Physics at 100 TeV
Review of the FCC-hh physics potential

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Outline

- The rationale and goals of the current efforts: the message for the CDR
- Higgs and EWSB physics
  - precision measurements (couplings and self-couplings)
  - EWSB beyond the SM
- BSM searches
  - high-mass reach
  - DM and other weakly-interacting BSM phenomena
- The role of HE-LHC
Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- Volume 1: SM processes (238 pages)  arXiv:1607.01831
- Volume 2: Higgs and EW symmetry breaking studies (175 pages)  arXiv:1606.09408
- Volume 3: beyond the Standard Model phenomena (189 pages)  arXiv:1606.00947
- Volume 4: physics with heavy ions (56 pages)  arXiv:1605.01389
- Volume 5: physics opportunities with the FCC-hh injectors (14 pages)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

To appear anytime now as a bound volume of CERN Yellow Reports

- FCC-hh events: http://indico.cern.ch/category/5258/
The goals of the Report

• Document what, today, we can anticipate of the physics landscape at 100 TeV:
  • report cross sections, rates and theoretical uncertainties for relevant proc’s, in the SM, Higgs and BSM sectors
  • expose aspects where 100 TeV goes beyond a mere extrapolation of the LHC potential
  • stimulate new ideas, starting from a few explicit examples of what 100 TeV and 20 ab$^{-1}$ can deliver
  • Identify useful benchmarks to focus the detector design and the performance requirements

• The goal was not to define a “physics case”, but to provide a first assessment, item by item, of the physics potential, and to outline prospects (for measurements and discoveries)
The goals of the Report

• With the firm belief that a FCC complex must appeal to more than the high-E physics programme, sections of the Report focused on the additional opportunities offered by
  • heavy ion collisions
  • the exploitation of the injector chain (including the option of lower-E collisions in the last component of the injectors, eg the LHC)
• These components will not be discussed here, but should be considered as essential elements of the whole FCC project. They will further develop their own physics case as new results, open issues and ideas arise
• Flavour physics is another important component of a possible pp programme, which has not been studied as yet. Efforts are now focused on defining a programme for HL-LHC. Depending on the outcome of these studies, and on the development of the various flavour anomalies recorded by LHCb and flavour factories, dedicated efforts will be started (possibly post-CDR)
The next steps towards the CDR

• Consolidate the preliminary projections of the Report with dedicated detector simulation studies, including more realistic estimates of the experimental systematics

• Put the FCC-hh potential in the perspective of the global FCC physics programme:
  • Assess the complementarity and synergy with the deliverables of FCC-ee and FCC-eh

• FCC-hh has more work to do to be ready for this cross-facilities comparison, but preliminary results of this exercise will be documented in the 1st volume of the FCC CDR
First discussions of complementarity/synergies

1st FCC Physics Workshop

16-20 January 2017
CERN
Europe/Zurich timezone

http://indico.cern.ch/event/550509/

199 registered participants

Topics:

- Higgs
- QCD
- EW precision measurements
- Top and flavour
- BSM searches
- Relation with cosmology: DM and neutrino mass probes
- Experimental opportunities at the FCC and novel techniques
- Physics with Heavy Ion collisions
- Physics at beam dumps, injectors, or forward region detectors

… plus the session on Tue afternoon in Berlin

… to be continued at the 2nd FCC physics workshop, Jan 15-19 2018
http://indico.cern.ch/event/618254/
Current focus on FCC-hh physics: Detector studies

• **Detector design** group leader: Werner Riegler
  • Indico site of mtgs: http://indico.cern.ch/category/8920/
  • join the mailing list

• **Physics Simulation** subgroup leaders: Heather Gray & Filip Moortgat
  • Indico site of mtgs: http://indico.cern.ch/category/6067/
  • join the mailing list

• Monthly mtgs of each group, if interested register to the mailing lists

=> see FCC-hh detector // sessions
The underlying rationale in building the physics case

• HEP has two priorities:

• explore the origin of known departures from the SM (DM, neutrino masses, baryon asymmetry of the universe)

• explore the physics of electroweak symmetry breaking:

• experimentally, via the measurement of Higgs properties, Higgs interactions and selfinteractions, couplings of gauge bosons, flavour phenomena, etc

• theoretically, to understand the nature of the hierarchy problem and identify possible natural solutions (to be subjected to exptl test)

The physics case of FCC project (ee, hh and eh) builds on the belief that these two directions are deeply intertwined
Key question for the future developments of HEP: Why don’t we see the new physics we expected to be present around the TeV scale?

- Is the mass scale beyond the LHC reach?
- Is the mass scale within LHC’s reach, but final states are elusive to the direct search?

These two scenarios are a priori equally likely, but they impact in different ways the future of HEP, and thus the assessment of the physics potential of possible future facilities.

Readiness to address both scenarios requires:
  - *precision*
  - *sensitivity (to elusive signatures)*
  - *extended energy/mass reach*
The physics potential of any future HEP facility should be weighed against criteria such as:

(1) the guaranteed deliverables:
   • knowledge that will be acquired independently of possible discoveries (the value of “measurements”)

(2) the exploration potential:
   • target broad and well justified BSM scenarios .... but guarantee sensitivity to more exotic options
   • ensure coverage of elusive signatures

(3) the potential to provide conclusive yes/no answers to relevant, broad questions
For the FCC, in particular:

- **Guaranteed deliverables:**
  - study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity
  - **tbd:** further clarification of the nature of new physics discovered at LHC or elsewhere

- **Exploration potential:**
  - mass reach enhanced by factor $\sim E / 14\,\text{TeV}$ (will be 5–7 at 100\,TeV, depending on integrated luminosity)
  - statistics enhanced by several orders of magnitude for BSM phenomena brought to light by the LHC
  - benefit from both direct (large $Q^2$) and indirect (precision) probes

- **Provide firm Yes/No answers** to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?
• The FCC-hh is part of the whole FCC, and it’s the full exploitation of the FCC complex that guarantees the maximal outcome

• But the FCC-hh experiments are extremely versatile, and potentially capable, stand alone, to address a major part of the whole FCC programme

• As FCC-hh, we must explore every corner of its potential, from the discovery reach, to the precision frontier.

• The same should be (and is being) done by the FCC-ee studies….

• This puts the value of the individual projects in the right perspective, vis a vis possible future developments in HEP (eg discoveries at the LHC), in technology progress (eg time scale for 16T magnets), in the overall HEP landscape (eg approval of ILC, …), and in the political landscape (costs).

