FCC-hh – Physics Requirements and Reference Detector

Martin Aleksa

Based on material from:

FCC-hh Yellow Report: https://e-publishing.cern.ch/index.php/CYRM/index
P. Janot and W. Riegler: Academic Training (https://indico.cern.ch/event/666889/)
FCC CDR Summary Volumes: https://fcc-cdr.web.cern.ch/, EPJ ST 228, 4 (2019) 755-1107

A 100 TeV Hadron Collider – FCC-hh

CDR: FCC-hh Parameter Table (100km, 100TeV)

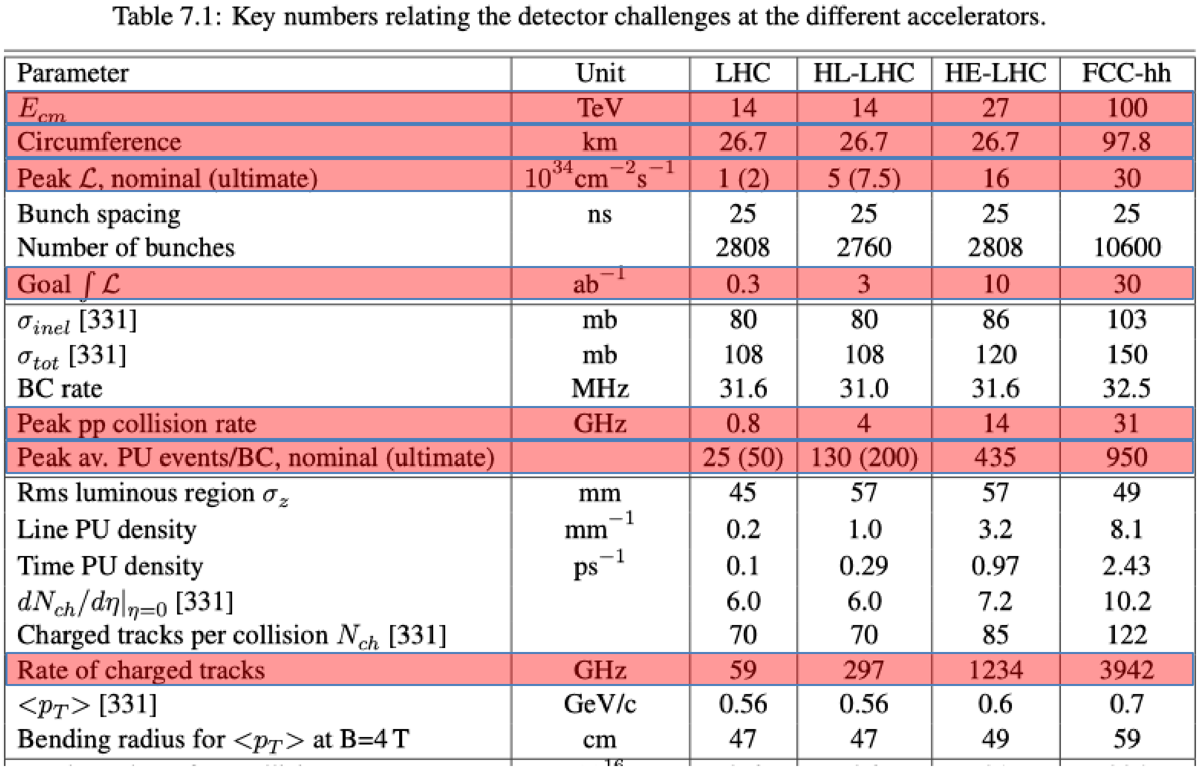

Table 7.1: Key numbers relating the detector challenges at the different accelerators.

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [331]	mb	80	80	86	103
σ_{tot} [331]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Rms luminous region σ_z	mm	45	57	57	49
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Time PU density	ps^{-1}	0.1	0.29	0.97	2.43
$dN_{ch}/d\eta\|_{\eta=0}$ [331]		6.0	6.0	7.2	10.2
Charged tracks per collision N_{ch} [331]		70	70	85	122
Rate of charged tracks	GHz	59	297	1234	3942
$<p_T>$ [331]	GeV/c	0.56	0.56	0.6	0.7
Bending radius for $<p_T>$ at B=4 T	cm	47	47	49	59

- $E_{cm} = 100$ TeV
- ~100 km circumference
- $\mathcal{L} = 30 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- $\int \mathcal{L} = 30\ \mathrm{ab}^{-1}$
- 31 GHz pp collisions
- Pile-up $<\mu> \approx 1000$
- 4 THz of charged tracks

Those were the parameters at the time of the **FCC CDR**
Now there are **several different scenarios**, see next slides or MichaIngelo's talk!

Scenarios (90.7km ring)

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
c.m. energy	TeV	72	72	72	84	102	120	14
dipole field	T	12	12	12	14	17	20	8.33
beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
bunch popul.	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
bunches/beam		9500	9500	9500	9500	9500	9500	(2760) 2808
rf voltage	MV	30	30	30	35	43	50	(16) 16
longit. emit.	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
norm. tr. emit.	μm	2.5	2.5	2.5	2.5	2.5	2.5	(2.5) 3.75
IP beta*	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
initial σ*	μm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min) 16.7
initial *L*	$nb^{-1}s^{-1}$	175	845	286	172	209	39	(50, lev'd) 10
initial pile up		580	2820	955	590	732	141	(135) 27
ΔE / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power/beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
tr.ε damp'g time	h	0.68	0.68	0.68	0.43	0.24	0.15	25.8
init *p*-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

Courtesy F. Zimmermann (link)

Scenarios (90.7km ring)

Courtesy F. Zimmermann (link)

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in								
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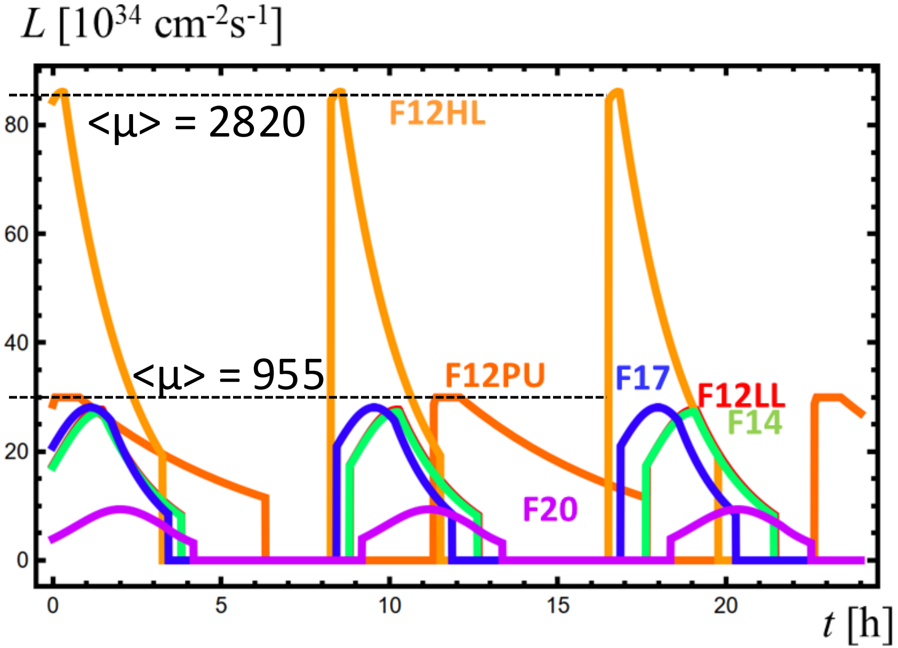
init *p*-burnoff time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40

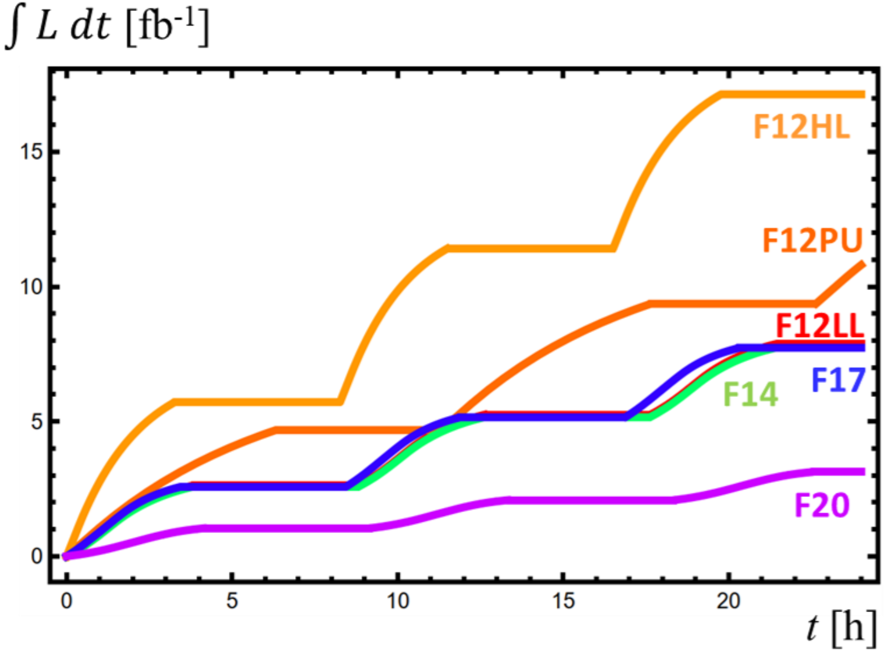
No baseline option so far, in this presentation will mostly assume 100TeV centre of mass energy and instantaneous luminosity of up to $\mathcal{L} = 30 \times 10^{34}\ cm^{-2}s^{-1}$ and will discuss the differences with respect to a possible scenario with 80TeV c.m. energy if any

Instantaneous and Integrated Luminosity

Simulation incl. beam-beam effects and optimal fill length for 5 hours interfill (F. Zimmermann)

Courtesy F. Zimmermann (link)

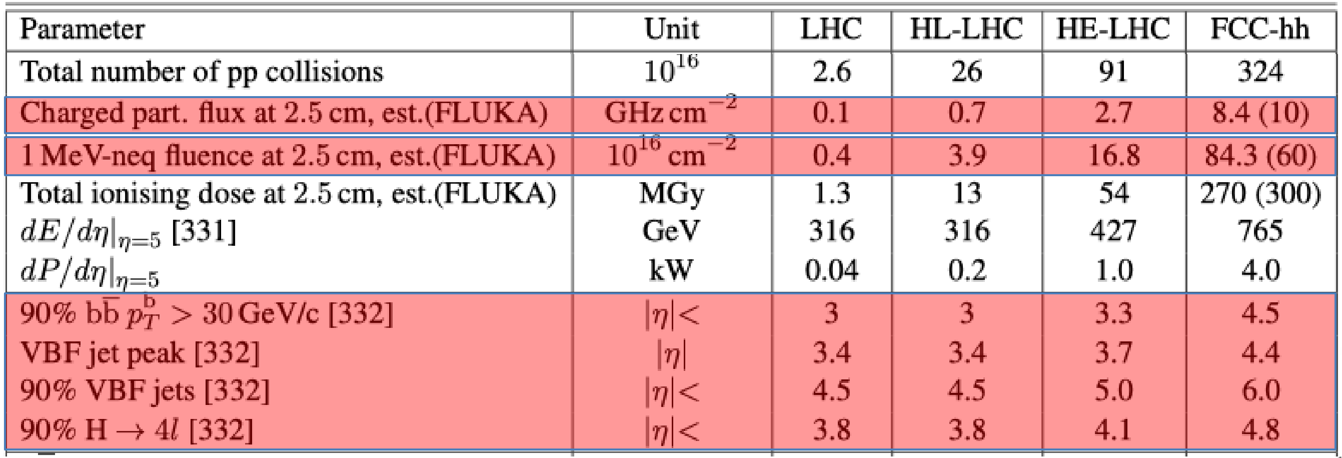




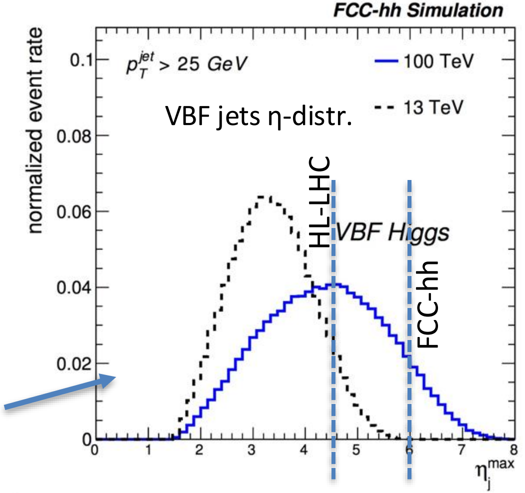
Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
ideal $\int L\,\mathrm{dt}$ /day	fb^{-1}	7.9	17.1	10.8	7.7	7.7	3,1	(1.9) 0.4
$\int L\,\mathrm{dt}$ / year	fb^{-1}	950	2000	1300	920	920	370	(240) 55

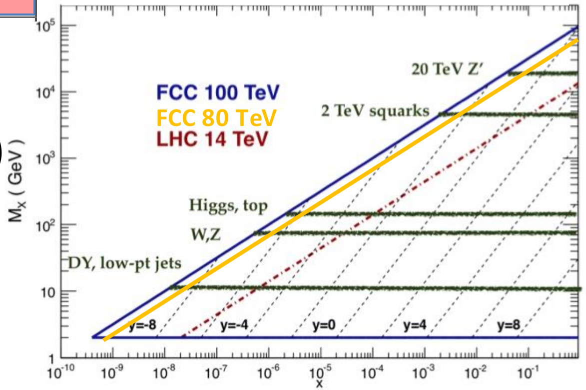
Parameter Table (100km, 100TeV)

Table 7.1: Key numbers relating the detector challenges at the different accelerators.



Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est.(FLUKA)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est.(FLUKA)	10^{16} cm^{-2}	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est.(FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\|_{\eta=5}$ [331]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [332]	$\|\eta\|<$	3	3	3.3	4.5
VBF jet peak [332]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [332]	$\|\eta\|<$	4.5	4.5	5.0	6.0
90% $H \rightarrow 4l$ [332]	$\|\eta\|<$	3.8	3.8	4.1	4.8



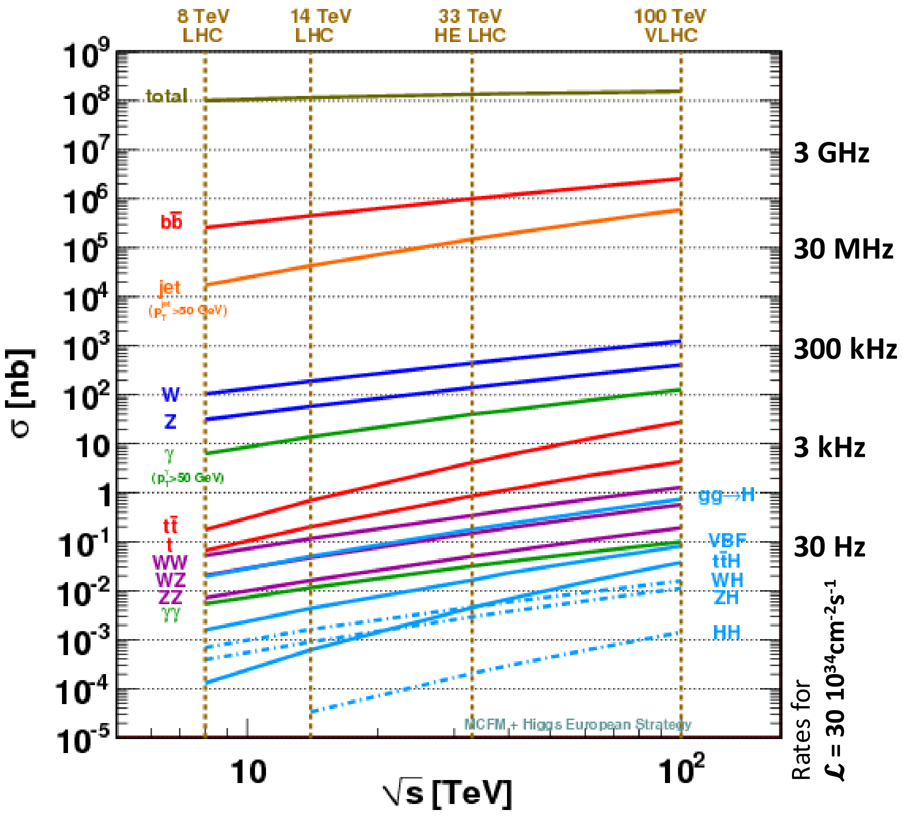


Unprecedented particle flux and radiation levels

- **10 GHz/cm^2 charged particles**
- **≈ 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30ab^{-1} (1st tracker layer, fwd calo)**
- **“Light” SM particles produced with increased forward boost**
  - → spreads out particles by 1-1.5 units of rapidity

→ Minimal changes only for 80TeV, but fluxes scale with luminosity!

Cross-Sections for Key Processes



- **Total cross-section and Minimum Bias Multiplicity** show only a **modest increase** from LHC to FCC-hh.
- The **cross-sections for interesting processes, however, increase significantly** (e.g. HH x 50!)!
- Higher luminosity to increase statistics → pileup of 140 at HL-LHC to **pileup of 1000** at FCC-hh → **challenge for triggering and reconstruction**
- **$\mathcal{L}$ = 30x10^{34}cm^{-2}s^{-1}:**
  - 100MHz of jets p_T>50GeV,
  - 400kHz of Ws,
  - 120kHz of Zs,
  - 11kHz of ttbars
  - 200Hz of gg→H

HH cross-section down by ~30% for 80 TeV!

FCC-hh Detector

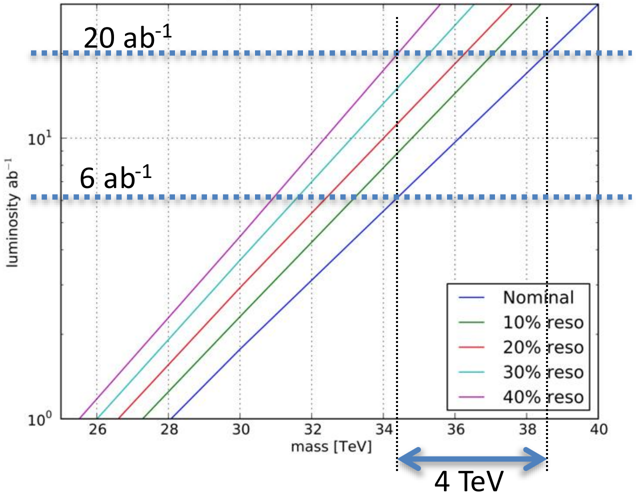
Physics Benchmarks – Detector Requirements

Physics at the $\mathcal{L}\sigma$-limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z’$_{SSM}$ discovery

luminosity versus mass for a 5σ discovery



Muon momentum resolution:

- **O(5%) at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**

Tracking – Resolution degrading with higher momentum!

$$\frac{\Delta p}{p} \propto \frac{\sigma_{\text{pos}} \cdot p}{BL^2}$$

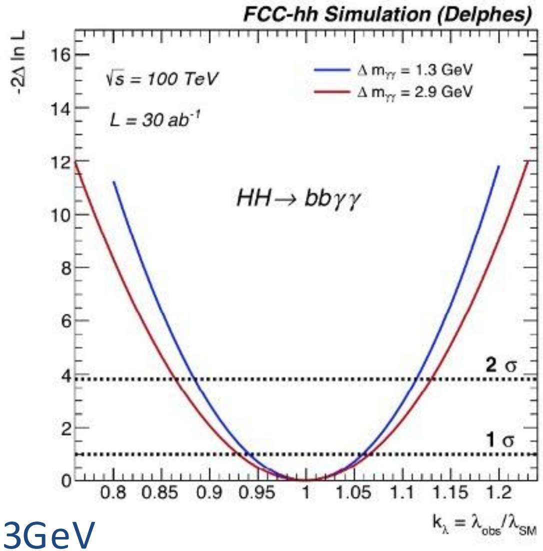
→ Have to improve on

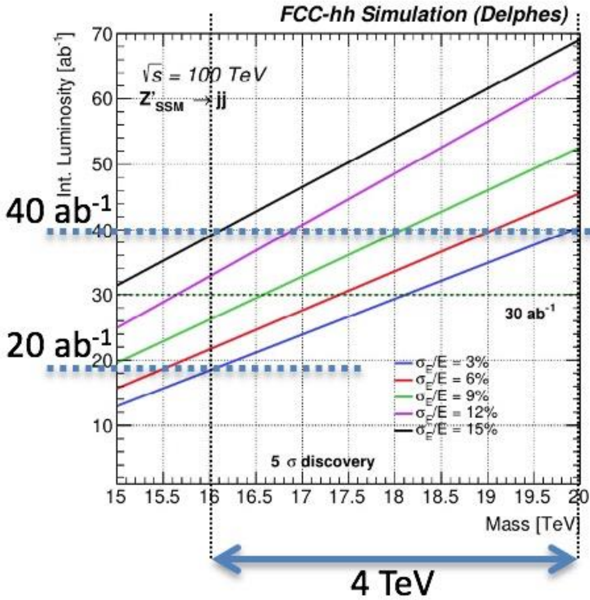
- σ_{pos}: difficult
- Magnetic field B: go from 2T (ATLAS) to 4T (FCC-hh)
- Lever arm L: magnet cost scales with ≈ volume$^{2/3}$ → very quickly very expensive

Physics Benchmarks – Detector Requirements

Calorimetry – Improving resolution with higher energy!

$$\frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$





Higgs self-coupling $\delta\lambda/\lambda$ = 7% for $\Delta m_{\gamma\gamma} < 3$GeV

- → **EM-calorimeter resolution**
  sampl. term *a ≈ 10%* and noise term *b < 1.5GeV* (including pile-up)!

Di-jet resonances: HCAL constant term of *c* = 3% instead of 15%: extend discovery potential by 4TeV (or same disc. pot. for 50% lumi)

- → **full shower containment is mandatory !**
- → Large **HCAL depth (~ 12 λ_{int})!**

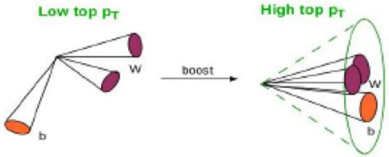
Better detector performance could compensate decreased HH statistics at 80 TeV

Requirements for FCC-hh Detector

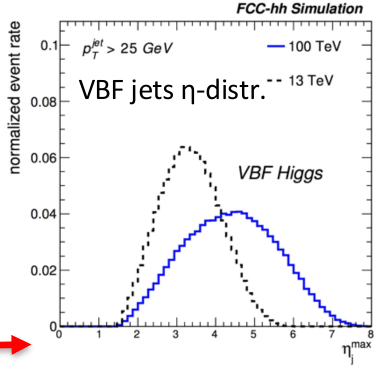
- **ID tracking target**: achieve σ_{pT} / p_T = 10-20% @ 10 TeV
- **Muon target**: σ_{pT} / p_T = 5% @ 10 TeV

Used in Delphes physics simulations

- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency vertex reconstruction, b-tagging, τ-tagging, particle ID**!
  - Pile-up of <μ>=1000 → 120μm mean vertex separation
- **High granularity** in tracker and calos (boosted obj.)

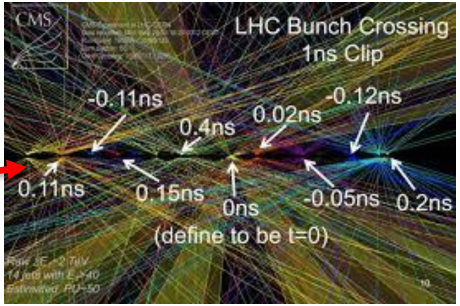


- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6

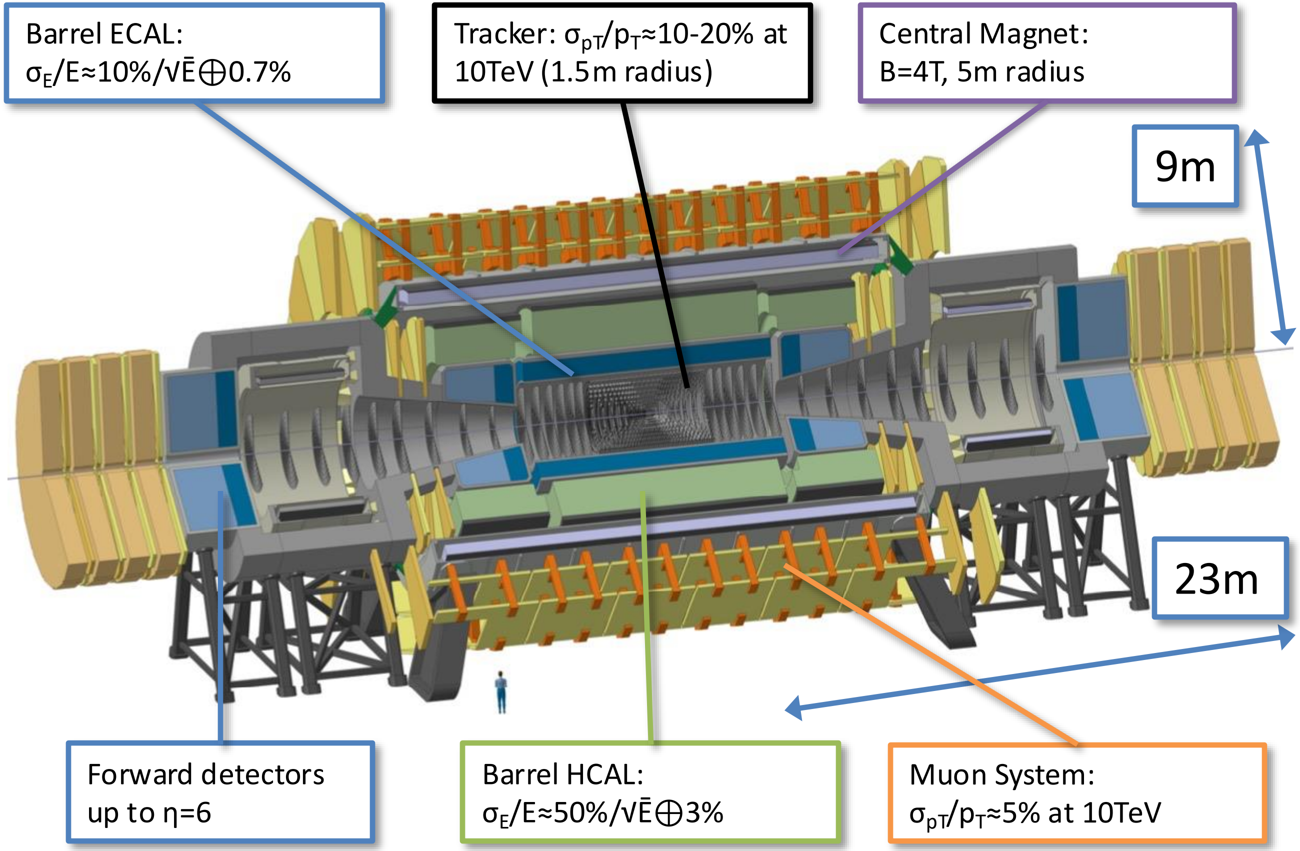


VBF jets η-distr.

- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**



A Possible FCC-hh Detector – Reference Design for CDR



Barrel ECAL:
$\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$

Tracker: $\sigma_{p_T}/p_T \approx$ 10-20% at 10TeV (1.5m radius)

Central Magnet:
B=4T, 5m radius

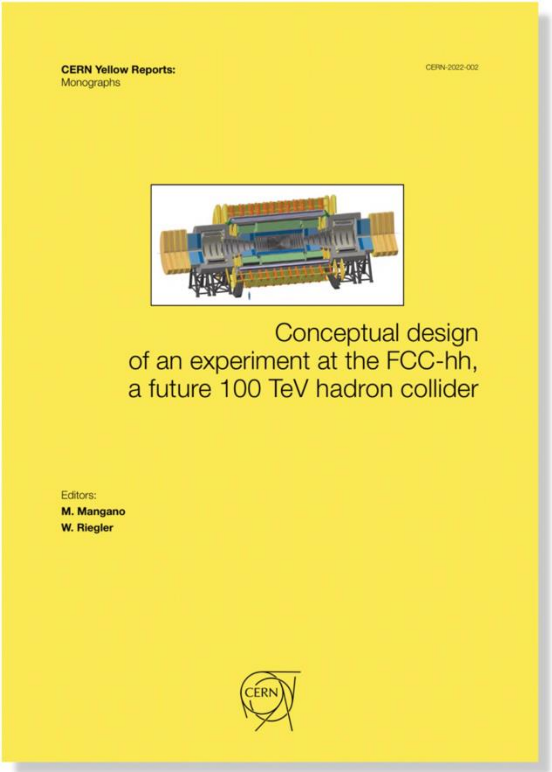
Forward detectors
up to η=6

Barrel HCAL:
$\sigma_E/E \approx 50\%/\sqrt{E} \oplus 3\%$

Muon System:
$\sigma_{p_T}/p_T \approx$ 5% at 10TeV

- Converged on **reference design for an FCC-hh experiment for the FCC CDR**
- Goal was to demonstrate, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
  - **Input for Delphes physics simulations**
  - **Radiation simulations**
- This is one example experiment, other choices are possible and very likely → A lot of **room for other ideas, other concepts and different technologies**

Documentation



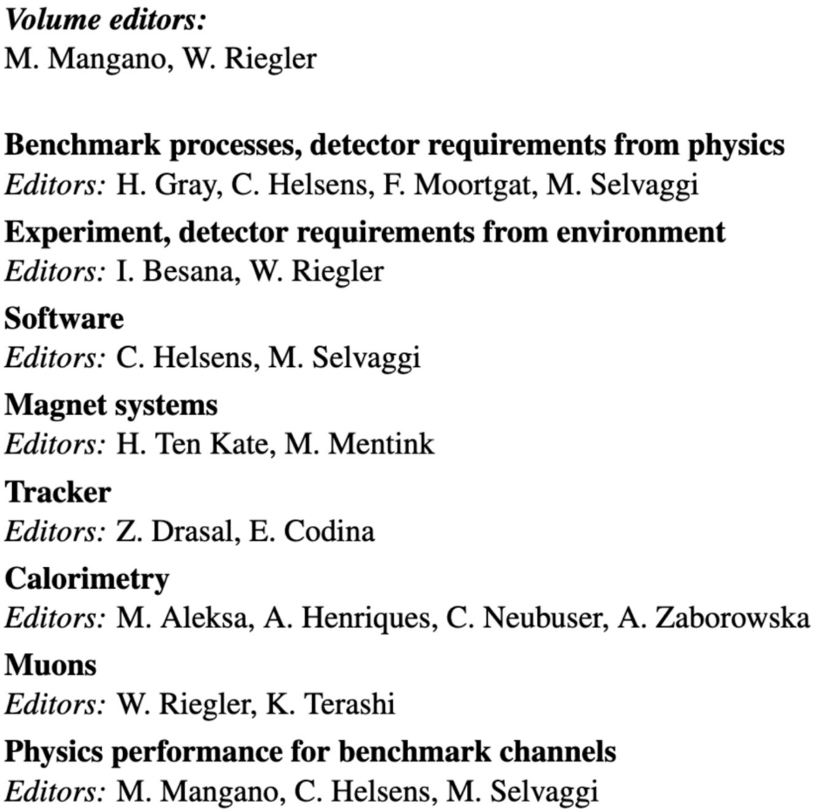
CERN Yellow Reports:
Monographs

CERN-2022-002

Conceptual design
of an experiment at the FCC-hh,
a future 100 TeV hadron collider

Editors:
M. Mangano
W. Riegler

FCC CDR (link) & Yellow report (link)



Volume editors:
M. Mangano, W. Riegler

Benchmark processes, detector requirements from physics
Editors: H. Gray, C. Helsens, F. Moortgat, M. Selvaggi

Experiment, detector requirements from environment
Editors: I. Besana, W. Riegler

Software
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Editors: Z. Drasal, E. Codina

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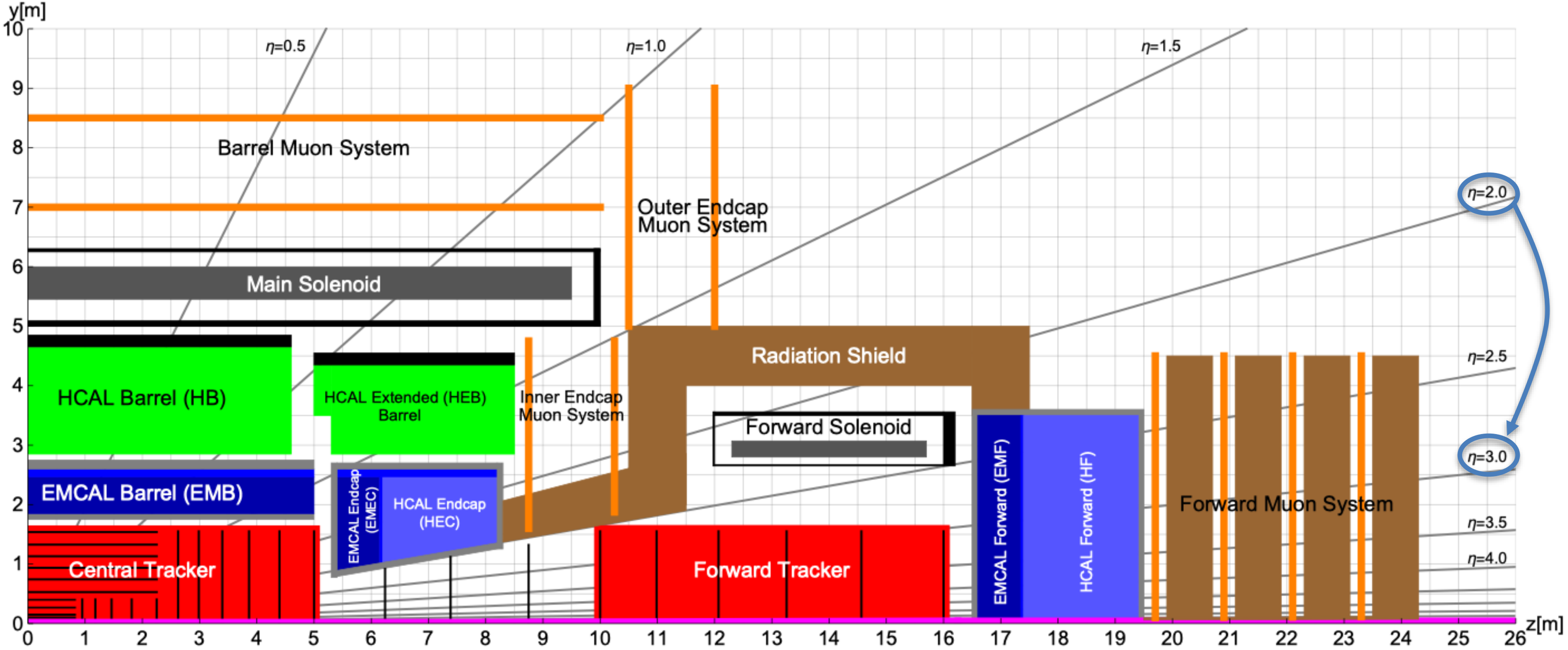
Muons
Editors: W. Riegler, K. Terashi

Physics performance for benchmark channels
Editors: M. Mangano, C. Helsens, M. Selvaggi

Reference Design for CDR

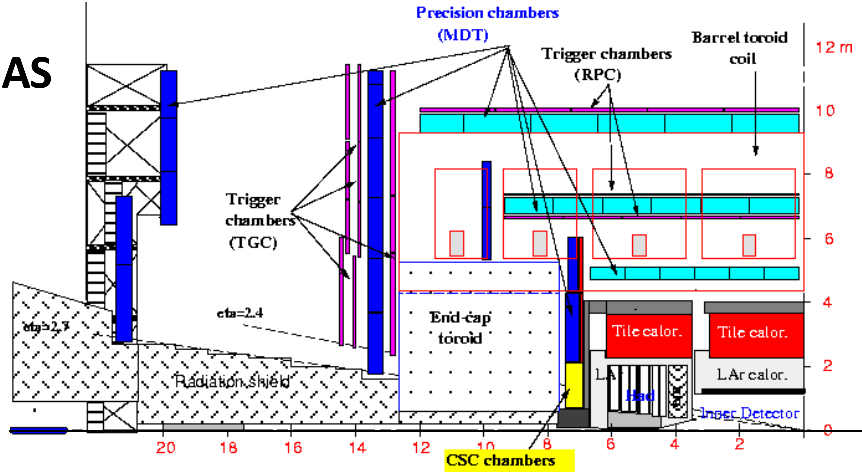


Forward solenoid adds about 1 unit of η with full lever-arm

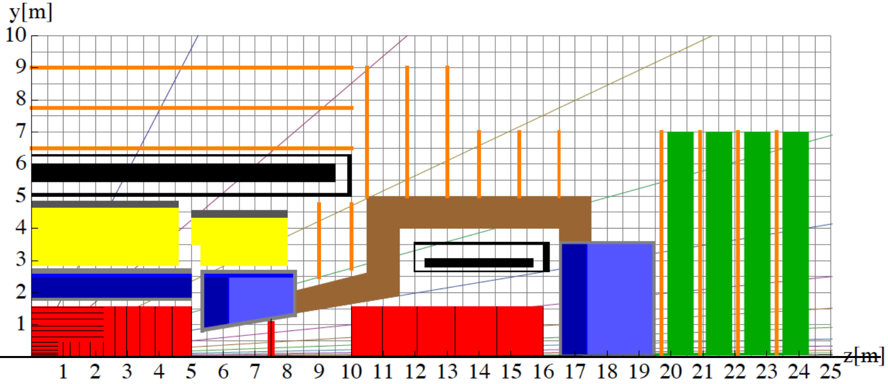
Forward solenoid requires additional radiation shield to connect endcap and forward calorimeter

FCC-hh Detector: Comparison to ATLAS & CMS

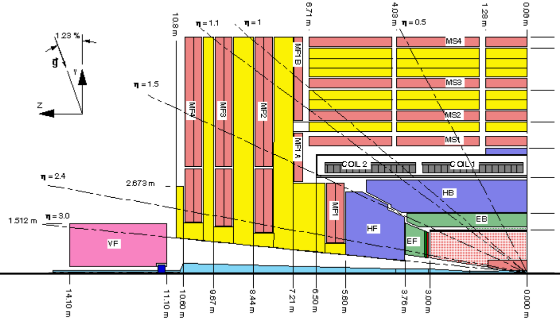
ATLAS

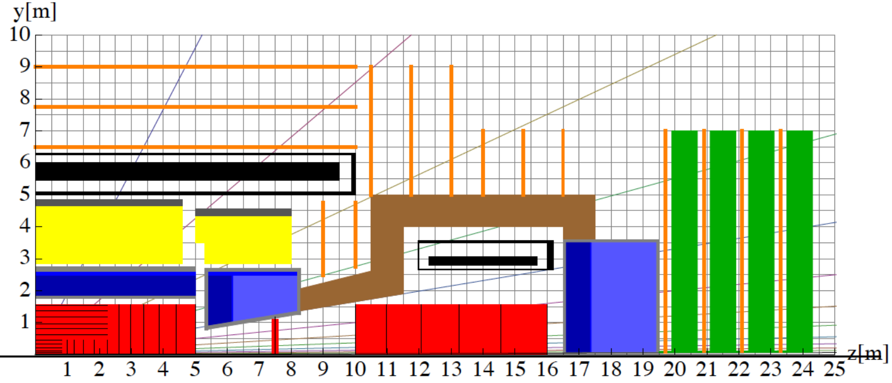


FCC-hh Reference Detector

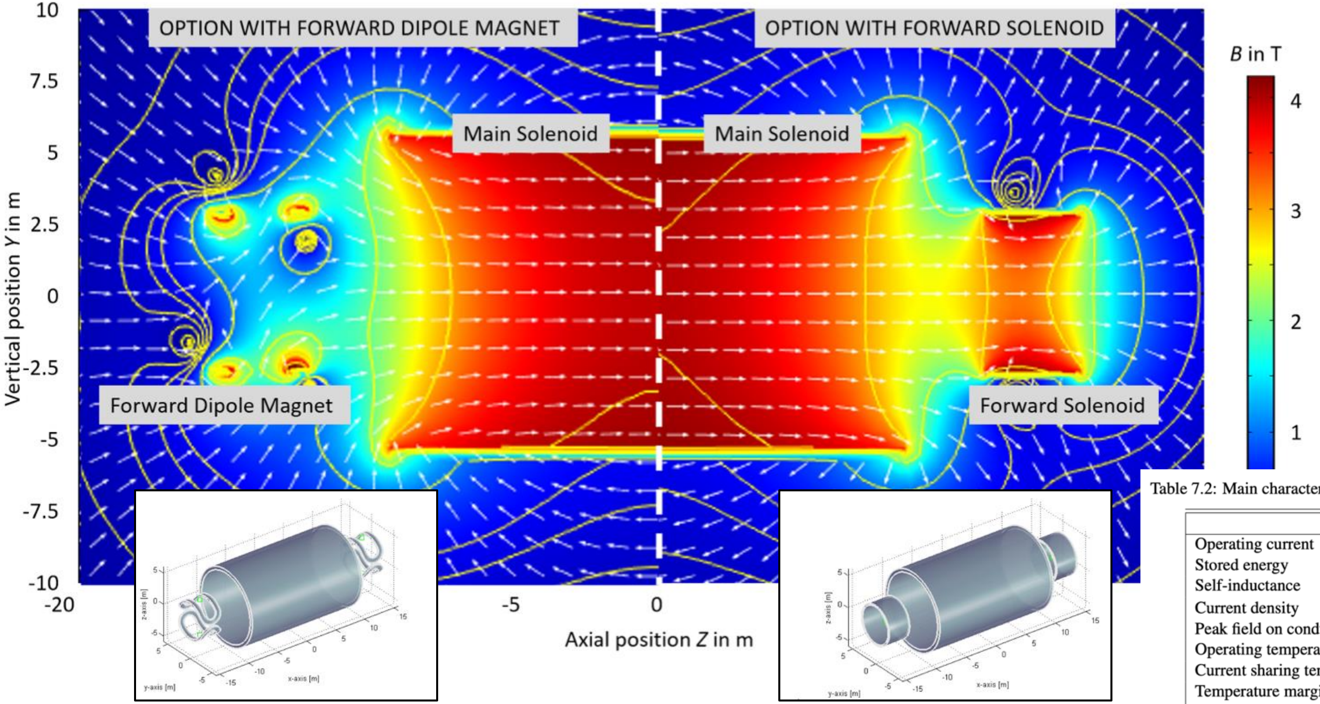


CMS





FCC-hh Magnet System



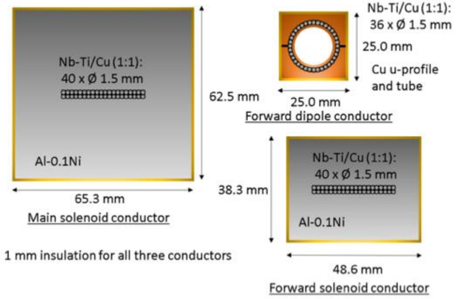


Table 7.2: Main characteristics of the central solenoid, a forward solenoid and a forward dipole magnet.

	Unit	Main solenoid	Forward solenoid	Forward dipole
Operating current	kA	30	30	16
Stored energy	GJ	12.5	0.43	0.20
Self-inductance	H	27.9	0.96	1.54
Current density	A/mm^2	7.3	16.1	25.6
Peak field on conductor	T	4.5	4.5	5.9
Operating temperature	K	4.5	4.5	4.5
Current sharing temp.	K	6.5	6.5	6.2
Temperature margin	K	2.0	2.0	1.7
Heat load cold mass	W	286	37	50
Heat load thermal shield	W	5140	843	1500
Cold mass	t	1070	48	114
Vacuum vessel	t	875	32	48
Conductor length	km	84	16	23

ATLAS Magnet System 2.7 GJ

CMS Magnet System 1.6 GJ

FCC-hh: ~13 GJ, cold mass + cryostat around 2000 tons.

Possible alternative solutions: Ultra-thin solenoid positioned inside the calorimeter (difficulty: muon measurement!)

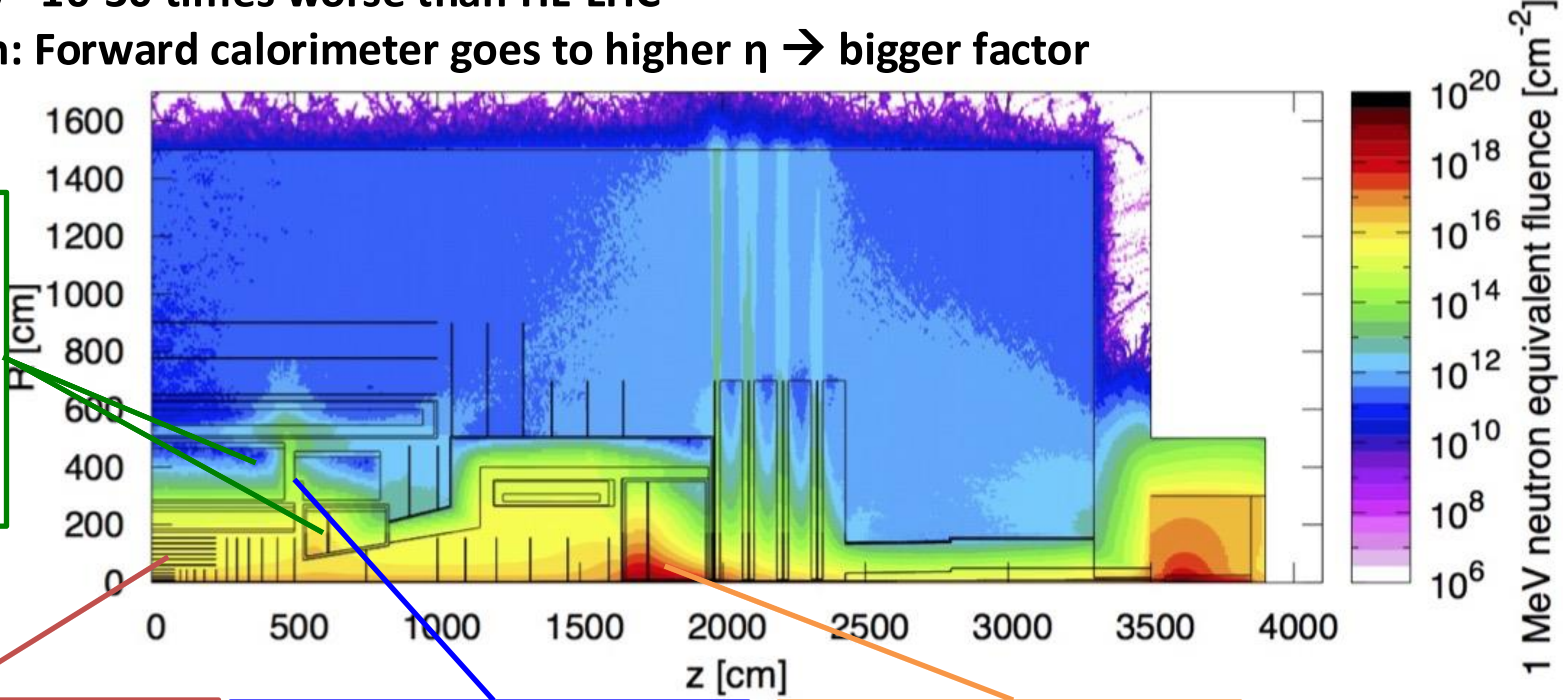
Challenges for the Magnet System – R&D Needs

- New orders of magnitude of **stored energy**!
- **R&D needs (4T, r = 5m, length ≈ 20m):** Conductor development, powering and quench protection, coil windings pre-stressing, conduction cooling techniques and force transfer to cryostat and neighbouring systems.
- **R&D needs** for the ultra-thin and radiation transparent solenoids: Study the limits of high yield strength Al stabilized NbTi/Cu conductor and its cold mass technology affecting the feasibility of the concept of such a challenging magnet.
- **Low material cryostats**, Al-alloy honeycomb or composite material (carbon-fibre)

1 MeV Neutron Equivalent Fluence for 30ab^{-1}

Generally ~10-30 times worse than HL-LHC

Exception: Forward calorimeter goes to higher η → bigger factor



Barrel calorimeter:

EM-calo: 4 10^{15} cm^{-2}

HAD-calo: 4 10^{14} cm^{-2}

End-cap calorimeter:

EM-calo: 2.5 10^{16} cm^{-2}

HAD-calo: 1.5 10^{16} cm^{-2}

Central tracker:

- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Calorimeter gap:

from 10^{16} cm^{-2} to 10^{14} cm^{-2}

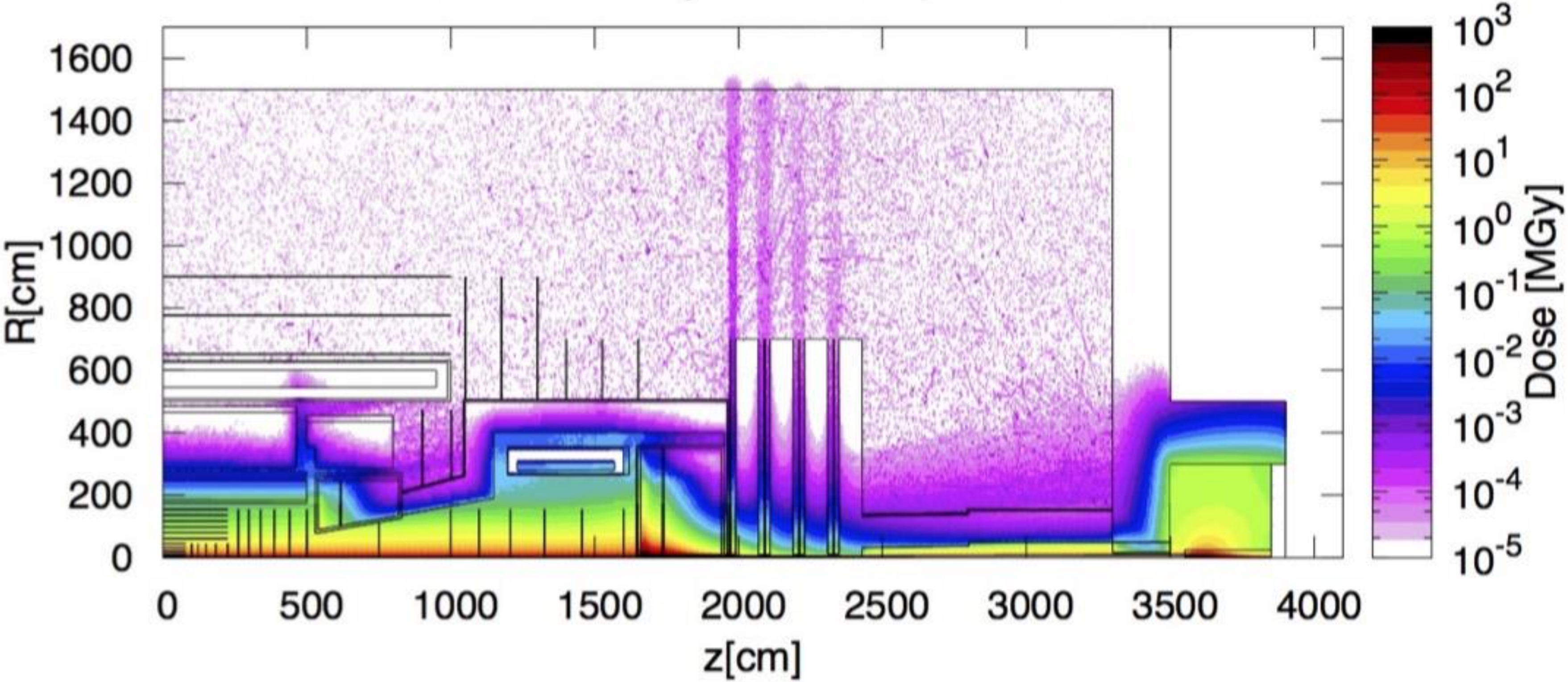
Forward calorimeters:

~5 10^{18} cm^{-2} for both the EM and the HAD-calo

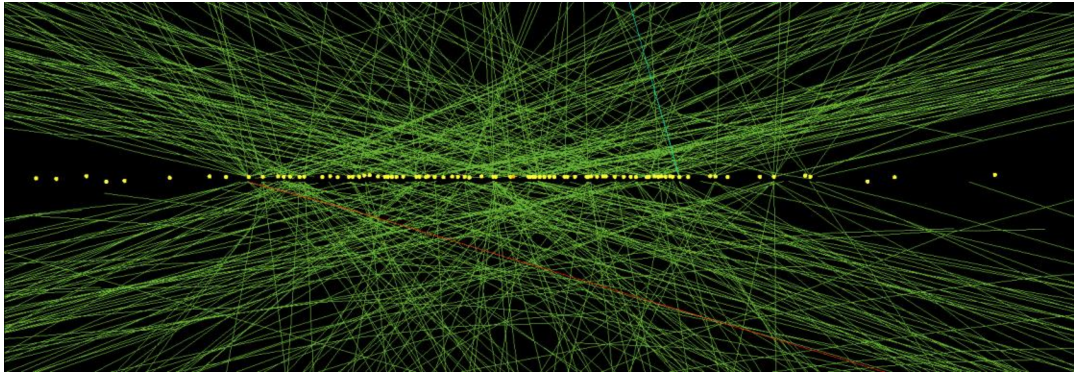
Total Ionizing Dose for 30ab^{-1}

Dose of 300 MGy (30 Grad) in the first tracker layers.

