Opportunities of TMD phenomenology at (HL) EIC

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High Luminosity EIC workshop
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IPARCOS   Comunidad de Madrid   VNIVERSITAS COMPLVTENSIS MATRITENSIS

Which physics might drive HL-EIC demands?
from TMD phenomenology perspective

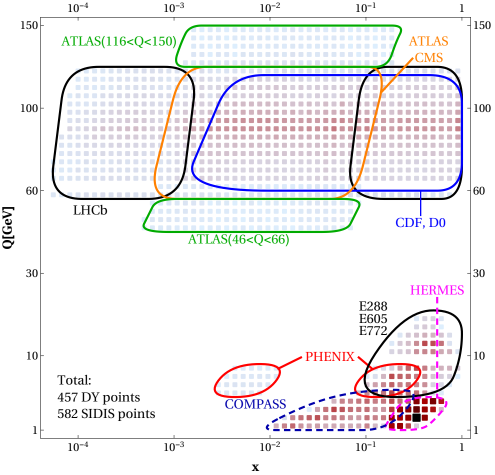
This is a very challenging topic to talk about.
In fact, we do not know what will be impact by EIC...

Outline

- Reminder: present state-of-the-art in TMD phenomenology
- Reminder: impact of EIC
- Possible issues with TMD theory
- New opportunities at EIC (HL-EIC?)
  - Direct extraction of CS kernel
  - Twist-3 distributions

You are welcome to **immediate discussions**
consider my slides as a jumping-off points for those discussions.

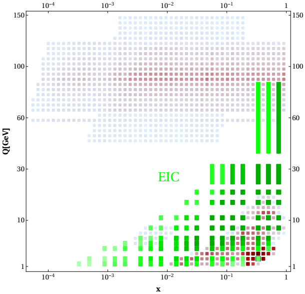
Present state-of-the-art (unpolarized)



Unpolarized sector

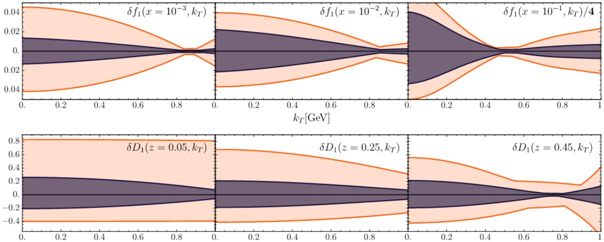
- Data
  - High-energy=DY
  - Mid-energy = fix-target DY
  - Low-energy = SIDIS
- Joined fits
  - SV19 [Scimemi, AV, 1912.06532]
  - MAP22 [Bacchetta, at al, 2206.07598]
- Theory
  - N^4LO evolution (!)
  - N^3LO coeff.functions

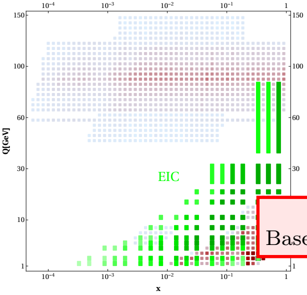
Present unpol.fit are LHC-driven.
There are issues with SIDIS description.



EIC:

- Large number of data-points in low-mid energies.
- Presicion compatible with LHC.
- SIDIS (!)
- Much better pt-resolution





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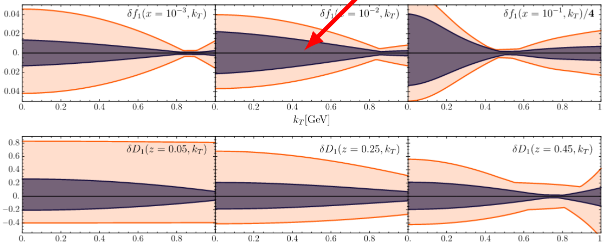
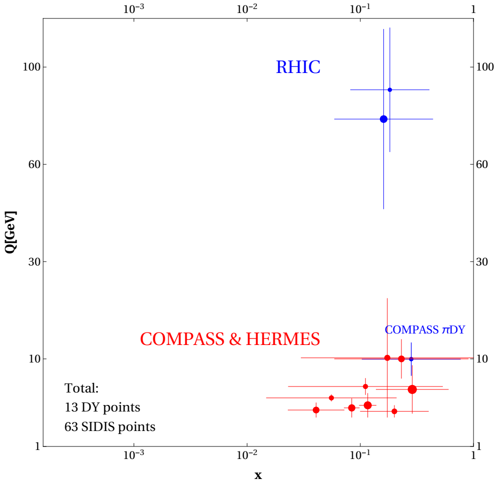
Do not trust it!
Based on the modern understanding...



