Detectors for future pp colliders

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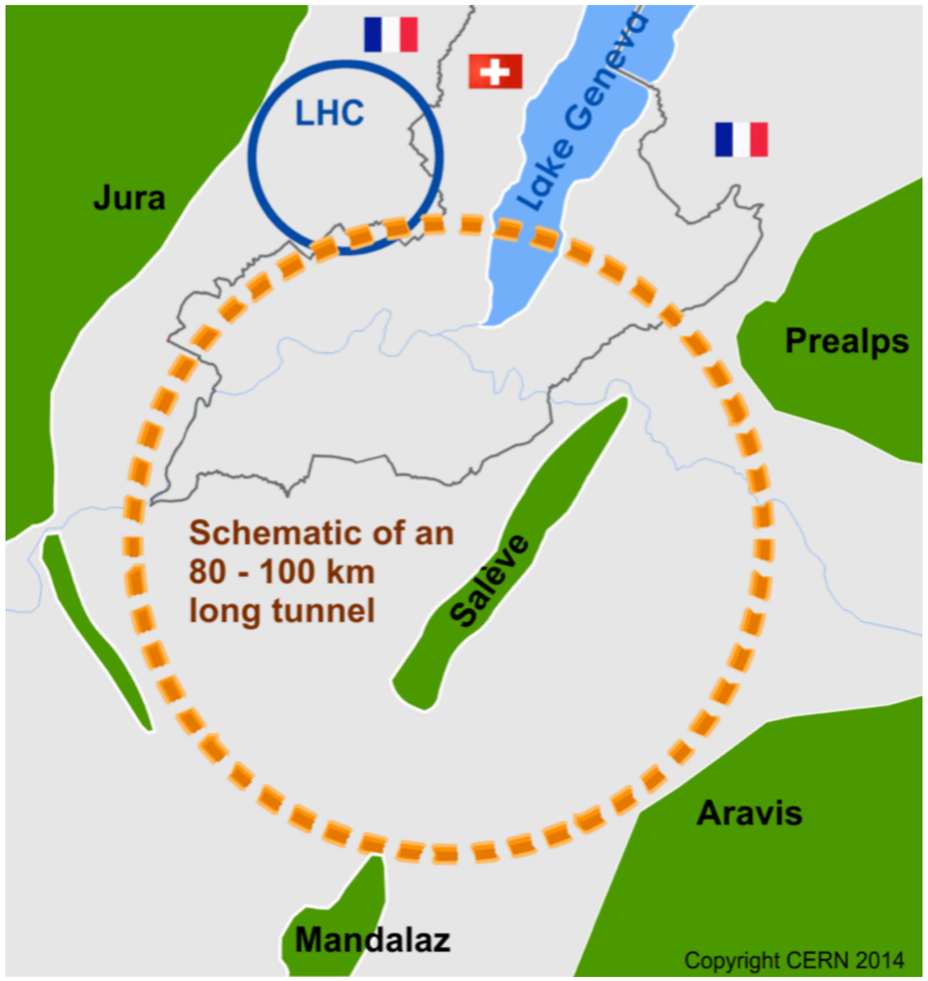
Motivations for pp colliders beyond the LHC

- Future projects in HEP such as the have two objectives:
  - explore the energy frontier, as solutions to known and unexplained phenomena beyond the standard model (might be within reach at the next high energy collider):
    - Dark Matter
    - Neutrinos
    - Matter-antimatter asymmetry
  - measure to high precision the physics of the electroweak symmetry breaking:
    - the shape of the Higgs potential
    - Higgs couplings, in particular to first two generations and gauge bosons → guaranteed deliverable!

see MLM talk for more…

The FCC project



Within the FCC collaboration (CERN as host lab), 4 main accelerator facilities have been studied:

- pp-collider (FCC-hh)
  - defines infrastructure requirements
  - 16 T → 100 TeV in 100 km tunnel
- ee-collider (FCC-ee):
  - as a (potential) first step
- ep collider (FCC-eh)
- HE-LHC :
  - 27 TeV (16T magnets in LHC tunnel)

CDRs and European Strategy documents have been made public in Jan. 2019

https://fcc-cdr.web.cern.ch/

Philosophy

- Goal of this talk is to walk you through the process that we went through in the CDR process in trying to design a multi-purpose detector for the FCC-hh 100 TeV collider

- Guiding principles are machine constraints and physics

- This generic detector serves as a starting point for:
  - benchmarking physics reach of the machine
  - identify:
    - challenges of building such an experiment
    - topics where R&D needed

- Most likely, this is not "THE OPTIMAL" detector. Maybe the optimal route will be to have several detectors optimized for specific signatures.

- Also, expected improvements in technology may lead to more ambitious and less-conventional approaches of detector concepts in the future

- Although this discussion will be based on the 100 TeV FCC-hh collider most of the challenges are common to any high energy/high luminosity project.

Physics goals for a 100 TeV collider

- Ultimate discovery machine
  - **directly** probe new physics up to **unprecendented** scale
  - discover/exclude:
    - heavy resonances "strong" m(q*) ≈ 50 TeV,
      "weak" m(Z') ≈ 40TeV,
    - SUSY m(gluino) ≈ 15 TeV,
      m(stop). ≈ 10 TeV

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      "weak" m(Z') ≈ 40TeV,
    - SUSY m(gluino) ≈ 15 TeV,
      m(stop). ≈ 10 TeV
- Precision machine
  - probe Higgs **self-coupling** to few % level, and %-level precision for top yukawa and 2nd generation.
  - measure **SM parameters** with high precision
  - exploit **complementarity with e^+e^-** by probing **high dim.operators** (EFT) in **extreme kinematic** regimes (boosted)

Physics program spans over very wide range of characters energy scales !

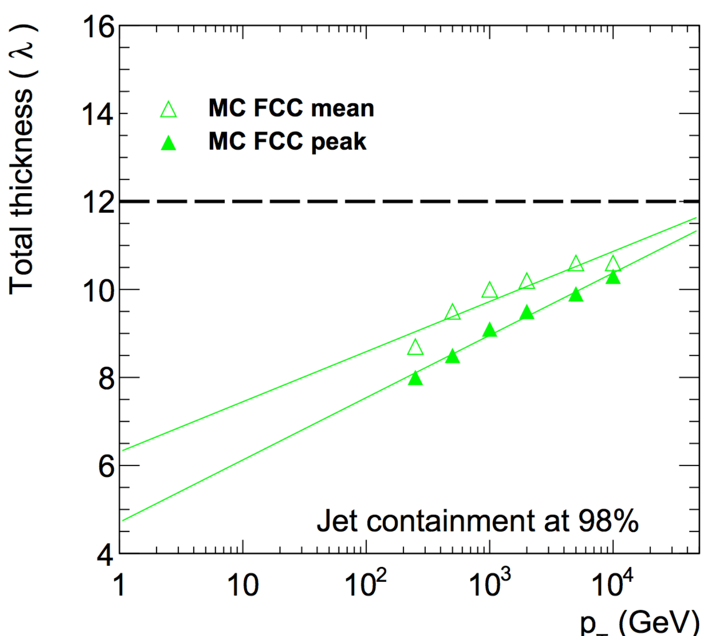
Towards defining the FCChh detector

Physics constraints

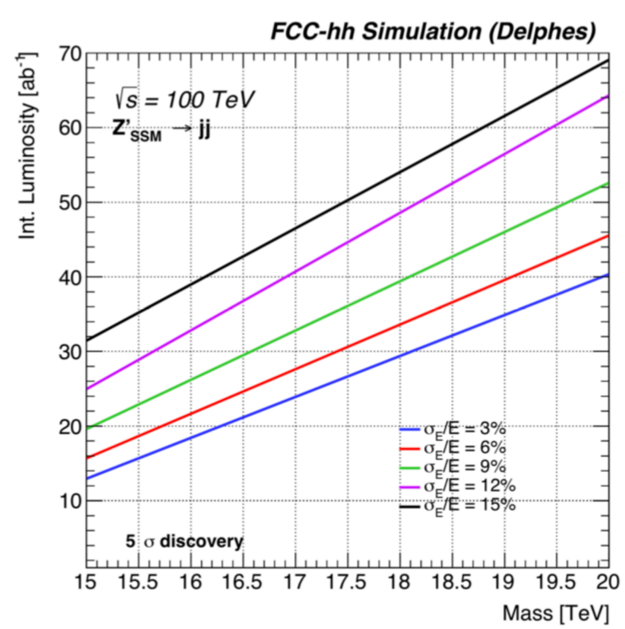
- The boosted regime:
  → measure leptons, jets, photons, muons originating multi-TeV resonances

Tracking: $\frac{\sigma(p)}{p} \approx \frac{p\sigma_x}{BL^2}$ Calorimeters: $\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} \bigoplus B$

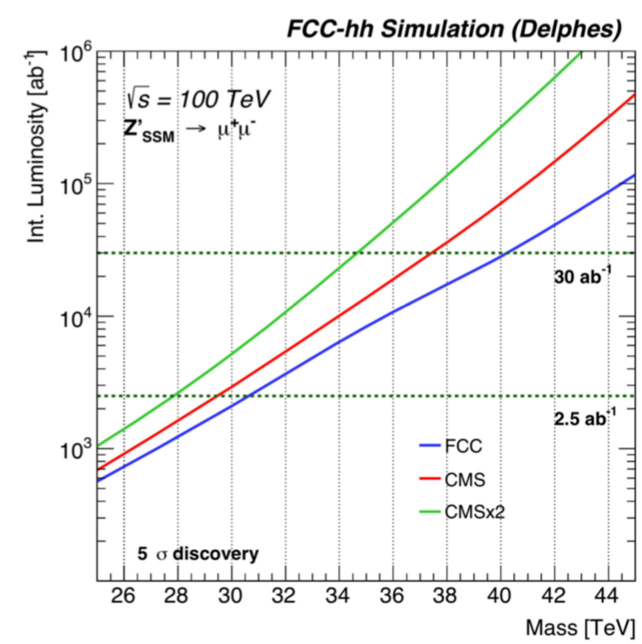
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



≳11 λ_I for EM + Had



high p_T jets



high p_T muons

Towards defining the FCChh detector

Physics constraints

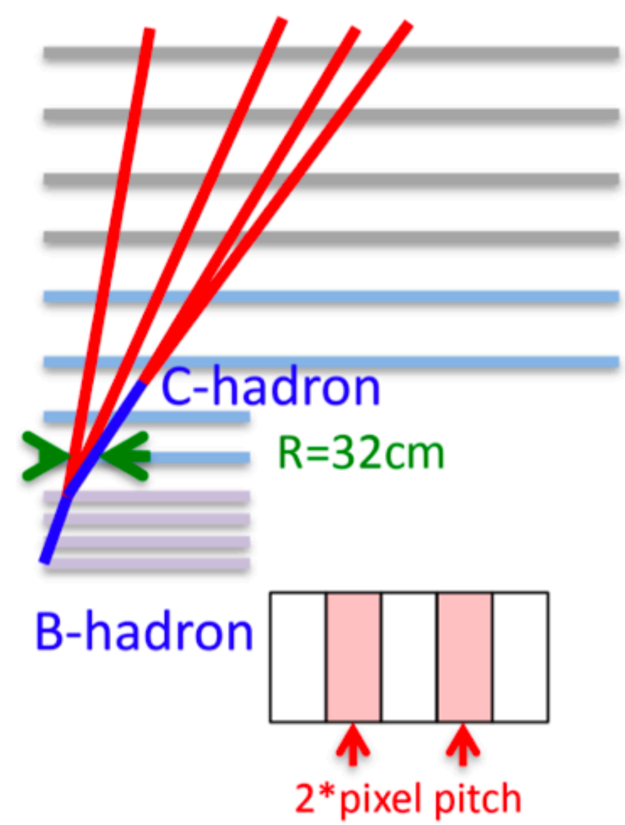
- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances

- Long-lived particles live **longer**:

ex: 5 TeV **b-Hadron** travels **50 cm** before decaying
5 TeV **tau lepton** travels **10 cm** before decaying

→ extend pixel detector further?
- useful also for exotic topologies (disappearing tracks and generic BSM Long-lived charged particles)
- number of channels over large area can get too high

→ re-think reconstruction algorithms:
- hard to reconstruct displaced vertices
- **exploit hit multiplicity discontinuity**



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices

Towards defining the FCChh detector

Physics constraints

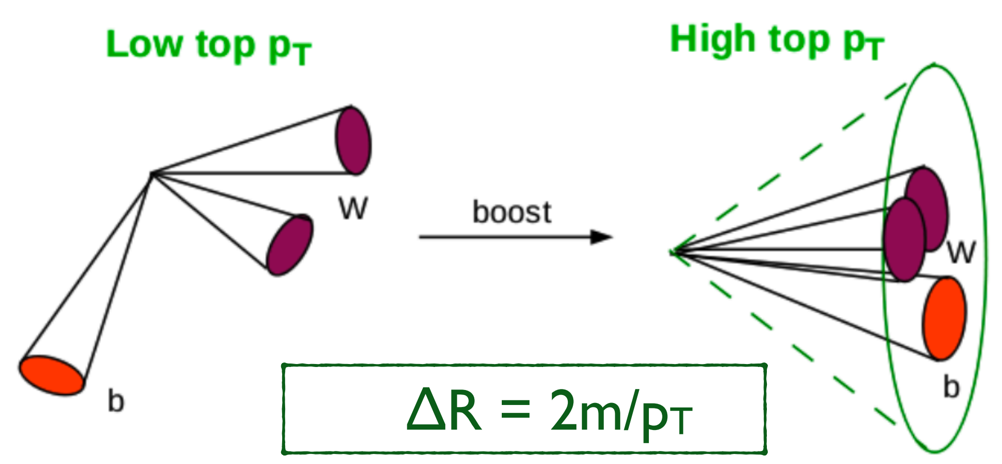
- The boosted regime:
  → measure W, H, top jets from multi-TeV resonances

  - Highly boosted hadronically decaying SM heavy states (W, Z, H or t) will have highly collimated decay products

  - The ability to distinguish such boosted states from vanilla QCD jets is an essential tool in many searches for BSM (such as top partners, Z', etc …)

    ex: W(10 TeV) will have decay products separated by DR = 0.01 = 10 mrad

- need highly granular sub-detectors:
  - Tracker - pixel: 10 μm @ 2cm → $\sigma_{\eta x \varphi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta x \varphi} \approx$ 10 mrad



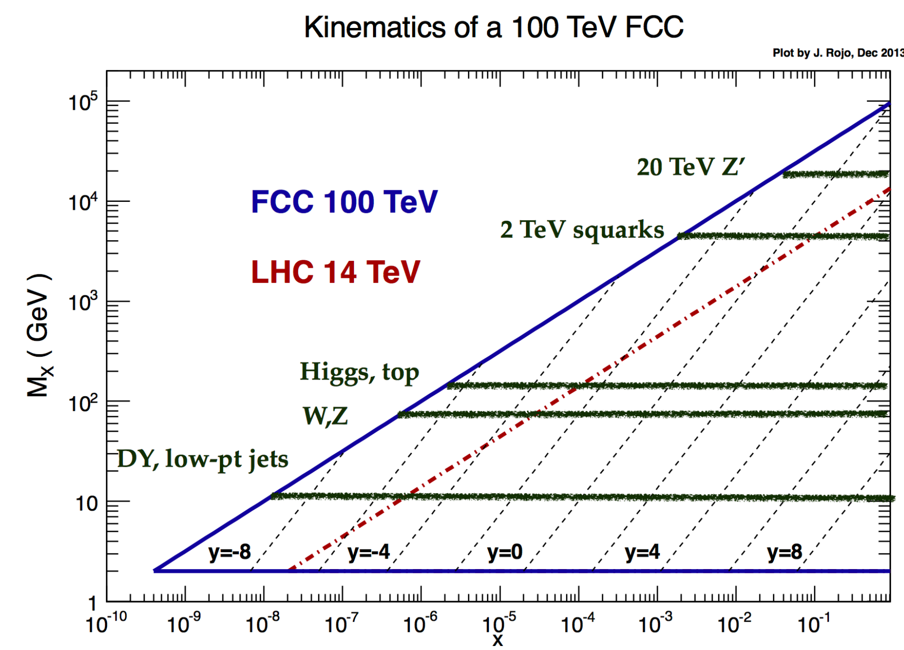
SM physics @ 100 TeV

$x_1 * x_2 * s = M^2$

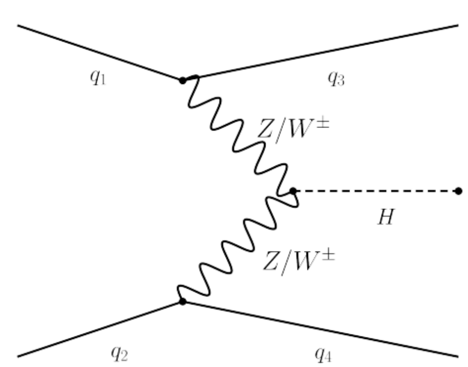
SM Physics is more forward @100TeV

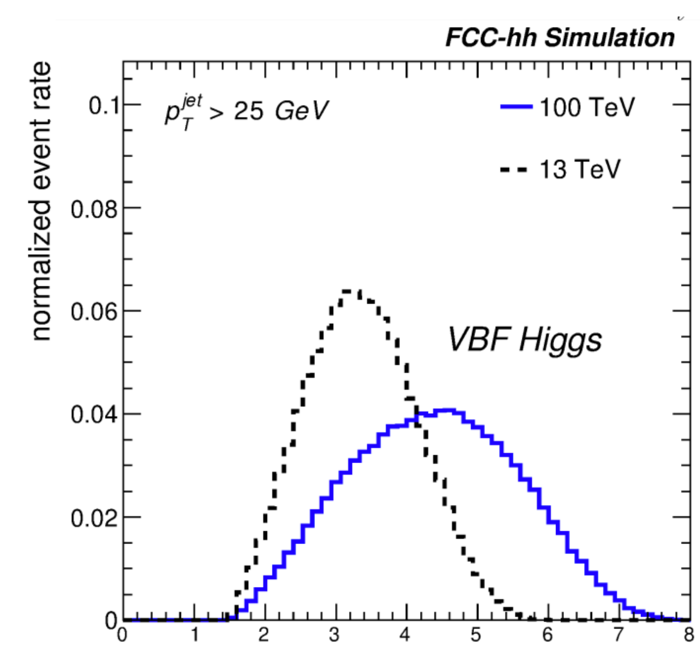
- in order to maintain sensitivity in need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities

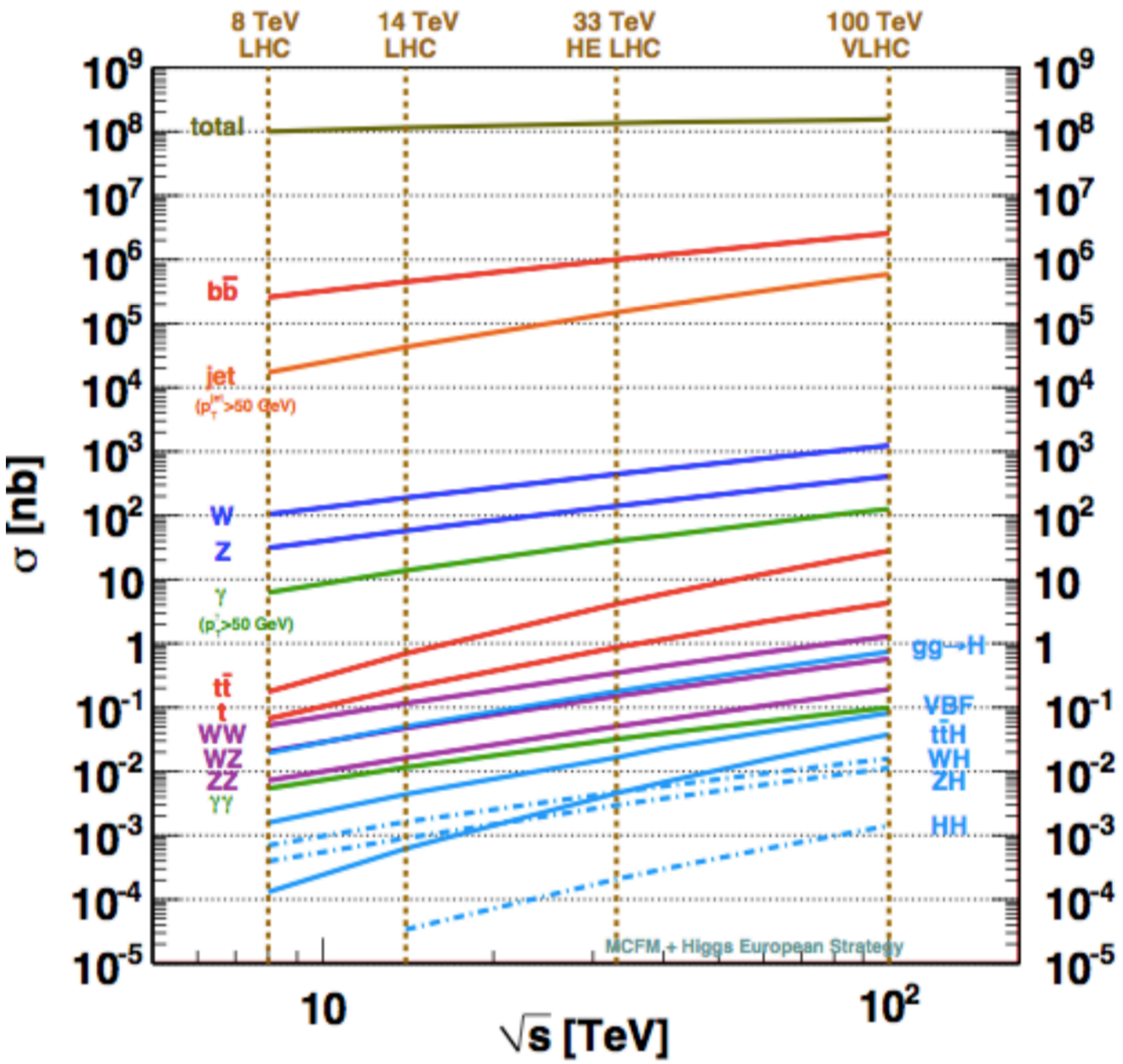


- Goals:
  - **Precision spectroscopy** and calorimetry up to **|η| < 4**
  - Tracking and calorimetry up to |η| < 6





SM physics processes@ 100 TeV



- Total pp cross-section and Minimum bias multiplicity show a modest increase from 14 TeV to 100 TeV

→ Levels of pile-up will scale basically as the instantaneous luminosity.

- Cross-section for relevant processes (HH) shows a significant increase.

→ interesting physics sticks out more !

Machine and detector requirements

parameter	unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
circumference	km	26.7	26.7	26.7	97.8
peak $\mathcal{L}\times 10^{34}$	$cm^{-2}s^{-1}$	1	5	25	30
bunch spacing	ns	25	25	25	25
number of bunches		2808	2808	2808	10600
goal $\int\mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel}	mbarn	85	85	91	108
σ_{tot}	mbarn	111	111	126	153
BC rate	MHz	31.6	31.6	31.6	32.5
peak pp collision rate	GHz	0.85	4.25	22.8	32.4
peak av. PU events/BC		27	135	721	997
rms luminous region σ_z	mm	45	57	57	49
line PU density	mm^{-1}	0.2	0.9	5	8.1
time PU density	ps^{-1}	0.1	0.28	1.51	2.43
$dN_{ch}/d\eta\|_{\eta=0}$		7	7	8	9.6
charged tracks per collision N_{ch}		95	95	108	130
Rate of charged tracks	GHz	76	380	2500	4160
$<p_T>$	GeV/c	0.6	0.6	0.7	0.76
Number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm est.(FLUKA)	$GHz\,cm^{-2}$	0.1	0.7	2.7	8.4 (12)
1 MeV-neq fluence at 2.5 cm est.(FLUKA)	$10^{16}\,cm^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm est.(FLUKA)	MGy	1.3	13	54	270 (400)
$dE/d\eta\|_{\eta=5}$	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	kW	0.04	0.2	1.0	4.0

Machine and detector requirements

lumi & pile-up

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→ x6 HL-LHC

LHC: 30 PU events/bc
HL-LHC: 140 PU events/bc
FCC-hh: 1000 PU events/bc

High granularity and precision timing needed to reduce occupancy levels and for pile-up rejection

Machine and detector requirements

rad. levels

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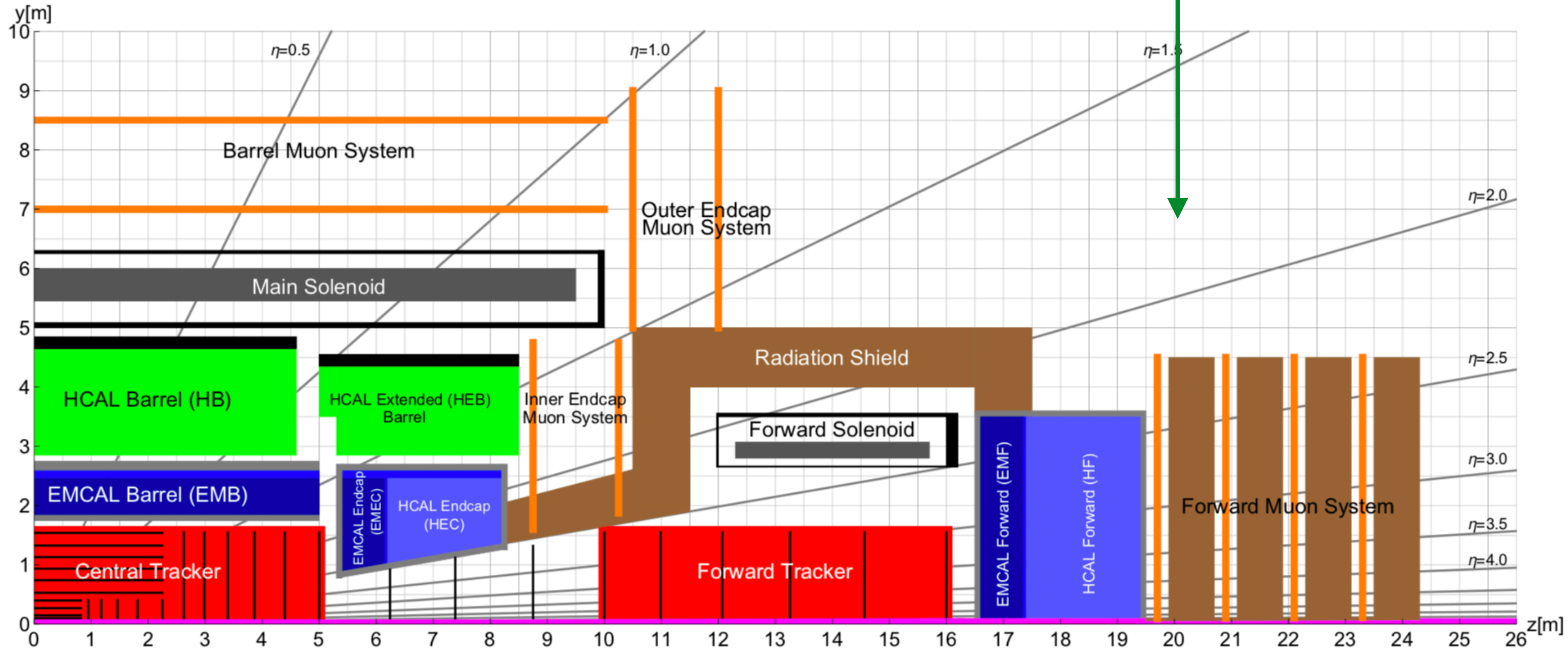
→ x50 HL-LHC

10^{18} cm^{-2} MeV-neq @ 2.5 cm !!

