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Probing the transverse momentum of
Longitudinally Polarized quarks

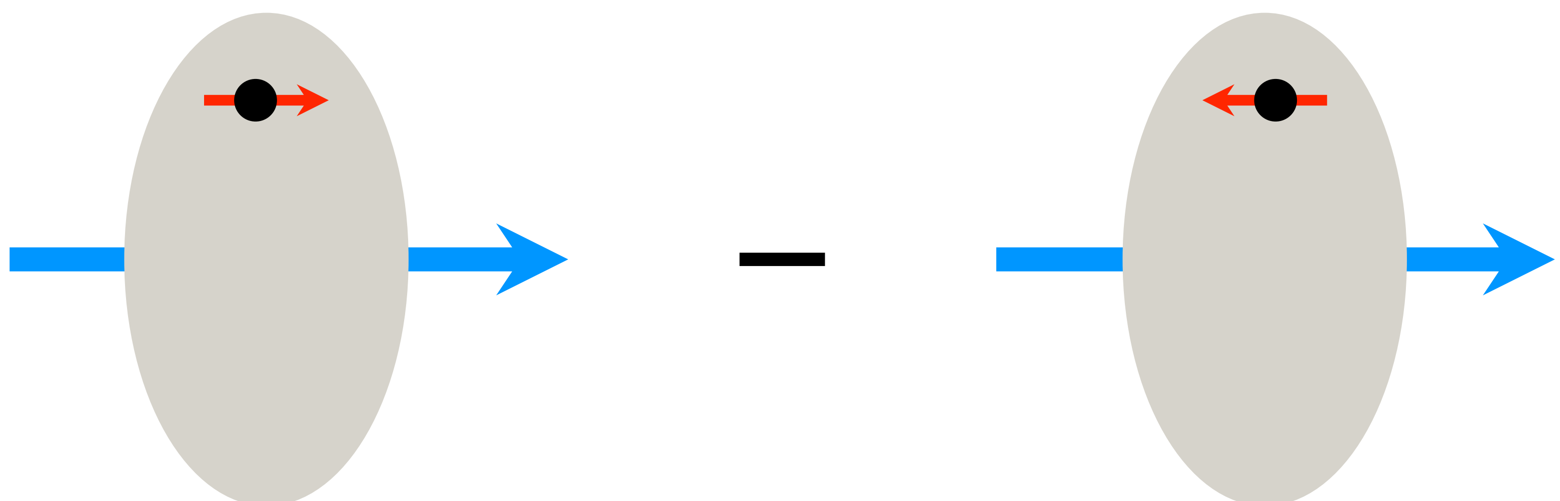
Matteo Cerutti

MAP Collaboration

MAP Collaboration, arXiv:2409.18078

HELICITY distribution

$$g_1^q(x) = q^+ - q^-$$

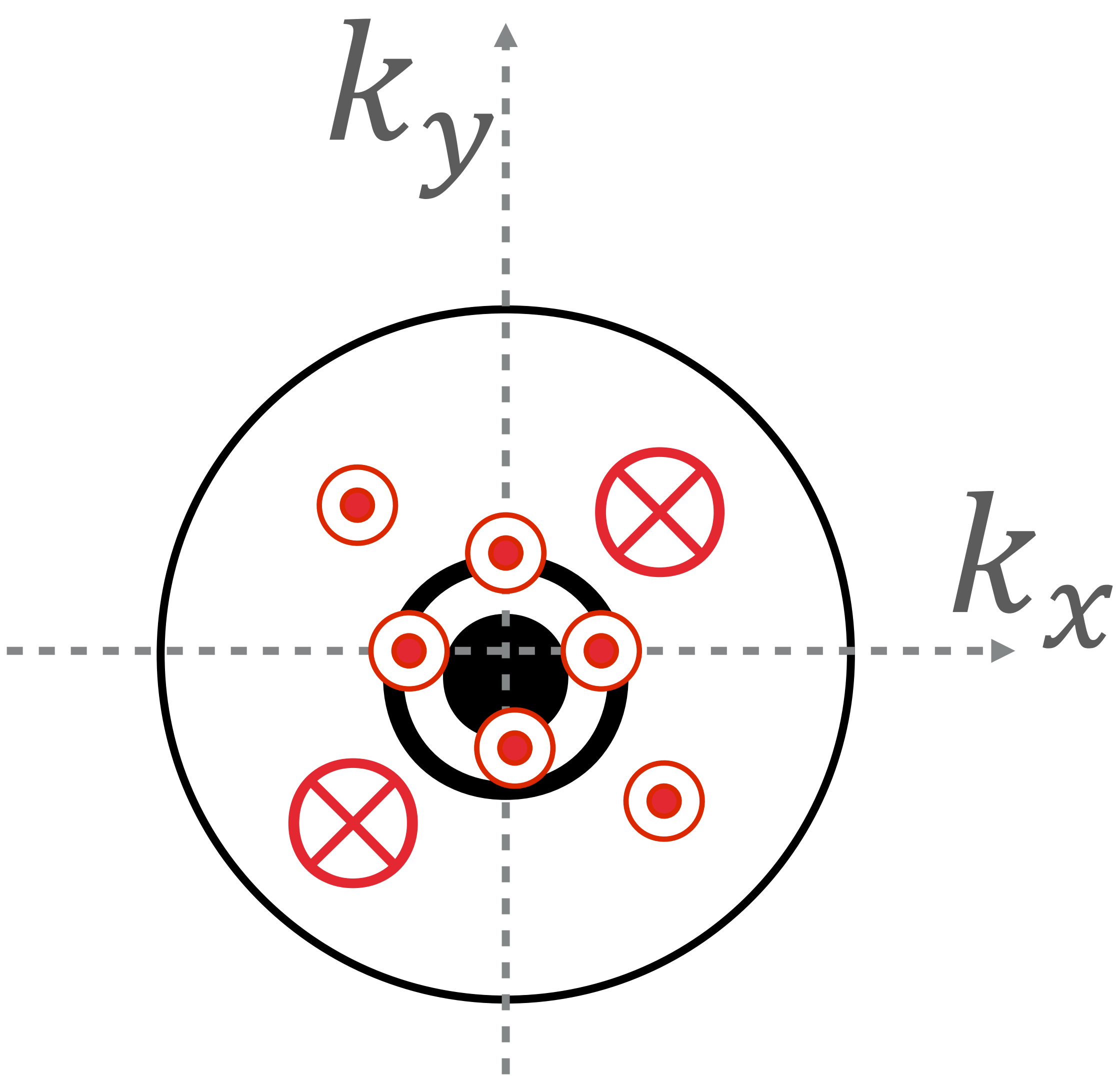


Quark Polarization

Nucleon Pol.		U	L	T
	U	$f_1(x)$		
	L		$g_1(x)$	
	T			$h_1(x)$

HELICITY distribution

$$g_1^q(x, k_\perp) = q^+ - q^-$$



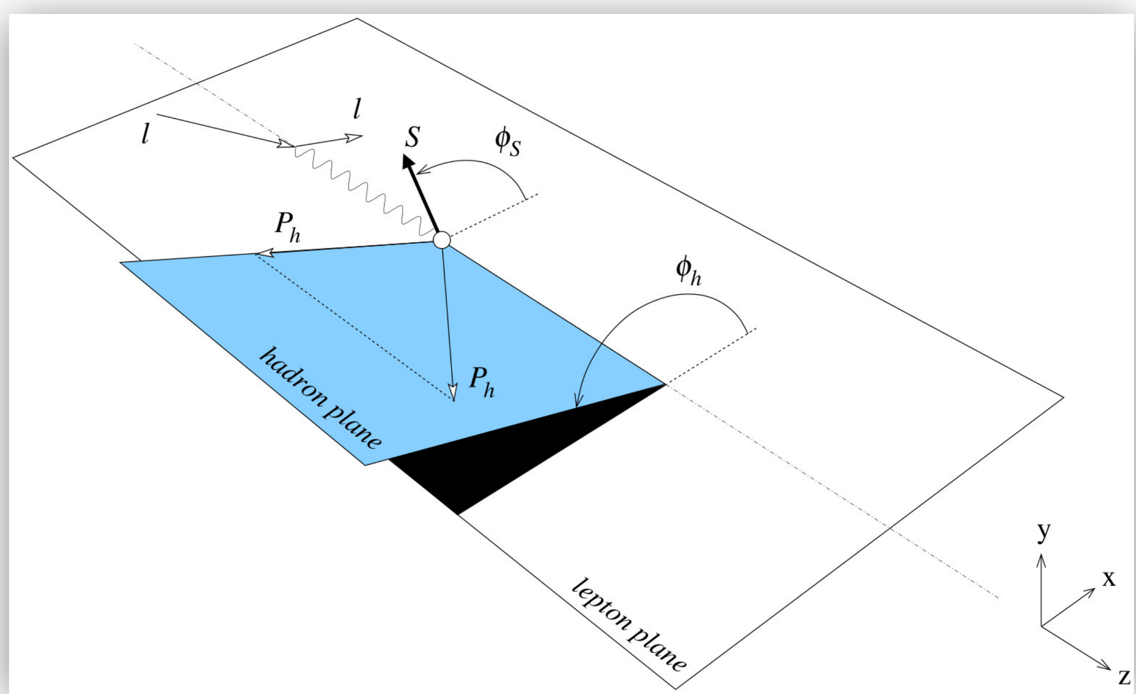
- How the polarization of the proton reflects on its internal structure in 3 dimensions?
- How the polarization of the quark **distorts** their transverse momentum?
- Do quarks with spin parallel to the proton's spin have smaller or larger transverse momentum?

HELICITY distribution

Analysis of longitudinally polarized process

SIDIS

$$\ell^{\rightleftarrows}(l) + N^{\leftrightarrows}(P) \rightarrow \ell(l') + h(P_h) + X$$



DOUBLE SPIN ASYMMETRY

$$A_1 = \frac{d\sigma^{\rightarrow\leftarrow} - d\sigma^{\rightarrow\rightarrow} + d\sigma^{\leftarrow\rightarrow} - d\sigma^{\leftarrow\leftarrow}}{d\sigma^{\rightarrow\leftarrow} + d\sigma^{\rightarrow\rightarrow} + d\sigma^{\leftarrow\rightarrow} + d\sigma^{\leftarrow\leftarrow}}$$

