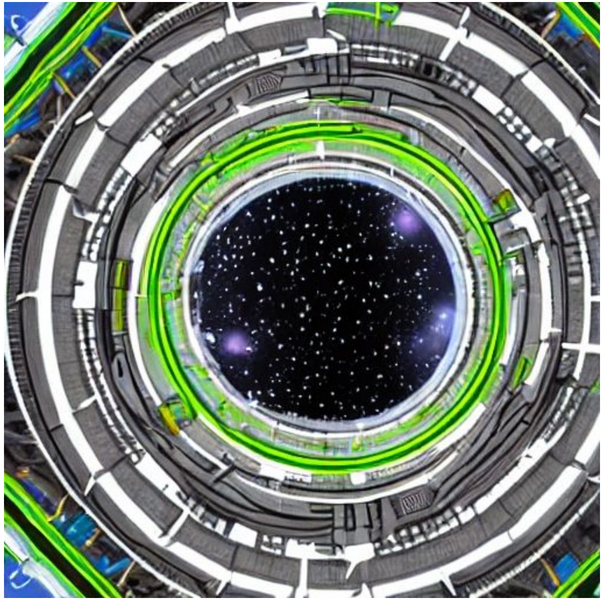
Hadron colliders: FCC-hh

FUTURE CIRCULAR COLLIDER

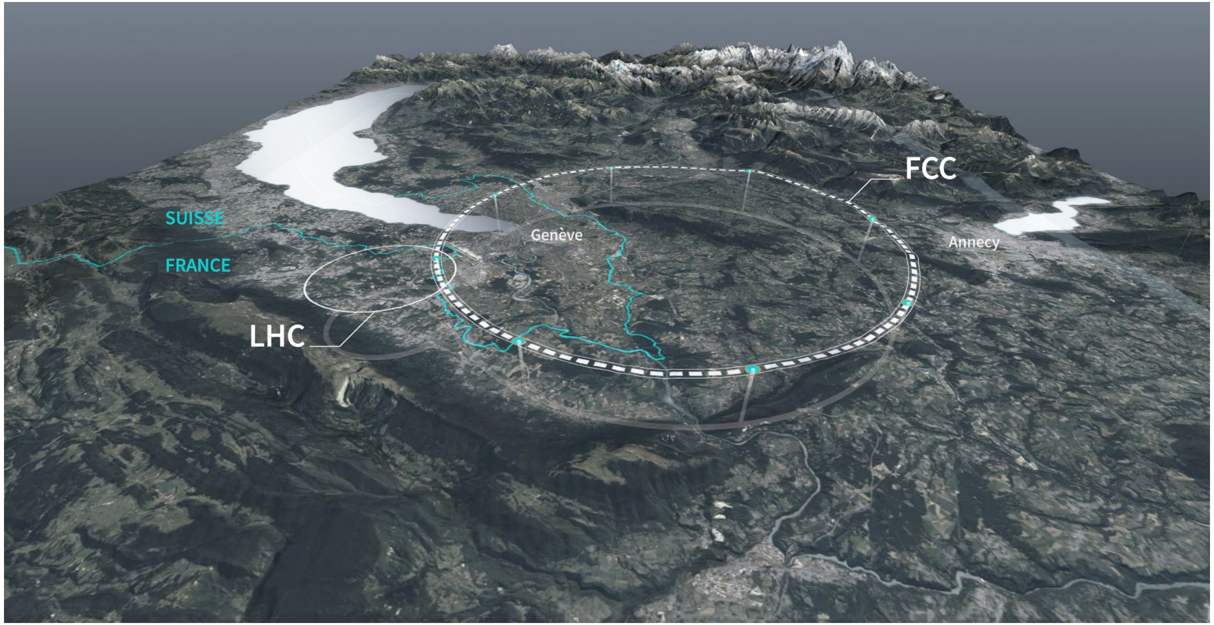


22.03.2024 Nikhef Topical Lectures “Future Colliders”

Birgit Stapf

Introduction & overview

- FCC-hh: Hadron collider phase of the FCC integrated programme
  - *pp*-collisions at 100 TeV (nominal)
  - Studies with 80 TeV or 120 TeV ongoing



Introduction & overview

- FCC-hh: Hadron collider phase of the FCC integrated programme
- FCC feasibility study is ongoing now - 2025
    - Midterm review recently concluded (status report)

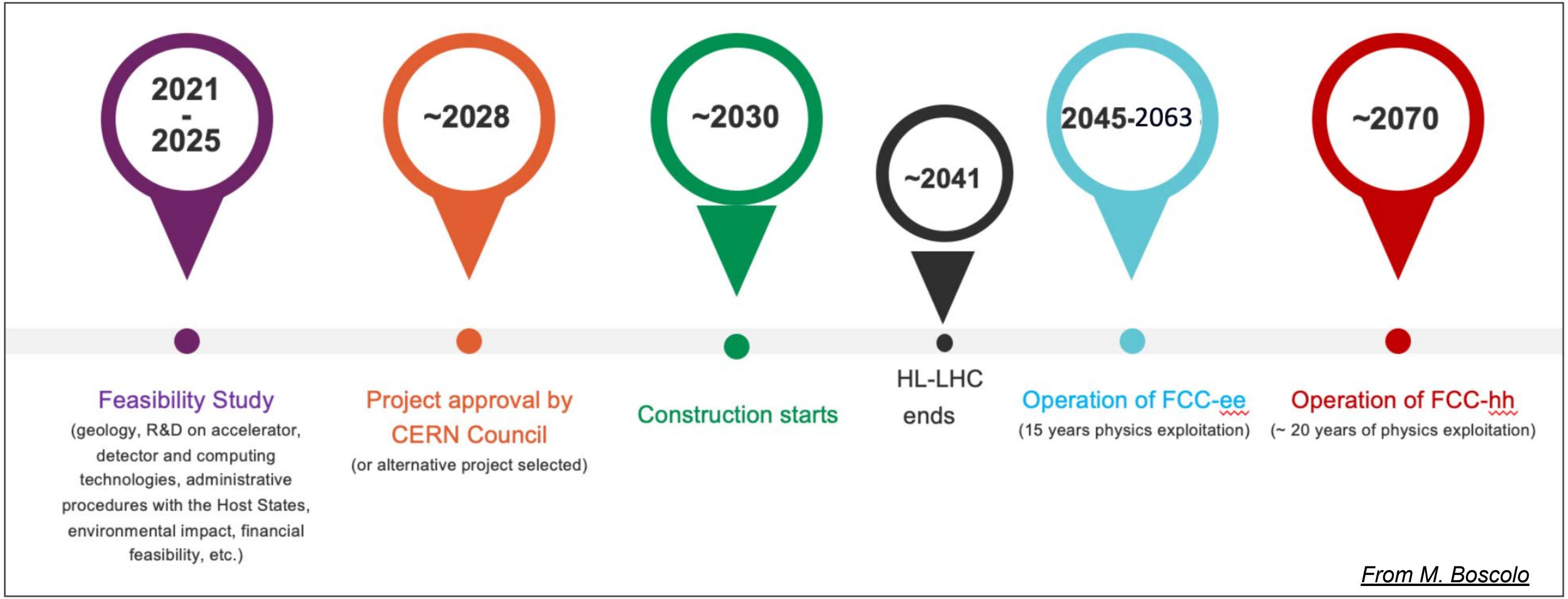
"There is no technical showstopper identified so far, but still a lot of work to be done to achieve greater accuracy and depth technical details, on geology or on the projected cost for instance." - Official FCC webpage

"Financial Committee underlines the need to make the project attractive from the physics viewpoint and takes the view that it would be unfortunate to sacrifice the attractiveness of the physics for the sake of reducing costs."

From C. Grojean

Introduction & overview

- FCC-hh: Hadron collider phase of the FCC integrated programme
- FCC feasibility study is ongoing now - 2025
- FCC-hh is ***far in the future*** - but need foundations ***now***



Introduction & overview

- FCC-hh: Hadron collider phase of the FCC integrated programme
- FCC feasibility study is ongoing now - 2025
- FCC-hh is *far in the future* - but need foundations now
- Conceptual Design Report from 2019
    - Collider design key parameters, reference detector and physics potential

353 pages

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THE EUROPEAN PHYSICAL JOURNAL
SPECIAL TOPICS

Regular Article

FCC-hh: The Hadron Collider

Future Circular Collider Conceptual Design Report Volume 3

Collider design: Key parameters & challenges

Parameter	(HL)-LHC	FCC-hh
E_{CM}	14 TeV	100 TeV
Peak inst. lumi.	(1 - 5) x 10^{34} cm^{-2} s^{-1}	(5 - 30) x 10^{34} cm^{-2} s^{-1}

Factor 7

Factor 6

Collider design: Key parameters & challenges

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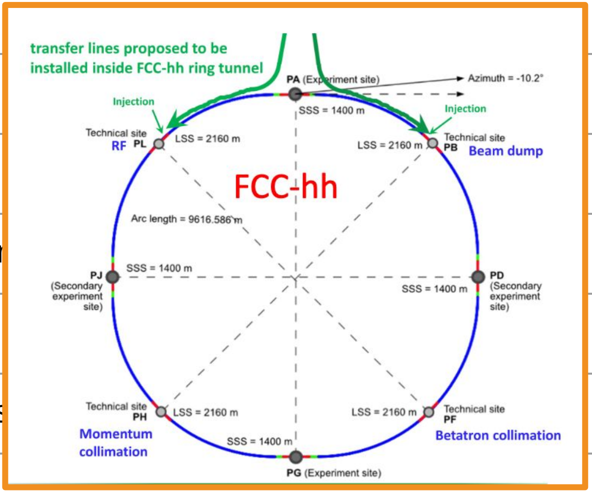
Collider design: Key parameters & challenges

Parameter	FCC-hh
E_{CM}	100 TeV
Peak inst. lu	(5 - 30) x 10^{34} cm^{-2} s^{-1}
Circumferen	90.7 km
Dipole field s	~ 16 T

Factor 7



Energy increase achieved by larger circumference and higher *B*-field

- E_b [GeV] = 0.3 ($B\ \rho$) [Tm]

Lowest risk baseline placement of tunnel chosen recently, considered geology, environment, infrastructure ..

Collider design: Key parameters & challenges

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E_{CM}	14 TeV	100 TeV
Peak inst. lumi.	(1 - 5) x 10^{34} cm^{-2} s^{-1}	(5 - 30) x 10^{34} cm^{-2} s^{-1}
Circumference	26.7 km	90.7 km
Dipole field strength	8.33 T	~ 16 T

Factor 7

Energy increase achieved by larger circumference and higher *B*-field

- E_b [GeV] = 0.3 (B ρ) [Tm]

Development of the magnets is one of the major challenges, and a big R&D effort → Details from Ewen in yesterday's lecture

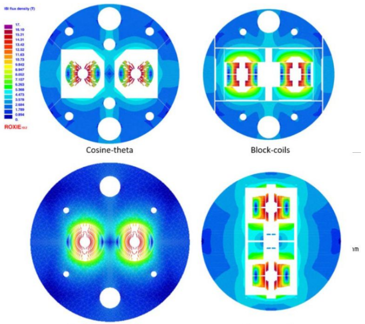

Fig. 3.7. Electromagnetic cross sections of the 16 T dipole design variants.

Collider design: Key parameters & challenges

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Dipole field strength	8.33 T	~ 16 T
Goal int. lumi.	3 ab^{-1}	30 ab^{-1}

- Total of >= 30 ab^{-1} during operation time of 25 years, with similar “scheduling” as LHC, i.e. split between (two) experiments, with planned “upgrade” phases

Collider design: Key parameters & challenges

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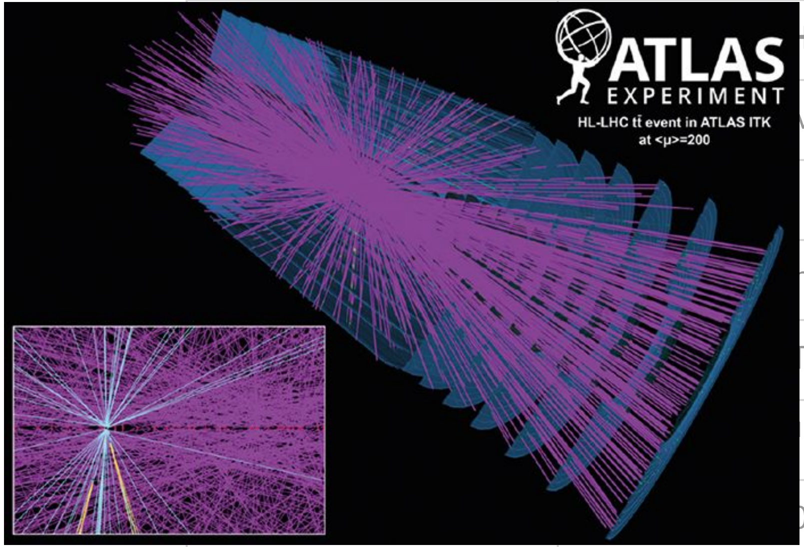
Events/crossing	O(10-100)	Max. 1000

Collider design: Key parameters & challenges

<μ> = 200



HC	**FCC-hh**
V	100 TeV
cm^{-2} s^{-1}	(5 - 30) x 10^{34} cm^{-2} s^{-1}
m	90.7 km
T	~ 16 T
	30 ab^{-1}
00)	Max. 1000

Avg. interactions/bunch cross.

Now — *O(10)* *LHC* — *O(100)* *HL-LHC* — *O(1000)* *FCC-hh* → *Future*

Note: Prospect studies assume that with the help of timing detectors we reduce this to LHC levels!

