FCC-hh: experimental challenges

Monica D'Onofrio

University of Liverpool

FCC UK 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 highlights of some interesting results depending substantially on experimental conditions and detector challenges and some current standings on detector ideas.

Lot of material available - used for this talk:

FCC Volume 1 and references + older or newer documents: https://arxiv.org/pdf/1606.00947.pdf, CERN-ACC-2018 -0056.pdf, Eur. Phys. J. C (2019) 79:569, CERN-FCC-PHYS-2020-0004

European Strategy Briefing book: https://arxiv.org/abs/1910.11775

These two in particular present comparative studies under different hypothesis for detector performance on searches for high mass resonances developed after the European Strategy

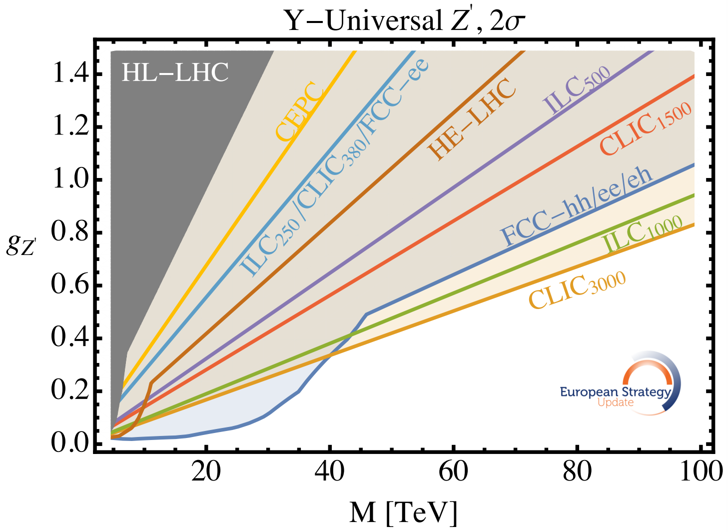
Disclaimers: (1) only a few examples based on searches which I know best
(2) I have not worked directly on detector studies at FCC-hh

Physics potential of FCC-hh: a few examples

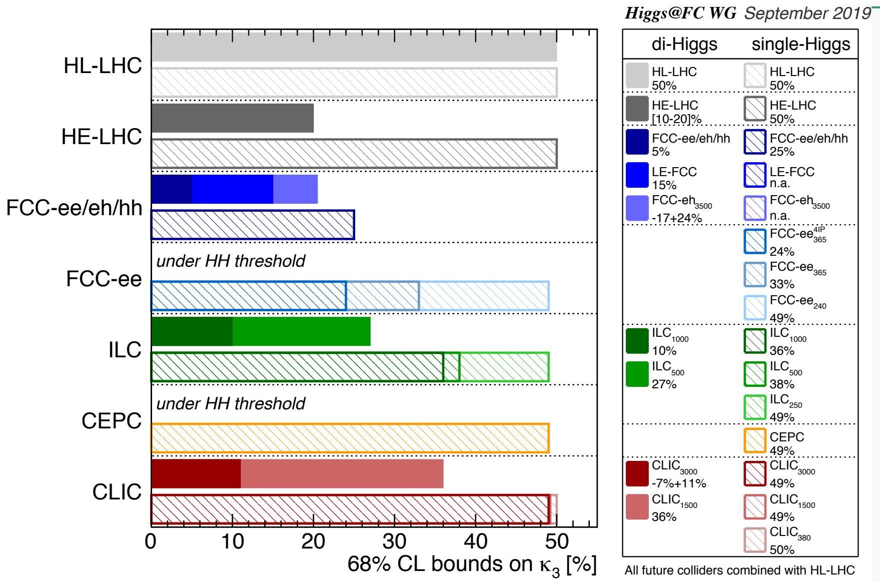
BSM searches, higgs measurements ..

All are examples of how FCC-hh can go far beyond any other machine as considered for the European Strategy