Present state-of-the-art (Sivers)



Sivers function

- Data
  - SIDIS
  - + a bit of DY
- Fits
  - [Bury, Prokudin, AV, 2012.05135]
  - [Echevarria, Kang, Terry,2009.10710]
  - [Bacchetta, Delcarro, et al, 2004.14278]
  - [Cammarota, et al 2002.08384]
  - ...
- Theory
  - N^4LO evolution (!)
  - NLO coeff.functions

We know almost nothing about Sivers function

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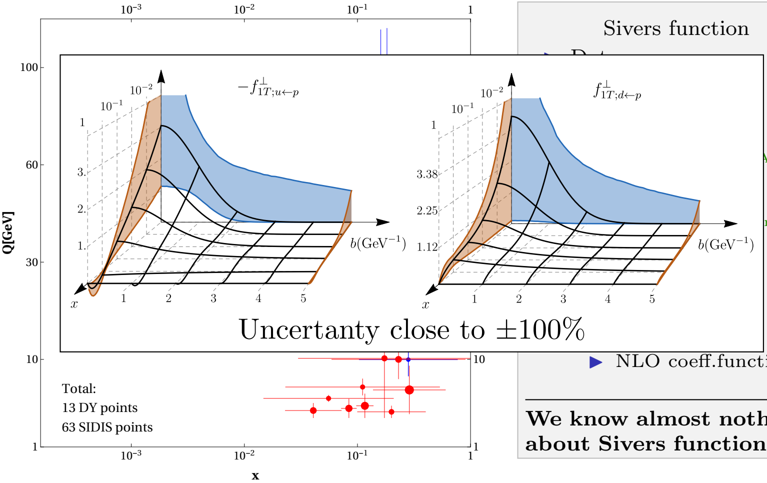

Sivers function

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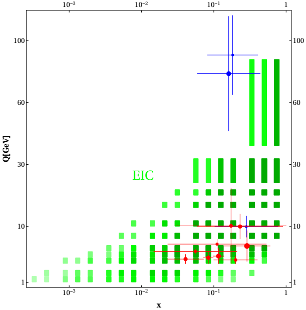
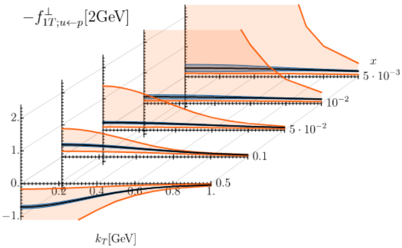
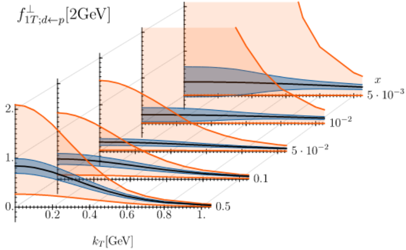
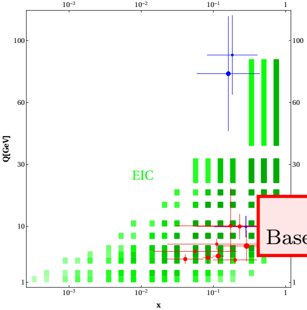


EIC:
Will replace all previous data (apart JLab12)







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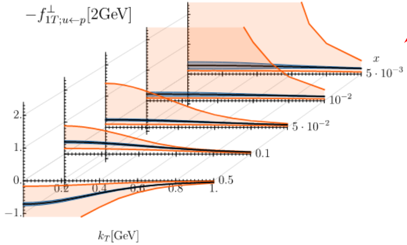

