

Hadron structure

A partial status of experimental and theory efforts

Reunión anual DPyC

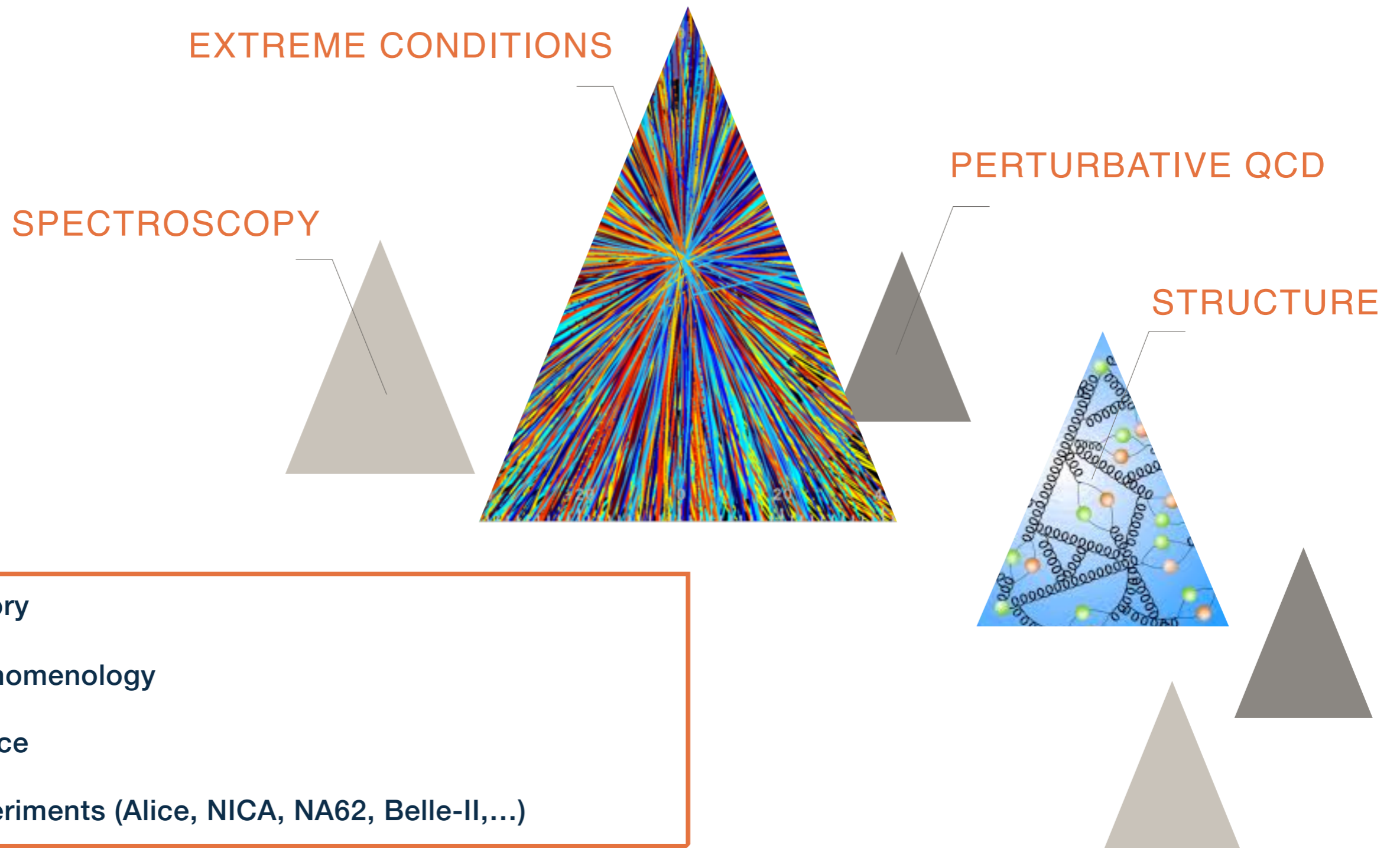
virtual

10/07/20

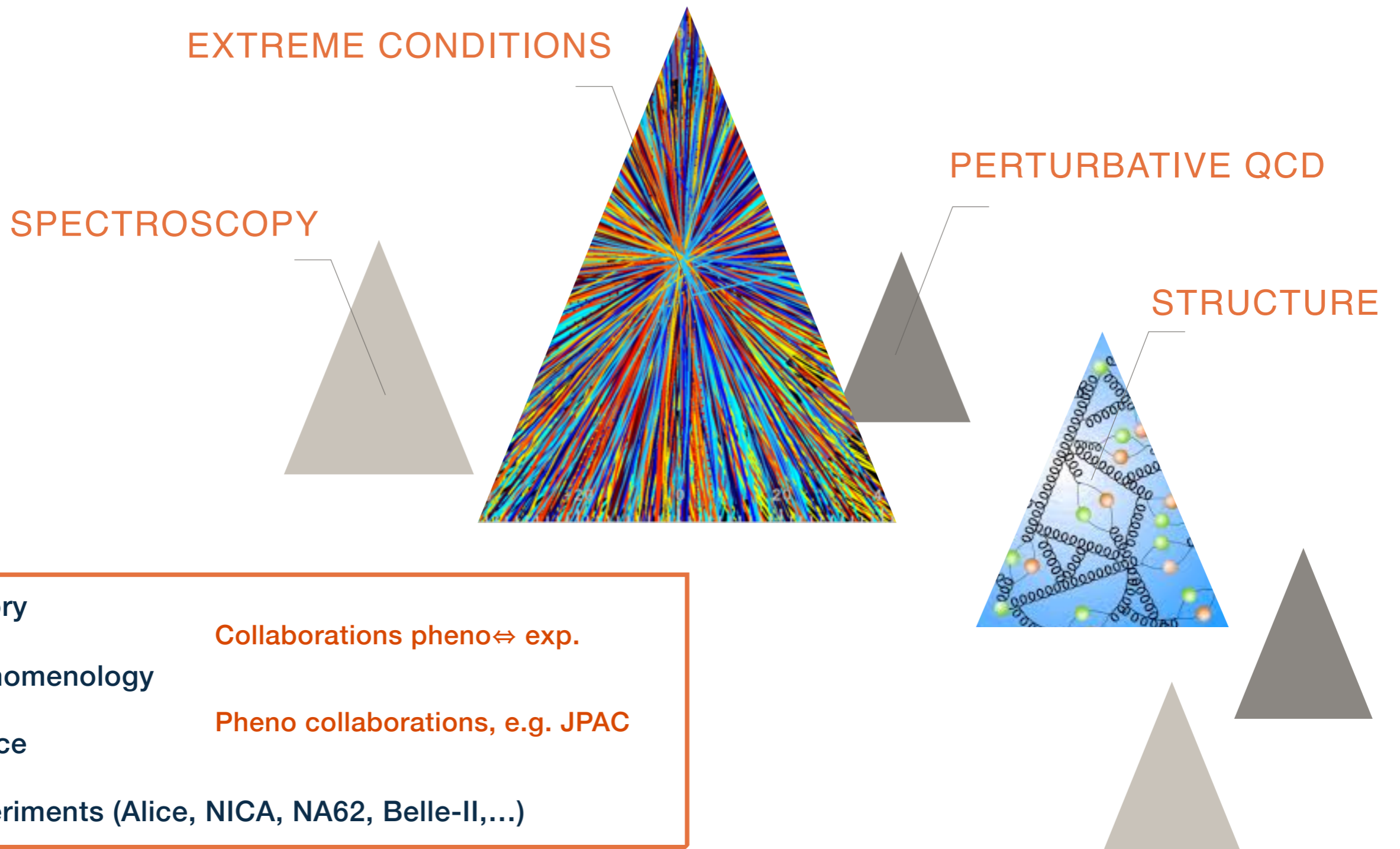
Aurore Courtoy

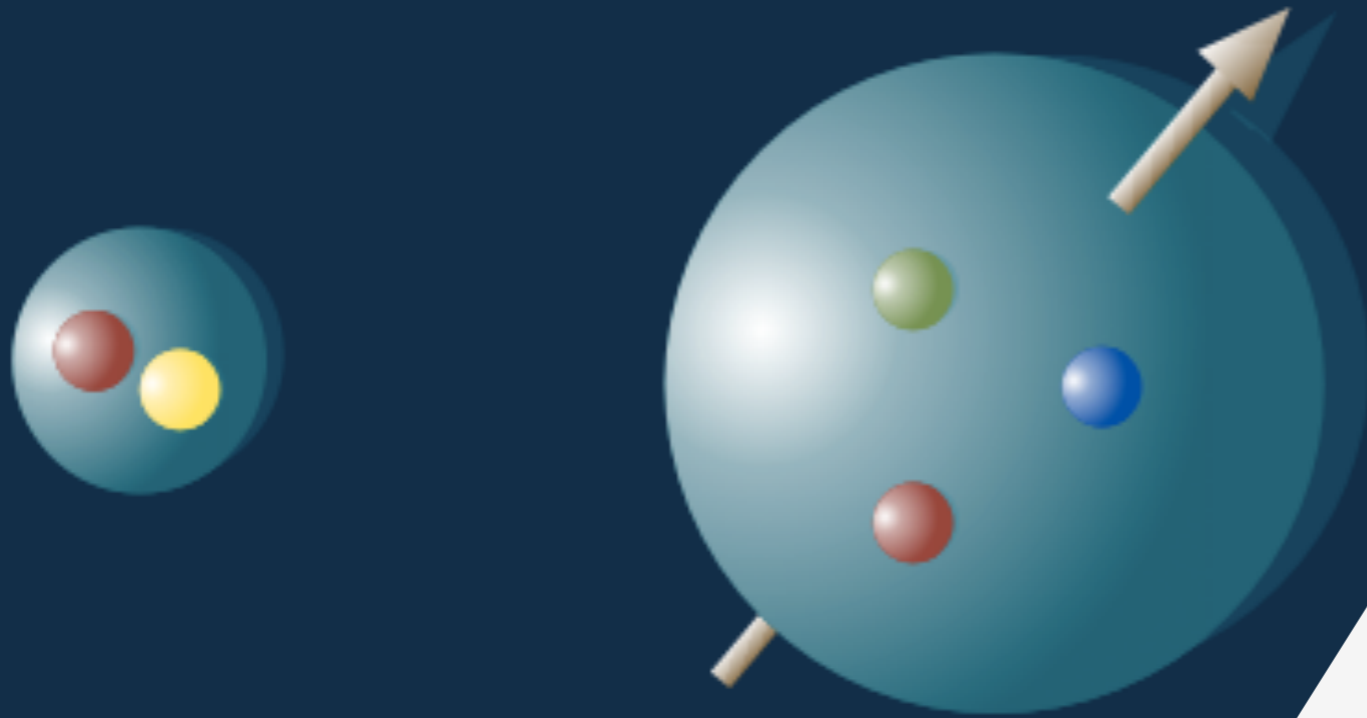
Instituto de Física, UNAM

QCD and Hadron Physics Community in Mexico



QCD and Hadron Physics Community in Mexico





HADRON STRUCTURE

PION AND PROTON

$u\bar{d}$

spin-0

$m_{\pi^+} \sim 140 \text{ MeV}$

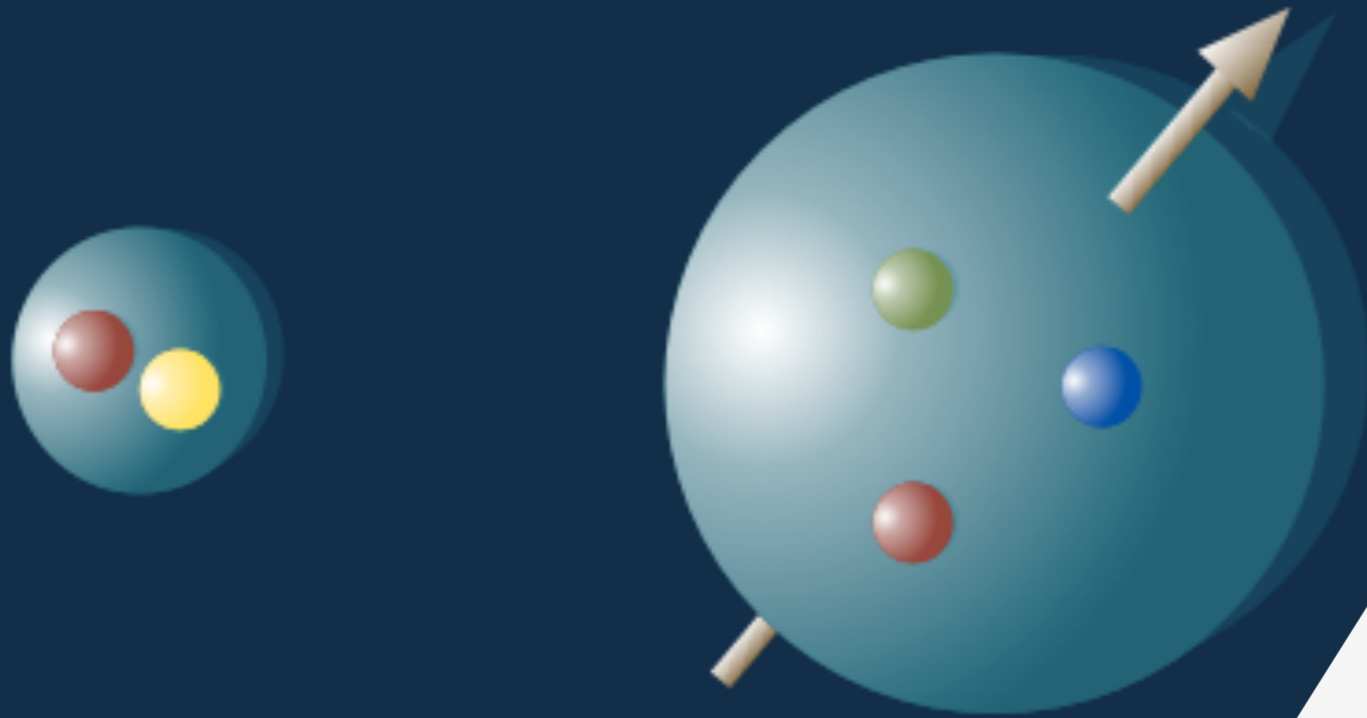
Pseudo Goldstone boson
Chiral symmetry breaking

uud

spin-1/2

$m_p \sim 1 \text{ GeV}$

Lightest baryon



HADRON STRUCTURE

PION AND PROTON

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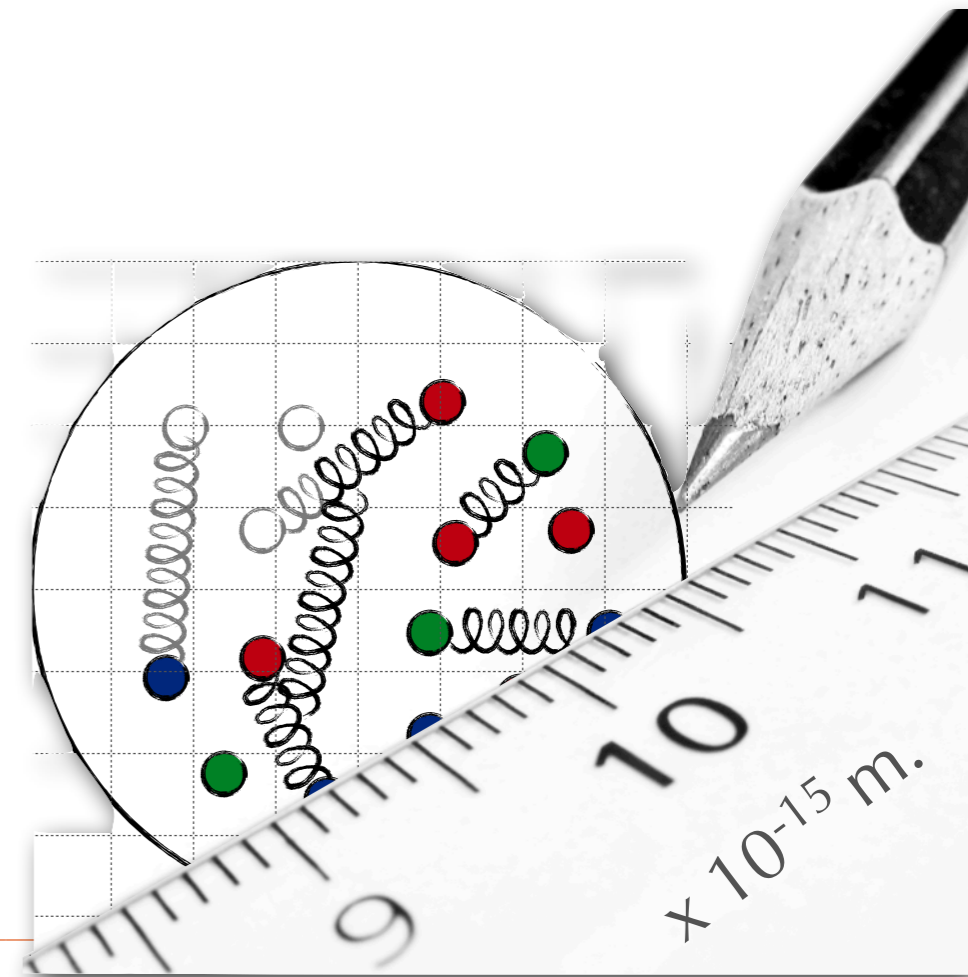
Lightest baryon

MY PARTIAL CHOICE:
CONSIDERING ONLY THOSE TWO HERE.

