FCC-hh Detector Summary

FCC week Washington
23-27 March 2015

W. Riegler

D. Denisov, H. ten Kate, L. Lienssen, F. Lanni, M. Abbrescia, R. Richter, Y. Onel, W. Smith, S. Chekanov

Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

What are the driving requirements for detector design ?

MDI Parameters

L^* [25, 40]m or larger (60m popular at the moment)

L_{peak} $[5 \times 10^{34}, 30 \times 10^{34}]$ $cm^{-2}s^{-1}$

→ N_{pileup} [170, 1020] at 25ns
→ N_{pileup} [34, 204] at 5ns

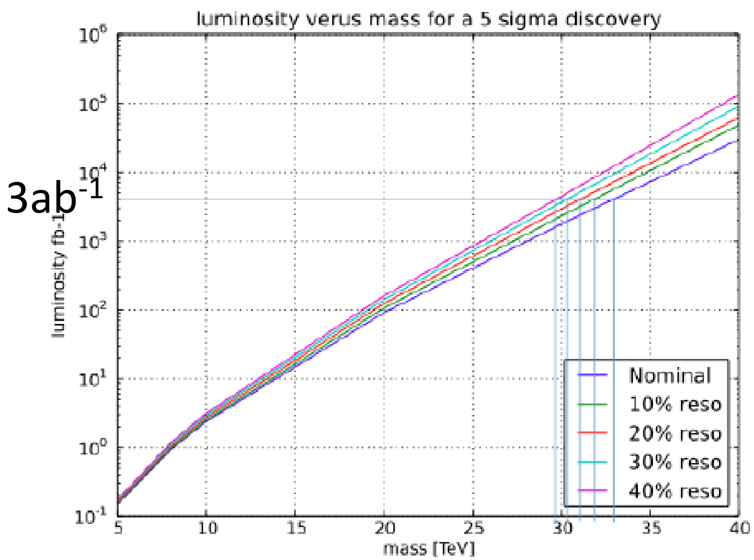
Focus, of course, on maximum integrated luminosity.

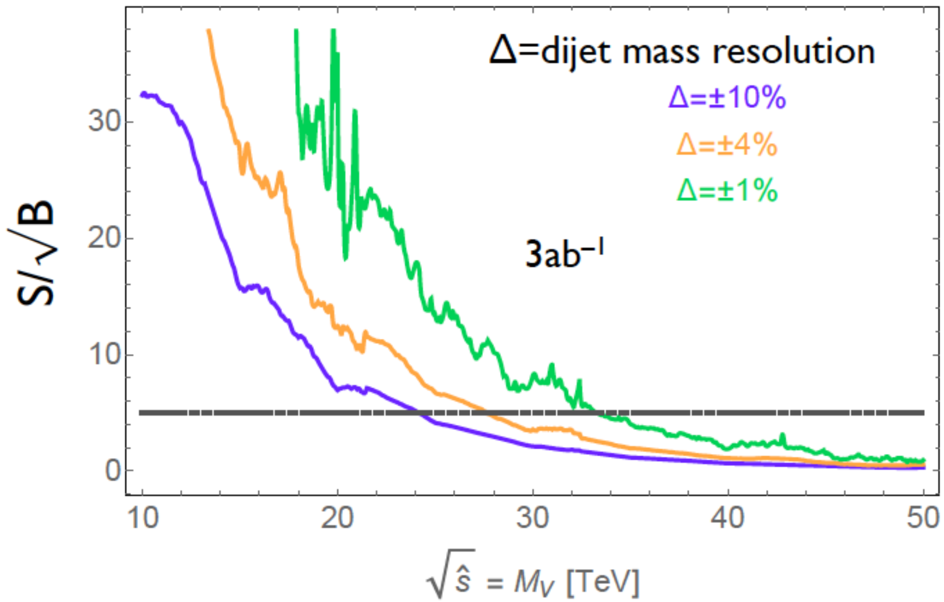
L_{int} [3, 30] ab^{-1}

Peak luminosity is only part of the game, specifically in the high burnoff regime.

(1) Physics at the Lσ Limit

C. Helsens, M. Mangano





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

$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} + k$$

Muon momentum resolution O(15%) at 10TeV.

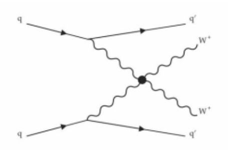
→ Constant term dominates, 1-2% goal

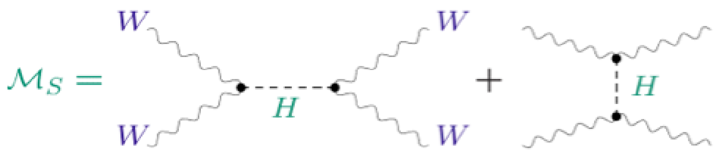
→ full shower containment is mandatory !

→ Do not compromise on 12 lambda !

(2) WW scattering by VBF Mechanism

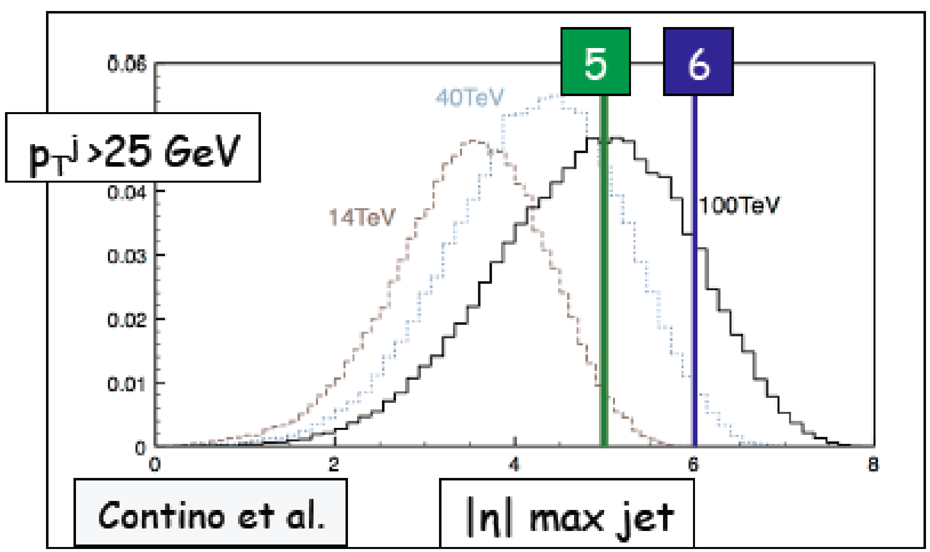
Is H playing it's role ? Unitarity at 1TeV ? Are there high mass resonances WW, ZZ, HH, …



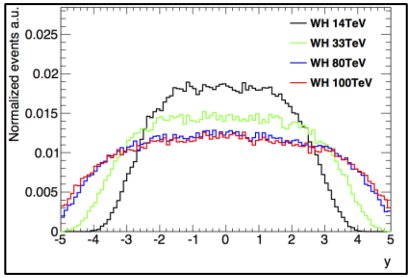


VBF jets between η~2 and η~6
need to be well measured and separated from pile-up

Muons (and electrons) around ~1 TeV p_T
need to be triggered, identified, precisely measured



(3) Higgs Measurements



H→ 4l acceptance vs η coverage (l p_T cuts applied)

	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**	0.80
ttH	0.84	1	**0.56**	0.90
VBF	0.75	0.98	**0.55**	0.87

H. Gray, C. Helsens

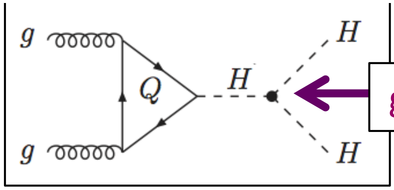
		|η| < 2.5	|η| < 4	|η| < 5
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1

→ 30-50% acceptance loss for H→ 4l at 100 TeV wrt 14 TeV if tracking and precision EM calorimetry limited to |η|<2.5 (as ATLAS and CMS)

→ can be recovered by extending to |η|~ 4

Examples:
ttH : x 60 (from LHC 14)
HH : x 42

"Heavy" final states require high √s, e.g.:
HH production (including measurements of self-couplings λ)
ttH (note: ttH→ ttμμ, ttZZ "rare" and particularly clean)



$g_{HHH} \sim \lambda v$

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

(4) Pileup, Boosted Objects

FCC Higgs & BSM Workshop
CERN, March 2015

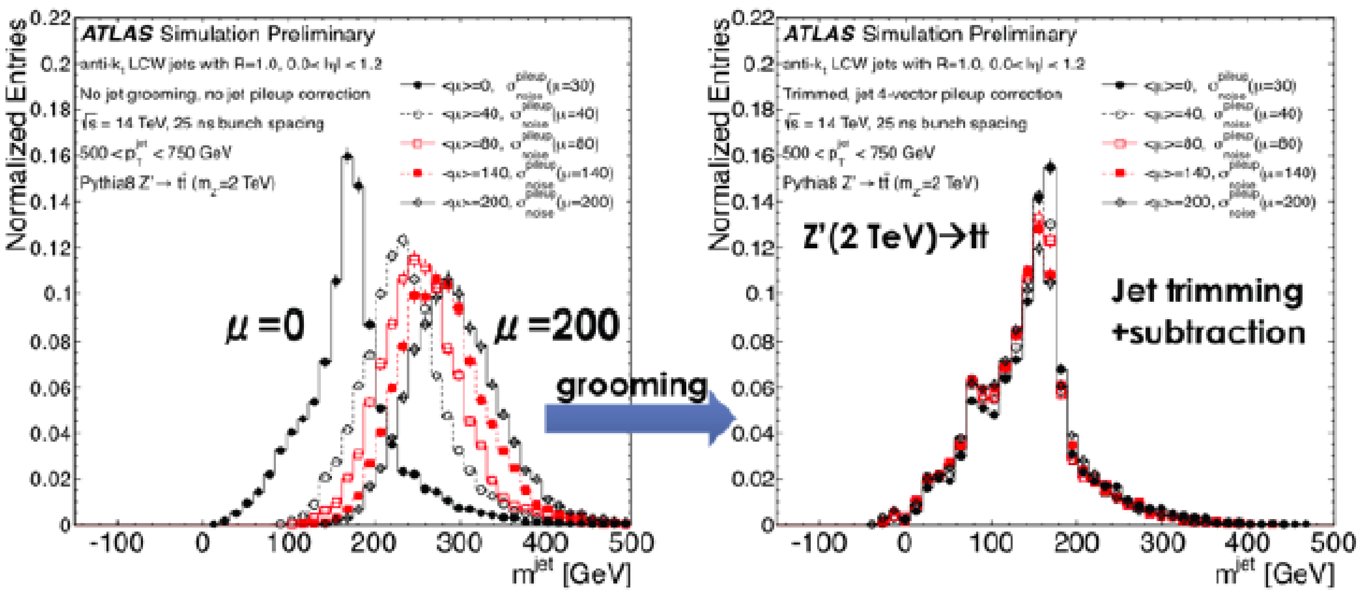
Principles of tagging multi-TeV boosted objects

Gavin Salam (CERN)

What changes at FCC?

