FCC-hh Detector: requirements and concept

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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 requirements**

- 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 **un-precendented** 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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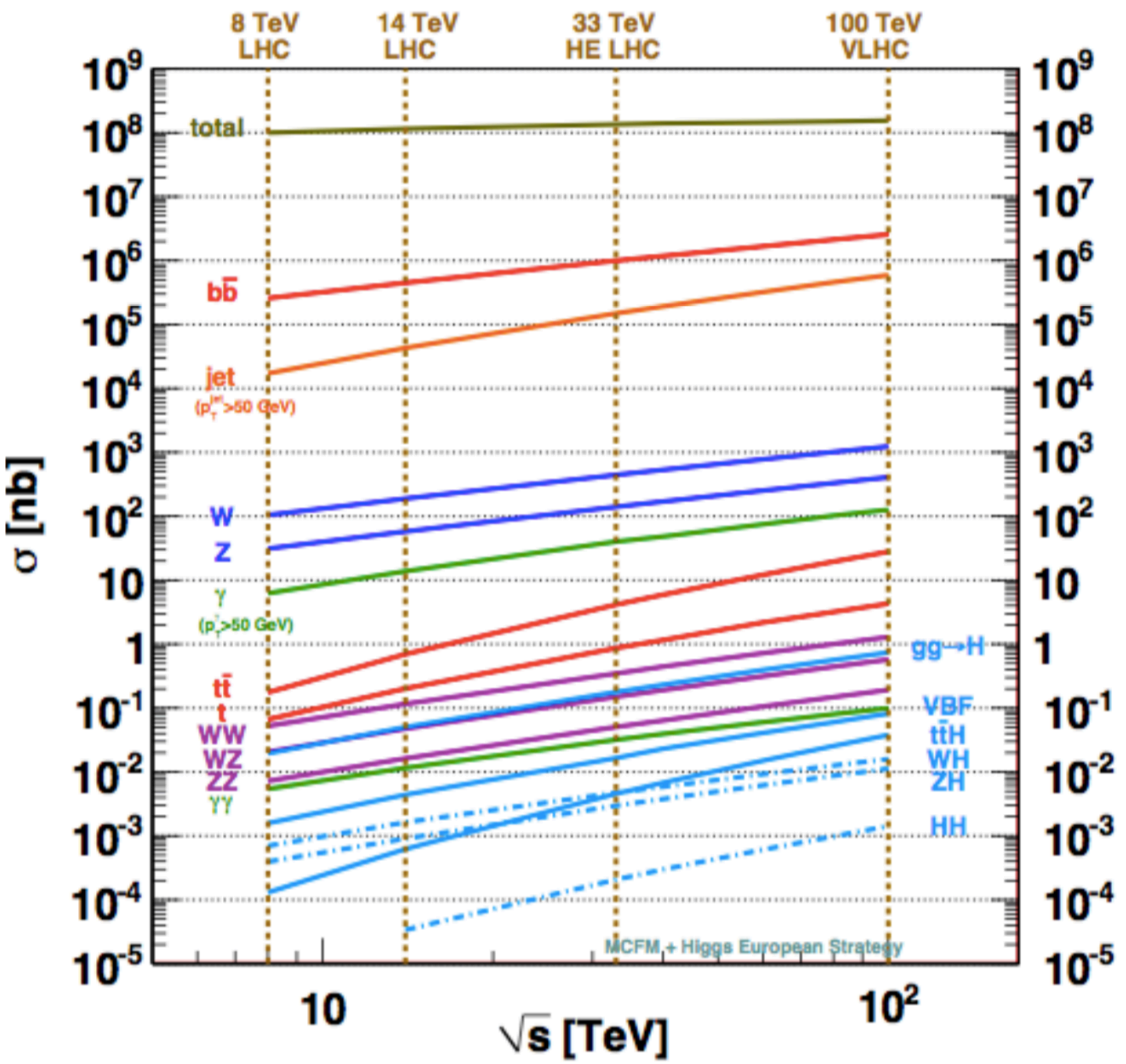
x7 LHC ?

- ## Precision machine (Higgs)
  - probe Higgs **self-coupling** to few % level
  - %-level precision for 3rd generation (top yukawa)
    - and **2nd generation (μμ, cc)**

  - exploit **complementarity with e^+e^-** by probing **high dim.operators** (EFT) in **extreme kinematic** regimes (boosted)

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

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 shows a significant increase.

→ interesting physics sticks out more !

Rate of increase from 14 TeV to 100 TeV:

- ggH x15
- HH x40
- ttH x55
- tt

→ reduction of **x10-20** statistical uncertainties

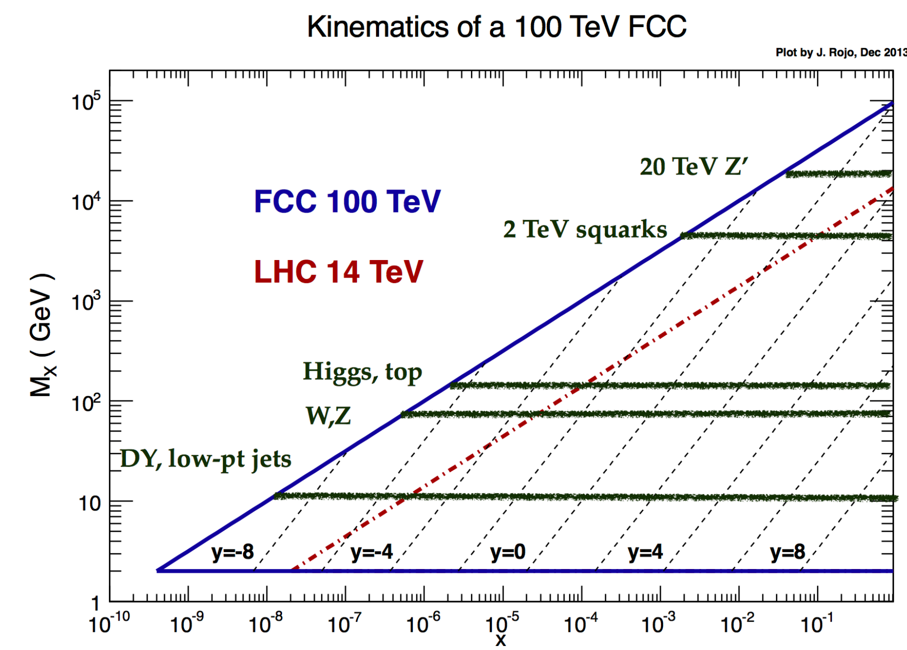
SM physics @ 100 TeV

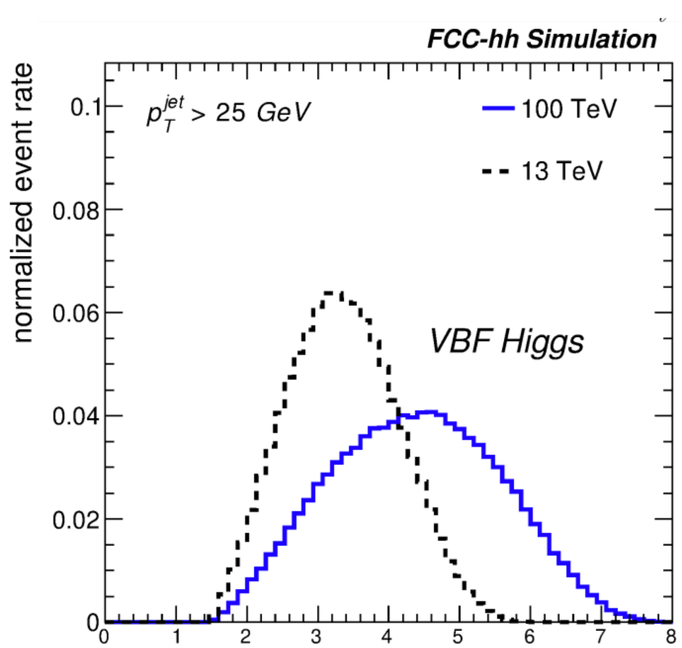
$x_1 * x_2 * s = M^2$

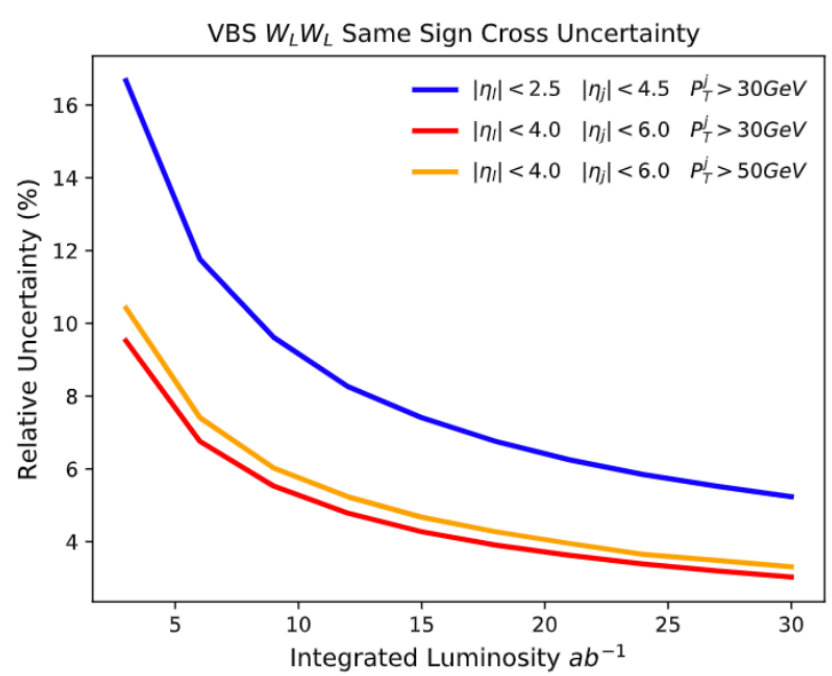
SM Physics is more forward @100TeV

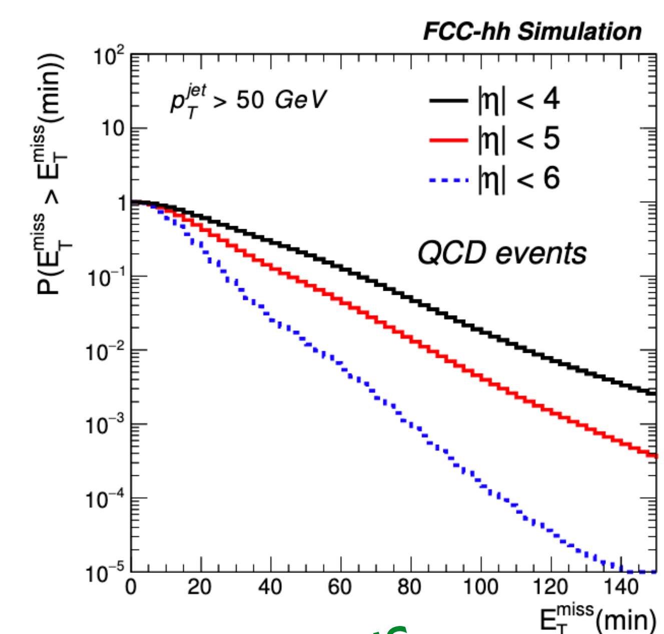
- If we want to maintain **high efficiency in states produced at threshold** need **large rapidity** (with tracking) and **low p_T** coverage

→ highly challenging levels of radiation at large rapidities





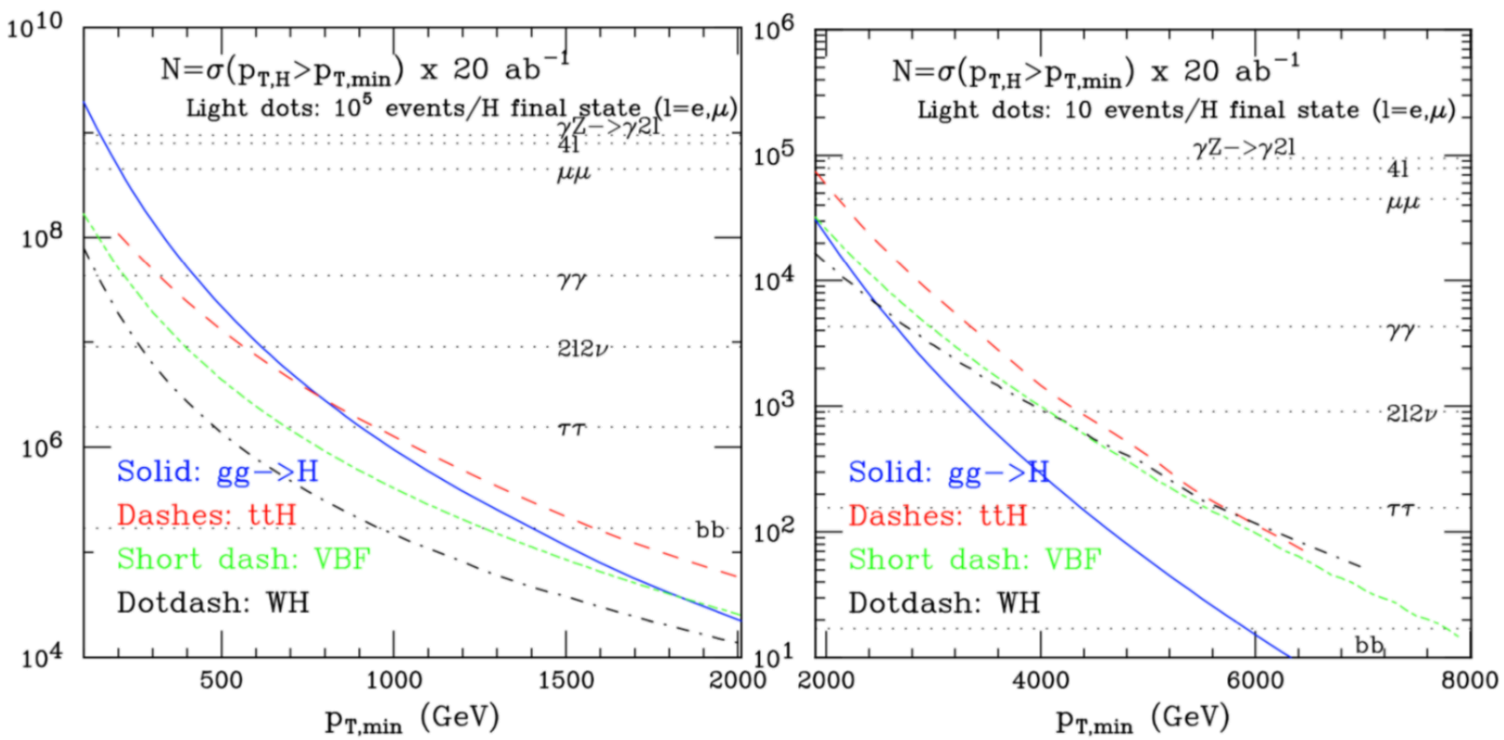




Tracking and calorimetry needed up to $|\eta| < 6$ for ~. VBF signatures

BONUS: Hermeticity E_T^{miss} resolution

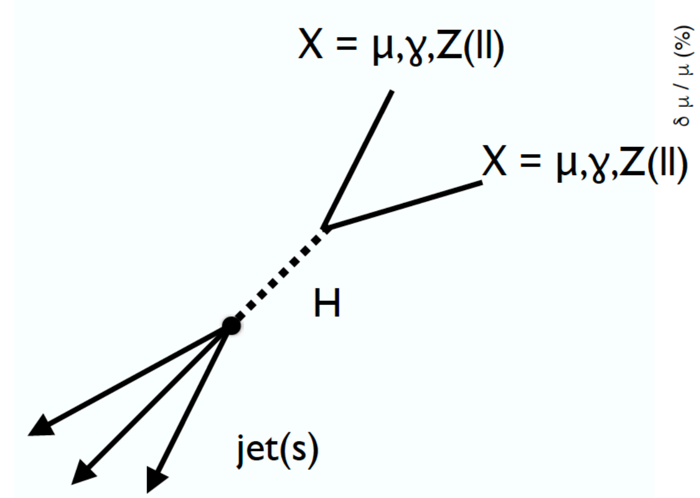
Higgs at high p_T

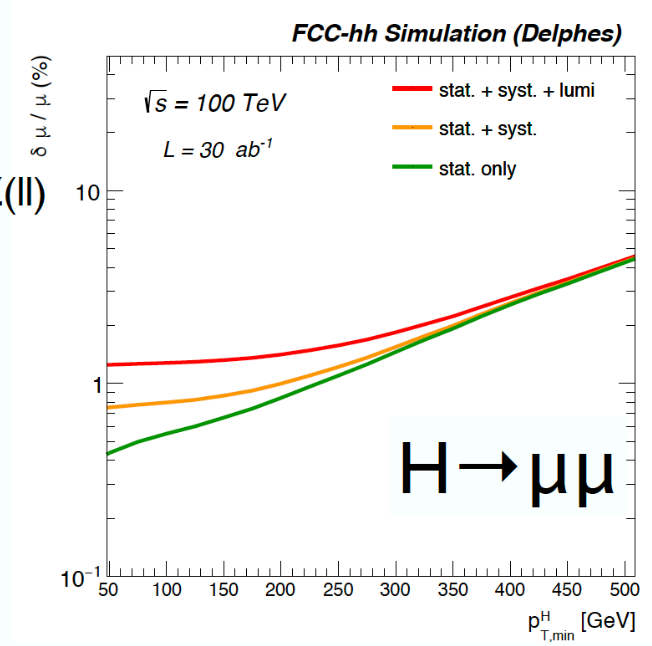


Huge rates at large p_T :
> **10^6 Higgs** produced with p_T > 1 TeV
rare decay modes can be accessed at large p_T

- Opportunity to measure the Higgs **in a new dynamical regime**
- Higgs p_T spectrum highly sensitive to new physics.

BR(H→μμ) ~ O(1-2%)
achievable up to
p_T = 200 GeV





Central Physics:

- less relative impact of PU
- smaller systematics

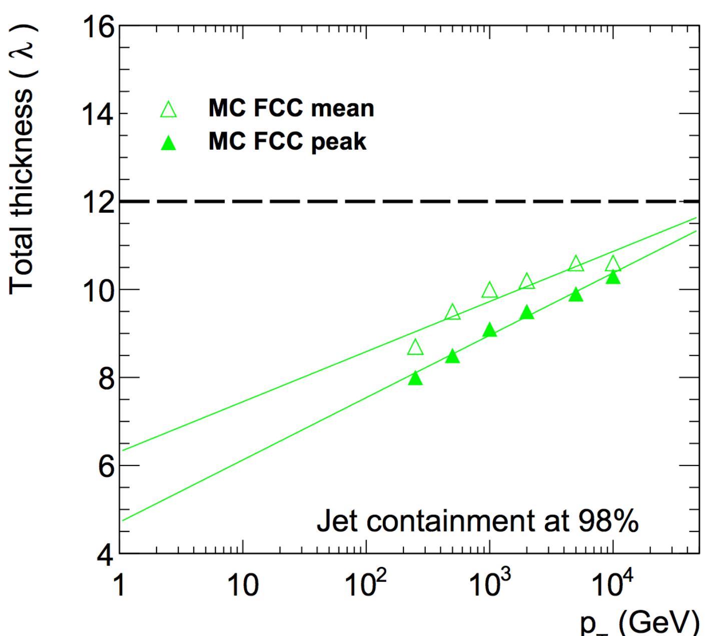
very forward coverage may not be needed here!

