The curious case of 3D hadron structure

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PSU Berks
Science Division Colloquium

Nov. 3 2017

Jefferson Lab

JSA

Outline of curiosities

1) how to organize and “map” the study of hadron structure

2) asymmetries associated to hadron structure as a non abelian AB effect

3) some research lines and a focus on my work

The speaker

Nov. 2016 - present |
postdoc
Jefferson Lab (VA, USA)

2012 - 2016 |
PhD candidate
Nikhef and Vrije Universiteit
Amsterdam (NL)

2012 | Summer intern
DESY - Hermes collaboration (GE)

2012 | undergrad
“Hadron structure and QCD” group
Pavia U. (IT)

The research line

galaxies, stars, ...

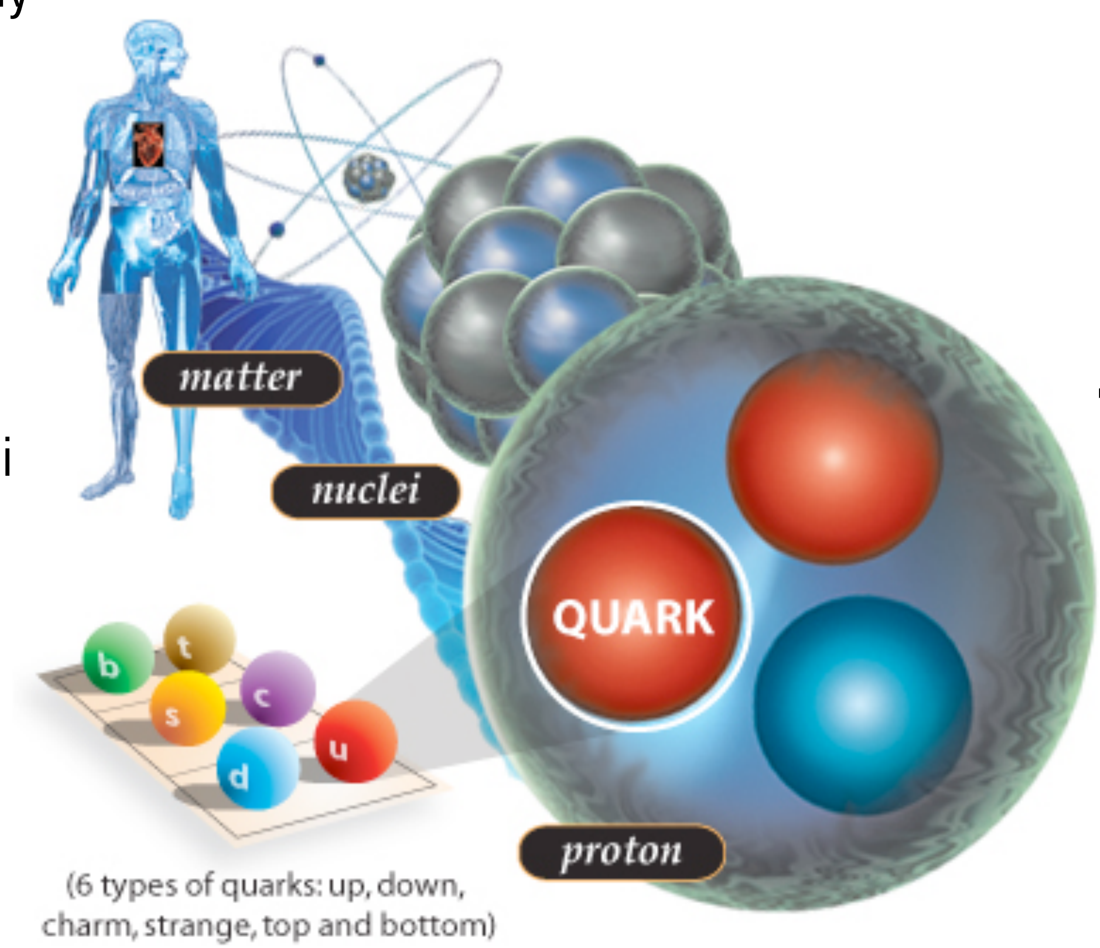
human body

molecules

DNA helix

atoms

nuclei



quark flavor

composite

elementary

hadrons
(protons and the like)

elementary particle physics

credit picture : Ohio State Univ.

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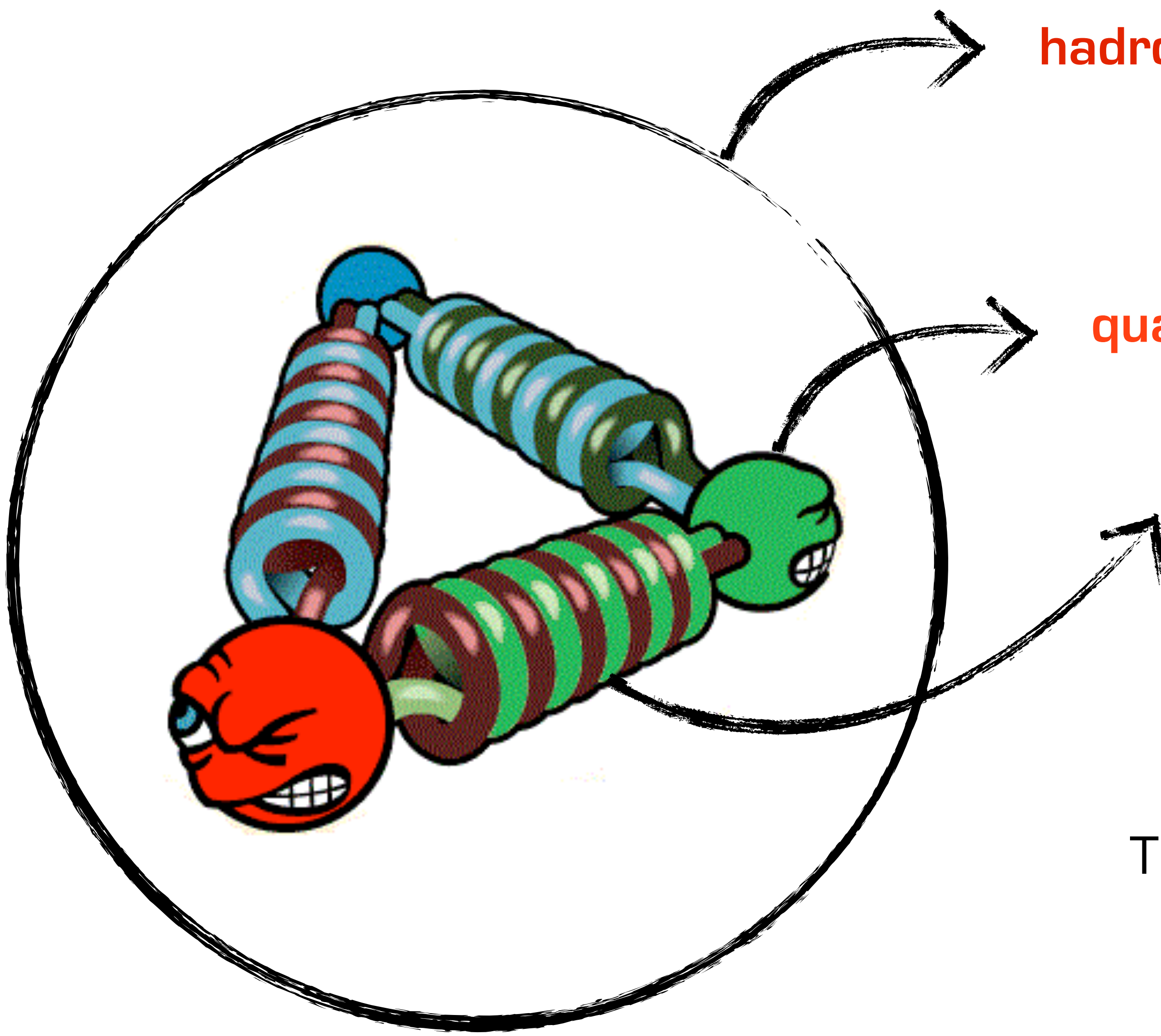
Hadron physics & QCD



hadrons (composite particles)

quarks (elementary particles)

gluons (elementary particles)

The gluons are the mediators of
the **strong force,**
described by means of
Quantum Chromodynamics
(QCD)

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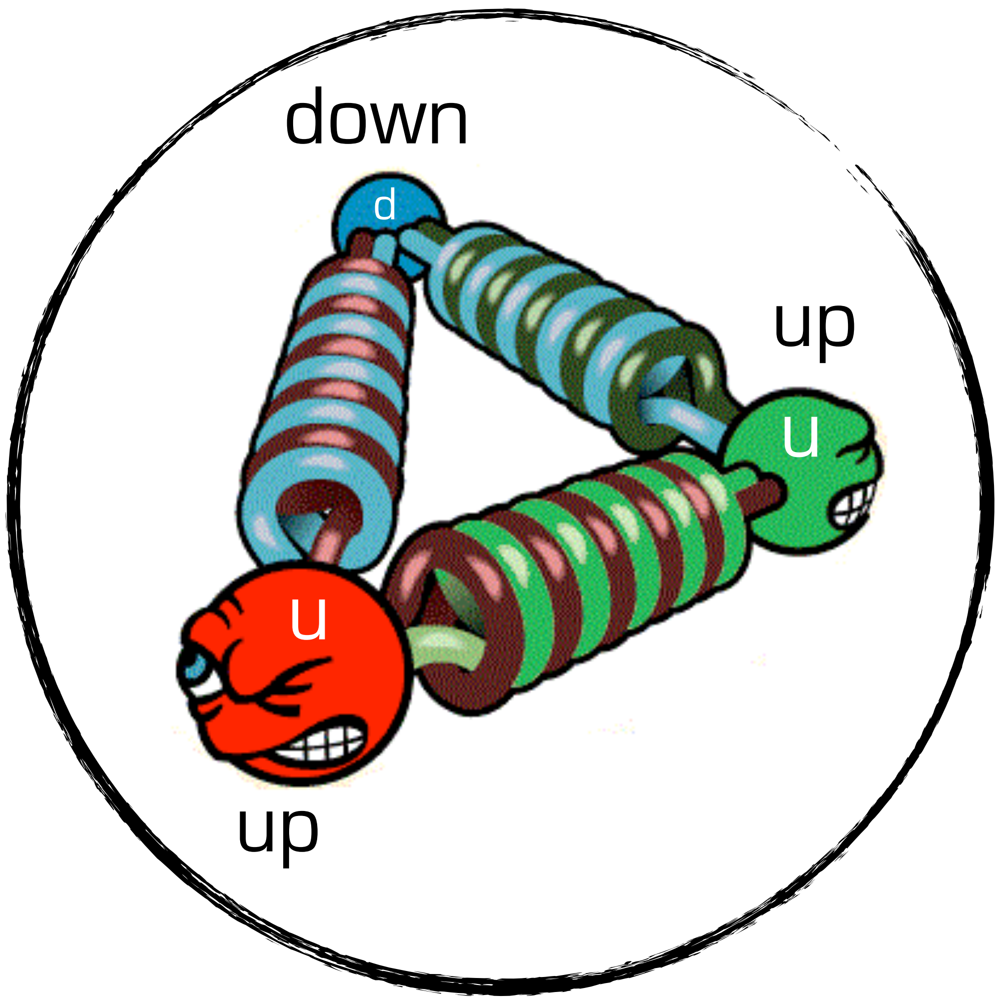
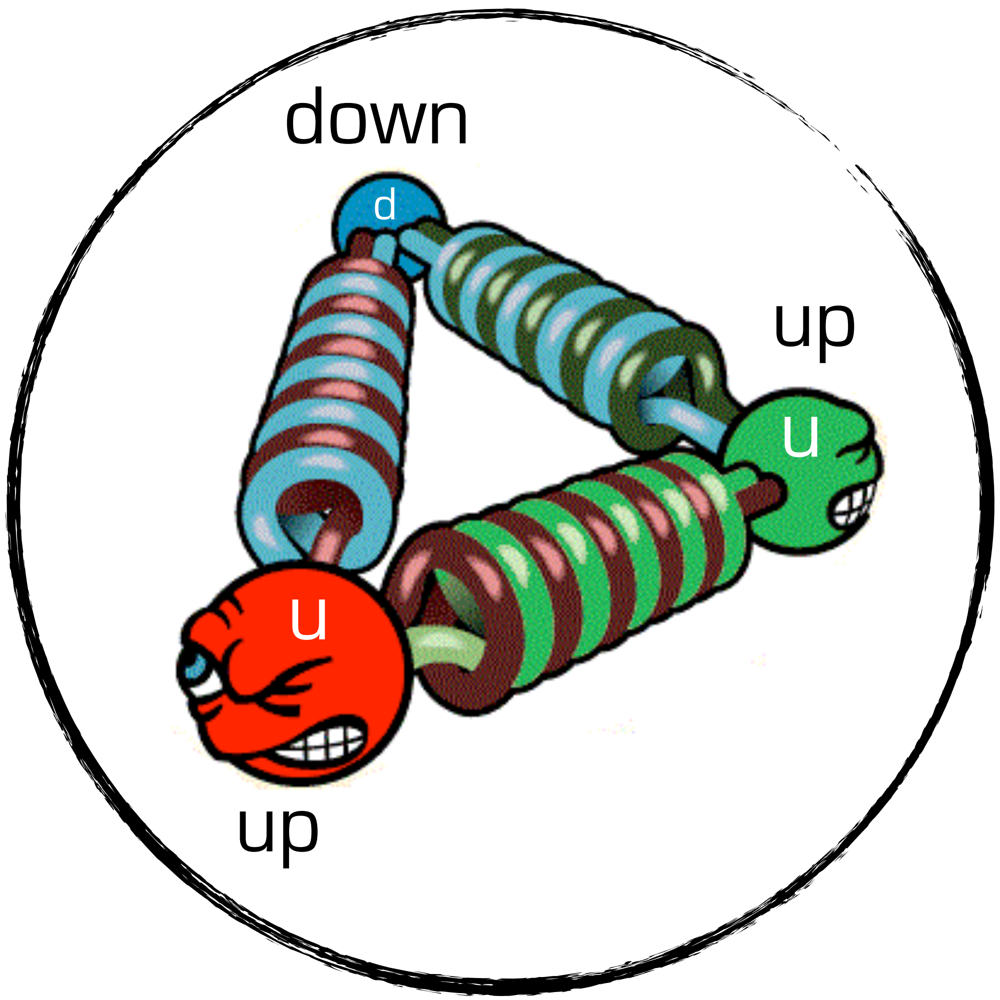
Why the proton?



- **building blocks** of our world:
  at the core of the atomic nucleus;
  ~ **99.97% of the mass** of the world we live in is accounted by protons +neutrons (hadrons)

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

Why the proton?



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HOW WELL DO WE KNOW THE PROTON ?

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Transverse looks at hadrons

How to map hadron structure in 3D momentum space in terms of quarks and gluons

Wigner distributions

position momentum density matrix for the studied system

$$W(q,p) = \frac{1}{\pi h} \int_{-\infty}^{+\infty} dy \, \langle q - y| \, \hat{\rho} \, |q + y\rangle \, e^{2ipy/h}$$

In 1932, Wigner formulated **quantum mechanics** in terms of a distribution W (q, p), the marginals of which yield the quantum probabilities for q and p separately.

- It provides a re-expression of quantum mechanics in terms of classical concepts
- quantum mechanical **expectation values** are now expressed as **averages** over **phase-space distributions**:

$$\mathrm{Tr}(\hat{\rho}\hat{A}) \longrightarrow \int dp \, dq \, A(q,p) \, W(q,p)$$

Wigner, TMDs, GPDs

position momentum density matrix for the studied system

$$W(q,p) = \frac{1}{\pi h}\int_{-\infty}^{+\infty} dy\ \langle q-y|\ \hat{\rho}\ |q+y\rangle\ e^{2ipy/h}$$

In 1932, Wigner formulated quantum mechanics in terms of a distribution W(q, p), the marginals of which yield the quantum probabilities for q and p separately.

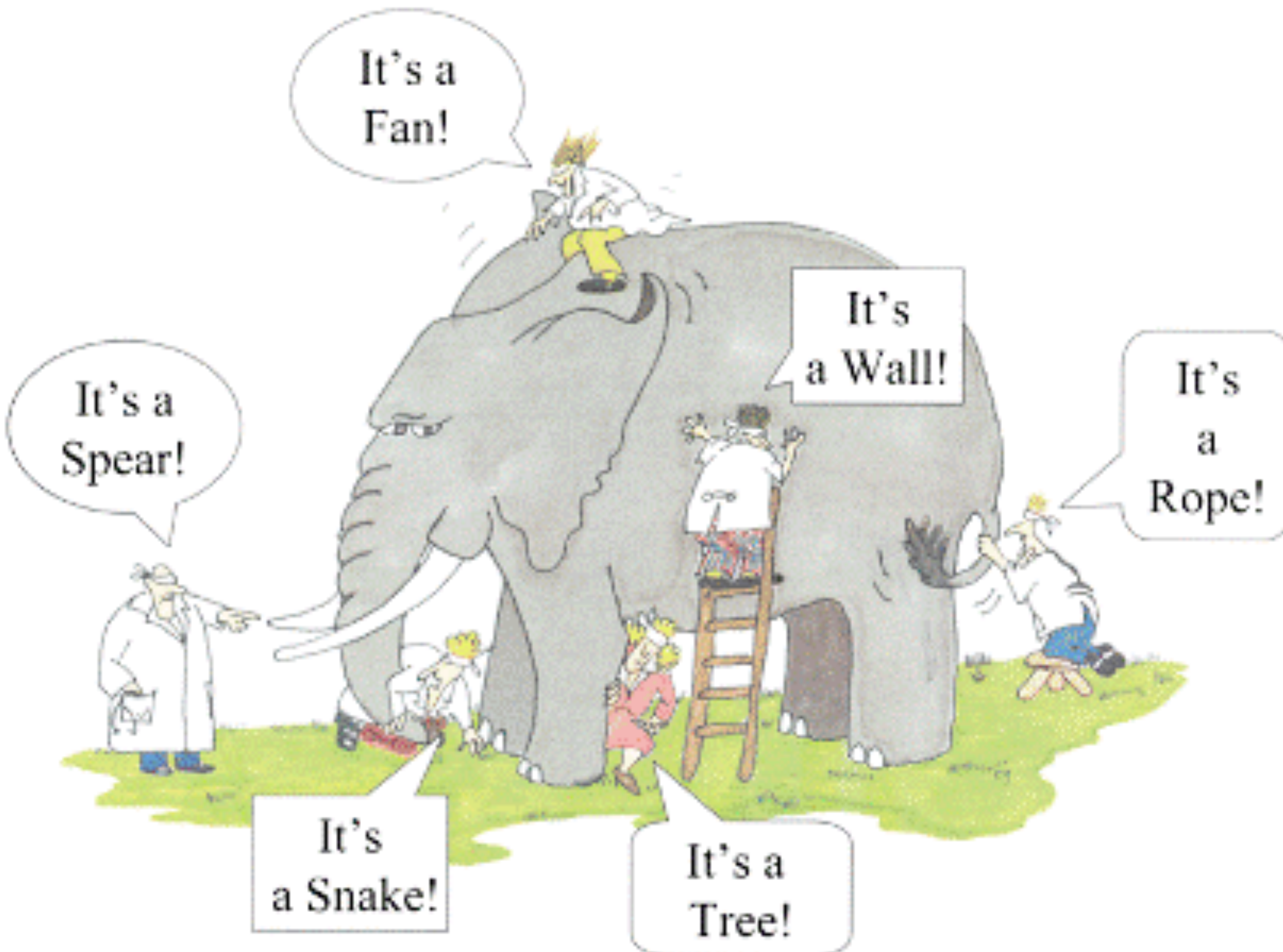
In perturbative **QCD** we do not know how to calculate the **density matrix of quarks/gluons** inside a proton, which is of **nonperturbative** nature.

We can define **projections** of **Wigner distributions**, as the **TMDs** and the **GPDs**, and link it to information **accessible in experimental data**.

