Standard Model phenomenology (theory)

Alexander Huss (CERN) and Mathieu Pellen (University of Freiburg)

Les Houches, France, 13th June 2023

“Les Houches is a bi-annual marriage-counselling retreat between theorists and experimentalists”

–Yacine Haddad

Why Les Houches is special…
… why you will enjoy being stuck in the mountains among physicists for 10 days…

- Talk to experimentalists … they won't be able to escape
- Mingle with the competition … and exchange ideas and pursue common interests

→ Start a project!

→ Typical scope of projects in SM phenomenology:
- Comparative studies
- Theory/experiment comparison
- Study theoretical & experimental aspects/challenges that needs clarification
- Les Houches accords
- **${your_project}**

→ Some sessions planned for the first few days, afterward **this is up to you!**

Some possible topics are advertised on the twiki

Techniques and calculations for SM phenomenology:

- Calculations/tools:
  - expected precision for fundamental Standard Model processes at 14 and 100 TeV; what calculations are needed to match this precision?
  - NNLO and N3LO; status/challenges/prospects
  - theory uncertainties; more rigorous estimates? correlations? In particular, theory uncertainty for EW corrections?
  - usage of NNLO results; grids seem to be a real bottleneck now for precision work
  - resummation in analytic and parton shower calculations
    - uncertainty for 'softly-vetoed' distributions
    - comparisons of jet veto calculations
    - tuned comparison of NLL parton showers; sub-leading power corrections

- PDFs:
  - followup on PDF4LHC21 benchmarking exercise; better understanding of tolerances, tensions
  - EW corrections/EW PDFs; how to provide consistent calculations (lepton definition with QED effects)
  - Electron-ion collider (EIC); what will EIC tell us? how do we prepare for that?
  - N3LO PDFS; how firm are changes to the gluon, and what should be done for benchmark Higgs cross sections; progress on splitting functions
  - PDF uncertainties, i.e. hopscotch vs Monte Carlo sampling
  - intrinsic charm
  - theory uncertainties/correlations in fit. Double counting?
  - quark-gluon discrimination for PDF determination

Just a collection of potentially interesting topics.
Feel free to come up with your own!

- Higgs:
  - understanding the SM for high Higgs pT; role of top mass corrections/scheme (MSbar vs on-shell); how to improve channel sensitivities;
  - VBF signal at high pT; gluon-fusion background in VBF phase-space
  - parton-shower uncertainties in VBF

- EW sector:
  - polarisation measurements (for diboson/VBS as well): theory/experiment interplay
  - prospects for tri-boson production. Are there any theoretical limitations for run III?
  - W mass:
    - (non-perturbative) modeling
    - new ideas/methods (asymmetry)
    - determination at e+e-
    - theory agnostic determination; how agnostic?
  - STXS for multiboson processes

