universal gluonic matter** ?

The EIC physics case : Theoretical tools



1) How are **partons** with their spins **distributed in**

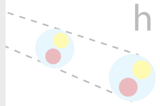
What do we know about these non perturbative MAPS ?

And what can we learn about them at the EIC ?

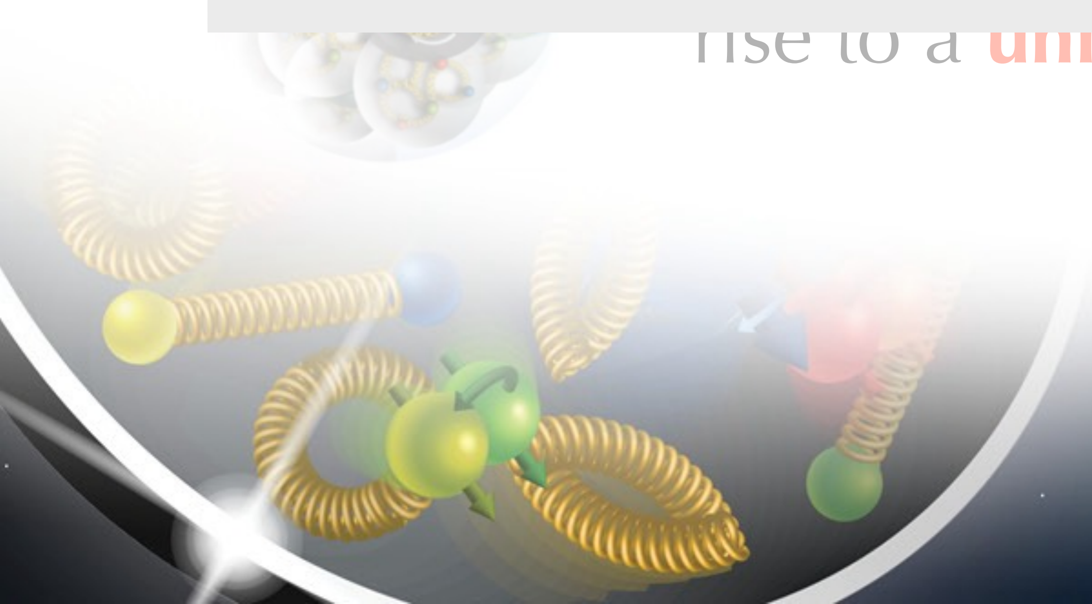
2) H

with

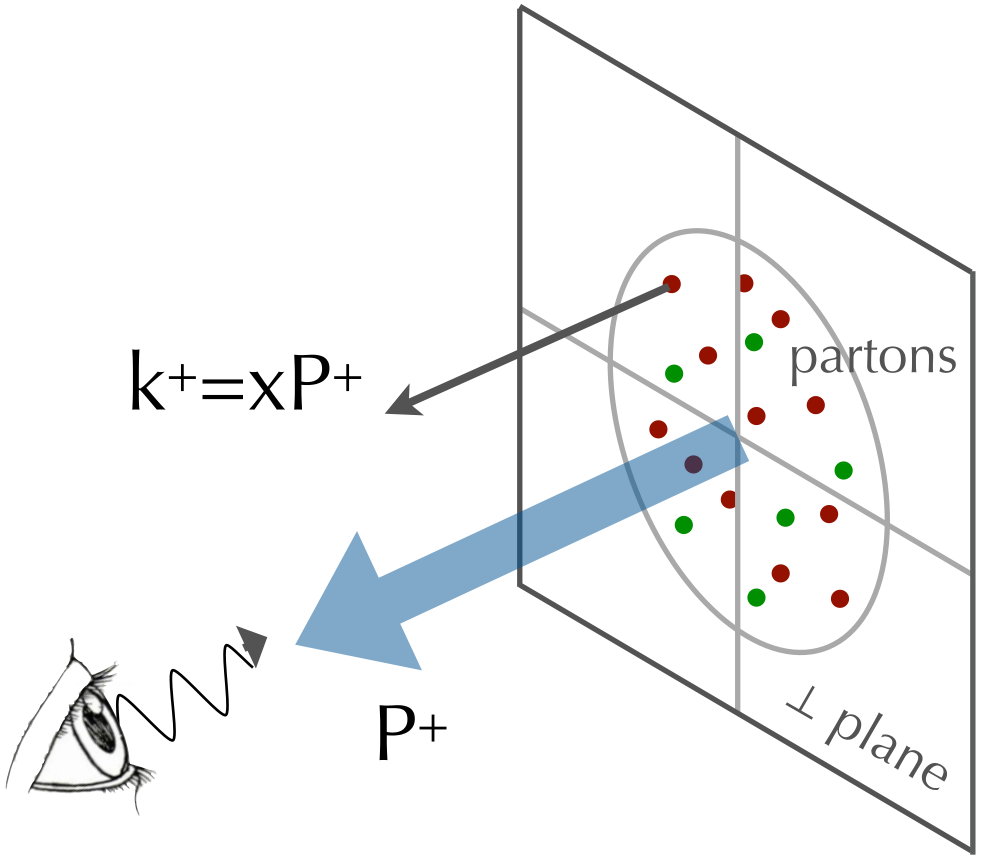
hadr



rise to a **universal gluonic matter** ?



The EIC physics tools



PDF (x)

Parton **D**istribution **F**unction

1-dim map

The EIC physics tools

Transverse Momentum Dependent PDF

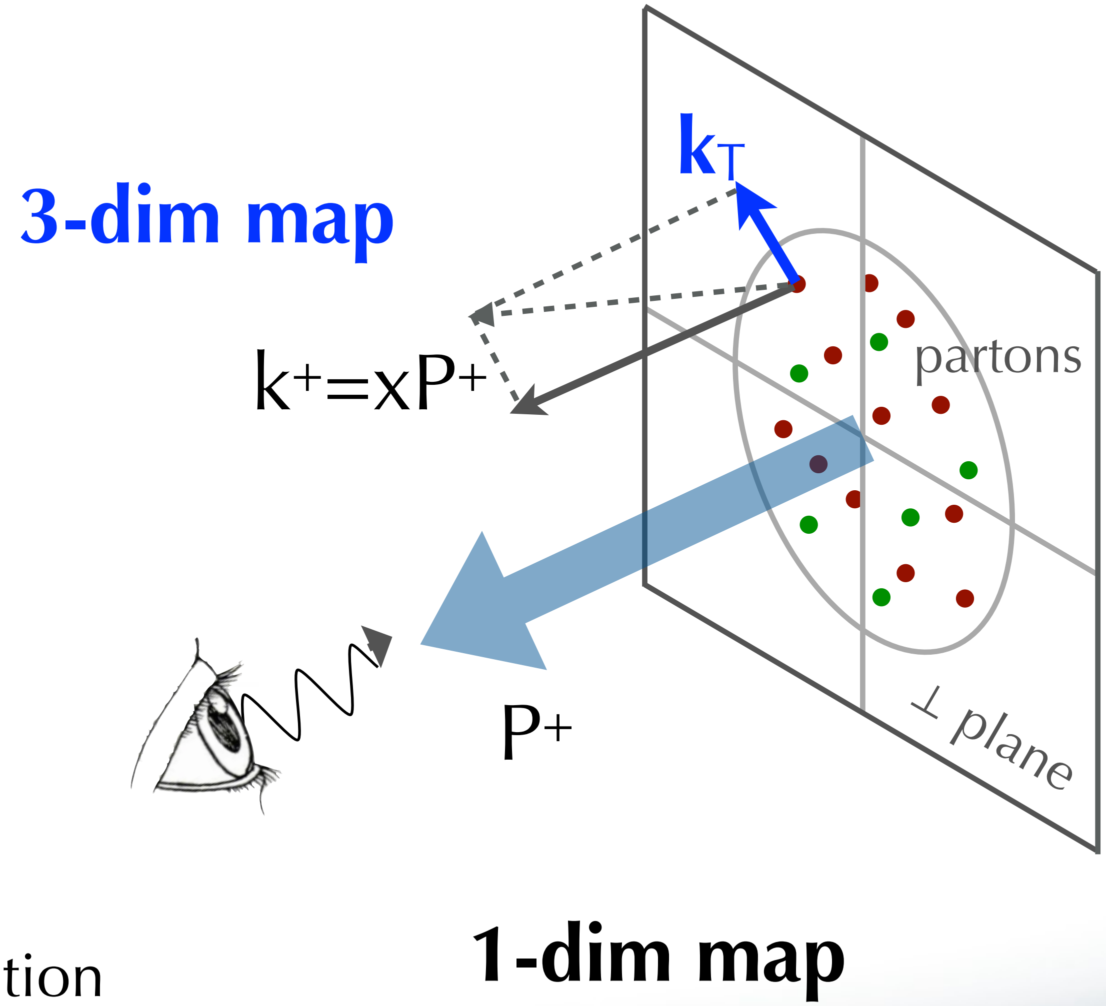
TMD

$(x, \mathbf{k}_T)$

$\int d\mathbf{k}_\perp$

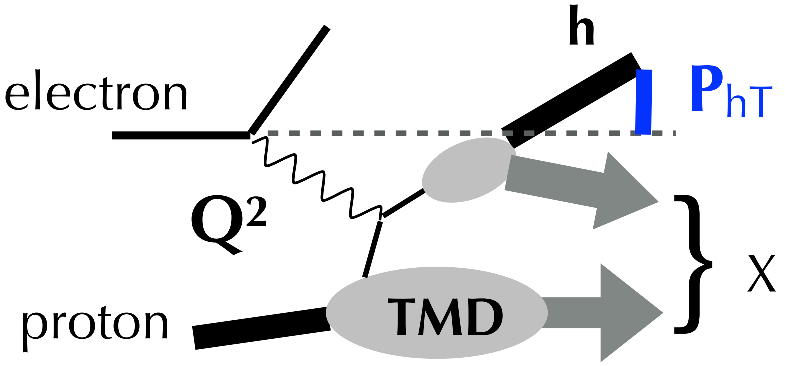
PDF (x)

Parton Distribution Function



3D-maps in momentum space

TMD (x,k_T) can be extracted only in semi-inclusive processes
e.g., semi-inclusive DIS (SIDIS)



soft scale $P_{hT}/z \ll Q$ to “feel” intrinsic k_T
related to confined motion

z fractional energy carried by h

factorization th.’s available for various final states:
h = light- and heavy-quark hadrons, jets, hadron-in-jet,..

*Ji, Yuan, Ma, P.R. D**71** (05)*
*Rogers & Aybat, P.R. D**83** (11)*
Collins, “Foundations of Perturbative QCD” (11)
*Echevarria, Idilbi, Scimemi, JHEP **1207** (12)*
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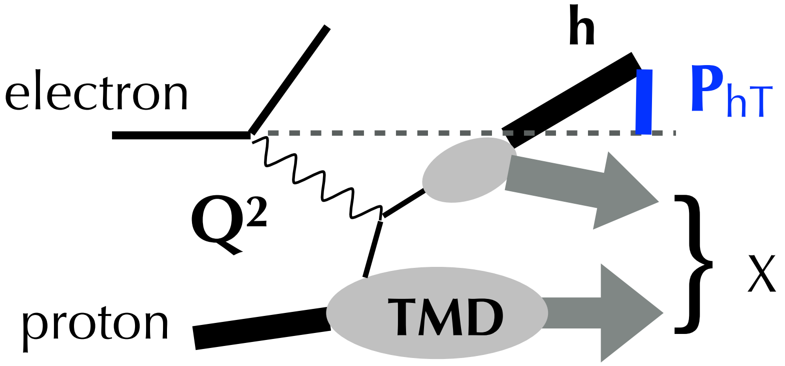

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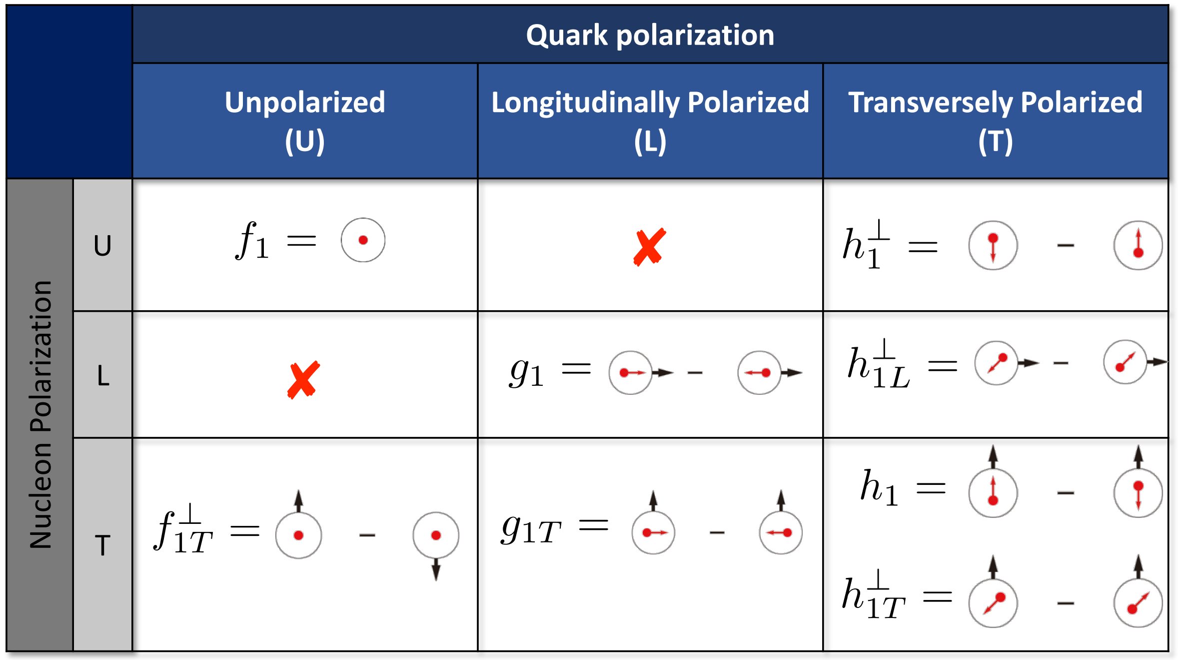
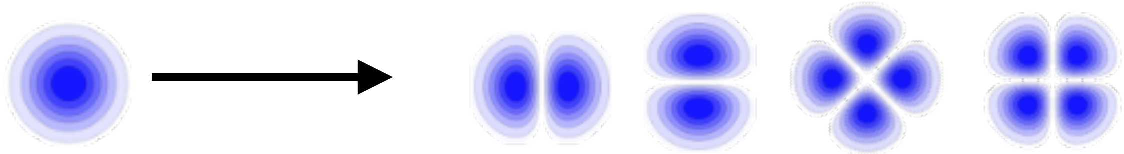
the TMD "zoo" at leading twist



		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	✘	$h_1^{\perp} =$ -
	L	✘	$g_1 =$ -	$h_{1L}^{\perp} =$ -
	T	$f_{1T}^{\perp} =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^{\perp} =$ -

deformations induced by
spin-momentum correlations



each TMD is connected to a specific
measurable SIDIS spin asymmetry

The EIC physics tools

localize partons → baseline info for MPI

(Multi-Particle Interactions)

3-dim map

Impact Parameter Distribution

$\boldsymbol{\rho}\,(x,\mathbf{b}_T)$

TMD

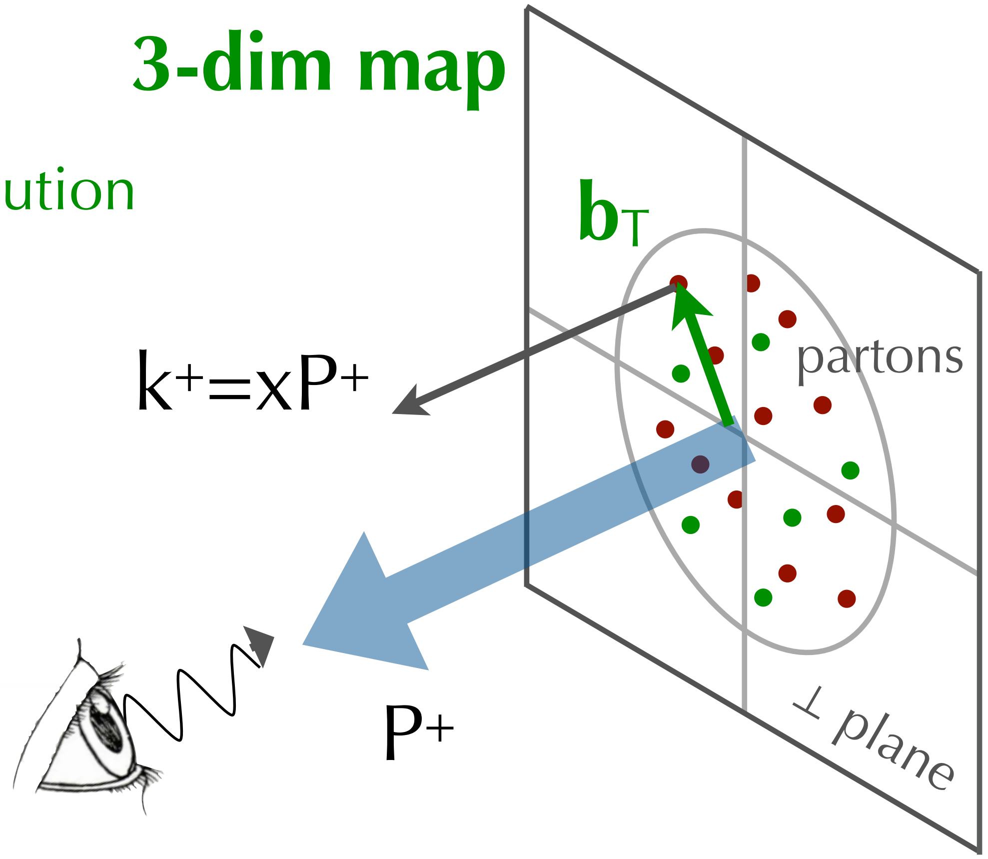
$(x,\mathbf{k}_T)$

$\int d\mathbf{k}_\perp$

$\int d\mathbf{b}_\perp$

PDF $(\,x\,)$

Parton **D**istribution **F**unction



1-dim map

The EIC physics tools

localize partons → baseline info for MPI

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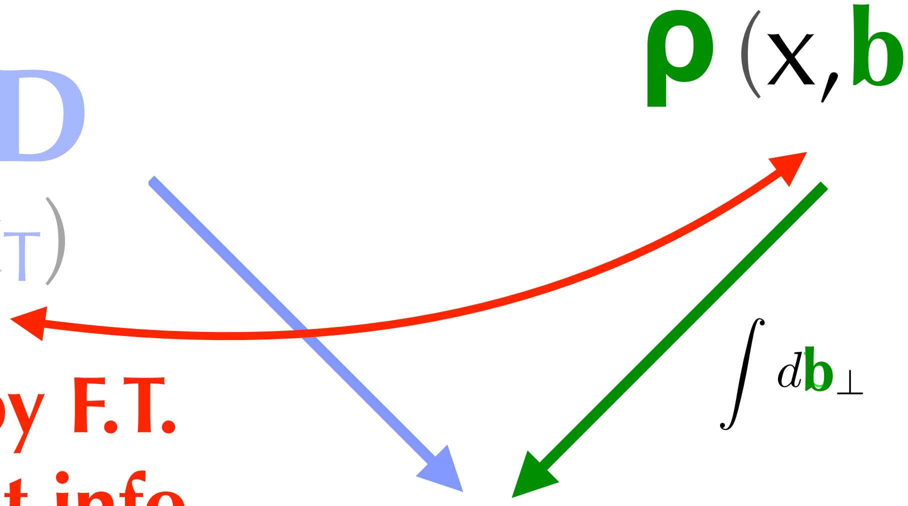


TMD

$(x, \mathbf{k}_T)$

not connected by F.T.
two independent info

Impact Parameter Distribution

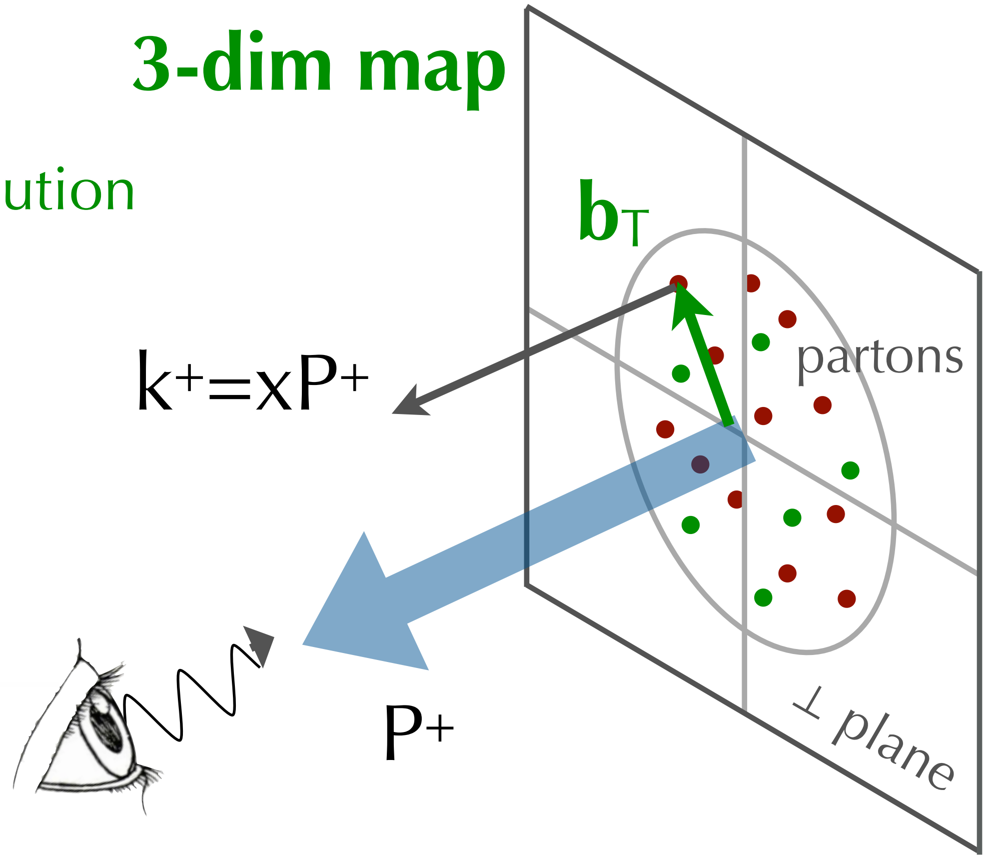
$\boldsymbol{\rho}\,(x, \mathbf{b}_T)$

$\int d\mathbf{b}_\perp$

PDF $(\ x\ )$

Parton **D**istribution **F**unction

3-dim map



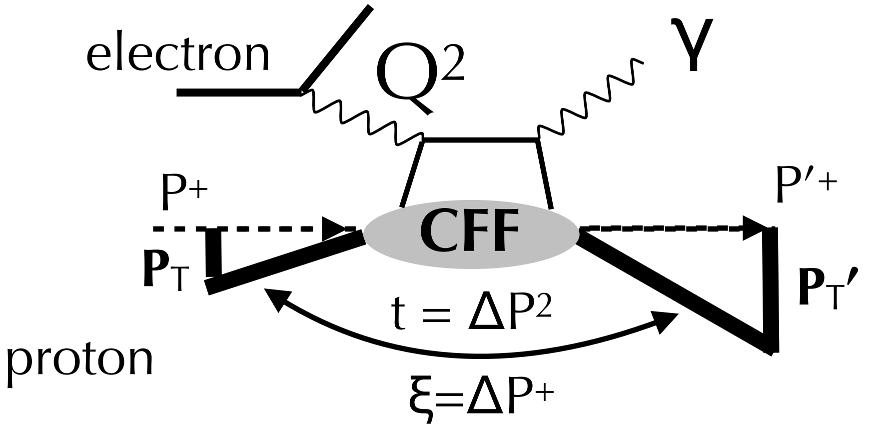
1-dim map

3D-maps in position space

ρ (x,$\mathbf{b}_T$) can not be directly extracted from experimental data

ρ (x,$\mathbf{b}_T$) **GPD** (x,Δ^+=0,$\mathbf{\Delta}_T$)

Fourier Transform



Generalized **P**arton **D**istribution GPD (x,ξ,t) can be indirectly extracted from exclusive **D**eeply-**V**irtual **C**ompton **S**catt.

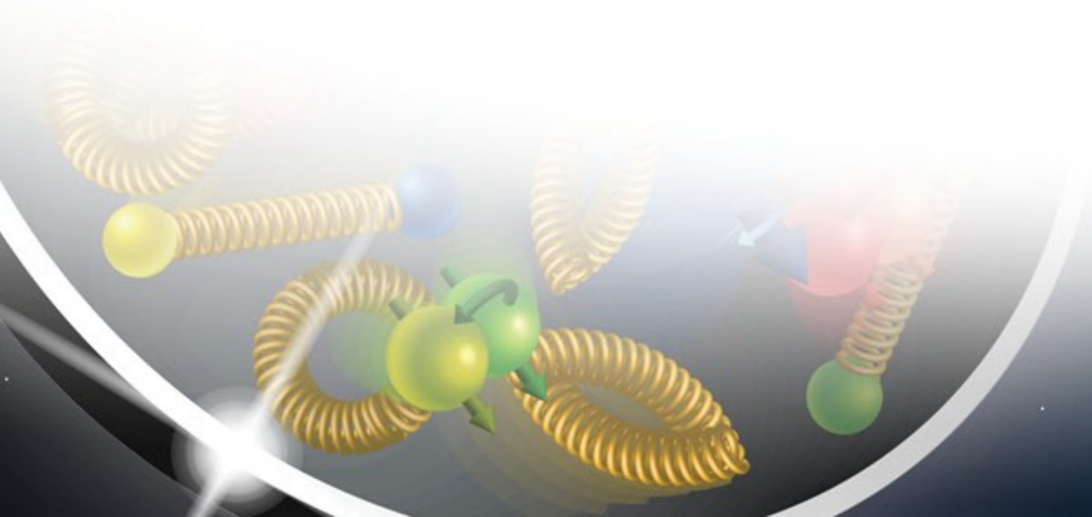
factorization th. for t≪Q²

Compton **F**orm **F**actor

$$\mathrm{CFF}(\xi,t) = \mathscr{P}\int dx \frac{GPD(x,\xi,t)}{x-\xi} + i\pi GPD(\xi,\xi,t) + \mathscr{O}(1/Q)$$

the GPD “zoo” at leading twist

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H	✘	$\mathcal{E}_T$
	L	✘	$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	H_T $\tilde{H}_T$



3D-maps in position space

Lorentz invariance → polynomiality of GPDs

$$\sum_q \int \mathrm{d}x\, x\, H^q(x,\xi,t) = M_2^Q(t) + \frac{4}{5}\, d_1^Q(t)\xi^2$$

$$\sum_q \int \mathrm{d}x\, x\, E^q(x,\xi,t) = 2J^Q(t) - M_2^Q(t) - \frac{4}{5}\, d_1^Q(t)\xi^2$$

QCD Energy-Momentum Tensor (EMT)

$$T^{\mu\nu} = \bar{\psi}\gamma^\mu \frac{i}{2}\overleftrightarrow{D}^\nu \psi - F^{a\mu\lambda}F^{a\nu}{}_\lambda + \frac{1}{4}g^{\mu\nu}F^2$$

$$\langle p|\, T^{Q,G}_{\mu\nu}\, |p'\rangle = \bar{u}(p')\left[M_2^{Q,G}(t)\frac{P_\mu P_\nu}{M_N} + J^{Q,G}(t)\frac{i(P_\mu\sigma_{\nu\rho} + P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} + d_1^{Q,G}(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N} + \bar{c}(t)g_{\mu\nu}\right]u(p)$$

3D-maps in position space

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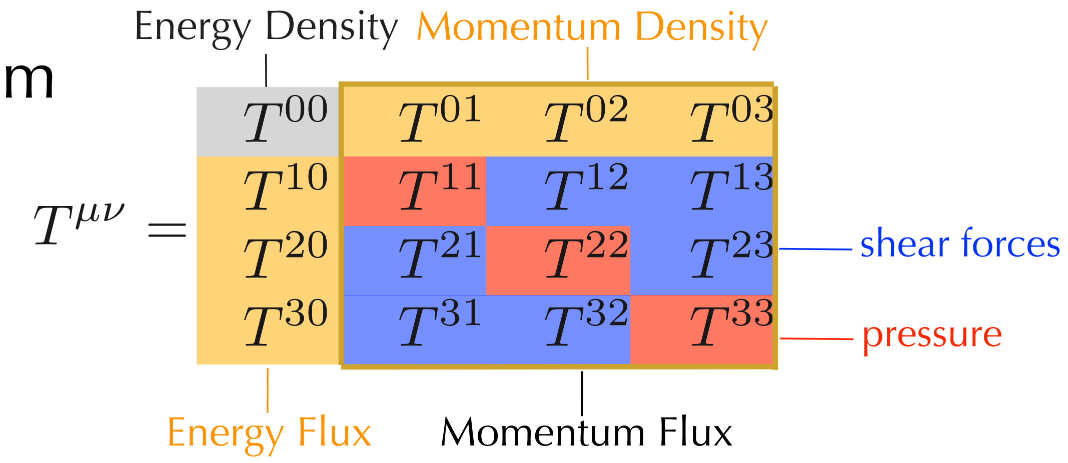
Charges

$M_2(0)$ = contribution of partons to mass and momentum

$J(0)$ = angular momentum of partons

$d_1(0)$ = "D-term" related to internal pressure

$\bar{c}$ = "anomalous" contribution to mass (trace $T^\mu{}_\mu$)



Energy Density Momentum Density

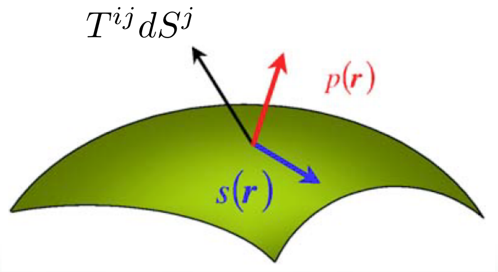
$$T^{\mu\nu} = \begin{array}{cccc} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{array}$$

shear forces

pressure

Energy Flux Momentum Flux

Mechanical properties of the Nucleon



Polyakov, P.L. ***B555*** *(03) 57*
Metz, Pasquini, Rodini, arXiv:2006.11171
Lorcé et al., arXiv:2109.11785
....

