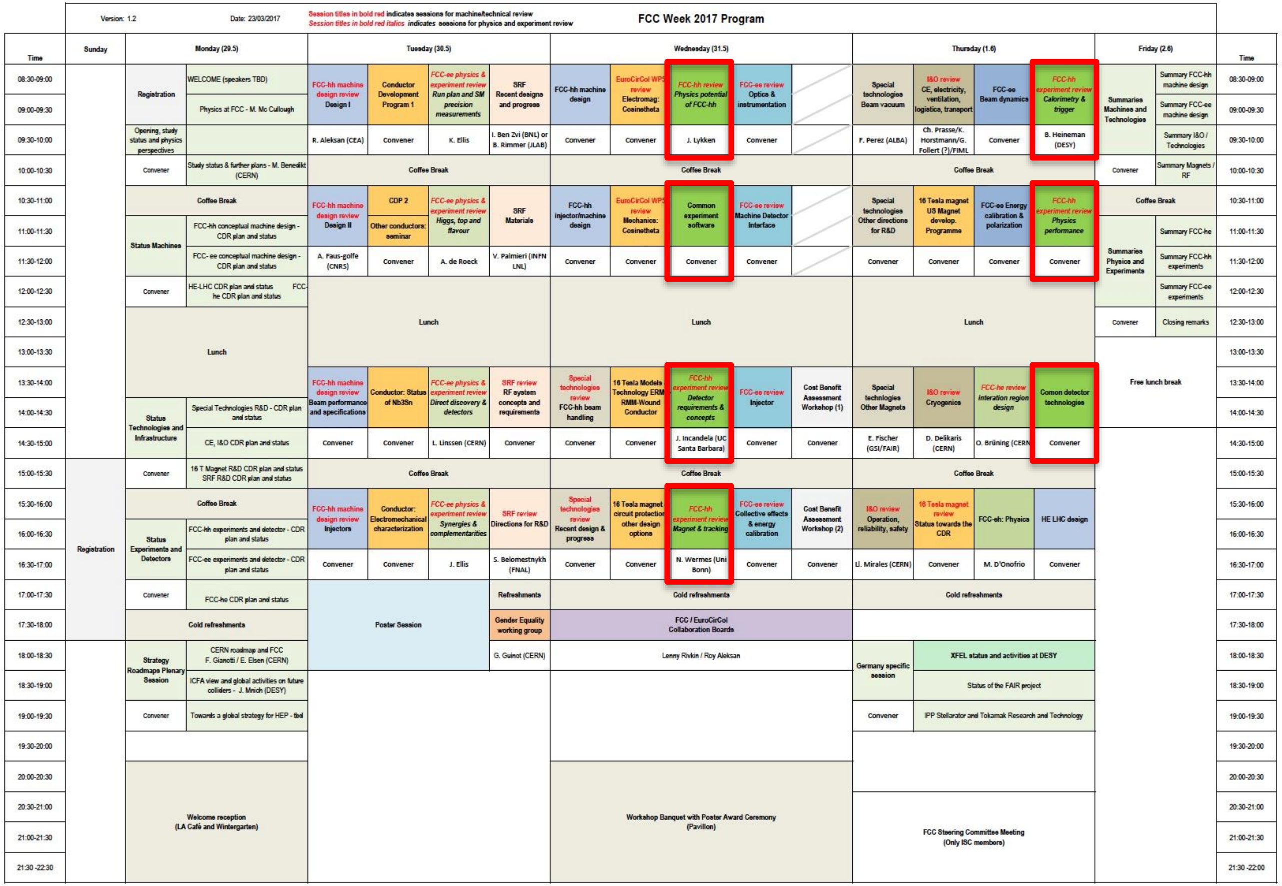
FCC-hh Experiments Summary

Summary of 7 Parallel Sessions

Martin Aleksa
on behalf of the FCC-hh Experiments WG

Scope of this Talk – Disclaimer

- This talk summary summarizes 7 sessions, 10.5 hours!
- Will not even try to do justice to all the 26 speakers!
- Apologies for having to drop important work that has been done
- Please go and have a look at the material from all the parallel sessions!



Version: 1.2

Date: 23/03/2017

Session titles in bold red indicates sessions for machine/technical review

Session titles in bold red italics indicates sessions for physics and experiment review

FCC Week 2017 Program

Time	Sunday	Monday (29.5)		Tuesday (30.5)				Wednesday (31.5)					Thursday (1.6)				Friday (2.6)		Time
08:30-09:00		Registration	WELCOME (speakers TBD)	FCC-hh machine design review Design I	Conductor Development Program 1	*FCC-ee physics & experiment review* *Run plan and SM precision measurements*	SRF Recent designs and progress	FCC-hh machine design	EuroCirCol WP5 review Electromag: Cosinetheta	*FCC-hh review* *Physics potential of FCC-hh*	FCC-ee review Optics & instrumentation		Special technologies Beam vacuum	I&O review CE, electricity, ventilation, logistics, transport	FCC-ee Beam dynamics	*FCC-hh experiment review* *Calorimetry & trigger*	Summaries Machines and Technologies	Summary FCC-hh machine design	08:30-09:00
09:00-09:30			Physics at FCC - M. Mc Cullough															Summary FCC-ee machine design	09:00-09:30
09:30-10:00		Opening, study status and physics perspectives		R. Aleksan (CEA)	Convener	K. Ellis	I. Ben Zvi (BNL) or B. Rimmer (JLAB)	Convener	Convener	J. Lykken	Convener		F. Perez (ALBA)	Ch. Prasse/K. Horstmann/G. Follert (?)/FIML	Convener	B. Heineman (DESY)		Summary I&O / Technologies	09:30-10:00
10:00-10:30		Convener	Study status & further plans - M. Benedikt (CERN)	Coffee Break				Coffee Break					Coffee Break				Convener	Summary Magnets / RF	10:00-10:30
10:30-11:00		Coffee Break		FCC-hh machine design review Design II	CDP 2	*FCC-ee physics & experiment review* *Higgs, top and flavour*	SRF Materials	FCC-hh injector/machine design	EuroCirCol WP5 review Mechanics: Cosinetheta	Common experiment software	FCC-ee review Machine Detector Interface		Special technologies Other directions for R&D	16 Tesla magnet US Magnet develop. Programme	FCC-ee Energy calibration & polarization	*FCC-hh experiment review* *Physics performance*	Coffee Break		10:30-11:00
11:00-11:30		Status Machines	FCC-hh conceptual machine design - CDR plan and status		Other conductors: seminar												Summaries Physics and Experiments	Summary FCC-he	11:00-11:30
11:30-12:00			FCC- ee conceptual machine design - CDR plan and status	A. Faus-golfe (CNRS)	Convener	A. de Roeck	V. Palmieri (INFN LNL)	Convener	Convener	Convener	Convener		Convener	Convener	Convener	Convener		Summary FCC-hh experiments	11:30-12:00
12:00-12:30		Convener	HE-LHC CDR plan and status FCC-he CDR plan and status	Lunch				Lunch					Lunch					Summary FCC-ee experiments	12:00-12:30
12:30-13:00		Lunch															Convener	Closing remarks	12:30-13:00
13:00-13:30																	Free lunch break		13:00-13:30
13:30-14:00				FCC-hh machine design review Beam performance and specifications	Conductor: Status of Nb3Sn	*FCC-ee physics & experiment review* *Direct discovery & detectors*	SRF review RF system concepts and requirements	Special technologies review FCC-hh beam handling	16 Tesla Models Technology ERM RMM-Wound Conductor	*FCC-hh experiment review* *Detector requirements & concepts*	FCC-ee review Injector	Cost Benefit Assessment Workshop (1)	Special technlogies Other Magnets	I&O review Cryogenics	*FCC-he review* *interation region design*	Comon detector technologies			13:30-14:00
14:00-14:30		Status Technologies and Infrastructure	Special Technologies R&D - CDR plan and status																14:00-14:30
14:30-15:00			CE, I&O CDR plan and status	Convener	Convener	L. Linssen (CERN)	Convener	Convener	Convener	J. Incandela (UC Santa Barbara)	Convener	Convener	E. Fischer (GSI/FAIR)	D. Delikaris (CERN)	O. Brüning (CERN	Convener			14:30-15:00
15:00-15:30	Registration	Convener	16 T Magnet R&D CDR plan and status SRF R&D CDR plan and status	Coffee Break				Coffee Break					Coffee Break						15:00-15:30
15:30-16:00		Coffee Break		FCC-hh machine design review Injectors	Conductor: Electromechanical characterization	*FCC-ee physics & experiment review* *Synergies & complementarities*	SRF review Directions for R&D	Special technologies review Recent design & progress	16 Tesla magnet circuit protection other design options	*FCC-hh experiment review* *Magnet & tracking*	FCC-ee review Collective effects & energy calibration	Cost Benefit Assessment Workshop (2)	I&O review Operation, reliability, safety	16 Tesla magnet review Status towards the CDR	FCC-eh: Physics	HE LHC design			15:30-16:00
16:00-16:30		Status Experiments and Detectors	FCC-hh experiments and detector - CDR plan and status																16:00-16:30
16:30-17:00			FCC-ee experiments and detector - CDR plan and status	Convener	Convener	J. Ellis	S. Belomestnykh (FNAL)	Convener	Convener	N. Wermes (Uni Bonn)	Convener	Convener	Ll. Mirales (CERN)	Convener	M. D'Onofrio	Convener			16:30-17:00
17:00-17:30		Convener	FCC-he CDR plan and status	Poster Session			Refreshments	Cold refreshments					Cold refreshments						17:00-17:30
17:30-18:00		Cold refreshments					Gender Equality working group	FCC / EuroCirCol Collaboration Boards											17:30-18:00
18:00-18:30		Strategy Roadmaps Plenary Session	CERN roadmap and FCC F. Gianotti / E. Elsen (CERN)				G. Guinot (CERN)	Lenny Rivkin / Roy Aleksan					Germany specific session	XFEL status and activities at DESY					18:00-18:30
18:30-19:00			ICFA view and global activities on future colliders - J. Mnich (DESY)											Status of the FAIR project					18:30-19:00
19:00-19:30		Convener	Towards a global strategy for HEP - tbd										Convener	IPP Stellarator and Tokamak Research and Technology					19:00-19:30
19:30-20:00																			19:30-20:00
20:00-20:30		Welcome reception (LA Café and Wintergarten)						Workshop Banquet with Poster Award Ceremony (Pavillon)											20:00-20:30
20:30-21:00													FCC Steering Committee Meeting (Only ISC members)						20:30-21:00
21:00-21:30																			21:00-21:30
21:30 -22:30																			21:30 -22:00

Why FCC-hh?

Physics Potential of FCC-hh

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

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

- Provide firm Yes/No answers to questions like:
  - is the SM dynamics all there is at the TeV scale?
  - is there a TeV-scale solution to the hierarchy problem?
  - is DM a thermal WIMP?
  - did baryogenesis take place during the EW phase transition?

Dedicated session Wednesday 8:30 – 10:00. Please have a look!

M. Mangano

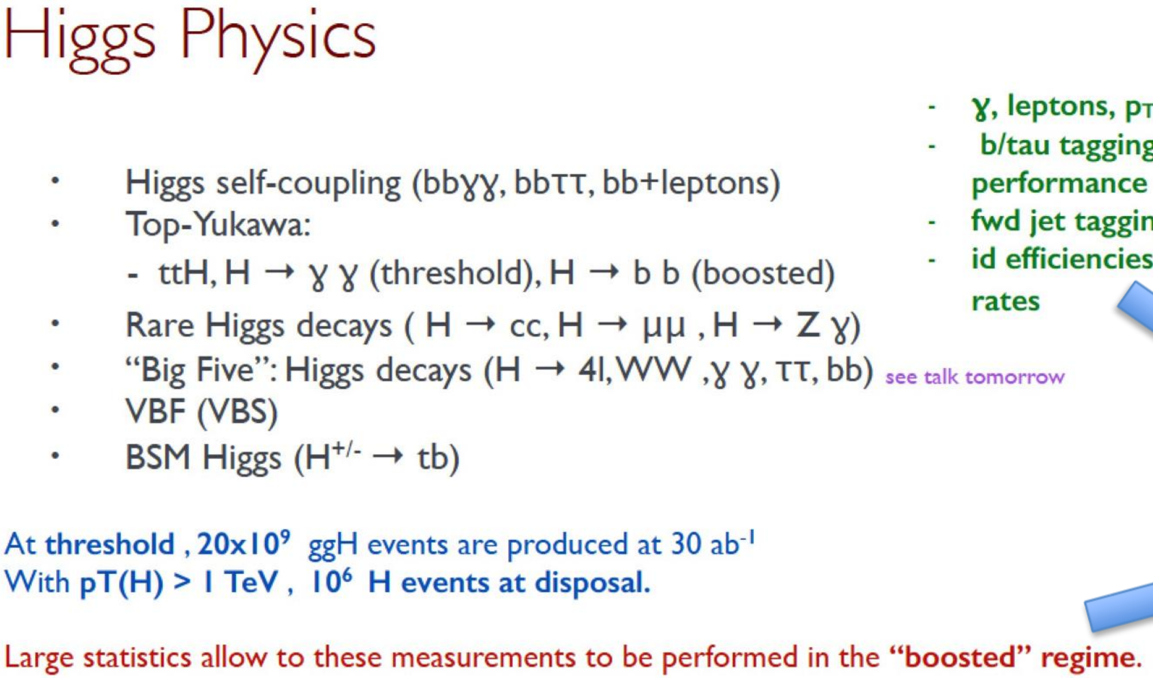
Physics Program in a Nutshell

- **FCC-hh — The ultimate discovery machine**
  - directly probe new physics up to unprecedented scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
    - "weak" m(Z') ≈ 30TeV,
    - SUSY m(gluino) ≈ 10 TeV,
    - m(stop) ≈ 5 TeV
- **Precision machine**
  - probe Higgs self-coupling to few % level, and %-level precision for top yukawa and rare decays
  - measure SM parameters with high precision
  - exploit complementarity with e^+e^- by probing high dim. operators in extreme kinematic regimes

Very interesting studies of FCC-hh measurements presented in the session Thursday 10:30 – 12:00. Please have a look!