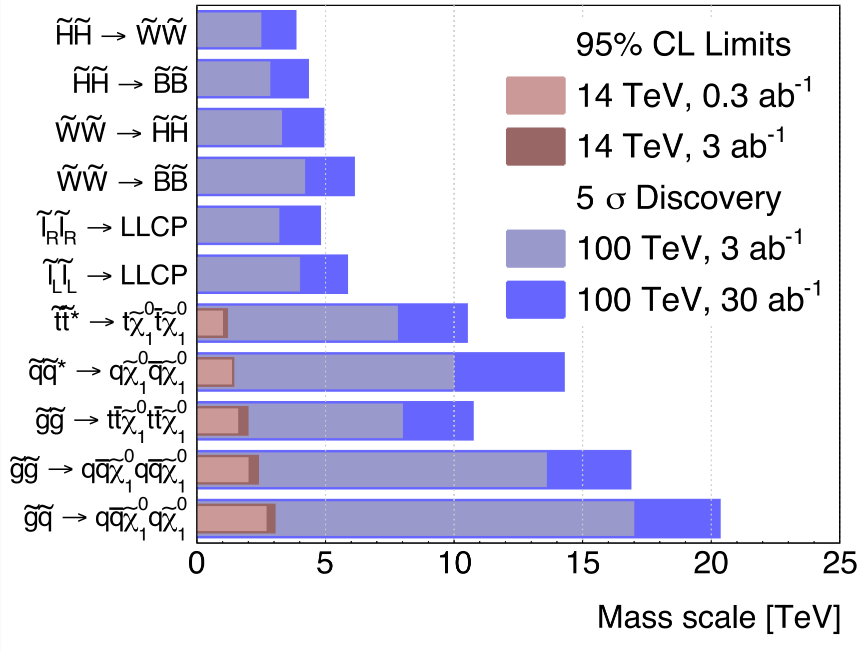
Searches for heavy resonances



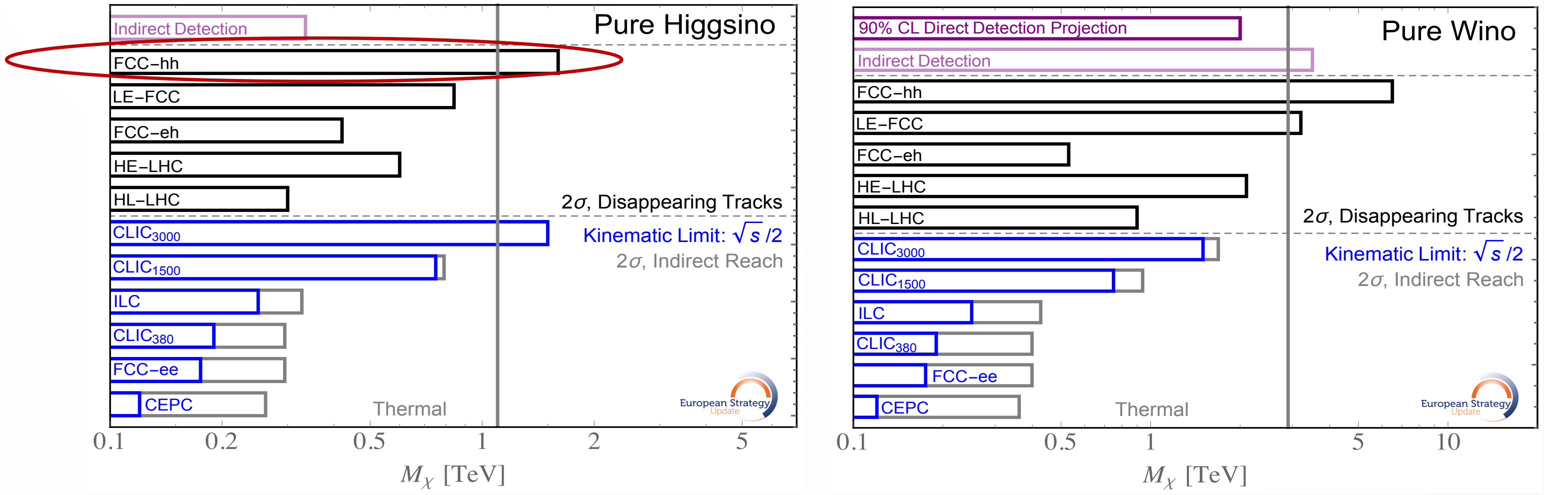
Di-higgs



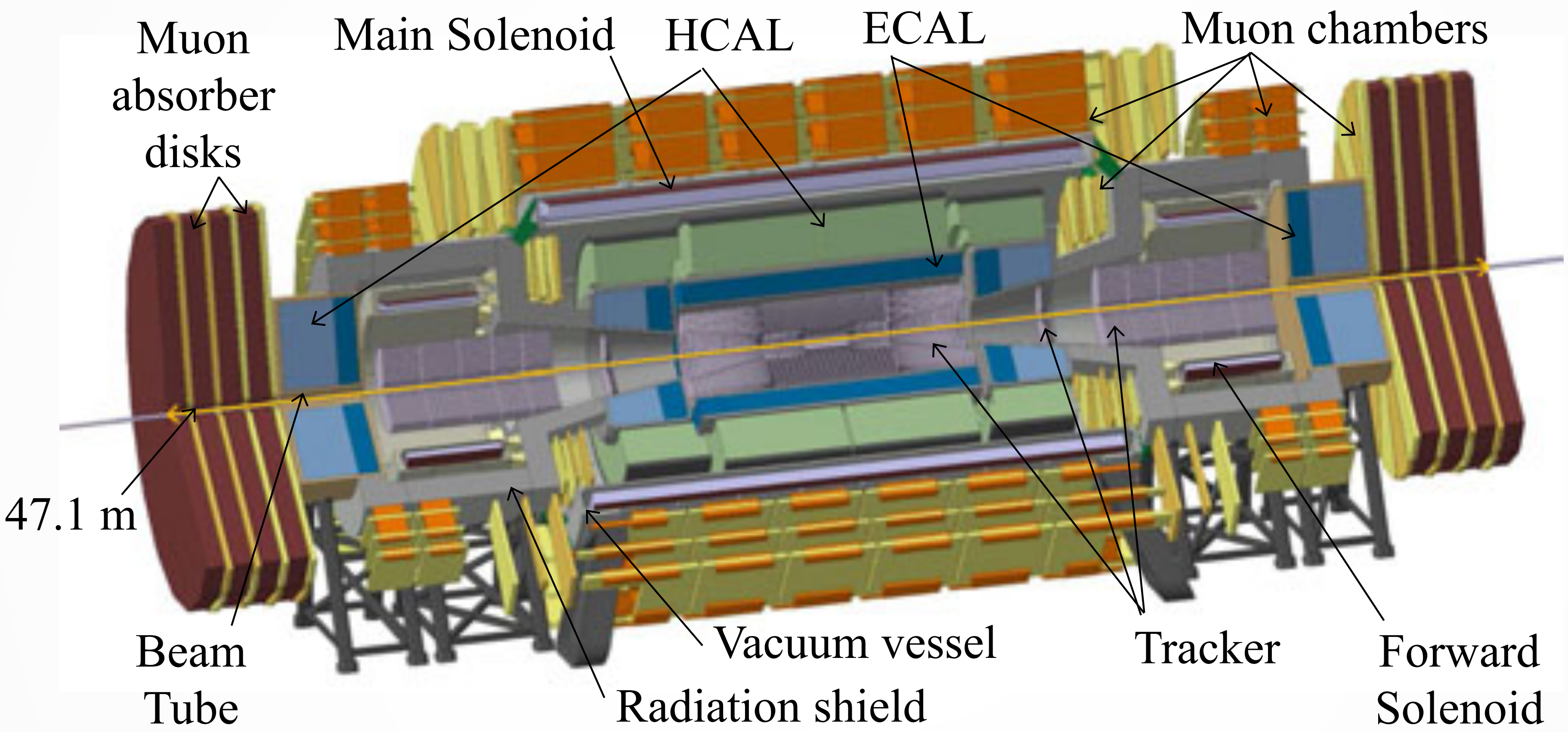
Searches for SUSY particles



dark matter wino/higgsino models



A possible layout of a detector for the FCC-hh

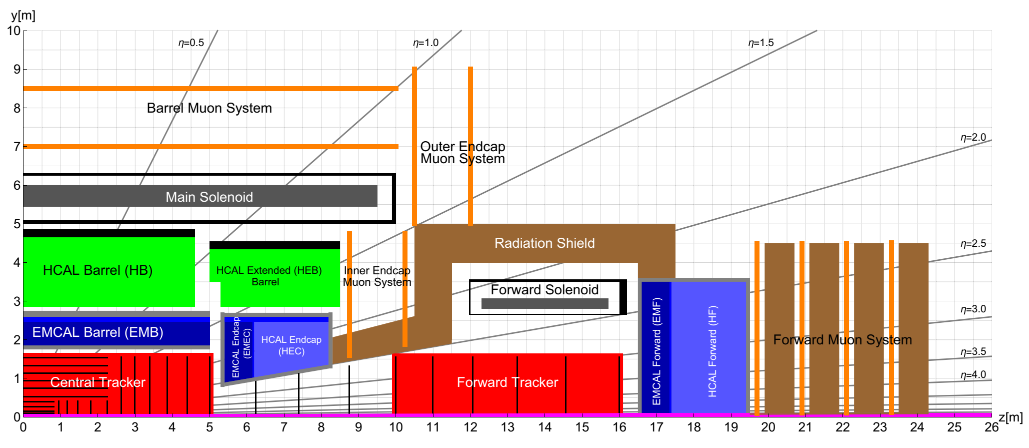


- Assume cavern length of 66 m
- In this case, 4-T main solenoid and forward solenoids
  - As for CMS, central tracker and calorimeters placed in the bore of the main solenoid.

From the FCC-hh CDR

https://link.springer.com/article/10.1140/epjst/e2019-900087-0

- Conceptual designs so far based on current detectors of course. In some cases, various options are explored
- **Tracker:** two proposed layouts
  - *Flat* geometry
  - *Tilted* geometry - 50% less material budget to be compromised with high rad deposits



total silicon surface amounts to 430 m^2 for the flat geometry and 391 m^2 for the tilted geometry.

