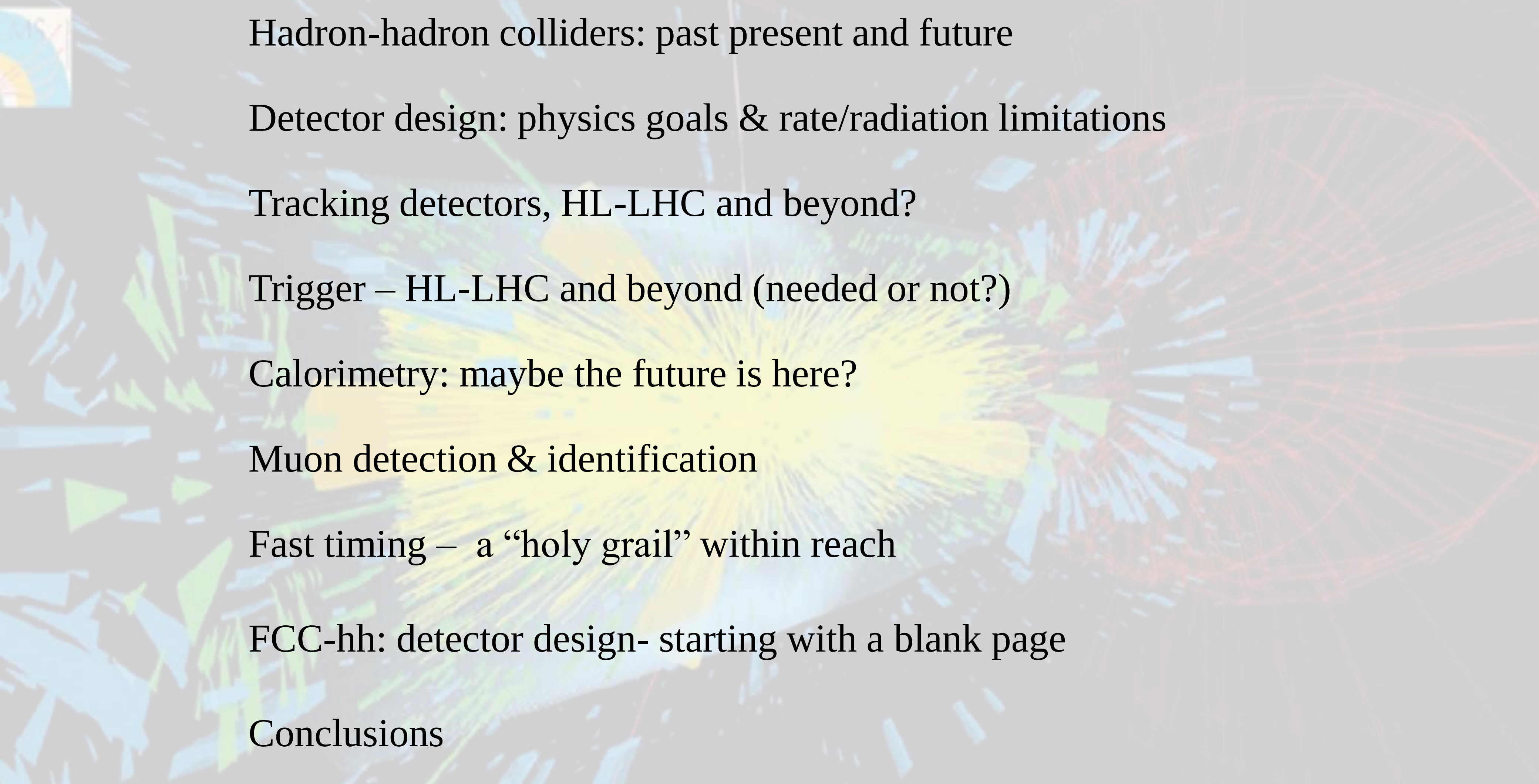
Instrumentation Challenges at future h-h colliders



Hadron-hadron colliders: past present and future

Detector design: physics goals & rate/radiation limitations

Tracking detectors, HL-LHC and beyond?

Trigger – HL-LHC and beyond (needed or not?)

Calorimetry: maybe the future is here?

Muon detection & identification

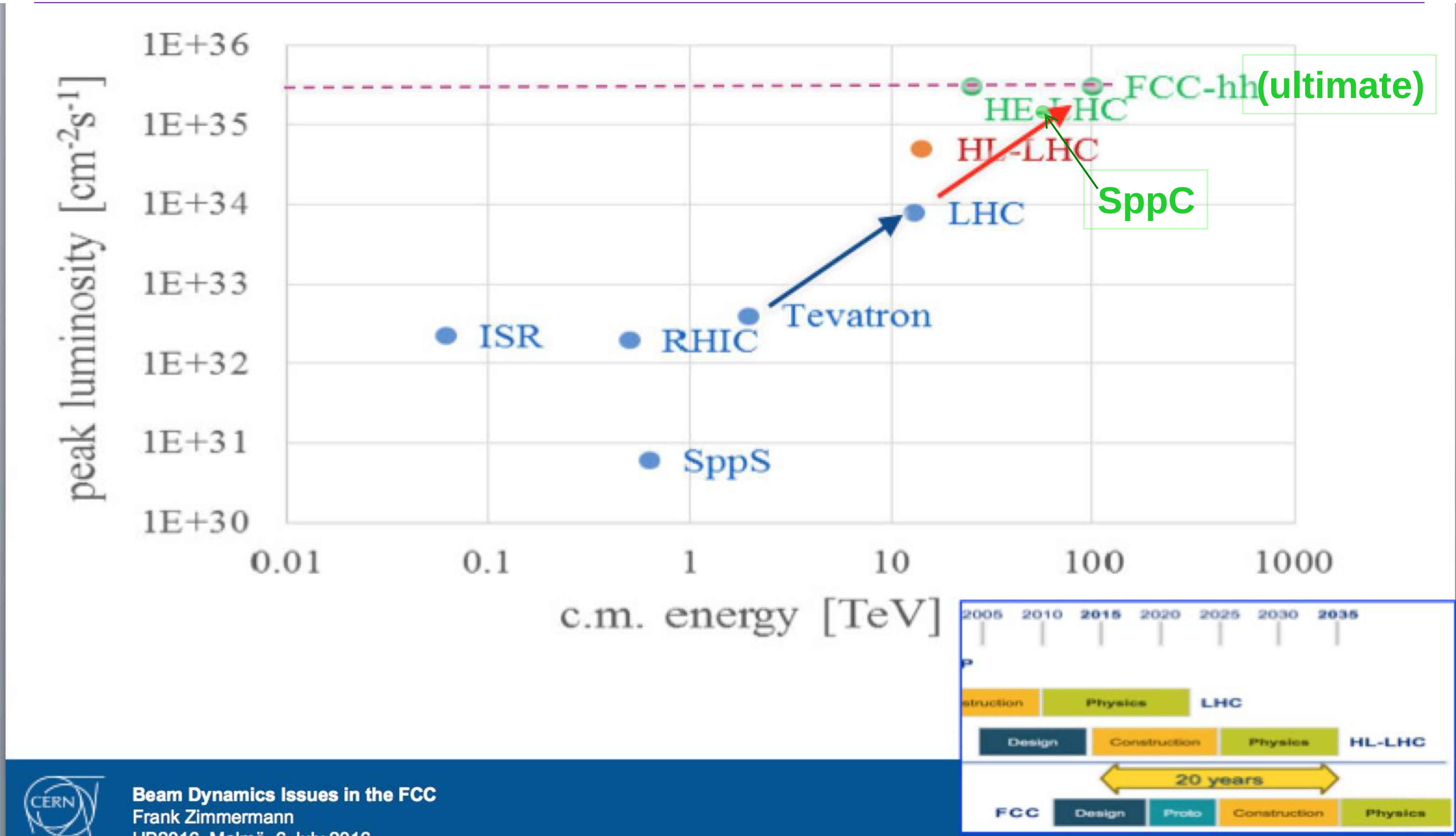
Fast timing – a “holy grail” within reach

FCC-hh: detector design- starting with a blank page

Conclusions

Particular thanks to:
Phil Allport, Dave Barney, Didier Contardo, Albert de Roeck, Kevin Einsweiler, Werner Riegler, Frank Zimmermann

h-h Colliders: past, present & future



Beam Dynamics Issues in the FCC
Frank Zimmermann

Future h-h colliders parameters

Machine parameters (p-p) ---> event rate issues (approximate numbers)

	HL-LHC nominal	**HL-LHC ultimate**	**HE-LHC**	**SPPC**	**FCC-hh Phase1**	**FCC-hh Phase 2**
Collision energy	14	14	>25	71.2	100	100
Bunch spacing	25	25	25	25	25	25 (5)
Lumi x 10^{34}	5 (lev)	7.5 (lev)	>25	12	5	20-30
<Pileup>	140	200	850	400	170	1000 (200)

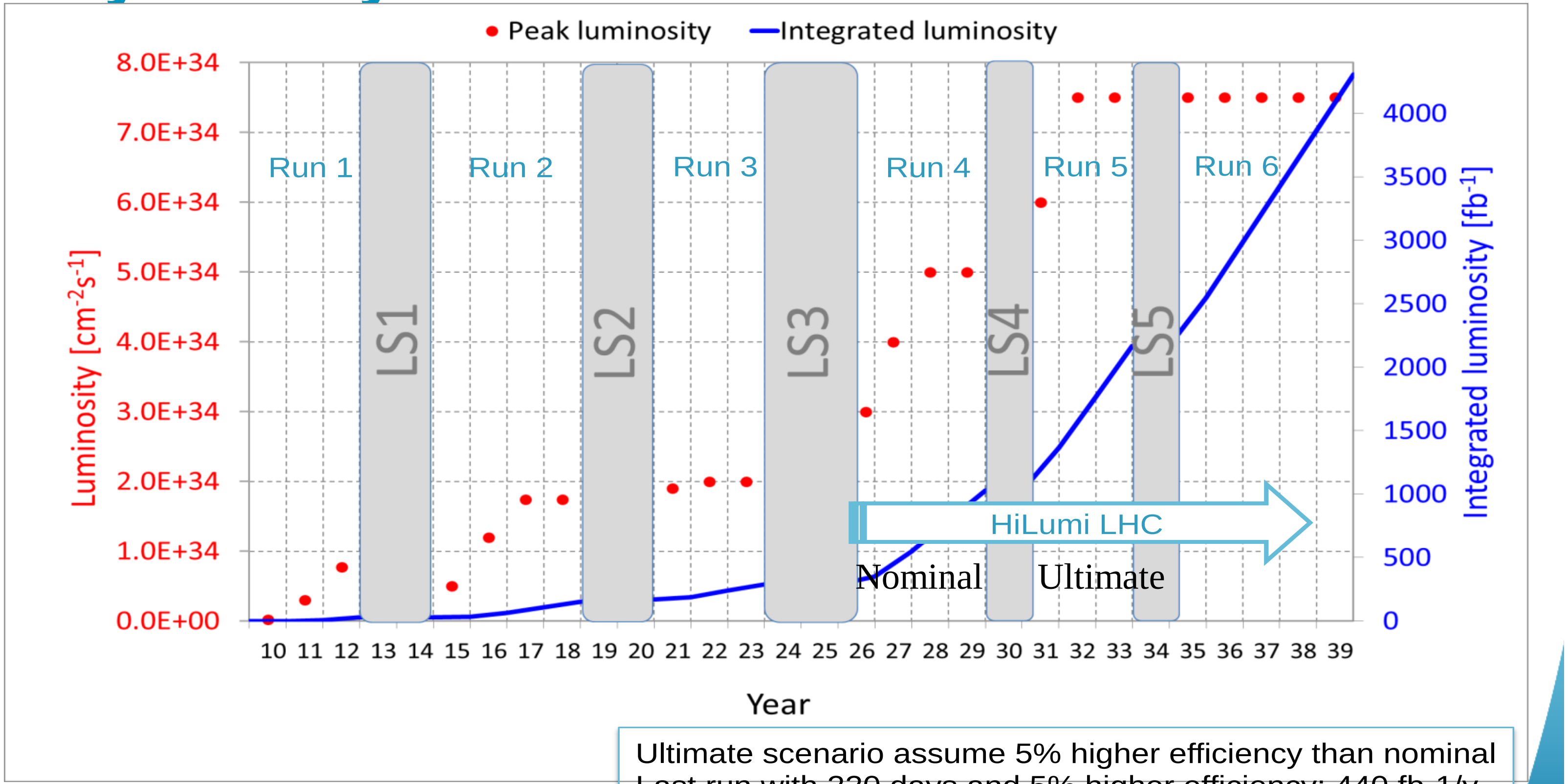
Remarks: FCC Phase1 : similar detector conditions to HL-LHC Phase 2 = ultimate)
HE-LHC and FCC- Phase 2 are a new scale of challenge