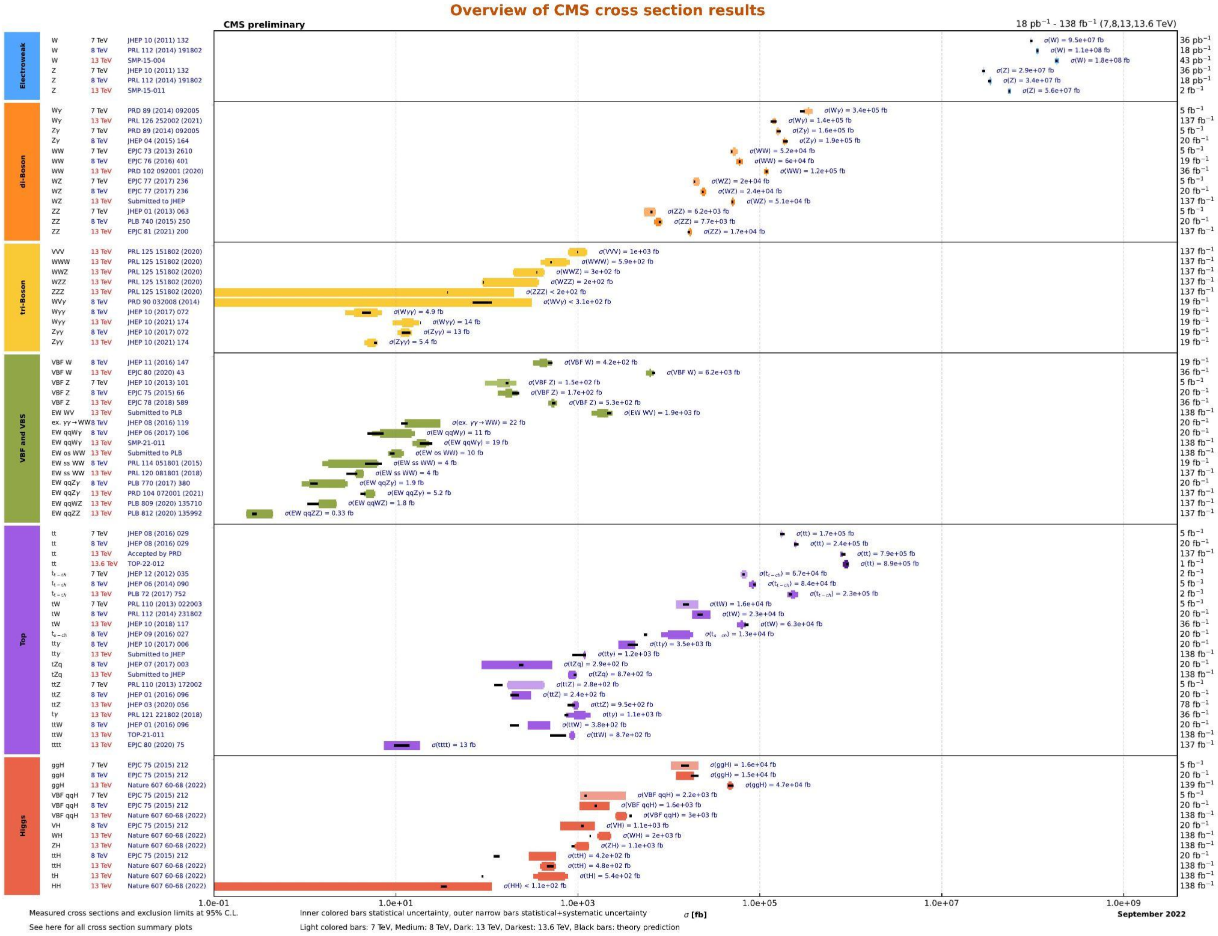
- Top:
  - ttW tension; multi-jet merging and other modelling aspects (including treatment in experiments)
  - merging of off-shell ttW with parton shower
  - modelling of ttbb
  - tt+X: on-shell vs. off-shell. role of single-top contributions
  - tt+gamma: modeling, in particular regarding on-shell/off-shell
  - Additional jet activity in top-quark pair production and decay

- Jets:
  - flavor tagging of jets; matching what theorists can predict (IR safety) and what experimentalists can measure [overlap with Jet substructure techniques, see below]
  - use heavy flavor jets for W+c (→strange quark PDFs) and Z+c (→intrinsic charm)
  - further investigations/understanding of jet R-dependent scale uncertainties

- Miscellaneous
  - forward physics → FASER. Anything needed from SM point of view?

- Machine Learning
  - Matrix Element calculation using ML
  - Interpretable models
  - Fast surrogate models for physics simulations
  - Workflows and interoperability with experimental software
  - Incorporating uncertainties in the training of ML models
  - ML-based unfolding techniques
  - Enforcing properties to ML models: Lorentz invariance/equivariance, permutation invariance, IRC safety

Precision at the LHC - Experiment



Precision at the LHC - Theory

Les Houches wishlist!

- Up-to-date reference of theory work at fixed order
  ... convenient to get a grasp of the current **state of the art**
- Define the next frontier
  … useful to get inspired what process to tackle next
- Interface theory–experiment
  ... communicate the **needs** from experiments to theorists

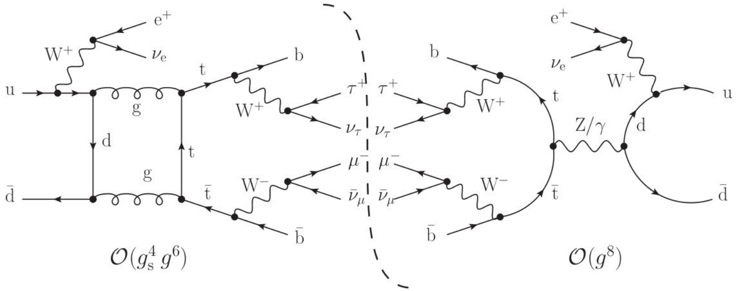
Dedicated session - XX:YY on ZZZZ:
→ Come to the meeting with a list of processes you think should computed better!