W(q, p) → **TMDs** (collinear momentum, **transverse momentum**)

W(q, p) → **GPDs** (collinear momentum, **transverse position**)

Wigner, TMDs, GPDs



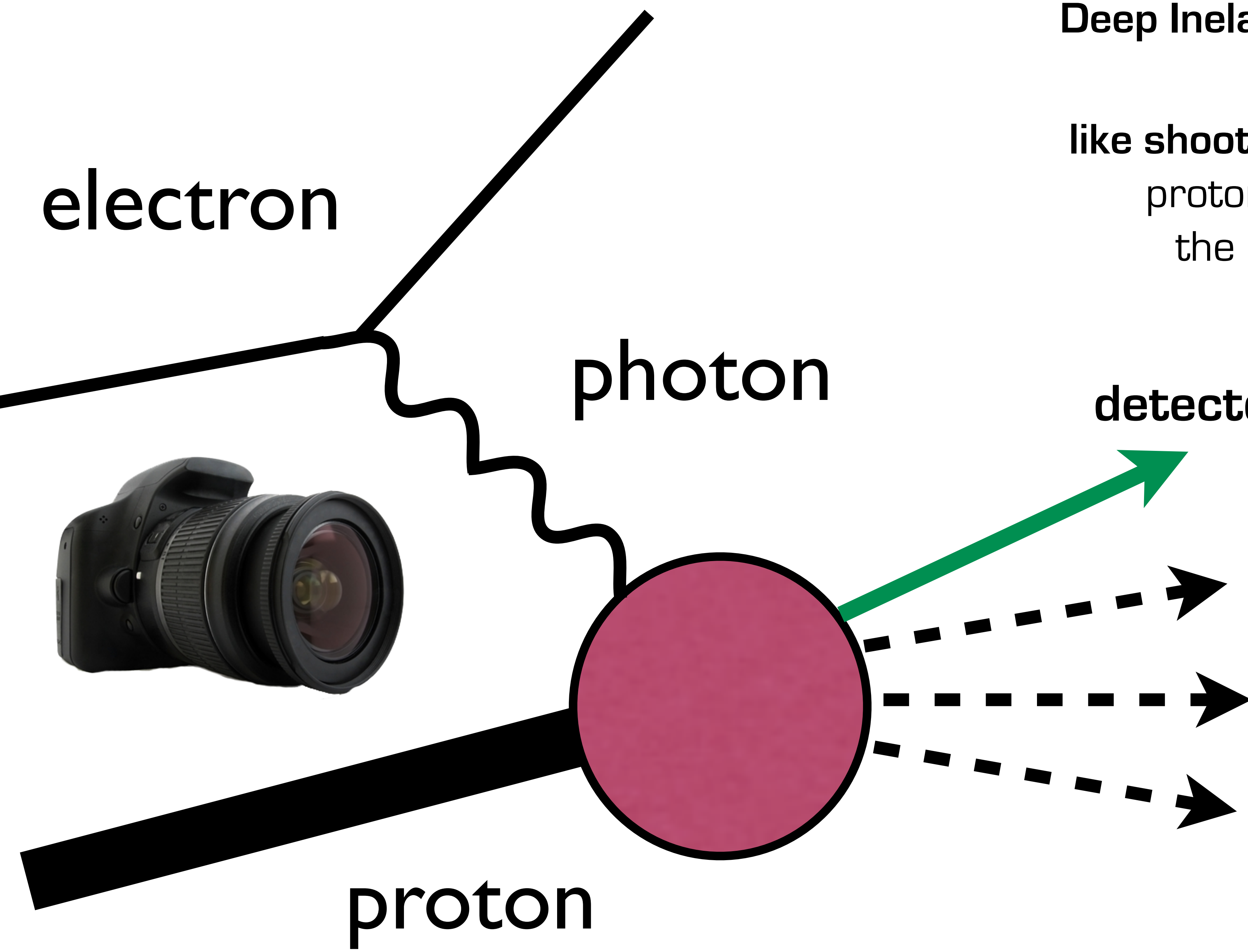
each projection
carries only a portion
of the
complete picture

complementary
information
(TMDs, GPDs, etc.)
is essential to
have a global
understanding of
hadron structure

Proton tomography

Deep Inelastic Scattering (DIS)

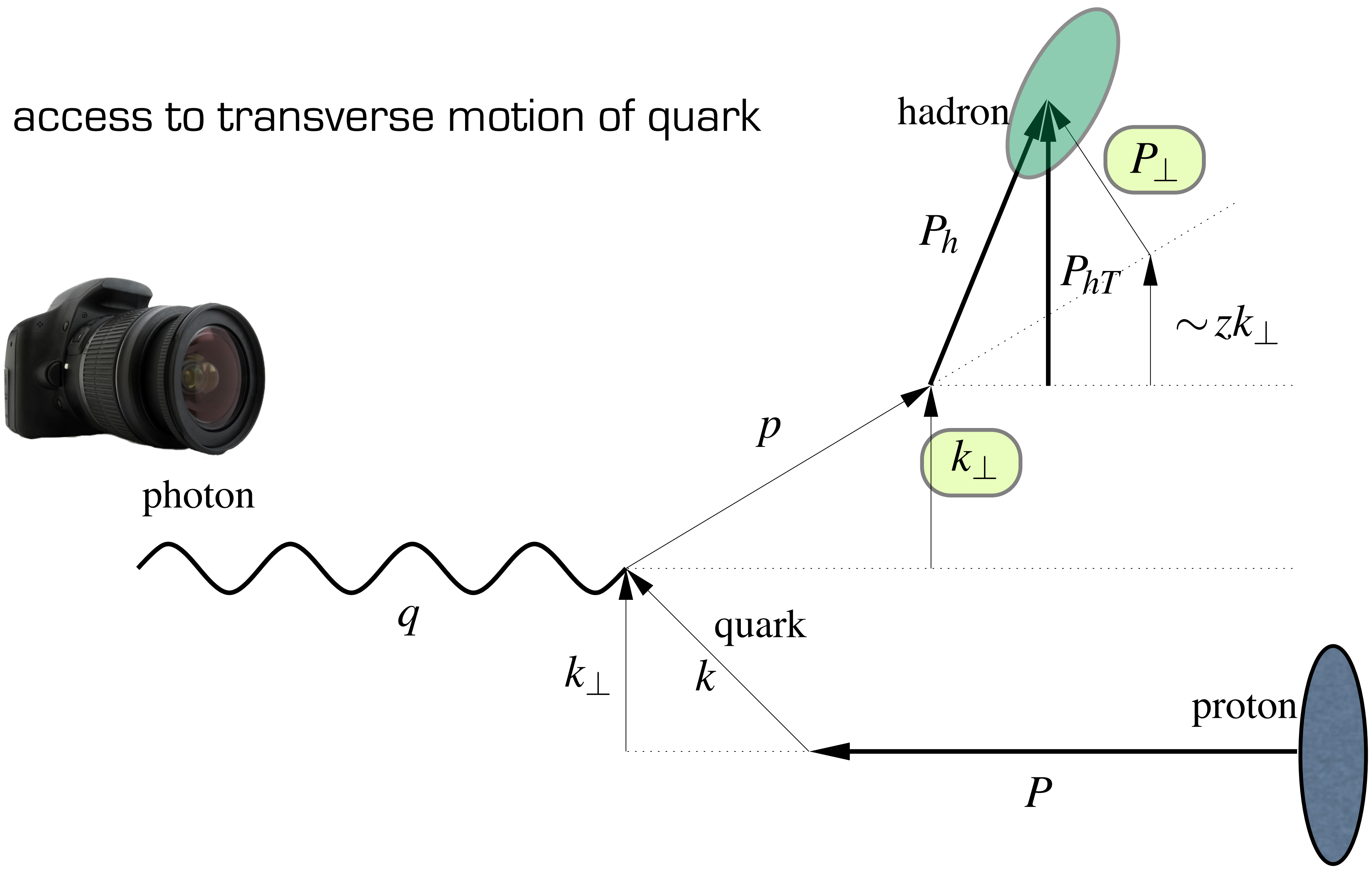
like shooting a "picture" of the proton using a **photon**: the proton "breaks"



we **reconstruct the internal structure** looking at the **produced particles**

Semi-inclusive DIS

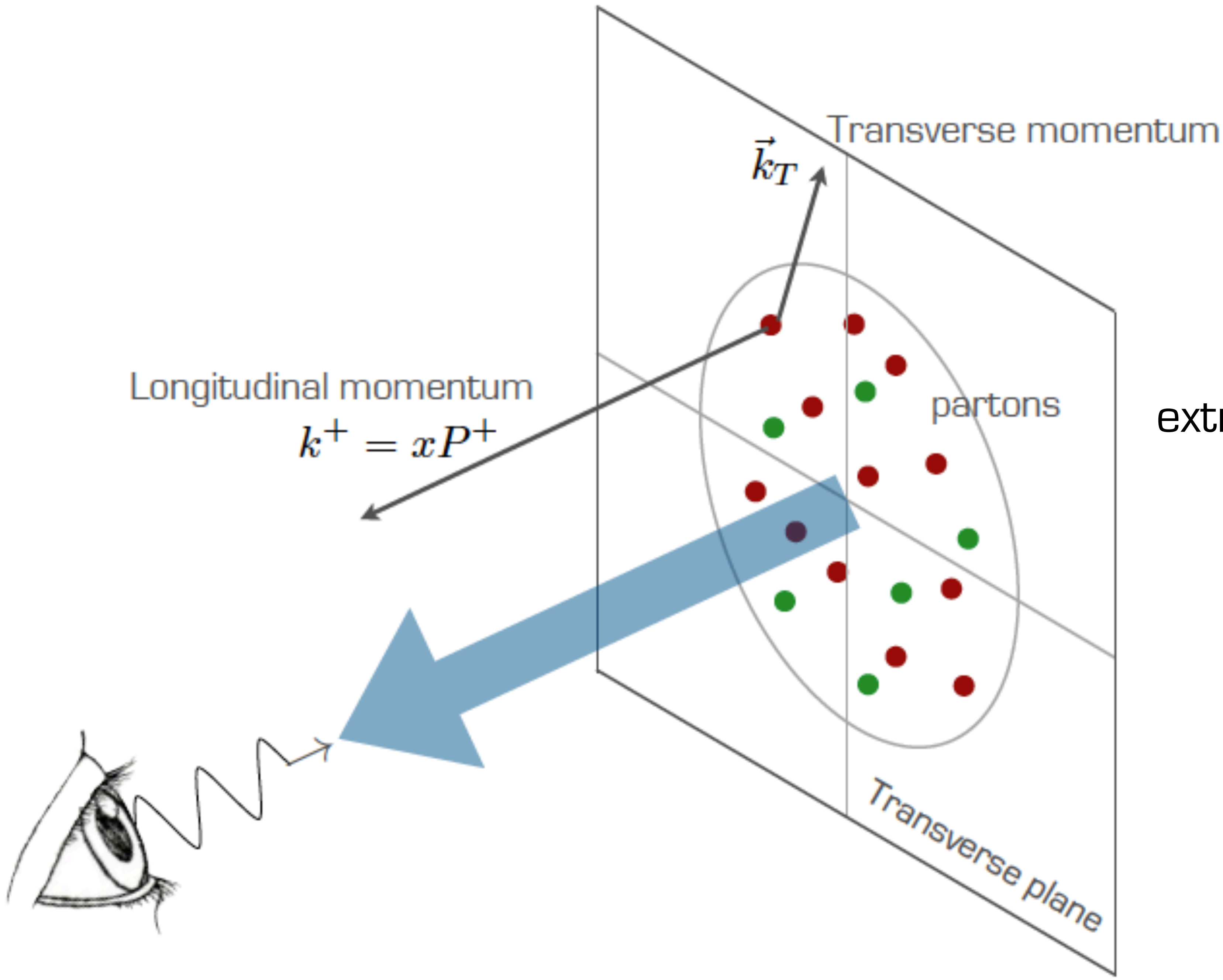
access to transverse motion of quark



TMD FF

TMD PDF

TMD PDFs



extraction of a **parton (quark/gluon)** **not** collinear with the proton

knowledge of the **proton structure** in **three-dimensional momentum space**

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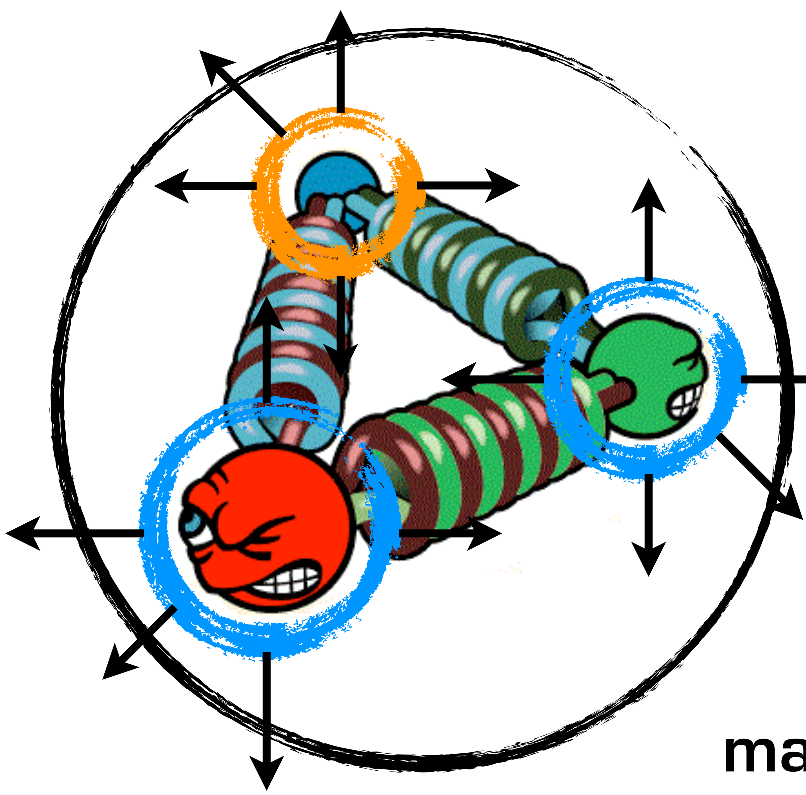
TMD PDFs



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

mathematical maps
of the structure

with coordinates :

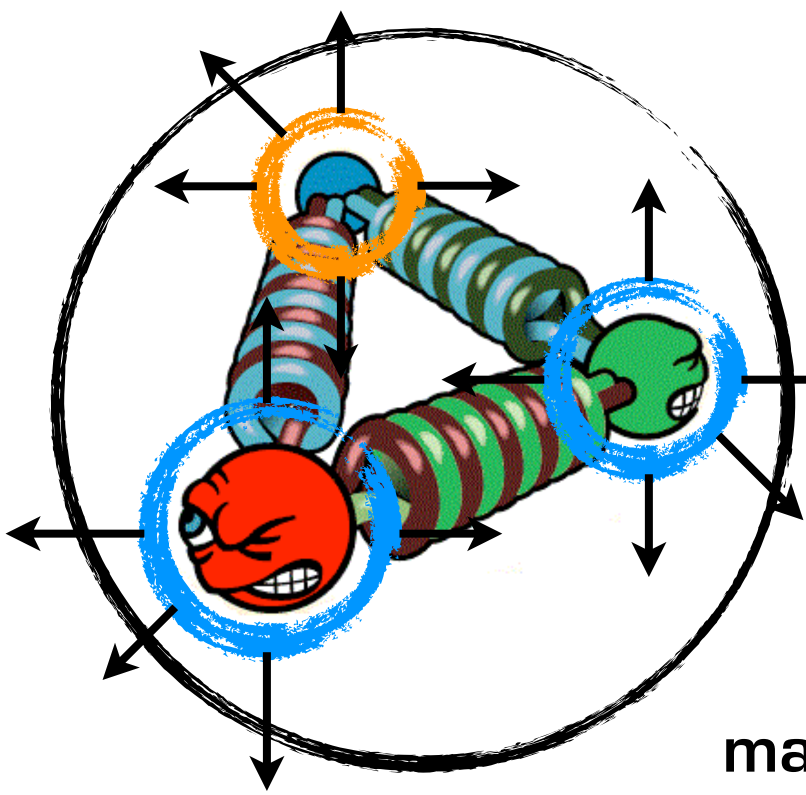
$$\{x,\ \vec{k}_T,\ Q\}$$

collinear (1D)
momentum
of the constituent

transverse (2D)
momentum

energy of the probe

TMD PDFs



mathematical maps
of the structure

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

TMDs

with coordinates :

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collinear (1D)
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energy of the probe

knowledge of the **proton structure** in
three-dimensional
momentum space

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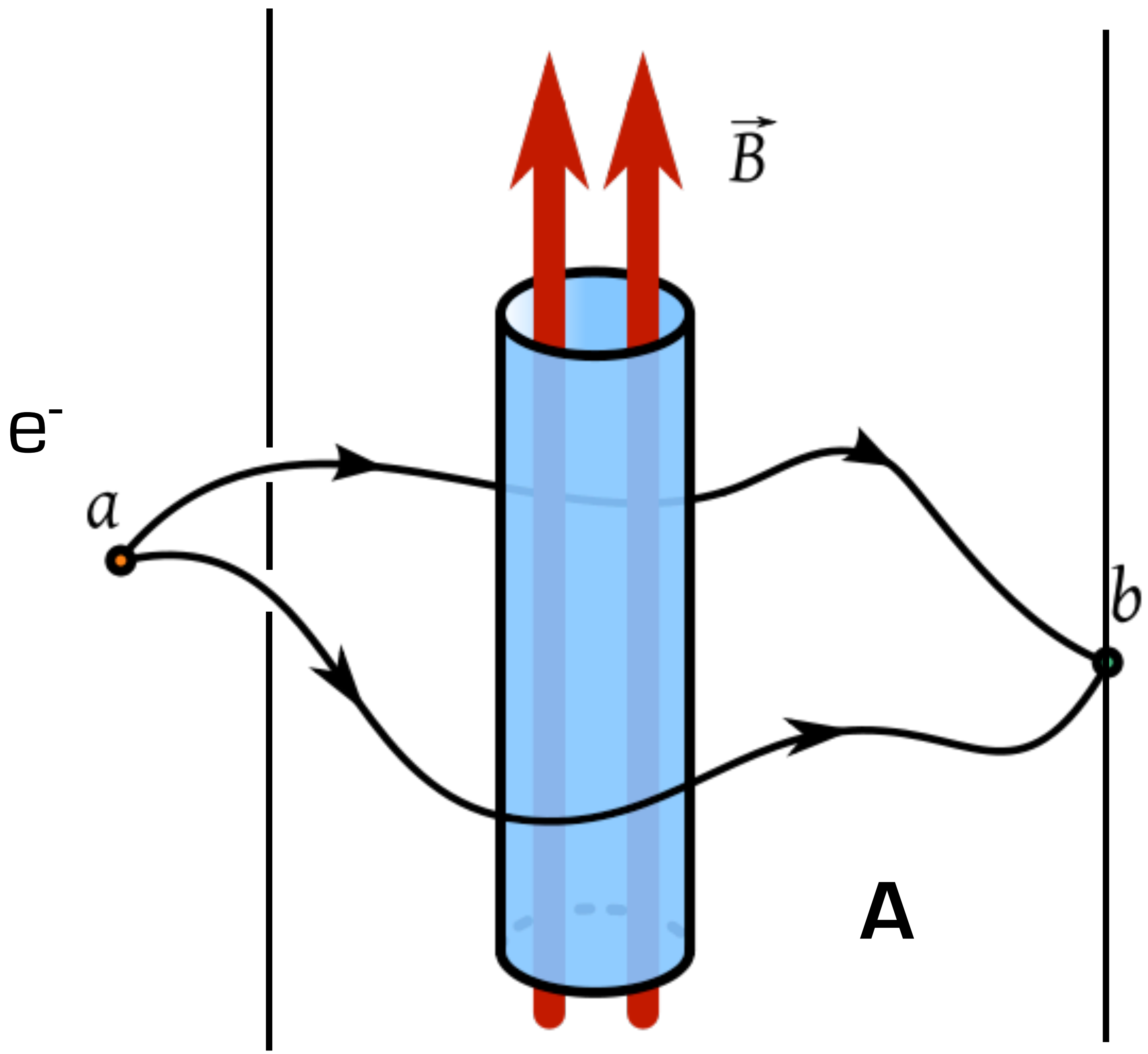
Geometry meets experiments

What **generates** the hadronic matter?
The color force is responsible for the generation of hadronic properties:

connection between the geometrical description of the theory and experimental measurements

A matter of connections



Ehrenberg and Siday -
Aharonov and Bohm (1950s)

It is possible to show that the **amplitude** of the **interference pattern** on the screen is proportional to a **phase** involving the integral of the electromagnetic **potential (connection)**

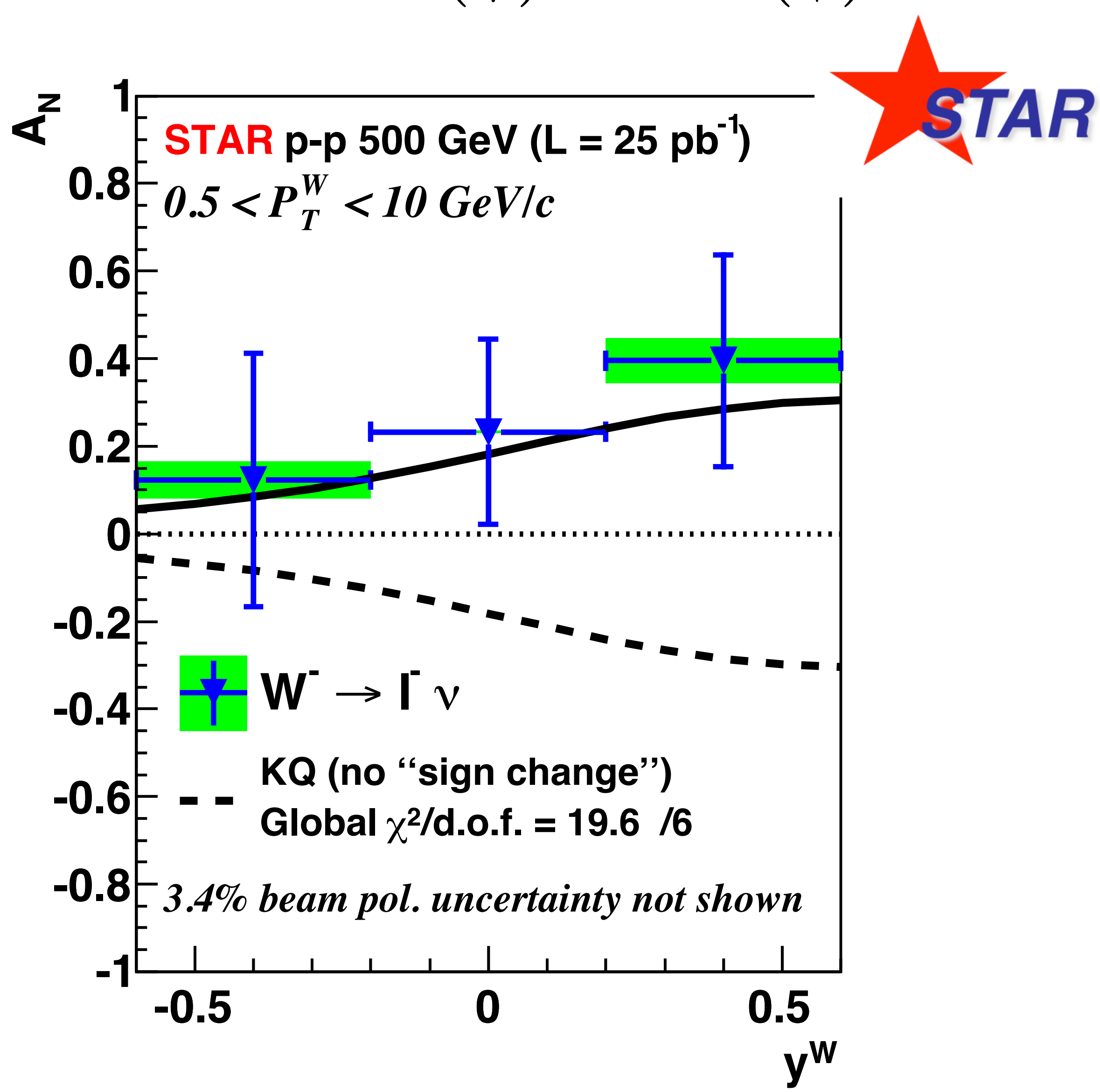
$$\exp\left\{ -ie \oint dx \cdot A(x) \right\}$$

effect induced by the connection U(1) !