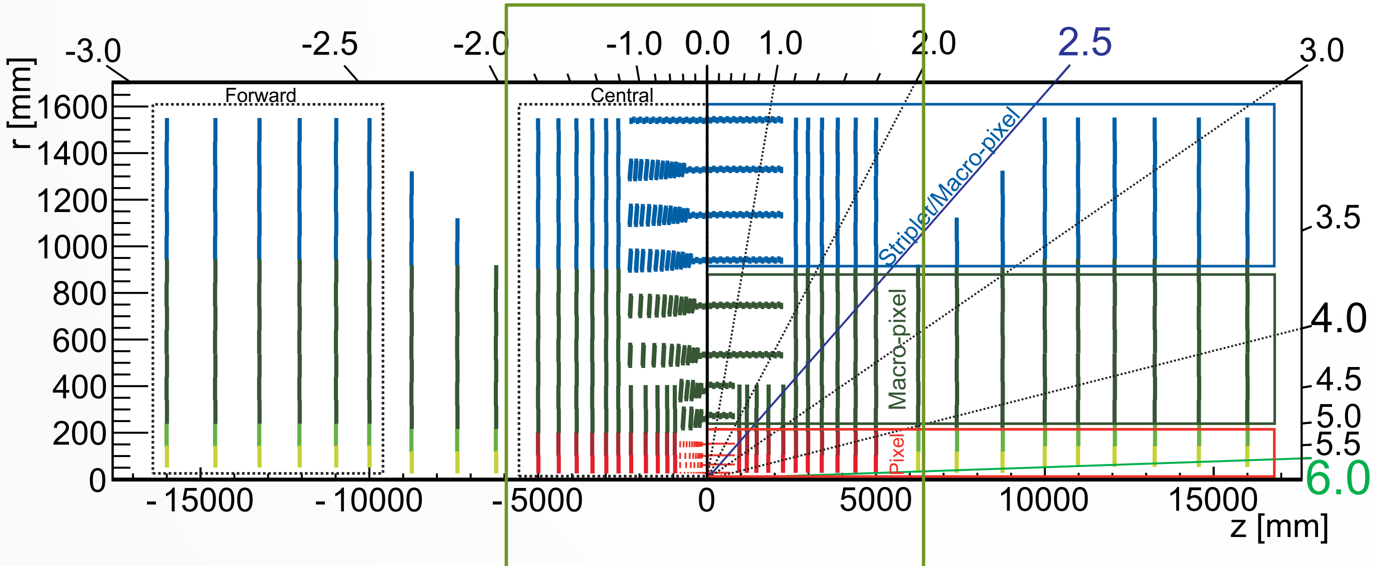
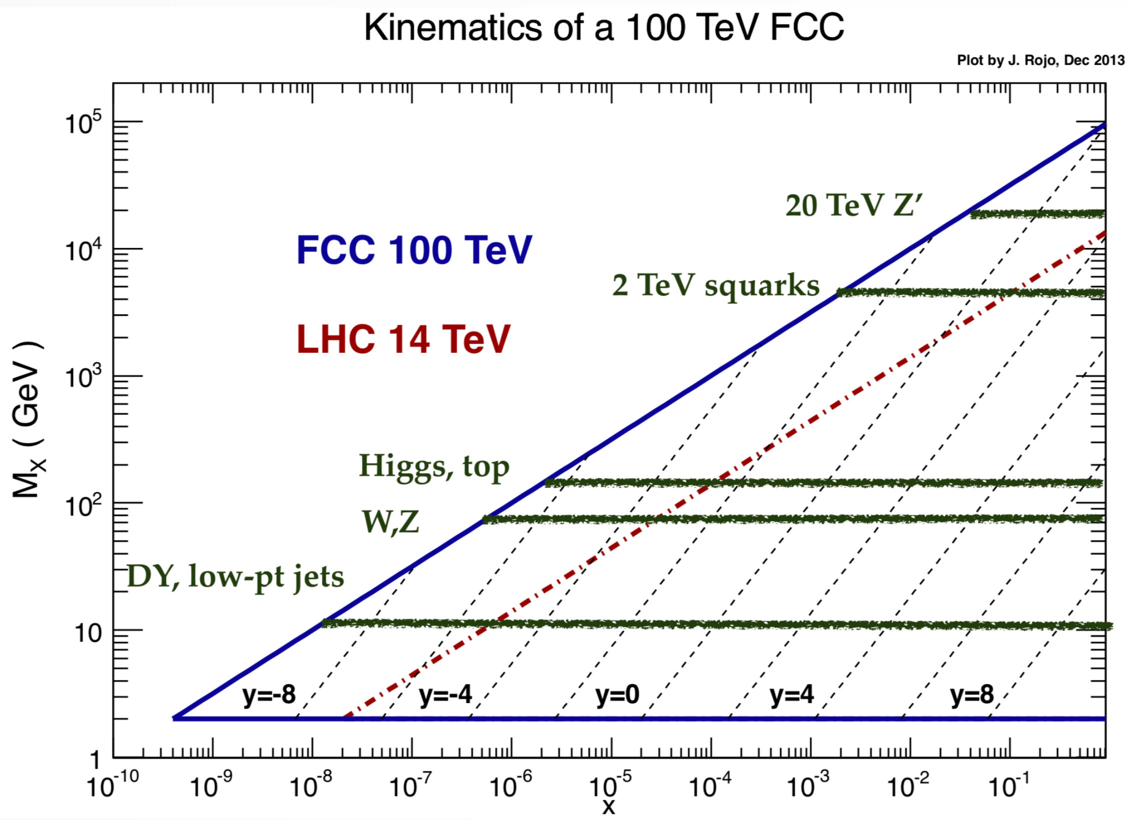