[Huss, Huston, Jones, Pellen; 2207.02122]

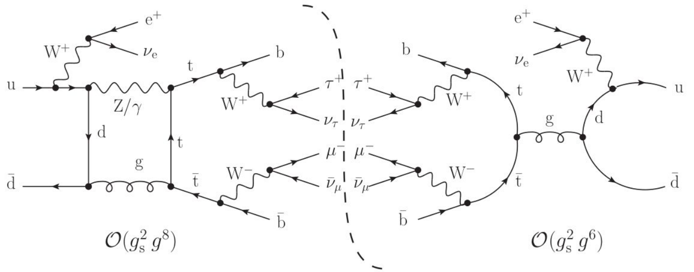
process	known	desired
$pp \to V$	$\text{N}^3\text{LO}_{\text{QCD}}$ $\text{N}^{(1,1)}\text{LO}_{\text{QCD}\otimes\text{EW}}$ NLO_{EW}	$\text{N}^3\text{LO}_{\text{QCD}} + \text{N}^{(1,1)}\text{LO}_{\text{QCD}\otimes\text{EW}}$ $\text{N}^2\text{LO}_{\text{EW}}$
$pp \to VV'$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ $+ \text{NLO}_{\text{QCD}}$ (gg channel)	NLO_{QCD} (gg channel, w/ massive loops) $\text{N}^{(1,1)}\text{LO}_{\text{QCD}\otimes\text{EW}}$
$pp \to V + j$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	hadronic decays
$pp \to V + 2j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (QCD component) $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (EW component)	NNLO_{QCD}
$pp \to V + b\bar{b}$	NLO_{QCD}	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
$pp \to VV' + 1j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	NNLO_{QCD}
$pp \to VV' + 2j$	NLO_{QCD} (QCD component) $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (EW component)	Full $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
$pp \to W^+W^+ + 2j$	Full $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
$pp \to W^+W^- + 2j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	
$pp \to VV'V''$	NLO_{QCD} NLO_{EW} (w/o decays)	$\text{NLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$
$pp \to W^{\pm}W^{+}W^{-}$	NLO_{QCD} + NLO_{EW}	
$pp \to \gamma\gamma$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	$\text{N}^3\text{LO}_{\text{QCD}}$
$pp \to \gamma + j$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$	$\text{N}^3\text{LO}_{\text{QCD}}$
$pp \to \gamma\gamma + j$	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$ $+ \text{NLO}_{\text{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	NNLO_{QCD}	$\text{NNLO}_{\text{QCD}} + \text{NLO}_{\text{EW}}$

Table 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.

