Les Houches 2021: jj, VV, V+j status and bottlenecks

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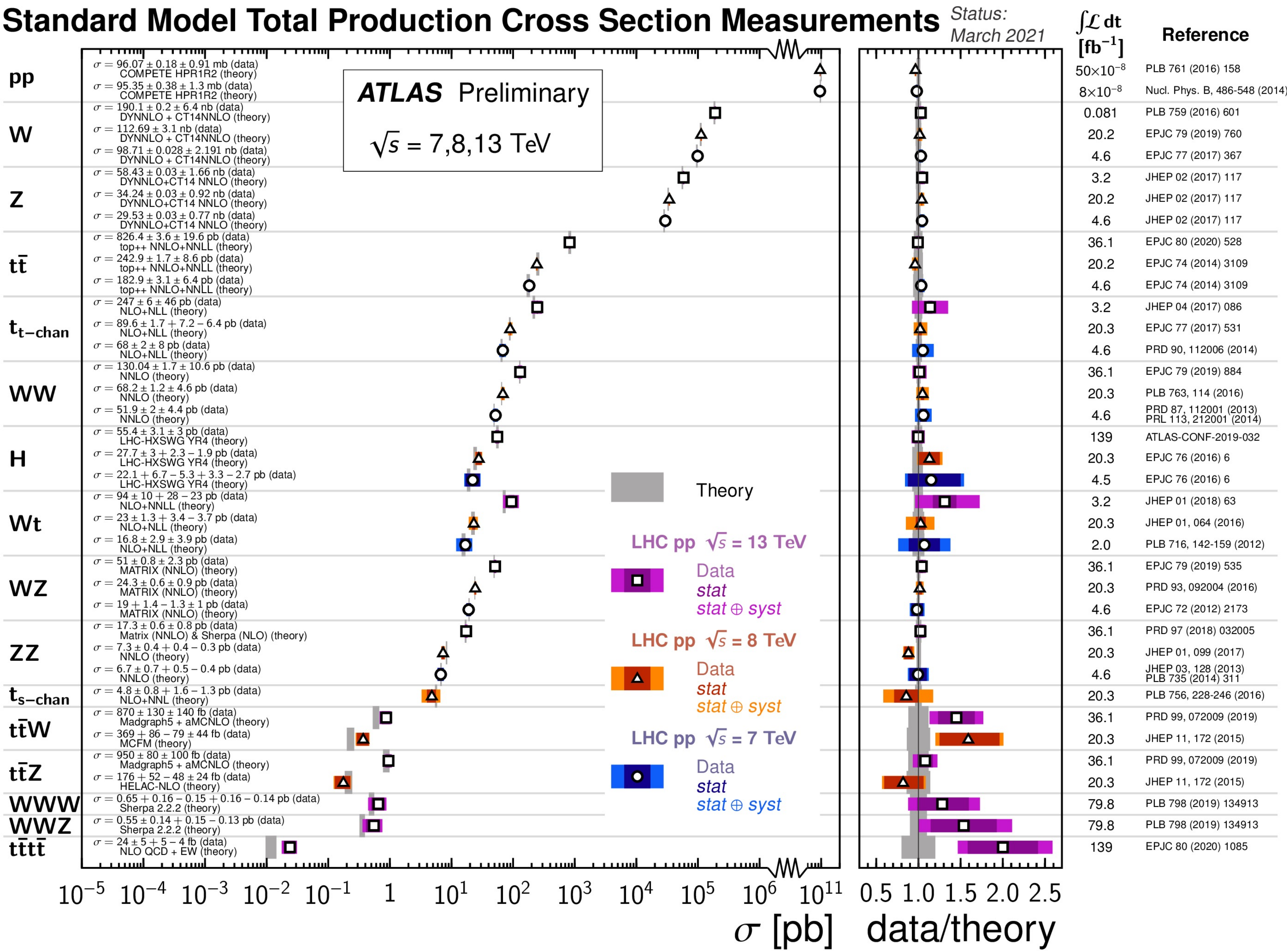
Les Houches online

June 15, 2021

The Path to Precision

- It’s clear by now that copious new physics isn’t jumping out at us
- In order to better understand the SM, and look for something beyond, we have to extend our precision (as well as our kinematic reach)
- This may involve improvements on both the theoretical and experimental fronts, for example
    - measurements of photons, leptons, jets, boosted objects
    - extension of NNLO to 2->3 processes
    - (more) inclusion of EW effects
    - more precise PDFs, better understanding of precision of PDFs, and of $\alpha_s(m_Z)$

This is generic for basically all processes at the LHC, but I will be concentrating on the ones assigned.



Standard Model Total Production Cross Section Measurements
Status: March 2021
ATLAS Preliminary
√s = 7,8,13 TeV
∫ℒ dt [fb⁻¹]
Reference
pp
σ = 96.07 ± 0.18 ± 0.91 mb (data) COMPETE HPR1R2 (theory) 50×10⁻⁸ PLB 761 (2016) 158
σ = 95.35 ± 0.38 ± 1.3 mb (data) COMPETE HPR1R2 (theory) 8×10⁻⁸ Nucl. Phys. B, 486-548 (2014)
W
σ = 190.1 ± 0.2 ± 6.4 nb (data) DYNNLO + CT14NNLO (theory) 0.081 PLB 759 (2016) 601
σ = 112.69 ± 3.1 nb (data) DYNNLO + CT14NNLO (theory) 20.2 EPJC 79 (2019) 760
σ = 98.71 ± 0.028 ± 2.191 nb (data) DYNNLO + CT14NNLO (theory) 4.6 EPJC 77 (2017) 367
Z
σ = 58.43 ± 0.03 ± 1.66 nb (data) DYNNLO+CT14 NNLO (theory) 3.2 JHEP 02 (2017) 117
σ = 34.24 ± 0.03 ± 0.92 nb (data) DYNNLO+CT14 NNLO (theory) 20.2 JHEP 02 (2017) 117
σ = 29.53 ± 0.03 ± 0.77 nb (data) DYNNLO+CT14 NNLO (theory) 4.6 JHEP 02 (2017) 117
tt̄
σ = 826.4 ± 3.6 ± 19.6 pb (data) top++ NNLO+NNLL (theory) 36.1 EPJC 80 (2020) 528
σ = 242.9 ± 1.7 ± 8.6 pb (data) top++ NNLO+NNLL (theory) 20.2 EPJC 74 (2014) 3109
σ = 182.9 ± 3.1 ± 6.4 pb (data) top++ NNLO+NNLL (theory) 4.6 EPJC 74 (2014) 3109
t t−chan
σ = 247 ± 6 ± 46 pb (data) NLO+NLL (theory) 3.2 JHEP 04 (2017) 086
σ = 89.6 ± 1.7 + 7.2 − 6.4 pb (data) NLO+NLL (theory) 20.3 EPJC 77 (2017) 531
σ = 68 ± 2 ± 8 pb (data) NLO+NLL (theory) 4.6 PRD 90, 112006 (2014)
WW
σ = 130.04 ± 1.7 ± 10.6 pb (data) NNLO (theory) 36.1 EPJC 79 (2019) 884
σ = 68.2 ± 1.2 ± 4.6 pb (data) NNLO (theory) 20.3 PLB 763, 114 (2016)
σ = 51.9 ± 2 ± 4.4 pb (data) NNLO (theory) 4.6 PRD 87, 112001 (2013) PRL 113, 212001 (2014)
H
σ = 55.4 ± 3.1 ± 3 pb (data) LHC-HXSWG YR4 (theory) 139 ATLAS-CONF-2019-032
σ = 27.7 ± 3 + 2.3 − 1.9 pb (data) LHC-HXSWG YR4 (theory) 20.3 EPJC 76 (2016) 6
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data) LHC-HXSWG YR4 (theory) 4.5 EPJC 76 (2016) 6
Wt
σ = 94 ± 10 + 28 − 23 pb (data) NLO+NNLL (theory) 3.2 JHEP 01 (2018) 63
σ = 23 ± 1.3 + 3.4 − 3.7 pb (data) NLO+NLL (theory) 20.3 JHEP 01, 064 (2016)
σ = 16.8 ± 2.9 ± 3.9 pb (data) NLO+NLL (theory) 2.0 PLB 716, 142-159 (2012)
WZ
σ = 51 ± 0.8 ± 2.3 pb (data) MATRIX (NNLO) (theory) 36.1 EPJC 79 (2019) 535
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory) 20.3 PRD 93, 092004 (2016)
σ = 19 + 1.4 − 1.3 ± 1 pb (data) MATRIX (NNLO) (theory) 4.6 EPJC 72 (2012) 2173
ZZ
σ = 17.3 ± 0.6 ± 0.8 pb (data) Matrix (NNLO) & Sherpa (NLO) (theory) 36.1 PRD 97 (2018) 032005
σ = 7.3 ± 0.4 + 0.4 − 0.3 pb (data) NNLO (theory) 20.3 JHEP 01, 099 (2017)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory) 4.6 JHEP 03, 128 (2013) PLB 735 (2014) 311
t s−chan
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data) NLO+NNL (theory) 20.3 PLB 756, 228-246 (2016)
tt̄W
σ = 870 ± 130 ± 140 fb (data) Madgraph5 + aMCNLO (theory) 36.1 PRD 99, 072009 (2019)
σ = 369 + 86 − 79 ± 44 fb (data) MCFM (theory) 20.3 JHEP 11, 172 (2015)
tt̄Z
σ = 950 ± 80 ± 100 fb (data) Madgraph5 + aMCNLO (theory) 36.1 PRD 99, 072009 (2019)
σ = 176 + 52 − 48 ± 24 fb (data) HELAC-NLO (theory) 20.3 JHEP 11, 172 (2015)
WWW
σ = 0.65 + 0.16 − 0.15 + 0.16 − 0.14 pb (data) Sherpa 2.2.2 (theory) 79.8 PLB 798 (2019) 134913
WWZ
σ = 0.55 ± 0.14 + 0.15 − 0.13 pb (data) Sherpa 2.2.2 (theory) 79.8 PLB 798 (2019) 134913
tt̄tt̄
σ = 24 ± 5 + 5 − 4 fb (data) NLO QCD + EW (theory) 139 EPJC 80 (2020) 1085
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory

Theoretical predictions

Theory must reach comparable precision target

Sotnikov RadCor/Loopfest 21

NNLO QCD and NLO EW corrections generally required

($\oplus$ parton shower, resummation, etc.)

$$\sigma \sim \overbrace{\underbrace{\sigma_{\mathrm{LO}}\Big(1+\alpha_s\sigma^{(1)}}_{\mathrm{NLO}}+\alpha_s^2\sigma^{(2)}}^{\mathrm{NNLO}}+\mathcal{O}(\alpha_s^3)\Big)$$

naively $\lesssim$ 1%

NB: both EW and non-perturbative corrections can be similar size to NNLO corrections;

…in addition to the calculation of higher order matrix elements, also need precision for PDFs and for $\alpha_s(m_Z)$

…where there is a restriction of phase space, need resummation

…where possible, need a translation into a form that may be more amenable to experimental comparison, i.e. ME+PS

…Les Houches accord/concensus: ME+PS predictions should agree with underlying fixed order prediction in non-Sudakov regions

Partial list of SM-related topics for LH21

Techniques and calculations for SM phenomenology:

` * Calculations:

- expected precision for fundamental Standard Model processes at 14 and 100 TeV; what calculations are needed to match this precision?
- 2→3 at NNLO; status/challenges/prospects   e.g. 3 jets at NNLO
- theory uncertainties; more rigorous estimates? correlations?
- theoretically sound definition of FONLL at the differential level, beyond incl. cross sections?

- PDFs:
  - followup on PDF4LHC15 benchmarking exercise; better understanding of tolerances, tensions   in progress
  - EW corrections/EW PDFs; how to provide consistent calculations
  - small x resummation; what is HERA trying to tell us?
  - EIC; what will EIC tell us? how do we prepare for that?

N3LO PDFs: how much do we need them and how do we get there?

- Higgs:
  - understanding the SM for high Higgs pT; role of top mass corrections/scheme (MSbar vs on-shell); improving channel sensitivities
  - polarisation measurements (for diboson/VBS as well)

- Top:
  - MSbar vs on-shell
  - ttW; tension; can new calculations resolve it?

- Jets:
  - flavor tagging of jets; matching what theorists can predict (IR safety) and what experimentalists can measure

e.g. W+c

Les Houches isn't occurring in a vacuum

Snowmass LOI Les Houches Wishlist:

T. Hobbs, A. Huss, J. Huston, S. Jones, S. Kallweit

August 31 2020

Contact: J. Huston, huston@msu.edu

In this LOI, we propose a coherent program between Les Houches 2021 and Snowmass21 to explore the higher-order calculations needed for 33/100 TeV and a projection of the technical capabilities available by that time. Experience at 13 TeV, and that expected at the HL-LHC, will be crucial in this extrapolation. The calculations needed will depend not only on the experimental errors expected, but the impact of higher order corrections at these higher energies.

1 Introduction

One of the legacies of the Les Houches workshops has been the precision standard model wishlist [1, 2]. This is an attempt to (1) summarize the start of the art for higher order QCD and EW calculations and (2) to determine the calculations needed for the full exploitation of the full-luminosity LHC. This list includes calculations that may not necessarily be accessible with current-day techniques, but that can be obtained in a reasonable time frame, given sufficient theoretical effort. The justification for the effort is the expected statistical and systematic precision of the relevant experimental measurements, and the importance of better theoretical predictions for those measurements.

Given the longer-term nature of the wishlist (2040), it seems natural to fit it into the Snowmass21 framework, by extending the scope to physics expected at a 33 or 100 TeV collider. This can also be considered the extension of the work conducted in Snowmass13 [3]. The higher energies allow for an extension of the kinematic reach, for example, for a high p_T Higgs boson to a region where new physics effects may become evident. Cross sections below the kinematic edge may reach a 1% or better precision. Scales well above the W/Z boson mass will result in the importance of higher order EW corrections, as well as combined QCD+EW corrections. QCD calculations at N^3LO will require PDFs at a similar order, as well as a combined QCD+EW evolution of these PDFs. The treatment of W/Z bosons, as well as top quarks, as partons present in the proton may become necessary.