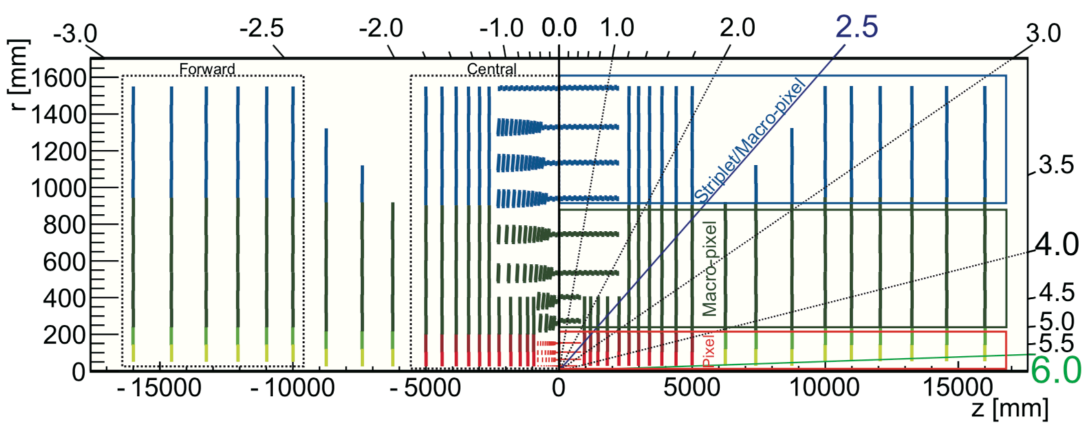
An FCC-hh detector

- Must be able to cope with:
  - very large dynamic range of signatures (E = 20 GeV -20 TeV)
  - hostile environment (1k pile-up and up to 10^{18} cm^{-2} MeV neq fluence)

- Characteristics:
  - large acceptance (for low p_T physics)
  - extreme granularity (for high p_T and pile-up rejection)
  - timing capabilities
  - radiation hardness

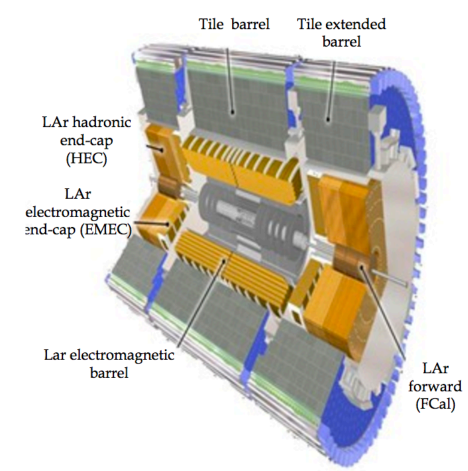


An FCC-hh detector that can do the job



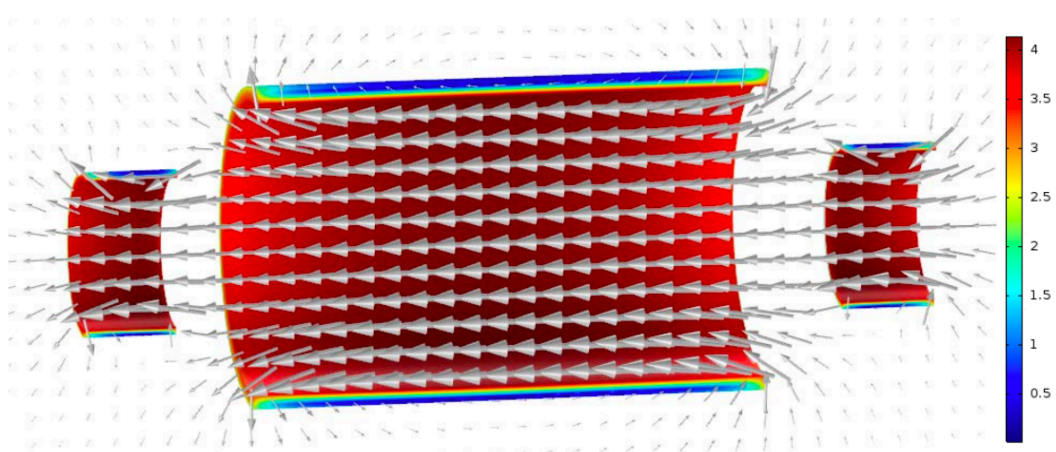
Tracker

- $-6 < \eta < 6$ coverage
- pixel : $\sigma_{r\phi}$ ~10µm, σ_Z ~15-30µm, X/X_0(layer) ~ 0.5-1.5%
- outer : $\sigma_{r\phi}$ ~10µm, σ_Z ~30-100µm, X/X_0(layer) ~ 1.5-3%



Calorimeters

- ECAL: LArg , $30X_0$, 1.6 λ, r = 1.7-2.7 m (barrel)
- HCAL: Fe/Sci , 9 λ, r = 2.8 - 4.8 m (barrel)

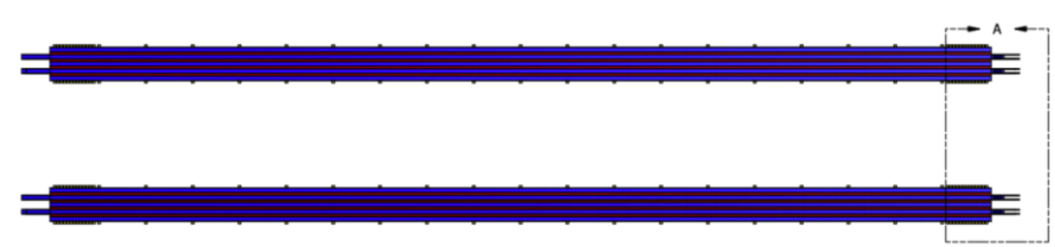


Magnet

- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 4T

Muon spectrometer

- Two stations separated by 1-2 m
- 50 µm pos., 70µrad angular

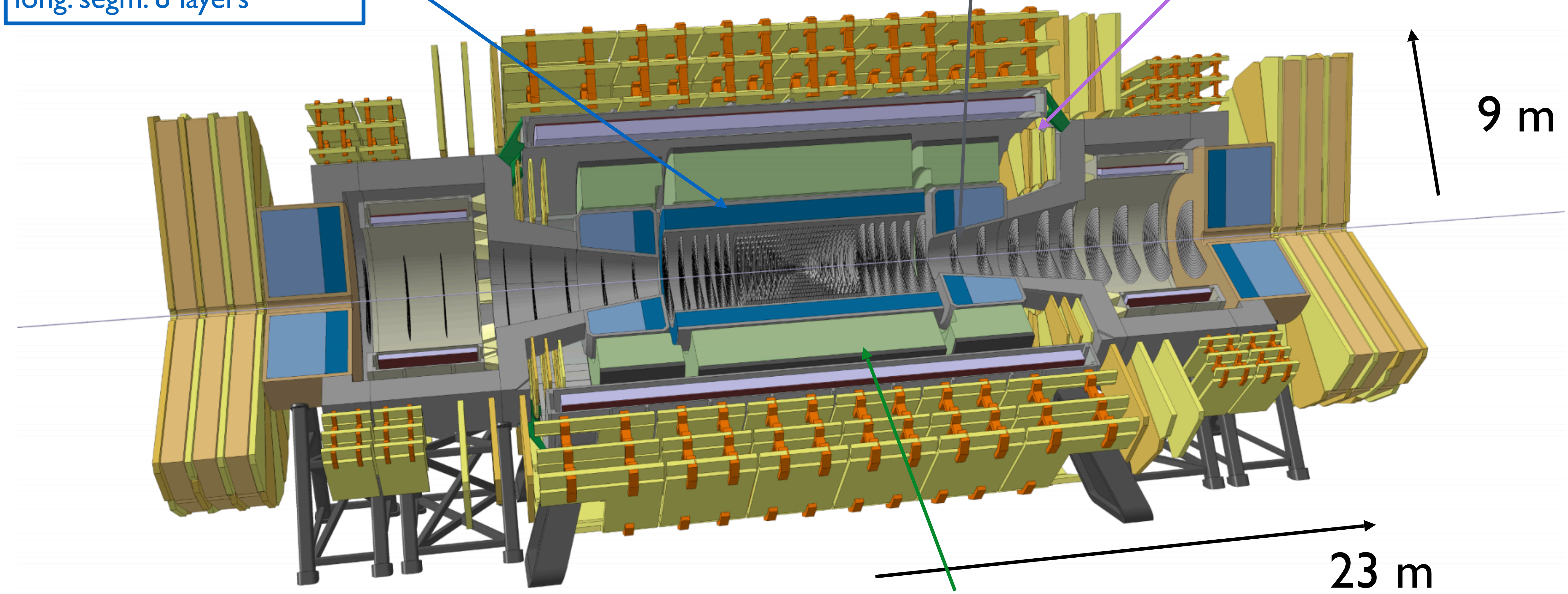


The FCC-hh detector

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

Barrel ECAL: LAr/Pb
σ_E/E ~10%/$\sqrt{E}$ ⊕ 0.7 %
30 X_0
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 8 layers

Central Magnet + Fwd solenoids

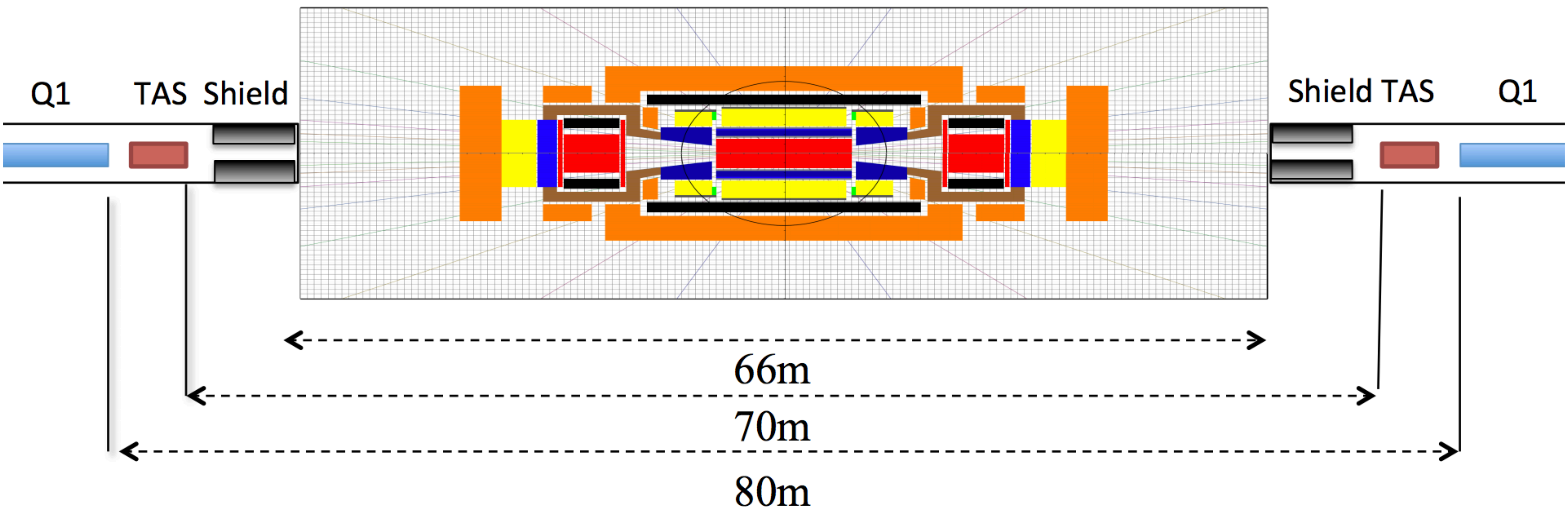


Fwd ECAL: LAr/Cu
σ_E/E ~30%/$\sqrt{E}$ ⊕ 1 %
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

Fwd HCAL: LAr/Cu
σ_E/E ~100%/$\sqrt{E}$ ⊕ 10 %
lat. segm: $\Delta\eta\Delta\phi \approx 0.05$
long. segm: 6 layers

Barrel HCAL: Sci/Pb/Fe
σ_E/E ~50-60%/$\sqrt{E}$ ⊕ 3 %
11 λ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

Cavern and MDI

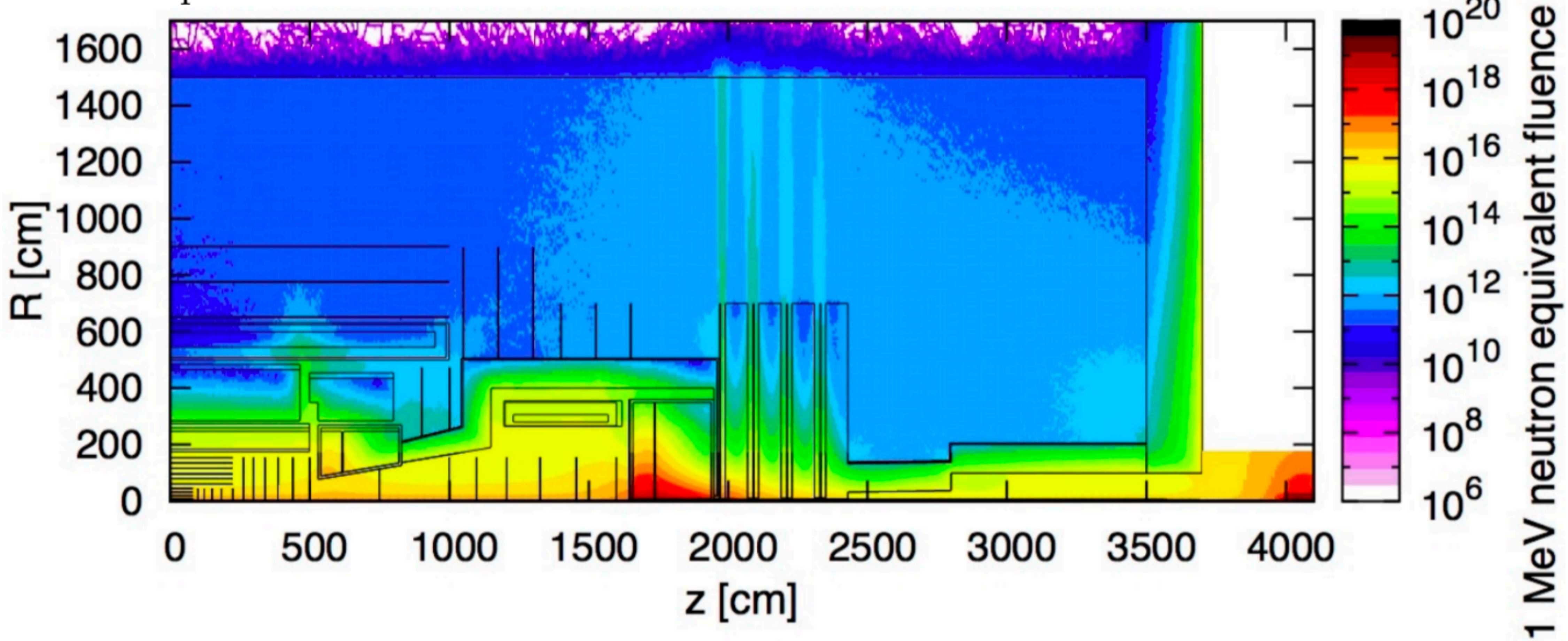


- $L^* = 40$m (as opposed $L^* = 23$ m in LHC experiments)
- Last focusing quadrupoles are outside the cavern
- MDI is not a concern (as opposed to e^+e^-)

Radiation tolerance

Tracker:
first IB layer (2.5 cm): $\sim 6{\cdot}10^{17}\mathrm{cm}^{-2}$
HL-LHC rad. tolerance limit @ R=27 cm: $\sim 10^{16}\mathrm{cm}^{-2}$
external part: $\sim 5{\cdot}10^{15}\mathrm{cm}^{-2}$

HL-LHC = **20**× LHC
FCC = **30** × HL-LHC

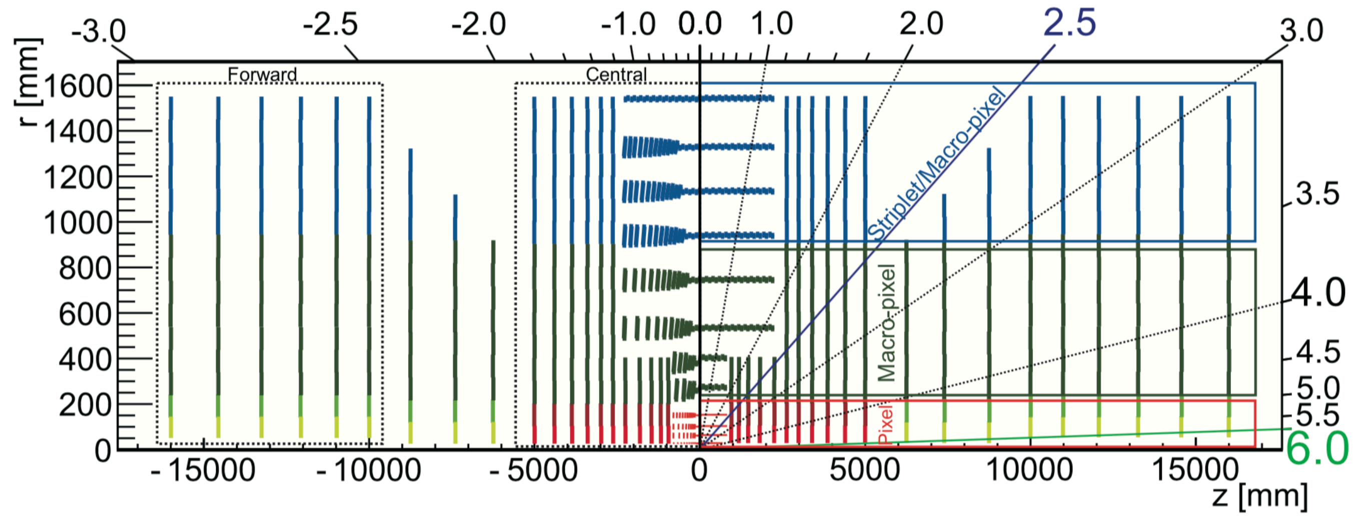


Forward calorimetry:
maximum at $\sim 10^{18}$ cm^{-2}

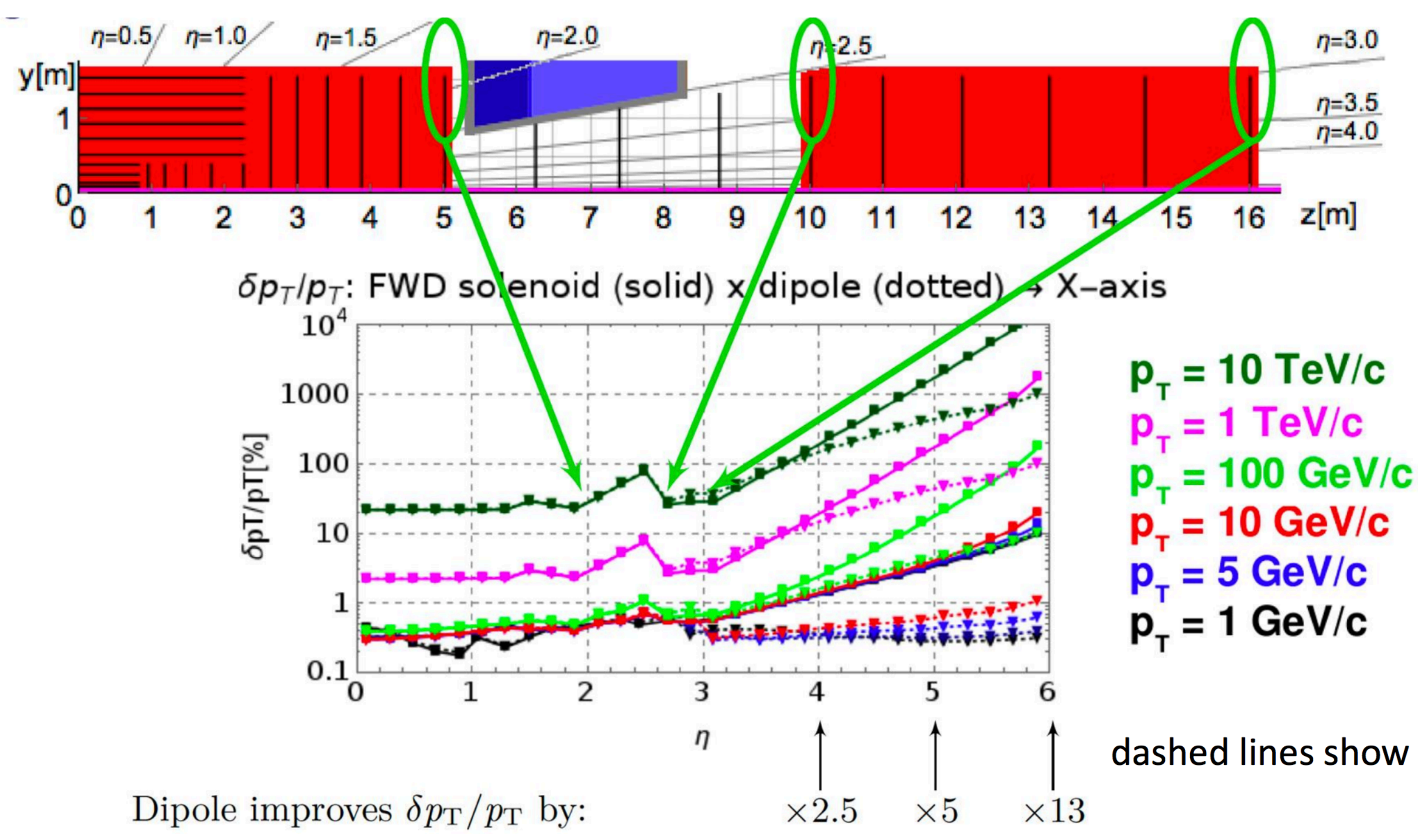
- A hadron fluence > 10^{16} cm^{-2} is very challenging for silicon sensors
- This limit is reached already @ 27 cm from the beam pipe
- Dedicated R&D needed to push the limit of radiation hardness

Tracker

- Binary readout
- 16 billions readout channels, x(3-10) phase II detectors)
- Radiation hardness is an issue for innermost layers

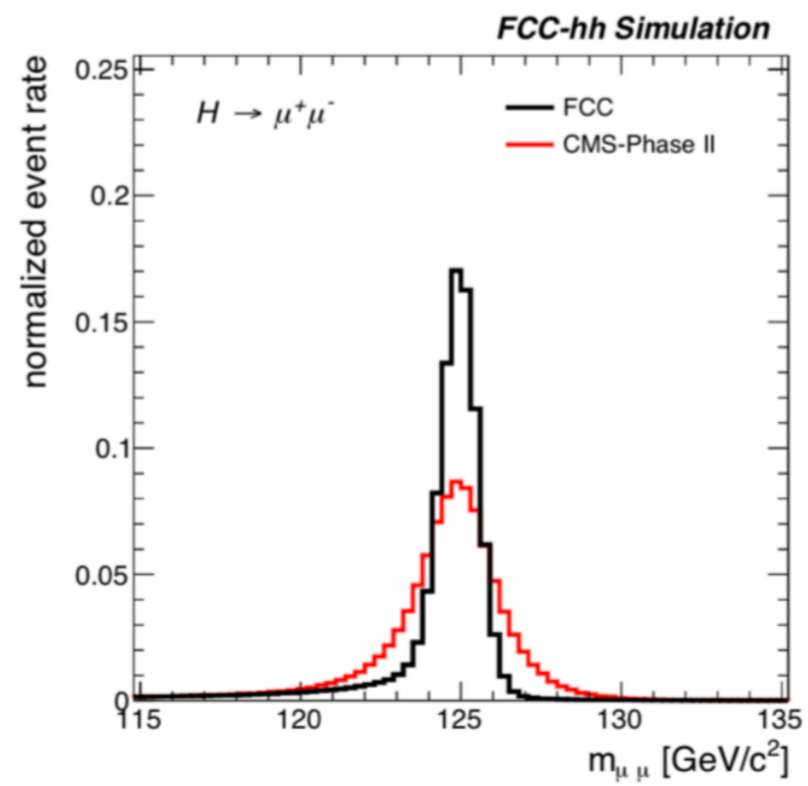


- Tilted geometry with inclined modules:
  - minimize effect of Multiple scattering (low material)
  - helps with pattern recognition