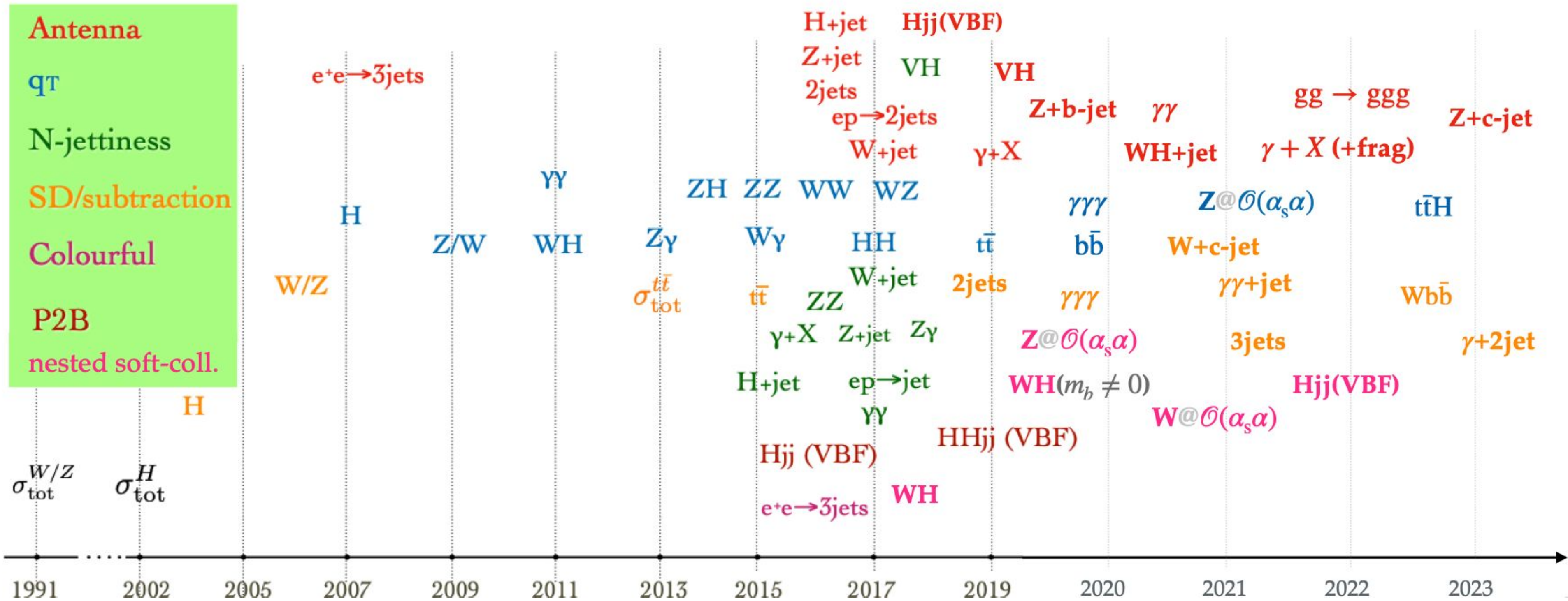
NLO automation: are we done?



- Frontiers:
  - off-shell & high-multiplicity (dedicated private codes):
    2→8: **ttW** @ NLO QCD+EW [Denner, Pelliccioli; 2102.03246],
    2→9: **ttW+j** @ NLO QCD [Bi, Kraus, Reinartz, Worek; 2305.03802]
  - mostly on-shell: 2→5/6 (readily available in public codes)
- Non-standard calculations
  - Loop induced
    - Done: HH, H+j, ZH, AA+j, gg→ZZ (amplitude only)
    - Desired: H+2j, H+3j, HH (@ NLO EW)
  - Polarisation
  - Matching consistent QCD/QED



The NNLO Timeline



Current frontiers in higher-order calculations

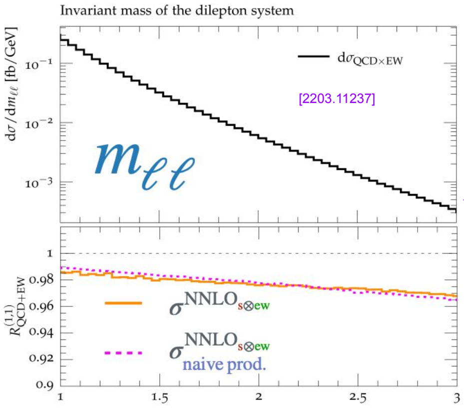
NNLO in good shape

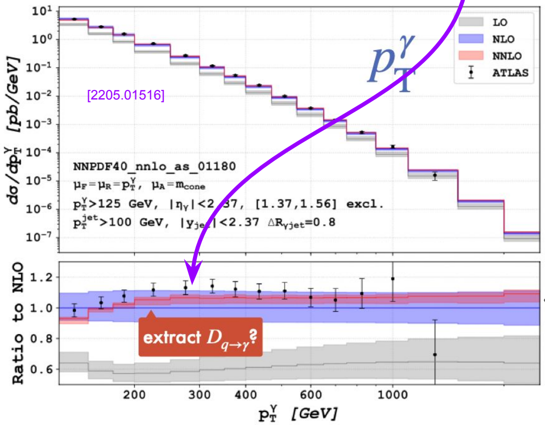
How good are they & how robust are the uncertainty estimates on them?
Transferable to other processes currently of reach?