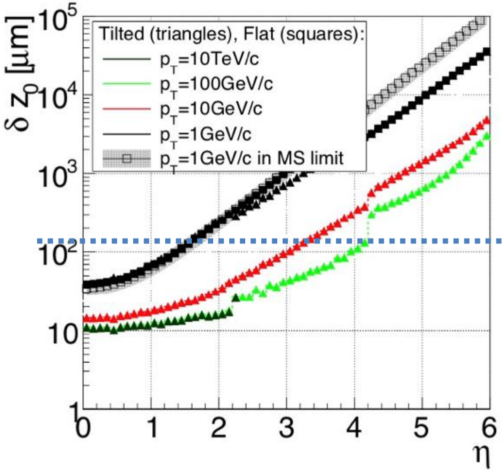
< 10 kGy in HCAL barrel and extended barrel.



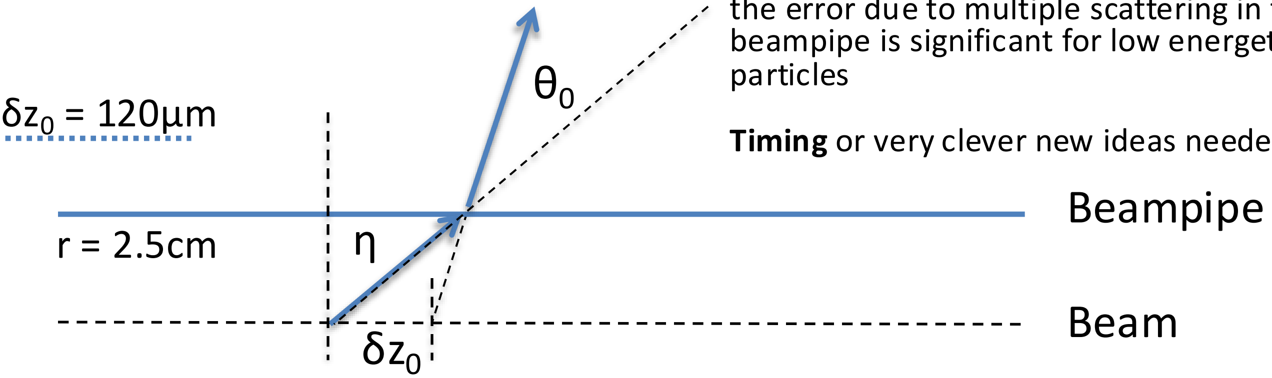
The Challenge of <μ> = 1000 Pile-Up



- HL-LHC average distance between vertices at z=0 is
  - **≈ 1mm in space and 3ps in time.**
- → For 6 times higher luminosity and higher c.m. energy at FCC-hh:
  - **≈ 120 μm in space and 0.4ps in time**
- **→ Future trackers will need to use both, position resolution and timing to identify the correct vertex!**



$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

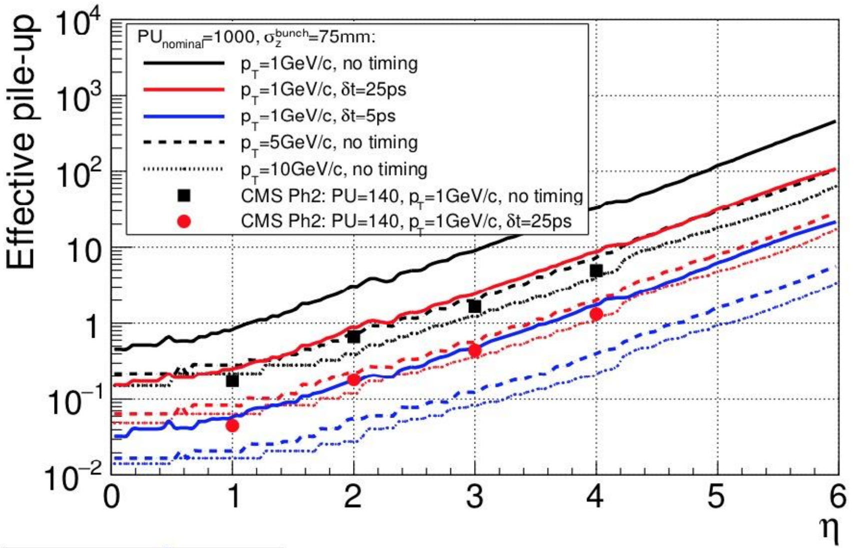


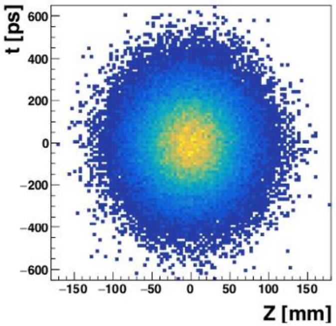
Multiple scattering in the beam pipe:
→ Even having a perfect tracking detector, the error due to multiple scattering in the beampipe is significant for low energetic particles

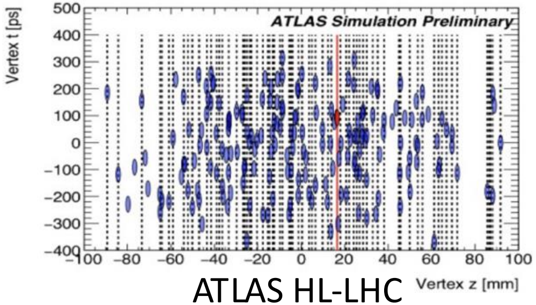
Timing or very clever new ideas needed …

Timing Information for Vertex Reconstruction

- **Goal is to identify the primary vertex!**
- **Effective pile-up:** number of vertices compatible with reconstructed tracks (95%CL)
  - Eff. pile-up = 1: Indication for unambiguous primary vertex identification
- **Example:** eff. pile-up = 1 for $p_T = 5$GeV:
  - η < |2| without timing (---)
  - η < |3.5| with 25ps timing accuracy (---)
  - η < |4.5| with 5ps timing accuracy (---)
- → **Very challenging!**

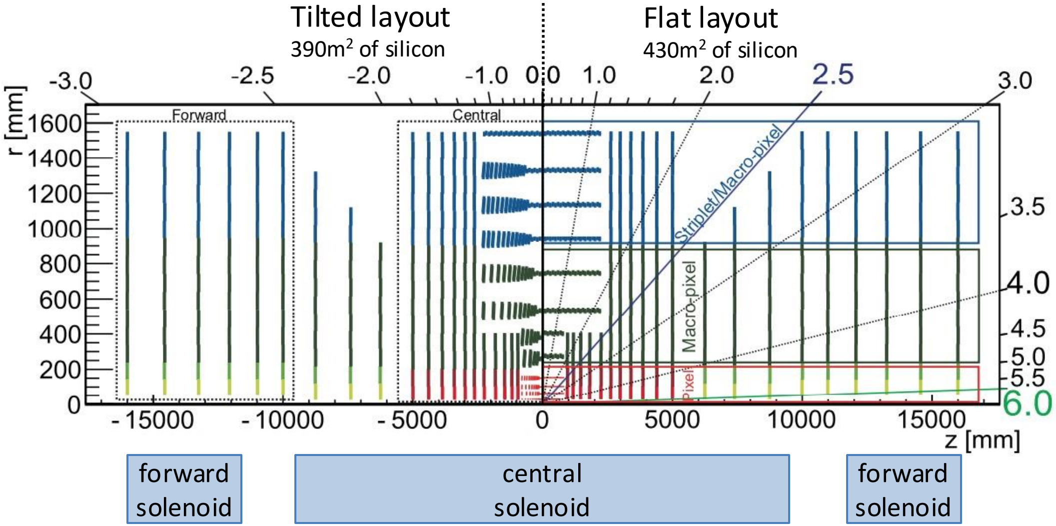


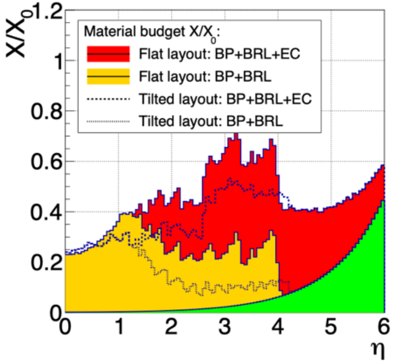


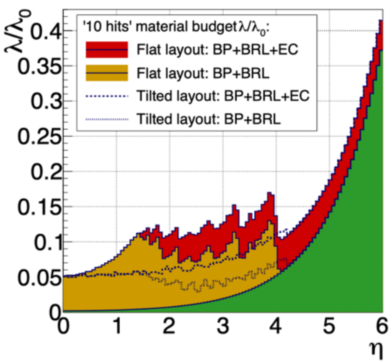


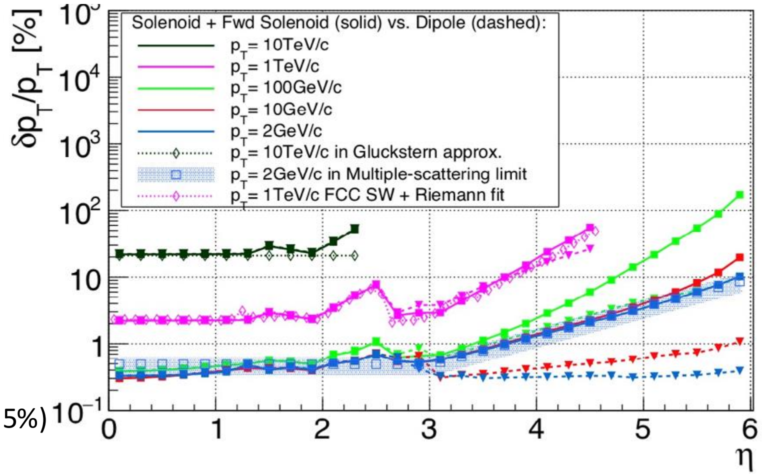
ATLAS HL-LHC

FCC-hh Tracker









Tilted layout:		
25 × 50 µm^2 (1–4th BRL)	33.3 × 400 µm^2	33.3 µm × 1.75 mm (BRL)
25 × 50 µm^2 (1st EC ring)		33.3 µm × 1.75 mm (EC)
33.3 × 100 µm^2 (2nd EC ring)		33.3 µm × 50 mm (12th BRL layer)
33.3 × 400 µm^2 (3–4th EC ring)		

Assuming an r-phi resolution of 7.5-9.5µm per detector layer

$\delta p_T/p_T \leq 10\%$ for

- ≤ 10 GeV/c and η ≤ 5.8
- ≤ 1 TeV/c and η ≤ 4.0

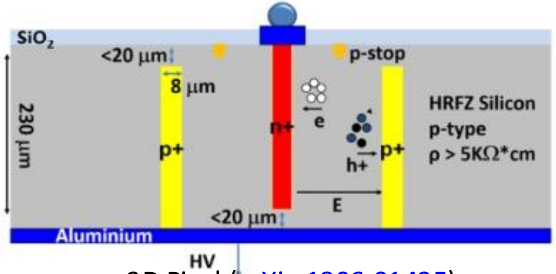
$\delta p_T/p_T = 20\%$ for 10 TeV/c in the central region

Momentum resolution dominated by **multiple scattering** up to 250GeV (limit at $\delta p_T/p_T = 0.5\%$)

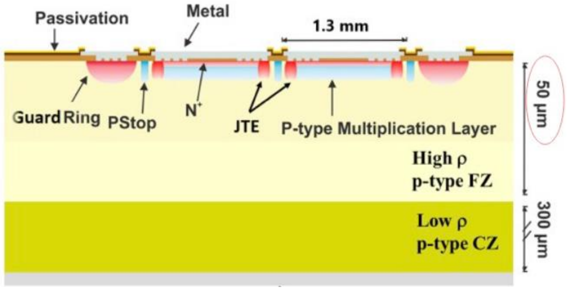
→ **low material tracker**!!

Challenges for the Tracker – R&D Needs

- **Radiation hardness:**
  - **Radius > 30cm: Existing technologies are applicable**
  - **Radius < 30cm: Radiation challenge has to be solved**
    - Ultra-rad. hardness of sensors and chip: up to 10^{18}cm^{-2} 1 MeV n.eq. fluence, TID of 300MGy
- **Timing** of tracks at the <10ps level
  - Either timing measurement of each pixel or dedicated timing layers
  - LGAD for timing O(30ps) achieved, ultra-thin LGADs ≤ 10ps
    - Improve rad. tolerance, now up to $2\text{x}10^{15}$ n/cm^2 (esp. gain layer, admixture of doping elements)
    - Limited to relatively large cells due to inefficient collection at pad edges → smaller cell sizes
  - 3D Pixel technology → radiation tolerance up to $3\text{x}10^{16}$ neutrons/cm^2 demonstrated, timing O(30ps)
  - R&D on new technologies to achieve <10ps timing resolution
- **Low material**
  - **Monolithic designs with integrated sensor and readout** (e.g. MAPS)
    - → R&D on improving radiation hardness to make it compatible with **outer layers** of future tracker.
  - **Outer layers:** waver scale CMOS sensors (potential to reduce power consumption and low-material)
- **Integration problems to be solved**:
  - Huge amount of data produced (1000TByte/s)
  - Power needs of sensors, FE-chips and optical links critical
  - Low-mass detector system integration: integrated services, power management, cooling, data flow, and multiplexing.
- **New sensor materials?** E.g. to work at room temperature?
- **Far future:** R&D on mass-minimized, or irreducible-mass tracker → mass budget is reduced to the active mass of the sensor

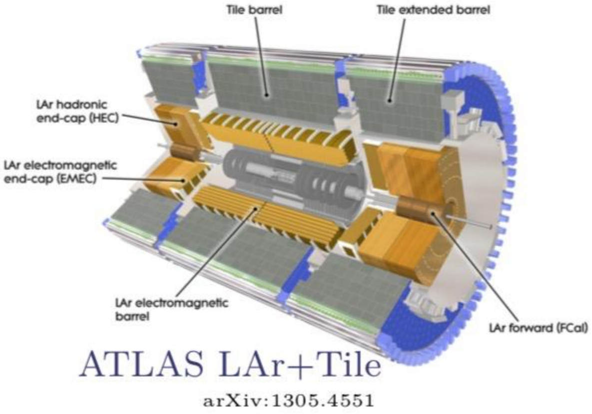


3D Pixel (arXiv:1806.01435)



LGAD

FCC-hh Calorimetry



ATLAS LAr+Tile

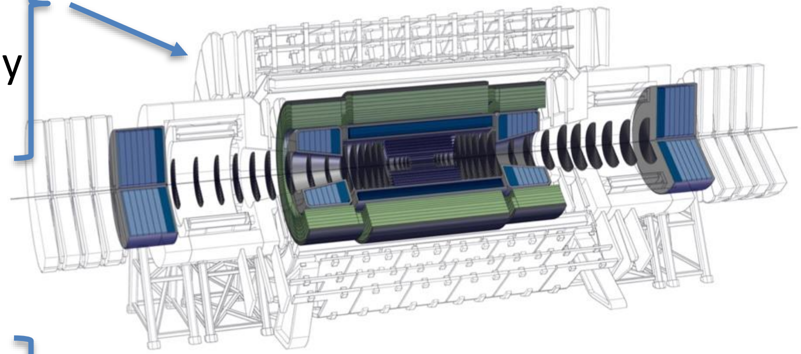
arXiv:1305.4551

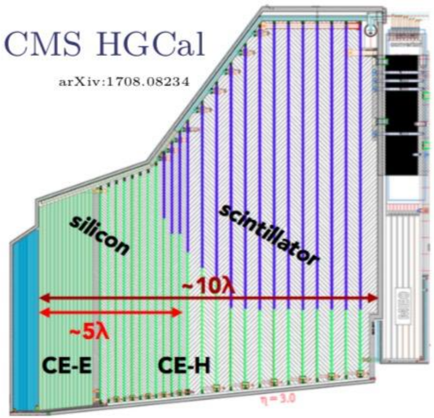
- Good intrinsic energy resolution
- Radiation hardness
- High stability
- Linearity and uniformity
- Easy to calibrate

FCC-hh Calorimetry

„conventional calorimetry“

optimized for particle flow





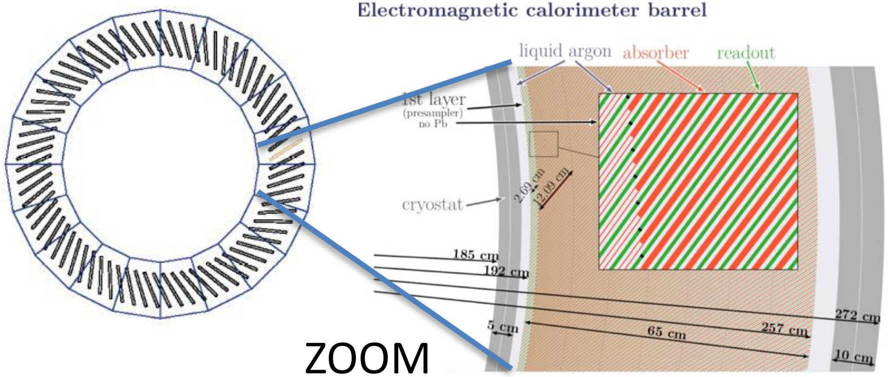
CMS HGCal

arXiv:1708.08234

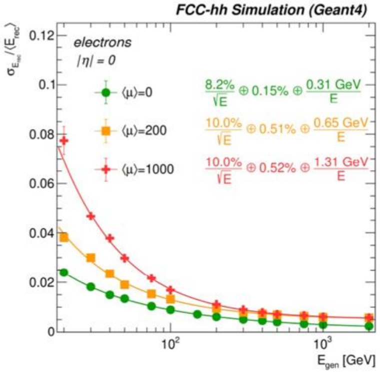
- High granularity
  - → Pile-up rejection
  - → Particle flow
  - → 3D/4D/5D imaging

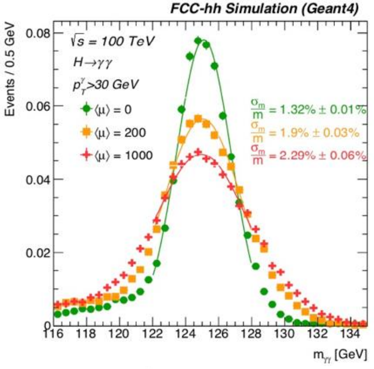
FCC-hh Calorimetry studies have been published at https://arxiv.org/abs/1912.09962

Electromagnetic Calorimeter (ECAL)

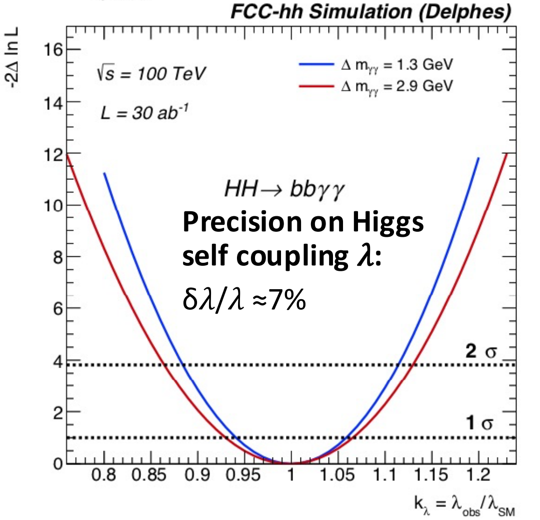


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **CDR Reference Detector: Performance & radiation considerations → LAr ECAL, Pb absorbers**
  - Options: LKr as active material, absorbers: W, Cu (for endcap HCAL and forward calorimeter)
- **Optimized for particle flow: larger longitudinal and transversal granularity** compared to ATLAS
  - 8-10 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$, first layer $\Delta\eta=0.0025$),
  - → ~2.5M read-out channels
- Possible only with **straight multilayer electrodes**
  - Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
  - Baseline: warm electronics sitting outside the cryostat (radiation, maintainability, upgradeability),
    - Radiation hard cold electronics could be an alternative option
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise (no in-time pile-up suppression)
  - →Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)



Precision on Higgs self coupling λ:

$\delta\lambda/\lambda \approx 7\%$

Hadronic Calorimeter (HCAL)

Barrel HCAL:

- **ATLAS type TileCal optimized for particle flow**
  - Scintillator tiles – steel,
  - Read-out via wavelength shifting fibres and SiPMs
- **Higher granularity** than ATLAS
  - $\Delta\eta$ x $\Delta\phi$ = 0.025 x 0.025
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

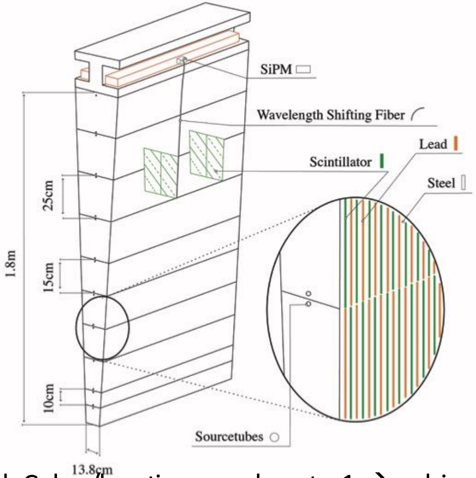
- Simple calibration: $44\%/\sqrt{\bar{E}}$ to $48\%/\sqrt{\bar{E}}$
- Calibration using neural network (calo only):
  - Sampling term of $37\%/\sqrt{\bar{E}}$

Jet resolution:

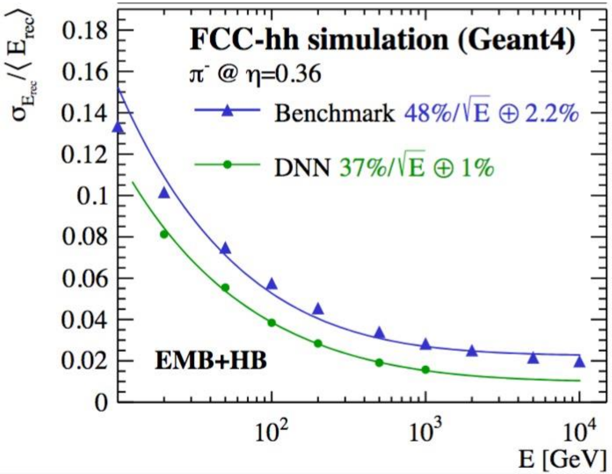
- Jet reconstruction impossible without the tracker @ 4T → particle flow.

