TMDs, a 3D look at the proton

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Nikhef Jamboree 2015

3D proton structure @ Nikhef

Piet Mulders (VU)

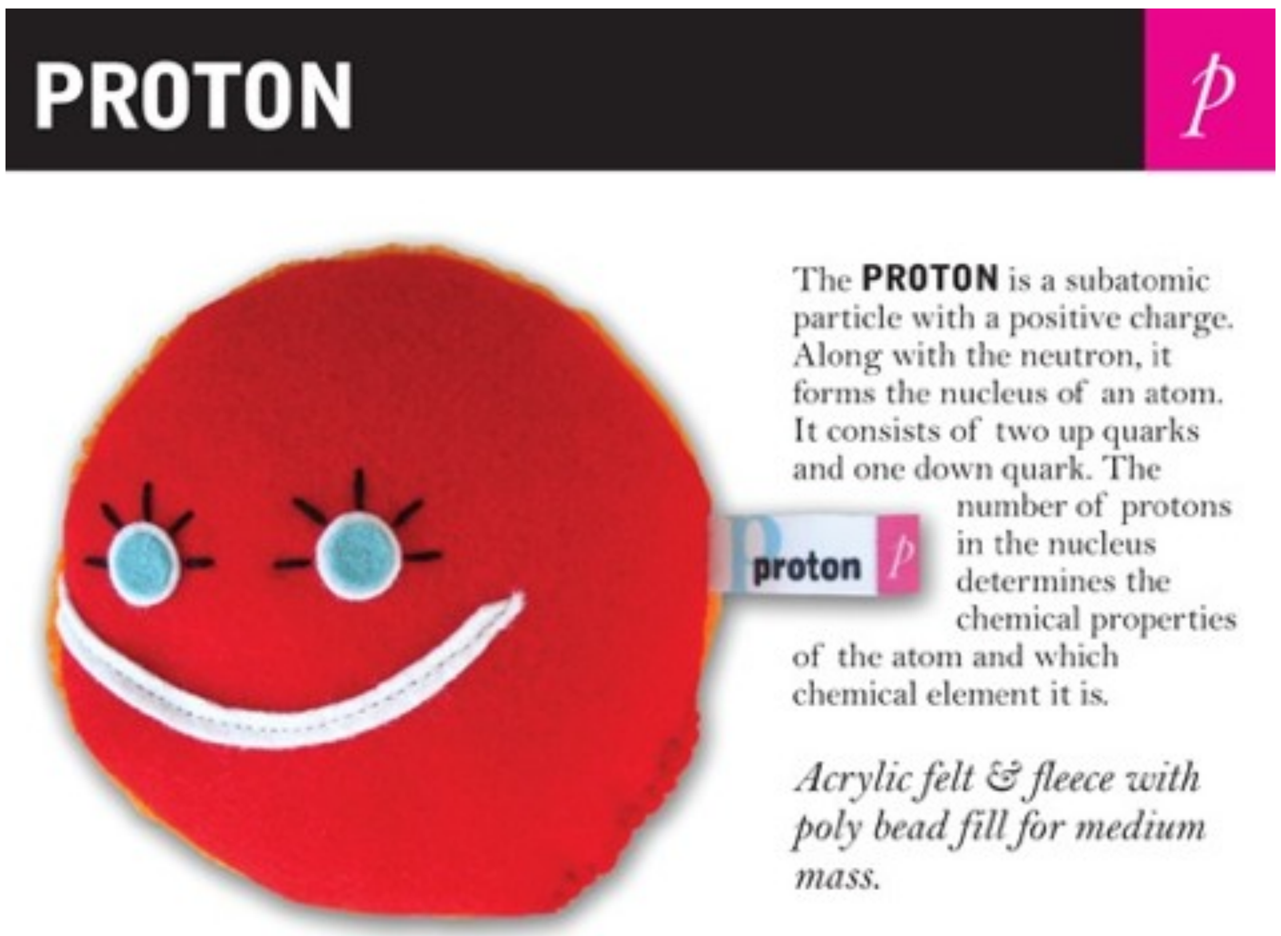
Amsterdam - Groningen

Daniel Boer (RUG)

Postdocs and visitors

PhD students

Why the proton ..?



- building blocks of our world: ~ **99.97% of the mass** of the world we live in is accounted by protons+neutrons

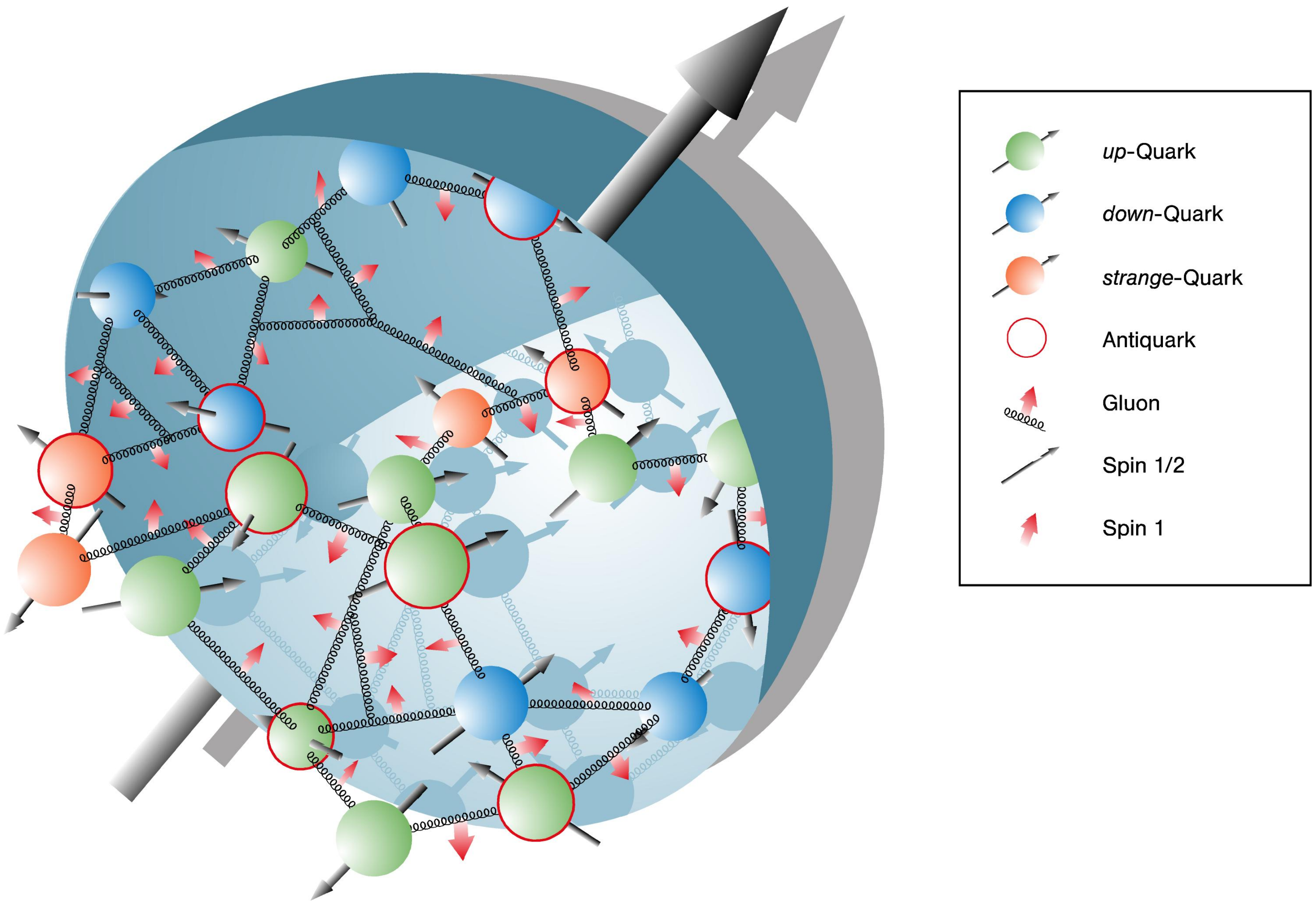
- **connection** between chemistry, atomic/ nuclear physics and the elementary building blocks of Nature

- **field theory** : subtle role in canceling some of the divergencies of the theory

HOW CAN WE DESCRIBE IT ?

The quest for the structure

quantum field theory:
Quantum Chromodynamics



Quarks & gluons

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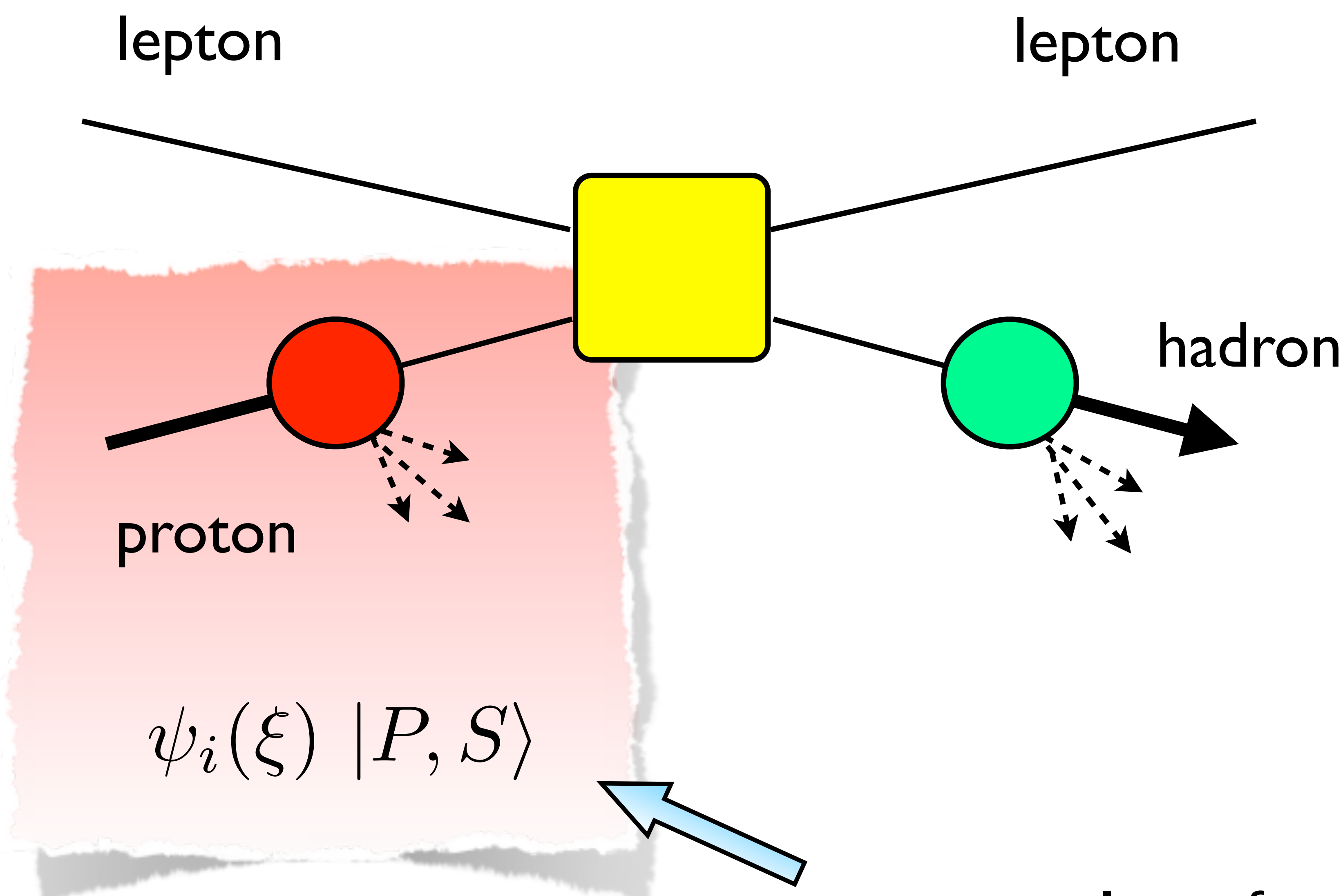
Observing protons

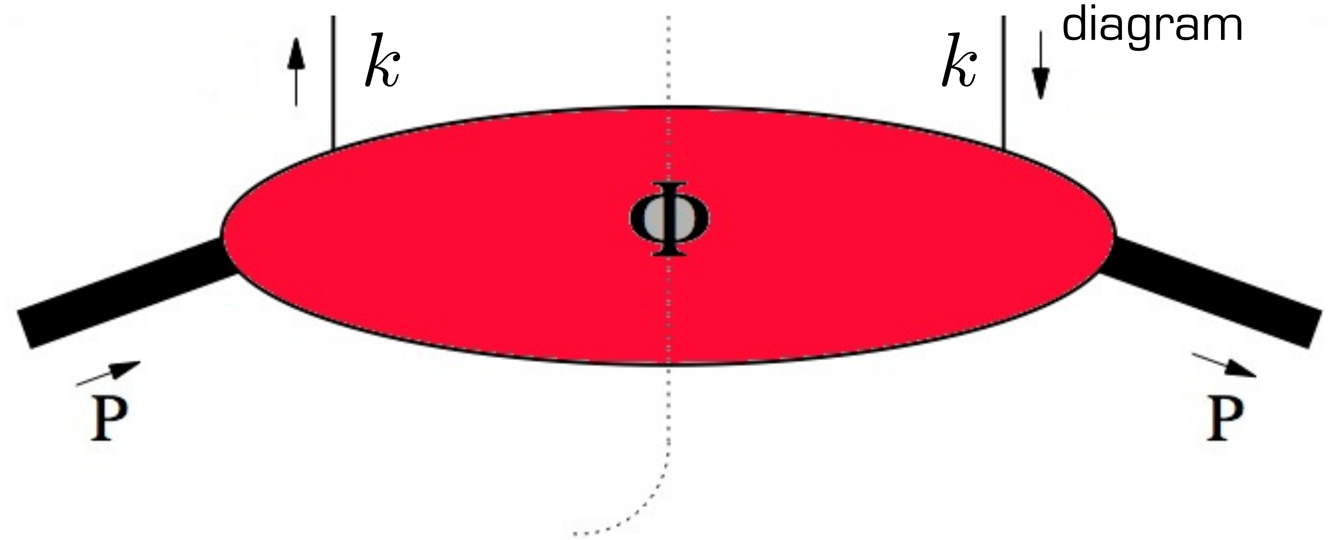


extraction of a quark
from the proton

Observing protons

how can we **define distribution functions** ?