A matter of connections

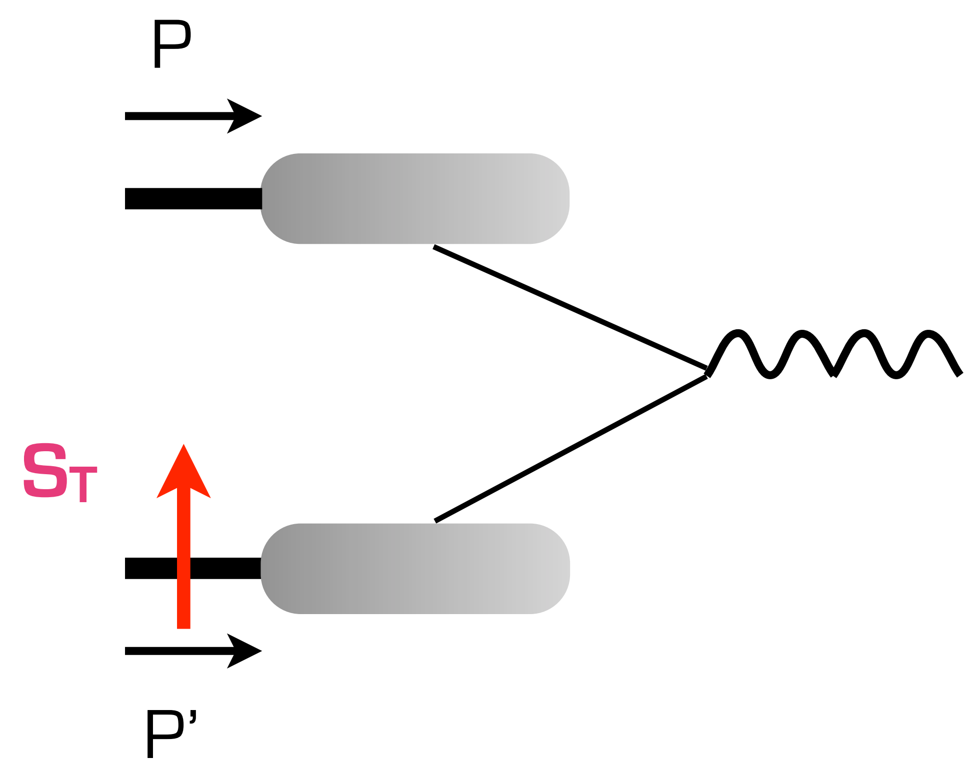
Single Spin Asymmetries in QCD

$$A_N \sim d\sigma(\uparrow) - d\sigma(\downarrow)$$



STAR Collab. arXiv:1511.06003

$$pp^\uparrow \to W^- \to \ell^- \bar{\nu}$$



Flipping the direction of the **transverse spin**, we observe an **asymmetry** **(A_N)** in the cross section

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A matter of connections

Single Spin Asymmetries : the first investigations

[144] A. Lesnik, D. M. Schwartz, I. Ambats, E. Hayes, W. T. Meyer, C. E. W. Ward, T. M. Knasel, E. C. Swallow, R. Winston, and T. A. Romanowski, *Observation of a Difference Between Polarization and Analyzing Power in Λ^0 Production with 6 GeV/c Polarized Protons*, Phys. Rev. Lett. **35** (1975) 770.

[145] G. Bunce et al., *Λ^0 Hyperon Polarization in Inclusive Production by 300 GeV Protons on Beryllium.*, Phys. Rev. Lett. **36** (1976) 1113–1116.

[146] E704, E581, D. L. Adams et al., *Comparison of spin asymmetries and cross sections in π^0 production by 200 GeV polarized anti-protons and protons*, Phys. Lett. **B261** (1991) 201–206.

[147] FNAL-E704, D. L. Adams et al., *Analyzing power in inclusive π^+ and π^- production at high $x(F)$ with a 200 GeV polarized proton beam*, Phys. Lett. **B264** (1991) 462–466.

[148] E704, E581, D. L. Adams et al., *Large $x(F)$ spin asymmetry in π^0 production by 200 GeV polarized protons*, Z. Phys. **C56** (1992) 181–184.

[149] K. Krueger et al., *Large analyzing power in inclusive $\pi^\pm$ production at high $x(F)$ with a 22 GeV/c polarized proton beam*, Phys. Lett. **B459** (1999) 412–416.

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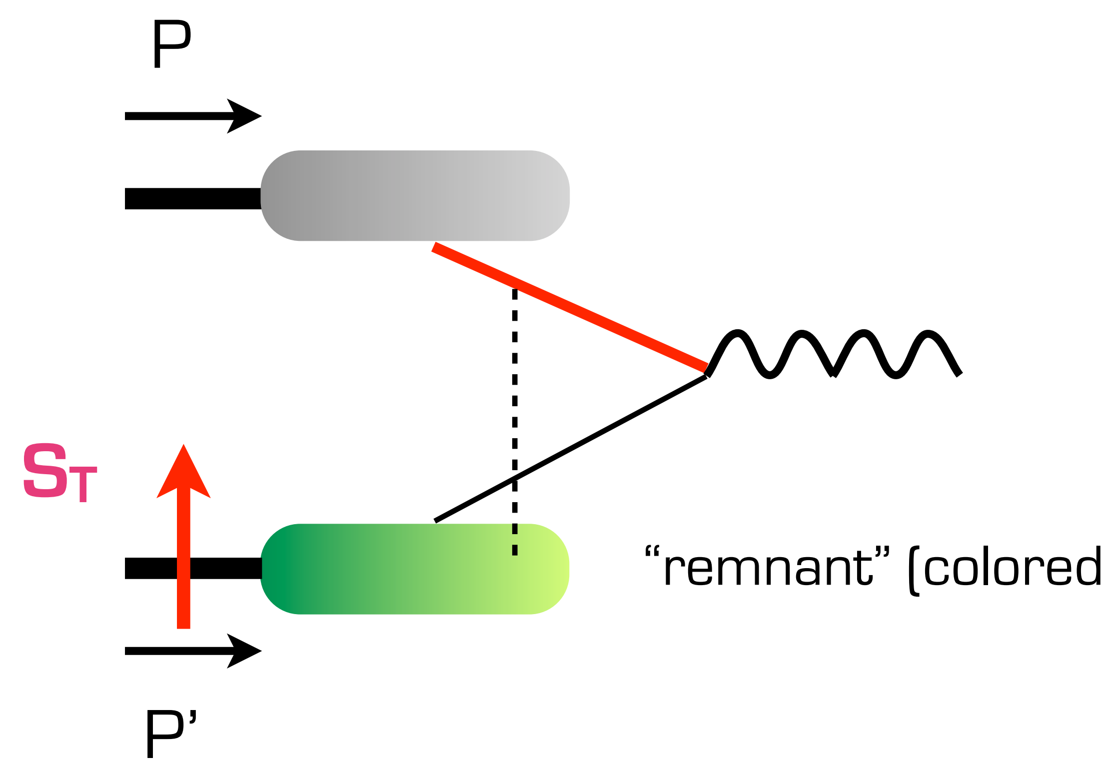
A matter of connections

Single Spin Asymmetries in QCD

$$pp^{\uparrow} \to W^{-} \to \ell^{-}\bar{\nu}$$



the first proposal relied on **interactions** of soft **gluons** from the target **remnants** with the active **partons** in the initial state

collinear twist-3 matrix elements

Qiu-Sterman [QS] function

$$T_F(x_q, x_g)$$

As in a **non-abelian Aharonov-Bohm effect**, the quark "**feels the connection**" *color, SU(3)* associated to the other hadron

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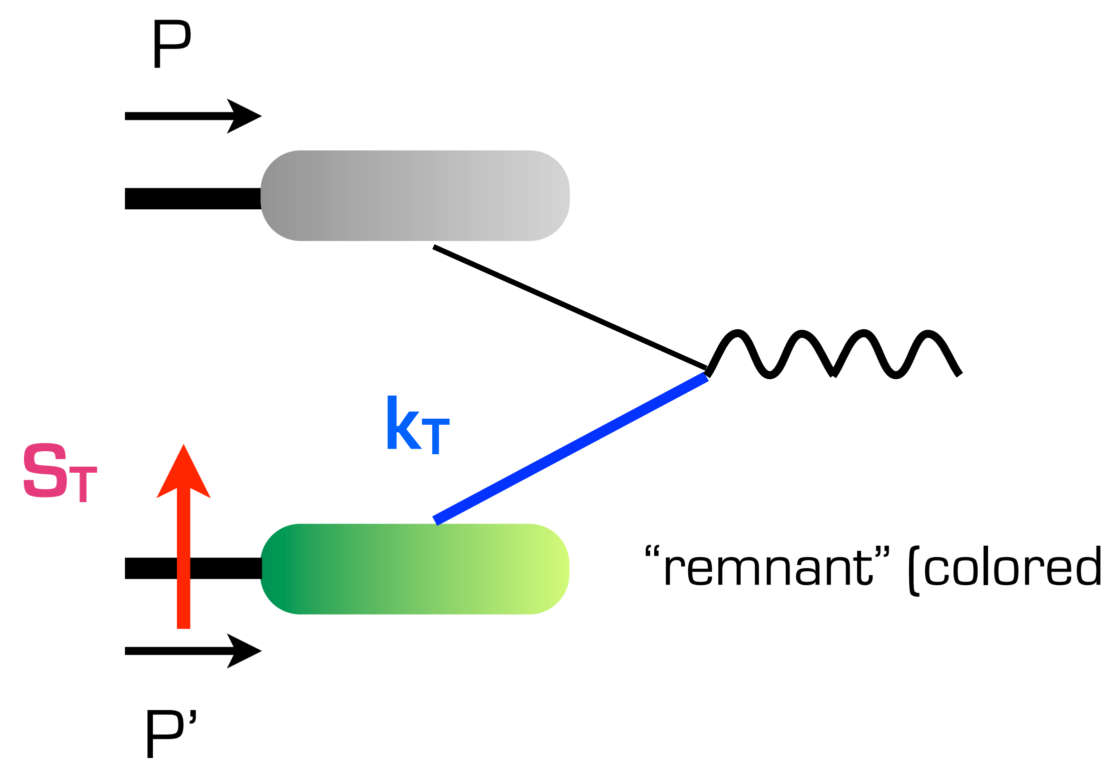
A matter of connections

Single Spin Asymmetries in QCD

$$pp^{\uparrow} \to W^{-} \to \ell^{-}\bar{\nu}$$

Later, D. Sivers proposed an explanation based on the **correlation** between the **transverse momentum k_T of the quark** and the **transverse spin S_T of the proton**

introducing the **Sivers TMD PDF**



$$\vec{k_T} \times \vec{S_T} \;\; \underline{f_{1T}^{\perp}(x, k_T^2)}$$

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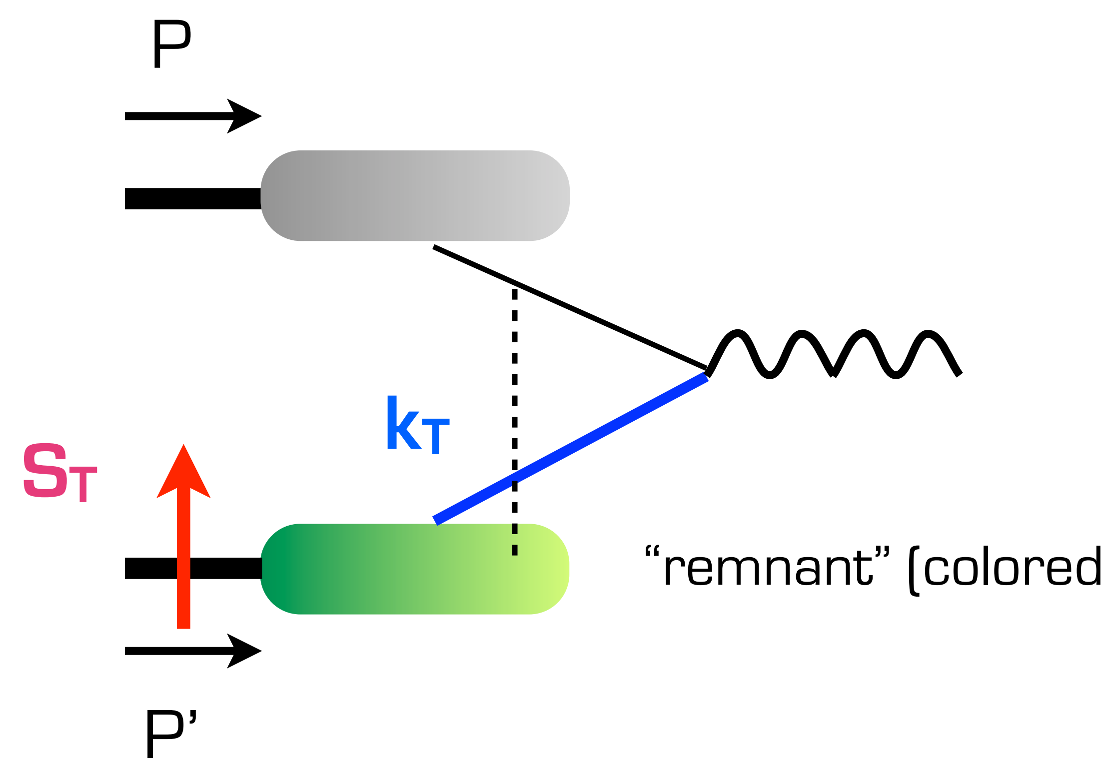
A matter of connections

Single Spin Asymmetries in QCD

$$pp^{\uparrow} \to W^- \to \ell^- \bar{\nu}$$

It turns out that to satisfy the **time reversal invariance** and **gauge invariance** of QCD, a gluon exchange is needed also in the case of the Sivers function: formal introduction of **gauge links** in TMD PDFs



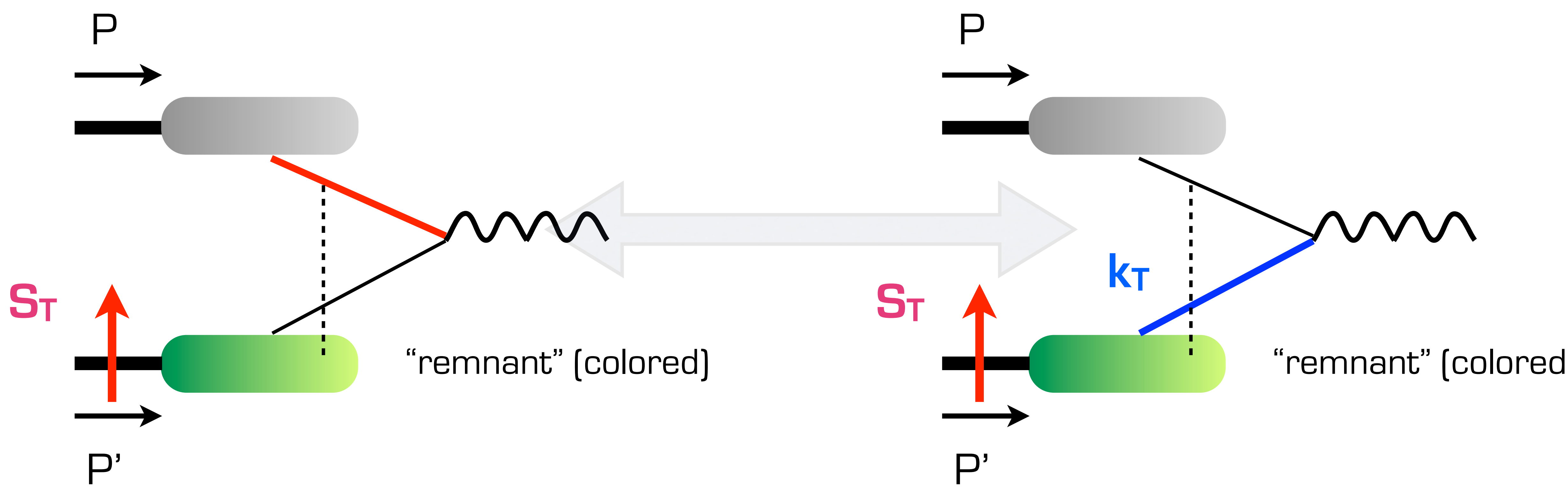
TMD and collinear twist-3 pictures are related!

$$\vec{k_T} \times \vec{S_T} \;\; \underline{f_{1T}^{\perp}(x, k_T^2)}$$

A matter of connections

Single Spin Asymmetries in QCD

$$pp^{\uparrow} \to W^- \to \ell^- \bar{\nu}$$



The **common feature**: the gluon exchange between the active parton and the remnant of the polarized hadron generates an **imaginary phase**, required for having a non-vanishing asymmetry

$$\mathcal{P}\ \exp\left\{ -ig \int_c ds_\mu\ A^{\mu,a}(s) \right\}$$

asymmetry induced by non-abelian connection
NON ABELIAN AB effect

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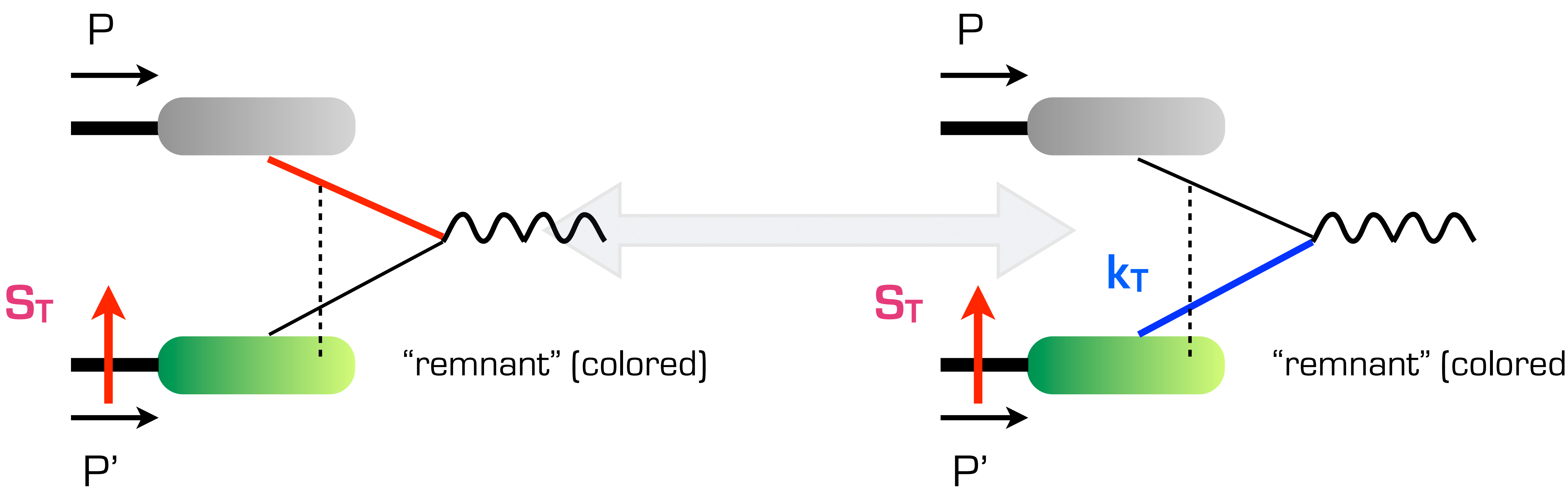
A matter of connections

