Theory Challenges in Precision Measurements

(Precision Measurements that Challenge Theory)

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Snowmass Oct 2020

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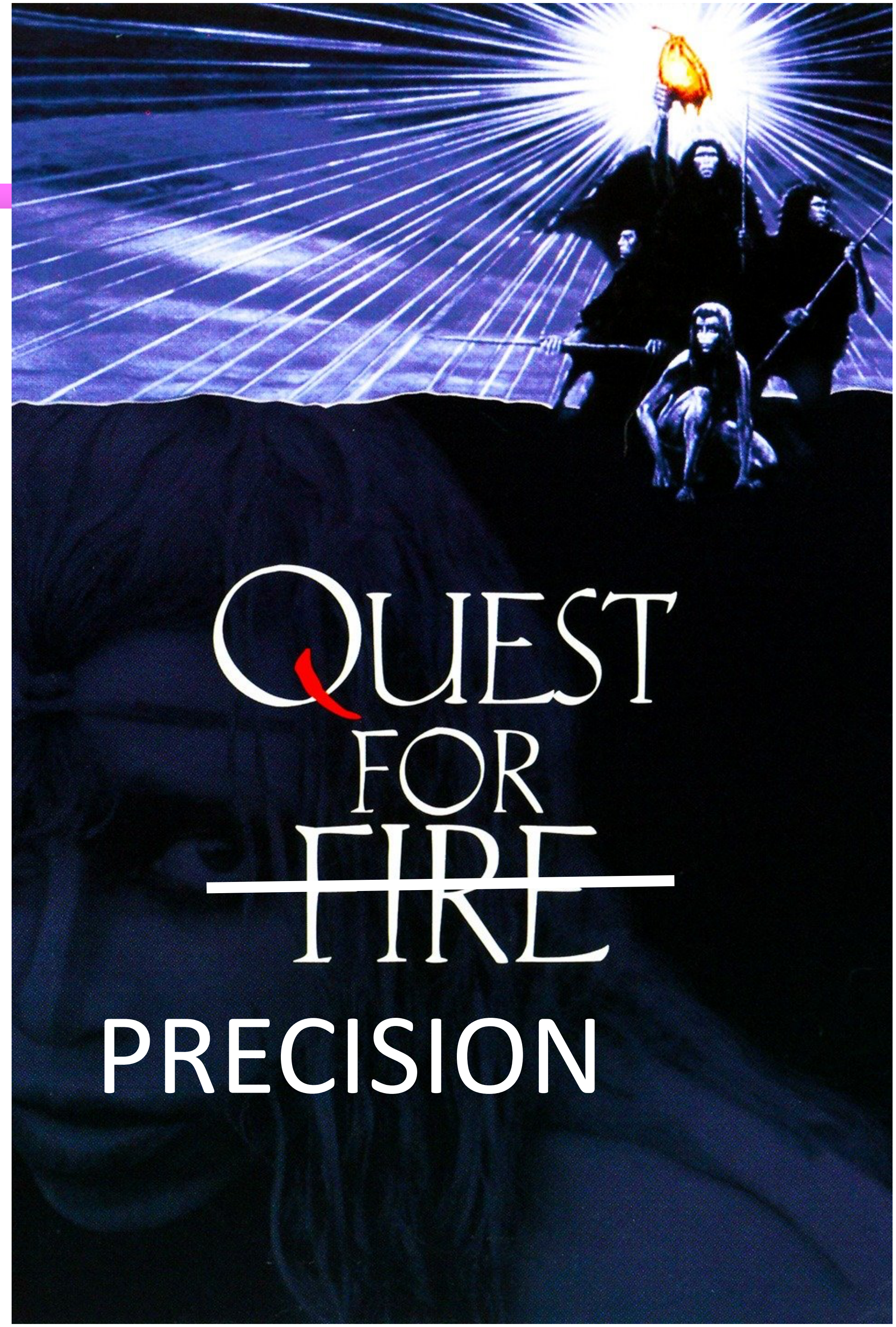
- It’s clear by now at the LHC that copious new physics isn’t jumping out at us
- 100 TeV (and nature) may be kinder to us
- But, to be prepared, and in order to better understand the SM, and especially, the Higgs sector, at the LHC we have to extend our current precision
- This may involve improvements 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
    - more precise determination of α_s



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!