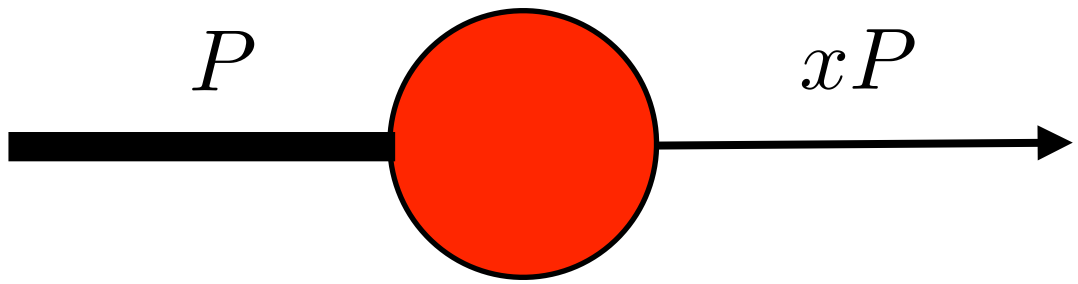
a squared Feynman diagram



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

Dirac matrix , **parametrized in terms of quark distribution functions**

Quarks in 1D - PDFs



extraction of a quark collinear with the proton

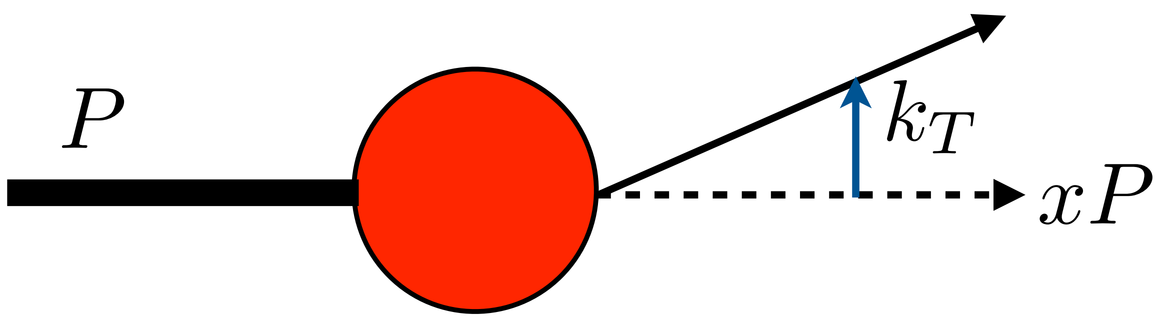
3 parton distribution functions (PDFs)

not computable in pert. theory

Proton **and** quark spin configuration:	unpolarized	longitudinal	transverse
	$f_1(x)$	$g_1(x)$	$h_1(x)$
level of knowledge:	very good	getting better	basic

$$\{\ f_1(x)\ ,\ g_1(x)\ ,\ h_1(x)\ \}$$

Quarks in 3D - TMDs



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

8 transverse-momentum-dependent
parton distribution functions (TMD PDFs)

partly not computable

$$f_1^q(x, \vec{k}_T)$$

! 3D functions !
richer than 1D PDFs

for **LHC**

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

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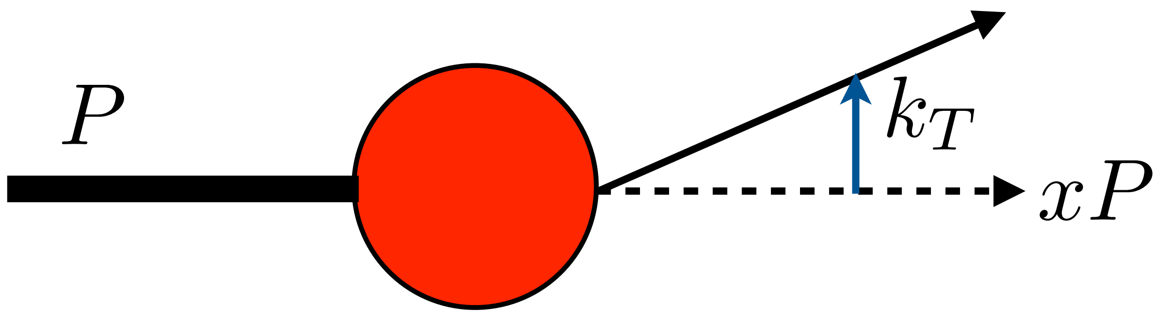
Gluons in 3D - TMDs



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

8 transverse-momentum-dependent
parton distribution functions (TMD PDFs)

<u>partly</u> not computable

for **LHC**

LEADING TWIST

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)

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Phenomenology of TMDs @ the LHC

useful references (Xmas reading):

AS et al. - 10.5506/APhysPolB.46.2501

Echevarria, Kasemets, Mulders, Pisano
10.1007/JHEP07(2015)158
AS, Bacchetta, Radici, Schnell
10.1007/JHEP11(2013)194
Bacchetta, Echevarria, Mulders, Radici, **AS**
10.1007/JHEP11(2015)076

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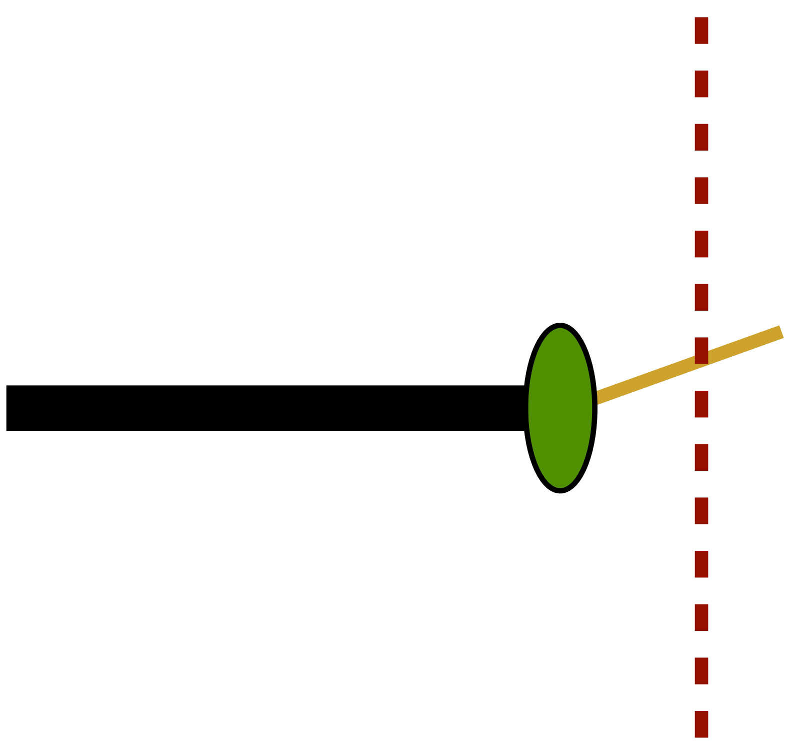
TMDs - a physical picture