Single Spin Asymmetries in QCD

$$pp^{\uparrow} \to W^{-} \to \ell^{-}\bar{\nu}$$



$T_F(x_q, x_g)$ $\qquad$ $f_{1T}^{\perp}(x, k_T^2)$

- matched at large transverse momentum (OPE)
- also work in progress in PSU Berks, JLab

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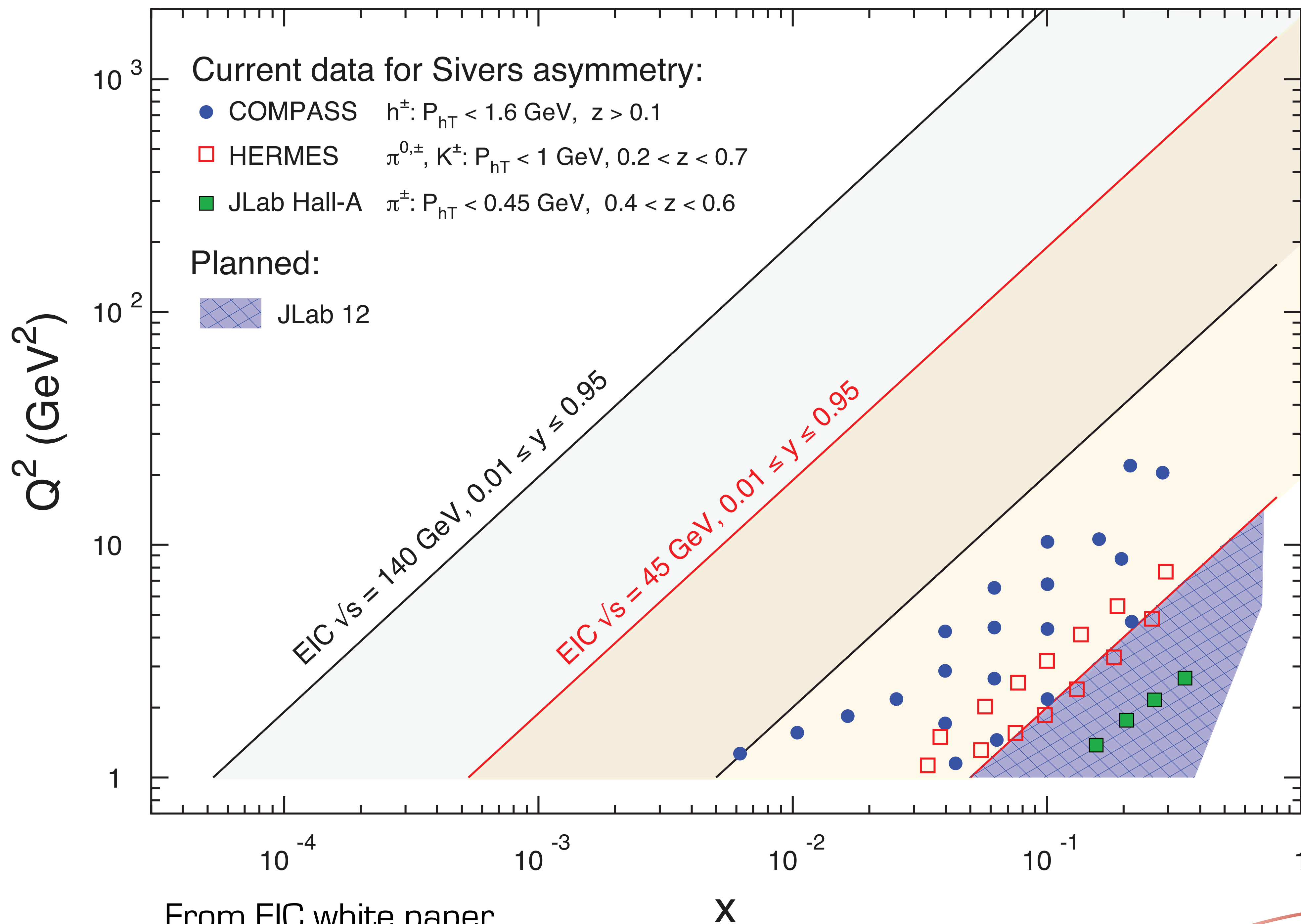
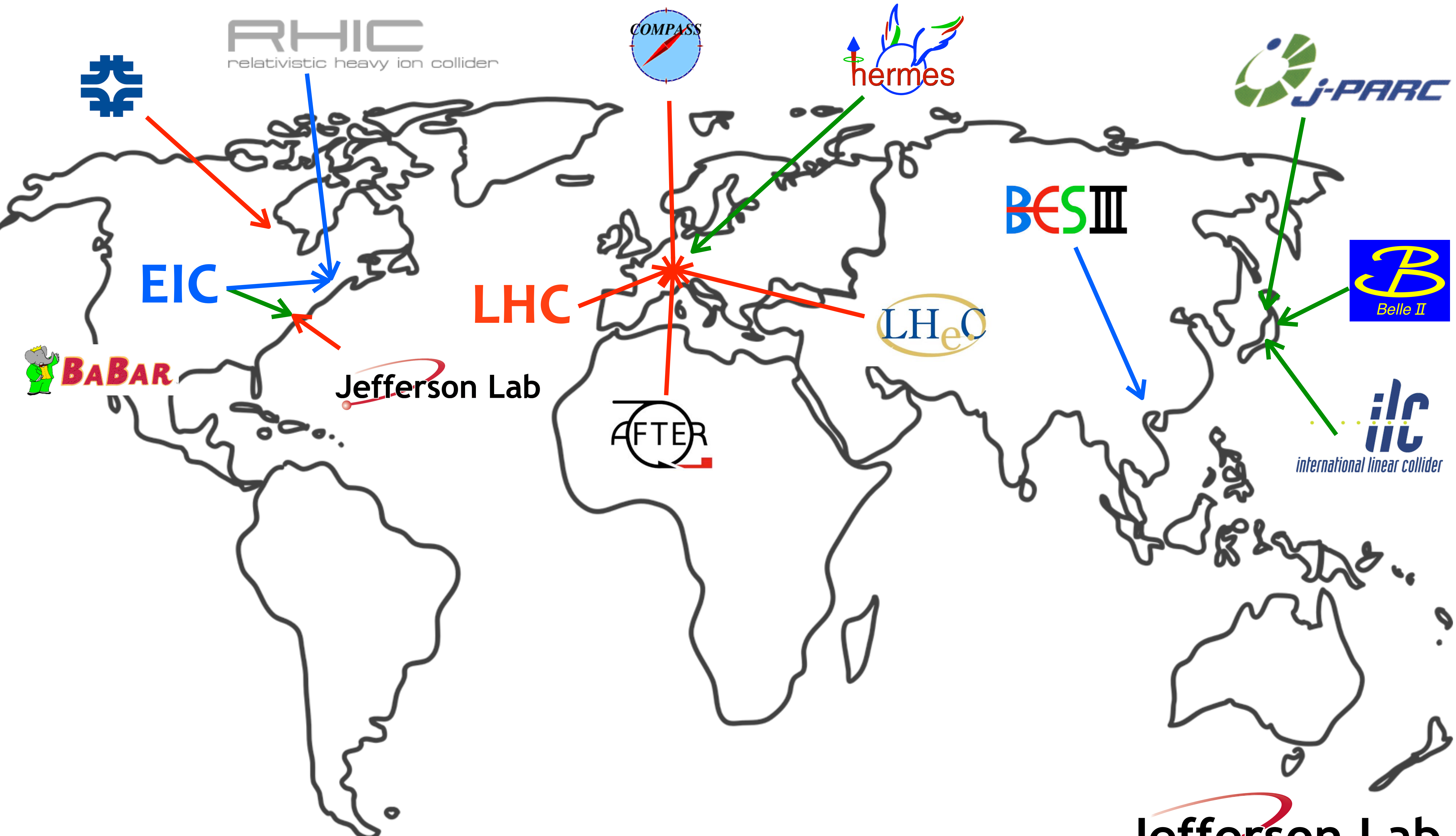
Experimental investigations



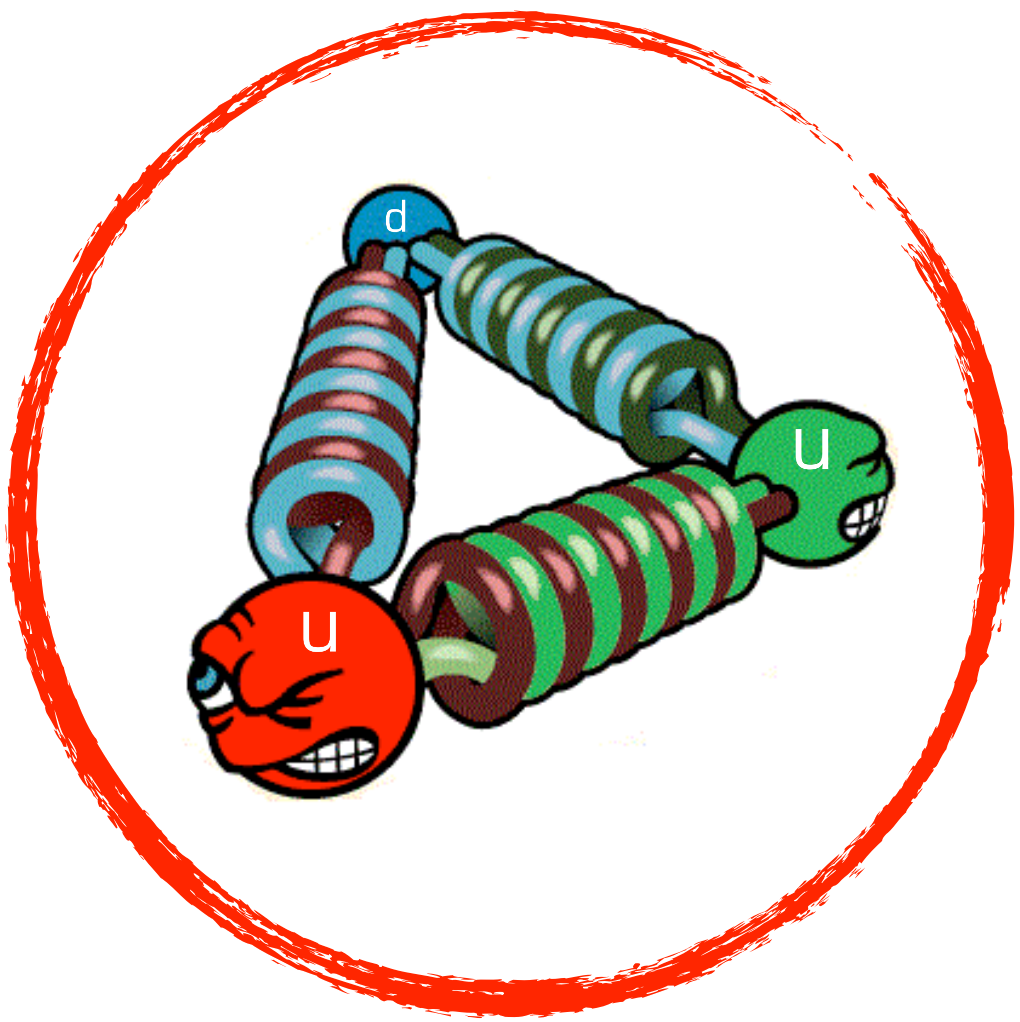
From EIC white paper

Experimental investigations



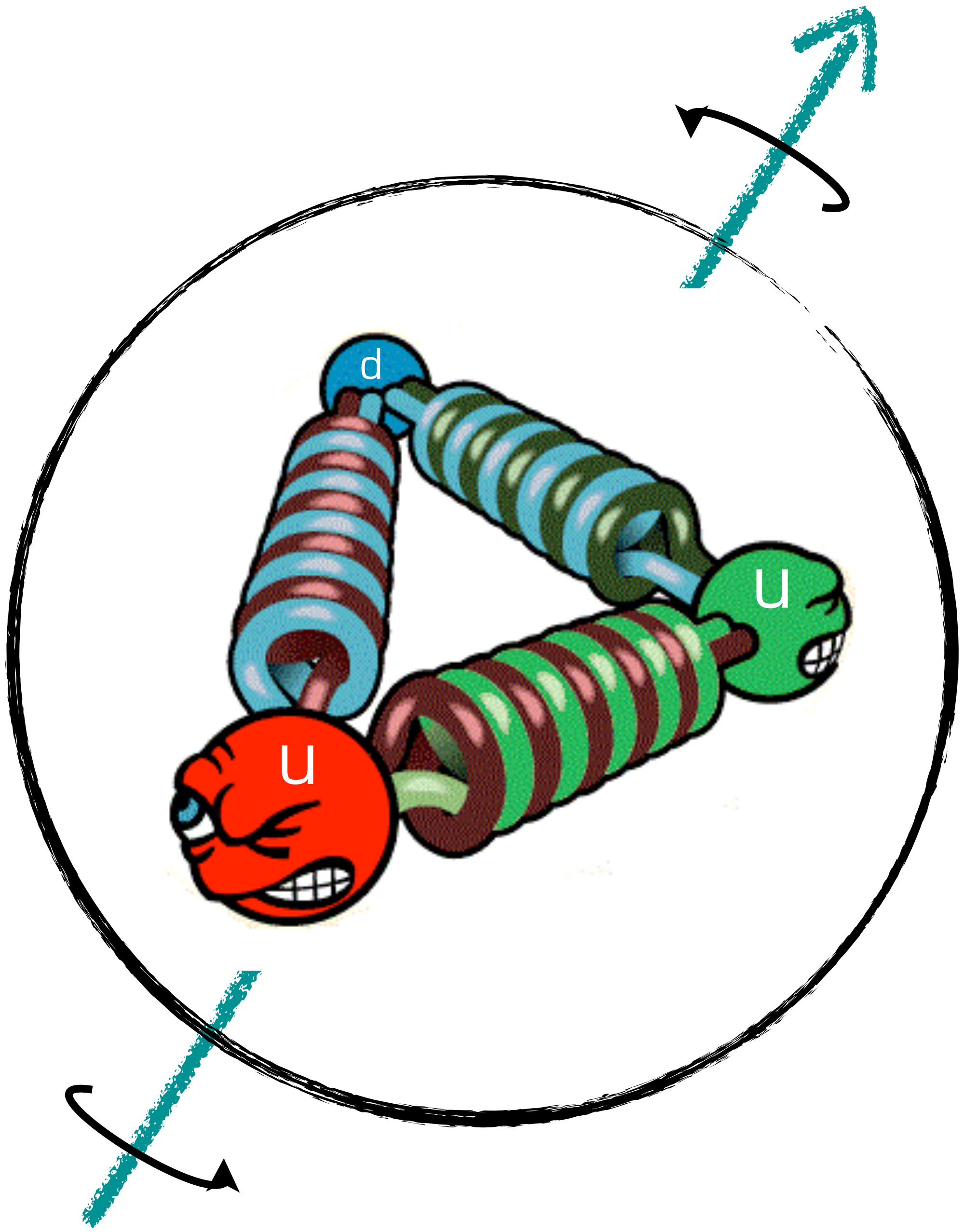
Some research lines

Hot topics



how does **confinement** work ?

Hot topics



how to describe
the proton spin ?

What about the
proton mass ?

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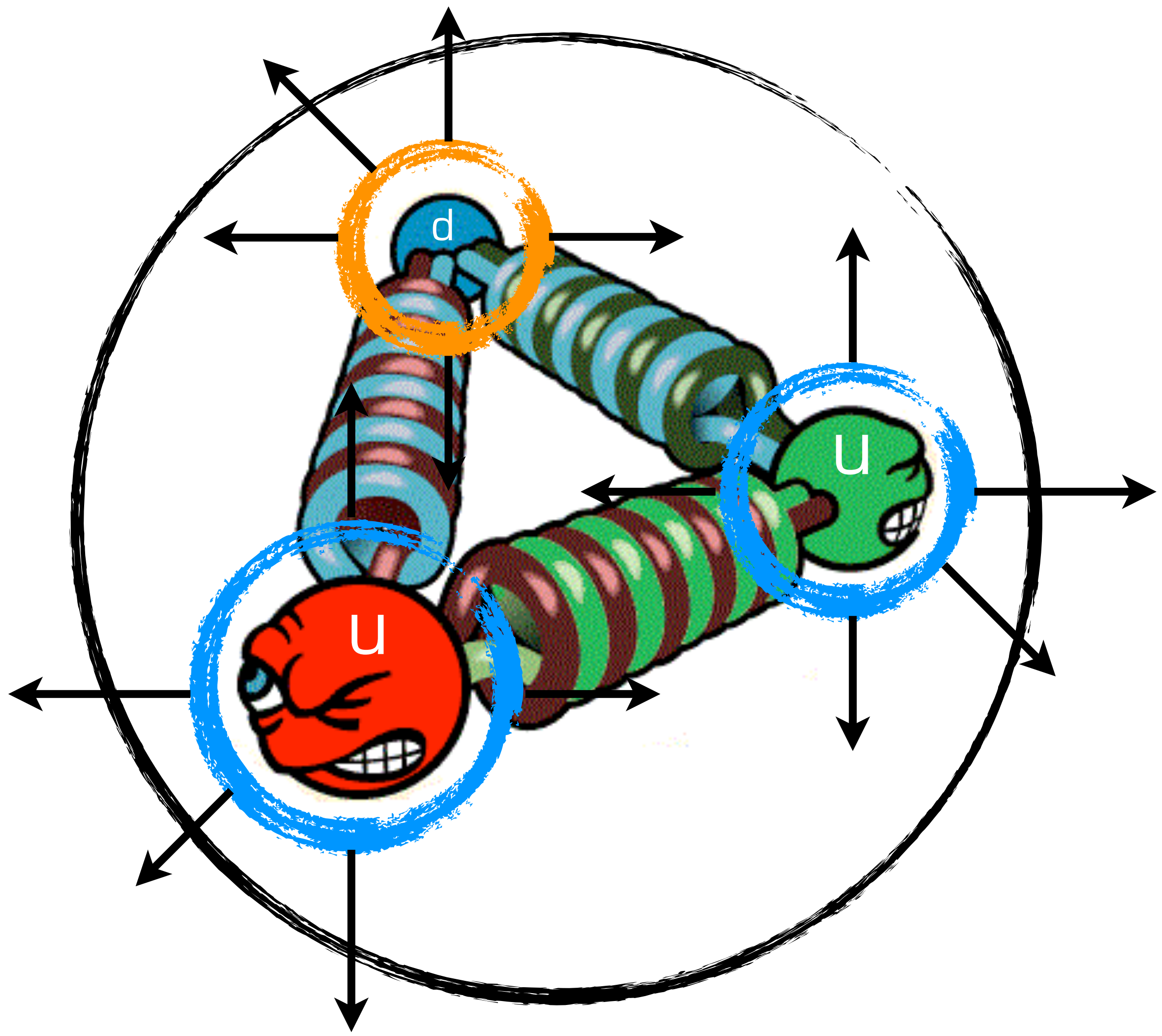
Hot topics



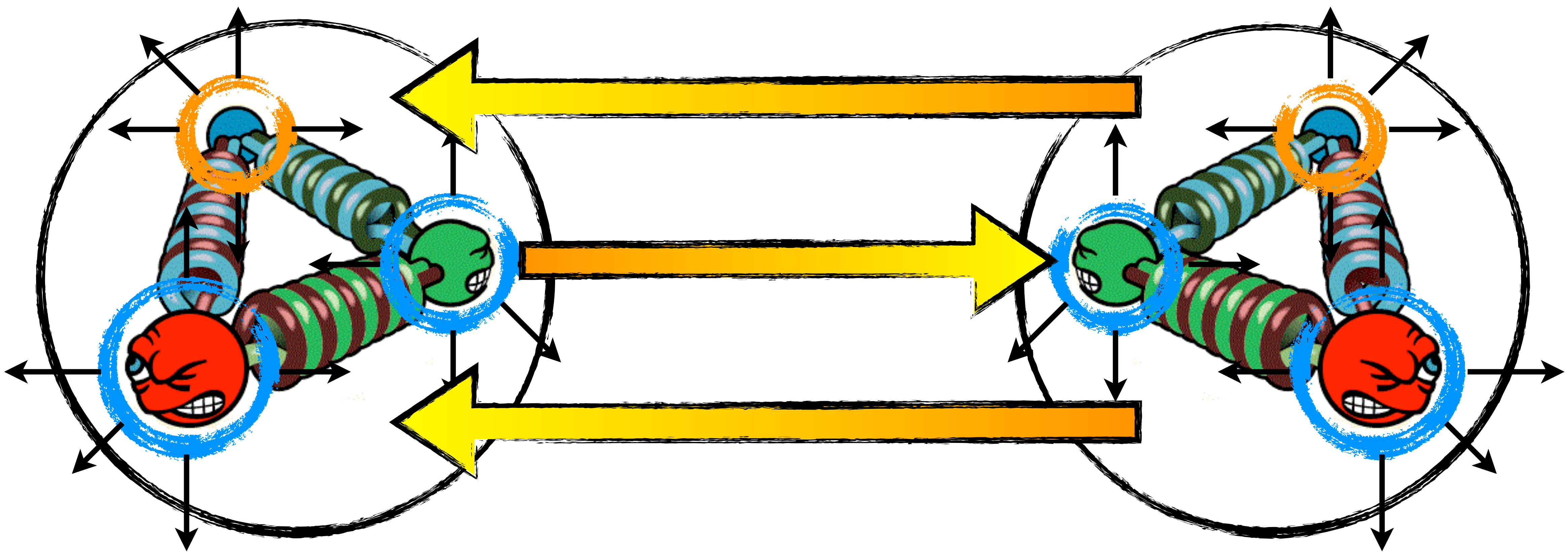
how are the elementary constituents distributed inside the proton?

