DIS in the big picture of HEP

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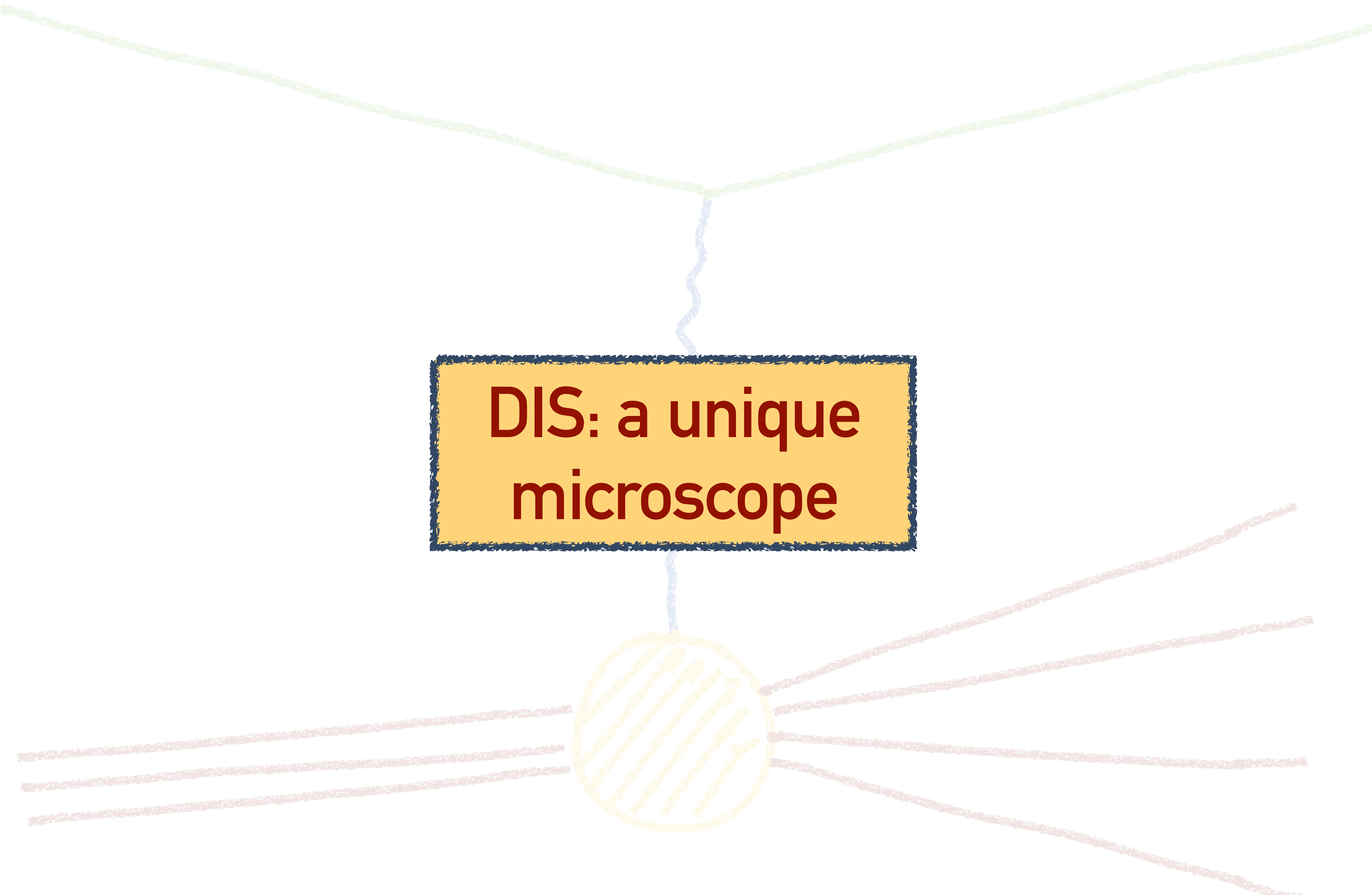
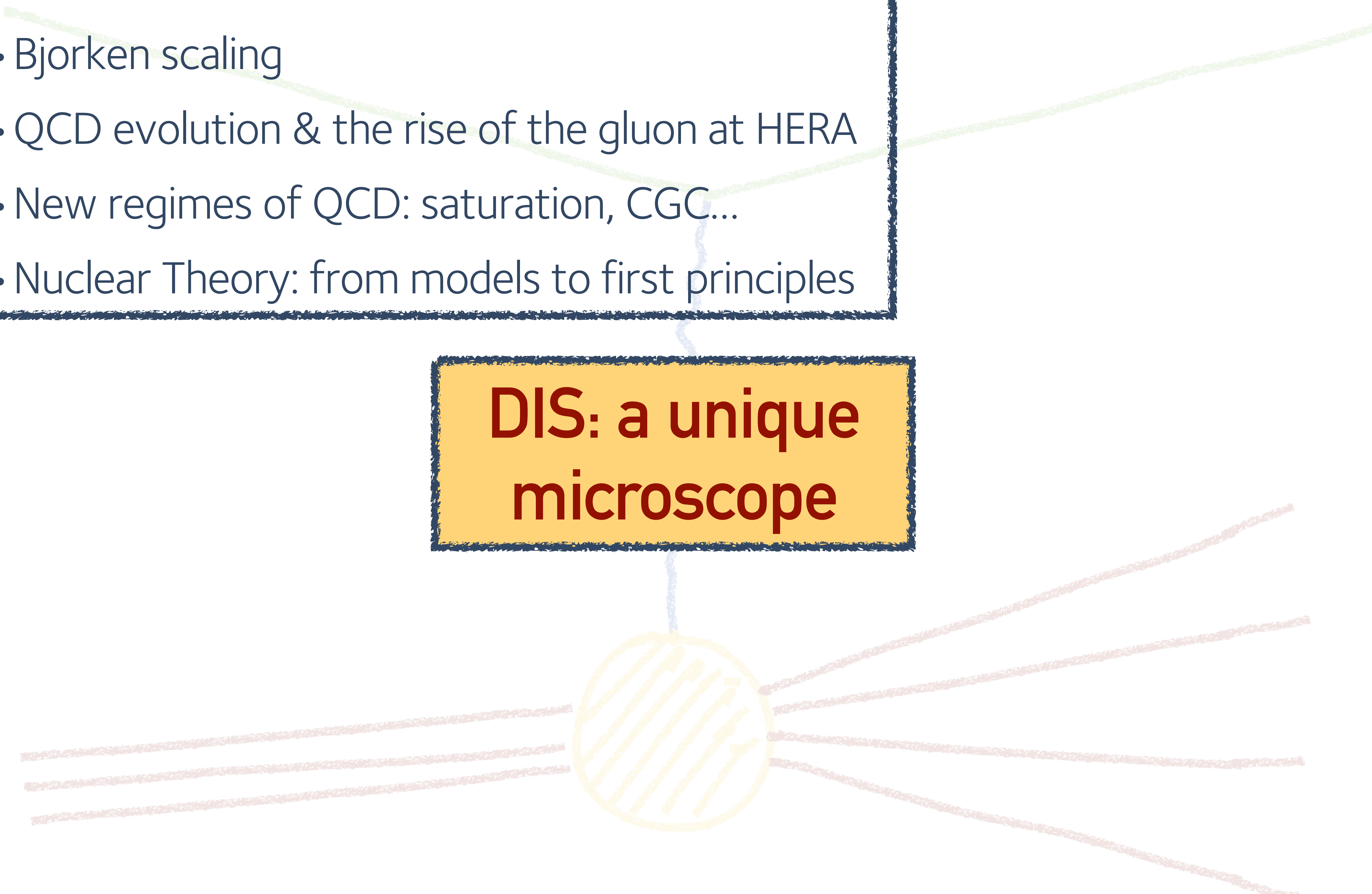
DIS: a unique microscope



Fundamentals of QCD in a clean environment

- Bjorken scaling
- QCD evolution & the rise of the gluon at HERA
- New regimes of QCD: saturation, CGC...
- Nuclear Theory: from models to first principles

DIS: a unique microscope



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DIS: a unique microscope

A precise mapping of the proton/nuclei

- PDFs at high precision → crucial for hadron colliders
- HERA: high-precision at hadron colliders is possible
- Beyond PDFs: TMDs, 3D tomography…
- Mass/spin of the proton

Fundamentals of QCD in a clean environment

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A high-energy probe

- EW physics in DIS
- Precision SM parameters
- Higgs couplings
- BSM models

DIS: a unique microscope

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This talk:

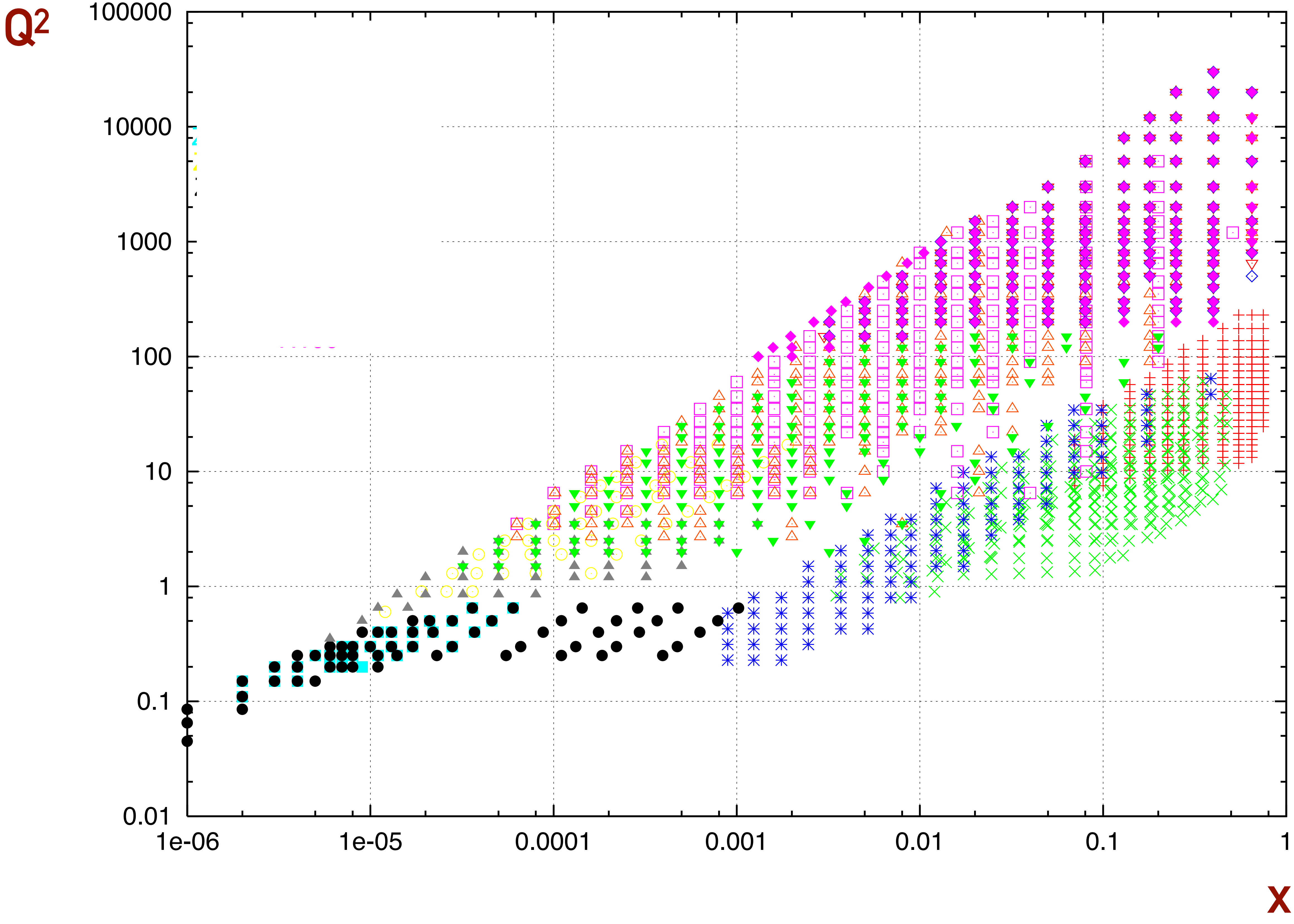
Some illustrative examples of the richness of the DIS program, emphasising their connection to a broader HE picture

Caveats

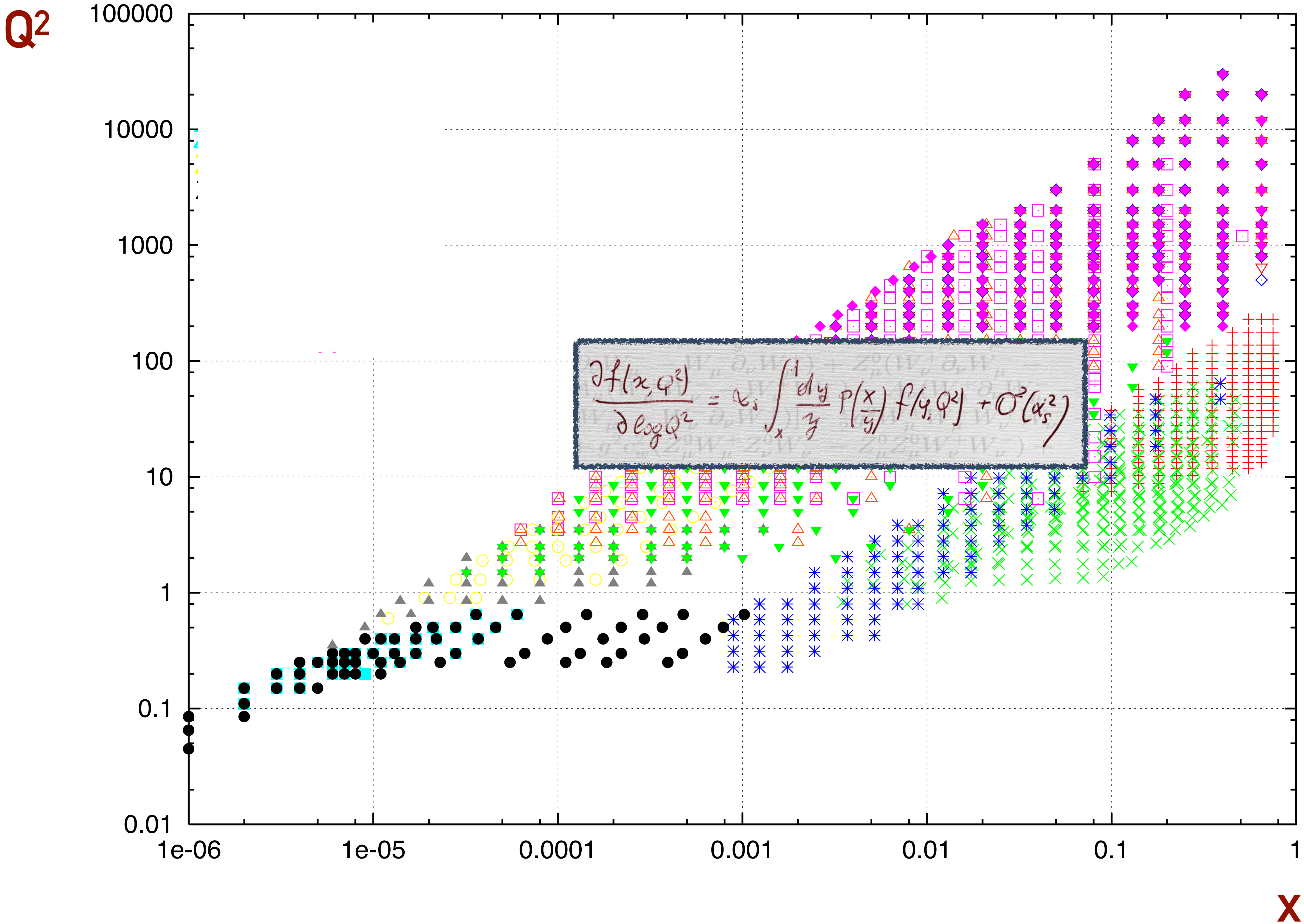
- Examples drawn mostly from topics I am familiar with. Apologies if your favourite subject is not here!
- Mostly focus on DIS now, but with an eye on the future.

