Giornata nazionale EIC_NET 2021, Torino 20-21 Dec. 2021

The Italian theoretical input to EIC physics

Marco Radici

INFN Istituto Nazionale di Fisica Nucleare Sezione Pavia

Users Group Steering Committee

ATHENA

Outline

- Theoretical activities of interest for the EIC are effectively identified with the INFN-CSN4 project
  NINPHA (**N**ational **IN**itiative in **P**hysics of **HA**drons)

- Short overview of NINPHA recent activities,
  - including support to EIC Yellow Report studies
    (M.R. Editor, B.Pasquini co-Convener of Exclusive WG)
  - covering also non-SIDIS, non-collider setups

- NINPHA support to the ATHENA detector proposal preparation
  (M.R. co-Convener of SIDIS WG)

NINPHA

6 research lines
linea 3: "Nuclear and Hadronic Physics

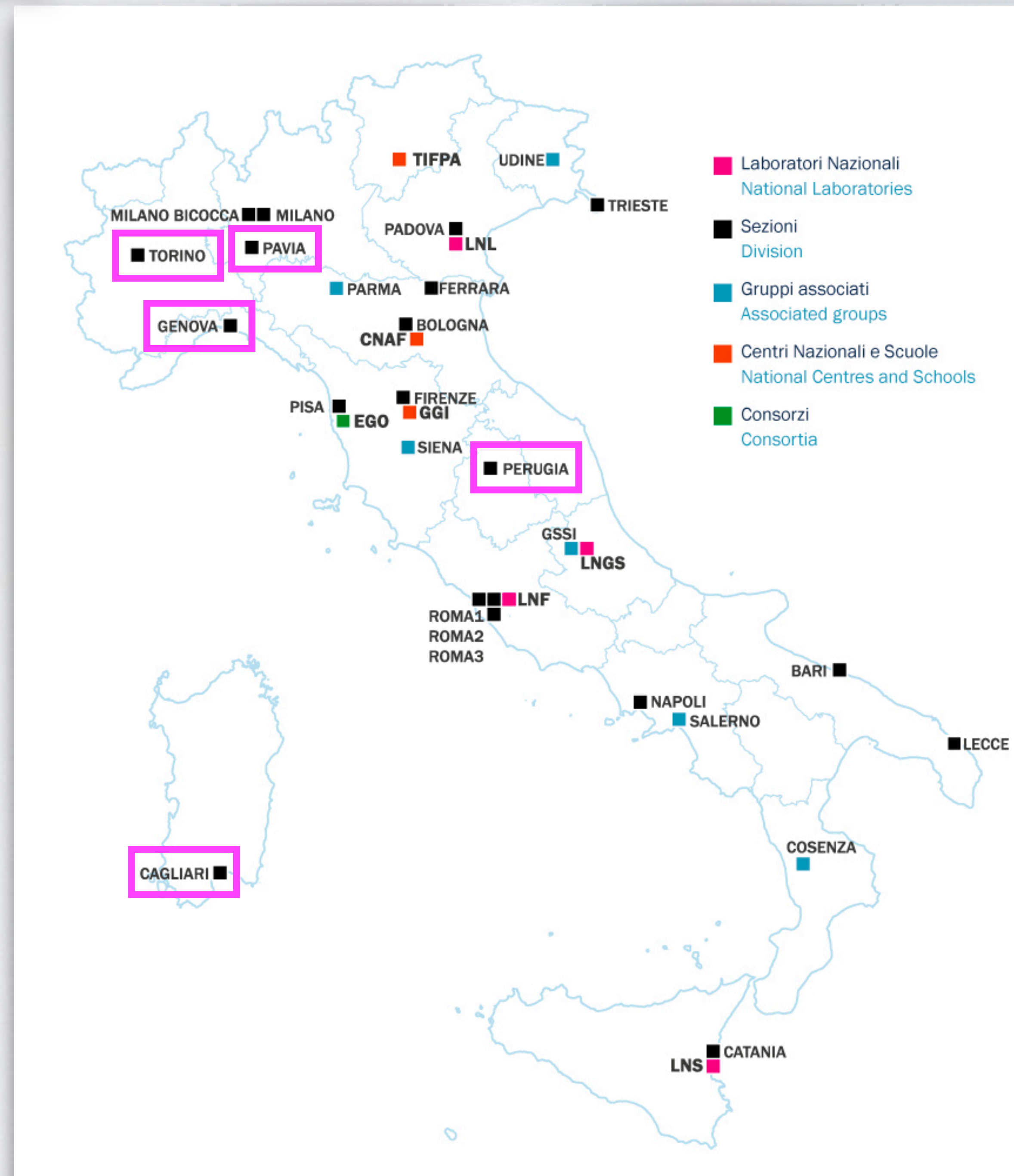
NINPHA

National Coordinator: M. Boglione (TO)

5 units	(local Coordinator)	# affiliates
Torino	M. Boglione	6
Pavia	M. R.	8
Genova	E. Santopinto	3
Perugia	S. Scopetta	7
Cagliari	F. Murgia	6

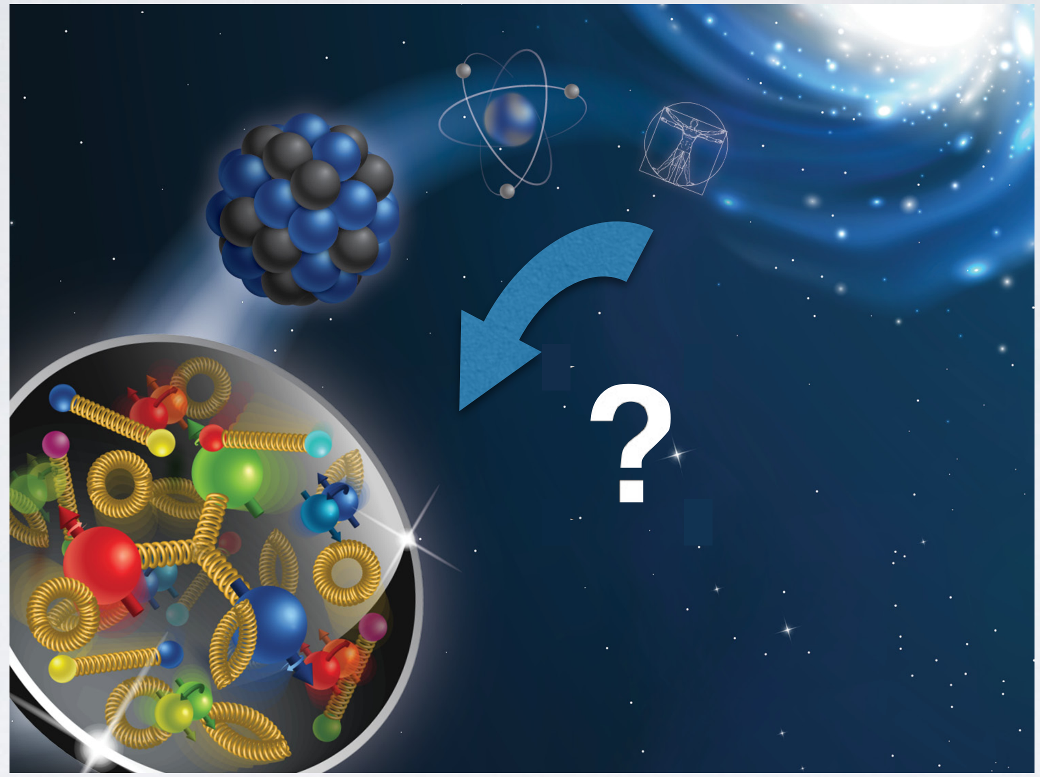
Tot. 30 (FTE = 23.35)

5 Ph.D. , 4 post-doc



NINPHA research goals

$\mathscr{L}_{\text{QCD}}$ and $T^{\mu\nu}_{\text{QCD}}$
symmetries
(breaking)



hadron
phenomenology:
masses, spins,
resonances, exotics…

perturbative
regime

highly non-linear mutual
interactions of partons

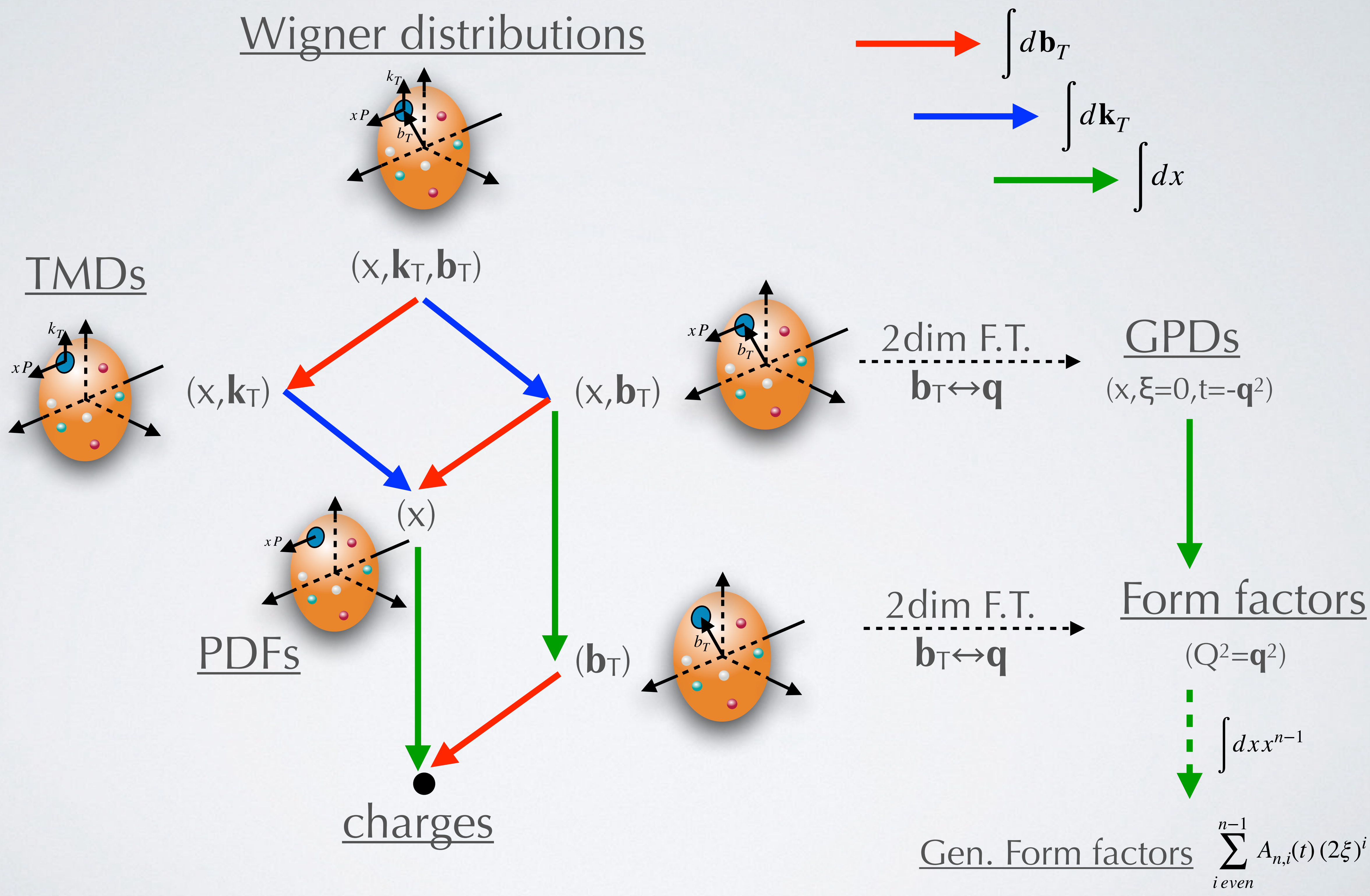
non-
perturbative
regime

Mapping internal parton dynamics	→	understand how QCD confinement comes about

New advanced non-perturbative "maps" needed…

Non-perturbative maps

Lorcé, Pasquini, Vanderhaeghen, JHEP05 (11) 041
Accardi et al., EPJ A52 (16) 9



NINPHA research lines

1. Theoretical properties of non-perturbative maps — TO, PV, CA

- factorisation theorems, (non-)universality, evolution equations, etc..
- gauge invariance of physical observables
- properties of Energy-Momentum Tensor (EMT) $T^{\mu\nu}_{\text{QCD}}$

2. Phenomenological extractions of TMDs — PV, CA, TO

robust fits of data from
- fixed-target (Hermes, Compass, JLab)
- collider data (Tevatron, RHIC, LHC, SLAC, KEK)

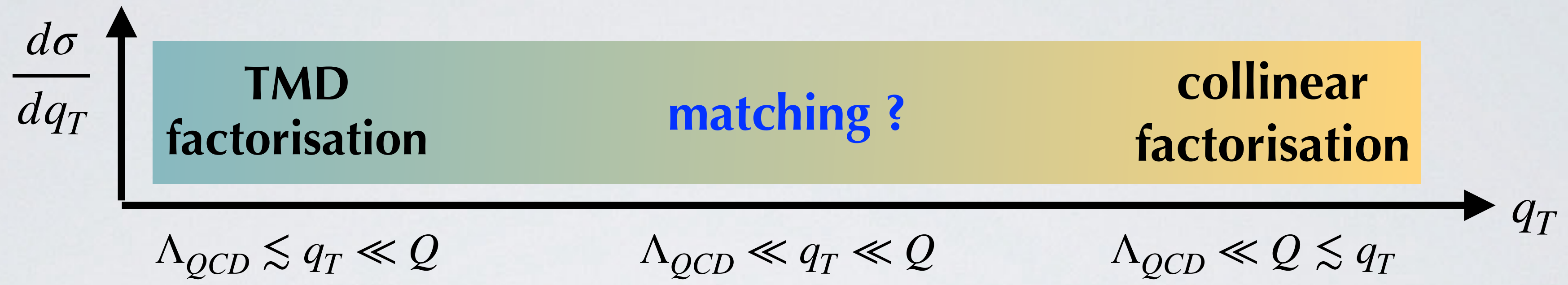
3. Models and support to experiments — PV, PG, GE

- unifying picture of quark TMDs for N and π
- gluon TMDs
- GPDs in light nuclei: incoherent DVCS vs. coherent DVCS
- parton dynamical correlations in Double Distributions (DDs)
- exotic hadron spectroscopy, EFTs of their decays

NINPHA research lines

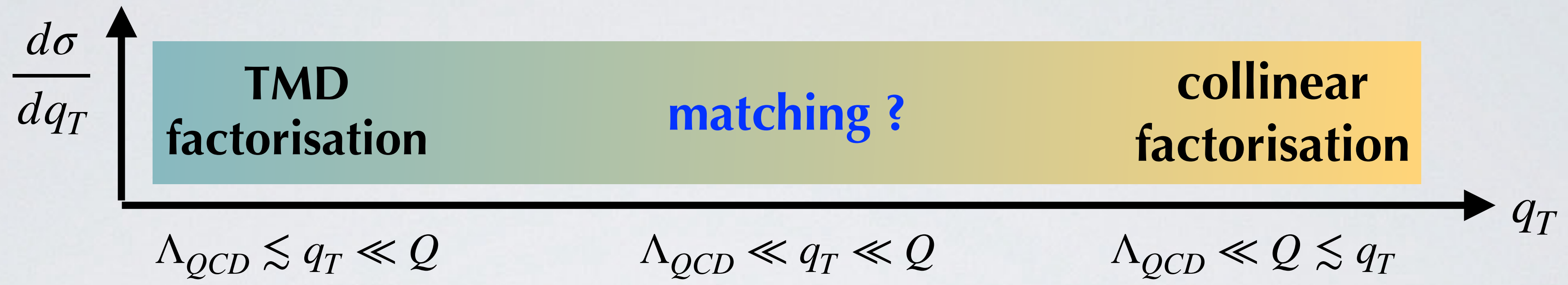
1. **Theoretical properties of non-perturbative maps** TO, PV, CA

NINPHA highlights: 1. Th properties



Matching problem ⇔ where TMD factorisation is valid?