M. Selvaggi

Physics Program → Requirements (e.g. Higgs)



Higgs Physics

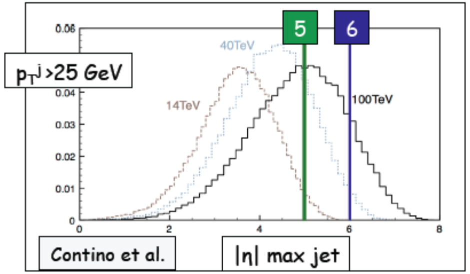
- Higgs self-coupling (bbɣɣ, bbττ, bb+leptons)
- Top-Yukawa:
  - ttH, H → ɣ ɣ (threshold), H → b b (boosted)
- Rare Higgs decays (H → cc, H → μμ , H → Z ɣ)
- “Big Five”: Higgs decays (H → 4l, WW ,ɣ ɣ, ττ, bb) see talk tomorrow
- VBF (VBS)
- BSM Higgs ($H^{+/-}$ → tb)

At threshold , 20×10^9 ggH events are produced at 30 ab^{-1}
With pT(H) > 1 TeV , 10^6 H events at disposal.

Large statistics allow to these measurements to be performed in the “boosted” regime.

- ɣ, leptons, p_T, η acc
- b/tau tagging performance
- fwd jet tagging
- id efficiencies and fake rates

VBF jets η-distr.



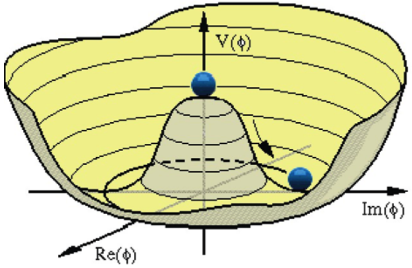
→ The FCC-hh experiments must be ‘general general’ purpose experiments with very large η-acceptance and extreme granularity (W. Riegler)

- → **Tracking target : achieve σ / p = 10-20% @10 TeV**
- → **Muons target: σ / p = 5% @10 TeV**
- → **Keep calorimeter constant term as small as possible.**
- → **Long-lived particles live longer (e.g. 5TeV B-hadron travels ~50cm before decaying)**
- → **High granularity in tracker and calos**

M. Selvaggi

Di-Higgs Studies

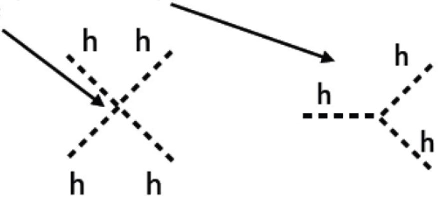
$$V(h) = \mu^2\frac{h^2}{2} + \lambda\frac{h^4}{4}$$



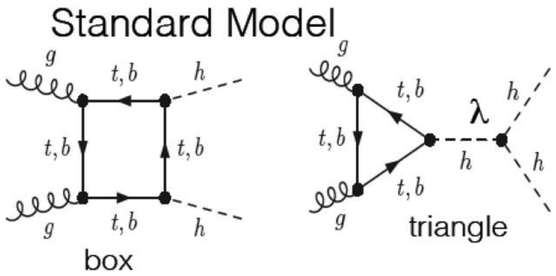
After spontaneous symmetry breaking:

$$\lambda h_0^2\eta^2 + \frac{\lambda}{4}\eta^4 + \lambda h_0\eta^3$$

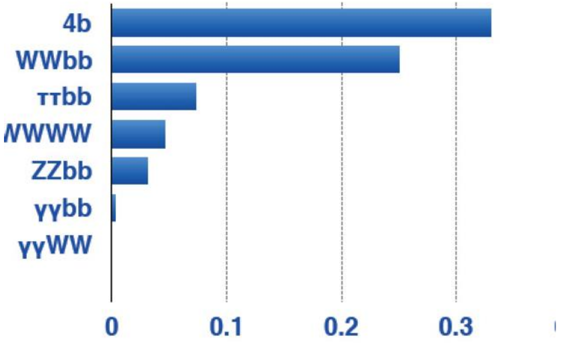
$$m_h^2 = 2\lambda h_0^2$$



The strength of the triple and quartic couplings is fully fixed by the potential shape.



Higgs decay branching fraction

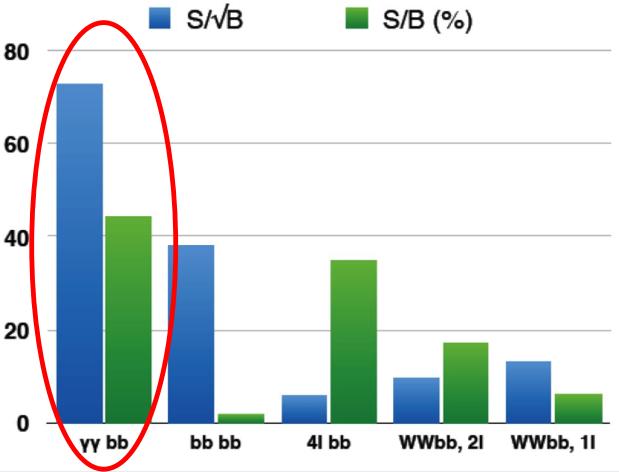


Why is Di-Higgs interesting?

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

H→γγbb is the golden channel for FCC-hh

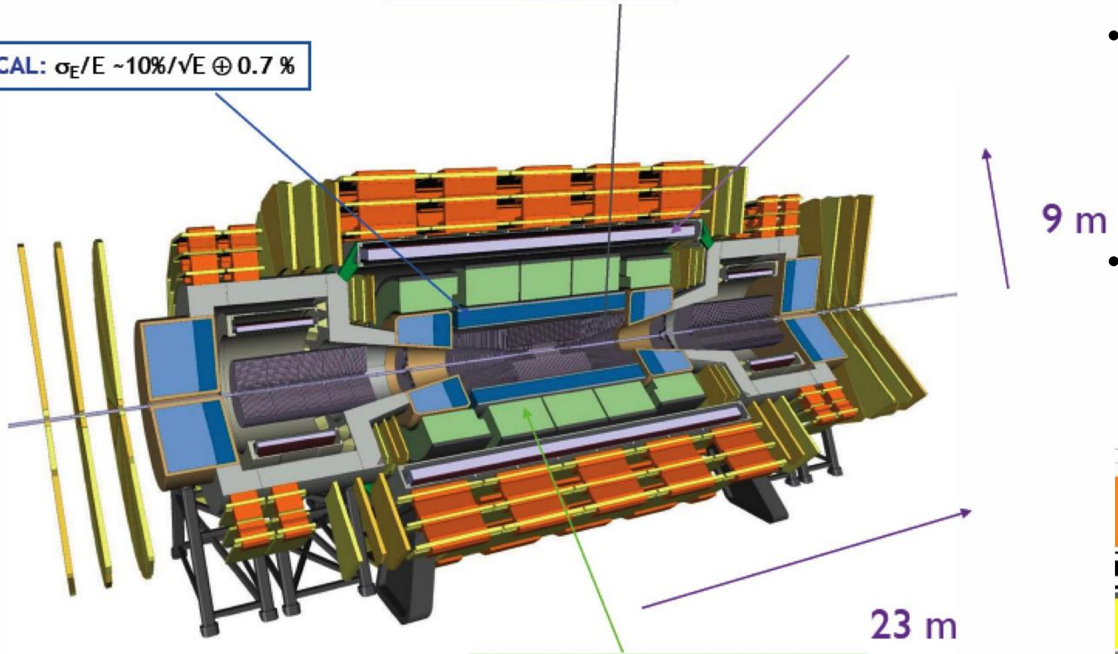
- Will derive requirements for detector (systematics, boosted objects)



B. Di Micco

How to Exploit Physics Potential?

FCC Detector – Reference Design



Tracker: σ_{pt}/pt ~ 20% at 10 TeV (1.5m radius)

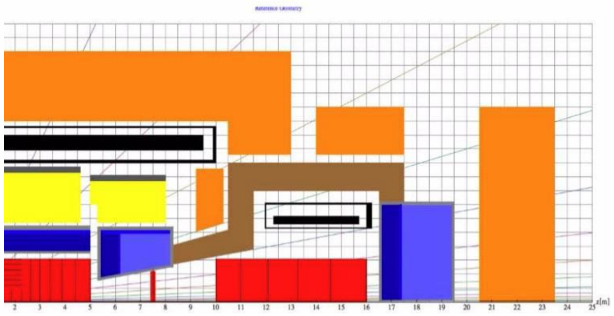
Central Magnet: 4T, 5m radius

Barrel ECAL: σ_E/E ~10%/√E ⊕ 0.7 %

Barrel HCAL: σ_E/E~50%/√E ⊕ 3 %

Fwd detectors: to η~6

- During last year converged on reference design for an FCC-hh Experiment
- Plan to demonstrate in the CDR document, that an experiment exploiting the full FCC-hh physics potential is technically feasible
- However, there is a lot of room for other ideas, other concepts and different technologies



Reference Design

6T, 12m bore solenoid, 10Tm dipoles, shielding coil

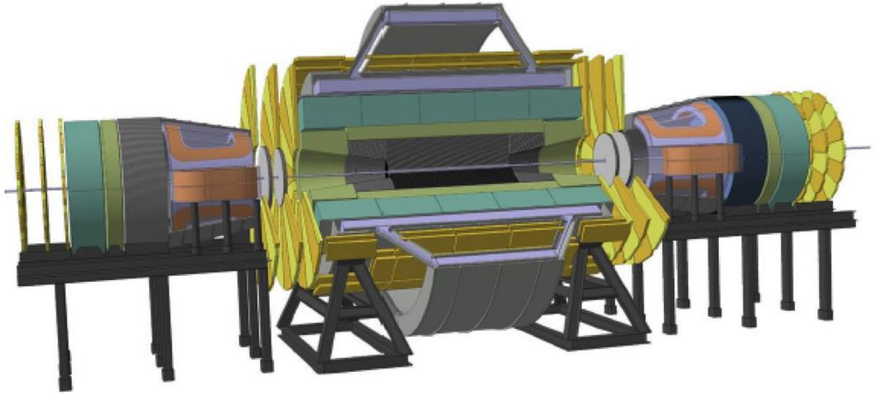
→ 65 GJ Stored Energy
→ 28m Diameter
→ >30m shaft
→ Multi Billion project

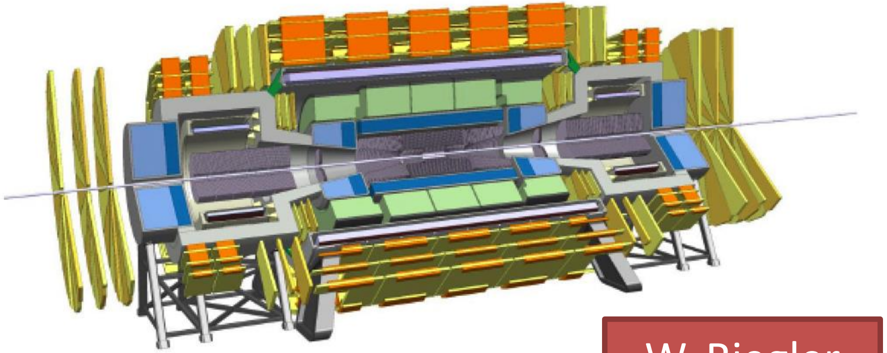
→

4T, 10m bore solenoid, 4T forward solenoids , no shielding coil

→ 14 GJ Stored Energy
→ Rotational symmetry for tracking and trigger !
→ 20m Diameter (≈ ATLAS)
→ 15m shaft
→ ≈ 1 Billion project

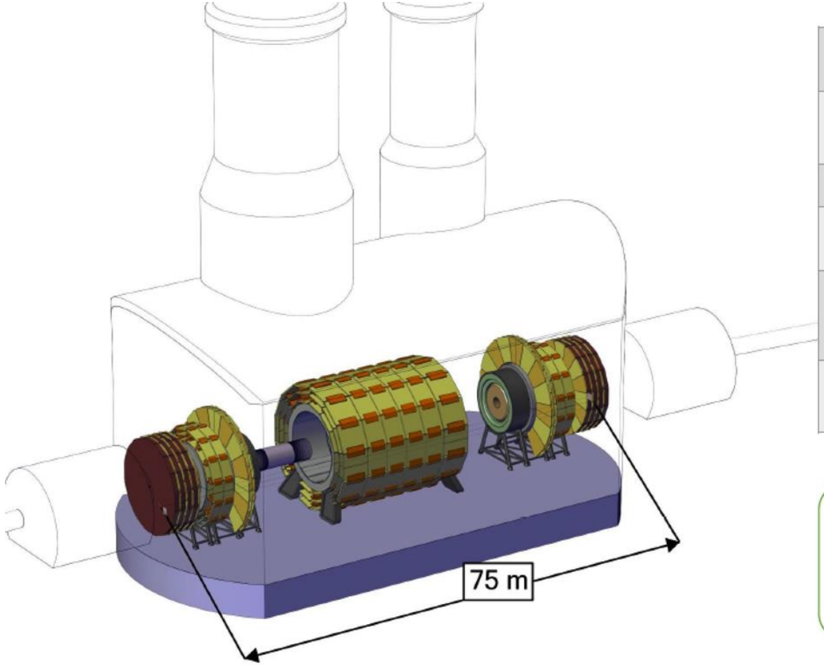
4T 10m solenoid
Forward solenoids
Silicon tracker
Barrel ECAL Lar
Barrel HCAL Fe/Sci
Endcap HCAL/ECAL LAr
Forward HCAL/ECAL LAr





