The proton and its spin in 3D momentum space

Andrea Signori

EDS Blois 2019

Quy Nhon, Vietnam (remote talk)

June 27th, 2019

Outline of the talk

Hadron structure … :

1) Transverse-momentum-dependent distributions (TMDs)

2) Transverse spin and the Sivers function

… and connection to high-energy physics:

3) The unpolarized TMD PDF

4) impact on W mass determination

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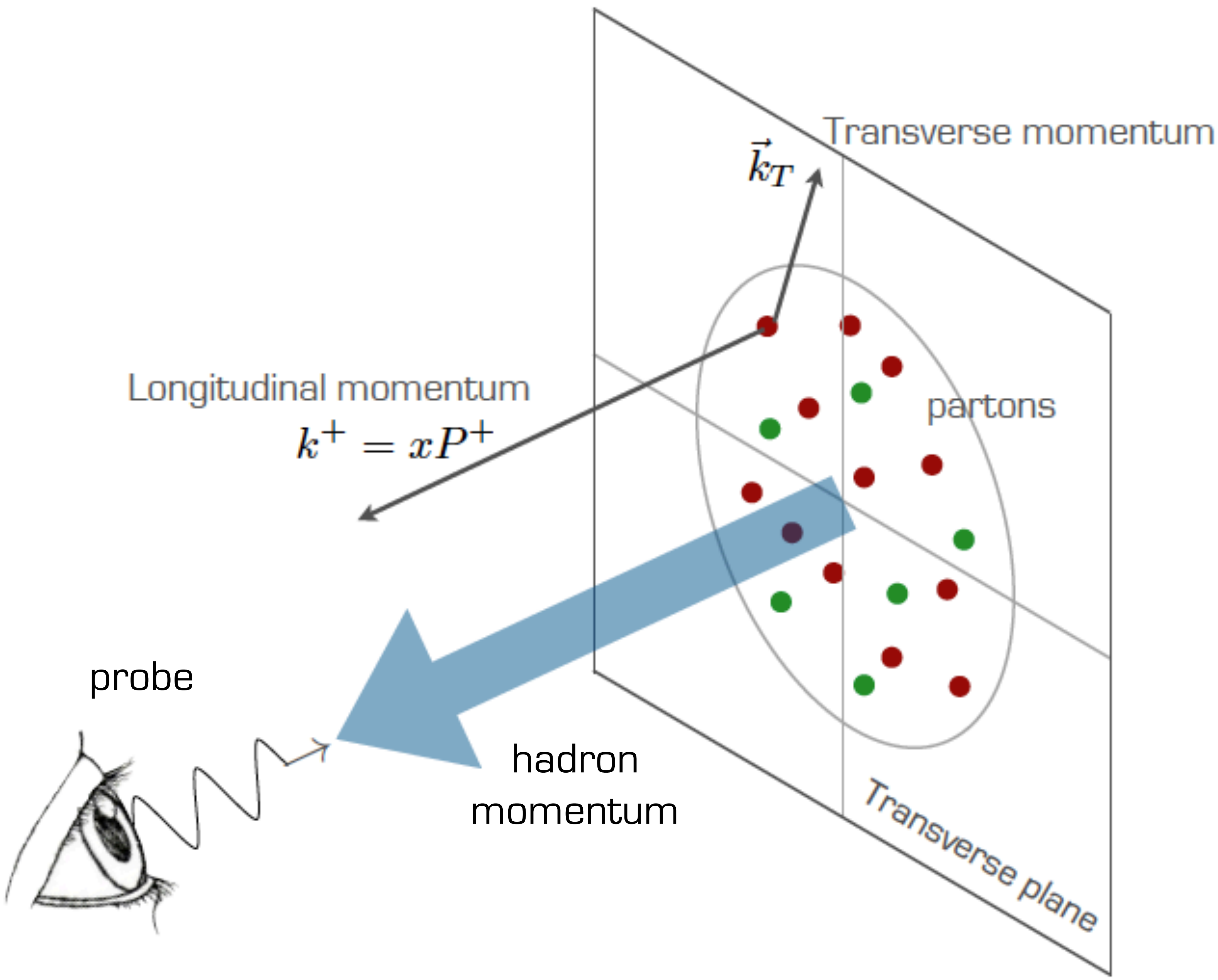
TMDs

TMD PDFs

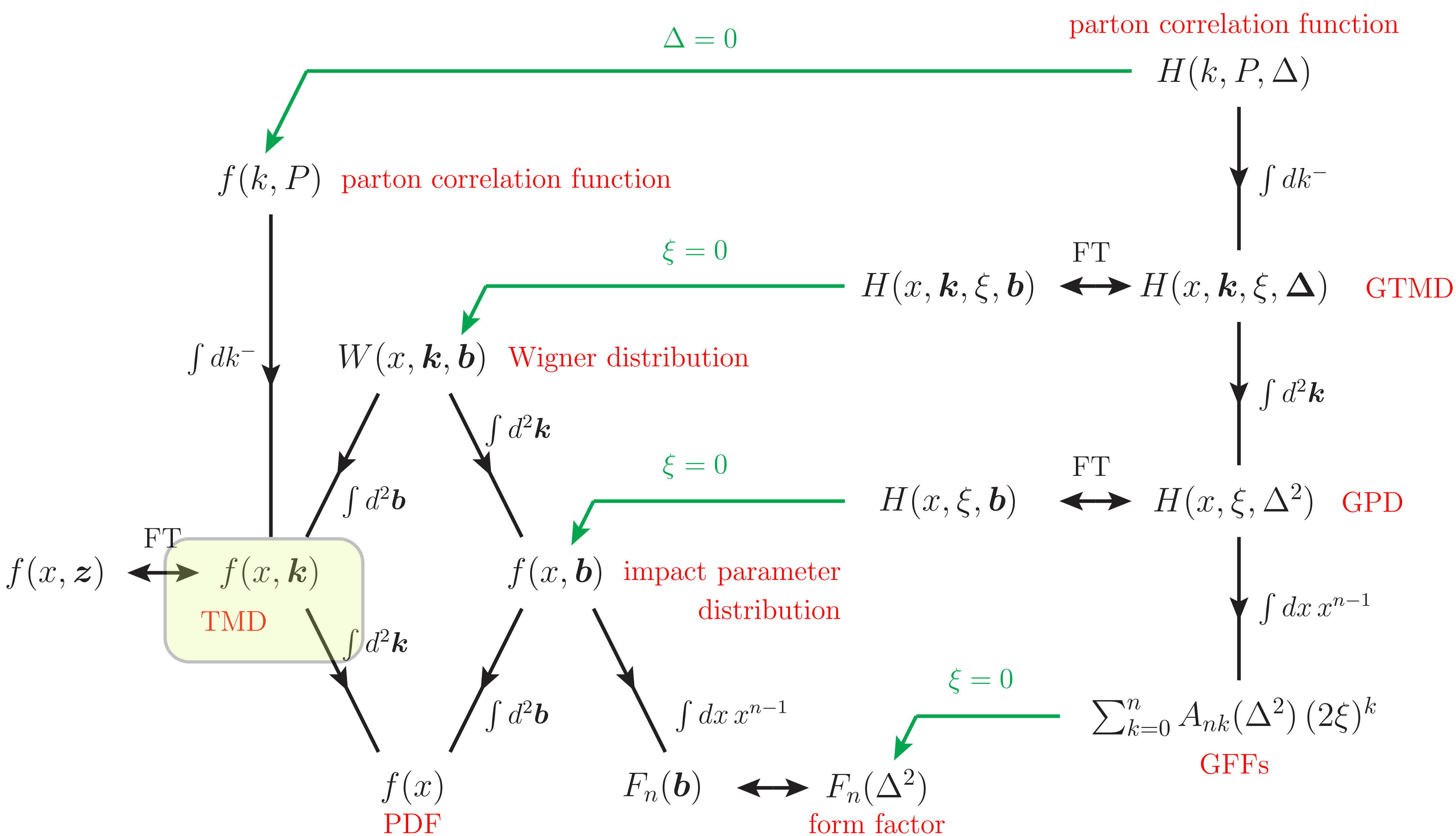


extraction of a **parton** whose momentum has **longitudinal** and **transverse components** with respect to the parent **hadron** momentum

richer structure than collinear PDFs

courtesy A. Bacchetta

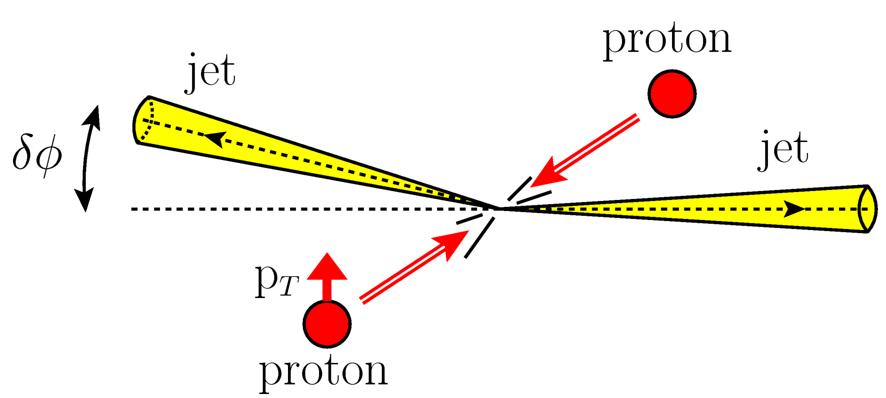
Hadron tomography



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

Motivations

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:
improve our understanding of 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!**

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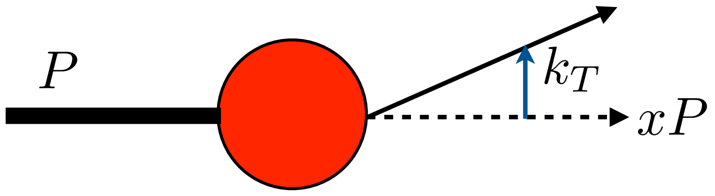
Quark TMD PDFs

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

	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 ($f_{1T}^\perp$)

unpolarized TMD PDF (f_1)



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

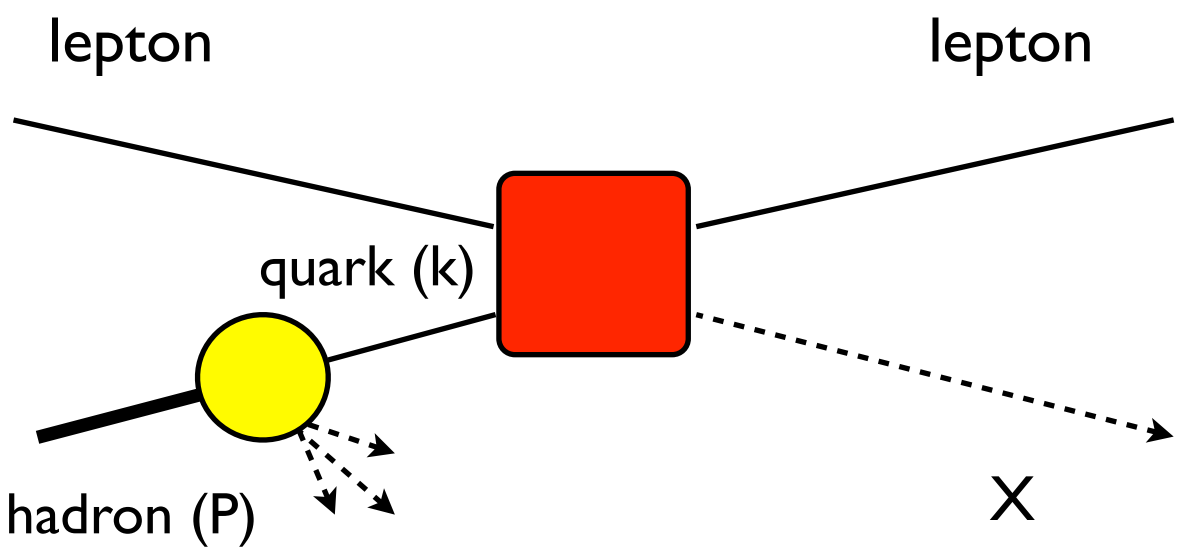
similar table for **gluons** and for **fragmentation**

bold : also collinear

red : time-reversal odd (universality properties)

The Sivers function

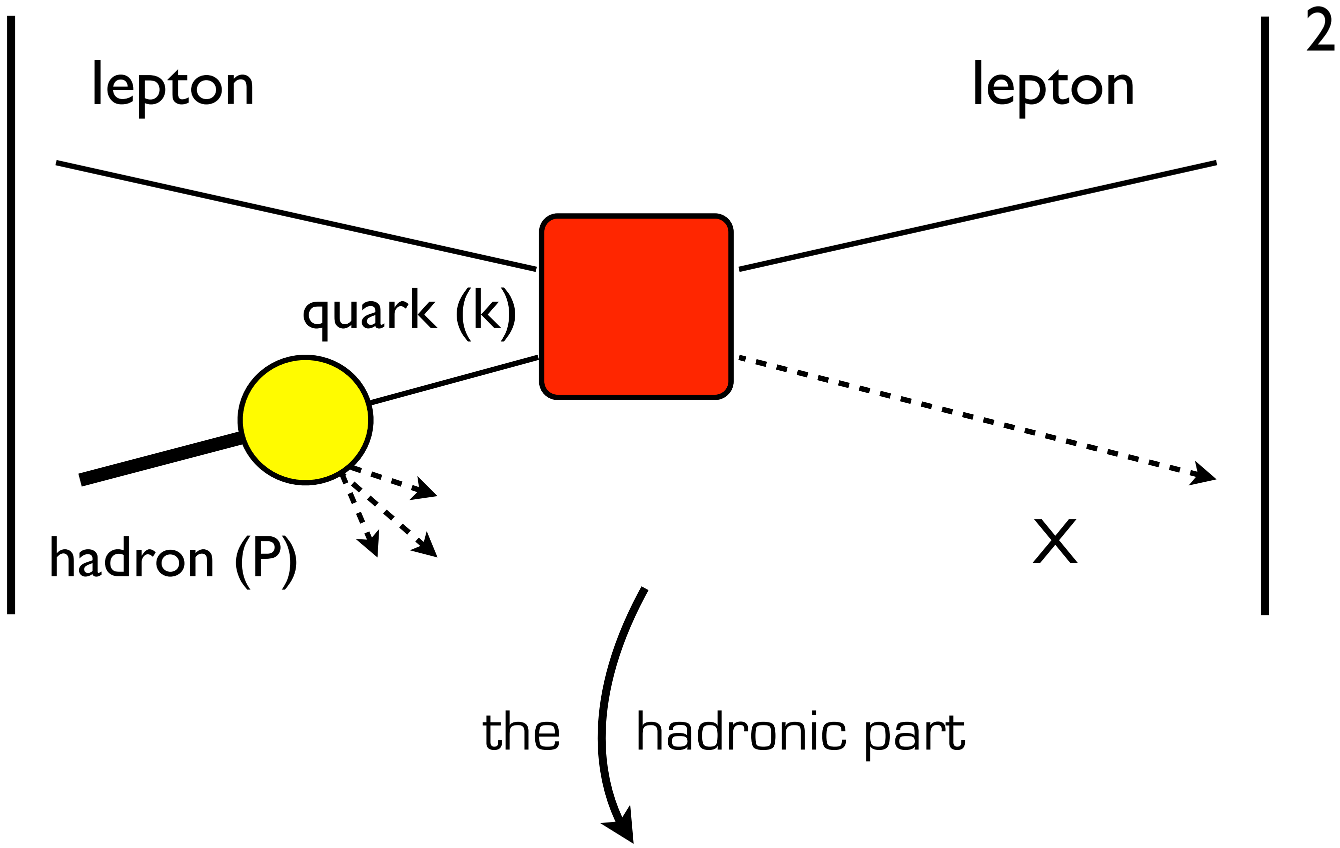
Quark correlations



scattering process participated
by a hadron :
need a “transition” from the hadron
to a parton

Parton Distribution Function - PDF

Quark correlations



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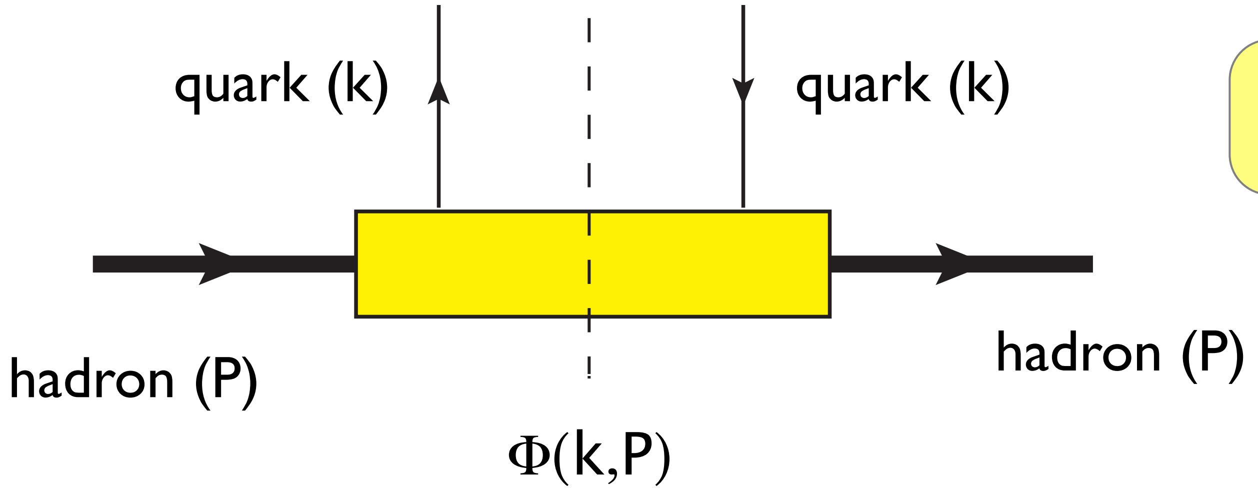

hadronic part
described as a **quark-quark correlation** in space-time

$$\Phi(k,P) = \text{F.T.} \langle P | \overline{\psi_j}(0)\ U\ \psi_i(\xi) | P \rangle$$

