- TMDs -

transverse connections between particle and nuclear physics

Andrea Signori

13th conference on the
intersections of
particle and **nuclear** physics

CIPANP 2018
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Jefferson Lab

JSA

Outline of the talk

1) Transverse-momentum-distributions (TMDs)

2) “intersections of particle and nuclear physics”

3) predictive power of TMDs

4) impact on LHC physics

Collaborations

I will present some research directions, in collaboration with:

- J. Qiu (JLab)
- M. Grewal, Z. Kang (UCLA)

- A. Bacchetta, G. Bozzi, M. Radici (Pavia U., INFN)
- P. Mulders, M. Ritzmann (Nikhef)

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**

The hadronic landscape

$$\begin{tikzcd}
 & & & & & & & \overset{\text{parton correlation function}}{H(k,P,\Delta)} \arrow[llllllld, "\Delta = 0"'] \arrow[dd, "\int dk^-"] \\
 & f(k,P)\ \text{parton correlation function} \arrow[dddd, "\int dk^-"'] & & & & & & \\
 & & & & & & H(x,\boldsymbol{k},\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}"] \arrow[lllld, "\xi = 0"'] & H(x,\boldsymbol{k},\xi,\boldsymbol{\Delta})\ \text{GTMD} \arrow[dd, "\int d^2\boldsymbol{k}"] \\
 & & W(x,\boldsymbol{k},\boldsymbol{b})\ \text{Wigner distribution} \arrow[ddl, "\int d^2\boldsymbol{b}"] \arrow[ddr, "\int d^2\boldsymbol{k}"] & & & & & \\
 & & & & & & H(x,\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}"] \arrow[llld, "\xi = 0"'] & H(x,\xi,\Delta^2)\ \text{GPD} \arrow[dd, "\int dx\, x^{n-1}"] \\
f(x,\boldsymbol{z}) \arrow[r, leftrightarrow, "\text{FT}"] & \underset{\text{TMD}}{f(x,\boldsymbol{k})} \arrow[ddr, "\int d^2\boldsymbol{k}"] & & f(x,\boldsymbol{b})\ \begin{array}{r}\text{impact parameter}\\ \text{distribution}\end{array} \arrow[ddl, "\int d^2\boldsymbol{b}"'] \arrow[ddr, "\int dx\, x^{n-1}"] & & & & \\
 & & & & & & & \underset{\text{GFFs}}{\sum_{k=0}^{n} A_{nk}(\Delta^2)\,(2\xi)^k} \arrow[lld, "\xi = 0"'] \\
 & & \underset{\text{PDF}}{f(x)} & & F_n(\boldsymbol{b}) \arrow[r, leftrightarrow] & \underset{\text{form factor}}{F_n(\Delta^2)} & &
\end{tikzcd}$$

M. Diehl - 10.1140/epja/i2016-16149-3

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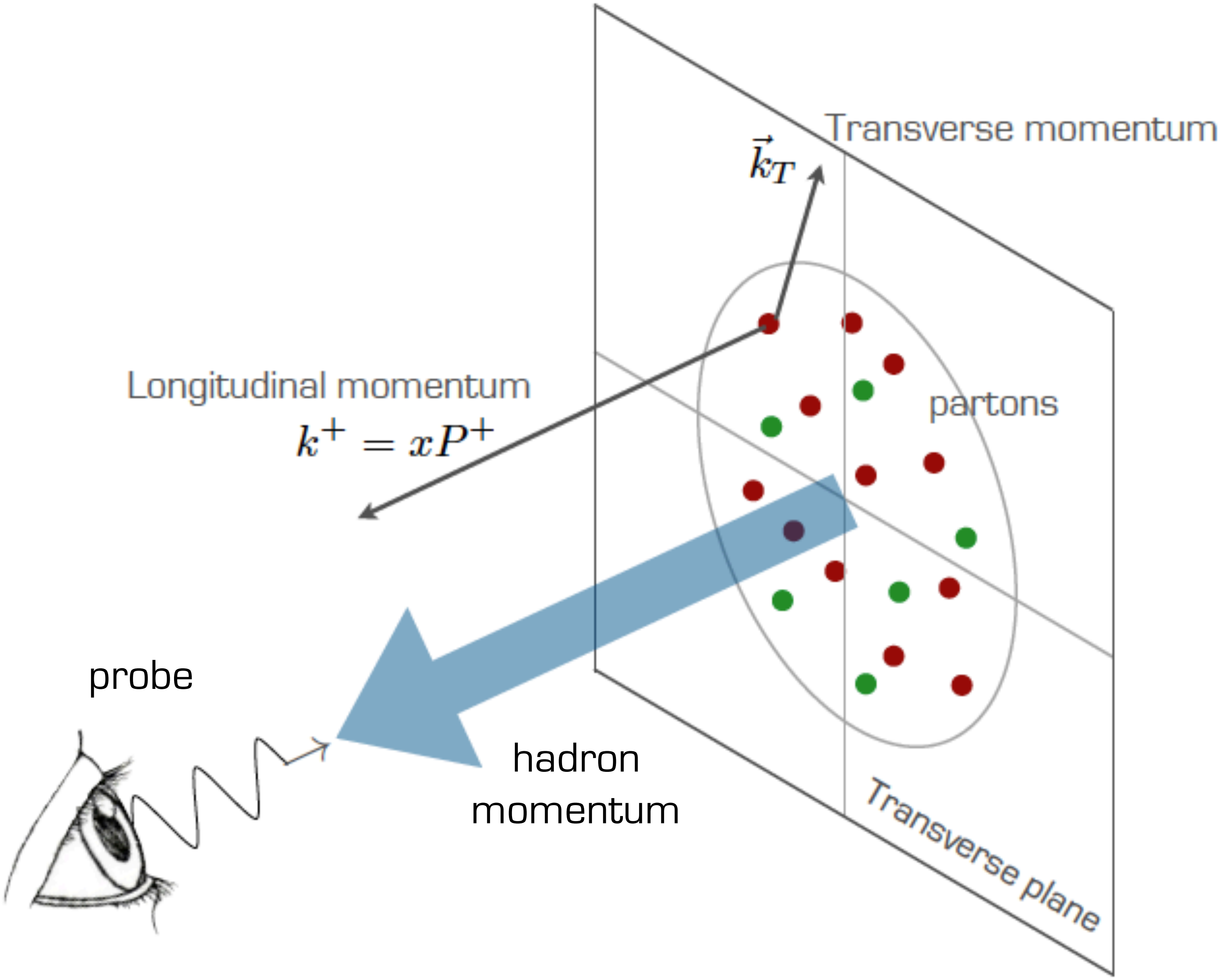
TMDs



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

richer than PDFs

How are TMDs **defined** ?

courtesy A. Bacchetta

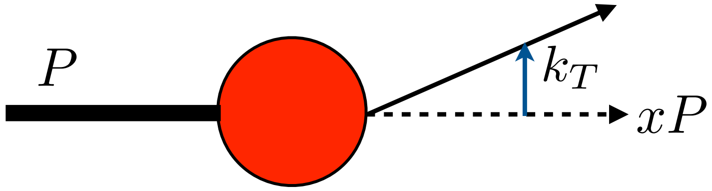
Quark TMD PDFs

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

	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)

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^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
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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**

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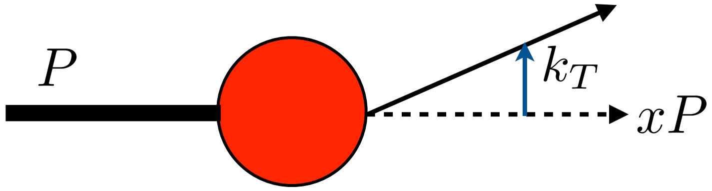

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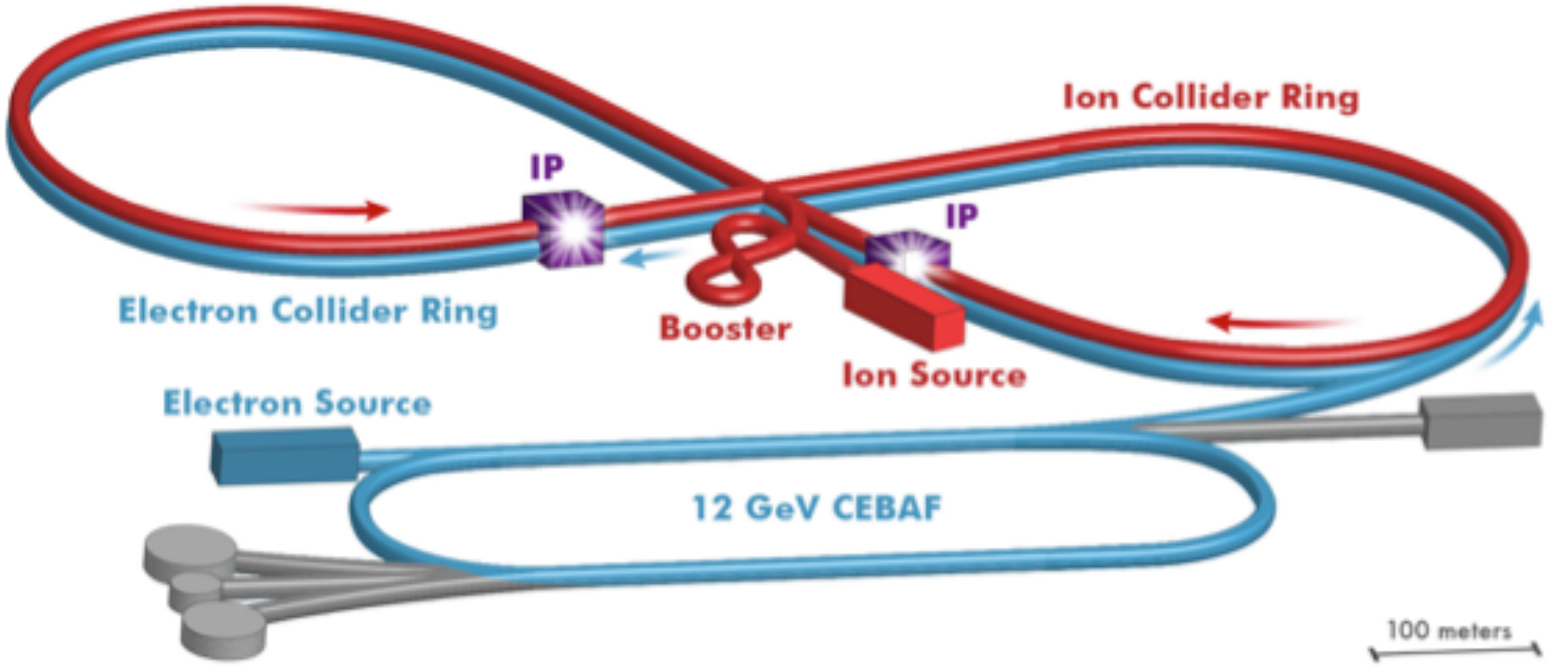


