QCD systematics for high-Q EW/Higgs measurements at FCC-hh

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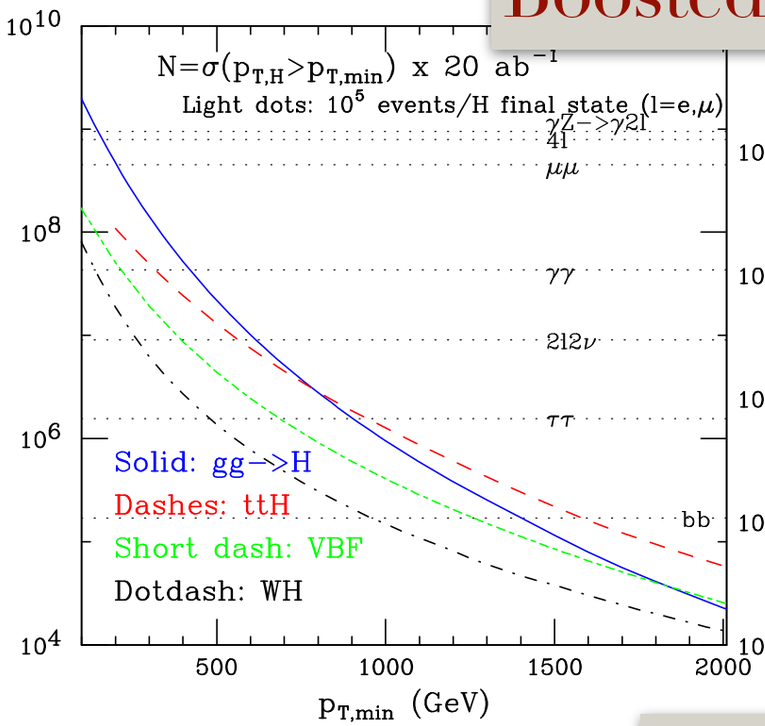
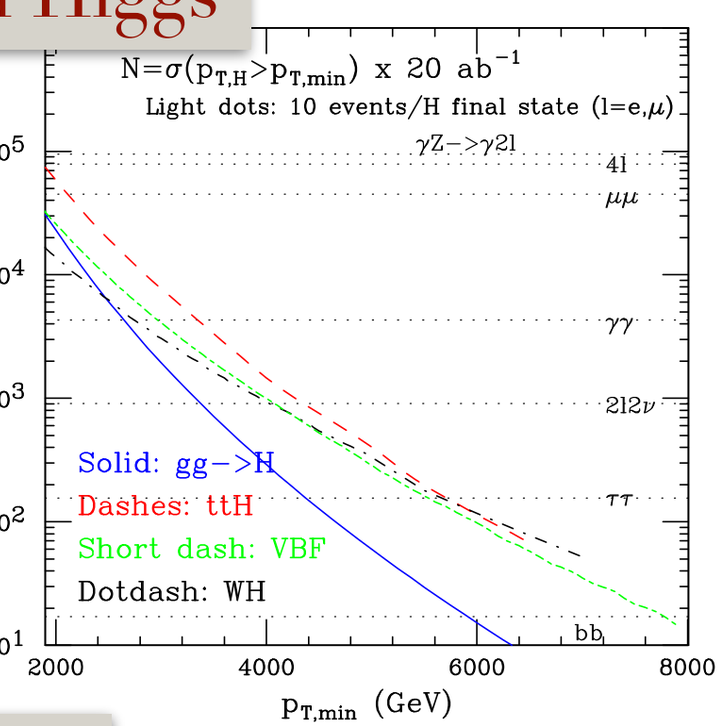
3rd FCC Physics and Experiments Workshop, CERN, Jan 15th 2020

[unless stated otherwise: results taken from MLM et al., arXiv:1606.09408-1607.01831]

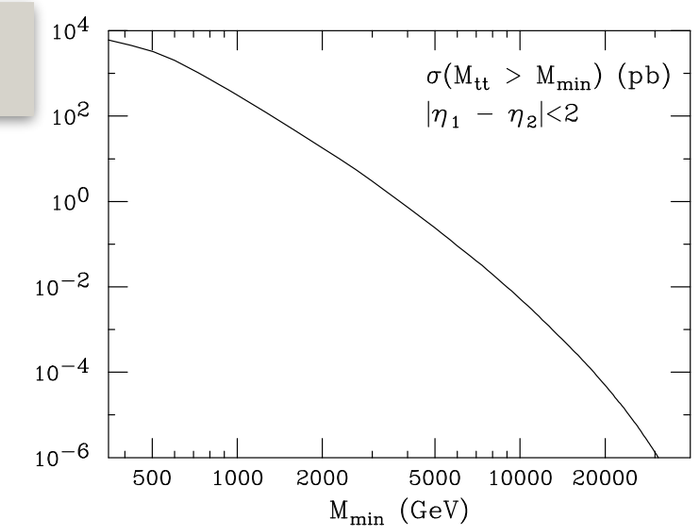
FCC: a wide kinematic coverage

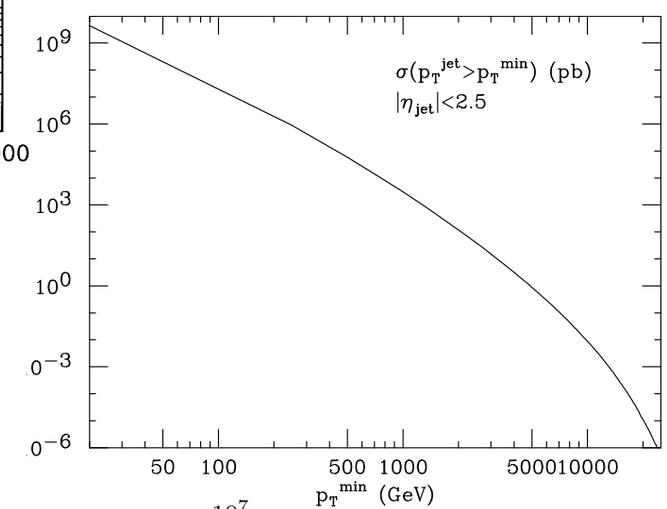
Boosted Higgs





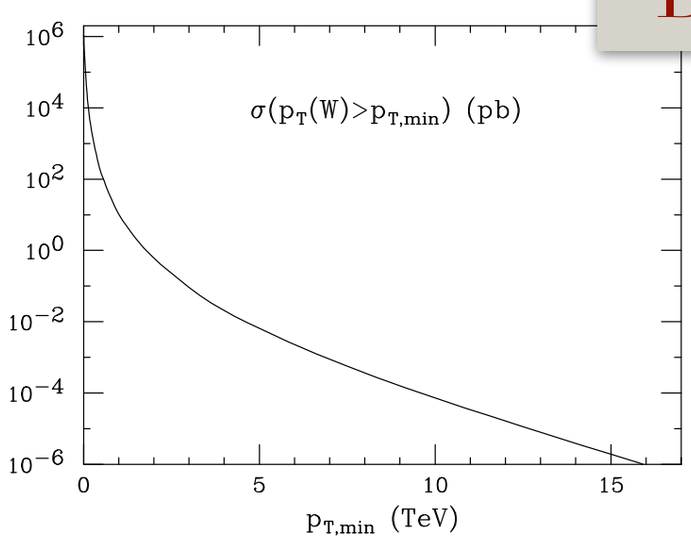
Top

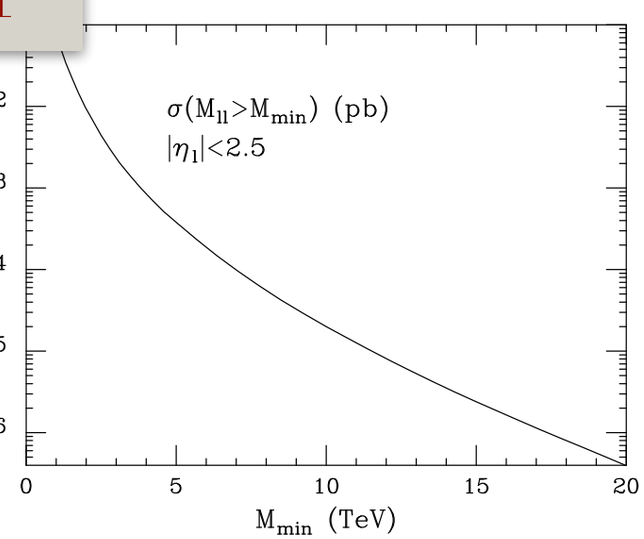


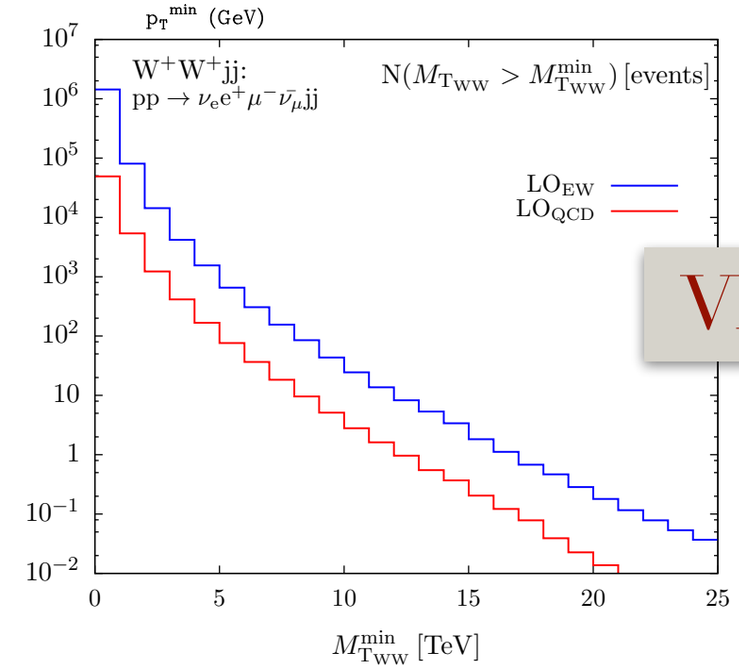


Jets

DY







VBS

- FCC-hh: thorough investigation at high-Q
- Q ~ 10 TeV will be explored

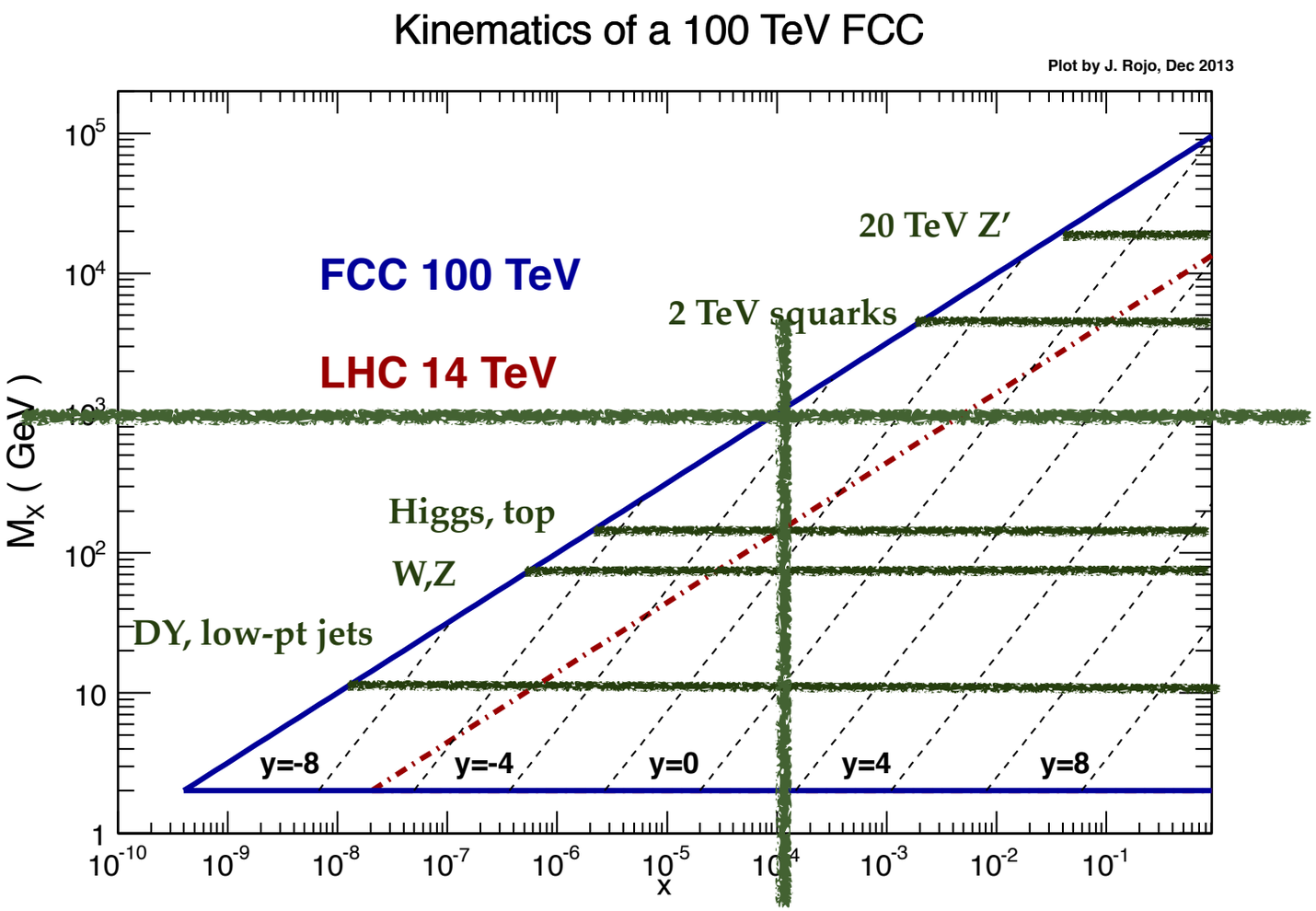
QCD at high-Q

1. In general, high-Q region very clean w.r.t. QCD
   - $\Lambda_{QCD}/Q \ll 1 \rightarrow$ robust first principle calculations
   - $\alpha_s(Q) \ll 1 \rightarrow$ good perturbative convergence
   - Can [to some extent] afford to to go away from region contaminated by soft/physics $\rightarrow$ robust computational frameworks