ξ is the Fourier-conjugated of
quark momentum k

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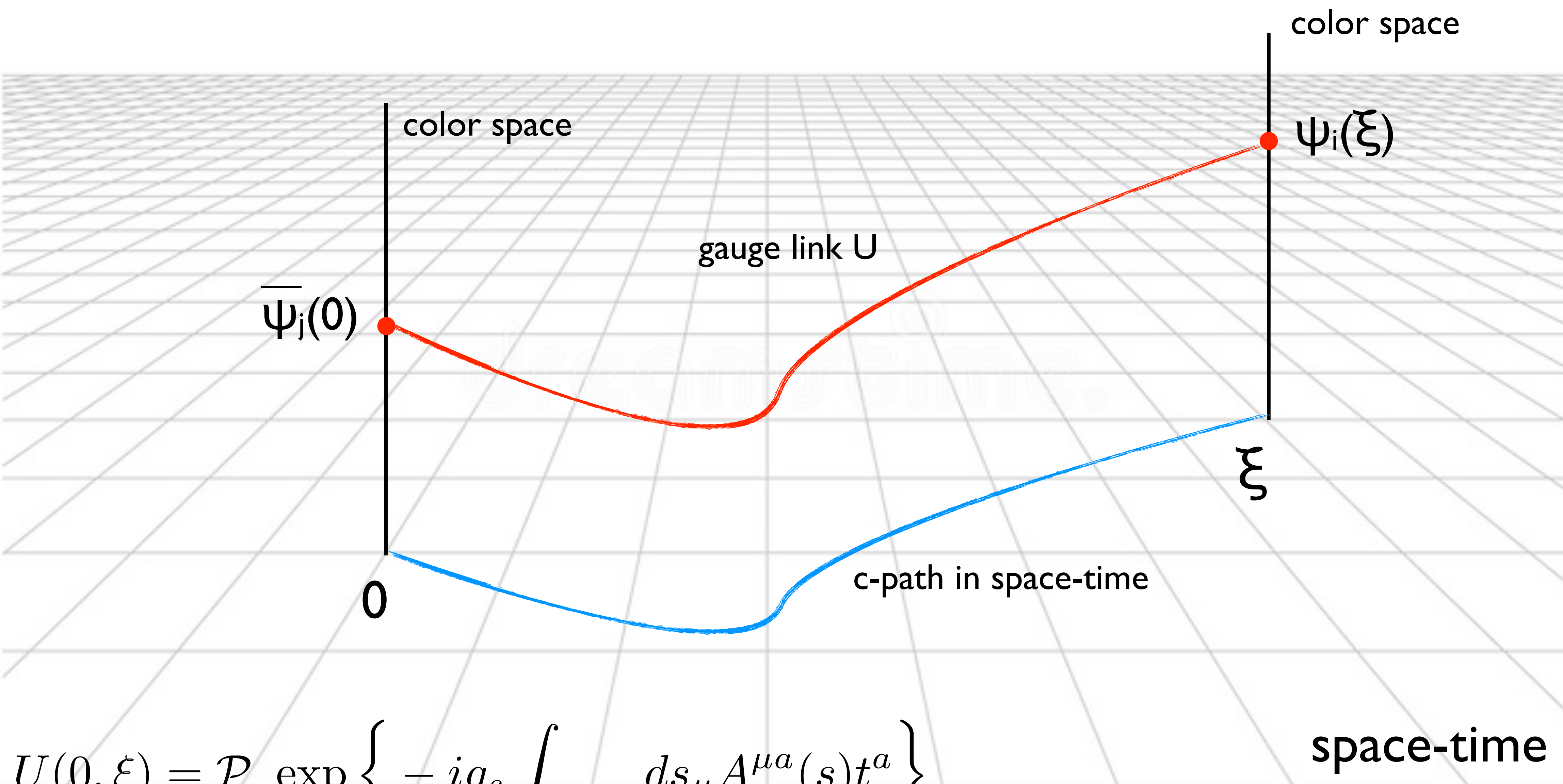
Gauge invariance

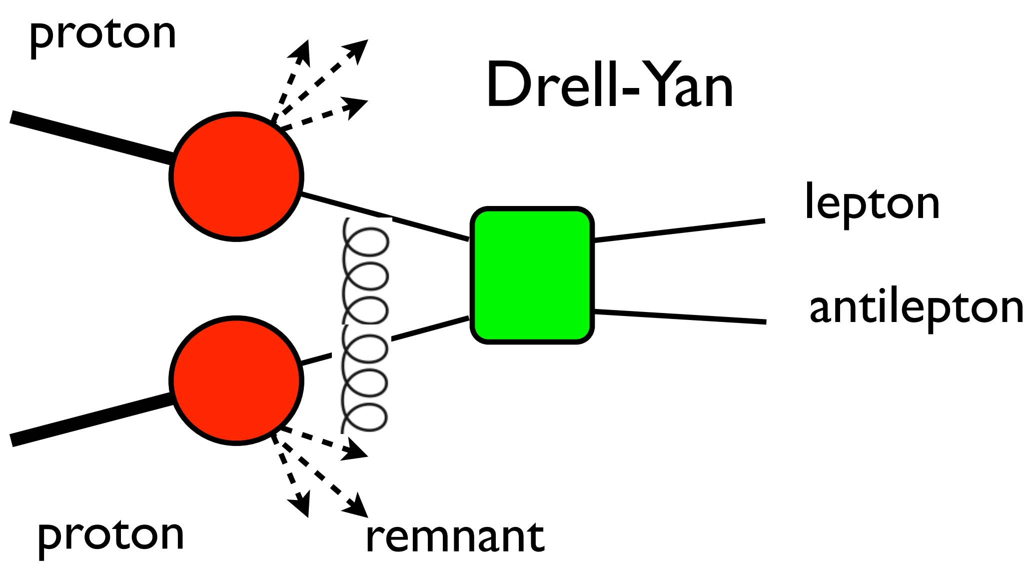
$$\Phi(k,P) = \text{F.T.}\langle P|\overline{\psi_j}(0)\; U\; \psi_i(\xi)|P\rangle \longrightarrow f_1^{a\;[U]}(x,k_T^2)\; \not{P} + \cdots$$



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

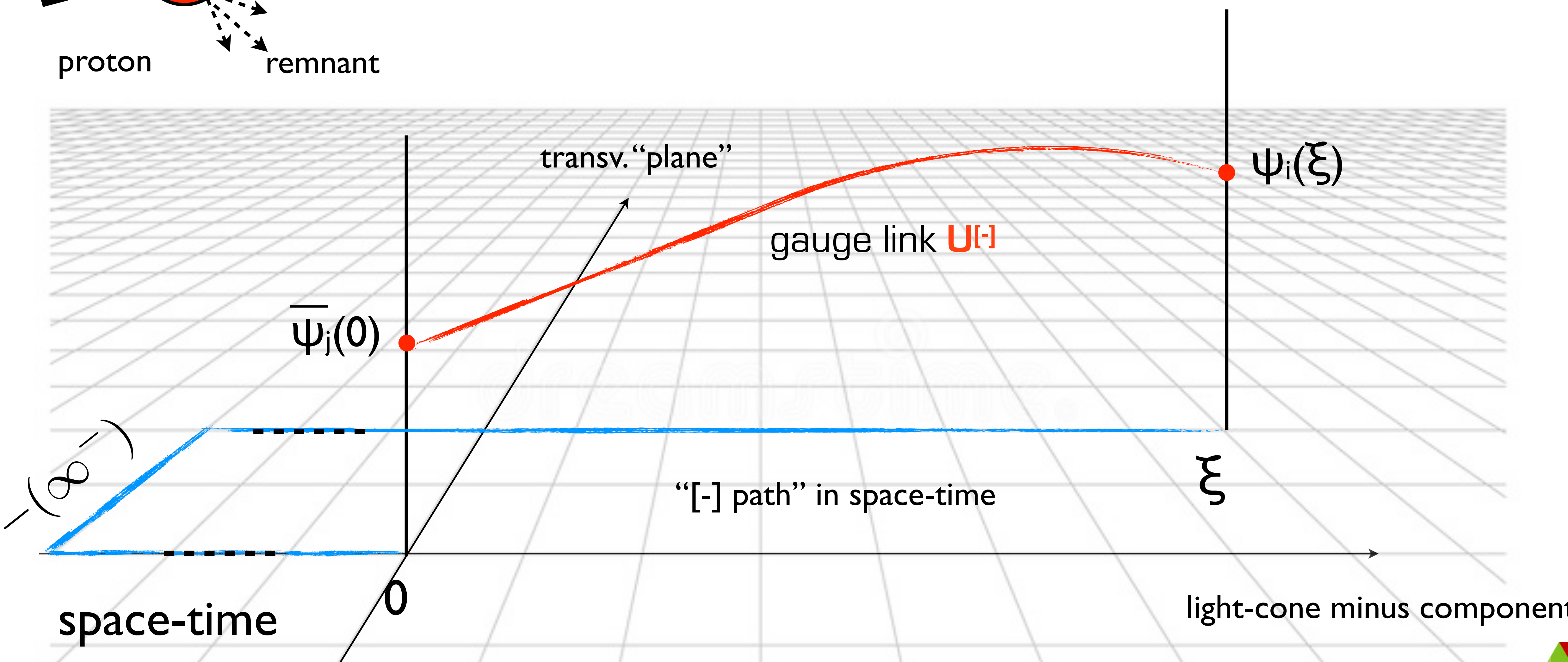
operator implementing the parallel transport equation for the spinor

Process dependence

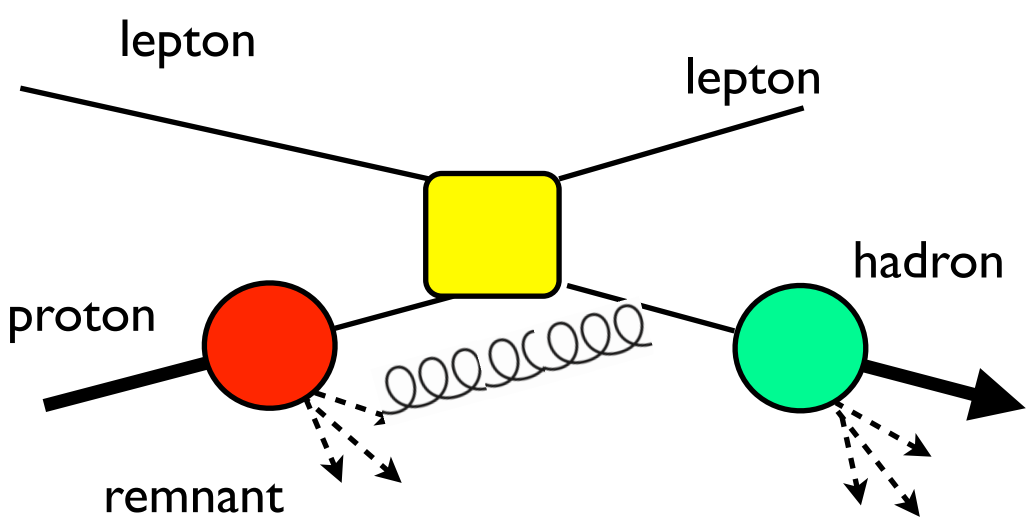


In **Drell-Yan** the **remnant** of the proton feels the color force of a **quark** in the **initial state**

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

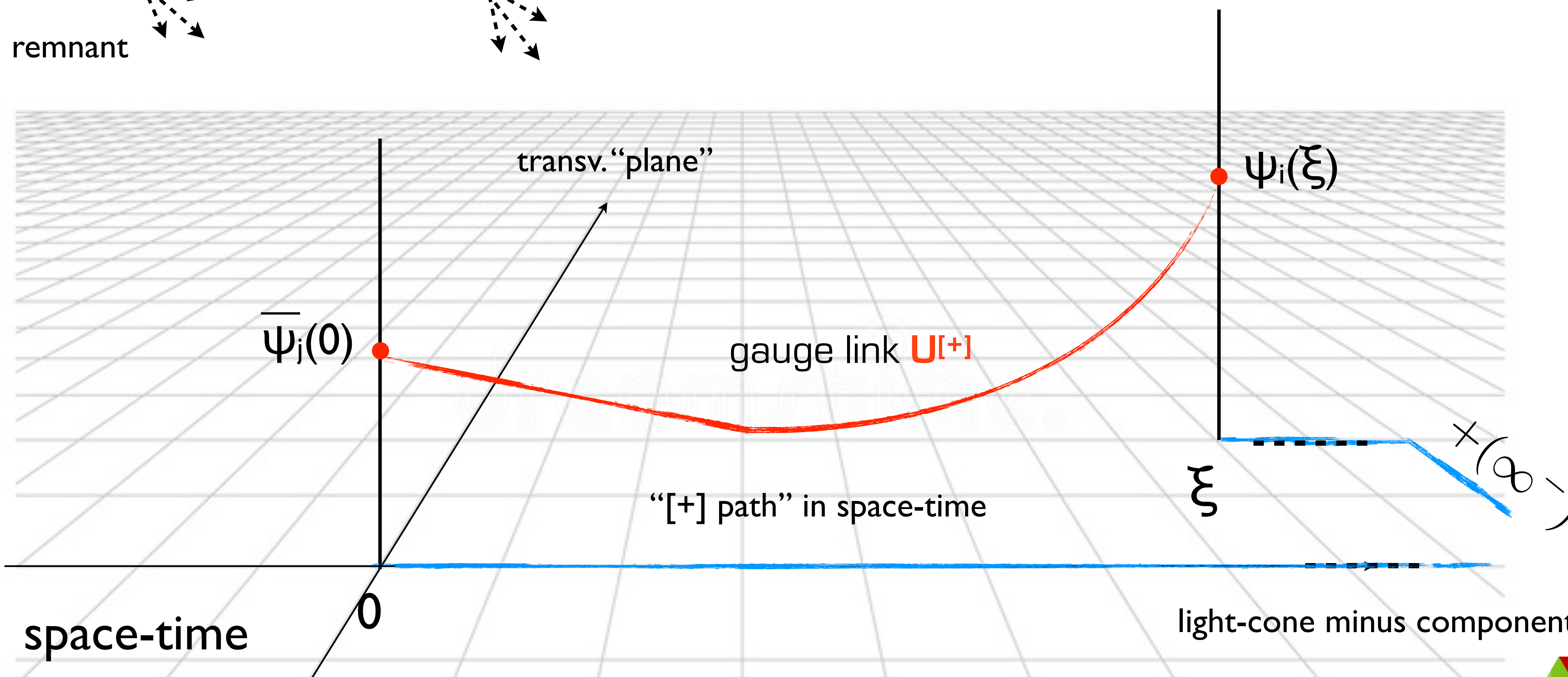


Process dependence



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

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



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Generalized universality

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

What happens to the concept of hadron structure?

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.**

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The sign change

See also talk by A. Quintero

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

The sign change

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Collins, PLB 536 (02)

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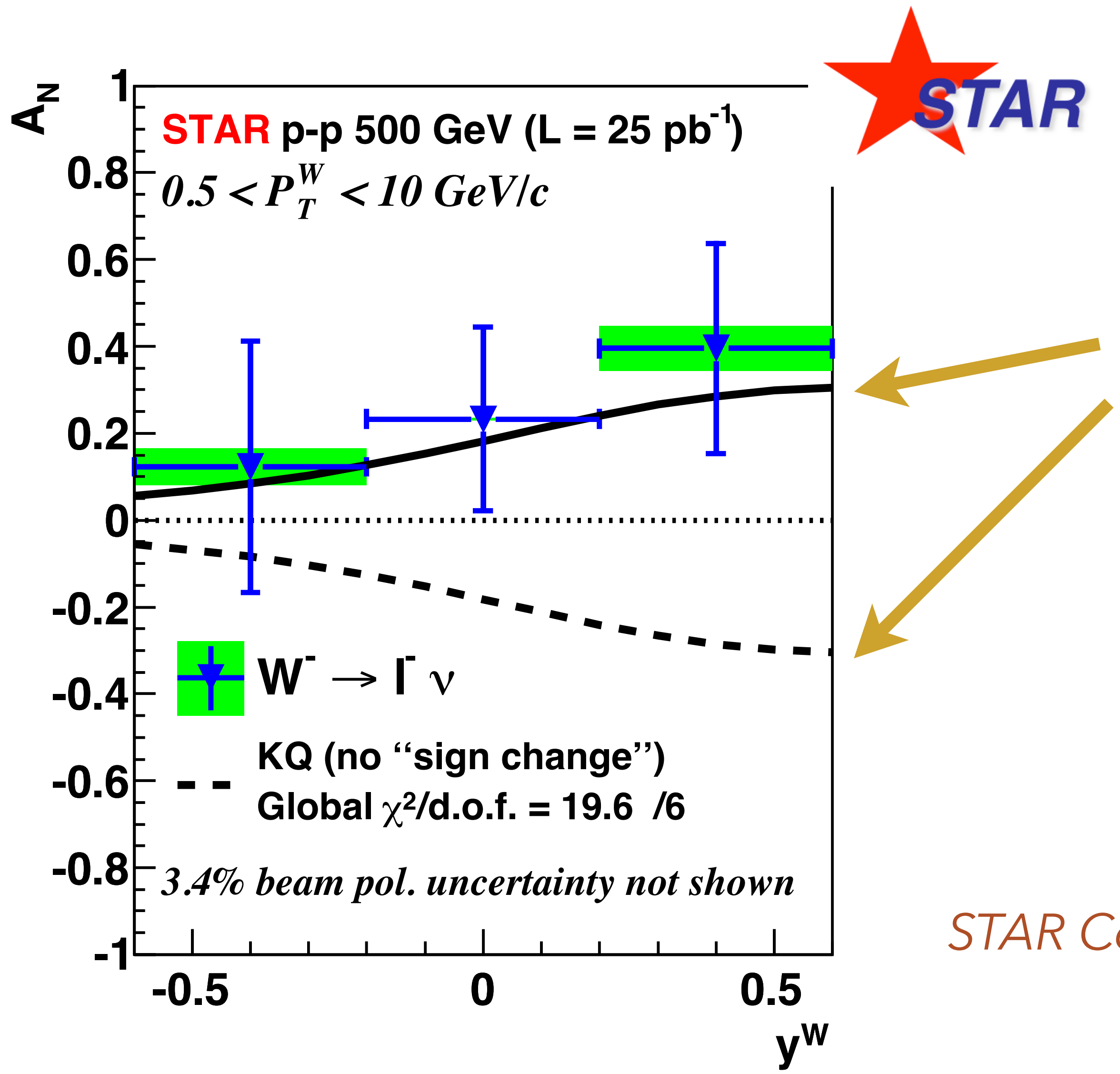

first evidence of sign change?

