CFNS workshop
“Precision QCD predictions for ep physics at the EIC”

Daniel de Florian, Werner Vogelsang

MIT, 09/21/2022

Outline:

- Goal and scope of our workshop
- A few selected highlights & trends

  (not a complete list!)

  pQCD precision frontier
  Hadronic structure

- Instead of conclusions …

Goal and scope of the workshop

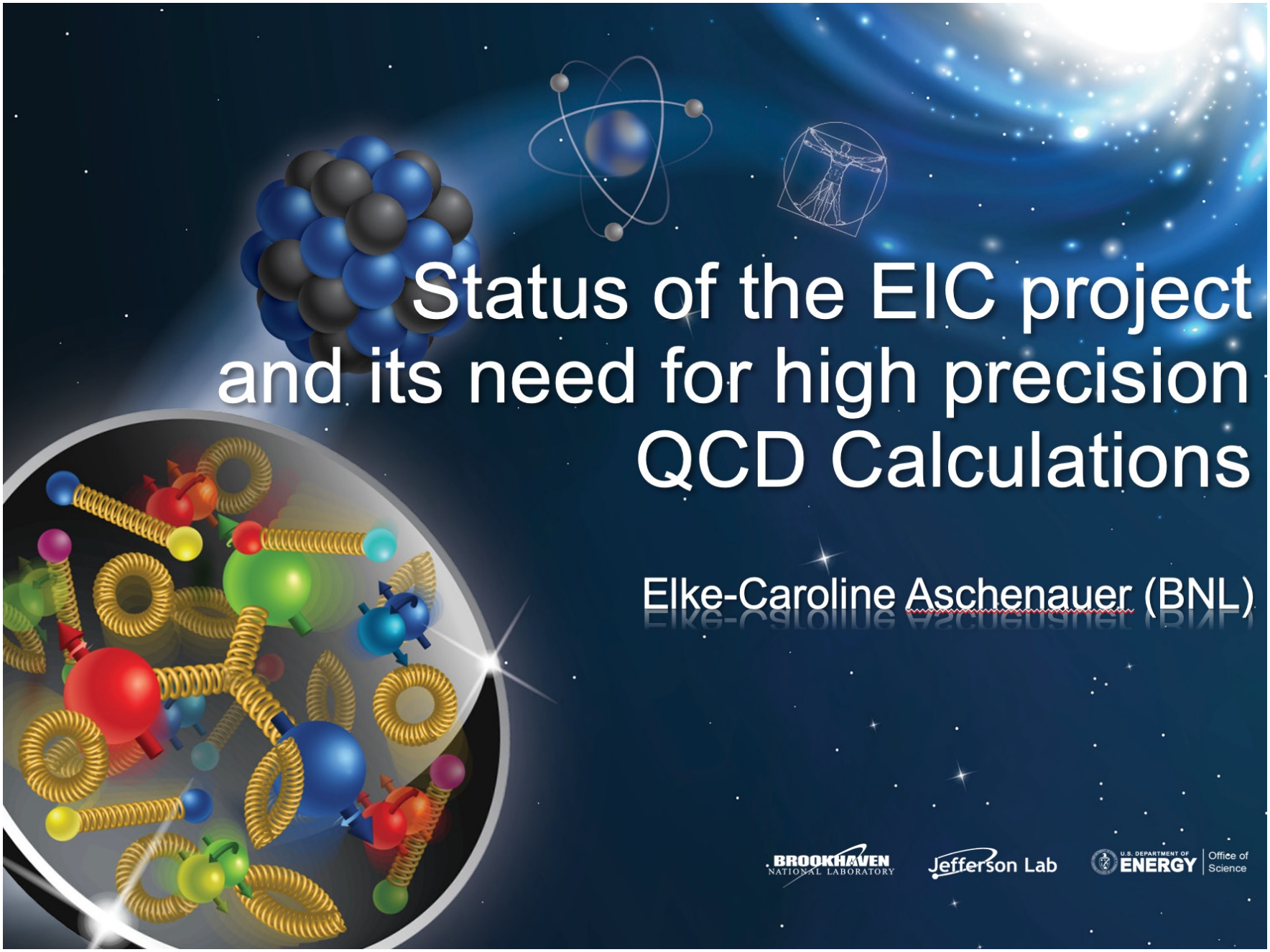
From our proposal:

"Ideally, by the time the EIC will turn on, it would be hoped that the precision of theoretical calculations should be on par with what has by now been achieved for the LHC, with NNLO corrections available for many observables and extractions of PDFs and FFs at NNLO standard and using numerically efficient tools.

With EIC construction now forthcoming, and with planning for EIC detectors underway, we believe it is timely to review the status of the theory for ep collisions at the EIC, to take stock of what has been achieved, to identify outstanding problems, and to forge new collaborations and alliances that will tackle them."

Numbers & format:

- ~25 participants
- 21 talks (4-5 per day -- only one per Zoom)
- 1 hour time slots, ~40 min. speaking time, no limit on discussions


Status of the EIC project
and its need for high precision
QCD Calculations
Elke-Caroline Aschenauer (BNL)
BROOKHAVEN
NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF
ENERGY
Office of
Science

back in 2001 ...

Fermilab / Les Houches

Campbell, Huston, Knuteson,…

An experimenter's wishlist

Run II Monte Carlo Workshop

Single Boson	Diboson	Triboson	Heavy Flavour
$W+ \leq 5j$	$WW+ \leq 5j$	$WWW+ \leq 3j$	$t\bar{t}+ \leq 3j$
$W + b\bar{b} \leq 3j$	$W + b\bar{b}+ \leq 3j$	$WWW + b\bar{b}+ \leq 3j$	$t\bar{t} + \gamma+ \leq 2j$
$W + c\bar{c} \leq 3j$	$W + c\bar{c}+ \leq 3j$	$WWW + \gamma\gamma+ \leq 3j$	$t\bar{t} + W+ \leq 2j$
$Z+ \leq 5j$	$ZZ+ \leq 5j$	$Z\gamma\gamma+ \leq 3j$	$t\bar{t} + Z+ \leq 2j$
$Z + b\bar{b}+ \leq 3j$	$Z + b\bar{b}+ \leq 3j$	$ZZZ+ \leq 3j$	$t\bar{t} + H+ \leq 2j$
$Z + c\bar{c}+ \leq 3j$	$ZZ + c\bar{c}+ \leq 3j$	$WZZ+ \leq 3j$	$t\bar{b} \leq 2j$
$\gamma+ \leq 5j$	$\gamma\gamma+ \leq 5j$	$ZZZ+ \leq 3j$	$b\bar{b}+ \leq 3j$
$\gamma + b\bar{b} \leq 3j$	$\gamma\gamma + b\bar{b} \leq 3j$		single top
$\gamma + c\bar{c} \leq 3j$	$\gamma\gamma + c\bar{c} \leq 3j$		
	$WZ+ \leq 5j$		
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	$Z\gamma+ \leq 3j$		

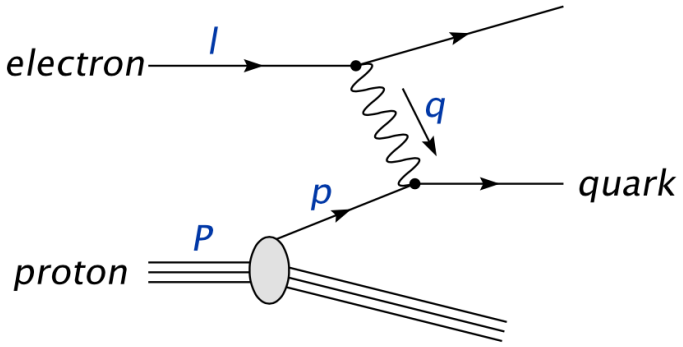
Now is the time to start this for EIC !

Selected highlights:
pQCD precision frontier

State of the art for QCD corrections in DIS

Moch

Deep-inelastic scattering



Kinematic variables

- momentum transfer $Q^2 = -q^2$
- Bjorken variable $x = Q^2/(2p \cdot q)$

- Structure functions (up to order $\mathcal{O}(1/Q^2)$)

$$F_a\left(x,Q^2\right) = \sum_i \left[C_{a,i}\left(\alpha_s(\mu^2),\mu^2/Q^2\right) \otimes f_i\left(\mu^2\right)\right](x)$$

- Coefficient functions up to N^{4}LO (work in progress)

$$C_{a,i} = \alpha_s^n\left(c_{a,i}^{(0)} + \alpha_s c_{a,i}^{(1)} + \alpha_s^2 c_{a,i}^{(2)} + \alpha_s^3 c_{a,i}^{(3)} + \alpha_s^3 c_{a,i}^{(4)} + \dots\right)$$

- Evolution equations up to N^{3}LO (work in progress)
  - non-singlet ($2n_f - 1$ scalar) and singlet (2×2 matrix) equations

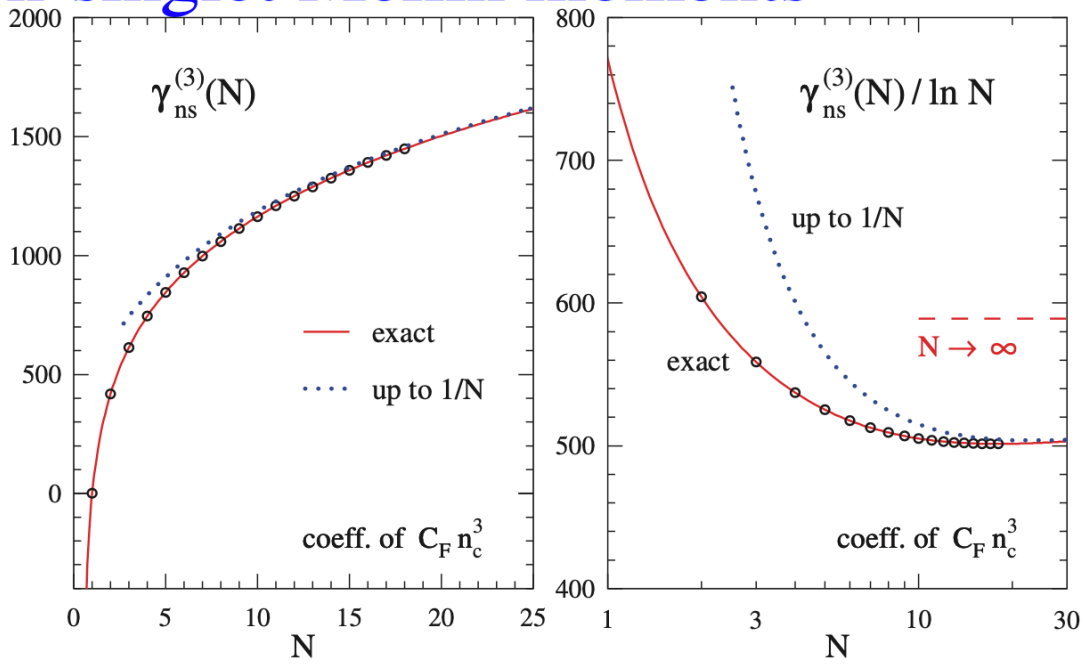
$$\frac{d}{d\ln\mu^2} f_i(x,\mu^2) \quad = \quad \left[P_{ij}(\alpha_s(\mu^2)) \otimes f_j(\mu^2)\right](x)$$

  - splitting functions $P_{ij} = \alpha_s P_{ij}^{(0)} + \alpha_s^2 P_{ij}^{(1)} + \alpha_s^3 P_{ij}^{(2)} + \alpha_s^4 P_{ij}^{(3)} + \dots$

Four-loop non-singlet Mellin moments

Moch
Rujil
Ueda
Vermaseren
Vogt

- Top:
  n_f^0 part of anomalous dimensions $\gamma_{\rm ns}^{(3)\pm}(N)$ in large-n_c limit and large-N expansion