intrinsic
transverse
momentum



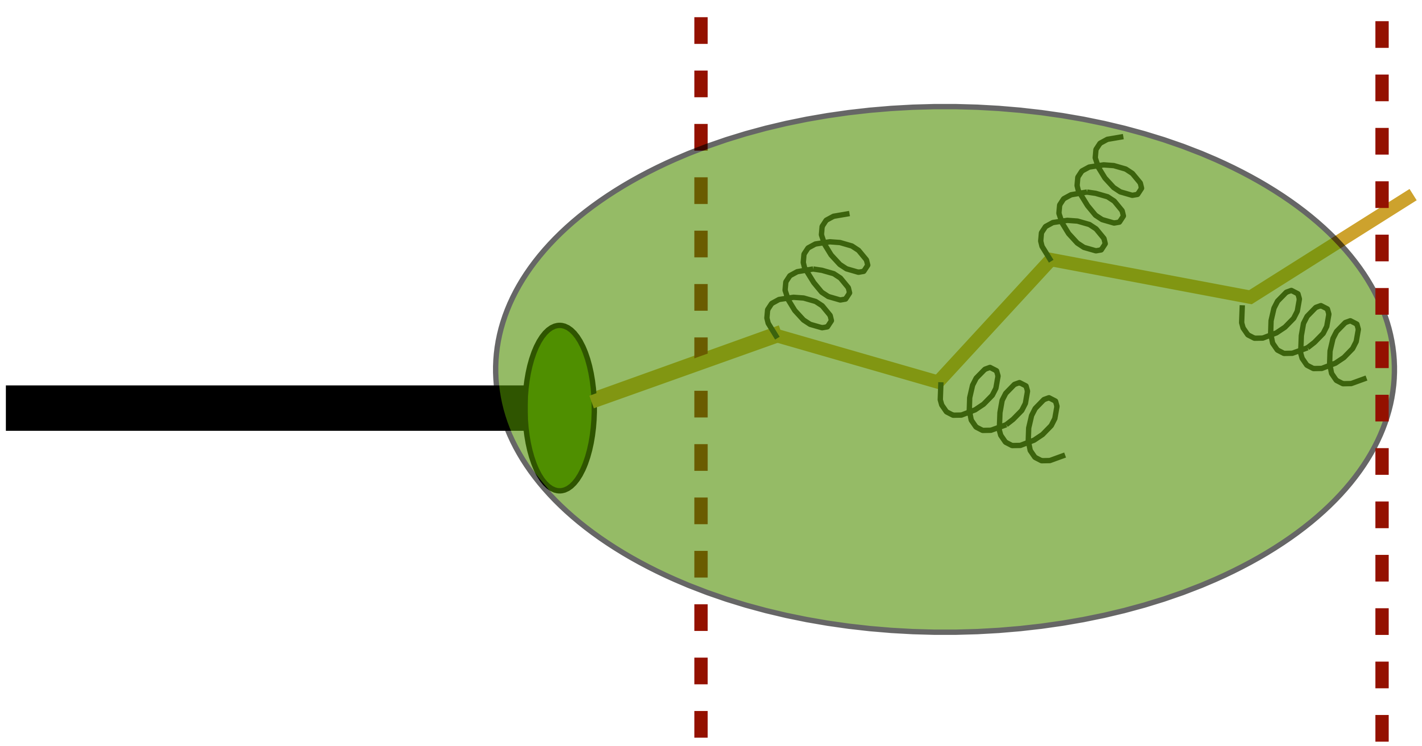
$$|k_\perp| \sim \Lambda_{\text{QCD}}$$

courtesy A. Bacchetta

TMDs - a physical picture

intrinsic
transverse
momentum

soft and collinear
gluon radiation



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

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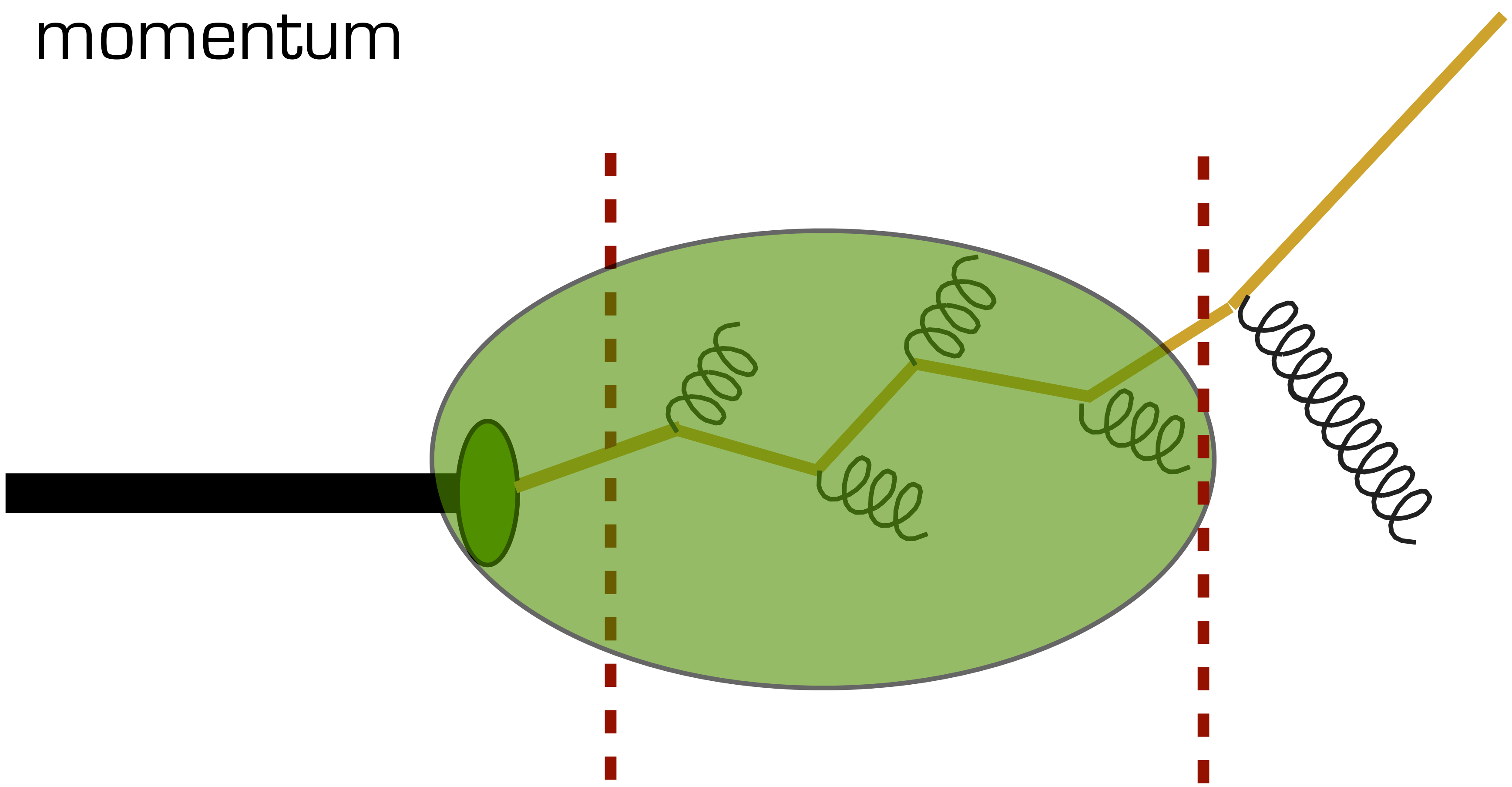
courtesy A. Bacchetta

TMDs - a physical picture

intrinsic transverse momentum

soft and collinear gluon radiation

hard gluon radiation



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

$|k_\perp| \ll Q$

$|k_\perp| \sim Q$

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courtesy A. Bacchetta

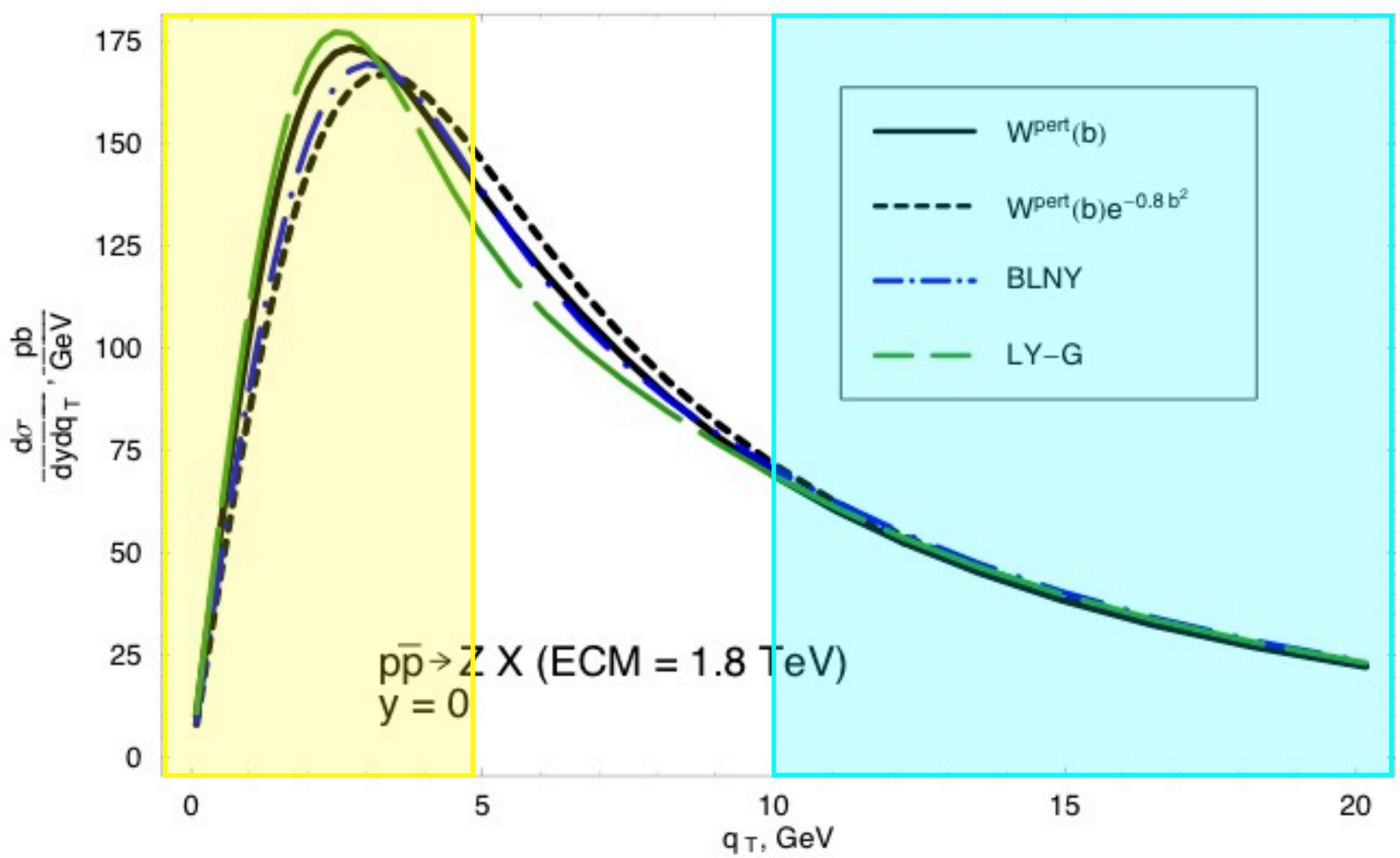
TMDs - from low to high momenta

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

intrinsic momentum +
soft/coll. gluon radiation

matching

hard gluon radiation



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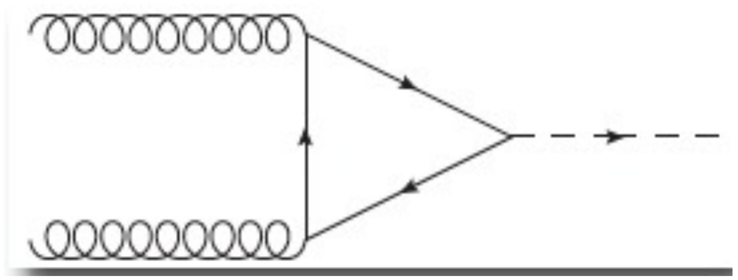
Gluons @ the LHC

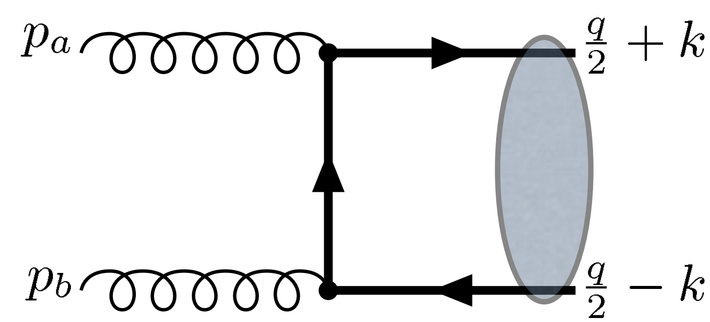
Higgs production



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

$$m_h = 125 \text{ GeV}$$

quarkonium production



+ crossed term

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

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

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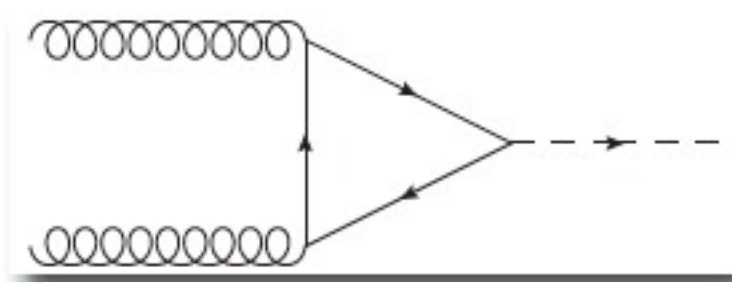
Gluons @ the LHC

Higgs production



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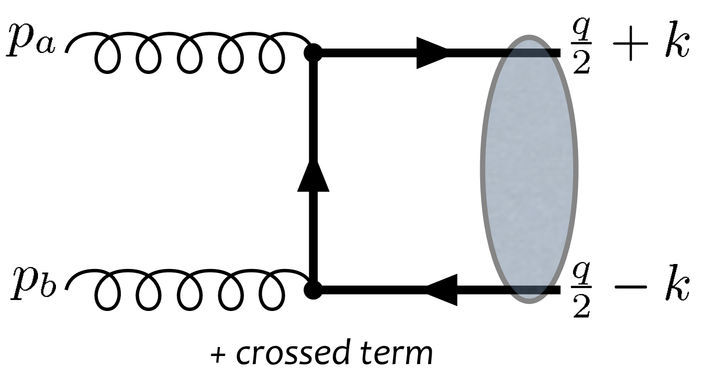
quarkonium production



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

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

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

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

unpolarized gluons

lin. polarized gluons

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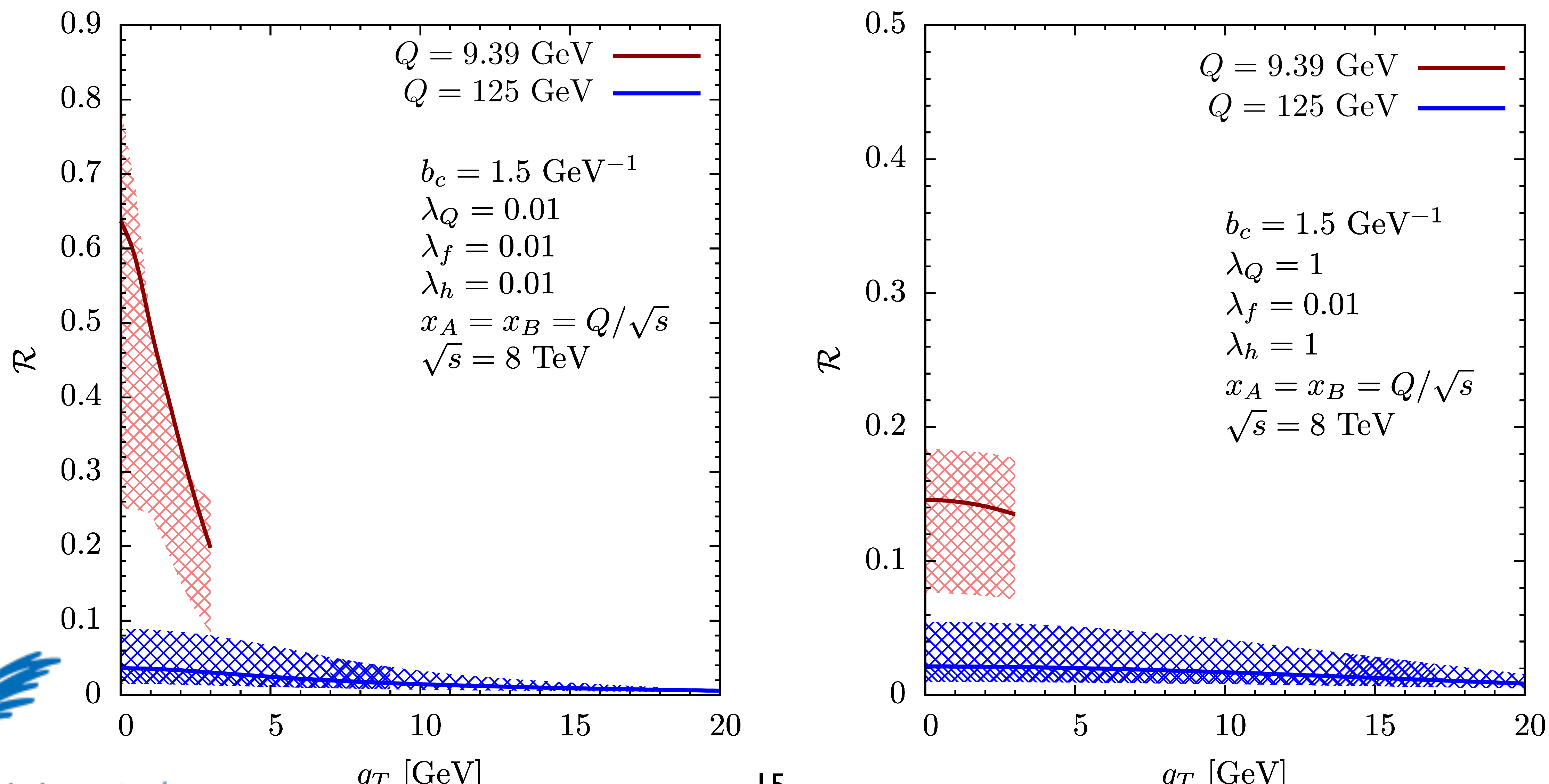
Linearly polarized vs unpolarized