Physics contraints - high p_T

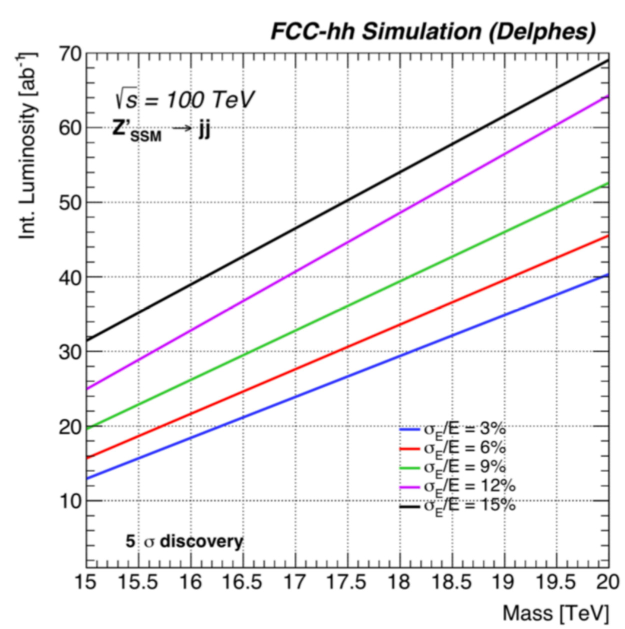
- The boosted regime:
  → measure leptons, jets, photons, muons originating ~ 40-50 TeV resonances

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

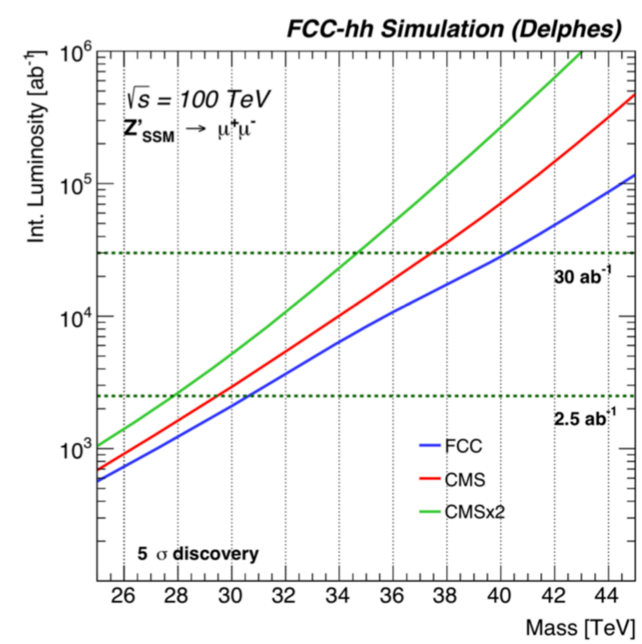
- Tracking target : **σ / p = 20% @10 TeV**
- Muons target: **σ / p = 10% @20 TeV**
- Calorimeters target: containment of p_T = 20 TeV jets



$\gtrsim 11\ \lambda_I$ for EM + Had



high p_T jets



high p_T muons

Physics contraints - high p_T

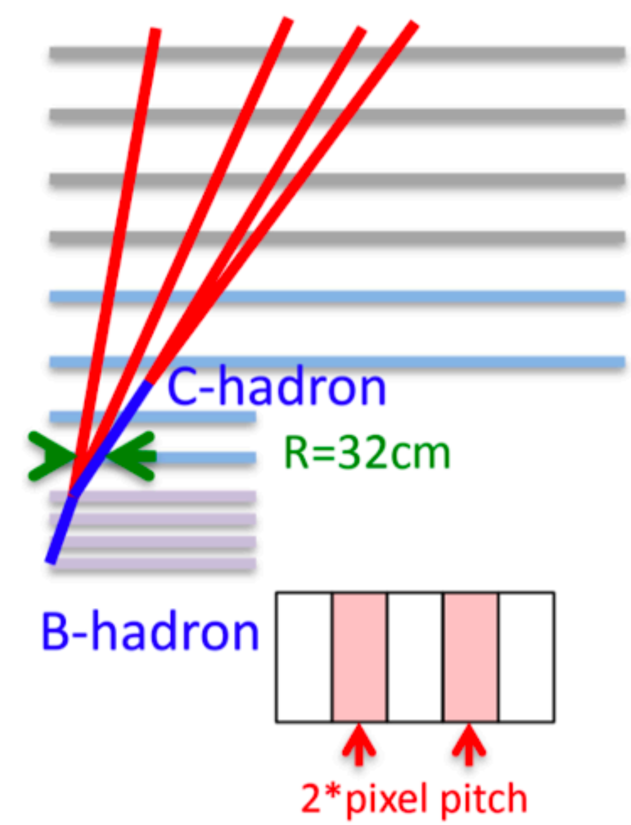
- The boosted regime:
  → measure b-jets, taus from multi-TeV resonances

- 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

Physics contraints - high p_T

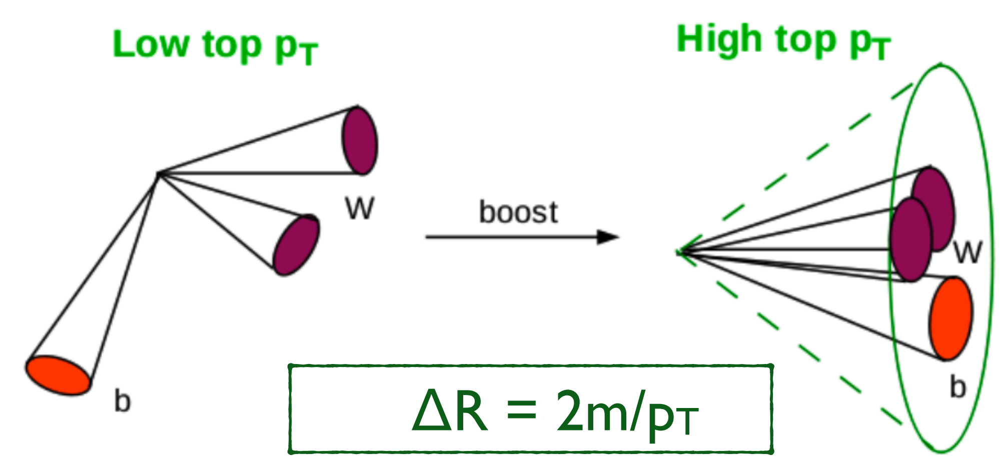
- The boosted regime:
  → measure W, H, top jets from multi-TeV resonances

  - 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 → $\sigma_{\eta\times\phi} \approx$ 5 mrad
  - Calorimeters: 2 cm @ 2m → $\sigma_{\eta\times\phi} \approx$ 10 mrad



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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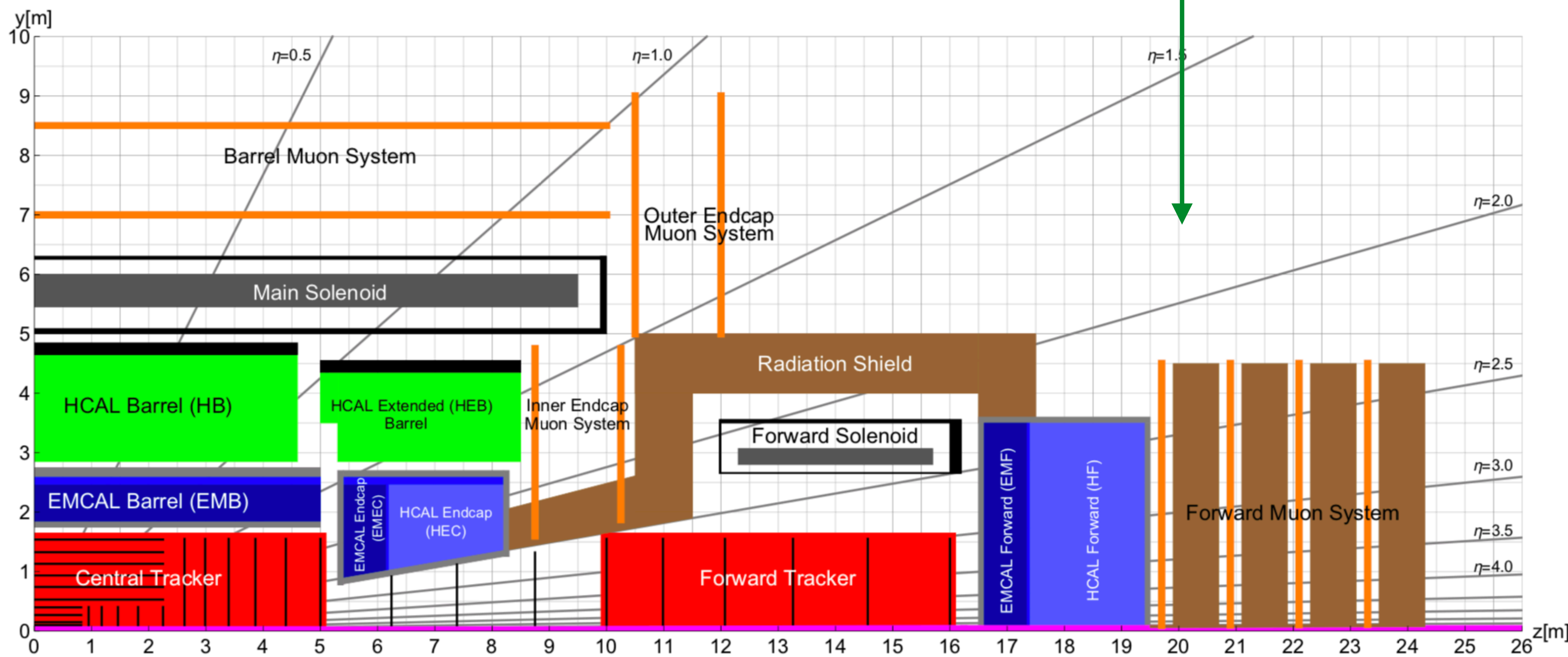
→ x50 HL-LHC

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

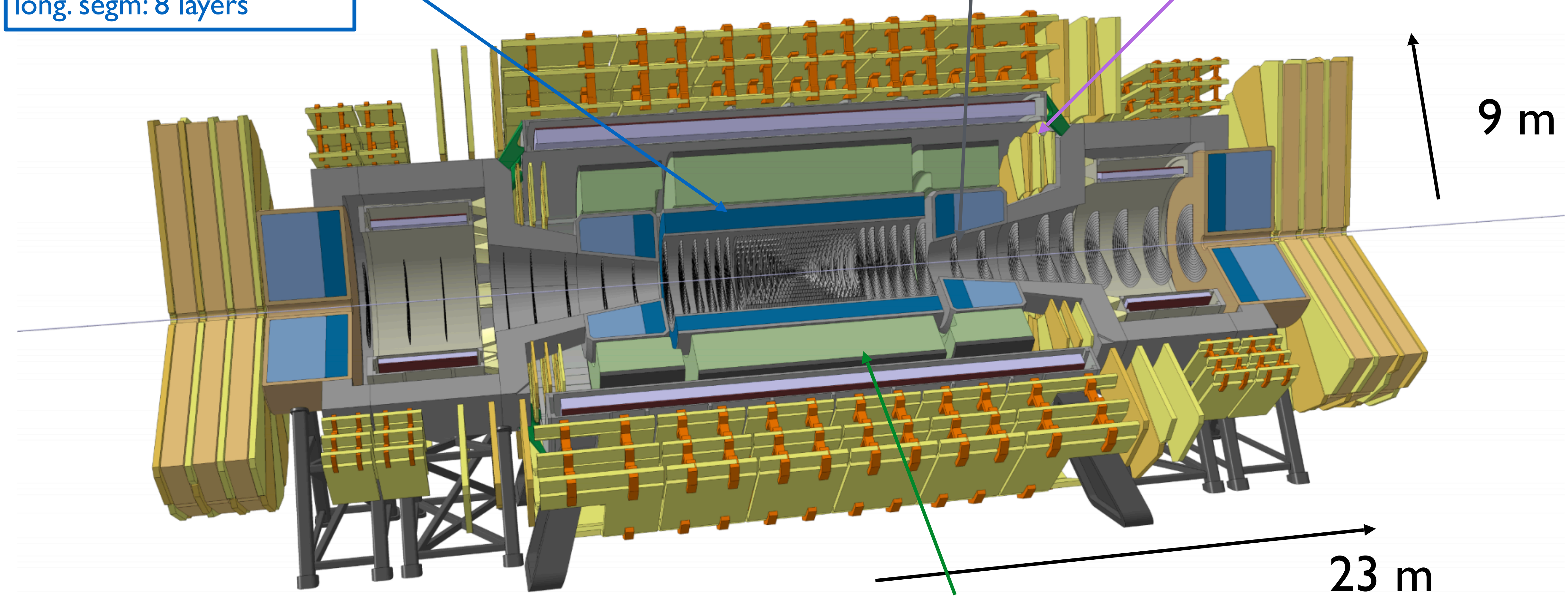


The FCC-hh detector

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

Tracker: $\sigma_{p_T}/p_T \sim 20\%$ at 10 TeV (1.5m radius)

Central Magnet + Fwd solenoids

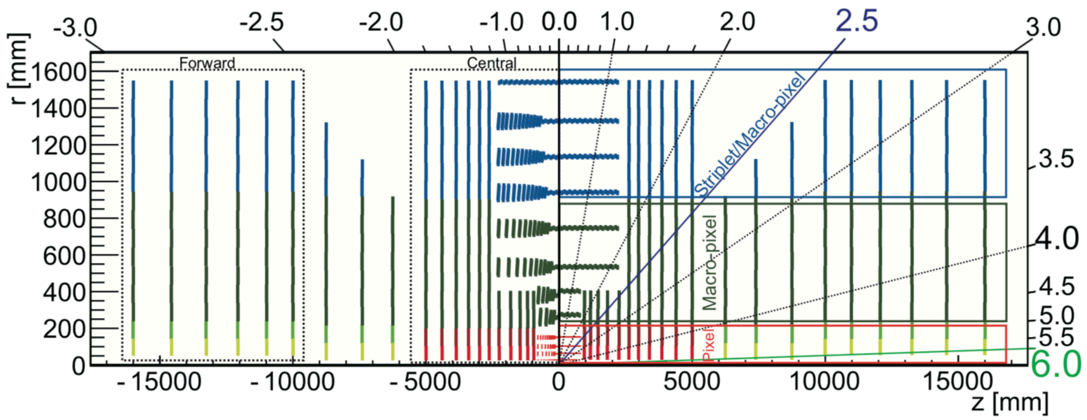


Fwd ECAL: LAr/Cu
$\sigma_E/E \sim 30\%/\sqrt{E} \oplus 1\ \%$
lat. segm: $\Delta\eta\Delta\phi \approx 0.01$
long. segm: 6 layers

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

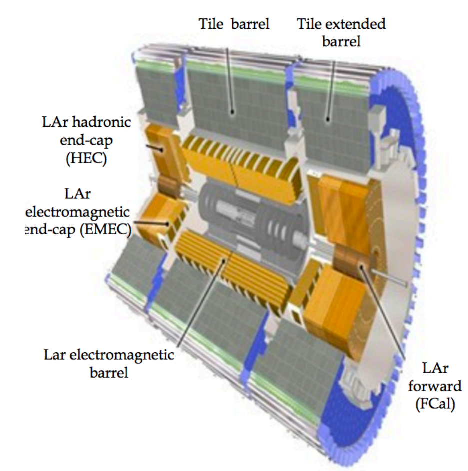
Barrel HCAL: Sci/Pb/Fe
$\sigma_E/E \sim 50\text{-}60\%/\sqrt{E} \oplus 3\ \%$
$11\ \lambda$ (ECAL+HCAL)
lat. segm: $\Delta\eta\Delta\phi \approx 0.025$
long. segm: 10 layers

An FCC-hh detector that can do the job



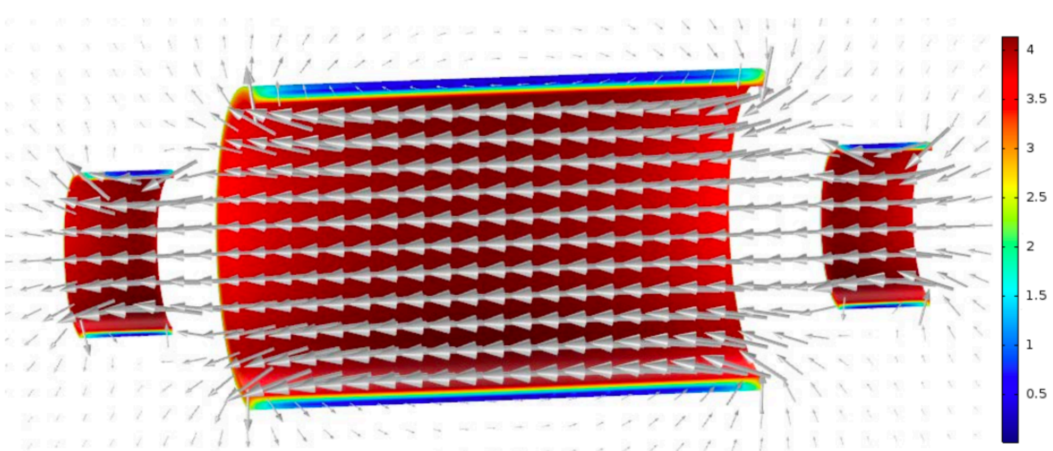
Tracker

- $-6 < \eta < 6$ coverage, 20-40% total X/X_0
- 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)

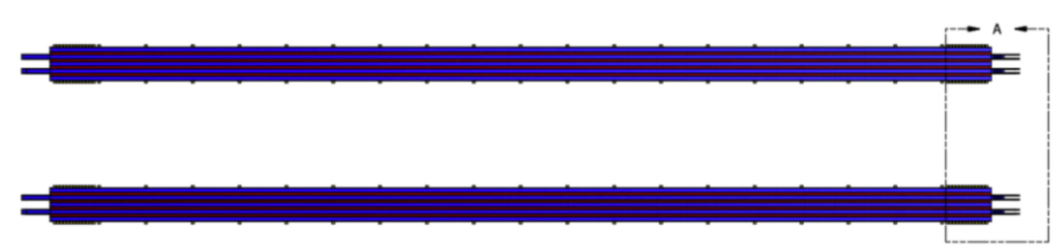


Magnet

- central R = 5, L = 10 m, B = 4T
- forward R = 3m , L = 3m , B = 3.5T

Muon spectrometer

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



Radiation tolerance

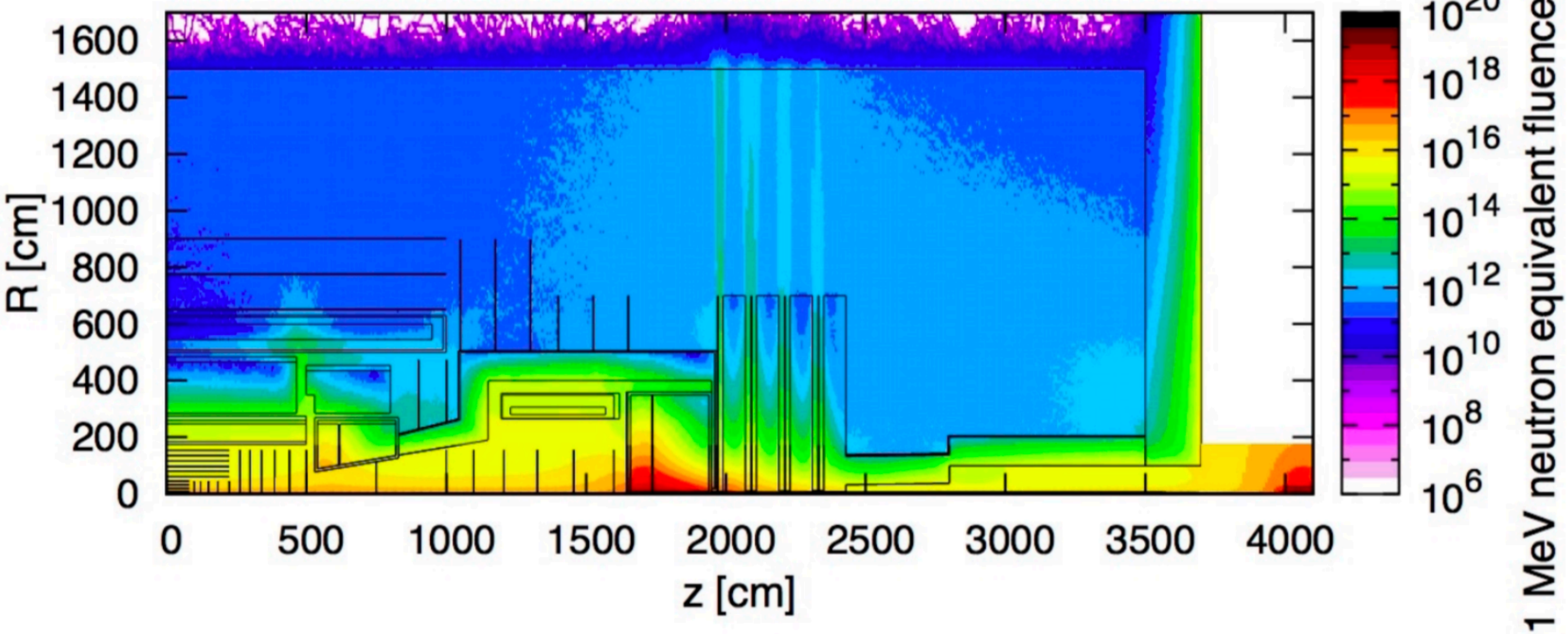
Tracker:

first IB layer (2.5 cm): $\sim 6 \cdot 10^{17} \text{cm}^{-2}$

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

HL-LHC rad. tolerance limit @ R=27 cm: $\sim 10^{16} \text{cm}^{-2}$

external part: $\sim 5 \cdot 10^{15} \text{cm}^{-2}$



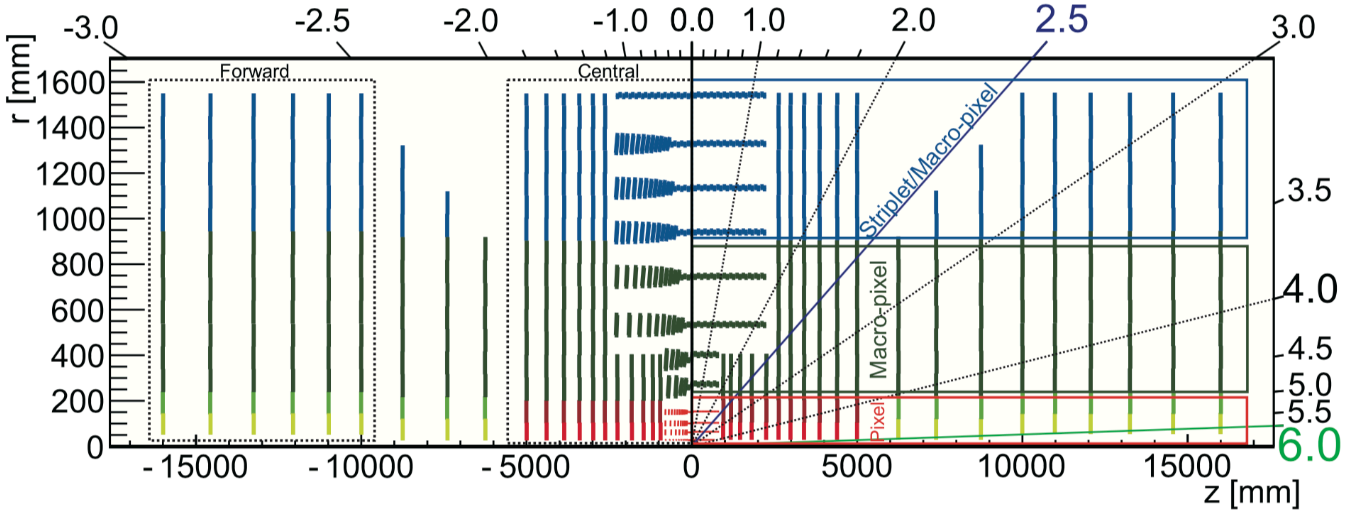
Forward calorimetry:

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

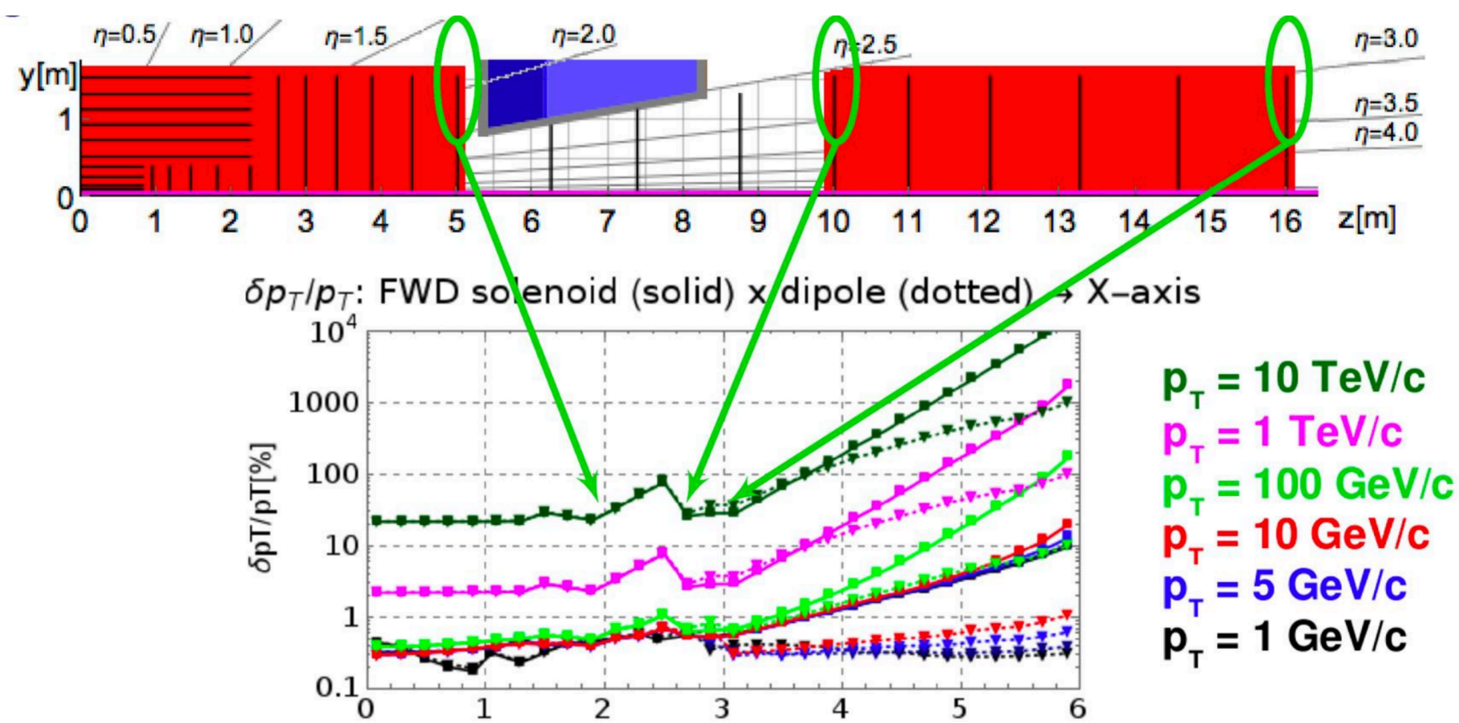
- A hadron fluence > 10^{16} cm^{-2} is very challenging for silicon sensors
- This limit is reached already @ 27 cm from the beam pipe
- Dedicated R&D needed to push the limit of radiation hardness (LHCb Upgrade II)

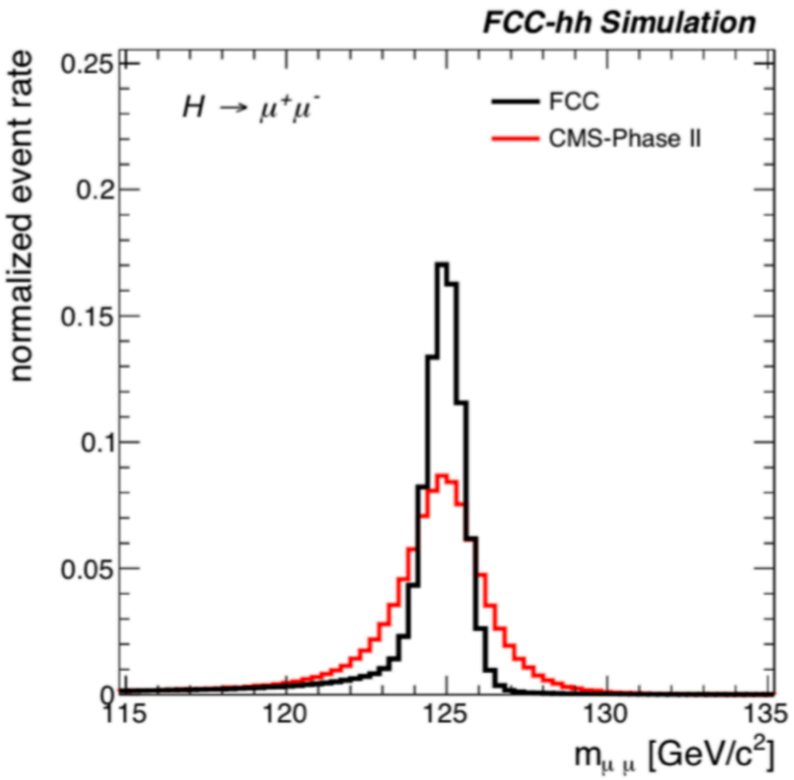
Tracker

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



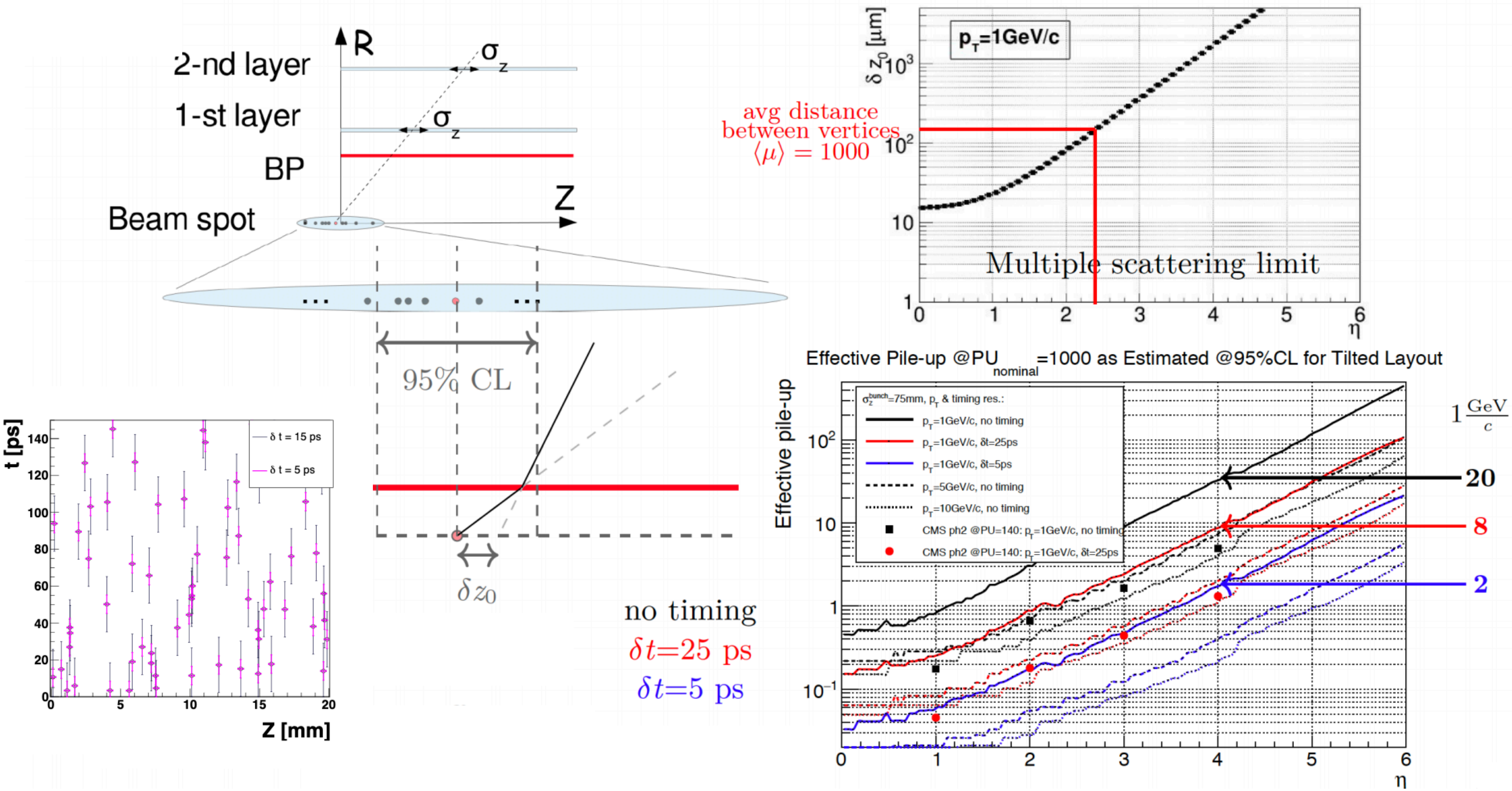
- Tilted geometry with inclined modules:
  - minimize effect of Multiple scattering (low material)
  - helps with pattern recognition





low p_T muons → resolution dominated by MS

Pile-up rejection

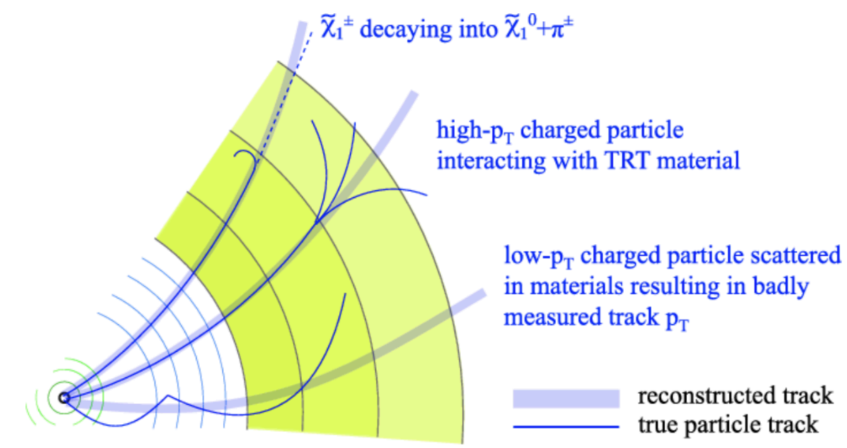


With PU density = 8 mm^{-1} need δz_0 ~ 100 μm resolution in track longitudinal impact parameter

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

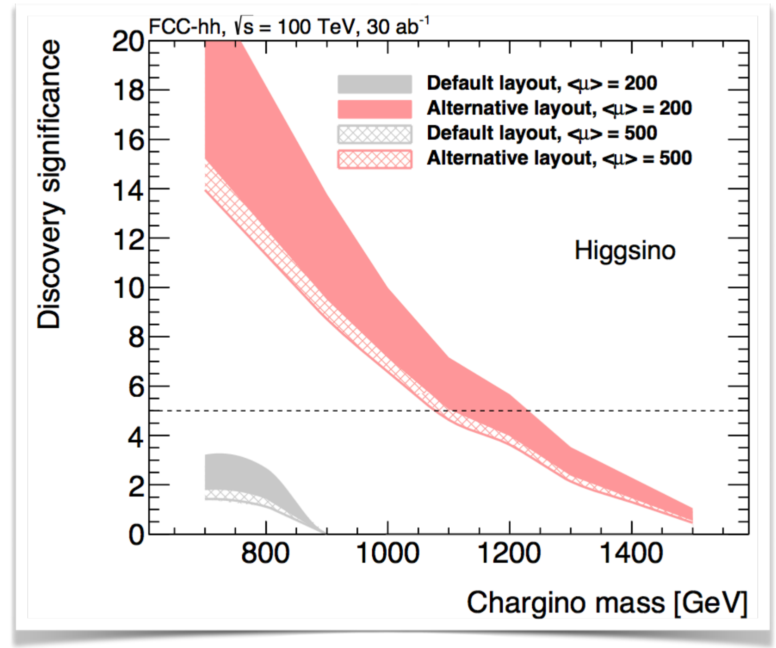
High resolution (~ 5-10 ps) timing information needed !!

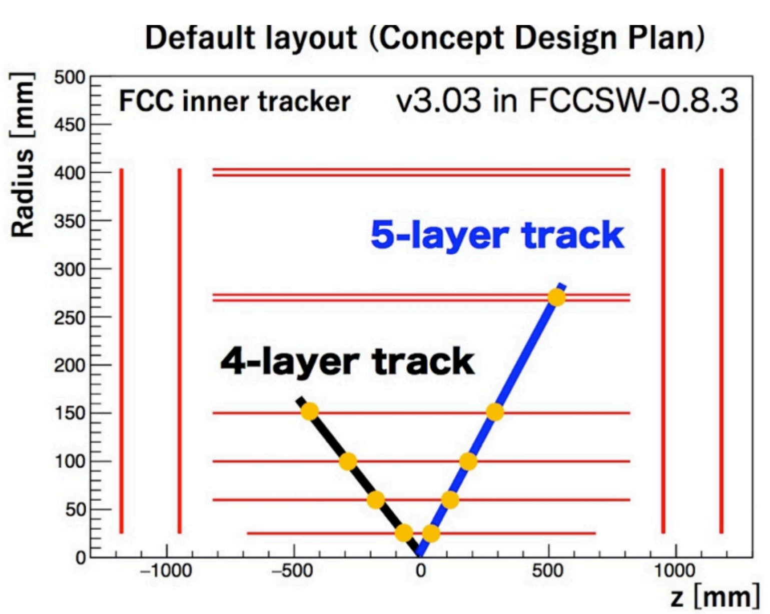
Tracking WIMPs

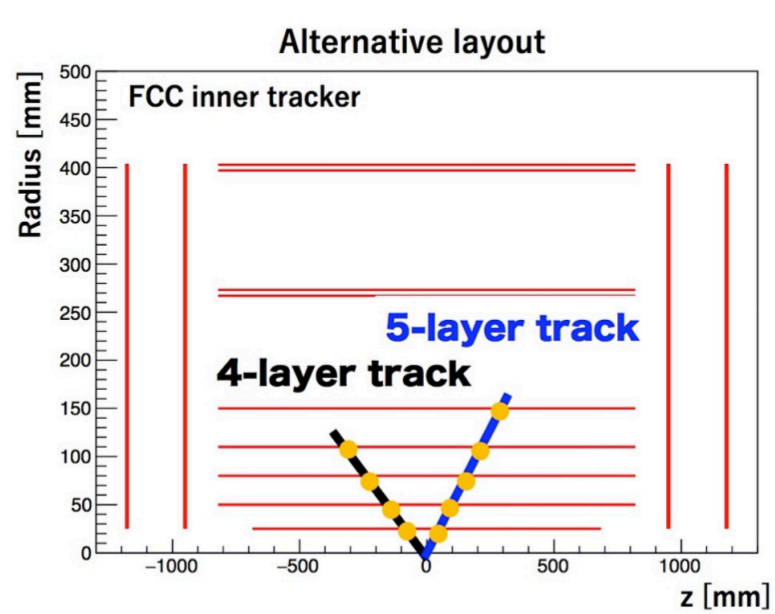


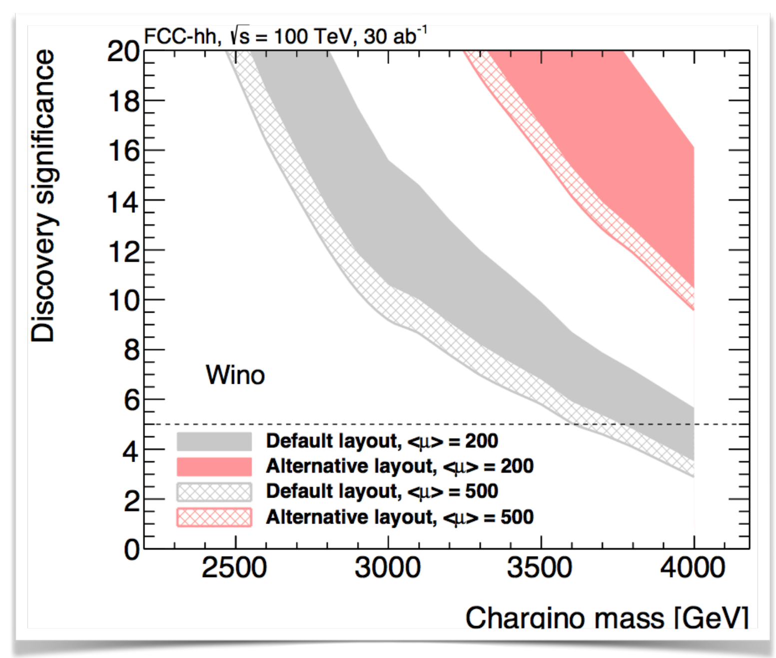
- Observed relic density of Dark Matter Higgsino-like: 1TeV, Wino-like: 3TeV
  - Mass degeneracy: wino 170MeV, Higgsino 350MeV
- Wino/Higgsino LSP meta-stable chargino, cτ= 6cm(wino) 7mm(higgsino)

