A path into TMD phenomenology

Andrea Signori

About the speaker

2012 - Master student

"Hadron structure and QCD" group, Pavia U. (IT)

Phenomenology of unpolarized TMDs at COMPASS

collaborators

A. Bacchetta (supervisor), M. Radici

2012 - Summer intern

DESY - Hermes collaboration (GE)

Transverse double spin asymmetry in inclusive hadron production

collaborators

G. Schnell (supervisor), A. Movsisyan

About the speaker

2012 - present | PhD candidate

Nikhef and Vrije Universiteit Amsterdam (NL)

Theory and phenomenology of TMDs

main collaborators

P.J. Mulders (supervisor), T. Kasemets, M. Ritzmann (VU, Nikhef)

A. Bacchetta, M. Radici (Pavia - IT)

M. Echevarria (Barcelona - ES)

C. Pisano (Antwerp - BE)

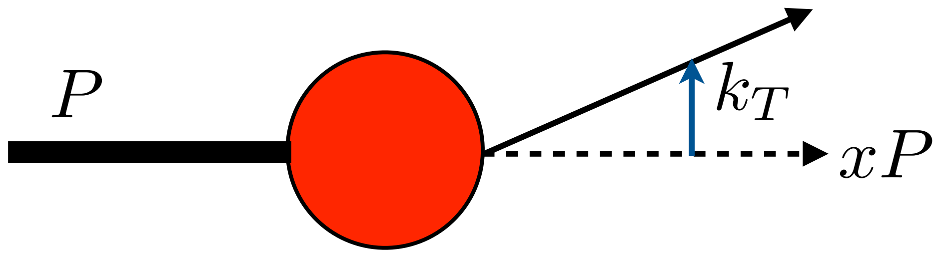
J.P. Lansberg (Orsay - FR)

2014 - present | blogger

“Quantum Diaries” (Interaction collaboration)

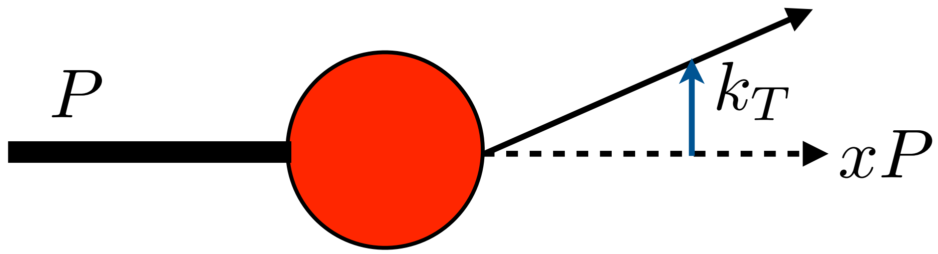
Thoughts on work and life from particle physicists around the world

Quark TMD PDFs



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

Quark TMD PDFs



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

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

a similar scheme
holds for fragmentation
and for gluons
in Lorentz space

spin-spin and spin-orbit
interactions

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How to access TMDs ?

flavor structure of unpolarized quark TMDs

TMDs and QCD evolution

How to access TMDs ?

Jefferson Lab

flavor structure of unpolarized quark TMDs

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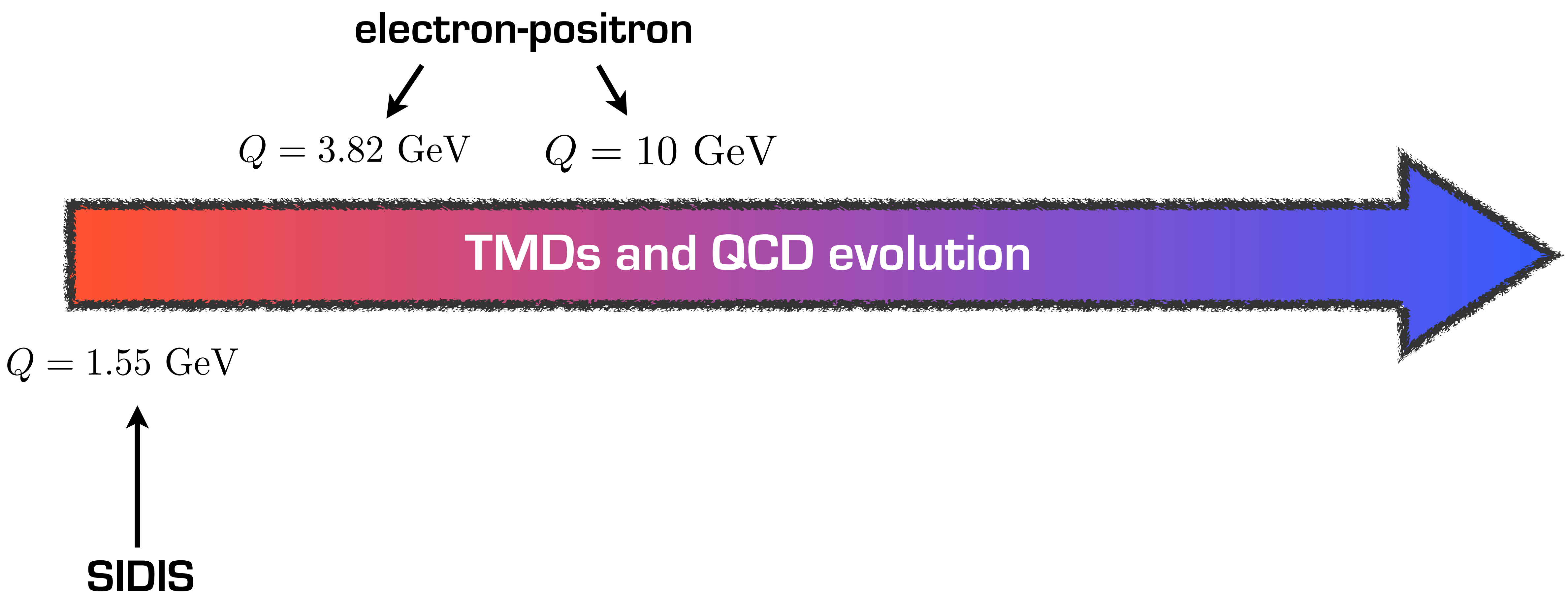
How to access TMDs ?

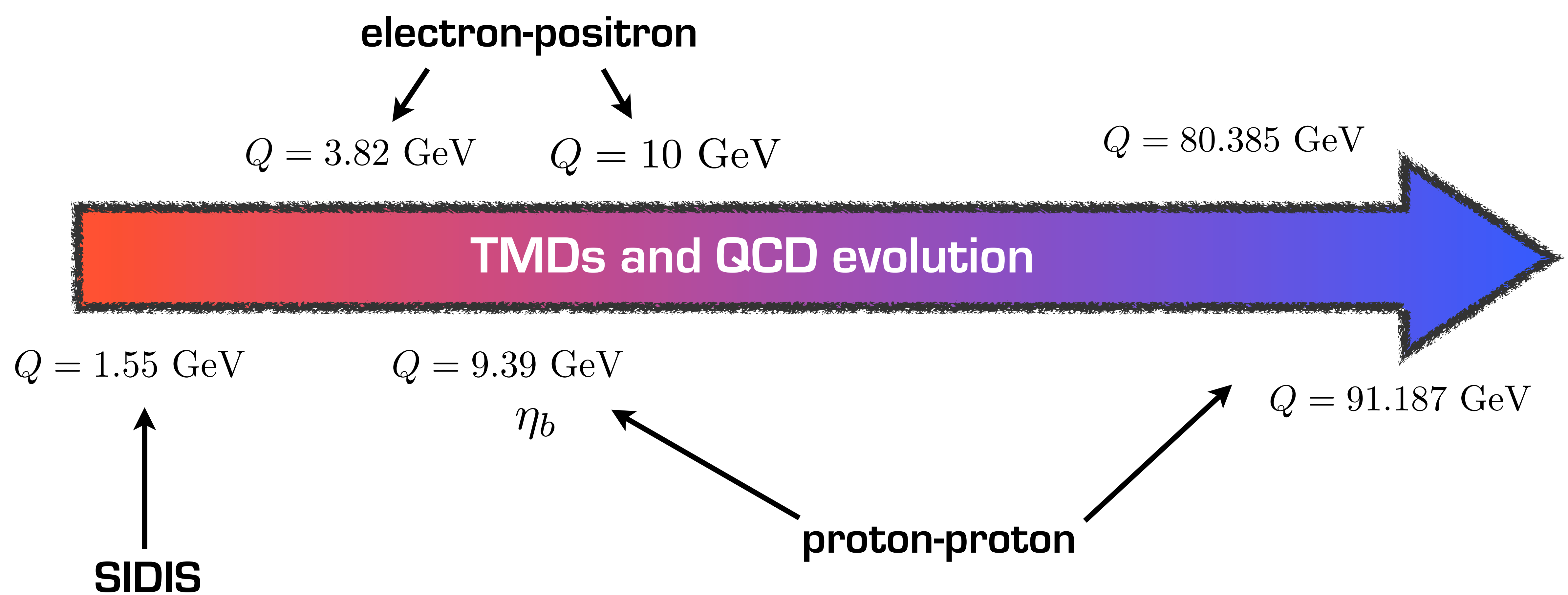
flavor structure of unpolarized quark TMDs



How to access TMDs ?

Jefferson Lab

flavor structure of unpolarized quark TMDs



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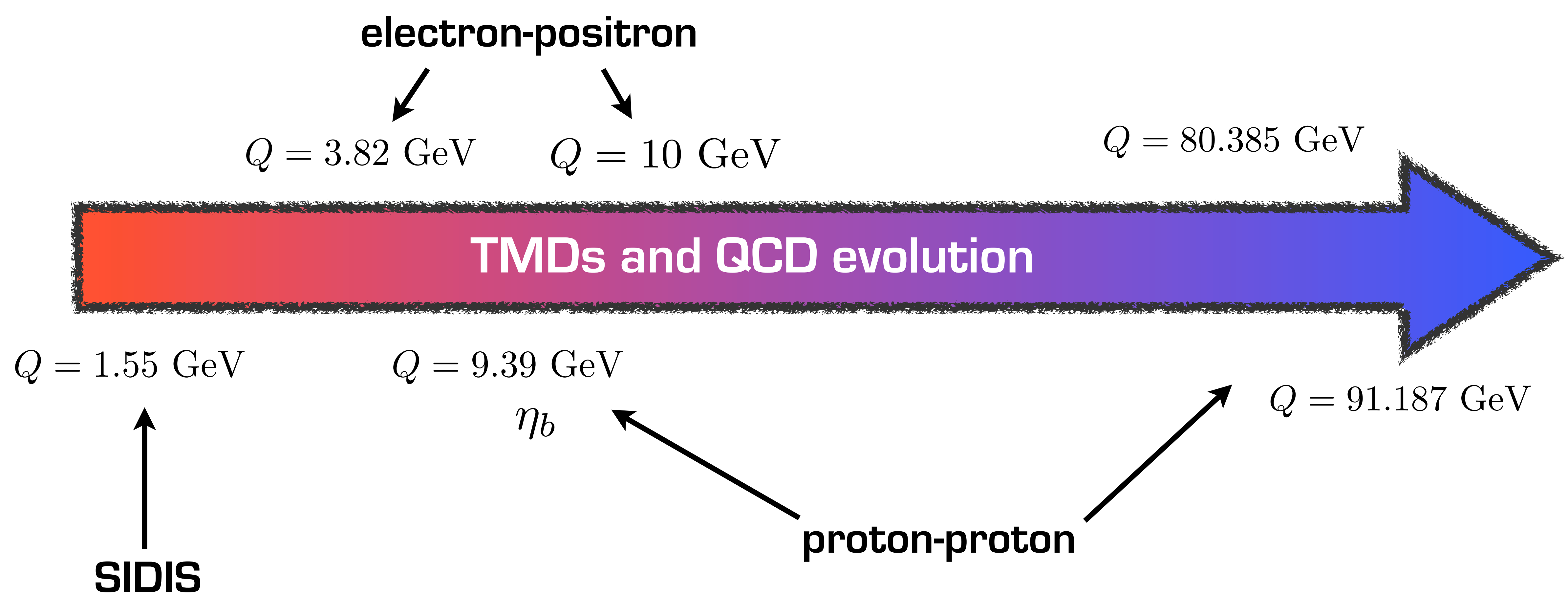
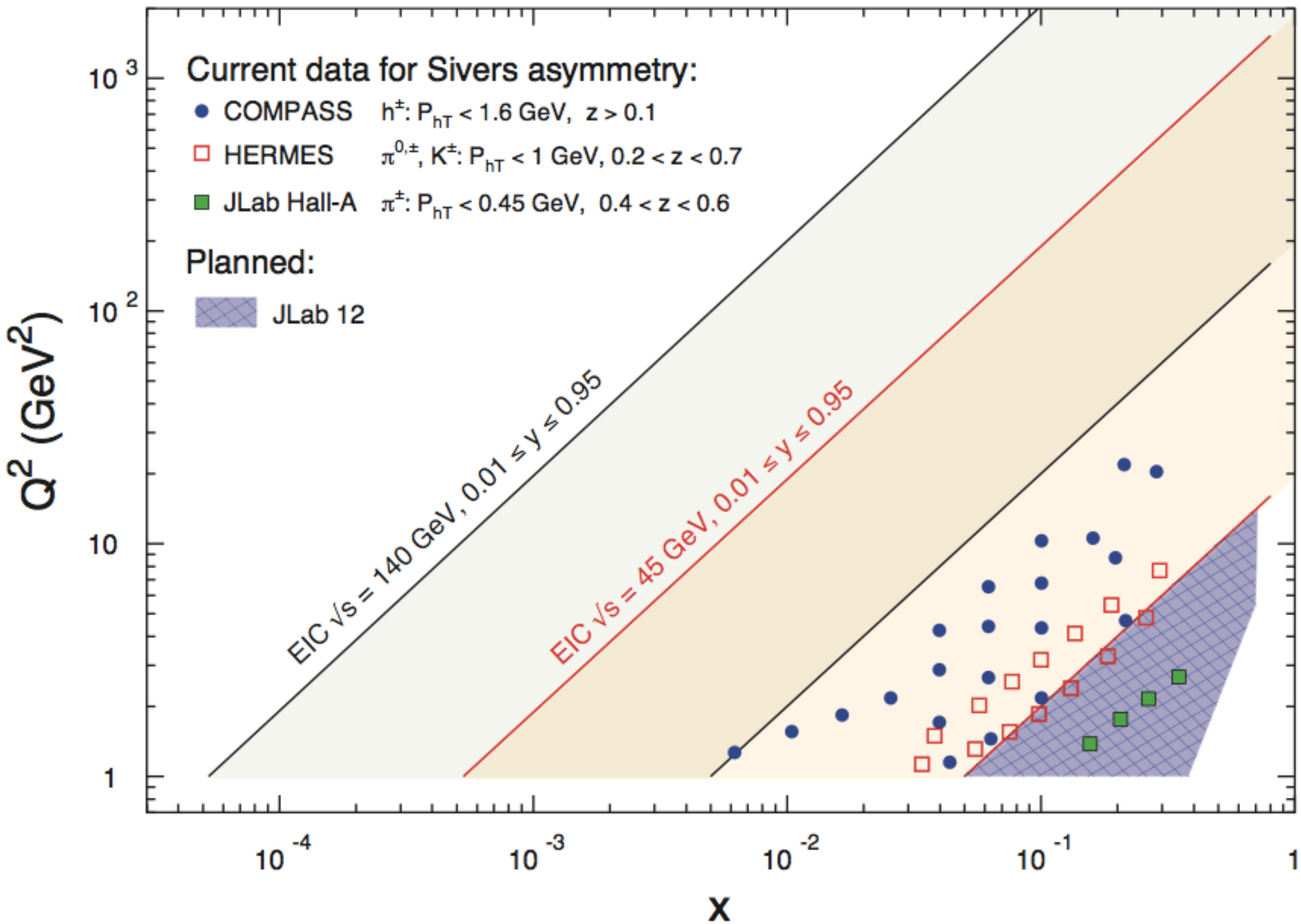
How to access TMDs ?

flavor structure of unpolarized quark TMDs



... and **new TMDs** !

How to access TMDs ?



Jefferson Lab

- high x

- high luminosity and statistic

- multidimensional analysis

$$e^{\pm} + P/D \longrightarrow e^{\pm} + \pi^{\pm}/K^{\pm} + X$$

TMDs at work in SIDIS

references :

AS, Bacchetta, Radici, Schnell
10.1007/JHEP11(2013)194
Bacchetta, Radici, **AS**
10.1142/S2010194514600209

Transverse momenta

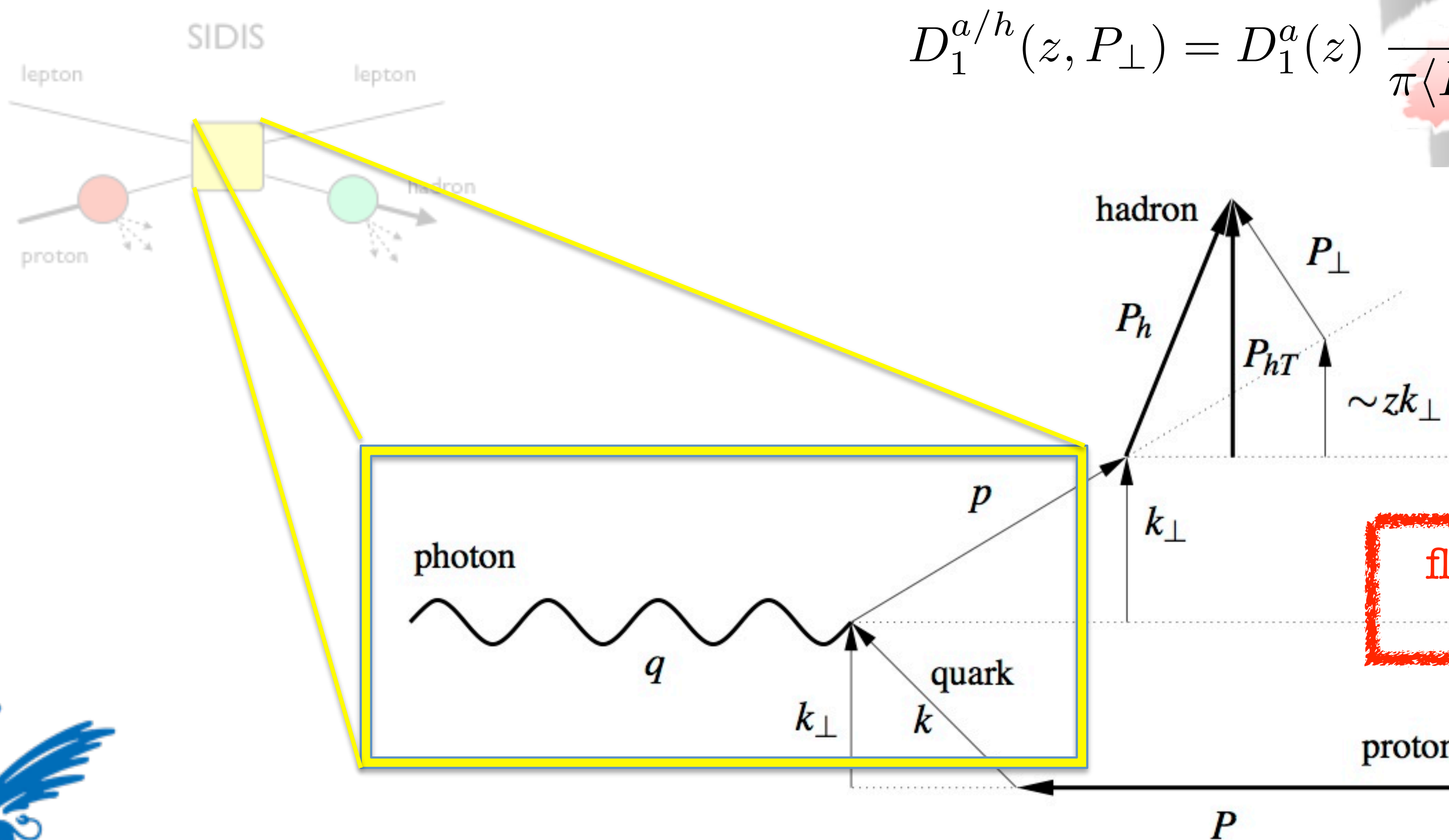
$$\sigma(P_{hT}^2) \sim \sum_a f_1^a(x, k_\perp^2) \otimes D_1^{a\to h}(z, P_\perp^2)$$

$$\langle P_{hT,q}^2 \rangle = z^2 \langle k_{\perp,q}^2 \rangle + \langle P_{\perp,q/h}^2 \rangle$$

Gaussian distributions

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

$$D_1^{a/h}(z, P_\perp) = D_1^a(z) \frac{1}{\pi \langle P_\perp^2 \rangle_{a/h}(z)} e^{-\frac{P_\perp^2}{\langle P_\perp^2 \rangle_{a/h}(z)}}$$



flavor- and kinematic-dependent widths

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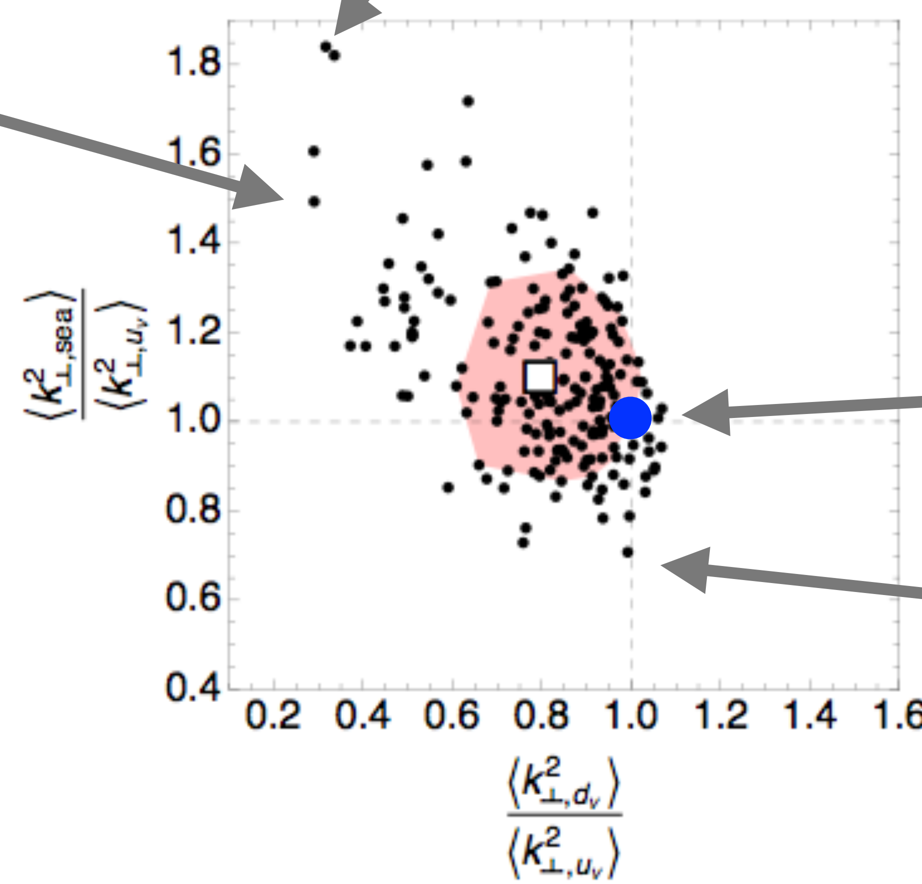
Flavor dependent TMD PDFs

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

replica 149
$\chi^2/\mathrm{dof} = 1.87$

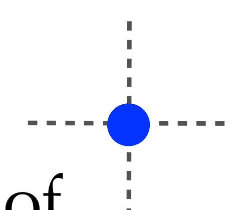
replica 73
$\chi^2/\mathrm{dof} = 1.70$



replica 130
$\chi^2/\mathrm{dof} = 1.77$

replica 186
$\chi^2/\mathrm{dof} = 1.38$

sea width
> (mostly)
$\mathrm{u_v}$ width



point of
no flavor dep.

$\mathrm{d_v}$ width < (mostly) $\mathrm{u_v}$ width

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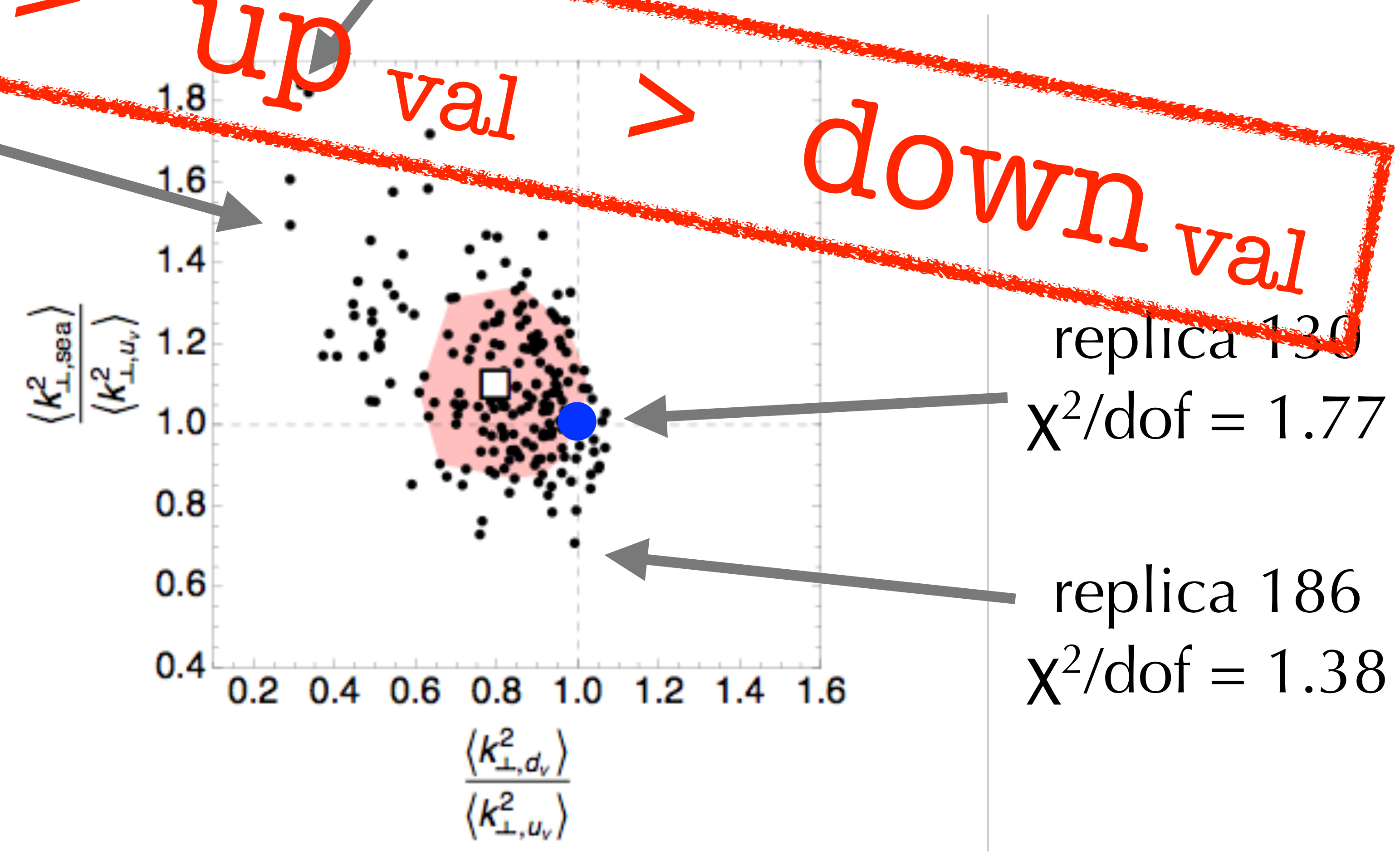
Flavor dependent TMD PDFs

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

sea > up val > down val



sea width
> (mostly)
u_v width

point of
no flavor dep.

