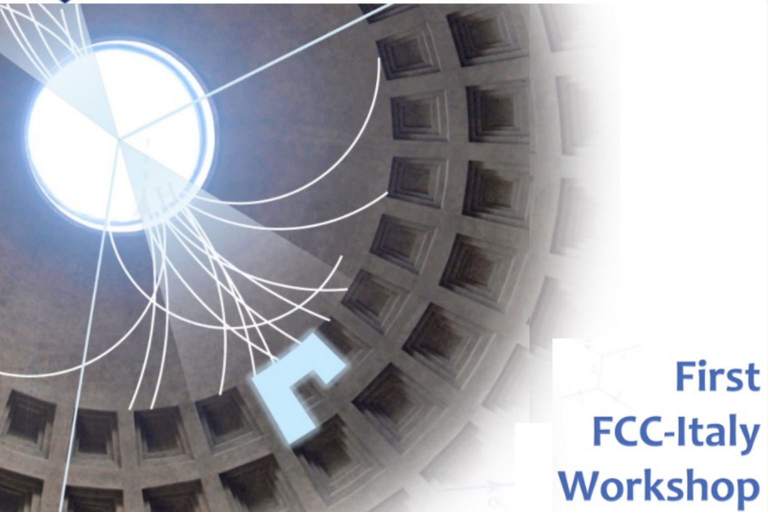


FCC-hh: Detector challenges

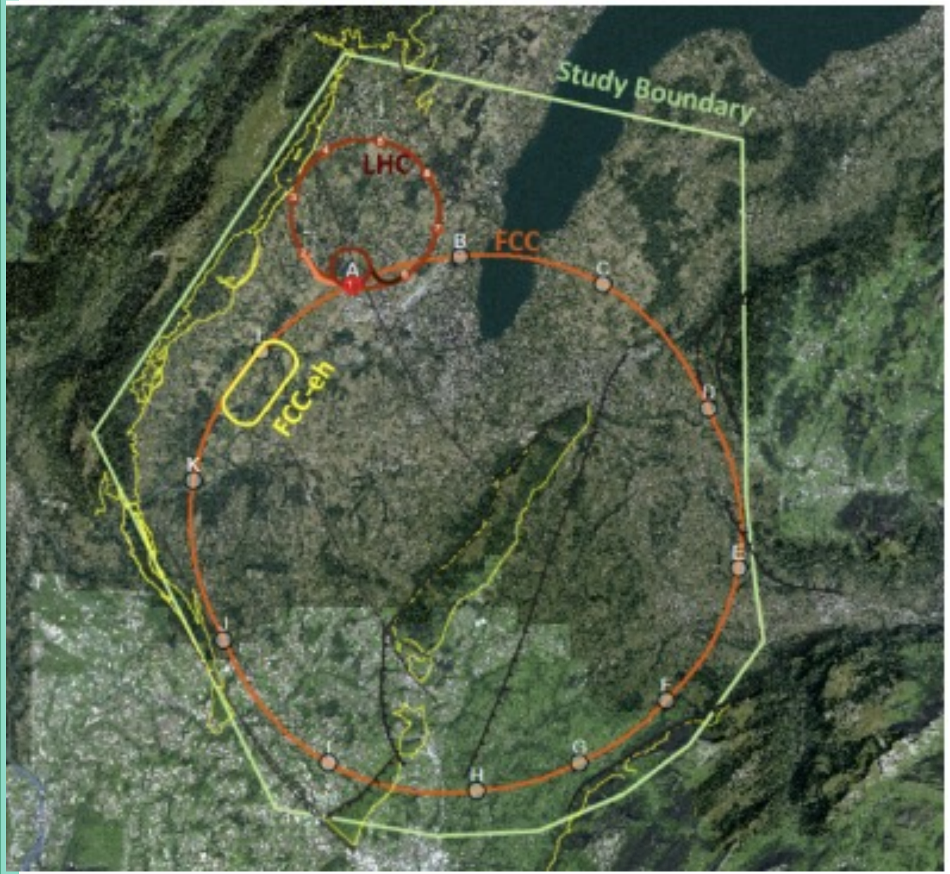
Monica D'Onofrio

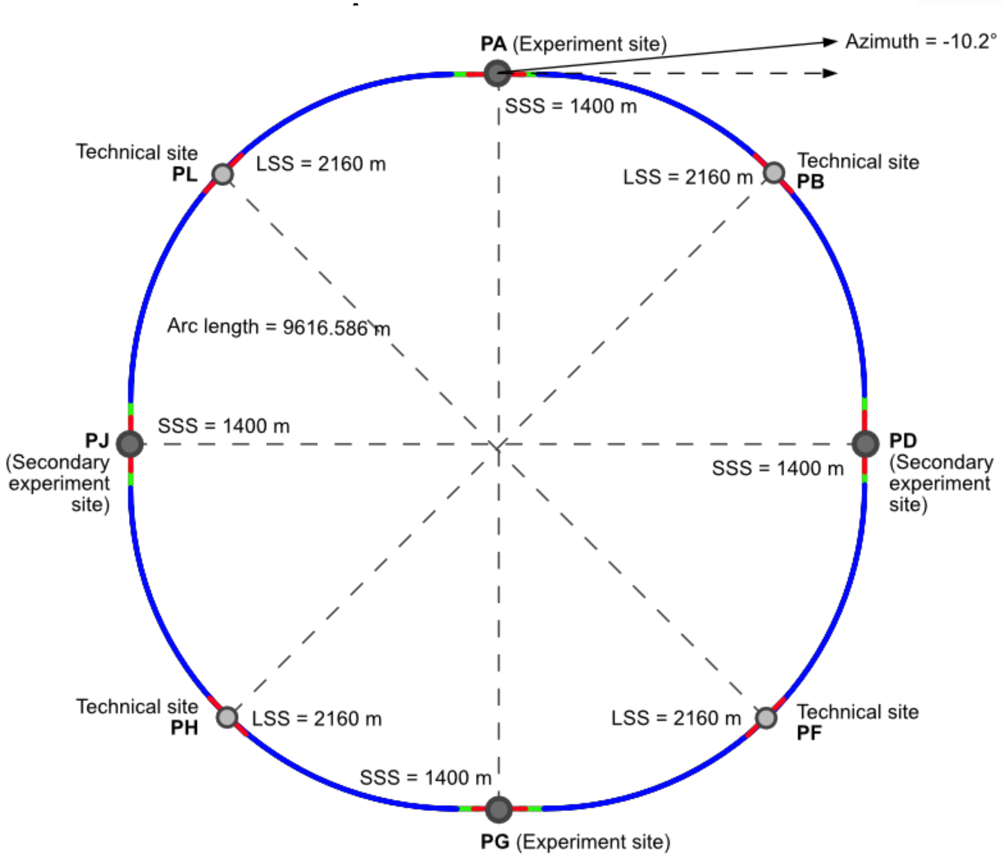
University of Liverpool

FCC-Italy Workshop, Rome
22/3/2022

The FCC-hh machine

- FCC-hh is currently the stage 2 of the FCC integrated programme **(now 2065+)**
  - It can be operated also in Ion-mode
  - Operations can happen **concurrently** with eh an ERL that provides an electron beam (~ 60 GeV)





20 ab^{-1} p.e.(accelerator goal)

30 ab^{-1} used as target foreseeing (at least partial) combination of datasets from two experiments

Recently, the idea of four experiment-points has been discussed + updates on FCC length and layout

Snowmass submission: 2203.07804

Outline

- The FCC-hh clearly has an enormous potential – 100 TeV c.o.m. energy, huge (+30/ab) datasets
- A detector at the FCC will have to operate in challenging conditions, i.e. high (~1K) pile-up
- Extreme granularity, excellent energy-momentum resolution beyond the LHC detectors, together with novel algorithms will be needed to achieve optimal object reconstruction and identification

The **physics programme** depends **substantially** on experimental conditions and **crucially** on detector developments → **I will use a few highlights of the physics goals to illustrate this**

Lot of material available and used for this talk
FCC Volume 1, FCC-hh, published in EPJ ST 228, 4 (2019) 755-1107

Physics studies from older or newer documents e.g.: https://arxiv.org/pdf/1606.00947.pdf, CERN-ACC-2018 -0056.pdf, Eur. Phys. J. C (2019) 79:569 from M.Mangano et al. for benchmark comparisons, CERN-FCC-PHYS-2020-0004, *Eur. Phys. J. C* **80**, 1030 (2020)
European Strategy Briefing book: https://arxiv.org/abs/1910.11775

Detector studies from ECFA Roadmap https://indico.cern.ch/e/ECFADetectorRDRoadmap
Presentations from Phil Allport, Martin Aleksa and other published documents in http://cds.cern.ch/record/2784893/files/

Disclaimer: selected topics + not yet considering in full recent results from Snowmass

Physics potential of FCC-hh: Higgs physics

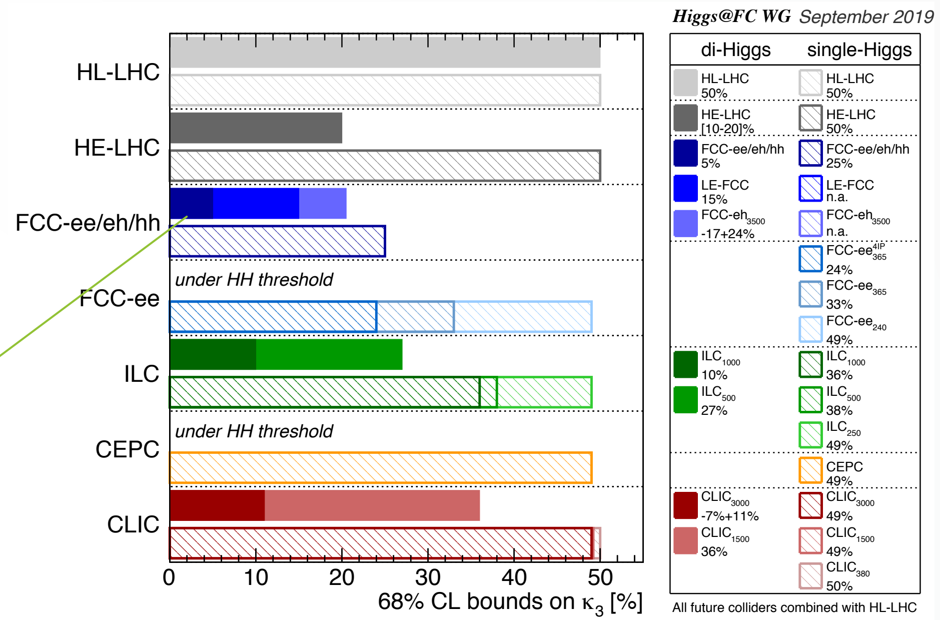
Di-higgs

Higgs **self-coupling** and nature of EWSB will remain unknown even after HL-LHC (which will get to a O(50%) precision) and FCC-ee (indirect only).

Di-Higgs: feasibility studies employed several final states

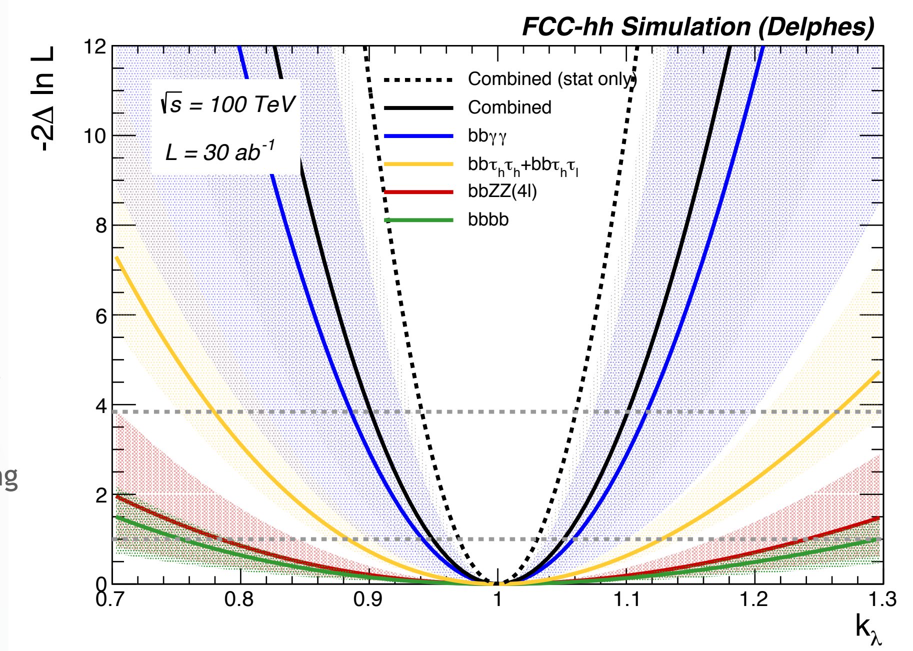
Updates after ESPPU20 indicates an expected precision on the self-coupling depending on systematics assumptions:

$$\boxed{\delta_{\kappa_\lambda} = 3.4 - 7.8\% \text{ at } 68\% \text{ CL}}$$



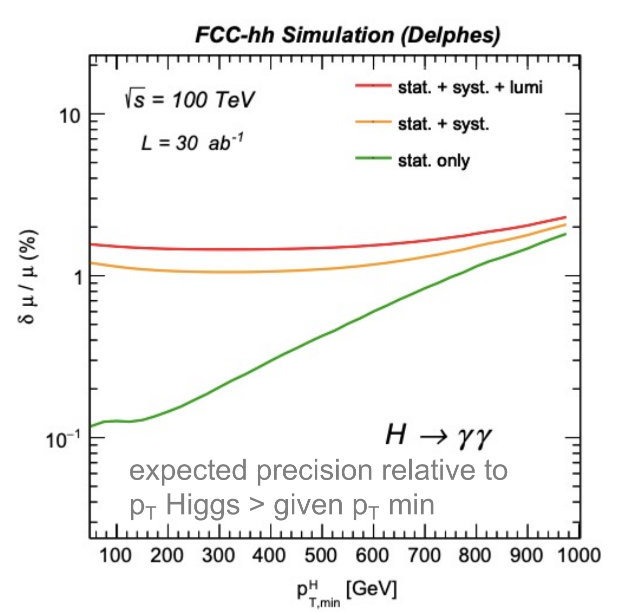
new result presented for Snowmass by another team very consistent,

Other studies with NN on-going



Eur. Phys. J. C **80**, 1030 (2020)

But also: **differential σ_{Higgs} measurements up to high p_T^{Higgs}** can probe new physics affecting Higgs dynamics up to scales of several TeV.

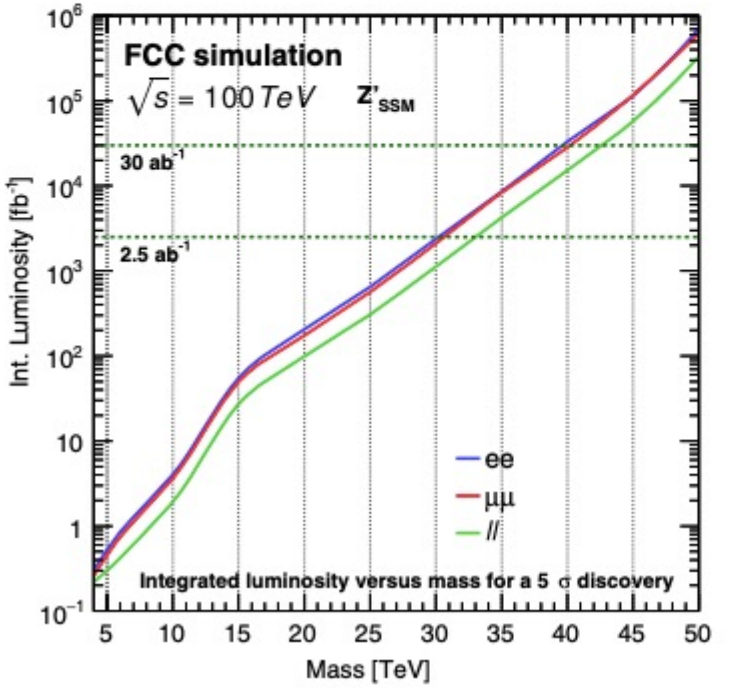


Physics potential of FCC-hh: high mass new particles

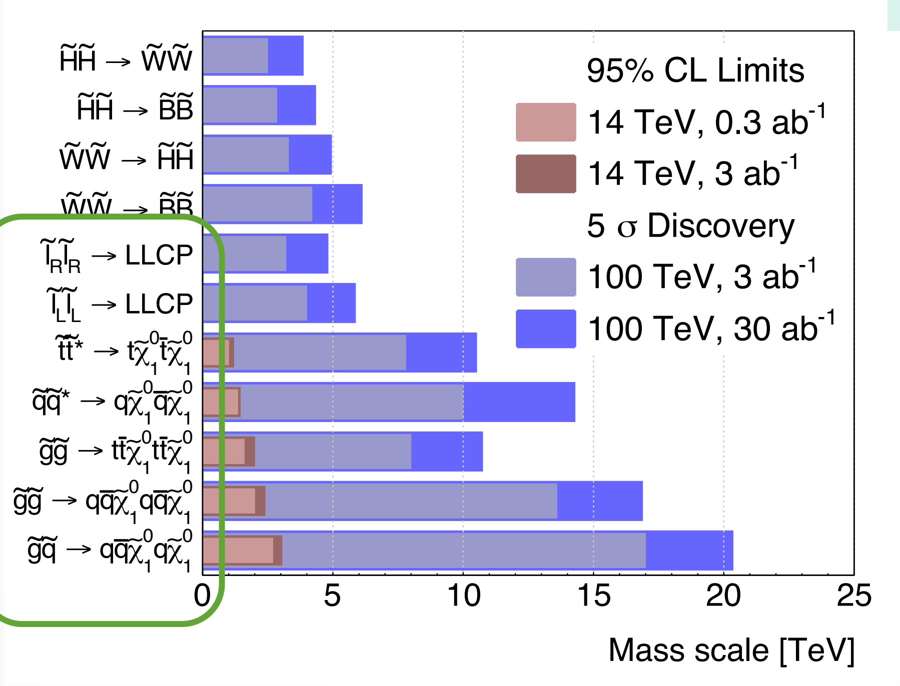
Evidence for the existence of heavier particles from flavour observables or precision EW/Higgs measurements will require direct probes → FCC-hh is the only machine that can achieve that within the current technological landscape