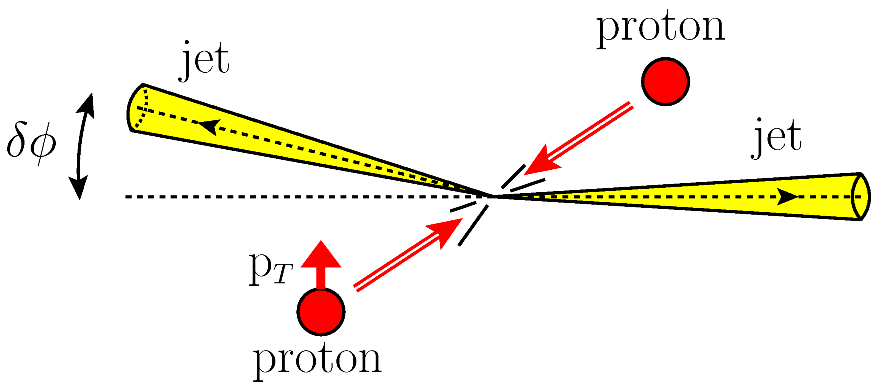
Motivations

Some references :

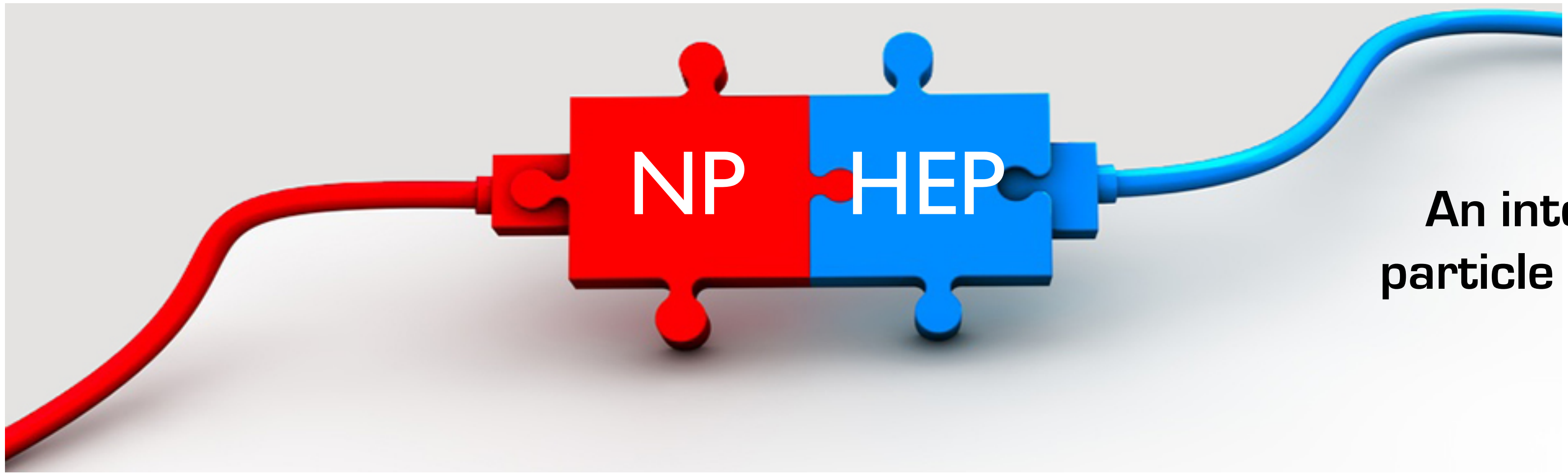
- Dudek et al. “Physics opportunities with the 12GeV upgrade at Jefferson Lab”
- Accardi et al. “Electron-Ion Collider: the next QCD frontier”
- AFTER@LHC study group “Physics opportunities with a fixed-target experiment at the LHC”
- … other existing and future facilities …

The frontier

Nucleon/nuclear tomography in momentum space: aimed at understanding how hadrons are built in terms of the elementary degrees of freedom of QCD



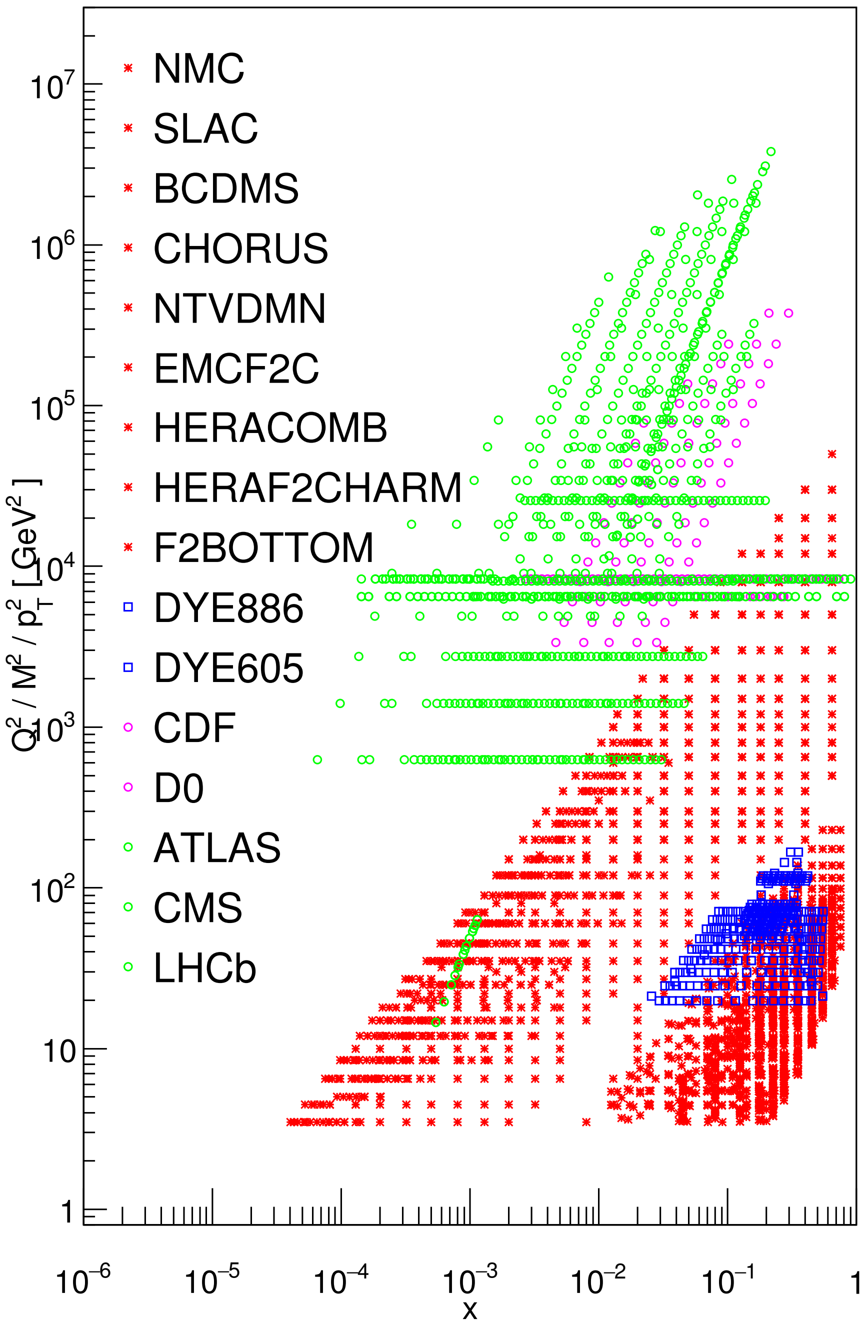
High-energy phenomenology: aimed at improving our understanding of high-energy scattering experiments and their potential to explore BSM physics assuming a certain degree of knowledge of hadron structure



An intersection between particle and nuclear physics!

Collinear vs TMD PDFs

see E. Nocera - POETIC2016



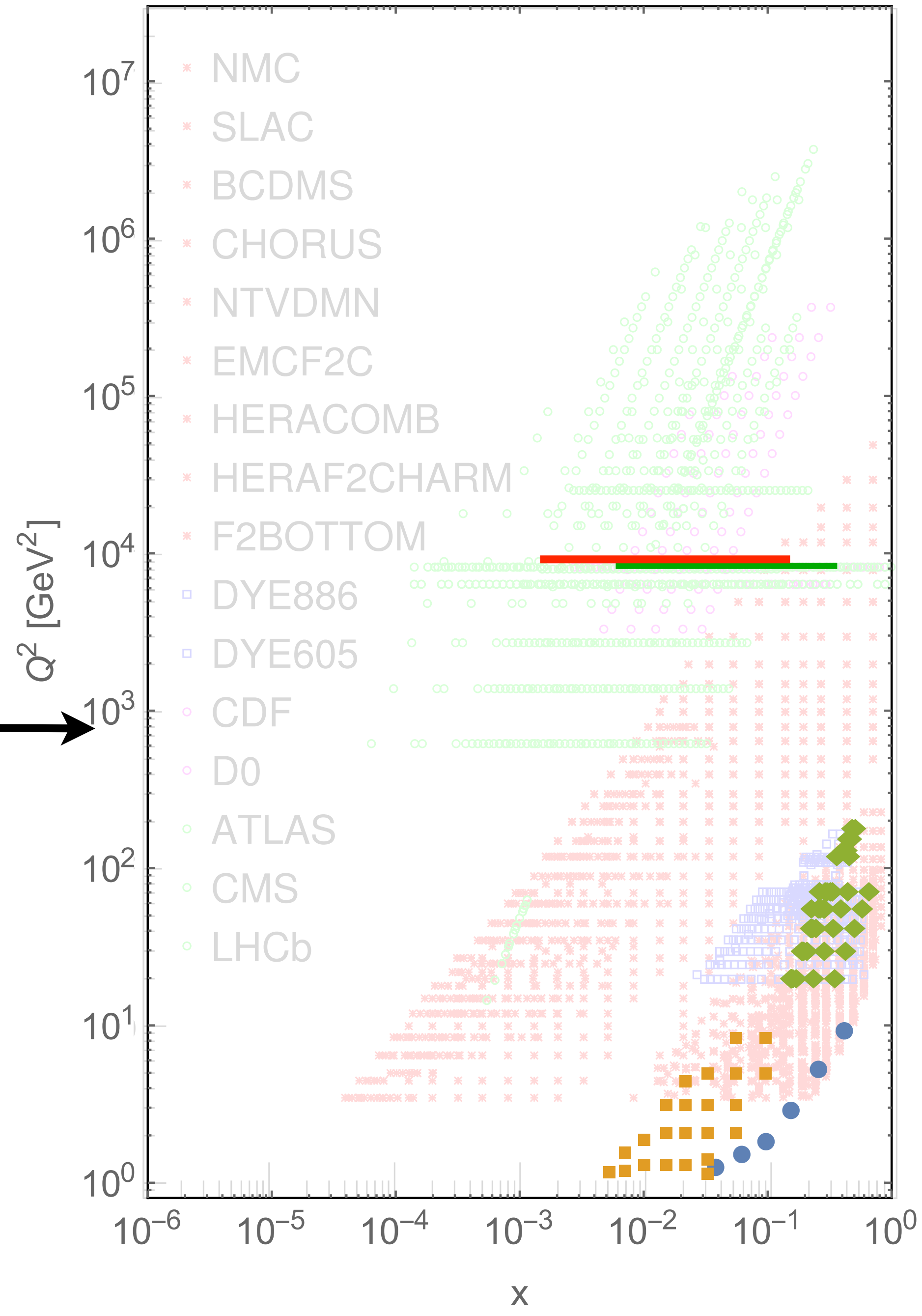
data driven science

data sets available:

collinear PDFs

vs

TMD PDFs



Q : resolution of the probe

x : momentum fraction carried by the parton

Jefferson Lab

Predictive power of TMDs

References :