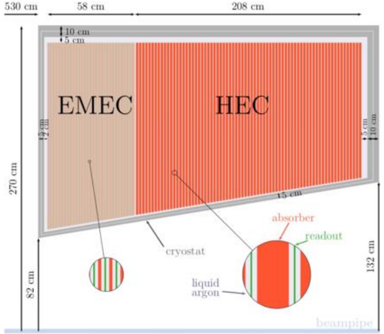
Endcap HCAL and forward calorimeter:

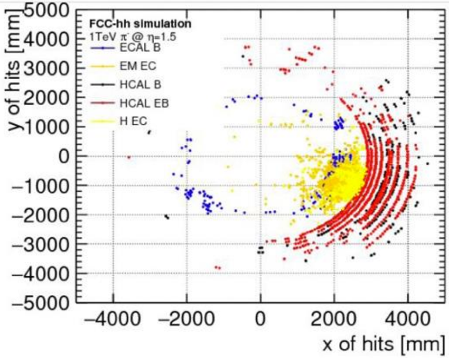
- Radiation hardness!
- LAr/Cu, LAr/W



TileCal: e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)







Challenges for Calorimetry – R&D Needs

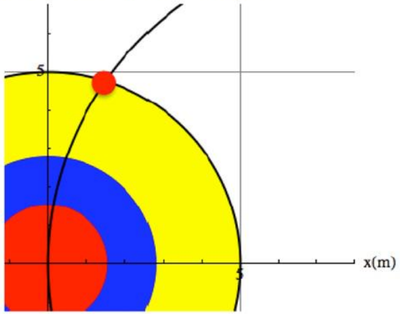
- **Radiation hardness:**
  - **Forward calo:** 5 10^{18} n_{eq}/cm^2, 5000MGy
    - Noble liquid calorimetry – intrinsic radiation hardness (of active material), other components (e.g. read-out electrodes!) need to be well chosen and tested. Electronics well shielded behind calorimeter outside the cryostat.
  - **Barrel and endcap ECAL:** 2.5 10^{16} n_{eq}/cm^2
    - Noble liquid calorimetry,
    - Si as active material maybe possible in the barrel ECAL → need to increase radiation tolerance by factor 3-5
    - Inorganic crystal scintillators: e.g. Cerium doped LYSO
    - SPACAL-type calorimeter with crystal fibres (e.g. YAG or GAGG) → need to increase radiation tolerance by factor 5
  - **Barrel HCAL:** 4 10^{14} n_{eq}/cm^2, <10kGy
    - Organic scintillator/steel possible in the barrel HCAL (R&D on radiation tolerance) → read-out by SiPMs or wavelenght shifting fibres + SiPMs
    - Many other existing technologies would also be applicable
- **Possible technologies – R&D needs**
  - **Noble liquid calorimetry:** Development of highly granular read-out electrodes and low-noise read-out, high-density signal feedthroughs, low-material cryostats (composite or Al-alloy honeycomb)
  - **Scintillator based calorimetry:** Radiation hardness of scintillators and SiPMs. R&D on radiation hard inorganic scintillators, crystal fibres (SPACAL type)
  - **Si-based calorimetry:** Radiation hardness, cost- and material reduction through monolithic designs with integrated sensor and readout
  - **For all technologies:** Timing resolution at the O(25ps) level or better would help to reduce pile-up

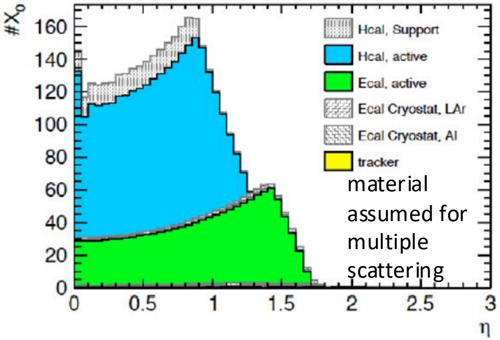
Challenges for Calorimetry – R&D Needs

- **High granularity** (lateral cell sizes of ≤2cm, like for the proposed reference detector LAr calorimeter)
  - **Particle flow (measure each particle where it can be best measured)**
  - **5D calorimetry (imaging calorimetry, including timing) → use of MVA based reconstruction (Neural Networks, …)**
  - **Pile-up rejection**
    - Efficient combined reconstruction together with the tracker
- **Timing for pile-up rejection, 5D calorimetry:**
  - O(25ps) to reduce pile-up by factor 5 (<μ> = 1000 → 200) → LGADs, 3D pixel sensors → R&D on pad sizes and rad. hardness
  - O(5ps) to reduce pile-up by factor 25 (<μ> = 1000 → 40) → ultra-fast inorganic scintillators, ultra-thin LGADs
- **Data rates – Triggering**
  - Noble-liquid calorimetry + scintillator/Fe HCAL: O(3M) channels 200 – 300TB/s
  - Si option: many more channels, zero suppression on-detector necessary
- **Crazy ideas for the future:** Possible "maximal information" calorimeter: divided into small detection volumes (voxels) that measure ionization, time, and Cherenkov and scintillation light simultaneously – e.g. noble liquid calorimetry

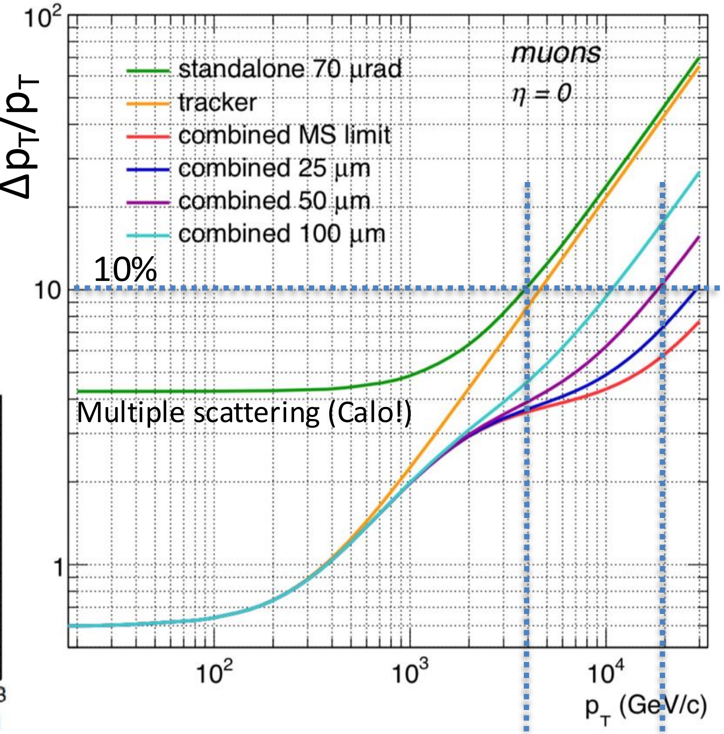
FCC-hh Muon System

p_t=3.9GeV enters muon system
p_t=5.5GeV leaves coil at 45 degrees





material assumed for multiple scattering



10%

Multiple scattering (Calo!)

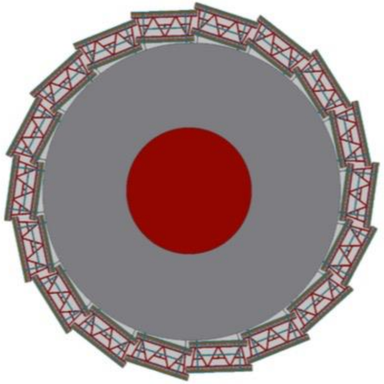
4TeV/c 20TeV/c

With 50µm position resolution and 70µrad angular resolution we find (η=0):

- ≤10% $\Delta p_T/p_T$ standalone up to 4TeV/c
- ≤10% $\Delta p_T/p_T$ combined up to 20TeV/c

Standalone muon performance not relevant, the task of muon system is **triggering and muon identification!**

Muon rate dominated by c and b decays → isolation is crucial for triggering W, Z, t!



Muon barrel: Rates of up to ~500Hz/cm^2 expected

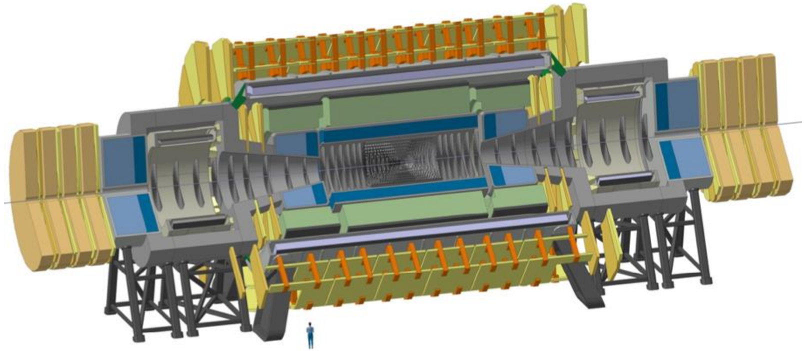
Muon detection in forward region:

Excpected rates up to 500kHz for r > 1m

→ **HL-LHC muon system gas detector technology will work for most of the FCC detector area**

Reading Out Such a Detector → Trigger/DAQ

- **Example ATLAS**:
  - ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
  - Muon system will also be read out at 40MHz to produce a L1 Trigger.
- **FCC-hh detector**:
  - calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
  - 40MHz readout of the tracker (using zero-suppression) would produce about 800TByte/s.



- **FCC-hh trigger strategy question:**
  - Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
    - Difficult: 400kHz of W's and 100MHz of jets (p_T > 50GeV)
  - Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

Challenges for Read-Out Electronics & Trigger

- **Huge amounts of data produced** (e.g. O(1000TByte/s ≈ 10Pbps) for zero-suppr. tracker)
  - **Streaming:**
    - Read-out everything → need fast low power radiation hard optical links
    - Alternative: summarize received data by higher-level quantities and only transmit and store those
  - **Triggered:** Read-out interesting events → challenge to achieve a data reduction of factor O(10) (HL-LHC aims for factor 40) with much higher pile-up
    - → need efficient triggering – intelligent decision as close to the sensor as possible (ML or AI on front-end, programmable ASICs, FPGAs?)
    - → radiation hard buffering/storage
- **→ High bandwidth, low power, radiation hard data links**
  - Industry at link speeds of 400Gbps, need to be adapted to radiation hardness, low power, low material and distributed data sources
  - Rad. hard link R&D targeting 25Gbps has started at CERN, but will need 50-100Gbps links to fulfil FCC-hh requirements
  - Low-power: 10Pbps = 1 million lpGBTs (~500mW) → 500kW for the links alone!
    - Cooling needs cause large amounts of dead material → minimize cooling needs
  - New technologies: CMOS with integrated photonics (Silicon Photonics)

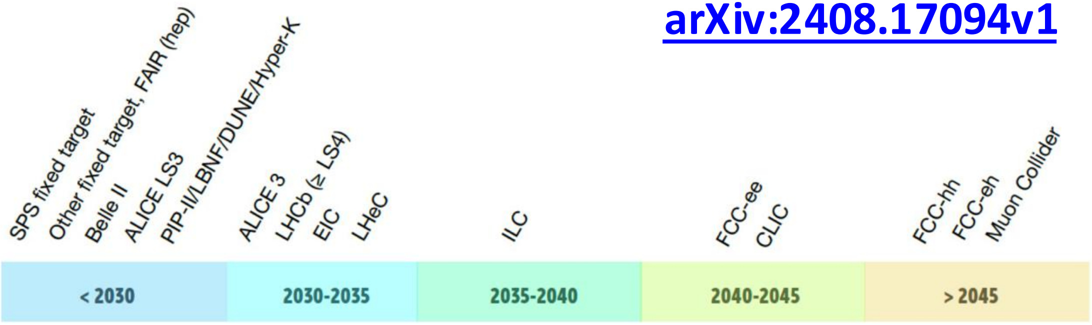
Challenges for Read-Out Electronics & Trigger

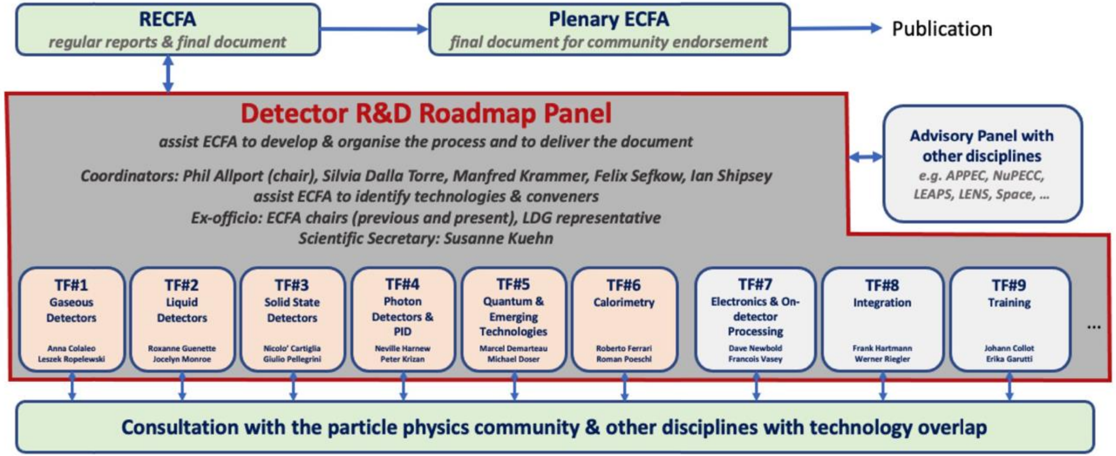
- **Wireless read-out systems:**
  - Potential to reduce material – interesting if wireless transmission can fulfil the low-power requirement
  - But main material contribution coming from power and cooling needs (and not from optical fibers)
- **Analogue to digital conversion** will be located at the front-end
  - Already the case for all HL-LHC upgrades, e.g. analogue calorimeter trigger Run1 and Run2 → digitization at the front-end for Run 3 and HL-LHC
  - Advantages: low noise, standardised and efficient digital transmission
  - But needs radiation hard and low-power ADCs and ASICs (300MGy, 10^{18}neutrons/cm^2)
    - For comparison: HL-LHC factor 30 less, 65nm ok up to O(3MGy)
- Develop **radiation hard power management blocks** (DC/DC converters, regulators)
- Develop **precision clock and timing circuits** (PLL, DLL, Timing Discriminators, Delay Lines, Picosecond TDCs)
  - Timing distribution with pico-second synchronization

DRD Collaborations

- European Strategy for Particle Physics (ESPP, link) encouraged the community to define a **Detector R&D Roadmap** identifying the most important technological developments in the domain of particle detectors required to reach the goals defined in the ESPP
- In autumn 2022, CERN SPC endorsed the **Detector Roadmap Implementation Plan** which foresees the formation of **Detector R&D Collaborations hosted at CERN**
- **DRD Collaborations** have been set-up and started working (approvals in Dec. 2023 and June 2024)

arXiv:2408.17094v1




RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, …

TF#1 Gaseous Detectors — Anna Colaleo, Leszek Ropelewski
TF#2 Liquid Detectors — Roxanne Guenette, Jocelyn Monroe
TF#3 Solid State Detectors — Nicolo' Cartiglia, Giulio Pellegrini
TF#4 Photon Detectors & PID — Neville Harnew, Peter Krizan
TF#5 Quantum & Emerging Technologies — Marcel Demarteau, Michael Doser
TF#6 Calorimetry — Roberto Ferrari, Roman Poeschl
TF#7 Electronics & On-detector Processing — Dave Newbold, Francois Vasey
TF#8 Integration — Frank Hartmann, Werner Riegler
TF#9 Training — Johann Collot, Erika Garutti
…

Consultation with the particle physics community & other disciplines with technology overlap

Conclusions

- **Detector Requirements for Future High-Energy Hadron Colliders extremely challenging!**
- **These detector requirements do not change a lot when considering 80 TeV c.m. energy.**
  - Lower statistics in some channels at 80 TeV could be compensated by better detector performance
  - Lower luminosity would alleviate the radiation hardness requirements
- An **FCC-hh Reference Detector** has been introduced that could fulfill physics requirements, but intense detector R&D necessary to achieve very ambituous design goals
- **Main challenges:**
  - Radiation hardness
  - Precision timing
  - Huge data rates, low-power read-out electronics and links
  - Low material for support structures, power and cooling
- **Expecting to profit from R&D for HL-LHC**
  - **Phase II Upgrades and future pixel inner layer replacements for ATLAS & CMS, future LHCb and ALICE upgrades**
- **Also some overlapping requirements with lepton collider experiments**
  - **Exceptions:** radiation hardness, which is only an issue for hadron collider experiments, but also more extreme requirements in many other areas, e.g. for timing detectors and data links
  - → **Need to continue strategic R&D in these areas!**
- **Detector R&D collaborations have been set-up to address these challenges (see e.g. arXiv:2408.17094v1)!**
- **Join in and contribute!**

Thank You for Your Attention!

Back-Up

From ESPPU 2020 Document

Under "3. High-priority future initiatives":

"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

Under "4. Other essential scientific activities for particle physics":

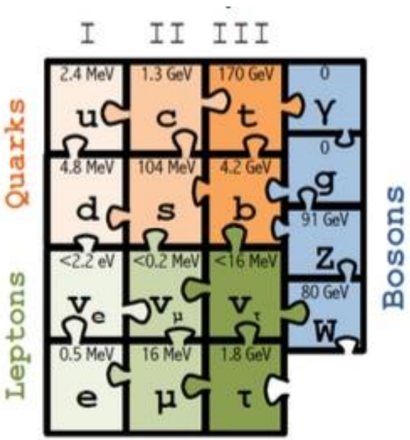
"Detector R&D programmes and associated infrastructures should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should define a global detector R&D roadmap that should be used to support proposals at the European and national levels."

https://europeanstrategyupdate.web.cern.ch/resources

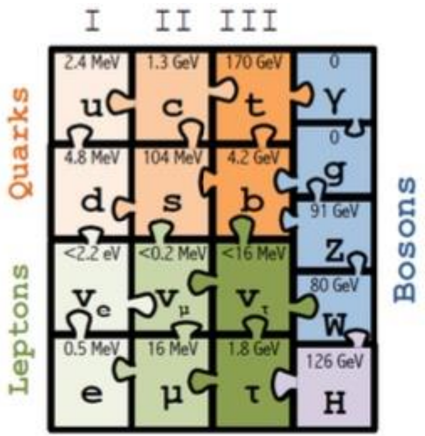
Why Future Colliders?

The Physics Landscape

1989–1999:
Top mass predicted
(LEP mZ and ΓZ)
Top quark observed
at the right mass
(Tevatron, 1995)
Nobel Prize 1999
(t'Hooft & Veltman)



1997–2013:
Higgs mass cornered
(LEP EW + Tevatron mtop , mW)
Higgs boson observed
at the right mass
(LHC 2012)
Nobel Prize 2013
(Englert & Higgs)

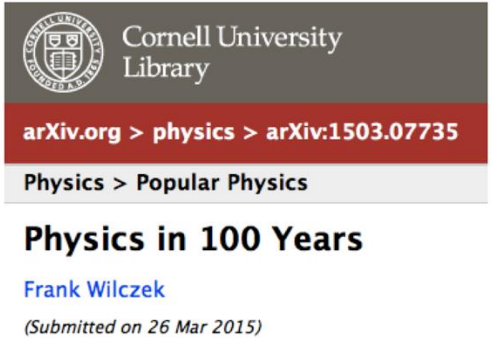


It looks like the **Standard Model** (SM) is a **complete and consistent theory**

- It describes **all observed collider phenomena** – and actually **all particle physics** (except neutrino masses)
- Was beautifully **verified** in a complementary manner at LEP, SLC, Tevatron, and LHC
- **EWPO radiative corrections** predicted **top** and **Higgs** masses assuming **SM and nothing else**

A Unique Moment in the History of Physics

- The **Higgs** discovery is the triumph of 20th century physics – combination of **Quantum Mechanics and Special Relativiy**
- For the first time in the history of physics we have a **consistent** description of the **fundamental constitutents of matter** and their **interactions** and this description can be **extrapolated to very high energies** (up to M_{Planck}?)



Cornell University Library

arXiv.org > physics > arXiv:1503.07735

Physics > Popular Physics

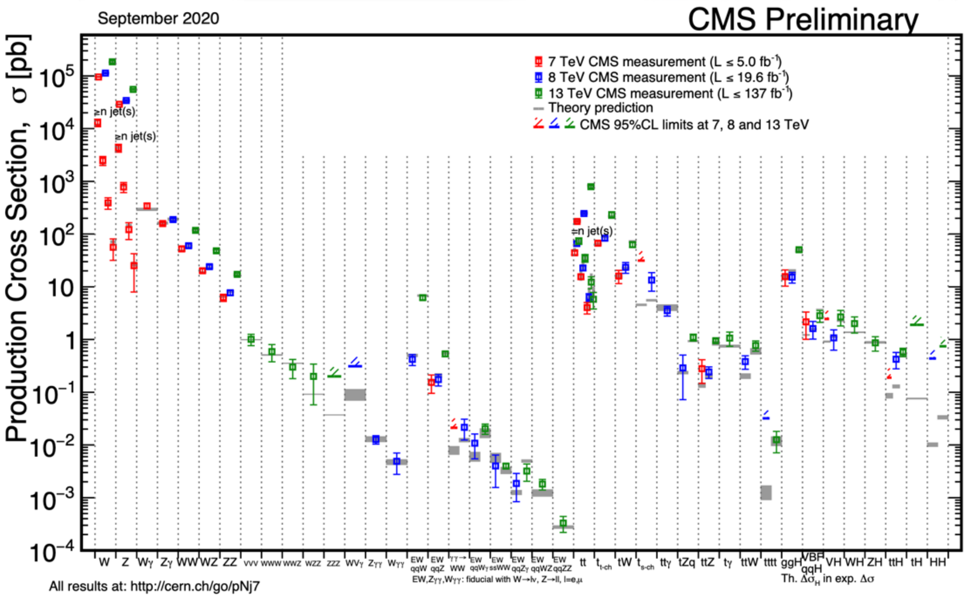
Physics in 100 Years

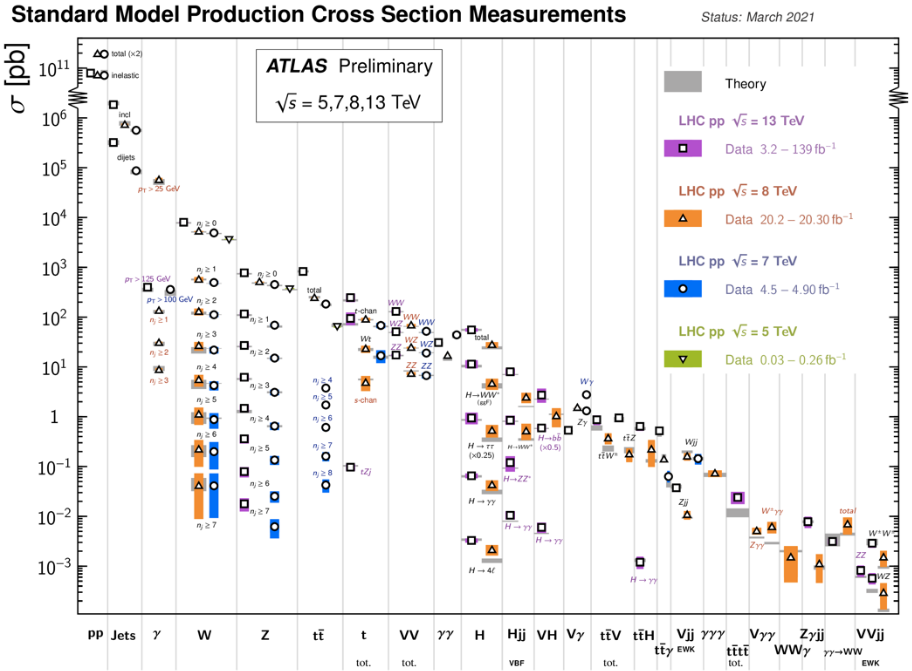
Frank Wilczek

(Submitted on 26 Mar 2015)

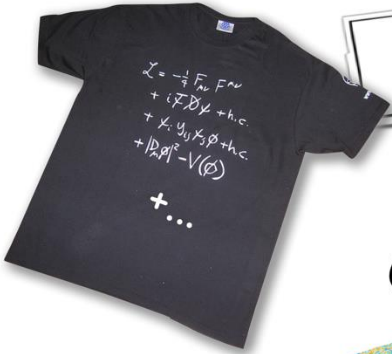
The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

The SM and … the LHC Data so Far





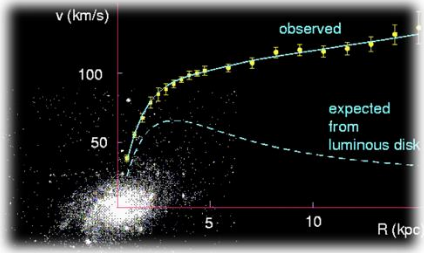
The SM and … the Rest of the Universe

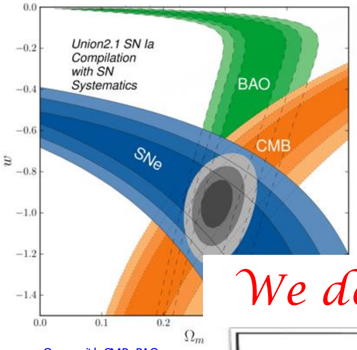


is not enough

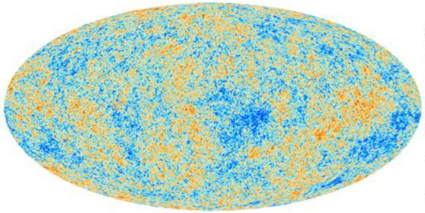
- Neutrino masses
- Dark Matter
- Dark Energy
- Quantum gravity

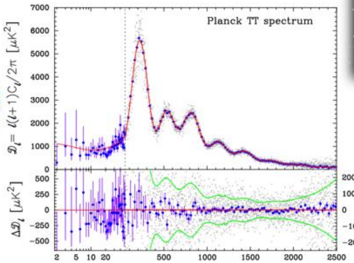
The observed rotation curve of the dwarf spiral galaxy M33 extends considerably beyond its optical image





Ω_m-w with CMB, BAO, and SCP Union2.1 SN Constraints, including SN systematics

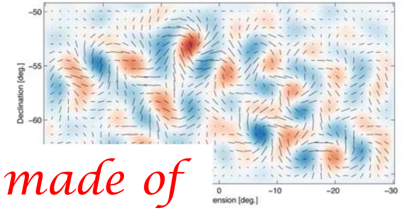




Angular power spectrum of CMB anisotropies measured from the latest Planck satellite data (© ESA and the Planck Collaboration). The wiggles seen in the spectrum are the feature of BAO, and the oscillation scale corresponds to the sound horizon at recombination. The best-fitting ΛCDM theoretical spectrum is plotted as the solid line in the upper panel.

COSMIC SWIRL Gravitational waves generated during a period of cosmic inflation twirl light from the cosmic microwave background, as seen in this sky map from the BICEP2 telescope. The lines trace the alignment, or polarization, of photons released after the Big Bang; the line lengths show the light's intensity. The colors indicate how strongly twisted the polarization is, both clockwise (red) and counterclockwise (blue).

BICEP2 COLLABORATION

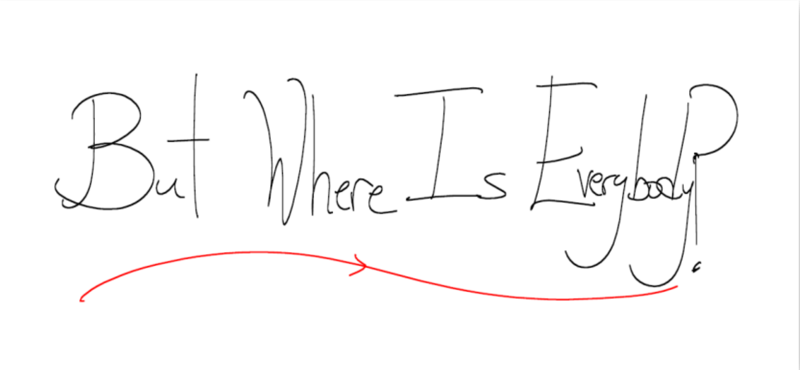


We do not understand the Matter the Universe is made of

Where and how does the SM break down?
Which machine(s) will reveal (best) this breakdown?