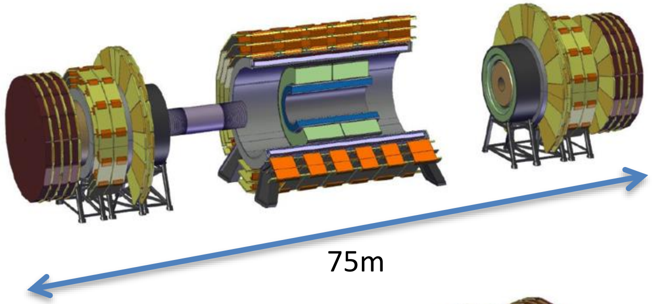
W. Riegler

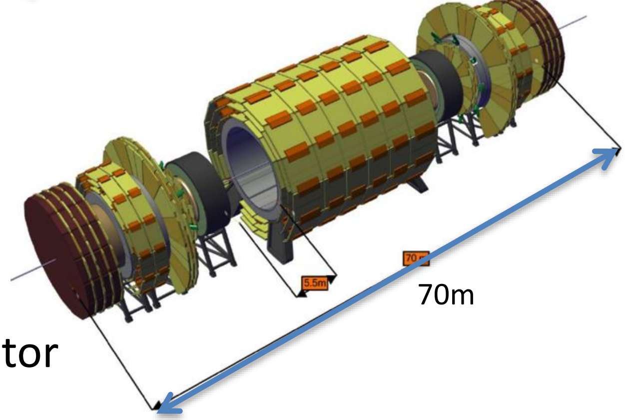
Cavern Size – Opening Scenarios



Maximum length experiment	*75m
Cavern Size (L x W x H) [m³]	75 x 30 x 35
Main Shaft diameter [m]	15
Secondary shaft diameter [m]	10
Main shaft crane requirement [kt]	2 or 3 (depends on HCAL modularity)
Secondary shaft crane requirement [kt]	0.6

* Depending on the compromises made, the open experiment length may vary from 70 m to 80m.





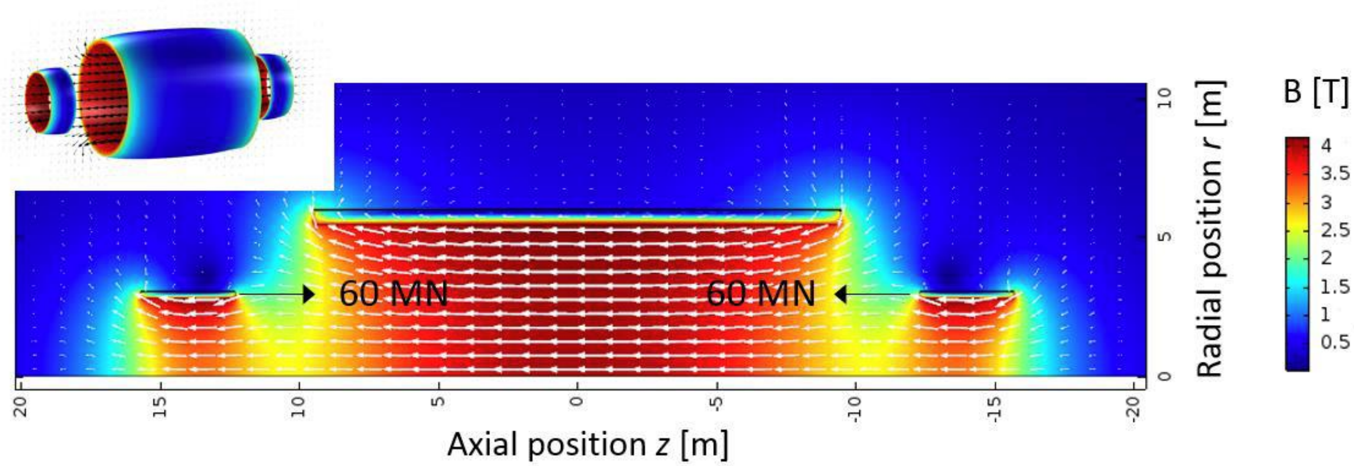
Impressive progress with opening scenarios of reference detector

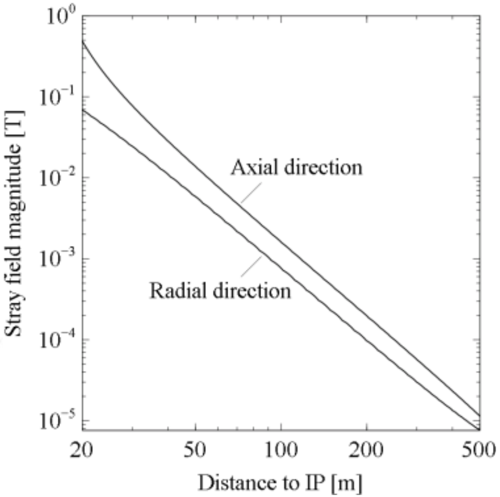
→ 75m cavern allows for tracker extraction

→ Two shafts, 15m and 10m

H. da Silva

Magnetic Field



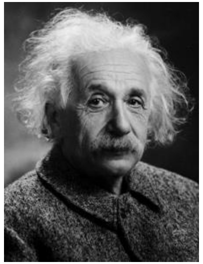


New reference design with three solenoids

- 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:

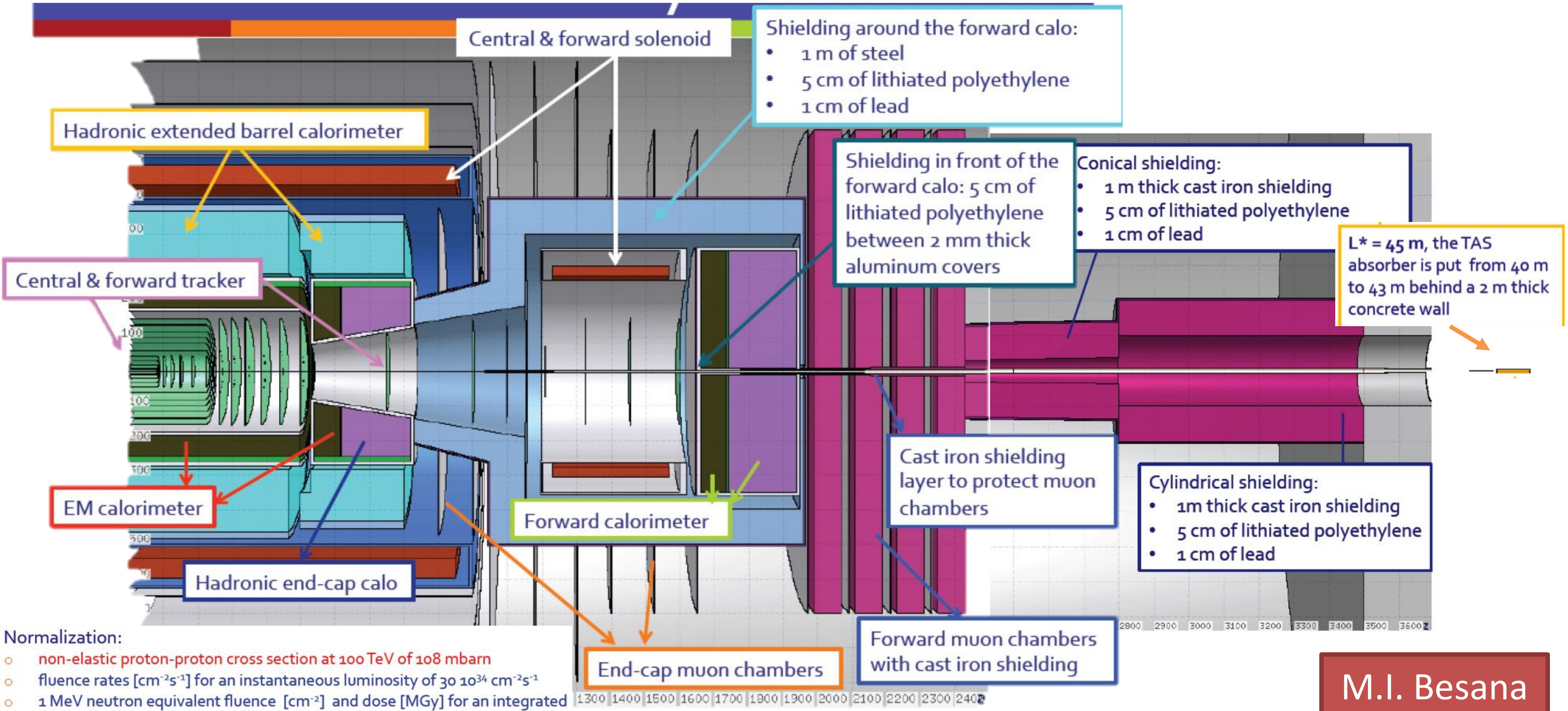
- Much simplified configuration
- Stored energy: 13.8 GJ
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field



Everything should be made as simple as possible, but not simpler (Quote attributed to Einstein)