Collider design: Key parameters

Parameter	(HL)-LHC	FCC-hh
E_{CM}	14 TeV	100 TeV
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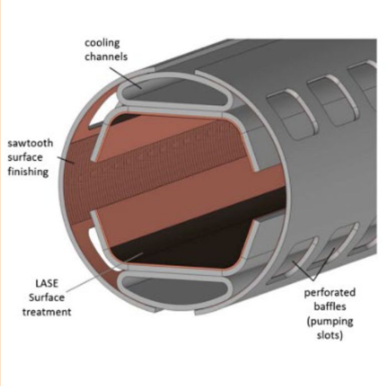
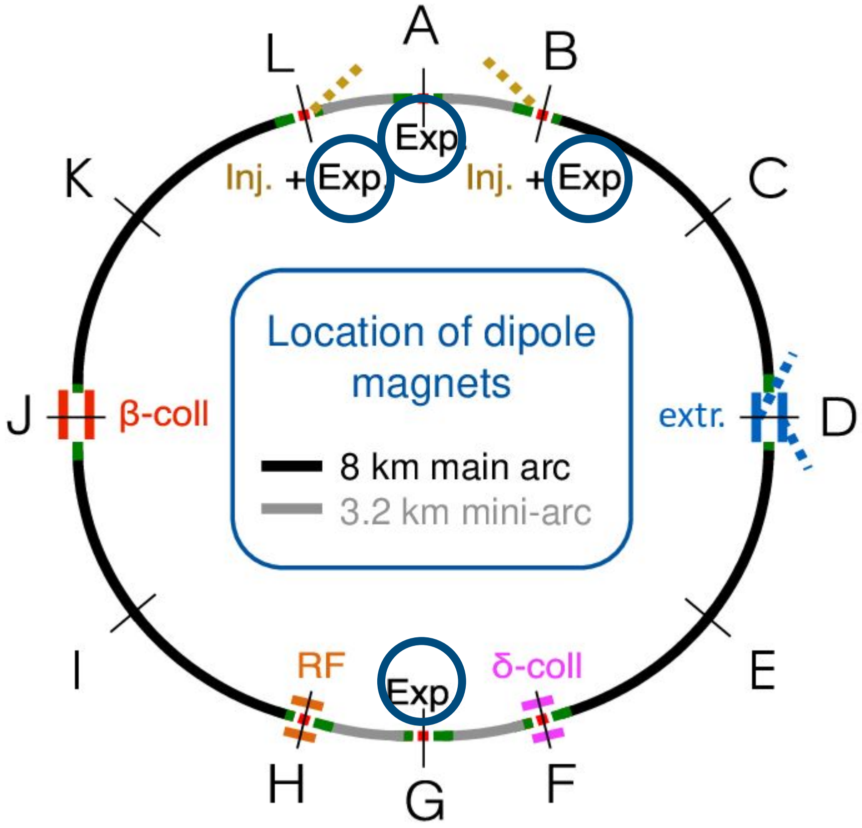
Dipole field strength	8.33 T	~ 16 T
Goal int. lumi.	3 ab^{-1}	30 ab^{-1}
Events/crossing	O(10-100)	Max. 1000
SR power loss/beam	< 0.01 MW	2.4 MW



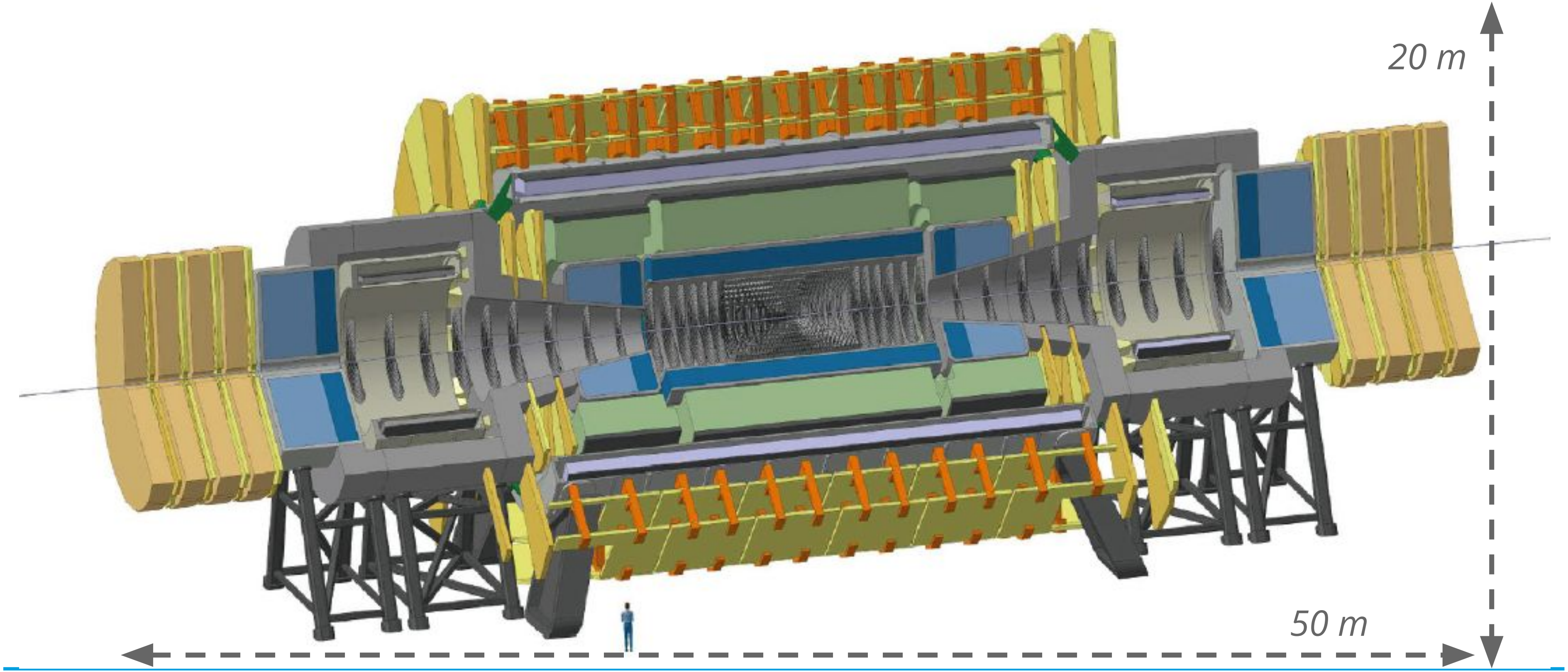
- Losses due to synchrotron radiation become sizeable, first at a hadron collider
  - Proportional to E^4

Experiments

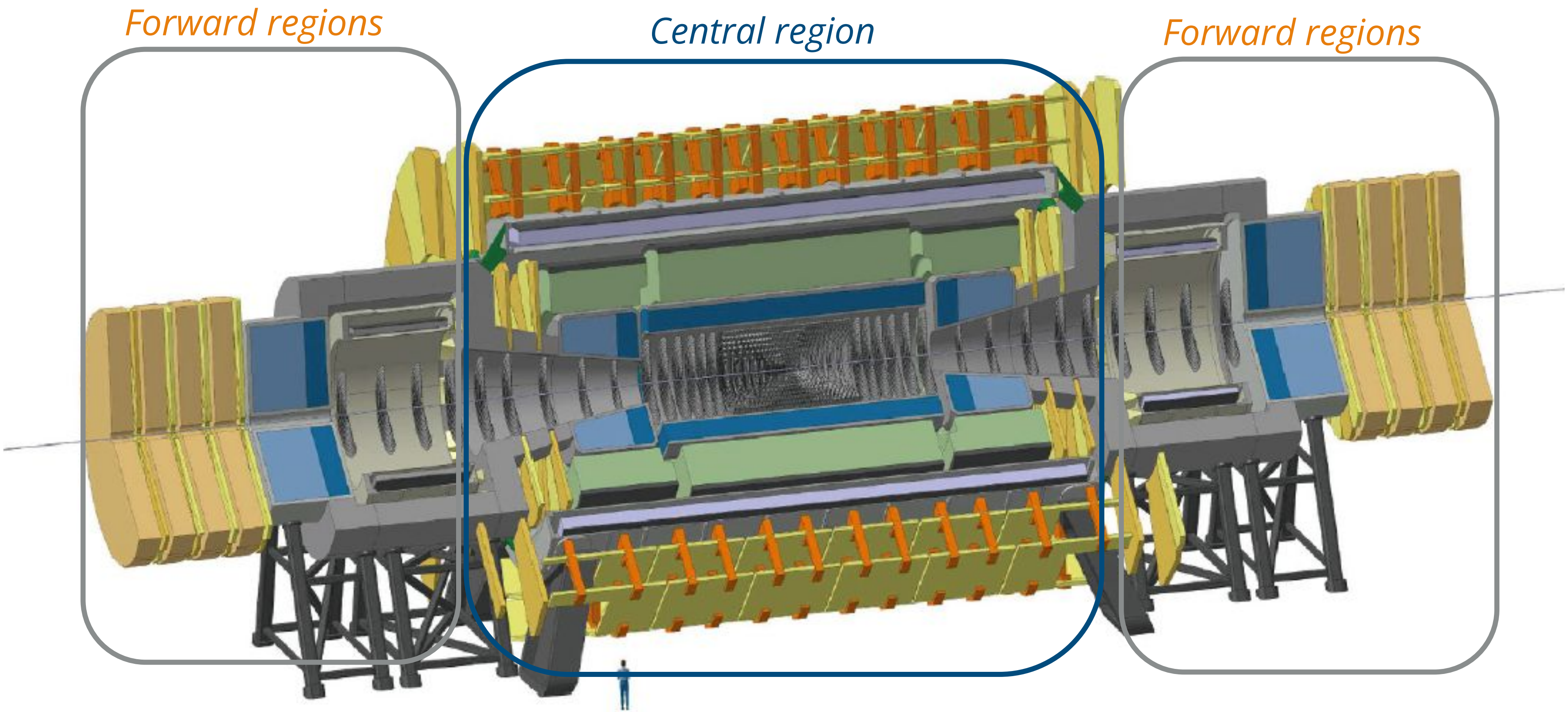


- Four interaction points:
- (SM) physics more forward + boosted @ 100 TeV
  - Precision up to $|\eta|$ ~ 4 , VBF jets up to $|\eta|$ ~ 6
  - High granularity e.g. resolve products of highly boosted tau
  - Contain multi-TeV jets
- Other challenges due to the much higher collision rates w.r.t. HL-LHC:
  - Radiation hardness
  - Pile-up
  - Huge data rates

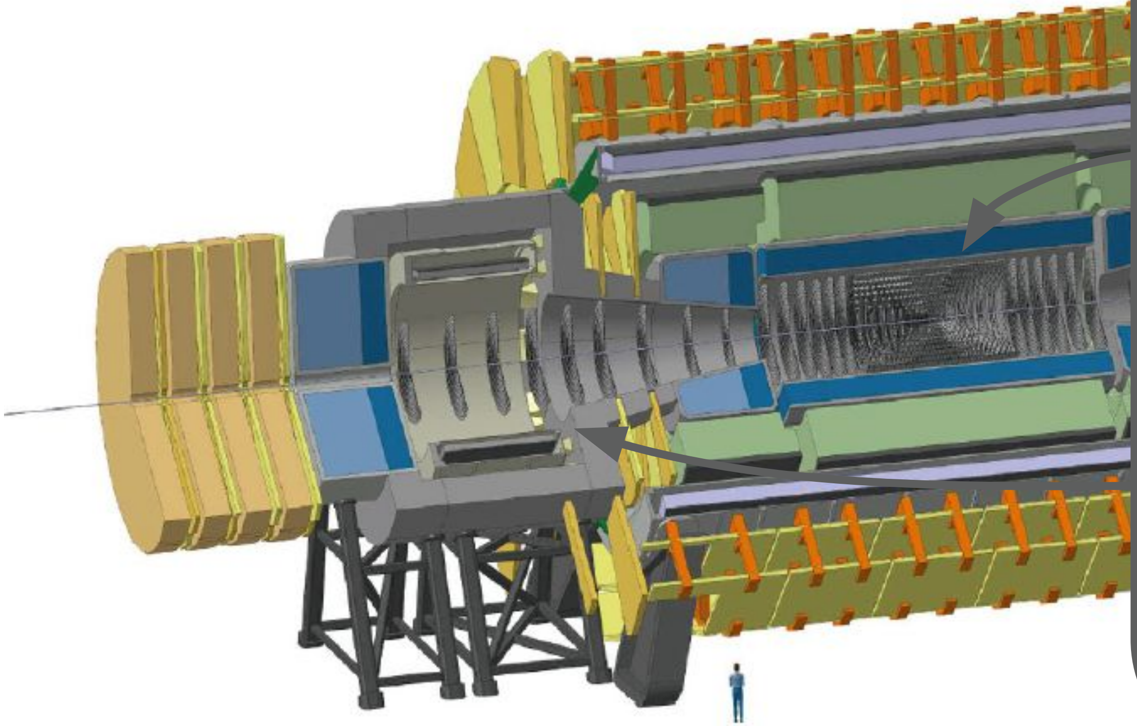
Reference detector



Reference detector

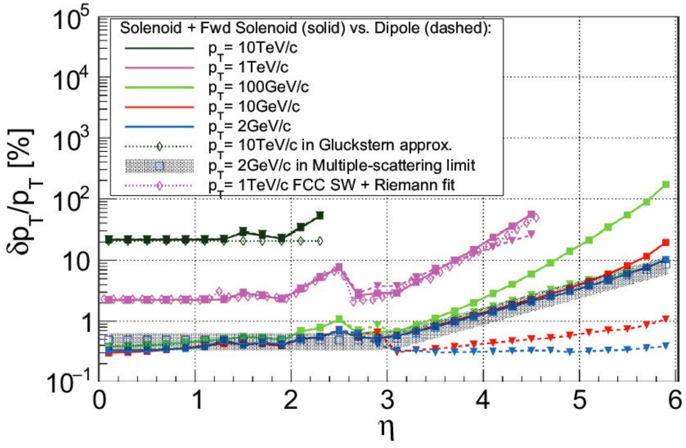


Reference detector



Tracking

- Si-Trackers using (macro-)pixels & strips



Reference detector

delphes / cards / FCC / scenarios / trackMomentumResolution_II.tcl

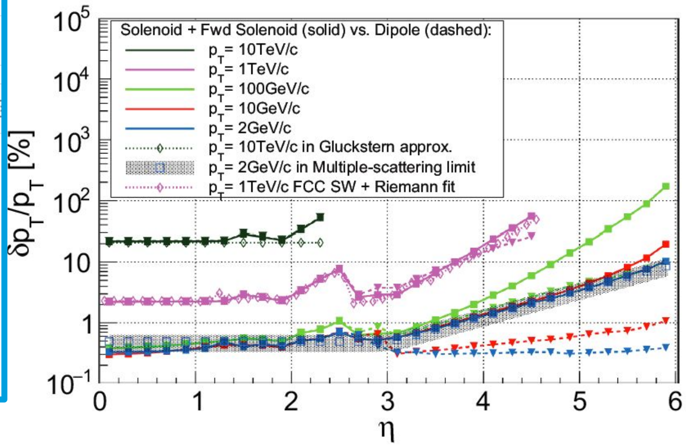
selvaggi beta v of Scenario II FCC-hh card ✓ 4c7a245 · 5 months ago History