d_v width < (mostly) u_v width

Flavor dependent TMD FFs

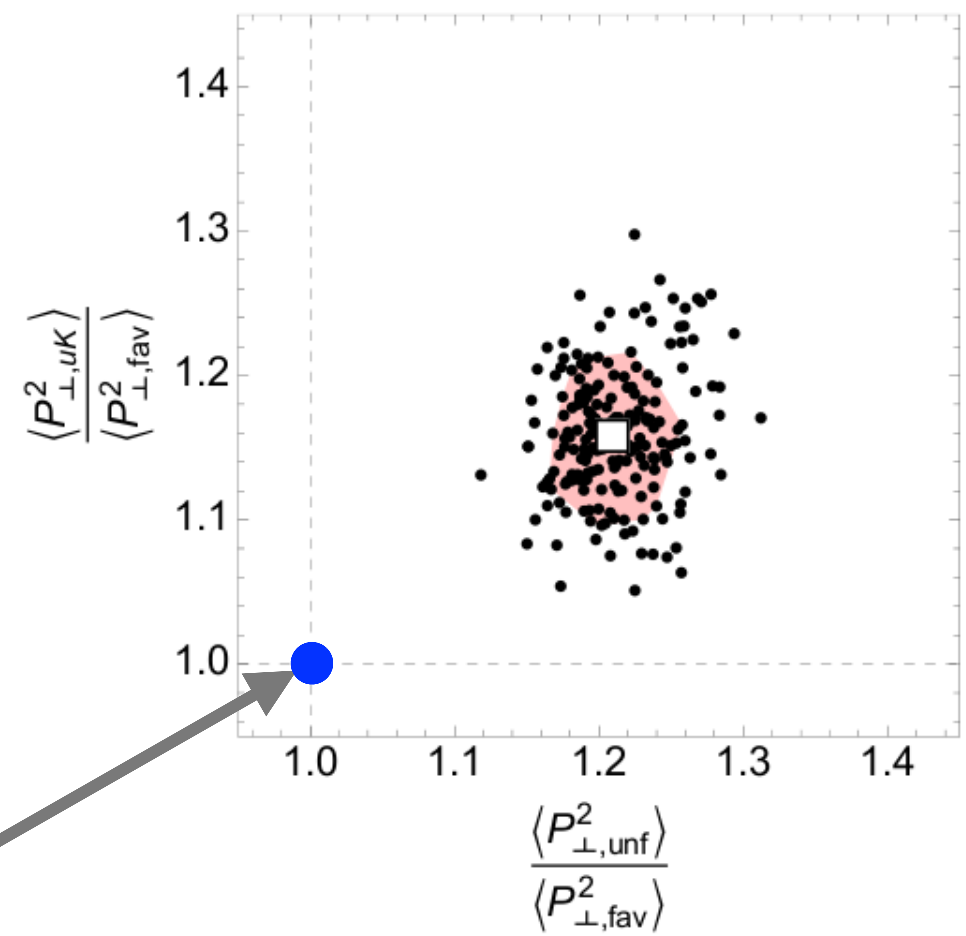
$$\left\langle \boldsymbol{P}^2_{\perp,u\to\pi^+}\right\rangle = \left\langle \boldsymbol{P}^2_{\perp,\bar{d}\to\pi^+}\right\rangle = \left\langle \boldsymbol{P}^2_{\perp,\bar{u}\to\pi^-}\right\rangle = \left\langle \boldsymbol{P}^2_{\perp,d\to\pi^-}\right\rangle \equiv \left\langle \boldsymbol{P}^2_{\perp,\mathrm{fav}}\right\rangle ,$$

$$\left\langle \boldsymbol{P}^2_{\perp,u\to K^+}\right\rangle = \left\langle \boldsymbol{P}^2_{\perp,\bar{u}\to K^-}\right\rangle \equiv \left\langle \boldsymbol{P}^2_{\perp,uK}\right\rangle ,$$

$$\left\langle \boldsymbol{P}^2_{\perp,\bar{s}\to K^+}\right\rangle = \left\langle \boldsymbol{P}^2_{\perp,s\to K^-}\right\rangle \equiv \left\langle \boldsymbol{P}^2_{\perp,sK}\right\rangle ,$$

$$\left\langle \boldsymbol{P}^2_{\perp,\text{all others}}\right\rangle \equiv \left\langle \boldsymbol{P}^2_{\perp,\mathrm{unf}}\right\rangle .$$

q→π favored width
<
q→K favored width



● point of
no flavor dep.

q→π favored width < unfavored

Flavor dependent TMD FFs

$$\langle \boldsymbol{P}^2_{\perp,u\to\pi^+}\rangle = \langle \boldsymbol{P}^2_{\perp,\bar{d}\to\pi^+}\rangle = \langle \boldsymbol{P}^2_{\perp,\bar{u}\to\pi^-}\rangle = \langle \boldsymbol{P}^2_{\perp,d\to\pi^-}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,\mathrm{fav}}\rangle$$

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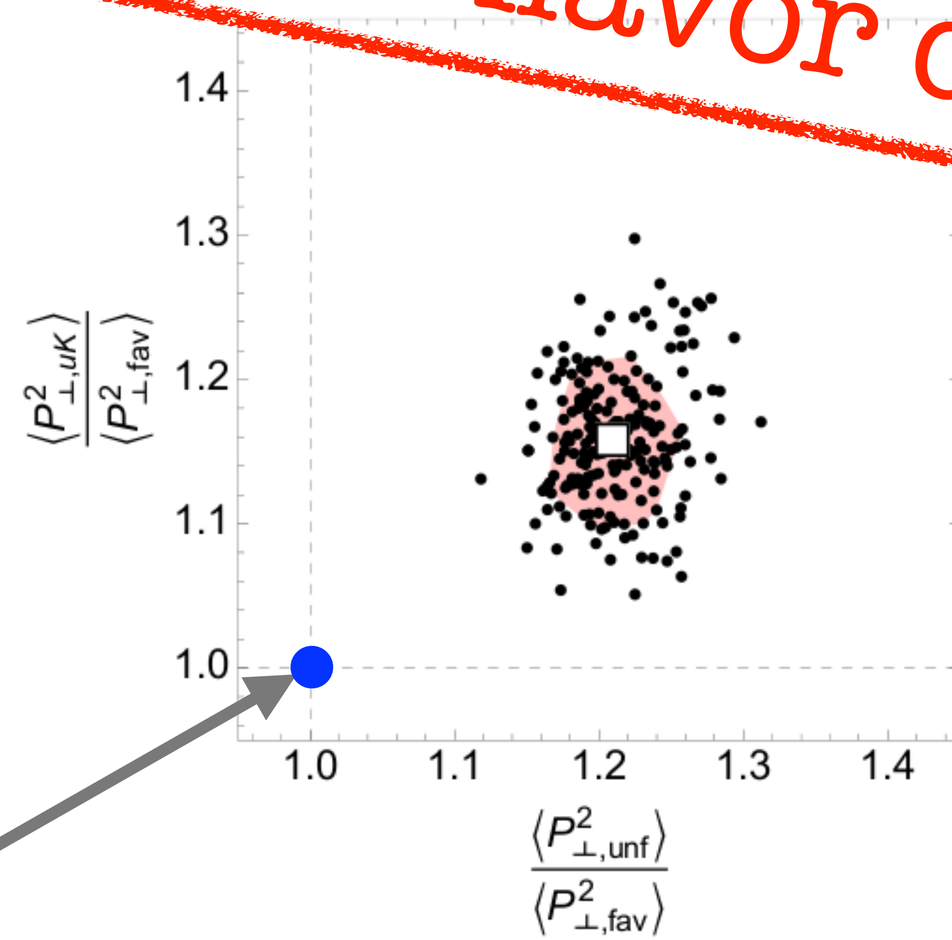
$$\langle \boldsymbol{P}^2_{\perp,\text{all others}}\rangle \equiv \langle \boldsymbol{P}^2_{\perp,\mathrm{unf}}\rangle\,.$$

good evidence for flavor dep.

q→π favored width
<
q→K favored width



● point of
no flavor dep.

q→π favored width < unfavored

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TMDs at work in e^+e^-

references :

Bacchetta, Echevarria, Mulders, Radici, **AS**
10.1007/JHEP11(2015)076
Bacchetta, Echevarria, Radici, **AS**
10.1142/S201019451560023X
10.1051/epjconf/20158502016

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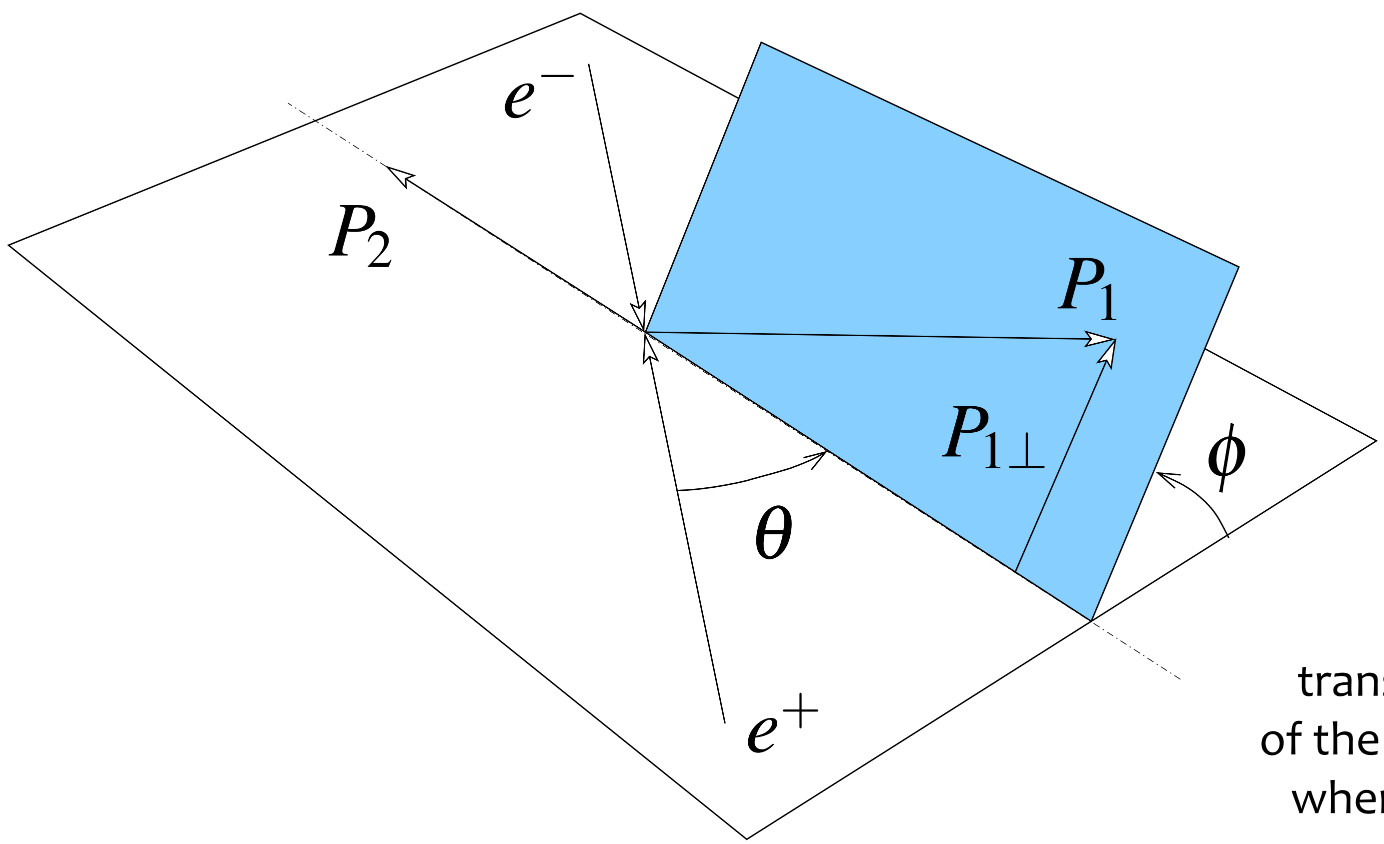
Kinematics and observables



e+e- CM frame:
production of two back-to-back jets
with leading hadrons h1 and h2

h1 only has transverse momentum wrt to z

$$q_T^\mu = -\frac{P_{1\perp}^\mu}{z_1} + O\left(\frac{M^2}{Q^2}\right)$$

transverse momentum
of the photon in the frame
where h1,2 are collinear

transverse momentum
of h1 wrt photon

The observable: normalized multiplicity,
poorly sensitive to perturbative corrections

$$M^{h_1 h_2}(z_1, z_2, q_T^2, y)/M^{h_1 h_2}(z_1, z_2, 0, y)$$

Multiplicity,
defined as in SIDIS

$$M^{h_1 h_2}(z_1, z_2, q_T^2, y) = \frac{d\sigma^{h_1 h_2}}{dz_1\ dz_2\ dq_T^2\ dy} \Big/ \frac{d\sigma^{h_1}}{dz_1\ dy}$$

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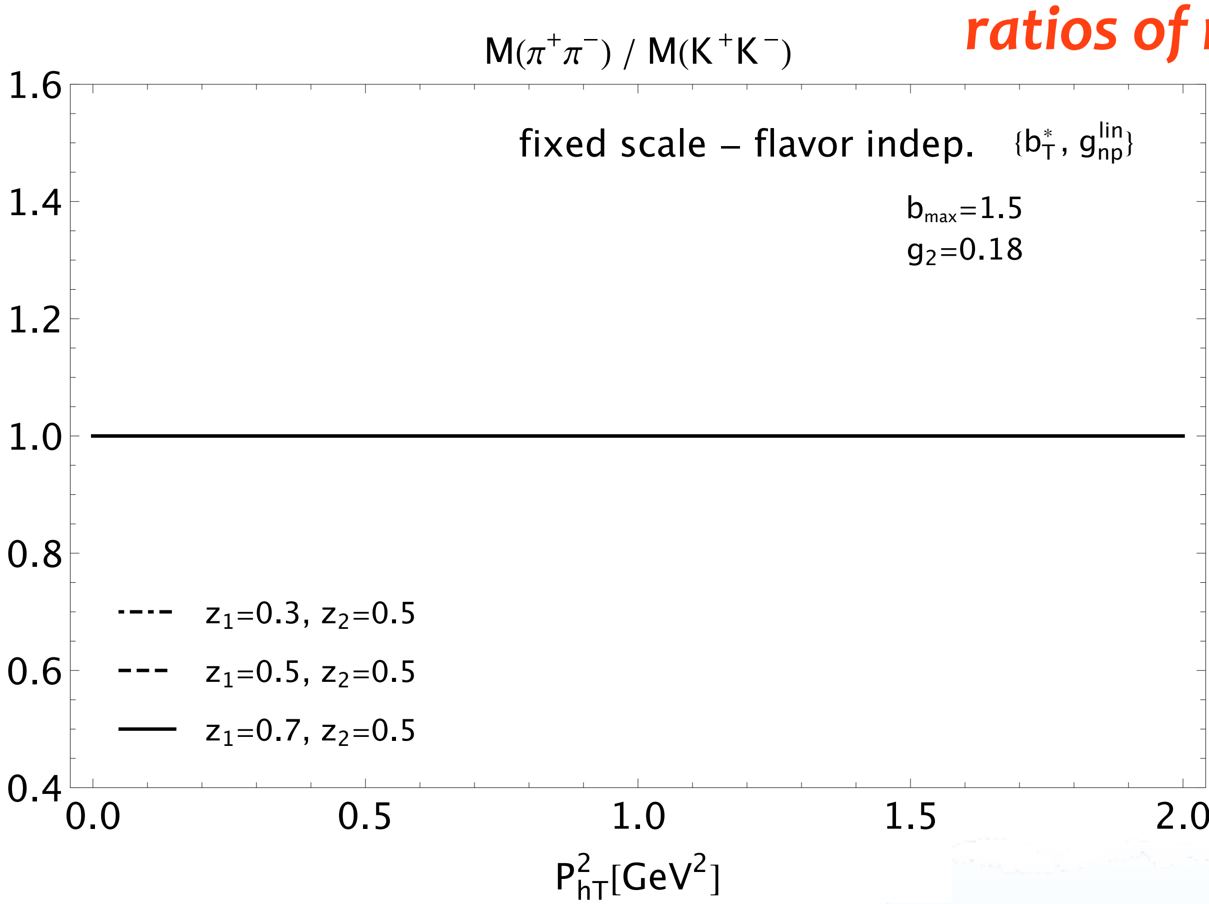
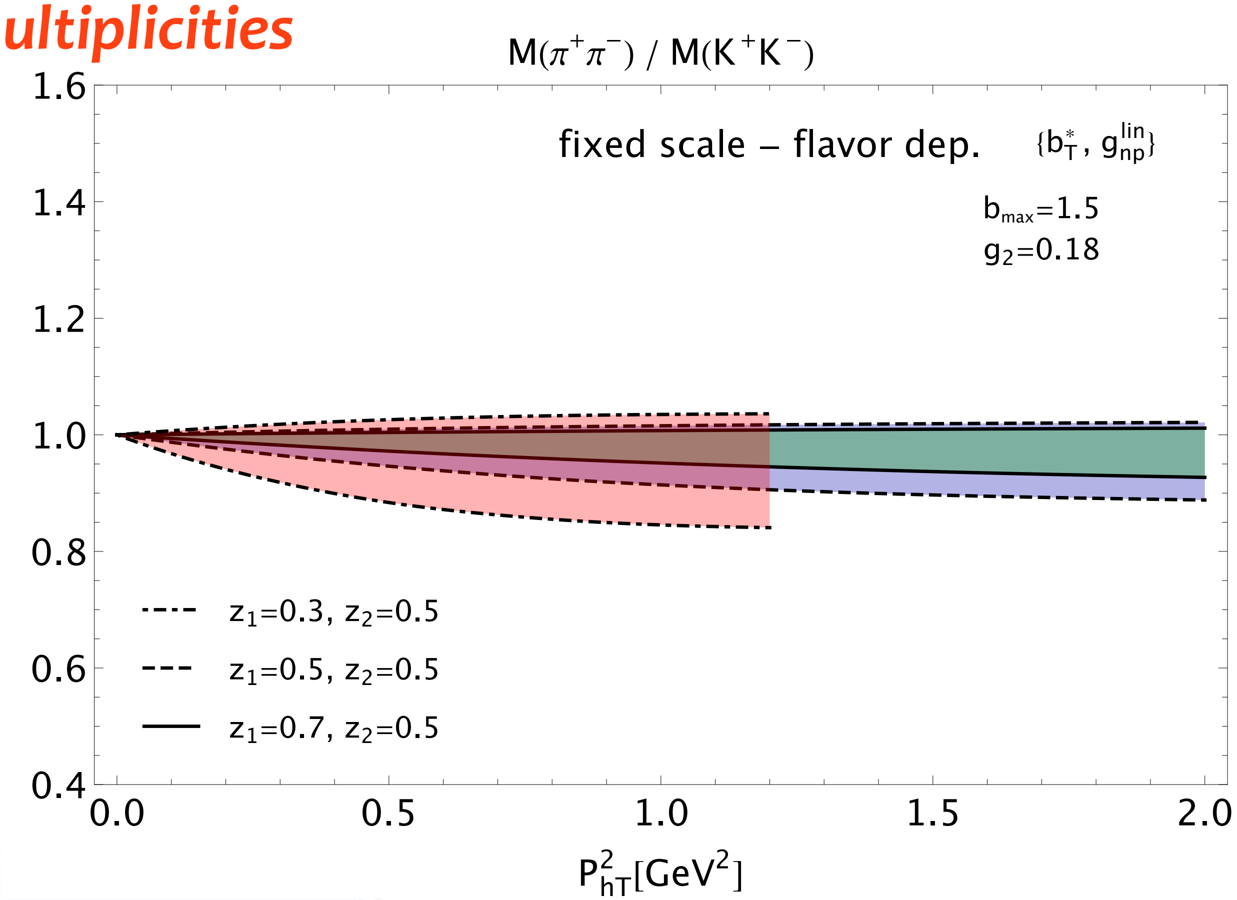
Partonic flavor

ratios of multiplicities





being flavor independent
they factor out and cancel:

no qT dependence is left

the transverse momentum
dependence is described
ONLY by the
Gaussian distributions

$$d_1^{q\to h}(z,Q_i)e^{-\frac{\langle k_T^2\rangle_{q\to h}(z)}{4}b_T^2}$$

being flavor dependent
they combine and give a
specific qT dependence

band width result from
intrinsic flavor dependence

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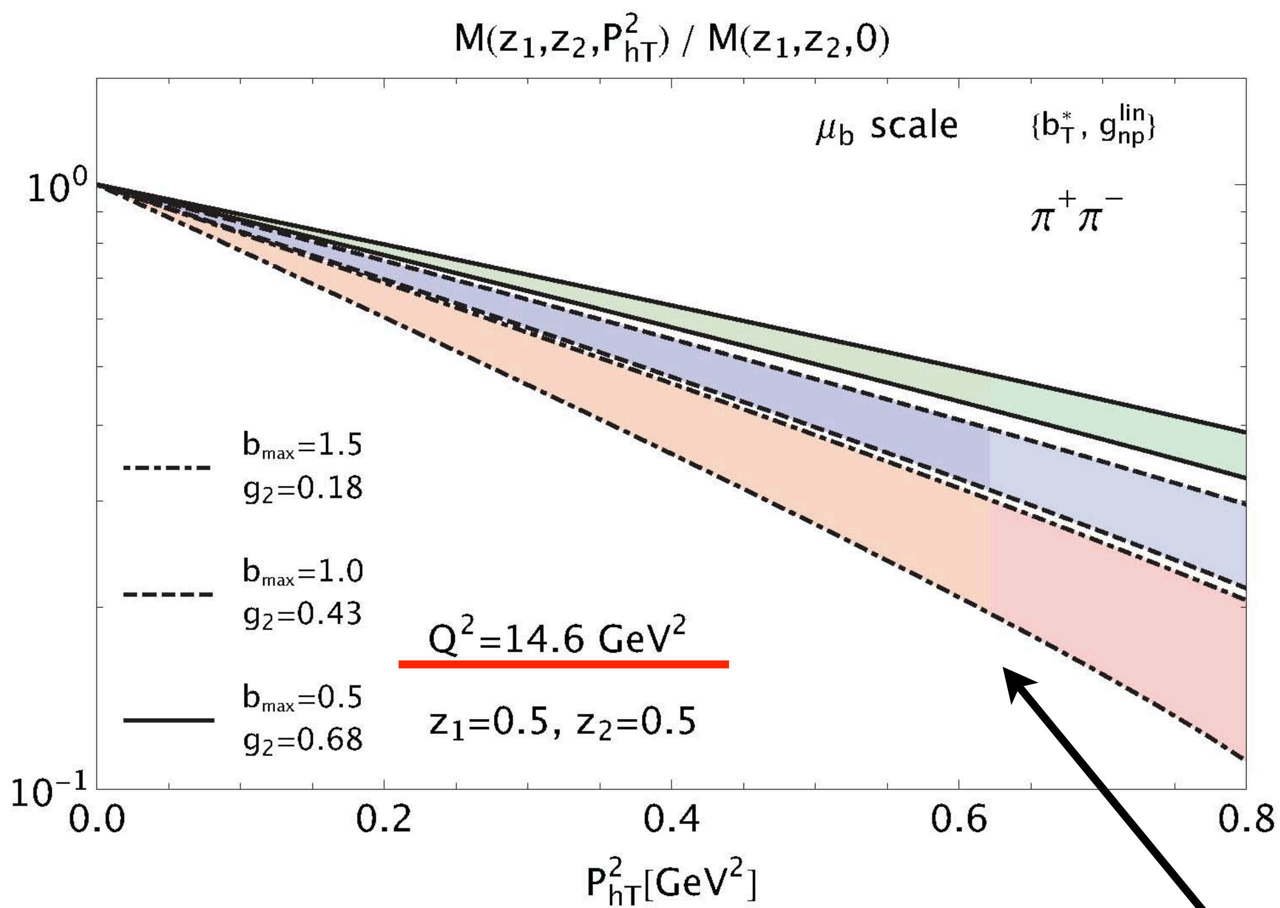
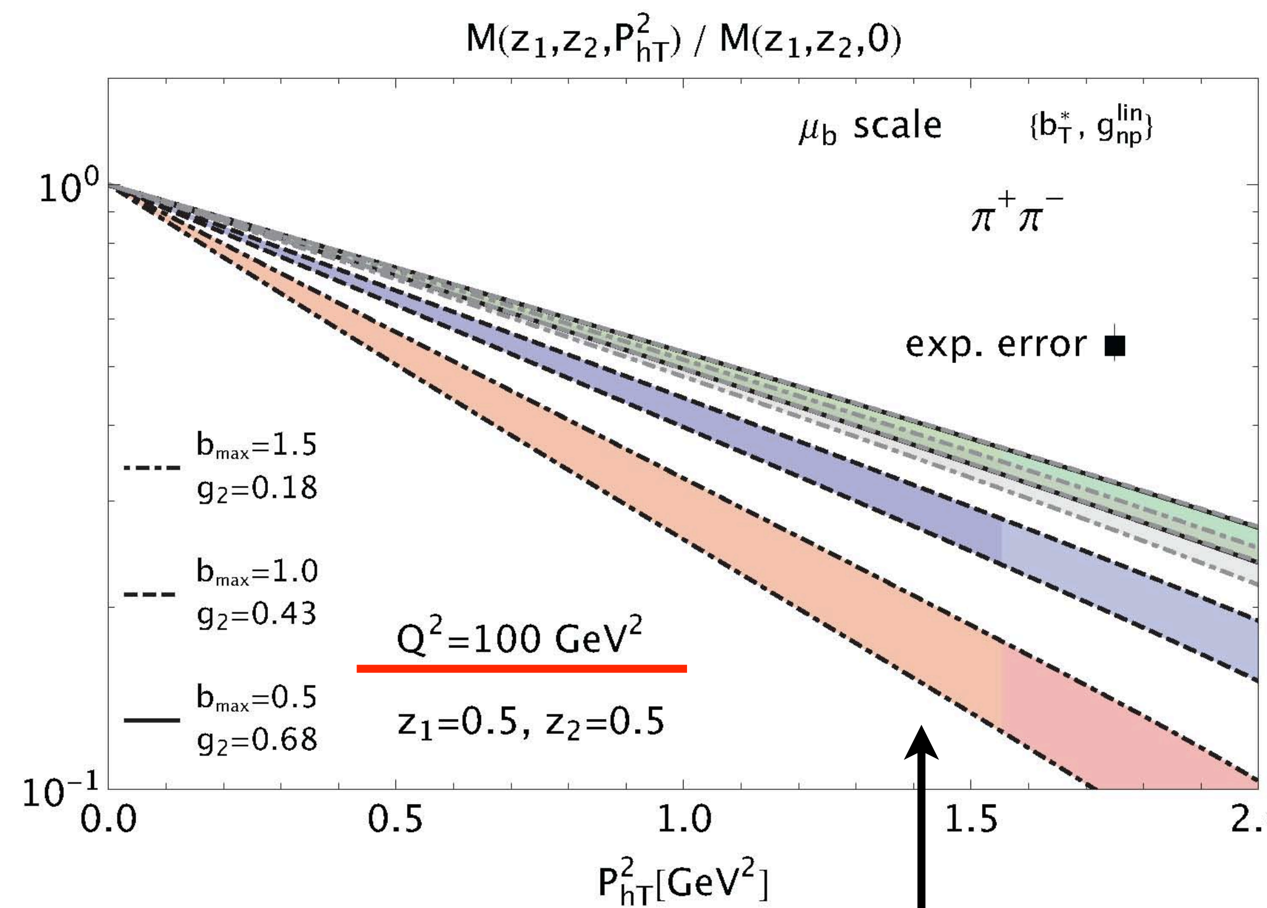
Evolution





model-dependent pieces

$$D_1^{a\to h}(z, b_T; Q) \sim e^{S_P} \; (C \otimes d_1) \boxed{e^{-\frac{\langle P_\perp^2 \rangle_a(z)}{4z^2} b_T^2}} \boxed{e^{-\frac{g_2}{4} b_T^2 \ln Q^2}}$$

intrinsic transverse momentum
(flavor, kinematics)

non-pert. evolution
(soft gluon emission)

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TMDs at work in pp

references :

AS et al.
10.5506/APhysPolB.46.2501
Bacchetta, Mulders, Radici, Ritzmann, **AS**
in preparation
Echevarria, Kasemets, Lansberg, Pisano, **AS**
in preparation

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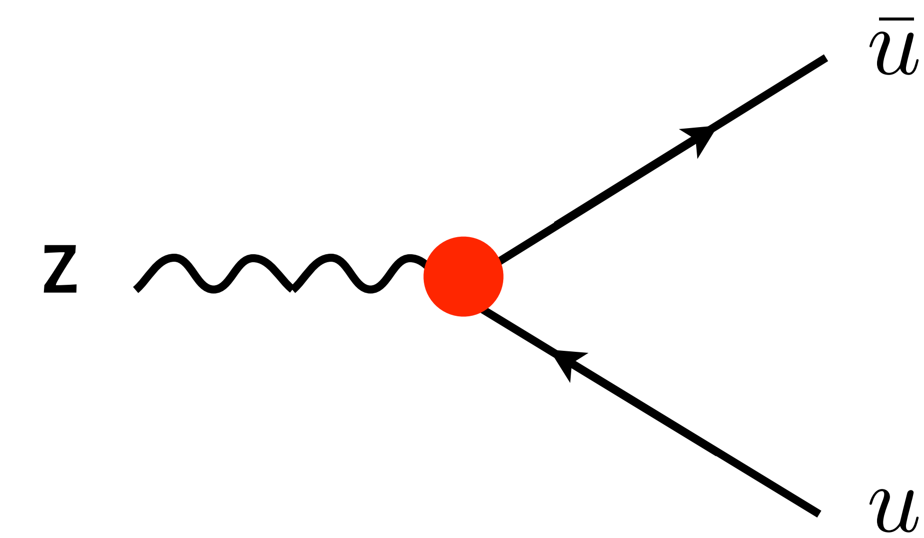
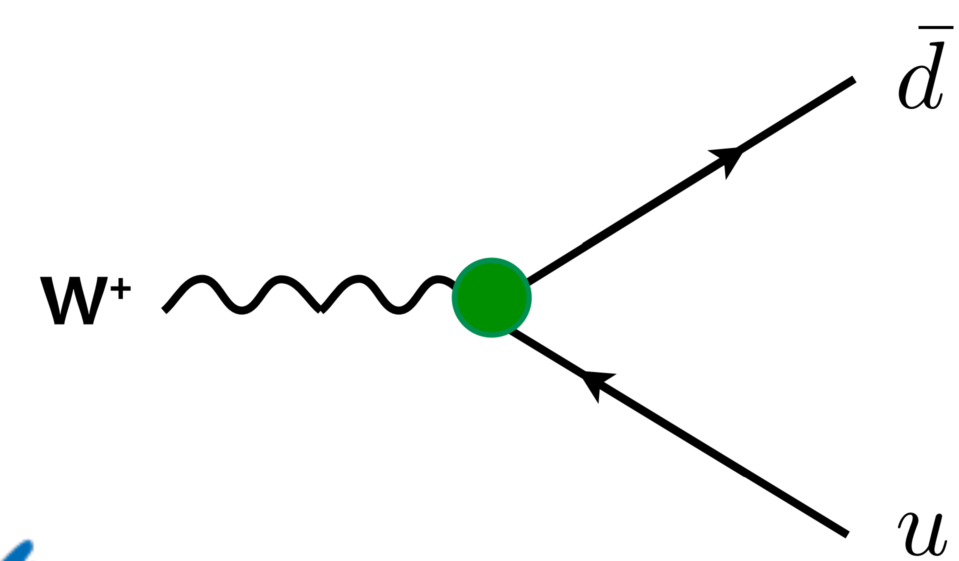
Quark TMDs at the LHC



