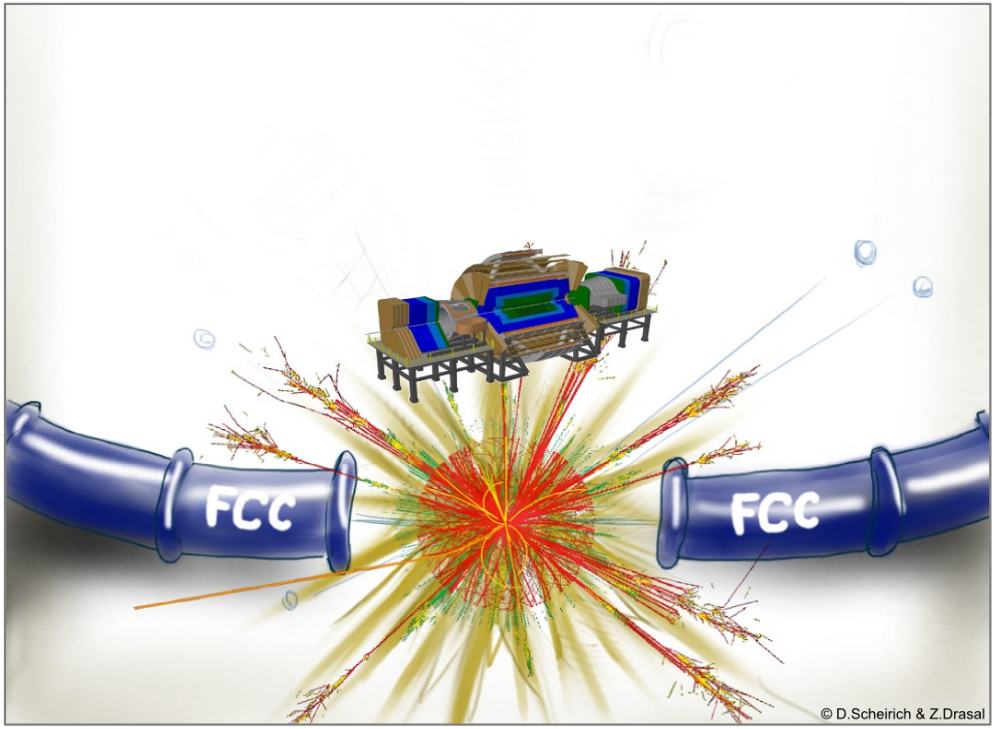
Status of FCC Detector & MDI Developments



Zbyněk Drásal
CERN

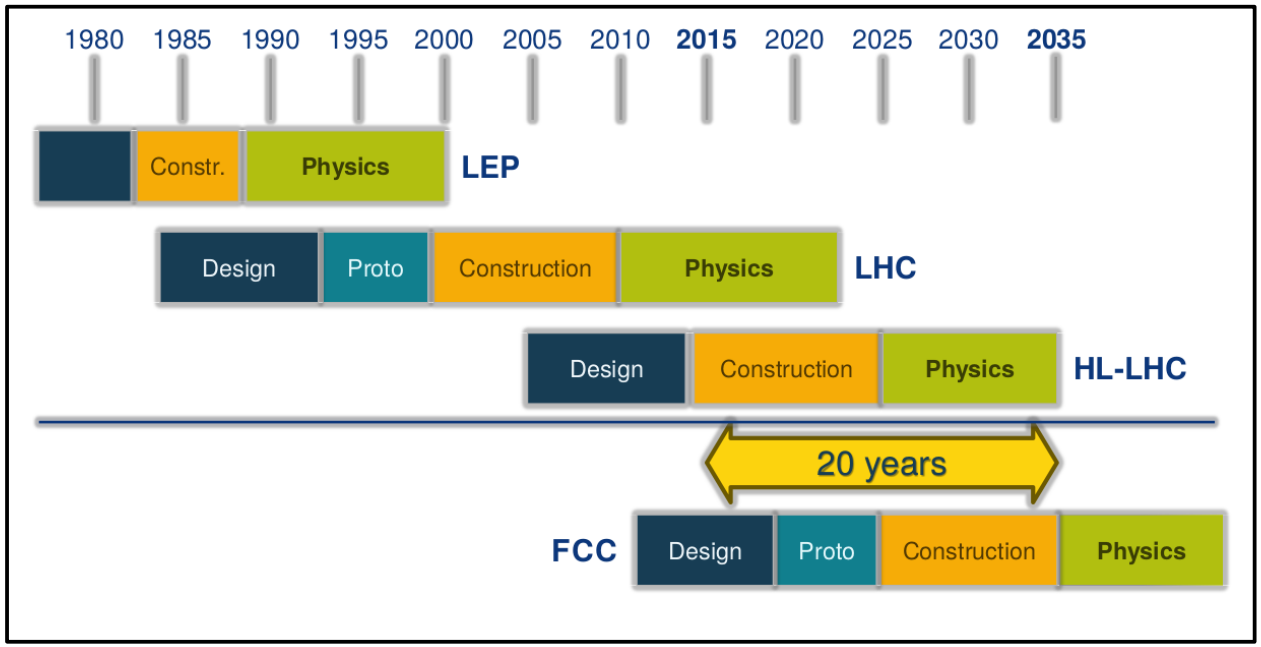
On behalf of FCC detector group

Overview

- Introduction
  - Motivation
  - Future Circular Collider (FCC) machine parameters
- Design of detector & machine detector interface (MDI)
  - Status of FCC-hh option (see WG progress @ https://indico.cern.ch/category/6069/):
  - Status of FCC-ee option (see progress @ http://tlep.web.cern.ch/):
- Common FCC Software (FCCSW) (see http://fccsw.web.cern.ch/fccsw):
- Summary & Outlook

Is it the right time?

- LHC detector R&D started in the 1980's, that for HL-LHC in the 2000's
  → large scale prototyping and radiation studies require long lead times



→ **The right time to plan for the period 2035-2040**

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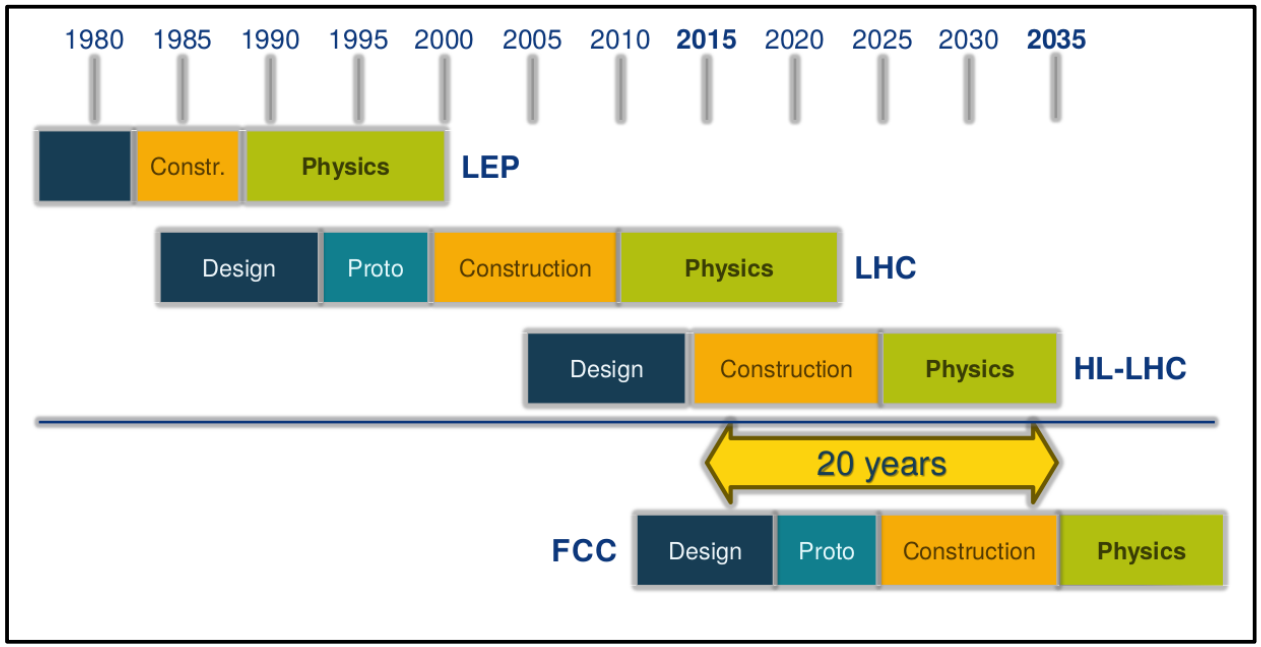
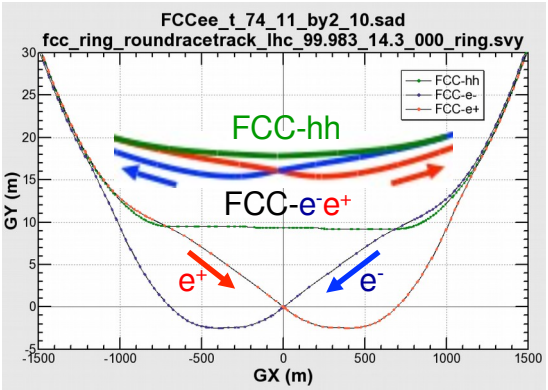


