Theory needs for the LHC

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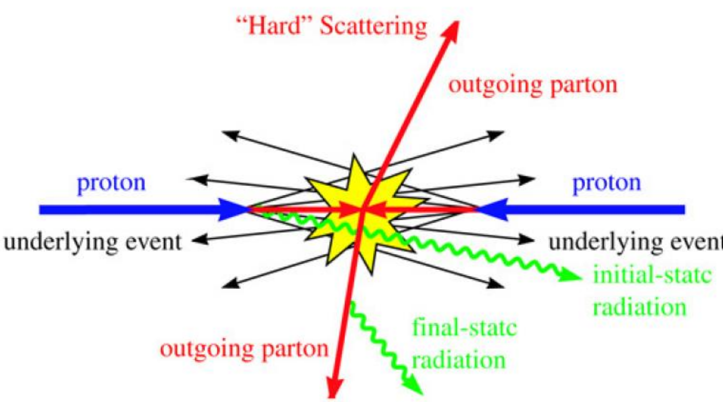
Loopfest 2024
conversation starter

To quote Tevye in Fiddler on the Roof

- Precision!
- …is one of the keys for better understanding SM Higgs production and looking for possible BSM physics



- PDFs, especially the determination of uncertainties
- L_2 sensitivity, hopscotch, ~N3LO, ~N3LO gluon and the Higgs
- $\alpha_s(m_Z)$, especially determinations at the LHC
- Matrix elements->the LH wishlist

->experimental uncertainties that require theory improvements

- STXS: multi-boson template cross sections for VBF/VBS
- Jet algorithms: issues with heavy flavor, issues with NNLO comparisons
- quark/gluon jet discrimination

->https://arxiv.org/abs/2003.01700

Theory predictions

- Predictions can be at fixed order, fixed order + resummed, or fixed order + parton shower, with both QCD and EW corrections

The perturbative corrections are defined with respect to the leading order prediction in QCD and the expansion with respect to the strong and electroweak couplings read as:

$$d\sigma_X = d\sigma_X^{\mathrm{LO}} \left(1 + \sum_{k=1} \alpha_s^k d\sigma_X^{\delta\mathrm{N}^k\mathrm{LO}_{\mathrm{QCD}}} + \sum_{k=1} \alpha^k d\sigma_X^{\delta\mathrm{N}^k\mathrm{LO}_{\mathrm{EW}}} + \sum_{k,l=1} \alpha_s^k \alpha^l d\sigma_X^{\delta\mathrm{N}^{(k,l)}\mathrm{LO}_{\mathrm{QCD}\otimes\mathrm{EW}}} \right) . \quad (5)$$

The mixed QCD–EW corrections are singled out to distinguish between additive predictions QCD+EW and mixed predictions QCD⊗EW. Equation (5) only applies to cases where the leading-order process is uniquely defined. For cases with multiple types of tree level amplitudes (requiring at least two jets at hadron colliders), it is customary to classify the Born process as the one with the highest power in α_s that is typically the dominant contribution. In the following, the notation $\mathrm{NLO}_{\mathrm{SM}}$ is used to denote NLO calculations that include the complete Standard Model corrections, i.e., all QCD and EW corrections to all leading-order contributions.

- Respect the fixed order in inclusive regions of phase space

The Les Houches wishlist (arXiv:2207.02122)