Future h-h colliders – HL-LHC

& at ultimate performance sets the design challenge for detectors installed in LS3

Ultimate scenario 7.5 10^{34}: 320 fb^{-1}/y for 160 days

Physics days: 160 Run4 → 200 Run5→ 220 Run6



Ultimate scenario assume 5% higher efficiency than nominal
Last run with 220 days and 5% higher efficiency: 440 fb-1/y

Detector design: physics drivers

1)Higgs physics remains a key objective -- until (hopefully) something else comes along,
---> maintain acceptance, efficiency & resolution for decays of 125GeV Higgs (a light object)
boost due to higher E_{cm}
2)…while simultaneously optimising search sensitivity for high mass discovery
---> dynamic range challenge (eg muon trigger p_T thresholds)
3) Forward processes, VBF, multi-Higgs etc.
----> extend acceptance (especially for jet reconstruction) to higher η

Basic Requirements:

Values quoted apply to FCC-hh or SppC

Precision tracking in magnetic field down to low p_T
Electromagnetic calorimetry to high η (η=4) [30-50% loss of H--->4l wrt HL-LHC if stay at 2.5]
Matched tracking and highly granular calorimetry to high η (η =6) [measure VBF jets & separate from pileup]

Hermetic calorimetry: constant term (1-2%) & full shower containment (12λ depth) [di-jet mass res]
Good Momentum resolution at highest p_T (~10-15% at p_T =10TeV)

Fine granularity calorimetry (esp high η) to measure jet structure & reject pile-up (0.025x0.025)
Efficient charged track/neutral cluster association with vertex (r,z or r,z,t) for pile-up rejection
Efficient secondary vertex tagging (b,c,τ) despite radiation levels near luminous region

Detector design: rate & radiation tolerance

$$\text{1MeV neq Fluence}[cm^{-2}] \approx \frac{N_0}{2r[cm]^2\pi} \times N_{pp} \qquad \text{Dose}[Gray] \approx 3.2 \times 10^{-10} \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

For a given N_{pp}, both are functions only of distance from beampipe

: ignoring effects of magnetic field

: considering only primary charged hadrons from pp collisions

valid up to r~ 10cm, beyond that curling particles and neutron cloud

---> For x 5 in lumi, feed in new technologies with better rad tolerance at low radius

Today's inner technology at LHC will likely still be in HL-LHC, but further out

Δ c.m energy (x7) does not change the radiation field that much

FCC- hh (nominal)

100mb inelastic pp crossection (+25% cf HL-LHC)

dN/dη = N0 = 8 (+50% cf HL-LHC)

for 3000 fb^{-1} = 3 * 10^{17} events

a Pixel tracker layer1 at r = 3.7cm will see

1MeVneq fluence = $3*10^{17}*8/(2*\pi*3.7^2)$ = $2.8*10^{16}$ cm^{-2}

Dose = $3.2x10^{-8}$ *2.8*10^{16} = 9MGy

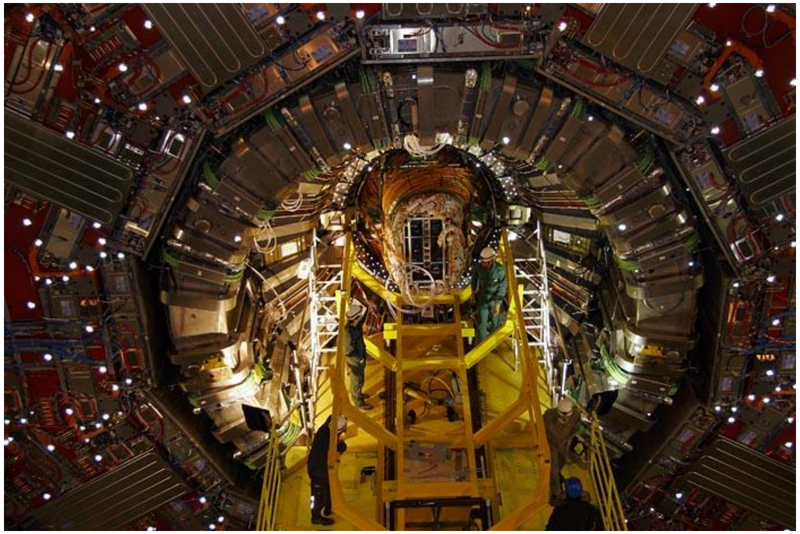
FCC-hh Phase 1 detector sees ~ 2 x the HL-LHC detector fluence and dose

	HL-LHC 3000 fb^{-1}	
	Outer layers	Innermost layer
Particle Rate (kHz/mm^2)	1000	10000
Fluence (n_{eq}/cm^2)	1 x 10^{15}	2 x 10^{16}
Dose in MGy	0.5	> 10

. HL-LHC solutions ~ OK for FCC-hh Phase 1, but not HE-LHC or FCC-hh Phase 2

Detector design: other factors

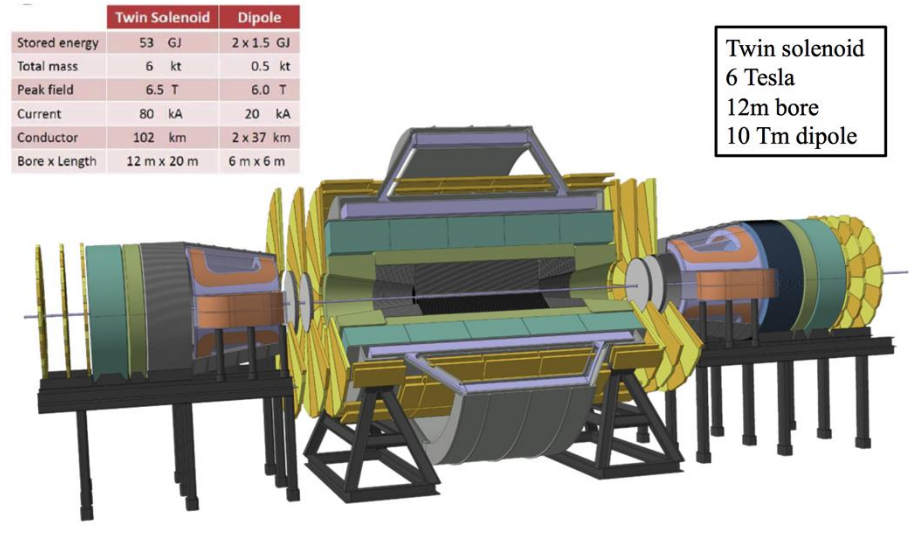
For HL-LHC (and quite probably HE-LHC) , one of the biggest challenges is to integrate new instrumentation into the original magnet and infrastructure and indeed a large fraction of the original detectors



For FCC-hh, exciting to start with a blank sheet of paper, but the design

a) won’t work as a simple extrapolation of what we have today, evolved for HL-LHC.

b) has to take into account from scratch all of the infrastructure/buildability/ installability/ maintainability factors



	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

Twin solenoid
6 Tesla
12m bore
10 Tm dipole

Tracking: Meeting the HL-LHC challenge

Improve	Patt. Rec. at high pileup	Tracking efficiency	δ(1/pT) low PT	δ(1/pT) high PT	impact param & vertex resolution	2- track sep	γ --> ee pollution
Granularity (high r)	●	●		●			
Granularity (low r)					●	●	
More pixelated layers	●				●		
Reduce X_0's		●	●				●

Extension to η=4 to help reconstruct forward jets

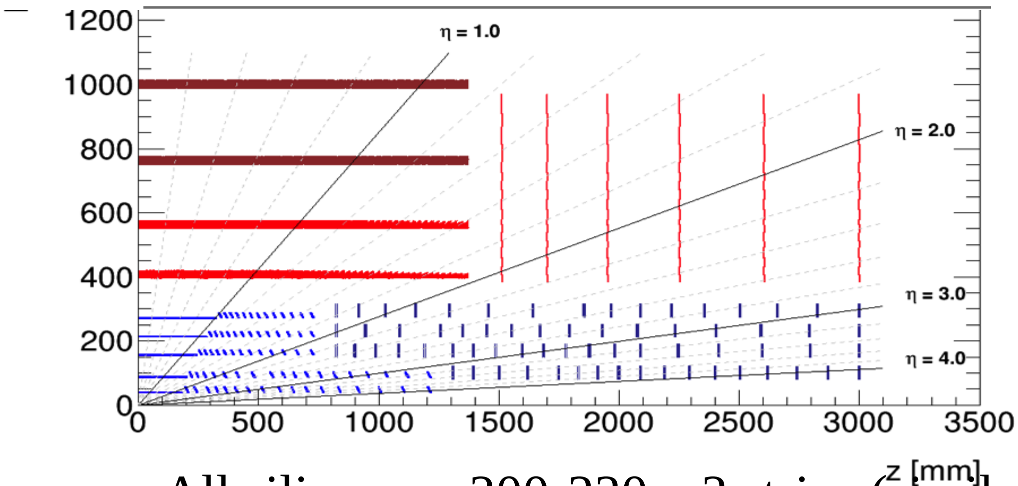
permanent cooling (to combat radiation damage effects on sensor characteristics)

compact, radiation-hard, low cost optical & electrical links to export data

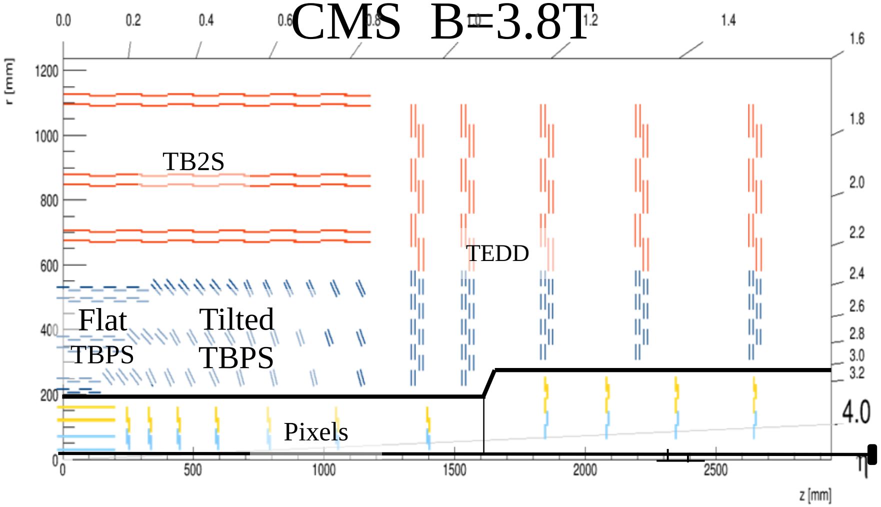
serial powering (very large numbers of channels running at low voltages
& drawing high currents → big potential power loss in cables)