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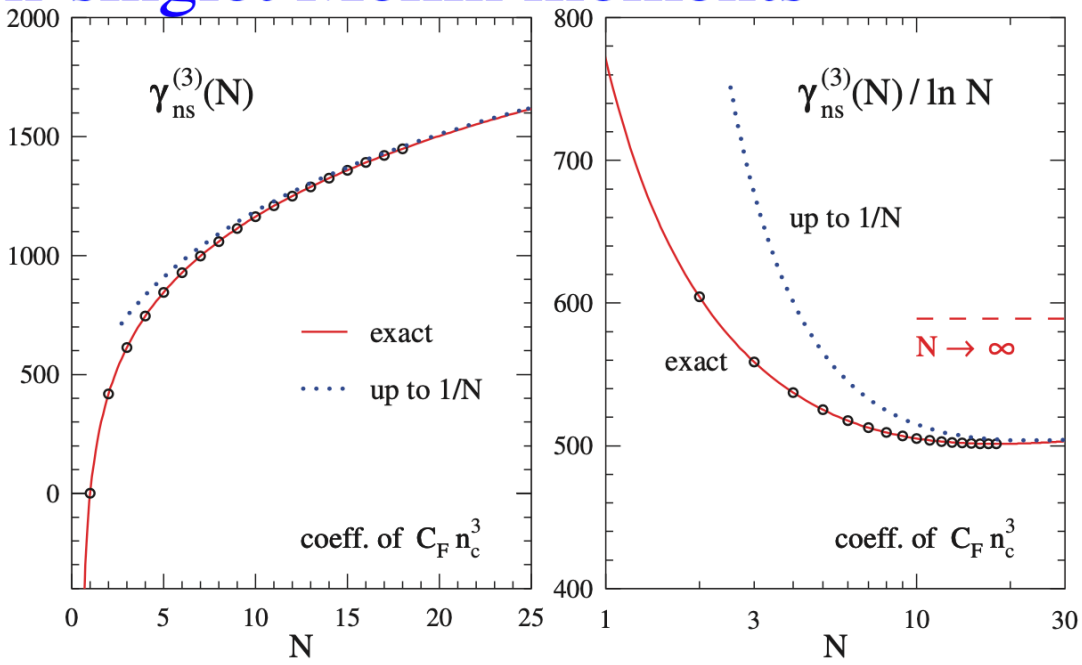
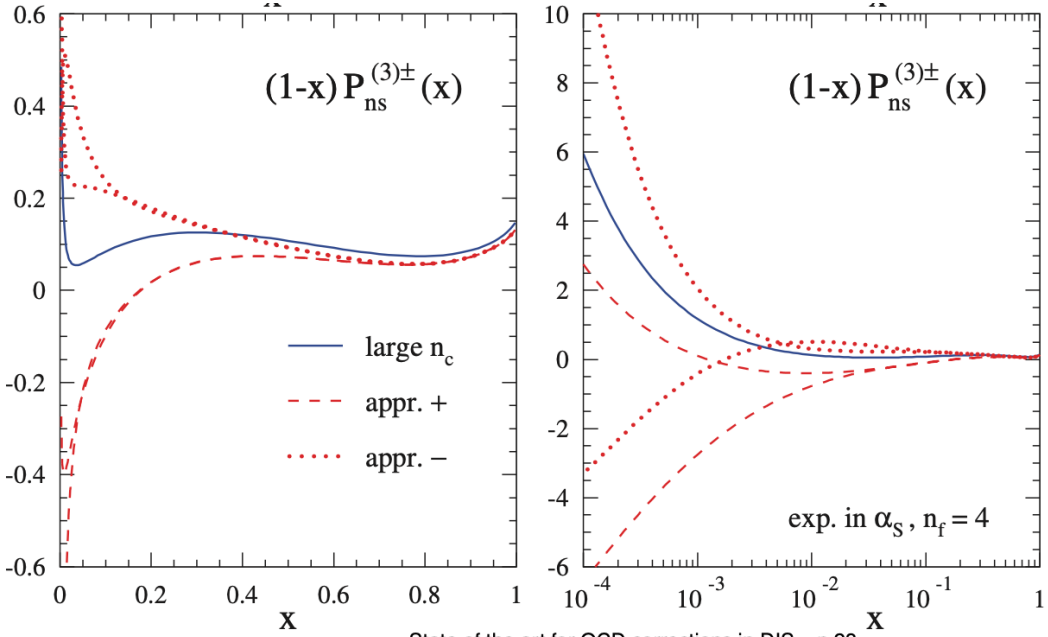
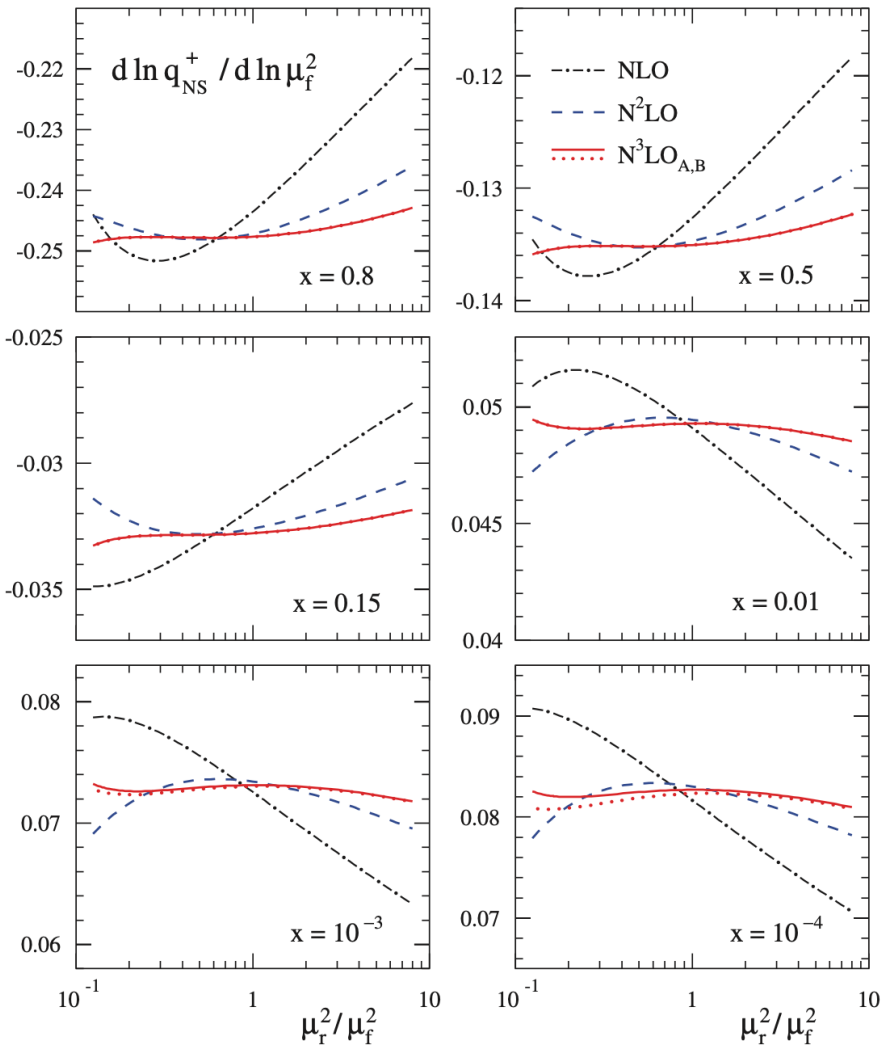


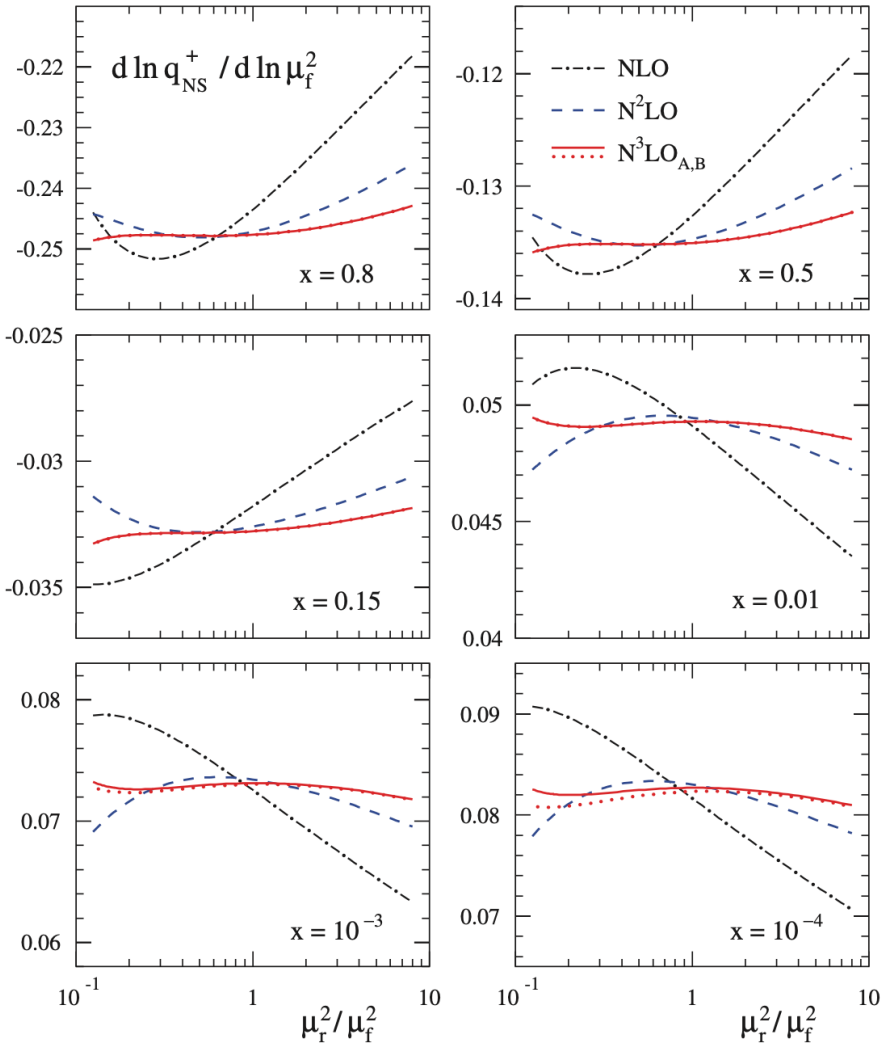
Four-loop non-singlet splitting functions

- Bottom:
  four-loop $P_{\rm ns}^{(3)\pm}(x)$ and uncertainty bands beyond large-n_c limit with $n_f = 4$




d ln q$_{NS}^{+}$ / d ln μ$_f^2$
NLO
N^{2}LO
N^{3}LO$_{A,B}$
x = 0.8
x = 0.5
x = 0.15
x = 0.01
x = 10^{-3}
x = 10^{-4}
-0.22
-0.23
-0.24
-0.25
-0.12
-0.13
-0.14
-0.025
-0.03
-0.035
0.05
0.045
0.04
0.08
0.07
0.06
0.09
0.08
0.07
10^{-1}
1
10
μ$_r^2$/μ$_f^2$

Singlet


$d \ln q_{NS}^{+} / d \ln \mu_f^2$
NLO
N^2LO
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x = 0.8
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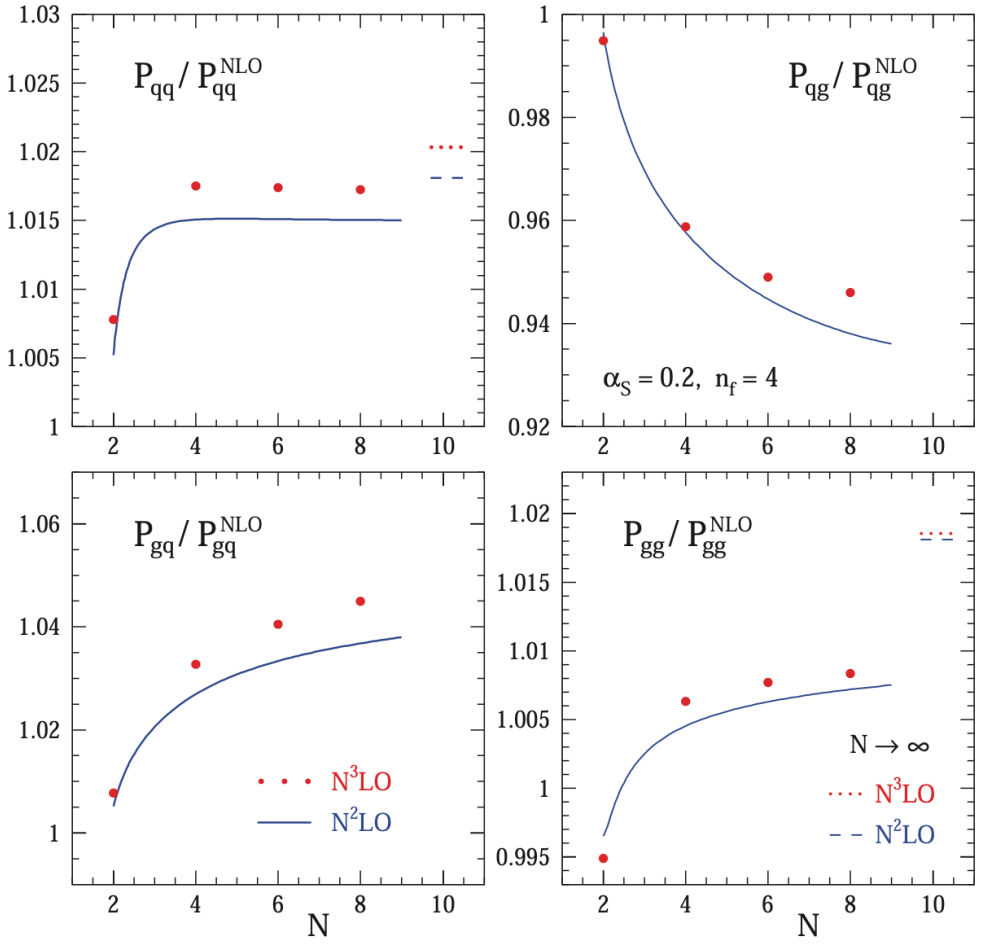
μ_r^2/μ_f^2
μ_r^2/μ_f^2


P_{qq} / P_{qq}^{NLO}
P_{qg} / P_{qg}^{NLO}
$\alpha_S = 0.2,\ n_f = 4$
P_{gq} / P_{gq}^{NLO}
P_{gg} / P_{gg}^{NLO}
N^3LO
N^2LO
$N \to \infty$
N^3LO
N^2LO
N
N

NNLO jets in in polarized DIS

Pedron

Precision opportunities in QCD and BSM physics at the EIC

Petriello

NNLO jets in in polarized DIS

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Precision opportunities in QCD and BSM physics at the EIC

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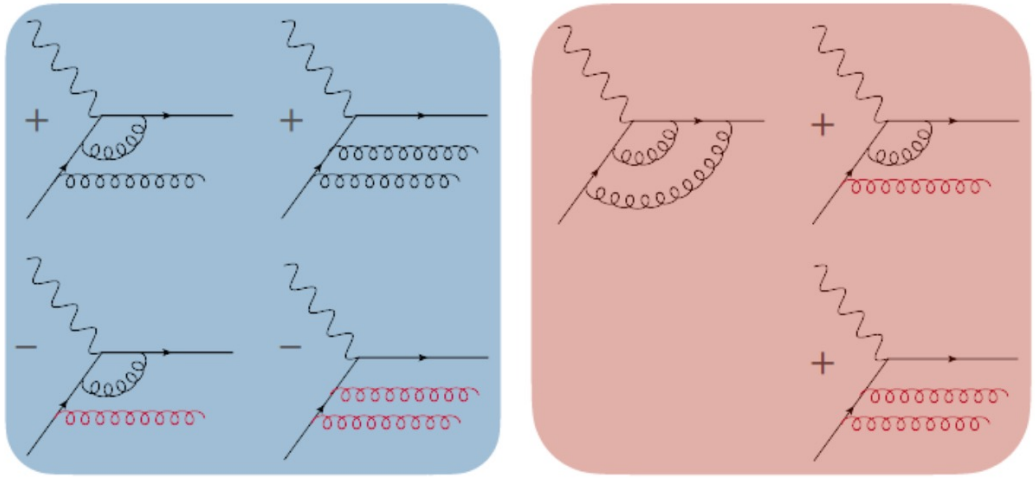
NNLO - PROJECTION TO BORN (P2B)