M. Mentink

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

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

Central & forward tracker

Cast iron shielding layer to protect muon chambers

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

EM calorimeter

Forward calorimeter

Hadronic end-cap calo

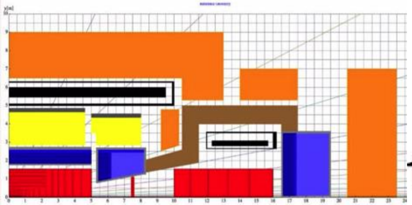
End-cap muon chambers

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}

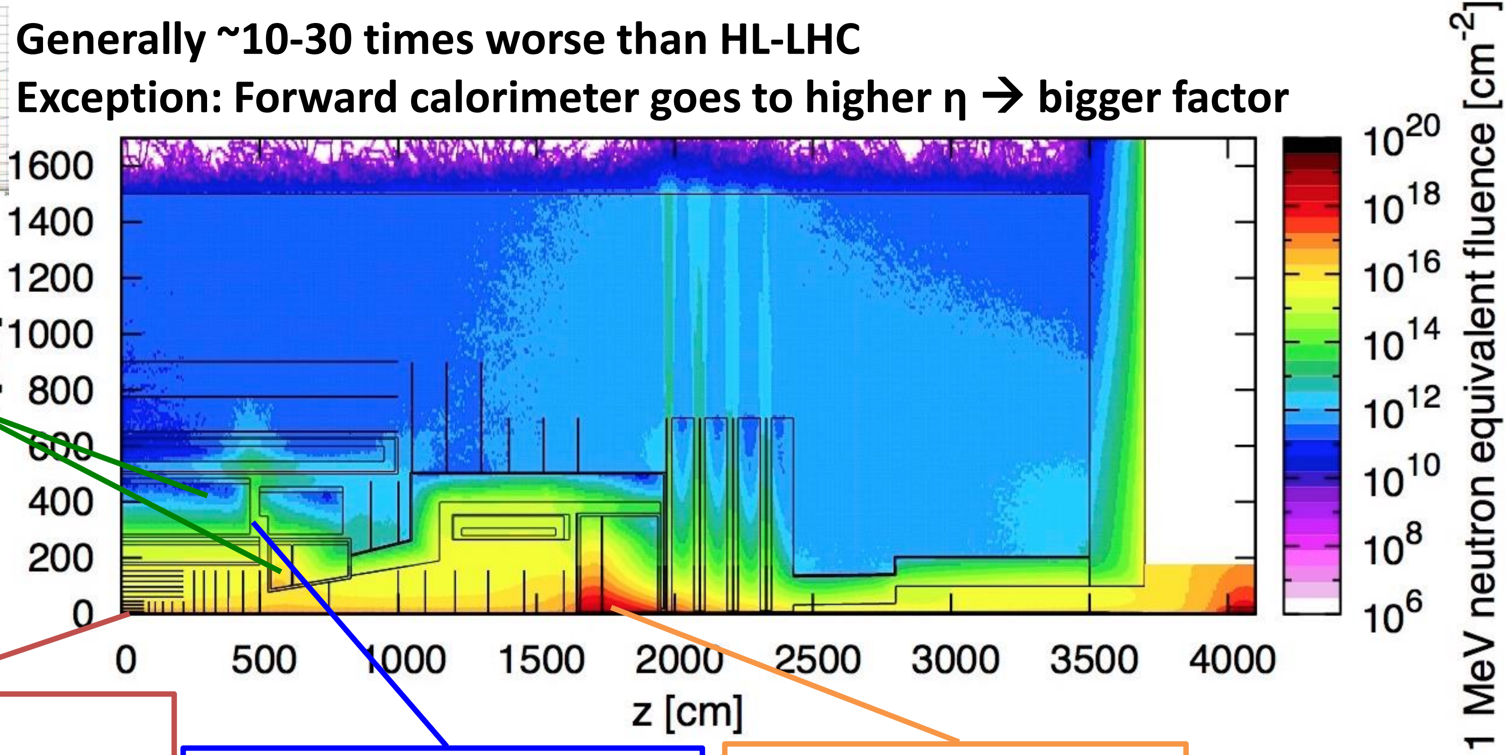
M.I. Besana

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

M.I. Besana

Software

FCC Software

Support experiments for all colliders: ee, hh & eh

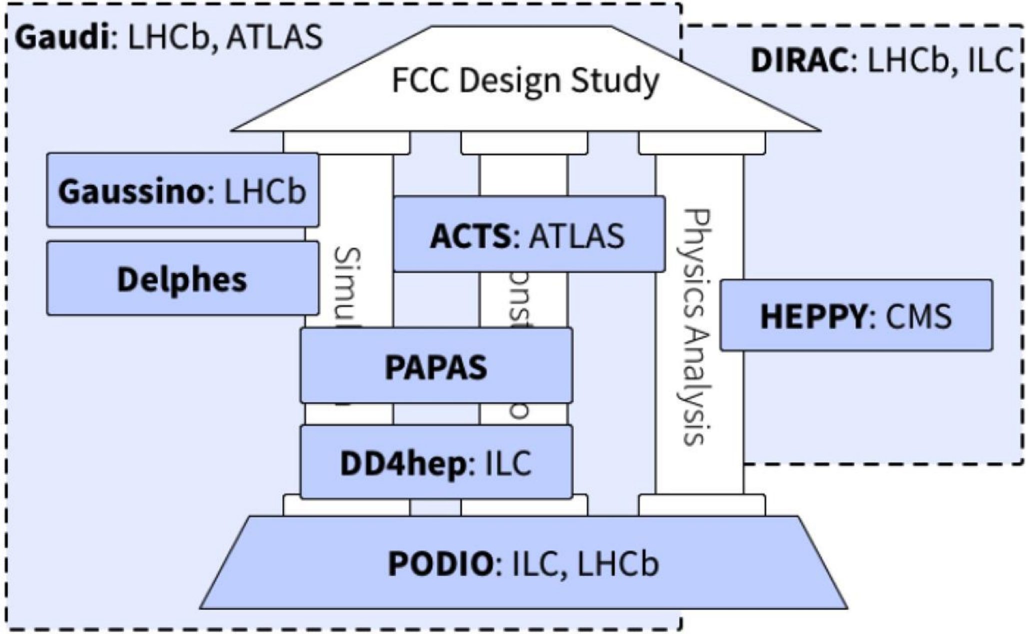
Support physics and detector studies

- Detector concepts: Moving targets
- Both fast and full simulation essential

Collaborative approach:

- Extract from the LHC experiments where possible
- Invest to new solutions where necessary

- Flexible event data model & detector description
- Simulation
  - Full simulation for detector studies
  - Fast simulation for physics benchmarks
- Reconstruction
  - pp: Extreme pile-up, extrapolation to 100 TeV
  - ee: Achieve the best possible precision
- Physics analysis
  - Allow use outside of framework
  - Python flexibility & C++ performance



Supporting GEANT4 full and fast simulation and parameterized simulation (DELPHES & PAPAS)

J. Lingemann

A Common Tracking Software Project (ACTS)

ACTS project:

- Idea: Extracting the ATLAS tracking SW to an independent tool-kit
  - Framework and experiment independent
- Integration into FCC-SW ongoing, large parts finalized
  - Geometry from DD4HEP can be read in (e.g. TkLayout FCC tracker geometry)

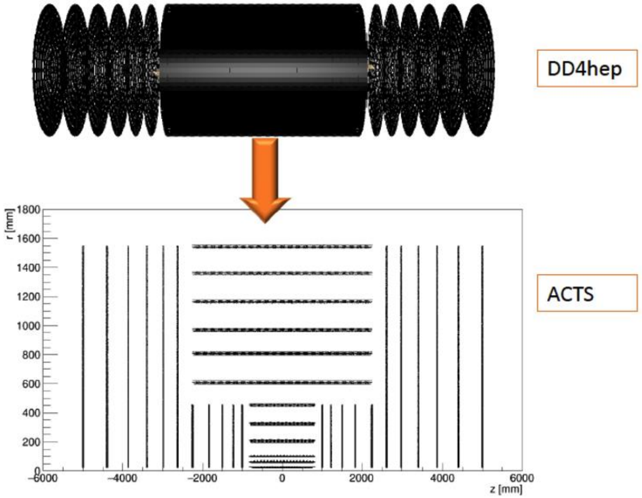
Geometry
done, validated

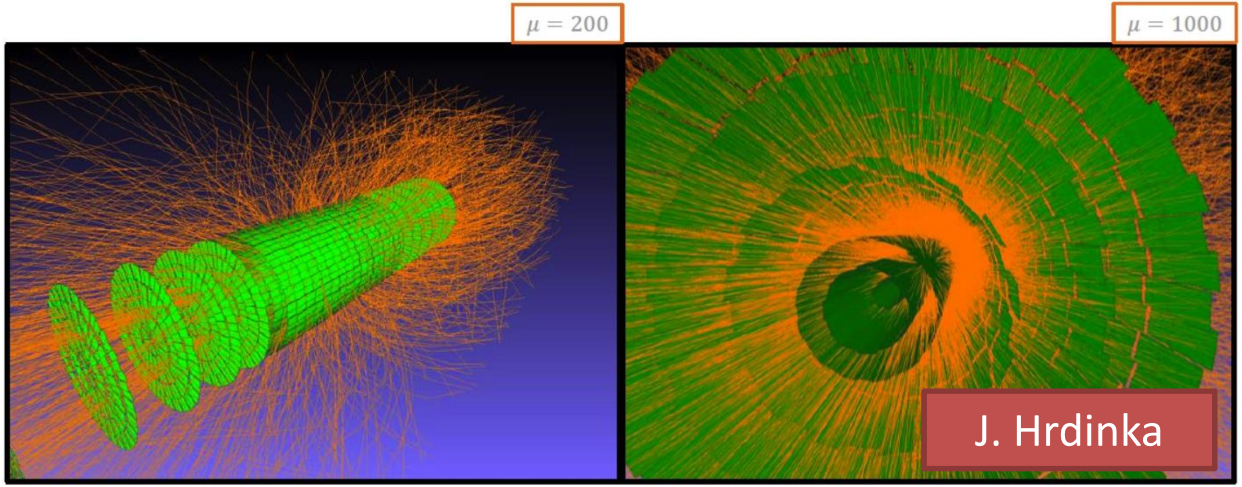
Event Data Model
done, validated

Pattern Recognition
started

Track Fitting
done, validation ongoing

- Events generated with Pythia and overlaid to a gg->H event
- FATRAS simulation w/o material effects
- Using current FCChh detector





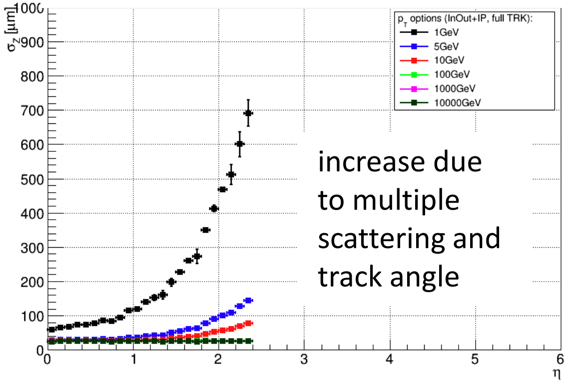
J. Hrdinka

Detector Studies

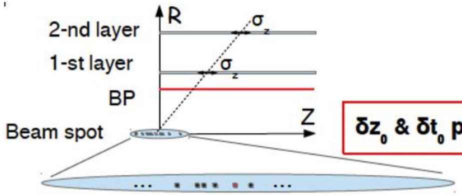
Tracker Studies

- **The challenge:** ultimate FCC-hh: ~1000 collisions per bunch crossing at 25ns bunch spacing scheme → **distance <200μm and 0.5ps in time**
- **Primary vertex identification:**
  - Important for many physics channels
  - Important for pile-up suppression
  - Important for B-tagging
  - However, σ_z resolution of single track suffers from beam-pipe material and tracker material
- **Background contamination level during track fitting:**
  - How many wrong background hits are included in the track fit?
  - Ratio of background hits in track-fit should be kept <20%
- **Both problems improved by tilted layout**
  - Material reduction → multiple scattering reduction
- **Also investigating how much timing information would help**

σ_z resolution of single track



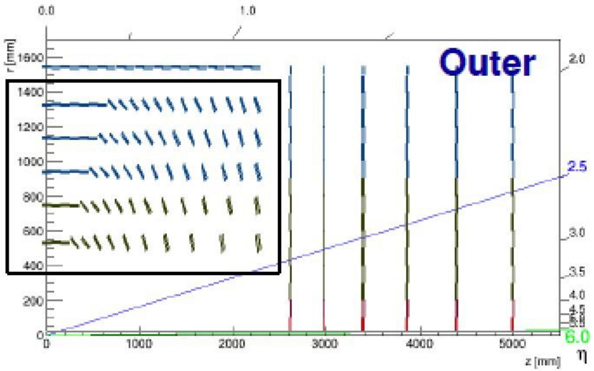
increase due to multiple scattering and track angle

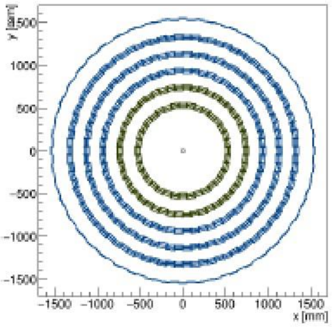


δz_0 & δt_0 play the crucial role!

Z. Drasal

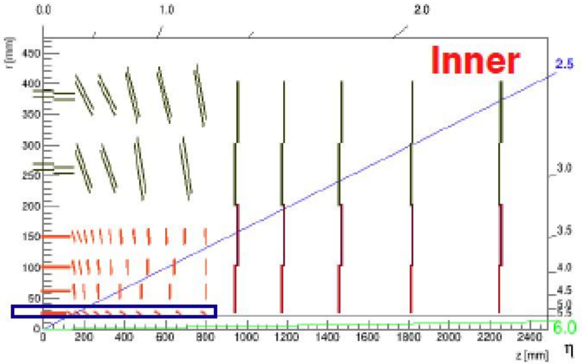
Recent Design Optimization Work (4.v01)

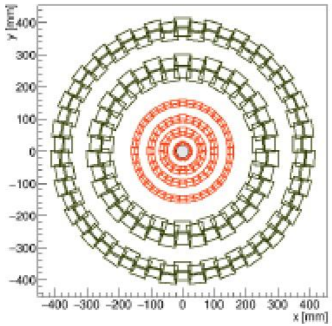




- Tilted layout of **outer tracker** driven by requirement to achieve ~**0.2 bkg. contam. level** (BCL) in PR:
  - → uppermost layer designed non-tilted to keep the highest possible lever-arm
  - → modules positioned to hermetically cover full luminous region ±75mm
  - → ECs strips res. in Z needed to be set to ~500um (~1mm OK)

TkLayout: fast detector simulation and layout design tool

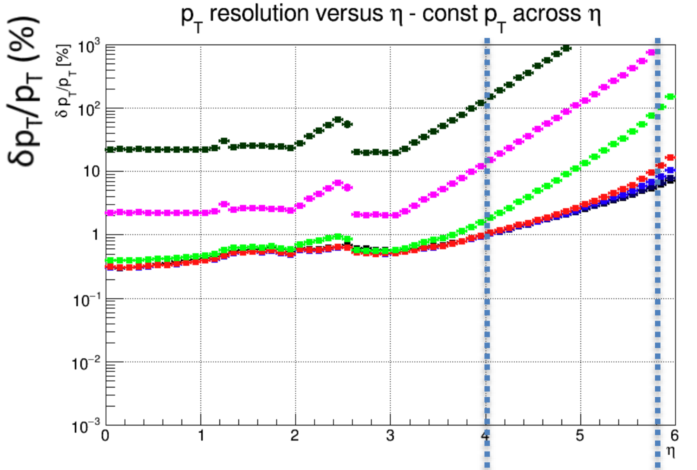




- Tilted layout of **inner tracker** driven by ~0.2 BCL in PR & **highest achievable z0 res.** (to deal with primary vertexing @PU~1000):
  - → tilt angle of 1st layer: $\vartheta_{tilt} \simeq 10^{\circ}$ optimized to achieve a compromise between low MB & higher radial position

Z. Drasal

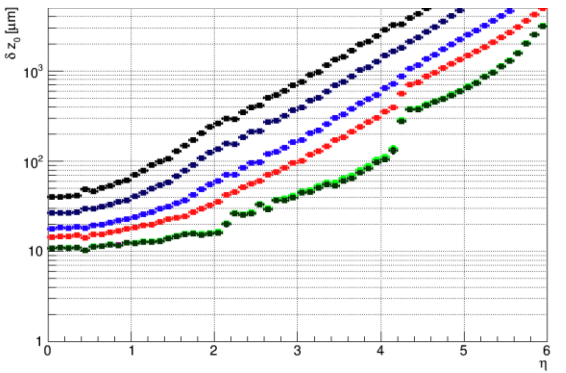
Good Performance with Tilted Layout



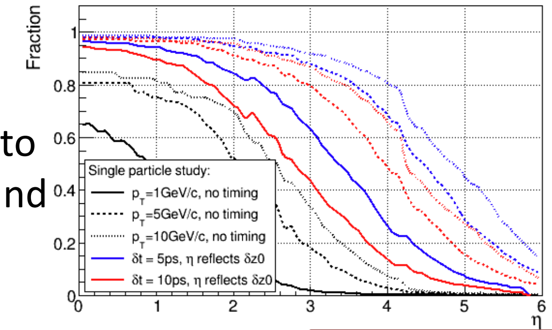
η=4.0 η=5.8

p_T = 1 GeV/c
p_T = 5 GeV/c
p_T = 10 GeV/c
p_T = 100 GeV/c
p_T = 1 TeV/c
p_T = 10 TeV/c