- 2→2 largely done (w/ independent calcs ↔ validation), good progress in 2→3
  - bottlenecks: performance of subtractions, availability of loop amplitudes
  - ⇒ approximate what we don't have: **VBF** (non-fact.), **Wbb** (mb≠0: massification), **ttH** (eikonal Higgs), …
- going beyond "standard" calculations
  - adding flavour, adding masses, mixed QCD-EW, identified particles (fragmentation functions)

naive product known to perform poorly around resonances/shoulders

High-energy Sudakov logarithms however largely factorize!





photon isolation studies at one order higher?

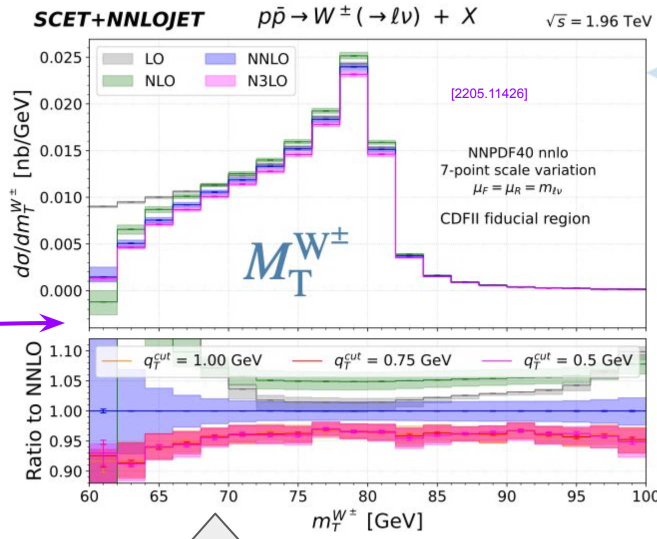
design observables sensitive to the fragmentation component to extract it?

Current frontiers in higher-order calculations

N3LO basically limited to "2→1" type processes so far

- Inclusive predictions σ(tot) mature for this class
  - ggH(H), bbH, VBF-H(H), DY, VH (DY-like), …
- Differential calculations with two approaches
  - Projection-to-Born: DIS, H→bb, ggH
  - qT subtraction: ggH, DY
- Towards 2→2 and beyond
  - Massless 3-loop amplitudes known
  - Stable "underlying" NNLO implementation
  - A general subtraction scheme?

What are good candidates?
How would they scale at N3LO?
Where do we anticipate bottlenecks?



Substantial computing cost for qT subtraction. Smarter approaches to perform calculation & provide to the public?

Dissemination of theory results (a very naive fixed-order perspective)

- Lv.0: Compute something and ask experimentalists to cite your work
- Lv.1: Provide predictions for an experimental analysis
- Lv.2: Write a (public) code so experimentalists can do Lv.1 themselves

→ All levels are far from trivial (even Lv.0)

→ There are levels going beyond 2 of course: e.g. matching to PS, …

→ Even at Lv.1 & 2, there are severe computing/storage bottlenecks to overcome:

- O(100k) CPU core hours for a typical 2→2 NNLO computation
  ⇝ grids for pre-defined histograms: APPLgrid, fastNLO, PineAPPL, …
- "Theory events" for flexible post-processing (huge number)
  ⇝ storage & access are key: LHE, nTuples, HighTea, …

Recent results from two of such approaches: interpolation grids / event files

Common interface?

- **NNLO interpolation grids for jet production at the LHC**

  D. Britzger[1], A. Gehrmann-De Ridder[2,3], T. Gehrmann[3], E.W.N. Glover[4], C. Gwenlan[5], A. Huss[6], J. Pires[7,8], K. Rabbertz[9,10], D. Savoiu[11], M.R. Sutton[12], J. Stark[9]

NNLO [grid]
v.s.
NLO [grid] × K-factor
?

Extensions for fragmentation functions? (photon, hadron, …)

- **HighTEA: High energy Theory Event Analyser**

  Michał Czakon,[a] Zahari Kassabov,[b] Alexander Mitov,[c] Rene Poncelet,[c] Andrei Popescu[c]

requirements, storage location, own server, …?