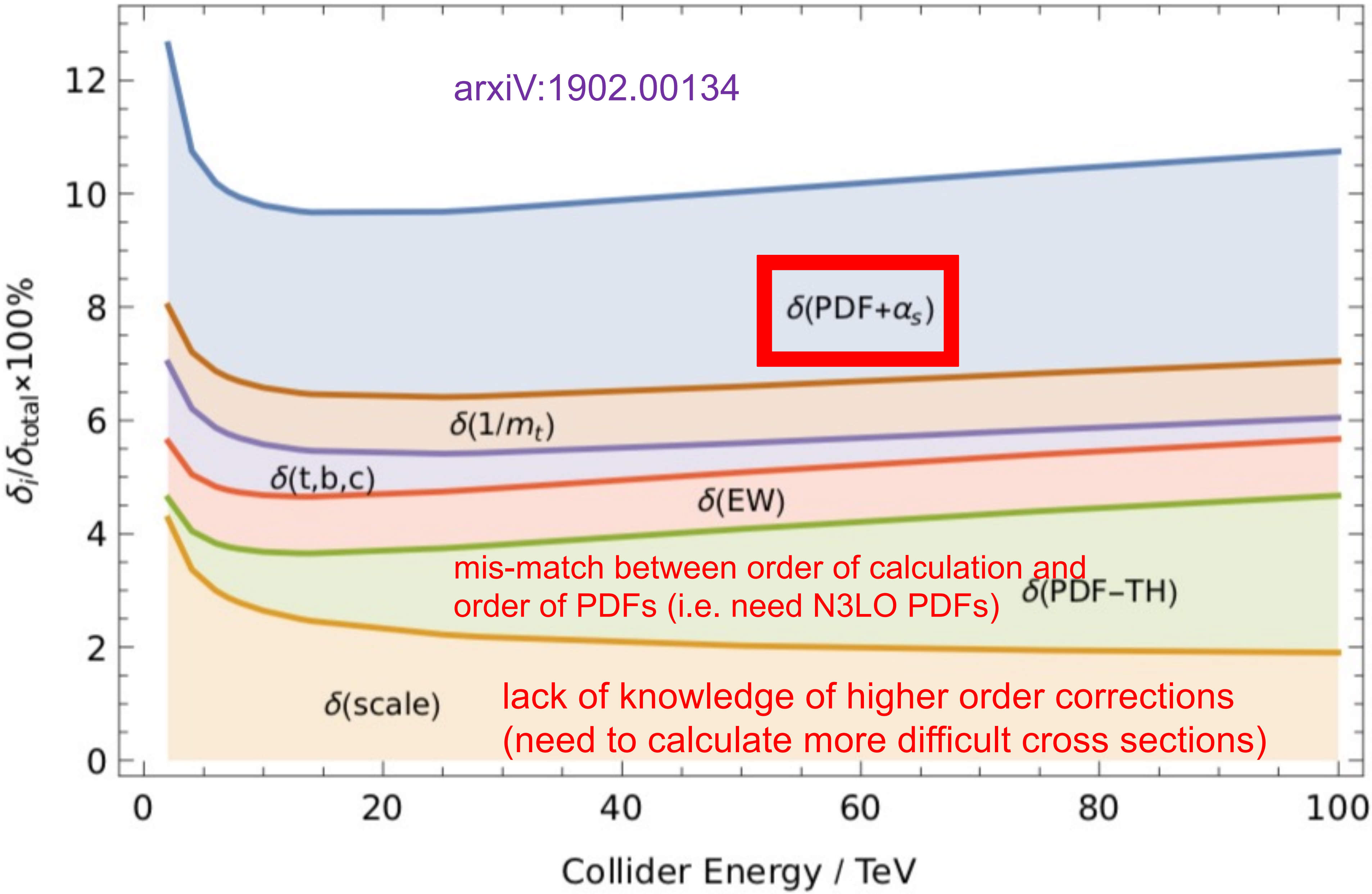
Another future accelerator that will require increased theoretical precision is the Electron-Ion-Collider (EIC), where higher-order $\alpha_s(m_Z)$ and electroweak corrections will have to be well-understood. Data taken at the EIC will also have the potential to provide more precise PDF information, both at $x \gtrsim 10^{-4}$ as well as high x, that will be crucial for precision predictions at a 33 or 100 TeV collider. The greater objective is to generalize beyond 1-D distributions, so further theoretical effort is required to develop factorization theorems, especially for robust extraction and interpretation of multi-dimensional distributions like TMDs and GPDs.

…in particular, there is a lot of overlap with what people are trying to accomplish in the Snowmass exercise (soon to arise from its 6-month slumber)

EF05: Precision QCD

EF06: Hadronic Structure and Forward QCD

Uncertainties (for ggF Higgs)



$\alpha_s(m_Z)$ uncertainties

importance of α_s uncertainties depends on order of calculation, so very important for Higgs through ggF at N3LO

- LO $\equiv \mathcal{O}(1)$,
- NLO QCD $\equiv \mathcal{O}(\alpha_s)$,
- NNLO QCD $\equiv \mathcal{O}(\alpha_s^2)$,
- NLO EW $\equiv \mathcal{O}(\alpha)$,
- NNNLO QCD $\equiv \mathcal{O}(\alpha_s^3)$,
- NNLO QCD+EW $\equiv \mathcal{O}(\alpha_s \alpha)$.

$$\alpha_s(M_Z^2) = 0.1176 \pm 0.0011\,, \qquad \text{(without lattice)}$$

$$\alpha_s(M_Z^2) = 0.1182 \pm 0.0008\,, \qquad \text{(lattice)}$$

$$\alpha_s(M_Z^2) = 0.1179 \pm 0.0010\,.$$

My opinion is that precision of lattice will improve faster than non-lattice.

2019; 2021 update underway

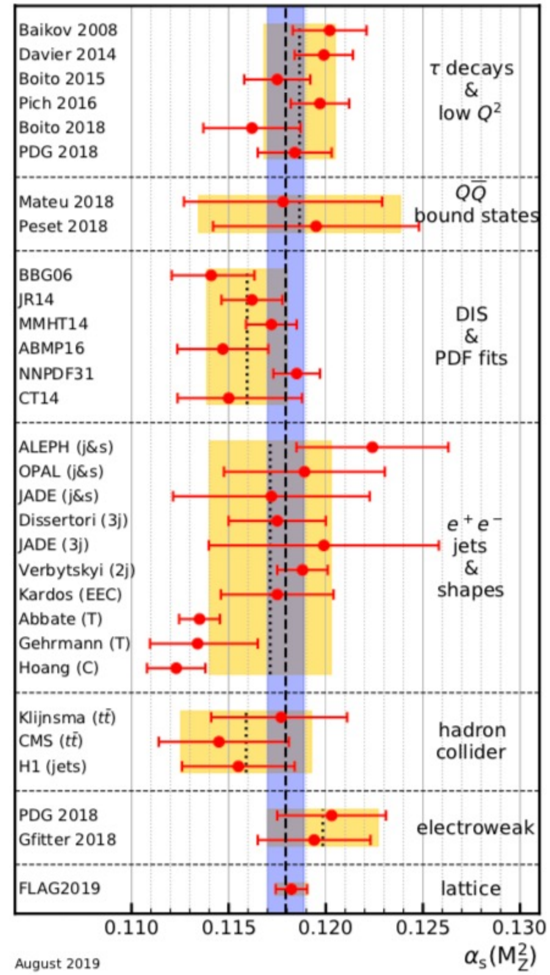


Figure 9.2: Summary of determinations of $\alpha_s(M_Z^2)$ from the seven sub-fields discussed in the text. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$.

PDFs

- Determined from global fits to data from a wide variety of processes, both from fixed target and collider experiments, with an increasing contribution from the LHC itself
- The 3 groups are CTEQ-TEA (CT), MSHT (new acronym) and NNPDF
- Each uses on order of 4000 data points to determine the best fit PDFs and their uncertainties
  - with CT and MSHT using a Hessian formalism and NNPDF using a neural net formalism
- Each group provides regularly updated sets of PDFs → to better understand similarities and differences, it is useful to periodically perform benchmarking exercises

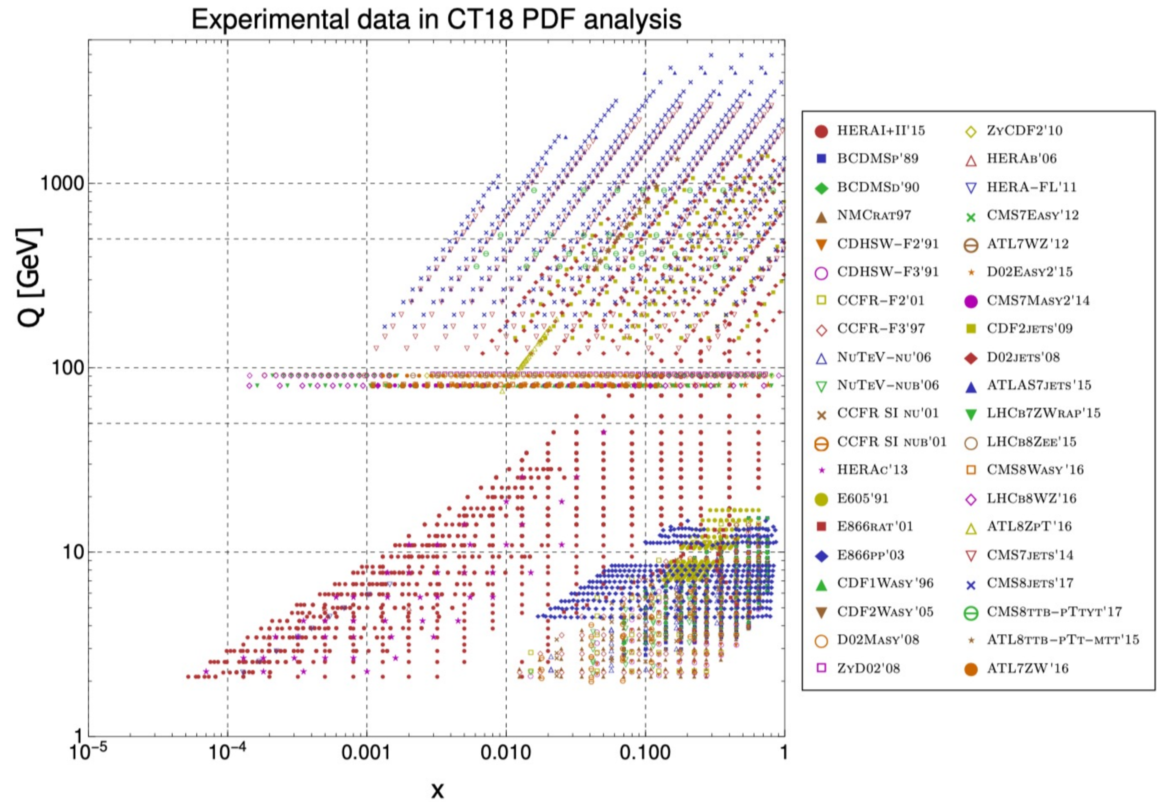


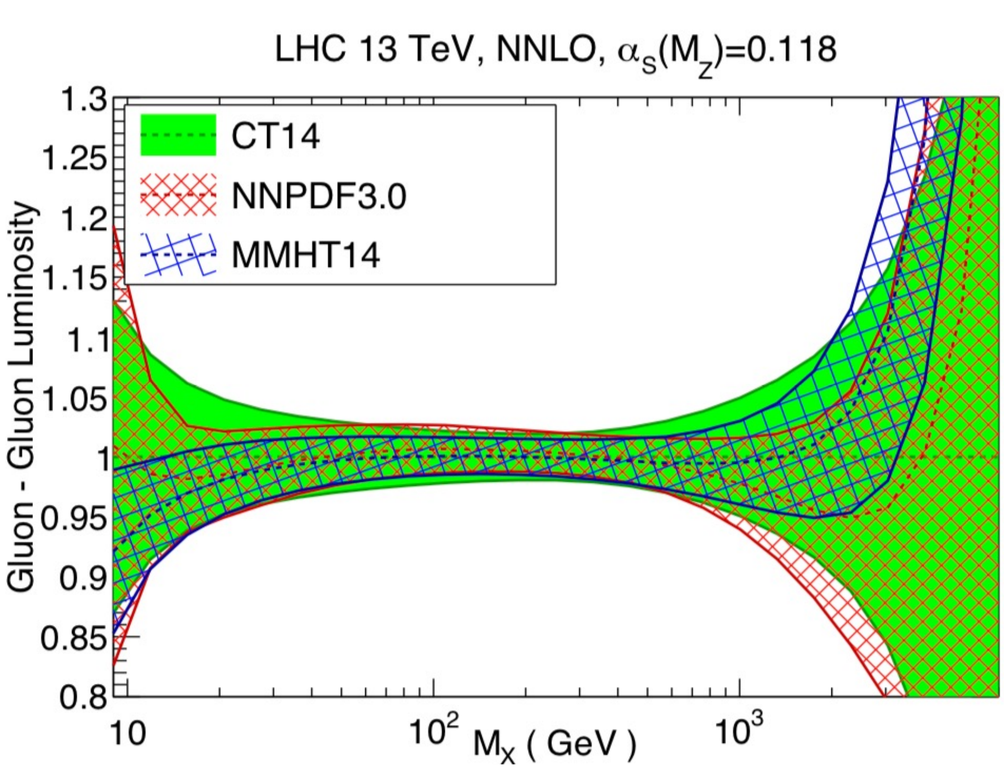
FIG. 1: The CT18 data set, represented in a space of partonic (x, Q), based on Born-level kinematical matchings, $(x, Q) = (x_B, Q)$, in DIS, *etc.*. The matching conventions used here are described in Ref. [20]. Also shown are the ATLAS 7 TeV W/Z production data (ID=248), labeled ATL7WZ'12, fitted in CT18Z.

