Theory Vision
Gavin P. Salam, CERN

*on leave from CNRS and University of Oxford/Royal Society
A theory view today

Gavin P. Salam, CERN*

*on leave from CNRS and University of Oxford/Royal Society
A typical “Vision” talk addresses the “big unanswered questions”

Nature of dark matter (& dark energy)
Fine-tuning (e.g. supersymmetry and similar)
Matter-antimatter asymmetry of the universe

[...]
Looking beyond the SM: searches for dark matter at LHC & elsewhere

Classic dark-matter candidate: a weakly-interacting massive particle (WIMP, e.g. from supersymmetry).

Masses ~ GeV upwards (search interpretations strongly model dependent)
and much less about the standard model (SM)...

since experiments have already found all its particles...
Searching for answers to the “big unanswered questions” is vitally important, 
(even if there’s no way of knowing if it will pay off)

But we shouldn’t forget the importance of “big answerable questions” 
and the issue of how we go about answering them
\[ L = -\frac{1}{4} F_{\mu \nu} F^{\mu \nu} + i F_{\mu \nu} \bar{\psi} \gamma^\mu \psi + \frac{1}{2} \lambda^2 F_{\mu \nu} F^{\mu \nu} + \lambda^3 \left( \frac{1}{2} \gamma^\mu \gamma^\nu \lambda_{\mu \nu} + 3 \gamma^\mu \lambda_{\mu \nu} \right) + y_{ij} (y_{ij} + y_{kl}) \phi + \text{h.c.} + m^2 \phi^2 - V(\phi) \]
This equation neatly sums up our current understanding of fundamental particles and forces.

This is what you get when you buy one of those famous CERN T-shirts.
This equation neatly sums up our current understanding of fundamental particles and forces.

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"understanding" = knowledge?
"understanding" = assumption?
Gauge part

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]

\[ + i \bar{F} D \gamma \]

\[ + \bar{X}_i Y_{ij} X_j \phi + \text{h.c.} \]

\[ + |D_m \phi|^2 - V(\phi) \]

This equation neatly sums up our current understanding of fundamental particles and forces.

E.g. \( qq\gamma, \ qqZ, \ qqg, \ evW, \ ggg, \) interactions — well established in ep, \( e^+e^- \), pp collisions, etc.

\( \equiv \text{KNOWLEDGE} \)

(also being studied at LHC — e.g. jets, DY/Z/W, V+jets, ttbar, etc.)
Many SM studies probe this part.

In some respects dates back to 1860’s, i.e. Maxwell’s equations.

If you test another corner of this (as one should), don’t be surprised if it works...
Yukawa couplings

until 6 years ago this was essentially conjecture

no such term had ever been seen in nature

hadn’t even been probed in electroweak precision tests

This equation neatly sums up our current understanding of fundamental particles and forces.
Why do Yukawa couplings matter?

(1) A part of the Higgs sector that’s unlike any other experimentally-probed interaction

\[-\mu^2 \phi^2 + \lambda \phi^4, \text{HHH}\] the keystone of the Higgs mechanism and Standard Model, familiar as QFT toy model, never probed in nature

(HWW, HZZ): A gauge interaction, with scalars rather than fermions; much like what we’ve seen before

(Hbb, Htt, etc.): not a gauge interaction, and unlike anything we’ve probed before
the status two years ago

➡️ A beautiful plot, appears to show SM working perfectly

➡️ But it mixes two very different kinds of interaction: gauge for W,Z, Yukawa for fermions

➡️ would not look anything like as convincing without underlying fit assumptions

➡️ no new particles in loops

➡️ no BSM decays
A year ago:
CMS >5-sigma H → ττ

35.9 fb⁻¹ (13 TeV)

This week:
ATLAS >5-sigma H → ττ

ATLAS Preliminary
(\sqrt{s} = 13 TeV, 36.1 fb⁻¹)

\tau_\text{lep} \tau_\text{had} VBF tight SR

Data 2015 + 2016
H → ττ (\mu = 1.09)
Z → ττ
W+jets
QCD multijet
Others
Bkg. unc.

