FCC-hh: physics potential and open questions

Monica D'Onofrio

University of Liverpool

FCC Physics Workshop
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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

In this talk, I will present few **highlights of the physics programme** stressing how they depend **substantially** on experimental conditions and **crucially** on detector developments

Disclaimer: only a few examples given here - see also contributions at this workshop!

Lot of material available – 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/

Physics potential of FCC-hh: Higgs physics

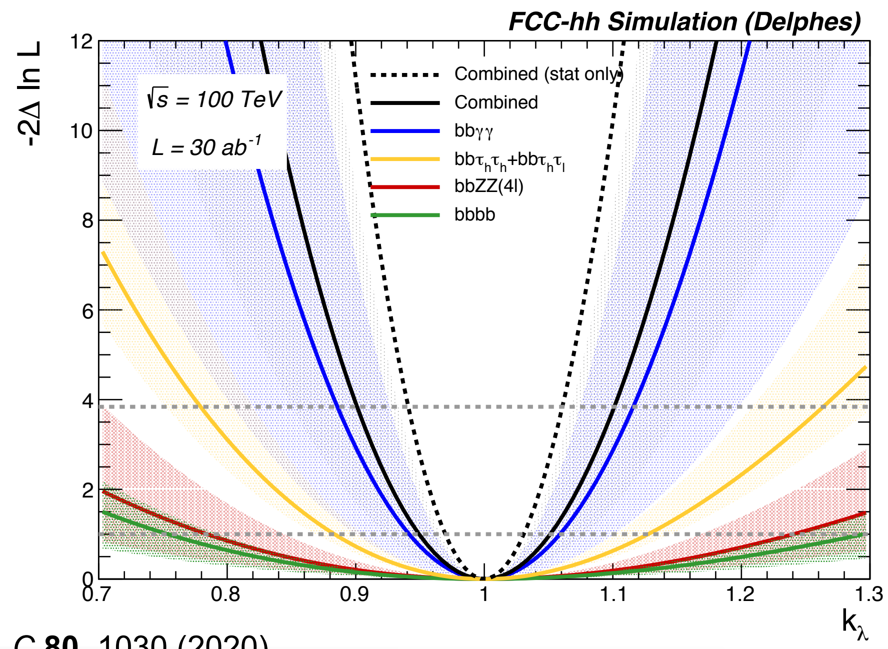
Di-higgs

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

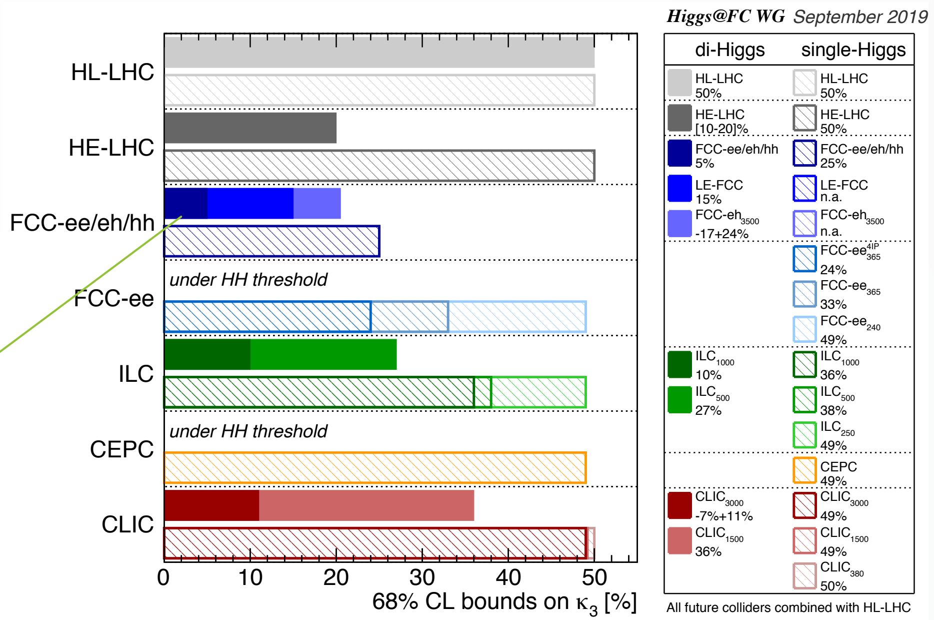
Updates after ESPPU20 indicates an expected precision on the self-coupling depending on systematics assumptions:

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

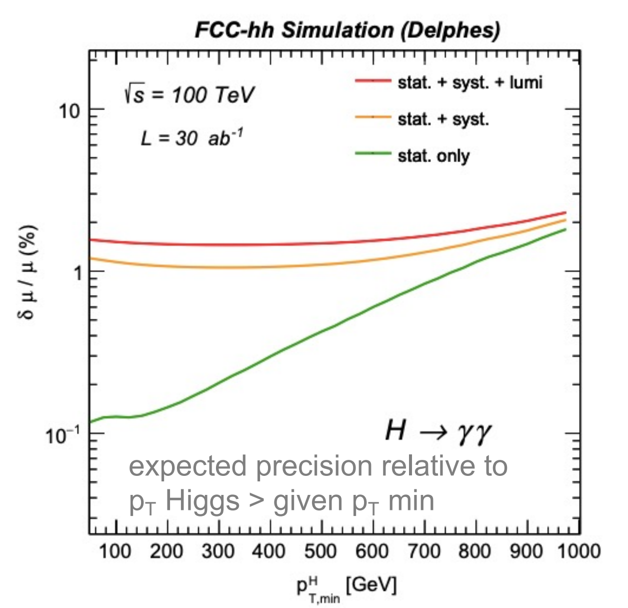


More studies on-going and presented at this workshop

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.



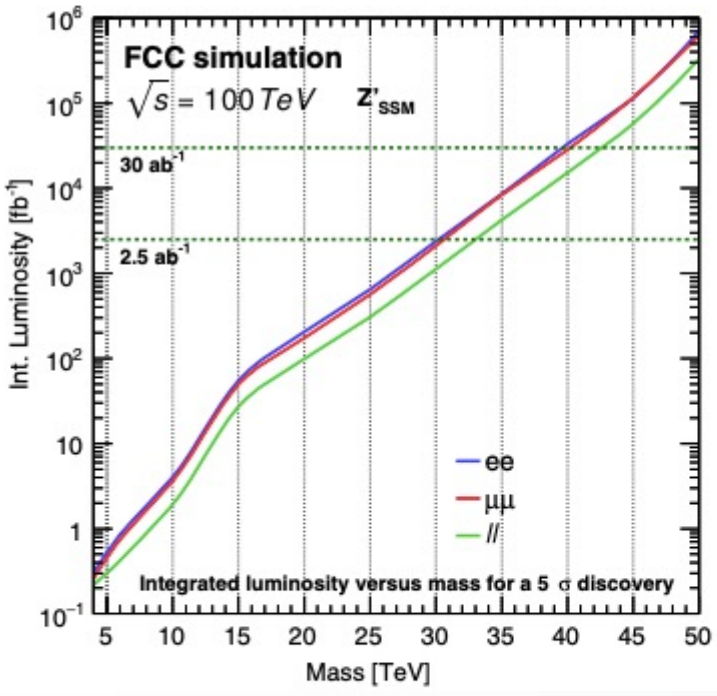
expected precision relative to p_T Higgs > given p_T min

Physics potential of FCC-hh: high mass new particles

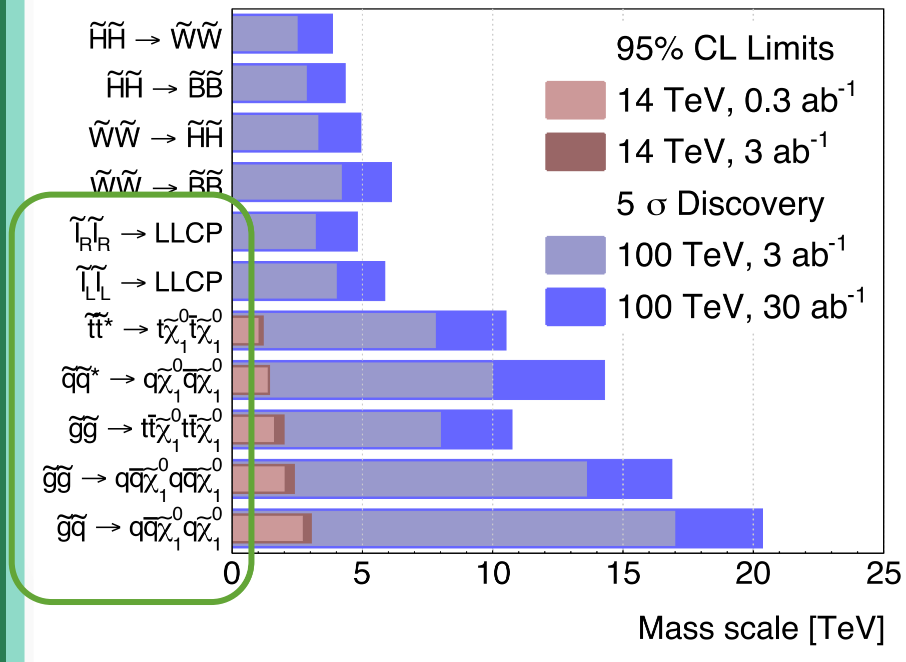
Evidence for the existence of heavier particles from flavour observables or precision EW/Higgs measurements will require direct probes → FCC-hh is the only machine that can achieve that within the current technological landscape

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

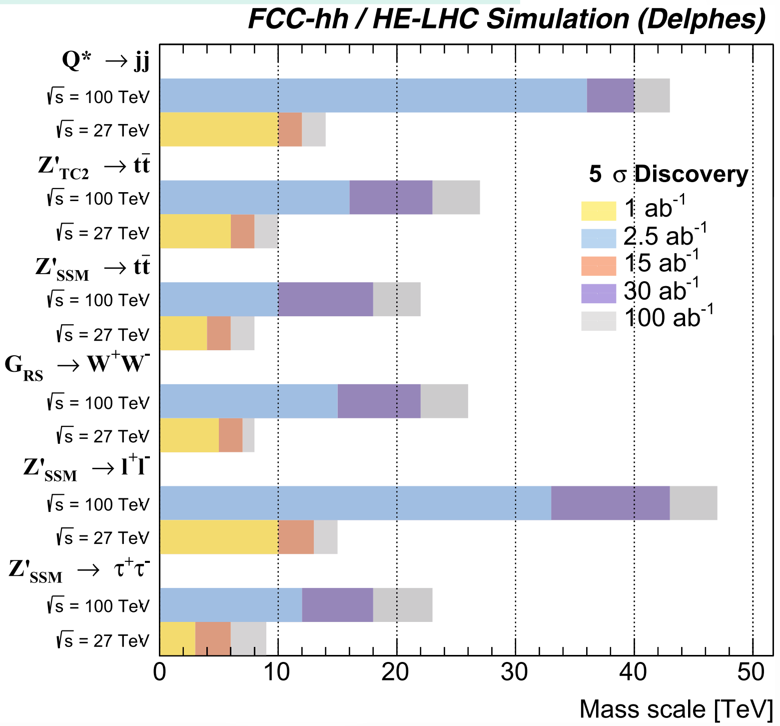
High statistics is crucial → define the needed dataset for discovery



Searches for SUSY particles



Searches for heavy resonances

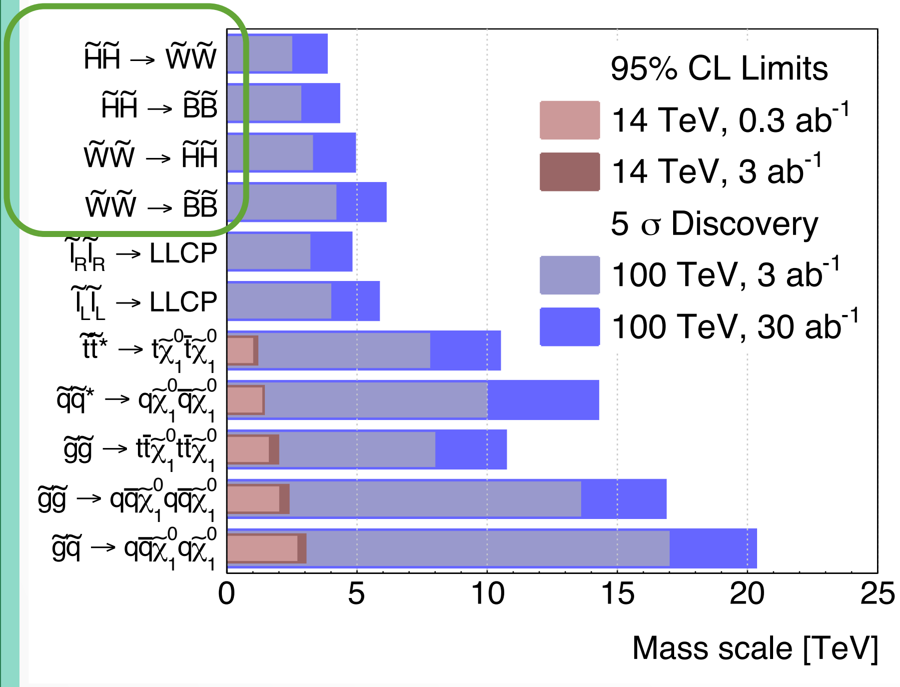


20 ab^{-1} as per accelerator goals, **30 ab^{-1}** used as target foreseeing (at least partial) combination of datasets from two experiments

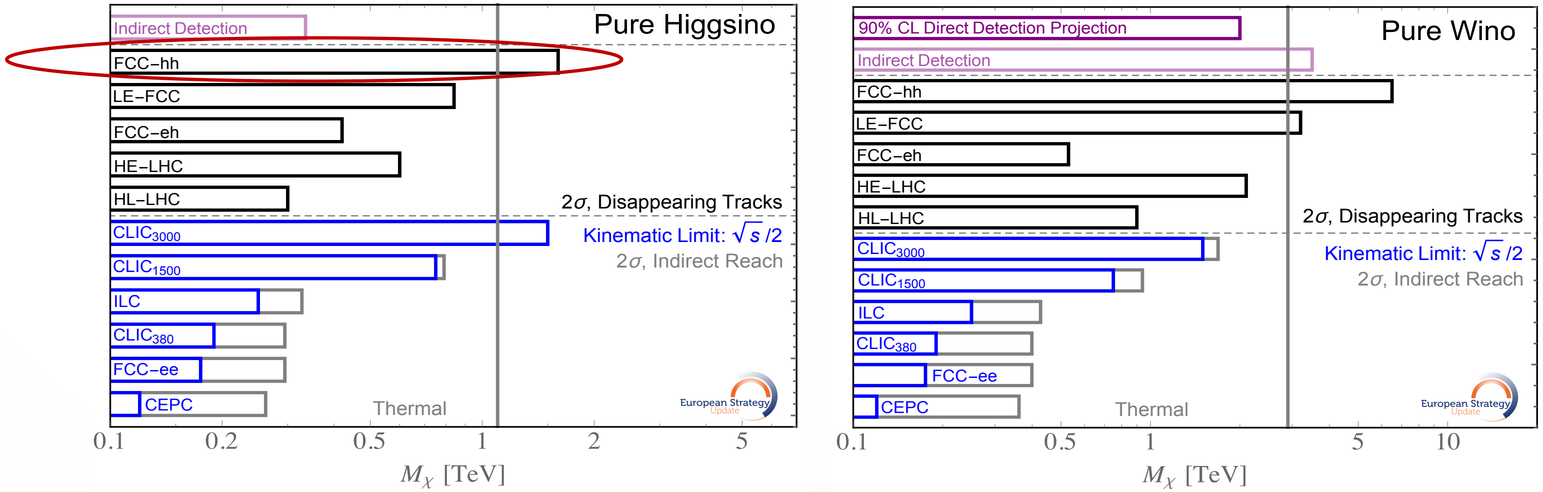
Physics potential of FCC-hh: dark matter

- 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 exploiting **disappearing track analyses**

Searches for SUSY particles (EWK)