NINPHA highlights: 1. Th properties

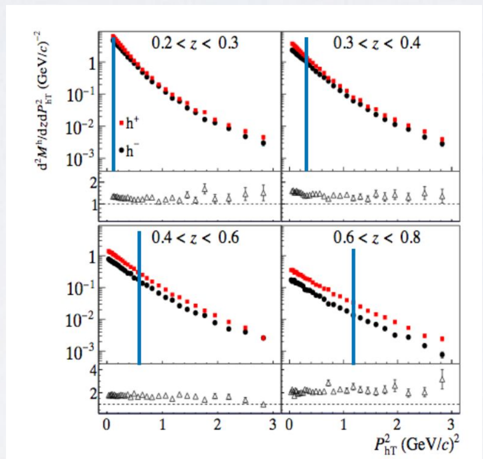


Matching problem ⇔ where TMD factorisation is valid?

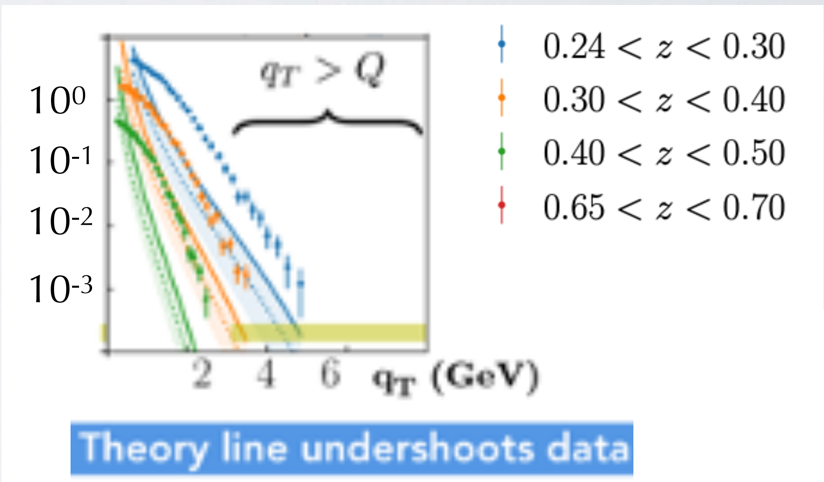
Affects phenomenology:

SIDIS multiplicities
$\langle Q^2 \rangle = 9.78$ GeV²
$\langle x \rangle = 0.149$

$q_T^2 = \frac{P_{hT}^2}{z^2} = 0.25\, Q^2$

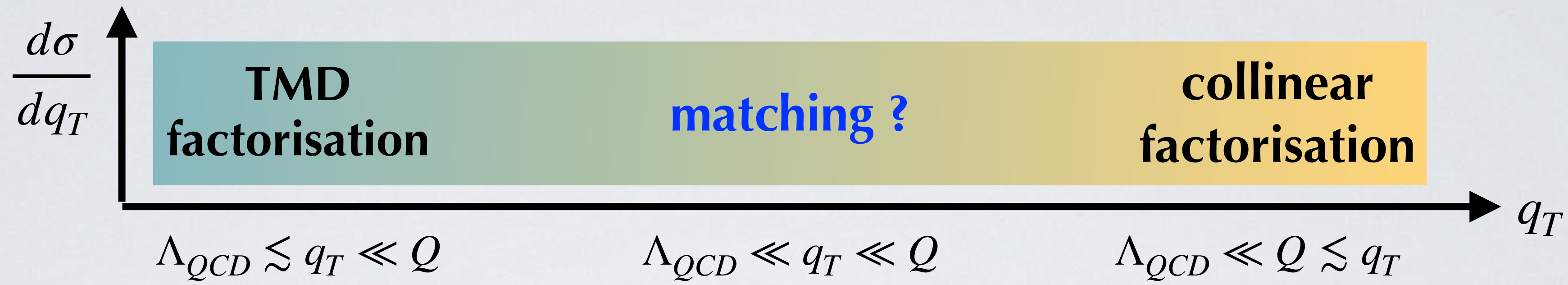


Compass, arXiv:1709.07374



Gonzalez et al., arXiv:1808.04396
F.Piacenza, Ph.D. thesis, Univ. PV (2020)
Bacchetta, talk at QCDN'21

NINPHA highlights: 1. Th properties



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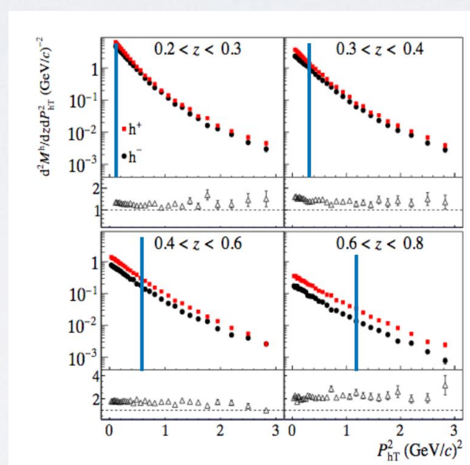
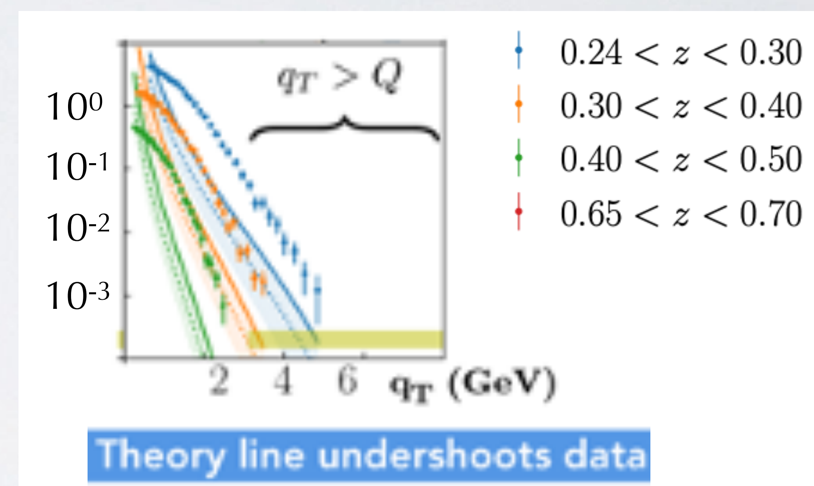


Compass, arXiv:1709.07374



Gonzalez et al., arXiv:1808.04396
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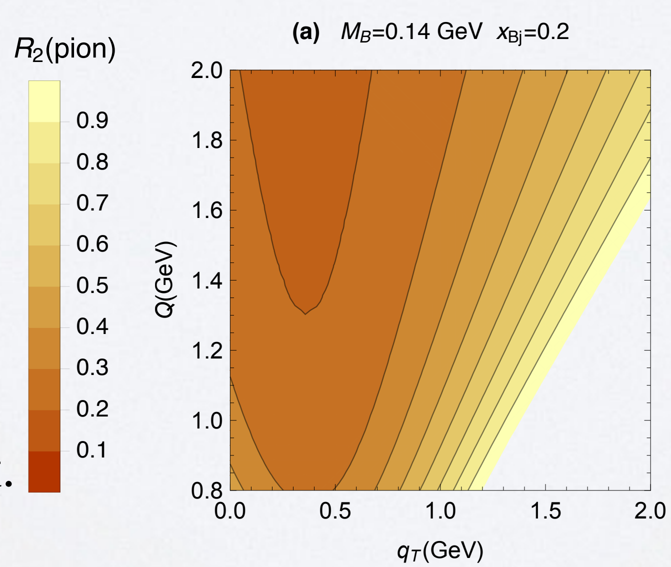
Possible criterium:

collinear fact.

Transverse hardness

$$R_2 = \frac{|k_q^2|}{Q^2}$$

TMD fact.



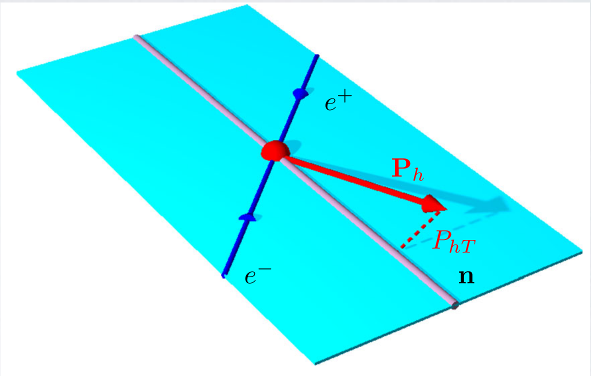
Warning:
need to first check that kinematics is in current fragmentation region; strongly depends on flavor of final detected hadron

Boglione et al., arXiv:1904.12882

NINPHA highlights: 1. Th properties

recent data for e+e- → h+X

arXiv:1902.01552



Thrust

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\rm CMS} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\rm CMS}|}$$

Proposed factorisation th. for $\dfrac{d\sigma}{dz\, d\mathbf{q}_T\, d\tau}$ $\quad q_T = \dfrac{P_{hT}}{z}$ $\quad \tau = 1 - T$

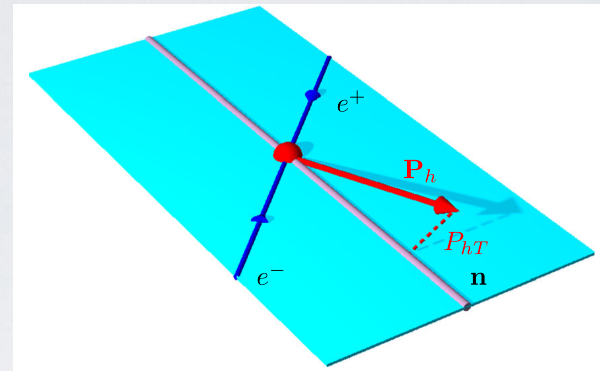
A) Boglione & Simonelli, arXiv:2109.11497
B) Makris et al., arXiv:2009.11871

NINPHA highlights: 1. Th properties

recent data for e+e- → h+X

BELLE

arXiv:1902.01552



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Proposed factorisation th. for $\dfrac{d\sigma}{dz\, d\mathbf{q}_T\, d\tau}$

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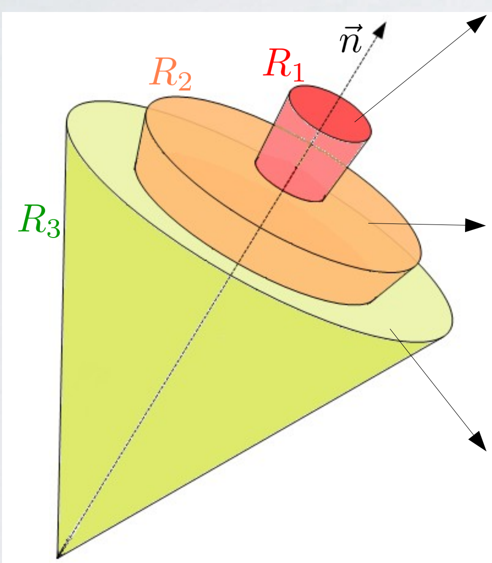


R_1 = h close to T axis $\tau \sim \dfrac{q_T}{Q} \ll \sqrt{\tau} \ll 1$ $d\sigma \sim \sum_i H_i(\mu) \otimes_\tau J(\mu) \otimes_\tau \mathrm{FT}\left[S(\mu,\nu) \otimes_\tau D_1^{i\to h}(\mu,\nu)\right]$

A) ≡ B)

hard — bckwd jet — fwd soft — TMDFF

hard — bckwd jet — thrust soft — FJF

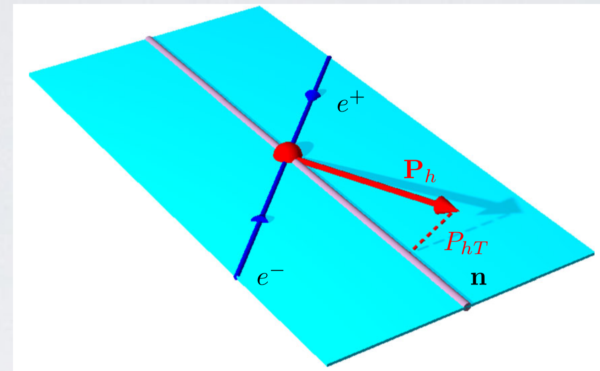
R_3 = h close to jet edges $\tau \ll \dfrac{q_T}{Q} \sim \sqrt{\tau} \ll 1$ $d\sigma \sim \sum_i H_i(\mu) \otimes_\tau J(\mu) \otimes_\tau S_T(\mu) \otimes_\tau \mathscr{G}^{i\to h}(\mu)$