- Useful tools to optimise detector concepts

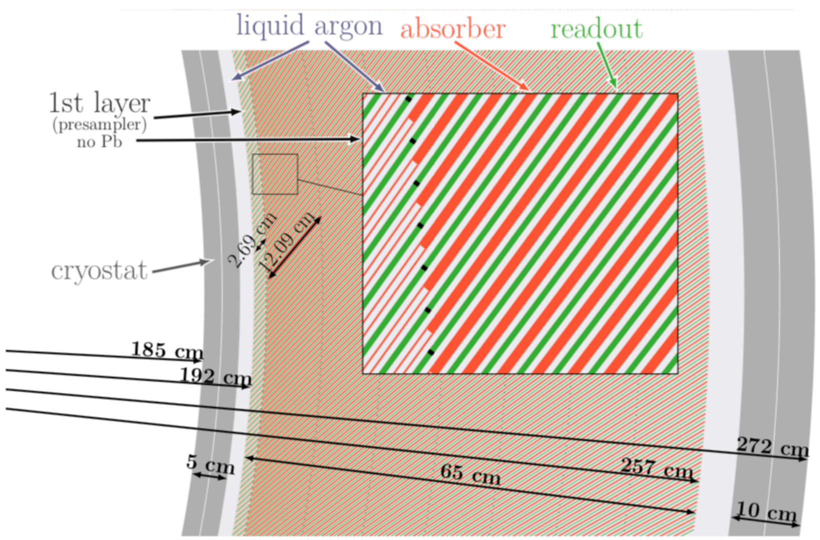






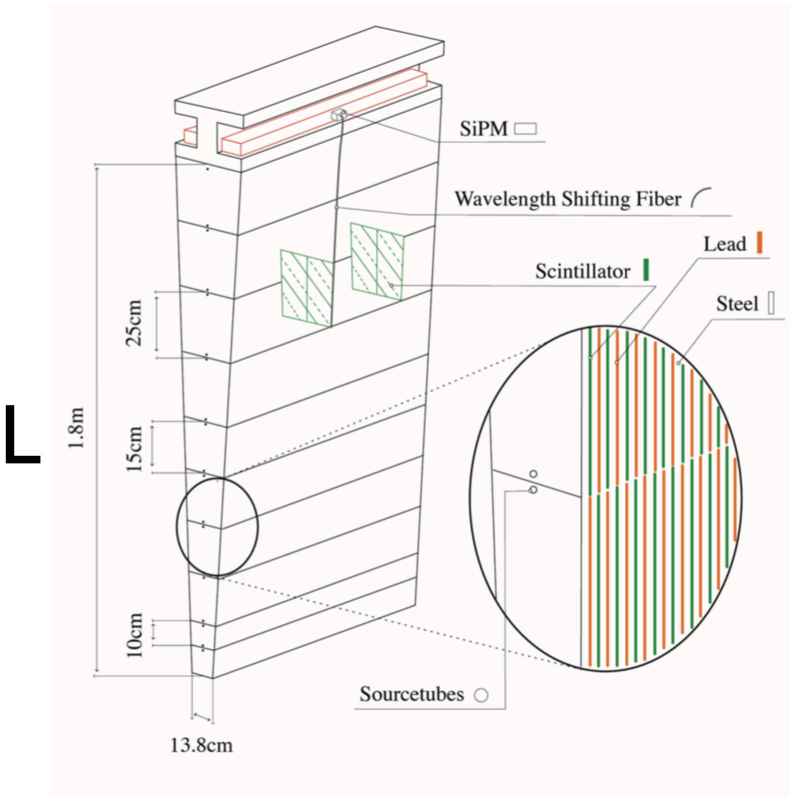


Calorimeters



ECAL

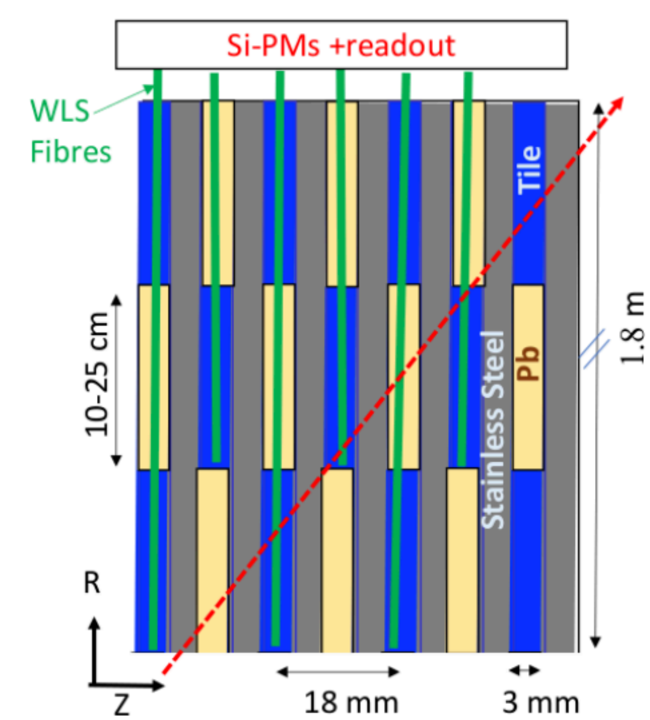
HCAL



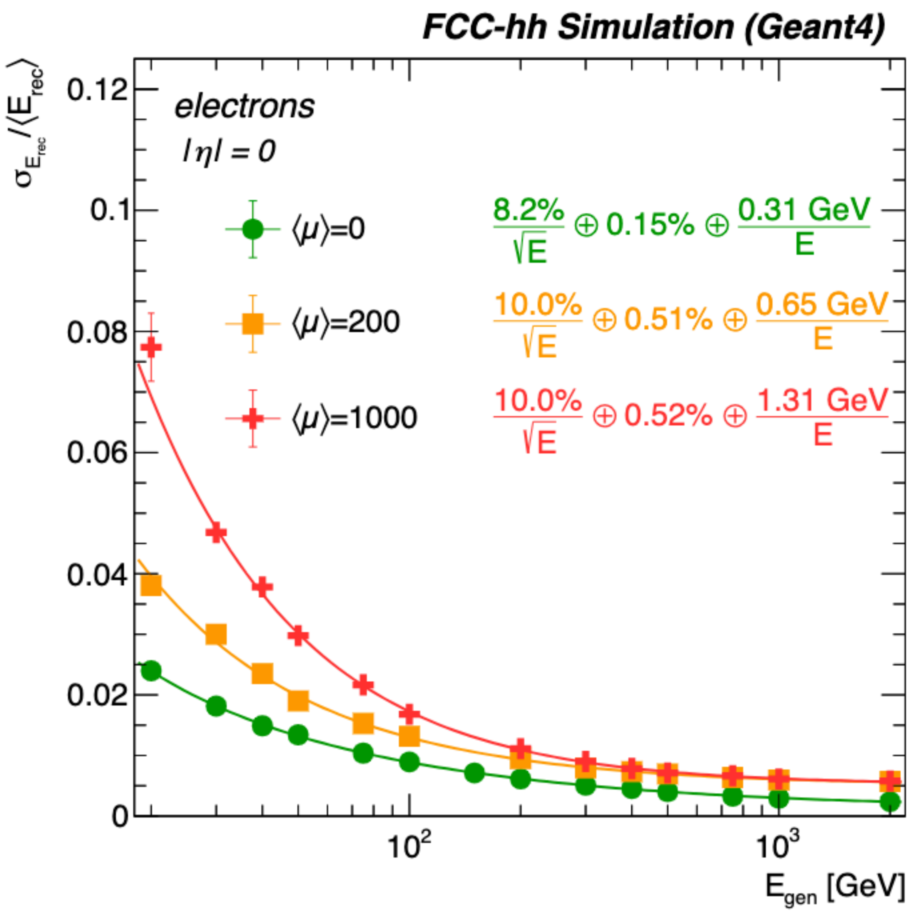
- ECAL: LAr + Pb technology driven by radiation hardness
- HCAL:
  - Organic scintillator + Steel, R/O with WLS fiber + SiPM
  - LAr in the forward (Dose > 10 MGy)

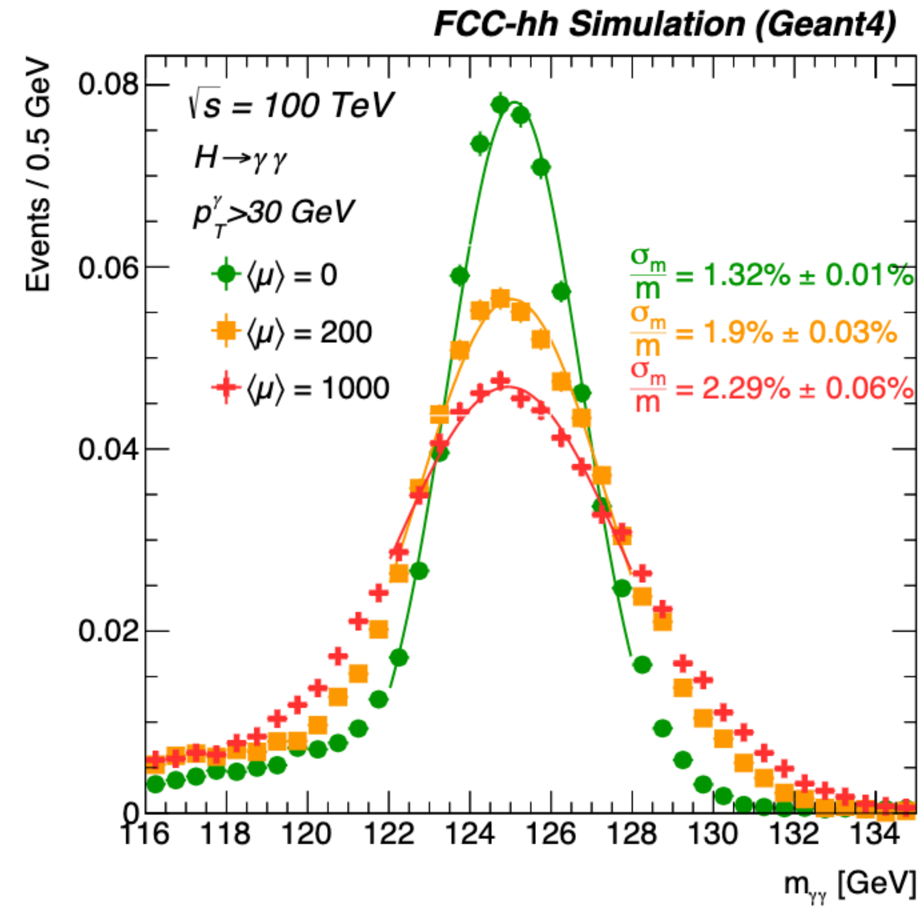
- Design goals:
  - High longitudinal (7+10 layers) + transverse segmentation (x4 CMS and ATLAS)
  - Particle-flow compliant
  - standalone PU rejection

FCC-hh Tile Barrel +Ext. Barrel

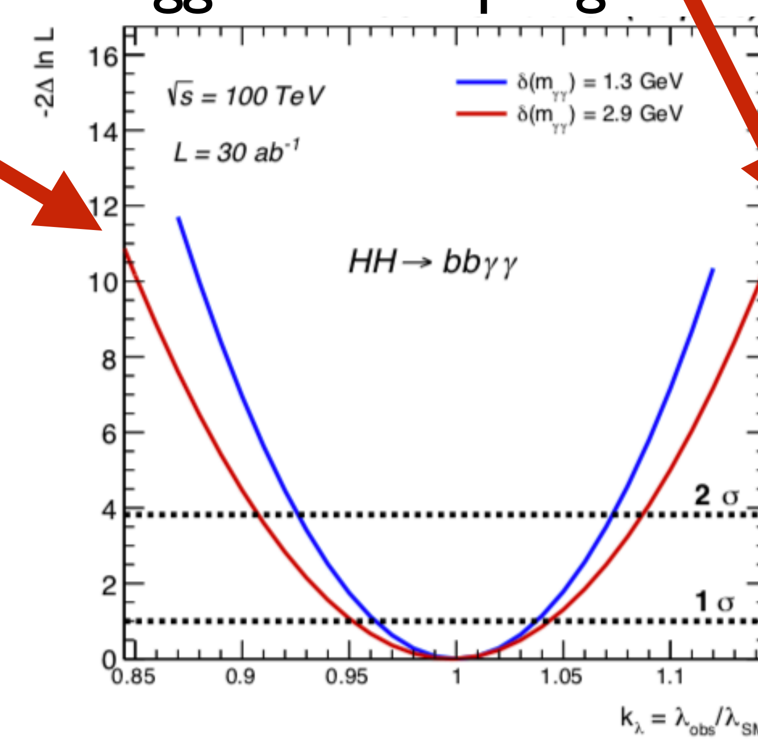


Photon resolution





Higgs self-coupling



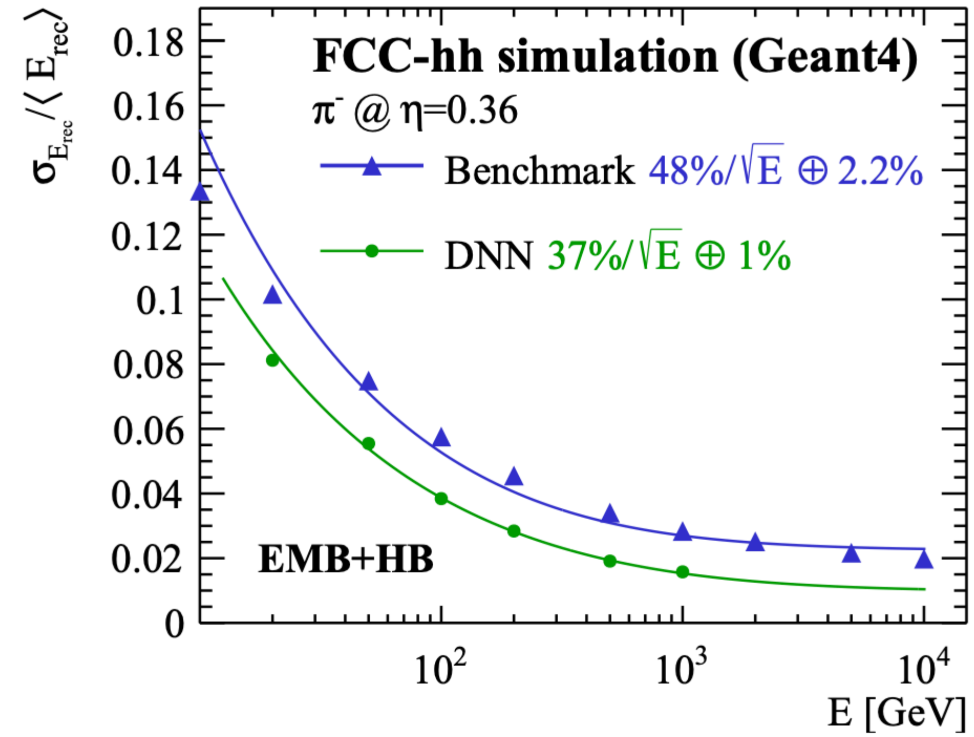
m(γγ) resolution

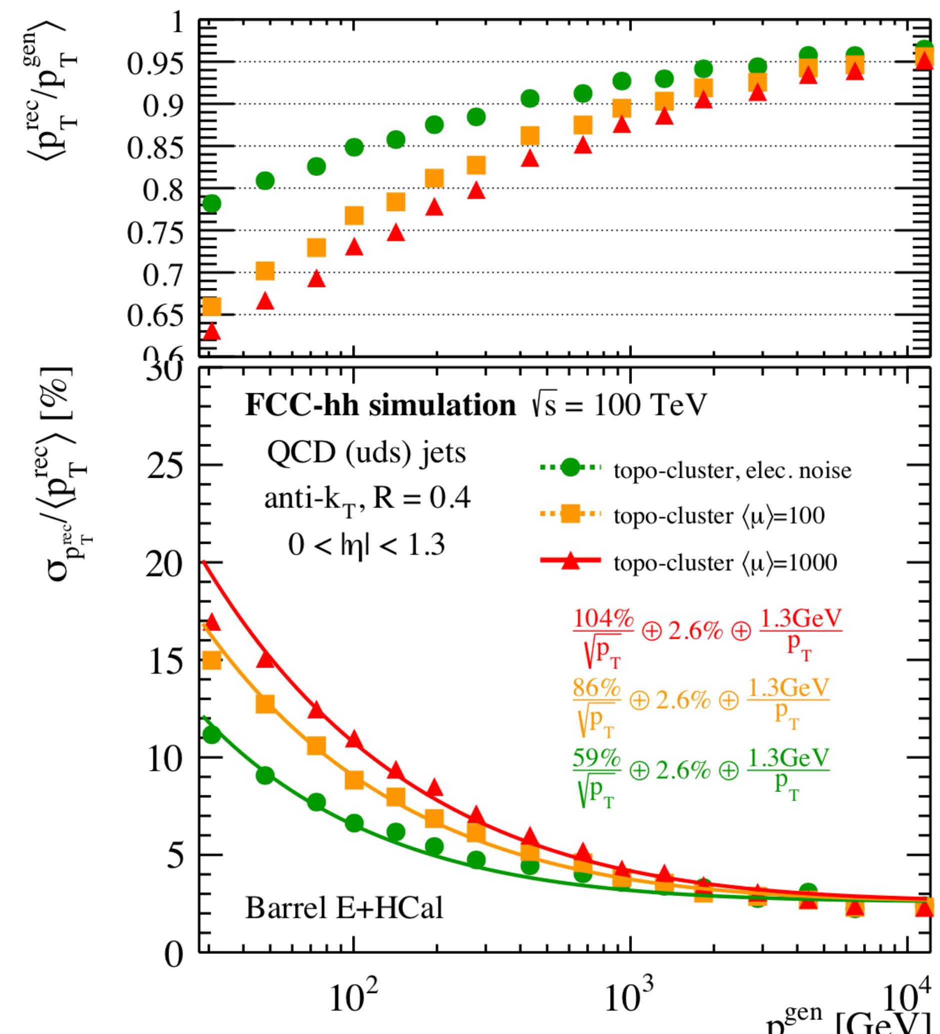
- Target: **σ/m as small as possible for HH→bbγγ**
- Large impact of in time PU on the noise term (out of the box with no improvements)!!
- severely degrades $m_{\gamma\gamma}$ resolution (improving clustering, not sliding windows may help)
- impacts Higgs self-coupling precision by $\delta\kappa_\lambda \approx 1\%$
- some thought needed (tracking, timing information can help?)

Hadron/Jet Performance with Full sim

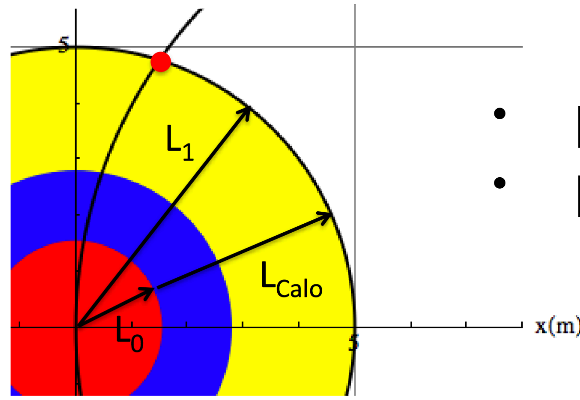
- Excellent resolution up to p_T =10 TeV !!
- Large impact of PU at low p_T (as expected)
  - crucial for low mass di-jet resonances (again, such as HH→**bb**ɣɣ)
  - Further motivation for Particle-flow

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

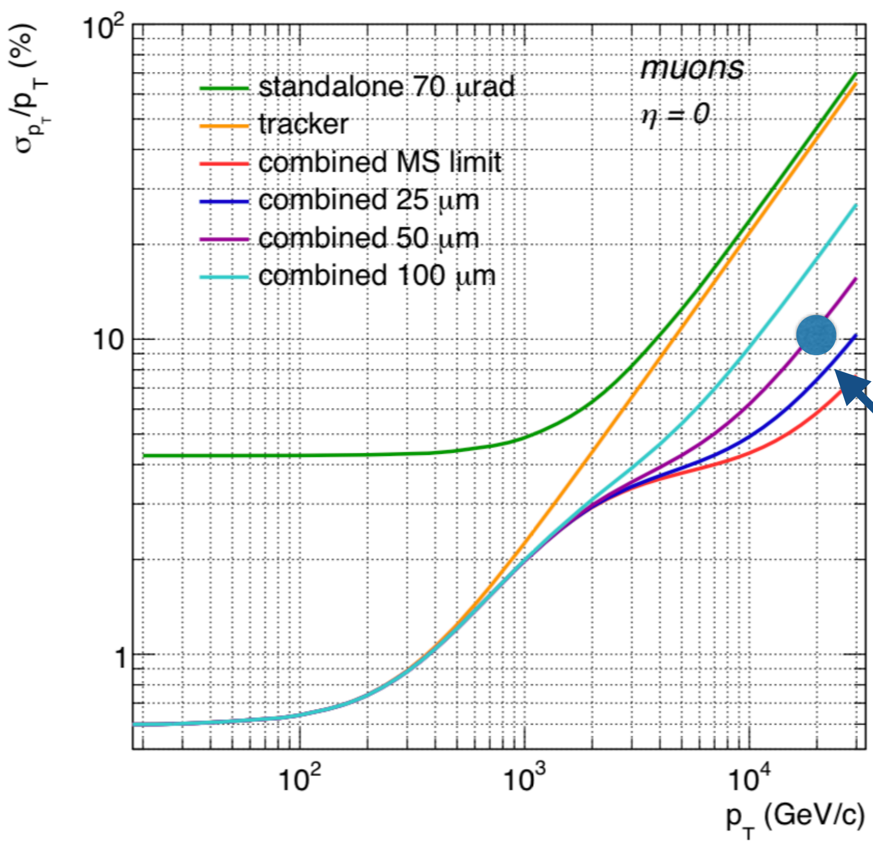




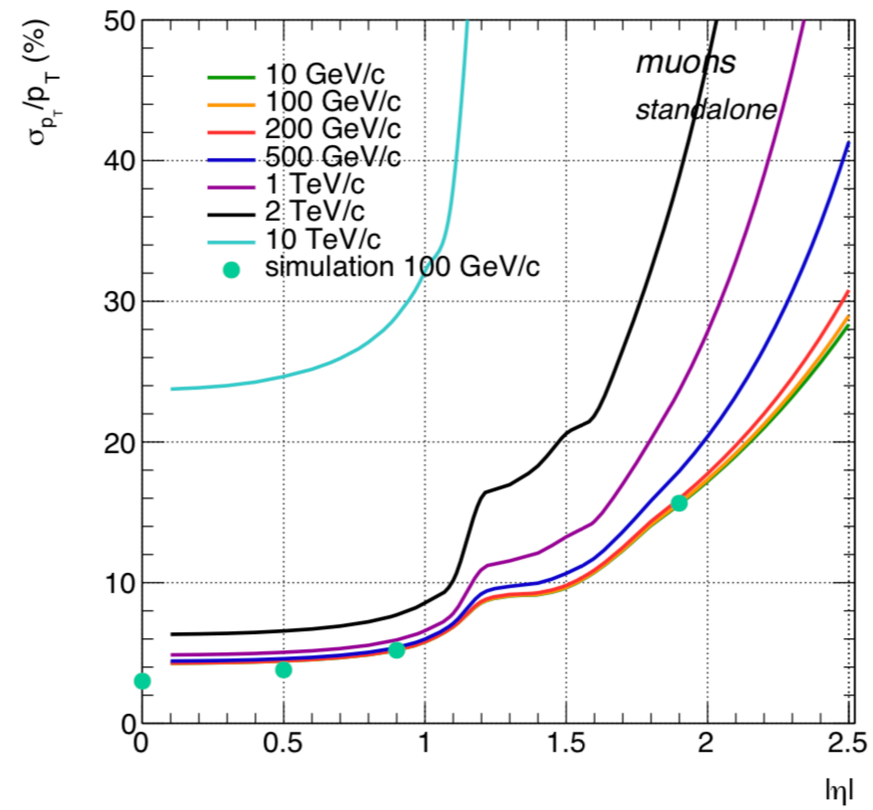
Muons



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



σ_p/p = 10% @20 TeV

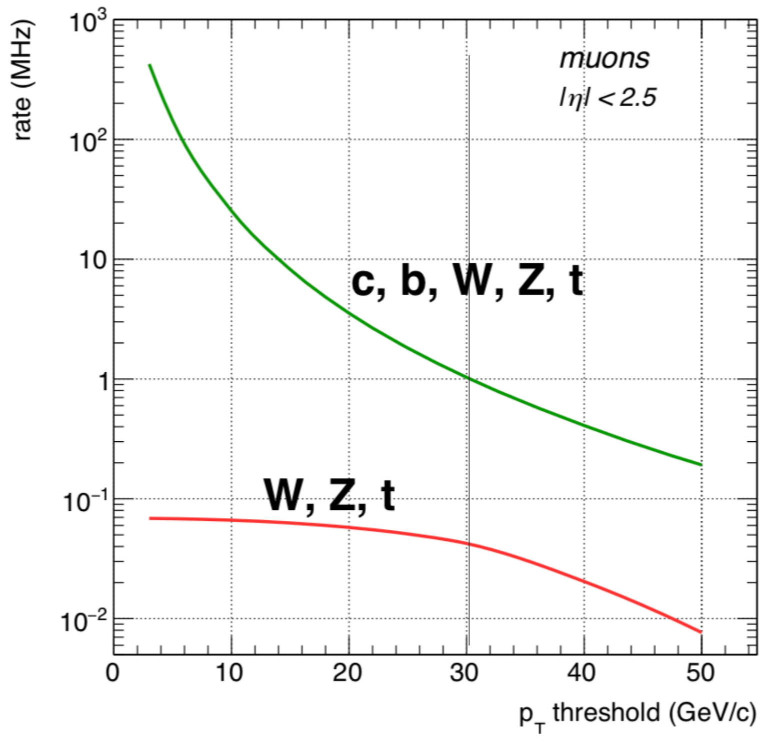


Calo + Coil = 180-280 X_0

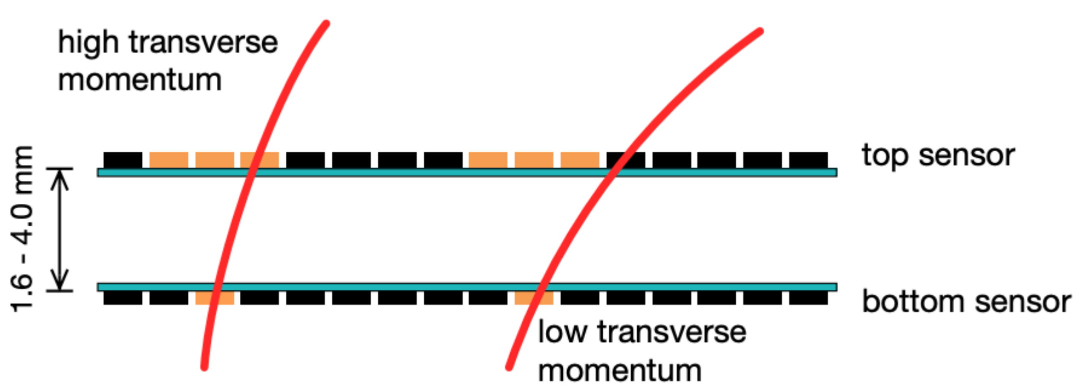
- Standalone muon measurement with angle of track exiting the coil
- Target muon resolution can be easily achieved with 50 µm position resolution (combining with tracker)
- Good standalone resolution below |η| < 2.5
- Rates manageable with HL-LHC technology (sMDT)