Code Blame 489 lines (488 loc) · 60.4 KB Raw

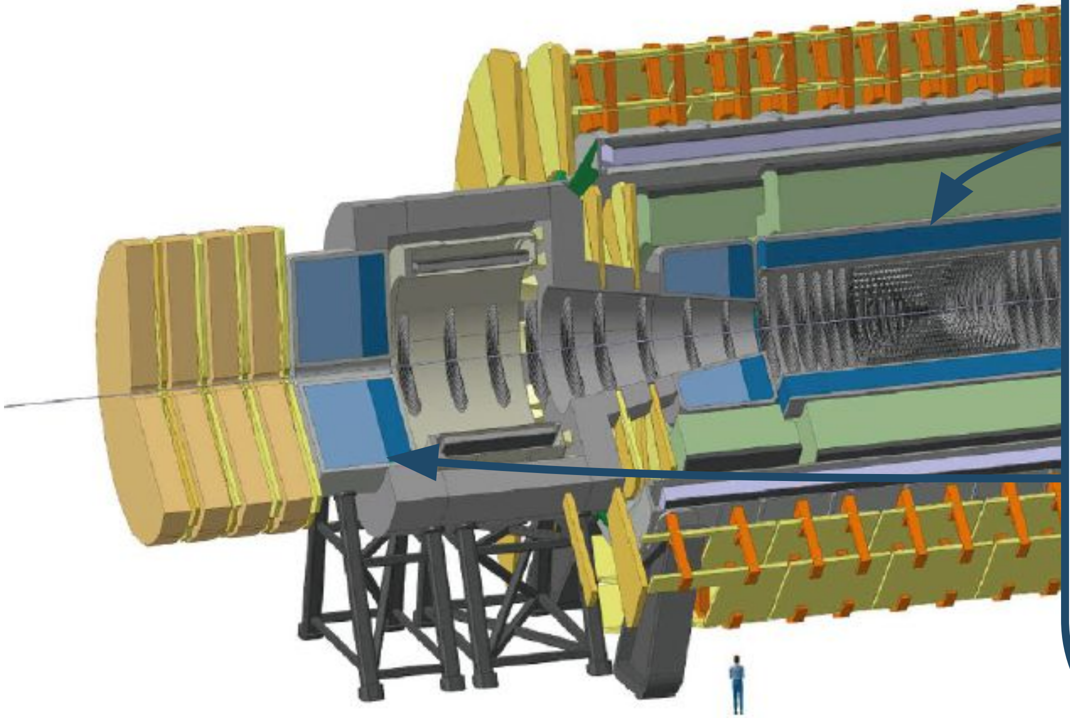
```
#
# Automatically generated tracker resolution formula dpt/pt (in eta & energy) for layout: FCChh_Option3.v02
#
#  By Z.Drasal(CERN) on: 2017-04-06.14:31:32
#
## degrading by a factor 2 wrt to scenario I

set ResolutionFormula {   2*( (abs(eta) >= 0.0000 && abs(eta) < 0.1000) * (energy >= 0.0000 && energy < 1.0000) * (0.00315864) + \
   (abs(eta) >= 0.0000 && abs(eta) < 0.1000) * (energy >= 1.0000 && energy < 2.0000) * (0.003159 + (energy-1.000000)* 0.000007) + \
   (abs(eta) >= 0.0000 && abs(eta) < 0.1000) * (energy >= 2.0000 && energy < 5.0000) * (0.003166 + (energy-2.000000)* 0.000011) + \
   (abs(eta) >= 0.0000 && abs(eta) < 0.1000) * (energy >= 5.0000 && energy < 10.0000) * (0.003198 + (energy-5.000000)* 0.000012) + \
   (abs(eta) >= 0.0000 && abs(eta) < 0.1000) * (energy >= 10.0000 && energy < 100.0000) * (0.003259 + (energy-10.000000)* 0.000010) + \
```

Tracking

- Si-Trackers using (macro-)pixels & strips

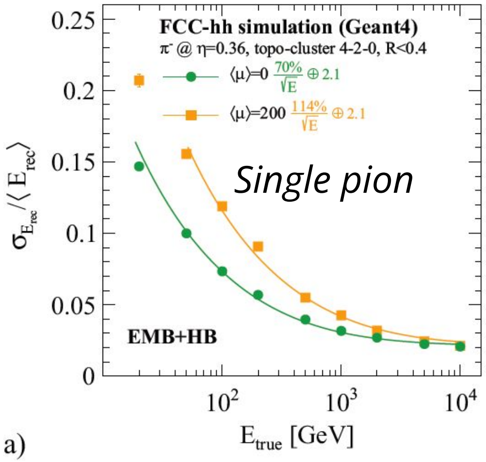


Reference detector



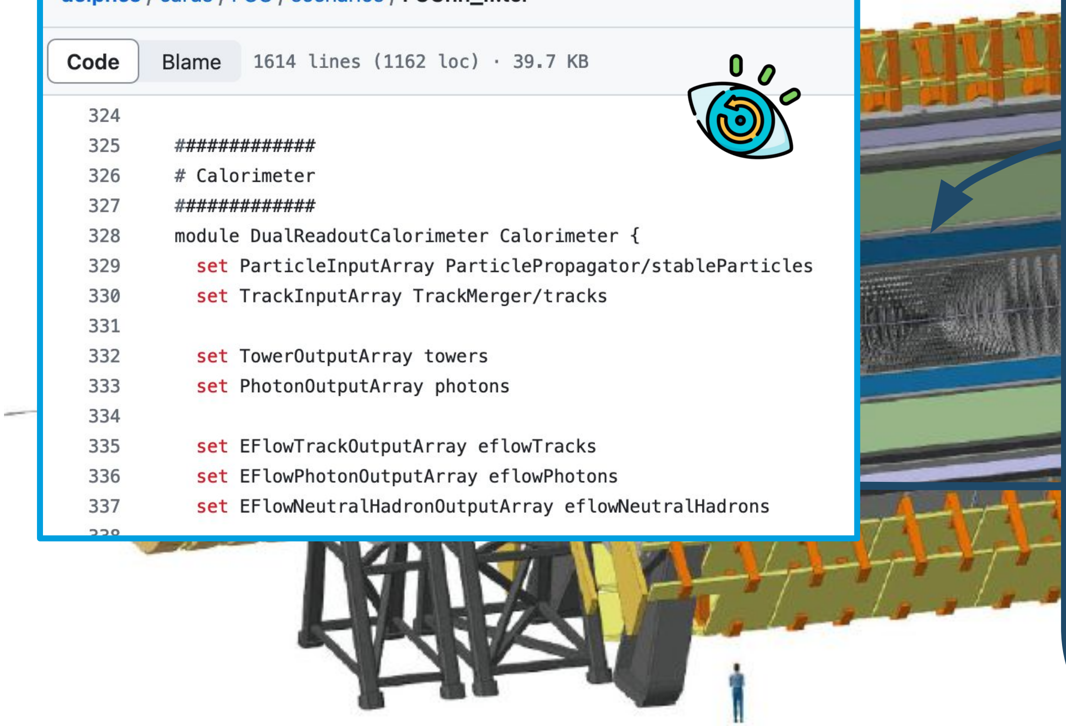
Calorimetry

- (Mostly) Inspired by ATLAS calorimetry, but further optimized
  - ECAL: LAr & Pb (Cu)
  - HCAL: Scintillating tiles & Fe/Pb in barrel, LAr on endcaps + forward



a)

Reference detector

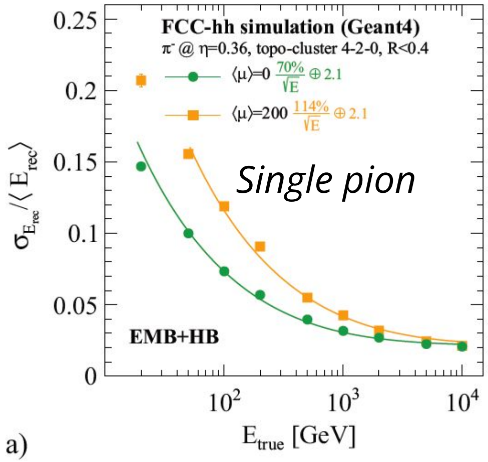


Code | Blame | 1614 lines (1162 loc) · 39.7 KB

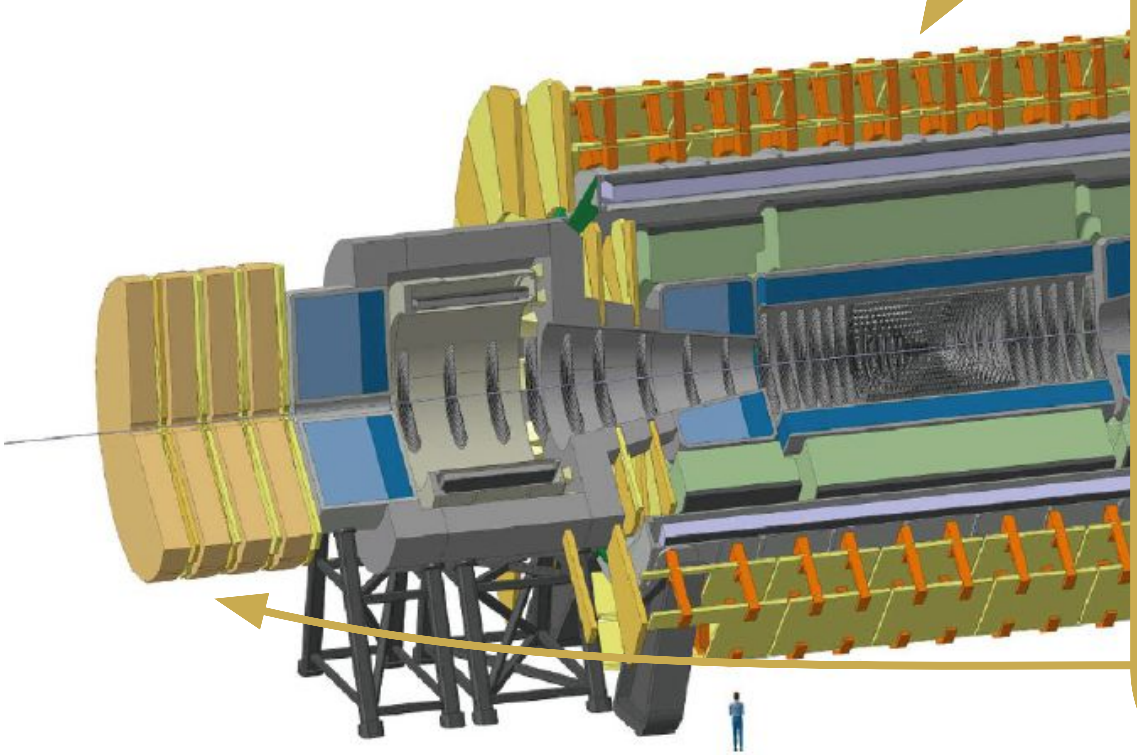
```
#############
# Calorimeter
#############
module DualReadoutCalorimeter Calorimeter {
  set ParticleInputArray ParticlePropagator/stableParticles
  set TrackInputArray TrackMerger/tracks

  set TowerOutputArray towers
  set PhotonOutputArray photons

  set EFlowTrackOutputArray eflowTracks
  set EFlowPhotonOutputArray eflowPhotons
  set EFlowNeutralHadronOutputArray eflowNeutralHadrons
```

<u>Calorimetry</u>

- (Mostly) Inspired by ATLAS calorimetry, but further optimized
  - ECAL: LAr & Pb (Cu)
  - HCAL: Scintillating tiles & Fe/Pb in barrel, LAr on endcaps + forward

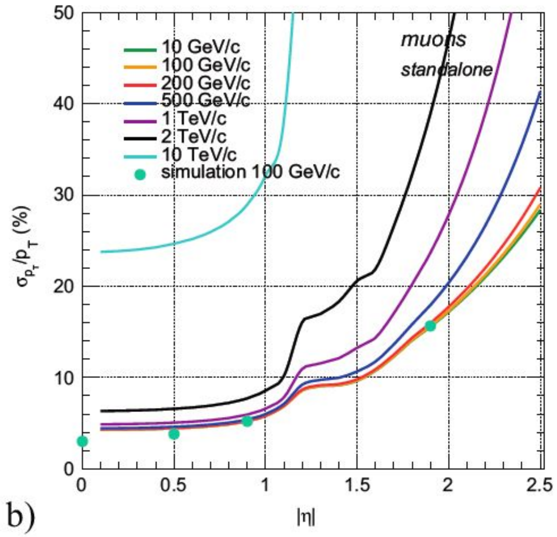


Reference detector

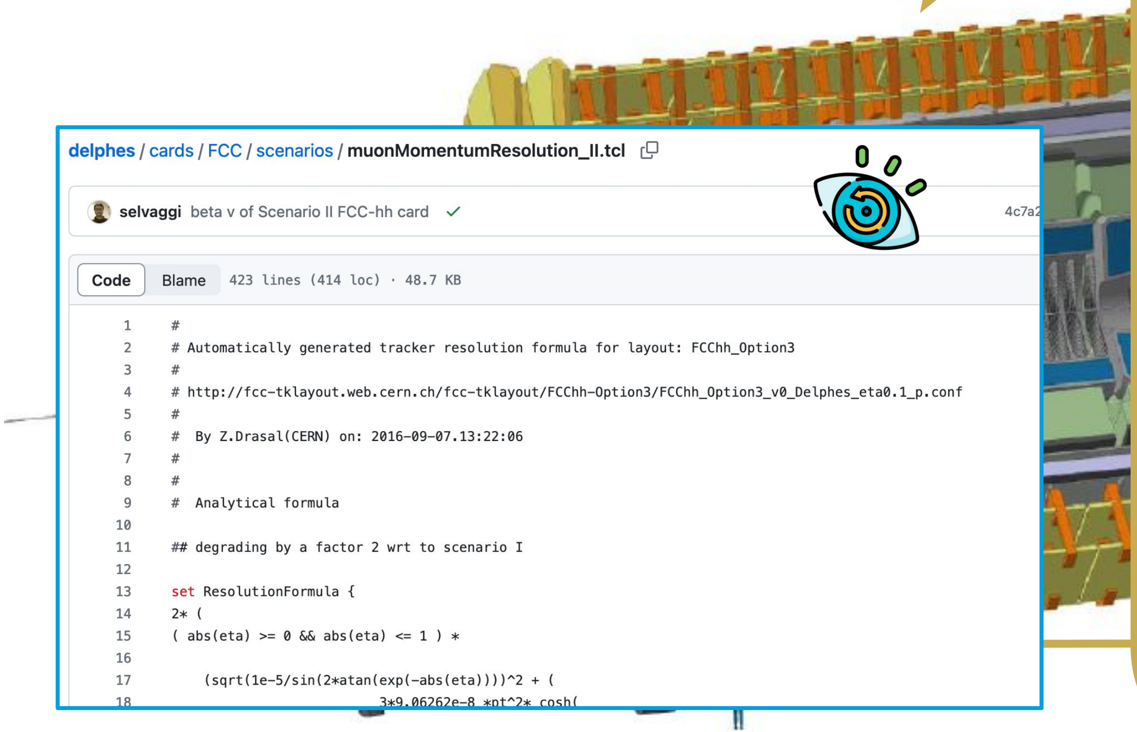


Muon systems

- Proposal: Combine drift tubes (sMDTs) & RPCs
- Mainly for muon identification + trigger



Reference detector



delphes / cards / FCC / scenarios / muonMomentumResolution_II.tcl

selvaggi beta v of Scenario II FCC-hh card ✓ 4c7a2

Code | Blame | 423 lines (414 loc) · 48.7 KB

```
#
# Automatically generated tracker resolution formula for layout: FCChh_Option3
#
# http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh-Option3/FCChh_Option3_v0_Delphes_eta0.1_p.conf
#
#  By Z.Drasal(CERN) on: 2016-09-07.13:22:06
#
#
#  Analytical formula

## degrading by a factor 2 wrt to scenario I

set ResolutionFormula {
2* (
( abs(eta) >= 0 && abs(eta) <= 1 ) *

    (sqrt(1e-5/sin(2*atan(exp(-abs(eta))))^2 + (
                              3*9.06262e-8 *pt^2* cosh(
```