2. Very different (theory) systematics w.r.t. physics EW scale
   - Very large Q: measurable rate, but not large statistics $\rightarrow$ ubiquitous sub-percent precision not required
   - Still, sizeable source of uncertainties. To some extent, different from uncertainty at the EW scale
   - In the following: some illustrative examples (not a comprehensive review)

Input parameters: PDFs

FCC-eh: see M. Klein's talk



FCC PDFs: generic

- A major problem for precision physics at FCC-hh: small-x PDFs
- Can systematically affect physics at the EW scale

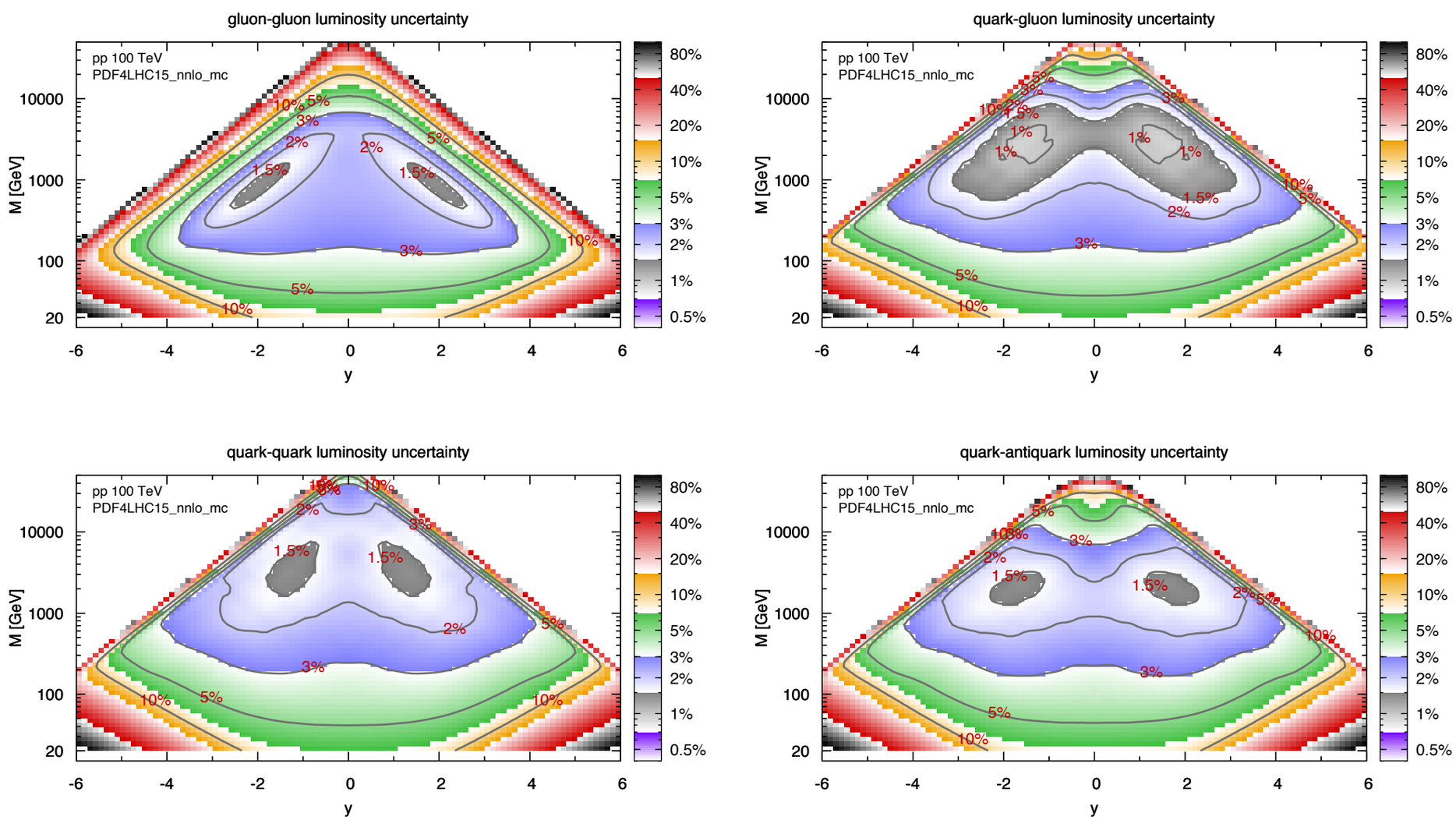
FCC PDFs: large Q

- This issue is not there at very large Q (central production…)
- Intermediate Q ~ TeV region@FCC_{100} ↔ EW region@LHC_{14}. Not affected by small-x physics

One caveat: N^3LO evolution and small-x. Should be clarified soon [this year?]

Main issue: large-x PDFs

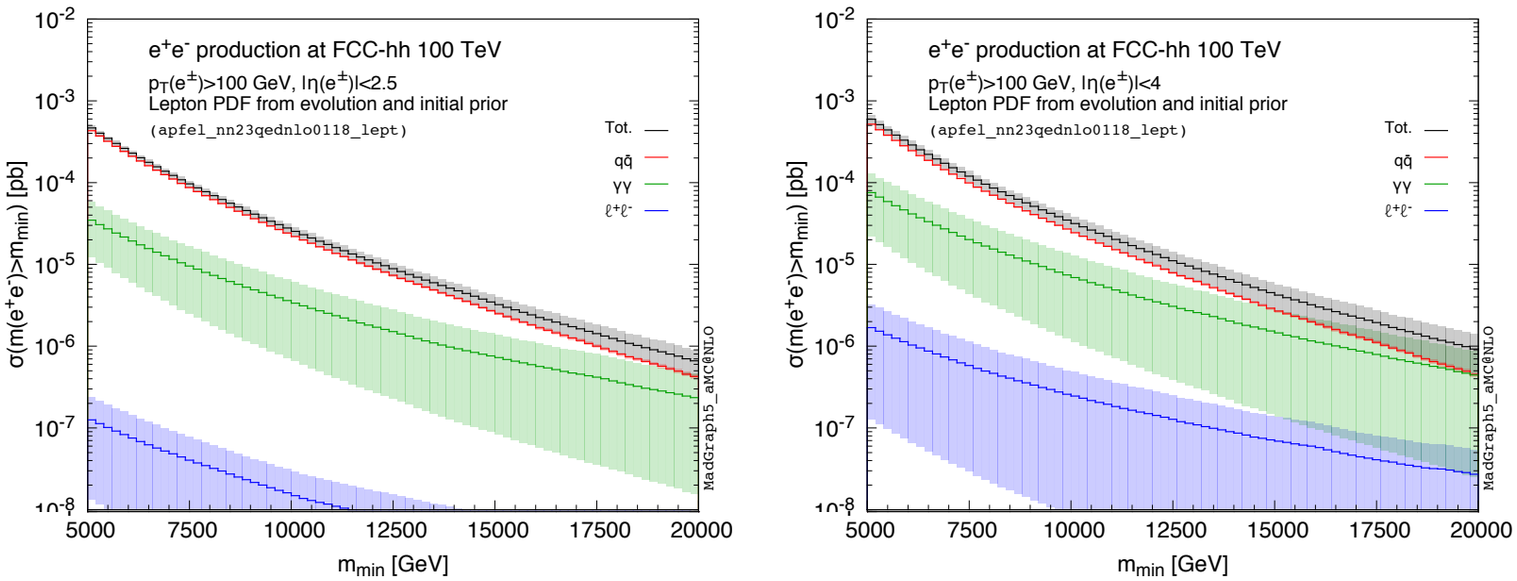
- By FCC: ``collider-only" sets, minimal contamination from higher twist, nuclear effects…
- Resumption effects: should be subdominant →
- At large Q: mostly ``experimental" issue, i.e. data to contain large-x region

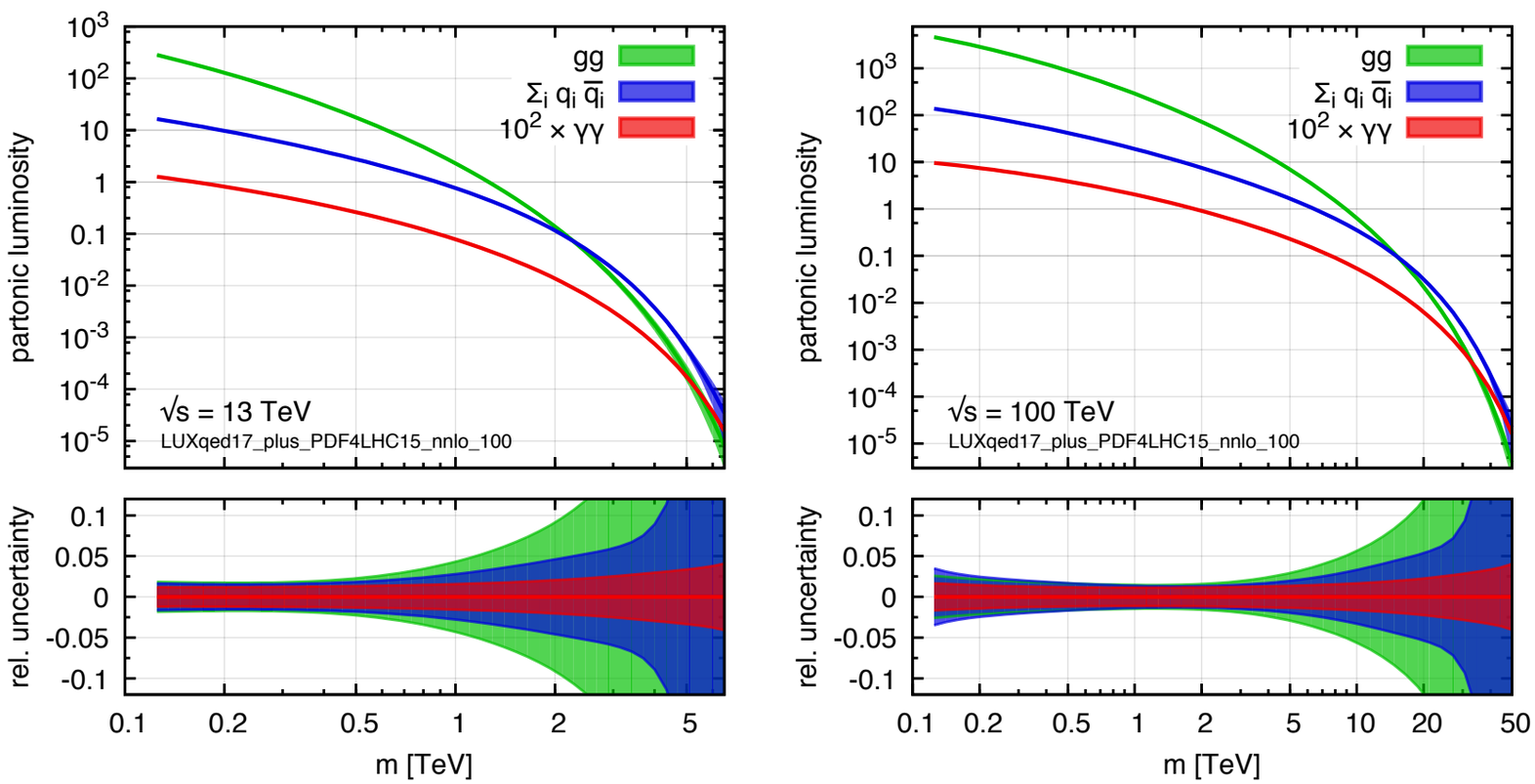


- Still good control in the multi-TeV region
- Loss of information at large x, M > 10-20 TeV