STAR Collab. arXiv:1511.06003

The sign change

See also talk by A. Quintero

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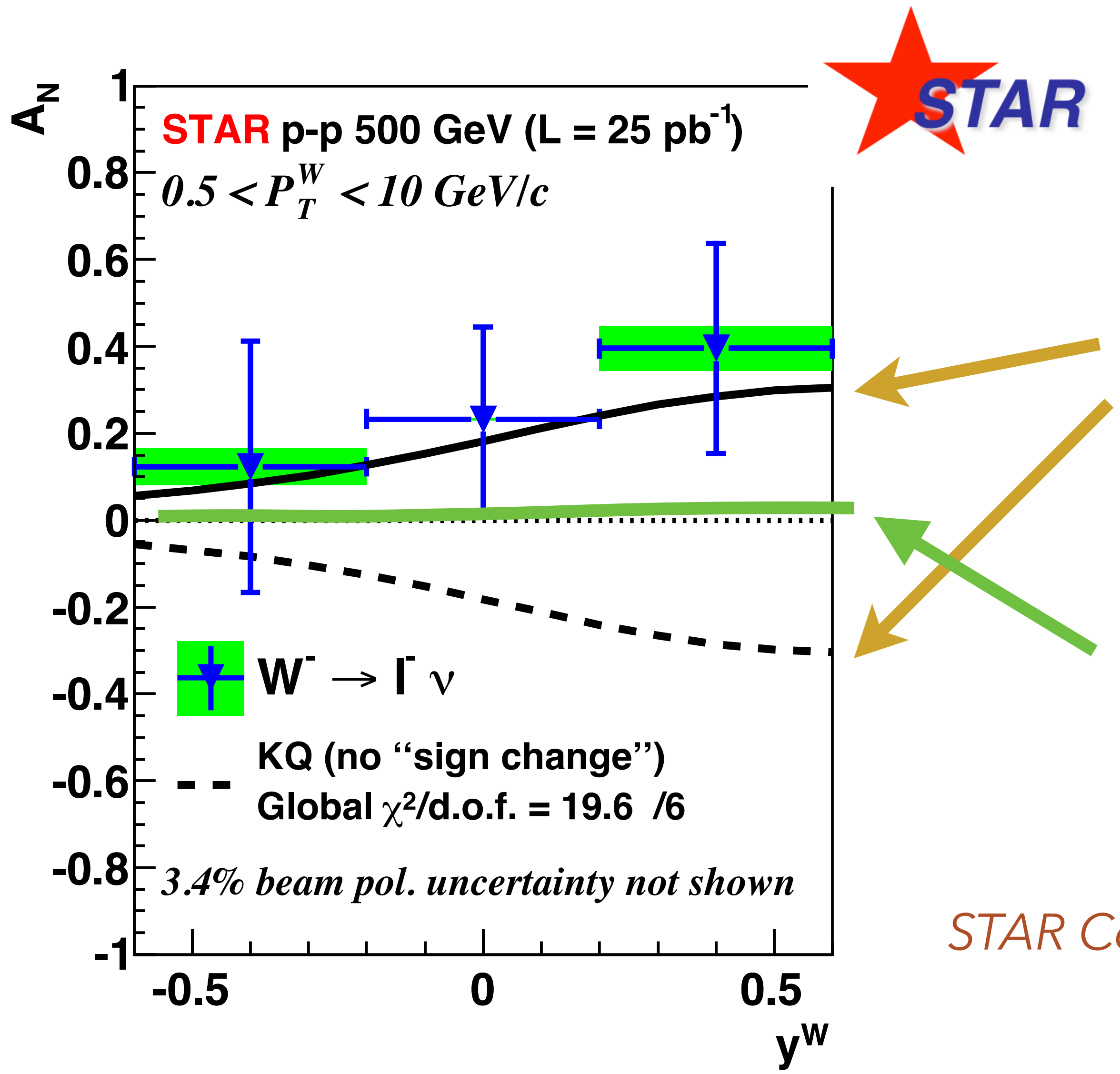


first evidence of sign change?

prediction with TMD evolution equations

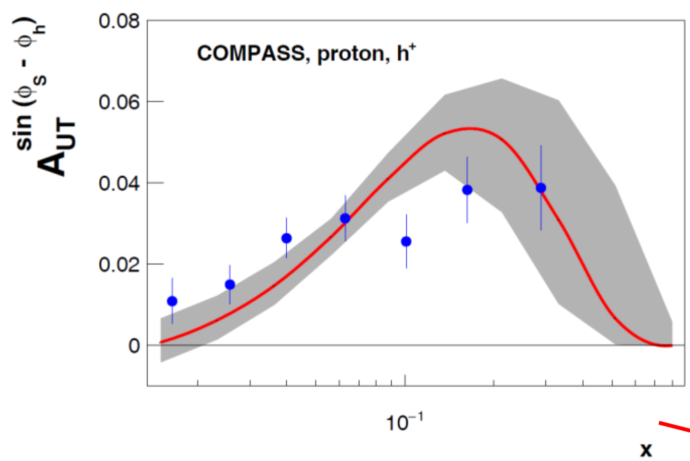
STAR Collab. arXiv:1511.06003

The sign change

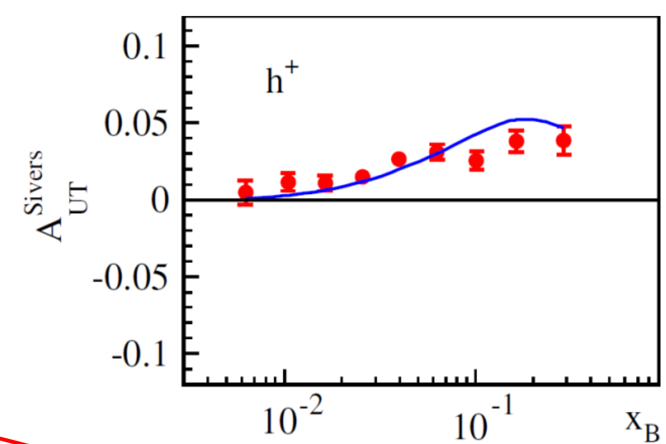
See also talk by M. Quaresma

Sivers asymmetry in Semi-Inclusive DIS

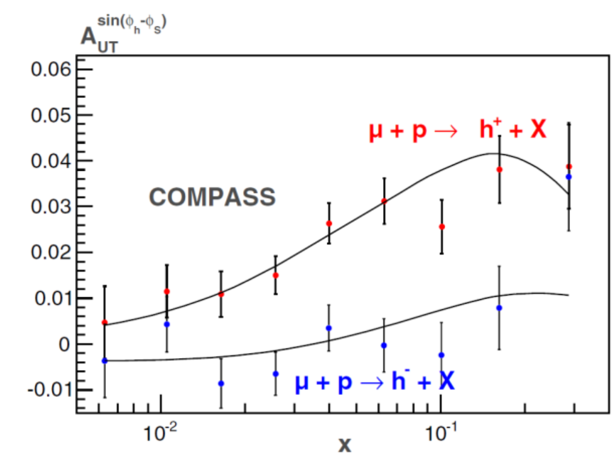
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



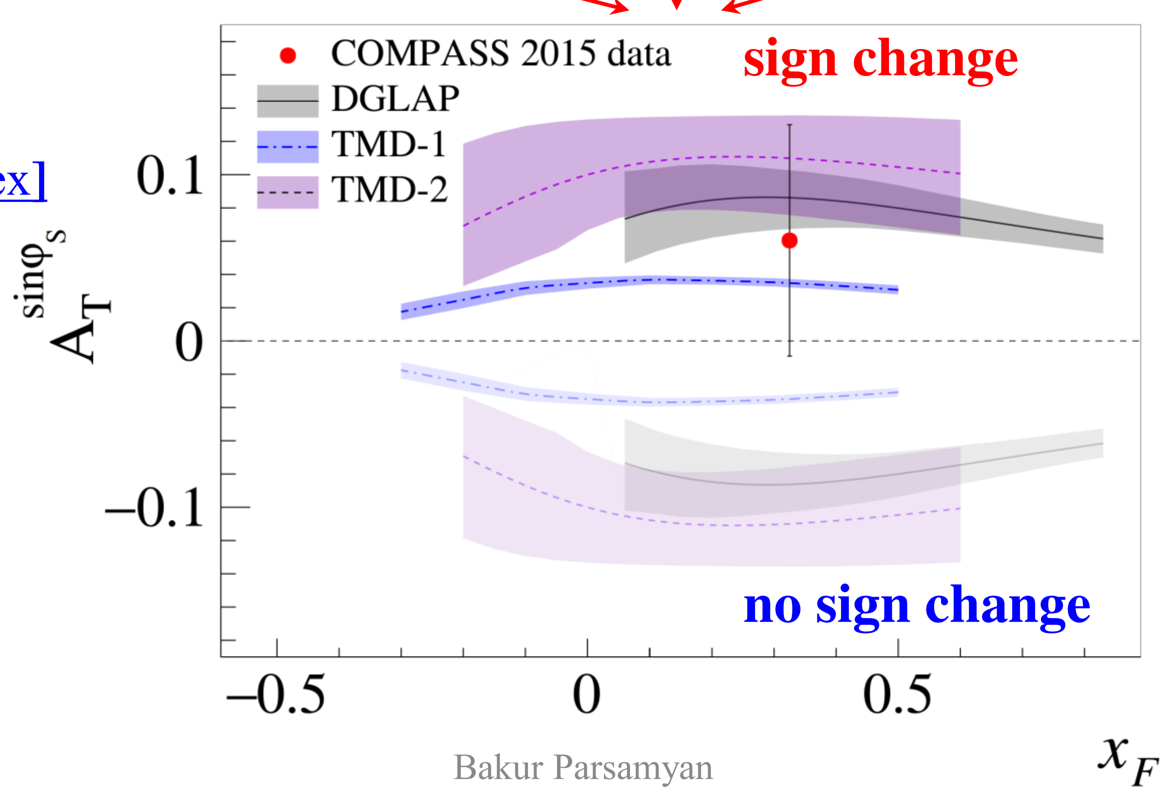
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



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



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



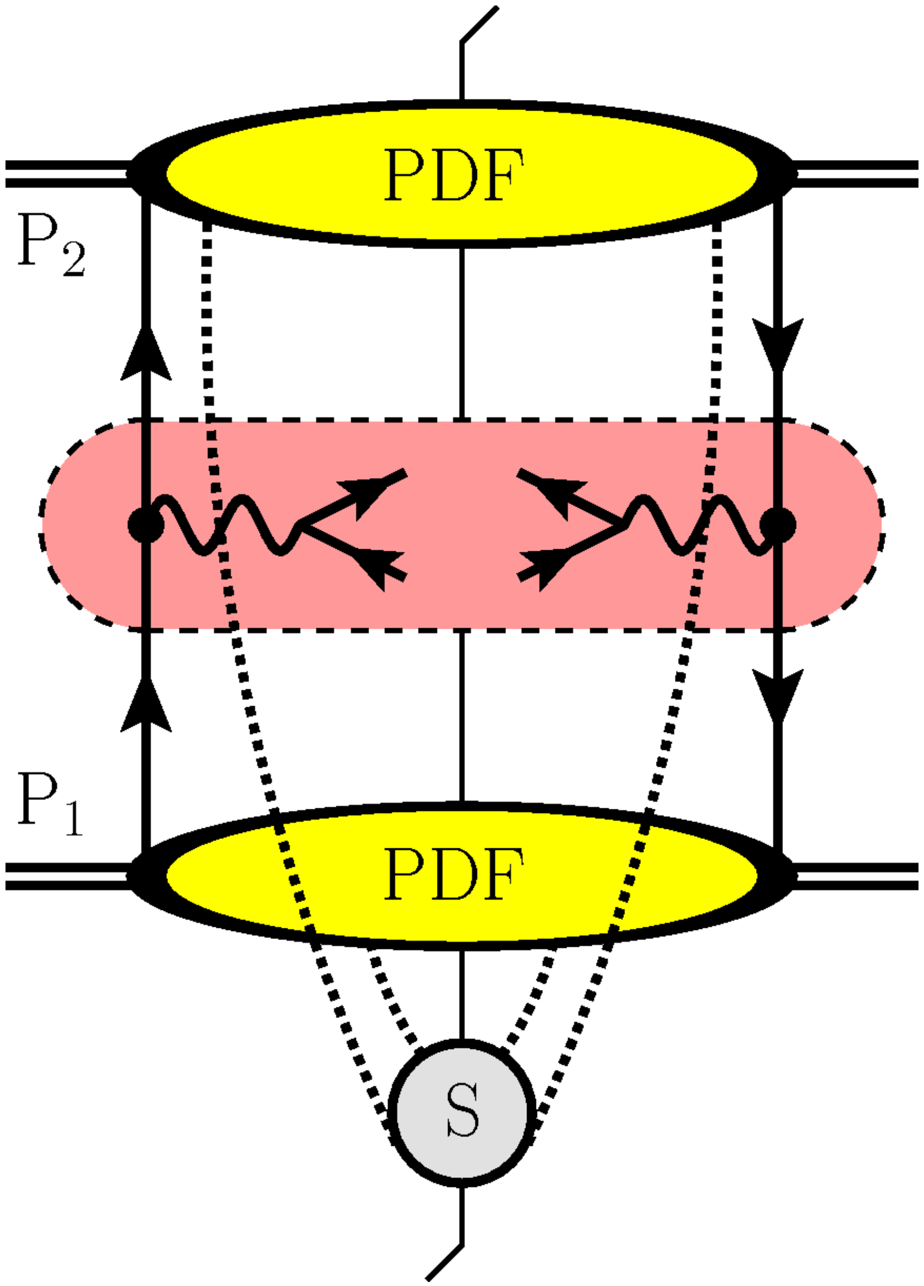
Sivers asymmetry in Drell-Yan

courtesy B. Parsamyan

The unpolarized TMD PDF

TMD factorization

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



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

credit picture: M. Buffing

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TMD evolution

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

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 b_T** on the 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 evolution

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

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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

Input TMD distribution can be **expanded at low b_T** on the collinear distributions

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

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Non-perturbative contributions

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

bT, Fourier conjugate of kT

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
$\zeta_i \to \zeta_f$

Non-perturbative structures

Input TMD distribution can be **expanded at low b_T** on the collinear distributions

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

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b_T, Fourier conjugate of k_T

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evolution in zeta
$\zeta_i \to \zeta_f$

Non-perturbative structures

Can these have an impact on precision HEP ?