3D-maps in position space

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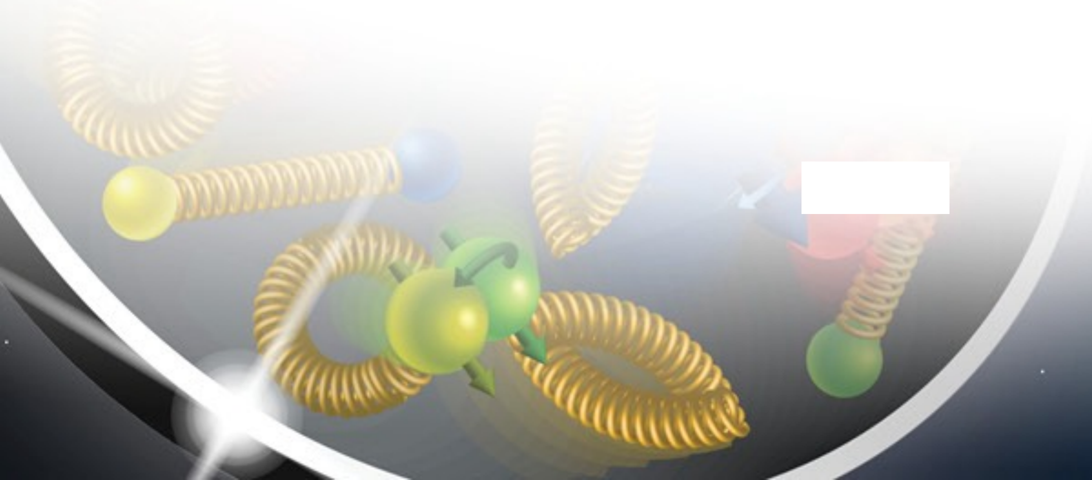
for each flavor q

Ji sum rule

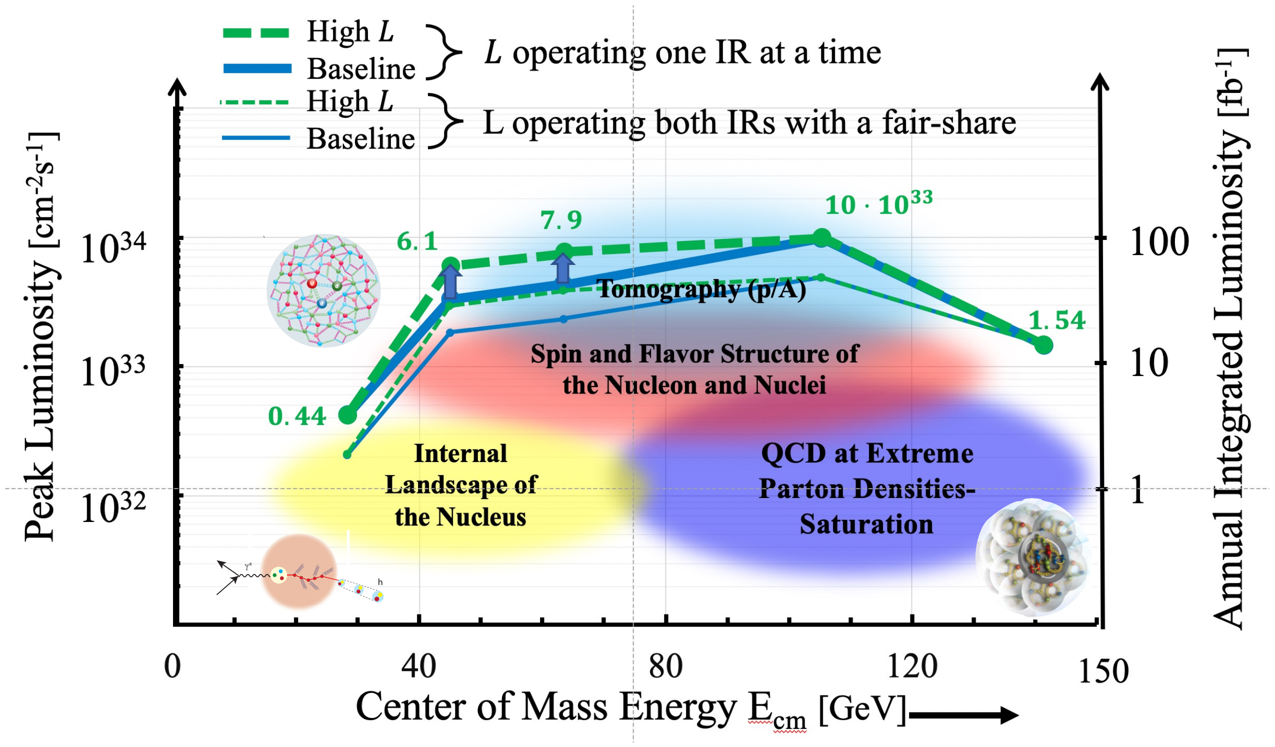
$$\frac{1}{2}\int dx\, x\left[H(x,0,0) + E(x,0,0)\right] = J$$

X. Ji, P.R.L. ***78*** *(97)*

quark angular momentum



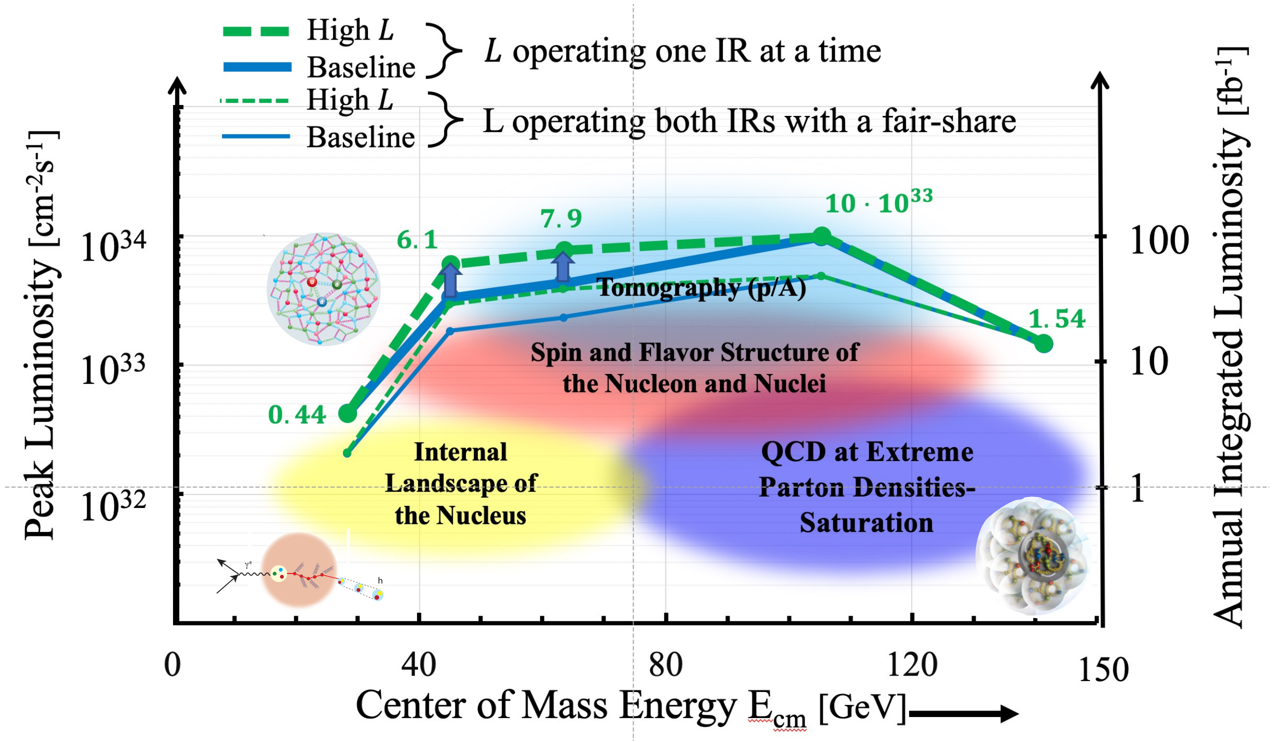
The EIC concept detector



	DIS	binning
GPD	exclusive	x,Q^2,t,θ_P
TMD	semi-inclusive	x,Q^2,z_h,P_h,θ_h
PDF	inclusive	x,Q^2

Detector: hermeticity, high PID over wide range,
high momentum resolution, calorimeter granularity,
coverage of far backward-forward region, …

The EIC concept detector



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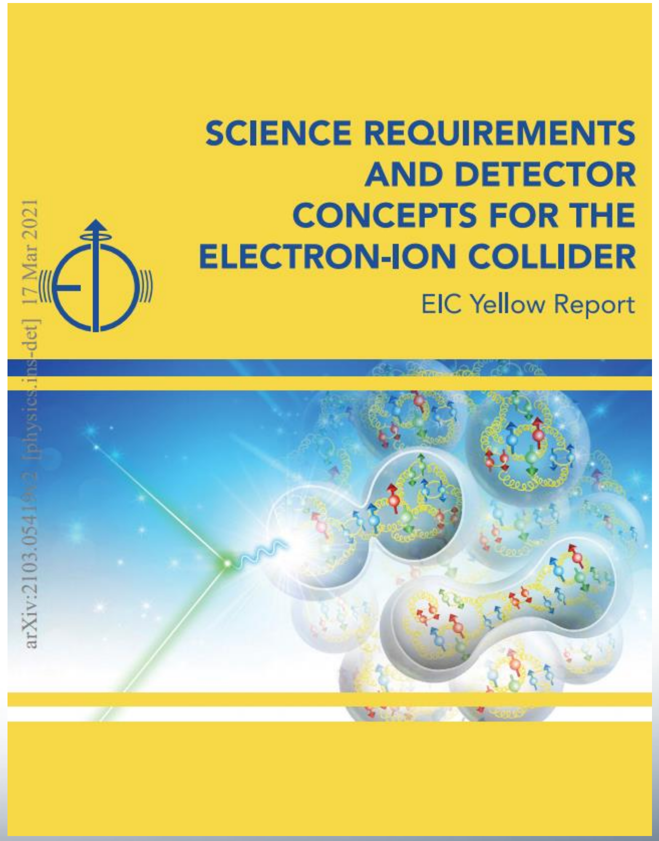
PDF	inclusive	x, Q^2

Detector: hermeticity, high PID over wide range,
high momentum resolution, calorimeter granularity,
coverage of far backward-forward region, …

Enormous community effort: 902 pp, 415 authors, 151 instit.'s
Vol I (Exec. Summary) , **Vol II** (Physics) , **Vol. III** (Detector)

arXiv:2103.05419 (N.P.**A** in press)

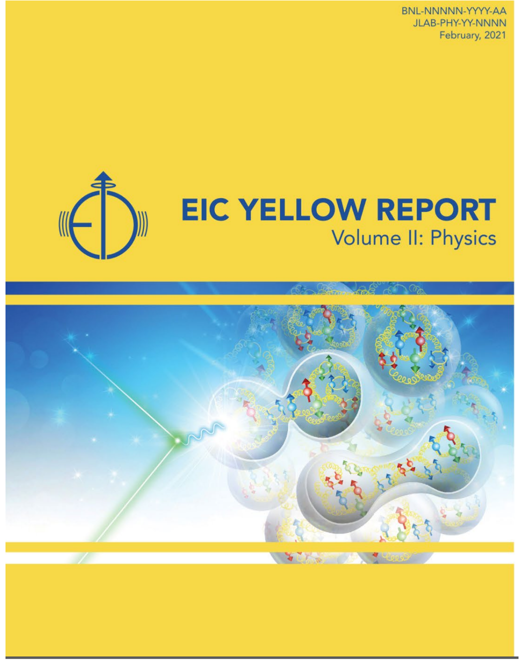


SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

EIC Yellow Report

arXiv:2103.05419v2 [physics.ins-det] 17 Mar 2021

The EIC Yellow Report

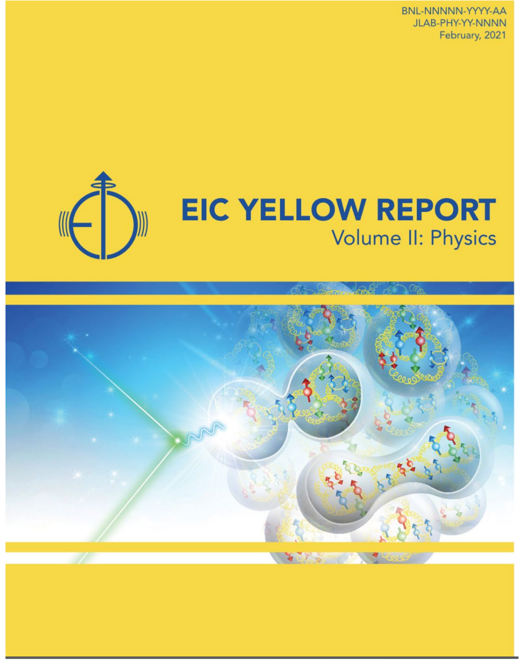

BNL-NNNNN-YYYY-AA
JLAB-PHY-YY-NNNN
February, 2021

EIC YELLOW REPORT
Volume II: Physics

5 Working Groups

- Inclusive reactions
- Semi-inclusive “
- Exclusive “
- Diffractive “
- Jets & Heavy Quarks

The EIC Yellow Report



Volume II: Physics 35

5 Working Groups

- Inclusive reactions
- Semi-inclusive "
- Exclusive "
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- Jets & Heavy Quarks

7.1 Global Properties and Parton Structure of Hadrons
- 7.1.1 Unpolarized parton structure of the proton and neutron
- 7.1.2 Spin structure of the proton and neutron
- 7.1.3 Parton structure of mesons
- 7.1.4 Origin of the mass of the nucleon and mesons
- 7.1.5 Multi-parton correlations
- 7.1.6 Inclusive diffraction and rapidity gap physics
- 7.1.7 Global event shapes and the strong coupling constant

7.2 Multi-Dimensional Imaging of Nucleons, Nuclei and Mesons
- 7.2.1 Nucleon and meson form factors
- 7.2.2 Imaging of quarks and gluons in position space
- 7.2.3 Imaging of quarks and gluons in momentum space
- 7.2.4 Wigner functions
- 7.2.5 Light (polarized) nuclei

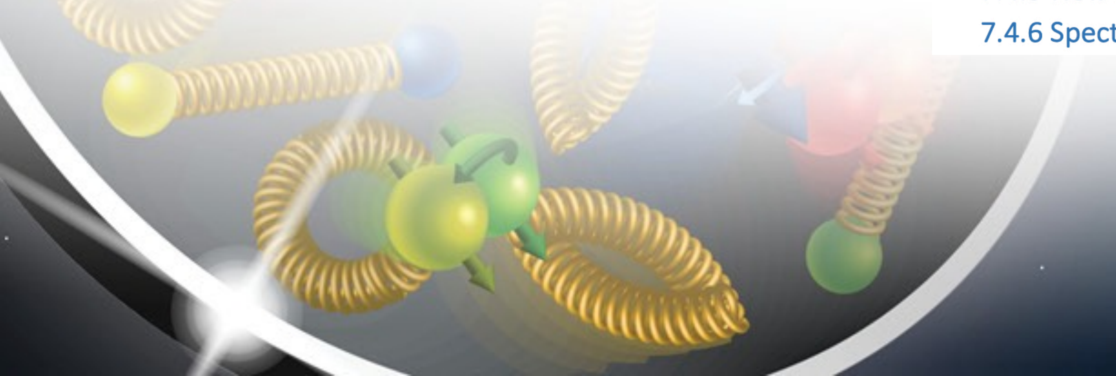
7.3 The Nucleus: A Laboratory for QCD
- 7.3.1 High parton densities and saturation
- 7.3.2 Diffraction
- 7.3.3 Nuclear PDFs
- 7.3.4 Particle propagation through matter and transport properties of nuclei
- 7.3.5 Collective effects
- 7.3.6 Special opportunities with jets and heavy quarks
- 7.3.7 Short-range correlations, origin of nuclear force
- 7.3.8 Structure of light nuclei
- 7.3.9 Coherent and incoherent photoproduction on heavy targets

7.4 Understanding Hadronization
- 7.4.1 Hadronization in the vacuum
- 7.4.2 Hadronization in the nuclear environment
- 7.4.3 Particle production for identified hadron species
- 7.4.4 Production mechanism for quarkonia and exotic states
- 7.4.5 New particle production mechanisms
- 7.4.6 Spectroscopy

7.5 Connections with Other Fields
- 7.5.1 Electro-weak and BSM physics
- 7.5.2 Neutrino physics
- 7.5.3 Cosmic ray/astro-particle physics
- 7.5.4 Other connections to pp, pA, AA
- 7.5.5 Connections with HEP and Snowmass Process

7.6 Related Theory Efforts
- 7.6.1 Lattice QCD
- 7.6.2 Radiative corrections at the EIC

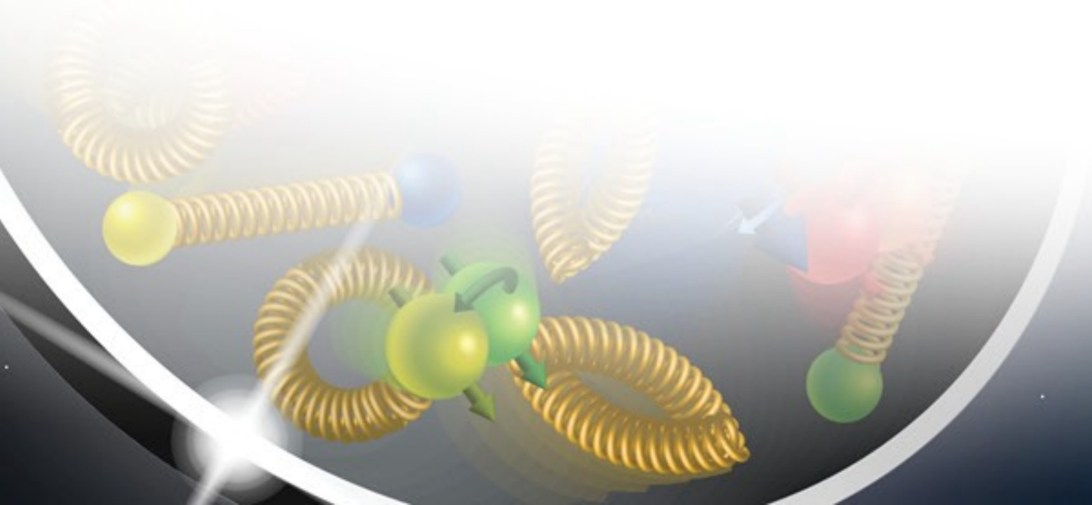
some highlights on projected performance about PDFs, TMDs, GPDs



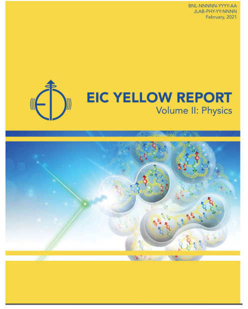
The EIC performance : PDFs

1-Dim Maps

collinear PDF (x)



The EIC performance : unpolarized PDFs

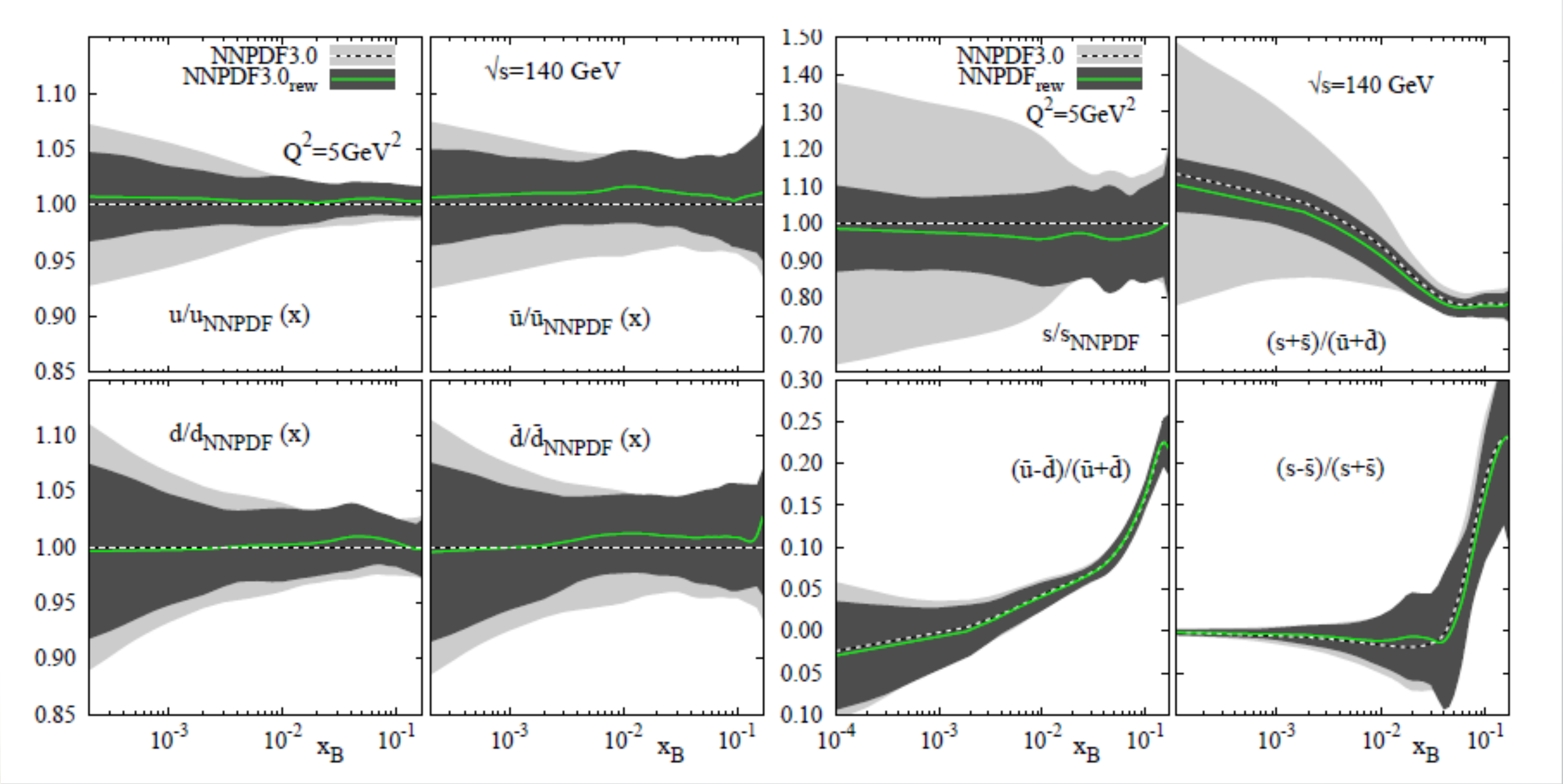


arXiv:2103.05419,
*N.P.**A** in press*

impact on unpolarized sea-quark PDFs

moderate on
$u\,,d\,,\bar{u}\,,\bar{d}$

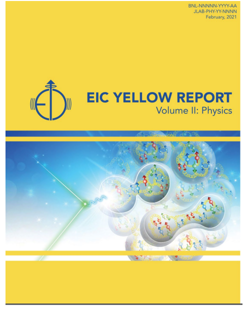
large improvement on
$s\,,\bar{s}$



EIC at $\sqrt{s}=140$ GeV SIDIS e p → e′ (K±,π±) X $\mathcal{L}$=10 fb^{-1}

*Aschenauer et al., P.R. D**99** (19) 094004*

The EIC performance : unpolarized PDFs



arXiv:2103.05419,
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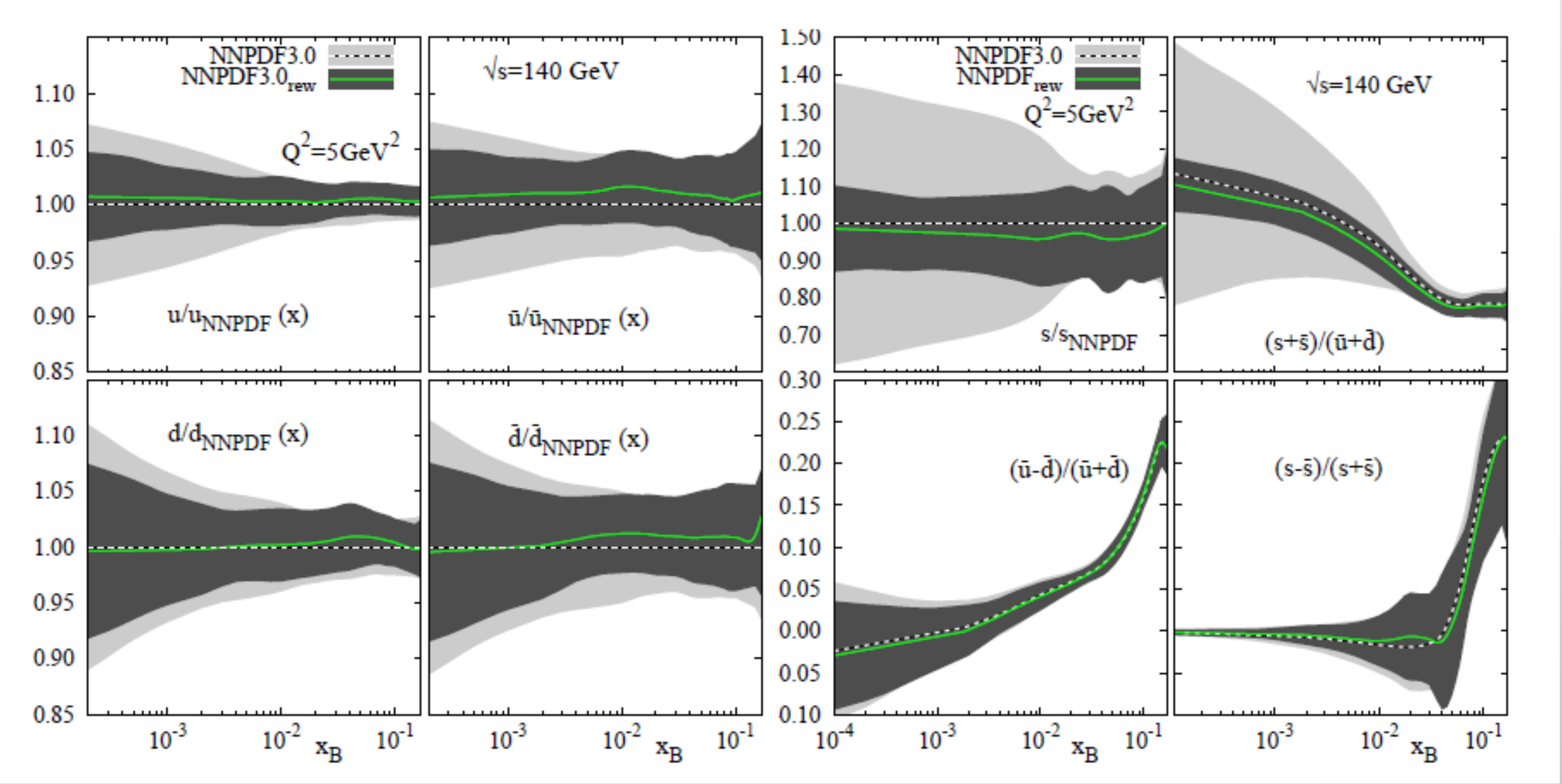
impact on unpolarized sea-quark PDFs

