TMD physics
between RHIC and JLab

Andrea Signori

RHIC & AGS
users' group meeting 2018

Brookhaven National Lab
June 12th, 2018

Jefferson Lab

Outline of the talk

1) Transverse-momentum-distributions (TMDs)

2) generalized universality

3) evolution and predictive power

4) “global” analysis of unpolarized TMDs

Most probably after this talk ...

6) impact on W production at LHC
7) gluon TMDs
8) small-x limit
9) jets, ...

Jefferson Lab

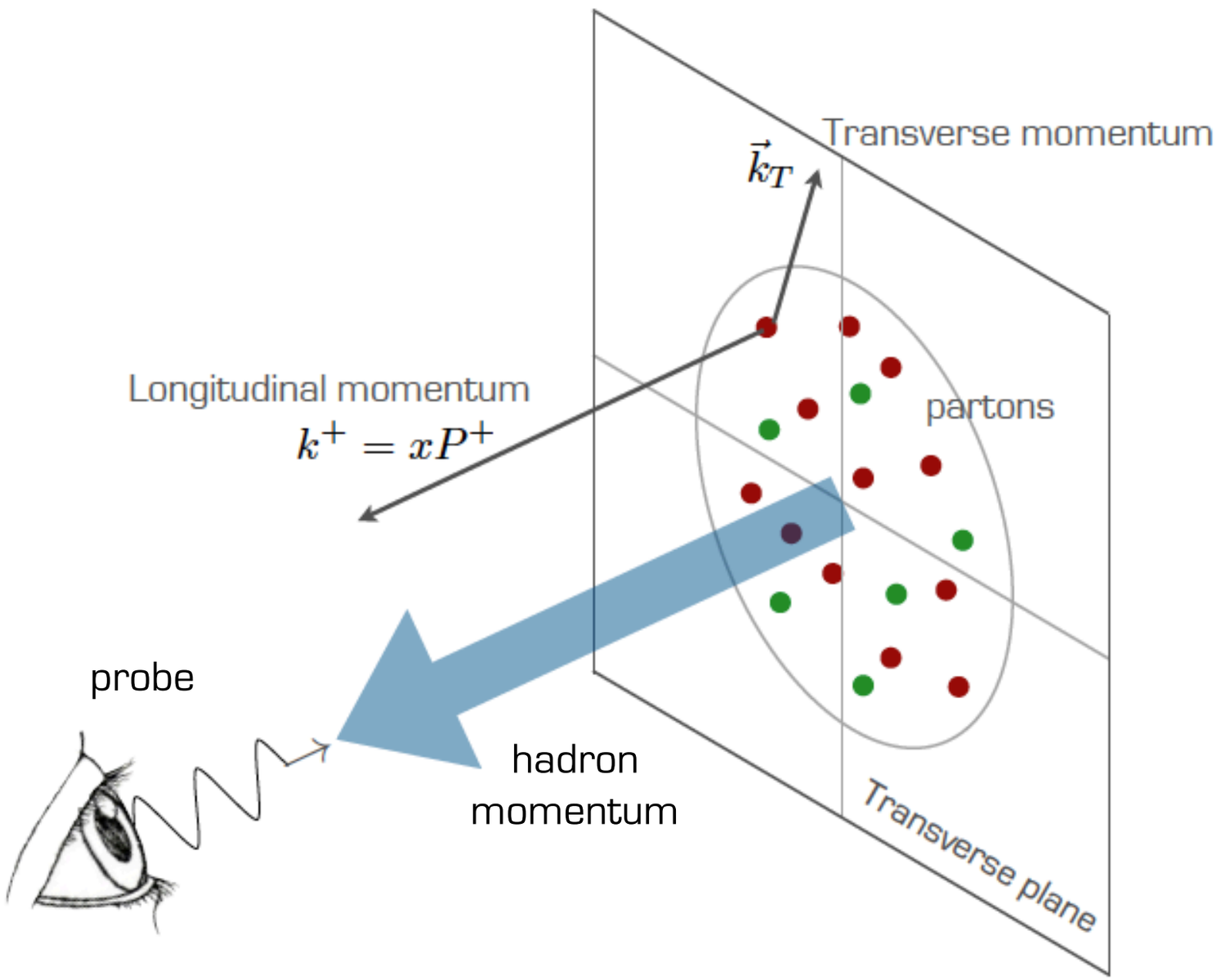
TMDs

References (intro and reviews) :

- "The 3D structure of the nucleon" **EPJ A (2016) 52**
- J.C. Collins "**Foundations of perturbative QCD**"
- material from the TMD collaboration **summer school**
- ...

Jefferson Lab

TMD PDFs



extraction of a **parton** whose momentum has **longitudinal** and **transverse components** with respect to the parent **hadron** momentum

richer structure than collinear PDFs

How are TMDs **defined** ?

courtesy A. Bacchetta

Jefferson Lab

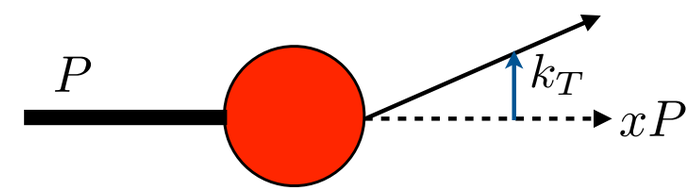
Quark TMD PDFs

$$\Phi_{ij}(k,P;S,T) \sim \text{F.T.}\ \langle PS\ \ |\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\ \ \rangle_{|LF}$$

	U	L	T
Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1},\ h_{1T}^\perp$

Sivers TMD PDF

unpolarized TMD PDF



extraction of a **quark**
not collinear with the proton

encode all the possible
spin-spin and **spin-momentum**
correlations
between the proton
and its constituents

similar table for **gluons** and for **fragmentation**

bold : also collinear
red : time-reversal odd (universality properties)

Jefferson Lab

Quark TMD PDFs

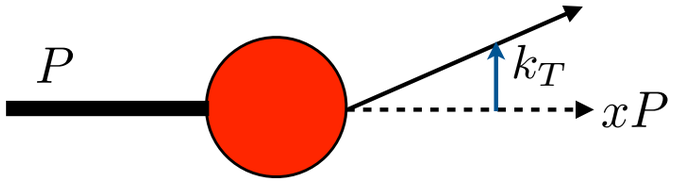
$$\Phi_{ij}(k,P;S,T) \sim \text{F.T. } \langle PST|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PST\rangle_{|LF}$$

	U	L	T
Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1}$, $h_{1T}^\perp$
LL	$\boldsymbol{f_{1LL}}$		$h_{1LL}^\perp$
LT	f_{1LT}	g_{1LT}	h_{1LT}, $h_{1LT}^\perp$
TT	f_{1TT}	g_{1TT}	h_{1TT}, $h_{1TT}^\perp$

similar table for **gluons** and for **fragmentation**

bold : also collinear

red : time-reversal odd (universality properties)



extraction of a **quark**
not collinear with the proton

encode all the possible
spin-spin and spin-momentum
correlations
between the proton
and its constituents

Jefferson Lab

Generalized universality

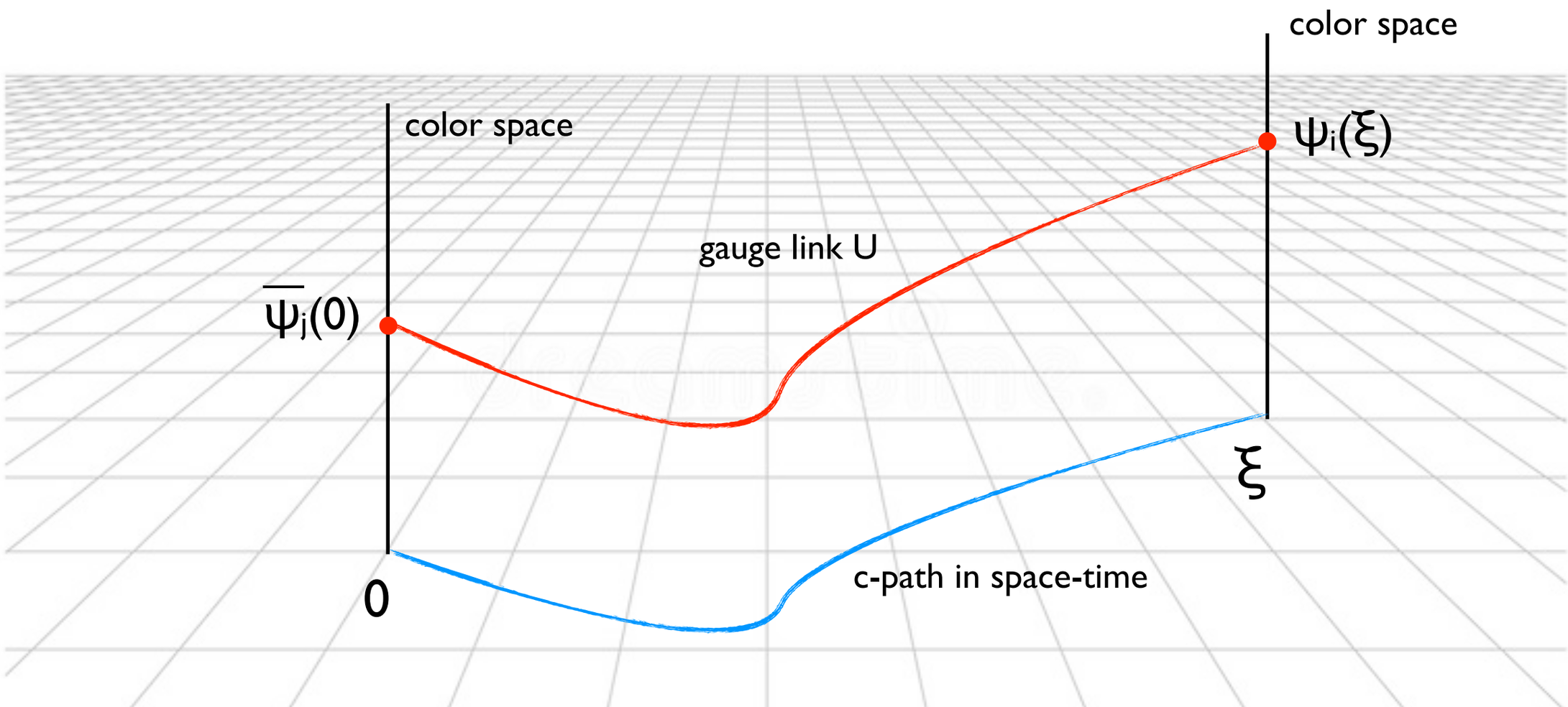
References :

- J.C. Collins "**Foundations of perturbative QCD**"
- "The 3D structure of the nucleon" **EPJ A (2016) 52**
- Aschenauer, D'Alesio, Murgia: "TMDs and SSAs in hadronic interactions" - **hep-ph/1410100**

Jefferson Lab

Distributions and correlations

$$\Phi(k,P) = \text{F.T.}\langle P|\overline{\psi_j}(0)\ U\ \psi_i(\xi)|P\rangle \longrightarrow f_1^{a\ [U]}(x,k_T^2)\ \not{P} + \cdots$$

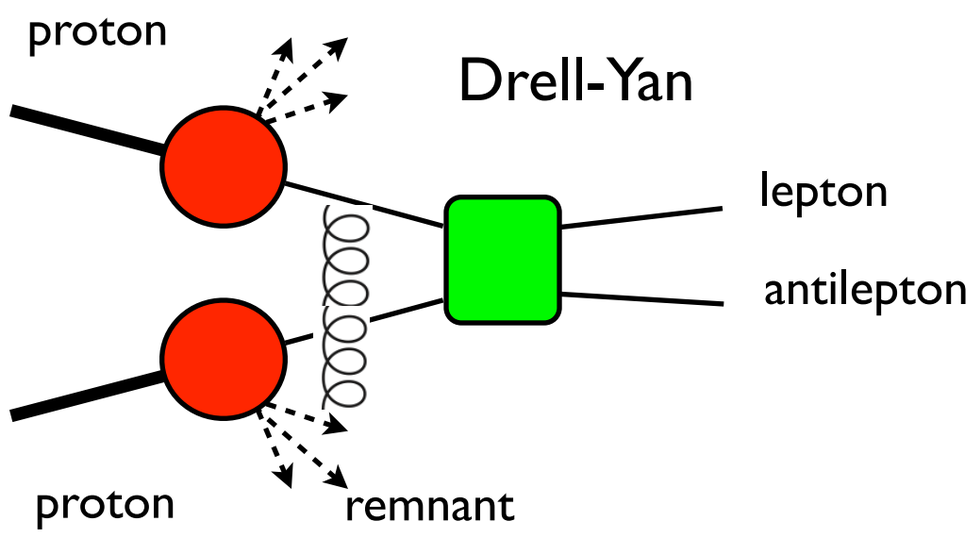


$$U(0,\xi) = \mathcal{P}\ \exp\left\{ -ig_s \int_{c(0,\xi)} ds_\mu A^{\mu a}(s) t^a \right\}$$

operator implementing the parallel transport equation for the spinor

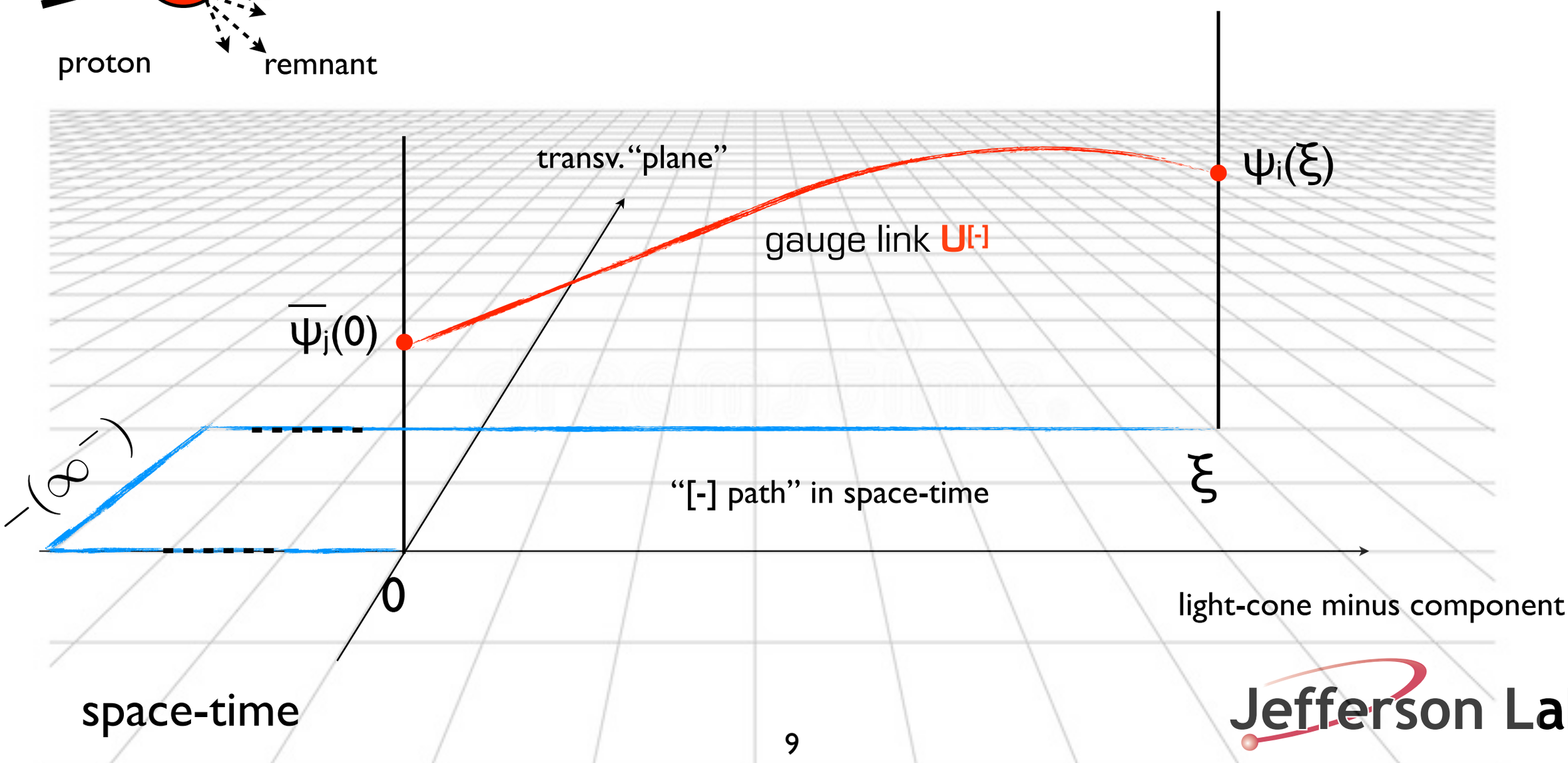
Jefferson Lab

Transverse paths



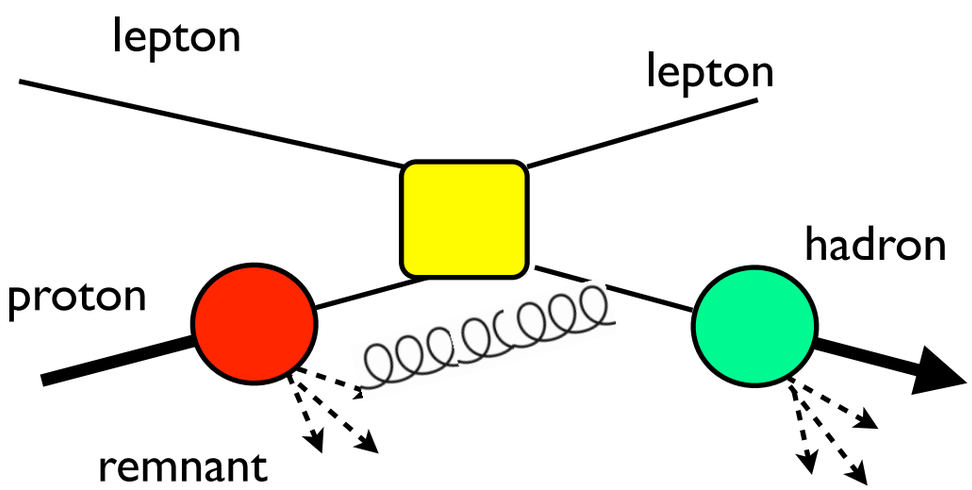
In **Drell-Yan** the **remnant** of the proton feels the color force of a **quark** in the **initial state**

$$\Phi(k,P) = \mathrm{F.T.}\langle P|\overline{\psi_j}(0)\ U^{[-]}(0,\xi)\ \psi_i(\xi)|P\rangle$$