HL-LHC trackers.. Pre TDR

ATLAS B=2T



CMS B=3.8T



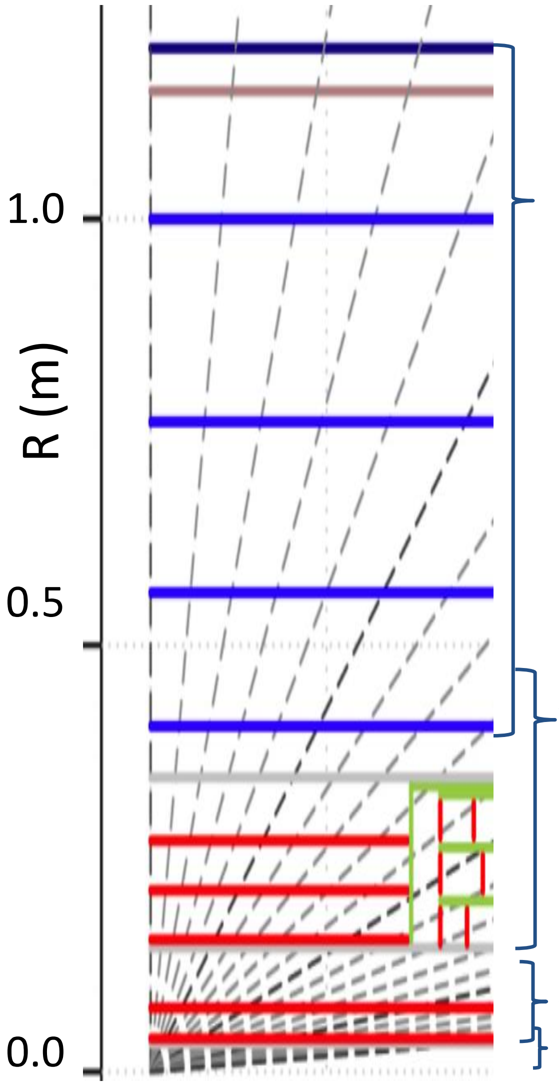
All silicon : ~ 200-220 m2 strips (similar CMS Tracker) +10-20m2 pixels
Pixels in 200-250 mm < r < 30-40mm
Extension to η ~4 (forward jets important)

fine granularity consistent with expected occupancy

good spatial resolution + low material budget over long path length in magnetic field

tolerance of expected:- - hit and data rates
- radiation environment (dose rate & integrated dose),

HL_LHC trackers (pre TDR)

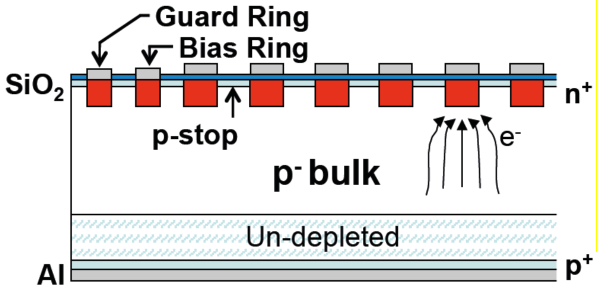


strips

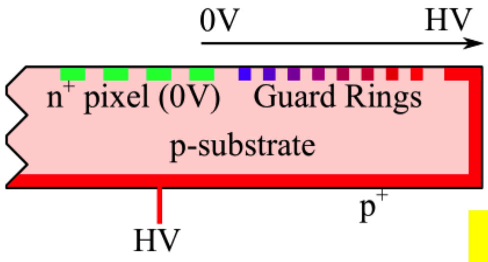
outer pixel

inner pixel

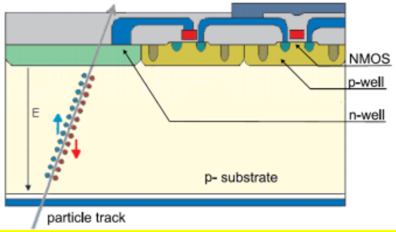
innermost pixel



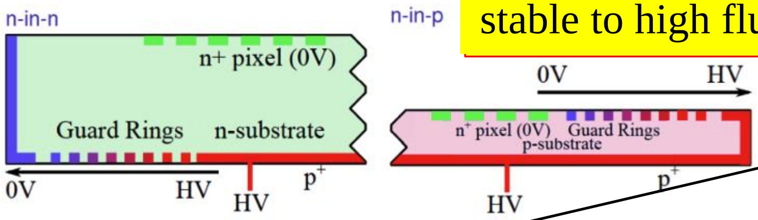
Strip module with
p-type substrate
charge collection
-fast (electrons)
high effic after irrad



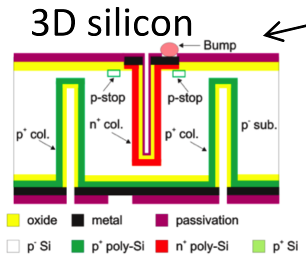
depl. CMOS pixels



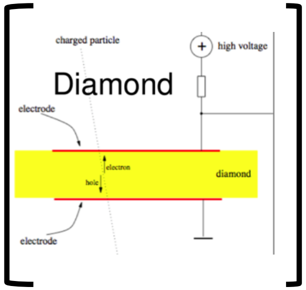
collected charge
stable to high fluence



Drift & depletion
zone size set by
electrode spacing
reducing
-collection time
-depletion voltage
-rad damge
Small scale
use in ATLAS IBL!

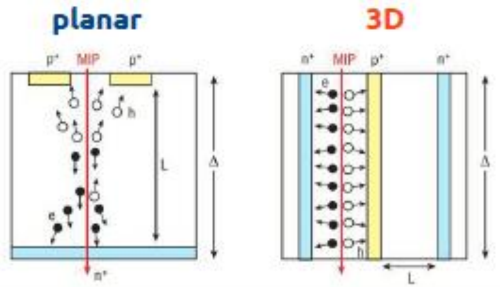


dedicated
rad.-hard
detectors



N. Wermes. 14th VCI Wien. 2/2016

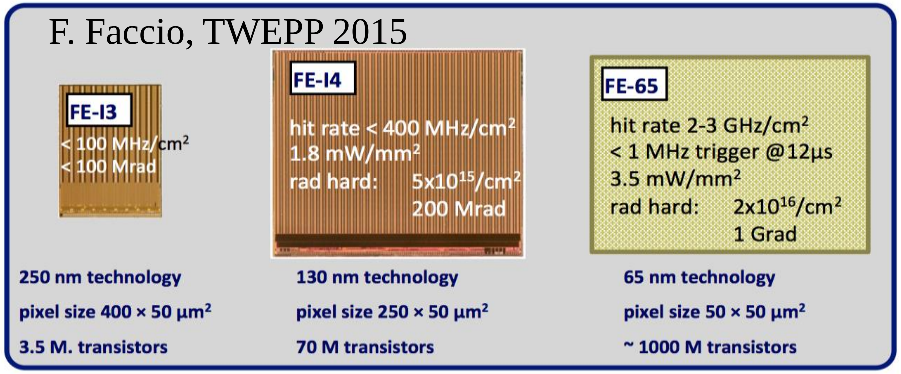
Tracking readout: challenges concentrate at low r



-Tests show HL-LHC assault: 2 x 10^{16} n_{eq}/cm^2, 10 MGy, pileup 200
can be withstood by the proposed inner layer sensor technologies
-3-D Si sensors (drift orthogonal to ionisation track) are installed
in ATLAS IBL – an excellent battle test.
Mechanisms leading to anomalously large signals mostly understood (& even exploited!)

Readout hopes focused on: common CMOS 65nm
ASIC development by CERN RD53.
(targeted at 50µm x 50µm pixel sizes).
Hopefully 65nm is the magic bullet for HL-LHC
as 250nm was at LHC. Many challenges met:
See eg Jorgen Christiansen & Maurice Garcia-Sciveres, LHCC May16

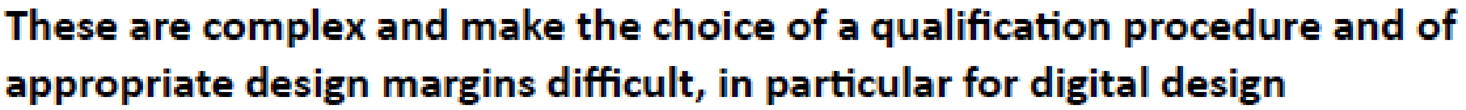
F. Faccio, TWEPP 2015



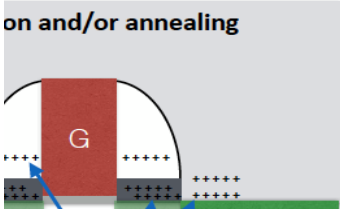
FE-I3	FE-I4	FE-65
< 100 MHz/cm² < 100 Mrad	hit rate < 400 MHz/cm² 1.8 mW/mm² rad hard: 5x10¹⁵/cm² 200 Mrad	hit rate 2-3 GHz/cm² < 1 MHz trigger @12µs 3.5 mW/mm² rad hard: 2x10¹⁶/cm² 1 Grad
250 nm technology	**130 nm technology**	**65 nm technology**
pixel size 400 × 50 µm²	**pixel size 250 × 50 µm²**	**pixel size 50 × 50 µm²**
3.5 M. transistors	**70 M transistors**	**~ 1000 M transistors**

but

difficult problems, specific to 65nm remain, especially in radiation tolerance [RINCE,RISCE]



These are complex and make the choice of a qualification procedure and of appropriate design margins difficult, in particular for digital design



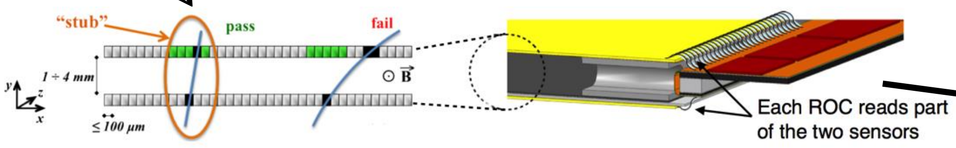
F. Faccio, ACES 2016

As was learned in the past,
radiation tolerance also varies between different fabrication facilities and can vary with time.

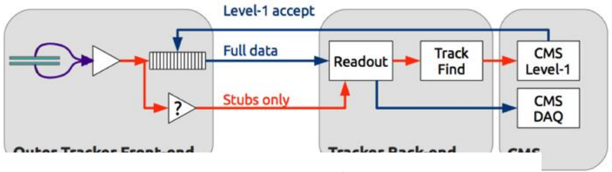
CMS HL-LHC Track-trigger

Needed to control trigger rate & threshold turn-on at high pile-up

Track stub compatible with Pt >2 GeV



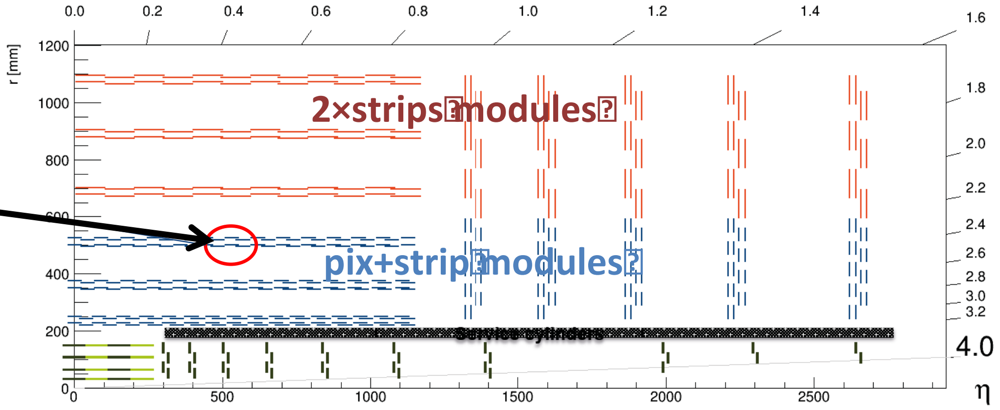
Stubs are processed in the back end to build L1 track primitives