Fig. 7.11. Tracker layout using the so called "tilted geometry" (left) and "flat geometry" (right).

A central tracker would cover |η|<2.5

A forward tracker would cover the region at higher rapidity, exploiting the presence of a forward solenoid (inspired by ALICE and LHCb spectrometers)

Kinematic coverage and geometrical acceptance

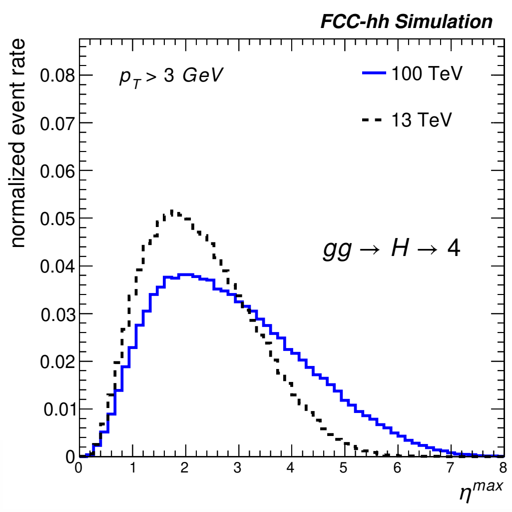


Studies from M. Mangano, C. Helsen, M Selvaggi

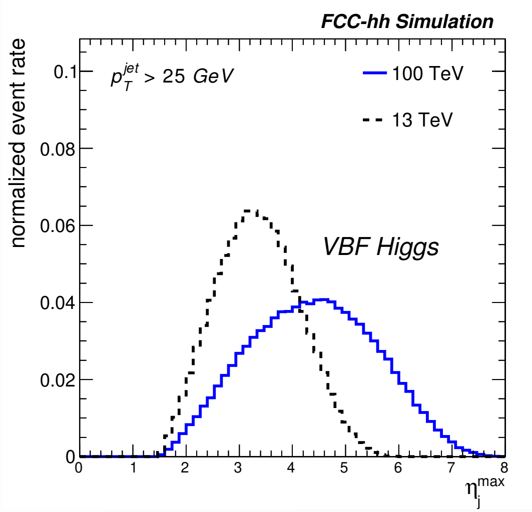
CERN-FCC-PHYS-2020-0004

- 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

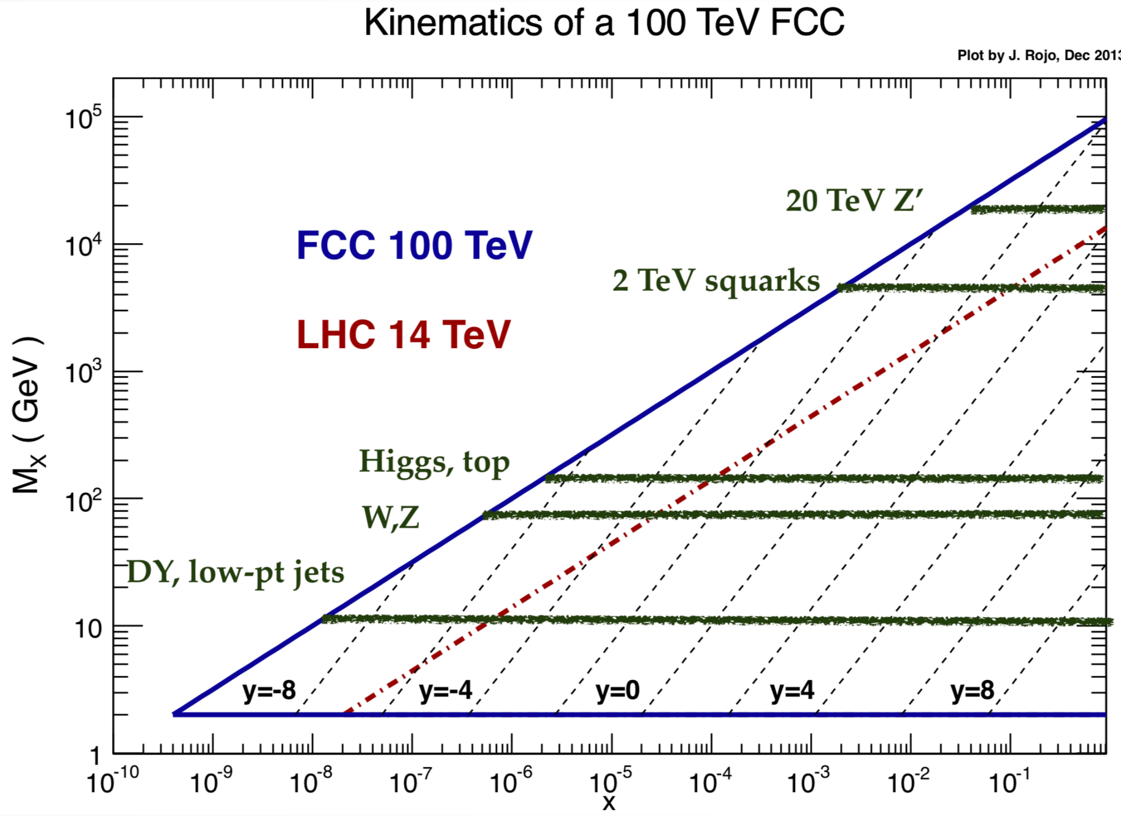