Main issue: large-x PDFs

- Photon PDF: progress w.r.t. FCC report *(ingenuity still plays a major role)*



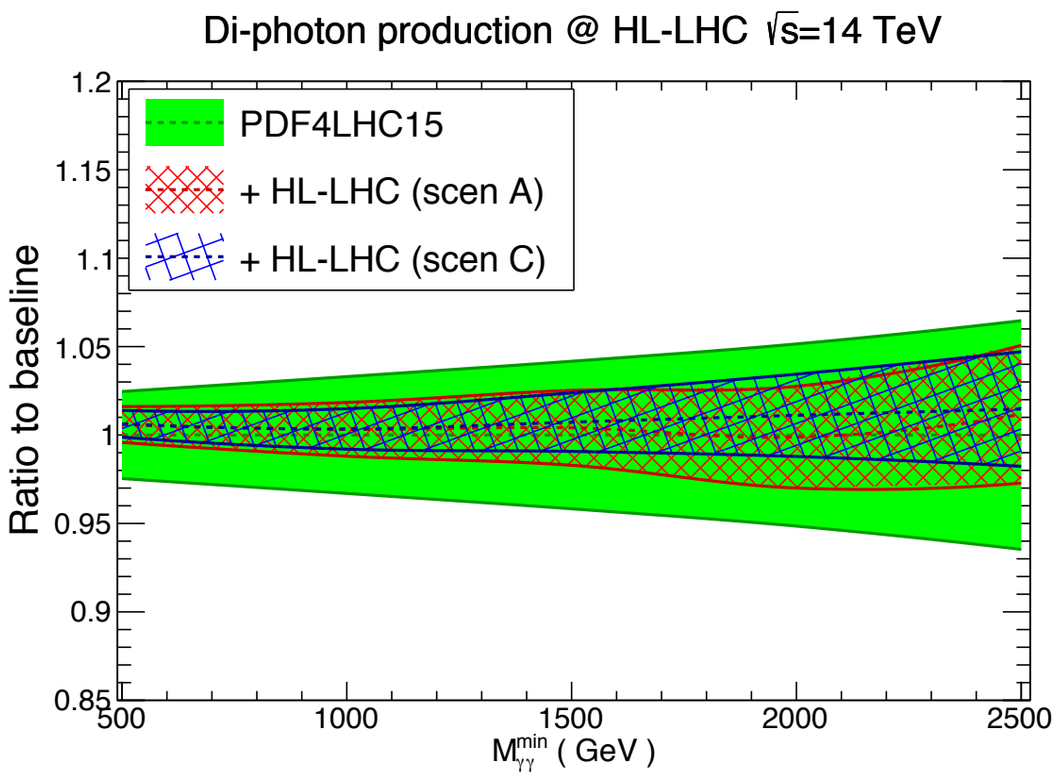


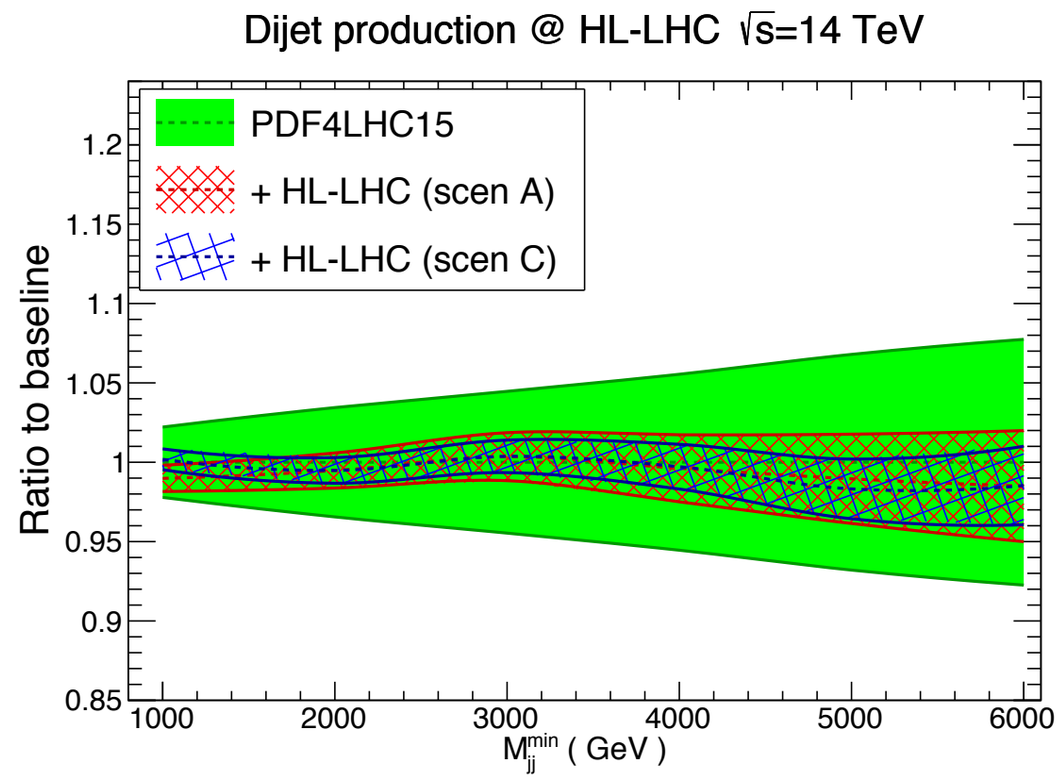
[Manohar et al. (2017)]

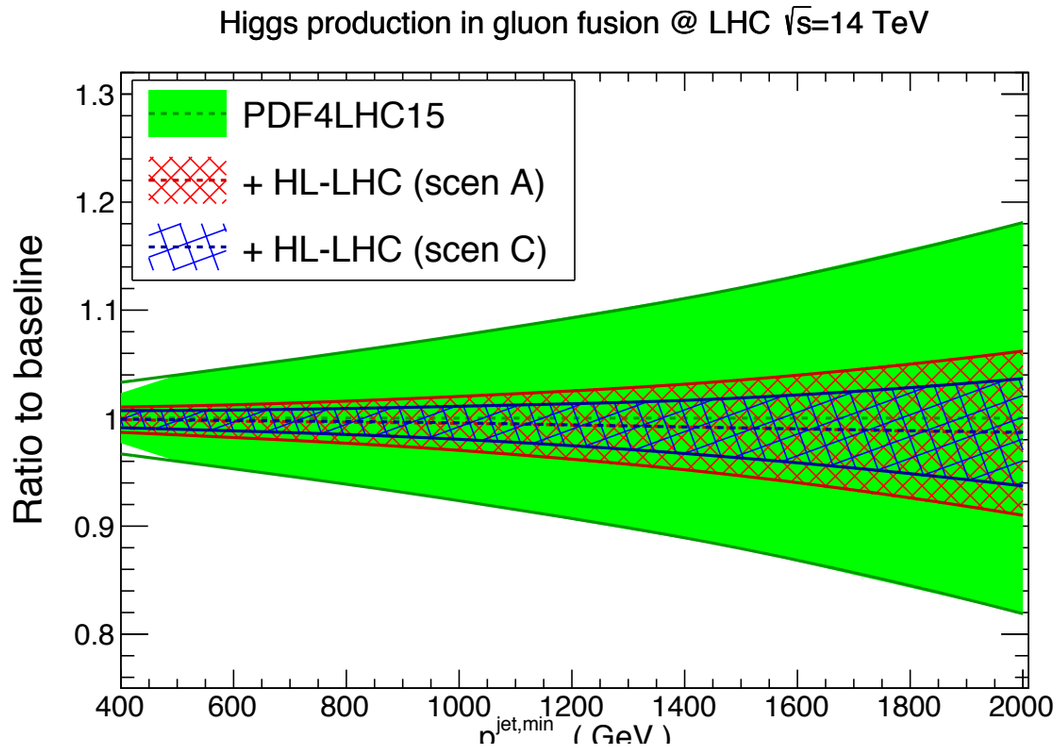
rule-of-thumb:
10 TeV@FCC_{100}
$\sim$
1 TeV@LHC_{14}

Large-x from collider data

[Khalek et al. (2018), ``Towards Ultimate PDFs at the HL-LHC"]







- It is now established that collider data (top, jet, V…) can significantly reduce large-x uncertainties
- HL-LHC: factor 2 or more in the TeV region
- Although no comprehensive dedicated FCC-study: reasonable to assume the same in the multi-TeV region

Higher precision for standard candles?

Extracting PDFs from collider data may benefit from higher theoretical prediction → N^3LO for standard candles?

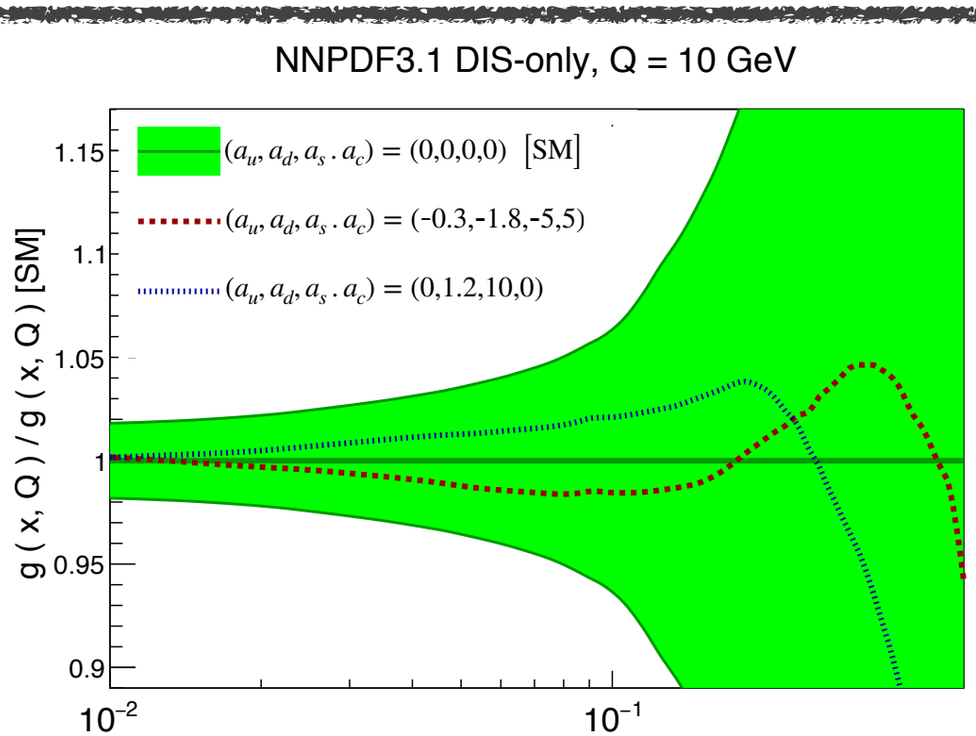
- N^3LO evolution almost available *(→small-x issues?)*
- N^3LO for color singlets within reach (see C. Duhr's talk)
- N^3LO for tops, jets: serious theoretical challenges
  - Very difficult technical calculations
  - Conceptual issues, may require going beyond ``standard" approaches to perturbative QCD
    - *$t\bar{t}$@N^3LO: $\delta\sigma \neq R+V$, non-analytic $|\alpha_s|$ terms* [see M. Beneke, Ruiz-Fermenia 1606.02434, Melnikov, Vainshtein, Voloshin 1402.5690]
    - Jets: factorisation violation [see e.g. Catani, de Florian, Rodrigo 1112.4405]

Crucial also for ``low-Q" EW physics

PDFs from collider: the usual issue

- Large-x PDFs constrained by high-Q data → ``*Q1: how can you be sure that you are not fitting new physics away into the PDFs?*"
- The standard answer: consistency checks, closure tests etc…
- Here situation slightly worse: very little info from other sources (<u>self-consistency not as powerful</u>)
- Crucial to over-constrain, use rapidity/asymmetries etc.
- Recently: first quantitative investigations of Q1

[Carrazza et al (2019)]

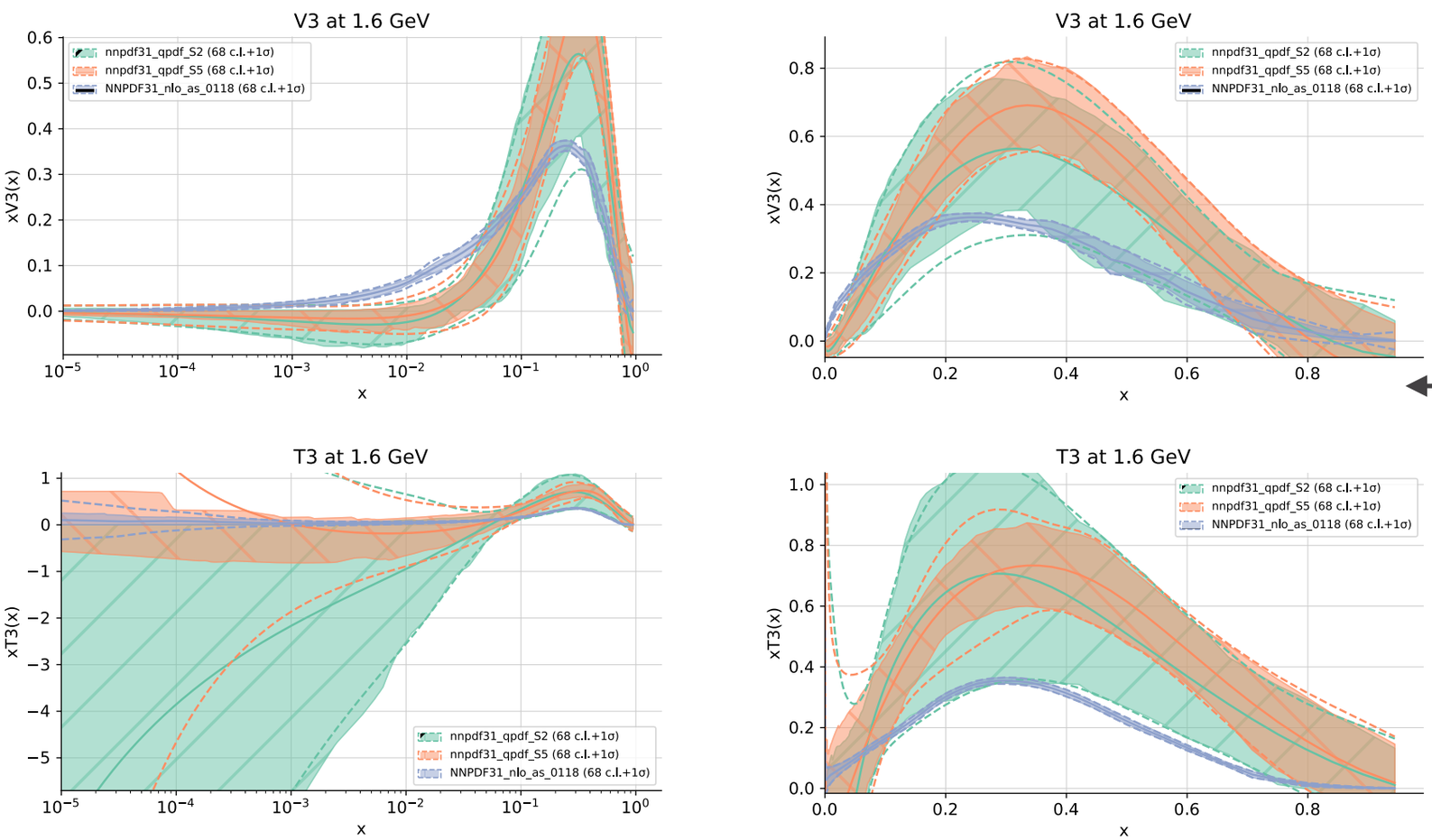


- NNPDF team: fit EFT and PDFs at the same time, study statistical indicators…
- Very relevant for PDFs vs BSM issue, a lot to be explored