How do they move ?

How different is the motion of gluons vs quarks? What about the flavor?

Internal tomography

Hot topics



Impact of the structure on
high-energy scattering experiments

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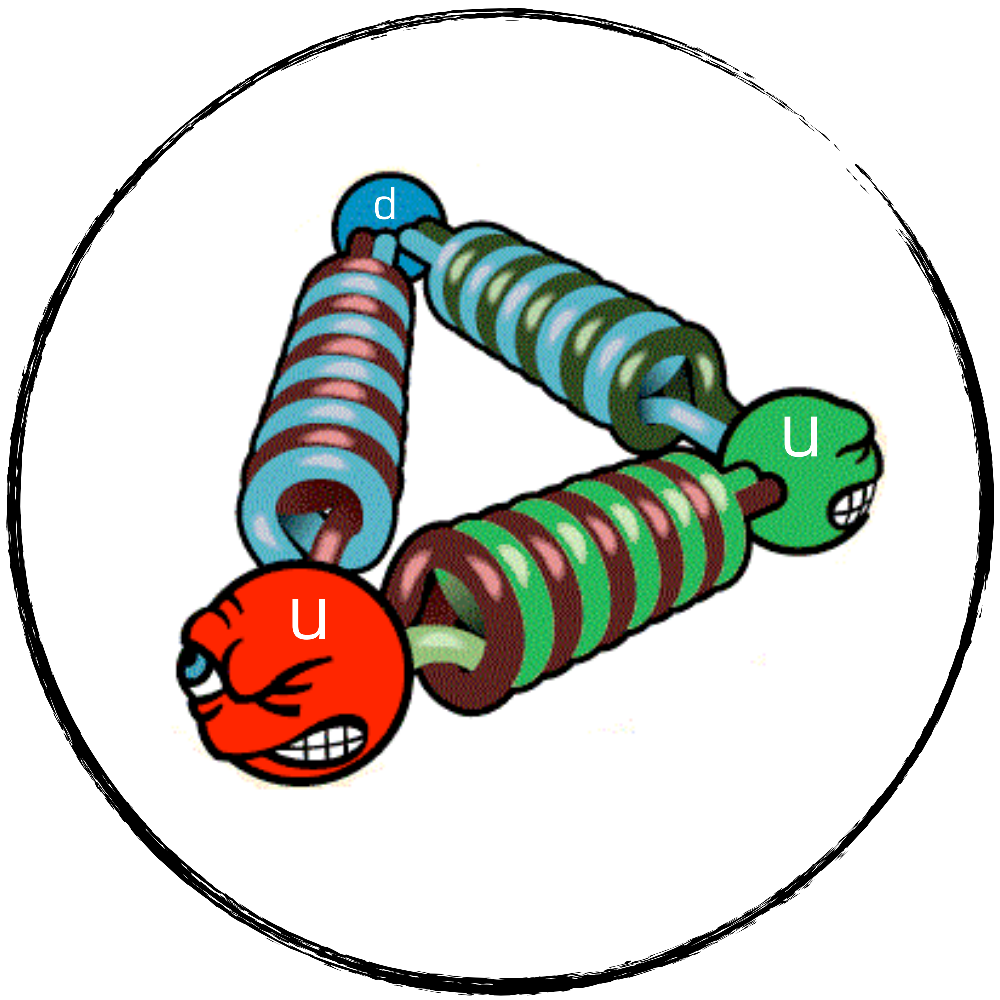
My focus



how does **confinement** work?

the proton **spin**

tomography of
the internal **structure**

impact of the structure
on high-energy **scattering**
experiments

...

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Evolution effects

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Evolution effects

What happens if we
change the resolution
of the picture?

QCD evolution equations

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Evolution effects

The roots of this question
are inside
factorization theorems

What happens if we
change the resolution
of the picture?

QCD evolution equations

Impact on high-energy physics
experiments?
Interplay with flavor effects?

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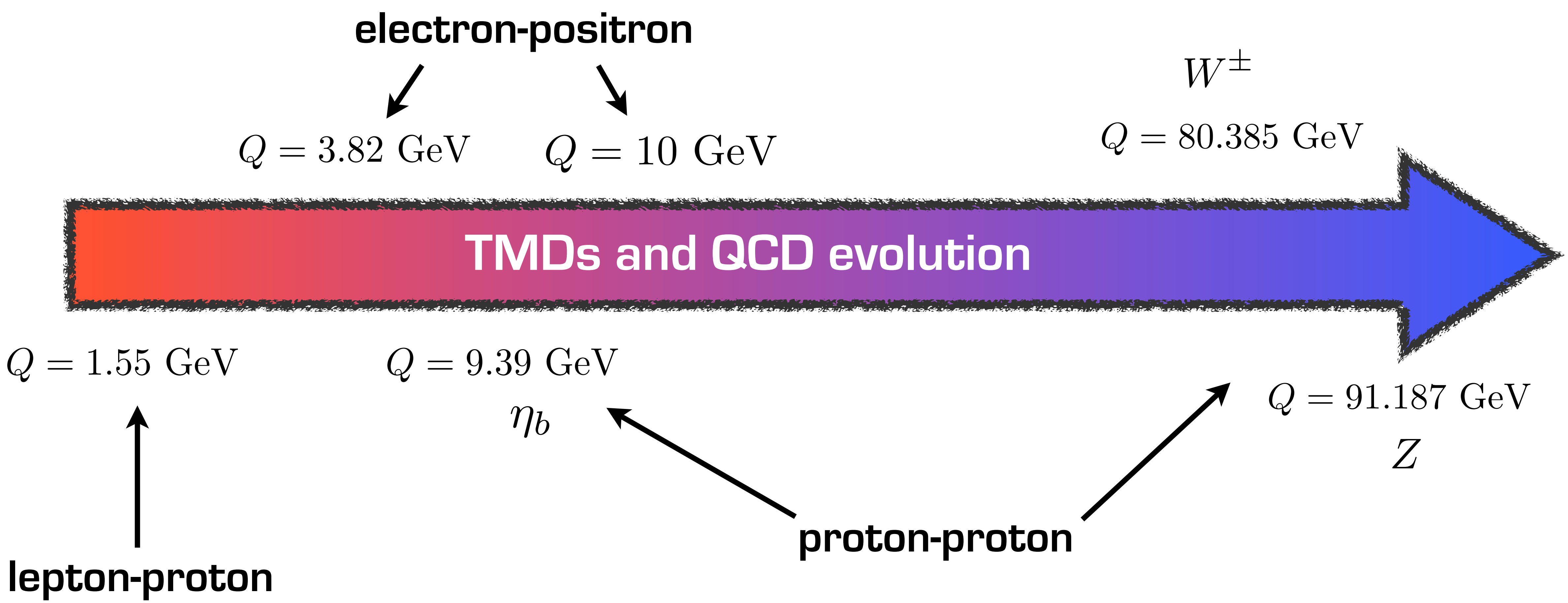
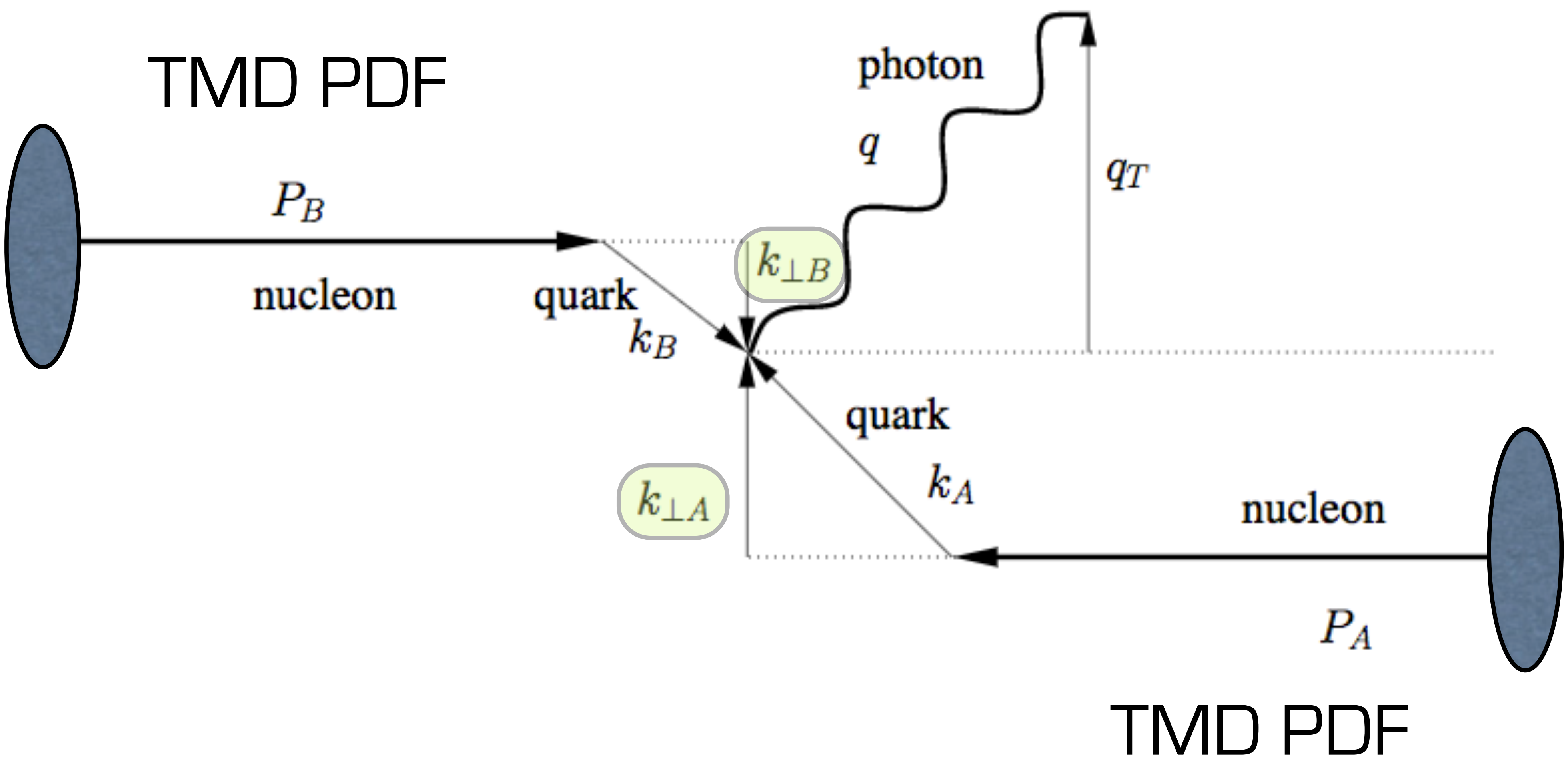
Need of TMD evolution



Drell-Yan



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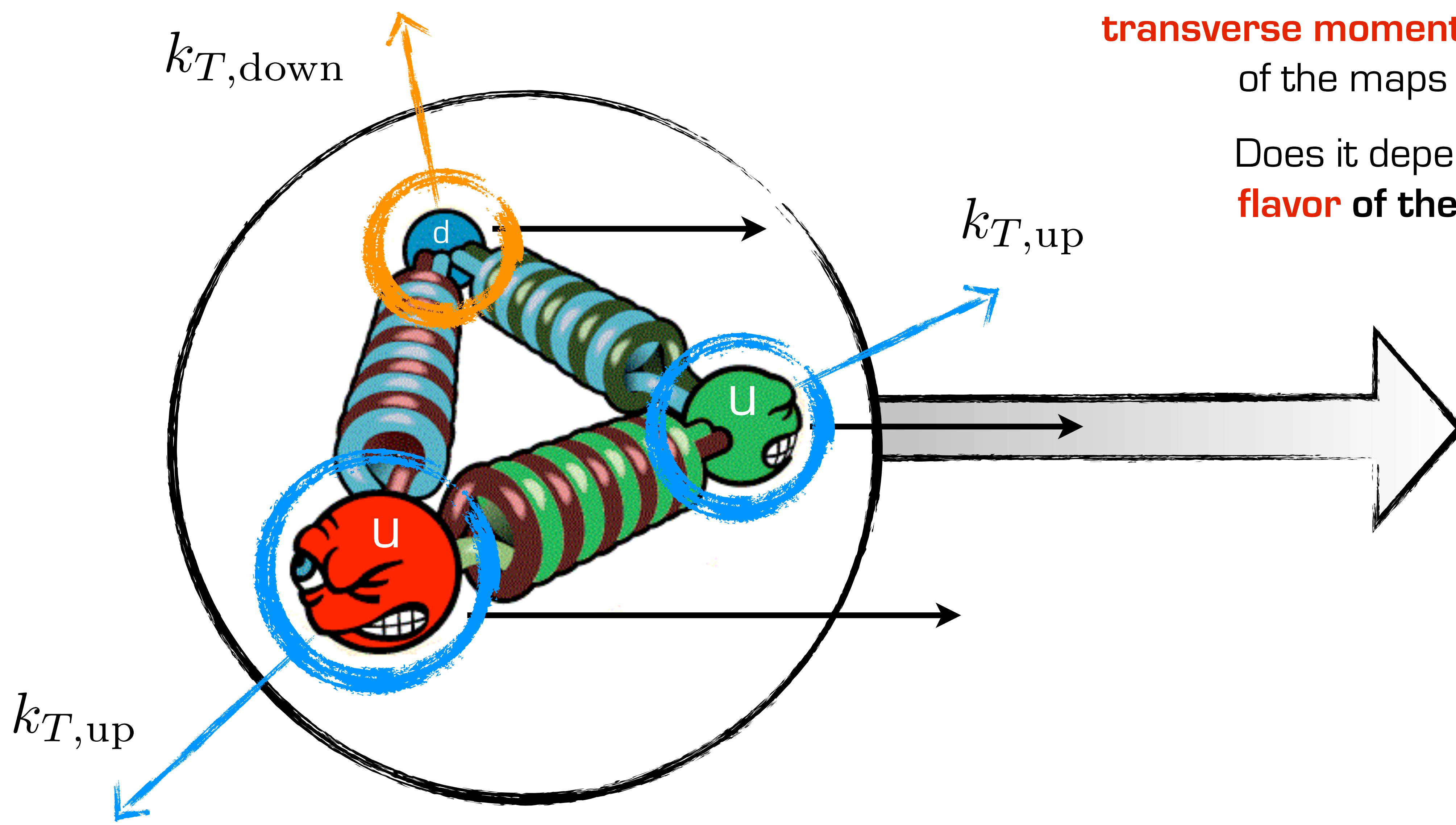
Flavor effects

AS, PhD thesis



What does the
transverse momentum dependence
of the maps look like?

Does it depend on the
flavor of the quarks?

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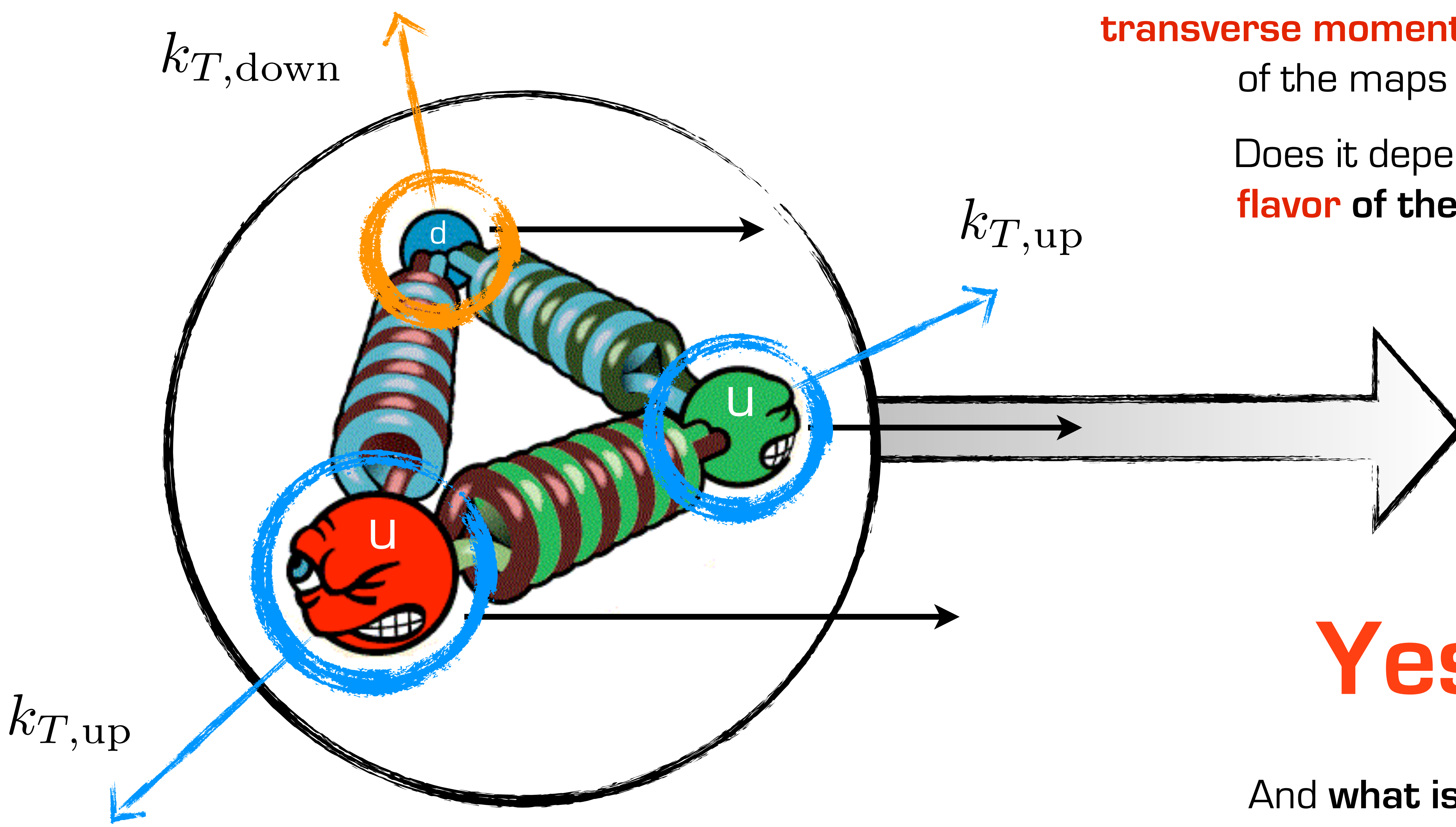
Flavor effects

AS, PhD thesis



What does the
transverse momentum dependence
of the maps look like?

Does it depend on the
flavor of the quarks?

Yes! *

And **what is its impact**
on high-energy physics
experiments?