LHC Sees No New Physics at the TeV Scale – Why?

- **Is the mass scale beyond the LHC reach?**
- **Is the mass scale within the LHC's reach but final states are elusive to the direct search?**
- A priori these scenarios are **equally likely**, but they impact in a different way the future of HEP and the assessment of the physics potential for possible future facilities.
- **To address both scenarios we need:**
  - Searches for the imprint of New Physics at lower energies, e.g. on the properties of Z, W, top, and Higgs particles
    - → precision
  - Direct searches for new heavy particles
    - → extended energy and mass reach
  - Sensitivity to elusive signatures



But Where Is Everybody?

Nima Arkani-Hamed (FCC-Week 2019)

→ Precision frontier

→ Energy frontier

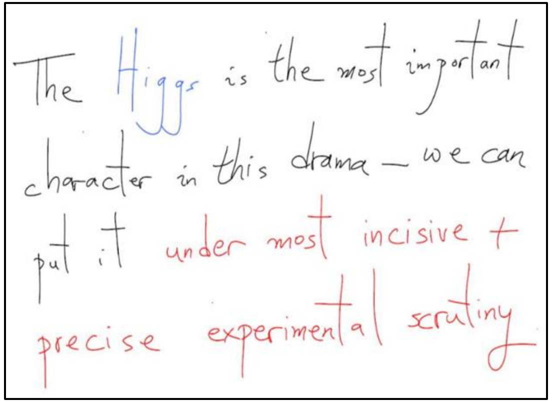
→ Luminosity & Detectors

What are our Handles – Why Future Colliders?

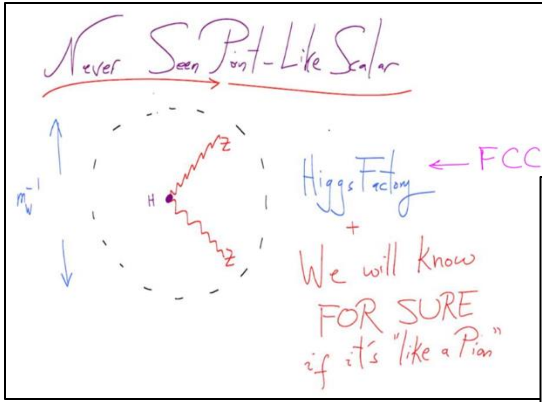
→ **High energy physics has two priorities:**

- **Explore the origin of known departures from the SM**:
  - Dark matter, neutrino masses, baryon asymmetry of the Universe
- **Explore the physics of electroweak symmetry breaking**:
  - Experimentally, via the measurement of Higgs properties, Higgs interactions and self-interactions, coupling of gauge bosons, flavour phenomena, etc.
  - Theoretically, to understand the nature of the hierarchy problem and identify possible solutions that can be tested experimentally

A Concrete Target – The Higgs Boson



The Higgs is the most important character in this drama – we can put it under most incisive + precise experimental scrutiny

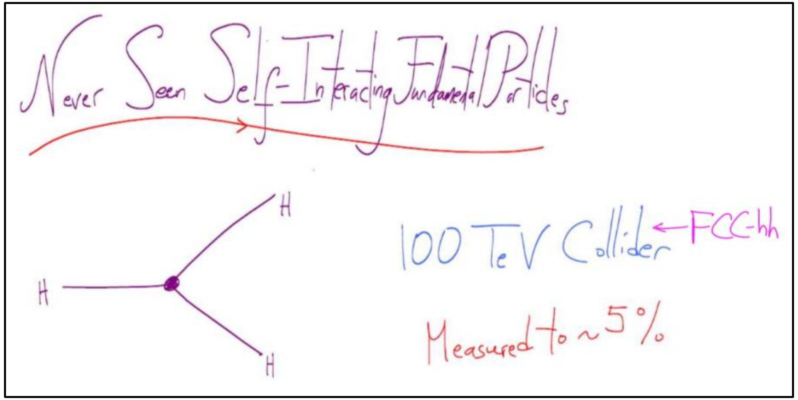


Never Seen Point-Like Scalar

Higgs Factory ← FCC-ee

+

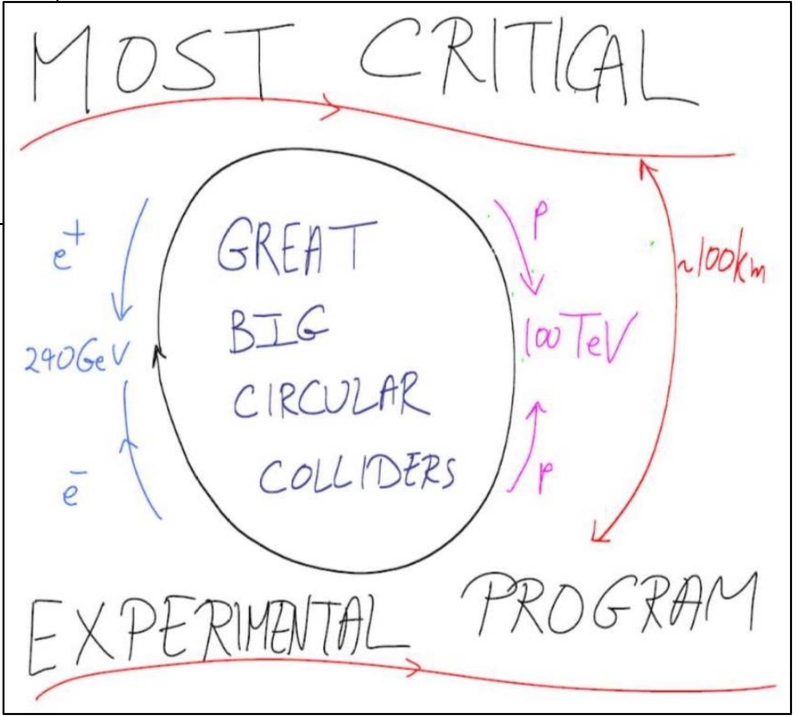
We will know FOR SURE if it's "like a Pion"



Never Seen Self-Interacting Fundamental Particles

100 TeV Collider ← FCC-hh

Measured to ~5%

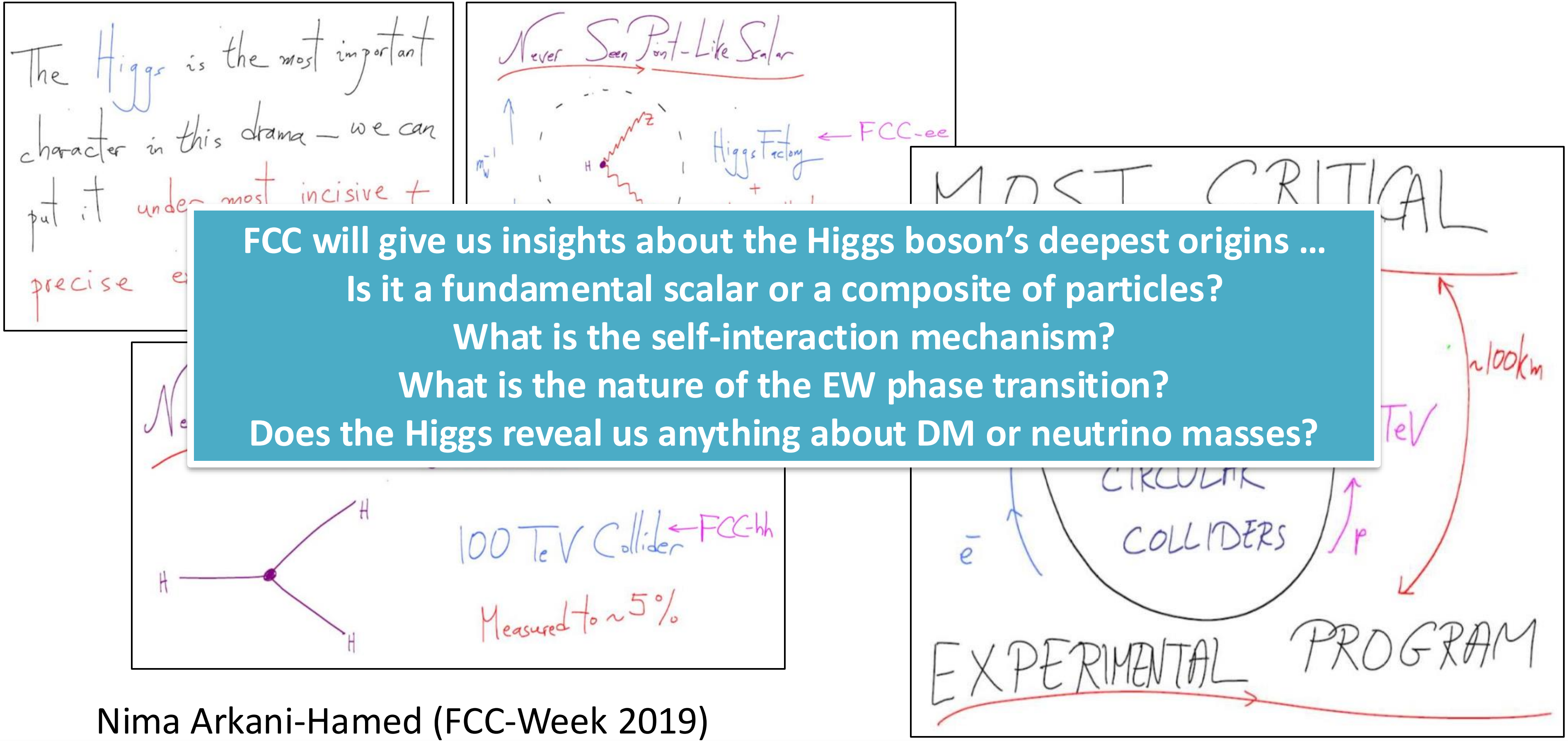


MOST CRITICAL EXPERIMENTAL PROGRAM

GREAT BIG CIRCULAR COLLIDERS

Nima Arkani-Hamed (FCC-Week 2019)

A Concrete Target – The Higgs Boson



The Higgs is the most important character in this drama – we can put it under most incisive + precise e

FCC will give us insights about the Higgs boson's deepest origins …
Is it a fundamental scalar or a composite of particles?
What is the self-interaction mechanism?
What is the nature of the EW phase transition?
Does the Higgs reveal us anything about DM or neutrino masses?

Nima Arkani-Hamed (FCC-Week 2019)

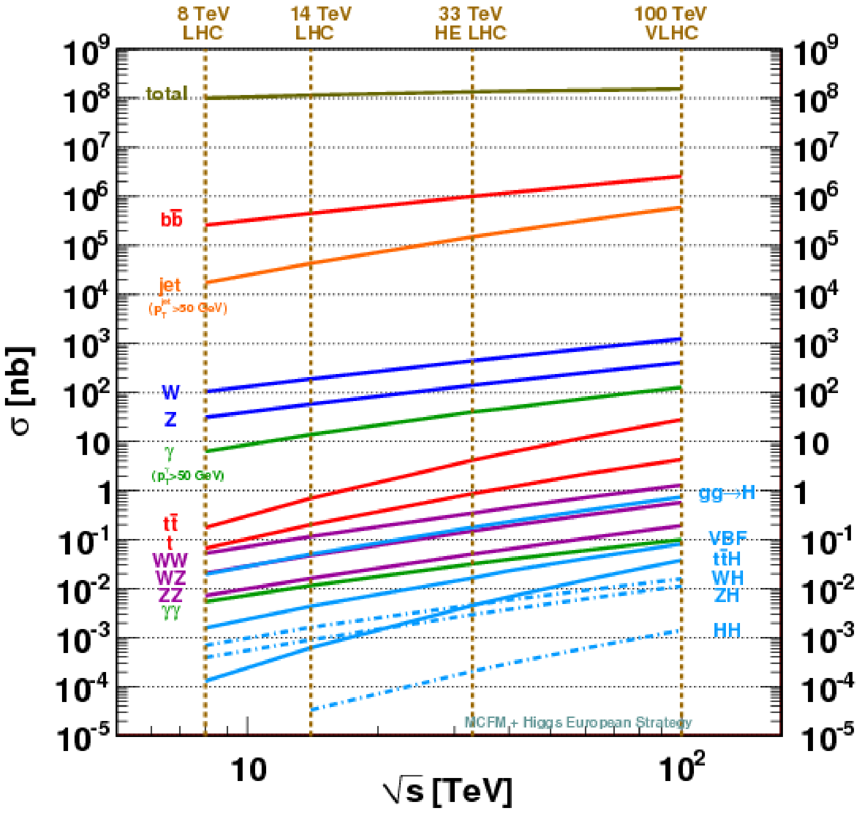
Historic Overview of Important Discoveries

Year	Discovery	Experiment	$\sqrt{s}$ [GeV]	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SPEAR/SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \to \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (PETRA/DESY)	30	$e^+e^- \to qqg$ Three-jet events
1983	**W, Z** (m ~ 80, 91 GeV)	pp ring (SPS/CERN)	900	$W \to \ell\nu$ $Z \to \ell^+\ell^-$
1989	**Three neutrino generations**	e^+e^- ring (LEP/CERN)	91	Z-boson lineshape *measurement*
1995	**t quark** (m=173 GeV)	pp ring (Tevatron/FNAL)	1960	Two semileptonic t-quark decays
2012	**Higgs boson** (m=125 GeV)	pp ring (LHC/CERN)	8000	$H \to \gamma\gamma$, $H \to Z^*Z \to 4\ell$

What do we see?

- Centre of mass energy increases
- Moving from fixed target to colliders
- Different types of particles colliding
- Alternance of e^+e^- and pp machines

Cross-Sections for Key Processes



- **Total cross-section and Minimum Bias Multiplicity** show only a **modest increase** from LHC to FCC-hh.
- The **cross-section for interesting processes** shows however **significant increase (**e.g. HH x 50!**)**!
- Higher luminosity to increase statistics → pileup of 140 at HL-LHC to **pileup of 1000** at FCC-hh → **challenge for triggering and reconstruction**

HEP Landscape

- Particle accelerators are built to answer some of the **most fundamental questions** about the natural world
- **Physics priorities** are likely to **shift swiftly**, as we advance in our exploration, both experimentally and theoretically
- There are **many unknowns ahead** of us that may reshuffle the cards (e.g. any discoveries of HL-LHC)
- → We need a **broad and bold program** capable of adapting to the swift changes in the physics landscape that are likely to happen
- → **100TeV hadron collider** – In times of uncertainty, bold exploration is the way to go

G.F.Giudice, ICFA, Nov. 2017

→ Complementarity and synergy with high-luminosity lepton colliders such as FCC-ee

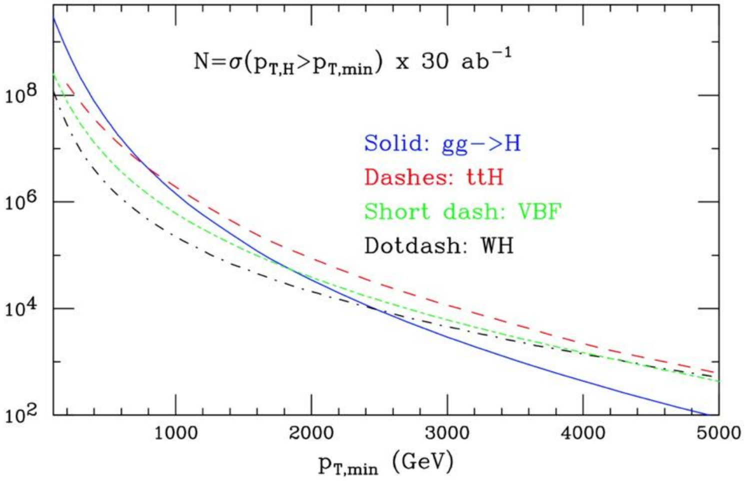
FCC-hh: Criteria for Physics Potential of Future Colliders

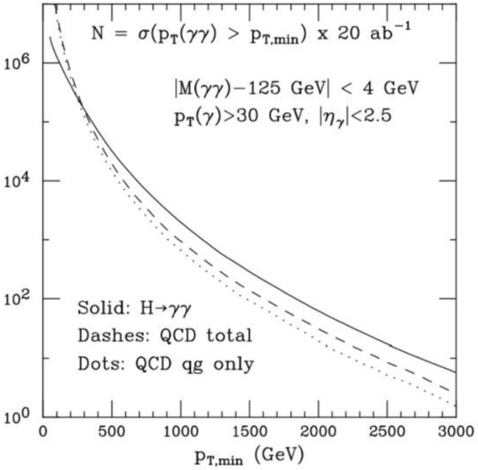
- **Guaranteed Deliverables:**
  - Study of Higgs and top quark properties, and exploration of EWSB phenomena, with unmatchable precision and sensitivity
    - Sensitivity to the shape of the Higgs potential (Higgs self coupling, mainly FCC-hh)
  - Ultimate precision standalone and in combination with FCC-ee and FCC-eh
- **Exploration Potential:**
  - Mass reach enhanced by factor ~ E / 14 TeV
    - will be 5–7 at 100 TeV, depending on integrated luminosity
  - Sensitivity to rare processes enhanced by orders of magnitude
  - Benefit from indirect precision probes at low and high Q^2
- **Provide YES/NO Answers:**

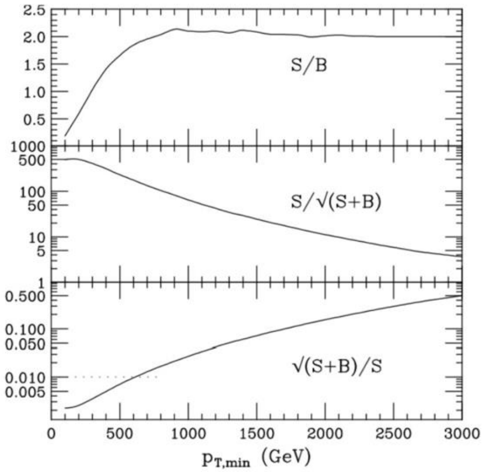
  ...to questions like…
  - Is the SM dynamics all there is at the TeV scale?
  - Is there a TeV-scale solution to the hierarchy problem?
  - Is DM a thermal WIMP?
  - Was the cosmological EW phase transition 1st order?
  - Could baryogenesis take place during the EW phase transition?

M. Mangano, Sept. 2018

Higgs at Large p_T





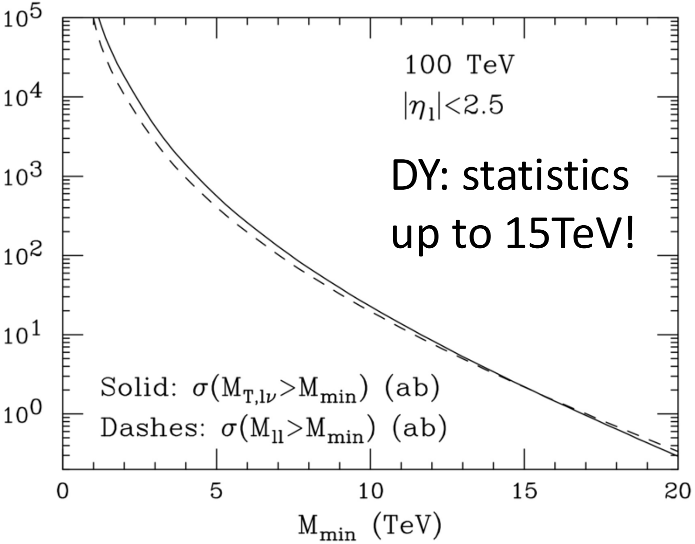


- Hierarchy of production channels changes at large $p_T(H)$:
  - σ(ttH) > σ(gg→H) above 800 GeV
  - σ(VBF) > σ(gg→H) above 1800 GeV

- At LHC, S/B in the H→γγ channel is O(few %) ≈1/30
- At FCC, for $p_T(H)$>300 GeV, S/B≈1
- Potentially accurate probe of the H p_T spectrum up to large p_T

$p_{T,min}$ (GeV)	δ_{stat}
100	**0.2%**
400	**0.5%**
600	**1%**
1600	10%

Indirect Sensitivity to High-Energy Scales



DY: statistics up to 15TeV!

- Improve constraints on oblique parameters W and Y by two orders of magnitude!
- → **Sensitivity up to the 100TeV range!**

$$\hat{W} = -\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \quad , \quad \hat{Y} = -\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$$

		LEP	ATLAS 8	CMS 8	LHC 13		FCC-hh	FCC-ee
	luminosity	$2 \times 10^7\ Z$	$19.7\ \mathrm{fb}^{-1}$	$20.3\ \mathrm{fb}^{-1}$	$0.3\ \mathrm{ab}^{-1}$	$3\ \mathrm{ab}^{-1}$	$10\ \mathrm{ab}^{-1}$	$10^{12}\ Z$
NC	W $\times 10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	±1.5	±0.8	±0.04	±1.2
	Y $\times 10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	±2.3	±1.2	±0.06	±1.5
CC	W $\times 10^4$	—	±3.9		±0.7	±0.45	±0.02	—

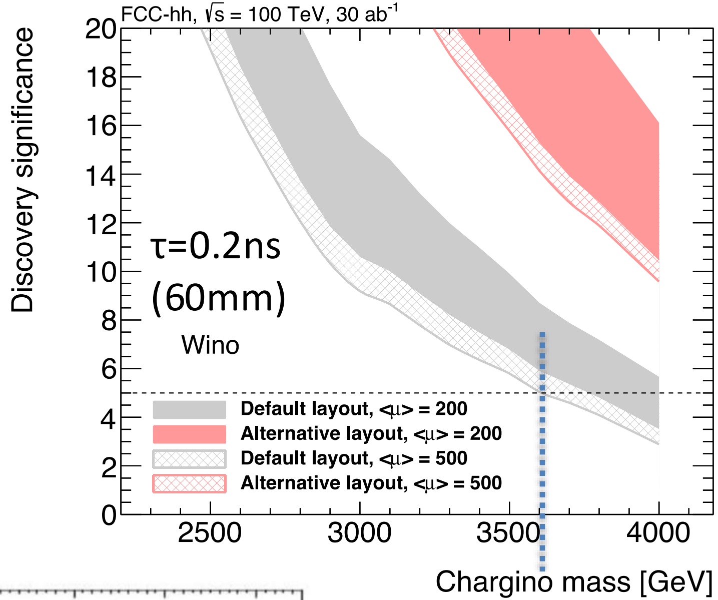
$g_*^2/\Lambda^2 = W/(4m_W^2) < 1/(100\ \mathrm{TeV})^2$ → **Λ > 100 TeV**

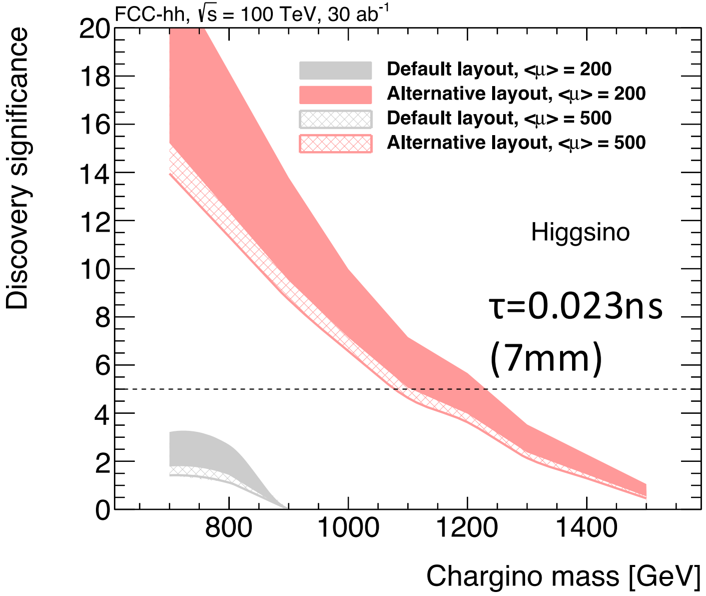
Yes/No Answers: WIMP DM

Disappearing tracks:

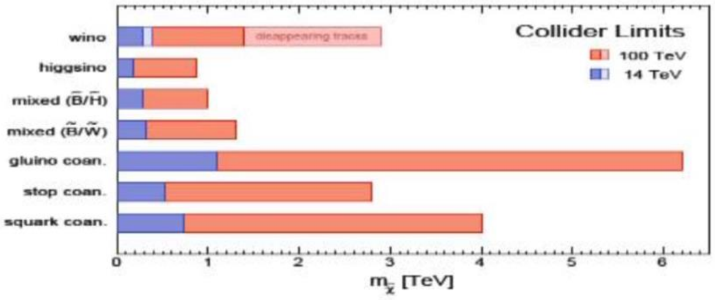
$$\chi^{\pm} \rightarrow \pi^{\pm}\chi^{0}$$

$\chi^{\pm}$ and χ^{0} degenerate
→ only 160MeV mass splitting (3 TeV Wino)
→ 0.2ns lifetime (60mm)