Dedicated session - 09:00 on Th. 15.06:
→ Presentation by APPLfast and HighTea

Uncertainties of theory predictions

In the precision era, it is becoming increasingly important to have more robust uncertainty estimates for theory predictions:

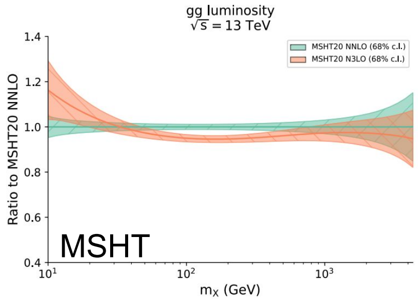
- Alternatives to scale variations
  (Pade approximants, sequence transformation, scheme variations, Bayesian inference, …)
- How to determine/treat theory correlations?
- Potential double-counting in case where PDF fits include TH uncertainties?
- In an era of approximate N3LO PDFs: how do we estimate uncertainties from the incomplete N3LO evolution & missing N3LO predictions in the fits?

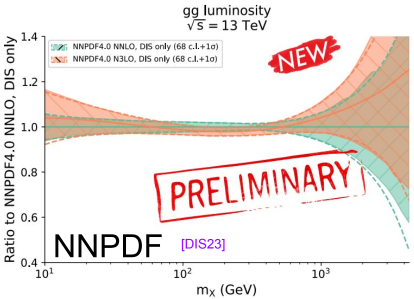
gg-lumi, ratio to PDF4LHC15 @ m_H

PDF4LHC15	1.0000	±	0.0184
PDF4LHC21	0.9930	±	0.0155
CT18	0.9914	±	0.0180
MSHT20	0.9930	±	0.0108
NNPDF40	0.9986	±	0.0058

×3

[from slide by G.Salam—Higgs21]





ggH using MSHT

$$\delta(\text{PDF-TH}) = \pm\tfrac{1}{2}\left|\sigma^{(2)}(\text{PDF}_{\text{NNLO}}) - \sigma^{(2)}(\text{PDF}_{\text{NLO}})\right| \rightsquigarrow \pm 1\%$$

$$\delta(\text{PDF-TH}^{(3)}) = \left|\sigma^{(3)}(\text{PDF}_{\text{aN3LO}}) - \sigma^{(3)}(\text{PDF}_{\text{NNLO}})\right| \rightsquigarrow 5\text{–}6\%$$

Dedicated session - XX:YY on ZZZZ:

Uncertainties for electroweak corrections

- Uncertainty in QCD predictions to estimate higher orders: **scale variation**
  → simple recipe that appears to work rather well
  → not working for EW corrections (would lead to almost zero uncertainty)

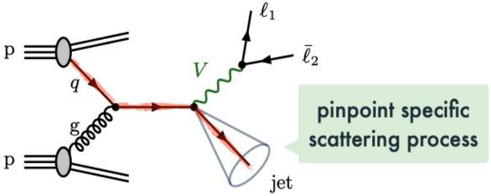
- EW corrections beyond NLO EW can be large (and have cancellations)
- Non trivial task as various source of corrections (QED, weak, pure and mixed corrections…)

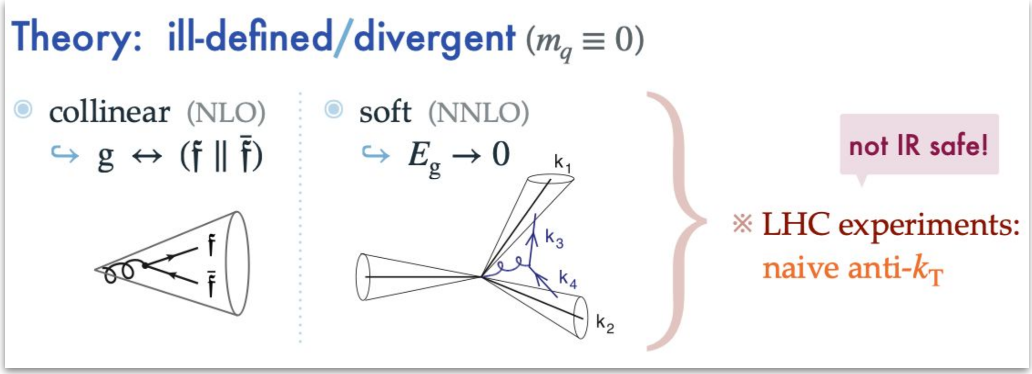
→ Can we find a (simple?) receipt for this?

