What a difference a decade makes.

LHC Research began March 2010. Just over 7 years ago. Let’s compare to 2012...

**Then:**

> \( \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0 \), \( m_{\tilde{t}_1} = 2m_{\tilde{\chi}_1^0} \)

\[
\int L \, dt = 4.7 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV}
\]

Leptons + b-jets combined

\( \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0 \) production

**Now:**

> \( \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^0 \), \( m_{\tilde{t}_1} = m_{\tilde{\chi}_1^0} + 10 \text{ GeV} \)

\[
\sqrt{s} = 13 \text{ TeV}, \text{ 36.1 fb}^{-1}
\]

All limits at 95% CL

**ATLAS**

\( m(\tilde{\chi}_1^0) = 10 \text{ GeV} \)
LHC Research began March 2010. Just over 7 years ago. Let’s compare to 2012...

What a difference a decade makes.

Then:

Now:
LHC Research began March 2010. Just over 7 years ago. Let’s compare to 2012...

A lot can change in a few years or, more accurately, an effective factor

$$L_{\text{Eff}} = \frac{\sigma_H(13 \text{ TeV})}{\sigma_H(7 \text{ TeV})} \frac{36 \text{ fb}^{-1}}{4.8 \text{ fb}^{-1}} \approx 22$$

or so in integrated luminosity.

What a difference a decade makes.
We currently stand just to the left of this plot, with analyses presented at 13 TeV with roughly 36 fb$^{-1}$ of data.

What can we expect with the next order of magnitude in data?
The Discovery Factor

In an optimal scenario, with uncertainties dominated by statistics, the significance is

\[ N_\sigma \approx \frac{S}{\sqrt{B}} \]

Thus, taking into account that the accelerator will, as always, exceed our expectations, and cross sections go up a bit for 14 TeV, then we can expect an order of magnitude increase in effective integrated luminosity.
The Discovery Factor

In an optimal scenario, with uncertainties dominated by statistics, the significance is

$$N_\sigma \approx \frac{S}{\sqrt{B}}$$

In the best case scenario a 1.6\(\sigma\) “fluctuation” today could be a 5\(\sigma\) discovery in ten years.
The Discovery Factor

Where would I put my money? It’s either Heaven:

- Higgs Couplings.
- Flavour.
- Exotic Exotica.

Or Hell:
Higgs Couplings: $\mu \mu$

**Now:**

ATLAS currently places 2$\sigma$ upper limit at a signal strength of 3xSM. With signal strength

$$\mu_\mu = -0.1 \pm 1.4$$

**Ten Years:**

300 fb$^{-1}$ will mark a paradigm shift for second generation couplings. Higgs 2.0.

If the value is currently 3xSM then this would show up as a 5$\sigma$ deviation in ten years from now.

---

From slides of Testa
Higgs Couplings: $\mu\mu$

Now:

ATLAS currently places a $2\sigma$ upper limit at a signal strength of $3\times$SM. With signal strength $\mu\mu = -0.1 \pm 1.4$

Ten Years:

If the value is currently $3\times$SM then this would show up as a $5\sigma$ deviation in ten years from now.

Given that we are talking about miniscule couplings here, and the flavour sector is an utter mystery, would be plausible that something could show up here...
ATLAS currently places 2σ upper limit at a signal strength of 6.6xSM. Upward fluctuation...

If the value is currently 3xSM then this would show up as a 5σ deviation in ten years from now.

ATLAS Simulation Preliminary
| s = 14 TeV; \(|\Delta t| = 300 fb^{-1} \); \(|\Delta t| = 3000 fb^{-1} |

Higgs Couplings: Zy

Now:

- ATLAS currently places 2σ upper limit at a signal strength of 6.6xSM. Upward fluctuation...
- If the value is currently 3xSM then this would show up as a 5σ deviation in ten years from now.

Ten Years:
- 300 fb⁻¹ will also mark a paradigm shift for rare Higgs decays:
  - H→Z\gamma (incl.)