VBF: \mu_\tau, e_\tau, e_\mu

m_{\tau\tau} (GeV)

S/(S+B) weighted events / GeV

m_{\tau\tau} (GeV)

\sigma = 3.0 ± 1.0 (stat)
\sigma = 125 GeV

\sigma = 125 GeV

\tau_\text{lep} \tau_\text{had} VBF tight SR

Events / GeV

Data / Bkg.

m_{\tau\tau}^{\text{MMC}} [GeV]
the news of the past 12 months

A few weeks ago: CMS >5-sigma ttH

This week: ATLAS >5-sigma ttH

Dominant uncertainties
• Statistical (~29%);
• ttH parton shower (8%);
• Photon isolation, energy resolution & scale (8%);
• Jet energy scale & resolution (6%);
• Background estimation and signal extraction performed by simultaneous unbinned fit of m_{\gamma\gamma} spectra (105-160 GeV) in all 7 categories.

Higgs signal parametrisation: double-sided Crystal Ball function;
Continuous background parametrisation: smooth function (power-law or exponential)

Target ttH + all Higgs decays with leptons in final state:
H \rightarrow (\ell\ell), H \rightarrow WW* and H \rightarrow ZZ*

Categorise events based on number of hadronic taus and light leptons
Large backgrounds from ttV, non-prompt leptons and jets faking taus depending on region
Dedicated BDTs to reject non-prompt leptons
Largest uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate

Obs. (exp.) excess of 4.1" (2.8"") for m_H = 125 GeV
Use BDT in each signal region to classify signal and background (jet and lepton kinematics)
Obs. (exp.) excess of 3.2" (2.8"") for m_H = 125 GeV
Why do Yukawa couplings matter?

(2) Because, within SM **conjecture**, they’re what give masses to all quarks

Up quarks (mass ~ 2.2 MeV) are lighter than down quarks (mass ~ 4.7 MeV)

**proton** (up+up+down): \(2.2 + 2.2 + 4.7 + \ldots = 938.3\) MeV

**neutron** (up+down+down): \(2.2 + 4.7 + 4.7 + \ldots = 939.6\) MeV

So protons are **lighter** than neutrons, \(\rightarrow\) protons are stable.

Which gives us the hydrogen atom, & chemistry and biology as we know it
Why do Yukawa couplings matter?

(3) Because, within SM conjecture, they’re what give masses to all leptons

\[ \alpha_0 = \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2} = \frac{\hbar}{m_e c \alpha} \]

Bohr radius

electron mass determines size of all atoms

it sets energy levels of all chemical reactions
what should we be saying about it?

The $>5\sigma$ observations of $ttH$ and $H \rightarrow \tau\tau$, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions.

Yukawa interactions are important not merely because they had never before been directly observed, but also because they are hypothesized to be responsible for the stability of hydrogen, and for determining the size of atoms and the energy scales of chemical reactions.
what should we be saying about it?

The $>5\sigma$ observations of $ttH$ and $H \to \tau\tau$, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions.

Yukawa interactions are important not merely because they had never before been directly observed, but also because they are hypothesized to be responsible for the stability of hydrogen, and for determining the size of atoms and the energy scales of chemical reactions.

Is this any less important than the discovery of the Higgs boson itself?

My opinion: no, because fundamental interactions are as important as fundamental particles
“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward [...]”
“the standard model, despite the glory of its vindication, is also a dead end. It offers no path forward […]”
Bottom-Yukawa coupling

How?

• Look for Higgs decays into the 1st generation
• Huge background from jet events and additional objects to tag: VH
• Complex final states ⇒ multi-jets to objects and to distinguish signal and background

Greatest challenges

• Good flavour tagging performance
• Large backgrounds from jet events

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT

Higgs potential:

\[ V(H) = \frac{1}{2} M_{H}^2 H^2 + \lambda_{SM} H^2 + \lambda_{Hbb} H^2 \]

Fixed values in the SM:

\[ \lambda_{Hbb} = \lambda_{SM} = \frac{M_{W}^2}{2 v^2} \]

Measuring \( \lambda_{Hbb} \) and \( \lambda_{SM} \) tests the SM

What can measuring \( \lambda_{Hbb} \) tell us?