…and was replaced on a high precision wishlist in 2013

Process	State of the Art	Desired
H	$d\sigma$ @ NNLO QCD (expansion in $1/m_t$) full m_t/m_b dependence @ NLO QCD and @ NLO EW NNLO+PS, in the $m_t \to \infty$ limit	$d\sigma$ @ NNNLO QCD (infinite-m_t limit) full m_t/m_b dependence @ NNLO QCD and @ NNLO QCD+EW NNLO+PS with finite top quark mass effects
H + j	$d\sigma$ @ NNLO QCD (g only) and finite-quark-mass effects @ LO QCD and LO EW	$d\sigma$ @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + 2j	σ_{tot}(VBF) @ NNLO(DIS) QCD $d\sigma$(VBF) @ NLO EW $d\sigma$(gg) @ NLO QCD (infinite-m_t limit) and finite-quark-mass effects @ LO QCD	$d\sigma$(VBF) @ NNLO QCD + NLO EW $d\sigma$(gg) @ NNLO QCD (infinite-m_t limit) and finite-quark-mass effects @ NLO QCD and NLO EW
H + V	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW σ_{tot}(gg) @ NLO QCD (infinite-m_t limit)	with $H \to b\bar{b}$ @ same accuracy $d\sigma$(gg) @ NLO QCD with full m_t/m_b dependence
tH and $\bar{t}$H	$d\sigma$(stable top) @ LO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
$t\bar{t}$H	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD and NLO EW
$gg \to HH$	$d\sigma$ @ NLO QCD (leading m_t dependence) $d\sigma$ @ NNLO QCD (infinite-m_t limit)	$d\sigma$ @ NLO QCD with full m_t/m_b dependence

Screenshot alias

Similar lists for vector boson, top and jet sectors.

arXiv:2003.01700 (seems like a lifetime ago)

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

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.
->Frank's talk

Why do we need to perform such difficult calculations?