Muon systems

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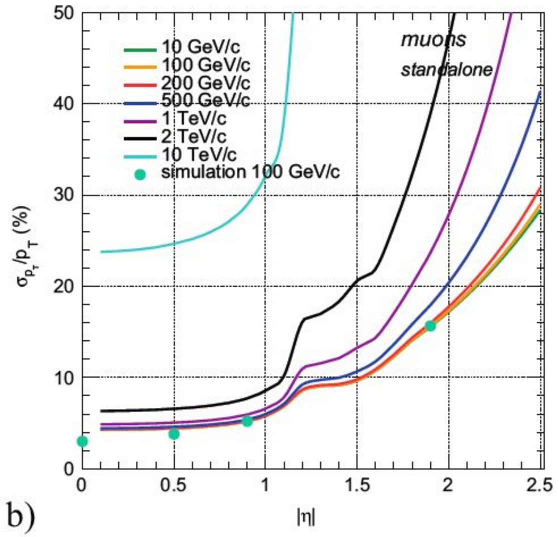
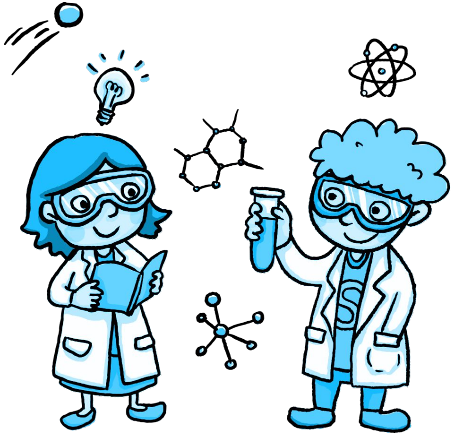
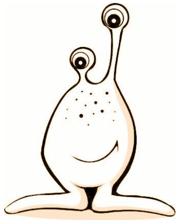
- Mainly for muon identification + trigger



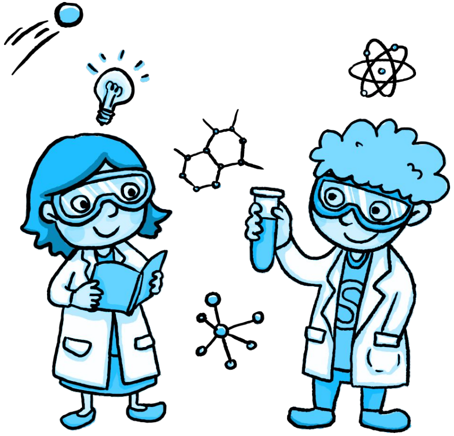
Physics potential



Us



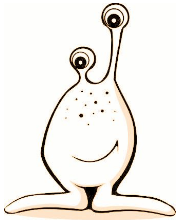
New physics



Us

FCC-hh true binoculars

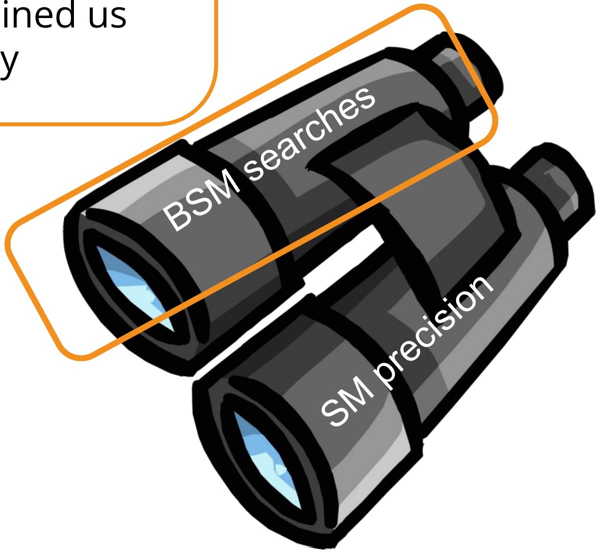
- Operates at the energy ***and*** precision frontier!

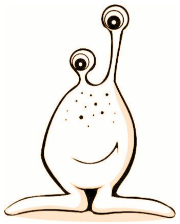


New physics

We don’t (currently) know what expects us there

Nature doesn’t “owe” us a new particle we can actually produce (directly) -> This has gained us negative publicity





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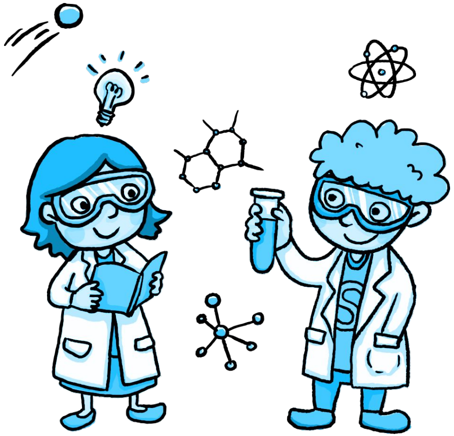
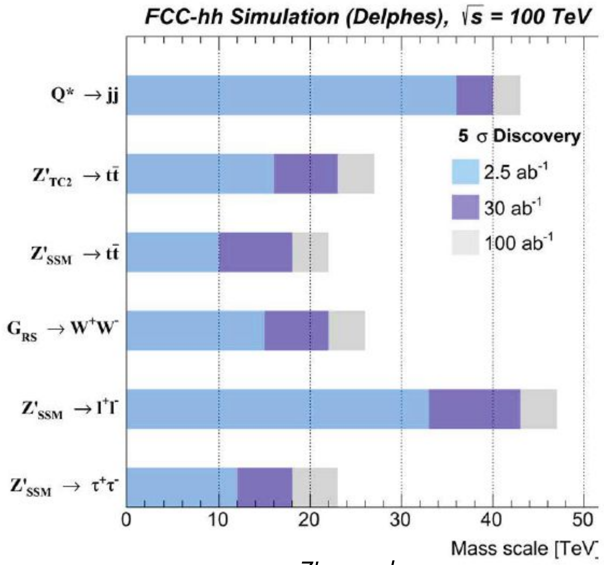


Us

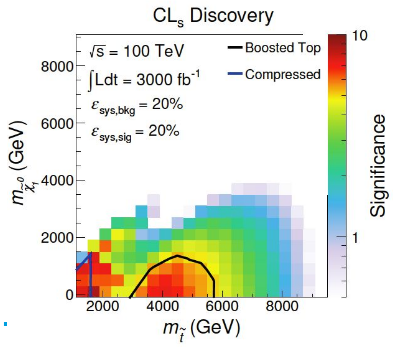
Direct BSM mass reach

- Collecting 20-30 ab^{-1} extends mass reach by factor ~ 7 ($\sigma(M) \sim 1/M^2$) from (HL-)LHC
  - Discovery potential in many models: SUSY, (WIMP) DM, Z', .. significantly extended
    - CDR report

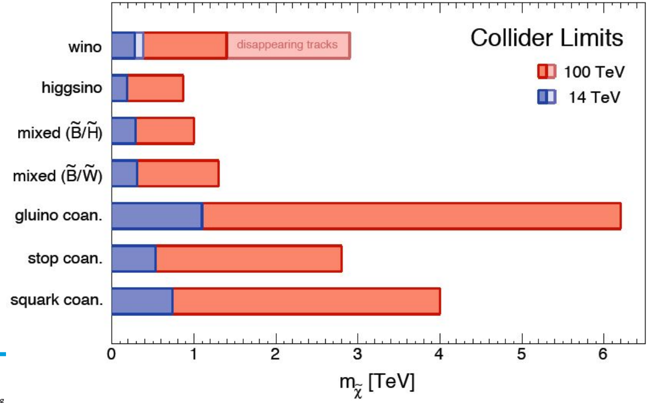


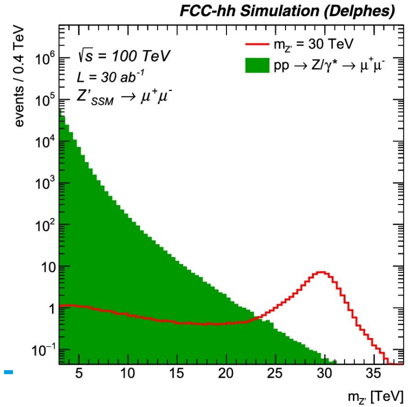
Z' search

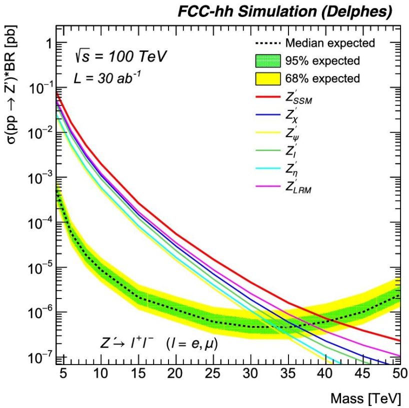
Search for $\tilde{t} \rightarrow t\tilde{\chi}_1^0$



WIMP DM with SM mediators

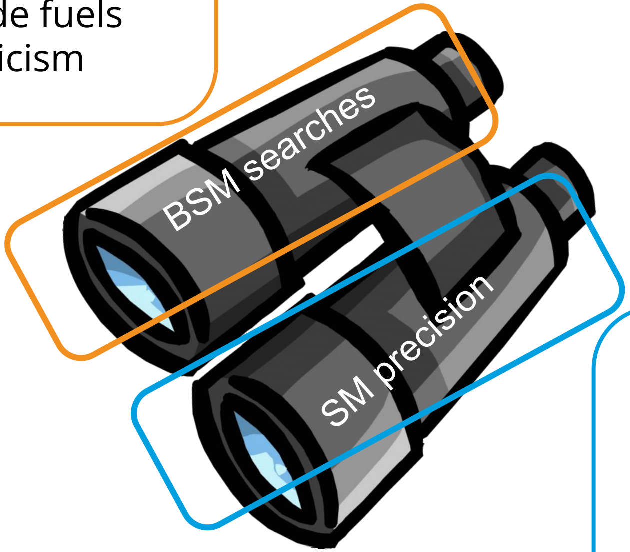


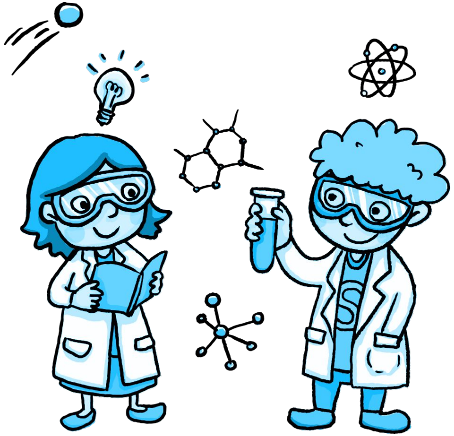




We don't (currently) know what expects us there

Nature doesn't "owe" us a new particle we can actually produce (directly) -> This attitude fuels controversy and criticism



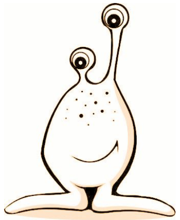


Us

Here, we have ***guaranteed deliverables,*** i.e. certain measurement precision levels

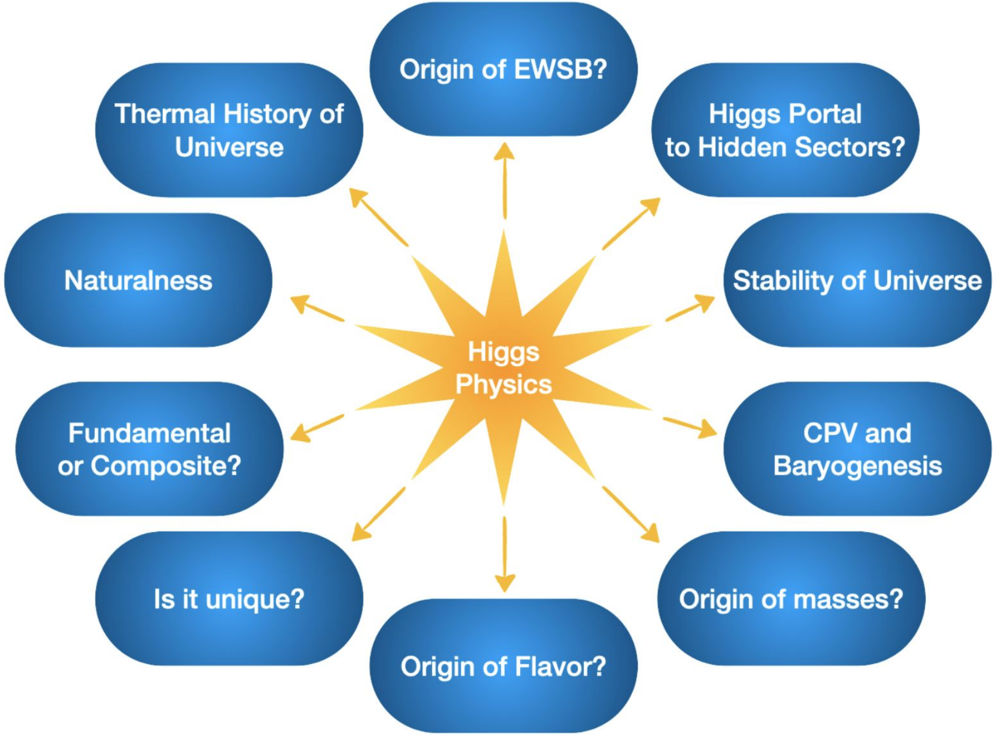
Exploration machine, not discovery

Focus here: Higgs Physics - 1H, ⭐2H, 3H !?



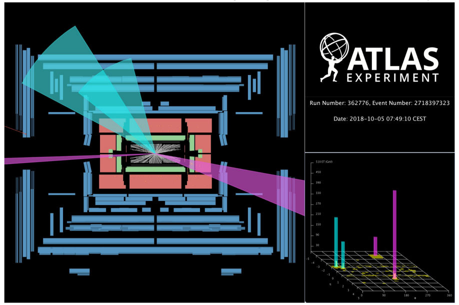
New physics

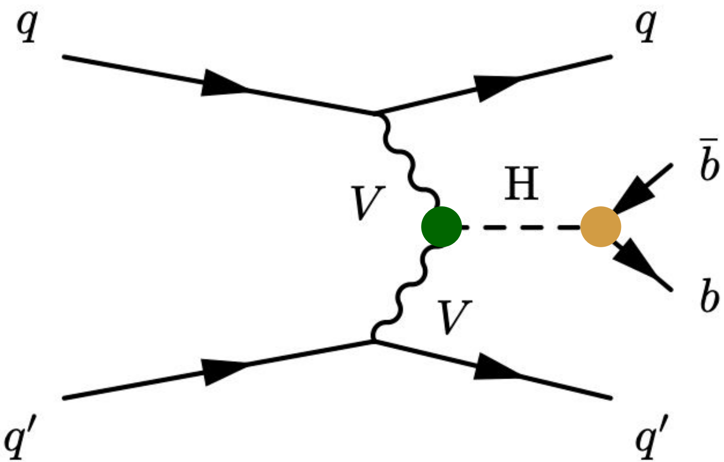
Why the Higgs?