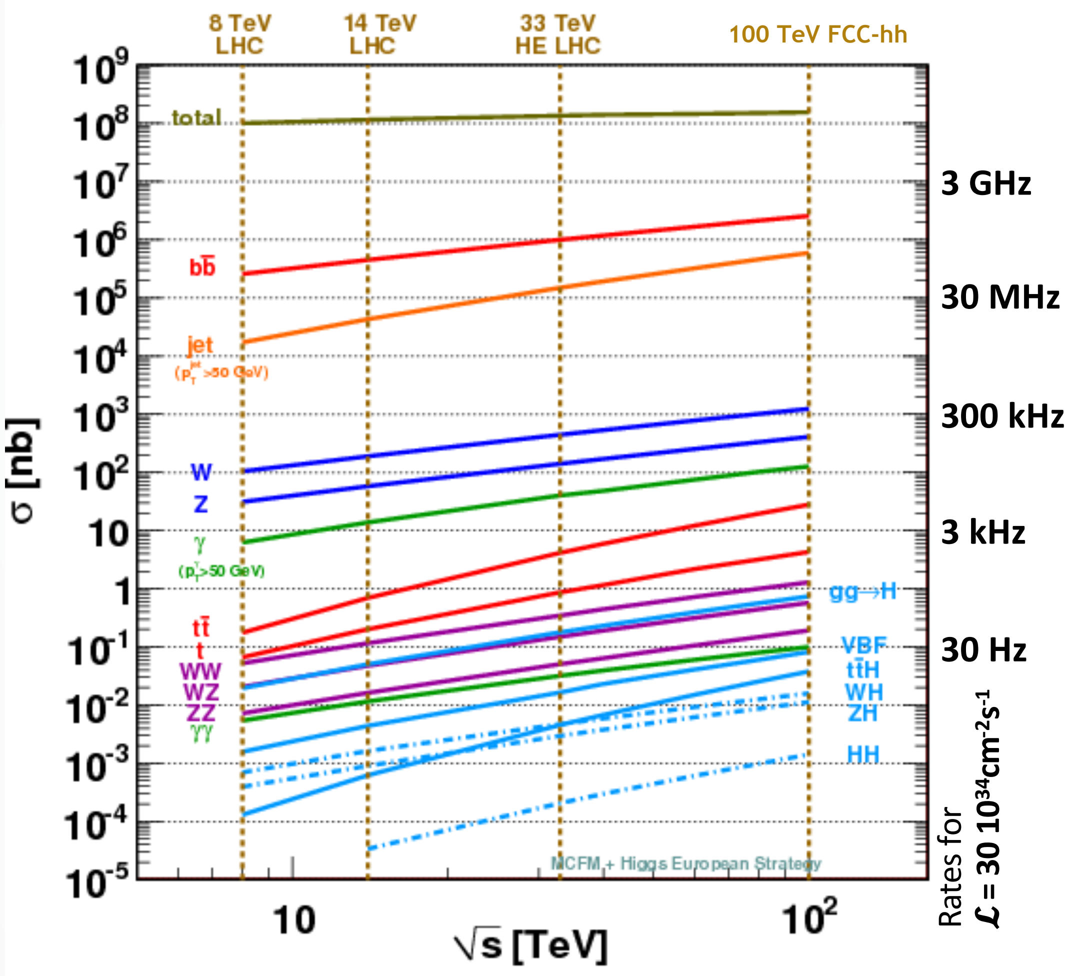
dark matter wino/higgsino models

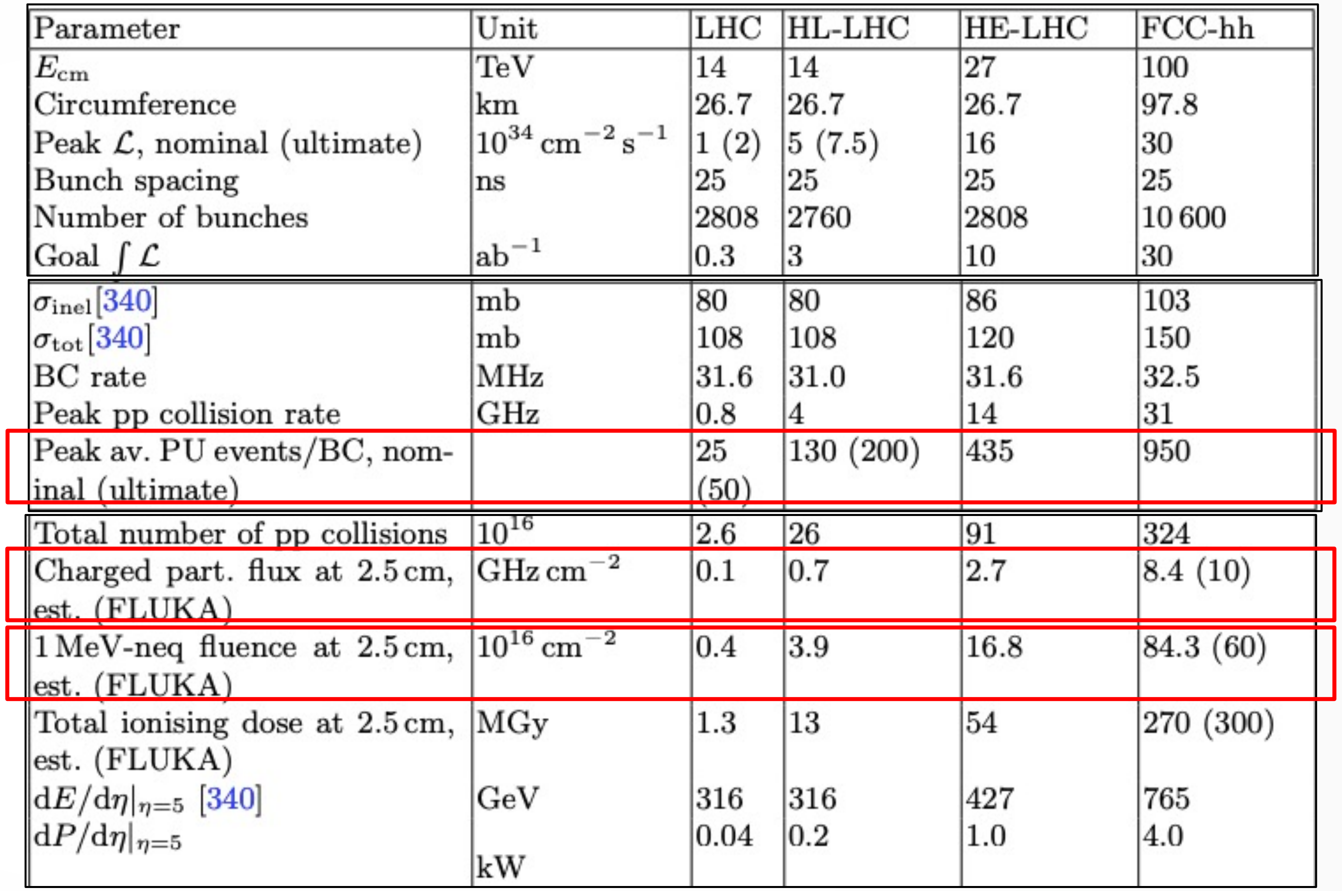


Also relevant: monojet, mono-X and **soft lepton** searches (e.g. for higgsino-like semi-compressed scenarios) – **see back-up**

Production rates and conditions

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



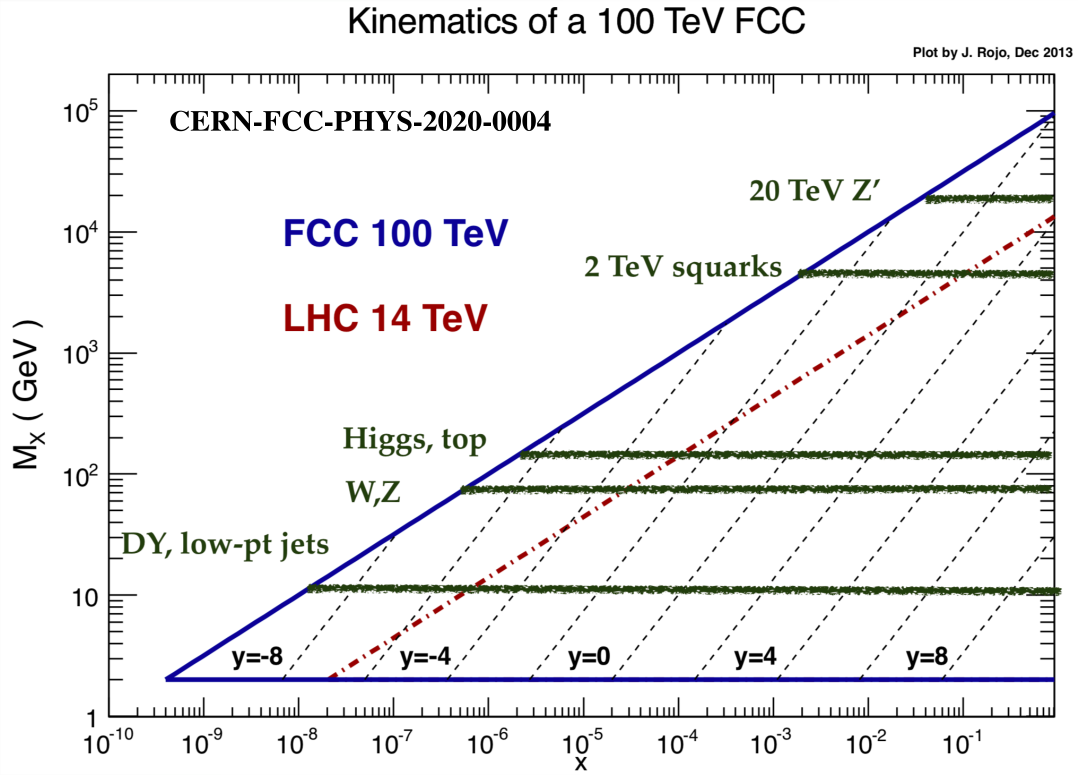


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	10^{34} cm^{-2} s^{-1}	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	0.3	3	10	30
σ_{inel} [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)	GHz cm^{-2}	0.1	0.7	2.7	8.4 (10)
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 (300)
$dE/d\eta\|_{\eta=5}$ [340]	GeV	316	316	427	765
$dP/d\eta\|_{\eta=5}$	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}

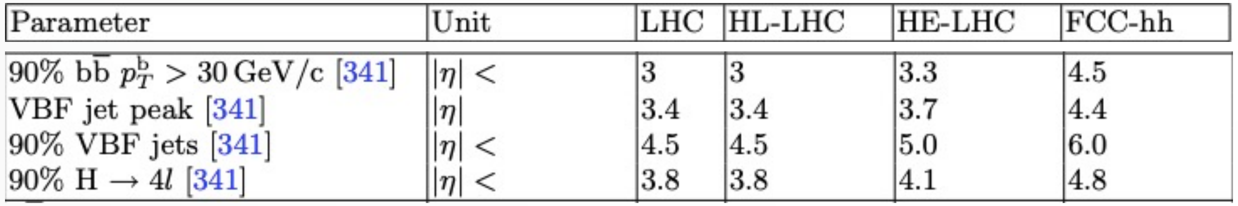
unprecedented particle flux and radiation levels