Much higher boost means decay opening angles ~ 0.02 instead of 0.2-0.3 relevant today

- Detector **granularity** becomes a critical issue
- W/Z/H become as collimated as τ leptons at LHC – can use similar "**isolation**" procedures (cut on radiation)
- top decay as collimated as b-decay at LHC – need to consider difference between **top quarks v. top jets**



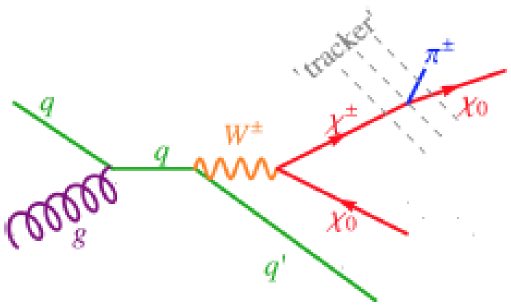
topoclustering + grooming + area subtraction shows very good performance up to 200 PU

(5) More Exotic

Disappearing Tracks - Introduction

$M_{\chi^\pm} - M_{\chi_0} = 165$ MeV $> m_\pi \quad \Rightarrow \quad$ lifetime $\tau \simeq 6\,\mathrm{cm} \simeq 0.2\,\mathrm{ns}$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors



Feng Strassler 1994

Feng Moroi Randall Strassler Su 1999

...

Low Wang 1404.0682

Filippo Sala

Approximate Overall Needs

Tracking: Momentum resolution H15% at p_t=10TeV

Precision tracking (momentum spectroscopy) and Ecal up to η=4

Tracking and calorimetry for jets up to η=6.

12 λ_{in} calorimetry, 1-2% constant term.

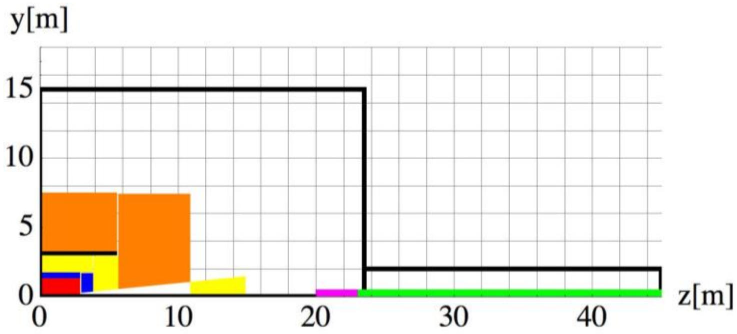
Calorimeter granularity of 0.05x0.05 or 0.025x0.025 to mitigate pileup and measure jet substructure and boosted objects.

B-tagging, timing for pileup rejection etc. …

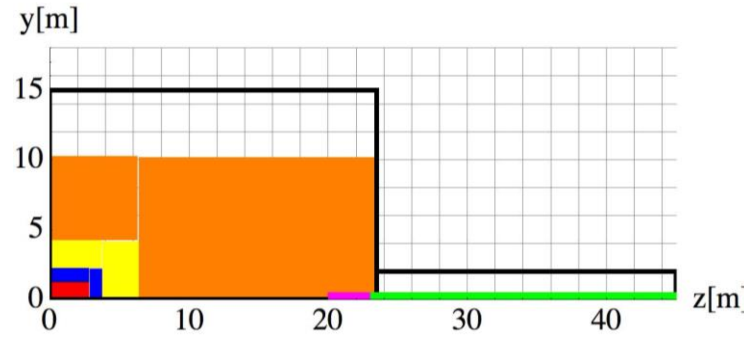
$$\frac{\Delta p_t}{p_t} \approx \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720}{N+4}}$$

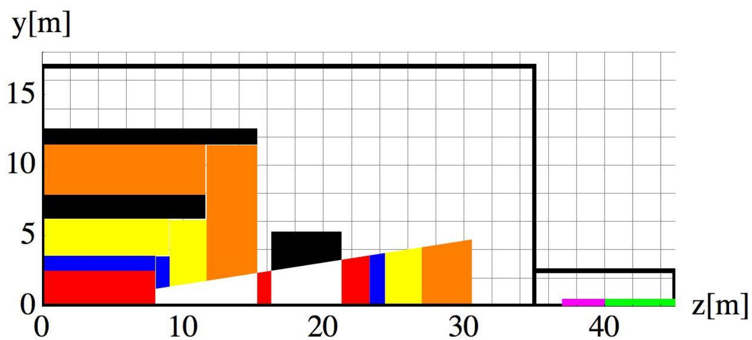
Same momentum resolution for 7x Energy (14→ 100TeV):

- 7x BL^2
- σ/7
- any combinations



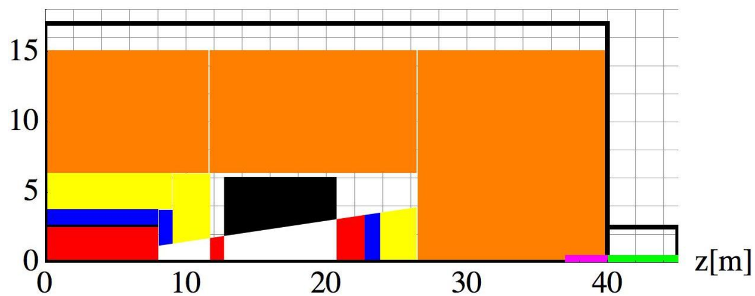
CMS & ATLAS





Twin Solenoid + Dipole, BL^2 scaled

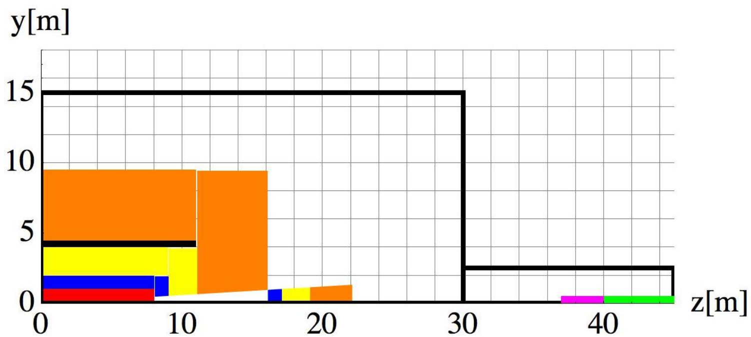
Tracker r=2.5m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =1m+2.5m
Coil R=6m, 6T, Shielding Coil
Forward Dipole 10Tm



Toroid + Dipole, BL^2 scaled

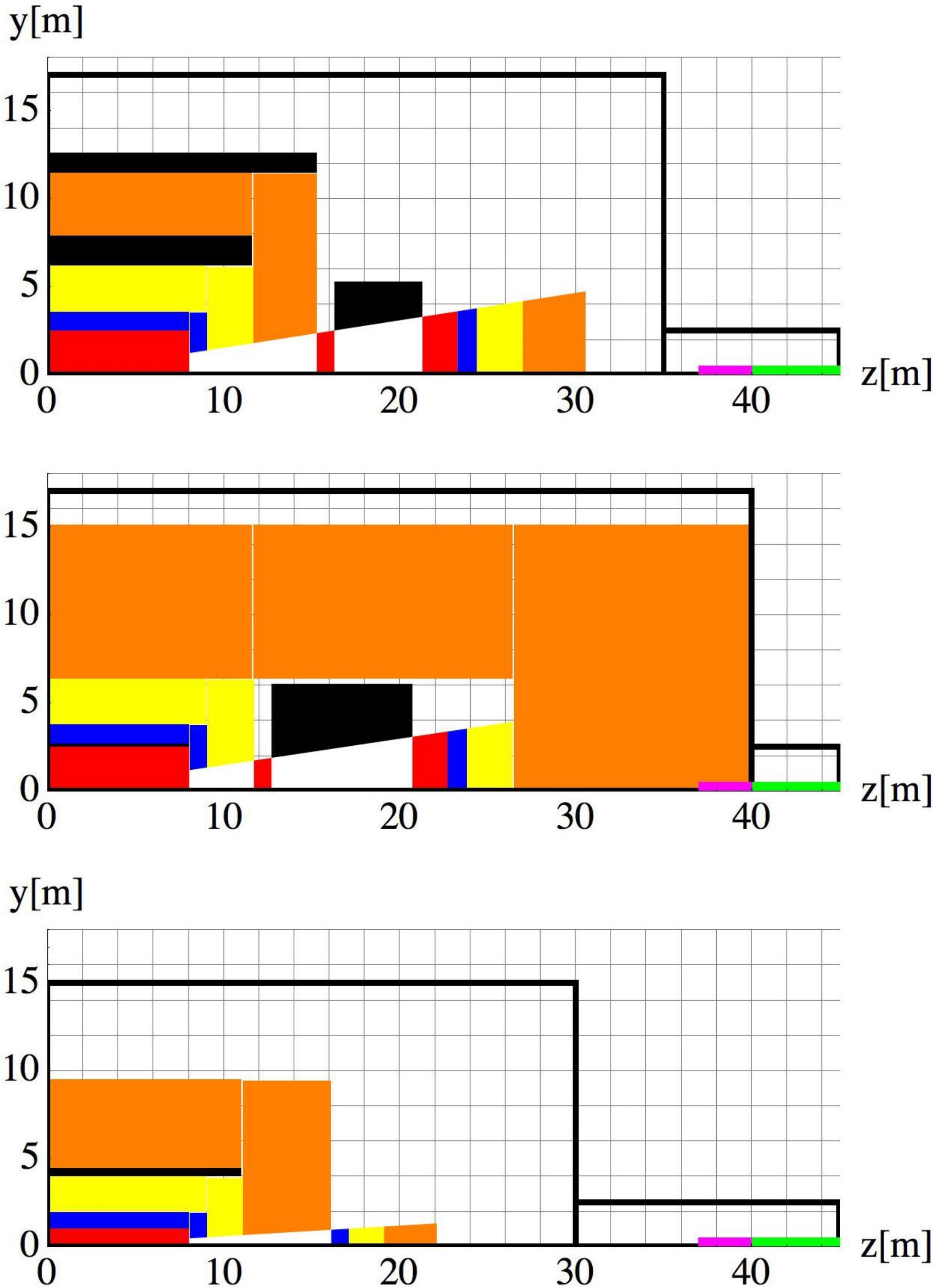
Tracker r=2.5m p_t reso 15% at 10TeV
Thin Coil R= 2.5m, B= 4T
12 lambda ECAL+HCAL =1m+2.5m
Muon Toroid
Forward Dipole 10Tm

Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet



CMS+, resolution scaled

Tracker r=1.2m p_t reso 15% at 10TeV
12 lambda ECAL+HCAL =0.6m+2.2m
Coil R=4m
Iron Return Yoke
→ Extreme detector technology push



Tracker

Emcal

Hcal

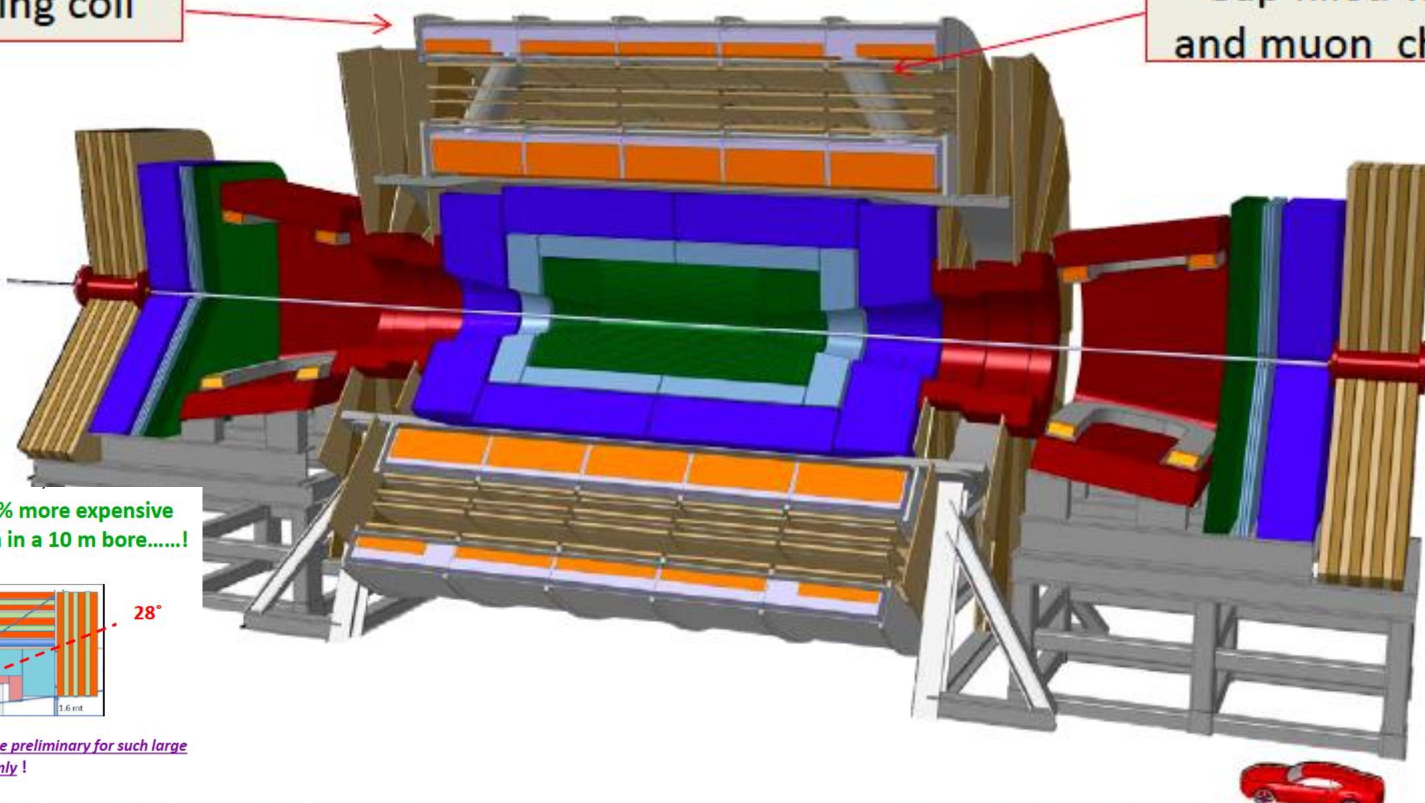
Muon

Coil

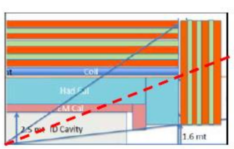
TAS

Triplet

2. Option 2: Twin Solenoid + Dipoles



✓ Example: 6 T is ~60% more expensive in a 12 m bore than in a 10 m bore……!



Disclaimer: these cost data are preliminary for such large systems, and a rough guide only !

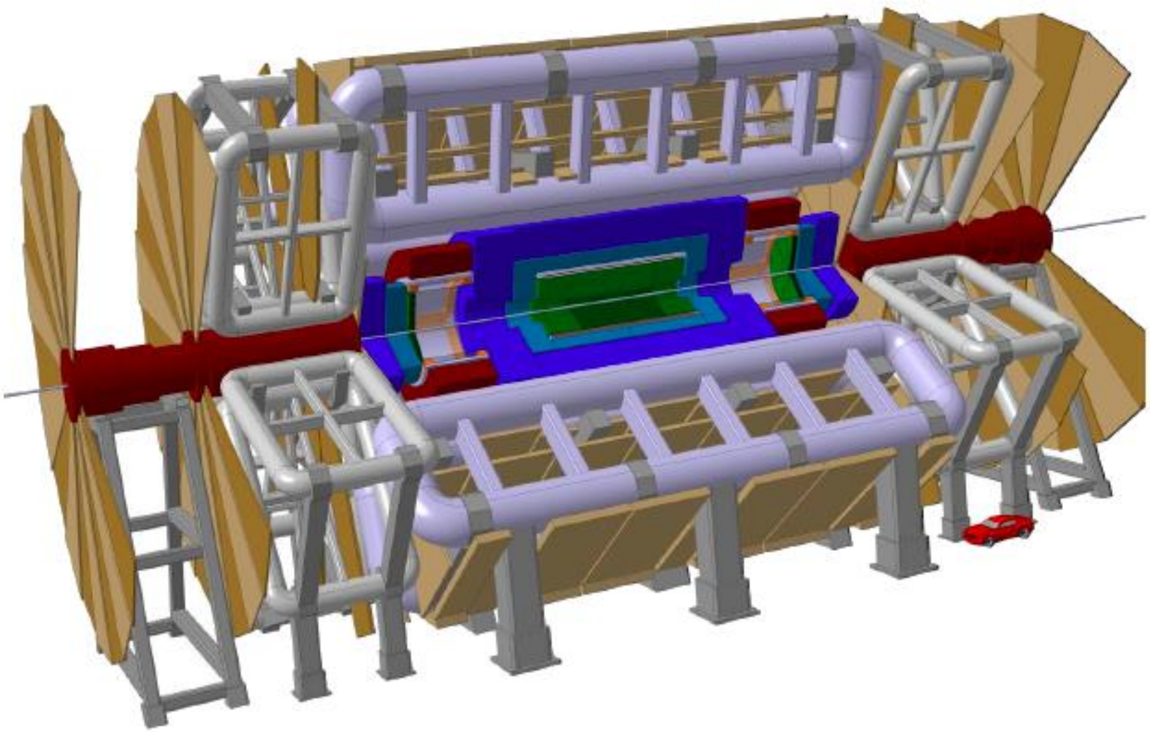
Twin Solenoid: 6 T, 12 m dia, 23 m long main solenoid + shielding coil

Important advantages:

- **Nice muon tracking space:** gap with ≈2-3 T for muon tracking in 4-5 layers.
- **Light:** shielding coil + structure ≈ 8 kt, much lighter than the iron yoke!

H. ten Kate

2. Option 3: Toroids + Solenoid + Dipoles (ATLAS+)



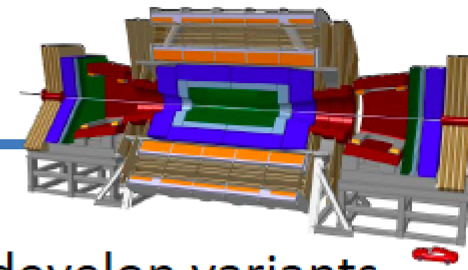
Stored energy	40 GJ (34 GJ BT + 2x 3 GJ ECT)
Conductor mass	3.3 kt (10x 280 t BT modules + 20x 25 t ECT modules)
Length BT [m]	36
Inner radius BT [m]	7
Outer radius BT [m]	15
Length ECT [m]	8
Inner radius ECT [m]	2.5
Outer radius ECT [m]	15

Variant with shorter Barrel Toroid and full diameter End Cap Toroids, both in open structure. Advantages:

- Shorter coils, easier to handle
- Open end cap toroids allowing muon chambers inside
- Improved coverage in overlap sections