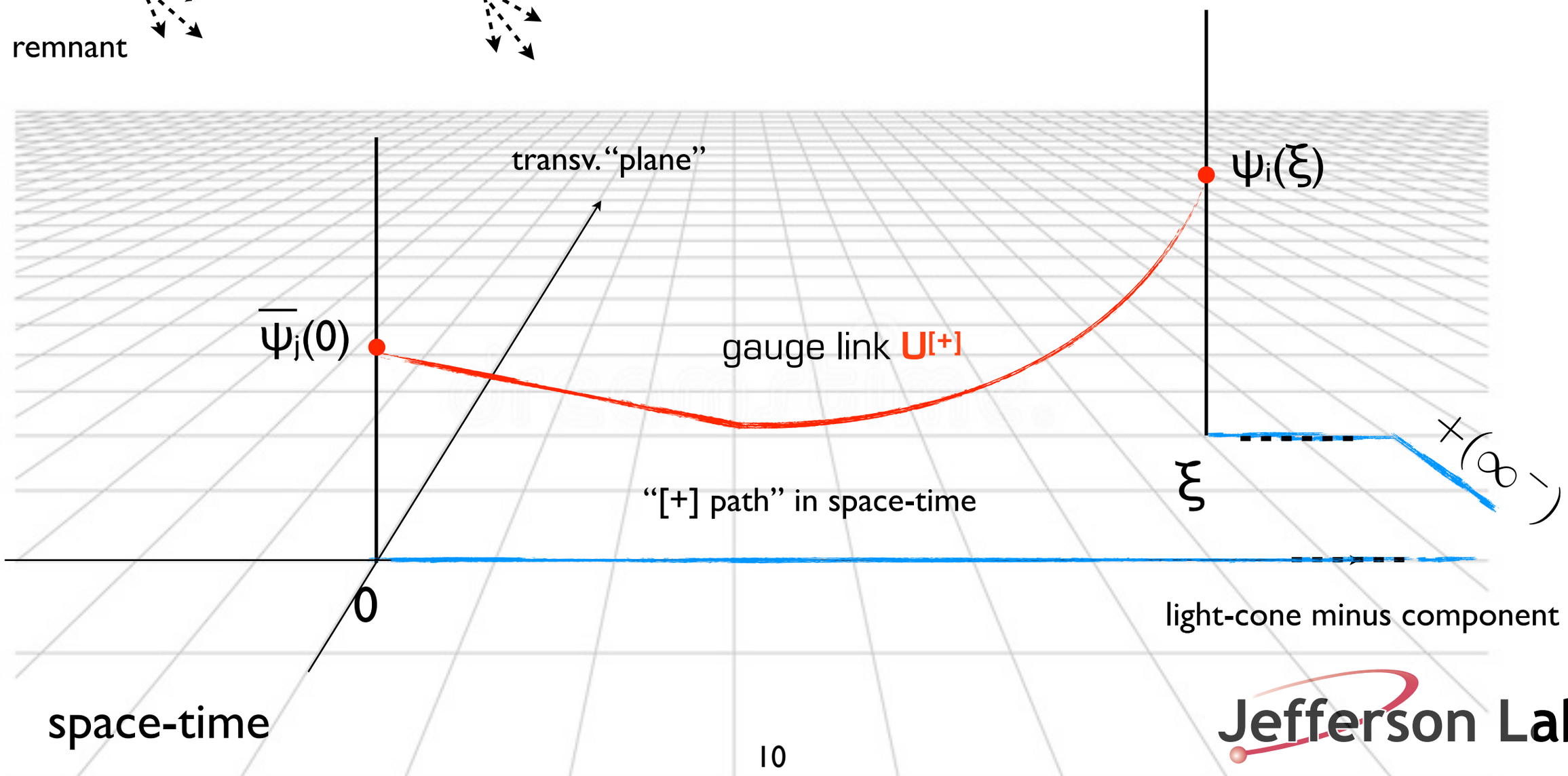
Jefferson Lab

Transverse paths



In **SIDIS** the **remnant** of the proton feels the color force of a **quark** in the **final state**

$$\Phi(k,P) = \mathrm{F.T.}\langle P|\overline{\psi_j}(0)\; U^{[+]}(0,\xi)\; \psi_i(\xi)|P\rangle$$



Generalized universality

The hard process determines the direction of the gauge link
Thus **the distributions depend on the process**

Is this a disaster ? What happens to the concept of hadron structure?
Does it become dependent on the process used to probe it?

Generalized universality

The interplay between **time-reversal** symmetry and **gauge** symmetry generates relations between the two different gauge link configurations. For example:

$$f_1^{a\ [+]}(x, k_T^2) = f_1^{a\ [-]}(x, k_T^2)$$

T-even distribution

striking consequence of the symmetries of QCD

$$f_{1T}^{a\perp\ [+]}(x, k_T^2) = -f_{1T}^{a\perp\ [-]}(x, k_T^2)$$

T-odd distribution

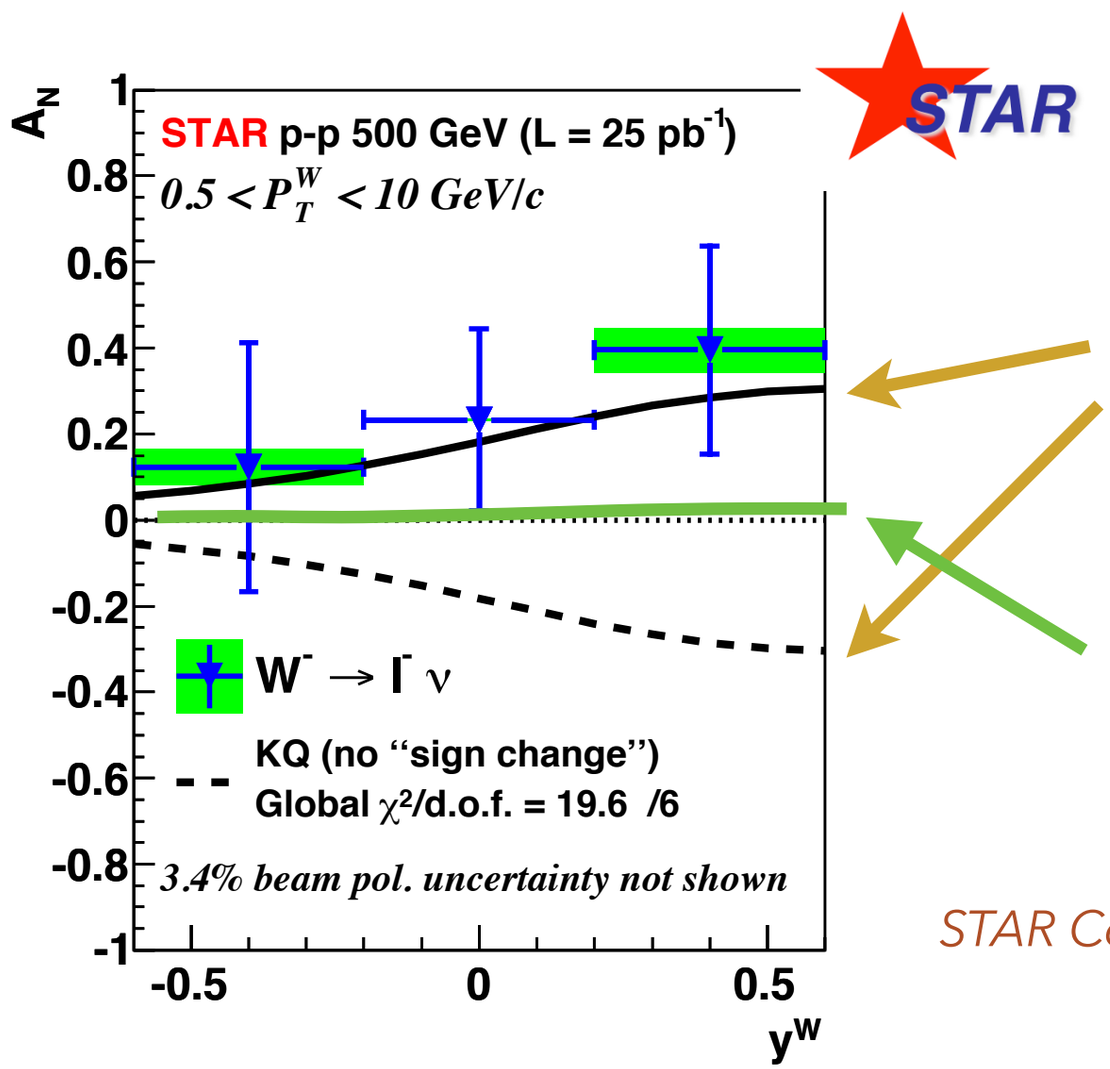
The "sign-change" relation for T-odd TMD PDFs, such as the Sivers function, is **yet to be proved experimentally.**

Jefferson Lab

Sivers - sign change test

$$f_{1T}^{a\perp\,[+]}(x,k_T^2) = -f_{1T}^{a\perp\,[-]}(x,k_T^2)$$

Collins, PLB 536 (02)



first evidence of sign change?

prediction with TMD evolution equations

STAR Collab. arXiv:1511.06003

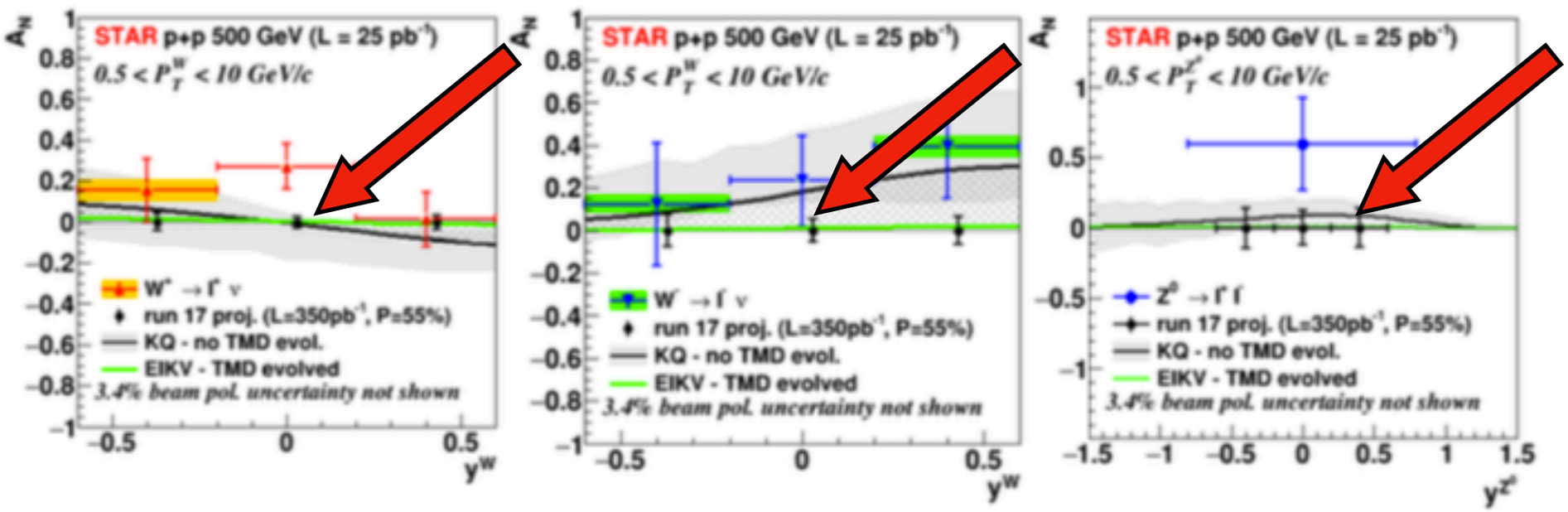
Jefferson Lab

Sivers - sign change test

Slide from O. Eyser - CIPANP 2018

- Successful completion of run 2017
  - $\sqrt{s} = 510$ GeV
  - $\mathcal{L}_{int} = 350\ \mathrm{pb}^{-1}$
  - $P_p = 55\%$

W^+, W^-, Z^0



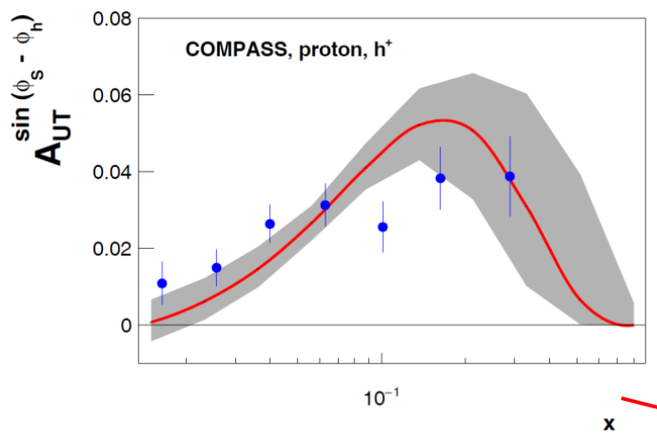
- Rigorous test of the universality of TMD spin-orbit effects
- Experimental constraint on strength of Q^2-evolution

Jefferson Lab

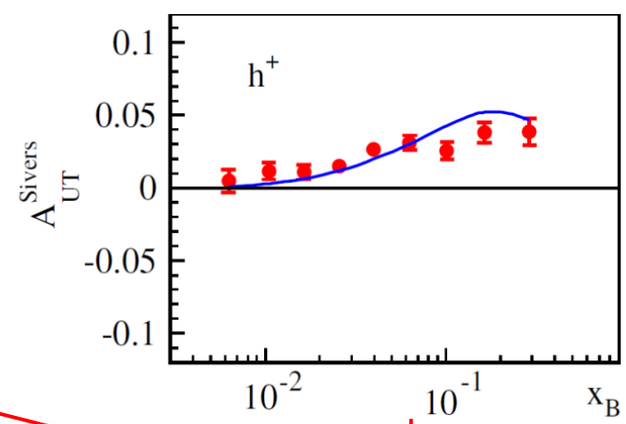
Sivers - sign change test

Sivers asymmetry in Semi-Inclusive DIS

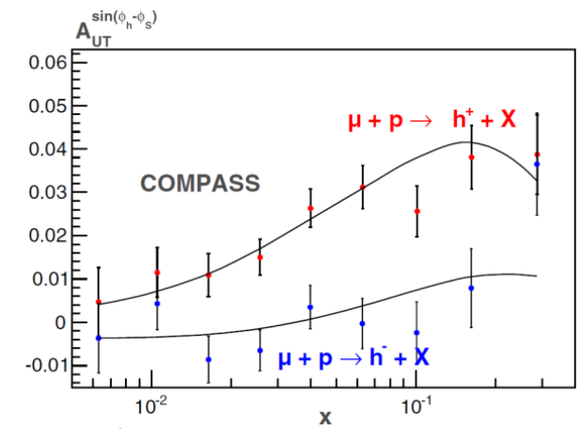
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