A. Bacchetta et al., Phys.Rev.D 70 (2004), 117504

M. Diehl and S. Sapeta, Eur. Phys. J. C 41, 515 (2005)

HELICITY distribution

TMD factorization

$$A_1(x, z, Q, |\boldsymbol{P}_{hT}|) = \frac{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{g}_1^a(x, |\boldsymbol{b}_T|^2, Q) \hat{D}_1^{a\to h}(z, |\boldsymbol{b}_T|^2, Q)}{\sum_{a=q,\bar{q}} e_a^2 \int_0^{+\infty} d|\boldsymbol{b}_T|^2 J_0\left(\frac{|\boldsymbol{b}_T||\boldsymbol{P}_{hT}|}{z}\right) \hat{f}_1^a(x, |\boldsymbol{b}_T|^2, Q) \hat{D}_1^{a\to h}(z, |\boldsymbol{b}_T|^2, Q)}$$

- Large energy scale $Q^2 \gg M^2$
- Small transverse momentum $q_T^2 \ll Q^2$

$\Rightarrow$ Experimental observables in terms of universal objects

HELICITY distribution

TMD factorization

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MAP Collaboration, Bacchetta et al., JHEP 10 (2022)

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$\Longrightarrow$ Experimental observables in terms of universal objects

HELICITY distribution

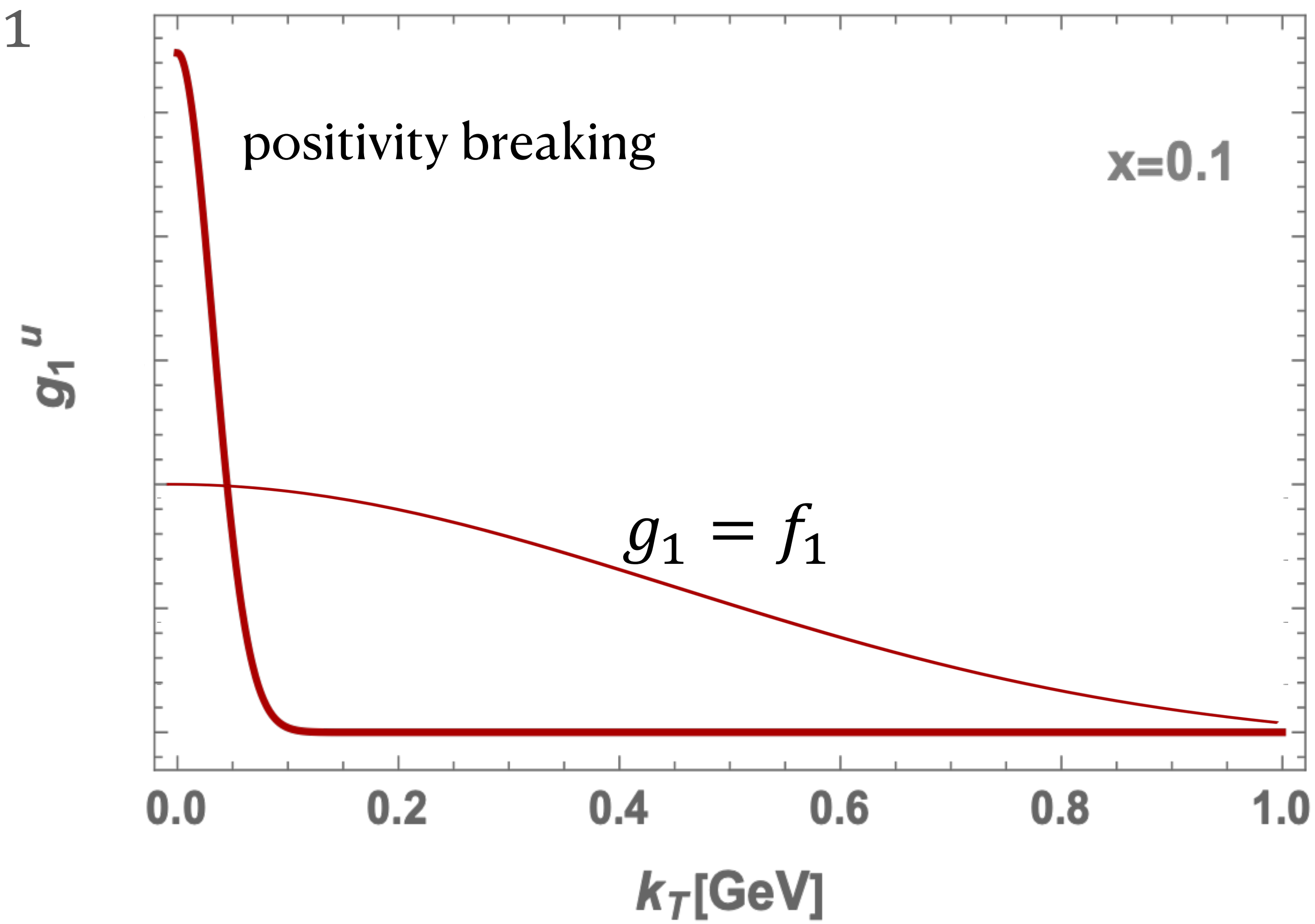
$$g_{NP}(x, \boldsymbol{k}_\perp^2, Q_0) = f_{NP}^{MAP22}(x, \boldsymbol{k}_\perp^2, Q_0) \frac{e^{-\frac{k_\perp^2}{\omega_1(x)}}}{k_{norm}(x)}$$