Increase in c.o.m energy → discovery reach @ high mass ~ 7 times larger than at the (HL-) LHC

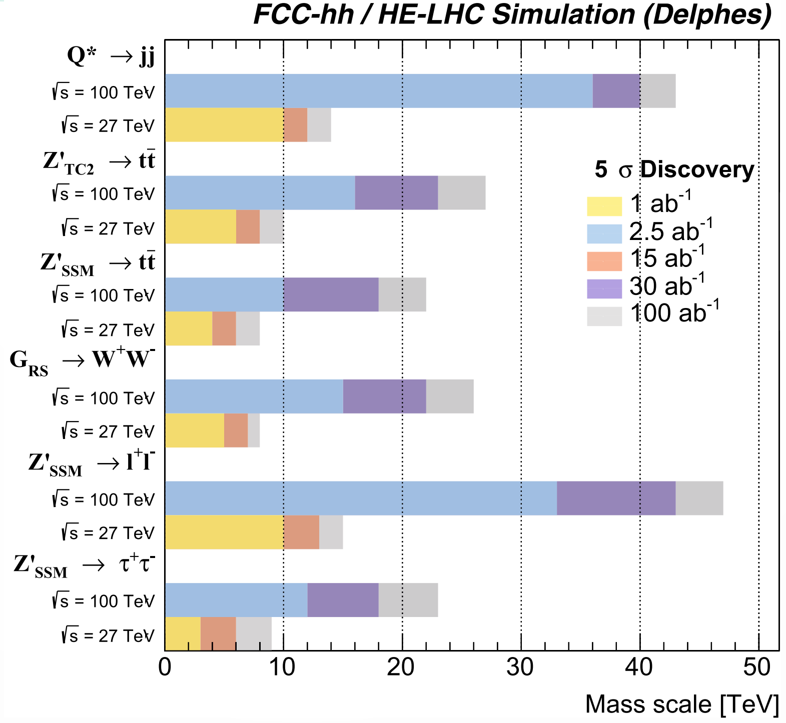
High statistics is crucial → define the needed dataset for discovery



Searches for SUSY particles



Searches for heavy resonances

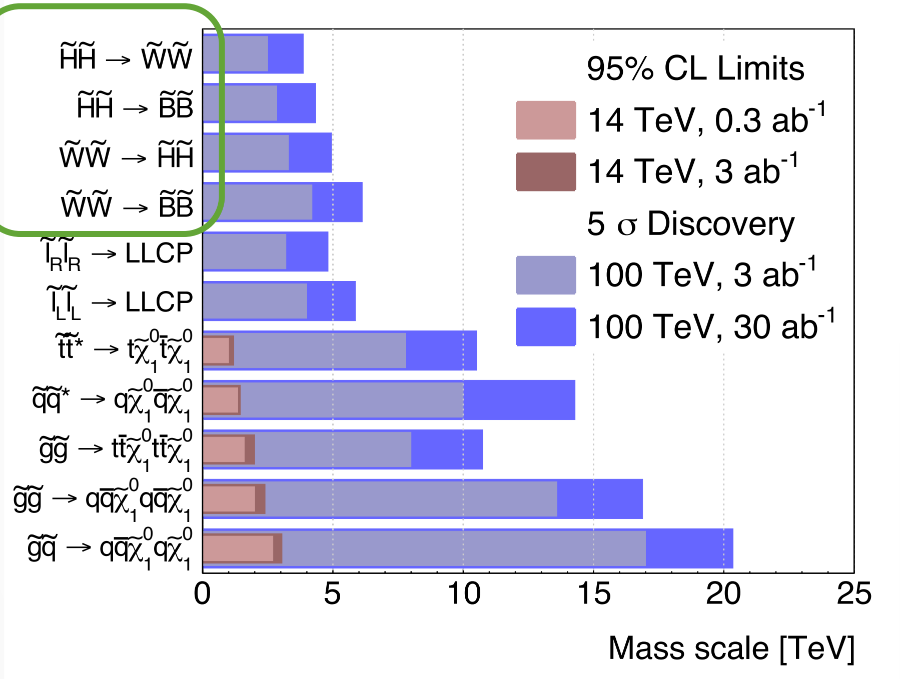


$30\ ab^{-1}$ used as target

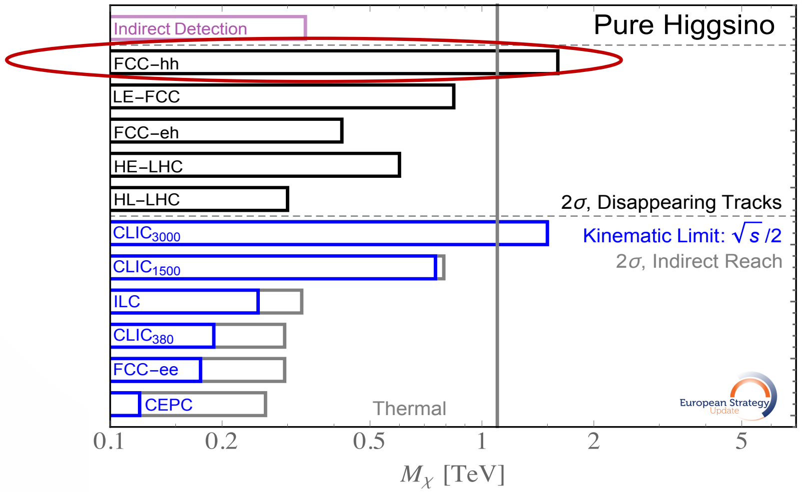
Physics potential of FCC-hh: dark matter

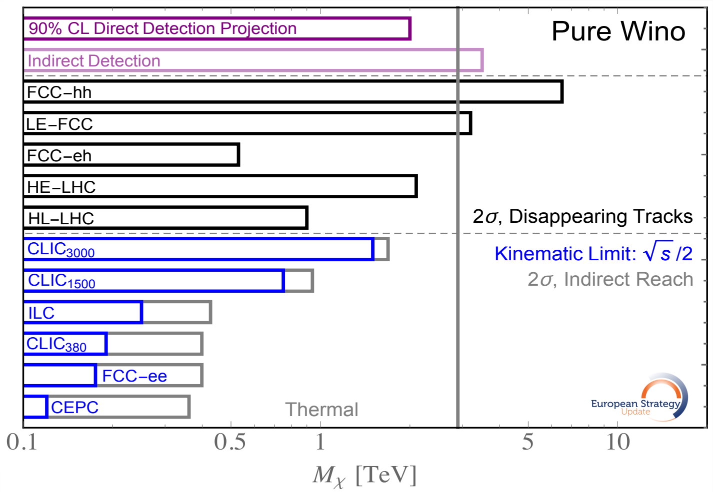
- FCC-hh will be the first collider capable of producing weakly-interacting particles with masses up to a few TeV, hence complementary to direct DM experiments
- SUSY and general WIMP DM models foresee a DM candidate with thermal relic mass in the **2-3 TeV** region (*Wino*, triplets under SU(2)) or in the **1-1.2 TeV** region (*Higgsino*, doublets under SU(2))
  - both reachable i.e. exploiting **disappearing track analyses**

Searches for SUSY particles (EWK)



dark matter wino/higgsino models

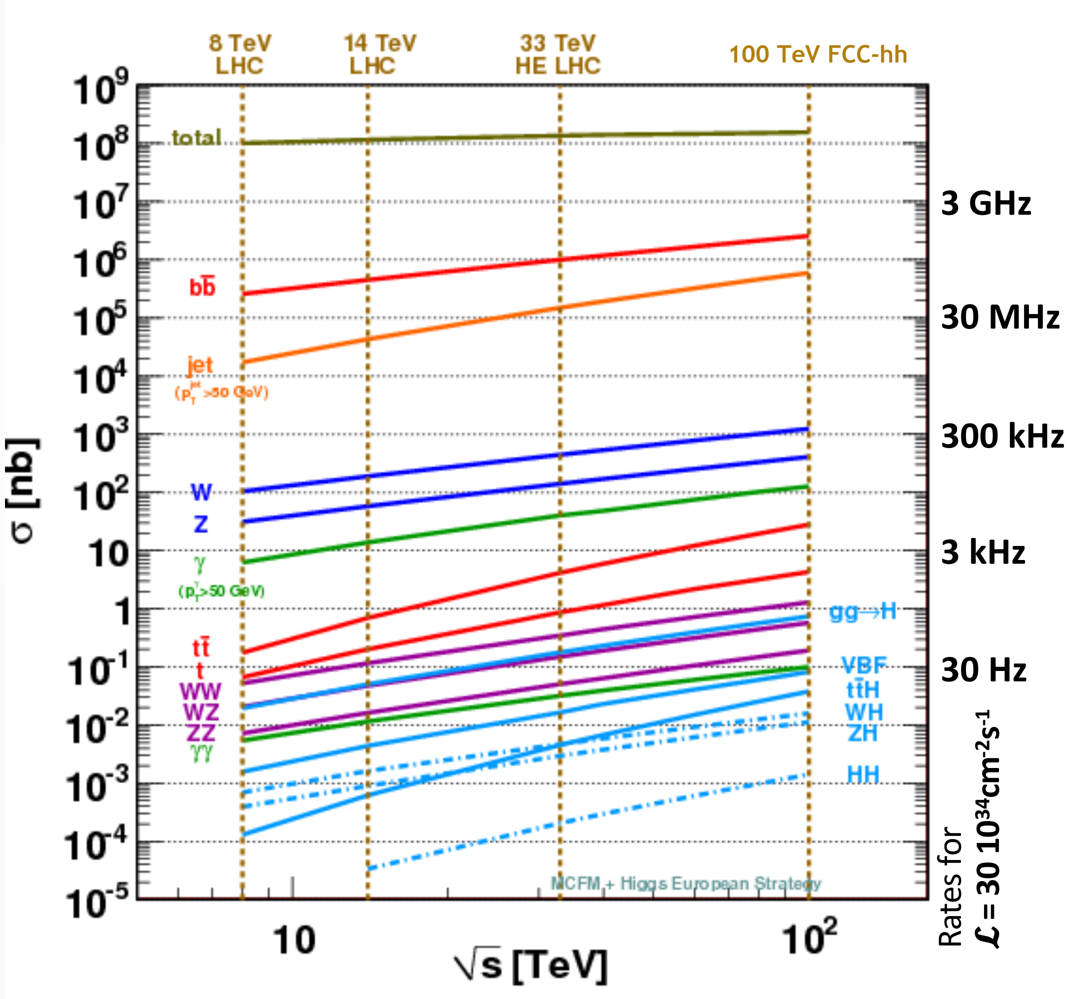




Also relevant: monojet, mono-X and **soft lepton** searches (e.g. for higgsino-like semi-compressed scenarios)

Production rates and conditions

- Cross sections for interesting processes increase substantially, but it comes at a price!
- Challenge for triggering and reconstruction

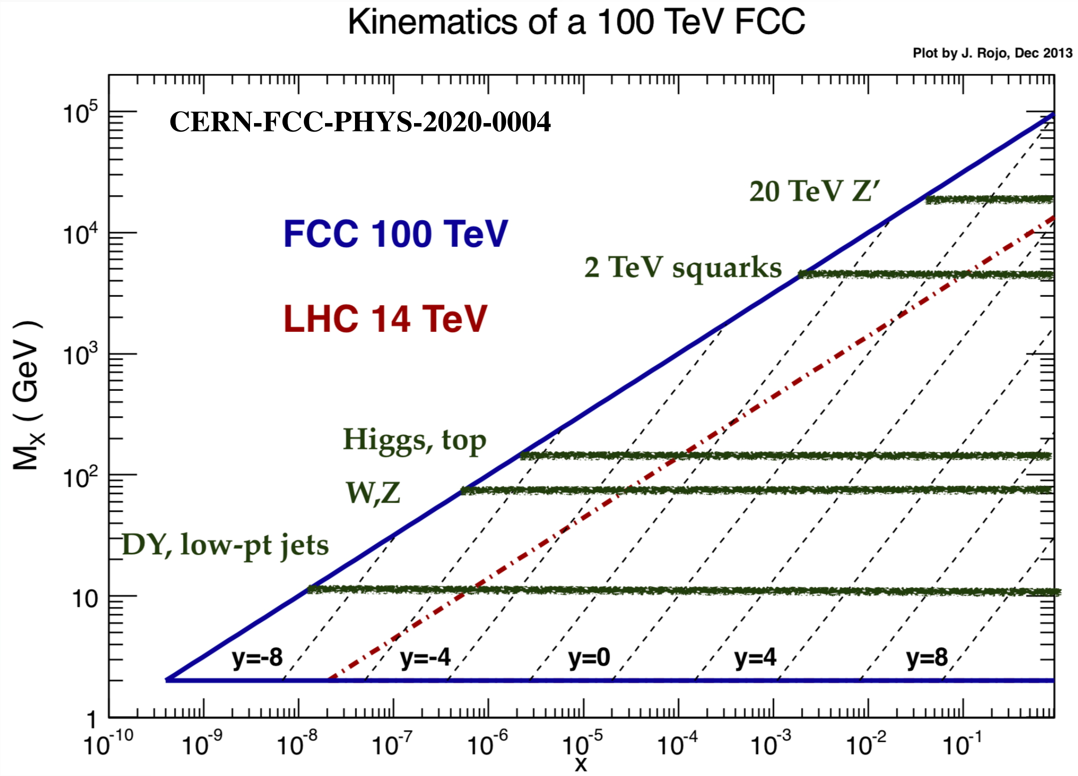


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [340]	mb	80	80	86	103
σ_{tot} [340]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950
Total number of pp collisions	10^{16}	2.6	26	91	324
Charged part. flux at 2.5 cm, est. (FLUKA)	$\mathrm{GHz\,cm}^{-2}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est. (FLUKA)	$10^{16}\ \mathrm{cm}^{-2}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est. (FLUKA)	MGy	1.3	13	54	270 (300)
$dE/d\eta\vert_{\eta=5}$ [340]	GeV	316	316	427	765
$dP/d\eta\vert_{\eta=5}$	kW	0.04	0.2	1.0	4.0

almost 1000 pile-up
10 GHz/cm^2 charged particles
Up to 10^{18} cm^{-2} 1 MeV-n.eq. fluence for 30 ab^{-1}

unprecedented particle flux and radiation levels

Kinematic coverage and geometrical acceptance

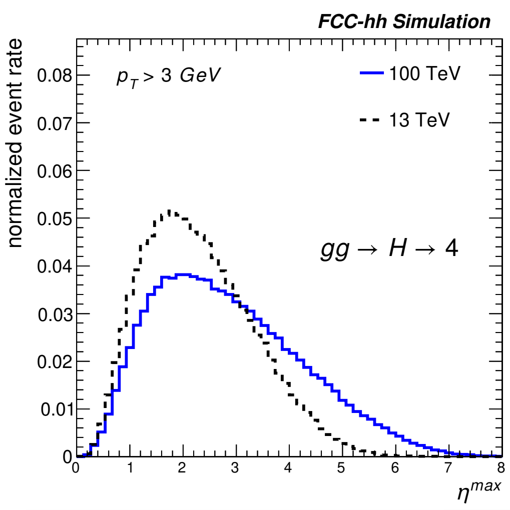


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [341]	$\|\eta\| <$	3	3	3.3	4.5
VBF jet peak [341]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [341]	$\|\eta\| <$	4.5	4.5	5.0	6.0
90% H → 4l [341]	$\|\eta\| <$	3.8	3.8	4.1	4.8

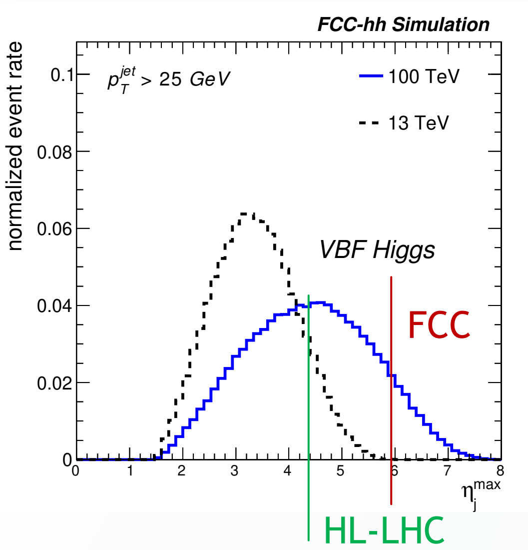
- Processes occurring at a given $Q^2 = M_X$ will be produced on average from collisions that are more asymmetric at 100 TeV compared to 14 TeV → particles will be produced **more forward**

