FCC-hh simulation studies work ahead

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Outline:

- Recap philosophy for the CDR
  - Benchmark studies
- What is missing? Ideas for future studies
  - Physics ⟵⟶ Detectors/reconstruction
- How to get started?

Physics in the CDR

Select physics benchmarks in order to:

- help define/refine detector concepts
- focus where FCC-hh really makes a difference complementarity w.r.t HL-LHC/FCC-ee

  - Standard Model:
    - Higgs
      - Rare Higgs Decays (complementary to FCC-ee)
        - $\gamma\gamma$, $Z\gamma$, $\mu\mu$, 4ℓ
      - Target production modes
        - ttH(bb), HH(bb$\gamma\gamma$) self-coupling
      - VBS $V_L V_L$ production
      - H$\rightarrow$ invisible

  - BSM:
    - high mass resonance benchmarks Z' $\rightarrow$ XX (X=e,μ,τ,j,W,Z)
    - Disappearing tracks

- Much more 100 TeV physics was discussed in the 2017 Yellow Report CERN-2017-003-M

Wishlist

- Using the various benchmarks, explore impact of different:
    - c.o.m. energies 80-100-120 TeV
    - luminosities
        - and corresponding trade-offs and detector design implications
            - 80 TeV with 2x nominal luminosity or
            - 120 TeV with 0.5x nominal luminosity ?
        - beyond σ vs. $\mathscr{L}$ considerations (500PU vs 3000PU !!)

- Review physics benchmarks and corresponding objects most affected by machine conditions in view of recent LHC experience
    - HH, ttH, VBS
        - identification: b/τ-tagging, forward jet tagging, photon fake-rate
        - resolution: m_{bb}, $m_{\tau\tau}$, $m_{\gamma\gamma}$, E_T^{miss}
        - triggering
    - High p_T:
        - τ, W, H substructure vs extreme PU/collimation

Wishlist/open questions

- Explore novel calibration/reconstruction/pu subtraction techniques
  - identify clean control samples with large stats to calibrate critical objects and reduce systematics (e.g. ɣ-id with Z→ μμɣ samples) for robustness
  - jet flavor tagging in extreme pile-up, impact of tracking geometry
  - 5D Particle-Flow reconstruction and PU subtraction (p,E,t)
    - conventional/AI based

- Explore new detector designs/ technologies, e.g:
  - ambitious technologies (LXe/LYSO calorimetry, MAPs, quantum sensors, ..)
    - for some far from rad. hardness/cost requirements
      - but R&D should be pursued with such goals in mind
  - new designs:
    - low PU detectors targeting low p_T physics
    - ATLAS without Toroid, muon det. simply to tag
      - enough selectivity with track triggering at L1?

Wishlist (single H)

- Add "missing" physics channels, exploring new ideas to reduce dependence on detector assumptions and systematics:
  - $H \to WW$, bb, cc, $\tau\tau$
  - use ratios/double ratios
    - focus on boosted regime/similar production modes
      - For rate, object, lumi (partial or total) cancellations
  - study tradeoff between boost (syst) and statistics

Single ratios:

- WH($\gamma\gamma$) / ZH($\gamma\gamma$) ~ $\kappa_{W,Z}$
- WH($\gamma\gamma$) / WZ(ee) ~ κ_W
- WH(bb,cc,$\tau\tau$) / WZ(bb,cc,$\tau\tau$) ~ κ_W
- ZH(bb,cc,$\tau\tau$) / ZZ (bb,cc,$\tau\tau$) ~ $\kappa_{b,c,\tau}$
- ttH(bb,$\tau\tau$) / ttZ(bb,$\tau\tau$) ~ κ_t

double-ratio:

$$\frac{H(bb,cc,\tau\tau)/Z(bb,cc,\tau\tau)}{H(\mu\mu,\,4\ell)/Z(\mu\mu,\,4\ell)} \sim \kappa_{b,c,\tau} / \kappa_{\mu,Z}$$

in ggH, VH? $p_T(H)^{min}$?