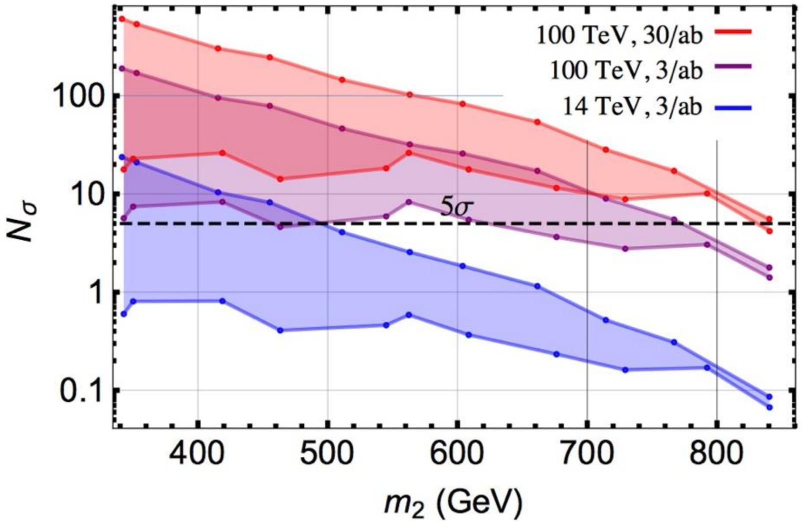
https://cds.cern.ch/record/2642474



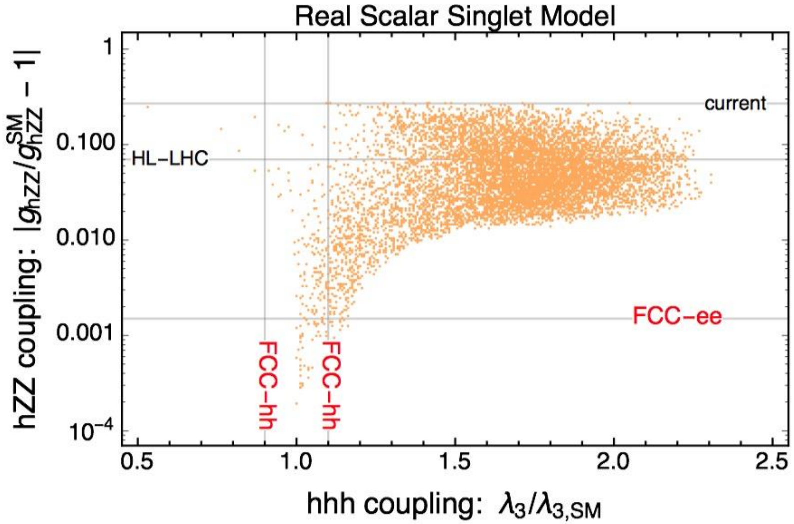
- If **DM is a WIMP**, then upper limit on M_{DM} of 110TeV (unitarity bound)
- Observed **relic abundance** of **DM → 1TeV (Higgsino-like), 3TeV (Wino-like)**
  - Disappearing tracks analysis shows discovery potential beyond upper limits of M_{DM}
- In a similar way FCC-hh can **explore conclusively EW charged WIMP models**

Yes/No Answers: 1st Order EW Phase Transition

arXiv:1605.06123

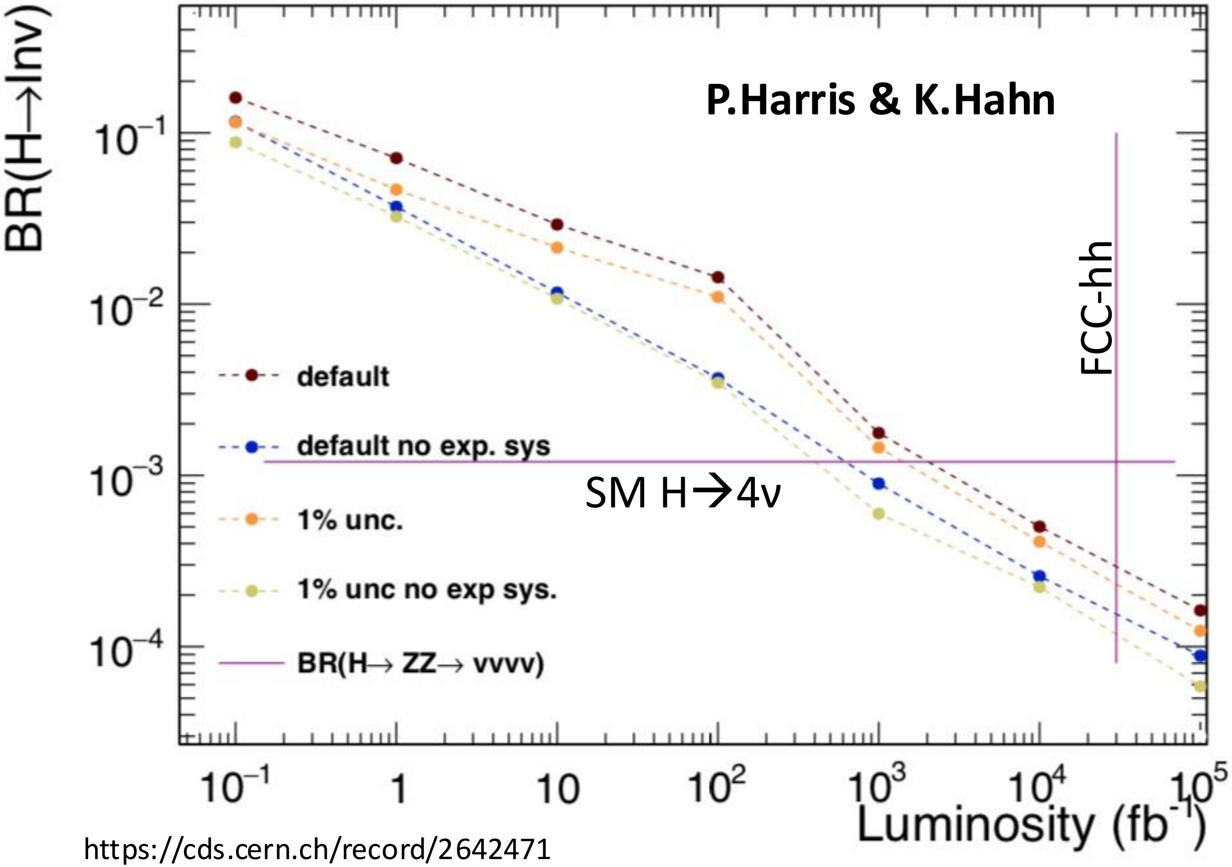


arXiv:1608.06619



- **Strong 1st order EWPT** required to induce **matter-antimatter asymmetry** at EW scale.
- **Example:** BSM scenarios with additional Higgs singlet m_2 decaying into SM Higgs pairs
- → **FCC-hh would enable direct discovery** over full possible mass range of m_2 (≤ 900GeV)
- → **Indirect: 7% precision on triple-Higgs coupling** will reduce number of possible BSM models → important redundancy

Example: BR (H→inv) in H+X Prod. at Large p_T(H)



https://cds.cern.ch/record/2642471

Leading background from W/Z+jets

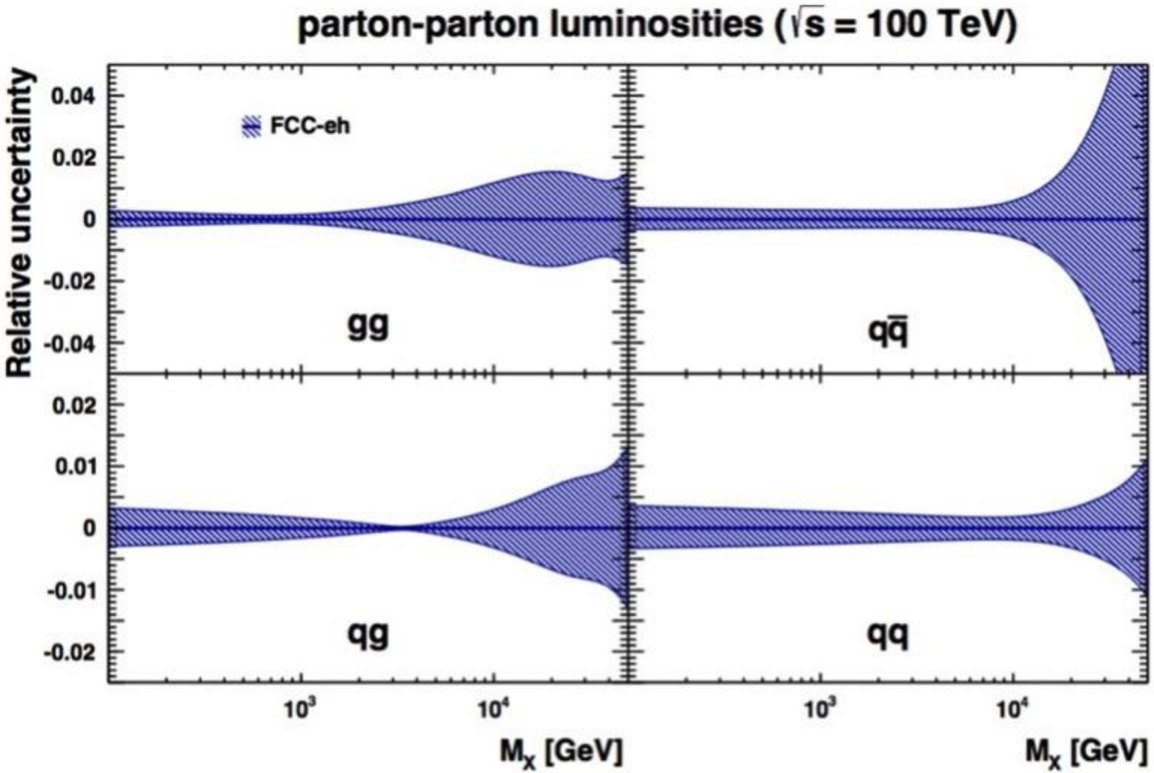
Constrain background p_T spectrum from Z→νν to the % level using NNLO QCD/EW to relate to measured Z→ee, W and γ spectra

Sensitivity of $2x10^{-4}$!

→ Implications on dark matter searches!

Ground Work for Precision at 100 TeV

PDF determination at FCC-eh



Uniqueness of FCC-hh Higgs Physics Potential

- **Huge Higgs Production Rates:**
  - Access (very) rare decay modes
  - Push to %-level Higgs self-coupling measurement
  - New opportunities to reduce systematic uncertainties (TH & EXP) and push precision
- **Large Dynamic Range for H Production (in p_T^H, m(H+X) , …):**
  - New opportunities for reduction of systematic uncertainties (TH and EXP)
  - Different hierarchy of production processes
  - Develop indirect sensitivity to BSM effects at large Q^2, complementary to that emerging from precision studies (e.g. decay BRs) at $Q \sim m_H$
- **High Energy Reach:**
  - Direct probes of BSM extensions of Higgs sector
    - SUSY Higgses
    - Higgs decays of heavy resonances
    - Higgs probes of the nature of EW phase transition (strong 1st order? crossover?)
    - …

FCC-hh: Beam and Luminosity Evolution

During the beams are in collision the instantaneous value of the luminosity will change:

$$\mathcal{L}(t) = A \frac{N_b^2(t)}{\sqrt{\epsilon_x(t)\epsilon_y(t)}}$$

The beam evolution with time is obtained by solving a system of four differential equations (dominant effects only shown here, more included in simulations):

$$\frac{\mathrm{d}N_b}{\mathrm{d}t} = -\sigma_{c,\mathrm{tot}} A \frac{N_b^2}{\sqrt{\epsilon_x \epsilon_y}}$$

Intensity

$$\frac{\mathrm{d}\epsilon_x}{\mathrm{d}t} = \epsilon_x(\alpha_{\mathrm{IBS},x} - \alpha_{\mathrm{rad},x})$$

Hor. Emittance

$$\frac{\mathrm{d}\epsilon_y}{\mathrm{d}t} = \epsilon_y(\alpha_{\mathrm{IBS},y} - \alpha_{\mathrm{rad},y})$$

Ver. Emittance

$$\frac{\mathrm{d}\sigma_s}{\mathrm{d}t} = \frac{1}{2}\sigma_s(\alpha_{\mathrm{IBS},s} - \alpha_{\mathrm{rad},s})$$

Bunch Length

with

$$A = f_{\mathrm{rev}} k_b / (4\pi\beta^*)$$

f_{rev} : revolution freq.
k_b : no. bunches/beam
β^* : β-function at IP
N_b : no. particles/bunch
ϵ : geom. emittances
σ_s : bunch length

$\sigma_{c,\mathrm{tot}}$: total cross-section
α_{IBS} : IBS growth rate
α_{rad} : rad. damping rate

J. Jowett, M. Schaumann,
FCC Week Washington 2015

Effects on the Emittance – A New Regime

Intra-Beam Scattering (IBS)

Multiple small-angle Coulomb scattering within a charged particle beam.

Emittance Growth

Growth rate dynamically changing with **beam properties**:

$$\alpha_{IBS} \propto \frac{r_0^2}{\gamma^4} \boxed{\frac{N_b}{\epsilon_x \epsilon_y \sigma_s \sigma_p}}$$

IBS is weak for initial beam parameters, but increases with decreasing emittance .

(Synchrotron) Radiation Damping

A charged particle radiates energy, when it is accelerated, i.e. bend on its circular orbit.

Emittance Shrinkage

Damping rate is **constant** for a given energy:

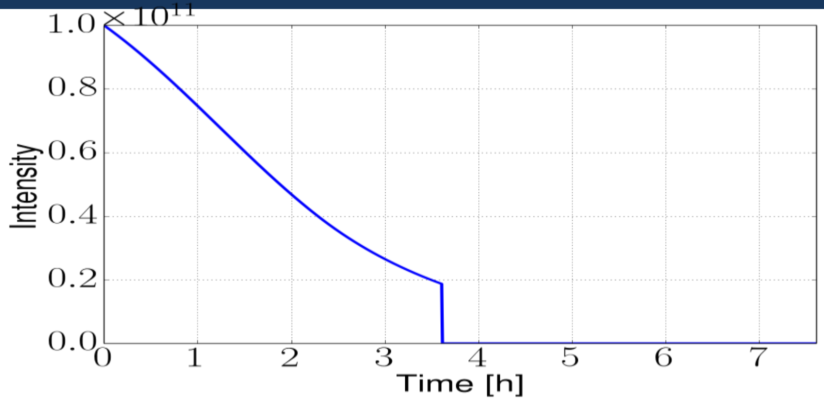
$$\alpha_{rad} \propto \frac{E^3 C_\alpha}{\rho_0 C_{ring}}$$

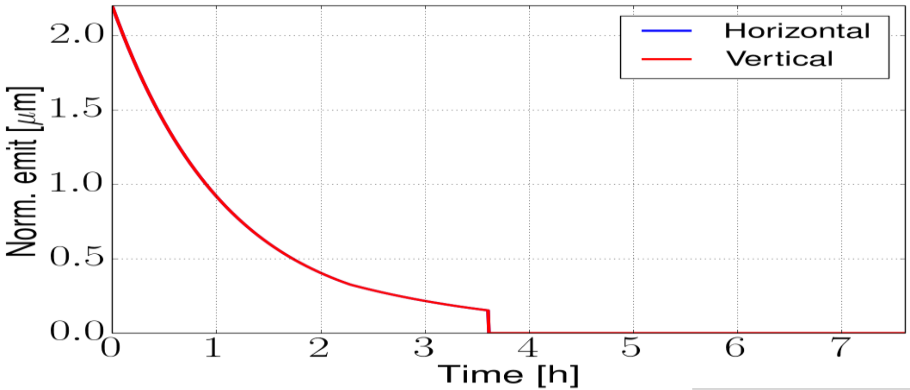
$$\frac{\alpha_{\mathrm{rad,FCC}}}{\alpha_{\mathrm{rad,LHC}}} \approx \frac{E^3_{\mathrm{FCC}}/C^2_{\mathrm{FCC}}}{E^3_{\mathrm{LHC}}/C^2_{\mathrm{LHC}}} \approx \frac{7^3}{4^2} \approx 22$$

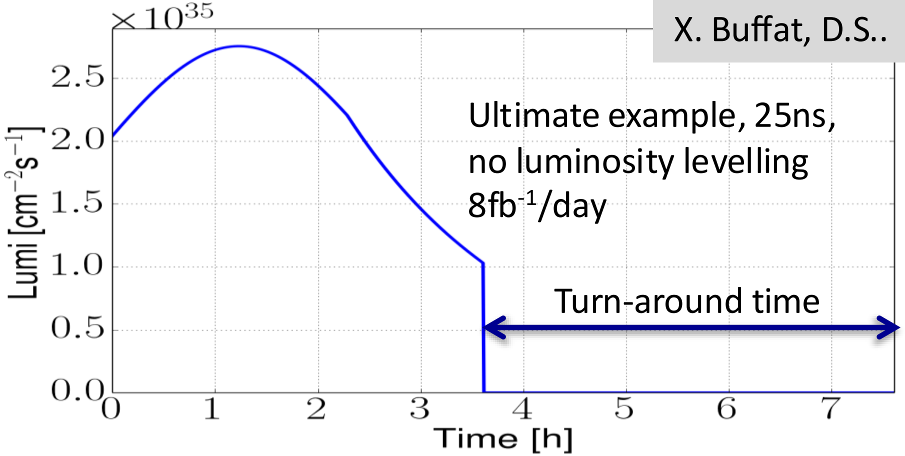
Fast emittance decrease at the beginning of the fill,
until IBS becomes strong enough to counteract the radiation damping.

J. Jowett, M. Schaumann,
FCC Week Washington 2015

Beam and Luminosity Evolution







X. Buffat, D.S..

Ultimate example, 25ns, no luminosity levelling 8fb^{-1}/day

D. Schulte, FCC Week Berlin 2017

Developed model including most relevant effects

- Improvement with more detail planned

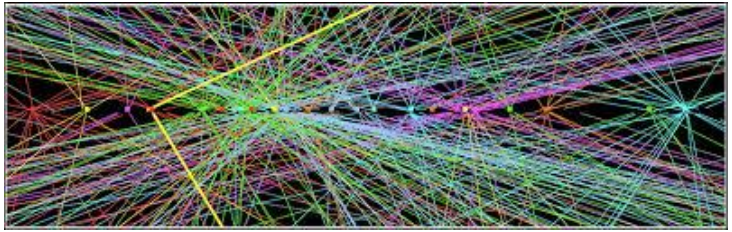
⇒ Reach 8fb^{-1}/day with ultimate for 25ns spacing

⇒ 5ab^{-1} per 5 year run

⇒ Beam is burned quickly

⇒ A reason to have enough charge stored

Pile-Up, Number of pp Collisions per BunchCrossing

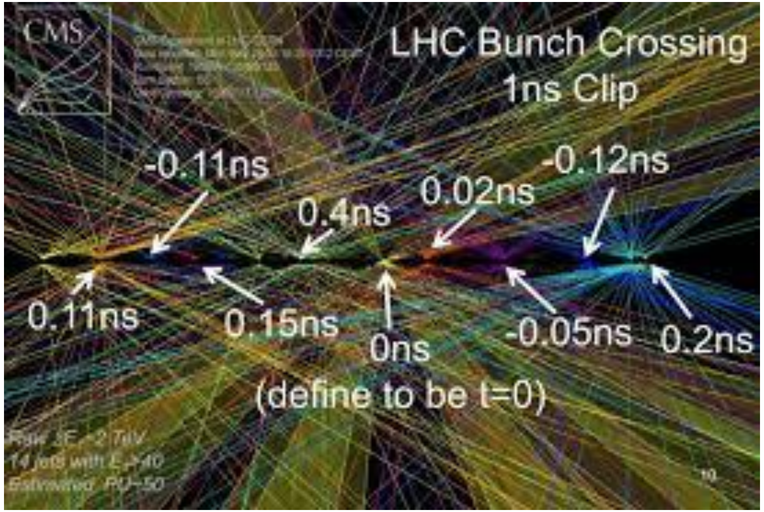


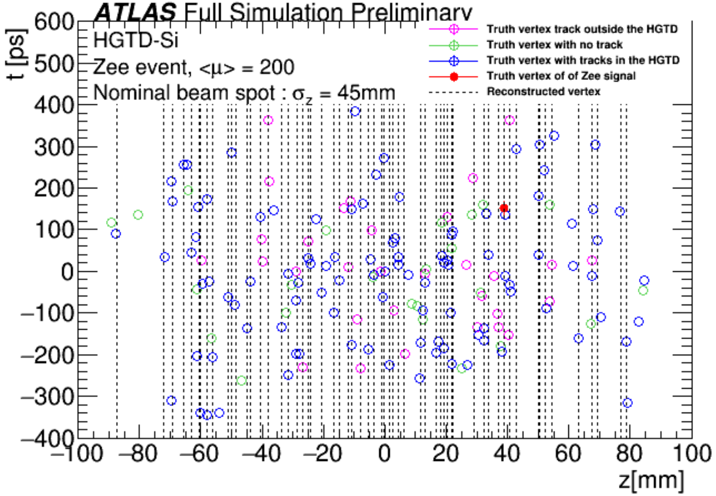
LHC ($2\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$)**: <μ> = 60**

HL-LHC: <μ> = 140

FCC-hh: <μ> = 1000

Small time differences between the individual collisions in one BC allow identification with detectors having order 10-20ps time resolution.

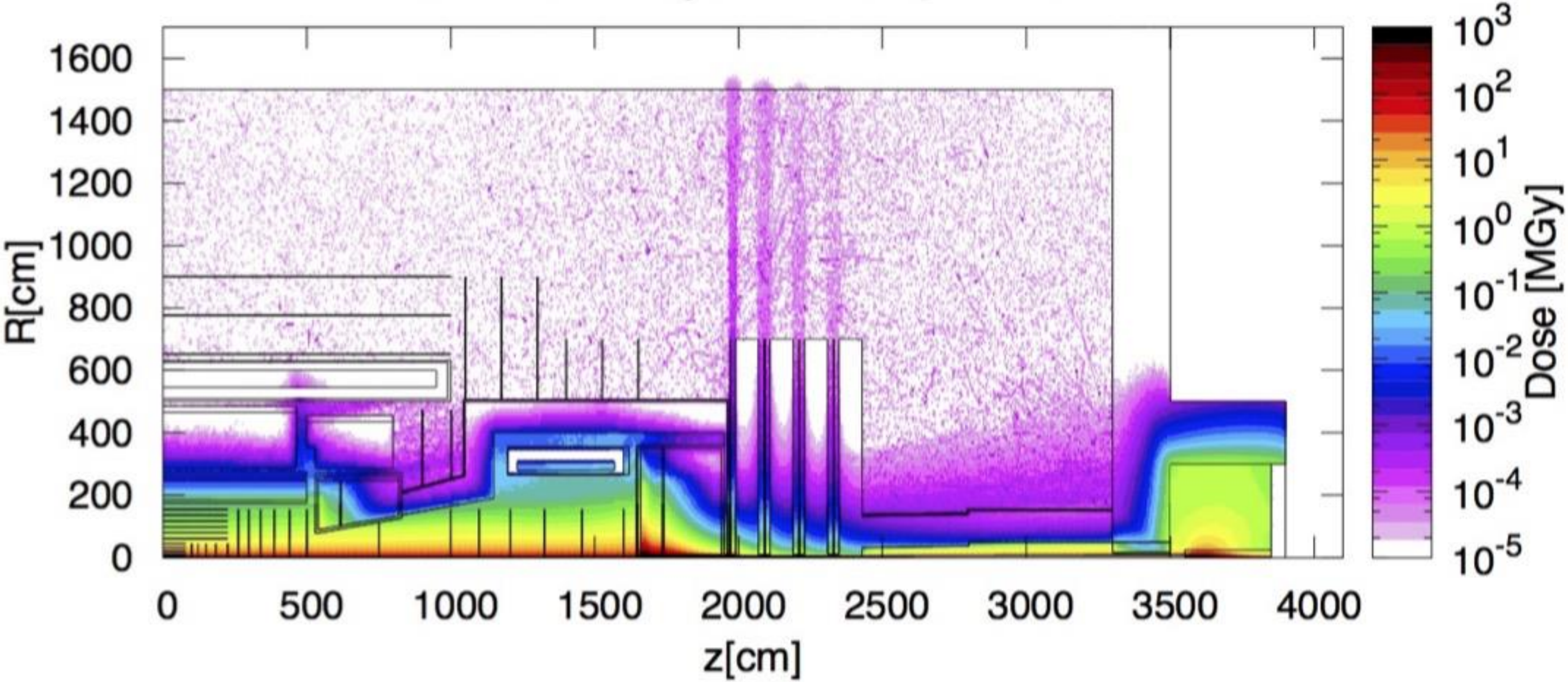




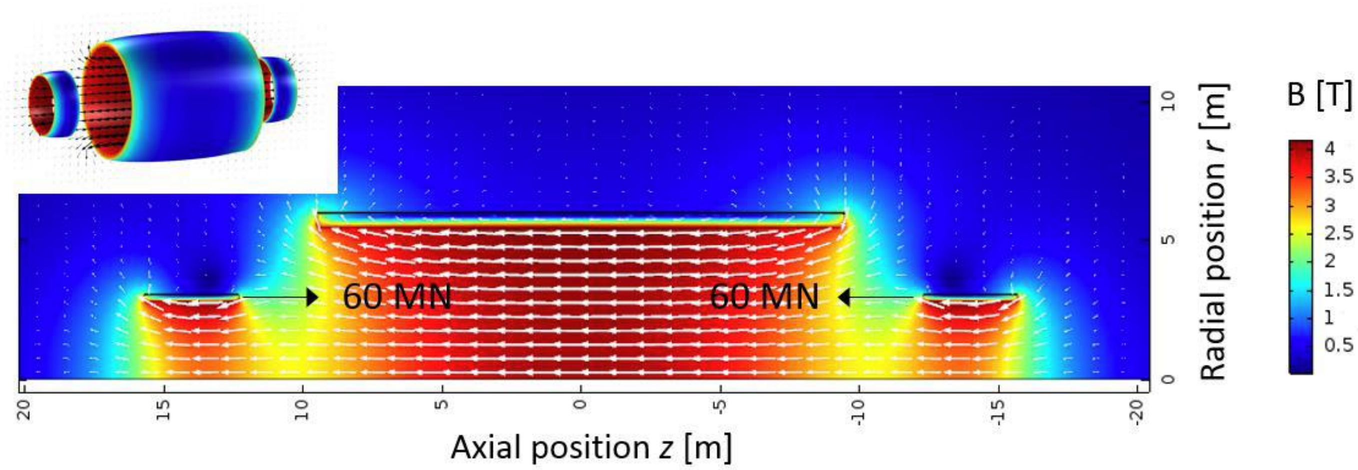
Total Ionizing Dose for 30ab^{-1}

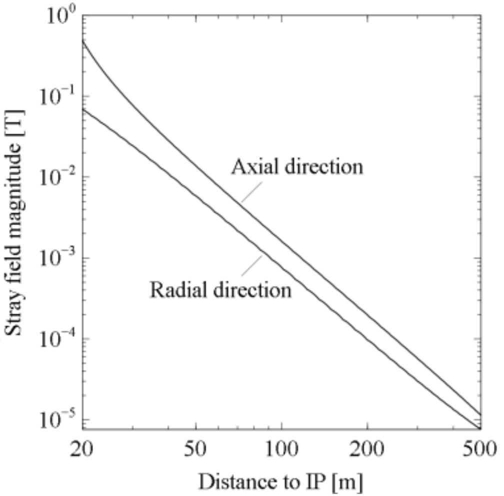
Dose of 300 MGy (30 Grad) in the first tracker layers.