NINPHA highlights: 1. Th properties

recent data for e+e- → h+X

BELLE

arXiv:1902.01552



Thrust

$$T \overset{\max}{=} \frac{\sum_h |\mathbf{P}_h^{\mathrm{CMS}} \cdot \hat{\mathbf{n}}|}{\sum_h |\mathbf{P}_h^{\mathrm{CMS}}|}$$

Proposed factorisation th. for $\frac{d\sigma}{dz\, d\mathbf{q}_T\, d\tau}$ $\quad q_T = \frac{P_{hT}}{z}$ $\quad$ τ=1-T

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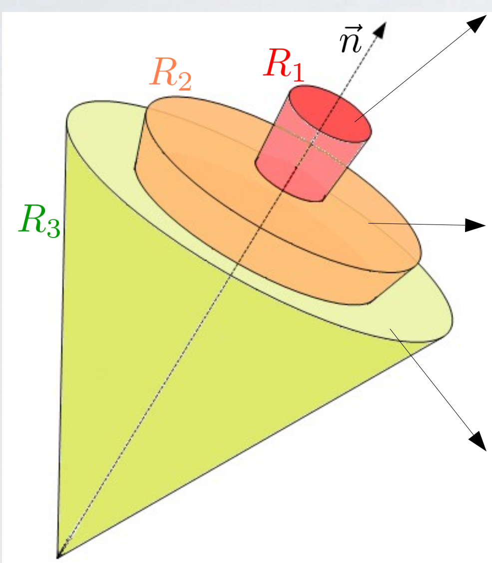


R_1 = h close to T axis $\quad \tau \sim \frac{q_T}{Q} \ll \sqrt{\tau} \ll 1$

$$d\sigma \sim \sum_i H_i(\mu) \otimes_\tau J(\mu) \otimes_\tau \mathrm{FT}\left[S(\mu,\nu) \otimes_\tau D_1^{i\to h}(\mu,\nu)\right]$$

A) ≡ B)

hard — bckwd jet — fwd soft — TMDFF

thrust — FJF

R_3 = h close to jet edges $\quad \tau \ll \frac{q_T}{Q} \sim \sqrt{\tau} \ll 1$

$$d\sigma \sim \sum_i H_i(\mu) \otimes_\tau J(\mu) \otimes_\tau S_T(\mu) \otimes_\tau \mathscr{G}^{i\to h}(\mu)$$

R_2 = intermediate $\quad \tau \ll \frac{q_T}{Q} \ll \sqrt{\tau} \ll 1$

hybrid factoriz. = collinear formula for TMDFF
problem: rapidity scale ν linked to observable T

A) ≠ B)

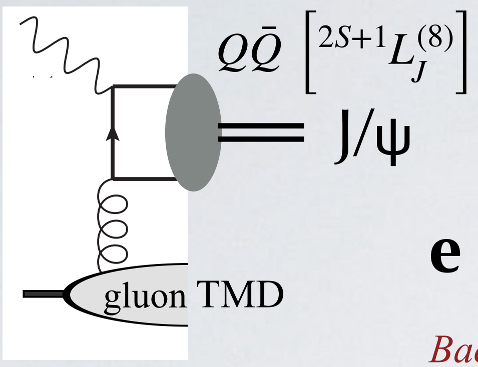
matching coefficients
$\mathscr{G} \to C \otimes D_1$

$$d\sigma \sim \sum_i \widetilde{H}_i(\mu,\nu) \otimes \mathrm{FT}\left[D_1^{i\to h}(\mu,\nu)\right]$$

$$d\sigma \sim \sum_i H_i(\mu) \otimes_\tau J(\mu) \otimes_\tau S_T(\mu) \otimes_\tau \mathrm{FT}\left[C(\mu,\nu) \otimes_\tau D_1^{i\to h}(\mu,\nu)\right]$$

NINPHA highlights: 1. Th properties

How to address gluon TMDs ?



$e\, p^{\uparrow} \to e + J/\psi + X$

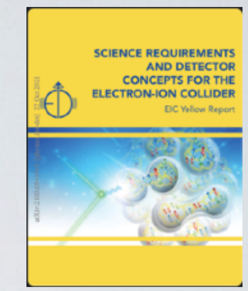
Bacchetta et al., arXiv:1809.02056

unpolarized $\quad d\sigma^0 \longrightarrow f_1^g\, A\left[{}^{2S+1}L_J^{(8)}\right]\,, \quad \cos 2\phi_{J/\psi}\, h_1^{\perp g}\, B\left[{}^{2S+1}L_J^{(8)}\right]$

polarized $\quad d\sigma^{\uparrow} \longrightarrow \sin(\phi_{S_p} - \phi_{J/\psi})\, f_{1T}^{\perp g}\, A\left[{}^{2S+1}L_J^{(8)}\right] \ldots$

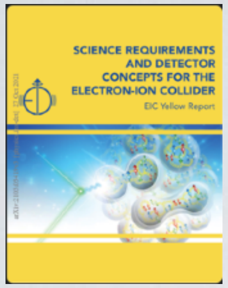
same structure as quark TMDs .. but ..

model dependent $Q\bar{Q} \to J/\psi$ matr. elem.



- various methods to constrain $Q\bar{Q} \to J/\psi$ matr. elem. (LDMEs) *Boer et al., arXiv:2102.00003*
- unpolarized $d\sigma^0$: matching between low $q_T^{J/\psi}$ (TMD) and high $q_T^{J/\psi}$ (collinear) *Boer et al., arXiv:2004.06740*
- angular dependence of $d\sigma^0 \to W_T$, W_L, W_{LT}, W_{TT} with low-high $q_T^{J/\psi}$ matching *D'Alesio et al., arXiv:2110.07529*
- flavor-dependence of Sivers asymmetry at EIC: $f_{1T}^{\perp g} \gg f_{1T}^{\perp q}$ *Rajesh et al., arXiv:2108.04866*

J/ψ Single-Spin Asymmetry



Abdul Khalek et al., arXiv:2103.05419

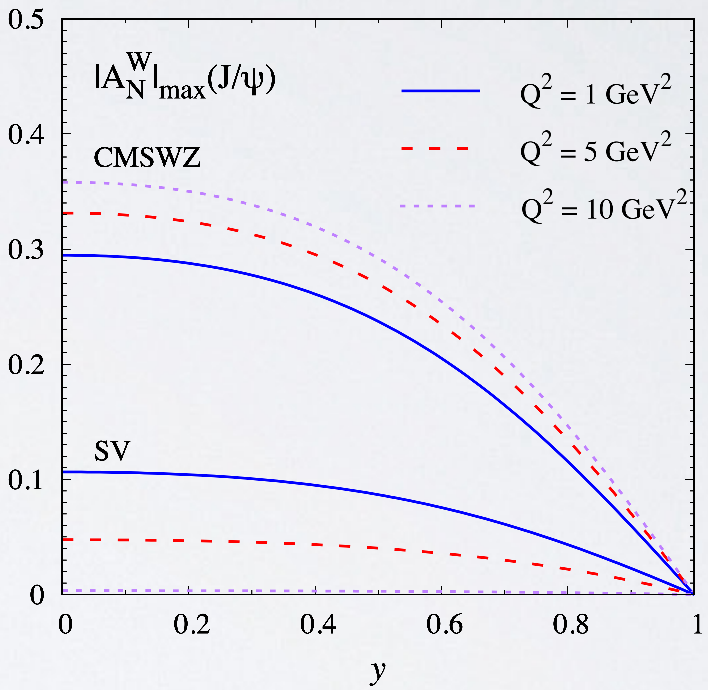
Sec. 7.2.3 Imaging of quarks and gluons in momentum space
Gluon TMD measurements

e p↑→ e+J/ψ+X

$\ell \quad P$

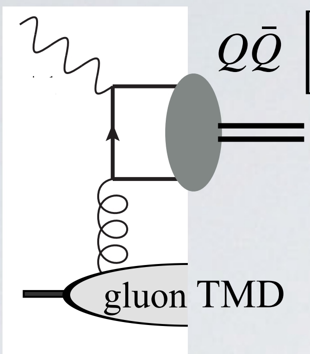
$$A^W_{N\,\max} = \max\{A^{\cos 2\phi}, A^{\sin(\phi_S-\phi)}, \ldots\}$$

$$y = \frac{P\cdot q}{P\cdot \ell}$$ inelasticity



NINPHA highlights: 1. Th properties

How to address gluon TMDs ?



$Q\bar{Q}\left[{}^{2S+1}L_J^{(8)}\right]$

J/ψ

e p↑→ e+J/ψ+X

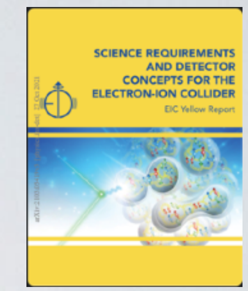
Bacchetta et al., arXiv:1809.02056

unpolarized $\quad d\sigma^0 \longrightarrow f_1^g\, A\left[{}^{2S+1}L_J^{(8)}\right], \quad \cos 2\phi_{J/\psi}\, h_1^{\perp g}\, B\left[{}^{2S+1}L_J^{(8)}\right]$

polarized $\quad d\sigma^\uparrow \longrightarrow \sin(\phi_{S_p} - \phi_{J/\psi})\, f_{1T}^{\perp g}\, A\left[{}^{2S+1}L_J^{(8)}\right]\ldots$

same structure as quark TMDs .. but ..

model dependent $Q\bar{Q} \to J/\psi$ matr. elem.



- various methods to constrain $Q\bar{Q} \to J/\psi$ matr. elem. (LDMEs) *Boer et al., arXiv:2102.00003*
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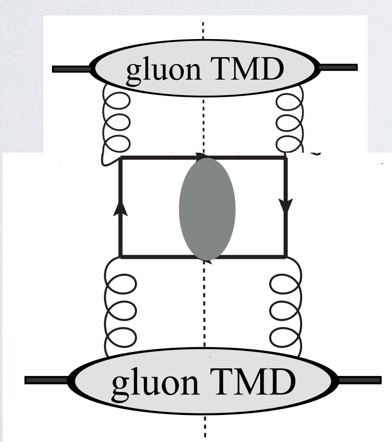
same in e p↑→ e+J/ψ+X



p↑ p→ J/ψ+X

different color gauge links:
WW-type Sivers ≫ DP-type

$f_{1T}^{\perp g[+,+]} \qquad f_{1T}^{\perp g[+,-]}$

D'Alesio et al., arXiv:2007.03353

complementarity of colliders

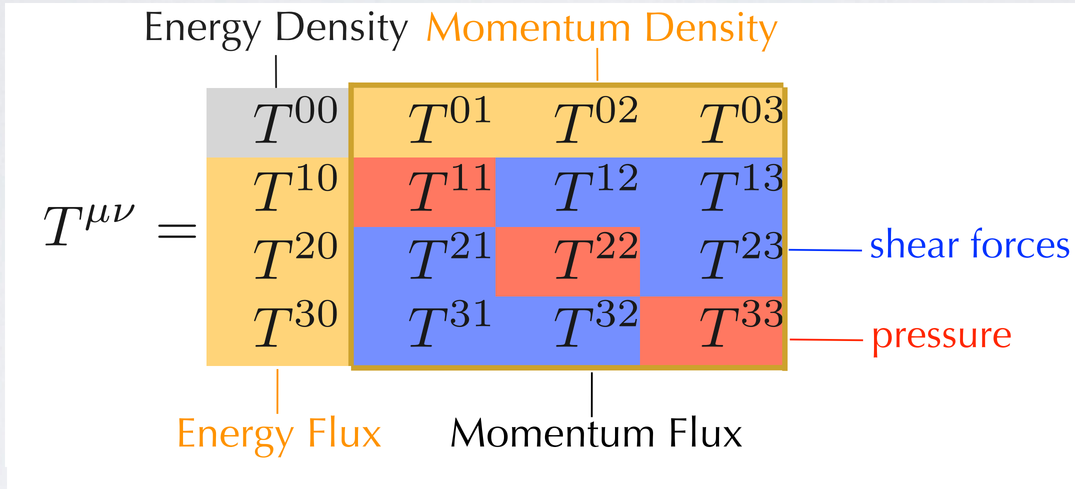
$f_1^{g\,[+,+]}$	$pp \to \gamma\, J/\psi\, X$	LHC
	$pp \to \gamma\, \Upsilon\, X$	LHC
$f_1^{g\,[+,-]}$	$pp \to \gamma$ jet X	LHC & RHIC
$h_1^{\perp g\,[+,+]}$	$e\,p \to e'\, Q\,\overline{Q}\, X$	EIC
	$e\,p \to e'$ jet jet X	EIC
	$pp \to \eta_{c,b}\, X$	LHC & NICA
	$pp \to H\, X$	LHC
$h_1^{\perp g\,[+,-]}$	$pp \to \gamma^*$ jet X	LHC & RHIC
$f_{1T}^{\perp g\,[+,+]}$	$e\,p^\uparrow \to e'\, Q\,\overline{Q}\, X$	EIC
	$e\,p^\uparrow \to e'$ jet jet X	EIC
$f_{1T}^{\perp g\,[-,-]}$	$p^\uparrow p \to \gamma\,\gamma\, X$	RHIC
$f_{1T}^{\perp g\,[+,-]}$	$p^\uparrow A \to \gamma^{(*)}$ jet X	RHIC
	$p^\uparrow\, A \to h\, X\ (x_F < 0)$	RHIC & NICA