H. ten Kate

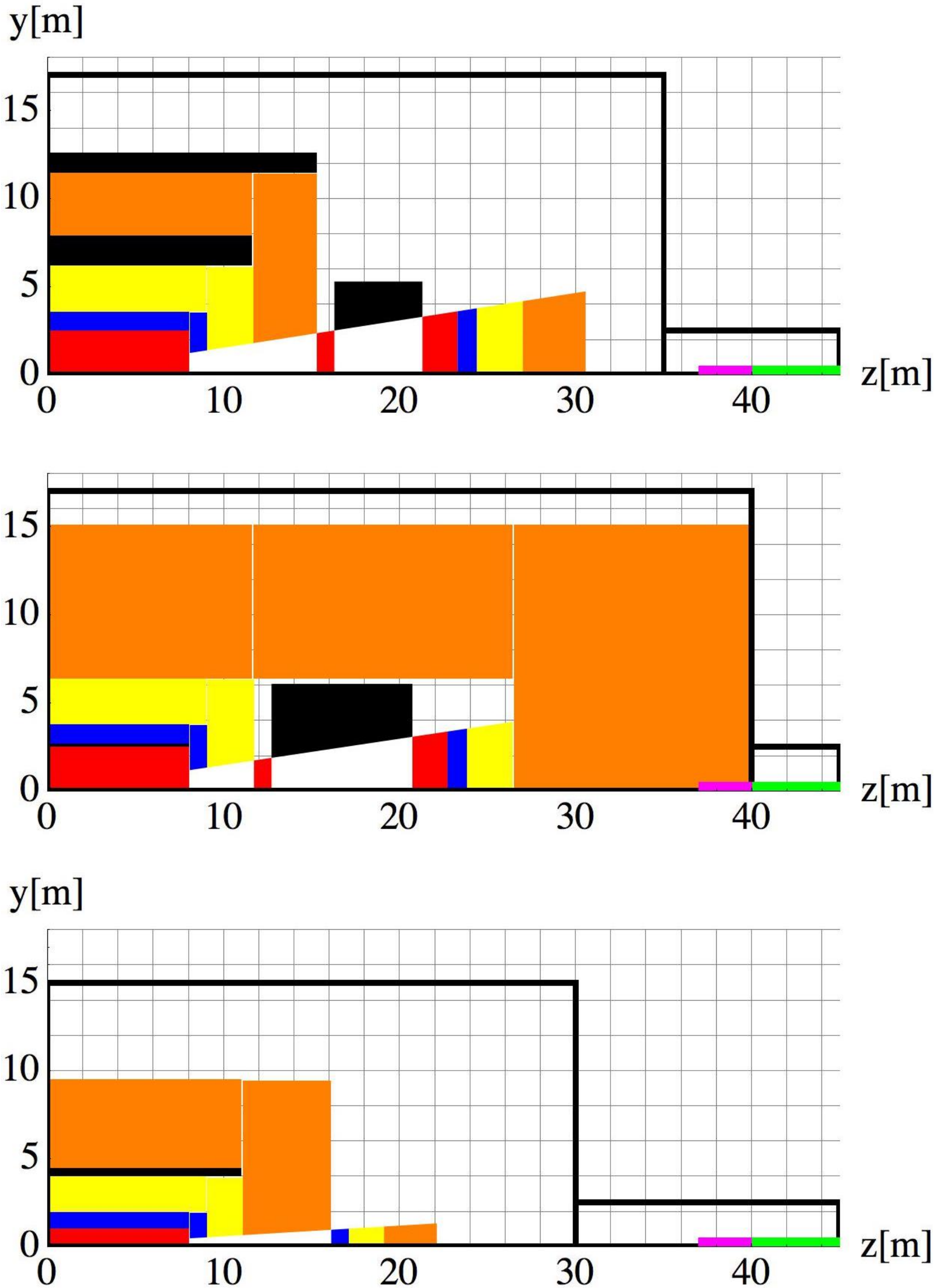
6. Conclusion



- ✓ 2 different detectors design are pursued, continue to develop variants.
- ✓ Solenoid + fully shielding yoke is very heavy and bulky, hardly feasible.
- ✓ Solenoid + minimum iron, looks more acceptable, what is minimum?
- ✓ Toroids give best BL^2 for most angles, more complex, certainly doable, but do we still need a high quality stand-alone muon spectrometer?
- ✓ The arguments for one of these and there sizing shall be extensively discussed regarding physics requirements, for guiding further work.
- ✓ Solenoid and toroids sizes can be reduced somewhat by altering the detector technologies, higher resolution inner tracker, change of absorber material; clear statements are needed on their feasibility.
- ✓ We have seen solenoids and toroids of unprecedented size and stored energy of 40-60 GJ, but so far no show stoppers identified.

The good news: there are no principle technical problems impeding the constructing of these magnets.