σ_z resolution of single track



Fraction of tracks being unambiguously assigned to PV @95% CL: $<\mu_{tot}>=1000$



Fraction of tracks correctly assigned to primary vertex w and w/o timing

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

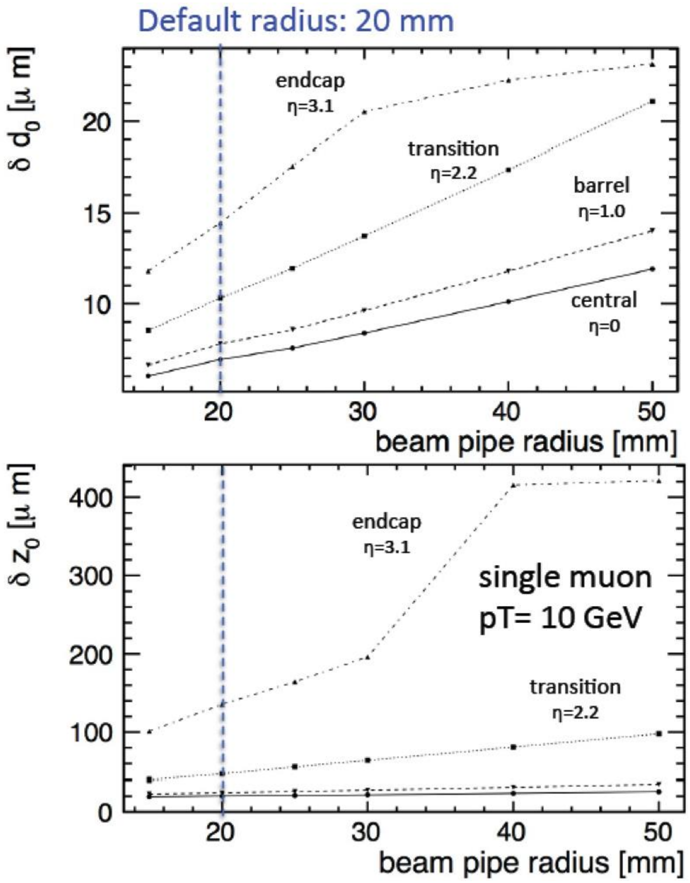
- **≤ 10 GeV/c and η ≤ 5.8**
- **≤ 1 TeV/c and η ≤ 4.0**

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

Primary vertexing @ PU~1000 seems very difficult for η>4.0, even with timing res. ~5ps!

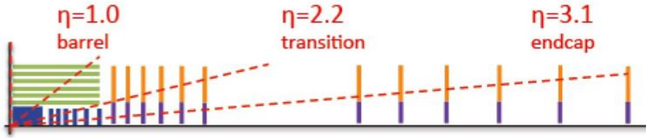
Z. Drasal

Tracking Performance



Impact parameter resolution as a function of the beam-pipe radius

Moving out the innermost barrel layer by **1 cm** would **degrade** the impact parameter resolution by **45%** for very forward tracks of pT=10 GeV. → keep radius as small as possible



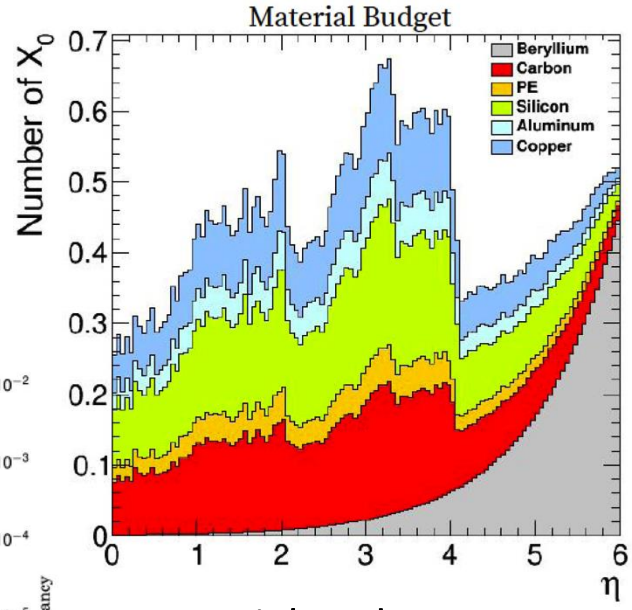
Many interesting studies!

- material studies
- beam-pipe radius
- tau decay vertex position efficiency
- B-hadron decay vertex position efficiency
- Flavor tagging

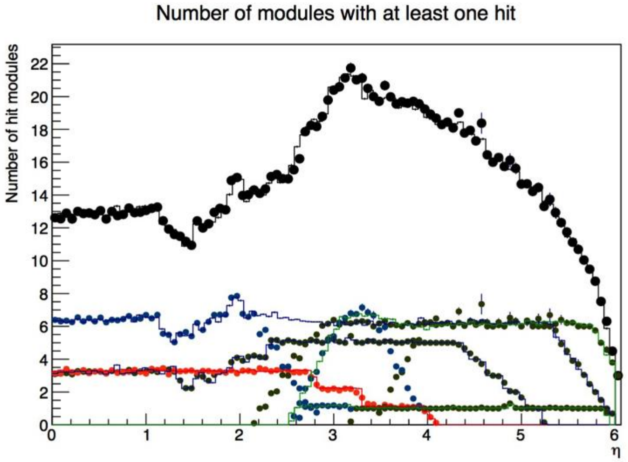
E. Perez

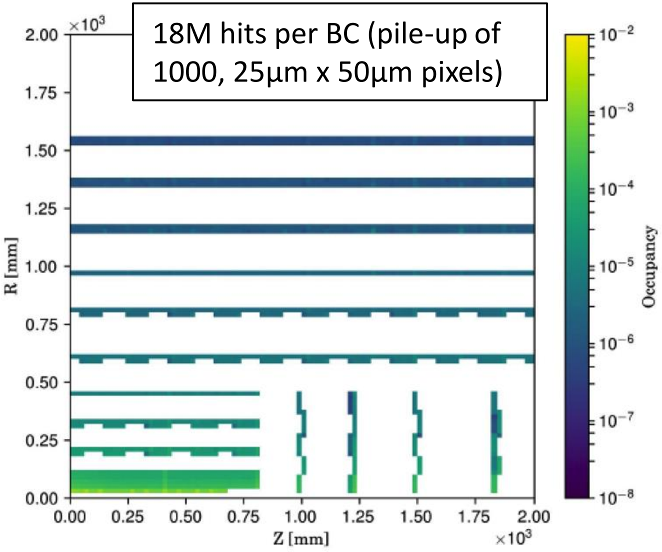
Full Simulation Tracking Studies

- Full simulation studies with FCC SW are complementing studies with TKLayout, some aspects can only be studied with full simulation
  - Needed to assess impact of pile-up on tracker performance
  - Only way to check feasibility of pattern recognition
  - Occupancy studies



Material Budget non-tilted layout (3.v02)

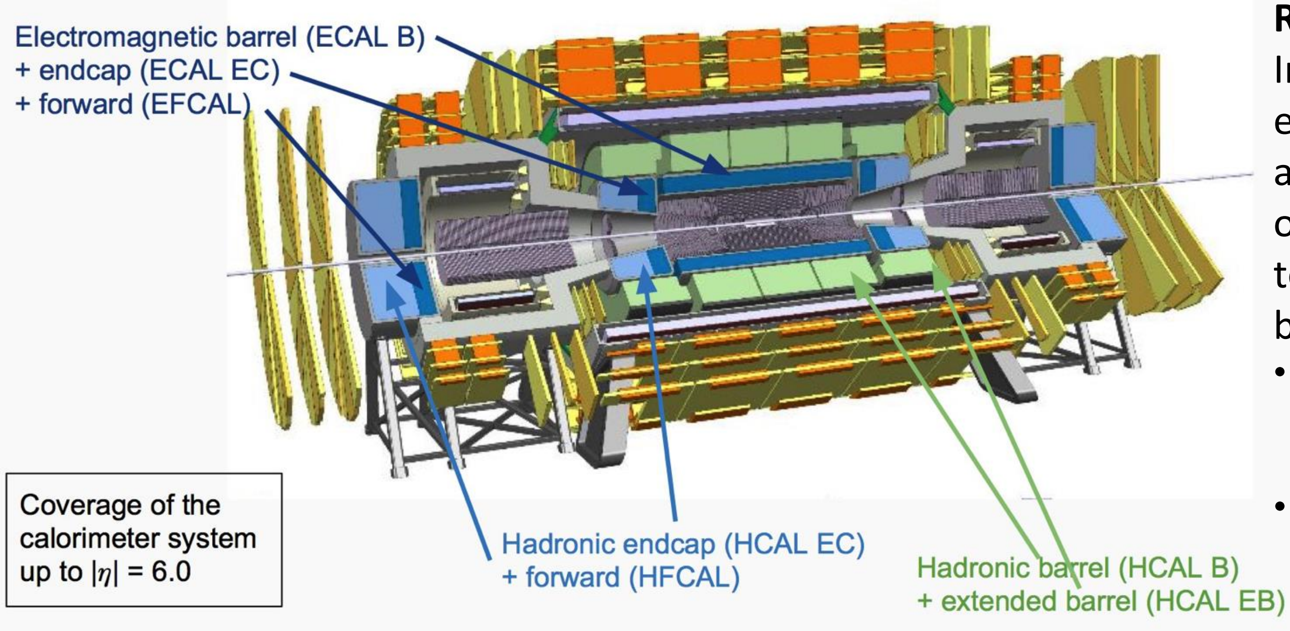




18M hits per BC (pile-up of 1000, 25µm x 50µm pixels)

V. Völkl

Calorimetry



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'….

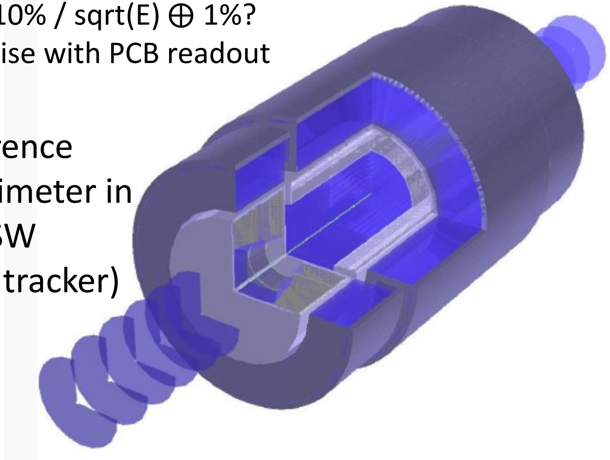
- **ECAL, Hadronic EndCap and Forward Calo:**
  - LAr / Pb (Cu) (J. Faltova)
- **HCAL Barrel and Extended Barrel:**
  - Scintillating tiles / Fe with SiPM (C. Neubüser)

Other options considered for ECAL

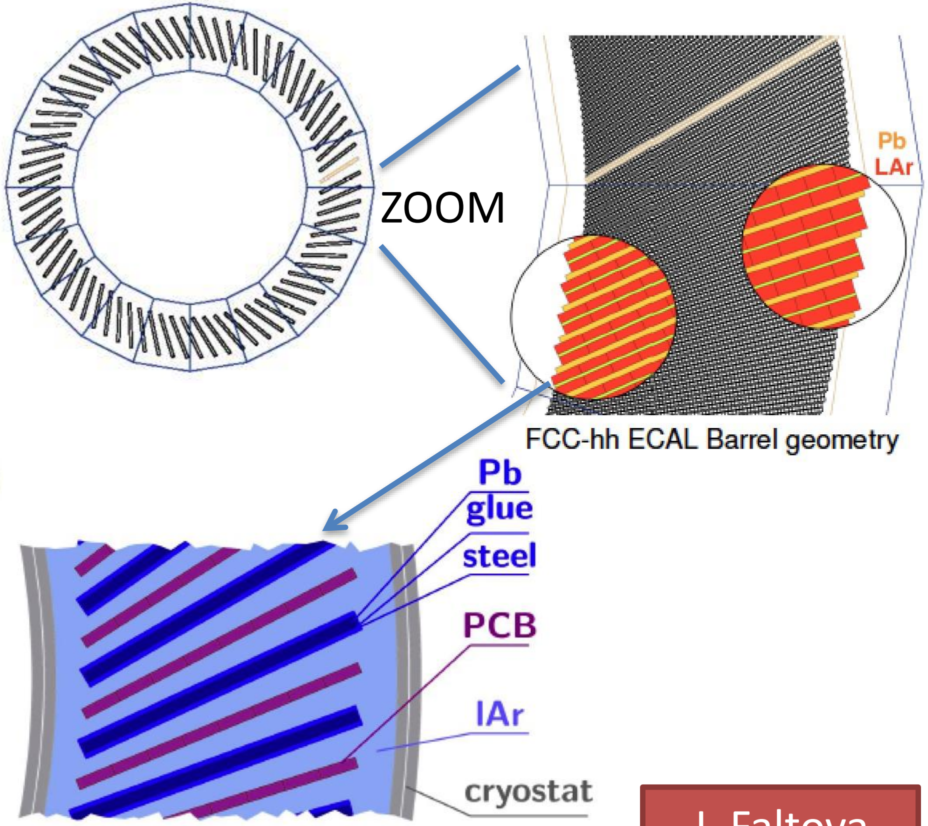
- Digital Si / W (T. Price)
- Analog Si / W (not yet studied, but will profit from CMS HGCal TDR)