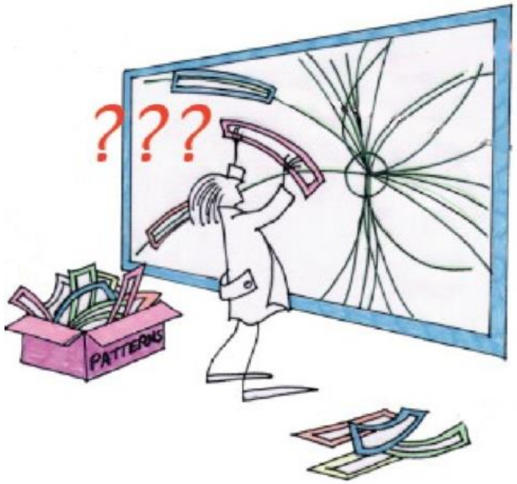


— @ 40 MHz (BX rate)

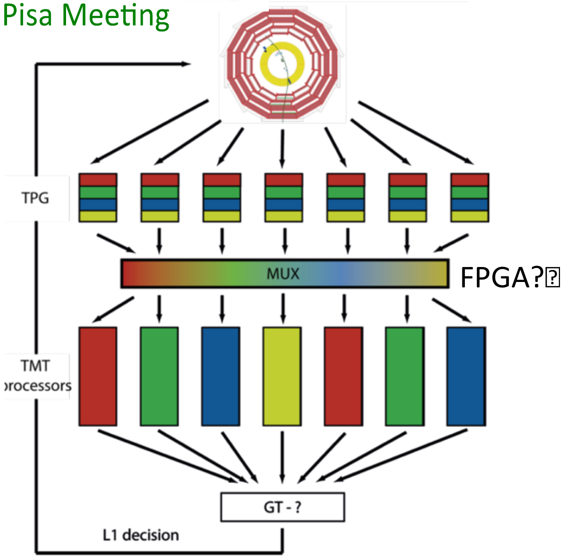
— @ 750 kHz (L1A rate)

see e.g. D. Abbaneo, CERN PH seminar, F. Ravera 13th Pisa Meeting

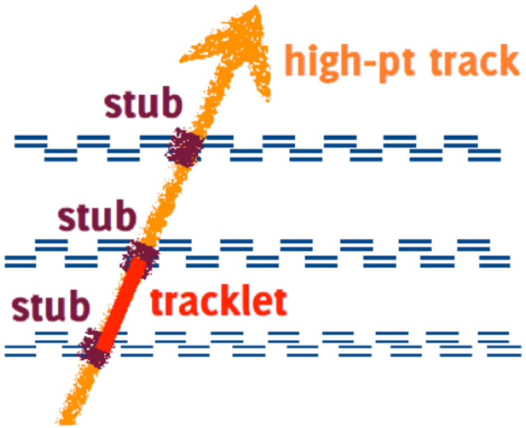




Track matching with a 10^8 pattern database- Associative Memories



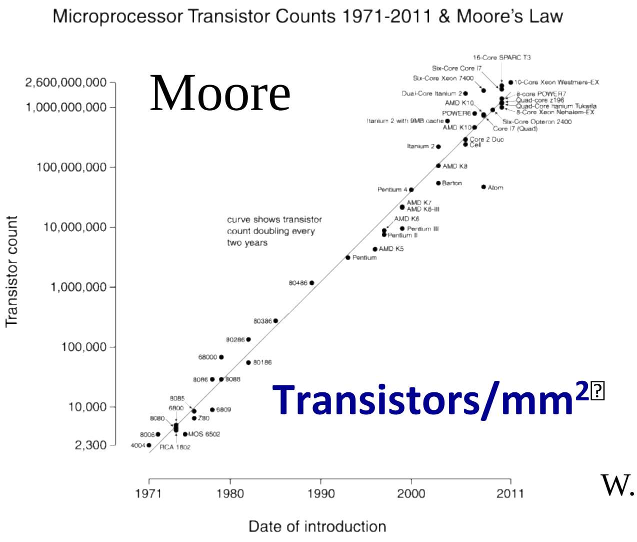
Time multiplexed trigger. Each processor deals with complete event



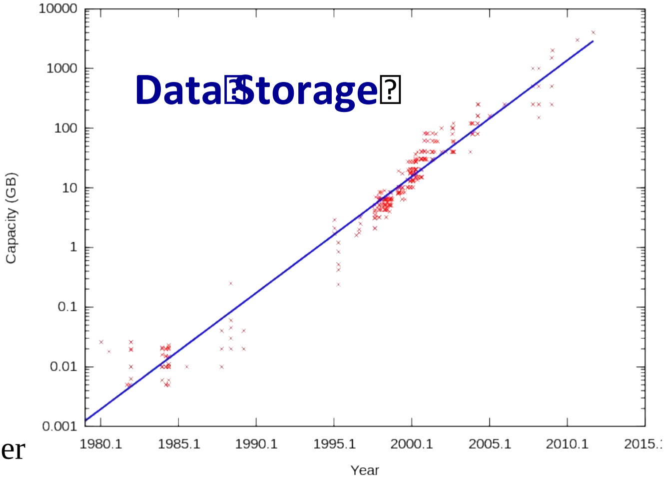
Track reconstruction seeded by pairs of stubs in adjacent layers

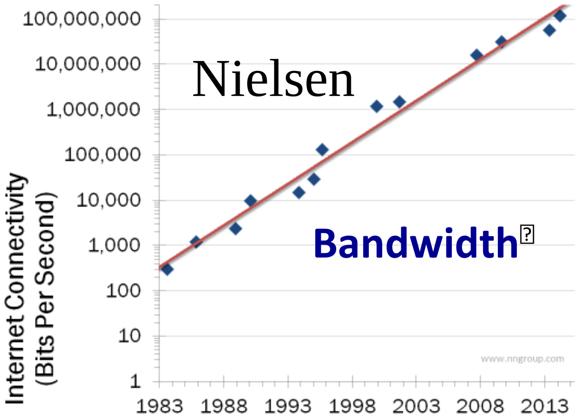
Will we need trigger at FCC-hh or even HL-LHC?

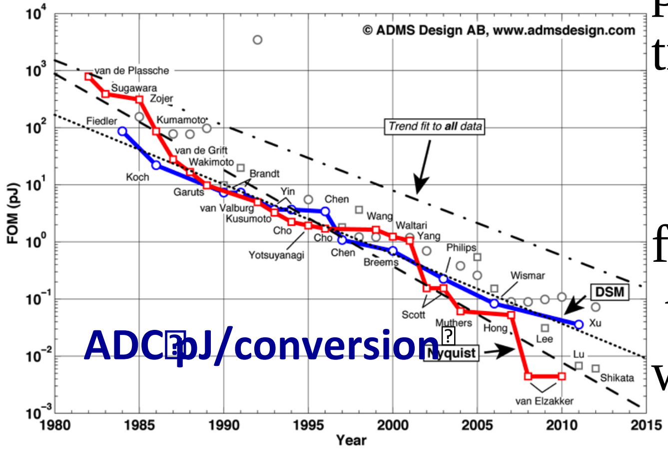
v. dangerous to predict further than a decade into the future
(some predictions for LHC good : telecommunications links, CPU, some bad: optical links)



W.Riegler







Superficially promising doubling times (~ 2 years). Project to 2026 and hope for a factor 1000?

ALICE & LHCb already planning multi TB/s transmission off detector

but

for CMS II at HL-LHC , triggerless output rate would be 200TB/s

Triggerless DAQ?

Assume 10Gb rad hard GBT + 400GB ethernet. 100TB SSD drives with 10GB/s/drive

40 MHz * 5 MB/event

= 200 TB/s = 1600 Tb/s

>100 times #links as of today

Impossible!

160.000 x 10 Gb/s links (VL)

Rad hard links are a real issue

10 times more links than LHCb is planning for Run-3

Maybe feasible

4000 x 400 Gb/s Ethernet

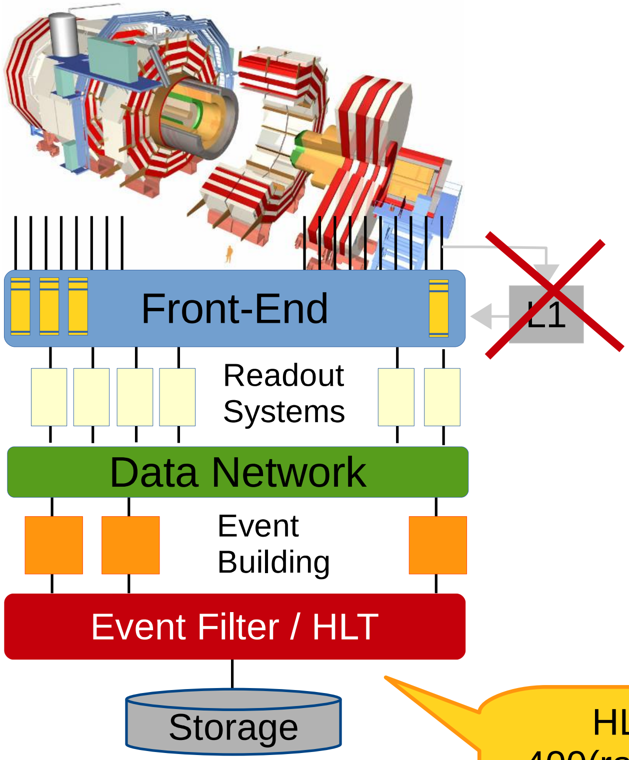
12 PB/min buffer

120 drives per minute of buffer...

No problem

…but to achieve the throughput with 10GB/s/drive → 20.000 drives

Huge discrepancy of storage vs bandwidth!



HLT CPU:
400(rate)*3(pileup)
~1000x today

From Moore ~100x

Maybe with GPU/FPGA

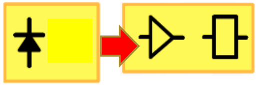
Fatal problem is getting data off detector
Rad-hard special links!
Material budget!!!!