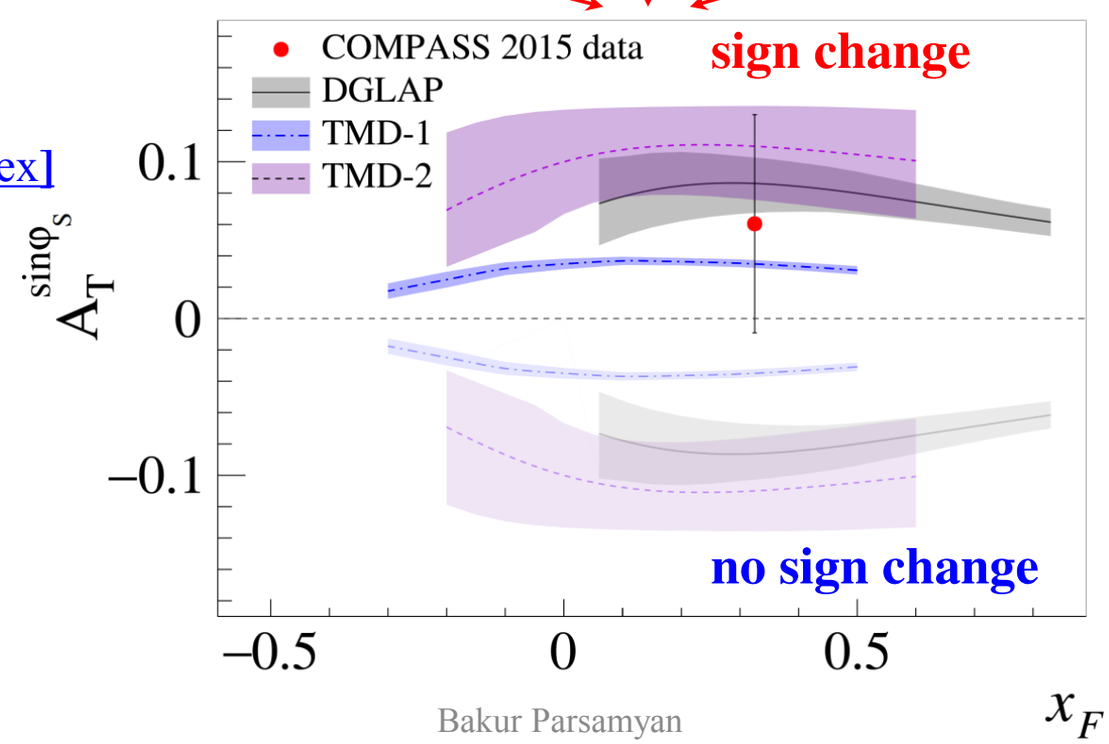
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



New! 03 April 2017
COMPASS
CERN-EP-2017-059
arXiv:1704.00488[hep-ex]

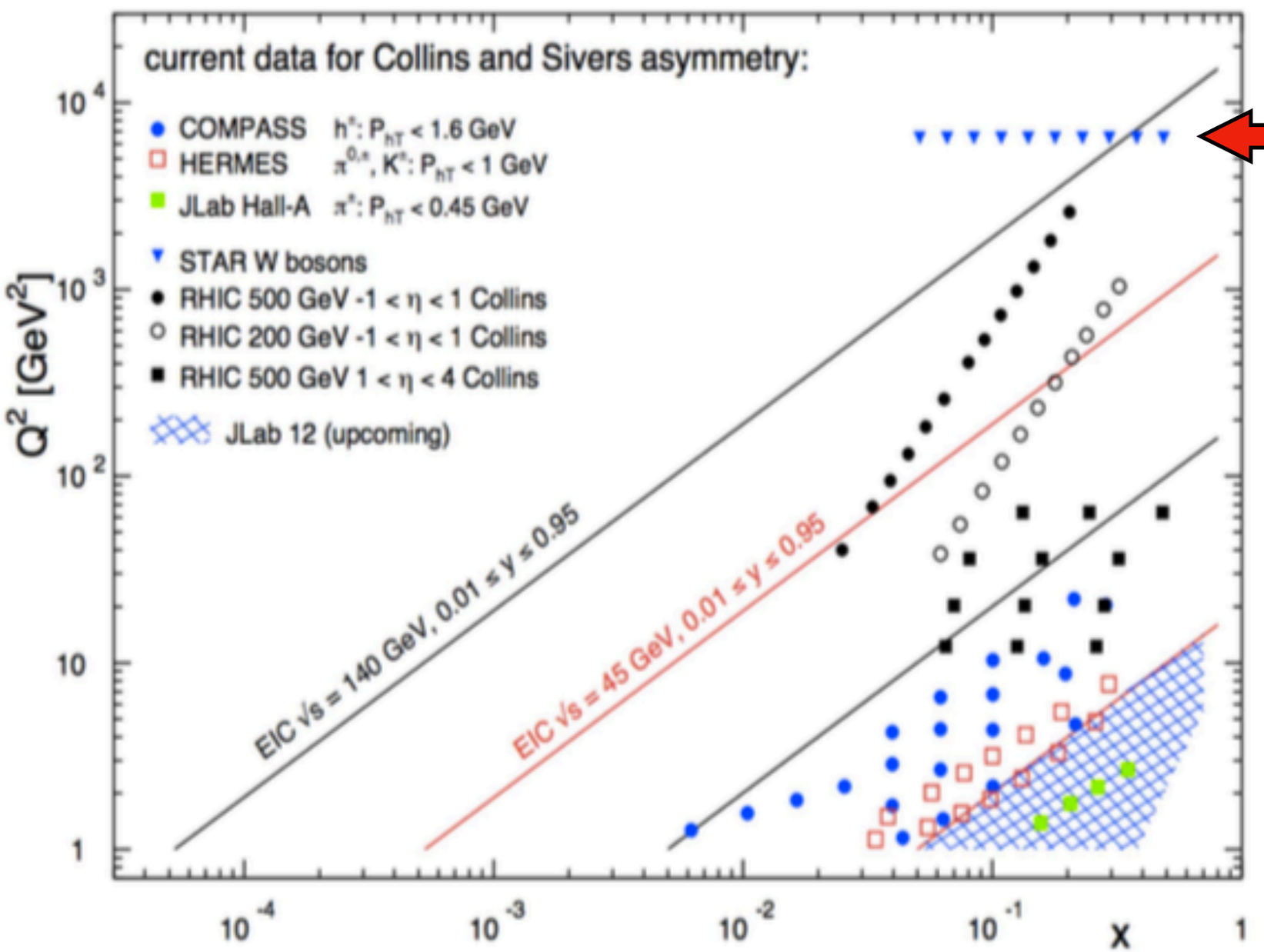


Sivers asymmetry in Drell-Yan

courtesy B. Parsamyan

n Lab

Kinematic coverage



STAR - W boson

Picture from O. Eyser - CIPANP 2018

Jefferson Lab

Evolution & predictive power

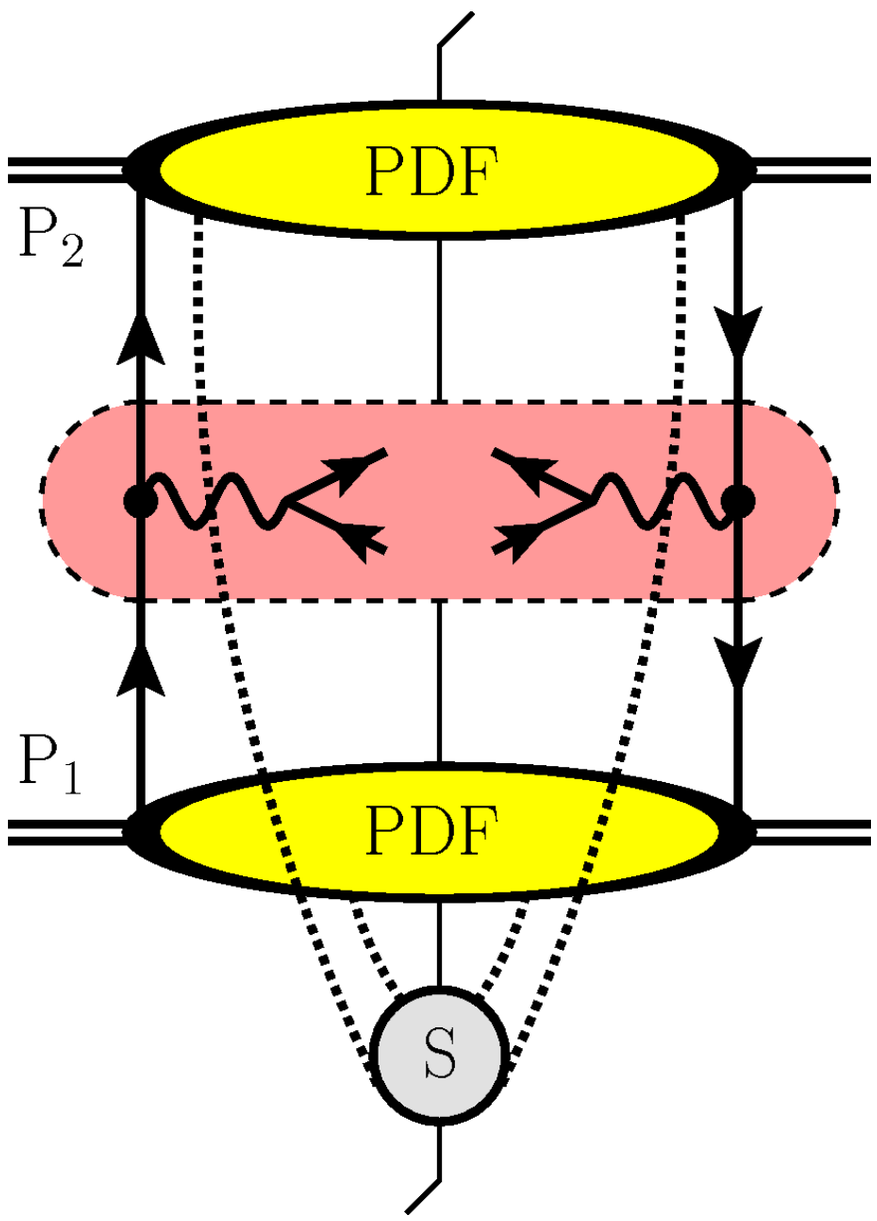
References :

- J.C. Collins "**Foundations of perturbative QCD**"
- Parisi, Petronzio: Nucl. Phys. B154, 427 (1979)
- Collins, Soper, Sterman: Nucl. Phys. B250, 199 (1985)
- Qiu, Berger: Phys. Rev. Lett. 91, 222003 (2003)
- Grewal, Kang, Qiu, **AS**: in preparation

Jefferson Lab

Factorization and evolution

$p\ p \to \ell\ \bar{\ell}\ X$



credit picture: M. Buffing

In certain processes
the cross section can be **factorized**
in contributions characterized by a specific
scaling of the momenta

$$d\sigma \sim \mathcal{H}\ f_1^{bare}\ f_1^{bare}\ \mathcal{S}$$
$$\sim \mathcal{H}\ f_1\ f_1$$

renormalized TMD PDF :

IR div. : long-distance physics
UV div. and **rapidity div.** cancelled
by UV-renormalization and soft factor S

$$f_1(x, k_T^2; \mu, \zeta)$$

Evolution with respect to two scales

Jefferson Lab

Evolution of TMDs

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$

b_T, Fourier conjugate of k_T

two "evolution scales"

$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$

evolution in mu
$\mu_i \to \mu_f$

$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i)}$$

evolution in zeta
$\zeta_i \to \zeta_f$

Input TMD distribution can be **expanded at low bT** onto a basis of collinear distributions

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i)$$

A sensible choice is to set the initial and final scale as:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$
$$\zeta_f = \mu_f^2 = Q^2$$

Jefferson Lab

Evolution of TMDs

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$

b_T, Fourier conjugate of k_T

two "evolution scales"

$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$

evolution in mu
$\mu_i \to \mu_f$

$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i) - g_K(b_T, \{\lambda\})}$$

evolution in zeta
$\zeta_i \to \zeta_f$

need corrections at large bT

Nonperturbative parts defined as
"**observed minus calculable**"

Input TMD distribution can be **expanded at low bT** onto a basis of collinear distributions

$$f_1^a(x, b_T^2, \mu_i, \zeta_i) = \sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i) \; F_{NP}^a(x, b_T; \{\lambda\})$$

A sensible choice is to set the initial and final scale as:

$$\zeta_i = \mu_i^2 = 4e^{-2\gamma_E}/b_T^2 \equiv \mu_b^2$$
$$\zeta_f = \mu_f^2 = Q^2$$

Jefferson Lab

Evolution of TMDs

electron-positron
(Bes-III - Belle-II)
$Q = 3.82\ \mathrm{GeV}$ $Q = 10\ \mathrm{GeV}$

W production
(RHIC, Tevatron, LHC)
$Q = 80.385\ \mathrm{GeV}$

SIDIS @ Compass
$Q \in [1, 3.2]\ \mathrm{GeV}$

p-Cu Drell-Yan
(E288, E605 @ Tevatron)
$Q \in [4, 18]\ \mathrm{GeV}$

SIDIS **@ JLab12** **Data sets and QCD evolution**

$Q = 1.55\ \mathrm{GeV}$
SIDIS @ Hermes

quarkonium production
(LHC, AFTER@LHC, ...)
(e.g.: $\eta_{b,c},\ J/\Psi(+\gamma),\ \mathrm{etc.}$ **)**
$\eta_b \quad Q = 9.39\ \mathrm{GeV}$

$Q = 91.187\ \mathrm{GeV}$
Z production
(RHIC, Tevatron, LHC)

Evolution of TMDs

$$f_1^a(x, b_T^2; Q) = \begin{cases} f_1^a(x, b_T^2; Q) & b_T \leq b_{max} \\ f_1^a(x, b_{max}^2; Q) F^{NP}(x, b_T, Q; b_{max}) & b_T > b_{max} \end{cases}$$

Calculable in pQCD (modulo PDFs)

To be modeled and fit to data!

Which one is the most **relevant** part and in which **kinematic region**?

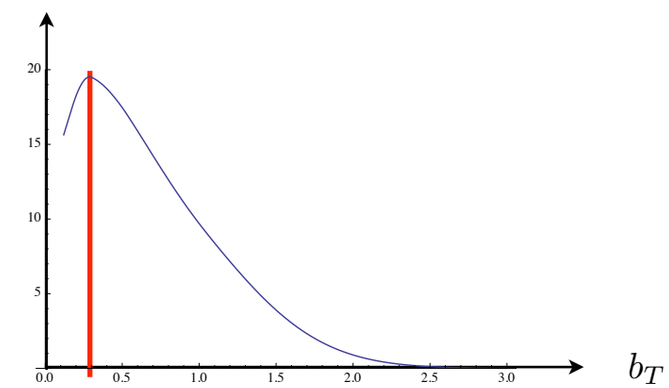
Jefferson Lab

Saddle point approximation

Given a generic function $f \in C^2(a,b)$ and a positive constant A

Given x_0, maximum in (a,b) for f :

$$I(x_0, A) = \int_a^b dx\ e^{Af(x)} = e^{Af(x_0)} \sqrt{\frac{2\pi}{A(-f''(x_0))}} \left(1 + \mathcal{O}\left(\frac{1}{A}\right)\right)$$



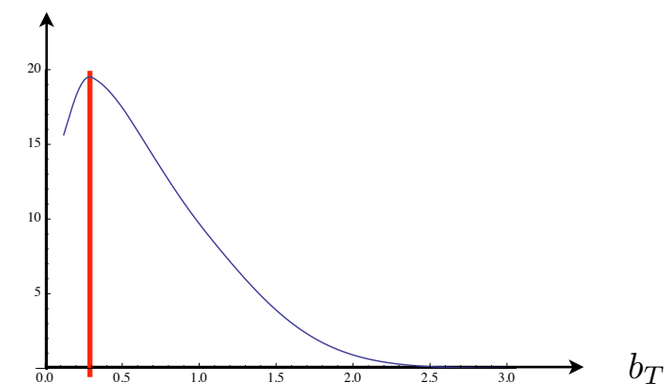
Jefferson Lab

Saddle point approximation

Given a generic function $f \in C^2(a,b)$ and a positive constant A

Given x_0, maximum in (a,b) for f :

$$I(x_0, A) = \int_a^b dx\ e^{Af(x)} = e^{Af(x_0)} \sqrt{\frac{2\pi}{A(-f''(x_0))}} \left(1 + \mathcal{O}\left(\frac{1}{A}\right)\right)$$



Let's apply this to a TMD PDF evaluated at kT = 0:

$$f_1^a(x, k_T; \mu_f, \zeta_f) = \mathrm{F.T.}\left[f_1^a(x, b_T; \mu_f, \zeta_f)\right]$$

$$f_1^a(x, k_T = 0; \mu_f, \zeta_f) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} d(\ln b_T^2) \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F\left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T, \mu_i) \ln \frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b} \otimes f_b\right]\right\}$$