Abstract

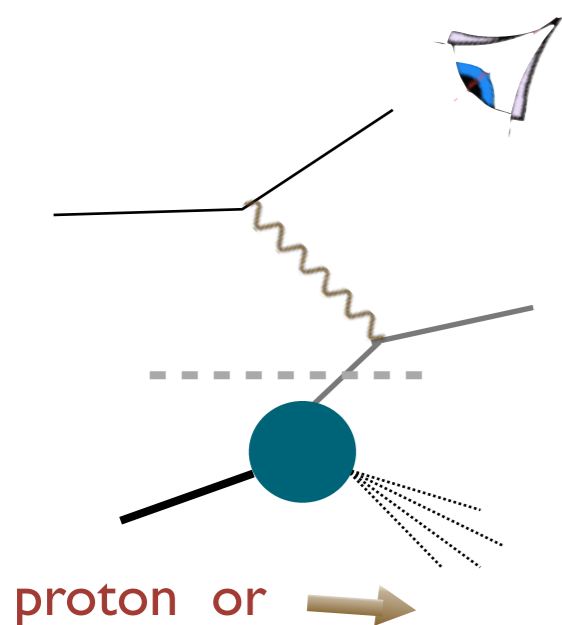
- ✦ **Objects defining hadron structure**
- ✦ **Status for the Proton**
 - ✦ PDF updates
 - ✦ Lattice improvements

} a beautiful marriage
- ✦ **Pheno prospect for the Proton**
 - ✦ EIC, JLab, LHCSpin,...
- ✦ **Pion in phenomenology**
 - ✦ EIC, JLab, AMBER/COMPASS++,...
- ✦ **Pion as a theoretical object**
 - ✦ Non-perturbative sophistication and elegance
 - ✦ Lattice improvements

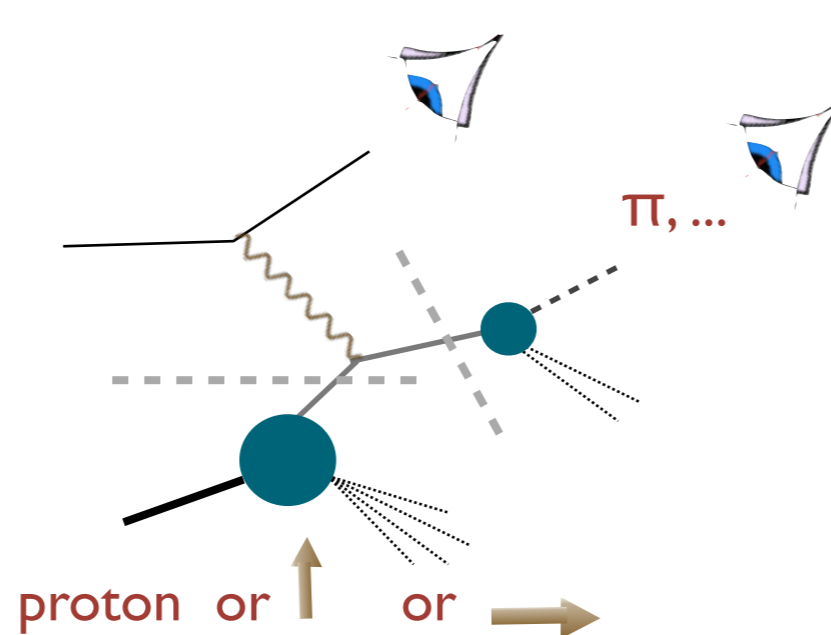


Hadron Structure

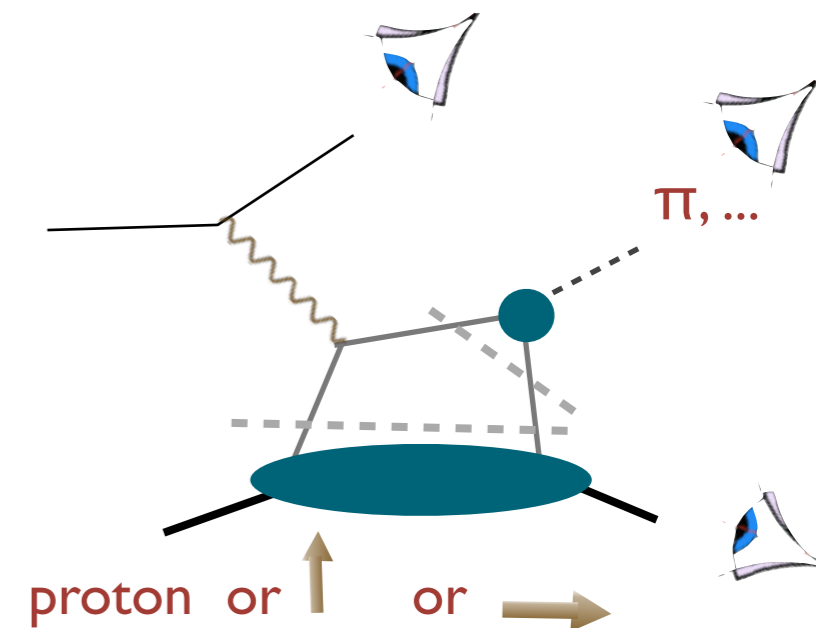
Examples of ...



Inclusive processes



Semi-inclusive processes



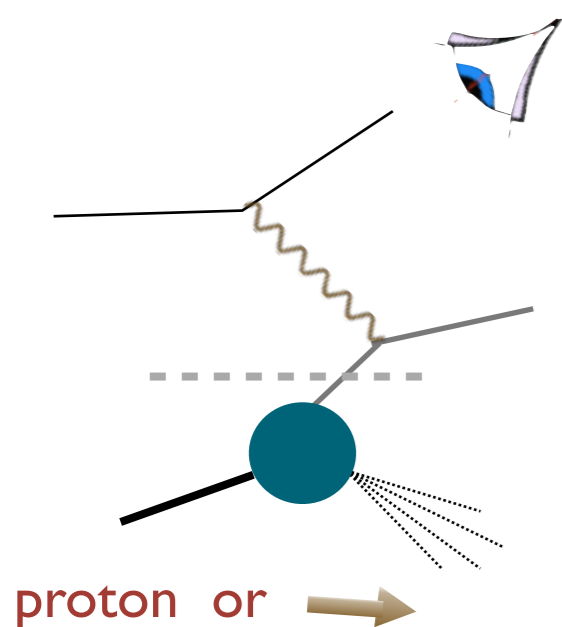
Exclusive processes

Factorization theorems.

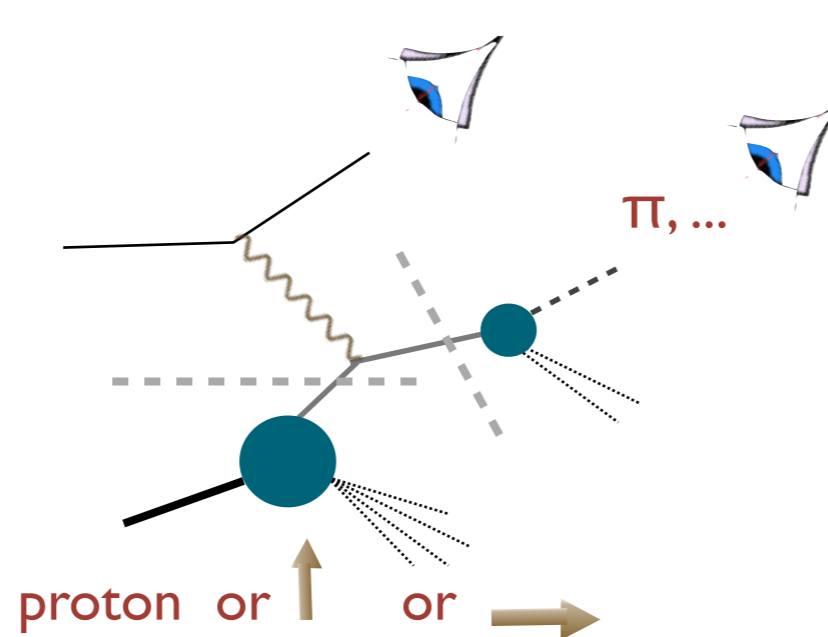
Definition of Non-Perturbative objects from pQCD.

Hard cross-section, corrections etc from pQCD too.

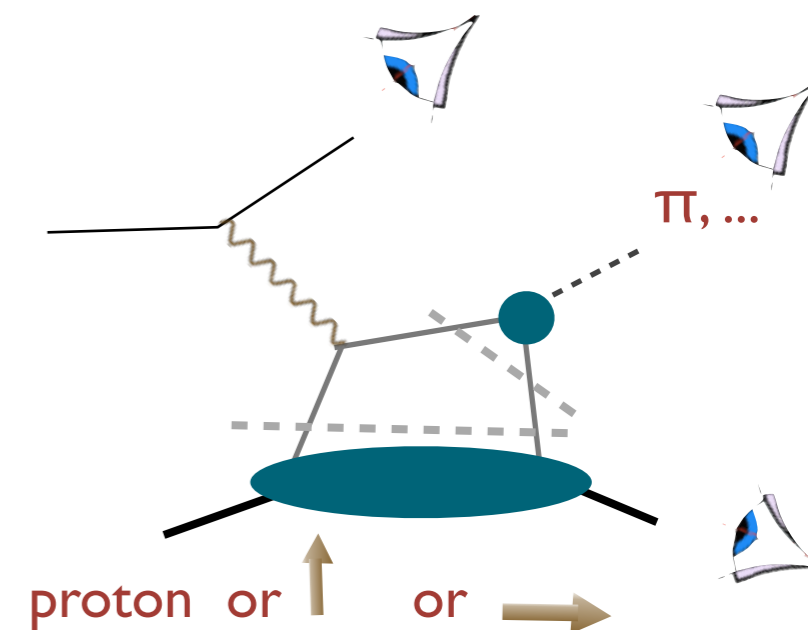
Hadron Structure



Inclusive processes



Semi-inclusive processes



Exclusive processes

Inclusive: Parton Distribution Functions $\rightarrow f(x, Q^2)$

Semi-inclusive: Transverse Momentum PDFs $\rightarrow f(x, k_T, Q^2)$ & Chiral-odd PDF

Exclusive: Generalized PDFs $\rightarrow f(x, \xi, t, Q^2)$

Fragmentation Functions $\rightarrow F(z, k_T, Q^2)$

Distribution Amplitude $\rightarrow \Phi(x, Q^2)$

Hadron Structure

to leading-twist

$$\phi_{ij}(k; p, s) = 2\pi \sum_X \int \frac{d^3\mathbf{P}_X}{2E_X} \delta^4(p - k - P_X) \langle p, s | \bar{\psi}_j(0) | X \rangle \langle X | \psi_i(0) | p, s \rangle$$

$$\phi(x, s) = \frac{1}{2} \left[\mathbf{f}_1(x) \not{n}_+ + s_L g_1(x) \gamma^5 \not{n}_+ + h_1 i \sigma_{\mu\nu} \gamma^5 n_+^\mu s_T^\nu \right]$$

The ubiquitous unpolarized PDF

Helicity PDF

Transversity PDF

Hadron Structure

to leading-twist

$$\phi_{ij}(k; p, s) = 2\pi \sum_X \int \frac{d^3\mathbf{P}_X}{2E_X} \delta^4(p - k - P_X) \langle p, s | \bar{\psi}_j(0) | X \rangle \langle X | \psi_i(0) | p, s \rangle$$

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The ubiquitous unpolarized PDF

Helicity PDF

Transversity PDF

Defined on the light-cone.

Bjorken-x: fraction of longitudinal momentum carried by active quark.

Factorization theorems to identify physical observables to connect to (see previous slide).

DGLAP evolution equations.

Status of Parton Distribution Functions-I

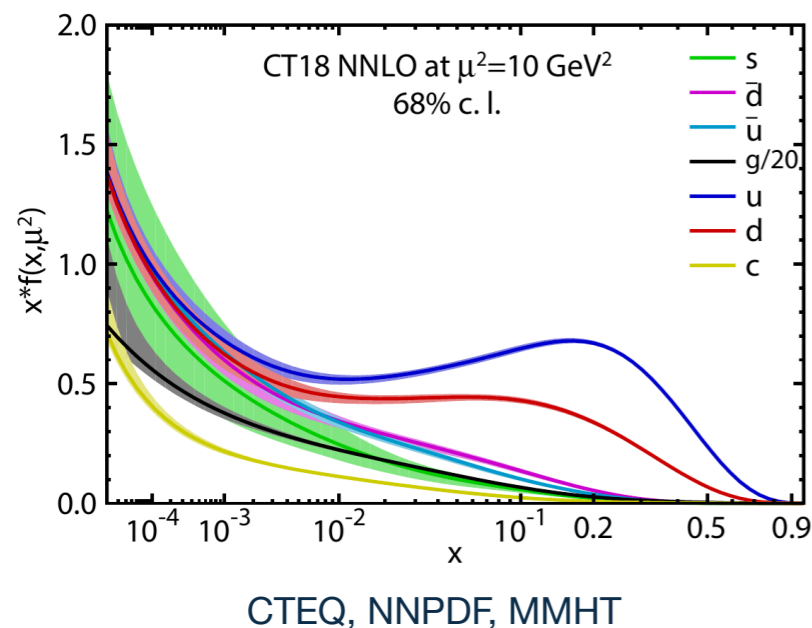
to leading-twist

PDFLattice [2006.08636]