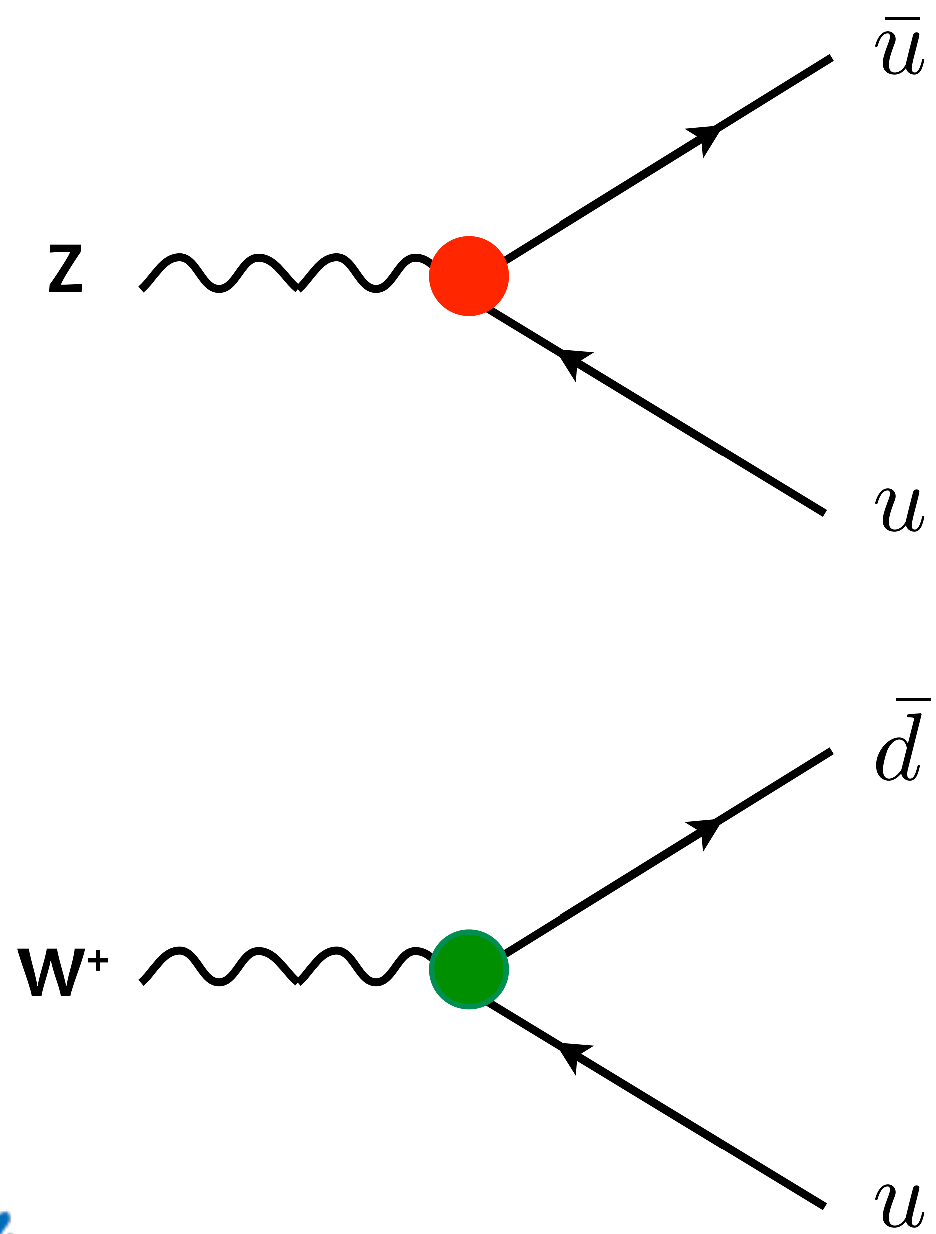


$$\frac{d\sigma^{Z/W^\pm}}{dq_T} \sim \mathrm{FT} \sum_{i,j} \exp\{-g_{ij}\, b_T^2\}$$

$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

g comes from 2 TMD PDFs
and ***controls the position of the peak***

Quark TMDs at the LHC



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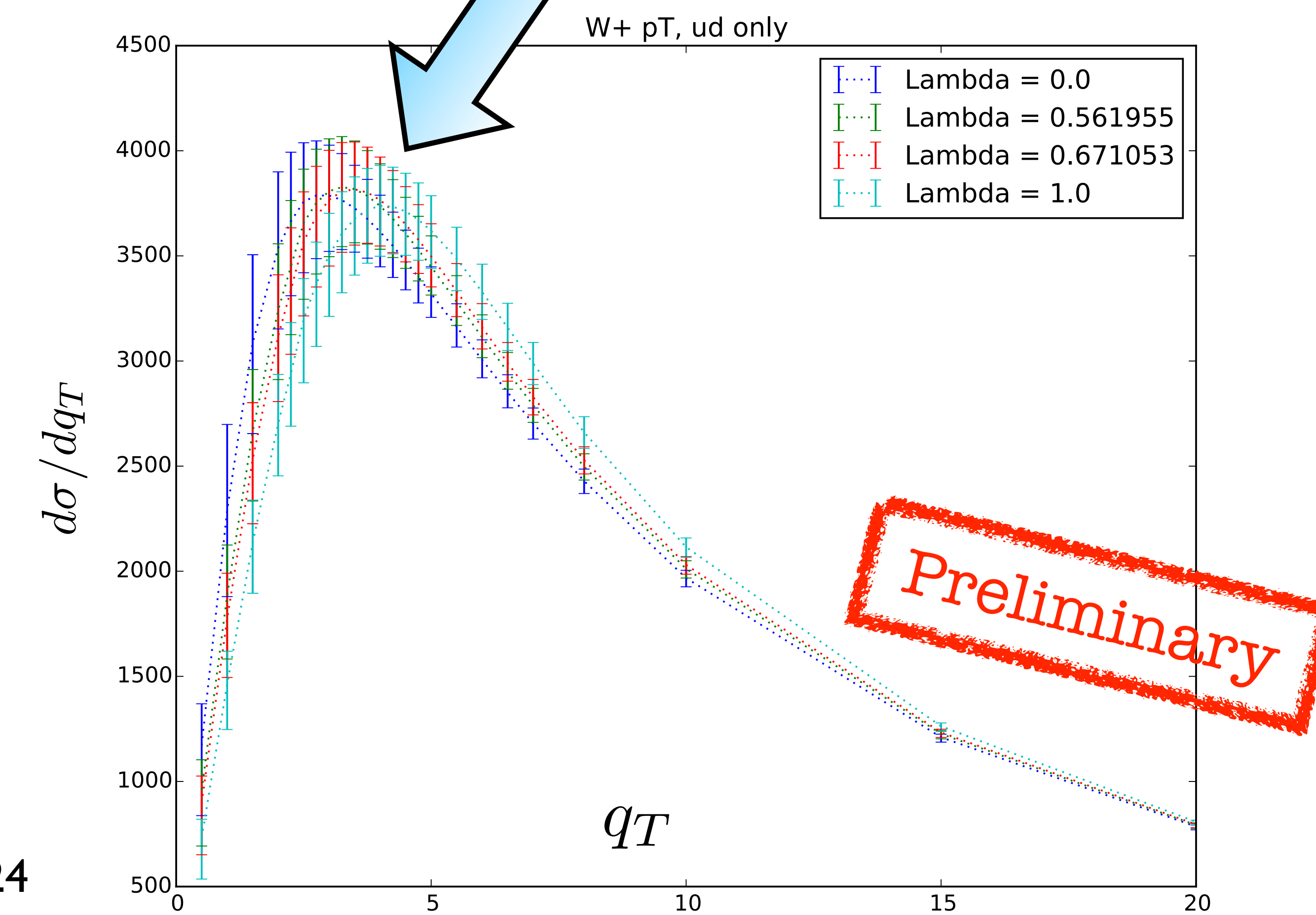
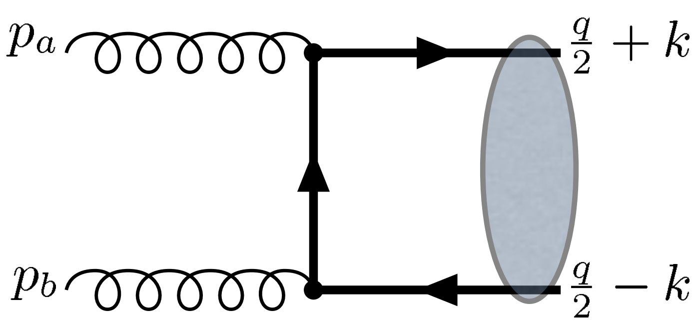


Gluon TMDs at work

(heavy) **quarkonium** production



+ crossed term

$$P_A + P_B \to \eta_b(q_T) + X$$

$$m_{\eta_b} = 9.39 \text{ GeV}$$

low/medium energy process:
we could **extract**
information on the non perturbative
part of gluon TMDs

but ... does TMD factorization hold ?

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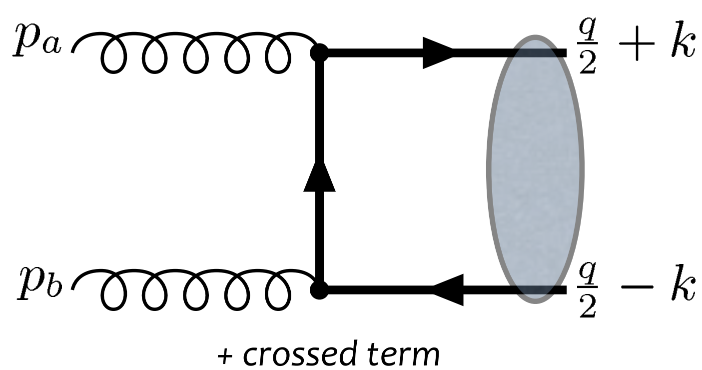
Gluon TMDs at work

(heavy) **quarkonium** production



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$$m_{\eta_b} = 9.39 \ \mathrm{GeV}$$

low/medium energy process:
we could **extract**
information on the non perturbative
part of gluon TMDs

but ... does TMD factorization hold ?

namely, are we allowed to use such an expression ?

$$\frac{d\sigma}{dq_T} \sim f_1^{g/A} \; f_1^{g/B} \; |\mathcal{M}|^2$$

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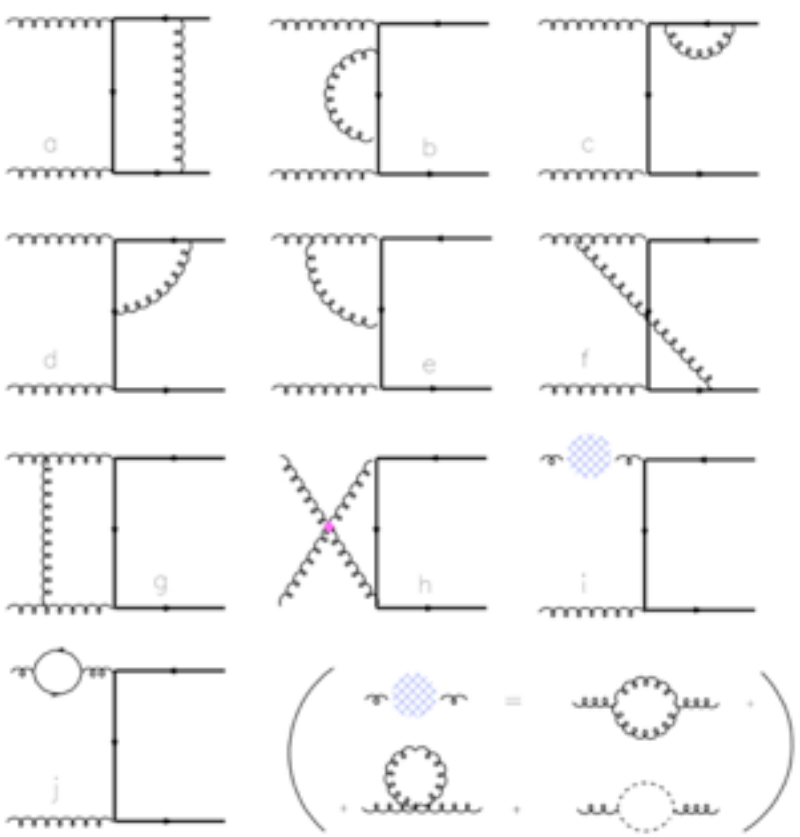
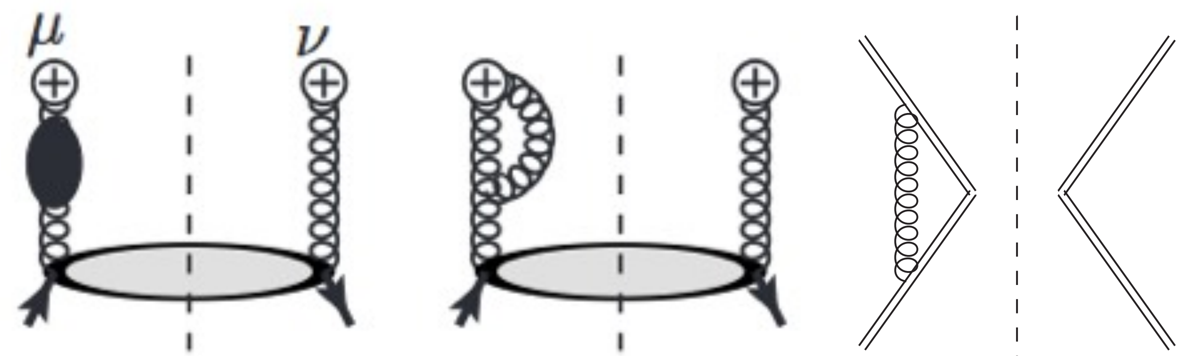
Factorization

$\mathrm{QCD} \to \mathrm{NRQCD} \oplus \mathrm{SCET}_{q_T}$



Philosophy : check (at NLO) if the structure of the IR divergencies is the same in the two expressions.



$$\sigma^{\mathrm{virt},(1)} \quad \longleftrightarrow \quad \{\mathcal{H}\ \tilde{f}_1^{g/A}\ \tilde{f}_1^{g/B}\}^{(1)}_{\mathrm{virt}}$$

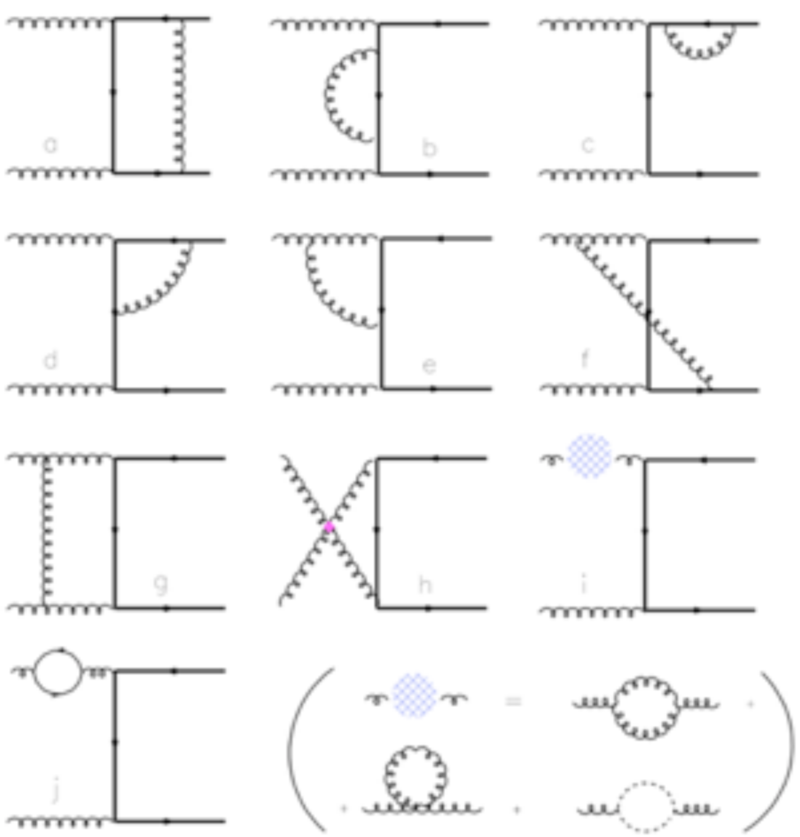
? same IR ?

no:
TMD fact. does not reproduce the physical (=QCD) result

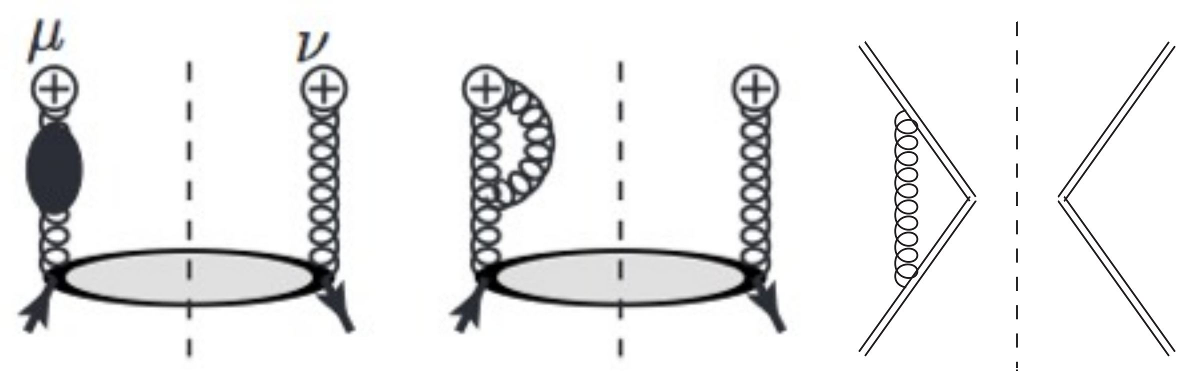
yes:
TMD fact. reproduces the physical result and the hard part can be calculated by subtraction

Factorization

$\mathrm{QCD} \to \mathrm{NRQCD} \oplus \mathrm{SCET}_{q_T}$



Philosophy : check (at NLO) if the structure of the IR divergencies is the same in the two expressions.



$$\sigma^{\mathrm{virt},(1)} \quad \longleftrightarrow \quad \{\mathcal{H}\ \tilde{f}_1^{g/A}\ \tilde{f}_1^{g/B}\}^{(1)}_{\mathrm{virt}}$$

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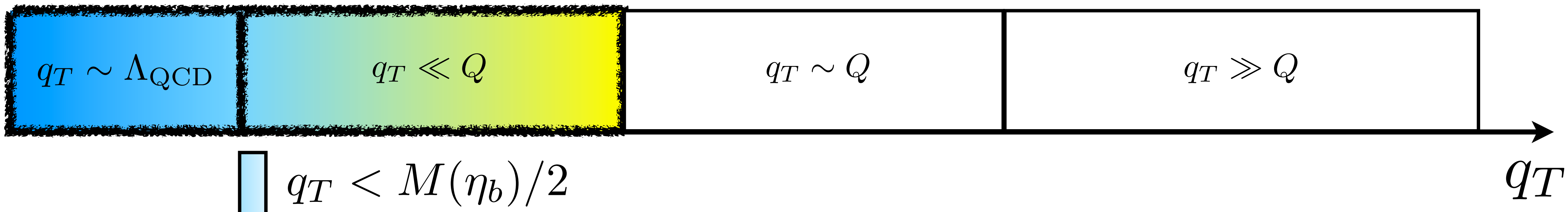
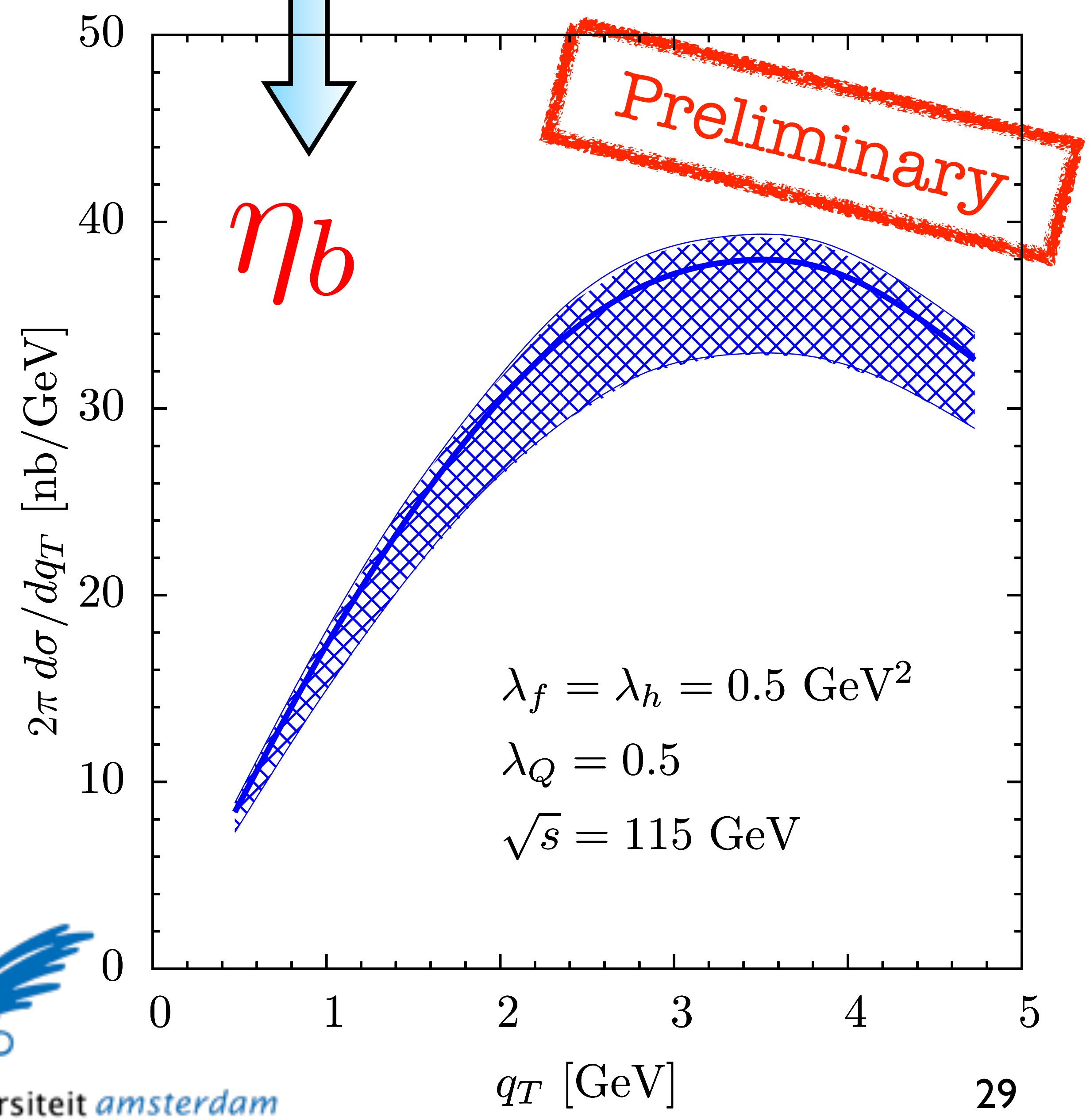
Unpolarized phenomenology





$$\frac{d\sigma_{UU}}{dq_T} \sim \{\mathcal{C}[f_1^g f_1^g] - \mathcal{C}[h_1^{\perp g} h_1^{\perp g}]\}$$

NRQCD from Phys. Rev. D 70, 054014
(Maltoni/Polosa)

$$e^{-b_T^2(\lambda_{f/h}+\lambda_Q \ln Q^2)}$$

Gaussian **model** at low q_T

We need data at low q_T!

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New TMD structures

references :

AS et al.
10.5506/APhysPolB.46.2501
Boer, Echevarria, Mulders, J. Zhou
arXiv:1511.03485
Amsterdam group
in preparation

Gluons in spin 1 hadrons

TMDs	quarks	gluons
spin 1/2	✓	✓
spin 1	✓	?

gluons in spin 1/2

$$\Phi^{\mu\nu}(k;P,S) \sim \text{F.T.}\ \langle PS|\ F^{+\mu}(0)\ U_{[0,\xi]}\ F^{+\nu}(\xi)\ U'_{[\xi,0]}\ |PS\rangle_{|_{LF}} \longrightarrow$$

8 functions at leading twist

gluons in spin 1

$$\Phi^{\mu\nu}(k;P,\underline{S,T}) \sim \text{F.T.}\ \langle PST|\ F^{+\mu}(0)\ U_{[0,\xi]}\ F^{+\nu}(\xi)\ U'_{[\xi,0]}\ |PST\rangle_{|_{LF}}$$

as for quarks,
we expect more structures

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Pomerons from the gauge connection ?

TMDs	quarks	gluons	nothing (non partonic)
spin 1/2	✓	✓	~~?~~ ✓
spin 1	✓	?	?

link with small-x physics

gluons in spin 1/2

$$\Phi^{\mu\nu}(k;P,S) \sim \text{F.T.}\ \langle PS|\ F^{+\mu}(0)\ U_{[0,\xi]}\ F^{+\nu}(\xi)\ U'_{[\xi,0]}\ |PS\rangle_{|LF}$$

removing the gluon fields from the gluon correlator:

$$\delta(x)\ \Phi(k_T;P,S,n) \sim \text{F.T.}\ \langle PS|\ U^{\square}\ |PS\rangle_{|LF} \longrightarrow e(k_T) - \frac{\mathbf{k_T}\times\mathbf{S_T}}{M}\, e_T^{\perp}(k_T)$$

only the gauge loop

"pomeron" **"odderon"**

exchange of color-singlet objects

Conclusions

1) There is **much to learn** about TMDs, and the **12 GeV program** at JLab is an excellent playground

2) **How to access TMDs?** Flexible and rich **models** + **perturbative** information (**TMD** **factorization** and **evolution**)

3) SIDIS data suggest a **flavor dependence** in the intrinsic transverse momentum of partons; this opens the path to **yet unexplored effects**

4) we can find its footprints in e+e- annihilation and it might have a non-negligible **impact on Z/W± production**

5) **new structures** can be introduced: factorization, universality, evolution, phenomenology, ...