moderate on
$u\,,d\,,\bar{u}\,,\bar{d}$

large improvement on
$s\,,\bar{s}$

current large uncertainties
in strange content



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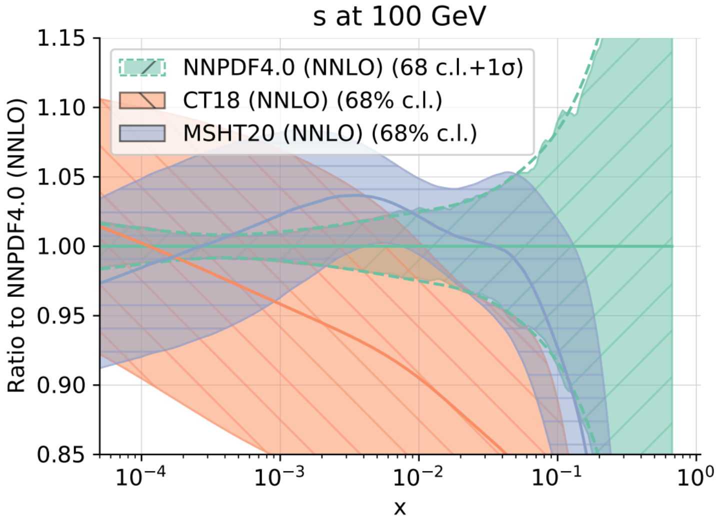
*Aschenauer et al., P.R. D**99** (19) 094004*



Rojo @QCD-N 2021

also projected precision could help to establish intrinsic charm content of the proton

important info for BSM searches from "BSM-independent" source

Electron-Ion Collider

The EIC performance : BSM explorations

Parity Violating DIS

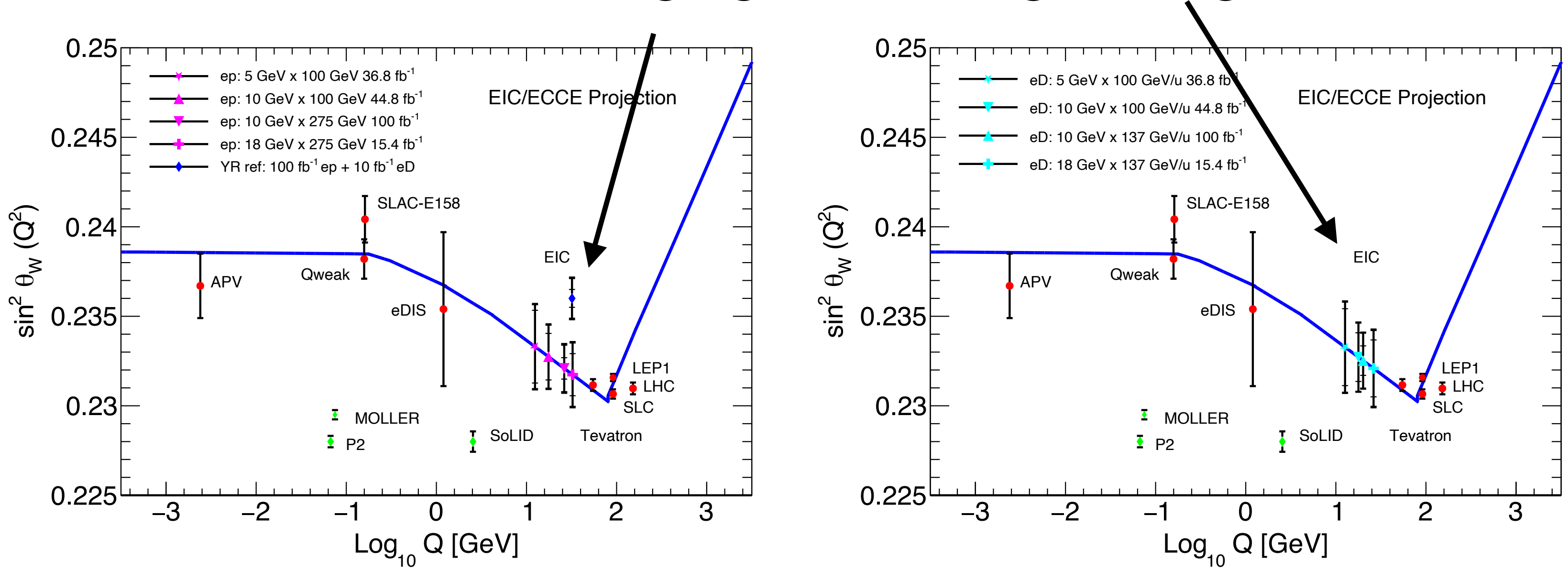
$$\overrightarrow{e} - p$$

$$A_{\mathrm{PV}} \longrightarrow \sin^2 \theta_W$$

<u>correlated PDF uncertainties</u>
CT18NLO
MMHT2014nlo_68cl
NNPDF3.1_nlo_as_0118

Abdul Khalek et al., "Snowmass 2021 White Paper: EIC for High Energy Physics"
arXiv:2203.13199

bridging low- to high-energies



The EIC performance : BSM explorations

Abdul Khalek et al., "Snowmass 2021 White Paper: EIC for High Energy Physics"
arXiv:2203.13199

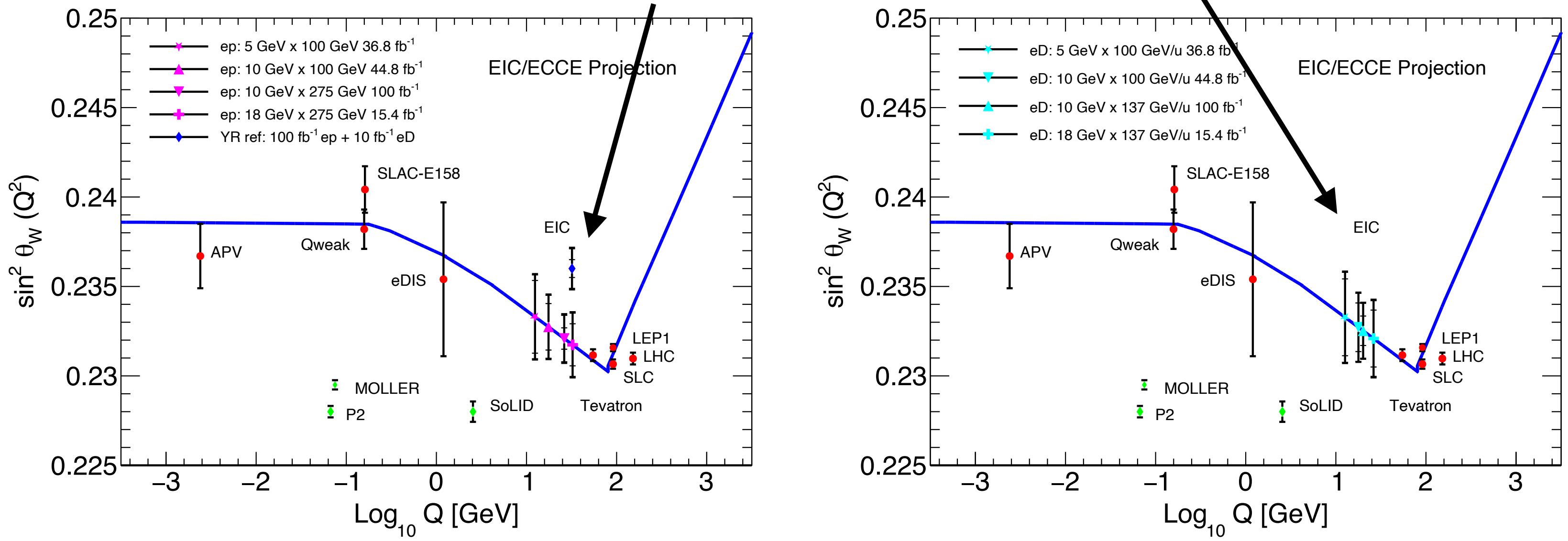
Parity Violating DIS

$$\vec{e} - p$$

$$A_{\mathrm{PV}} \longrightarrow \sin^2\theta_W$$

<u>correlated PDF uncertainties</u>
CT18NLO
MMHT2014nlo_68cl
NNPDF3.1_nlo_as_0118

bridging low- to high-energies



SMEFT

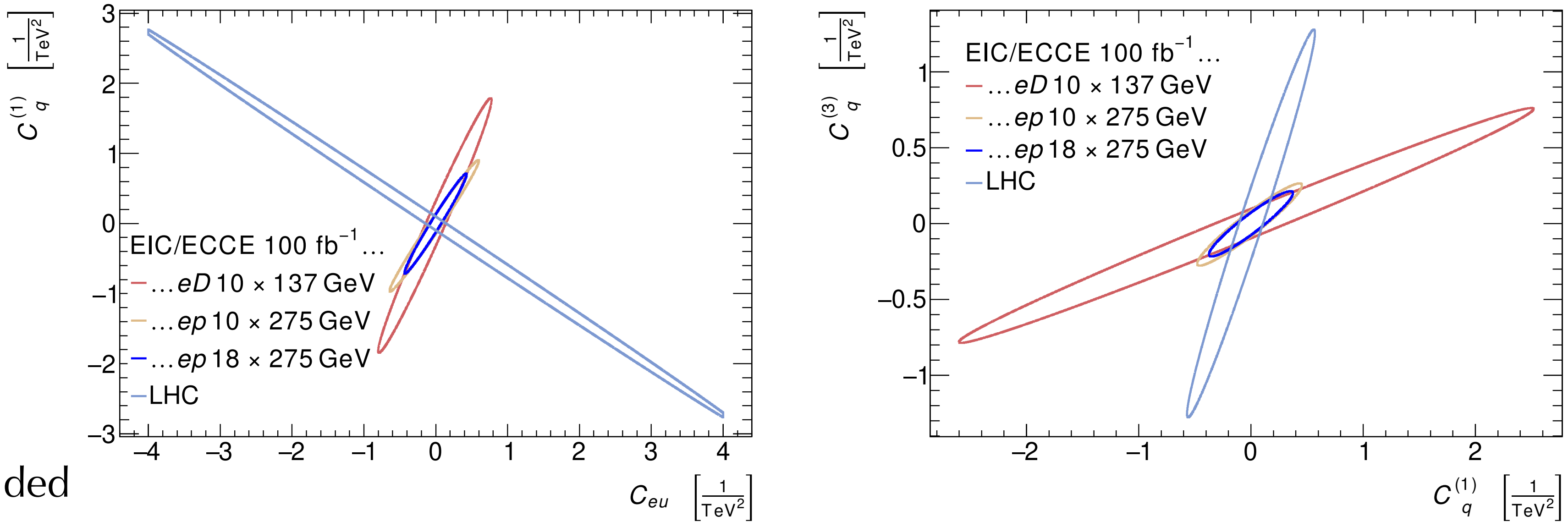
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i C_i \mathcal{O}_i + \ldots$$

$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{q}\gamma_\mu q)$
$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}\gamma^\mu \tau^I \ell)(\bar{q}\gamma_\mu \tau^I q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{\ell u}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{\ell d}$	$(\bar{\ell}\gamma^\mu \ell)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$

u, d, e right-handed

q, ℓ left-handed doublets

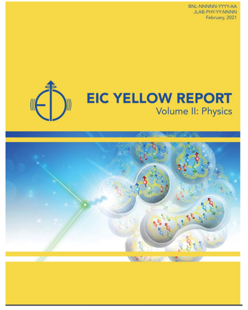
reducing degeneracy



fit of - ATLAS Drell-Yan data
- EIC PVDIS pseudodata

Aad et al., arXiv:1606.01736

The EIC performance : polarized PDFs



EIC YELLOW REPORT
Volume II: Physics

arXiv:2103.05419,
*N.P.**A** in press*

N spin sum rule $\frac{1}{2} = \Delta\Sigma + \Delta g + L_q + L_g$

impact on gluon & quark helicities

singlet
$x\Delta\Sigma = x\sum_q \Delta q$

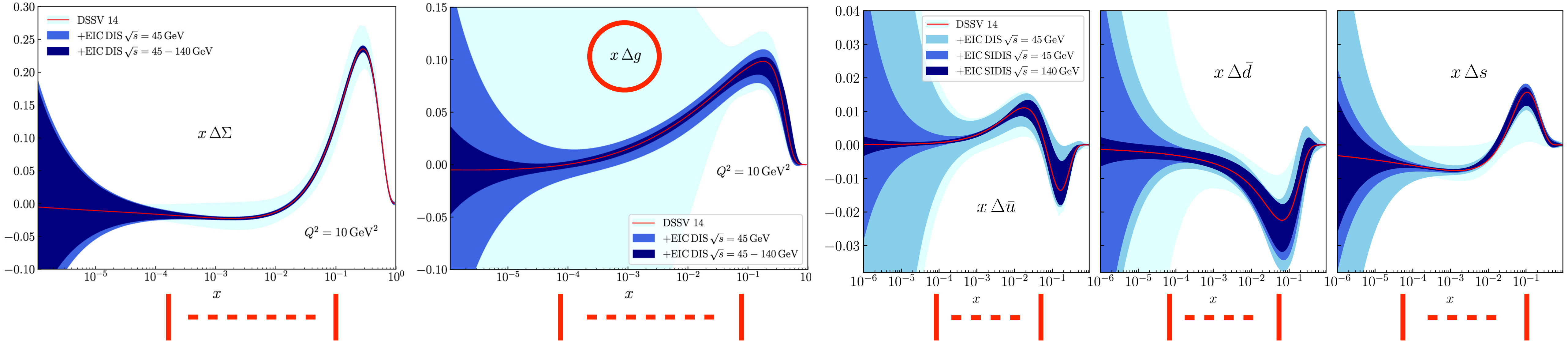
$x\Delta g$

$x\Delta\bar{u}$

$x\Delta\bar{d}$

$x\Delta s$

▨ no EIC ▨ EIC $\sqrt{s} = 45$ GeV ▨ EIC $\sqrt{s} = 45 - 140$ GeV DIS & SIDIS pseudo-data



*Borsa et al., P.R. D**102** (20) 094018*

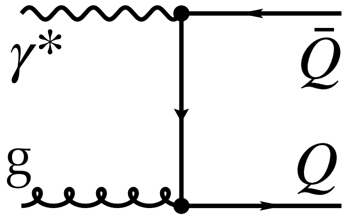
remarkable constraints in range $10^{-4} < x < 10^{-1}$, particularly for gluon helicity

still large uncertainties for $x < 10^{-4}$ beyond reach of the EIC

The EIC performance : polarized PDFs

impact on gluon helicity

Heavy-flavor production represents ~15% of inclusive DIS cross section at EIC kin.
Main channel **γ-g fusion sensitive to Δg at tree level**

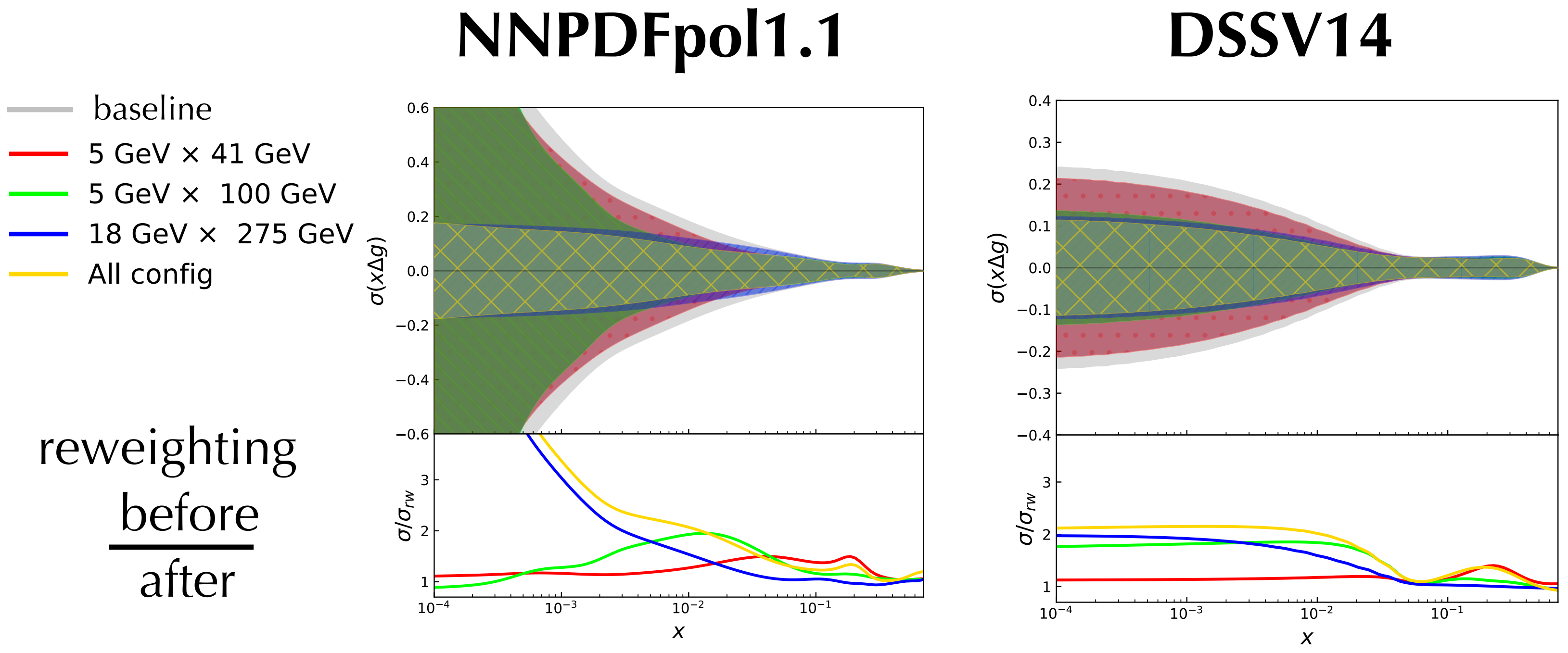


Simulation of $\vec{e}\,\vec{p} \to e' + D^0 + X$ at EIC
with Q^2=10 GeV^2 and $\mathcal{L}$=100 fb^{-1}

Observable: $A_{LL}^{c\bar{c}} \propto \dfrac{g_1^{c\bar{c}}}{F_1^{c\bar{c}}}$,

Impact on uncertainty σ of xΔg(x)

Anderle et al, arXiv:2110.04489

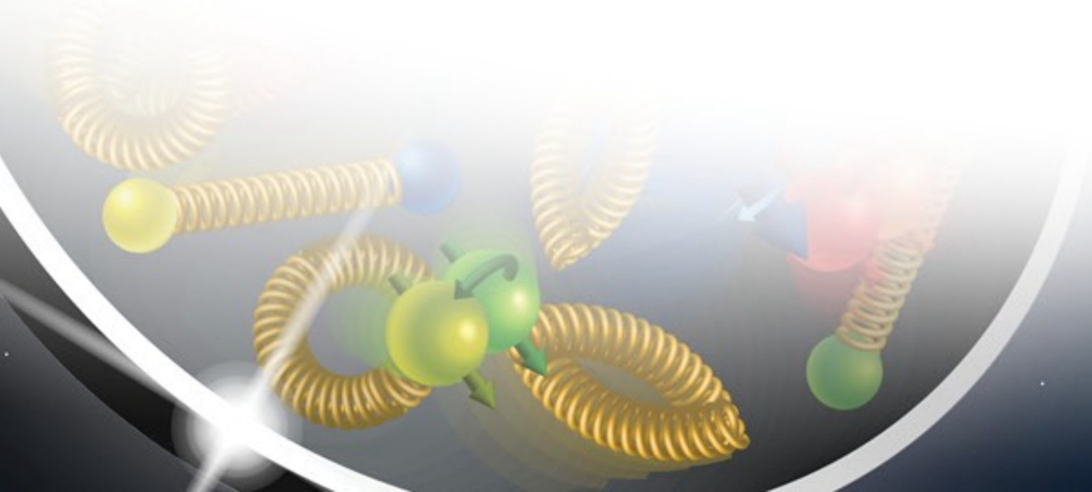


reweighting $\dfrac{\text{before}}{\text{after}}$

The EIC performance : TMDs

3-Dim Maps in momentum space

$$\mathrm{TMD}\ (x, k_T)$$



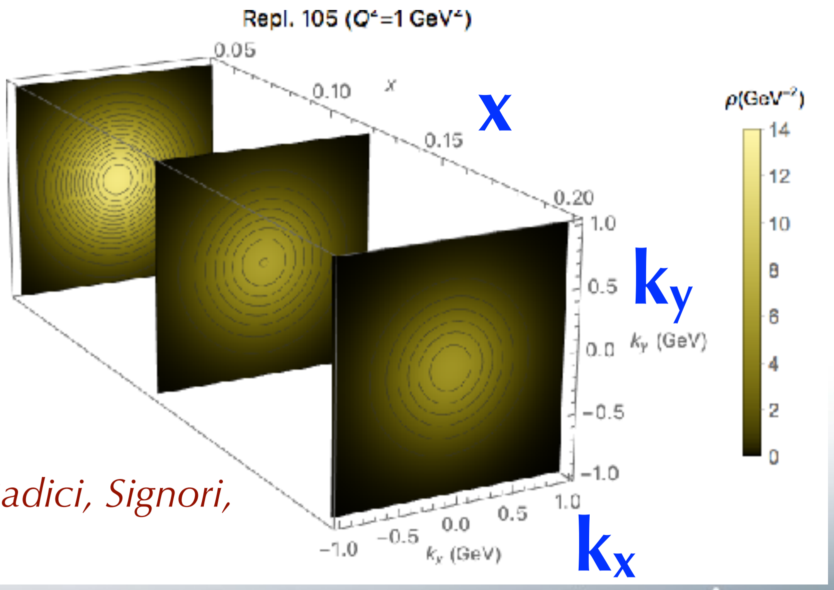
The EIC performance : unpolarized TMDs

the unpolarized quark TMD $f_1^q\,(x,k_T)$

the best known TMD (most recent fits)

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
PV 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.5
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL’	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^{3}LL	✔	✔	✔	✔	1039	1.06
PV 2019 arXiv:1912.07550	N^{3}LL	✘	✘	✔	✔	353	1.07
MAP 2022 in preparation	N^{3}LL	✔	✔	✔	✔	2031	1.06

tomography in
momentum space



PV 2017
Bacchetta, Delcarro, Pisano, Radici, Signori,
JHEP ***06*** *(17) 081*

The EIC performance : unpolarized TMDs

the unpolarized quark TMD $f_1^q\,(x,k_T)$

Lessons to be learnt :

- non-perturbative k_T dependence is not a simple Gaussian
- average $\langle k_T^2 \rangle$ strongly depends on x, and might depend on flavor (in particular for fragmentation)
- Gaussian non perturbative evolution seems preferred
- modern fits can reach N^{3}LL+NNLO perturbative accuracy with reduced $\chi^2 \sim 1$ on thousands data points

the best known TMD (most recent fits)