maximum jet pseudo-rapidity



→ Set stringent requirements on detector acceptance
→ Forward detectors will have to operate in extreme environment (large radiations, high pile-up)

Kinematic coverage and geometrical acceptance

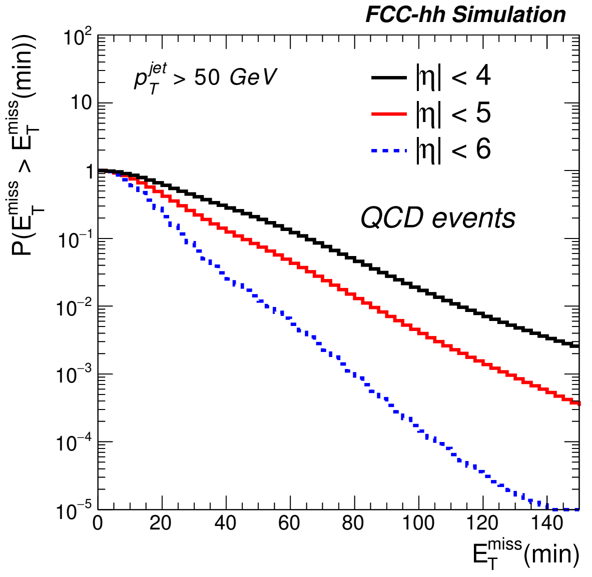


Studies from M. Mangano, C. Helsen, M Selvaggi

CERN-FCC-PHYS-2020-0004

- 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 ET resolution (better coverage in eta)

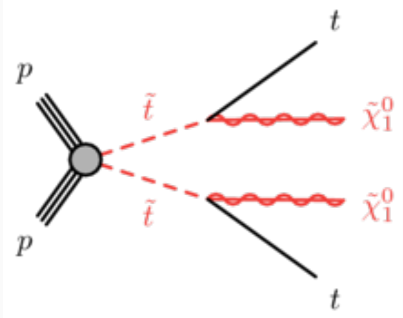


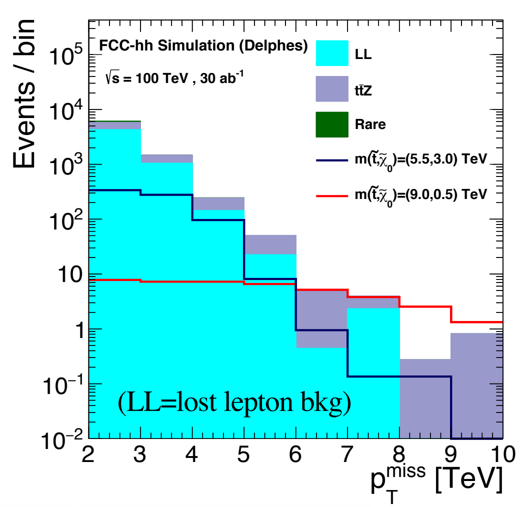
Probability of reconstructing E_{miss} greater than ET_{miss} (min) in di-jet QCD events