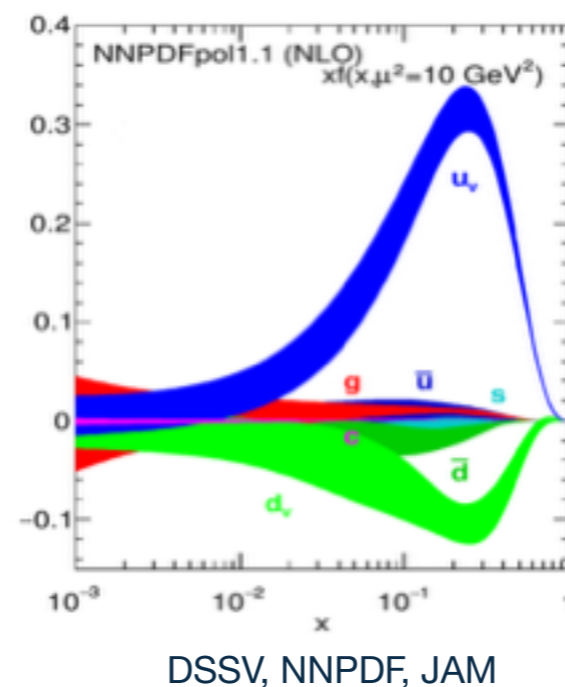
$$\phi_{ij}(k; p, s) = 2\pi \sum_X \int \frac{d^3\mathbf{P}_X}{2E_X} \delta^4(p - k - P_X) \langle p, s | \bar{\psi}_j(0) | X \rangle \langle X | \psi_i(0) | p, s \rangle$$

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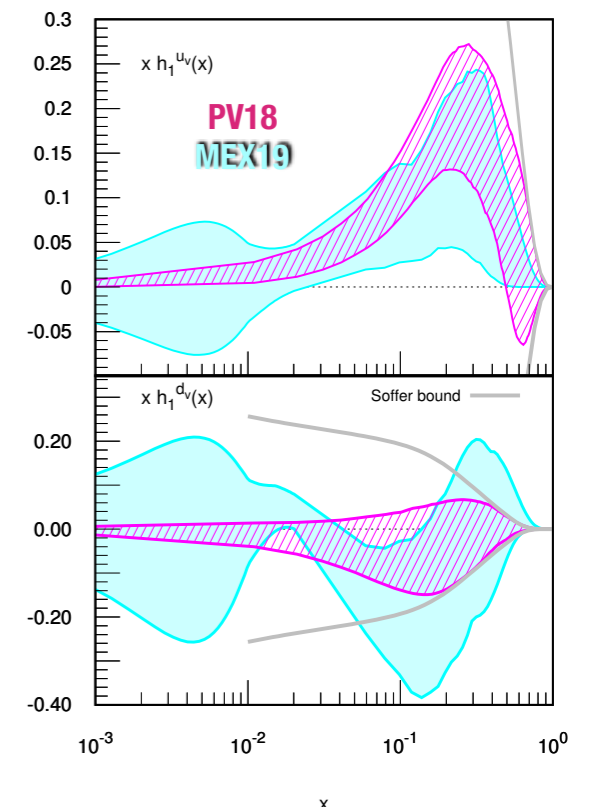
The ubiquitous unpolarized PDF



Helicity PDF



Transversity PDF



The Unpolarized PDF

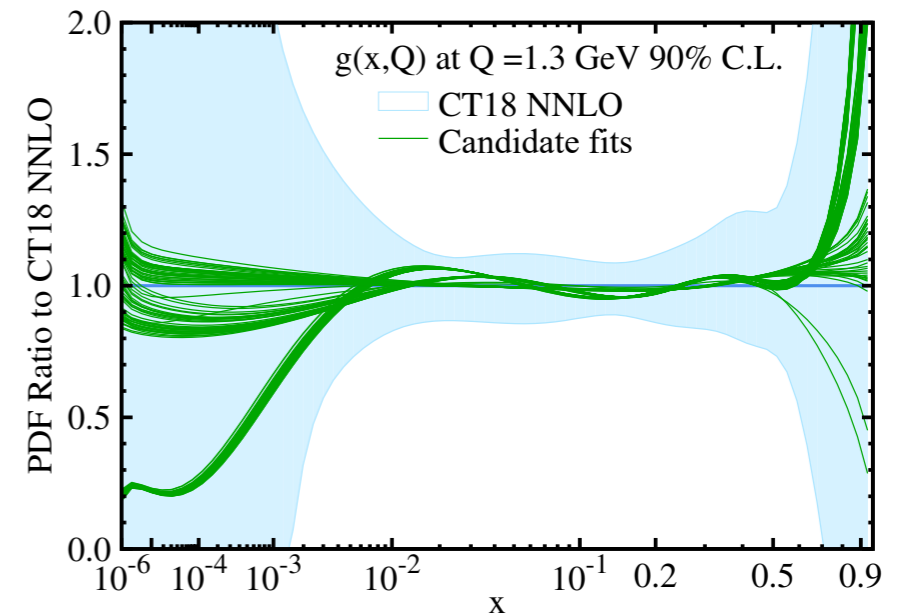
The ubiquitous unpolarized

- small and high- x ;
- PDF4LHC;
- First principle constraints
 - positivity
 - counting rules
 - charge and momentum sum rule
- Error treatment:
 - large data sets
 - theoretical errors from higher orders
 - error coming from the parametrizations

→ high degree of sophistication in statistical analysis

e.g. [Kovarik et al., 1905.06957]

Gluon PDF, an example



Different functional forms span the error band.

The Unpolarized PDF

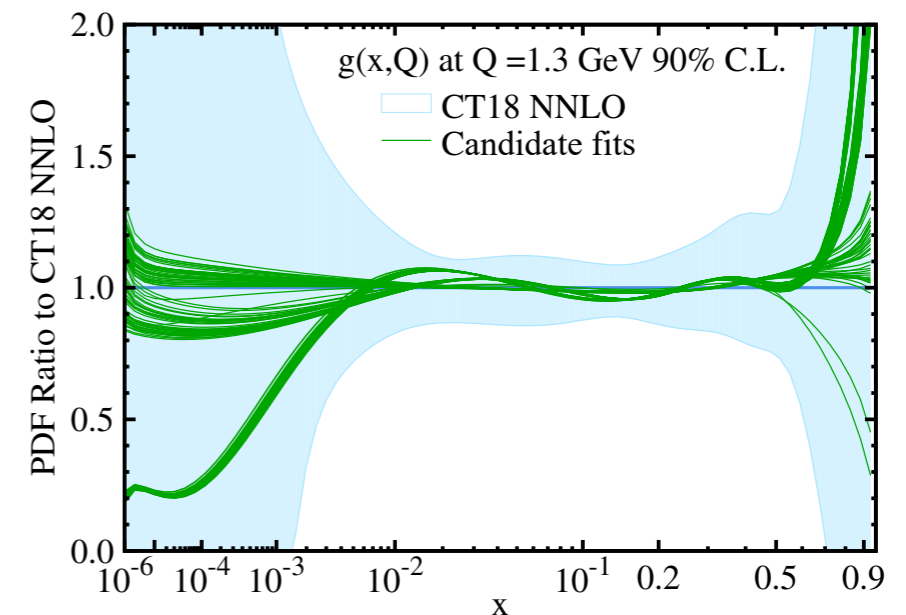
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Different functional forms span the error band.

The unpolarized PDFs are the best known PDFs.
Yet, they are characterized by an envelope or central value+error
especially at very small and very large x values.

The Unpolarized PDF

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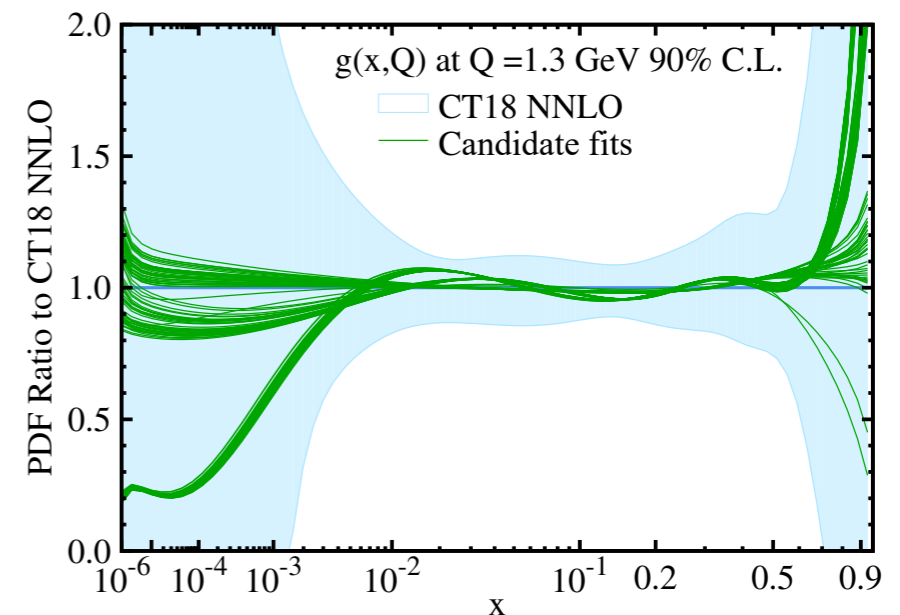
e.g. [Kovarik et al., 1905.06957]

→ recurrent question: which PDF set to use?

recommendations in PDF4LHC

[Butterworth, J., et al., J. Phys. G43, 023001, 1510.03865]

Gluon PDF, an example



Different functional forms span the error band.

The unpolarized PDFs are the best known PDFs.
Yet, they are characterized by an envelope or central value+error especially at very small and very large x values.

The Transversity PDF

The chiral-odd PDF

First principle based constraints on the Transversity

- Support, e.g. $x \in [0,1]$
- Endpoint behavior, e.g. $h_1(x=0,1)=0$
- Positivity bounds: Soffer bound

$$|h_1^q(x)| \leq \frac{1}{2} (f_1^q(x) + g_1^q(x))$$

Much less data than f_1

Chiral-odd partner

The Transversity PDF

The chiral-odd PDF

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→ **choice of functional form: a crucial step and a physical statement**

The Transversity PDF

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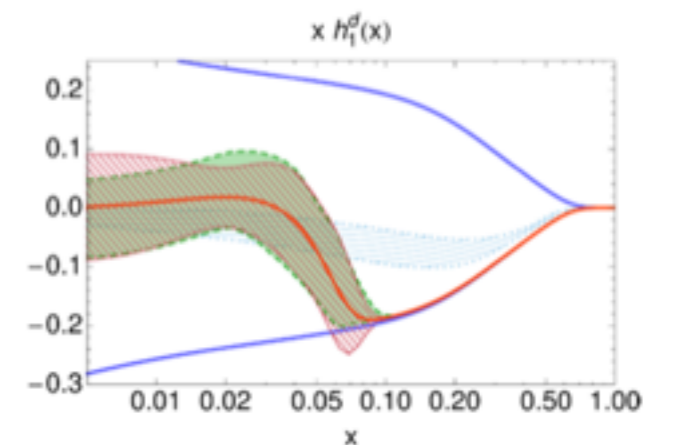
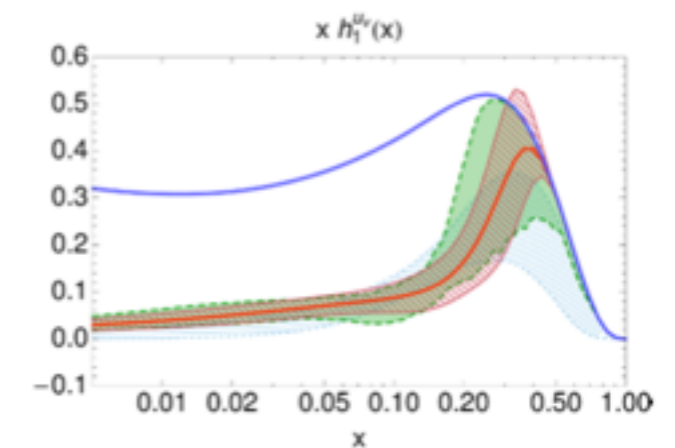
→ choice of functional form: a crucial step and a physical statement

$$x h_1(x) = \frac{F(x)}{|F(x)|} \times x \text{ Soffer Bound}$$

$$F(x) \propto x^\alpha (1-x)^\beta$$

Explicit: 1st choice

- comes from
1. the wisdom of previous leading-twist PDF fits
 2. based themselves on first principles



[Bacchetta, A.C., Radici, JHEP1303]

The Transversity PDF

→ increase flexibility to the fitting procedure

[Benel, AC, Ferro-Hernandez, Eur.Phys.J.C 80 (2020)]

Weight

$$\chi_r^2(\{p^I\}) = \sum_j w_j \frac{\left[x_j h_{1,\text{theo}}^{p/D}(x_j; \{p^I\}) - \left(x h_1^{p/D}(x) \right)_{j,r \text{ data}} \right]^2}{\sigma_j^2}$$

by the probability of the bound

Bootstrap

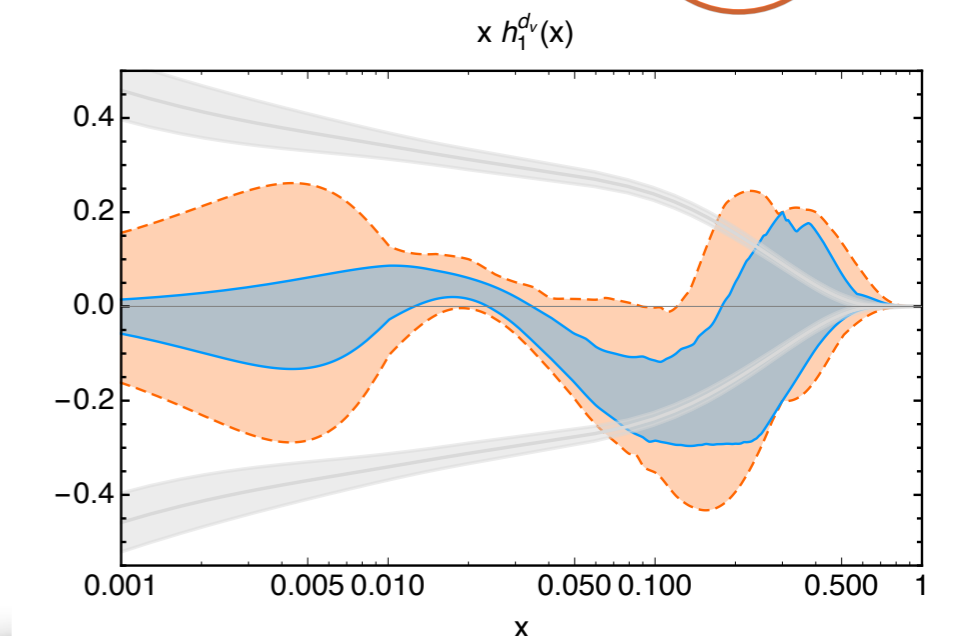
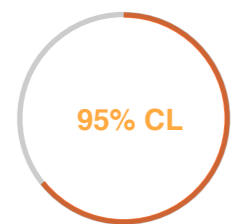
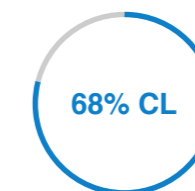
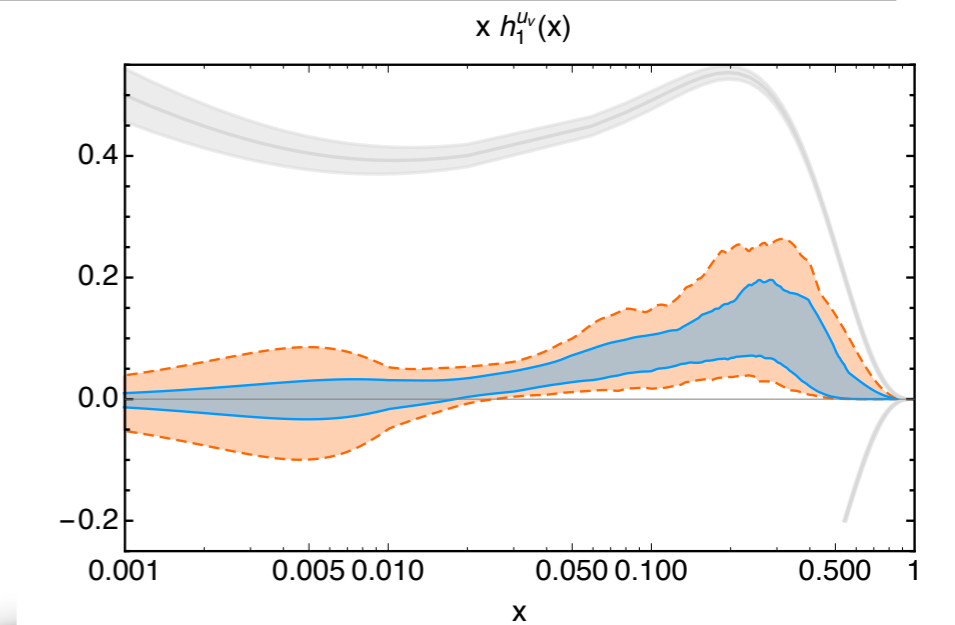
$$x h_{1,i}^{qv}(x; p_{i,k}^q) = x^{1.25} \sum_{k=\{\kappa_{q,i}\}} p_{i,k}^q B_{k,n_i}(g(x))$$