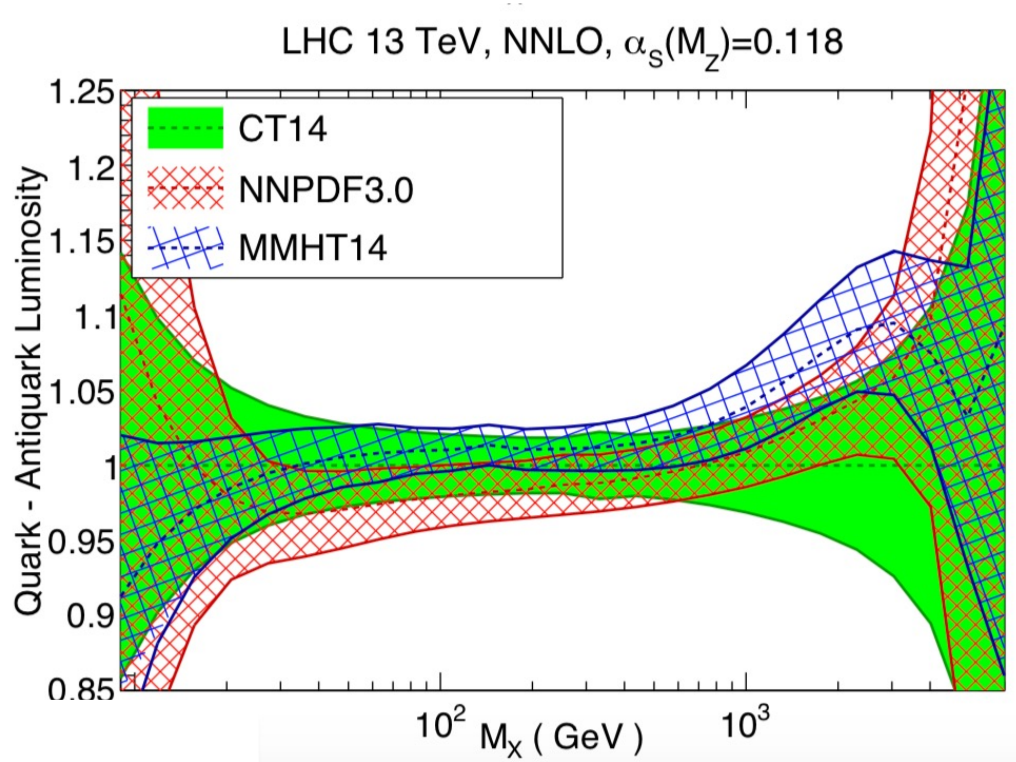
…as for example, PDF4LHC15

- combination of CT14, MMHT2014, NNPDF3.0

…over 1200 citations

  - 1 year benchmarking exercise comparison of above PDFs
  - comparing theory and treatment of experimental data from each group
  - 300 Monte Carlo replicas generated for each of the above PDFs
  - condensed to Hessian sets with from 30-100 members for distribution to users with central PDFs and error PDFs representing the three published PDFs
  - good (too good?) agreement for gluon-gluon luminosity



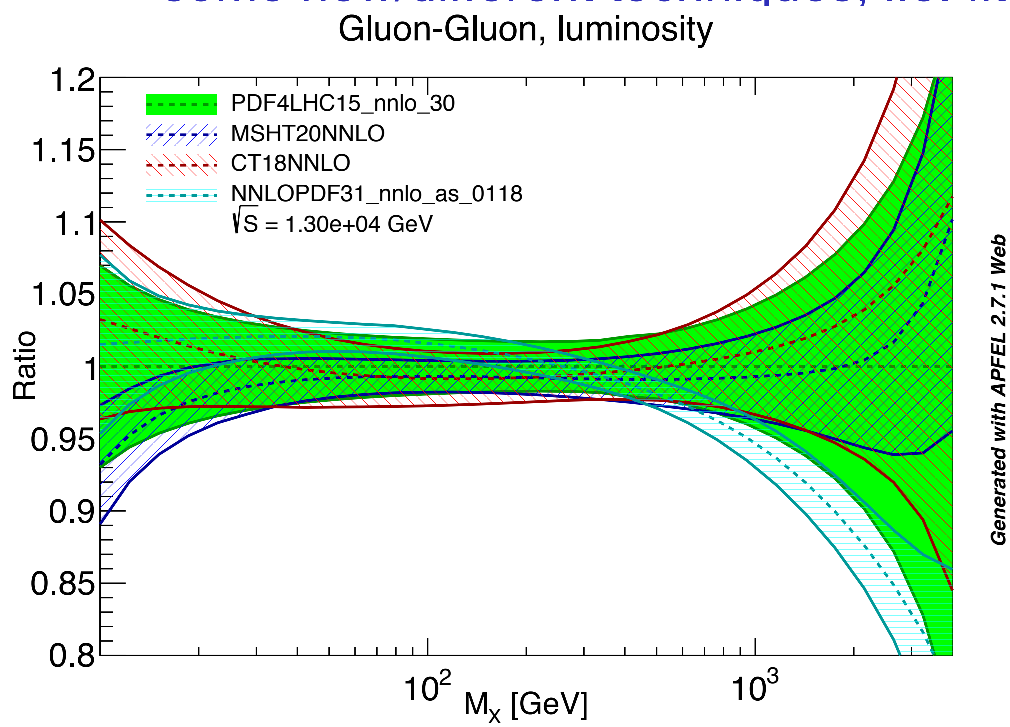


…in the meantime

- New critical data sets from the LHC on Drell-Yan, top, jets, W/Z+jets
- NNLO predictions available for all of above allowing this data to be included in PDF fits
  - transferring NNLO information to global PDF fits still a bit of an issue, i.e. precision of K-factors (statistical jitter->need to smooth and/or use statistical error), availability of grids
- New NNLO PDFs available (CT18, MSHT20, NNPDF3.1) that make use of this LHC data (NNPDF4.0 not yet publically available)
  - additional technical improvements to the PDF fits
- These PDF sets will be used for the construction of PDF4LHC21

PDF4LHC21

- new PDFs CT18, MSHT2020, NNPDF3.1, containing large amount of LHC data
- some new/different techniques, i.e. fitted charm* for NNPDF3.1



consistency with PDF4LHC15, a bit more of a spread of the gg uncertainty bands than for the 2015 combination; some of gg fusion Higgs uncertainty will be due to spread of central values

*charm is fit as a free PDF rather then being generated through evolution

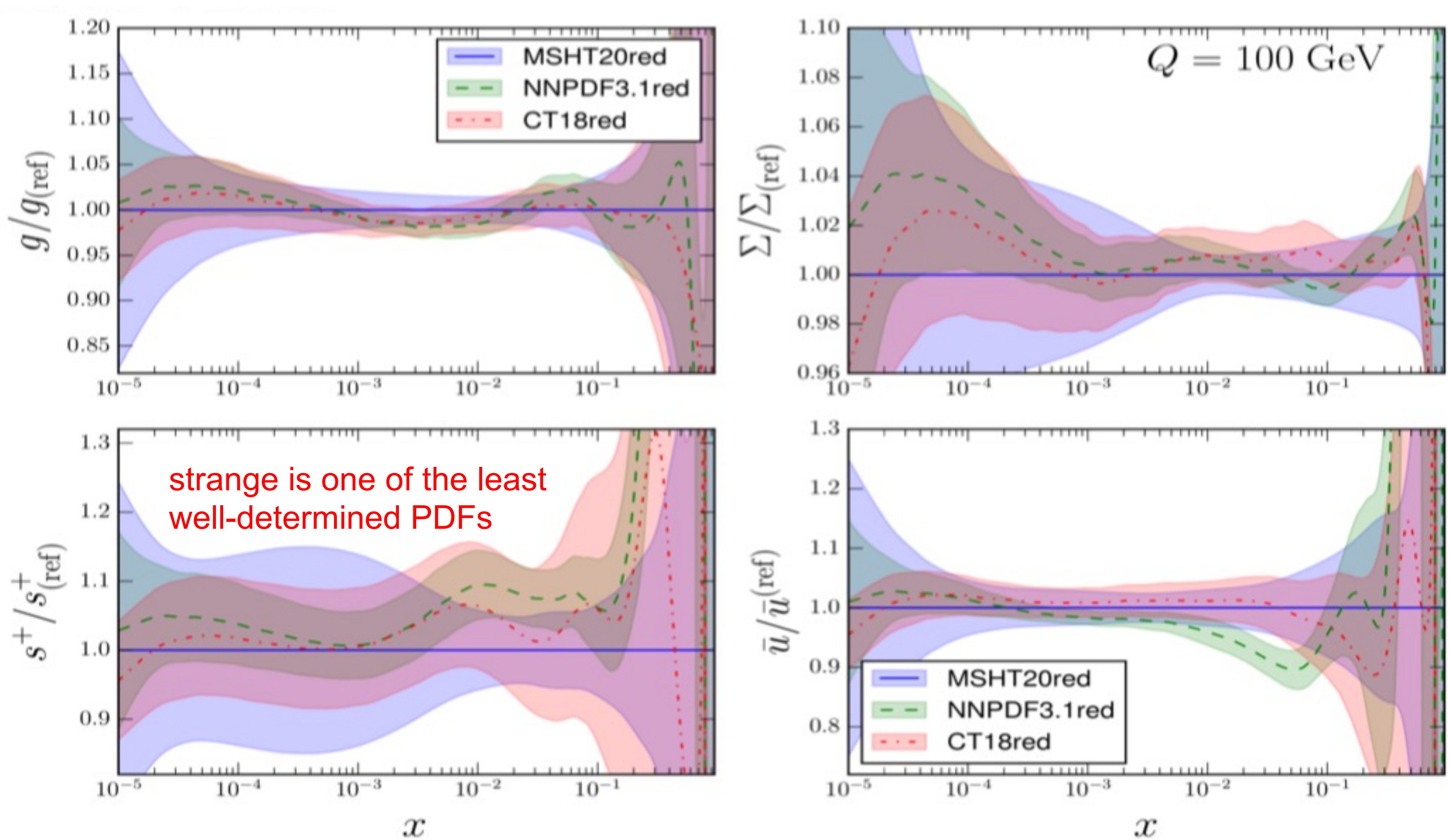
- exercise: start with a reduced data set large enough to provide constraints, small enough that resulting PDFs should be similar for the different groups
  - add more data sets, ttbar, jets … leading to something close to full data sets
- end result in ~few months: central PDFs and Hessian error sets representing the 3 published PDFs->30-50 error PDFs should be sufficient
- paper will appear on archive (PDF4LHC15 paper has 1200 citations)

Aside: uncertainties

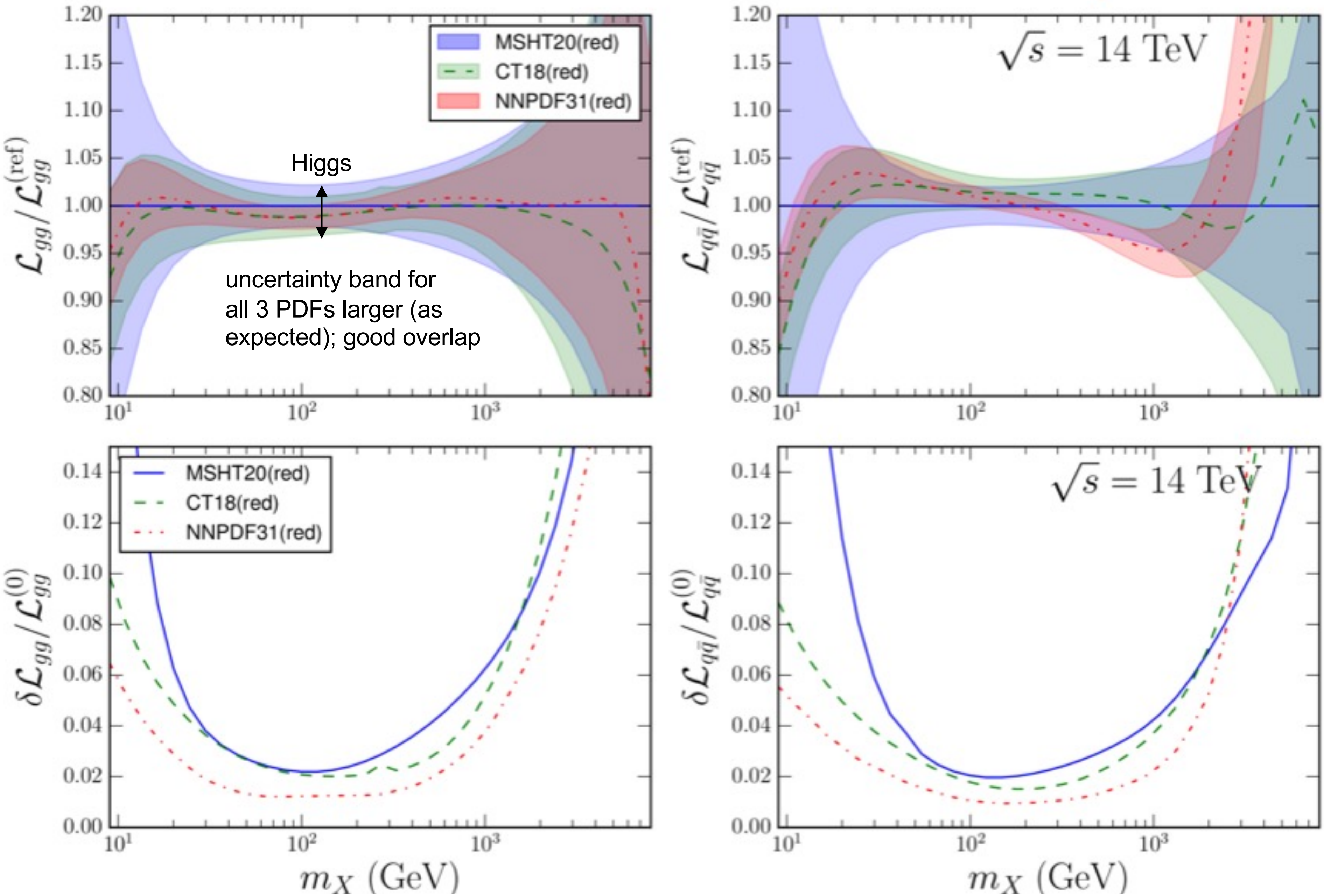
- PDF uncertainties depend first on the experimental uncertainties of the data (the path to 1% precision goes through the data)
- Data from two measurements, or even from within the same measurement, can both be very precise, but the result of adding both to the PDF fit can be an increase in the PDF uncertainty (or more likely) a smaller decrease in uncertainty than expected) if the data are in tension with each other
- The resultant PDF uncertainty relies on the definition of a tolerance, i.e. (in the Hessian fit perspective) what is a significant increase from the global minimum χ^2, i.e. PDF uncertainty can be adjusted by changing the tolerance
- $\Delta\chi^2=1$ is not applicable for ~4000 data points from different experiments
- NB: CT (Tier 2) and MSHT (dynamic tolerance) have introduced criteria to restrict the pull of data sets that disagree with global fit; can lead to non-Gaussian behavior

Reduced fits

Reasonable agreement for the most part.