IN OUR CASE:

We compute the polarized **NNLO cross section for 1-jet**, using our NLO calculation for 2-jets (dipoles) and the NNLO inclusive cross sections that are already available



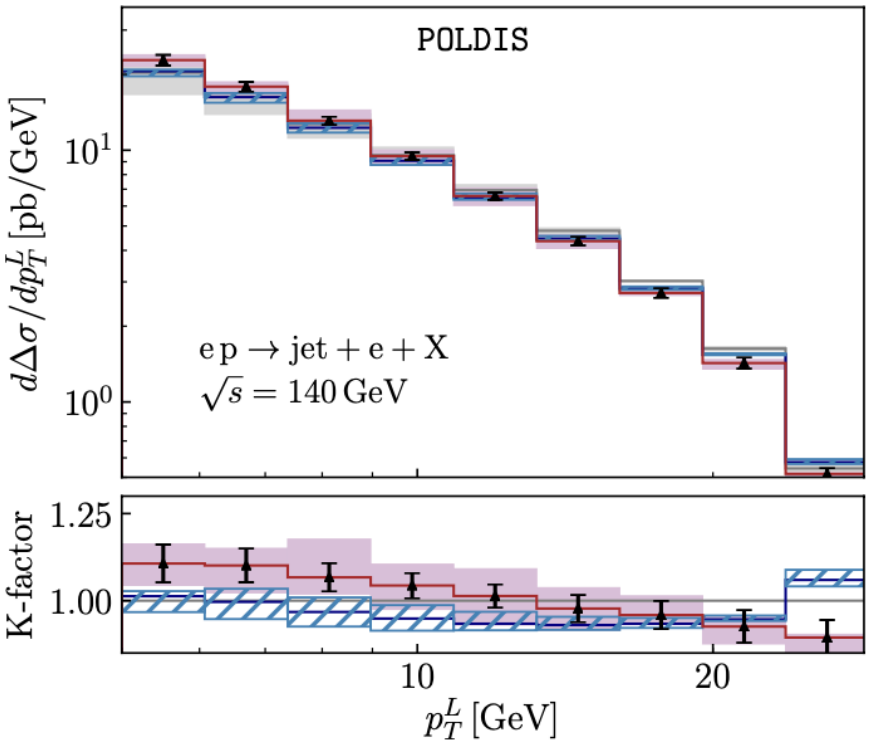
Pedron

$$d\sigma^{\mathrm{NNLO}}_{1jet} = d\sigma^{\mathrm{NLO}}_{2jet} - d\sigma^{\mathrm{NLO}}_{2jet,\mathrm{P2B}} + d\sigma^{\mathrm{NNLO,\ incl}}_{1jet}$$

Dipoles

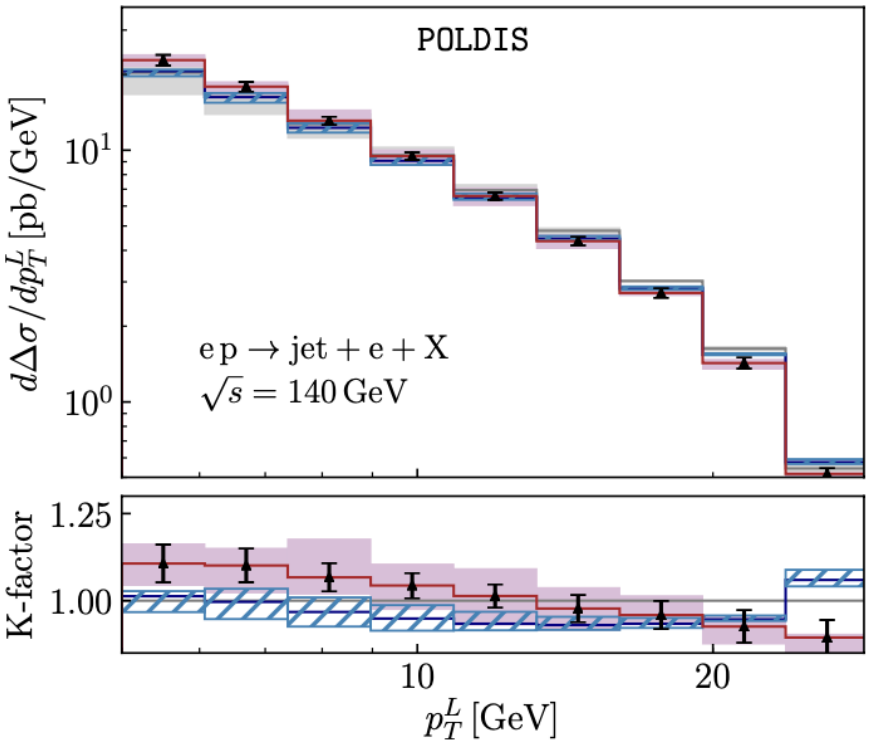
van Neerven, Zijlstra (1994)

$\vec{e}\vec{p} \to e\,\mathrm{jet}X$



Borsa, de Florian, Pedron

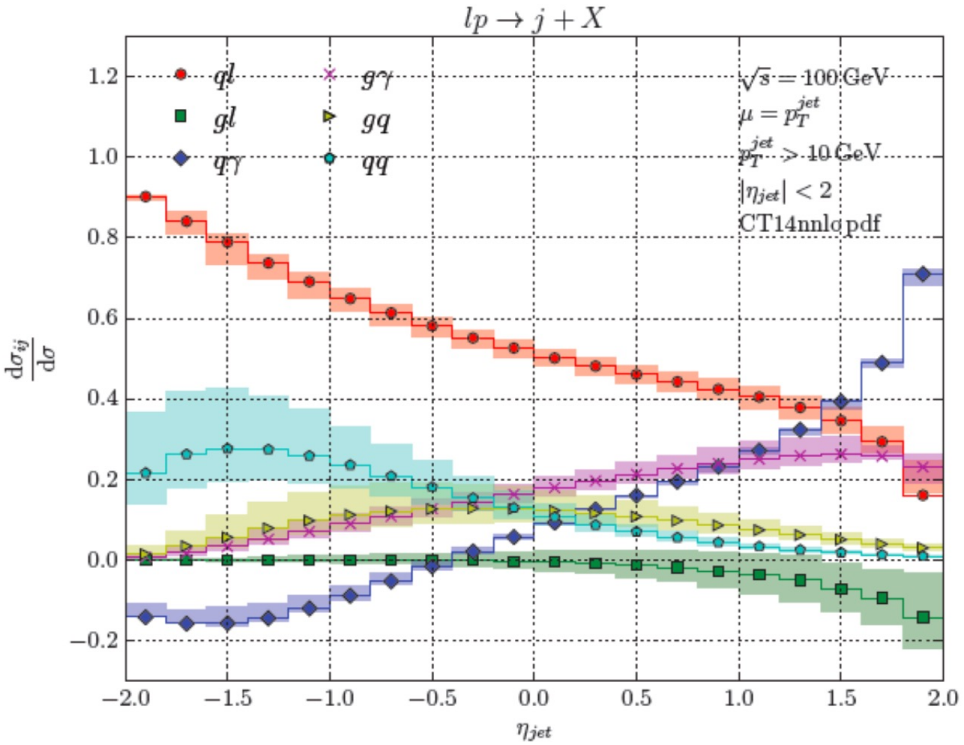
$\vec{e}\vec{p} \to e\,\mathrm{jet}X$



Borsa, de Florian, Pedron

$ep \to \mathrm{jet}X$

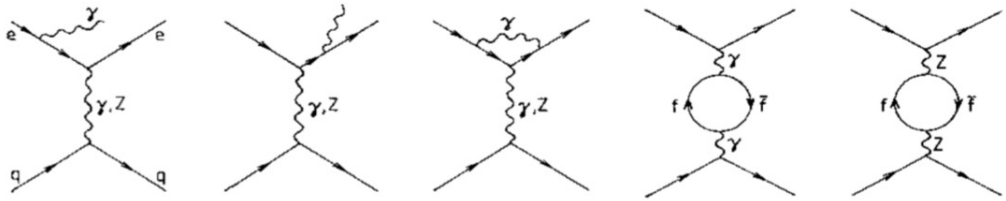
Boughezal, Petriello, Xing



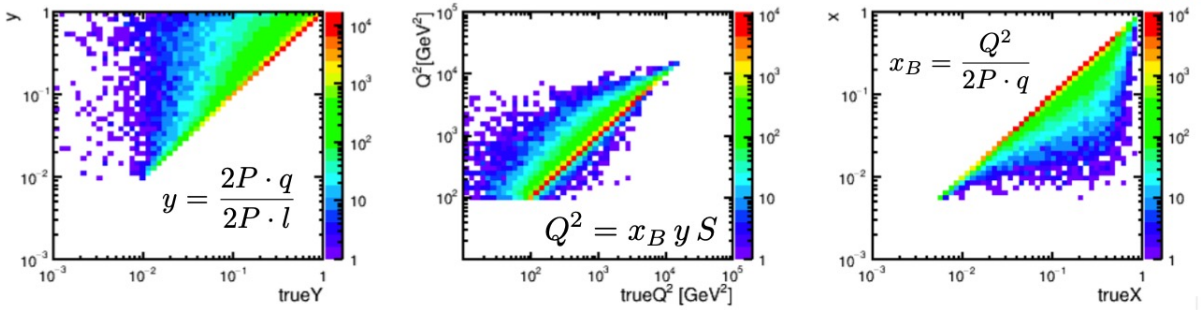
Collision with a large momentum transfer induces strong QED radiation

- **"Probe" for the hadron is smeared by the induced QED radiation:**

Data sample : Int L = 10 fb^{-1}, Kinematics settings: 0.01<y<0.95, 10^2 GeV^2 <Q^2<10^5 GeV^2



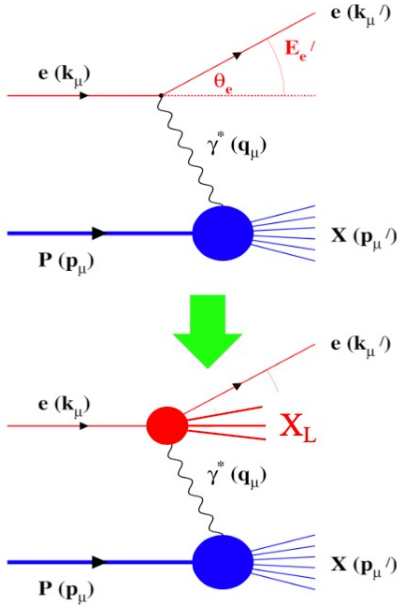
See Xiaoxuan Chu @2nd EIC YR workshop



Instead of a straight line – linear correlation,

the kinematic variables, y, Q^2 , x_B, from the leptons are smeared so much to make them different from what the scattered "quark" experienced!

Ill-defined "photon-hadron" frame?!



$$q_\mu \rightarrow \hat{q}_\mu$$

$$Q^2 = -q^2 \rightarrow \widehat{Q}^2 = -\hat{q}^2$$

$$x_B = \frac{Q^2}{2P \cdot q} \rightarrow \hat{x}_B = \frac{\widehat{Q}^2}{2P \cdot \hat{q}}$$

Jefferson Lab

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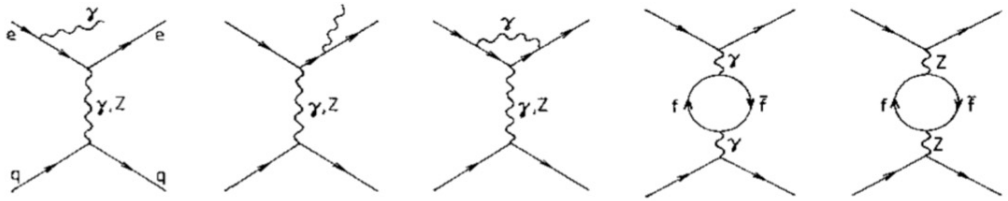

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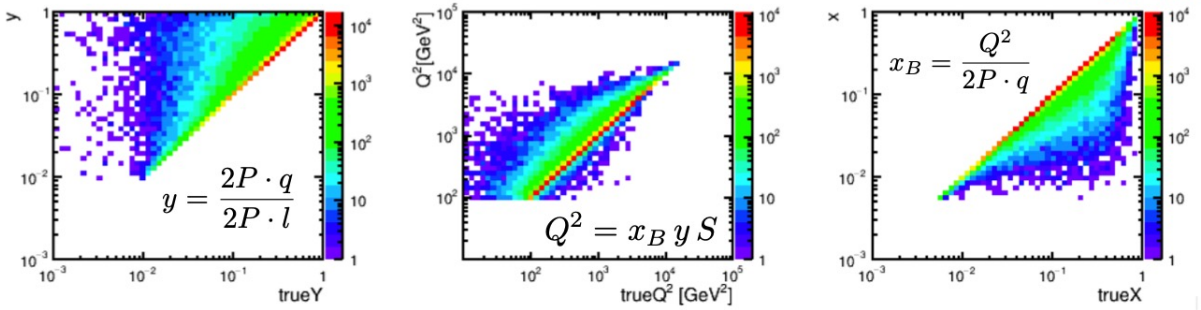

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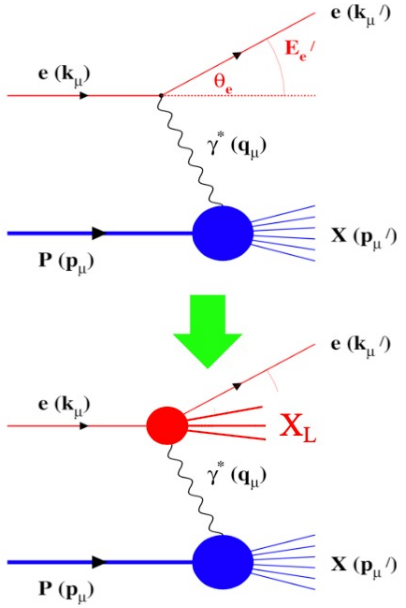