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

quarkonium - low energy

higgs - high energy



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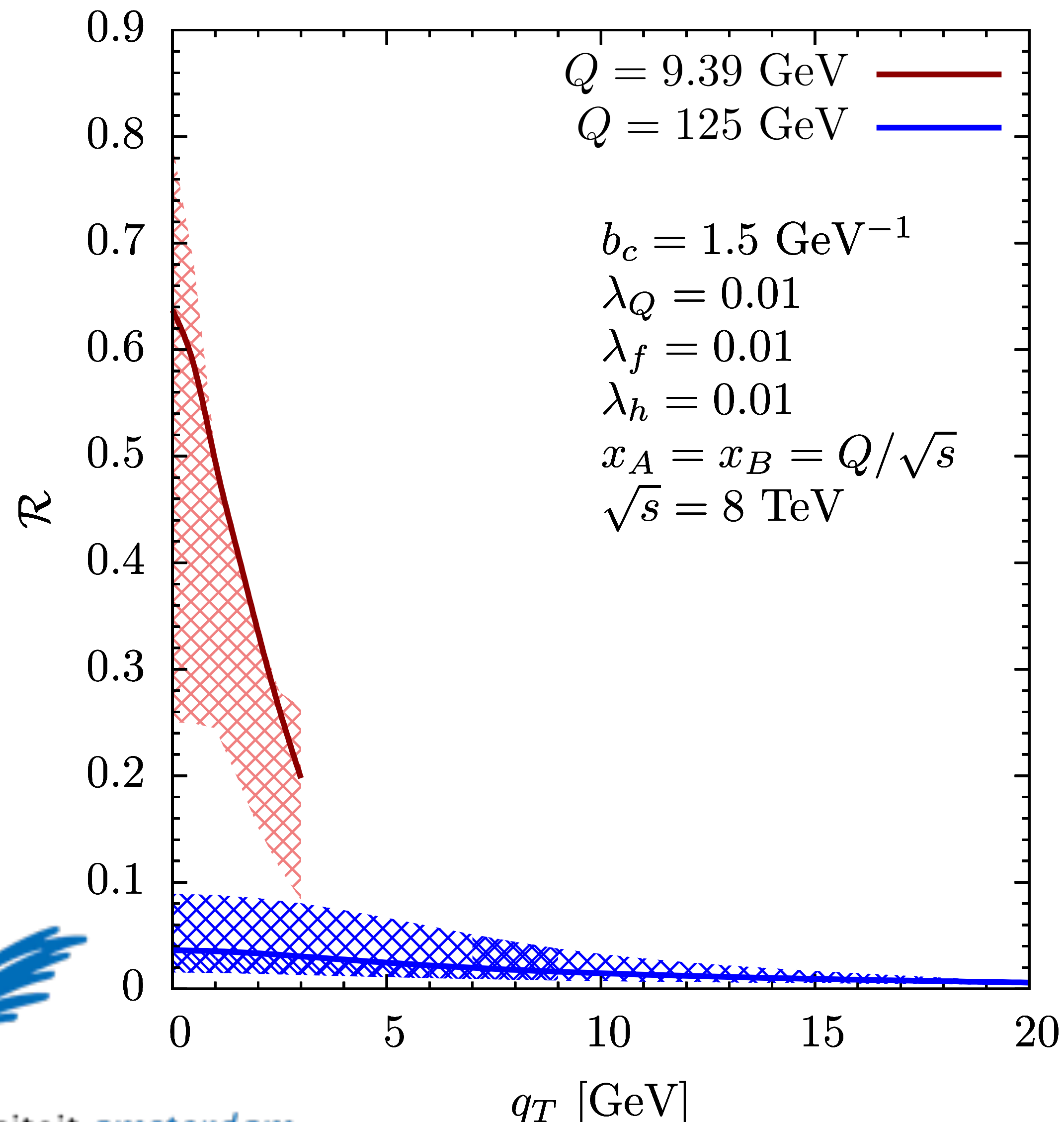
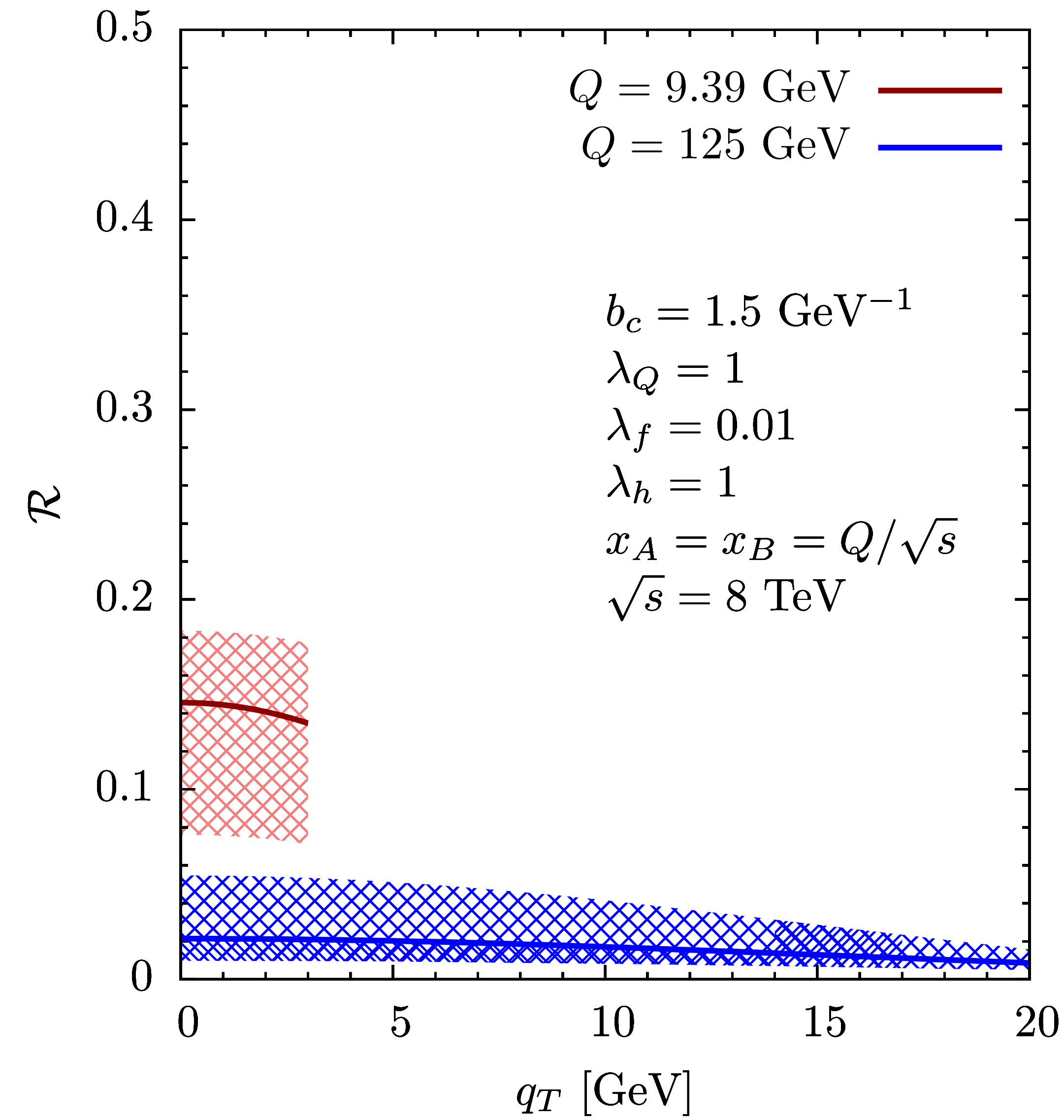
Linearly polarized vs unpolarized

Nonperturbative physics enhanced at low Q





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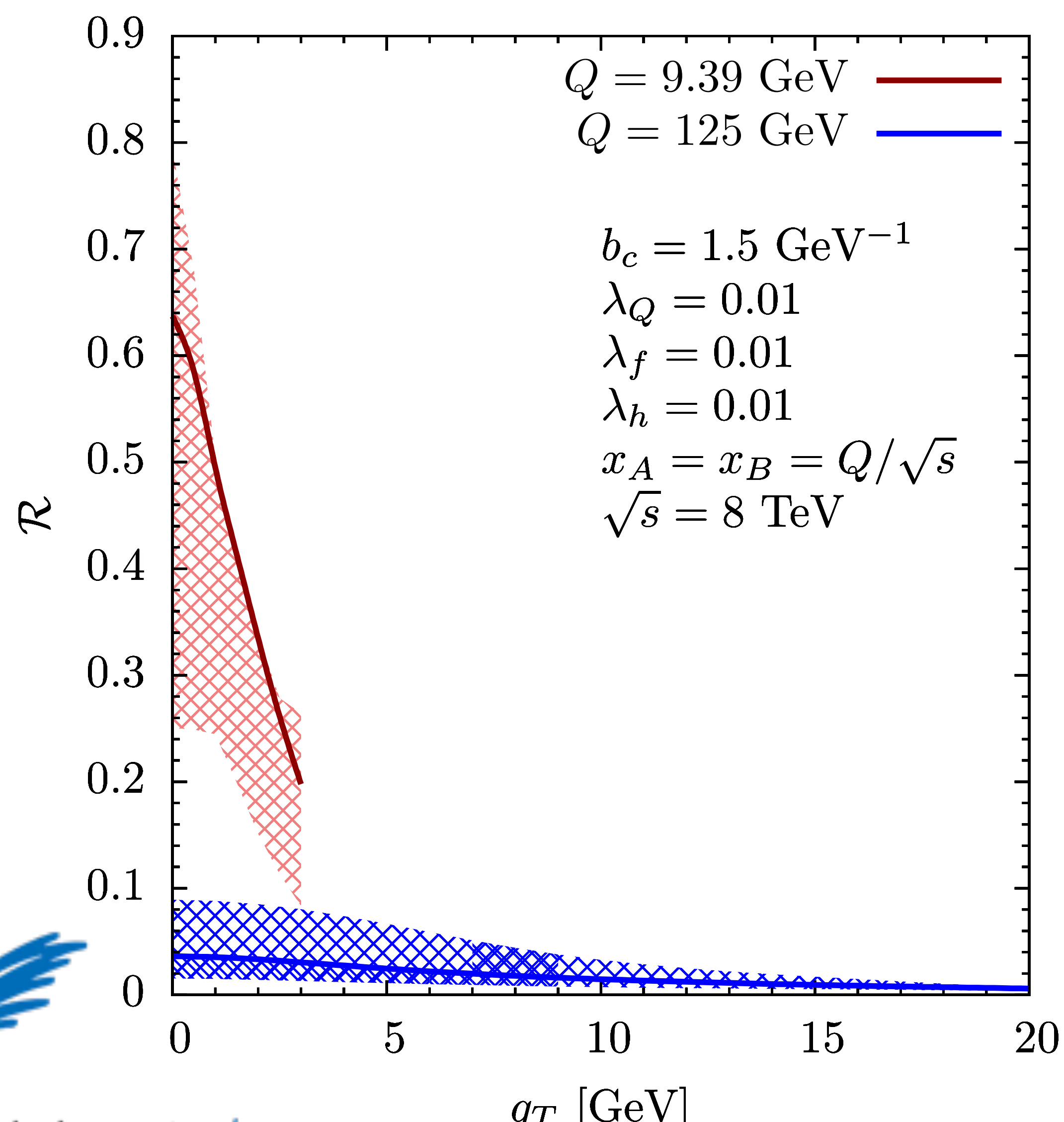
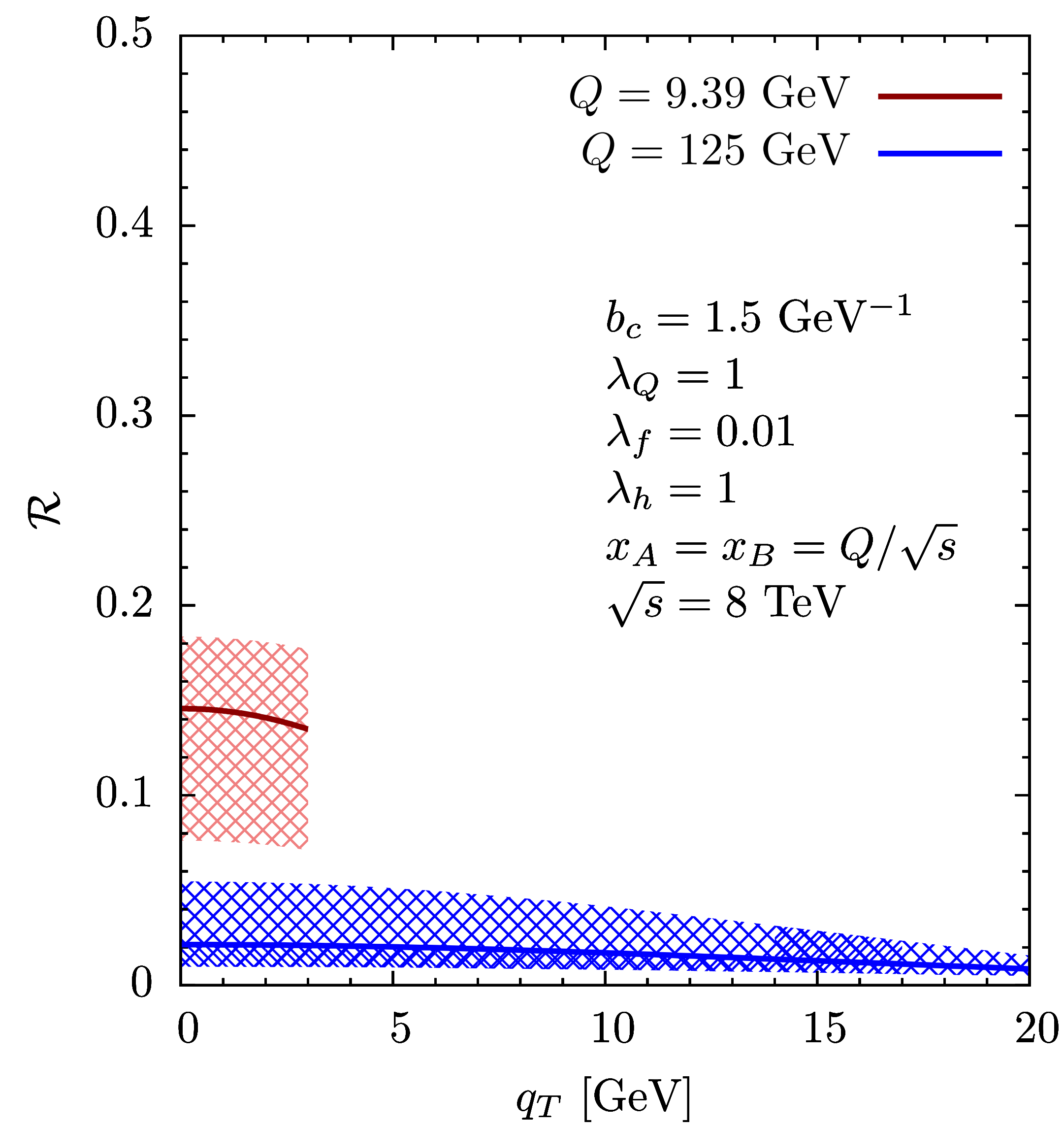
Linearly polarized vs unpolarized