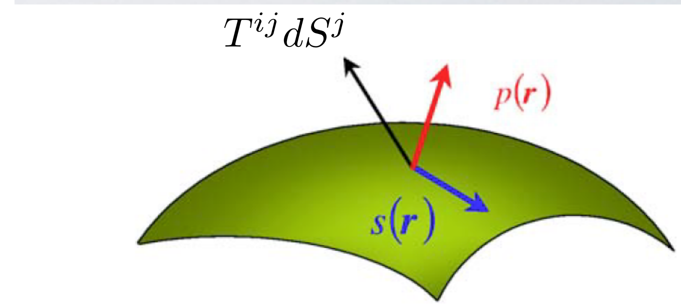
Boer, talk at IWHSS2020

NINPHA highlights: 1. Th properties

QCD Energy-Momentum Tensor (EMT) → Nucleon mechanical properties

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





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

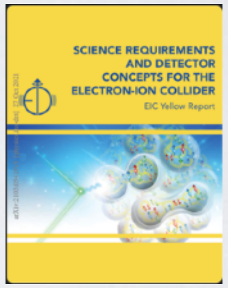
Charges ← Generalised Form Factors

$M_2(0)$ = momentum of partons

$J(0)$ = angular momentum of partons

$d_1(0)$ = "D-term" related to internal pressure → stability of the Nucleon

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



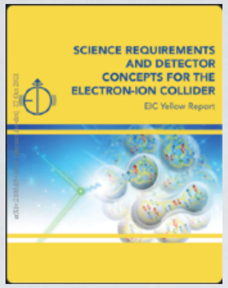
- Properties of the energy-momentum tensor $T^{\mu\nu}$ (renormalisation, scheme dependence, operator mixing, etc..):

  QED at one loop: electron mass sum rules *Rodini, Metz, Pasquini, arXiv:2004.03704*

  QCD at three loops: N mass decomposition, trace anomaly and sigma term *Metz, Pasquini, Rodini, arXiv:2006.11171*

  Renormalization of $T^{\mu\nu}$ and interpretation of terms in N mass decomposition *Lorcé et al., arXiv:2109.11785*

The EMT trace anomaly



Abdul Khalek et al., arXiv:2103.05419

Sec. 7.1.4 Origin of hadron mass

$$M = \begin{cases} \sum_{i=q,g} \langle T_i^{00} \rangle = \sum_{i=q,g} \left[M_2^i(0) + \bar{c}_i(0) \right] M \\ \sum_{i=q,g} g_{\mu\nu} \langle T_i^{\mu\nu} \rangle = \sum_{i=q,g} \left[M_2^i(0) + 4\bar{c}_i(0) \right] M \end{cases}$$

$$\langle T_i^{\mu\nu} \rangle \equiv \frac{1}{2M} \langle P | T_i^{\mu\nu}(0) | P \rangle |_{P=0}$$

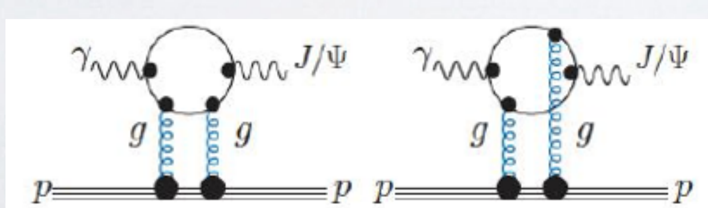
$$\sum_{i=q,g} M_2^i(0) = 1 \qquad \sum_{i=q,g} \bar{c}_i(0) = 0$$

$M_2^i(0) = \int dx\, x\, f_1^i(x)$ momentum of parton *i*

$\bar{c}_q(0) = \langle \bar{\psi} m \psi \rangle$ σ-term from πN scattering

$\bar{c}_g(0) = \langle \frac{\beta(g)}{2g} F^2 + \gamma_m \bar{\psi} m \psi \rangle \equiv M_a$ trace anomaly ($F^{\mu\nu}$ = gluon field)

<F^2> from threshold photo-/electro-production of J/ψ and Υ



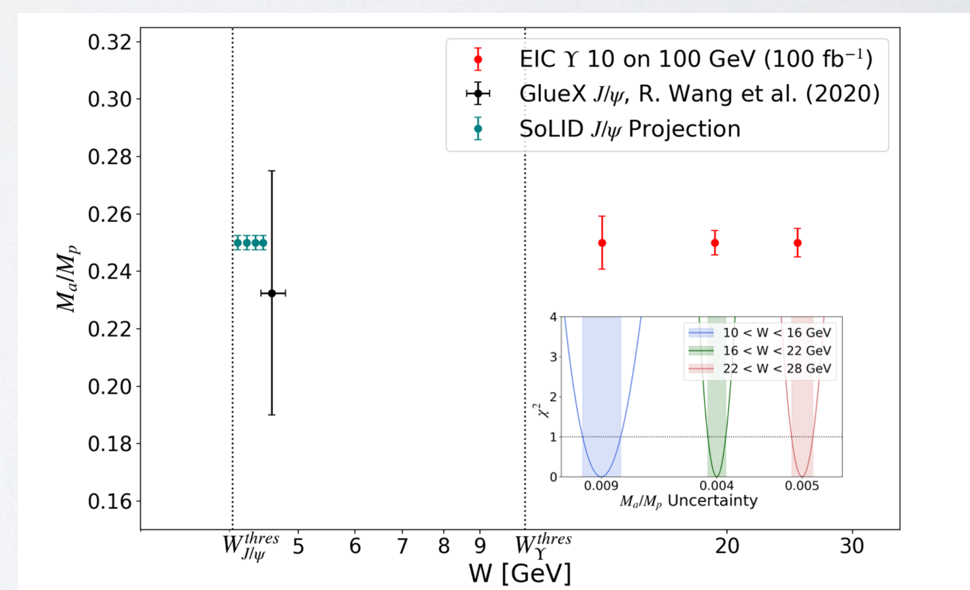


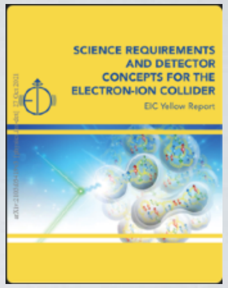
Figure 7.26: Projection of the trace anomaly contribution to the proton mass (M_a/M_p) with Υ photoproduction on the proton at the EIC in 10 × 100 GeV electron/proton beam-energy

NINPHA research lines

2. **Phenomenological extractions of TMDs** PV, CA, TO

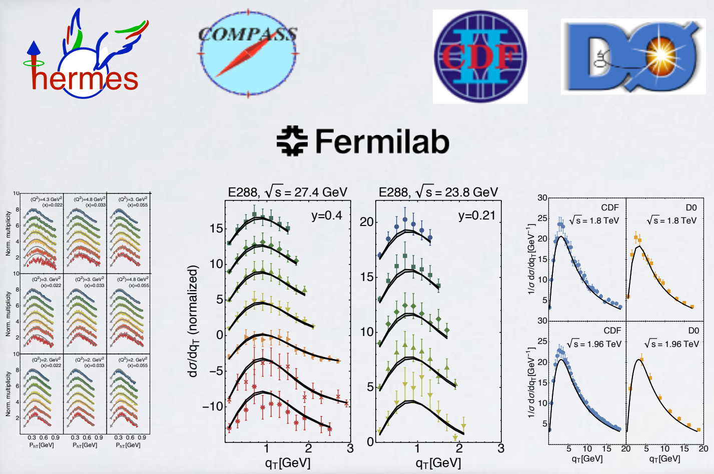
NINPHA highlights: 2. Phenomenology

3D proton tomography with unpolarized quarks



the PV17 fit the first fit of SIDIS + Drell-Yan + Z-production at NLL

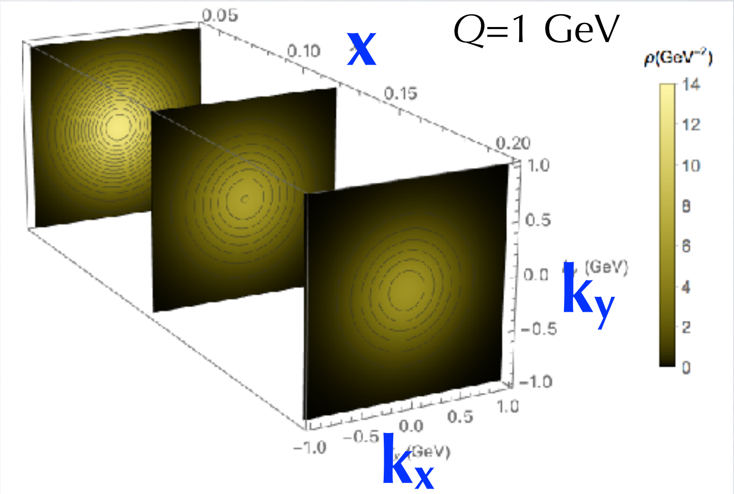
Bacchetta et al., arXiv:1703.10157



data points
8059

 # fit parameters
11

global χ^2/d.o.f.
1.55 ± 0.05



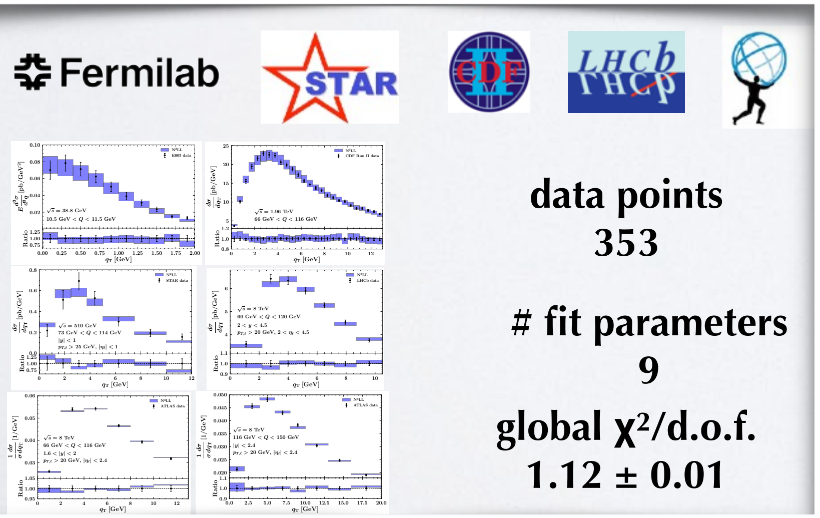
up

$f_1^q(x, k_T; Q)$

down

the PV19 fit fit of Drell-Yan at N³LL top accuracy

Bacchetta et al., arXiv:1912.07550

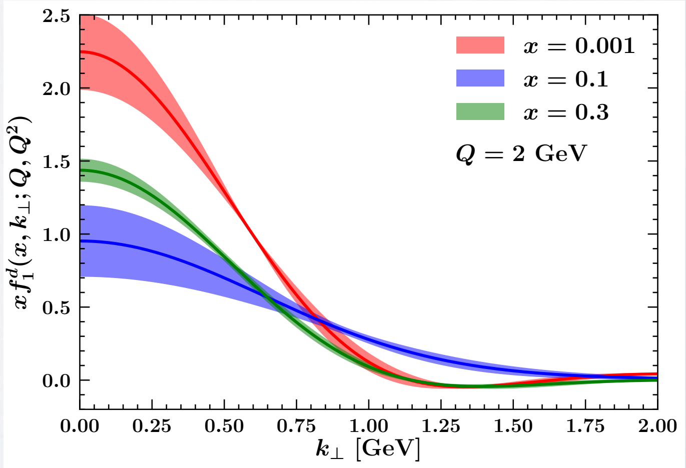


data points
353

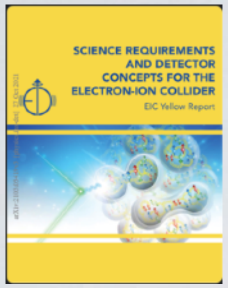
 # fit parameters
9

global χ^2/d.o.f.
1.12 ± 0.01

included in set of benchmark codes by CERN - EW WG



TMD Sensitivity coefficients



Abdul Khalek et al., arXiv:2103.05419

Sec. 8.2.2 Hadron PID impact and 4D TMD measurements

the PV17 fit *Bacchetta et al., arXiv:1703.10157*

non-perturb. TMD PDF

Gaussian $$f_{\rm NP}(x,\boldsymbol{k}_T^2) = \frac{1}{\pi}\,\frac{1+\lambda \boldsymbol{k}_T^2}{g_1+\lambda g_1^2}\, e^{-\boldsymbol{k}_T^2/g_1}$$

width $$g_1(x) = N_1\,\frac{(1-x)^\alpha\, x^\sigma}{(1-\hat{x})^\alpha\, \hat{x}^\sigma}$$

non-perturb. TMD FF

Sum of Gaussians $$D_{\rm NP}(z,\boldsymbol{P}_T^2) = \frac{1}{\pi}\,\frac{1}{g_3+\frac{\lambda_F}{z^2}\,g_4^2}\left[e^{-\boldsymbol{P}_T^2/g_3} + \lambda_F\frac{P_T^2}{z^2}\,e^{-\boldsymbol{P}_T^2/g_4}\right]$$

widths $$g_{3,4}(z) = N_{3,4}\,\frac{(z^\beta+\delta)\,(1-z)^\gamma}{(\hat{z}^\beta+\delta)\,(1-\hat{z})^\gamma}$$

non-perturb. evolution kernel $$g_K(b_T) = -\,g_2\,\frac{b_T^2}{4}$$

Sensitivity coefficients

$$S[f_i,\mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle\mathcal{O}\rangle\langle f_i\rangle}{\delta\mathcal{O}\,\Delta f_i}$$