  ``Future of DIS//new facilities" → J. d'Hondt, M. d'Onofrio's talks

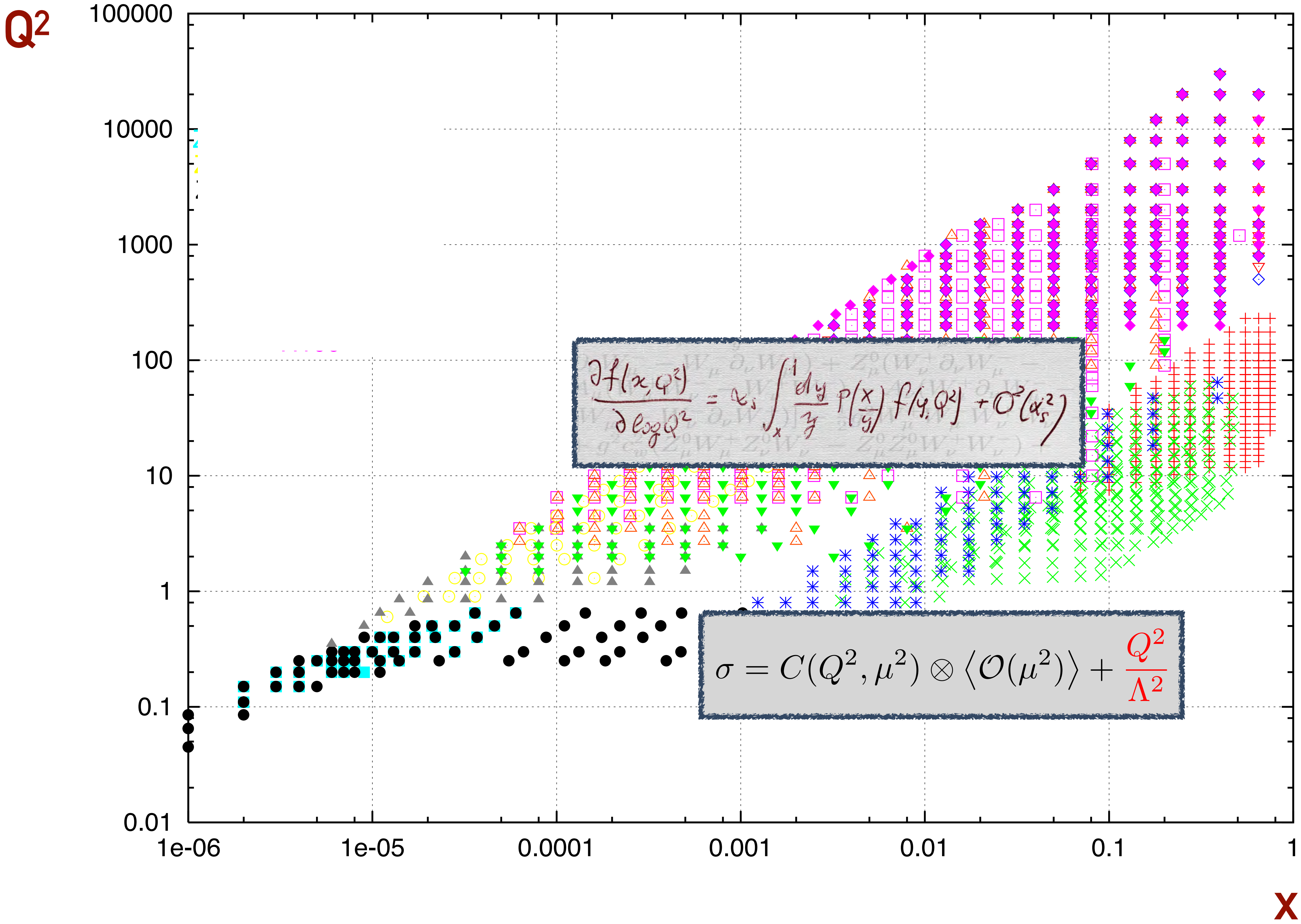
DIS kinematics



DIS kinematics



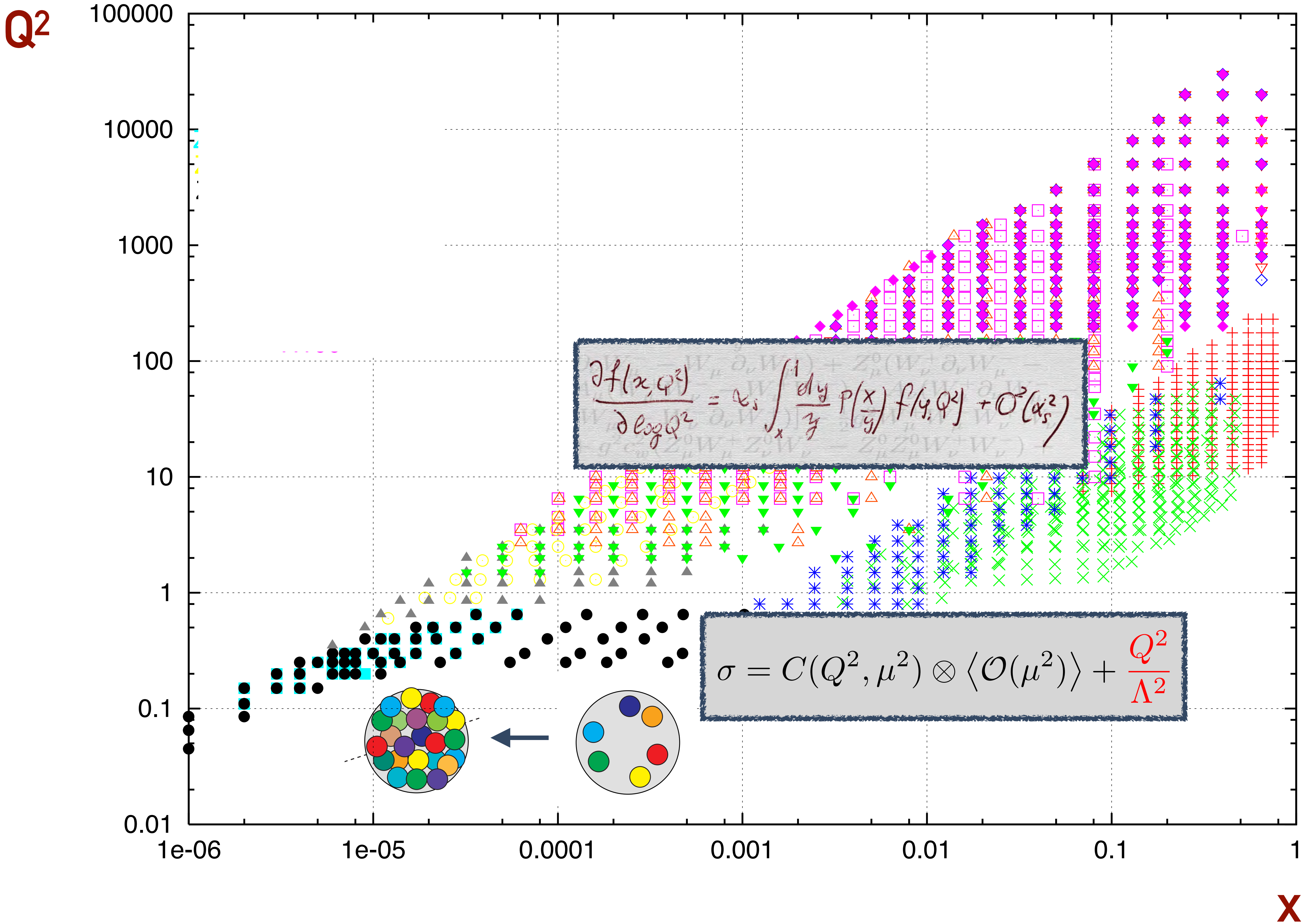
DIS kinematics



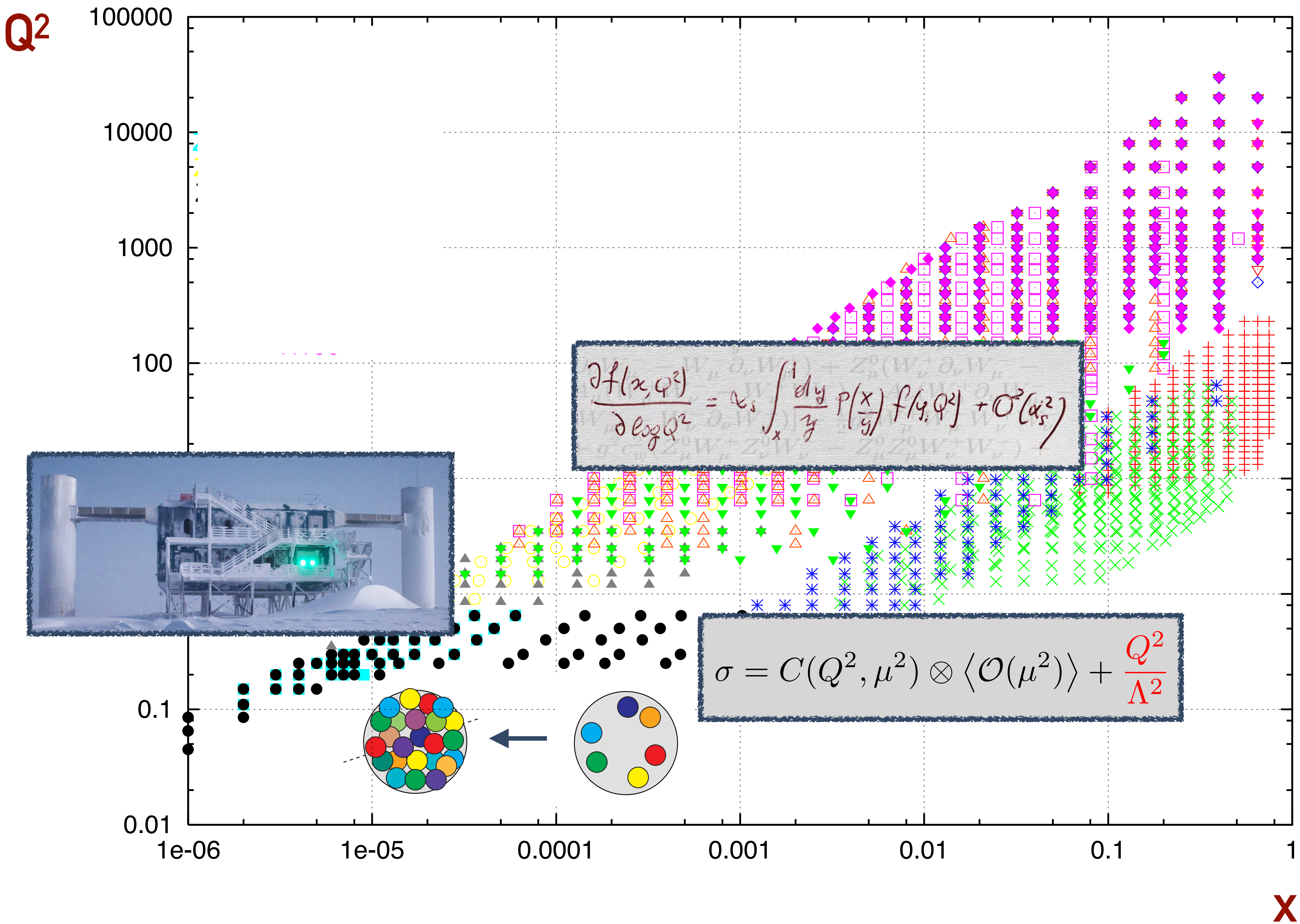
$$\frac{\partial f(x,Q^2)}{\partial \log Q^2} = \alpha_s \int_x^1 \frac{dy}{y} P\left(\frac{x}{y}\right) f(y,Q^2) + \mathcal{O}(\alpha_s^2)$$

$$\sigma = C(Q^2,\mu^2) \otimes \langle \mathcal{O}(\mu^2) \rangle + \frac{Q^2}{\Lambda^2}$$

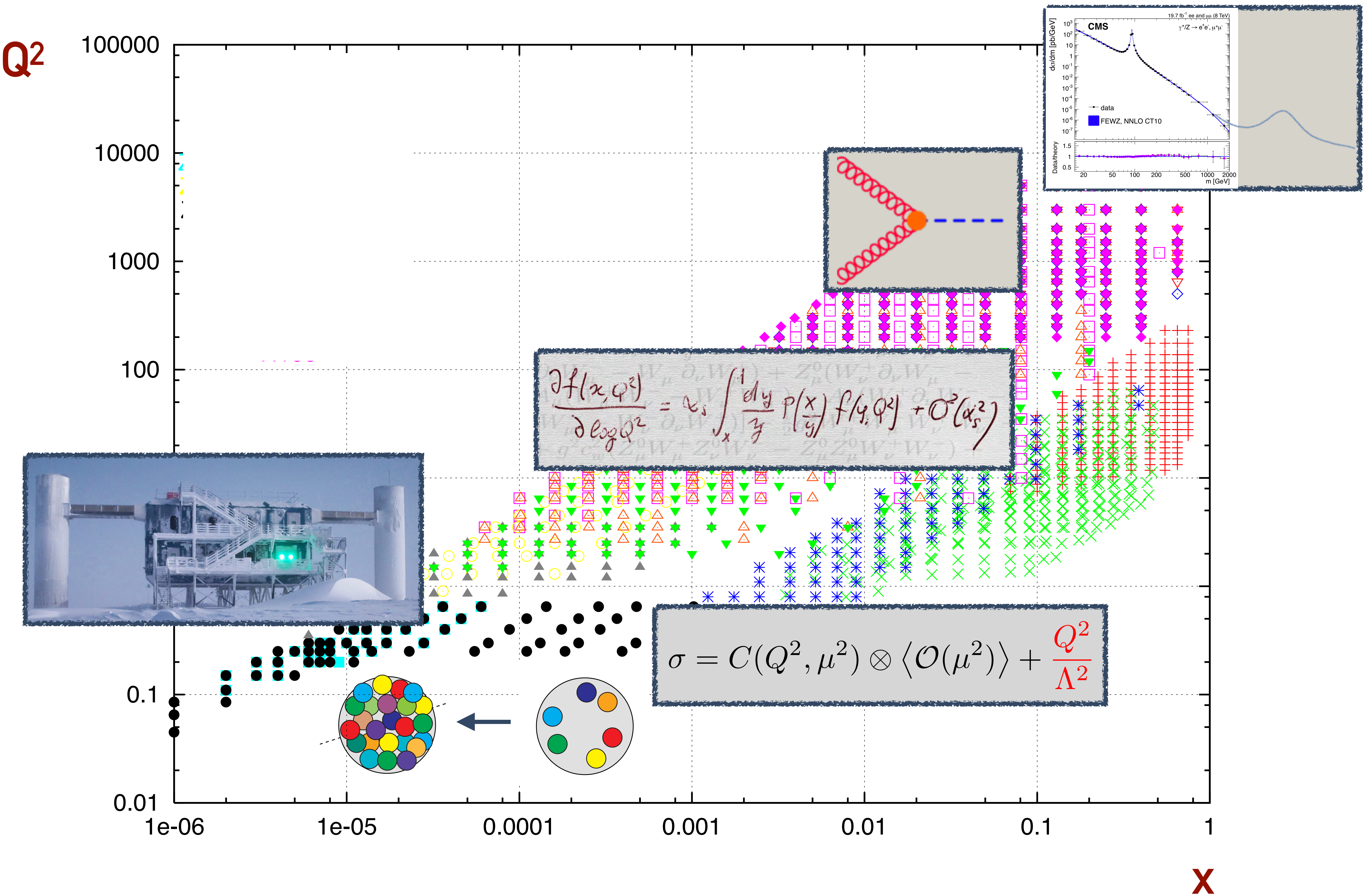
DIS kinematics



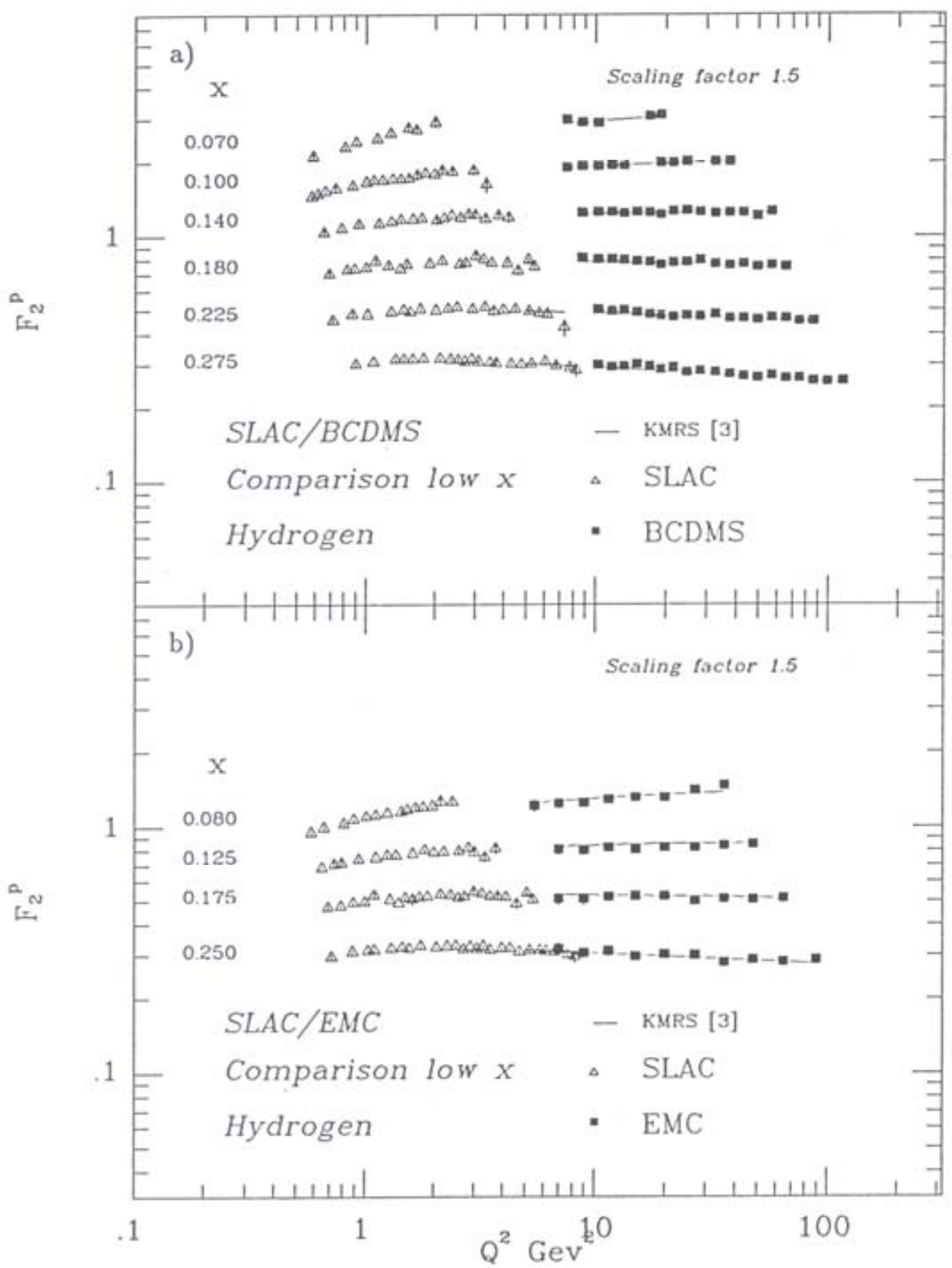
DIS kinematics

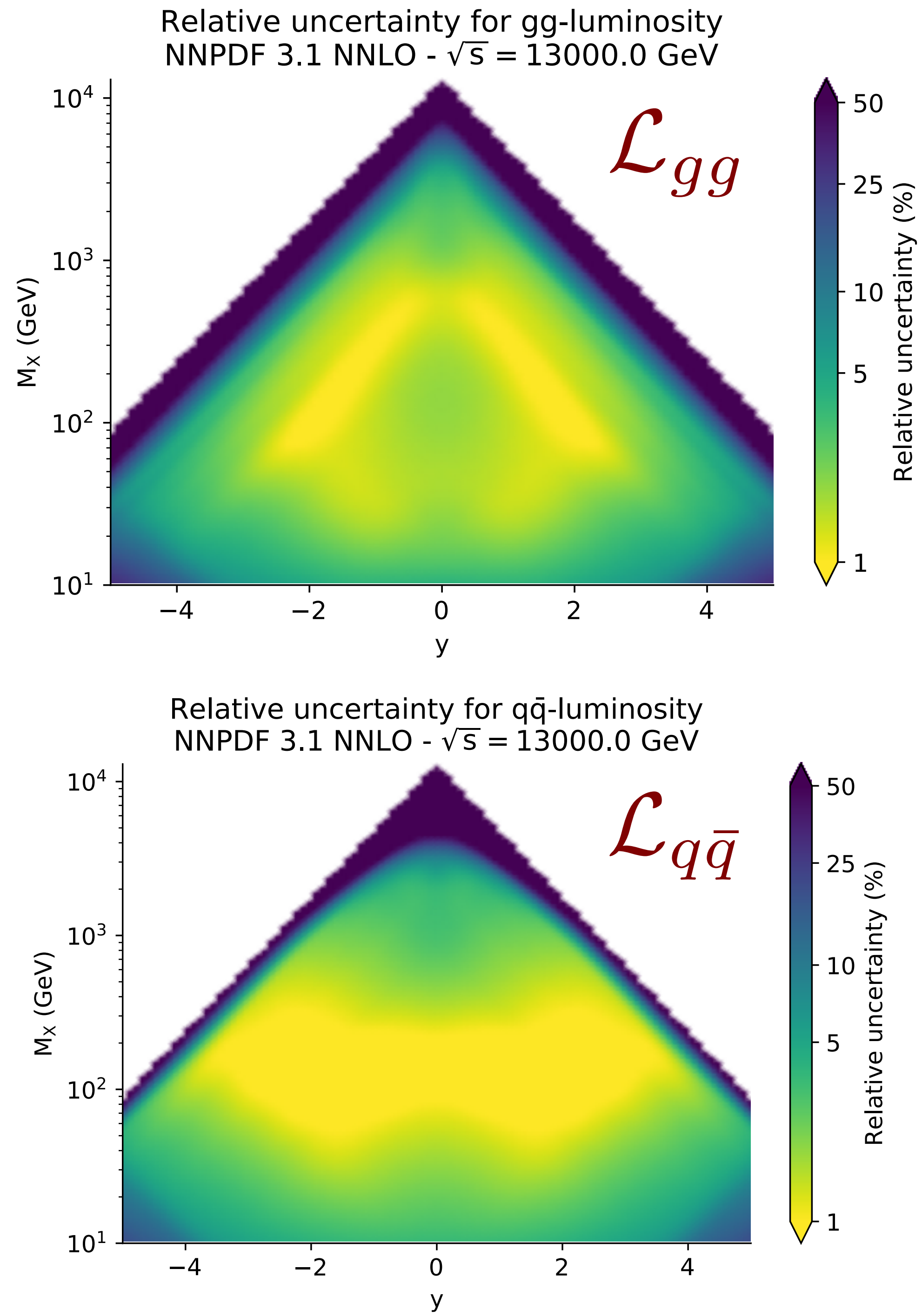


DIS kinematics



PDFs: at the core of any hadron collider



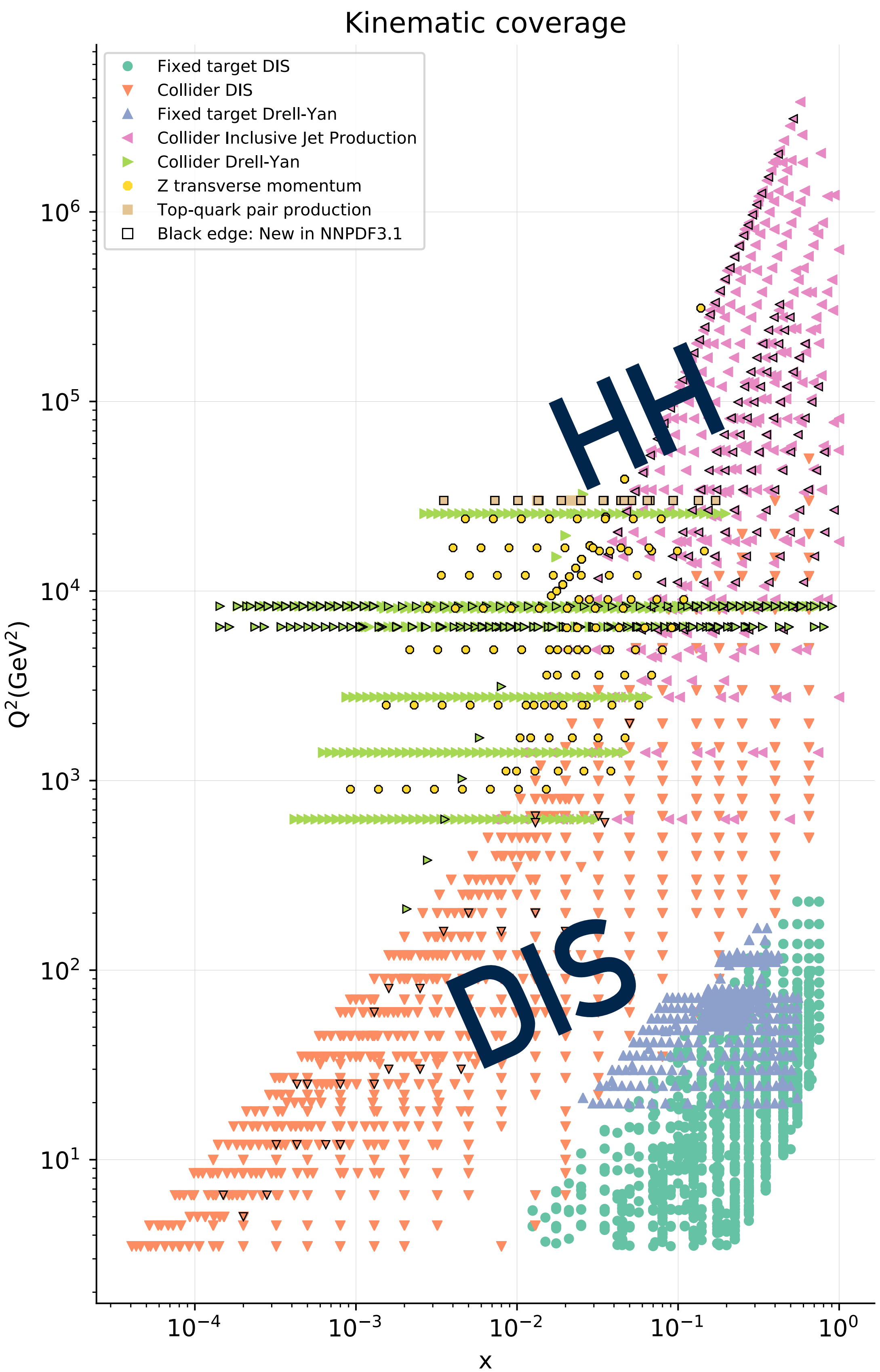


[NNPDF31]

From scaling violations to physics at the few percent

PDFs: at the core of any hadron collider

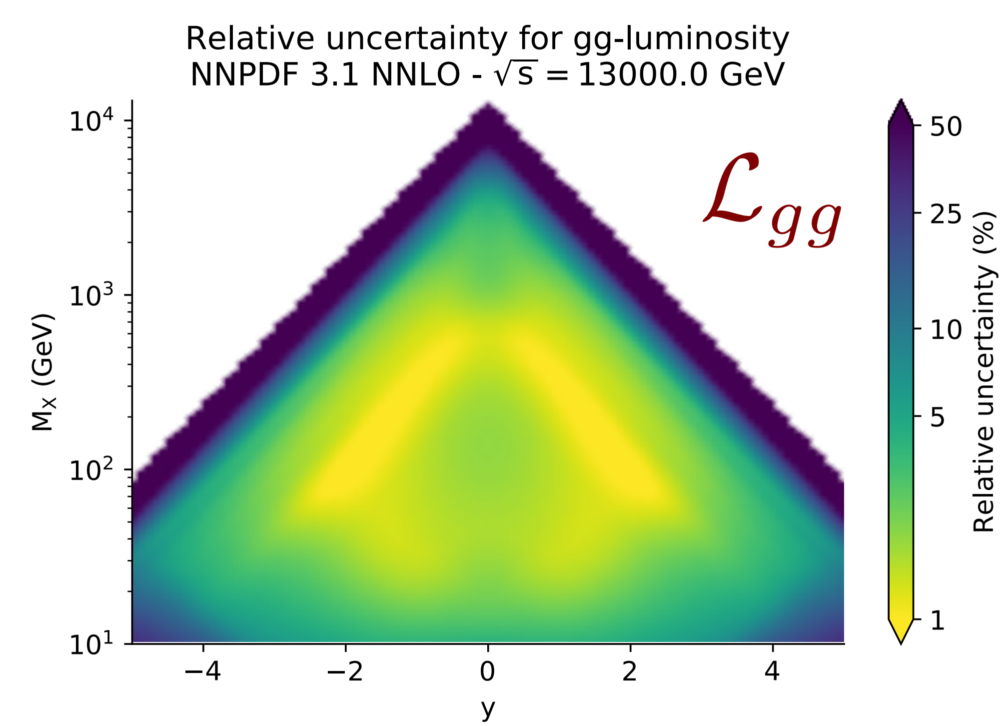
[NNPDF31]