Electromagnetic Calorimeter (ECAL)

- Detector with larger longitudinal and transversal granularity compared to ATLAS
  - ~8 longitudinal layers, fine lateral granularity ($\Delta\eta \times \Delta\phi = 0.01 \times 0.01$), ~2M channels
- Possible only with straight multilayer electrodes
  - Proposal: Inclined plates of absorber (Pb) + active material (LAr) + multilayer readout electrodes (PCB)
- Pros: Easy construction (compared to ATLAS accordion), higher precision
- Cons: Sampling fraction changes with radius:
  - Possible to achieve targetted electron/photon energy resolution of 10% / sqrt(E) ⊕ 1%?
  - Electronics noise with PCB readout



Reference calorimeter in FCC SW (incl. tracker)

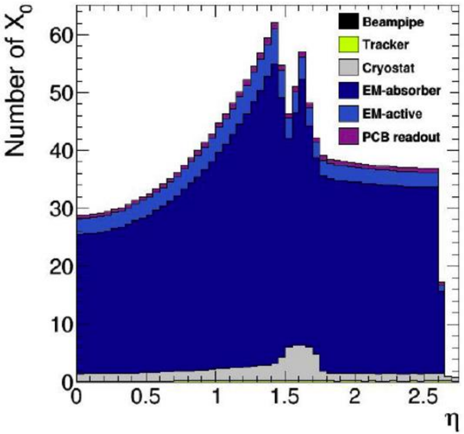


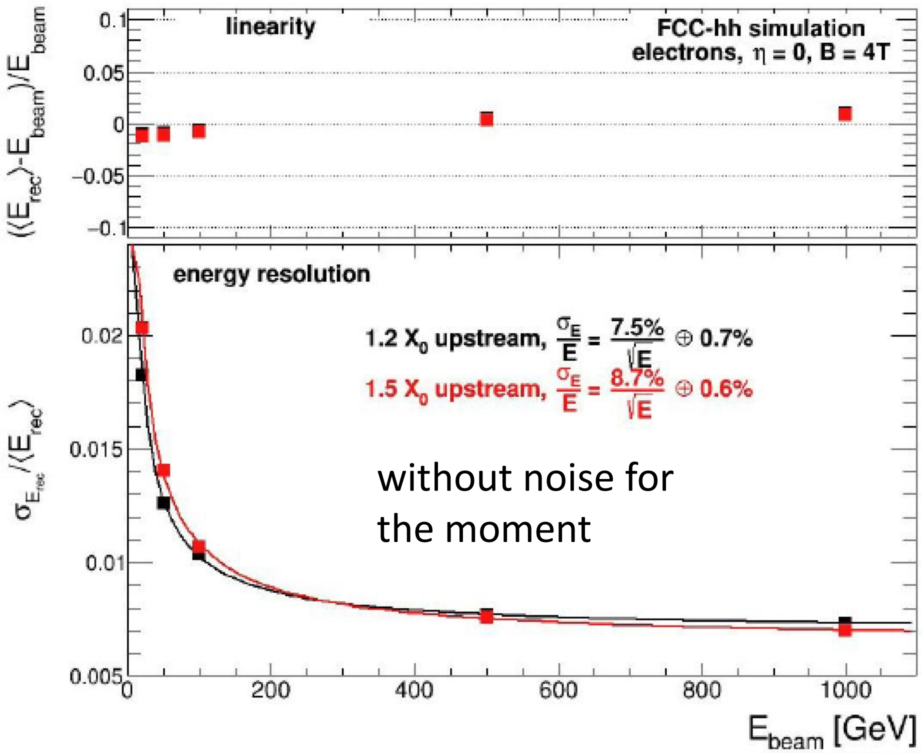
FCC-hh ECAL Barrel geometry

J. Faltova

ECAL First Performance Results

- First performance results very encouraging
- Very critical dependence on upstream material (tracker, services and cryostat)
  - Dead material correction applied
- Next steps: Add electronics noise, pile-up, geometry optimization, other absorber materials





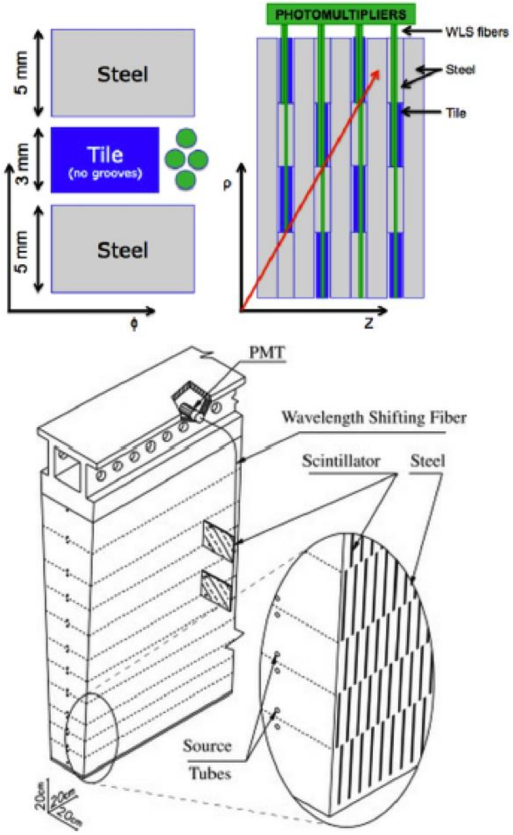
without noise for the moment

J. Faltova

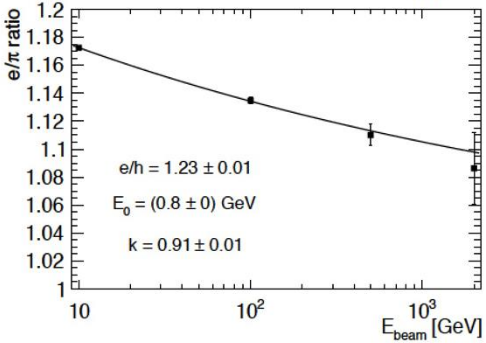
HCAL Barrel

Reference Detector:

- 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 (Calos in magnetic field)
- SiPM readout → faster, less noise, less space



$$e/\pi = \frac{e/h}{1 - \left[1 - \left(\frac{E_{beam}}{E_0}\right)^{1-k}\right](1 - e/h)} \qquad (1)$$

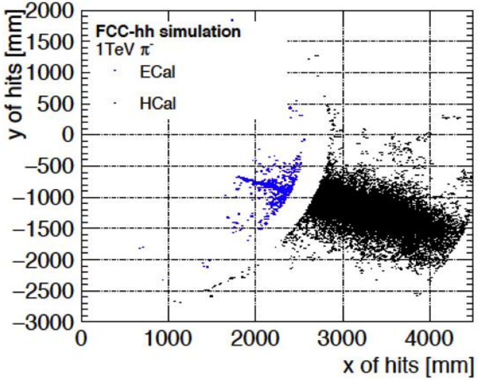


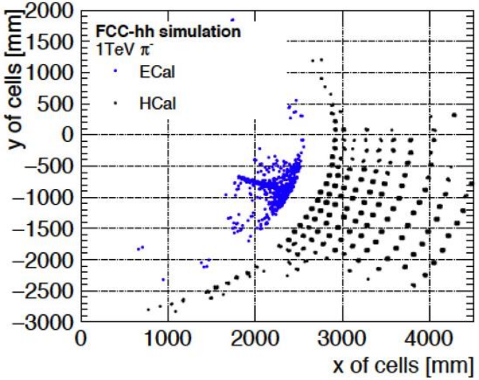
How could we achieve compensation?

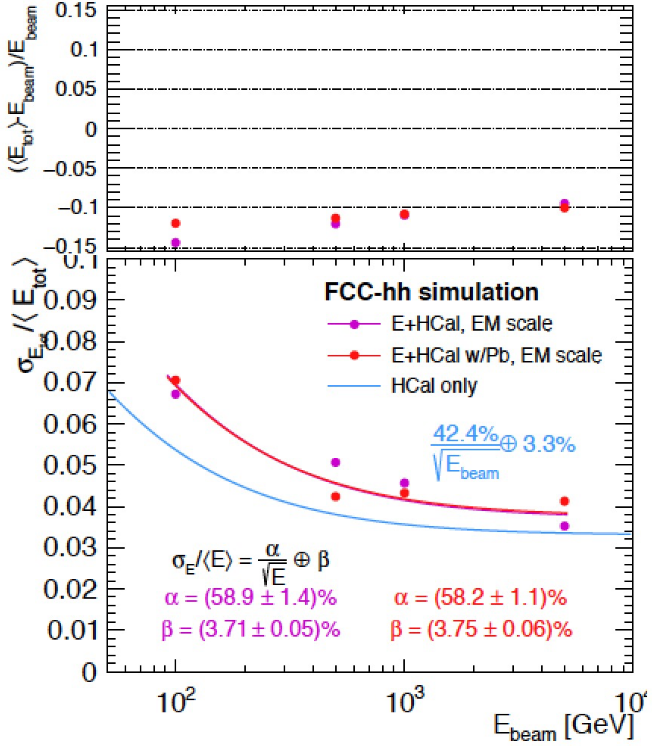
→ Higher Z material (e.g. Pb spacers)

C. Neubüser

ECAL & HCAL Barrel First Performance Results





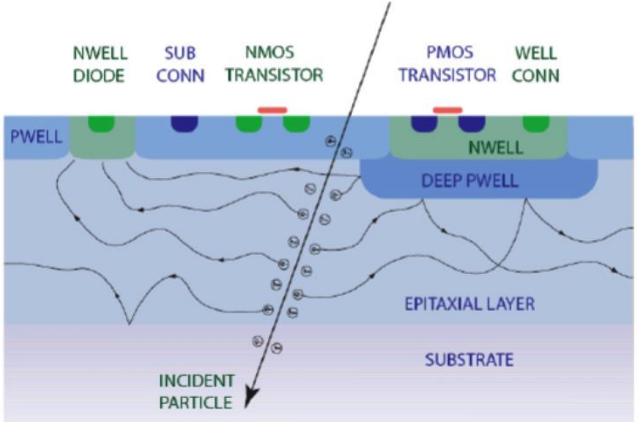


- ECAL and HCAL in EM scale
  - Comparable with ATLAS results
  - Calibrated pion resolution will be better
  - In addition fine granularity will be exploited for particle flow
- Next steps: corrections/calibration, clustering, jet algorithms, particle flow

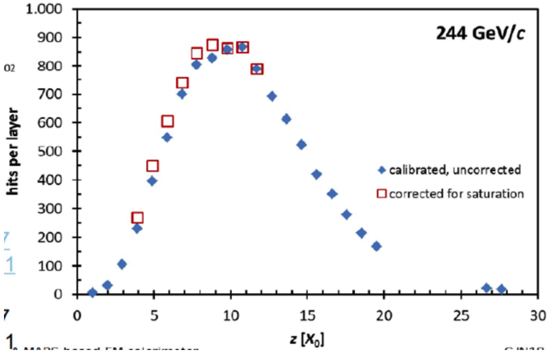
C. Neubüser

Digital ECAL

Interesting digital ECAL option using CMOS MAPS



- Can achieve the ultra high granularity with the use of CMOS Monolithic Active Pixel Sensors
- Thin sensitive region, usually 12-25um
- Thin substrates, low material budget
- Low noise
- Readout on the sensor so no need for separate chip
- Developments in HV/HR CMOS to deplete the sensor improve charge collection speed and radiation hardness



Number of hits per layer defines necessary granularity

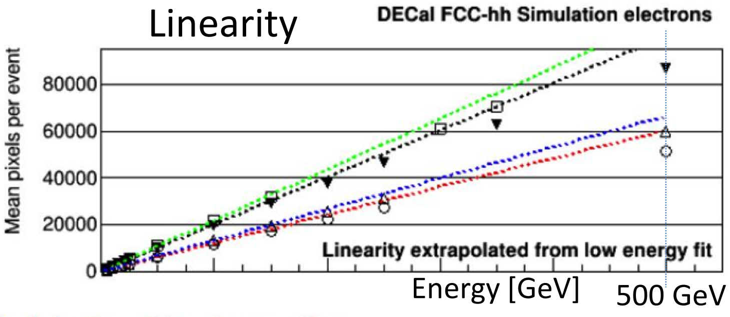
Generally the more active layers the better the resolution (speaking about 30 – 50 layers)

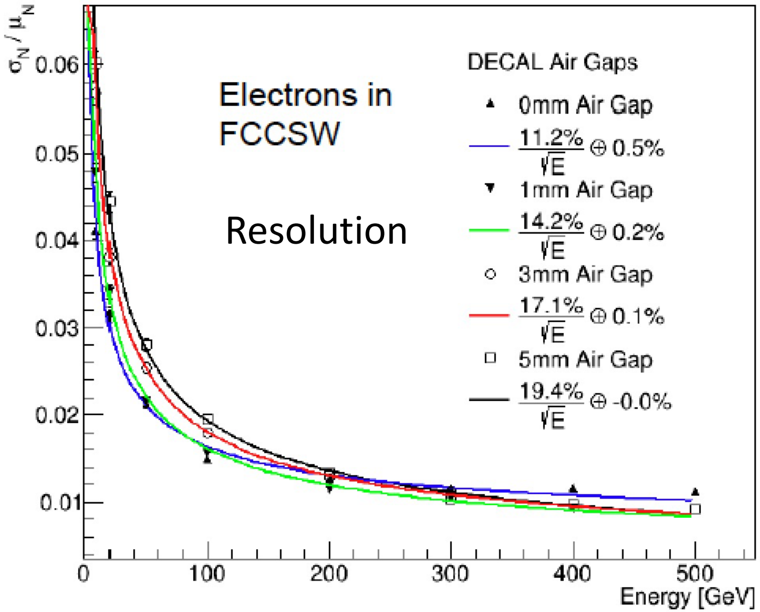
Absorber material: Pb and W equivalent in terms of resolution, but Pb lead shows better linearity (wider shower)