• And of course identifying areas where both ee and pp have independent sensitivity stimulates the assessment of synergy and complementarity …. 
Status of SM calculations and tools reviewed in the SM volume

1 Parton distribution functions
2 Introduction
3 PDFs and their kinematical coverage at 100 TeV
4 PDF luminosities at 100 TeV
5 The top quark as a massless parton
6 Photon- and lepton-initiated processes at 100 TeV
7 Electroweak gauge bosons as massless partons
8 High-energy resummation of PDF evolution
9 Global event properties
10 Minimum bias collisions
11 Underlying event in high-\(p_T\)-triggered events
12 Inclusive vector boson production
13 Inclusive \(W/Z\) rates and distributions
14 \(W/Z\) boson production at small \(q_T\)
15 \(c\bar{c}\) production at large \(p_T\) and at large mass
16 \(b\bar{b}\) production at large \(p_T\)
17 Production of gauge bosons at the highest energies
18 \(W^+W^-\) production
19 \(W^+Z\) production
20 \(Z\gamma\) production
21 \(W^+W^-\) production
22 Single gauge-boson production via VBF
23 Benchmark cross sections
24 Jets
25 Inclusive jet and dijet production
26 Spectroscopy with high-mass dijets
27 SM physics of boosted objects
28 Boosted boson tagging
29 Jet fragmentation at large \(p_T\)
30 Multijets
31 Computational setup
32 Leading order inclusive cross sections and distributions
33 NLO cross sections and K-factors
34 Scaling behaviour in multi-jet production
35 Heavy flavour production
36 Inclusive bottom production
37 Inclusive top pair production
38 Bottom and top production at large \(Q^2\)
39 Single top production
40 Associated production of top quarks and gauge bosons
41 \(t\bar{t}W\) production
42 \(t\bar{t}H\) production
43 Photon emission off the top quark decay products
44 Top properties
45 Production of multiple heavy objects
46 Production of multiple gauge bosons
47 Multi-top and top-vector-boson associated production
48 Multi Higgs boson production by gluon fusion and VBF
49 Multi Higgs boson production in association with top quarks or gauge bosons
50 Loop-induced processes
51 Cross-sections at 100 TeV
52 Electroweak corrections
53 Tools
54 Drell-Yan
55 Gauge boson pairs and Higgsstrahlung
56 \(V + jets\)
57 Di-jets
58 \(t\bar{t}, t\bar{t} + jets\) and \(t\bar{t}H\)
59 Real radiation
60 Sources of missing transverse energy
**TH progress, an example**

Anastasiou et al, arXiv:1602.00695

Figs H-1,2

**Table 3:** Various sources of uncertainties of the inclusive gluon fusion Higgs production cross section at a 100 TeV proton-proton collider.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{PDF}$</td>
<td>$\pm 2.5%$</td>
</tr>
<tr>
<td>$\delta_{\alpha_S}$</td>
<td>$\pm 2.9%$</td>
</tr>
<tr>
<td>$\delta_{\text{scale}}$</td>
<td>$\pm 0.8%$</td>
</tr>
<tr>
<td>$\delta_{\text{PDF-theo}}$</td>
<td>$\pm 2.5%$</td>
</tr>
<tr>
<td>$\delta_{\text{EW}}$</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>$\delta_{\text{thc}}$</td>
<td>$\pm 0.8%$</td>
</tr>
<tr>
<td>$\delta_{\mu}$</td>
<td>$\pm 1%$</td>
</tr>
</tbody>
</table>

$$\sigma = 802 \text{ pb} \: ^{+6.1\%}_{-7.2\%} (\delta_{\text{theo}}) ^{+2.5\%}_{-2.5\%} (\delta_{PDF}) ^{+2.9\%}_{-2.9\%} (\delta_{\alpha_S})$$
• We’ve seen fantastic and unexpected progress in TH calculations since the start of the LHC.

• The most extreme kinematical regions covered by FCC-hh may pose new challenges, but HL-LHC will keep driving TH improvement efforts, and will allow crucial validation and tuning

• It’s impossible to predict how far this will go and what to expect by the time FCC-hh is running

Ex: studies of EW corrections to DY in the multi-TeV mass region

Fig SM-176
Higgs physics
Experimental observation of isolated large transverse energy electrons with associated missing energy at s=540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland, G. Arnison¹, A. Astbury¹, B. Aubert², C. Bacci³, G. Bauer¹, A. Bézaguer², R. Böck³, T. J. V. Bowcock³, M. Calvetti³, T. Carroll³, P.

Observation of single isolated electrons of high transverse momentum in events with missing transverse energy at the CERN pp collider

The UA2 Collaboration, M. Banner⁴, R. Battiston¹, ², Ph. Bloch⁴, F. Bonaud⁵, K. Borer⁵, M. Borghini⁵, J.-C. Chollet⁵, A. G. Clark⁵, C. Conta⁵, P. Darrilat⁵, L. Di Lella⁵, J. Dines-
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Measurement of the $W$-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

A measurement of the mass of the $W$ boson is presented based on proton–proton collision data recorded in 2011 at a centre-of-mass energy of 7 TeV with the ATLAS detector at the LHC, and corresponding to 4.6 fb$^{-1}$ of integrated luminosity. The selected data sample consists of $7.8 \times 10^6$ candidates in the $W \rightarrow \mu\nu$ channel and $5.5 \times 10^6$ candidates in the $W \rightarrow e\nu$ channel. The $W$-boson mass is obtained from template fits to the reconstructed distributions of the charged lepton transverse momentum and of the $W$ boson transverse mass in the electron and muon decay channels, yielding:

$$m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.)} \text{ MeV}$$

$$= 80370 \pm 19 \text{ MeV}.$$  

where the first uncertainty is statistical, the second corresponds to the experimental systematic uncertainty, and the third to the physics-modelling systematic uncertainty. A measurement of the mass difference between the $W^+$ and $W^-$ bosons yields $m_{W^+} - m_{W^-} = -29 \pm 28$ MeV.
34 years, and still open issues ….

BR(τ) / BR(e/μ) \sim 1.066 \pm 0.025 \Rightarrow \sim 2.5 \sigma

That we like it or not, to anticipate 40 years of work to pin down the structure of the Higgs sector should not be seen as an outrageous prospect!
### Higgs couplings @ FCC-ee

<table>
<thead>
<tr>
<th>g_{HXY}</th>
<th>240</th>
<th>240+350 (4IP)</th>
<th>240+350 (2IP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>0.16%</td>
<td>0.15%</td>
<td>0.18%</td>
</tr>
<tr>
<td>WW</td>
<td>0.85%</td>
<td>0.19%</td>
<td>0.23%</td>
</tr>
<tr>
<td>bb</td>
<td>0.88%</td>
<td>0.42%</td>
<td>0.52%</td>
</tr>
<tr>
<td>cc</td>
<td>1.0%</td>
<td>0.71%</td>
<td>0.87%</td>
</tr>
<tr>
<td>gg</td>
<td>1.1%</td>
<td>0.80%</td>
<td>0.98%</td>
</tr>
<tr>
<td>tt</td>
<td>0.94%</td>
<td>0.54%</td>
<td>0.66%</td>
</tr>
<tr>
<td>μμ</td>
<td>6.4%</td>
<td>6.2%</td>
<td>7.6%</td>
</tr>
<tr>
<td>γγ</td>
<td>1.7%</td>
<td>1.5%</td>
<td>1.8%</td>
</tr>
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</tr>
<tr>
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<td>1.7%</td>
<td>1.5%</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