Input TMD distribution can be **expanded at low b_T** on the collinear distributions

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

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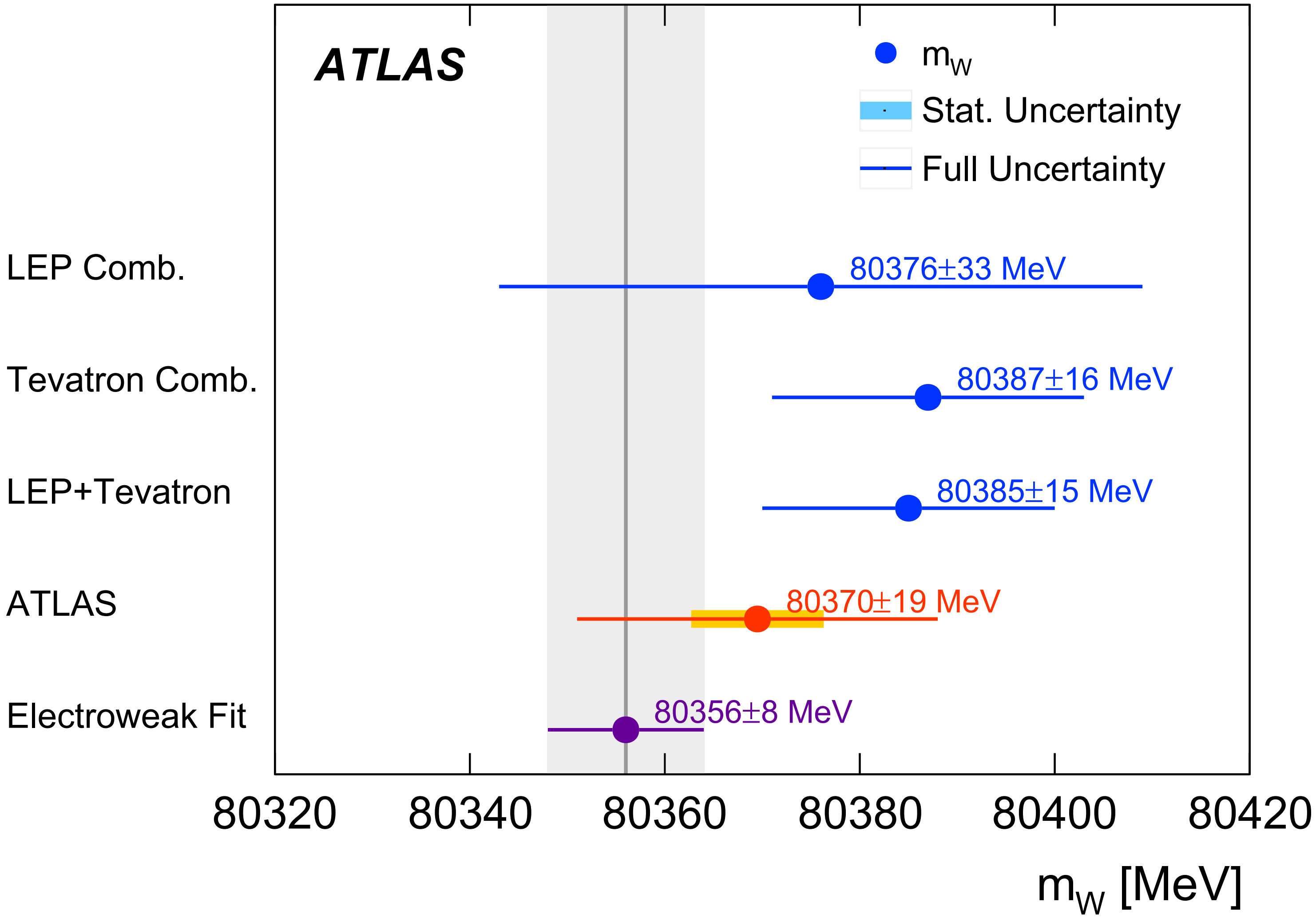
The W mass determination

References :

- Bacchetta, Bozzi, Radici, Ritzmann, AS - 1807.02101
- Bozzi, AS - 1901.01162

The W mass

ATLAS Collab. arXiv:1701.07240

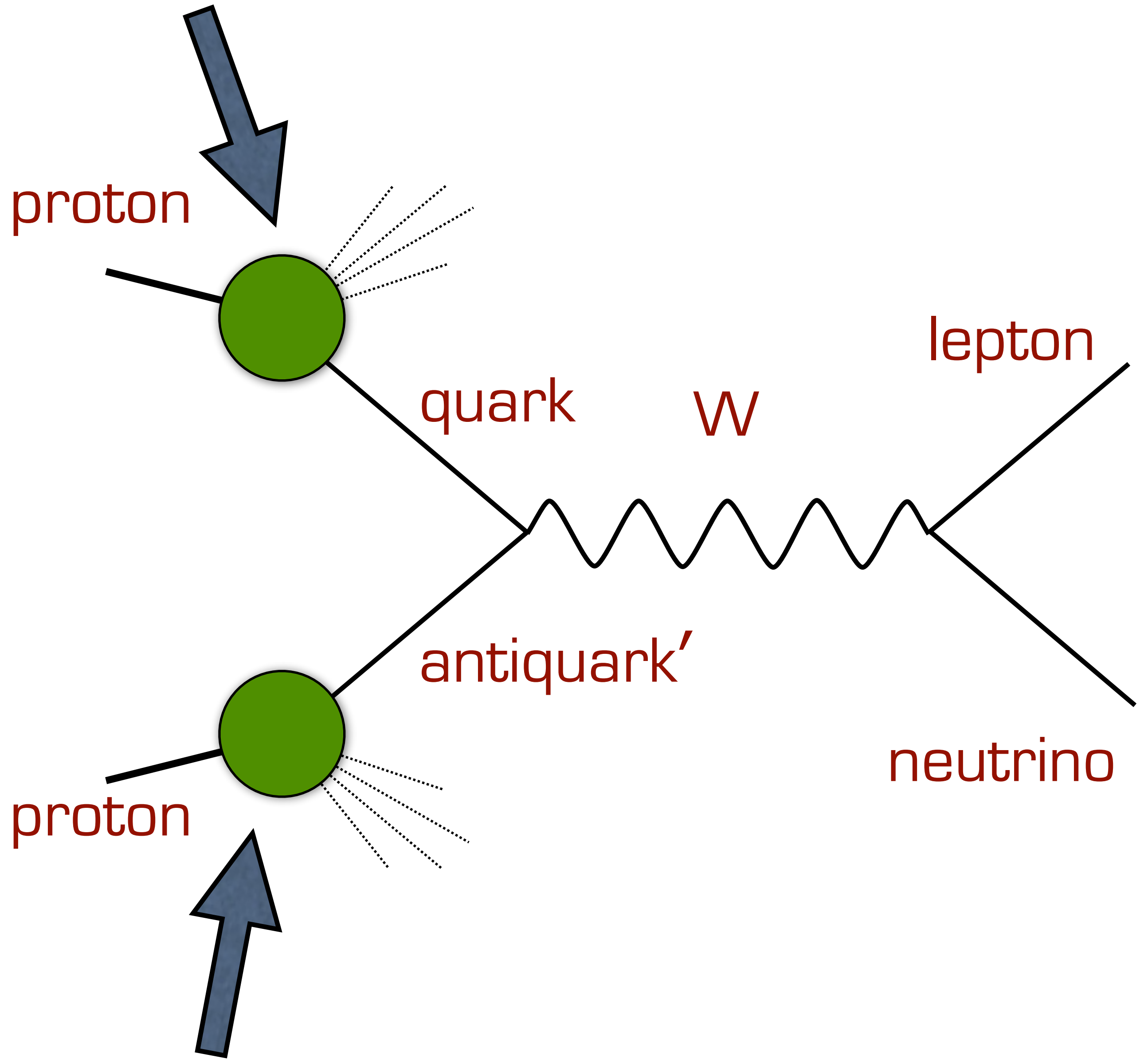


$$m_W = 80370 \pm 7\ \text{(stat.)} \pm 11\ \text{(exp. syst.)} \pm 14\ \text{(mod. syst.) MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

W boson production

(TMD) parton distribution functions



(TMD) parton distribution functions

Kinematics (W)

$Q = m_W$	mass
y	rapidity
q_T	Transverse momentum

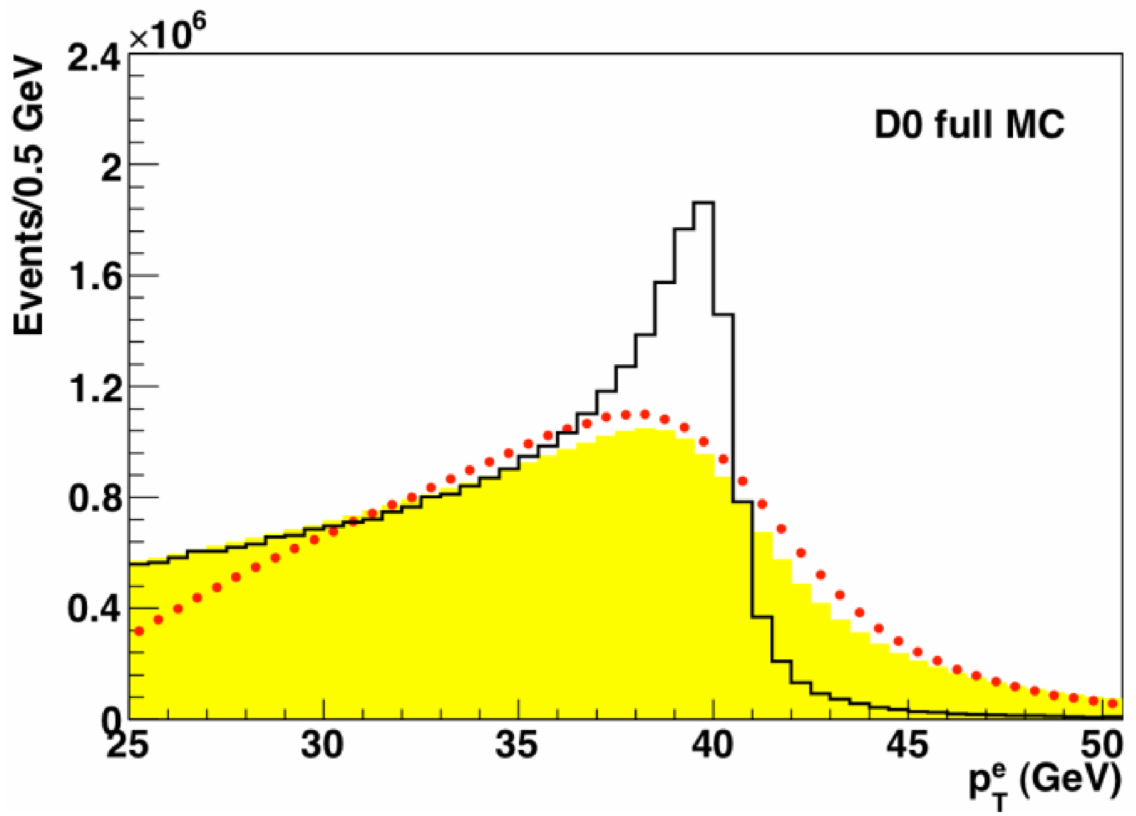
Kinematics (partons)

$$x_{1,2} = \frac{Q}{\sqrt{s}} e^{\pm y}$$

Collinear momentum fractions

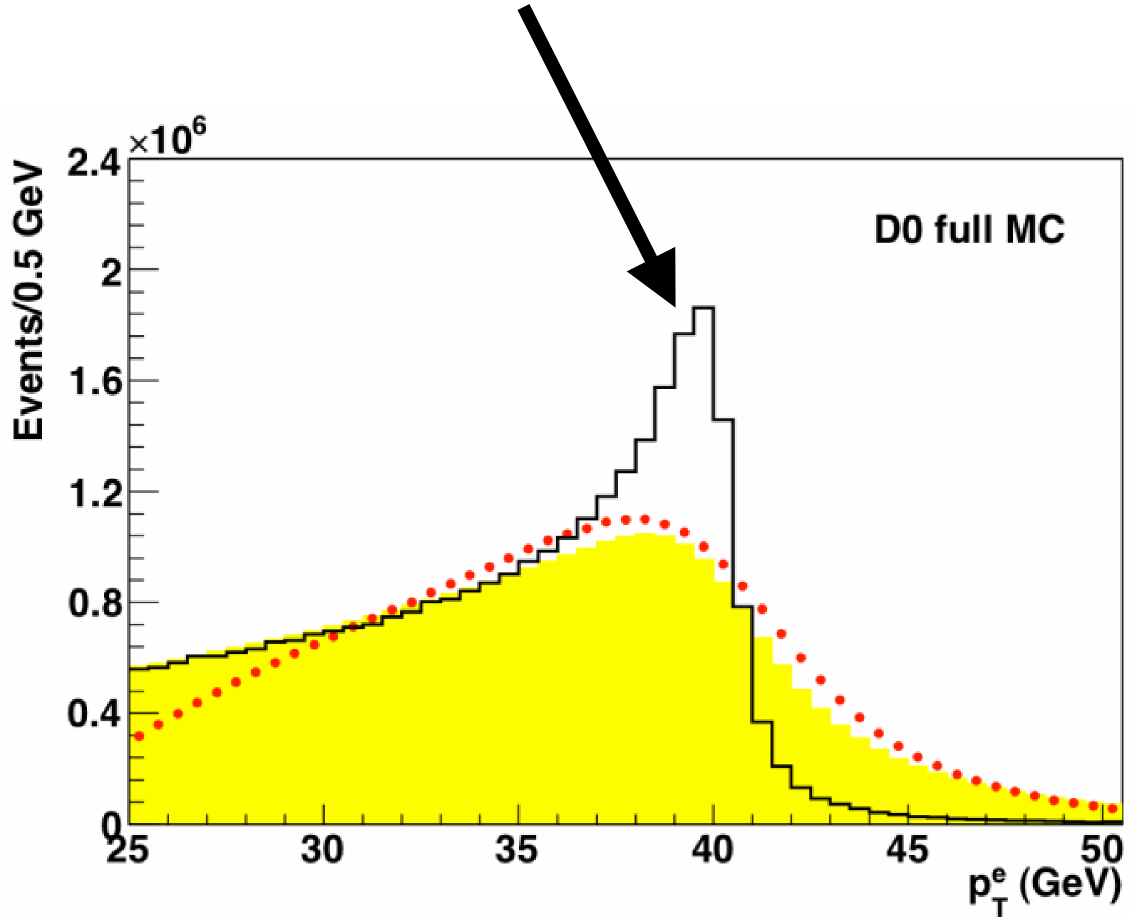
$k_{T\,1,2}$ Transverse momenta

Lepton pT distribution



Lepton pT distribution

If the W were exactly collinear (p_{TW}=0, no TMD effects), the distribution of events would look like this



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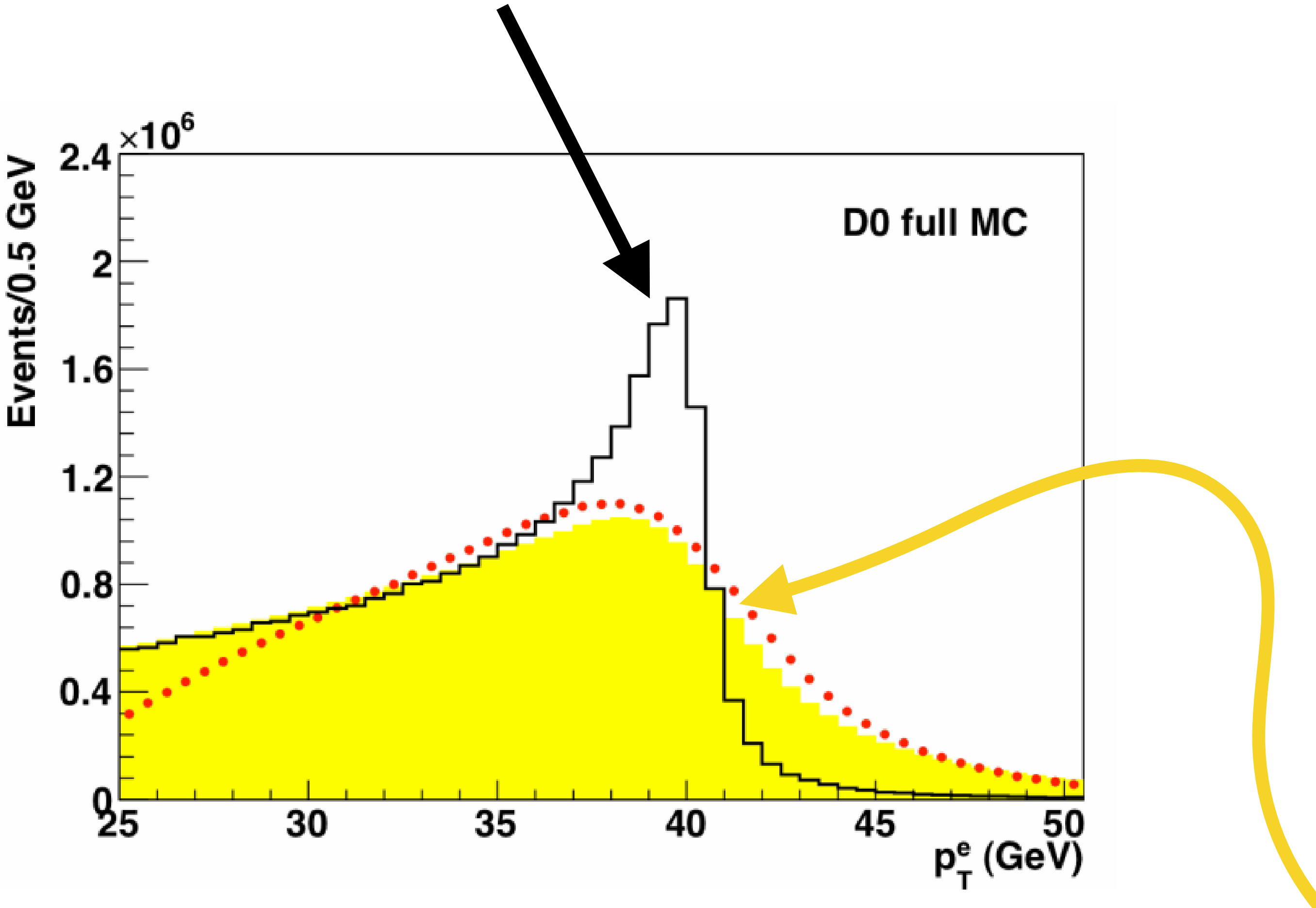