1H: Higgs couplings

Candidate VBF H(bb) event display

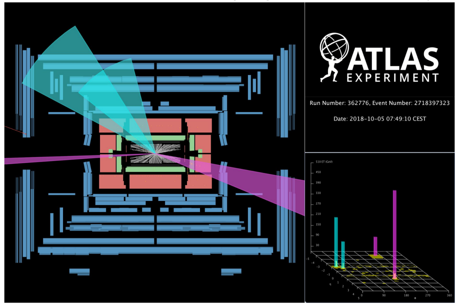


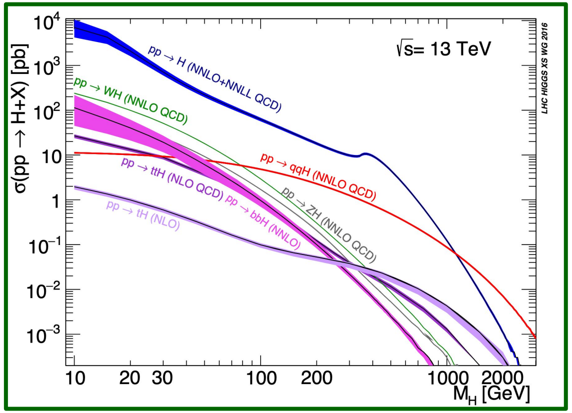


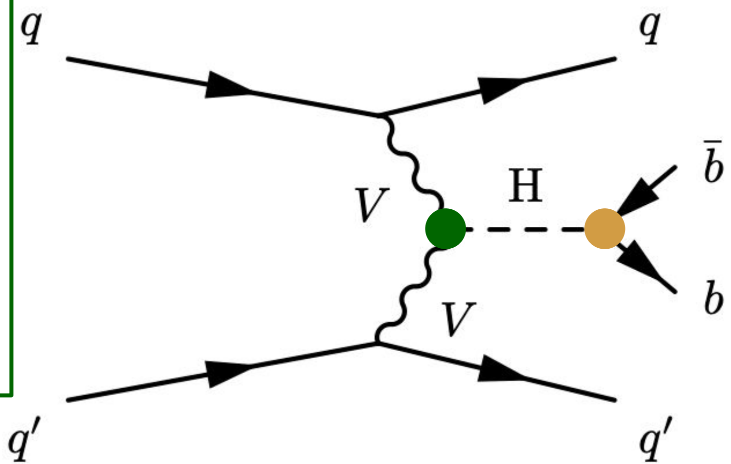
Higgs couples to other (SM) particles in both its **production** and **decay**

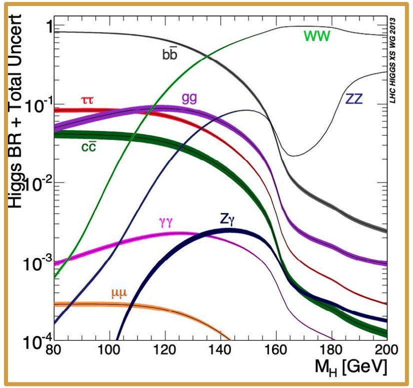
1H: Higgs couplings

Candidate VBF H(bb) event display









Higgs couples to other (SM) particles in both its **production** and **decay**

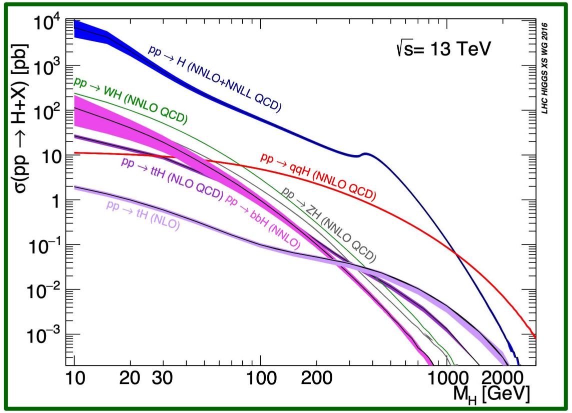
- Different modes for each possible, involving different couplings
  - Bosons: *Gauge couplings* | Fermions: *Yukawa couplings*

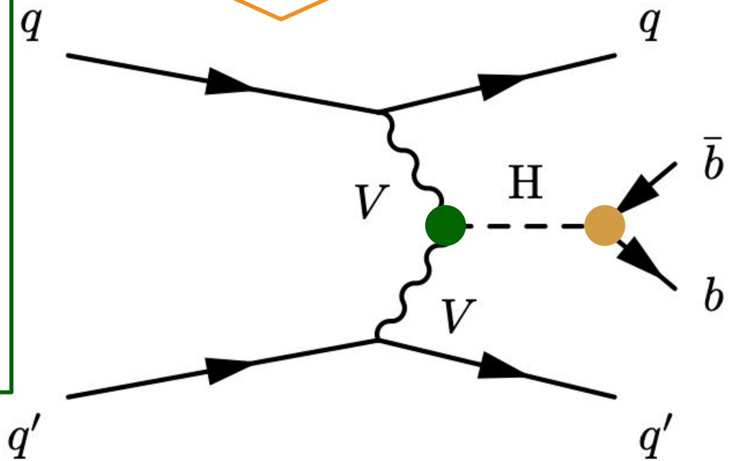
With the Higgs mass known the SM predicts cross-sections and branching fractions !

1H: Higgs couplings

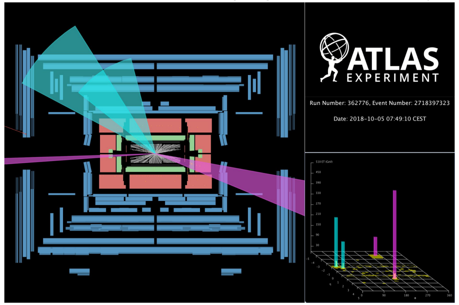
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}.$$

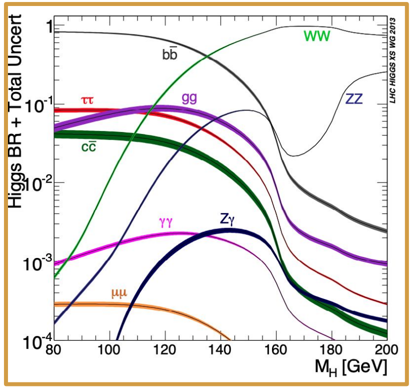
Production *Decay*





Candidate VBF H(bb) event display



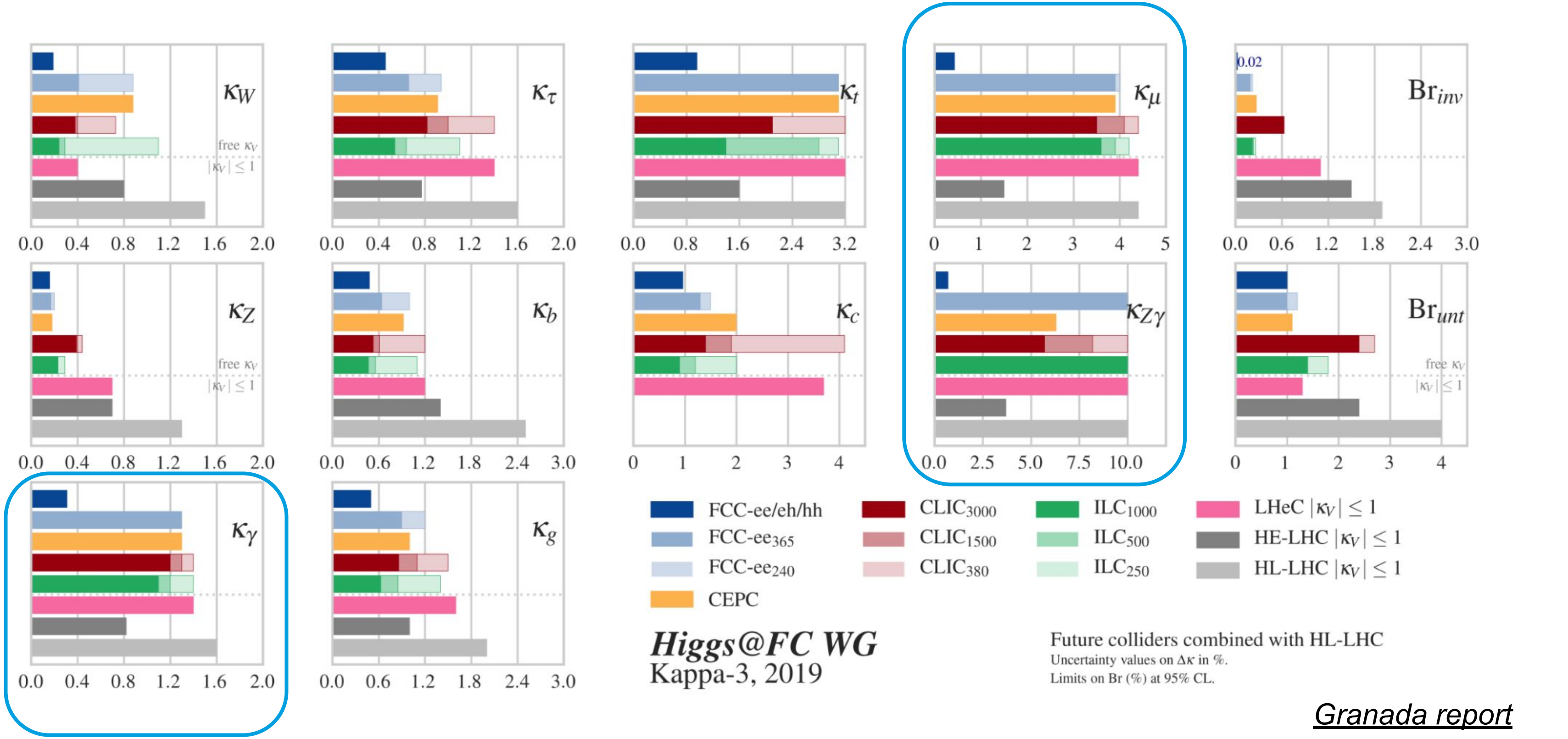


Higgs couples to other (SM) particles in both its **production** and **decay**

- Different modes for each possible, involving different couplings
  - Bosons: *Gauge couplings* | Fermions: *Yukawa couplings*

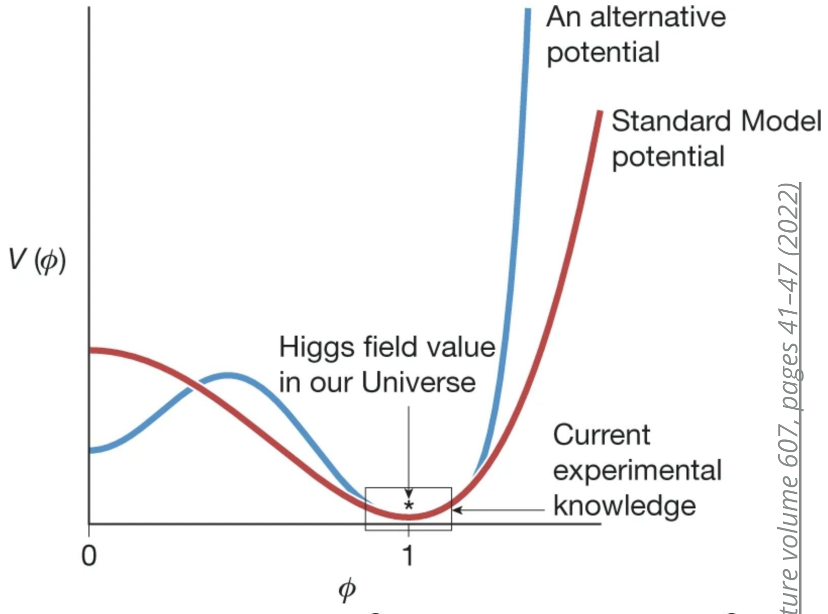
With the Higgs mass known the SM predicts cross-sections and branching fractions !

1H: Higgs couplings



Granada report

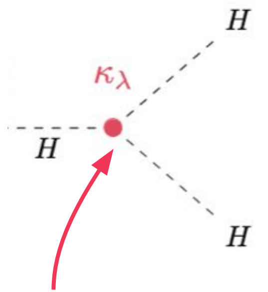
⭐ 2H: Trilinear Higgs self-coupling measurement



Nature volume 607, pages 41–47 (2022)

$$V(\Phi^{+}\Phi) = \mu^{2}\Phi^{+}\Phi + \lambda(\Phi^{+}\Phi)^{2}$$

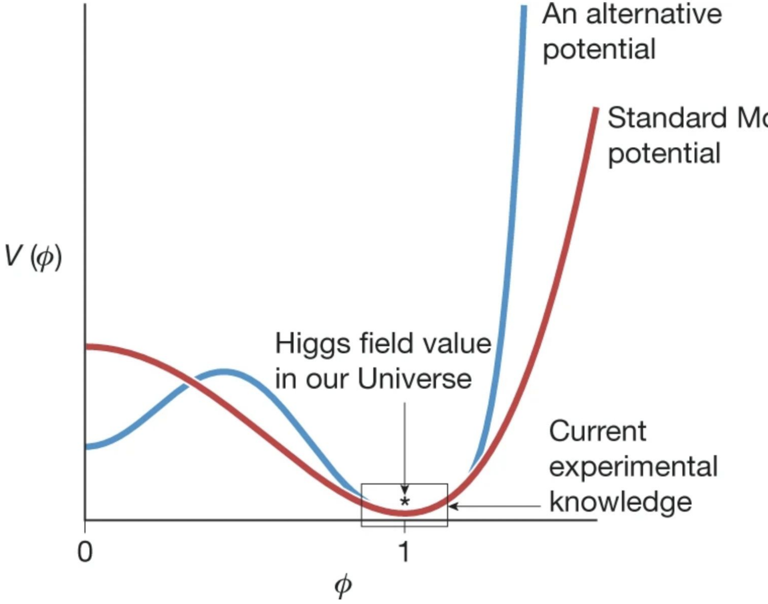
$$V(h) \approx m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4$$



Higgs self-coupling modifier: $\kappa_\lambda = \lambda^{meas}/\lambda^{SM}$

- Measuring the Higgs self-coupling allows us to gain insight into the nature of the Higgs potential and electroweak symmetry breaking → of our universe
  - It would be the first evidence of a particle interacting with itself