Kinematic coverage and geometrical acceptance


Kinematics of a 100 TeV FCC

Plot by J. Rojo, Dec 2013

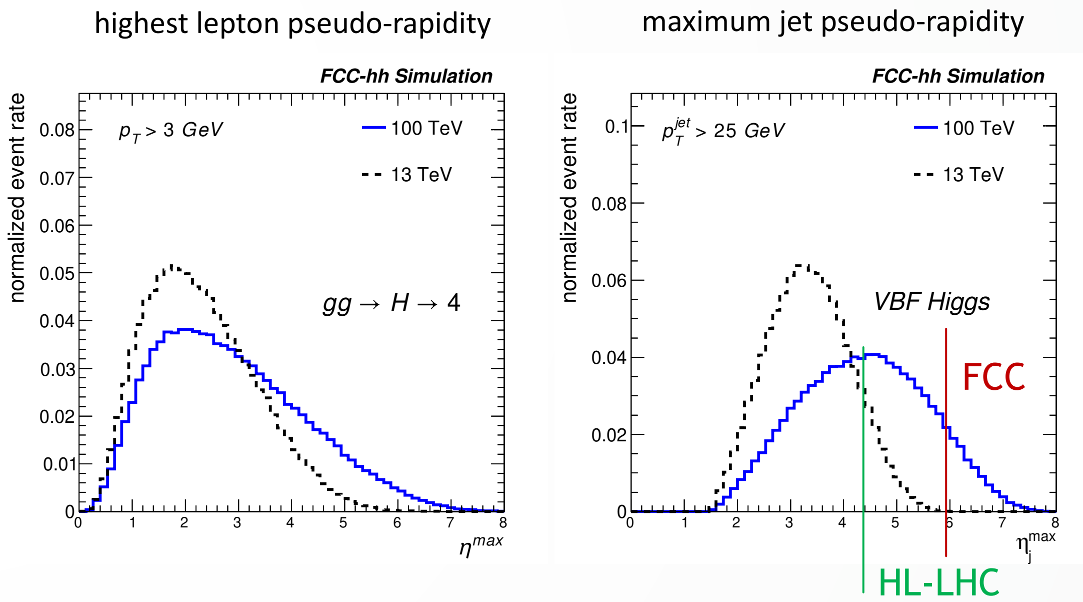
CERN-FCC-PHYS-2020-0004



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**

Example for ggF and VBF Higgs production

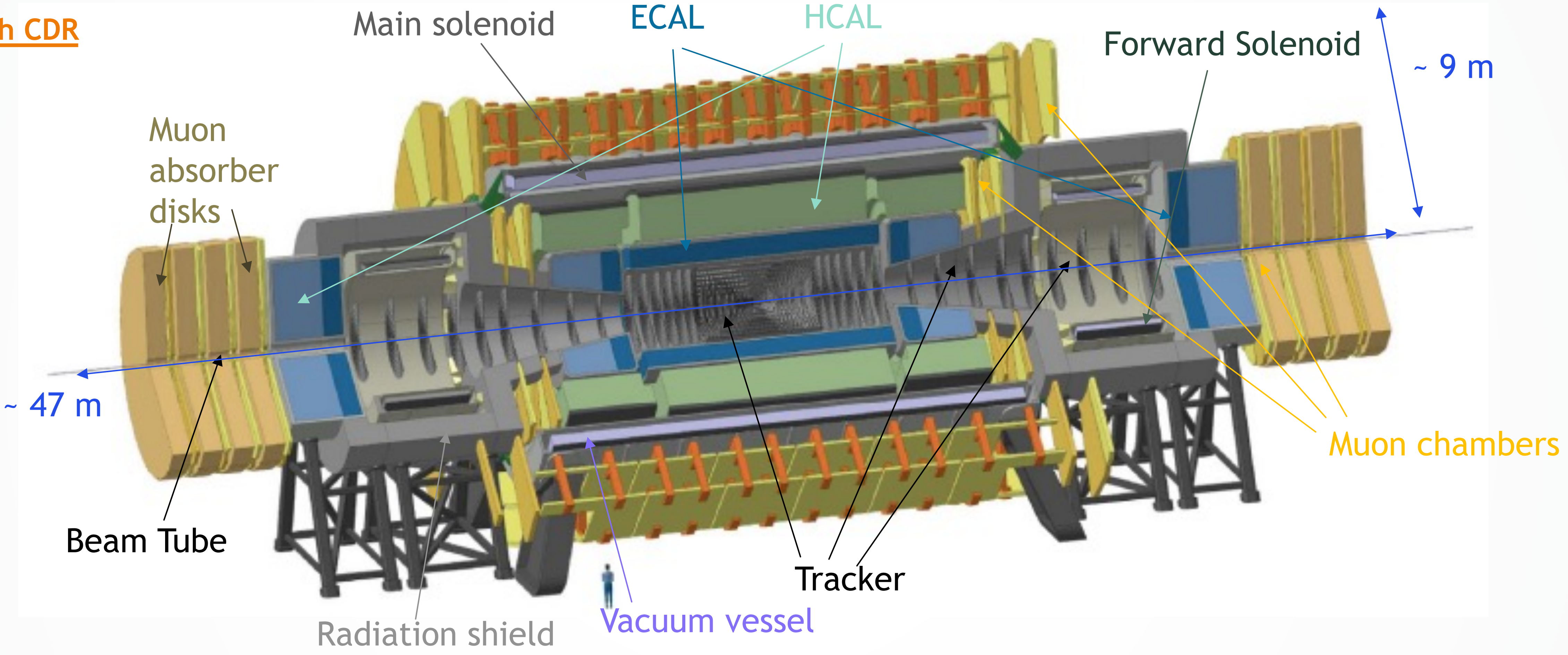

highest lepton pseudo-rapidity

maximum jet pseudo-rapidity

→ Set stringent requirements on detector acceptance

A possible layout of a detector for the FCC-hh

FCC-hh CDR

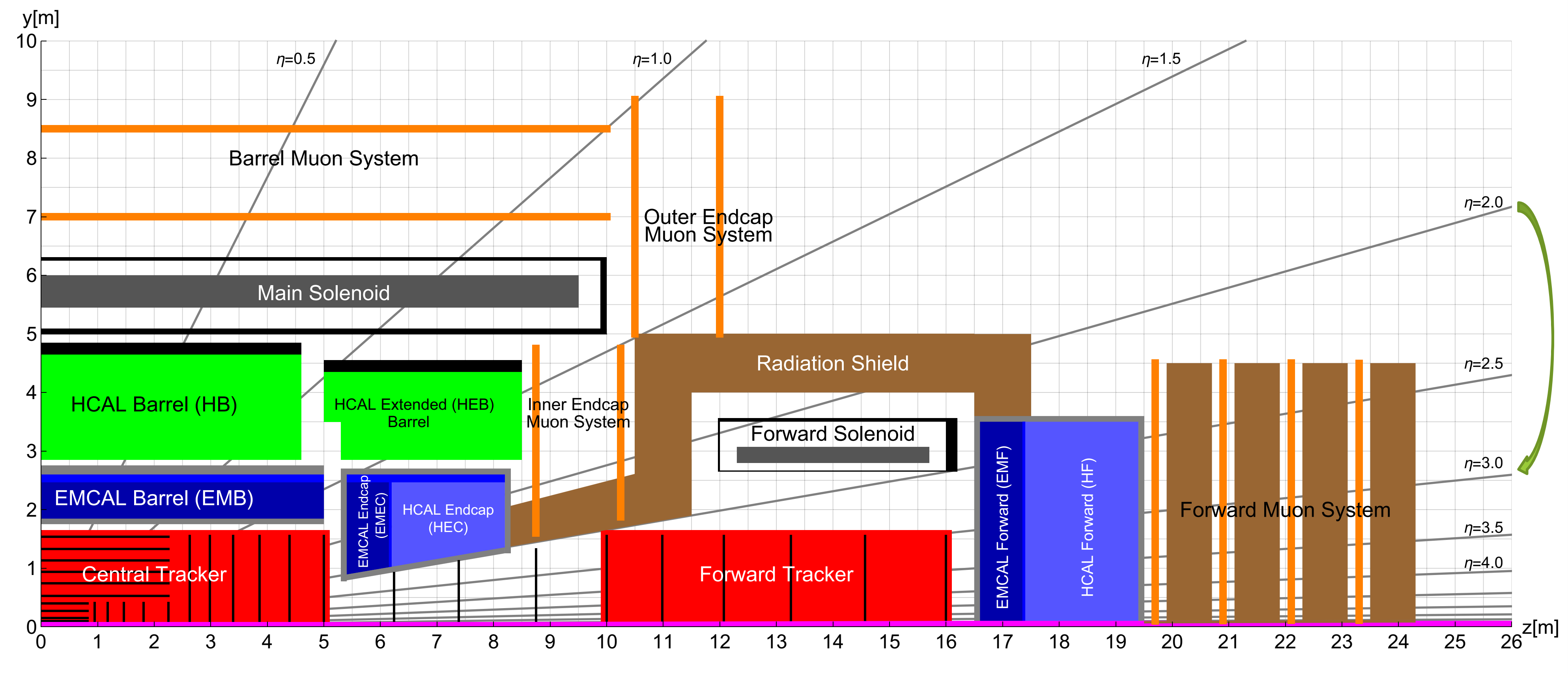


- Conceptual designs so far based on current detectors. In this case, 4-T main solenoid and forward solenoids
  - As for CMS, central tracker and calorimeters placed in the bore of the main solenoid.
- Assume cavern length of 66 m

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.



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

Radiation shield needed to cope with high fluxes

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

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

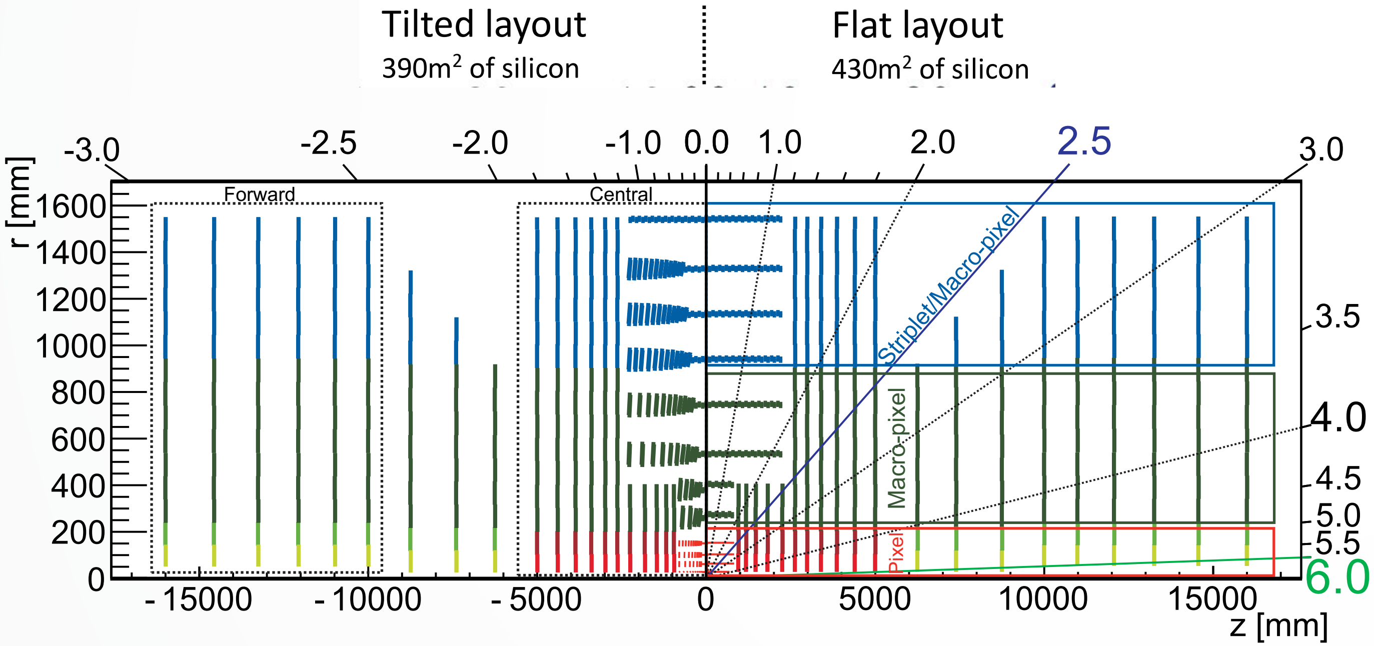


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

Detector options considered so far:

- hybrid (either macro-pixel + strip) solutions;
- CMOS monolithic active pixel sensor (MAPS) options.

Radiation tolerance is an issue even at $r > 30\mathrm{cm}$, requiring $\sim 10^{16}\ n_{eq}/cm^2$

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

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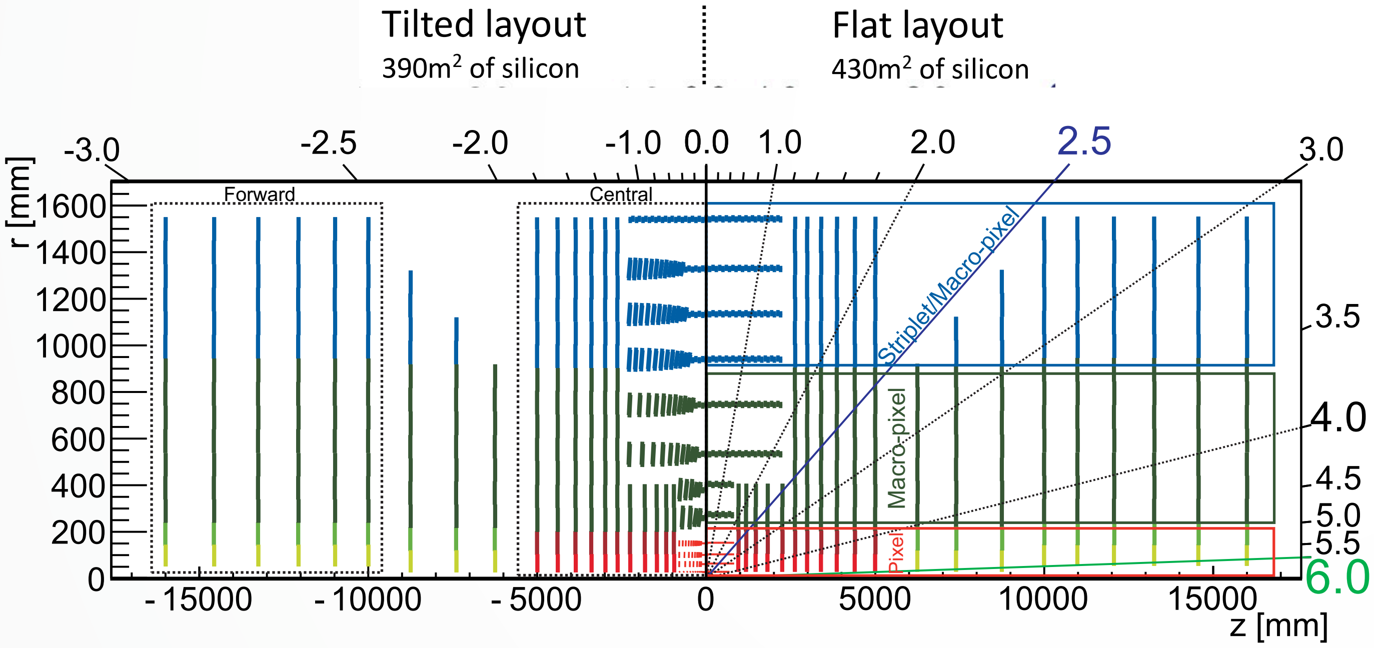
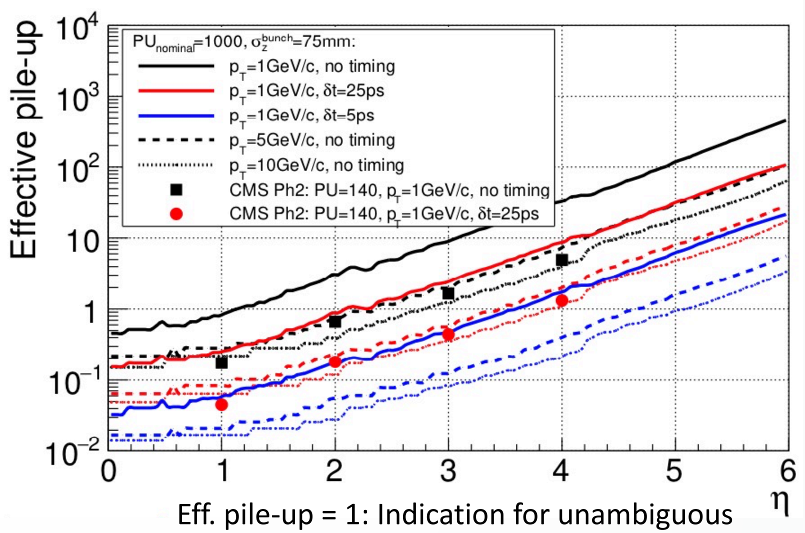


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

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 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
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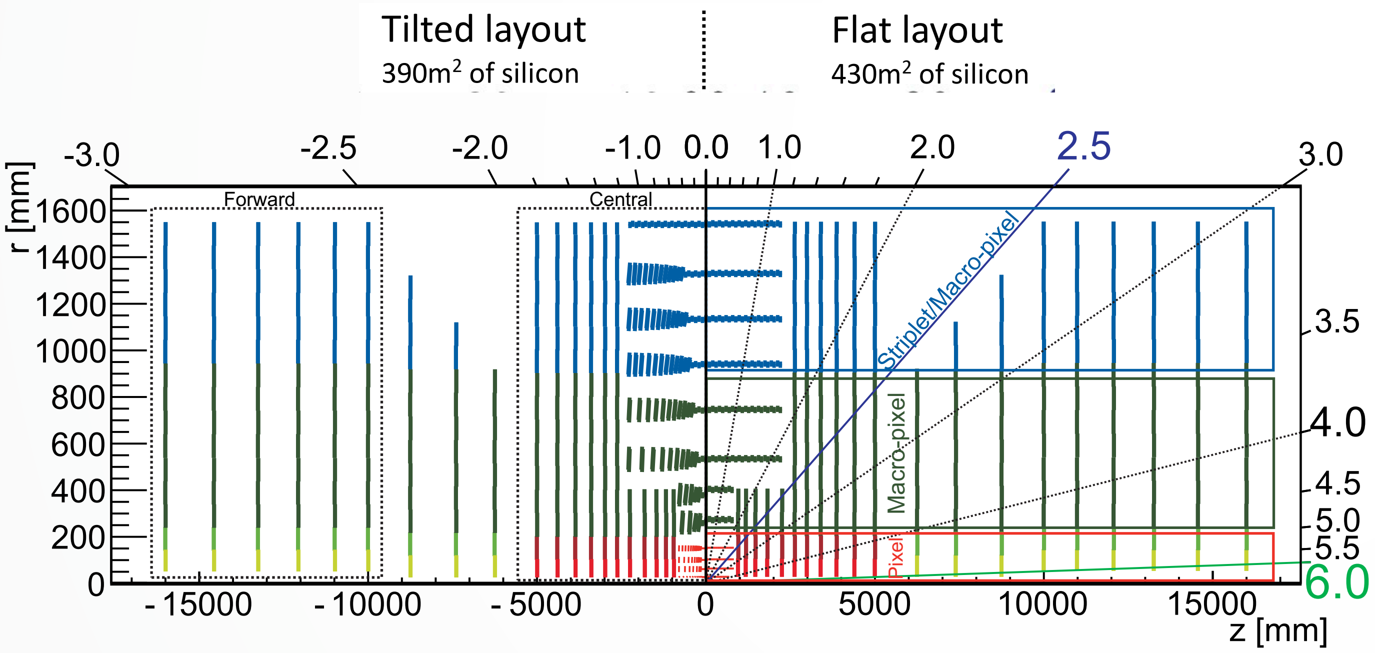
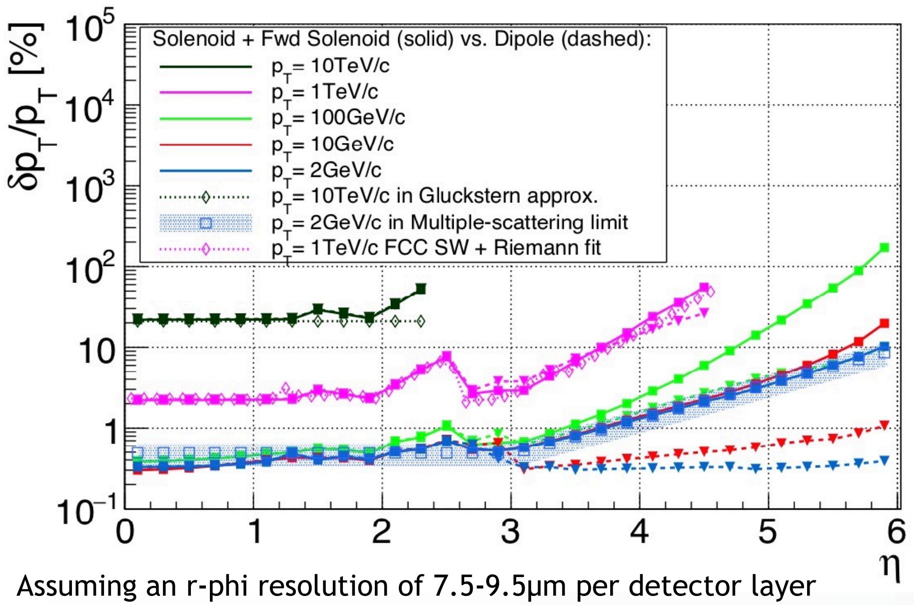


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

Tracking resolution



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

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

$p_T < 200$ GeV → dominated by Multiple scattering (need **low material budget**)

Relevance of tracking for DM searches

- Disappearing track analyses relies on the reconstruction of short tracks from charged NP (in SUSY, chargino)

- Results at HL-LHC based on strong reduction of fakes background
  - **Assumptions on tracking capability and background are crucial**