PDF luminosities

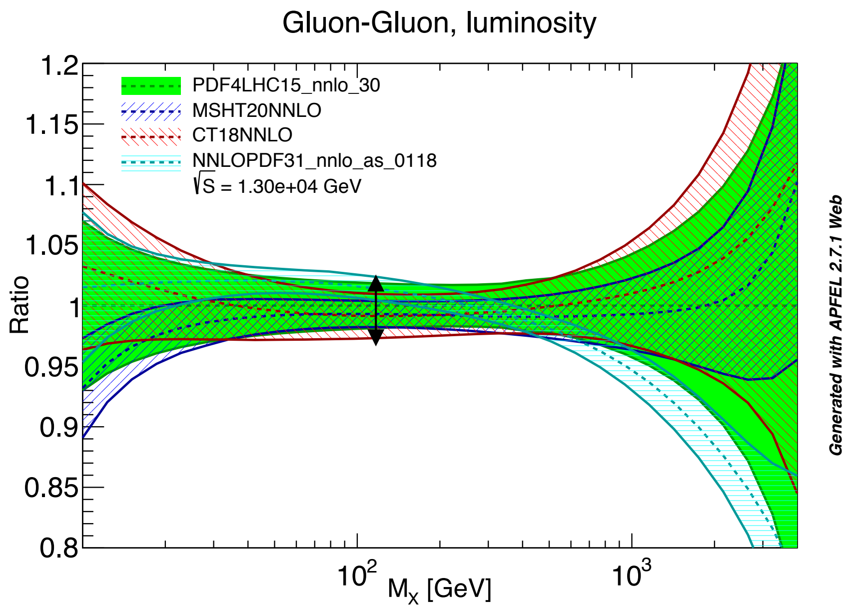


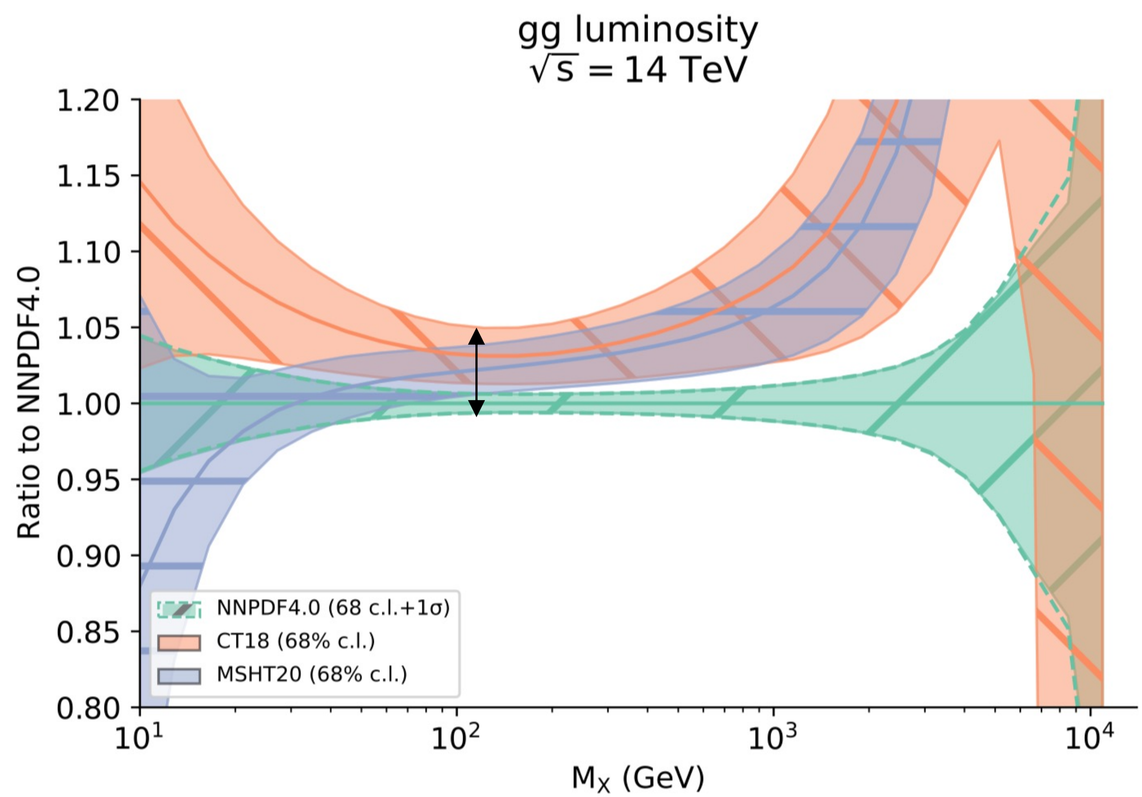
ok, what's the plan

- Add additional jet data sets into reduced set (in progress), consider impact on ATLAS tt and on gluon distribution
  - ATLAS and CMS 7 TeV data (CMS 8 TeV already in)
- Use L2 sensitivity to understand impact of each data set on PDF fits (in progress)
  - differences between impact of Tier 2/dynamic tolerances on full fit compared to reduced fit
- Expand to complete CT18, MSHT20, NNPDF3.1 global fits
- Provide PDF4LHC21 PDF sets, collect even more citations

PDF4LHC21 and NNPDF4.0

the situation for gg looks different
for NNPDF4.0 than for 3.1; spread of central
PDFs would still contribute to gg PDF uncertainty
(but plan is to use NNPDF3.1 in PDF4LHC21)





Calculations: input to Les Houches

Experimenters ⟶ Theorists

- theory predictions needed to exploit physics potential, i.e. V+n jets at NNLO
- form of theory predictions needed, i.e. NNLO grids, K-factors, inclusion in MEPS programs…
- experimental precision achievable in forseeable future->drives theoretical precision needed

The Les Houches NLO wishlist

- …started in 2003 and was retired in 2011

process ($V \in \{Z, W, \gamma\}$)	relevant for
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
3. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
4. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
5. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
6. $pp \to V + 3$ jets	various new physics signatures
7. $pp \to V\,V\,V$	SUSY trilepton

Why retired? Because all calculations were finished, and additional calculations can be done ‘automatically’. Viva la NLO revolution!

arXiv:2003.01700 (seems like a lifetime ago)

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ (incl.) $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$ $\mathrm{NNLO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{N^3LO_{HTL}}$ (partial results available) $\mathrm{NNLO_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO^{(VBF)}_{QCD} + NLO^{(VBF)}_{EW}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to H + V$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	$\mathrm{NLO^{(t,b)}_{gg\to HZ}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$

Table I.1: Precision wish list: Higgs boson final states. $\mathrm{N^xLO^{(VBF^*)}_{QCD}}$ means a calculation using the structure function approximation.

Primer

- $\mathrm{LO} \equiv \mathcal{O}(1)$,
- $\mathrm{NLO\ QCD} \equiv \mathcal{O}(\alpha_s)$,
- $\mathrm{NNLO\ QCD} \equiv \mathcal{O}(\alpha_s^2)$,
- $\mathrm{NLO\ EW} \equiv \mathcal{O}(\alpha)$,
- $\mathrm{NNNLO\ QCD} \equiv \mathcal{O}(\alpha_s^3)$,
- $\mathrm{NNLO\ QCD{+}EW} \equiv \mathcal{O}(\alpha_s \alpha)$.

in many of regions probed, EW corrections are significant, as are mixed QCD/EW

Note I haven't mentioned logarithmic accuracy, which will also be important in regions with restricted phase space.

Les Houches precision wishlist

NLO automation and (N)NLO techniques

1 Update on the precision Standard Model wish list [1]

Identifying key observables and processes that require improved theoretical input has been a key part of the Les Houches programme. In this contribution we briefly summarise progress since the previous report in 2017 and explore the possibilities for further advancements. We also provide an estimate of the experimental uncertainties for a few key processes. A summary of this sort is perhaps unique in the field and serves a useful purpose for both practitioners in the field and for other interested readers. Given the amount of work that has been, and is being, done, this summary will no doubt be incomplete, and we apologize for any omissions.[2]

[1] A. Huss, J. Huston, S. Jones, S. Kallweit

[2] The Les Houches Disclaimer

Les Houches wishlist often used as motivation

Motivation

See for example half of the talks at RadCor+Loopfest

- Experimental precision will increase with more statistics.
- Need two-loop amplitudes to match with NNLO precision.
- Master integrals required.
- 5-point 1-mass relevant for W/Z/H-plus-two-jets production at the LHC.

  [See Bayu's talk for $W + b\bar{b}$]

process	known	desired
⋮	⋮	⋮
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
⋮	⋮	⋮
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ incl. $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO^{(VBF)}_{QCD}} + \mathrm{NLO^{(VBF)}_{EW}}$
⋮	⋮	⋮

[Les Houches precision wishlist '19]

Emanuele upped the ante for the level of complexity

Les Houches precision wishlist: jets

process	known	desired
$pp \to 2\,\text{jets}$	NNLO_{QCD} $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
$pp \to 3\,\text{jets}$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}

Table I.2: Precision wish list: jet final states.

1.5 Jet final states

An overview of the status of jet final states is given in Table I.2.

j+X: *LH17 status:* Differential NNLO_{QCD} corrections calculated in the NNLOJET framework [236] with a detailed study of scale choices performed in Ref. [499].

Single-jet inclusive rates with exact colour at $\mathcal{O}(\alpha_s^4)$ were recently completed in the sector-improved residue subtraction formalism [261]. This full calculation confirmed that the approximation applied in the previous one, i.e., leading-colour approximation in the case of channels involving quarks and exact calculation in colour only in the pure-gluon channel, is perfectly justified for phenomenological applications.

2j: *LH17 status:* NNLO_{QCD} corrections calculated in the NNLOJET framework [237]; complete NLO QCD+EW corrections available [500].

Building upon the NNLOJET framework, which implements the antenna subtraction formalism, in Ref. [501] a first dedicated NNLO_{QCD} study of triple-differential 2-jet cross sections has been performed.

≥3j: *LH17 status:* NLO_{QCD} corrections for 3-jet [502], 4-jet [503, 504] and 5-jet [505] known.

NLO_{EW} corrections for 3-jet production were first reported inclusively, calculated in the automated framework MADGRAPH5_aMC@NLO [171]. A full NLO_{SM} calculation for 3-jet production was performed using SHERPA and amplitudes from RECOLA in Ref. [506].

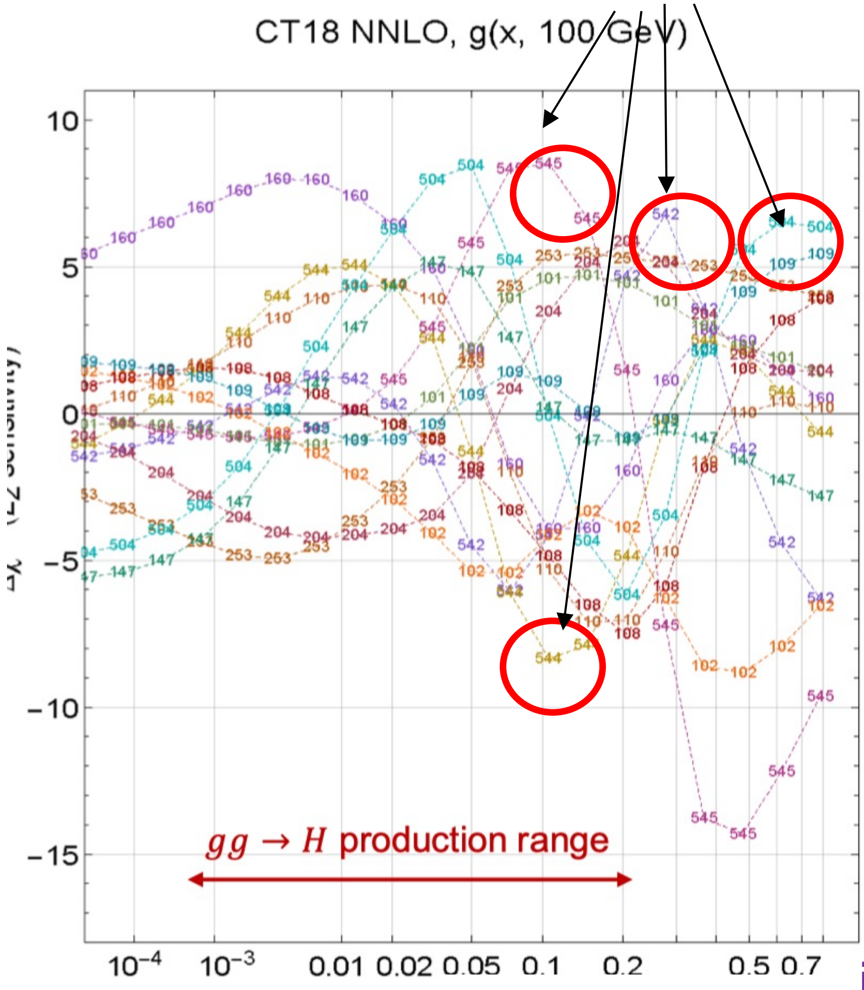
Complete NNLO_{QCD} corrections could not be achieved to date, but huge progress was made on the calculation of 5-point two-loop amplitudes for that process as summarised in Sect. 1.2.3.

Inclusive jet data has proven to be crucial for determination of gluon PDF

Estimated χ^2 pulls from experiments

(L_2 sensitivity, T. Hobbs et al., arXiv:1904.00222, v. 2)

notice importance of jet data



Plots of L_2 sensitivities to various PDFs:
https://ct.hepforge.org/PDFs/ct18/figures/L2Sensitivity/

CT18 NNLO, gluon at Q=100 GeV

15 core-minutes

Most sensitive experiments

- 253 ATL8ZpTbT
- 542 CMS7jtR7y6T
- 544 ATL7jtR6uT
- 545 CMS8jtR7T
- 160 HERAIpII
- 101 BcdF2pCor
- 102 BcdF2dCor
- 108 cdhswf2
- 109 cdhswf3
- 110 ccfrf2.mi
- 147 Hn1X0c
- 204 e866ppxf
- 504 cdf2jtCor2

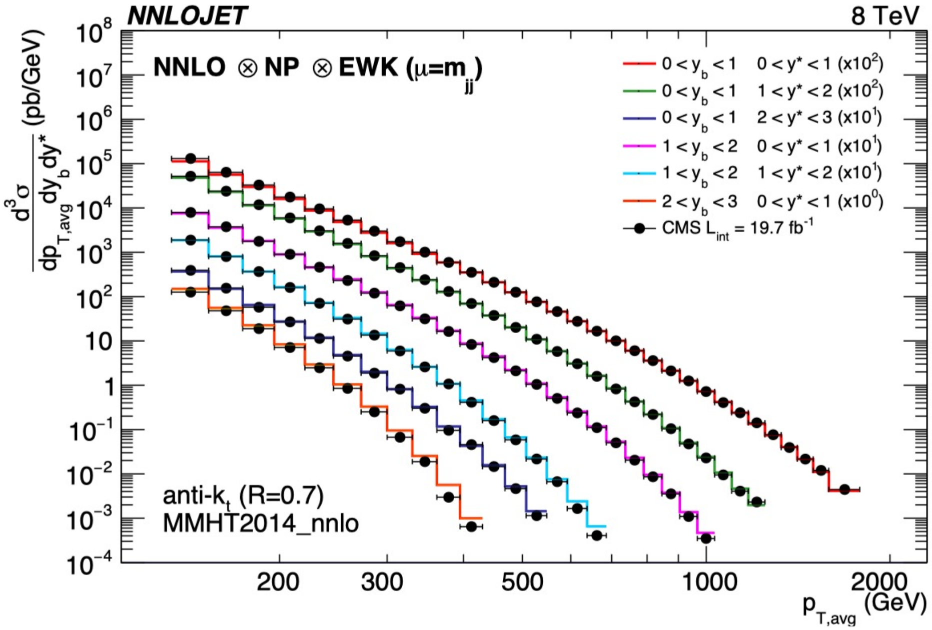
Experiments with large $\Delta\chi^2 > 0$ [$\Delta\chi^2 < 0$] pull $g(x, Q)$ in the negative [positive] direction at the shown x

ideally, the sum at any x value should be zero; non-zero indicates non-Gaussianity