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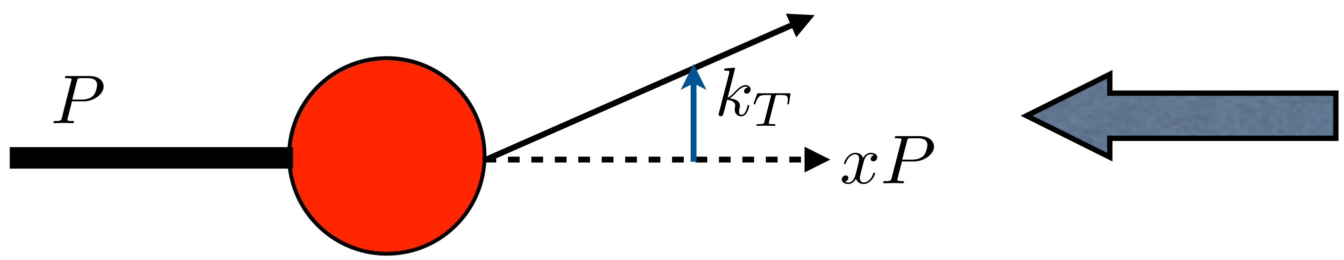
Backup slides

Quark TMD PDFs

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



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

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

add references

a similar scheme holds for gluons in Lorentz space

spin-spin and **spin-orbit** interactions

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Gluon TMD PDFs

$$\Phi^{\mu\nu}(k;P,S) \sim \mathrm{F.T.}\ \langle PS|\ F^{+\mu}(0)\ U_{[0,\xi]}\ F^{n\nu}(\xi)\ U'_{[\xi,0]}\ |PS\rangle|_{LF}$$

hermiticity, parity,
time-reversal
invariance

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_{1T}^g,\ h_{1T}^{\perp g}$

Mulders, Rodriguez
PRD 63 (2001)

LEADING
TWIST

spin-spin and **spin-orbit** interactions
between the proton and its constituents

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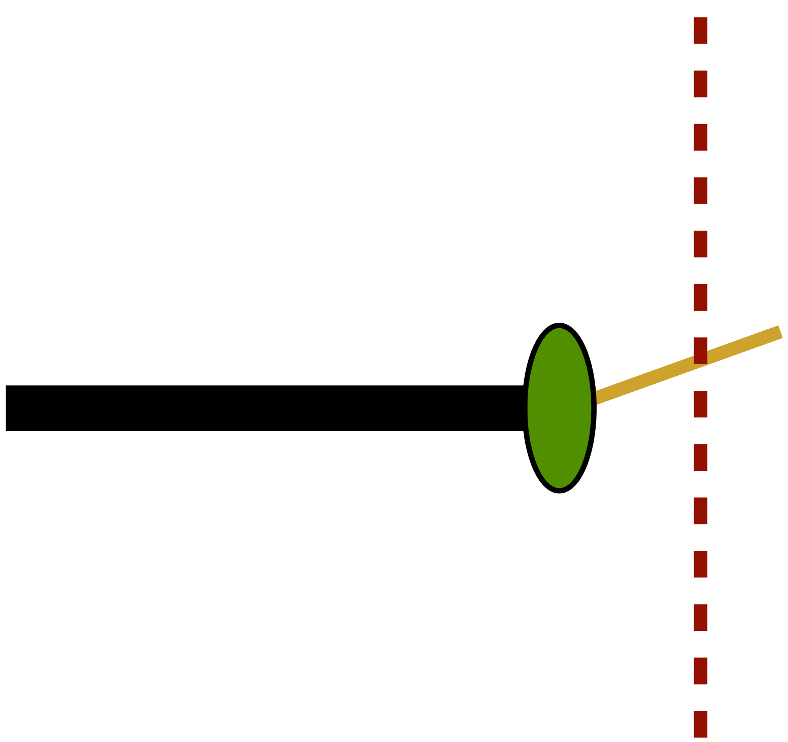
Transverse momentum spectrum

intrinsic
transverse
momentum

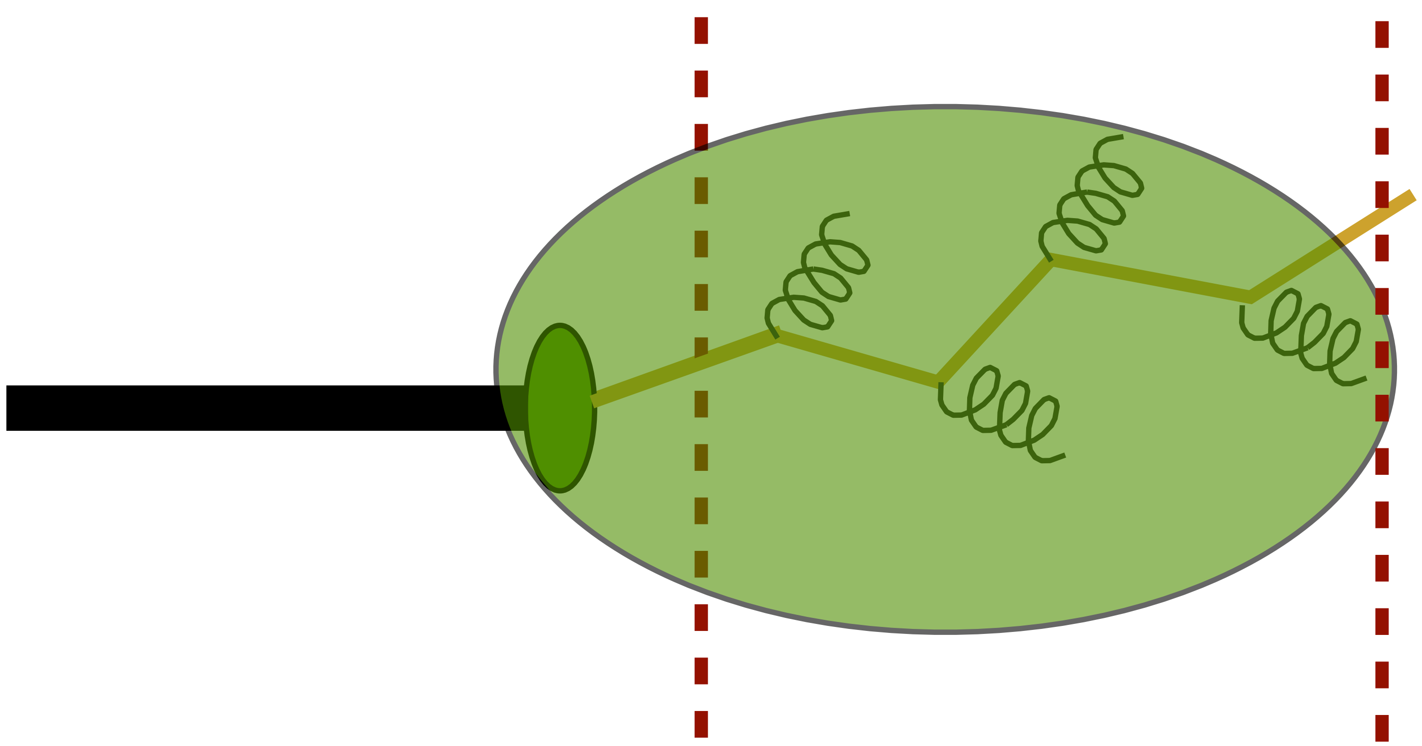


$$|k_\perp| \sim \Lambda_{\rm QCD}$$

Transverse momentum spectrum

intrinsic
transverse
momentum

soft and collinear
gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$ $\qquad$ $|k_\perp| \ll Q$

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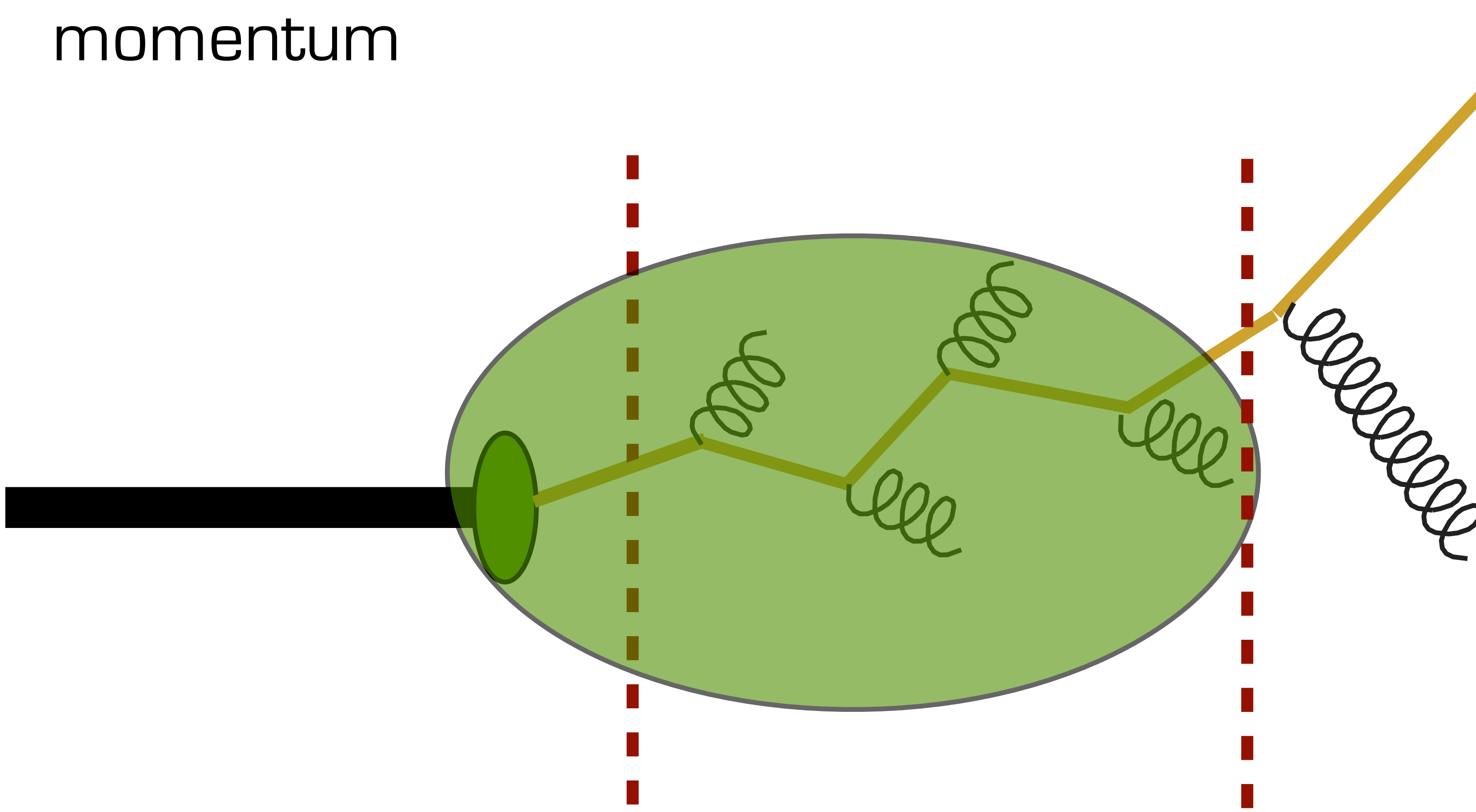
courtesy A. Bacchetta

Transverse momentum spectrum

intrinsic transverse momentum

soft and collinear gluon radiation

hard gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$ $|k_\perp| \ll Q$ $|k_\perp| \sim Q$

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courtesy A. Bacchetta

Transverse momentum spectrum

OPE - matching coefficient

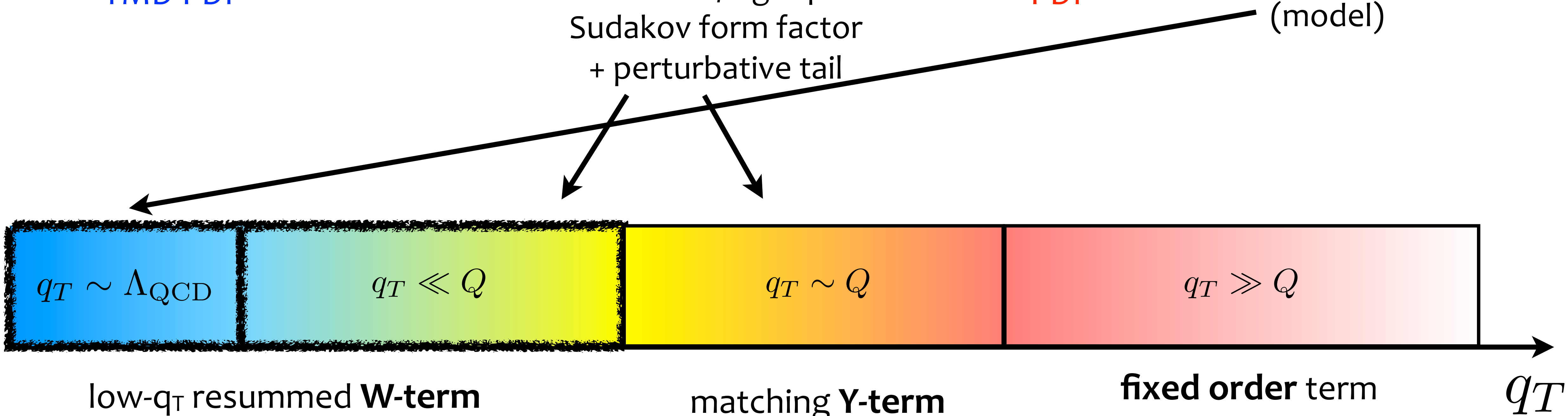
$$\tilde{T}_{g/A}(x, b_T; \mu, \zeta) = \sum_{j=q,\bar{q},g} \tilde{C}^T_{g/j}(x, b_T; \mu, \zeta) \otimes t_{j/A}(x; \mu) + \mathcal{O}(b_T \Lambda_{QCD})$$

TMD PDF

medium/high qT
Sudakov form factor
+ perturbative tail

PDF

intrinsic low q_T
(model)



low-q_T resummed **W-term**
TMD factorization/evolution

matching **Y-term**

fixed order term
collinear factorization

transverse momentum spectrum of physical observables

Transverse momentum spectrum

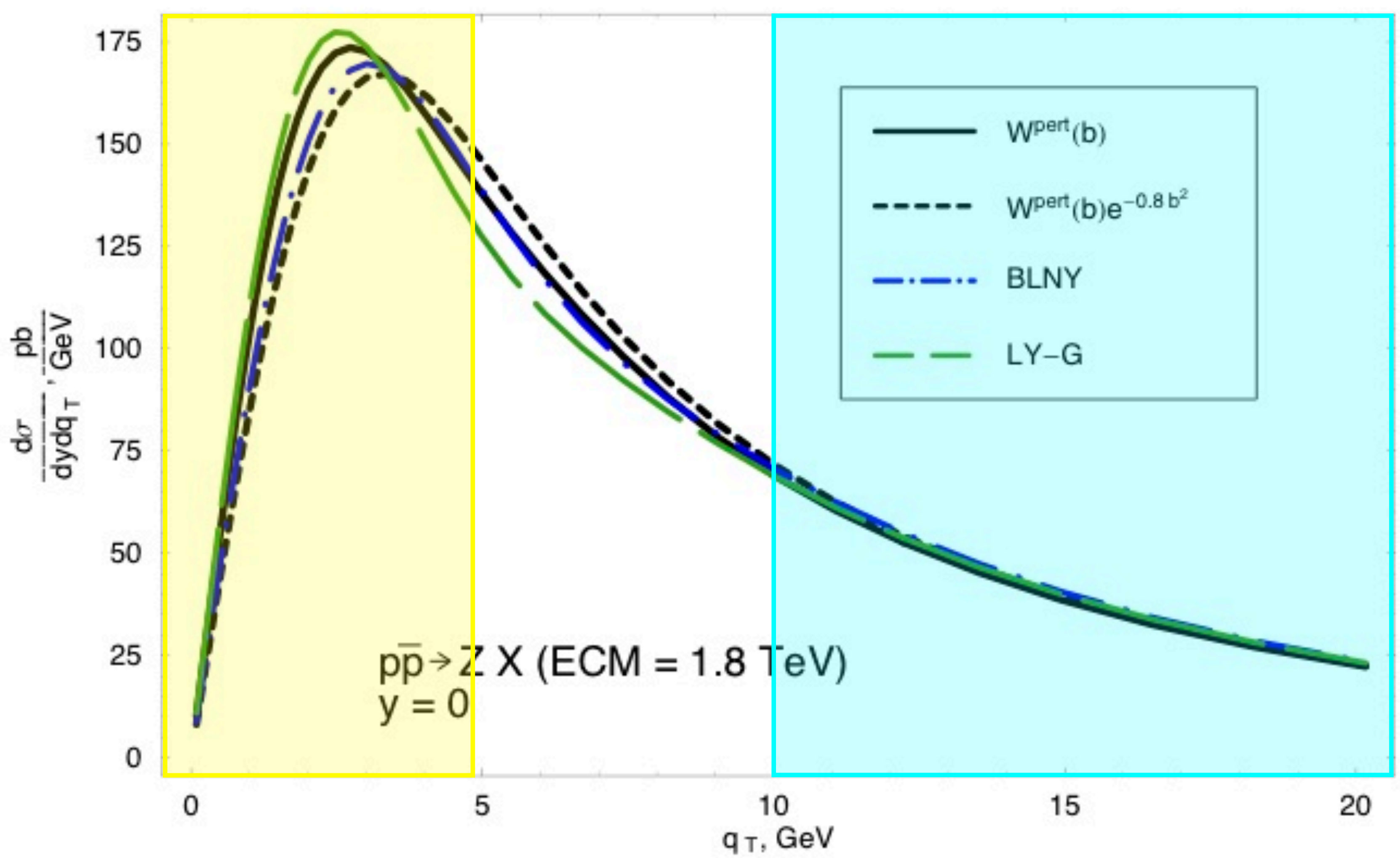
TMDs generate the q_T dep. of cross sections : but **how in practice** ?

intrinsic momentum +
soft/coll. gluon radiation

correct the color code

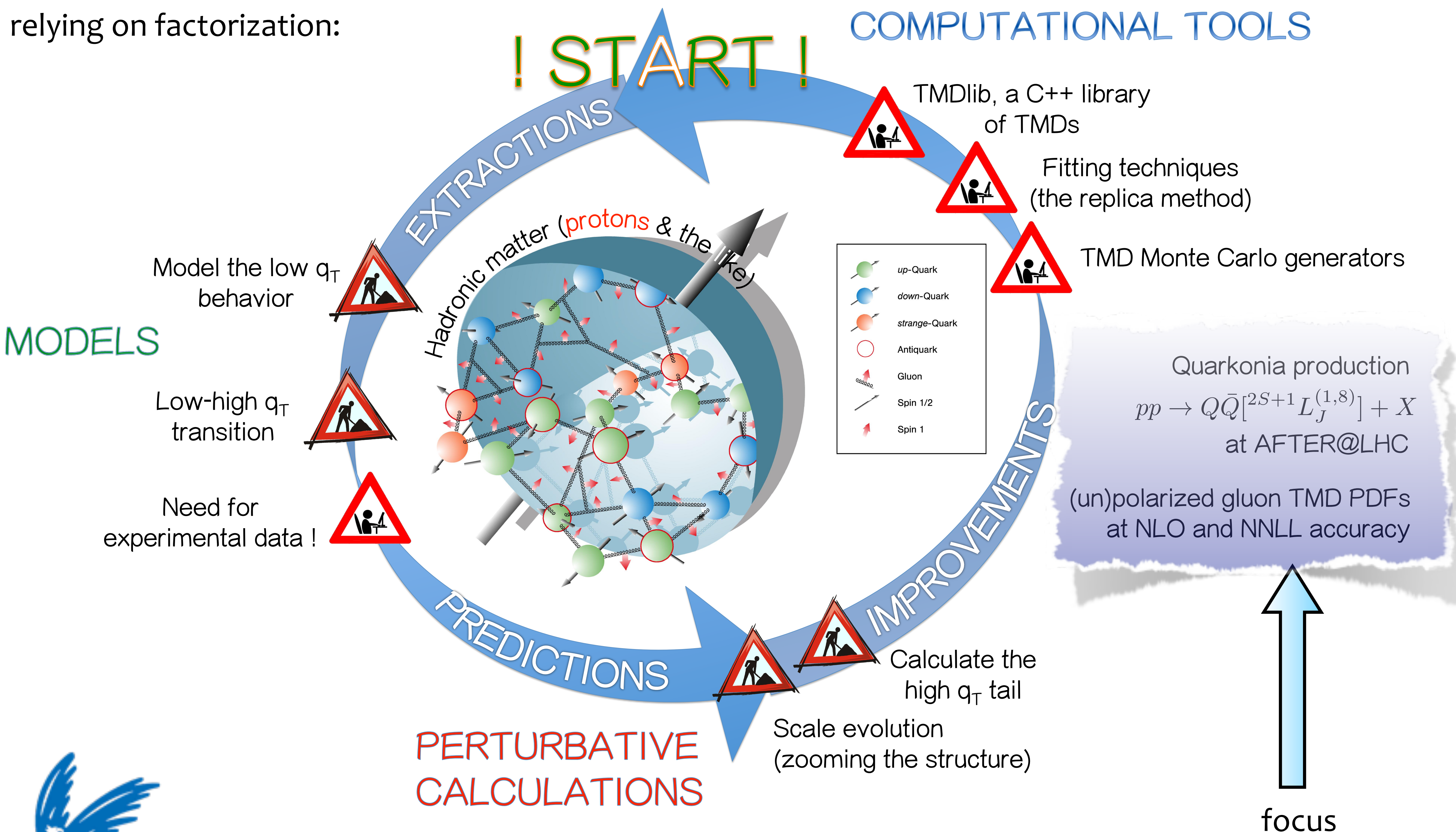
matching

hard gluon radiation



The road to TMD phenomenology

relying on factorization:



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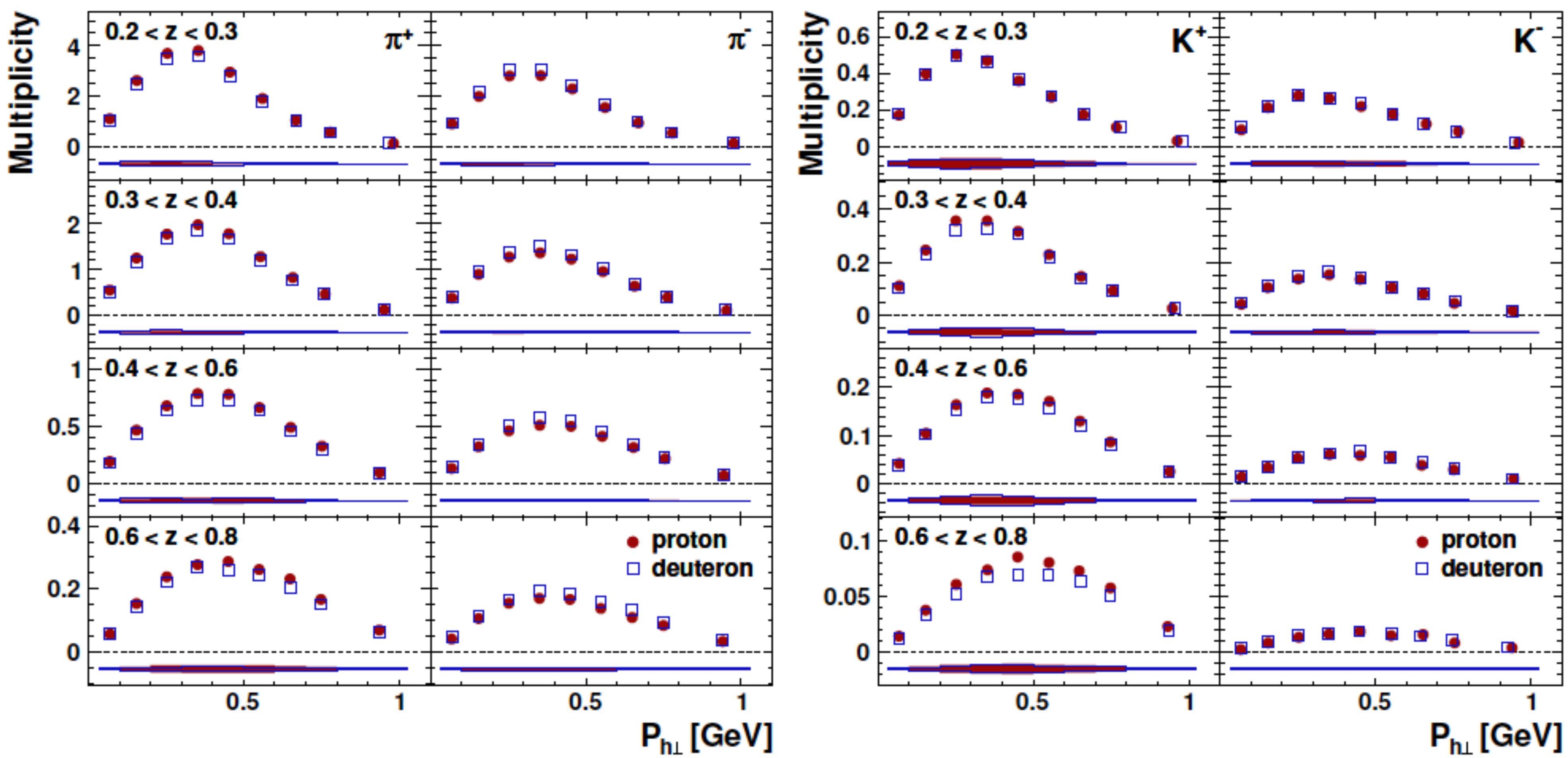
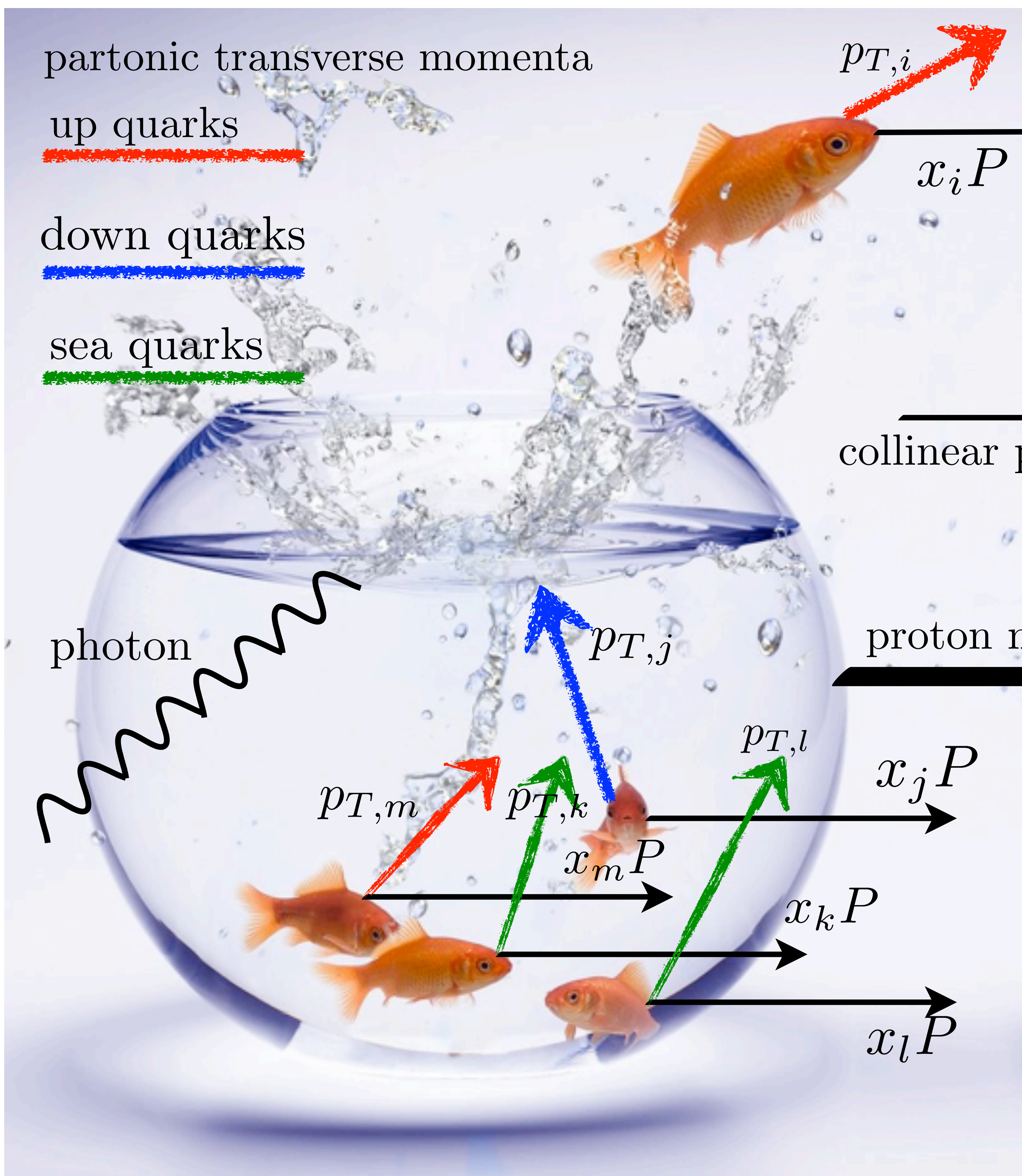
SIDIS @ Hermes

$$e^{\pm} + \boxed{P/D} \rightarrow e^{\pm} + \underline{\{\pi^{\pm}/K^{\pm}\}} + X$$



Intrinsic flavor dependence: a way to account for
differences between cross sections related to different final state hadrons

Flavor in transverse momentum



collinear partonic momenta

P

proton momentum

UNPOLARIZED

$$\boxed{D_1^a(z, P_\perp^2, Q^2)}$$

do the TMD parts
depend on the quark flavor?

$$\boxed{f_1^a(x, k_\perp^2, Q^2)}$$

UNPOLARIZED

Kinematic dependence

$$\langle \boldsymbol{k}_{\perp,\,q}^2 \rangle(x) = \widehat{\langle \boldsymbol{k}_{\perp,\,q}^2 \rangle} \, \frac{(1-x)^{\alpha}\, x^{\sigma}}{(1-\hat{x})^{\alpha}\, \hat{x}^{\sigma}}$$

$$\widehat{\langle \boldsymbol{k}_{\perp,\,q}^2 \rangle} = \langle \boldsymbol{k}_{\perp,\,q}^2 \rangle(\hat{x} \,=\, 0.1)$$

$$\langle \boldsymbol{P}_{\perp,\,q\to h}^2 \rangle(z) = \widehat{\langle \boldsymbol{P}_{\perp,\,q\to h}^2 \rangle} \, \frac{(z^{\beta}+\delta)\,(1-z)^{\gamma}}{(\hat{z}^{\beta}+\delta)\,(1-\hat{z})^{\gamma}}$$

$$\widehat{\langle \boldsymbol{P}_{\perp,\,q\to h}^2 \rangle} = \langle \boldsymbol{P}_{\perp,\,q\to h}^2 \rangle(\hat{z} \,=\, 0.5)$$

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Best fit parameters

Parameters for TMD PDFs					
	$\langle \hat{\boldsymbol{k}}^2_{\perp,d_v} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{k}}^2_{\perp,u_v} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{k}}^2_{\perp,\mathrm{sea}} \rangle$ [GeV^2]	α (random)	σ (random)

5 parameters

interval [0,2]

interval [-0.3,0.1]

Parameters for TMD FFs							
	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{fav}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,\mathrm{unf}} \rangle$ [GeV^2]	$\langle \hat{\boldsymbol{P}}^2_{\perp,sK} \rangle$ [GeV^2] (random)	$\langle \hat{\boldsymbol{P}}^2_{\perp,uK} \rangle$ [GeV^2]	β	δ	γ

7 parameters

interval [0.125,0.250]