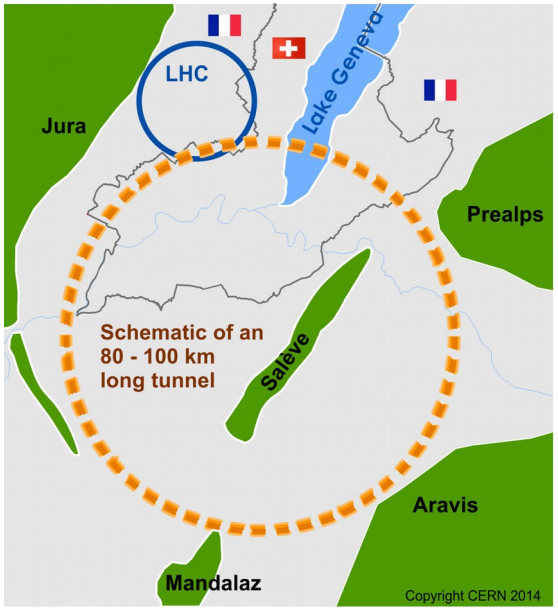
→ **The right time to plan for the period 2035-2040**

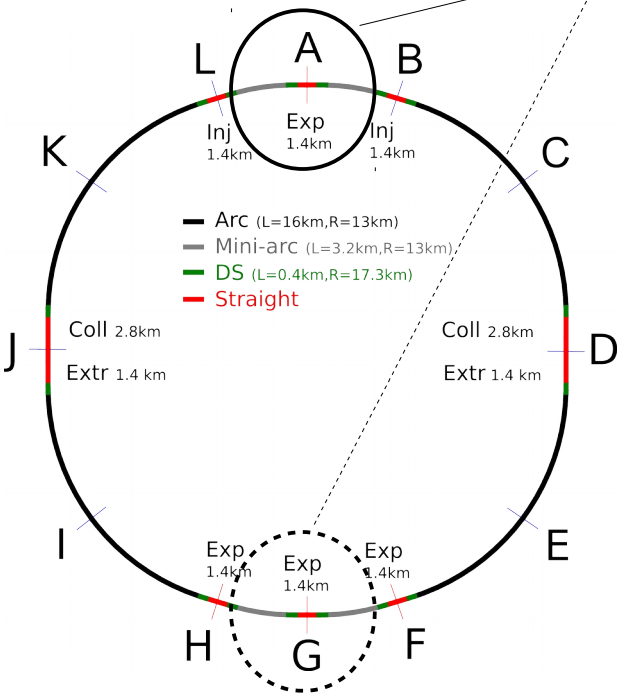
→ **Aim to prepare the FCC Conceptual Design Report for 2019 EU Strategy Update**

Future Circular Collider

- **FCC machine:**
  - FCC-hh (pp collider): final goal defining the whole infrastructure
    → ~ 16T magnets → 100TeV pp collider in ~ 80-100km tunnel
  - FCC-ee: as a potential first step
  - FCC-eh: as an option







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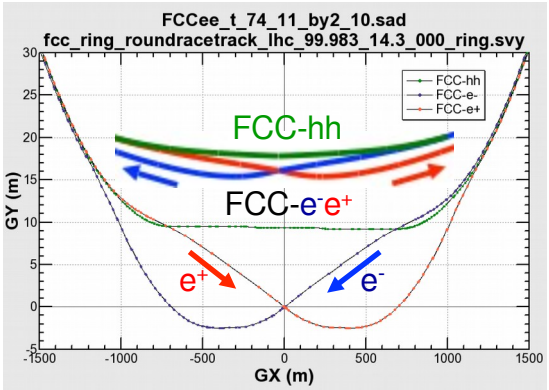
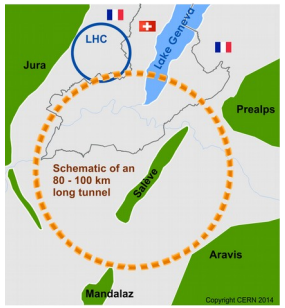
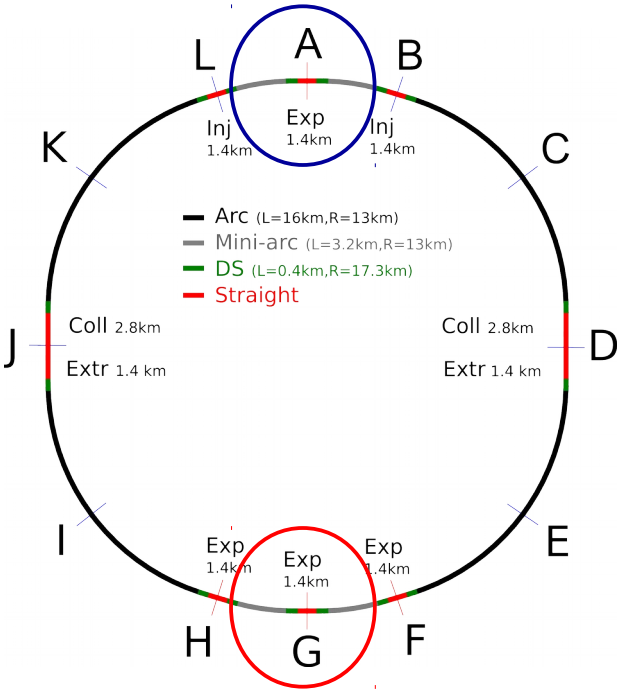


- **2 high luminosity experiments** (A & G)

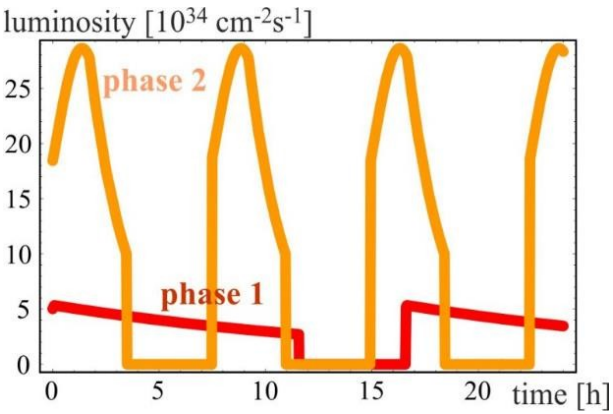
  + 2 other experiments: H, F grouped with G





Key FCC-hh Parameters

Parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
Collision cms energy [TeV]	100		>25	14
Dipole field [T]	16		16	8.3
Circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
Beam current [A]	0.5		1.12	(1.12) 0.58
Bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
Bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	5	20 - 30	>25	(5) 1
# Events/bunch crossing	170	<1020 (204)	850	(135) 27
Stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
Synchrotron rad. [W/m/beam]	30		3.6	(0.35) 0.18