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





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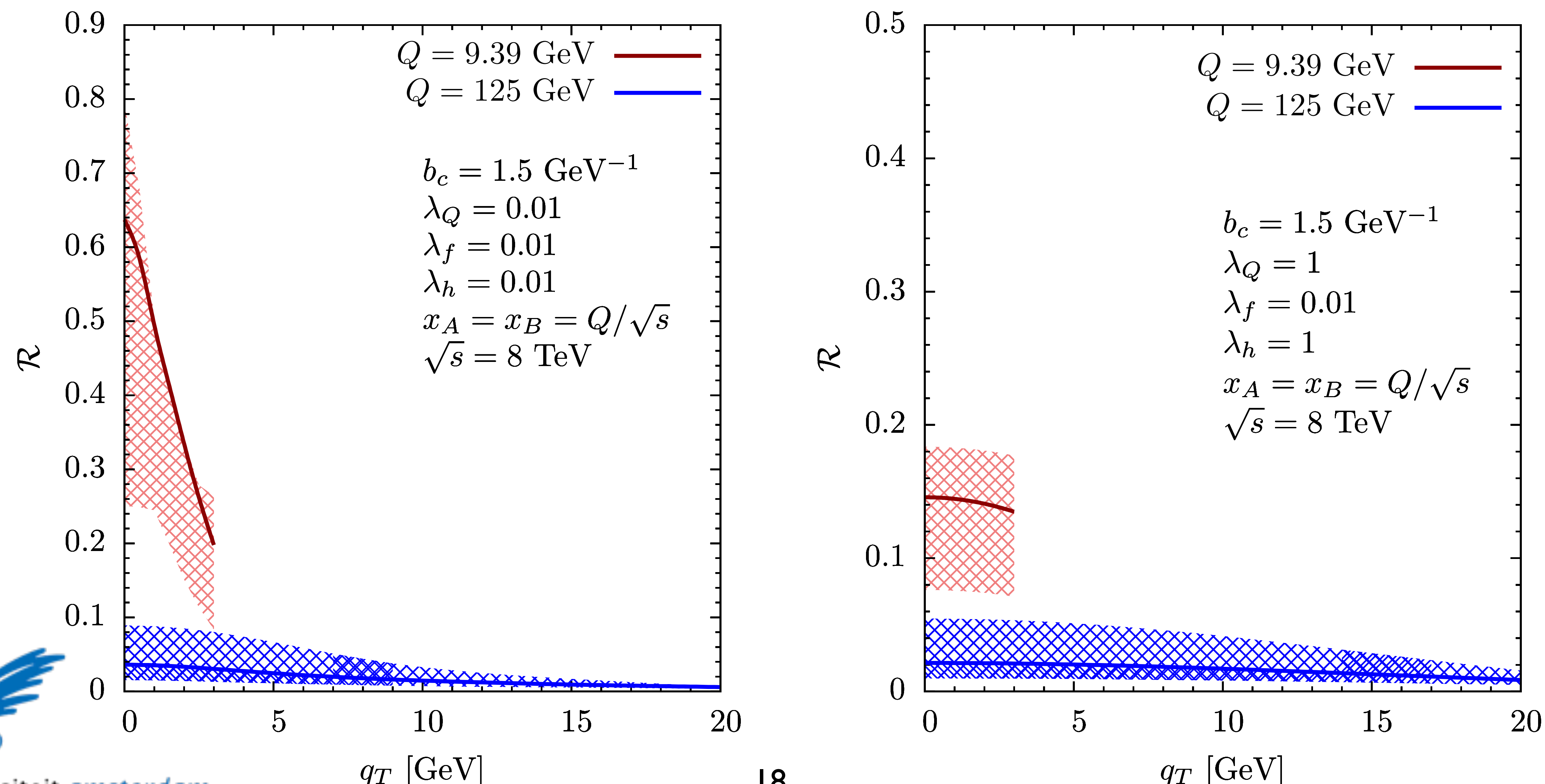
Linearly polarized vs unpolarized

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



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Gluons @ the LHC - take home

Lin. polarized gluons
are **not negligible**
when studying
TMD observables!

puzzling interplay :
the proton structure
manifests in different ways

ITS PHENOMENOLOGY IS NOT UNIQUE

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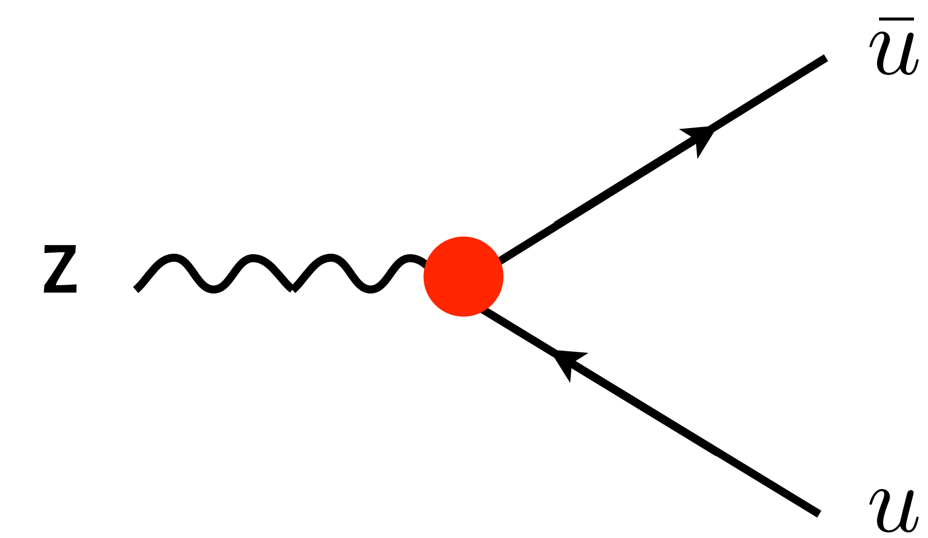
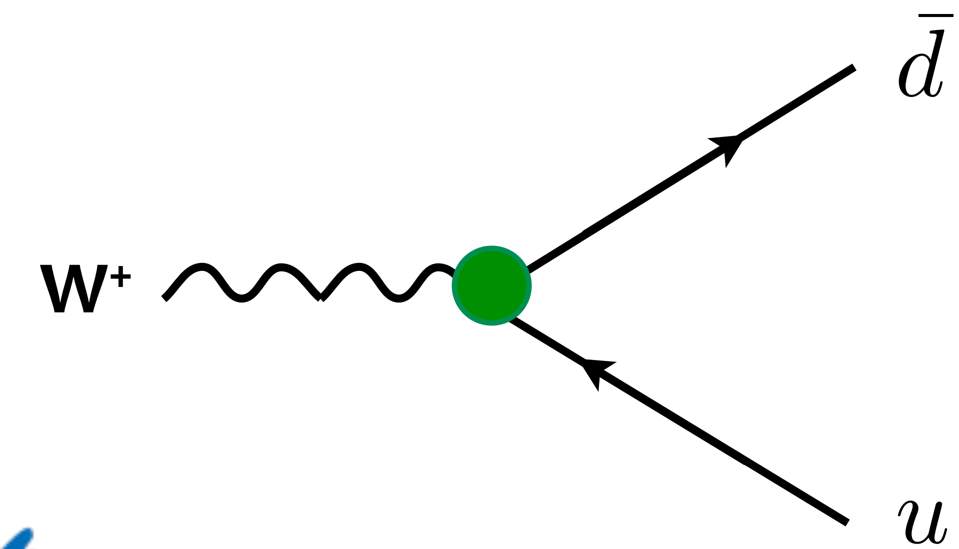
Quarks @ the LHC





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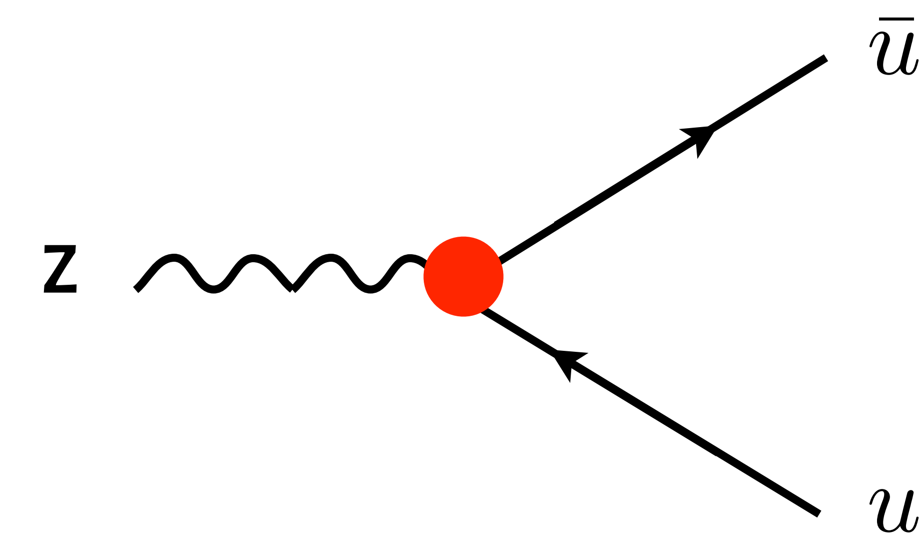
Quarks @ the LHC

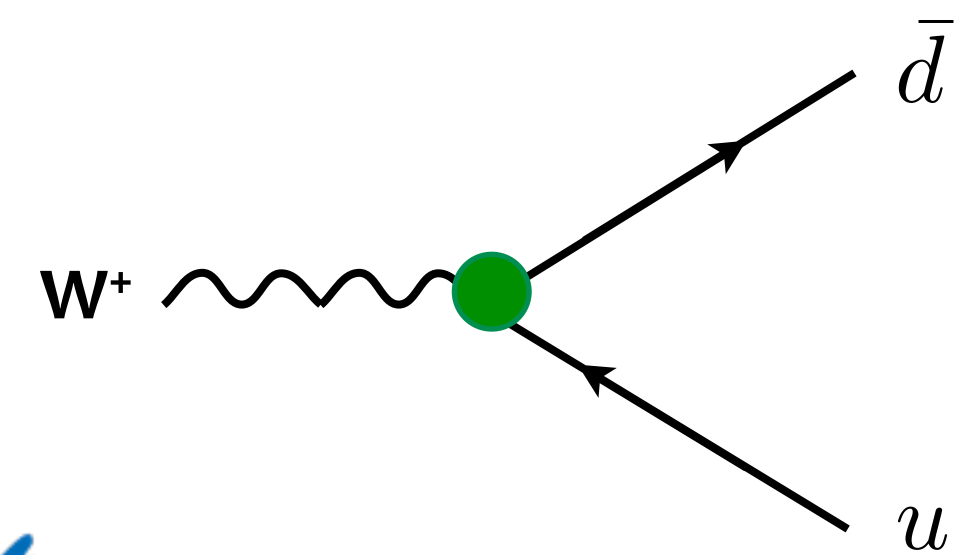
$$\frac{d\sigma}{dq_T} \sim \Phi_A^U \, \Phi_B^U \, |\mathcal{M}|^2$$