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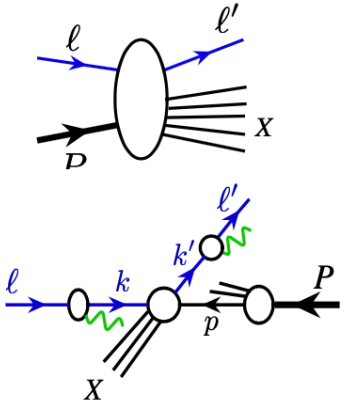
Jefferson Lab

- especially an issue for SIDIS, azimuthal asymm., TMDS

Liu, Melnitchouk, Qiu, Sato

Inclusive lepton-hadron deep inelastic scattering (DIS)

- **Inclusive production of single high p_T lepton in lepton-hadron collision:**



$$e(\ell, \lambda_\ell) + N(P, S) \to e(\ell') + X$$

$$d\sigma_{\ell(\lambda_\ell)P(S)\to\ell' X} = \frac{1}{2s}\left|M_{\ell(\lambda_\ell)P(S)\to\ell' X}\right|^2 d\mathrm{PS}$$

$$E'\frac{d\sigma_{\ell P\to\ell' X}}{d^3\ell'} \approx \frac{1}{2s}\sum_{ija}\int_{\zeta_{\min}}^1 \frac{d\zeta}{\zeta^2}\int_{\xi_{\min}}^1 \frac{d\xi}{\xi} D_{e/j}(\zeta,\mu^2)\, f_{i/e}(\xi,\mu^2)$$

$$\times \int_{x_{\min}}^1 \frac{dx}{x} f_{a/N}(x,\mu^2)\, \widehat{H}_{ia\to jX}(\xi\ell, xP, \ell/\zeta, \mu^2) \;+\; \cdots$$

Collinear QED & QCD factorization

Lepton distribution functions (LDFs): $f_{i/e}(\xi,\mu^2)$

Lepton fragmentation functions (LFFs): $D_{e/j}(\zeta,\mu^2)$ $\quad i.j = e,\gamma,\bar{e},...,q,g,...$

Parton distribution functions (PDFs): $f_{a/N}(x,\mu^2)$ $\quad a = q,g,\bar{q},e,\gamma,\bar{e},...$

Short-distance hard coefficients: $\widehat{H}_{ia\to jX}(\xi\ell, xP, \ell/\zeta, \mu^2)$

- **No DIS "Structure Functions"!**
  Concept of one-photon exchange
- **QED & QCD contribution are factorized at the same scale: μ**

$$(x_B, Q^2) \;\to\; (y, \ell'_T)$$

- **Corrections suppressed by power**

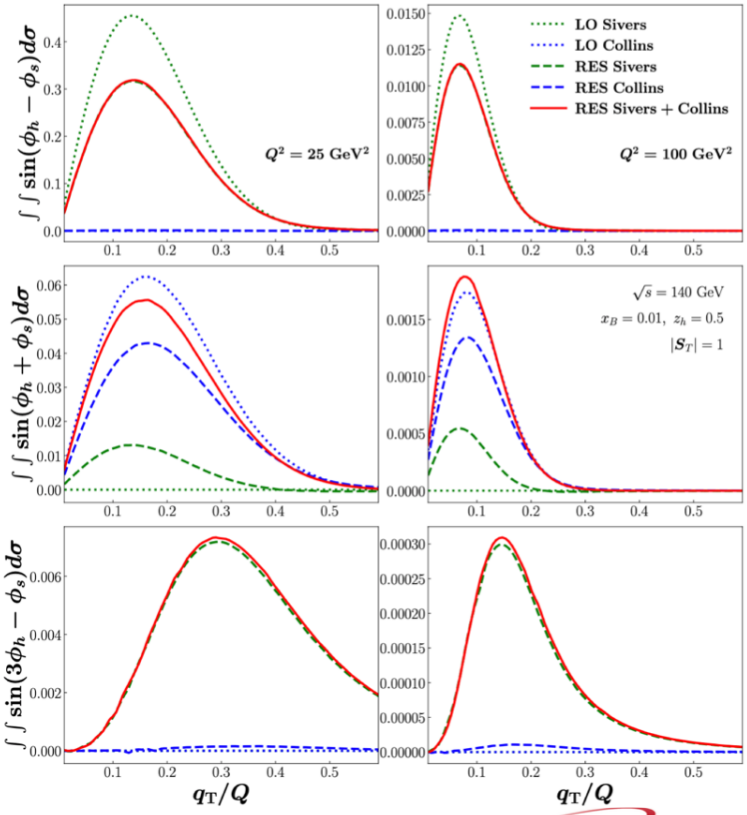
$$\mathcal{O}\left(\left(\frac{\Lambda_{\mathrm{QCD}}}{p_T}\right)^{\mathrm{power}}, \left(\frac{m_\ell}{p_T}\right)^{\mathrm{power}}\right)$$

Lepton-hadron semi-inclusive deep inelastic scattering (SIDIS)

- **Case study – single transverse spin asymmetry:**

Liu, Melnitchouk, Qiu, Sato
2008.02895, 2108.13371

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&+|\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}\right. \\
&\quad\left.+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}
\end{aligned}
$$



Jefferson Lab

- All-order QCD threshold resummation for differential distributions → application to SIDIS at EIC

Forte

- All-order QCD threshold resummation for differential distributions → application to SIDIS at EIC

Forte

- Power corrections to QCD hard scattering: Threshold resummation / low-scale behavior of strong coupling, eikonal approximation.

Sterman

→ for $pp \to \gamma X$ power corrections start at $\frac{1}{p_T^2}$

Selected highlights:
Hadronic structure

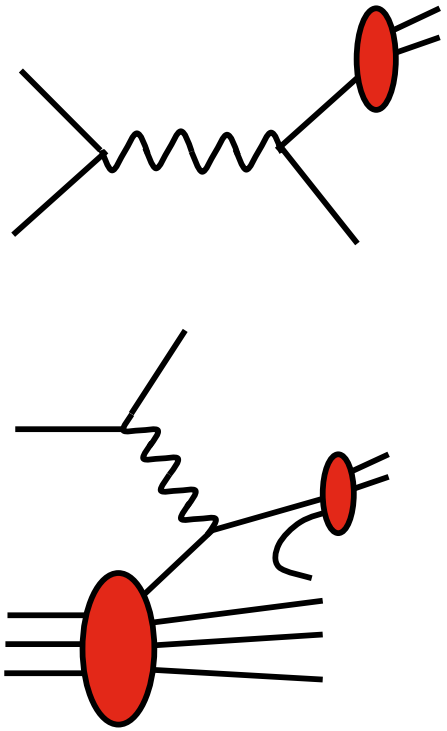
Trends in extractions of distribution functions:

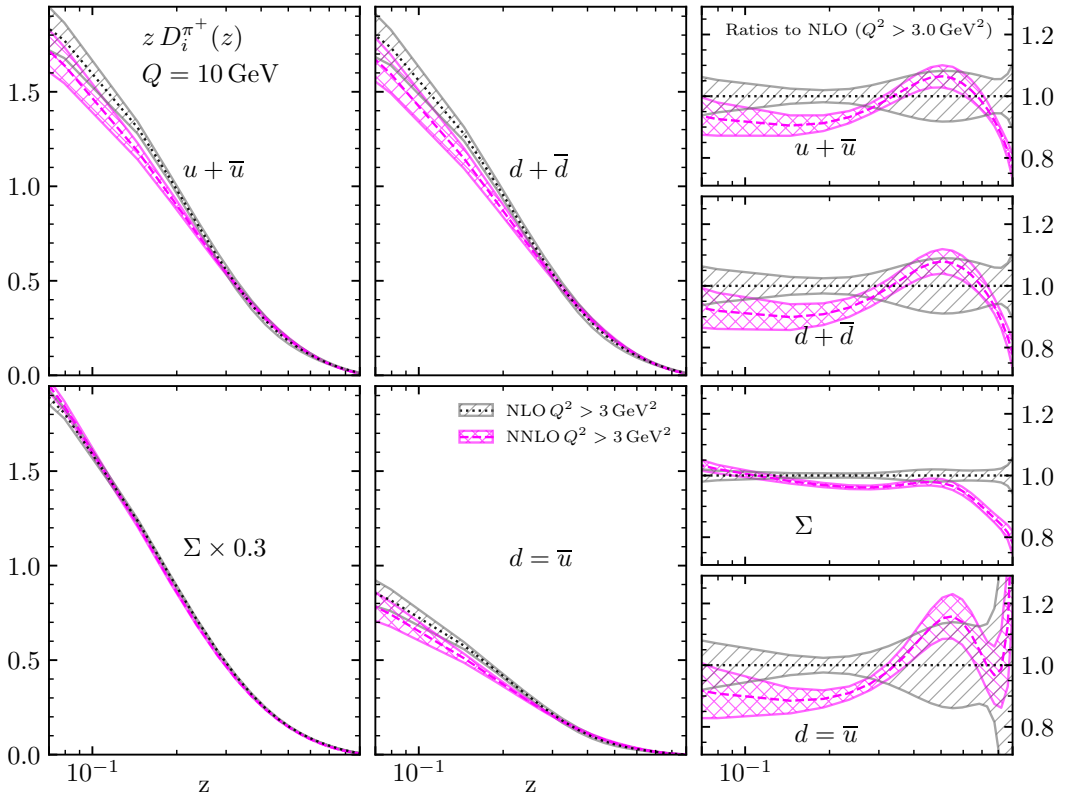
- higher orders:

  global analysis of fragmentation functions at “nearly NNLO”

  Borsa

$$e^+e^- \to hX, \;\; ep \to ehX$$



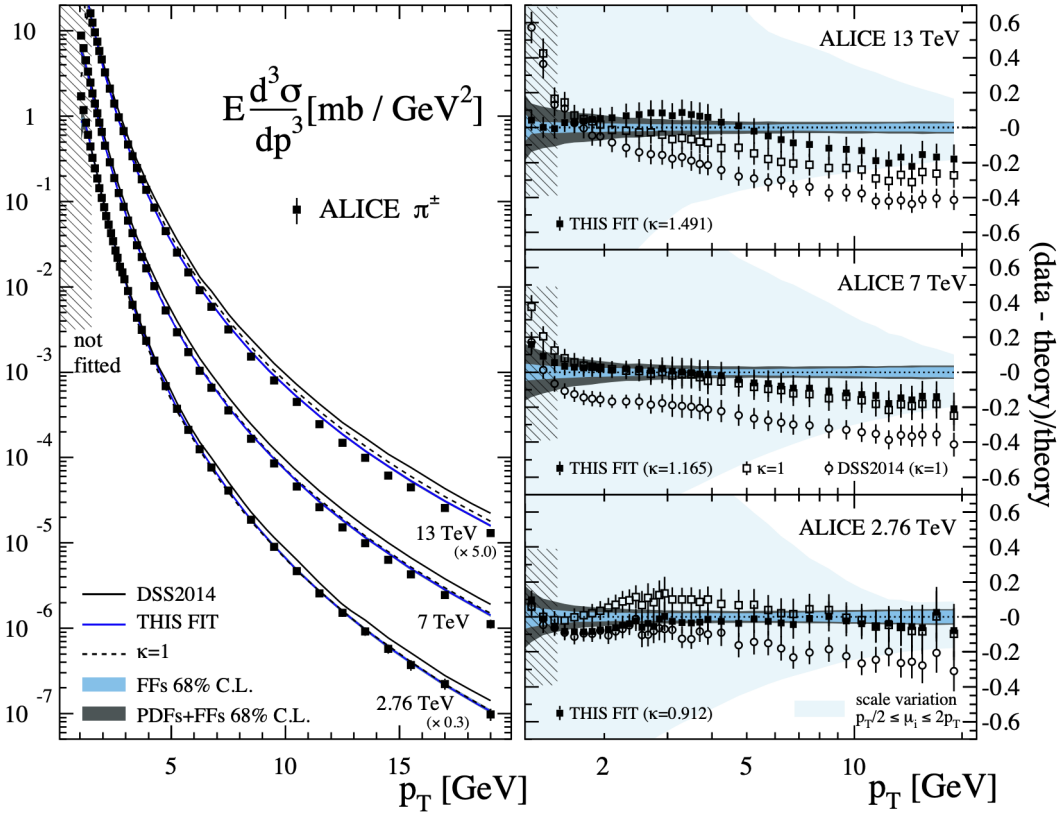


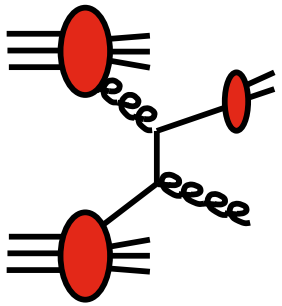
Fragmentation Functions at NLO:

a case for higher order corrections

Rodolfo Sassot
Universidad de Buenos Aires

Borsa, de Florian, **Sassot**, Stratmann





$$\mu = \kappa p_T$$

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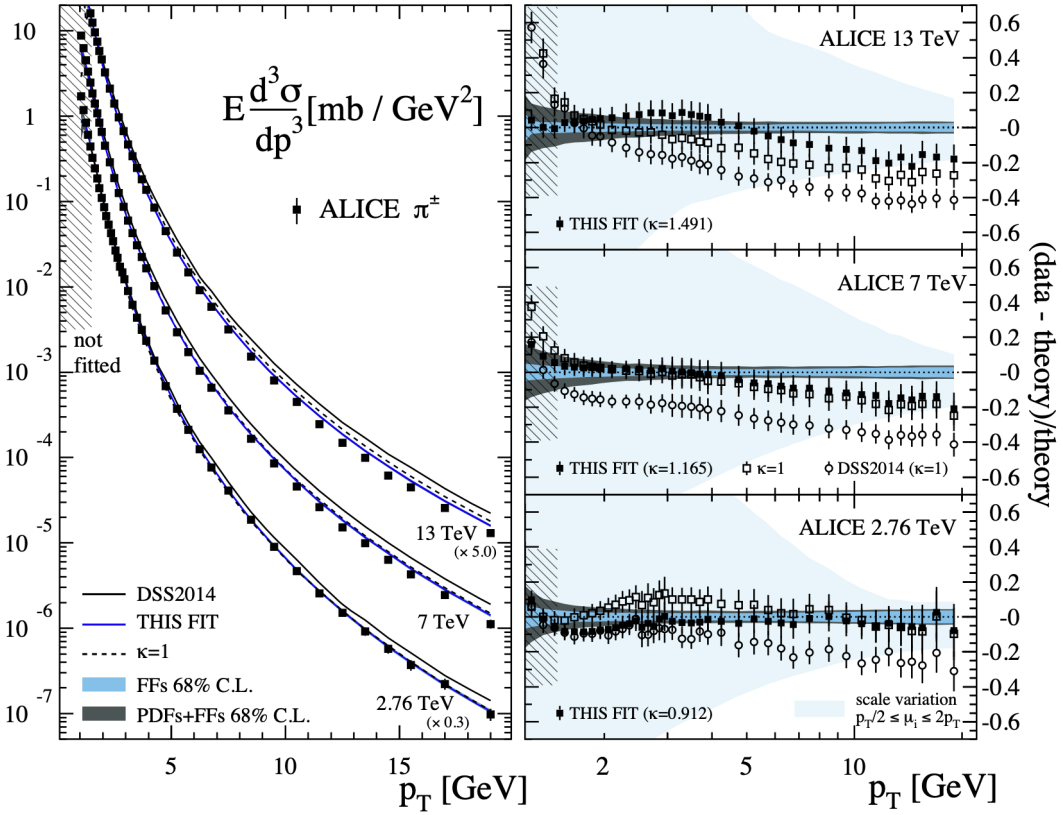
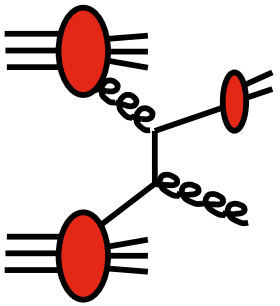
Universidad de Buenos Aires