Phase 1: β*=1.1 m, t_{ta}=5 h, 250 fb^{-1} / year

Phase 2: β*=0.3 m, t_{ta}=4 h, 1 ab^{-1} / year

- 5 years long operation periods (3.5 years run & 1.5 year shutdown)

→ **Baseline** (phase 1): 10 yrs of operation @ L_{peak} = 5x10^{34}cm^{-2}s^{-1} → **2.5 ab^{-1}** (per detector)

→ **Ultimate** (phase 2): 15 yrs of operation @ L_{peak} ≤ 30x10^{34}cm^{-2}s^{-1} → **15 ab^{-1}** (per detector)

→ **Total: O(20)ab^{-1}/experiment**

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14TeV → 100 TeV

$\sigma_{inelastic}$: 80mb → 108mb

average p_T: 0.6 → 0.8 GeV/c

multiplicity$_{charged/unit\ \eta}$: 5.4 → 8

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By factor of ~ 5 increase wrt HL-LHC

→ the minimum bias events @FCC are quite similar to ones @HL-LHC, but …

→ 5x higher event pile-up → keeping 5ns (versus 25ns) operation scheme as option

→ in general, expected huge particle/data rates & significantly higher radiation level in the inner/fwd detector

Physics Requirements & FCC-hh Design

- **The experimental future will importantly depend on the results from LHC**, but no matter what LHC discovers, **understanding a complete picture of physics requires a new machine** far beyond the LHC reach & **general purpose detector** (as CMS/ATLAS):

→ one of the natural benchmarks driving the detector design: **unique properties of Higgs boson**

→ **FCC-hh versus LHC** (see: "Physics at 100 TeV" report)

- Immense increase in cross-sections, particularly for ttH & HH
- FCC opens us new kinematic & dynamical regime for Higgs physics

Physics at 100 TeV pp collider Report

	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420

FCC-hh/ HL-LHC

Table 20: Indicative total event rates at 100 TeV (N_{100}), and statistical increase with respect to the statistics of the LHC run 1 (N_8) and the HL-LHC (N_{14}), for various prodution channels. We define here $N_{100} = \sigma_{100\ TeV} \times 20\ \mathrm{ab}^{-1}$, $N_8 = \sigma_{8\ TeV} \times 20\ \mathrm{fb}^{-1}$, $N_{14} = \sigma_{14\ TeV} \times 3\ \mathrm{ab}^{-1}$.

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→ **See a few examples to get an intuitive picture ...**

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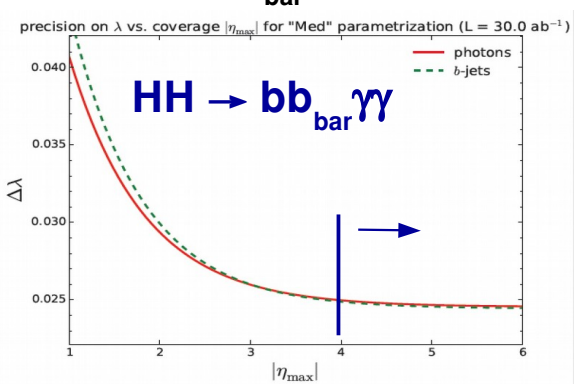
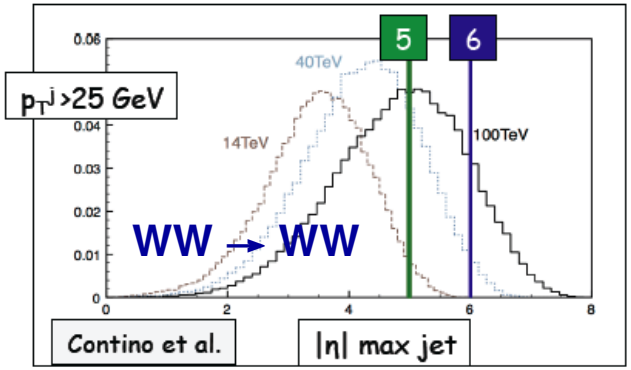
– **HH → bb$_{bar}$γγ** (H self-coupling), **WW → WW, ...**



	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	0.56	0.88
WH	0.66	0.97	0.45	0.77
ZH	0.69	0.98	0.48	0.8
ttH	0.84	1	0.56	0.9
VBF	0.75	0.98	0.55	0.87

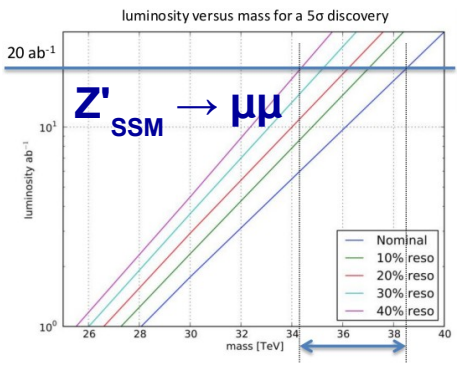


→ Need **extended** tracking/ECAL coverage **up-to |η| ~ 4,** efficient jet measurement **up-to |η| ~ 6**

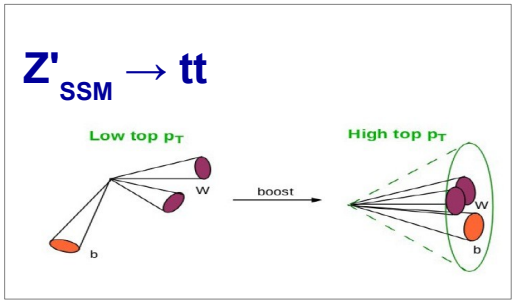
Physics Requirements & FCC-hh Design

– **Direct searches,** e.g. **Z' → μμ** or **Z' → tt** (high boosted objects) → heavy final states require high √s

Z' discovery potential versus muon p_T res.



$$\frac{\Delta p_T}{p_T} \propto \frac{p_T}{BL^2}$$



Expected highly-collimated (high boosted) final states (min distance between 2 partons ~ m/p_T)

→ Need for **high p_T resol. ~10-15% @10TeV** (cf. HL-LHC: 10% @1TeV), but still keeping **sensitivity for low p_T tracks**

→ **High E/HCAL granularity** (ΔR≤0.05x0.05 or 0.025x0.025) to resolve jet-substructure, rejec bkg...

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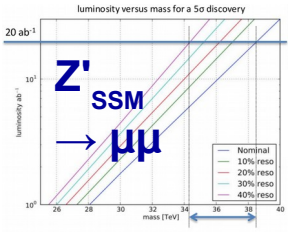

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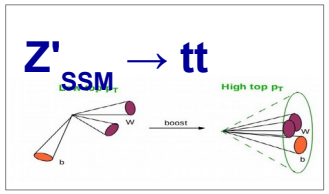

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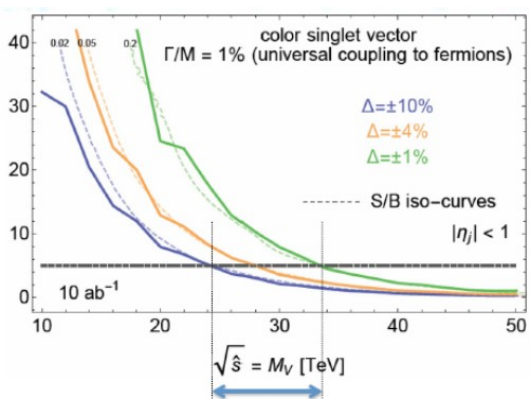
Dijet resonance discovery potential

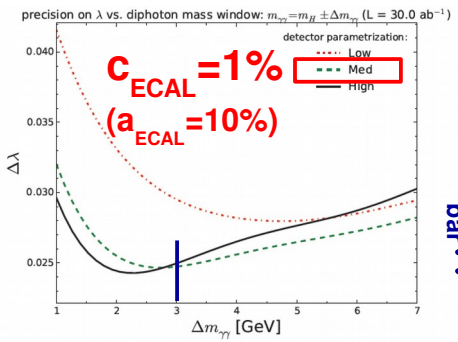


Calorimeter res. → for high E the const. term dominates:

$$\frac{\Delta E}{E} \propto \frac{a}{\sqrt{E}} \oplus c$$

Sampling term

Const. term (precise calibration, mechanics, containment,...)