H. ten Kate



Tracker

Emcal

Hcal

Muon

Coil

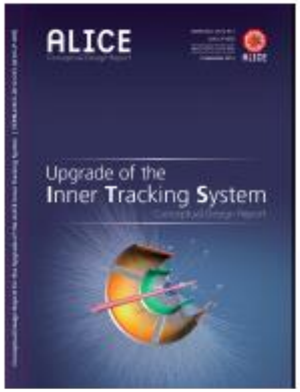
TAS

Triplet

ALICE 2018 upgrade, 20x20um monolithic pixels

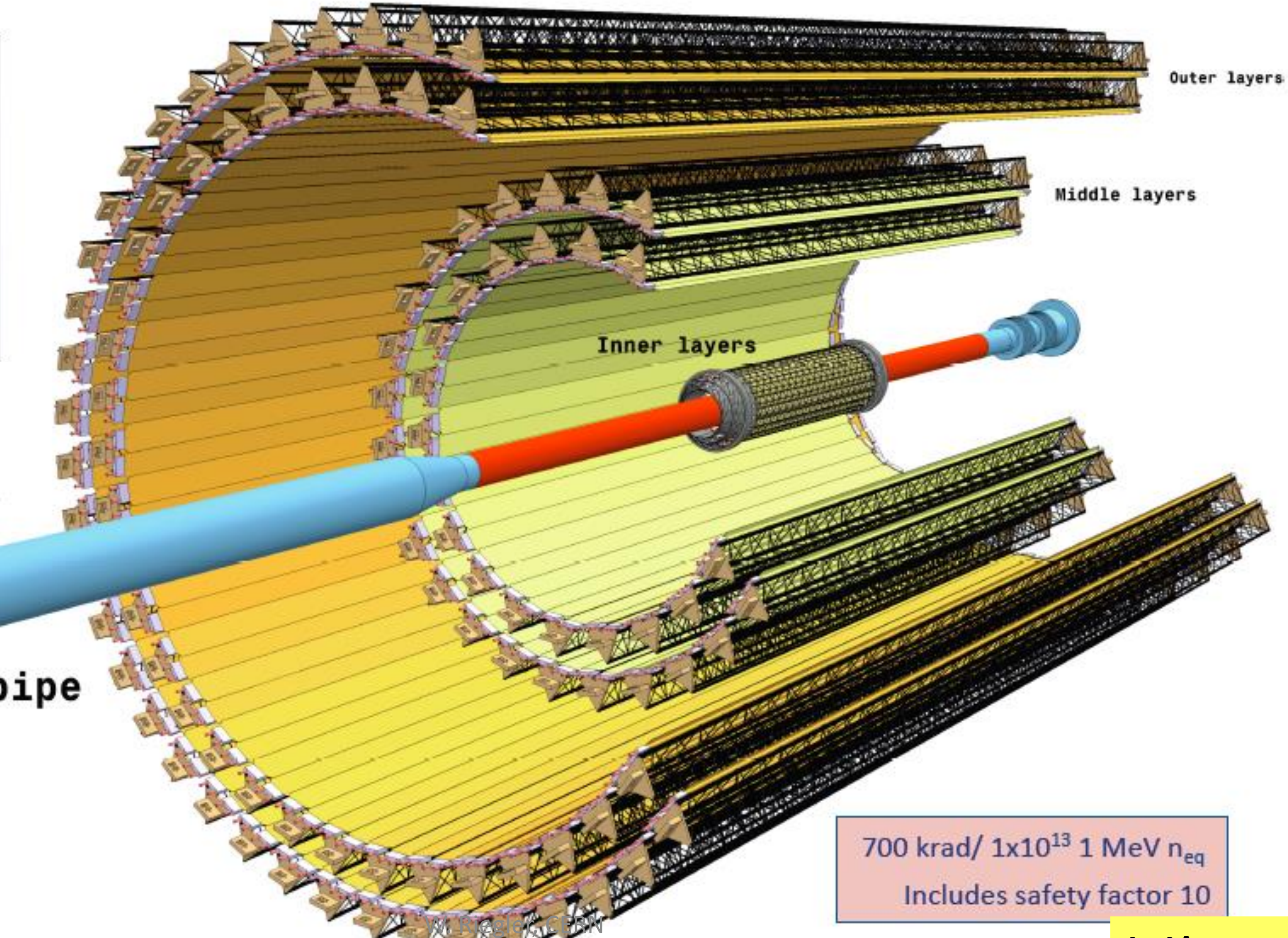
New ITS Layout

25 G-pixel camera
($10.3\ m^2$)



CERN-LHCC-2013-024

7 layers of MAPS



Radial coverage
22 – 406 mm

700 krad/ $1\mathrm{x}10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

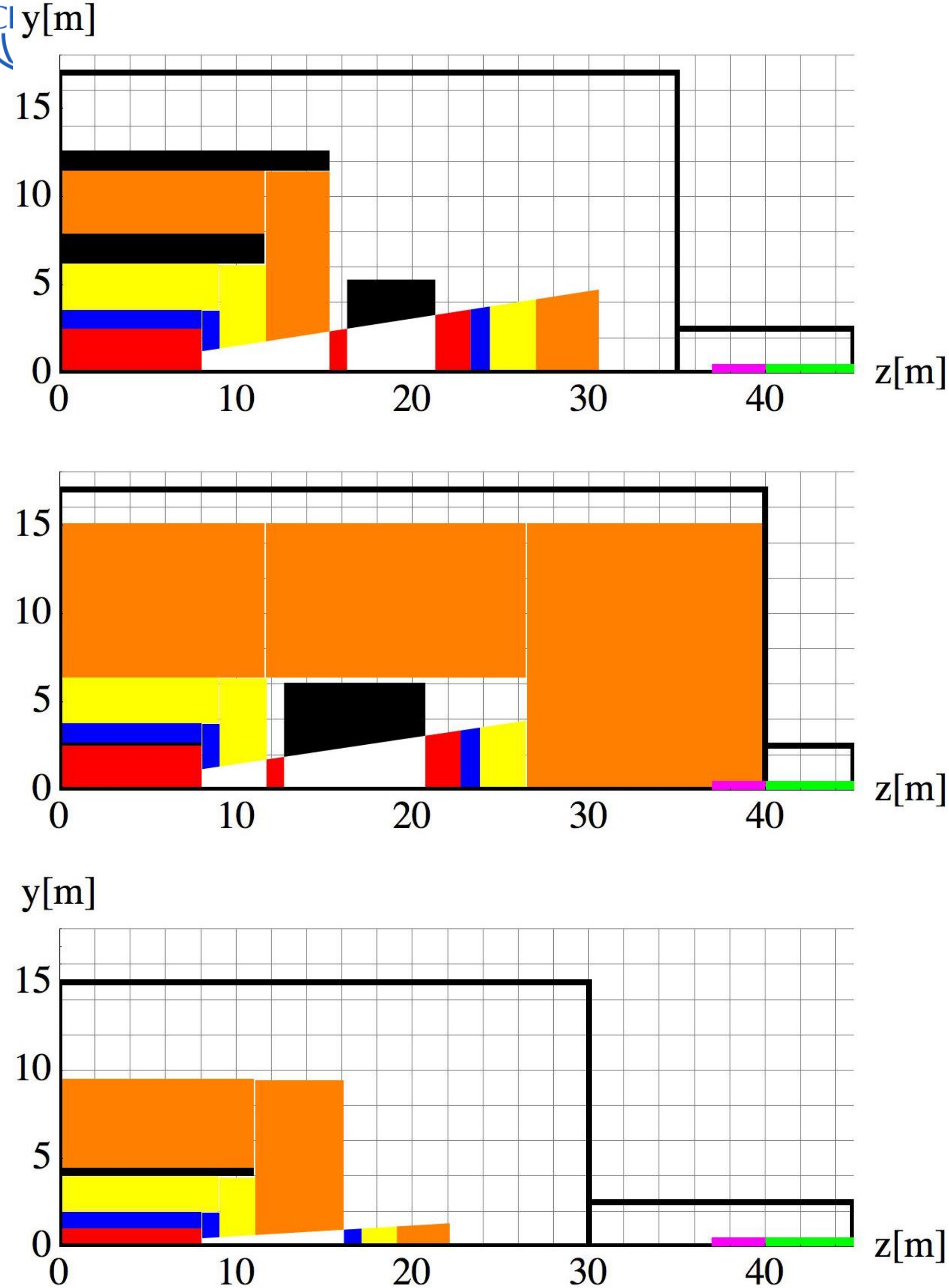
L. Lienssen

Conclusions

- Detectors for FCC-hh inner tracking are considered feasible
- ~ns time resolution, ~micron-level space resolution and radiation tolerance to ~30×10^{16} appear as natural evolution of present technologies.
- Minimal FCC-hh target specifications are almost already achieved in dedicated detectors.
- However, no single technology reaches all design specs at the same time.
- The main issue: coverage at small radius with radiation hardness, fine granularity.
- Several sensor technologies are promising => consider them all
- Microstrips will most likely be replaced by pixels everywhere.
- Big technology step: integrated electronics => to be pursued closely
- Important to develop all integrated design details among physicists, microelectronics experts, mechanical engineers and material scientists

Room for several future projects to join forces

L. Lienssen



Tracker

Emcal

Hcal

Muon

Coil

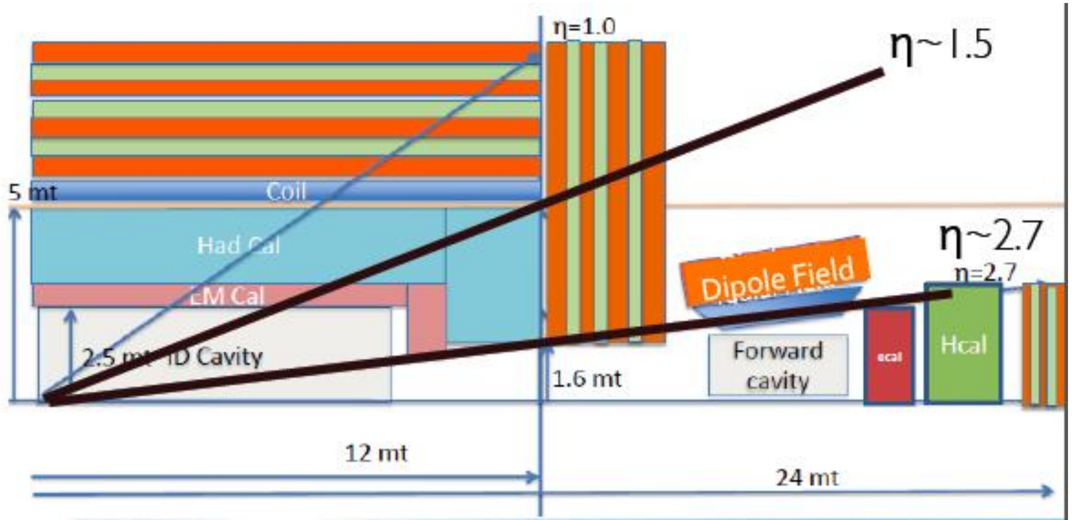
TAS

Triplet

Calorimetry

3(4) Regions in η

- Barrel: $0<|\eta|<1.5$
- Extended Barrel: $1.5<|\eta|<2.7$
- Endcap: $2.7<|\eta|<4(6)$
- (Forward: $4<|\eta|<6$)



What technology? A single one? Likely each region will need to be optimised separately.

F. Lanni

Calorimetry

Requirements:

Pileup mitigation

- Pileup conditions can be as much as 900 @ 25 ns (180 @ 5 ns) min-bias events/crossing.
- Calorimeters with excellent timing resolution (10-20ps) may be required to mitigate pileup effects

Si-HGC parameters for FCC-hh

- **Electromagnetic 26 ~ 28 X^0 (~ 1 l)**
  - **30 sampling layers**
    - ***Silicon surface (very rough estimate!)***
      - For Large CMS-like Solenoid ~ 3'000m²
      - *For Very Large Double Solenoid ~ 10'000m²*

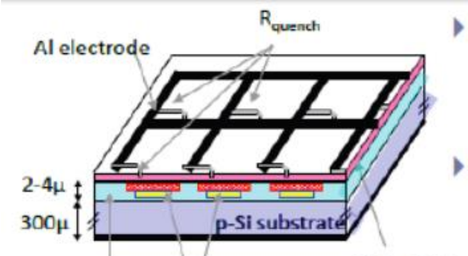
Organic Scintillators

- Organic scintillator calorimetry well established detector technology for hadronic calorimeters @ LHC and for their upgrades.
  - Scintillating tiles and fibers coupled to photodetectors on the outer periphery.
  - Cost effective solution
  - Promising for central HCAL in a FCC-hh experiment where radiation levels are expected to be moderate (50kRad/yr @ 10^{36})

Granularity

Sampling fraction/frequency, transverse and longitudinal granularity tuned to the application.

- E.g ATLAS LAr EM barrel calorimeter (http://cds.cern.ch/record/883909/files/phep-2005-034.pdf?version=1)
  - Pointing
  - Transverse segmentation (η) determined by strip-line design in kapton electrodes
  - Granularity in φ by ganging electrodes through PC boards installed in front (inner R) and in the back (outer R)
  - 3(4) layers of longitudinal segmentation is achievable by developed techniques (ATLAS). ***More will require substantial R&D on large area multi-layer kapton structures***



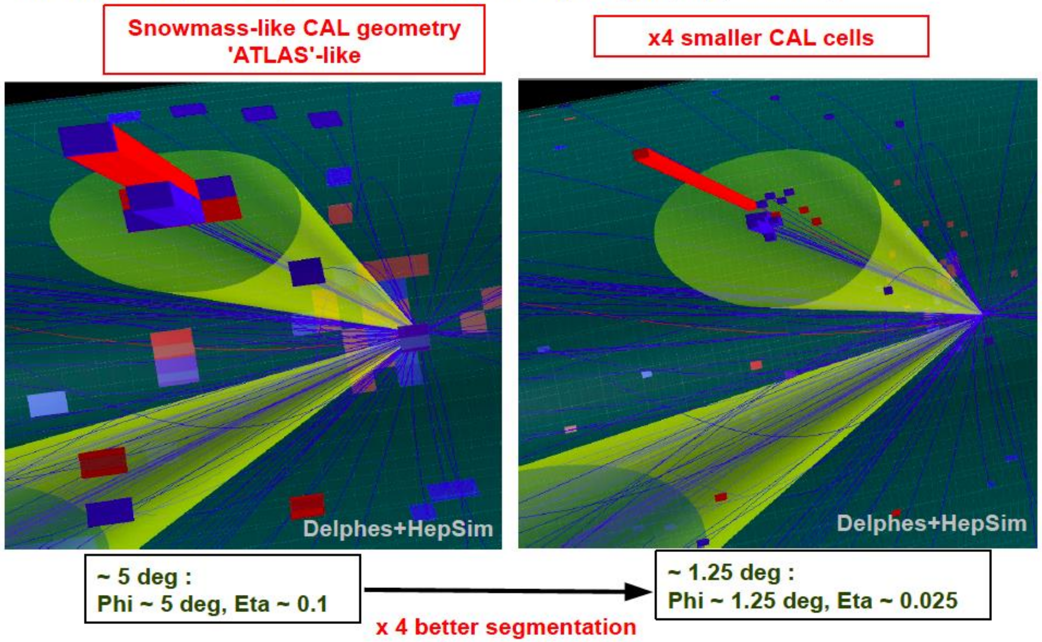
Typical SiPM size: 5x5 mm²
Typical cell size: 50 μm× 50 μm

- **Advantages**
  - Immunity to B-field
  - High PDE (~30-50% includir
  - Timing can be excellent (<5(
- **Limiting factors**
  - Dynamic range
  - Dark rate
  - Radiation soft

F. Lanni

Calorimetry

Example: Z'(10 TeV) → $t\bar{t}$ → 2 antiKT05 jets (pT(top)> 3 TeV)



- **12 λ in depth**
- **Energy resolution with C~3% and below**
- **Longitudinal segmentation for 3D clusters**
- **Δη x Δφ = 0.05 x 0.05 (and smaller)**
  - Based on resolution studies of substructure variables
- **Δη x Δφ = 0.025 x 0.025 (and smaller) for pT(jet)~10 TeV**
  - ~4 better than for ATLAS/CMS
  - x2 → increase of the distance from IP
  - x2 → improvement in instrumentation

S. Chekanov

Calorimetry

<u>4π Calorimeter Parameters</u>

Electromagnetic thickness	25 X_0,	~1λ ± 5X_0
Precision Hadronic	5λ	
Total Precision EM + Hadr.	6λ	± 1λ
Hadronic tail catcher	6λ	± 1λ
Total	12λ	± 2λ
Transverse Segmentation		
EM Δy x Δφ	.03 x .03	± .01
Hadronic Δy x Δφ	.06 x .06	
Tail Catcher Δy x Δφ	.06 x .06	
Longtitudional Segmentation		
EM	3	± 1
Hadronic	2	± 1
Tail Catcher	2	± 1