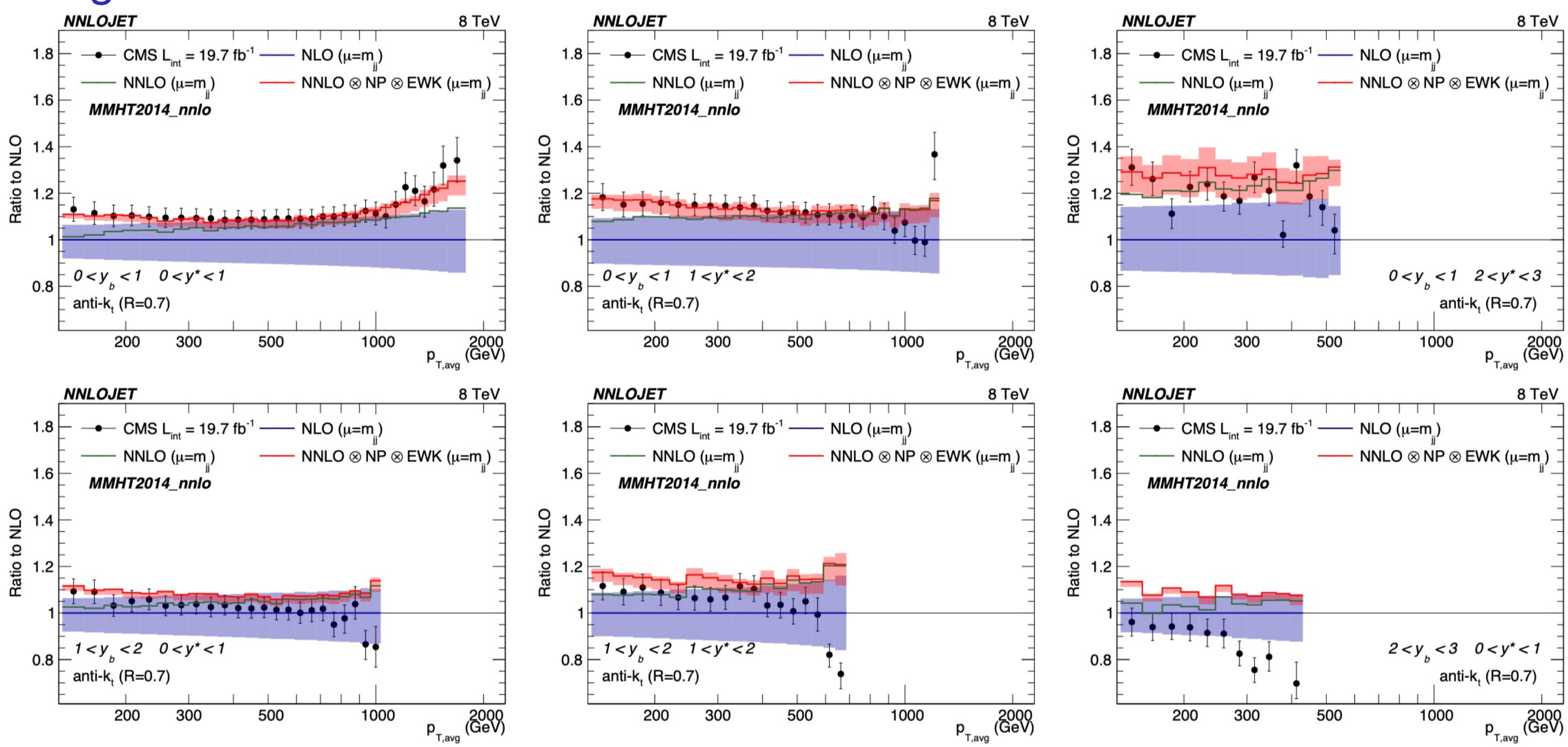
2021-04-09

n_mtg

arXiv:1905.09047)Gehrmann-de Ridder et al)



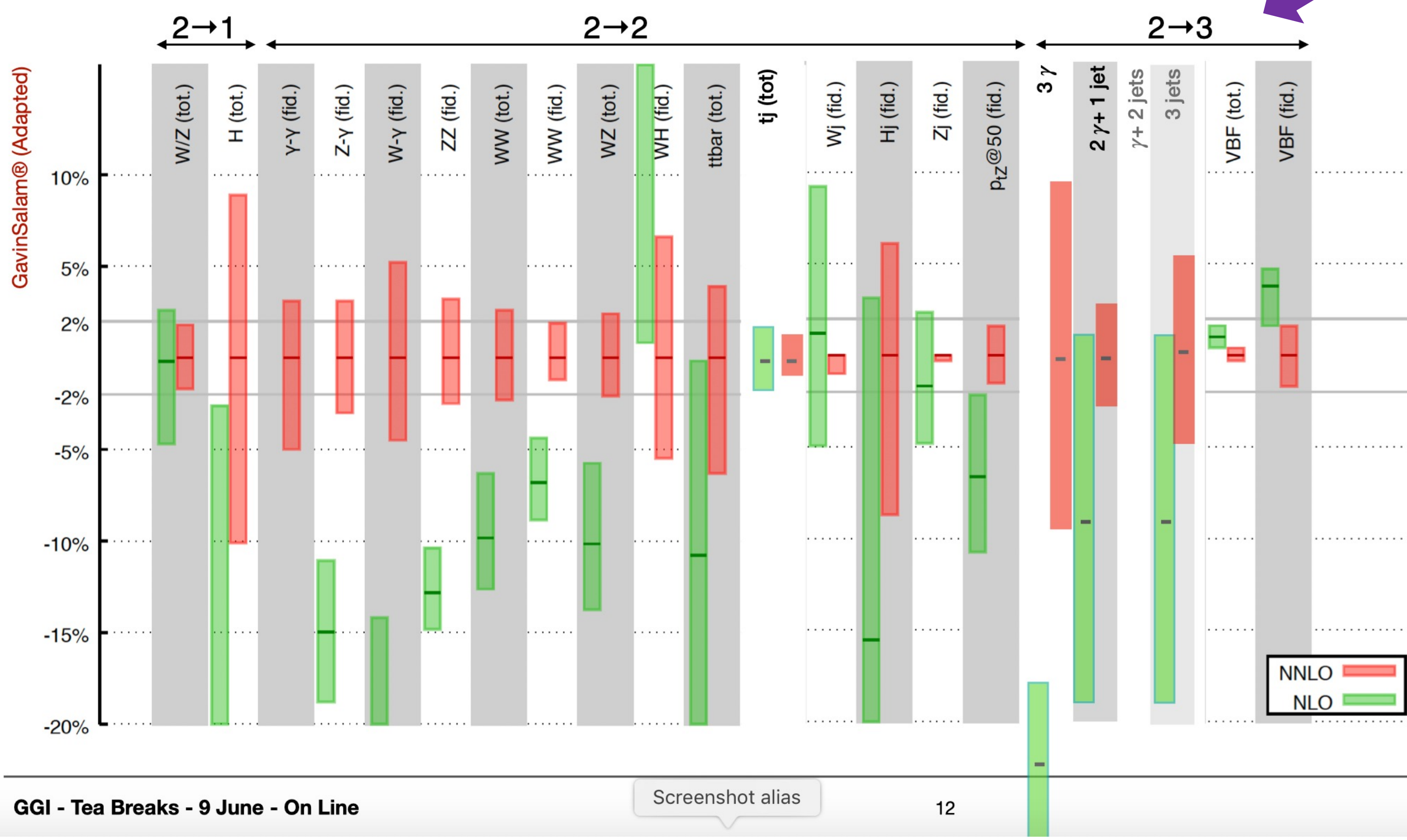
More discrimination potentially available using dijet information, or including both inclusive and dijet data, taking into account the correlations. Knowledge of systematic uncertainties (and possible correlations/ decorrelations) in different rapidity regions crucial for global PDF fits.



Fabio Maltoni talk from last week (GGI)

Precision calculations for the LHC

Status: Fixed Order



- NNLO brings us in the few percent arena
- Several NNLO computations move the central value out of the NLO uncertainties
- The 2→3 wall broken

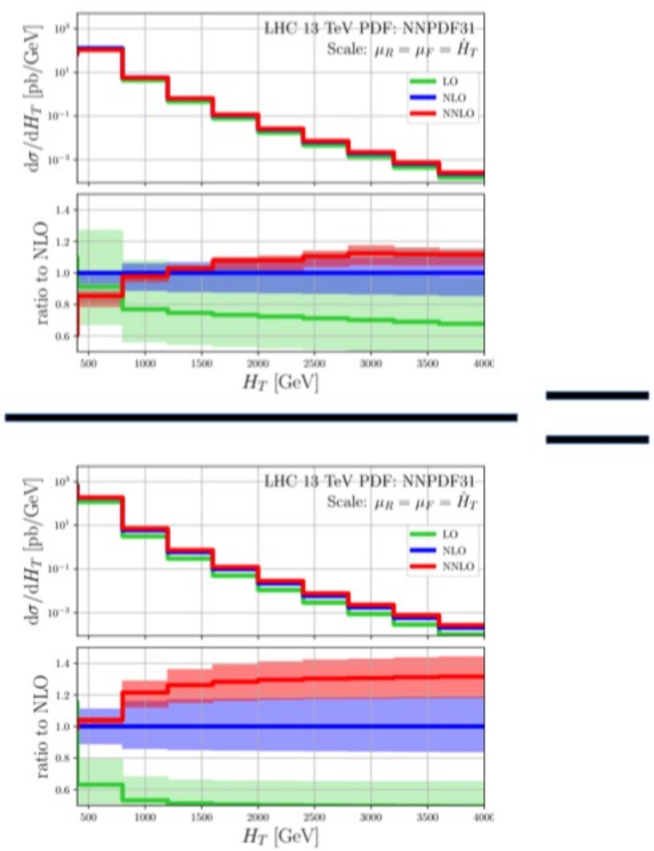
GGI - Tea Breaks - 9 June - On Line

Screenshot alias

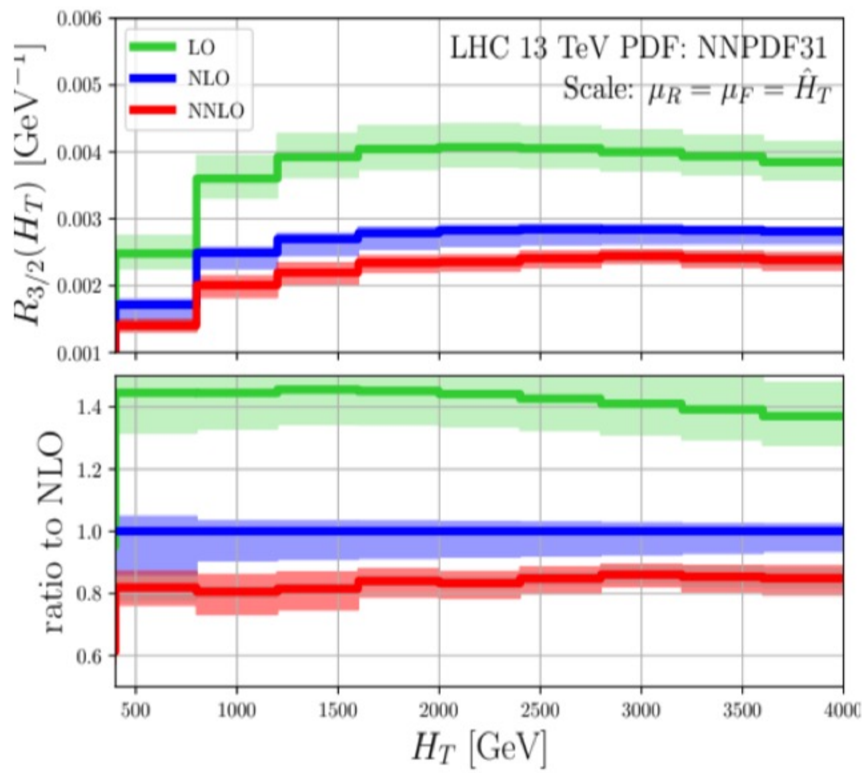
12

UC

Three jet production - R32(HT)



HT = Σ ρT(jet)