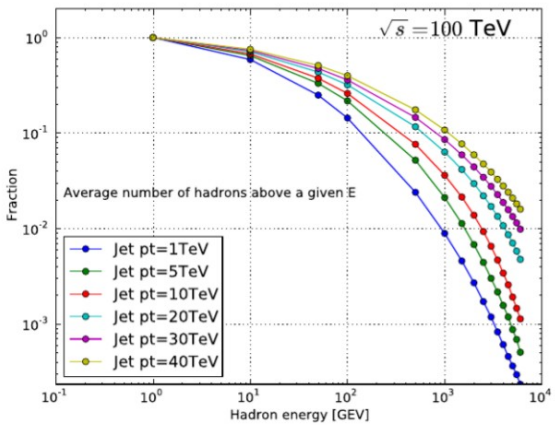
HH → $bb_{bar}\gamma\gamma$

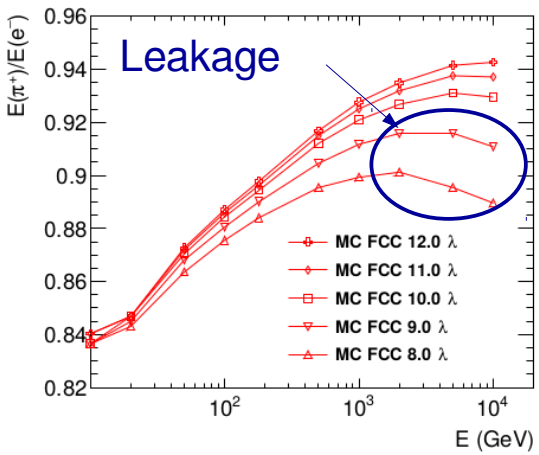
→ **Need few % jet energy resol.**, so target **c ~2% (HCAL), ~1% (ECAL) + hermetic calorimeter**

Physics Requirements & FCC-hh Design

- **Jet containment:** 30 TeV jet → 15% of hadrons with E>1 TeV!

Average #hadrons above a given E





→ **98% containment (ECAL+HCAL) requires 12λ_{int} (arXiv:1604.01415)**

FCC-hh: Magnet & Detector Baseline Geometry

- **The magnet group studied several options to fit the requirements on tracking ($\Delta p_T/p_T$ @ 10TeV/c ~ 10-15%) & calorimetry (12 λ_{int} – jet containment):**

  → coil with high B field & low material budget in front of ECAL/HCAL very difficult → ~~**ATLAS approach**~~

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  - → leaving tracker radius @ LHC values ~ 1m + 12 λ_{int} CAL → ~~**challenging**~~ → R_{coil} ~ 4m **(an option)**
  - → **current design: twin solenoid B=6T** (max for NbTi, 12m bore, ~20m length) **+ 2 dipoles (10Tm)**

Beam-pipe (Be): R=20-21mm

Tracker: R=25mm-2.4m, L=16m

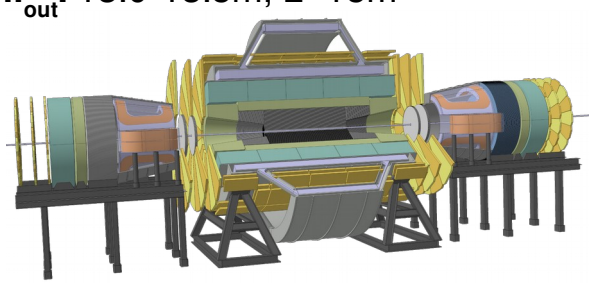
ECAL: R=2.5-3.6m

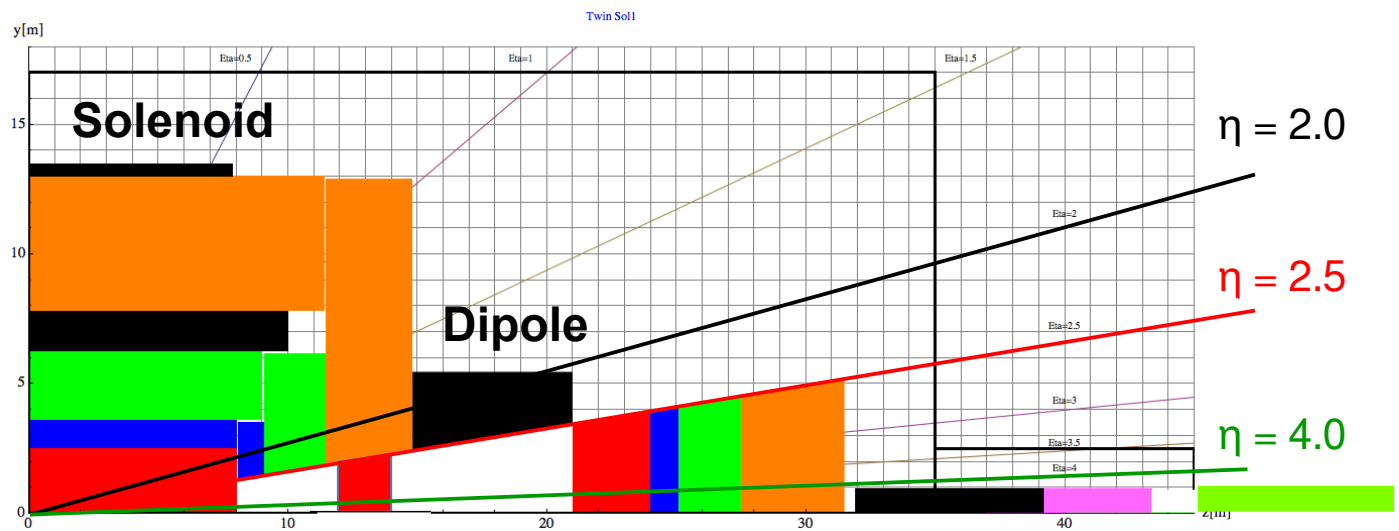
HCAL: R=3.6-6.0m

$Coil_{in}$+Cryostat: 6.0-7.8m, L=20m

Muon space: 7.8-13.0m

$Coil_{out}$: 13.0-13.5m, L=15m





Dipole: 10Tm, Z=14.8-21m

F-Tracker: Z=12-14m, Z=21-24m

F-ECAL: Z=24-25.1m

F-HCAL: Z=25.1-27.5m

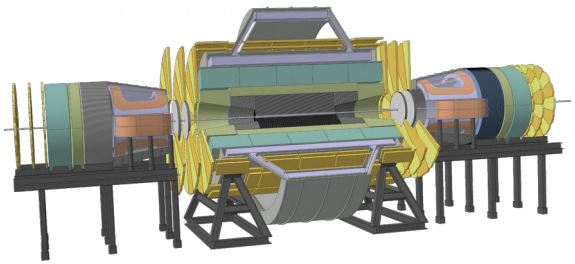
F-Muon: Z=27.5-31.5m

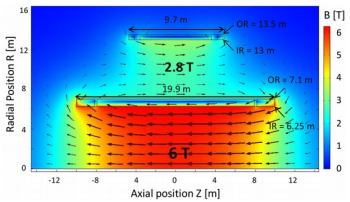
Dipole comp., TAS, Triplet

Tracker Design for FCC-hh

- **Tracker design driven by: $\Delta p_T/p_T$ resol. @10TeV/c & pattern recognition capabilities**
  - **2 magnet scenarios studied** (using **tkLayout** SW - developed for CMS (HL-LHC) tracker studies)**:**

Twin solenoid (6T) with dipoles (10Tm, standalone system) **in FWD region**:





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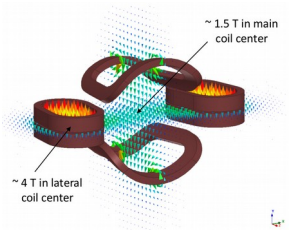
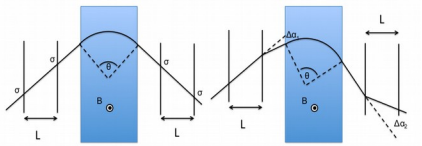