$f_i = N_1,\ \sigma,\ g_2,\ N_3,\ \lambda_F$

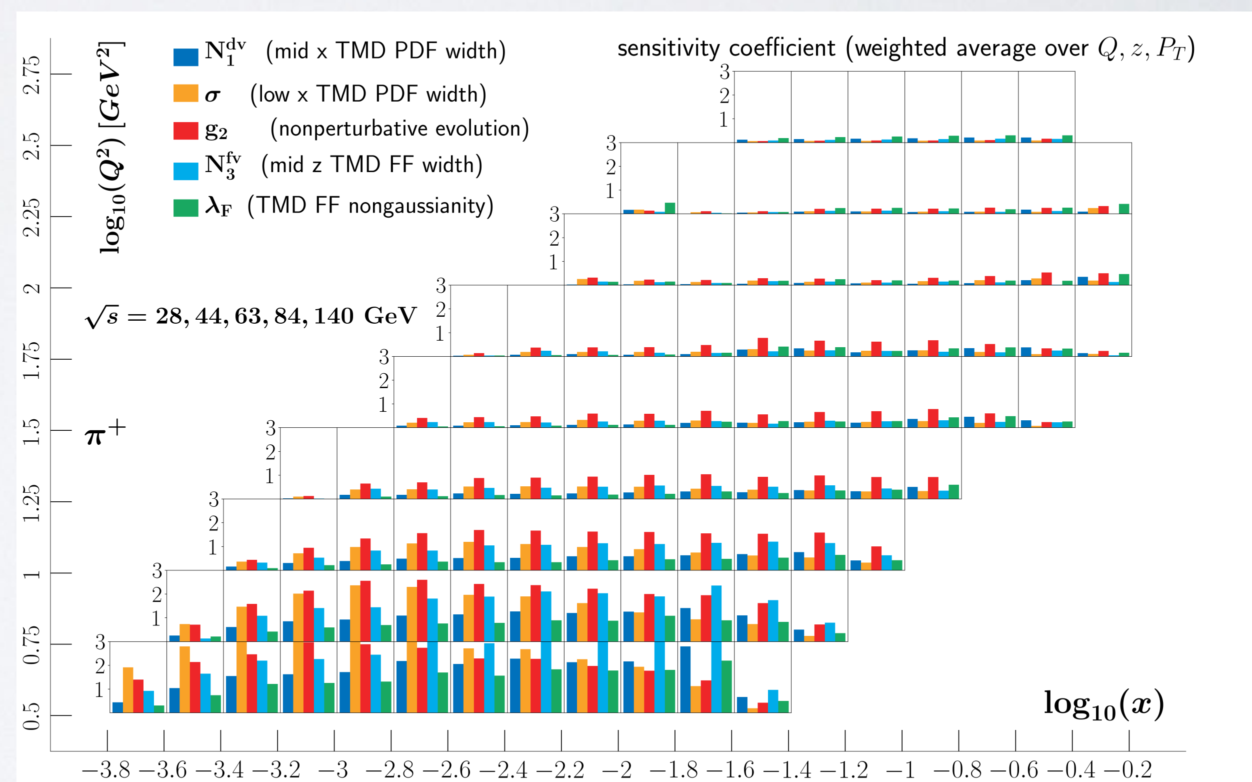


Figure 8.30: Expected sensitivities to various TMD PDF and FF parameters, as well as the TMD evolution as shown for the verious collision energy options and for detected final-state positive pions. The impact has been averaged over final state hadron transverse momentum and fractional energy for better visibility.

NINPHA highlights: 2. Phenomenology

3D proton tomography with unpolarized quarks (cont′ed)

unpol. quark in ⊥ pol. Nucleon = **Sivers effect**

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

constraints

1- TMD framework requires same non-perturb. evolution

2- positivity bound $\frac{k_T}{M}\left|f_{1T}^{\perp}(x,k_T^2)\right| \leq f_1(x,k_T^2)$

NINPHA highlights: 2. Phenomenology

3D proton tomography with unpolarized quarks (cont′ed)

unpol. quark in ⊥ pol. Nucleon = **Sivers effect**

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

constraints

1- TMD framework requires same non-perturb. evolution

2- positivity bound $\frac{k_T}{M}\left|f_{1T}^{\perp}(x,k_T^2)\right| \leq f_1(x,k_T^2)$

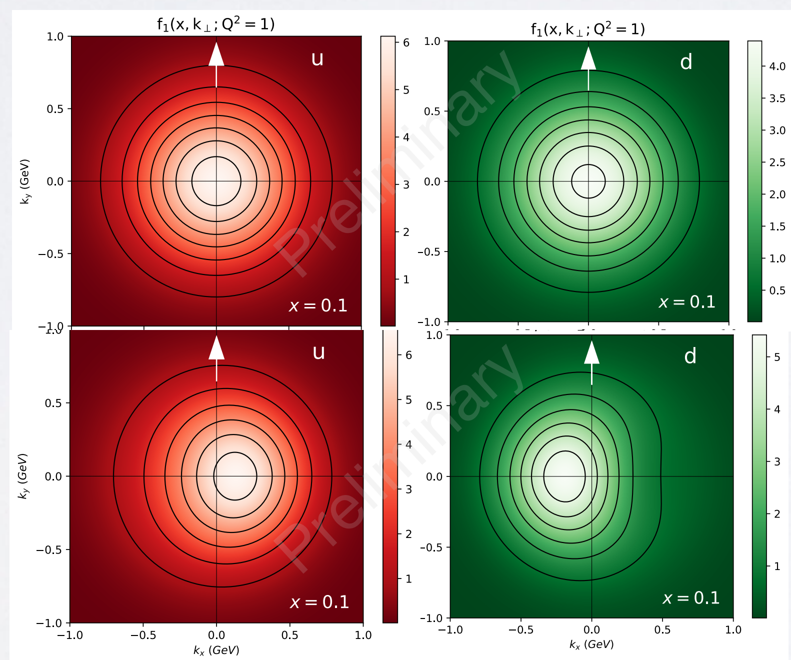
the PV-Sivers fit (based on PV17 fit) is the first to implement these constraints

Bacchetta et al., arXiv:2004.14278
v2 in preparation

data points
125

 # fit parameters
17

global χ²/d.o.f.
1.12 ± 0.04

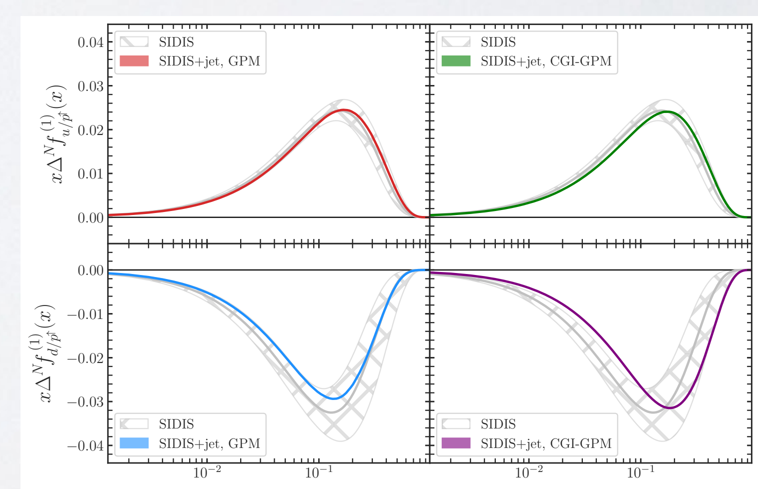


$$\rho^q(x,\boldsymbol{k}_T) = f_1^q(x,\boldsymbol{k}_T^2)$$

$$\rho^q(x,\boldsymbol{k}_T) = f_1^q(x,\boldsymbol{k}_T^2) - f_{1T}^{\perp q}(x,\boldsymbol{k}_T^2)\,\frac{(\boldsymbol{k}_x \times \boldsymbol{S}_y)\cdot \hat{\boldsymbol{P}}_z}{M}$$

Using reweighing technique, study impact of STAR data on previous fit of Sivers effect in SIDIS

Boglione et al., arXiv:2101.03955



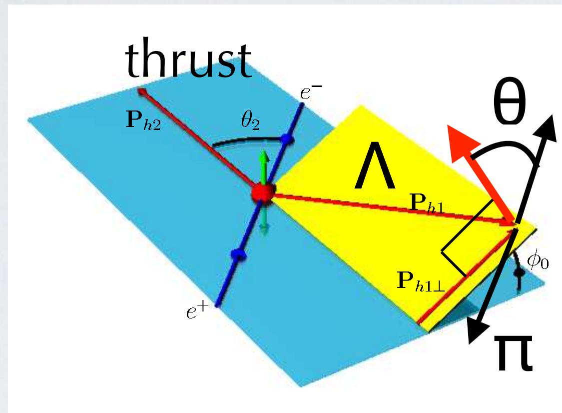
u

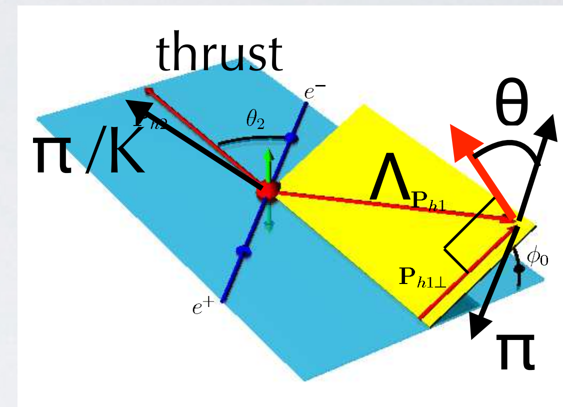
d

NINPHA highlights: 2. Phenomenology

Belle data on $e^+ e^- \rightarrow \Lambda^\uparrow + X$ $e^+ e^- \rightarrow \Lambda^\uparrow + \pi/K + X$

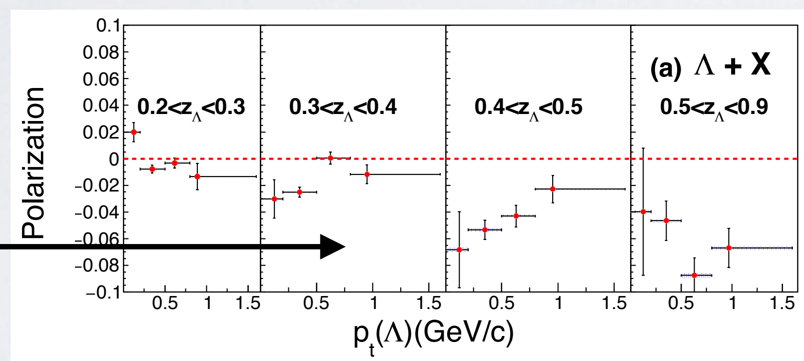
arXiv:1808.05000

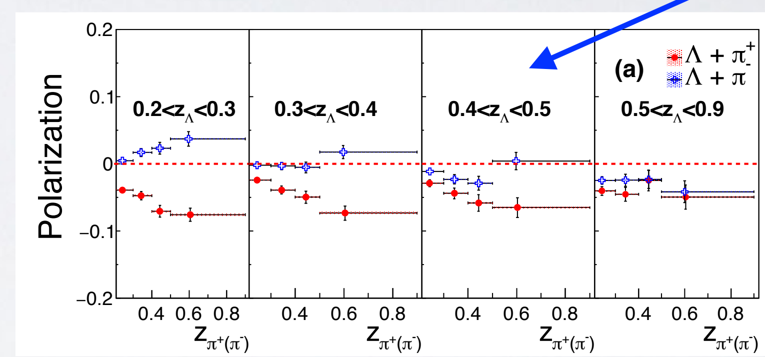




change sign

strange oscillations

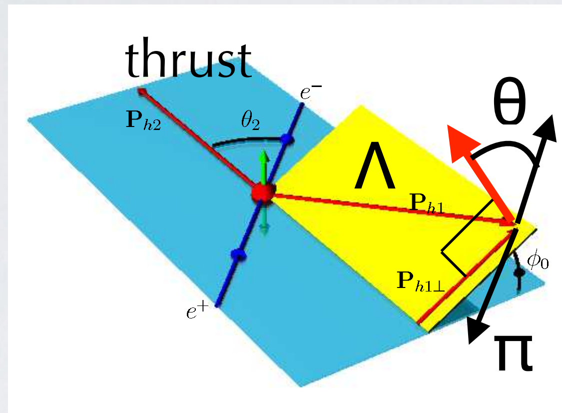


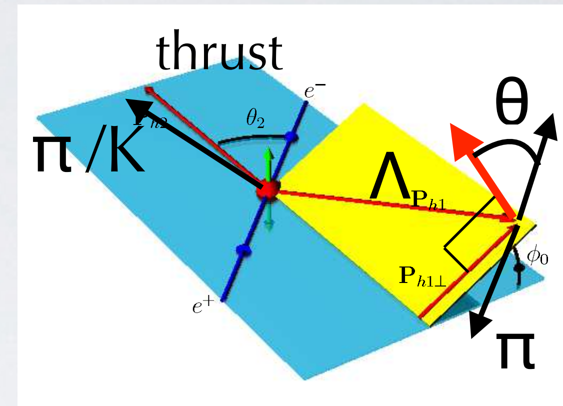


NINPHA highlights: 2. Phenomenology

Belle data on $e^+ e^- \to \Lambda^\uparrow + X$ $\quad$ $e^+ e^- \to \Lambda^\uparrow + \pi/K + X$