- Parisi, Petronzio: Nucl. Phys. B154, 427 (1979)
- Collins, Soper, Sterman: Nucl. Phys. B250, 199 (1985)
- Qiu, Zhang: Phys. Rev. D63, 114011 (2001)
- Qiu, Berger: Phys. Rev. Lett. 91, 222003 (2003)
- Grewal, Kang, Qiu, **AS**: in preparation

Evolution of TMDs

$$f_1^a(x, b_T^2, \mu_f, \zeta_f) = f_1^a(x, b_T^2, \mu_i, \zeta_i)$$
$$\times \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\mu}{\mu} \gamma_F \left[\alpha_s(\mu), \frac{\zeta_f}{\mu^2} \right] \right\}$$
$$\times \left(\frac{\zeta_f}{\zeta_i} \right)^{-K(b_T, \mu_i)}$$

two “evolution scales”

bT, Fourier conjugate of kT

evolution in mu
$\mu_i \to \mu_f$

evolution in zeta
$\zeta_i \to \zeta_f$

need correction at large bT

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:

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

TMD PDF with large b$_T$ corrections

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

Calculable in pQCD (modulo PDFs)

To be modeled and fit to data!

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

TMD PDF with large b_T corrections

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$$F^{NP}(x, b_T, Q; b_{max}) = \exp\Big\{ - \ln\left(\frac{Q^2 b_{max}^2}{c^2}\right)\{g_1[(b^2)^\alpha - (b_{max}^2)^\alpha]\} - \ln\left(\frac{Q^2 b_{max}^2}{c^2}\right)\{g_2(b^2 - b_{max}^2)\} - \bar{g}_2(b^2 - b_{max}^2)\Big\}$$

"extrapolation term" (see also Qiu-Zhang PRD63 114011)

$g_1 \;, \alpha$

fixed as a function of the other parameters, requiring continuity of the first and second derivatives

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Correction to evolution

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"extrapolation term" (see also Qiu-Zhang PRD63 114011)

Correction to evolution

Correction to OPE at small bT (intrinsic transverse momentum)

g_1 , α

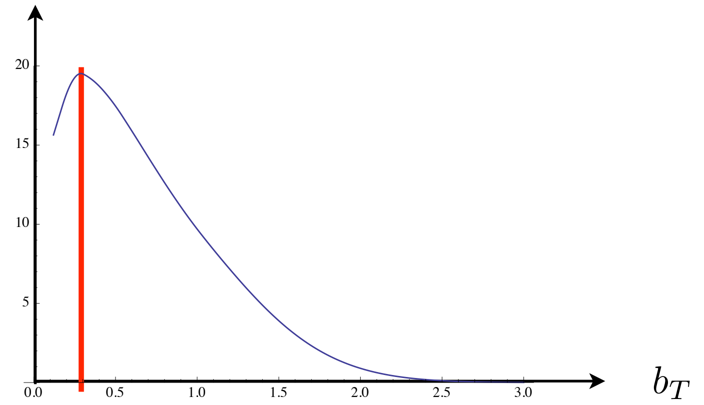
fixed as a function of the other parameters, requiring continuity of the first and second derivatives

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 :

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



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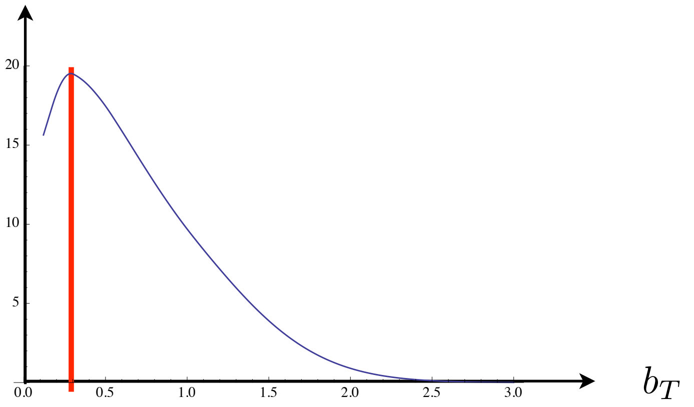

Let's apply this to a TMD PDF evaluated at kT = 0:

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

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

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

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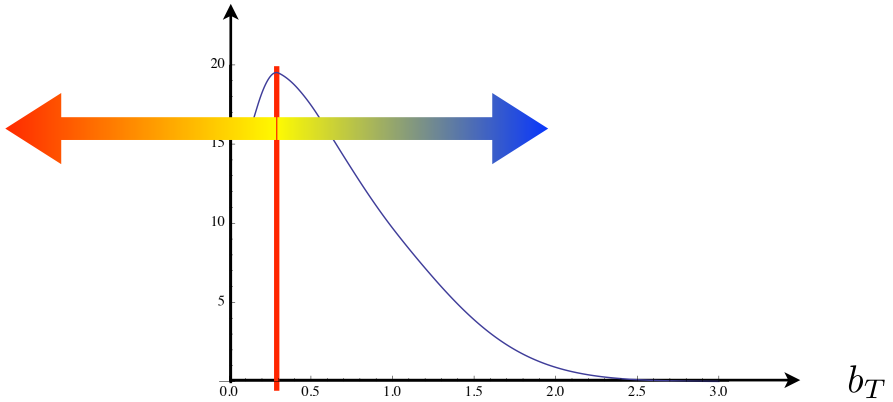

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To determine the **saddle point bTsp of the TMD PDF** we have to find the **stationary point of the exponent**

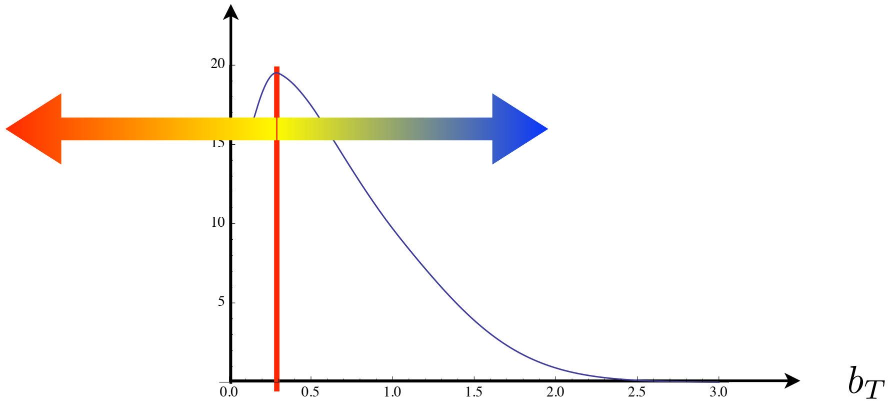
Determination of the saddle point

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

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**

Determination of the saddle point

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

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

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

Parisi and Petronzio (1979) and Collins, Soper, Sterman (1982) : the same analysis at the level of the cross section, **neglecting the x-dependent part**:

Determination of the saddle point

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

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Parisi and Petronzio (1979) and Collins, Soper, Sterman (1982) : the same analysis at the level of the cross section, **neglecting the x-dependent part**:

Conclusion : the large bT corrections are more relevant at low Q

Working at O[α] + LL we can find the following solution :

$$b_T^{sp\ 0}=\frac{c}{\Lambda}\left(\frac{Q}{\Lambda}\right)^{-\Gamma_1^{\rm cusp}/\left(\Gamma_1^{\rm cusp}+8\pi b_0\right)}$$

Determination of the saddle point

$$
\begin{aligned}
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+ \ln b_T^2 \\
+ \ln \left[\sum_b C_{a/b}(x, b_T^2, \mu_i, \zeta_i) \otimes f_b(x, \mu_i) \right] \Bigg\}_{b_T = b_T^{sp}} = 0
\end{aligned}
$$

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

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

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

Determination of the saddle point

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

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 :

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

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

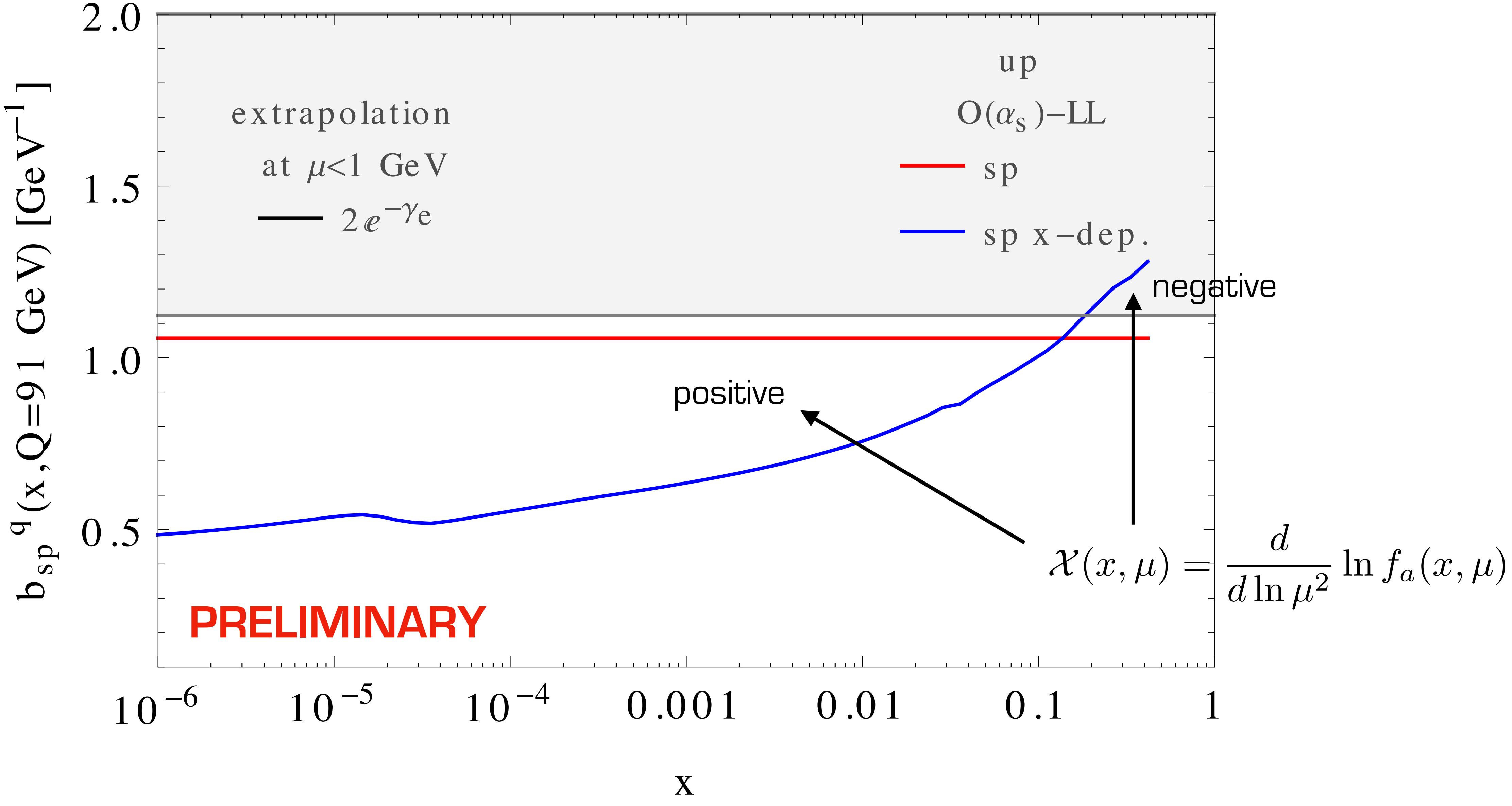
$$\mu_b^\star = 2e^{-\gamma_E}/b_T^{sp}$$

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!