A. Huss, J. Huston, S. Jones, M. Pellen

Higgs sector

2023 revision in progress with above plus Raoul Rontsch

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO^{(t)}_{QCD}}$ $\mathrm{N^{(1,1)}LO^{(HTL)}_{QCD\otimes EW}}$	$\mathrm{N^4LO_{HTL}}$ (incl.) $\mathrm{NNLO^{(b,c)}_{QCD}}$
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL} \otimes LO_{QCD}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	$\mathrm{NNLO_{HTL} \otimes NLO_{QCD} + NLO_{EW}}$ $\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ $\mathrm{NNLO^{(VBF)}_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO^{(VBF)}_{QCD}}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$
$pp \to VH$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$ $\mathrm{NLO^{(t,b)}_{gg\to HZ}}$	
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$	$\mathrm{NNLO_{QCD} + NLO_{EW}}$
$pp \to HH$	$\mathrm{N^3LO_{HTL} \otimes NLO_{QCD}}$	$\mathrm{NLO_{EW}}$
$pp \to HH + 2j$	$\mathrm{N^3LO^{(VBF^*)}_{QCD}}$ (incl.) $\mathrm{NNLO^{(VBF^*)}_{QCD}}$ $\mathrm{NLO^{(VBF)}_{EW}}$	
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD} + NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (off-diag.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD} + NLO_{EW}}$

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

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experimental justification

The experimental uncertainty on the total Higgs boson cross section is currently of the order of 8% [401] 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} [402]. Most Higgs boson couplings will be known to 2-5%. To achieve the desired theoretical uncertainty, it may be necessary to also consider the finite-mass effects at $\mathrm{NNLO_{QCD}}$ from b and c quarks, combined with fully differential $\mathrm{N^3LO_{HTL}}$ corrections.

need combination exercise of mixed QCD/EWK

$\mathrm{N^4LO}$ doable within timescale of Run 3

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$pp \to H + j$	$\mathrm{NNLO}_{\mathrm{HTL}}$ $\mathrm{NLO}_{\mathrm{QCD}}$ $\mathrm{N}^{(1,1)}\mathrm{LO}_{\mathrm{QCD}\otimes\mathrm{EW}}$	$\mathrm{NNLO}_{\mathrm{HTL}} \otimes \mathrm{NLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}}$

The current experimental uncertainty on the Higgs $+ \geq 1$ 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 [424, 425]. With a sample of 3000 fb^{-1} of data, 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 $\mathrm{NNLO}_{\mathrm{HTL}}$ results with the full $\mathrm{NLO}_{\mathrm{QCD}}$ results, similar to the reweighting procedure that has been done one perturbative

N3LO HTL+matching to resummation for intermediate regime; may need to do better than HTL NNLO+NLO QCD for high p_T regime; mass uncertainties and perturbative stability may become issue at high p_T; EWK corrections for ggF at high p_T are still incomplete

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2->3 at NNLO is current frontier; techniques almost complete

NNLO HTL probably most crucial; help with understanding VBF background

probably fine

effectively 2->2

soft Higgs approximation

~NNLO available; still need 2 loop virtuals but impact should be small, or is it? singularity structure is very complex; see Manfred's talk on Monday

only 2->2, but with two masses

Improvements in Monte Carlos

- Ongoing effort towards NLL-accurate parton showers, by Panscales (see Silvia's talk) as well as Sherpa and Herwig; NLL is important but not all-important
- For example, for multi-jet final states such as Higgs+jets, matching/merging uncertainties are probably more important than shower logarithmic accuracy
- For many Monte Carlo predictions at the LHC, non-perturbative effects can dominate (->VBF production; for both signal and ggF background; are these non-reducible?)
- Above issues are being addressed in a study in progress, specifically looking at the ggF backgrounds to VBF production
- Many LHC results have at least a partial veto of phase space, for example with jet binning (1 jet, 2 jet,…)
  - can quote exclusive cross sections, but where possible also provide inclusive cross sections, e.g. Higgs+>=1 jet
  - perhaps can estimate the size of binning for inclusive cross sections by using Caesar-style resummation in parton shower Monte Carlos
- Complex final states (such as Higgs + 3 jets at NLO) have an issue with negative weights; cell resampling (arXiv:2303.15246) seems to be a great way of speeding up Monte Carlo production in the presence of many negative weight events

Scale dependence of NNLO cross sections with jets

- By looking at the scale dependence of jet cross sections as a function of R, it becomes clear that there can be an artificial reduction of the 'true' scale dependence at NNLO due to accidental cancellations resulting from the restriction in phase space
- For example for dijet, Z+jet, there are R-values near 0.4 for which the scale uncertainty is apparently zero->**artifact**
- Idea: view the differential cross section as a combination of a fixed-order term and the normalized all-orders result (1602.01110), i.e. the production of a parton and then the fragmentation of that parton into a jet of size R
  - combine through multiplicative matching
  - re-expand to fixed order

$$\sigma(R) = \sigma(R_0)\frac{\sigma(R)}{\sigma(R_0)} \approx \sigma(R_0)\cdot\left(1 + \alpha_S\,\partial_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0} + \alpha_S^2\,\partial^2_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0}\right)\,.$$

- There are several possible choices as to the implementation of the factorization on RHS
- There's more work to be done on this. It's on my to-do list.