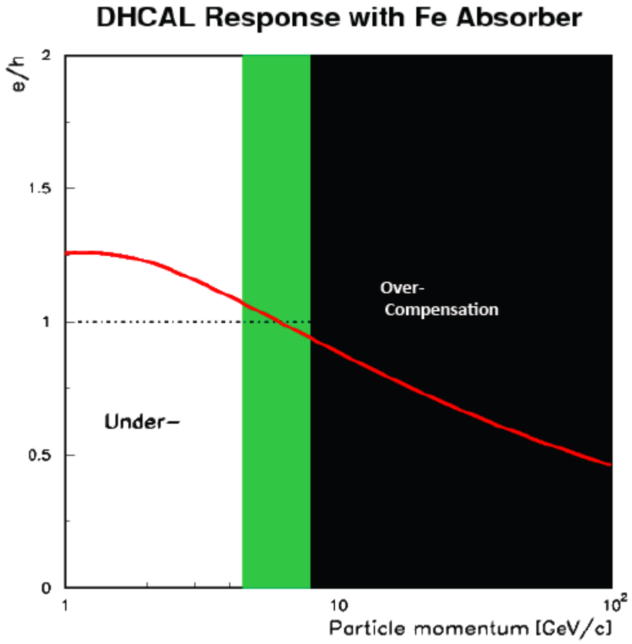
Detectors for the SSC: Summary report - Williams, H.H.
In *Snowmass 1986, Proceedings, Physics of the Superconducting Supercollider* 327-349

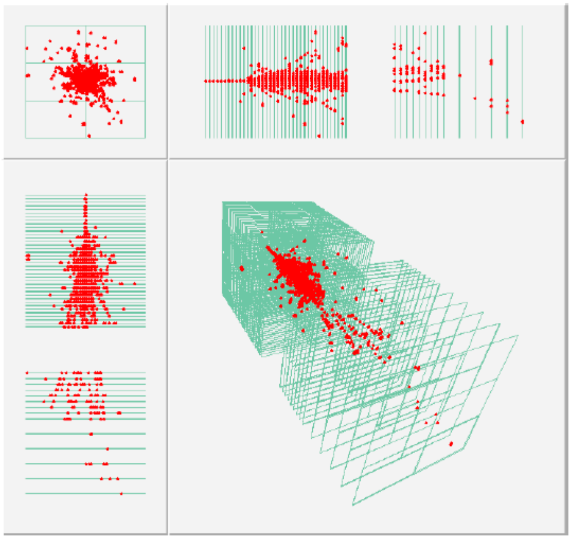
Amazingly close to FCC-hh specs

A calorimeter from 1986 for 2036 ?

S. Chekanov

Digital Calorimetry

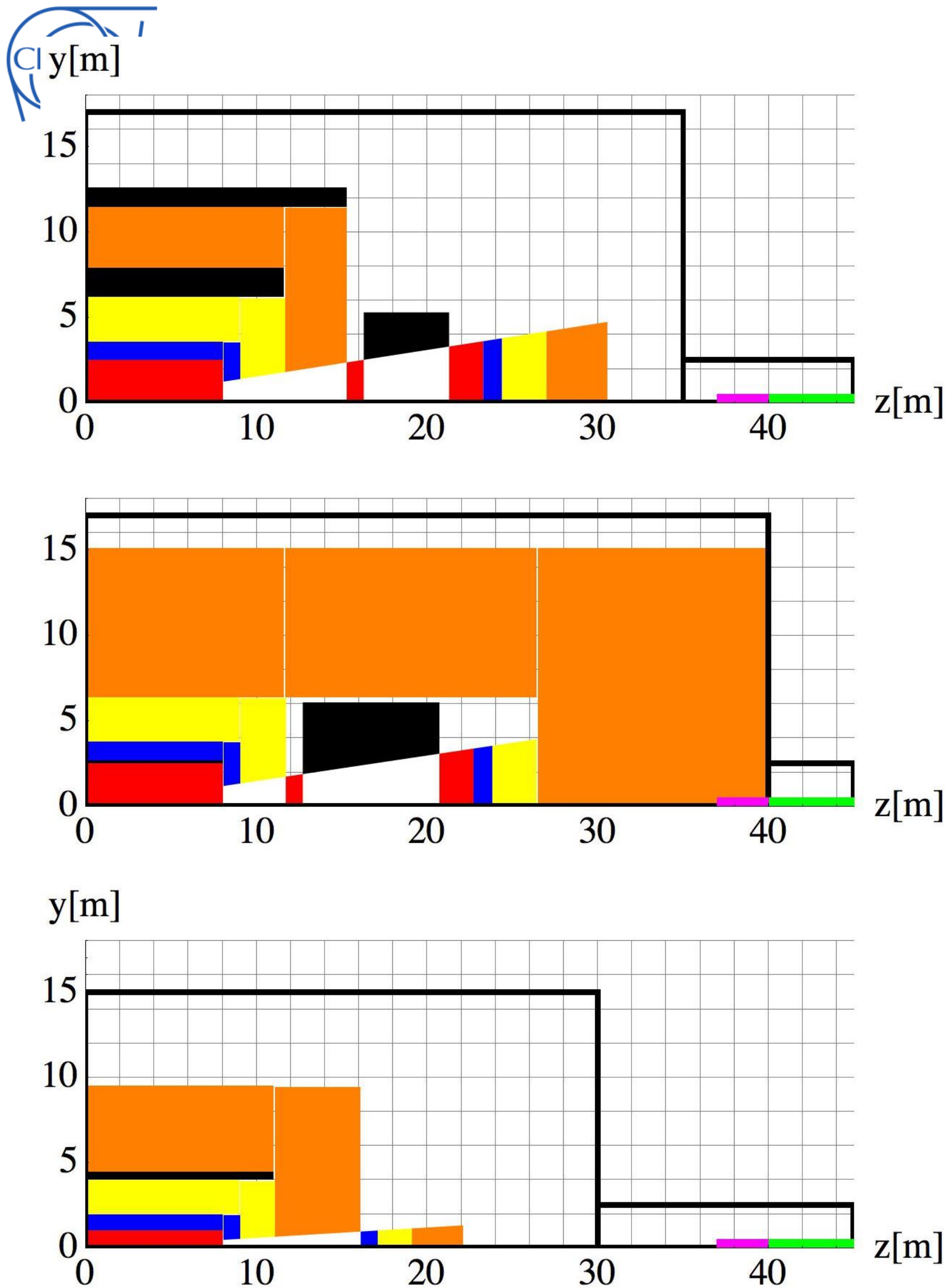




Comment:

- **Digital Calorimetry is very popular in the context of ILC detectors optimized for the 100GeV scale (CALICE)**
- **Whether digital calorimeters are a good way to go for FCC-hh detectors is to be understood**
- **High granularity → YES ! Analog/digital → ?**

Y. Onel



Tracker

Emcal

Hcal

Muon

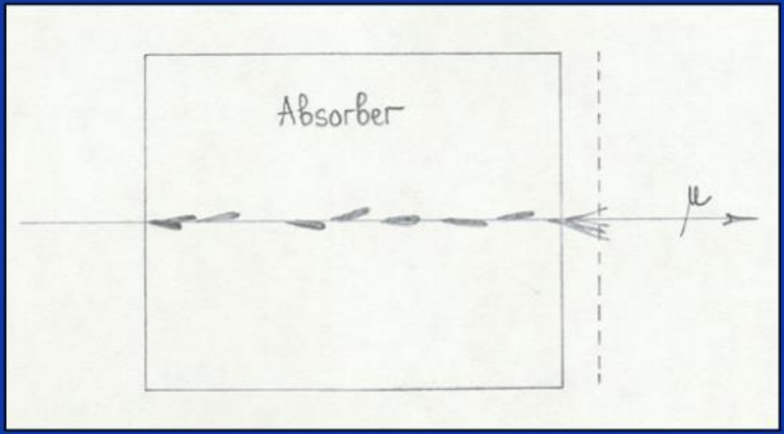
Coil

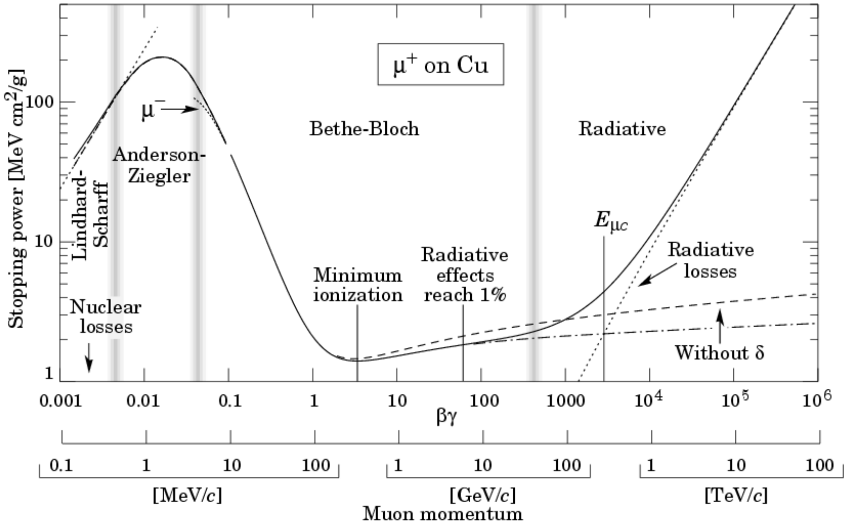
TAS

Triplet

Muon Systems

- **High energy muons start to irradiate γ (em showers) and loose more energy due to radiation losses then due to ionization at a few hundred GeV**
  - **Creates backgrounds in the muon tracking detectors and requires corrections for momentum measurements**





Also to be careful here: Critical Energy E_c: Electrons 550MeV/Z, Muons ≈20TeV/Z

Muons in Iron ≈ 800GeV !

Energy loss due to radiative processes dominates !

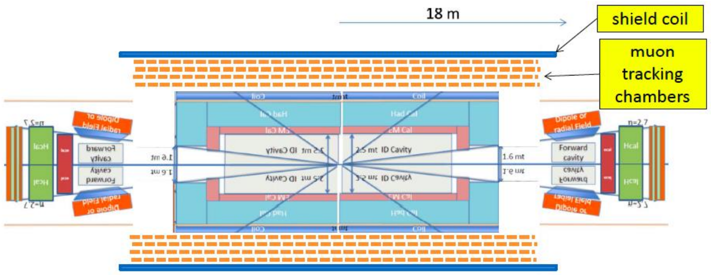
How are muons doing behind 12 λ_{int} of Calo ?

D. Denisov

Muon systems for FCC-hh will be very large:

Considering a large solenoid (similar order of magnitudes in other cases as well)

✓o(10000) m^2 in the barrel
✓~ 3000 m^2 in the endcap
✓~ 300 m^2 in the very forward



➢Given the requirement on the area, almost unthinkable to use technologies different from gaseous detectors.