Electroweak baryogenesis requires

\[ \lambda_{Hbb} / \lambda_{Hbb,SM} < 1.5 \quad \Rightarrow \quad \phi_c / T_c < 1 \]

EW baryogenesis is disfavoured

\[ \lambda_{Hbb} / \lambda_{Hbb,SM} > 2 \quad \Rightarrow \quad \phi_c / T_c > 1 \]

EW baryogenesis is favoured

so much more to do with the Higgs sector
EFT (expressive formulation of constraints) or not?

- If you’ve observed a given channel, and it agrees roughly (±30%) with SM, then go to EFT.
- If you’ve not observed it, e.g. charm Yukawa, Higgs self coupling, then use of EFT is more debatable.

\[ \mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2} \mathcal{O}_{i}^{d=6} + \sum \frac{c_i}{\Lambda^4} \mathcal{O}_{i}^{d=8} + \ldots \]

Establish SM first, then use (lack of) any deviations to (constrain) characterise new physics.

BSM effects \quad SM particles
Probing the top-Higgs interaction

14TeV projection

Combination:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

Current limits using LHC measurements

impact of recent ttH observation

Azatov et al arXiv:1608.00977

Maltoni, EV, Zhang arXiv:1607.05330

Vryonidou
the hierarchy of masses between generations remains a mystery (even if it’s one that some people consign to the “hopeless” category)

- Does not necessarily come from hierarchy of dimensionless Yukawa coefficients

- E.g. the Giudice-Lebedev mechanism (and follow-up work)

\[-\mathcal{L}_Y = Y_{ij}(\phi)\bar{\psi}_i\psi_j\phi + \text{h.c.}\]

\[Y_{ij}(\phi) = c_{ij}\left(\frac{\phi^\dagger\phi}{M^2}\right)^{n_{ij}}\]

- smallness of certain masses is consequence of vev$^2$/M$^2$ suppression, not small $c_{ij}$

- measured Hqq interaction larger by factor $(2n_{ij} + 1)$

- cf. also various more recent discussions, e.g. by Bauer, Carena, Carmona
dark matter & other searches
“Finding dark matter and studying it will be the biggest challenge for the Large Hadron Collider’s second run

-a large LHC experiment’s spokesperson [2015]

Classic dark-matter candidate: a weakly-interacting massive particle (\textbf{WIMP}, e.g. from supersymmetry).

Masses \sim \text{GeV} upwards

(search interpretations strongly model dependent)
musn’t be (too) disappointed at lack of dark matter signal at LHC

Evidence for dark matter exists since the 1930s.

Today we know that

➢ there are many possible models
➢ the range of parameters they span is large

We must deploy full ingenuity in searching for dark matter, including at LHC.

But must also recognise that it has remained elusive for 80–90 years, and chances of finding it in any given year are small!
don’t underestimate the value of luminosity

Suppose we had a choice between

- HL-LHC (14 TeV, 3ab^{-1})
- or going to higher c.o.m. energy but limited to 80fb^{-1}.

How much energy would we need to equal the HL-LHC?

<table>
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<tr>
<th>today’s reach (13 TeV, 80fb^{-1})</th>
<th>HL-LHC reach (14 TeV 3ab^{-1})</th>
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<td>4.7 TeV SSM Z'</td>
<td>6.7 TeV</td>
<td>20 TeV</td>
</tr>
<tr>
<td>2 TeV weakly coupled Z'</td>
<td>3.7 TeV</td>
<td>37 TeV</td>
</tr>
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</table>

estimated with [http://collider-reach.cern.ch](http://collider-reach.cern.ch), Weiler & GPS
don’t underestimate the value of luminosity

➤ Suppose we had a choice between
  ➤ HL-LHC (14 TeV, 3ab⁻¹)
  ➤ or going to higher c.o.m. energy but limited to 80fb⁻¹.

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<td>3.7 TeV</td>
<td>37 TeV</td>
</tr>
<tr>
<td>680 GeV chargino</td>
<td>1.4 TeV</td>
<td>54 TeV</td>
</tr>
</tbody>
</table>
We have seen in the previous section that beyond the strict leading logarithmic approximation method, to assess the impact of some subleading terms on the LL result, non-global logarithms and multiple emission effects related to the over-soft drop grooming or from one-prong virtual corrections. For the analytic curves, we show the result including only the leading logarithms in Fig. 3.