If TMDs are taken into consideration, the distribution gets modified like this

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Lepton pT distribution

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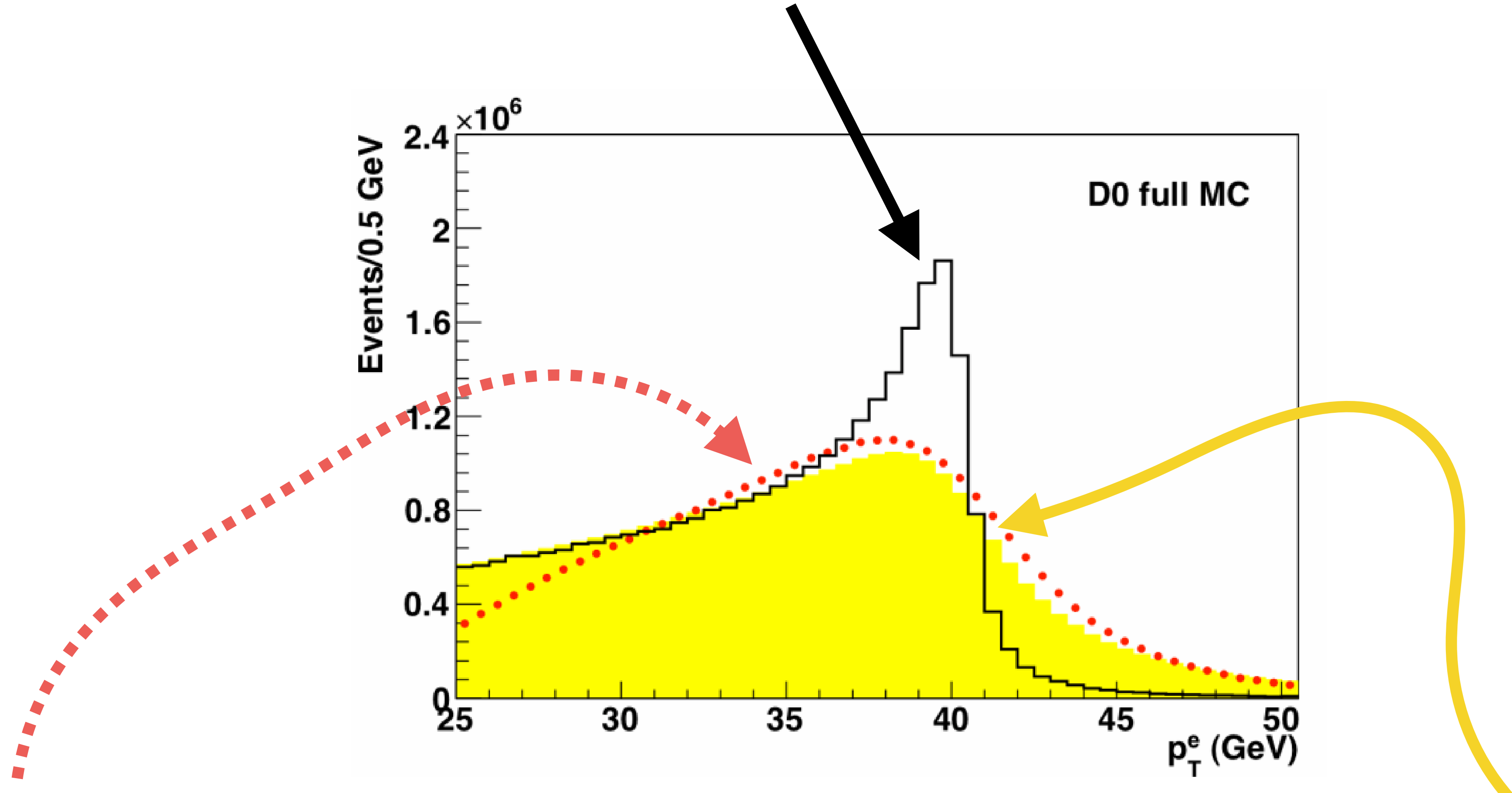
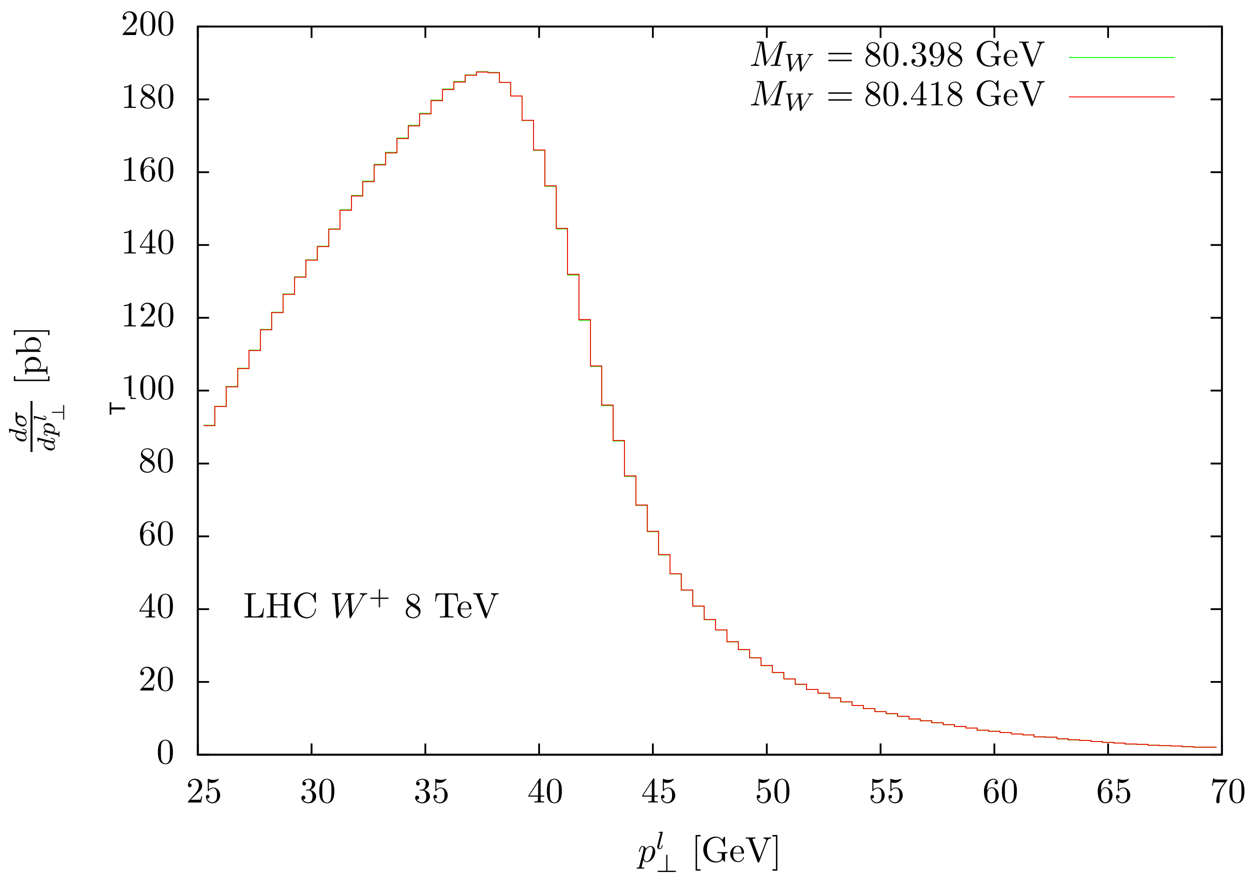


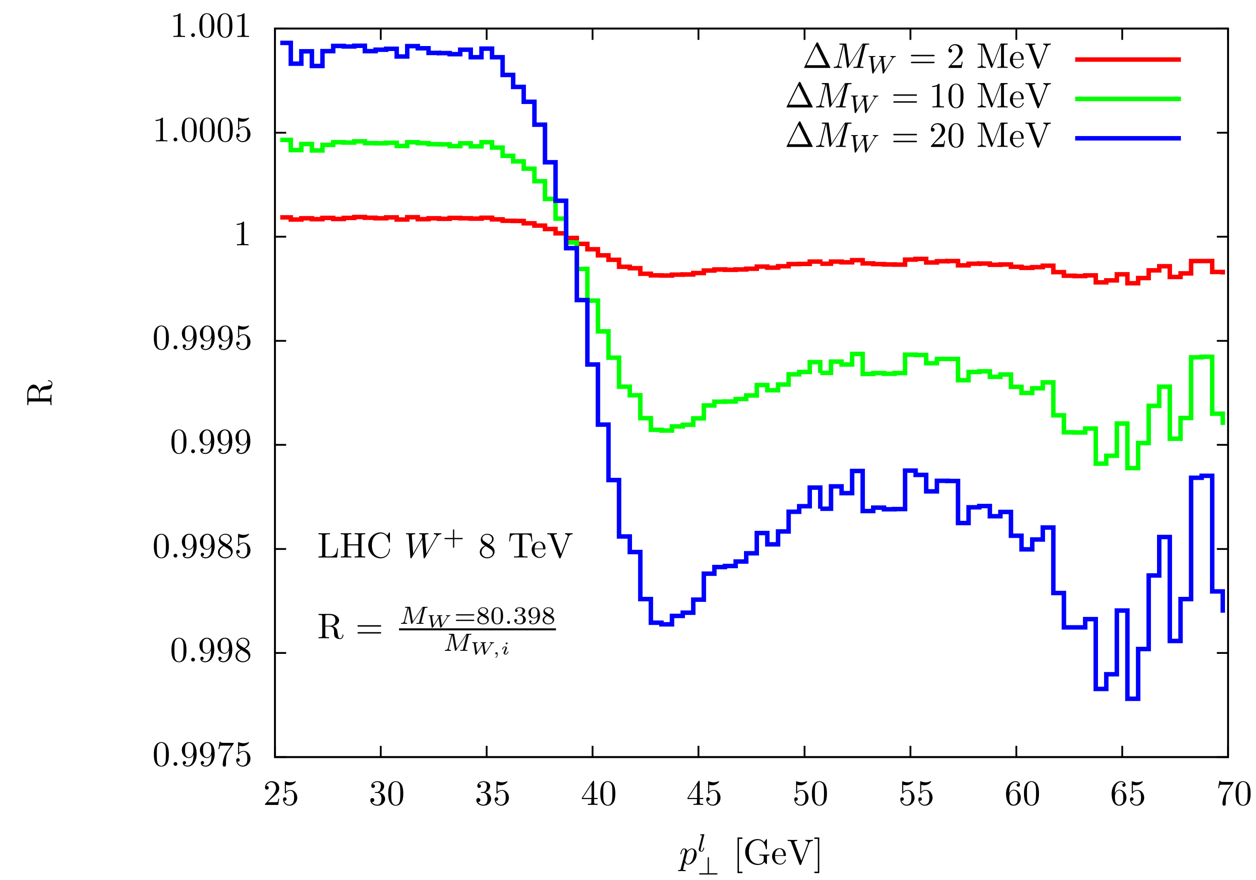
Detector effects cause further changes

If TMDs are taken into consideration, the distribution gets modified like this

Which kind of effect are we after?

see, e.g., Bozzi, Rojo, Vicini, arXiv:1104.2056





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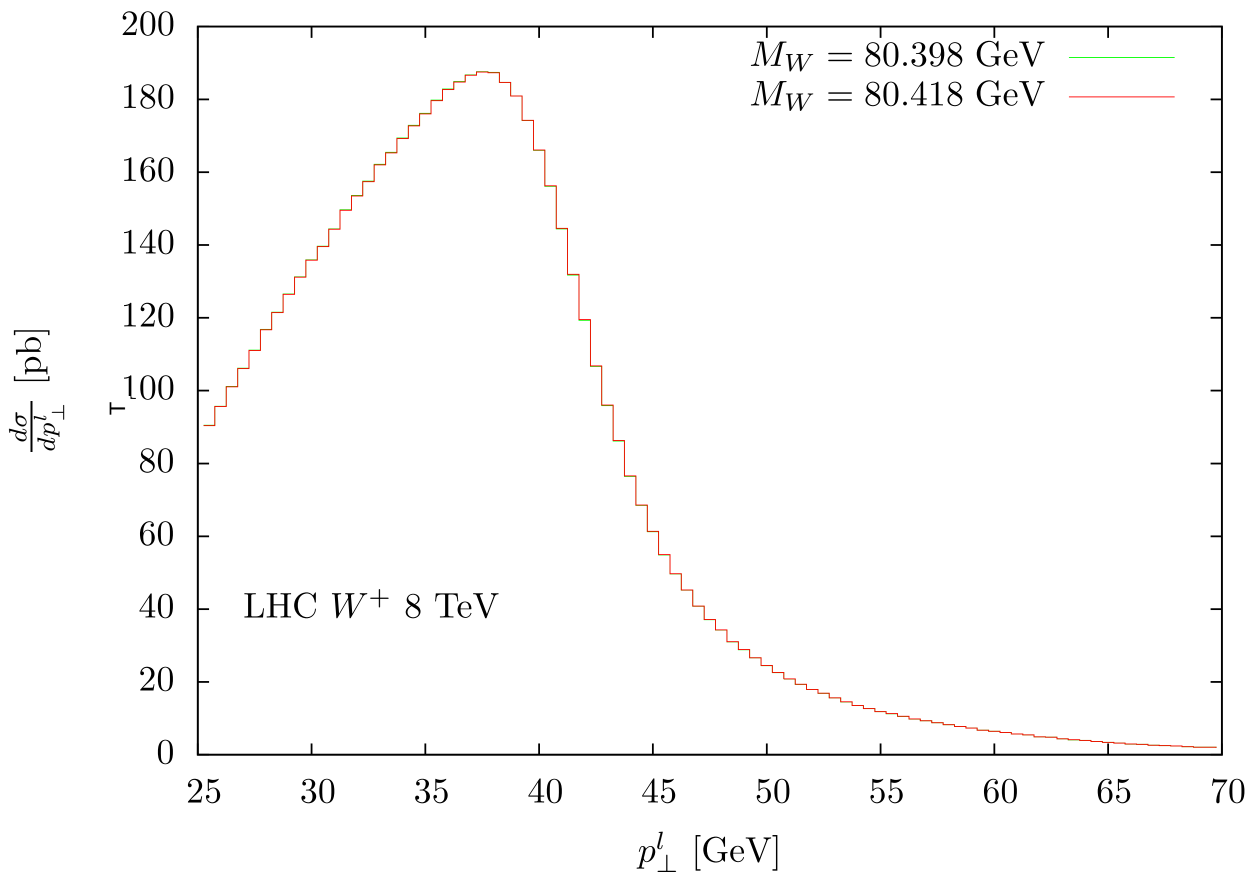