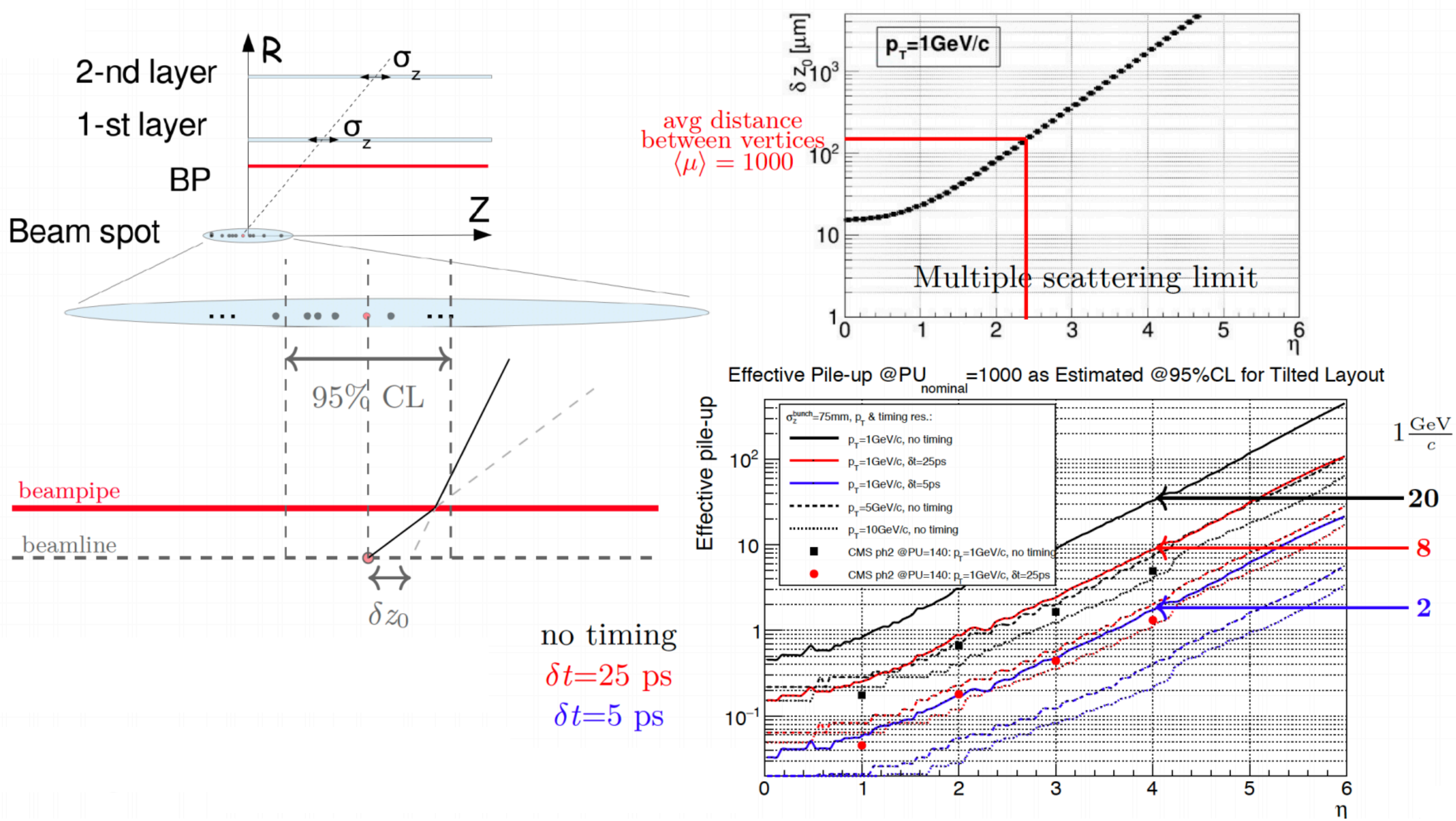
p_T = 10 TeV/c
p_T = 1 TeV/c
p_T = 100 GeV/c
p_T = 10 GeV/c
p_T = 5 GeV/c
p_T = 1 GeV/c

dashed lines show the



low p_T muons → resolution dominated by MS

Pile-up rejection

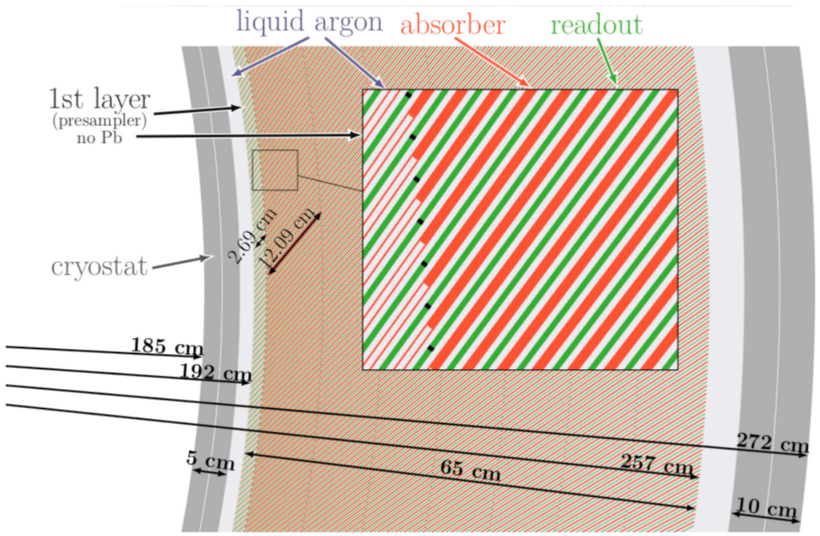


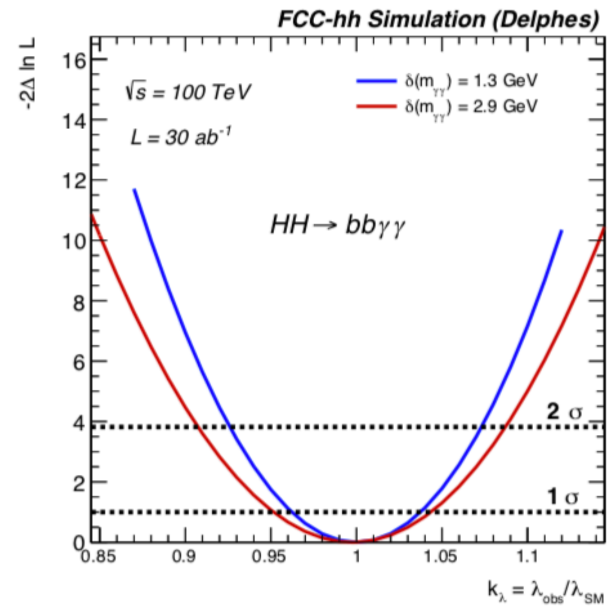
With PU density = 8 mm^{-1} need δz_0 ~ 100 μm resolution in track longitudinal impact parameter

→ at large angles this corresponds to beam-pipe contribution alone !!!

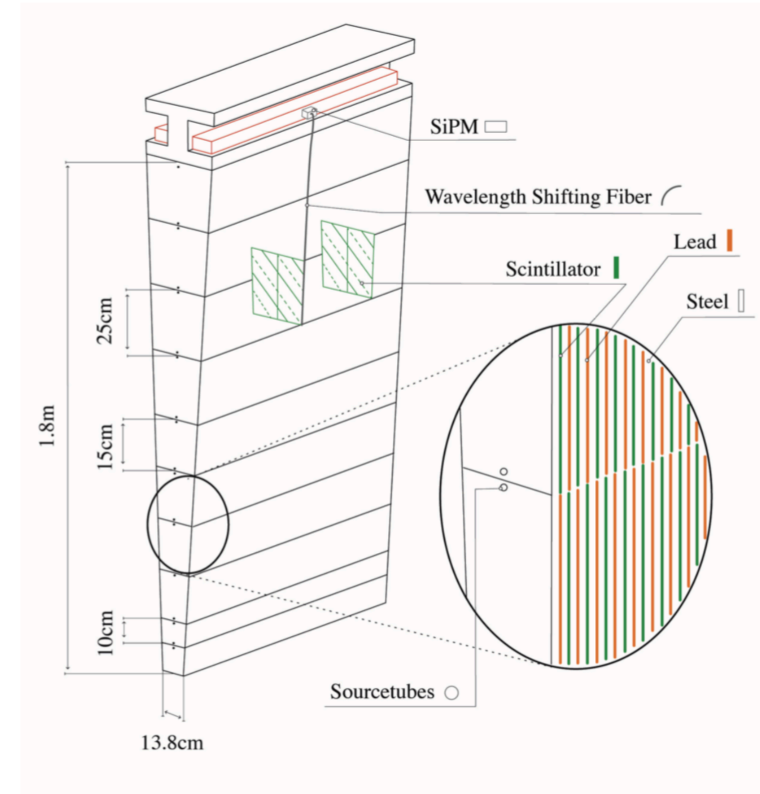
High resolution (~ 5-10 ps) timing information needed !!

Calorimeters

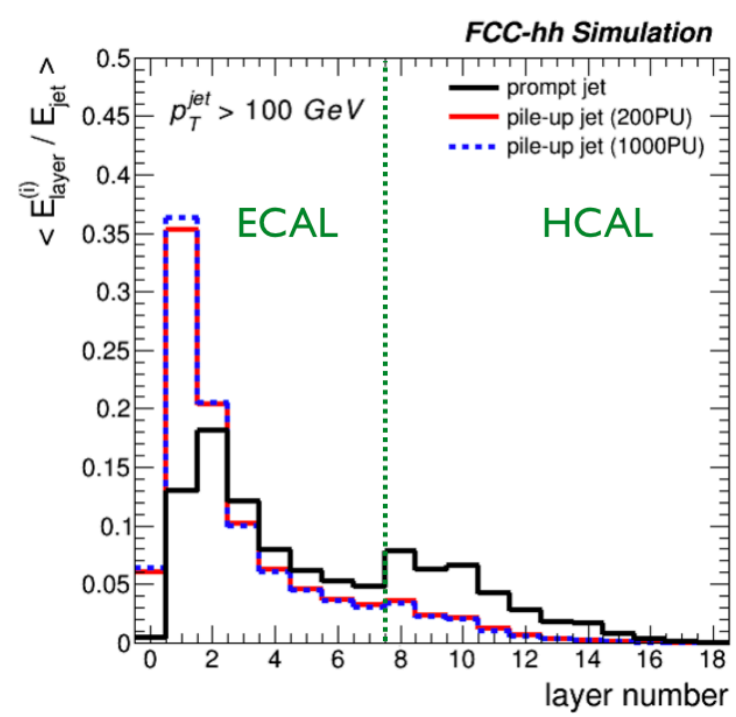




m(γγ) resolution



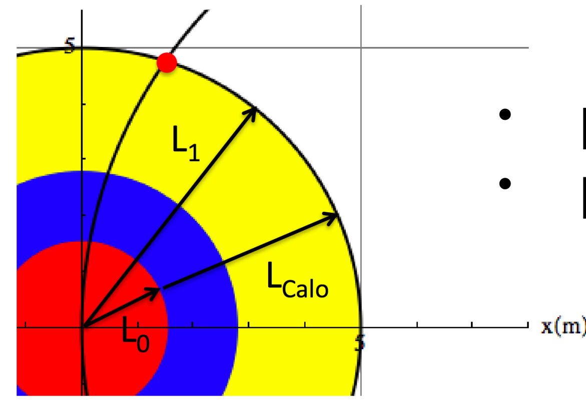
- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
  - Organic scintillator + Steel, R/O with WLS fiber + SiPM
  - LAr in the forward (Dose > 10 MGy)



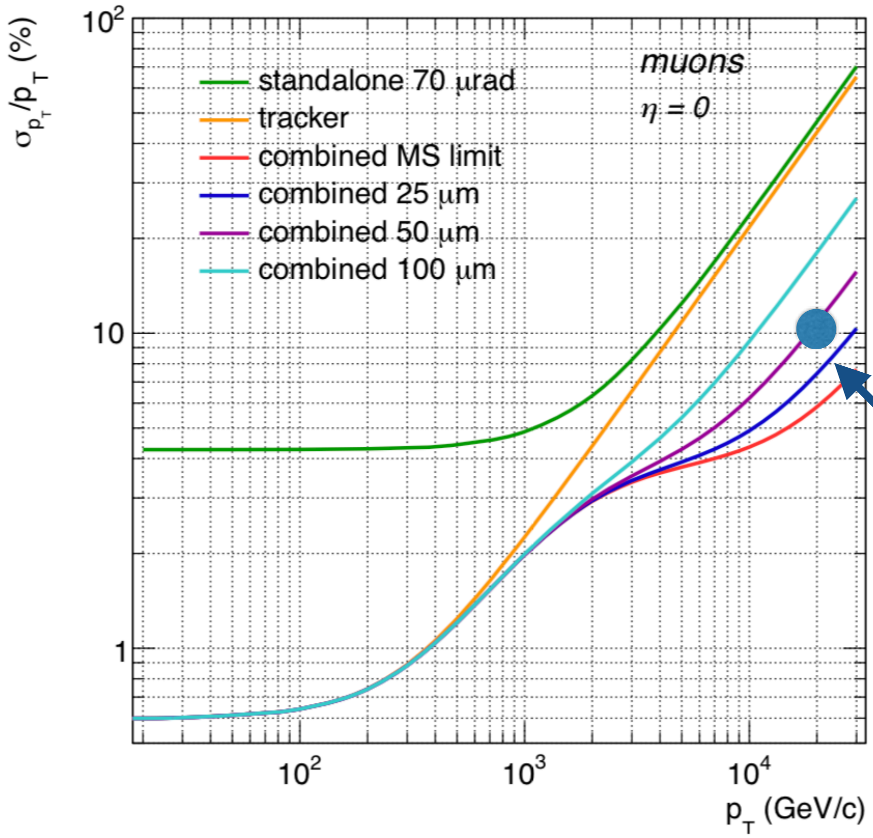
- Design goals:
  - High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
  - Particle-flow compliant
  - standalone PU rejection

Challenges: LAr cryo, especially in forward region, 2e6 channels (200 Tb/s at 16 bit)

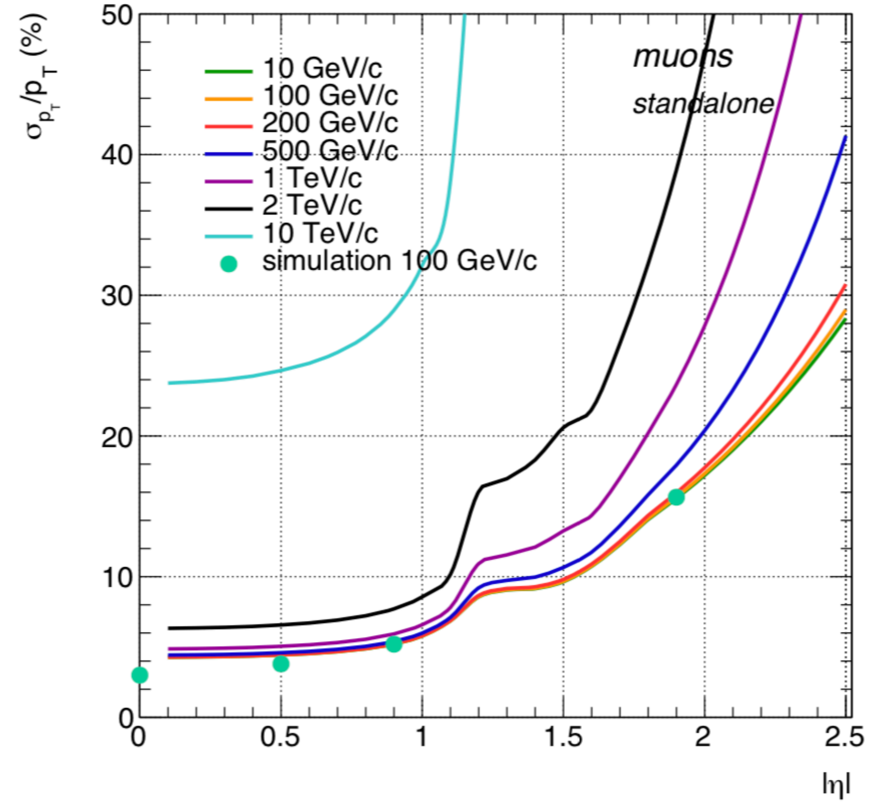
Muons



- pT = 4 GeV muons enter the muon system
- pT = 5.5 GeV leave coil at 45 degrees



σ_p/p = 10%
@20 TeV

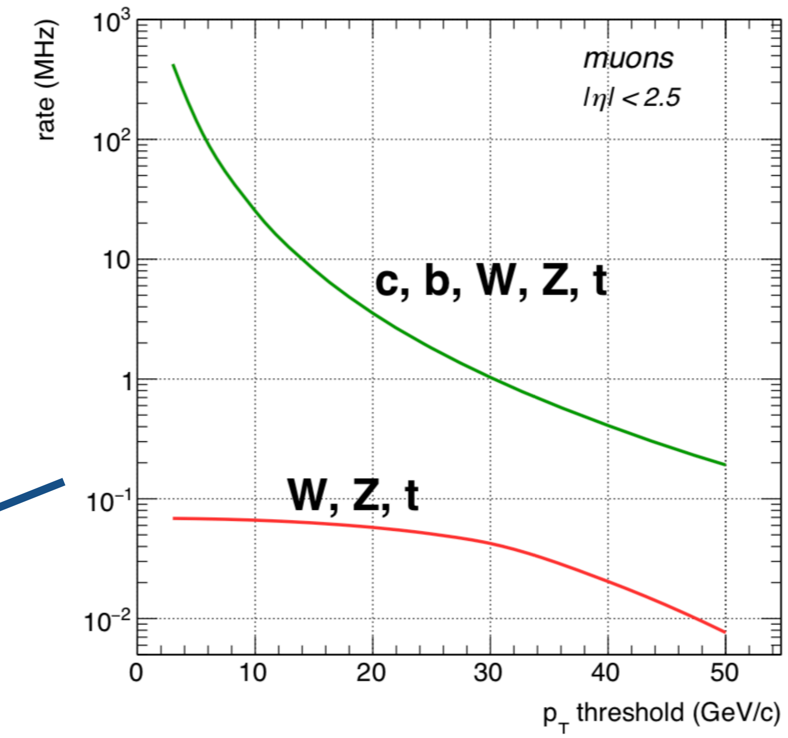


Calo + Coil = 180-280 X_0

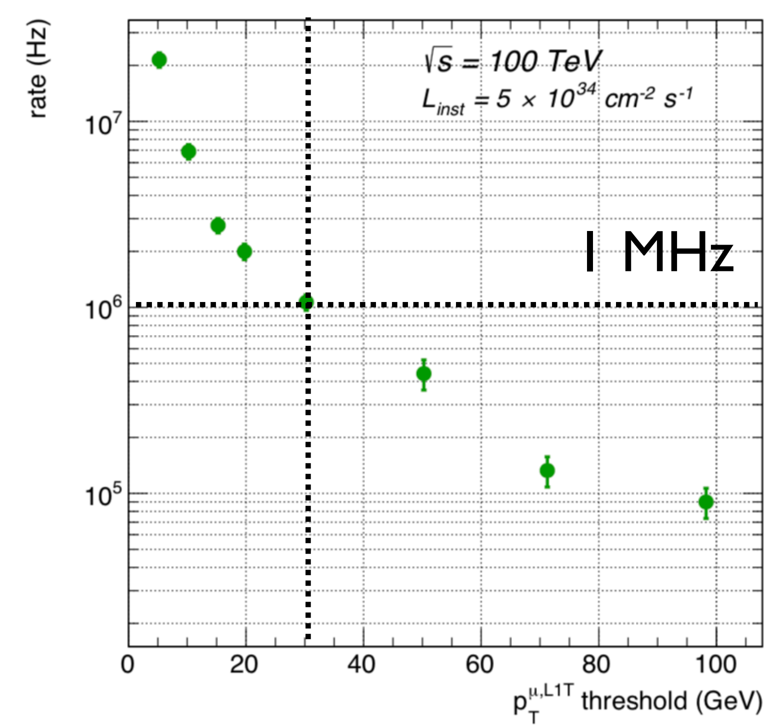
- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 µm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5
- Rates manageable with HL-LHC technology (sMDT)

Data rates and trigger

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^b > 30$ GeV/c cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^b > 30$ GeV/c rate	MHz	0.02	0.08	1	8
Jets $p_T^{jet} > 50$ GeV/c cross-section [341]	μb	21	21	56	300
Jets $p_T^{jet} > 50$ GeV/c rate	MHz	0.2	1.1	14	90



Need more selectivity at Level 1 (full allocated PhaseII bandwidth for single muon pt > 30 GeV)!



- Phase II:
  - ATLAS/CMS calorimeters/muons readout @40MHz and sent via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions (25 Tb/s)
  - Full detector readout @1MHz (@40MHz ~ 200 Tb/s)
- FCC-hh:
  - At FCC-hh Calo+Muon would correspond to 250 Tb/s (seems feasible)
  - However full detector would correspond to 1-2 Pb/s
    - Seems hardly feasible (30 yrs from now)
  - More selectivity needed @L1 (4D hit information?)

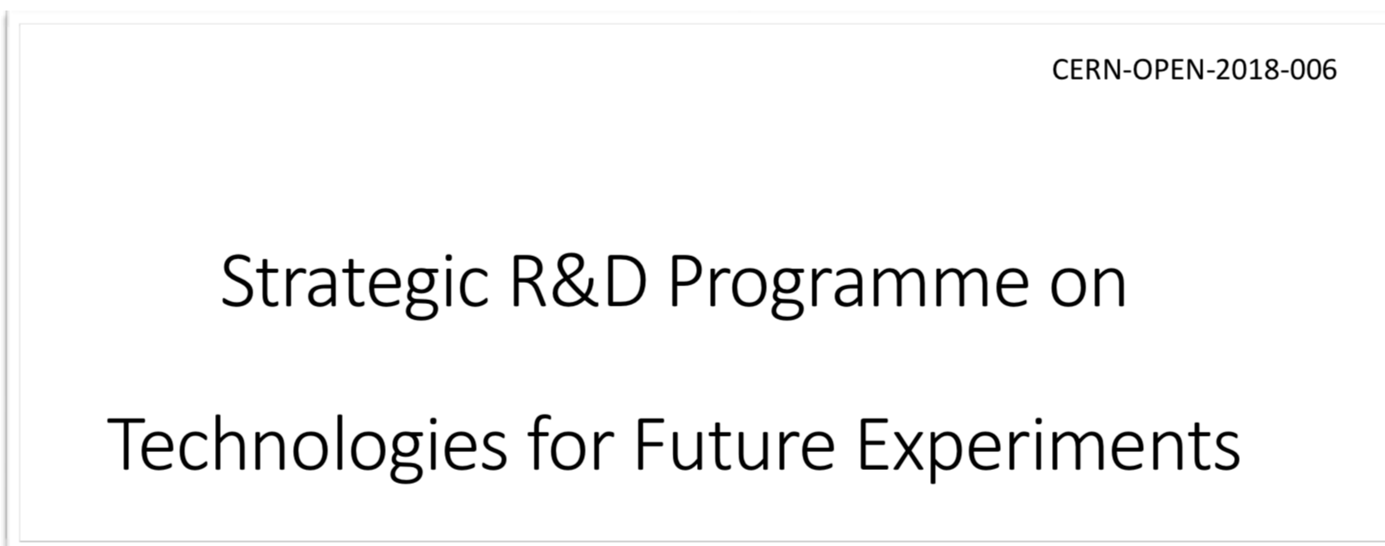
Strategy for R & D

- High profile R&d program needs to be carried on to make this possible, (leverage HL-LHC efforts)

- Possible Directions:

  - Radiation hard silicon detectors
  - High precision timing
  - Low power, high speed links
  - Highly segmented calorimeters
  - Software, reconstruction algorithms (4D particle-flow, boosted object tagging)
  - Large scale muon systems
  - Magnets
  - Cryogenics

CERN has released a document
On plans for R&D as input to
European Strategy:


CERN-OPEN-2018-006

Strategic R&D Programme on

Technologies for Future Experiments

Conclusions

- A next generation of accelerators is needed to study the Higgs and explore the energy frontier
- A detector operating at 100 TeV collider must feature excellent performance in a wide energy range
- Physics (low and high Q^2) and machine (1000PU) impose several constraints on the detector design
- A general purpose reference detector has been designed to set the scale of the challenges of performing experiments with such machine
- We think that detectors able to extract all the physics potential from such a machine can be built, but a high profile R&D programme for detectors and electronics technologies has to be conducted:
  - radiation hardness, picosecond timing, granularity, high speed low power optical links