⭐ 2H: Trilinear Higgs self-coupling measurement



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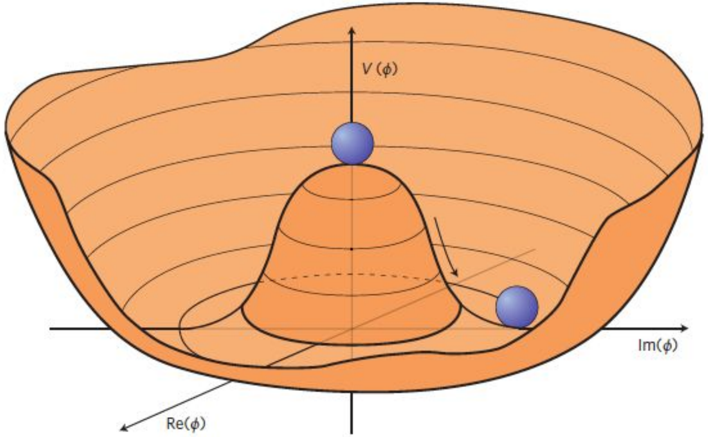
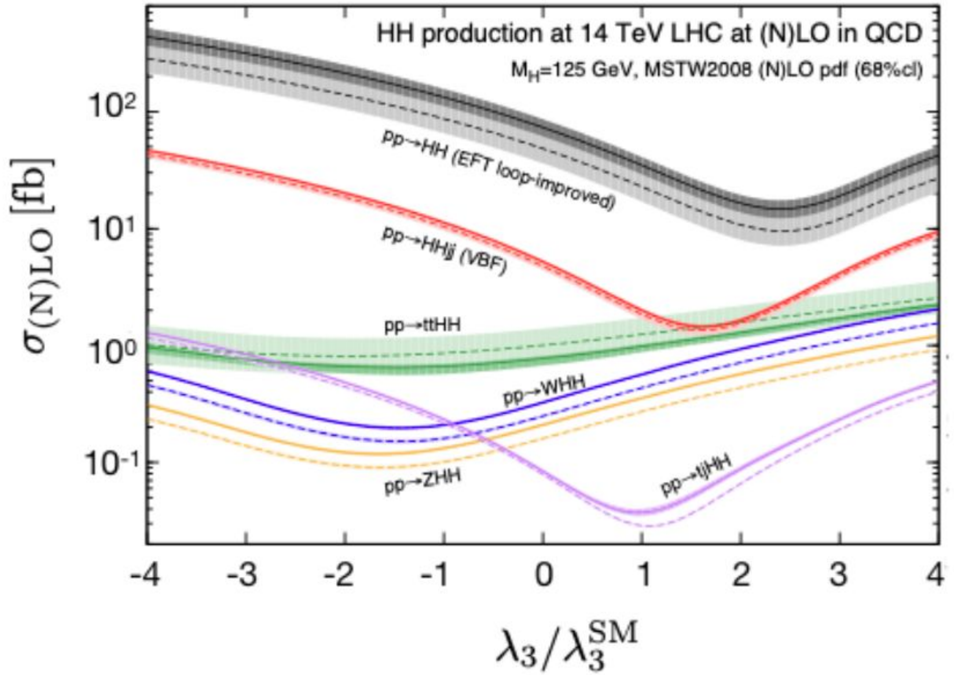
- Wait why do we even care?



Shape of potential linked to type of the electroweak phase transition, which *could* explain origin of baryon asymmetry [Sakharov conditions]

⭐ 2H: Trilinear Higgs self-coupling measurement

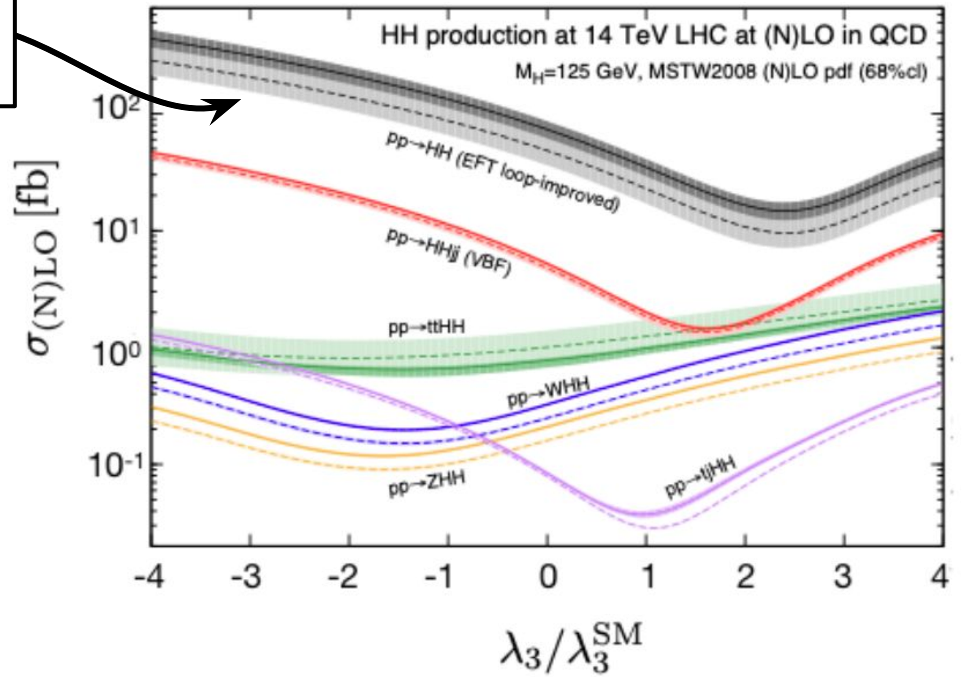
- Cross-section of Higgs pair production is proportional to κ_λ



⭐ 2H: Trilinear Higgs self-coupling measurement

- Cross-section of Higgs pair production is proportional to κ_λ

What does this interaction look like?



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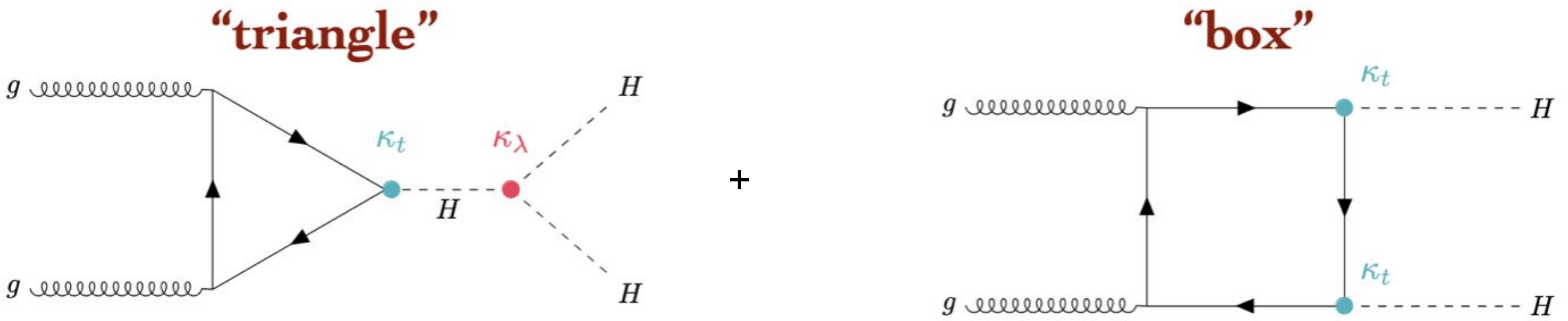


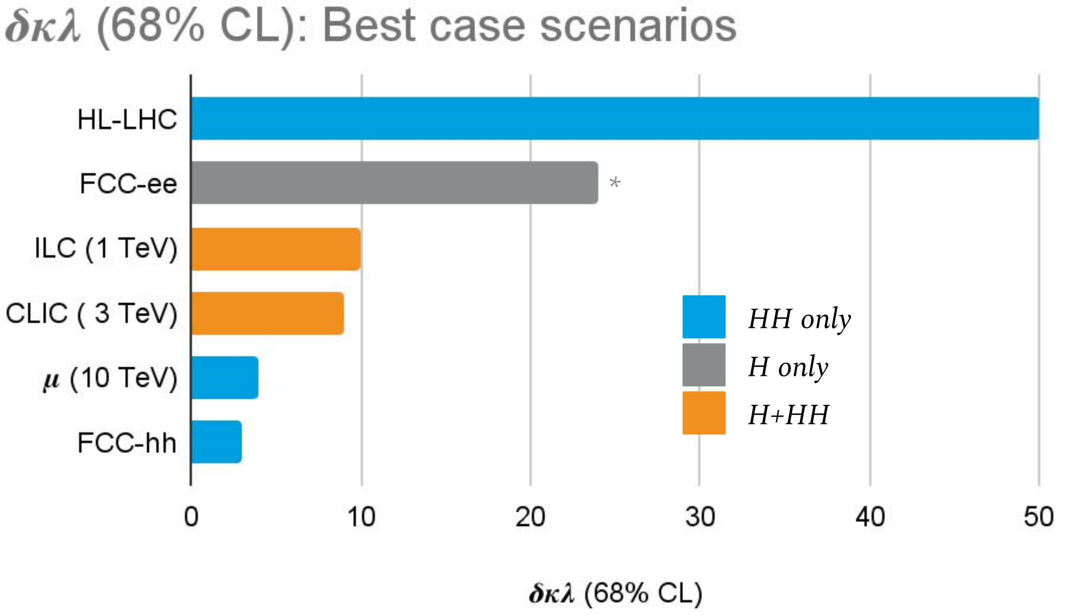
- But, there is destructive interference of triangle and box contributions
  - Tiny cross-section in the SM: $\sigma(ggHH)$ ~ $O(1000)$ smaller than $\sigma(ggH)$
  - Experimentally very challenging !

⭐ 2H: Trilinear Higgs self-coupling measurement

- At LHC we set limits: -0.4 < κ_λ < 6.3 (*ATLAS-HDBS-2022-03*)

⭐ 2H: Trilinear Higgs self-coupling measurement

- At LHC we set limits: $-0.4 < \kappa_\lambda < 6.3$ (ATLAS-HDBS-2022-03)
- Only at future colliders we will reach a precision measurement



Details & references in back-up

* For FCC-ee the Higgs self-coupling is measured indirectly via one loop-effect in the ZH process

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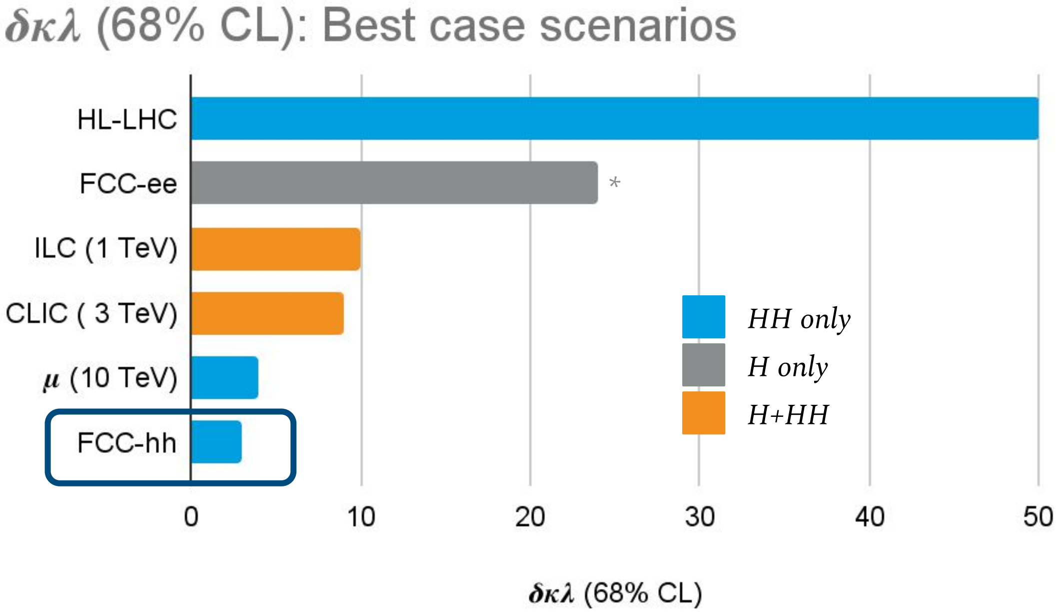

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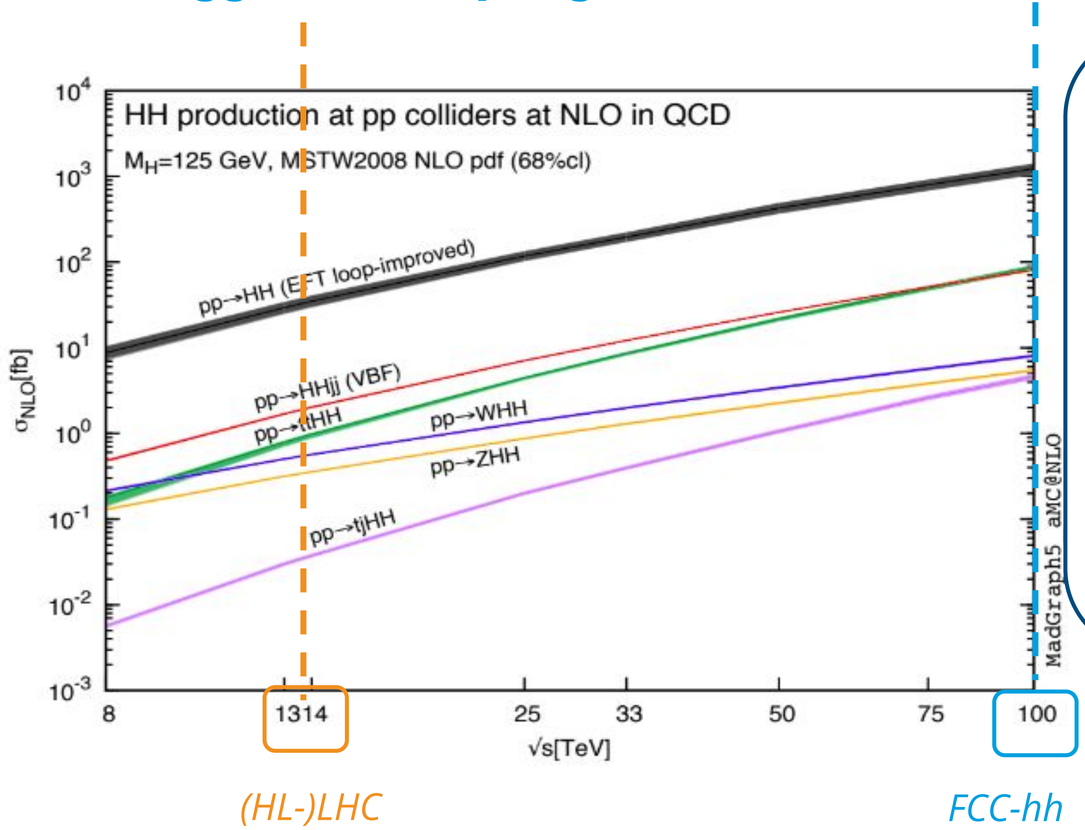


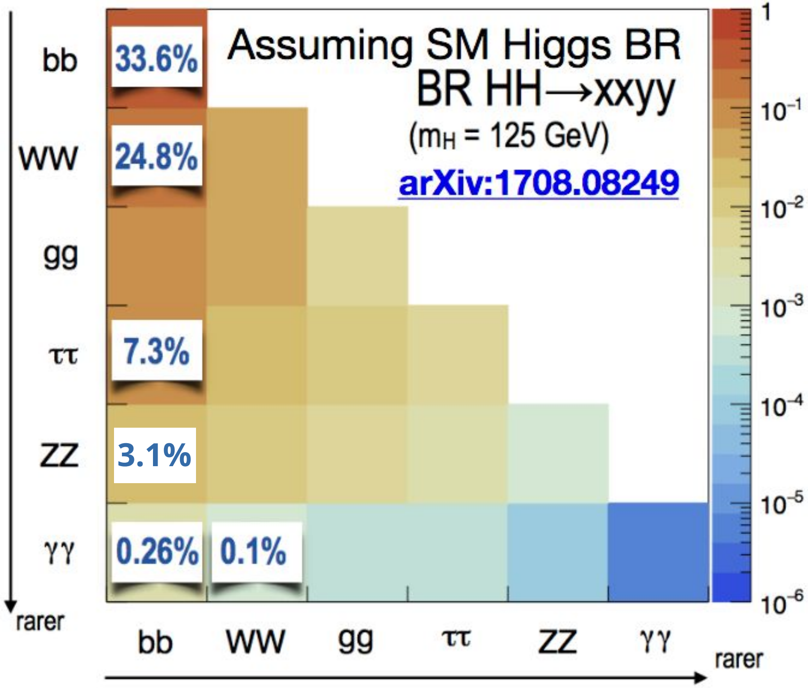
Cross-section increases by factor 40

FCC-hh database (30ab-1) = 10 x HL-LHC

Observe 400 times more HH events

Statistical precision increases by a factor 20!