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



- Phase II:
  - ATLAS/CMS readout **calorimeters/muons** @40MHz and send via optical fibres to Level 1 trigger outside the cavern to create L1 trigger decisions
  - CMS reads out (part of) the tracker at L1 50 Tb/s
  - Full detector readout @1MHz (5Mb/event)
    - @40MHz it would correspond to 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)
  - How much data can be transferred out, without spoiling the performance?

The FCC-hh

Volume editors:
M. Mangano, W. Riegler

Benchmark processes, detector requirements from physics
Editors: H. Gray, C. Helsens, F. Moortgat, M. Selvaggi

Experiment, detector requirements from environment
Editors: I. Besana, W. Riegler

Software
Editors: C. Helsens, M. Selvaggi

Magnet systems
Editors: H. Ten Kate, M. Mentink

Tracker
Editors: Z. Drasal, E. Codina

Calorimetry
Editors: M. Aleksa, A. Henriques, C. Neubuser, A. Zaborowska

Muons
Editors: W. Riegler, K. Terashi

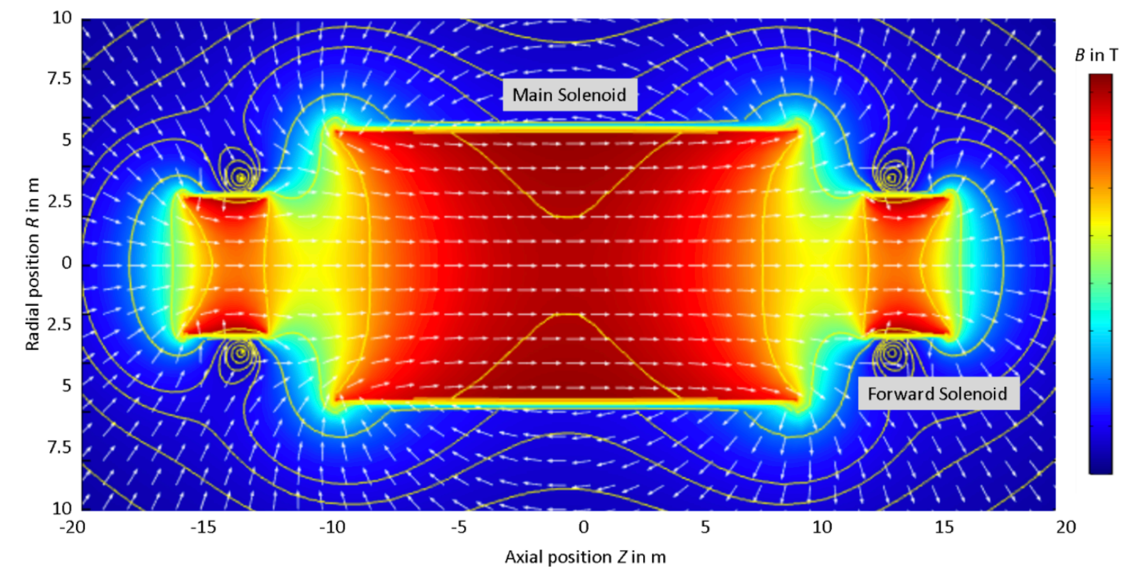
Physics performance for benchmark channels
Editors: M. Mangano, C. Helsens, M. Selvaggi

Conceptual Design Report

Yellow Report (Extended CDR) in. 2022

Beyond the CDR: magnets?

Magnets often drive exp. cost



Initial Design

- B= 6T, R=6m, cost = 900 MCHF !!
  - (Too expensive, and not needed)

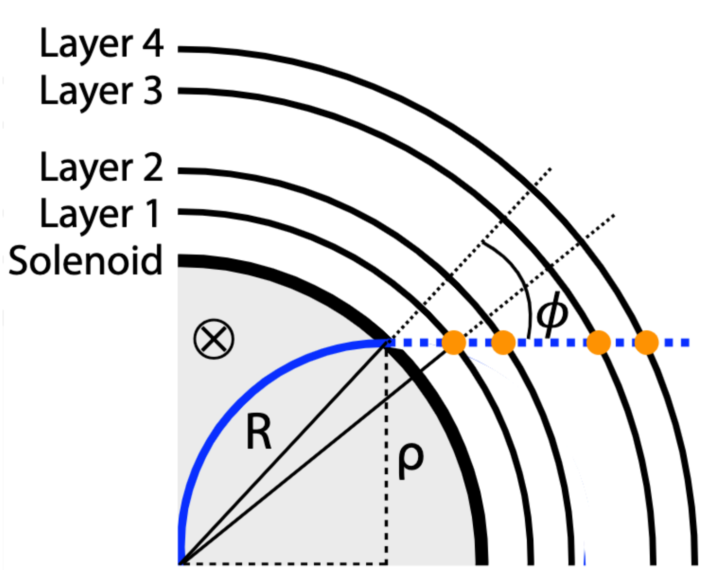
CDR Design

- B=4T, R=5m, cost = 300 MCHF
  - a la CMS
    - BUT no return (stray field concerning?)

Alternative Design

- Solenoid before ECAL,
  - return field through the HCAL
    - ATLAS without Toroid
- B=4T, R=2m, cost 50 MHCF
- only have muon ID
- do we have enough selectivity with a track trigger at L1?

TO BE STUDIED,
would reduce cost substantially



Road to 1% precision on the self-coupling ?

$\delta\kappa_\lambda$ (stat) ~ 2-3%

[MLM, Ortona, MS]

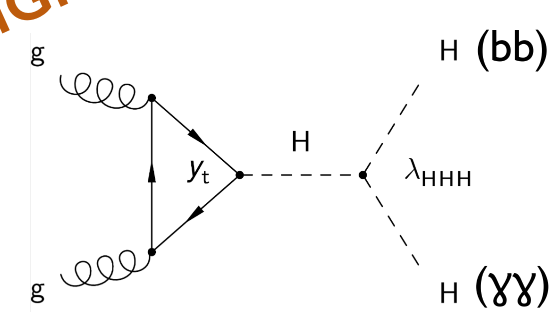
[Taliercio et al.]

- Photons
  - energy/momentum resolution
    - Homogenous LXe calorimeter ?
      - M_R ~ 5 cm, X_0 ~ 2.5 cm
      - 3%/√E
  - Eff - low misID
    - Pile-up rejection (~ 10 ps timing)

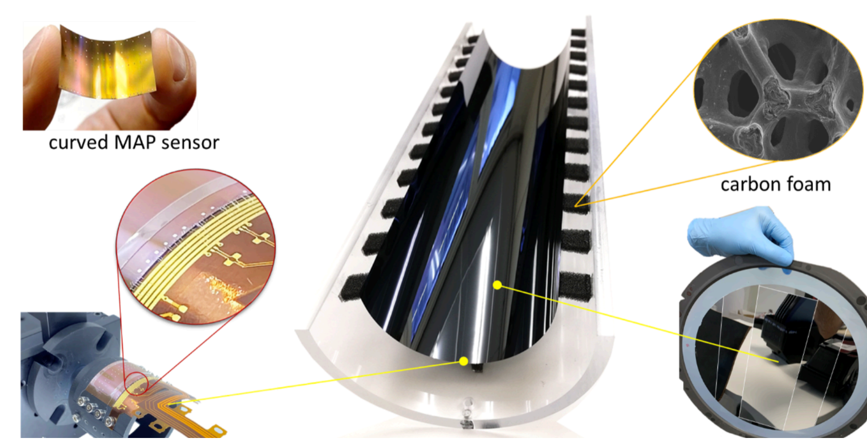
- (B-)jet energy momentum resolution
  - Intrinsic HCAL resolution,
  - Calorimeter segmentation for optimal particle-flow
  - Timing for pile-up rejection

- Flavor Tagging
  - Close to IP (radiation damage !!!) (1/d)
    - ~ @1cm → 1e19 1 MeV neq/cm^2
  - Light vertex detector (√X_0)
    - but power/cooling needed to extract data
  - target single point resolution ~ 10 µm x 10 µm

DISCLAIMER:
HIGHLY SPECULATIVE



XENONnT:



maps ~ 1e15 1 MeV neq/cm^2

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 (1e18 MeV neq/cm^2)
  - **High precision timing (< 10 ps)**
  - Low power, high speed links (Silicon Photonics)
  - Highly segmented calorimeters (4D imaging calorimeters)
  - Software, reconstruction algorithms (4D particle-flow, boosted object tagging)

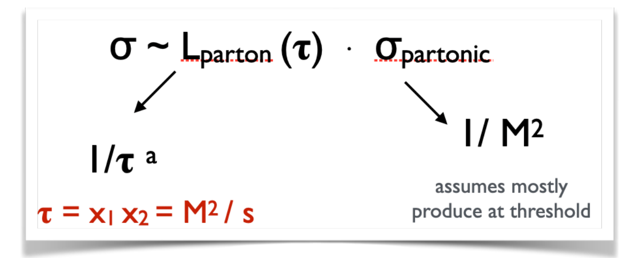
Conclusions

- 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, high rad levels and data rates) 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 if we want to go beyond
  - radiation tolerance, picosecond timing, granularity, high speed low power optical links

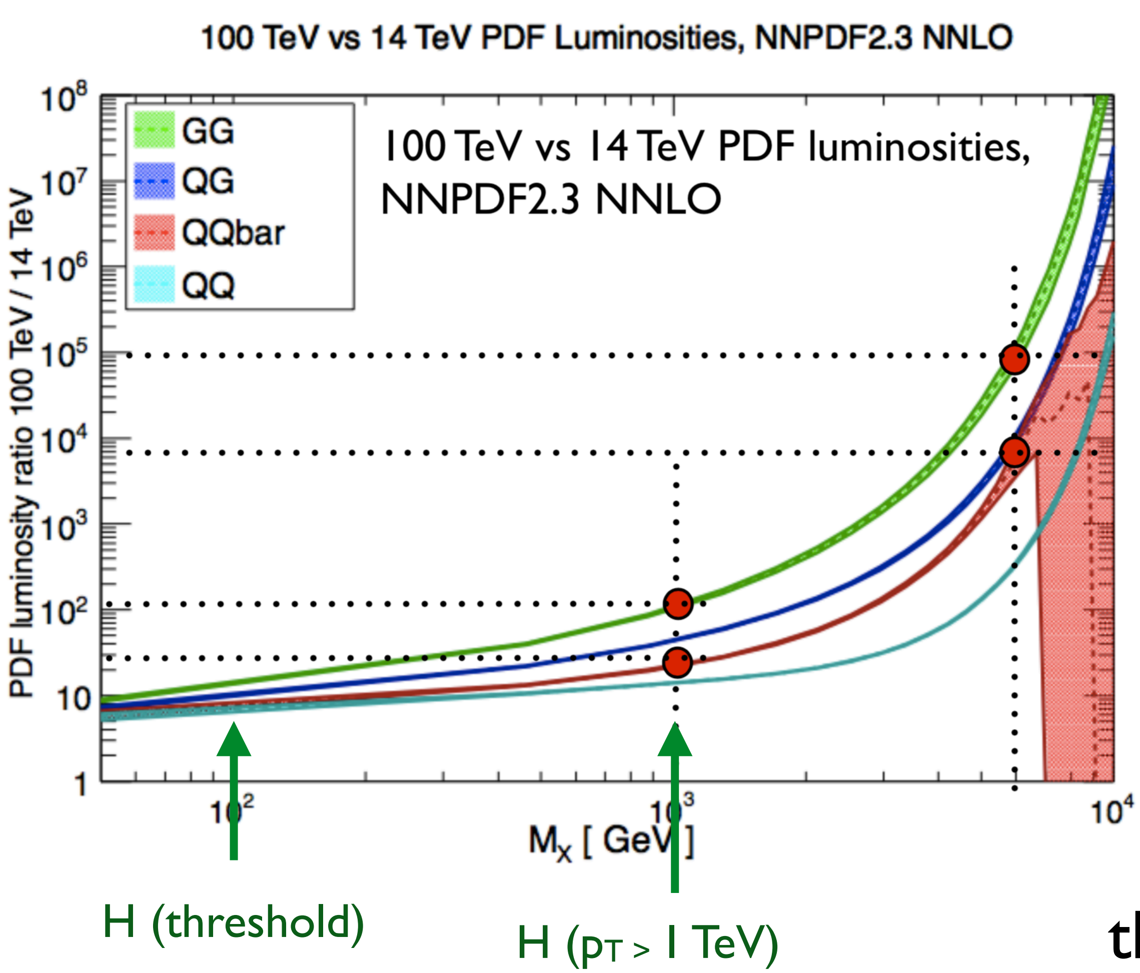
Backup

Reach at high energies

How does the rate of a **given process** (e.g. single Higgs production) scale from 14 TeV to 100 TeV



$$\frac{\text{cross-section } (\sqrt{s2}, M)}{\text{cross-section } (\sqrt{s1}, M)} \approx L_1(M) \,/\, L_2(M) \approx (s_2 \,/\, s_1)^{a(M)}$$



	σ(27)/σ(14)	σ(100)/σ(14)
ggH	3	15
HH	4	40
ttH	5	55
H (p_T > 1 TeV)	7	400

Very large rate increase by increasing center of mass energy

NB: this improvement only comes from the cross-section (neglects integrated luminosity)

Reach @100TeV

$\mathscr{L}$ = integrated luminosity

L = parton luminosity

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

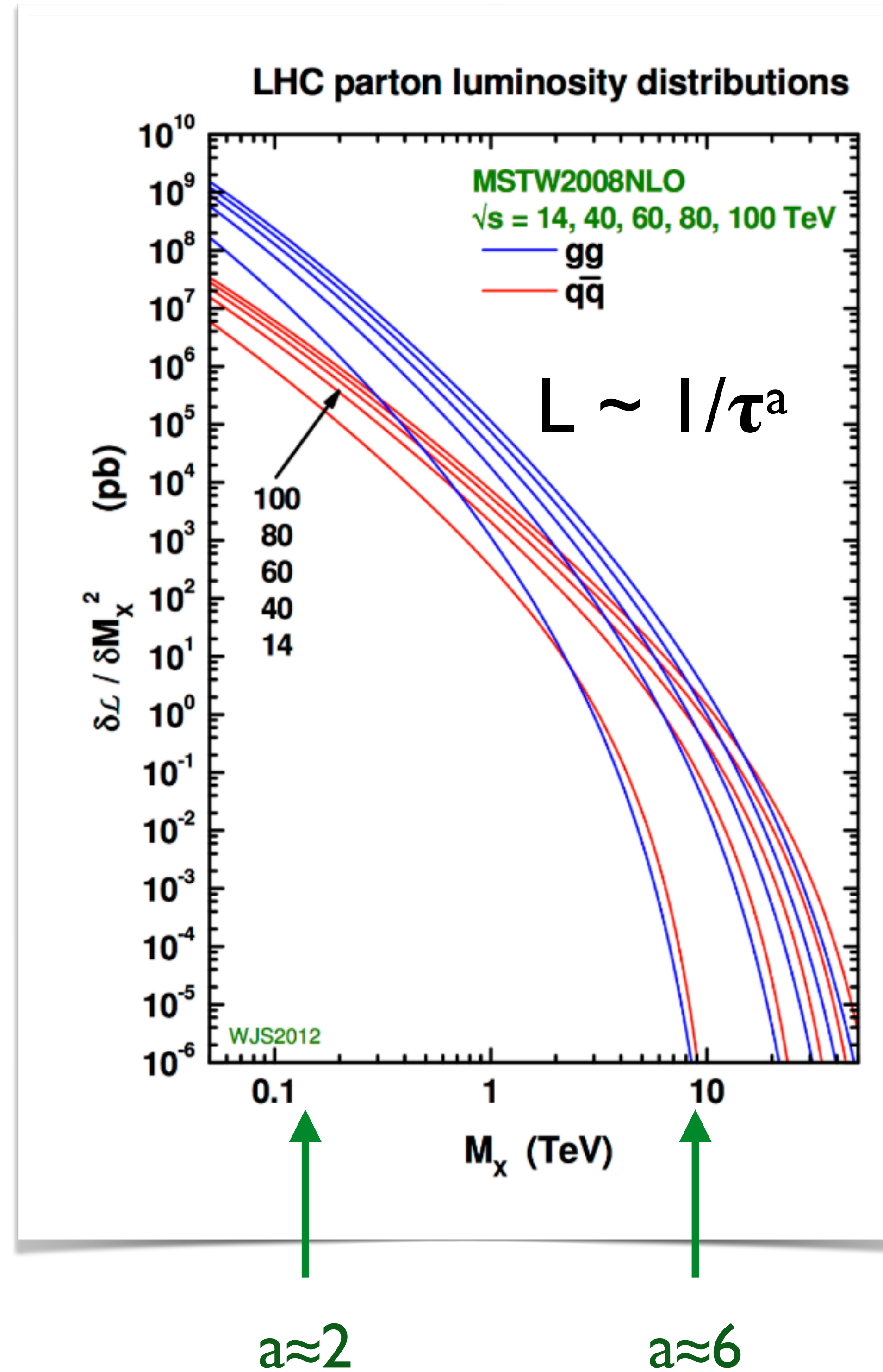
$L \sim (s/M^2)^a$

σ (part) $\sim 1/M^2$

events = $\sigma \mathscr{L}$

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

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



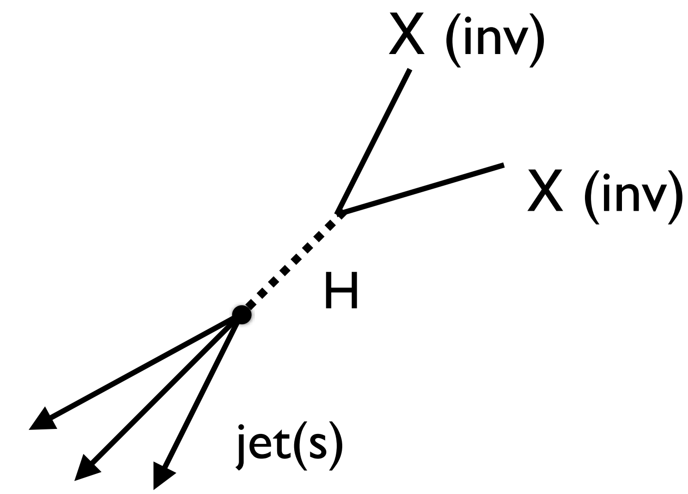
Reach of collider at $\sqrt{s_1}$ vs $\sqrt{s_2}$:

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

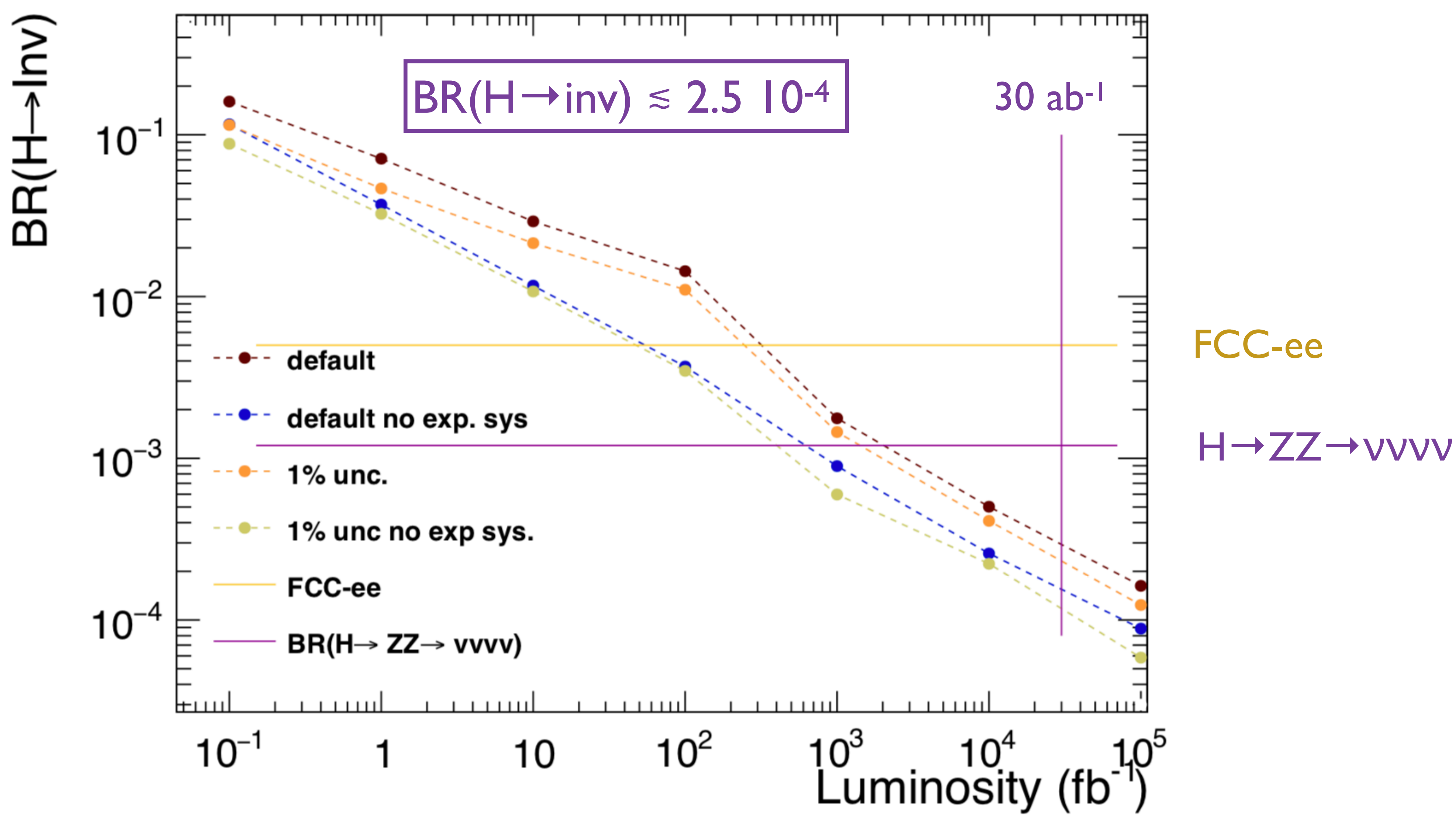
At high mass (high x), a >> 1:

Mass reach goes up by factor 7 (roughly)

H→invisible



- Measure it from H + X at **large p_T(H)**
- Fit the **E_T^{miss}** spectrum
- Constrain background p_T spectrum from **Z→νν** to the % level using NNLO QCD/EW to relate to measured Z,W and γ spectra (low stat)
- Estimate Z→νν (W→lν) from Z→ee/μμ (W→lν) control regions (high stat).



Self-coupling at the FCC-hh

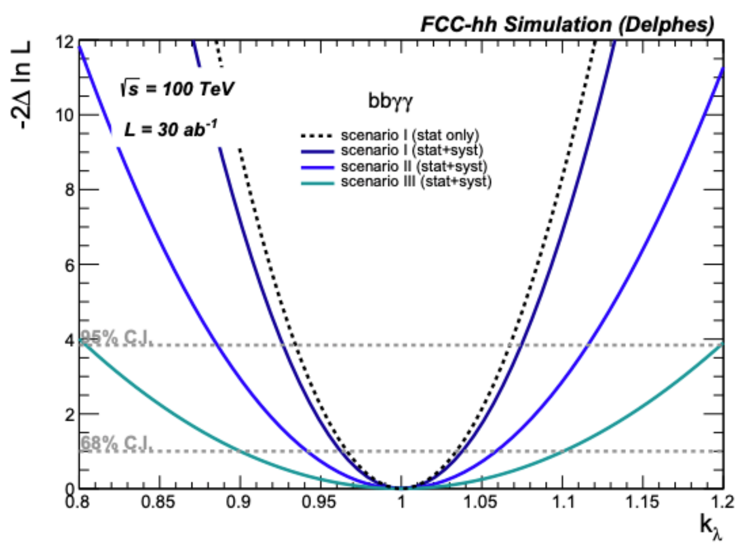
2004.03505 [hep-ph]

parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
τ-jet ID eff	80-70%	78-67%	75-65%
τ-jet mistag (jet)	2-1%	2-1%	2-1%
τ-jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
m_{bb} resolution [GeV]	10	15	20

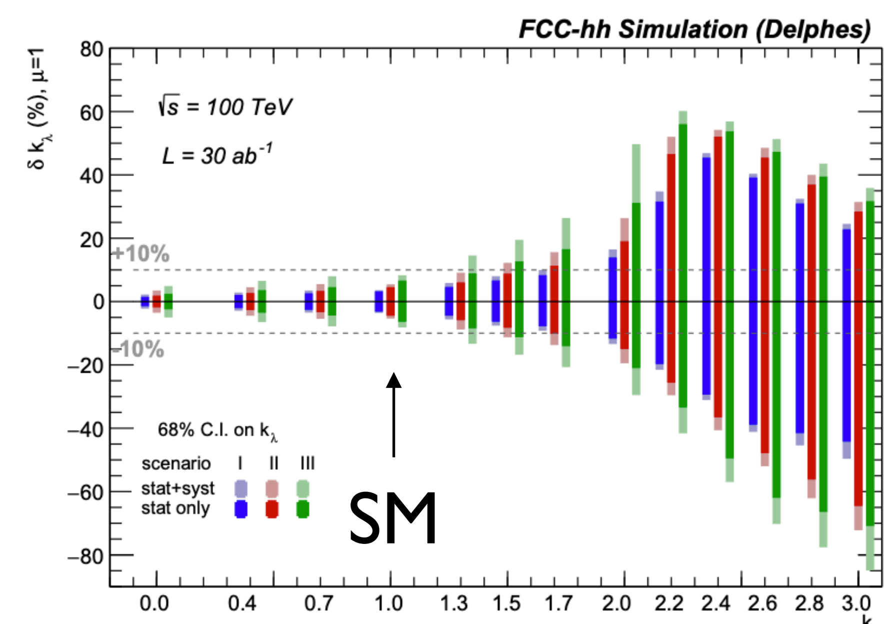
- Expected precision:

@68% CL	scenario I	scenario II	scenario III
$bb\gamma\gamma$	3.8	5.9	10.0
$bb\tau\tau$	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8

- Combined precision:
  - 3.5-8% for SM (**3% stat. only**)
  - **10-20%** for $\lambda_3 = 1.5^* \lambda_3^{SM}$



[2203.08042]



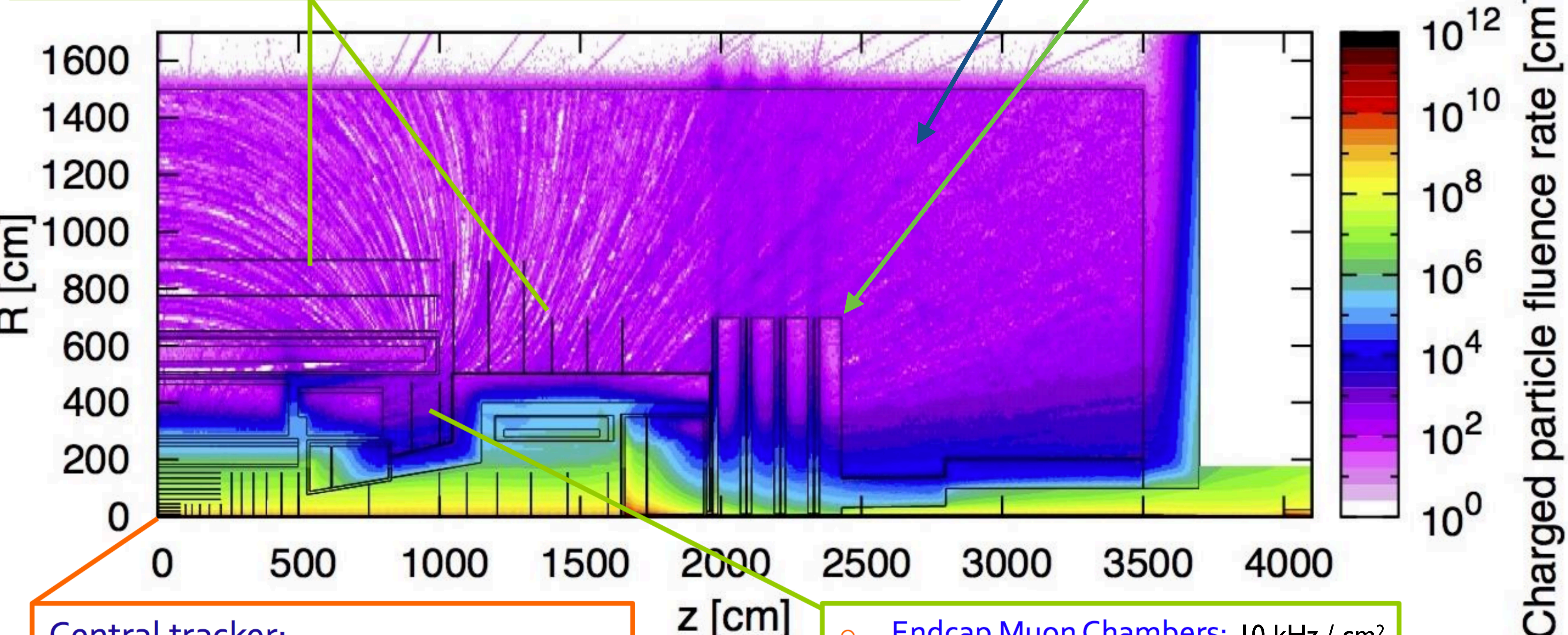
	$HH \to b\bar{b}\gamma\gamma$	$HH \to b\bar{b}\tau\tau$	$HH \to 4b$	**HH combination**
Precision on the signal strength at 68% CL				
stat only	2.4	2.6	3.9	1.6
scen 0	3	3.4	4	2
scen 1	5.5	5.3	18.2	3.6
Precision on the k_λ at 68% CL%				
stat only	2.6	3.3	8	2
scen 0	3.1	4	9.4	2.4
scen 1	5.6	6.6	13.5	3.9

Charged Particle fluence

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

- Barrel muon chambers: 300-500Hz / cm²

Fwd chambers: 25-250 kHz / cm²



Central tracker:

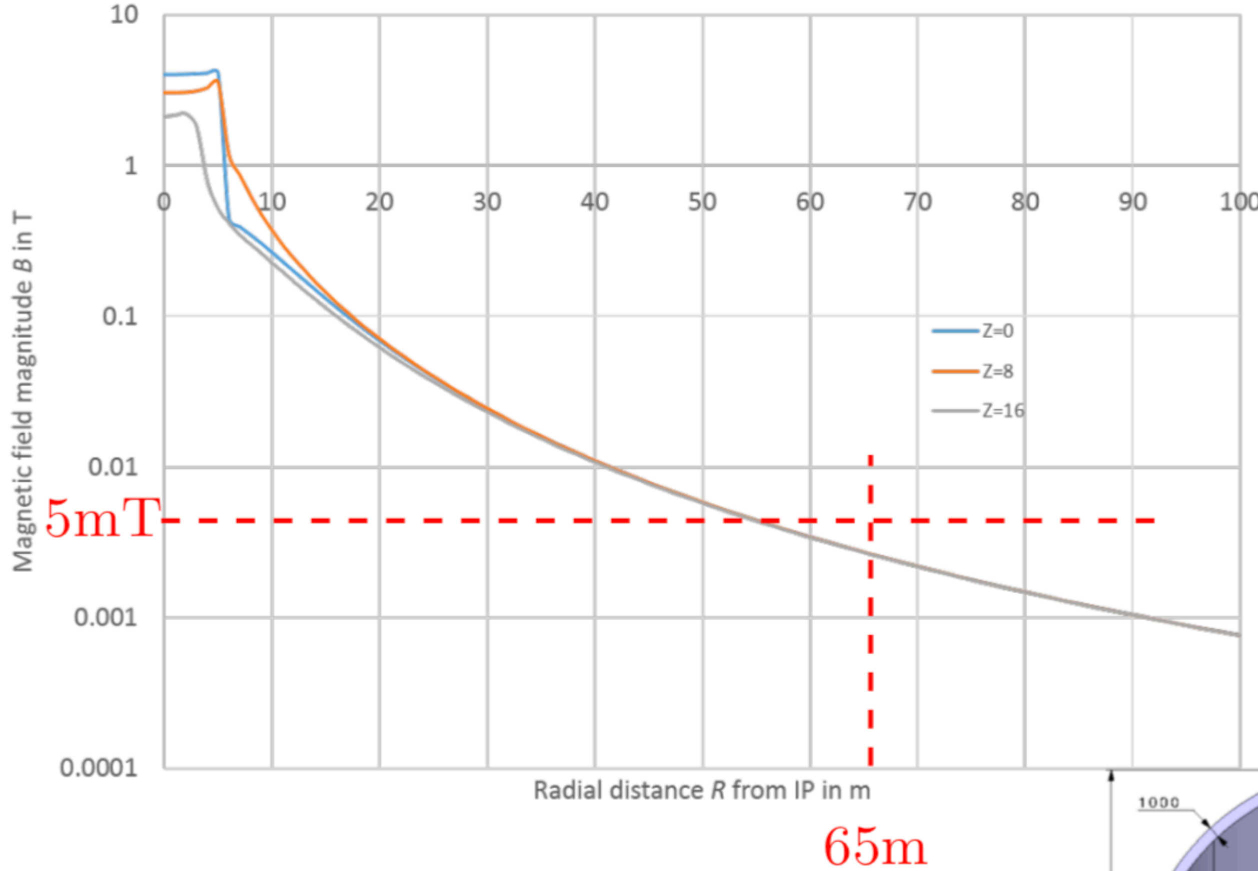
- first IB layer (2.5 cm): ~1.2 10^{10} $cm^{-2}s^{-1}$
- external part: 3 10^{6} $cm^{-2}s^{-1}$

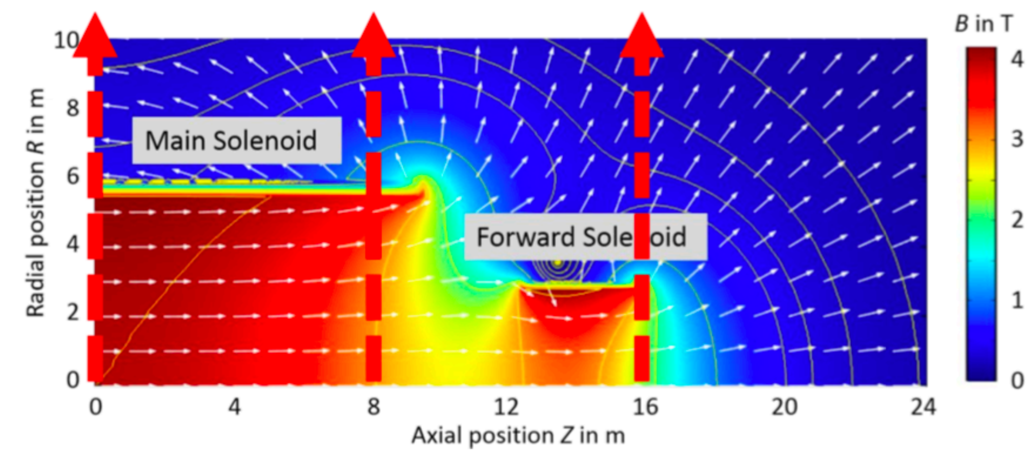
- Endcap Muon Chambers: 10 kHz / cm²

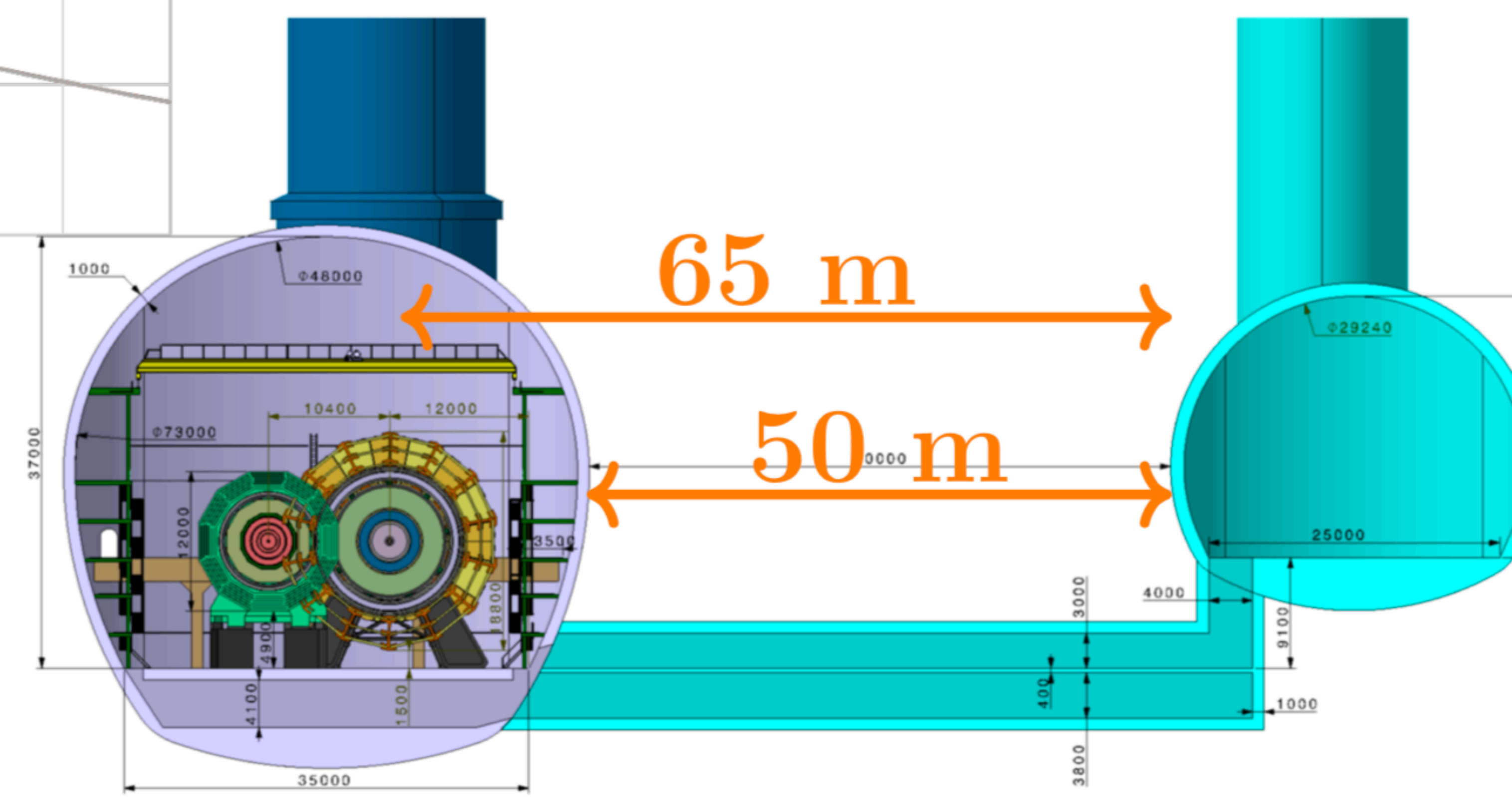
Silicon sensors in the very forward region for muons?