Determination of the saddle point



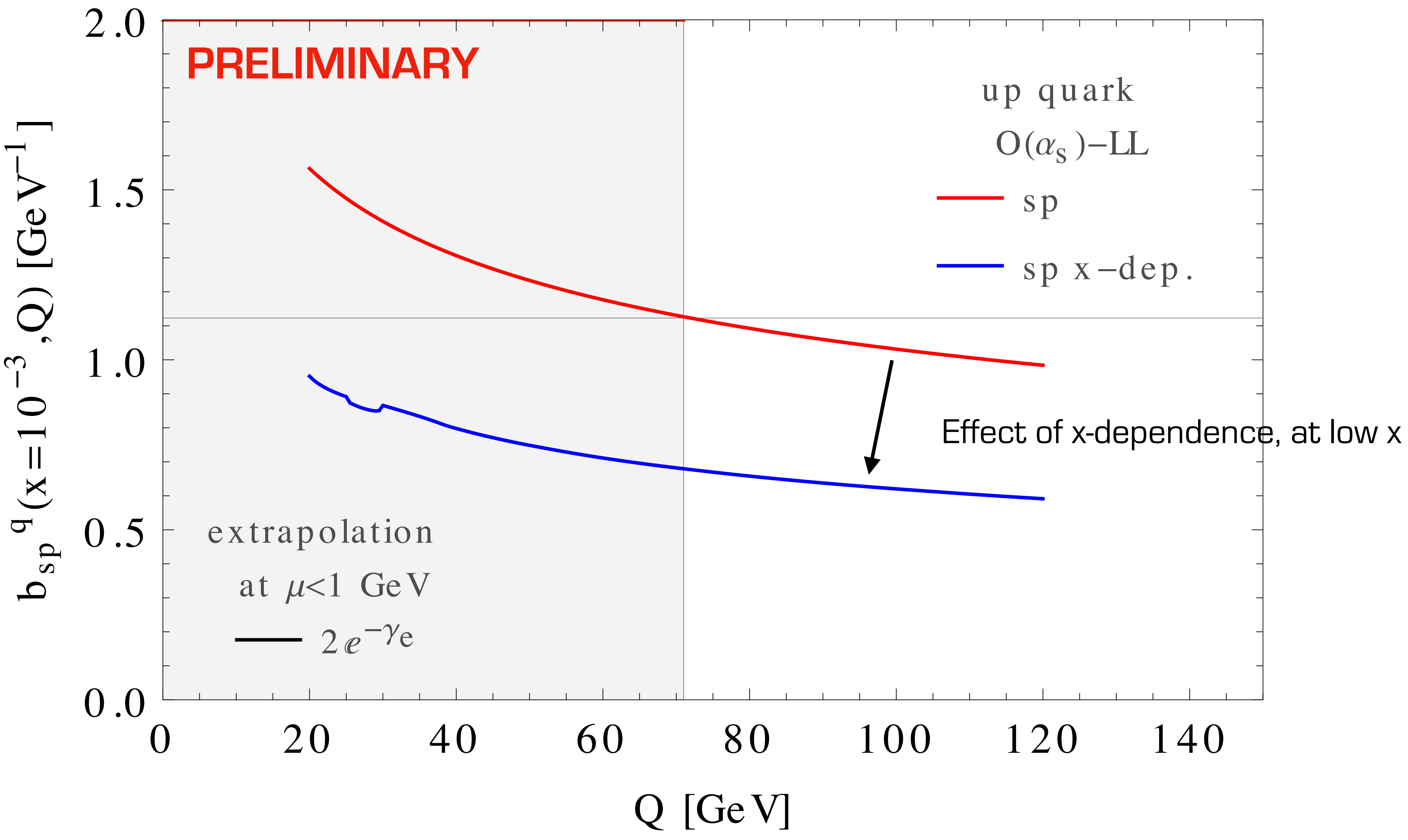
$$\mathcal{X}(x,\mu) = \frac{d}{d\ln\mu^2}\ln f_a(x,\mu)$$

Fixed Q = 91 GeV, change x

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

What happens if we include BFKL effects at very low x?

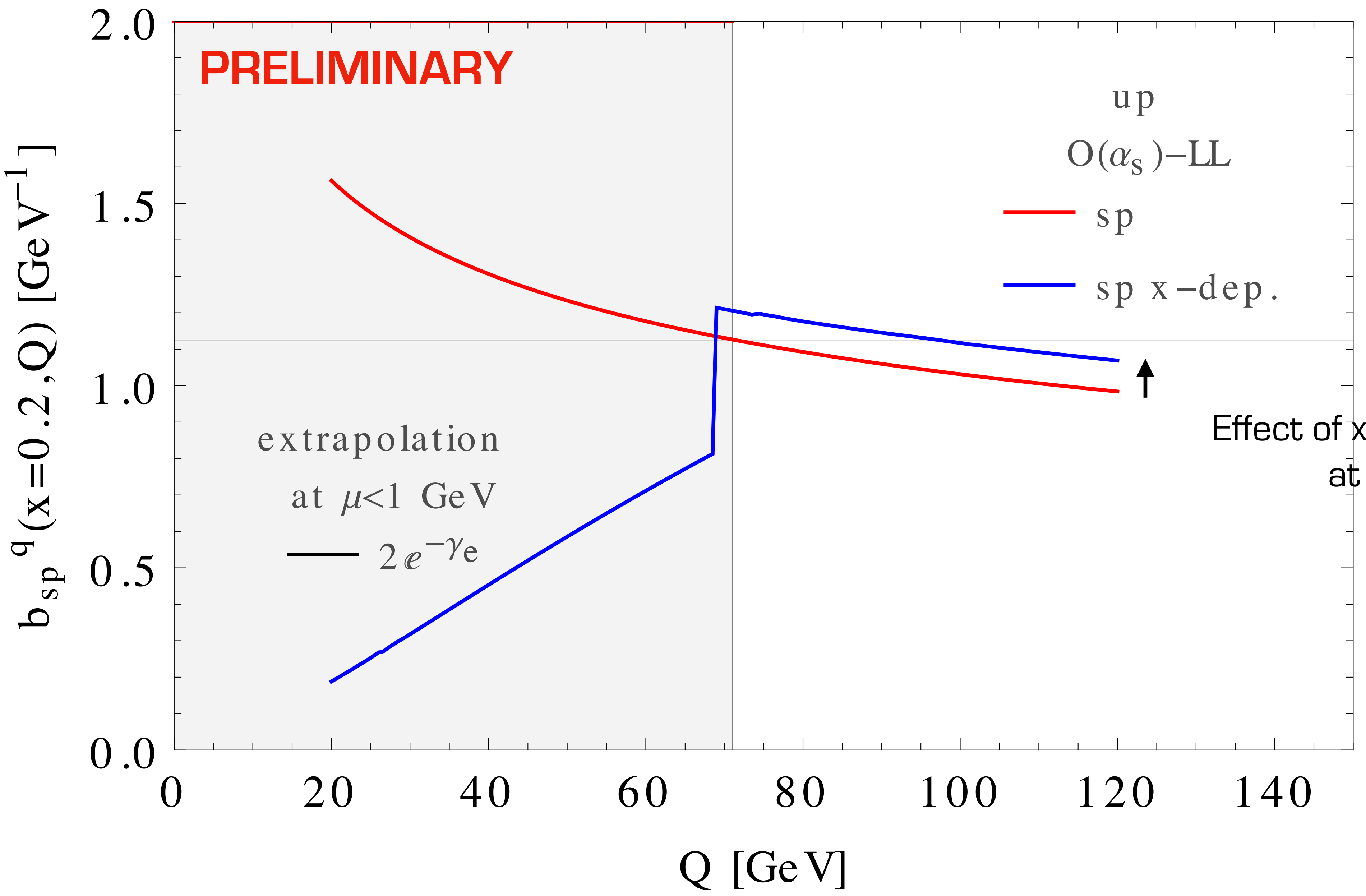
Determination of the saddle point



Fixed x = 0.001, change Q

At **low x**, the x-dependent solution is **reduced** uniformly with respect to the CSS-like solution