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
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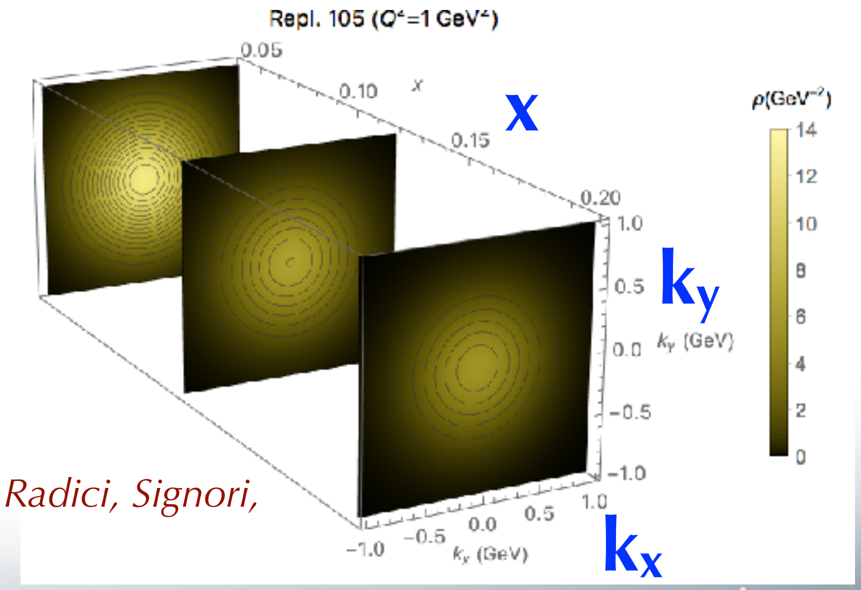
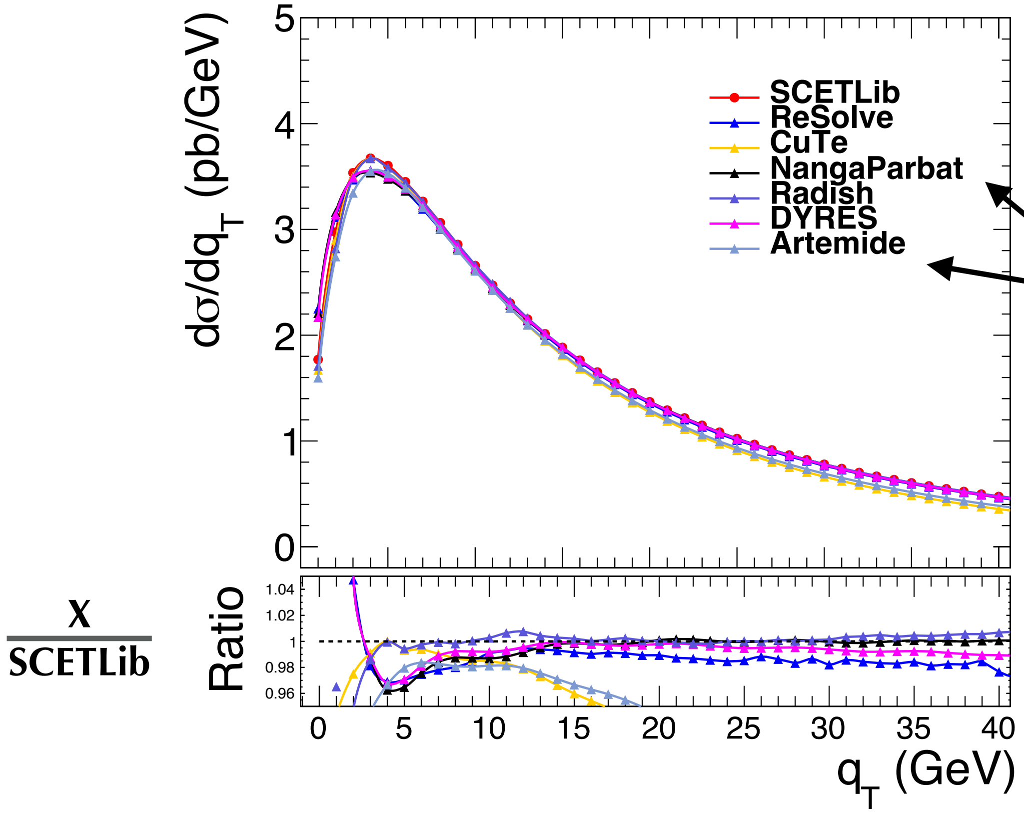


PV 2017
Bacchetta, Delcarro, Pisano, Radici, Signori,
JHEP ***06*** *(17) 081*

The EIC performance : unpolarized TMDs

the unpolarized quark TMD $f_1^q\ (x,k_T)$

same accuracy as PDF
benchmarking codes @LHC



Z production at η=0 (ATLAS kin)

G. Bozzi, I. Scimemi (eds.) et al.,
Yellow Report of CERN EW WG, in preparation

the best known TMD (most recent fits)

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
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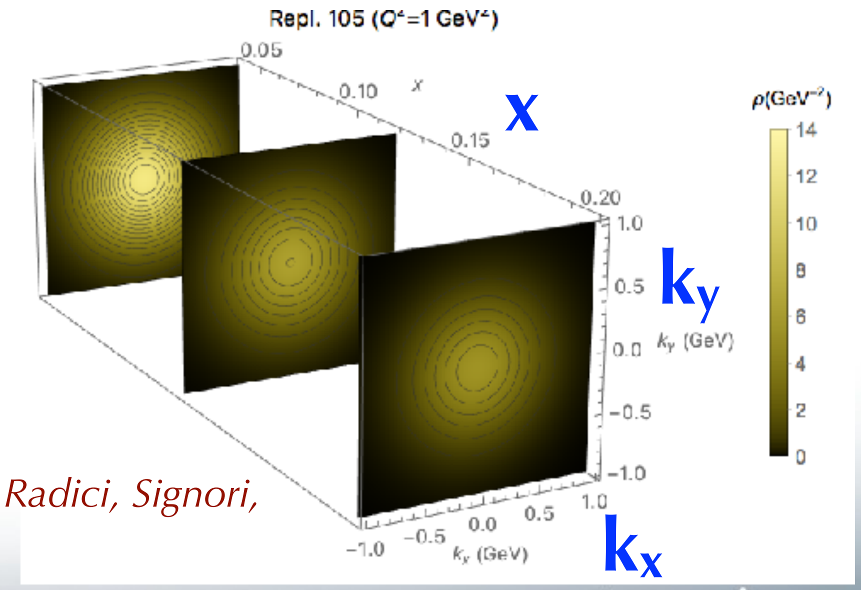

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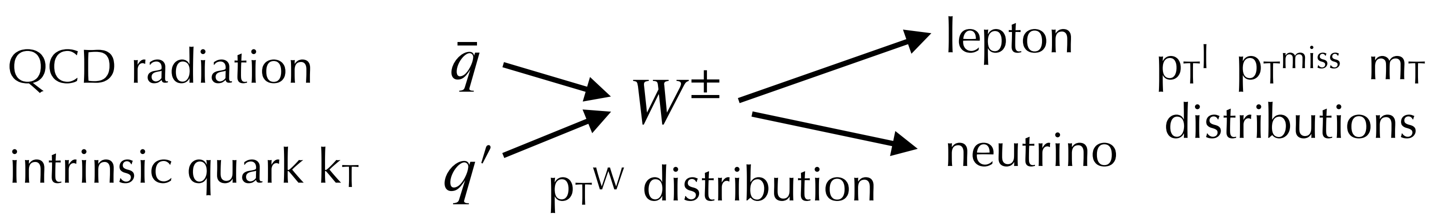
Impact on M_W extraction



QCD radiation

intrinsic quark k_T

$\bar{q}$ → $W^{\pm}$ ← q'

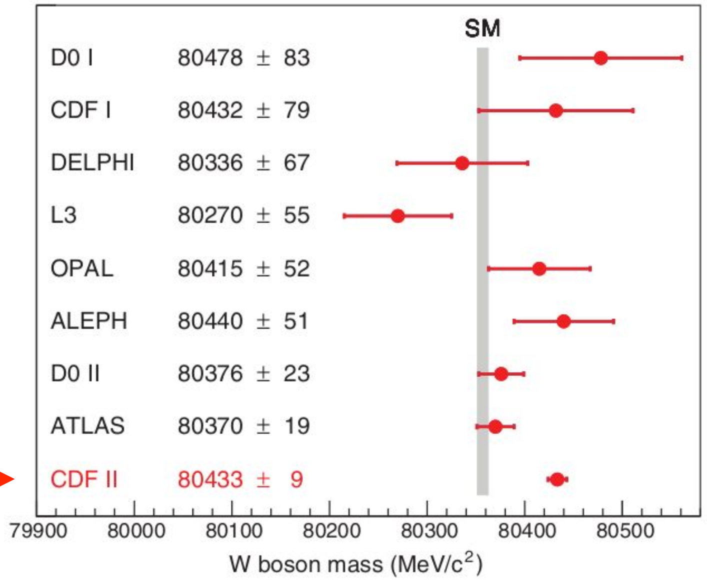
p_T^W distribution

lepton

neutrino

p_T^l p_T^{miss} m_T distributions

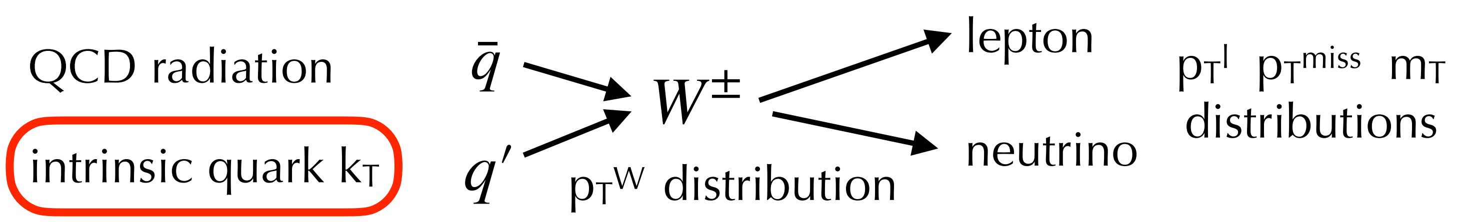
surprising CDF result



~ 7σ ! →

SM expectation: $M_W = 80357 \pm 6$ MeV

Impact on M_W extraction



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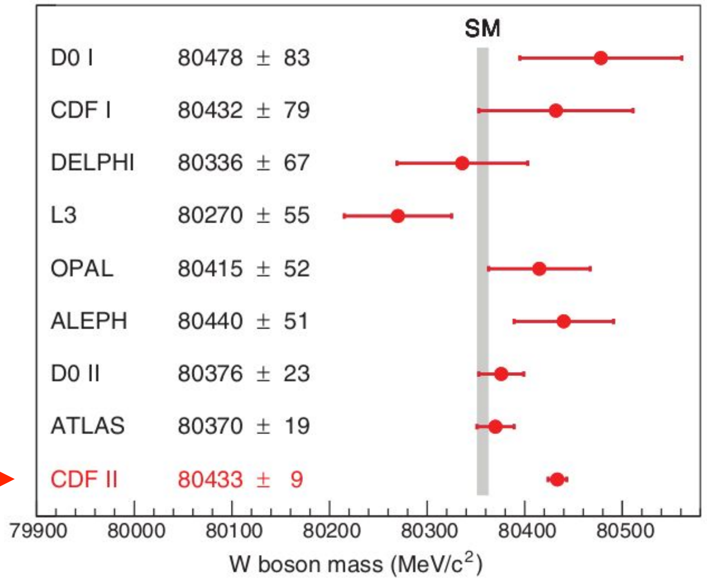

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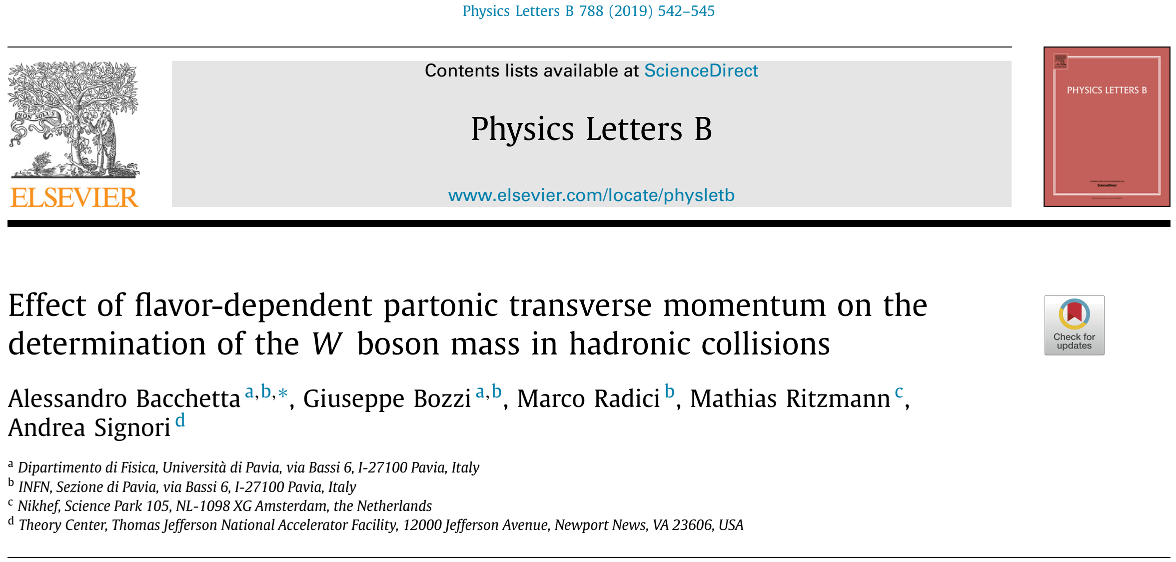

Physics Letters B 788 (2019) 542–545

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Physics Letters B

www.elsevier.com/locate/physletb

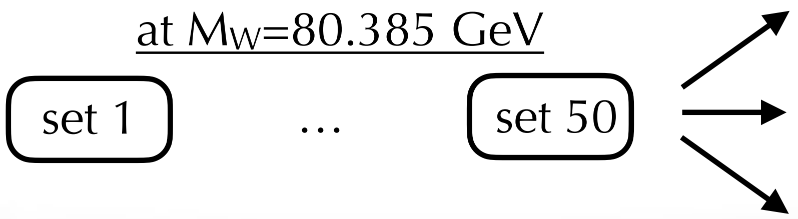
Effect of flavor-dependent partonic transverse momentum on the determination of the W boson mass in hadronic collisions

Alessandro Bacchetta [a,b,*], Giuseppe Bozzi [a,b], Marco Radici [b], Mathias Ritzmann [c], Andrea Signori [d]

[a] Dipartimento di Fisica, Università di Pavia, via Bassi 6, I-27100 Pavia, Italy
[b] INFN, Sezione di Pavia, via Bassi 6, I-27100 Pavia, Italy
[c] Nikhef, Science Park 105, NL-1098 XG Amsterdam, the Netherlands
[d] Theory Center, Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA

template fit

50 **pseudo-data sets** of "Z-equivalent"
flavor-dep. k_T-distrib.
at M_W=80.385 GeV



set 1 … set 50

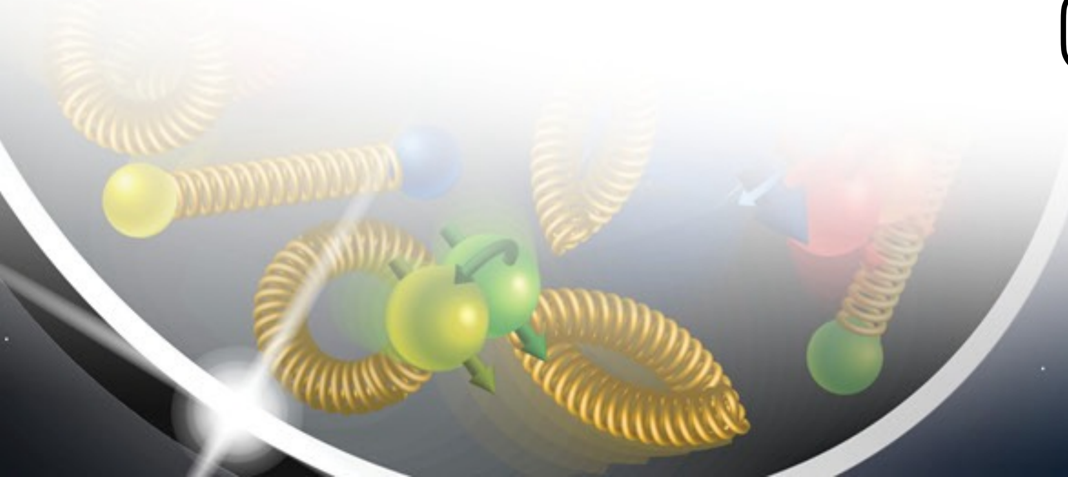
30 **templates** of **flavor-indep.** k_T-distrib.

template 1: M_W=80.370 $\chi^2_{\text{set-i}}$ (1)

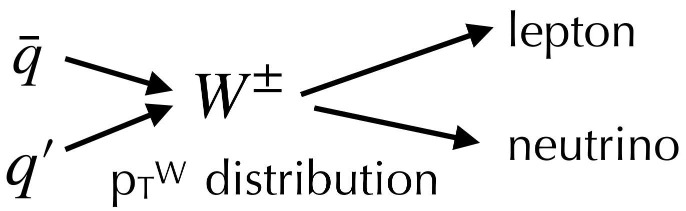
⋮ best $\chi^2_{\text{set-i}}$ (…)

template 30: M_W=80.400 $\chi^2_{\text{set-i}}$ (30)

*Signori et al., JHEP**11** (13) 194*



Impact on M_W extraction



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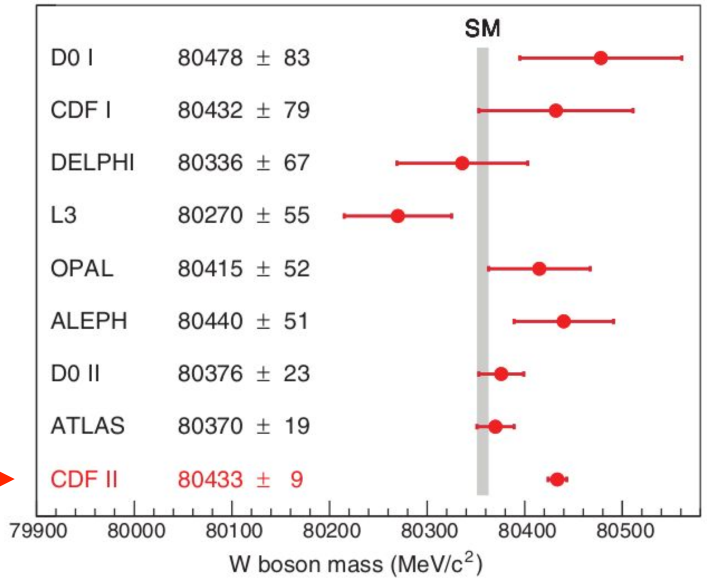
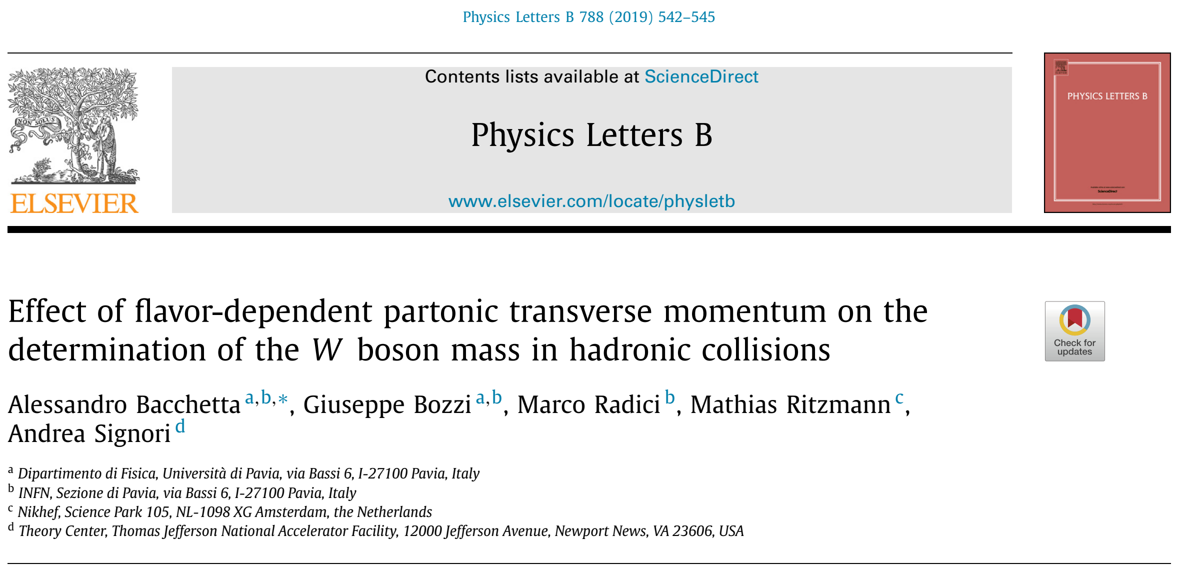


~ 7σ !

but all analyses assume a flavor-independent Gaussian



Physics Letters B 788 (2019) 542–545

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SM expectation: $M_W = 80357 \pm 6$ MeV

additional uncertainty

$$-6 \leq \Delta M_{W^+} \leq 9$$

$$-4 \leq \Delta M_{W^-} \leq 3$$

in opposite directions !

±2.5 MeV stat. uncertainty

template fit

50 **pseudo-data sets** of "Z-equivalent"
flavor-dep. k_T-distrib.
at M_W=80.385 GeV

set 1 … set 50

30 **templates** of **flavor-indep.** k_T-distrib.

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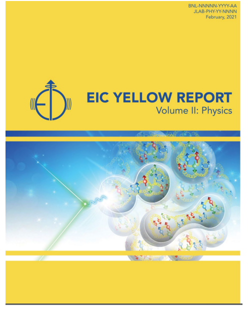
*Signori et al., JHEP**11** (13) 194*

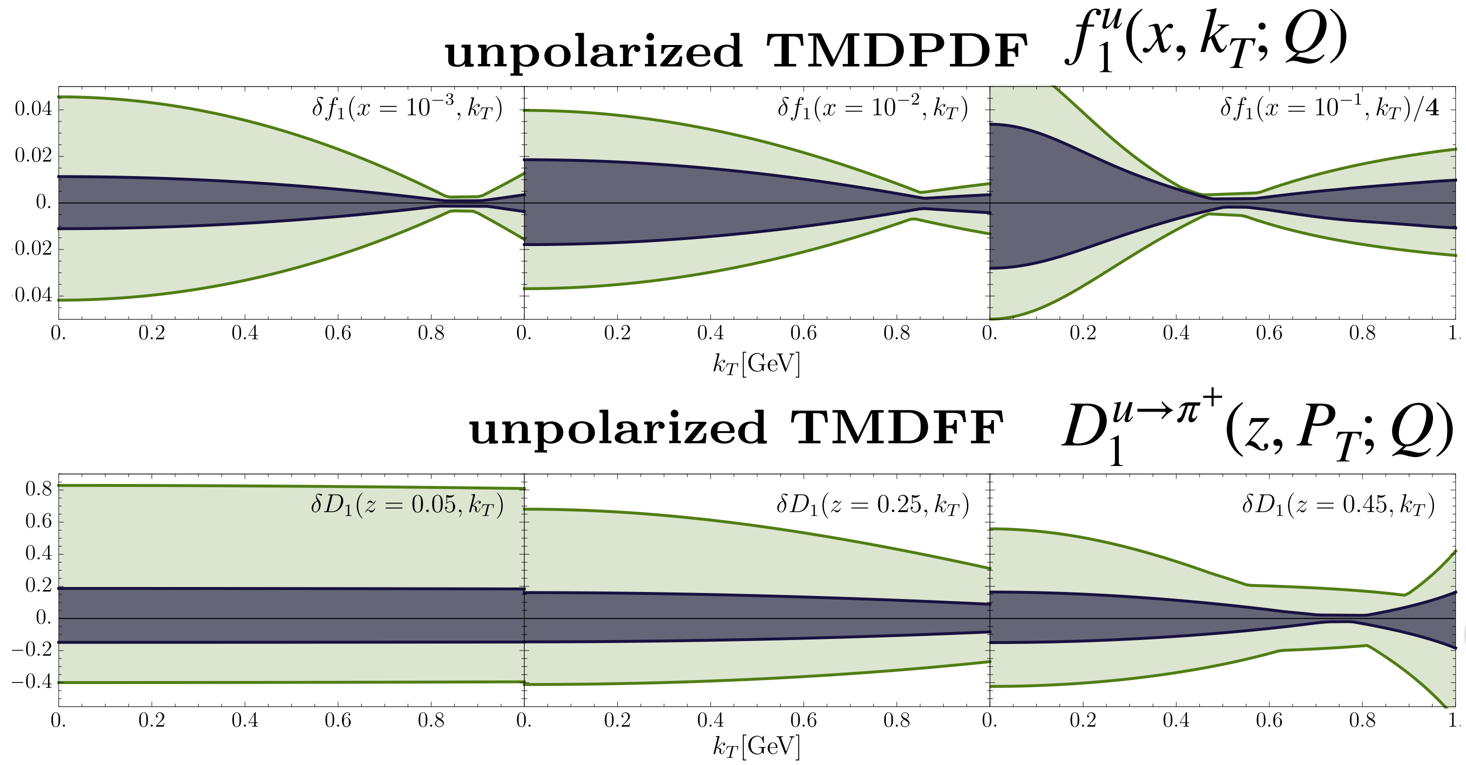
The EIC performance : unpolarized TMDs



arXiv:2103.05419,
*N.P.**A** in press*

EIC impact

Q = 2 GeV SIDIS e p → e′ π± X $\mathcal{L}$=10 fb-1


unpolarized TMDPDF $f_1^u(x, k_T; Q)$

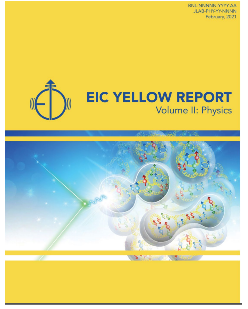
unpolarized TMDFF $D_1^{u\to\pi^+}(z, P_T; Q)$

🟩 SV 2019

▨ + EIC

e- → ← p
5 × 41
5 × 100
10 × 100
18 × 100
18 × 275
GeV

The EIC performance : unpolarized TMDs

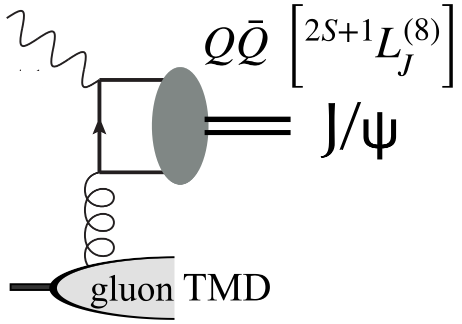

EIC YELLOW REPORT
Volume II: Physics

arXiv:2103.05419,
*N.P.**A** in press*

EIC : explore the unknown gluon TMD

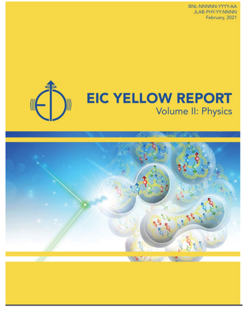
- gluons carry “two color charges” → difficult to neutralize

- useful channels: heavy-quarkonium → production of J/ψ, …
  back-to-back di-jet production



Bacchetta et al., arXiv:1809.02056
D’Alesio et al., arXiv:1908.00446

The EIC performance : unpolarized TMDs



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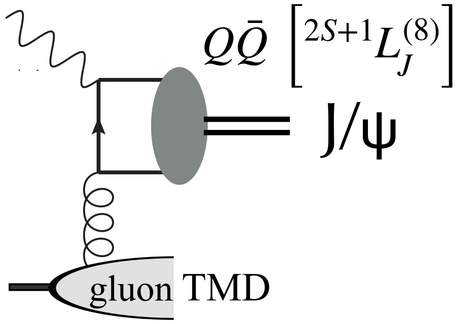


- useful channels: heavy-quarkonium → production of J/ψ, …
  back-to-back di-jet production

Bacchetta et al., arXiv:1809.02056
D'Alesio et al., arXiv:1908.00446

- unknown "Shape function" $Q\bar{Q} \to J/\psi$

Boer et al., arXiv:2004.06740
Boer et al., arXiv:2102.00003
D'Alesio et al., arXiv:2110.07529
Fleming et al., arXiv:1910.03586
Echevarria, arXiv:1907.06494
….