error treatment

Constrain

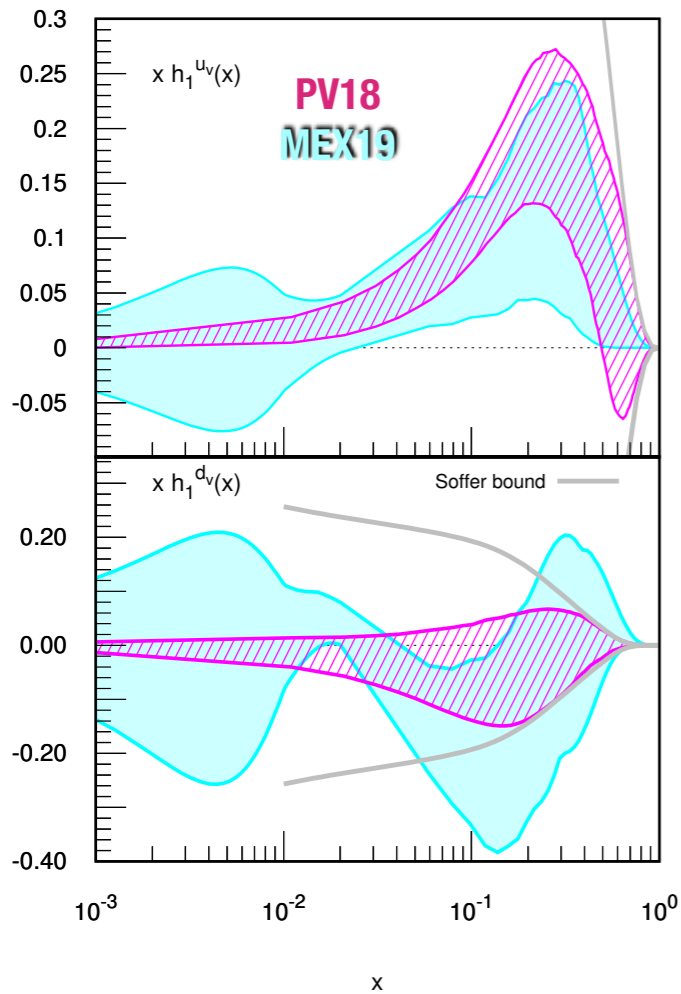
$$\begin{aligned} C_{i,j}^{dv}(p_{i,k}^{dII}) &= h_{1,i}^{qv}(x_j; p_{i,k}^{dII}) < \epsilon_j \\ C_{i,j}^{dv}(p_{i,k}^{dII}) &= h_{1,i}^{qv}(x_j; p_{i,k}^{dII}) > -\epsilon_j \end{aligned}$$

the large-x behavior to make it physical



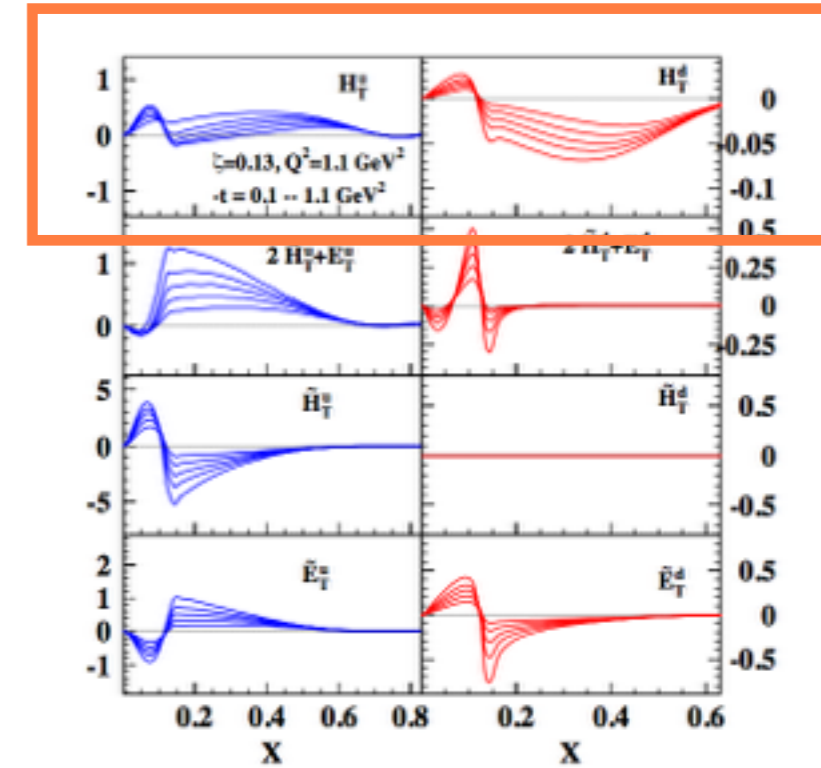
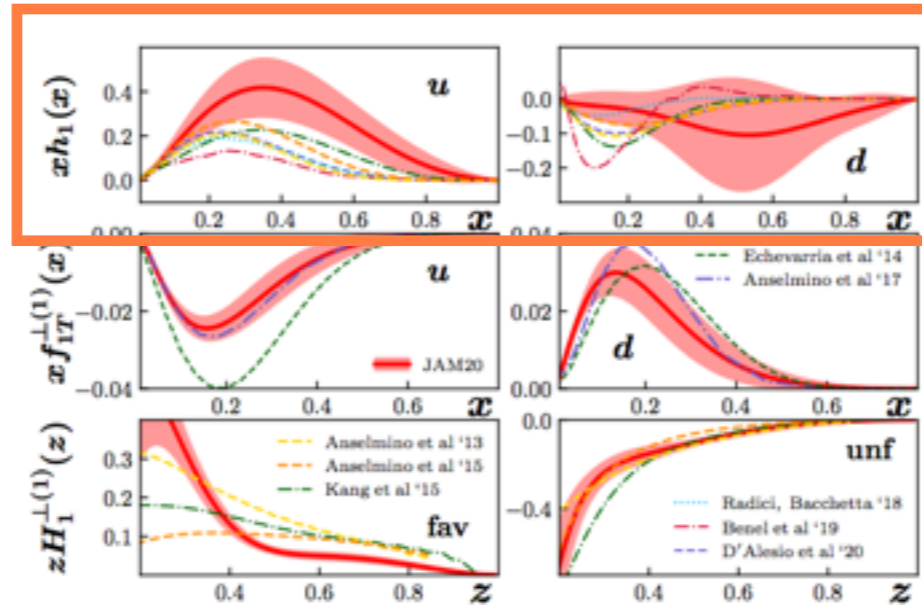
The Transversity: PDF – TMD – GPD

Radici and Bacchetta, PRL120 (2019)
 Benel, AC, Ferro-Hernandez, Eur.Phys.J.C 80 (2020)



$$f^q(x, k_T^2) = f^q(x) G_f^q(k_T^2),$$

Cammarota et al. 2002.08384



Goldstein et al, PRD 2015

$$H_T(X, 0, 0) = h_1(X),$$

Multidimensional partonic structure

Phenomenology:

→ Global fits including TMDs: JAM20: Cammarota et al. 2002.08384

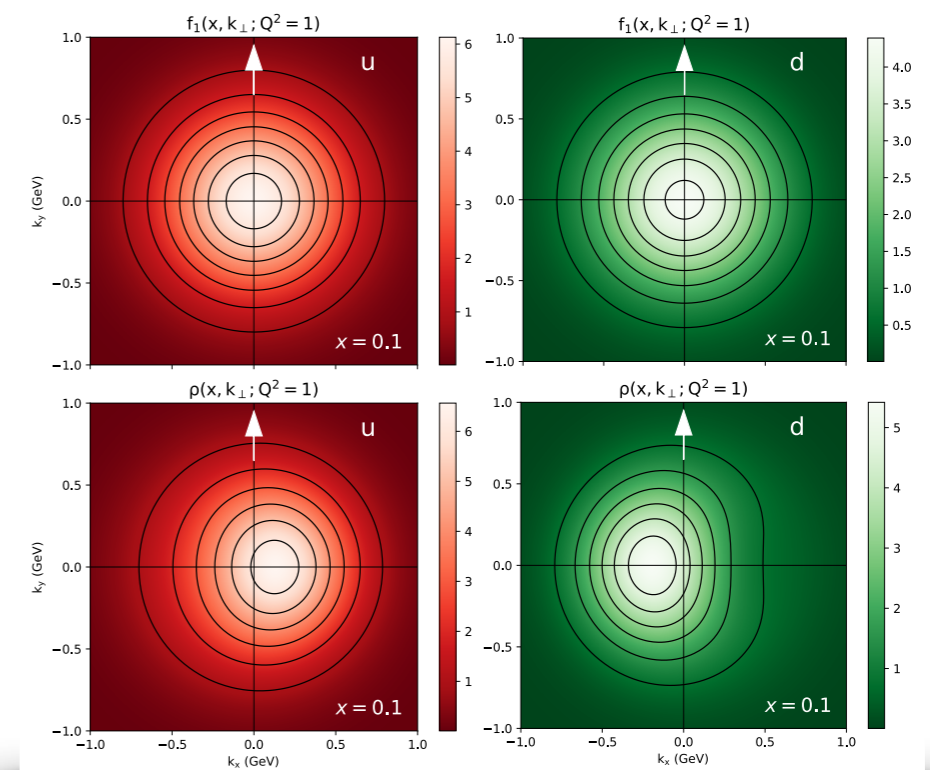
→ Focused fits of TMDs

- unpolarized: PV17: Bacchetta et al. JHEP 06, 081,1703.10157
- polarized: PV20: Bacchetta et al. 2004.14278

$$f_{q/N^\uparrow}(x, k_x, k_y) = f_1^q(x, k_T^2) - f_{1T}^{\perp q}(x, k_T^2) \frac{k_x}{M}$$



Sivers function



Multidimensional partonic structure

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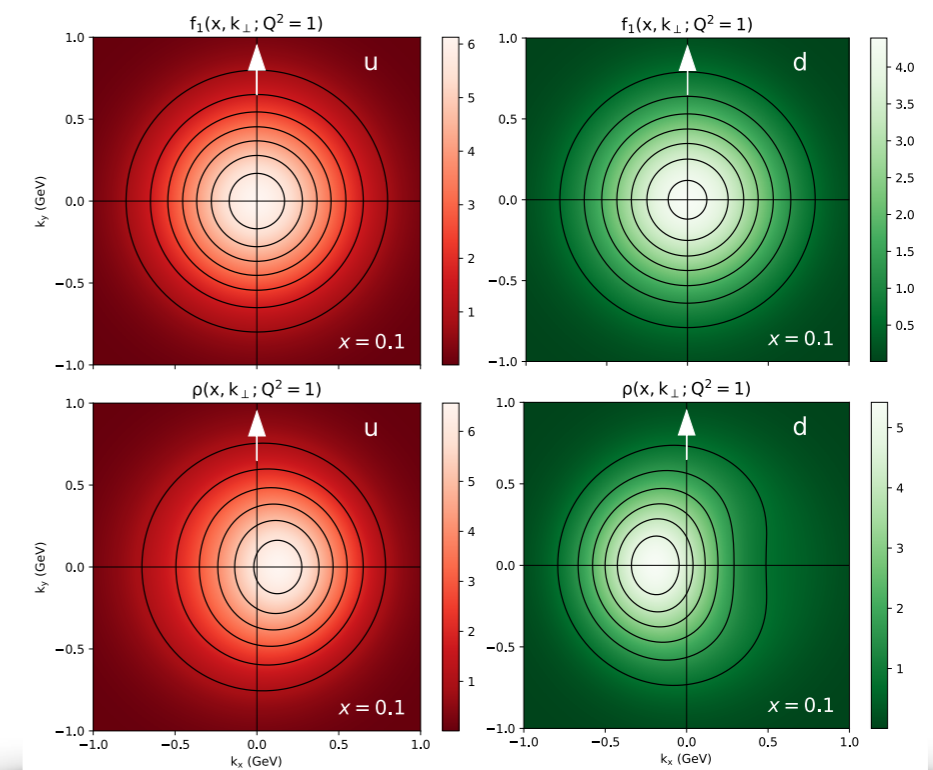
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Sivers function



Involve improvements from the theory side

→ TMD factorization and evolution (CSS)

→ see Collins, Rogers ; Scimemi, Vladimirov for recent developments

Applied to pheno:

Pion-induced Drell-Yan

in: Vladimirov, JHEP 10 (2019),1907.10356

More on this in the next part

Lattice and PDFs

I—Mellin Moments

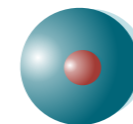
Mellin moments

$$\langle x^n \rangle = \int_0^1 dx x^n f(x)$$

$$n = 0, 1, \dots$$

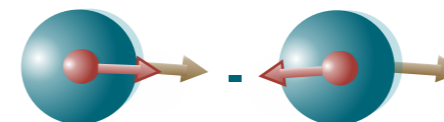
Benchmark quantities

$$\langle x \rangle_{u^+ - d^+}(\mu^2) \Big|_{\mu^2=Q^2} = \int_0^1 dx x \{ u(x, Q^2) + \bar{u}(x, Q^2) - d(x, Q^2) - \bar{d}(x, Q^2) \}$$



$$\langle x \rangle_{u^+}, \quad \langle x \rangle_{d^+}, \quad \langle x \rangle_{s^+}, \quad \langle x \rangle_g$$