Determination of the saddle point

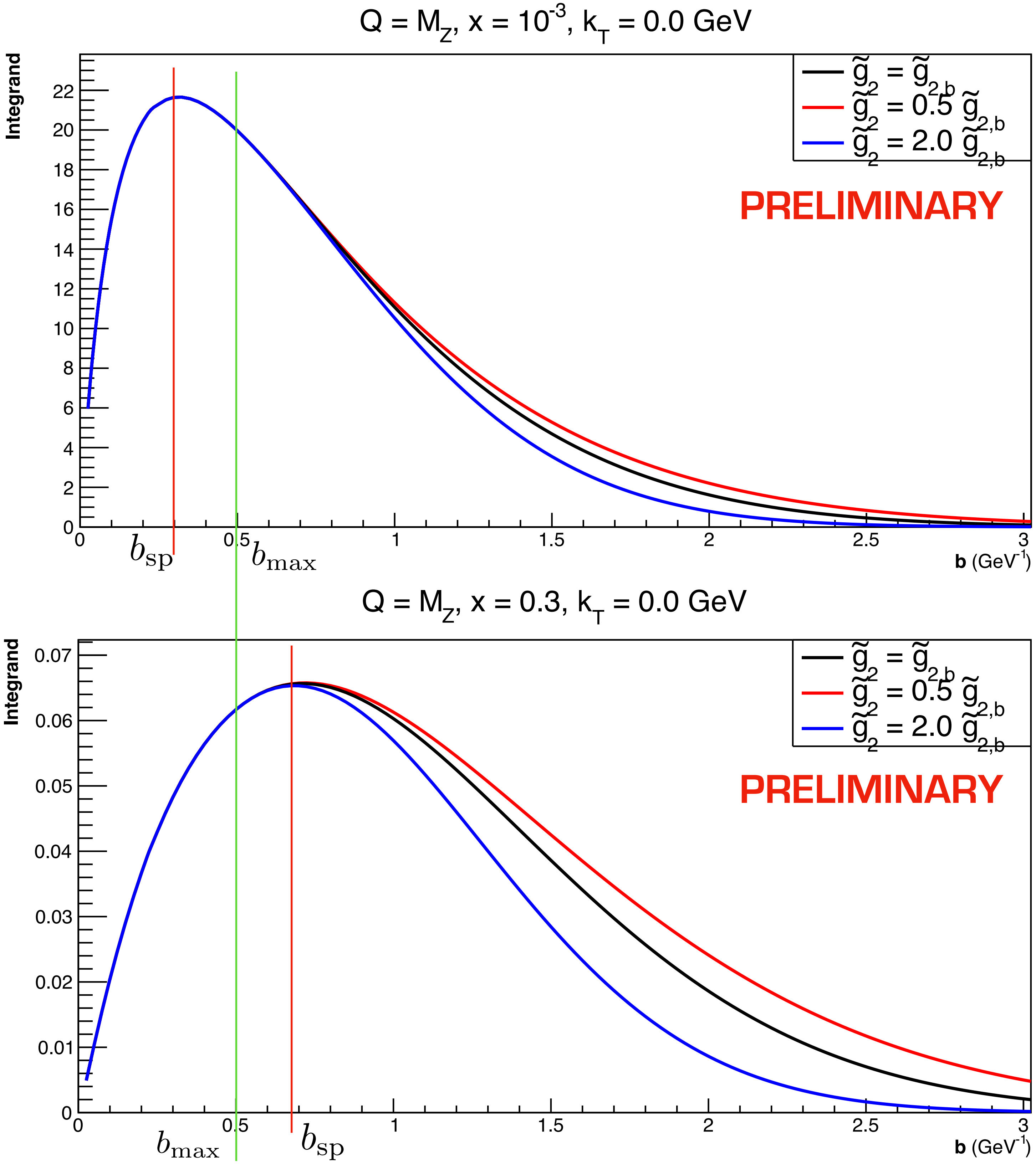


Effect of x-dependence, at high x

Fixed x = 0.2, change Q
At **high x**, the x-dependent solution is **enhanced** uniformly with respect to the CSS-like solution

Quark TMD PDFs

NNLO and NNLL



Predictive power is maximum at large Q and small x.

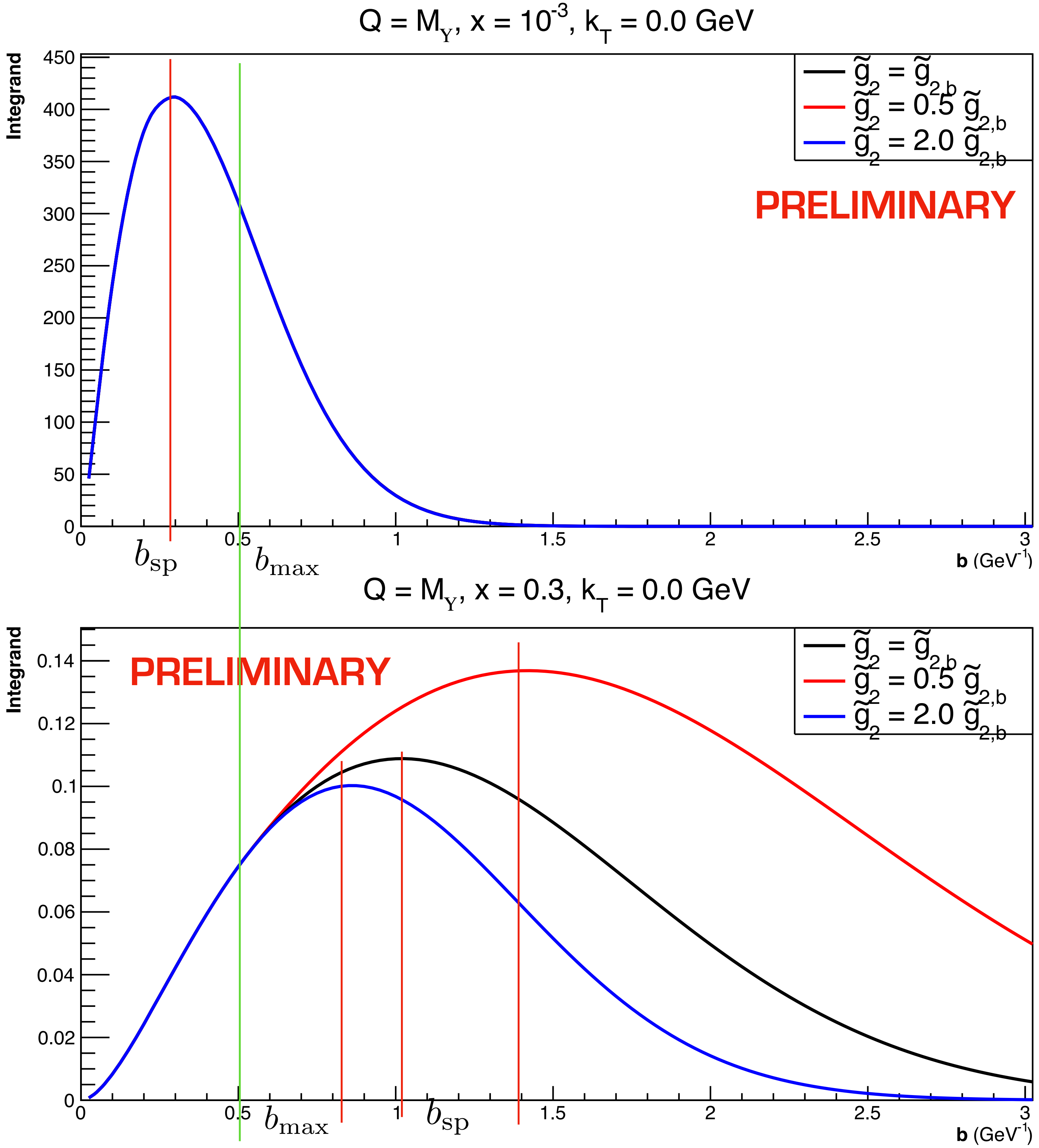
But Q alone does not provide the full picture:

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

Gluon TMD PDFs

NNLO and NNLL



For **gluons the evolution is stronger** and the NP is less relevant already at lower Q.

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

Partial summary

The **predictive power of TMD PDFs** is maximum in the **high Q and small-x** corner of the phase space (e.g. VB production at the LHC)

On the contrary, the relevance of the large bT corrections is maximum at low Q and high x

- the "**sweet spot" to study 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.);

An example: W boson production at central rapidity at RHIC

We should also understand what happens in the region of high Q and small x (for example W boson production at the LHC), where the relevance should be "minimal"

How small is "minimal" ?

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

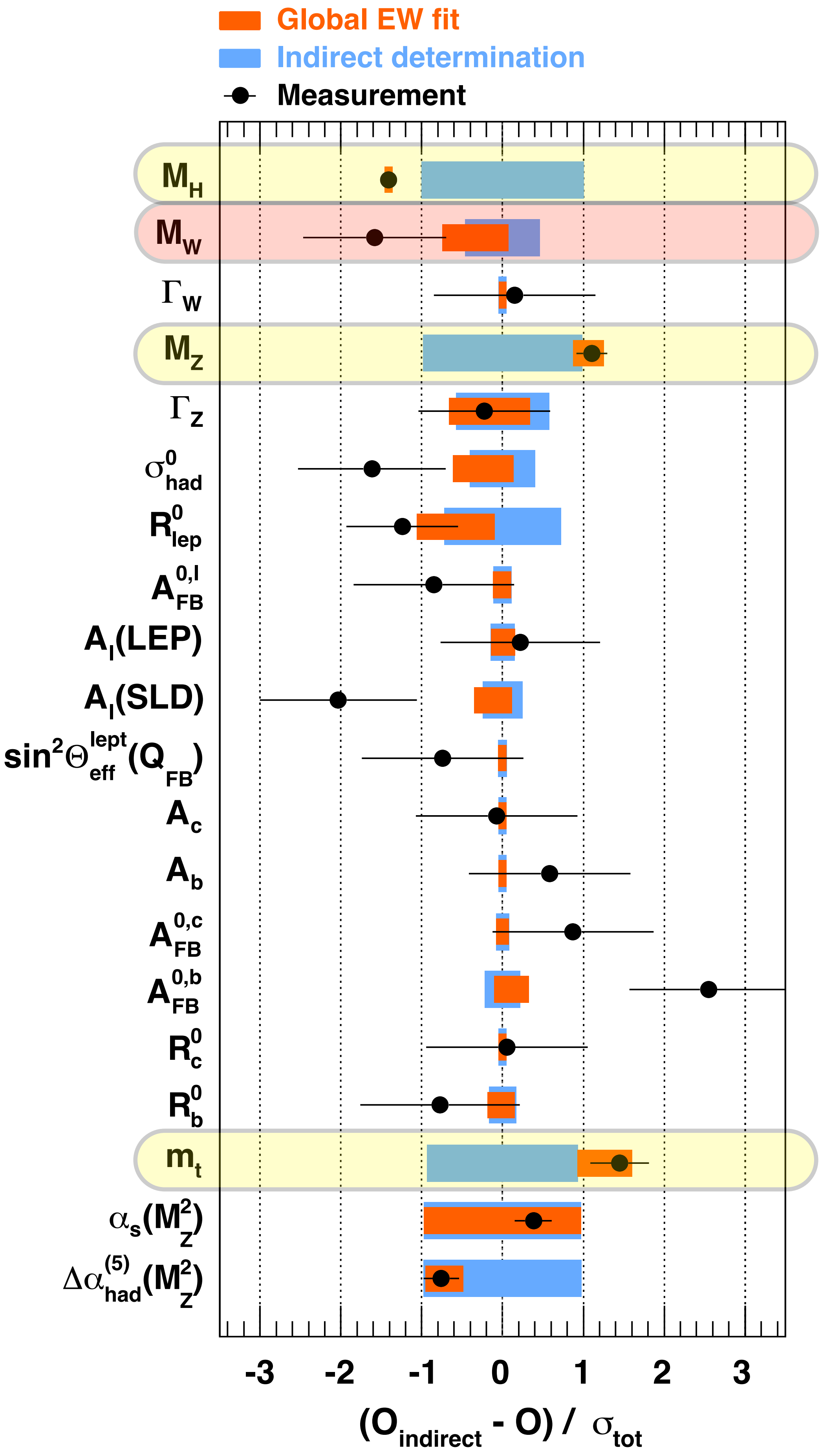
2) Looking for hints of physics **beyond** the SM

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** !