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

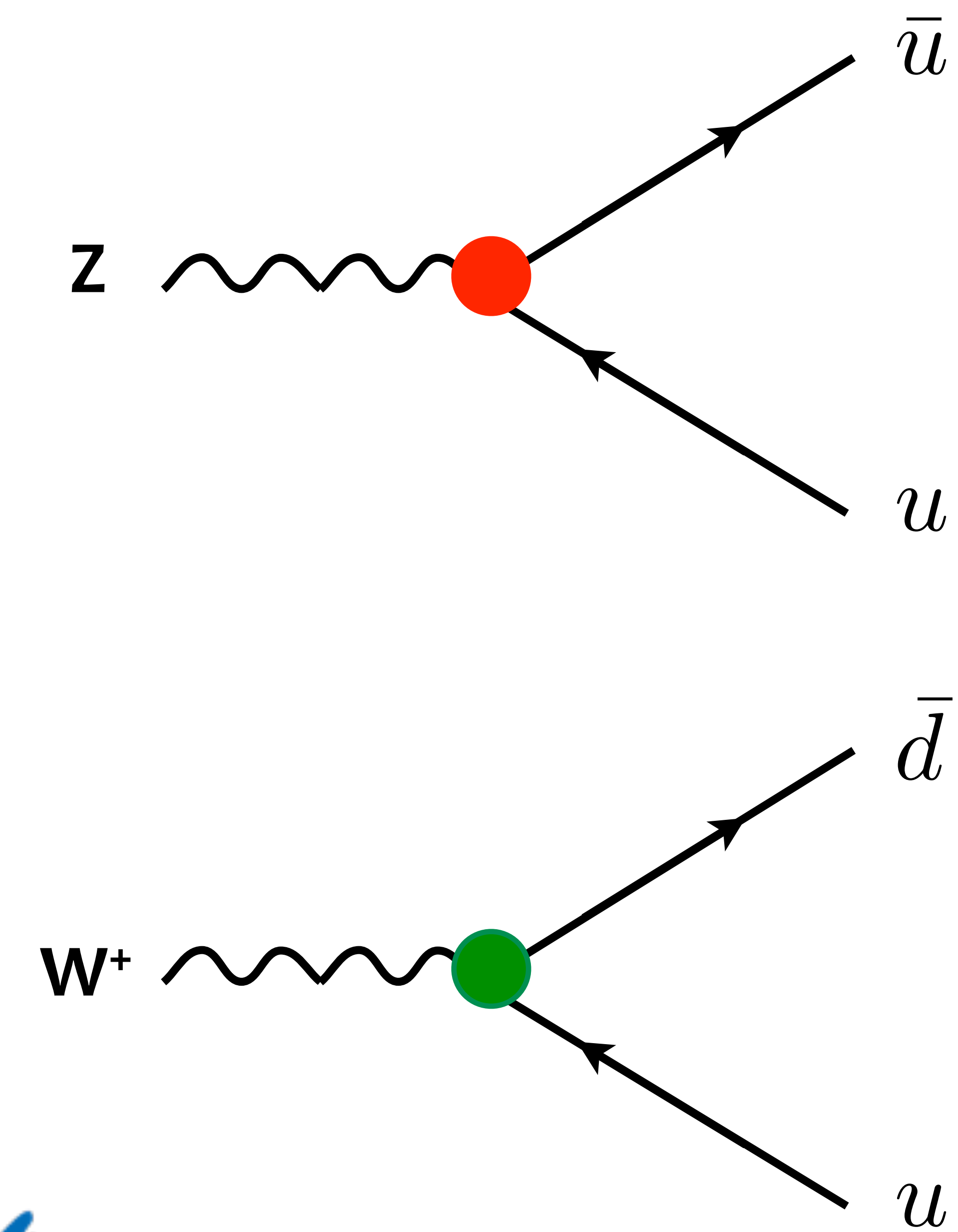
unpolarized quarks

transv. polarized quarks





Quarks @ the LHC



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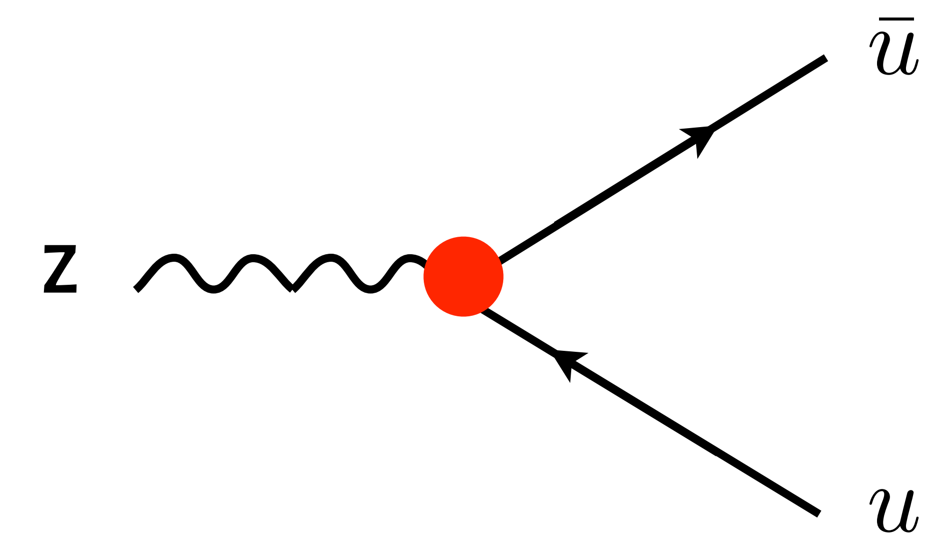
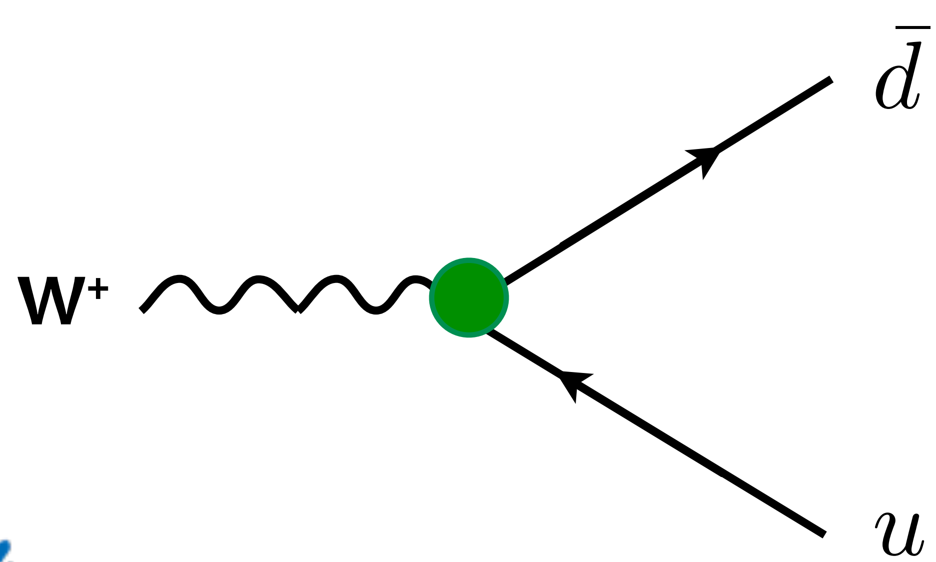
unpolarized quarks

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

no sufficient knowledge

Quarks @ the LHC





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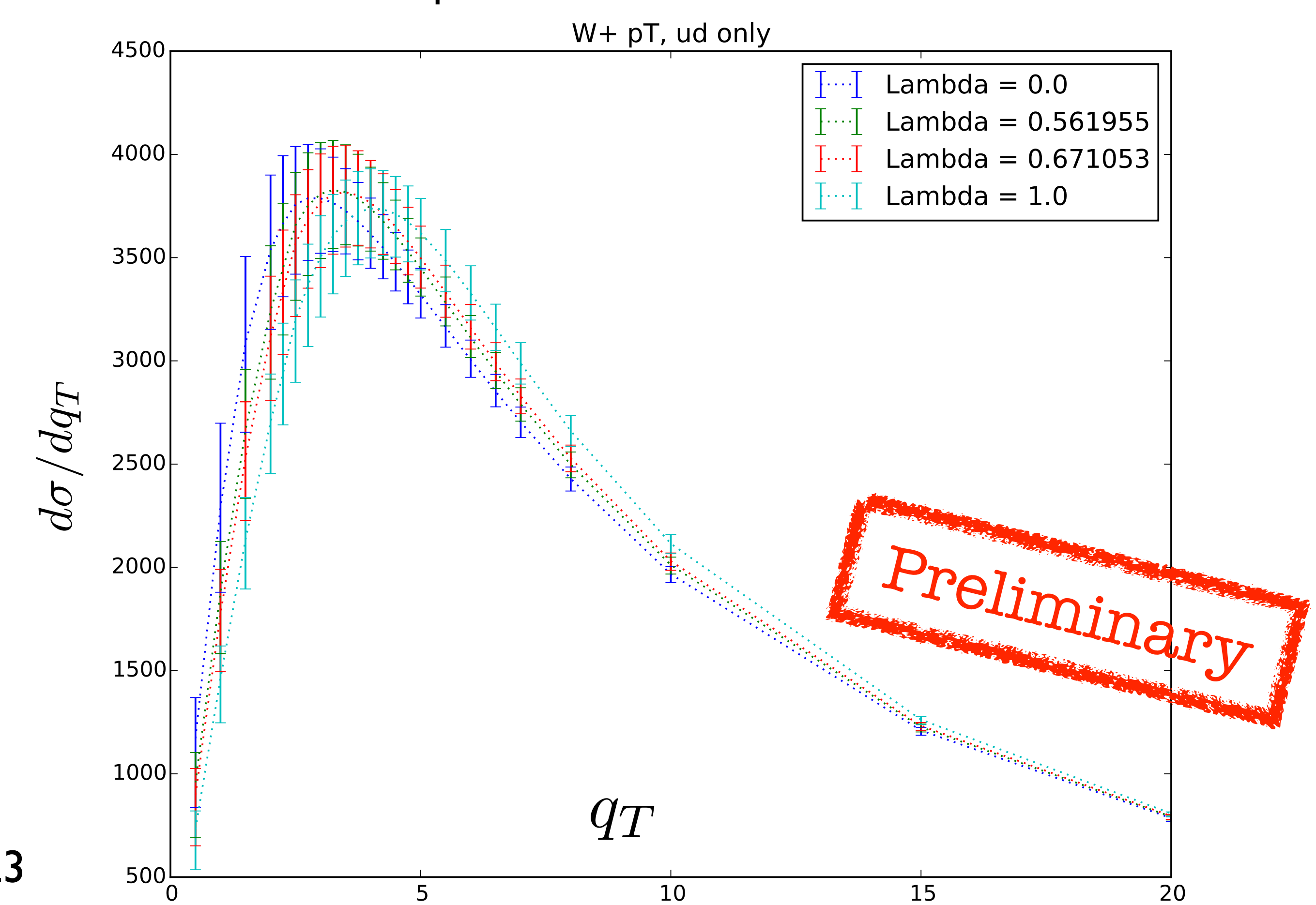
$$\sim \mathcal{C}[\, f_1^{q/A} \;\; f_1^{q/B} \,] \pm \mathcal{C}[\, h_1^{\perp q/A} \;\; h_1^{\perp q/B} \,]$$

unpolarized quarks | **transv. polarized** quarks

no sufficient knowledge

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



Conclusions

1) We are opening a window on the **structure of the proton in 3D** momentum space

2) It's an interesting endeavor , with very **close connections between theory and experiments** - **also with the LHC**

3) Questions? Interested? Come to the 3rd floor !