T. Prize

Digital ECAL First Performance Results

- Optimal granularity: pixel pitch ~50µm
- Sensor thickness ~18µm
- With realistic geometry (1mm air gap for read-out, cooling, power) achieving 14% / Sqrt(E) at η = 0.
- Linearity is of concern (more than one particle per pixel)





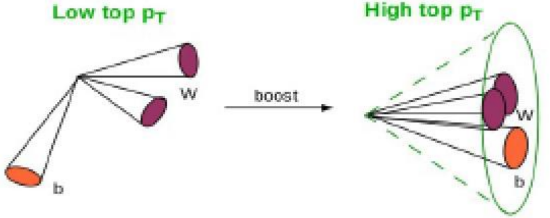
☐ Radiation Hardness
  - Forward region of FCC-hh detectors Si not an option
  - Depleted CMOS currently under development (HV/HR) with results to 10^{15} n_{eq}/cm^2 and beyond presented recently by other groups so feasible for Barrel region

☐ Cost
  - Cost of CMOS imaging sensors needs to decrease to make affordable but over 20 years this is expected to fall dramatically.
  - A cost of 30 cents / cm² would mean an ECAL of ~$30M.
  - Much more compact ECAL would also reduce costs of other systems

T. Prize

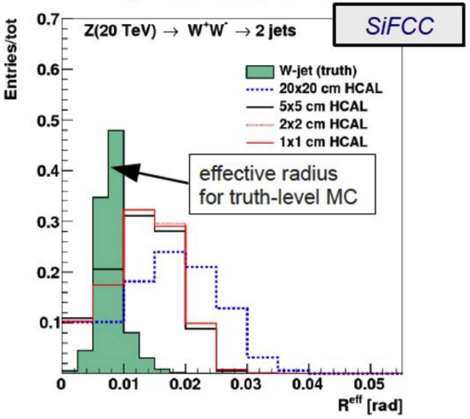
Calorimeter Granularity Studies

- Almost every physics channel will show boosted signatures at 100 TeV → important requirement for HCAL
- Look at hits associated with two close-by particles

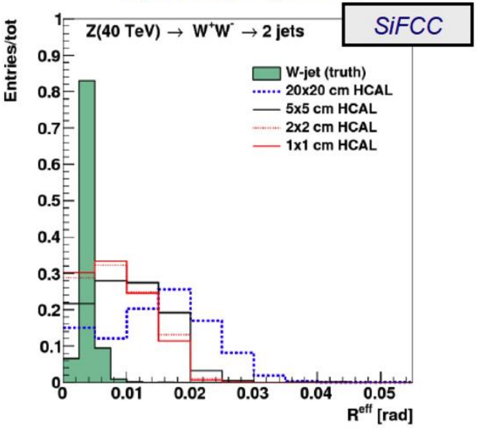


- What is the required lateral segmentation for FCC calorimetry?
  - Studies based on SLIC SW.
  - Jet substructure studies for jets up to 20 TeV:
    - Optimal HCAL size using is 5x5 cm (vs ~20x20 cm for ATLAS/CMS)
      - almost no improvement anymore for smaller cell sizes
    - Corresponds well to Δη x Δϕ = 0.025 x 0.025 in reference detector.

W-jets from Z'(20 TeV)

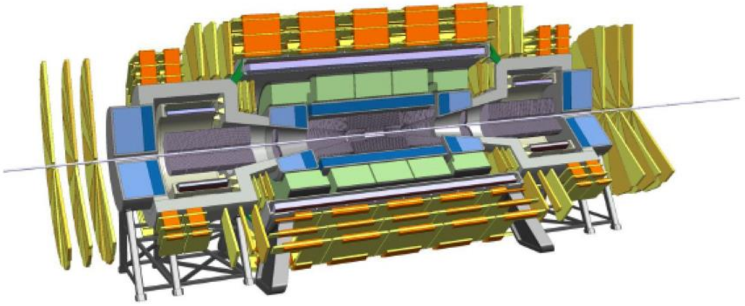


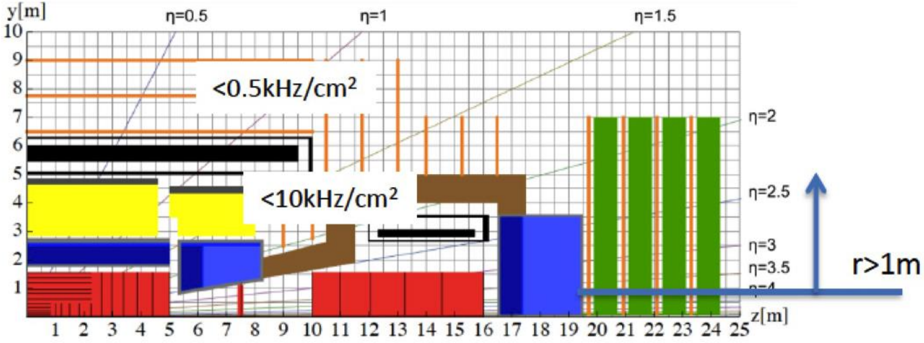
W-jets from Z'(40 TeV)



S. Chekanov

Muon System





<0.5kHz/cm²

<10kHz/cm²

r>1m rate<500kHz/cm²

ATLAS muon system HL-LHC rates (kHz/cm²):

MDTs barrel:	0.28
MDTs endcap:	0.42
RPCs:	0.35
TGCs:	2
Micromegas und sTGCs:	9-10

Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

LHCb

Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3

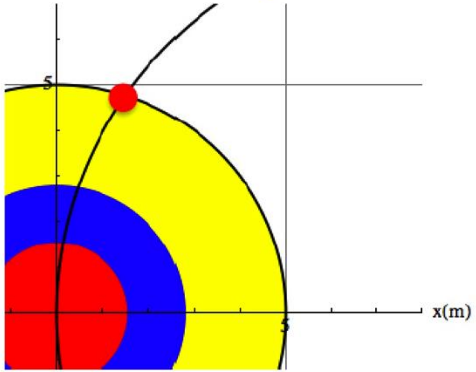
W. Riegler

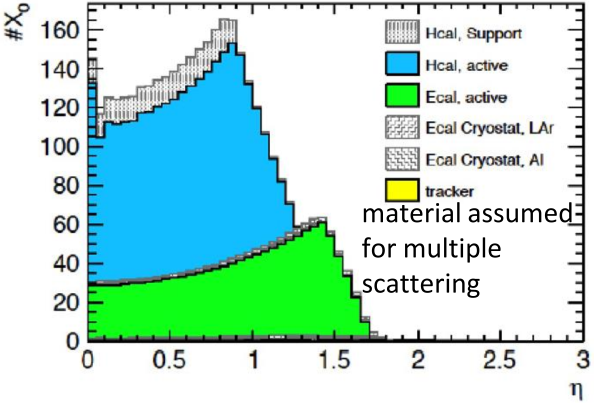
HL-LHC muon system gas detector technology will work for most of the FCC detector area

Muon System

p_t=3.9GeV enters muon system

p_t=5.5GeV leaves coil at 45 degrees

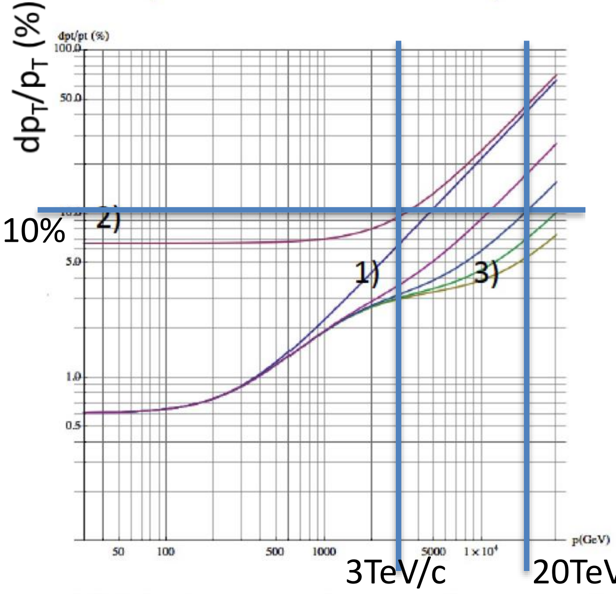




material assumed for multiple scattering

Three ways to measure the muon momentum

1) Tracker only with identification in the muon system
2) Muon system only by measuring the muon angle where it exits the coil
3) Tracker combined with the position of the muon where it exists the coil



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

- **≤10% standalone momentum resolution up to 3TeV/c**
- **≤10% combined momentum resolution up to 20TeV/c**

All within reach of ‘standard’ muon system technology

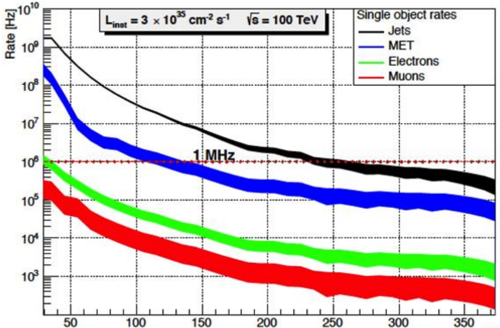
W. Riegler

Trigger & DAQ

- **Do we require a trigger for FCC-hh ?**
  - Yes ! We're not going to store every bunch-crossing forever
  - Depends what you mean by trigger…
- **Where is the data buffered whilst events are being selected ?**
  - On-detector ? Off-detector ? A combination of them both ?
  - Depends on link speeds, power, material budget, DAQ capacity
- **How are the events selected ?**
  - Depends on what data is available, processing capabilities, backgrounds and physics goals…

		Threshold L=5E34	Threshold L=3E35
electron	60 kHz	55 GeV	90 GeV
muon	60 kHz	35 GeV	60 GeV
MET	60 kHz	160 GeV	*>350 GeV*

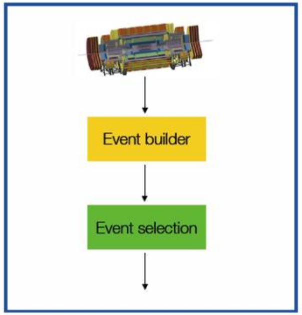
Thresholds are **indicative**, *clearly depend on details of bandwidth allocation*



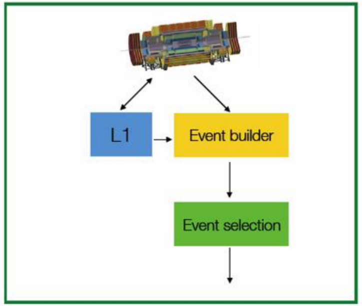
100 TeV L = 30×10^{34} cm^{-2}s^{-1}

Scaling up from CMS

- Front end detector data rates are *substantial* :
  - **Tracker** : ~800 TB/s [1]
  - **LAr+Tile Calo** : ~200 TB/s [2]
  - **Si/W Calo** : *O(1000 TB/s) ?* guesstimate !



Rad hard link capacity ?
Link power / material budget ?
Event builder bandwidth ?
Event selection processing / power ?

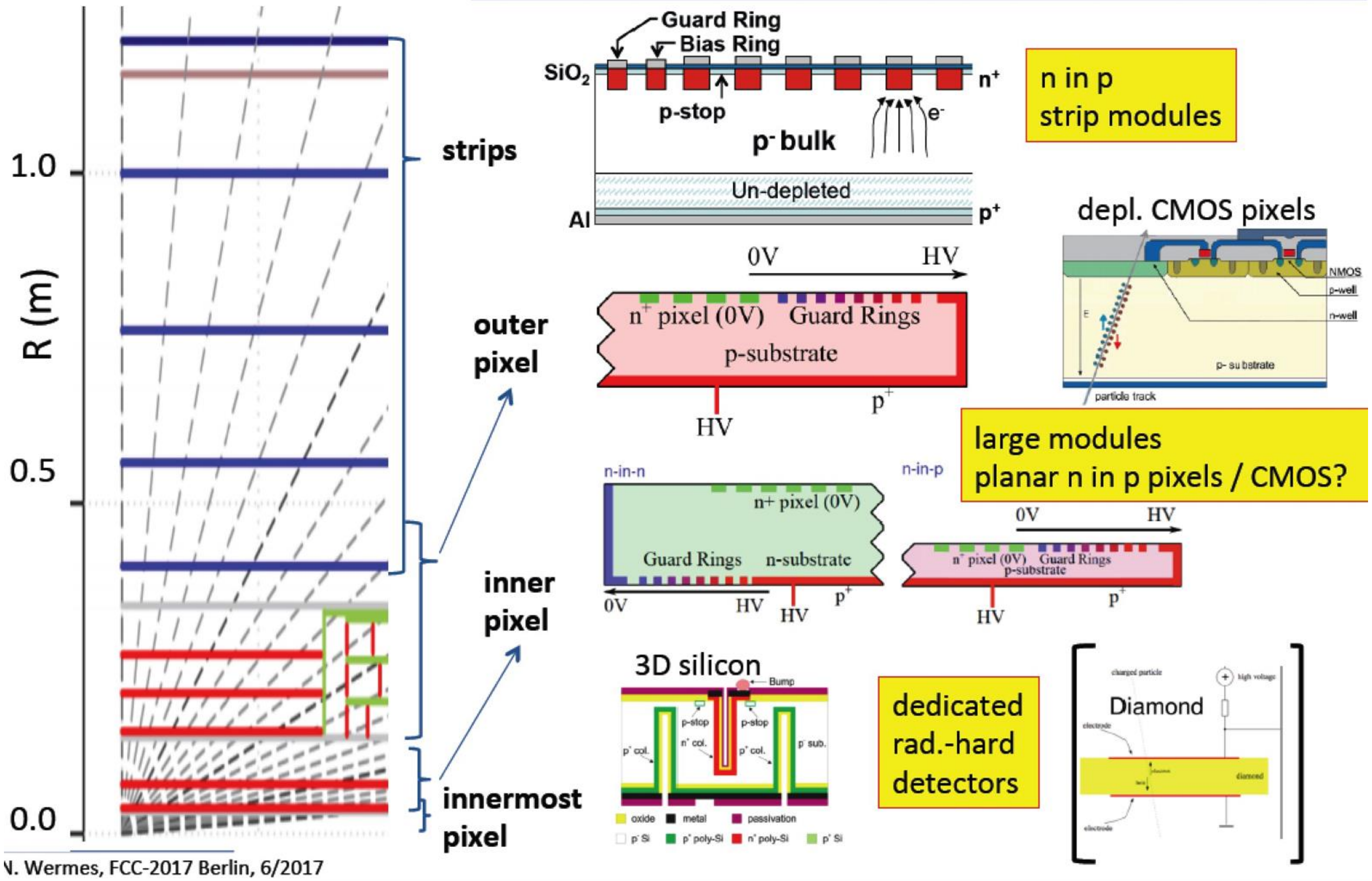


Which detectors need a trigger ?
Which detectors can provide a trigger ?
Trigger data bandwidth requirements ?
Latency constraints ?
Trigger performance ?