Another strategy: PDFs from lattice

- Recent progress in obtaining PDFs from lattice
- In a nutshell: find σ such that *a)* it obeys a factorisation theorem *b)* it can be computed on the lattice → ``lattice experimental data", on a par with experimental data

$$\sigma = \hat{\sigma} \otimes f$$



Lattice proof-of-concept vs NNPDF

[Cichy, Del Debbio, Giani (2019)]

PDFs from lattice

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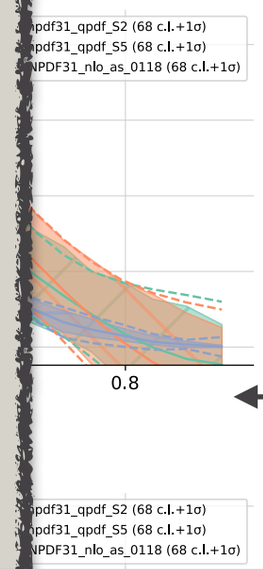

Lattice proof-of-concept vs NNPDF

Parton distributions and lattice QCD calculations: a community white paper

Huey-Wen Lin[1,2], Emanuele R. Nocera[3,4], Fred Olness[5], Kostas Orginos[6,7], Juan Rojo[8,9] (editors), Alberto Accardi[7,10], Constantia Alexandrou[11,12], Alessandro Bacchetta[13], Giuseppe Bozzi[13], Jiunn-Wei Chen[14], Sara Collins[15], Amanda Cooper-Sarkar[16], Martha Constantinou[17], Luigi Del Debbio[4], Michael Engelhardt[18], Jeremy Green[19], Rajan Gupta[20], Lucian A. Harland-Lang[3,21], Tomomi Ishikawa[22], Aleksander Kusina[24], Keh-Fei Liu[25], Simonetta Liuti[26,27], Christopher Monahan[28], Pavel Nadolsky[5], Jian-Wei Qiu[7], Ingo Schienbein[23], Gerrit Schierholz[29], Robert S. Thorne[21], Werner Vogelsang[30], Hartmut Wittig[31], C.-P. Yuan[1], and James Zanotti[32]

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DESY 17-185, IFJPAN-IV-2017-19,
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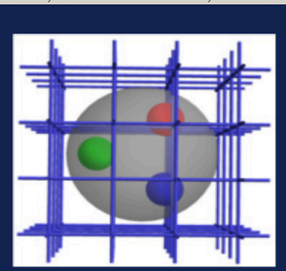

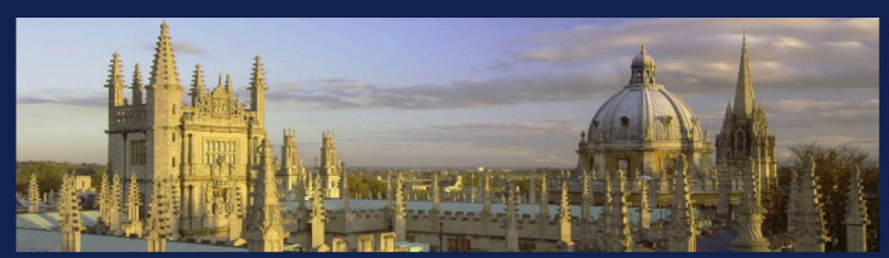

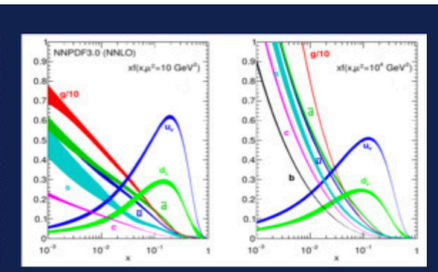

Parton Distributions and Lattice Calculations in the LHC era
(PDFLattice 2017)

22-24 March 2017, Oxford, UK

PDFs from lattice

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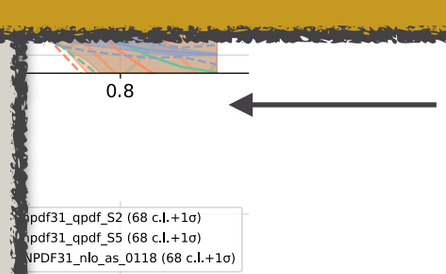
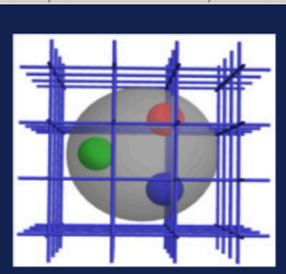
For high-Q processes: HOW EASY IS TO CONTROL THE *X→1* REGION ON THE LATTICE (resonances…)?

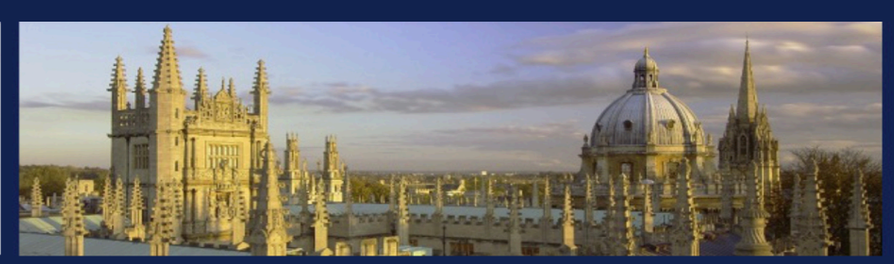
Does not need to happen tomorrow…

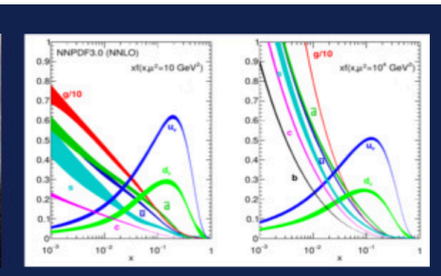
f-



concept vs NNPDF







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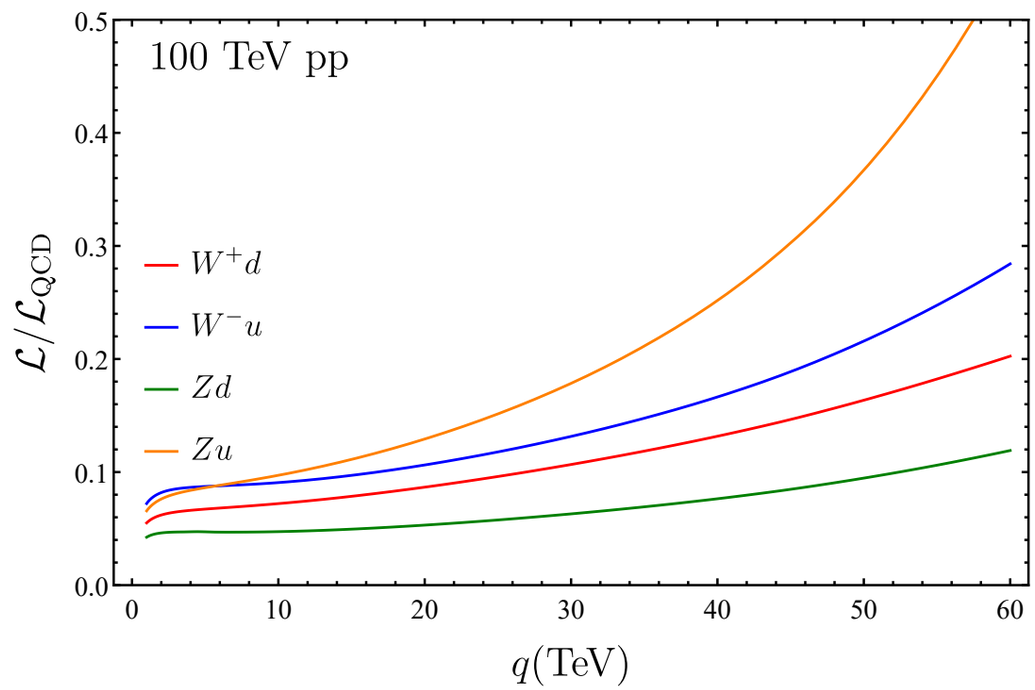
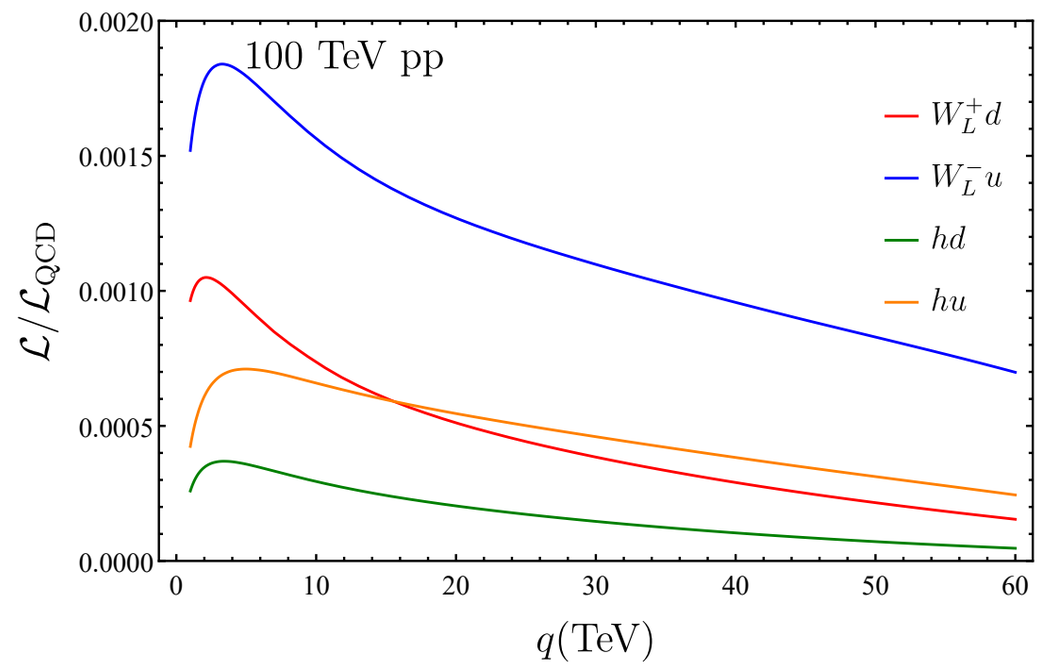
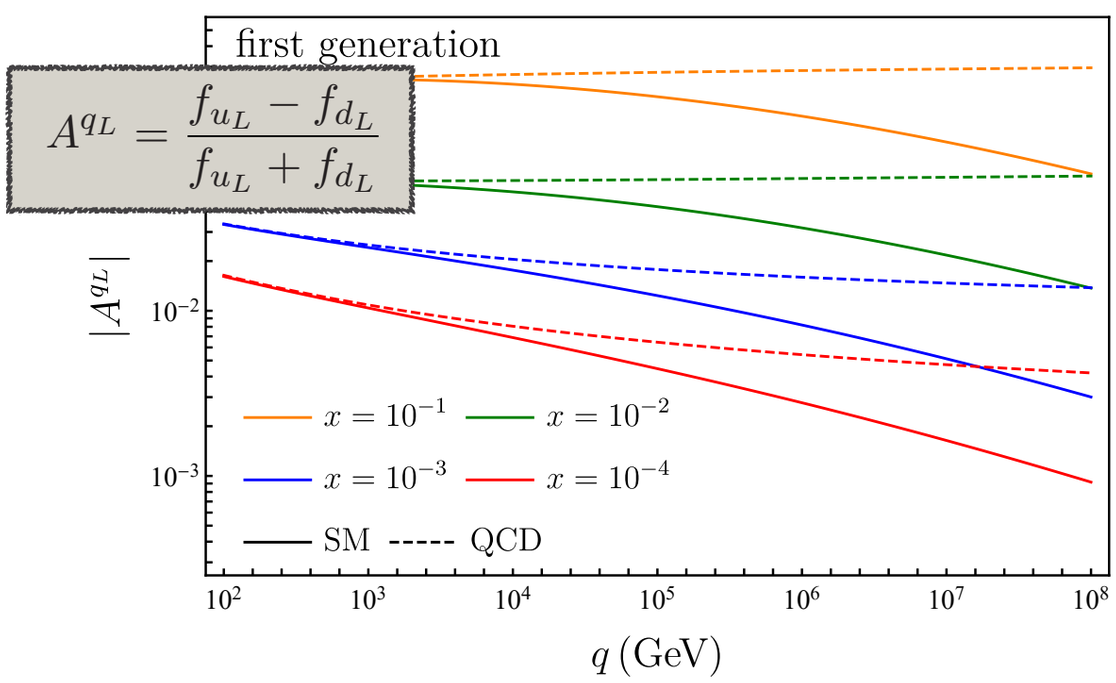
High-Q: the top/EW content of the proton