→ Measure $p_L(p)$ using forward tracker + dipole → use cotg($\vartheta_{emission}$) meas. to determine p_T from p_L (p)



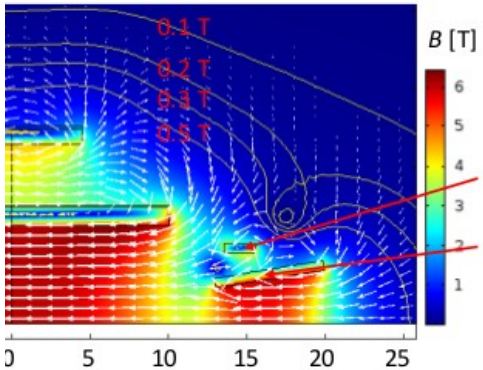
$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{2\sigma\, p_L}{0.3L \int B_T dl}\right)^2 + \left(\frac{0.0136}{0.3 \int B_T dl}\sqrt{2\frac{x_f}{X_0}}\right)^2$$

Tracking resolution — MS resolution

Twin solenoid (6T) with balanced conical shape in FWD region:

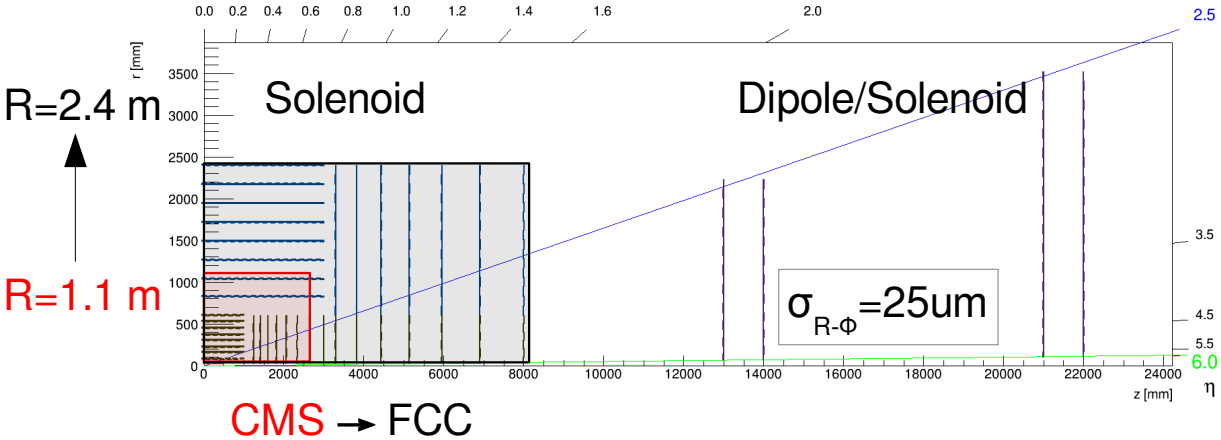
- Rotational symmetry important for physics measurement (E_T^{miss}, ...)
- Less complex system compared to dipole

→ **Is performance the same?**



Tracker Design for FCC-hh

- **Geometry** (compared to CMS)**:**



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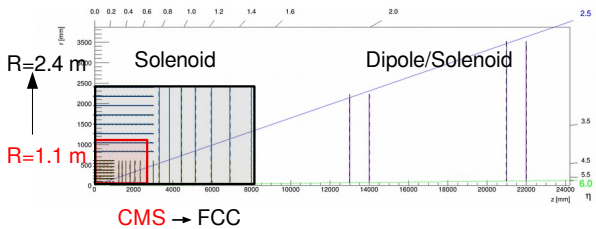
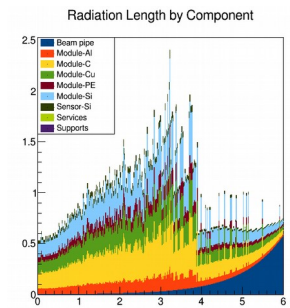


Conservative material assumptions (in %):

- Si 20%, C 42%, Cu 2%, Al 6%, Plastic 30%

  → **x/X_0 = 3% per layer** (of 0.43cm)



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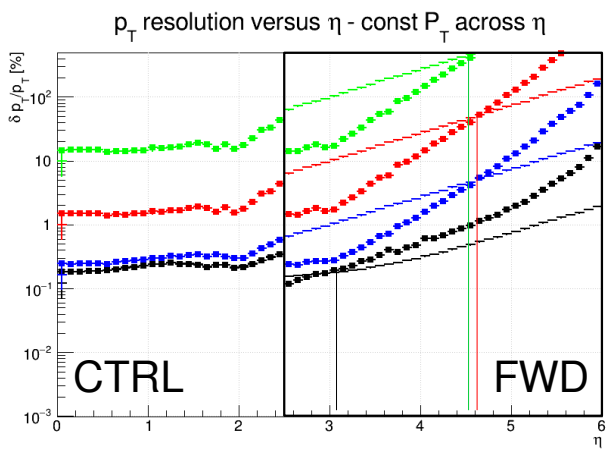

Simulated p_T:

- **10 GeV/c → @η=5 p~700GeV/c**
- **100 GeV/c → @η=5 p~7TeV/c**

} Important p_T range

- **1 TeV**
- **10 TeV**

· solenoid
– dipole

→ **Solenoid comparable to dipole**

→ **$\Delta p_T/p_T$ ~10% up to η=5!**

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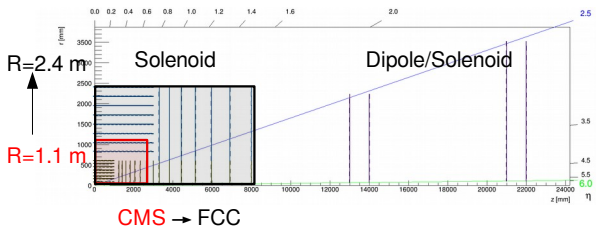

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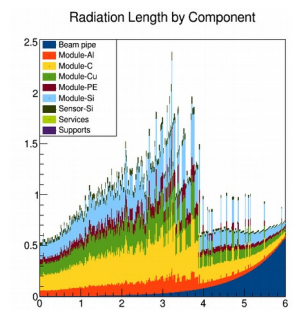

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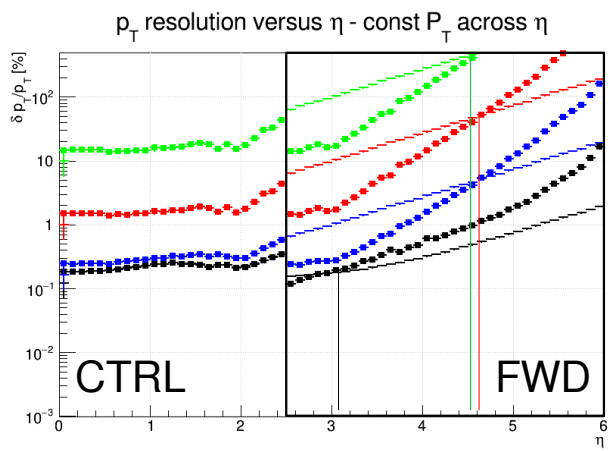

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→ **$\Delta p_T/p_T$ ~10% up to η=5!**

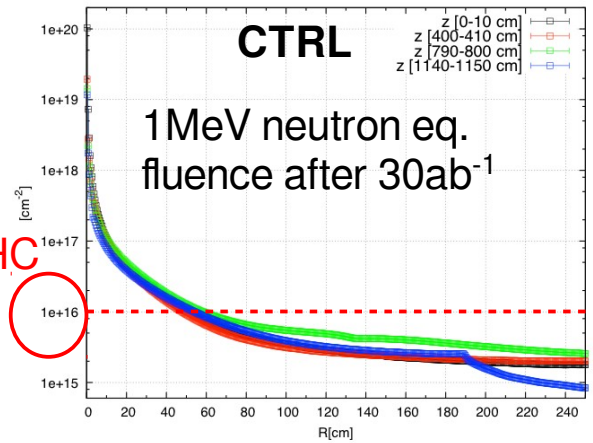
→ **6T scenario** → technology challenging option with cost ~ 0.7-0.9 BEuros → as the cost of detector should be ~20-30% of magnet → ~~**multi-billion detector**~~ **(probably not well justified)**