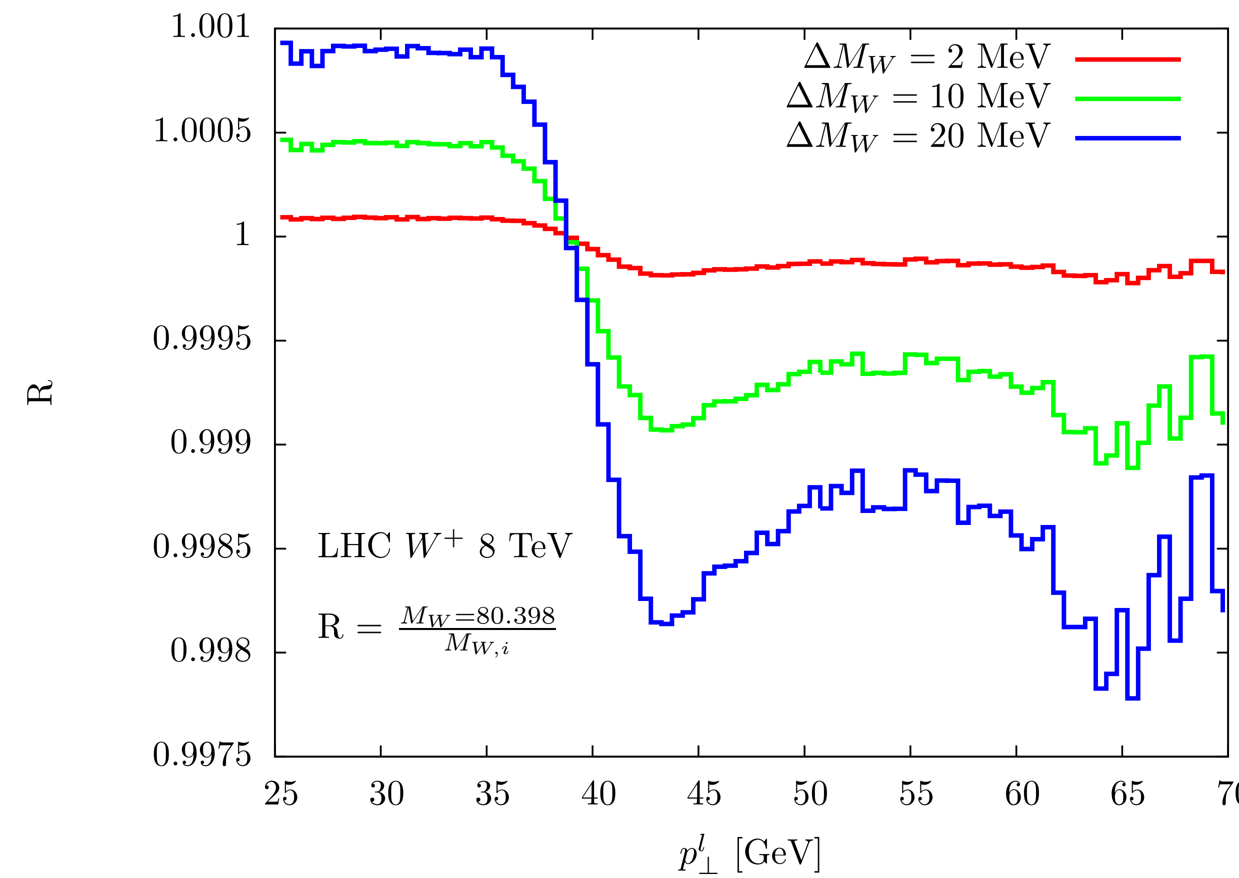

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

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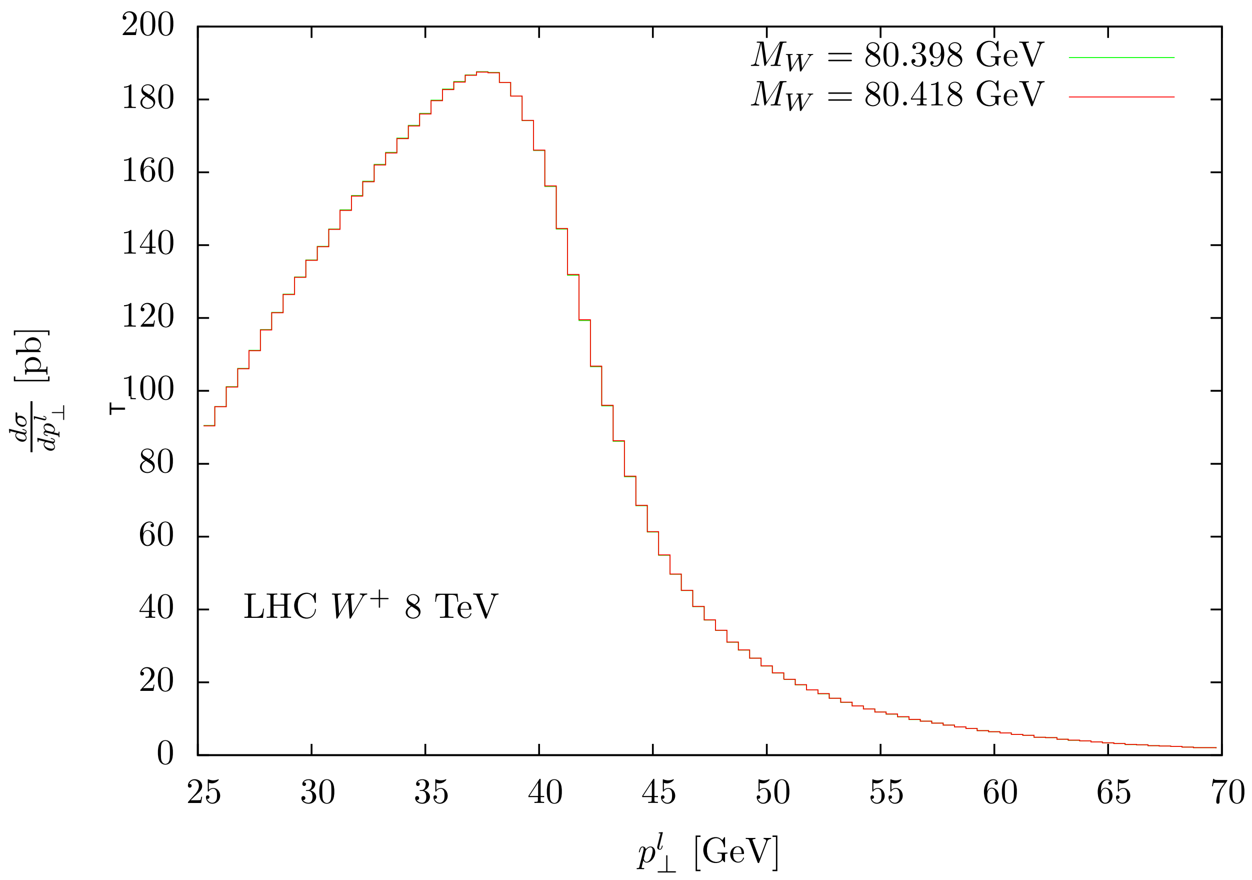

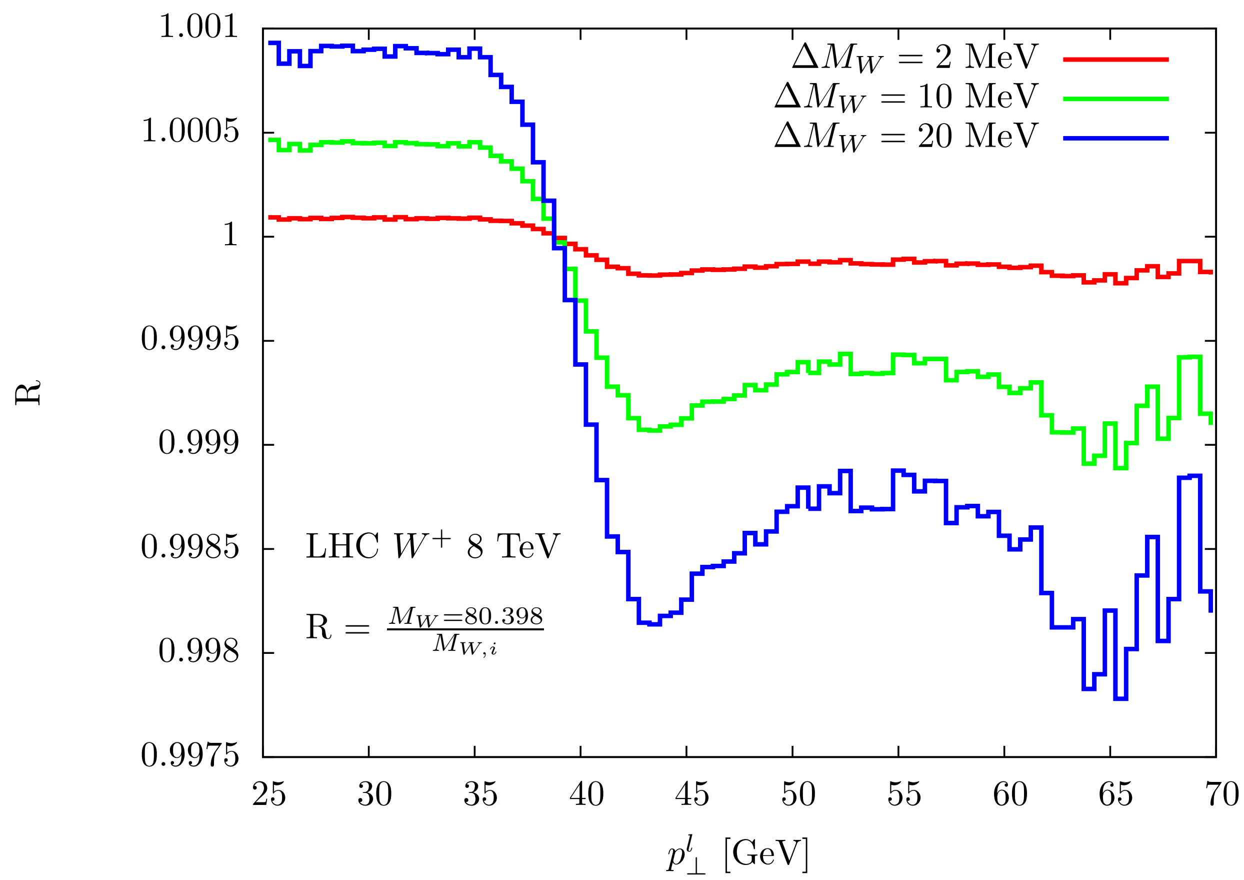

A change of 10 MeV in the W mass induces distortions at the per mille level only: challenging

the key: nonperturbative TMD effects can have an impact at this level of precision

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Our findings

The fact that quark intrinsic transverse momentum can be flavor-dependent leads to an additional uncertainty on M_W, not considered so far:

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

$$-4 \leq M_{W^-} \leq 3 \text{ MeV}$$

Statistical uncertainty: ±2.5 MeV

- The four-loop QCD corrections generates a shift of -2.2 MeV
- The expectation from missing higher orders is 4 MeV

Eur.Phys.J. C74 (2014) 3046

Conclusions

Transverse-momentum-dependent parton distribution functions are a precious tool to map hadron structure in a 3D momentum space

The **symmetries of QCD** (in particular the gauge symmetry and time-reversal invariance) predict a **sign change** for certain distributions, such as the Sivers function

More progress from the theoretical and experimental point of view is needed to confirm this striking prediction of the theory

As for collinear PDFs, the transverse structure and its flavor-dependence can have an impact on precision studies at high-energies

This is an example of the **connection** between
hadron structure studies beyond the collinear picture and **HEP**

We need **more flavor-sensitive data** (e.g. SIDIS) to constrain the flavor-dependence of the unpolarized TMD PDFs (**Electron-Ion Collider**)

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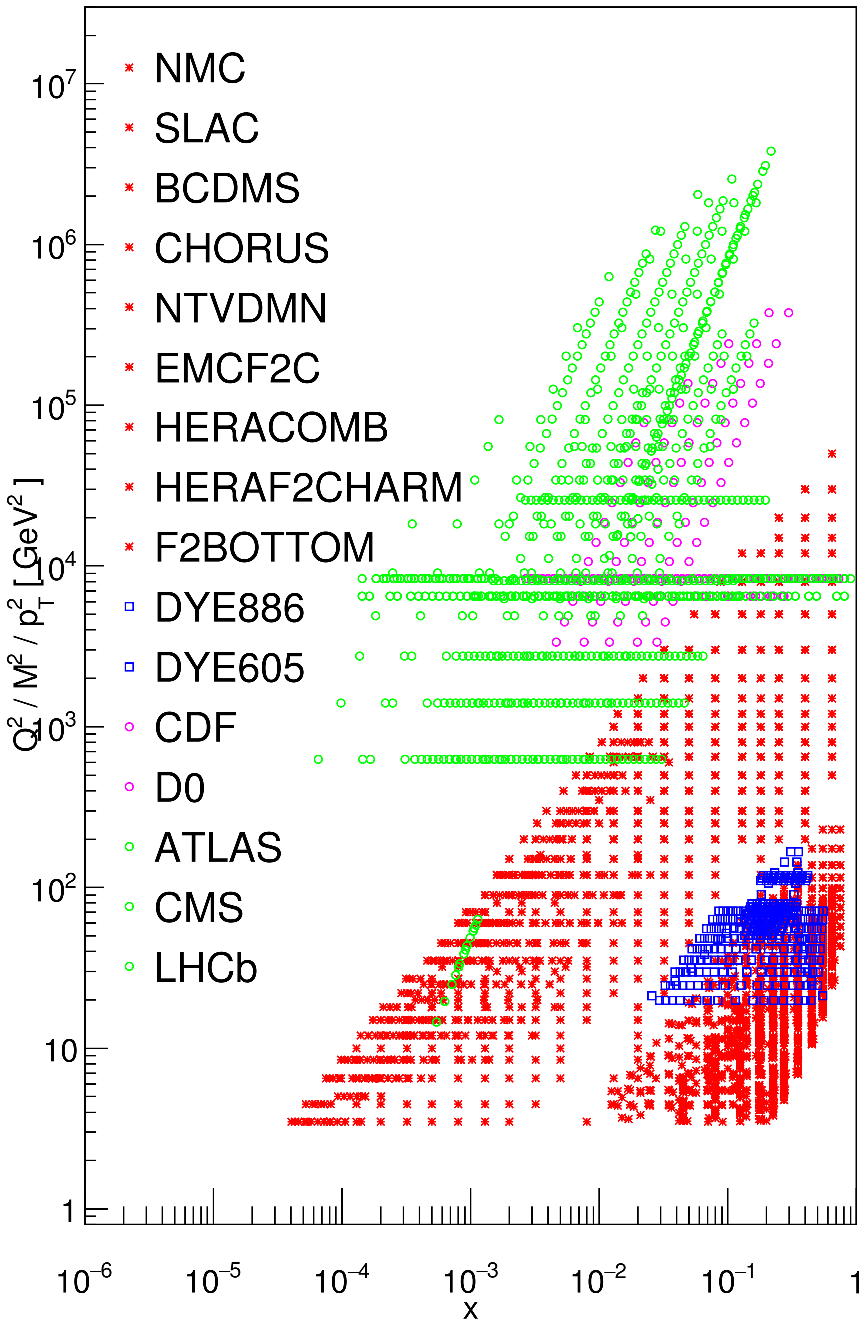
Backup

Data

see E. Nocera - POETIC2016



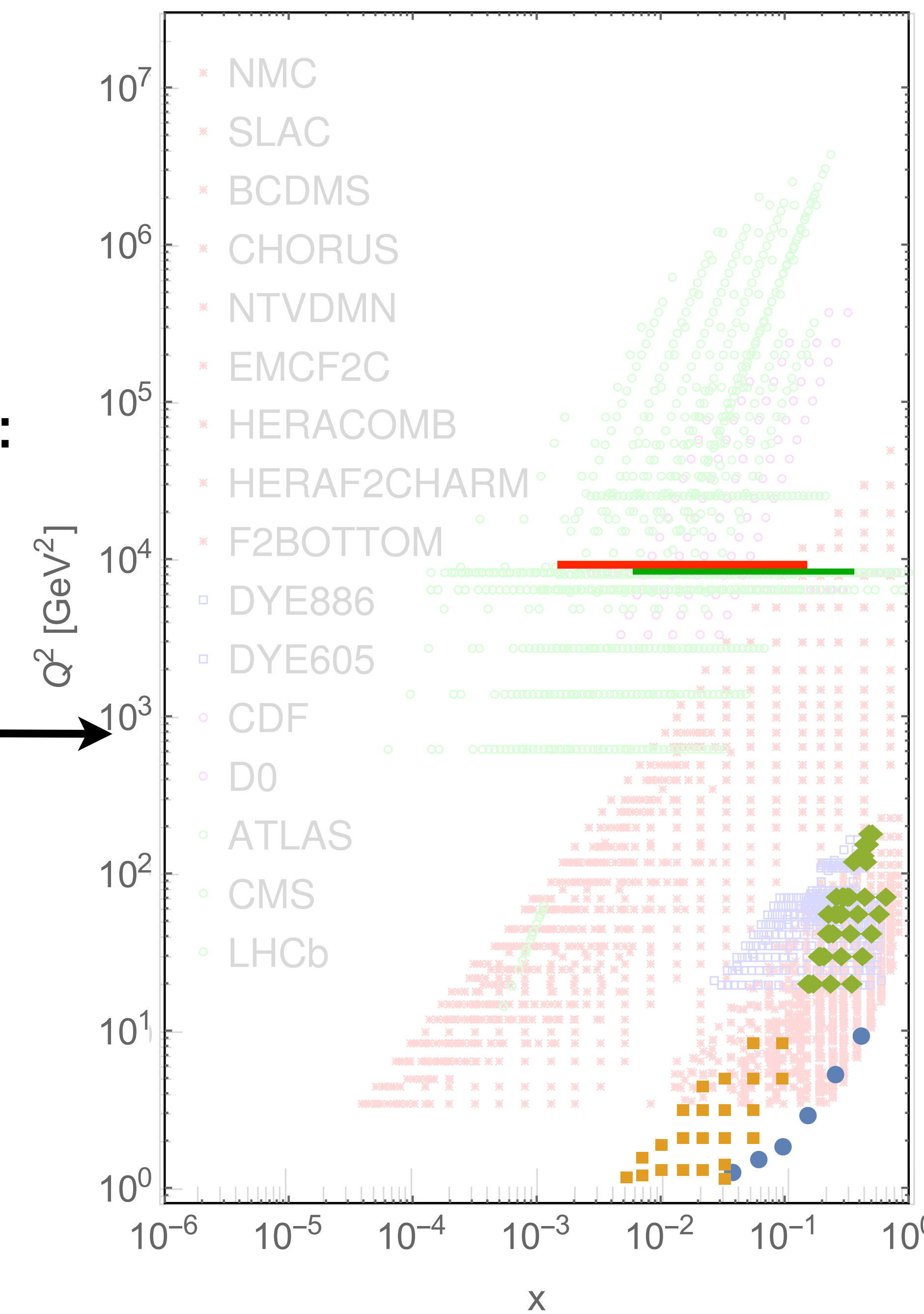
data driven science

data sets available:

collinear PDFs ←

vs

TMD PDFs →



Q : resolution of the probe

x : momentum fraction carried by the parton

Towards an EIC

New kinematic windows :