Frank Winklmeier, CERN AT 12 May 2016

Future Trackers: CMOS pixels

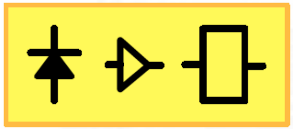
See Norbert Wermes VCI Wien Feb 2016 for review

Hybrid:

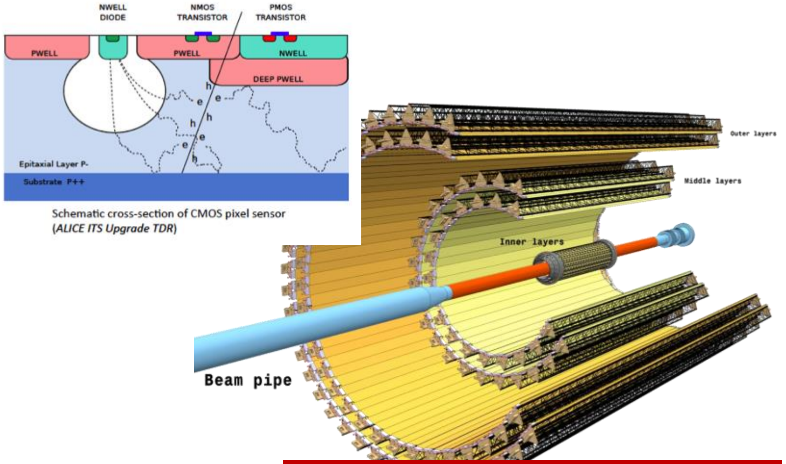


Bump bonding

Monolithic
Active



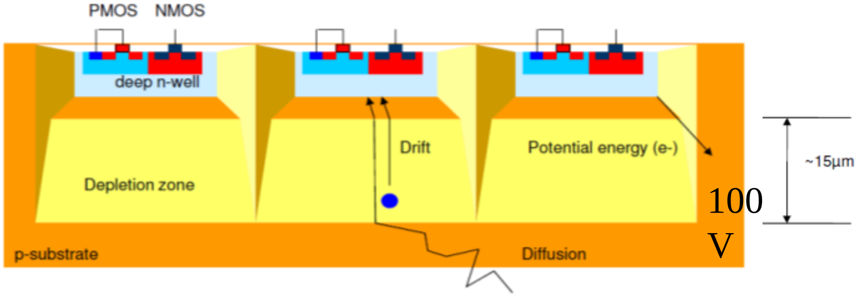
MAPS: lower material budget,
cost, power
+ better resolution
STAR, ALICE ITS upgrade



Schematic cross-section of CMOS pixel sensor
(ALICE ITS Upgrade TDR)

~ 10 m^2 **12.5 G pixel**

Developing MAPS for HL_LHC and beyond
challenge of rate & rad tolerance: HR/HV CMOS
fast charge collection of reasonably large signals (4000e-)
not too large a drift distance to avoid trapping effects
HV add-ons: increase voltage handling capacity
HR add-ons: higher resistivity Si wafers – depletion layer→DMAPS
130-180nm features: Rad hard processes, multiple nested wells
Backside processing: make backside contact after CMOS processes



: charge collection through drift space
improves speed & rad hardness
Many detailed variants, of which some reach tolerance of
5 x $10^{15} n_{eq}/cm^2$ and 7MGy
---- no beam tests of large scale detectors yet

---> substantial ATLAS programme toward full-scale monolithic DMAPS devices

Particle flow & Imaging Calorimeters

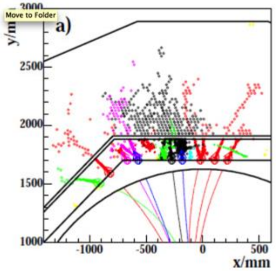
First succesfully applied in ALEPH @LEP:

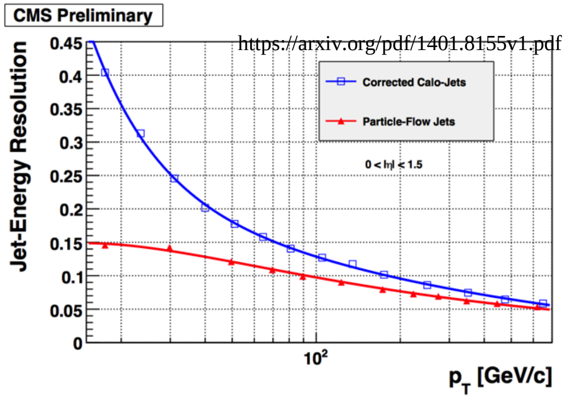
- much studied for linear collider applications eg CALICE

Re-construct entire event in detail including each jet: E jet = E track + Eγ + Eneutral

----> much improved E_{jet} res.

Excellent performance of Si Trackers suited to particle flow technique (70% of event info from tracks)

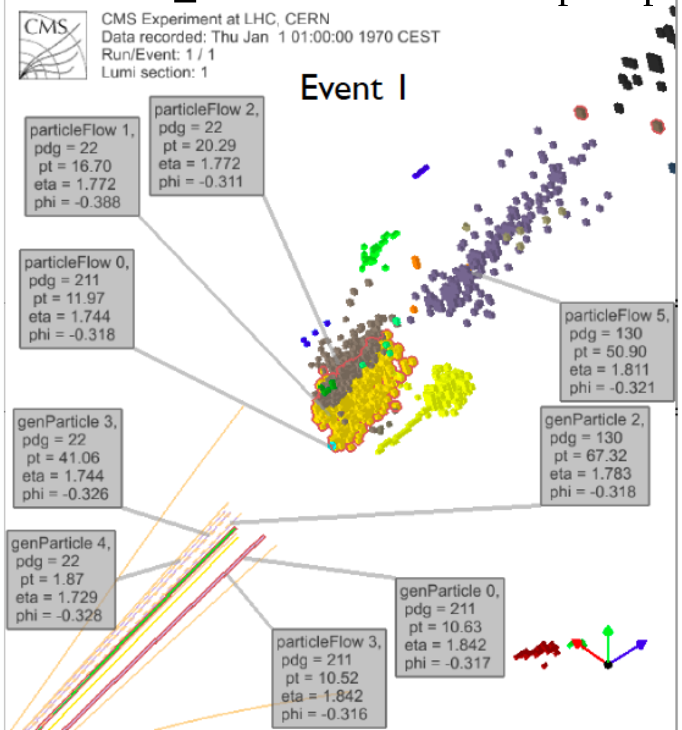




https://arxiv.org/pdf/1401.8155v1.pdf

Jim Virdee, Oxford Sem Sep 2016

CMS HL_LHC simulation 140 pileup



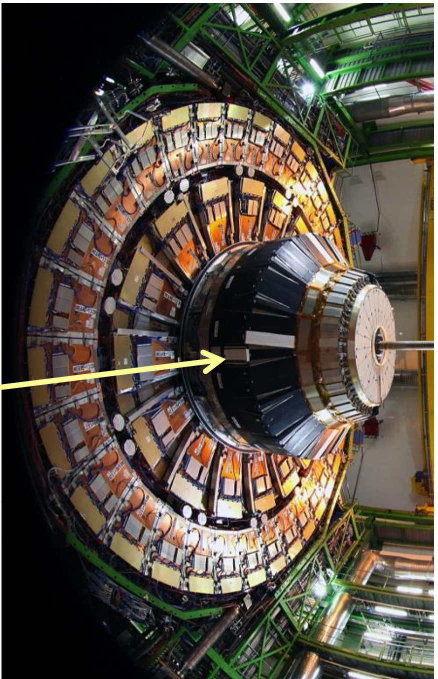
Calorimeters for particle flow need:

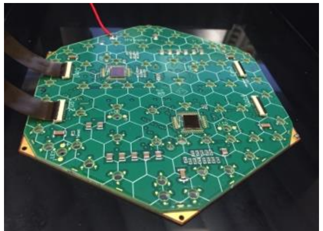
-granularity more than resolution,

-small Moliere radius in ECAL (shower sep) for jet core separation

+ high sampling density ---> Si + W

Radiation damage forces CMS to replace endcap calorimetry in LS3

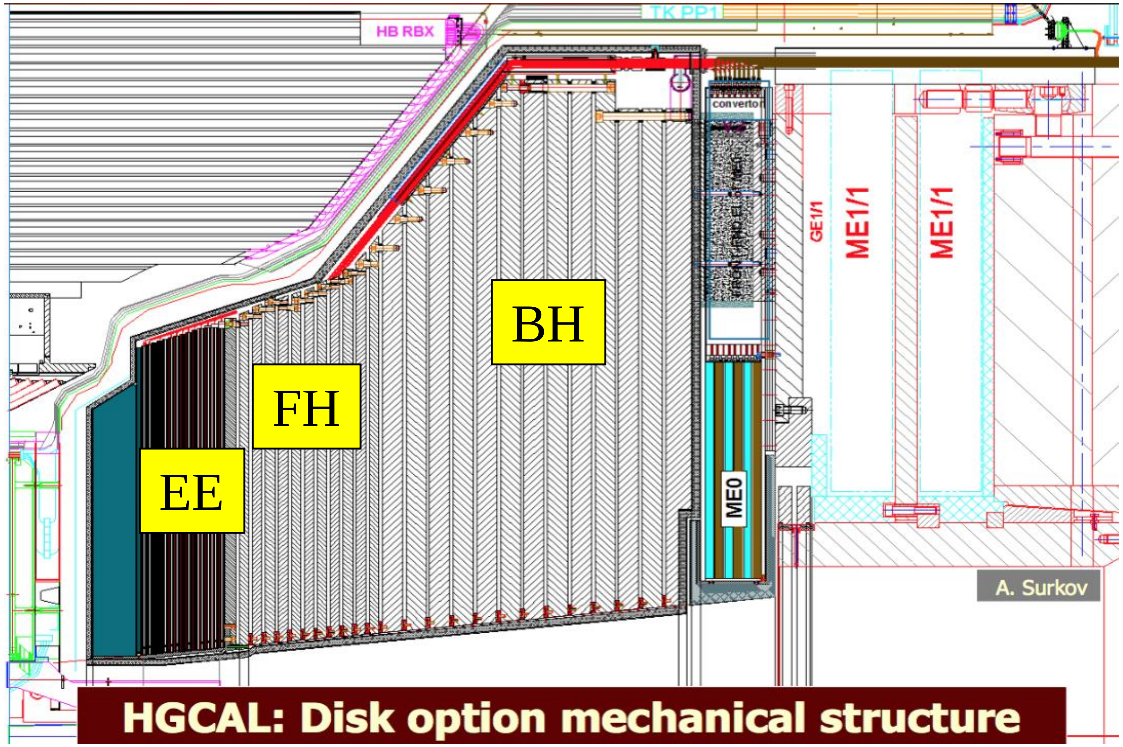




---> High Granularity Calorimeter

CMS EC Calorimeter : Some Current Thoughts

One of several mechanical options opened up by recent decision to use stainless steel absorber



Jim Virdee, seminar Univ Oxford Sep 2016

Construction:

- *Hexagonal Si-sensors built into modules.*
- *Modules with a W/Cu backing plate and PCB readout board.*
- *Modules mounted on copper cooling plates to make wedge-shaped cassettes.*
- *Cassettes inserted into absorber structures at integration site (CERN)*

Key parameters:

- *593 m^2 of silicon*
- *6M ch, 0.5 or 1 cm^2 cell-size*
- *21,660 modules (8” or 2x6” sensors)*
- *92,000 front-end ASICS.*
- *Power at end of life 115 kW.*

System Divided into three separate parts:

EE – Silicon with tungsten absorber – 28 sampling layers – 25 X_o + ~1.3 λ
FH – Silicon with SS absorber – 12 sampling layers – 3.5 λ
BH – Scintillator with SS absorber – 11 layers – 5.5 λ

In this variant EE, FH and BH are maintained at – 30^{o}C : cold-warm transition at back of absorber challenge of new cooling distribution, thermal insulation & dew point control

HL-LHC: the relentless march of Silicon sensors:

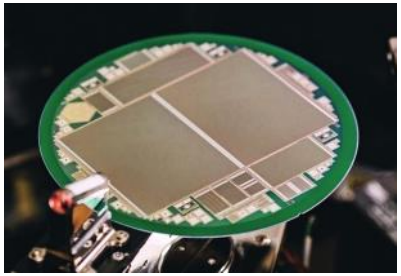
Production:

Particle physics community has experience with

a host of small producers:	10 - few 100 wafers per year
one dedicated large-scale producer:	1000-10,000 wafers per year

Now considering very large scale producers 50000 wafers ***per week***

to benefit from reduced costs and semiconductor industry push towards 8" and maybe 12 " wafers



Potential pathway to cheap & reliable mass-production

but

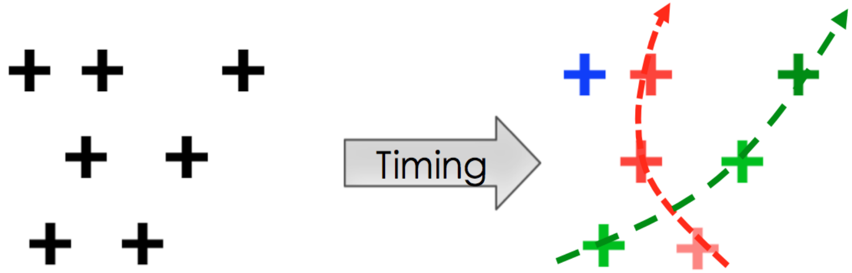
A completely new problem of prototyping & QA/QC