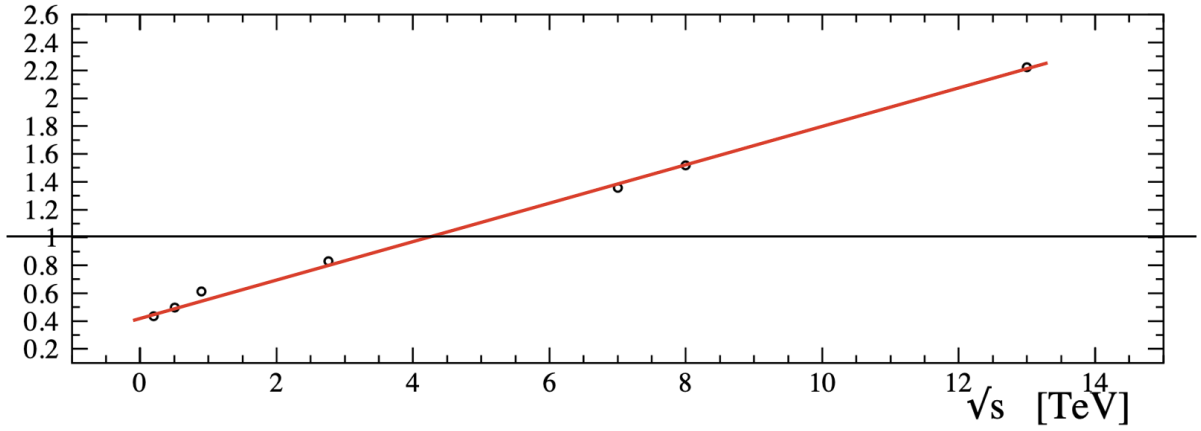
Borsa, de Florian, **Sassot**, Stratmann





$$\mu = \kappa p_T$$

$$\kappa^2 = \frac{\mu^2}{p_T^2}$$



- simultaneous global analyses

Sato

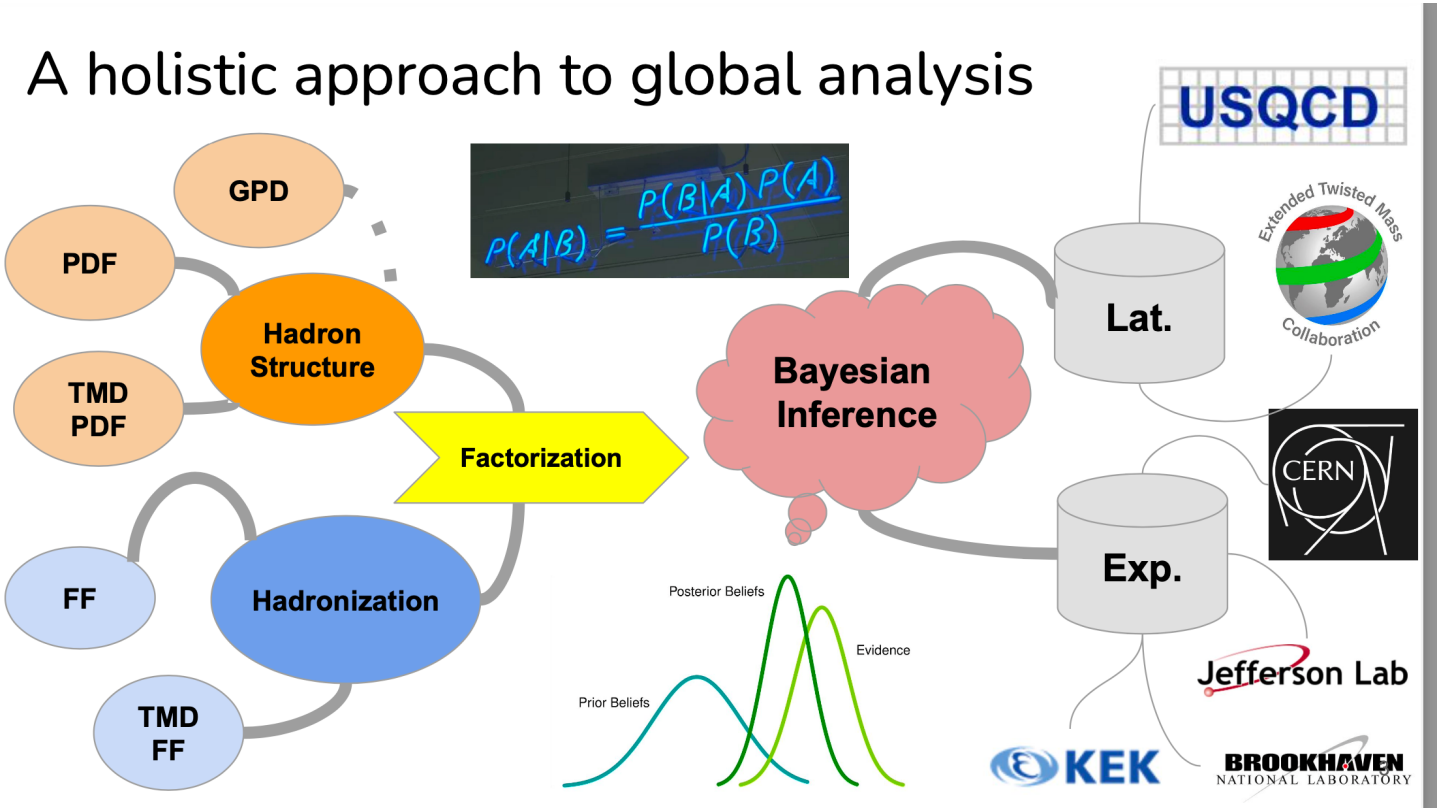
Recent results from JAM

Nobuo Sato

CFNS: precision QCD predictions for *ep* physics at the EIC

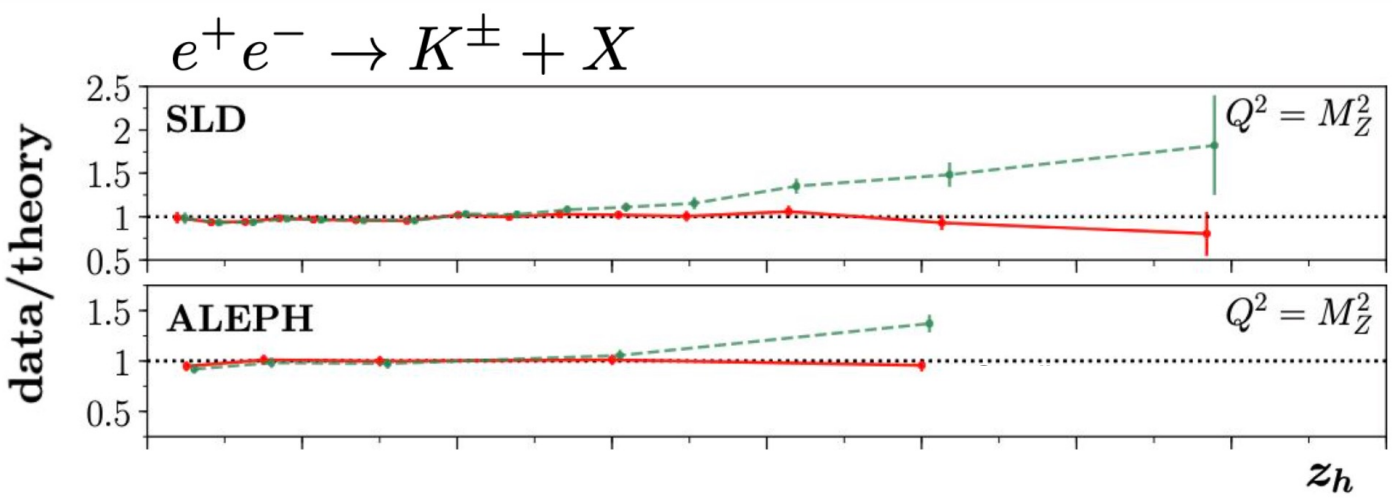
Aug. 1, 2022

Jefferson Lab

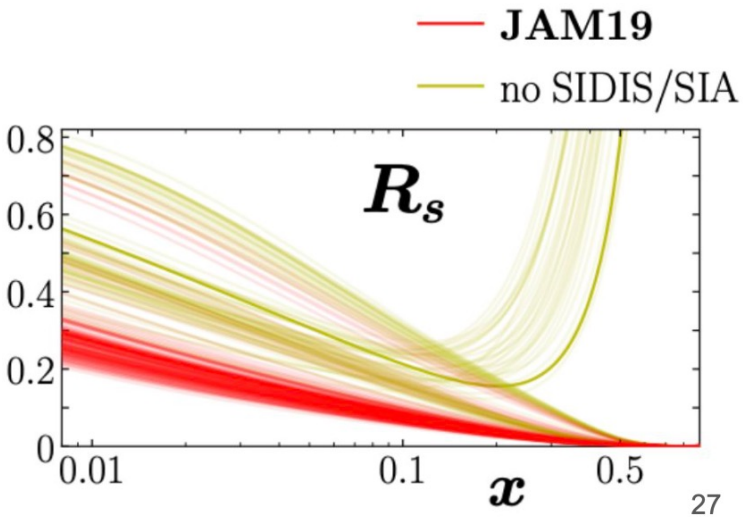


- first joint analysis of unpol. PDFs and FFs

Sato, Andres, Ethier, Melnitchouk (JAM)

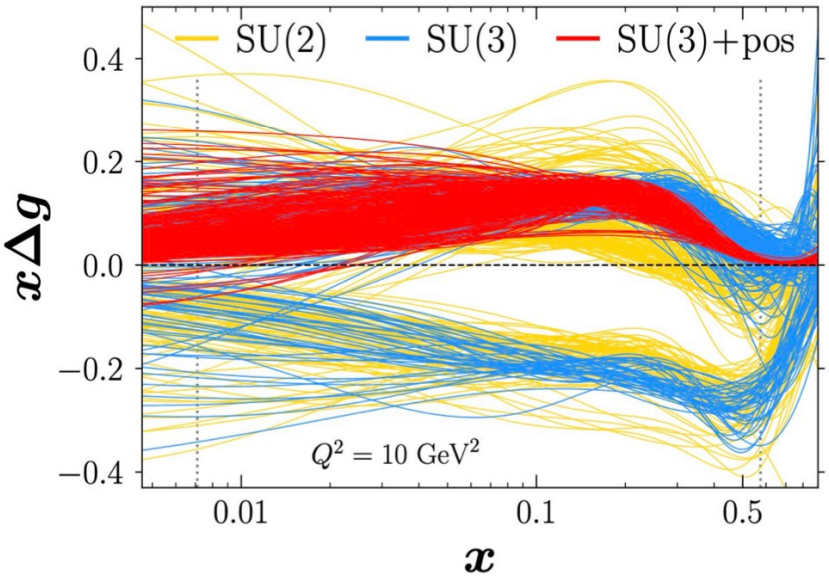


$$R_s = \frac{s + \bar{s}}{\bar{u} + \bar{d}}$$



- LEP kaon data disfavor small *s* --> *K* fragmentation
- SIDIS data compensate large strange FF by suppressing strange PDF

- polarized glue



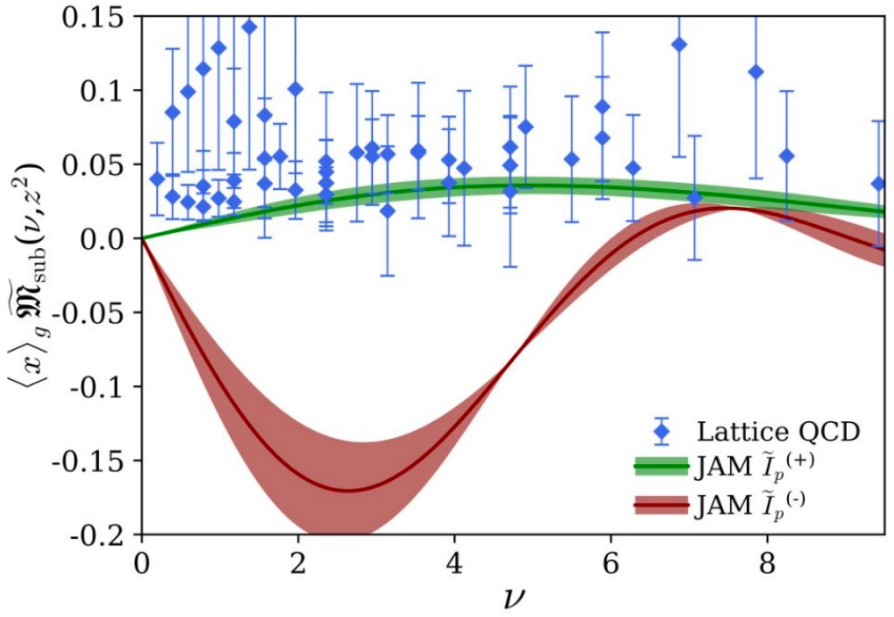
$\Delta g > 0$

$\Delta g < 0$

Polarized jet data cannot discriminate positive and negative solutions

HadStruc Collaboration

Egerer et al ('22)



Negative gluon helicity is ruled out by LQCD?