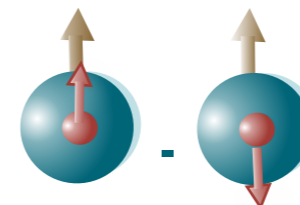
$$\langle 1 \rangle_{\Delta u^+ - \Delta d^+}(\mu^2) \Big|_{\mu^2=Q^2} = \int_0^1 dx \{ \Delta u(x, Q^2) + \Delta \bar{u}(x, Q^2) - \Delta d(x, Q^2) - \Delta \bar{d}(x, Q^2) \}$$



$$\langle 1 \rangle_{\delta u^-}, \quad \langle 1 \rangle_{\Delta d^+}, \quad \langle 1 \rangle_{\Delta s^+},$$

$$\langle x \rangle_{\Delta u^- - \Delta d^-};$$

$$g_T(Q^2) \equiv \langle 1 \rangle_{\delta u^- - \delta d^-}(Q^2) = \int_0^1 dx \{ h_1^{u^-}(x, Q^2) - h_1^{d^-}(x, Q^2) \}$$



$$\langle 1 \rangle_{\delta u^-}, \quad \langle 1 \rangle_{\delta d^-}.$$

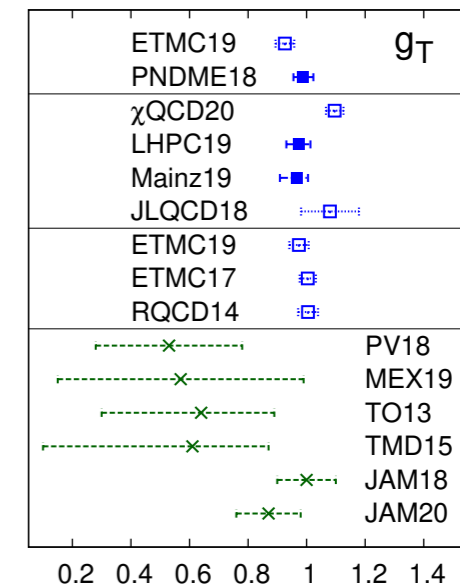
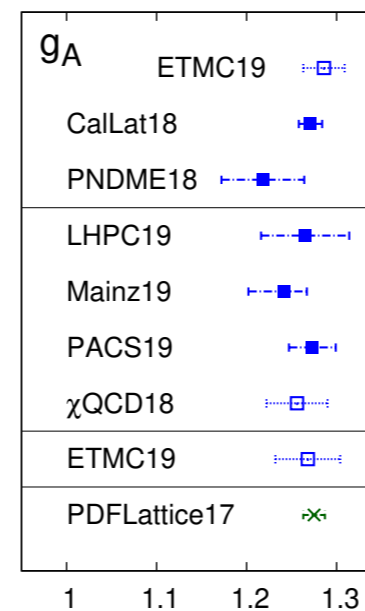
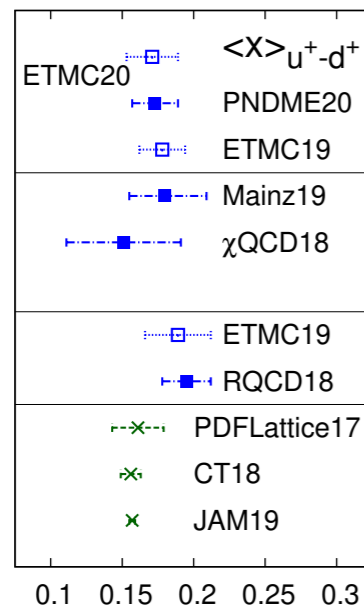
Lattice and PDFs

I—Mellin Moments

Summary tables of results for both Lattice and Global Fits of PDFs

→ “FLAG” for moments from pheno and lattice altogether

→ available here: PDFLattice: Constantinou, AC, Ebert et al. [2006.08636]



Moment	Lattice QCD	Global Fit
$\langle x \rangle_{u^+ - d^+}$	0.153 — 0.194 ^a	0.161(18)
	0.111 — 0.209 ^b	
	0.166 — 0.212 ^c	

Moment	Lattice QCD	Global Fit
g_A	1.179 — 1.309 ^a	1.258(28)
	1.202 — 1.314 ^b	
	1.268(36) ^{c,†}	

Moment	Lattice QCD	Global Fit
g_T	0.894 — 1.023 ^a	0.10 — 1.1
	0.909 — 1.175 ^b	
	0.941 — 1.039 ^c	

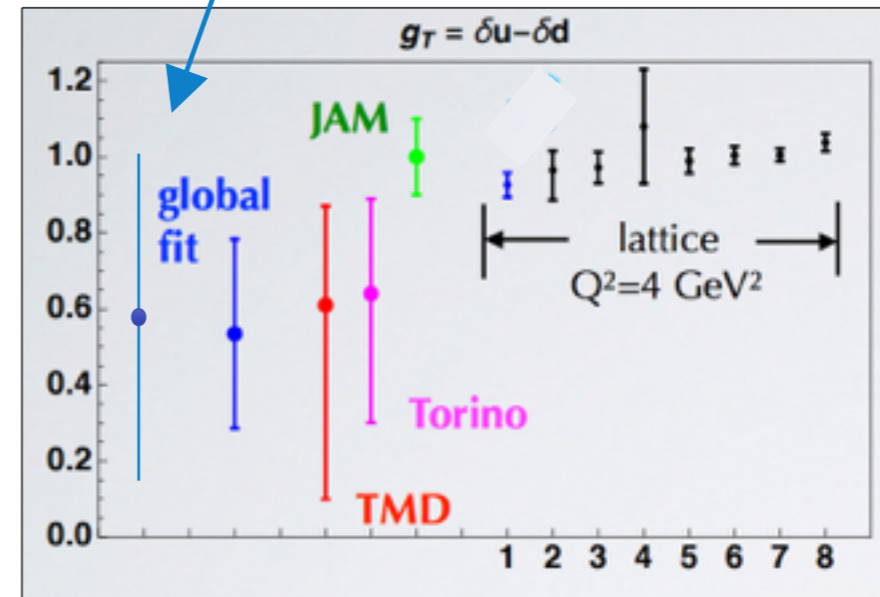
^a $N_f = 2 + 1 + 1$ ^b $N_f = 2 + 1$ ^c $N_f = 2$

Tensor Charge: An Open Question

It is possible to get an **accordance with lattice g_T** with more flexibility in the functional form.

Mex19

From M. Radici at PDFLattice 2019

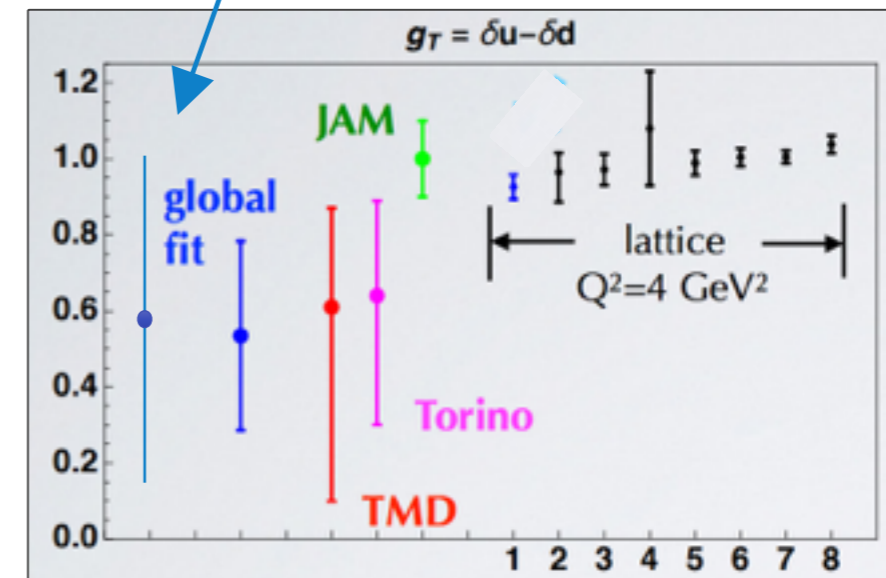


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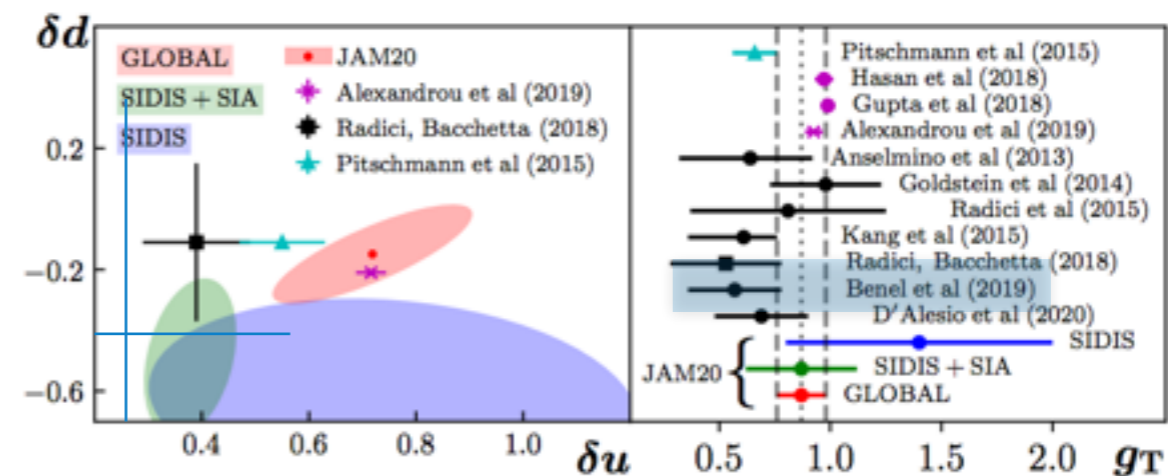
It is possible to get an **accordance with lattice g_T** with more flexibility in the functional form.



Recent analyses with a **wild** relaxation of the SB get a full agreement with lattice.

Cammarota et al. 2002.08384

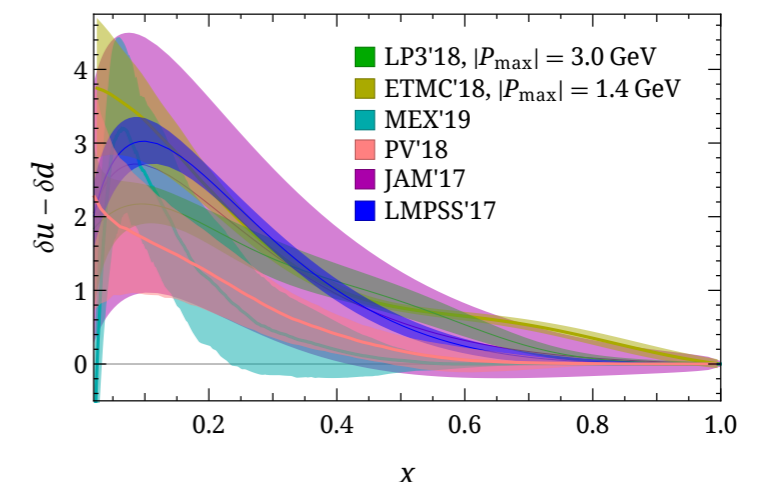
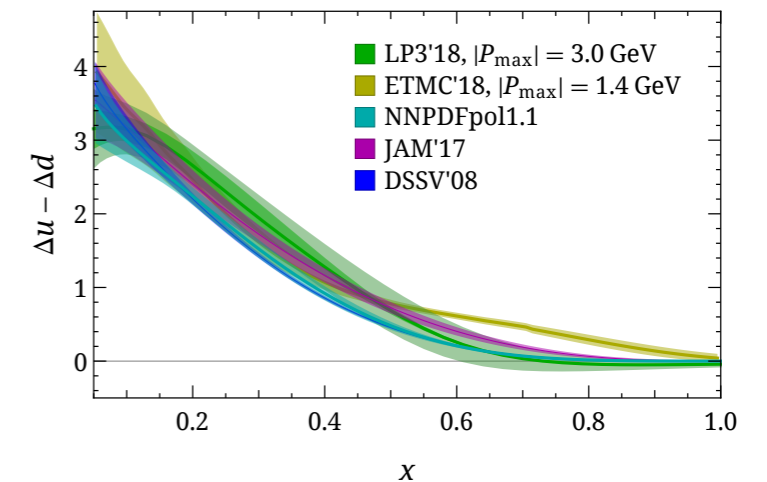
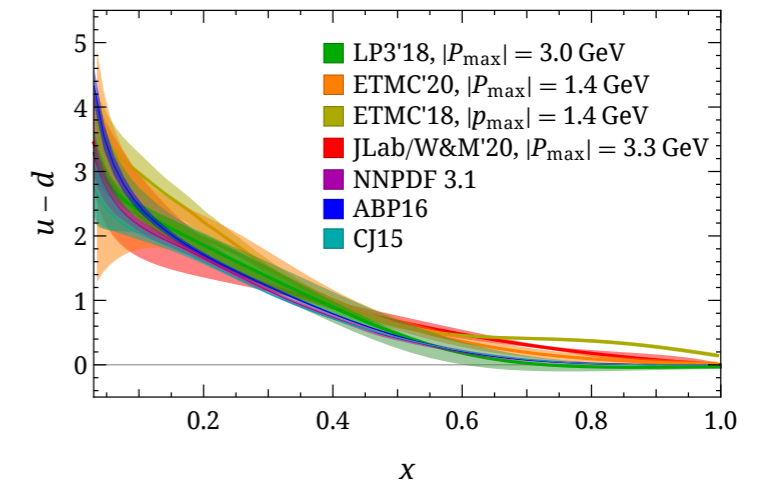
δu is the most problematic and yet most determined.



Lattice and PDFs

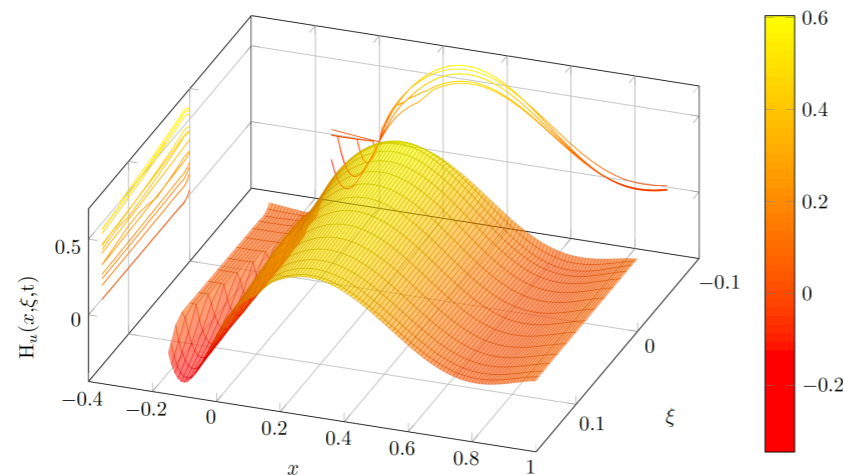
II – Bi-local PDFs

- Quasi-PDF and/or Pseudo-PDFs → Minkowski version of the light-cone PDFs
- Transform and matching procedure to light-cone PDFs
 - Each step is associated to systematic uncertainties and theoretical challenges



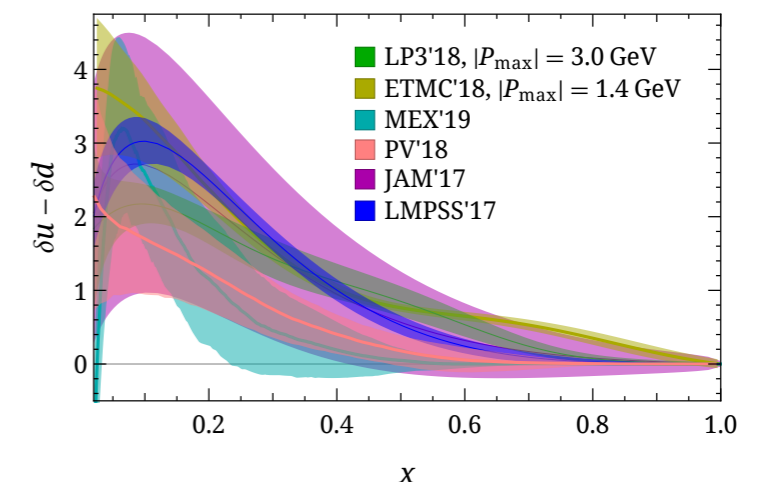
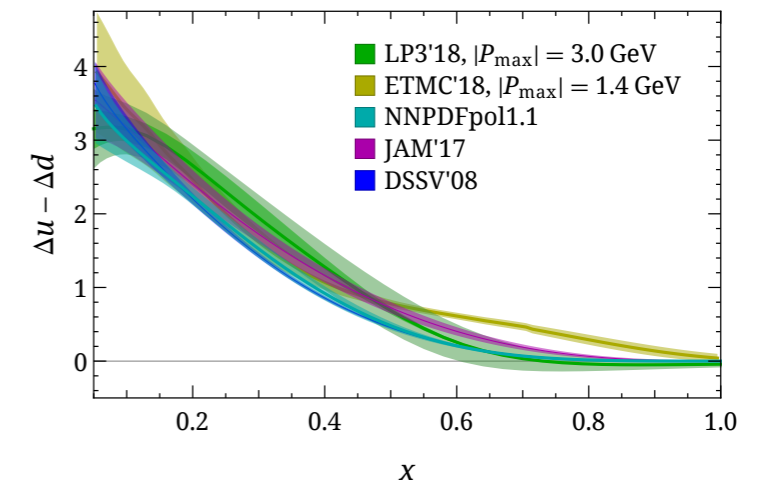
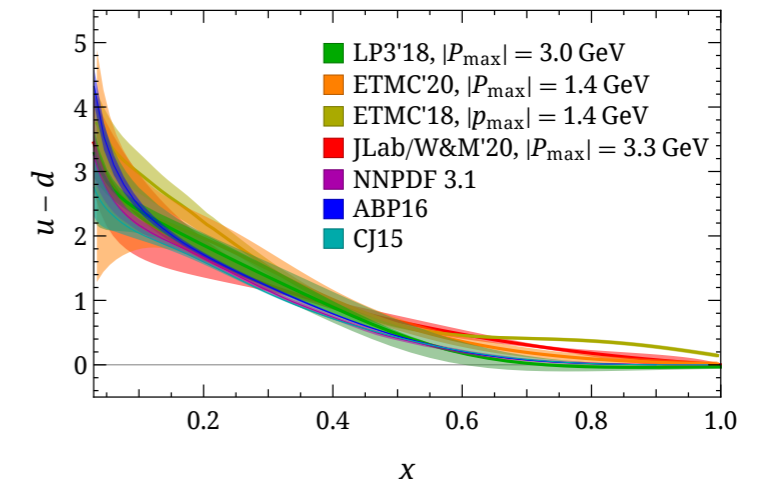
Lattice and PDFs

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- Exploiting Lattice QCD
 - Using lattice moments to reconstruct/reweight PDFs
 - Using lattice moments as data
 - ...