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Backup slides

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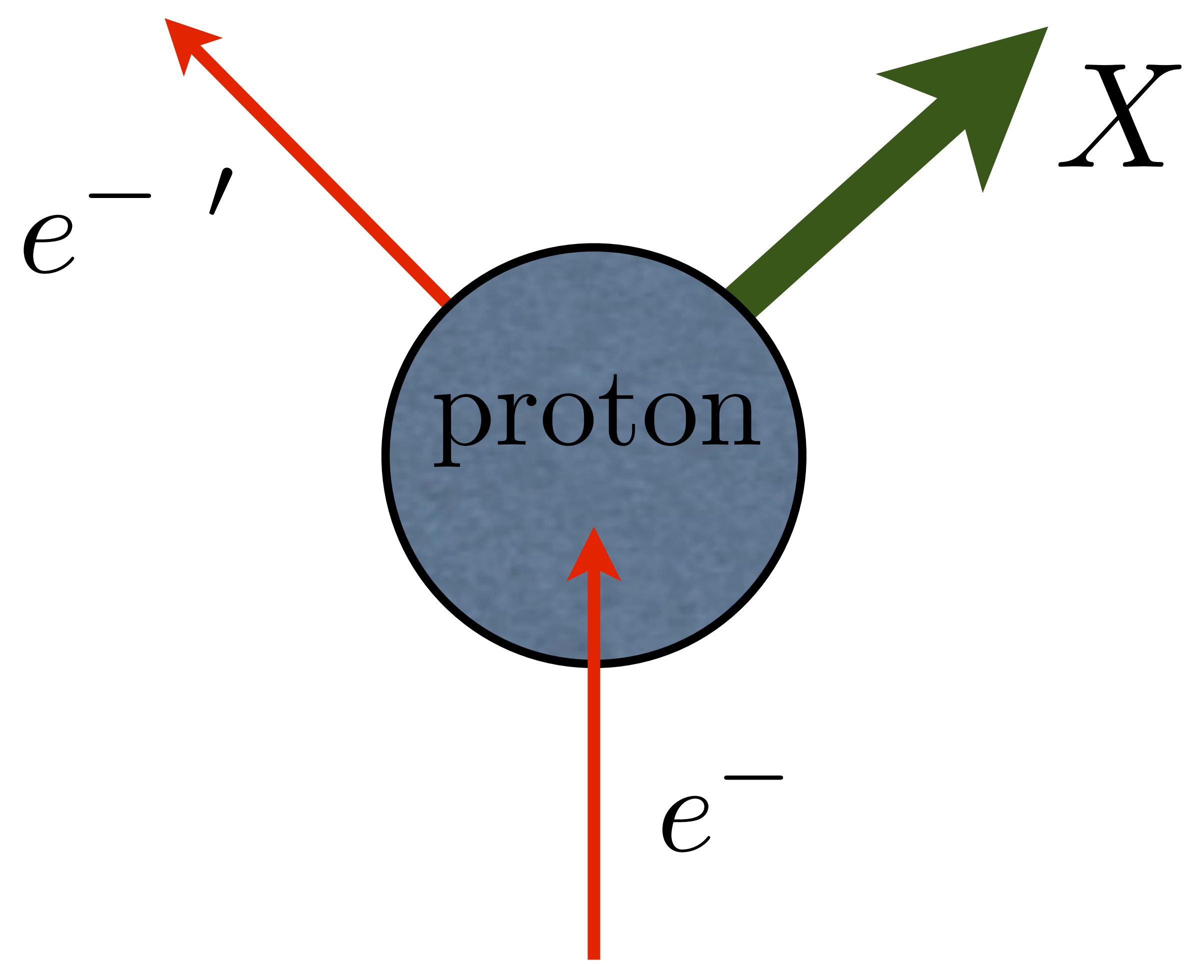
The quest for the structure

Electron-proton deep inelastic scattering
(MIT/SLAC -1960)
to test the
inner structure of the proton

scattering techniques

what happened ..?

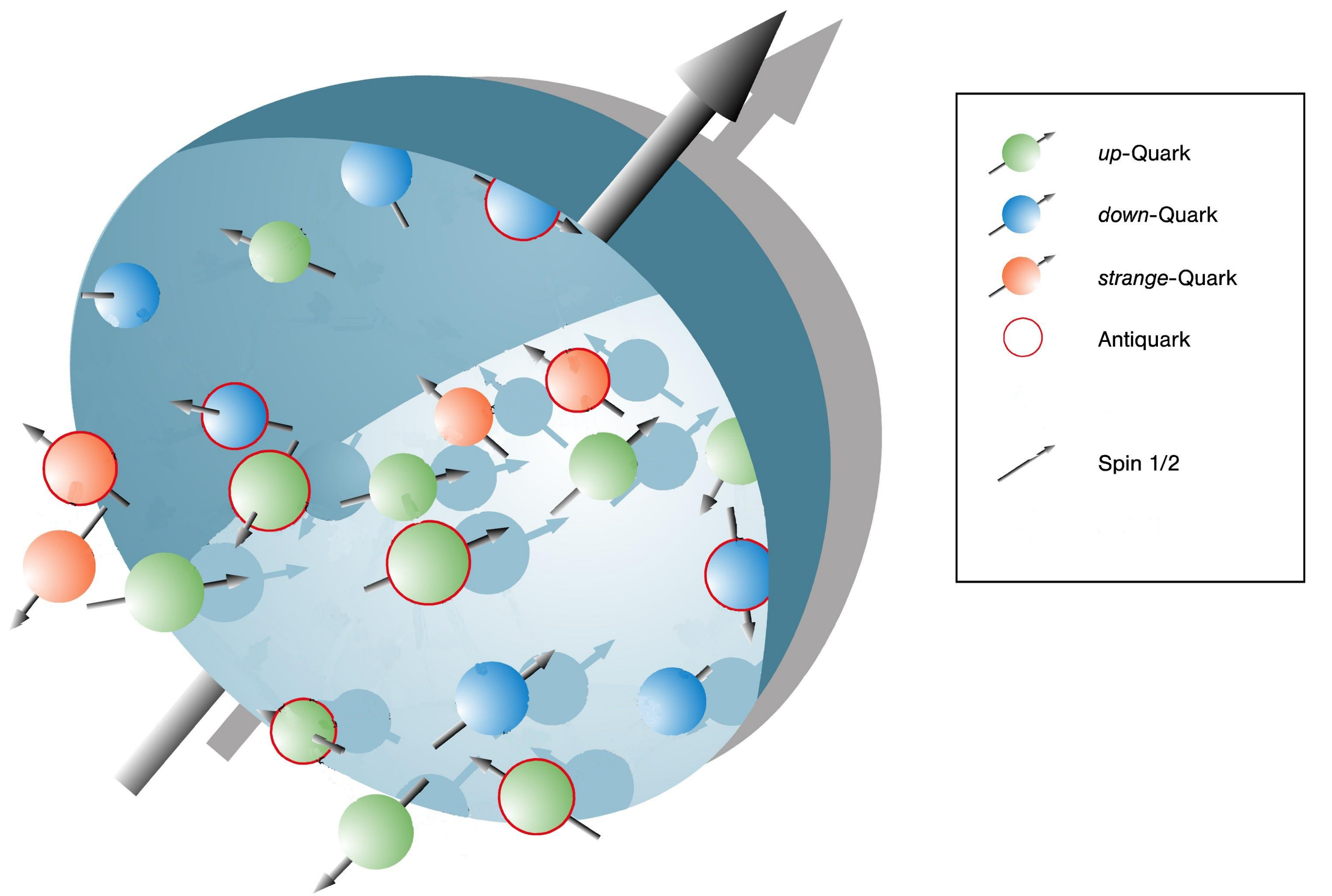
$$e^- P \rightarrow e^{-\,\prime} X$$



The quest for the structure

Experimental data are compatible with elastic scattering
off **pointlike, free, spin ½ particles**

The partons
[Feynman, Bjorken]

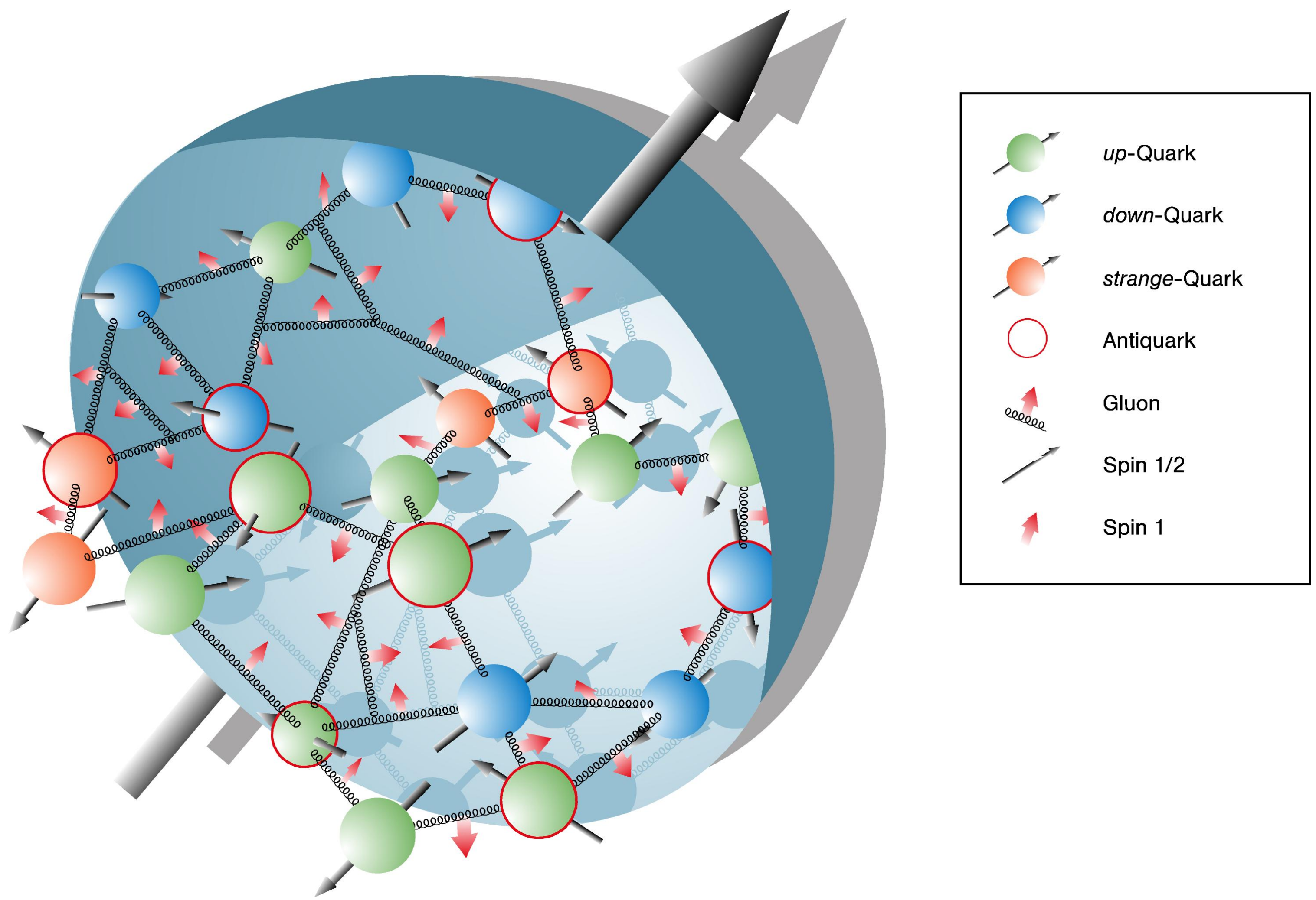


The quest for the structure

Experimental data are compatible with elastic scattering off **pointlike, free, spin ½ particles**

The partons
[Feynman, Bjorken]

Quantum Chromodynamics: they are the physical degrees of freedom of the theory at high-energies