To determine the **saddle point bTsp of the TMD PDF** we have to find the **stationary point of the exponent**

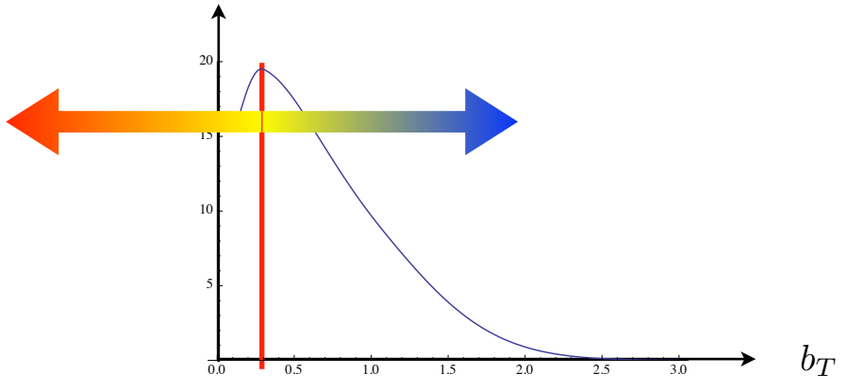
Jefferson Lab

Saddle point approximation

Given a generic function $f \in C^2(a,b)$ and a positive constant A

Given x_0, maximum in (a,b) for f :

$$I(x_0, A) = \int_a^b dx\ e^{Af(x)} = e^{Af(x_0)} \sqrt{\frac{2\pi}{A(-f''(x_0))}} \left(1 + \mathcal{O}\left(\frac{1}{A}\right)\right)$$



Let's apply this to a TMD PDF evaluated at kT = 0:

$$f_1^a(x, k_T; \mu_f, \zeta_f) = \mathrm{F.T.}\left[f_1^a(x, b_T; \mu_f, \zeta_f)\right]$$

$$f_1^a(x, k_T = 0; \mu_f, \zeta_f) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} d(\ln b_T^2) \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F\left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2}\right] - K(b_T, \mu_i) \ln \frac{\zeta_f}{\zeta_i} + \ln b_T^2 + \ln\left[\sum_b C_{a/b} \otimes f_b\right]\right\}$$

To determine the **saddle point bTsp of the TMD PDF** we have to find the **stationary point of the exponent**

Jefferson Lab

Determination of the saddle point

$$\frac{d}{db_T}\left\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]\right.$$
$$-K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$
$$+\ln b_T^2$$
$$\left.+\ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\right\}_{b_T=b_T^{sp}}=0$$

Generate the **Q-dependence** of the saddle point

Generate the **x-dependence** of the saddle point (new term)

Working at O(α) + LL we can find the following solution :

$$b_T^{sp}=\frac{c}{\Lambda}\left(\frac{Q}{\Lambda}\right)^{-\Gamma_1^{\rm cusp}/\left[\Gamma_1^{\rm cusp}+8\pi b_0\left(1-\mathcal{X}(x,\mu_b^\star)\right)\right]}$$

$$\mathcal{X}(x,\mu)=\frac{d}{d\ln\mu^2}\ln f_a(x,\mu)$$

$$\mu_b^\star=2e^{-\gamma_E}/b_T^{sp}$$

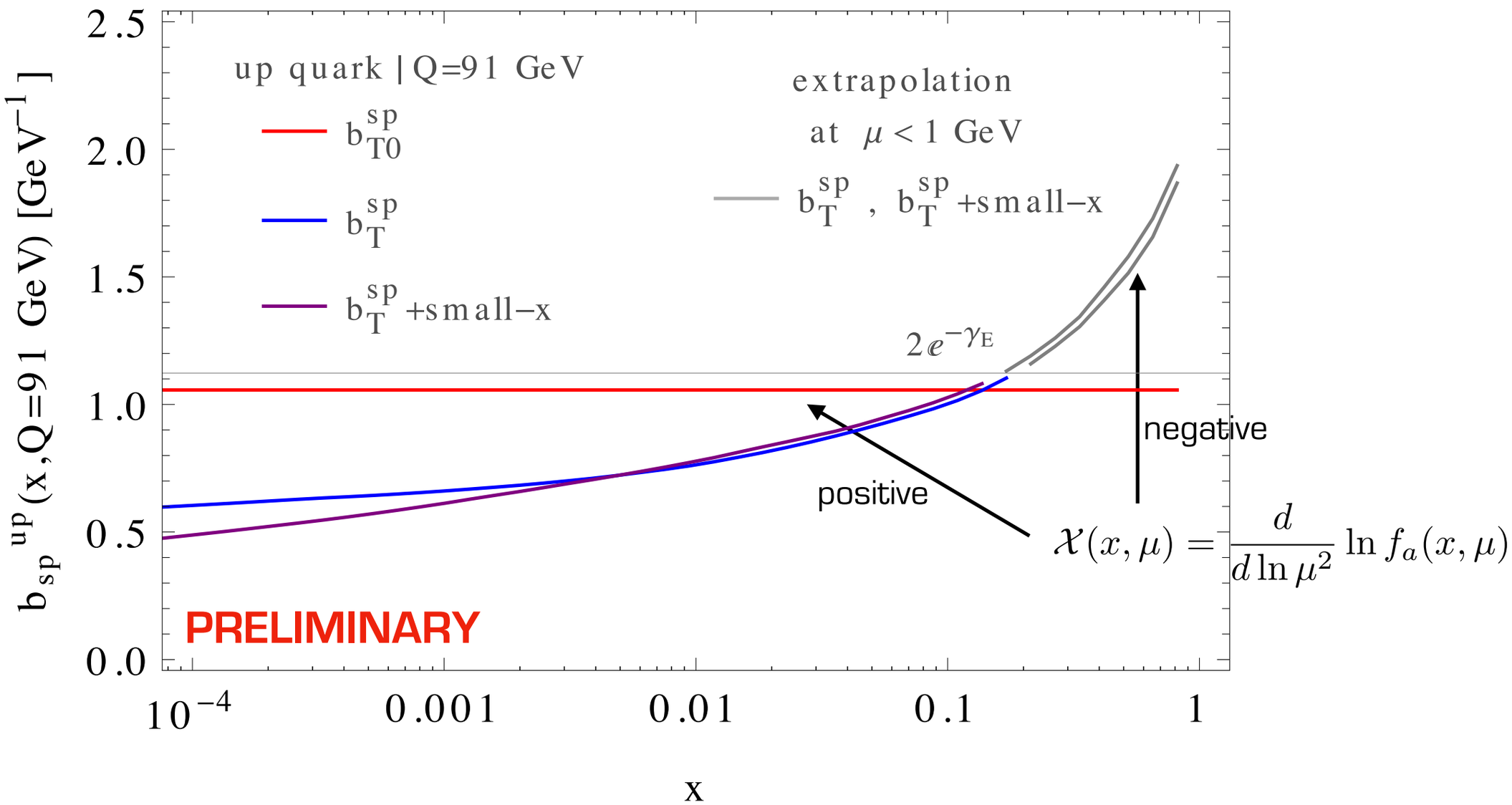
Requires iterative solution

Qiu, Zhang (2001) introduced the x-dependent term in the analysis at the level of the cross section.
We repeat the same at the level of the TMD PDF

Conclusion : the relevance of large bT corrections is governed by both Q and x!

Jefferson Lab

Determination of the saddle point

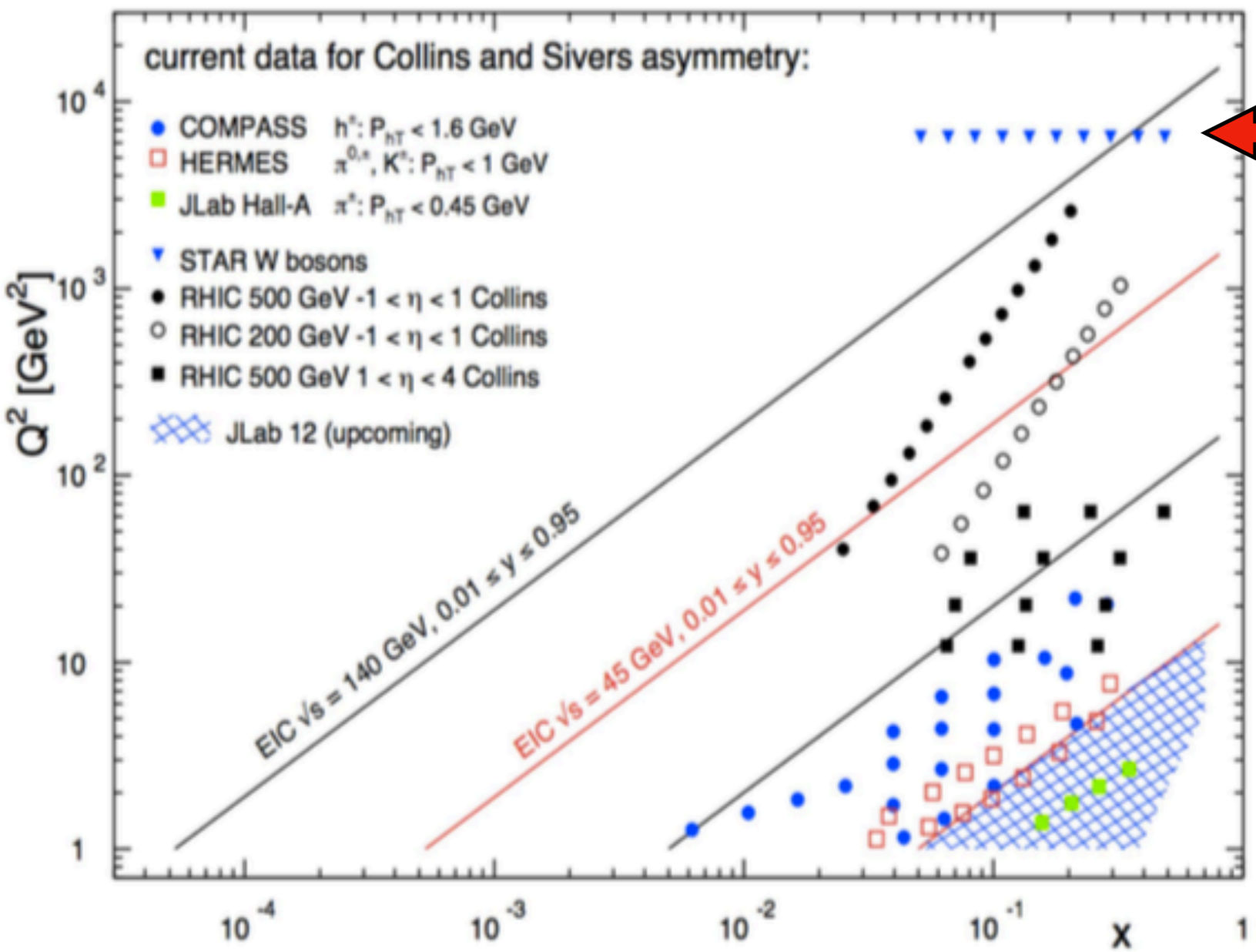


Fixed Q = 91 GeV, change x

the **x dependence determines a change with respect to CSS-like solution**

Sensitivity to NP effects enhanced at high x !

Kinematic coverage



W-boson production at RHIC probes TMDs in the high Q - high x region

High Q : TMD factorization under control

High x : enhanced sensitivity to nonperturbative effects

A very good combination!

Picture from O. Eyser - CIPANP 2018

Jefferson Lab

Global analysis of unpolarized TMDs

References :

- Bacchetta, Delcarro, Pisano, Radici, **AS**: JHEP 1706 (2017) 081

What do we know ?

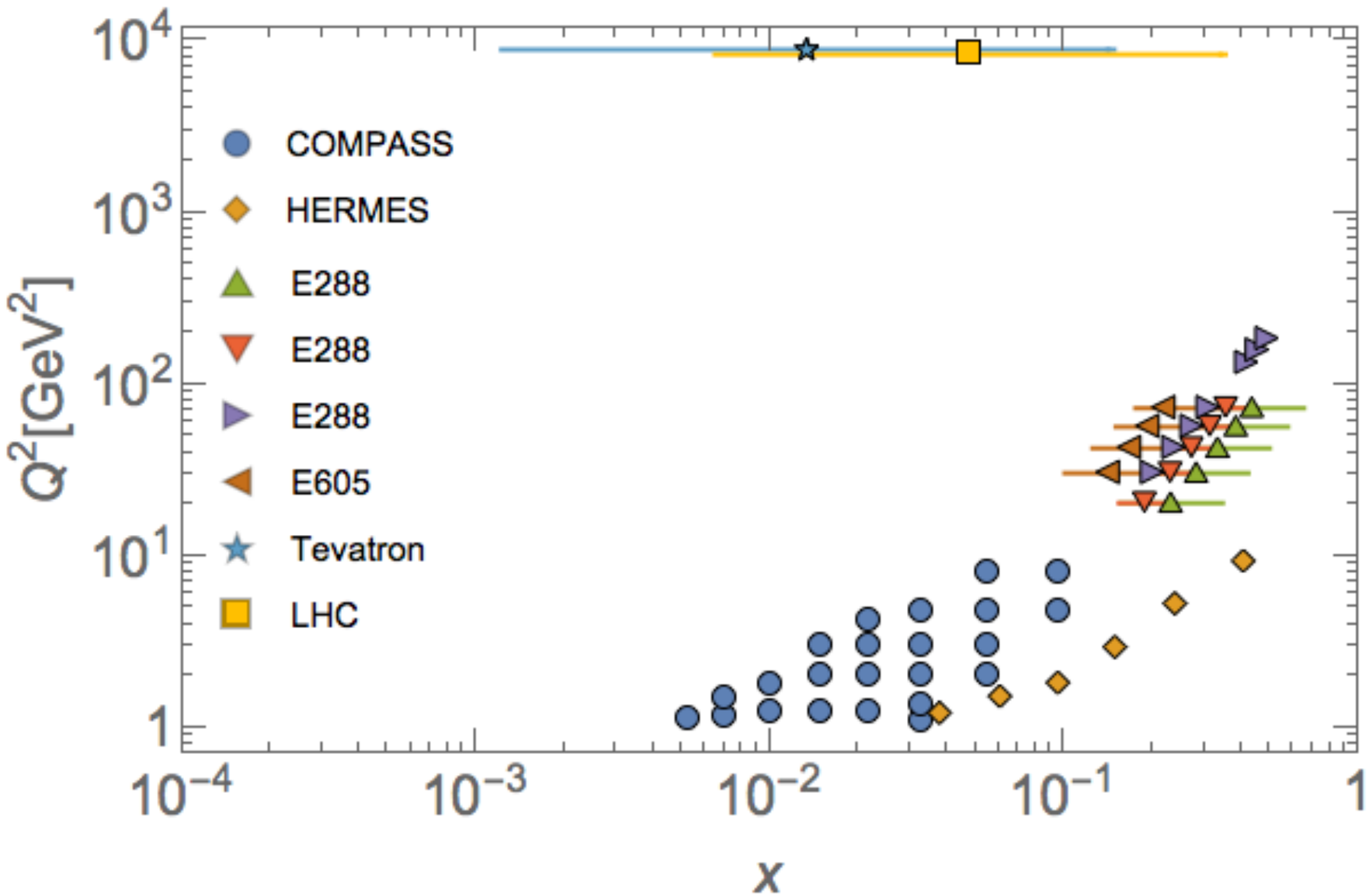
(only a selection of results!)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

[courtesy A. Bacchetta]

Jefferson Lab

Data sets and kinematic coverage



Electron-positron annihilation data are still **missing**
(only some azimuthal asymmetries are available)

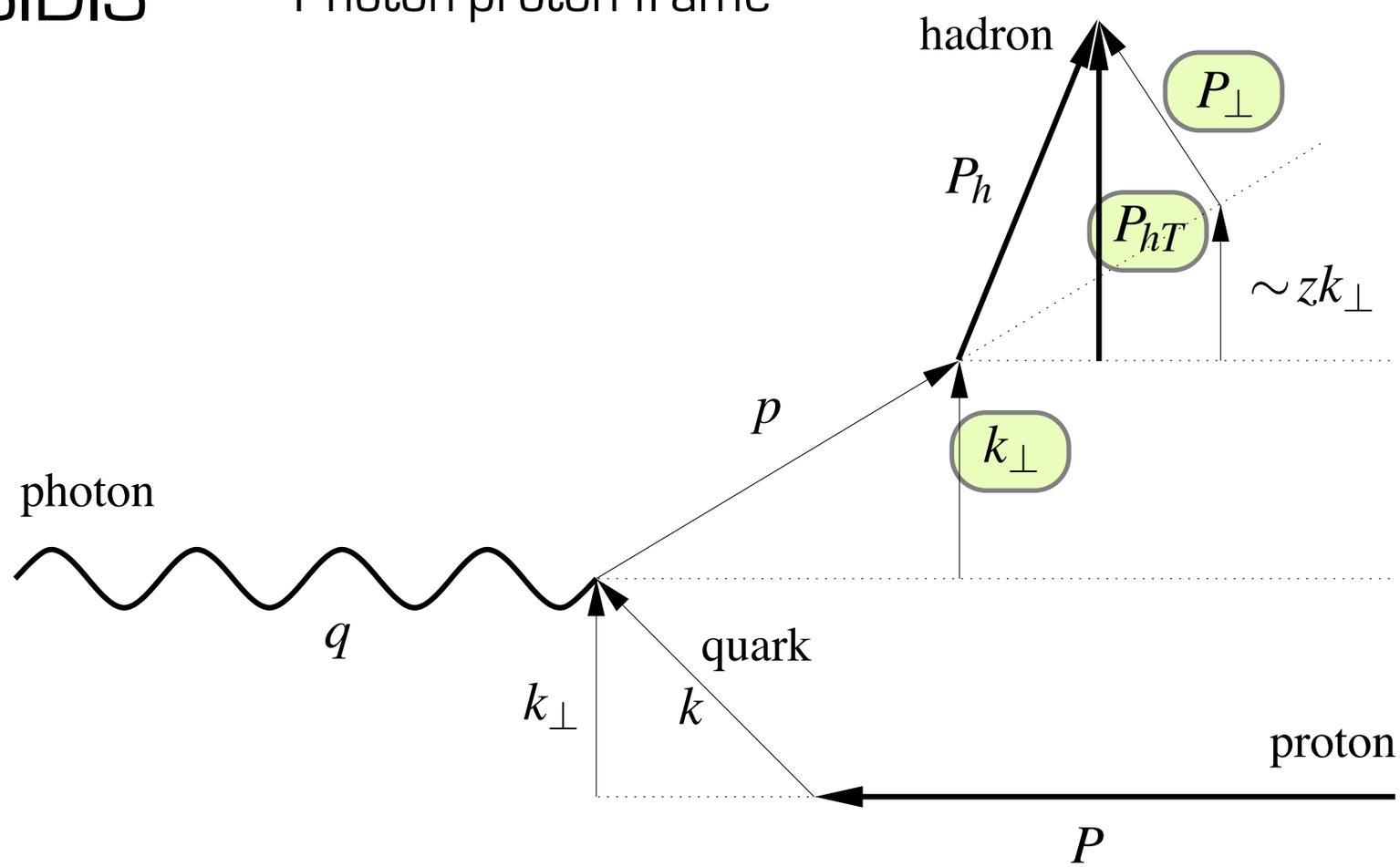
crucial for analyses of TMD FFs !!