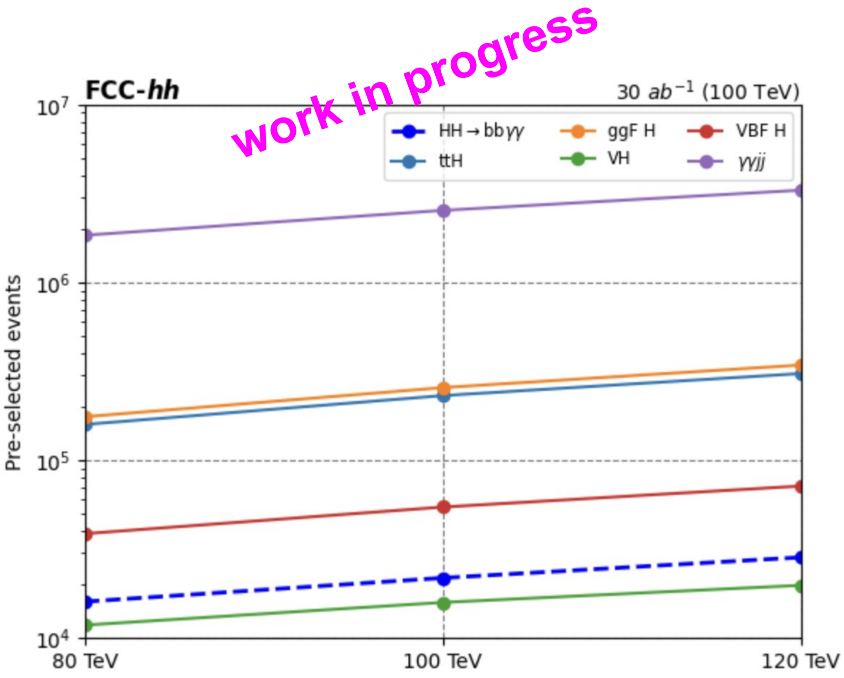
exploit absolute model independent κ_Z , ttZ measurements from FCC-ee

Wishlist (HH)

- Self-coupling HH
  - Focus on most sensitive channels bbγγ, bbττ
    - κ_λ sensitivity vs c.o.m / luminosity / detector assumptions (being covered)
    - (κ_λ , κ_t) scan with/without input from ttH/ttZ
    - (κ_V , κ_{2V}) sensitivity from VBF - HH (4b) ?
  - production mode dependent categorisation
  - boosted regime to be revisited (bbbb, bbττ)
  - bbZZ, bbWW
  - γγττ, .. ? unexplored