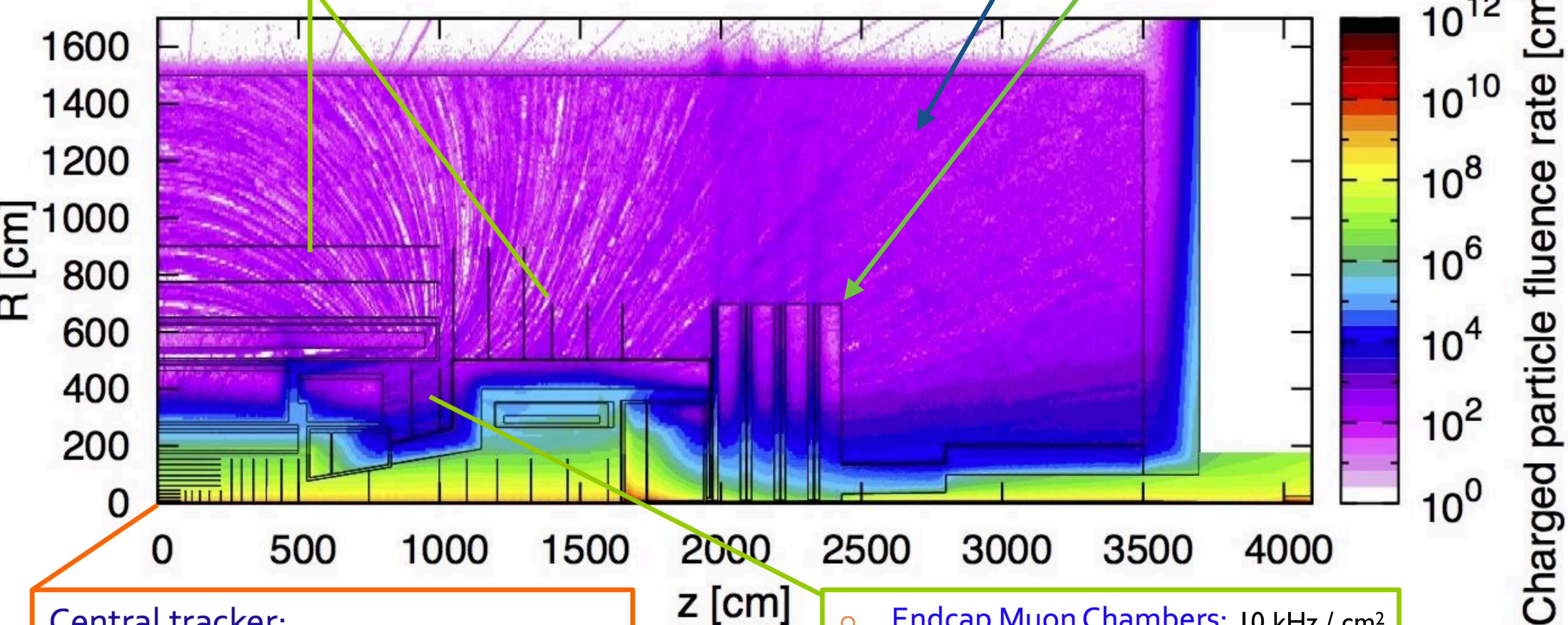
Backup

Charged Particle fluence

γ (→ee) created from thermalisation/neutron capture in calorimeters

- Barrel muon chambers: 300-500Hz / cm²

Fwd chambers: 25-250 kHz / cm²



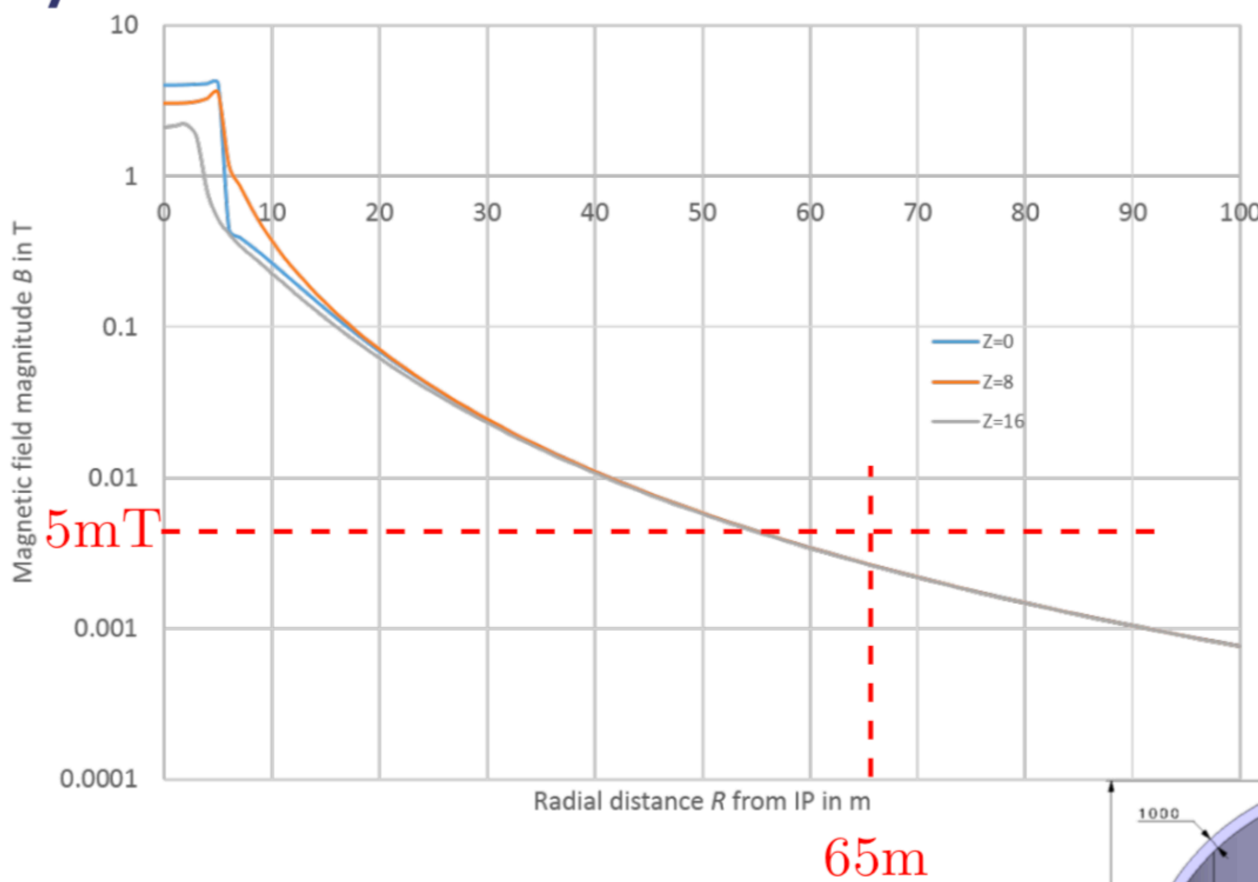
- Endcap Muon Chambers: 10 kHz / cm²

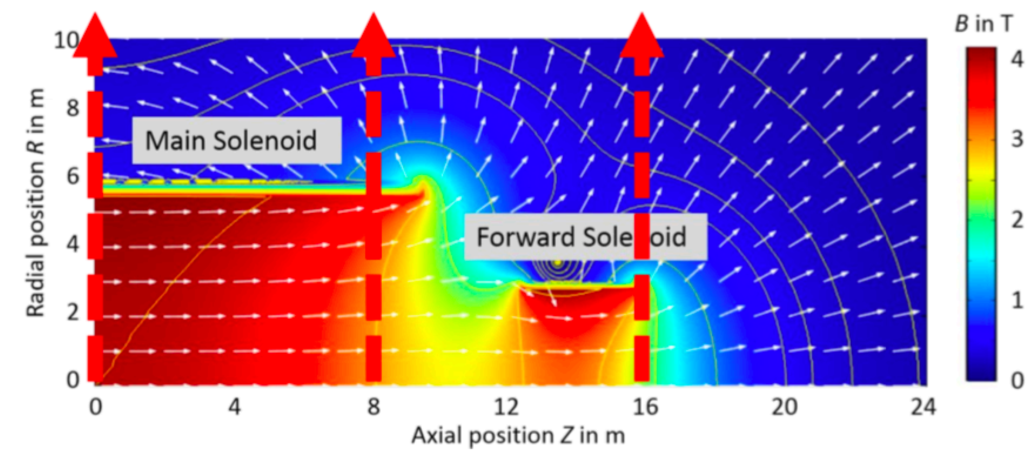
Central tracker:
- first IB layer (2.5 cm): ~1.2 10^{10} cm^{-2}s^{-1}
- external part: 3 10^{6} cm^{-2}s^{-1}

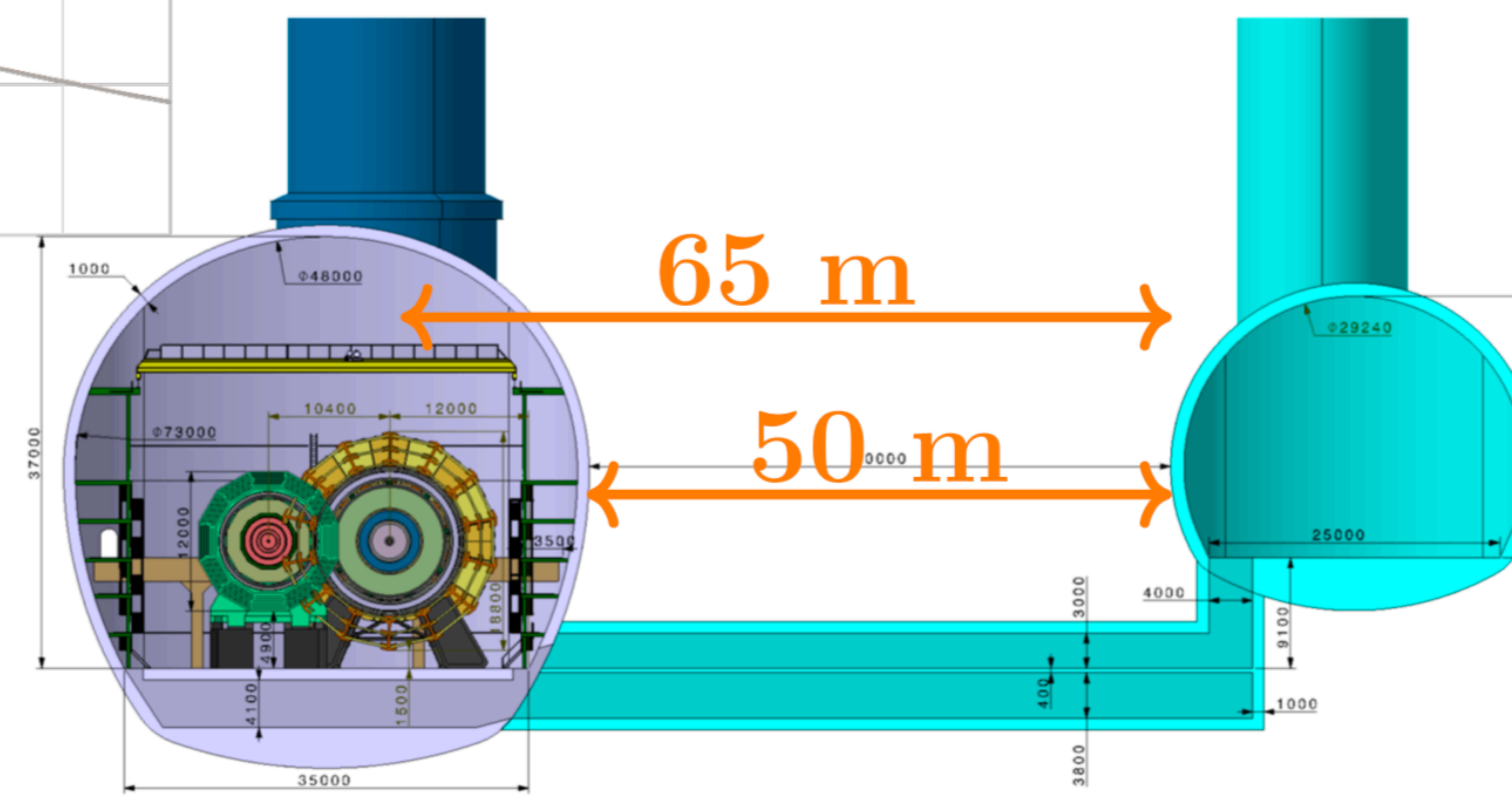
Silicon sensors in the very forward region for muons?

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

Stray field and service cavern







No shielding: too expensive

Dipole vs. Solenoid

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

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

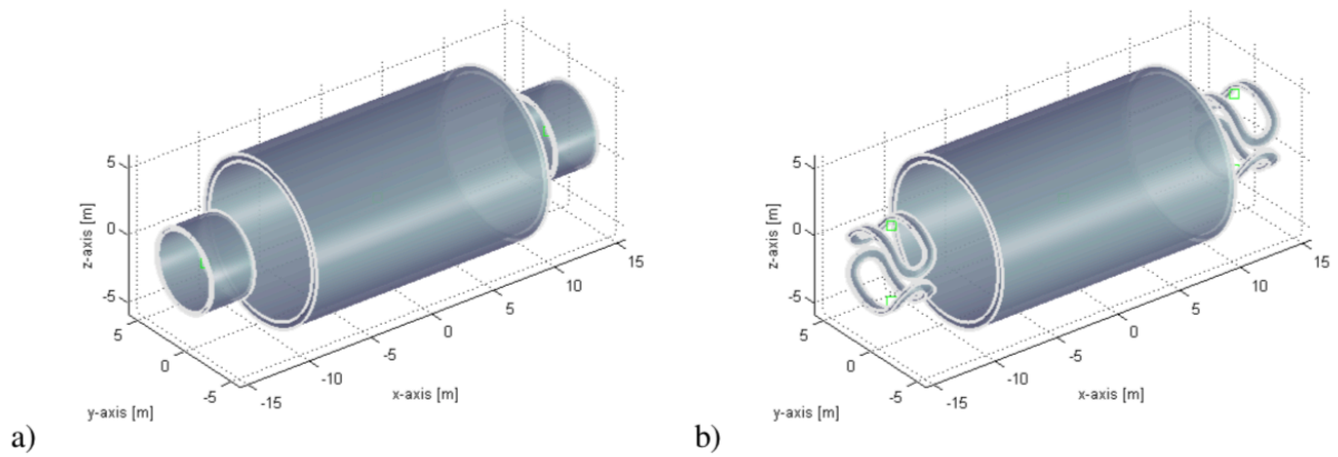


Figure 7.6: a) Cold mass for a central solenoid of 4 T with two forward solenoids and b) a central solenoid of 4 T and two forward dipole magnets with field integral of 4 Tm.

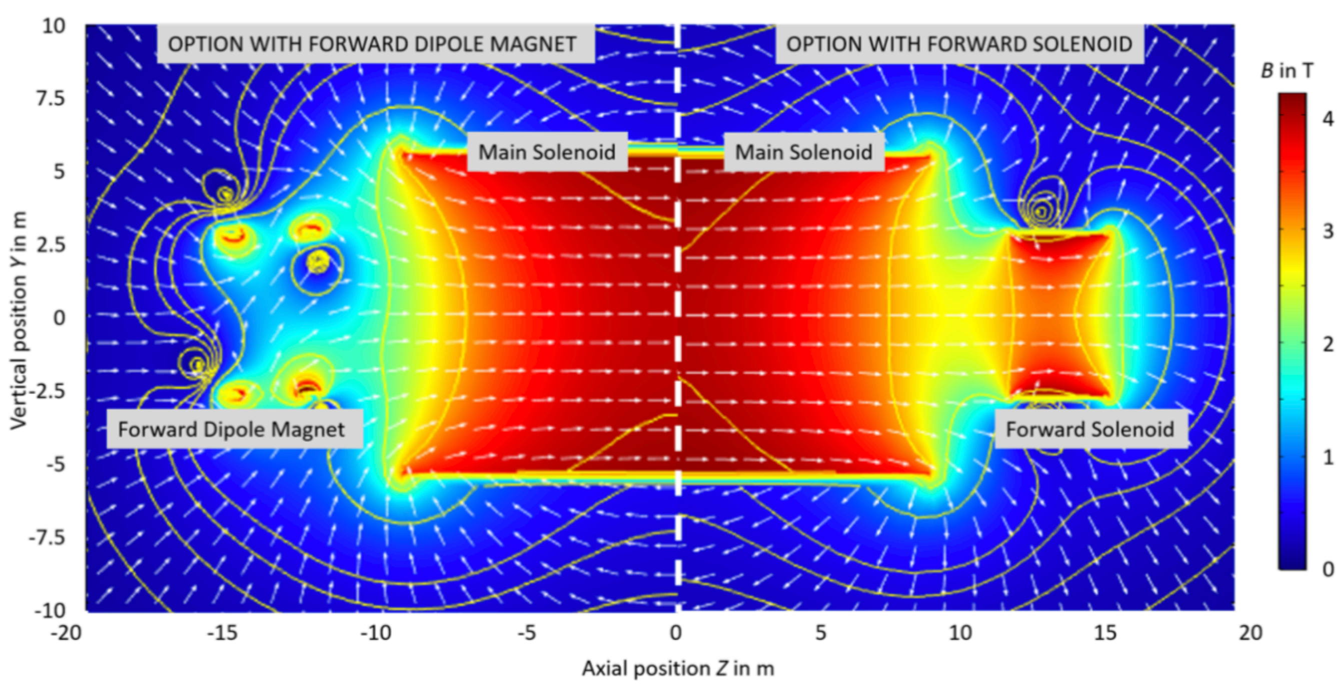
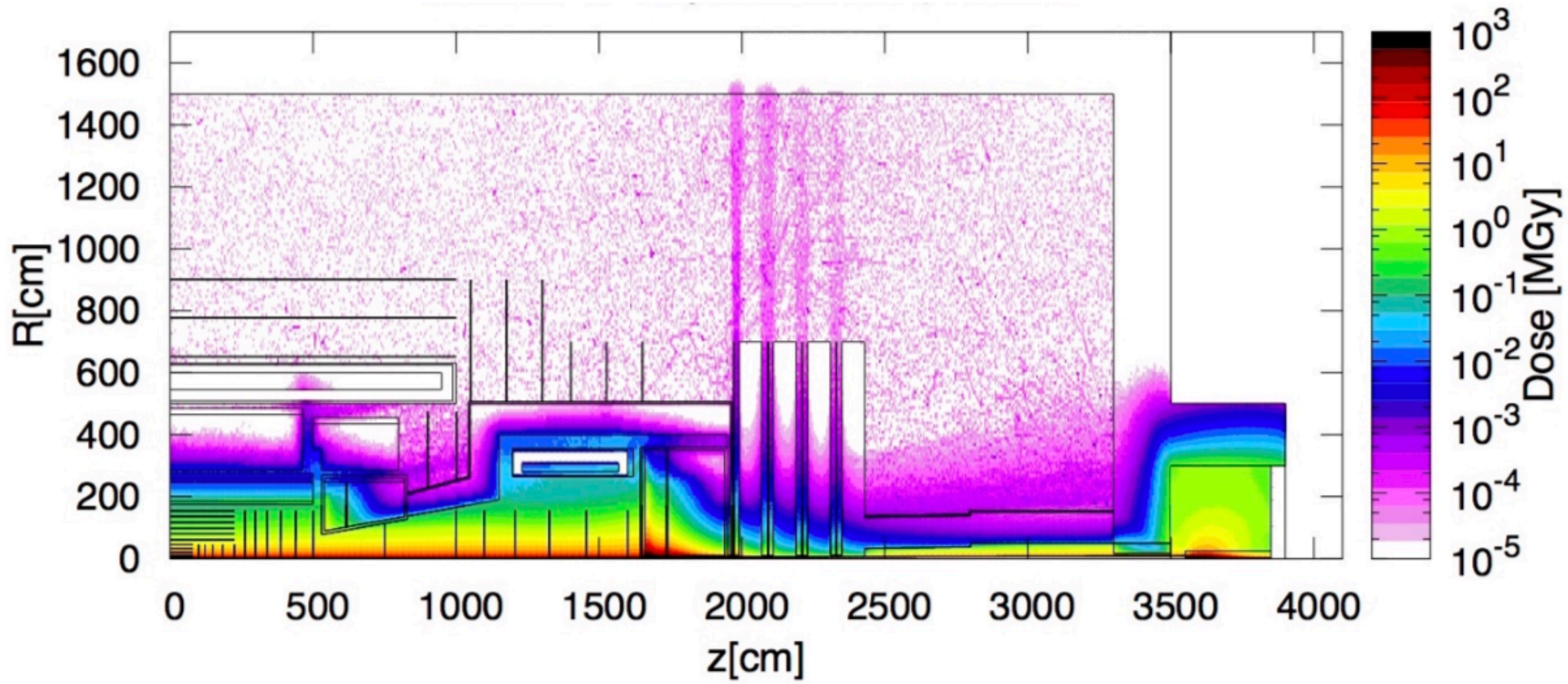


Figure 7.7: Longitudinal half-sections of the two versions of the magnet system. Magnetic fieldmap for a central solenoid of 4 T with a forward dipole (left) and a forward solenoid (right).

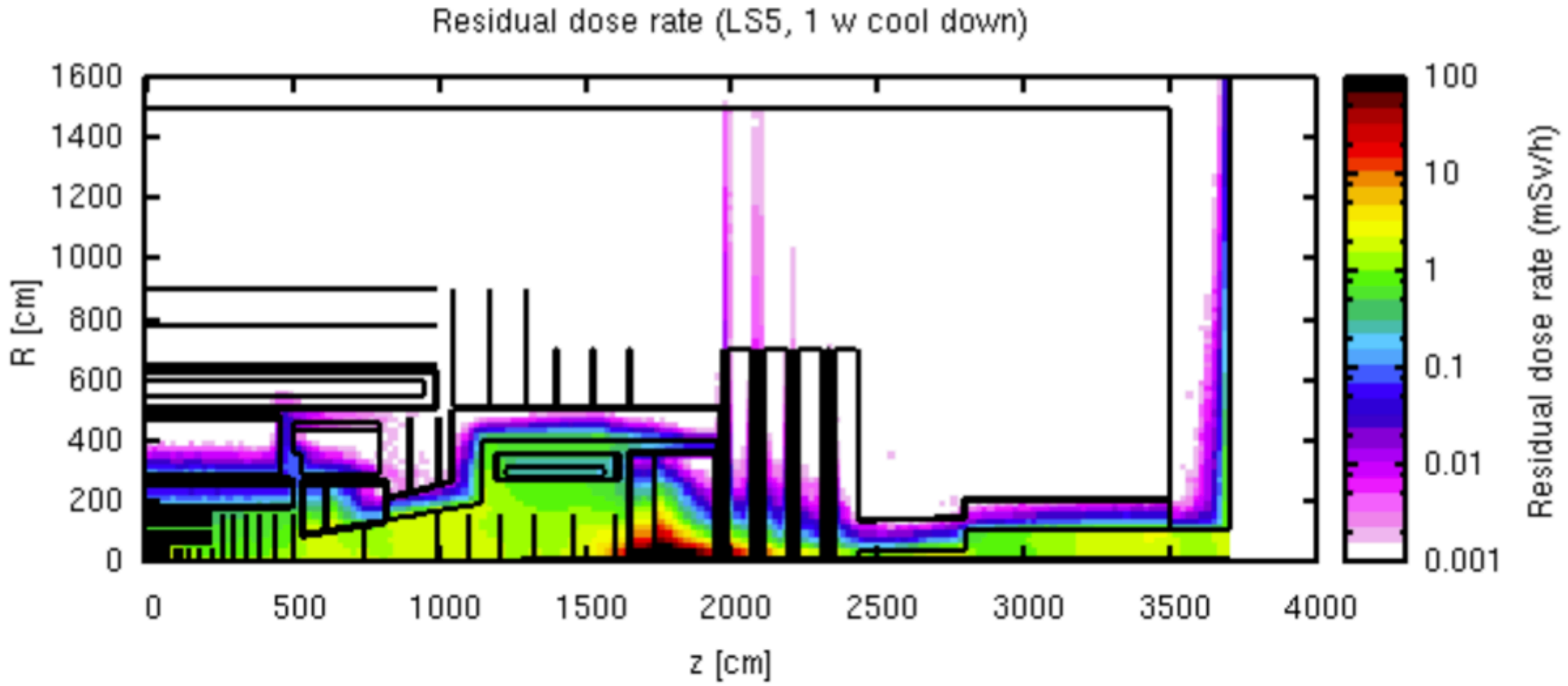
Dipole:

- Loose rotational symmetry
- Need compensation system for the hadron beam
- Better tracking performance however

Total and residual ionizing dose



a)



b)

Material budget

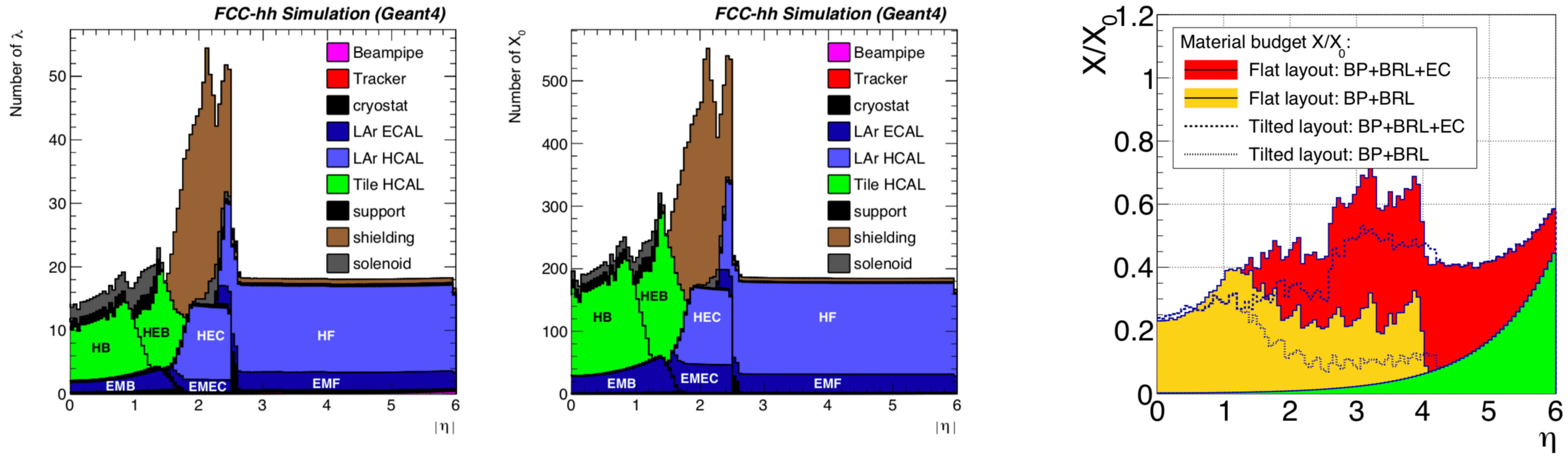
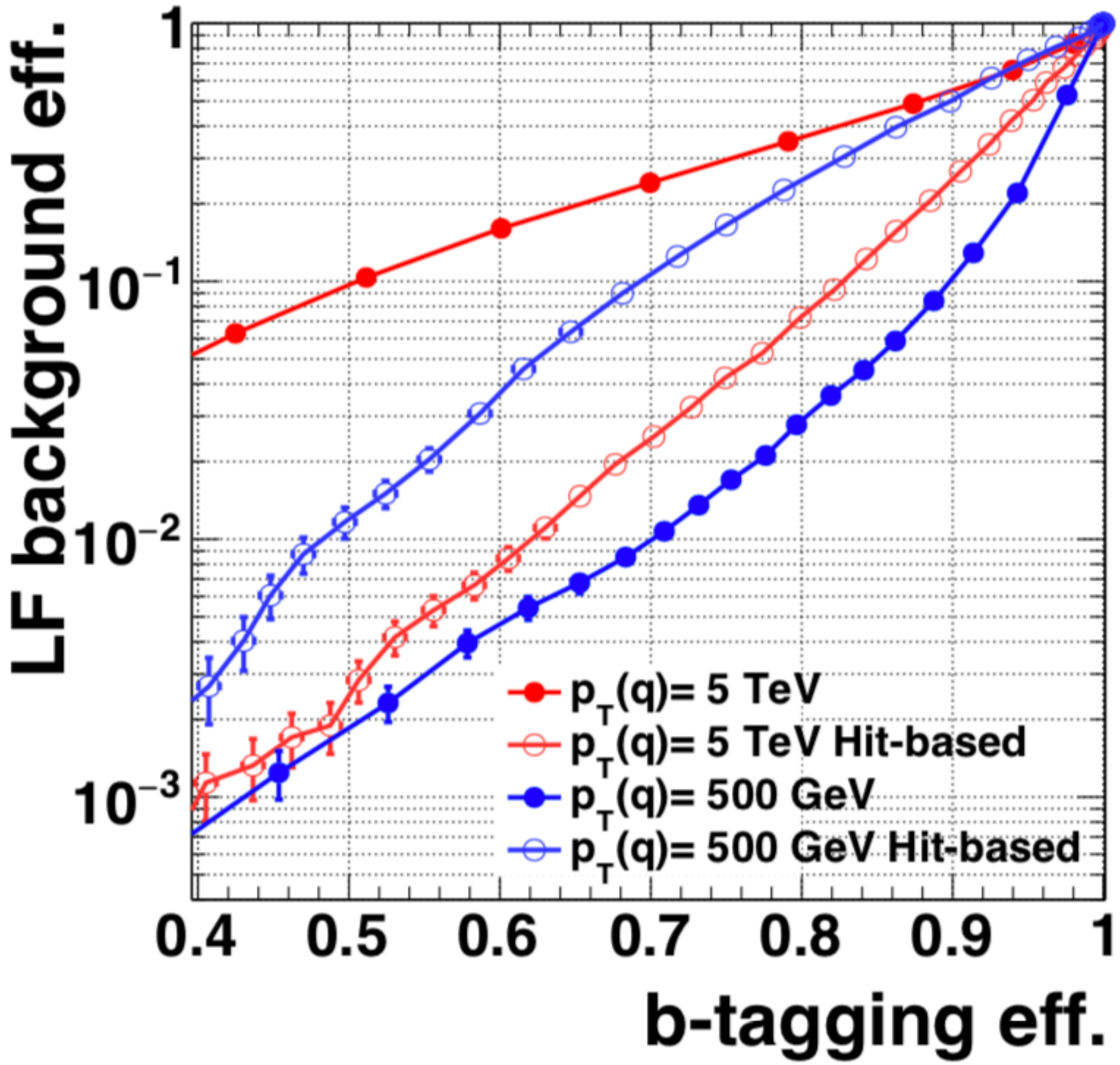


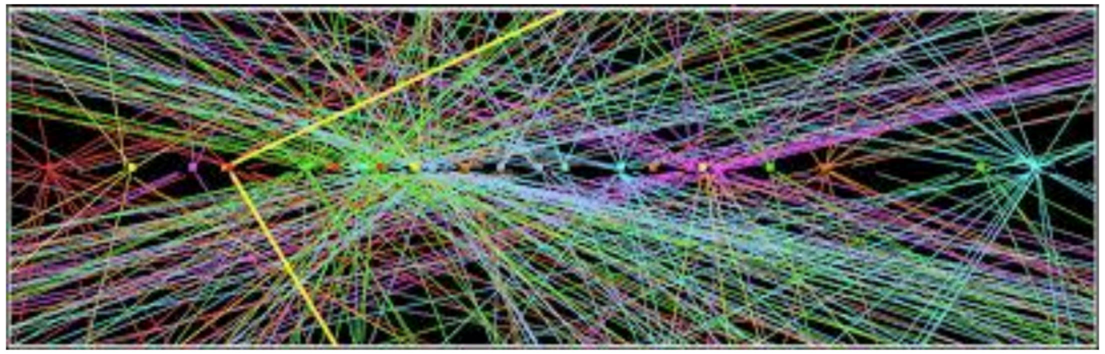
Figure 7.10: Material budget of the different sub-systems. The calorimetry provides $\geq 10.5\,\lambda$ nuclear interaction lengths to maximise shower containment and the total detector material represents between 180 and 280 X_0 radiation lengths.