An entire tracker could be produced (right or wrong!) in a few days

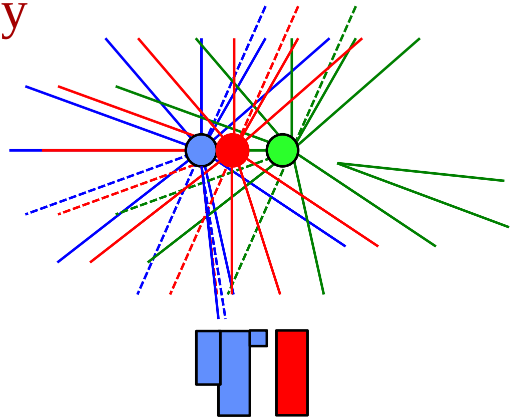
Previous experience suggests caution: long R & D to qualify ≥ 2 vendors for production
feedback as close to manufacturer as possible

4D tracking: the holy grail of fast timing

Pattern recognise only time-compatible points reducing combinatorial options dramatically



Powerful anti-pile-up weapon

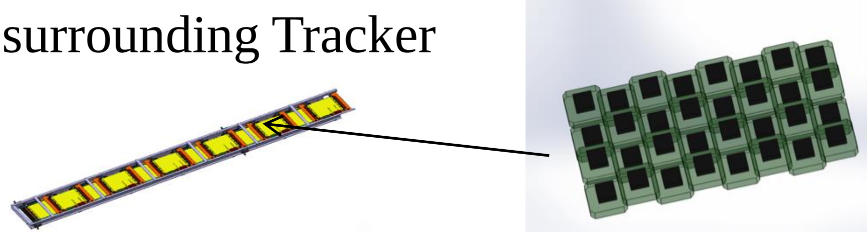


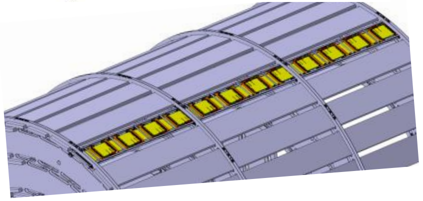
-prevent E_t^{miss} contamination by wrong (3d) merged vertex

-associate time-stamped jet or neutral to correct vertex & thus other components of same event.

-associate secondary vertex with right primary

Eg CMS investigating thin, MIP-sensitive LYSO crystal layer with SiPM readout surrounding Tracker

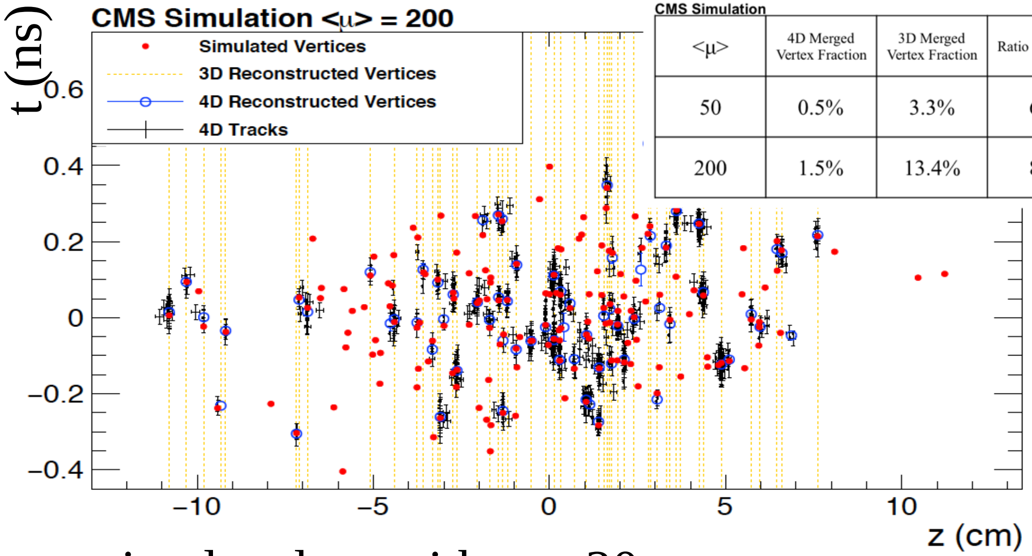




Promising, but:

-very late in Phase 2 design

-no deferral option



CMS Simulation

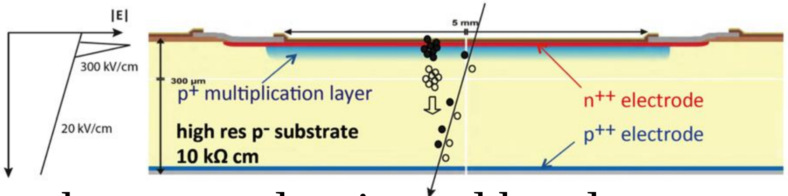
<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

simulated z-t with σ ~ 20ps

Other approaches to ~ 10ps timestamp?

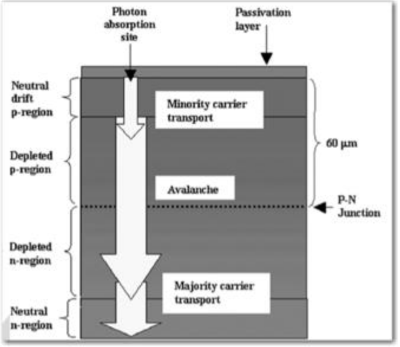
P. Allport, SWEPPS , August 2016

-Low Gain Avalanche Detector
thin p-implant near p-n junction
~ low gain APD



σ_t becomes dominated by slew-rate
minimise balance of thickness & gain.
integratable as a layer in Tracker? – if soon

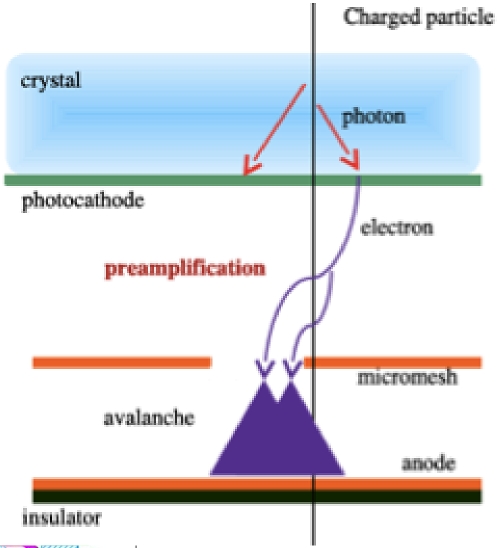
-Deep depleted APD



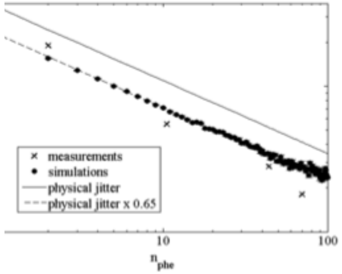
-MCP-PMT, etc

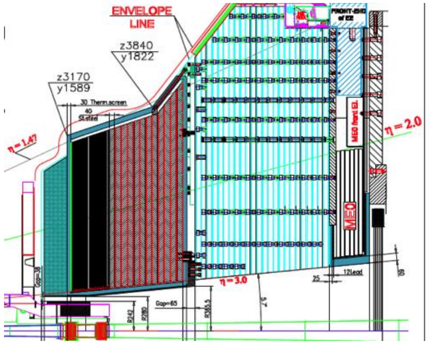
See eg S. White, Pisa seminar Mar 2015

crystal (Cerenkov radiator)+photocathode+Micromegas

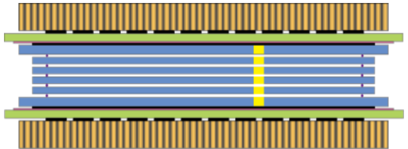


Potential for 50ps





Note that existing detectors in Phase II Baseline achieve useful time res.
eg CMS HGCAL simulated ~20ps
(> 20 MIPS seen by 5mm pads)
CMS barrel: 30ps target (neutrals)

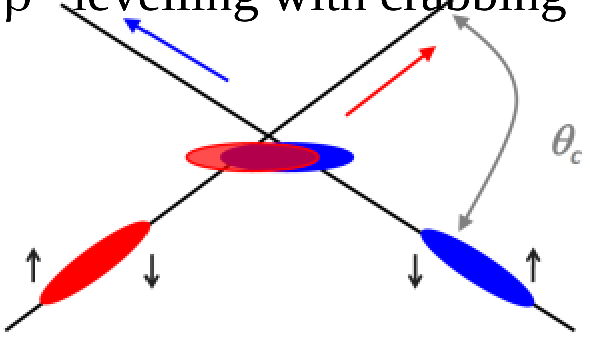


Muon system glass RPC stack: 100ps

The potential of crab cavities

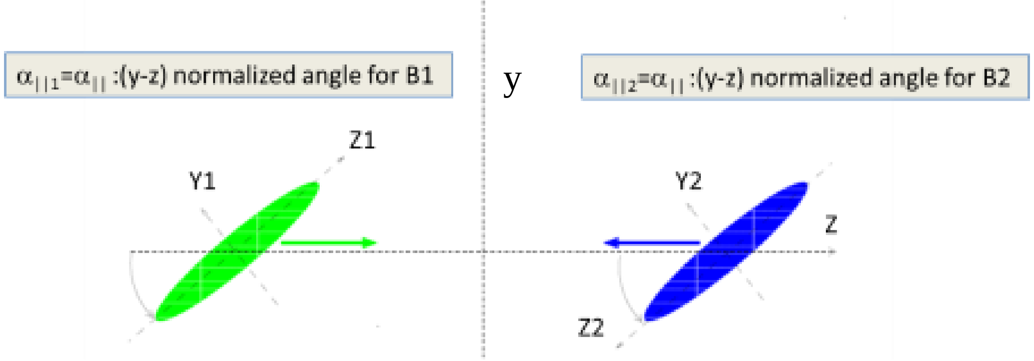
Stephane Fartouk, ECFA workshop, 2014

Plane of crossing angle
β* levelling with crabbing



45mm (150ps) rms luminous region
1.2 vertices/mm @ mean pile-up 140
need ~10ps time res to be useful

Parallel plane



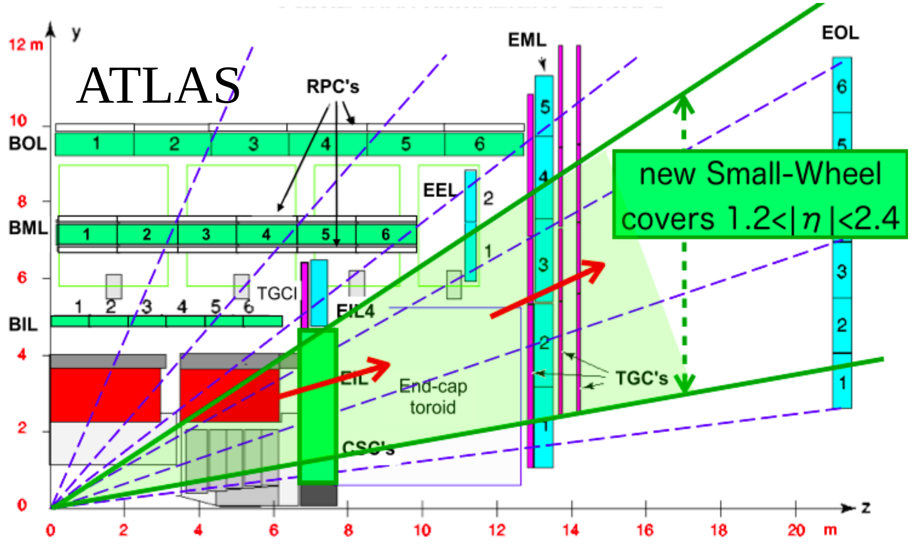
Intriguing options for adjusting the
shape of the luminous region in 4D
with the full complement of crab cavities