The GPD H for the u quark at $t = 0.1 \text{ GeV}^2$ reconstructed using the Generalized Form Factors calculated on the lattice.
Liuti & Rajan

II – Bi-local PDFs



New Experiments

→ unpolarized PDFs

sensitive to high-energy experiments (e.g. LHC)
& low- and mid-energy experiments
(did we mention it was ubiquitous?)

→ polarized PDFs

accessible with polarized target
mainly low- and mid-energy experiments

→ Multidimensional Distribution Functions

more involved experimentally
mainly low- and mid-energy experiments

New Experiments

→ unpolarized PDFs

sensitive to high-energy experiments (e.g. LHC)
& low- and mid-energy experiments
(did we mention it was ubiquitous?)

→ polarized PDFs

accessible with polarized target
mainly low- and mid-energy experiments

→ Multidimensional Distribution Functions

more involved experimentally
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The only good news of 2020: EIC to be built



Ongoing

Proposal



Next: JLab Hall A too

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Ongoing



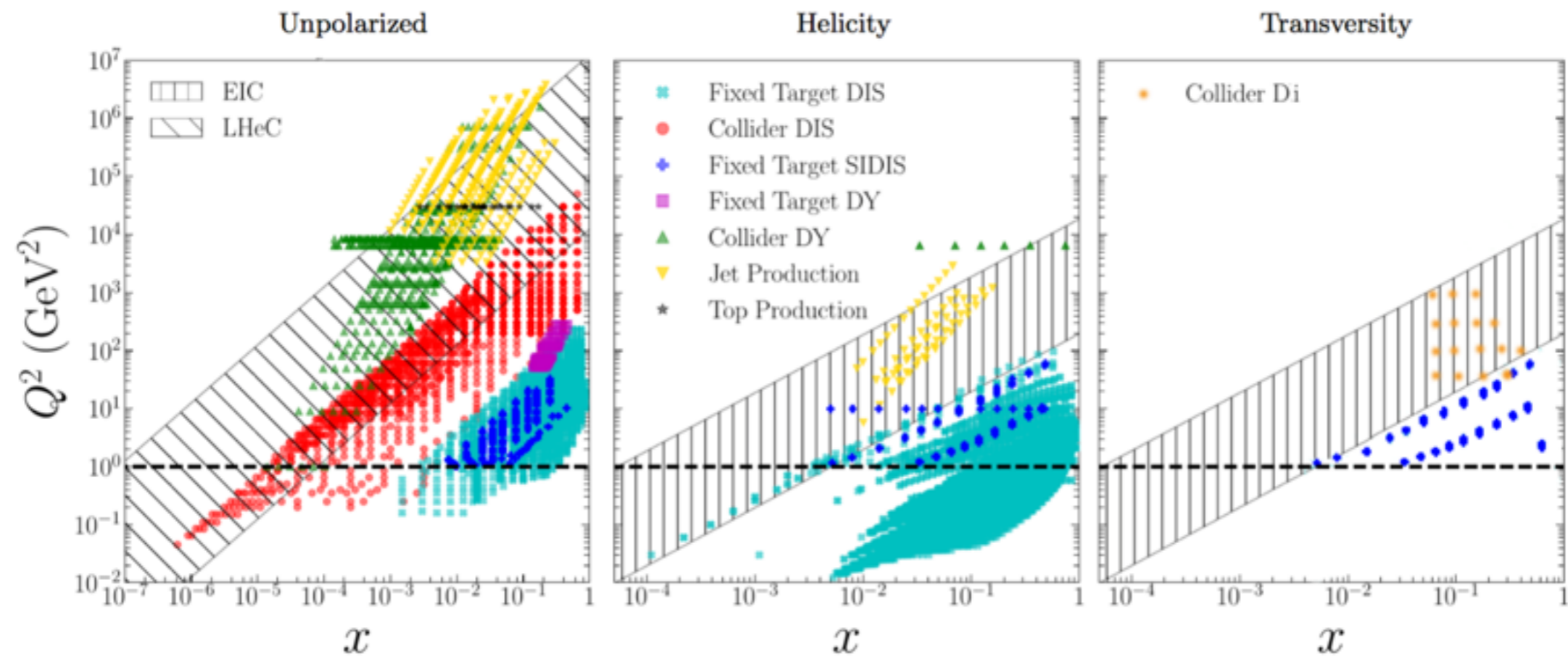
Proposal



Next: JLab Hall A too

PDF kinematics coverage: EIC and future experiments

PDFLattice [2006.08636]



Data Coverage and Fit Sensitivity

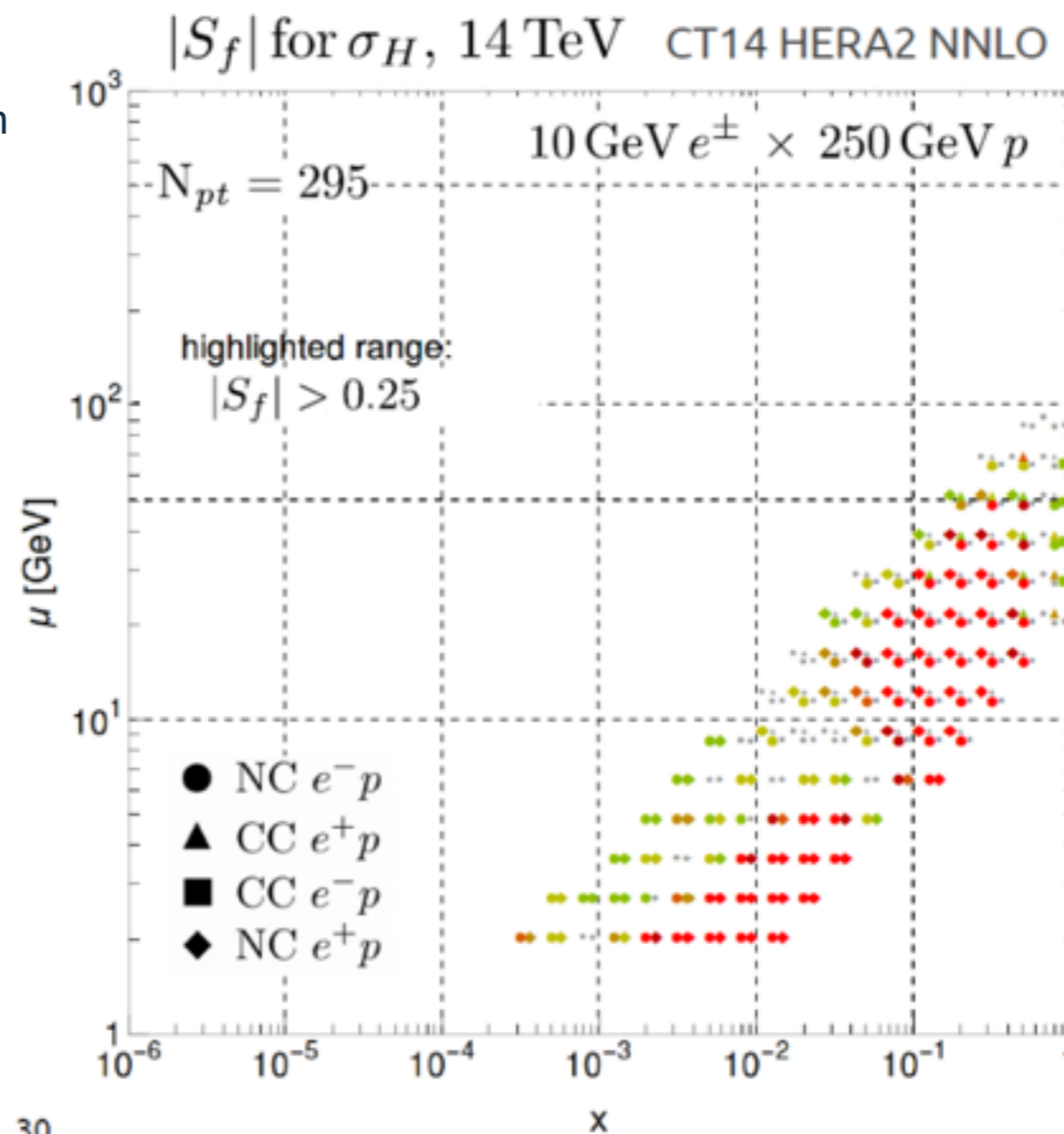
Impact of EIC on unpolarized PDFs

- Deep Inelastic
- Gluon PDF through scaling violations
- Gluon PDF relevant for, *e.g.*, Higgs production

Sensitivity

- PDFSense: correlation between observable and objective function of a given fit.
- More info here: Phys.Rev. D98 (2018) & Phys.Rev.D 100 (2019)

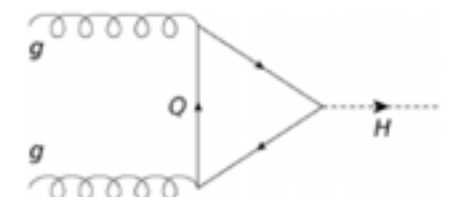
Slide by T. Hobbs and P. Nadolsky, DIS19



...a US-based EIC will also have important HEP consequences, *e.g.*, on Higgs physics

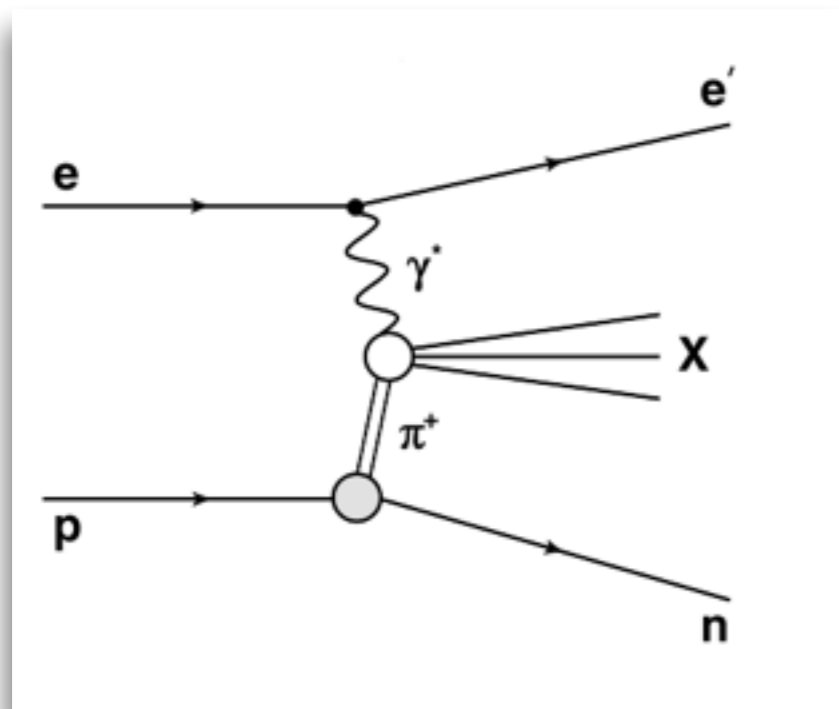
- the impact of an EIC upon the theoretical predictions for inclusive Higgs production arises from a very broad region of the kinematical space it can access

- impact rather closely tied to that of the integrated gluon PDF:



Experiments: the pion

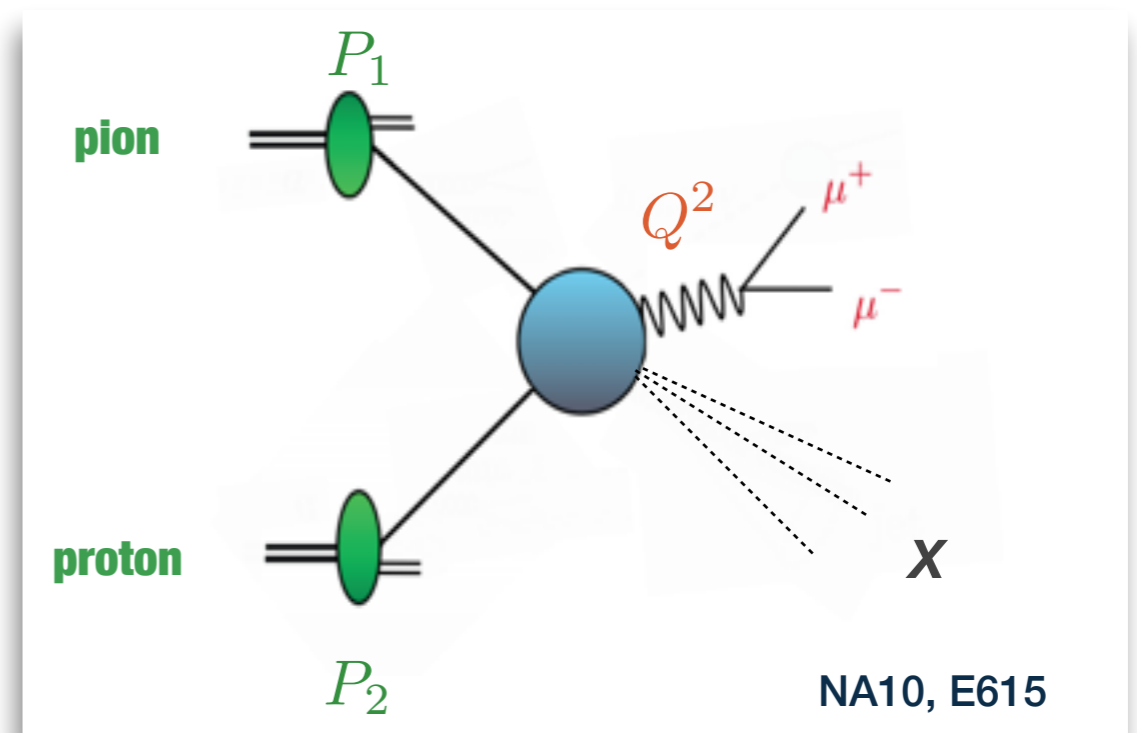
Sullivan processes



also called “leading neutron”