Boosted b-tagging



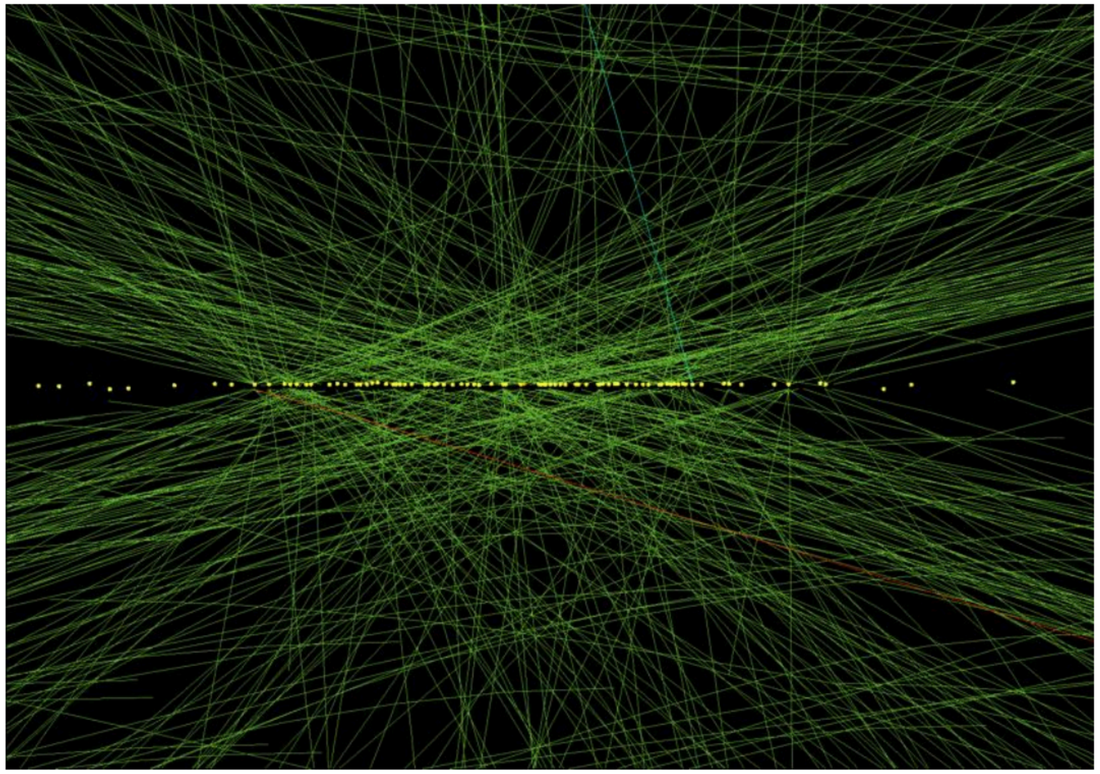
Machine and detector requirements

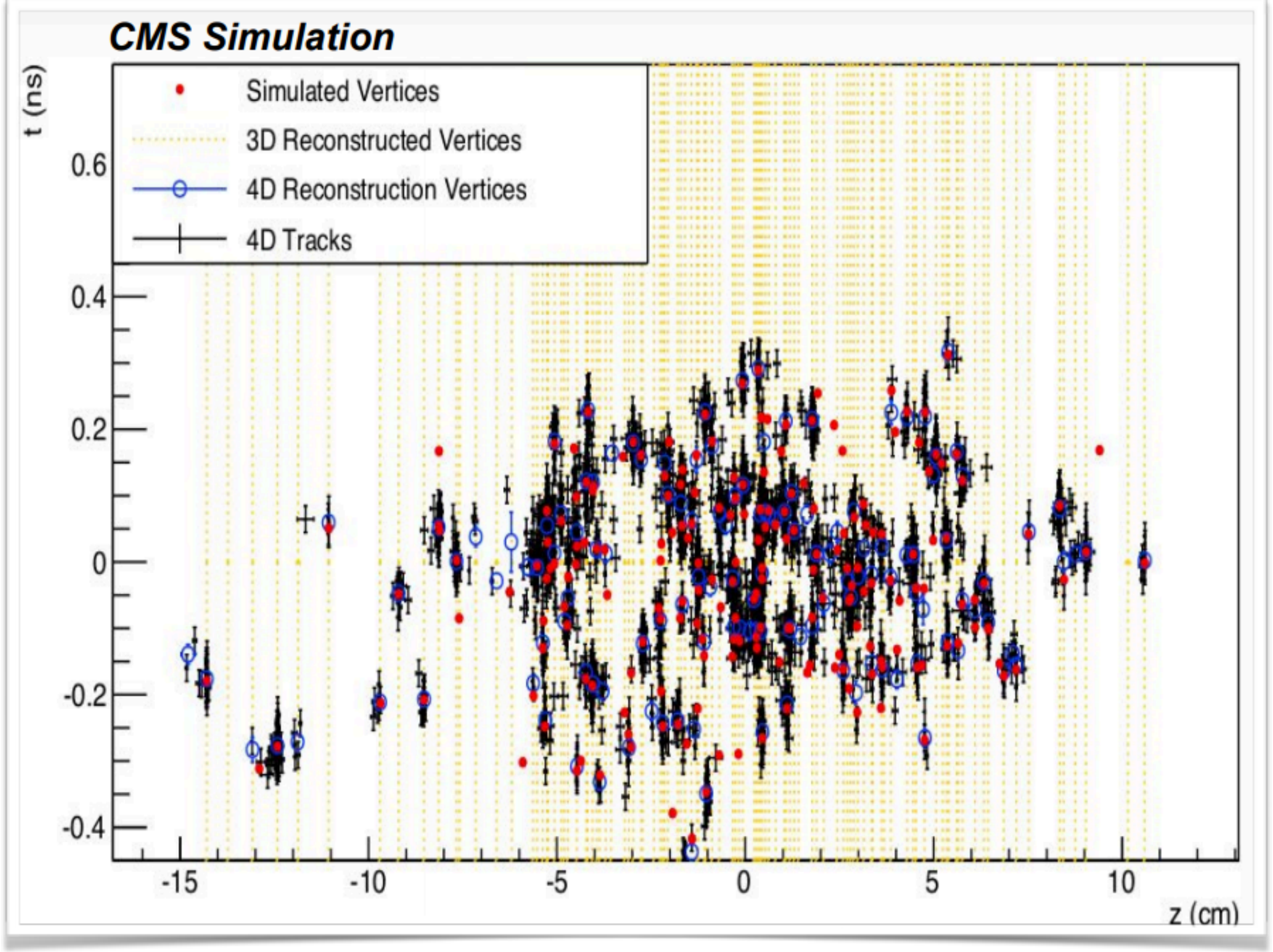
lumi & pile-up



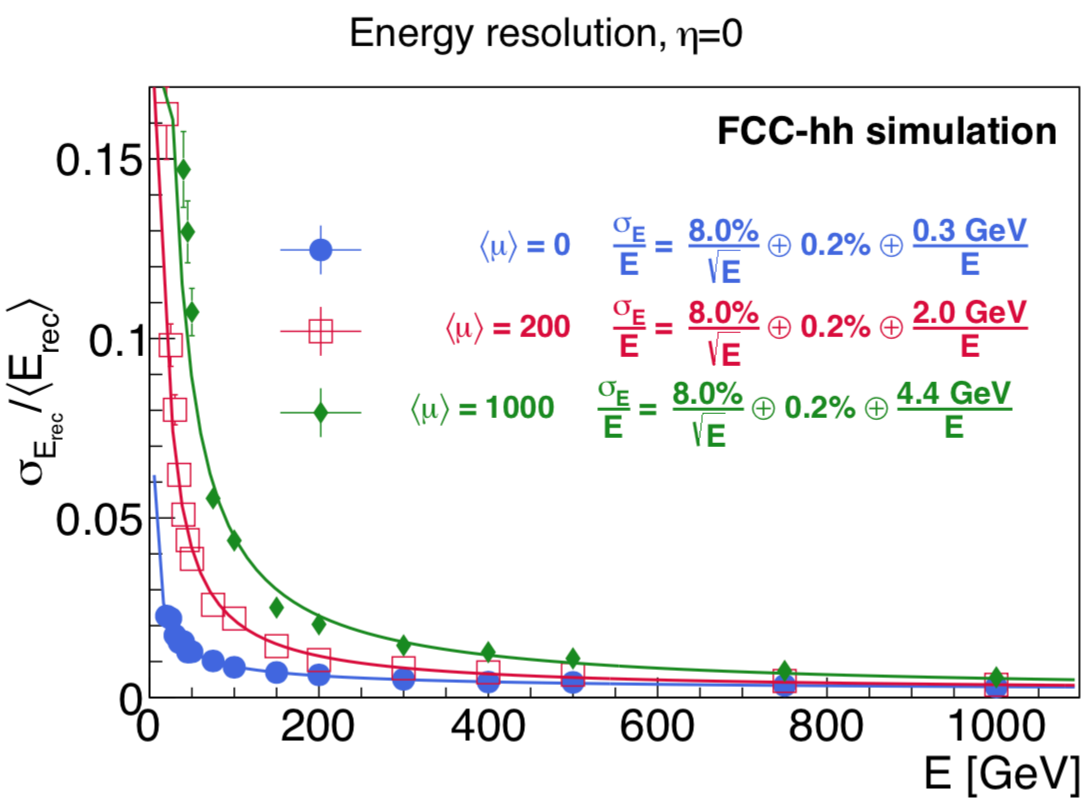
- LHC: 30 PU events/bc
- HL-LHC: 140 PU events/bc
- FCC-hh: 1000 PU events/bc

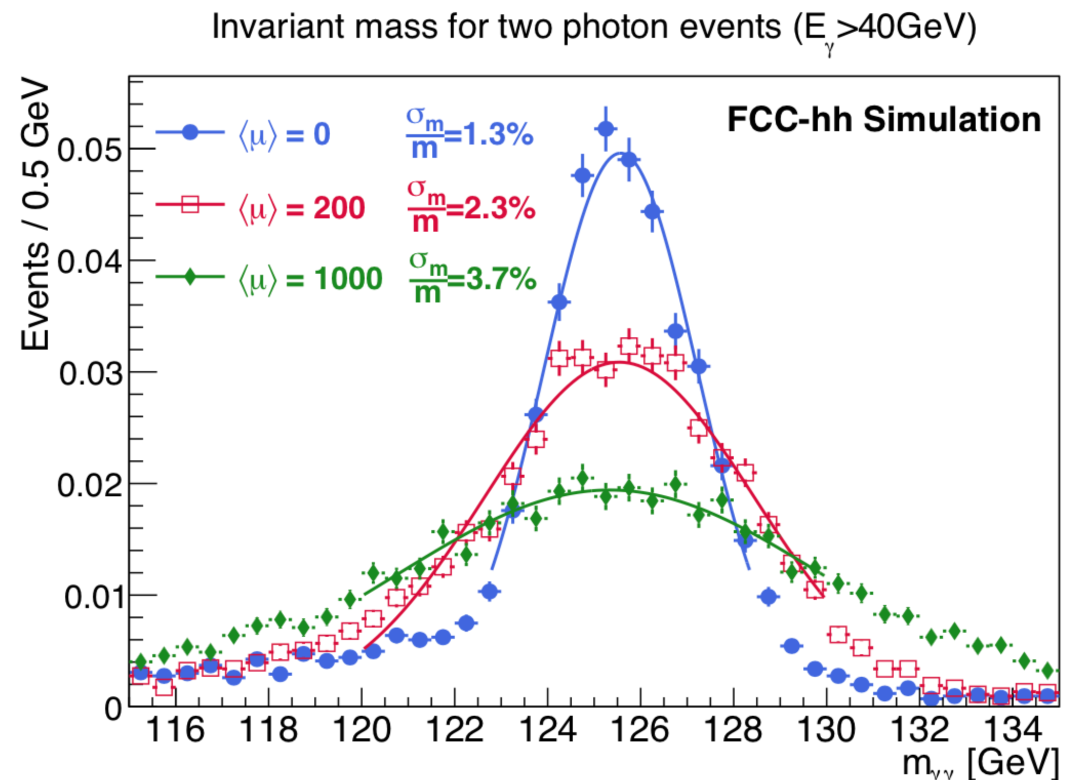
Timing helps in identifying PU vertices

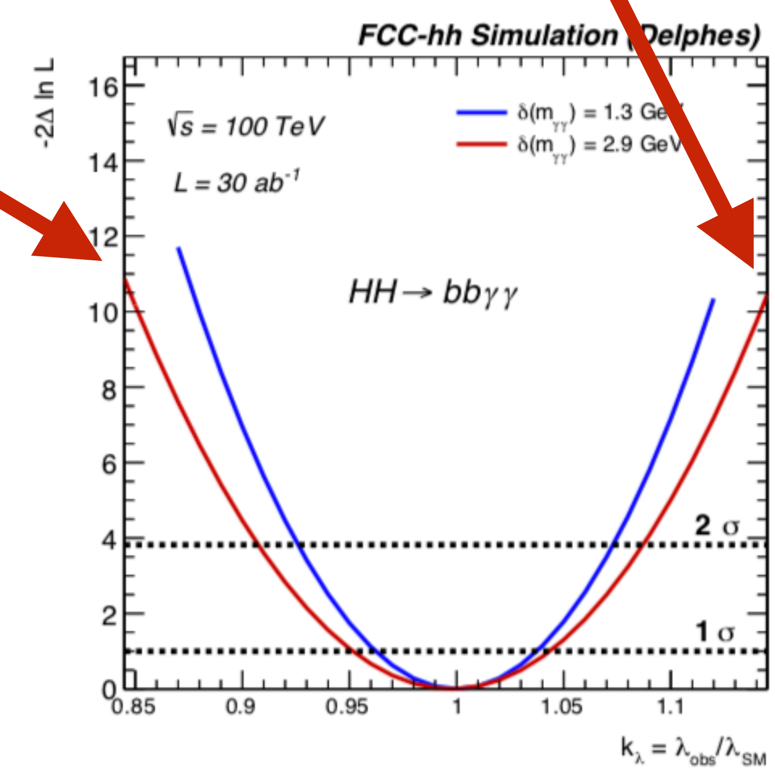




Photon resolution with PU







m(γγ) resolution

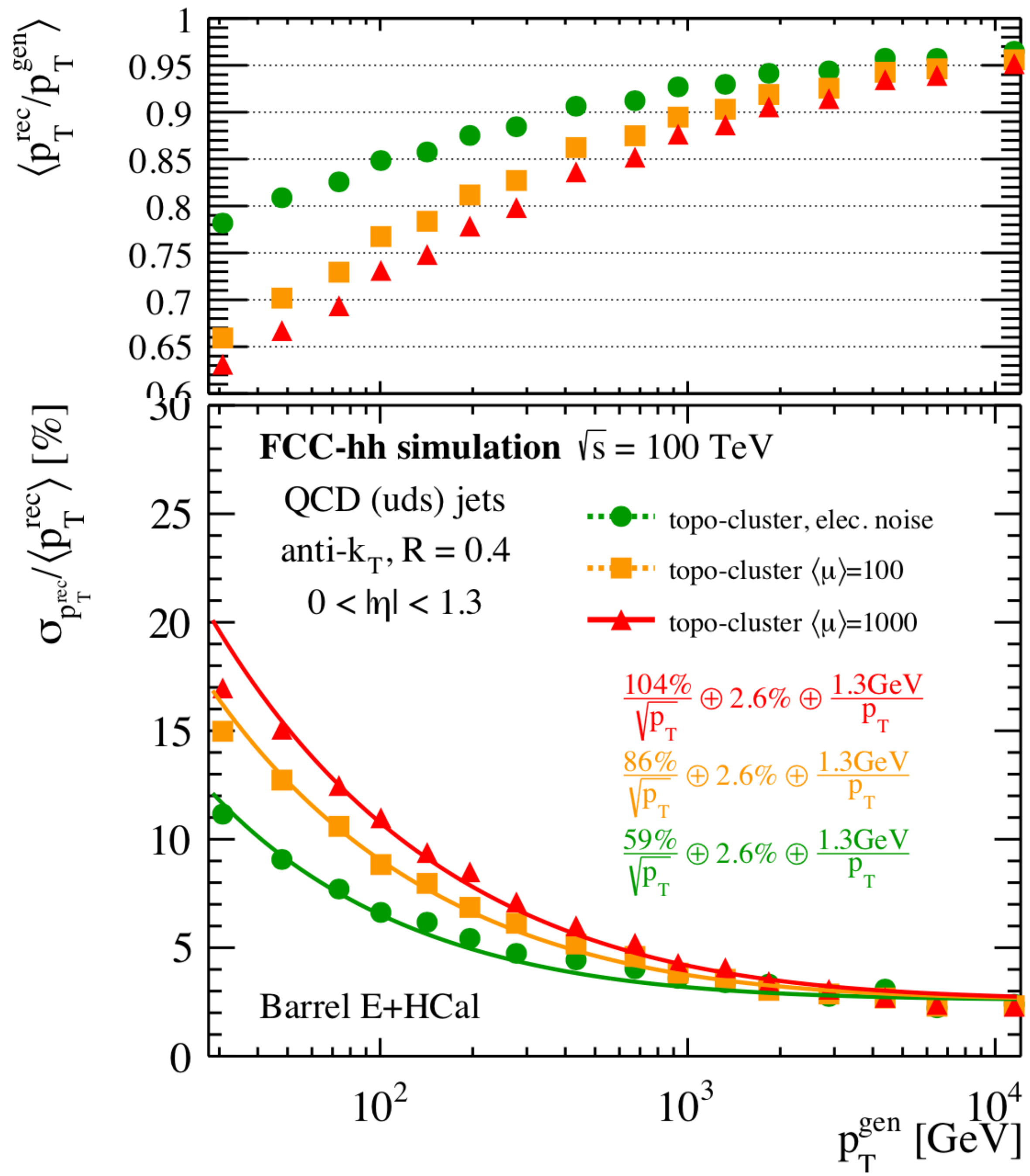
Large impact of in time PU on the noise term (out of the box with no improvements)!!

- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)

Jet Performance with Full sim

- Excellent resolution up to $p_T = 10$ TeV !!
- Large impact of PU at low p_T (as expected)
    - crucial for low mass di-jet resonances (again, such as $HH \to bb\gamma\gamma$)
    - Further motivation for Particle-flow

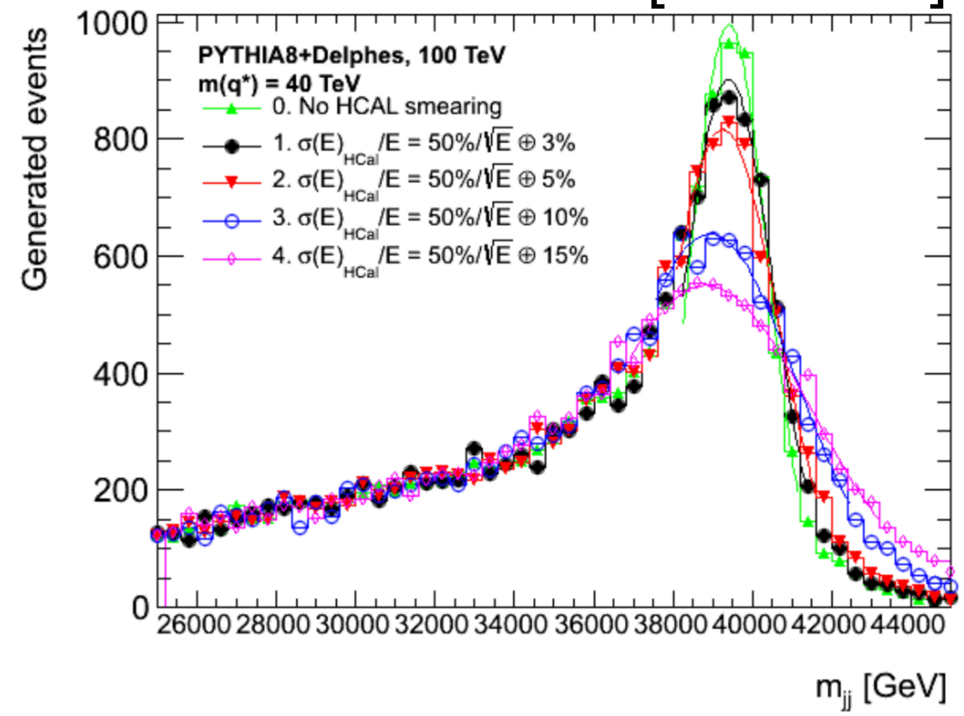
→ since charged PU contribution can be easily subtracted (Charged Hadron Subtraction)



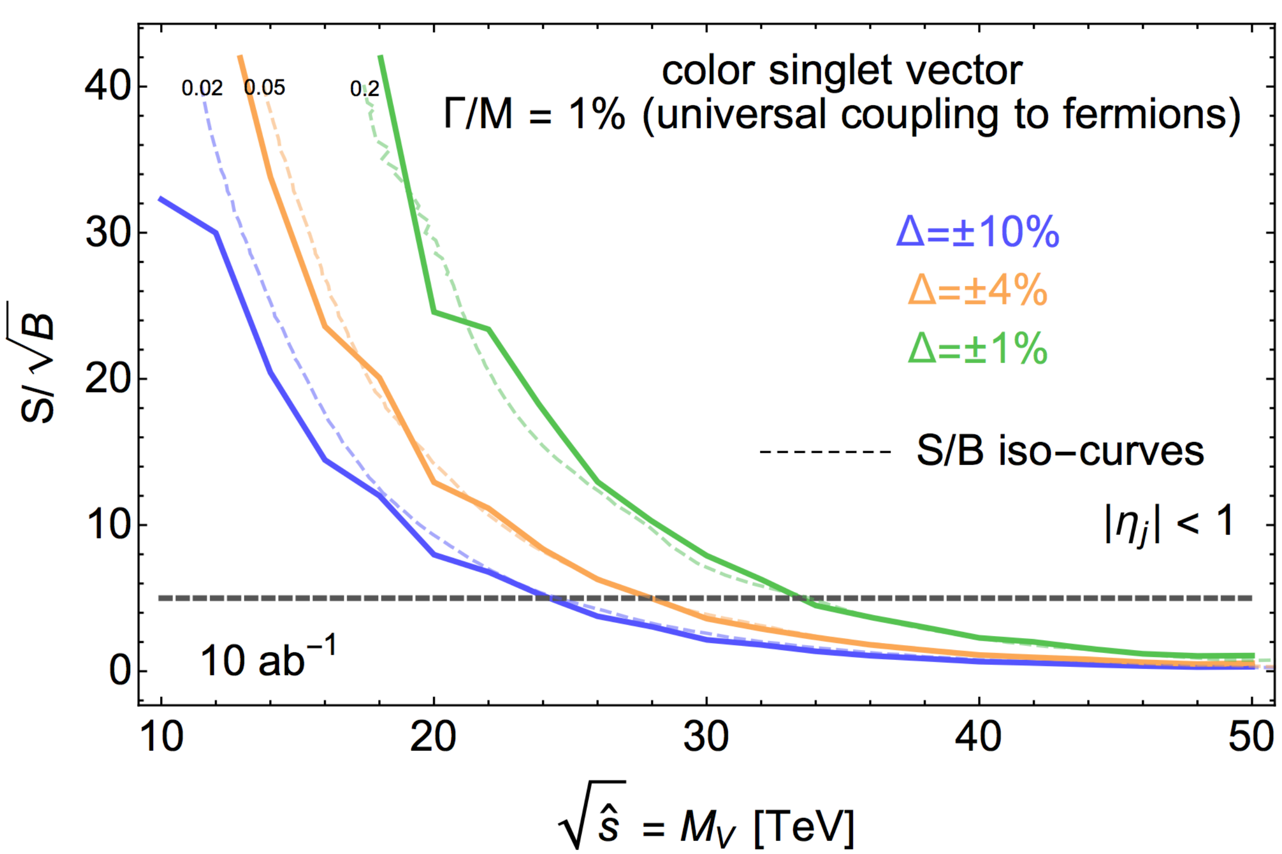
High Mass resonances

- Constant term drives jet energy resolution at high p_T
- Directly impacts sensitivity for excluding discovering narrow resonance high mass resonances $Z' \rightarrow j\,j$
- Small impact on strongly coupled (wide) resonances