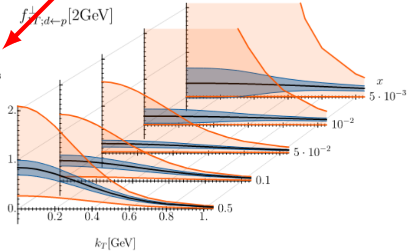

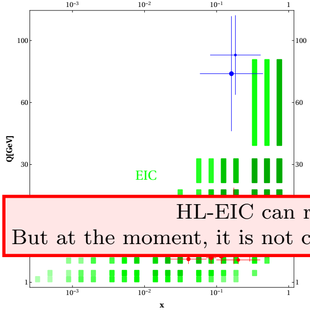

EIC:
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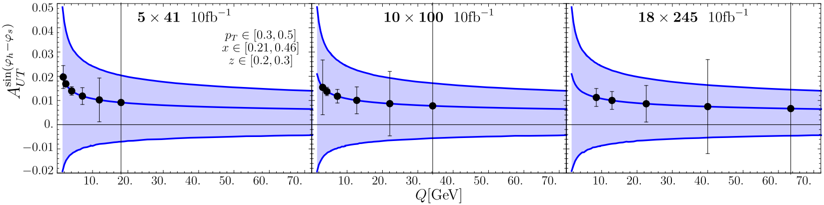
HL-EIC can reduce the uncertanties here.
But at the moment, it is not clear how large is contribution of systematics.



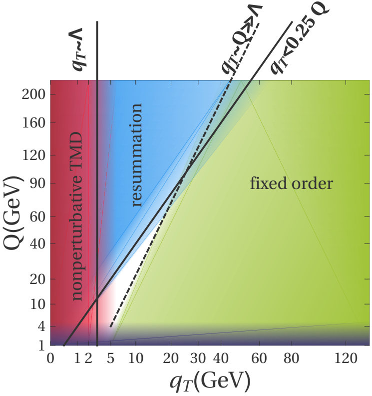
More TMD topics see [EIC YR]

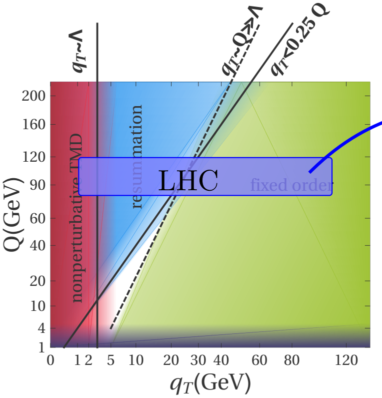
- CS kernel
- Transversity [tensor charge]
- Gluon TMDs
- TMDs with jets
- ...

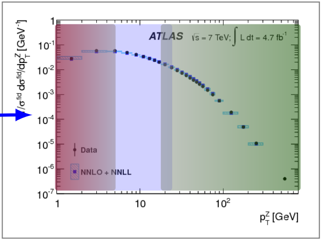
In all cases the situation is the same: EIC will go beyond our knowledge

It will be very challenging for theory

Moreover, (I think) the whole (TMD) factorization approach must be revisited/reorganized


q_T~Λ
q_T~Q≫Λ
q_T<0.25 Q
nonperturbative TMD
resummation
fixed order
Q(GeV)
200
160
120
90
60
40
20
10
4
1
0 1 2 5 10 20 30 40 60 80 120
q_T(GeV)