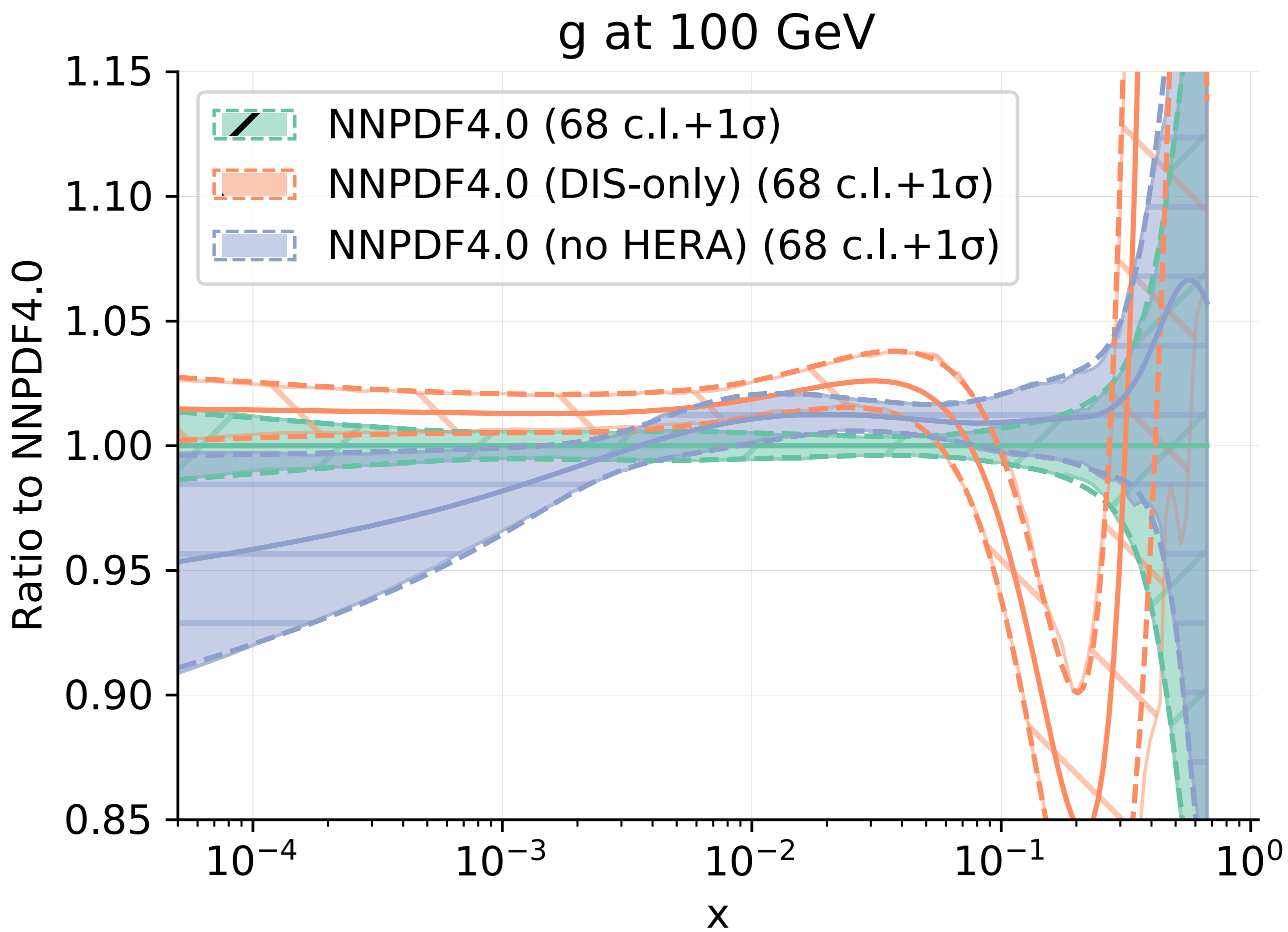
An incredible synergy between DIS and HH

QCD works over many order of magnitudes, in a very precise way. No obvious signs of breakdown

Combining DIS + HH: luminosities with few percent error possible in the bulk of the EW region



PDFs: DIS vs hadron-hadron



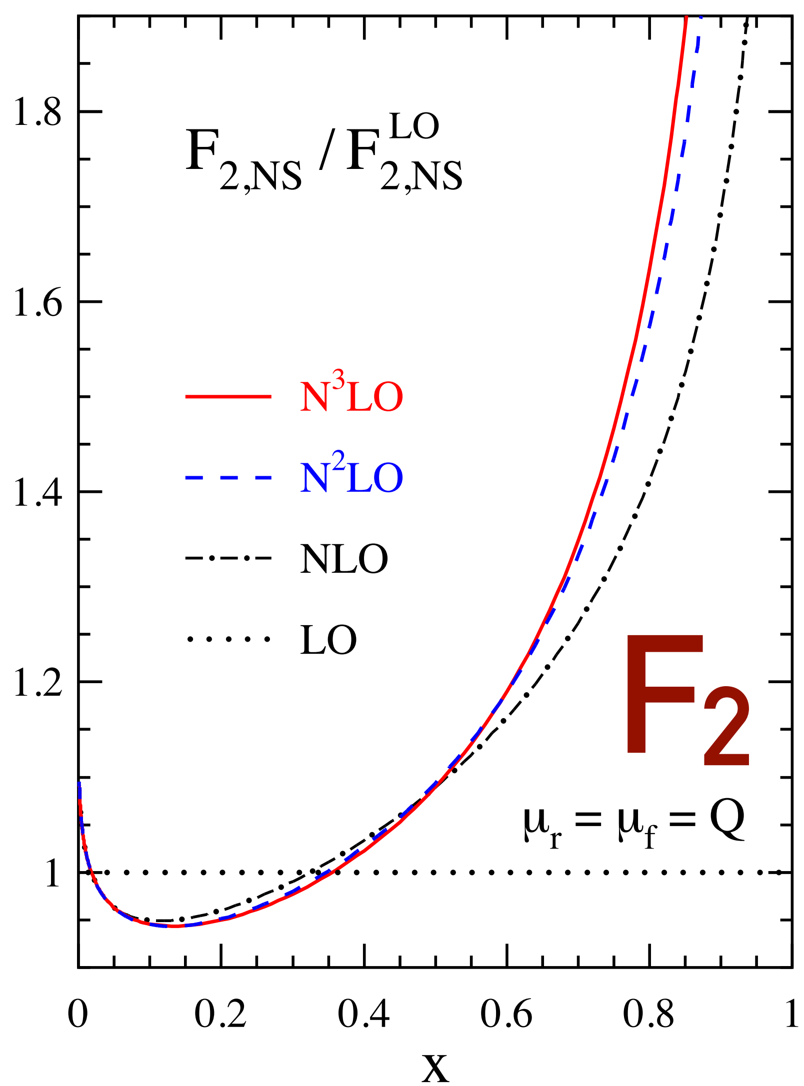
LHC bringing in more and more constraining power, but DIS here to stay

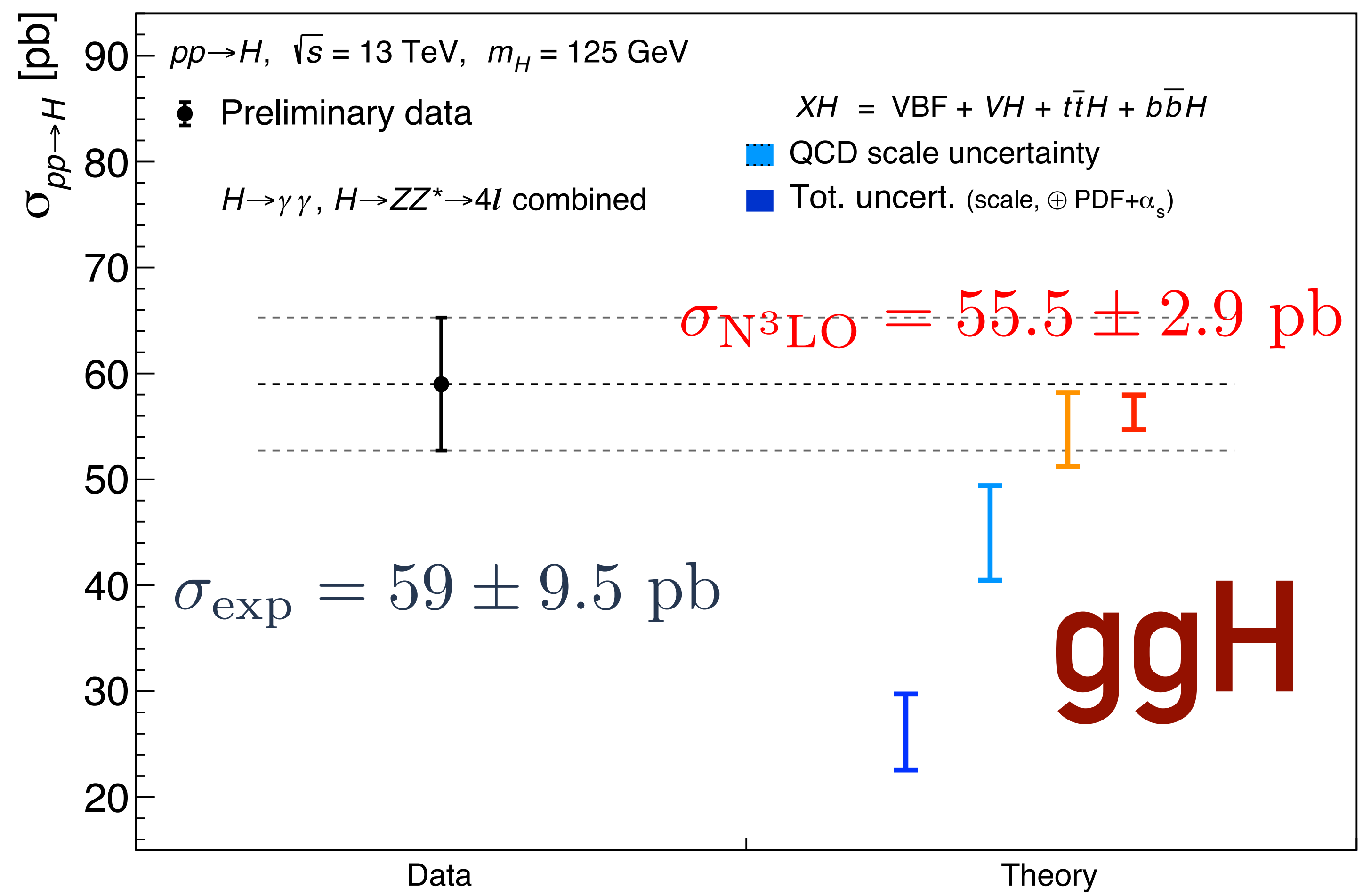
HERA legacy dataset:

- very robust, extremely well-understood dataset. Solid backbone
- LHC: often more complex observables/analysis, tensions (Z p_t, jets…)
- DIS: QCD theory under better control…

The perturbative expansion in DIS and @LHC

[Moch,Vermaseren,Vogt]





[Anastasiou et al; Mistlberger]

- In general, perturbative expansion much better behaved in DIS
- ggH is an extreme case, but larger K-factors at the LHC [→ M. Bonvini's talk]
- LHC: more differential, complex observables, often quite delicate
- Understanding of source of large K-factors not yet fully-satisfactory

The perturbative expansion in DIS and @LHC

Consequences for PDFs

[MSHT2020]

Data set	Points	NLO χ^2/N_{pts}	NNLO χ^2/N_{pts}
DØ W asymmetry	14	0.94 (2.53)	0.86 (14.7)
$\sigma_{t\bar{t}}$ [93]- [94]	17	1.34 (1.39)	0.85 (0.87)
LHCb 7+8 TeV $W+Z$ [95, 96]	67	1.71 (2.35)	1.48 (1.55)
LHCb 8 TeV $Z \to ee$ [97]	17	2.29 (2.89)	1.54 (1.78)
CMS 8 TeV W [98]	22	1.05 (1.79)	0.58 (1.30)
CMS 7 TeV $W+c$ [99]	10	0.82 (0.85)	0.86 (0.84)
ATLAS 7 TeV jets $R=0.6$ [18]	140	1.62 (1.59)	1.59 (1.68)
ATLAS 7 TeV $W+Z$ [20]	61	5.00 (7.62)	1.91 (5.58)
CMS 7 TeV jets $R=0.7$ [100]	158	1.27 (1.32)	1.11 (1.17)
ATLAS 8 TeV Z p_T [75]	104	2.26 (2.31)	1.81 (1.59)
CMS 8 TeV jets $R=0.7$ [101]	174	1.64 (1.73)	1.50 (1.59)
ATLAS 8 TeV $t\bar{t} \to l+j$ sd [102]	25	1.56 (1.50)	1.02 (1.15)
ATLAS 8 TeV $t\bar{t} \to l^+l^-$ sd [103]	5	0.94 (0.82)	0.68 (1.11)
ATLAS 8 TeV high-mass DY [73]s	48	1.79 (1.99)	1.18 (1.26)
ATLAS 8 TeV W^+W^-+ jets [104]	30	1.13 (1.13)	0.60 (0.57)
CMS 8 TeV $(d\sigma_{\bar{t}t}/dp_{T,t}dy_t)/\sigma_{\bar{t}t}$ [105]	15	2.19 (2.20)	1.50 (1.48)
ATLAS 8 TeV W^+W^- [106]	22	3.85 (13.9)	2.61 (5.25)
CMS 2.76 TeV jets [107]	81	1.53 (1.59)	1.27 (1.39)
CMS 8 TeV $\sigma_{\bar{t}t}/dy_t$ [108]	9	1.43 (1.02)	1.47 (2.14)
ATLAS 8 TeV double differential Z [74]	59	2.67 (3.26)	1.45 (5.16)
Total, LHC data in MSHT20	1328	1.79 (2.18)	1.33 (1.77)
Total, non-LHC data in MSHT20	3035	1.13 (1.18)	1.10 (1.18)
Total, all data	4363	1.33 (1.48)	1.17 (1.36)

... but more in general, QCD ``cleaner” in DIS

Example of subtleties: CMS jets and NNLO

[Chen, Gehrmann, Glover, Huss, Mo (2022)]

- CMS 8 TeV dijet data, differential in $p_{t,avg}$, $y^*=|\Delta y|/2$ and $y_b=|y_1+y_2|/2$
- Strongest constraining power among jets, but strong pull for gluon at x~0.3
- Tension with legacy DIS/DY → discarded

- NNPDF4.0: single-differential CMS 8TeV. Underlying TH: best prediction available at the time of fitting → NNLOQCD+NP, only leading-colour contributions

$$\delta\sigma_{\mathrm{NNLO}} = A\,N_c^2 + B\,n_f N_c + C\,n_f^2 + \cancel{D\,N_c^0 + E\,\frac{n_f}{N_c} + \frac{G}{N_c^2}}$$

- Recently: full-colour calculations available [Czakon, van Hameren, Mitov, Poncelet (2019); Chen, Gehrmann, Glover, Huss, Mo (2022)]

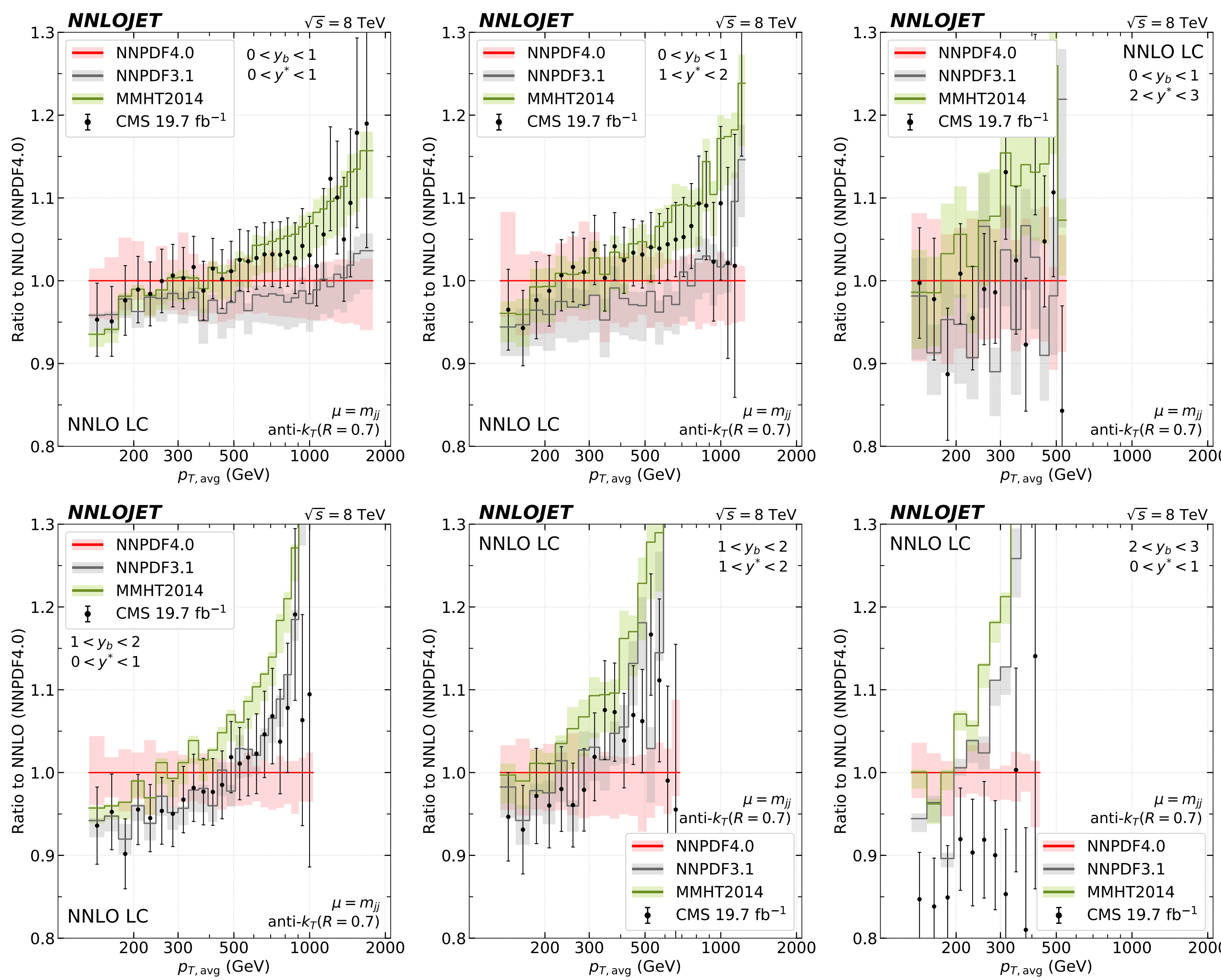
[→ see talk by J. Mo]

Example of subtleties: CMS jets and NNLO

- Full-colour analysis

$$\delta\sigma_{\mathrm{NNLO}} = A\,N_c^2 + B\,n_f N_c + C\,n_f^2 + D\,N_c^0 + E\,\frac{n_f}{N_c} + \frac{G}{N_c^2}$$

[Chen, Gehrmann, Glover, Huss, Mo (2022)]



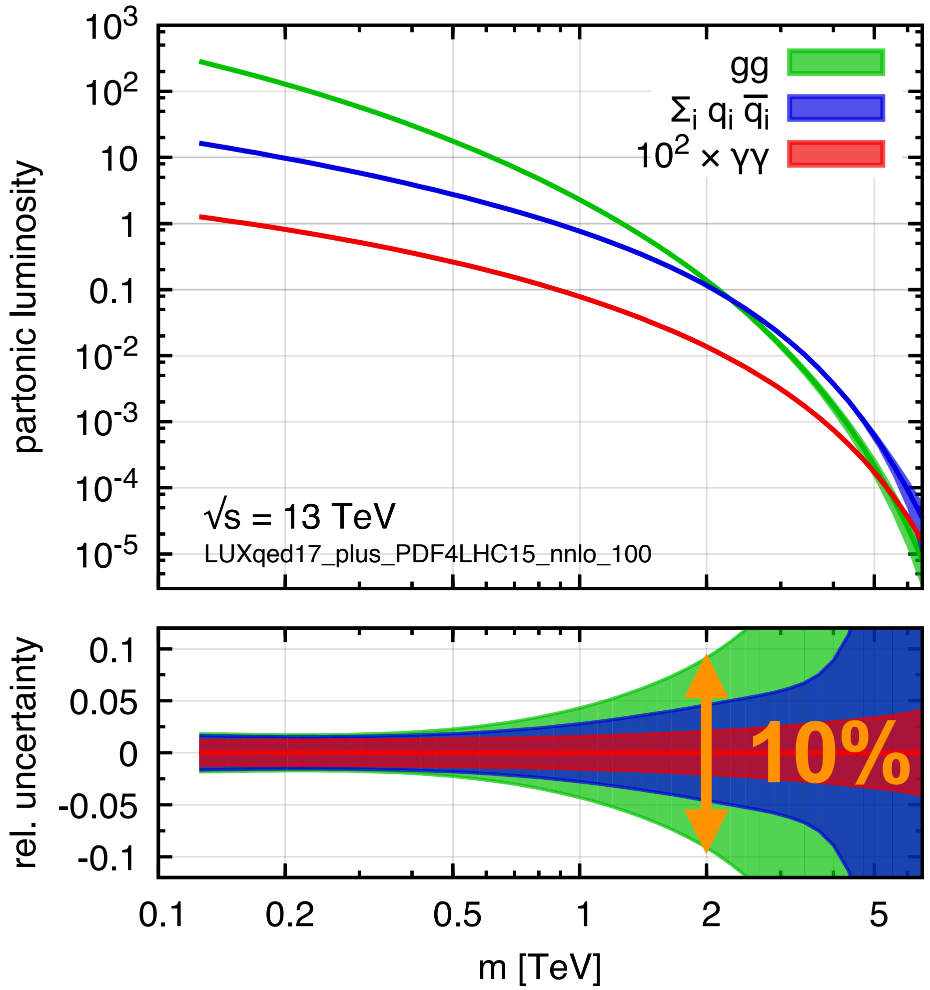
- Sets without CMS8 jet data seem to fit better
- Jury still out, but this example shows that the LHC can be tricky…
- General comment: robust TH uncertainty in the PDFs most welcome