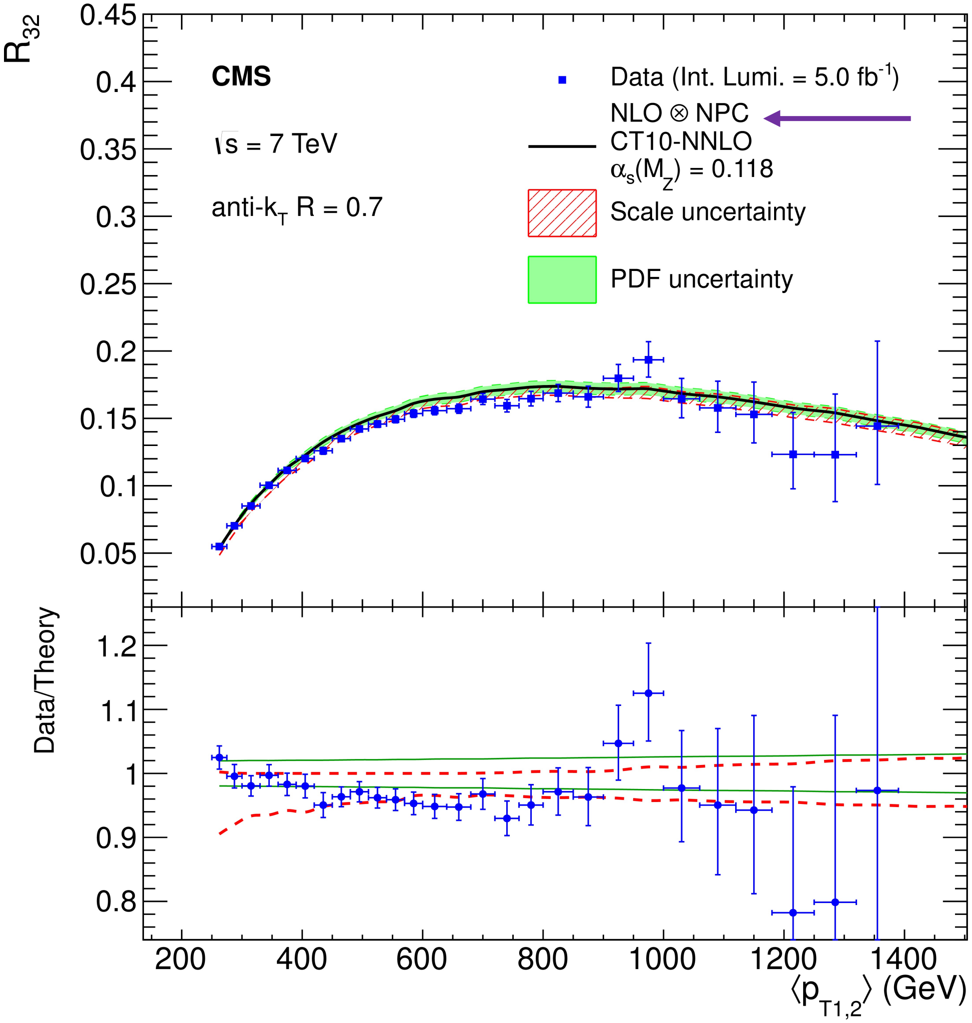
Scale dependence correlated in ratio

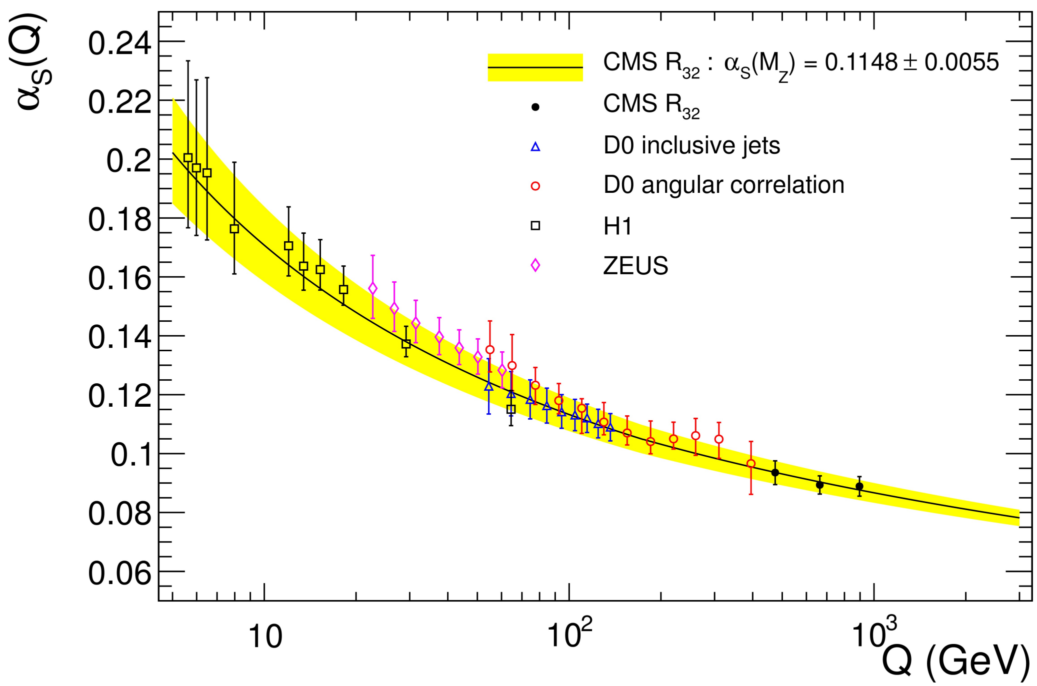
→ reduction of scale dependence

→ flat k-factor

→ scale bands in ratio barely overlap

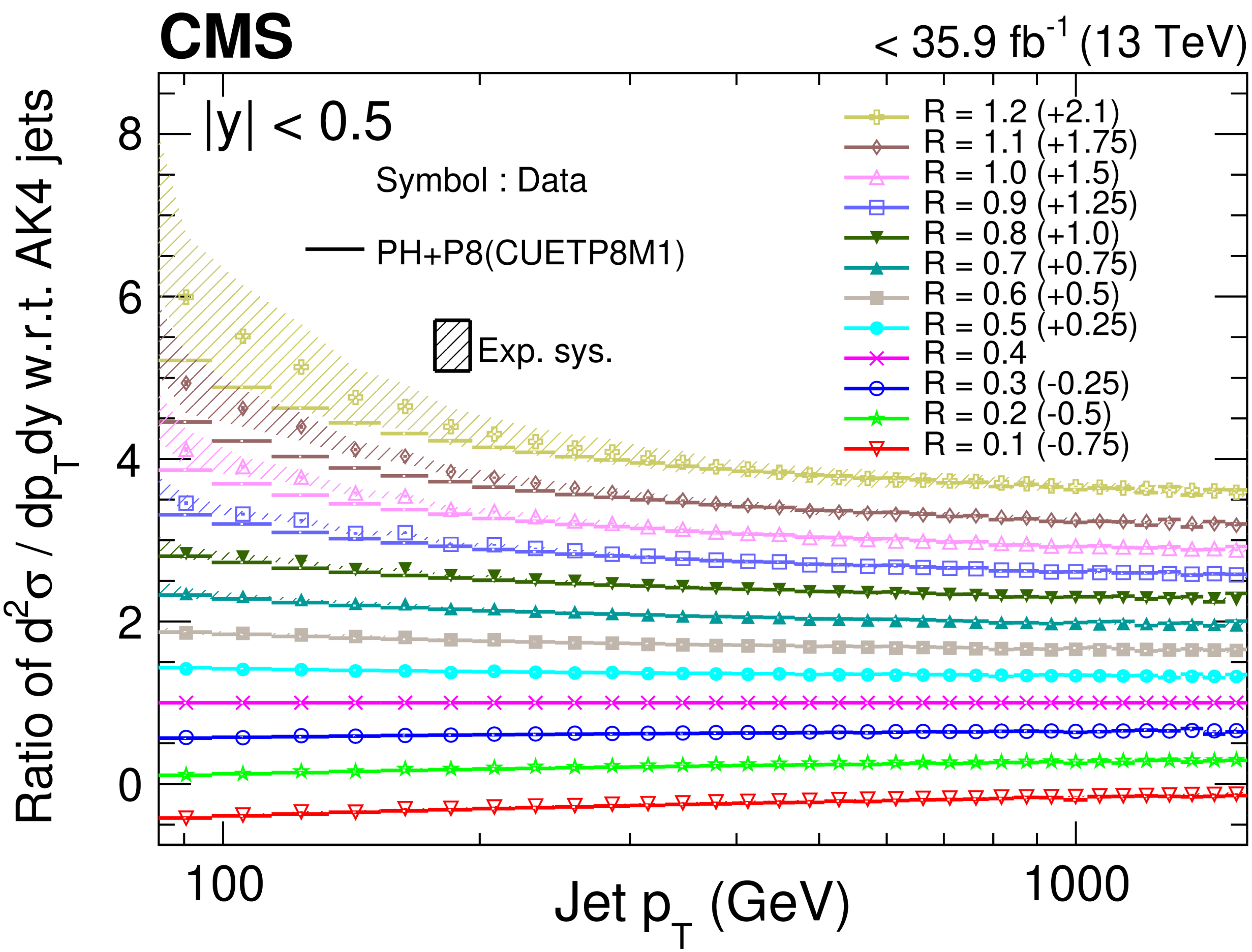
…will allow more precise determinations of the running of $\alpha_s(m_Z)$





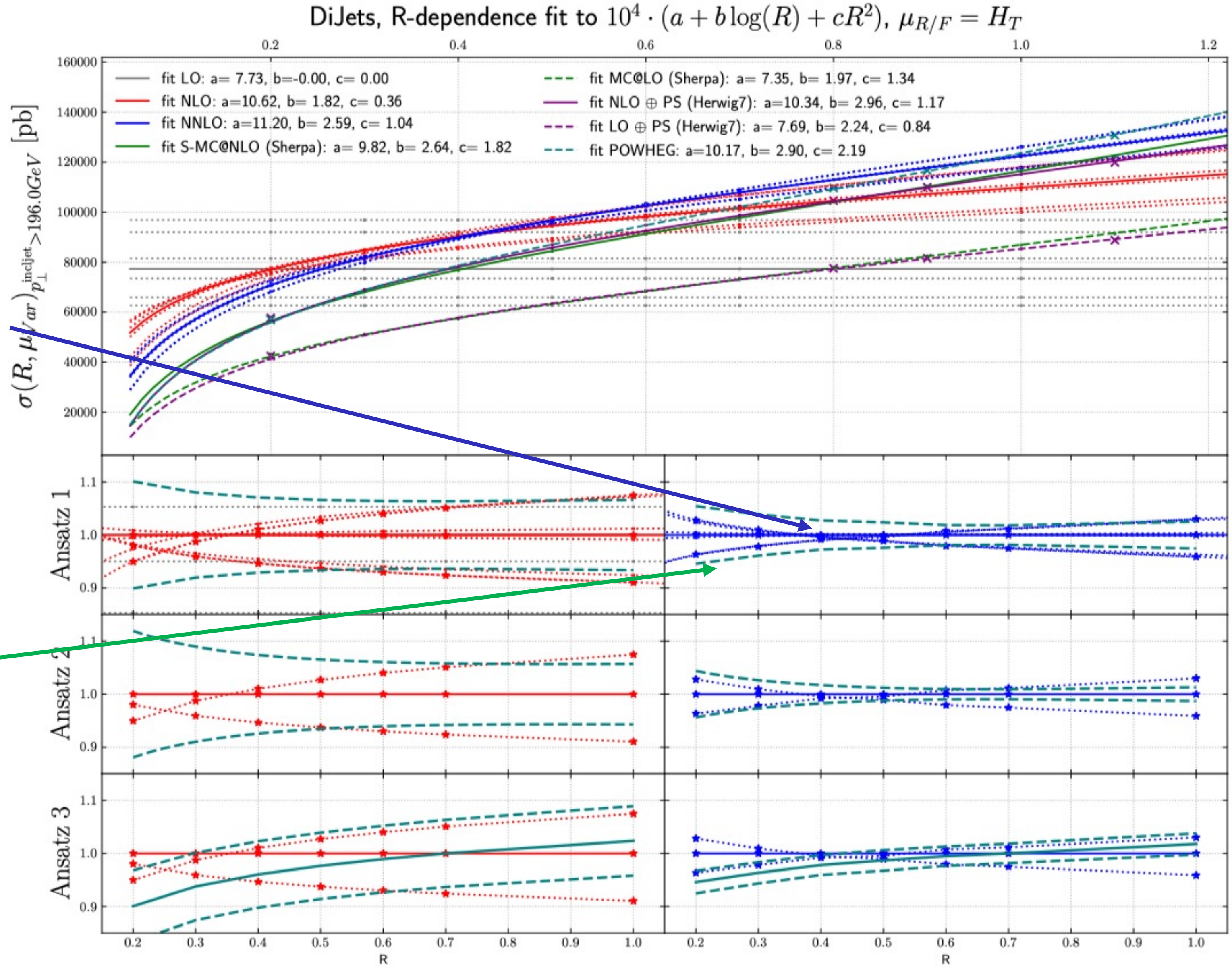
Jet R-dependence

It's often illuminating to look at the R-dependence of a cross section involving jets. You may find out more both from the experimental side and from the theory side.



…as for example, arXiv:1903.12563 (LH17)

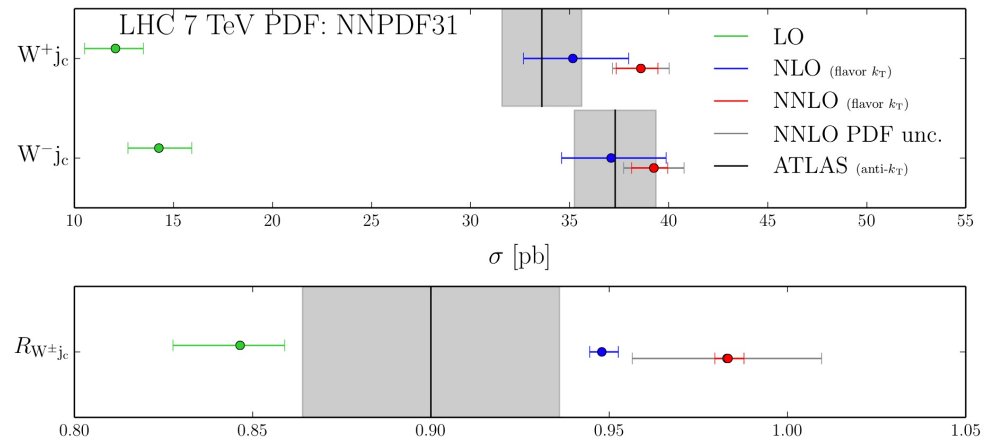
- At NNLO, there are accidental cancellations, that lead to an artificially low scale uncertainty for processes with small R (0.4) jets
- Similar for Z+jet
- Prescription(s) for restoring reasonable uncertainty estimate
- A Les Houches accord?
- See also arXiv:2105.11399 for H+2 jets



Heavy flavor jets

- V+HF is an interesting cross-section in its own right, but also provides handles on the s,c,b PDFs
- NNLO W+c (Pellen et al), Z+b (Gauld et al) calculations available (at the parton level), as well as corresponding measurements (at the hadron level)
- An IR-safe flavor jet algorithm is also available (Banfi, Salam, Zanderghi)
- But for most precise comparisons need the inclusion of the charm fragmentation function (e.g. for W+c) to allow for direct comparisons of data to theory (or unfolding data to parton level, which has its own dangers)

W+c



[Czakon, Mitov, MP, Poncelet; 2011.01011]

- PDF uncertainty dominant over NNLO scale uncertainty
- NNLO QCD prediction tends to be larger for the + signature
  → Not statistically relevant

See presentation of Alex Huss on Monday.

See presentation of Miha Muskinja in LH open session.

process	known	desired
$pp \to V$	$\mathrm{N^3LO}_{\mathrm{QCD}}^{(z\to 0)}$ (incl.) $\mathrm{N^3LO_{QCD}}$ (incl., γ^*) $\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD} + N^2LO_{EW} + N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $+\mathrm{NLO_{QCD}}$ (gg channel)	$\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) gg->ZZ known (at amp level)
$pp \to V + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$ on the horizon (next Les Houches?)
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^+W^+ + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to W^{\pm}W^+W^-$	$\mathrm{NLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	N3LO calculated
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$	
$pp \to \gamma\gamma + j$	$\mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ NNLO calculated
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	

Table I.3: Precision wish list: vector boson final states. $V = W, Z$ and $V', V'' = W, Z, \gamma$. Full leptonic decays are understood if not stated otherwise.