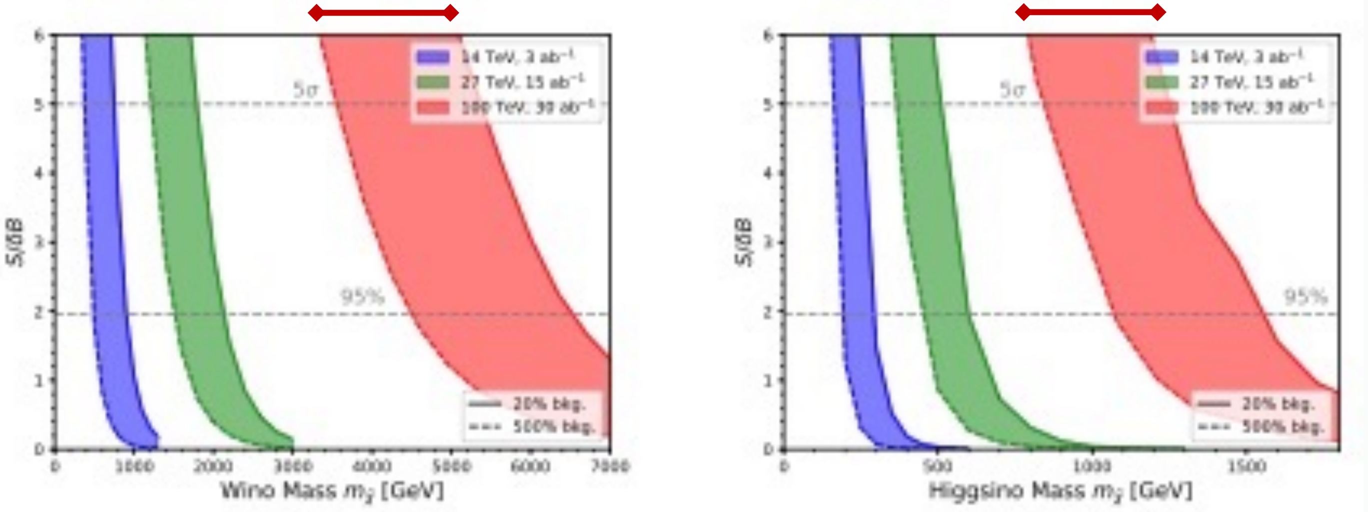
- Transverse charged track length must be in specific ranges to retain sensitivity

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

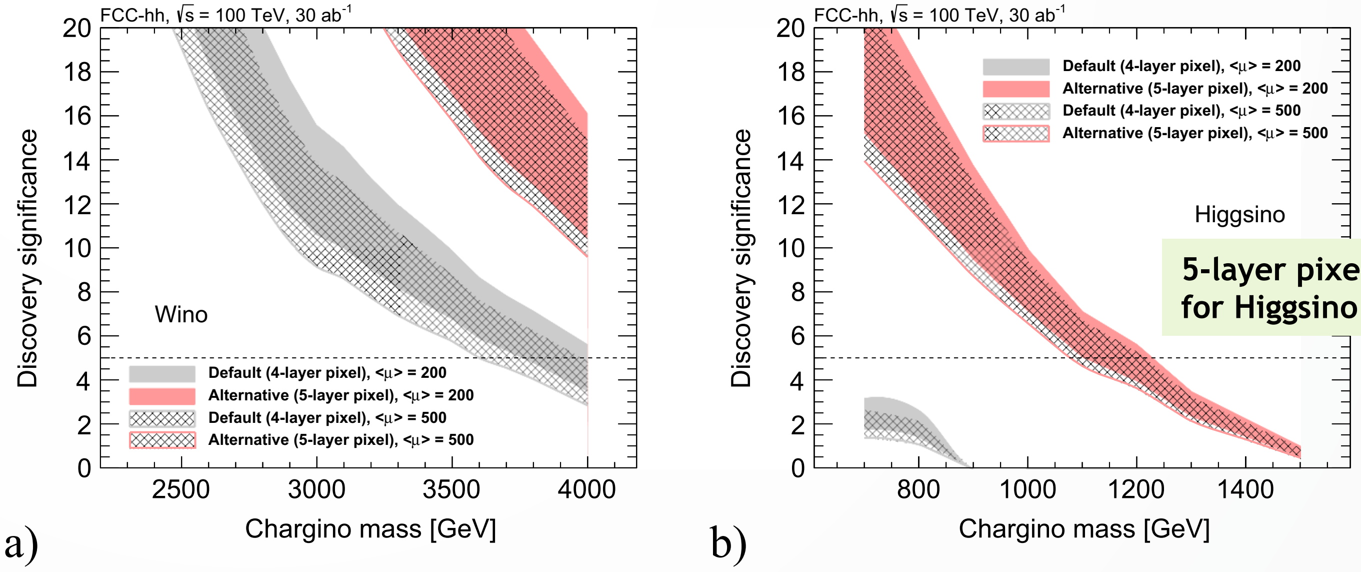
Choice of layout in terms of N pixel layers has crucial **implication** for discovery reach

HL-LHC/HE-LHC/FCC-hh

Variation of bkg by factor 5



(Section 4.1 of arxiv:1812.07831)

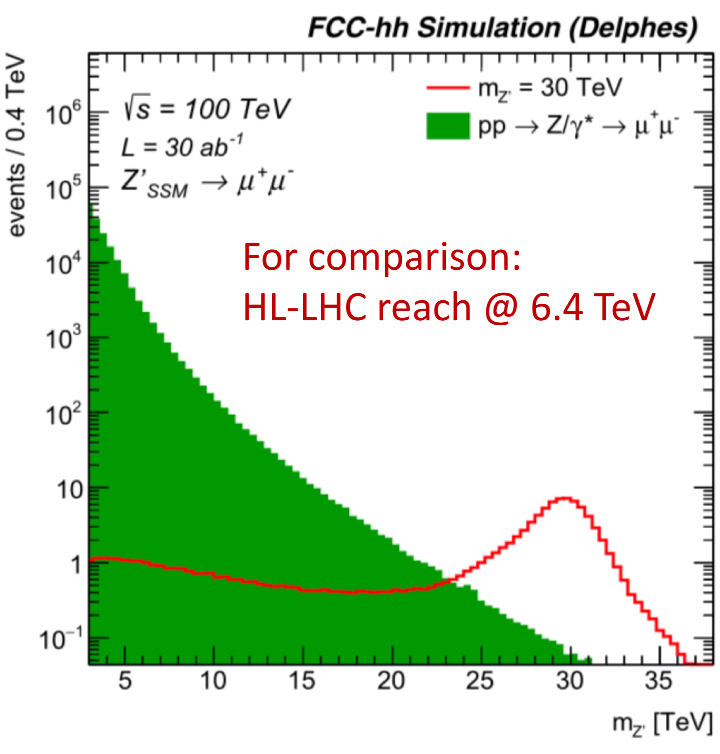


5-layer pixel needed for Higgsino!

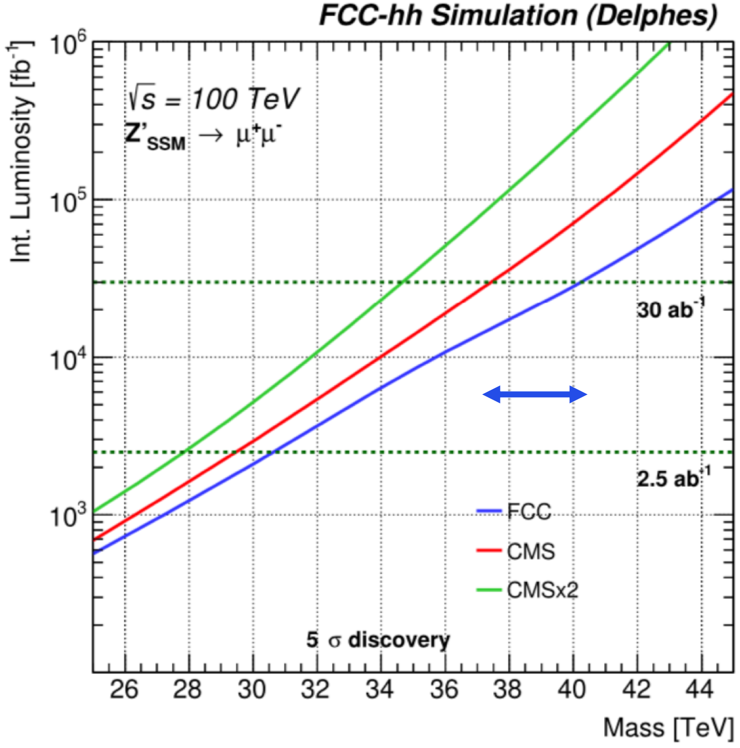
Band: different QCD models of pile-up simulation

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:



For comparison:
HL-LHC reach @ 6.4 TeV



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

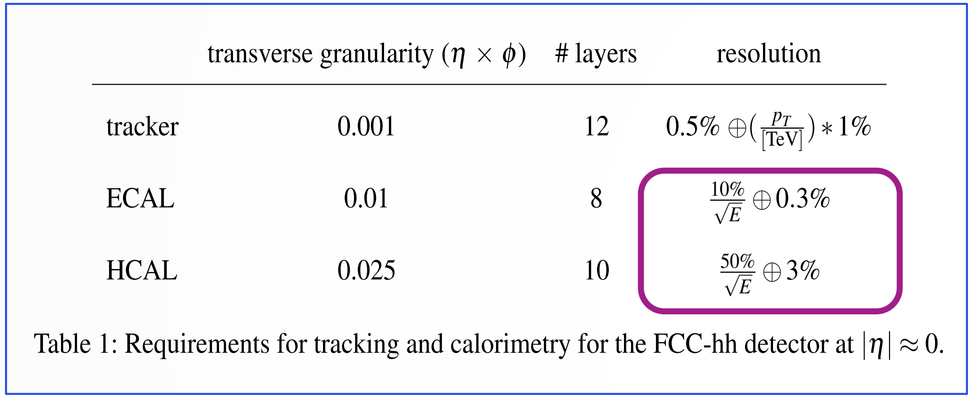
	FCC-hh
$B_z\ (T)$	4
Length (m)	10
Radius (m)	1.5
ϵ	0.95
$\sigma(\eta, \phi)(mrad)$	1
$\sigma(p_T)/p_T$ (tracks)	$0.02 \cdot p_T$ (TeV/c)
$\sigma(p_T)/p_T = 5\%$ (muons)	$p_T = 15$ TeV

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

Calorimetry: ECAL and HCAL

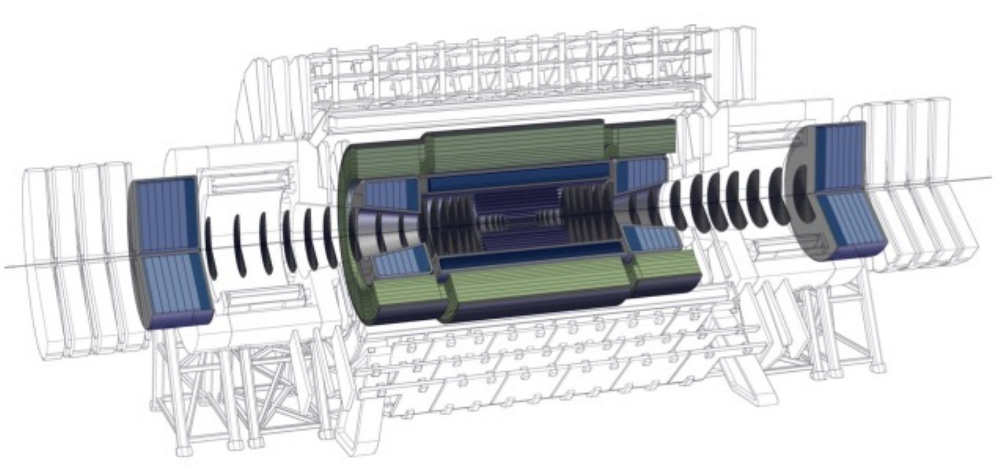
https://arxiv.org/abs/1912.09962

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



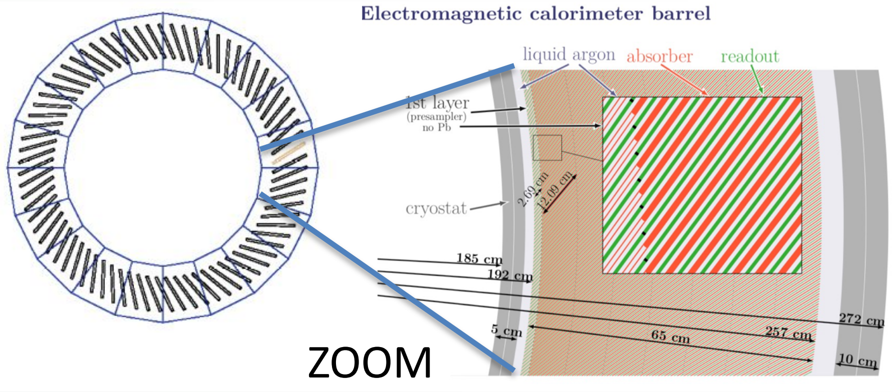
	transverse granularity ($\eta \times \phi$)	# layers	resolution
tracker	0.001	12	$0.5\% \oplus (\frac{p_T}{[\mathrm{TeV}]}) * 1\%$
ECAL	0.01	8	$\frac{10\%}{\sqrt{E}} \oplus 0.3\%$
HCAL	0.025	10	$\frac{50\%}{\sqrt{E}} \oplus 3\%$

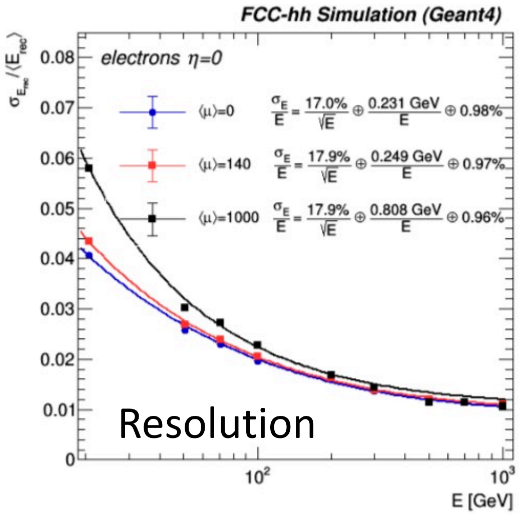
Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

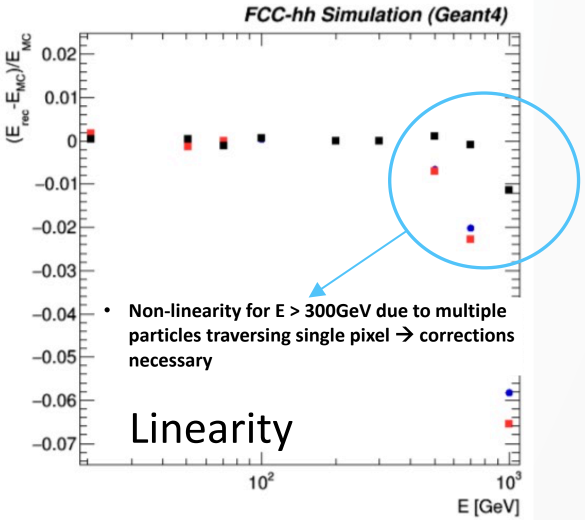


Pile-up might **degrade** performance considerably
→`Efficient in-time pile-up suppression will be crucial (using the tracker and timing information)

LAr ECAL, Pb absorbers (but several options considered)







- Non-linearity for E > 300GeV due to multiple particles traversing single pixel → corrections necessary

Calorimetry: ECAL and **HCAL**

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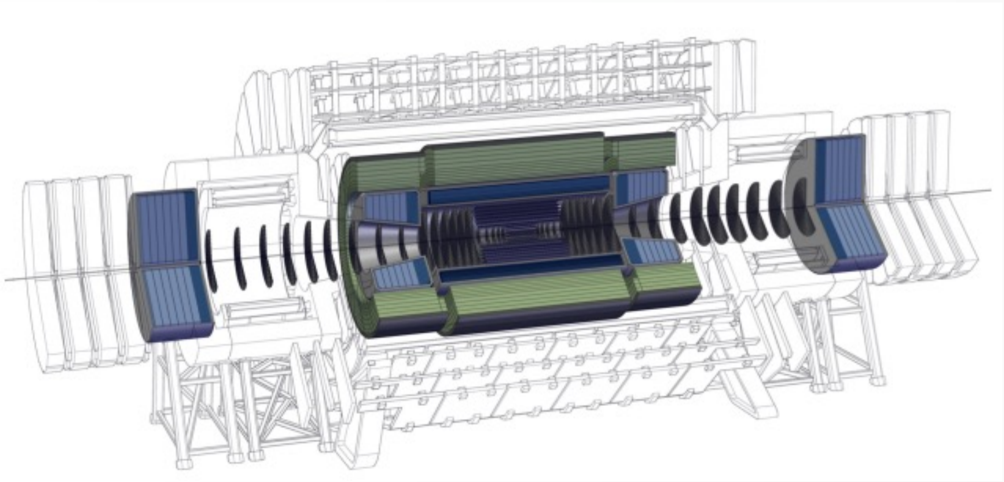

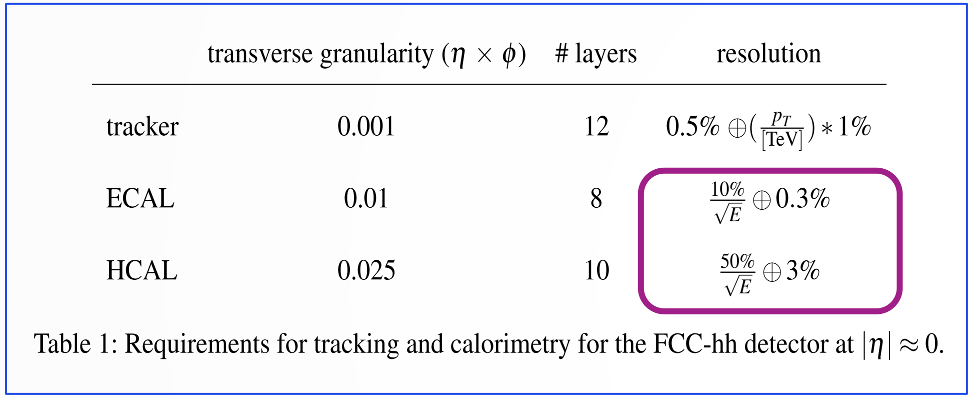

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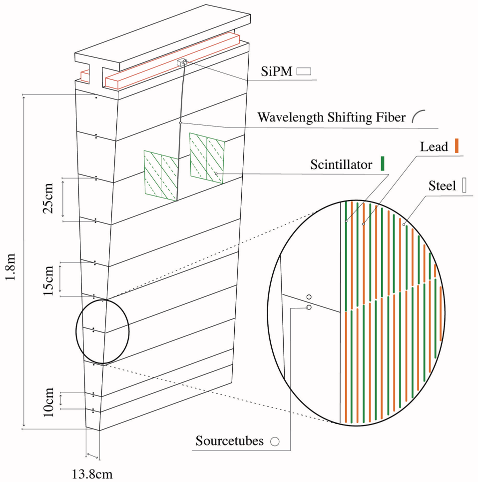
Table 1: Requirements for tracking and calorimetry for the FCC-hh detector at $|\eta| \approx 0$.