[→ talks by Z. Kassabov, J. McGowan, M. Bonvini]

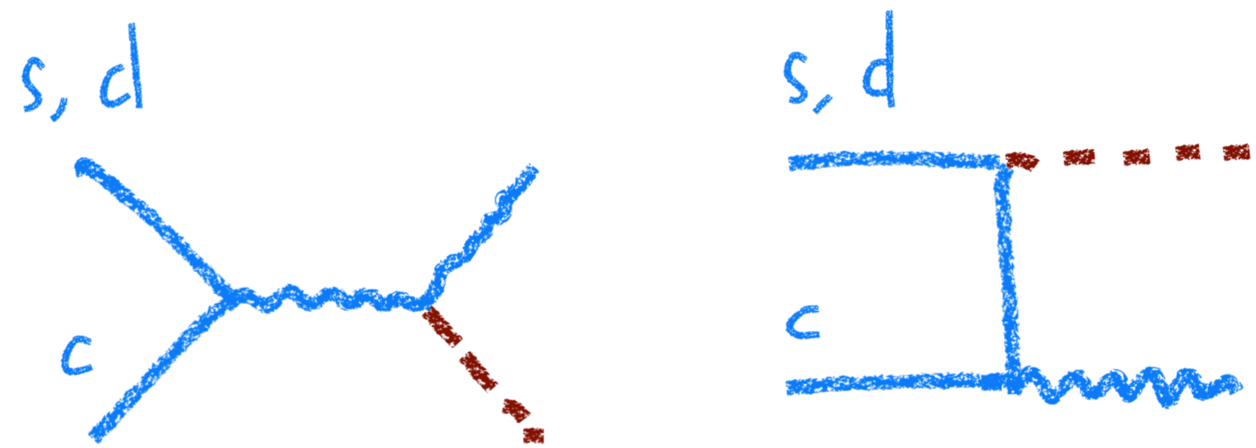
PDFs: important information still missing

High-mass searches require large-x PDFs

[plot by G. Salam]



Interesting ideas for constraining 2nd generation Yukawa require good s, c and $\bar{d}$/d control



[F. Yu (2016)]

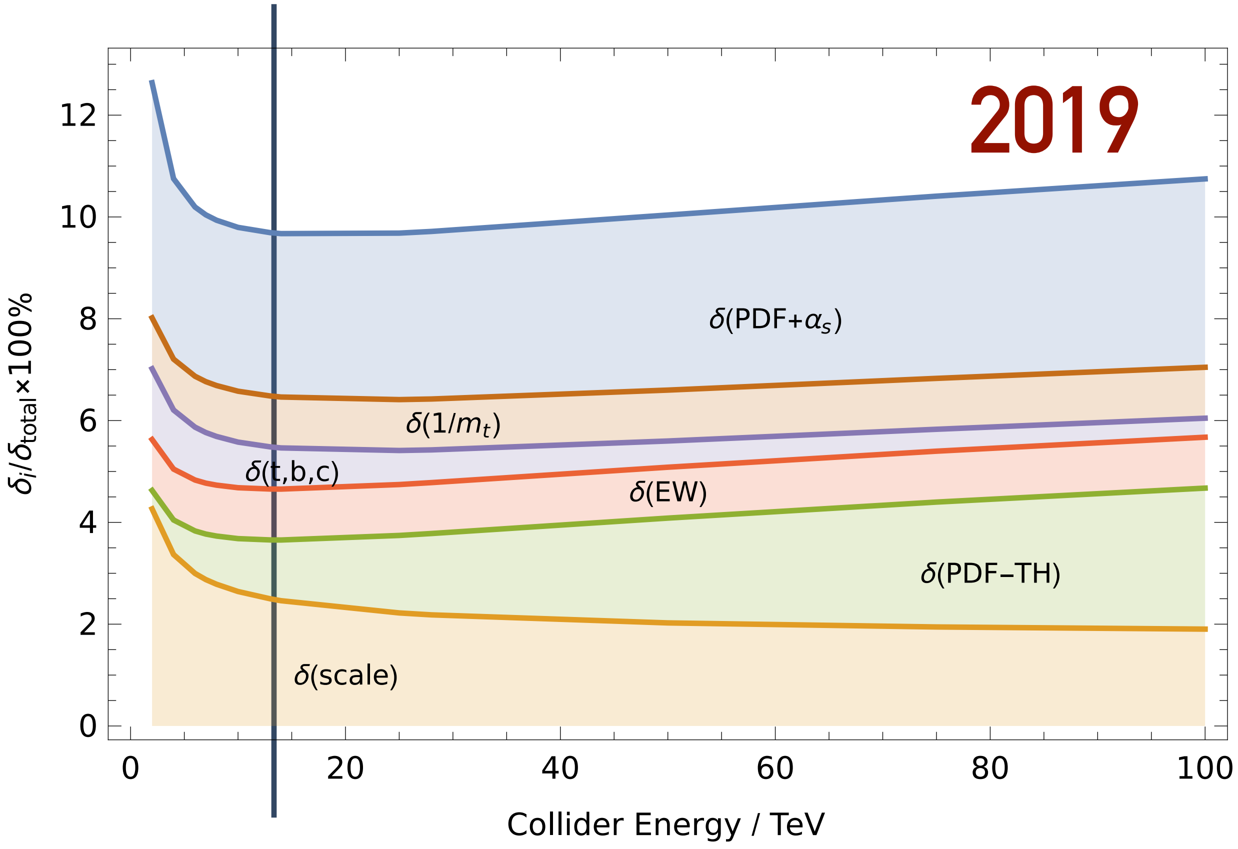
UHE neutrinos, prompt ν flux → small-x, charm

Any progress in these directions welcome

PDFs: also a theory problem…

N^3LO PDFs not available → order mismatch

ggH theory error budget



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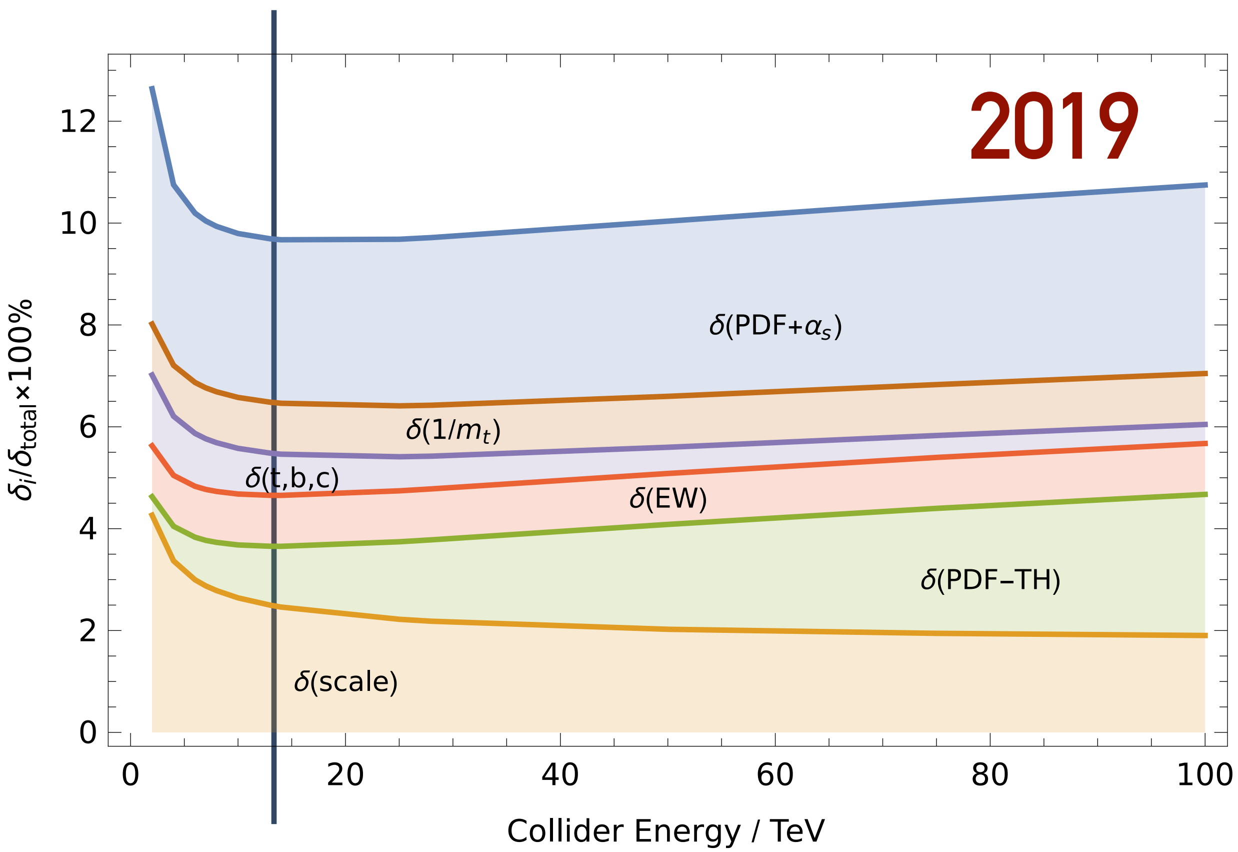
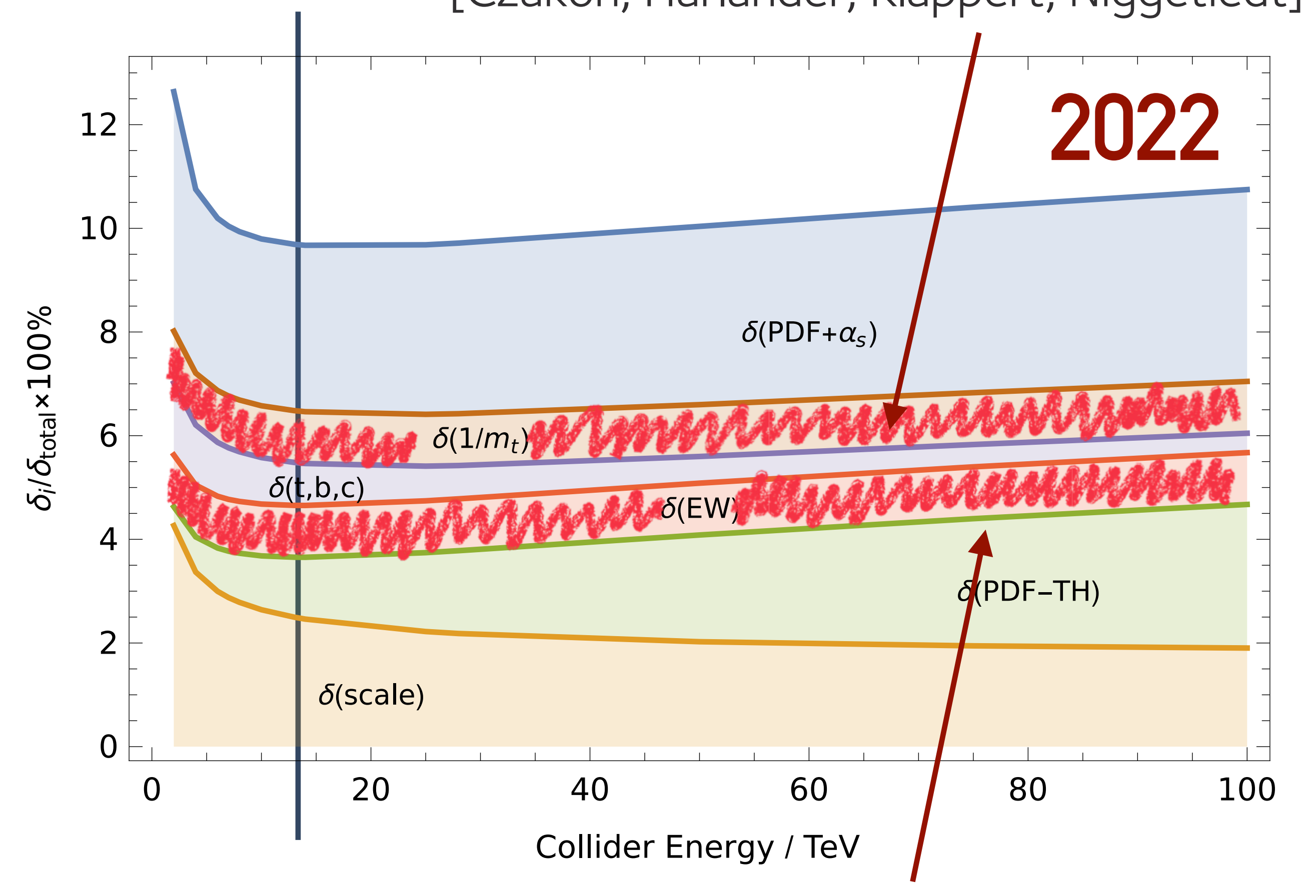


[Czakon, Harlander, Klappert, Niggetiedt]



[Becchetti, Bonciani, del Duca, Hirschi, Moriello, Schweitzer; Bonetti, Panzer, Smirnov, Tancredi, Melnikov]

Missing N^{3}LO PDFs, as well as α_s+PDFs uncertainty: significant

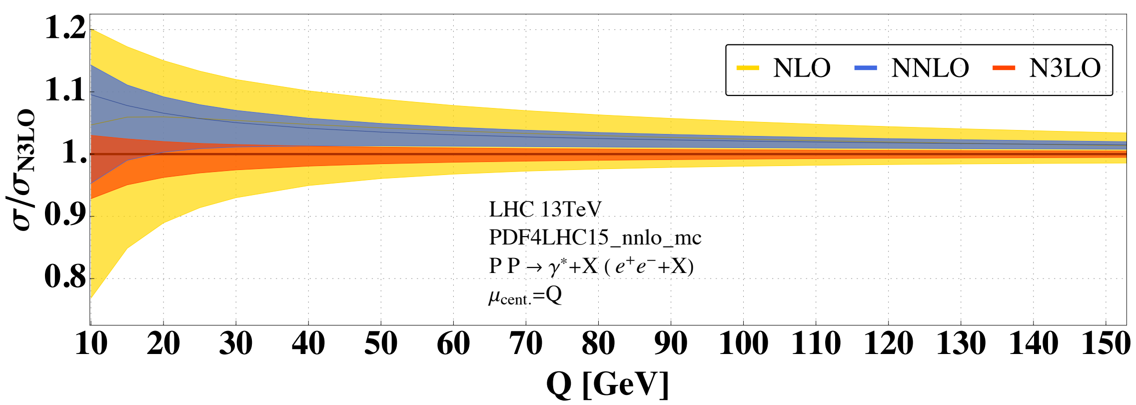
[Recent progress towards N^{3}LO → talks by J. McGowan, K. Schönwald]

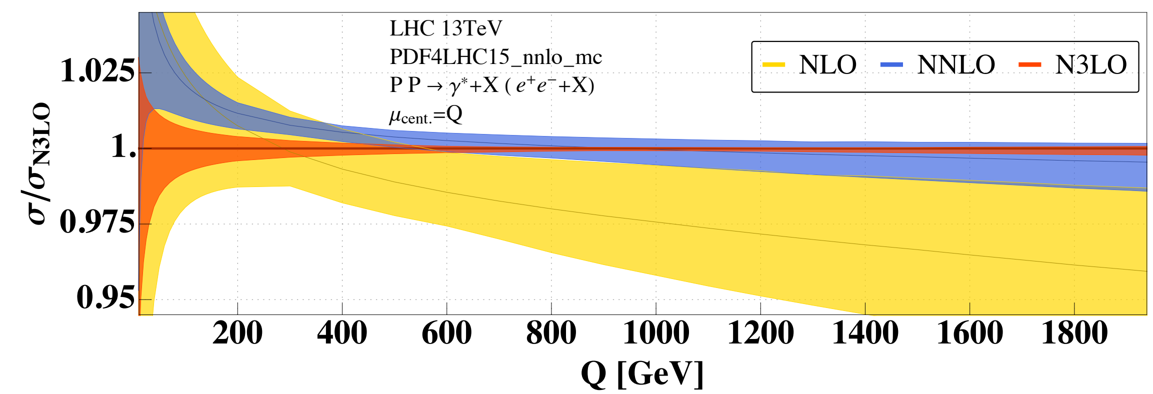
Inclusive Drell-Yan at N^{3}LO

In the EW region Q~100 GeV: ~2-3% N^{3}LO vs per-mill NNLO

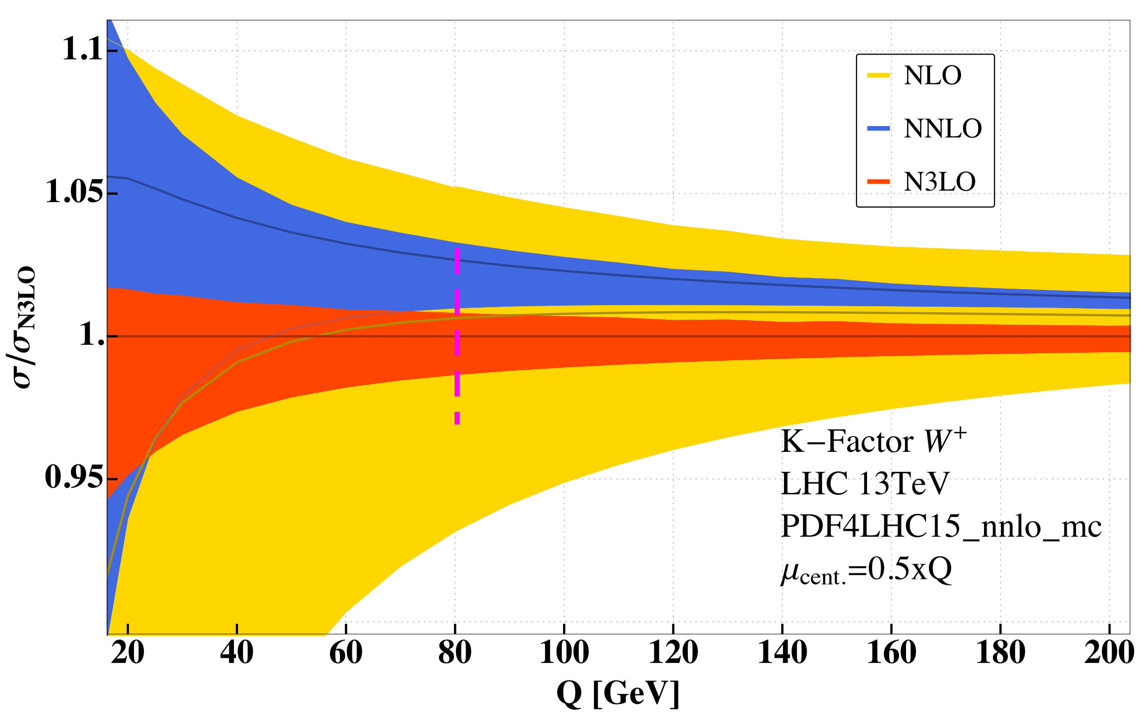
[Duhr, Dulat, Mistlberger (2020-21)]