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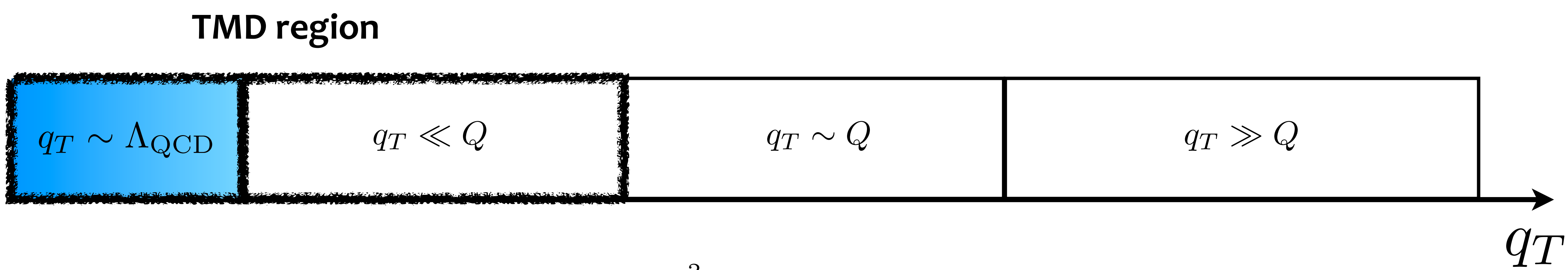
Parton model picture



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

$$D_1^{a/h}(z, P_\perp) = D_1^a(z)\, \frac{1}{\pi \langle P_\perp^2 \rangle_{a/h}(z)}\, e^{-\frac{P_\perp^2}{\langle P_\perp^2 \rangle_{a/h}(z)}}$$

$$\langle Q^2 \rangle = 2.4\ \mathrm{GeV}^2$$

neglect QCD evo = parton model

$\boxed{\text{Flavor and kinematic dependent widths}}$

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

$$\begin{aligned}
\langle \boldsymbol{P}_{\perp,u\to\pi^+}^2 \rangle = \langle \boldsymbol{P}_{\perp,\bar{d}\to\pi^+}^2 \rangle = \langle \boldsymbol{P}_{\perp,\bar{u}\to\pi^-}^2 \rangle = \langle \boldsymbol{P}_{\perp,d\to\pi^-}^2 \rangle &\equiv \langle \boldsymbol{P}_{\perp,\mathrm{fav}}^2 \rangle , \\
\langle \boldsymbol{P}_{\perp,u\to K^+}^2 \rangle = \langle \boldsymbol{P}_{\perp,\bar{u}\to K^-}^2 \rangle &\equiv \langle \boldsymbol{P}_{\perp,uK}^2 \rangle , \\
\langle \boldsymbol{P}_{\perp,\bar{s}\to K^+}^2 \rangle = \langle \boldsymbol{P}_{\perp,s\to K^-}^2 \rangle &\equiv \langle \boldsymbol{P}_{\perp,sK}^2 \rangle , \\
\langle \boldsymbol{P}_{\perp,\text{all others}}^2 \rangle &\equiv \langle \boldsymbol{P}_{\perp,\mathrm{unf}}^2 \rangle .
\end{aligned}$$

The replica method

200 **statistical replicas** of **HERMES** data

A fit is performed on each replica

200 best-fit values for the parameters

clean access to uncertainties

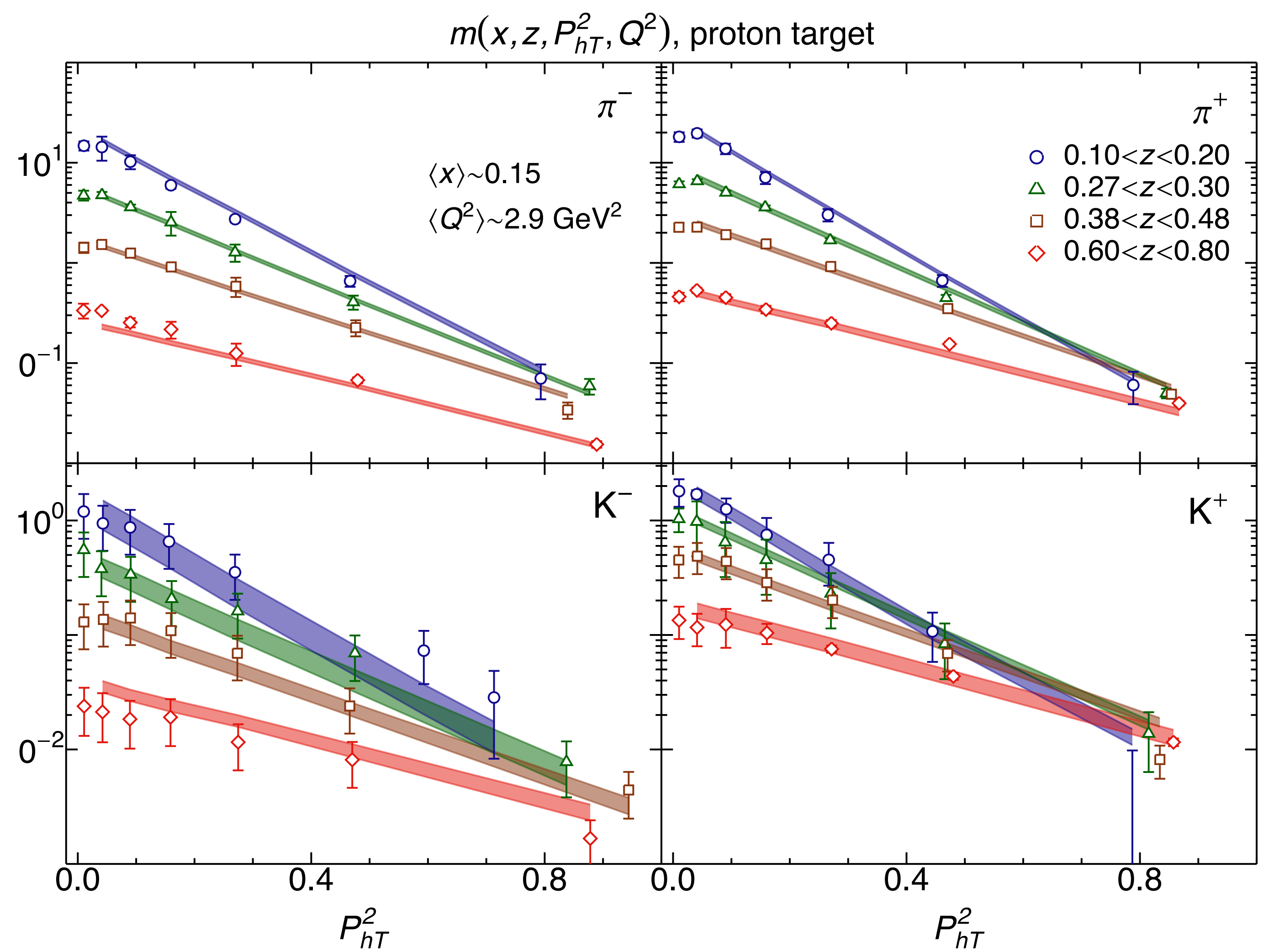
We get a **distribution**, not a single value;
physically reacher

More complete exploration of the minima in the space of fit parameters

Fits of multiplicities

proton target global χ^2 / d.o.f. = 1.63 ± 0.12
no flavor dep. 1.72 ± 0.11

π^-		π^+
1.80 ± 0.27		2.64 ± 0.21
1.83 ± 0.25		2.89 ± 0.23
K^-		K^+
0.78 ± 0.15		0.46 ± 0.07
0.87 ± 0.16		0.43 ± 0.07



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Best fit values

68% confidence intervals of best-fit parameters for TMD FFs in the different scenarios

Parameters for TMD FFs				
	Default	$Q^2 > 1.6$ GeV^2	Pions only	Flavor-indep.
$\langle \hat{\boldsymbol{P}}^2_{\perp,\text{fav}} \rangle$ [GeV^2]	0.15 ± 0.04	0.15 ± 0.04	0.16 ± 0.03	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,\text{unf}} \rangle$ [GeV^2]	0.19 ± 0.04	0.19 ± 0.05	0.19 ± 0.04	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,sK} \rangle$ [GeV^2]	0.19 ± 0.04	0.19 ± 0.04	-	0.18 ± 0.03
$\langle \hat{\boldsymbol{P}}^2_{\perp,uK} \rangle$ [GeV^2]	0.18 ± 0.05	0.18 ± 0.05	-	0.18 ± 0.03
β	1.43 ± 0.43	1.59 ± 0.45	1.55 ± 0.27	1.30 ± 0.30
δ	1.29 ± 0.95	1.41 ± 1.06	1.20 ± 0.63	0.76 ± 0.40
γ	0.17 ± 0.09	0.16 ± 0.10	0.15 ± 0.05	0.22 ± 0.06

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Conclusions - SIDIS

0) SIDIS (Hermes) multiplicities are also compatible with flavor dependent configurations in the intrinsic transverse momentum of partons

$\boxed{\text{1) on average : sea > u-val > d-val \& unf > fav}(\pi)\text{, fav(K) > fav}(\pi)}$

2) Despite not producing dramatic effects on SIDIS, the flavor decomposition of TMDs opens the way to yet unexplored effects

3) flavor dependence in TMD FFs can be investigated at e+e- experiment, together with information on the non-perturbative evolution

4) we need to look at different observables with multi-D kinematic ranges

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Implementation of evolution

$$\frac{d\sigma^{h_1 h_2}}{dz_1 dz_2 dq_T^2 dy} \sim H(Q^2,\mu) \longrightarrow$$ 1, no alpha corrections

$$\times \sum_q e_q^2 \int_0^\infty db_T b_T \; J_0(q_T b_T) \Big[z_1^2 D_1^{q\to h_1}(z_1, b_T;\mu,\zeta_1) z_2^2 D_1^{\bar q \to h_2}(z_2, b_T; \mu, \zeta_2) + (q \leftrightarrow \bar q) \Big]$$

$$+ \cancel{Y(q_T^2/Q^2)} + \cancel{\mathcal{O}(M^2/Q^2)}$$

no high qT tail
(collinear factorization)

no higher twist

$$D_1^{q\to h}(z, b_T;\mu,\zeta) = \underbrace{[C \otimes d_1^{q\to h}](z, b_T;\mu,\zeta)}_{\text{small } b_T/\text{medium } k_T} + \underbrace{\mathcal{O}(b_T \Lambda_{\rm QCD})}_{\text{high } b_T/\text{small } k_T} \longrightarrow$$

flavor and kinematic
dependent
Gaussian model
(JHEP 1311 (2013) 194)

$$e^{-\frac{\langle k_T^2 \rangle_{q/h}(z)}{4} b_T^2}$$

LO and NLL
pert. Sudakov
quark form factor

OPE coefficients
are delta on the
flavors

models for
non-pert.
Sudakov quark f.f.

$$g_{\rm np}^{\rm lin/log}(b_T^2; g_2)$$

models for
the small/high bT
separation

$$\hat b_T(b_T; b_{\max}) = \{ b_T^* \,,\, b_T^\dagger \}$$

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Implementation of evolution

$$b_T^* = \frac{b_T}{\sqrt{1+\frac{b_T^2}{b_{\max}^2}}} \xrightarrow[b_T\to\infty]{} b_{\max}$$

$$b_T^\dagger = b_{\max}\left\{1-\exp\left[-\frac{b_T^4}{b_{\max}^4}\right]\right\}^{\frac{1}{4}} \xrightarrow[b_T\to\infty]{} b_{\max}$$

two different ways
to approach bmax,
the point where we stop
trusting the perturbative result

for b larger than bmax
a model is needed
also in the evolution

$$g_{\rm np}^{\rm lin}(b_T^2;g_2) = \frac{g_2}{4}b_T^2$$

$$g_{\rm np}^{\rm log}(b_T^2;g_2) = g_2\ln\left(1+\frac{b_T^2}{4}\right)$$

bmax and g2
are anticorrelated
parameters

see also PhysRevD.91.074020
(Collins, Rogers)

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... factorization scale (evolution scheme)

$$\sigma^{\mathrm{F.O.}} \sim \ln \frac{Q}{q_T} \xrightarrow[\text{at scale } \mu]{\text{factorization}} \ln \frac{Q}{\mu} \cdot \frac{\mu}{\mu_b} = \ln \frac{Q}{\mu} + \ln \frac{\mu}{\mu_b}$$

factorization in a nutshell

hard part H

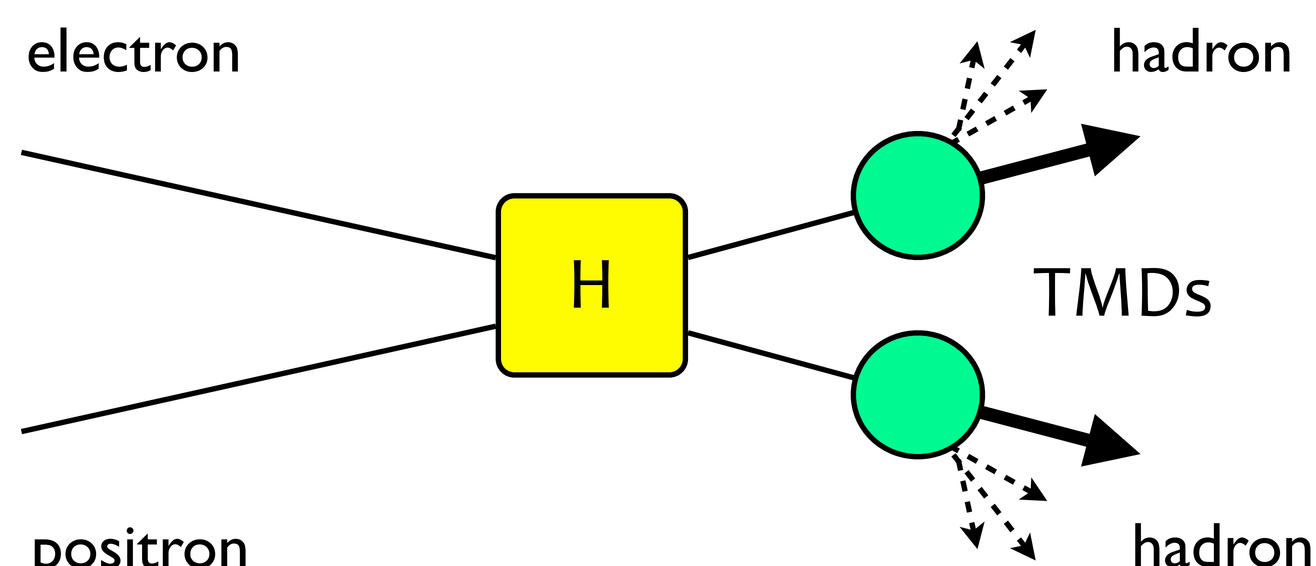
perturbative
part of W term
(TMDs)

Different choices
are possible for the
factorization scale, with
different implications:

resumming these logarithms
we get a finite cross section
at low qT

$\mu \to \mu_b \sim 1/b \;, q_T$ minimize logs in W

$\mu \to Q$ minimize logs in H



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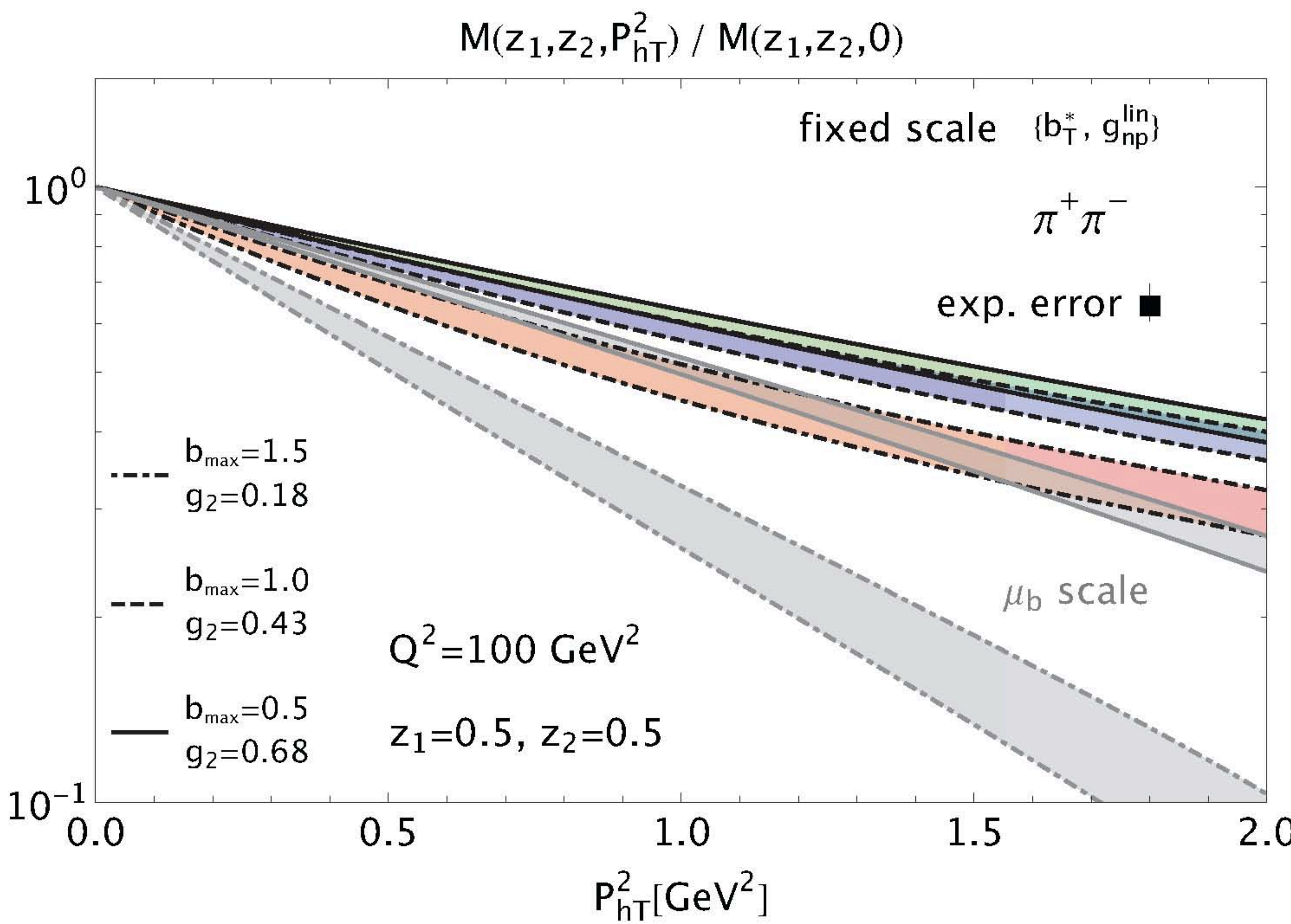
... factorization scale (evolution scheme)



Q enhances the logs in the evolved TMDs, mub minimizes them:

$$\ln Q/\mu_b$$

$$\ln \mu_b/\mu_b = 0$$

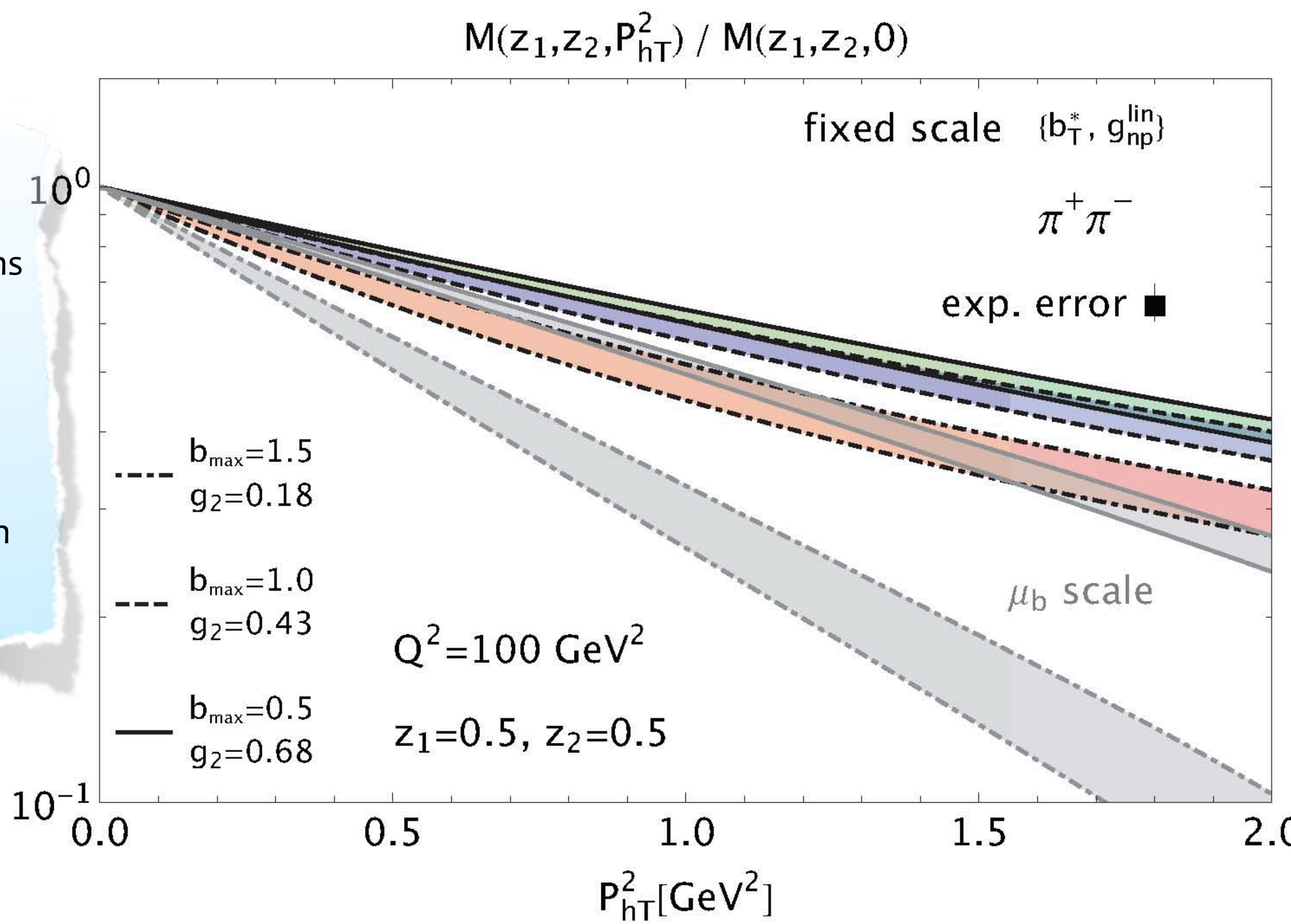
using Q rather than mub we get very different predictions

overall effect: larger distributions, more perturbative content

... factorization scale (evolution scheme)

overlap between the two prescriptions for different NP parameters

can't we distinguish them ?



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using Q rather than mub we get very different predictions

overall effect: larger distributions, more perturbative content

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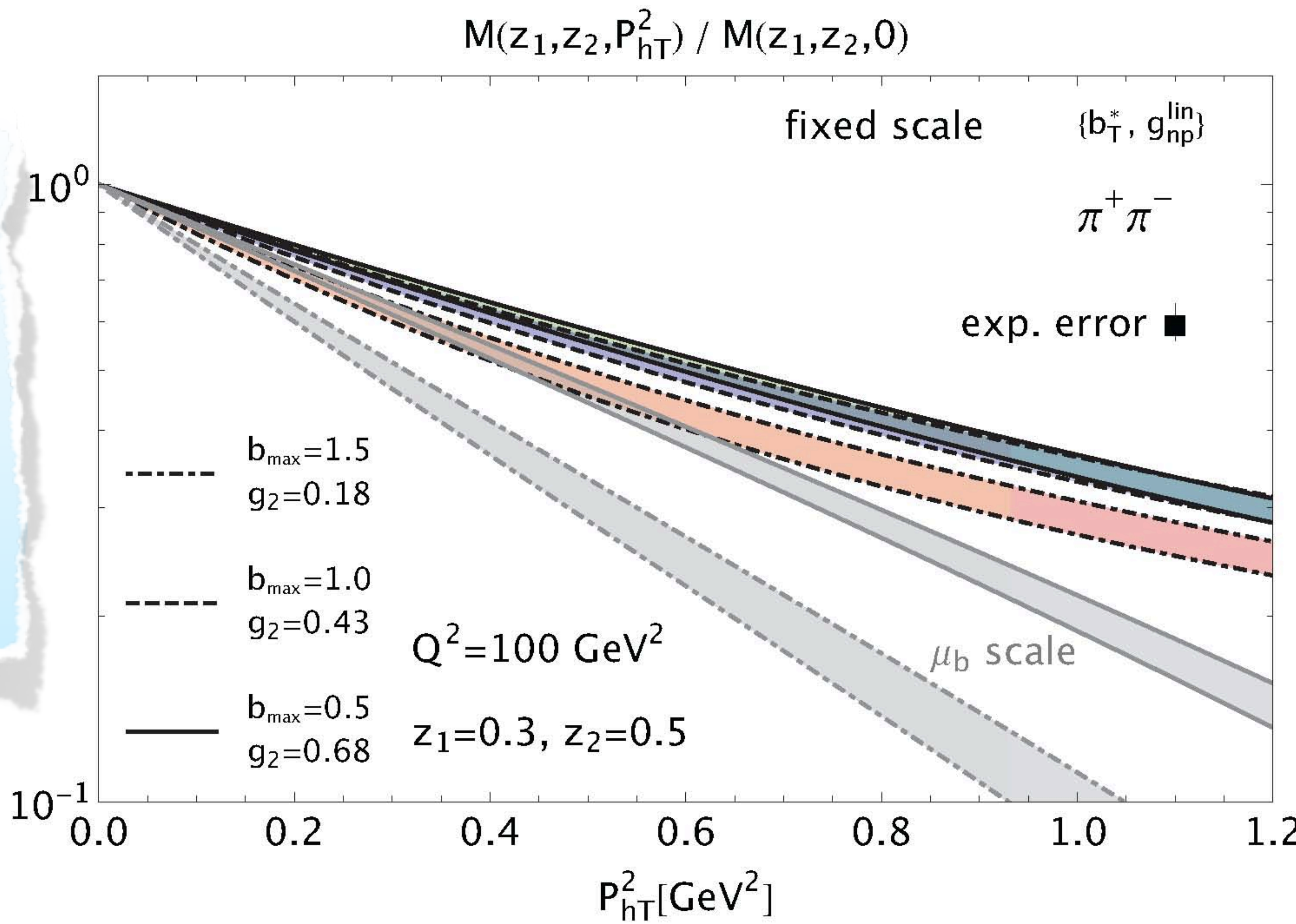
... factorization scale (evolution scheme)

Yes, but only taking into account the z dependence too!

it requires combined information on P1\perp and z1, z2



Q enhances the logs in the evolved TMDs, mub minimizes them:

$$\ln Q/\mu_b$$

$$\ln \mu_b/\mu_b = 0$$

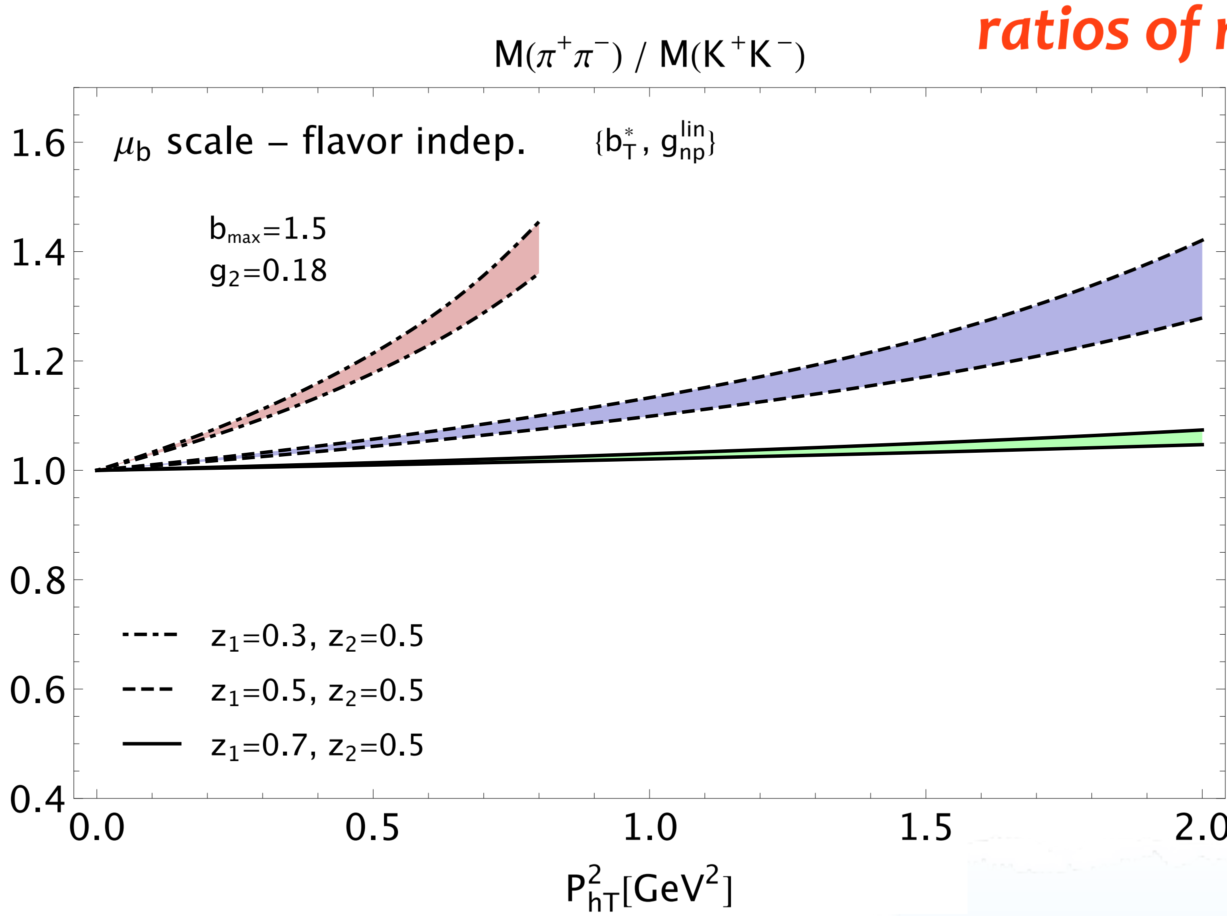
using Q rather than mub we get very different predictions