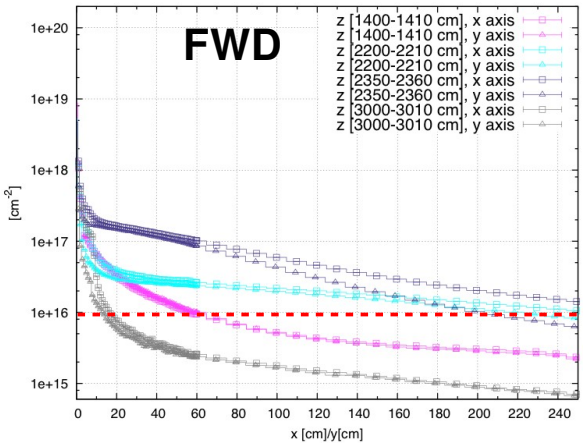
→ **Focus on scenario with more aggressive detector technologies: x/X_0=0.5-1.0%** (cf. ALICE ITS with MAPS, but radiation hard), **σ_{res} ~ 5-10um**, sensors in tilted geometry**, B=4T/10m** (4Tm dipoles)

Tracker Design (FCC-hh) – Limits, Triggering

- **The technology for inner/fwd tracker is challenged due to high radiation** (Fluka with DPMJET-III):

HL-LHC limit





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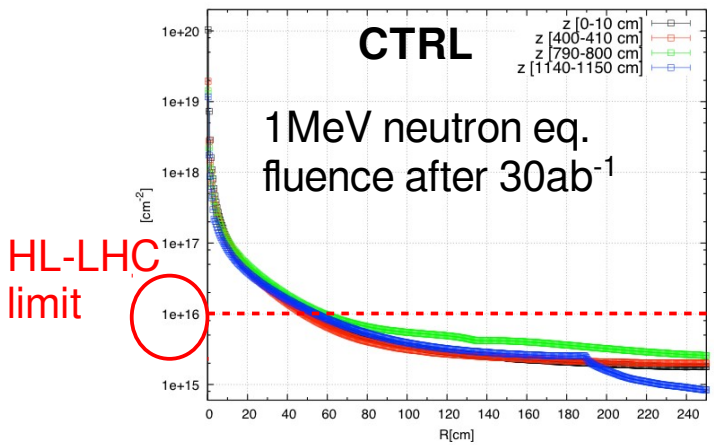

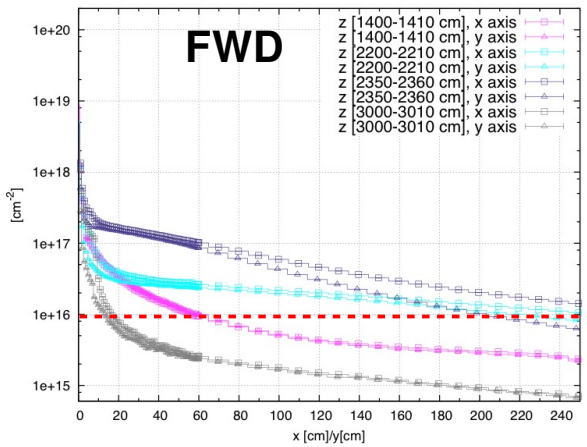

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- **Trigger & Data rates**
  - **Pipelined hardware trigger** versus **software trigger**? Need to start with trigger design in parallel …
  - For illustration - 40MHz versus 1MHz data output from binary pixels @ given fluences:

Data rate per module - 40Mhz,spars [Gb/s]:	3697.74	439.35
Data rate per module - 1Mhz,spars [Gb/s]:	92.44	10.98

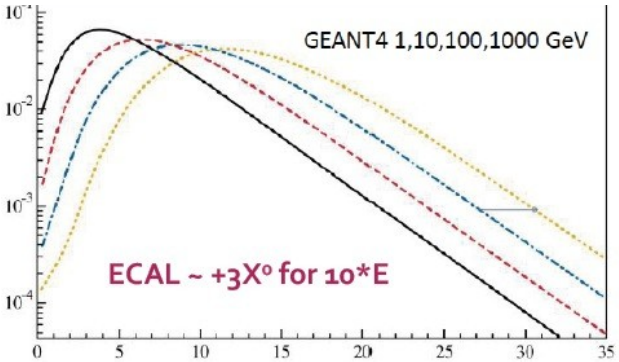
380 (44) Gb/s/cm^2
9.5 (1.1) Gb/s/cm^2

1100TB/s/(pixel BRL+FWD)
30TB/s/(pixel BRL+FWD)

  - For comparison: the largest Google data centers ~ 1Pb/s

Electromagnetic Calorimeter for FCC-hh

- **ECAL Design:**
  - |η| up-to 6 + high granularity
  - Linear response (cf. ATLAS m_H measurement → non-linearity a dominant systematic)
  - Const. res. term <1% essential (affects width of $m_{\gamma\gamma}$ → H self-coupling measurement, etc.)
  - **Depth moderately sensitive on √s → 30X_0 sufficient** (ATLAS ~22X_0) → **FCCSW simulations ongoing** with **LAr/Pb** (Si/W as option) → rad-hard technologies



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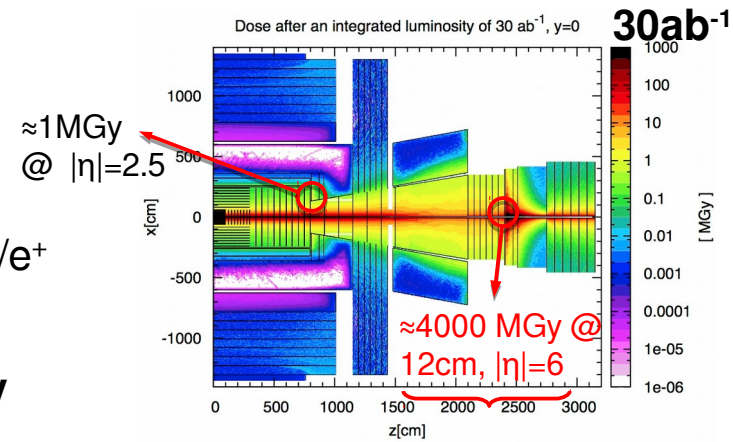
- **Challenges:**
  - **High radiation tolerance, especially in the FWD region**
  - High B field/large R affect bremsstrahlung to be away from e^-/e^+ (~30cm for 20GeV e^-)

    → **Clever matching between ECAL & tracker necessary**

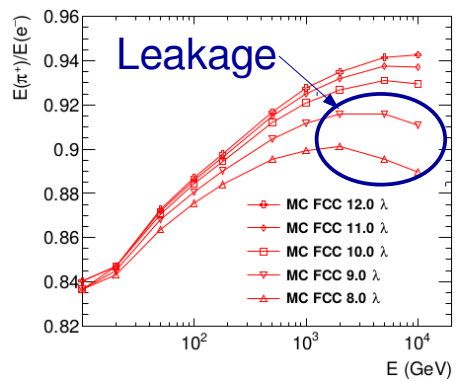


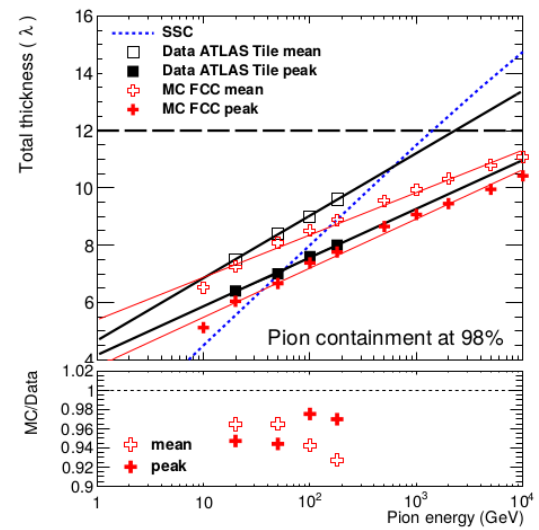
~1000 x worse than 1pxl layer @ HL-LHC

Hadronic Calorimeter for FCC-hh

- **HCAL Design:**
  - |η| up-to 6 + high granularity (as for ECAL)
  - **jet containment:** 30 TeV jet: 15% of hadrons with E>1 TeV! → **98% containment (ECAL+HCAL) requires 12λ$_{int}$** (arXiv:1604.01415)