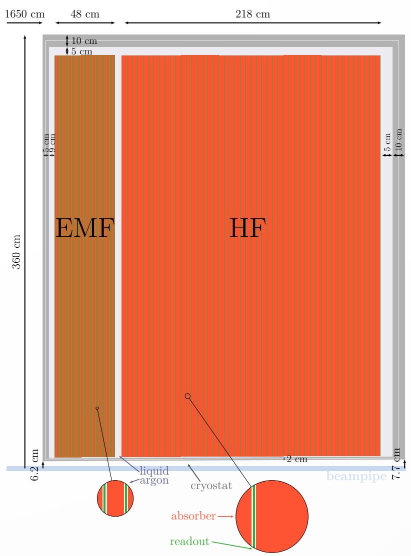
Barrel HCAL:
- ATLAS type TileCal optimized for particle flow with higher granularity
- combined pion resolution can be improved with NN calibration

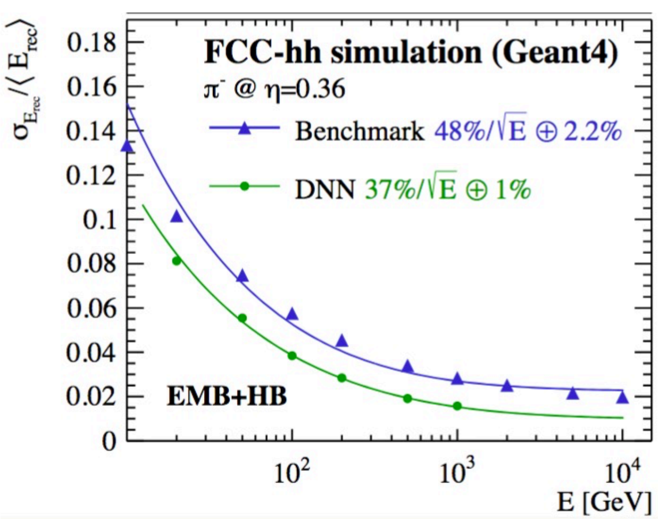
Endcap and Forward HCAL:
- Radiation hardness major challenge

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)

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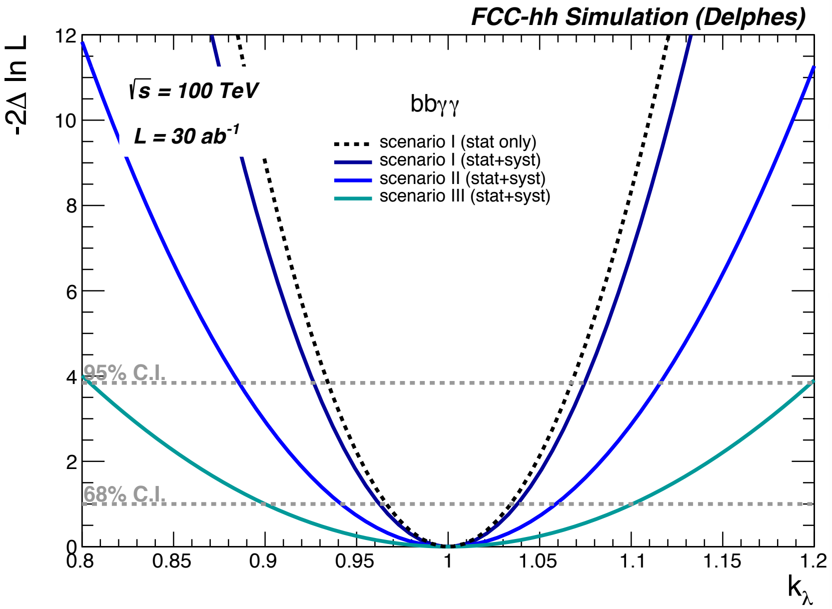

δ_{κ_λ}=3.8-10% depending on assumptions for systematics and resolution

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 $\rightarrow \gamma$ 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	$0.5\% \oplus (\frac{p_T}{[\text{TeV}]}) * 1\%$
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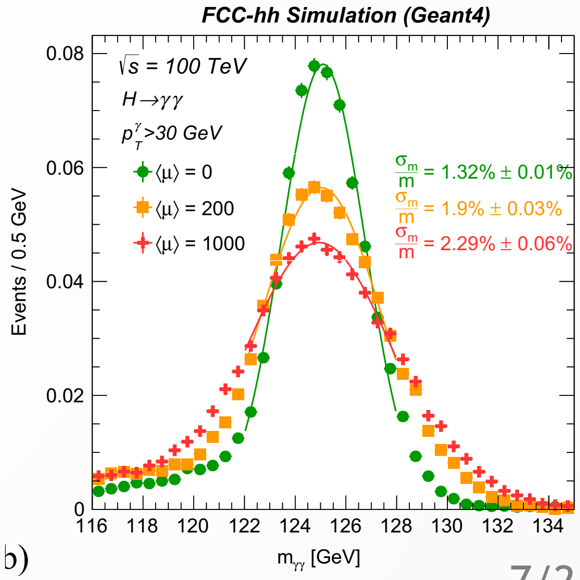
Should achieve 1% γγ

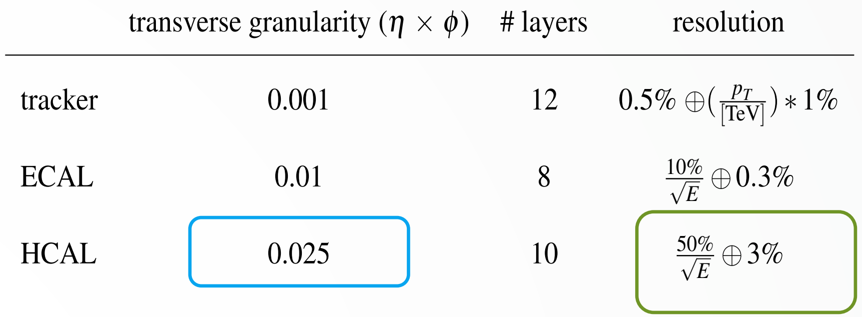
Pile-up could degrade this considerably



Searches for NP: high p_T jets and boosted objects

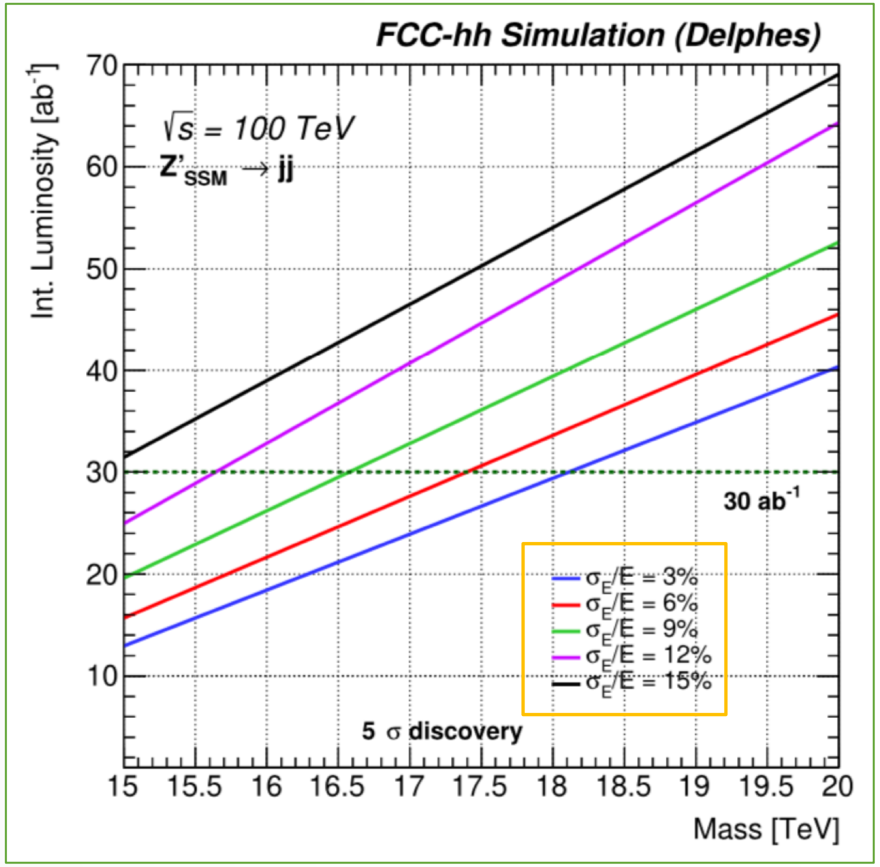
For di-jet resonances, HCAL constant term has huge impact on the luminosity needed to get the same reach. Furthermore:

- Need full shower containment
- Large HCAL depth (~ 12 λ_{int})



	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 $|\eta| \approx 0$.

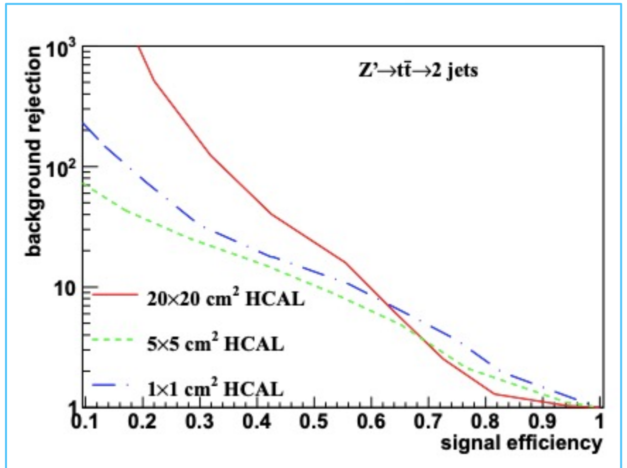


Eur. Phys. J. C (2019) 79:569

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

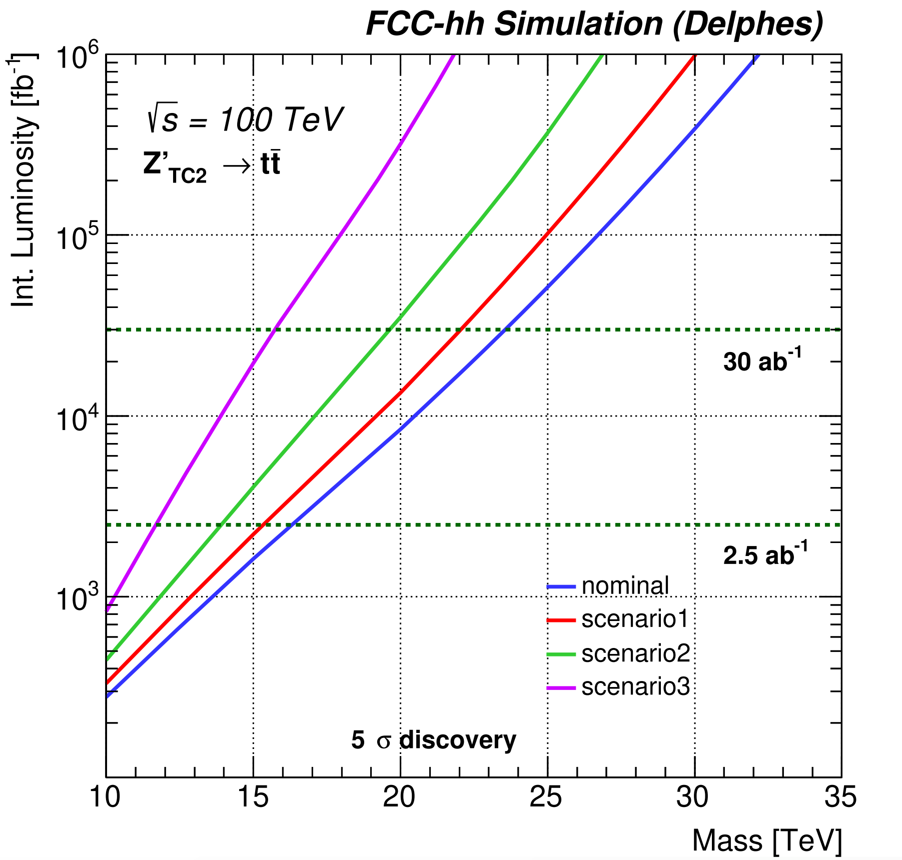
https://arxiv.org/pdf/1901.11146.pdf

b-tagging requirement

- Capability of efficiently identify b-jets is fundamental
- 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)
$(1 - p_\mathrm{T}\ [\mathrm{TeV}]/15)\cdot 1\%$	$(1 - p_\mathrm{T}\ [\mathrm{TeV}]/15)\cdot 5\%$	$(8/9 - p_\mathrm{T}\ [\mathrm{TeV}]/30)\cdot 1\%$

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



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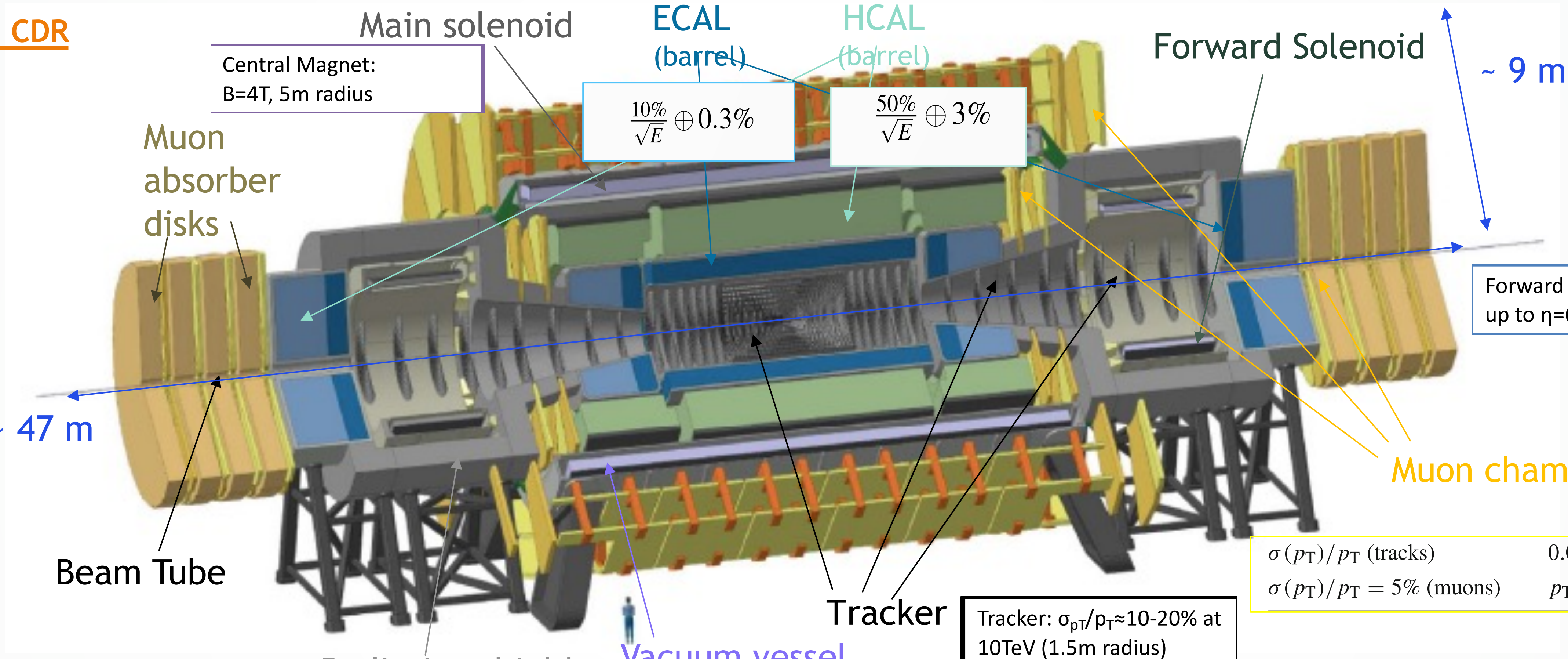
Requirements for an FCC-hh detector