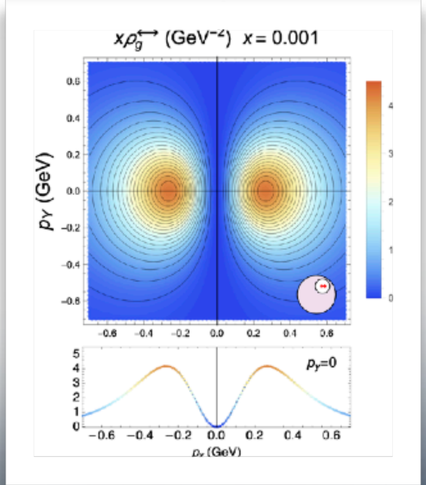
depend on angular momentum and color structure of $Q\bar{Q}$
must be extracted from experiment ← opportunity at the EIC

- also model calculation

Bacchetta et al., arXiv:2005.02288

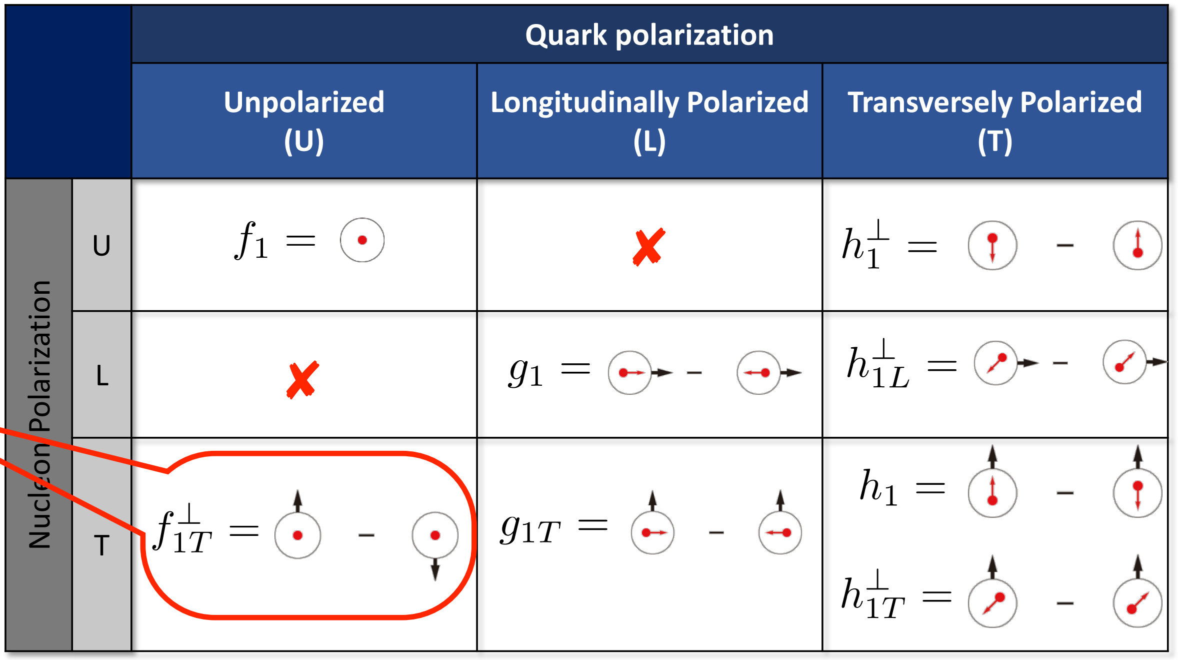
gluon density in unpol. proton

$$\rho_g^{\leftrightarrow} = \frac{1}{2}\left[f_1^g + \frac{k_x^2 - k_y^2}{2M^2}\, h_1^{\perp g}\right]$$



The EIC performance : polarized TMDs

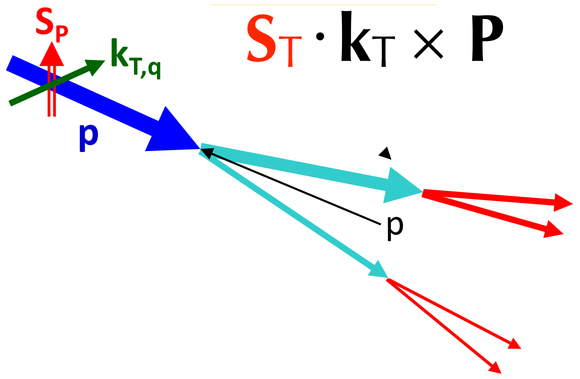
the Sivers TMD $f_{1T}^{\perp q}(x,k_T)$



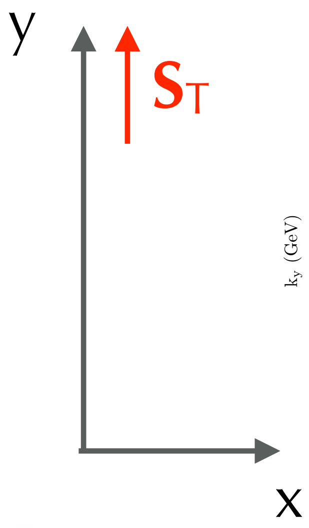
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	✘	$h_1^{\perp} =$ -
	L	✘	$g_1 =$ -	$h_{1L}^{\perp} =$ -
	T	$f_{1T}^{\perp} =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^{\perp} =$ -

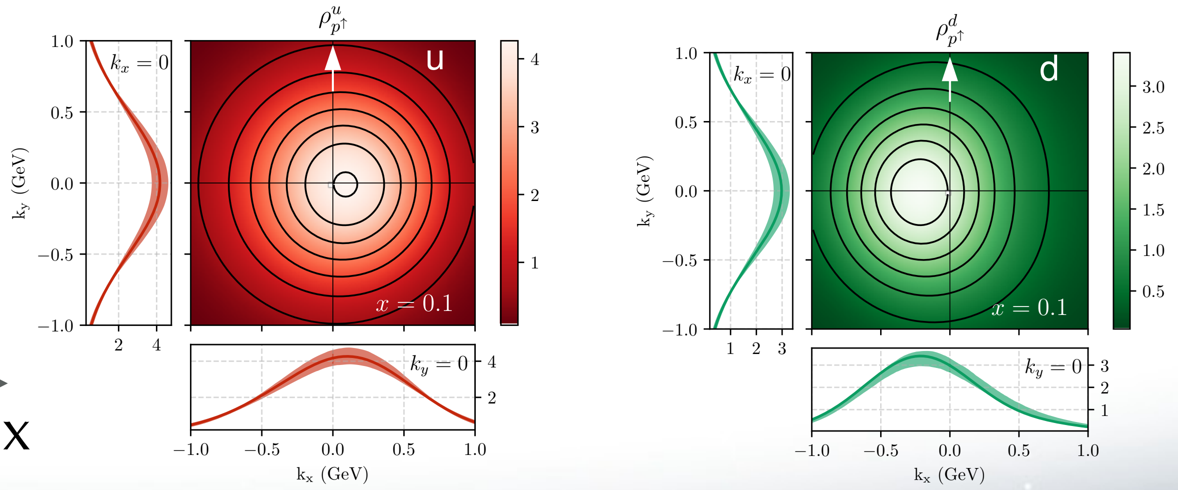
how the momentum distribution of unpolarized quarks is distorted by the transverse polarization of the nucleon

→ access to quark orbital angular momentum



$S_T \cdot k_T \times P$

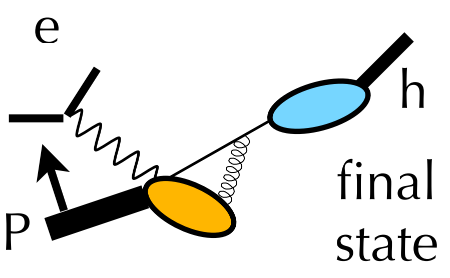




*Bacchetta et al., P.L. **B827** (22) 136961, arXiv:2004.14278*

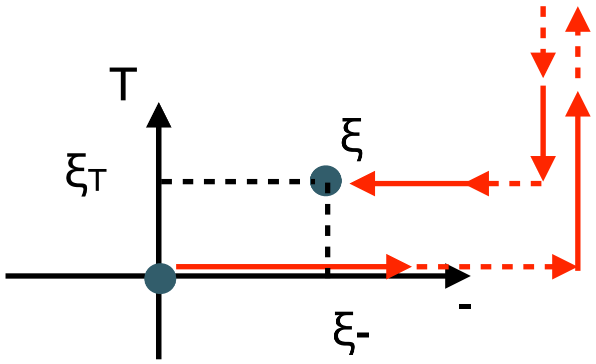
The EIC performance : polarized TMDs

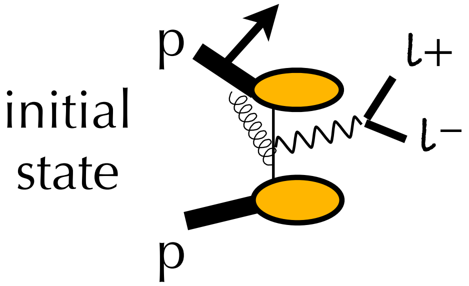
the quark Sivers TMD is not universal !



SIDIS

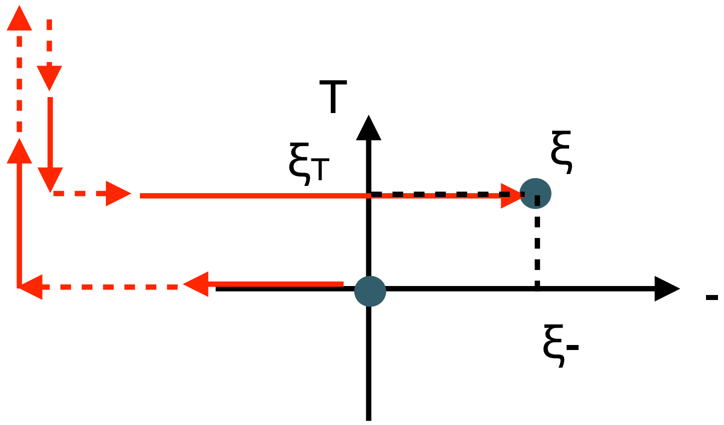
in SIDIS, gauge link structure
is “future pointing” → describes
residual color final-state interactions





Drell-Yan

in Drell-Yan, gauge link structure
is “past pointing” → describes
color initial-state interactions



Prediction of QCD:
Sivers TMD (SIDIS) = - Sivers TMD (Drell-Yan)

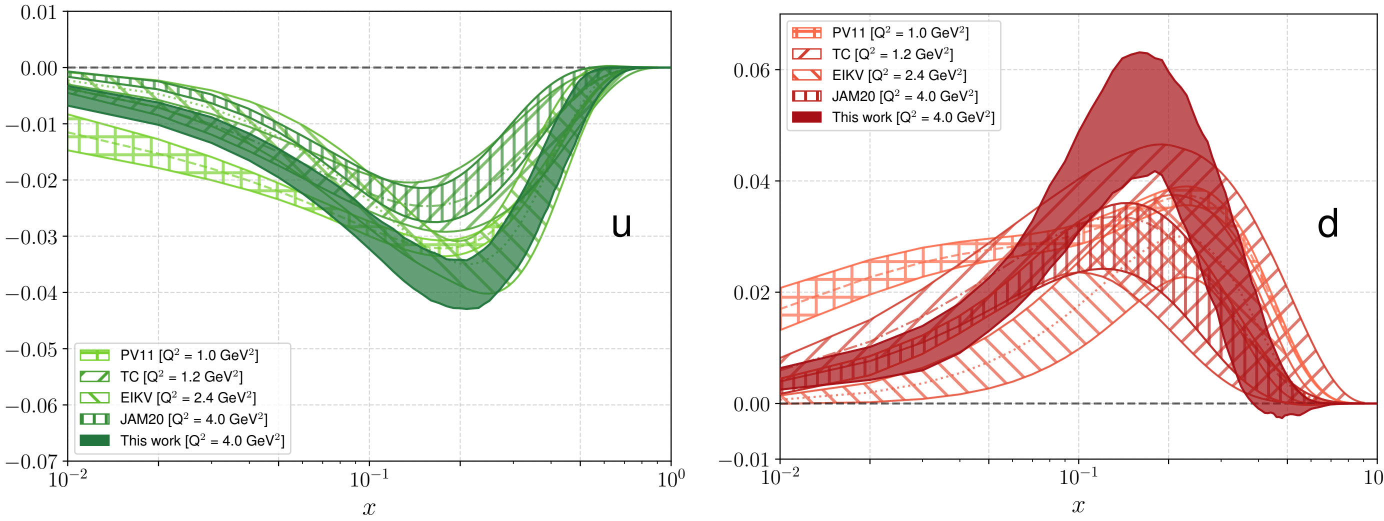
The EIC performance : polarized TMDs

most recent extractions of quark Sivers

	Framework	SIDIS	DY	W/Z production	e+e-	N of points
JAM 2020 arXiv:2002.08384	extended parton model	✔	✔	✔	✔	517
Pavia 2020 arXiv:2004.14278	LO+NLL	✔	✔	✔	✘	150
EKT 2020 arXiv:2009.10710	NLO+N^{2}LL	✔	✔	✔	✘	243
BPV 2020 arXiv:2012.05135 arXiv:2103.03270	ζ prescription	✔	✔	✔	✘	76

all parametrizations are in fair agreement for valence flavors

sea-quarks ~ $O(10^{-3})$ smaller

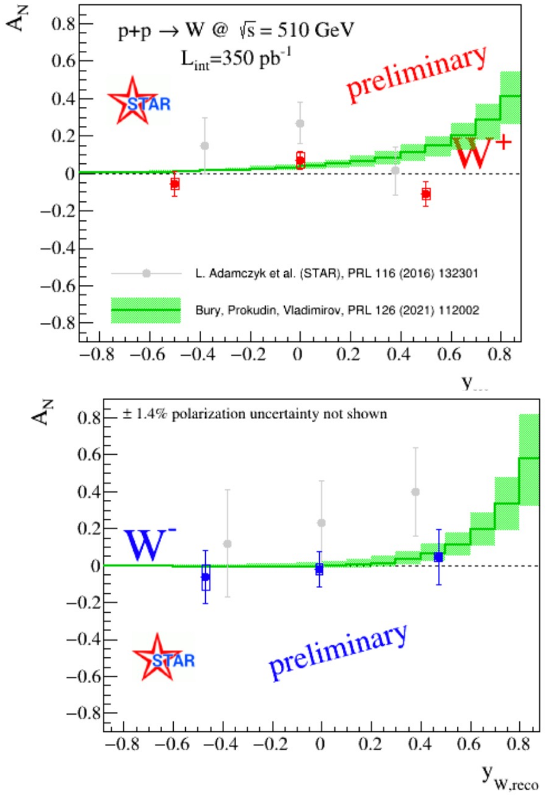


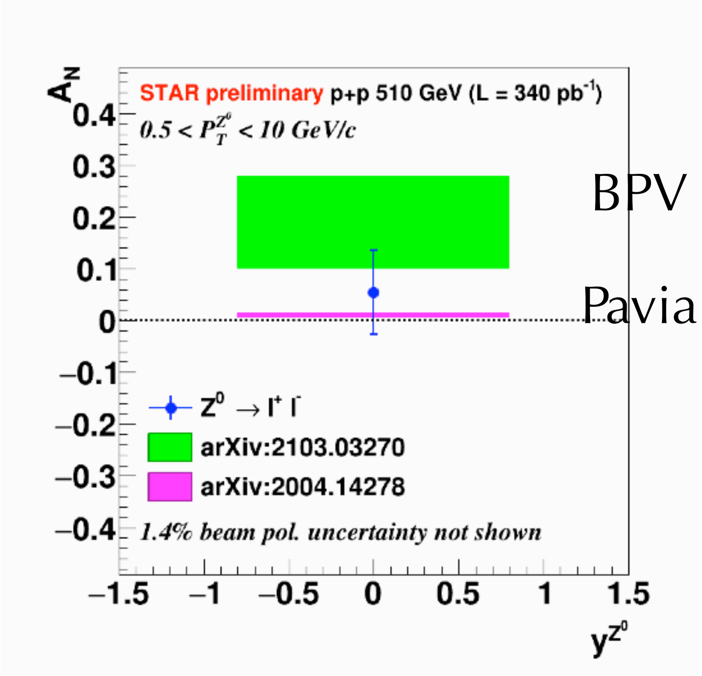
Bacchetta et al., arXiv:2004.14278

Electron-Ion Collider

The EIC performance : polarized TMDs

predictions on recent STAR Drell-Yan data

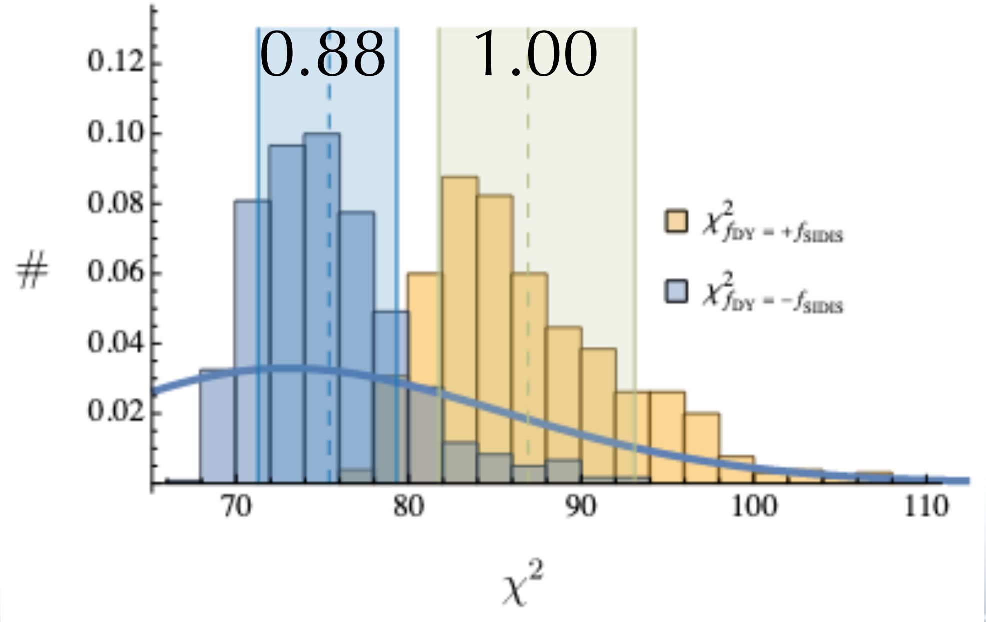




BPV 2020

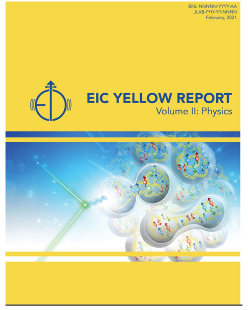
Pavia 2020

still not enough to confirm sign change:



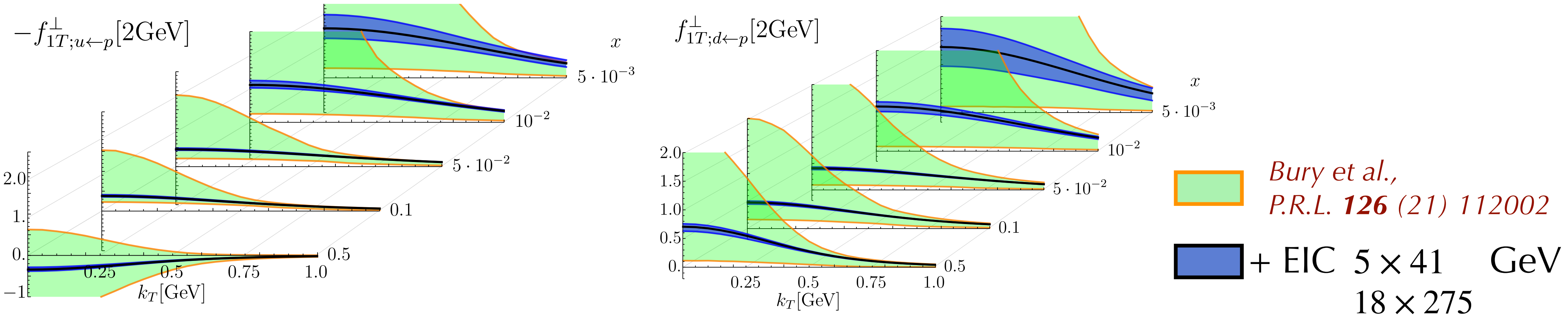
Bury et al., arXiv:2103.03270

The EIC performance : polarized TMDs

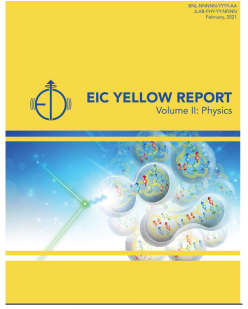


arXiv:2103.05419,
*N.P.**A** in press*

EIC impact



The EIC performance : polarized TMDs



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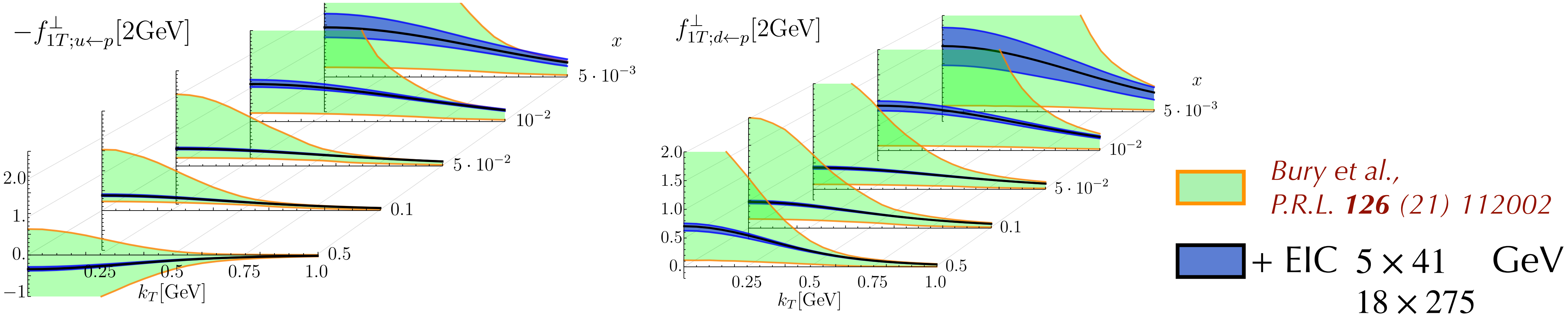
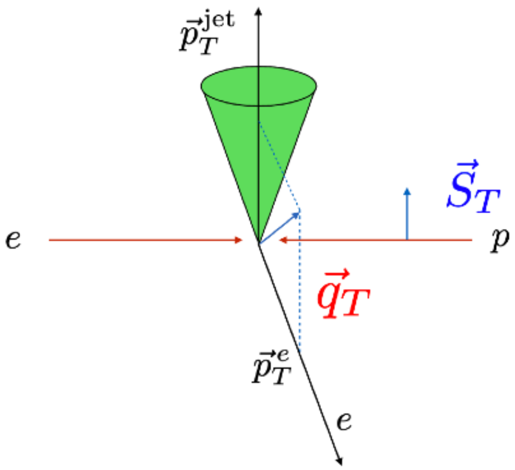


🟩 *Bury et al., P.R.L. **126** (21) 112002*

▬ + EIC 5×41 GeV
18×275

opportunities with jets and Heavy Flavors



electron-jet azimuthal correlations

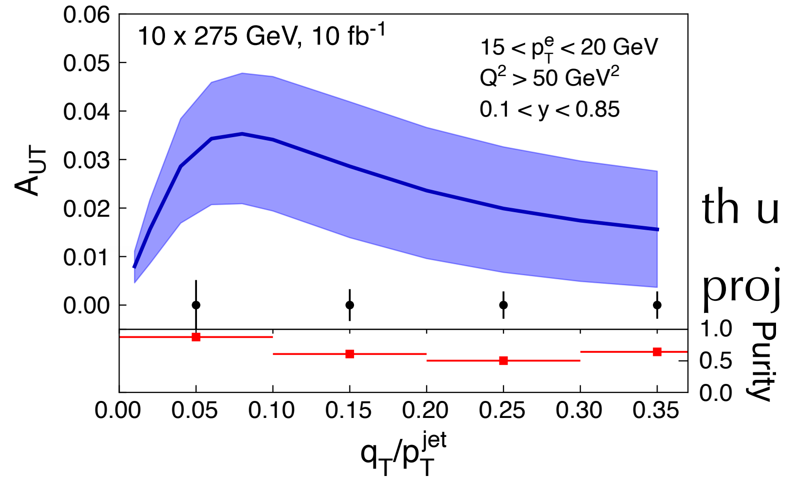
$$|\vec{q}_T| = |\vec{p}^{\,e}_T + \vec{p}^{\,jet}_T| \ll |\vec{p}^{\,jet}_T|$$

$$\downarrow$$

$A_{UT} \sim d\sigma(S_T) - d\sigma(-S_T)$

Sivers effect free from TMD FF

Arratia et al., arXiv:2007.07281



th uncertainty

projected precision

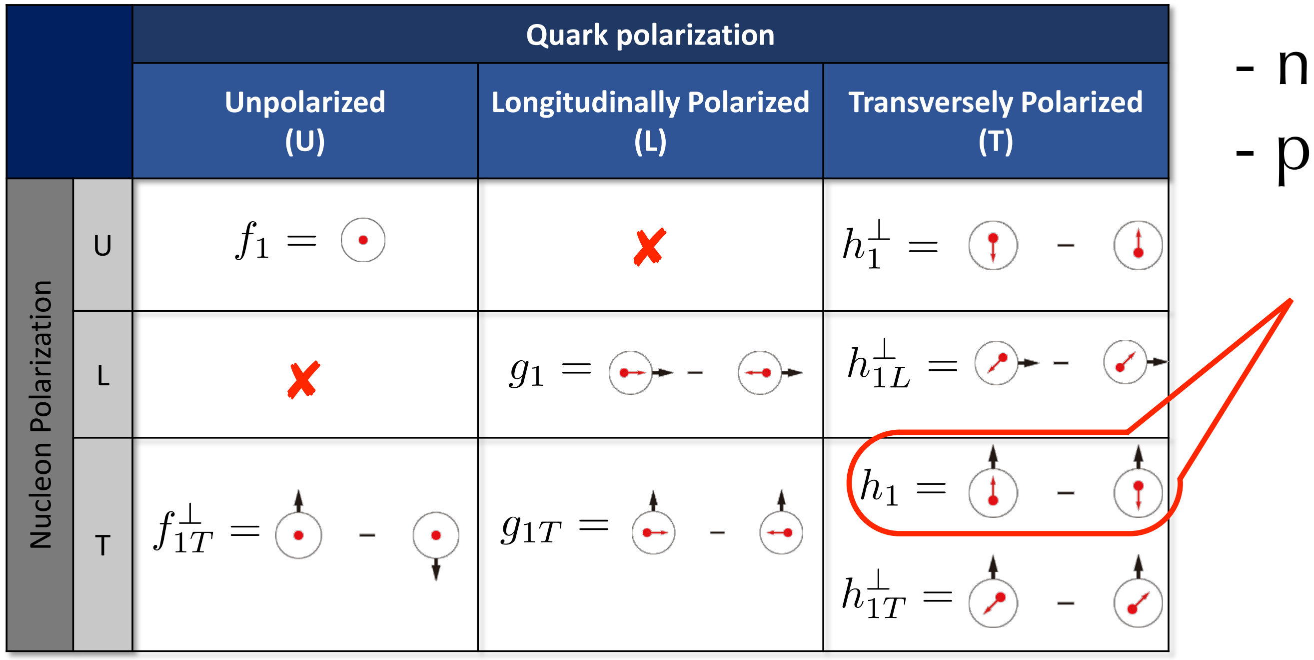
also access to gluon Sivers TMD from $D^0\bar{D}^0$, charm di-jets
and J/ψ production