    → **FCCSW simulation on the way** with TileCal (ATLAS HCAL) as a prototype (rad. level lower → scintillators OK)

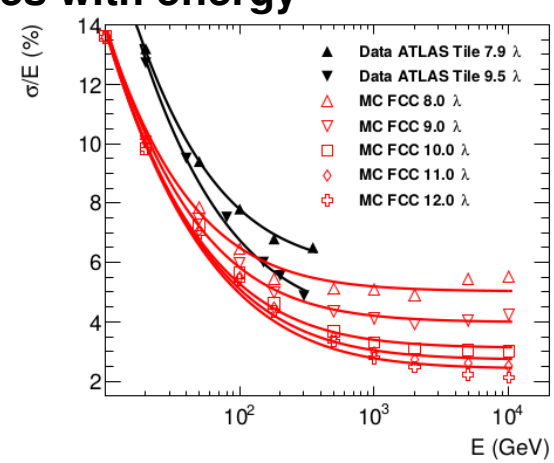




Total thickness to contain signle π⁺

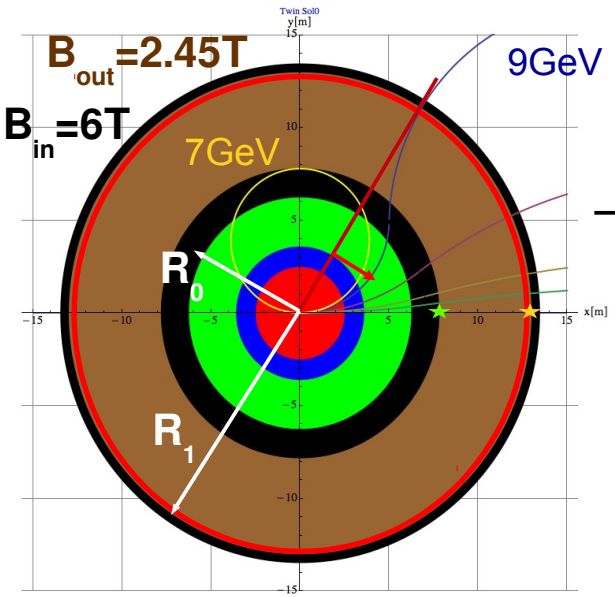
- **Challenges:**
  - **Performance of calorimeter improves with energy**

    → for p_T>5TeV/c the const. term dominates → **target ~2%**

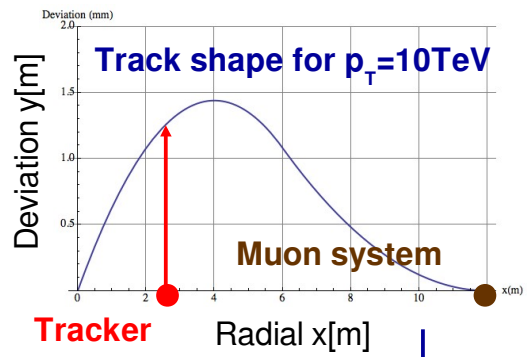


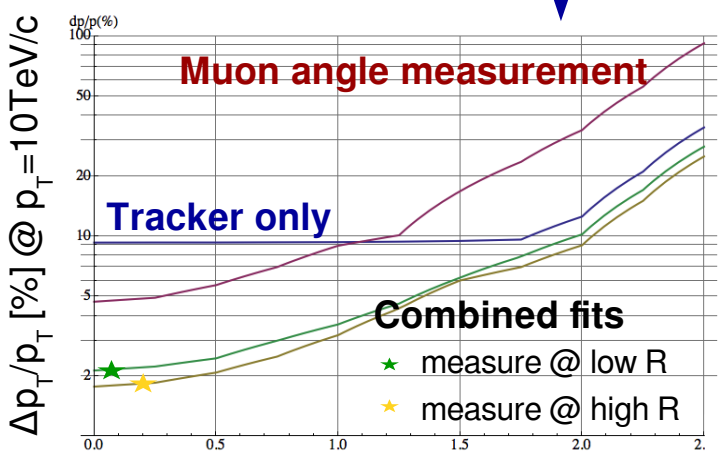
Muon System (FCC-hh)

- **Design of muon system:**
  - Combine tracker & muon system (utilizing magnet design with return yoke) → **measure track shape**



✔ B~0T for $R>R_1$ → **tangent @ $R=R_1$ points to origin!**





→ **2% res. @ 10 TeV/c, η=0**

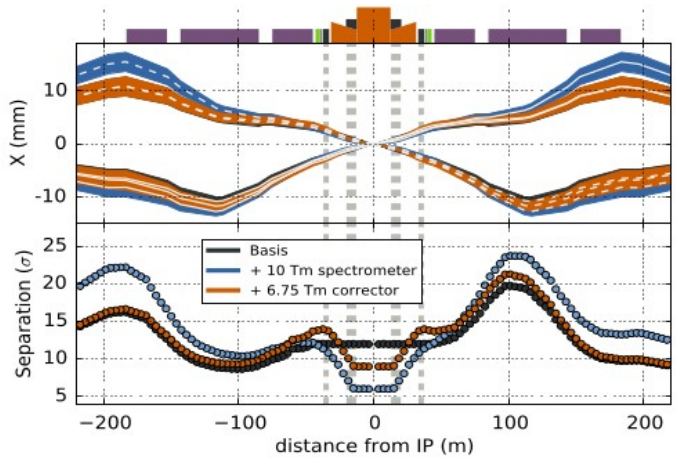
(8% res. @ 10 TeV/c, η=2)

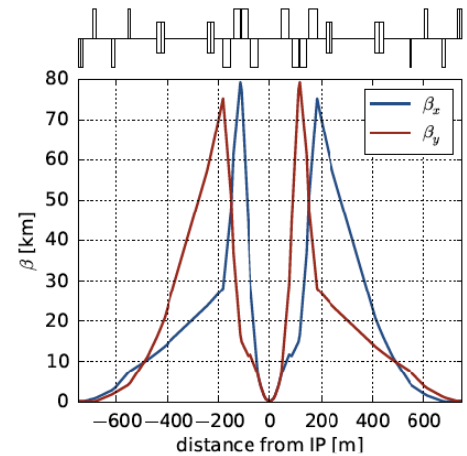
Shielding coil can be @ lower R
Muon system can be slimmer

FCC-hh Machine Detector Interface (MDI)

- Studied L*=36, 61m (focus length) → **consensus with detector people on L*=45m**

→ New optics design with longer triplets (~130m), dipole compensator (6.75Tm) & more beam-stay-clear to separate beams:





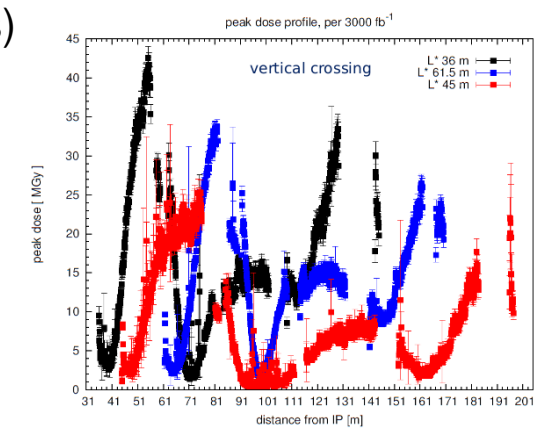
Optics for β*=0.3
→ Phase 2

→ Optimization of triplet region to prevent from collision debris (mostly pions)

+ TAS/TAN & triplet shielding (tungsten):

- Studied vertical versus horizontal beam crossing, influence of dipole compensator magnet, ...