→ Can we reach a **Les Houches accord** for this?

Dedicated session - 09:00 on Fr. 16.06

The flavour of jets





Original solution:
Adjust the jet definition: flavour-kt
[Banfi, Salam, Zanderighi; hep-ph/0601139]

→ Much interest recently:

- VH(→bb) [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer; 1907.05836], [Behring, Bizoń,Caola, Melnikov, Röntsch; 2003.08321]
- Z+b [Gauld, Gehrmann-De Ridder, Glover, Huss, Majer ; 2005.03016]
- W+c [Czakon, Mitov, Pellen, Poncelet; 2011.01011, 2212.00467], [Bevilacqua, Garzelli, Kardos, Toth; 2106.11261], [Ferrario Ravasio, Oleari; 2304.13791]
- W+bb [Hartanto, Poncelet, Popescu, Zoia; 2205.01687, 2209.03280], [Buonocore, Devoto, Kallweit, Mazzitelli, Rottoli, Savoini; 2212.04954]
- Z+c [Gauld, Gehrmann-De Ridder, Glover, Huss, Rodriguez Garcia; 2302.12844]

Flavour jet algorithms

(towards a flavour definition for anti-kt jets)

Could it also be useful for quark-gluon discrimination?

- **Infrared-safe flavoured anti-k_T jets**

  Michal Czakon,[a] Alexander Mitov,[b] Rene Poncelet[b]

- Practical Jet Flavour Through NNLO

  Simone Caletti[1], Andrew J. Larkoski[2], Simone Marzani[1] and Daniel Reichelt[3]

- **A Fragmentation Approach to Jet Flavor**

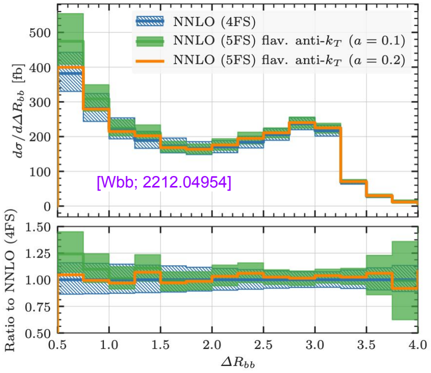
  Simone Caletti,[1] Andrew J. Larkoski,[2] Simone Marzani,[1] and Daniel Reichelt[3]

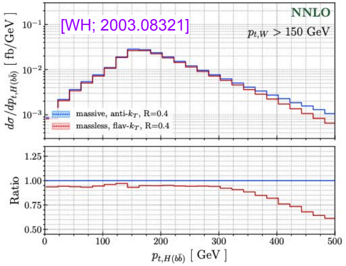
- **A dress of flavour to suit any jet**

  Rhorry Gauld[1], Alexander Huss[2], Giovanni Stagnitto[3]

→ Open questions:

- Differences between these algorithms?
- Use in measurements?
  (fastjet API for standardised flavour information?)
- Fixed-order vs. PS-matched?
- Massless vs. (approx.) massive?
- Impact from MPI can be sizeable
  (Z+c in fwd)
- …