FCC-hh CDR



Central Magnet:
B=4T, 5m radius

$\frac{10\%}{\sqrt{E}} \oplus 0.3\%$

$\frac{50\%}{\sqrt{E}} \oplus 3\%$

Forward detectors
up to η=6

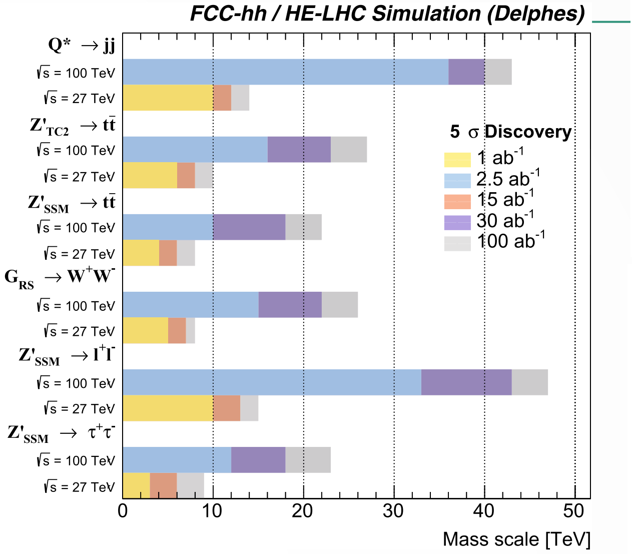
$\sigma(p_\mathrm{T})/p_\mathrm{T}$ (tracks) $0.02 \cdot p_\mathrm{T}$ (TeV/c)
$\sigma(p_\mathrm{T})/p_\mathrm{T} = 5\%$ (muons) $p_\mathrm{T} = 15$ TeV

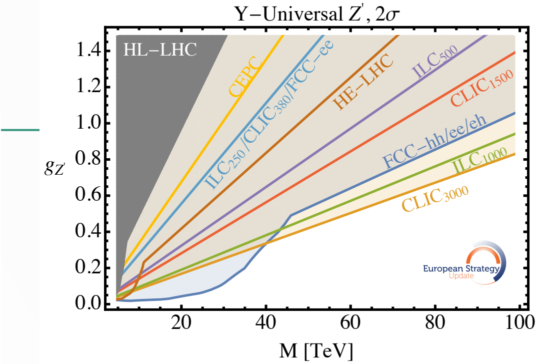
Tracker: $\sigma_{p_T}/p_T \approx 10\text{-}20\%$ at
10TeV (1.5m radius)

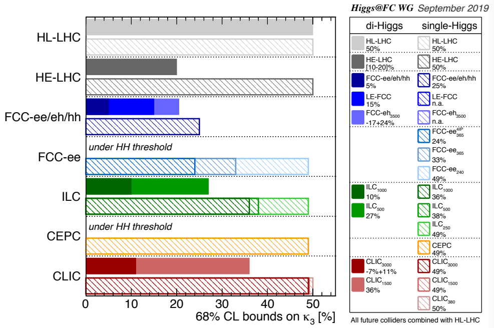
- High granularity of tracker and calorimeters, high efficiency for vertex reco, b-tag, τ-tag, particles ID, low calo constant term and high resolution → achieve all this with pile-up of 100 (timing) and radiation hardness detectors
- Not mentioned here: studies (and challenges) for magnets, read-out electronics, triggers, power and cooling

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 [not discussed here]
  - Highest reach in sensitivity also for di-higgs studies, dark matter searches and more
    - E.g. can conclusively test the hypothesis of thermal DM







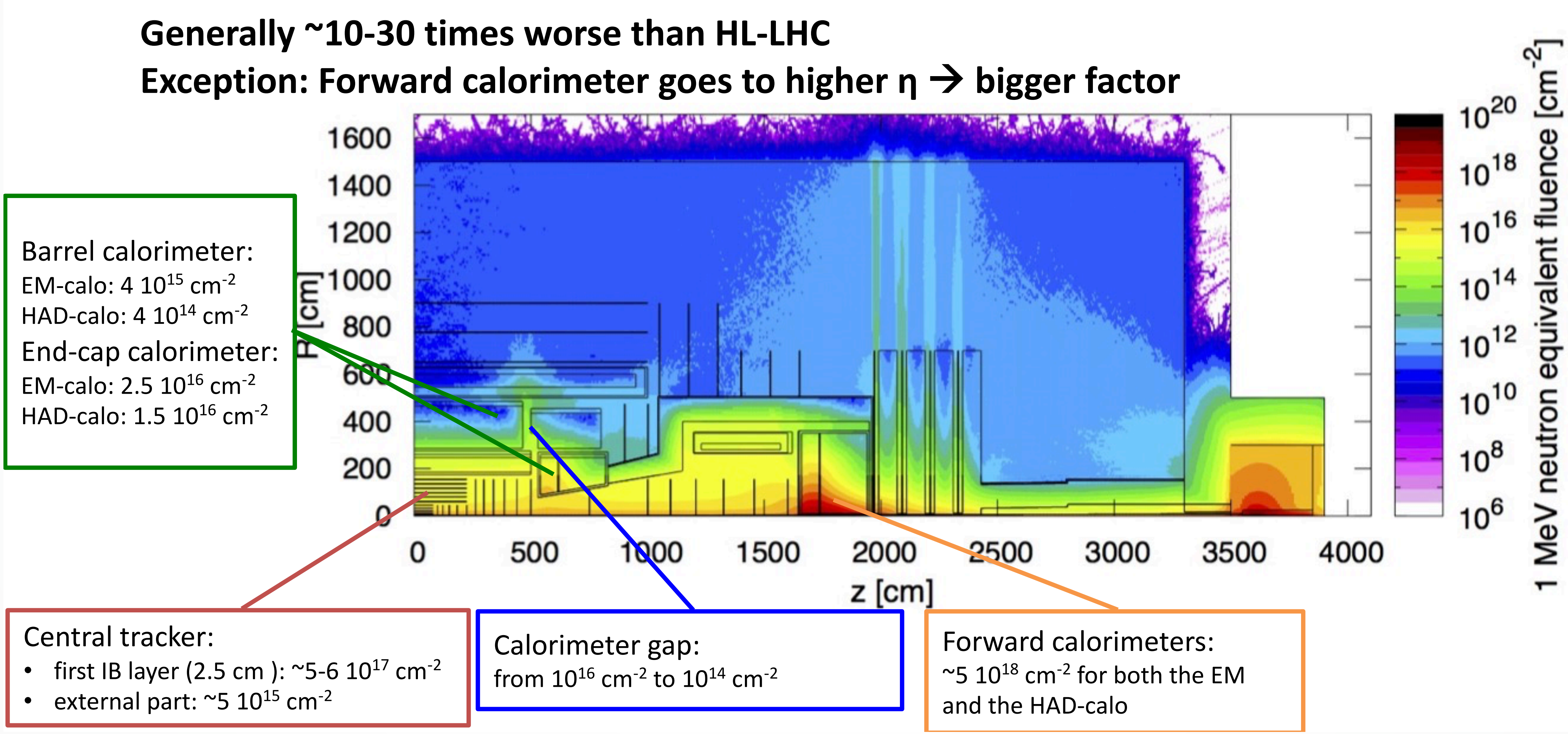
- Extreme granularity, excellent energy-momentum resolution beyond the LHC detectors, together with novel algorithms will be needed to achieve optimal object reconstruction and identification
- Comparative studies considering different hypotheses for detector performance have been made using some searches 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
  - Quoting P. Allport: ***Without the required investment in detector R&D, the opportunities this offers will be squandered***

Back up

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

- From Martin Aleksa overview

Generally ~10-30 times worse than HL-LHC
Exception: Forward calorimeter goes to higher η → bigger factor



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}

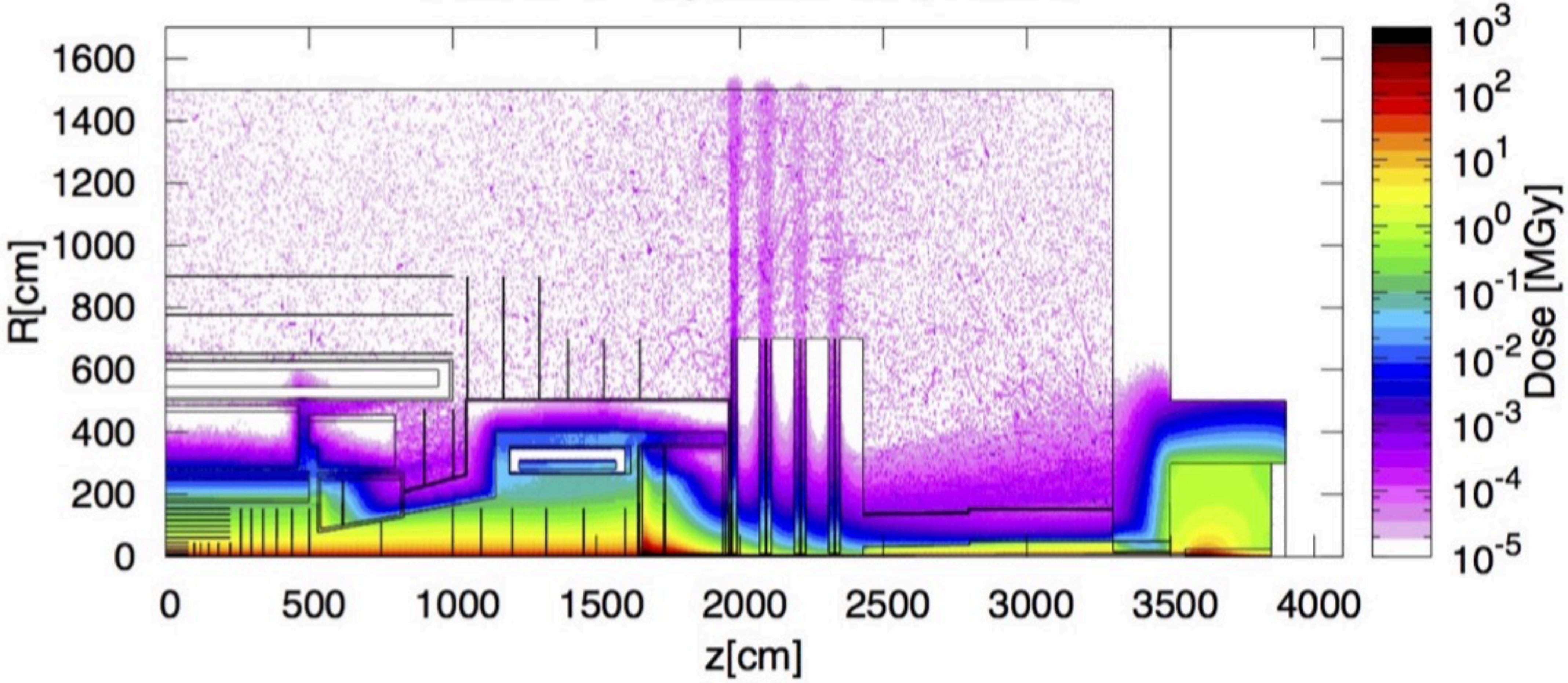
Forward calorimeters:
~5 10^{18} cm^{-2} for both the EM and the HAD-calo

Total Ionizing Dose for 30ab^{-1}

- From Martin Aleksa overview

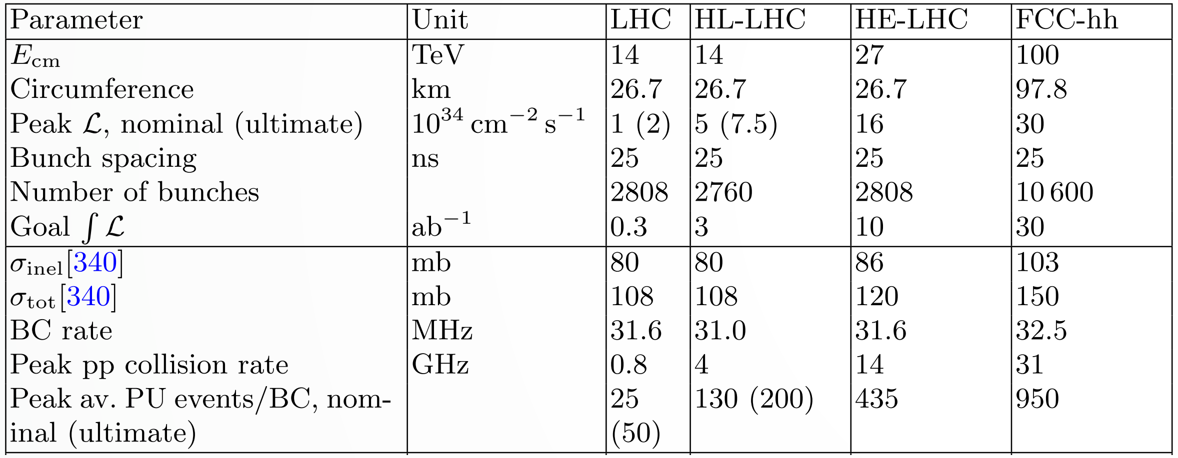
Dose of 300 MGy (30 Grad) in the first tracker layers.

< 10 kGy in HCAL barrel and extended barrel.