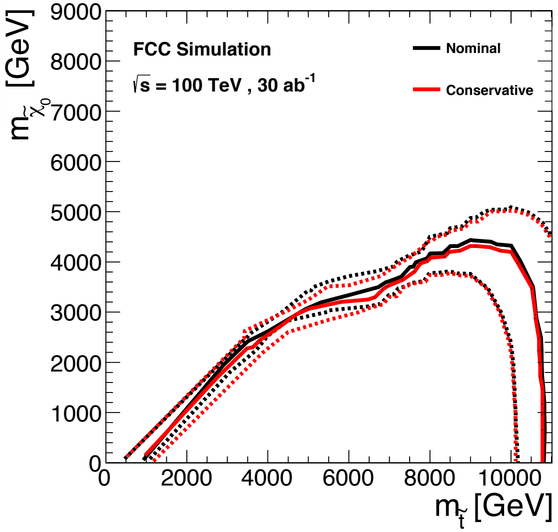
Missing ET is fundamental for Dark Matter searches in mono-X final states, SUSY particles and more

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

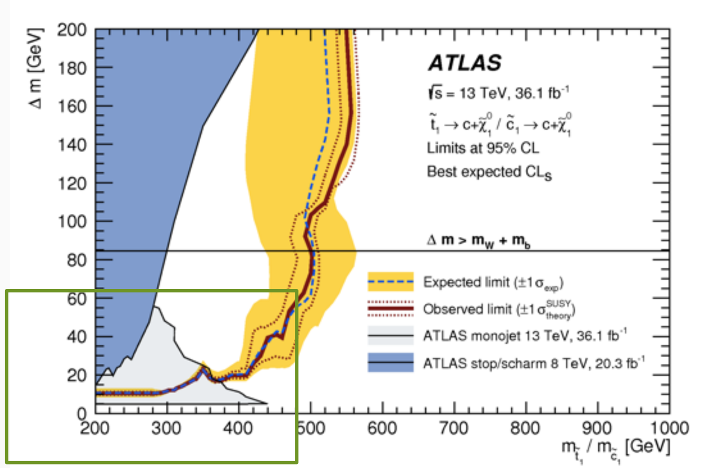






Discovery potential at 30/ab up to 8 TeV

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



JHEP 09 (2018) 050

ΔM ~ 2 – 10 GeV

Results for FCC-hh are projections

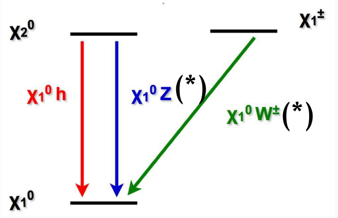
with ColliderReachTool:
HL-LHC → 0.95 TeV; [confirmed exp.]
HE-LHC → 2 TeV;
FCC-hh → **5 TeV**

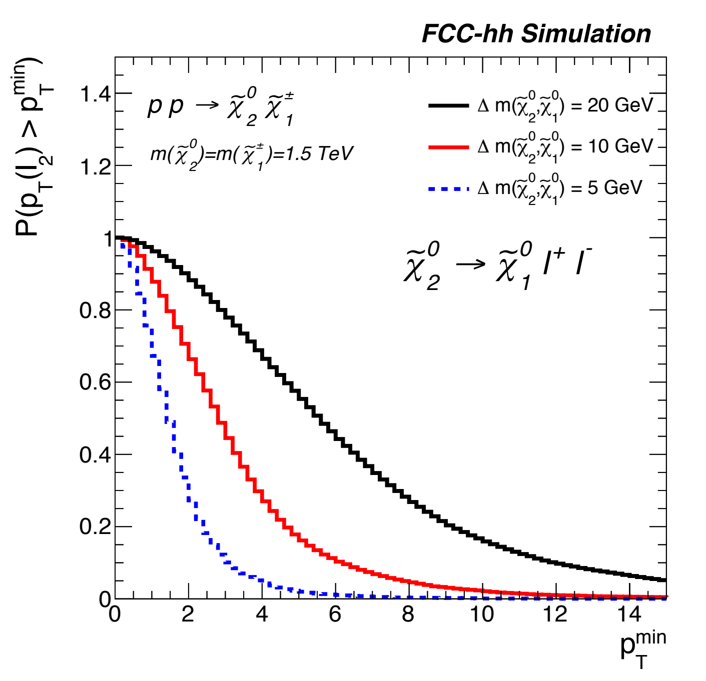
→ recoil-jet pt thresholds can be adjusted

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

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 → soft leptons
    - Estimate probability of having pT(l) above a threshold