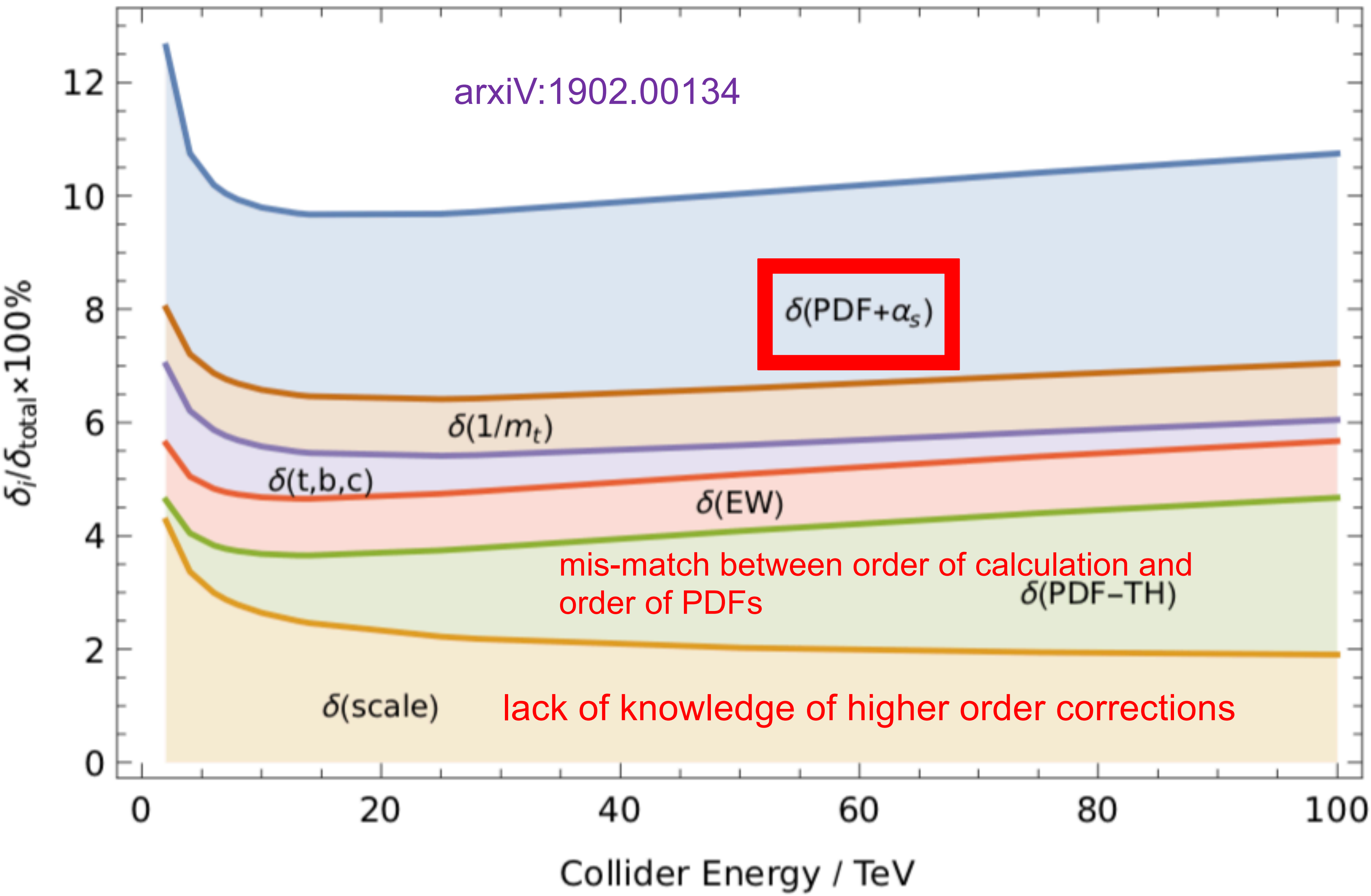
- Besides keeping QCD theorists off the street?
- Because of the needs of the HL-LHC (and 100 TeV)
- For example, for inclusive Higgs

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) $\mathrm{NNLO_{QCD}}$

The experimental uncertainty on the total Higgs boson cross section is currently of the order of 8% [387] based on a data sample of 139 fb^{-1}, and is expected to reduce to the order of 3% or less with a data sample of 3000 fb^{-1} [388]. To achieve the desired theoretical uncertainty, it may be necessary to calculate the finite-mass effects to $\mathrm{NNLO_{QCD}}$, combined with fully differential $\mathrm{N^3LO_{HTL}}$ corrections.

Much of this experimental improvement is due to something that will definitely happen, i.e. statistical uncertainties. Some of it is due to expected improvements in experimental systematic errors.

Uncertainties for ggF



$\alpha_s(m_Z)$ 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 $\equiv \mathcal{O}(\alpha_s \alpha)$.