- Proportional to f_{NP}^{MAP22}
- x-dependent

$k_{norm}(x) \to \int d^2\boldsymbol{k}_\perp g_{NP} = 1$

$\omega_1(x) \to$ crucial to satisfy $|g_1| \le f_1$

- $\omega_1(x) \to +\infty \Leftrightarrow g_1(k_T) = f_1(k_T)$
- $\omega_1(x) \ll 1 \Leftrightarrow g_1(k_T \sim 0) > f_1(k_T \sim 0)$



HELICITY distribution

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$k_{norm}(x) \rightarrow \int d^2\boldsymbol{k}_\perp g_{NP} = 1$

$\omega_1(x) \rightarrow$ crucial to satisfy $|g_1| \leq f_1$

At $Q_0 = 1\,GeV$, the ratio g_1/f_1 reads:

$$\frac{g_1(x, \boldsymbol{k}_\perp^2, Q_0)}{f_1(x, \boldsymbol{k}_\perp^2, Q_0)} = \frac{g_1(x, Q_0)}{f_1(x, Q_0)}\, \frac{e^{-\frac{k_\perp^2}{\omega_1(x)}}}{k_{norm}(x)}$$

$$\frac{g_1(x, Q_0)}{f_1(x, Q_0)}\, \frac{1}{k_{norm}(x)} \leq 1 \longrightarrow$$

$$\omega_1(x) = f_{pos.}(x) + N_{1g}^2\, \frac{(1-x)^{\alpha_{1g}^2} x^{\sigma_{1g}}}{(1-\hat{x})^{\alpha_{1g}^2} \hat{x}^{\sigma_{1g}}}$$

HELICITY distribution

Airapetian et al. (HERMES), Phys. Rev. D (2019)

Experiment	N_{dat}	$\chi^2_{\mathrm{NLL}}/N_{\mathrm{dat}}$	$\chi^2_{\mathrm{NNLL}}/N_{\mathrm{dat}}$
HERMES ($d \to \pi^+$)	47	1.34	1.30
HERMES ($d \to \pi^-$)	47	1.10	1.08
HERMES ($d \to K^+$)	46	1.26	1.25
HERMES ($d \to K^-$)	45	0.93	0.89
HERMES ($p \to \pi^+$)	53	1.17	1.21
HERMES ($p \to \pi^-$)	53	0.86	0.86
Total	291	1.11	1.09

- MAP22 kinematic cuts
- 291 fitted data points
- Perturbative order: **NLO**

Highest possible

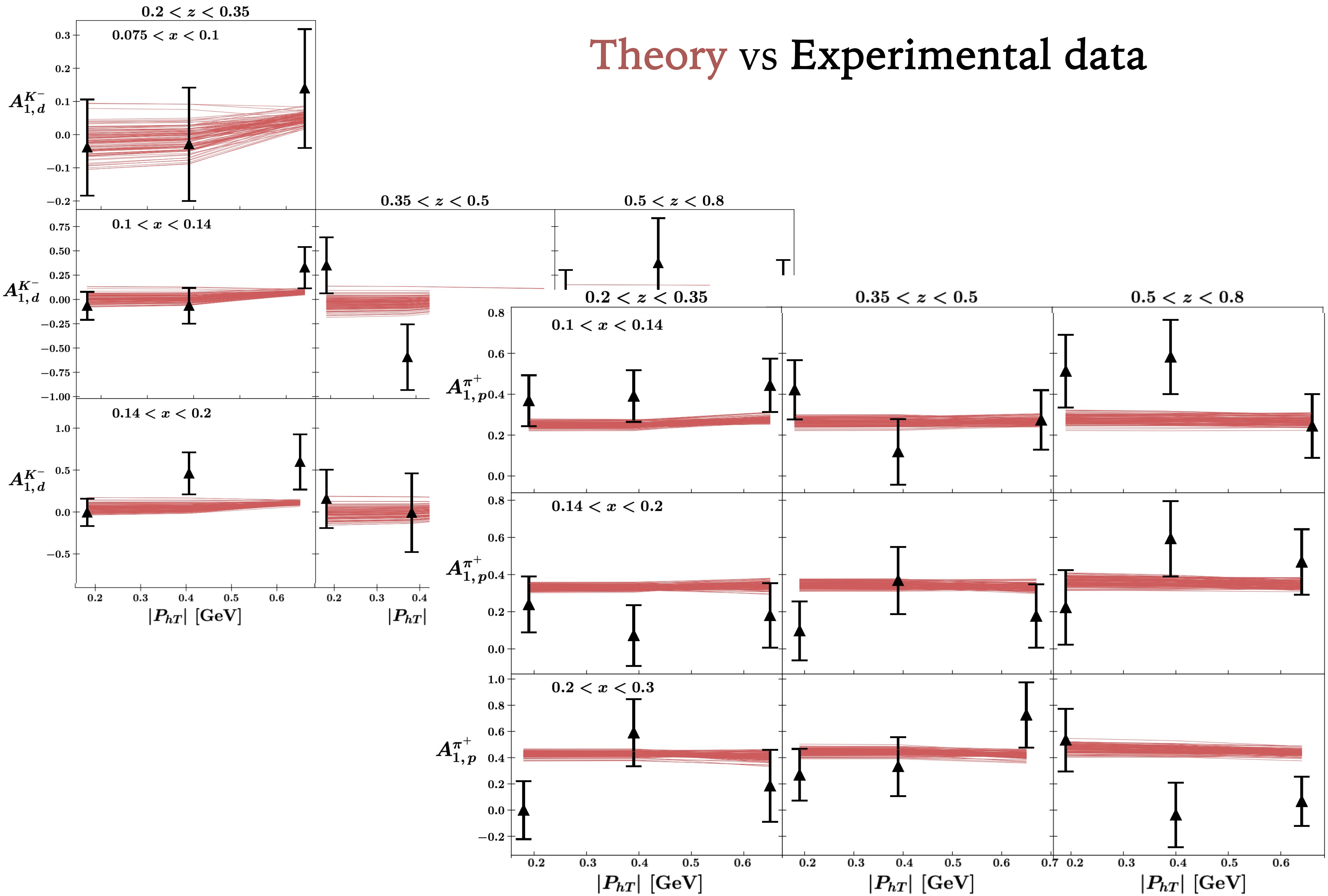
since C^g known up to NLO

Gutiérrez-Reyes et al., Phys. Lett. B (2017)