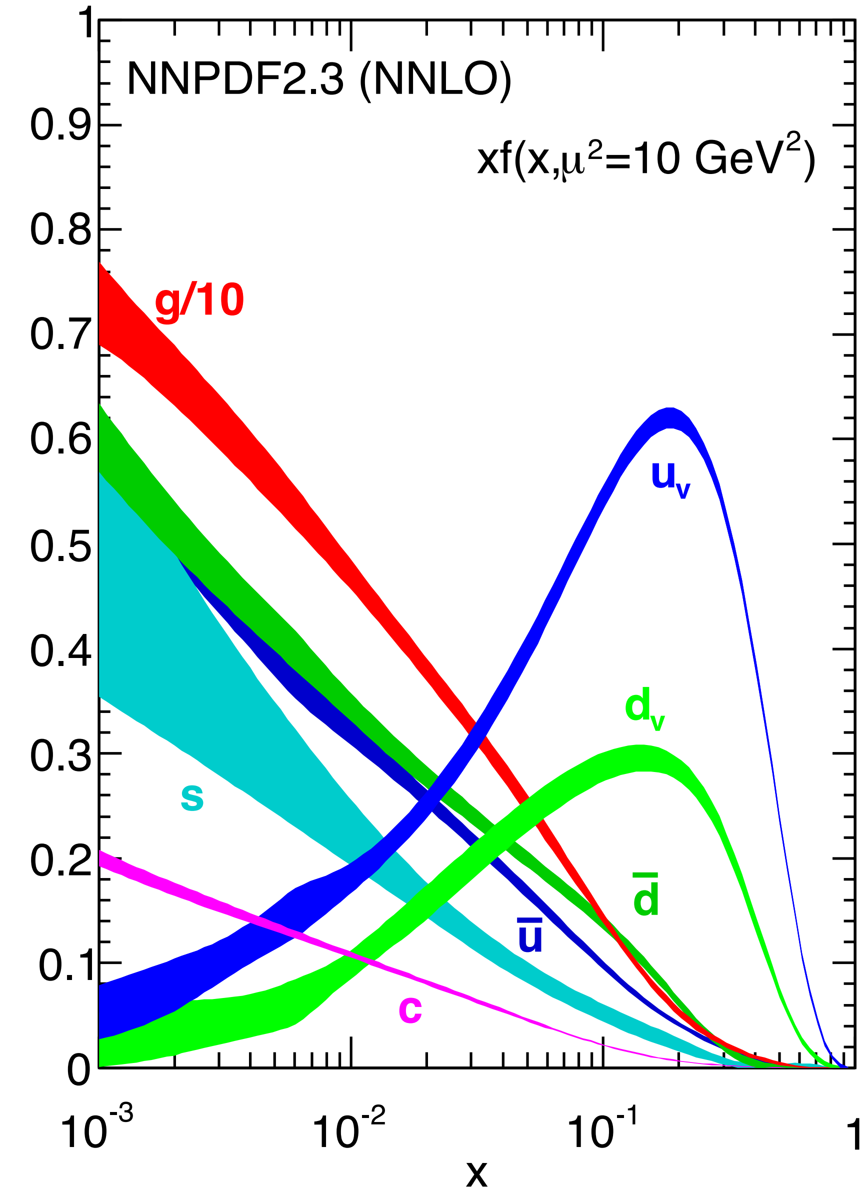
JLab12 will explore the **valence** quark region (large x)
EIC will explore the region dominated by **sea quarks** and **gluons**

see R. Ent - INT 17-3 program

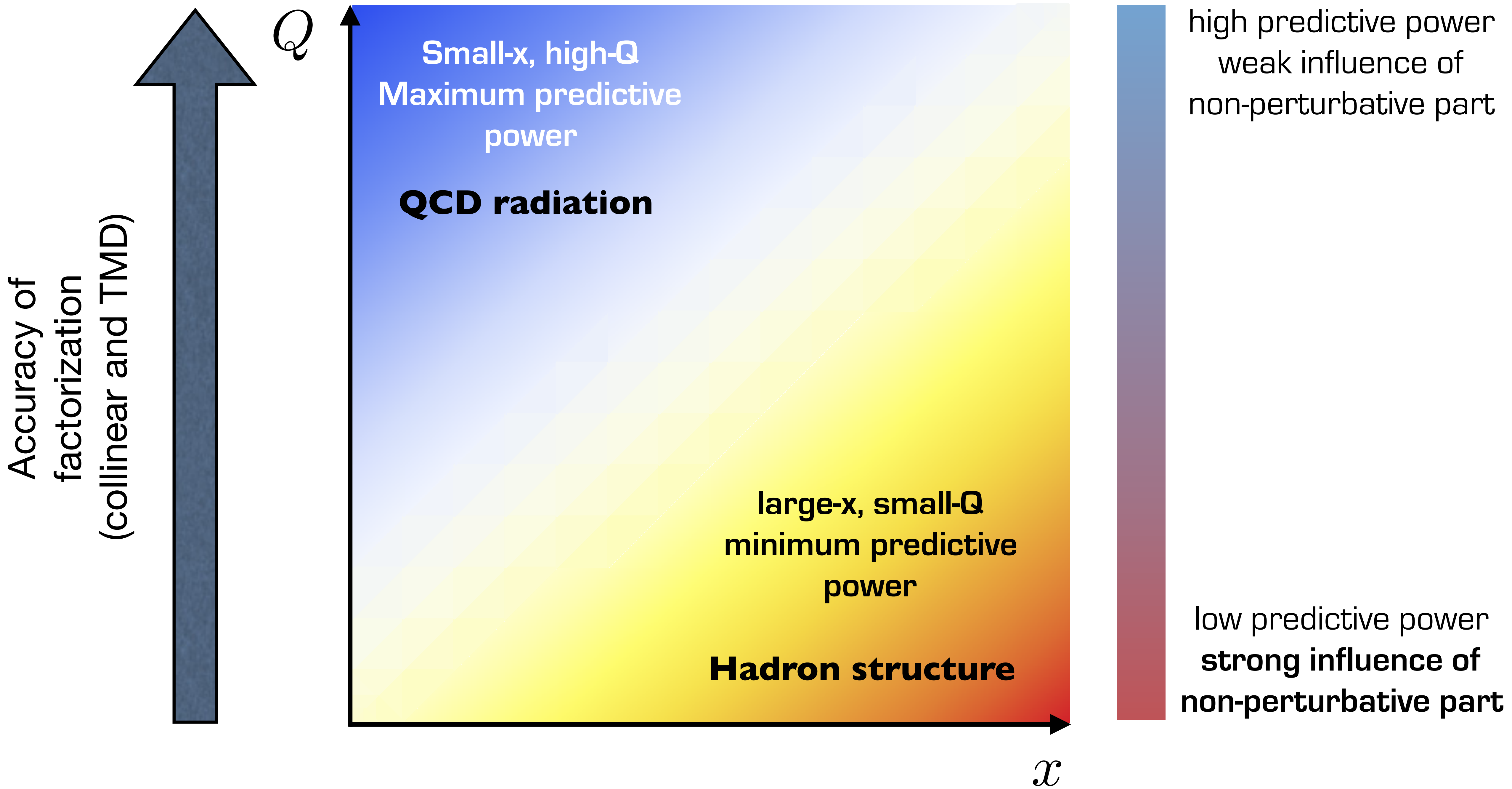
The "sweet spot" for the EIC parameters is a balance of

- High enough **energies** to probe hadron structure in new kinematic windows and better control factorization
- High enough **luminosity** for **precise** nucleon imaging
- multi-purpose and specialized detectors

unpolarized collinear PDF - f1(x)

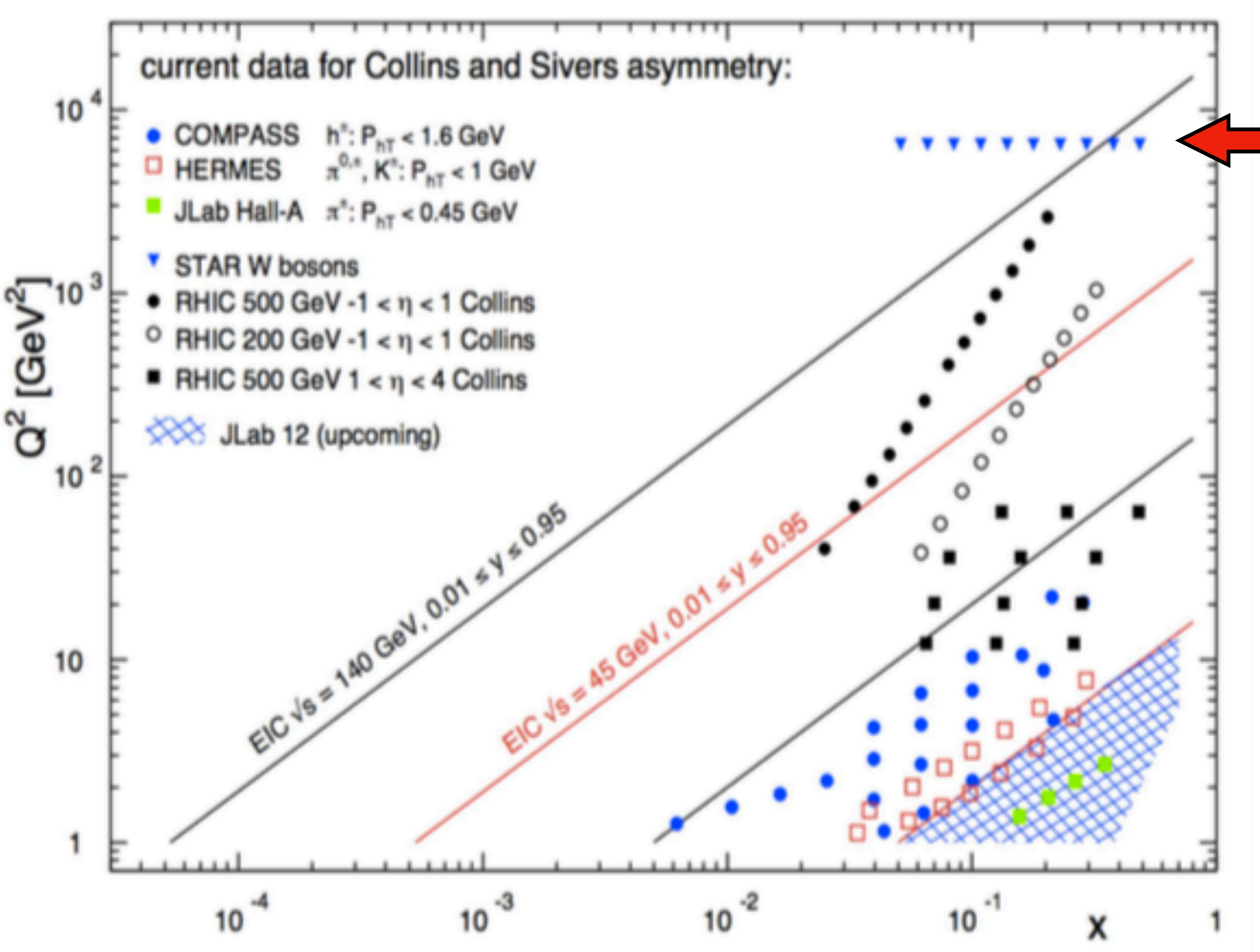


Structure vs radiation



Can we prove this formally? Yes : saddle point approximation

Experimental data



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 non-perturbative effects

Interesting combination

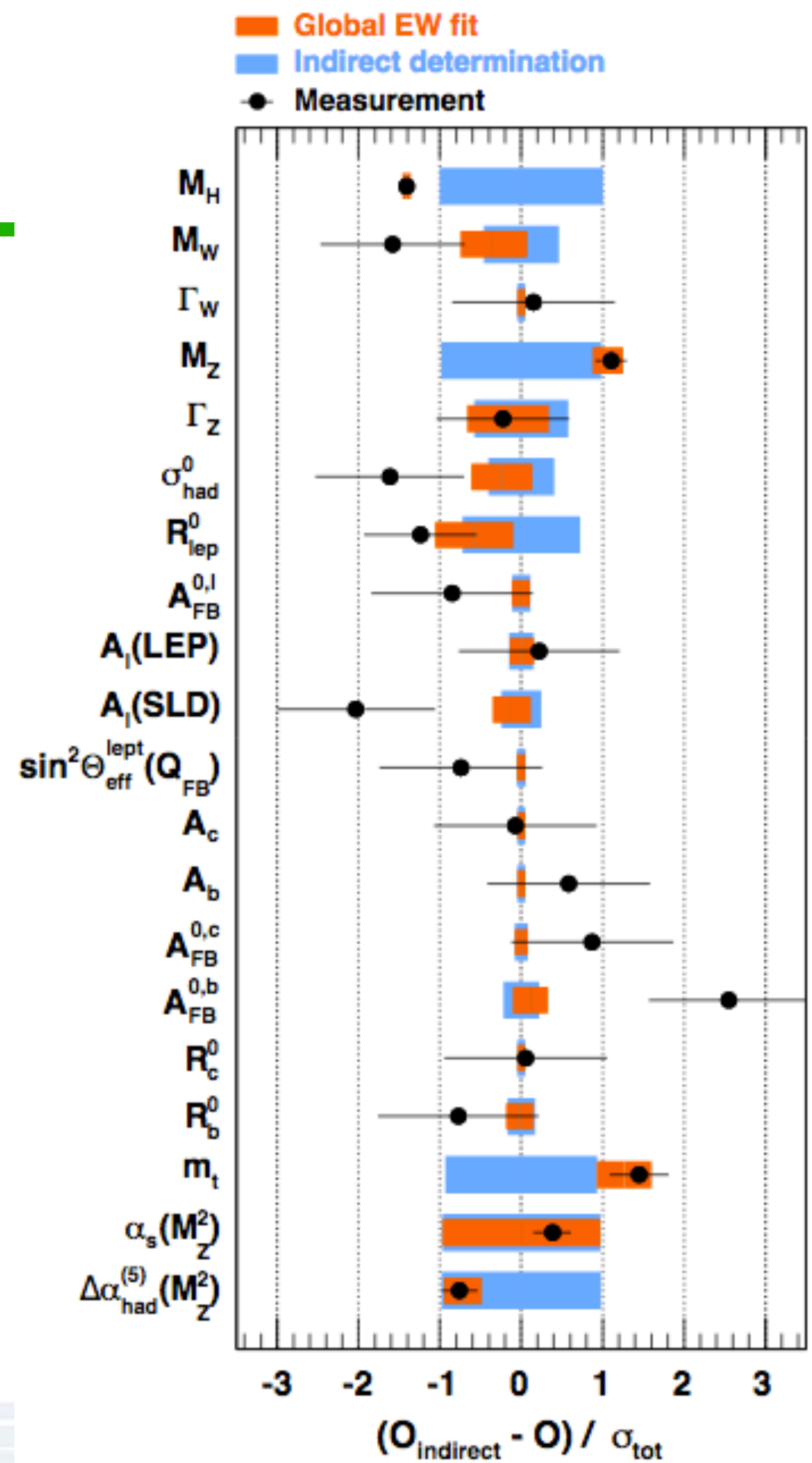
Picture from O. Eyser - CIPANP 2018

EW observables

Eur.Phys.J. C74 (2014) 3046

- tension between direct measurements and indirect determinations/global EW fit

- larger uncertainty in direct determinations



Systematic uncertainties @ ATLAS

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

ATLAS Collab. arXiv:1701.07240

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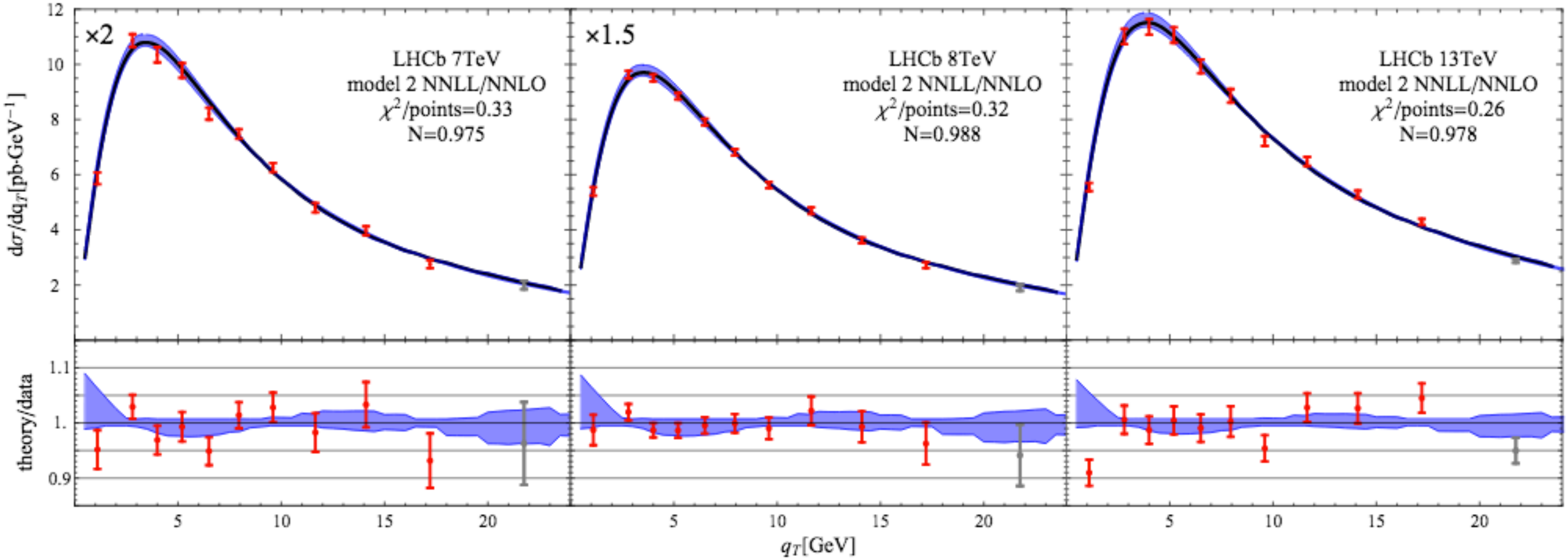
This contribution contains also intrinsic transverse momentum of partons. The MC has been tuned to describe Z-boson data

ATLAS Collab. arXiv:1701.07240

TMD factorization

Scimemi, Vladimirov [Eur.Phys.J. C78 2018 89]



Schematically :

$$\frac{d\sigma}{dq_T} \sim \underline{\mathcal{H}\ f_1(x_a, k_{Ta}, Q)\ f_1(x_b, k_{Tb}, Q)\ \delta^{(2)}(q_T - k_{Ta} - k_{Tb})} + \mathcal{O}(q_T/Q) + \mathcal{O}(m/Q)$$