⭐ 2H: Trilinear Higgs self-coupling measurement

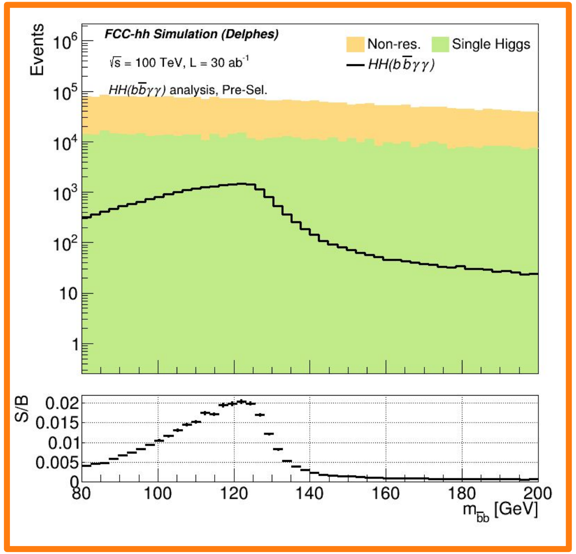


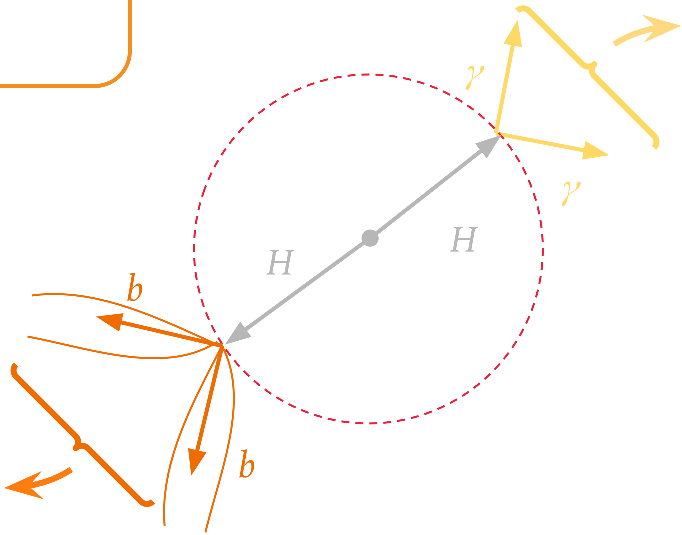
Measurement nonetheless not easy due to Higgs decays

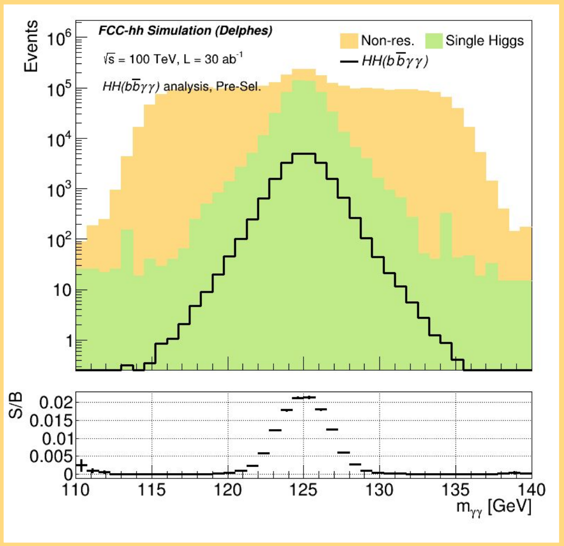
- Challenging final state
- Trade off between purity and high branching ratio

2H: Trilinear Higgs self-coupling measurement

"Golden channel": $\bar{b}b\gamma\gamma$ due to very clean final state, despite low branching ratio



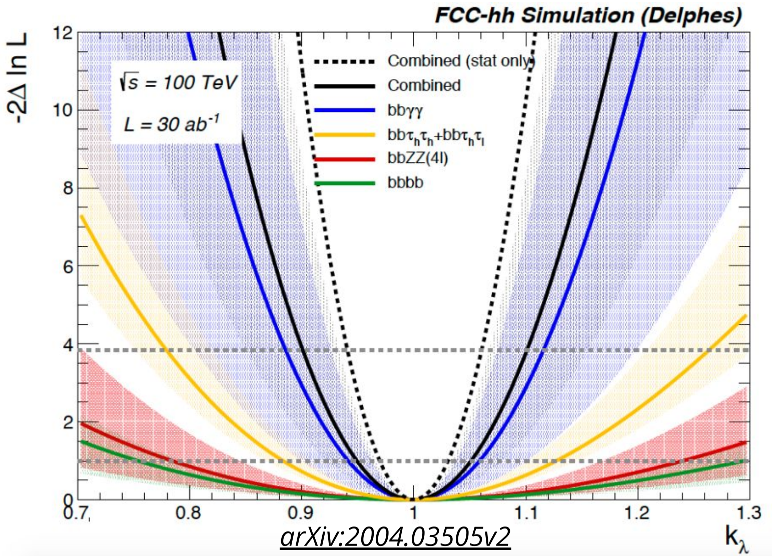




- 2 b-jets & 2 photons with invariant masses near m_H

- Backgrounds:
  - Non-resonant QCD: $\gamma\gamma$+jets and γ+jets
  - Single Higgs production

⭐ 2H: Trilinear Higgs self-coupling measurement



arXiv:2004.03505v2

	Combined precision
$\delta\kappa_\lambda$ (68% CL)	3.4% - 7.8%

parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\rightarrow \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

We can derive detector requirements from our precision goals (benchmarking)!

⭐ 2H: Trilinear Higgs self-coupling measurement

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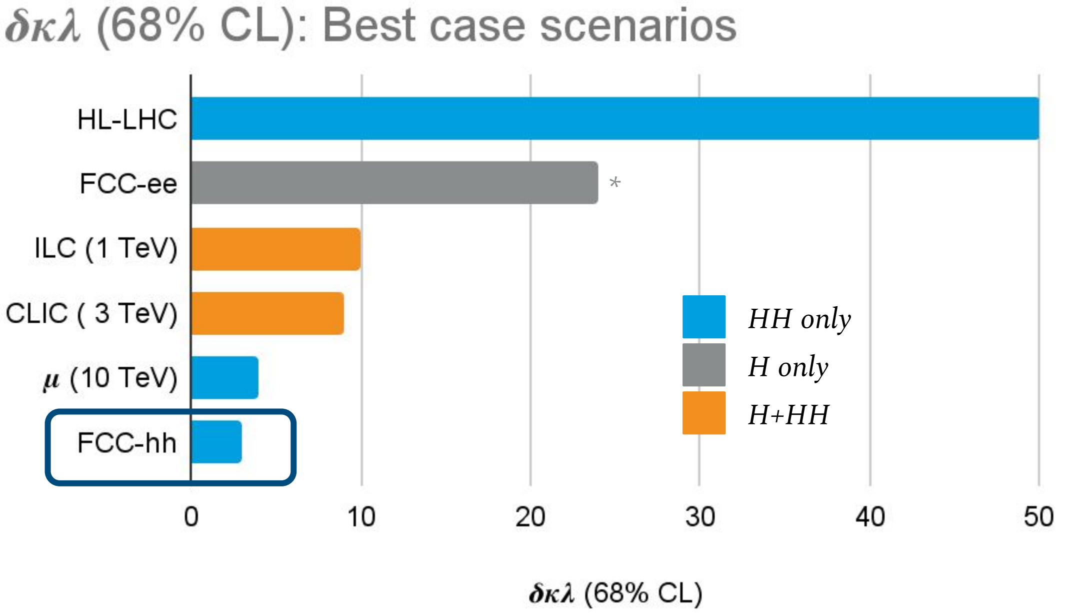
- Only at future colliders we will reach a precision measurement

FCC-hh offers best prospects for %-level measurement from Higgs pair production
But there is a caveat here!



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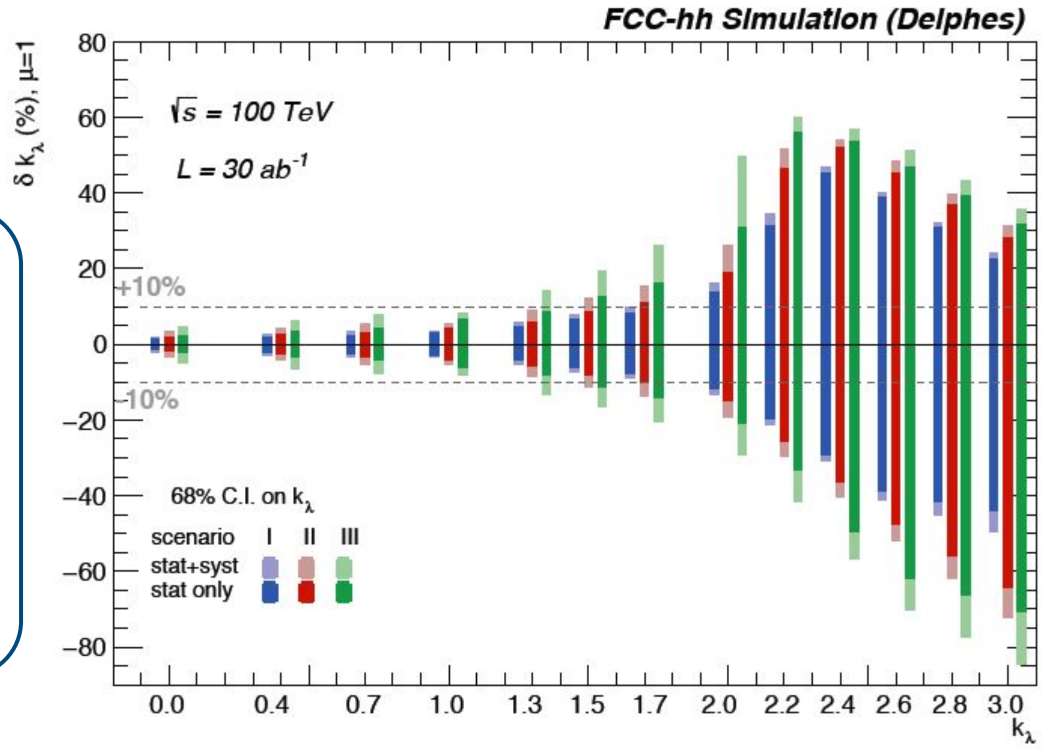
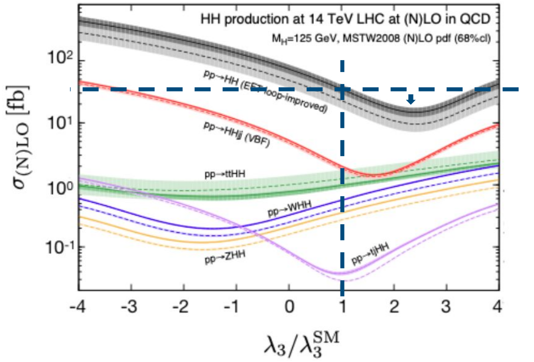


[arXiv:2004.03505v2](https://arxiv.org/abs/2004.03505v2)

The benchmark is determined for the SM case!

With increasing κ_λ our precision decreases! Why?



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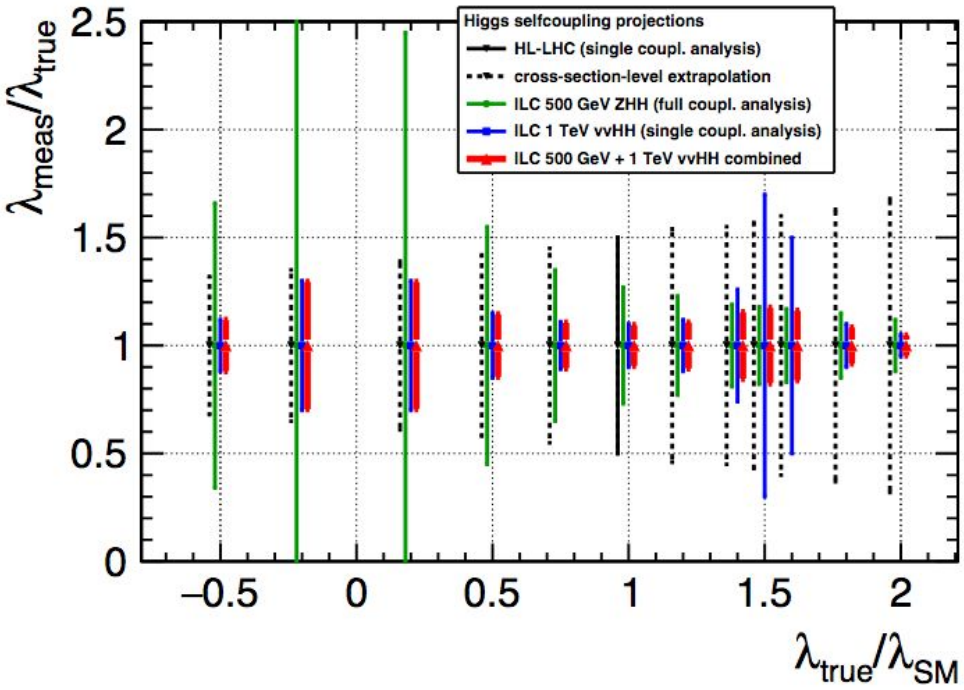


arXiv:2203.07622v2

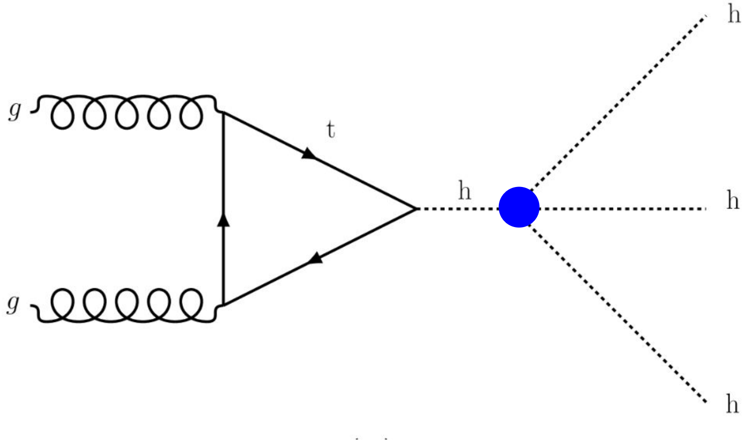
The opposite is true for Higgs pair production in *ee*-collisions

Cross-section of *ZHH* production rises with κ_λ: Better precision for a non-SM measurement!