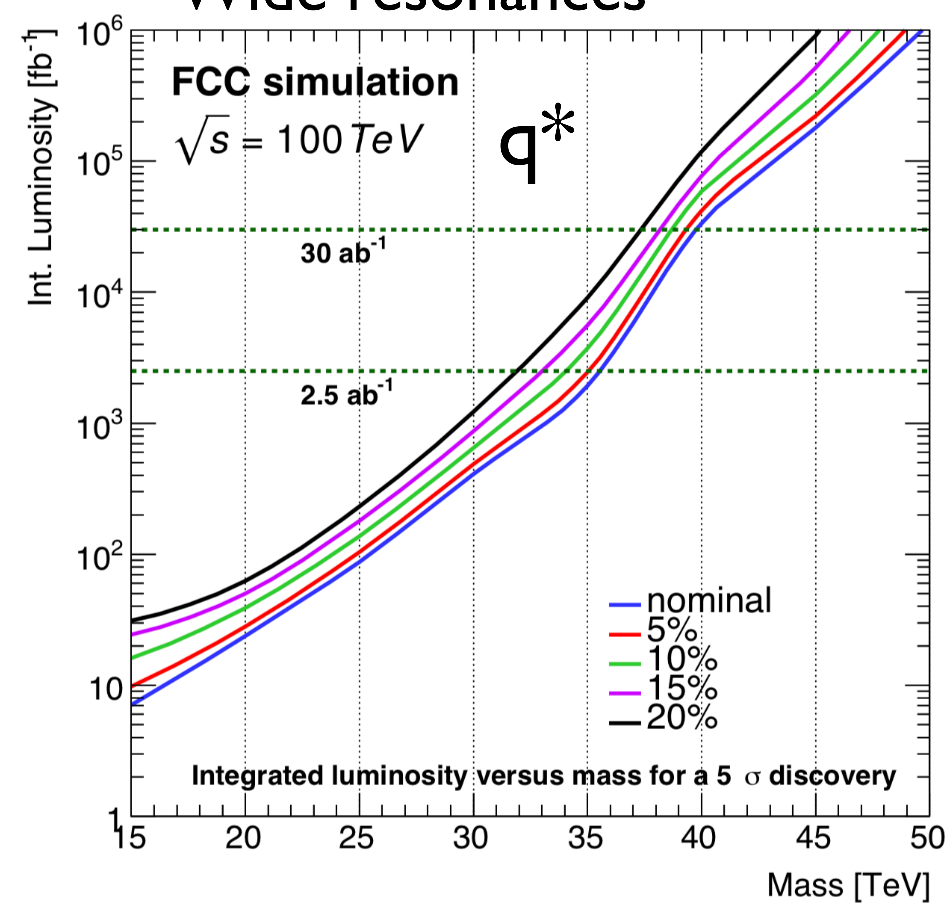
[1606.00947]



Narrow resonances



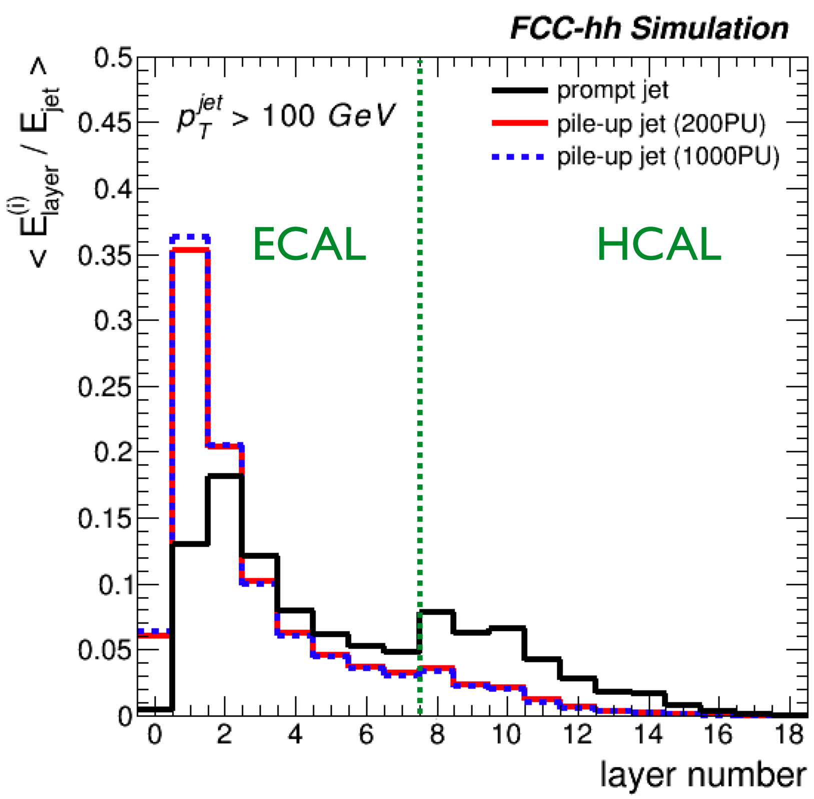
Wide resonances



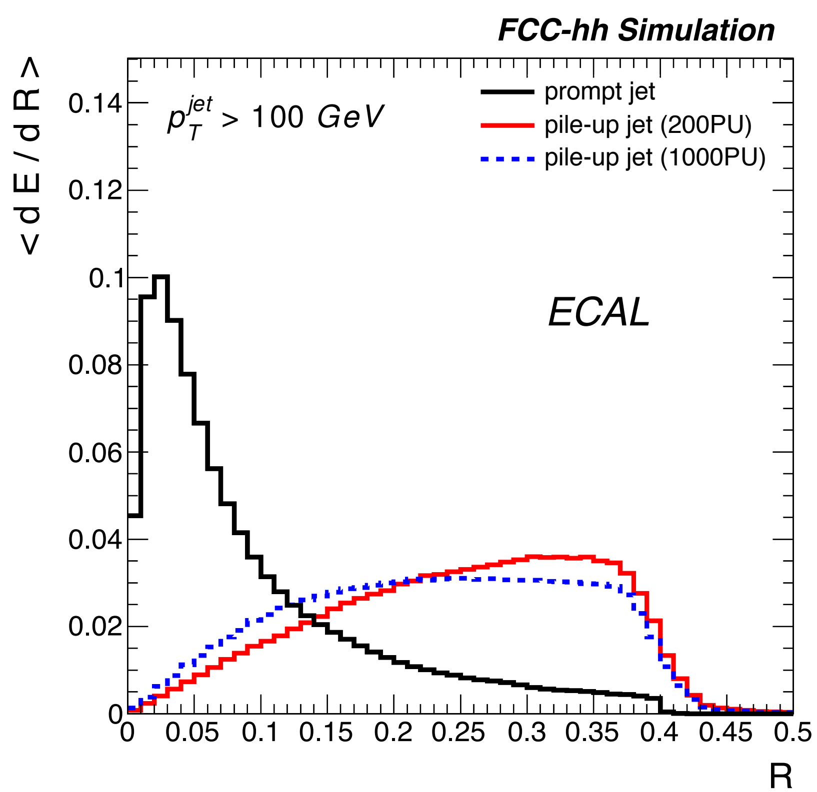
Jet Pile-Up identification

- With 200-1000PU, will get huge amount of fake-jets from PU combinatorics
- need both longitudinal/lateral segmentation for PU identification
- Simplistic observables show possible handles, pessimistic.. (in reality tracking will help a lot)

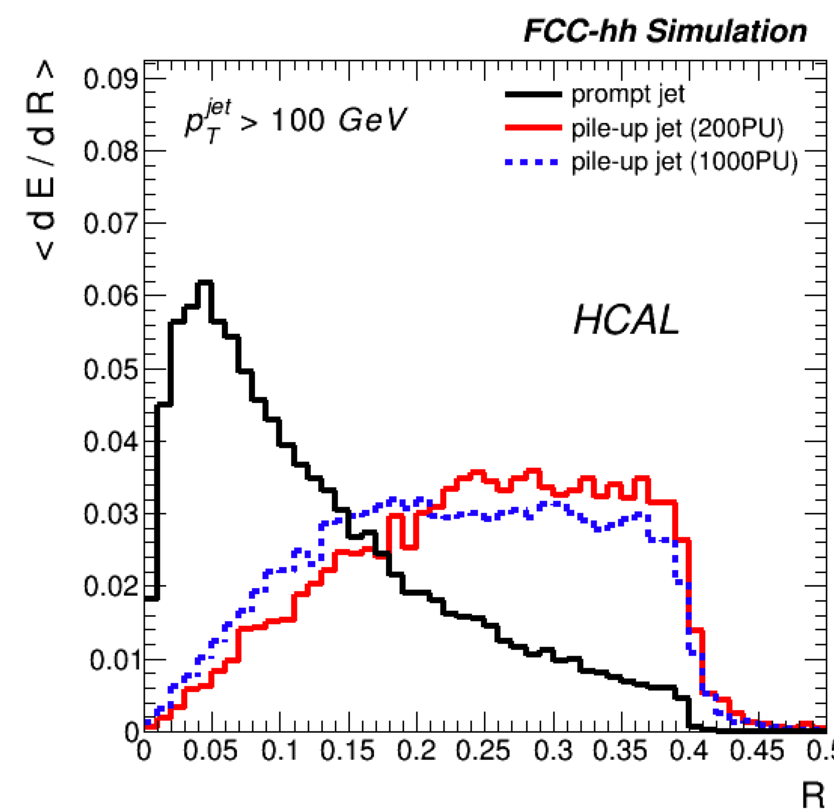
longitudinal



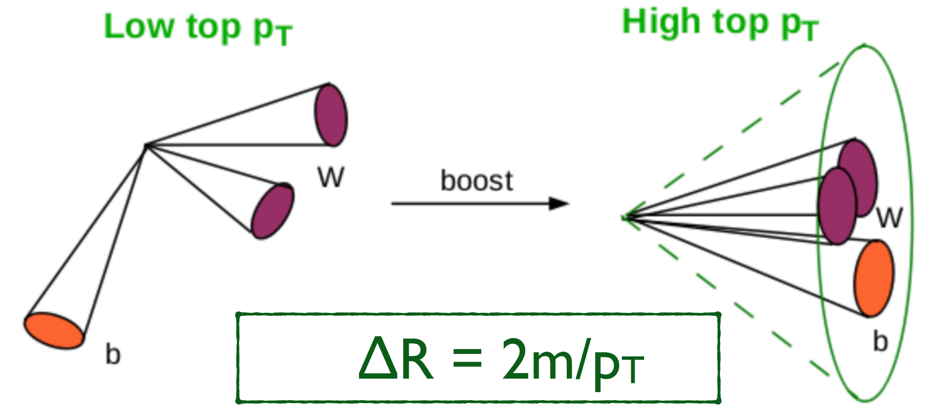
lateral (ECAL)

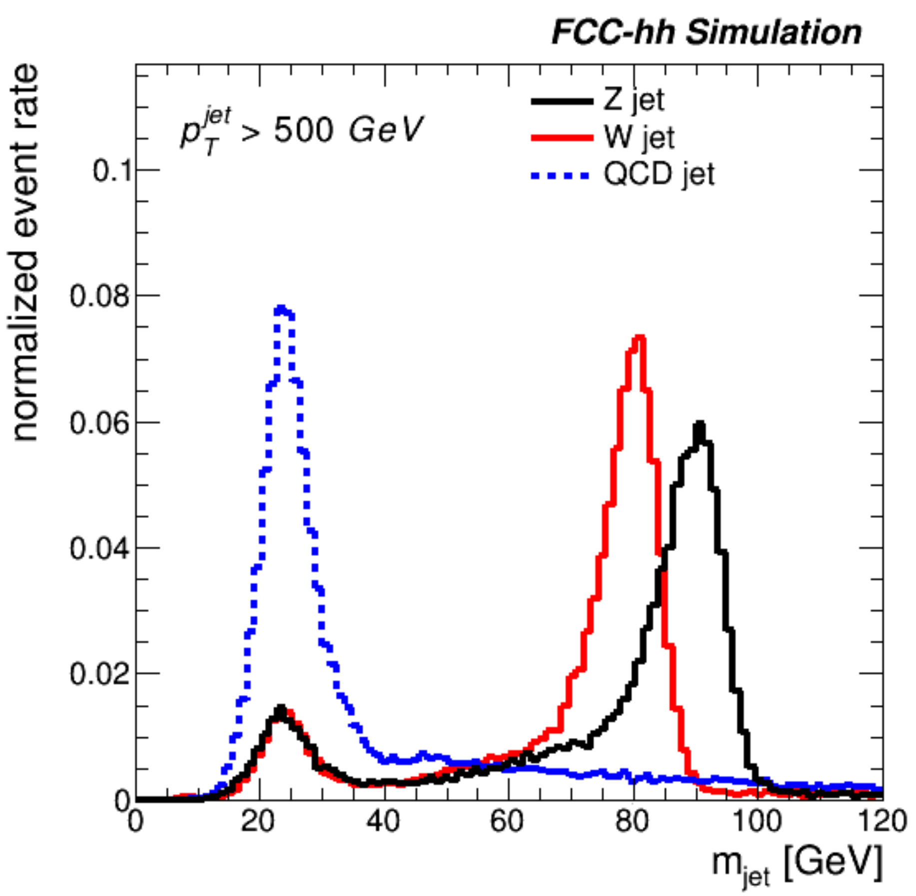


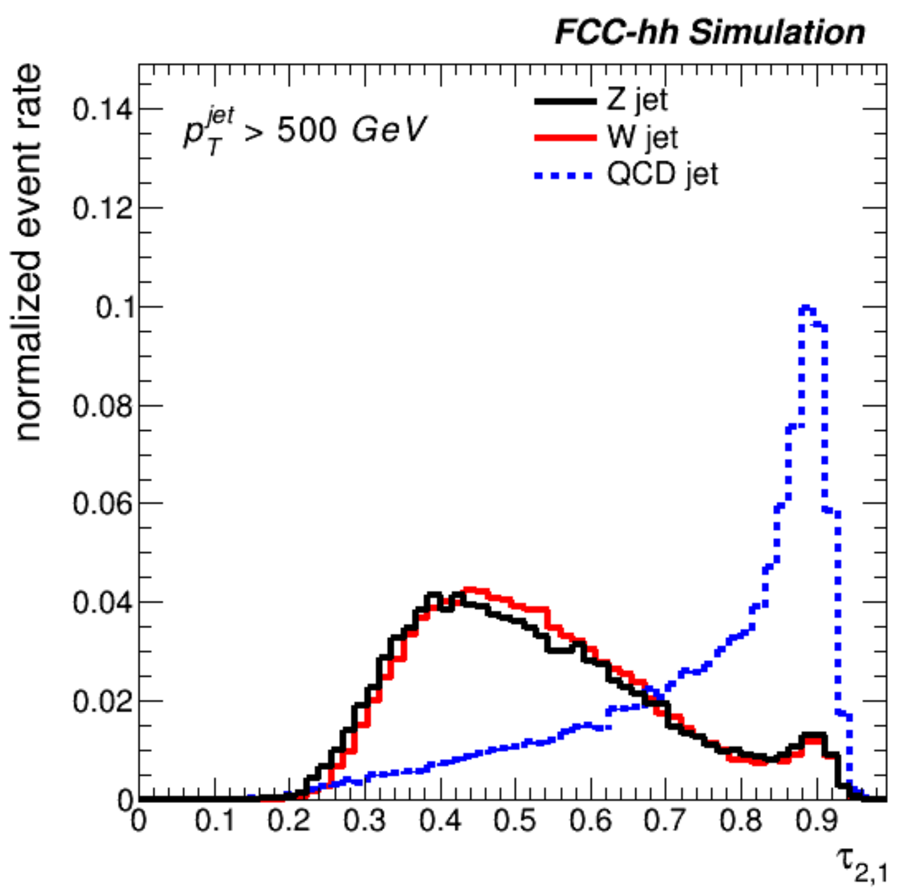
lateral (HCAL)



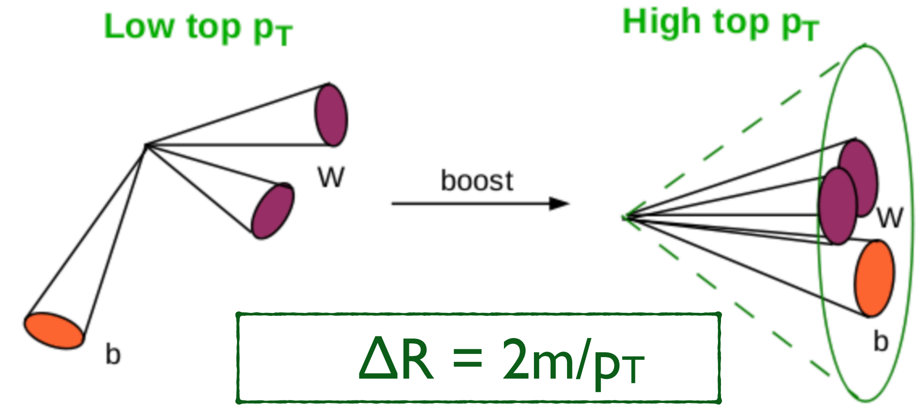
Jet substructure

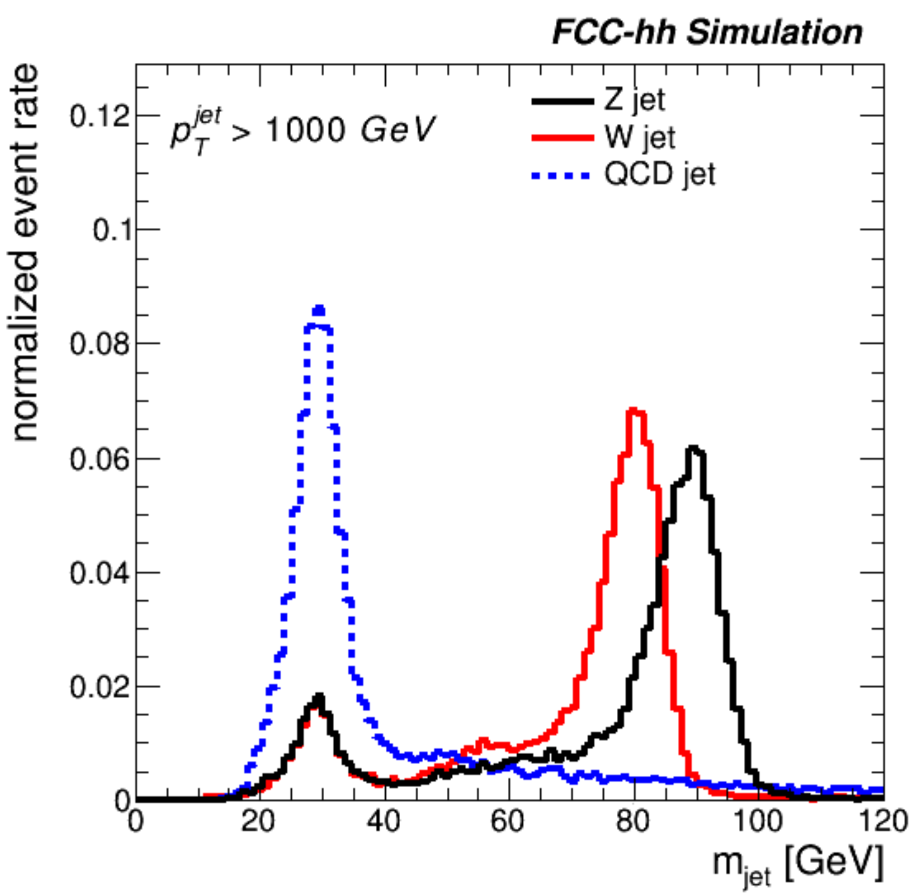


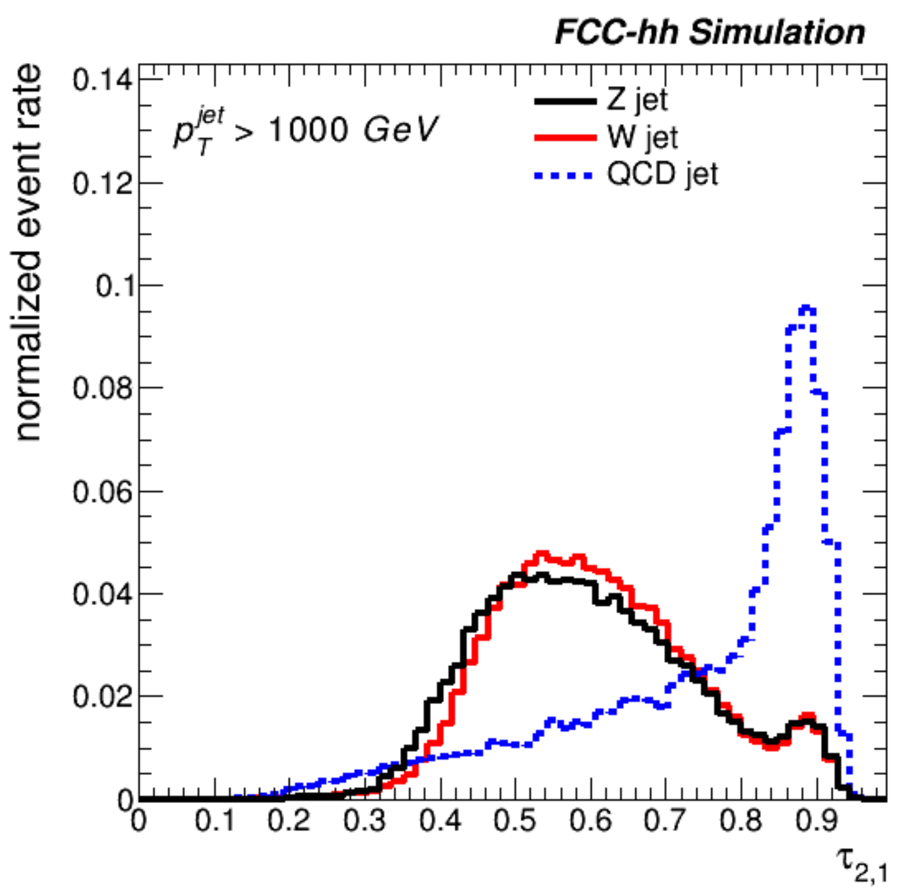




Jet substructure







- Performance good up to 1 TeV, with Calorimeter standalone, and without B field!
- Far from having explored everything possible:
  - Particle-Flow tracks and B field (decrease local occupancy) will improve
  - Machine Learning techniques will help a lot (train on 3D shower image)

100 TeV machine parameters

Table S.1: Key FCC-hh baseline parameters compared to LHC and HL-LHC parameters.

	LHC	HL-LHC	FCC-hh	
			Initial	Nominal
Physics performance and beam parameters				
Peak luminosity[1] $[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.0	5.0	5.0	< 30.0
Optimum average integrated luminosity / day $[\mathrm{fb}^{-1}]$	0.47	2.8	2.2	8
Assumed turnaround time [h]			5	4
Target turnaround time [h]			2	2
Peak number of inelastic events / crossing	27	135 levelled	171	1026
Total / inelastic cross section σ proton [mbarn]	111 / 85		153 / 108	
Luminous region RMS length [cm]			5.7	5.7
Distance IP to first quadrupole, L^* [m]	23		40	40
Beam parameters				
Number of bunches n	2808		10400	
Bunch spacing [ns]	25	25	25	
Bunch population N $[10^{11}]$	1.15	2.2	1.0	
Nominal transverse normalised emittance [µm]	3.75	2.5	2.2	2.2
Number of IPs contributing to ΔQ	3	2	2+2	2
Maximum total b-b tune shift ΔQ	0.01	0.015	0.011	0.03
Beam current [A]	0.584	1.12	0.5	
RMS bunch length[2] [cm]	7.55		8	
IP beta function [m]	0.55	0.15 (min)	1.1	0.3
RMS IP spot size [µm]	16.7	7.1 (min)	6.8	3.5
Full crossing angle [µrad]	285	590	104	200[3]

[1] For the nominal parameters, the peak luminosity is reached during the run.
[2] The HL-LHC assumes a different longitudinal distribution; the equivalent Gaussian is 9 cm.
[3] The crossing angle will be compensated using the crab crossing scheme.

MDI

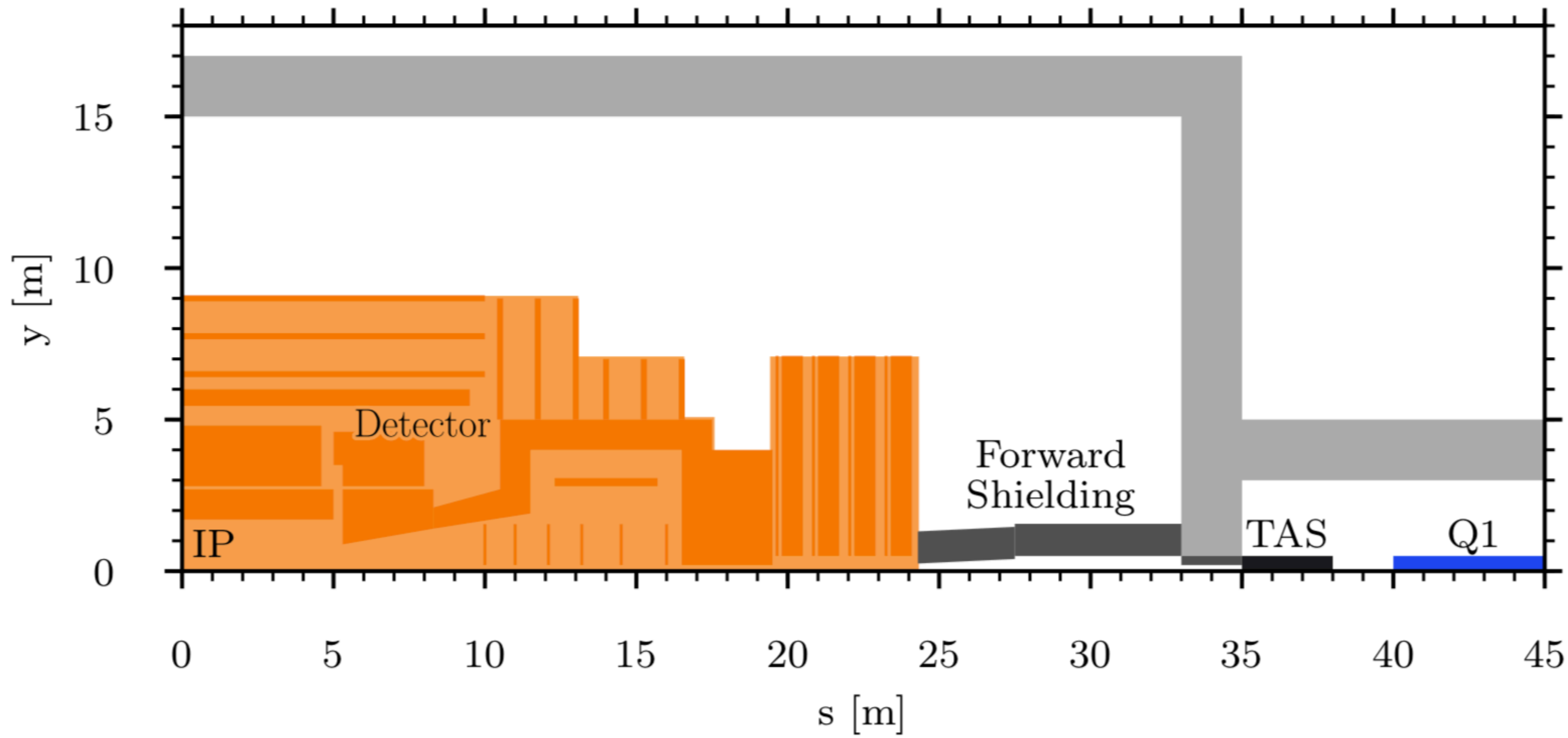


Figure 2.4: Detector region layout.