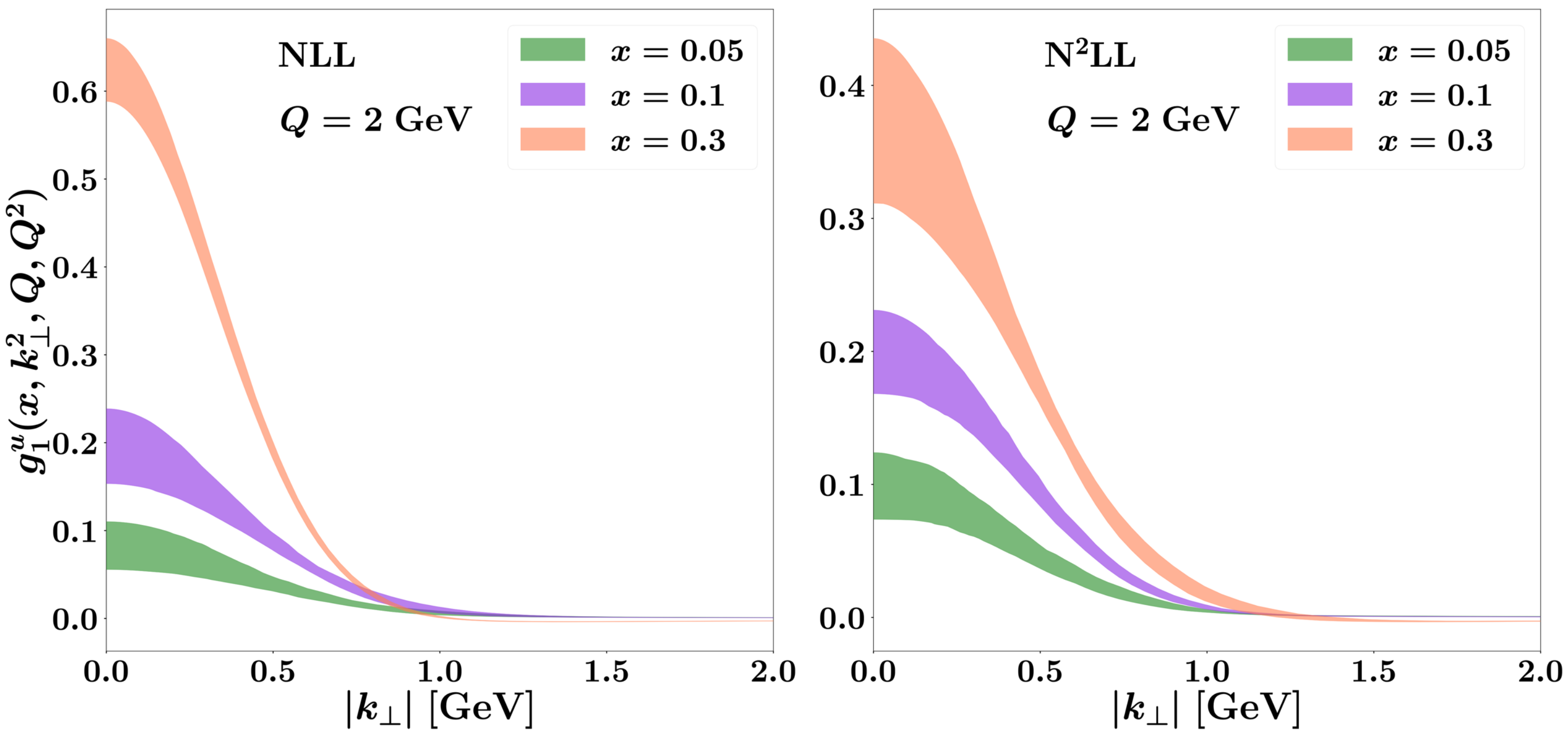
- Collinear PDFs: NNPDFPol, MMHT, DSS
- Perturbative accuracy: **NLL** & **N2LL**
- 3 fitted parameters
- Error analysis with bootstrap method