< 10 kGy in HCAL barrel and extended barrel.



Magnetic Field





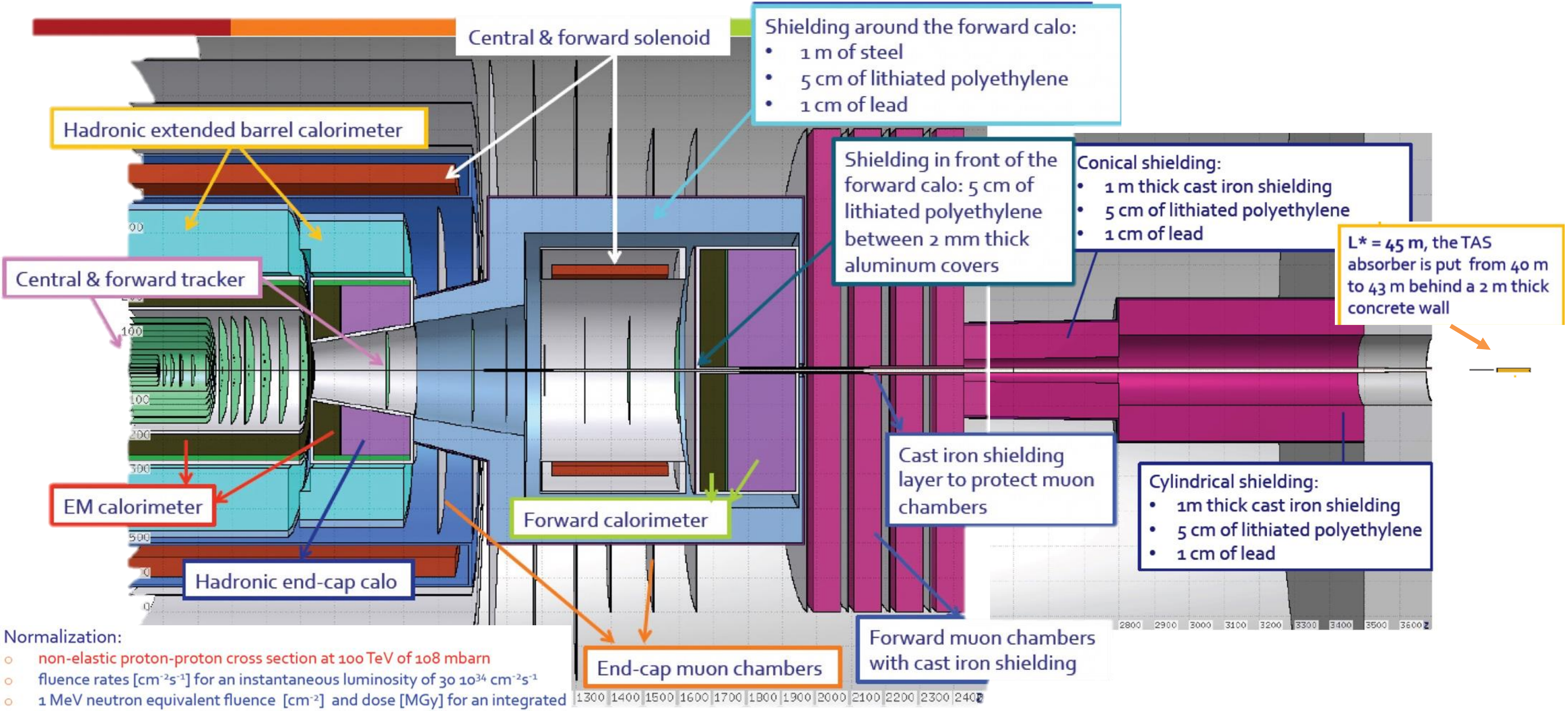
New reference design with three solenoids

- 4 T in 10 m free bore
- 60 MN net force on forward solenoids handled by axial tie rods
- No shielding solenoid anymore (cost! smaller shaft!)
- Forward solenoids instead of forward dipoles → rotational symmetry important for performance physics
  - Solenoids extend high precision tracking by one unit of η

Result:

- Much simplified configuration
- Stored energy: 13.8 GJ
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field

Radiation Levels Simulation



Central & forward solenoid

Shielding around the forward calo:
- 1 m of steel
- 5 cm of lithiated polyethylene
- 1 cm of lead

Hadronic extended barrel calorimeter

Shielding in front of the forward calo: 5 cm of lithiated polyethylene between 2 mm thick aluminum covers

Conical shielding:
- 1 m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

Central & forward tracker

L* = 45 m, the TAS absorber is put from 40 m to 43 m behind a 2 m thick concrete wall

EM calorimeter

Forward calorimeter

Cast iron shielding layer to protect muon chambers

Cylindrical shielding:
- 1m thick cast iron shielding
- 5 cm of lithiated polyethylene
- 1 cm of lead

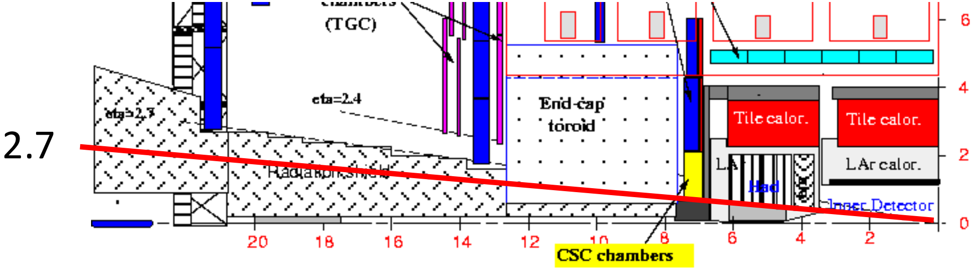
Hadronic end-cap calo

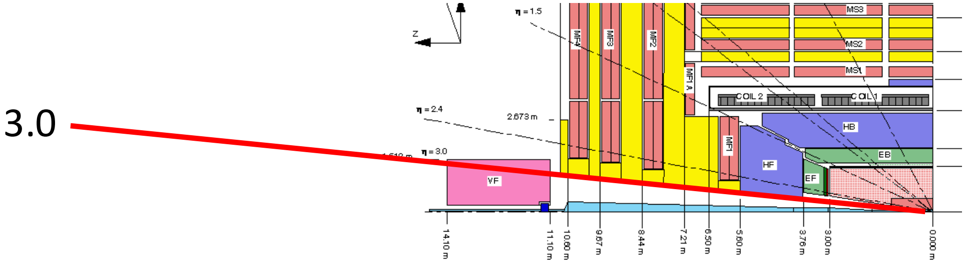
End-cap muon chambers

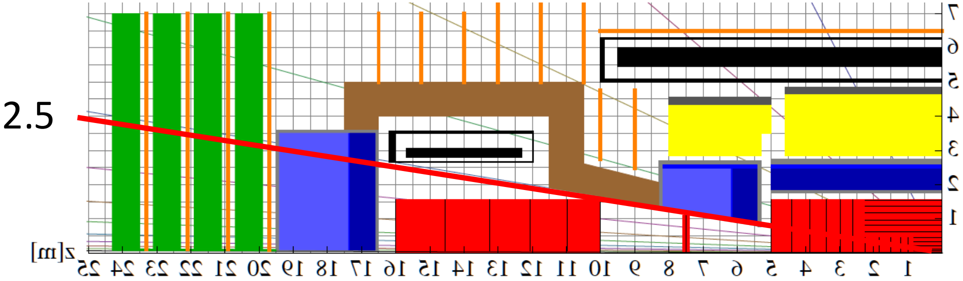
Forward muon chambers with cast iron shielding

Normalization:
- non-elastic proton-proton cross section at 100 TeV of 108 mbarn
- fluence rates [$cm^{-2}s^{-1}$] for an instantaneous luminosity of 30 10^{34} $cm^{-2}s^{-1}$
- 1 MeV neutron equivalent fluence [cm^{-2}] and dose [MGy] for an integrated luminosity of 30 ab^{-1}

Radiation: Comparison to ATLAS & CMS

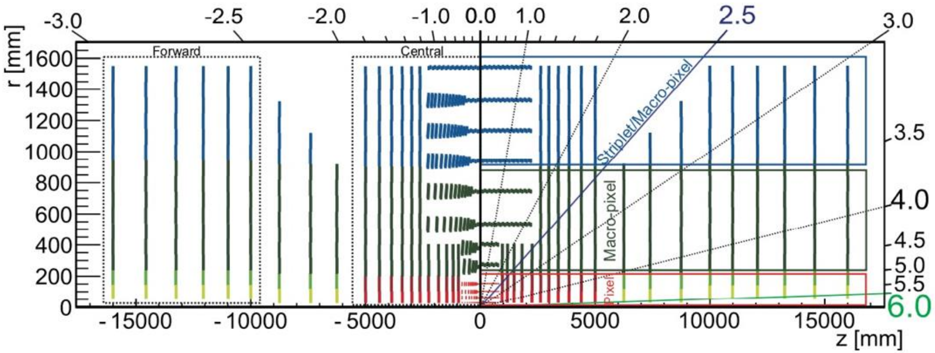


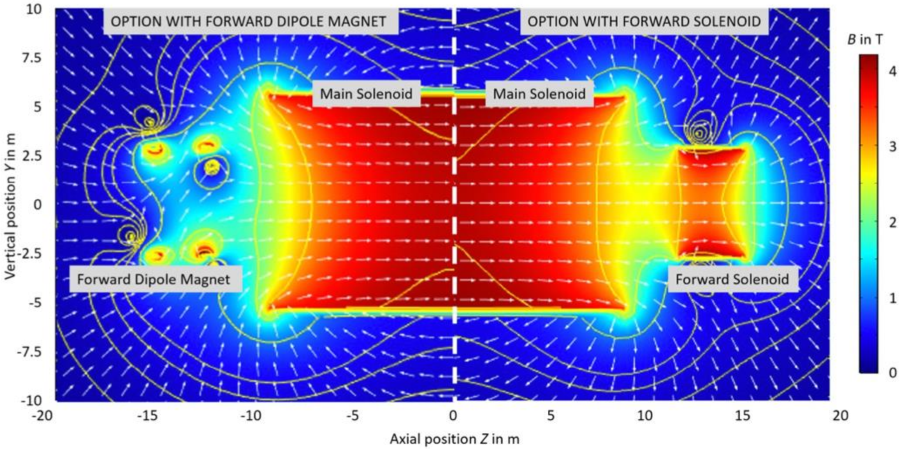


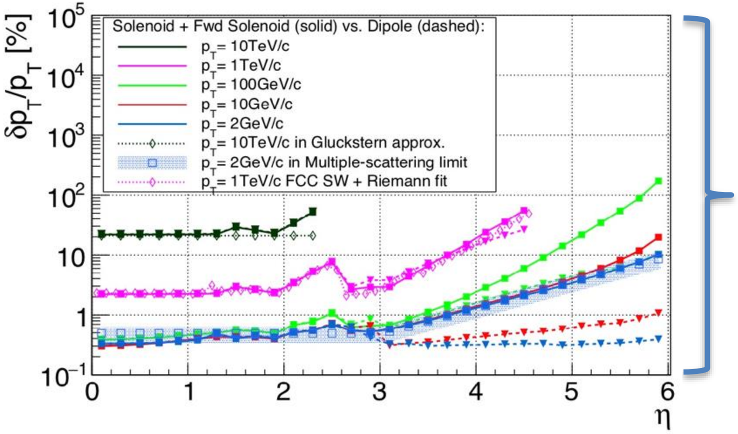


- The forward calorimeters are a very large source of radiation (diffuse neutron source).
- In ATLAS the forward calorimeter is inside the endcap calorimeter, in CMS the forward calorimeter is enclosed by the return Yoke.
- For the FCC, the forward calorimeter is moved far out in order to reduce the radiation load and increase granularity.
- → A shielding arrangement is needed to stop the neutrons to escaping into the cavern hall and the muon system.

Magnetic Field, Tracking







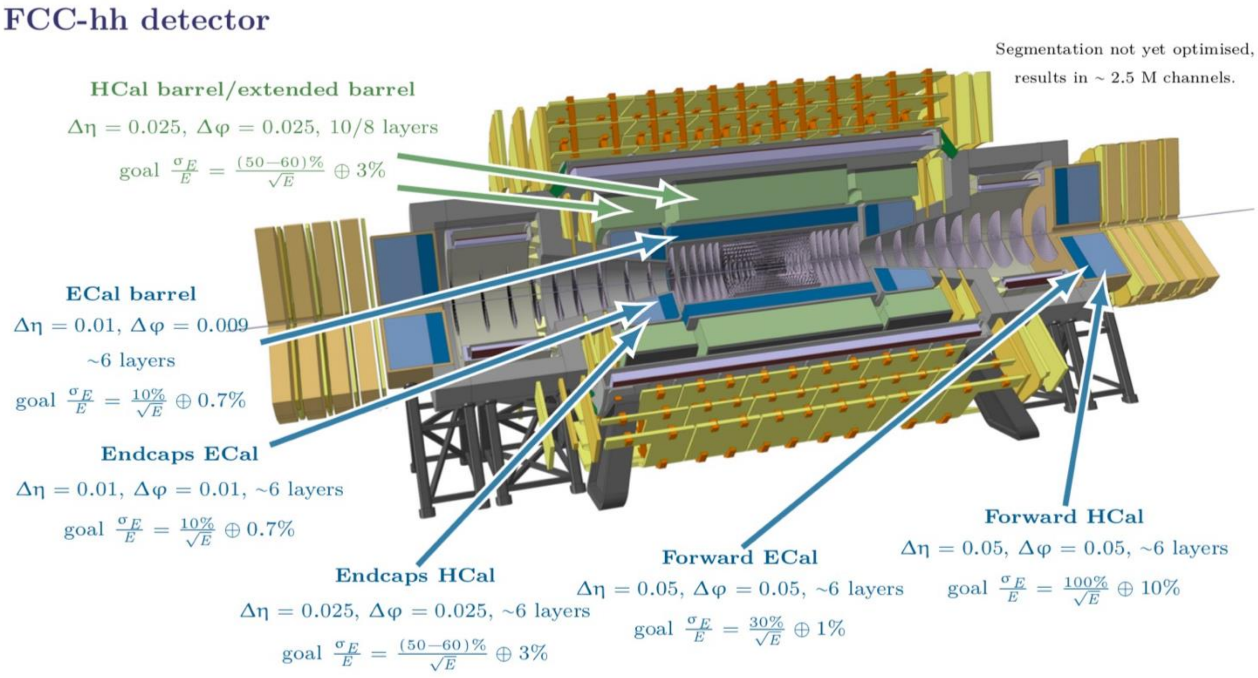
$\delta p_T/p_T \leq 10\%$ for
- **$\leq$ 10 GeV/c and $\eta \leq 5.8$**
- **$\leq$ 1 TeV/c and $\eta \leq 4.0$**

$\delta p_T/p_T = 20\%$ for 10 TeV/c and $\eta = 0.0$

Forward solenoid adds about 1 unit of η to full lever arm acceptance (right field map).

Option using forward dipoles (left field map) also studied

Calorimetry



FCC-hh detector

Segmentation not yet optimised, results in ~ 2.5 M channels.

HCal barrel/extended barrel
$\Delta\eta = 0.025,\ \Delta\varphi = 0.025$, 10/8 layers
goal $\frac{\sigma_E}{E} = \frac{(50-60)\%}{\sqrt{E}} \oplus 3\%$

ECal barrel
$\Delta\eta = 0.01,\ \Delta\varphi = 0.009$
~6 layers
goal $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Endcaps ECal
$\Delta\eta = 0.01,\ \Delta\varphi = 0.01$, ~6 layers
goal $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$

Endcaps HCal
$\Delta\eta = 0.025,\ \Delta\varphi = 0.025$, ~6 layers
goal $\frac{\sigma_E}{E} = \frac{(50-60)\%}{\sqrt{E}} \oplus 3\%$

Forward ECal
$\Delta\eta = 0.05,\ \Delta\varphi = 0.05$, ~6 layers
goal $\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}} \oplus 1\%$

Forward HCal
$\Delta\eta = 0.05,\ \Delta\varphi = 0.05$, ~6 layers
goal $\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$

Reference Detector

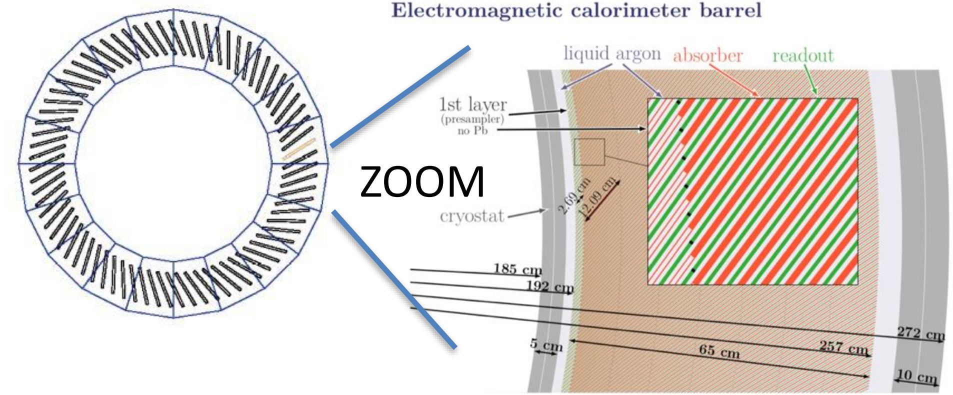
Inspired by ATLAS calorimetry with excellent conventional calorimetry and in addition high granularity to optimize for Particle Flow techniques, pile-up rejection, boosted objects….

- **ECAL, Hadronic EndCap and Forward Calo:**
  - LAr / Pb (Cu)
- **HCAL Barrel and Extended Barrel:**
  - Scintillating tiles / Fe(+Pb) with SiPM

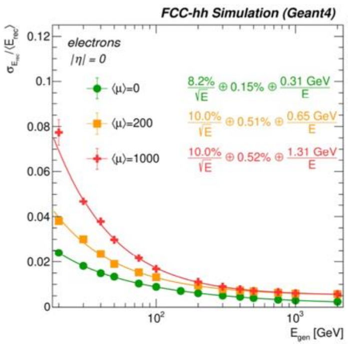
Other options considered for ECAL

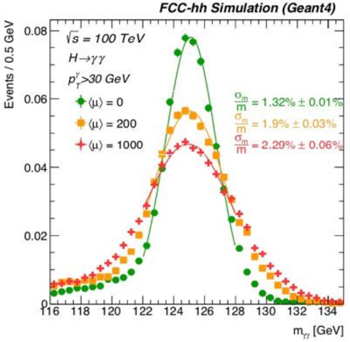
- Digital Si / W
- Analog Si / W (not yet studied, but will profit from CMS HGCal TDR)

Electromagnetic Calorimeter (ECAL)

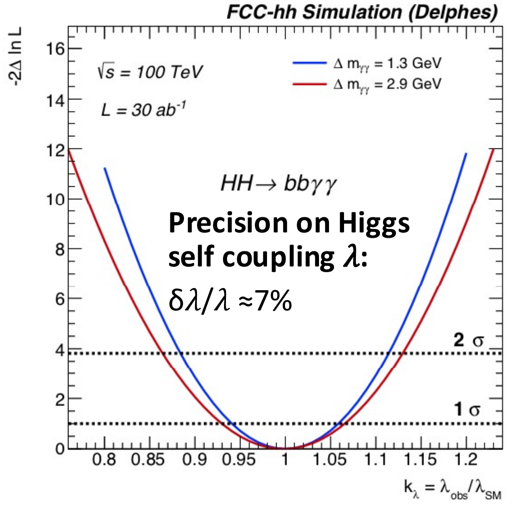


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- **Performance & radiation considerations → LAr ECAL (Pb absorbers)**
- Detector with **larger longitudinal and transversal granularity** compared to ATLAS
  - Optimized for particle flow
  - ~8 longitudinal layers, fine lateral granularity (Δη x Δϕ = 0.01 x 0.01), ~2.5M channels
- Possible only with **straight multilayer electrodes**
  - **Proposal:** Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√Ē, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise
  - →Efficient in-time pile-up suppression will be crucial (using the tracker)



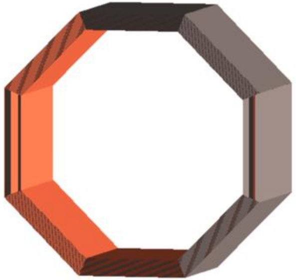
Precision on Higgs self coupling λ:

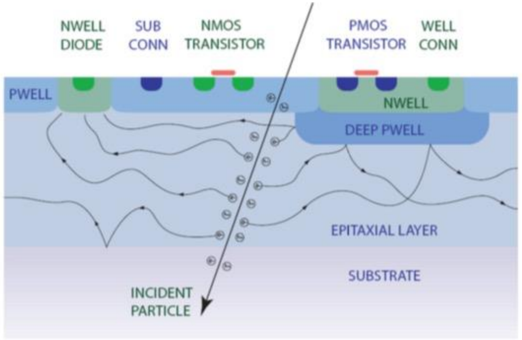
$\delta\lambda/\lambda \approx 7\%$

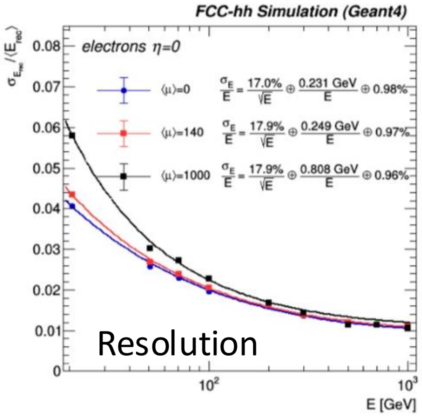
Barrel ECAL – Other Options

Other options considered for ECAL Barrel:

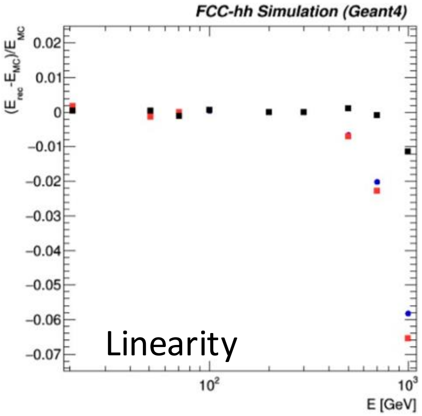
- **Digital Si/W DECal (MAPS):**
  - 18µm epitaxial thickness, on a substrate of 300µm.
  - 50×50 μm^2 pitch pixels are summed into 5×5 mm^2
  - 2.1 mm thick tungsten absorber is located directly after the two silicon layers, followed by a 3 mm air gap (space foreseen for services, cooling,…)
  - Threshold at $6\sigma_{noise} = 480e^-$
  - MIP signal in 18µm Si: $1400e^-$
  - **Non-linearity for E > 300GeV due to multiple particles traversing single pixel → corrections necessary**
- **Option: Analog Si/W:** Will profit from experience of CMS HGCal







Resolution

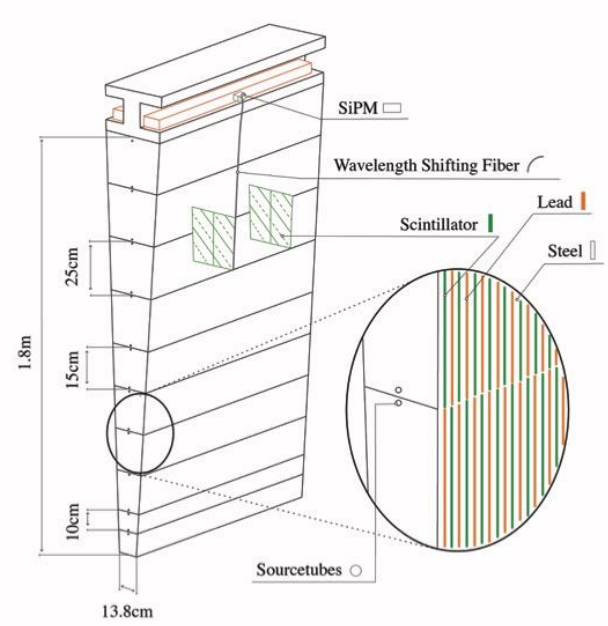


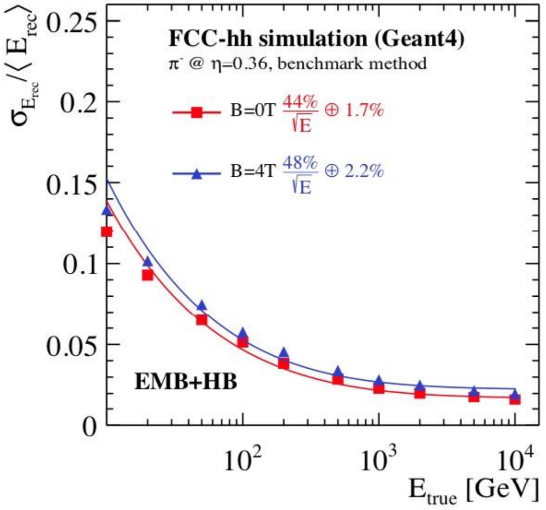
Linearity

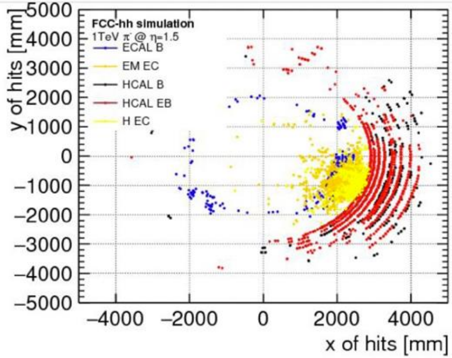
Hadronic Calorimeter Barrel (HCAL)