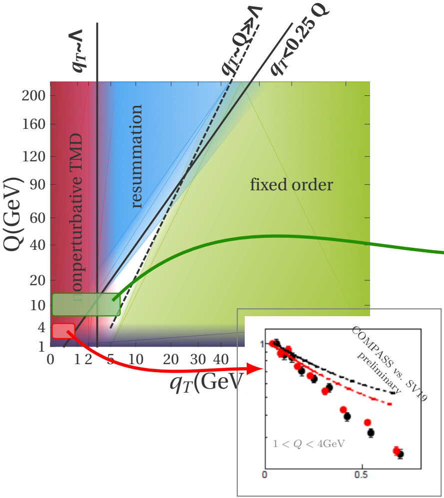


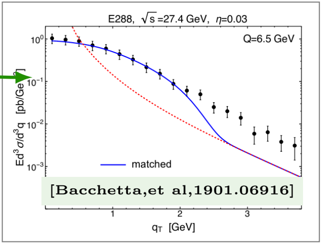


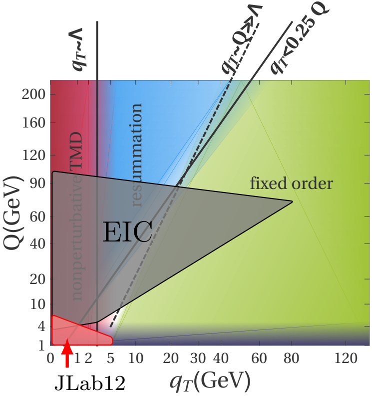
At high-energy (such as LHC)
different factorization regions overlap
therefore, the interpolation makes a good job.

LP TMD factorization has limited region of application.

For SIDIS it cuts **the most part** of the data



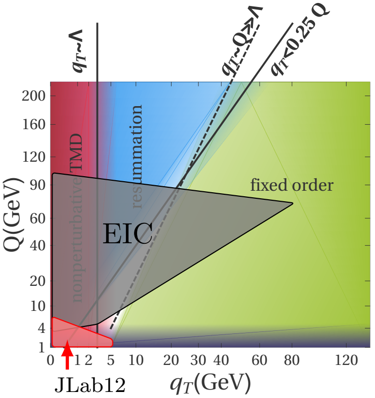




Phase space of EIC is centered directly in the transition region

COMPASS, JLab have large contribution of power corrections

A lot of work for theoretists



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(Assuming, that present formulation of TMD factorization will hold)
The precision of EIC will grant us many new possibilities, which nowadays we cannot think of.

What I can imagine

- Access to power corrections and power suppressed distributions
- Control on uncertainty of extractions for “exotic” TMDs
- Direct extraction of CS kernel
- Flavor-dependence of TMDs
- Comparison of gluon/quark CS-kernels
- Test of twist-3 evolution
- Extraction of higher-twist **collinear** distributions
- Gluon TMDs
- ...

I will explain some of these points

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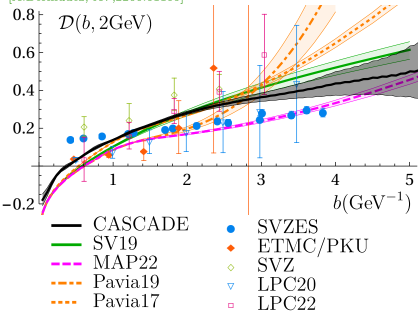
TMD evolution & Collins-Soper kernel

[A.Bermudez, AV,2206.01105]



CS-kernel is
the function specifically sensitive
to the QCD vacuum structure.

$$\frac{d \ln F^q{}_h(x, b)}{d \ln \zeta} = -\mathcal{D}(b)$$

- Pheno.extractions biased
$\mathcal{D}_{\text{pert}}(b^*) + \lambda_0 b^2$

- Lattice extractions
large systematic uncer.

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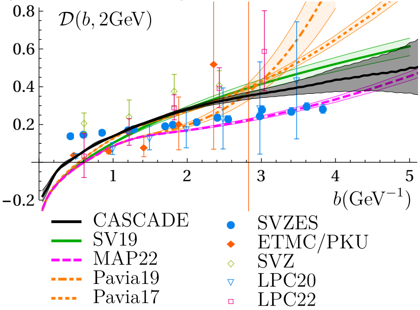

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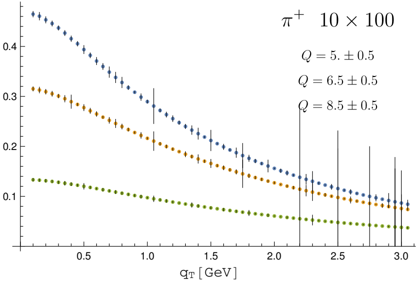
With EIC we will be able to extract CS kernel directly!