Jefferson Lab

Transverse momenta

SIDIS

Photon-proton frame



TMD FF

TMD PDF

Longitudinal scaling variable

$$z = \frac{P \cdot P_h}{P \cdot q}$$

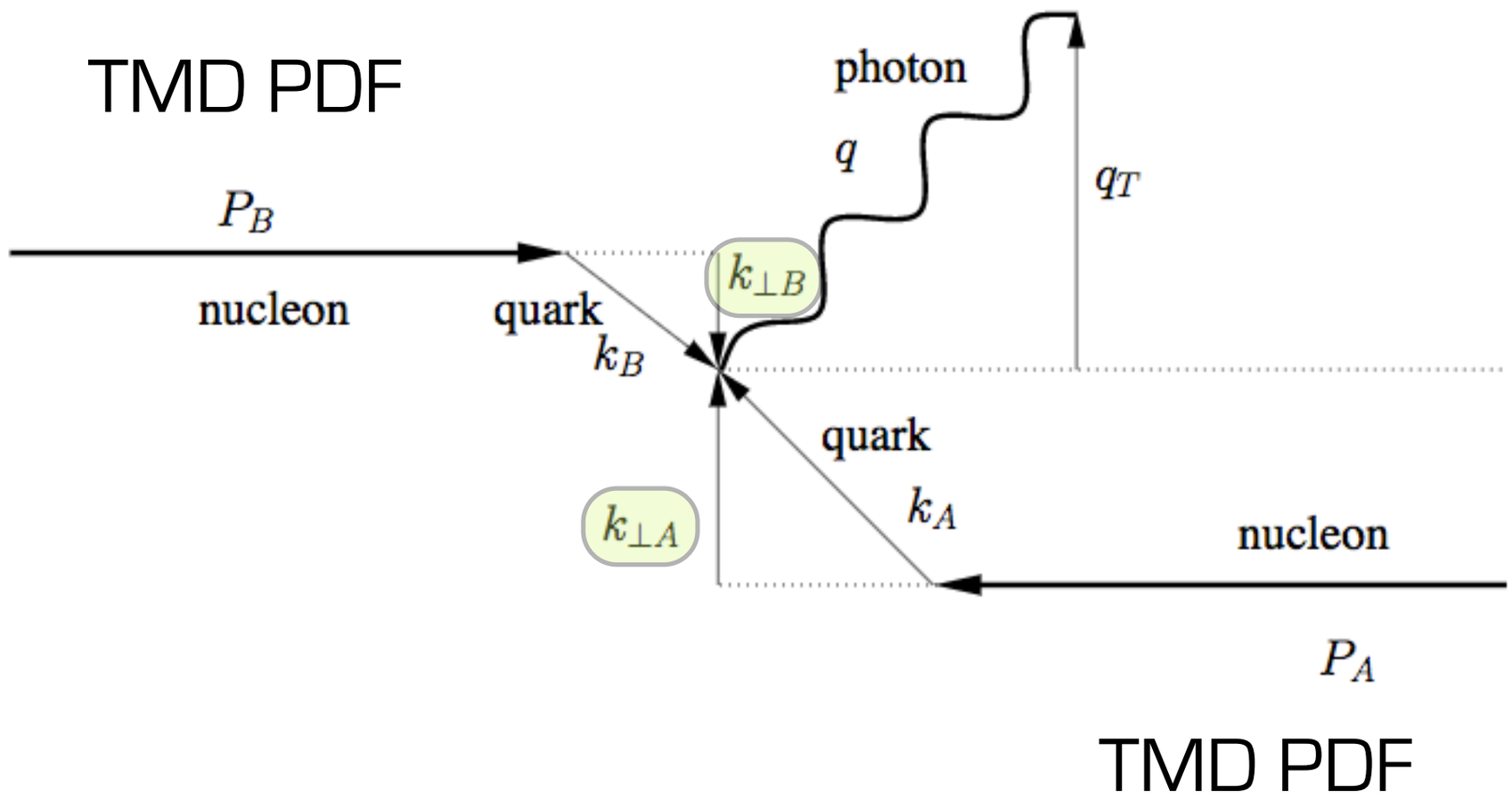
Observed transverse momentum

$$P_{hT} \approx zk_\perp + P_\perp$$

Jefferson Lab

Transverse momenta

DY



Jefferson Lab

Features

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059

PROs

almost a **global fit** of quark unpolarized TMDs

includes **TMD evolution**

replica (bootstrap) fitting methodology

kinematic dependence in intrinsic part of TMDs

intrinsic momentum: **beyond the Gaussian** assumption

CONs

no “pure” info on TMD FFs

accuracy of TMD evolution : not the state of the art

only “low” transverse momentum (no fixed order and Y-term)

flavor separation in the transverse plane : problematic

Jefferson Lab

Intrinsic transverse momentum

$$f^a_{1NP}(x,k_\perp^2) = \frac{1}{\pi}\frac{(1+\lambda k_\perp^2)}{g_{1a}+\lambda g_{1a}^2}\, e^{-\frac{k_\perp^2}{g_{1a}}}$$

$$\hat{x} = 0.1$$
$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

weighted sum of two Gaussian distributions:

same widths for TMD PDFs

different widths for TMD FFs

$$\hat{z} = 0.5$$
$$g_{3,4}(z) = N_{3,4} \frac{(z^\beta+\delta)(1-z)^\gamma}{(\hat{z}^\beta+\delta)(1-\hat{z})^\gamma}$$

$$D^{a\to h}_{1NP}(z,P_\perp^2) = \frac{1}{\pi}\frac{1}{g_{3a\to h}+(\lambda_F/z^2)g^2_{4a\to h}}\left(e^{-\frac{P_\perp^2}{g_{3a\to h}}} + \lambda_F \frac{P_\perp^2}{z^2}\, e^{-\frac{P_\perp^2}{g_{4a\to h}}}\right)$$

Inspired by **model calculations**:

Matevosyan et al.
Phys. Rev. D85, 014021 (2012), 1111.1740
Bacchetta et al.
Phys. Lett. B659, 234 (2008), 0707.3372
Bacchetta at al.
Phys. Rev. D65, 094021 (2002),
hep-ph/0201091

There are **11 free parameters** in a flavor independent scenario (one for evolution)

Jefferson Lab

Agreement data-theory

Flavor independent scenario

Flavor independent configuration | 11 parameters

Points	Parameters	χ^2	χ^2/d.o.f.
8059	11	12629 ± 363	1.55 ± 0.05

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Points	190	190	189	187
χ^2/points	4.83	2.47	0.91	0.82

Hermes P/D into π+:
problems at low z

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Points	190	190	189	189	3125	3127
χ^2/points	3.46	2.00	1.31	2.54	1.11	1.61

	E288 [200]	E288 [300]	E288 [400]	E605
Points	45	45	78	35
χ^2/points	0.99	0.84	0.32	1.12

Hermes kaons better than pions:
larger uncertainties from FFs

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Points	31	14	37	8
χ^2/points	1.36	1.11	2.00	1.73

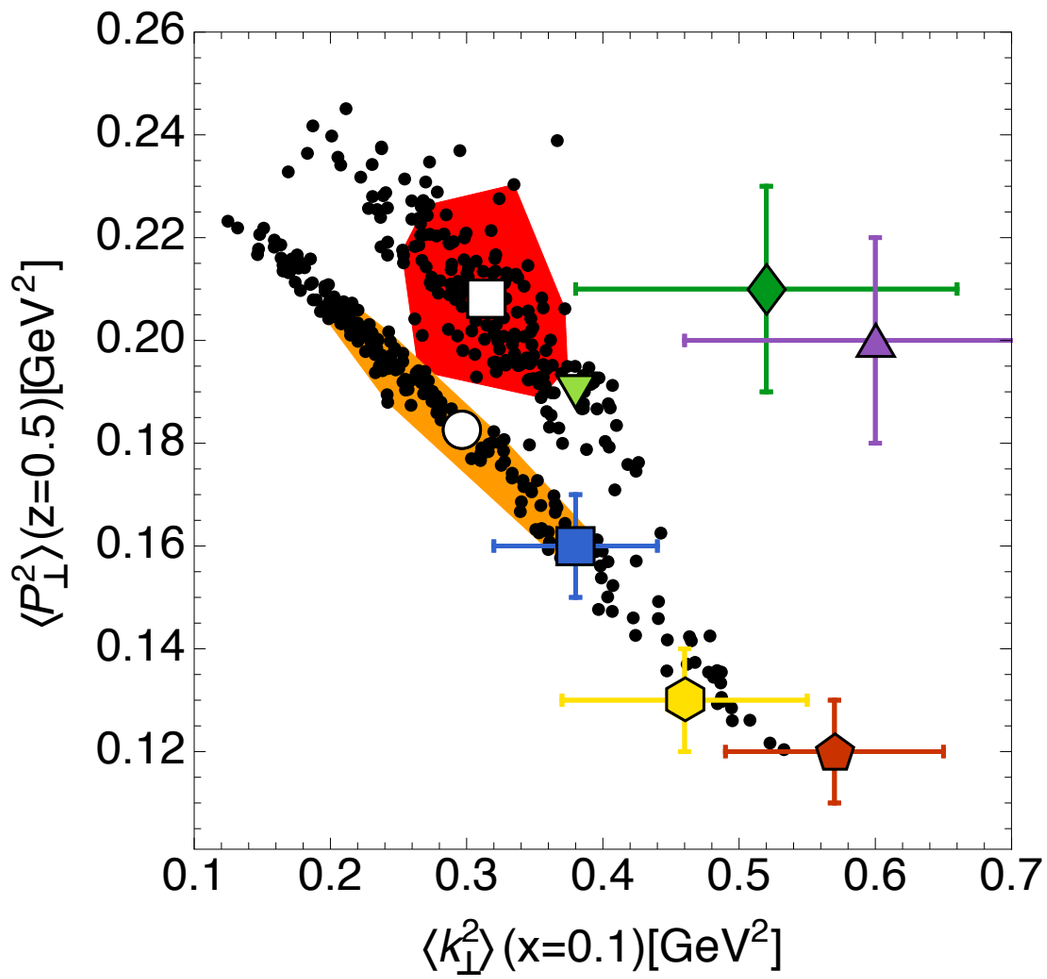
Compass : better agreement due to
#points and normalization

Let's see what
happens with the new data

Jefferson Lab

Average transverse momenta

Flavor ind. scenario



Bacchetta, Delcarro, Pisano, Radici, Signori (JHEP 2017)
Signori, Bacchetta, Radici, Schnell arXiv:1309.3507
Schweitzer, Teckentrup, Metz, arXiv:1003.2190
Anselmino et al. arXiv:1312.6261 [HERMES]
Anselmino et al. arXiv:1312.6261 [HERMES, high z]
Anselmino et al. arXiv:1312.6261 [COMPASS, norm.]
Anselmino et al. arXiv:1312.6261 [COMPASS, high z, norm.]
Echevarria, Idilbi, Kang, Vitev arXiv:1401.5078 (Q = 1.5 GeV)

Red/orange regions : **68% CL** from replica method

Inclusion of **DY/Z diminishes the correlation**

Inclusion of **Compass** increases the $\langle P_\perp^2 \rangle$ and reduces its spread

e+e- data would further reduce the correlation

Jefferson Lab

Conclusions

The generalized universality of TMDs is a rigorous prediction of QCD, whose experimental verification constitutes a test of the symmetries of the theory

An interesting region to **perform this test and to extract the nonperturbative contributions** to TMD PDFs (what usually we fit to data) could be the region at **high Q** (to better control the corrections to factorization) and **high x** (to enhance the sensitivity to the large bT region)
(but beware of thresholds effects, etc.);

RHIC can provide data in this region, e.g. **W-boson production** to study both **polarized and unpolarized TMDs**, providing a complementary view on the results available from JLab

A first attempt to a **global fit of TMD PDFs and FFs** has been attempted; RHIC data will provide additional valuable information

For example, W-production will be helpful to **shed light on the flavor decomposition of TMDs**

Backup

Status of TMD phenomenology

Theory, data, fits : we are in a position to start validating the formalism

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Twist-2 TMDs

Only first attempts

Limited data, theory, fits

see, e.g, Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
Anselmino, Boglione, D'Alesio, Murgia, Prokudin, arXiv: 1612.06413
Anselmino et al., PRD87 (13)
Kang et al. arXiv:1505.05589

Lu, Ma, Schmidt, arXiv:0912.2031
Lefky, Prokudin arXiv:1411.0580
Barone, Boglione, Gonzalez, Melis, arXiv:1502.04214

Jefferson Lab

Other measurements @ RHIC

Initial and Final State Effects

8

Sivers function $f_{1T}^{\perp}$	$\cos\phi_S$	$W^{\pm}, Z^0$, Drell-Yan γ^*
quark transversity h_1		
⊗ Collins fragmentation function $H_1^{\perp}$	$\cos(\phi_S - \phi_h)$	hadrons in jets
⊗ interference fragmentation $H_1^{\sphericalangle}$	$\cos\phi_R$	hadron pairs
gluon linear polarization h_1^g		
⊗ Collins-like fragmentation $H_1^{\perp,g}$	$\cos(\phi_S - 2\phi_h)$	hadrons in jets
quark-gluon correlator $T_{q,F}$	$\cos\phi_S$	jets, hadrons, γ_{direct}
gluon-gluon correlator T_G	$\cos\phi_S$	heavy flavor

Slide from O. Eyser
CIPANP 2018

Jefferson Lab

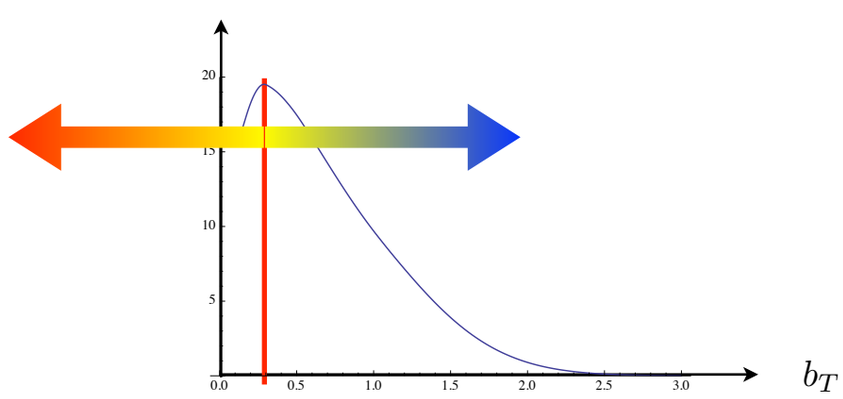
Determination of the saddle point

$$\frac{d}{db_T}\left\{\int_{\mu_i}^{\mu_f}\frac{d\mu}{\mu}\gamma_F\left[\alpha_s(\mu),\frac{\zeta_f}{\mu^2}\right]\right.$$
$$-K(b_T,\mu_i)\ln\frac{\zeta_f}{\zeta_i}$$
$$+\ln b_T^2$$
$$\left.+\ln\left[\sum_b C_{a/b}(x,b_T^2,\mu_i,\zeta_i)\otimes f_b(x,\mu_i)\right]\right\}_{b_T=b_T^{sp}}=0$$