From slides of Testa
Higgs Couplings: $Z\gamma$

Now:

ATLAS currently places $2\sigma$ upper limit at a signal strength of 6.6xSM. Upward fluctuation..

Ten Years:

If the value is currently $3x$SM then this would show up as a $5\sigma$ deviation in ten years from now.

300 fb$^{-1}$ will also mark a paradigm shift for rare Higgs decays:

Given a SM-like diphoton rate currently observed, I would not really put my money here...
Exotic Higgs Decays

Due to its tiny width, the Higgs can have significant exotic decay channels, even for small couplings. Consider one example:

\[ \text{BR} < 0.0005 \] corresponds to about 200 events.

Ten Years?

With the extra luminosity we can afford to cut harder and search for very rare signatures: Displaced, High Multiplicity, Leptons...
Boosted Higgses

High Velocity Higgs:

For comparison, what we can do with a $p_T = 120$ GeV Higgs boson now, we should be able to do with a $p_T = 260$ GeV Higgs in ten years!

Since heavy new physics can give corrections scaling as

$$\mathcal{M} \propto \frac{p_T^2}{\Lambda^2}$$

We will be able to indirectly access higher scales of new physics.
Flavour of the Month

**Tree-level in the SM:**

\[ B \rightarrow D^{(*)} \tau \nu \]

Currently 4σ tension:

"R" is \( \tau/\mu \)

**One-loop FCNC in the SM:**

\[ B \rightarrow K^{(*)} \mu^+ \mu^- \]

A number of 2σ tensions that can combine to exceed 4σ.

"R" is \( \mu/e \)
Flavour of the Month

One-loop FCNC in the SM:

A number of $2\sigma$ tensions that can combine to exceed $4\sigma$.

Tree-level in the SM:

Currently $4\sigma$ tension:

\[ B \rightarrow D^{(*)} \tau \nu \]

\[ B \rightarrow K^{(*)} \mu^+ \mu^- \]

If already this level of tension, where will we stand in 2027?

"R" is $\tau/\mu$

"R" is $\mu/e$
Flash forward to LHCb and Belle II expectations:

<table>
<thead>
<tr>
<th>Year</th>
<th>Run III</th>
<th>Run IV</th>
<th>Run V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
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<td>2020</td>
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<td>2033+</td>
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<thead>
<tr>
<th>Experiment</th>
<th>Year 2019</th>
<th>Year 2020</th>
<th>Year 2021</th>
<th>Year 2022</th>
<th>Year 2023</th>
<th>Year 2024</th>
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<th>Year 2026</th>
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<th>Year 2028</th>
<th>Year 2029</th>
<th>Year 2030</th>
<th>Year 2031</th>
<th>Year 2032</th>
<th>Year 2033+</th>
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</thead>
<tbody>
<tr>
<td>LHCb 40 MHz</td>
<td>$L = 2 \times 10^{33}$</td>
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<td>Upgrade</td>
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<tr>
<td>ATLAS Phase I Upgr</td>
<td>$L = 2 \times 10^{34}$</td>
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<tr>
<td>CMS Phase I Upgr</td>
<td>$L = 300 \text{ fb}^{-1}$</td>
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<tr>
<td>Belle II</td>
<td>$5 \text{ ab}^{-1}$</td>
<td>$L = 8 \times 10^{35}$</td>
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</table>

Estimated operating scenarios are:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>SM prediction</th>
<th>Current World Average</th>
<th>Current Uncertainty</th>
<th>Projected Uncertainty$^1$</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>LHCb</td>
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<td>Belle II</td>
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<td>5ab$^{-1}$</td>
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<td>50ab$^{-1}$</td>
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<td>8fb$^{-1}$</td>
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<td>22fb$^{-1}$</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>50fb$^{-1}$</td>
</tr>
<tr>
<td>$R(D)$</td>
<td>$(0.299 \pm 0.003)$</td>
<td>$(0.403 \pm 0.040 \pm 0.024)$</td>
<td>11.6%</td>
<td>5.6%</td>
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<tr>
<td></td>
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<td></td>
<td>3.2%</td>
</tr>
<tr>
<td>$R(D^*)$</td>
<td>$(0.257 \pm 0.003)$</td>
<td>$(0.310 \pm 0.015 \pm 0.008)$</td>
<td>5.5%</td>
<td>3.2%</td>
</tr>
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<td>2.2%</td>
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</tbody>
</table>