HELICITY distribution

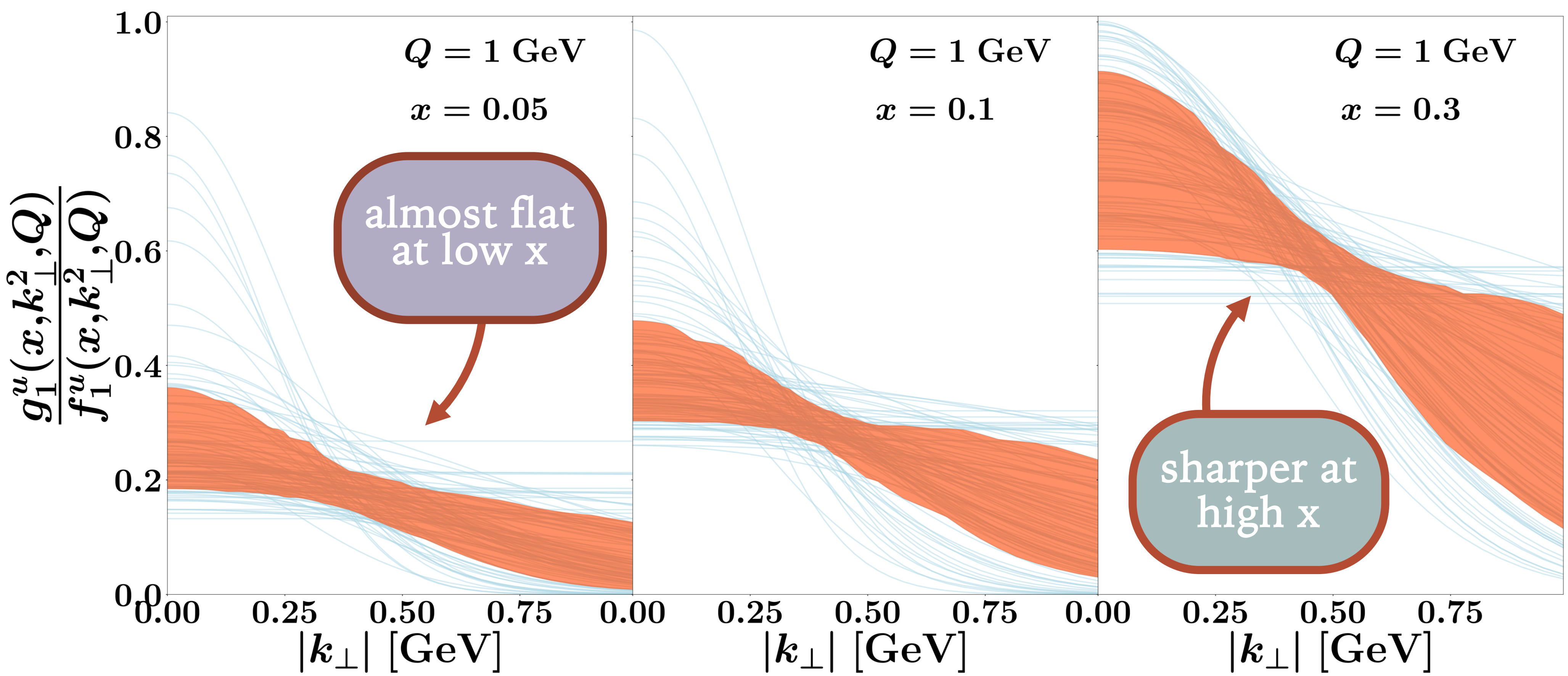
Theory vs Experimental data



HELICITY distribution

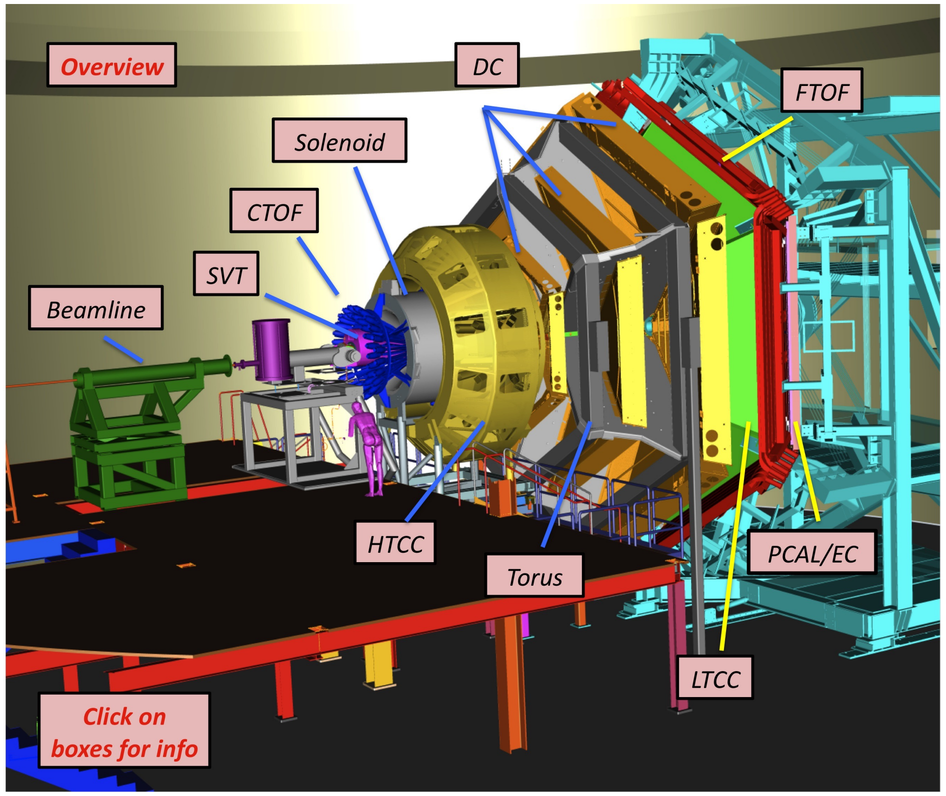


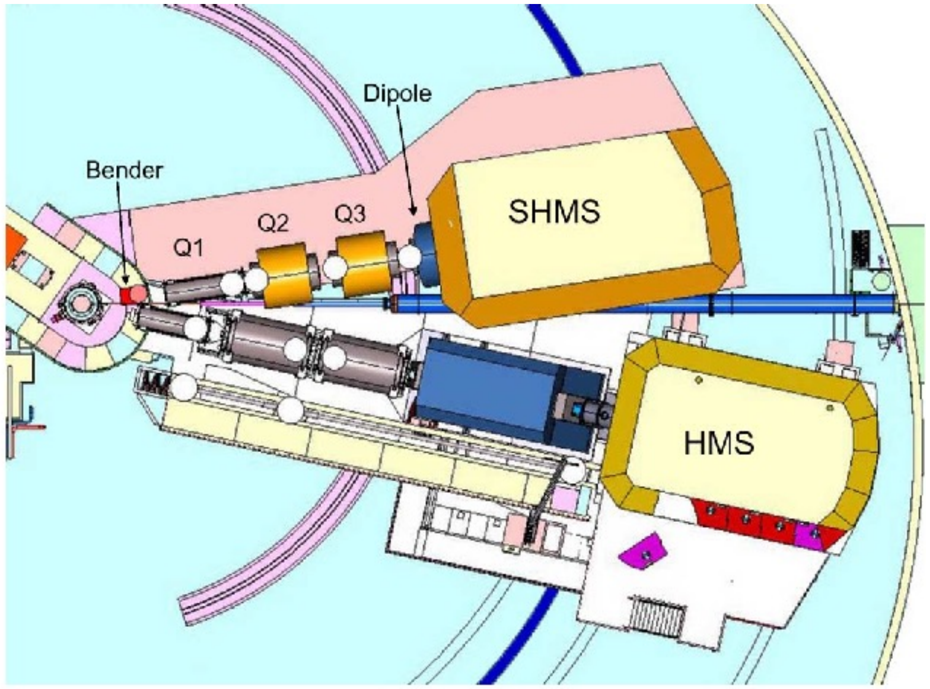
Extracted helicity TMDs



Helicity ratio

More data are needed: present





CLAS12 **Hall C**

+ SoLID (?)

New experimental data: intermediate- large-x region

small exp. errors!

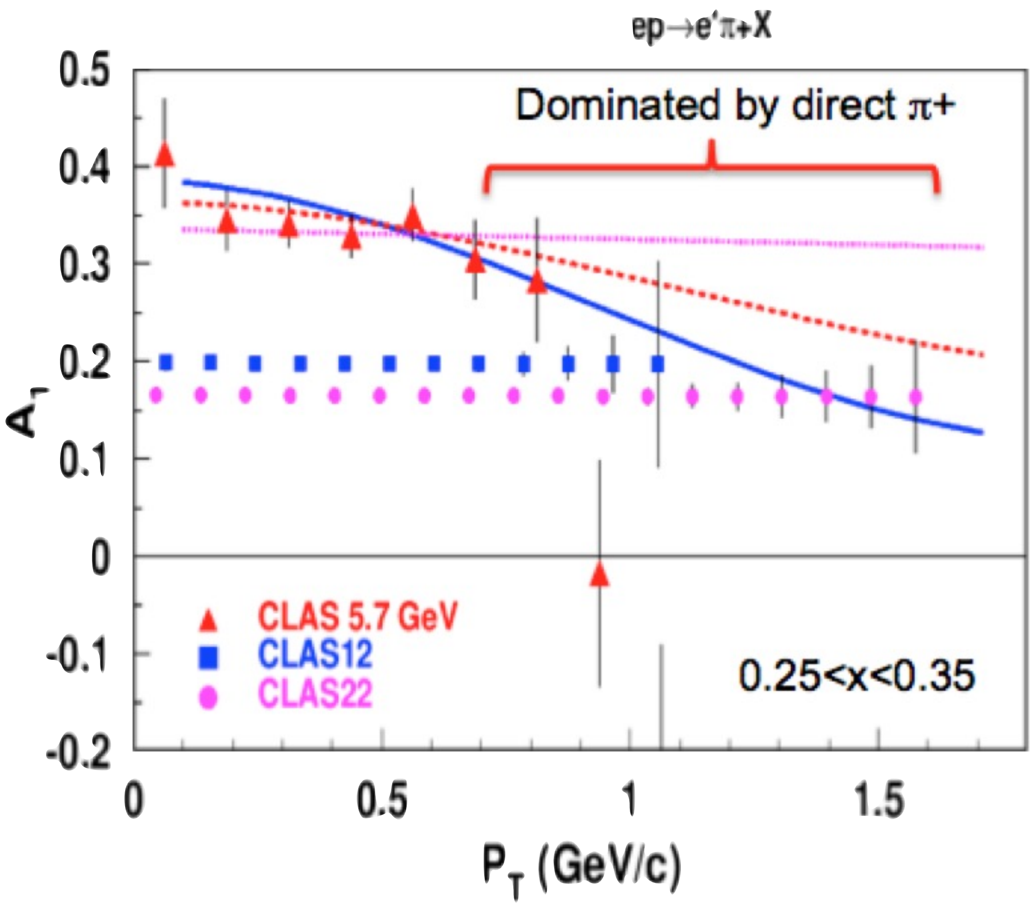
More data are needed: future

Calculation of A_1 asymmetry in JLab22 kinematics

+ study of ρ meson subtraction

see Harut's talk

A_1 asymmetry at JLab22



JLab22 white paper, Eur.Phys.J.A 60 (2024) 9, 173

Target: proton

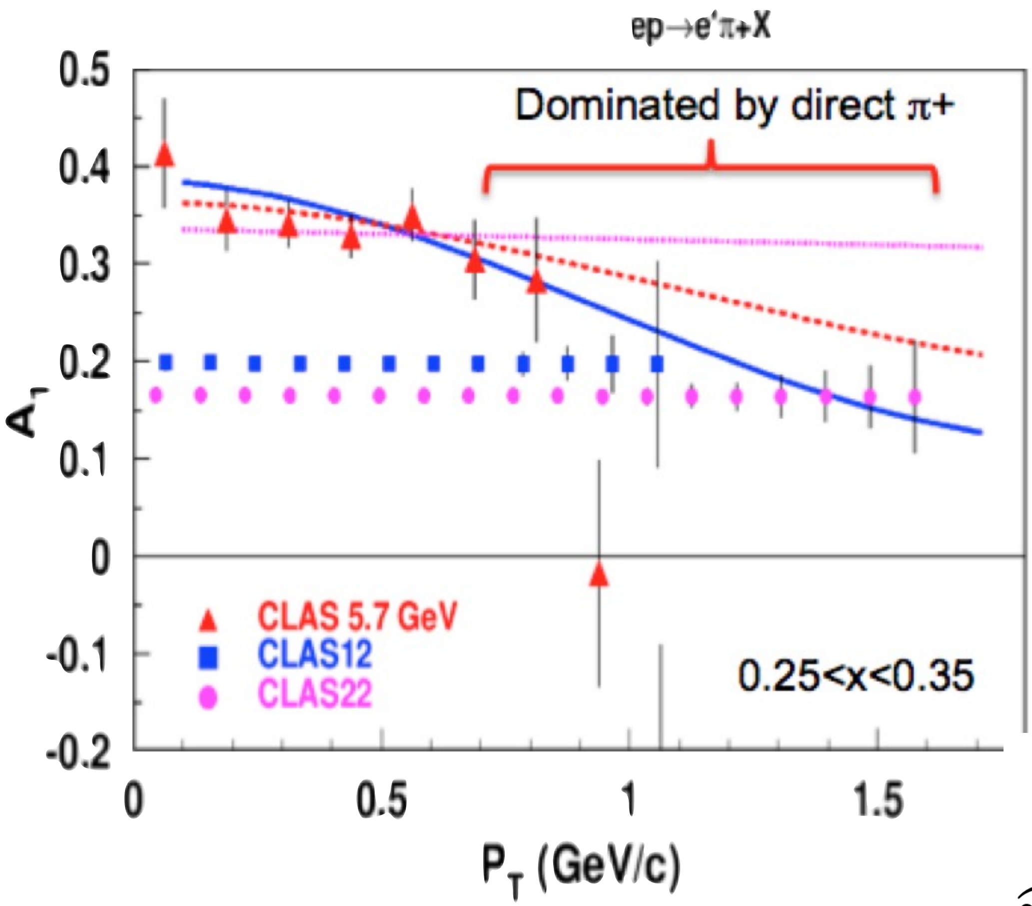
Final state: pion(-)