Personal opinion: If we cannot prove that an existing measurements or search forbids new physics in a given final state/topology, we have to look!
flavour anomalies

the current place where there are hints of something happening
charged current

\[ R(D^*) \equiv \frac{\mathcal{B}(B^0 \to D^* \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \to D^- \mu^+ \nu_\mu)} \]

neutral current

\[ R(K^*) = \frac{\mathcal{B}(B \to K^*(\mu^+ \mu^-))}{\mathcal{B}(B \to K^*(e^+ e^-))} \]

**R(D*) and R(D) combination**

Combine LHCb’s \( R(D^*) \) results with results from \( B \) factories:

\[ \Rightarrow R(D^*) \text{ and } R(D) \text{ average } \sim 4 \sigma \text{ from SM} \]

(lastest SM computation: JHEP 11 (2017) 061)

**R(K) and R(K*) results**

\( \chi^2 = 1.0 \) contours

- All LHCb results below SM expectations:
  - \( R(K) = 0.745^{+0.099}_{-0.074} \pm 0.036 \) at central \( q^2 \), \( \sim 2.6 \sigma \) from SM;
  - \( R(K^+) = 0.66^{+0.11}_{-0.07} \pm 0.03 \) at low \( q^2 \), \( \sim 2.2 \sigma \) from SM;
  - \( R(K^*) = 0.69^{+0.07}_{-0.05} \pm 0.05 \) at central \( q^2 \), \( \sim 2.4 \sigma \) from SM;
- \( B \) factories have less precise but compatible results.
The expected mass scale depends on flavor. The size of the effect – current hints for SM deviation – in $R_K(\ast)$ is “natural”, in the core of parameter space. How about $R_D(\ast)$?

Tree-level in SM, similar order of anomalous data as $R_K(\ast)$ implies large couplings and very low BSM:

<table>
<thead>
<tr>
<th>flavor</th>
<th>generic</th>
<th>minimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_K(\ast)$ tree</td>
<td>30 TeV</td>
<td>6 TeV</td>
</tr>
<tr>
<td>$R_K(\ast)$ loop</td>
<td>few TeV</td>
<td>0.5 TeV</td>
</tr>
<tr>
<td>$R_D(\ast)$ tree</td>
<td>$\sim$ a TeV</td>
<td>0.3 TeV</td>
</tr>
</tbody>
</table>

Linking the anomalies is intriguing however not straightforward, lower deviation in $R_D(\ast)$, in particular $R_D\ast$ more ”natural”.

- In general the main observable generating tensions is $R(D(\ast))$, with EW precision tests and $B_s$-mixing.
- Still work has to be done to find a completely satisfying NP model for the B-anomalies.
standard model theory
Summary & Outlook

**Huss**

### precision Drell–Yan predictions:
- fixed order: NNLO QCD, NLO EW, mixed QCD–EW (pole approx.)
- $\mathcal{O}(\alpha_s\alpha)$ mass shift: $\Delta M_W^{\alpha_s\alpha} \sim -14$ MeV
- compatible with NLO(QCD+EW)$\otimes$PS(QCD+QED): $\Delta M_W^{\alpha_s\alpha} \sim -16 \pm 3$ MeV

► **the inclusive $p_T^V$ spectrum:**
  - $N^3LL+$NNLO: excellent agreement vs. data & residual uncertainties $\sim$ few %
  - bottom-quark effects: $\sim \pm 0.5\%$ ($\Delta M_W < 5$ MeV)
  - $(NLL+NLO)_{QED}$: $\sim \pm 0.5\%$

► **$V$ + jet production**
  - NNLO QCD available \quad $V = W^\pm, Z/\gamma^*, \gamma$
  - NLO EW important in tails of distributions
  - first steps towards multi-jet merging including EW corrections

► **Di-boson production**
  - NNLO QCD available \quad $VV' \in \{W^\pm, Z/\gamma^*, \gamma\}$
  - NNLO$\otimes$PS: NNLO accuracy in inclusive quantities & captures soft-g effects
  - NLO EW: prediction for off-shell processes
Summary & Outlook

Advanced precision Drell-Yan predictions:
- fixed order: NNLO QCD, NLO EW, mixed QCD-EW (pole)
- \( \mathcal{O}(\alpha_s^3) \) mass shift: \( \Delta M_W^{\alpha_s^3} \sim -14 \text{ MeV} \)
- compatible with NLO(QCD+EW)×PS(QCD+QED): \( \Delta M_W \)