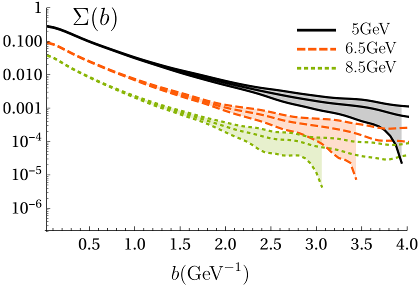
$$\frac{d\sigma}{dxdzdQ^2d\mathbf{p}_\perp^2} = \frac{\alpha_{em}^2\pi}{Q^4}\frac{y^2}{1-\varepsilon}\sum_f e_f^2 \int db\, bJ_0\left(b\frac{p_\perp}{z}\right)|C_V(Q)|^2 f_1(x,b;Q,Q^2)d_1(z,b;Q,Q^2)$$

- Having precise and fine-binned data, one can invert the Fourier transform

$$\Sigma(b) = \frac{\alpha_{em}^2\pi}{Q^4}\frac{y^2}{1-\varepsilon}\sum_f e_f^2|C_V(Q)|^2 f_1(x,b;Q,Q^2)d_1(z,b;Q,Q^2)$$

EIC pseudo-data 10fb^{-1}





Multiplied by a factor for visibility

$$\frac{d\sigma}{dxdzdQ^2 d\mathbf{p}_\perp^2} = \frac{\alpha_{em}^2 \pi}{Q^4} \frac{y^2}{1-\varepsilon} \sum_f e_f^2 \int db\, b J_0\left(b\frac{p_\perp}{z}\right) |C_V(Q)|^2 f_1(x,b;Q,Q^2) d_1(z,b;Q,Q^2)$$

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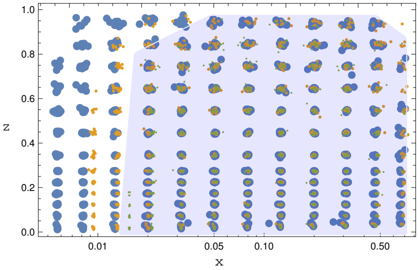
- Select **the same range** of x and z at two different energies.



Large (x,z)-coverage increase precision

$$\frac{d\sigma}{dxdzdQ^2d\mathbf{p}_\perp^2} = \frac{\alpha_{em}^2\pi}{Q^4}\frac{y^2}{1-\varepsilon}\sum_f e_f^2 \int db\, bJ_0\left(b\frac{p_\perp}{z}\right)|C_V(Q)|^2 f_1(x,b;Q,Q^2)d_1(z,b;Q,Q^2)$$

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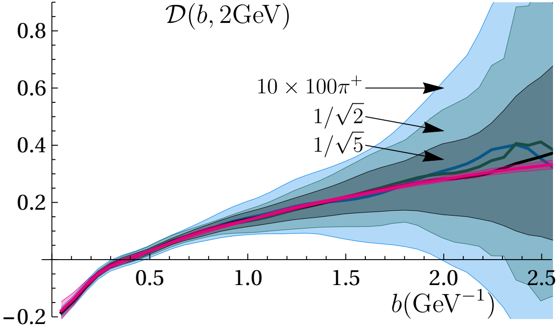
- Select **the same range** of x and z at two different energies.
- Consider ratio of Σ's.

$$\frac{\Sigma(b,Q_1)}{\Sigma(b,Q_2)} = \underbrace{Z(Q_1,Q_2,\mu_0)}_{\substack{\text{perturbative}\\ \text{N}^4\text{LO}}}\left(\frac{Q_1}{Q_2}\right)^{-4\mathcal{D}(b,\mu_0)}$$

[A.Bermudez, AV,2206.01105]

- Determine $\mathcal{D}$

This picture is generated from theory, BUT using uncertanties from ECCE pseudo-data



- Unbiased extraction
- Ultimate test of factorization approach & perturbation theory
- Some systematics cancel in the ratio
- Possible at EIC (?), definitely possible at HL-EIC

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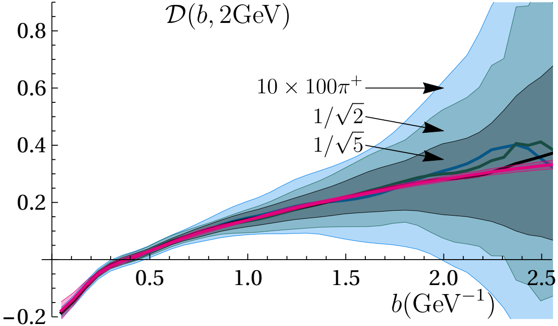

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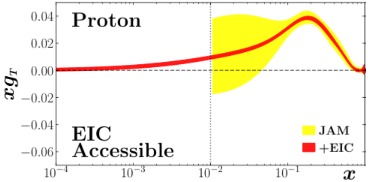
Higher-twist physics is "terra incognito". Very difficult to measure.
EIC will already make impact on some tw-3 distributions.