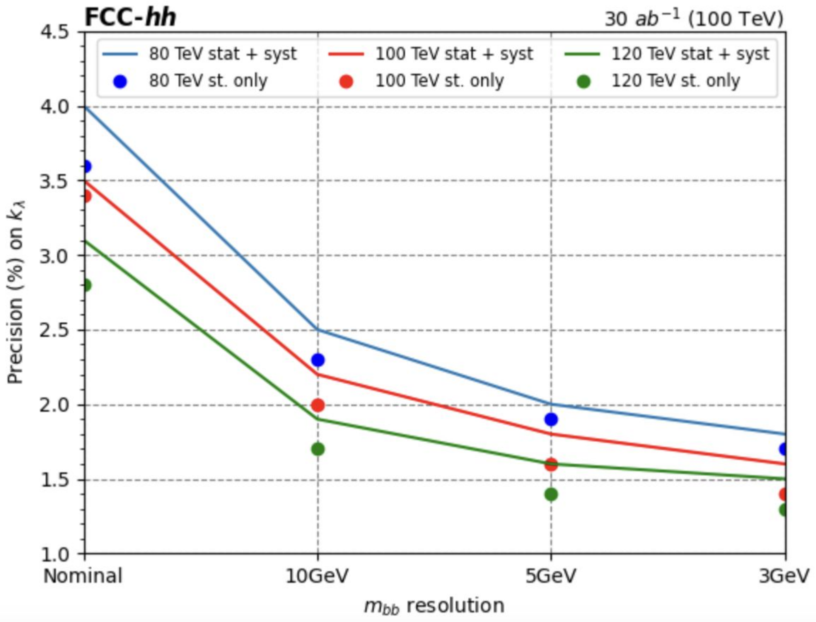
Plenty of space to contribute …

Recent highlights: HH → bbγγ



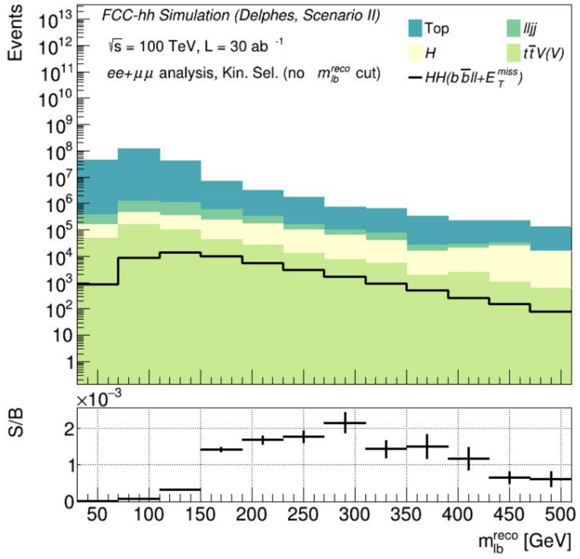
$80 < m_{bb} < 200$ GeV
$100 < m_{\gamma\gamma} < 180$ GeV

De Filippis, Mastrapasqua, Taliercio, Stapf



Recent highlights: HH → bbWW, bbττ

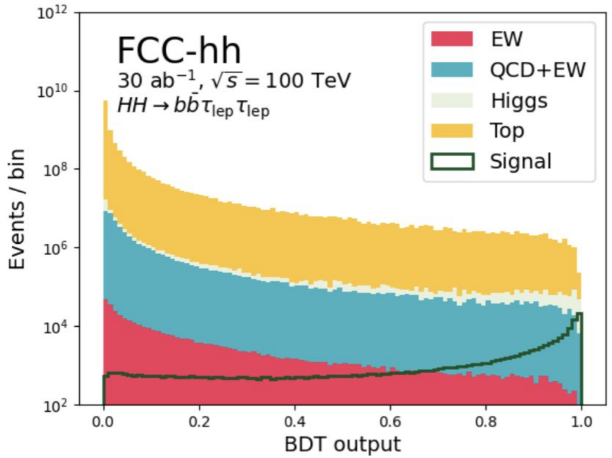
Stapf, Gallo, Tackman



Case	$\delta\kappa_\lambda$ (68% CL)
Scen I, stat. only	22.4%
Scen II, stat. only	25.8%
Scen II, syst. 1	30.7 %
Scen II, syst. 2	36.1 %
Scen II, syst. 3	42.7 %

work in progress

Sam Valentine, Cristiano Sebastiani, Jordy Degens, Monica D'Onofrio, Carl Gwilliam



Improved precision w.r.t to previous studies

To do:

- e.c.m /lumi/syst. variations
- combination with bbγγ

	HH+jet study	WIP study
	Yield [fb^{-1}]	
Signal	0.14	1.22
Background	0.96	38.94
	$S/\sqrt{B}$	
$\tau_\ell\tau_h$	24.97	32.32

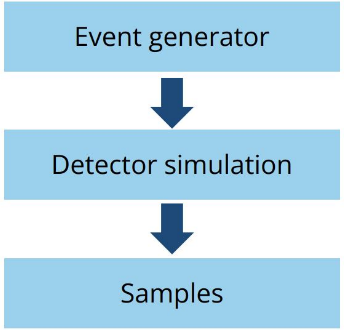
$b\bar{b}\tau_\ell\tau_h$ comparison

In practice, how to proceed

FUTURE CIRCULAR COLLIDER

- Two FCC-hh detectors cards are available in the Delphes repository:

Birgit Stapf



Across all p_T and η bins, up to $|\eta| < 6$

- Our analyses employ two detector scenarios
  - Scenario I: Optimistic case
  - **Scenario II:** Baseline, more realistic
    - I.e. baseline LaR calorimeter from CDR, lower efficiencies, ...

→ Use for new channel $\bar{b}bll+E_T^{miss}$

Relevant objects

	Relative p resolution		Efficiency	
	Scen I	Scen II	Scen I	Scen II
Electrons	0.4-1%	0.8-3%	76-95%	72-90%
Muons	0.5-3%	1-6%	90-99%	88-97%
Medium b-tagging			80-90%	76-86%

- Latest Delphes samples will appear here
- Tutorial: FCCAnalyses
  - (for now focused on FCC-ee, will add an FCC-hh example soon)

Organisation

- General group: **fcc-ped-hh-espp25**

  → main group, general monthly meetings announcements

  Coordinators:
  Christophe Grojean (DESY/CERN), Michelangelo Mangano, Matthew McCullough, Michele Selvaggi (CERN)