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





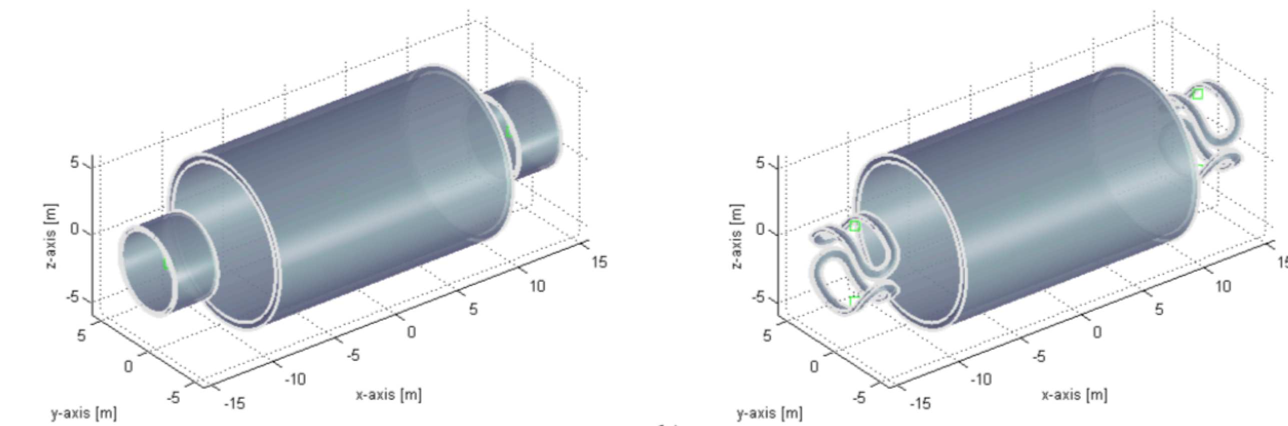


No shielding: too expensive

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



a) b)

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.

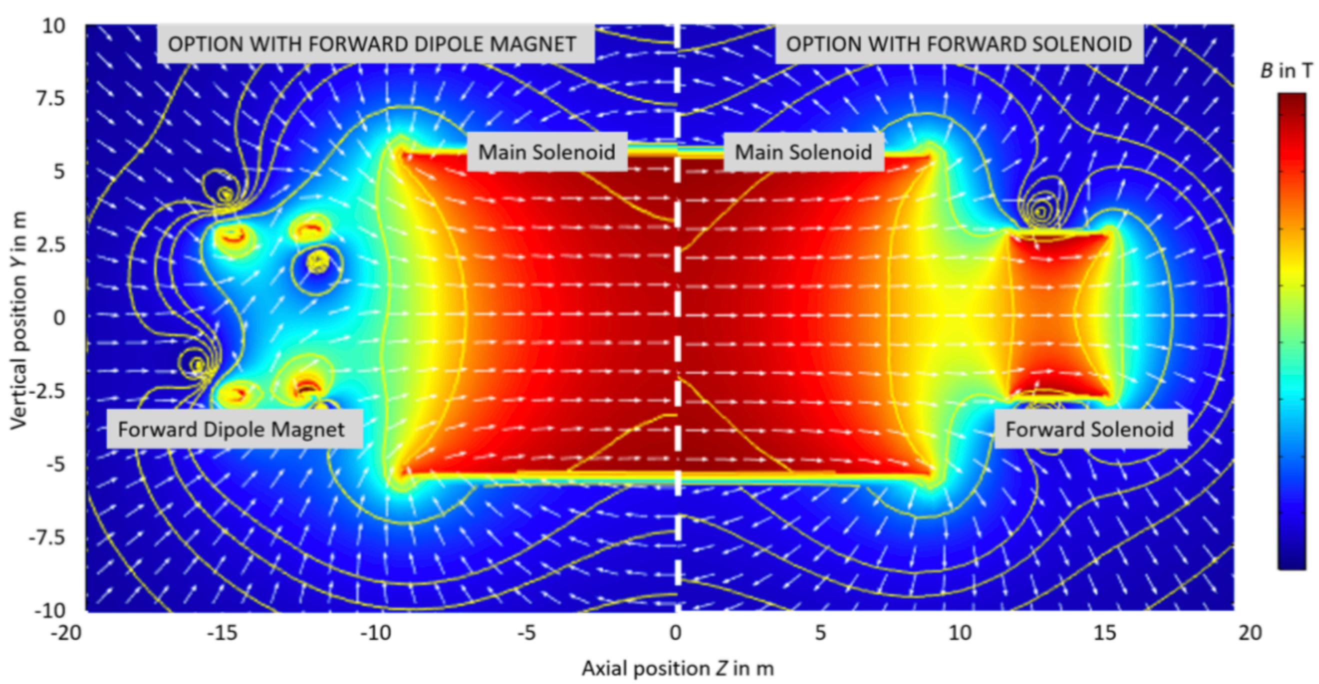
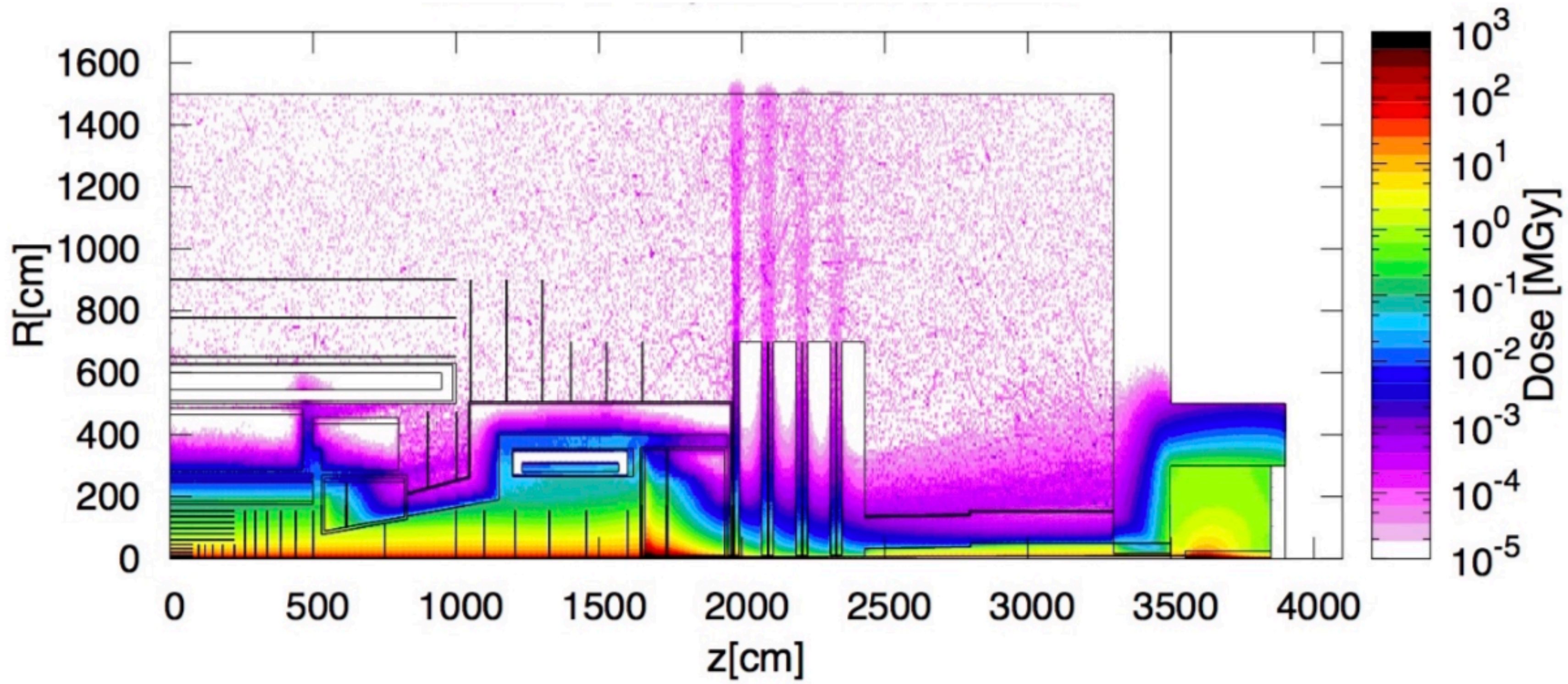


Figure 7.7: Longitudinal half-sections of the two versions of the magnet system. Magnetic fieldmap for a central solenoid of 4 T with a forward dipole (left) and a forward solenoid (right).

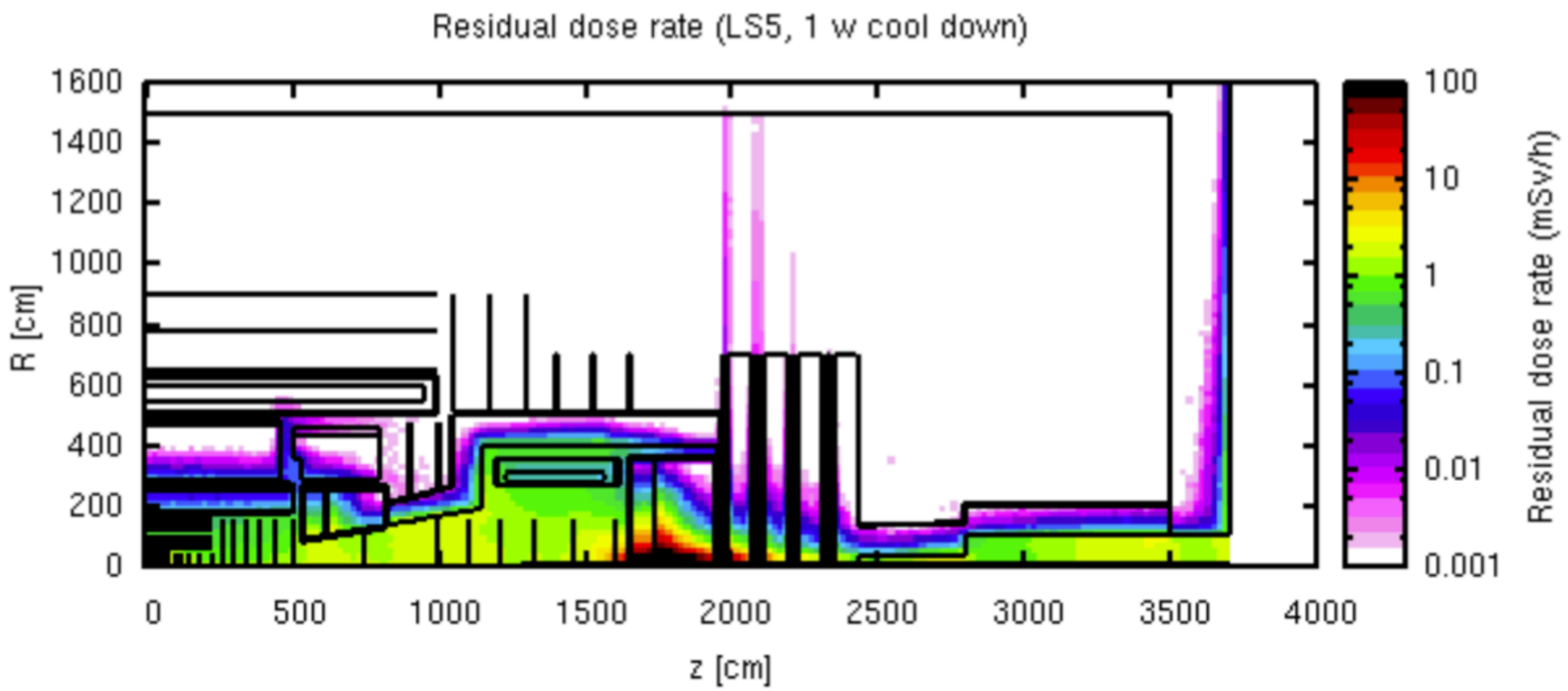
Dipole:

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

Total and residual ionizing dose



a)



b)

Material budget

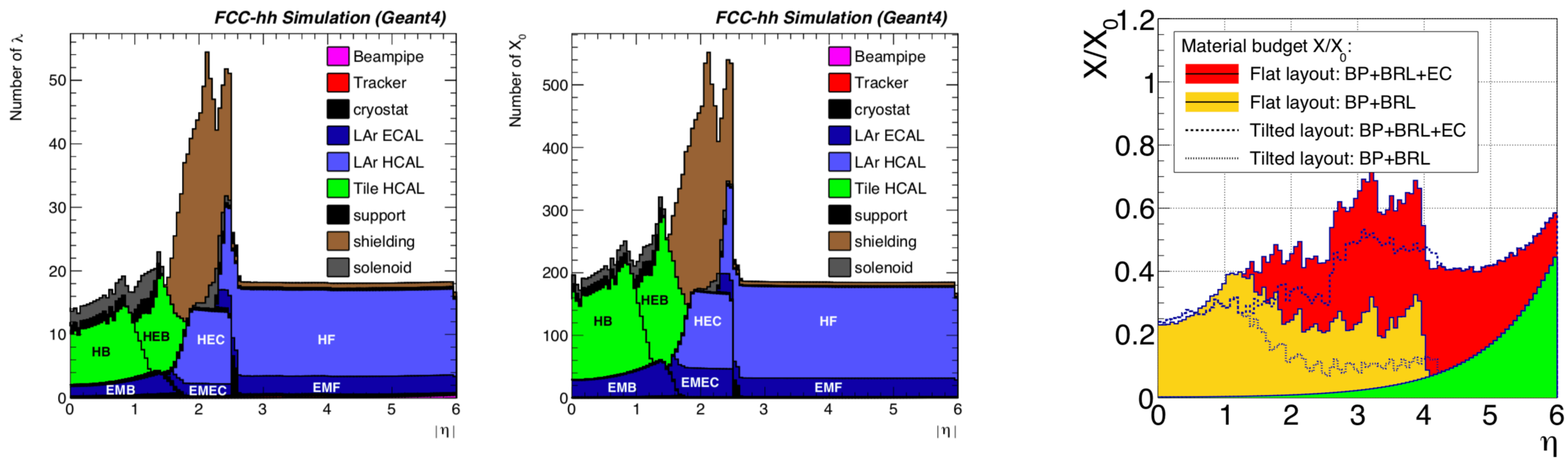
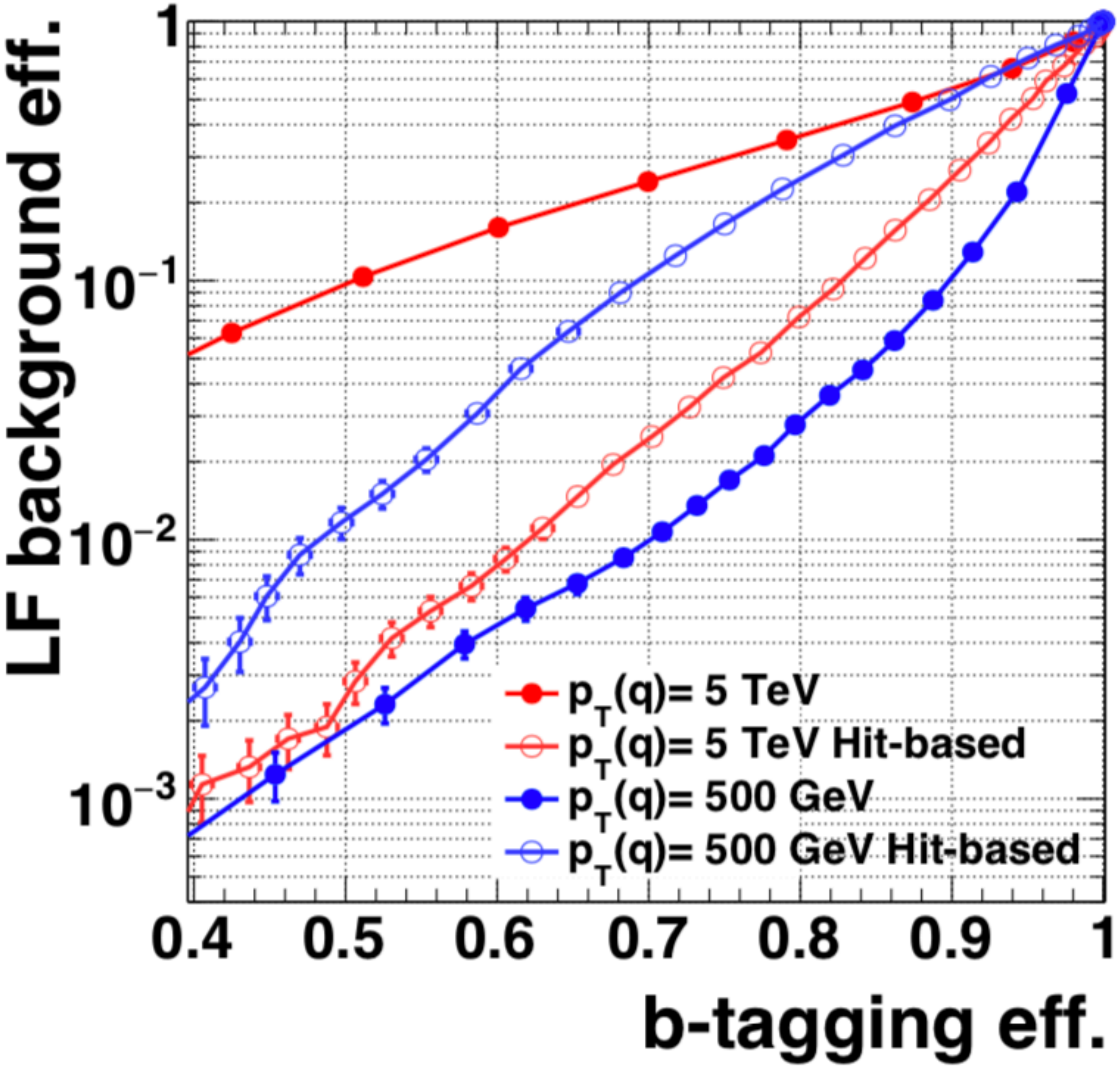


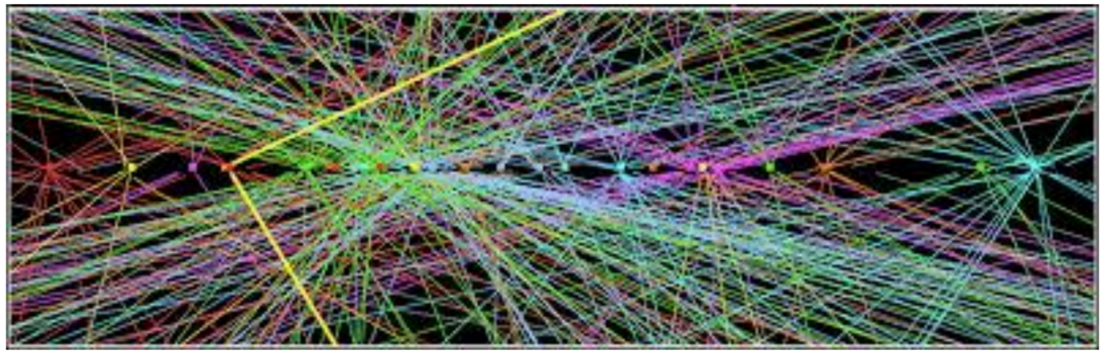
Figure 7.10: Material budget of the different sub-systems. The calorimetry provides $\geq 10.5\,\lambda$ nuclear interaction lengths to maximise shower containment and the total detector material represents between 180 and 280 X_0 radiation lengths.