Example for ggF and VBF Higgs production

highest lepton pseudo-rapidity

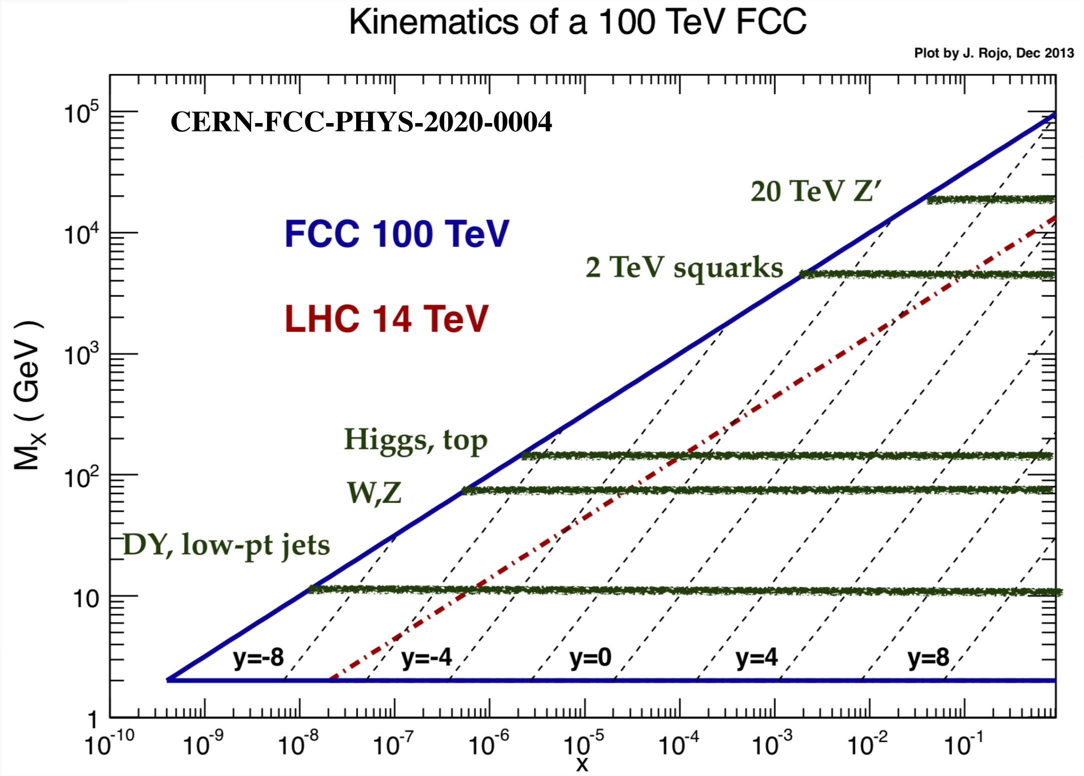


maximum jet pseudo-rapidity



→ Set stringent requirements on detector acceptance

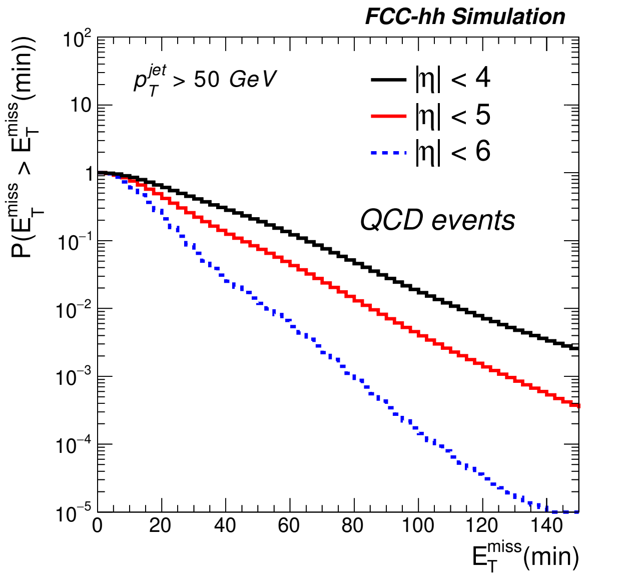
Kinematic coverage and geometrical acceptance



Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
90% $b\bar{b}$ $p_T^b > 30$ GeV/c [341]	$\|\eta\| <$	3	3	3.3	4.5
VBF jet peak [341]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [341]	$\|\eta\| <$	4.5	4.5	5.0	6.0
90% $H \to 4l$ [341]	$\|\eta\| <$	3.8	3.8	4.1	4.8

- Processes occurring at a given $Q^2 = M_X$ will be produced on average from collisions that are more asymmetric at 100 TeV compared to 14 TeV → particles will be produced **more forward**

Assuming that forward detectors can operate in extreme environment, this could be an advantage for Missing E_T resolution (better coverage in eta)

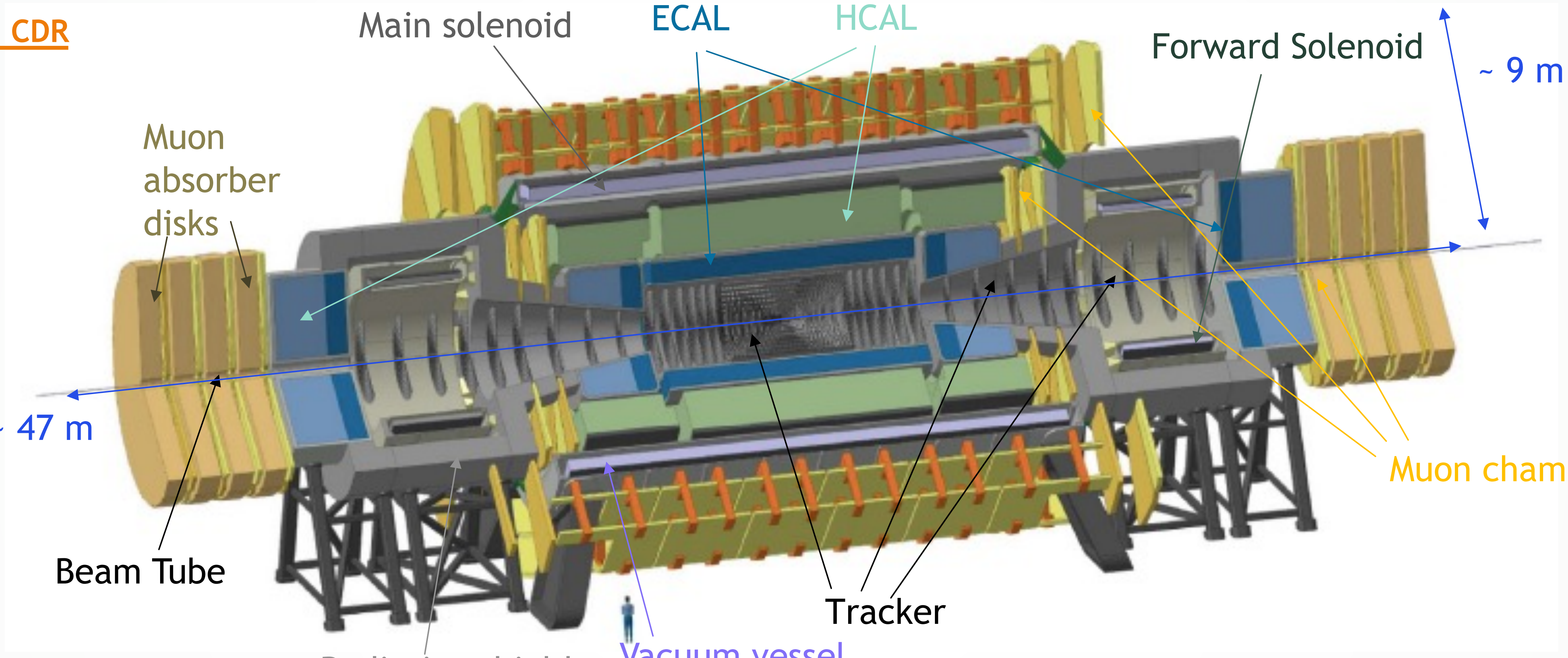


Missing E_T is fundamental for Dark Matter searches in mono-X final states, SUSY particles and more

Probability of reconstructing E_T^{miss} greater than E_T^{miss} (min) in di-jet QCD events

A possible layout of a detector for the FCC-hh

FCC-hh CDR

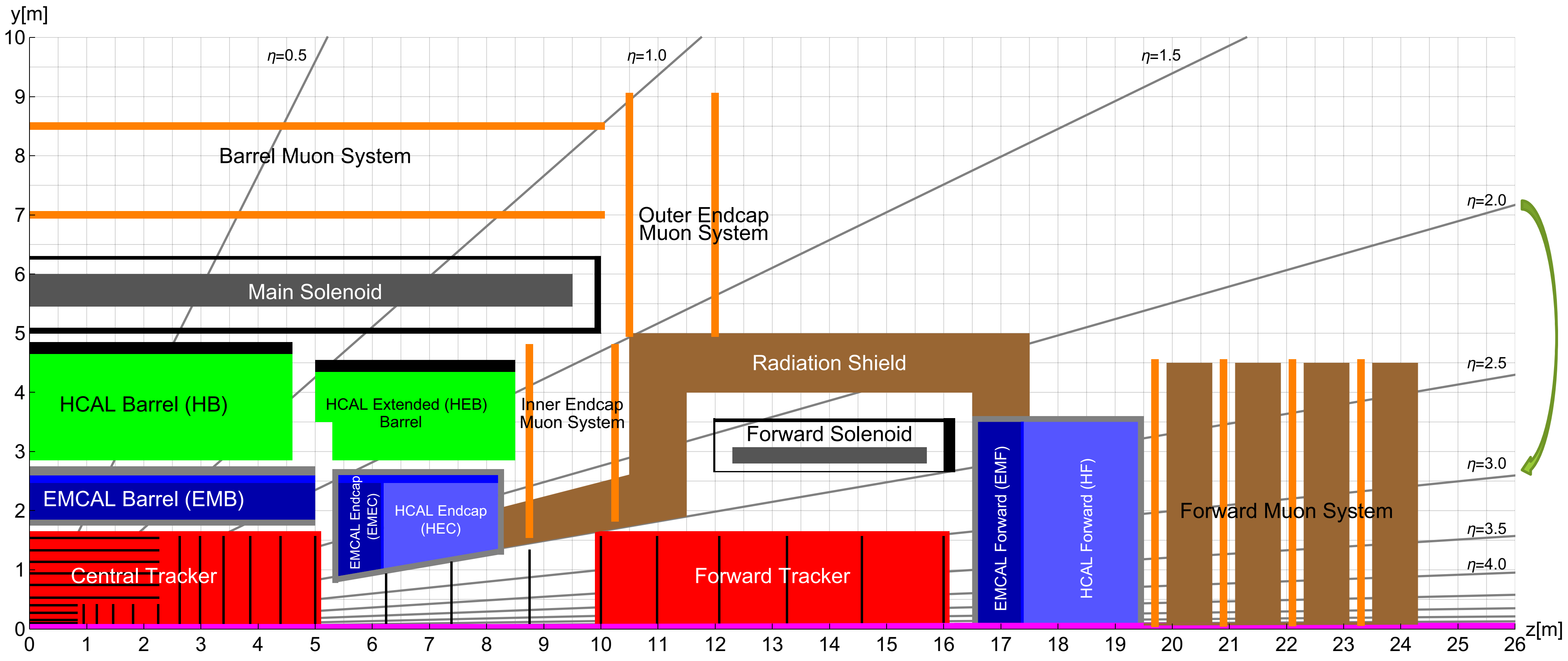


- Conceptual designs so far based on current detectors. In this case, 4-T main solenoid and forward solenoids
  - As for CMS, central tracker and calorimeters placed in the bore of the main solenoid.
- Assume cavern length of 66 m

Used in default DELPHES simulations

A possible layout of a detector for the FCC-hh (2)

- Various options are explored → aim of CDR was to prove that with known detector techniques the primary physics goals could be met and study potential limitations
- More on feasibility studies planned for 2025 (as highlighted in Michael talk yesterday)



Forward detectors up to eta ~ 6 (and forward solenoid needed)

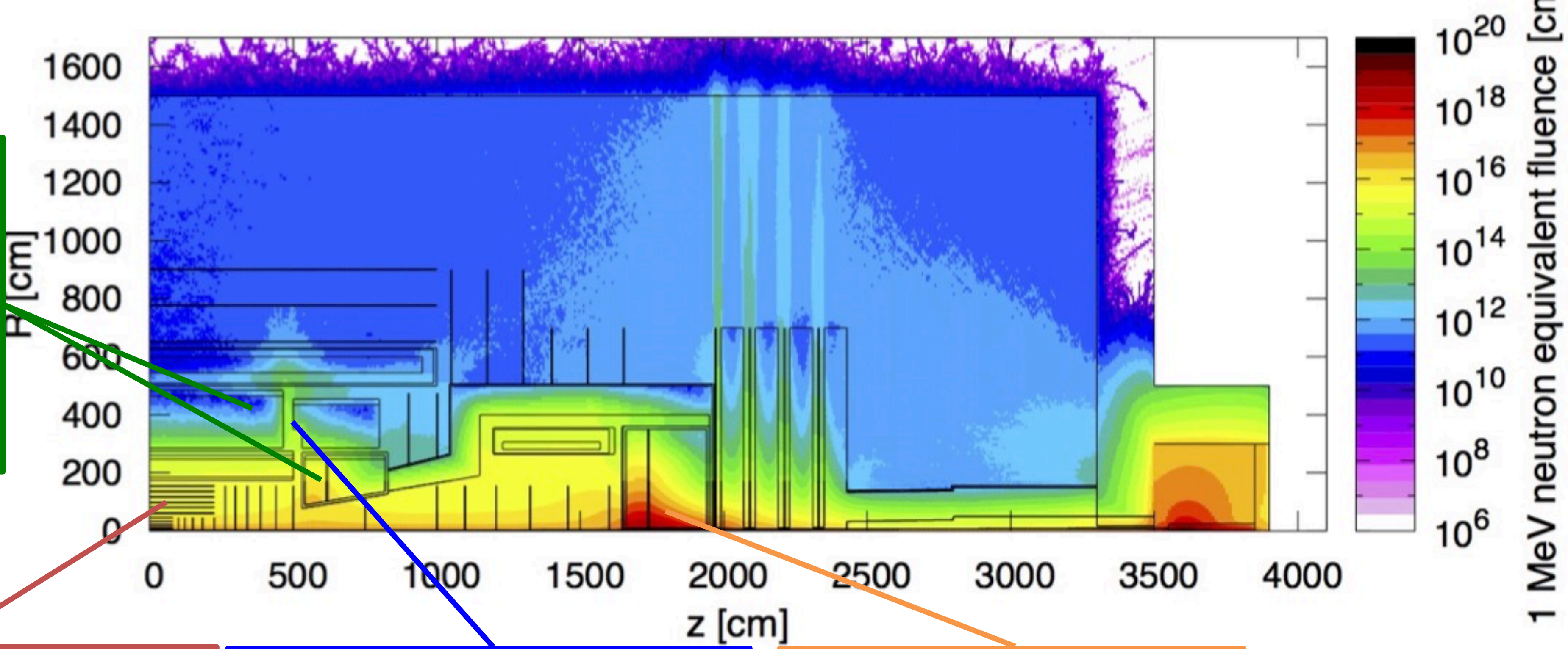
Radiation shield needed to cope with high fluxes and connect endcap and forward calorimeter

1 MeV Neutron Equivalent Fluence for 30ab^{-1}

OVERALL: Radiation levels beyond current capabilities for detector technologies
Generally ~10-30 times worse than HL-LHC BUT much bigger for fwd calo and innermost tracking layers

Technologies used for the HL-LHC detectors are only applicable for r > 30 - 40 cm

Barrel calorimeter:
EM-calo: 4 10^{15} cm^{-2}
HAD-calo: 4 10^{14} cm^{-2}
End-cap calorimeter:
EM-calo: 2.5 10^{16} cm^{-2}
HAD-calo: 1.5 10^{16} cm^{-2}