TMD fits

Available global fits

Cerutti (MAP Collab.)

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL^-	✔	✔	✔	1039	1.06
MAPTMD22	***N^3LL^-***	✔	✔	✔	***2031***	***1.06***

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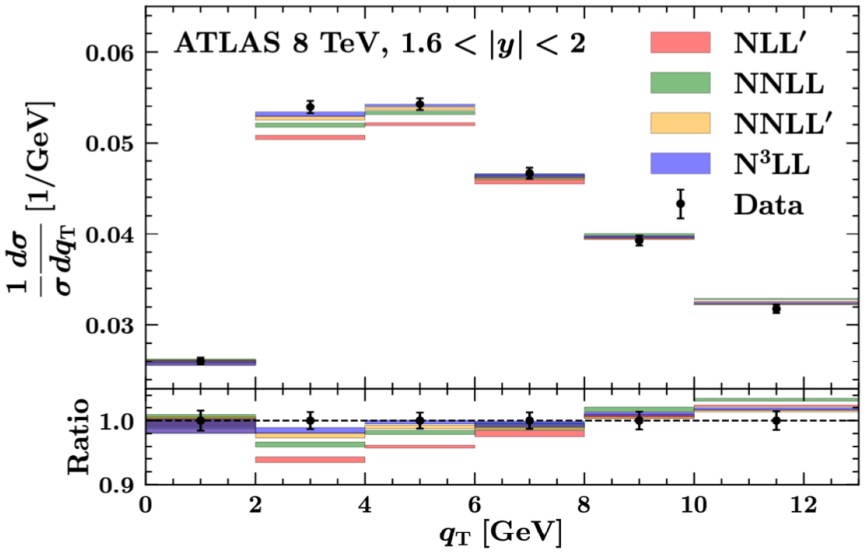
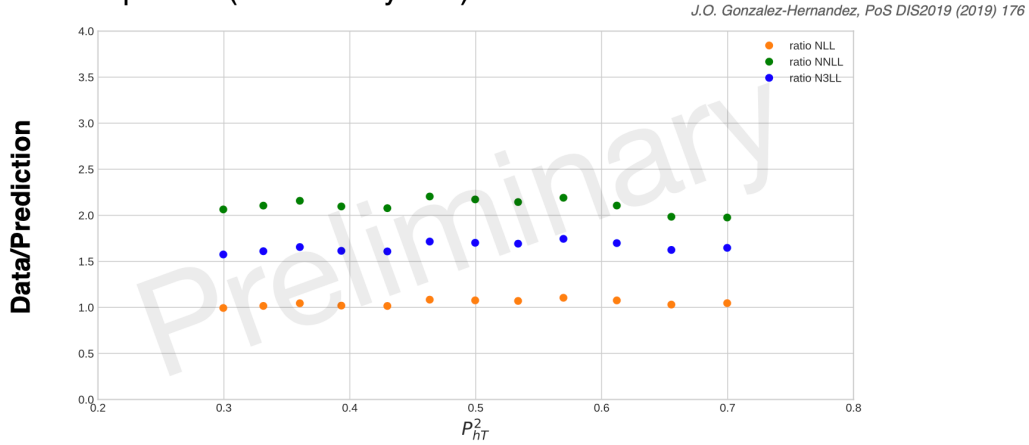
$Q \sim 100$ GeV



MAPTMD22 — Normalization of SIDIS

COMPASS multiplicities (one of many bins)



Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

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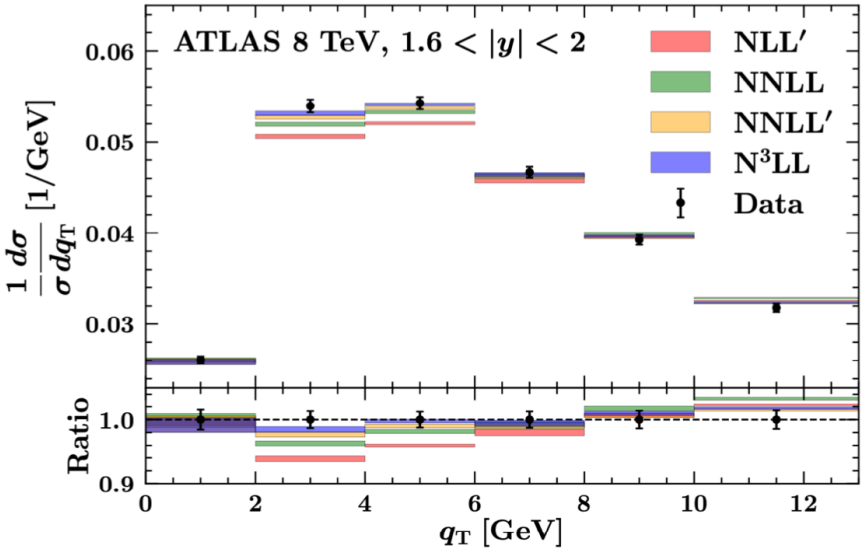

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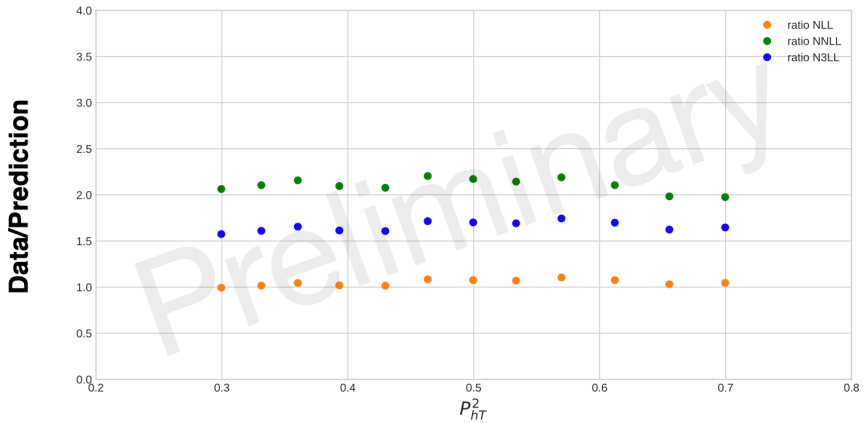
MAPTMD22 — Normalization of SIDIS

COMPASS multiplicities (one of many bins)

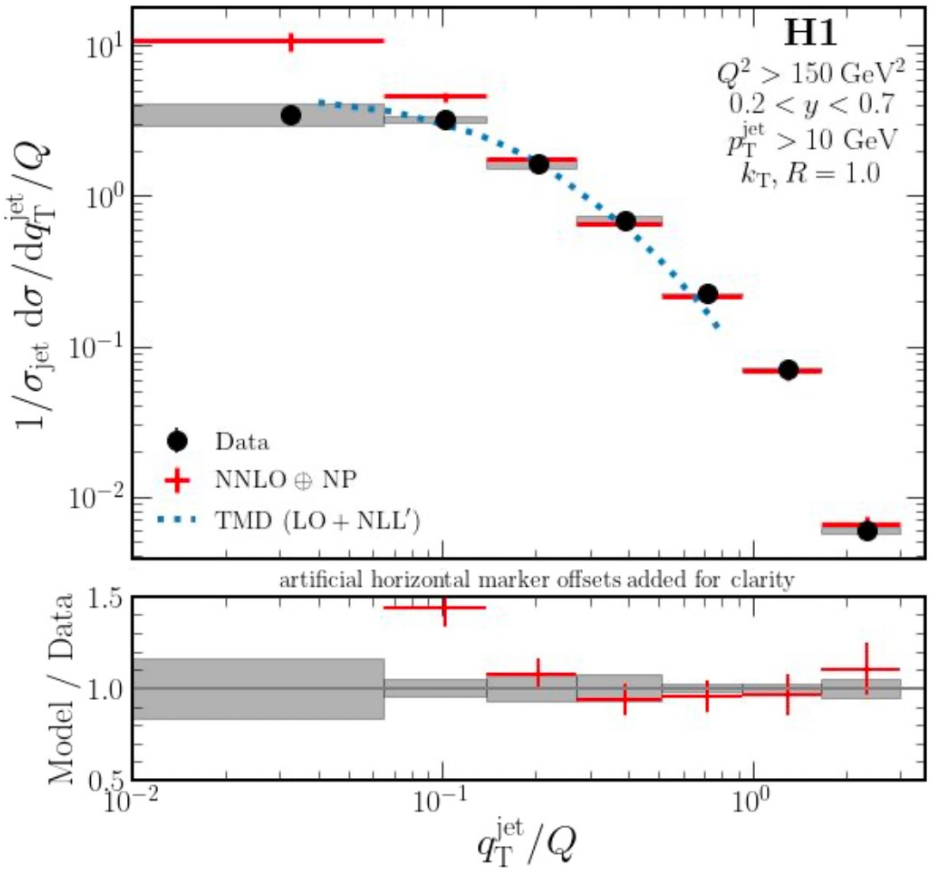
J.O. Gonzalez-Hernandez, PoS DIS2019 (2019) 176



crucial for JLab and EIC

“back to the future”: H1 data

Arratia



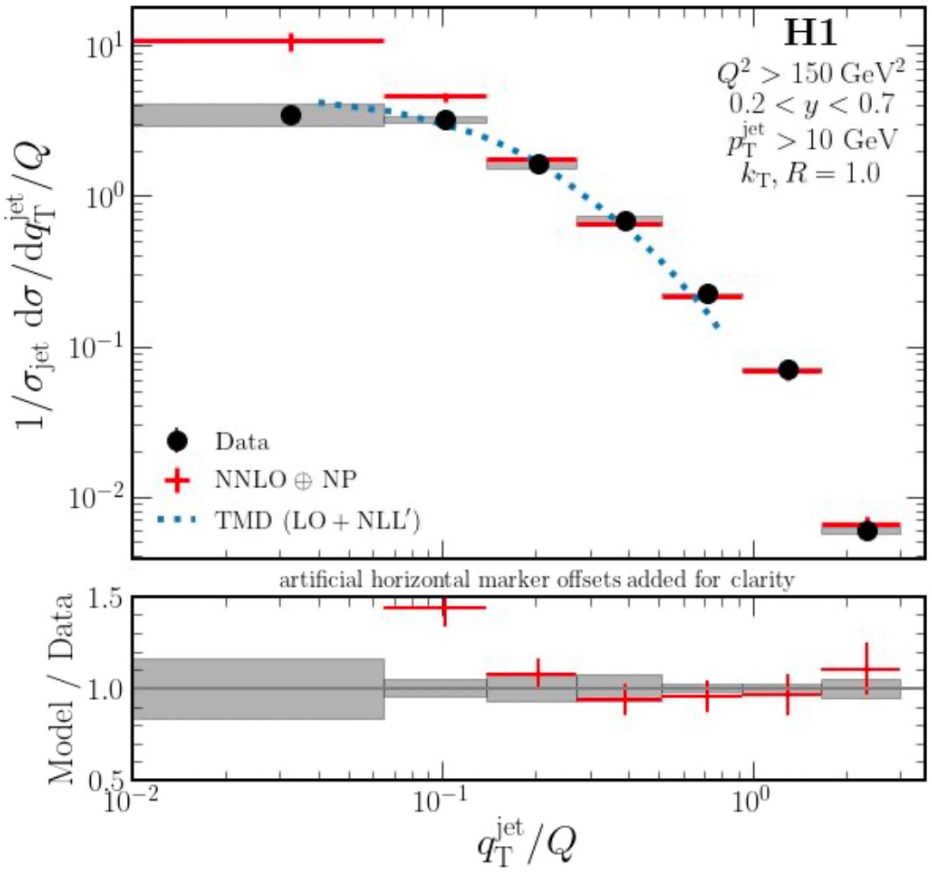
Textbook example of “matching” between collinear and TMD frameworks

First time seen in DIS!

(not seen in fixed-target DIS)

“back to the future”: H1 data

Arratia



Textbook example of “matching” between collinear and TMD frameworks

First time seen in DIS!