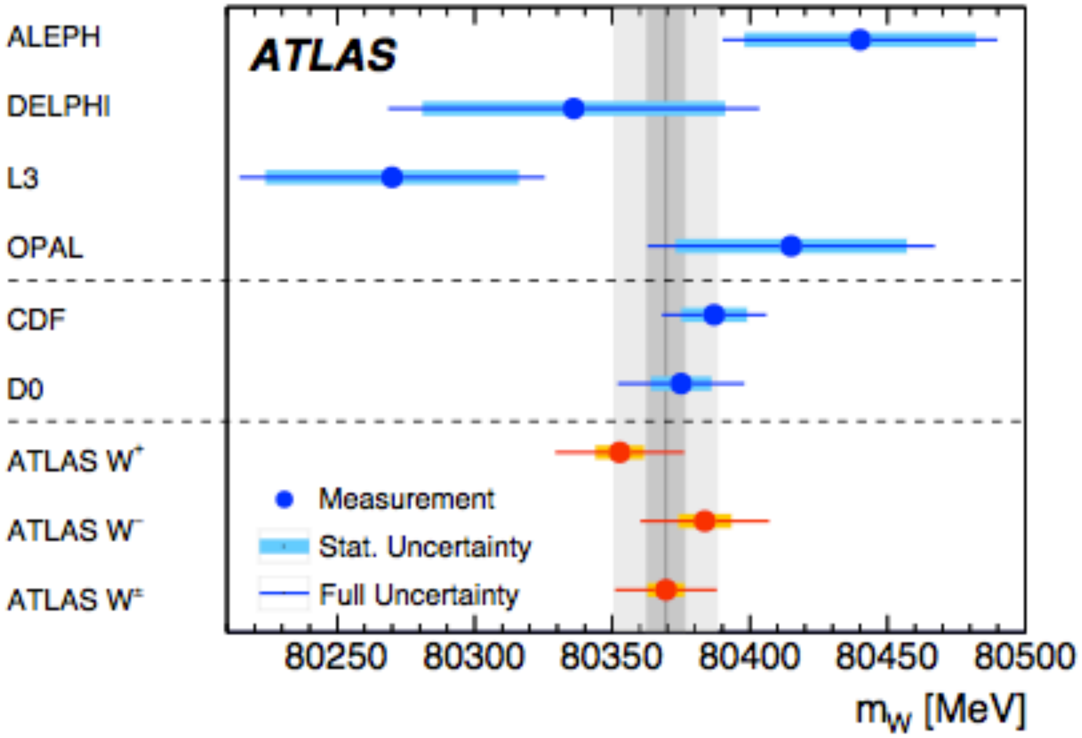
see:

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



W mass

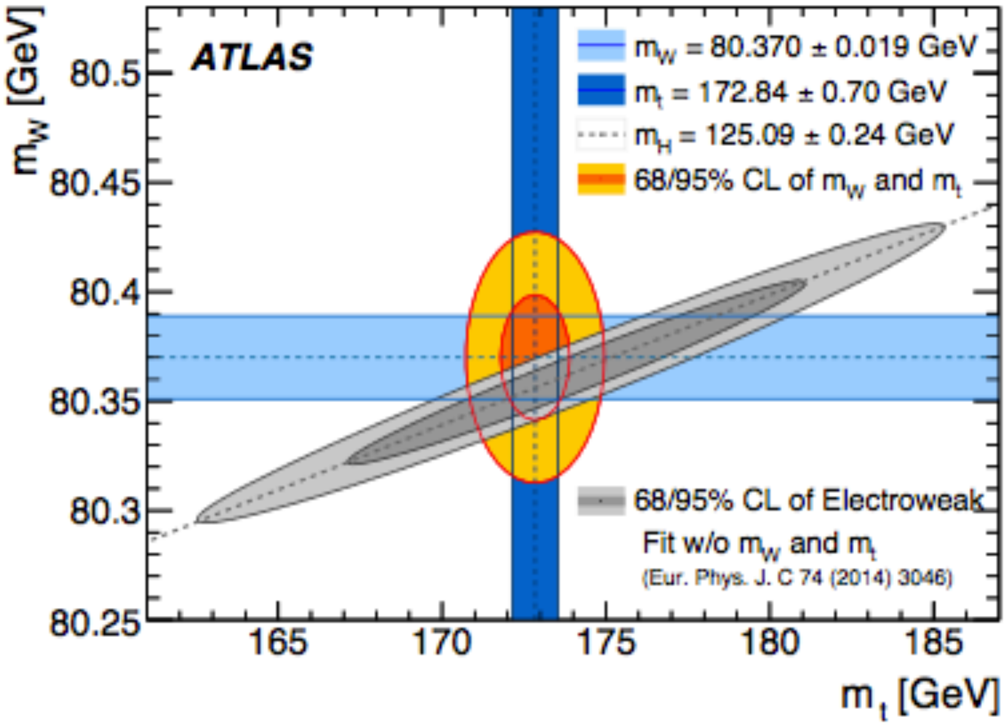
ATLAS, arxiv:1701.07240



Experimental measurements

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

(7 stat, 11 exp, 14 th)



Global EW fit

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

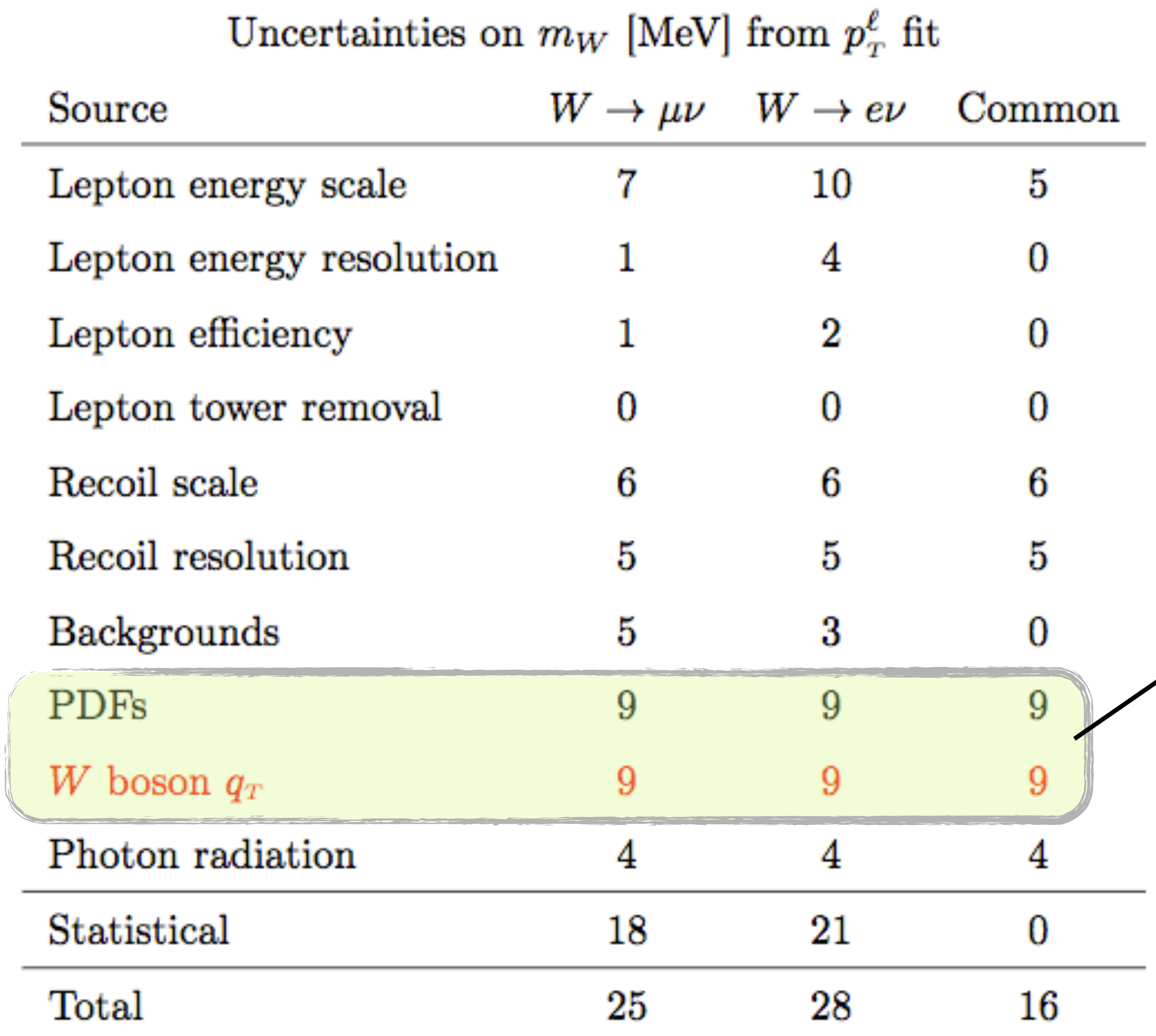
Need to **better control the uncertainties**
associated to
direct determinations of mW

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?

Uncertainties on W mass

AS - PhD thesis



Uncertainties on m_W [MeV] from p_T^ℓ fit

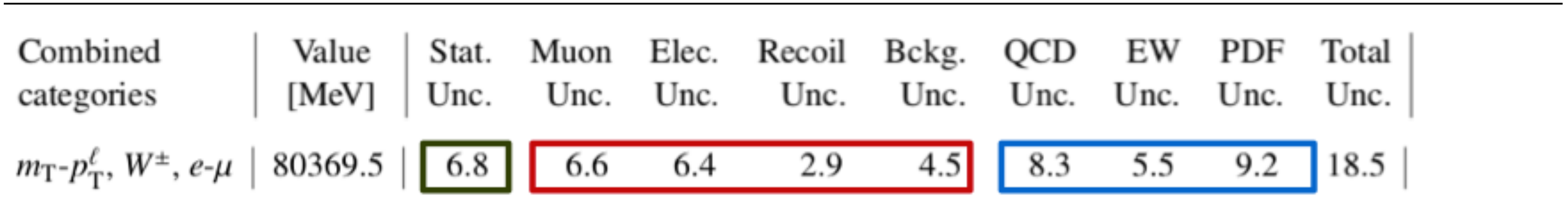
Source	$W \to \mu\nu$	$W \to e\nu$	Common
Lepton energy scale	7	10	5
Lepton energy resolution	1	4	0
Lepton efficiency	1	2	0
Lepton tower removal	0	0	0
Recoil scale	6	6	6
Recoil resolution	5	5	5
Backgrounds	5	3	0
PDFs	9	9	9
W boson q_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

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

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
  ⇨ no universal (flavour-independent) model

- 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

Impact on mW: preliminary results

- Select 15 *flavour-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 (*flavour-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)]

Conclusions

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(but beware of thresholds effects, etc.);