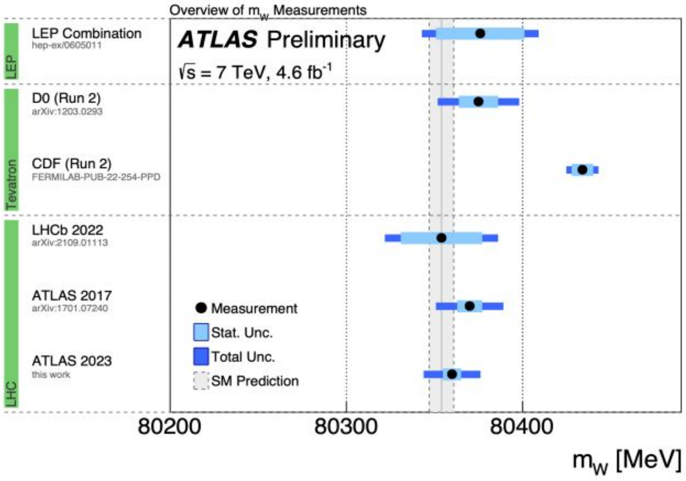


Dedicated session - 09:00 on Wed. 14.06

The W-boson mass

- As you might have heard… recent interest in W-mass measurements
  → tension in latest CDF measurement; still needs to be understood
  → **basic assumption for session I**: there is a unique W-boson mass in the Universe

- Experimental work is certainly needed
- Theory insights might also help to resolve tensions
  - (non-perturbative) modeling
  - new ideas/methods (asymmetry)
  - determination at future lepton colliders
  - theory agnostic determination; how agnostic?



[Dedicated session - 16:30 on Tue. 15.06]

Gauge-boson pT spectra

Important in MW measurement (W/Z ratio)

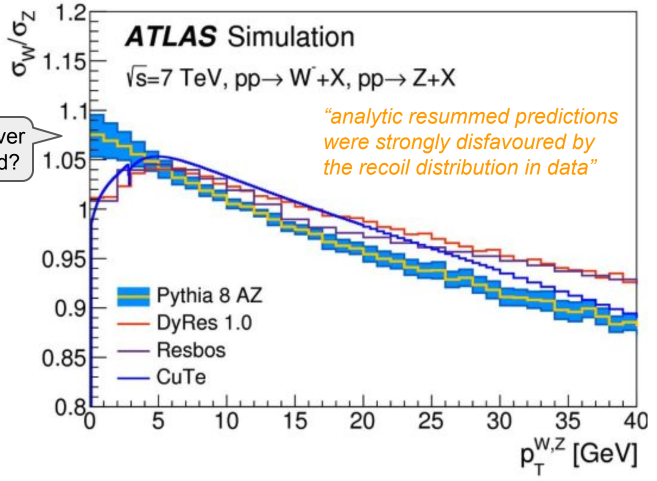
- So far: Pythia 8 AZ tune
- New resummed calculations at N3LL or approx. N4LL appear to be in far better agreement with data (how? NNLL →N3LL tiny?)
- NLL-accurate Parton Showers for PT(V); how do they compare? Herwig, PanScales … (Alaric, Deductor?)

PTZ also recently used for αs extraction (note: O(αs^3) is NNLO for this observable)

- How robust are the error estimates? Treatment of different PDFs? (spread between PDFs ≳ final error?)
- non-perturbative modelling based on ansatz by Collins Rogers '14 (robust error estimates?)

Reliable TH predictions are crucial
(ongoing resummation comparison in EWWG)

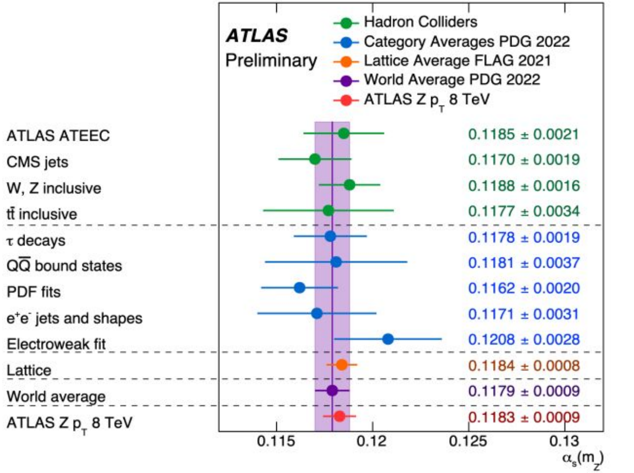
Was this ever understood?



"analytic resummed predictions were strongly disfavoured by the recoil distribution in data"

[ATLAS-CONF-2023-015]

PDF set	$\alpha_s(m_Z)$
MSHT20 [32]	0.11839
NNPDF40 [78]	0.11779
CT18A [79]	0.11982
HERAPDF20 [63]	0.11890



Enjoy Les Houches!

or

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