Quarks & gluons

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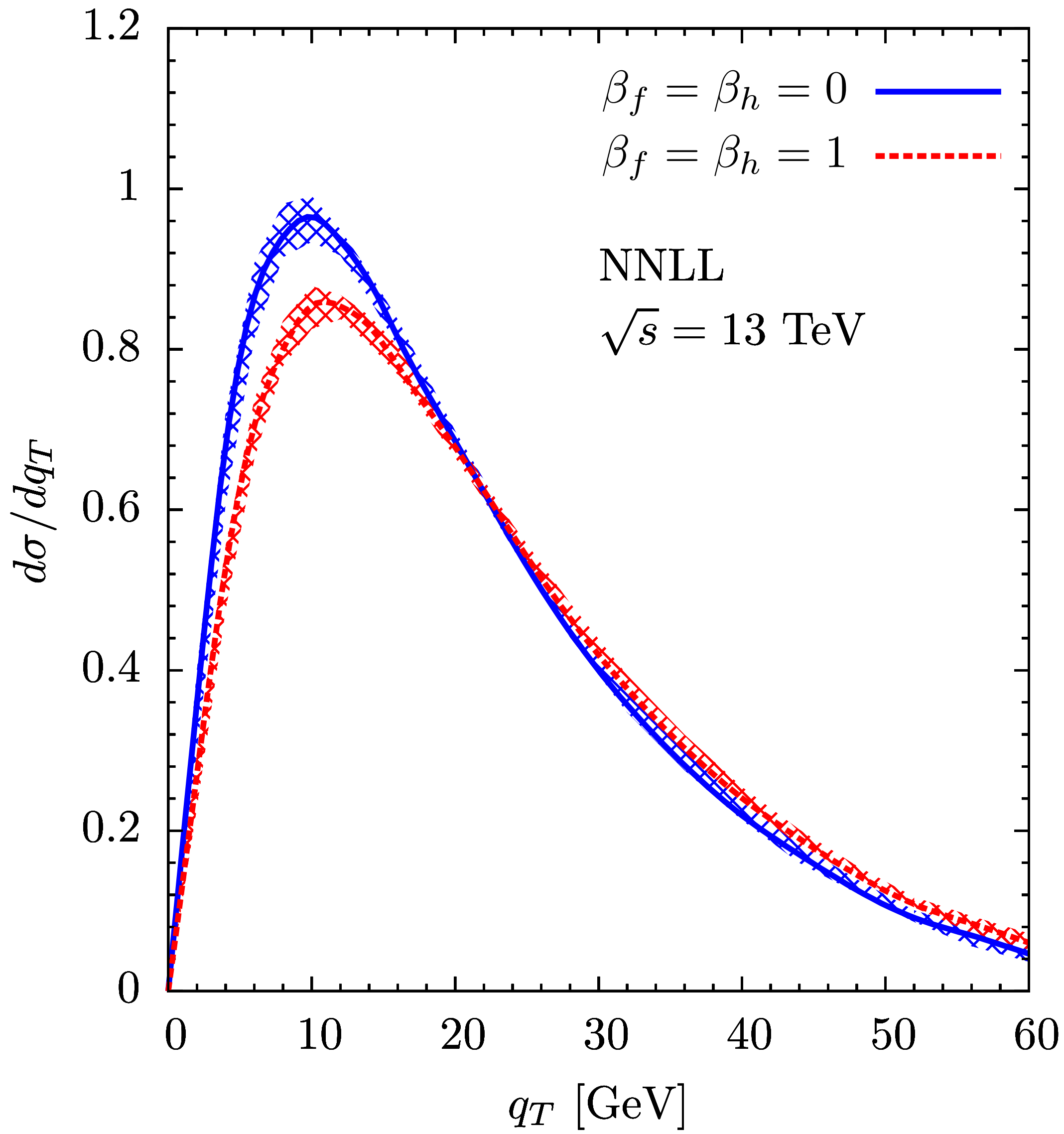
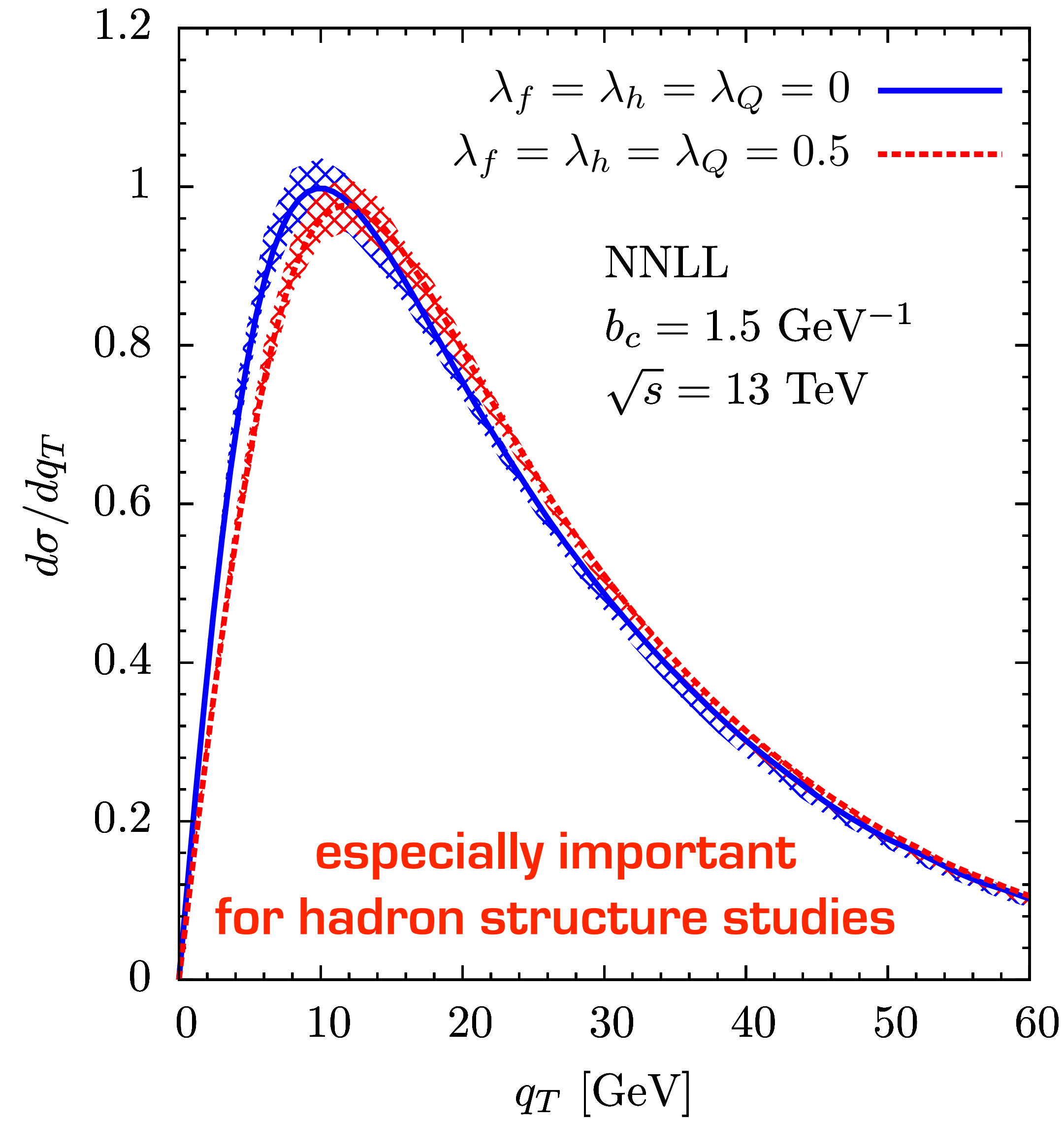
Perturbative & nonperturbative

momentum space resummation



position space resummation



"**freedom**" in the perturbative part leads to
different descriptions of the NP part (the core of proton structure)

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Philosophy of TMD phenomenology

***REMEMBER* :**

dependence on non-perturbative parameters vanishes in the limit $Q/\Lambda_{QCD} \to \infty$ (Parisi, Petronzio 1979).

If we want to explore effects at low qT we should look at relatively low Q values.

BUT not *too* low: problems with factorization and/or pollution from higher twist effects

At medium values of Q we could appreciate and extract the low qT effects applying TMD evolution properly

"in medio stat virtus"

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The Sivers effect

$\odot$

S

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

interaction between **spin of the proton** and **OAM of the quark**

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The Sivers effect

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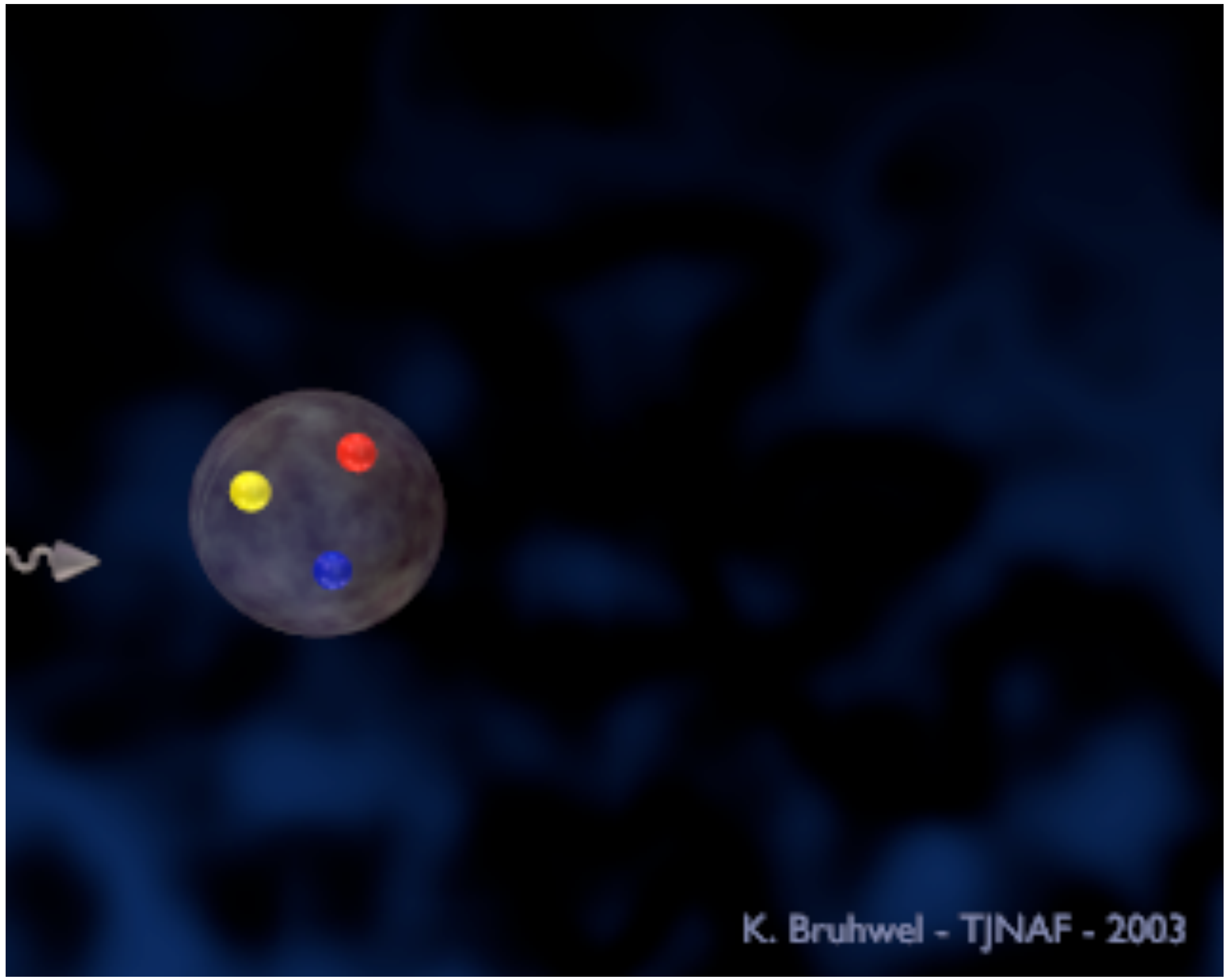

$f_{1T}^{\perp}$

interaction between **spin of the proton** and **OAM of the quark**

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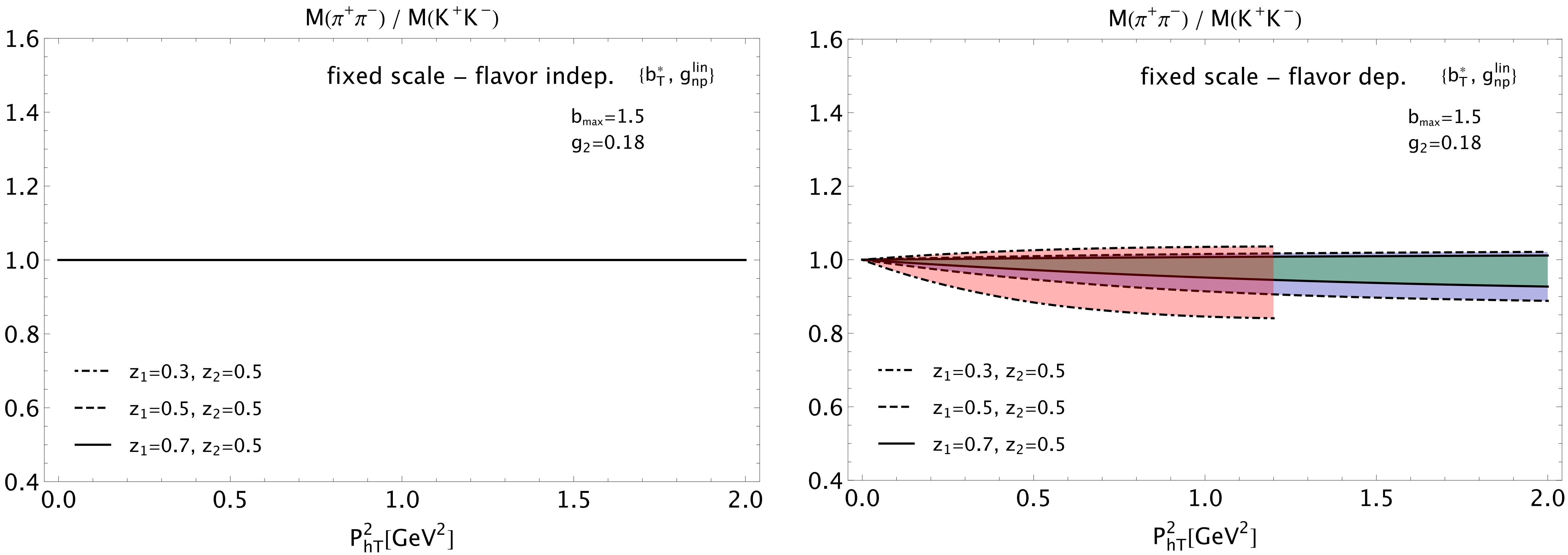
Quarks @ e+e- colliders - TMD FFs



Estimated **impact of flavor dependent intrinsic transverse momentum** on electron-positron annihilation into two hadrons

Gluon correlator

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

This is a **Lorentz matrix** ,
parametrized in terms of gluon distributions