Jet tagging

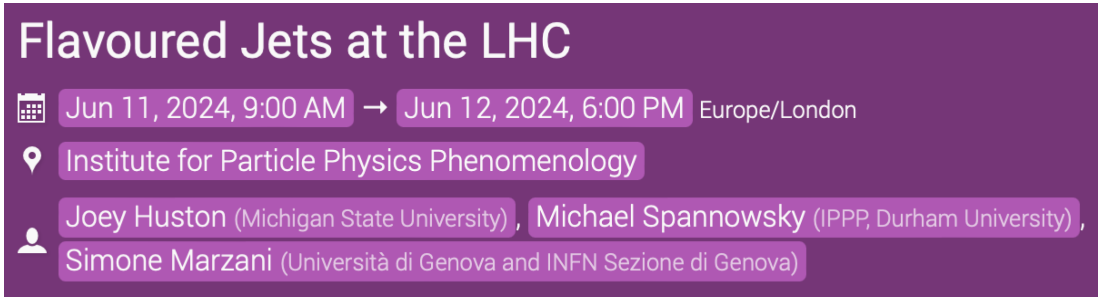
- There is also the issue of how heavy flavor jets are tagged; the theory predictions use a flavor tagging k_T jet algorithm in which the distance between pseudo-jets *i* and *j* (d_{ij}) are dependent on the flavour of the considered partons

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} max\,(k_{\mathrm{T}i}, k_{\mathrm{T}j})^2 & \text{if softer of } i,j \text{ is flavored} \\ min\,(k_{\mathrm{T}i}, k_{\mathrm{T}j})^2 & \text{if softer of } i,j \text{ is unflavored} \end{cases}$$

  - the distance to the beam is also flavour-dependent

$$d_{i\beta} = \begin{cases} max\,(k_{\mathrm{T}i}, k_{\mathrm{T}\beta}\,(y_i))^2 & \text{if } i \text{ is flavored} \\ min\,(k_{\mathrm{T}i}, k_{\mathrm{T}\beta}\,(y_i))^2 & \text{if } i \text{ is unflavored} \end{cases}$$

- The experimental measurements typically use the anti-k_T jet algorithm with later flavor identification (*Eur.Phys.J.C* 47 (2006) 113)
- The difference between the two may not be small (10-15%)
- There are a plethora of theory solutions to this issue; how well do they work in an experimental environment
- Workshop at Durham in June