Central tracker:
- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

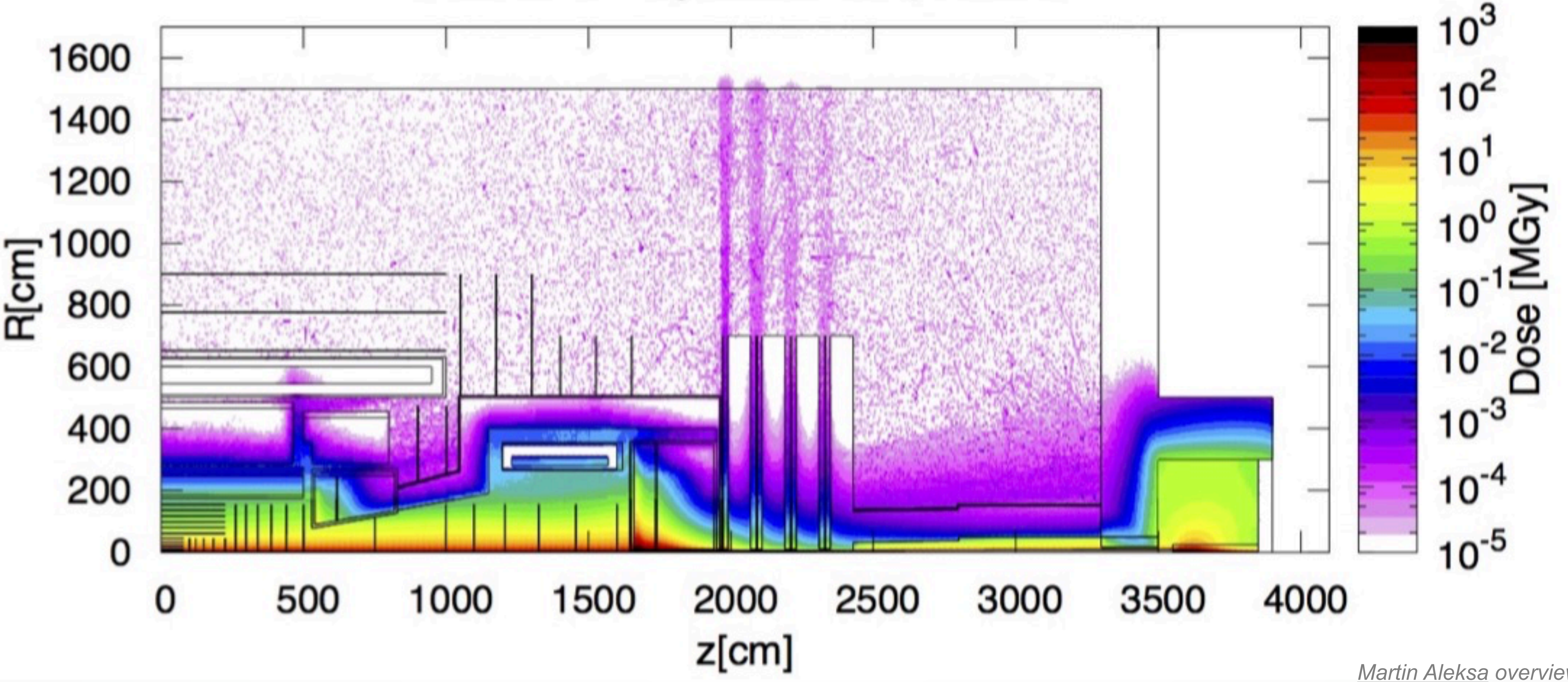
Calorimeter gap:
from 10^{16} cm^{-2} to 10^{14} cm^{-2}

Forward calorimeters:
~5 10^{18} cm^{-2} for both the EM and the HAD-calo

Martin Aleksa overview, 2021

Total Ionizing Dose for $30ab^{-1}$

Dose of 300 MGy (30 Grad) in the first tracker layers.
< 10 kGy in HCAL barrel and extended barrel.

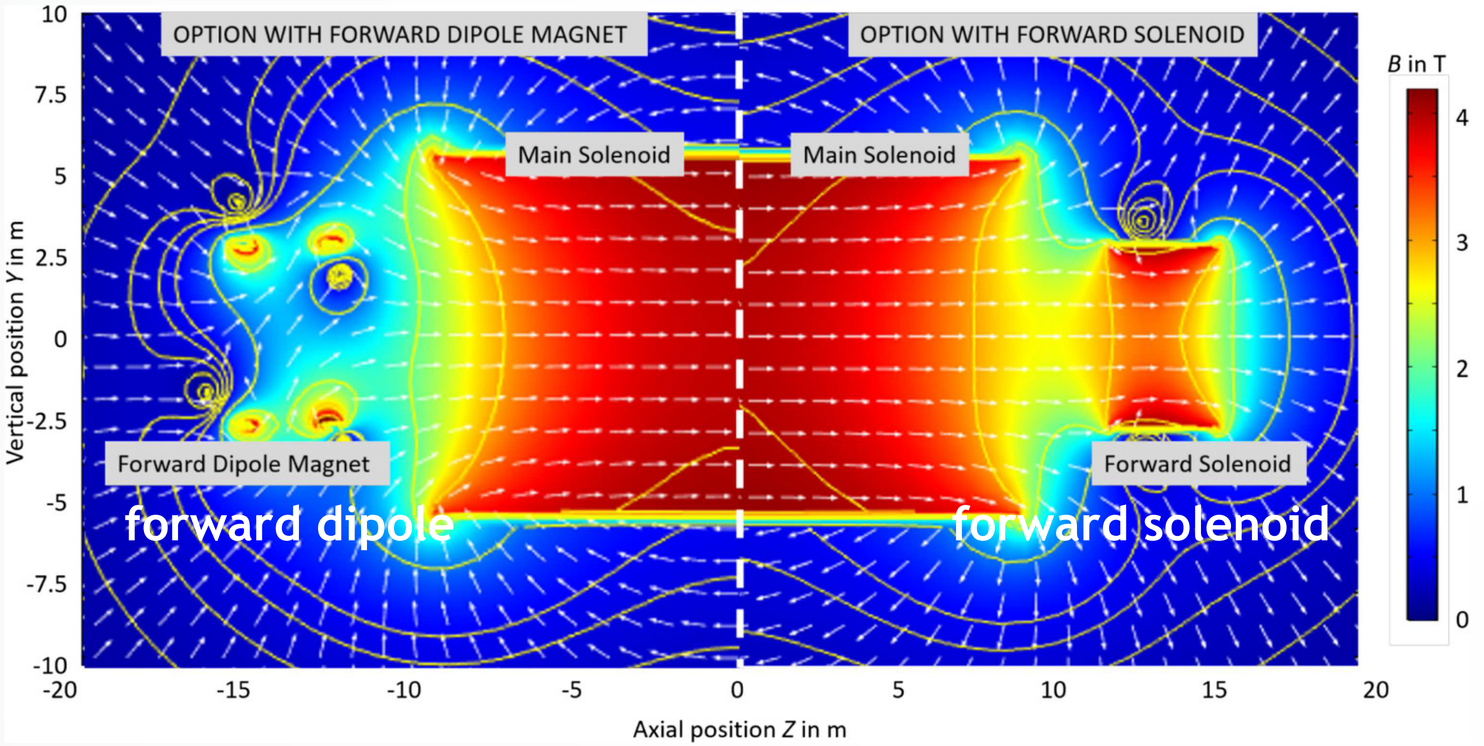


Martin Aleksa overview, 2021

FCC-hh magnet system

- Designed to provide an axial magnetic field of 4 T in the tracker volume:
  - Comprising of a **central solenoid** and **two forward solenoids.**
  - More complex alternatives: two dipoles with a magnetic field of about 4 Tm in both forward regions

cold mass + cryostat around 2000 tons.



Magnetic fieldmap for a central solenoid of 4T

Stored magnetic energy
FCC-hh: ~13 GJ,
ATLAS Magnet System 2.7 GJ
CMS Magnet System 1.6 GJ

Proposed **conductors** for the solenoids are Al stabilised Nb–Ti/Cu Rutherford cables following the experience with ATLAS and CMS

Cryogenic plant: 20 K helium gas at 20 bar pressure to the cavern; magnets cooling based on a thermosiphon that circulates helium through the cold masses.

A global challenge: the tracking detector

- Forward coverage and pile-up have huge impact on the tracking system
- Two proposed layouts, **central ($|\eta|<2.5$) + forward ($|\eta|$ up to 6)**
  - *Flat* geometry
  - *Tilted* geometry - 50% less material budget to be compromised with high rad deposits

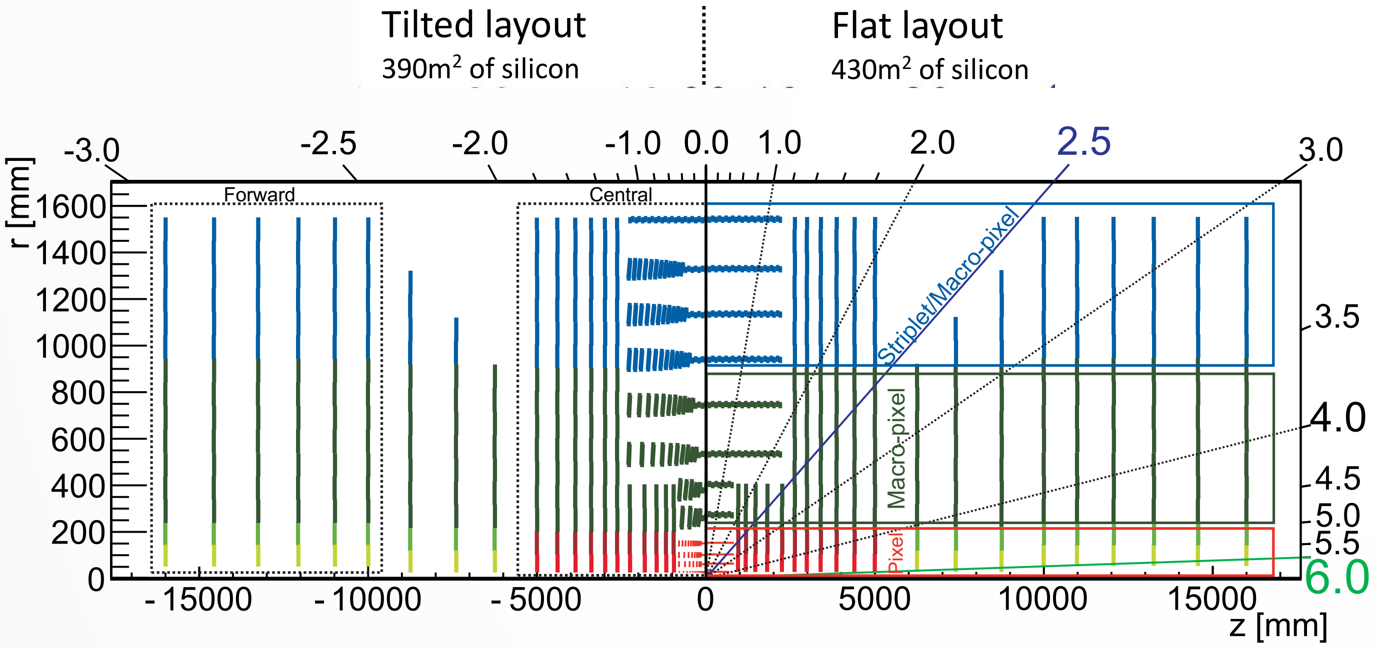


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

Detector options considered so far:

- hybrid (either macro-pixel + strip) solutions;
- CMOS monolithic active pixel sensor (MAPS) options (also to achieve low material).

Survival can be achieved with HL-LHC hybrid pixels but **needs more work.**

BUT: ~300 MGy for micro-electronics and integrated fluence for the sensors of ~ 10^{18} 1 MeV n_{eq}/cm^2 at **r=2.5cm**

→ no current technology can really work under these conditions

A global challenge: the tracking detector

- Forward coverage and pile-up have huge impact on the tracking system
- Two proposed layouts, **central (|η|<2.5) + forward (|η| up to 6)**
  - *Flat* geometry
  - *Tilted* geometry - 50% less material budget to be compromised with high rad deposits

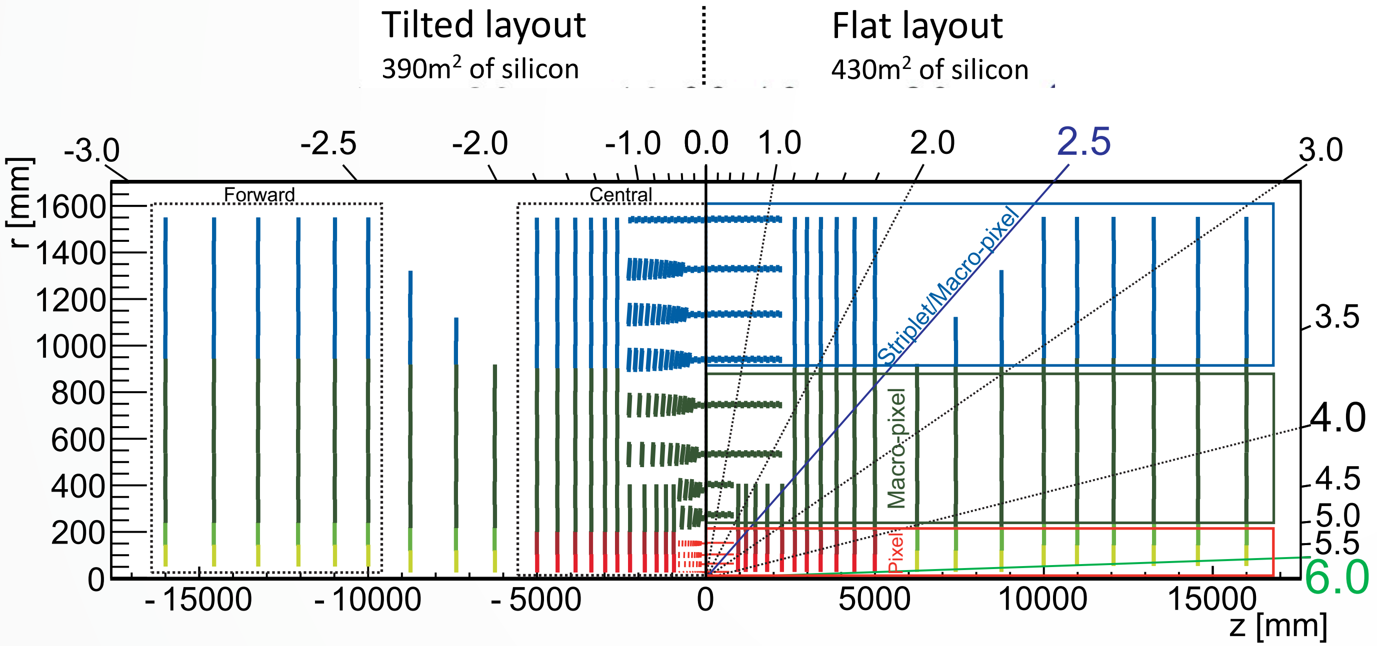
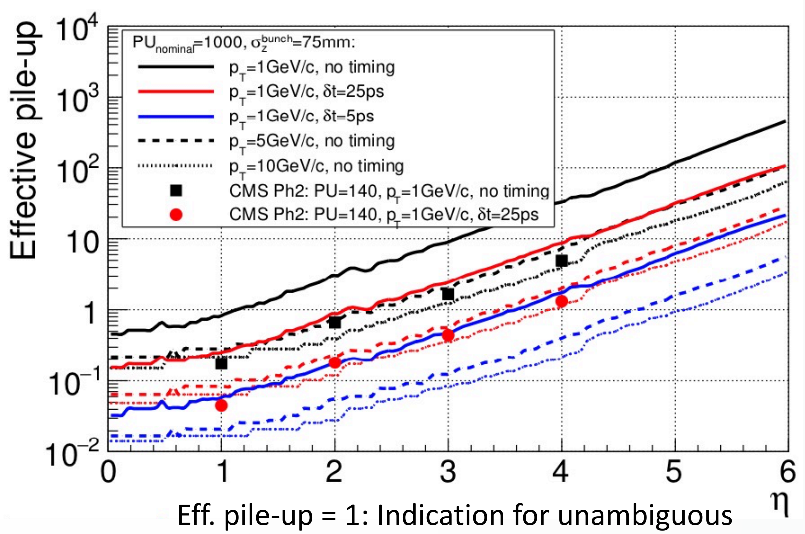


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

Vertex Reconstruction



Eff. pile-up = 1: Indication for unambiguous primary vertex identification

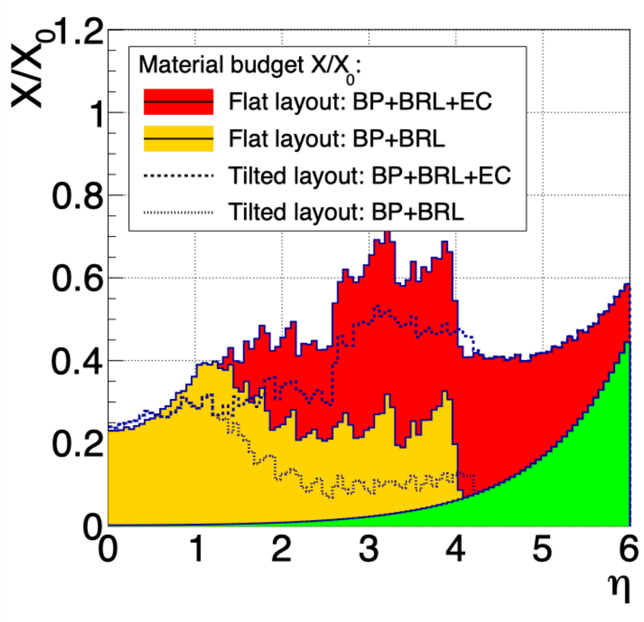
For pile-up suppression: 4D-tracking (with <25 ps timing via **Low-Gain Avalanche Detector** or with 3D Pixel sensors, or other technologies) as opposed to just timing layers (such as LHC high granularity timing detectors).