From my talk yesterday

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

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

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

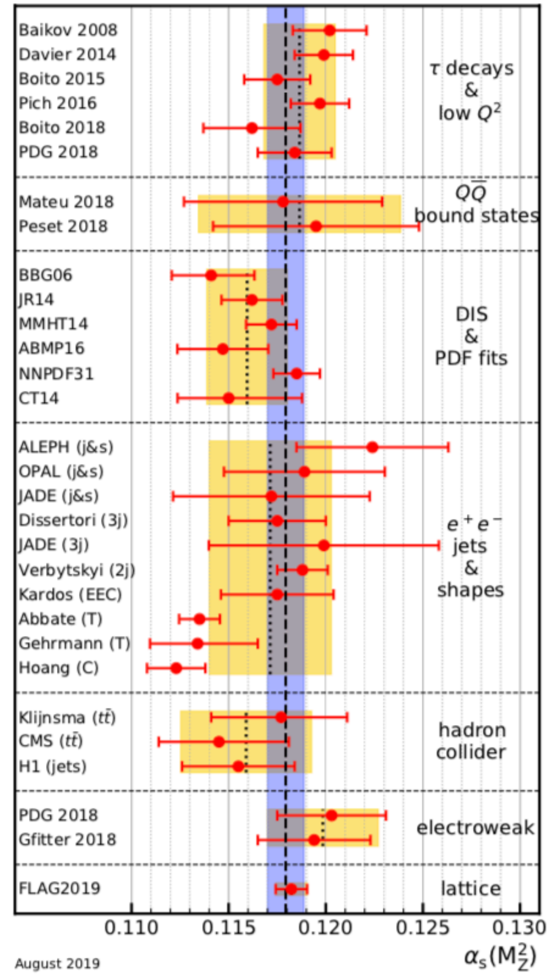
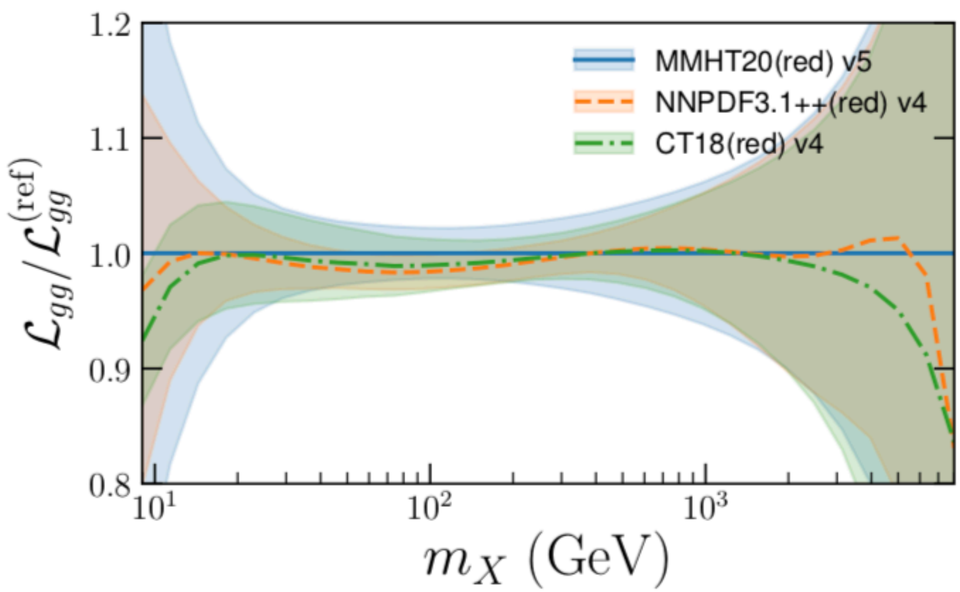


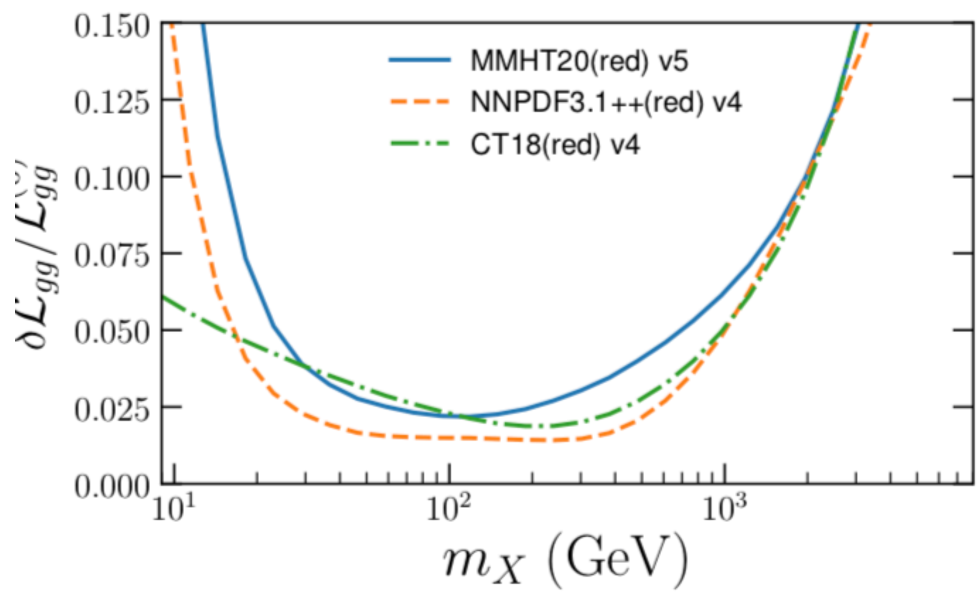
Figure 9.2: Summary of determinations of $\alpha_s(M_Z^2)$ from the seven sub-fields discussed in the text. The yellow (light shaded) bands and dotted lines indicate the pre-average values of each sub-field. The dashed line and blue (dark shaded) band represent the final world average value of $\alpha_s(M_Z^2)$.