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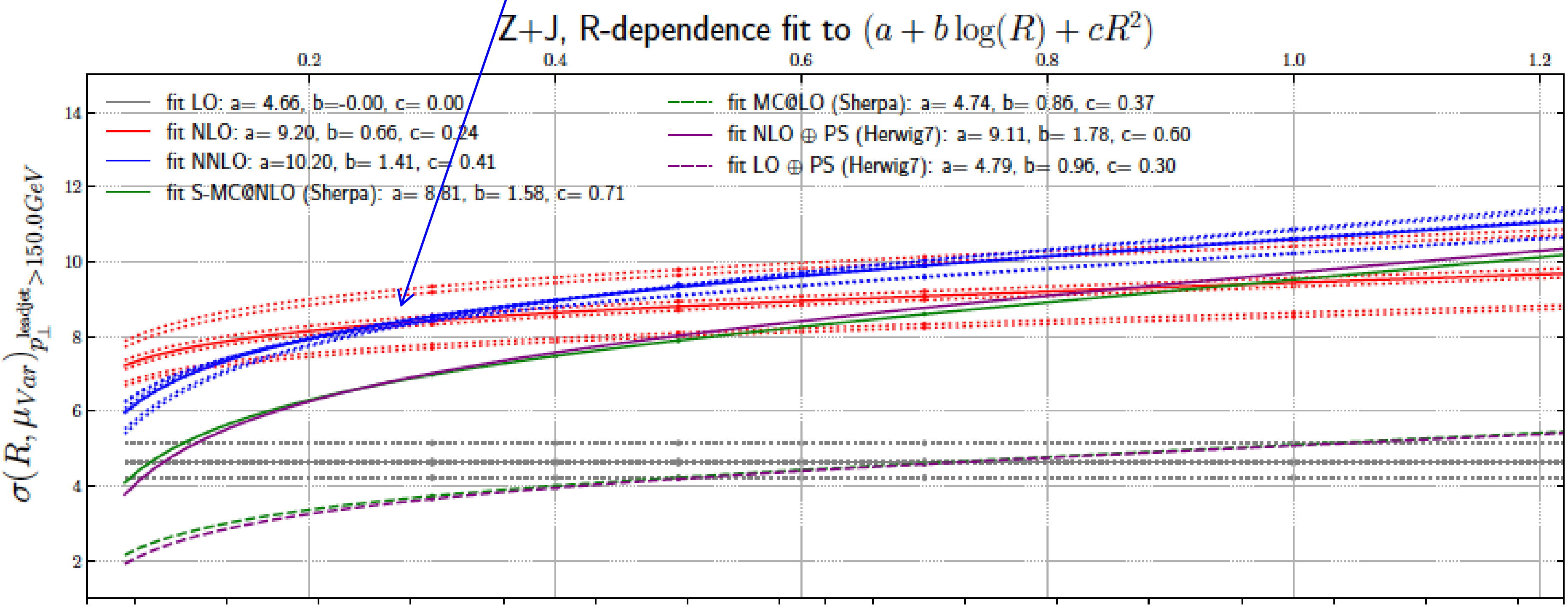
VBF paper plans

- Lack of time resulted in not having complete comparison of ggF backgrounds from different ME+PS predictions to VBF in this previous paper
- We are working on that problem in this next study
- We also did not produce plots at the hadron level for the previous paper, as that was not the primary goal
- We will do so in this paper, having the MC authors chose their best tune/parameters, as well as the ATLAS/CMS tunes and look for differences in the resulting distributions
  - comparing cluster and string fragmentation within same MC framework
- We have collected the information for current MC running in ATLAS and CMS (see extra slides)
  - reference p_{T0} values, primordial k_T and PDFs for evolution different between ATLAS and CMS, but nothing alarming
- Would be nice to ultimately have a common tune between ATLAS and CMS, but perhaps the tuning is too tied to the detector-specific environment
- If we see a smaller difference between Monte Carlo predictions in this study for VBF and ggF, and larger differences in official ATLAS/CMS predictions, then we need to understand why
- Will have both differential and STXS distributions (see extra slides)
  - Rivet routine(s) will be made available

R-dependence of scale uncertainty (Z+j)

- Again, scale dependence decreases from LO->NLO->NNLO and as R decreases
- Scale uncertainty at NNLO~0 for R=0.3



Ansatz

$$\sigma(R) = \sigma(R_0)\frac{\sigma(R)}{\sigma(R_0)} \approx \sigma(R_0)\cdot\left(1 + \alpha_S\,\partial_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0} + \alpha_S^2\,\partial^2_{\alpha_S}\frac{\sigma(R)}{\sigma(R_0)}\Big|_{\alpha_S=0}\right)\,.$$

1. $\sigma(R)/\sigma(R_o)$ on RHS not expanded, and combine the parton and fragmentation uncertainties in quadrature
2. Determine scale uncertainties from fits to coefficients a,b and c and combine them in quadrature

$$f(R) = a + b\log(R) + cR^2$$

3. Original ansatz in 1602.01110; use the expansion shown on the top of the slide