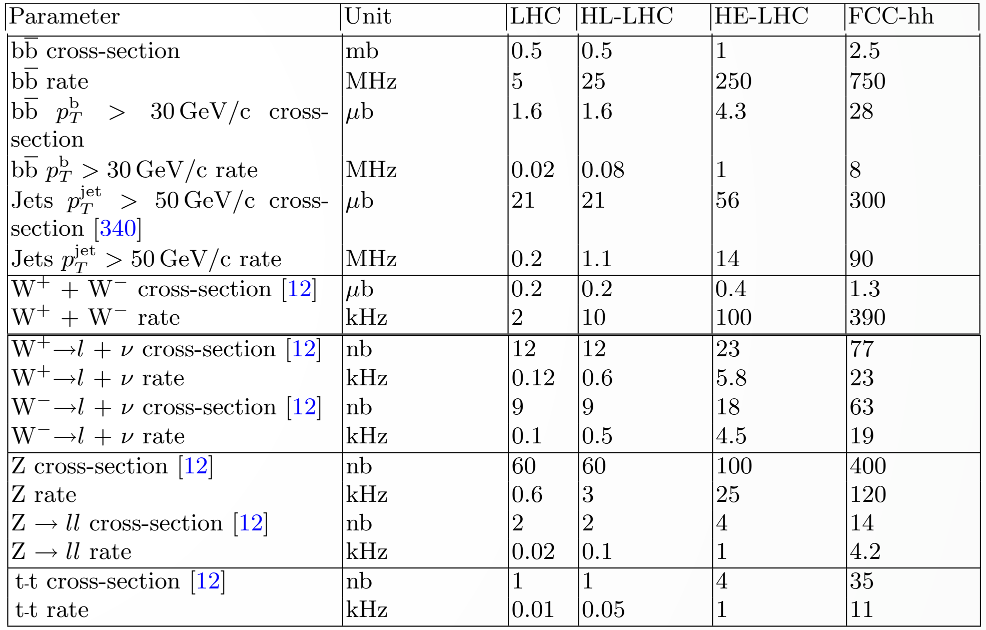


Parameters and cross-sections

- Parameters

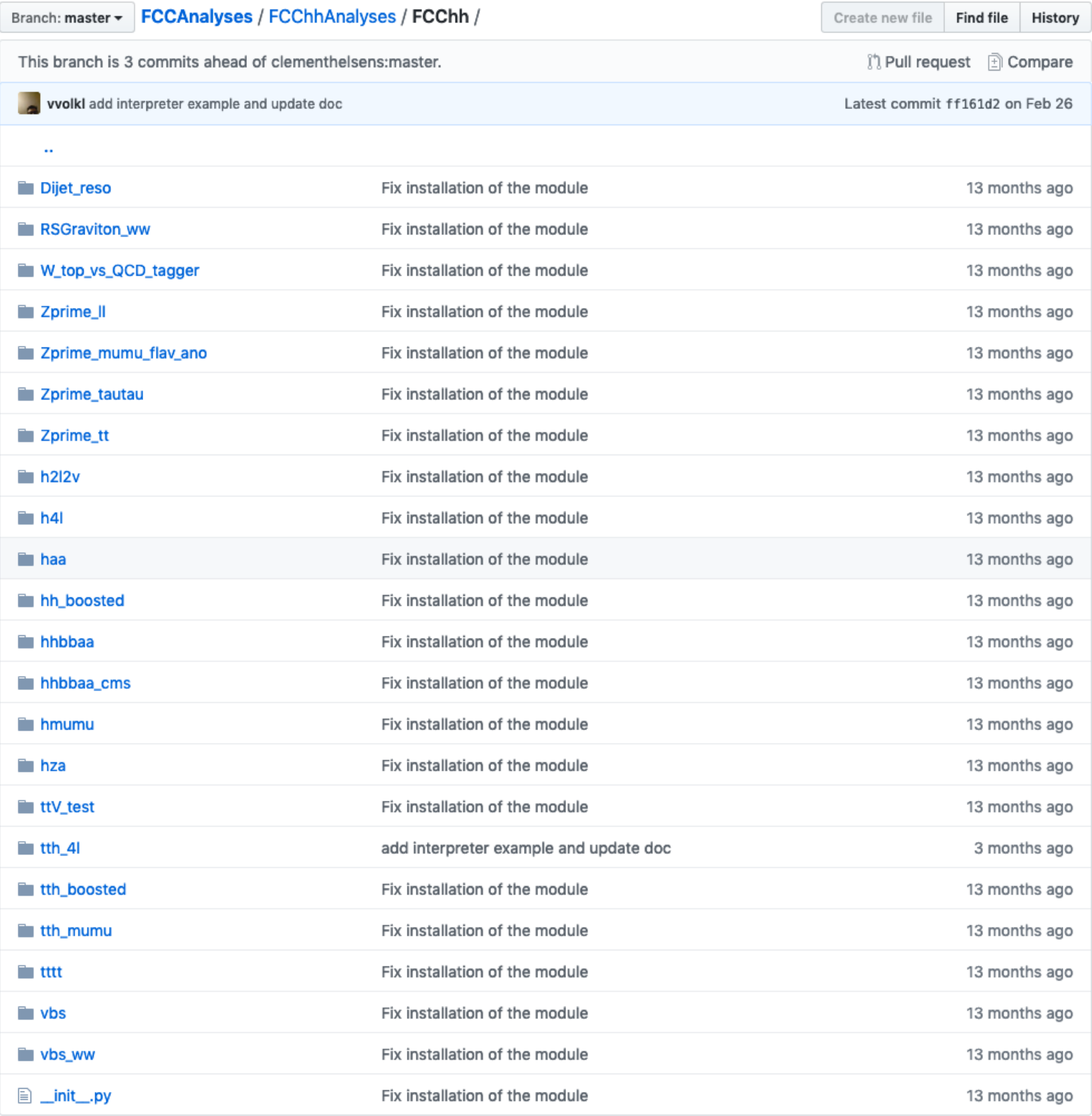


Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	1 (2)	5 (7.5)	16	30
Bunch spacing	ns	25	25	25	25
Number of bunches		2808	2760	2808	10 600
Goal $\int \mathcal{L}$	ab^{-1}	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
$\mathrm{b\bar{b}}$ cross-section	mb	0.5	0.5	1	2.5
$\mathrm{b\bar{b}}$ rate	MHz	5	25	250	750
$\mathrm{b\bar{b}}$ $p_T^{\mathrm{b}} > 30\,\mathrm{GeV/c}$ cross-section	μb	1.6	1.6	4.3	28
$\mathrm{b\bar{b}}$ $p_T^{\mathrm{b}} > 30\,\mathrm{GeV/c}$ 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
$\mathrm{W}^+ + \mathrm{W}^-$ cross-section [12]	μb	0.2	0.2	0.4	1.3
$\mathrm{W}^+ + \mathrm{W}^-$ rate	kHz	2	10	100	390
$\mathrm{W}^+ \rightarrow l + \nu$ cross-section [12]	nb	12	12	23	77
$\mathrm{W}^+ \rightarrow l + \nu$ rate	kHz	0.12	0.6	5.8	23
$\mathrm{W}^- \rightarrow l + \nu$ cross-section [12]	nb	9	9	18	63
$\mathrm{W}^- \rightarrow l + \nu$ 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
$\mathrm{Z} \rightarrow ll$ cross-section [12]	nb	2	2	4	14
$\mathrm{Z} \rightarrow ll$ 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

Repository



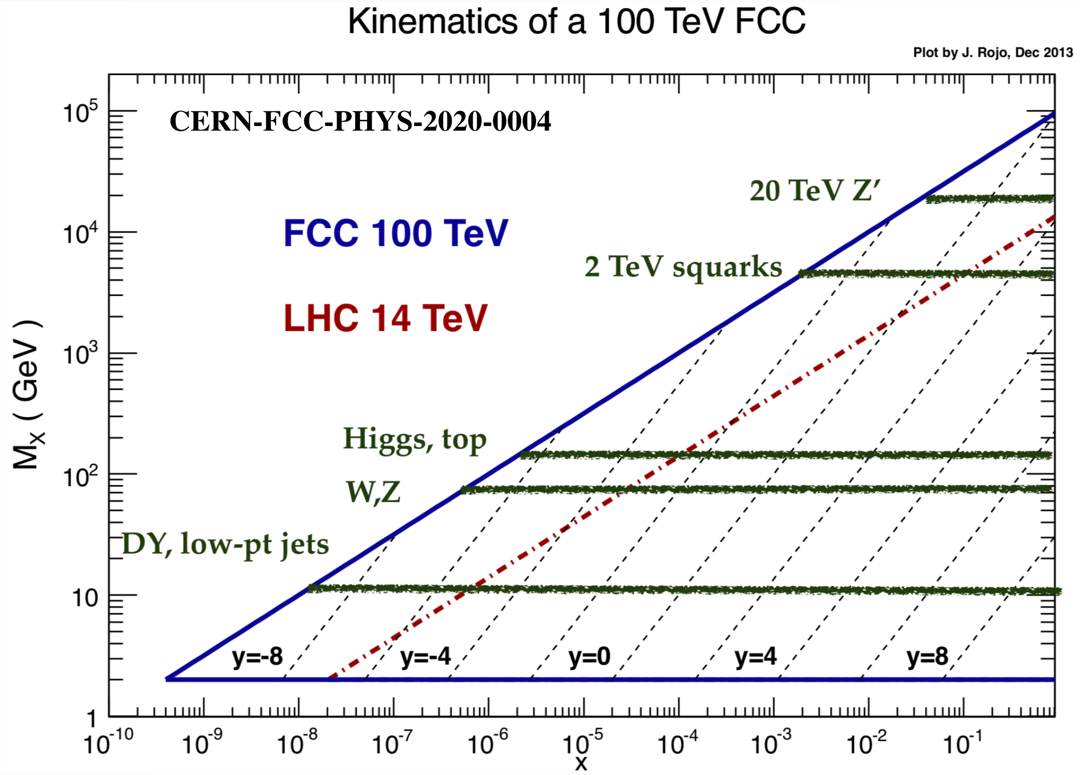
FCCAnalyses / FCChhAnalyses / FCChh /

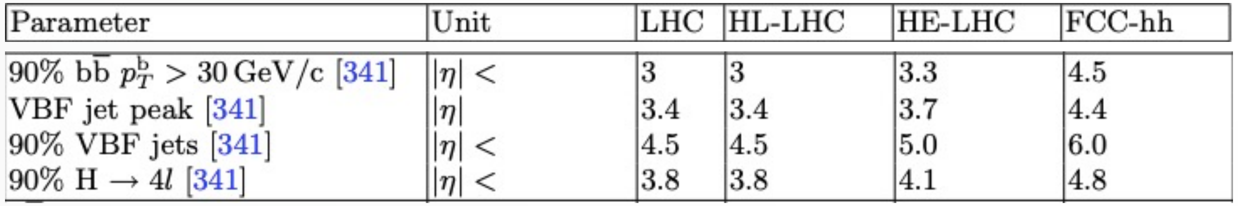
This branch is 3 commits ahead of clementhelsens:master.

vvolkl add interpreter example and update doc — Latest commit `ff161d2` on Feb 26

..		
Dijet_reso	Fix installation of the module	13 months ago
RSGraviton_ww	Fix installation of the module	13 months ago
W_top_vs_QCD_tagger	Fix installation of the module	13 months ago
Zprime_ll	Fix installation of the module	13 months ago
Zprime_mumu_flav_ano	Fix installation of the module	13 months ago
Zprime_tautau	Fix installation of the module	13 months ago
Zprime_tt	Fix installation of the module	13 months ago
h2l2v	Fix installation of the module	13 months ago
h4l	Fix installation of the module	13 months ago
haa	Fix installation of the module	13 months ago
hh_boosted	Fix installation of the module	13 months ago
hhbbaa	Fix installation of the module	13 months ago
hhbbaa_cms	Fix installation of the module	13 months ago
hmumu	Fix installation of the module	13 months ago
hza	Fix installation of the module	13 months ago
ttV_test	Fix installation of the module	13 months ago
tth_4l	add interpreter example and update doc	3 months ago
tth_boosted	Fix installation of the module	13 months ago
tth_mumu	Fix installation of the module	13 months ago
tttt	Fix installation of the module	13 months ago
vbs	Fix installation of the module	13 months ago
vbs_ww	Fix installation of the module	13 months ago
__init__.py	Fix installation of the module	13 months ago

Kinematic coverage and geometrical acceptance

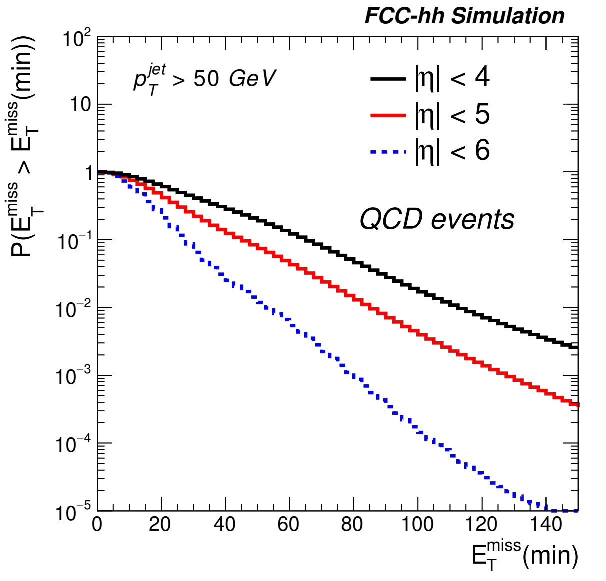




Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
90% $b\bar{b}$ $p_T^b > 30\,\mathrm{GeV/c}$ [341]	$\lvert\eta\rvert <$	3	3	3.3	4.5
VBF jet peak [341]	$\lvert\eta\rvert$	3.4	3.4	3.7	4.4
90% VBF jets [341]	$\lvert\eta\rvert <$	4.5	4.5	5.0	6.0
90% H → 4l [341]	$\lvert\eta\rvert <$	3.8	3.8	4.1	4.8

- 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)

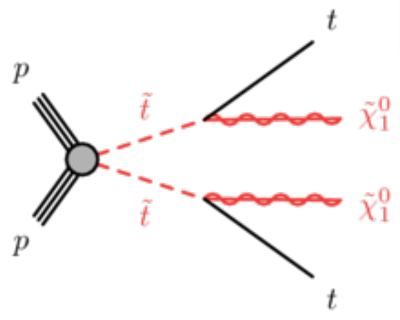


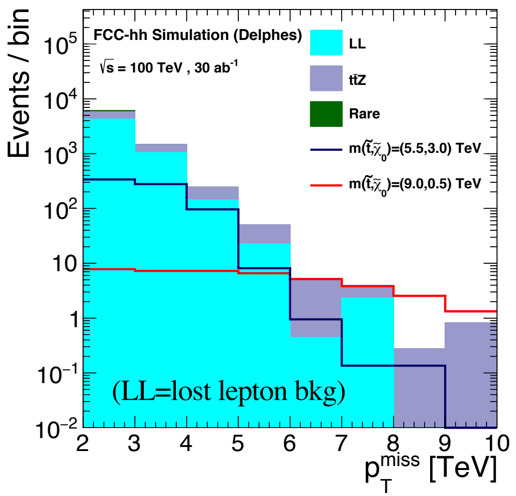
Probability of reconstructing E_T^{miss} greater than E_T^{miss} (min) in di-jet QCD events

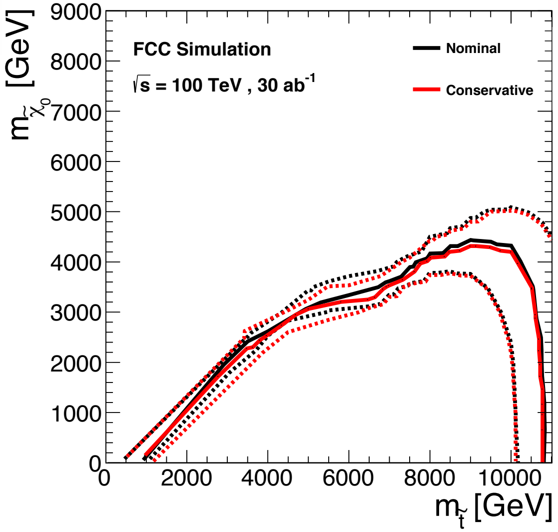
Missing E_T is fundamental for Dark Matter searches in mono-X final states, SUSY particles and more

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

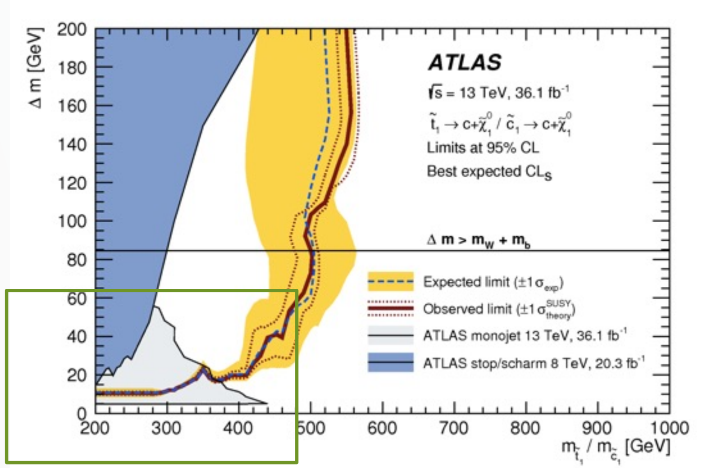






Discovery potential at 30/ab up to 8 TeV

- Monojet analyses (jet+MET) sensitive to compressed scenarios, small ΔM = m_{stop} – m_{LSP} :



JHEP 09 (2018) 050

ΔM ~ 2 – 10 GeV

Results for FCC-hh are projections

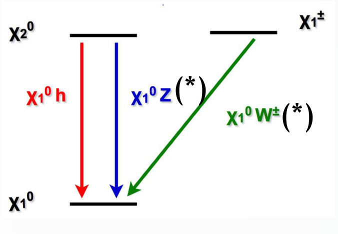
with ColliderReachTool:
HL-LHC → 0.95 TeV; [confirmed exp.]
HE-LHC → 2 TeV;
FCC-hh → 5 TeV

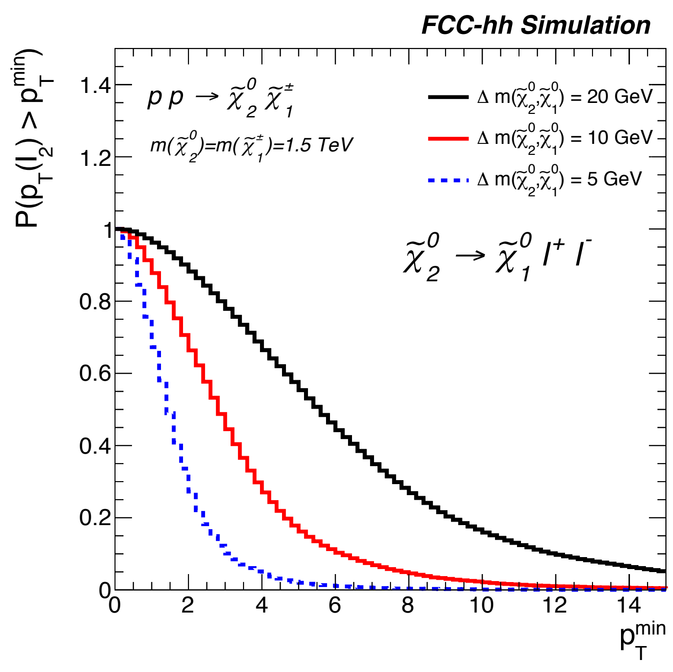
→ recoil-jet pt thresholds can be adjusted