- **g_{HXY}**
  - **ZZ**: 0.16%, 0.15%, 0.18%
  - **WW**: 0.85%, 0.19%, 0.23%
  - **bb**: 0.88%, 0.42%, 0.52%
  - **cc**: 1.0%, 0.71%, 0.87%
  - **gg**: 1.1%, 0.80%, 0.98%
  - **tt**: 0.94%, 0.54%, 0.66%
  - **μμ**: 6.4%, 6.2%, 7.6%
  - **γγ**: 1.7%, 1.5%, 1.8%

- **BR_{inv}**
  - **< 0.48%**
  - **< 0.45%**
  - **< 0.55% (SM: 0.12%)**

- **Γ_{tot}**
  - **1%**

---

**Additional Information**

- Total Integrated Luminosity (ab^{-1})
  - 240 GeV: 10
  - 350 GeV: 2.6

- Number of Higgs bosons from e^+e^- → HZ
  - 240 GeV: 2,000,000
  - 350 GeV: 340,000

- Number of Higgs bosons from boson fusion
  - 240 GeV: 50,000
  - 350 GeV: 70,000

**Notes**

- The value of tt runs goes beyond top physics.
- Sub-% precision.
- The table displays couplings for different fermion combinations and boson fusion processes, with variations at 240 GeV and 350 GeV.
- BR_{inv} values are shown for various processes.
- Γ_{tot} is the total width in percentage, with SM values provided for comparison.
## SM Higgs rates at 100 TeV

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{100}$</th>
<th>$N_{100}/N_8$</th>
<th>$N_{100}/N_{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H$</td>
<td>$16 \times 10^9$</td>
<td>$4 \times 10^4$</td>
<td>110</td>
</tr>
<tr>
<td>VBF</td>
<td>$1.6 \times 10^9$</td>
<td>$5 \times 10^4$</td>
<td>120</td>
</tr>
<tr>
<td>$WH$</td>
<td>$3.2 \times 10^8$</td>
<td>$2 \times 10^4$</td>
<td>65</td>
</tr>
<tr>
<td>$ZH$</td>
<td>$2.2 \times 10^8$</td>
<td>$3 \times 10^4$</td>
<td>85</td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>$7.6 \times 10^8$</td>
<td>$3 \times 10^5$</td>
<td>420</td>
</tr>
</tbody>
</table>

$N_{100} = \sigma_{100\,\text{TeV}} \times 20\,\text{ab}^{-1}$

$N_8 = \sigma_{8\,\text{TeV}} \times 20\,\text{fb}^{-1}$

$N_{14} = \sigma_{14\,\text{TeV}} \times 3\,\text{ab}^{-1}$
Remarks

- Higher statistics shifts the balance between systematic and statistical uncertainties. It can be exploited to define different signal regions, with better S/B, better systematics, pushing the potential for better measurements beyond the “systematics wall” of low-stat measurements.
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- We often talk about “precise” Higgs measurements. What we actually aim at, is “sensitive” tests of the Higgs properties, where sensitive refers to the ability to reveal BSM behaviours.
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We often talk about “precise” Higgs measurements. What we actually aim at, is “sensitive” tests of the Higgs properties, where sensitive refers to the ability to reveal BSM behaviours.

Sensitivity may not require extreme precision

Going after “sensitivity”, rather than just precision, opens itself new opportunities …
Higgs as a BSM probe: precision vs dynamic reach

\[ L = L_{SM} + \frac{1}{\Lambda^2} \sum_k O_k + \cdots \]

\[ O = |\langle f | L | i \rangle|^2 = O_{SM} \left[1 + O(\mu^2/\Lambda^2) + \cdots \right] \]
Higgs as a BSM probe: precision vs dynamic reach

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\[ O = |\langle f | L | i \rangle|^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \cdots \right] \]

For H decays, or inclusive production, \( \mu \sim O(v, m_H) \)

\[ \delta O \sim \left( \frac{v}{\Lambda} \right)^2 \sim 6\% \left( \frac{\text{TeV}}{\Lambda} \right)^2 \quad \Rightarrow \text{precision probes large } \Lambda \]

\[ \text{e.g. } \delta O = 1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV} \]
Higgs as a BSM probe: precision vs dynamic reach

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\[ O = | \langle f | L | i \rangle |^2 = O_{SM} \left[ 1 + O(\mu^2/\Lambda^2) + \ldots \right] \]

For H decays, or inclusive production, \( \mu \sim O(\nu,m_H) \)

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\[ \text{e.g. } \delta O = 1\% \Rightarrow \Lambda \sim 2.5 \text{ TeV} \]

For H production off-shell or with large momentum transfer \( Q \), \( \mu \sim O(Q) \)

\[ \delta O \sim \left( \frac{Q}{\Lambda} \right)^2 \quad \Rightarrow \text{kinematic reach probes large } \Lambda \text{ even if precision is low} \]

\[ \text{e.g. } \delta O = 15\% \text{ at } Q = 1 \text{ TeV } \Rightarrow \Lambda \sim 2.5 \text{ TeV} \]
Examples

$\delta \text{BR}(H \rightarrow WW^*)$

or

$Q = m(WH)$

$Q = p_T(H)$
Examples

\[ \delta \text{BR}(H \rightarrow WW^*) \]

or

\[ \delta \text{BR}(H \rightarrow gg) \]

\[ Q = m(WH) \]

\[ Q = p_T(H) \]
Examples

(See also Azatov and Paul arXiv:1309.5273v3)

Table 3: The benchmark points shown in Fig. 7. We set $\tan\beta = 10$, $M_{\tilde{g}} = 500$ GeV, $M_2 = 1000$ GeV, $\mu = 200$ GeV and all trilinear couplings to a common value $A_t$. The remaining sfermion masses were set to 1 TeV and the mass of the lightest $CP$-even Higgs was set to 125 GeV.

<table>
<thead>
<tr>
<th>Point</th>
<th>$m_{\tilde{t}_1}$ [GeV]</th>
<th>$m_{\tilde{t}_2}$ [GeV]</th>
<th>$A_t$ [GeV]</th>
<th>$\Delta \sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_1$</td>
<td>171</td>
<td>440</td>
<td>490</td>
<td>0.0026</td>
</tr>
<tr>
<td>$P_2$</td>
<td>192</td>
<td>1224</td>
<td>1220</td>
<td>0.013</td>
</tr>
<tr>
<td>$P_3$</td>
<td>226</td>
<td>484</td>
<td>532</td>
<td>0.015</td>
</tr>
<tr>
<td>$P_4$</td>
<td>226</td>
<td>484</td>
<td>0</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Banfi, Martin Sanz, arXiv:1308.4771

Grojean, Salvioni, Schlaffer, Weiler arXiv:1312.3317
At 1 TeV, statistical sensitivity (accounting for bg) well below 10% !!