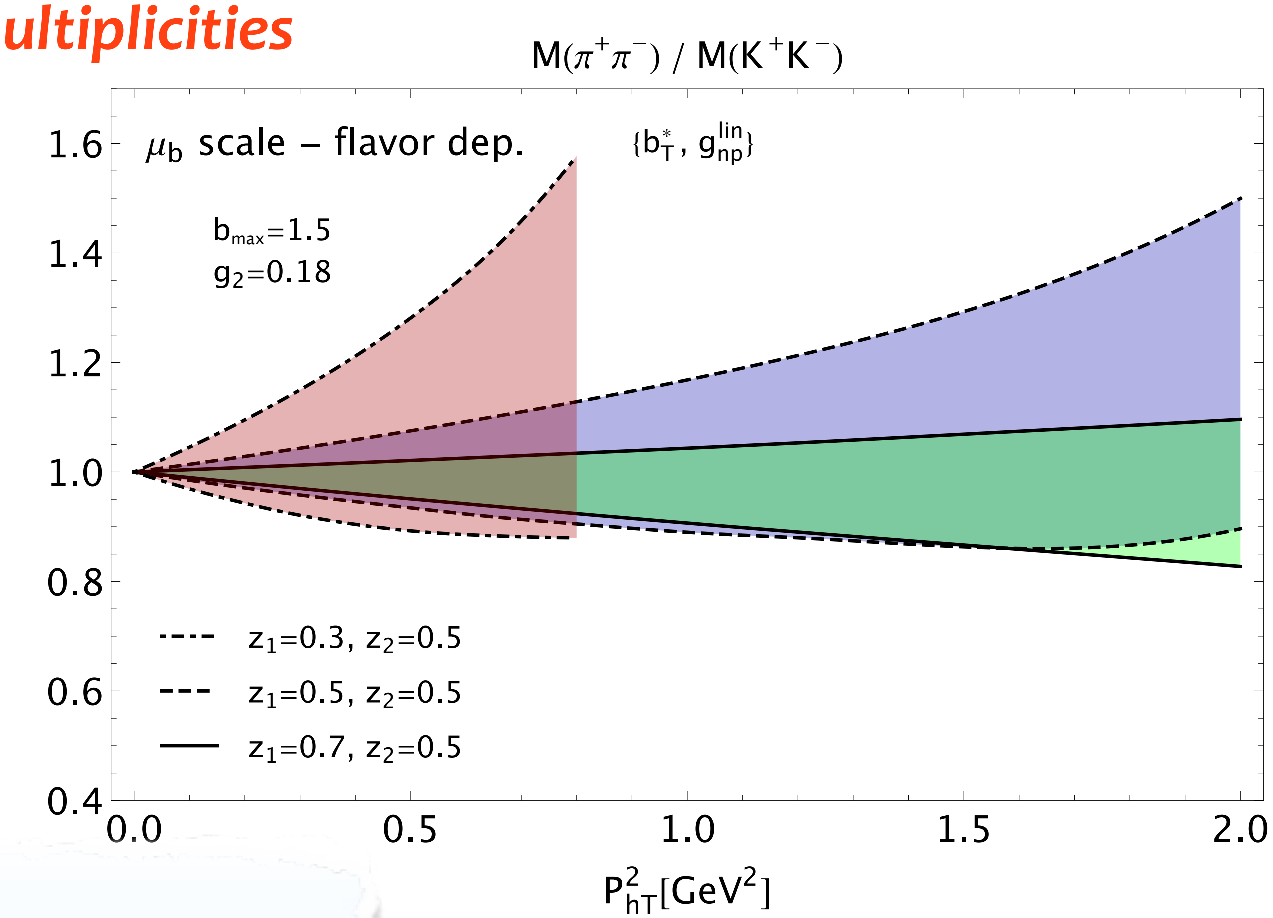
overall effect: larger distributions, more perturbative content

... partonic flavor

mu_b scale evolution

ratios of multiplicities





this is the effect of the
perturbative flavor dependence ONLY:

it is induced by RGE equations
with flavor dependent
initial conditions (collinear FF)

the transverse momentum
dependence is described
BOTH by the input NP
Gaussian distributions
and the collinear FF

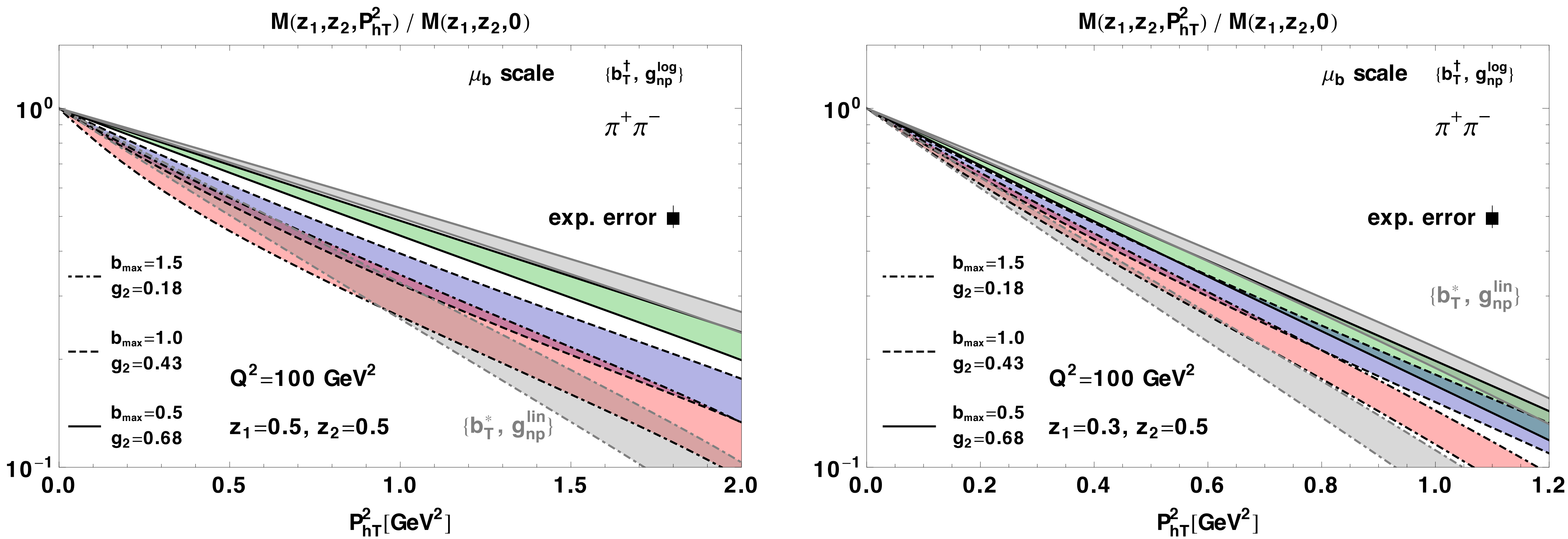
$$d_1^{q\to h}(z, \mu_b(b_T))e^{-\frac{\langle k_T^2\rangle_{q\to h}(z)}{4}b_T^2}$$

larger effect,
combination of
perturbative and NP
flavor dependence

but the two are
difficult to disentangle!

exp. data may be useful
to discriminate among the replicas

... transition low/medium qT



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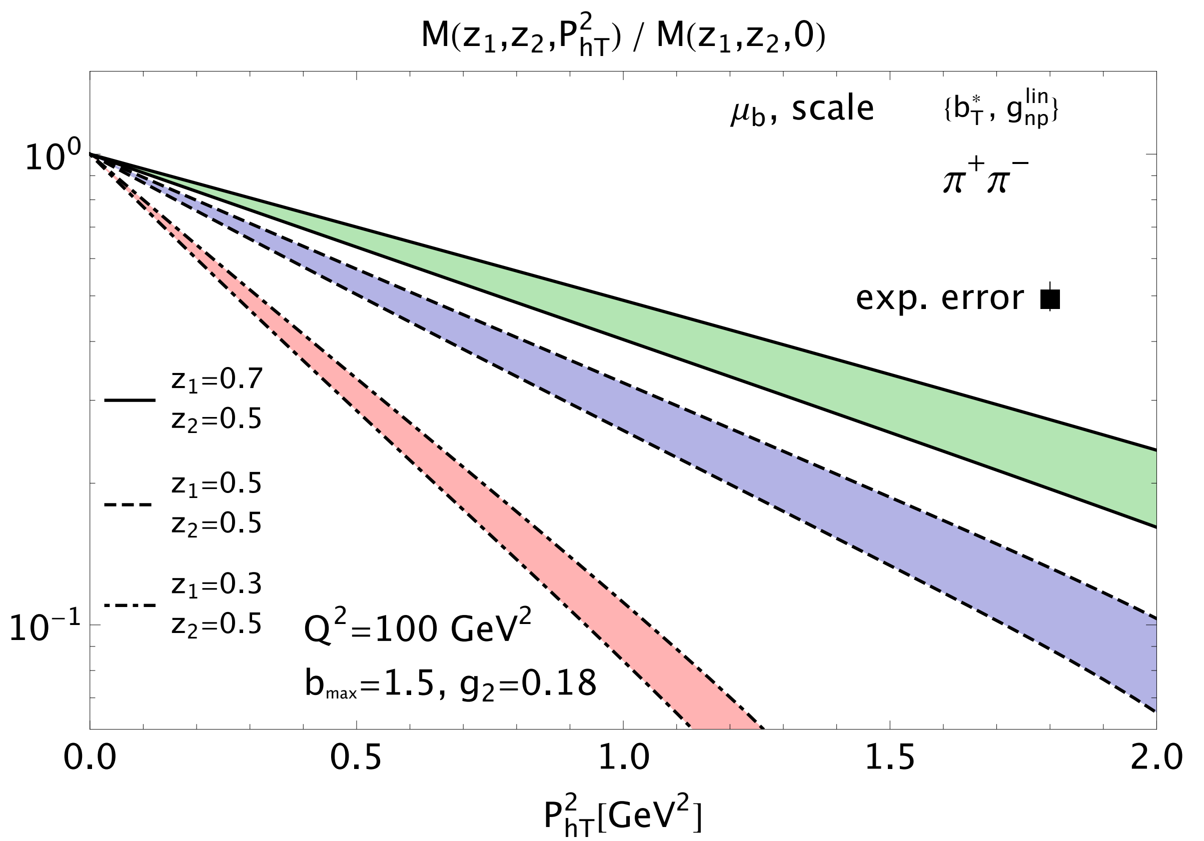
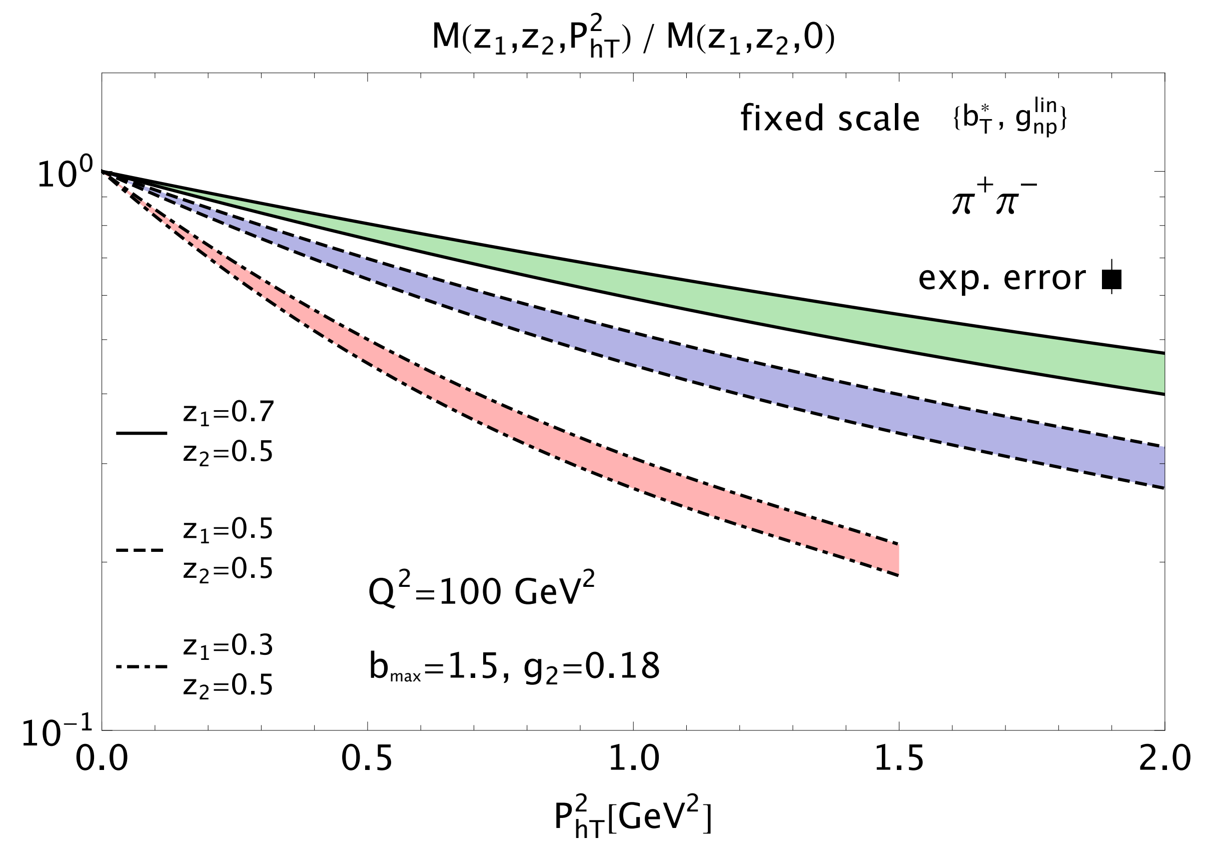
... collinear energy fractions $z_{1,2}$





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Conclusions - e+e-

Five take-home messages :

0) The way we implement QCD evolution affects the extraction of non-perturbative information - [*very important*]

1) At Belle scale (100 GeV^2) we can discriminate evolution schemes and pin down non-perturbative evolution parameters (g2, bmax)

2) Annihilations at BES scale (14.6 GeV^2) can be very useful to select non-perturbative intrinsic parameters of TMD FFs

3) Annihilations to different final states {π, K} can be useful to constrain flavor dependence of TMD FFs

4) knowledge of unpolarized TMD FFs helps in constraining both (un)polarized TMD PDFs and polarized TMD FFs

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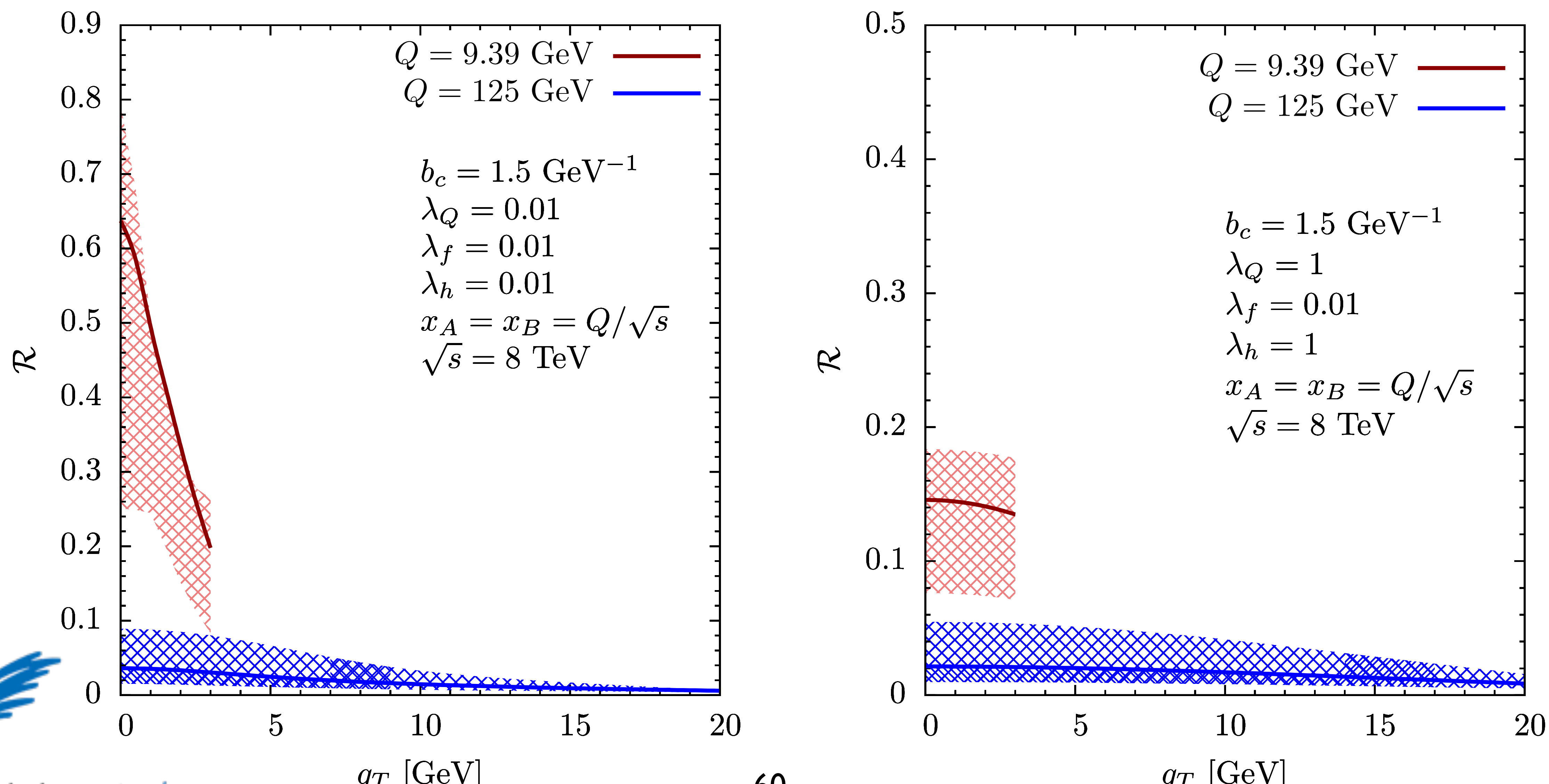
Linearly polarized vs unpolarized

$$\mathcal{R}(q_T;Q) = \frac{\mathcal{C}[\, h_1^{\perp g/A} \; h_1^{\perp g/B} \,]}{\mathcal{C}[\, f_1^{g/A} \; f_1^{g/B} \,]}$$

quarkonium - low energy

higgs - high energy



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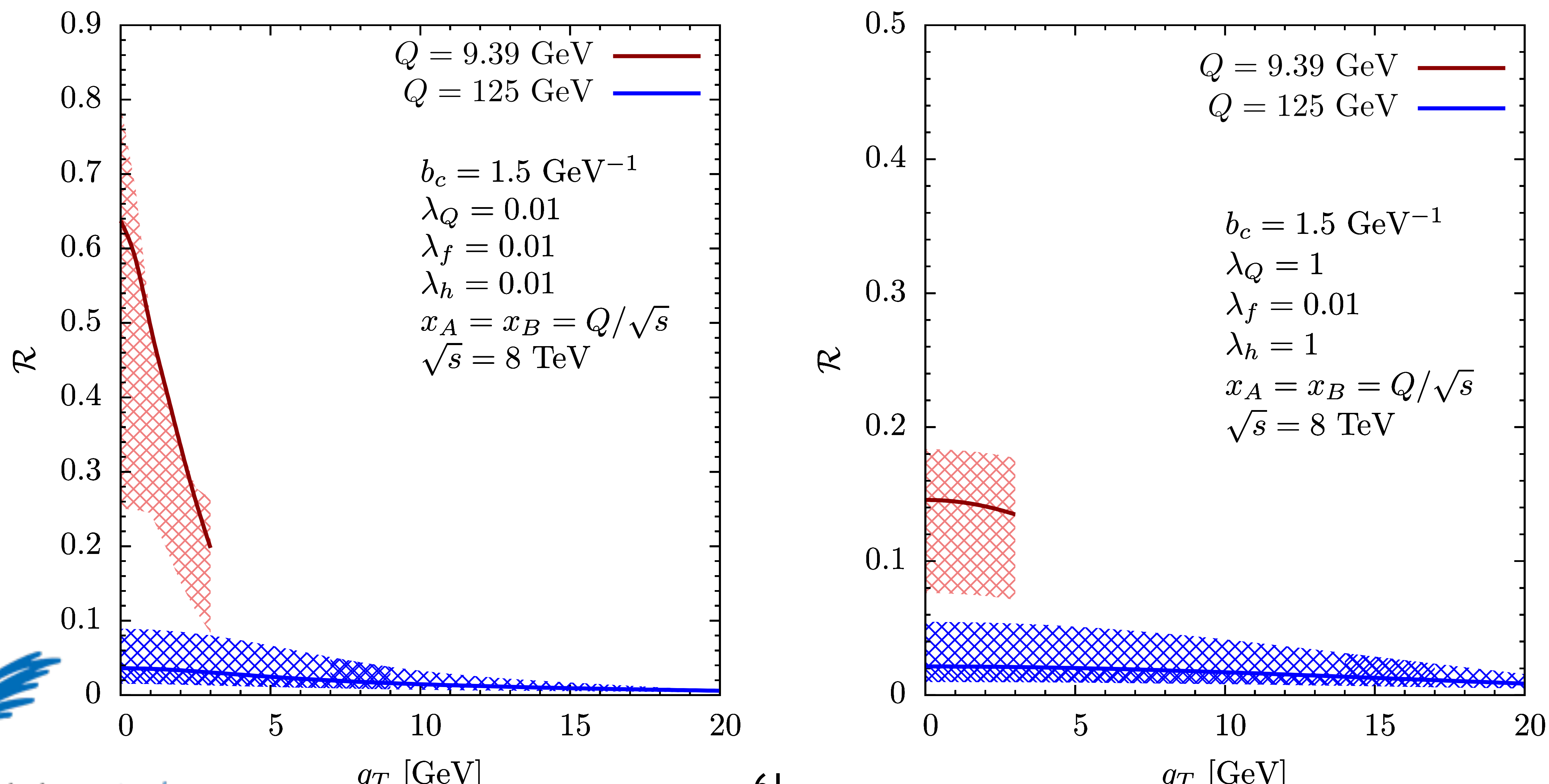
Linearly polarized vs unpolarized

Nonperturbative physics
enhanced at low Q



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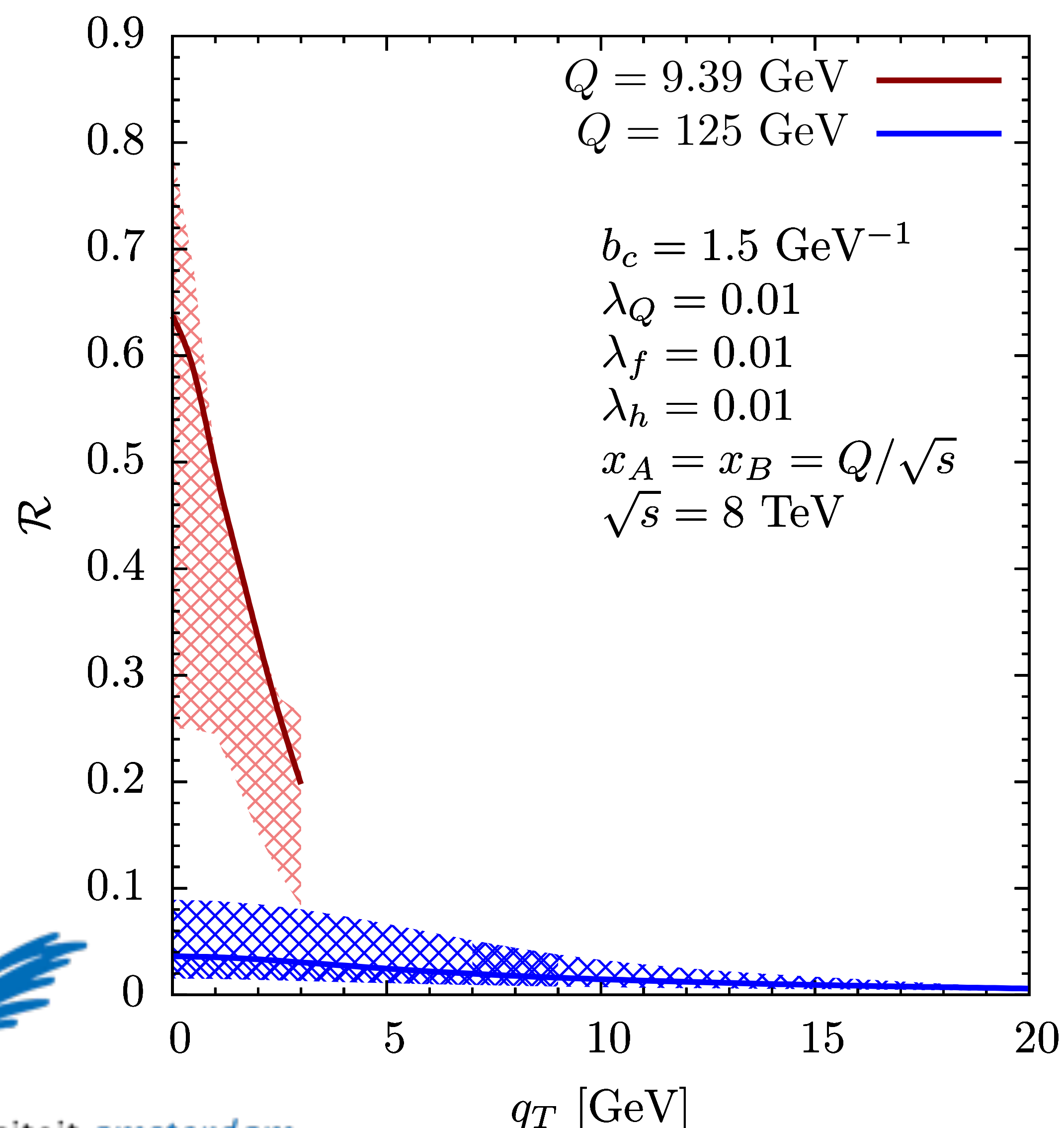
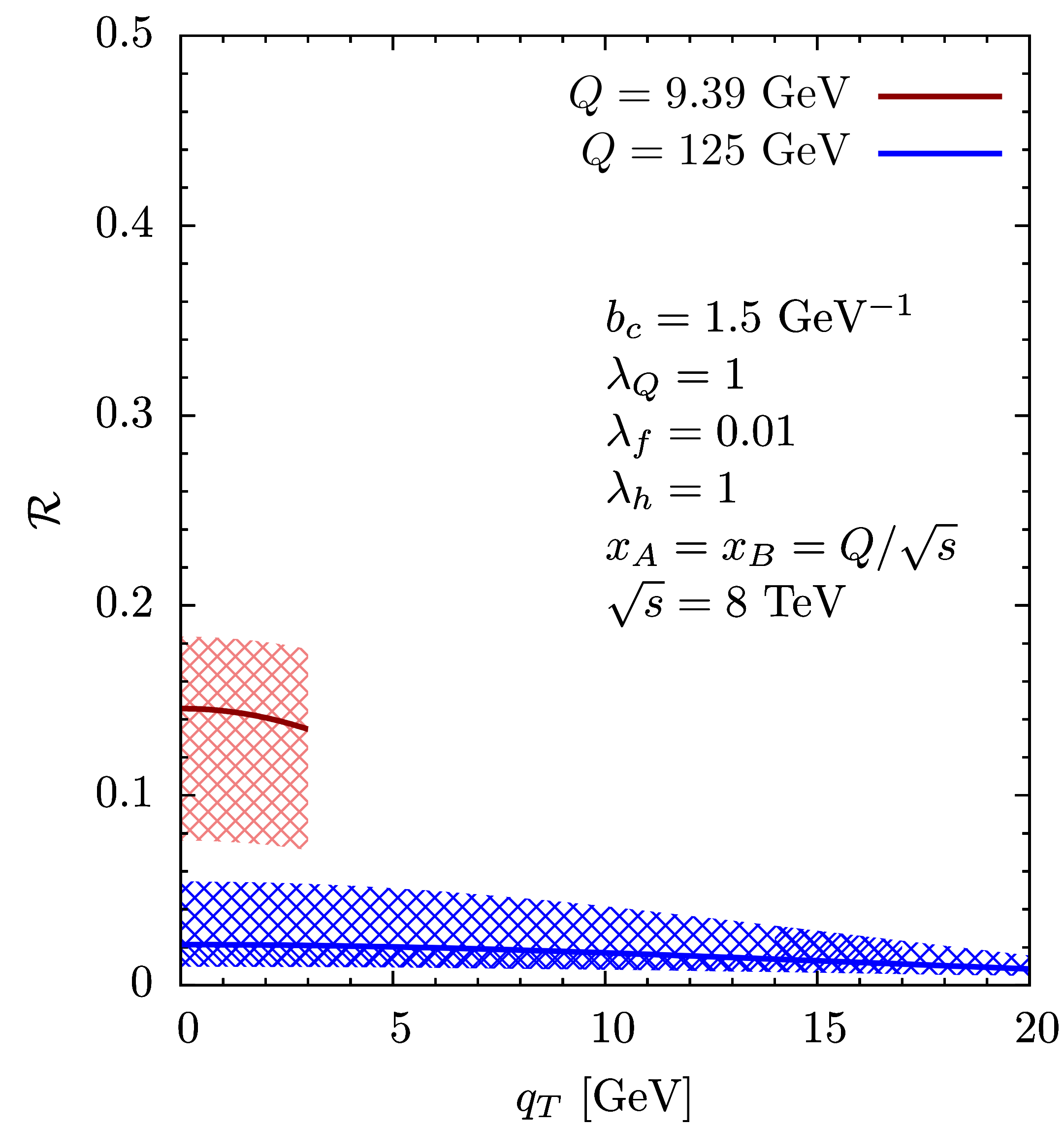
Linearly polarized vs unpolarized