An example: W boson production at central rapidity at RHIC

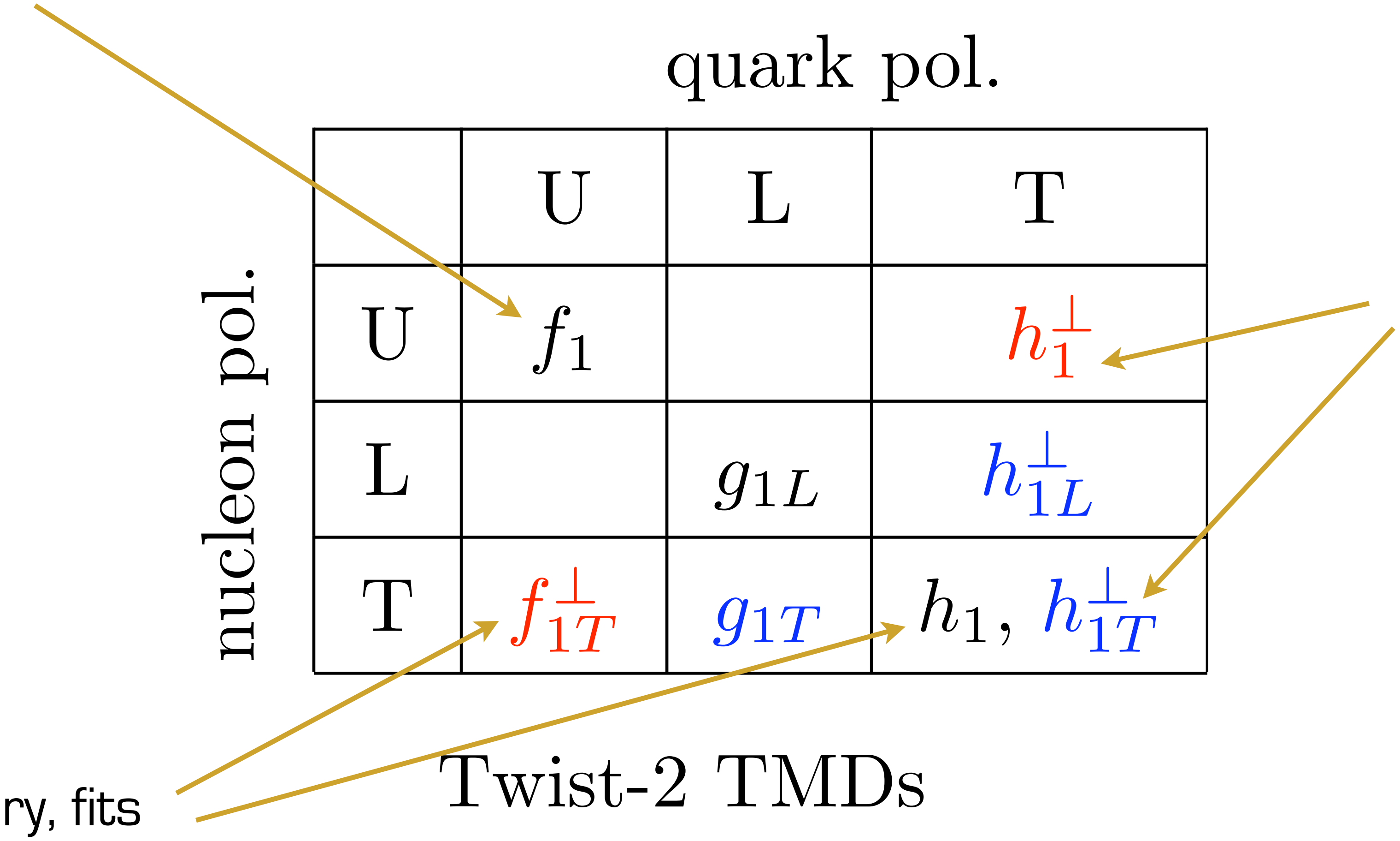
We should also understand what happens in the region of high Q and small x (for example W boson production at the LHC), where the relevance should be "minimal"

How small is "minimal" ? "Minimal" is non-negligible!!

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

Structure functions

$\ell P \to \ell' h X$

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\quad \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\qquad +\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\qquad +S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\qquad +S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\qquad +|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad\qquad +\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad\qquad +\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\qquad +|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad\qquad +\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
\tag{2.7}
$$

Cross section
expanded in terms of
structure functions

criterion:
Lorentz symmetry

indexes = **polarization** state
first: lepton
second: hadron
(third: photon)

Structure functions

$\ell P \to \ell' h X$

$$
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&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_\parallel\biggl[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\biggr] \\
&\quad+S_\parallel\lambda_e\biggl[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\biggr] \\
&\quad+|\boldsymbol{S}_\perp|\biggl[\sin(\phi_h-\phi_S)\,\Bigl(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Bigr) \\
&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\biggr] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\biggl[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\biggr]\biggr\}, \qquad (2.7)
\end{aligned}
$$

Cross section
expanded in terms of
structure functions

For each:
different factorization theorems
at low and high transverse
momentum

How to match these?

Structure functions

$\ell P \to \ell' h X$

$$
\begin{aligned}
&\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad +\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad +S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad +S_{\|}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad +|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad +\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad +\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad +|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad +\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}, \qquad (2.7)
\end{aligned}
$$

structure functions :

convolutions of

TMD PDFs and FFs

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

+ higher-twist contributions

Structure functions

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&\quad + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
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Jefferson Lab

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&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,\overset{\text{e(x) - twist 3}}{F_{LU}^{\sin\phi_h}} \\
&+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
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&\qquad\qquad\qquad\qquad\text{Boer-Mulders} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad+S_{\|}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
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&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}, \qquad (2.7)
\end{aligned}
$$

structure functions :

convolutions of

TMD PDFs and FFs

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

+ higher-twist contributions

Structure functions

$\ell P \to \ell' h X$

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad +\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad +S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad +S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad +|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(\overset{\text{Sivers}}{\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}}}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\qquad +\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad +\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&\quad +|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
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Twist-2 TMDs

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Jefferson Lab

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&\qquad+\varepsilon\,\sin(\phi_h+\phi_S)\,\overset{\text{transversity}}{F_{UT}^{\sin(\phi_h+\phi_S)}}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
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\end{aligned}\tag{2.7}$$

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	T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Twist-2 TMDs

+ higher-twist contributions

More motivations

f_1

unpolarized TMD PDF:
- test of factorization formalism
- improve our description of qT spectra (e.g. at **W at LHC**)
- baseline to extract polarized TMDs from asymmetries

e

collinear twist 3 PDF e(x):
- insights in quark-gluon-quark correlations
- scalar charge of the nucleon

$h_1^\perp \; , \quad f_{1T}^\perp$

T-odd Boer-Mulders and Sivers TMD PDFs:
- rigorous tests of the symmetry properties of QCD (sign change between SIDIS and Drell-Yan)

h_1

transversity (TMD) PDF:
- access to the tensor charge of the nucleon
- window on BSM physics
- also accessible via jets ?

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$$f_1$$

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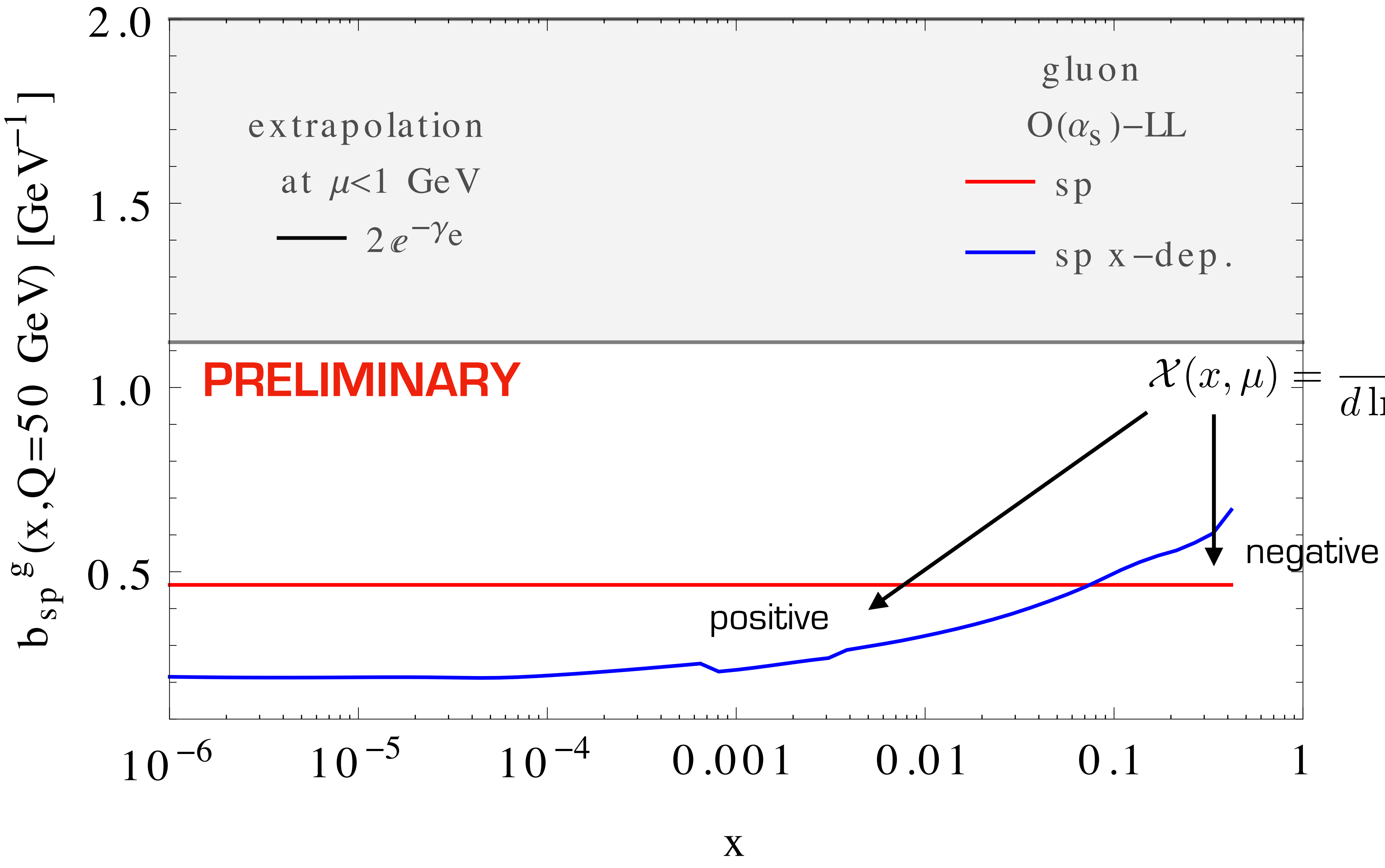
$$h_{1LT}$$

collinear spin-1 function:
- another rigorous test of QCD symmetries
- T-odd effects in **spin-1** hadrons