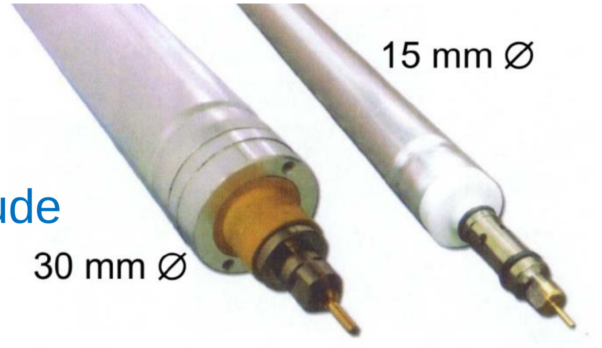
	Detector surface	Foil Area
LHCb Muon system (now)	0.6 m^2	4 m^2
ALICE TPC	45 m^2	180 m^2
CMS Muon system	335 m^2	1100 m^2
ATLAS (MMs)	140 m^2	560 m^2

GEMS

Future use of MPGDs in ATLAS, CMS, ALICE is a huge step forward

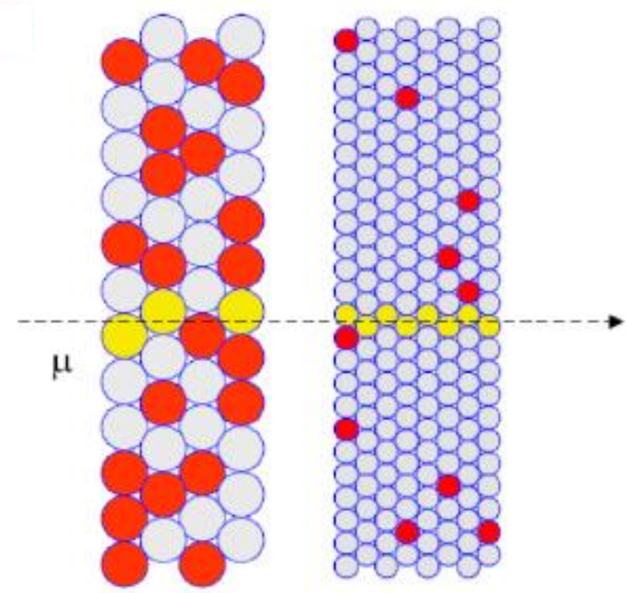
M. Abbrecsia

ATLAS sMDT



Change tube parameters + improve electronics

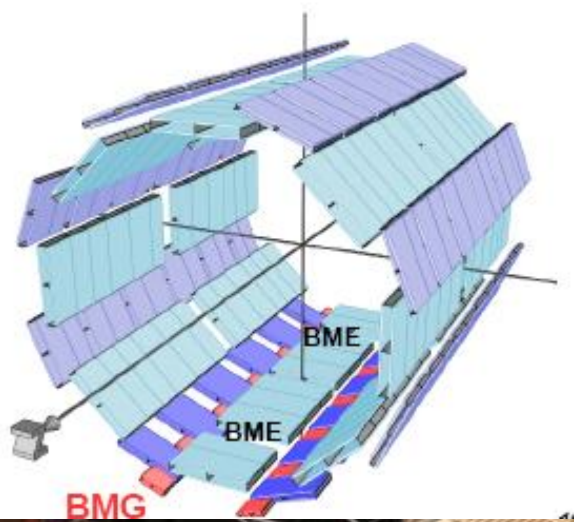
- ➢ Drift tube diameter reduced by a factor 2: MDT → sMDT
  - ✓Increase rate capability by almost an order of magnitude
  - ✓Chamber thickness reduced by a factor 2
  - ✓Occupancy reduced by a factor 8
  - ✓Improved signal/background ratio



Advantages:

- ✓Reuse and optmize of the present proven technology (no aging up to 6 C/cm)
- ✓Full compatibility with existing services, software and alignement system

Will be used to complement or replace MDT chambers where needed



R. Richter

Key Point and Strategy

Much of detector technology is driven by silicon technology and computing power i.e. we can count on significant improvements.

Since the maximum energy an delivered luminosity are the key goals for the FCC-hh machine, the detector efforts should put minimal constraints at the machine efforts.

L_{int} [3, 30] ab^{-1}

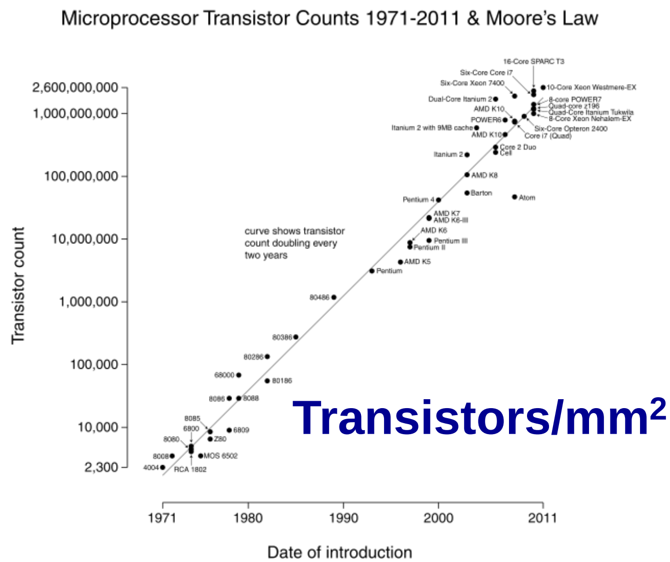
L_{peak} [5×10^{34}, 30×10^{34}] $cm^{-2}s^{-1}$

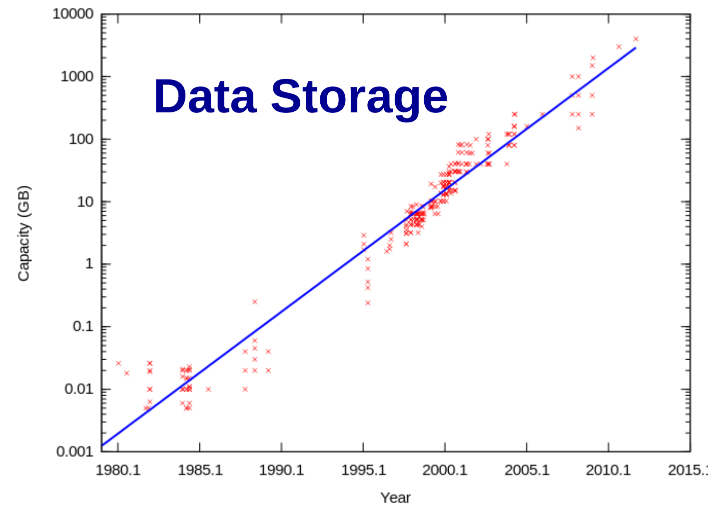
→ N_{pileup} [170, 1020] at 25ns
→ N_{pileup} [34, 204] at 5ns

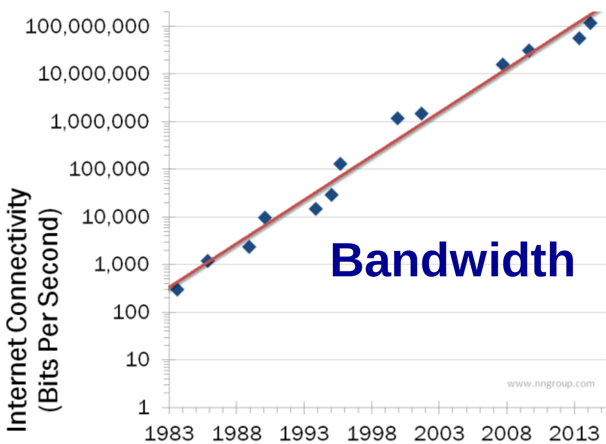
Focus, of course, on maximum integrated luminosity.

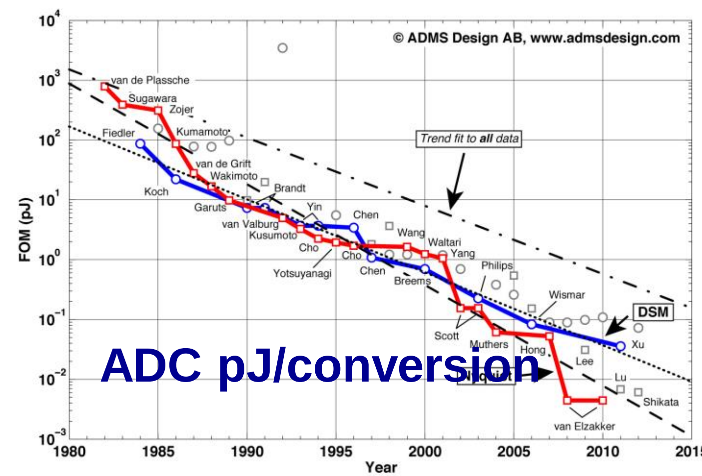
Peak luminosity is only part of the game, specifically in the high burnoff regime.

Prospects for ‚Microelectronics‘





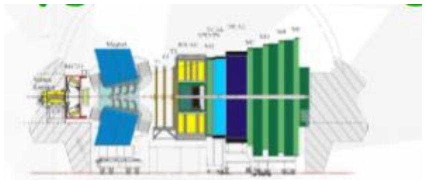




All these figures showed doubling times of < 2 years up to now ! Some scalings will stop, but different tricks might come in.

May dream about a factor 2^{10} = 1024 from 2014 – 2034 (of course optimistic)
This will allow major detector improvements !

LHCb & ALICE in 2018, no Hardware Trigger



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

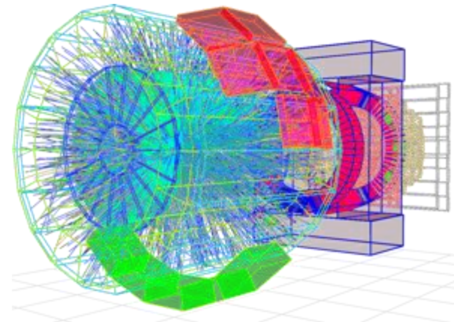
HLT: event recon.