(not seen in fixed-target DIS)

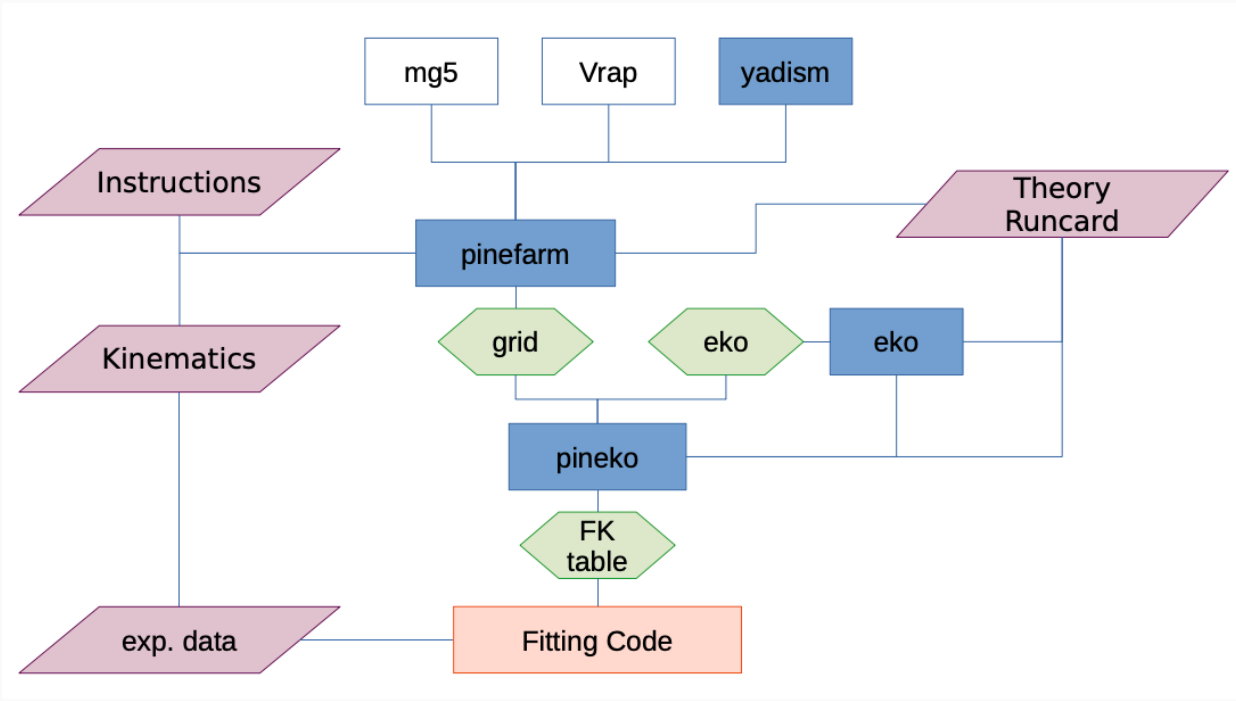
- advances & new ideas in theory in past decade
- new techniques for unfolding based on ML

- tool development

Hekhorn (NNPDF Collab.)

New Theory Prediction Pipeline

Produce FastKernel (FK) tables!



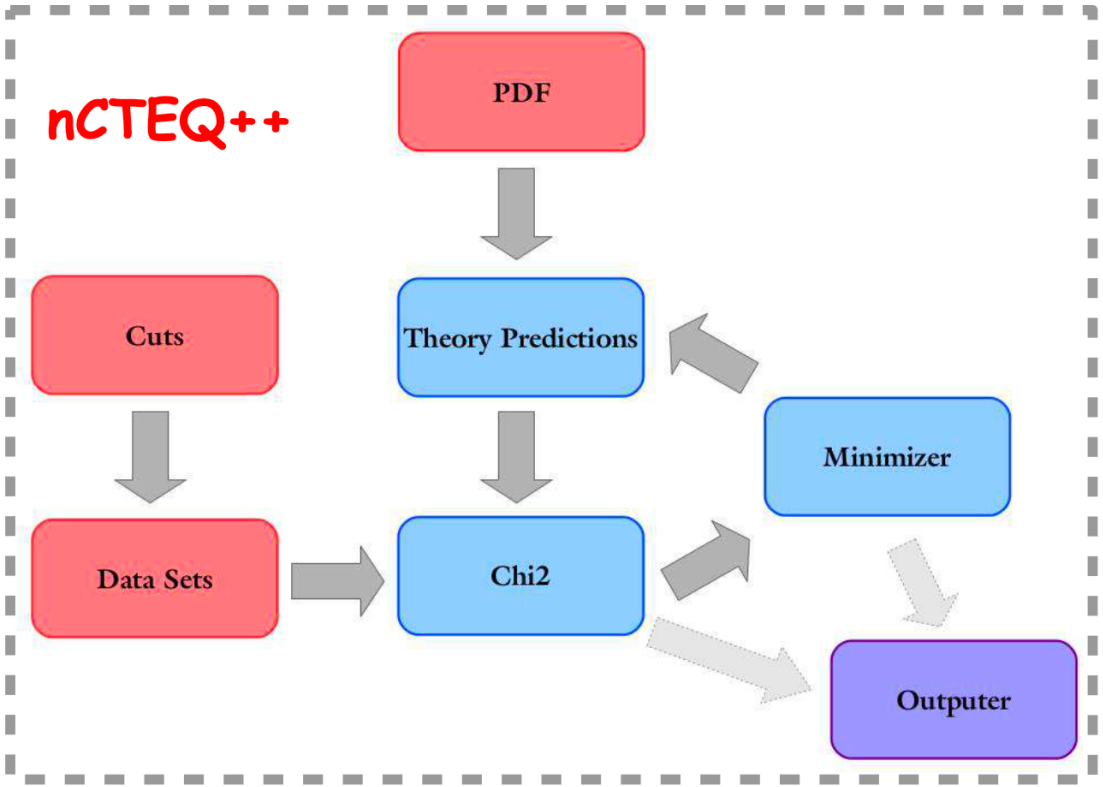
The workhorse in the background: PineAPPL

4

fully open-source

nCTEQ++ … a complete rewrite in C++

Top level C++, modular structure, output to YAML & Python scripts



Use external programs

- Minuit
- HOPPET
- MCFM
- APPLgrid

Pre-Computed Grids

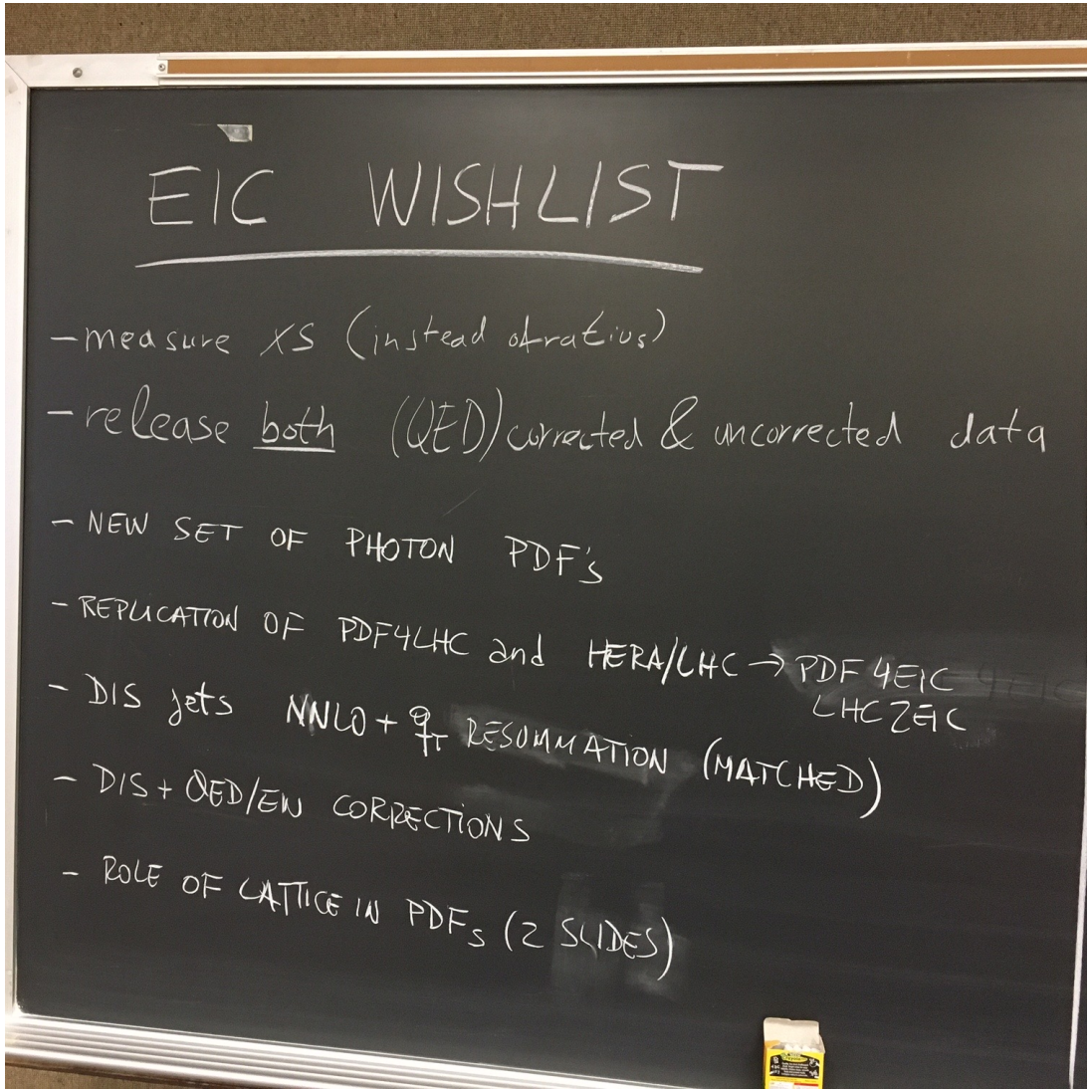
Tremendous speed-up for higher order calculation

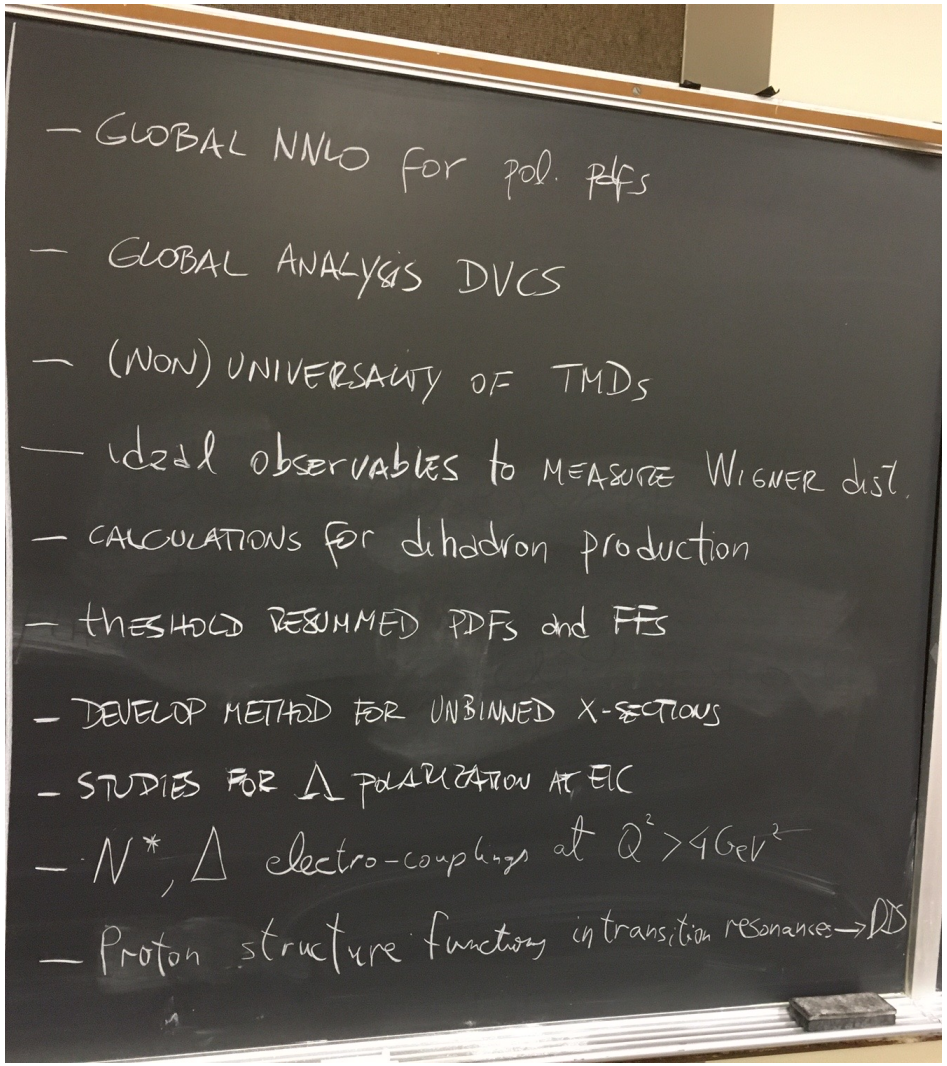
… for example …

High order DIS processes (Peter Risse)

Special thanks to:
Tomas Jezo
Eric Godat
Florian Lyonnet
Aleksander Kusina

- so, how about the “EIC wish list”?