Just as usual (for impact studies) this picture is a bit misleading.
It does not take into account that g_T is not a proper QCD distribution.

$$g_T^{\text{tw3}}(x) = 2\int [dx] \int_0^1 d\alpha \left(\frac{\delta(x+\alpha x_1)}{x_1 x_3} + \frac{\delta(x+x_1+\alpha x_2)}{x_2 x_3} + \frac{\delta(x+x_1)}{x_1 x_2} \right) S^-(x_1,x_2,x_3).$$

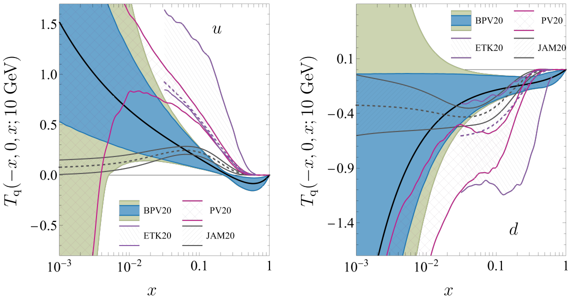
Extraction of twist-3 distributions is **very complicated** (up to impossible).
TMD distributions could play a crucial role in this research.

Example

[M.Bury,A.Prokudin,AV,2103.03270]

$$T_q(-x,0,x;\mu_b)=-\frac{1}{\pi}\left(1+C_F a_s(\mu_b)\frac{\pi^2}{6}\right)f_{1T;q\leftarrow h}^{\perp}(x,b)$$

$$-\frac{a_s(\mu_b)}{\pi}\int_x^1\frac{dy}{y}\left[\frac{\bar{y}}{N_c}f_{1T;q\leftarrow h}^{\perp}\left(\frac{x}{y},b\right)+\frac{3y^2\bar{y}}{2x}G^{(+)}\left(-\frac{x}{y},0,\frac{x}{y};\mu_b\right)\right]+\mathcal{O}(a_s^2)+\mathcal{O}(b^2)$$



Extraction of function $T(-x,0,x)$ From Sivers function.

In principle one could extract $T(-x,0,x)$ directly from the high-p_T tale, but it is much less precise.

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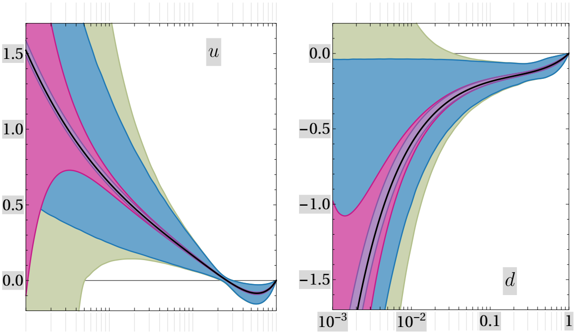

Extraction of function
$T(-x,0,x)$
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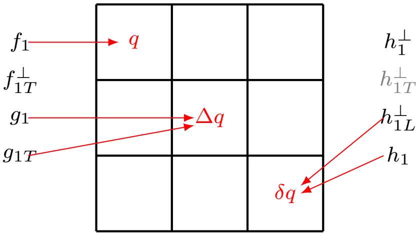
In principle one could extract $T(-x,0,x)$ directly from the high-p_T tale, but it is much less precise.

$$F(x,b) = C(x, \ln b) \otimes f(x) + O(b^2)$$

Twist-2



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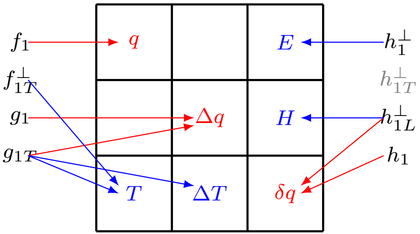