lin. pol. gluons :
10% - 70% at low Q





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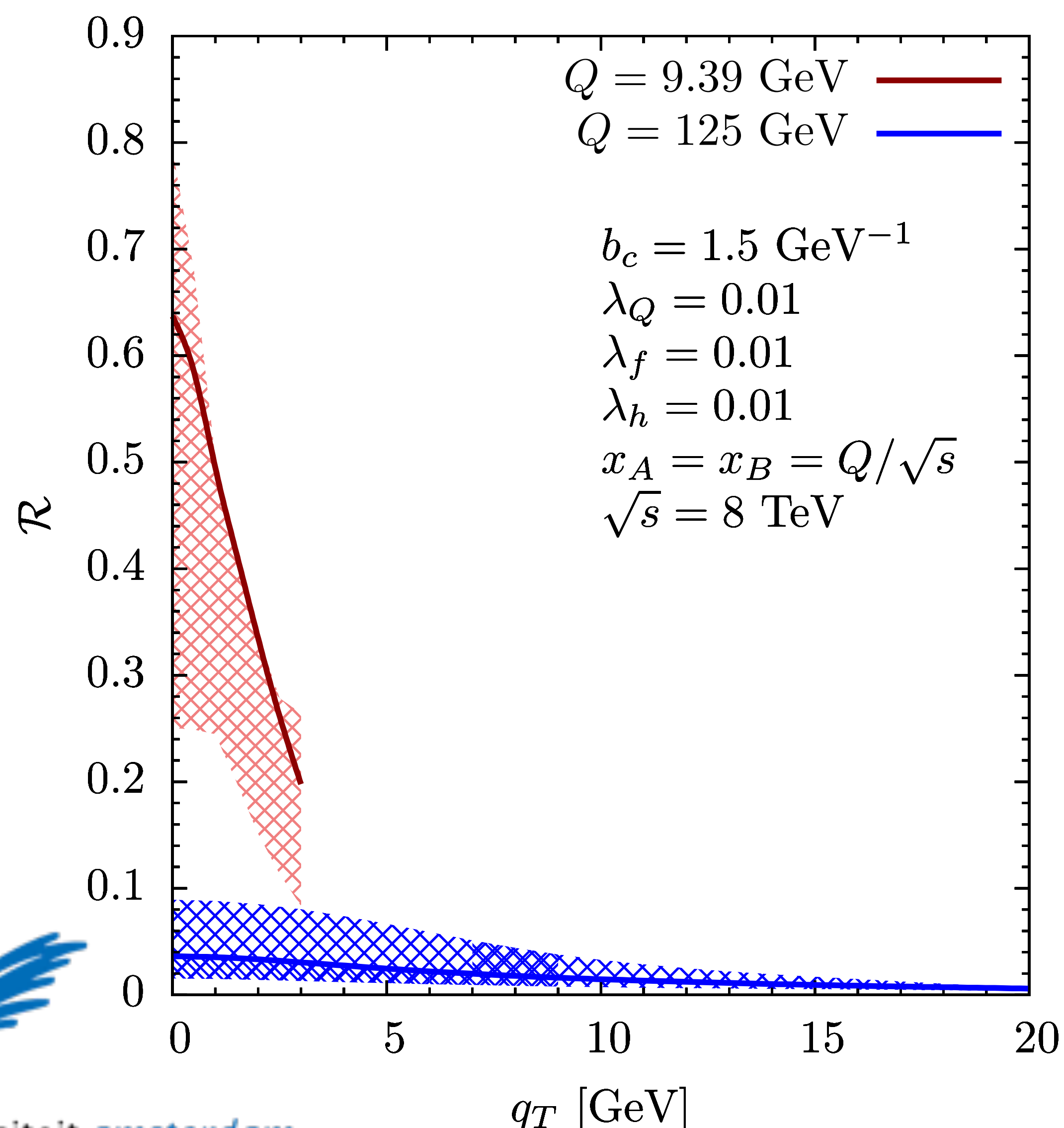
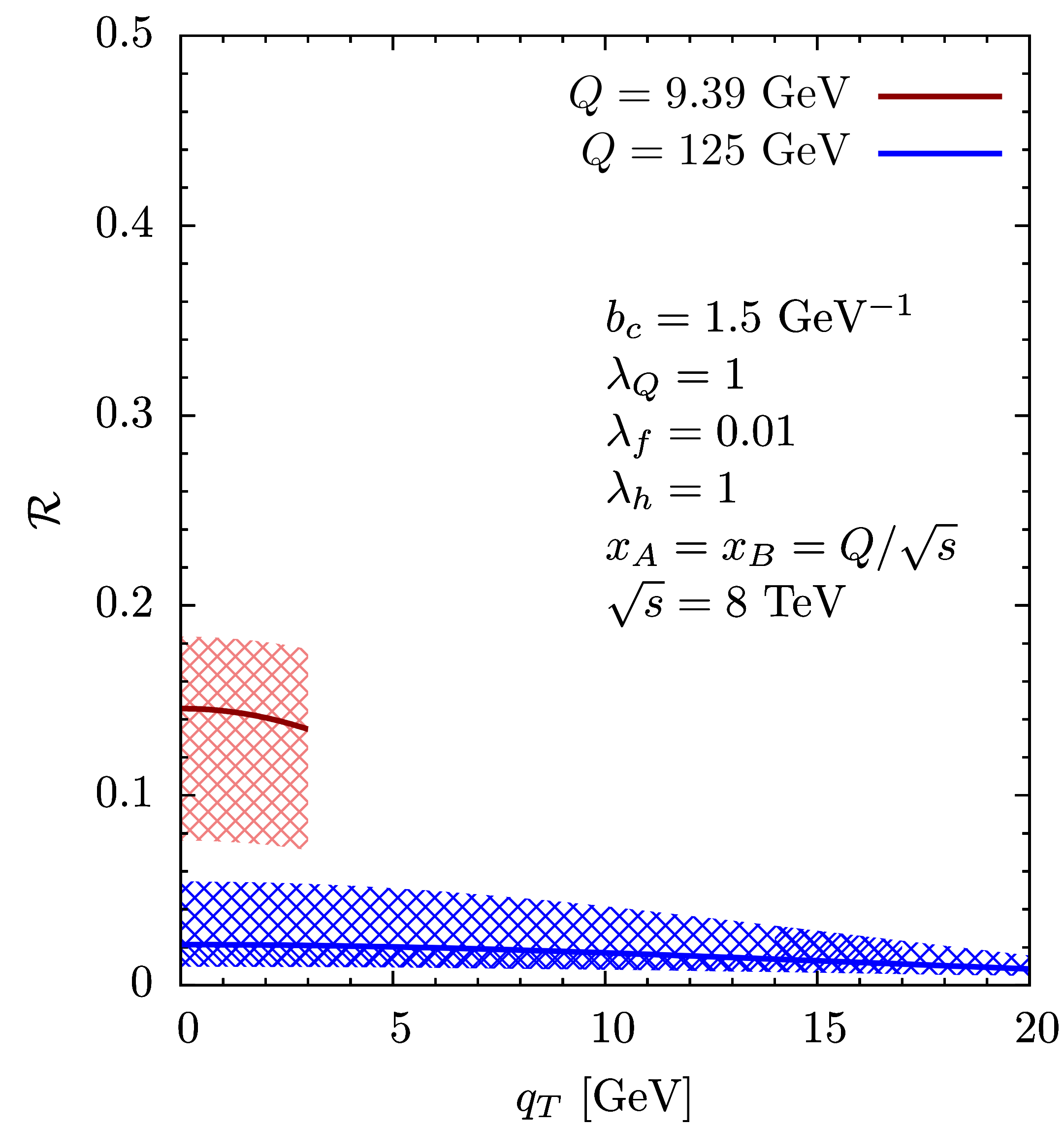
Linearly polarized vs unpolarized

lin. pol. gluons :
1% - 9% at high Q





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SCET in a nutshell

1) It is an effective theory of QCD

2) based on a systematic expansion of the QCD lagrangian in powers of small parameters

3) describes QCD interaction among low and high energy modes on the base of separate lagrangians for (ultra)soft and (anti)collinear modes

5) ASSUMPTION : SCET reproduces the IR structure of QCD ; need for a "matching" coefficient

6) useful to implement resummation | good for phenomenology

$$\mathcal{L}_{\mathrm{QCD}} \longleftrightarrow \mathcal{L}_n + \mathcal{L}_{\bar{n}} + \mathcal{L}_{\mathrm{soft}}$$

Philosophy : check if the structure of the IR divergencies is the same as in 'full' QCD. If so, the SCET-factorized form works as QCD, namely factorization is "established"

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A multistep matching process

$$\mathrm{QCD}$$

factorization of the cross section
in terms of TMD PDFs

spin-independent
matching coefficient:
(square root of "hard part")

$$C_H$$

$$\mathrm{NRQCD} \oplus \mathrm{SCET}_{q_T}$$

re-factorization of TMD PDFs
on the basis of PDFs

spin-dependent
matching coefficient:
(OPE Wilson coeffs.)

$$\tilde{C}^T_{g/j}$$

$$\mathrm{NRQCD} \oplus \mathrm{SCET}_{\Lambda_{\mathrm{QCD}}}$$

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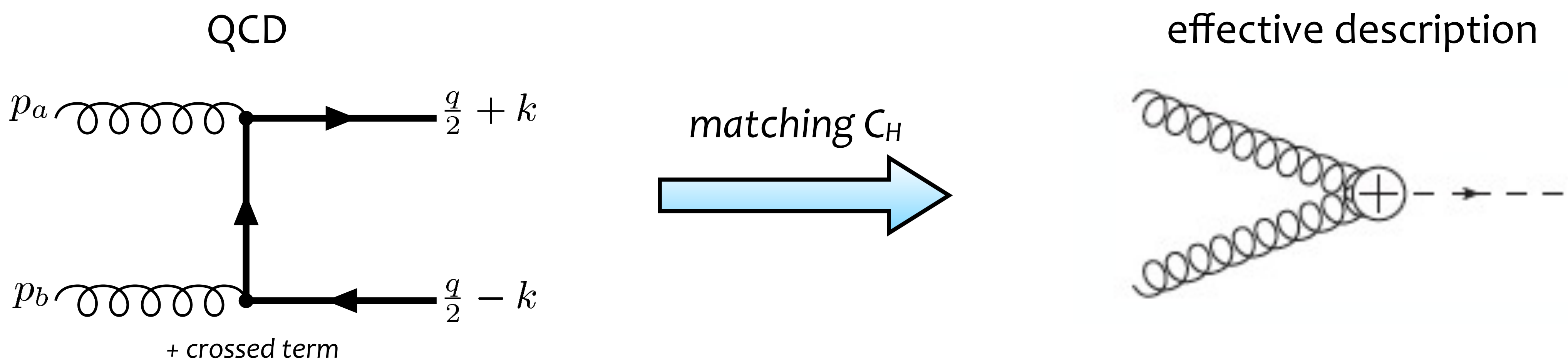
1 : factorization

$\mathrm{QCD} \to \mathrm{NRQCD} \oplus \mathrm{SCET}_{q_T}$



$$\mathcal{O}_{\mathrm{QCD}} = C_H(-q^2;\mu^2)\ \{\chi^\dagger \Gamma^{(\eta_q)}_{\mu\nu} \psi\ \mathcal{B}^{\mu,a}_{n\perp} (\mathcal{S}^\dagger_n \mathcal{S}_{\bar{n}\perp})^{ab} \mathcal{B}^{\nu,b}_{\bar{n}\perp}\}$$

quark fields

gluon field

soft Wilson lines

$$d\sigma = \frac{1}{2s}\frac{d^3q}{(2\pi)^3 2E_q}\int d^4y e^{-iq\cdot y}\sum_X \langle PS_A, \bar{P}S_B|\mathcal{O}(y)|X+\eta_q\rangle\langle X+\eta_q|\mathcal{O}(0)|PS_A,\bar{P}S_B\rangle$$

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1 : factorization

$\mathrm{QCD} \to \mathrm{NRQCD} \oplus \mathrm{SCET}_{q_T}$

$$\frac{d\sigma}{dy d^2 q_\perp} \sim \mathcal{O}^{q\bar{q}}(\eta_q)|C_H|^2 \Gamma^\dagger_{\mu\alpha}\Gamma_{\nu\beta}$$

$$\times\, \hat{\mathrm{FT}}\,\big[\, \underline{\tilde{G}^{\mu\nu}_{g/A}(x_A, b_T, S_A; \mu, \zeta_A)\; \tilde{G}^{\alpha\beta}_{g/B}(x_B, b_T, S_B; \mu, \zeta_B)}\,\big]$$

$$+\, \mathcal{O}(q_T/M)$$

gluon correlators in IPS
(see M. Echevarría's talk)

medium/high q_T corrections

TMD factorization region

1) |CH|² is the "hard part" : at this point still not known

2) NRQCD matrix element

$$\mathcal{O}^{q\bar{q}}(\eta_q) = |\langle 0|\chi^\dagger \psi(y)|\eta_q\rangle|^2 = \frac{N_c}{2\pi}|R_{nl}(0)|^2[1 + \mathcal{O}(v^4)]$$

3) Gamma structure fixed to reproduce the LO QCD result

$$\Gamma_{\mu\nu} = \frac{\alpha_s \pi}{3\sqrt{M}}\, \frac{2\sqrt{2}\epsilon^\perp_{\mu\nu}}{\sqrt{(d-2)(d-3)}}\sqrt{N_c^2 - 1}$$

but no pole structure yet: go to next order!

1 : factorization

$\text{QCD} \to \text{NRQCD} \oplus \text{SCET}_{q_T}$

$$\frac{\sigma^v}{\sigma_{\text{Born}}}|_{\text{ren}} = \frac{\alpha_s}{2\pi}\Big[-2\frac{C_A}{\epsilon_{\text{IR}}^2} - \frac{2}{\epsilon_{\text{IR}}}\left(\frac{\beta_0}{2} + C_A \ln\frac{\mu^2}{M^2}\right) + 2C_F\frac{\pi^2}{2v} - C_A \ln^2\frac{\mu^2}{M^2} + 2C_A\left(1+\frac{\pi^2}{3}\right) + 2C_F\left(-5+\frac{\pi^2}{4}\right)\Big]$$

Coulomb singularity absorbed by NRQCD matrix element

renormalization takes care of UV

$$\tilde{f}_1^g = \frac{\alpha_s}{2\pi}\left[\frac{C_A}{\epsilon_{\text{UV}}^2} + \frac{1}{\epsilon_{\text{UV}}}\left(\frac{\beta_0}{2} + C_A \ln\frac{\mu^2}{\zeta_A}\right) - \frac{C_A}{\epsilon_{\text{IR}}^2} - \frac{1}{\epsilon_{\text{IR}}}\left(\frac{\beta_0}{2} + C_A \ln\frac{\mu^2}{\zeta_A}\right)\right]$$

X 2 TMDs

Yes!

SCET correctly reproduces QCD at NLO

$$\mathcal{H} = \left[\ \sigma^{\text{virt},(1)} - \{\tilde{f}_1^{g/A}\tilde{f}_1^{g/B}\}^{(1)}_{\text{virt}}\ \right]$$

on-shell renormalization scheme

$$\mathcal{H} = 1 + \frac{\alpha_s}{2\pi}\left[-C_A \ln^2\frac{\mu^2}{M^2} + 2C_A\left(1+\frac{\pi^2}{3}\right) + 2C_F\left(-5+\frac{\pi^2}{4}\right)\right]$$

see *Phys. Rev. D 70, 054014* (Maltoni&Polosa), Phys.Rev. D48 (1993) (Kuhn&Mirkes)

Useful

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2 : re-factorization

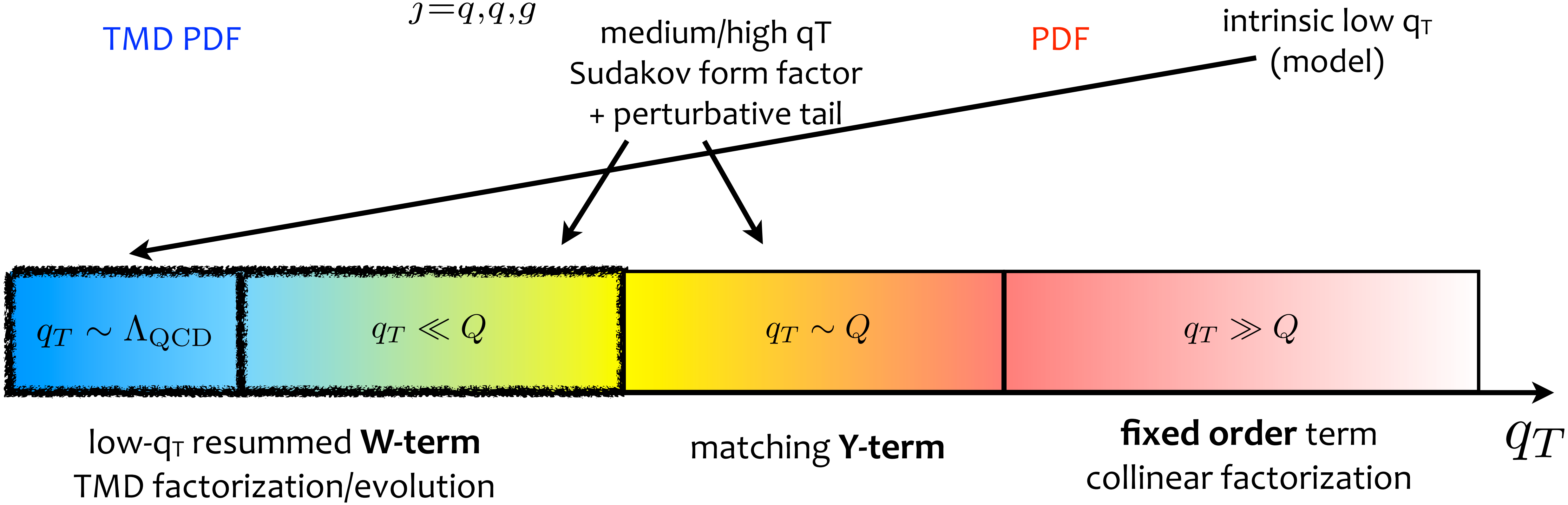
$\mathrm{NRQCD} \oplus \{\mathrm{SCET}_{q_T} \to \mathrm{SCET}_{\Lambda_{\mathrm{QCD}}}\}$

OPE - matching coefficient

$$\tilde{T}_{g/A}(x, b_T; \mu, \zeta) = \sum_{j=q,\bar{q},g} \tilde{C}^T_{g/j}(x, b_T; \mu, \zeta) \otimes t_{j/A}(x; \mu) + \mathcal{O}(b_T \Lambda_{QCD})$$

TMD PDF

PDF



transverse momentum spectrum of physical observables

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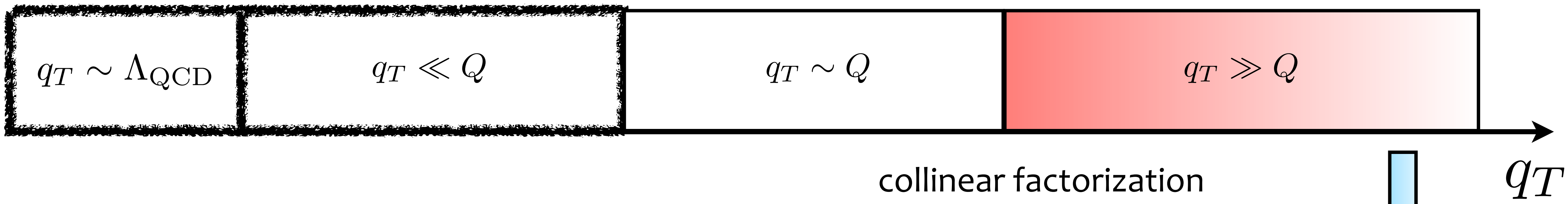
Unpolarized phenomenology

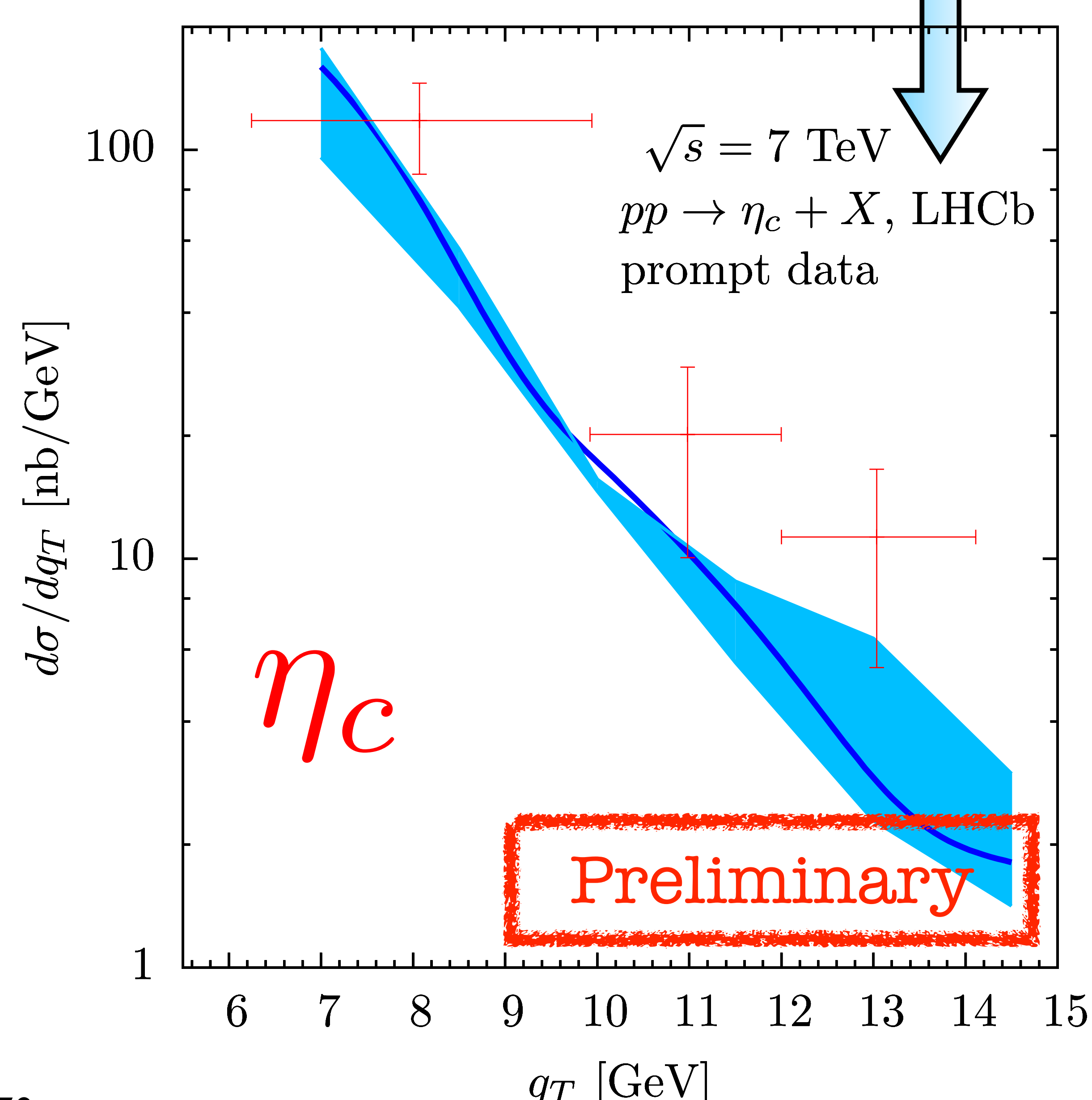


high q_T spectrum

LHCb data
Eur. J. Phys. C75 (2015) 311

partonic calculation from
Phys.Rev. D48 (1993) 179-189
(Kuhn&Mirkes)

NRQCD from Phys. Rev. Lett. 114, 092004



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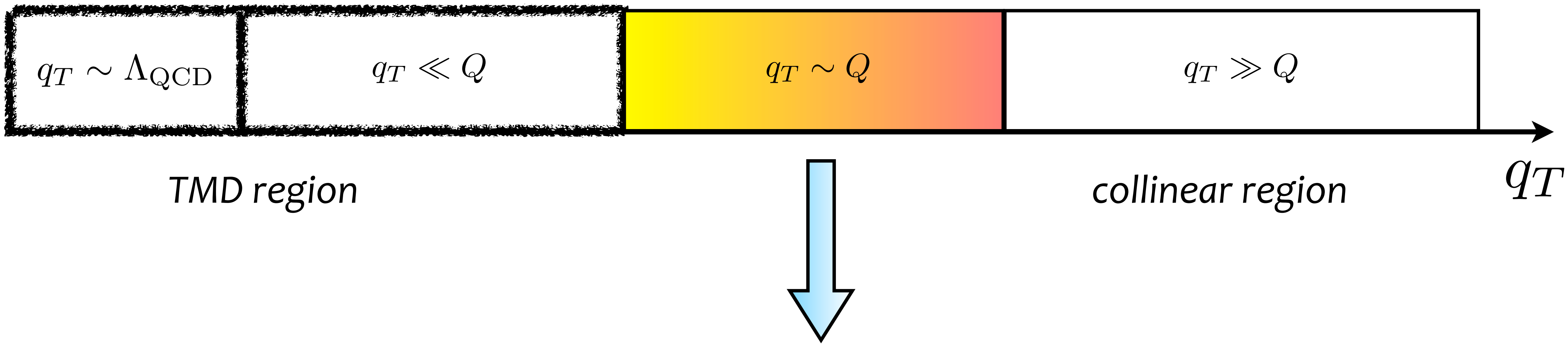
Unpolarized phenomenology



Y term :
matching between
low and high transverse momenta

(see O. Gonzalez's talk)

$$Y = \frac{d\sigma^{q_T \gg Q}}{dq_T} - \frac{d\sigma^{\rm ASY}}{dq_T}$$

On the to-do list!

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Conclusions

1) **Factorization** for q_T spectrum of quarkonium has been established at NLO using the SCET methodology

2) we can make solid **predictions** for (un)polarized TMD cross sections for LHC, RHIC, AFTER@LHC

3) implementing perturbative content we can set the grounds for the **extraction** of information about the **proton structure**
(provided that we'll get data!)