Zheng et al., arXiv:1805.05290

Rajesh et al., arXiv:2108.04866

The EIC performance : polarized TMDs

transversity $h_1^q\,(x,k_T)$



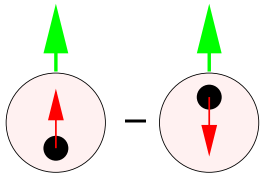
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	✘	$h_1^\perp =$ −
	L	✘	$g_1 =$ −	$h_{1L}^\perp =$ −
	T	$f_{1T}^\perp =$ −	$g_{1T} =$ −	$h_1 =$ − $h_{1T}^\perp =$ −

- net density of ⊥-pol. quark in ⊥-pol. proton
- prototype of chiral-odd parton densities

survives k_T integration

↓

collinear PDF $h_1^q\,(x)$



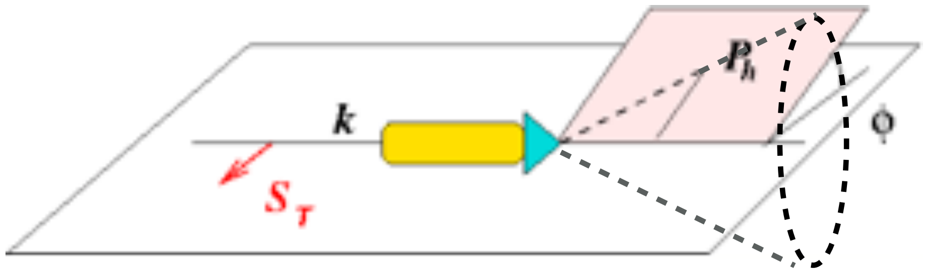
- no chiral-odd structures in SM Lagrangian; potential doorway to BSM physics

Example: SMEFT studies of strong CP violation via neutron EDM d_n

bounds from exp. ⟶ $d_n = \enclose{circle}{\delta u}\, d_u + \enclose{circle}{\delta d}\, d_d + \enclose{circle}{\delta s}\, d_s$ tensor charge $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x,Q^2)$

The EIC performance : polarized TMDs

transversity is chiral-odd → needs a chiral-odd partner in the cross section
two different fragmentation mechanisms:

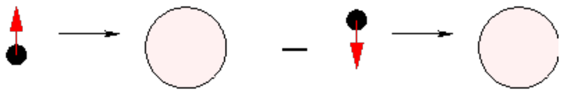


Collins effect

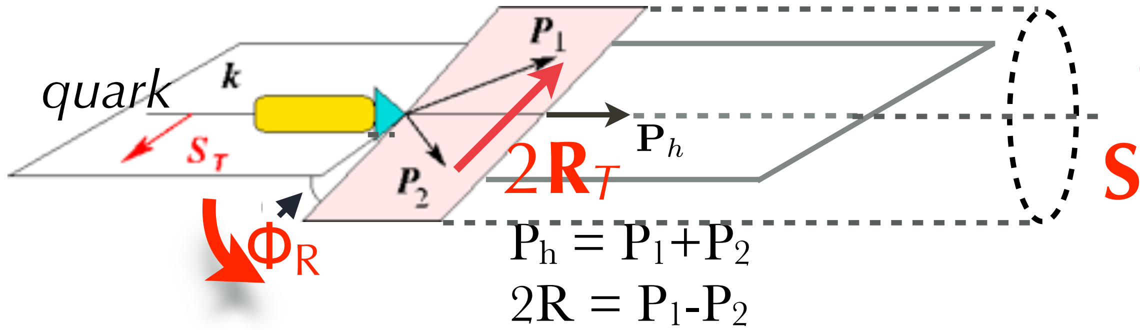
$\mathbf{S}_\mathrm{T} \cdot \mathbf{k} \times \mathbf{P}_\mathrm{hT}$

Collins, N.P. ***B396*** *(93) 161*

requires knowledge of chiral-odd
Collins TMD FF $H_1^\perp$



probes transversity as TMD PDF



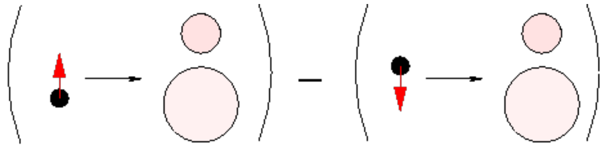
$P_h = P_1 + P_2$
$2R = P_1 - P_2$

di-hadron mechanism

$\mathbf{S}_\mathrm{T} \cdot \mathbf{P}_2 \times \mathbf{P}_1 = \mathbf{S}_\mathrm{T} \cdot \mathbf{P}_\mathrm{h} \times \mathbf{R}_\mathrm{T}$

Collins et al., N.P. ***B420*** *(94)*

requires knowledge of
chiral-odd DiFF $H_1^{\sphericalangle}$



probes transversity as PDF

if $R_T^2 \propto M_{h_1h_2}^2 \ll Q^2$ define di-hadron fragmentation function (DiFF)

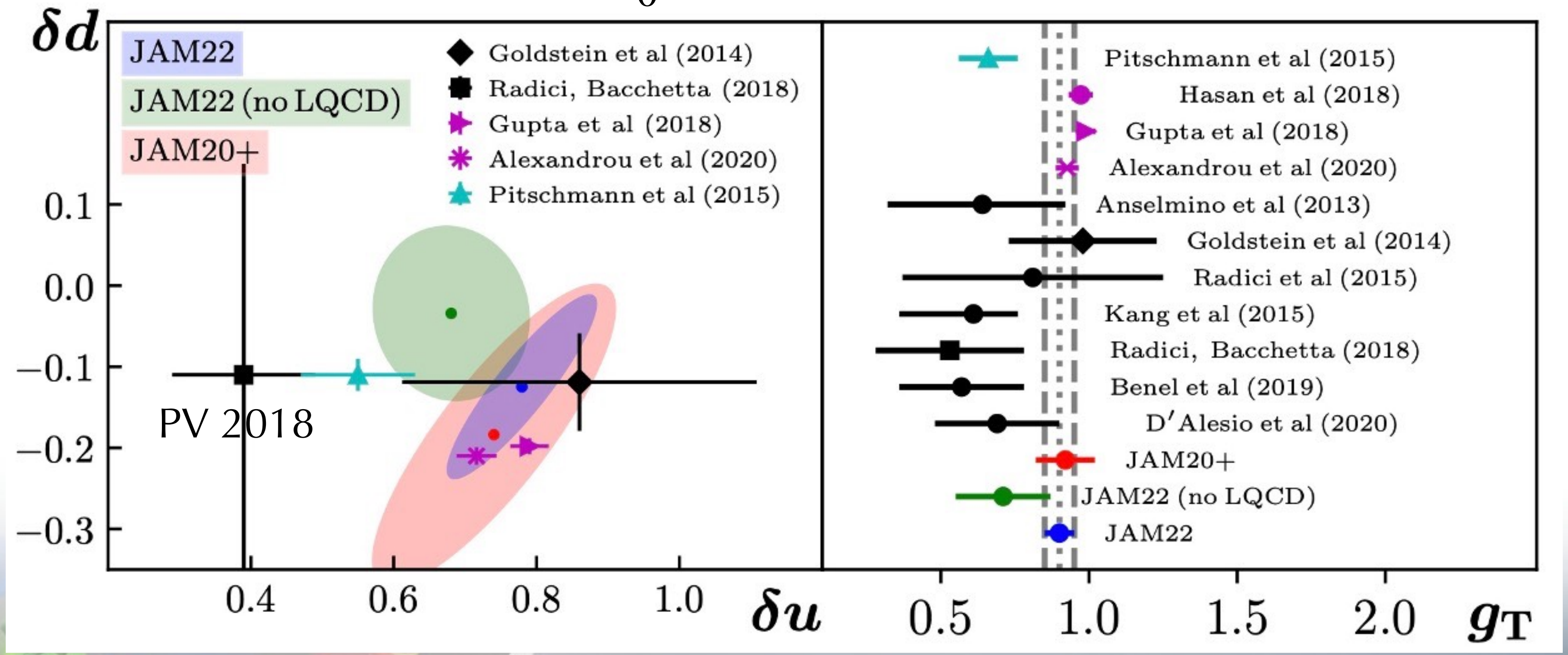
The EIC performance : polarized TMDs

most recent extractions

	Mechanism	Framework	SIDIS	e+e-	p-p collisions	N pts
PV 2018 arXiv:1802.05212	collinear DiFF	LO	✔	✔	✔	78
JAM 2020 arXiv:2002.08384	Collins effect	generalized parton model	✔	✔	✔	517
MEX 2019 arXiv:1912.03289	collinear DiFF	LO	✔	✔	✘	68
CA 2020 arXiv:2001.01573	Collins effect	generalized parton model	✔	✔	✘	76
JAM 2022 arXiv:2205.00999	Collins effect	generalized parton model	✔	✔	✔	634

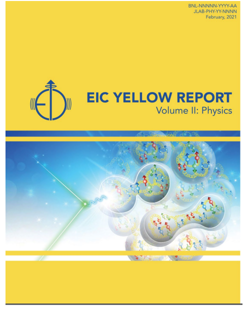
tensor charge $\delta^q(Q^2) = \int_0^1 dx\, h_1^{q-\bar{q}}(x, Q^2)$ $g_T = \delta u - \delta d$

Q=2 GeV



Electron-Ion Collider

The EIC performance : polarized TMDs



EIC YELLOW REPORT
Volume II: Physics

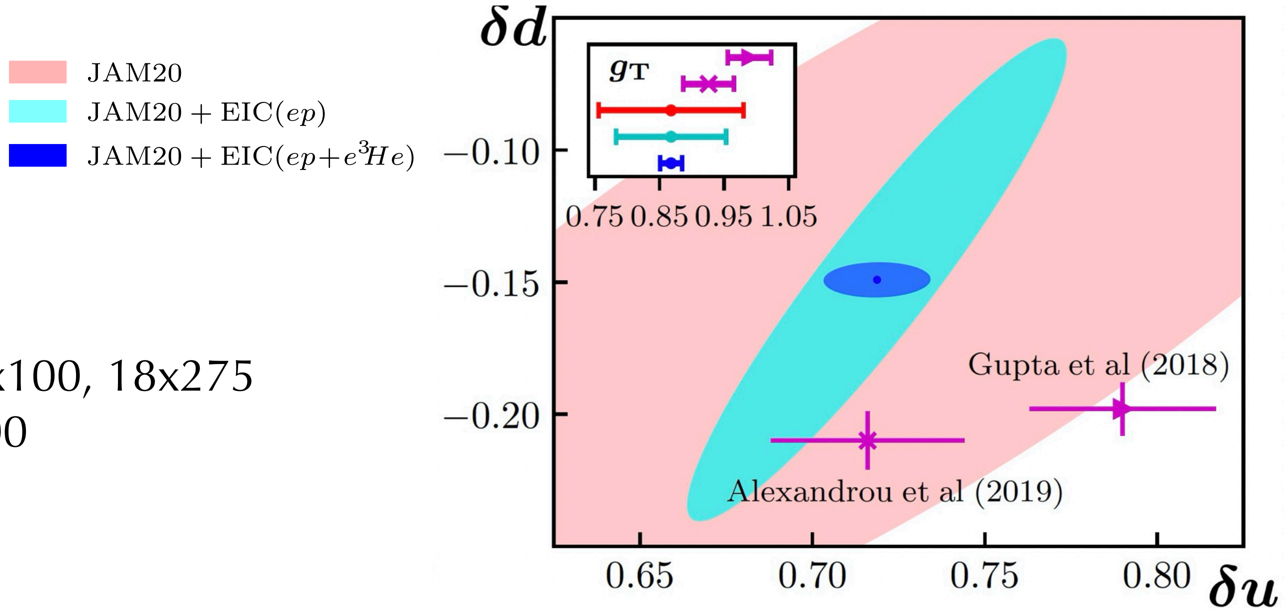
arXiv:2103.05419,
*N.P.**A** in press*

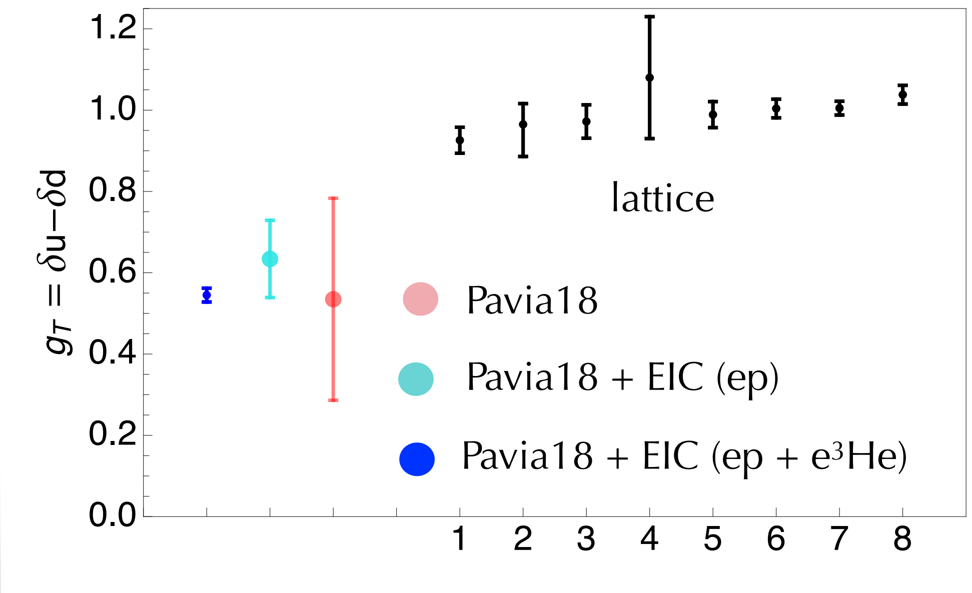
EIC impact

Collins effect

$\mathcal{L}$=10 fb^{-1} , 8223 data pts.

proton [GeV]: 5x41, 5x100, 10x100, 18x275
^{3}He [GeV]: 5x41, 5x100, 18x100



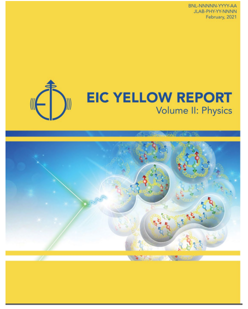


di-hadron mechanism

$\mathcal{L}$=10 fb^{-1} , 3852 data pts, proton&^{3}He [GeV]: 10x100

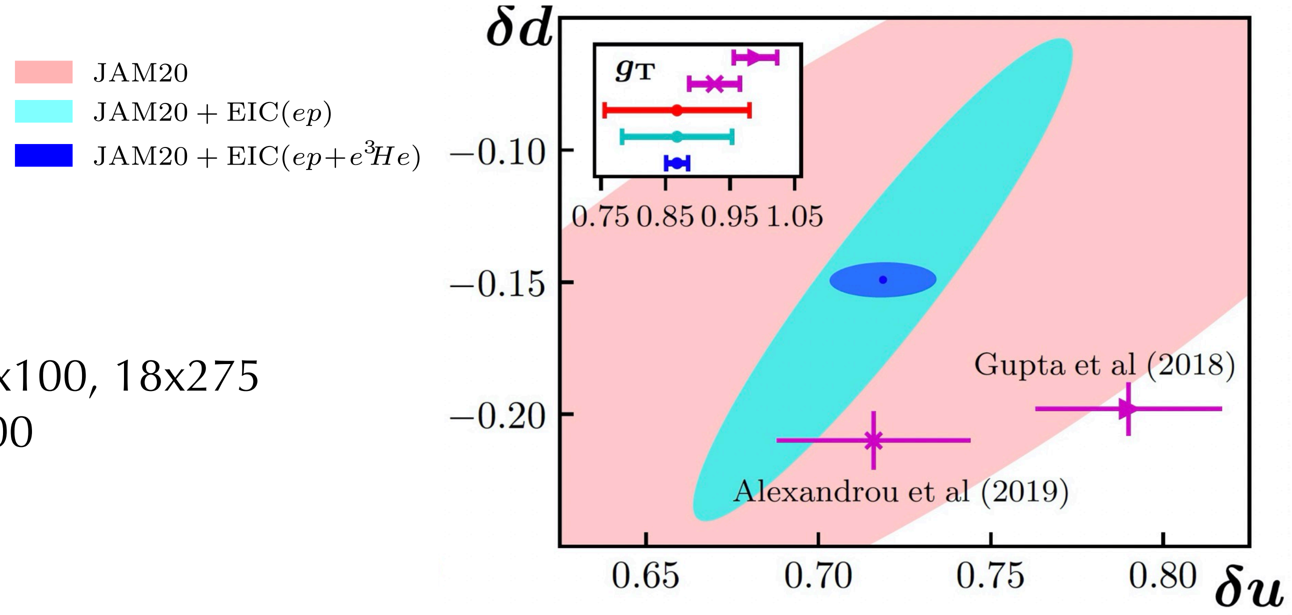
1)	**ETMC '19**	*Alexandrou et al., arXiv:1909.00485*
2)	**Mainz '19**	*Harris et al., P.R. D**100** (19) 034513*
3)	**LHPC '19**	*Hasan et al., P.R. D**99** (19) 114505*
4)	**JLQCD '18**	*Yamanaka et al., P.R. D**98** (18) 054516*
5)	**PNDME '18**	*Gupta et al., P.R. D**98** (18) 034503*
6)	**ETMC '17**	*Alexandrou et al., P.R. D**95** (17) 114514; (E) P.R. D**96** (17) 099906*
7)	**RQCD '14**	*Bali et al., P.R. D**91** (15) 054501*
8)	**LHPC '12**	*Green et al., P.R. D**86** (12) 114509*

The EIC performance : polarized TMDs



arXiv:2103.05419,
*N.P.**A** in press*

EIC impact



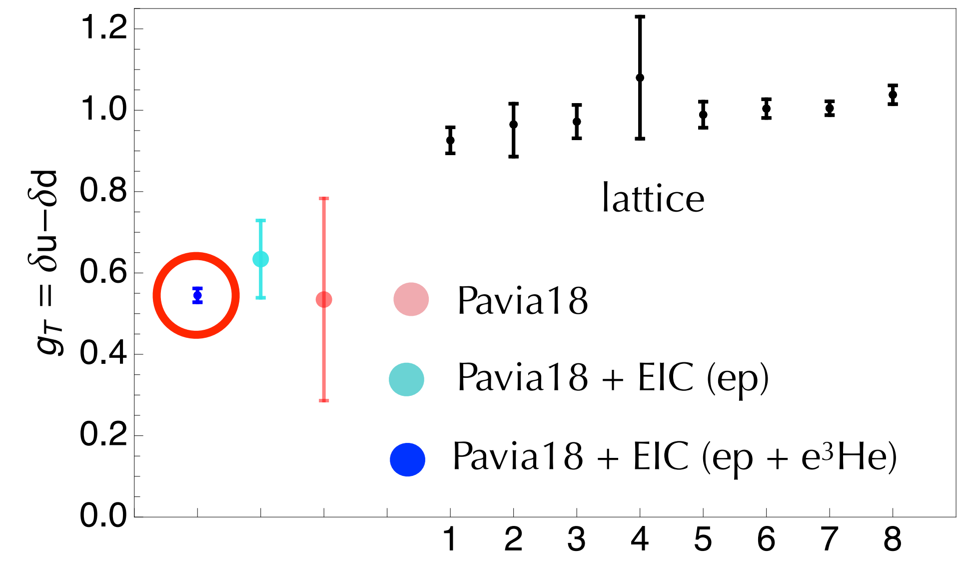
Collins effect

$\mathcal{L}$=10 fb^{-1} , 8223 data pts.

proton [GeV]: 5x41, 5x100, 10x100, 18x275

^{3}He [GeV]: 5x41, 5x100, 18x100

comparable/higher precision than lattice



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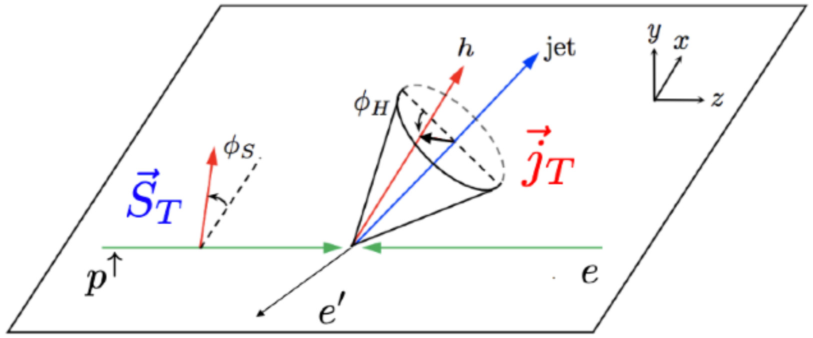
8) **LHPC '12** *Green et al., P.R. D**86** (12) 114509*

The EIC performance : polarized TMDs

a new opportunity: jet substructure



e + p → e′ + jet (h) + X

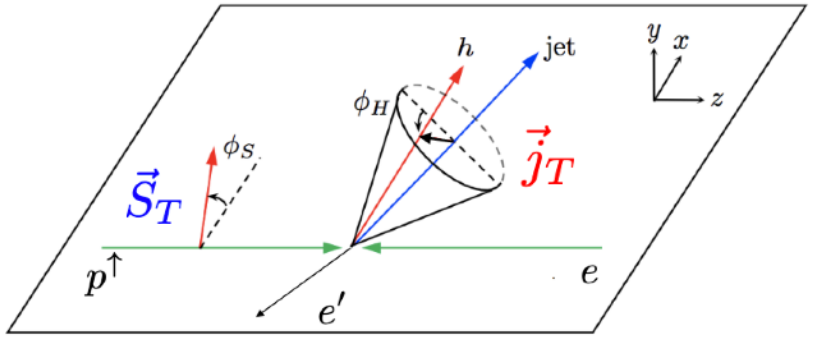
if $j_T^2 \ll (P_T^{jet})^2$ hybrid factorisation scheme:
- TMD framework for fragmentation
- collinear framework for collision

requires knowledge of
Collins TMD FF $H_1^{\perp}$
but probes transversity as PDF

hadron-in-jet Collins effect

The EIC performance : polarized TMDs

a new opportunity: jet substructure



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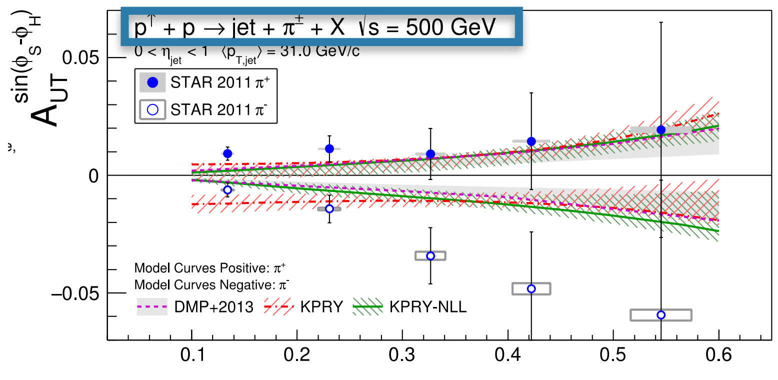
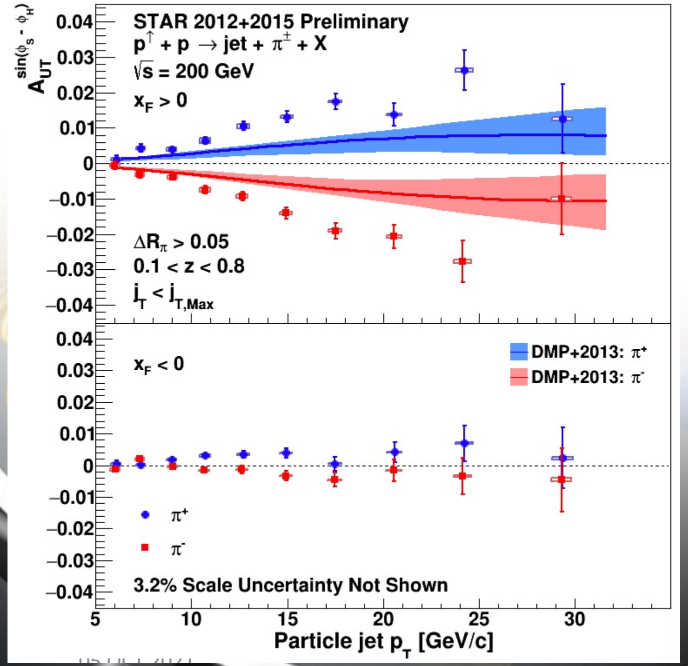
hadron-in-jet Collins effect



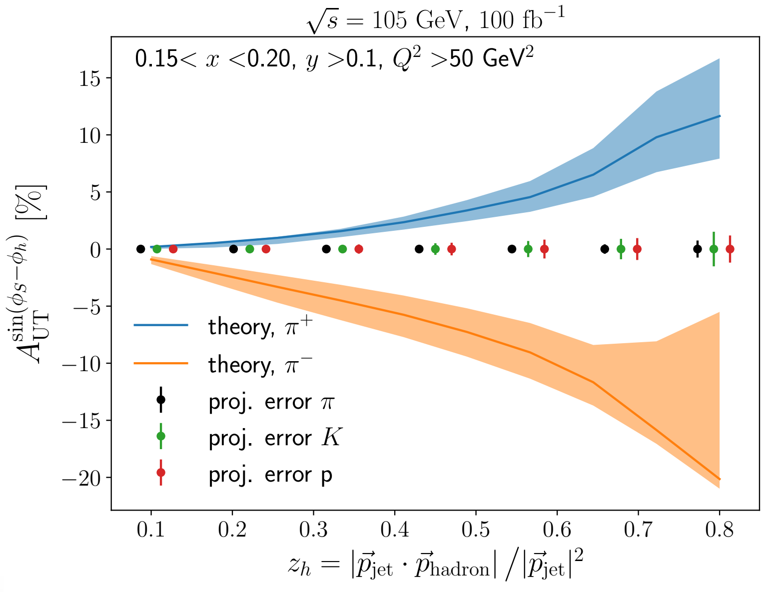


measured in
p-p collision
at STAR

KPRY
Kang et al.,
P.L. ***B774*** *(17) 635*

DMP
D'Alesio et al.,
P.L. ***B773*** *(17) 300*

predicted
at the EIC



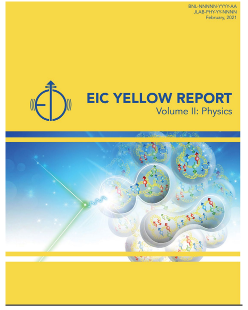
Arratia et al., arXiv:2007.07281

The EIC performance : nuclear PDF

1-Dim Maps in nuclei

nuclear PDF (x)

The EIC performance : nuclear PDF



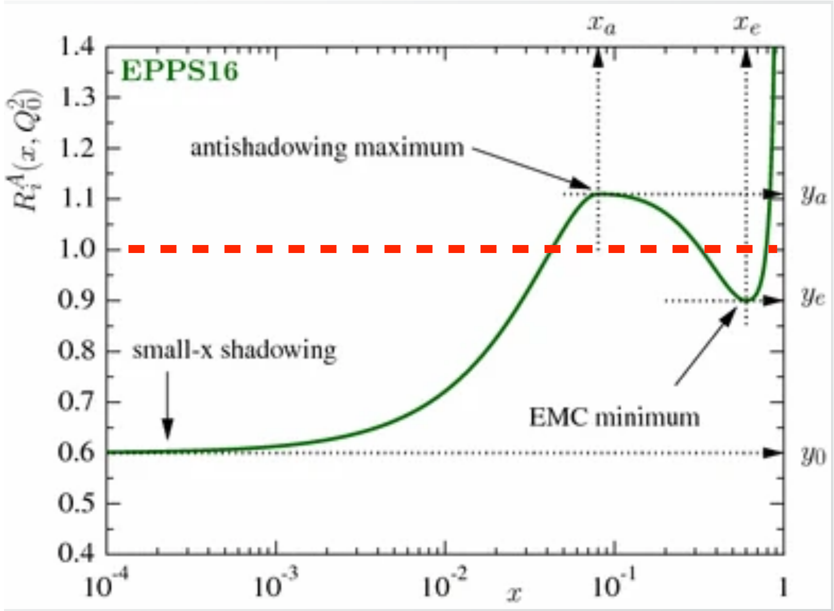
arXiv:2103.05419,
*N.P.**A** in press*

the nuclear modification factor R_A

nuclear PDFs are different from free proton PDFs :