Determination of the saddle point

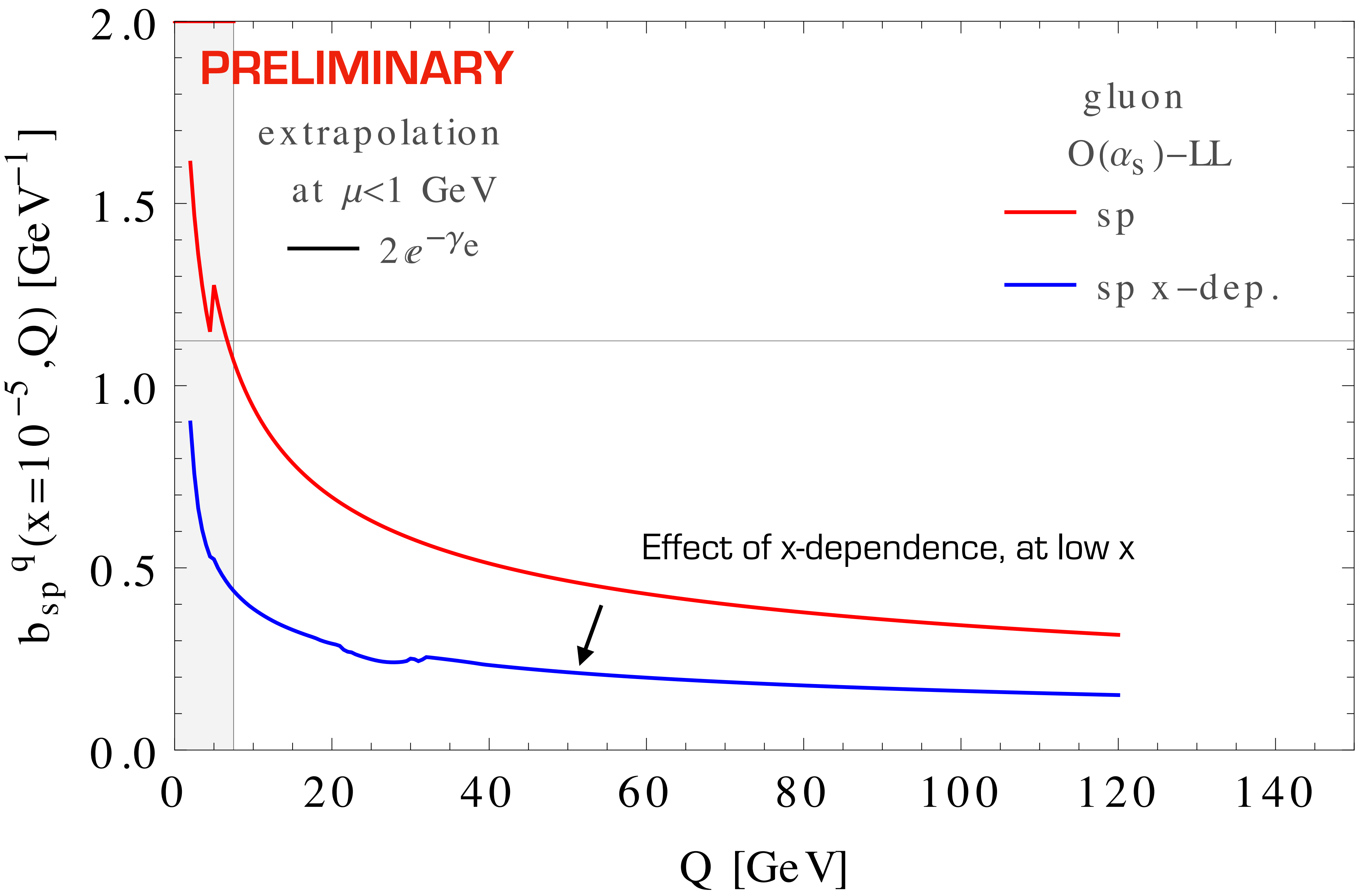


$$\mathcal{X}(x,\mu) = \frac{d}{d\ln\mu^2}\ln f_a(x,\mu)$$

Fixed Q = 50 GeV, change x
the x dependence determines a change with respect to CSS-like solution

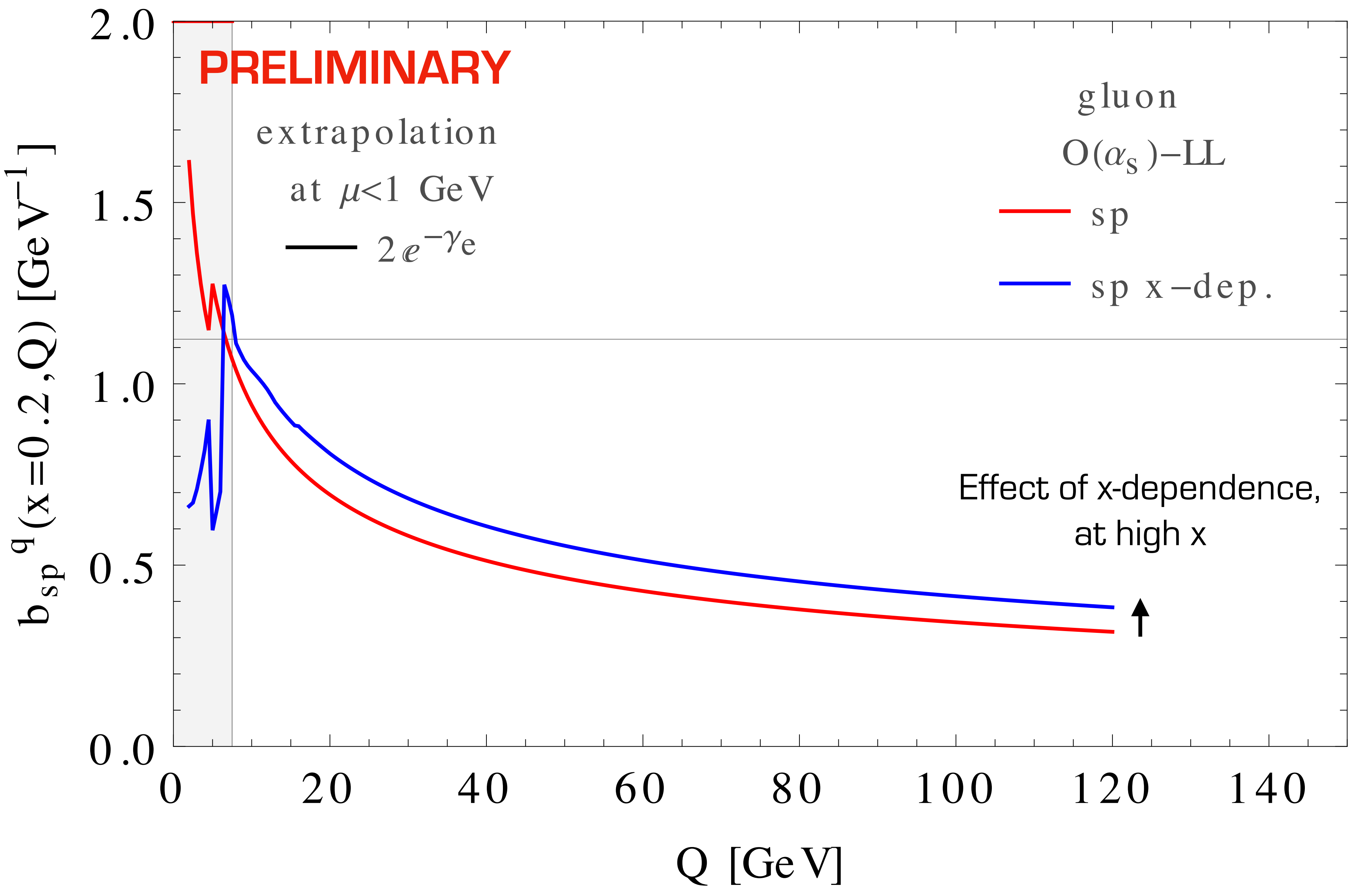
What happens if we include BFKL effects at very low x?

Determination of the saddle point



Fixed x = 0.00001, change Q
At low x, the x-dependent solution is reduced uniformly with respect
to the CSS-like solution

Determination of the saddle point

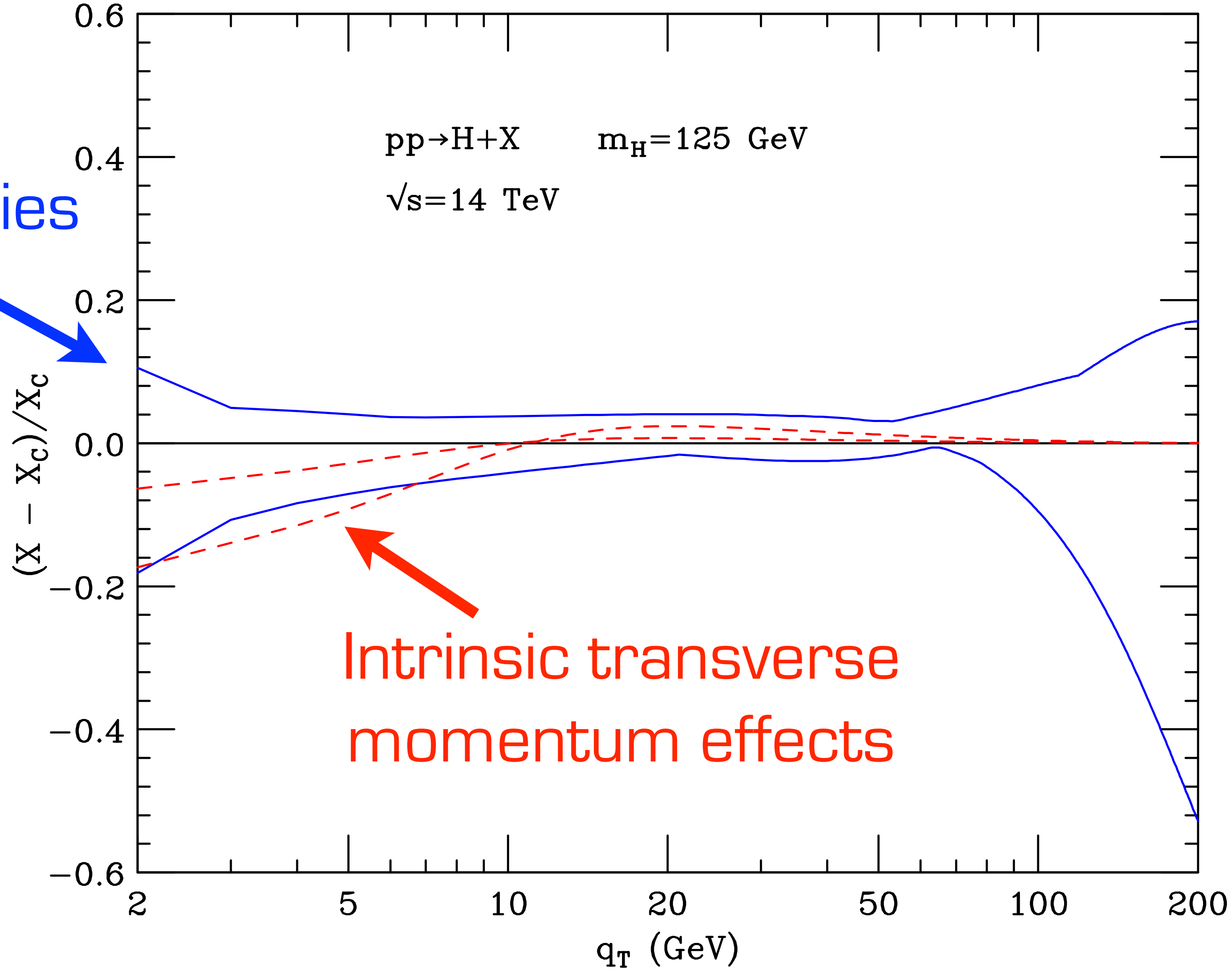


Fixed x = 0.2, change Q
At high x, the x-dependent solution is enhanced uniformly with respect to the CSS-like solution

Impact on Higgs physics

G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

PDF uncertainties



Intrinsic transverse momentum effects