→ 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





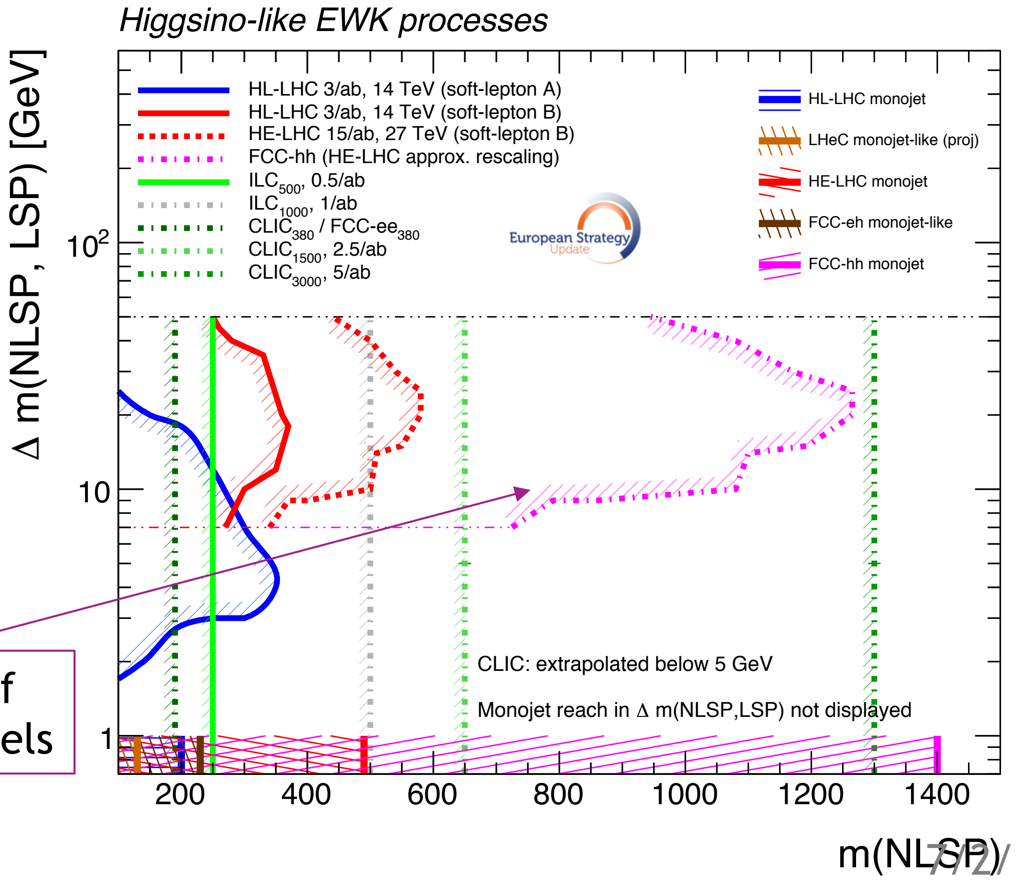
CERN-FCC-PHYS-2020-0004

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

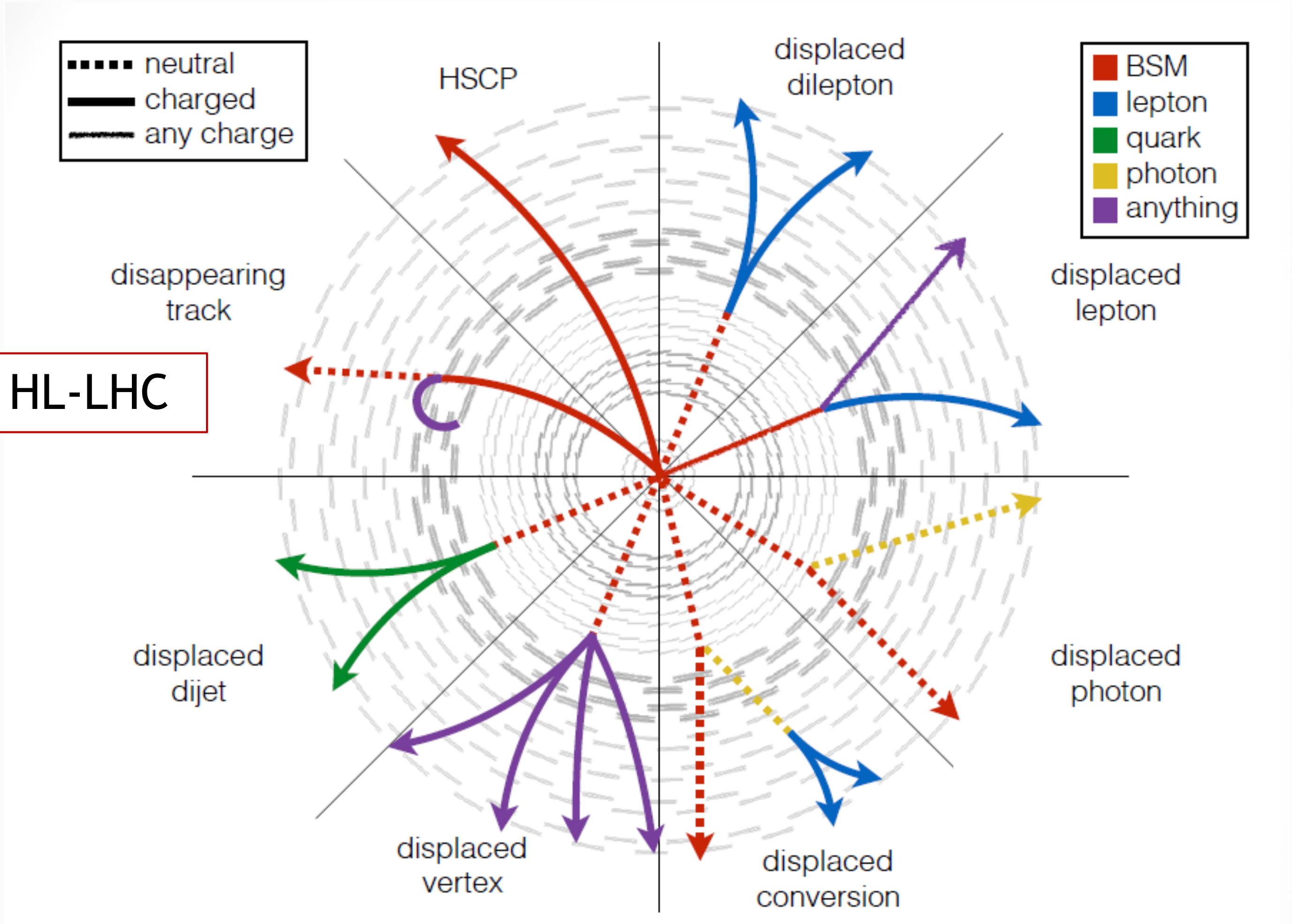
Higgsino-like EWK processes



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)

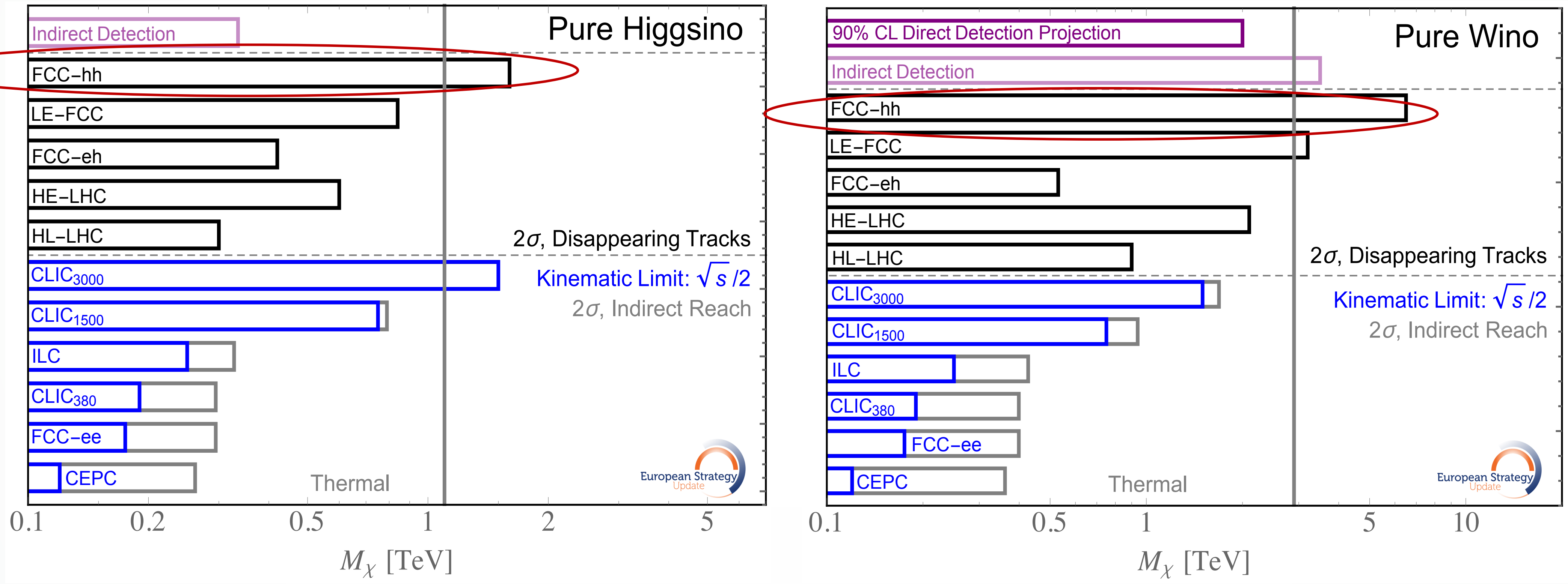
E.g. @ HL-LHC



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.

Example: disappearing track

- Disappearing track signatures appear in a variety of models for Dark Matter:
  - SUSY …
  - Thermal freeze-out mechanism: massive particle with EW gauge interactions only. Spin-1/2 particles transforming as doublets or triplets under SU(2) symmetry, usually referred to as Higgsino and Wino

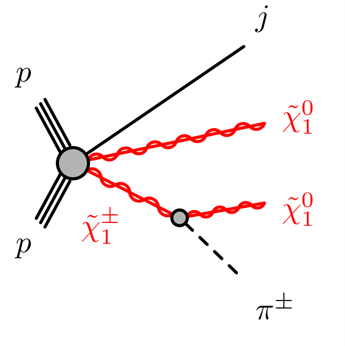


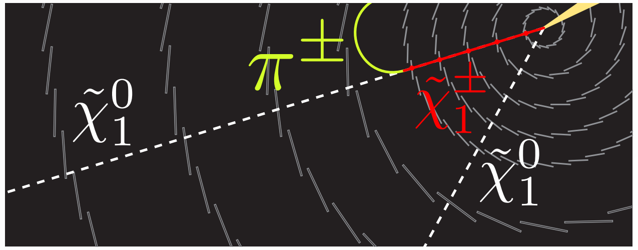
FCC-hh can conclusively test the hypothesis of thermal DM in both scenarios - but what are the assumptions?

Disappearing track signatures @ HL-LHC

Section 4.1 of arxiv:1812.07831

ATL-PHYS-PUB-2018-031





Very challenging with high pile-up → not shown in this sketch

A disappearing track occurs when the decay products of a charged particle, like a supersymmetric chargino, are not detected (disappear) because they either interact only weakly or have soft momenta and hence are not reconstructed.

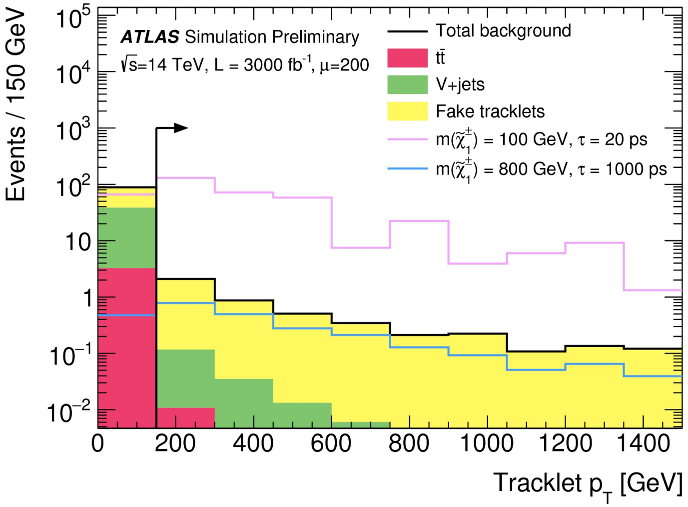
Variable	SR Selection
Lepton veto p_T [GeV]	>20
$\min\{\Delta\phi(\text{jet}_{1-4}, E_T^{\text{miss}})\}$	> 1
E_T^{miss} [GeV]	> 300
Leading jet p_T [GeV]	> 300
Leading tracklet p_T [GeV]	> 150
$\Delta\phi(E_T^{\text{miss}}, \text{trk})$	< 0.5

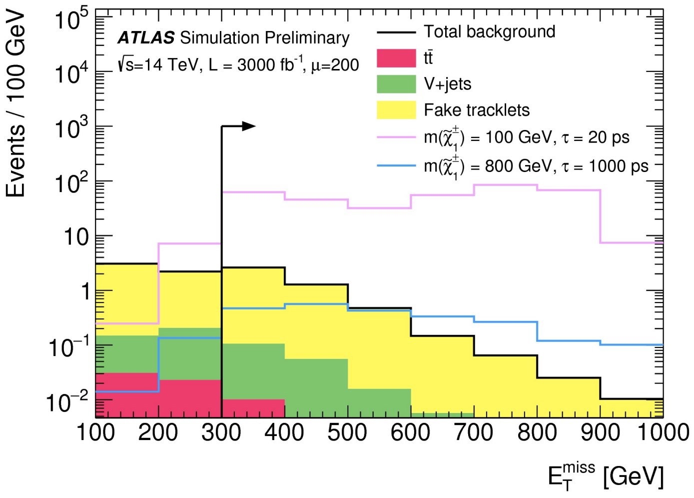
Tracklet reconstruction:

- “standard” tracks are reconstructed;
- track reconstruction is then rerun with looser criteria → >= 4 pixel hits using only input hits not associated with tracks
- Tracklets are then extrapolated to the strip detectors
- p_T > 5 GeV and $|\eta|$ < 2.2

Event selection:

- Use boosts from ISR jets to trigger events
- Lepton veto and kinematic selections applied to reduce background

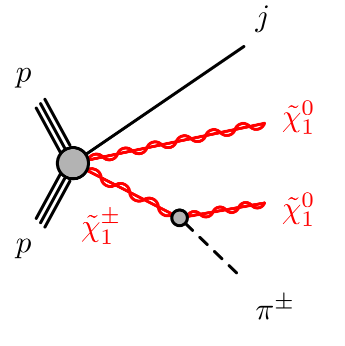


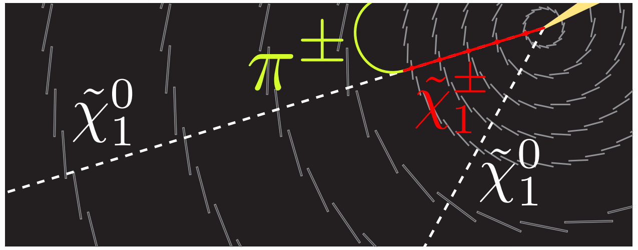


Disappearing track signatures @ HL-LHC

Section 4.1.1 of arxiv:1812.07831

ATL-PHYS-PUB-2018-031





Very challenging with high pile-up → not shown in this sketch

A disappearing track occurs when the decay products of a charged particle, like a supersymmetric chargino, are not detected (disappear) because they either interact only weakly or have soft momenta and hence are not reconstructed.

Two sources of background contributions:

- SM particles that are reconstructed as tracklets, i.e. **hadrons** scattering in detector material or **electrons** undergoing bremsstrahlung

1) use samples of single e or π passing through the current ATLAS detector layout to estimate the probability that an isolated e or hadron leave a disappearing track
2) Scale it to account for ratio of material in the current ATLAS inner detector and the upgraded inner tracker

- Events which contain **fake tracklets**:
  - from Z → νν or W → lν where lepton is lost
  - Scaled by the expected fake tracklet probability
  - Fakes are also the largest source of uncertainties **(~30% of total backgro**und)

$$p^{\mathrm{ITk}}_{\mathrm{fake,tight}} = p^{\mathrm{ATLAS}}_{\mathrm{fake,tight}} \times \frac{R^{\mathrm{ITk}}_{\mathrm{fake,loose}}}{R^{\mathrm{ATLAS}}_{\mathrm{fake,loose}}} \times \frac{\epsilon^{\mathrm{ITk}}_{z_0}}{\epsilon^{\mathrm{ATLAS}}_{z_0}}.$$

~ 200 (depends strongly on pile up)

~ 0.12 (due to differences in tracket selection)