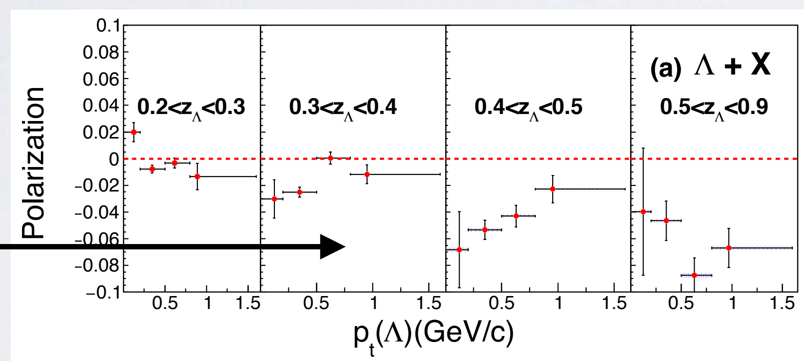
arXiv:1808.05000

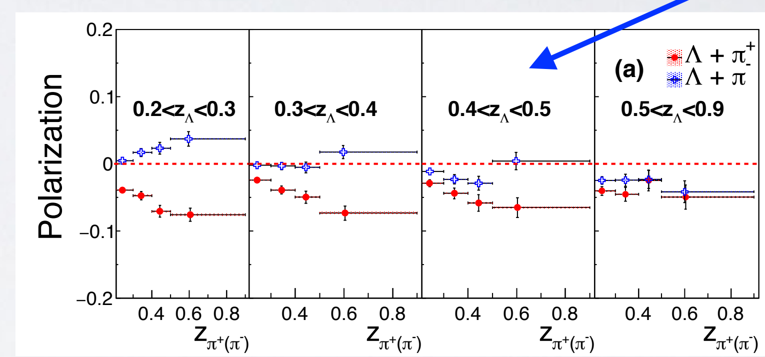




change sign

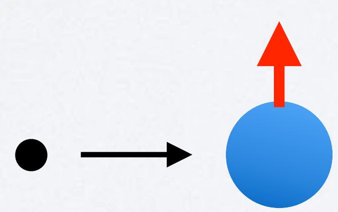
strange oscillations



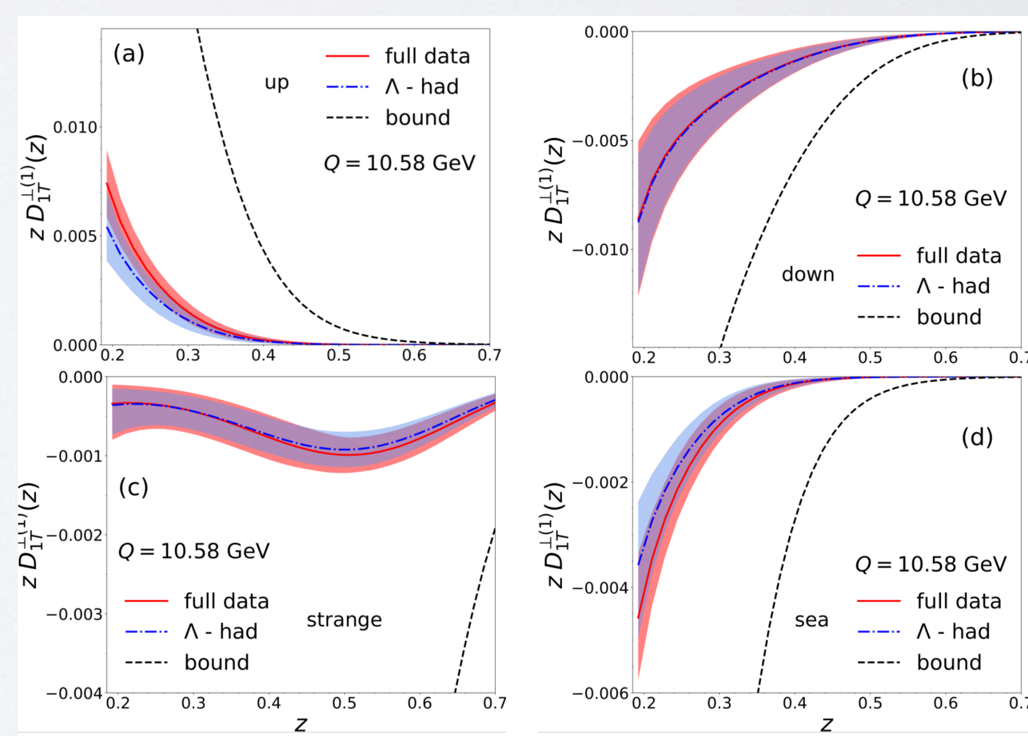


fit based on extended parton model
→ extract polarising FF

$D_{1T}^{\perp}$

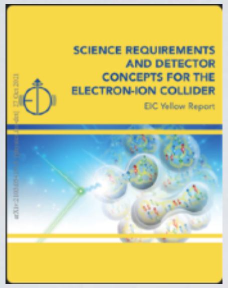


$$D_{1T}^{\perp(1)}(z_\Lambda, Q) = \int d\mathbf{p}_\perp \, \frac{\mathbf{p}_\perp^2}{2 z_\Lambda^2 M_\Lambda^2} \, D_{1T}^{\perp}(z_\Lambda, \mathbf{p}_\perp^2, Q)$$



D'Alesio et al., arXiv:2003.01128

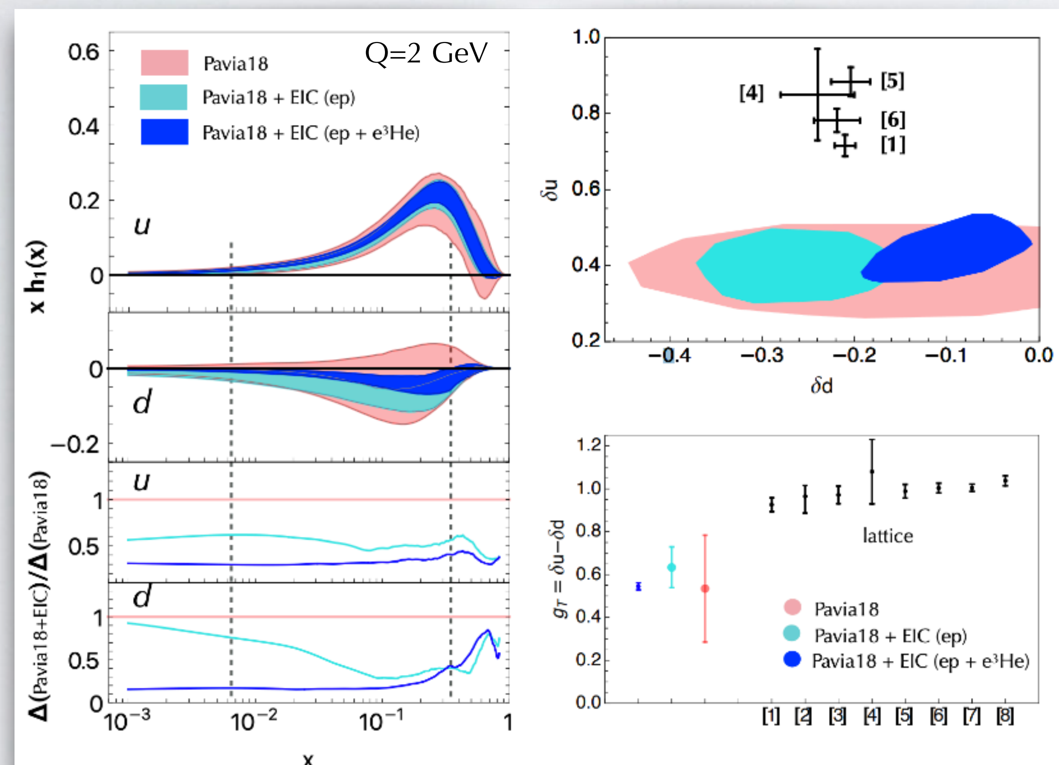
EIC impact on chiral-odd transversity



Abdul Khalek et al., arXiv:2103.05419

Sec. 7.2.3 Imaging of quarks and gluons in momentum space
Chiral-odd distributions via di-hadron measurements

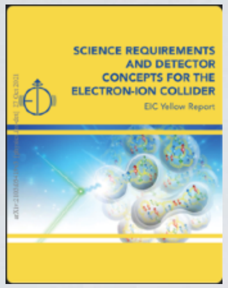
based on **the PV18 fit** of data for di-hadron production in SIDIS, p-p, e+e- *Bacchetta & M.R., arXiv:1802.05212*



- Soffer bound $\left|h_1^q(x,Q^2)\right| \leq \frac{1}{2}\left(f_1^q(x,Q^2) + g_1^q(x,Q^2)\right)$ automatic

tensor charge $\delta q = \int_{x_{min}}^{1} dx \left[h_1^q - h_1^{\bar{q}}\right]$

EIC impact on chiral-odd transversity

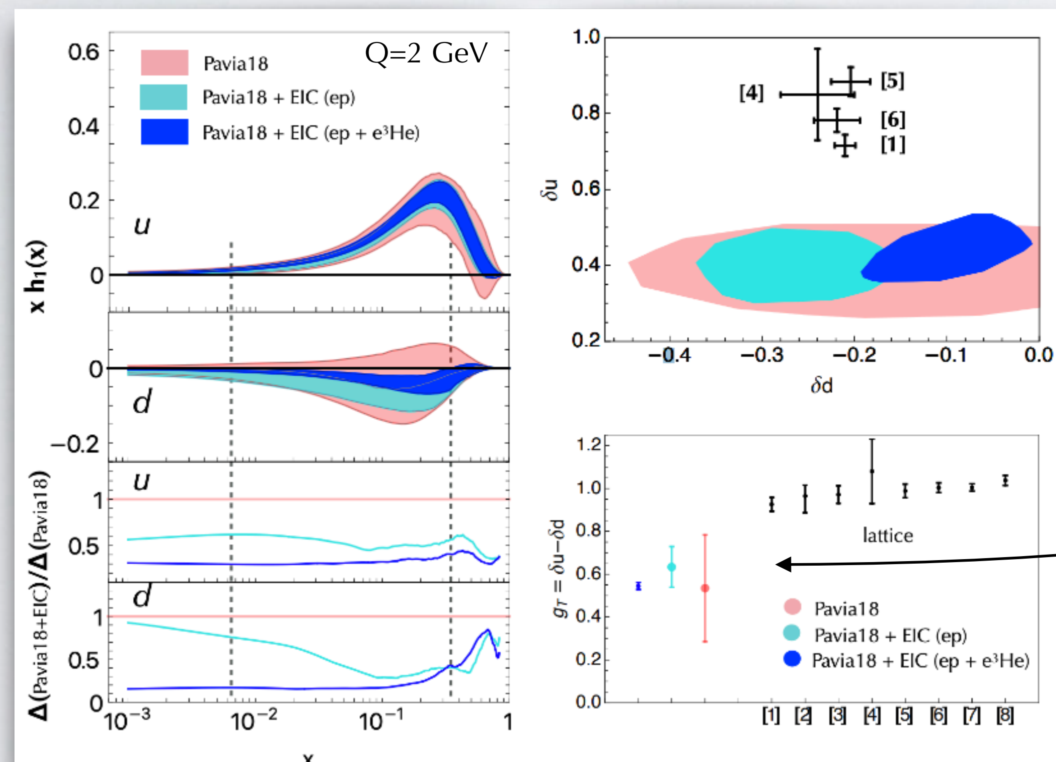


Abdul Khalek et al., arXiv:2103.05419

Sec. 7.2.3 Imaging of quarks and gluons in momentum space
Chiral-odd distributions via di-hadron measurements

based on **the PV18 fit** of data for di-hadron production in SIDIS, p-p, e+e-

Bacchetta & M.R., arXiv:1802.05212



- Soffer bound $\left|h_1^q(x,Q^2)\right| \leq \frac{1}{2}\left(f_1^q(x,Q^2)+g_1^q(x,Q^2)\right)$ automatic

tensor charge $\delta q = \int_{x_{min}}^{1} dx \left[h_1^q - h_1^{\bar{q}}\right]$

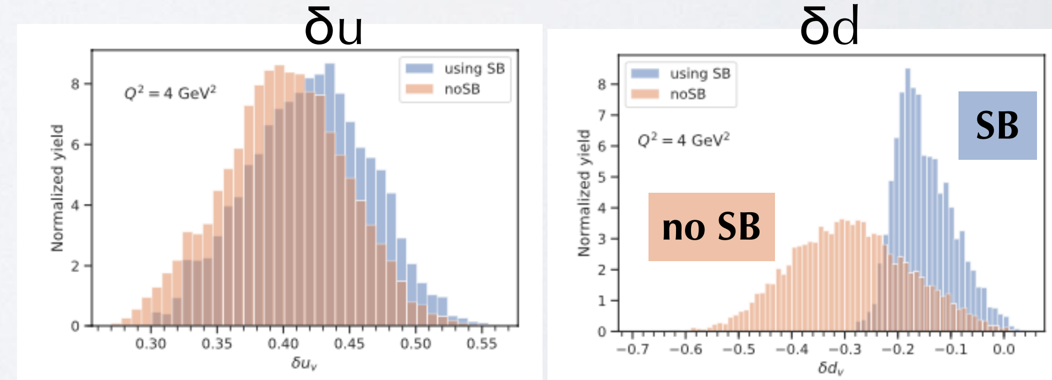
- g_T=δu-δd : disagreement with lattice (not confirmed by analysis of Collins effect by JAM Collaboration)

at the EIC, potential precision $\gtrsim$ lattice !

"exploratory" fit of Collins effect in SIDIS

D'Alesio et al., arXiv:2001.01573

δu δd



NINPHA research lines

3. **Models and support to experiments** PV, PG, GE

NINPHA highlights: 3. Models

pion-induced Drell-Yan $\pi^- p^\uparrow \to \ell^+ \ell^- + X$

$A_{UU}^{\cos 2\phi}$ access to Boer-Mulders $h_1^\perp$ in π and p

$A_{UT}^{\sin \phi_S}$ access to Sivers in p↑

$A_{UT}^{\sin(2\phi-\phi_S)}$ access to $h_1^\perp$ in π and transversity in p↑

.....

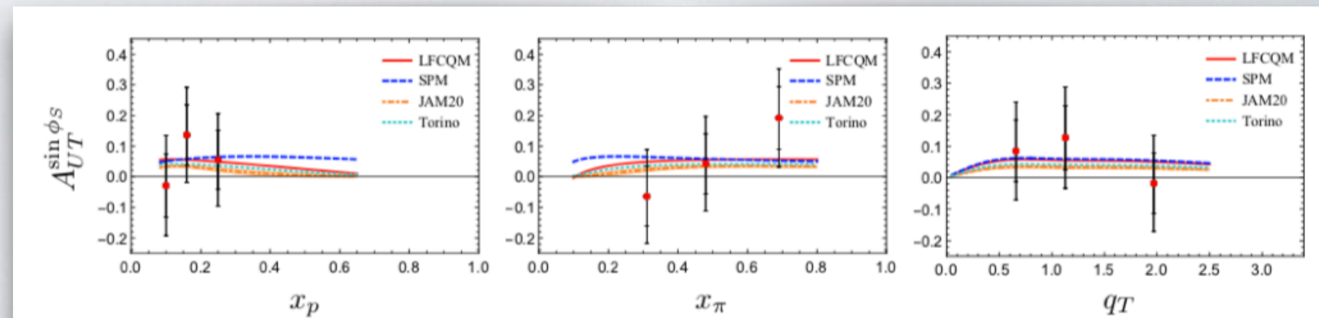


Figure 5. $A_{UT}^{\sin\phi}$ as a function of x_p (left), x_π (middle) and q_T (right) vs COMPASS data [46].