Twist-2

Twist-3

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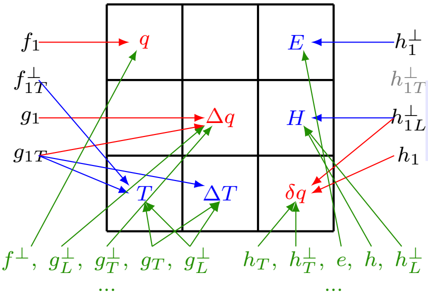


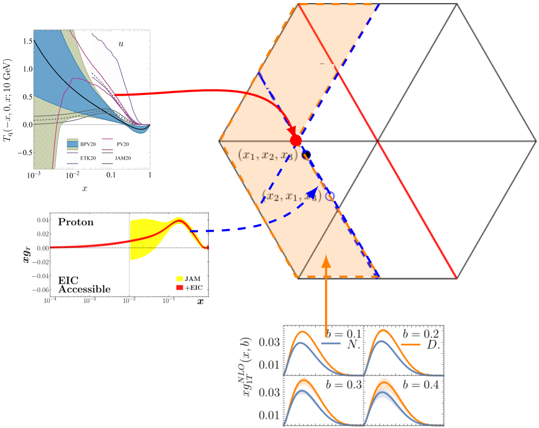
Twist-2

Twist-3

Pow.TMDs

I think at EIC,
we will see these relations
at work.

EIC & HL-EIC will be ideal machines for investigation of twist-3 dynamics through the joined collinear & TMD analysis.



LO

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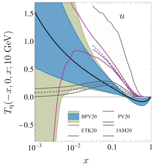

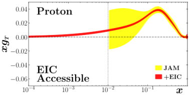

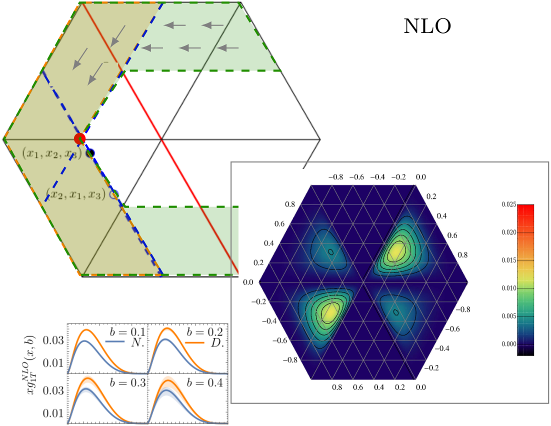

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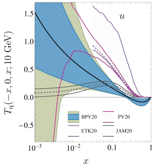

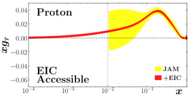

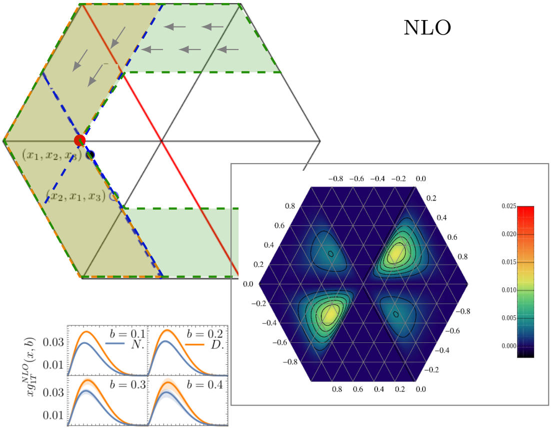

EIC will open many new possibilities, which are not possible now.
HL-EIC will allow to study these possibilities (if systematics is reasonable).

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- Test of twist-3 evolution
- Extraction of higher-twist **collinear** distributions
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However, most probably the essential theory update will be required.

EIC will open many new possibilities, which are not possible now.
HL-EIC will allow to study these possibilities (if systematics is reasonable).

What I can imagine

- Access to power corrections and power suppressed distributions
- Control on uncertainty of extractions for "exotic" TMDs
- Direct extraction of CS kernel
- Comparison of gluon/quark CS-kernels
- Flavor-dependence of TMDs
- Test of twist-3 evolution
- Extraction of higher-twist **collinear** distributions
- Gluon TMDs
- ...

However, most probably the essential theory update will be required.