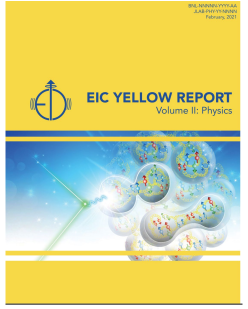
$$f^i_{p/A}(x;Q^2) = R^i_A(x;Q^2)\, f^i_p(x;Q^2)$$

- provides input on initial state for heavy-ion collisions
- complementary to LHC and RHIC p-A collisions



*Eskola et al., E.P.J. C**77** (16) 163*

The EIC performance : nuclear PDF



arXiv:2103.05419,
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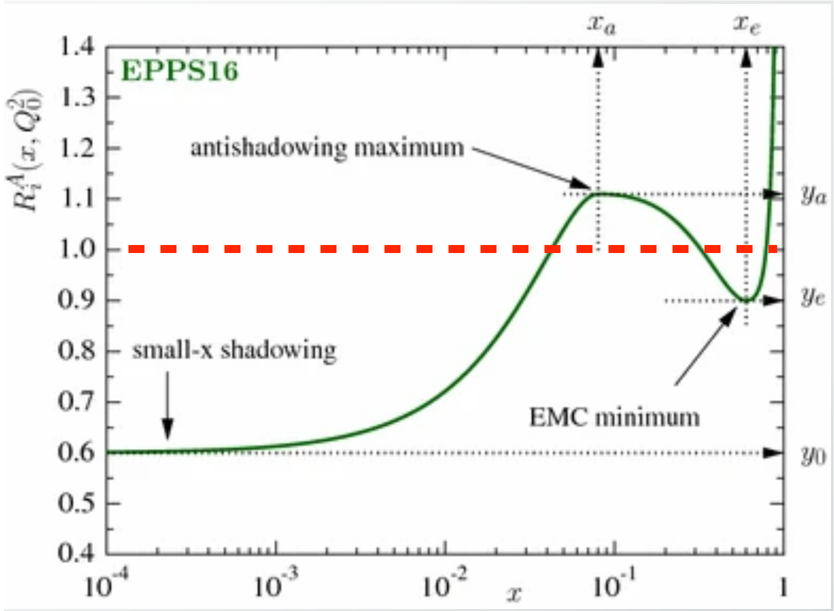
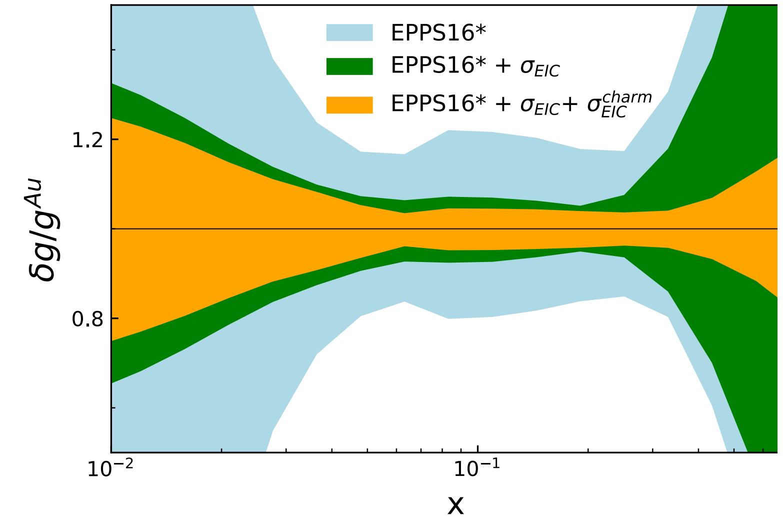
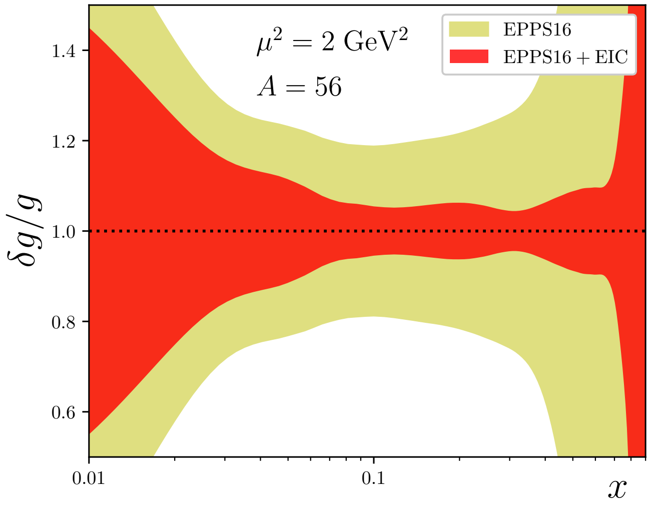


*Eskola et al., E.P.J. C**77** (16) 163*

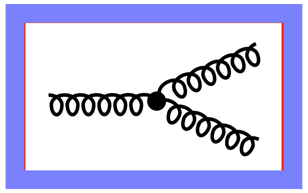




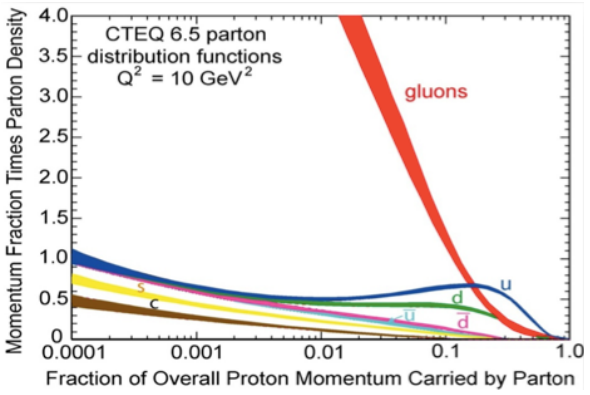
EPPS16nlo

importance of F$_2^{\text{charm}}$
for high x gluons

The EIC performance : saturation

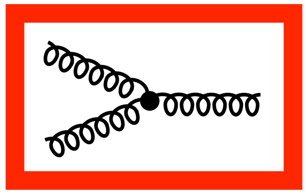


gluon self-interaction
→ proliferation of # gluons



dramatic rise of gluon density @ low x

unitarity → gluons must recombine to balance splitting (**saturation**)



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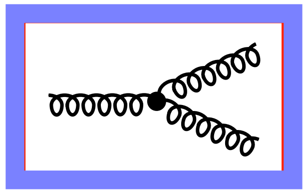
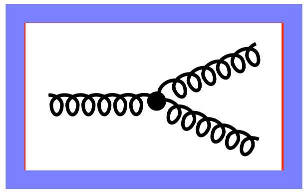


effect not clearly seen at HERA

The EIC performance : saturation



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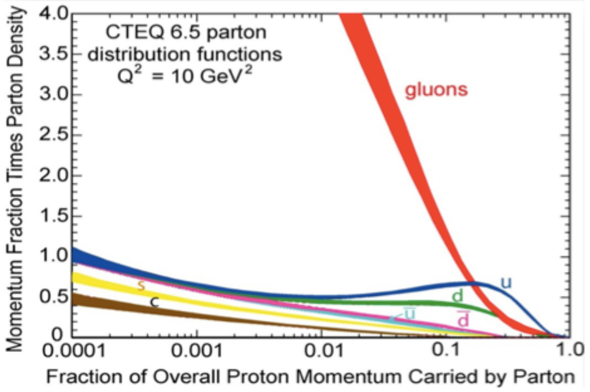

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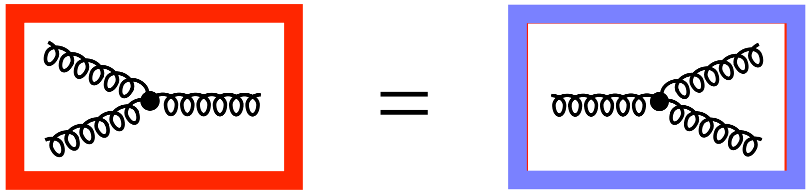

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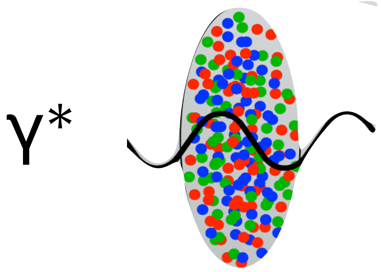
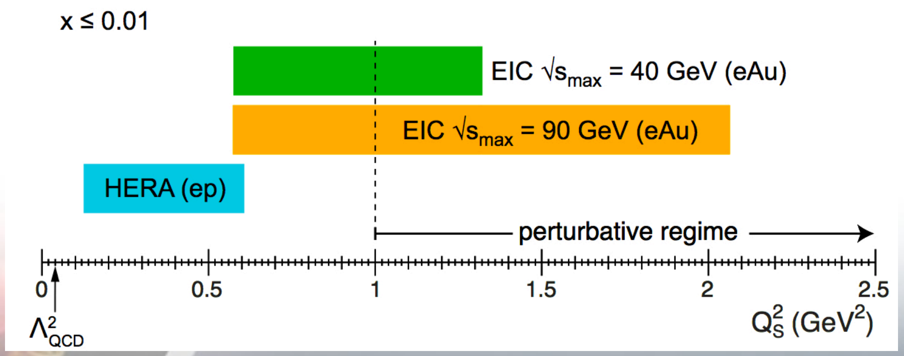


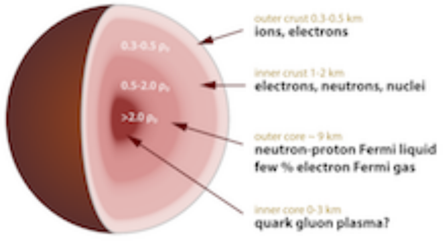
the Color Glass Condensate model

Iancu et al., P.L. ***B510*** *(01) 133*

- **EIC: reach same saturation scale Q_s at larger *x* → smaller $\sqrt{s}$**
- **nucleus acts as Q_s amplifier**

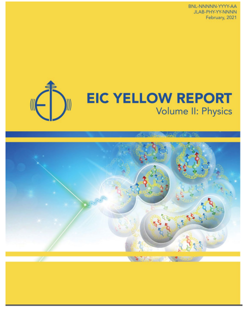
$$[Q_s(x,A)]^2 \sim \left(\frac{A}{x}\right)^{\frac{1}{3}}$$



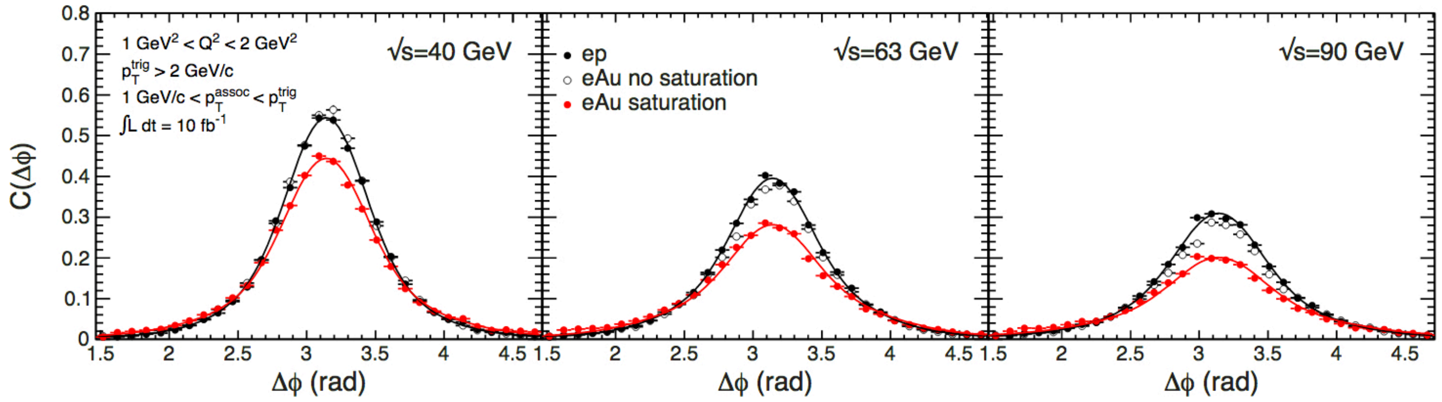


implications for astrophysics of neutron stars

The EIC performance : saturation



arXiv:2103.05419,
*N.P.**A** in press*



Aschenauer et al., Rept.Prog.Phys. ***82*** *(19) 024301*

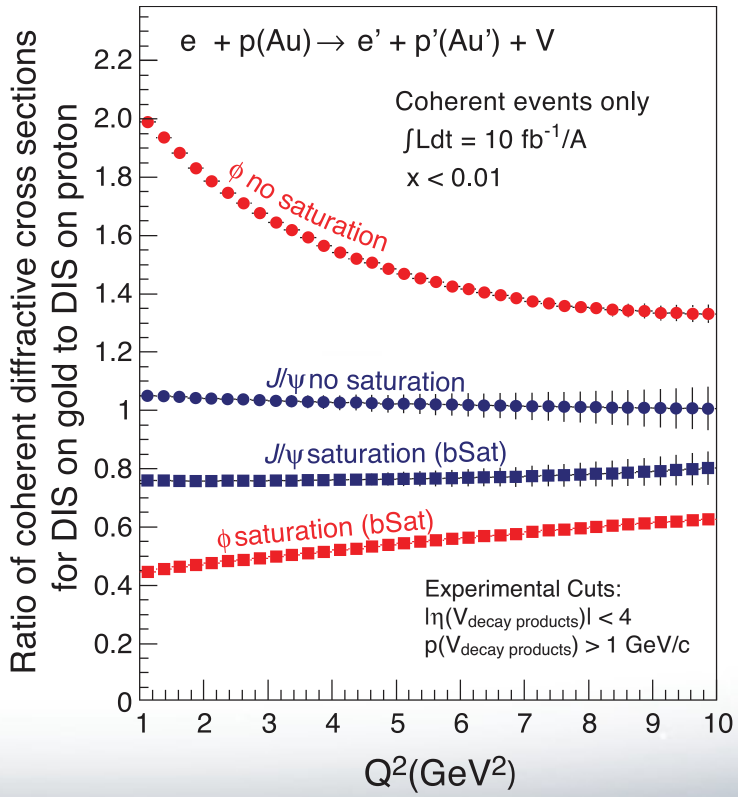
1- key observable:

di-hadron correlations in **e-A** vs. e-p

2- key observable:

diffractive scatt. $\sigma_{diff} \sim [\, \text{gluon}(x,Q^2) \,]^2$

complementary to vector-meson photo-production in UPC @CERN



Abdul Khalek et al.,
"Snowmass 2021 White Paper:
EIC for High Energy Physics"
arXiv:2203.13199

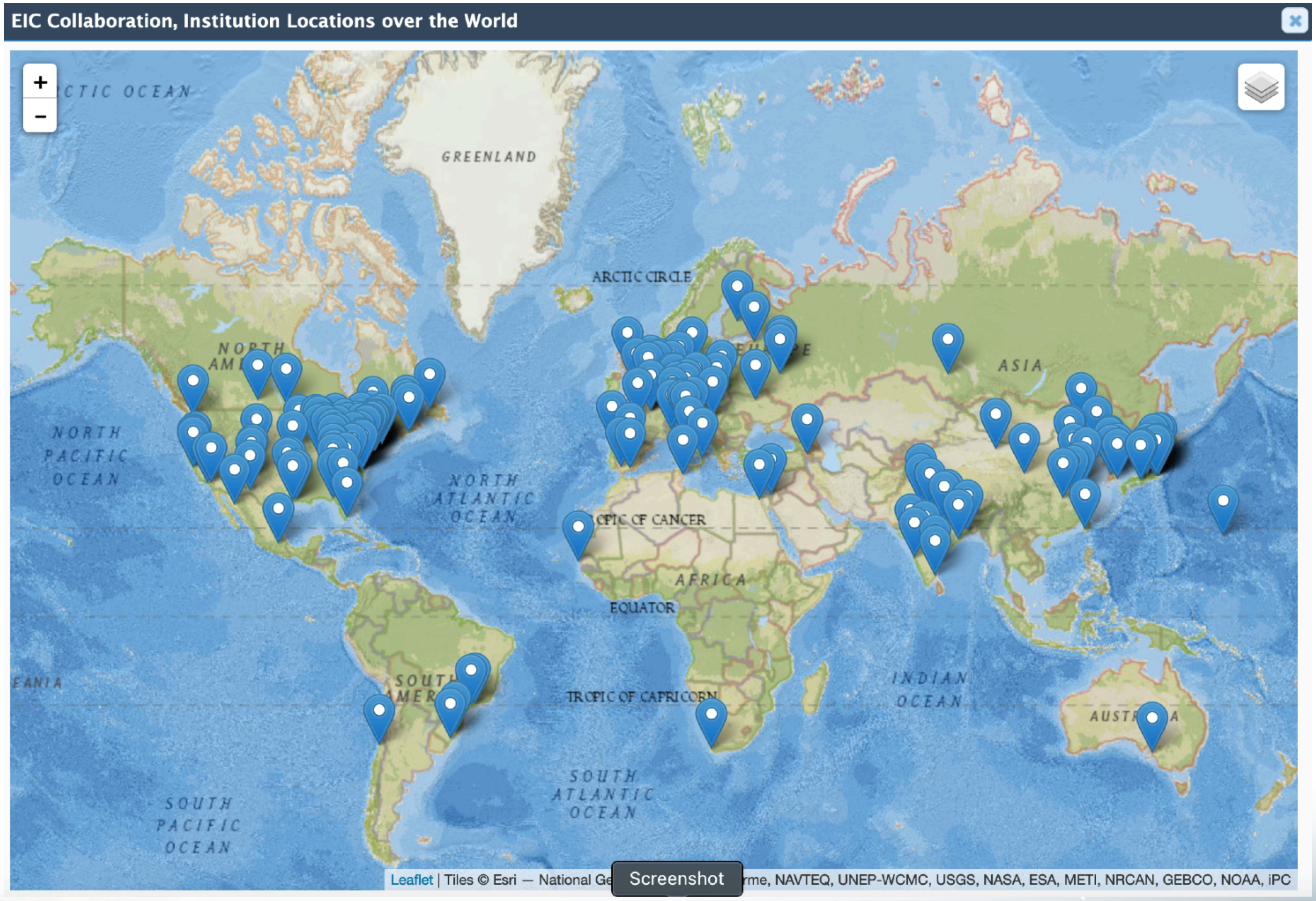
Electron-Ion Collider

The EIC Users Group map

www.eicug.org

at Jun. 6th 2022

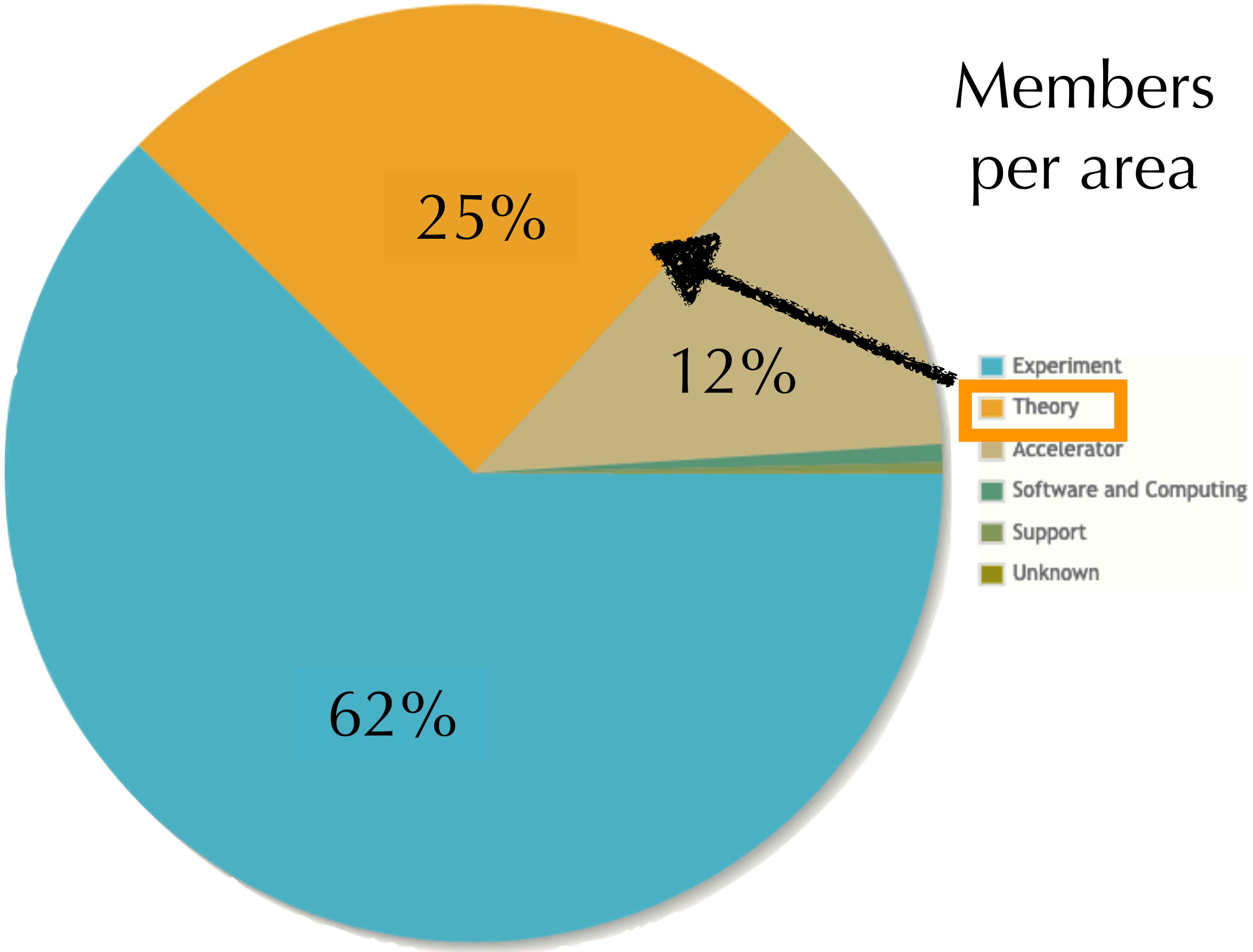
36 countries
266 Institutions
1330 members



The EIC Users Group composition

at Jun. 6th 2022

strong community
of theorists



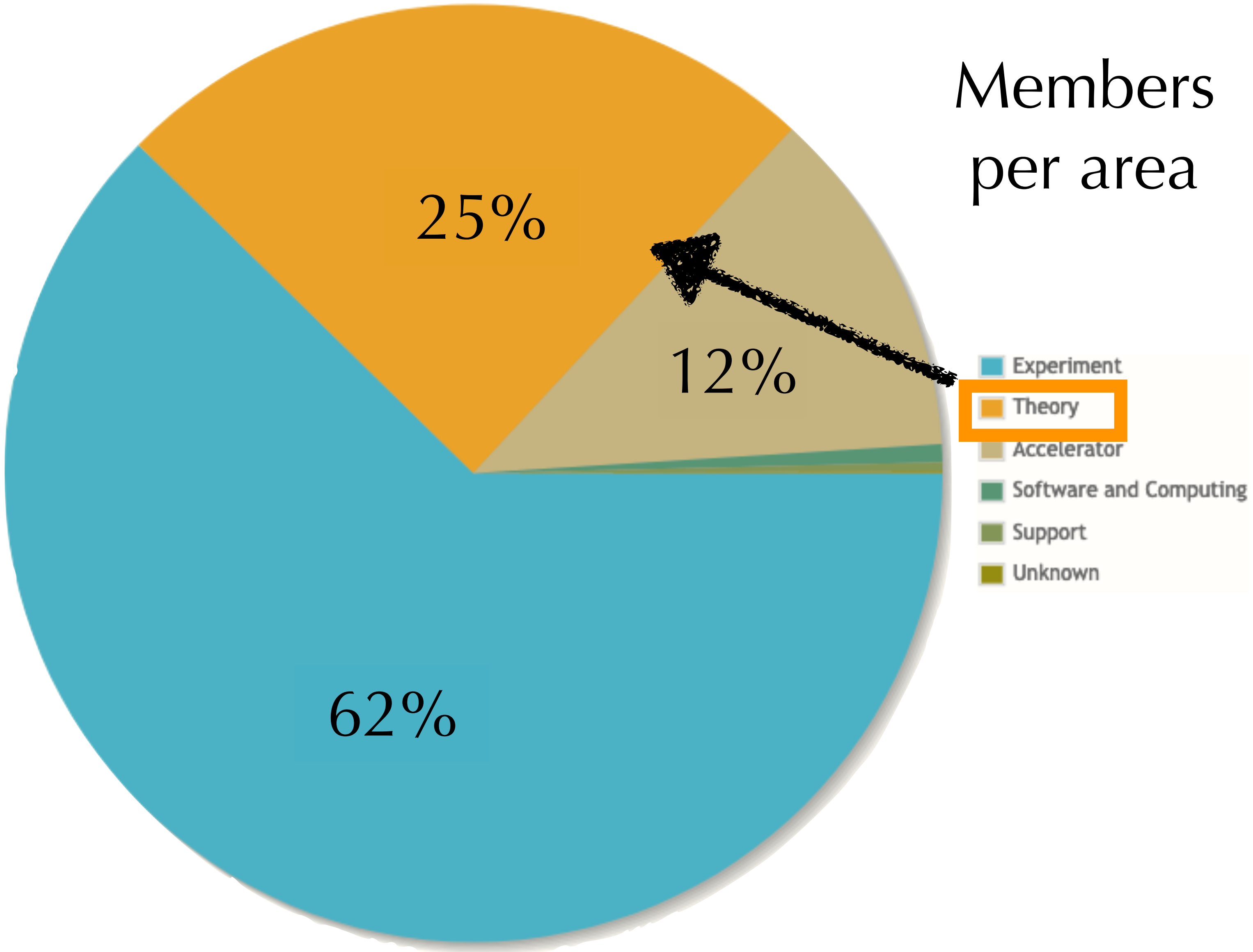
Members
per area

The EIC Users Group composition

at Jun. 6th 2022

strong community
of theorists

**young students
and/or postdocs
welcome to join!**



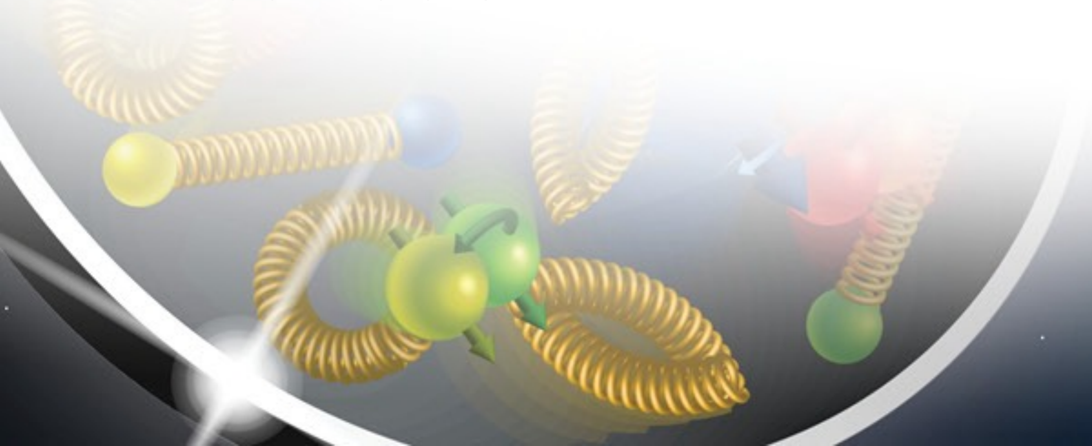
Members
per area

Recap

- the EIC addresses fundamental (open) questions about visible matter:
  - spin and flavor partonic structure of nucleons and nuclei
  - 3D-imaging (tomography) in momentum and position space
  - matter at extreme parton densities → onset of saturation

- As high-luminosity, high-polarization collider with wide range in energy and ion species, the EIC is unique in the panorama of next two decades

- The EIC offers unprecedented opportunities to advance our knowledge of the confined partonic structure of hadrons, with scientific outcomes that are complementary to the LHC and other colliders




THANK YOU
for your
ATTENTION!