W/Z cross sections

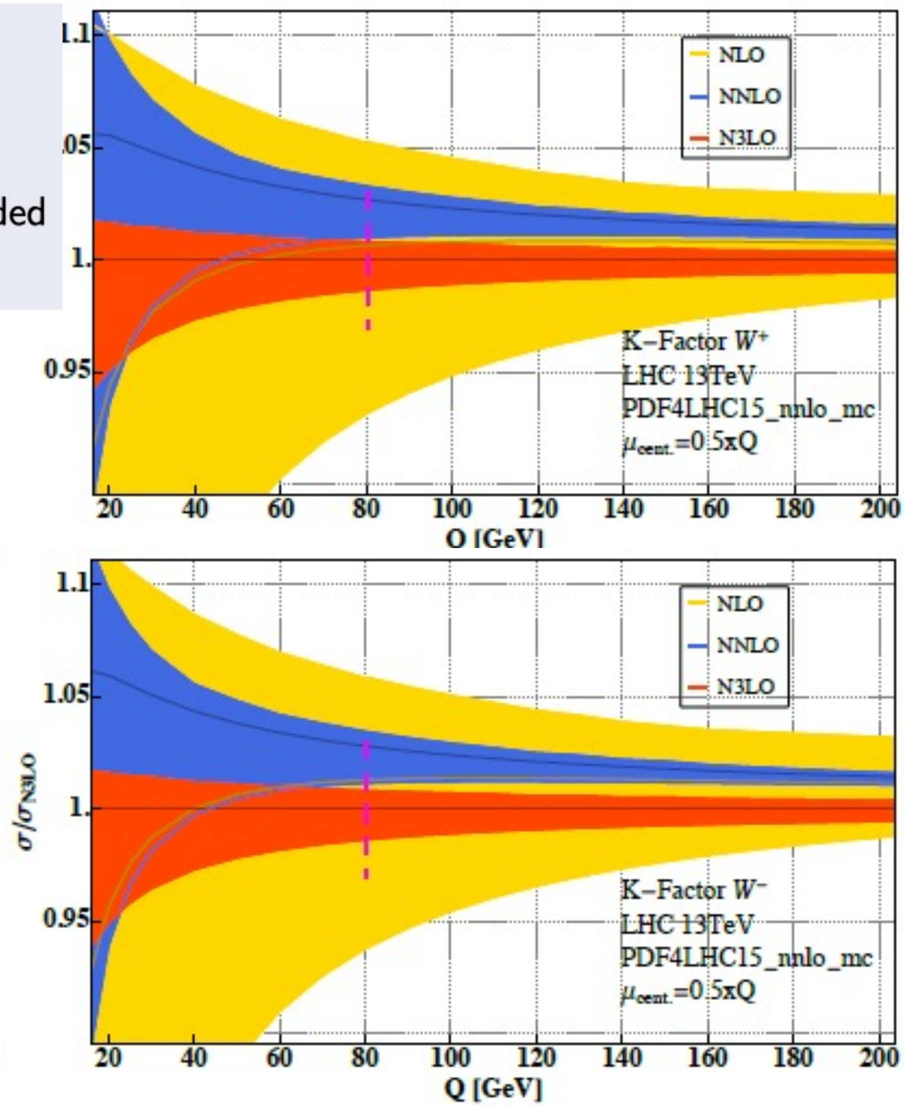
- W and Z production lend themselves to precision measurements and thus require precision calculations

Drell-Yan: best measured process at the LHC

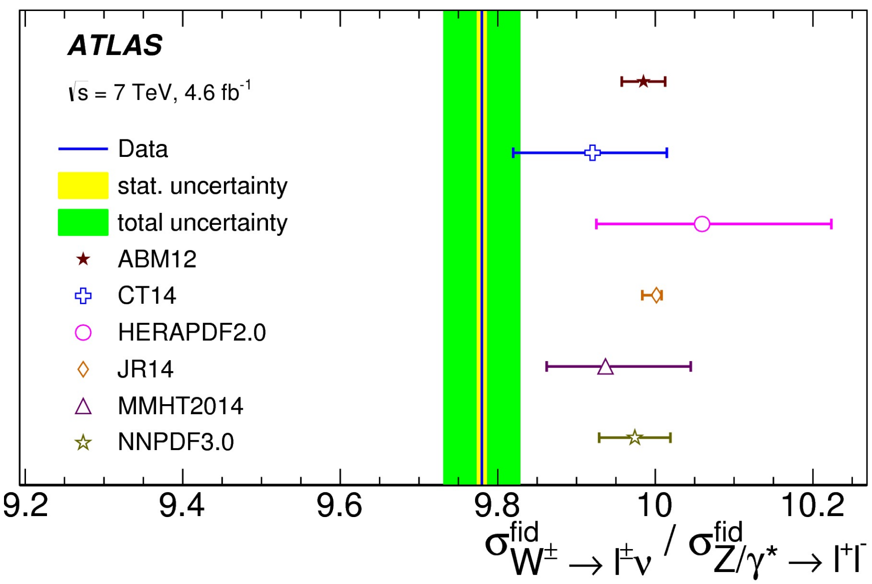
- Highest theoretical precision required
- In addition to QCD and EW corrections
  → mixed corrections of $\mathcal{O}(\alpha\alpha_s)$ for pp → 2ℓ are needed
- First step in this direction: $\mathcal{O}(n_F\alpha\alpha_s)$ corrections

M. Pellen

Duhr, Dulat, Mistlberger



PDFS: ATLAS 7 TeV data for example leads to an increase in the strange quark distribution when included in global PDF fits (similar for 8 and 13 TeV)

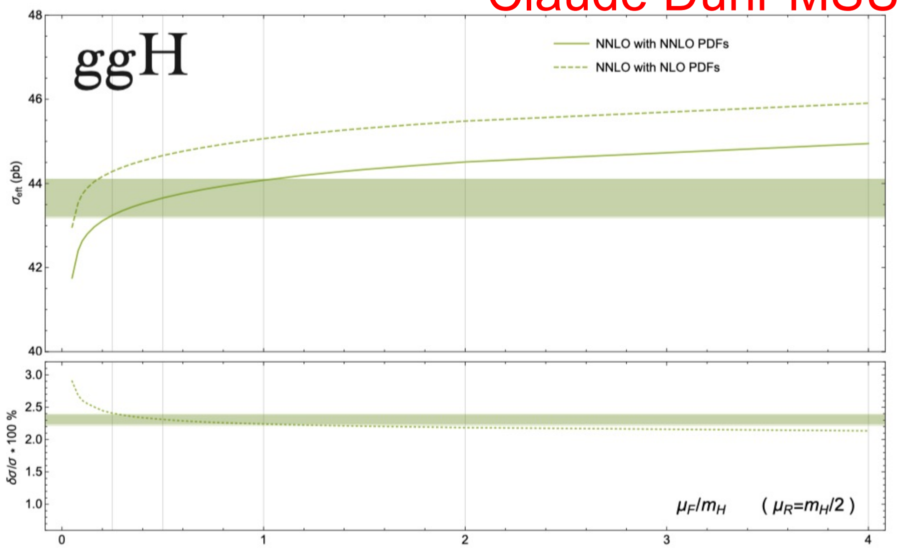


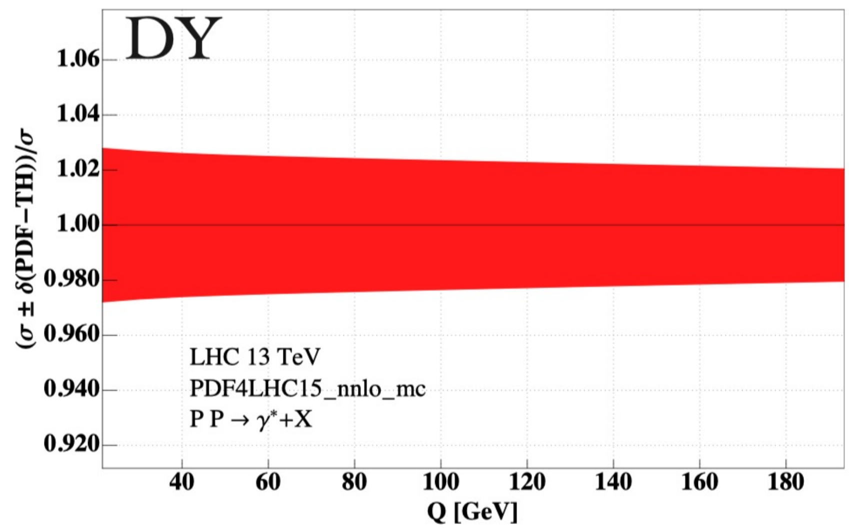
differential γ^* at N3LO underway, see X. Chen, RadCor

Prime candidate for N3LO PDFs

Missing N3LO PDFs

Claude Duhr MSU seminar





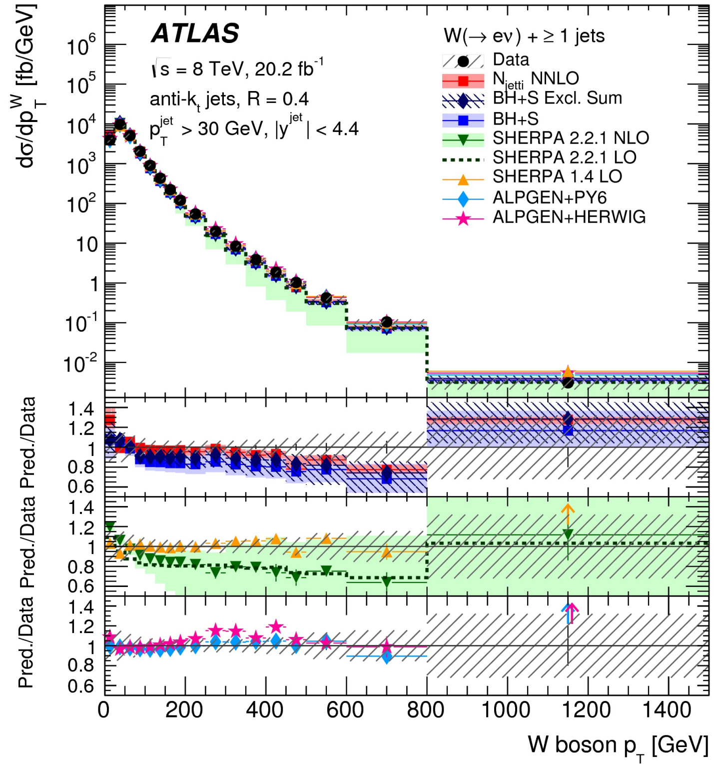
- In all cases we observe $\delta_{\mathrm{PDF}}^{\mathrm{N^3LO}} \sim 1 - 3\%$.
- N.B.: Current PDF sets use NNLO Drell-Yan data in the fits.
  - ➡ Some higher-order corrections fitted into PDFs?
  - ➡ Impact on scale variation for DY?

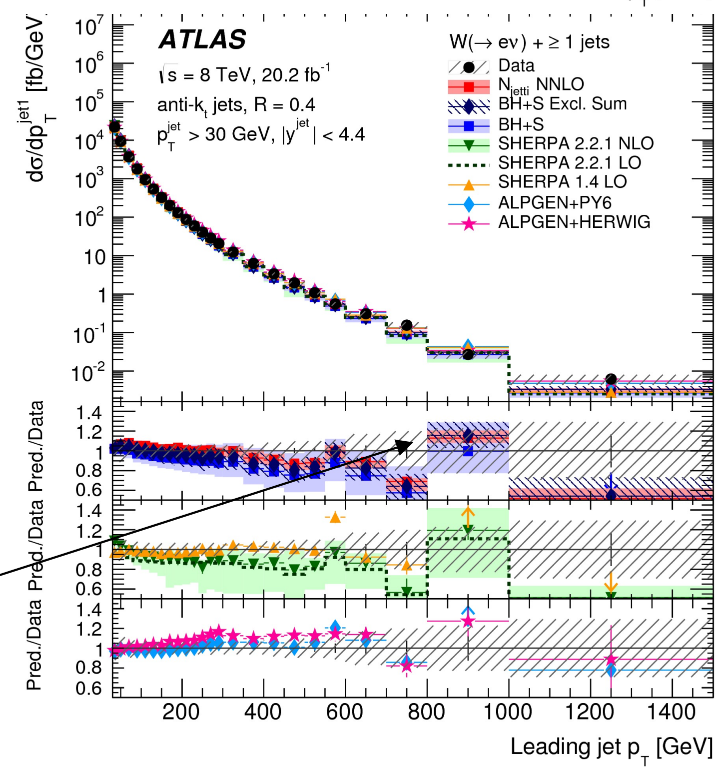
Screenshot alias

W/Z+jets

- A great process to study
  - wide kinematic range
  - recent input to PDF fits; handle on d-quark
  - many kinematic variables
  - large jet multiplicities
    - testing ground for example for impact of un-ordered emissions in the parton shower
  - EW corrections become sizeable at high p_T
    - NNLO QCD combined with NLO EW and leading NNLO EW effects in Sudakov approximation
  - W/Z bosons at low ΔR to jet can test EW parton showers
  - progress towards calculation of V+2 jets at NNLO QCD

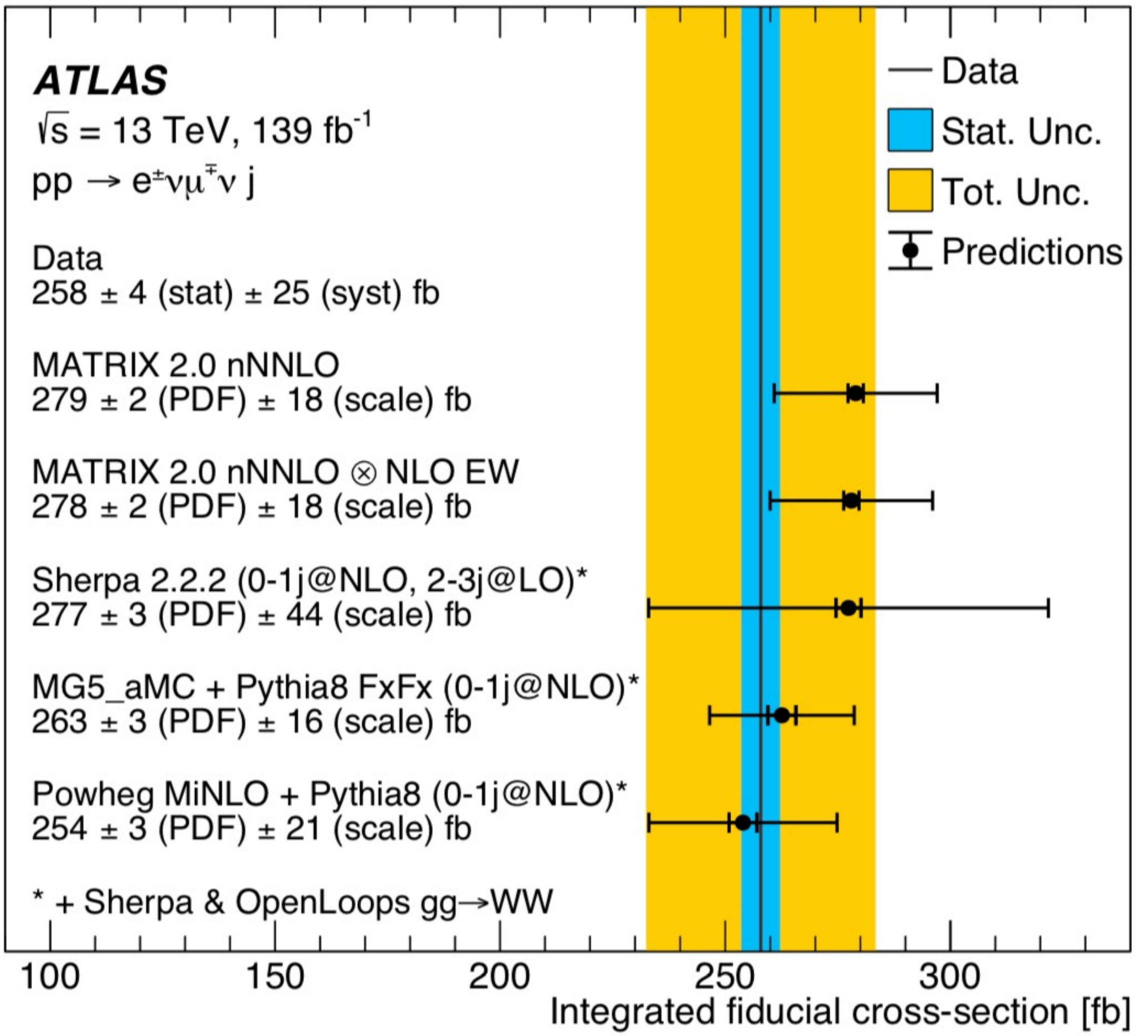
Note large reduction in uncertainty at NNLO; however, small R issue not taken into account