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*J. Albrecht, F. U. Bernlochner, M. Kenzie, S. Reichert, D. M. Straub, A. Tully*

Flavour of the Month

\[ B \rightarrow D^{(*)}\tau \nu \]

If average value holds then in ten years anomaly could pass the technically arbitrary, but still meaningful, “Bazillion Sigma” mark:

From slides of Camalich
Flavour of the Month

\[ B \rightarrow K^{(*)} \mu^+ \mu^- \]

Current status of uncertainties in the regime of 10’s %.

At Belle II and LHCb these uncertainties would be at a few %:

<table>
<thead>
<tr>
<th>LHCb Preliminary</th>
<th>low-(q^2)</th>
<th>central-(q^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{K^{*0}} )</td>
<td>0.660 ± 0.110 ± 0.024</td>
<td>0.685 ± 0.113 ± 0.047</td>
</tr>
<tr>
<td>95% CL</td>
<td>[0.517–0.891]</td>
<td>[0.530–0.935]</td>
</tr>
<tr>
<td>99.7% CL</td>
<td>[0.454–1.042]</td>
<td>[0.462–1.100]</td>
</tr>
</tbody>
</table>

If true, would also far surpass “discovery” level...

From slides of Camalich
Flavour of the Month

Current status of anomalies in the regime of 10’s %.

At Belle II and LHCb these uncertainties would be at a few %:

If true, would also far surpass “discovery” level…

\[ B \rightarrow K^{(*)} \mu^+ \mu^- \]

**A taste of the future?**

Other modes to watch:

\[ B_s \rightarrow \mu^+ \mu^- \]

\[ B \rightarrow K \nu \nu \]

If true, would also far surpass “discovery” level…
Away from the lampost.

There are still be new places to look...

- hep-ph
- hep-ex

- Linear Dilaton
- Fourier Space
- Twin Higgs
- Higgs Portal & Displaced
- pNGB Higgs
- RS/LED
- SUSY
- Black Holes
- MET
- Z’, W’ Higgs Couplings
Some Fun (Serious) Ideas

Are we plotting on the wrong axes? Always expecting to see a plot like this:

Particles = Bumps, right?

But what if the new physics looks like this?

There are genuine sensible theories that generate this:

\[ m_n \sim k \left( 1 + \frac{n^2}{2(kR)^2} \right) \]

Linear dilaton/clockwork.
Some Fun (Serious) Ideas

Maybe we should be looking in Fourier space?

Fourier Space

Maybe the next step is to start thinking like cosmologists with LHC data?
Some Fun (Serious) Ideas

What if new neutral scalars only couple to the photon?

Why not let the heavy ions do the heavy lifting:

High-Z is intensity frontier, but at high energies!

In ten years we can realistically expect $3 \text{nb}^{-1}$. Is something going to show up in forward physics?

In 2016, ATLAS took $480 \mu \text{b}^{-1}$ of data and found a peak in the invariant mass of the di-photons at $m = 709.071\text{ GeV}$. This peak was not seen in any other experiment.

The data suggests a new particle with a mass of $709.071\text{ GeV}$ and a width of $1.071\text{ GeV}$.

The significance of this peak is that it is $3.5 \sigma$ above the background.

The new particle is not consistent with the Standard Model and might be a Higgs boson.
Conclusions

One order of magnitude in integrated luminosity can bring us to new territory, if we look in the right places.

I honestly don’t know what to expect. Your bet is as good as mine!