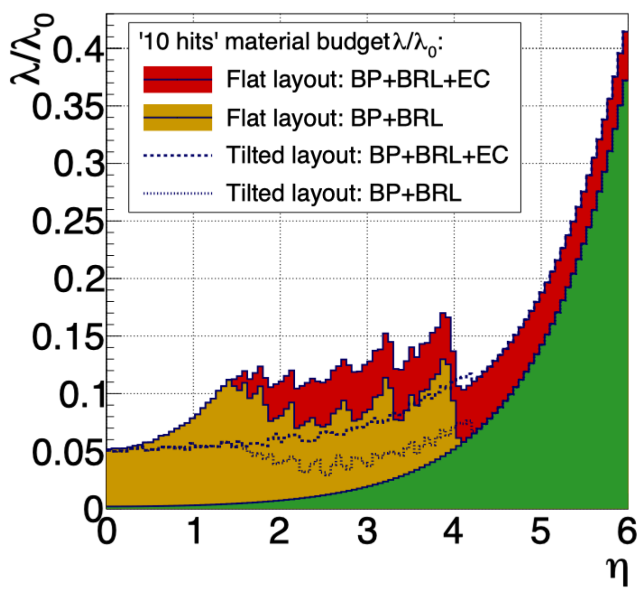
R&D on new technologies needed to achieve <10 ps timing resolution

A global challenge: the tracking detector

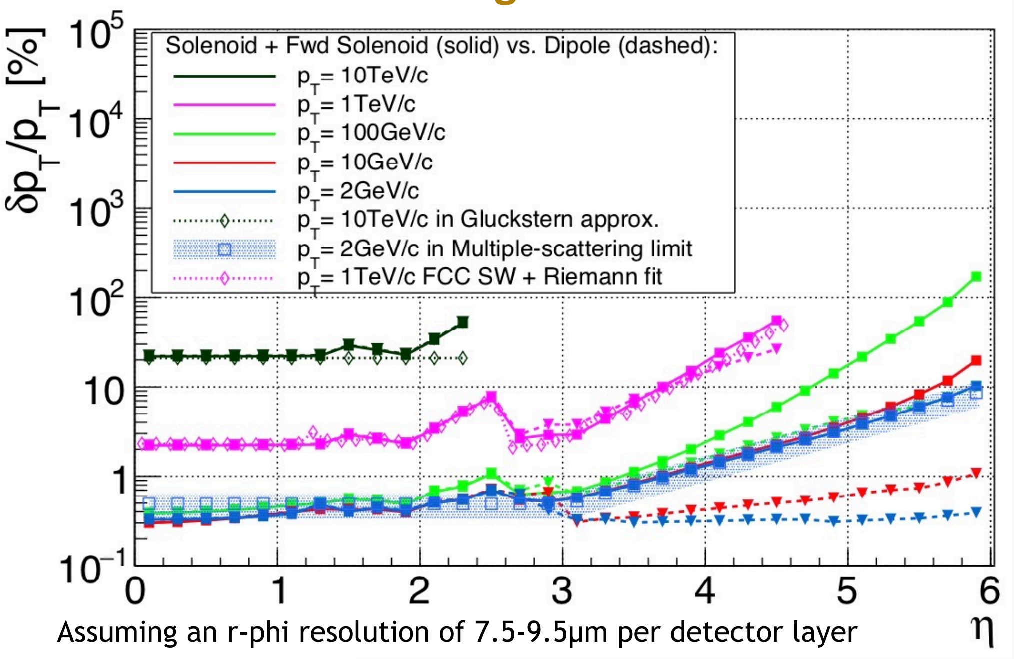
- Forward coverage and pile-up have huge impact on the tracking system
- Two proposed layouts, **central (|η|<2.5) + forward (|η| up to 6)**
  - *Flat* geometry
  - *Tilted* geometry - 50% less material budget to be compromised with high rad deposits

Momentum resolution dominated by **multiple scattering** up to 250 GeV
→` need **low material tracker** (e.g. MAPS)!





Tracking resolution



Assuming an r-phi resolution of 7.5-9.5μm per detector layer

$\delta p_T/p_T \leq$ 10% for
≤ 10 GeV/c and η ≤ 5.8
≤ 1 TeV/c and η ≤ 4.0
$\delta p_T/p_T$ = 20% for 10 TeV/c up to η ~ 2

An example: Relevance of tracking for DM searches

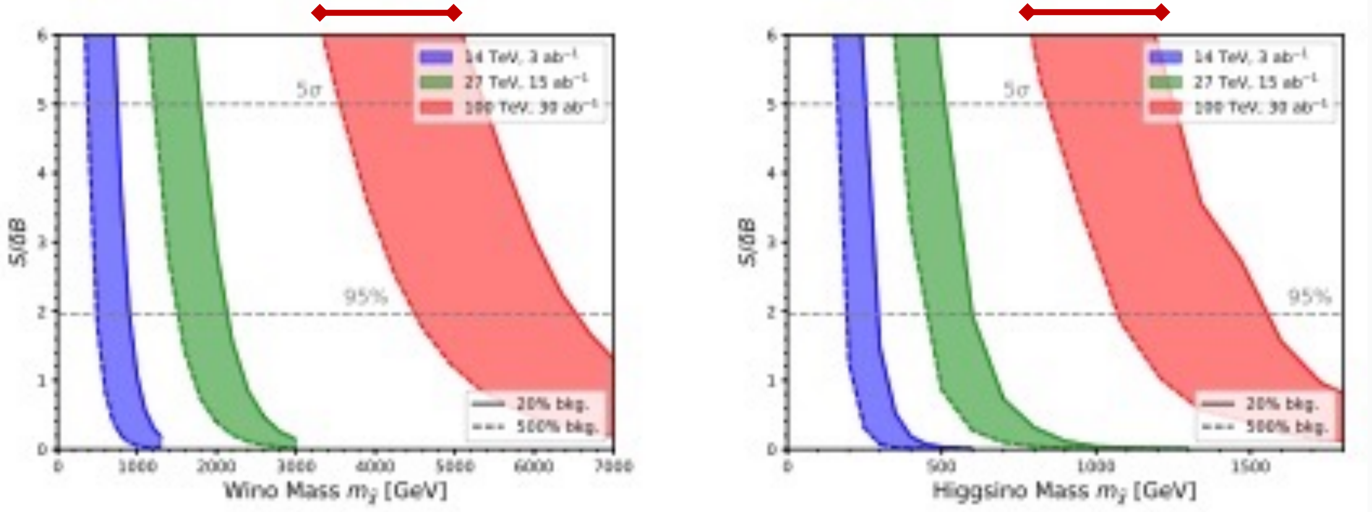
- Disappearing track analyses relies on the reconstruction of short tracks from charged NP (in SUSY, chargino)
- The FCC-hh could provide the ultimate reach for an entire class of DM candidates
- Results at HL-LHC based on strong reduction of fakes background
  - **Assumptions on tracking capability and background are crucial**
- Transverse charged track length must be in specific ranges to retain sensitivity

  12 < d < 30 cm
  @FCC: p_T track in 1-1.4 TeV range

Choice of layout in terms of N pixel layers has crucial **implication** for discovery reach

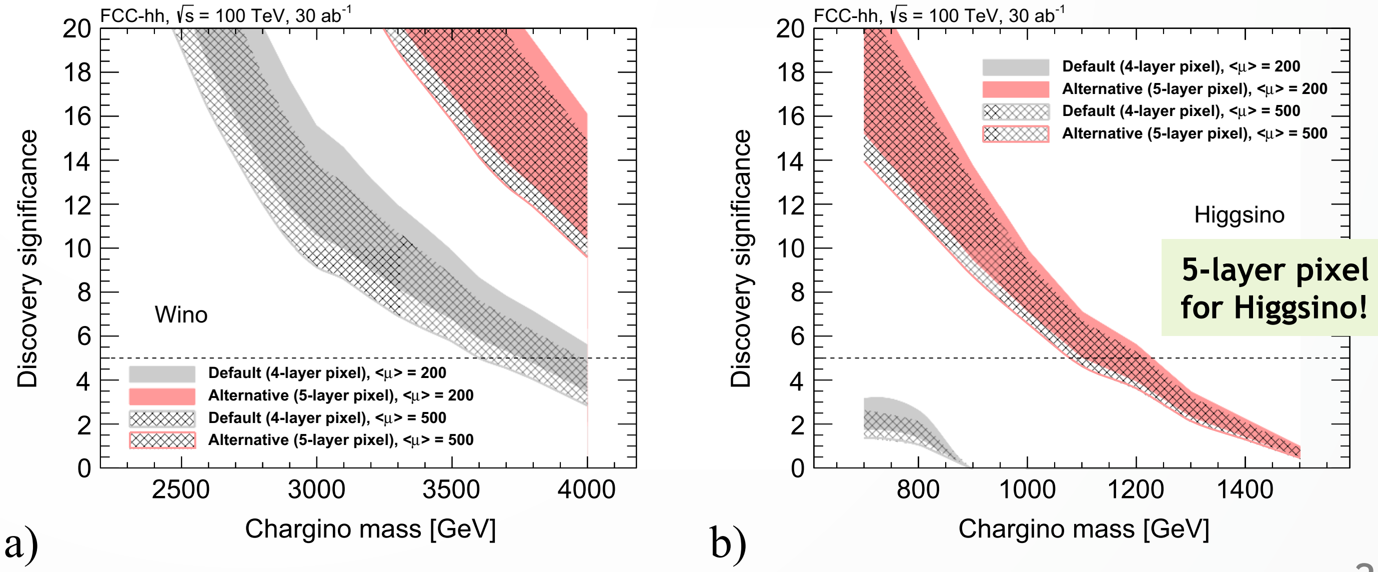
HL-LHC/HE-LHC/FCC-hh

Variation of bkg by factor 5



(Section 4.1 of arxiv:1812.07831)

Band indicates different QCD models of pile-up simulation

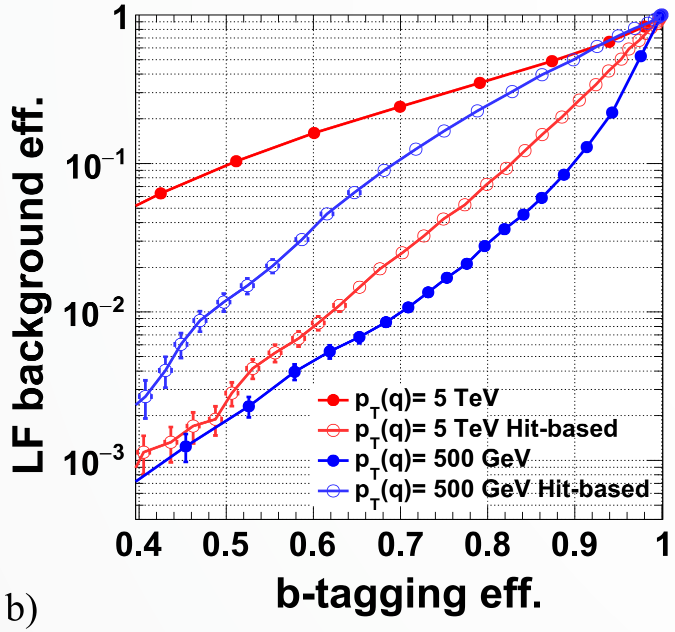


5-layer pixel needed for Higgsino!

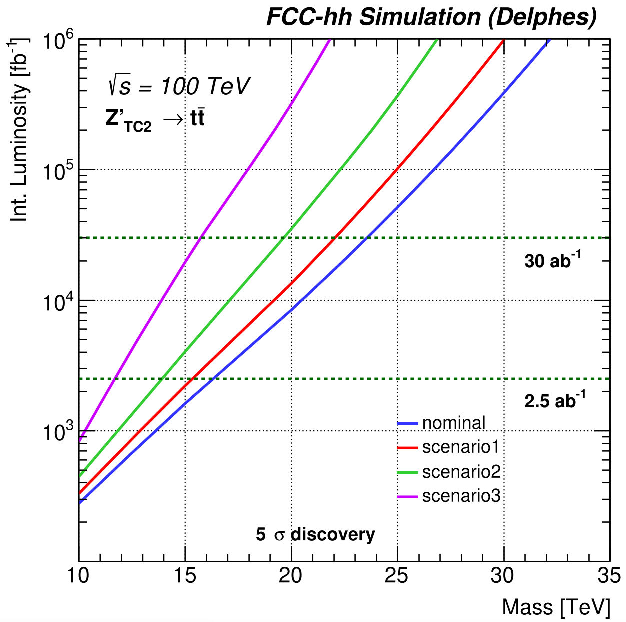
b-tagging requirements: resonances

- Capability of efficiently identify b-jets is fundamental, and closely depending on tracking
- Various scenarios compared in the context of a search for **Z' into a top pair**:
  - 1,2 and 3 corresponding to reduction in efficiency respectively by a factor 25%, 33% and 50% of the nominal efficiency
- Nominal assumptions: B-tag Efficiency $(1 - p_{\mathrm{T}}\ [\mathrm{TeV}]/15) \cdot 85\%$
  - mis-identification efficiency:

Light (b-tag)	Charm (b-tag)	QCD (τ-tag)
$(1 - p_{\mathrm{T}}\ [\mathrm{TeV}]/15) \cdot 1\%$	$(1 - p_{\mathrm{T}}\ [\mathrm{TeV}]/15) \cdot 5\%$	$(8/9 - p_{\mathrm{T}}\ [\mathrm{TeV}]/30) \cdot 1\%$



b)

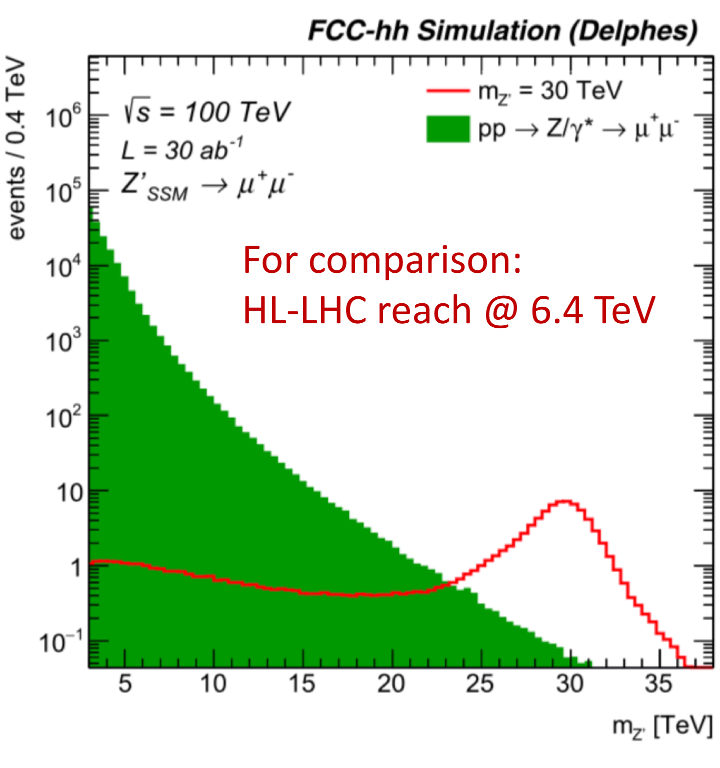


Degrading the performance by 50% increases the needed lumi for a discovery by more than an order of magnitude regardless the mass

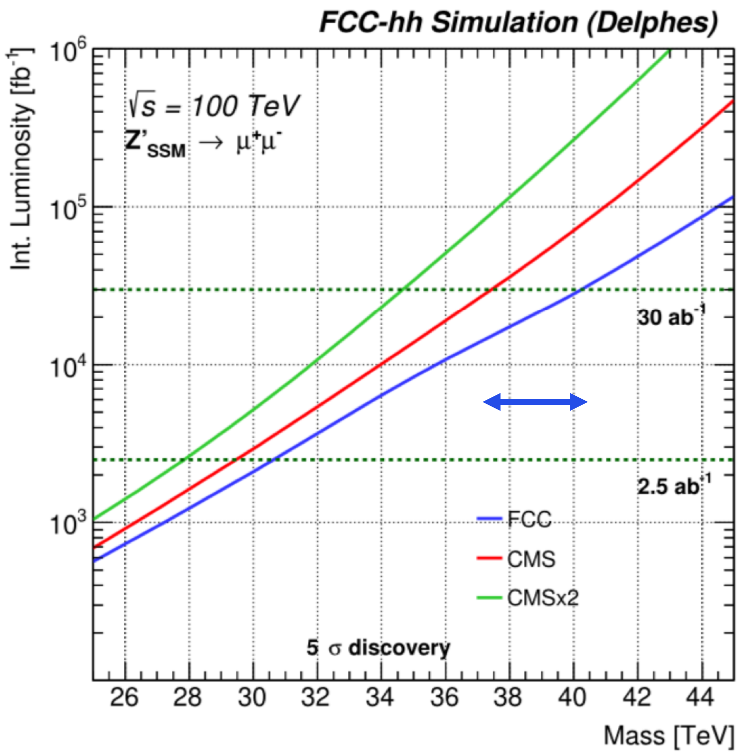
Eur. Phys. J. C (2019) 79:569

High p_T tracking and muons: resonances

- Good reconstruction efficiency and resolution for high p_T objects is fundamental.
- In the case of muons, accurate measurements of the momentum require excellent spatial resolution and precise alignment of the tracking plus muon systems.
- Use **SSM Z-prime into μμ** as benchmark:



Eur. Phys. J. C (2019) 79:569



- Assume **95%** efficiency for reco
- Muon and tracking assumptions used for DELPHES:

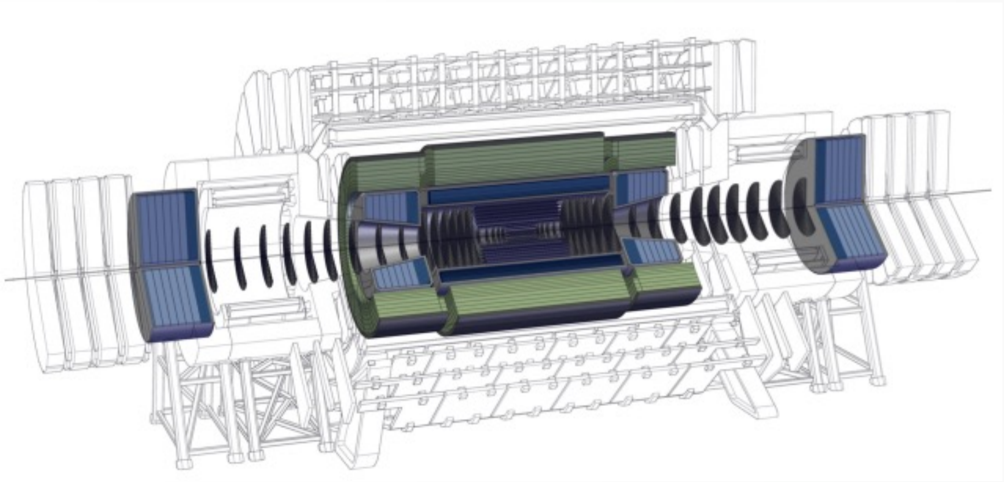
	FCC-hh
$B_z\ (T)$	4
Length (m)	10
Radius (m)	1.5
ϵ	0.95
$\sigma(\eta,\phi)(mrad)$	1
$\sigma(p_T)/p_T$ (tracks)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(p_T)/p_T = 5\%$ (muons)	$p_T = 15$ TeV

If muon resolution is degraded to 40% (straightforward projections of current CMS), 2-3 TeV difference in reach

Calorimetry: ECAL and HCAL

https://arxiv.org/abs/1912.09962

- Issues include unprecedented doses, massive size and huge particle flux
- Optimized for **particle flow**: high longitudinal and transversal granularity crucial

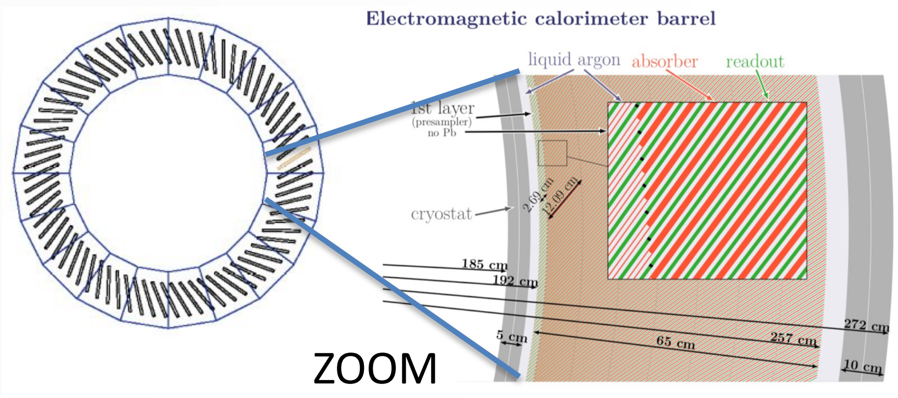


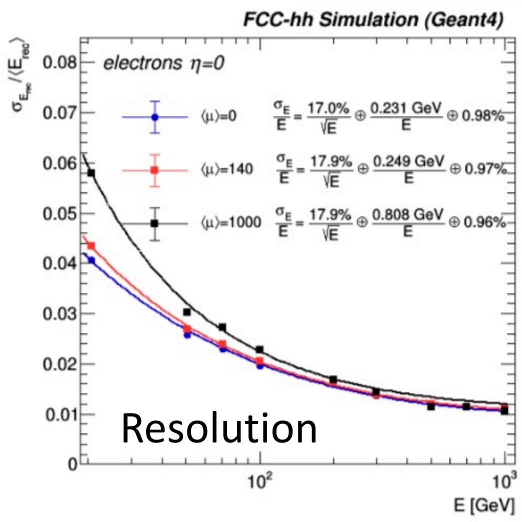
	transverse granularity ($\eta \times \phi$)	# layers	resolution
tracker	0.001	12	$0.5\% \oplus (\frac{p_T}{[\mathrm{TeV}]}) * 1\%$
ECAL	0.01	8	$\frac{10\%}{\sqrt{E}} \oplus 0.3\%$
HCAL	0.025	10	$\frac{50\%}{\sqrt{E}} \oplus 3\%$

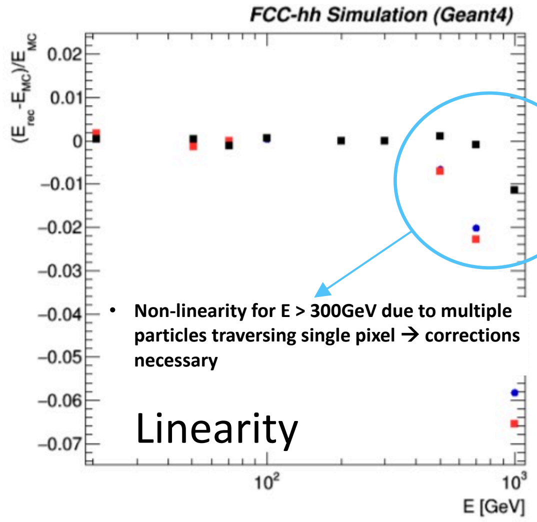
Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

Pile-up might **degrade** performance considerably
→ Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)

LAr ECAL, Pb absorbers (but several options considered)

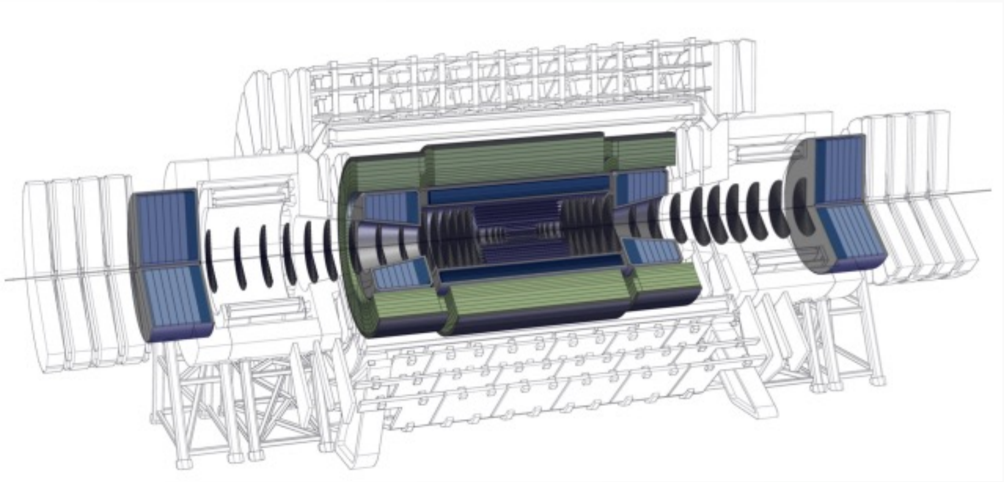






Calorimetry: ECAL and HCAL

- Issues include unprecedented doses, massive size and huge particle flux
- Optimized for **particle flow**: high longitudinal and transversal granularity crucial

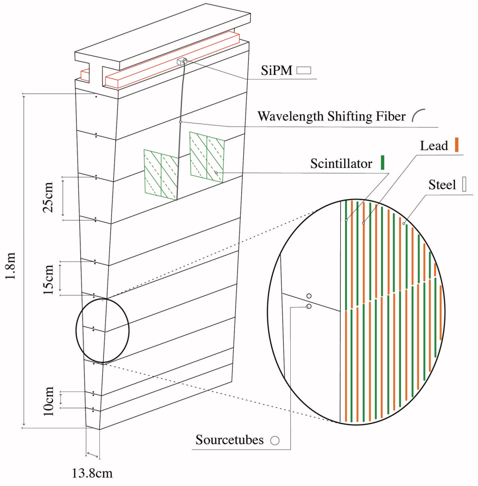


	transverse granularity ($\eta \times \phi$)	# layers	resolution
tracker	0.001	12	$0.5\% \oplus (\frac{p_T}{[\text{TeV}]}) * 1\%$
ECAL	0.01	8	$\frac{10\%}{\sqrt{E}} \oplus 0.3\%$
HCAL	0.025	10	$\frac{50\%}{\sqrt{E}} \oplus 3\%$

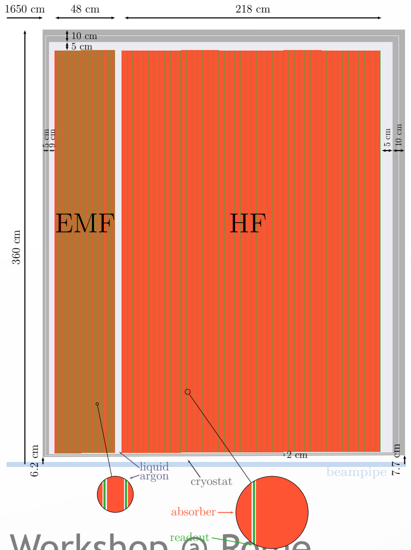
Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

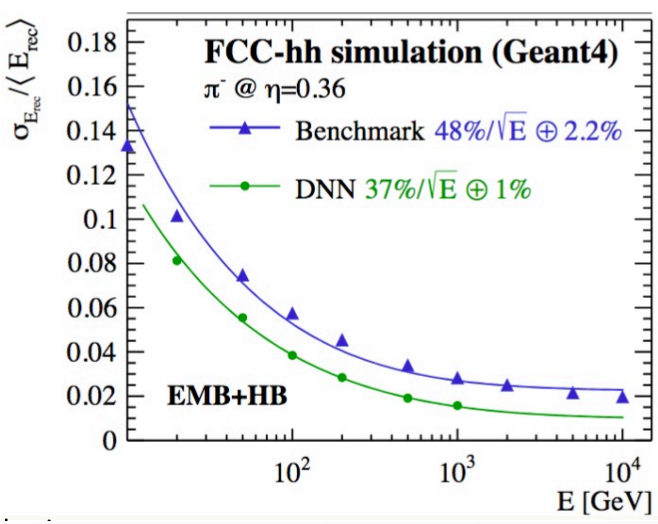
Barrel HCAL:
• ATLAS type TileCal optimized for particle flow with higher granularity
• combined pion resolution can be improved with NN calibration
Endcap and Forward HCAL:
• Radiation hardness major challenge

Tile Barrel HCAL



Forward CAL (E+H)

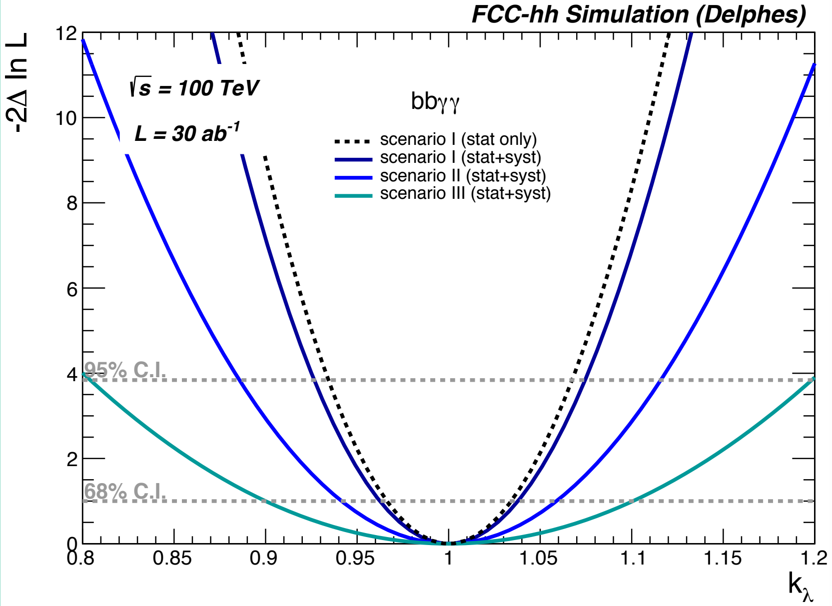




Di-higgs: impact of e/γ resolutions

- For di-higgs studies but also rare decay processes (e.g. Zγ), maximizing the performance requires minimizing the impact of multiple-scattering – i.e. minimizing material budget
  - For the HH → $b\bar{b}\gamma\gamma$ decay mode, excellent energy photon resolution is needed in the E = 50 – 100 GeV energy range → stringent requirements for ECAL (stochastic ~ 10%, and noise term < 1.5 GeV with pile-up)

Eur. Phys. J. C **80**, 1030 (2020)



δ_{κ_λ}=3.8-10% depending on assumptions for systematics and resolution

Scenario I – target detector performance

Scenario III – pessimistic detector performance, assuming extrapolated HL-LHC performance using present-day algorithms

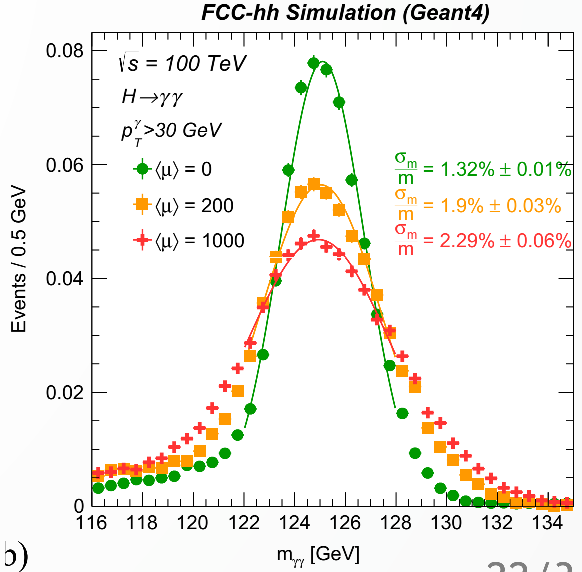
parameterisation	scenario I	scenario II	scenario III
γ ID eff.	90	90	90
jet $\to \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9

	transverse granularity ($\eta \times \phi$)	# layers	resolution
tracker	0.001	12	$0.5\% \oplus (\frac{p_T}{[\mathrm{TeV}]}) * 1\%$
ECAL	0.01	8	$\boxed{\frac{10\%}{\sqrt{E}} \oplus 0.3\%}$
HCAL	0.025	10	$\frac{50\%}{\sqrt{E}} \oplus 3\%$

Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

Should achieve 1% γγ

Pile-up could degrade this considerably



b)

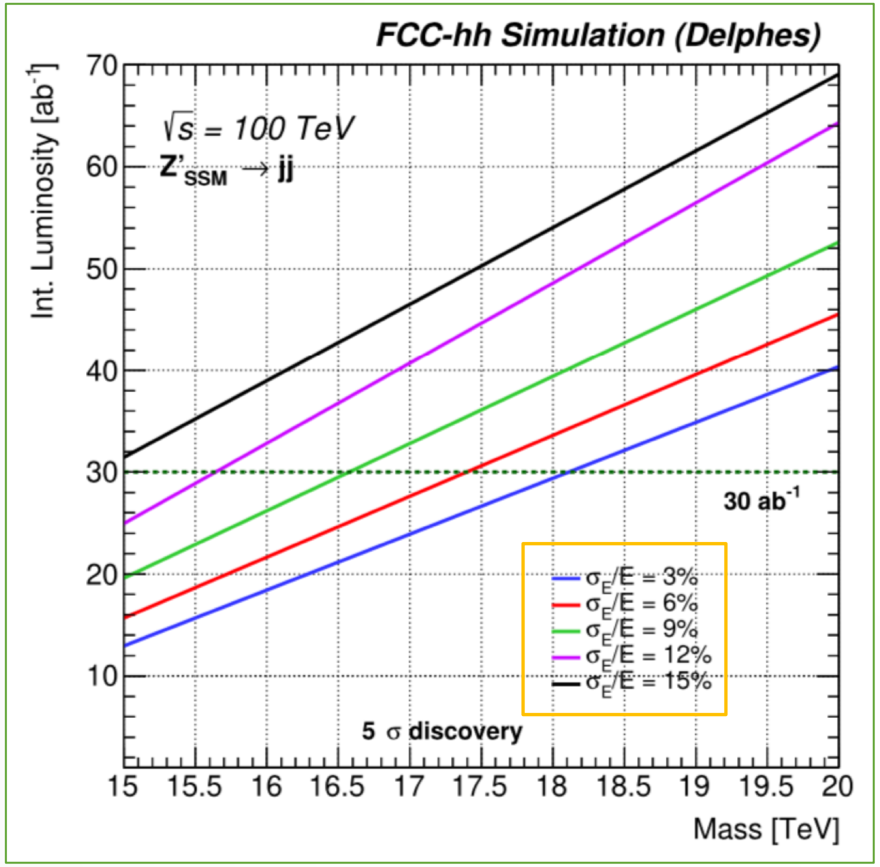
Searches for NP: high p_T jets and boosted objects

For di-jet resonances, HCAL constant term has huge impact on the luminosity needed to get the same reach. Furthermore:

- Need full shower containment (ECAL+HCAL ~ 98% ideally)
- Large HCAL depth (~ 12 λ_{int})

	transverse granularity ($\eta \times \phi$)	# layers	resolution
tracker	0.001	12	$0.5\% \oplus (\frac{p_T}{[\mathrm{TeV}]}) * 1\%$
ECAL	0.01	8	$\frac{10\%}{\sqrt{E}} \oplus 0.3\%$
HCAL	$\boxed{0.025}$	10	$\boxed{\frac{50\%}{\sqrt{E}} \oplus 3\%}$

Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

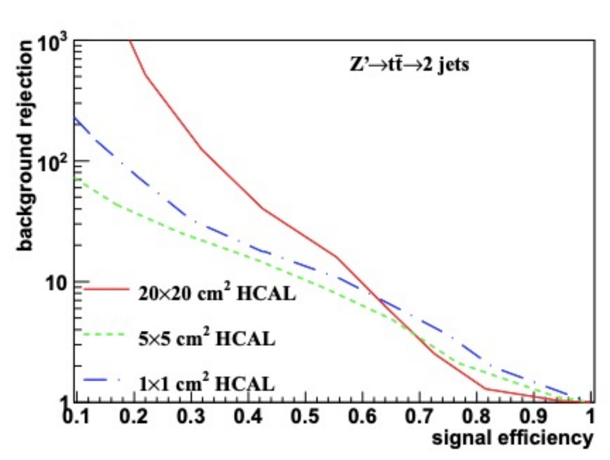


Eur. Phys. J. C (2019) 79:569

Heavy particles can decay into **highly boosted** top/W/Z

→ collimated jets - @ 10 TeV, R = 0.02 for W boson!