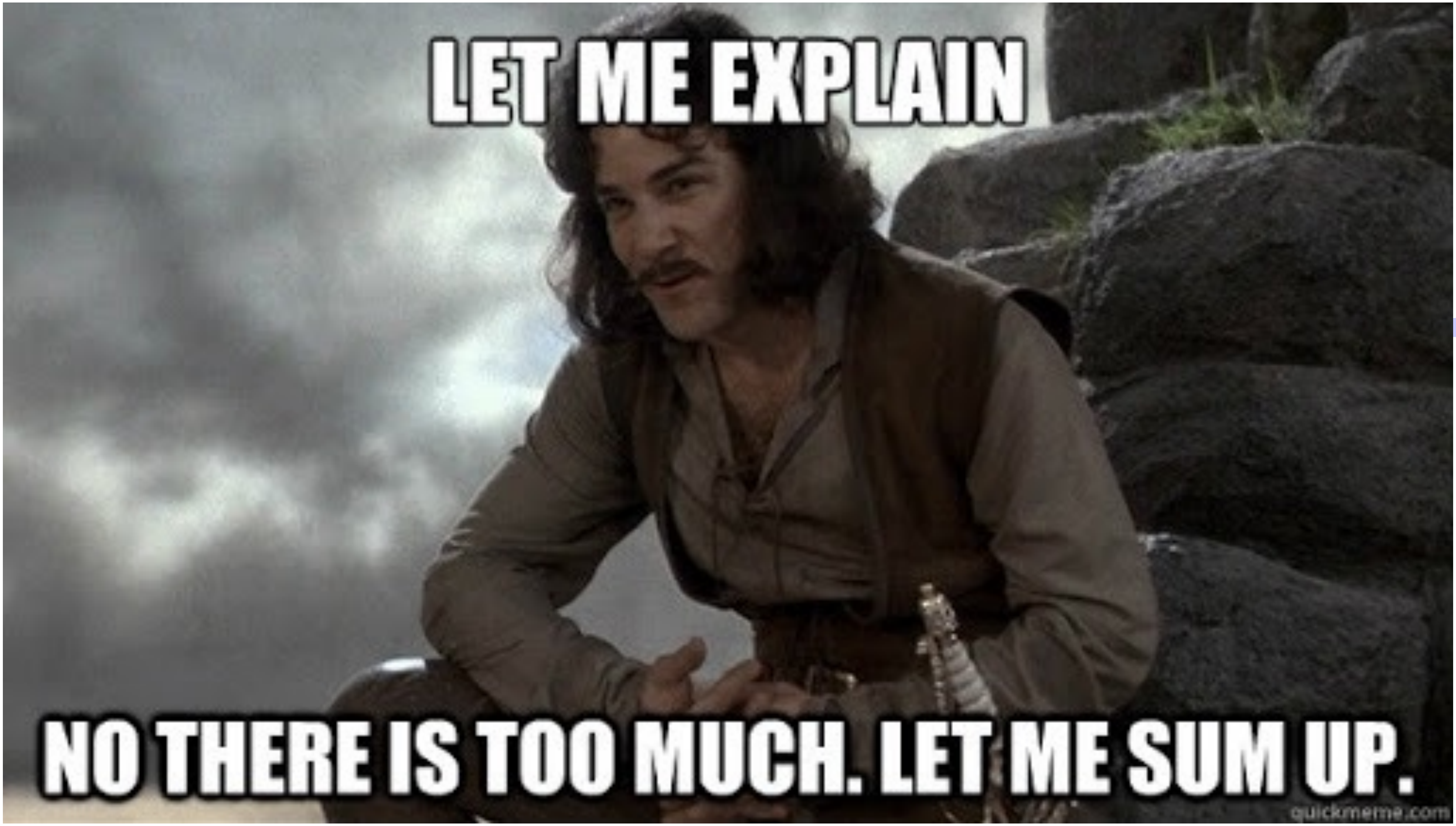


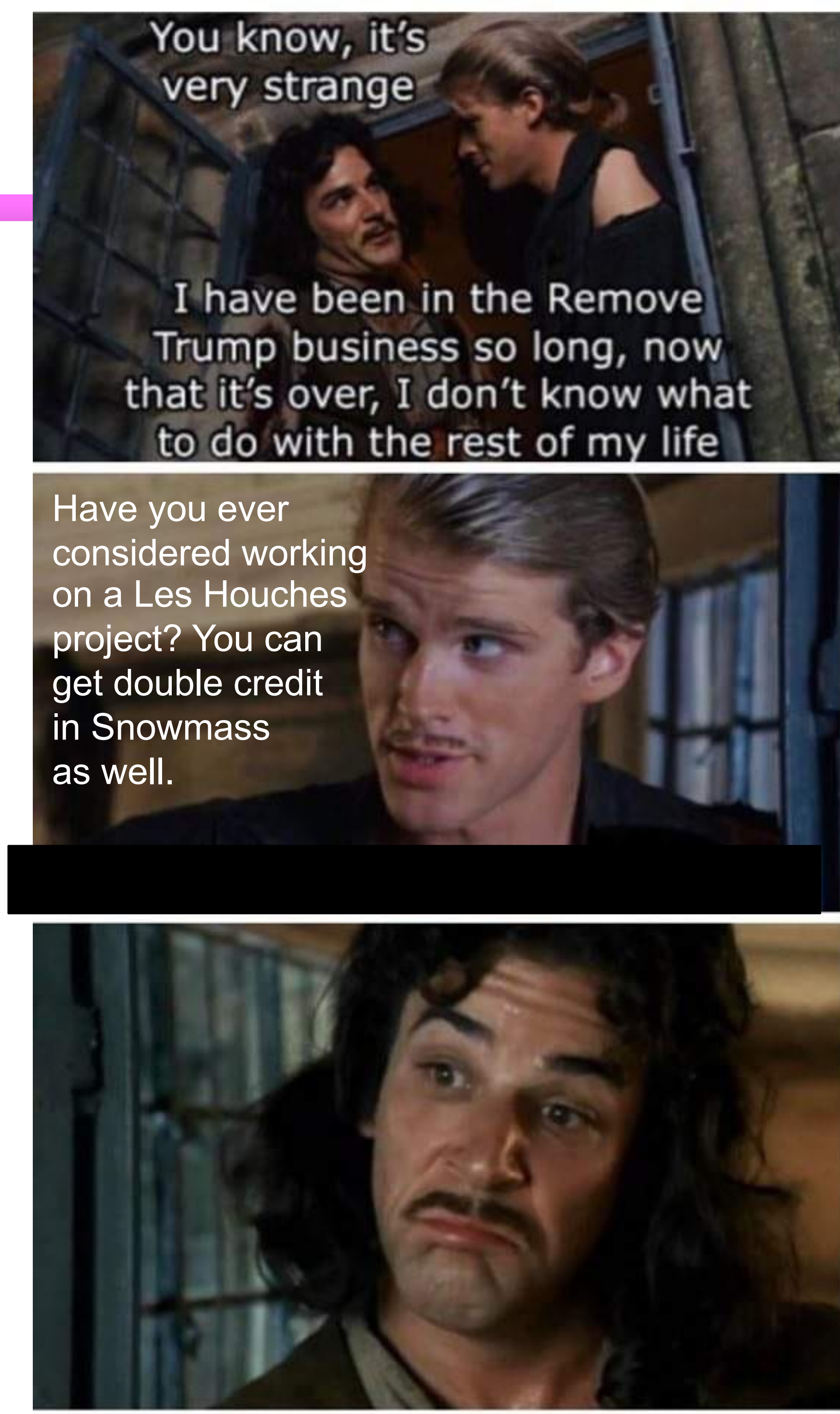
WWj

- Full data sample at 13 TeV used
- Desired level in wish-list is NLO QCD +NLO EW
- Theory uncertainty at same level as experimental uncertainty
- Experimental uncertainty will improve
- Maybe VVj at NNLO needed?



…finally


LET ME EXPLAIN
NO THERE IS TOO MUCH. LET ME SUM UP.
quickmeme.com


You know, it's very strange
I have been in the Remove Trump business so long, now that it's over, I don't know what to do with the rest of my life
Have you ever considered working on a Les Houches project? You can get double credit in Snowmass as well.
[redacted]

Extras

Monte Carlo topics for Les Houches

Monte Carlo:

Josh McFayden's talk

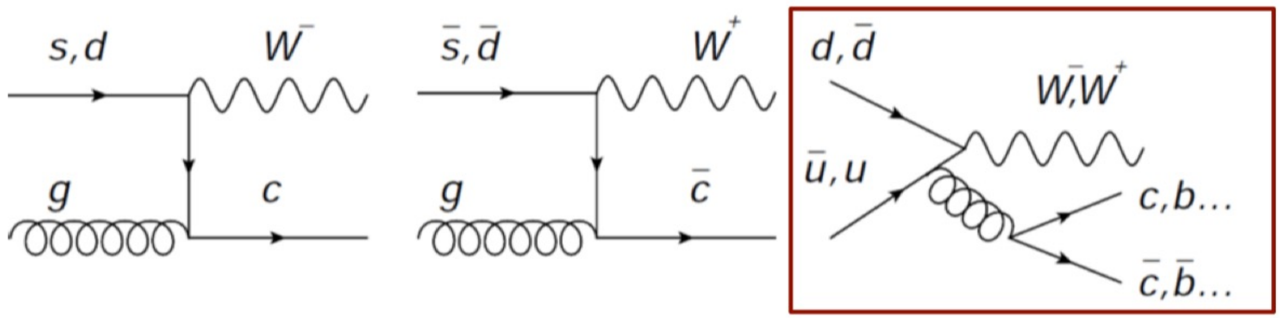
- Non-perturbative uncertainties
  - common hadronisation interface and variations
  - theoretical understanding
  - differences in tuned comparisons
  - pheno impact for certain classes of processes (e.g. VBF/VBS)
- Shower accuracy studies
  - comparing different schemes on higher orders, evaluate phenomenological impact
  - Subleading colour and interplay with colour reconnection
  - New sampling methods and algorithms versus machine learning techniques
  - Accuracy of merging resummed calculation versus ME+PS paradigms
- Photon physics, modelling of fragmentation
- Heavy flavour matching
  - review of existing measurements
  - Connecting precision calculation, fragmentation and decays
  - partons at 100 TeV
- Common LHC event bazaar
- Status and needs for electroweak corrections and radiation in shower algorithms
- Machine learning and adaptive Monte Carlo methods

Jet substructure topics for Les Houches

Jet substructure techniques:

- Interplay of jet substructure with other groups (e.g. jet substructure for EW measurements like VBF, semileptonic VV, etc.)
- Snowmass jet substructure report (JSS at future colliders) [work + discussion]
- What can we do with previous colliders, in light of the LHC [discussion]
- Comparing new unfolding methods
  - Accord on unbinned results (?)
- Probing the latest MC generators (PB algorithm, PANScales, Deductor…) with jet substructure
  - Finite N_C, beyond LL, …

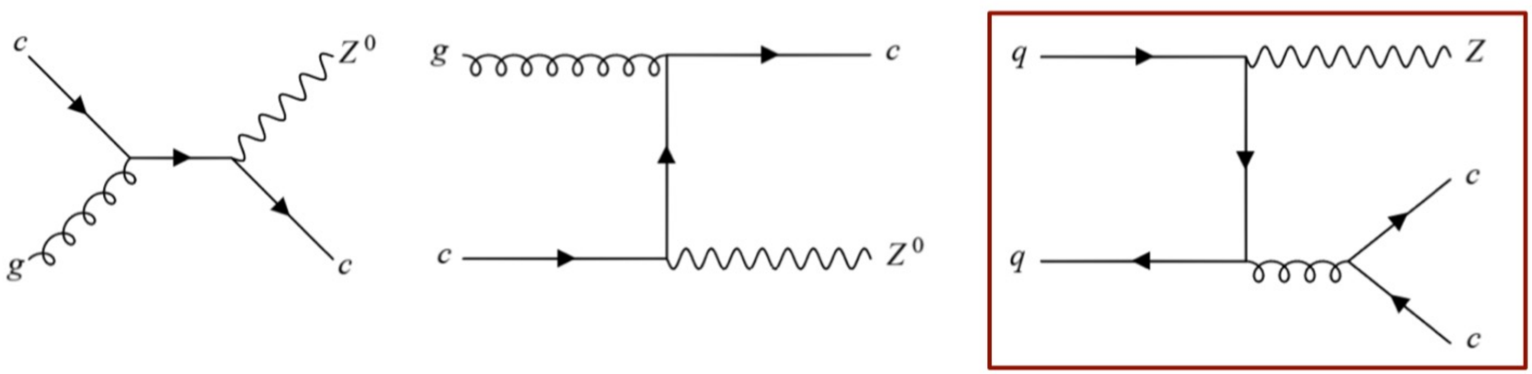
- W+c measurements can exploit the charge correlation between the W and c-quark to suppress the charge-symmetric background from gluon splitting,



Can be greatly reduced using the 'OS-SS' subtraction.

Open question: How well does this hold at NNLO?

- Z+c measurements do not have the same luxury, so coherent definitions of gluon splitting and an appropriate treatment of the c-quark PDF are needed and must be consistently applied in theory and in experimental measurements.



Can not be easily suppressed.