- the inclusive \( p_T^V \) spectrum:
  - \( N^3LL+NNLO \): excellent agreement vs. data & residual NNLO QCD corrections
  - bottom-quark effects: \( \sim \pm 0.5\% \) (\( \Delta M_W < 5 \text{ MeV} \))
  - \( (NLL+NLO)_{QED} \): \( \sim \pm 0.5\% \)

- \( V+j\)et production
  - NNLO QCD available \( \forall V = W^\pm, Z/\gamma^*, \gamma \)
  - NLO EW important in tails of distributions
  - first steps towards multi-jet merging including EW corrections

- Di-boson production
  - NNLO QCD available \( \forall VV' \in \{W^\pm, Z/\gamma^*, \gamma\} \)
  - NNLO×PS: NNLO accuracy in inclusive quantities & cuts
  - NLO EW: prediction for off-shell processes

**VIRTUAL CORRECTIONS: REDUCTIONS**

Generalized unitarity provides a different approach to the reduction to master integrals; reduction coefficients are reconstructed from cuts of scattering amplitudes. Very successful method at one-loop; attempts to generalise to two-loops.

Recent progress with the evaluation of planar (large \( N_c \)) contribution to five-gluon two-loop amplitude.

An impressive proof of concept that unitarity works at two-loops but still far from a real computation of the full scattering amplitude and e.g. the phenomenology of the three-jet NNLO cross sections.

| \( A \) | \( c^{-4} \) | \( c^{-3} \) | \( c^{-2} \) | \( c^{-1} \) | \( c^{0} \) |
|---|---|---|---|---|
| \( A^{(2)}[0]_{++} \) | 12.5 | 27.7526 | -23.773 | -168.117 | -175.207±0.004 |
| \( P^{(3)}[0]_{++} \) | 12.5 | 27.7526 | -23.773 | -168.116 | — |
| \( A^{(2)}[0]_{--} \) | 12.5 | 27.7526 | 2.5029 | -35.8094 | 69.661±0.009 |
| \( P^{(3)}[0]_{--} \) | 12.5 | 27.7526 | 2.5028 | -35.8086 | — |

Badger, Bronnum-Hansen, Hartano, Peraro

Similar results in Abreu, Cordero, Ita, Page, Zeng
Summary & Outlook

**Huss**

- Precision Drell-Yan predictions:
  - $O(\alpha_s^0)$ mass shift: $\Delta M_W^0 \sim -14$ MeV
  - $O(\alpha_s^0)$ mass shift: $\Delta M_W^0 \sim -14$ MeV
  - Fixed order: NNLO QCD, NLO EW, mixed QCD–EW (polishing)
  - $O(\alpha_s^0)$ mass shift: $\Delta M_W^0 \sim -14$ MeV
  - Compatible with NLO(QCD+EW)$\otimes$PS(QCD+EED): $\Delta M_W^0 \sim -14$ MeV

- The inclusive $p_T^V$ spectrum:
  - $N^2LL+NNLO$
  - Bottom-quark correction
  - $(N\otimes NLO)_0$

- $V +$ jet production:
  - NNLO QCD at $\mathcal{O}(\alpha_s^2)$
  - NLO EW improvement
  - First steps to mixed QCD–EW

- Di-boson production:
  - NNLO QCD at $\mathcal{O}(\alpha_s^2)$
  - NNLO@PS: NLO@PS
  - NLO EW: precision calculations

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**VIRTUAL CORRECTIONS: REDUCTIONS**

Generalized unitarity provides a different approach to the reduction to master integrals; reduction coefficients are reconstructed from cuts of scattering amplitudes. Very successful method at one-loop; attempts to generalise to two-loops.

Recent progress with the evaluation of planar (large $N_c$) contribution to five-gluon two-loop amplitude.

**VIRTUAL CORRECTIONS: INTEGRALS**

Master integrals can also be computed upon numerical integration over Feynman parameters (SecDec). This method has been successfully applied to double Higgs and Higgs + jet production at the LHC with full top mass dependence.

\[
\bar{F} = \int_0^1 \cdots \int_0^1 \frac{N(x_1, x_2, \ldots, x_n)}{D(x_1, x_2, \ldots, x_n)}
\]

**Double-Higgs production**

\[ gg \rightarrow HH \]

Borowka, Greiner, Heinrich, Kerner, Jones, Schenk, Zirke
The top quark is special.