What is a best BSM probe: BR($\gamma\gamma$) or shape of $p_T(H)$?

- answer likely BSM-model dependent
- ==> synergy/complementarity !!
VH production at large $m(VH)$

$$W_L \sim \partial H^\pm$$

In presence of a higher-dim op such as:

$$L_{D=6} = \frac{ig c_W}{2 \Lambda^2} \left( H^\dagger \sigma^a D^\mu H \right) D^\nu V^a_{\mu\nu}$$

$$\frac{\sigma}{\sigma_{SM}} \sim \left( 1 + c_W \frac{\hat{s}}{\Lambda^2} \right)^2$$

See e.g. Biekötter, Knochel, Krämer, Liu, Riva, arXiv:1406.7320

Mimasu, Sanz, Williams, arXiv:1512.02572v
WH→Wbb at large $M_{WH}$

100 TeV

$\sigma(M(Wbb) > M_{min}) \times 20 \text{ ab}^{-1}$

$|m_{bb} - m_H| < 25 \text{ GeV}$

$|\eta_{bb}, |\eta_W| < 2.5$

$W \rightarrow l\nu, l = e, \mu$

**Wbb production**

![Graph showing Wbb production](image)

**Figure H-49**

![Graph showing S/B](image)

**S/B**

![Graph showing $\sqrt{S+B}/S$](image)

**$\sqrt{S+B}/S$**
Lesson: Hierarchy of production channels changes at large $p_T(H)$:

- $\sigma(ttH) > \sigma(gg\rightarrow H)$ above 800 GeV
- $\sigma(VBF) > \sigma(gg\rightarrow H)$ above 1800 GeV

![Graph showing hierarchy of production channels at large $p_T(H)$](image)
H at large $p_T$

Statistics in potentially visible final states out to several TeV

**Fig H-40**

\[ N = \sigma(p_{T,H} > p_{T,min}) \times 20 \text{ ab}^{-1} \]

Light dots: 1 event/H final state ($l=e,\mu$)

- $\gamma\gamma \rightarrow \gamma 2l$
- $\mu\mu$
- $\gamma\gamma$
- $2l2\nu$
- Solid: $gg \rightarrow H$
- Dashes: $ttH$
- Short dash: VBF
- Dotdash: WH
Opportunities for % - level measurements at intermediate $p_T$ (100-500 GeV)

see M.Selvaggi in the FCC-hh physics/detector // session Thursday for more recent Delphes-based studies
Acceptance studies vs $p_T(H)$

**Figs H-41/44**
gg→H→ZZ*→4l at large p_T

- S/B ~ 1 for inclusive production at LHC
- Practically bg-free at large p_T at 100 TeV, maintaining large rates

<table>
<thead>
<tr>
<th>p_T,min (GeV)</th>
<th>δ_stat</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.3%</td>
</tr>
<tr>
<td>300</td>
<td>1%</td>
</tr>
<tr>
<td>1000</td>
<td>10%</td>
</tr>
</tbody>
</table>
gg→H→γγ at large p_T

- At LHC, S/B in the H→γγ channel is O( few % )
- At FCC, for p_T(H)>300 GeV, S/B~1
- Exptl systematics on BR(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst's)
- Exptl mass resolution at large pt(H)?
- Potentially accurate probe of the H pt spectrum up to large pt

**Fig H-45**

### Table

<table>
<thead>
<tr>
<th>p_T,min (GeV)</th>
<th>δ_{stat}</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.2%</td>
</tr>
<tr>
<td>400</td>
<td>0.5%</td>
</tr>
<tr>
<td>600</td>
<td>1%</td>
</tr>
<tr>
<td>1600</td>
<td>10%</td>
</tr>
</tbody>
</table>
• Stat reach $\sim 1\%$ at $p_T \sim 100$ GeV

• Exptl systematics on $\text{BR}$(μμ)/BR(γγ)? (use same fiducial selection to remove H modeling syst’s)
\textbf{gg\rightarrow H\rightarrow Z\gamma\rightarrow \ell\ell\gamma at large p_T}

- S/B $\rightarrow$ 1 at large $p_T$
- Stat reach $\sim$1% at $p_T$$\sim$100 GeV
- Exptl systematics on BR(Z\gamma)/BR(\gamma\gamma)?

<table>
<thead>
<tr>
<th>$p_T,\text{min}$ (GeV)</th>
<th>$\delta_{\text{stat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1%</td>
</tr>
<tr>
<td>900</td>
<td>10%</td>
</tr>
</tbody>
</table>
Using $\text{BR}(H \to ZZ^*)$ from FCC-ee (known at $\sim 0.3\%$ from $\delta g_{HZZ} \sim 0.15\%$), production ratios $\sigma(H \to XY)/\sigma(H \to ZZ^*)$ for $p_T > 100$ GeV return the following stat precision on the absolute value of rare BRs

<table>
<thead>
<tr>
<th>$\delta$ BR</th>
<th>$\gamma\gamma$</th>
<th>$Z\gamma$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 0.5%$</td>
<td>$\sim 1%$</td>
<td>$\sim 1%$</td>
<td></td>
</tr>
</tbody>
</table>
One should not underestimate, however, the value of FCC-hh standalone precise “ratios-of-BRs" measurements:

- independent of $\alpha_S, m_b, m_c, \Gamma_{\text{inv}}$ systematics
- sensitive to BSM effects that typically influence BRs in different ways. Eg

| & $\frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow ZZ^*)}$ & $\frac{\text{BR}(H \rightarrow \mu\mu)}{\text{BR}(H \rightarrow ZZ^*)}$
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>loop-level</td>
<td>tree-level</td>
</tr>
<tr>
<td>2nd gen’n Yukawa</td>
<td>gauge coupling</td>
</tr>
</tbody>
</table>

$\frac{\text{BR}(H \rightarrow \gamma\gamma)}{\text{BR}(H \rightarrow Z\gamma)}$

different EW charges in the loops of the two procs
### Top Yukawa from $ttH/ttZ$

Events/20ab$^{-1}$, with $tt \rightarrow \ell \nu + \text{jets}$

$\Rightarrow$ huge rates, exploit boosted topologies

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events/ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H \rightarrow 4\ell$</td>
<td>$2.6 \cdot 10^4$</td>
</tr>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>$4.6 \cdot 10^5$</td>
</tr>
<tr>
<td>$H \rightarrow 2\ell2\nu$</td>
<td>$2.0 \cdot 10^6$</td>
</tr>
<tr>
<td>$H \rightarrow b\bar{b}$</td>
<td>$1.2 \cdot 10^8$</td>
</tr>
</tbody>
</table>

**Diagram:**
- **ttH at 100 TeV**
  - Solid: $\sigma(p_{T,H}>p_{T,min})$ (fb)
  - Dashes: $\sigma(p_{T,top}>p_{T,min})$ (fb)
Top Yukawa from $ttH/ttZ$