Very high-Q: top/EW bosons generated by SM collinear evolution → modified QCD evolution [Bauer & Webber (2018-19)]



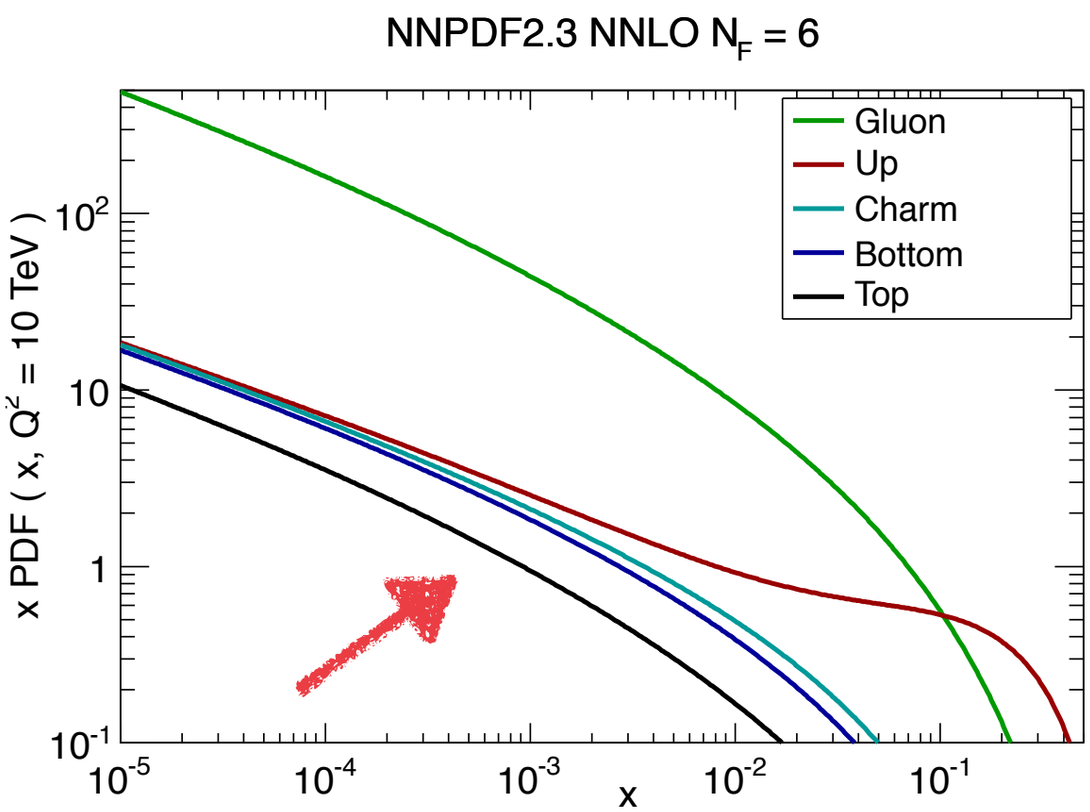


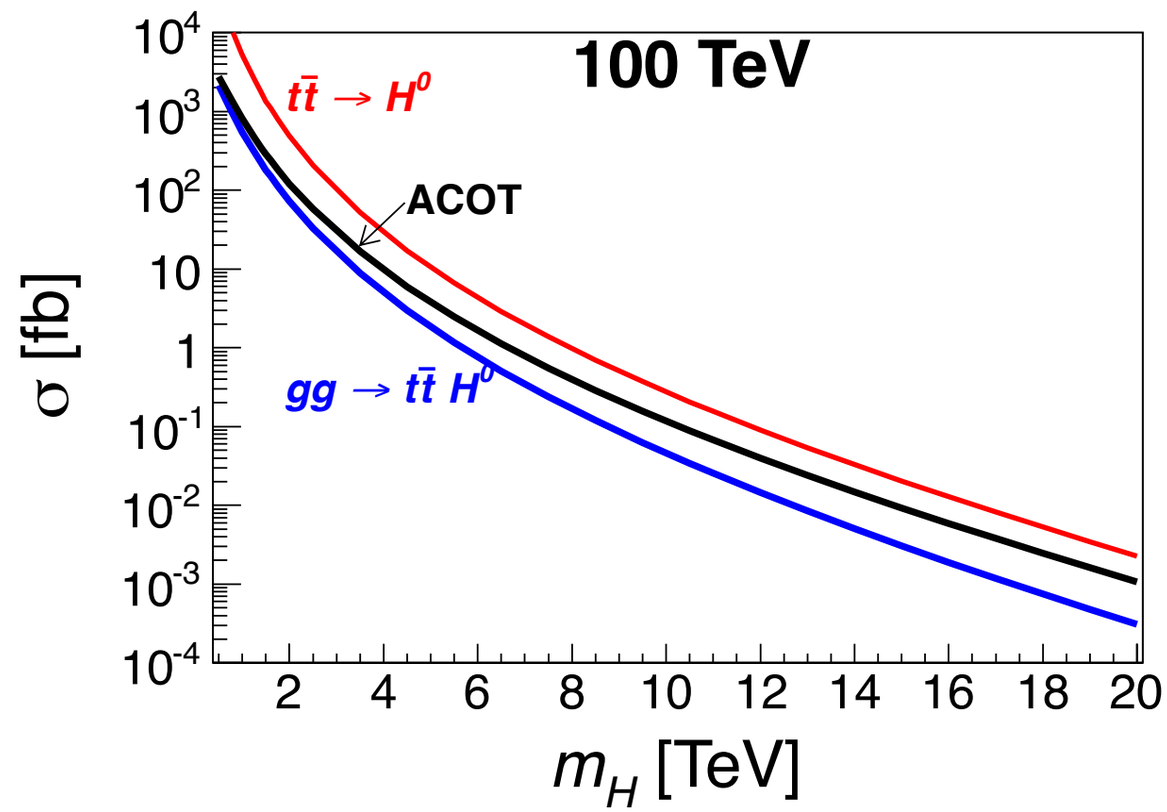


- SM is chiral: L/R difference
- L PDFs: 5-10% correction at 10 TeV
- Sizeable W_L content of the proton
- Isospin restoration
- Higher log: small → robust
- *Ready for thorough phenomenological studies*

High-Q: the top/EW content of the proton

Large-Q top-induced processes: resum $\ln(Q^2/m_t^2)$



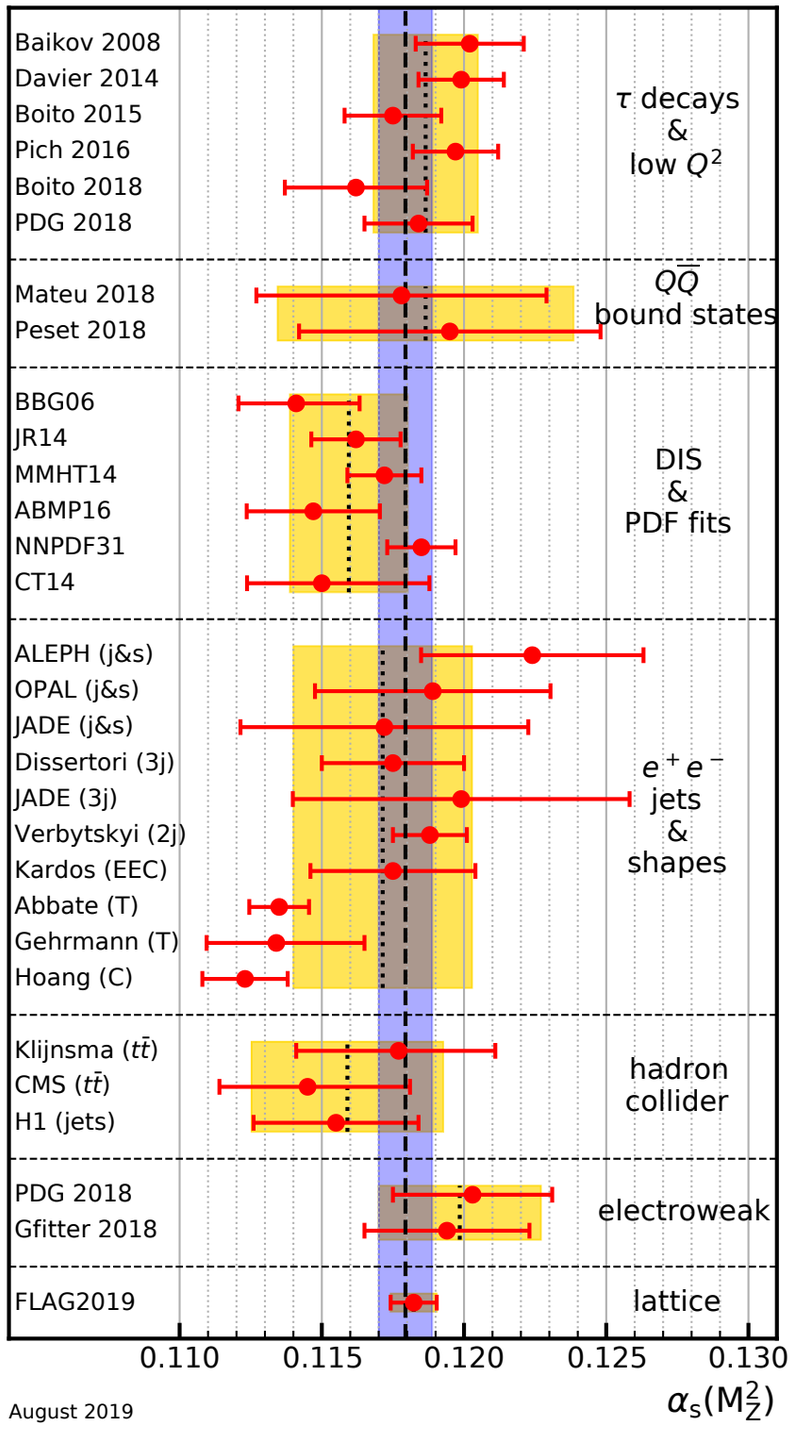


[Han, Sayre, Westhoff (2015)]

- Order-of-magnitude estimate: $m_b/m_H \sim$ 4-5 TeV/m_t
- Top becomes effectively massless at very high-scales → matching is crucial
- Investigating matching/``massive" PDFs: interesting non-trivial problem in QFT…

Parameters: α_s

Current status [PDG2019]