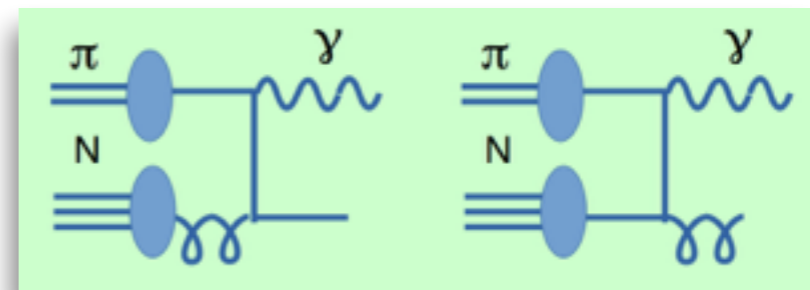
HERA

Pion-induced Drell-Yan



NA10, E615

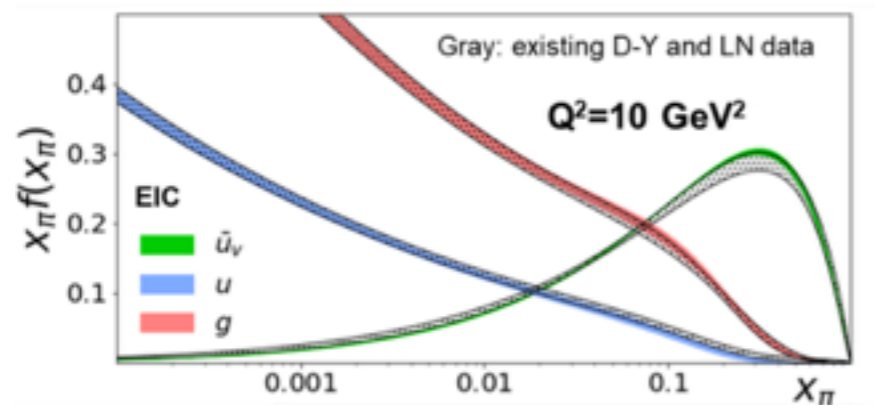
Direct photon production



WA67

Future experiments: the pion

Impact of EIC on pion and kaon PDFs



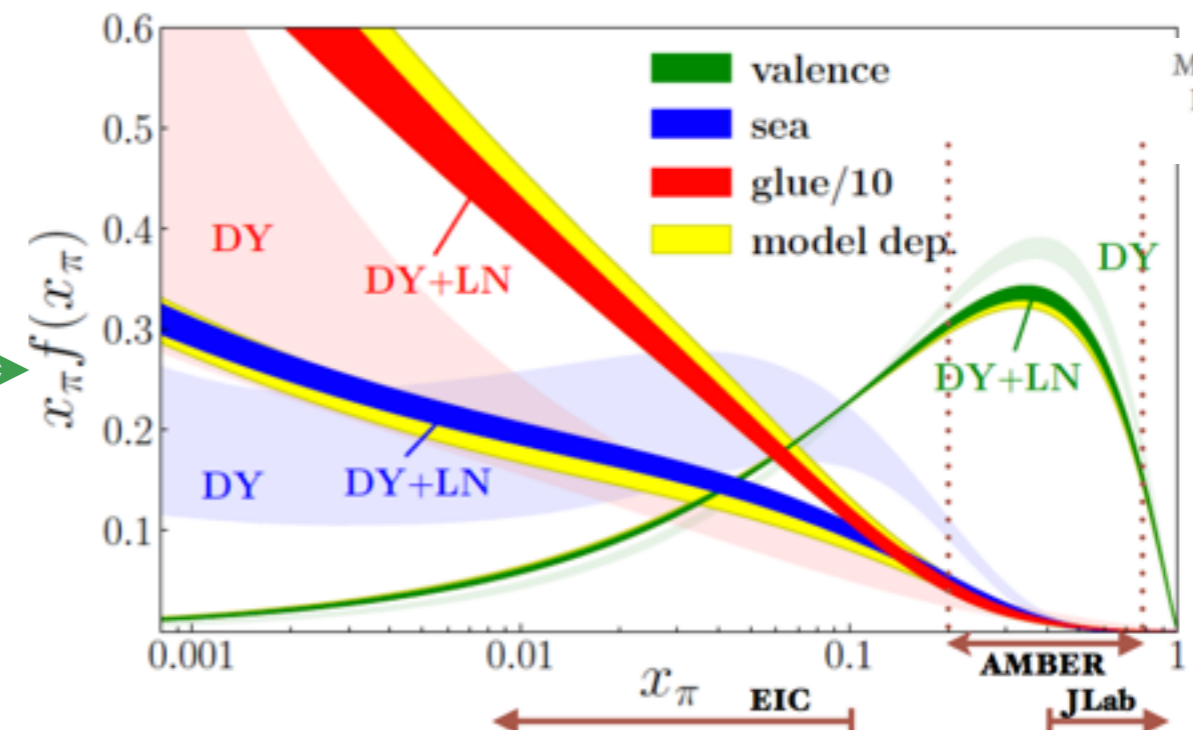
Aguilar, et al., Eur.Phys.J.A 55 (2019) 10, 190,1907.08218

Recent fits of pion & kaon PDFs:

- xFitters: 2002.02902
- JAM: Phys.Rev.Lett.121 (2018),1804.01965

Impact of COMPASS++/AMBER and COMPASS

- COMPASS: pion-induced DY
- COMPASS++/AMBER:
 - pion-induced DY
 - anti-proton and kaon-induced DY

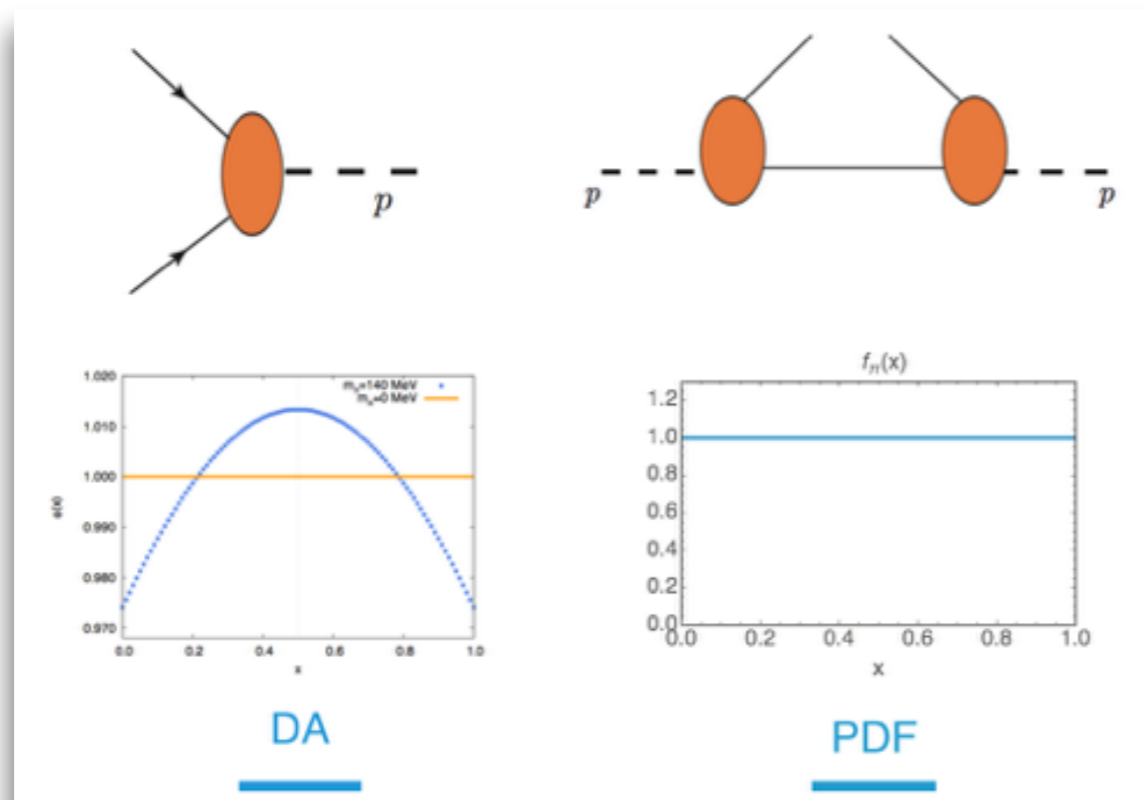


Márcia Quaresma
 EHM workshop
 30 March 2020

Pion and the emergence of mass

Chiral symmetry

- influences the shape of the distributions
- relates the PDF and the PDA
- Nambu – Jona-Lasinio: $f_\pi(x)=\phi(x)=1$ at the *hadronic scale* and in the chiral limit
- significance in the end-point behavior



Gap eq.: constituent quark mass

$$1 = 2iG N_c N_f \int \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m^2}$$

Goldstone mode mass

$$m_\pi^2 \propto \frac{m_0}{m} \quad \text{to give the Gellman-Oakes-Renner relation}$$

[Ruiz-Arriola & Broniowski, PRD66]
[Davidson & Ruiz-Arriola, APB33]

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- Key observables:
 - Pion and kaon PDFs and pion GPDs
 - Gluon energy in the pion and kaon
 - but also: pion TMDs

Pion and the emergence of mass

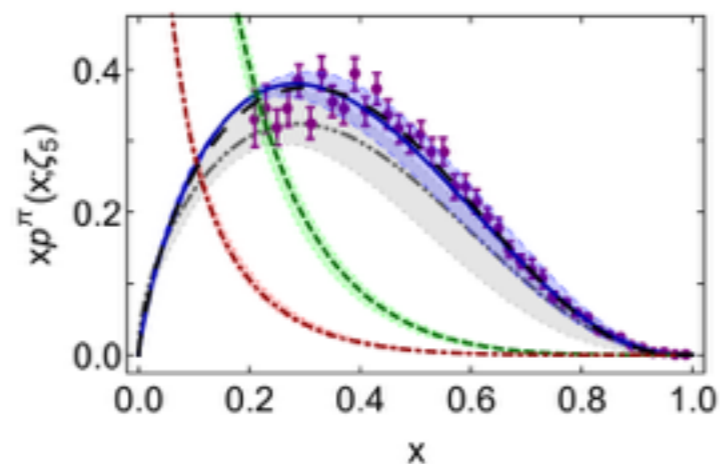
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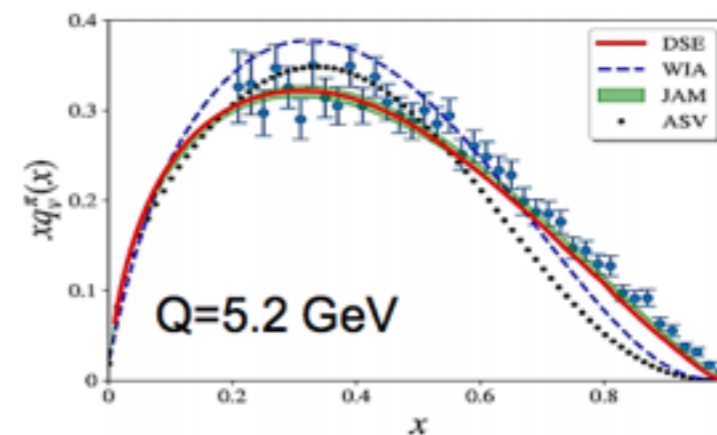
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DSE calculations



Ding et al., PRD101(2020), 1905.05208



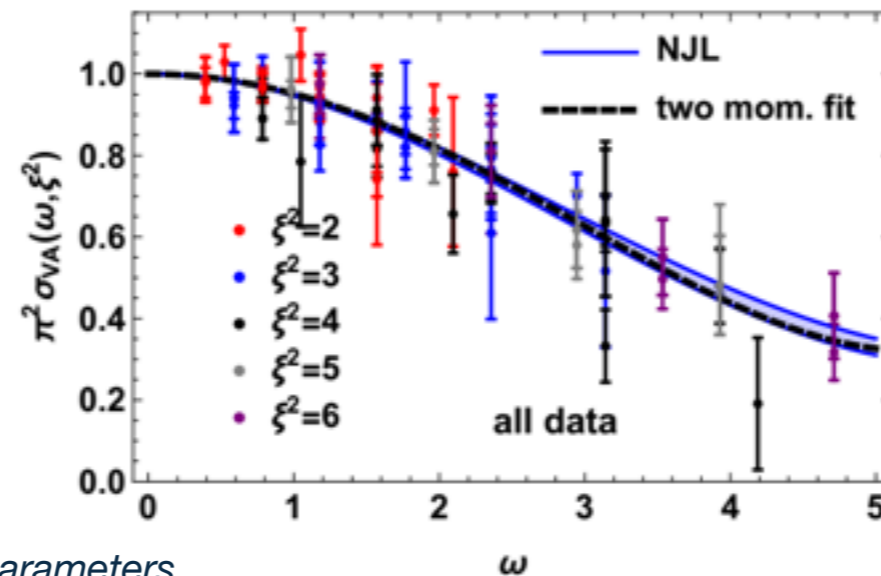
Bednar et al., PRL124 (2020), 1811.12310

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-
- Key observables:
 - Pion PDF from the lattice

Lattice cross-section expressed in terms of moments



NJL: Q_0 is the only free parameter

In statistical agreement with fit of 2,3,4 parameters

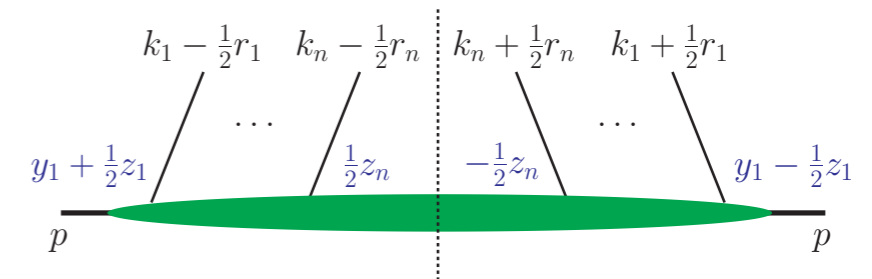
$\omega = p \cdot \xi$ is the Ioffe time

Broniowski & Ruiz-Arriola, 2006.03832

Pion in multiparton scattering

Multiparton interactions

- more than one active quark
- suppressed/averaged out for *sufficiently* inclusive processes
- high-energy hadron-hadron collision: very relevant
- introduction of multiparton Distribution Functions



Diehl and Schäfer, PLB 698 (2011), 1102.3081

Pion in multiparton scattering

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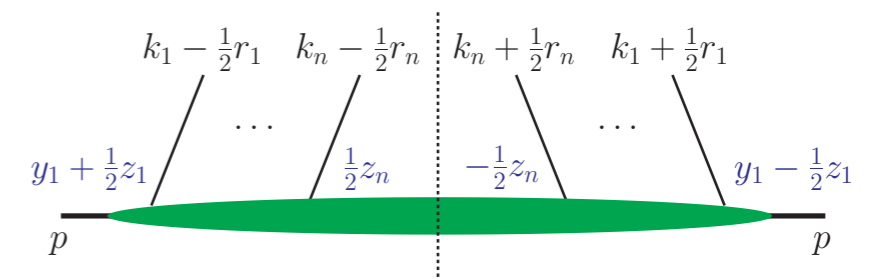
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• Proton dPDFs

- *evaluated in models: Chang, Waalewijn & Manohar ; Rinaldi, Vento, Scopetta, Traini ; ...*