Events/20ab$^{-1}$, with $tt\rightarrow \ell\nu+\text{jets}$

$\Rightarrow$ huge rates, exploit
boosted topologies

$ttH$ at 100 TeV

- $\delta y_\ell$ (stat + syst $\tau_H$) $\sim$ 1%
- great potential to reduce to similar levels $\delta_{\text{exp syst}}$
- consider other decay modes, e.g. $2\ell2\nu$

<table>
<thead>
<tr>
<th>$H \rightarrow 4\ell$</th>
<th>$H \rightarrow \gamma\gamma$</th>
<th>$H \rightarrow 2\ell2\nu$</th>
<th>$H \rightarrow b\bar{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2.6 \cdot 10^4$</td>
<td>$4.6 \cdot 10^5$</td>
<td>$2.0 \cdot 10^6$</td>
<td>$1.2 \cdot 10^8$</td>
</tr>
</tbody>
</table>

Top fat C/A jet(s) with $R = 1.2$, $|y| < 2.5$, and $p_{T,j} > 200$ GeV

$\delta y_\ell (\text{stat + syst } \tau_H) \sim 1\%$
• These examples prove that TH uncertainties do not need to be a limiting factor for very precise measurements, once statistics are large and allow for new and diverse measurements.

• Needless to say, careful work on the exptl systematics (eg absolute and relative detection efficiencies for the individual final states, pileup, etc) must be done to consolidate these naive estimates.

• The role of the the highest $p_T$ Higgs production (multi-TeV) in probing higher-dim op’s of the EFT must still be studied. Can they compete with, or outplay, the BSM sensitivity of BR and coupling measurements?
New analysis of HH production for the FCC report


- Goals:
  1. improve on previous studies and get a commonly-agreed estimate
  2. study dependence on efficiencies and systematics

Previous analyses:
W. Yao arXiv:1308.6302 (Snowmass Summer Study 2013)
Barr, Dolan, Englert, de Lima, Spannowsky JHEP 1502 (2015) 016
Azatov, R.C., Panico, Son PRD 92 (2015) 035001
H-J. He, J. Ren, W. Yao PRD 93 (2016) 015003

Signal: double Higgs production via gluon fusion \((gg \rightarrow hh)\)

\[
\begin{align*}
\sim const. & & \sim \lambda_3 \times \frac{m_h^2}{\delta} \log^2 \left( \frac{m_t^2}{\delta} \right)
\end{align*}
\]

Most sensitivity on trilinear coupling comes from threshold events
Results of the recent full-m$_{\text{top}}$ NLO calculation (Borowka et al, arXiv: 1604.06447) not included here (as yet....)

<table>
<thead>
<tr>
<th>Energy (TeV)</th>
<th>Signal cross section [fb] at NNLO+NNLL*</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 TeV</td>
<td>$45.05^{+4.4%}_{-6.6%} \pm 3.0% \pm 10%$</td>
</tr>
<tr>
<td>100 TeV</td>
<td>$1749^{+5.1%}_{-6.8%} \pm 2.7% \pm 10%$</td>
</tr>
</tbody>
</table>

Theoretical uncertainties:
- scale
- PDFs
- infinite $m_t$ approx.
- $+\alpha_s$

$\sim 40 \times$ increase

# Higgs pairs to $\bar{b}b\gamma\gamma$

<table>
<thead>
<tr>
<th>Source</th>
<th># Higgs pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC: 14TeV 300fb$^{-1}$</td>
<td>36</td>
</tr>
<tr>
<td>HL-LHC: 14TeV 3ab$^{-1}$</td>
<td>360</td>
</tr>
<tr>
<td>FCC: 100TeV 20ab$^{-1}$</td>
<td>$92 \times 10^3$</td>
</tr>
</tbody>
</table>

Backgrounds:
- $\bar{b}b\gamma\gamma$
- $t\bar{t}h(\gamma\gamma)$
- $b\bar{b}h(\gamma\gamma)$
- $jj\gamma\gamma$ (two fake b-jets)
- $\bar{b}\bar{b}j\gamma$ (one fake photon)
Montecarlo Simulation: MadGraph5_aMC@NLO \rightarrow Pythia 6 \rightarrow Delphes (FCC card)

Three benchmark scenarios for ECAL and HCAL resolution:

\[ \Delta E = \sqrt{a^2 E^2 + b^2 E} \]

<table>
<thead>
<tr>
<th></th>
<th>ECAL</th>
<th></th>
<th>HCAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(</td>
<td>\eta</td>
<td>\leq 4)</td>
</tr>
<tr>
<td>low</td>
<td>a</td>
<td>b</td>
<td>a</td>
</tr>
<tr>
<td>medium</td>
<td>0.02</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>high</td>
<td>0.007</td>
<td>0.06</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig H-63

High
\[ \Delta m(\gamma\gamma) = 1.5 \text{ GeV} \]

Med
\[ \Delta m(\gamma\gamma) = 2.0 \text{ GeV} \]

Low
\[ \Delta m(\gamma\gamma) = 3.0 \text{ GeV} \]
- overall rescaling of background rate \( n_B \rightarrow r_B \times n_B \) using “medium” calorimeter resolution

- uncertainty on signal rate

\[
\Delta_S = \frac{\Delta \sigma(pp \rightarrow hh)}{\sigma(pp \rightarrow hh)}
\]

For \( \Delta_S \gtrsim 2.5\% \) the precision on \( \lambda_3 \) is dominated by the theory error on the signal: \( \Delta \lambda_3 \simeq 2\Delta_S \)

<table>
<thead>
<tr>
<th>( r_B )</th>
<th>( \Delta_S = 0.00 )</th>
<th>( \Delta_S = 0.01 )</th>
<th>( \Delta_S = 0.015 )</th>
<th>( \Delta_S = 0.02 )</th>
<th>( \Delta_S = 0.025 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.7%</td>
<td>3.4%</td>
<td>4.1%</td>
<td>4.9%</td>
<td>5.8%</td>
</tr>
<tr>
<td>1.0</td>
<td>3.4% (green)</td>
<td>3.9%</td>
<td>4.6%</td>
<td>5.3%</td>
<td>6.1%</td>
</tr>
<tr>
<td>1.5</td>
<td>3.9%</td>
<td>4.4%</td>
<td>5.0%</td>
<td>5.7%</td>
<td>6.4%</td>
</tr>
<tr>
<td>2.0</td>
<td>4.4%</td>
<td>4.8%</td>
<td>5.4%</td>
<td>6.0%</td>
<td>6.8%</td>
</tr>
<tr>
<td>3.0</td>
<td>5.2%</td>
<td>5.6%</td>
<td>6.0%</td>
<td>6.6%</td>
<td>7.3%</td>
</tr>
</tbody>
</table>

Tab H-30

Results updated/confirmed with improved analysis by M.Selvaggi, [https://indico.cern.ch/event/613195/]
impact of detector performance, 1

Fig H-65

precision on $\lambda$ vs. diphoton mass window: $m_{\gamma\gamma} = m_\mu \pm \Delta m_{\gamma\gamma}$ (L = 30.0 ab$^{-1}$)

detector parametrization:
- Low
- Med
- High

precision on $\lambda$ vs. coverage $|\eta_{\text{max}}|$ for "Med" parametrization (L = 30.0 ab$^{-1}$)

- photons
- $l$-jets
impact of detector performance, 2

Fig H-66

$p_{b \rightarrow b}$

$p_{c \rightarrow b}$

$\Delta \Lambda$

$p_{j \rightarrow b}$

$p_{j \rightarrow \gamma}$

$\Delta \Lambda$

$p_{j \rightarrow \gamma} = \alpha \times e^{-p_{T,j}/30\text{GeV}}$

$\alpha$
other channels, first assessments ....

\[ \lambda \] dependence at 14 and 100 TeV are similar.