J. Brooke

Common Technologies

Common Technologies: Si Sensors



strips

outer pixel

inner pixel

innermost pixel

n in p
strip modules

depl. CMOS pixels

large modules
planar n in p pixels / CMOS?

3D silicon

dedicated
rad.-hard
detectors

Diamond

N. Wermes, FCC-2017 Berlin, 6/2017

Extremely interesting survey over different kinds of Si sensors

- very fast development
- for tracking (Hybrid vs MAPS)
- for timing (e.g. LGAD)

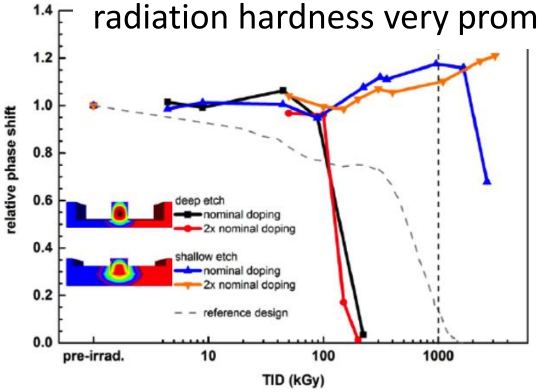
Need to make sure that high momentum in this field is maintained after HL-LHC → **Strategic R&D**

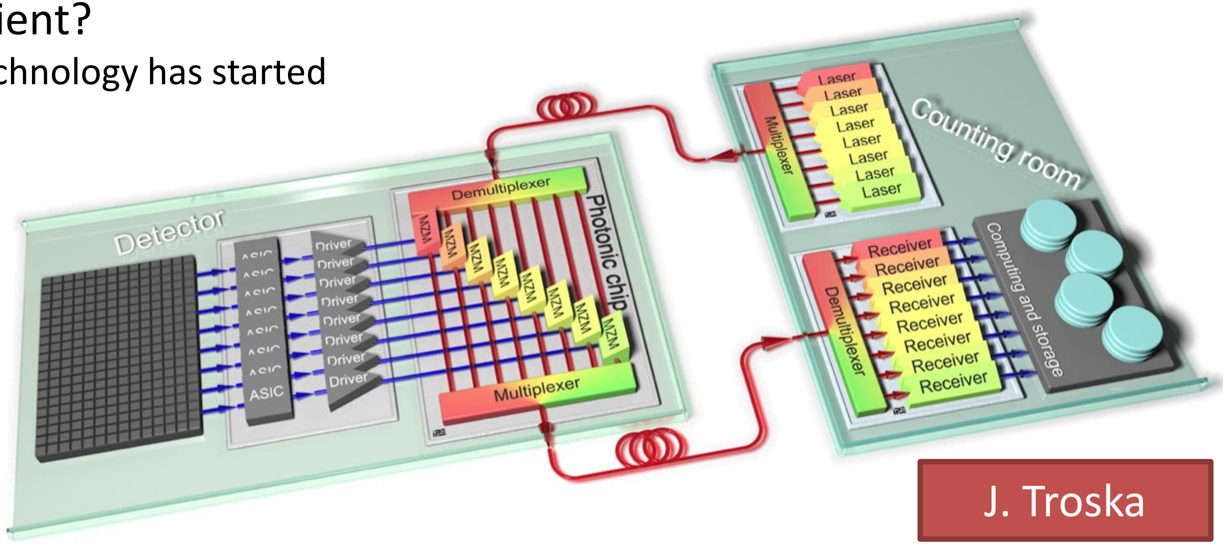
N. Wermes

Silicon Photonics for HEP?

- Silicon Photonics:
  - Use of silicon substrate and ASIC production techniques to pattern waveguide and optical field manipulating structures
  - Allows the fabrication of optical modulators and high level of integration of optical circuits like couplers and gratings
  - Promise of lower power & cost
  - But still need a source of optical power (that could be located remotely)
- Is radiation resistance sufficient?
  - Some work assessing this technology has started

First attempts to improve radiation hardness very promising





J. Troska

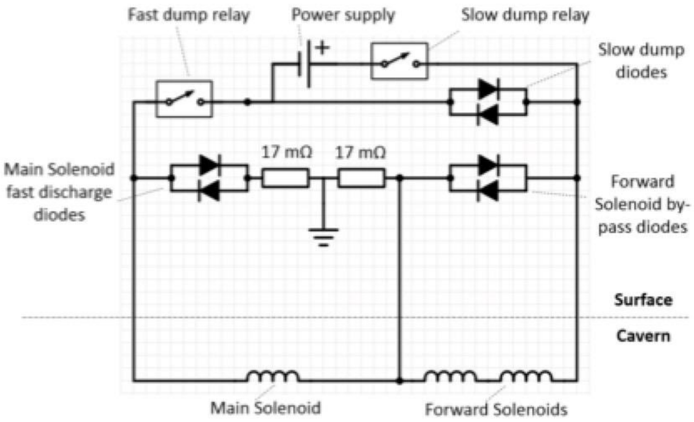
Conclusions

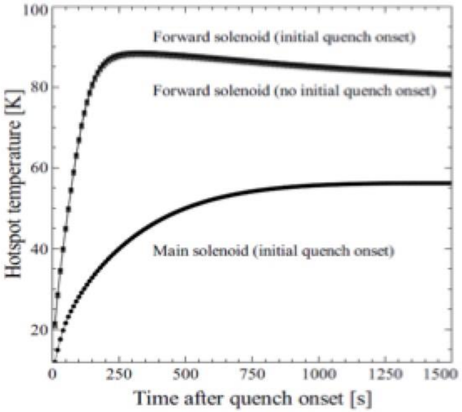
- Great progress since last FCC Week
- New reference design with 4T solenoid (10m diameter) and forward solenoids
- Detector studies reach impressive level of detail
  - Results from extrapolations from HL-LHC and FCC simulation (full simulation, fast simulation, parameterized simulation)
  - No show-stoppers to build an FCC-hh detector exploiting the full physics potential – however, challenging environment, detailed work on detector design and performance important
- Getting prepared for the CDR
  - Outline exists
  - Next step: starting to write!

Thank You for Your Attention!

Back-Up

Magnet – Electrical Scheme and Quench Protection





Electrical scheme

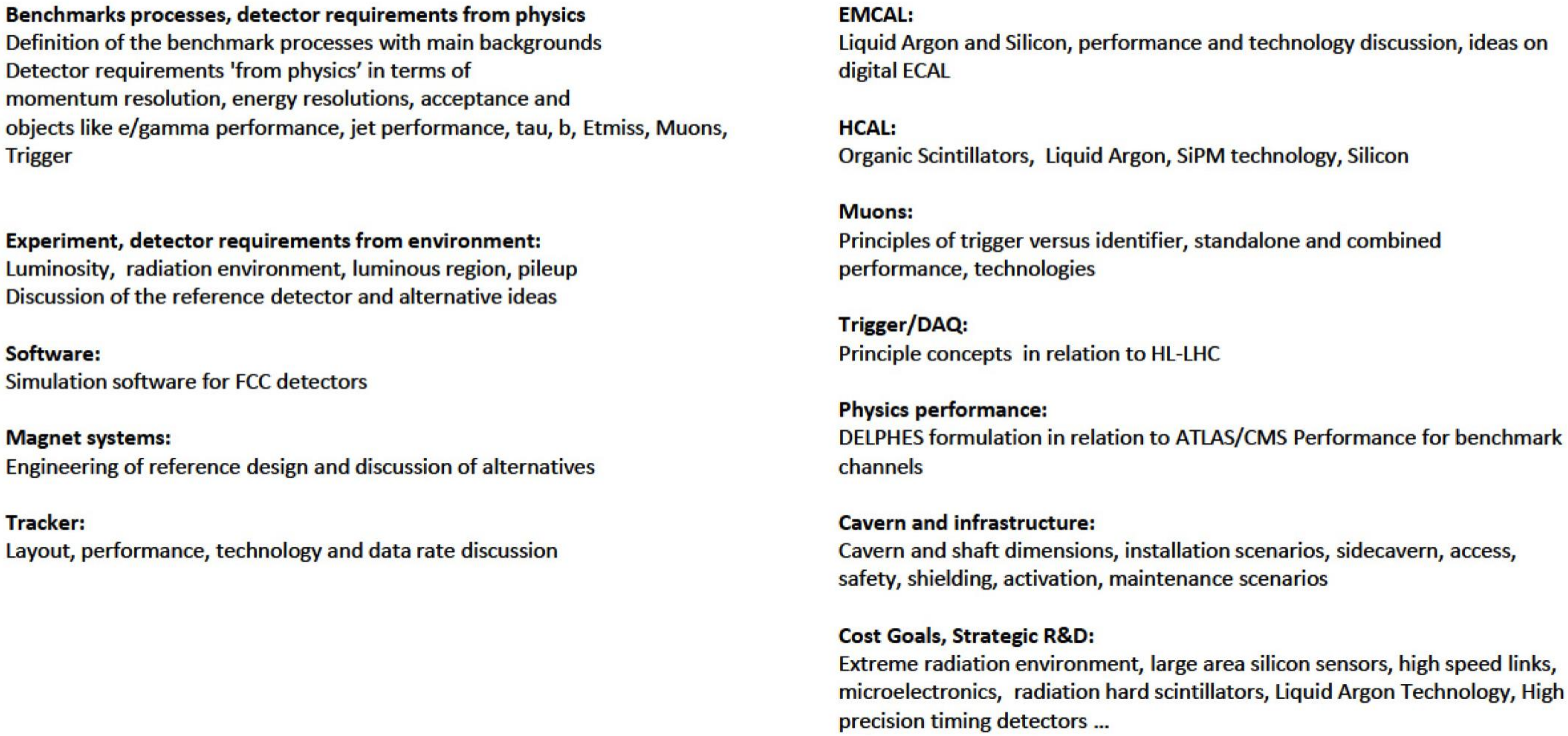
- All Solenoids powered in series
- Main solenoid decoupled from forward solenoids during quench (bypass diodes parallel to forward solenoids)
- Requires three current leads

Quench protection (using Quench code Quench 2.7)

- Conductor RRR = 400
- Main solenoid: Extraction (Quench-back) + Quench heaters
- Forward solenoid: Quench heaters
- Nominal Quench: 56 K in main solenoid, 89 K in forward solenoid, 73% extraction
- Worst case fault (no working heaters): 142 K in main solenoid, 133 K in forward solenoids

M. Mentink

FCC-hh Detector and Experiments CDR Outline



Benchmarks processes, detector requirements from physics
Definition of the benchmark processes with main backgrounds
Detector requirements 'from physics' in terms of
momentum resolution, energy resolutions, acceptance and
objects like e/gamma performance, jet performance, tau, b, Etmiss, Muons, Trigger

Experiment, detector requirements from environment:
Luminosity, radiation environment, luminous region, pileup
Discussion of the reference detector and alternative ideas

Software:
Simulation software for FCC detectors

Magnet systems:
Engineering of reference design and discussion of alternatives

Tracker:
Layout, performance, technology and data rate discussion

EMCAL:
Liquid Argon and Silicon, performance and technology discussion, ideas on digital ECAL

HCAL:
Organic Scintillators, Liquid Argon, SiPM technology, Silicon

Muons:
Principles of trigger versus identifier, standalone and combined performance, technologies

Trigger/DAQ:
Principle concepts in relation to HL-LHC

Physics performance:
DELPHES formulation in relation to ATLAS/CMS Performance for benchmark channels

Cavern and infrastructure:
Cavern and shaft dimensions, installation scenarios, sidecavern, access, safety, shielding, activation, maintenance scenarios

Cost Goals, Strategic R&D:
Extreme radiation environment, large area silicon sensors, high speed links, microelectronics, radiation hard scintillators, Liquid Argon Technology, High precision timing detectors …