- Physics analysis group: **fcc-ped-hh-physicsperformance-espp25**

  → physics analysis focussed monthly meetings (will be announced soon)

  Coordinators:
  Birgit Stapf (CERN) and *Angela Taliercio (NorthWestern)* .
  open call for a BSM analysis expert

Useful references

Physics at the FCC-hh CERN-2017-003-M

FCC-hh CDR CERN-ACC-2018-0058

FCC-hh Yellow Report (extended CDR) CERN-2022-002

Physics potential of a low-energy FCC-hh CERN-FCC-PHYS-2019-0001

Higgs Physics Potential of FCC-hh Standalone CERN-FCC-PHYS-2019-0002

FCC-hh Detector Requirements CERN Seminar

Conclusion

- Many interesting topics to contribute
  - physics reach
  - detector design and technologies, R&D
  - optimisation of the machine layout
  - reconstruction , object identification, PU removal
  - software, AI …

- FCC-hh is an order of magnitude more complex than HL-LHC
  - radiation hardness, amount of data real challenge
  - it will be the next generation hadron machine, R&D should not stop after HL-LHC

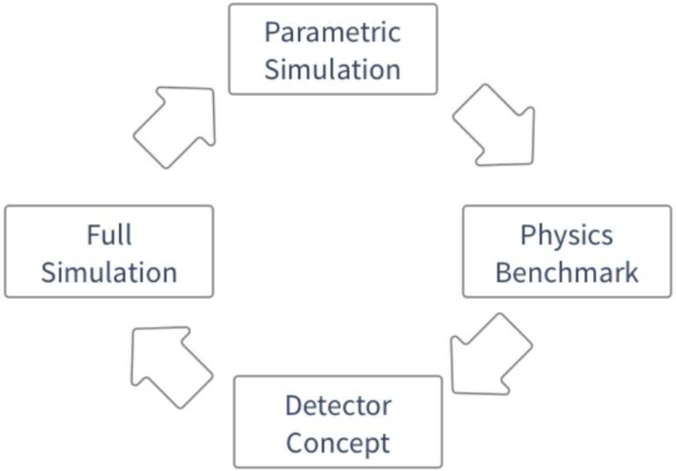
- Subscribe to **fcc-ped-hh-espp25** and **fcc-ped-hh-physicsperformance-espp25**, mailing lists for more info to come:
  - monthly general meeting
  - focused analysis meeting, tutorials