$x = 0.3$

$Q^2 = 4\ \mathrm{GeV}^2$

$z = 0.45$

A_1 asymmetry at JLab22



JLab22 white paper, Eur.Phys.J.A 60 (2024) 9, 173

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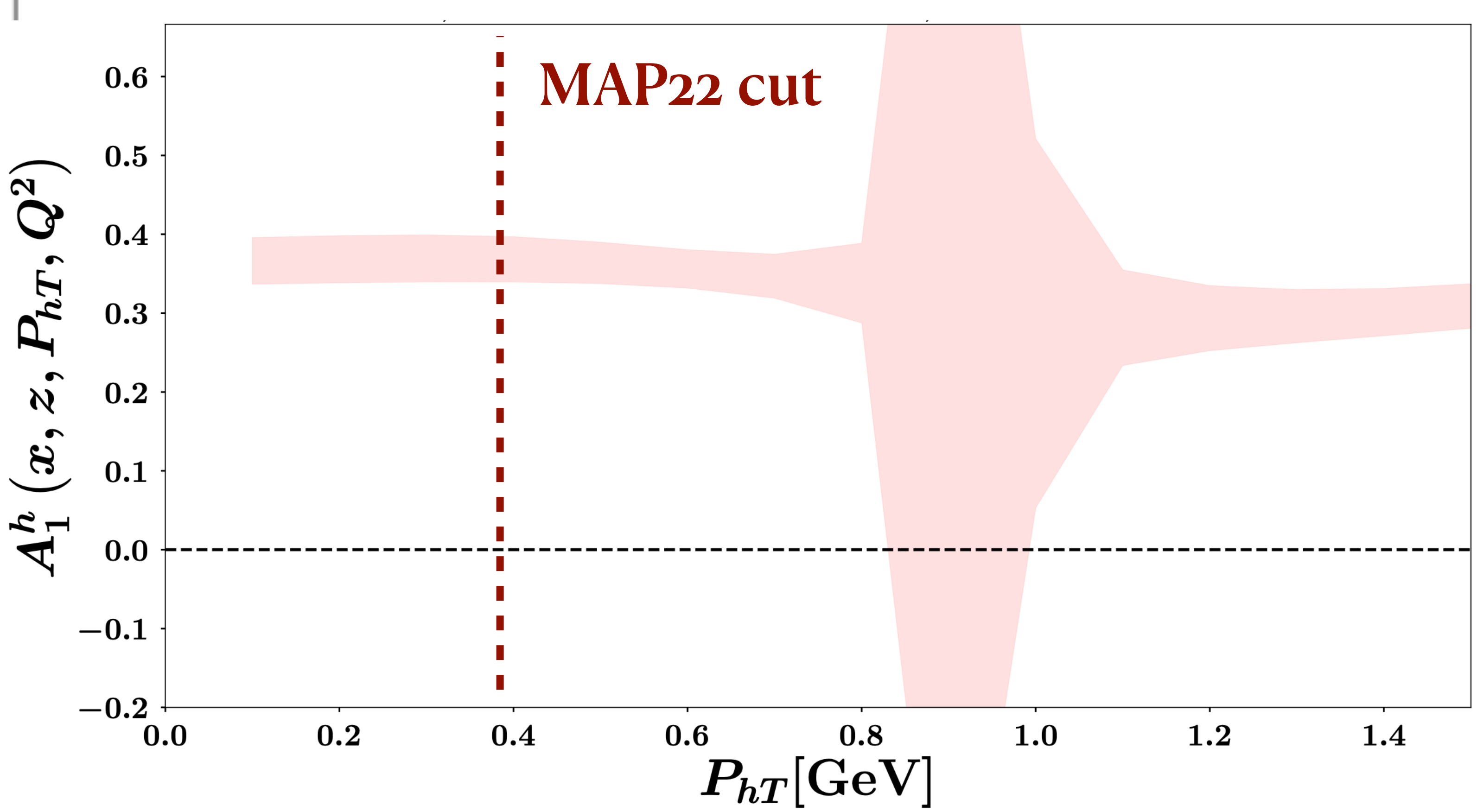
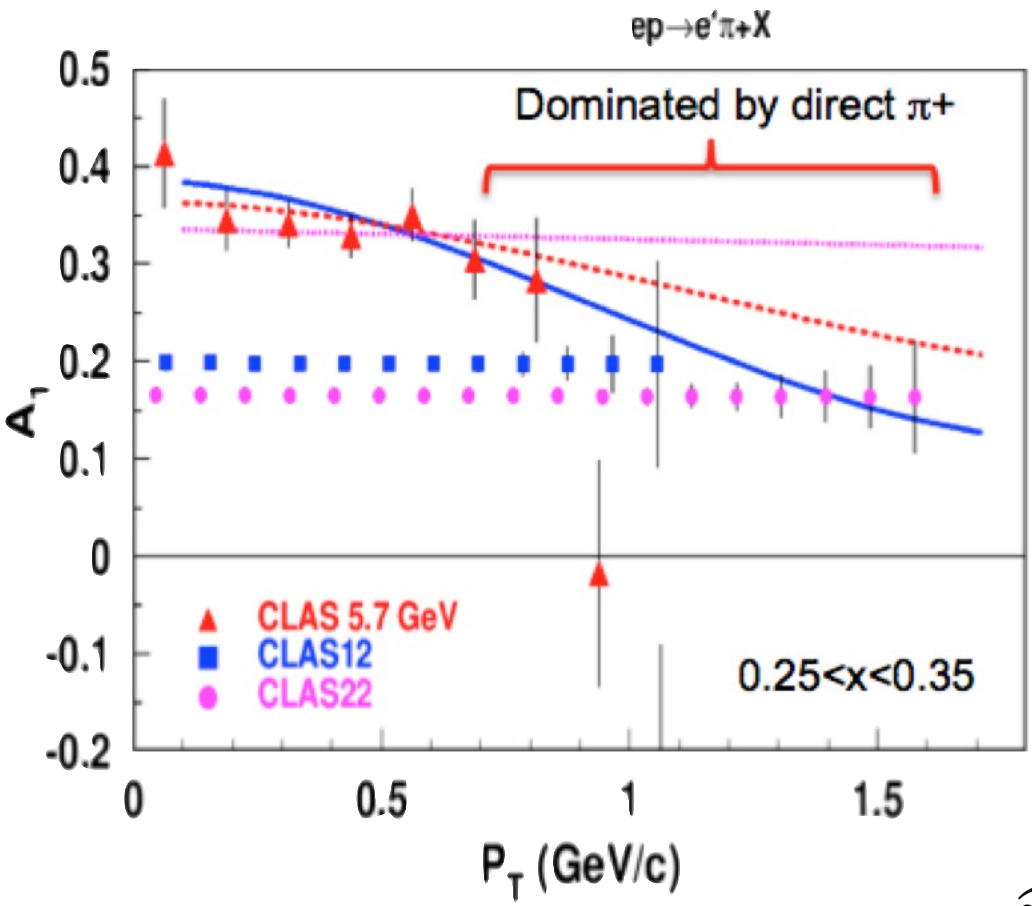
PRELIMINARY



Be careful:

- Predictions beyond MAP22 cut are not reliable (power corrections, Y-term, ...)
- unpol. W-term→ 0 at large P_{hT}

A_1 asymmetry at JLab22



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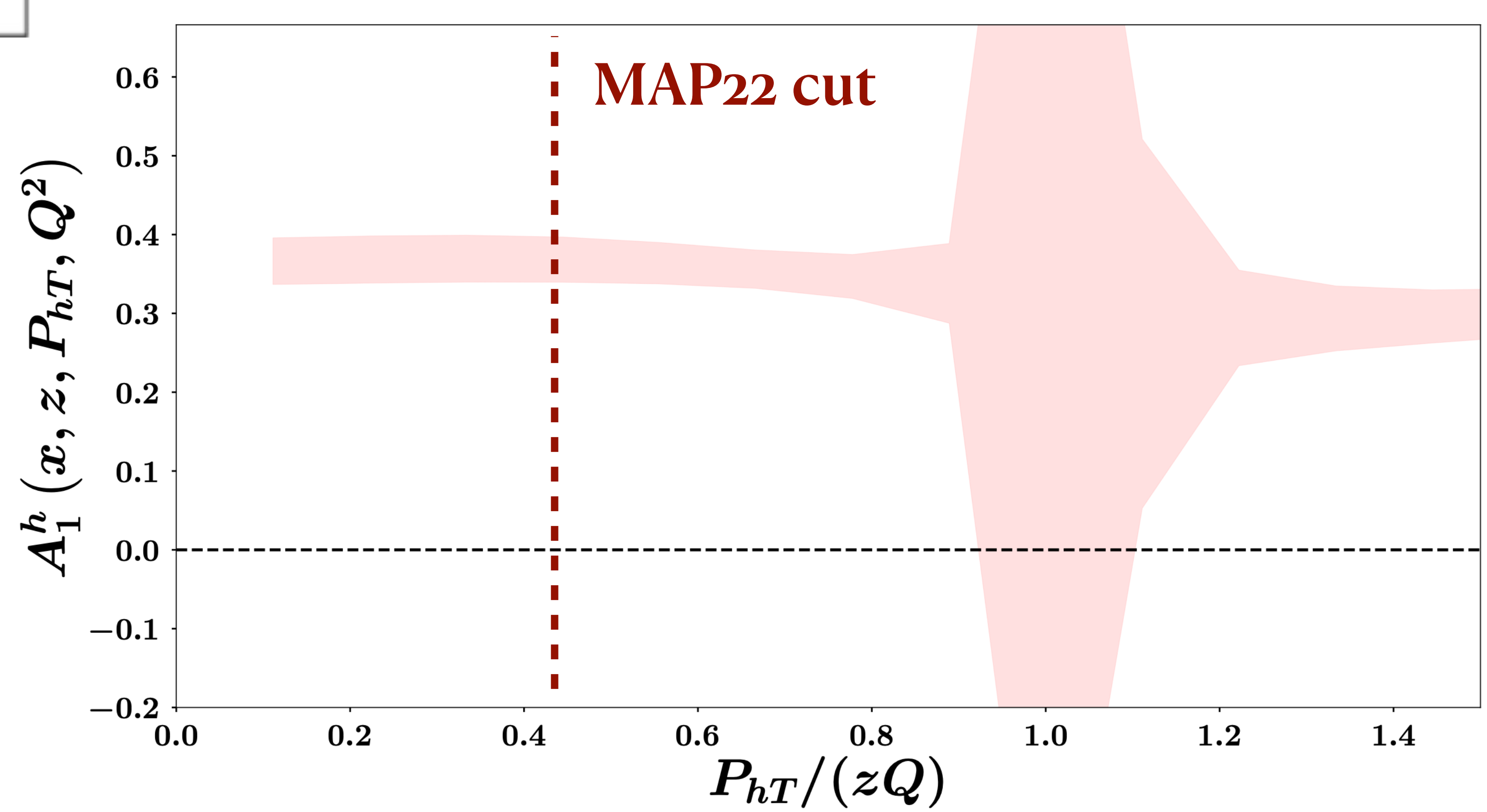
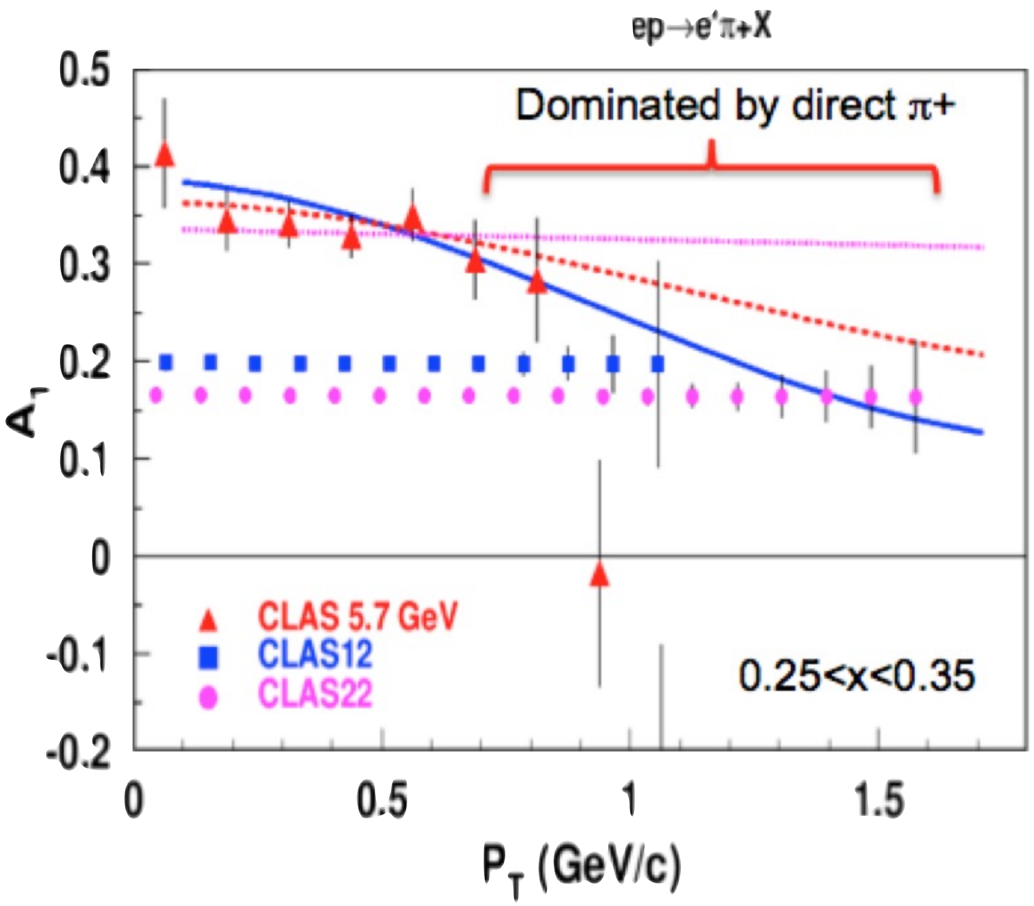
Distribution in q_T/Q