Sec H-5.2.3,5.2.4

<table>
<thead>
<tr>
<th>process</th>
<th>precision on ( \sigma_{SM} )</th>
<th>68% CL interval on Higgs self-couplings</th>
</tr>
</thead>
<tbody>
<tr>
<td>( HH \to b\bar{b}\gamma\gamma )</td>
<td>3%</td>
<td>( \lambda_3 \in [0.97, 1.03] )</td>
</tr>
<tr>
<td>( HH \to b\bar{b}b\bar{b} )</td>
<td>5%</td>
<td>( \lambda_3 \in [0.9, 1.5] )</td>
</tr>
<tr>
<td>( HH \to b\bar{b}4\ell )</td>
<td>( O(25%) )</td>
<td>( \lambda_3 \in [0.6, 1.4] )</td>
</tr>
<tr>
<td>( HH \to b\bar{b}\ell^+\ell^- )</td>
<td>( O(15%) )</td>
<td>( \lambda_3 \in [0.8, 1.2] )</td>
</tr>
<tr>
<td>( HH \to b\bar{b}\ell^+\ell^-\gamma )</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

See B.DiMicco HH status review, Thu // session
Quartic Higgs self-coupling

\[ \lambda_4 \text{ in } [-4, 16] \text{ at } 95\% \text{CL} \]

Sec H-5.3.4

=> \( \lambda_4 \) in \([-4, 16]\) at 95\%CL
Further ongoing studies for HH discussed at the Wshop

Preliminary studies on $hh \rightarrow VVbb$ decay channels

B. Di Micco
Università degli Studi di Roma Tre e I.N.F.N

S. Braibant, N. De Filippis, M. Testa

see Biagio’s talk Thu morning

Double Higgs Production in VBF

1611.03860 FB, R. Contino, and J. Rojo

Fady Bishara
\[ \mathcal{L} \supset \frac{1}{2} (\partial_{\mu} h)^2 - V(h) + \frac{v^2}{4} \text{Tr} (D_\mu \Sigma \Sigma^\dagger D^{\mu} \Sigma) \left[ 1 + 2 c_V \frac{h}{v} + c_{2V} \frac{h^2}{v^2} + \ldots \right] - m_i \bar{\psi}_L i \Sigma \left( 1 + c \frac{h}{v} + \ldots \right) \psi_R \]

\[ V(h) = \frac{1}{2} m_h^2 h^2 + c_3 \frac{1}{6} \left( \frac{3m_h^2}{v} \right) h^3 + c_4 \frac{1}{24} \left( \frac{3m_h^2}{v^2} \right) h^4 + \ldots \]

e.g. in minimal SO(5)/SO(4) models

\[ c_V = \sqrt{1 - \xi}, \quad c_{2V} = 1 - 2\xi \]

\[ \xi = \frac{v^2}{f^2} \]

\[ c = \sqrt{1 - \xi}, \quad c = \frac{1 - 2\xi}{\sqrt{1 - \xi}} \] for 4 of SO(5)

\[ c = \frac{1 - 2\xi}{\sqrt{1 - \xi}} \] for 5 of SO(5)

\[ \mathcal{A}(V_L V_L \rightarrow hh) \simeq \frac{s}{v^2} (c_{2V} - c_V^2) \]
\[ \delta_{C_{2V}} = C_{2V} - 1 \]

\[ \delta_{C_{2V}} \approx g^2 v^2 / \Lambda^2 \]

See, e.g., [Giudice, Grojean, Pomarol, Rattazzi: hep-ph/0703164]
NB model-by-model, correlations exist between BR deviations and $\delta_{c2V}$

E.g. in the SO(5)/SO(4) models shown before, and for the embedding in the fundamental rep of SO(5) (5) with the fermion couplings modified by

$$c = \frac{1 - 2\xi}{\sqrt{1 - \xi}}$$

=> 1% sensitivity to $\delta_{c2V}$ is equivalent to < 1% sensitivity in BR(H->WW*)
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>BSM aspects of Higgs physics and EWSB</td>
<td>106</td>
</tr>
<tr>
<td>6.1</td>
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</tr>
<tr>
<td>6.5</td>
<td>The Origins of Neutrino Mass and Left-right symmetric model</td>
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<td>6.6</td>
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<td>136</td>
</tr>
<tr>
<td>6.7</td>
<td>BSM Higgs Sectors</td>
<td>146</td>
</tr>
</tbody>
</table>
Constrain bg pt spectrum from $Z \rightarrow \nu\nu$ to the % level using NNLO QCD/EW\(^*\) to relate to measured $Z \rightarrow ee, W$ and $\gamma$ spectra.

* arXiv:1705.04664

SM sensitivity with $1\text{ab}^{-1}$, can reach few $\times 10^{-4}$ with $30\text{ab}^{-1}$
Unmixed SM+Singlet.
No exotic H decay, no H-S mixing, no EWPO, …

Two regions with strong EWPT
Only Higgs Portal signatures:
$h^* \rightarrow SS$ direct production
Higgs cubic coupling
$\sigma(Zh)$ deviation (> 0.6% @ TLEP)

⇒ Appearance of first “no-lose” arguments for classes of compelling scenarios of new physics
MSSM Higgs $@ 100$ TeV

N. Craig, J. Hajer, Y.-Y. Li, T. Liu, and H. Zhang, arXiv:1605.08744


Fig H-88
Precision EW observables at 100 TeV
Probes of dim-6 op’s with high-mass DY @ 100 TeV

Trade extreme precision for dynamical range, in pursuit of high-scale sensitivity

\[
\begin{align*}
\text{universal form factor (L)} \\
W & = -\frac{W}{4m_W^2}(D_\rho W^{a\mu}_\nu)^2 \\
Y & = -\frac{Y}{4m_W^2}(\partial_\rho B^{\mu\nu})^2
\end{align*}
\]