Low transverse momentum (TMD) region

$$q_T \ll Q$$

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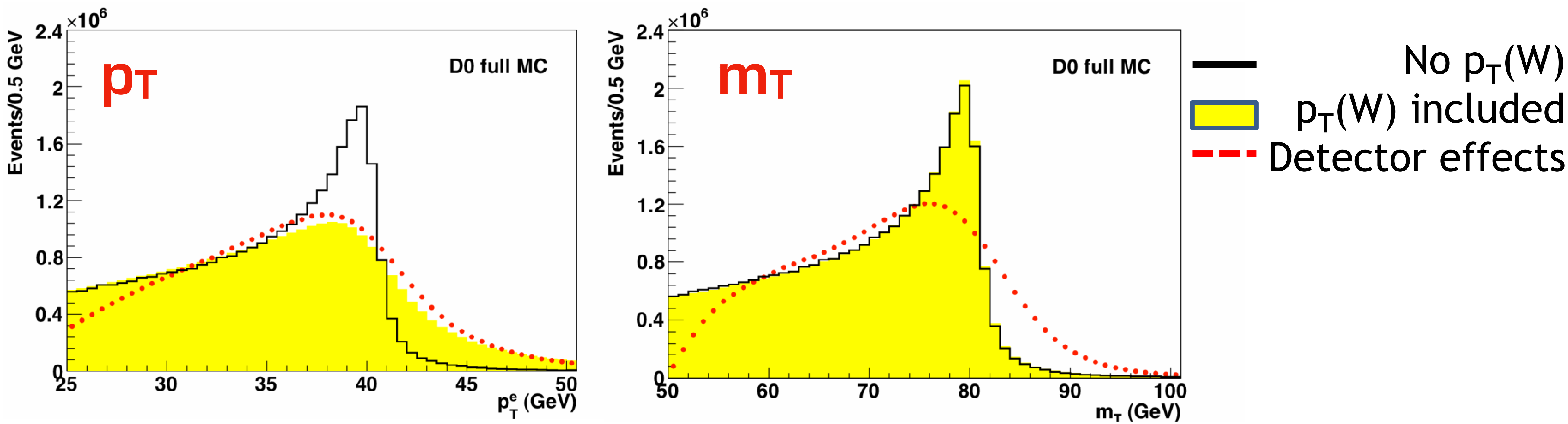
Transverse mass

p_T

m_T

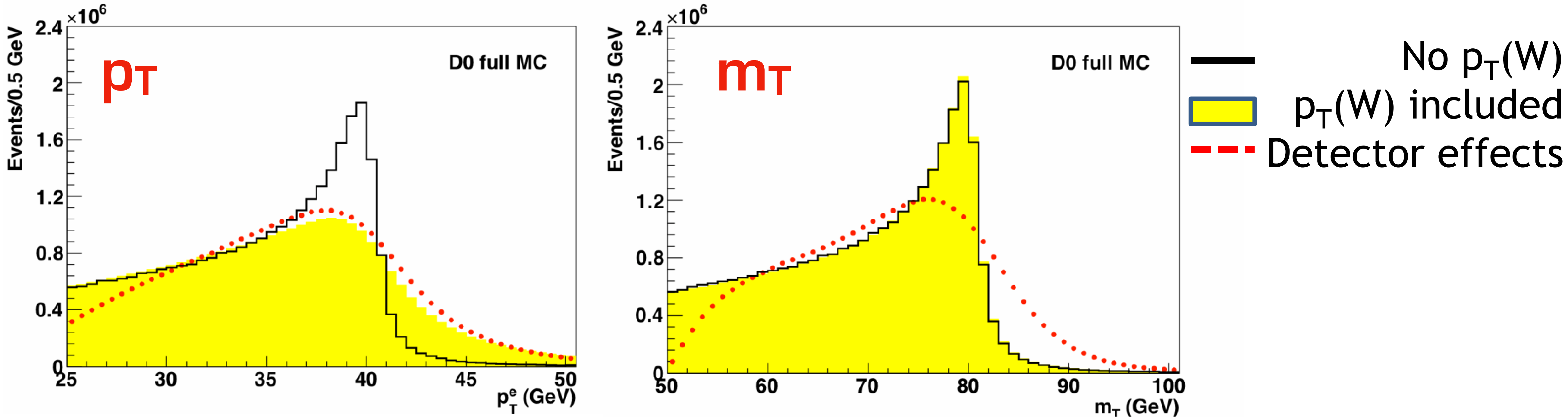
Transverse mass



Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

Transverse mass



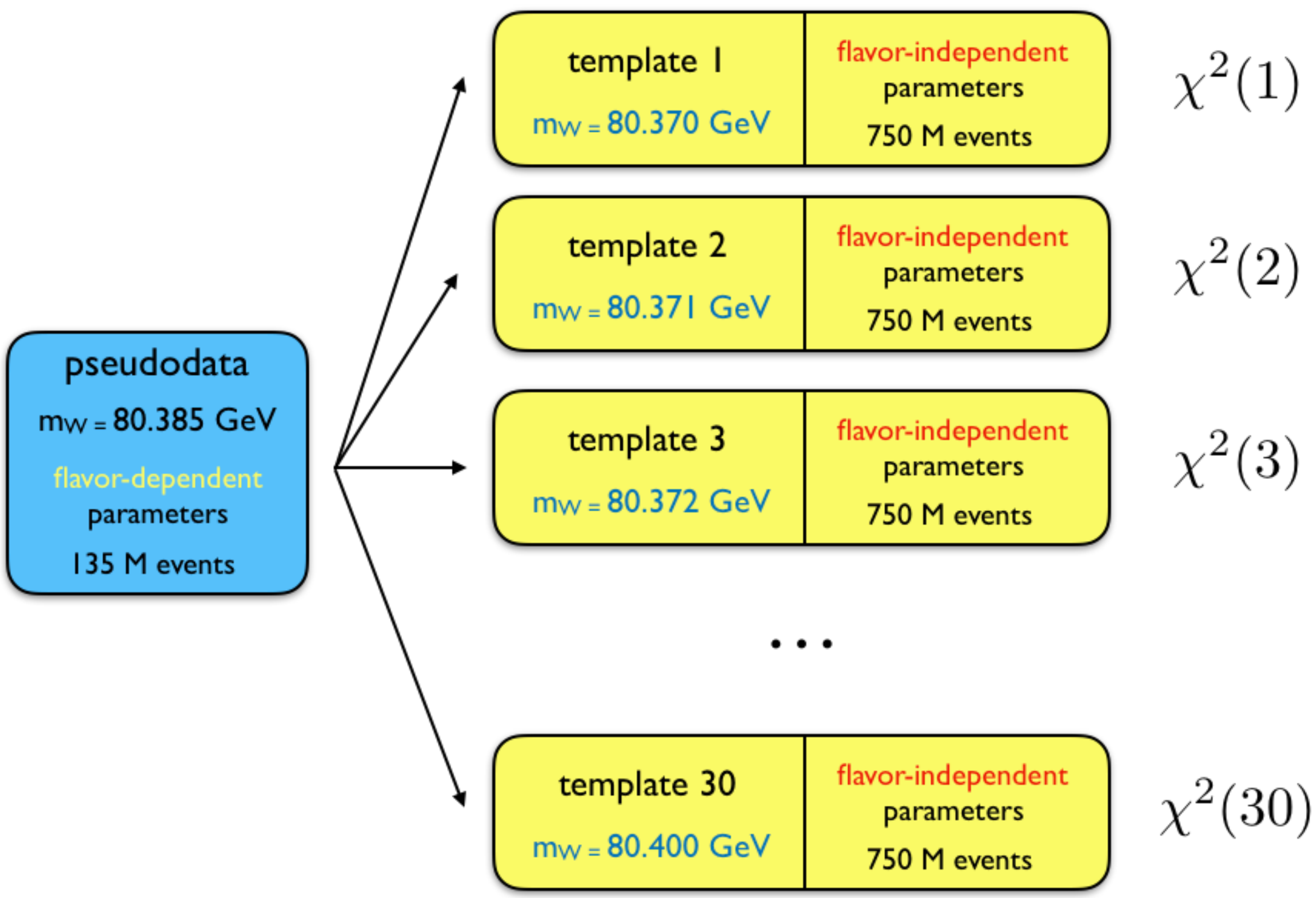
Transverse mass: important detector smearing effects, weakly sensitive to p_{TW} modelling

Lepton p_T: moderate detector smearing effects, extremely sensitive to p_{TW} modelling

p_{TW} modelling depends on flavour and all-order treatment of QCD corrections

Results

We compute the chi2 between templates and pseudo data, find which template gives the best description and determine ΔM_W



	ΔM_{W+}		ΔM_{W-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

Statistical uncertainty: ±2.5 MeV

The statistical uncertainty of the template-fit procedure has been estimated by considering statistically equivalent those templates for which $\Delta\chi^2 = \chi^2 - \chi^2_{min} \leq 1$

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W^+ vs W^-

ATLAS finding : $m_{W^+} - m_{W^-} = -29 \pm 28$ MeV.

$m_{W^-} > m_{W^+}$

ATLAS Collab. arXiv:1701.07240

Part of the discrepancy between the mass of the W+ and the W- can be **artificially induced** by not considering the flavor structure in transverse momentum.

For example, sets 1 and 2 imply $\Delta m_{W^-} > \Delta m_{W^+}$

This implies that building templates with sets 1,2, instead of flavor-independent values, the **difference would be reduced**.

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

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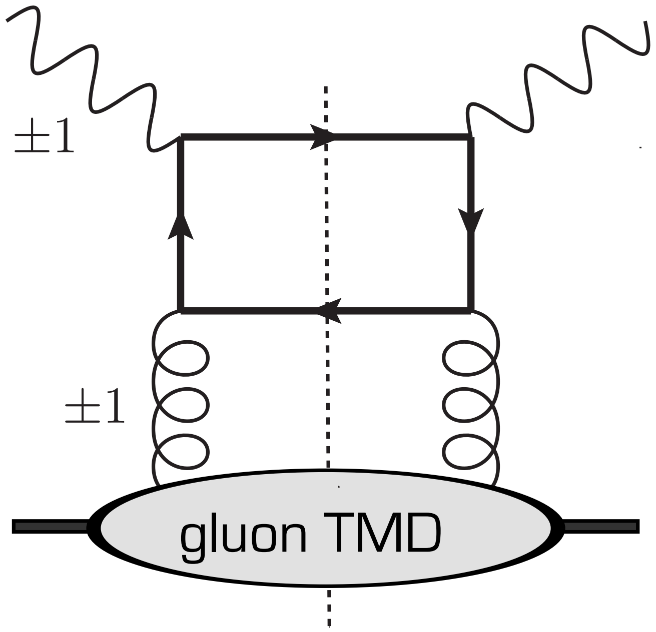
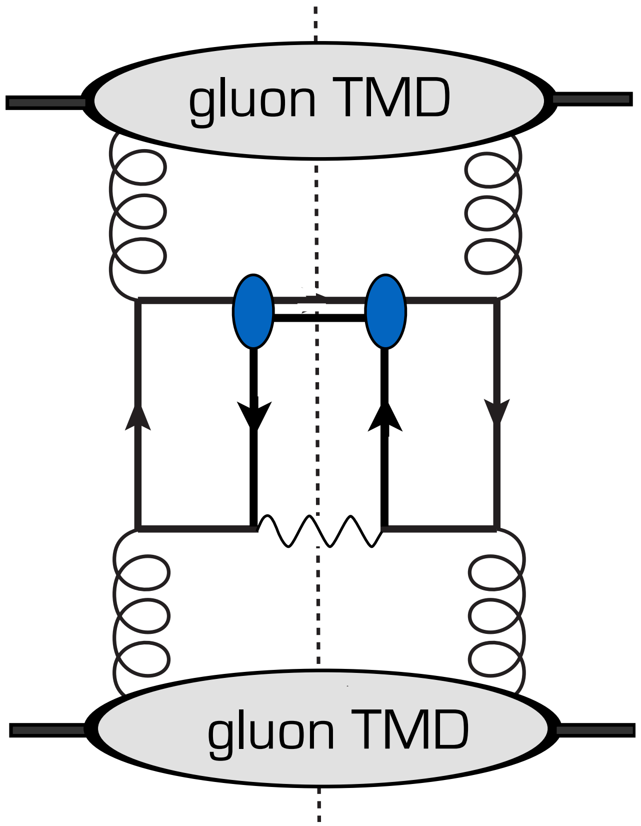
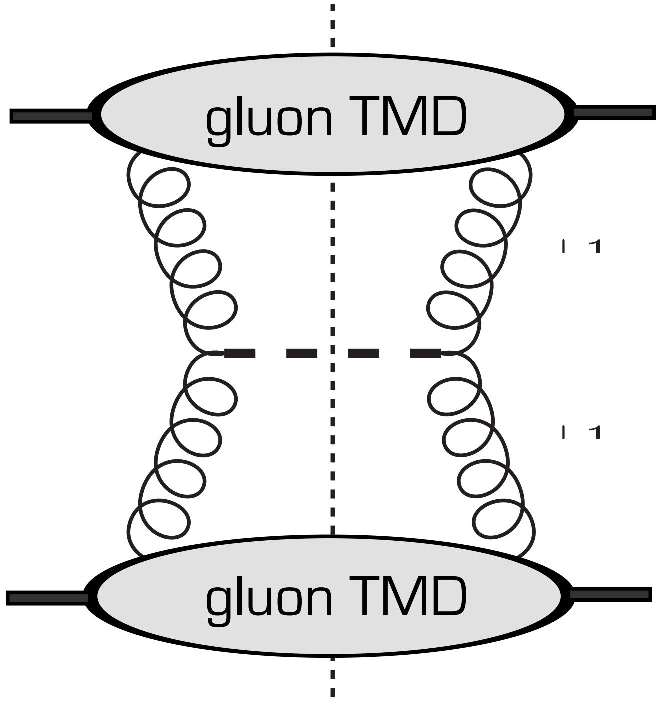
Gluon TMDs

$e\,p \to e\;\text{jet jet}\;X$ $\qquad$ $p\,p \to J/\psi\,\gamma\,X$ $\qquad$ $p\,p \to \eta_c\,X$

EIC !

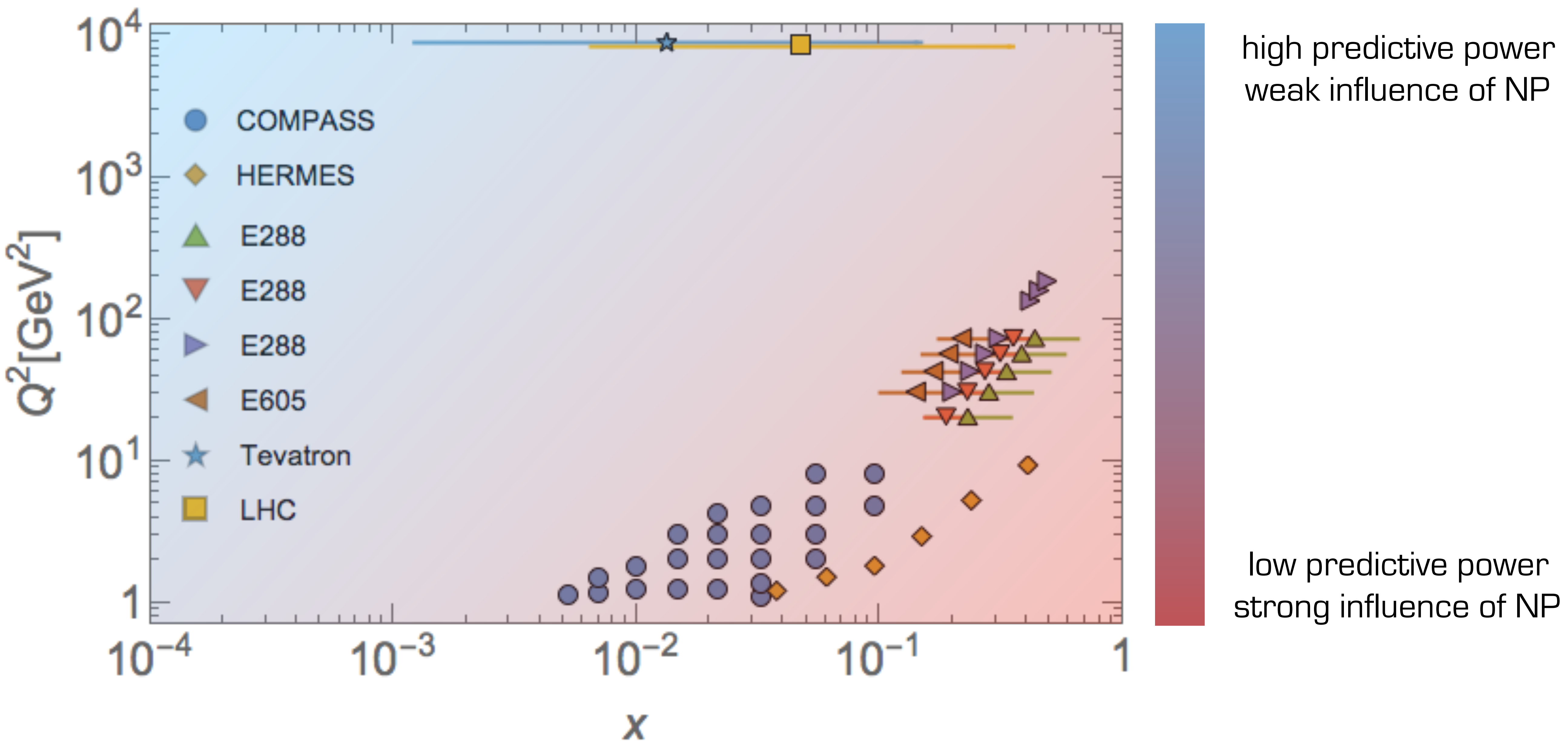






- factorization properties in effective theories
- first extraction of the unpolarized gluon TMD PDF from quarkonium-pair production at LHC (1710.01684)

Data in unpolarized TMD “global” fit



Small-x, high-Q :
strong predictive power

Rapidity dependence too

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