Bastami et al., arXiv:2005.14322

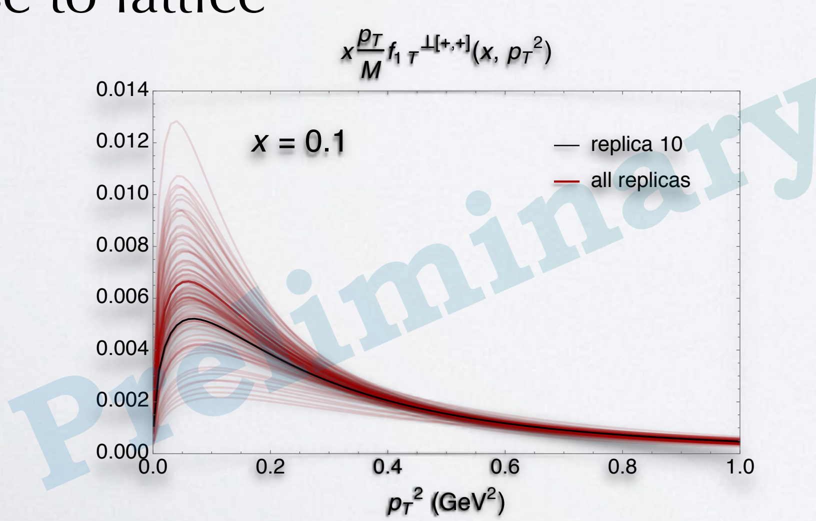
comparing models of π and p TMDs and parametrizations (when available) with Compass data

gluon TMDs in a spectator model

- model proton-gluon-X vertex ⊗ spectral function (M_X)
- fix parameters to $f_1(x)_{\text{NNPDF3.1}}$, $g_1(x)_{\text{NNPDFpol1.1}}$
- $\langle x\rangle_g$ very close to lattice

- T-odd TMDs

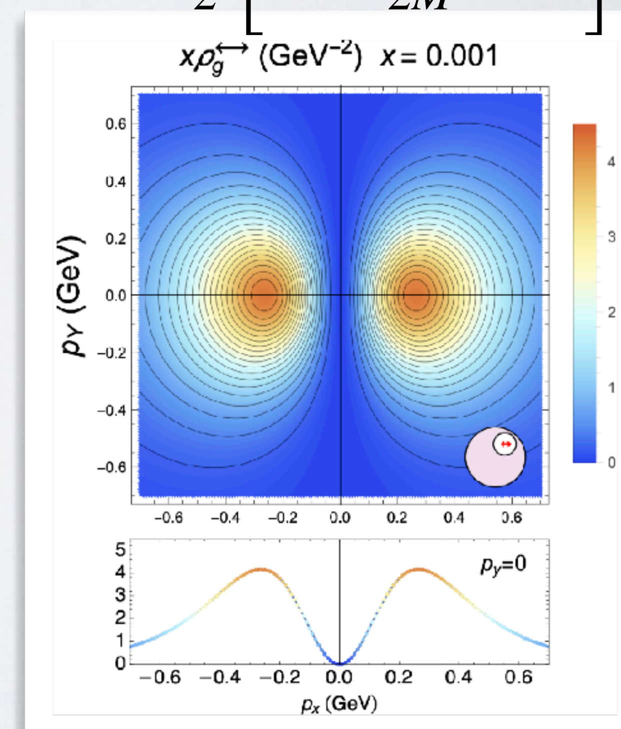
in preparation



- T-even TMDs

Bacchetta et al., arXiv:2005.02288

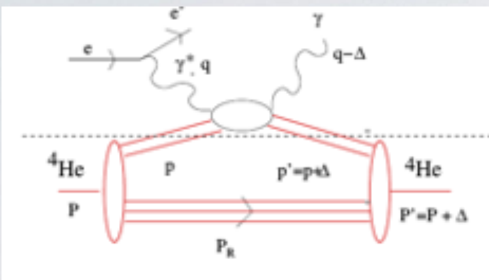
$$\rho_g^{\leftrightarrow} = \frac{1}{2}\left[f_1^g + \frac{k_x^2 - k_y^2}{2M^2} h_1^{\perp g}\right]$$



NINPHA highlights: 3. Models

GPDs in light nuclei

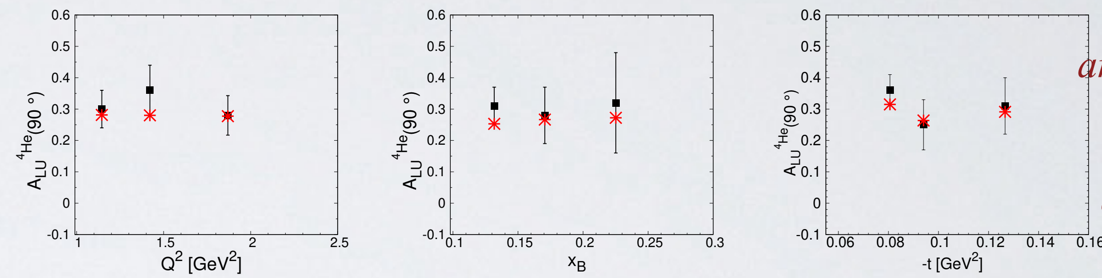
- coherent DVCS on ⁴He $H_A^q(x,\xi,t) = S_A \otimes H_N^q$



spin-dependent spectral function computed from AV18-UIX nuclear potential

$$\Im(H_A) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t) \qquad \Re(H_A) = \mathcal{P}\int_{-1}^{1} dx \frac{H_A(x,\xi,t)}{x-\xi}$$

$$A_{LU}(\phi) = \frac{a_0 \Im(H_A)}{a_1 + a_2 \Re(H_A) + a_3(\Re^2(H_A) + \Im^2(H_A))}$$



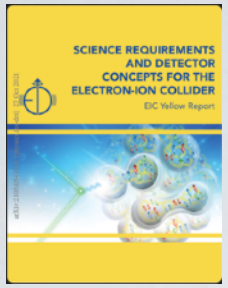
■ *CLAS, arXiv:1707.03361*

Fucini et al., arXiv:1805.05877

Figure 7.61: ⁴He azimuthal beam-spin asymmetry $A_{LU}(\phi)$, for $\phi = 90°$: results of Ref. [672]

b_x

Possibilities with light nuclei at the EIC



Abdul Khalek et al., arXiv:2103.05419

Sec. 7.2.5 Light (polarized) nuclei
Coherent DVCS on light nuclei

- coherent DVCS on ^{4}He

$$A_{LU}(\phi) = \frac{a_0 \Im(H_A)}{a_1 + a_2 \Re(H_A) + a_3(\Re^2(H_A) + \Im^2(H_A))}$$

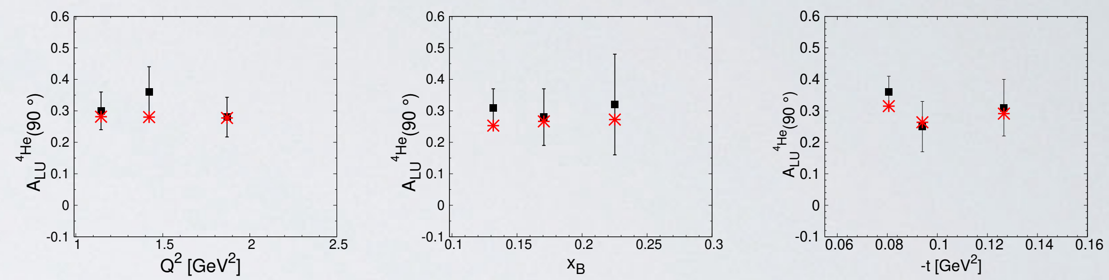


Figure 7.61: ^{4}He azimuthal beam-spin asymmetry $A_{LU}(\phi)$, for $\phi = 90°$: results of Ref. [672] (red stars) compared with data (black squares) from the CLAS Collaboration at JLab [656].

Sec. 8.4.3 DVCS off Helium
The Orsay-Perugia event generator (TOPEG)

large acceptance effects in far forward detector

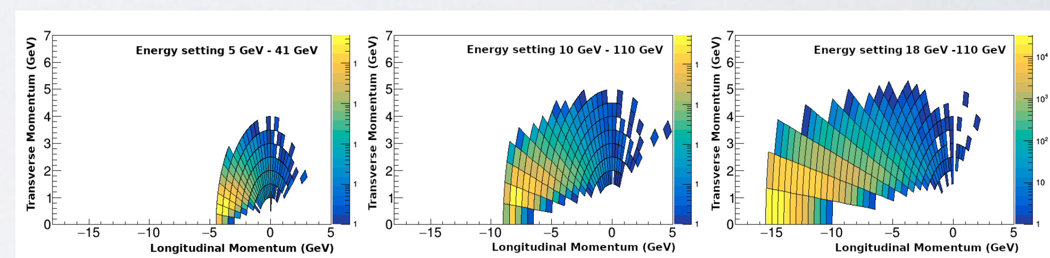
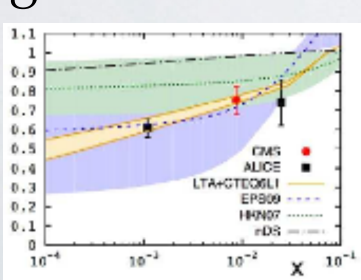


Figure 8.66: Kinematic distribution of the photons produced in coherent DVCS on helium-4 as generated with TOPEG for the three energy configurations envisioned for the EIC.

Sec. 7.3.8 Structure of light nuclei
Coherent scattering off lightest nuclei

- gluon shadowing in UPC@LHC γA → ρ(J/ψ)+A



$$\frac{g_A(x, Q^2)}{g_N(x, Q^2)}$$

At Q^2~few GeV^2, x$_B$~10^{-3}, coherence length → 2-3 nucleons involved
complementarity of light nuclei!

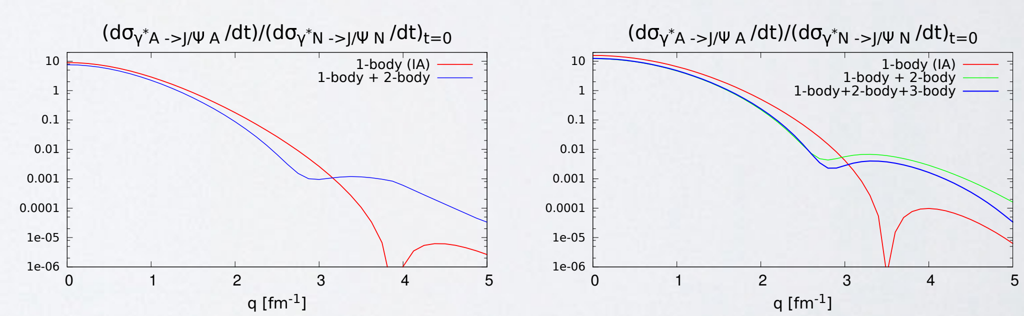


Figure 7.81: Coherent J/Ψ production on ^{3}He (left panel) and ^{4}He (right panel) at $x = 10^{-3}$. The cross section ratio to the $t = 0$ value for production on the nucleon is shown, as a function of $q = \sqrt{-t}$. Red curves do not include rescattering effects, green (blue) curves include double (triple) rescatterings.

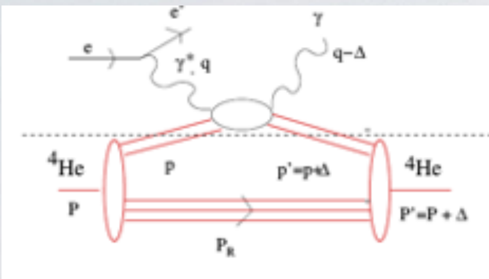
NINPHA highlights: 3. Models

GPDs in light nuclei

$$\Im(H_A) = H_A(\xi,\xi,t) - H_A(-\xi,\xi,t) \qquad \Re(H_A) = \mathscr{P}\int_{-1}^{1} dx\, \frac{H_A(x,\xi,t)}{x-\xi}$$

$$A_{LU}(\phi) = \frac{a_0 \Im(H_A)}{a_1 + a_2\Re(H_A) + a_3(\Re^2(H_A) + \Im^2(H_A))}$$

- coherent DVCS on ^{4}He $\quad H_A^q(x,\xi,t) = S_A \otimes H_N^q$



↗ spin-dependent spectral function computed from AV18-UIX nuclear potential

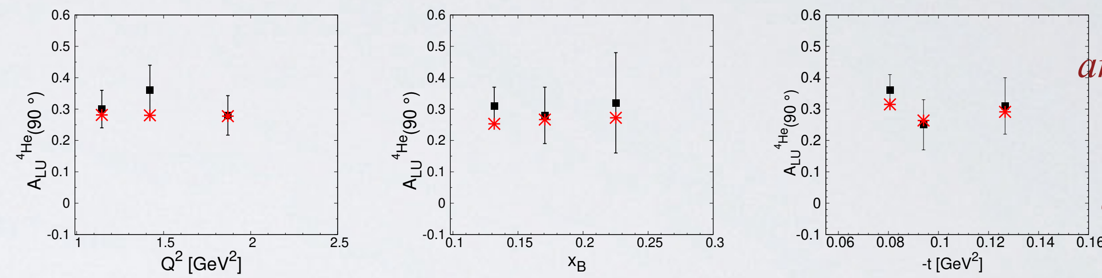
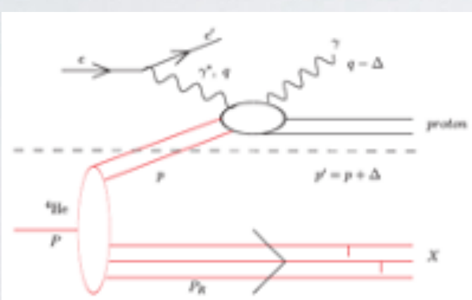


Figure 7.61: ^{4}He azimuthal beam-spin asymmetry $A_{LU}(\phi)$, for $\phi = 90°$: results of Ref. [672]

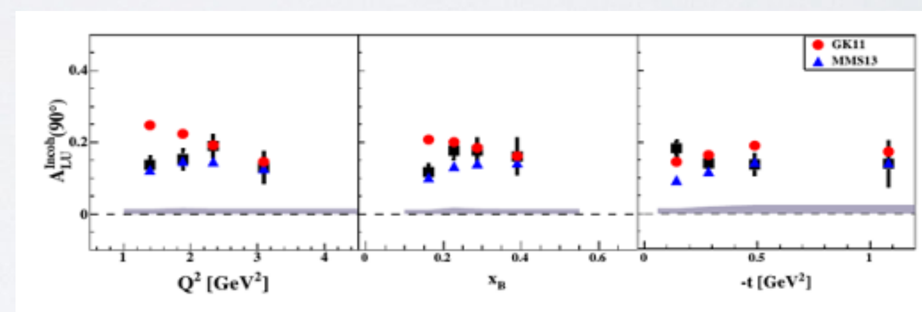
■ *CLAS, arXiv:1707.03361*

Fucini et al., arXiv:1805.05877

- incoherent DVCS on ^{4}He $\quad H_A^{N,q} = \int dE d\mathbf{p} S_A^N(\mathbf{p},E) H_N^q$



↗ diagonal spectral function H_N computed at off-shell kin. ↔ EMC effect ?