Barrel HCAL:

- ATLAS type
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - Δη x Δϕ = 0.025 x 0.025
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels





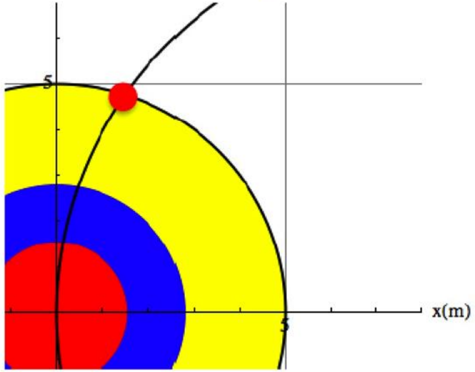


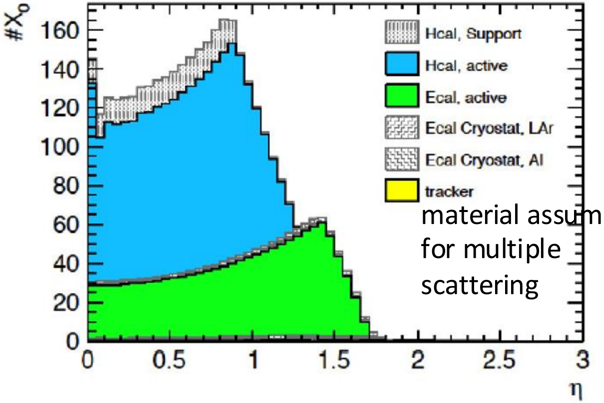
e/h ratio very close to 1 achieved using steel absorbers and lead spacers (high Z material)

Muon System

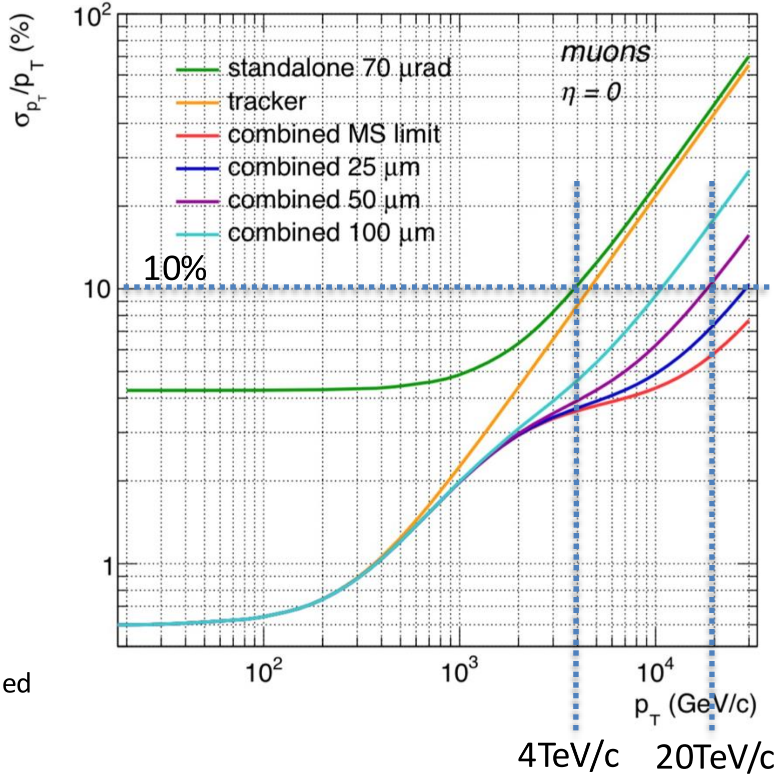
p_t=3.9GeV enters muon system

p_t=5.5GeV leaves coil at 45 degrees





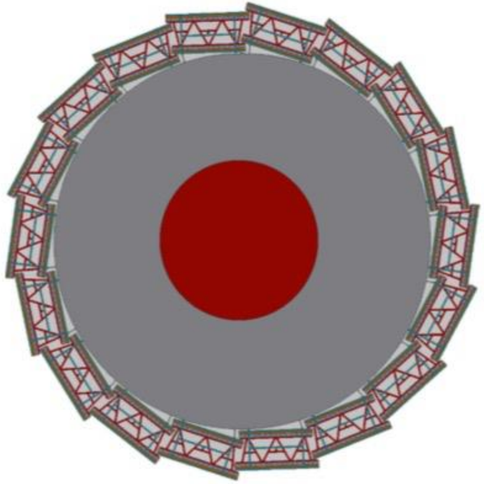
material assumed for multiple scattering



4TeV/c 20TeV/c

With 50μm position resolution and 70μrad angular resolution we find (η=0):

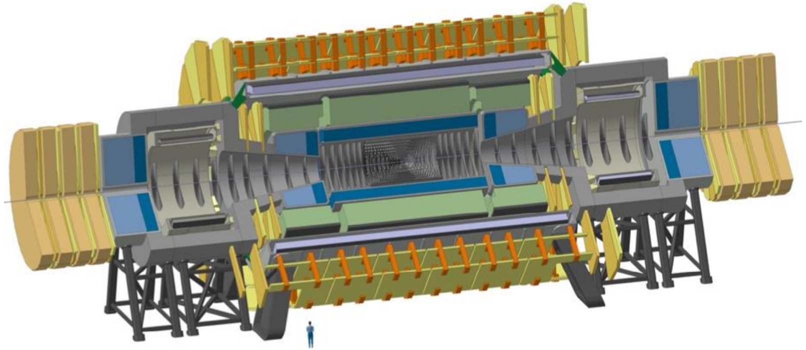
- **≤10% standalone momentum resolution up to 4TeV/c**
- **≤10% combined momentum resolution up to 20TeV/c**



Rates of up to ~500Hz/cm^2 expected in muon barrel

Reading Out Such a Detector → Trigger/DAQ

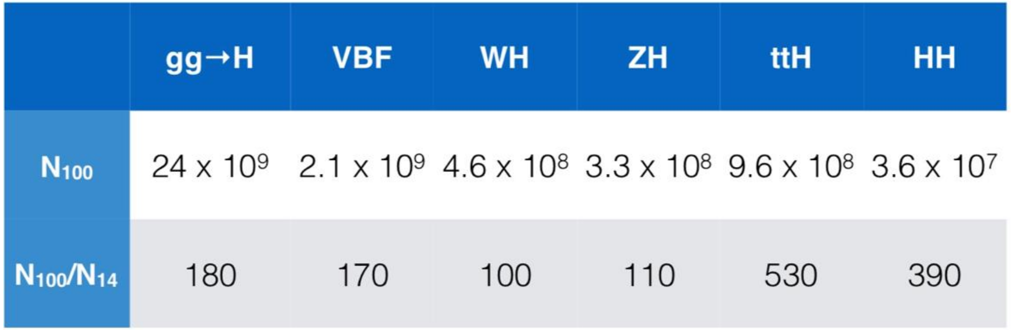
- **Example ATLAS**:
  - ATLAS Phase II calorimetry will be digitized at 40MHz and sent via optical fibers to L1 electronics outside the cavern at 25TByte/s to create the L1 Trigger.
  - Muon system will also be read out at 40MHz to produce a L1 Trigger.
- **FCC-hh detector**:
  - calorimetry and muon system at 40MHz will result in 200-300 TByte/s, which seems feasible.
  - 40MHz readout of the tracker would produce about 800TByte/s.



- **FCC-hh trigger strategy question:**
  - Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
  - Or: un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.

FCC-hh Physics Program (Examples)

SM Higgs: Event Rates at 100TeV



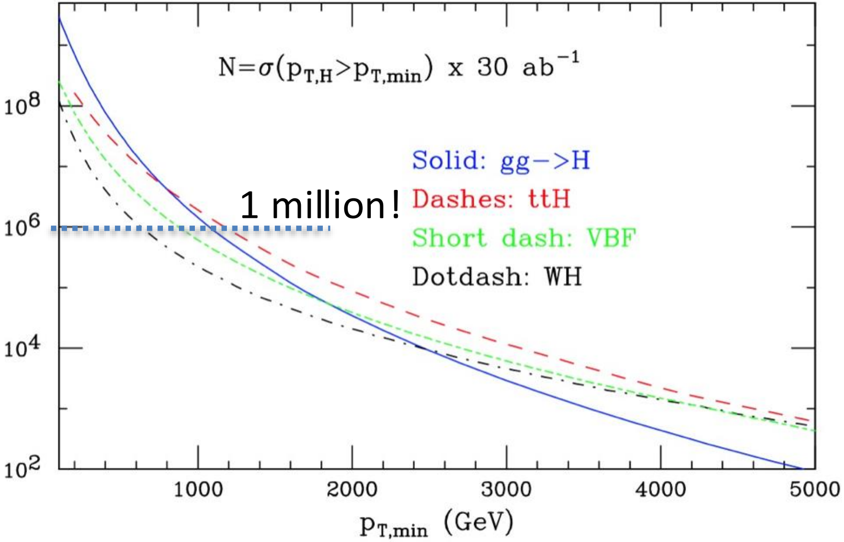
	gg→H	VBF	WH	ZH	ttH	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

$$N_{100} = \sigma_{100\text{TeV}} \times 30\text{ab}^{-1}$$

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

Large statistics!

FCC-hh – The ultimate Higgs Factory!

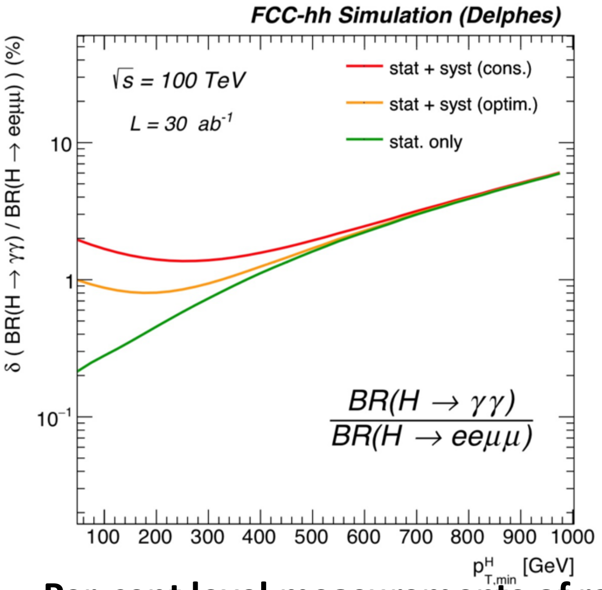


Large kinematic range of Higgs production

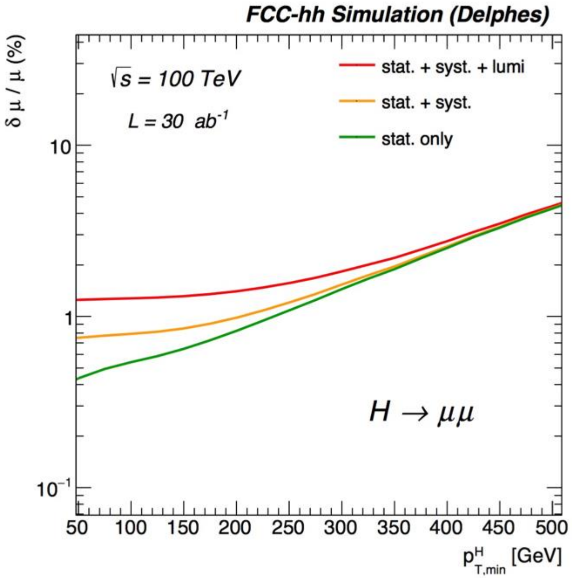
Hierarchy of production channels **changes at large p_T(H):**

- σ(ttH) > σ(gg→H) above 800 GeV
- σ(VBF) > σ(gg→H) above 1800 GeV

Example: Higgs Couplings

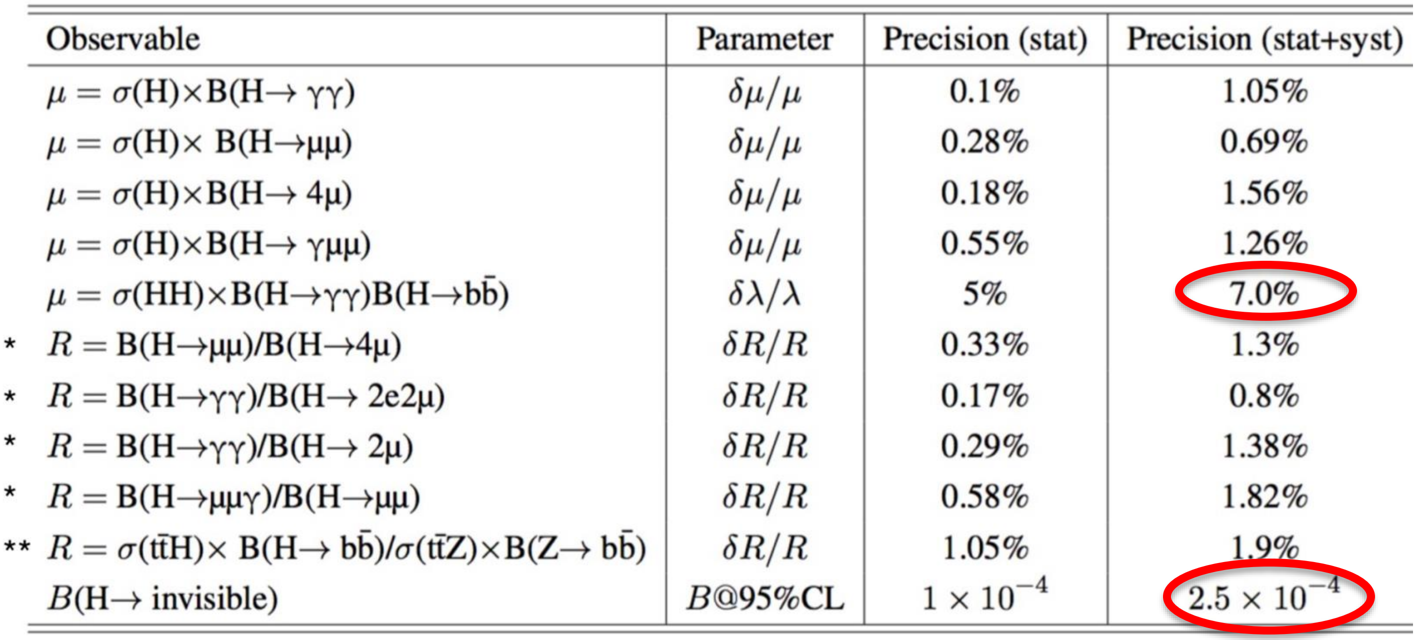


Delphes simulation of realistic detector including systematic uncertainties



- **Per-cent level measurements of ratios of branching ratios**
  - Model independent sensitivity to BSM
- Ratios of BR: Well defined fiducial region → **remove production and modeling systematics**
- **Normalise to BR (4 leptons) from FCC-ee** (known at the few per-mille, see before)
- **High p_T region:** Reduced systematics (e.g. from pile-up, from background)
- **→ Absolute sub-% measurements for rare decays → Precision on Higgs couplings in the sub-% range**

Precision Higgs Measurements

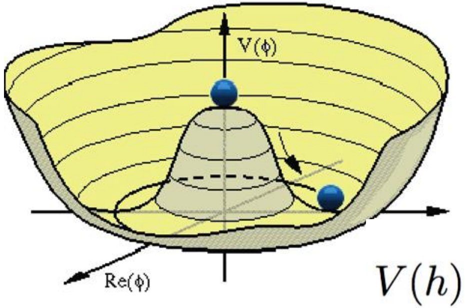


Observable	Parameter	Precision (stat)	Precision (stat+syst)
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.05%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta\mu/\mu$	0.28%	0.69%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.56%
$\mu = \sigma(\mathrm{H})\times\mathrm{B}(\mathrm{H}\to\gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.26%
$\mu = \sigma(\mathrm{HH})\times\mathrm{B}(\mathrm{H}\to\gamma\gamma)\mathrm{B}(\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}})$	$\delta\lambda/\lambda$	5%	7.0%
* $R = \mathrm{B}(\mathrm{H}\to\mu\mu)/\mathrm{B}(\mathrm{H}\to 4\mu)$	$\delta R/R$	0.33%	1.3%
* $R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
* $R = \mathrm{B}(\mathrm{H}\to\gamma\gamma)/\mathrm{B}(\mathrm{H}\to 2\mu)$	$\delta R/R$	0.29%	1.38%
* $R = \mathrm{B}(\mathrm{H}\to\mu\mu\gamma)/\mathrm{B}(\mathrm{H}\to\mu\mu)$	$\delta R/R$	0.58%	1.82%
** $R = \sigma(\mathrm{t\bar{t}H})\times\mathrm{B}(\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}})/\sigma(\mathrm{t\bar{t}Z})\times\mathrm{B}(\mathrm{Z}\to\mathrm{b}\bar{\mathrm{b}})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H}\to\text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

* Measurements of ratios of BRs, combined with the absolute measurement of the HZZ coupling at FCC-ee, will yield absolute coupling measurements in FCC-hh

** Will use results from FCC-ee: BR(H→bb), ttZ EW coupling

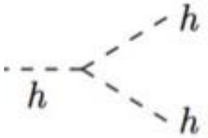
Higgs Self Coupling



$$V(\mathcal{H}) = \underbrace{M_{\mathcal{H}}^2|\mathcal{H}|^2 + \frac{\lambda_{\mathcal{H}}}{2}|\mathcal{H}|^4}_{\text{SM}} + \underbrace{\frac{1}{\Lambda^2}|\mathcal{H}|^6}_{\text{BSM}}$$

$$V(h) = \overbrace{\frac{1}{2}M_H^2H^2 + \underbrace{\frac{1}{3!}\sqrt{3\lambda_H}M_HH^3} + \frac{1}{4!}\lambda_HH^4}$$

$$\mathcal{H} = (0, \frac{H+v}{\sqrt{2}})$$



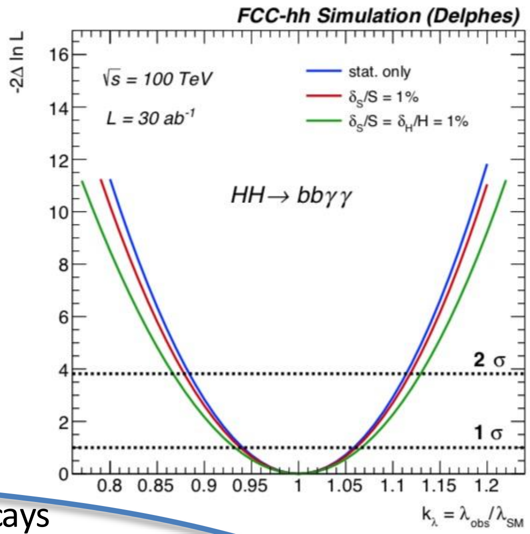
Why is Higgs self coupling interesting?

- Study shape of Higgs potential
- Study EW phase transition → cosmological implications
- Impact on vacuum stability
- Self-coupling sensitive to new physics

HH→$b\bar{b}\gamma\gamma$ is the golden channel for di-Higgs meas. in FCC-hh:

→ Important input for detector requirements

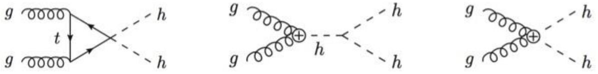
→ ECAL performance, b-tagging,…



study di-Higgs decays

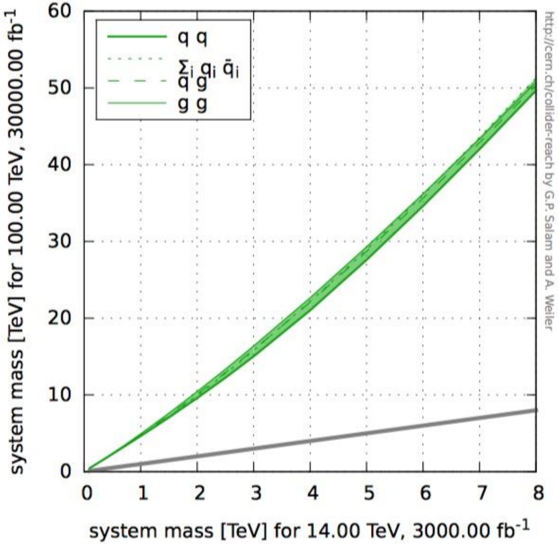
SM:

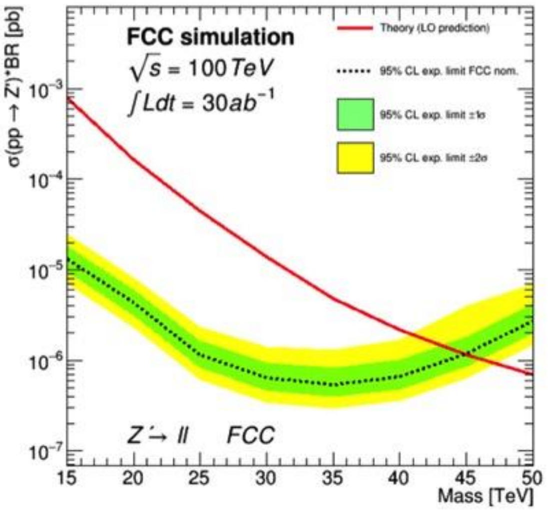
BSM:

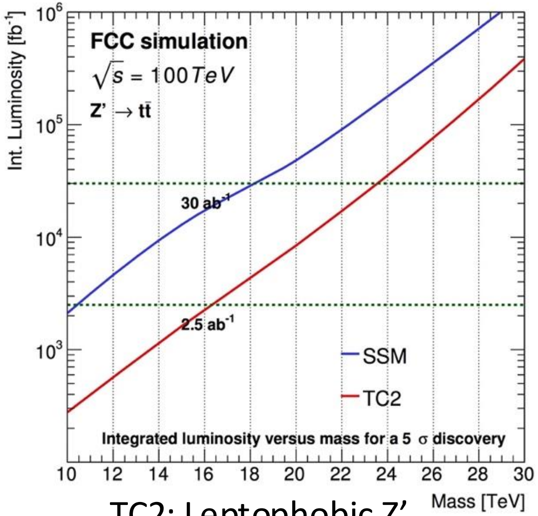


	$b\bar{b}\gamma\gamma$	$b\bar{b}ZZ^*[\to 4\ell]$	$b\bar{b}WW^*[\to 2j\ell\nu]$	4b+jet
$\delta\kappa_\lambda$	6.5%	14%	40%	30%

Exploration Potential: Direct Mass Reach



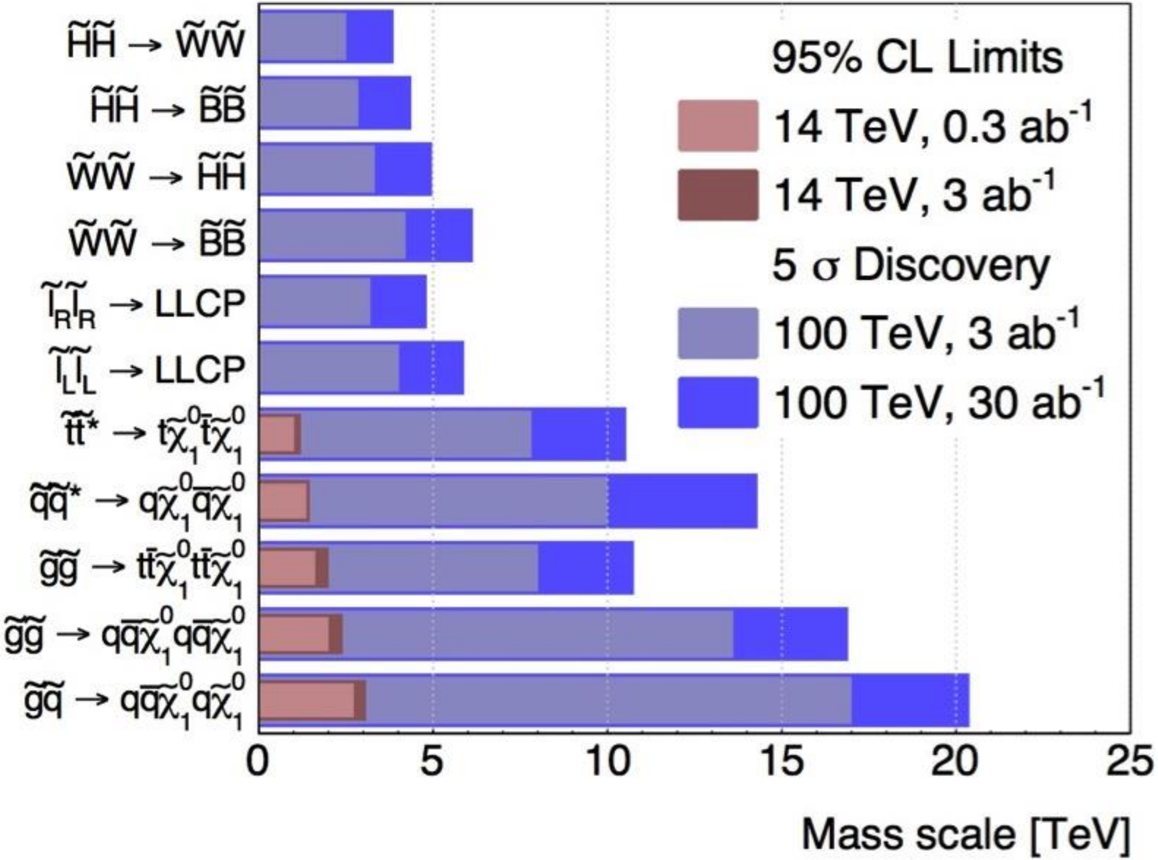




TC2: Leptophobic Z'

- **Mass reach of FCC-hh about 5-6 x HL-LHC**
- **Delphes simulation of realistic detector** including systematic uncertainties
  → Demonstrate that we can fully exploit this potential

Exploration Potential: SUSY Reach at 100 TeV



arXiv:1606.00947