Backup Slides

The EIC performance : GPDs

Impact parameter distributions

$$\rho\ (x,b_T)$$

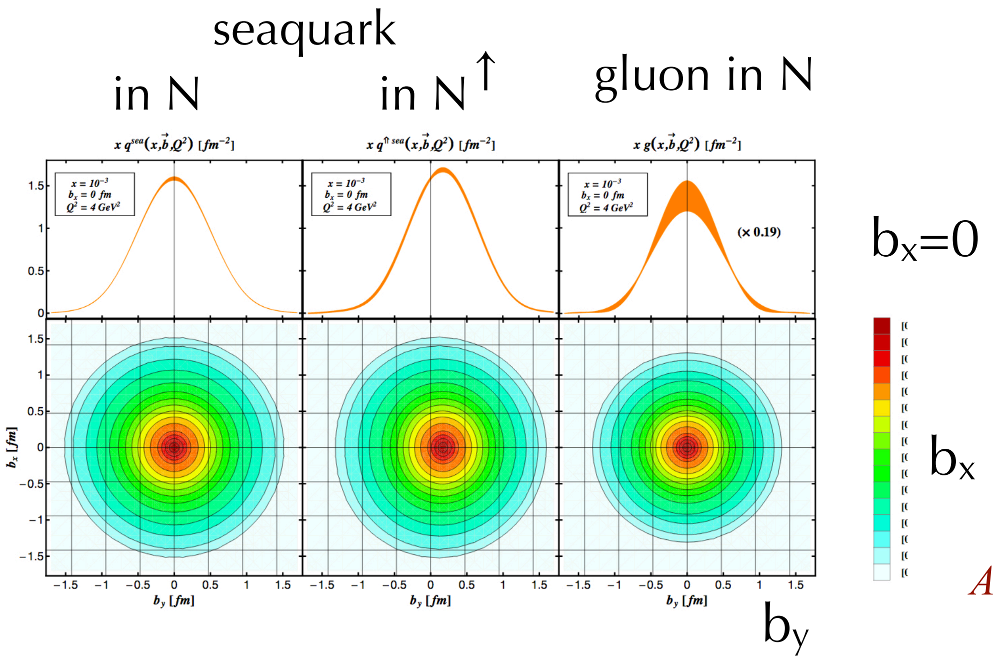
The EIC performance : GPDs

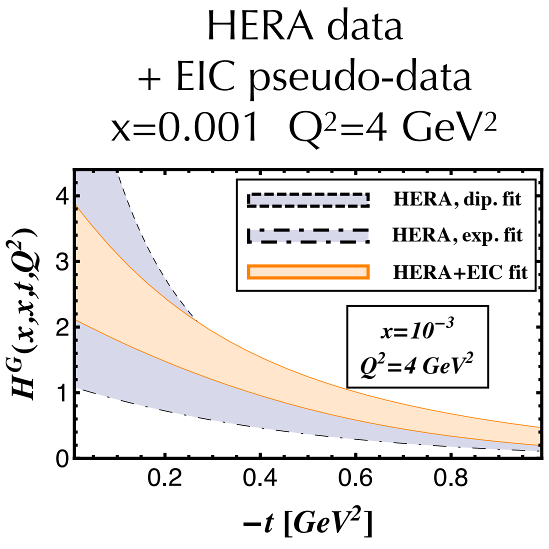
impact parameter distribution ρ (x,b_T)

Phenomenology

- local fits of GPD

  (of DVCS in given kinematic bins)





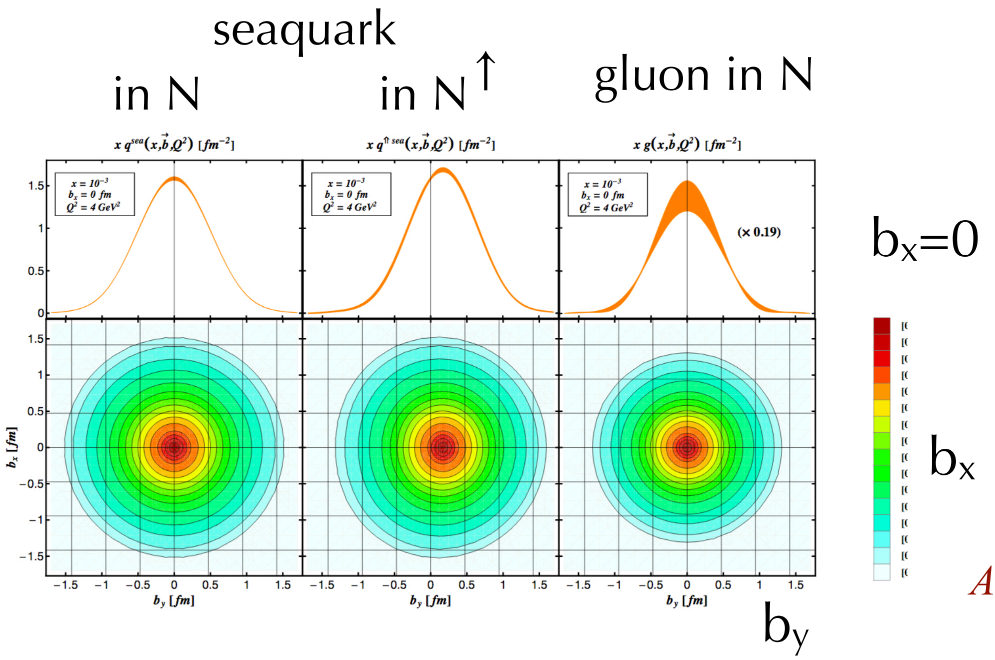
*Aschenauer et al., JHEP**09** (13) 093*

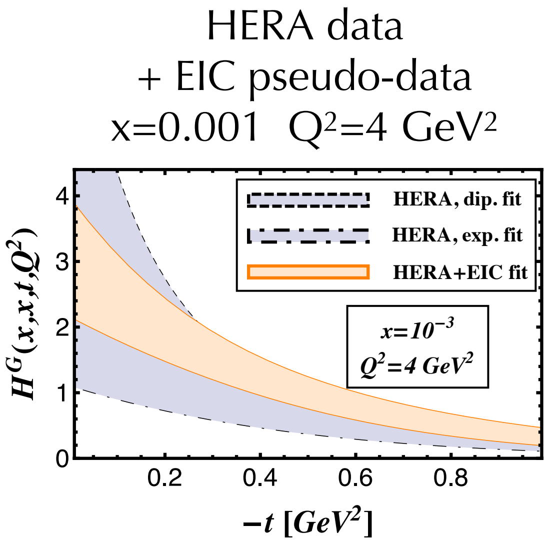
The EIC performance : GPDs

impact parameter distribution ρ (x,b_T)

Phenomenology

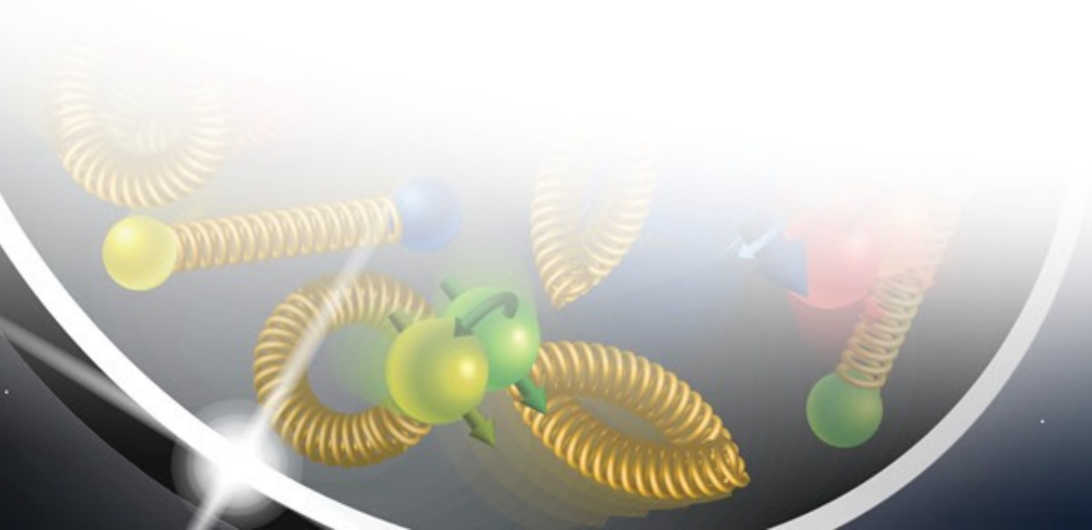
- local fits of GPD
  (of DVCS in given kinematic bins)





*Aschenauer et al., JHEP**09** (13) 093*

- models: GK *Goloskokov & Kroll, EPJ C**42** (05) 281* VGG *Vanderhaeghen et al., PRL **80** (98) 5064* reggeized diquark *Goldstein et al., PR D**84** (11) 034007*



Electron-Ion Collider

The EIC performance : GPDs

impact parameter distribution $\rho\ (x, b_T)$

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- local fits of GPD
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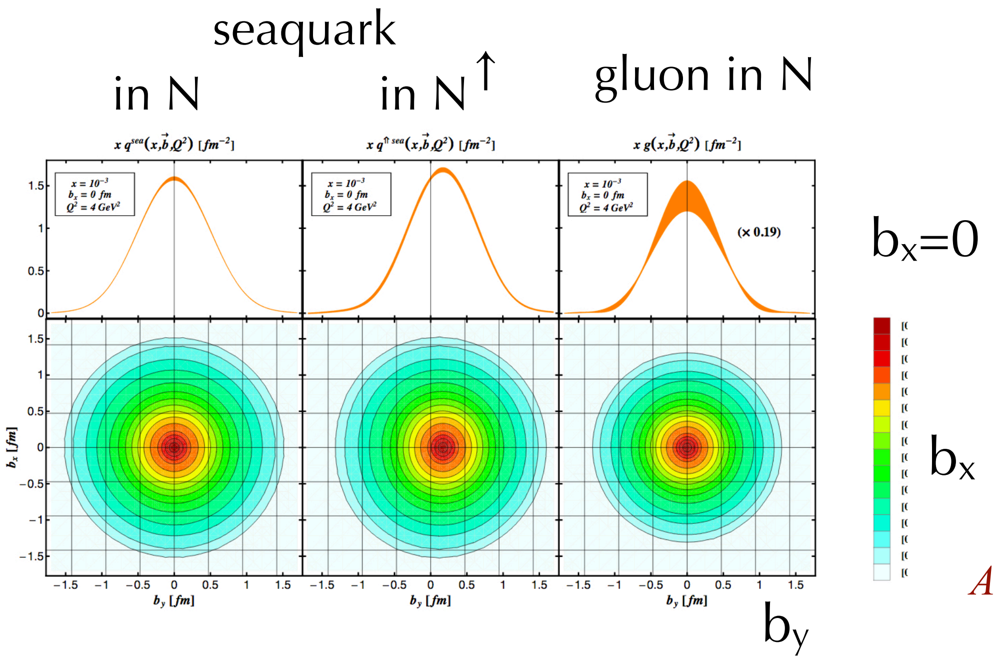
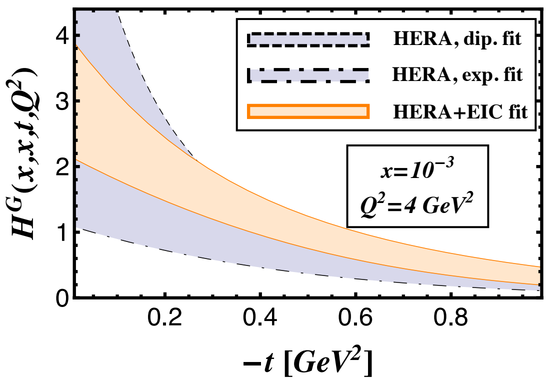


HERA data
+ EIC pseudo-data
x=0.001 Q²=4 GeV²



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- global fits of CFF
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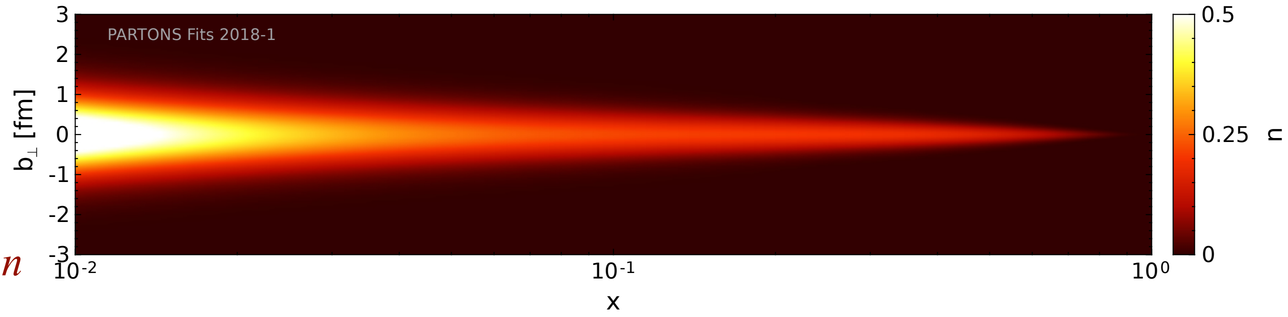
*Kumericki et al., NP**B794** (08) 244*

*Moutarde et al., EPJ C**78** (18) 890*
PARTON *Collaboration*



The EIC performance : GPDs

impact parameter distribution ρ (x,b_T)

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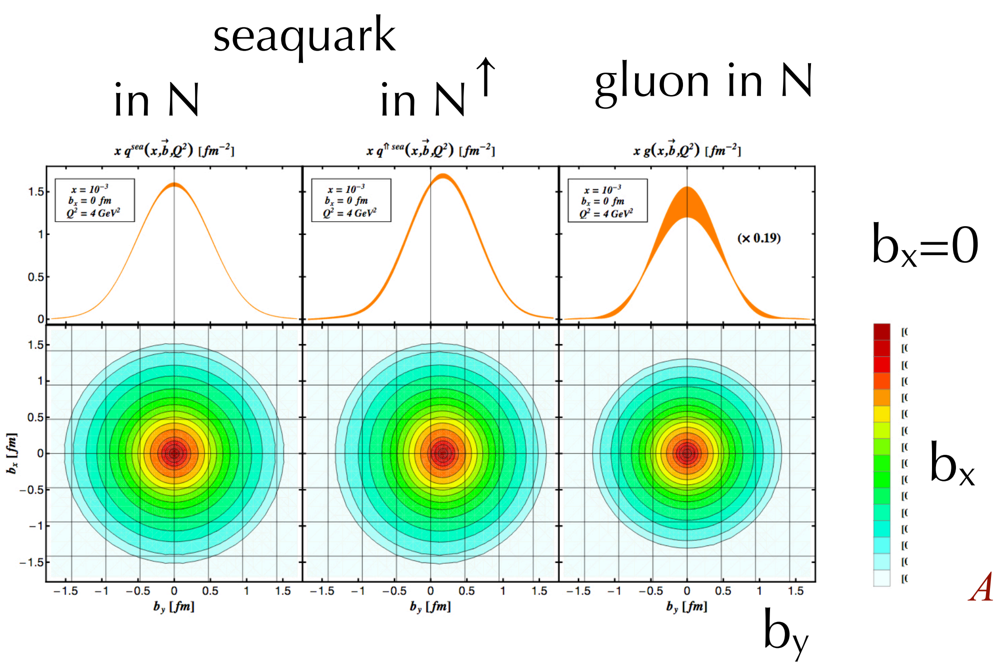

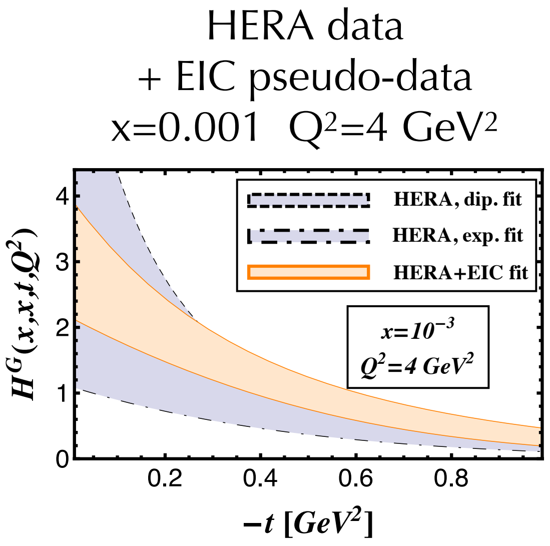

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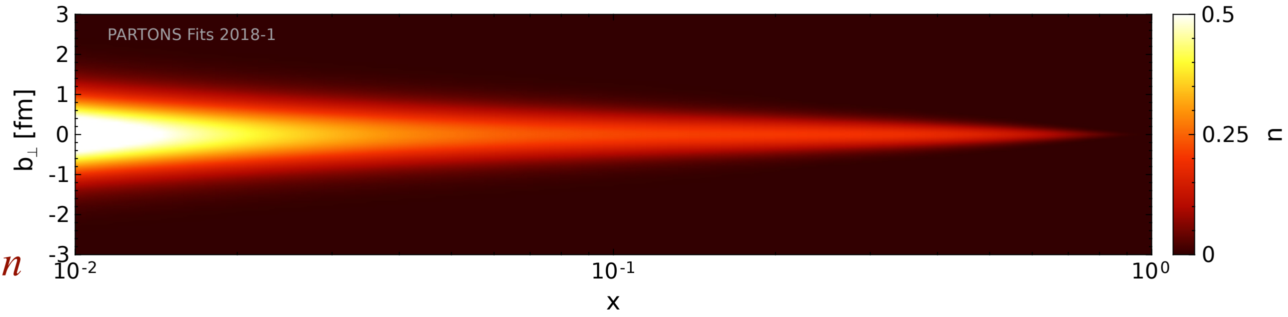
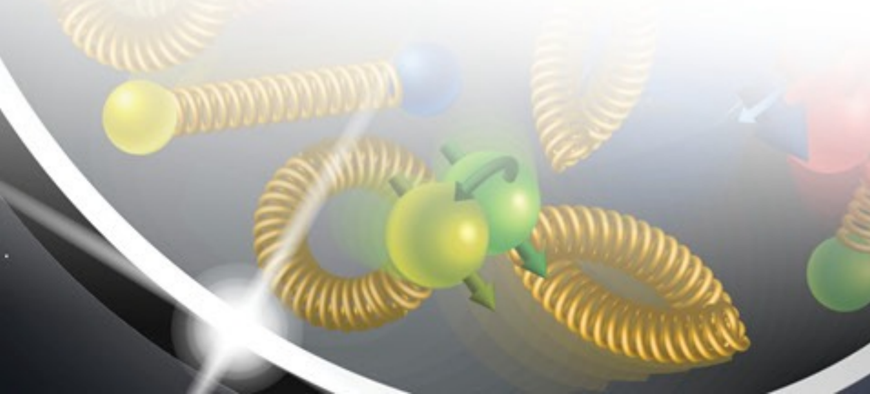


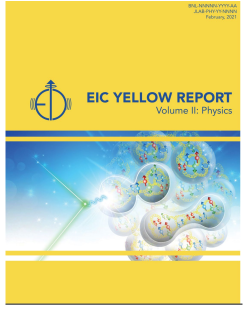
future developments: neural network techniques for GPDs
combine DVCS, DVMP, TCS to solve ambiguity
in extraction of GPD from CFF



The EIC performance : origin of N mass

Decomposition of
Nucleon mass

The EIC performance : origin of N mass



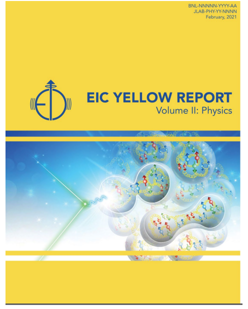
EIC YELLOW REPORT
Volume II: Physics

arXiv:2103.05419,
*N.P.**A** in press*

Nucleon mass decomposition with QCD EMT $T^{\mu\nu}$

$$\langle p|\, T_{\mu\nu}^{Q,G}\, |p'\rangle = \bar{u}(p')\left[M_2^{Q,G}(t)\frac{P_\mu P_\nu}{M_N} + J^{Q,G}(t)\frac{i(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M_N} + d_1^{Q,G}(t)\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M_N} + \bar{c}(t)g_{\mu\nu}\right] u(p)$$

The EIC performance : origin of Nucleon mass



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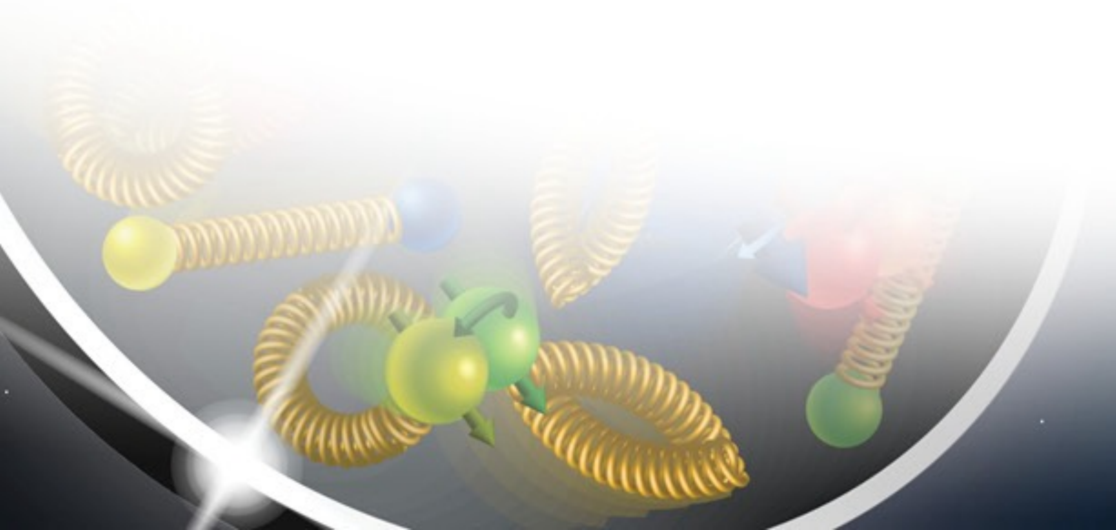
forward matrix elements
(Δ=p-p′=0 → t=Δ²=0)

$$M_N = E_Q + E_G \quad + \bar{c}_q(0)\left(= \langle\bar{\psi} m\psi\rangle\right) \quad + \bar{c}_g(0)\left(= \langle\frac{\beta(g)}{2g}F^2 + \gamma_m\bar{\psi} m\psi\rangle\right)$$

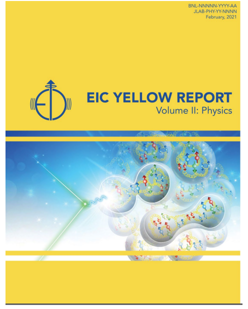
relativistic motion
of quarks and gluons
(~70% ?)

quark condensate
σ-term from πN scatt.
(~9%?)

trace anomaly
?



The EIC performance : origin of Nucleon mass



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relativistic motion
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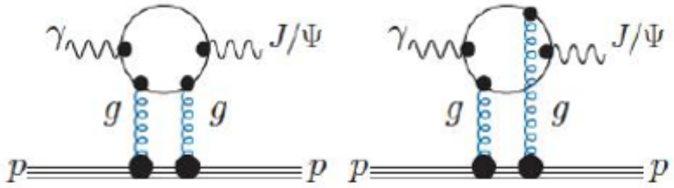
<*F*²> from threshold γ- / e-production of J/ψ and Υ



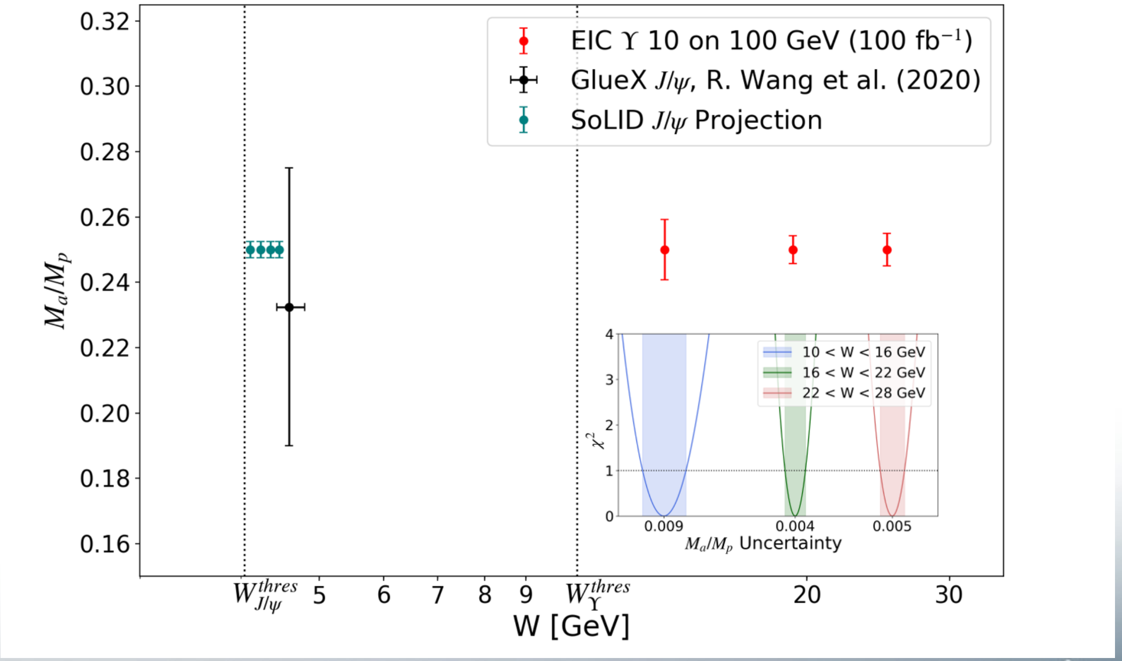


Figure 7.26: Projection of the trace anomaly contribution to the proton mass (M_a/M_p) wit
Υ photoproduction on the proton at the EIC in 10 × 100 GeV electron/proton beam-energ