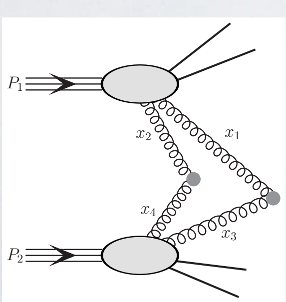


beam-spin asym. A_{LU}

■ *CLAS, arXiv:1812.07628*

Fucini et al., arXiv:2008.11437

double PDFs (dPDFs)



dPDFs in multi-parton interactions at LHC like pp → J/ψ + J/ψ + X

⊥ distance of partons → GPDs?

Rinaldi & Ceccopieri, arXiv:1812.04286
arXiv:2103.13480

$F_{gg}(x_1, x_2, \mathbf{b}_T, Q^2=m_H^2)$

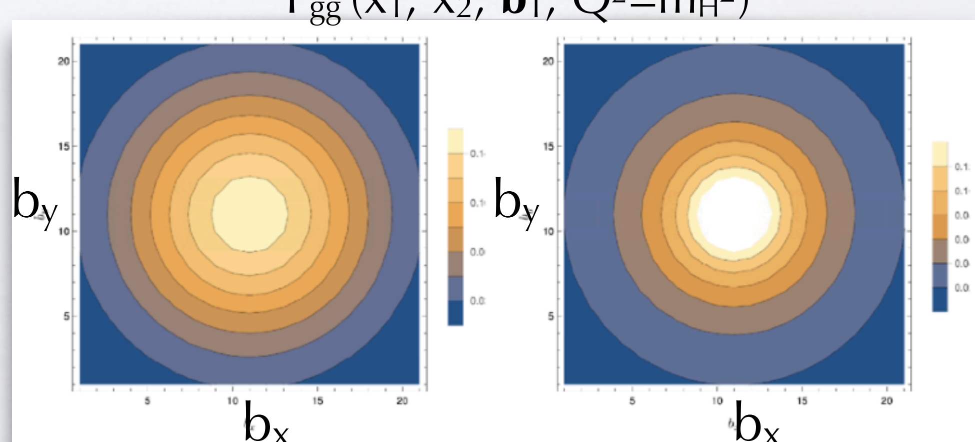
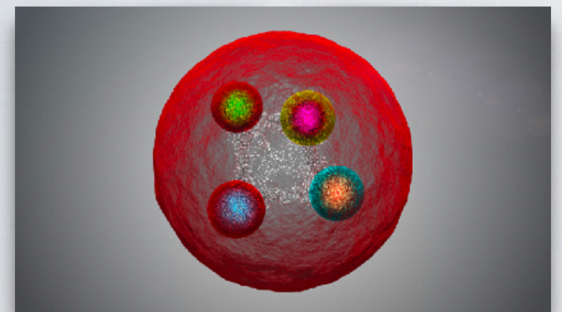


Figure 1. The digluon distribution $\tilde{F}_{gg}(x_1 = 10^{-4}, x_2 = 10^{-2}, b_\perp, Q^2 = m_H^2)$. Left panel: calculation within the HO model. Right panel: calculation within the HP model. Partonic distance expressed in [GeV^{-1}].

NINPHA highlights: 3. Models

modeling structure and decays of heavy exotic mesons and baryons

Tetraquarks



- Diquark model → spectrum of fully heavy tetraquarks $cc\bar{c}\bar{c}, bb\bar{b}\bar{b}, bc\bar{b}\bar{c}, bb\bar{c}\bar{c}, \ldots$
  and of fully-heavy baryons

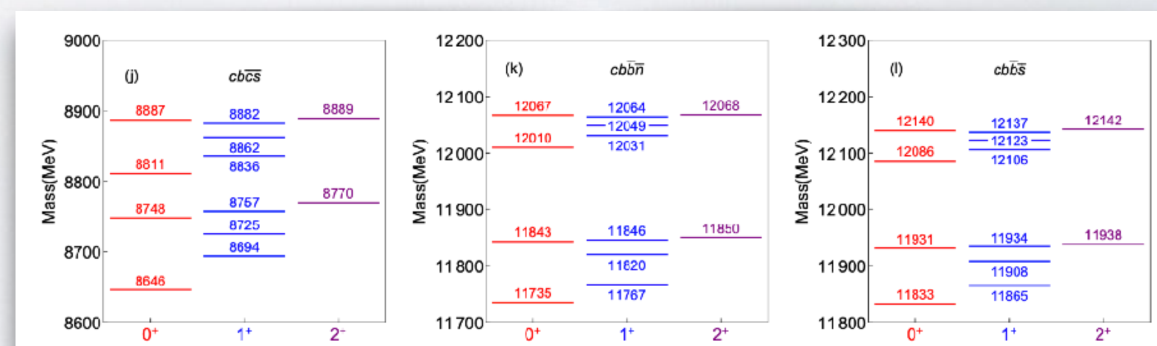
Bedolla et al., arXiv:1911.00960

- decay $cc\bar{c}\bar{c} \to 4\mu$ and $D^{(*)}\bar{D}^{(*)} \to e\mu$ in $J^{PC} = 0^{++}, 2^{++}$
  can be detected at LHCb

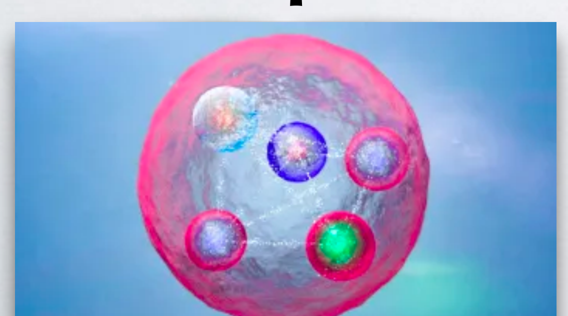
Becchi et al., arXiv:2006.14388

- relativized 4-body Hamiltonian → spectrum of triply-heavy tetraquarks $cc\bar{c}\bar{q}, bb\bar{c}\bar{q}, \ldots$
  decay in heavy quarkonium plus heavy-light meson

Lü et al., arXiv:2107.13930



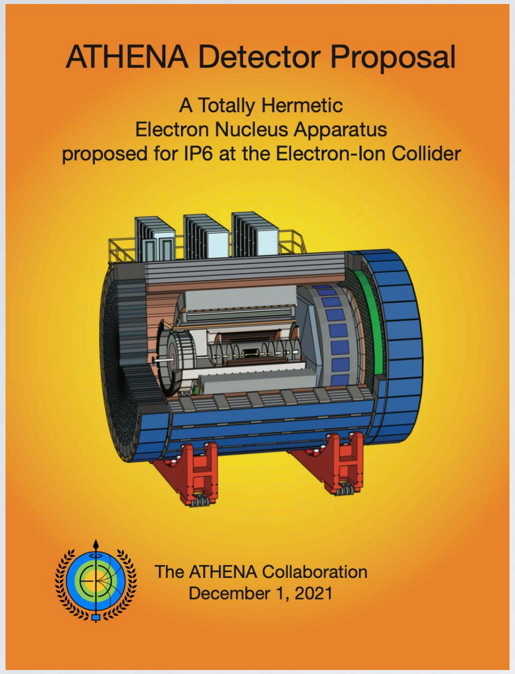
Pentaquarks



- hidden-charm pentaquark as
  $uudc\bar{c}$ coupled to superposition of $\Lambda_c\bar{D}^{(*)}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}$)
  spectrum and decays of $P_c^+(4312), P_c^+(4440), P_c^+(4457)$

Yamaguchi et al., arXiv:1907.04684

NINPHA contributions to ATHENA proposal



Sec. 3.2 Origin of Spin and 3D Nucleon imaging

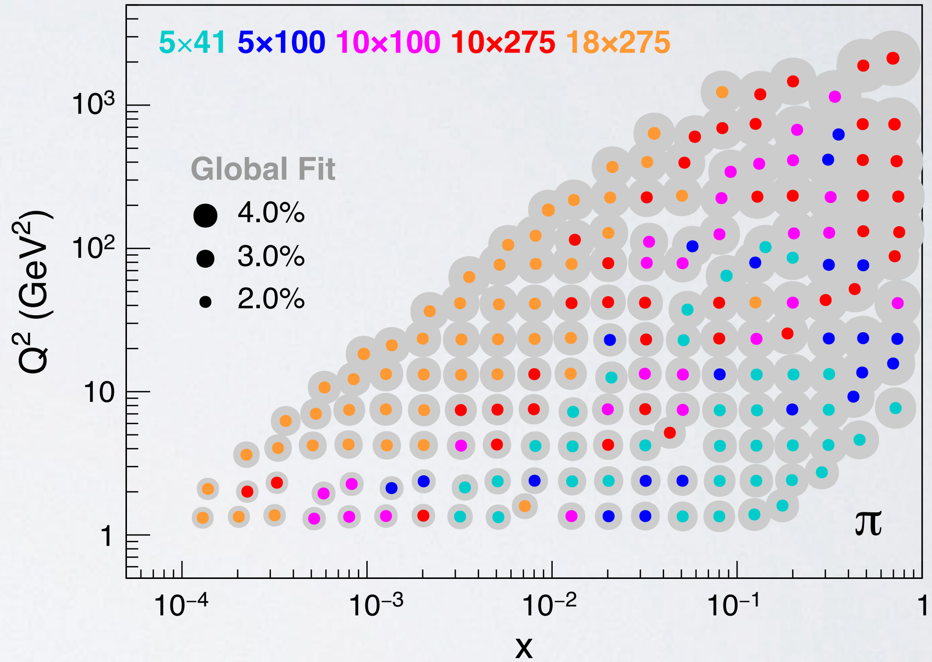
Sec. 3.2.2 3D parton imaging with hadrons

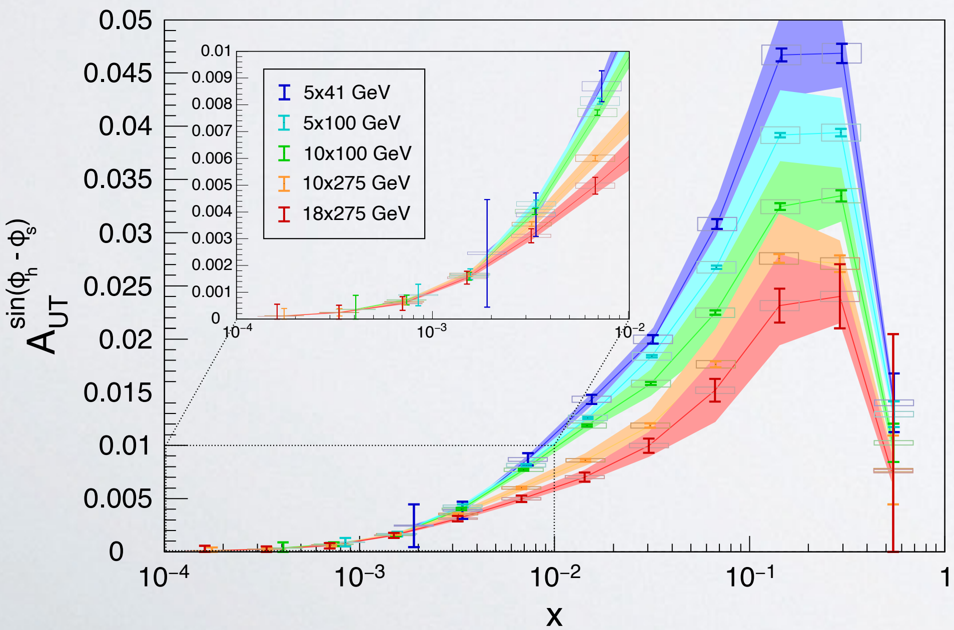
unpolarized cross section
$e\,p \rightarrow e' + \pi^+ + X$

th. uncertainty from PV17 fit

ATHENA projected errors
(2% pt-to-pt + 3% scale syst.)

In each (Q^2,x), largest impact shown





$A_{UT}^{\sin(\phi_h-\phi_S)}$ **Sivers effect**
$e\,p^{\uparrow} \rightarrow e' + \pi^+ + X$

same color code

bands from PV-Sivers fit