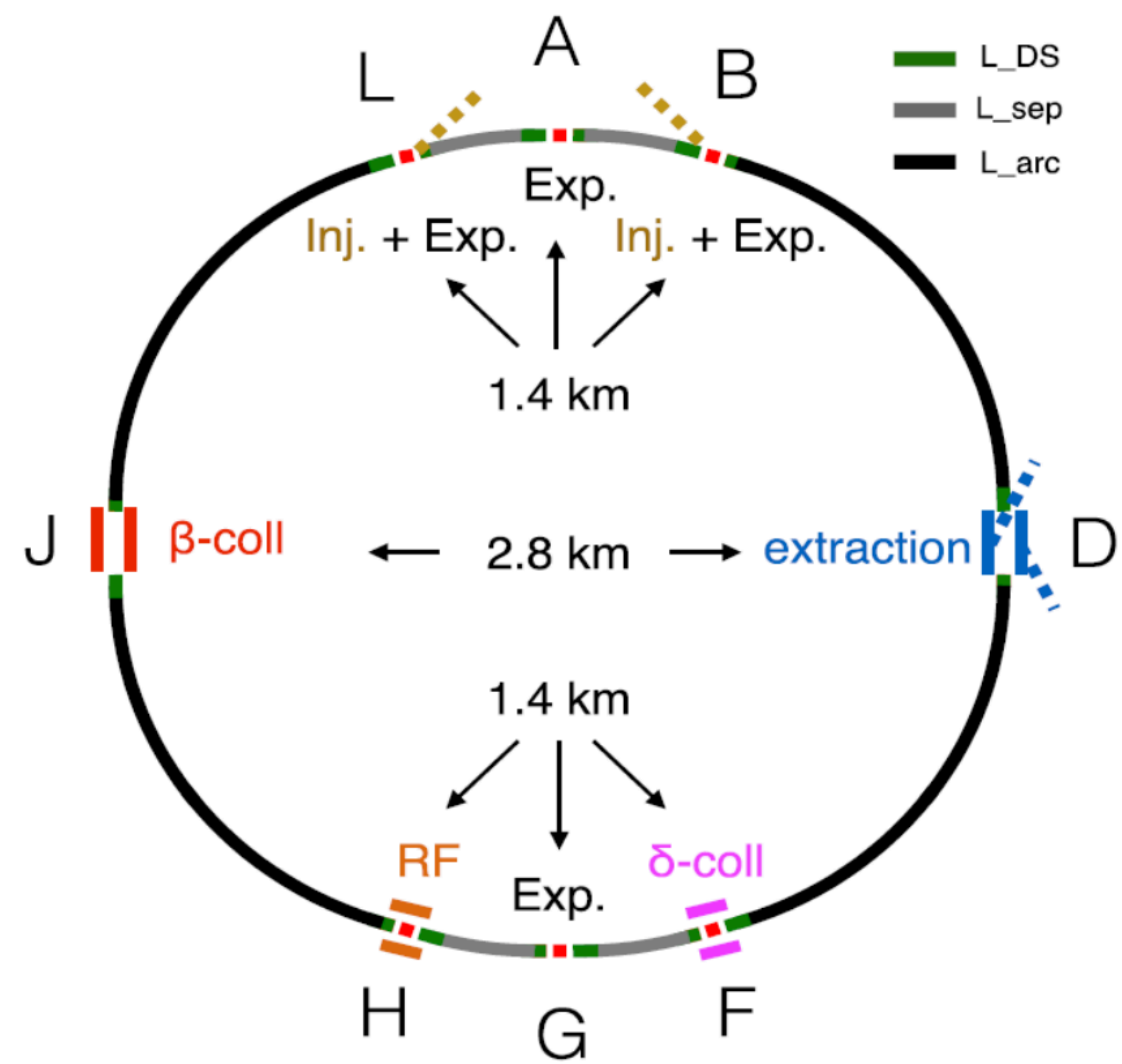
- 2m thick shielding wall to protect front of final focus system from collision debris

Possible future colliders: FCC-hh

- Circumference = 100 km
- Need dipoles that generate B = 16 T

$\sqrt{s}$ = 100 TeV

8 GJ kinetic energy per beam
- Airbus A380 at 720 km/h
- 2000 kg TNT
- O(20) times LHC

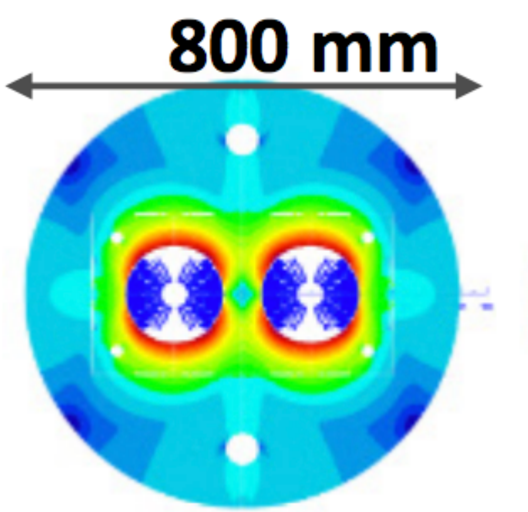


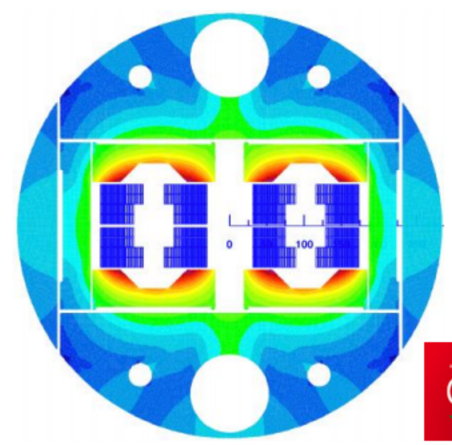
	FCC-hh Initial	FCC-hh Ultimate
Luminosity L [$10^{34}cm^{-2}s^{-1}$]	5	20-30
Background events/bx	170 (34)	<1020 (204)
Bunch distance Δt [ns]	25 (5)	
Bunch charge N [10^{11}]	1 (0.2)	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	0.03
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8 (3)	3.5 (1.6)
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

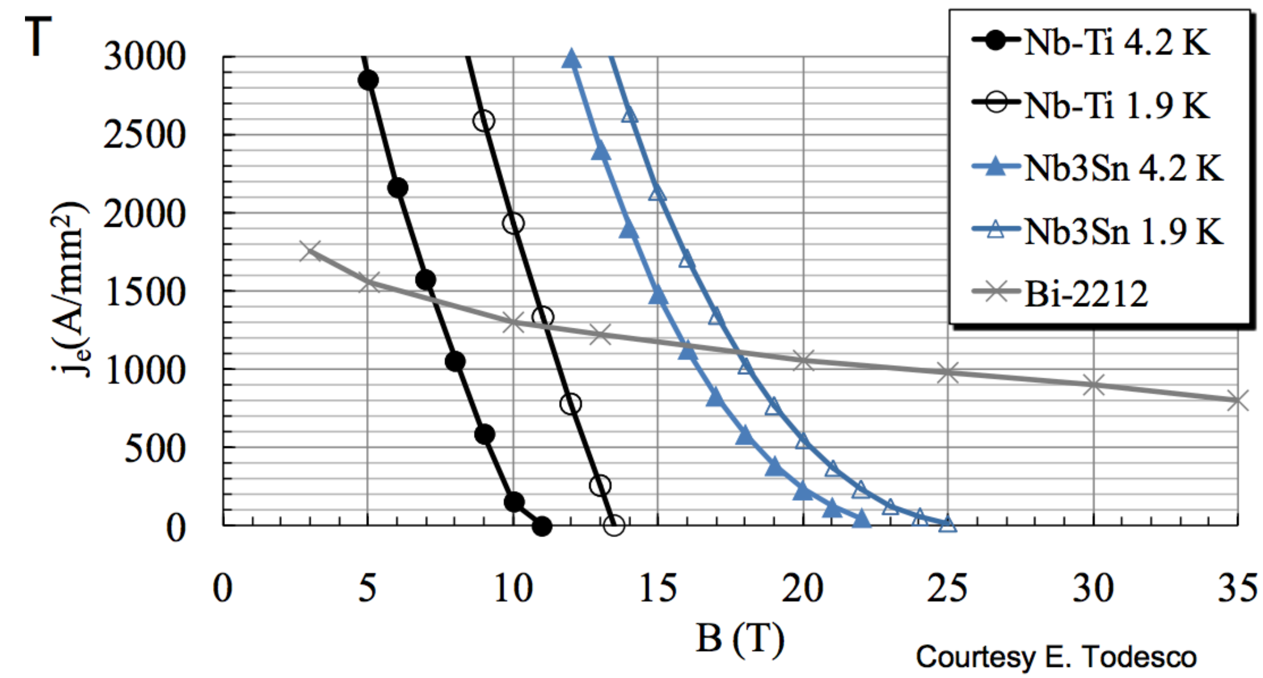
In its high luminosity phase, FCC-hh produces **1000 PU interactions** per bunch crossing

High Field Dipoles Magnets (16T)

- Nb-Ti not suited anymore (4-10T)
- Focus on Nb3Sn (also HLLHC)







Courtesy E. Todesco

Goal: Jc = 1500 A/mm² @ 4.2 K

- High Temperature Superconductors (Bi-2212) are promising, but stress sensitive, also low current density (but constant)

Many challenges:

- Need margin B ~ 20 T
- Conductor instabilities
- NbSn3 stress sensitivity …
- Cost?

How long? Manageable in ~ 15-20 yrs?

Precision vs. sensitivity

- We often talk about "**precise**" SM measurements. What we actually aim at is "**sensitive**" tests of the Standard Model, where *sensitive* refers to the ability to reveal BSM behaviours.
- **Sensitivity** may not require extreme precision. Going after "sensitivity", rather than *just* precision, opens itself new opportunities .
- For example, in the context of dim. 6 operators in EFT, some operators grow with energy:

BR measurement: $\delta O \sim \left(\frac{v}{\Lambda}\right)^2 \sim 6\% \left(\frac{\mathrm{TeV}}{\Lambda}\right)^2$ ⇒ **precision** probes large Λ

e.g. δO=1% ⇒ Λ ~ 2.5 TeV

$\sigma(p_T > X)$: $\delta O \sim \left(\frac{Q}{\Lambda}\right)^2$ ⇒ **kinematic reach** probes large Λ

e.g. δO=15% at Q=1 TeV ⇒ Λ~2.5 TeV

Reach @100TeV

$\mathscr{L}$ = integrated luminosity

L = parton luminosity

$L \sim 1/\tau^a$, $\tau = x_1 x_2 = M^2 / s$

$L \sim (s/M^2)^a$

σ (part) $\sim 1/M^2$

events = $\sigma \mathscr{L}$

$\sigma \approx \sigma$ (part) L

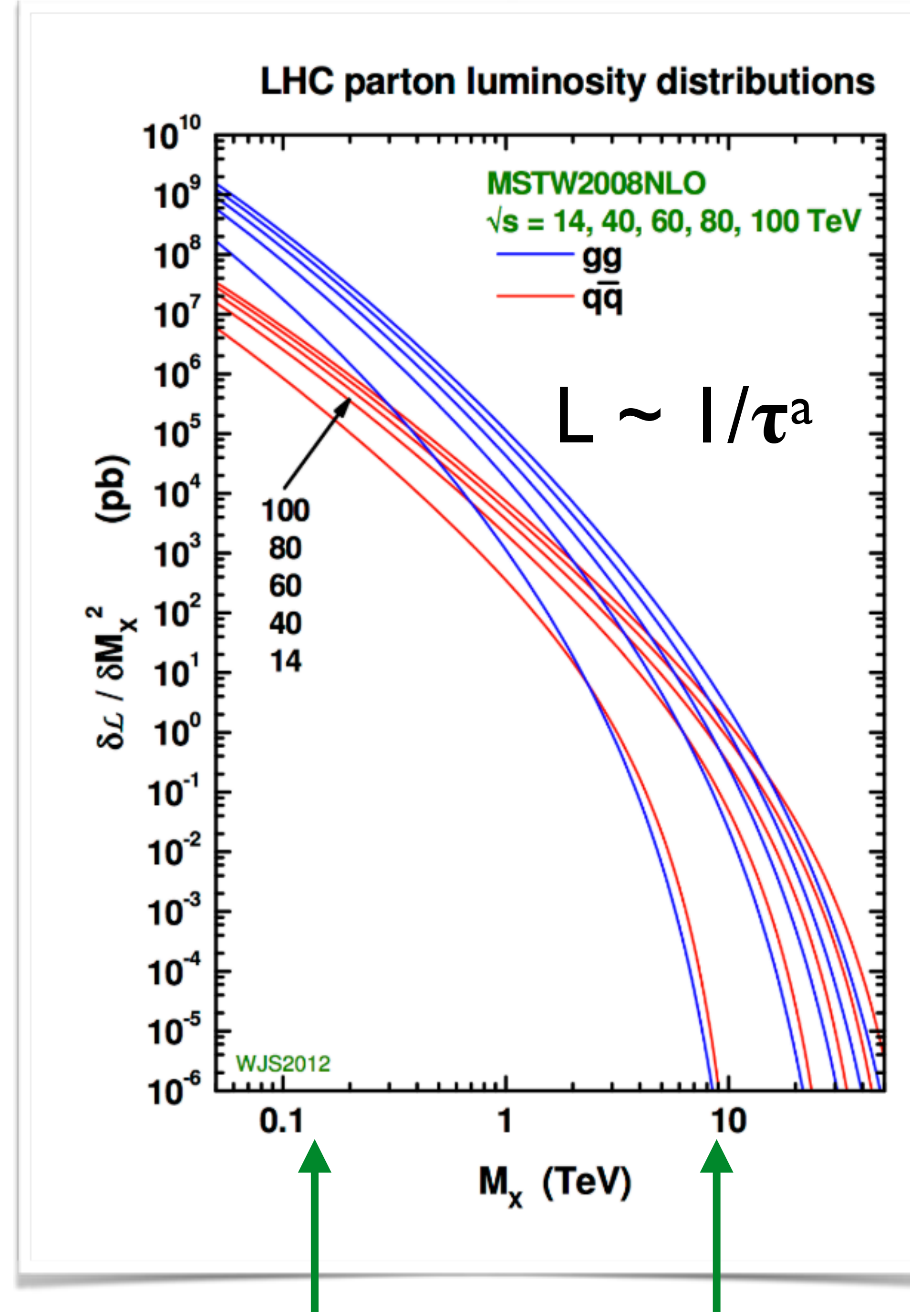
$\sigma \approx (s / M^{2+2/a})^a$

<u>Reach of collider at $\sqrt{s_1}$ vs $\sqrt{s_2}$:</u>

$(M_2 / M_1) \sim (s_2 / s_1)^{1/2} \, [(s_1/s_2)(\mathscr{L}_1/\mathscr{L}_2)]^{1/(2a+1)}$

At high mass (high x), a >> 1:

Mass reach goes up by factor 7 (roughly)

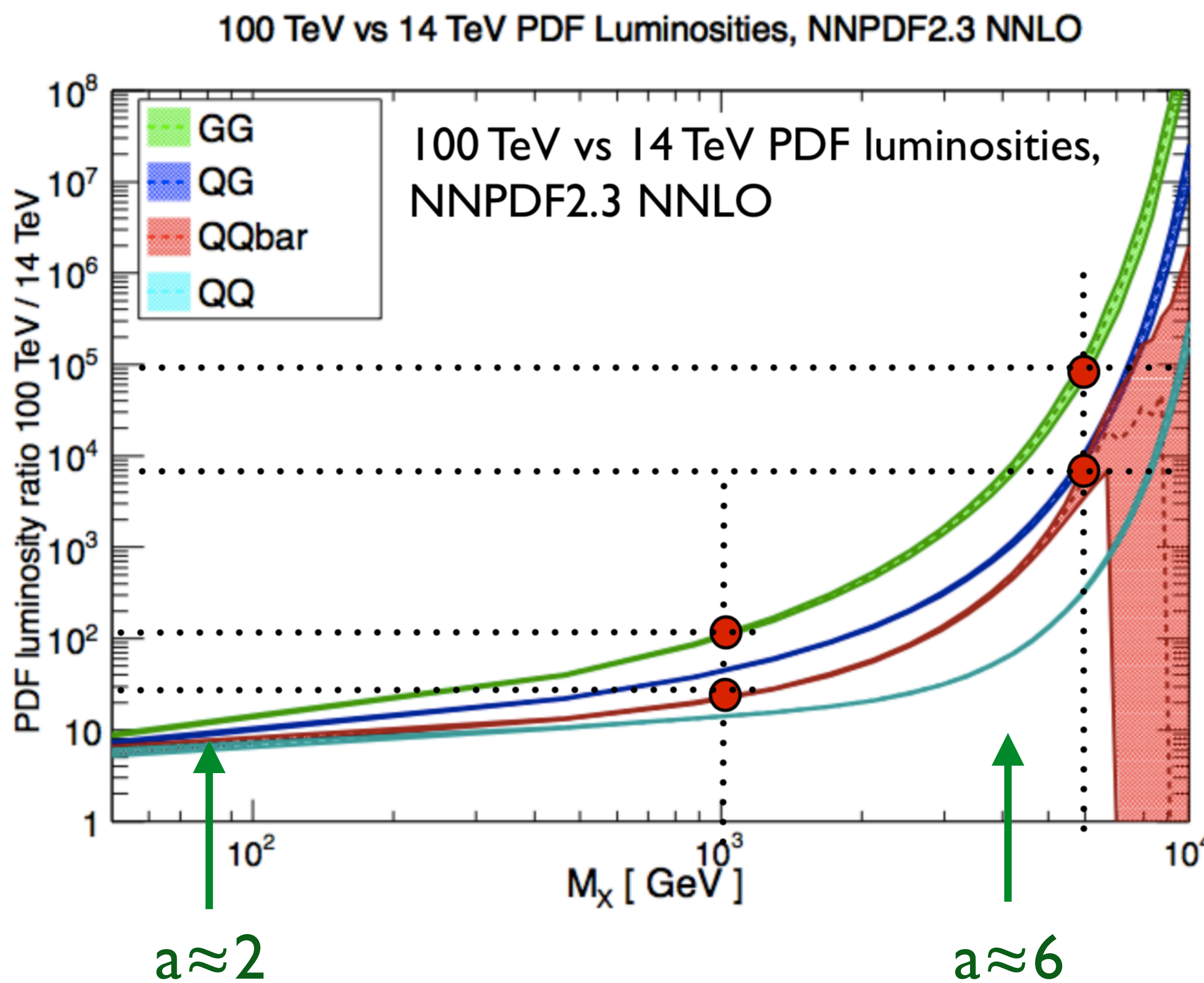


a≈2 a≈6

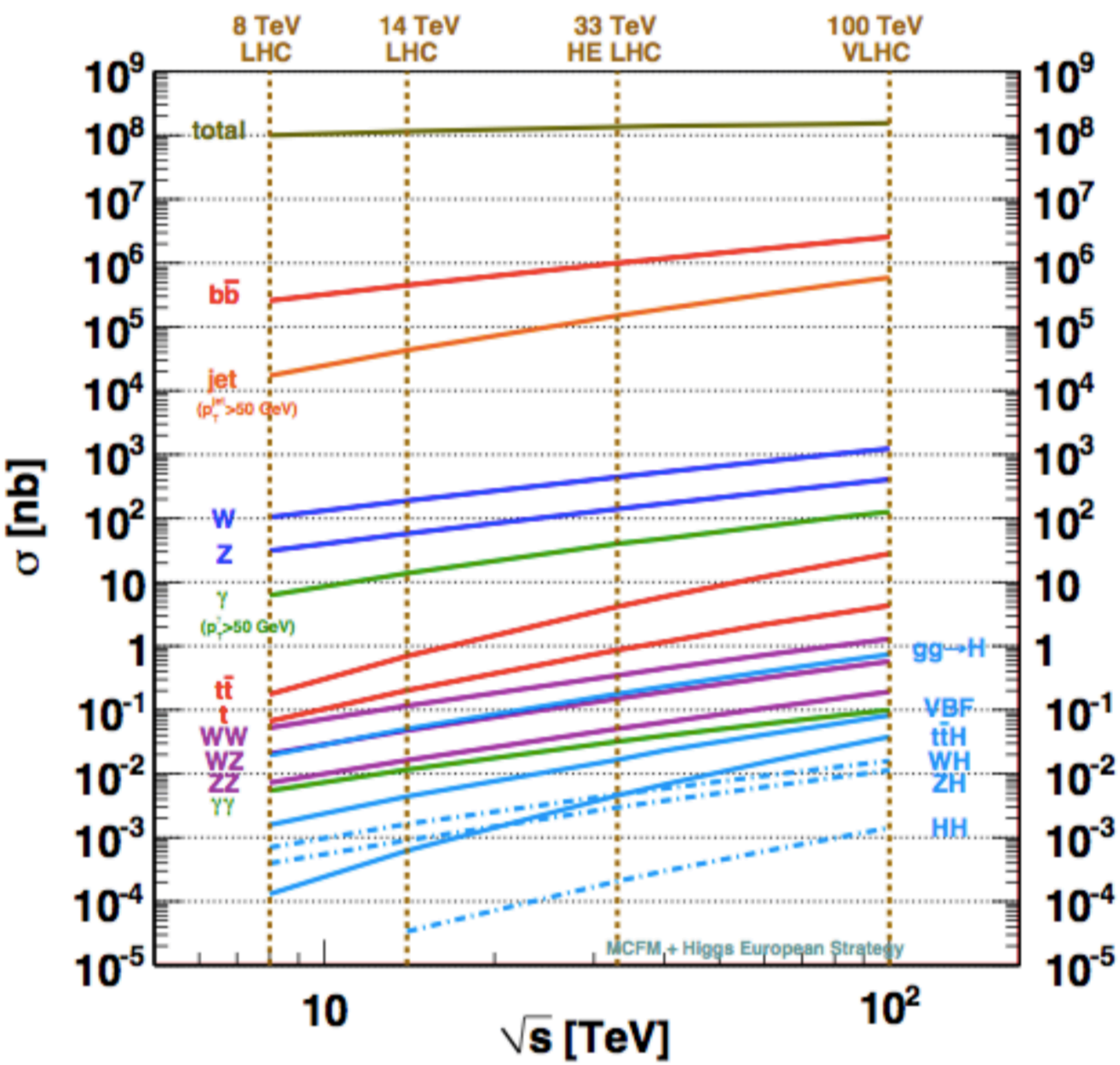
Ratio parton-luminosity

Indicates how rate of **given process** (e.g. single Higgs production) scales from 14 TeV to 100 TeV:

$$\frac{\#\text{ events }(\sqrt{s} = 100\text{ TeV})}{\#\text{ events }(\sqrt{s} = 14\text{ TeV})} \approx L_1 / L_2 \approx (s_2/s_1)^a \approx (100/14)^{2a}$$



Rates at 100 TeV

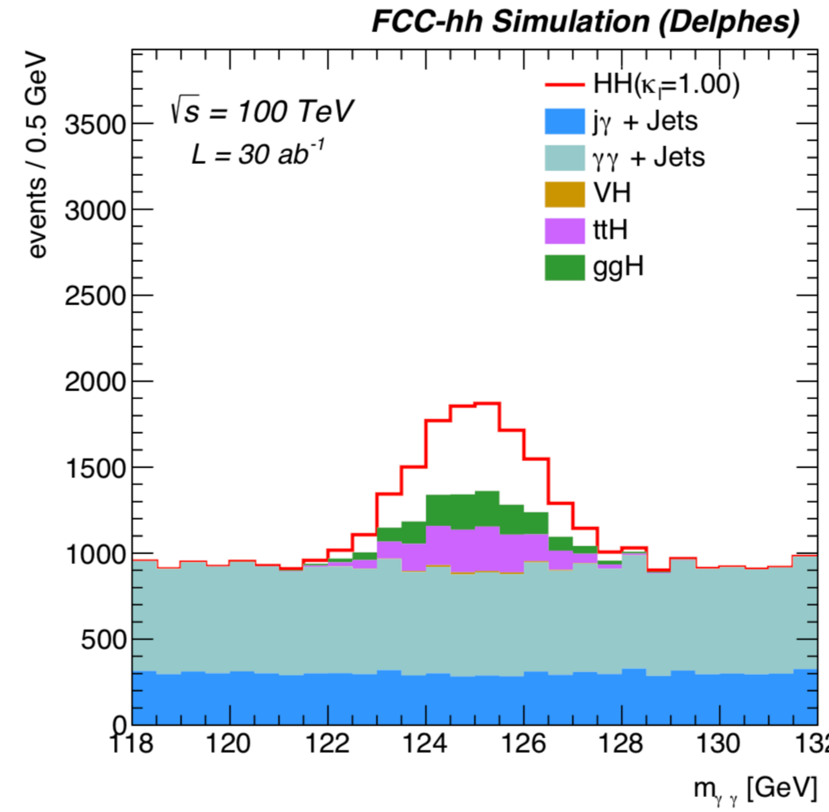


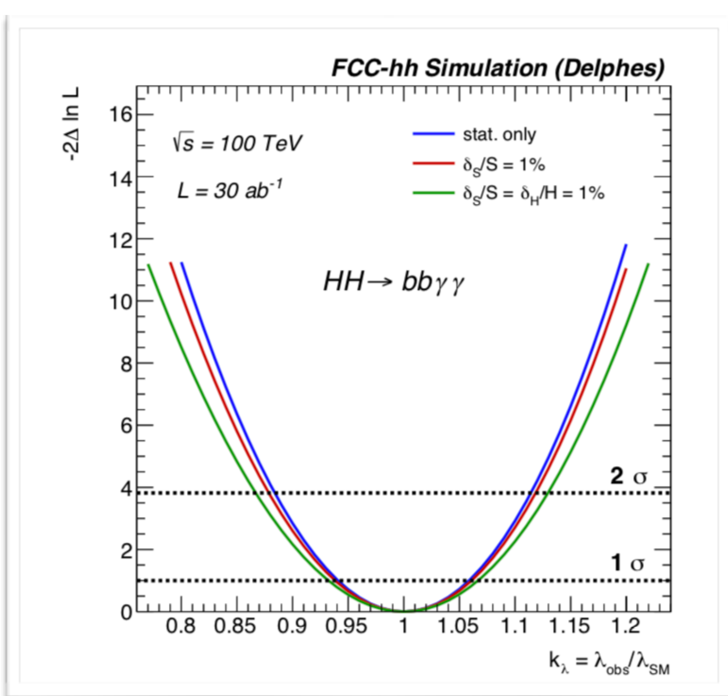
final state	$N_{ev}/10ab^{-1}$
W	10^{13}
t tbar	3×10^{11}
H	10^{10}
HH	10^{6}
jets (p_T>5 TeV)	10^{6}
jets (p_T>10 TeV)	10^{4}