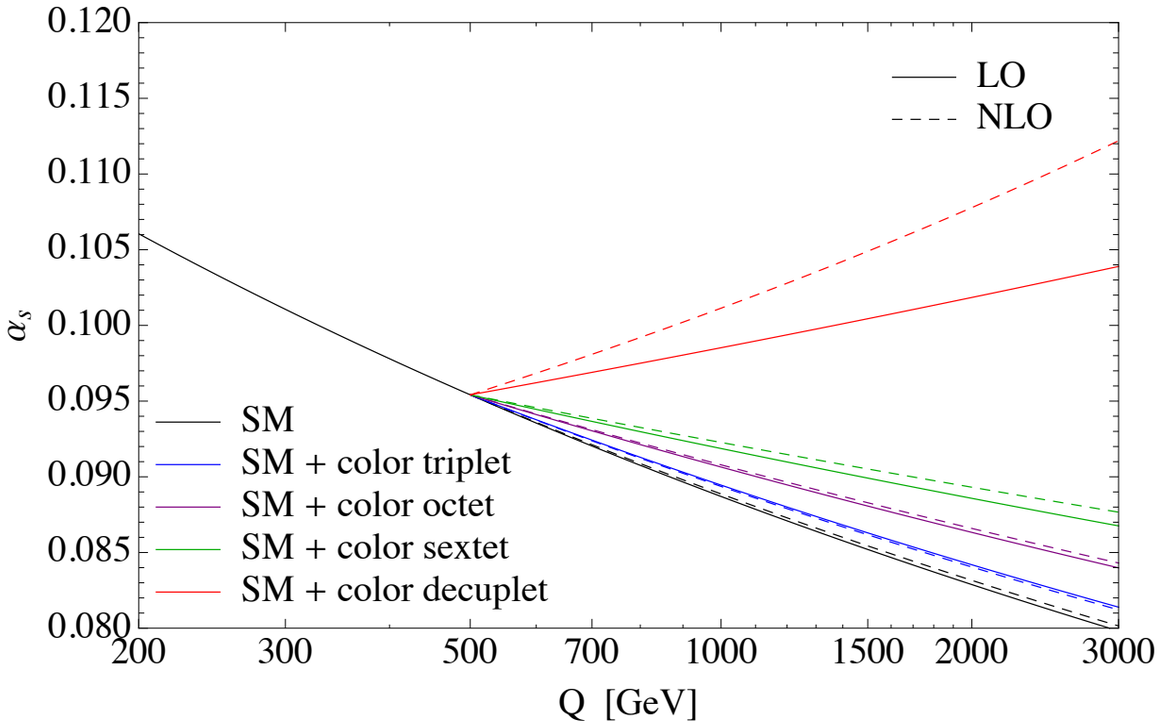


Prospects

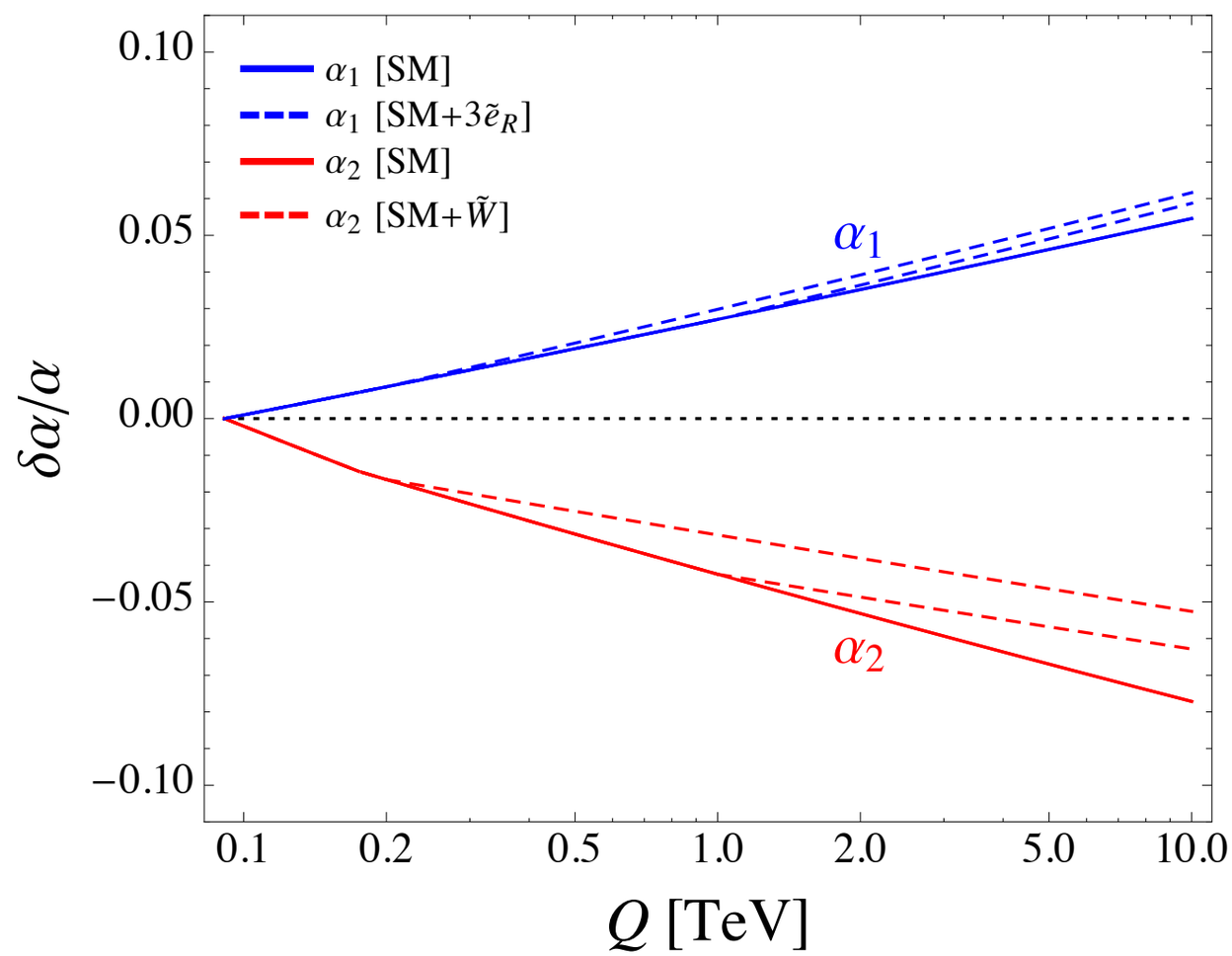
- hadronic decays, global fits → potential to reach 0.15%. QCD-robust, but *some model dependence*
- e^+e^-, event shapes/jet rates → good potential, but remember the LEP lesson
  - Thrust, C parameter: 0.113, 1%
  - Jet rates: 0.119, 1%
  - Must understand better underlying theory (*NP corrections, formally subleading terms…*)
- Hadron collider observables / PDF fits → very high accuracy, but same problems as PDF fits (*low Q contamination, theory uncertainties, correlations with PDFs*)
- Lattice very robust. Most robust determination → new approach. Assuming computer improvements → 0.3%, promising

α as a probe

[Sannino (2015)]



[Alves, Galloway, Ruderman, Walsh (2015)]



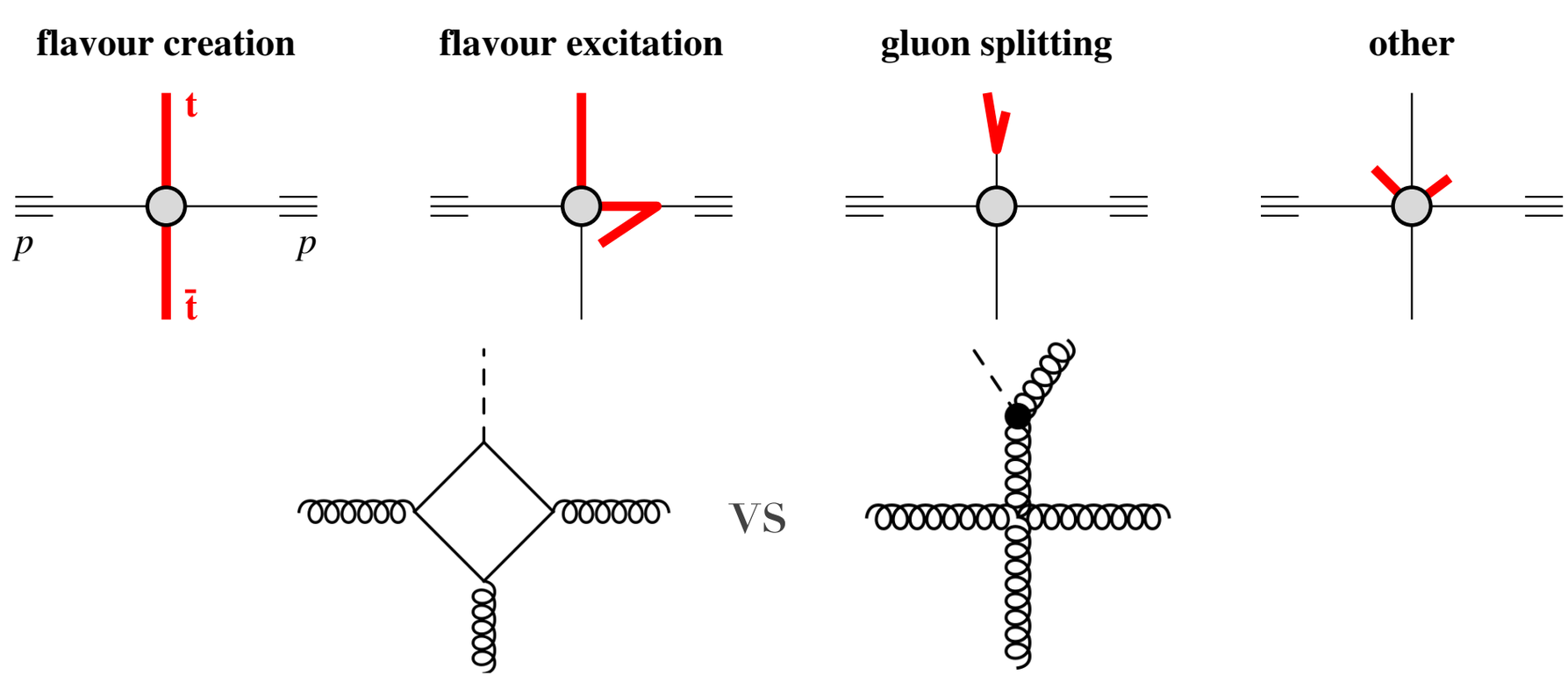
Large Q coverage: test running Coupling → NP in the loops

- Require very good theoretical (and exp) control
- High-mass DY: theoretical uncertainty (*see C. Durh's talk*), QCD-EW interplay
- α_s in the TeV regime: $R_{3/2}$, higher order corrections *(see comment at slide 8)*
- Understanding jet dynamics

Jet dynamics

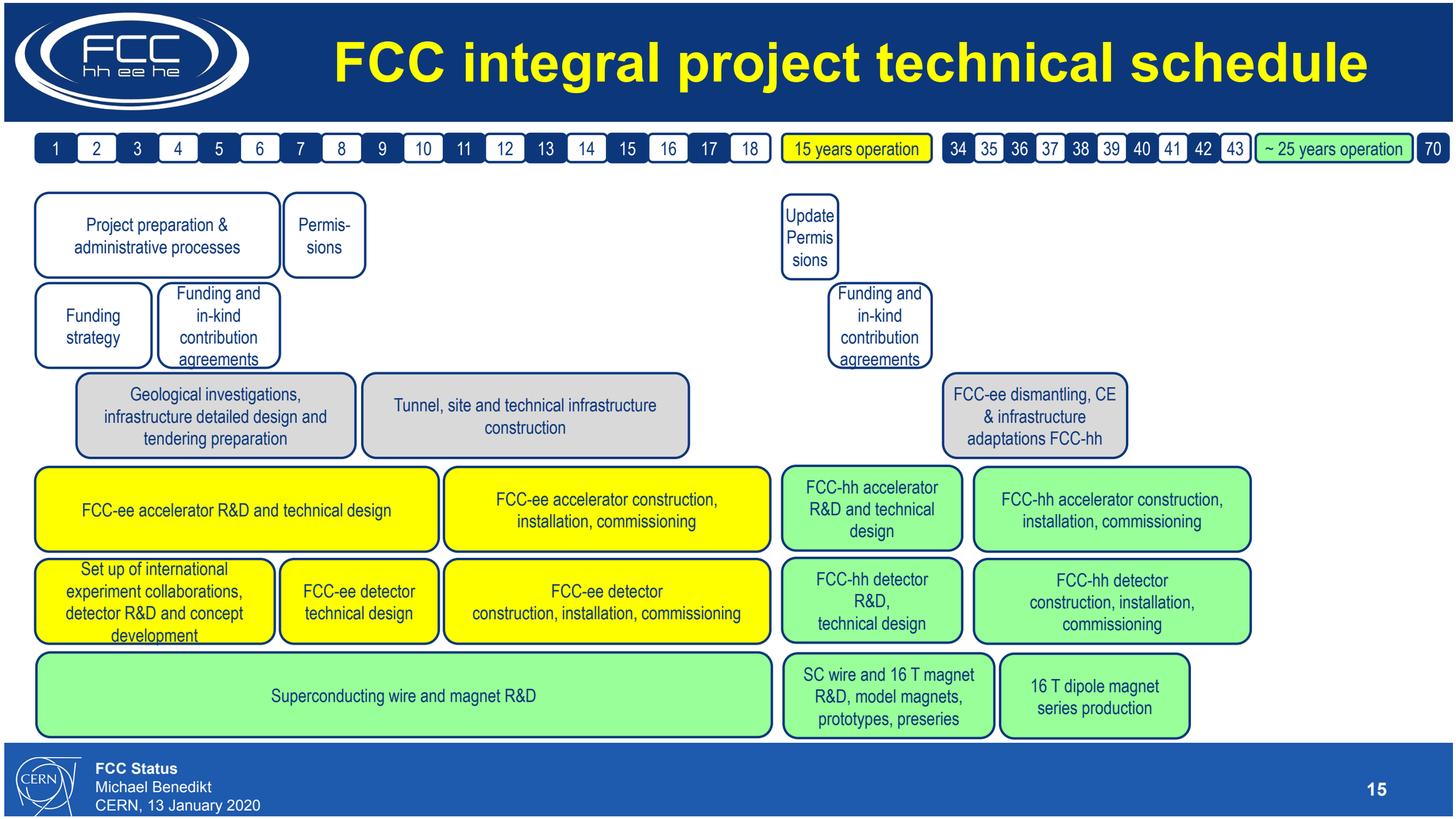
FCC-hh: possible to study jet dynamics through the whole p_t spectrum

- Large-Q: non-standard fragmentation (EW, top, Higgs…) → *see e.g. [Bauer & Webber (2018), Tweedie et al (2017-18)]*
- Examples:

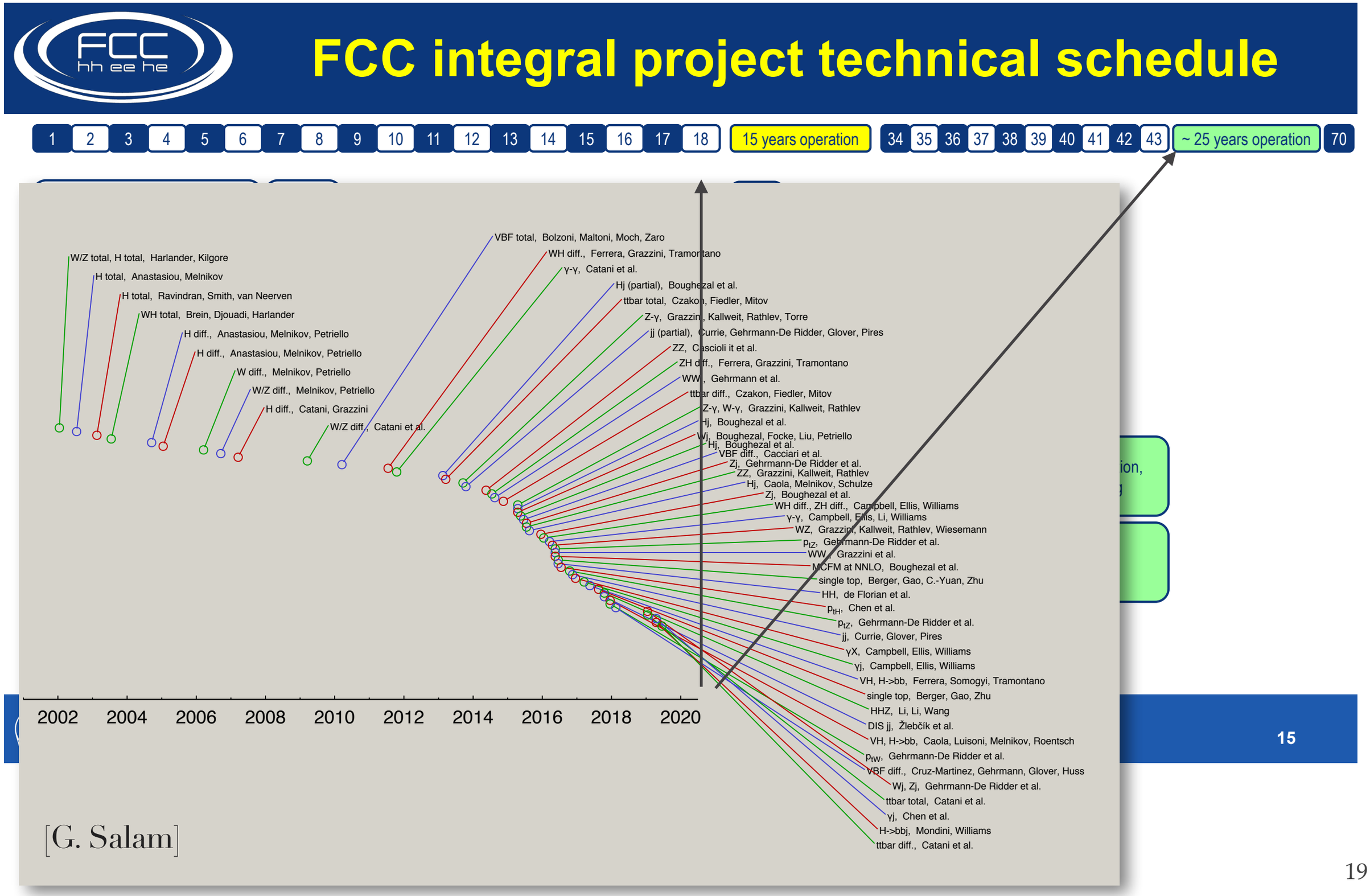


- Would require better pheno understanding, better generators, better calculations…

Intrinsic uncertainties: theory calculations

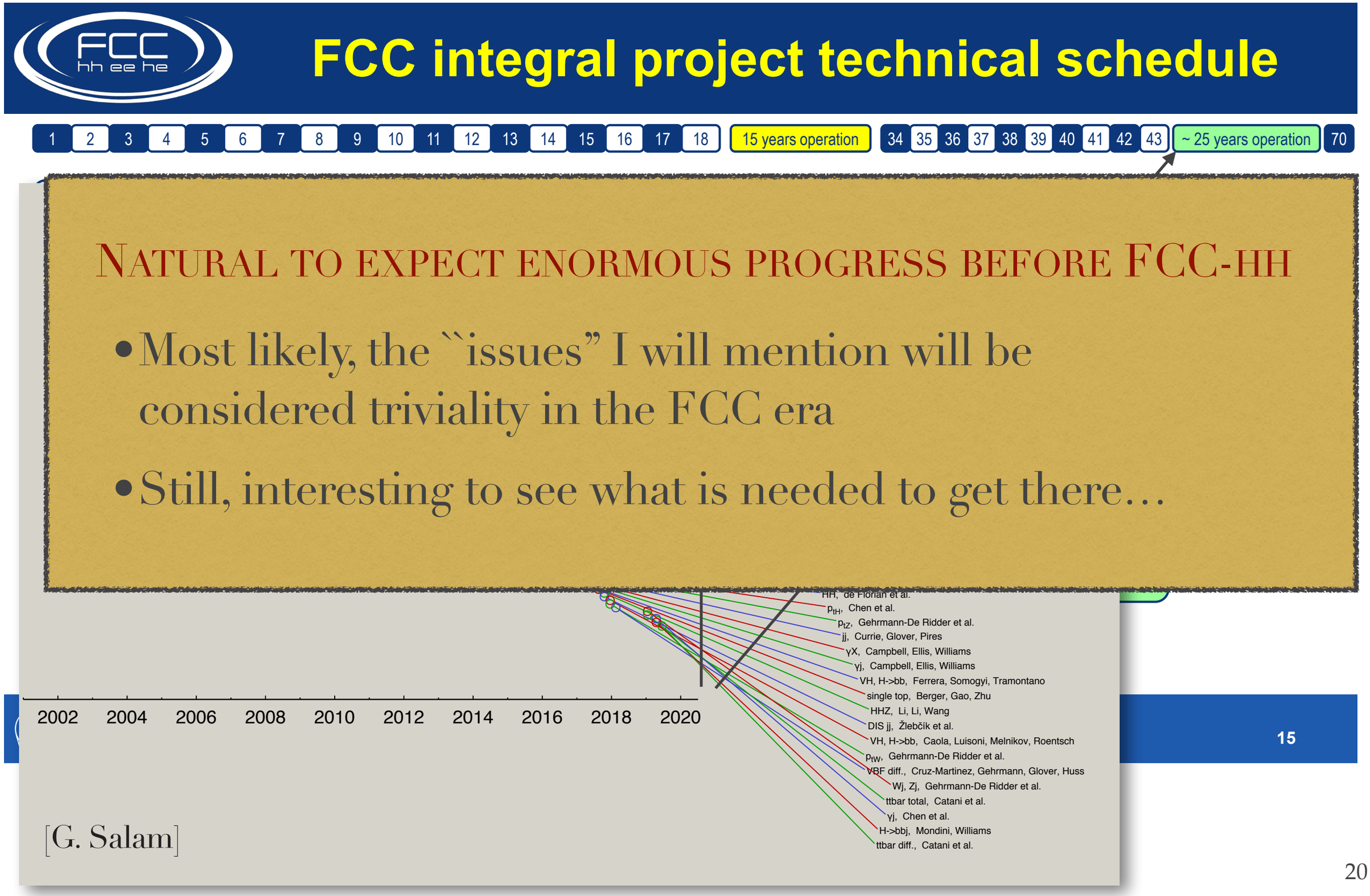


Intrinsic uncertainties: theory calculations



[G. Salam]

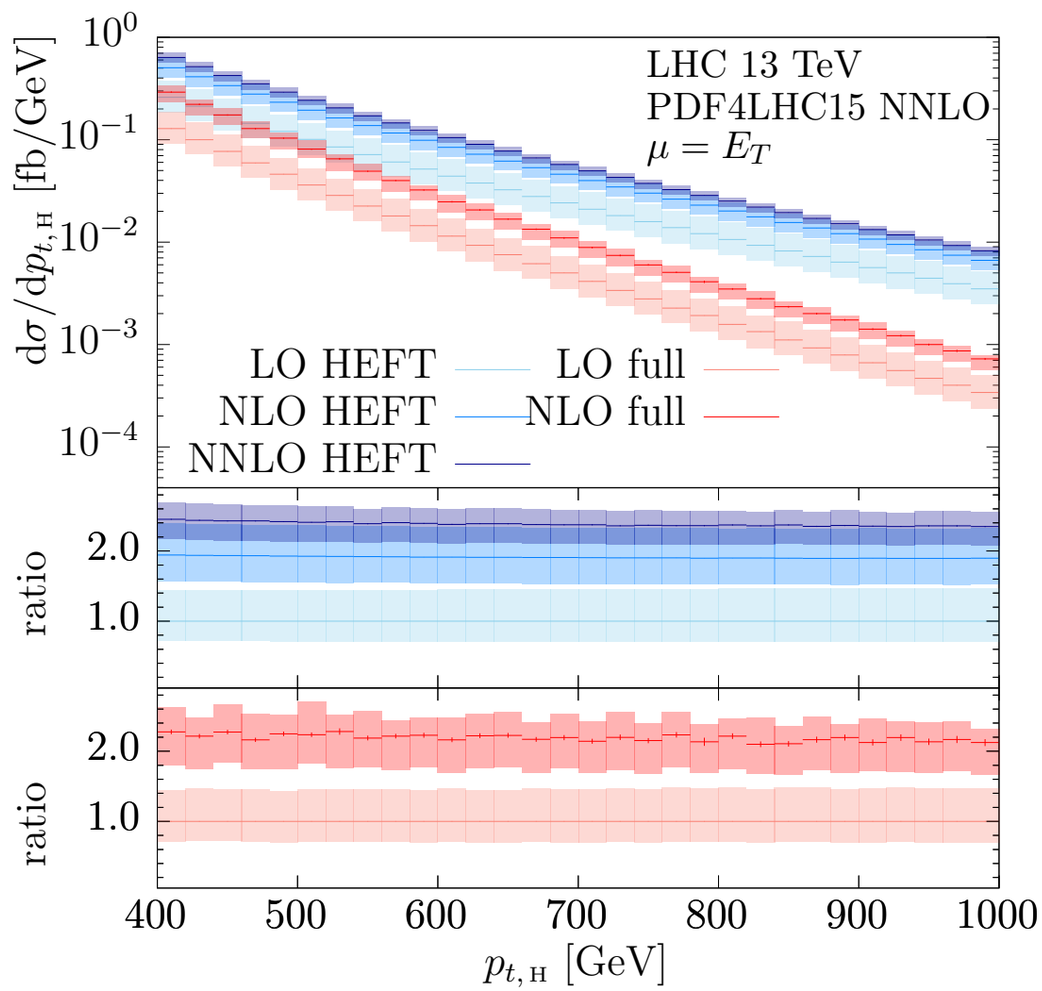
Intrinsic uncertainties: theory calculations



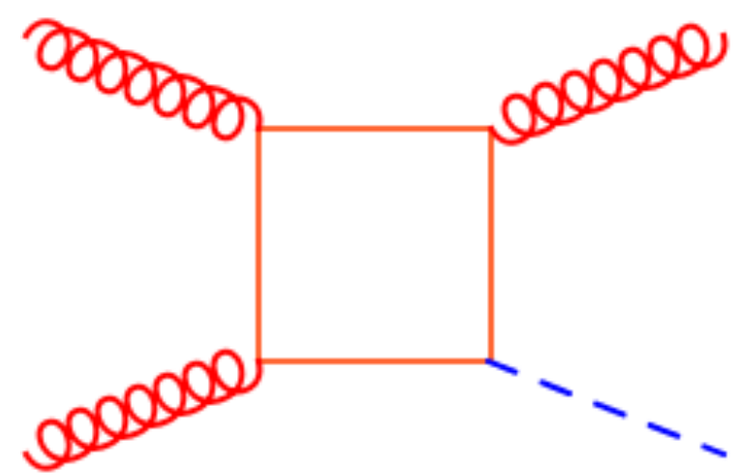
Case study 1: Higgs p_t in ggF

- Prototype of loop induced process *(so I won't consider other channels, even if dominant)*
- Status today, large-Q: NLO, with approximated analytical/exact numerical two-loop amplitude

[Monni et al, lHCXHSWG 2020]



LO



NLO: out of reach of ``standard" analytic techniques *(see C. Duhr's talk)*

Case study 1: Higgs p_t in ggF

Lessons learned:

- No full analytic control → numerical approach [Jones, Kerner, Luisoni (2018)]. Issue: large logs, numerical stability in the TeV region
- Clever use of hierarchies → approximate analytic result [Kudashkin, Melnikov, Tancredi, Wever (2017-18)]. Issue: how to do this systematically?