M. Farina et al, arXiv:1609.08157

Josh Ruderman at the Wshop

<table>
<thead>
<tr>
<th>assumed syst’s at 100 TeV:</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutral: $\delta_{\text{corr}} = \delta_{\text{unc}} = 2%$</td>
</tr>
<tr>
<td>charged: $\delta_{\text{corr}} = \delta_{\text{unc}} = 5%$</td>
</tr>
</tbody>
</table>

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|}
\hline
& \text{LEP} & \text{ATLAS} & \text{CMS} & \text{LHC 13} & \text{100 TeV} & \text{ILC} & \text{TLEP} & \text{ILC 500 GeV} \\
\hline
\text{luminosity} & 2 \times 10^7 Z & 19.7 fb^{-1} & 20.3 fb^{-1} & 0.3 \text{ ab}^{-1} & 3 \text{ ab}^{-1} & 10 \text{ ab}^{-1} & 10^9 Z & 10^{12} Z & 3 \text{ ab}^{-1} \\
\hline
\text{NC} & W \times 10^4 & [-19, 3] & [-3, 15] & [-5, 22] & \pm 1.5 & \pm 0.8 & \pm 0.04 & \pm 3 & \pm 0.7 & \pm 0.3 \\
\hline
\text{Y} & X \times 10^4 & [-17, 4] & [-4, 24] & [-7, 41] & \pm 2.3 & \pm 1.2 & \pm 0.06 & \pm 4 & \pm 1 & \pm 0.2 \\
\hline
\text{CC} & W \times 10^4 & -- & -- & \pm 3.9 & \pm 0.7 & \pm 0.45 & \pm 0.02 & -- & -- & -- \\
\hline
\end{array}
\]
\[ \mathcal{L}_{\text{eff}} \supset \frac{1}{\Lambda_Y^2} (\partial_\mu B_{\mu \nu})^2 + \frac{1}{\Lambda_W^2} (D_\rho W^a_{\mu \nu})^2 + \frac{1}{\Lambda_Z^2} (D_\rho G^a_{\mu \nu})^2 \]

- FCC-pp reach:
  - \( \Lambda_Y \gtrsim 70 \text{ TeV} \)
  - \( \Lambda_W \gtrsim 110 \text{ TeV} \)
  - \( \Lambda_Z \gtrsim 90 \text{ TeV} \)

**Complementarity of direct and indirect searches**

Josh Ruderman at the Wshop

ex) heavy vector triplet

\[ \mathcal{L} \supset -\frac{1}{4} W^a_{\mu \nu} W^a_{\rho \sigma} - \frac{1}{4} V^a_{\mu \nu} V^a_{\rho \sigma} - \frac{\epsilon}{2} W^a_{\mu \nu} V^a_{\rho \sigma} + \frac{M^2}{2} V^2 \]

- Thamm, Torre, Wulzer 1502.01701
Running Electroweak Couplings at 100 TeV

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Direct discovery potential at the highest masses

at high mass, the mass reach of LHC searches for BSM phenomena like Z’, W’, SUSY, LQs, top partners, etc. etc. scales trivially by ~5-7, depending on total luminosity …
New gauge bosons discovery reach

Example: $W'$ with SM-like couplings

$NB$ For SM-like $Z'$, $\sigma_{Z'} BR_{\text{lept}} \sim 0.1 \times \sigma_{W'} BR_{\text{lept}}$, $\Rightarrow$ rescale lum by $\sim 10$

$M(W')=46.5 \text{ TeV} @ 100 \text{ab}^{-1}$

$M(W')=39 \text{ TeV} @ 10 \text{ab}^{-1}$

$M(W')=31.5 \text{ TeV} @ 1 \text{ab}^{-1}$

$W'$ production, SM-like couplings to quarks
Int Lum (ab$^{-1}$) for 100 Events at 100 TeV

At $L=O(\text{ab}^{-1})$, $\text{Lum} \times 10 \Rightarrow \sim M + 7 \text{ TeV}$
Sensitivity to $t\bar{t}$ resonances

Auerbach, Chekanov, Proudfoot, Kotwal, arXiv:1412.5951
Discovery reach for pair production of strongly-interacting particles

\[ \sigma(pp \rightarrow QQ) \ (ab) \text{ at } 100 \text{ TeV} \]

- \( Q = \text{stop} \)
- \( Q = \text{top} \)
- \( Q = \text{gluino} \)

100 evts/10ab\(^{-1}\)
SUSY and DM reach at 100 TeV

- possibility to find (or rule out) thermal WIMP DM candidates
- see P.Harris DM review in FCC-hh detector/physics // session, Thu afternoon
Larger statistics, giving access to more extreme kinematical regions, allow to exploit new powerful analysis tools, and gain sensitivity to otherwise elusive signatures.

Example from the LHC: search for low-mass resonances $V \rightarrow 2$ jets

search impossible at masses below few hundred GeV, due to large $gg \rightarrow gg$ bg’s and trigger thresholds.

At large $p_T$

- $S/B$ improves ($qg$ initial state dominates both $S$ and $B$)
- use boosted techniques to differentiate $V \rightarrow qq$ vs QCD dijets
- $\varepsilon_{\text{trig}} \sim 100\%$
These techniques will be extremely powerful at 100 TeV. Only partly explored so far ....
If no discoveries are made at the LHC, the simplest versions of low-energy supersymmetry would be ruled out. [...] the era of natural supersymmetry would come to an end. However, in such an instance it would be incorrect to conclude that the naturalness principle is misguided. Excluding new dynamics at the weak scale would mean ruling out our favoured solutions to the naturalness problem, but not the problem itself, and knowing how nature deals with Higgs naturalness will remain a standing issue. **This reframing of the naturalness question would imply the loss of the logical connection between Higgs naturalness and new phenomena at the TeV scale. If this connection is lost, what would be so special about the energy scale explored by a 100 TeV collider and why should we expect new phenomena in that range?**

Speculations have been made about logical schemes that deal with Higgs naturalness without dynamics at the weak scale, such as the anthropic principle or cosmological relaxation. Intriguingly, even within these very different schemes, motivations for supersymmetry emerge, although at a scale different than the weak scale and also for different reasons. In the context of unnatural setups, *considerations about dark matter, gauge coupling unification, or the Higgs mass, or the limited cutoff that can be achieved in cosmological relaxation scenarios call for supersymmetry with a certain preference for the O(10's) TeV range.*

Speculations about the role of supersymmetry in ‘unnatural’ theories suggest that a future physics program should not be regarded as an extension of LHC searches, but rather as conceptually different. If the LHC is the machine of the naturalness era, future colliders would become the machine of the post-naturalness era. An era in which we are forced to change the focus of our basic questions about particle physics, in which we contemplate partly unnatural theories or theories where naturalness is realised in unconventional ways, and in which supersymmetry may enter in a new guise.
100 TeV ?