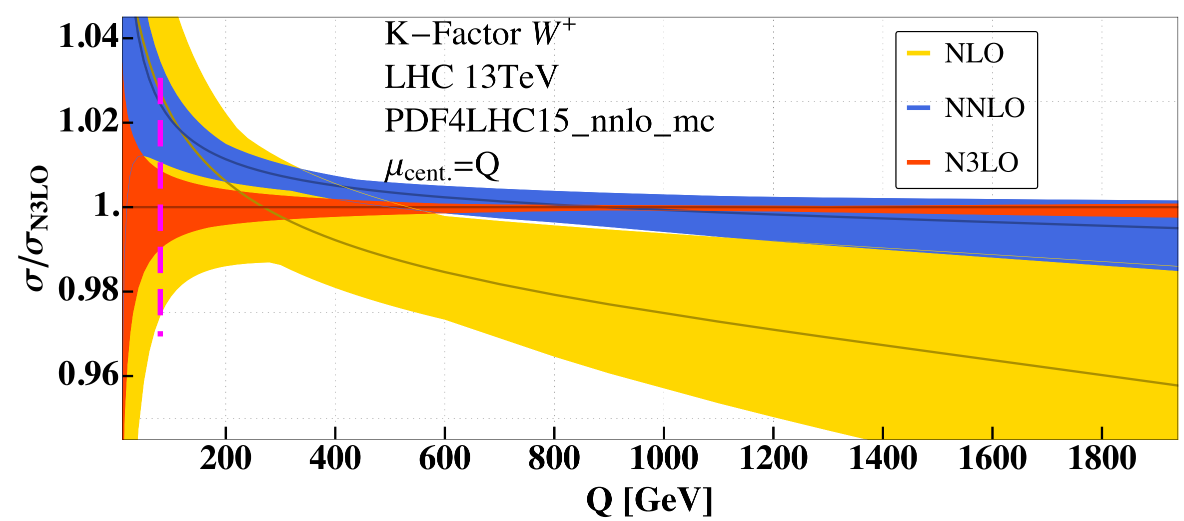
γ^*





W+

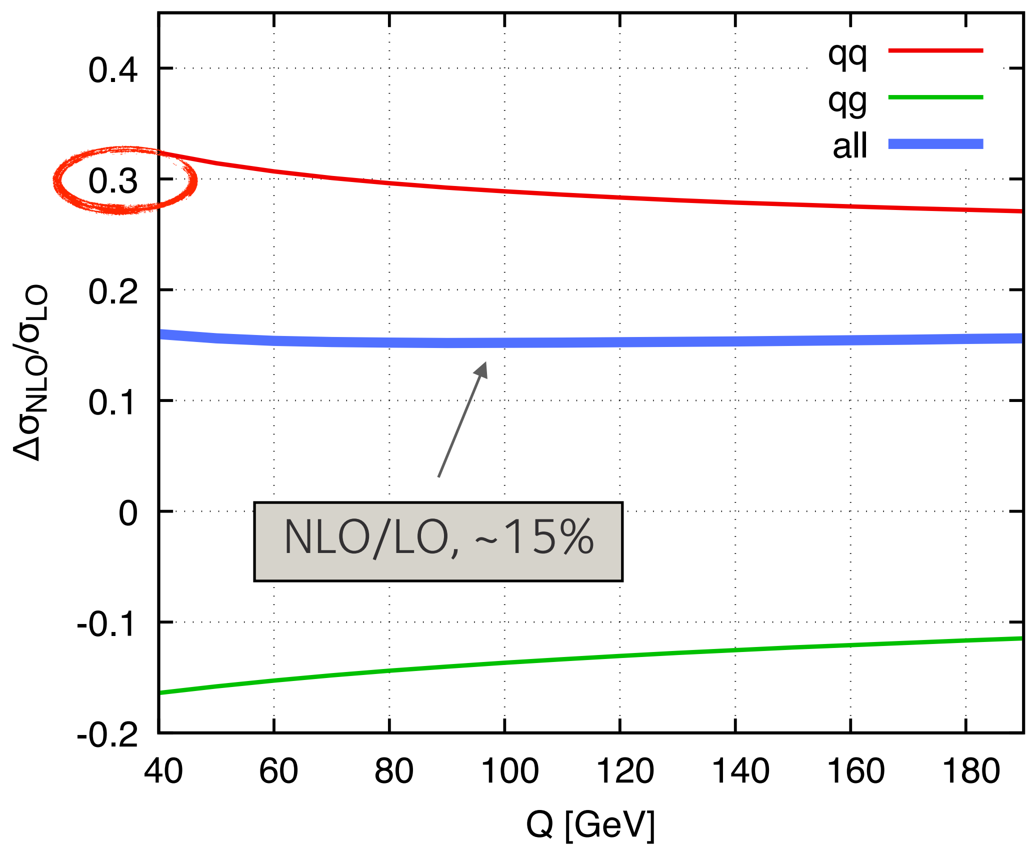


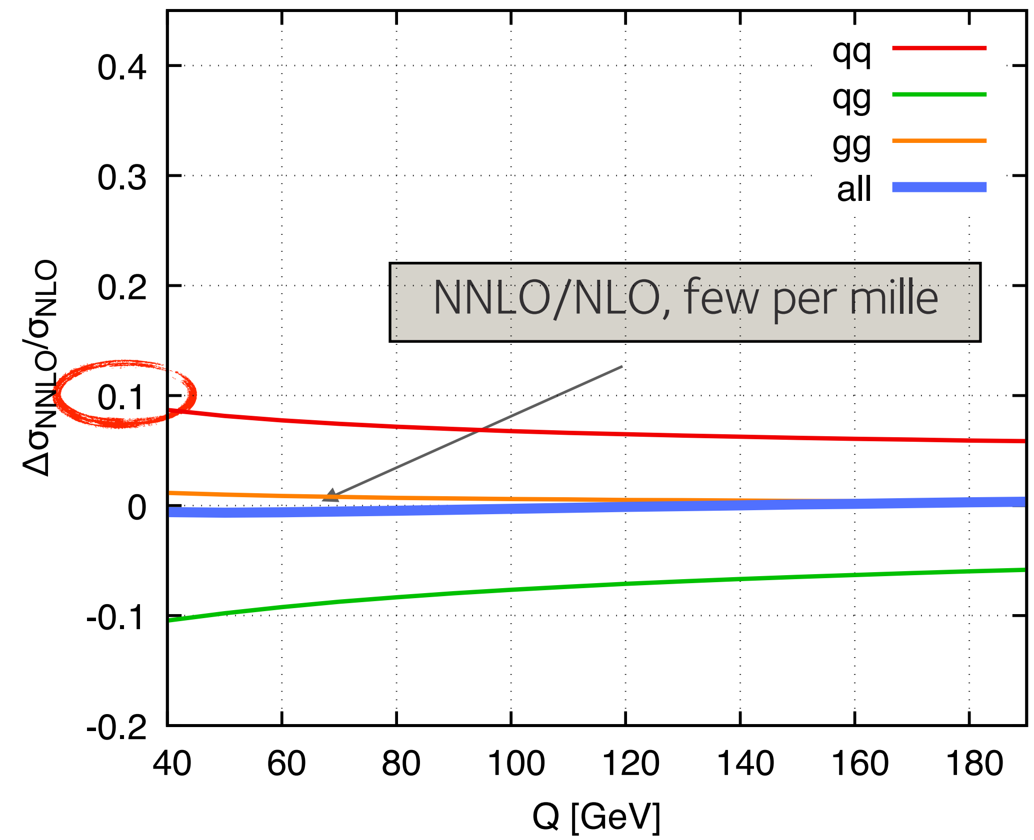


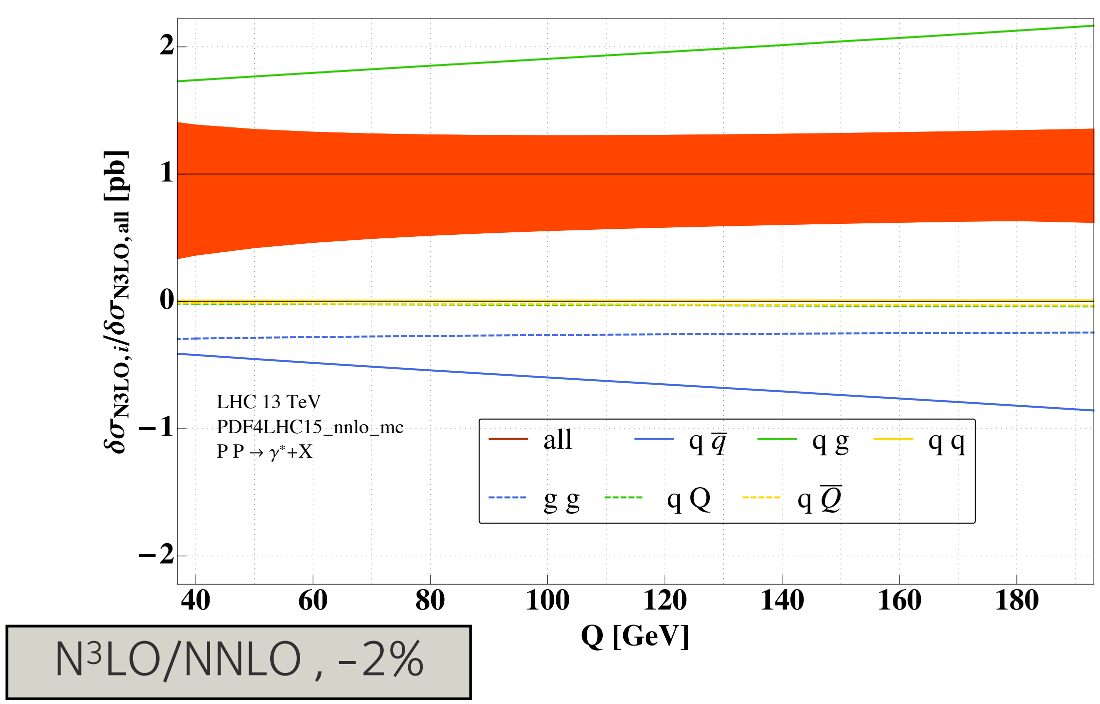
Band only overlap at large Q^2 → trouble in the high-precision region?

Neutral-current DY: flavour decomposition

Per-mille NNLO: unnaturally small. Very large cancellations







- Individual channels (μ=Q) much larger than final result, delicate cancellation pattern
- Individual channels: perturbative convergence
- N^3LO ``natural”, tiny PDFs changes can significantly affect this picture

N^3LO PDFs issues: evolution

N^3LO: evolution and the problems of small-x

NNLO: an issue at low-mass, not quite so at the EW scale. N^3LO?

$$\chi_0(M) = \frac{C_A}{\pi}\left[2\psi(1) - \psi(M) - \psi(1-M)\right] \to$$

$$\gamma_{\rm LL}(N) = \frac{\bar{\alpha}_s}{N} + 0 \cdot \alpha_s^2 + 0 \cdot \alpha_s^3 + 2\zeta_3 \frac{\bar{\alpha}_s^4}{N^4} \quad , \qquad \bar{\alpha}_s = \alpha_s C_A/\pi$$

Spurious leading pole in 0, starting at N^3LO (vs pole at N~0.3).

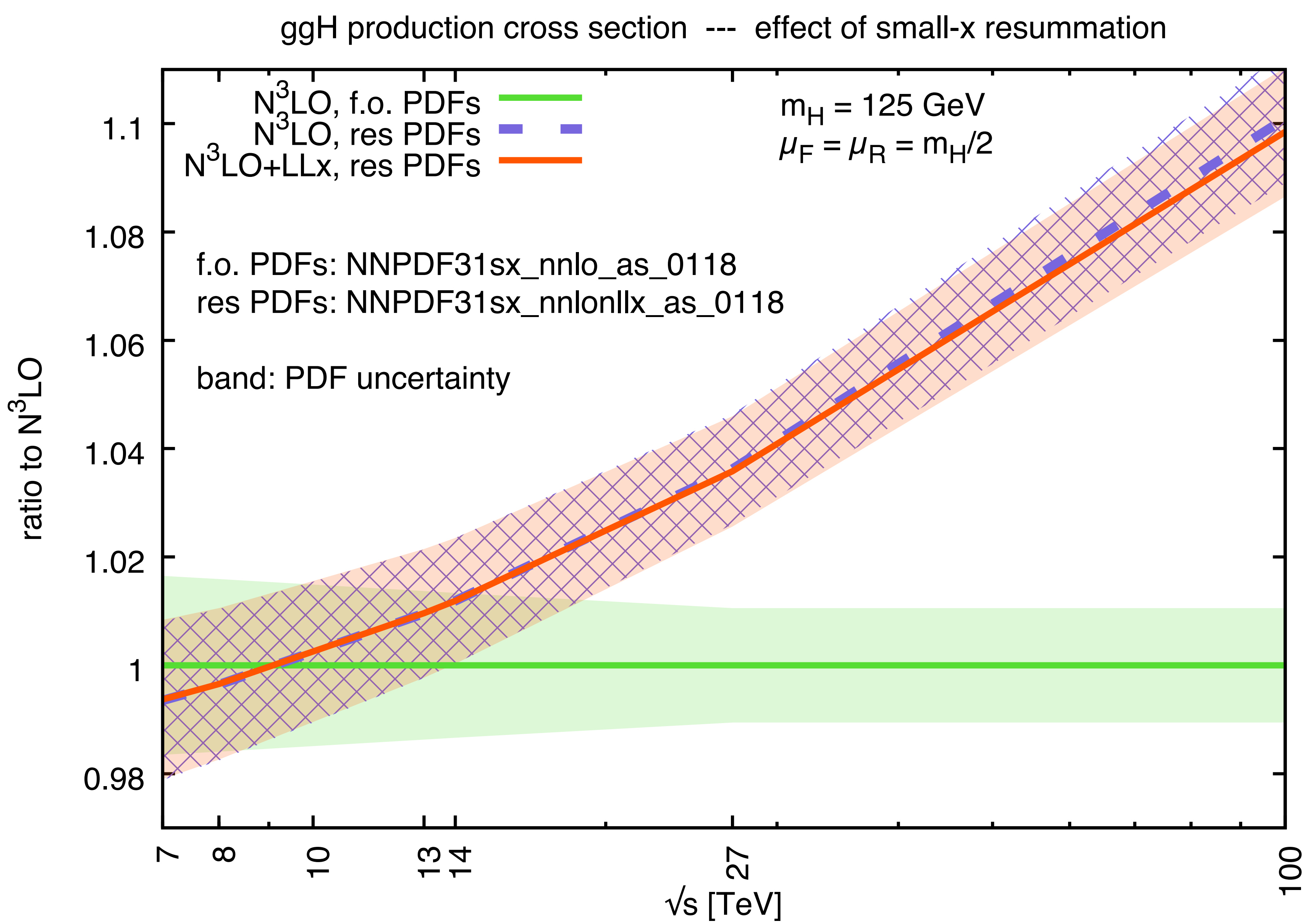
Is this an issue for precision physics (at the EW scale and beyond)?

- How dangerous is the spurious N^3LO growth?
- Are subleading terms under control?
- To which extent DGLAP evolution washes out small-x effects?
- Control-sample with effectively no evolution (i.e. DIS vs LHC-only fits)?

[Resummed evolution → talk by A. Stasto]

Small-x physics and high-energy colliders

Proper understanding of small-x crucial for precision EW physics at future hadron colliders



[Bonvini, Marzani (2018)]

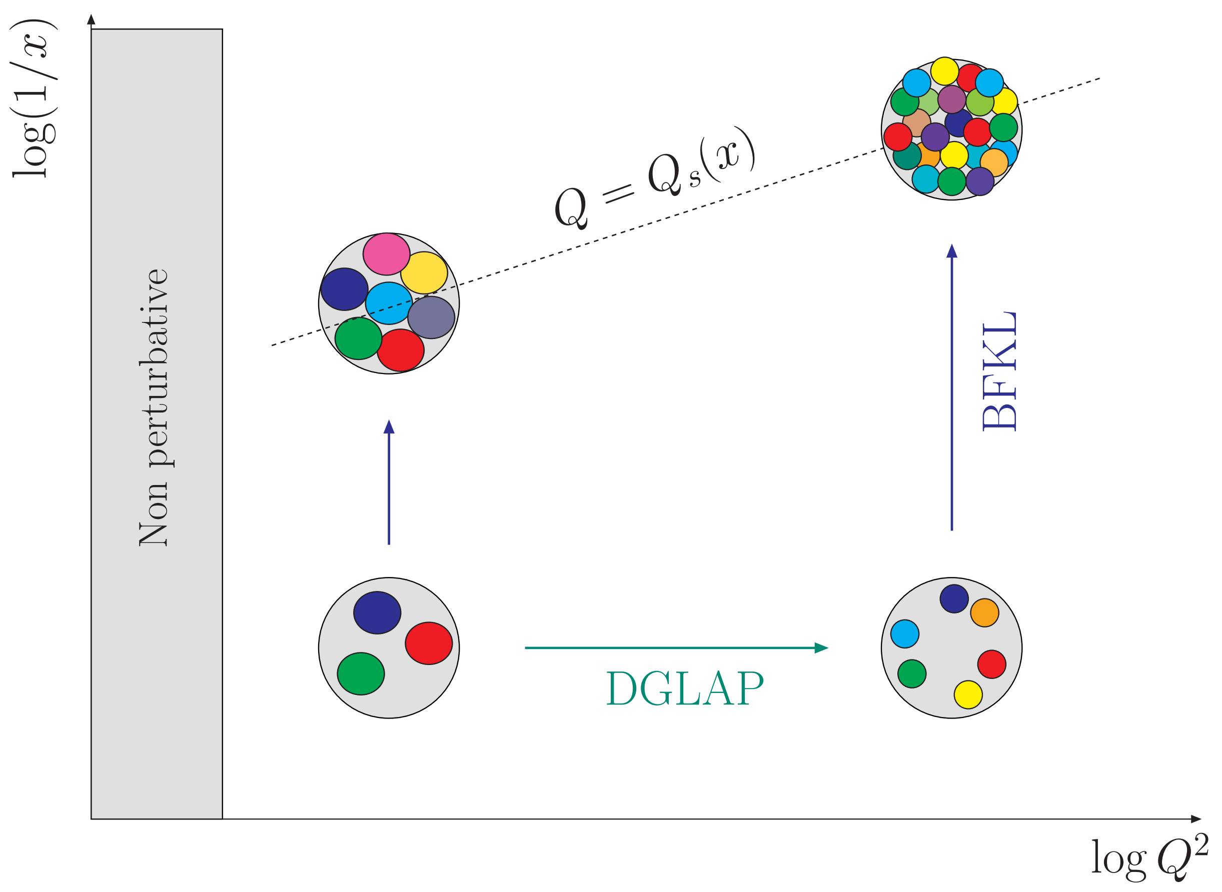
What is the impact of sub-leading terms?

How robust is this picture?

Small-x physics: beyond standard evolution

Small-x physics extremely interesting in its own merit.

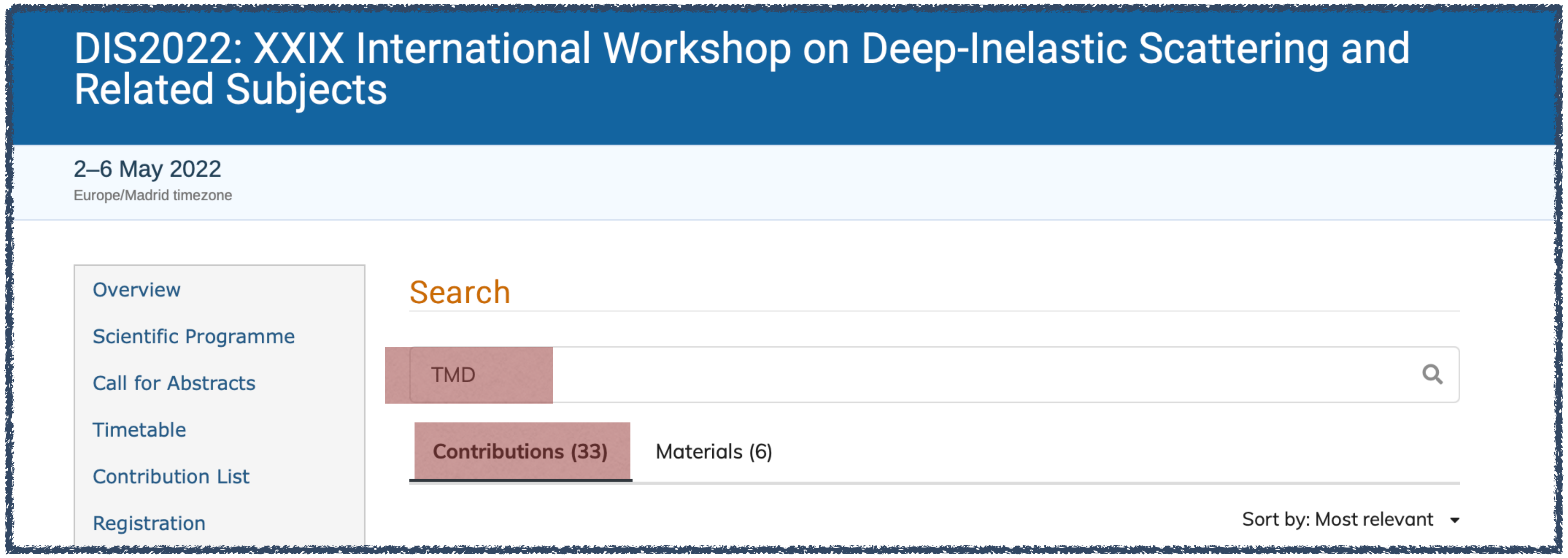
QCD in a new regime



- A lot of recent progress towards making predictions more precise and accurate → see B. Xiao's talk
- Effects larger in pA, $A^{1/3}$ enhancement of the saturation scale
- Also can be studied from diffraction, in a relative clean fashion [see E. Iancu's talk]

Can we study the onset of saturation and its connection to (resummed) DGLAP with as little modelling as possible, in a clean (=protons, perturbative) setting?

Beyond PDFs: TMDs



A lot of progress... In a nutshell

- better determinations
- better theoretical understanding (from phenomenological models to first principles)

Understanding the intrinsic transverse momentum of partons plays an important role for highest-precision LHC studies...

Beyond PDFs: TMDs and the W mass

Legacy LHC measurement: W mass.