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

PDF uncertainties

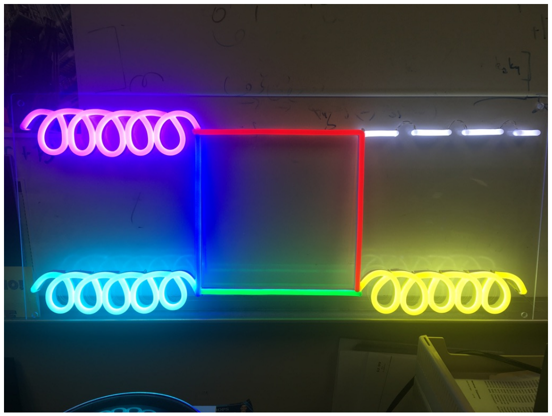
- See Maria's talk yesterday and Juan Rojo's talk from last Friday's PDF4LHC meeting
- More data doesn't necessarily mean more precision or better agreement among global PDF fits
- We're in the process of carrying out benchmark studies with the goal of an ultimate combination similar to what was done for PDF4LHC15
- Starting from a reduced set simple enough that each group should get similar results, but complete enough that the results make sense
- Useful, for example, to normalize the uncertainty definition which is different for the three groups
- This is experiment-driven in the sense that the PDF uncertainties depend on the experimental errors (and tensions) of the data. We are starting to get input from lattice. This will only improve.





What about Higgs+jet?

- Something near and dear to my heart



$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$

The current experimental uncertainty on the Higgs + ≥ 1 jet differential cross section is of the order of 10–15%, dominated by the statistical error, for example the fit statistical errors for the case of the combined $H \to \gamma\gamma$ and $H \to 4\ell$ analyses [387]. With a sample of 3000 fb^{-1}, the statistical error will nominally decrease by about a factor of 5, resulting in a statistical error of the order of 2.5%. If the remaining systematic errors (dominated for the diphoton analysis by the spurious signal systematic error) remain the same, the resultant systematic error would be of the order of 9%, leading to a total error of approximately 9.5%. This is similar enough to the current theoretical uncertainty that it may motivate improvements on the $H+j$ cross section calculation. Of course, any improvements in the systematic errors would reduce the experimental uncertainty further. Improvements in the theory could entail a combination of the $\mathrm{NNLO_{HTL}}$ results with the full $\mathrm{NLO_{QCD}}$ results, similar to the reweighting procedure that has been done one perturbative order lower.