  → Current design OK: can fulfill ~100MGy limit per O(20ab^{-1})

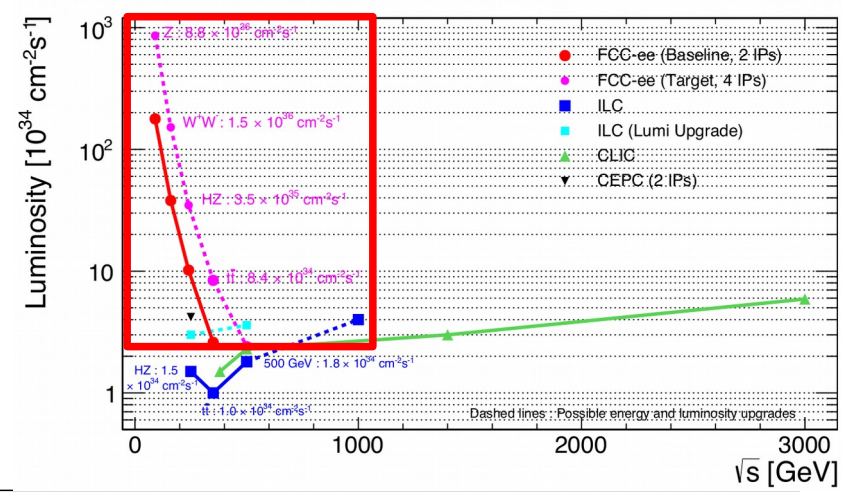


Key FCC-ee Parameters

Parameter	FCC-ee (400 MHz)					LEP2
Physics working point	Z		WW	ZH	tt_{bar}	
Energy/beam [GeV]	45.6		80	120	175	105
Bunches/beam	30180	91500	5260	780	81	4
Bunch spacing [ns]	7.5	2.5	50	400	4000	22000
Bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
Beam current [mA]	1450	1450	152	30	6.6	3
Luminosity/IP x 10^{34}cm^{-2}s^{-1}	210	90	19	5.1	1.3	0.0012
Energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
Synchrotron power [MW]	100					22

Same FCC optics for all energies

- Precision measurements require high luminosity → **FCC-ee: an ultimate Z, W, H, t factory**



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RF cavity needs to compensate it

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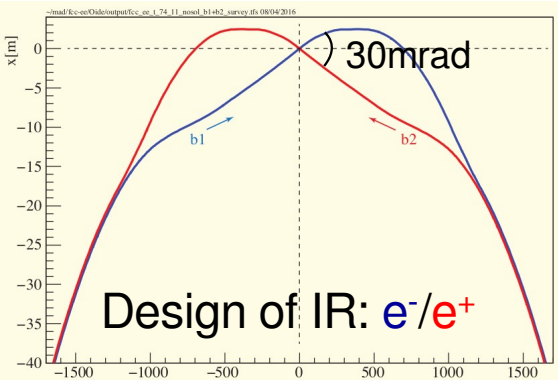
  - Huge number of bunches per beam → **need for crossing angle (30 mrad) & 2 separate rings to avoid parasitic interactions**
  - **Large amount of synchrotron radiation**, especially at tt_{bar} (energy loss, background)
  - Extreme luminosity values → **small beam size & L* (~2m) necessary → focusing quads close to IP + "packed design for the forward instrumentation"**

→ **IR design a crucial part of detector design study**

FCC-ee IR & Detector Design

- **IR** design driven by the hardest: tt_{bar} option → **study to limit the synchrotron radiation**



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→ **Studies show that SR γ rates similar to LEP2 level → OK**

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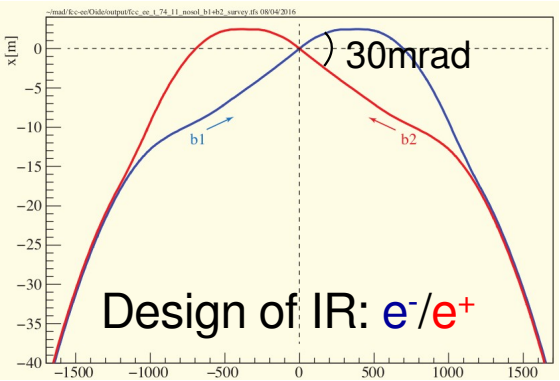

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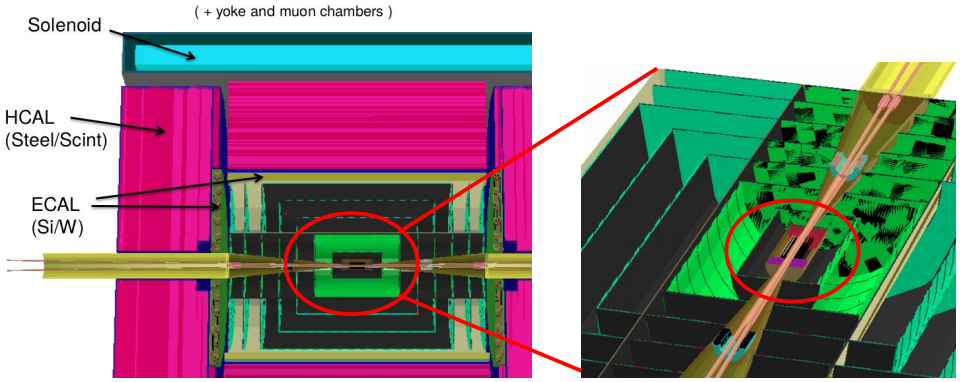
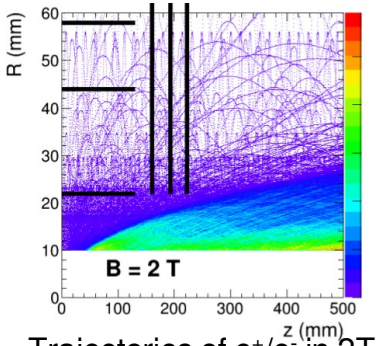
- **Using CLIC detector & CLIC software** as a natural starting point

→ detector minimally adapted to FCC-ee conditions (IR design → VXD + Tracker)



→ **Full simulations started to understand** the key limits of detector design due to background (SR, beamsstrahlung):



Trajectories of e^+/e^- in 2T

→ **Starting to formulate the key physics requirements on detector design**

Common Software Framework

- Aim of FCC SW project is to support all FCC options and share software among them:
  - Sharing the collaborative experience with: **ATLAS** (tracking), **CMS** (analysis interface), **LHCb** (simulation frame, infrastructure), **CLIC** (grid processing)
  - **Central building blocks:**
    - **GAUDI** (underlying framework) **+ PODIO** (C++ library supporting handling of event-data models)
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    - **Externals: Geant4, DD4Hep** (for data description), **Delphes** (for parametrized simulations)
  - **Simulations, Reconstruction & Analysis::**
    - Delphes: FCC-hh prepared a common detector description for parametrized physics studies
    - Participation in CMS tkLayout project (tracker design studies)
    - Technical infrastructure developed for combined fast/full simulation with Geant4
    - Joint project with ATLAS: ACTS - ATLAS track reconstruction software
    - PAPAS for fast simulation and particle-flow reconstruction
    - HEPPY (CMS) as python-based analysis framework
    - Standalone reader for FCC data model

  → see https://github.com/HEP-FCC , http://fccsw.web.cern.ch/fccsw

Summary & Outlook

- There is **a lot of progress since the FCC kick-off meeting in February 2014** in all FCC related projects: FCC-hh, FCC-ee and FCC-eh (not covered here)
- **The FCC detector & MDI** studies **can heavily draw from the LHC experiments** and their upgrade plans (FCC-hh) or **CLIC/ILC projects** (FCC-ee)
- As for the detector technology, the **FCC detectors (particularly for FCC-hh) require a significant R&D on detectors and electronics.** Once the LHC Phase II R&D is finished, there is a crucial need for installing a dedicated R&D program
- **The FCC project is an excellent environment to transfer an immense amount of knowledge and experience in our field to the young generation**

Thank you!

My sincere thanks belongs to the whole team of

FCC-hh & FCC-ee colleagues

working on the detector & MDI design