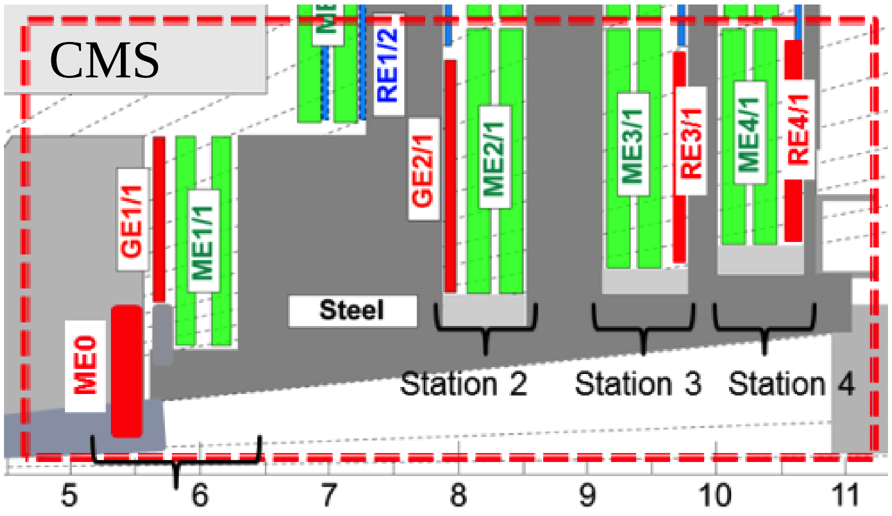
Necessary hardware currently deferred to HL-LHC Phase 1, but note that

4-D tuning of luminous region shape + fast timing detectors = powerful anti-pile-up weapon

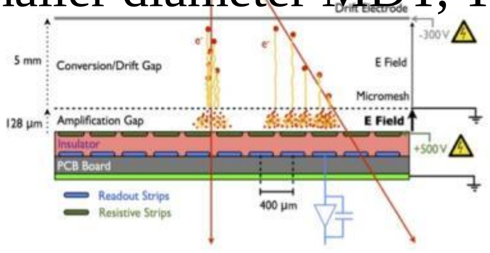
Muon detectors at HL-LHC

In the forward region, rates near limit, and pressure to extend max-η
New generation (micro-pattern) gaseous detectors (TGC's Micromegas, GEM's) offer a cost-effective solution for spatial resolution & improved timing.
Low ρ RPC's (bakelite/glass – multigap) look promising for detection+ time-stamp (100ps)





Smaller diameter MDT, TGC



- Triple GEM - 140 μm pitch, single mask and new assembly technique
- iRPC's - few kHz/cm^2 low-ρ Bakelite/Glass - multi-gap - thinner electrodes - higher gain FE - time resolution ≲ 100 ps

Muon detectors

Over most of the solid angle (except high η – next slide), existing ATLAS & CMS gas ionisation-based muon detection systems are expected to tolerate 3-4 fb-1

-"time in environment" might be enough to cause unexpected degradation
humidity, HV insulator degradation, gas-structure interaction

-replace electronics becoming unreliable/un-maintainable
or incompatible with latency of revised trigger

-might need to shield against increasing ambient n backgrounds

- pressure to phase out release of gas mixture components with high GWP
(C2H2F4, CF4, SF6) ---> recuperation systems
---> low GWP gas mixtures

unlikely signal (& possibly HV) characteristics matched to today's HV & FE
----> v major, possibly impractical, refit

Muon systems, having a large number of ~autonomous detectors, are labour-intensive to operate if the required >98% functional fraction is to be sustained.

who exactly will be willing (& able) to do this into the late 2030's??

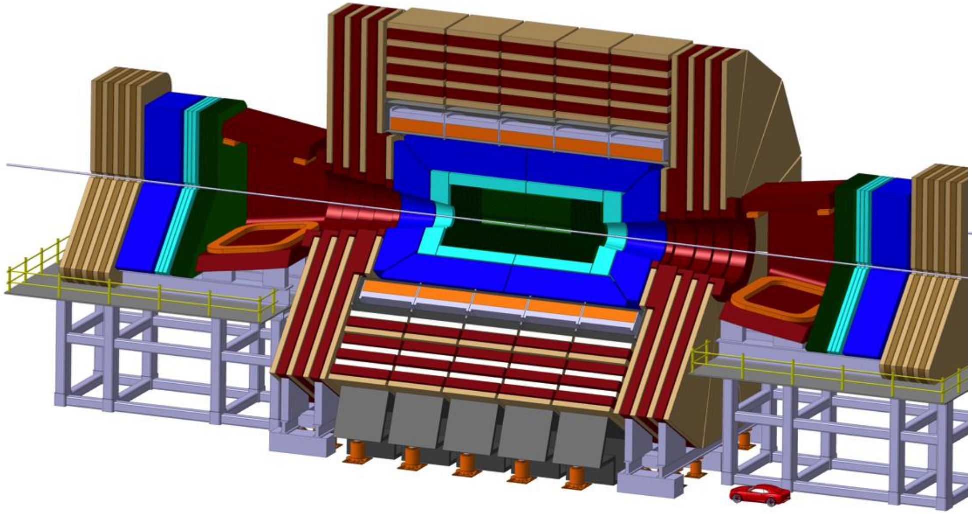
FCC-hh detectors: start with blank page!

Most material from FCC-HH detector working group,W.Riegler & FCC Rome meeting

$$\frac{\Delta p_T}{p_T}\Big|_{reso.} = \frac{\sigma\, p_T}{0.3BL(\eta)^2}\sqrt{\frac{720}{N(\eta)+4}} \qquad \frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{0.0136}{0.3\,BL(\eta)}\sqrt{\frac{x}{X_0}(\eta)}$$

First brainstorming:

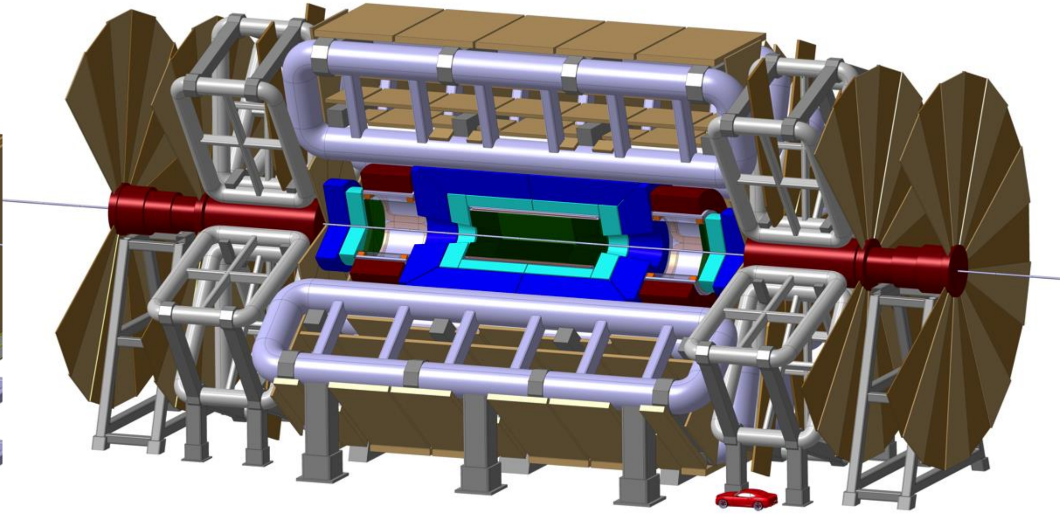
sensor performance same as today, calorimeter depth 12 λ



CMS-like:

Forward dipoles extend effective tracking

Yoke fully containing return field is prohibitive: 120kton



ATLAS-like:

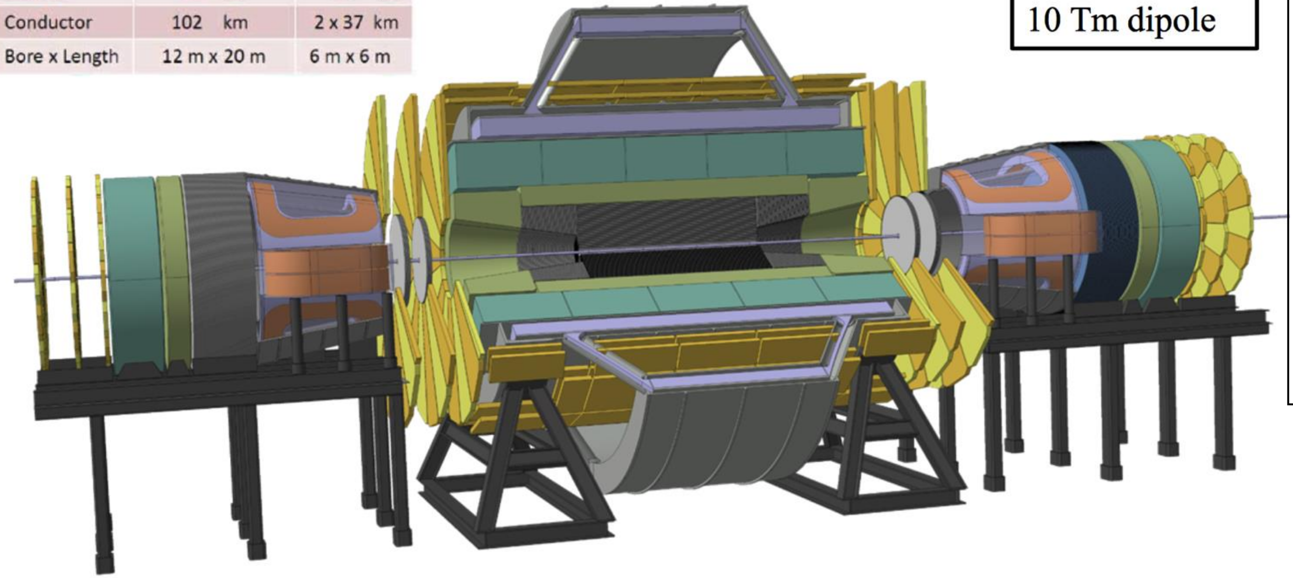
Standalone muon measurement of questionable value based on LHC experience ….and comes at v. high cost

Forward toroids awkward at inner radius

1st baseline:

Twin solenoid with opposite field directions(outer to to guide return flux of inner). Forward dipole system. Magnet system challenging mainly because of size & cancelling effect of outer coil field on inner coil field (inner actually a 9T solenoid).

	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m



Twin solenoid
6 Tesla
12m bore
10 Tm dipole

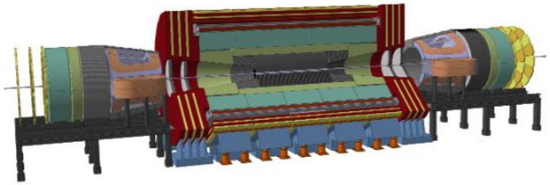
?????'s

- -Construction Modularity
- -Shaft & cavern sizes
- -Mechanical support structure
- -Maintenance

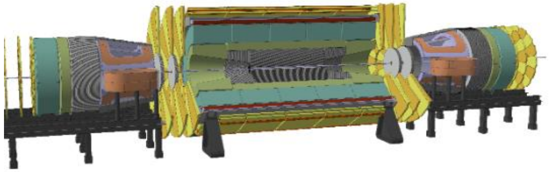
27m diameter x 60m length: detector elements all feasible - dimensional scale-up from LHC

- Important to establish that this beast could be built: but it is a beast! Est magnet cost $1000M!