Generate the **Q-dependence** of the saddle point

Generate the **x-dependence** of the saddle point (new term)

The closer the **saddle point is to the small bT region**, the more the **TMD PDF is determined by the perturbative part** only and thus there is predictive power

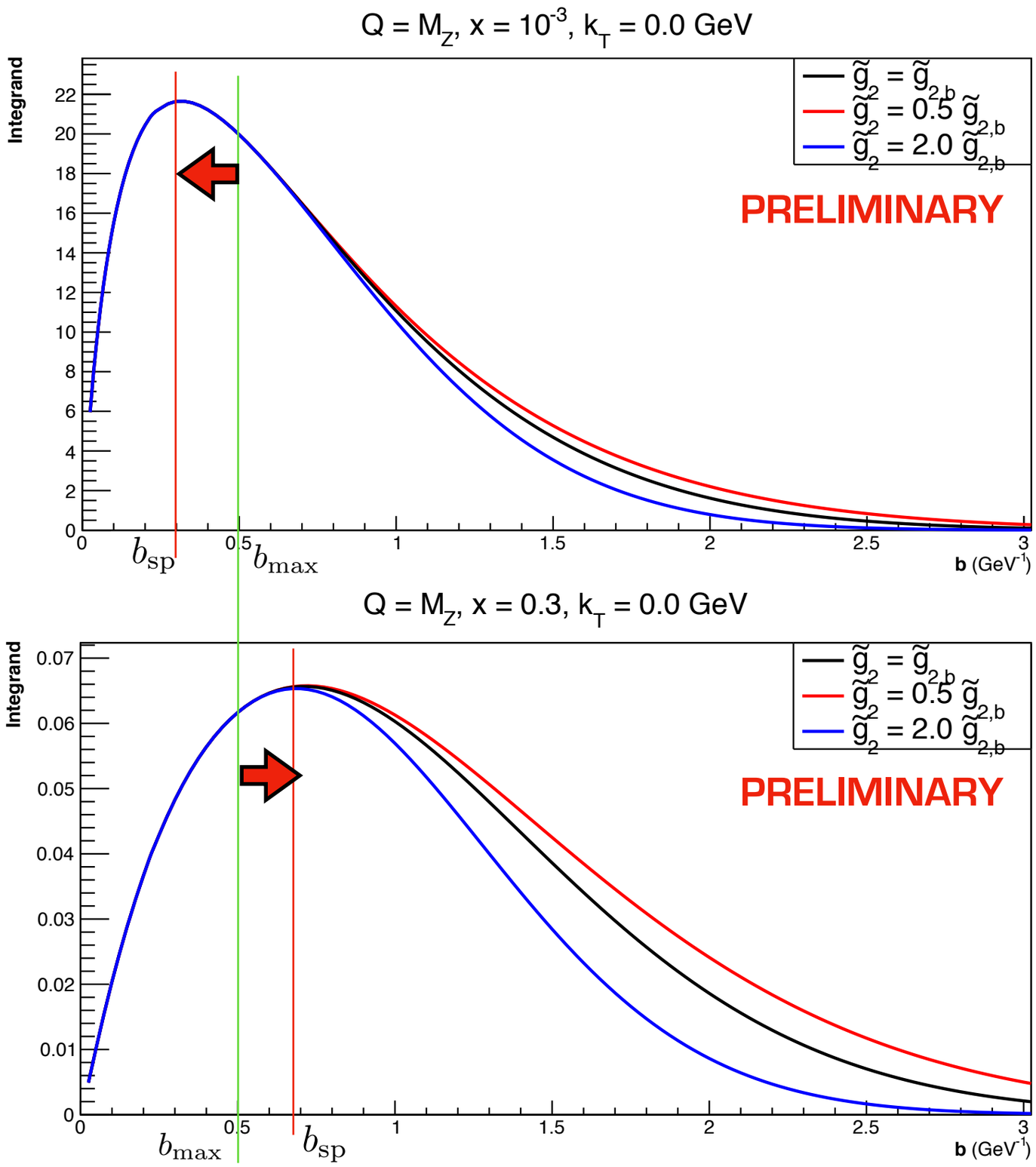


At the same time, we can understand in which kinematic regions the **saddle point drifts towards the large bT region** (bT > bmax) and thus the **nonperturbative corrections become more important**

Jefferson Lab

Quark TMD PDFs

NNLO and NNLL



Predictive power is maximum at large Q and small x.

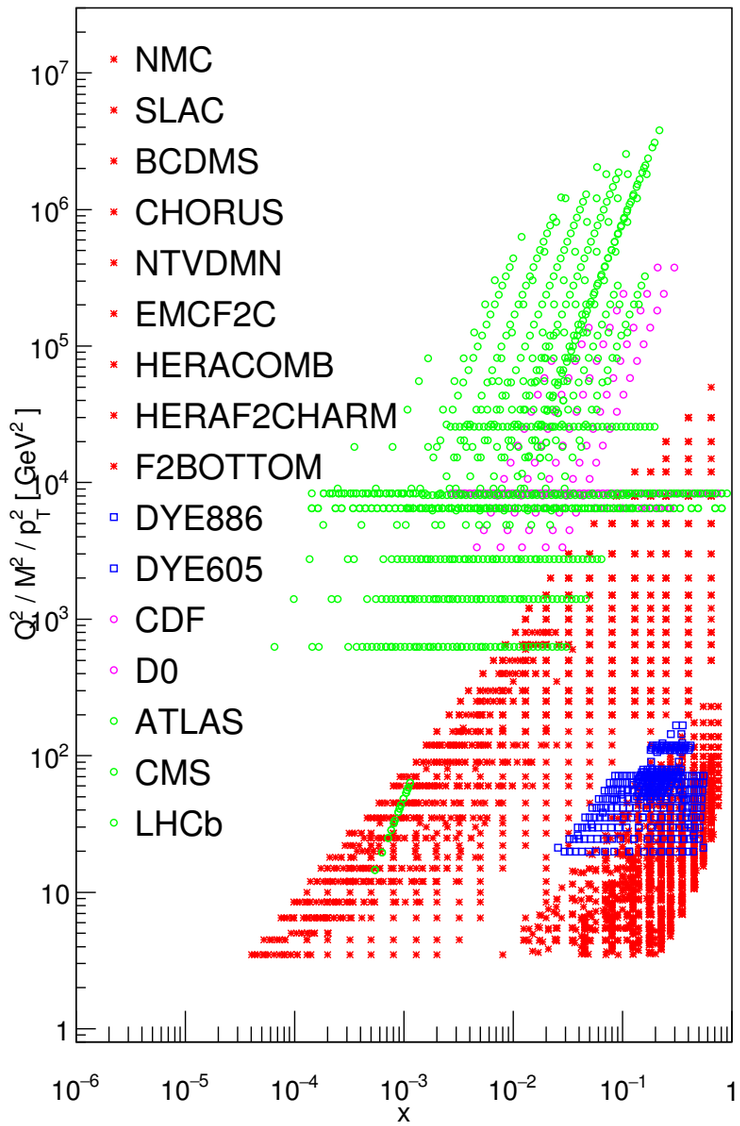
But Q alone does not provide the full picture:

at **higher x** the saddle point drifts towards the large bT region and the **nonperturbative corrections have** a bigger impact on the TMD PDF

Jefferson Lab

Comparison with collinear PDF fits

see talk by E. Nocera at POETIC2016

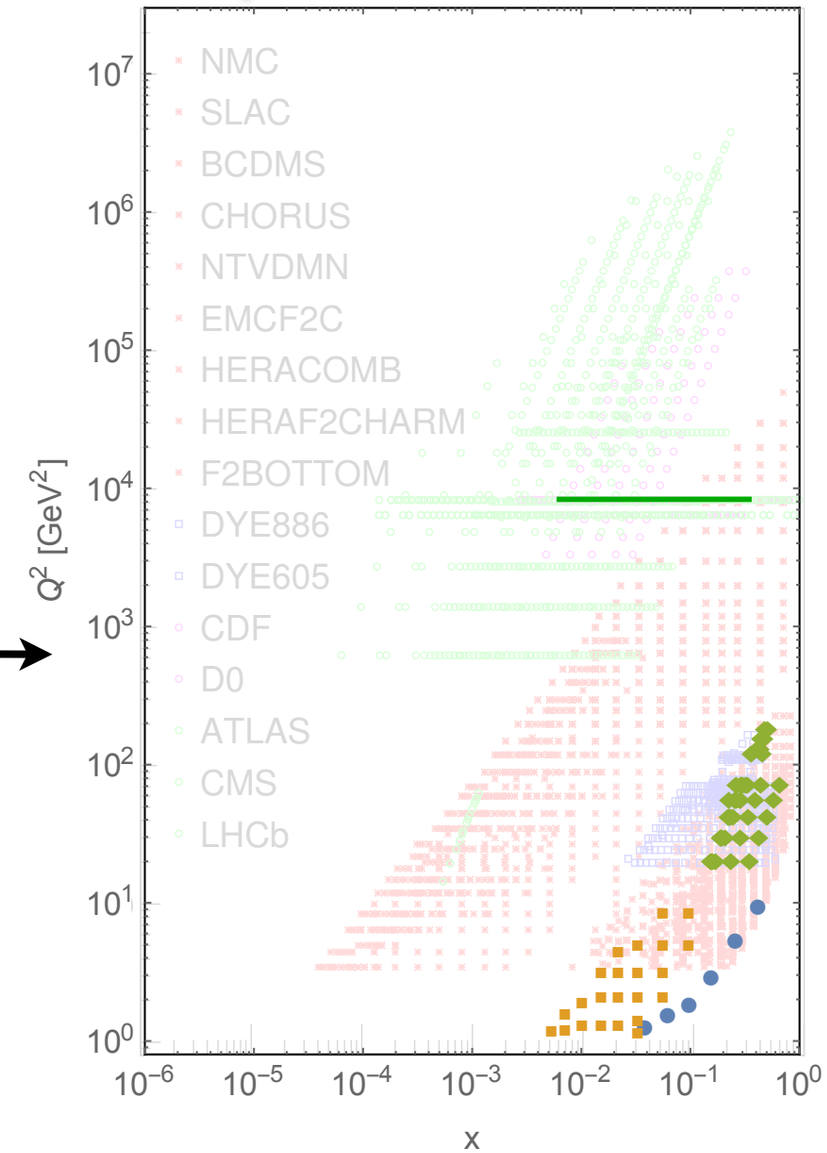


data sets available:

collinear PDFs

vs

TMD PDFs



Jefferson Lab

Models - evolution and b_T regions

$$g_K(b_T; g_2) = -g_2 \frac{b_T^2}{2}$$

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

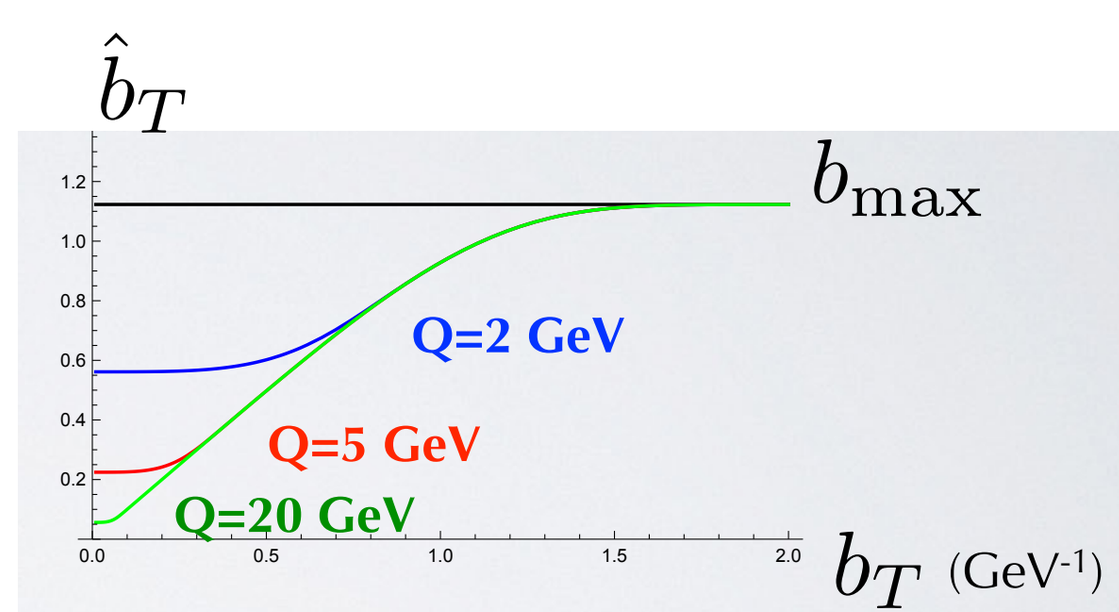
$\nearrow$ $b_{\max}$, $b_T \to +\infty$

$\searrow$ $b_{\min}$, $b_T \to 0$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$

These choices guarantee that for Q=1 GeV the TMD coincides with the NP model



Models - evolution and b_T regions

$$g_K(b_T; g_2) = -g_2 \frac{b_T^2}{2}$$

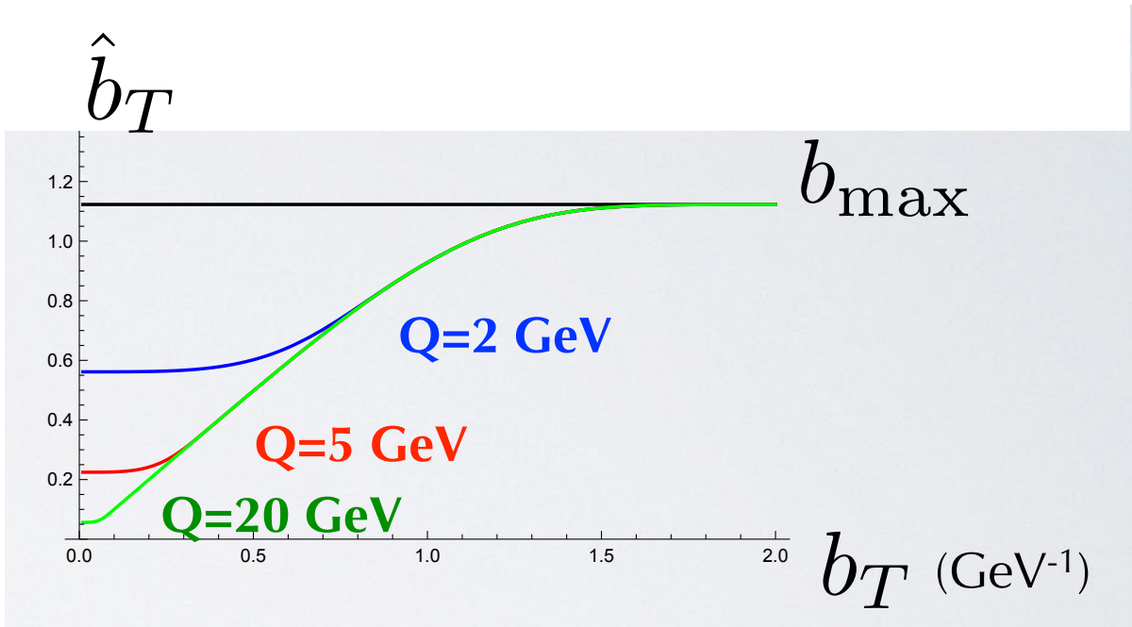
$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

$\nearrow$ $b_{\max}$, $b_T \to +\infty$

$\searrow$ $b_{\min}$, $b_T \to 0$

$$b_{\min} \sim 1/Q \ , \quad \mu_{\hat{b}} < Q$$

The phenomenological importance of b_{min} is a signal that -especially in SIDIS data at **low Q**- we are exiting the TMD region, entering the collinear factorization region



Data sets and selections - SIDIS

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Reference	[61]			
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \mathrm{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV			
Points	190	190	189	187
Max. Q^2	9.2 GeV^2			
x range	$0.06 < x < 0.4$			

TMD factorization
($P_{hT}^2/z^2 \ll Q^2$)

avoid target fragmentation [?]
(low z)
and exclusive contributions [?]
(high z)