- Best handle at the LHC: W transverse momentum distribution
- Require (sub) per-mill control over p_t spectra → impossible theoretically
- Idea: calibrate Z using data, only need to control differences between Z and W → PDFs, EW
- Few per-mill distortion of spectra ↔ O(10 MeV) shift in m_W
- Right now: $\Delta m_{W,ATLAS}$ = ~19 MeV [CDF: ~10 MeV, EW precision: ~8 MeV]

Good control of flavour-dependence of intrinsic k_t crucial → TMD

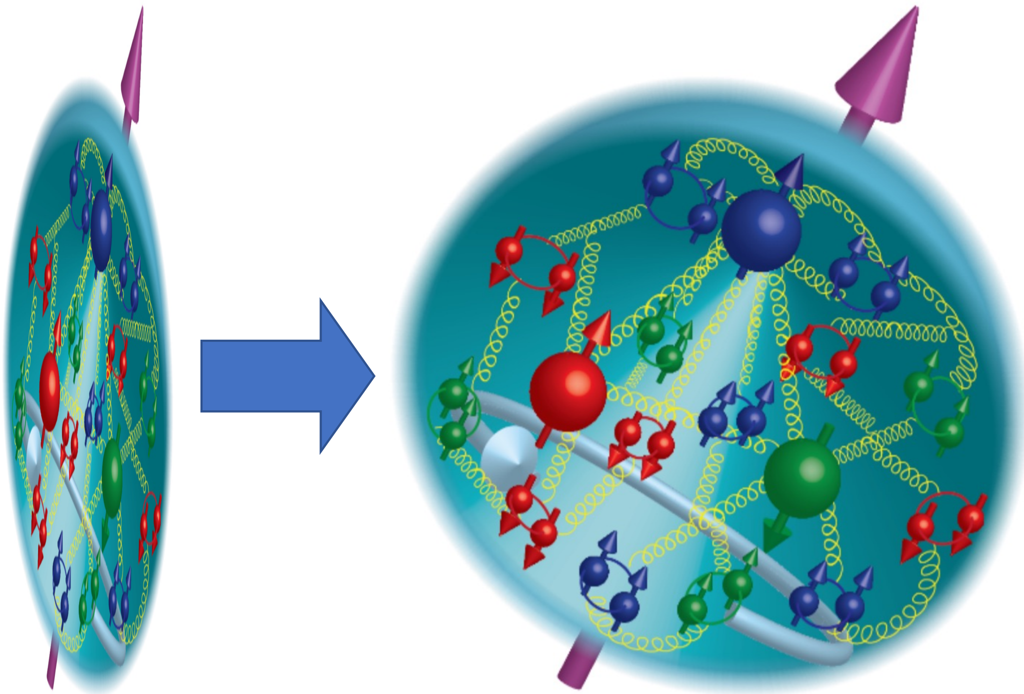
[Bacchetta, Bozzi, Radici, Signore (2019)]

	ΔM_{W^+}			ΔM_{W^-}		
Set	m_T	$p_{T\ell}$	$p_{T\nu}$	m_T	$p_{T\ell}$	$p_{T\nu}$
1	0	-1	-2	-2	3	-3
2	0	-6	0	-2	0	-5
3	-1	9	0	-2	4	-10
4	0	0	-2	-2	-4	-10
5	0	4	1	-1	-3	-6
6	1	0	2	-1	4	-4
7	2	-1	2	-1	0	-8
8	0	2	8	1	7	8
9	0	4	-3	-1	0	7

- Shifts uncomfortably large…
- Better control would be very welcome
- … especially after the CDF new measurement

Towards a 3D image of the proton

[graphics by O. Hen]

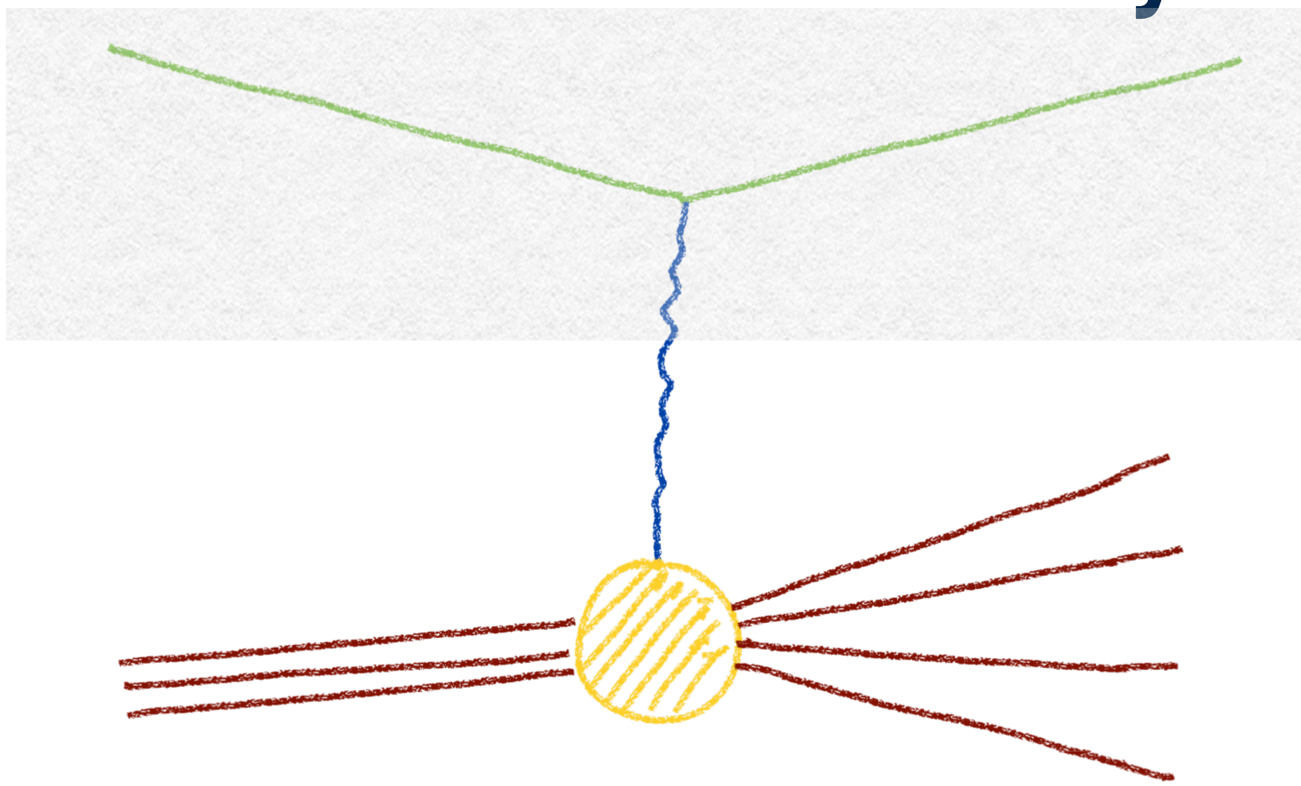


Eventually, we want to map the full 3D structure of the proton → Wigner's functions

Interesting in its own merit, but in the long run may be important for general studies at hadron colliders, beyond QCD

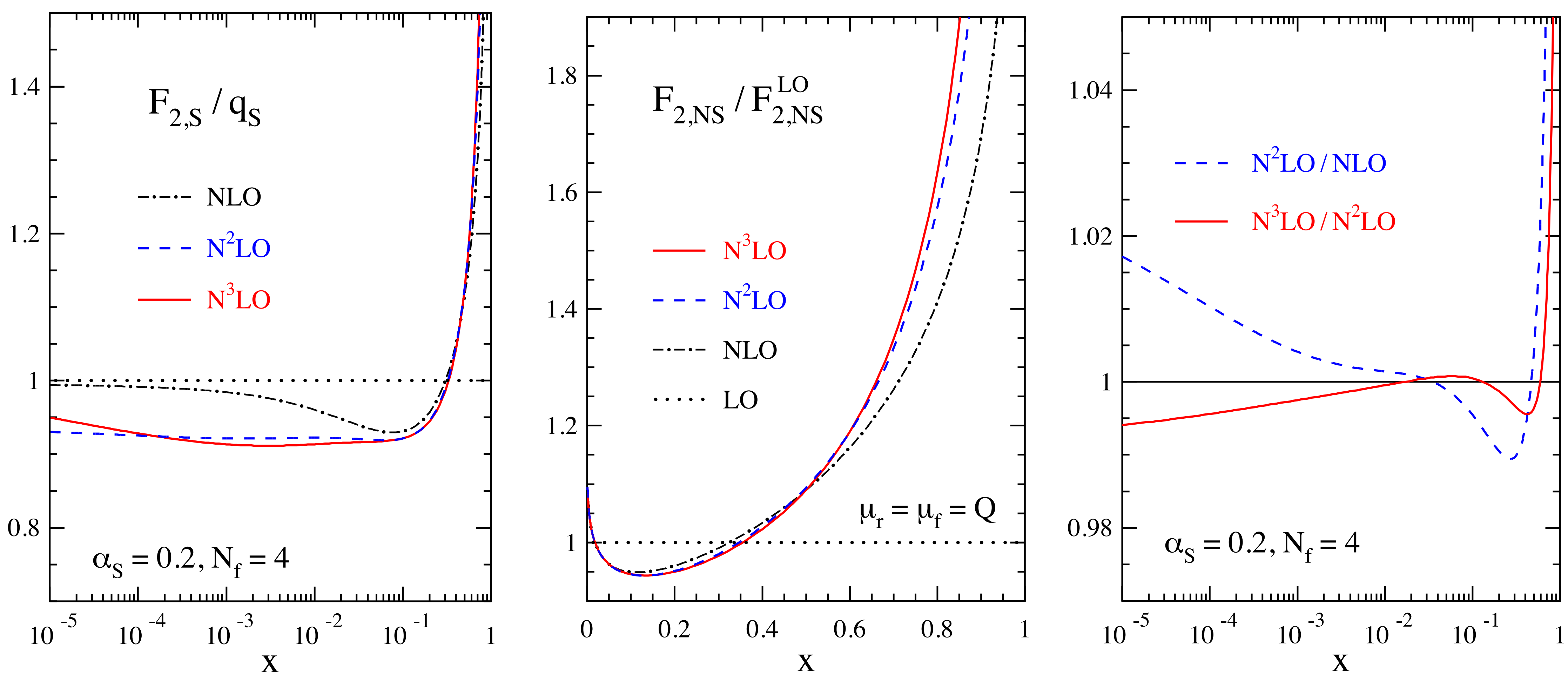
- PS, bread and butter of colliders, are getting better and better = under quantifiable theoretical control [→ see M. Dasgupta's talk]
- Non-perturbative bit still from phenomenological models. Ideally, rely less and less on models, and more and more on data
- Example: MPI. VBF Higgs: +5% at low p_t [NNLO QCD: 4-7%]
- Still very far from tomography-informed MPI, but a lot of progress on tomography expected from the EIC…

DIS and HEP theory



- <u>The simplest, yet non-trivial example of hadron collider</u>
- Many techniques developed for DIS then successfully applied to the LHC
- Crucial results in pQCD [QCD evolution…]
- Tools [nested sums, iterated integrals…] widely used for state-of-the-art calculations
- Clean settings for NP studies, solid grounds in QFT (this is less the case for hadron-hadron colliders…)

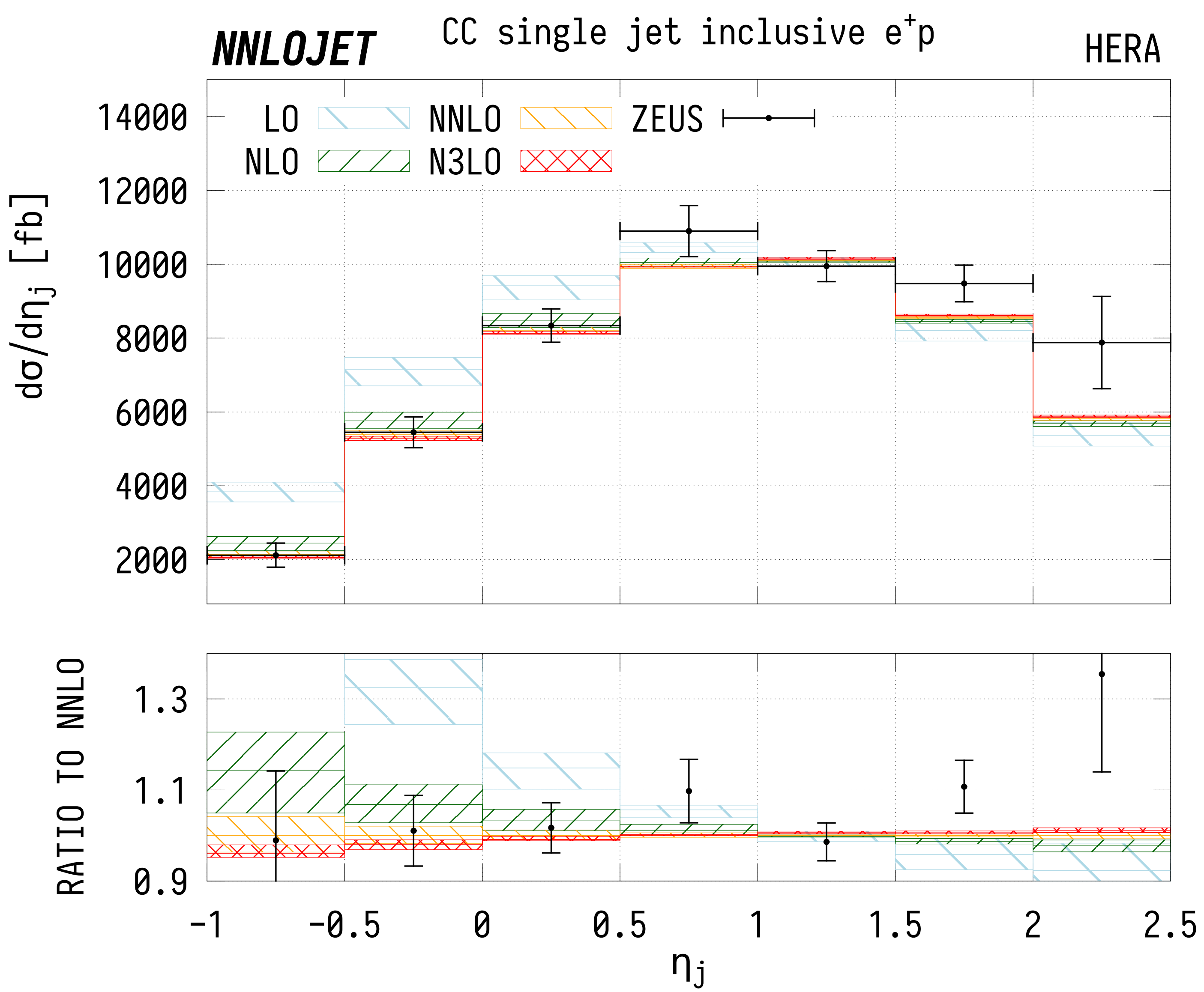
DIS: the first N³LO inclusive calculation…



[Moch,Vermaseren,Vogt (2005)]

- Good perturbative convergence (away from small-x)
- Naive α_s power counting works well
- Crucial for high-precision fits

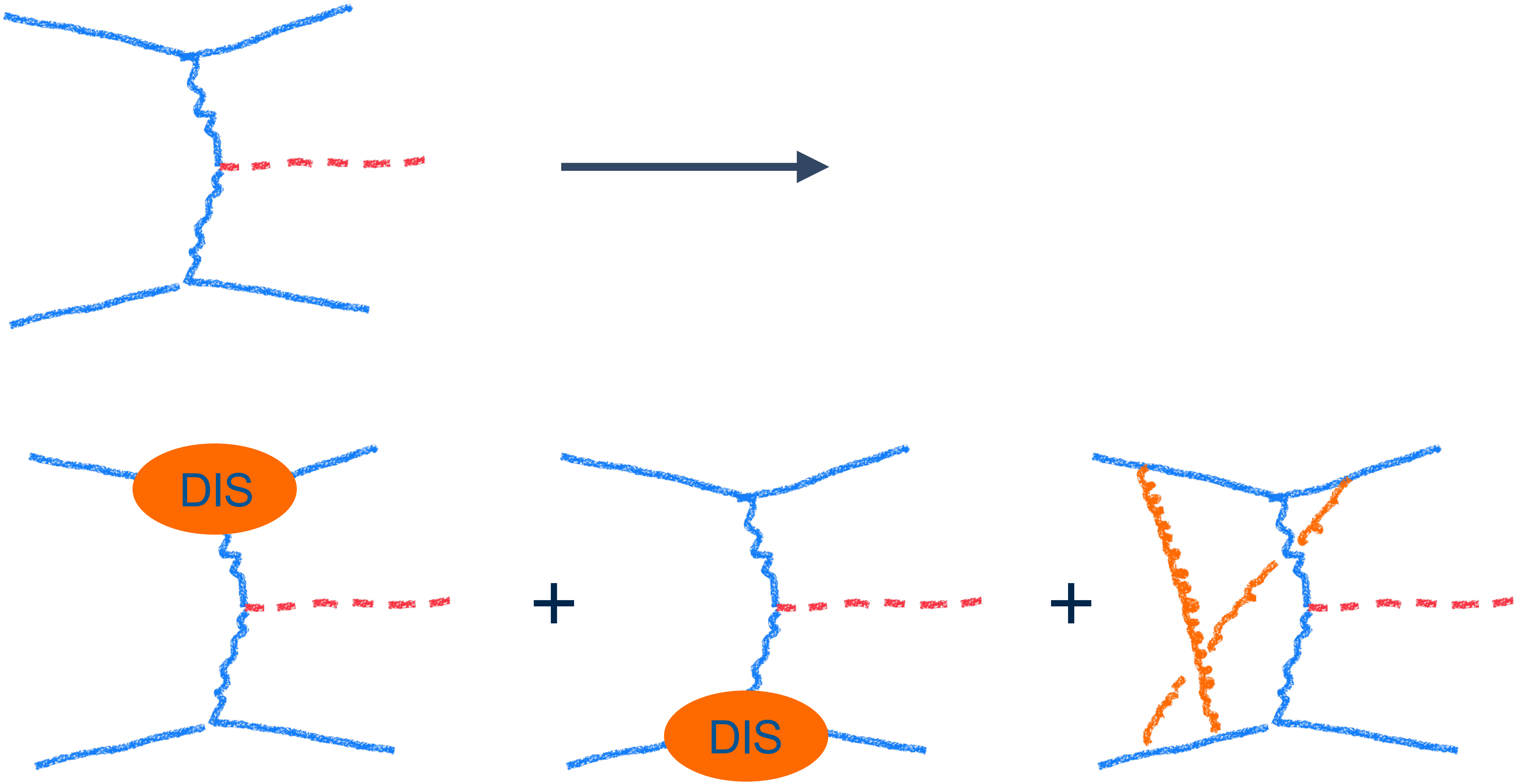
DIS: … and the first fully-exclusive one



[Gehrmann, Huss, Niehues, Vogt, Walker (2018)]

- Also in this case good convergence
- Testing grounds for similar calculations at hadron colliders

DIS in disguise: VBF@LHC



$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha_s^2/N_c^2)$

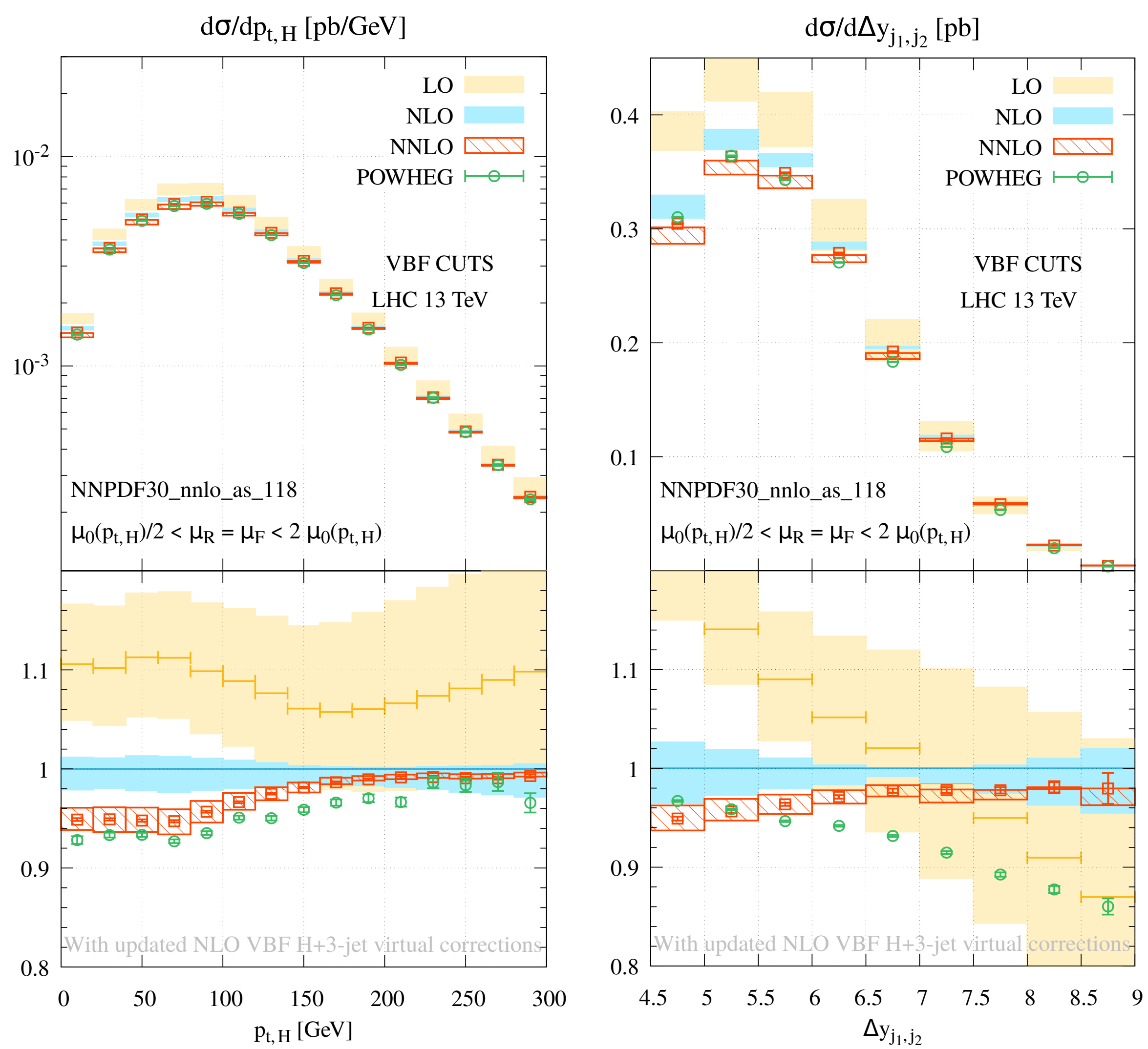
- Double-DIS approximation very good

DIS in disguise: VBF@LHC

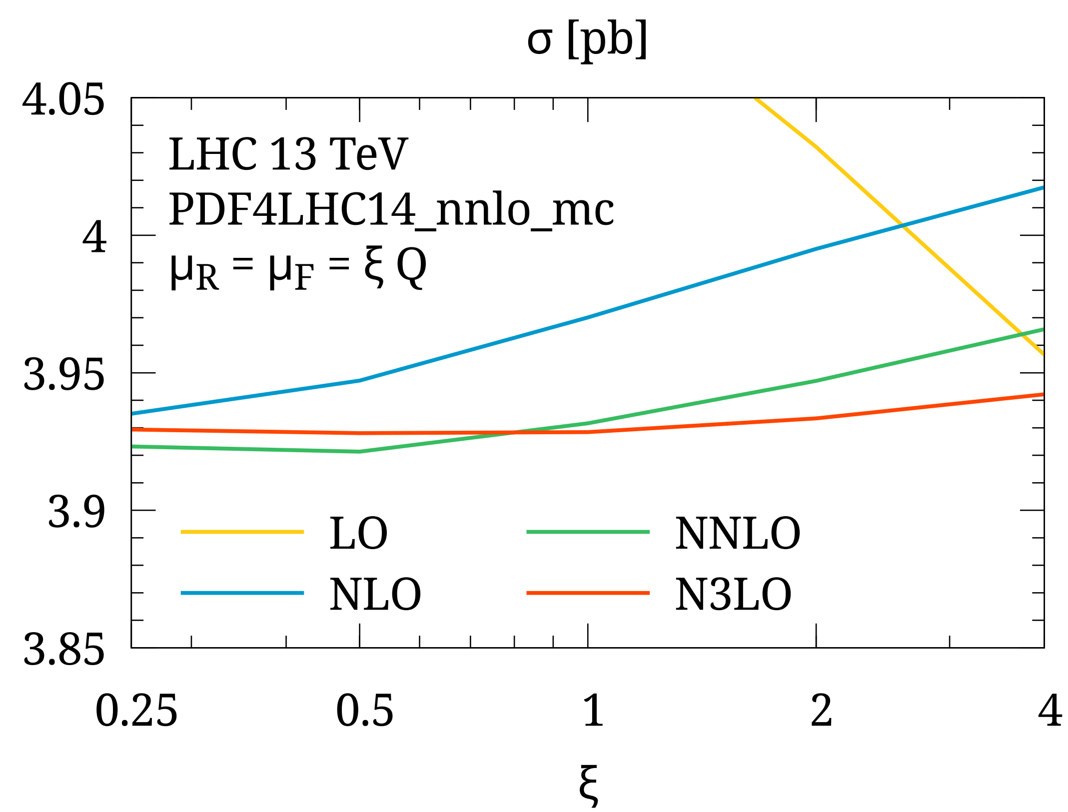
Using DIS in a clever way:

NNLO exclusive

[Cacciari et al (2015)]



N³LO inclusive

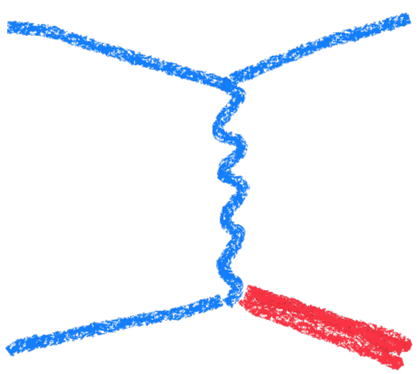


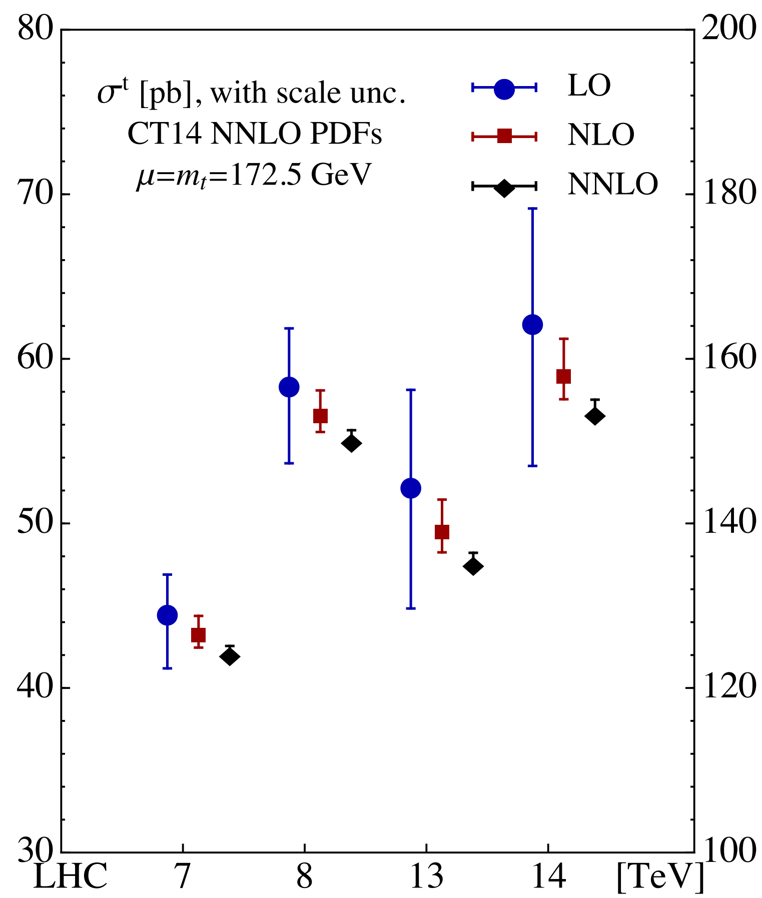
[Dreyer, Karlberg (2016)]

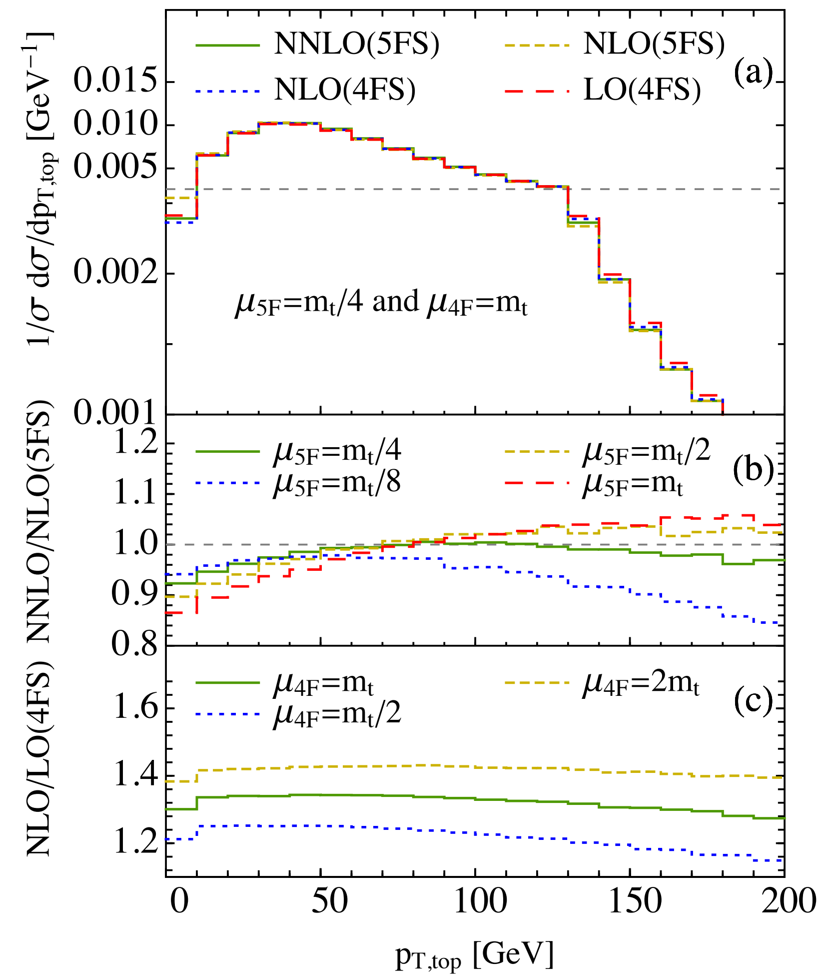
- Double-DIS approximation very good… although careful at Glauber phases, π^2/N_c^2 is not small [Melnikov, Penin (2019)]

DIS in disguise: t-channel single top

A similar argument holds for t-channel single-top





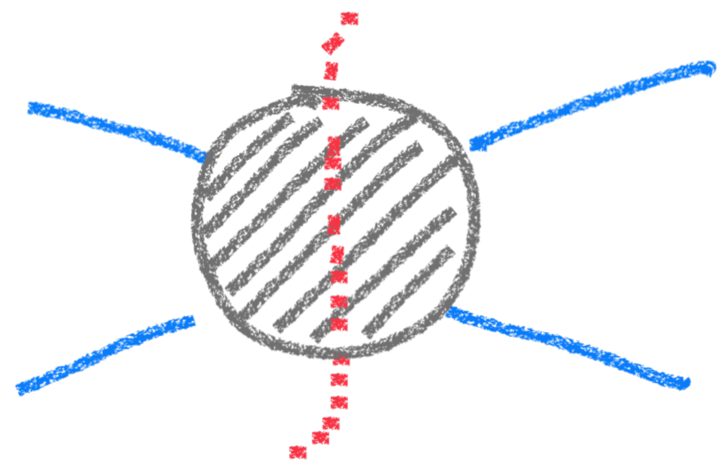


[Berger, Gao + Yuan, Zhu (2016-20)]

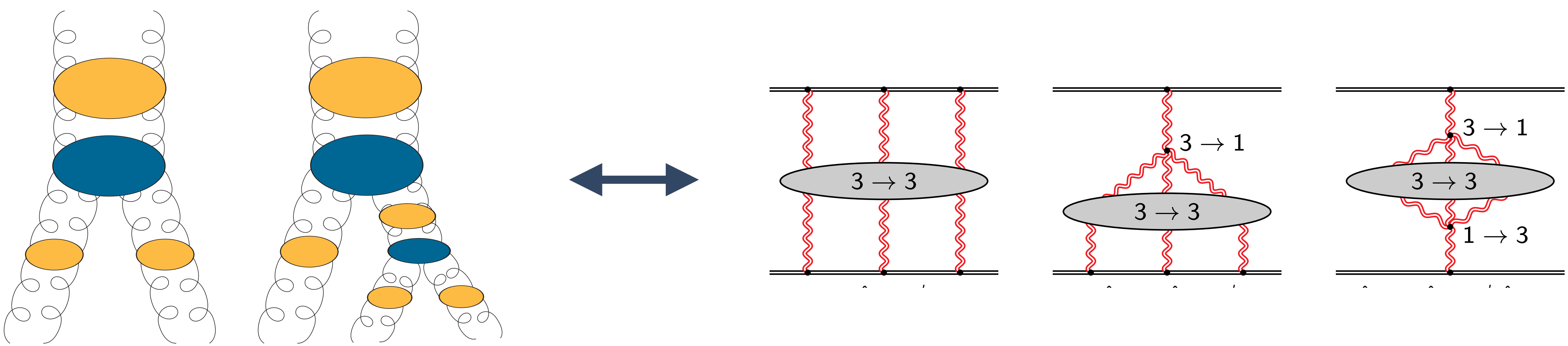
- Also requires massless → massive DIS transitions [Berger, Gao, Li, Liu, Zhu (2016)]
- Double-DIS approximation very good... although careful at Glauber phases, π^2/N_c^2 is not small [→ see C. Brønnum-Hansen's talk]

Non-linear evolution in disguise

- Unitarity: parton evolution ↔ forward scattering of elastic amplitudes



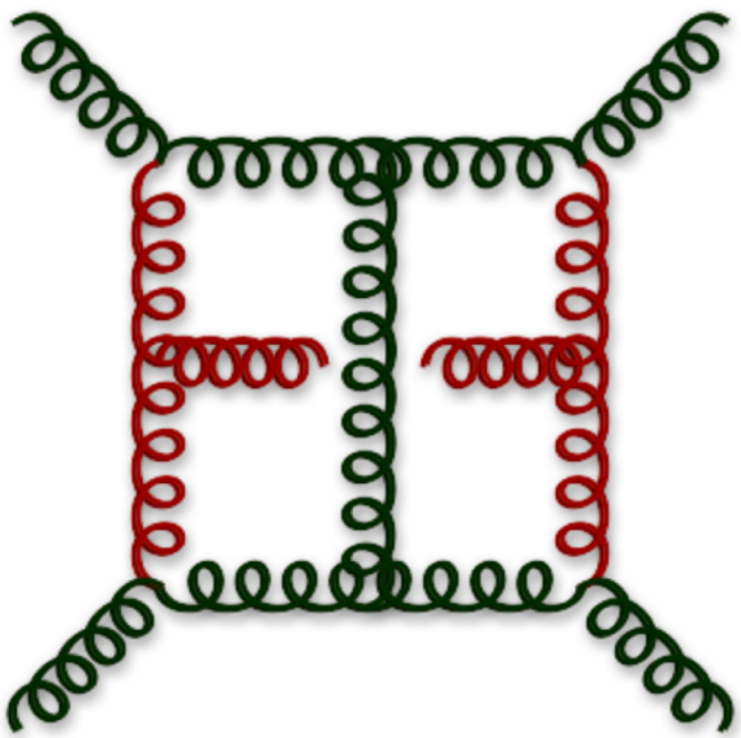
- High-enough logarithmic order: sensitive to full Balitsky-JIMWLK evolution



[formalism spelled out in Caron-Huot (2013) + del Duca, Falcioni, Gardi, Maher, Milloy, Vernazza (2013-2022); Fadin, Lipatov (2018)]

Non-linear evolution in disguise

- 2→2 QCD scattering amplitudes@3L recently computed [Chakraborty, Gambuti, von Manteuffel, Tancredi, FC (2021)]



Can test Regge factorisation at NNLL

$$\mathcal{H}_{\mathrm{ren},\pm} = Z_g^2 \, e^{L \mathbf{T}_t^2 \tau_g} \sum_{n=0}^{3} \bar{\alpha}_s^n \sum_{k=0}^{n} L^k \mathcal{O}_k^{\pm,(n)} \mathcal{H}_{\mathrm{ren}}^{(0)},$$

Regge trajectory

Multi-Reggeon interactions (SLC)

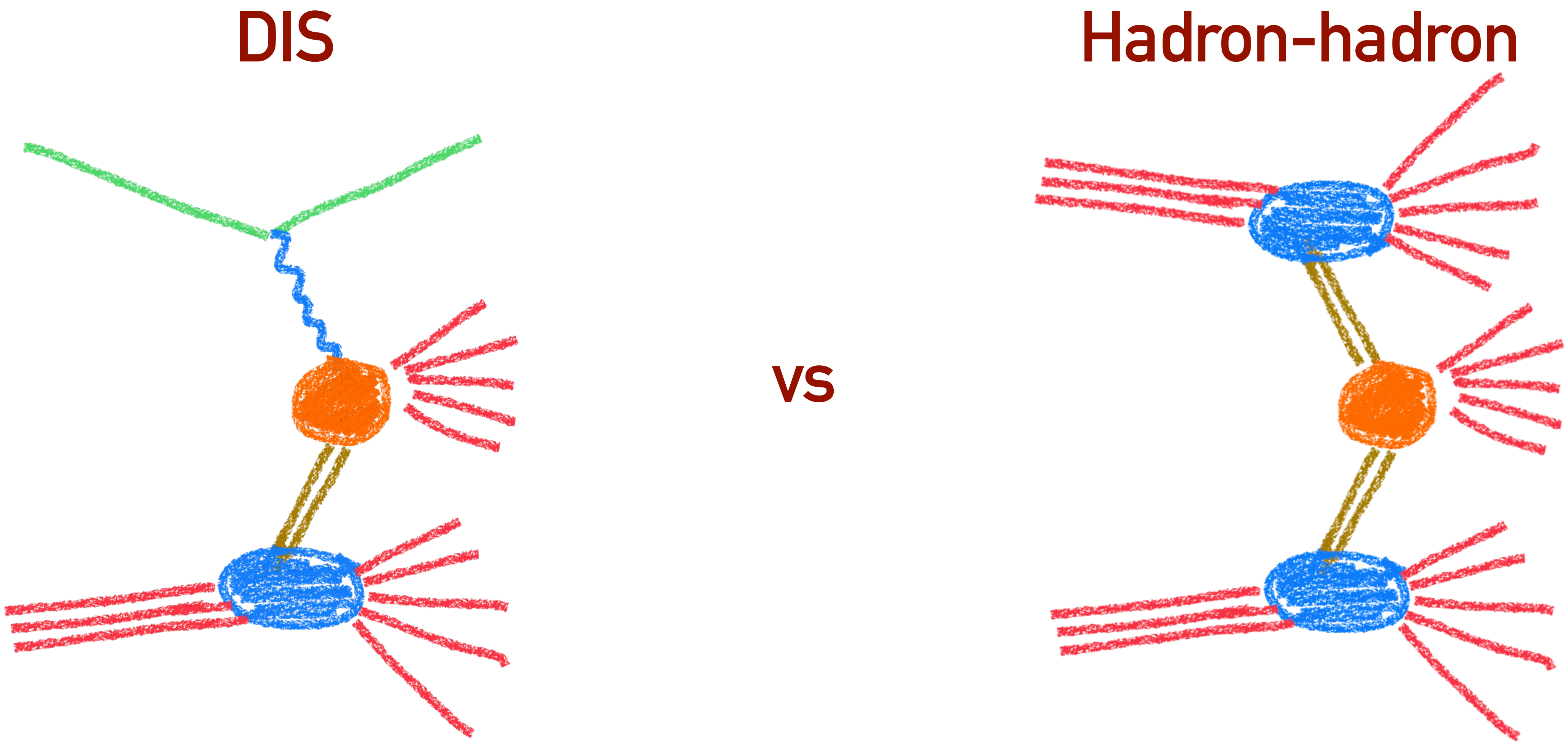
$$\mathcal{O}_0^{-,(0)} = 1, \quad \mathcal{O}_0^{-,(1)} = 2\mathcal{I}_1^g,$$

$$\mathcal{O}_0^{-,(2)} = \left[2\mathcal{I}_2^g + (\mathcal{I}_1^g)^2\right] + \mathcal{C}^{-,(2)}[(\mathbf{T}_{s-u}^2)^2 - \tfrac{N_c^2}{4}],$$

$$\mathcal{O}_1^{-,(3)} = \mathcal{C}_1^{-,(3)} \mathbf{T}_{s-u}^2 [\mathbf{T}_t^2, \mathbf{T}_{s-u}^2] + \mathcal{C}_2^{-,(3)} [\mathbf{T}_t^2, \mathbf{T}_{s-u}^2] \mathbf{T}_{s-u}^2,$$

Everything as predicted!

LHC: almost DIS2, but not always…



QCD with intrinsic heavy quarks:

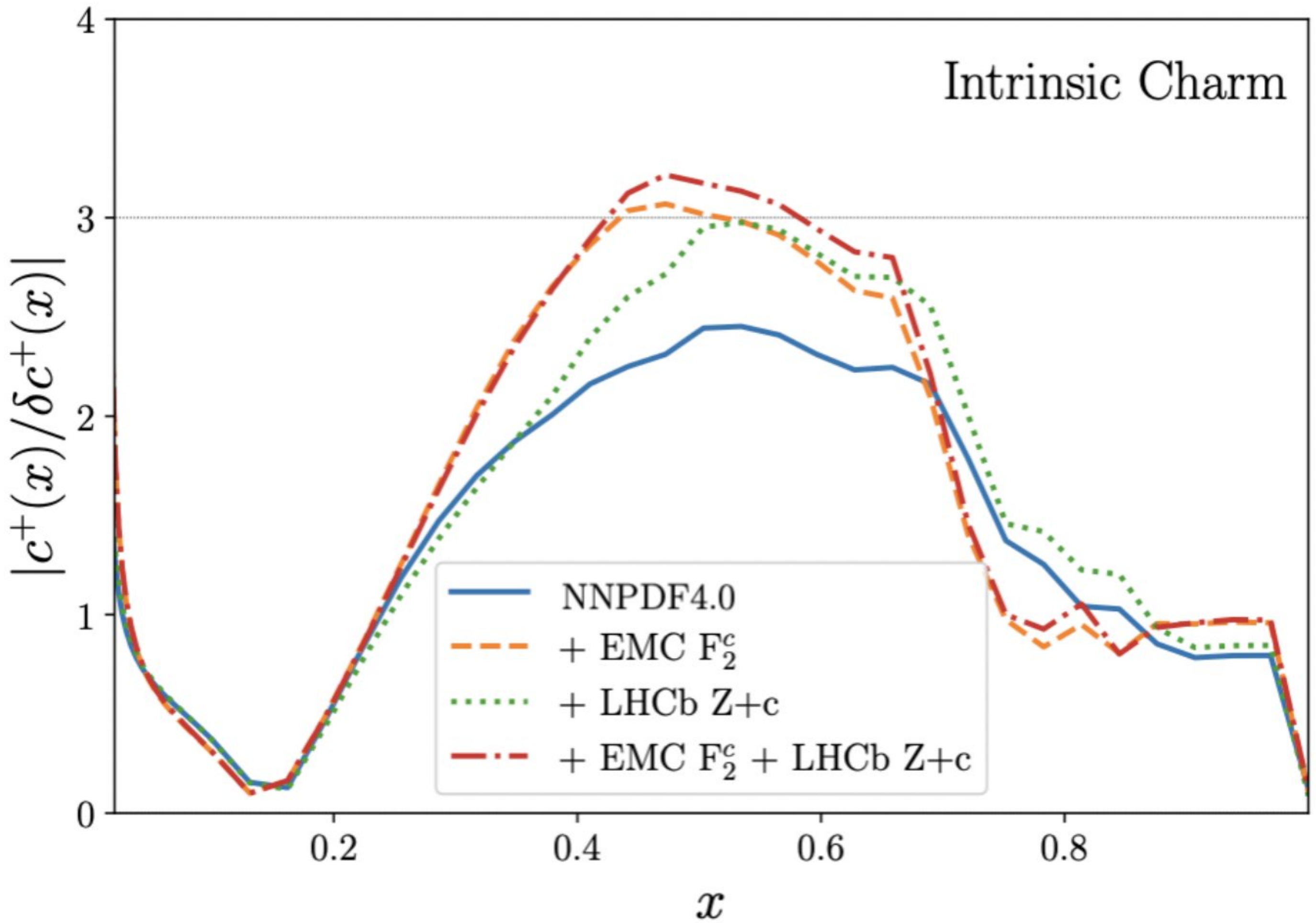
- collinear factorisation violated at NNLO in hadron–hadron (i.e. R+V+ren = ∞)
- no problem in DIS

[Doria, Frenkel, Taylor (1980); many subsequent studies. See e.g. Melnikov, Napoletano, Tancredi, FC (2020) for a modern derivation and discussion]

A new twist to an old story: intrinsic charm!