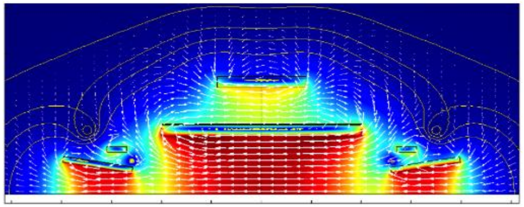
..evolutionary options:



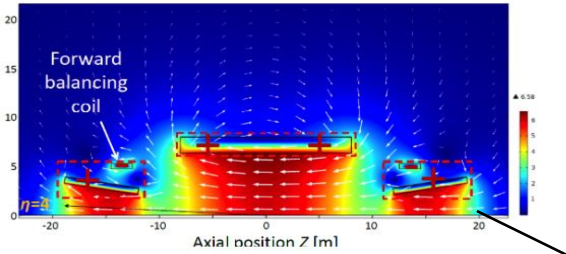
Single solenoid with “partial return yoke”
+ forward dipoles



Single solenoid with no return yoke + dipoles



Twin solenoid + balanced conical forward solenoids



Single solenoid with no return yoke
+ balanced conical (or cylindrical) forward solenoids

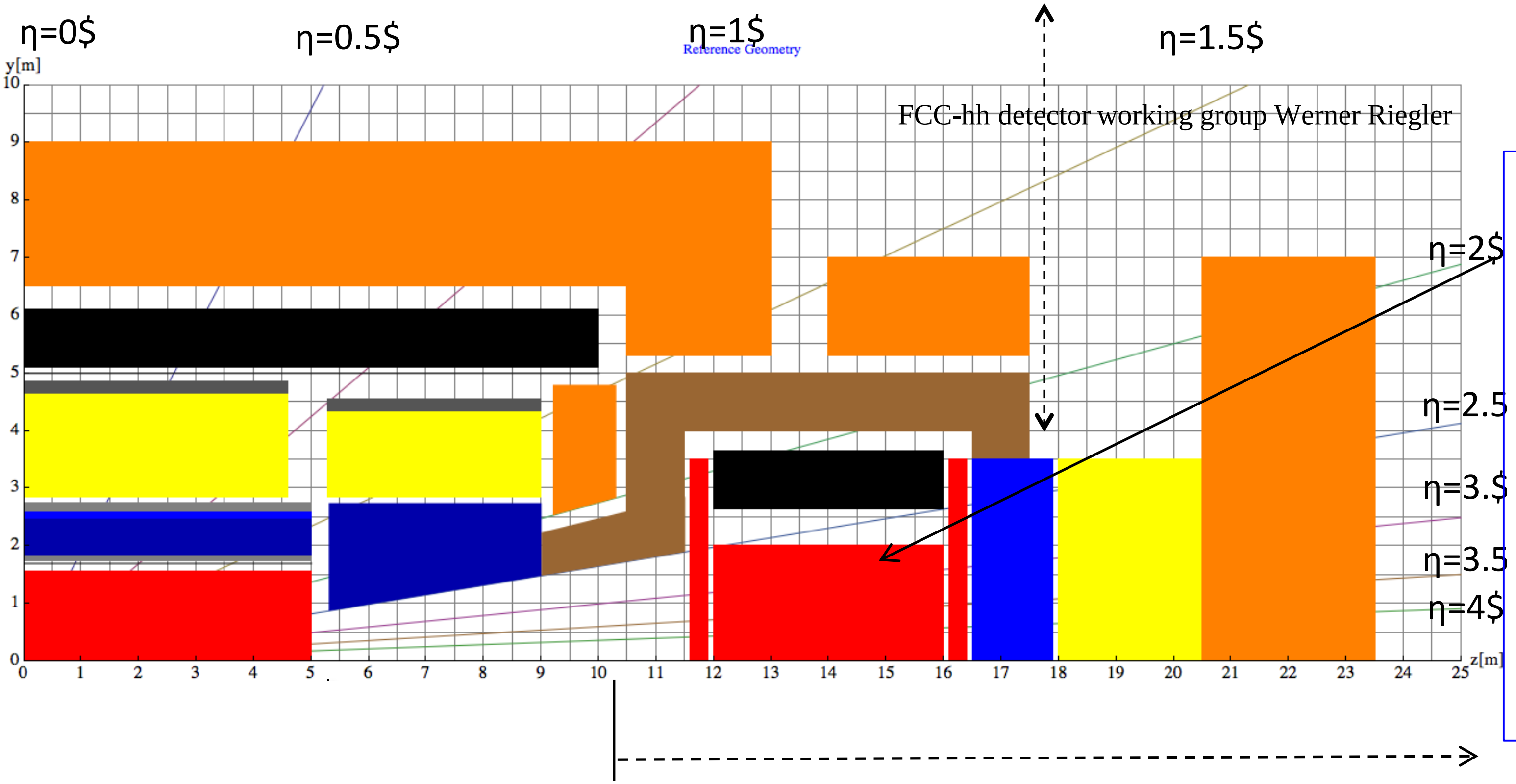
H. Ten Kate, M. Mentink

developing into a new baseline?

Zeroing in on the next baseline

No return yokes: large fringe fields extend throughout cavern ----> issues

Reduction in the central solenoid radius 6m ---> 5m: assumes improved detector point resolution (+ lower material budget).



FCC-hh detector working group Werner Riegler

Forward Solenoids:
~ same forward $\Delta p_T/p_T$ performance as the 10Tm dipoles.
- smoother field continuity
- lower backgrounds & cleaner shielding scenario.

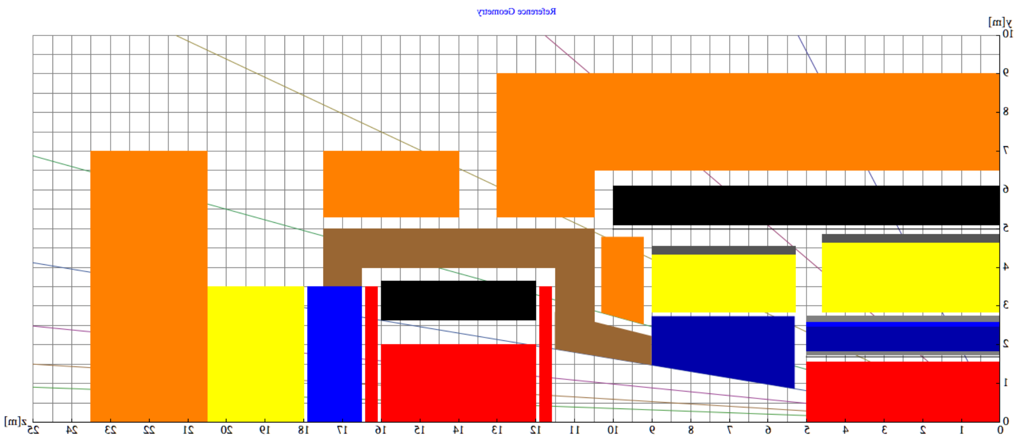
Maintenance scenario still cumbersome (9m x or 12m z movement of fwd system inc sc coil!)

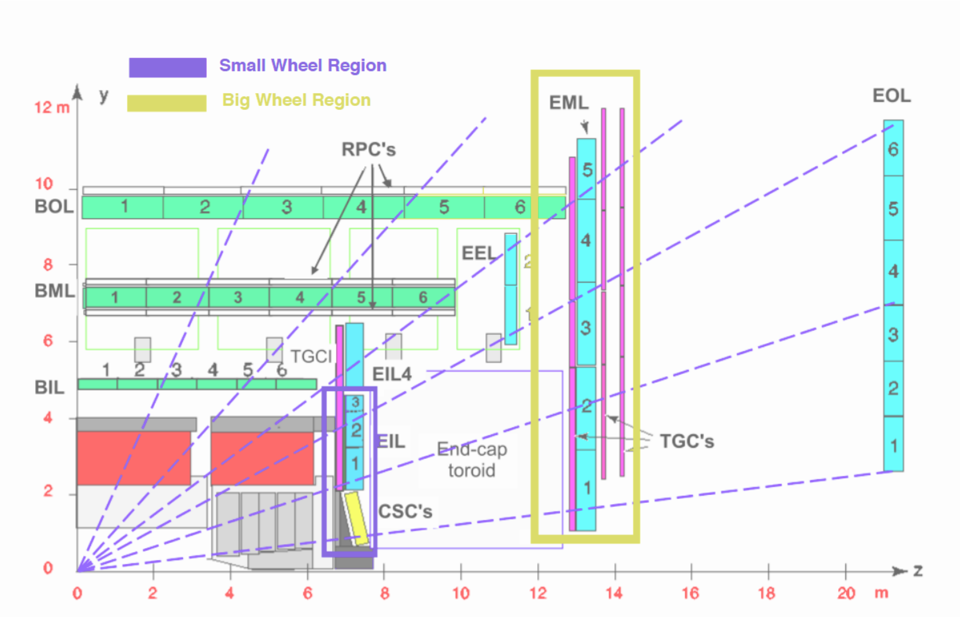
Instrumentation solutions ---> Construction solutions

Required shaft size similar to ATLAS

Cavern dimensions: superficially also similar, strongly affected by maintenance scenarios

Uncontrolled return flux could give rise to many problems…..





FCC-hh Ref. enveloping radius 10m
Length 50m

ATLAS enveloping radius 12m
Length 44m

Instrumentation solutions ---> Construction solutions ?

CMS Coil & ATLAS toroids

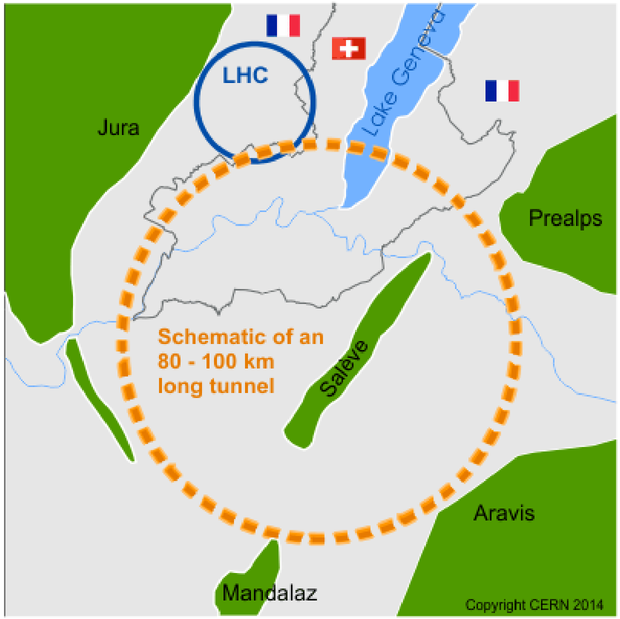
Preferred model would be worldwide modular construction
Feasibility for FCC expt dimensions??

Expt location/surface site should allow:

- Access for heavy, outsize & unusual loads

-Direct routing of large components to site from manufacturer.

-complete construction of large elements on site (surface or underground)



eg FCC-hh at CERN

Assuming GP expt sites diametrically opposite, both will need substantial facilities & autonomy.

Optimisation of expt dimensions has far-reaching consequnces

Concluding Remarks

Standard-model-like light Higgs is a conundrum for detector designers as well as theorists:

Future detectors have to : -be optimised for precision Higgs & SM physics
-provide best sensitivity for new phenomena at high mass

HL-LHC is the known future, but the proposed detectors are not yet a done deal
65nm pixel readout
imaging calorimetry
mass industrialisation of Si wafer production?

- opportunities to test the technologies that could enable realistic solutions for FCC (at least from moderate radii outwards) and do precision physics in higher η regions

For the hypothetical future:

- high resolution , low mass, low power tracking over large volumes is critical
- compact calorimetry (perhaps imaging calorimeters) will help reduce magnet costs
- pile-up probably needs 2 solutions: 5ns bunch spacing in collider
~10ps time-stamping of tracks, clusters & vertices
by detector (hopefully exploited already at HL-LHC)

HE-LHC: -could come much earlier than earliest projection for FCC
- close to the same rate/radiation tolerance challenge.