Problem with normalization
in the previous release

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Reference	[74]				[75]	
Cuts	$Q^2 > 1.4$ GeV^2 $0.20 < z < 0.74$ $P_{hT} < \mathrm{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV					
Points	190	190	189	189	3125	3127
Max. Q^2	9.2 GeV^2				10 GeV^2	
x range	$0.04 < x < 0.4$				$0.005 < x < 0.12$	
Notes					Observable: $m_{\mathrm{norm}}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$, eq. (3.1)	

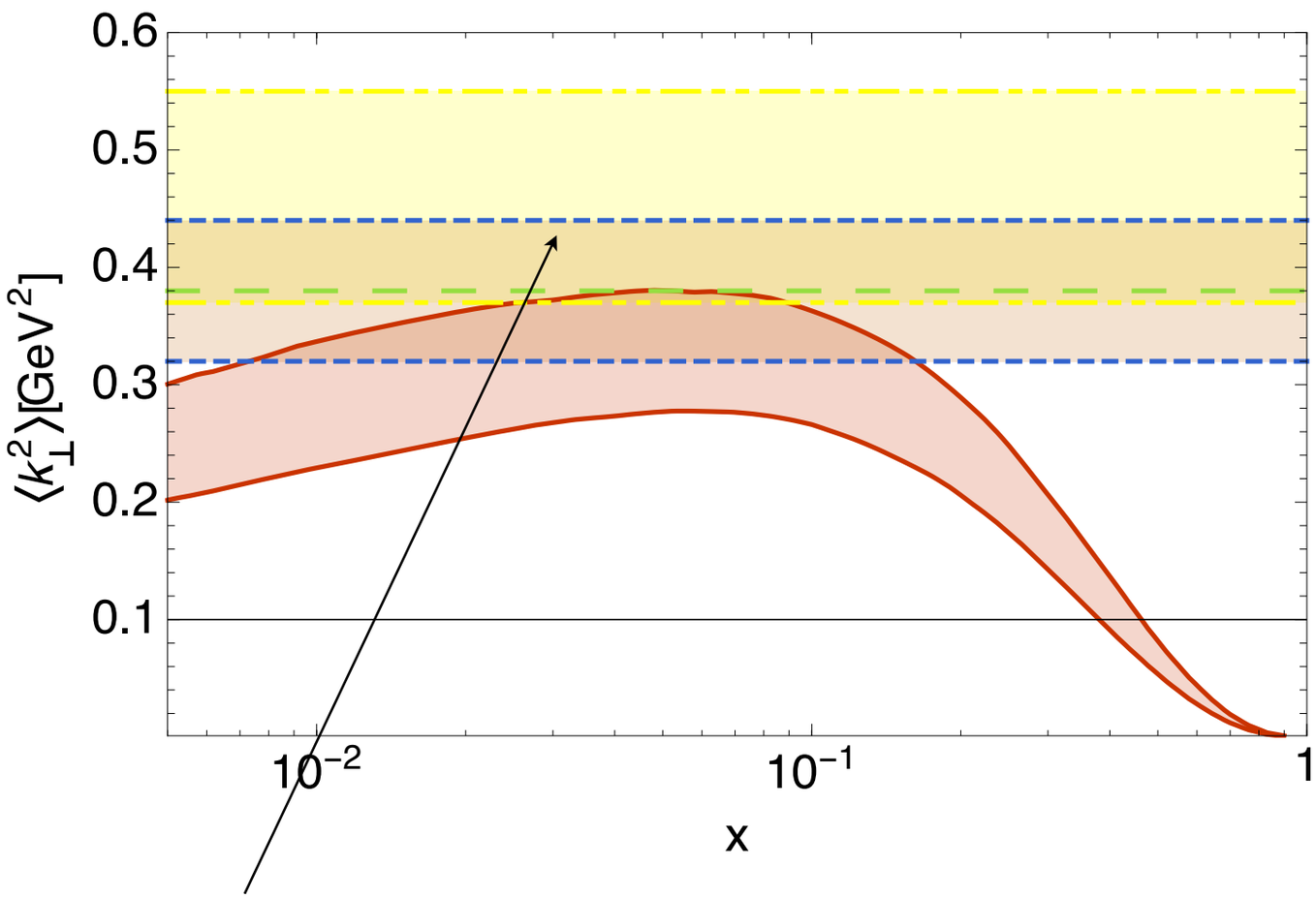
?

son Lab

Kinematic dependence

$$\langle k_\perp^2 \rangle(x) = \frac{\int d^2k_\perp \; k_\perp^2 \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}{\int d^2k_\perp \; f_1^a(x, k_\perp^2, Q = 1 \text{ GeV})}$$

Average square transverse momentum in TMD PDF



x-independent extractions

Color code : same as previous slide

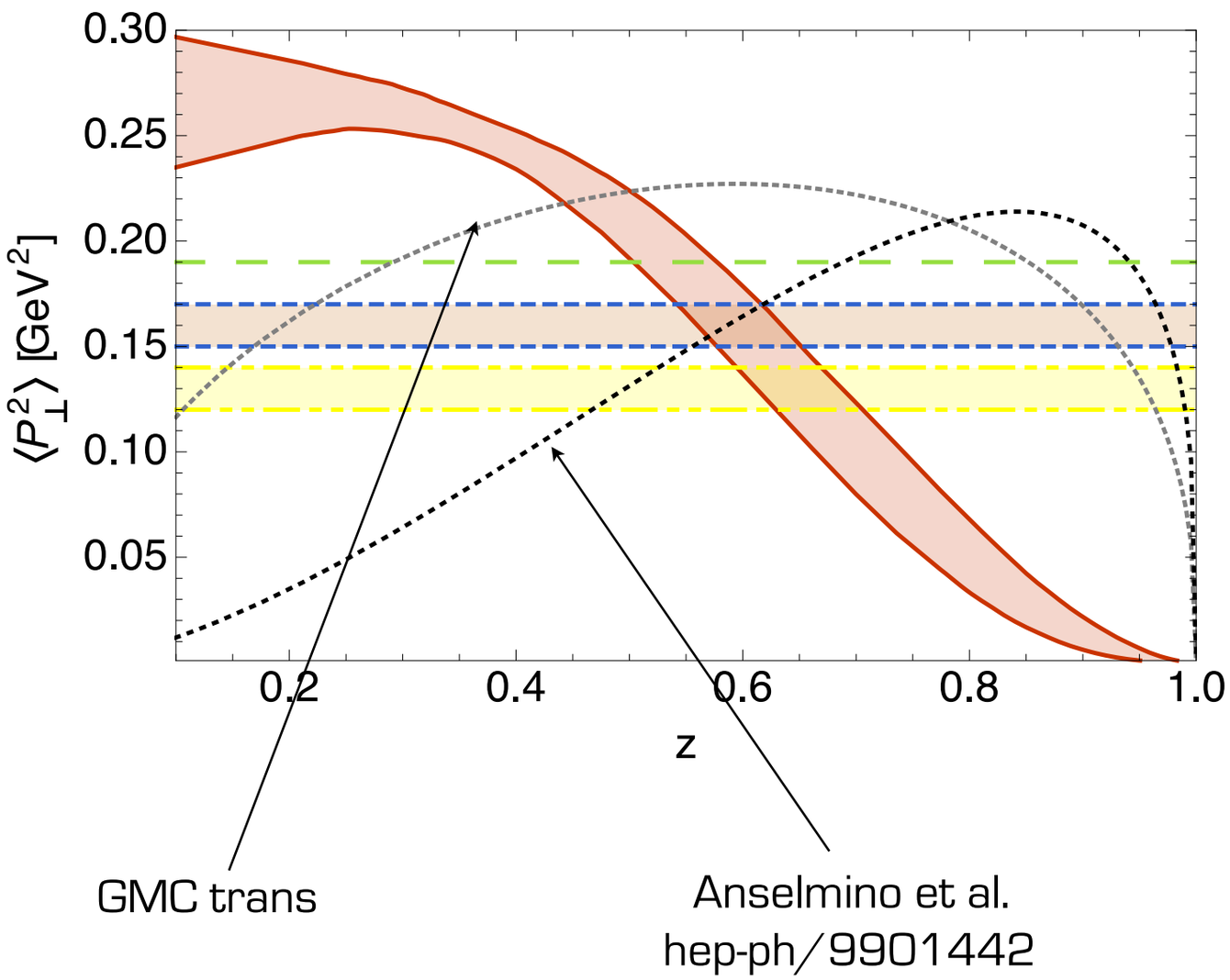
Flavor-independent scenario: no differences in quark/hadron flavor

Jefferson Lab

Kinematic dependence

$$\langle P_\perp^2 \rangle(z) = \frac{\int d^2P_\perp \; P_\perp^2 \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}{\int d^2P_\perp \; D_1^{a\to h}(z, P_\perp^2, Q = 1 \text{ GeV})}$$

Average square
transverse momentum in TMD FF



Color code : same as previous slide

Flavor-independent scenario:
no differences in quark/hadron
flavor

z-dependence :
important to fit the data

Jefferson Lab

W production at LHC

References:

- Bozzi, Rojo, Vicini: Phys.Rev. D83 (2011) 113008
- Bozzi, Citelli, Vicini: Phys.Rev. D91 (2015) no.11, 113005
- AS, PhD thesis
- Bacchetta, Bozzi, Radici, Mulders, Ritzmann, AS - in preparation

EW precision measurements

Eur.Phys.J. C74 (2014) 3046

Precise measurements of electroweak quantities allow:

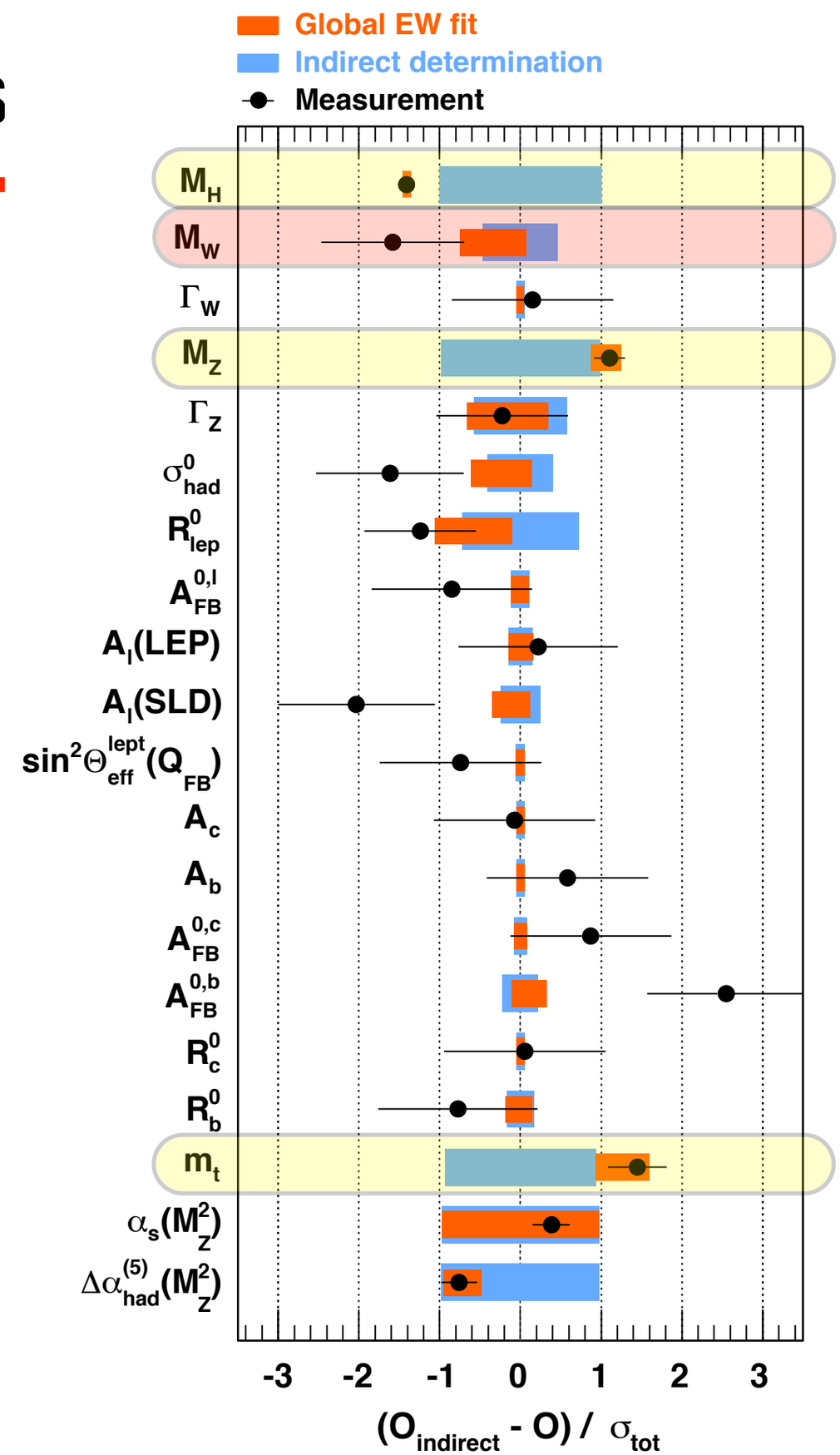
1) Stringent **tests** of the self consistency of the SM

2) Looking for hints of physics **beyond** the SM

In particular the values of the **masses** of the gauge bosons, the Higgs and the top quark can help in **discriminating among different BSM scenarios**.

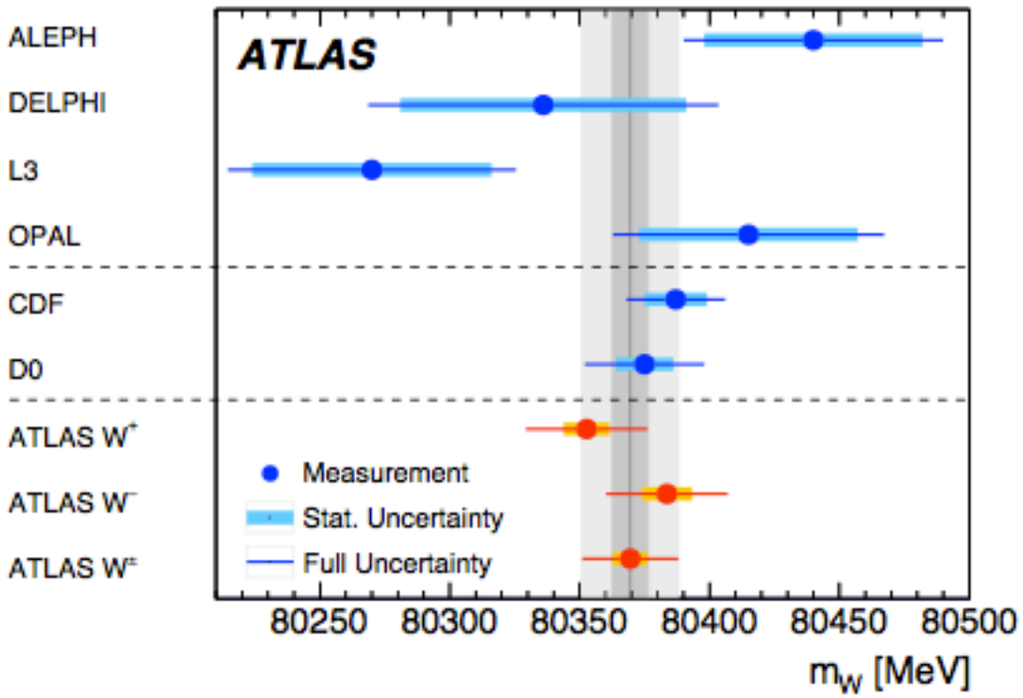
H, Z, t : direct determinations more precise than indirect; **not for W** !