(* = under specific assumptions)

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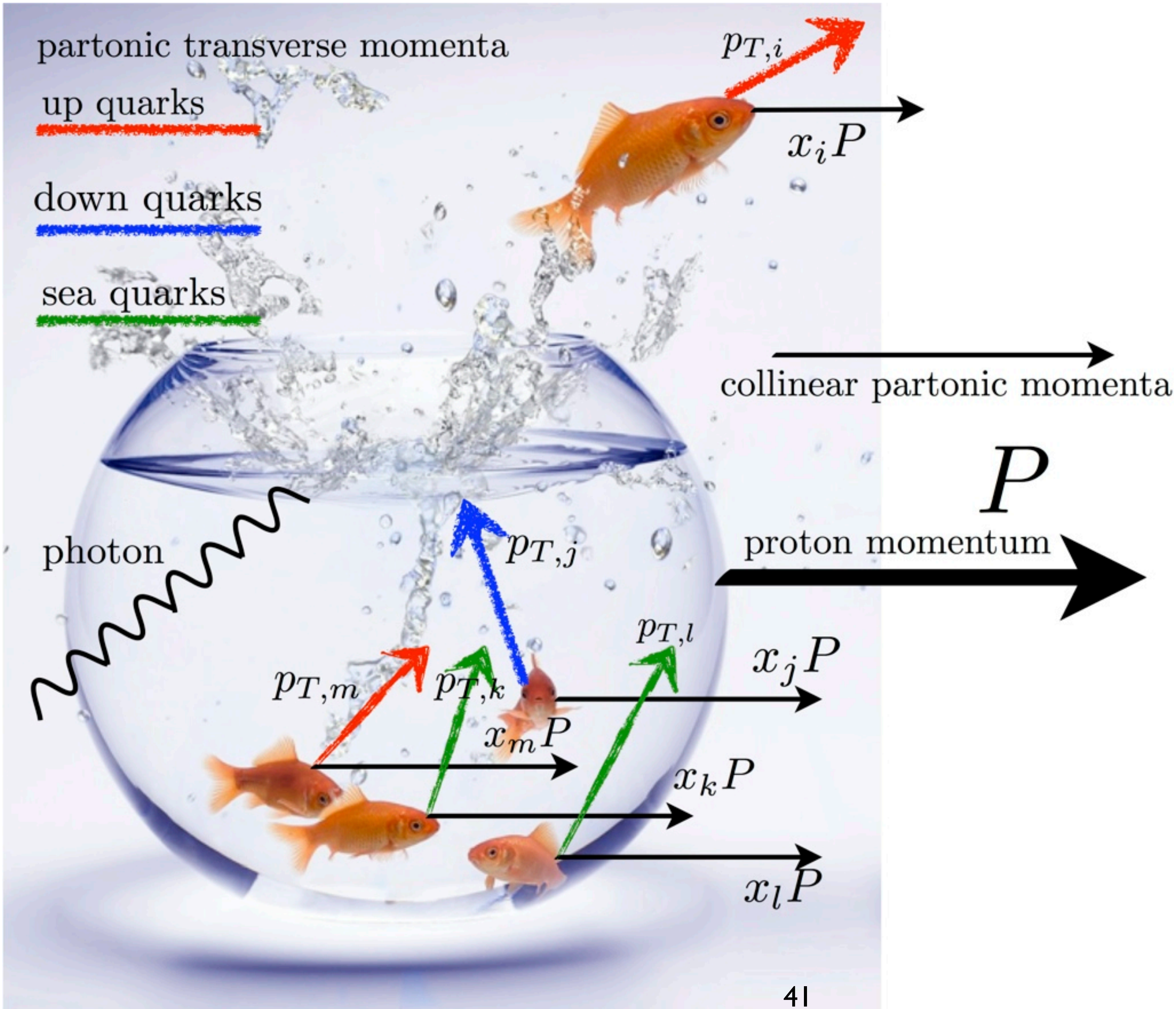
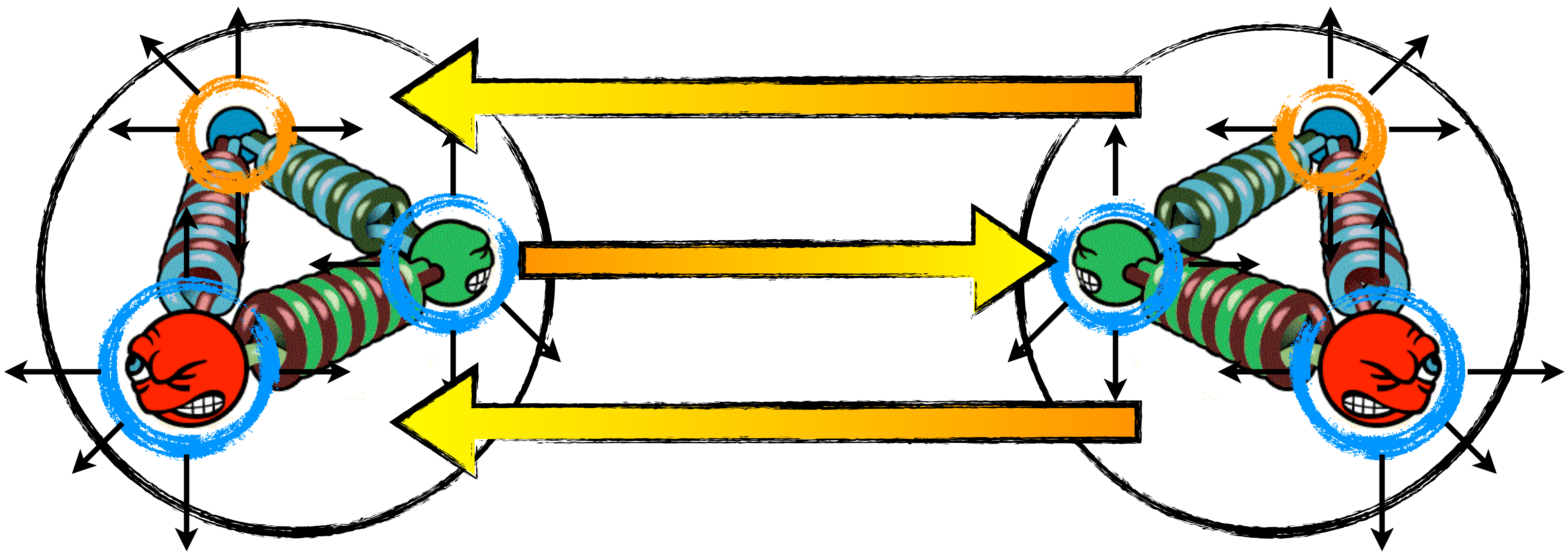
Flavor effects

AS, PhD thesis



extraction from **lepton-proton data**

Hot topics



Impact of the structure on
high-energy scattering experiments

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EW precision measurements

Eur.Phys.J. C74 (2014) 3046

After the measurement of the Higgs mass, all the free parameters of the Standard Model are known.

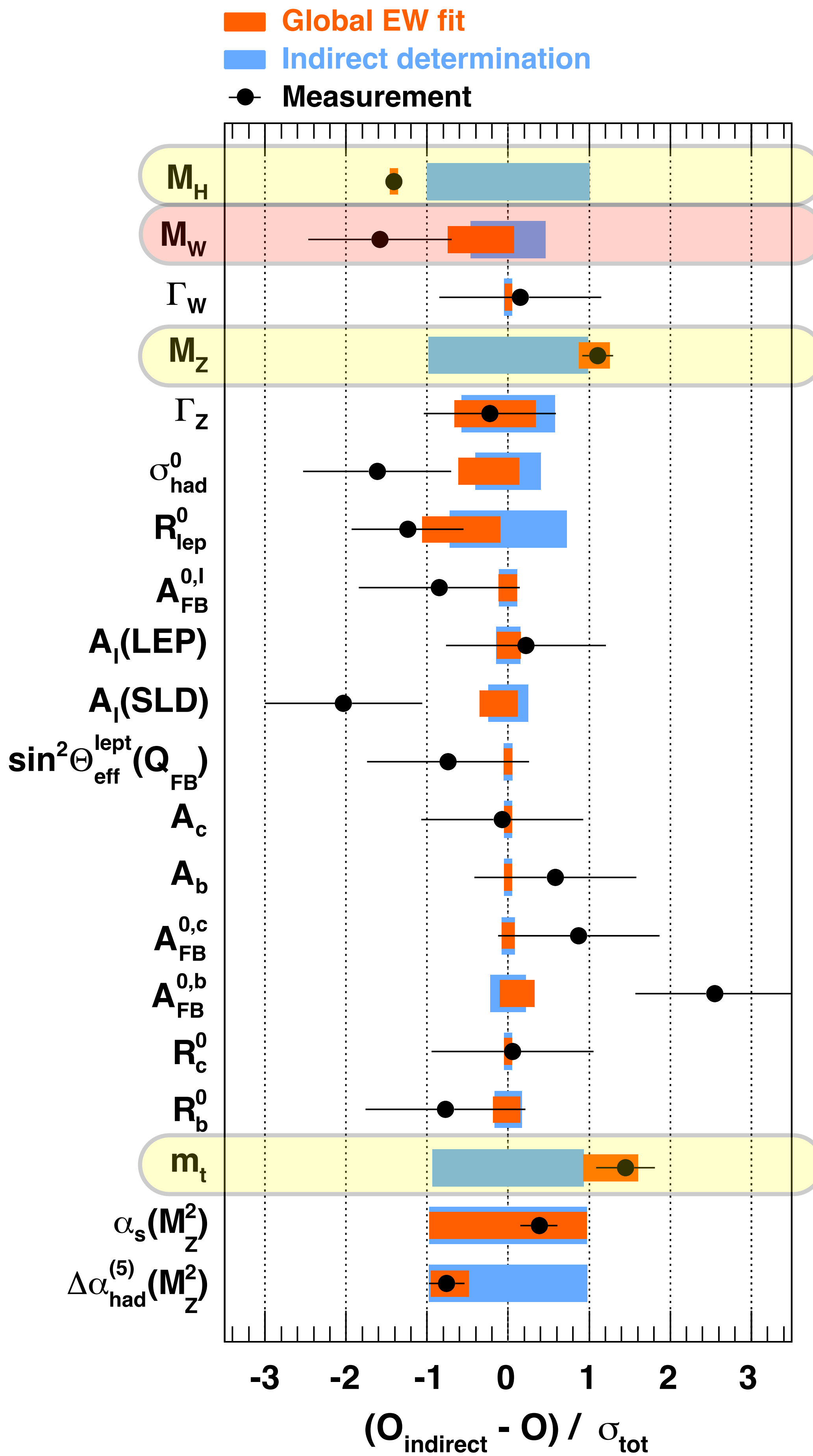
Precise measurements of electroweak quantities allow:

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

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

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

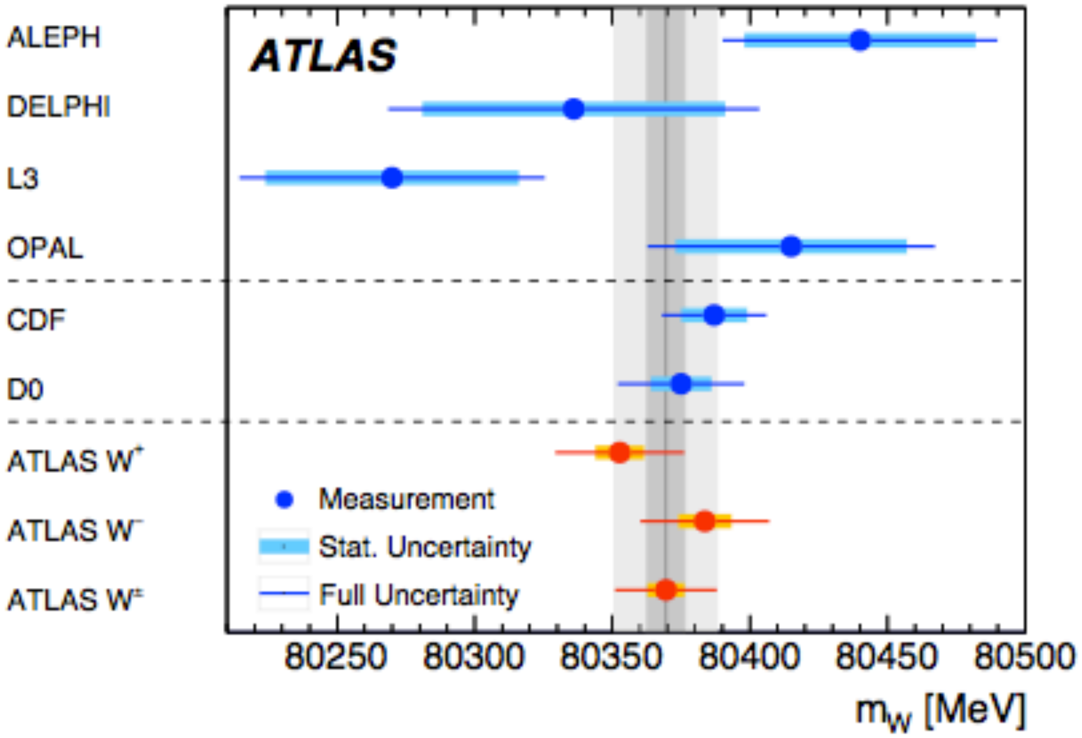
H, Z, t : direct determinations more precise than indirect; **not for W** !

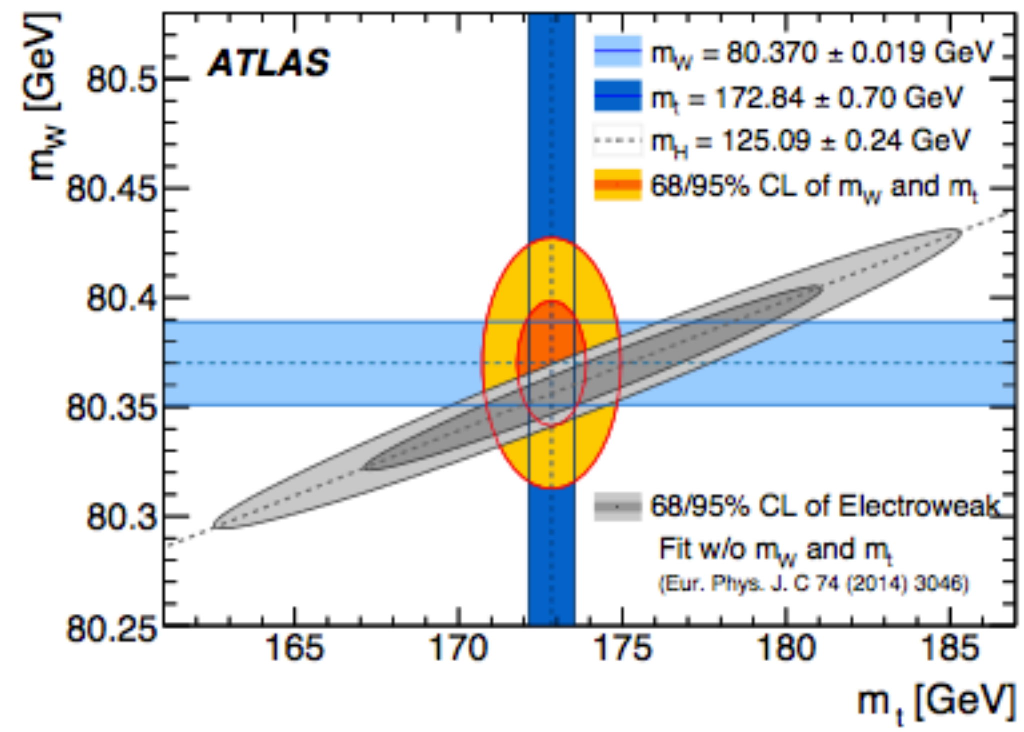


see:
* S. Camarda - Measurement of the W mass with ATLAS EPS 2017

W mass

ATLAS, arxiv:1701.07240





Experimental measurements

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

(7 stat, 11 exp, 14 th)

Global EW fit

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

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

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

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

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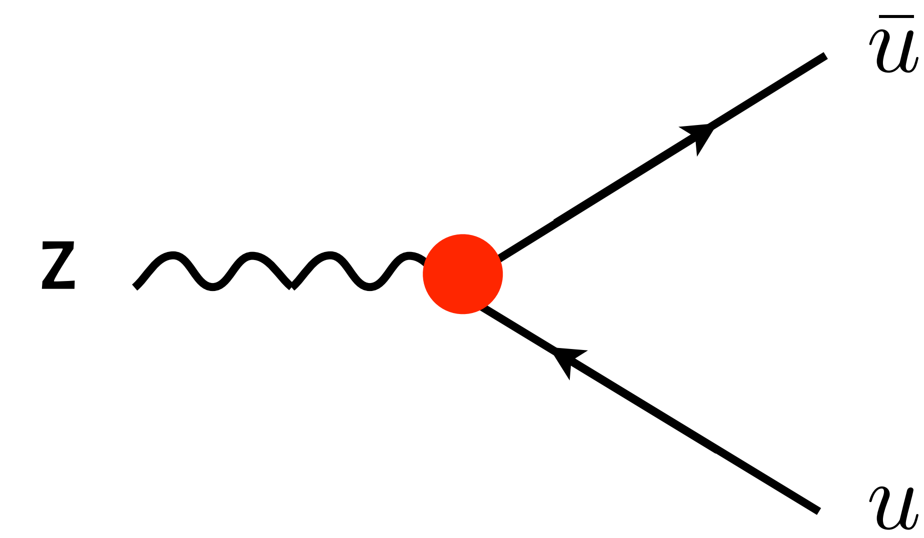
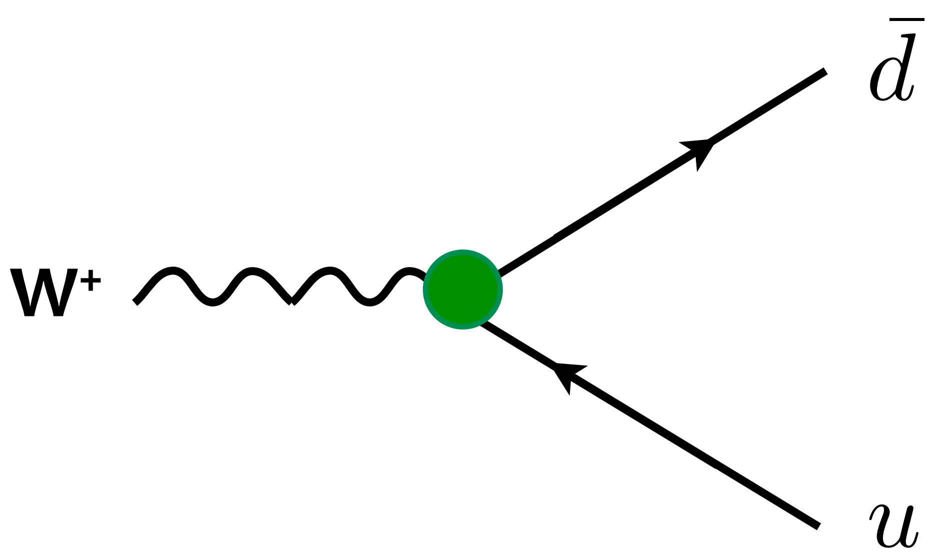
Z vs W : flavor content

AS - PhD thesis



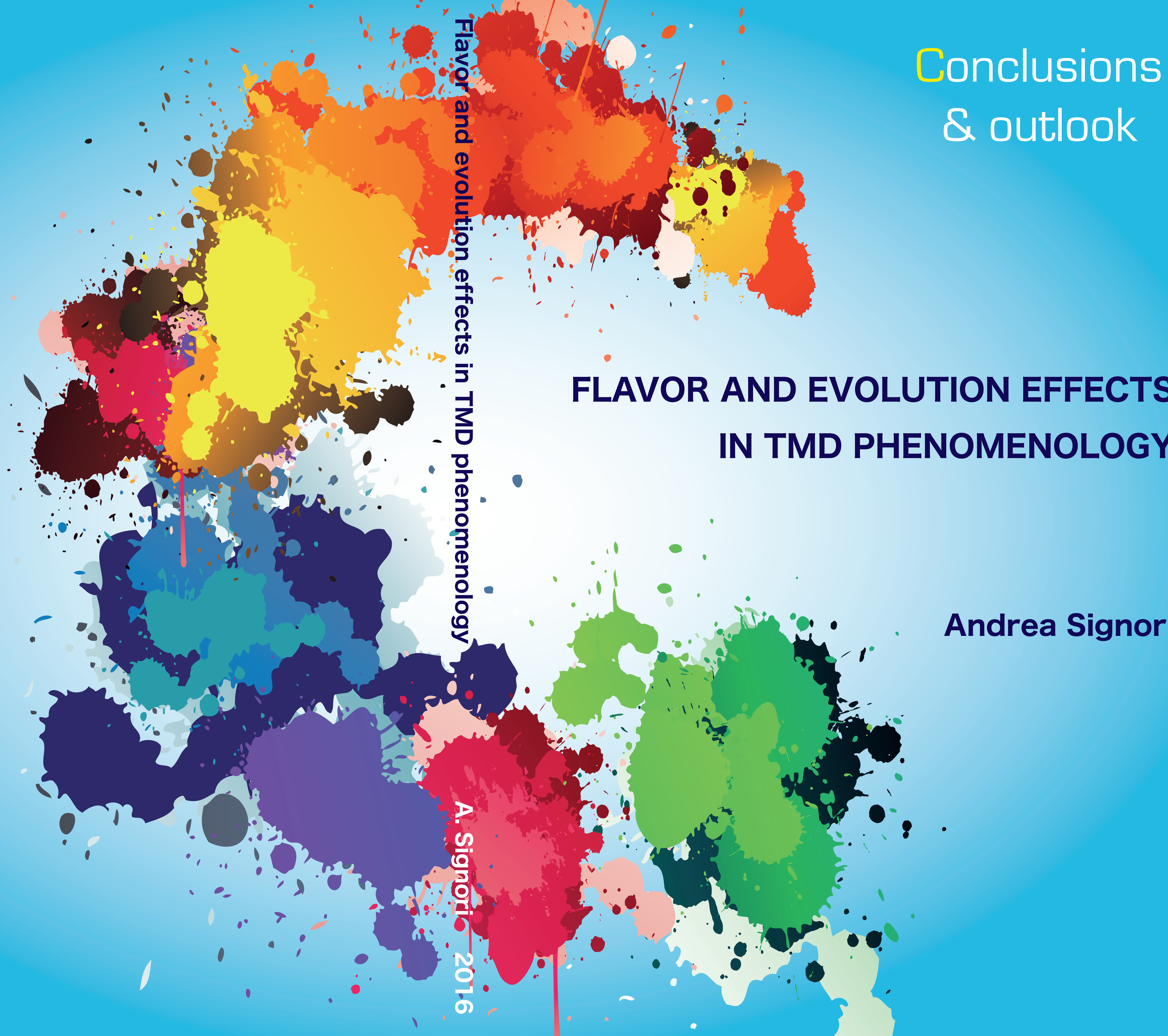
hadronic uncertainties **have been estimated on Z data**
and used to predict the W distribution,
assuming they are the same for Z and W