Recent developments:

- Analytic result as a patch of different series expansion [Frellesvig, Hidding, Maestri, Moriello, Salvatori (2017-18)]. Issue: how does this generalise to multi-scale processes?
- "*AN ANALYTIC RESULT IS A RESULT THAT CAN GIVE A NUMBER*" E. Remiddi

Open questions:

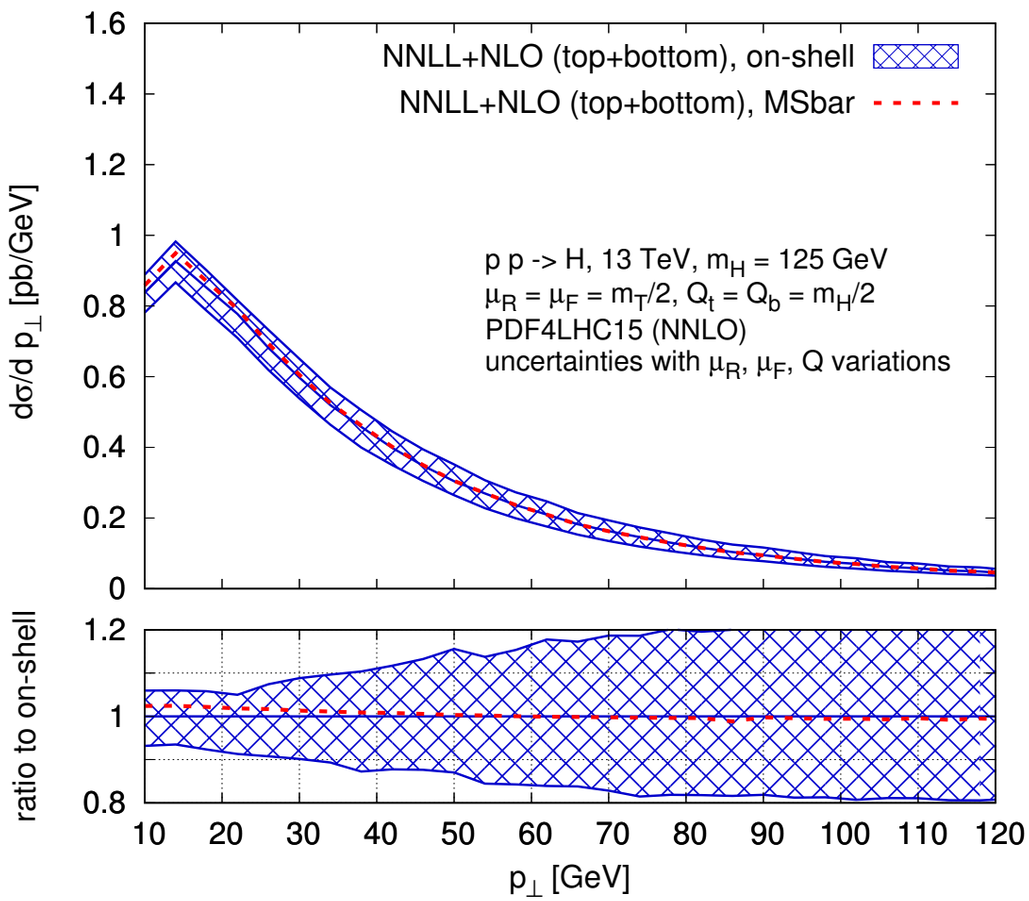
- Large non-Sudakov (double) logarithms, not well understood [Penin, Melnikov, Liu (2017-2019)]. Crucial to obtain analytic insight from analytic results.

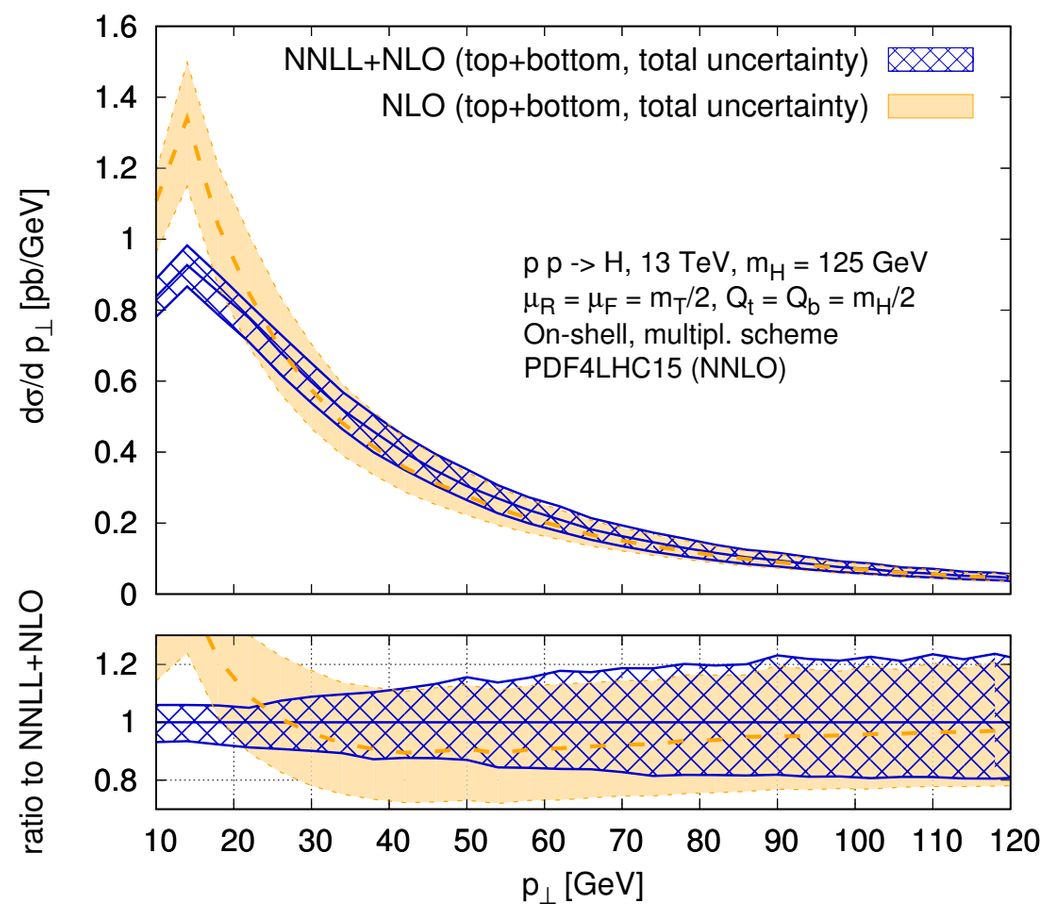
Case study 1: Higgs p_t in ggF

The (likely) biggest uncertainty: top mass scheme

Guidance: bottom effects at LHC_{14}

[FC, Lindert et al (2018)]





Same feature appearing in other processes, e.g. HH [Baglio et al (2019)]

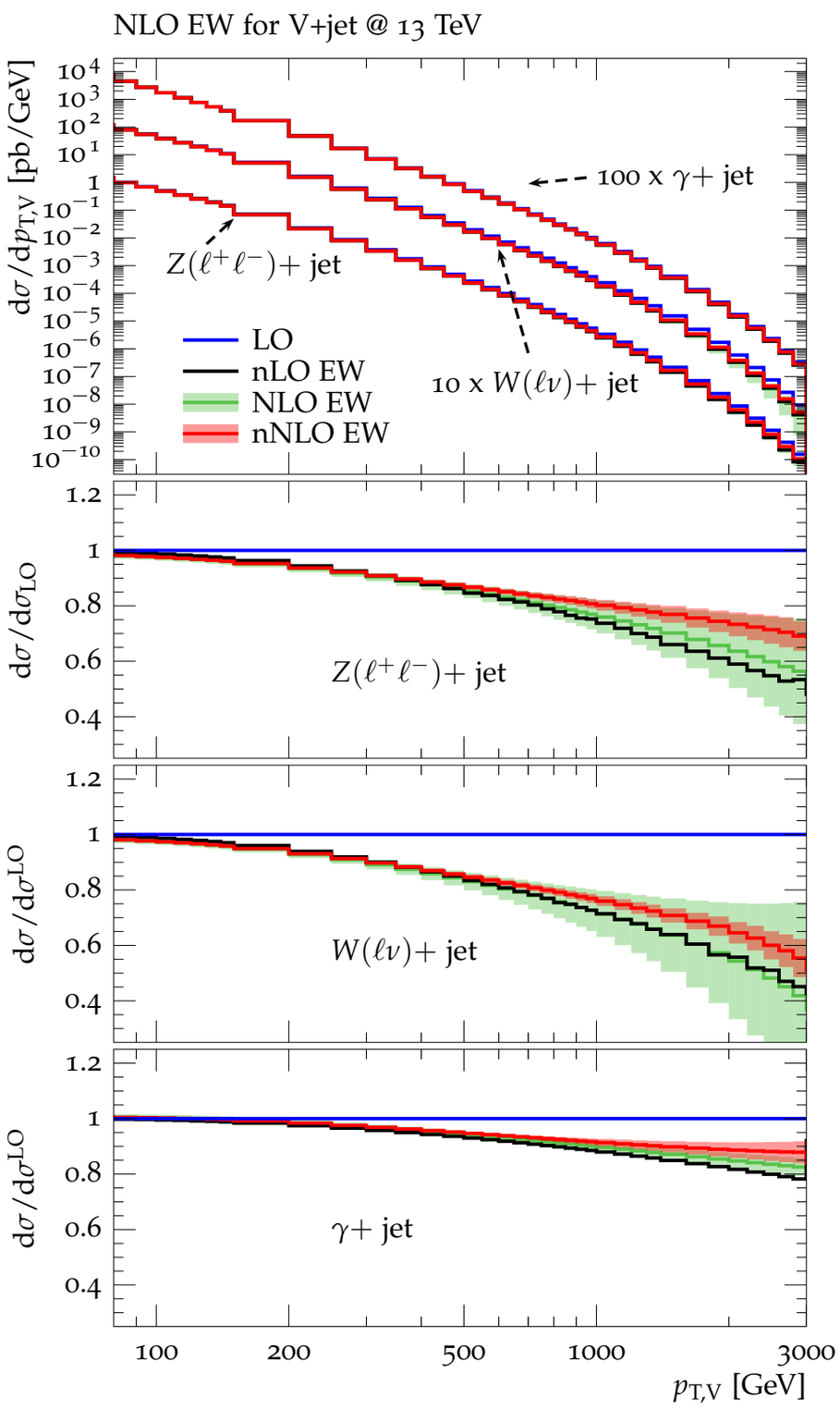
Case study 1: Higgs p_t in ggF

The (likely) biggest uncertainty: top mass scheme

- Genuine perturbative correction, little way out → compute higher orders
- Higher orders: highly non-trivial (we can barely do NLO)
- NNLO = fully differential N^3LO, with full top mass dependence
  - 2 → 2 @ 3 loops, internal masses. Beyond GPLs, two-variable problem → well beyond current analytic techniques
  - 2 → 3 @ 2 loops, internal masses. Same as above, probably even more complicated?
  - Numerical approaches: large logs, stability, many variables…

It will keep us busy for a while, don't hold your breath…

Case study 2: mixed QCD-EW in the tails



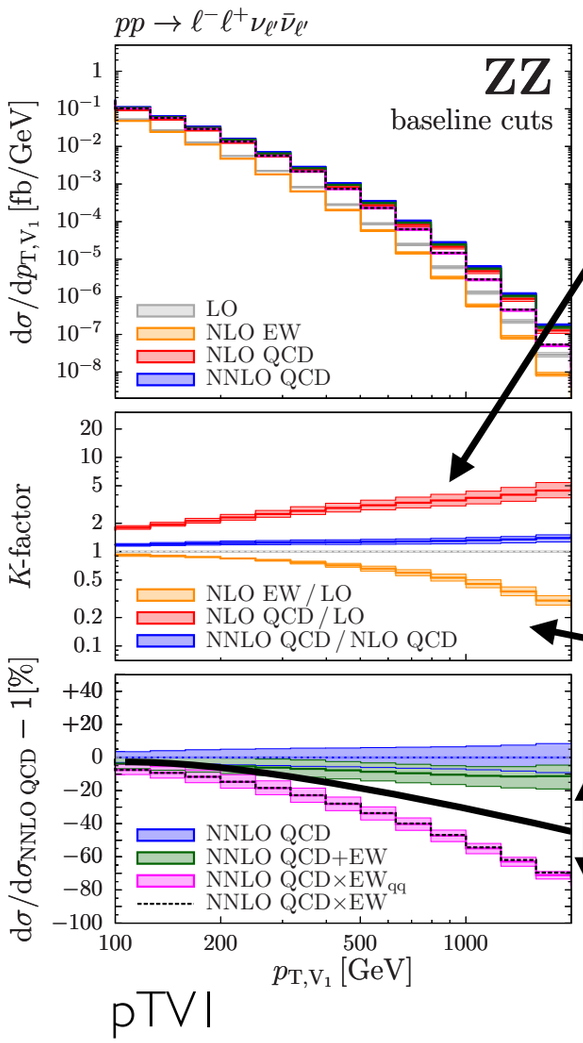
[Lindert et al (2017)]

- High-Q: electroweak Sudakov (double) logs → enhanced EW corrections
- First approximation: trivial interplay with QCD (fully factorized)
- We may want to go beyond this approximation. Currently: major source of theoretical uncertainty for high p_T V production (DM searches…)
- Tools are becoming available: thorough study of QCDxEW corrections for standard candles within reach (quantify Sudakov…)

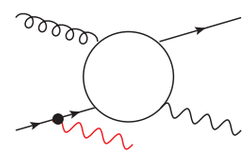
Case study 2: mixed QCD-EW in the tails

[J. Lindert, talk at the XXVI Epiphany Conference, January 2020]

Giant QCD K-factors and EW corrections: pTV1



- NLO QCD/LO=2-5! ("giant K-factor" [Rubin, Salam, Sapeta,'10])
- at large pTV1: VV phase-space is dominated by V+jet (w/ soft V radiation)



$$\frac{d\sigma^{V(V)j}}{d\sigma^{\rm LO}_{VV}} \propto \alpha_S \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \qquad \text{at} \quad Q = 1\,\text{TeV}$$

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%
- Very large difference $d\sigma_{\rm NNLO\ QCD+EW}$ vs. $d\sigma_{\rm NNLO\ QCD\times EW}$
- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process
- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW

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- First results appearing → thorough phenomenological studies are starting
- Problems are being identified → input for FCC-hh discussion

Conclusions

- FCC-hh offers a unique opportunity to study the multi-TeV region
- Despite high-Q being ``clean" w.r.t. QCD, several sources of non-trivial theoretical uncertainty
- High-Q: uncertainties different from EW region → different problems, different techniques
- In some cases, way forward is clear. In other not so much (as of now…)
- I presented SOME EXAMPLES of potentially important issue to be addressed. Choice due to time constraints and personal ignorance
- In general: highly non-trivial theoretical problems, that would most likely require developing further our understanding of QFT and collider phenomenology → *interesting times ahead!*

Thank you very much!