DISCOVERY OF INTRINSIC CHARM

[NNPDF]



MORE THAN 3 σ EVIDENCE

Evidence for intrinsic charm in DIS + LHC data

- How to properly deal with it at NNLO at the LHC unclear
- DIS: solid foundation → guide and benchmark

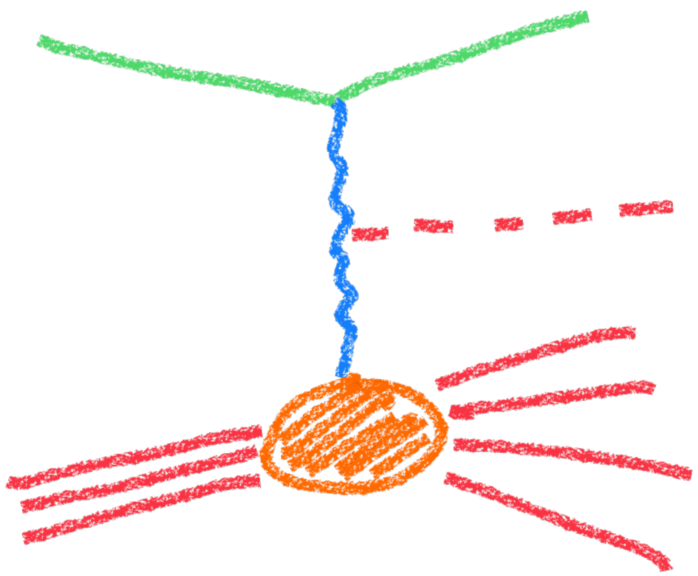
[→ see K. Kudashkin's talk and G. Magni's poster]

DIS as a high-energy probe

DIS in the past did probe EW interactions (NC vs CC, γ/Z interference…)

Future DIS facilities: clean environment (low pile-up, controlled bkgd…) for precision EW studies

- A famous example: b/c Higgs Yukawa



- S/B ~ 3!
- Constrain signal strength to 0.8% (bb) and 7.4% (cc)

- Not the only one! W-mass in the t-channel, top polarisation, radiation zeros, hidden sectors, axions… rich program at future facilities

→ see J. d'Hondt & M. d'Onofrio's talks

Conclusion I

``Interesting physics'' $\neq$ ``BSM''

… as any physicist not working on particle physics would tell you

- If a collider can deliver new discoveries, that's of course great
- Looking at the future: the era of ``guaranteed new physics deliveries'' (like the Higgs for the LHC) may well be over
- But there is a rich set of unexplored areas in the SM that are worth pursuing

Many interesting open questions in QCD. For example

- Mass/spin proton/nuclei
- The structure of the proton [PDFs, TMDs, tomography…]
- Nuclear physics: from models to first principles
- QCD evolution and new phases of QCD (saturation, QGP…)
- …

Future DIS facilities (EIC, LHeC, FCC-eh) would shed light on these issues

Conclusion II

DIS: the simplest hadron collider machine

- In this case: simple ↔ powerful (clean, well-understood)
- Hard to overstate the importance of accurate, precise and reliable determinations of the structure of the proton for the HE program at hadron colliders → legacy DIS data augmented with LHC information, interesting cross-talks

  Extreme regions (small/large-x) and individual quarks remain elusive → limiting factor for different physics programs

- HE DIS: clean probe of EW scale and beyond
- <u>Interesting synergies with other experiments</u>
- Many interesting QCD questions
- Techniques developed for DIS have much broader applications

DIS: very interesting and important role in the HEP landscape

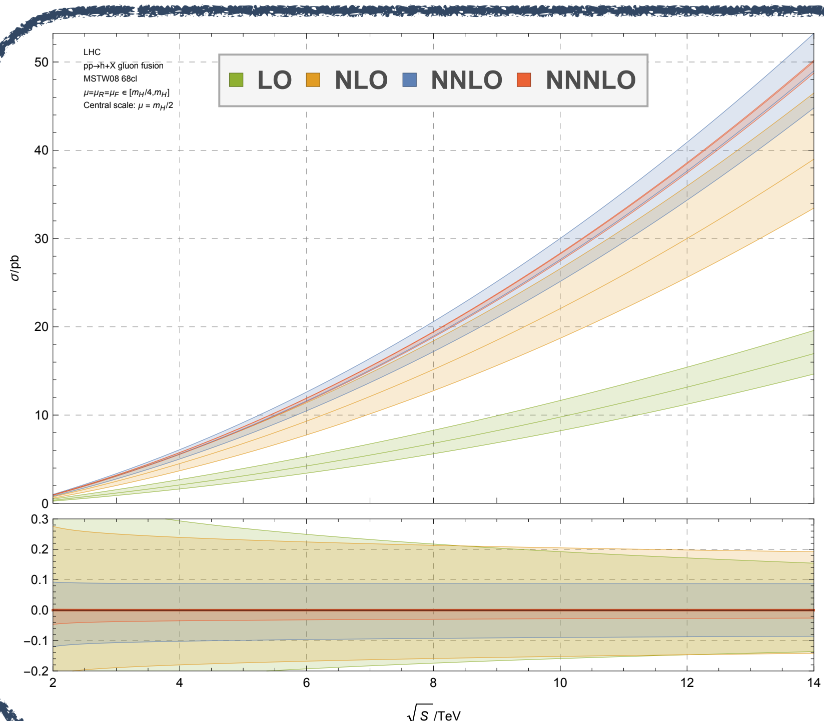
Thank you very much for your attention!

Backup

N³LO: inclusive results

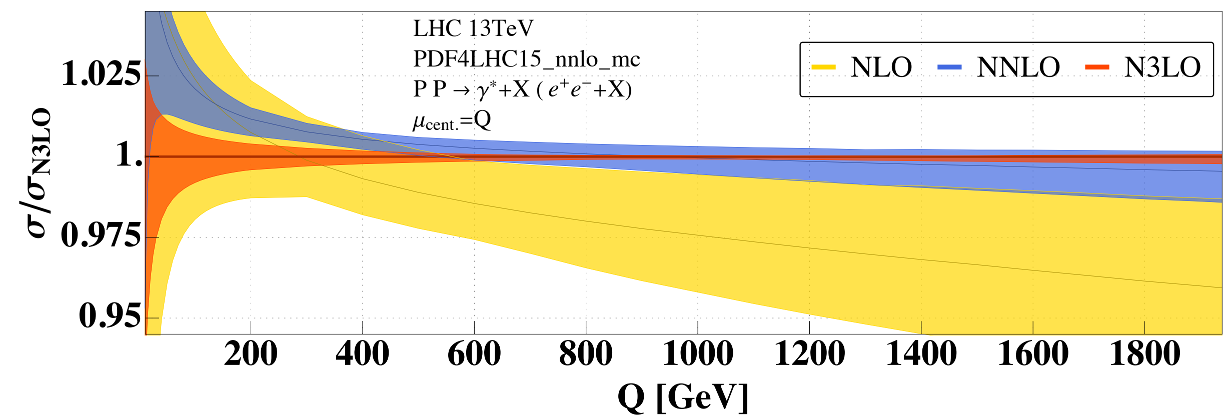
To a large extent, inclusive N³LO for 2 → 1 processes has been solved

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger (2016-...);
Duhr, Dulat, Mistlberger (2020-21)]

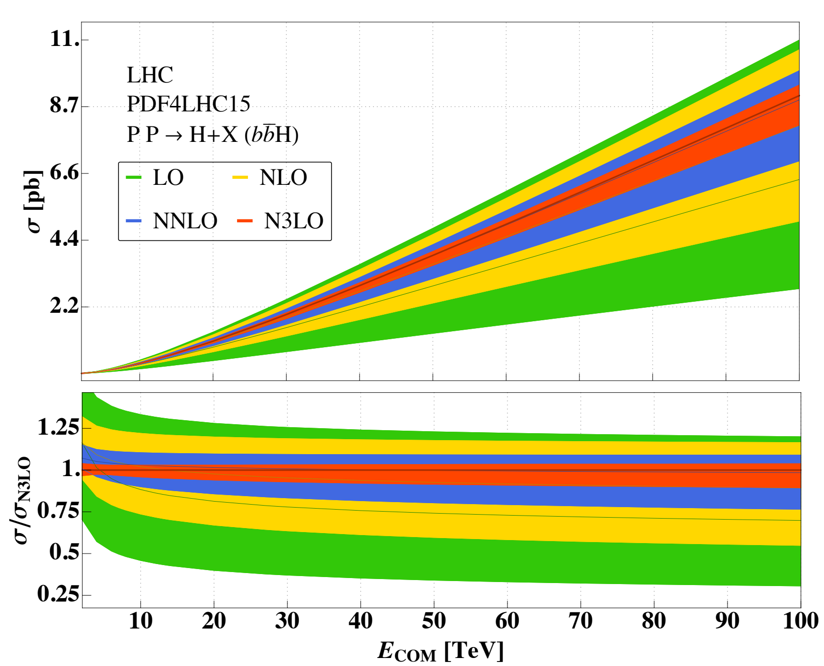


ggH

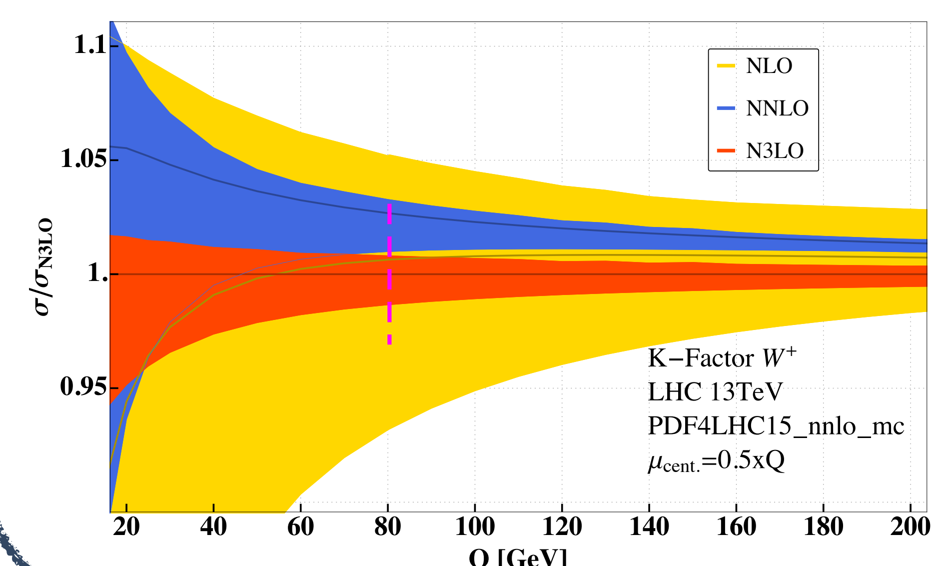
Drell-Yan



γ*



bbH



W

N^3LO: PDFs

N^3LO PDFs not available → order mismatch

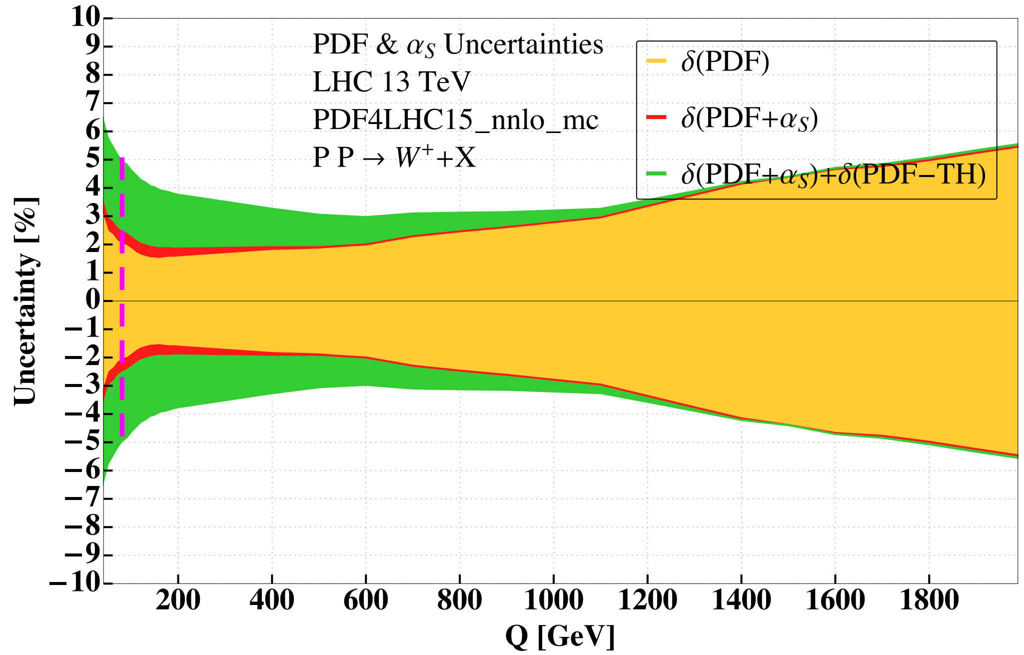
γ^*

Q/GeV	$K_{QCD}^{N^3LO}$	δ(scale)	δ(PDF+α_S)	δ(PDF-TH)
30	0.952	$^{+1.5\%}_{-2.5\%}$	$\pm4.1\%$	$\pm2.7\%$
50	0.966	$^{+1.1\%}_{-1.6\%}$	$\pm3.2\%$	$\pm2.5\%$
70	0.973	$^{+0.89\%}_{-1.1\%}$	$\pm2.7\%$	$\pm2.4\%$
90	0.978	$^{+0.75\%}_{-0.89\%}$	$\pm2.5\%$	$\pm2.4\%$
110	0.981	$^{+0.65\%}_{-0.73\%}$	$\pm2.3\%$	$\pm2.3\%$
130	0.983	$^{+0.57\%}_{-0.63\%}$	$\pm2.2\%$	$\pm2.2\%$
150	0.985	$^{+0.50\%}_{-0.54\%}$	$\pm2.2\%$	$\pm2.2\%$

Error: estimate from previous orders

$$\delta(\text{PDF-TH}) = \frac{1}{2}\left|\frac{\sigma_{W^\pm}^{(2),\ \text{NNLO-PDFs}} - \sigma_{W^\pm}^{(2),\ \text{NLO-PDFs}}}{\sigma_{W^\pm}^{(2),\ \text{NNLO-PDFs}}}\right| .$$

W^+

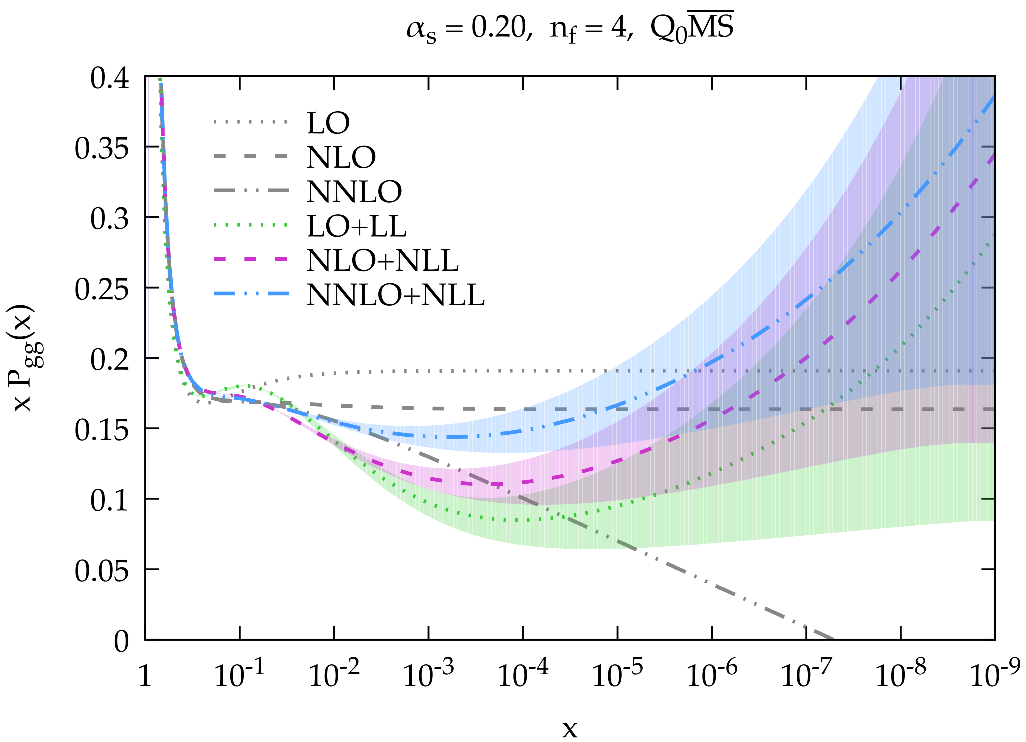


- ~ 2% PDF-TH error in the EW region
- significant fraction of the error budget
- same order of ``standard" PDF+α_s

N³LO PDFs issues: evolution

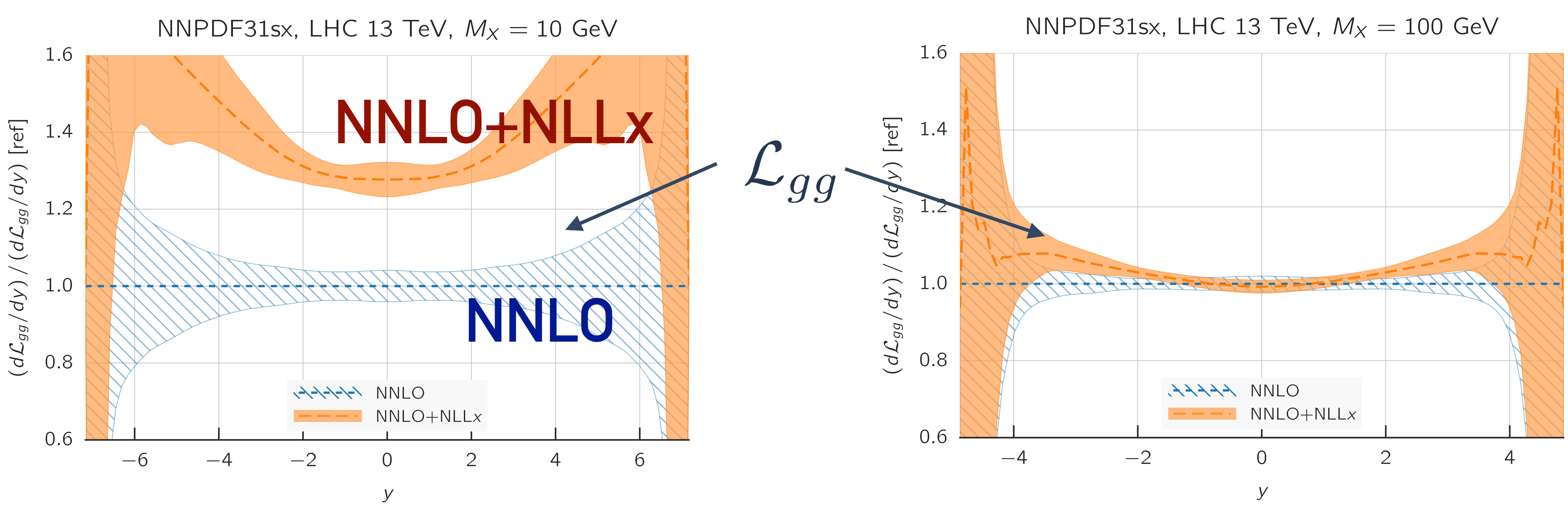
N³LO: evolution and the problems of small-x

[Bonvini, Marzanni, Muselli (2017-18)]



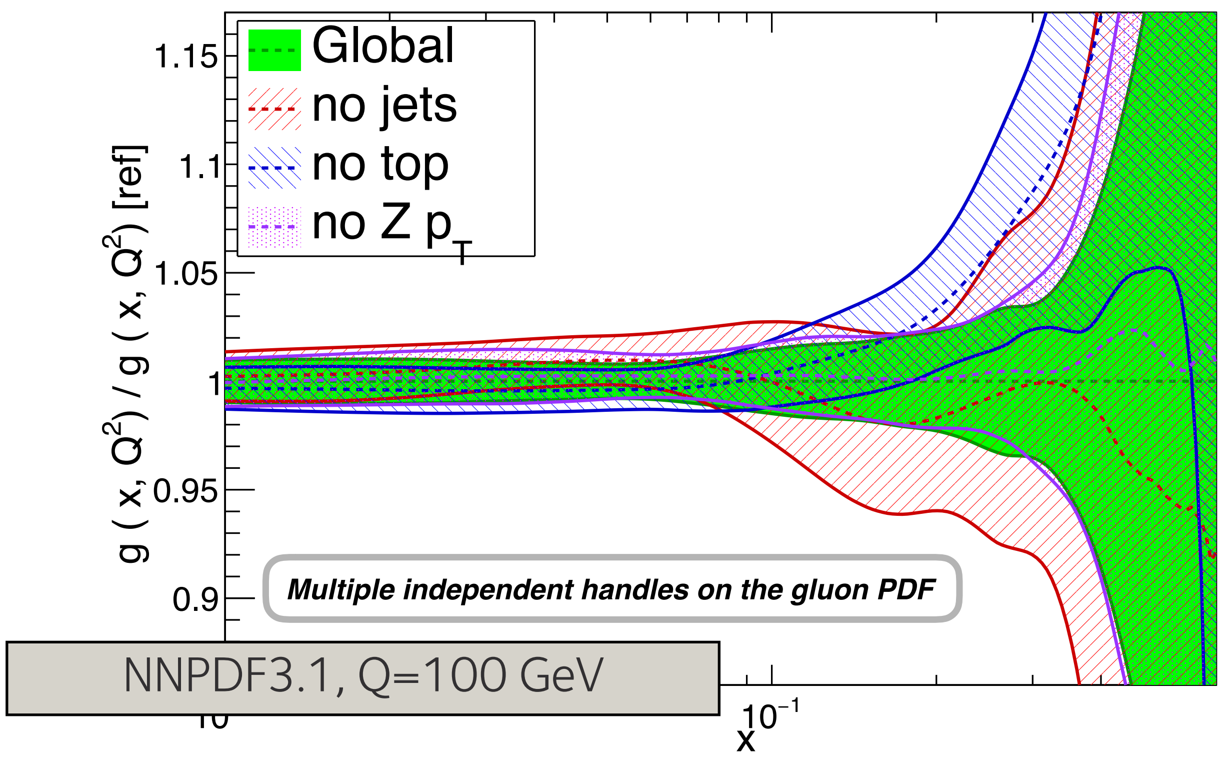
- N³LO calculation underway [Herzog, Moch, Ruijl, Ueda, Vermaseren, Vogt, in progrress]
- N³LO: rapid small-x growth ➞ perturbative instabilities@N³LO
- NLL resummation known, but large subleading effects [Bonvini, Marzani (2018)]

[Ball, Bertone, Bonvini, Marzani, Rojo, Rottoli (2018)]



NNLO: an issue at low-mass, not quite so at the EW scale

N^3LO PDFs issues: data



- Collider data crucial to reduce perturbative uncertainty → fully-consistent N^3LO fit would require top, Z p_t, jets @ N^3LO

N^3LO for PDFs: status and prospects

- DIS ✔
- DY ✔
- Z p_t: ~ (unknown, but should be possible)
- Top: ~ (unknown, but should be possible given current understanding)
- Jets: ✘ (unknown, and there may be serious problems…)