This reflects a flavor independent approach
and might not be optimal
because of the **different flavor content:**

the intrinsic contributions
are ***different in Z and W± production***

Conclusions & outlook



Backup

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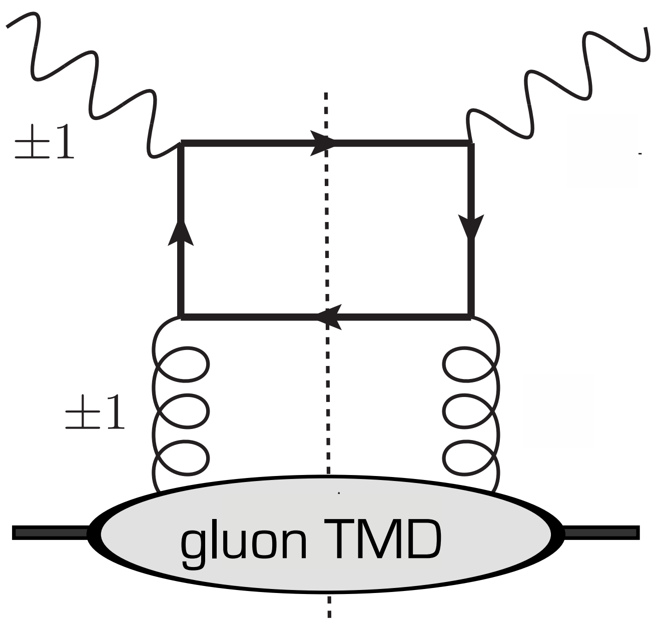
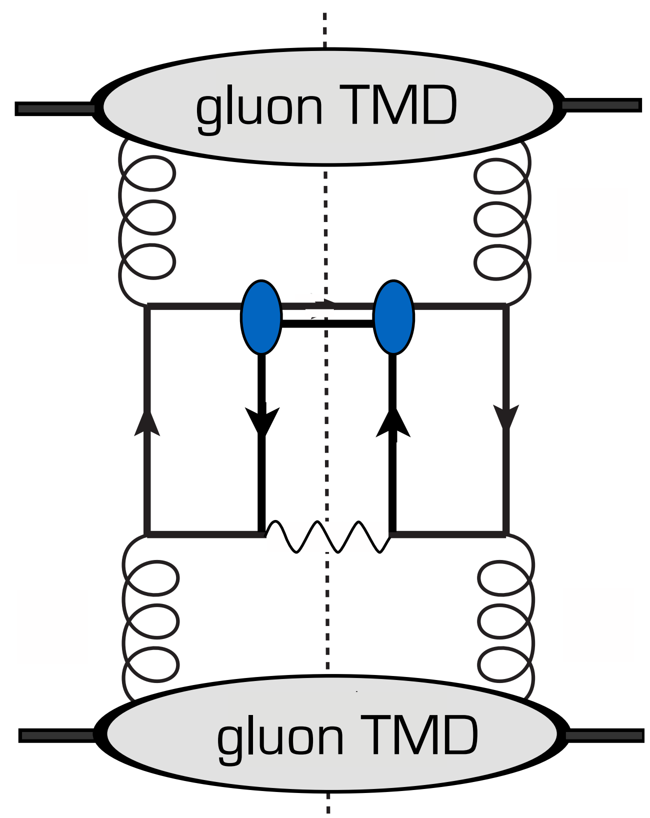
Gluon TMDs

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

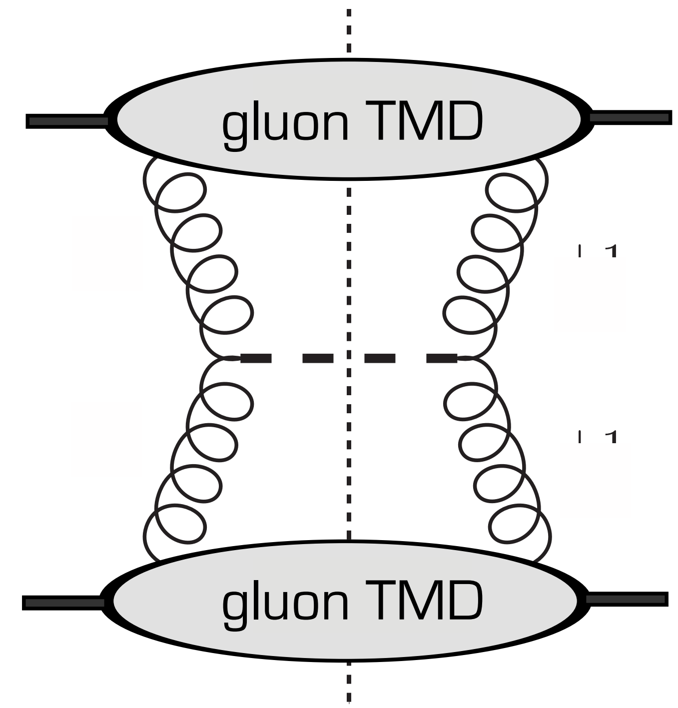
EIC !



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



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



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.. and why would you do that ?

f_1

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

e

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

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

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

h_1

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

h_{1LT}

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

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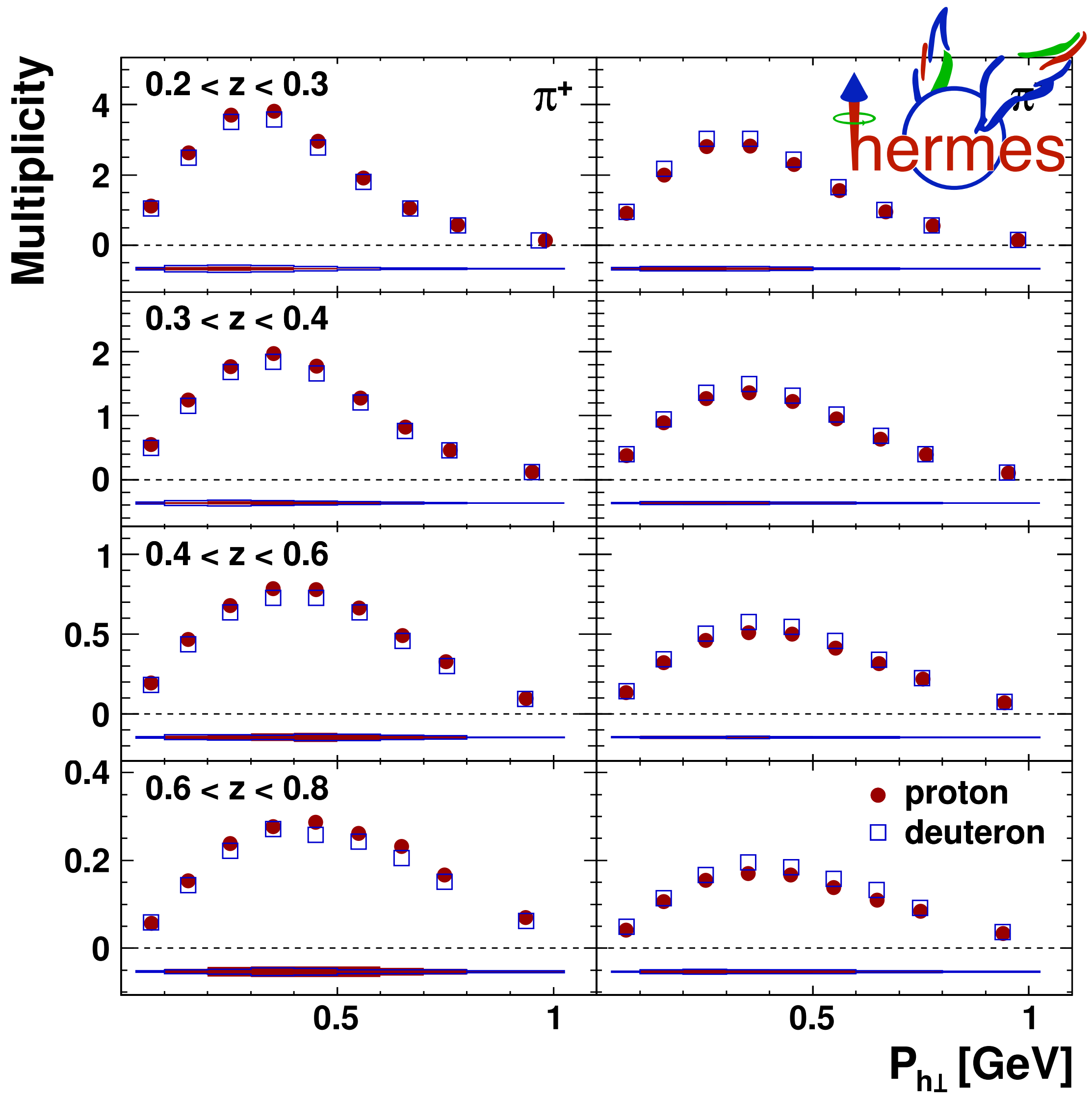
Need of TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

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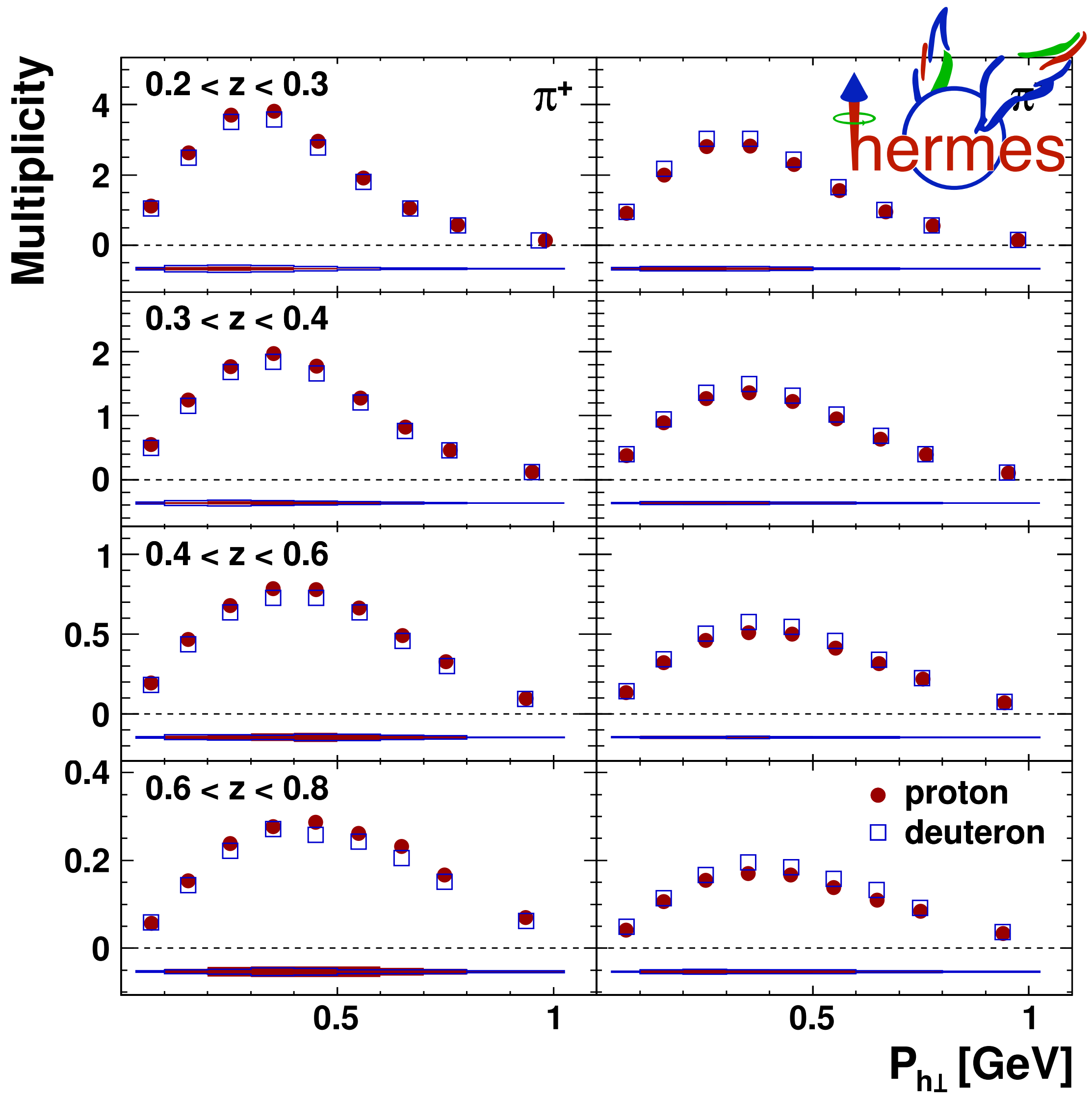
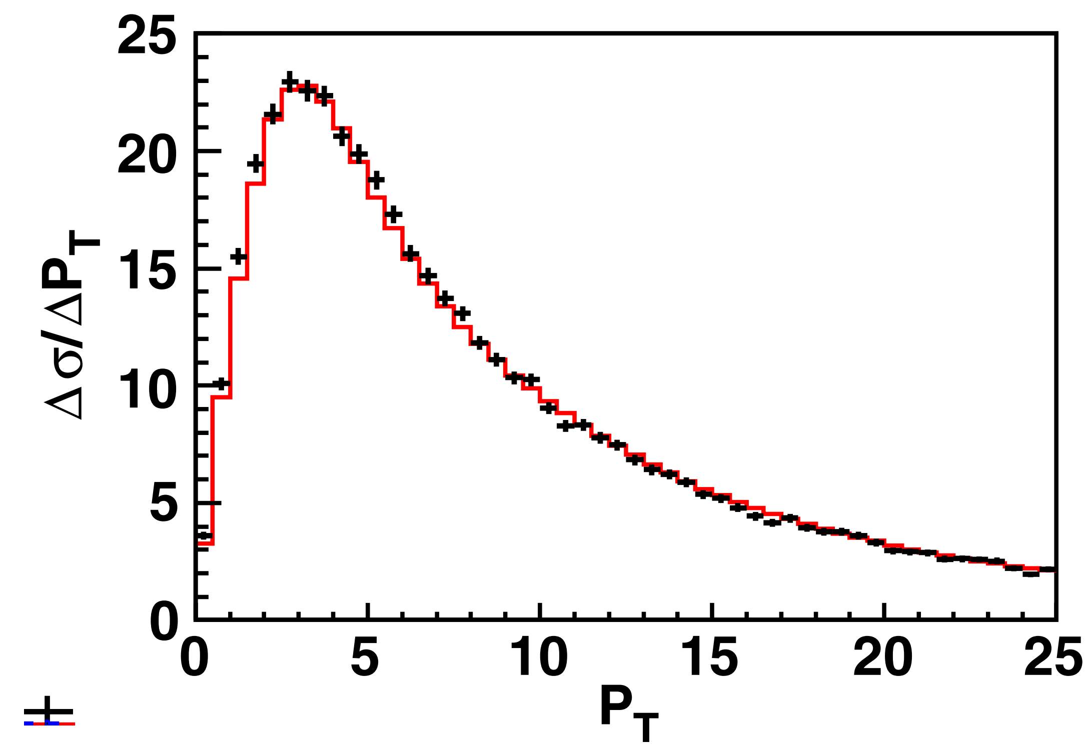
Need of TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

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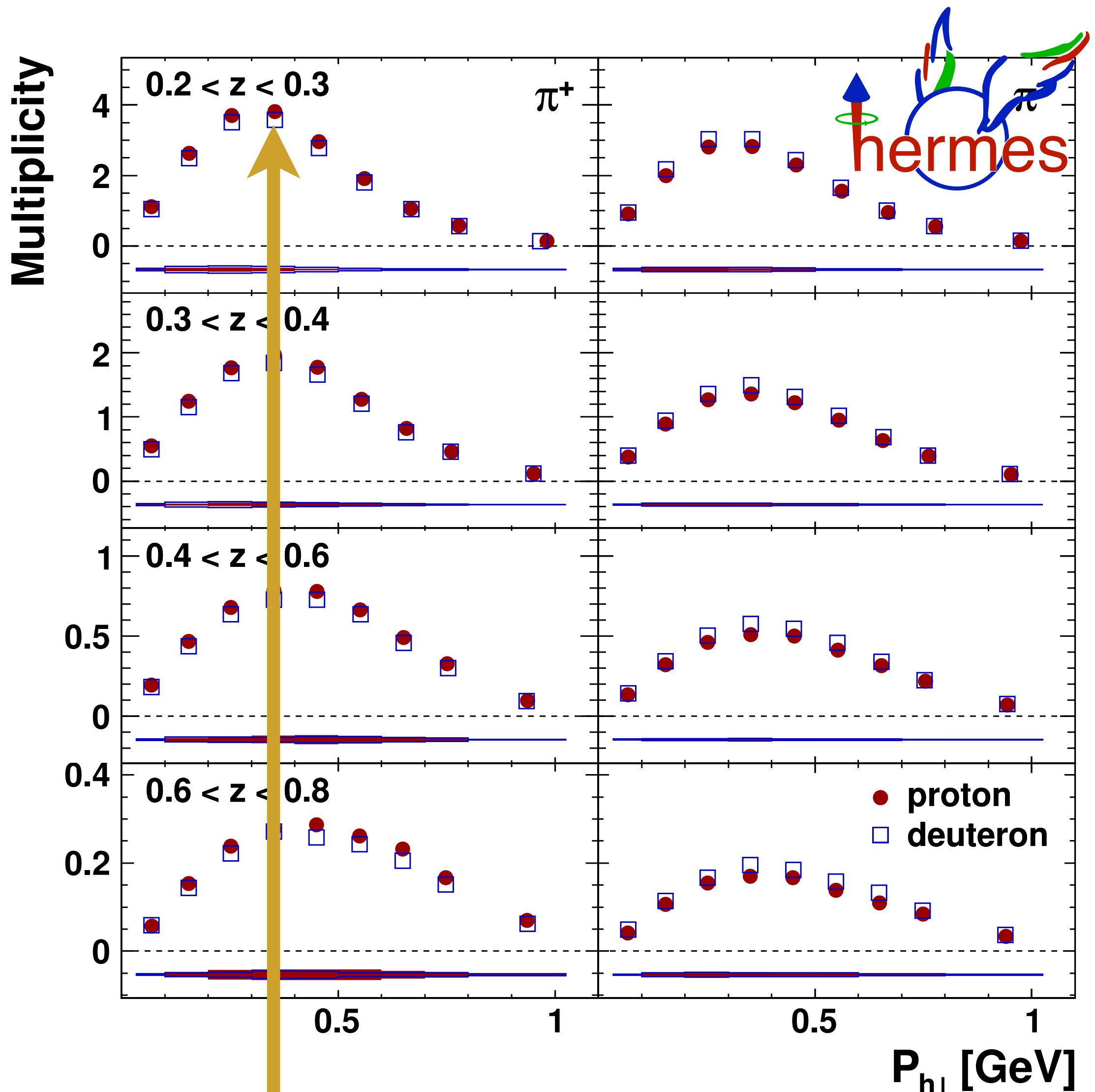
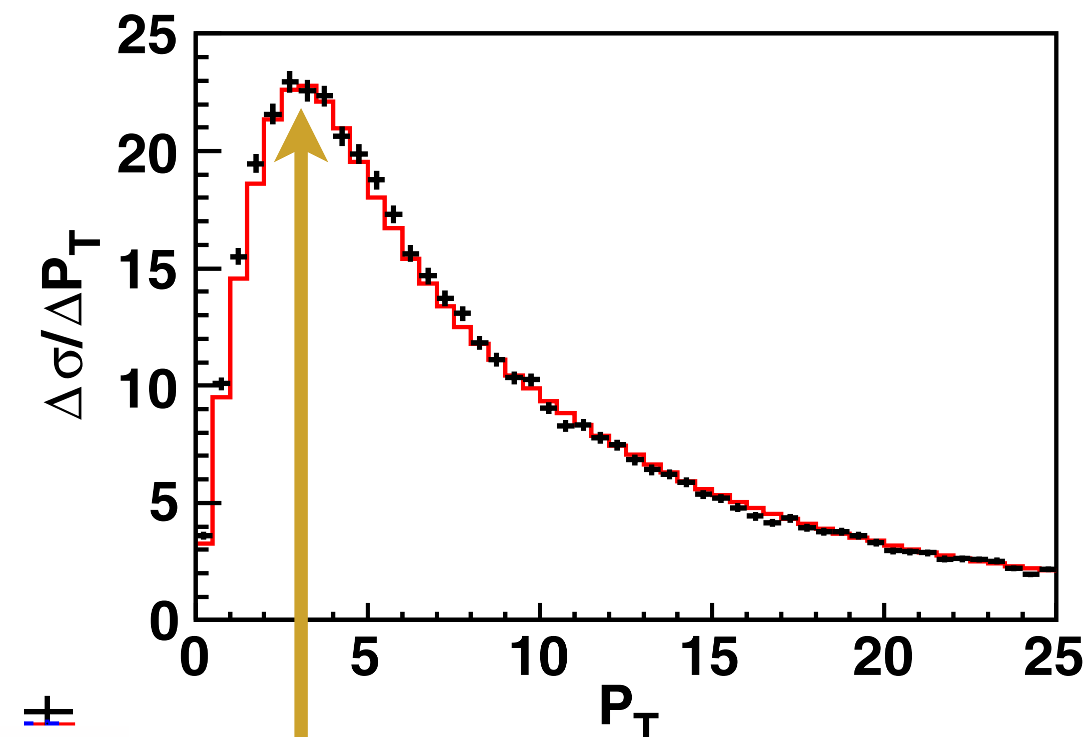
Need of TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