✔ $q_T^2 \ll Q^2$

PRELIMINARY



A_1 asymmetry at JLab22



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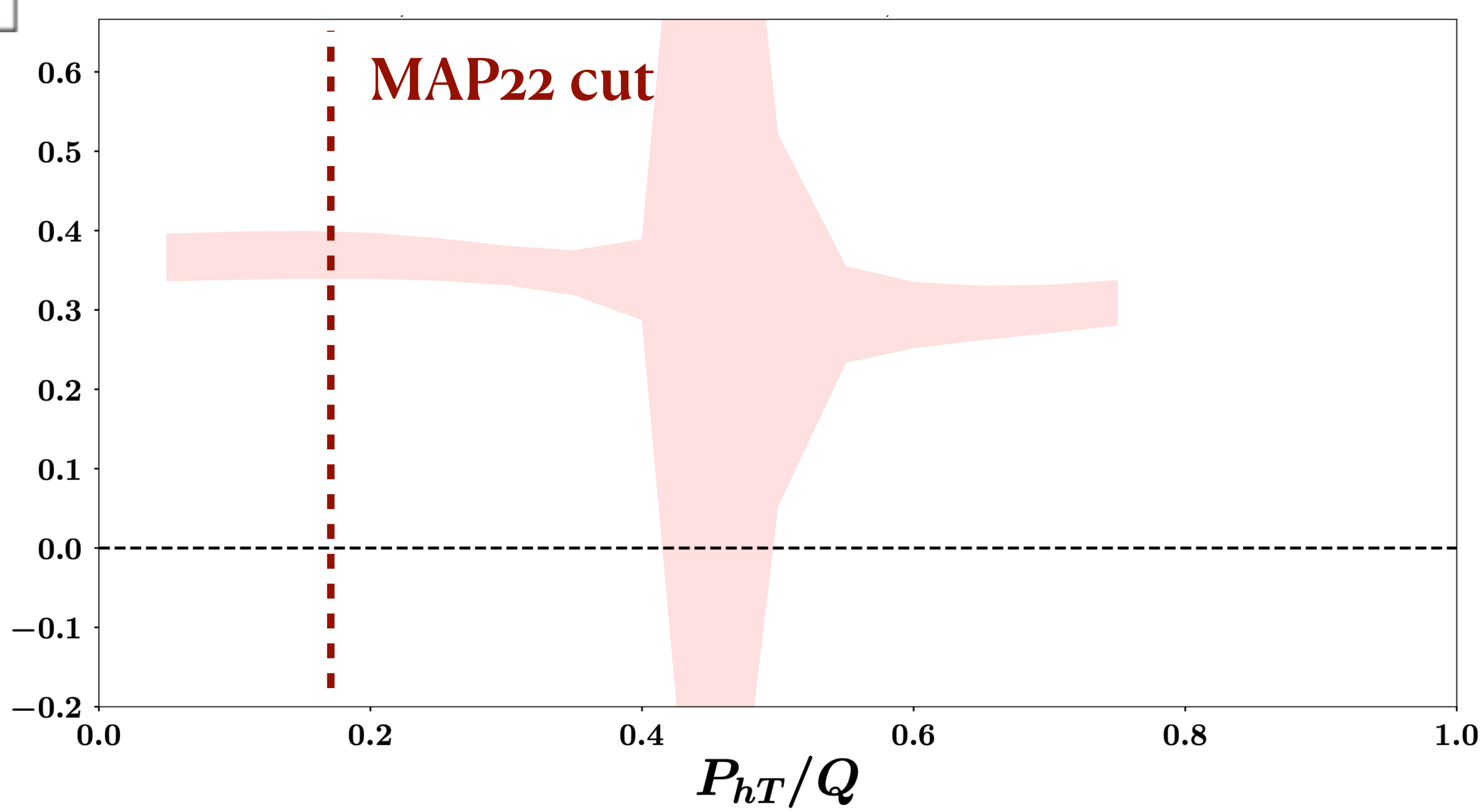


Distribution in P_{hT}/Q

pay attention to the value of z

ρ-subtraction exercise

see Harut's talk

"Effective" subtraction of ρ-meson (diffractive) contribution

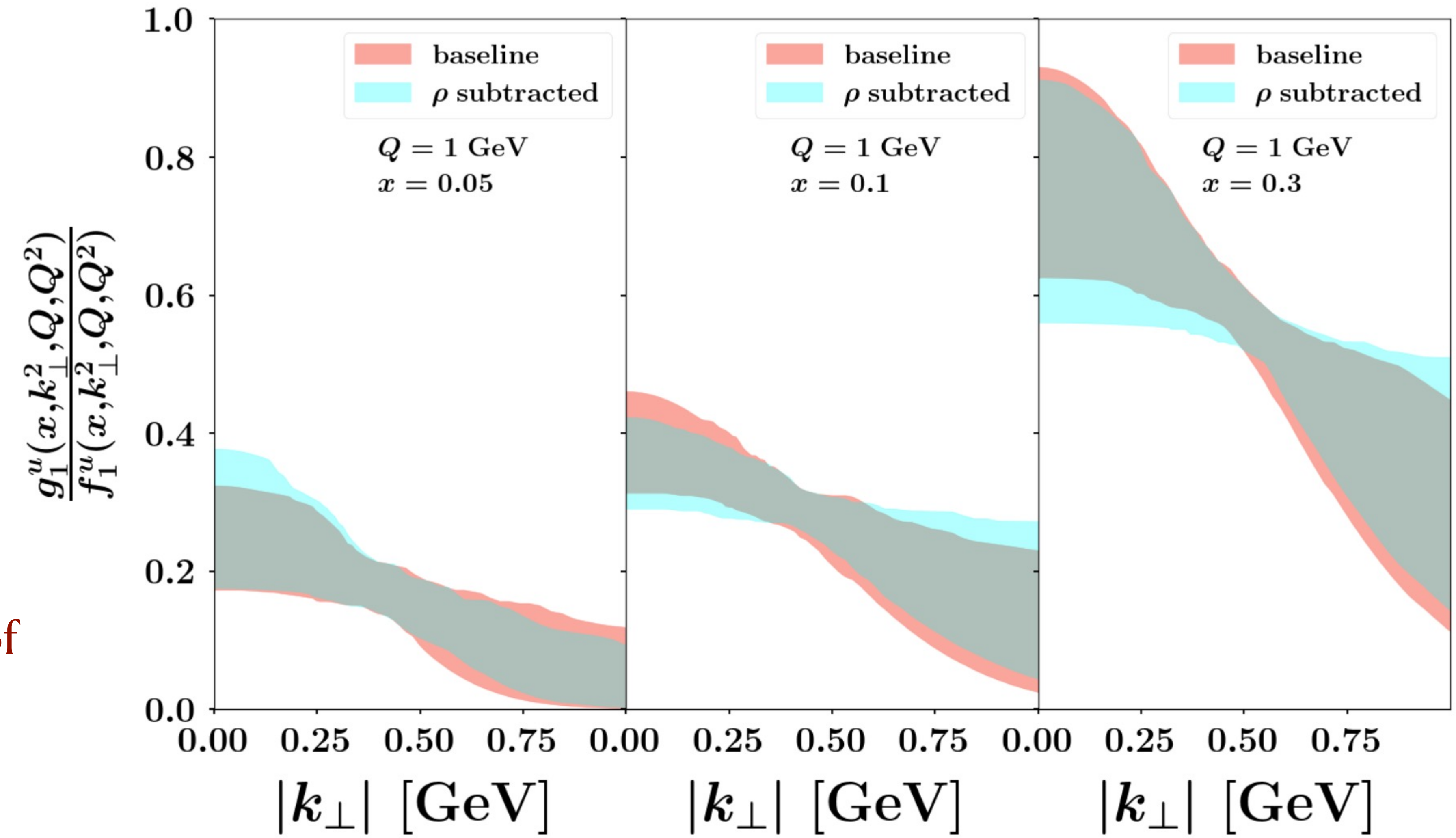
$$A_1^{\rho-sub} = \frac{A_1}{\Omega_\rho}$$

"**deRHOification**" factor $\Omega_\rho = 1 + e^{-6P_{hT}^2}$

Only for final-state π

- baseline fit (only π)
  $\chi^2/N = 1.10$
- ρ-subtracted fit
  $\chi^2/N = 1.86$
- Impact on the shape of g_1/f_1 ratio

PRELIMINARY



Conclusions and Outlook

- We can extract the **transverse momentum distribution** $g_1(x, k_\perp)$ of longitudinally polarized quarks in longitudinally polarized nucleons
- We impose to the validity of **positivity constraints** *a priori*
- Current experimental errors from HERMES are **poorly constraining** the $g_1(x, k_\perp)$
- **JLAB22**: new experimental data with (expected) high precision
  - study of the extension of MAP extraction at **larger** P_{hT}
  - study of fit "effectively" excluding **diffractive** ρ**-mesons**