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The gluon Sivers effect

$f_{1T}^{g\perp}$

Review Boer-Lorcé-Pisano-Zhou
Message : the effect is not constrained!

usual argument : since BSM holds,
we know it should be suppressed

two **objections**:

1) the numerical extractions are strongly model dependent and performed at LO

2) we know that any gluon Sivers is given by the sum of two universal gluon Sivers function (process dependence), one of each is constrained by BSM and the other not
(since the momentum operator is C-even, the C- even function is constrained, but the C-odd on no

then there is need for improved predictions
and extractions: we need the theoretical tools

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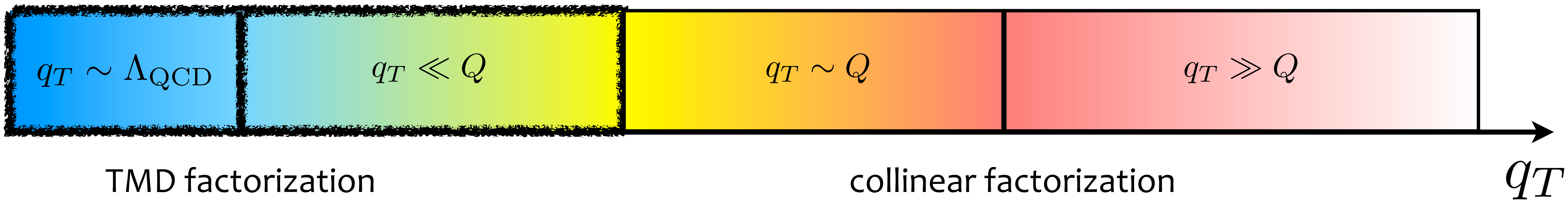
Unpolarized phenomenology



$$\hat{b}_T(b_T) = b_c\left(1 - e^{-(b_T/b_c)^2}\right)^{1/2}\ , \ b_c = 1.5\ \mathrm{GeV}^{-1}$$

$$\mu_{\hat{b}} = 2e^{-\gamma_E}/\hat{b}_T$$

prescriptions to separate between low and high transverse momenta

$$\exp\left[-b_T^2(\lambda_f^T + \lambda_Q \ln(Q^2/Q_0^2))\right]$$

model for low/intrinsic transverse momentum

choices with important phenomenological impact (at medium energies)

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SCET gluon fields

$$\mathcal{B}^{\mu}_{n\perp} = \frac{1}{g}[\bar{n} \cdot \mathcal{P} W_n^{\dagger} \; i D^{\mu}_{n\perp} \; W_n]$$

$$W_n(x) = P \exp\left[\int_{-\infty}^{0} ds \bar{n} \cdot A_n^a(x + \bar{n}s) t^a \right]$$

$$\mathcal{S}_n(x) = P \exp\left[\int_{-\infty}^{0} ds n \cdot A_s^a(x + ns) t^a \right]$$

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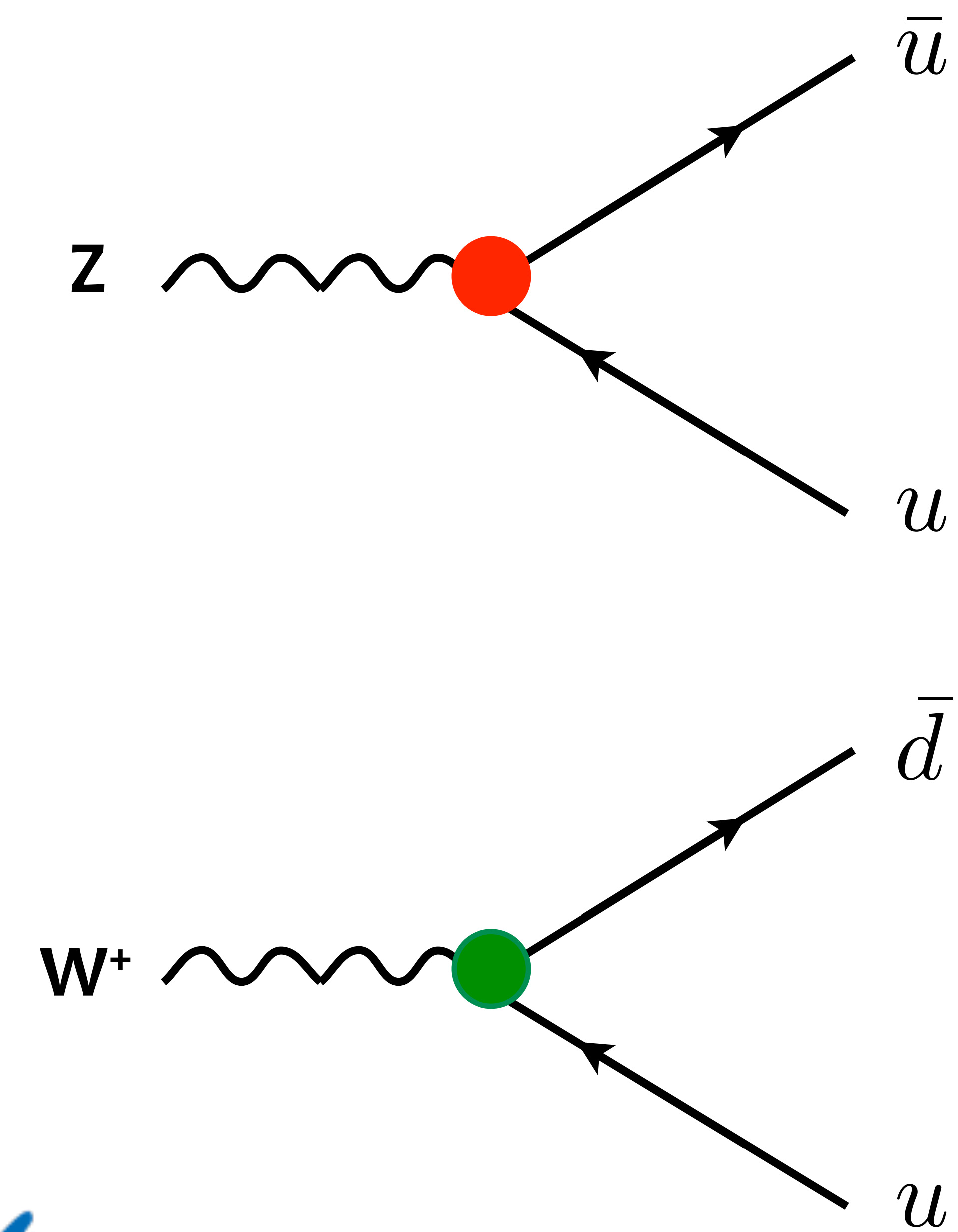
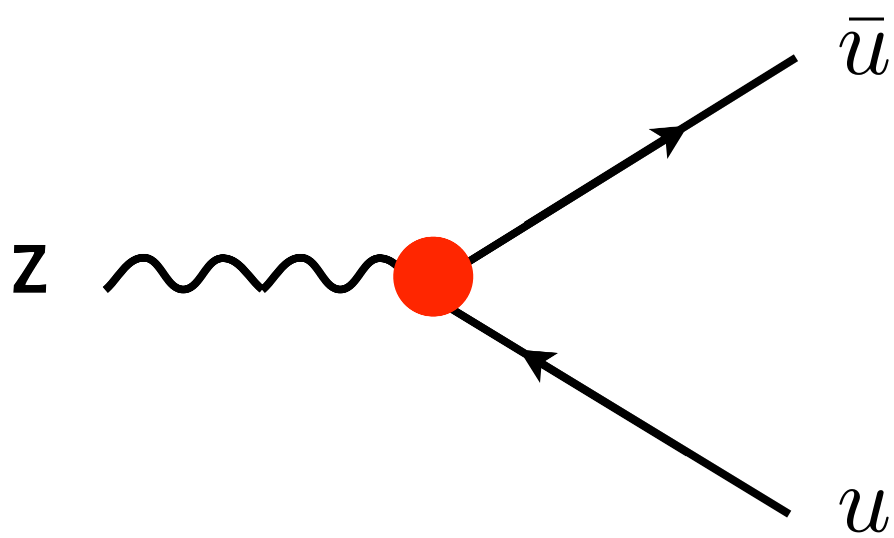
Quark TMDs at the LHC

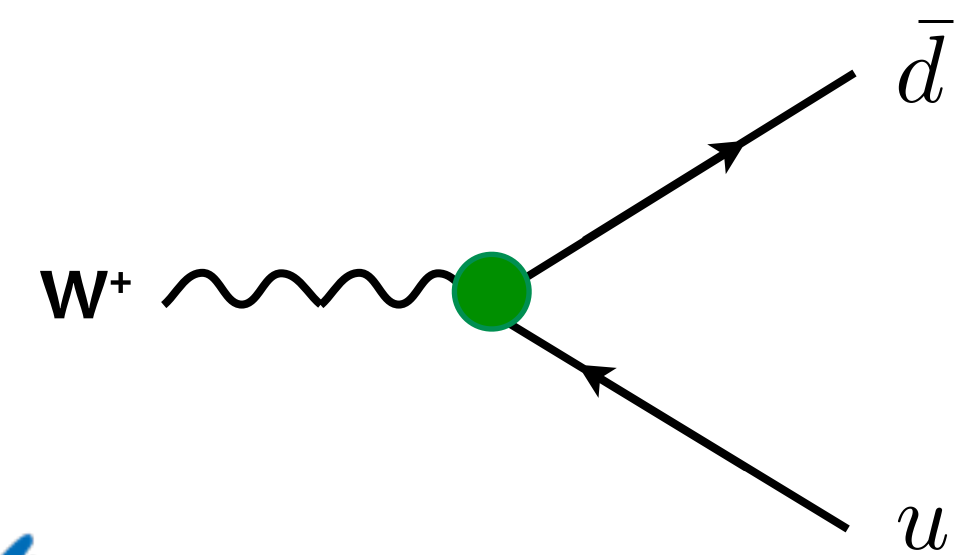
$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2$$

$$\sim \underbrace{\boxed{\mathcal{C}[\, f_1^{q/A} \;\; f_1^{q/B} \,]}}_{\textbf{unpolarized}\text{ quarks}} \pm \underbrace{\boxed{\mathcal{C}[\, h_1^{\perp q/A} \;\; h_1^{\perp q/B} \,]}}_{\textbf{transv. polarized}\text{ quarks}}$$



Quark TMDs at the LHC





$$\frac{d\sigma}{dq_T} \sim \Phi_A^U\ \Phi_B^U\ |\mathcal{M}|^2$$

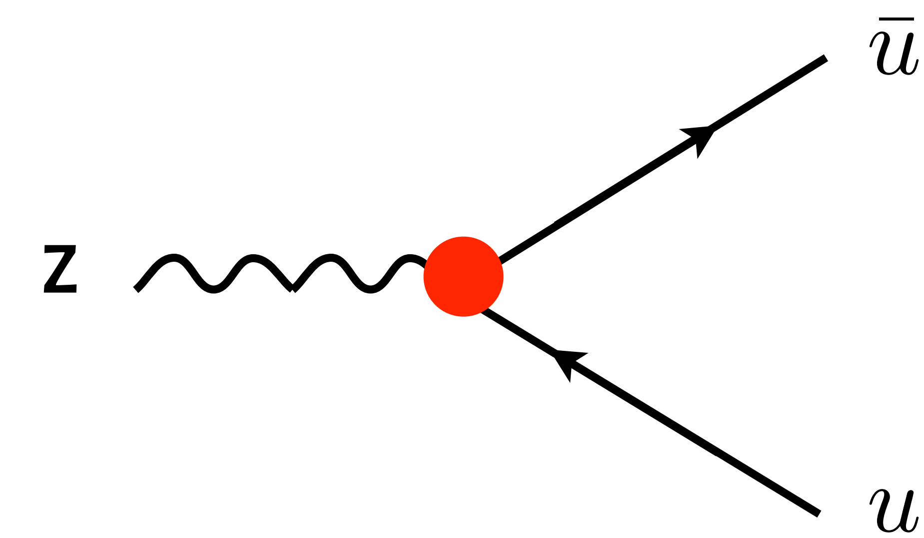
$$\sim \boxed{\mathcal{C}[\ f_1^{q/A}\ \ f_1^{q/B}\ ]} \pm \cancel{\boxed{\mathcal{C}[\ h_1^{\perp q/A}\ \ h_1^{\perp q/B}\ ]}}$$

unpolarized quarks

~~**transv. polarized** quarks~~

no sufficient knowledge

Quark TMDs at the LHC



$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2$$

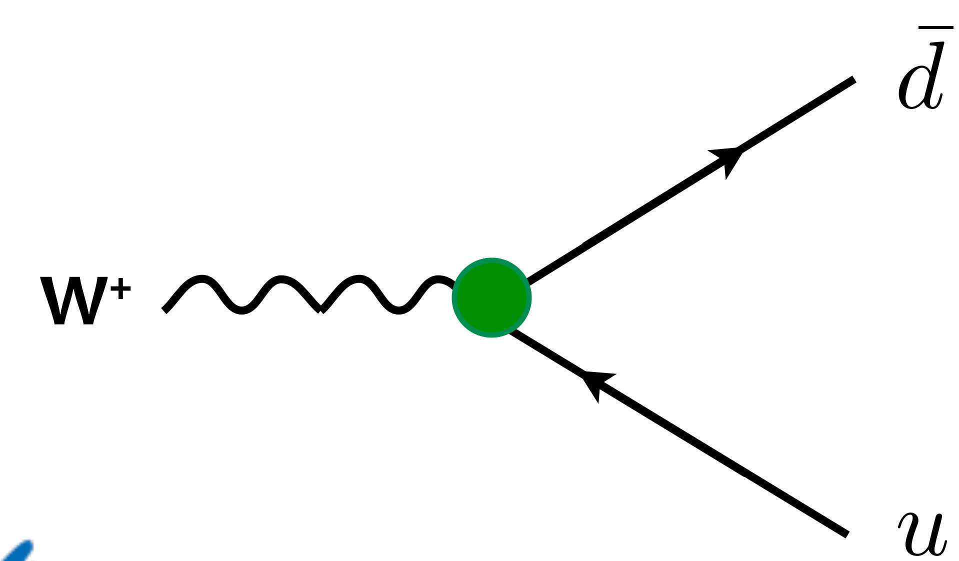
$$\sim \boxed{\mathcal{C}[\, f_1^{q/A} \;\; f_1^{q/B} \,]} \pm \cancel{\boxed{\mathcal{C}[\, h_1^{\perp q/A} \;\; h_1^{\perp q/B} \,]}}$$

unpolarized quarks

transv. polarized quarks

focus on the **flavor structure** of the NP part

no sufficient knowledge



Intrinsic <k_T> effects **have been measured on Z data** and used to predict the W q_T spectrum, **assuming they are the same.**

This is not optimal, because the intrinsic contributions are, in principle, ***different in Z and W± production***

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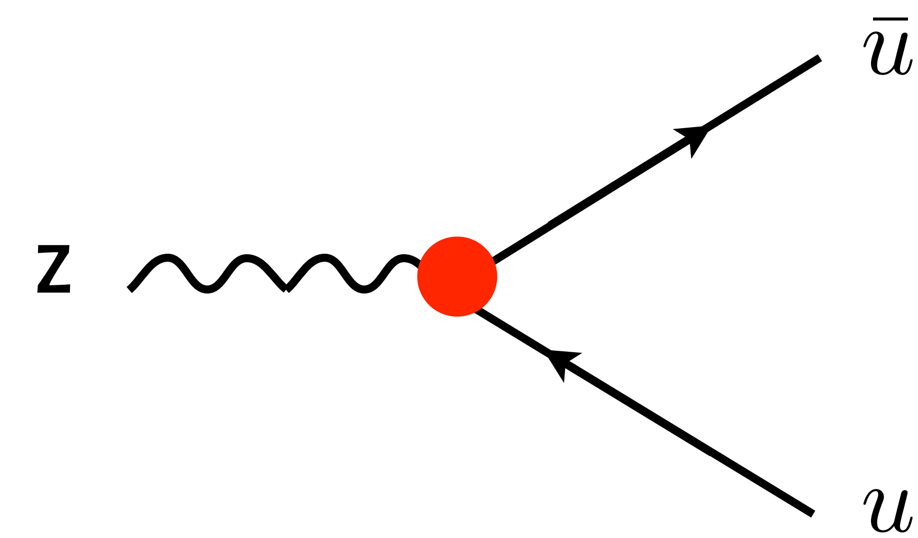
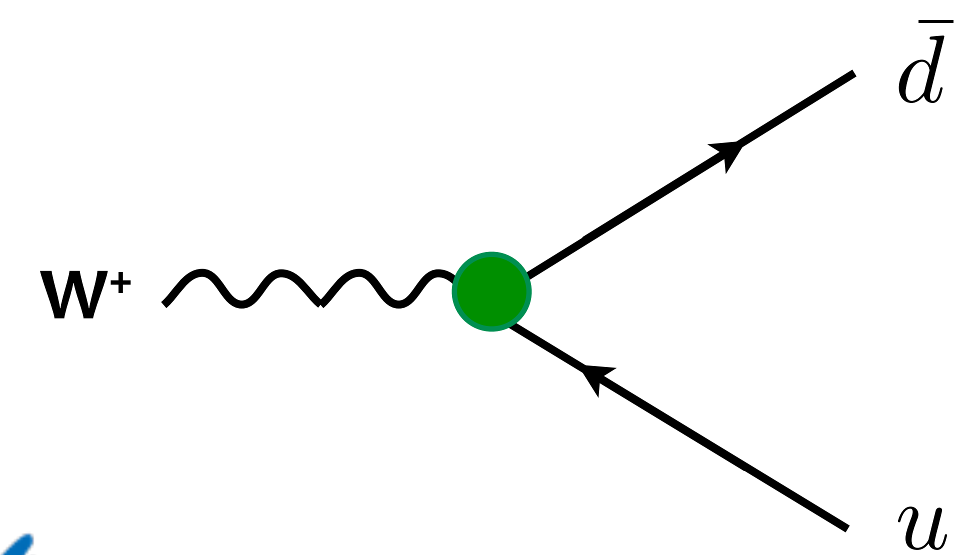
Quark TMDs at the LHC





$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2$$

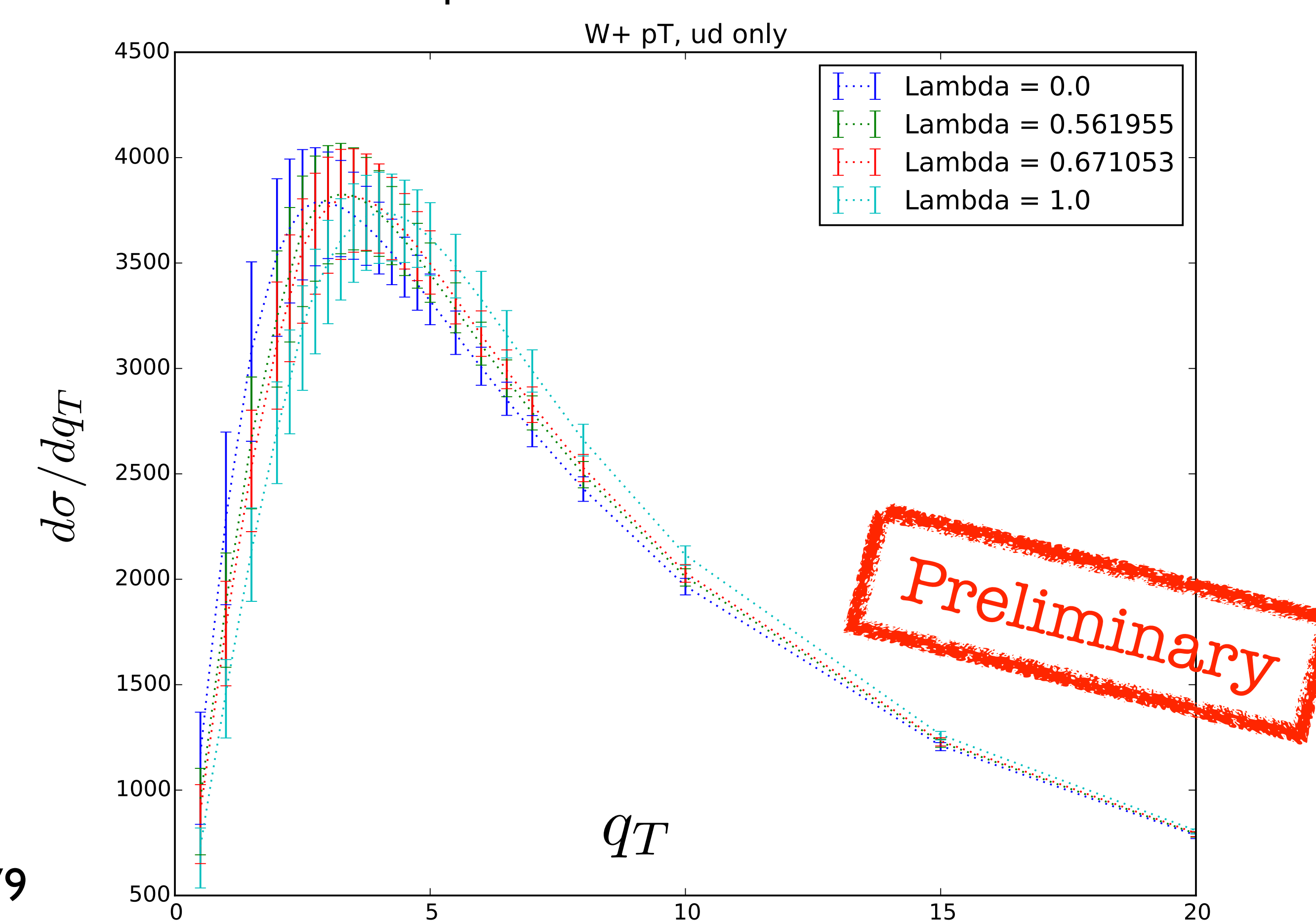
$$\sim \boxed{\mathcal{C}[\, f_1^{q/A} \;\; f_1^{q/B} \,]} \pm \cancel{\boxed{\mathcal{C}[\, h_1^{\perp q/A} \;\; h_1^{\perp q/B} \,]}}$$

unpolarized quarks

~~**transv. polarized** quarks~~

no sufficient knowledge

focus on the
flavor structure
of the NP part



W mass determination @ CDF

PhysRevD.89.072003

TABLE X: Uncertainties on M_W (in MeV) as resulting from charged-lepton transverse-momentum fits in the $W \to \mu\nu$ and $W \to e\nu$ samples. The last column reports the portion of the uncertainty that is common in the $\mu\nu$ and $e\nu$ results.

p_T^ℓ fit uncertainties			
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 p_T	9	9	9
Photon radiation	4	4	4
Statistical	18	21	0
Total	25	28	16

TABLE XI: Uncertainties on M_W (in MeV) as resulting from neutrino-transverse-momentum fits in the $W \to \mu\nu$ and $W \to e\nu$ samples. The last column reports the portion of uncertainty that is common in the $\mu\nu$ and $e\nu$ results.

p_T^ν fit uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Lepton energy scale	7	10	5
Lepton energy resolution	1	7	0
Lepton efficiency	2	3	0
Lepton tower removal	4	6	4
Recoil scale	2	2	2
Recoil resolution	11	11	11
Backgrounds	6	4	0
PDFs	11	11	11
W boson p_T	4	4	4
Photon radiation	4	4	4
Statistical	22	25	0
Total	30	33	18

$$M_W = 80.387 \pm 0.019 \text{ GeV}$$

controlled **mainly** by soft gluons

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W mass determination @ D0

PhysRevD.89.012005

TABLE VI: Systematic uncertainties on M_W (in MeV). The section of this paper where each uncertainty is discussed is given in the Table.

Source	Section	m_T	p_T^e	$\not{E}_T$
Experimental				
Electron Energy Scale	VII C 4	16	17	16
Electron Energy Resolution	VII C 5	2	2	3
Electron Shower Model	V C	4	6	7
Electron Energy Loss	V D	4	4	4
Recoil Model	VII D 3	5	6	14
Electron Efficiencies	VII B 10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$(Experimental)		18	20	24
W Production and Decay Model				
PDF	VI C	11	11	14
QED	VI B	7	7	9
Boson p_T	VI A	2	5	2
$\sum$(Model)		13	14	17
Systematic Uncertainty (Experimental and Model)		22	24	29
W Boson Statistics	IX	13	14	15
Total Uncertain[illegible]		[illegible]	[illegible]	33

controlled **only** by soft gluons

Are there ***yet unexplored uncertainties*** on the Z/W transverse spectrum?

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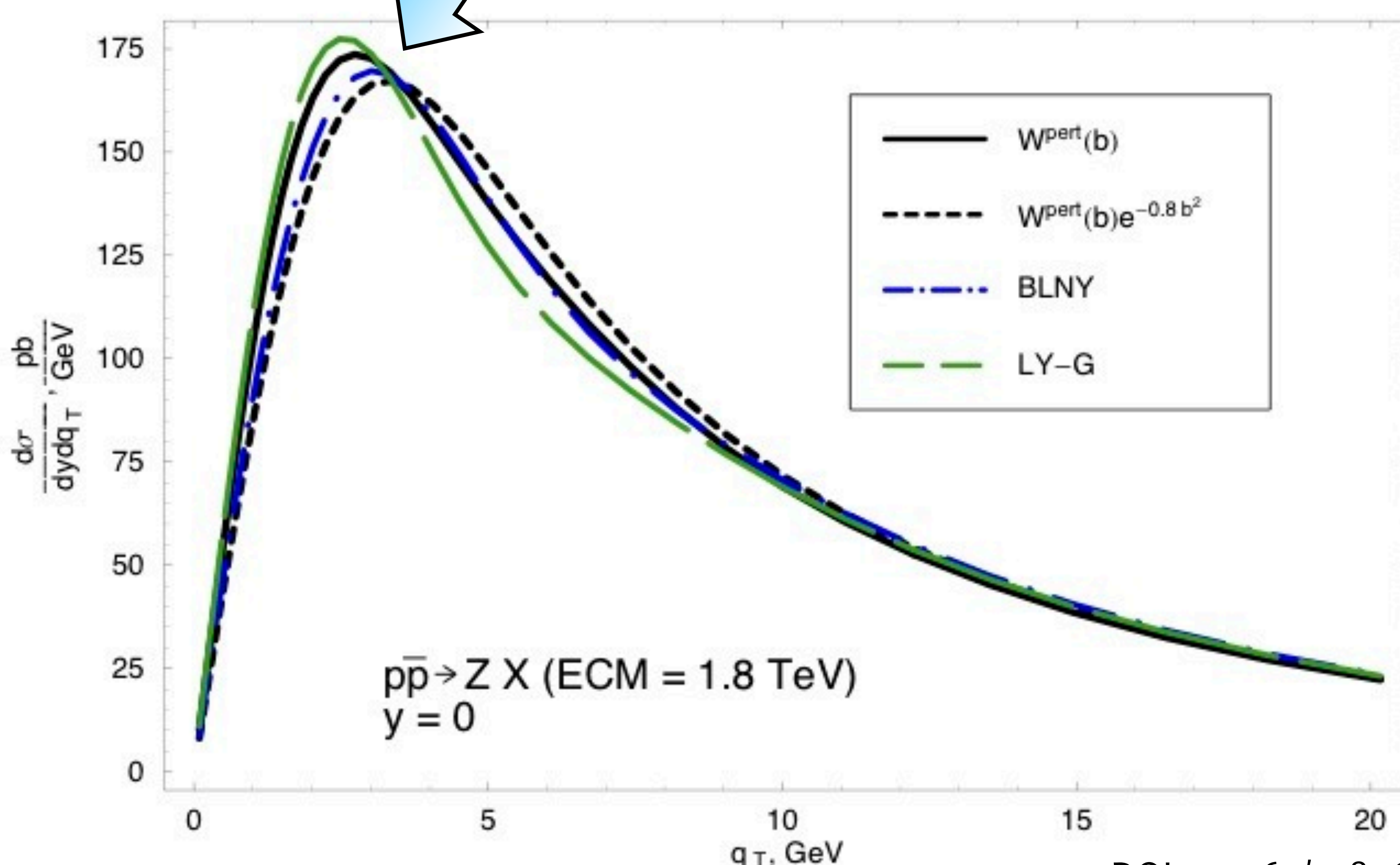
Nonperturbative effects

$$\frac{d\sigma^{Z/W^{\pm}}}{dq_T} \sim \mathrm{FT} \sum_{i,j} \exp\left\{ -\, g_{ij}\; b_T^2 \right\}$$

$$g_{ij} \sim \langle k_T^2 \rangle_i + \langle k_T^2 \rangle_j + \text{soft gluons}$$

g comes from 2 TMD PDFs
and ***controls the position of the peak***



DOI 10.1063/1.1896698

Impact on the peak

We study flavor dependent configurations that ***respect the experimental constraint on Z producing different distributions for W±***

$$g_{ij}(Z) \; : \; [\mathrm{GeV}^2] \; 0.7 = u + \bar{u} = 0.2 + 0.5$$
$$= d + \bar{d} = 0.3 + 0.4$$
$$= \cdots = 0.6 + 0.1 = \ldots$$
$$g_{ij}(W) \; : \; [\mathrm{GeV}^2] \; 0.6 = u + \bar{d} = 0.2 + 0.4 = \ldots$$

Preliminary

shifts of peak position in GeV

	W^+		W^-		Z	
$\mu_R = \mu_c/2, 2\mu_c$	+0.30	−0.09	+0.29	−0.06	+0.23	−0.05
pdf (90% cl)	+0.03	−0.05	+0.06	−0.02	+0.05	−0.02
$\alpha_S = 0.121, 0.115$	+0.14	−0.12	+0.14	−0.14	+0.15	−0.15
$\Lambda_{NP} = 0.7, 0.5$ ($\langle \mathbf{k}_\perp^2 \rangle = 1.0, 1.96$)	+0.16	−0.16	+0.16	−0.14	+0.16	−0.15
non-universal $\langle \mathbf{k}_\perp^2 \rangle$ (maximal W^+ effect)	+0.09			−0.06	±0	
non-universal $\langle \mathbf{k}_\perp^2 \rangle$ (maximal W^- effect)		−0.03	+0.05		±0	

MESSAGE:

the ***uncertainty*** *on the peak position* ***is not negligible***

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(Un)polarized cross sections

TMDs known at NLO, NNLL

$$\frac{d\sigma_{UU}}{dq_T} \sim \Big\{ \underbrace{\mathcal{C}[f_1^g f_1^g]}_{\text{unpolarized gluons}} - \underbrace{\mathcal{C}[h_1^{\perp g} h_1^{\perp g}]}_{\text{lin. polarized gluons}} \Big\}$$

rich phenomenology

$$\frac{d\sigma_{UL}}{dq_T} = 0$$

by parity arguments

gluon Sivers

gluon pretzelosity/1

gluon pretzelosity/2

$$\frac{d\sigma_{UT}}{dq_T} \sim \Big\{ \mathcal{C}[f_1^g f_{1T}^{\perp g}] + \mathcal{C}[h_1^{\perp g} h_{1T}^{g}] + \mathcal{C}[h_1^{\perp g} h_{1T}^{\perp g}] \Big\}$$

gluon Sivers, pretzelosity 1/2 : OPE still unknown

Conclusions

0) Phenomenology suggests a **flavor dependence** in the intrinsic transverse momentum of partons; this opens the way to **yet unexplored effects**

1) it might have a non-negligible **impact on Z/W± production**

2) are there contributions from transversely polarized quarks ? (Boer-Mulders effect still not included)

3) **3D proton structure is of interest for high-energy physics**: nonperturbative effects should be extracted and their impact tested

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