Width of TMDs changes of one order of magnitude:
we can we explain this with TMD evolution

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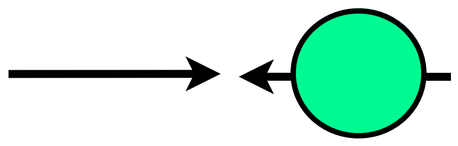
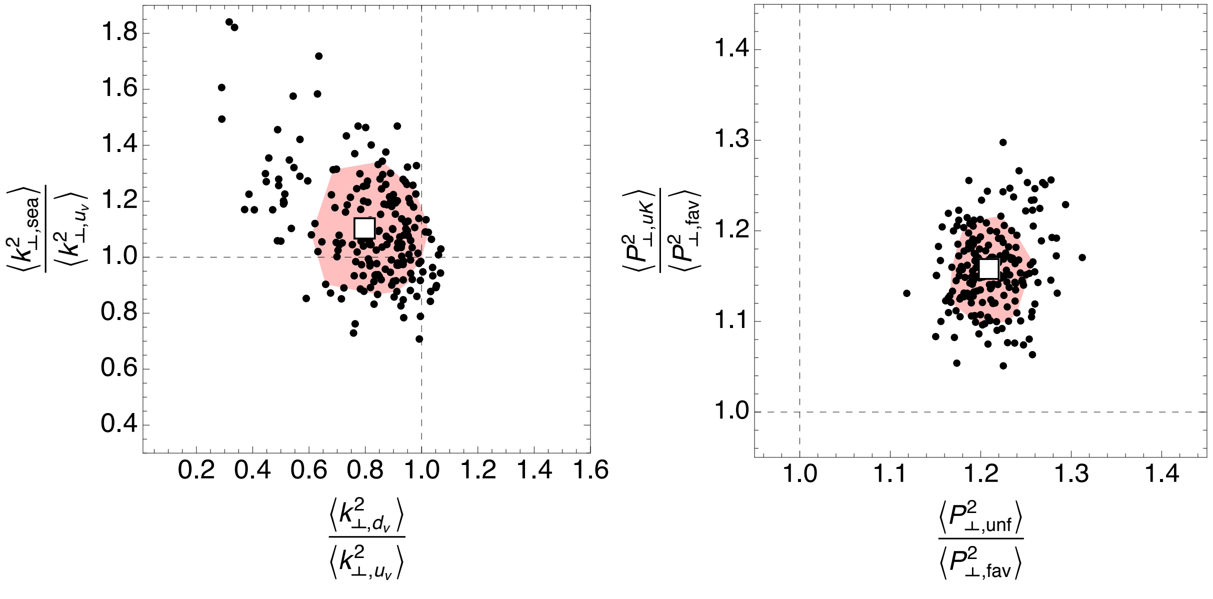
Flavor effects

AS, PhD thesis

lepton-proton



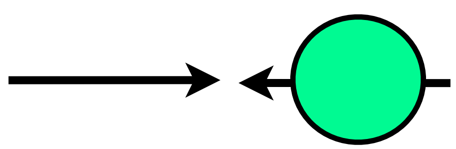
extraction



Flavor effects

AS, PhD thesis

lepton-proton



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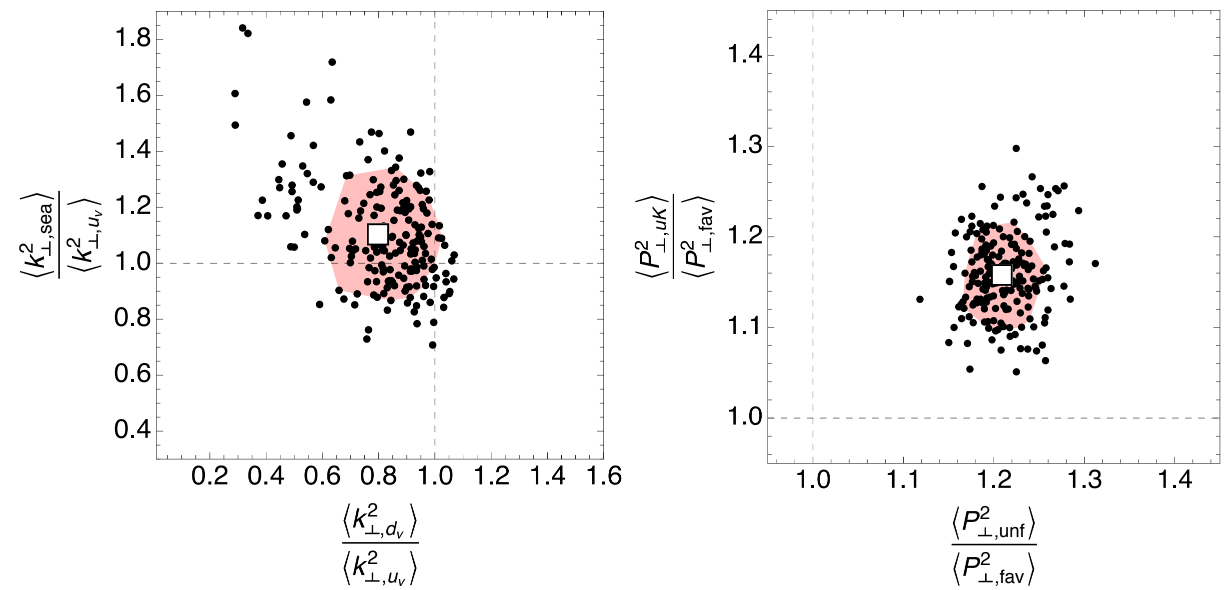
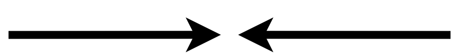
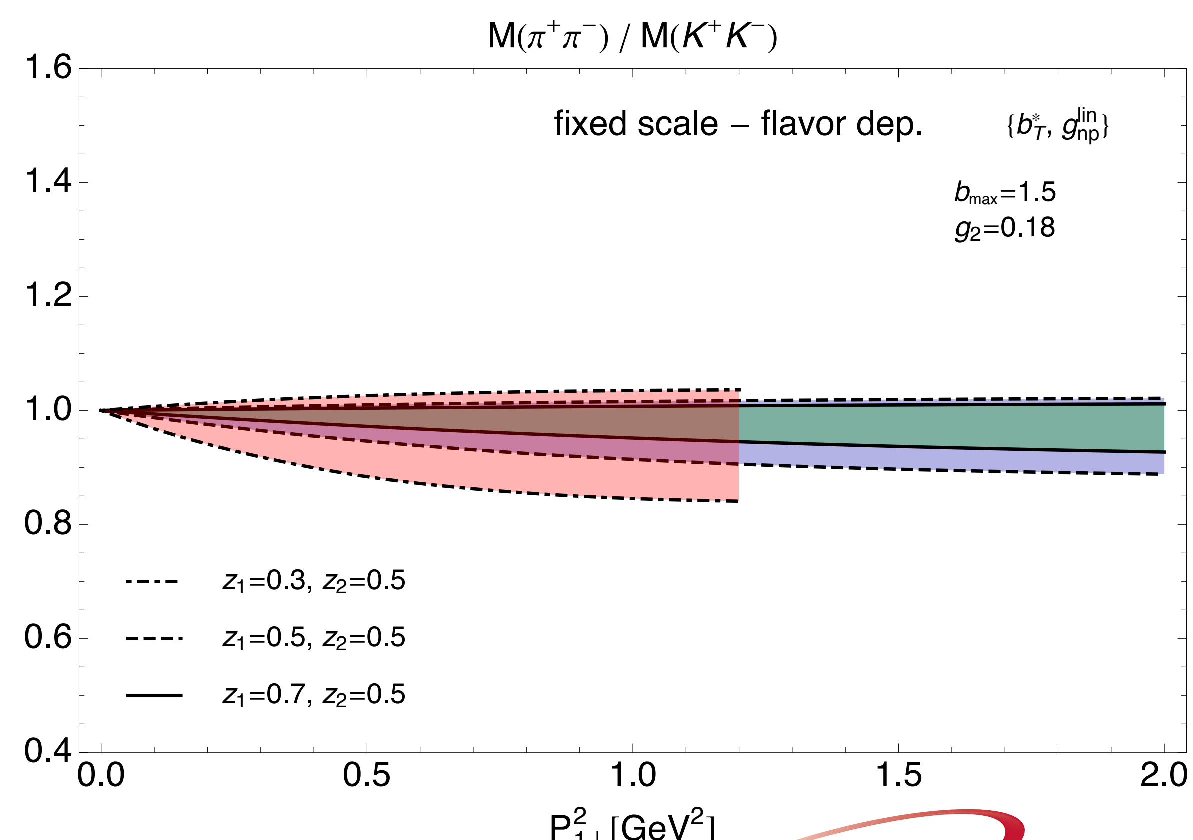


electron-positron



predictions



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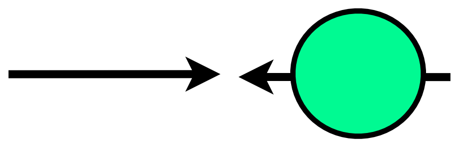
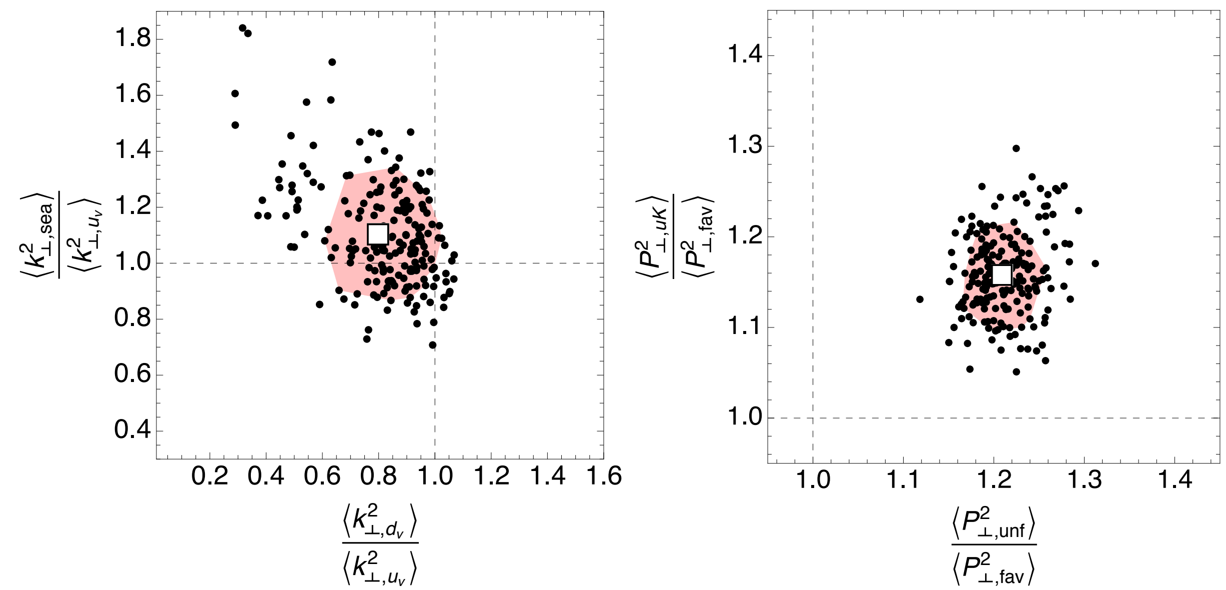
Flavor effects

AS, PhD thesis

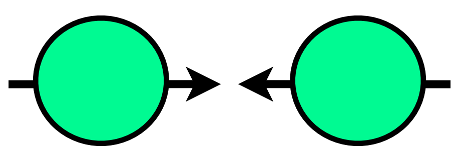
lepton-proton



extraction



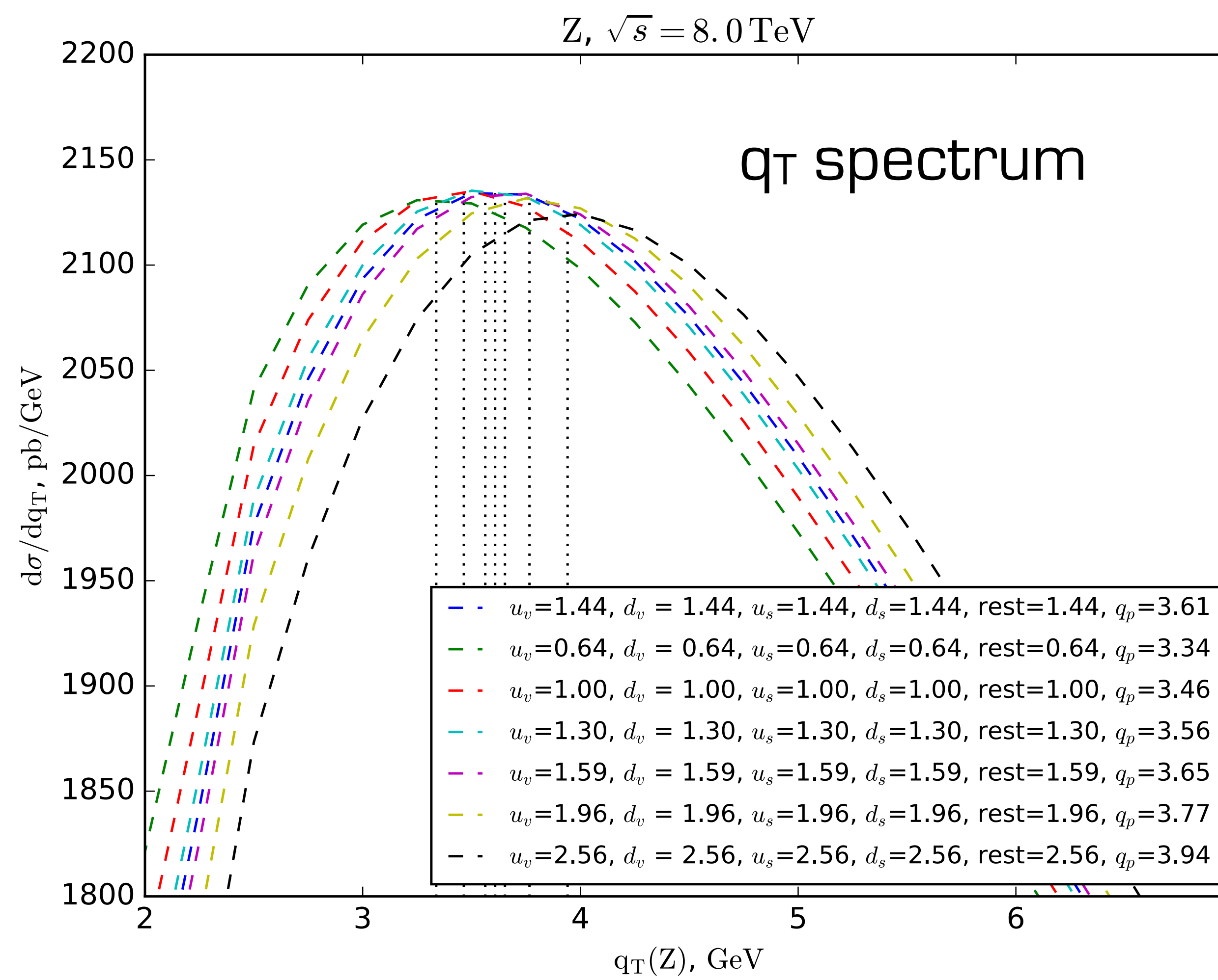
proton-proton



predictions

uncertainties
associated to
m_W extractions

work in progress!



W pT & mass

The **W pT spectrum** is sensitive to:

* **perturbative and non-perturbative parts of TMDs**

in particular the **flavor decomposition** of the TMDs in the **transverse momentum** has **not been taken into account yet!**

Observable sensitive to the **W mass** are:

* the **lepton pT distribution** (very sensitive to the treatment of W pT distribution)

* the **transverse mass**, defined as $m_T = \sqrt{2\ p_T^\ell\ p_T^\nu\ (1 - \cos(\phi_\ell - \phi_\nu))}$

(less sensitive to W pT distribution, due to its high sensitivity to detector effects)

see: S. Camarda - Measurement of the W mass with ATLAS - EPS 2017
G. Bozzi - Flavor dependent effects on the determination of mW (INT 17-68W)

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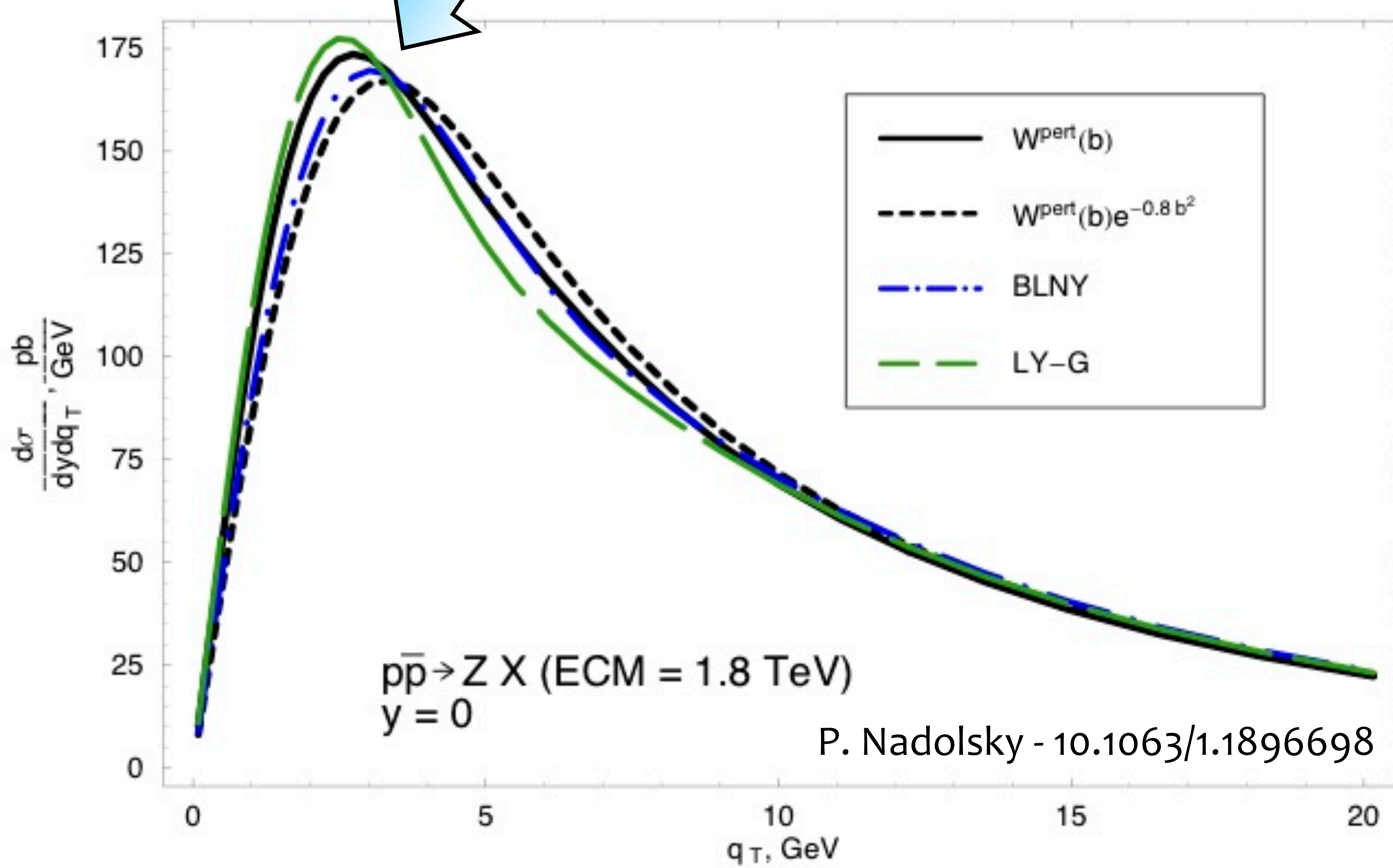
Nonperturbative effects

AS - PhD thesis

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

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

g_{ij} : determined by 2 TMD PDFs
affects the position of the peak



P. Nadolsky - 10.1063/1.1896698

Lab

Uncertainties: peak

AS - PhD thesis

	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
f.i. $\langle \mathbf{k}_T^2 \rangle = 1.0, 1.96$	$+0.16$	-0.16	$+0.16$	-0.14	$+0.16$	-0.15
f.d. $\langle \mathbf{k}_T^2 \rangle$ (max W^+ effect)	$+0.09$			-0.06	± 0	
f.d. $\langle \mathbf{k}_T^2 \rangle$ (max W^- effect)		-0.03	$+0.05$		± 0	

Table 7.2. Summary of the shifts in GeV for the peak position for q_T spectra of $W^\pm/Z$ arising from different sources. The colors for the flavor dependent (f.d.) and independent (f.i.) variations match the ones in Sec. 7.4.6.

anticorrelated shifts for W±, which keep the Z peak unchanged

the flavor dependence of the intrinsic partonic transverse momentum is inspired to the results in 10.1007/JHEP11(2013)194 (AS et al.)