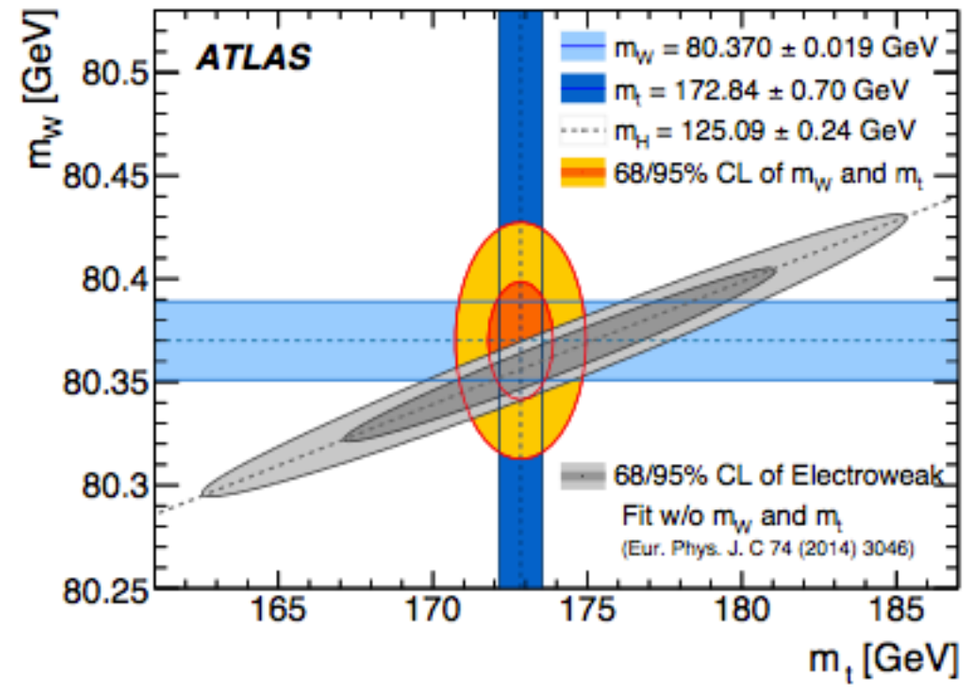
see:
* S. Camarda - Measurement of the W mass with ATLAS
EPS 2017



W mass

ATLAS, arxiv:1701.07240





Experimental measurements

$$m_W = 80370 \pm 19 \text{ MeV}$$

(7 stat, 11 exp, 14 th)

Global EW fit

$$m_W = 80356 \pm 8 \text{ MeV}$$

Need to **better control the uncertainties** associated to **direct** determinations of mW

Is it possible to reduce the uncertainty to less than 10 MeV ?

Are we estimating all the **uncertainties of hadronic nature** in the best way possible?

Jefferson Lab

Uncertainties on W mass

AS - PhD thesis

Uncertainties on m_W [MeV] from p_T^ℓ fit

Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson q_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

Tevatron case

sizable uncertainties from hadron structure

associated to α_s and NP evolution;

no intrinsic transverse momentum

ATLAS (arxiv:1701.07240)

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5

The extraction of physical quantities

Observables

- accessible via counting experiments: cross sections and asymmetries

Pseudo-Observables

- functions of cross sections and symmetries
- require a model to be properly defined
  - M_Z at LEP as pole of the Breit-Wigner resonance factor
  - Mw at hadron colliders as fitting parameter of a template fit procedure (of mT, pTlep, pTmiss)

Template fit

1. generate several histograms with the highest available theoretical accuracy and degree of realism in the detector simulation, and let the fit parameter (e.g. Mw) vary in a range
2. the histogram that best describes data selects the preferred (i.e. measured) Mw

➡ the result of the fit depends on the hypotheses used to compute the templates (PDFs, scales, non-perturbative, different prescriptions, ...)

➡ these hypotheses should be treated as theoretical systematic errors

Jefferson Lab

p_{TW} and the modelling of intrinsic-k_T

- p_{Tl} ⇦ p_{TW} ⇦ QCD initial state radiation + intrinsic k_T (usually, a Gaussian in k_T)

- PDF uncertainties and k_T-modelling entangled
  ⇨ <u>no universal (flavour-independent) model</u>

- Intrinsic *kT* effects measured on *Z* data and used to predict *W* distributions, *assuming universality* Konychev, Nadolsky, PLB 633, 710 (2006)

but

different flavour structure

different phase space available

—> *different Gaussian factors for different flavors*

$$f_1^a(x, k_T) = f_1^a(x) \, \frac{1}{\pi \langle k_T^2 \rangle_a(x)} \, e^{-\frac{k_T^2}{\langle k_T^2 \rangle_a(x)}}$$

$$\langle k^2_{\perp,\mathrm{u_v}} \rangle \neq \langle k^2_{\perp,\mathrm{d_v}} \rangle \neq \langle k^2_{\perp,\mathrm{sea}} \rangle$$

Flavor and kinematic dependent widths

ab

Impact on mW: preliminary results

- Select 15 *flavor-dependent* NP sets for which Δ(Z peak) < 100 MeV and compute *low-statistics* m_T and p_{Tl} distributions

  ➡ these are our **pseudodata**

- Select a universal (*flavor-independent*) NP parameter and compute *high-statistics* m_T and p_{Tl} distributions for 30 different values of M_W

  ➡ these are our **templates**

- **perform the template fit procedure and compute the shifts induced by flavour effects**

- transverse mass: few MeV shifts, generally favouring lower values (preferred by EW fit)

- lepton pt & missing pt: quite important shifts (envelope: 21 MeV)

transverse mass

Set	ΔMW
1	−3
2	−3
3	−1
4	−1
5	−3
6	−1
7	−3
8	−2
9	−2
10	−1
11	−3
12	−2
13	−2
14	−3
15	−3

lepton pt

Set	ΔMW
1	2
2	2
3	2
4	−4
5	−11
6	−4
7	−14
8	1
9	−15
10	5
11	1
12	−1
13	6
14	−3
15	0

missing pt

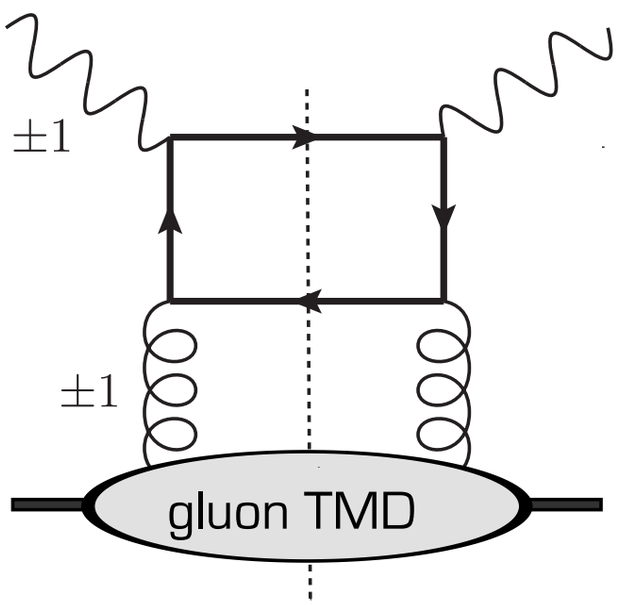
Set	ΔMW
1	−6
2	−6
3	−3
4	−13
5	−15
6	−13
7	−15
8	−4
9	−15
10	1
11	−4
12	−4
13	−5
14	−10
15	−6

NLL+LO QCD analysis obtained through a modified version of the **DYRes** code [Catani, deFlorian, Ferrera, Grazzini, JHEP 1512, 047 (2015)]

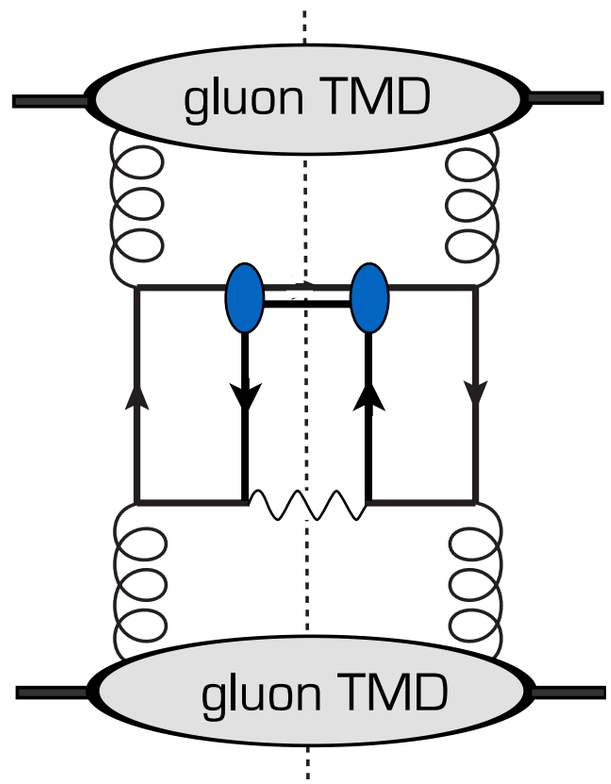
Gluon TMDs

$e\,p \to e$ jet jet X

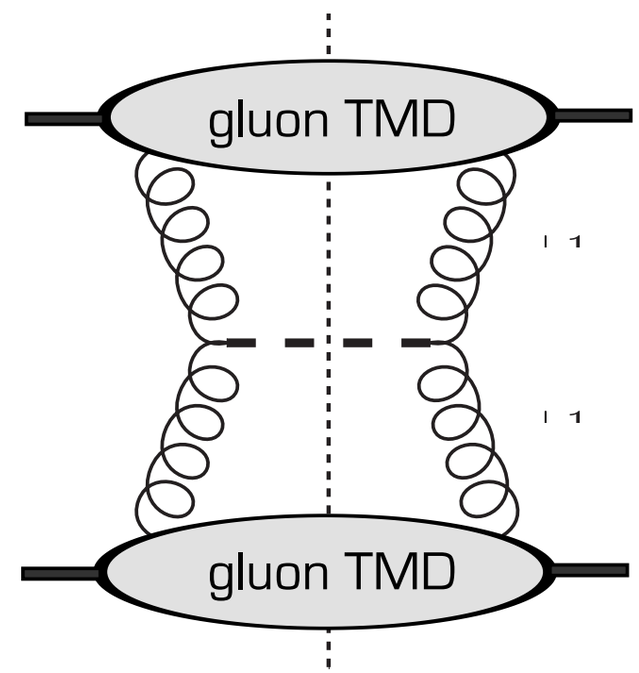
EIC !



$p\,p \to J/\psi\,\gamma\,X$



$p\,p \to \eta_c\,X$



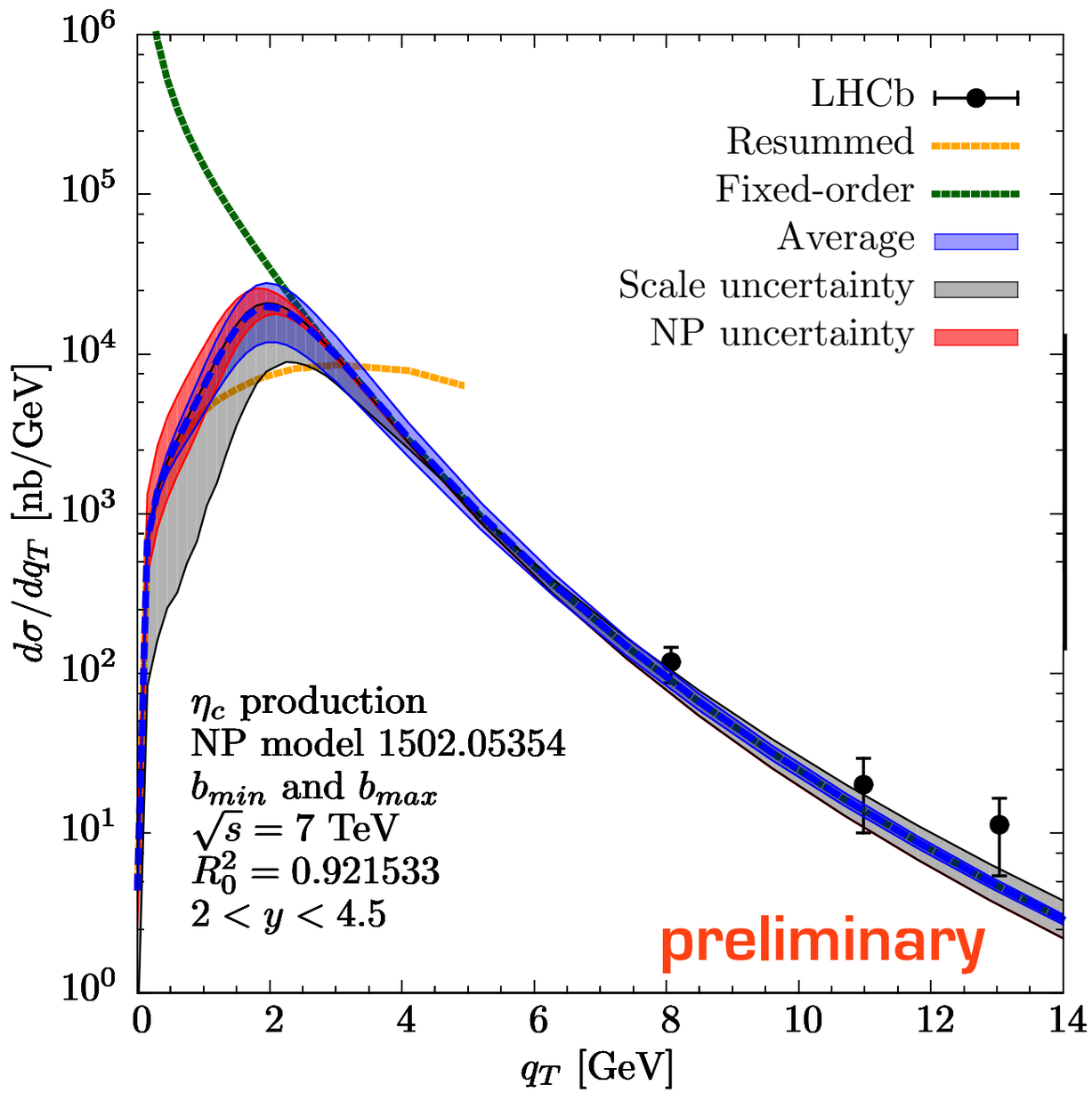
Factorization properties and phenomenology

Jefferson Lab

η_c production at LHC

full transverse momentum spectrum: inverse-error weighting :

Echevarria, Kasemets, Lansberg, AS, Pisano
Phys.Lett. B781 (2018) 161-168



blue band: uncertainty from matching

grey band: scale uncertainty

red band: uncertainty associated to the nonperturbative evolution and intrinsic transverse momenta

the formalism is in good shape!
we need the data at low q_T

Jefferson Lab

Gluon TMDs

gluon correlator

$$\Gamma^{\alpha\beta}(x, \mathbf{k}_T) \sim \text{F.T. } \langle P| F^{+\alpha}(0)\; U_{[0,\xi]}\; F^{+\beta}(\xi)\; U'_{[\xi,0]} |P\rangle_{|_{\xi^+=0}}$$

loop correlator

$$\Gamma_0(x, \mathbf{k}_T) \sim \delta(x) \text{ F.T. } \langle P| U^{[+]}_{[0,\xi]}\; U^{[-]}_{[\xi,0]} |P\rangle_{|_{\xi^+=0}}$$

	Ref. [30]	Ref. [7]	Rank	T	C	Limit $x \to 0$
xf_1	xf_1	xG	0	even	even	$e^{(1)}$
$xh_1^\perp$	$xh_1^\perp$	$xH^\perp$	2	even	even	e
xg_1	xg_{1L}	$-x\Delta G_L$	0	even	odd	0
$xh_{1L}^\perp$	$xh_{1L}^\perp$	$-x\Delta H_L^\perp$	2	odd	even	0
$xf_{1T}^\perp$	$xf_{1T}^\perp$	$-xG_T$	1	odd	odd	$e_T^{(1)}$
xg_{1T}	xg_{1T}	$-x\Delta G_T$	1	even	even	0
xh_1	$xh_{1T} + xh_{1T}^{\perp(1)}$	$-x\Delta H_T$	1	odd	odd	$e_T^{(1)}$
$xh_{1T}^\perp$	$xh_{1T}^\perp$	$-x\Delta H_T^\perp$	3	odd	odd	$-e_T$
xf_{1LL}			0	even	even	$e_{LL}^{(1)}$
$xh_{1LL}^\perp$			2	even	even	e_{LL}
xf_{1LT}			1	even	odd	$e_{LT}^{(1)}/2$
xg_{1LT}			1	odd	even	0
xh_{1LT}			1	even	odd	$e_{LT}^{(1)}/2$
$xh_{1LT}^\perp$			3	even	odd	$-e_{LT}$
xf_{1TT}			2	even	even	$e_{TT}^{(1)}/3$
xg_{1TT}			2	odd	odd	0
xh_{1TT}			0	even	even	$e_{TT}^{(2)}$
$xh_{1TT}^\perp$			2	even	even	$-2\,e_{TT}^{(1)}/3$
$xh_{1TT}^{\perp\perp}$			4	even	even	e_{TT}

Table 1. An overview of the leading twist gluon TMDs for unpolarized, vector polarized, and tensor polarized hadrons. In the second and third column, the names of the functions in this paper are compared to the ones in refs. [7, 30]. In the fourth column we list the rank of the function. Furthermore, we list the properties (even/odd) under time reversal (T) and charge conjugation (C), see appendix A. In the last column it is indicated to which e-type function the TMD reduces in the limit $x \to 0$. As a shorthand, we use the moment notation $f_{\dots}^{(n)}(x, \boldsymbol{k}_T^2) \equiv [\boldsymbol{k}_T^2/(2M^2)]^n\, f_{\dots}(x, \boldsymbol{k}_T^2)$.

Boer, Cotogno, van Daal, Mulders, Signori, Zhou
JHEP 1610 (2016) 013