1. It is rich
2. It is strong
3. It is naked
4. It is popular
5. It goes beyond

The top quark is the Ronaldo of elementary particles.
Why do we still care about the top quark?

Top quarks are key to almost everything!

Search for new physics

Search for rare processes

b-tagging calibration

Stability of the Universe
m_{top} summary, $\sqrt{s} = 7-13$ TeV

September 2017

m_{top} = total (stat + syst) 

$\sqrt{s}$ Ref.

172.31 ± 1.55 (0.75 ± 1.35) 7 TeV [1]
173.09 ± 1.63 (0.64 ± 1.50) 7 TeV [2]
173.49 ± 1.06 (0.43 ± 0.97) 7 TeV [3]
172.50 ± 1.52 (0.43 ± 1.46) 7 TeV [4]
173.49 ± 1.41 (0.69 ± 1.23) 7 TeV [5]
173.29 ± 0.95 (0.35 ± 0.88) 7 TeV [6]
173.34 ± 0.76 (0.36 ± 0.67) 1.96-7 TeV [7]

(*) Superseded by results shown below the line

ATLAS, l+jets (*)
172.33 ± 1.27 (0.75 ± 1.02) 7 TeV [8]
173.79 ± 1.41 (0.54 ± 1.30) 7 TeV [8]
175.1 ± 1.8 (1.4 ± 1.2) 7 TeV [9]
172.2 ± 2.1 (0.7 ± 2.0) 8 TeV [10]
172.99 ± 0.85 (0.41 ± 0.74) 8 TeV [11]
173.72 ± 1.15 (0.55 ± 1.01) 8 TeV [12]
172.08 ± 0.91 (0.38 ± 0.82) 8 TeV [13]
172.5 ± 0.50 (0.27 ± 0.42) 7+8 TeV [13]
172.35 ± 0.51 (0.16 ± 0.48) 8 TeV [14]
172.82 ± 1.23 (0.19 ± 1.22) 8 TeV [14]
172.32 ± 0.64 (0.25 ± 0.59) 8 TeV [14]
172.95 ± 1.22 (0.77 ± 0.95) 8 TeV [15]
172.44 ± 0.48 (0.13 ± 0.47) 7+8 TeV [14]
172.25 ± 0.63 (0.08 ± 0.62) 13 TeV [16]

(*) Superseded by results shown below the line
We remind that

1. Some authors implicitly claim that the Pole Mass and the Monte Carlo mass parameter (or “Monte Carlo Mass”) in direct measurements differ by terms of order $\alpha_s(m_t)$.

2. Other authors, also advocating the “Monte Carlo Mass” concept, claim differences relative to the Pole Mass of order of a hadronic scale (Hoang, Stuart 2008).

Our view is in clear contrast with (1), but is not in substantial contradiction with (2): we prefer to say that direct measurements measure the Pole Mass up to corrections of the order of a hadronic scale, rather than saying that they measure a “Monte Carlo Mass”.
**Pythia8, hvq, tt\_dec, b\bar{b}4l comparison**

<table>
<thead>
<tr>
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<th>No smearing</th>
<th>15 GeV smearing</th>
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<tbody>
<tr>
<td></td>
<td>MEC</td>
<td>MEC – no MEC</td>
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<tr>
<td>(b\bar{b}4\ell)</td>
<td>172.793 ± 0.004 GeV</td>
<td>−12 ± 6 MeV</td>
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<tr>
<td>(tt\text{dec})</td>
<td>172.814 ± 0.003 GeV</td>
<td>−4 ± 5 MeV</td>
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<tr>
<td>(hvq)</td>
<td>172.803 ± 0.003 GeV</td>
<td>+61 ± 5 MeV</td>
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**POWHEG-b\bar{b}4l, Herwig7 - Pythia8 comparison**