Boosted b-tagging



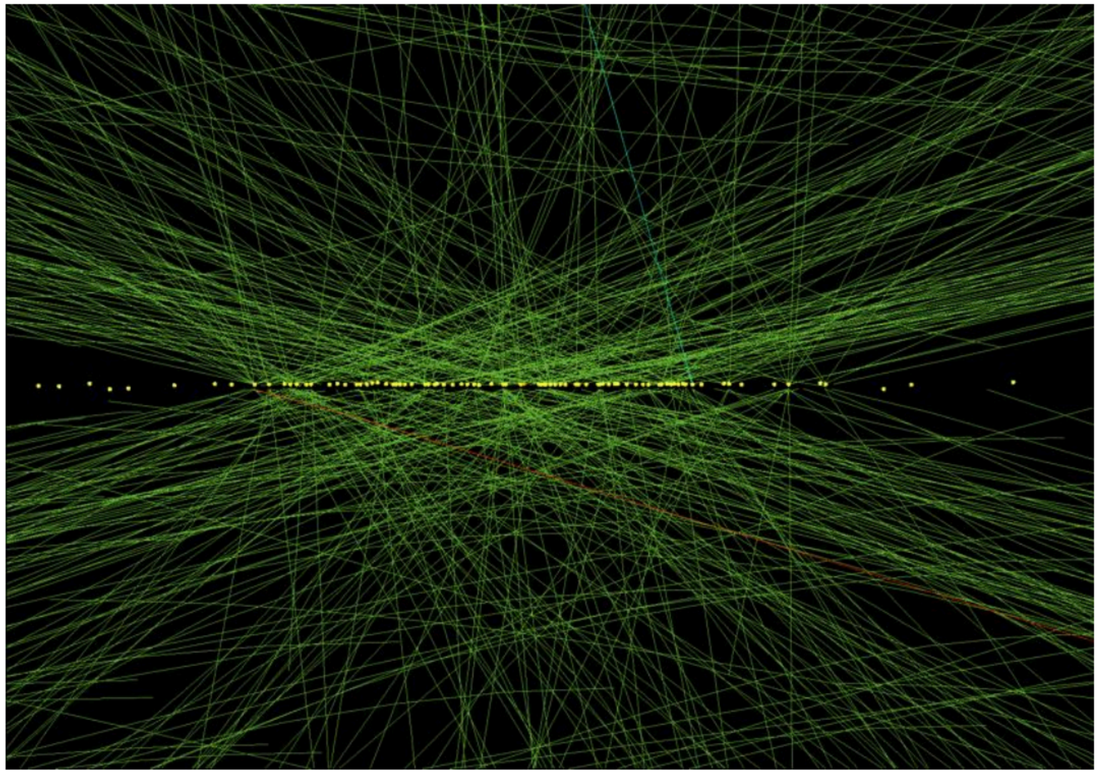
Machine and detector requirements

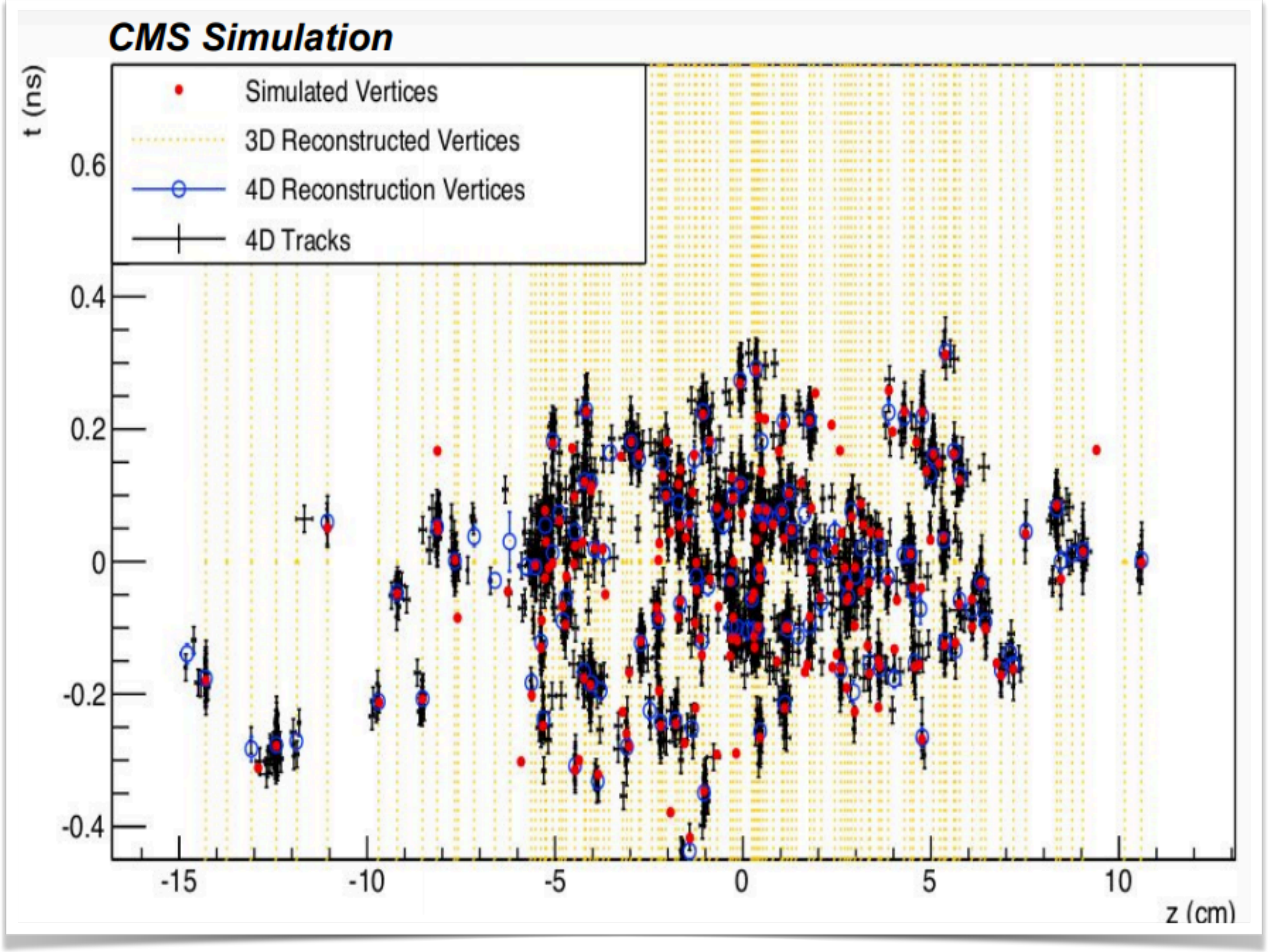
lumi & pile-up



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

Timing helps in identifying PU vertices

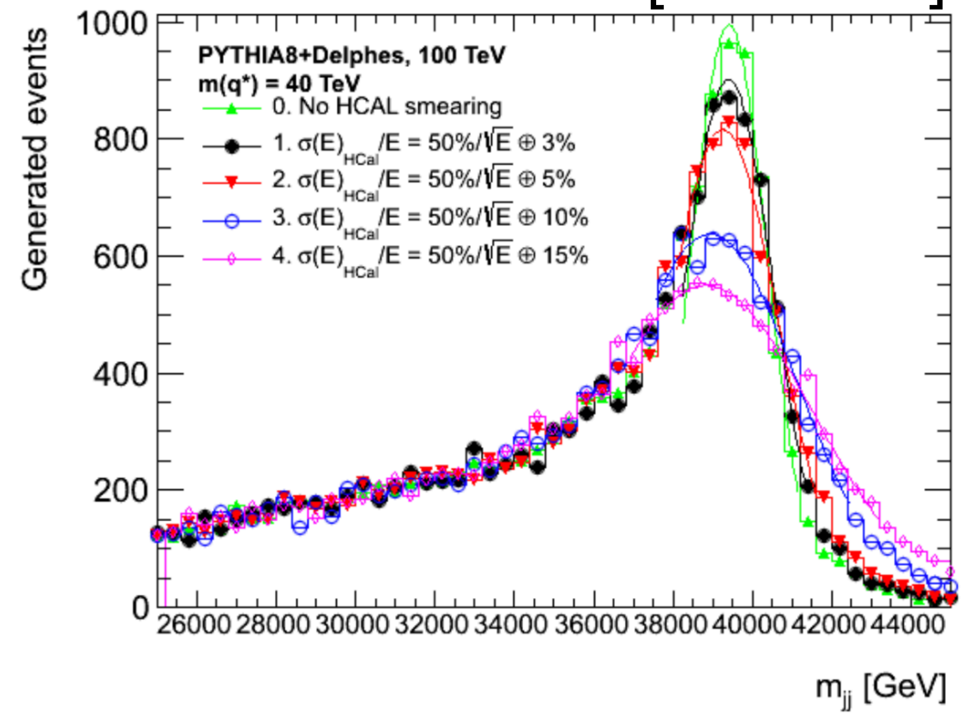




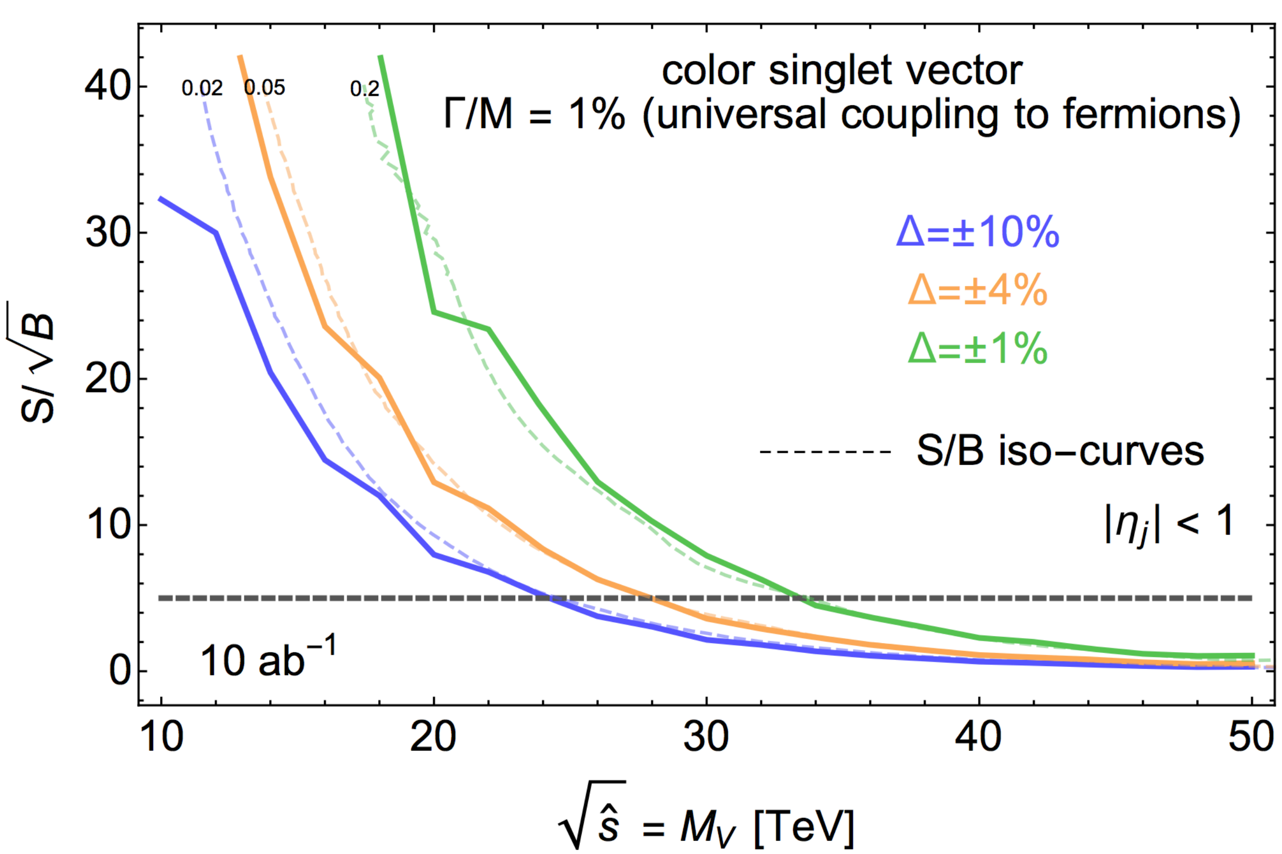
High Mass resonances

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

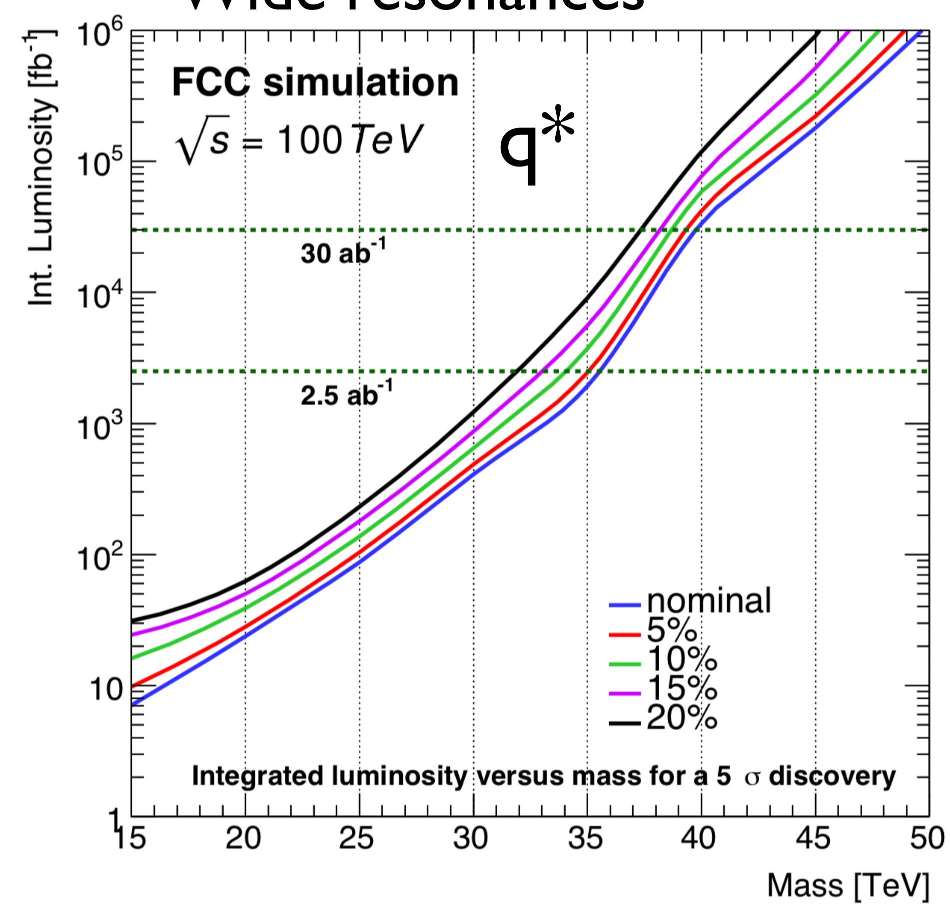
[1606.00947]



Narrow resonances



Wide resonances



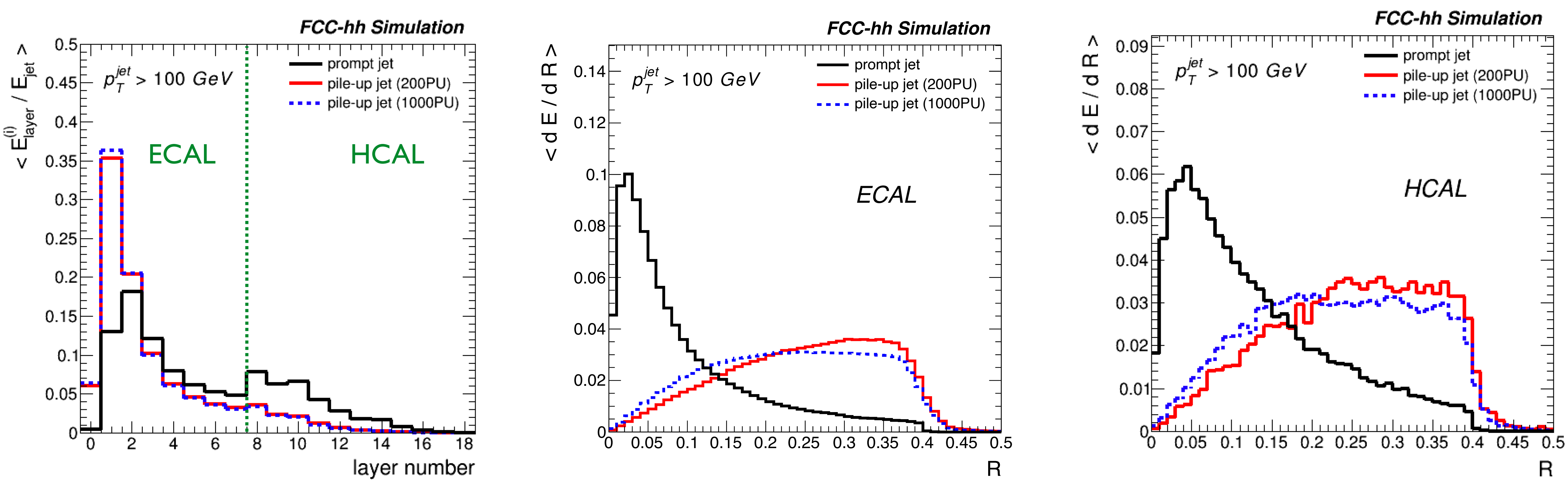
Jet Pile-Up identification

- 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)



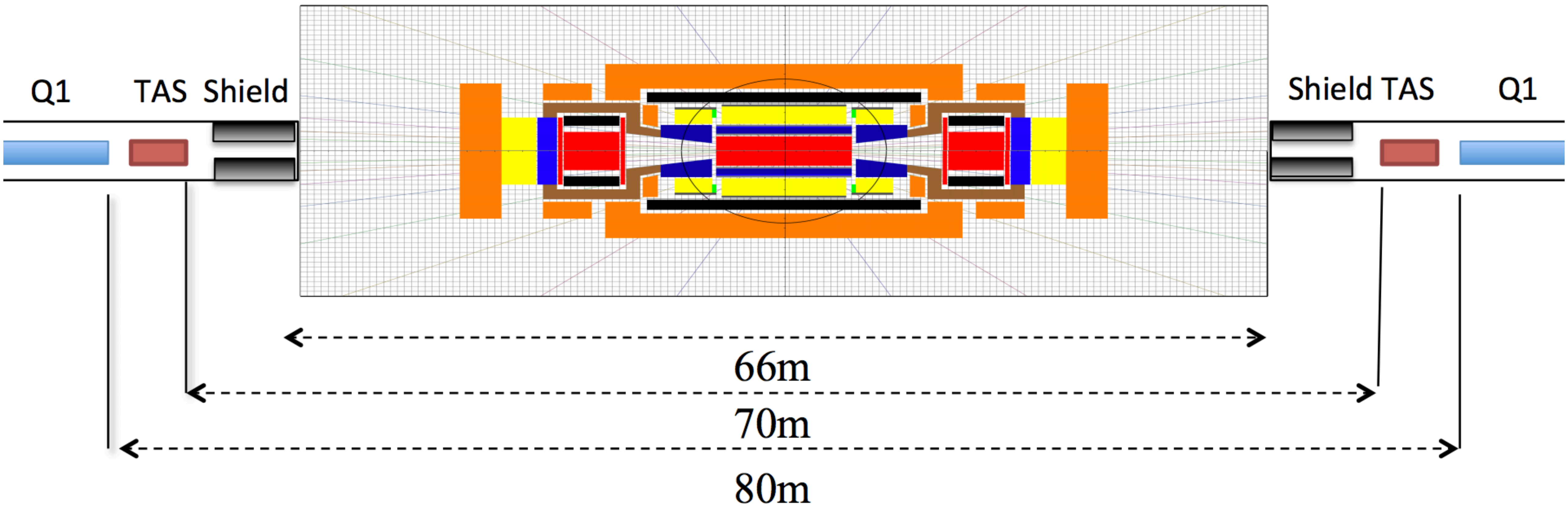
100 TeV machine parameters

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.

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^-)

MDI

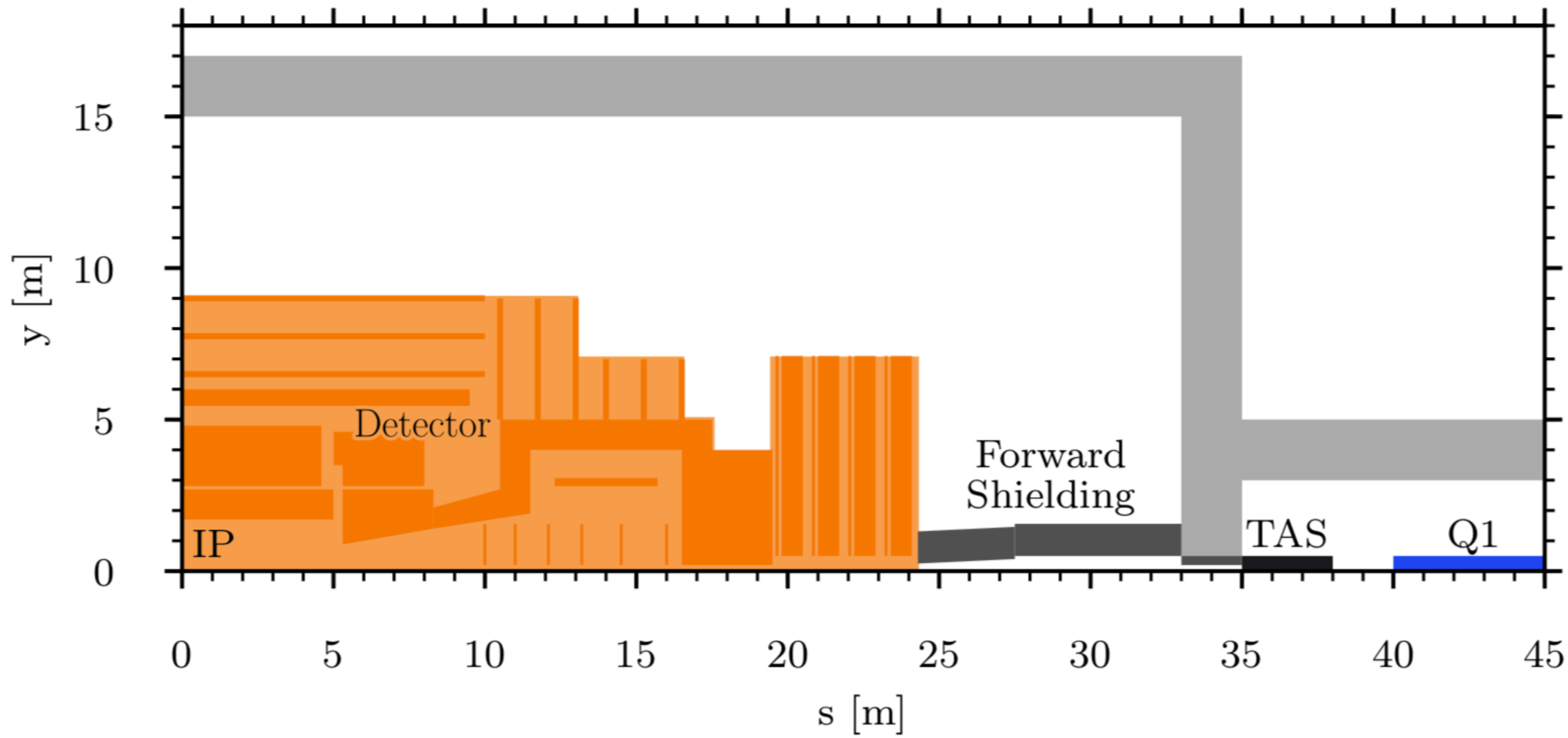


Figure 2.4: Detector region layout.

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