20 kHz (0.1 MB/event)

Storage

2 GB/s

4 TByte/s into PC farm for HLT selection.



1 TByte/s into PC farm for data compression. All events to disc.

50 kHz

Reconstruction + Compression

50 kHz (1.5 MB/event)

Storage

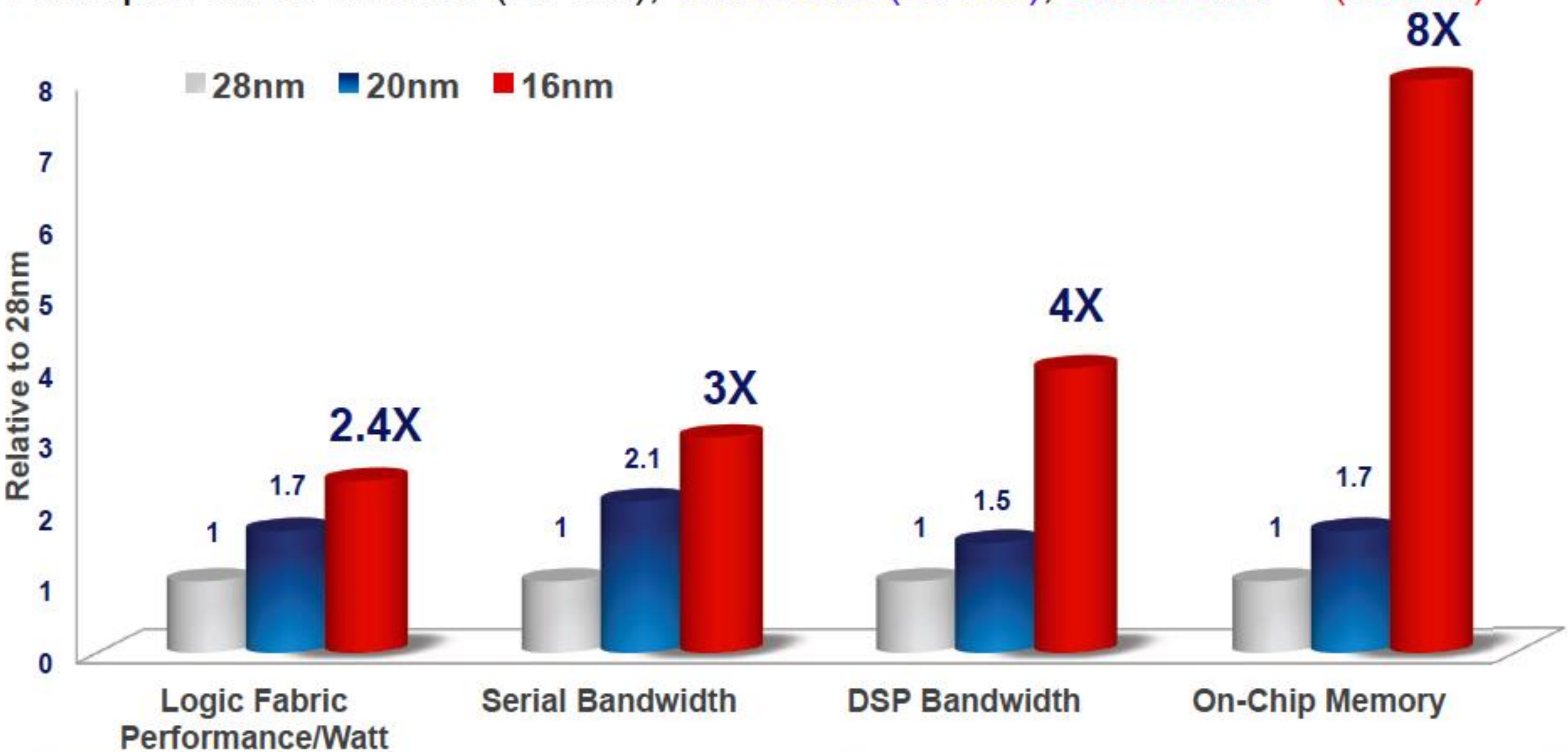
75 GB/s

← PEAK OUTPUT →

W. Smith

Tools for Triggers: FPGAs

Example: Xilinx Virtex 7 (28 nm), Ultrascale (20 nm), Ultrascale + (16 nm)

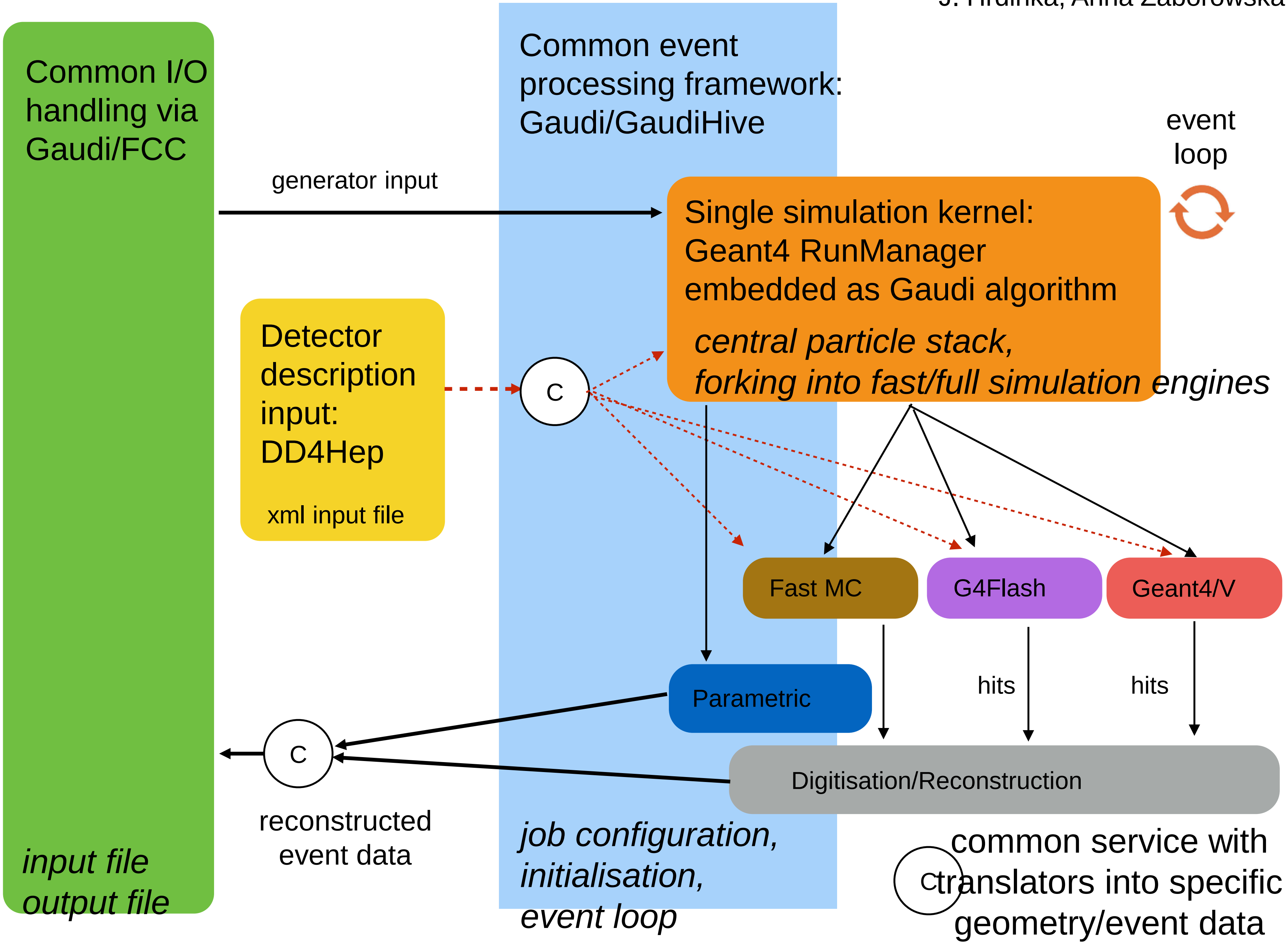


Enhanced Fabric with FinFET performance	Up to 128 transceivers at up to 32.75 Gb/s	~12,000 DSP slices running at ~900 MHz	UltraRAM for SRAM device replacement

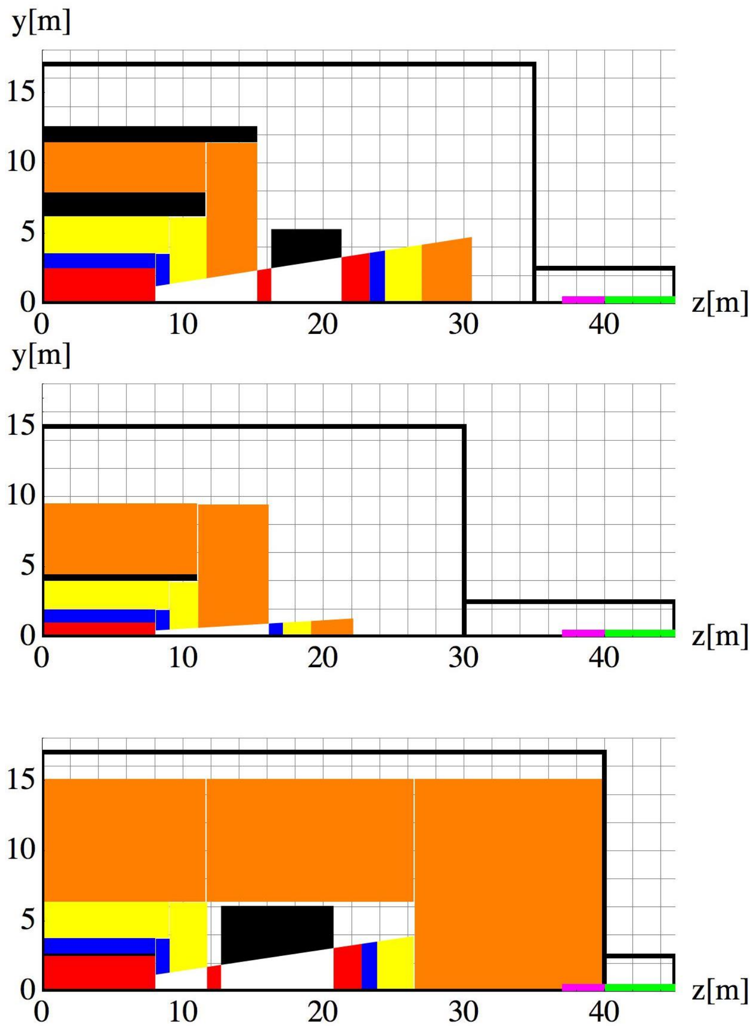
W. Smith

Important effort on simulation tools

A. Salzburger, B. Hegner,
J. Hrdinka, Anna Zaborowska



Conclusion



Prospects for FCC-hh detectors are good !

Next:

Define granularities and basic parametrization.

Simulation of benchmark channels with parametrized detector response and consequently more detail.

Explore magnets, technologies.

Many studies to be done → projects, students
Still 'bottom up' approach for now.

Medium term:

Develop strategy to push R&D in an effective way once the HL-LHC R&D is concluded.