But .. we need high energy for this (ideally > 500 GeV), feasible only with linear ee-colliders

3H: Quartic Higgs self-coupling

$$V(h) \approx m_h^2 h^2 + (1+\kappa_3)\lambda_{hhh}^{SM} v h^3 + \frac{1}{4}(1+\kappa_4)\lambda_{hhhh}^{SM} h^4$$



Triple Higgs production measurements will remain challenging, even at FCC-hh due to very low cross-section

Again ~ O(1000) smaller than the *HH* cross-section

Studies in final states with 4bs, tau pairs and photon pairs

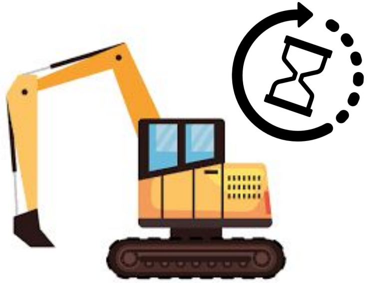
Number of expected signal events is =< 10!

Combining several channels 3σ may be reached

Summary & concluding remarks

- Ample perspectives for answers to questions which might remain open after HL-LHC and aiming to collect 30 ab^{-1} of data over 25 years it operates at energy and precision frontier
- Baseline design is a ~91 km collider with 100 TeV *pp*-collisions
  - Highest energy hadron collider considered feasible from today's view
  - Main challenges of technical feasibility are the need for 16 T magnets and cryogenic system
- A reference detector has been conceptualised
  - Main challenges for the detector are boosted+forward physics, high radiation & pile-up
  - *We do not have full simulation! All studies are based on Delphes, making assumptions!*
- Physics potential well established: Direct BSM mass reach extends to O(10) TeV, Higgs (and other SM) precision measurements, especially our star-player Higgs self-coupling
- It is far ahead in our future, but if (when) it gets realized FCC will be ***the*** project until the end of the 21st century. ***You can help to make it happen!***

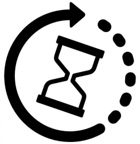
For something completely different?



Tunnel Boring Machine (TBM)

For something completely different?

Local cheese factories especially interested in the heat produced



Tunnel Boring Machine (TBM)

Need to run two TBMs 24/7 to complete tunnel in 8 years

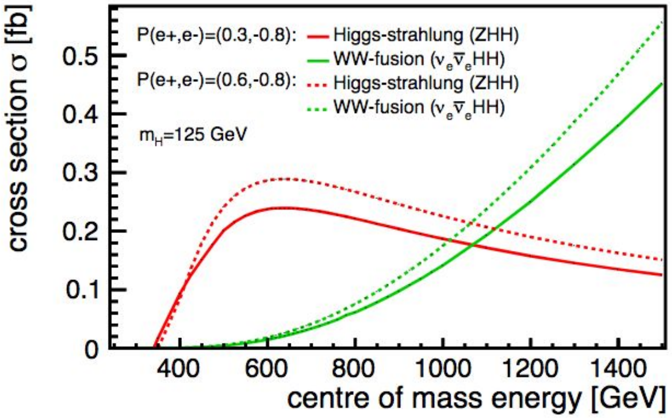
Energy stored in magnets >~ 35 tons of TNT

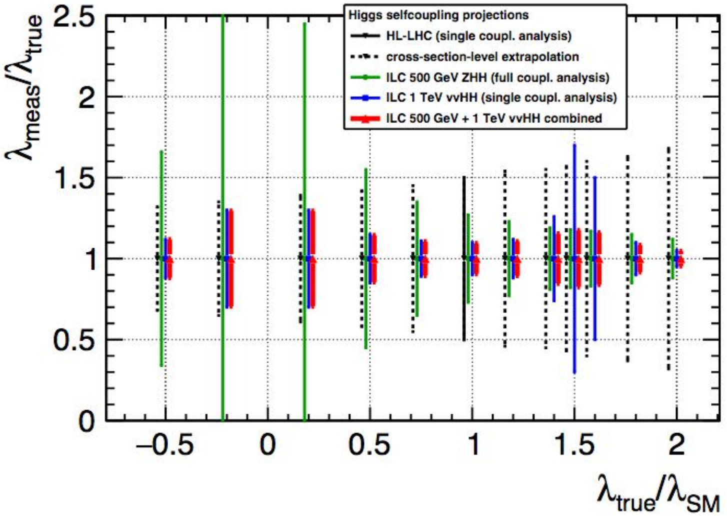
What to do with the soil that is dug out? Sustainable, accelerated transformation with funghi

Bonus

arXiv:2203.07622v2

Higgs self-coupling @ ILC





- Two production modes:
  - Higgsstrahlung, peaks ~500 GeV
  - WW-fusion, above ~1 TeV
  - → need runs at both energies for maximum κ_λ precision

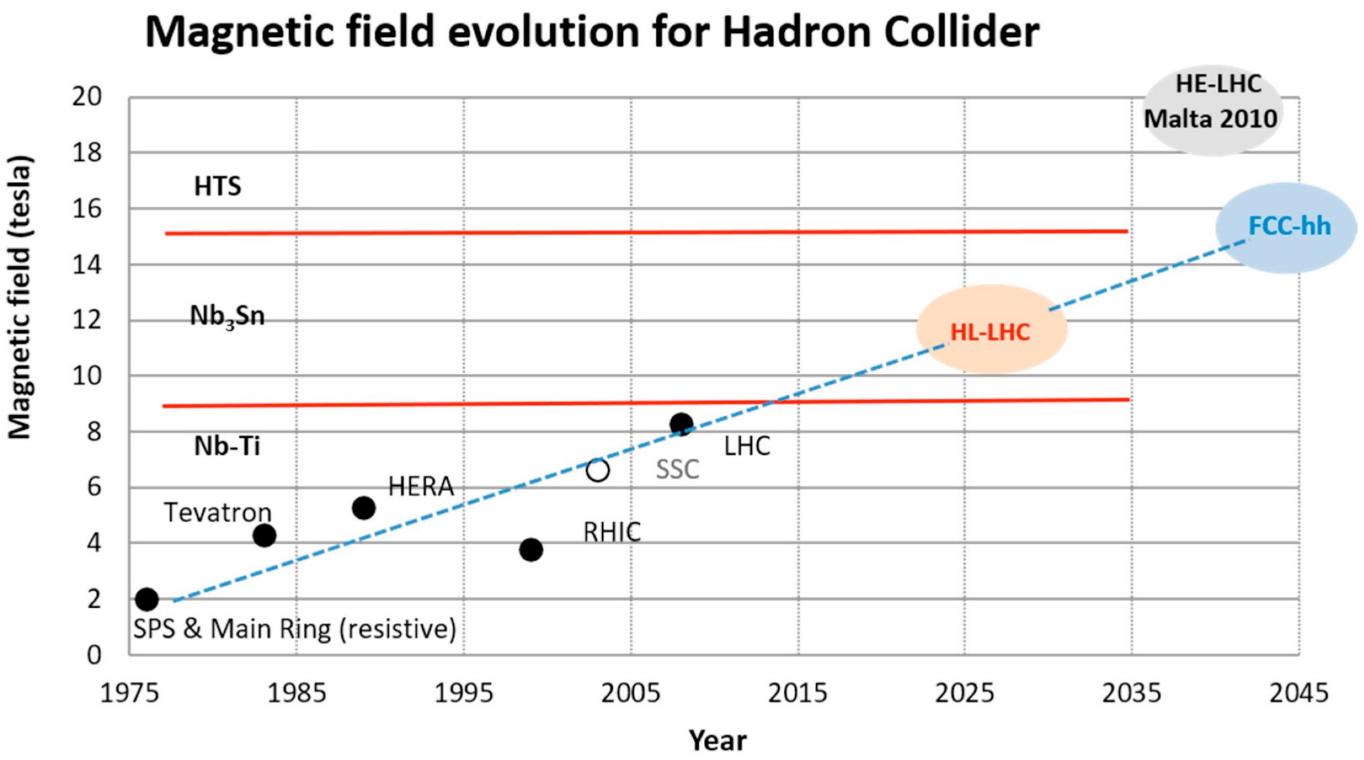
- Studied dominant channels $4b$ and $bbWW$
- Advantage of ee-collider: ZHH cross-section increases with κ_λ, hence better constraints at values $\kappa_\lambda > 1$ than pp-colliders

Collider design: Parameters of magnet system

Parameter	(HL)-LHC	FCC-hh
Peak dipole field (T)	8.33	~16
# Long arcs w. dipoles	8	8
Length arc (km)	3	8
# Dipoles/arc	154	438
# main dipoles	1232	4668
Tot. energy stored in dipoles (GJ)	8.8	108 - 176

140 GJ ~ 35 tons of TNT

Reaching 16 T magnets: Historical view



Source

Forward physics

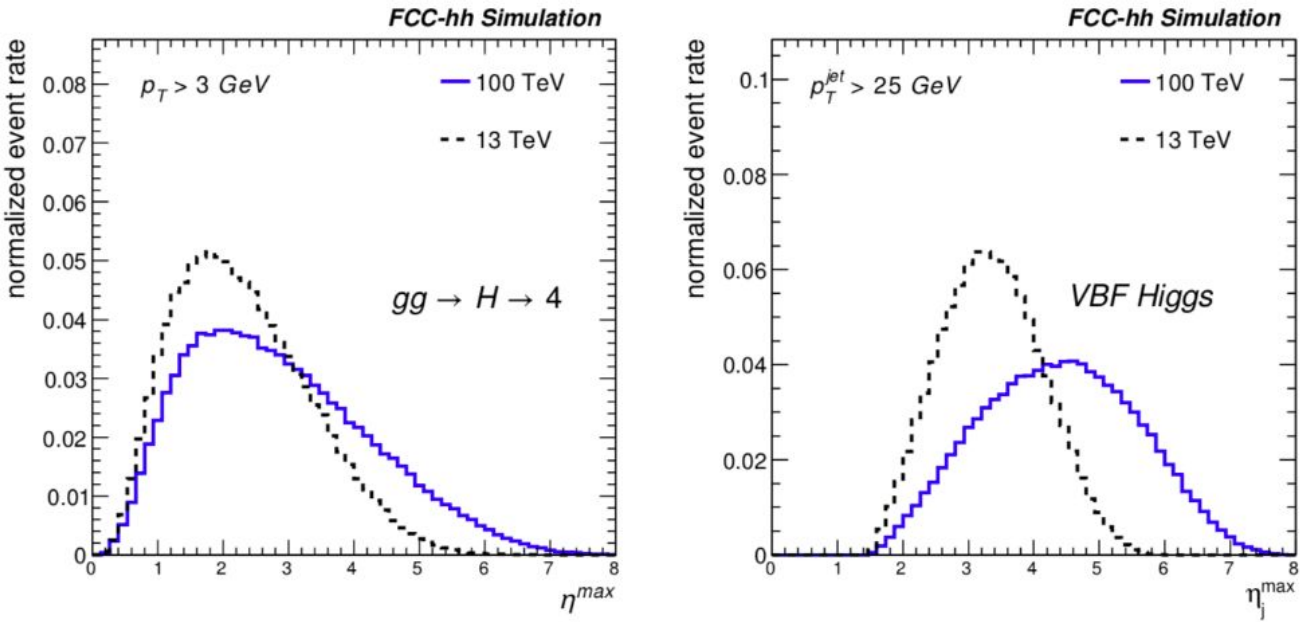


Fig. 2.2: highest lepton pseudo-rapidity for gluon-gluon fusion Higgs decaying to 4 leptons (left) and maximum jet pseudo-rapidity for vector-boson fusion Higgs (right)

Reference detector

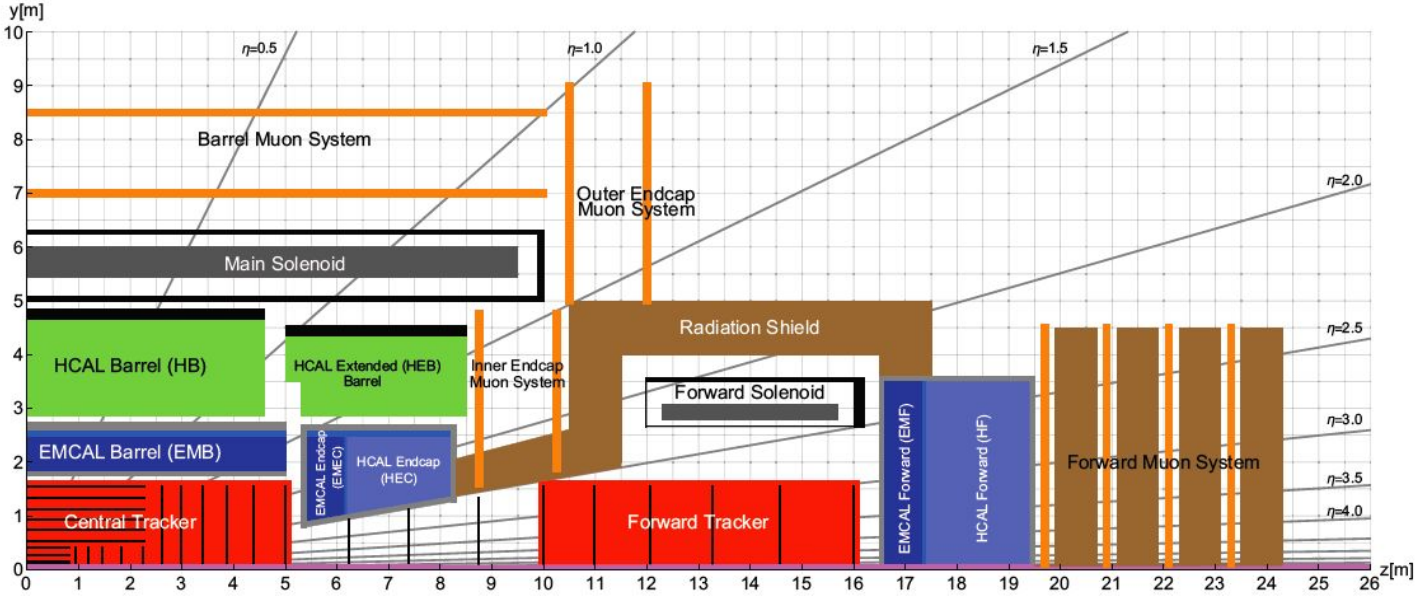


Fig. 7.2. Longitudinal cross-section of the FCC-hh reference detector. The installation and opening scenario for the detector requires a cavern length of 66 m, which is compatible with the baseline assumption of $L^* = 40$ m for the FCC-hh machine.