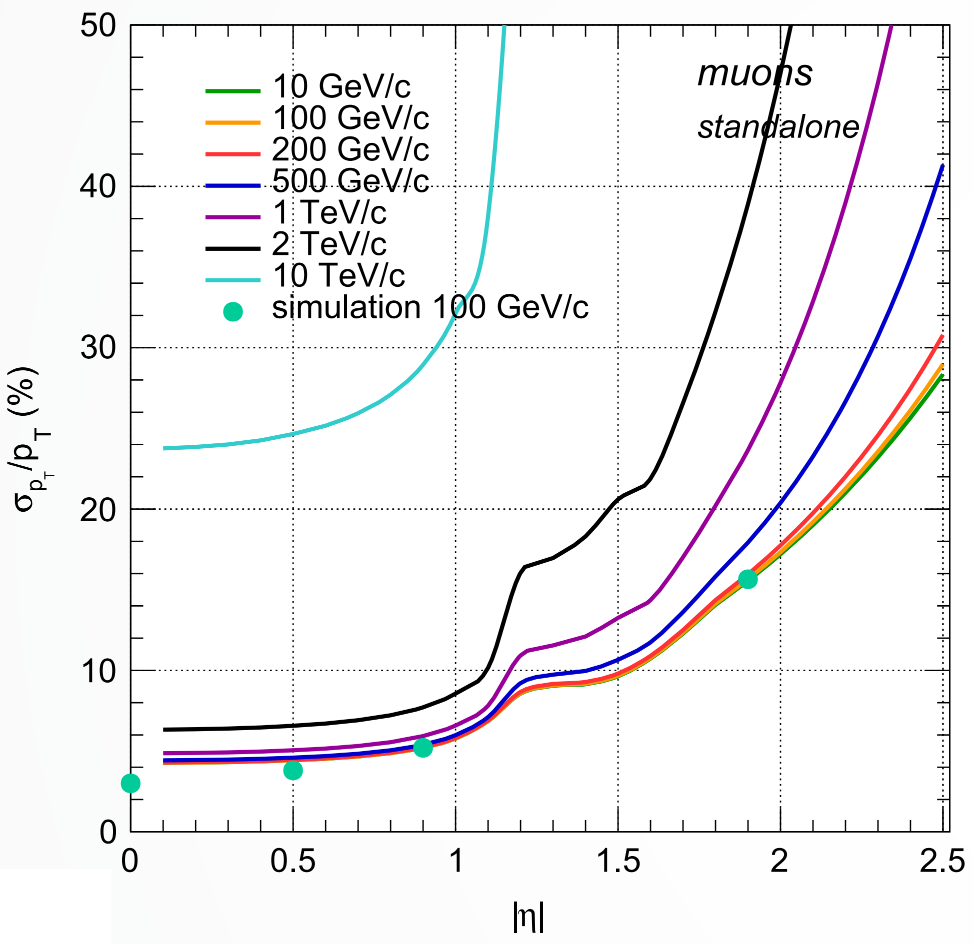
- **Particle flow** exploit complementarity of tracking and calo
- reconstruction of jet substructure variables also benefit from small cell sizes of the hadronic calorimeters



(b) $M(Z') = 10$ TeV

https://arxiv.org/pdf/1901.11146.pdf

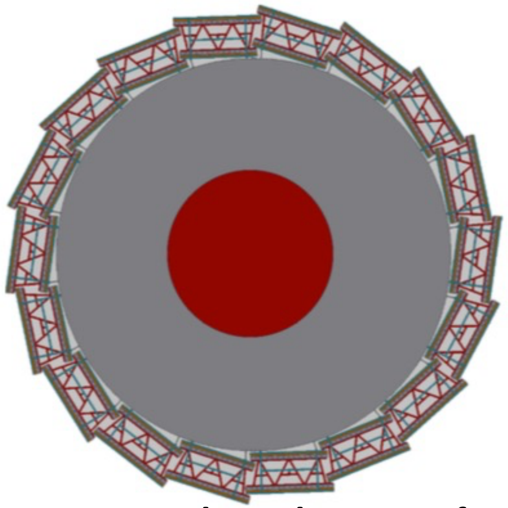
FCC-hh muon system



- With 50 μm position resolution and 70 μrad angular resolution we find (η=0):
  - ≤10% standalone momentum resolution up to 4 TeV/c
  - ≤10% combined momentum resolution up to 20 TeV/c
- Resolution deteriorates considerably at high eta
- Standalone muon performance not relevant, the task of muon system is **triggering** and muon identification
- Muon rate dominated by c and b decays: isolation is crucial for triggering W, Z, t!

Muon detection in forward region:
Expected rates up to 500kHz for r > 1m

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

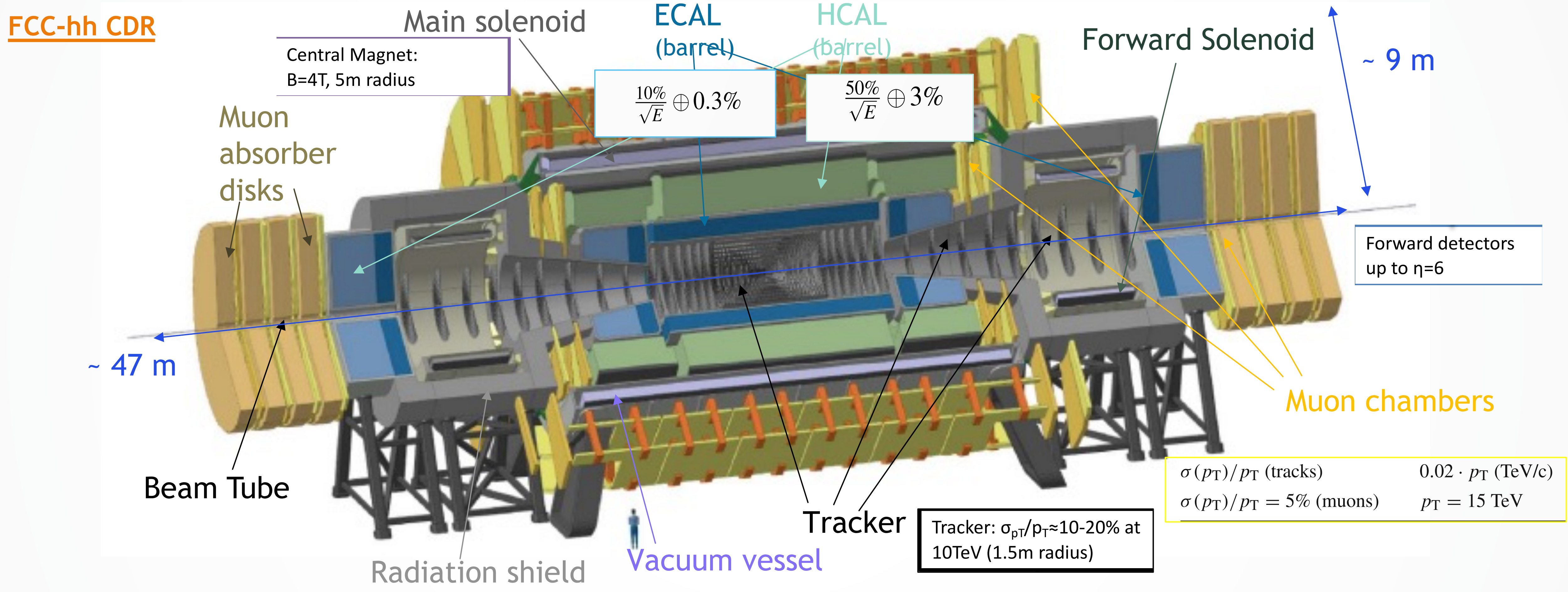


Muon barrel: Rates of up to ~500Hz/cm^2 expected

Trigger and DAQ for a FCC-hh detector

- Calorimetry and muon system at 40 MHz will result in **200-300 TByte/s**
  - For ATLAS Phase II, digitized at 40 MHz and sent outside the cavern at **25 Tbyte/s** for L1 Trigger
  - **→ 10 times size foreseen at HL-LHC: Seems feasible but more studies required**
- Tracker would produce 1-2 PB/s, using zero-suppression would produce about **800TByte/s.**
  - Not clear if this will be possible, otherwise needs reduction
- Can the L1 Calo+Muon Trigger have enough selectivity to allow readout of the tracker at a reasonable rate of e.g. 1MHz?
    - Difficult: 400kHz of W's and 100MHz of jets (pT > 50GeV)
    - un-triggered readout of the detector at 40MHz would result in 1000-1500TByte/s over optical links to the underground service cavern and/or a HLT computing farm on the surface.
    - Ideally one would need offline performance of today transferred online (e.g. j/γ discrimination)
- **Difficulties:**
  - Huge amounts of data produced (relevant for streaming and triggering itself)
  - Need high-bandwidth, low power, radiation hard data links
    - New technologies are needed: i.e. CMOS with integrated photonics (Silicon Photonics)

Requirements for an FCC-hh detector



- High granularity of tracker and calorimeters, high efficiency for vertex reco, b-tag, τ-tag, particles ID, low calo constant term and high resolution → achieve all this with pile-up of 100 (timing) and radiation hardness detectors

Summary of the Challenges and R&D needed (in 1 slide)

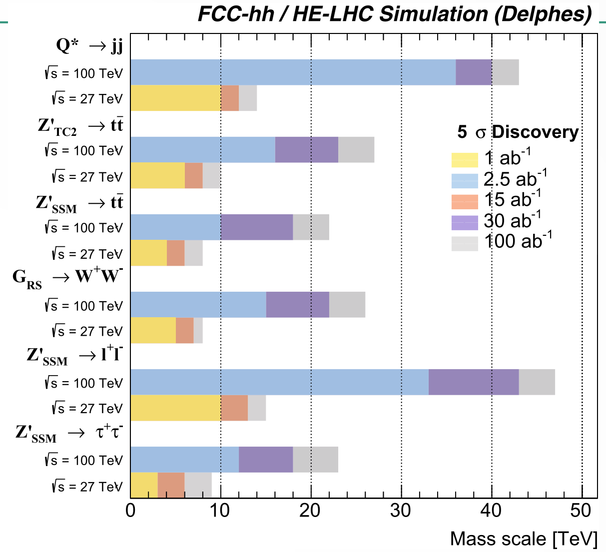
Disclaimer: In no way exhaustive list of challenges

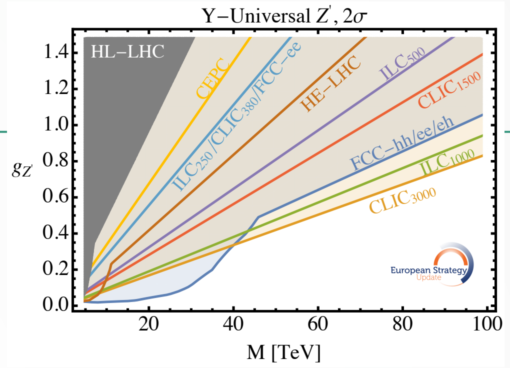
R&D activities covered within **Detector R&D ECFA**

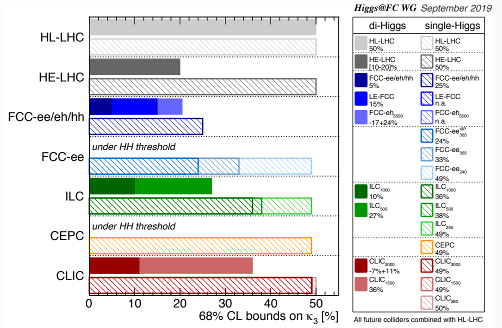
- **Magnet system:**
  - C: Stored energy orders of magnitude larger than ATLAS/CMS
  - C: Low material cryostats
  - R&D needed: conductor, powering, protection, ultra-thin and radiation transparent solenoids
- **Pile-up and vertexing:**
  - C: $<\mu> = 1000$, challenging for reconstruction and triggering
  - R&D needed: trackers will need to use position resolution and timing information (e.g. ultra-thin LGAD)
  - R&D needed: low material detectors (e.g. monolithic designs with integrated sensors and readouts)
- **Forward coverage and radiation hardness:**
  - C: forward coverage requires fwd tracking and calorimeters, huge doses for all (c+f) regions **within r > 30-40 cm**
  - R&D needed (tracking): Ultra-radiation hard sensors and read-out chip
  - R&D needed (calo): Noble liquid calorimetry, Scintillator based calorimetry or Si-based calorimetry
- **Granularity:**
  - C: super busy environment challenging for b-tagging, tau-tagging, boosted jets etc
  - R&D needed (e.g. calo): achieve lateral cell sizes of ≤2cm, use imaging calorimetry (e.g. NN)
- Stability, Data rates, Triggering etc.. → all need dedicated R&D

Summary

- **The potential of the FCC-hh** is enormous:
  - New possible heavy particles could be directly discovered if they have masses up to 20-40 TeV
  - Huge potential also from indirect searches
  - Highest reach in sensitivity also for di-higgs studies, dark matter searches and more
    - E.g. can conclusively test the hypothesis of thermal DM







- Extreme granularity, excellent energy-momentum resolution beyond the LHC detectors, together with novel algorithms will be needed to achieve optimal object reconstruction and identification
- Comparative studies considering different hypotheses for detector performance have been made using some searches as benchmarks → **more should/could be done for interesting and challenging scenarios**
  - Developments on theoretical calculations, modeling of backgrounds, PDFs, studies of synergies of the ee/eh/hh programmes and continuous collaborations between theorists and experimentalists are fundamental and should be pushed further
- Finding technologies that function adequately given the extreme conditions and requirements is a **challenge** → at least 20 years should be anticipated for most demanding technology aspects, also profiting from R&D for HL-LHC