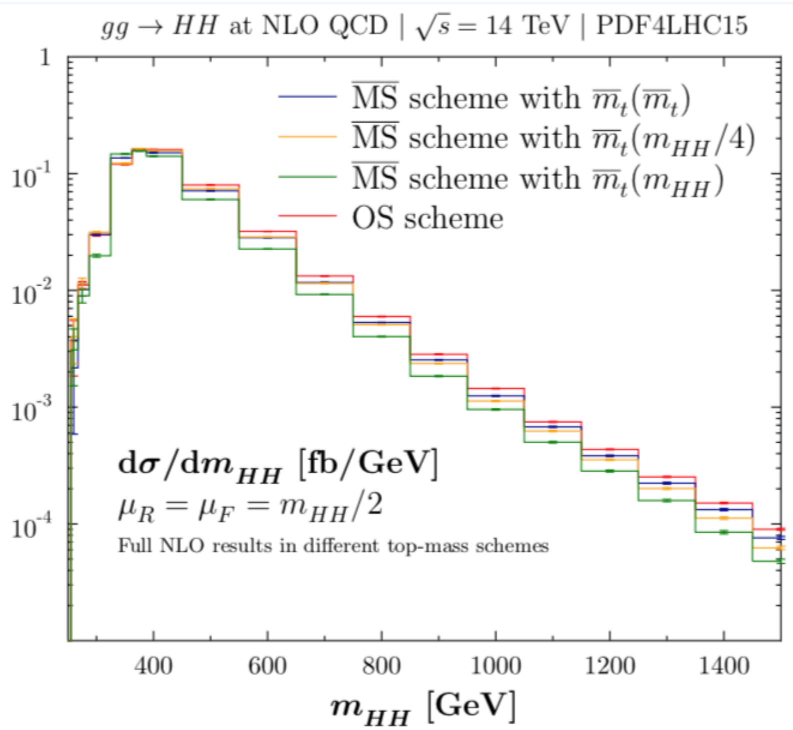
Note that inclusive jet distributions, i.e. H+>=1 jet are more powerful, from both experimental and theoretical considerations, than exclusive distributions, i.e. H+==1 jet.

Finite top mass effects

- We’re interested in Higgs, but especially at high p_T, where new physics effects might be found
- Higgs+>=1 jet has been calculated to NNLO by several groups, but in the EFT
- Higgs+>=1 jet has been calculated to NLO in the full theory
- There is a significant difference between the two above the top quark threshold, where the top quark loop starts to be resolved
- arXiv:2005.07762 uses histogram-level reweighting to correct NNLO calculation for finite top mass effects
- Ongoing study to perform reweighting in point-by-point manner, Xuan Chen et al

Top Mass Scheme Uncertainties

HH production



Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18

on-shell vs MSbar top mass; what scale to use for running of MSbar

M.Spira @ Les Houches

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\mathrm{MS}}$)

  $\to$ modification of mass CT

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$

  uncertainty = envelope

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\ \mathrm{GeV}} = 0.031(1)^{+10\%}_{-22\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\ \mathrm{GeV}} = 0.1609(4)^{+7\%}_{-7\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\ \mathrm{GeV}} = 0.03204(9)^{+0\%}_{-26\%}\ \mathrm{fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\ \mathrm{GeV}} = 0.000435(4)^{+0\%}_{-30\%}\ \mathrm{fb/GeV}$$

preliminary interpolation:

$$\sigma_{NLO} = 32.78(7)^{+13.5\%}_{-12.5\%}\ fb$$

"usual" uncertainty

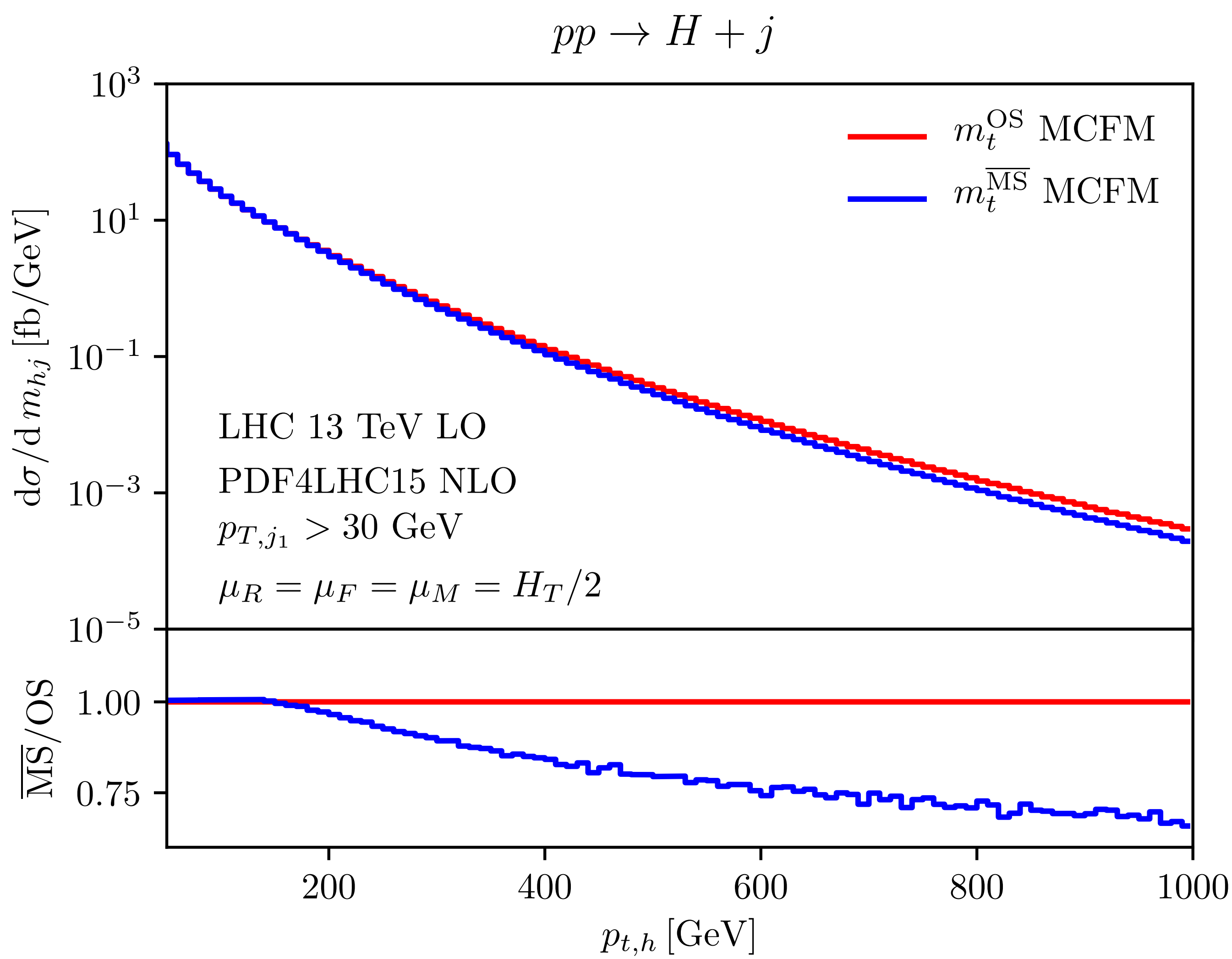
need to combine them

$$\sigma(gg \to HH) = 32.78^{+4\%}_{-17\%}\ \mathrm{fb}$$

extra top mass uncertainty

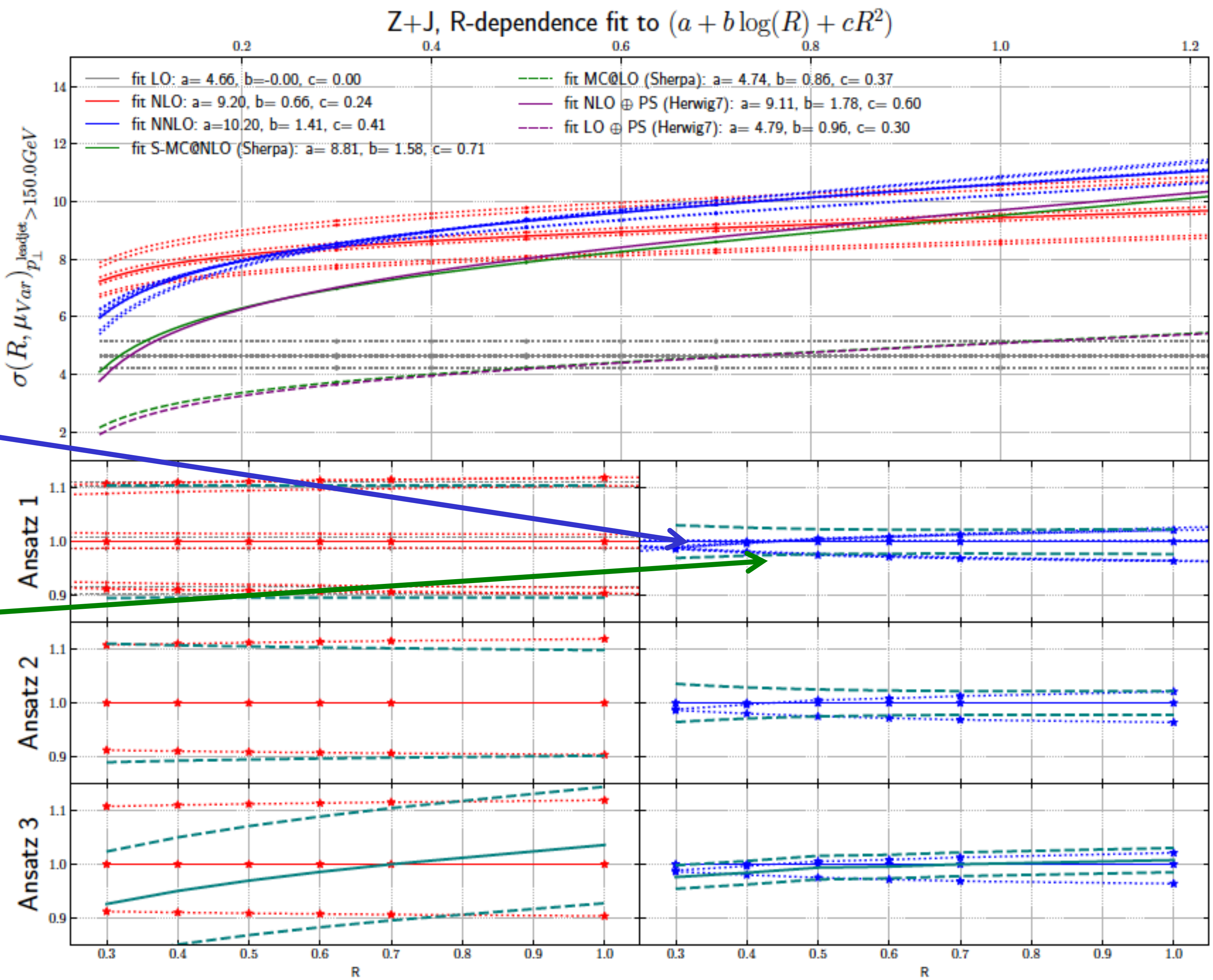
…also relevant for H*, H+jet, gg->ZZ

It's also there for single Higgs production



arXiv:1903.12563: uncertainties at NNLO

- At NNLO, there are accidental cancellations, that lead to an artificially low scale uncertainty for processes with small R (0.4) jets
- Prescription for restoring reasonable uncertainty estimate
- Worse for dijets; ~ok for Higgs
- A Les Houches accord?



Summary

- Searches for new physics, as well as a better understanding of standard model physics, require an increasing level of precision, both for measurement and for theory
- On the theory side, an increase in precision also requires an increase in precision for the inputs to the calculations (i.e. PDFs, $\alpha_s(m_Z)$...)
  - we will need to understand the impact of the new LHC data on the PDFs and their uncertainties
- For differential distributions, the highest level of precision is currently obtained with NNLO calculations
- Matched NLO+PS start from less-accurate fixed order results, but provide a more complete description of event structure, including resummation effects at leading log accuracy
- Accidental cancellations can lead to unphysical estimates for the scale uncertainties for small R jets

Snowmass LOI

Snowmass LOI Les Houches Wishlist: placeholder

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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-Collier (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.

Extra

before resummation

after resummation

next-to-next-to leading logs

next to leading logs

leading logs