200 TeV ?

28 TeV ?
HE-LHC
• Technological dimension. Eg
  • does the FCC-hh need a demonstrator?
HE-LHC

• Technological dimension. Eg
  • does the FCC-hh need a demonstrator?
• Political dimension. Eg
  • acceptable cost?
  • keep community active during a possibly long wait for the FCC
  • …
HE-LHC

- Technological dimension. Eg
  - does the FCC-hh need a demonstrator?
- Political dimension. Eg
  - acceptable cost?
  - keep community active during a possibly long wait for the FCC
  - ...
- Physics dimension
  - some first considerations to follow …

not for this discussion
Evolution, with beam energy, of scenarios with the discovery of a new particle at the LHC

\[
\frac{\sigma(pp\to X)[\sqrt{S}]}{\sigma(pp\to X)[14 \text{ TeV}]}
\]

\begin{align*}
gg\to X & \quad m_X(\text{TeV}) = 6, 4, 2, 1, 0.5 \\
qq\to X & \quad m_X(\text{TeV}) = 6, 4, 2, 1, 0.5
\end{align*}
Possible questions/options
Possible questions/options

• If $m_X \sim 6 \text{ TeV}$ in the gg channel, rate grows $\times 200 \ @28 \text{ TeV}:
Possible questions/options

- If $m_X \sim 6 \text{ TeV}$ in the gg channel, rate grows $\times 200$ @28 TeV:
- Do we wait 40 yrs to go to pp@100 TeV, or fast-track 28 TeV in the LHC tunnel?
Possible questions/options

• If $m_X \sim 6 \text{ TeV}$ in the gg channel, rate grows $\times 200$ @28 TeV:
• Do we wait 40 yrs to go to pp@100 TeV, or fast-track 28 TeV in the LHC tunnel?
• Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$)?
Possible questions/options

- If $m_X \sim 6$ TeV in the gg channel, rate grows $\times 200$ @28 TeV:
  - Do we wait 40 yrs to go to pp@100 TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$)?
  - .... and the answers may depend on whether we expect partners of $X$ at masses $\approx 2m_X$ ($\Rightarrow 28$ TeV would be insufficient ....)
Possible questions/options

• If $m_X \sim 6$ TeV in the gg channel, rate grows $\times 200$ @28 TeV:
  • Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  • Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$) ?
  • .... and the answers may depend on whether we expect partners of $X$ at masses $\approx 2m_X$ ($\Rightarrow 28$ TeV would be insufficient ....)

• If $m_X \sim 0.5$ TeV in the qqbar channel, rate grows $\times 10$ @100 TeV:
Possible questions/options

- If $m_X \sim 6 \text{ TeV}$ in the gg channel, rate grows $\times 200$ @28 TeV:
  - Do we wait 40 yrs to go to pp@100 TeV, or fast-track 28 TeV in the LHC tunnel?
  - Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$)?
  - ... and the answers may depend on whether we expect partners of $X$ at masses $\approx 2m_X$ ($\Rightarrow 28 \text{ TeV would be insufficient}$ ....)

- If $m_X \sim 0.5 \text{ TeV}$ in the qqbar channel, rate grows $\times 10$ @100 TeV:
  - Do we go to 100 TeV, or push by $\times 10 \int L$ at LHC?
Possible questions/options

• If $m_X \sim 6$ TeV in the $gg$ channel, rate grows $\times 200$ @28 TeV:
  • Do we wait 40 yrs to go to $pp@100$ TeV, or fast-track 28 TeV in the LHC tunnel?
  • Do we need 100 TeV, or 50 is enough ($\sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4$, $\sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3$)?
  • .... and the answers may depend on whether we expect partners of $X$ at masses $\approx 2m_X$ (⇒ 28 TeV would be insufficient ....)

• If $m_X \sim 0.5$ TeV in the $qqbar$ channel, rate grows $\times 10$ @100 TeV:
  • Do we go to 100 TeV, or push by $\times 10\int L$ at LHC?
  • Do we build CLIC?
Possible questions/options

• If \( m_X \sim 6 \text{ TeV} \) in the gg channel, rate grows \( x \, 200 @28 \text{ TeV} \):
  • Do we wait 40 yrs to go to pp@100TeV, or fast-track 28 TeV in the LHC tunnel?
  • Do we need 100 TeV, or 50 is enough (\( \sigma_{100}/\sigma_{14} \sim 4 \cdot 10^4 \), \( \sigma_{50}/\sigma_{14} \sim 4 \cdot 10^3 \))?
  • .... and the answers may depend on whether we expect partners of \( X \) at masses \( \approx 2m_X \) (\( \Rightarrow 28 \text{ TeV would be insufficient ....} \))

• If \( m_X \sim 0.5 \text{ TeV} \) in the qqbar channel, rate grows \( x10 @100 \text{ TeV} \):
  • Do we go to 100 TeV, or push by \( x10 \int \mathcal{L} \) at LHC?
  • Do we build CLIC?

• etc.etc.
HE-LHC (27 TeV), prelim performance estimates

HE-LHC: pile up & performance

with 160 days of physics, 70% availability, 3 h turnaround time

$\beta^* = 25 \text{ cm}: 920 \text{ fb}^{-1}/\text{year}$

$\beta^* = 15 \text{ cm}: 1100 \text{ fb}^{-1}/\text{year}$

$O(15 \text{ ab}^{-1})$ over 15-20 years

M. Benedikt, S. Fartoukh, F. Zimmermann
Systematics studies* of the full physics potential at \(O(28)\) TeV, with \(O(15 \text{ ab}^{-1})\), need to be carried out

* except for straightfwd mass-reach extrapolations from LHC

E.g. HH at 28 TeV (back of the envelope)

\[
\frac{\sigma_{HH}(28 \text{ TeV})}{\sigma_{HH}(14 \text{ TeV})} \sim 4 ; \quad \text{Lum}(28) \sim 4 \text{ Lum}(14 \text{ TeV})
\]

\[
\Rightarrow N_{HH}(28) \sim 16 \; N_{HH}(14)
\]

\[
\Rightarrow \delta\lambda_{HHH} (28) \sim \delta\lambda_{HHH} (\text{HL-LHC}) / 4 \sim 10\%
\]

Expect to carry out an overall evaluation of the physics potential during 2018 (likely in the context of the HL-LHC Physics workshop)
Final remarks

- FCC-hh physics studies today focus on exploring possible scenarios, assessing the physics potential, defining benchmarks for the accelerator and detector design and performance, in order to better inform the discussions that will take place when the time for decisions comes...

- The interplay of the three colliders (ee, eh and hh) is crucial to the full exploitation of the FCC physics potential

- The physics case of a 100 TeV collider is very clear as a long-term goal for the field, simply because no other proposed or foreseeable project can have direct sensitivity to such large mass scales.

- Nevertheless, the precise route followed to get there must take account of the fuller picture, to reflect the future data (and the impact they will have on the theoretical thinking) from the LHC, as well as other current and future experiments in areas ranging from flavour physics to searches for dark matter, axions, ALPs, …