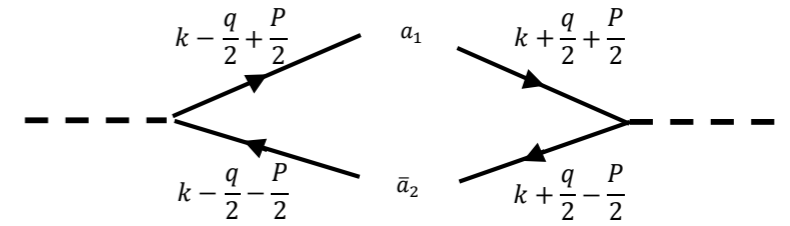
• Pion dPDFs

- *evaluated in models:*
 - *Rinaldi et al [EPJC 78 (2018), 1806.10112]*
 - *AC, Noguera & Scopetta [JHEP 12 (2019), 1909.09530]*
 - *Broniowski & Ruiz-Arriola [PRD 101 (2020), 1910.03707]*
- *evaluated on the lattice: Bali et al [2006.14826]*

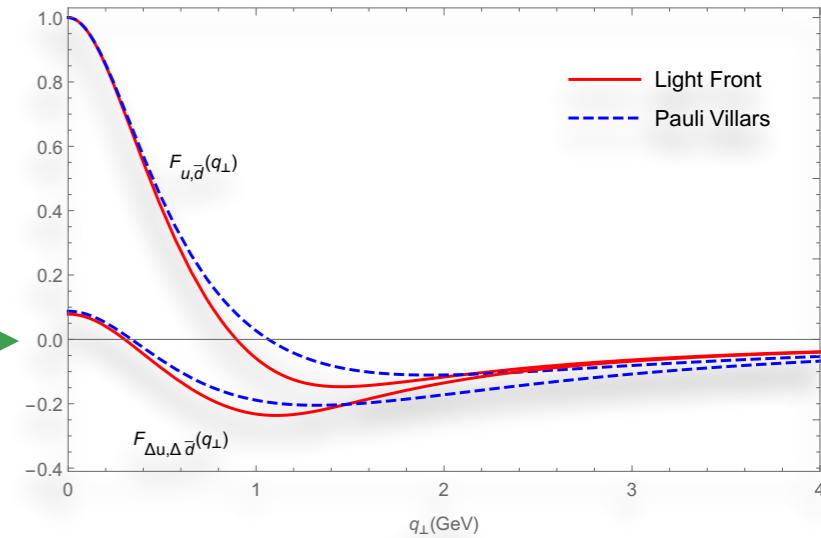


Diehl and Schäfer, PLB 698 (2011), 1102.3081

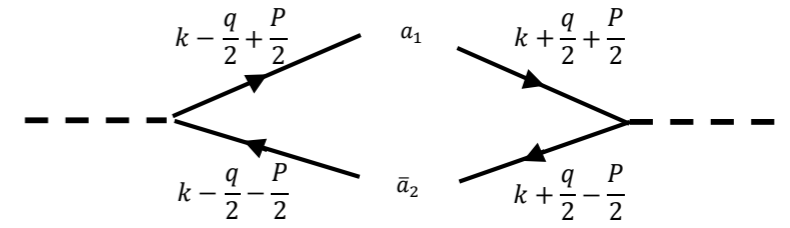
Double PDF of the pion



- A field theoretical approach (NJL) is possible for the pion
 - The two quarks are active quarks
 - Sum rules ensured
 - Importance of regularization of the model
 - no probability density interpretation in transverse distance b/w partons

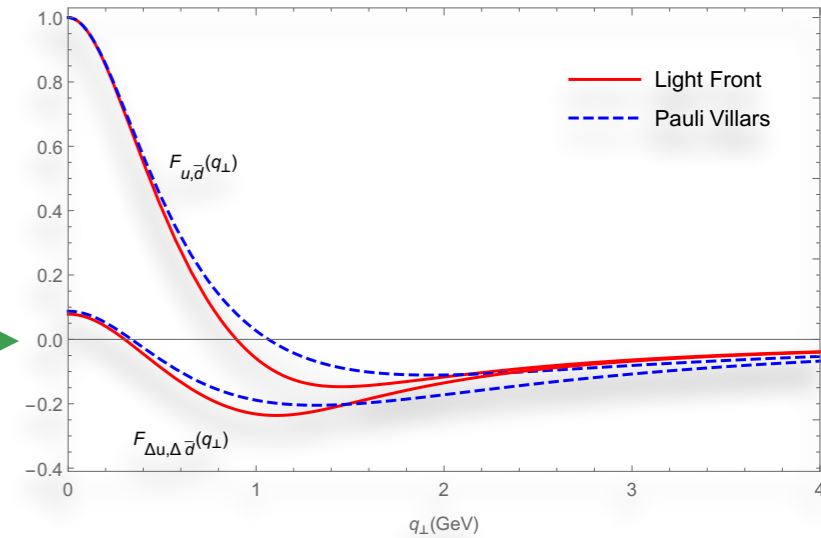


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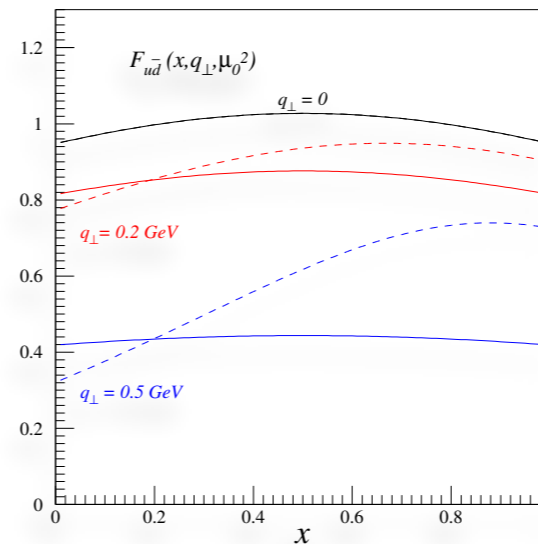
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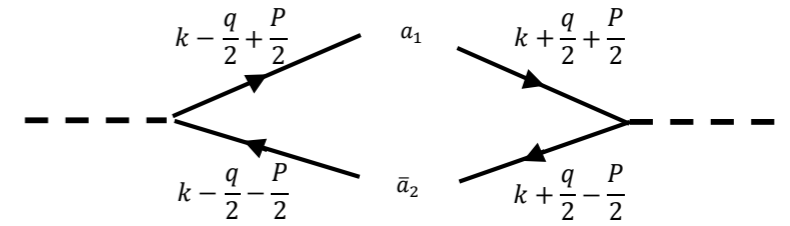


Factorization into GPDs

- from two-body to 2 one-body objects
- holds for 0-transverse distance only

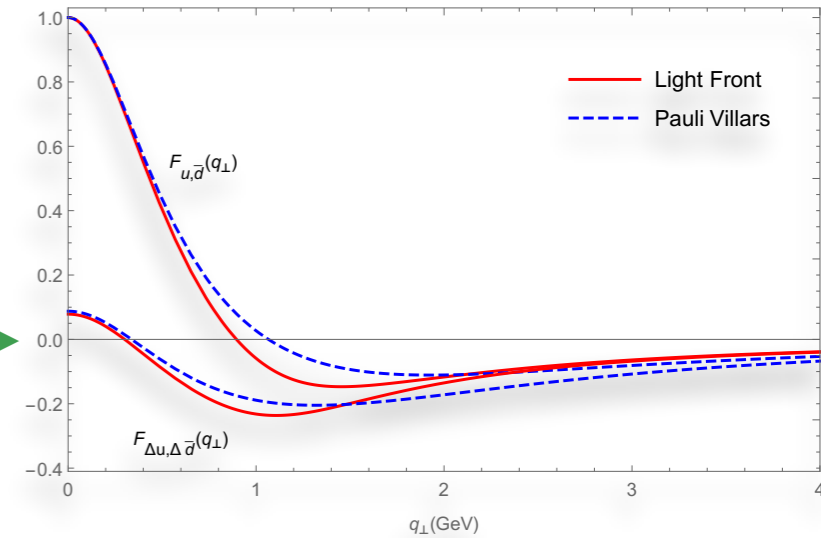


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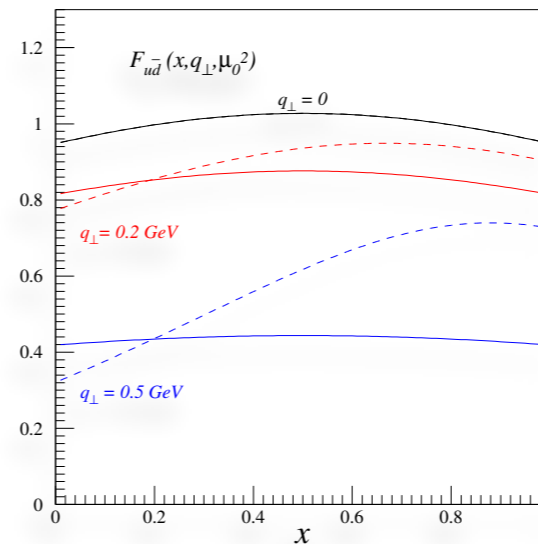
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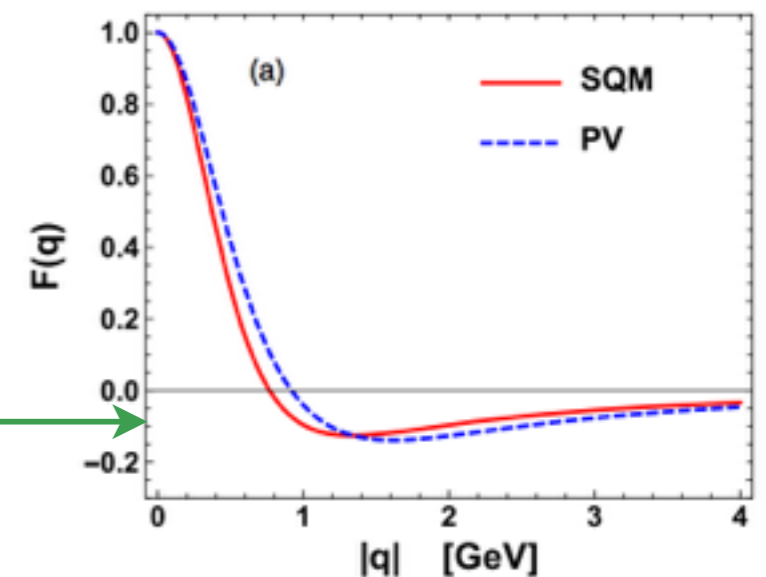
Factorization into GPDs

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Factorization longitudinal & transverse variables

- vector-vector in the chiral limit
- trivial x dependence and F(q)



Two parton correlations

Bali et al, JHEP 12 (2018), 1807.03073
AC, Noguera & Scopetta, 2006.05300

Lattice and model comparison where there are no possible data

- Theoretical guidance
- Relation to dPDF moments
- Two current correlations of the pion

$$\left\langle \pi^k(P) \left| \mathcal{O}_i^{q_1 q_2}(y) \mathcal{O}_j^{q_3 q_4}(0) \right| \pi^{k'}(P) \right\rangle,$$

- time-component

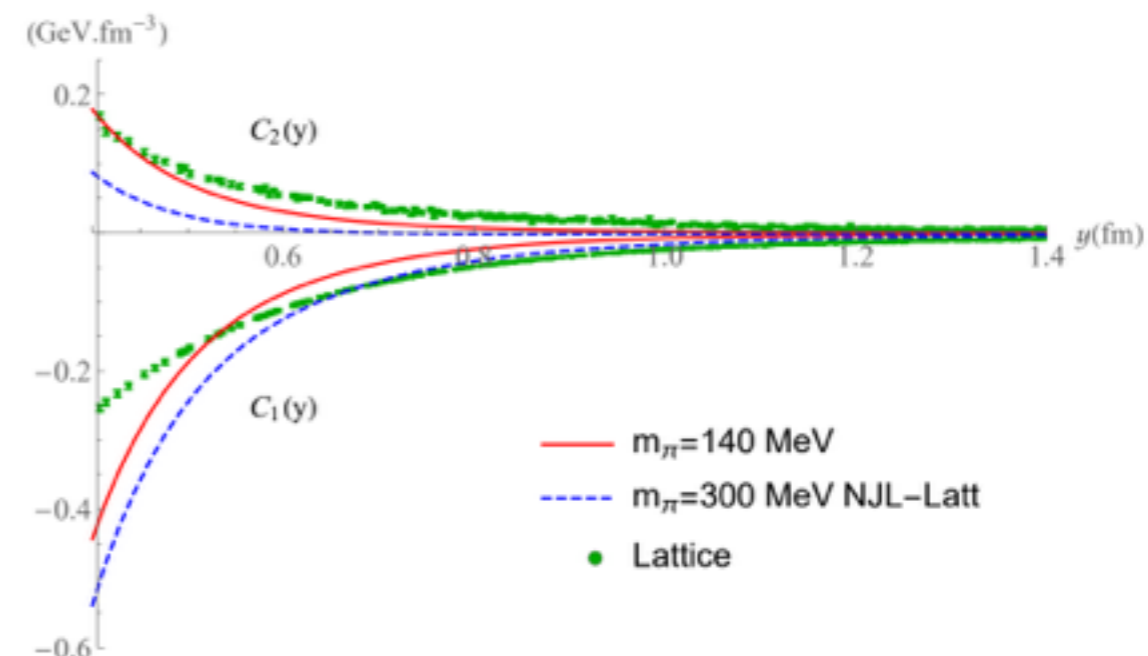
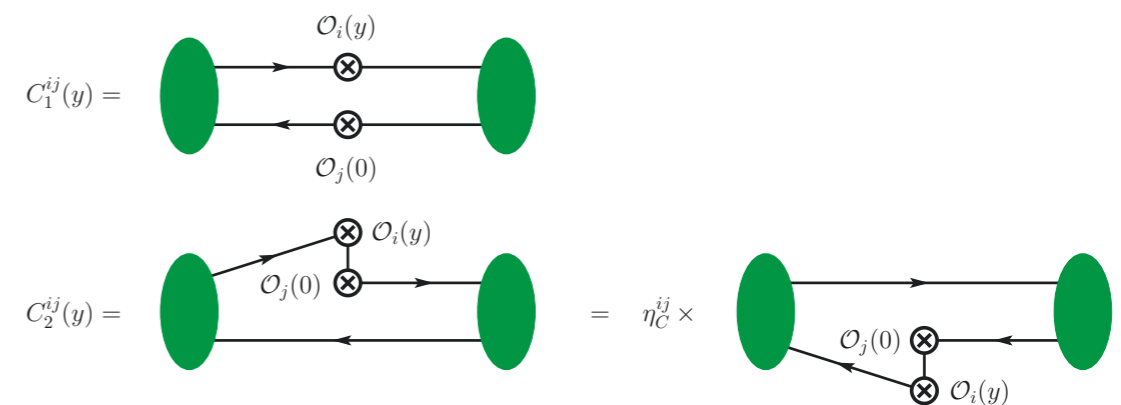
$$\mathcal{O}_{V^0}^{qq'}(y) = \bar{q}(y) \gamma^0 q'(y)$$

- Factorization

- in the absence of correlations, C_1 factorizes

$$-\mathcal{M}_{V^0 V^0}(\vec{q}^2) \stackrel{?}{=} \frac{(m_\pi + E_q)^2}{2E_q} \left[F_V (2m_\pi E_q - 2m_\pi^2) \right]^2$$

- in the model, it can come from C_2



Conclusions

- **Extensive phenomenology for the proton**
 - windows for improvements to be covered by new experiments and/or lattice
 - spin-dependent objects are entering the game
 - multidimensional structures gaining insights

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Machine Learning and similar

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Parton distributions and lattice QCD calculations: toward 3D structure [2006.08636]

Yellow Report for the EIC under construction.

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EIC User Group:
open to everybody who wants to join
Mexico~10 participants

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Theoretical guidance from both sides of the transition

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Workshops on the

Emergence of Mass (March 2020)

Pion and Kaon Structure Functions at the EIC (June 2020)

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Joint effort of a community