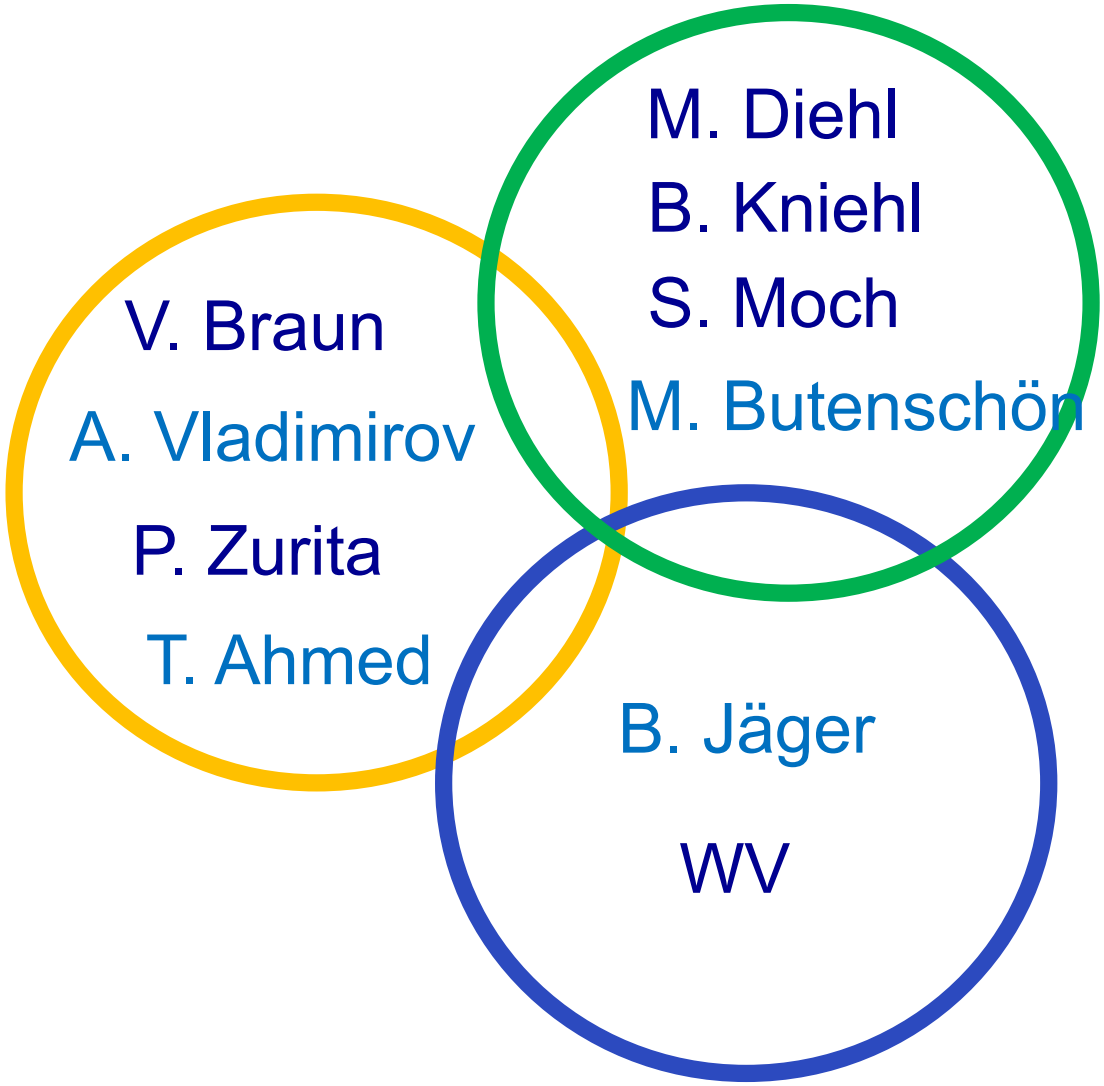


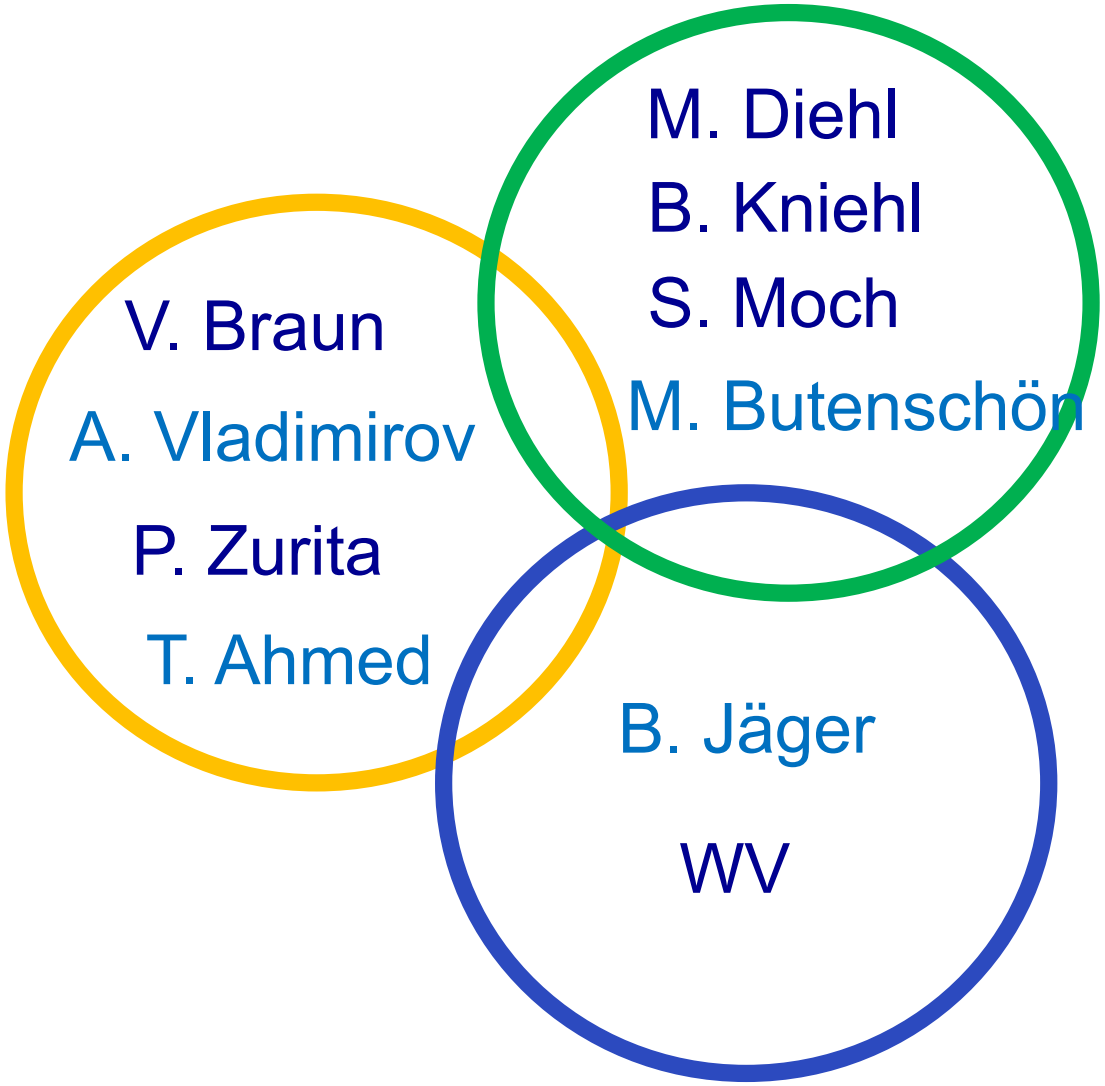


Instead of conclusions

Next Generation Perturbative QCD for Hadron Structure: Preparing for the Electron-Ion Collider

- Research Unit FOR2926: Hamburg, Regensburg, Tübingen
- Spokesperson: V. Braun
- so far, 2019-2022


M. Diehl
B. Kniehl
S. Moch
M. Butenschön
V. Braun
A. Vladimirov
P. Zurita
T. Ahmed
B. Jäger
WV



E. Aschenauer

D. Boer

K. Chetyrkin

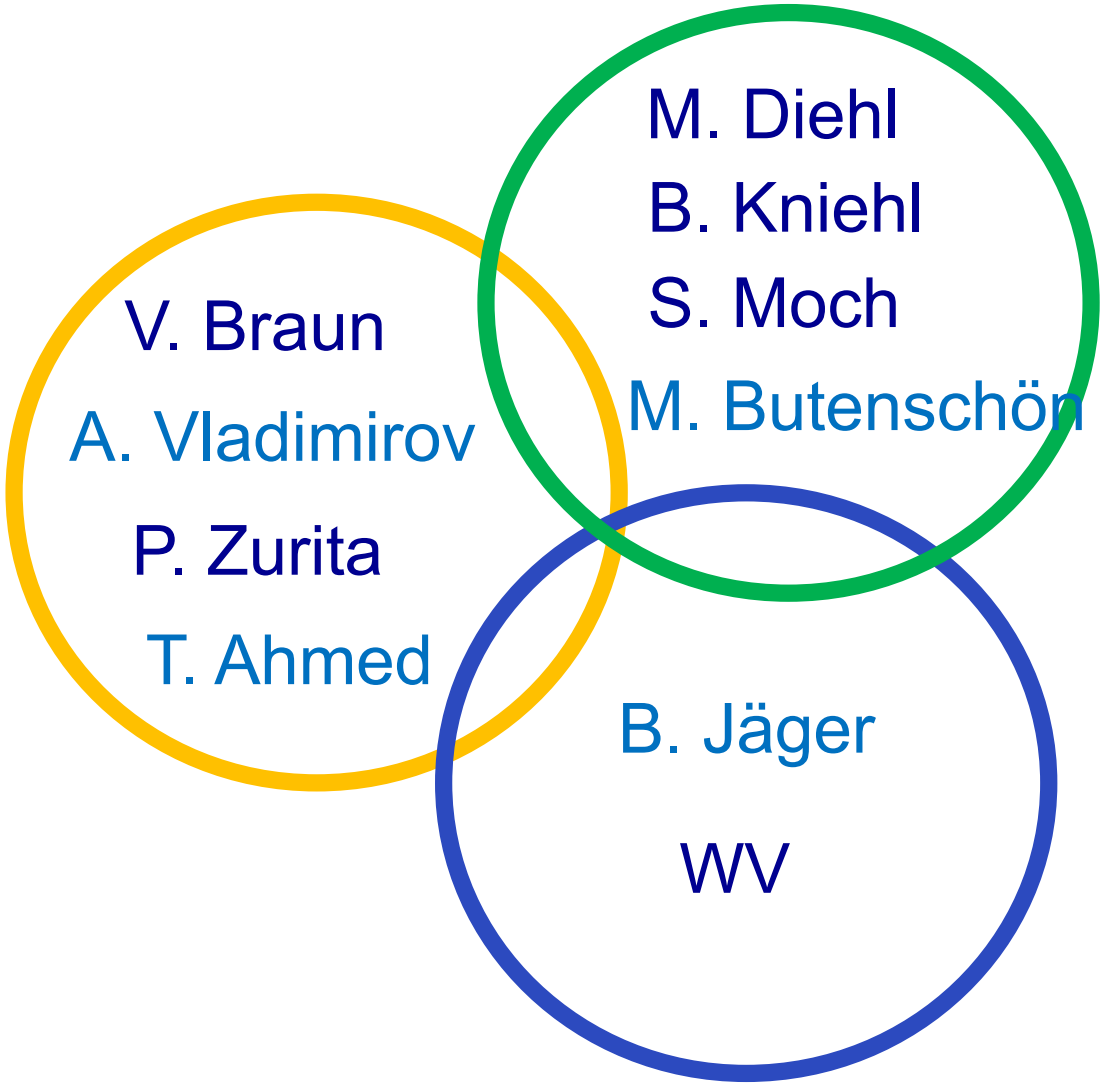
D. de Florian

A. Schäfer

M. Schlegel

I. Scimemi

M. Stratmann



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M. Stratmann

- high-order pQCD computations:
  evolution, SIDIS, DVCS, TMDs, J/ψ
- high-order extractions of PDFs, nPDFs, FFs, TMDs

- funds primarily used for hiring postdocs and PhD students
- so far, around 50 publications
- substantial contributions to EIC Yellow Report

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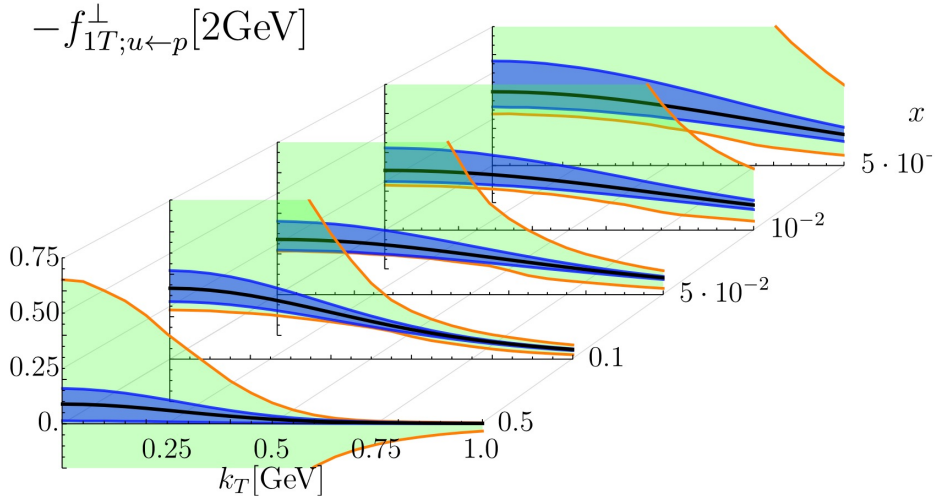

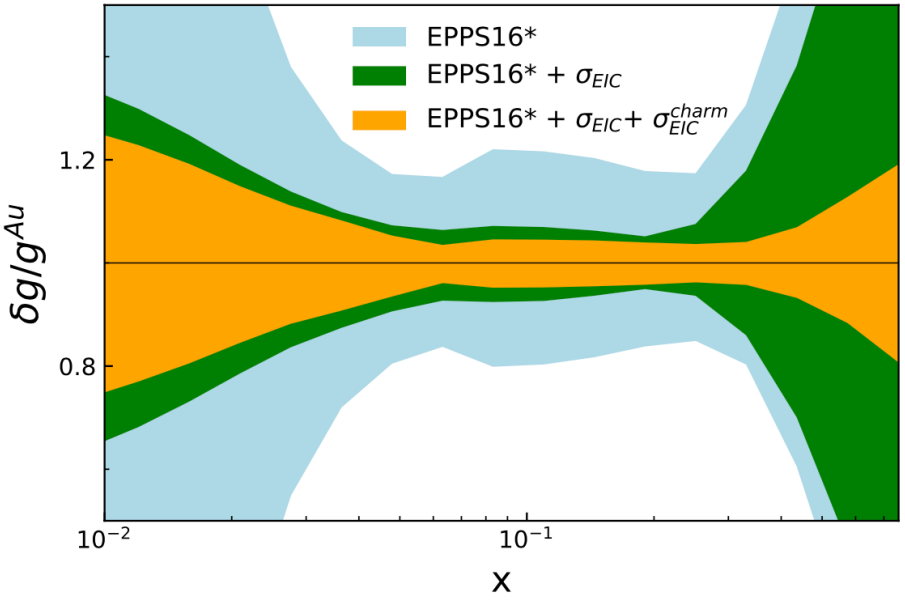

- EIC equal opportunity program (EICEO):
  special visitor program for international female scientists

- short-term fellowship for early-career female scientist
  (e.g., after career break)

- two-year scholarship for excellent female PhD student
  (Hamburg)

- FOR2926 master program for female student