Back up

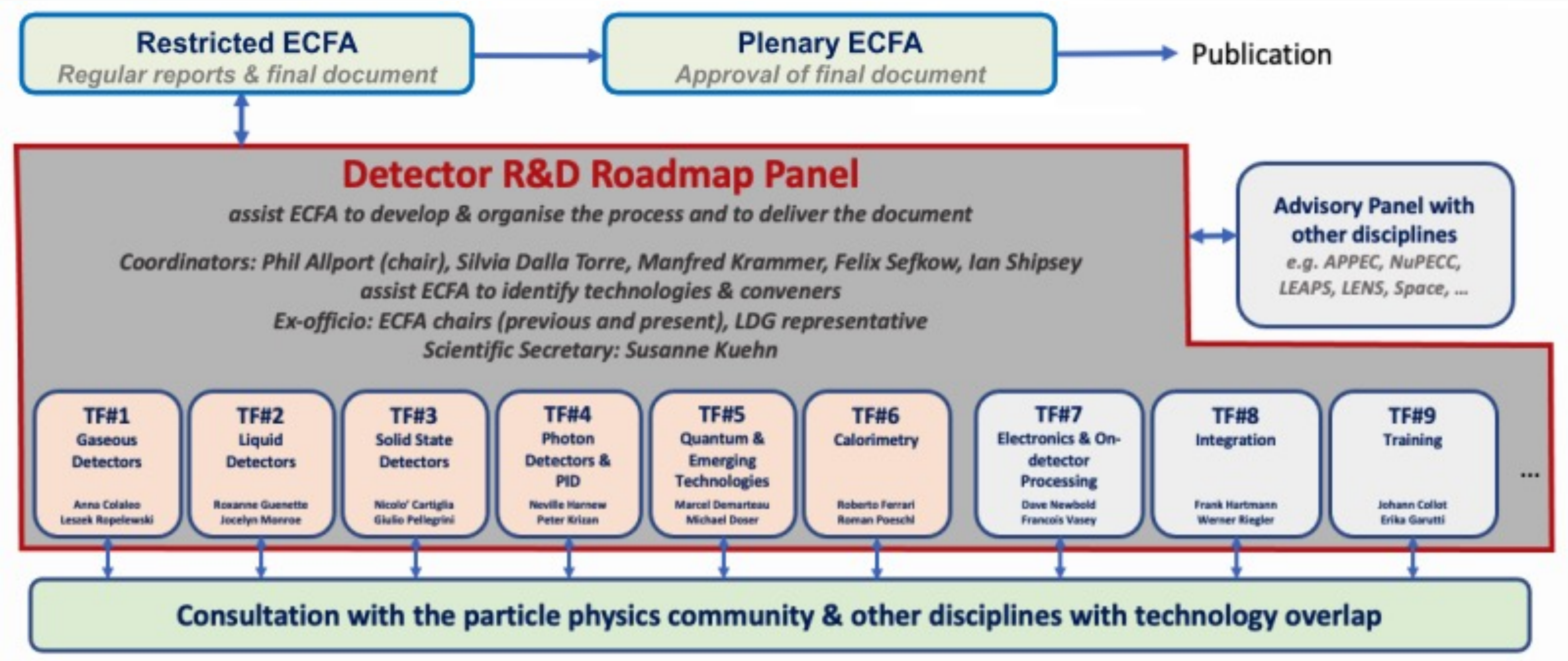
Parameters and cross-sections

- Parameters

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 $\mathcal{L}$, nominal (ultimate)	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [340]	mb	80	80	86	103
σ_{tot} [340]	mb	108	108	120	150
BC rate	MHz	31.6	31.0	31.6	32.5
Peak pp collision rate	GHz	0.8	4	14	31
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950

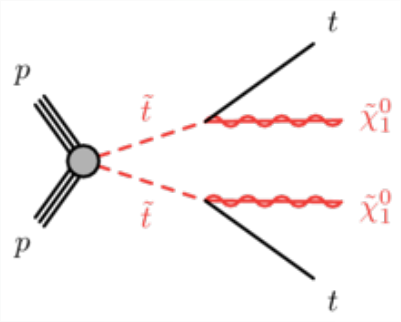
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^{b} > 30\,\mathrm{GeV/c}$ cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^{b} > 30\,\mathrm{GeV/c}$ rate	MHz	0.02	0.08	1	8
Jets $p_T^{\mathrm{jet}} > 50\,\mathrm{GeV/c}$ cross-section [340]	μb	21	21	56	300
Jets $p_T^{\mathrm{jet}} > 50\,\mathrm{GeV/c}$ rate	MHz	0.2	1.1	14	90
$W^+ + W^-$ cross-section [12]	μb	0.2	0.2	0.4	1.3
$W^+ + W^-$ rate	kHz	2	10	100	390
$W^+ \to l + \nu$ cross-section [12]	nb	12	12	23	77
$W^+ \to l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \to l + \nu$ cross-section [12]	nb	9	9	18	63
$W^- \to l + \nu$ rate	kHz	0.1	0.5	4.5	19
Z cross-section [12]	nb	60	60	100	400
Z rate	kHz	0.6	3	25	120
$Z \to ll$ cross-section [12]	nb	2	2	4	14
$Z \to ll$ rate	kHz	0.02	0.1	1	4.2
t-t cross-section [12]	nb	1	1	4	35
t-t rate	kHz	0.01	0.05	1	11

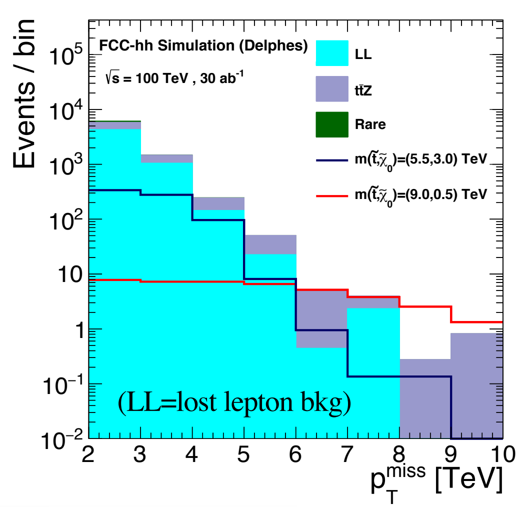
ECFA Roadmap Organisation

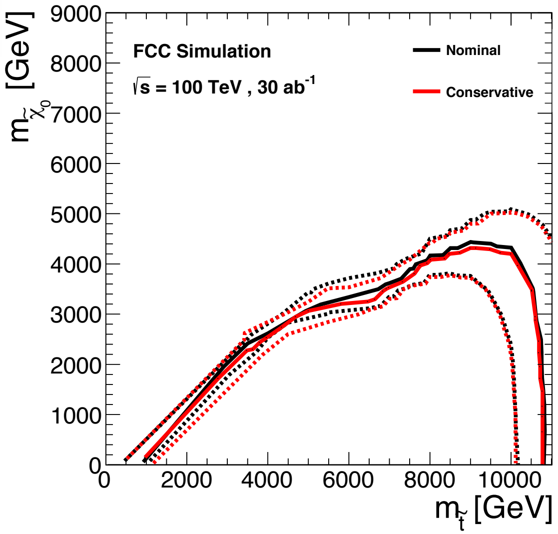


Examples of prospects relying on MET: top squarks

- Analyses for large and medium ΔM (stop, N1): ETMiss could be as high as 5-10 TeV

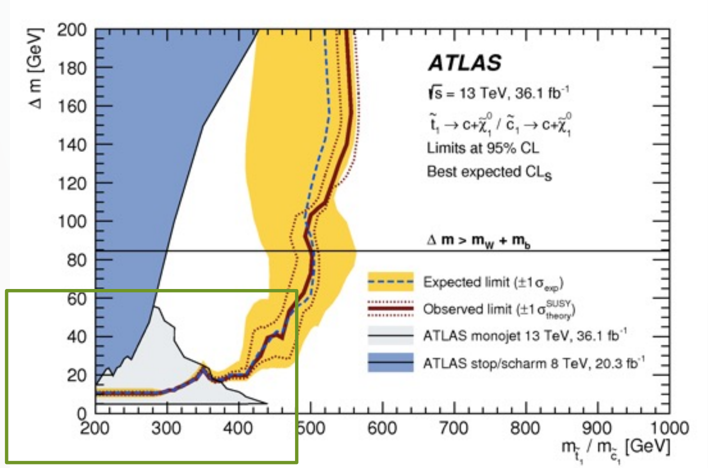






Discovery potential at 30/ab up to 8 TeV

- Monojet analyses (jet+MET) sensitive to compressed scenarios, small $\Delta M = m_{stop} - m_{LSP}$:



JHEP 09 (2018) 050

ΔM ~ 2 – 10 GeV

Results for FCC-hh are projections

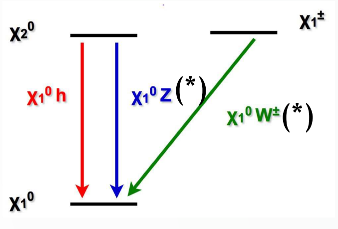
with ColliderReachTool:
HL-LHC → 0.95 TeV; [confirmed exp.]
HE-LHC → 2 TeV;
FCC-hh → 5 TeV

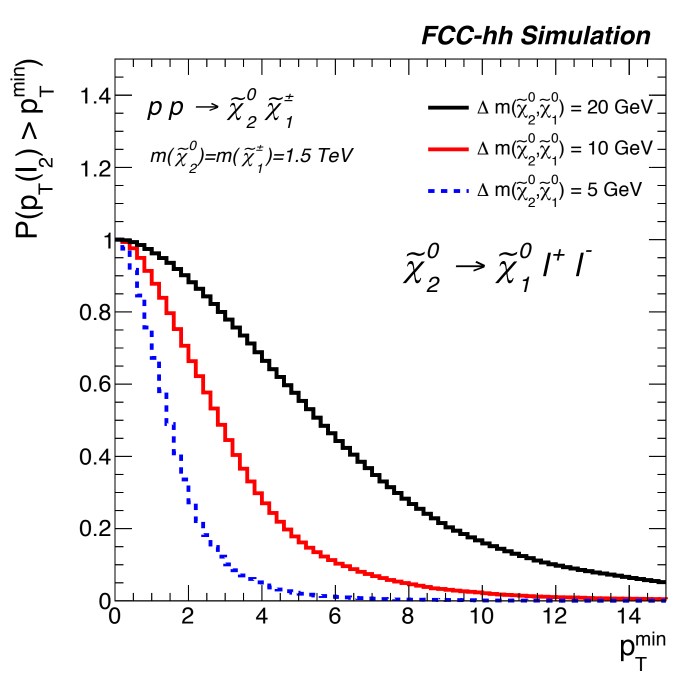
→ recoil-jet pt thresholds can be adjusted

→ Depends on capability of reconstructing real MET in high-pT tails

SUSY searches: lepton pT resolution

- Low momentum objects are fundamental for several SM and BSM processes
  - Precision measurements: e.g. Higgs in 4 leptons (one of them very soft, pT ~ 5 GeV)
  - **Searches:** electro-weakly produced SUSY particles: $\chi^{\pm}{}_1\chi^0{}_2$ = NSLP, $m(\chi^{\pm}{}_1) = m(\chi^0{}_2)$
    - in compressed models, W and Z might be off-shell
    - Estimate probability of having pT(l) above a threshold



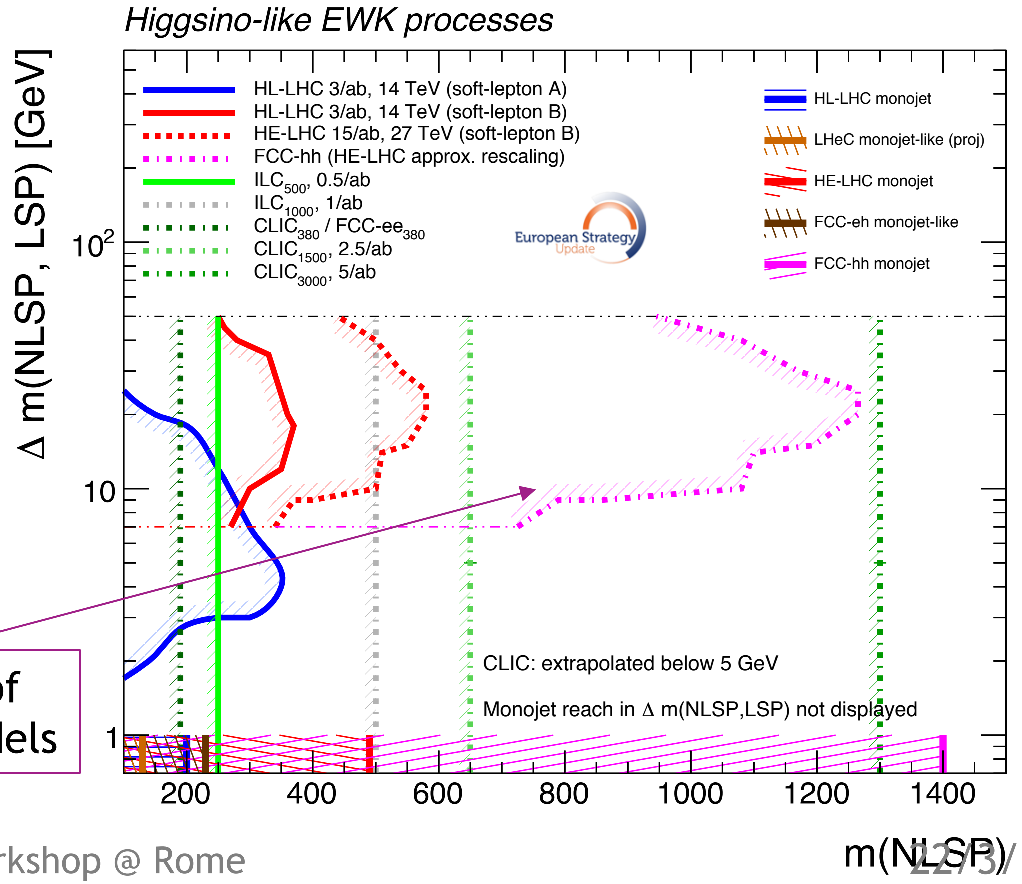


CERN-FCC-PHYS-2020-0004

pT min must be kept as low as possible

Target: ~ 4 GeV for electrons
~ 6-7 GeV for muons

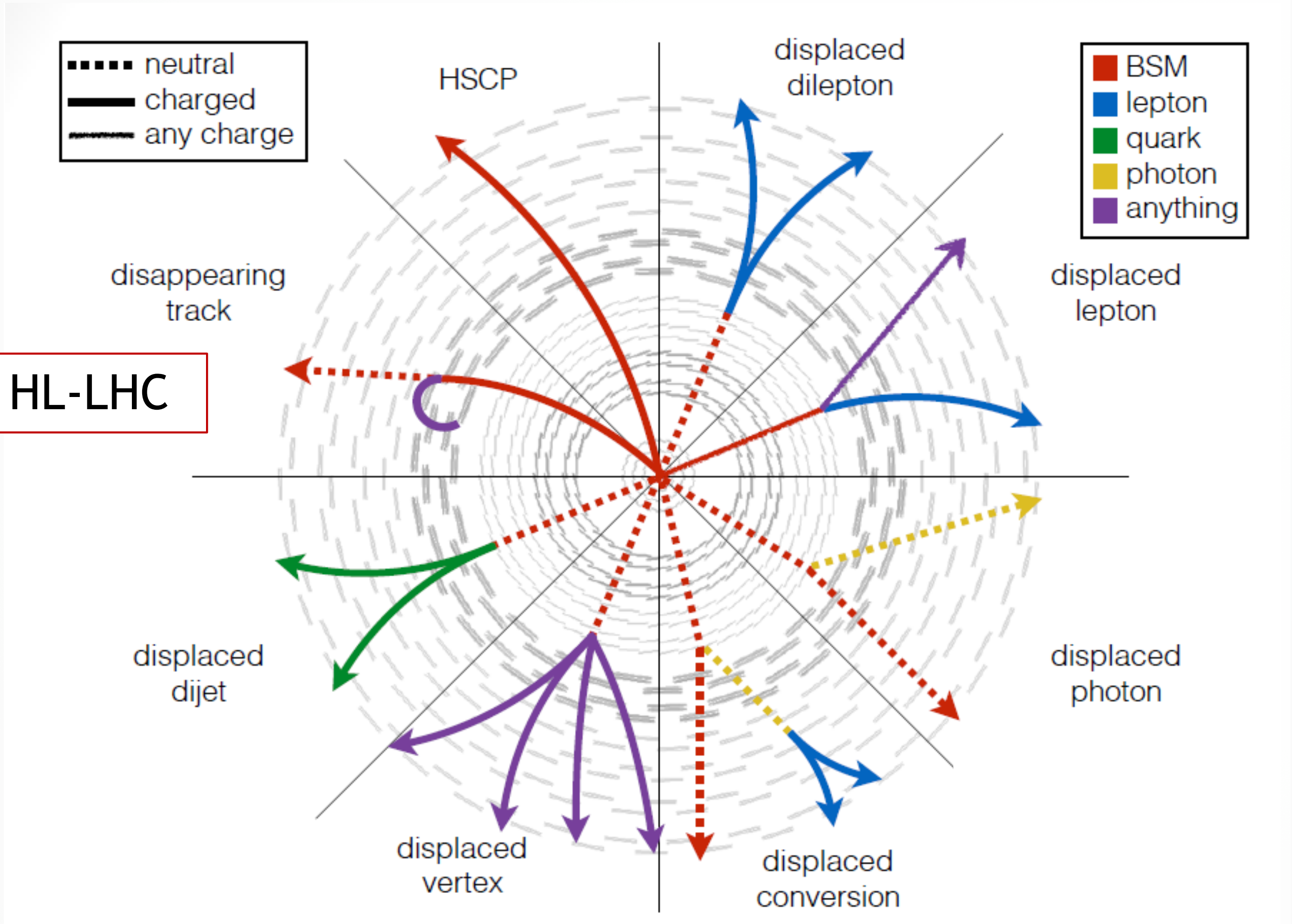
Needed assumption for validity of projections for higgsino-like models



Long lived particles: a challenge

- Several new physics models predict existence of long-lived particles:
  - Small couplings
  - Small mass-splittings
- Phenomenology depends on lifetime and decays (hadrons, charged leptons, neutrals)

E.g. @ HL-LHC



Detailed studies are very difficult without a proper detector layout - even HL-LHC projections need ‘assumptions’ e.g. on the capability of reducing the background to zero.