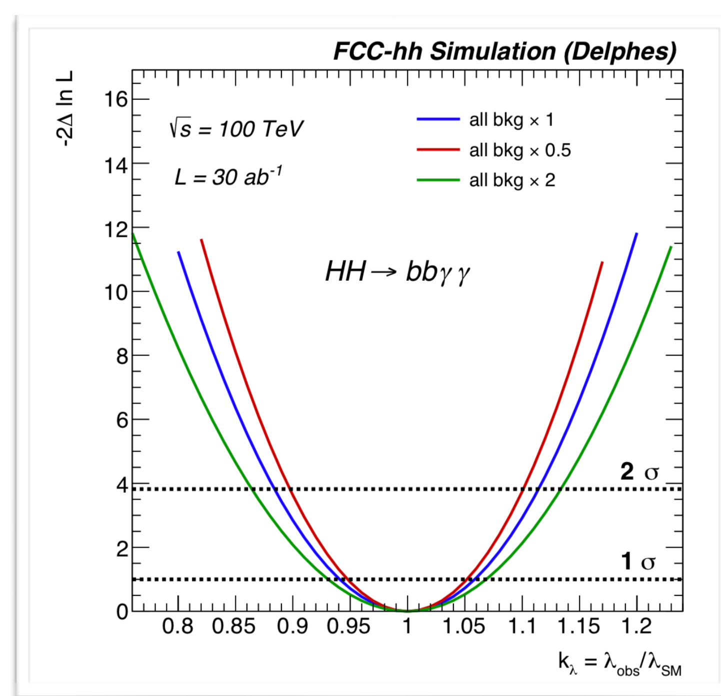
Huge statistics allow for **great potential of further exploration of SM particles** at 100 TeV

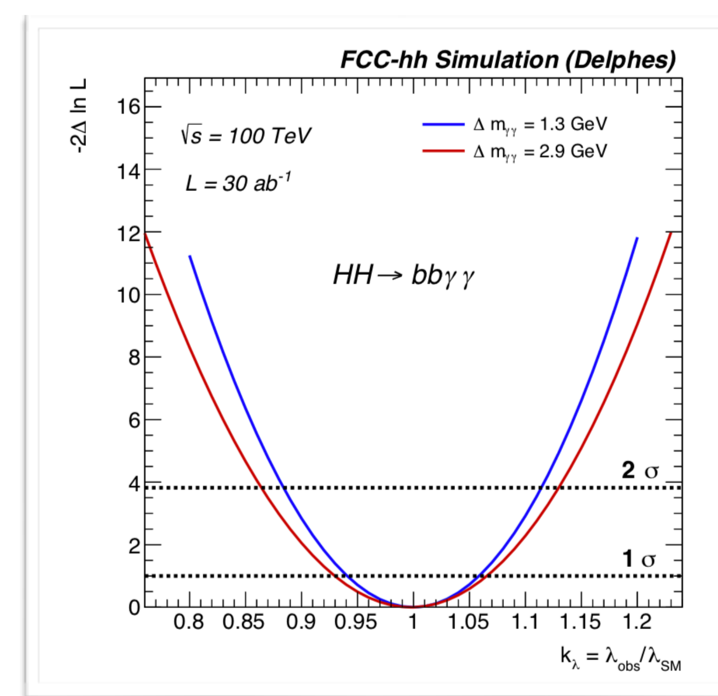
HH → bbγγ

- **Large QCD** backgrounds (jjγγ and γ+jets)
- Main difference w.r.t LHC is the very large **ttH background**
- Strategy:
  - exploit **correlation of means in ($m_{\gamma\gamma}$, m_{hh})** in signal
  - build a **parametric model in 2D**
  - perform a **2D Likelihood fit** on the coupling modifier k_λ
  - **$\delta k_\lambda / k_\lambda$ = 5-7%** (stat - stat+syst.) in this channel alone









$\delta k_\lambda / k_\lambda$ = 5 % doable by combining with other channels

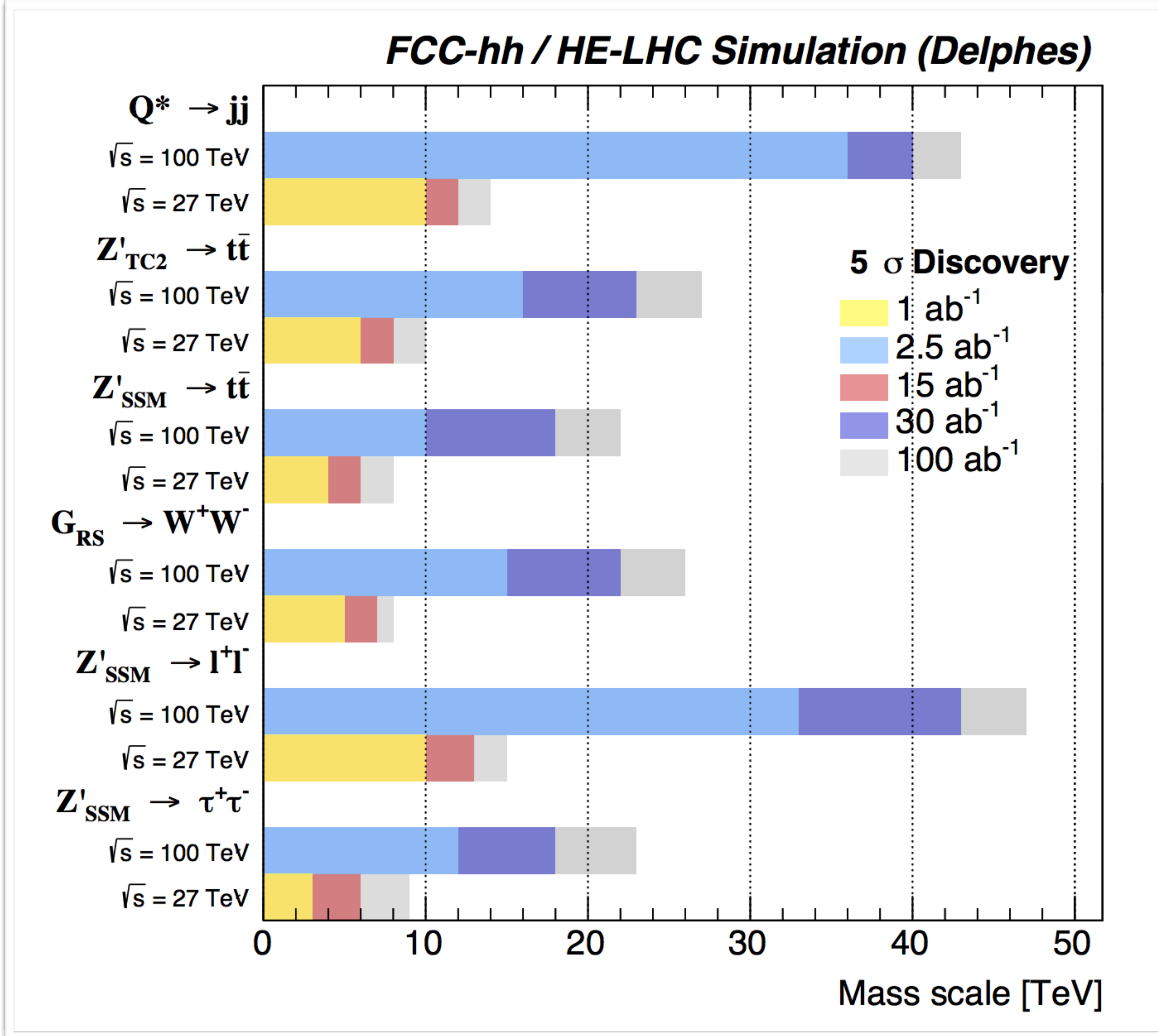
Summary direct measurements

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65 (*)**
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4 (*)**
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	–	**0.95 (**)**
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.91 (*)**
$\delta g_{HHH} / g_{HHH}$ (%)	50	~30 (indirect)	**7**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

* From BR ratios wrt B(H→4l) @ FCC-ee

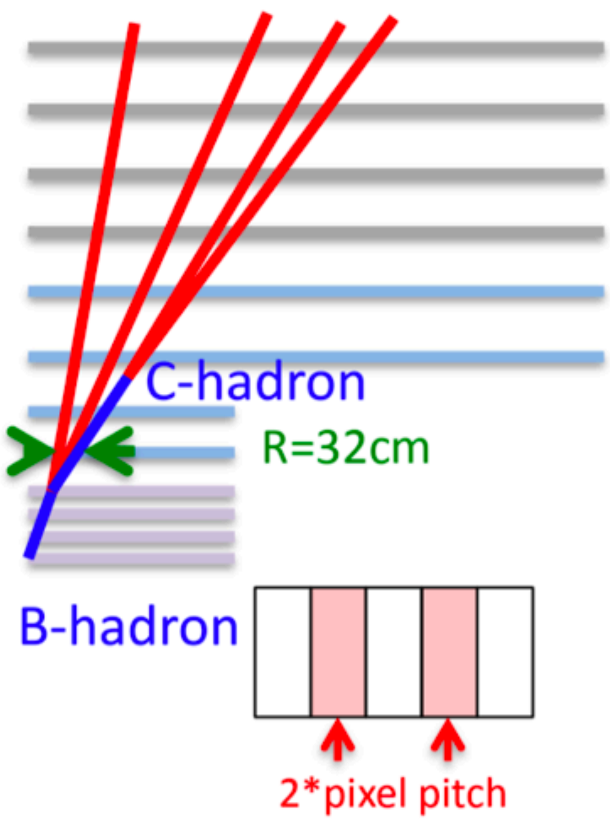
** From pp→ttH / pp→ttZ, using B(H→bb) and ttZ EW coupling @ FCC-ee

Heavy resonances @ 100 TeV



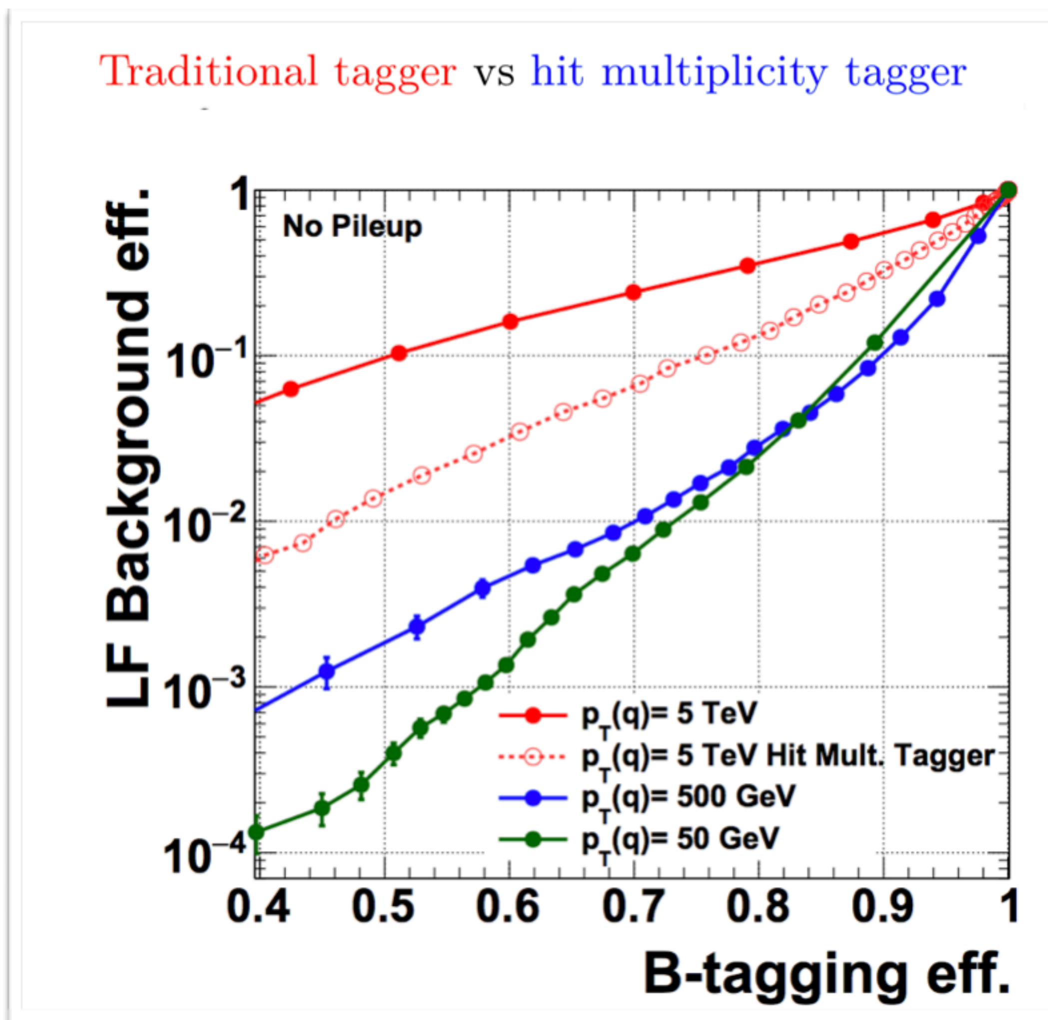
Detector requirements from high p_T searches

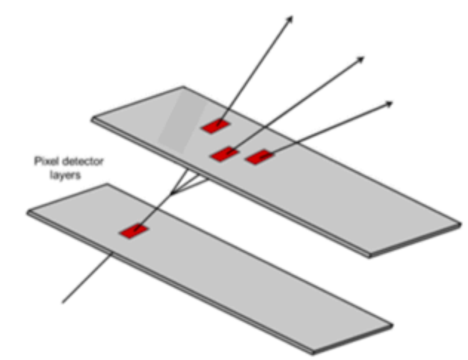
- Change in paradigm: heavy flavour tagging
- multi-TeV b-Hadrons decay outside the pixel volume
- Need to adapt identification algorithms for maintaining sensitivity in in high mass searches .



Only 71% 5 TeV b-hadrons decay < 5th layer.

- displaced vertices



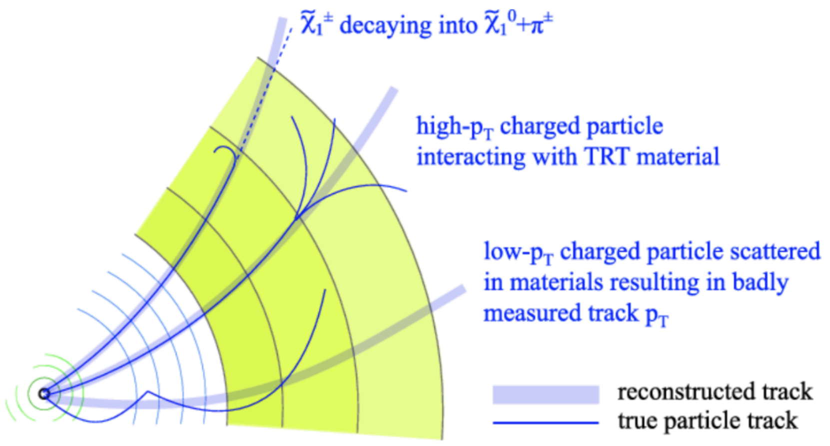


arXiv:1701:06832

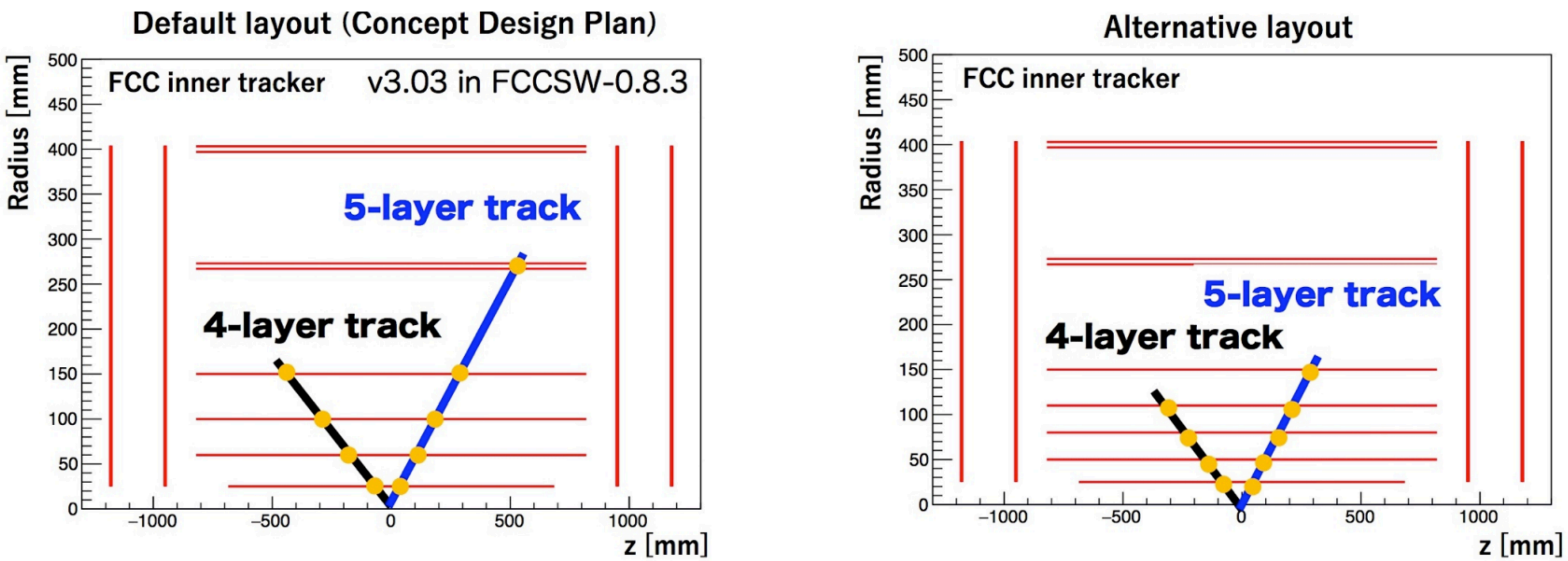
To be verified in high pile-up environment.

Disappearing Tracks

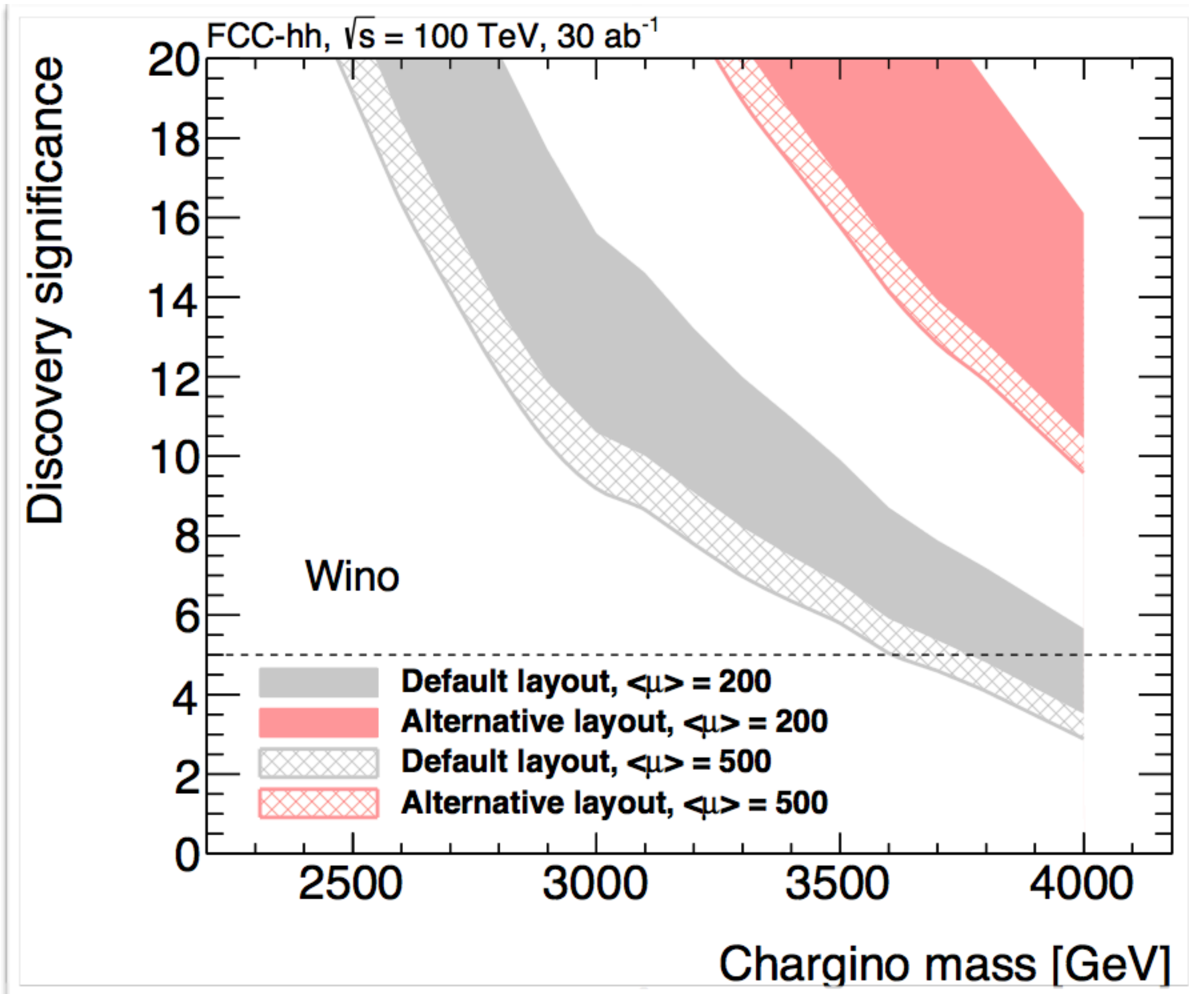
- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
- Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, cτ= 6cm(wino) 7mm(higgsino)

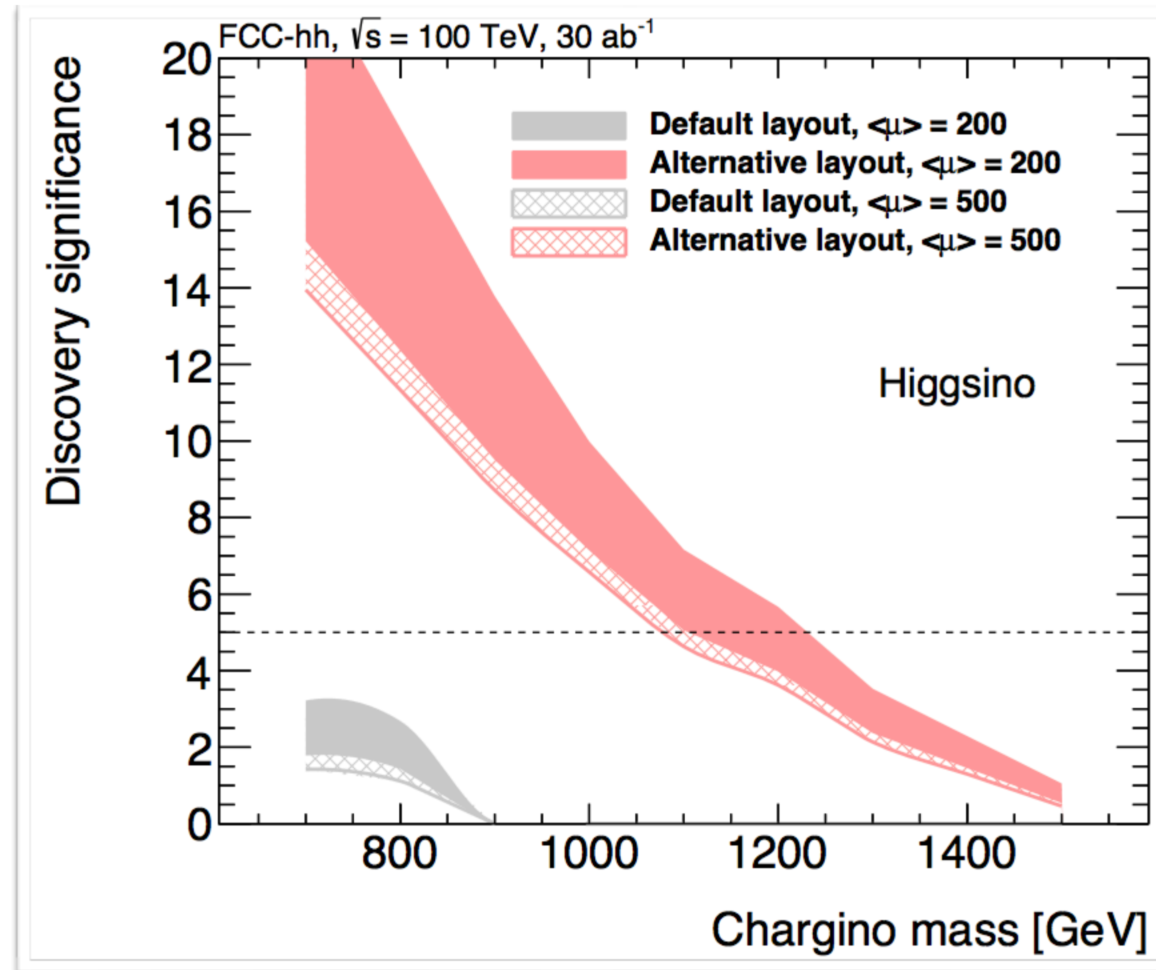


- Disappearing tracks analysis shows discovery reach beyond upper limits of MDM
- In a similar way FCC-hh can explore conclusively EW charged WIMP models, (low multiplets)



Heavy resonances @ 100 TeV





- M = 1 TeV Higgsino can be discovered
- M = 3 TeV Wino can be discovered