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<td>Hw7.1</td>
<td>Py8.2 – Hw7.1</td>
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<tr>
<td>(b\bar{b}4\ell)</td>
<td>172.727 ± 0.005 GeV</td>
<td>+66 ± 7 MeV</td>
</tr>
<tr>
<td>(tt\text{dec})</td>
<td>172.775 ± 0.004 GeV</td>
<td>+39 ± 5 MeV</td>
</tr>
<tr>
<td>(hvq)</td>
<td>173.038 ± 0.004 GeV</td>
<td>−235 ± 5 MeV</td>
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Stability (to within 300 MeV) of top-mass peak in different MC formulations (Pythia8 + X)

Pythia v. Herwig comparison shows up to 1 GeV differences
Pythia8, $hvq$, $t\bar{t}\_dec,b\bar{b}4l$ comparison

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<td>$172.775 \pm 0.004$ GeV</td>
<td>$+39 \pm 5$ MeV</td>
</tr>
<tr>
<td>$hvq$</td>
<td>$173.038 \pm 0.004$ GeV</td>
<td>$-235 \pm 5$ MeV</td>
</tr>
</tbody>
</table>

There can be two sources of difference:

1) the parton shower (and its interface with NLO)

2) non-perturbative effects

stability (to within 300 MeV) of top-mass peak in different MC formulations (Pythia8 + X)

Pythia v. Herwig comparison shows up to 1 GeV differences
Recent developments in Monte Carlo Event Generators

- Improving the fixed-order **perturbative precision** of event generators:
  - Many color-singlet processes described at NNLO+PS with MINLO
  - Inclusion of NLO EW effects in full swing in AMC@NLO and SHERPA

- Interesting developments in defining **shower at higher order**:
  - Treatment of subleading color relevant, even for leading-color PS
  - Can systematically correct PS through fully differential NLO calculation in exponent.

- Continuous improvements of **non-perturbative physics**:
  - Improved models of complete cross section and photoproduction.
  - More sophisticated color reconnection models.
  - Exciting new ideas in modelling of collectivity (in pp and heavy-ion)
important if we want to take parton showers to the next level of accuracy

Dasgupta, Dreyer, Hamilton, Monni, GPS, 1805.09327
heavy-ion collisions

and hints of a continuum between pp and PbPb
True collectivity in small systems!

on one hand, discovering that heavy-ion observables and methods reveal surprises to understand about basic pp physics
Probing the time structure of the quark-gluon plasma with top quarks

Liliana Apolinário, José Guilherme Milhano, Gavin P. Salam, * and Carlos A. Salgado

finite top lifetime
reconstructed top mass tells you something about time structure of the medium
interplay between heavy-ion physics and Higgs physics

Higgs properties revealed through jet quenching in heavy ion collisions

Edmond L. Berger,1,* Jun Gao,2,† Adil Jueid,2,‡ and Hao Zhang3,4

![Graph showing di-mb̄ distribution with various contributions from different processes like ZH (vac.), ZH (que.), Zb̄b, t̄t, and ZH after all selections.](image)

**long Higgs lifetime**

no jet b-jet quenching, so enhancement of $H \to bb$ signal relative to pp collisions
Higgs properties revealed through jet quenching in heavy ion collisions

Edmond L. Berger,1,* Jun Gao,2,† Adil Jueid,2,‡ and Hao Zhang3, 4

open question of how much luminosity is needed (both for Higgs and top) and whether lumi is achievable.

But for now, these are fun questions to think about.

long Higgs lifetime
no jet b-jet quenching, enhancement of $H \rightarrow b \bar{b}$ signal relative to pp collisions

arXiv:1804.06858v2
conclusions
I personally expect supersymmetry to be discovered at the LHC

-a Nobel prize-winning theorist [2008]
it would be so much more exciting if we’d discovered new physics, right?

not everyone would agree

Back in 1995:

1. The Desert. A fun aspect of supersymmetry is that it allows us to obtain exact results about strongly interacting gauge theories. However in the MSSM we have nothing but boring perturbative physics to explore below the Planck scale and the interesting dynamics of supersymmetry breaking is hidden.
some theorists

it’s interesting if it’s what everyone is thinking about right now

experimenter

it’s interesting if it’s never been measured before

both have a point (don’t let one side dampen the other side’s interest)
we must not underestimate our ignorance about the Higgs sector
we must not undersell the value of exploring and establishing it

e.g. accessing the triple-Higgs coupling, keystone of SM
I think Nature is smarter than physicists. We should have the courage to say: "Let Nature tell us what is going on."

-Carlo Rubbia [2008]