Backup

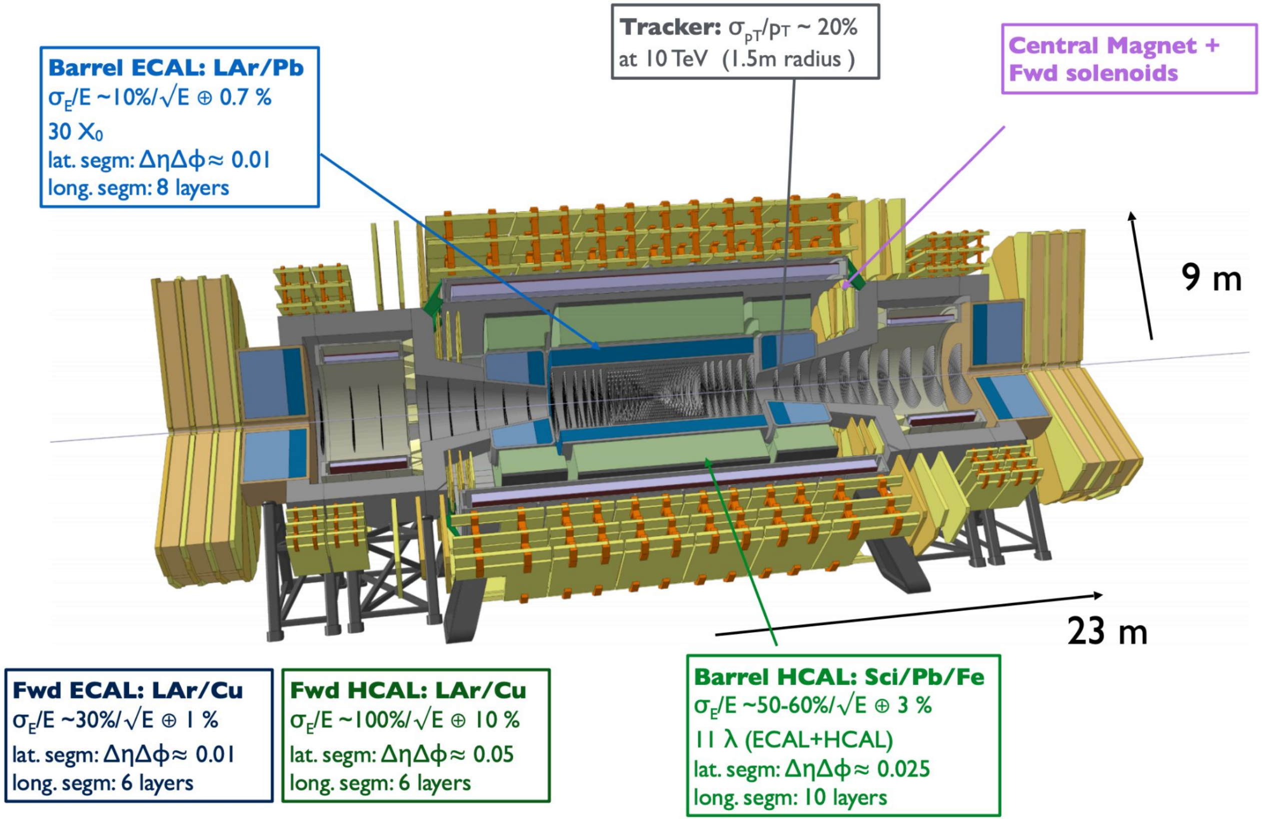
Recap, how we proceeded for the CDR

- Baseline detector concept in Delphes
- Physics benchmarks
  - Higgs and SM
  - BSM
- Refined detector requirements
- Implementation on detector concept in full simulation
  - Study performance in full sim
- Improve detector parameterisation in Delphes

  …



A detector concept that does the job …



Guiding principles for FCC-hh detector

- Guiding principles were machine constraints and physics requirements

- This generic detector serves as a starting point for:
    - benchmarking physics reach of the machine
    - identify: challenges of building such an experiment
    - topics where R&D needed

- Most likely, this is not “THE OPTIMAL” detector.

- Maybe the optimal route will be to have several detectors optimized for specific signatures (low? vs high lumi)

- Also, expected improvements in technology may lead to more ambitious and less-conventional approaches of detector concepts in the future
    - most of the challenges common to any high energy/high luminosity project.

Collider options

name	F12LL	F12HL	F12PU	F14	F17	F20
√s (TeV)	72	72	72	84	102	120
current (A)	0.5	1.12	1.12	0.5	0.5	0.2
PU	600	3000	1000	600	700	150
SR power (MW) 2 beams	1.3	2.9	2.9	2.4	5.2	4.0
Lumi/yr (ab-1)	1	2	1.3	0.9	0.9	0.4

Limiting factor: 5MW synchrotron power

Tracking for flavor tagging in Delphes

```
########################################
# Smearing for charged tracks
########################################

module TrackCovariance TrackSmearing {

    set InputArray TrackMergerPre/tracks
    set OutputArray tracks

    ## minimum number of hits to accept a track
    set NMinHits 6

    ## magnetic field
    set Bz $B

    ## uses https://raw.githubusercontent.com/selvaggi/FastTrackCovariance/master/GeoIDEA_BASE.txt
    set DetectorGeometry {
```

# barrel	name	zmin	zmax	r	w (m)	X0	n_meas	th_up (rad)	th_down (rad)	reso_up (m)	reso_down (m)	flag
1	PIPE	-100	100	0.015	0.001655	0.2805	0	0	0	0	0	0
1	VTXLOW	-0.12	0.12	0.017	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXLOW	-0.16	0.16	0.023	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXLOW	-0.16	0.16	0.031	0.00028	0.0937	2	0	1.5708	3e-006	3e-006	1
1	VTXHIGH	-1	1	0.32	0.00047	0.0937	2	0	1.5708	7e-006	7e-006	1
1	VTXHIGH	-1.05	1.05	0.34	0.00047	0.0937	2	0	1.5708	7e-006	7e-006	1

TrackCovariance module

- **Requires:**
  - Geometry input
    - cylinder coaxial
    - planar disks
  - Magnetic field