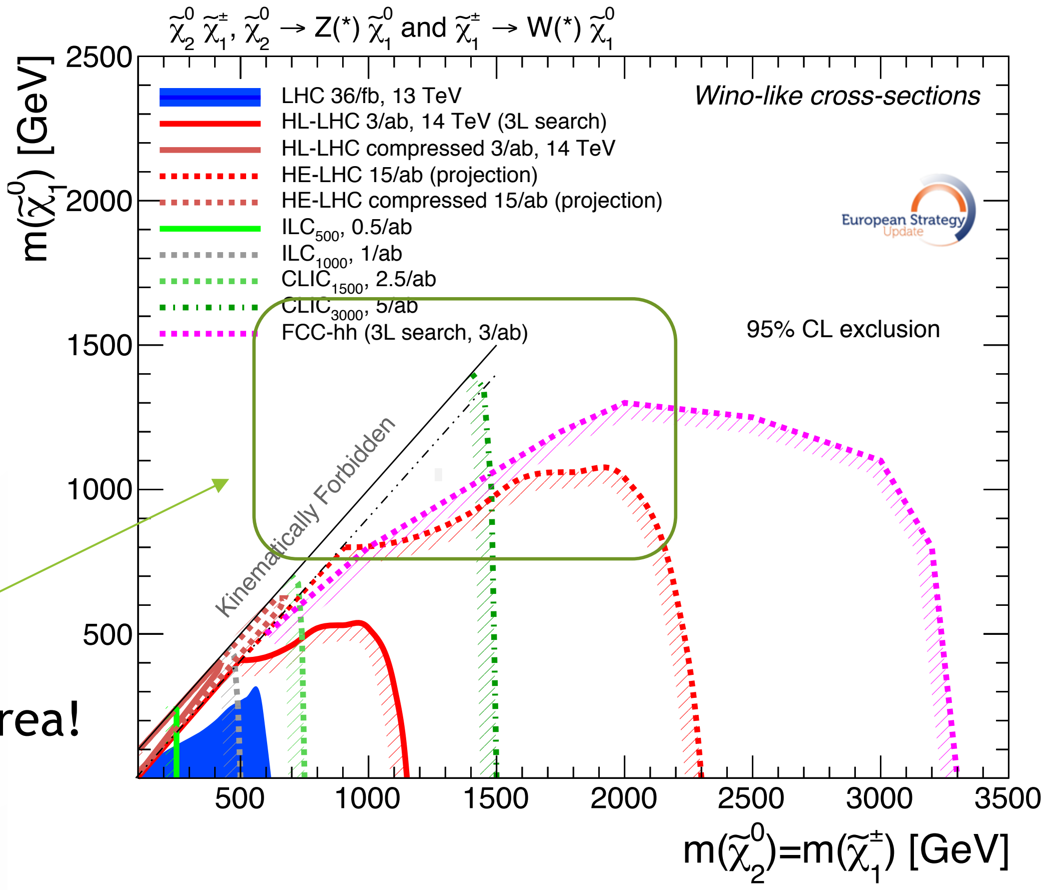




CERN-FCC-PHYS-2020-0004

pT min must be kept as low as possible

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



Fundamental to cover this area!

Lepton pT resolution

- Low momentum objects are fundamental for several SM and BSM processes
  - Precision measurements: 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, $m(\chi^{\pm}_1) = m(\chi^0_2)$
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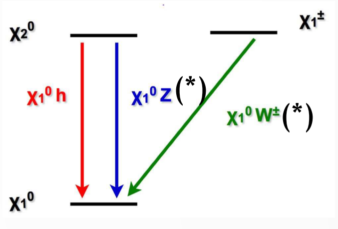
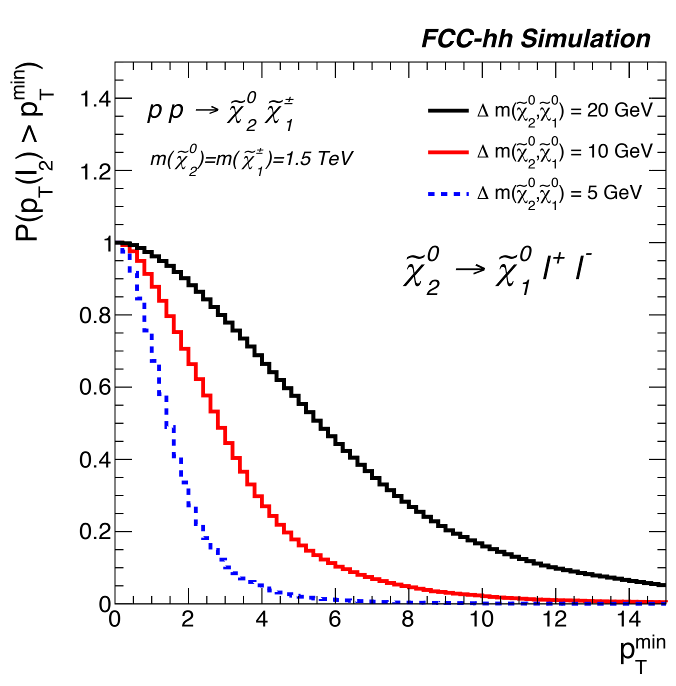


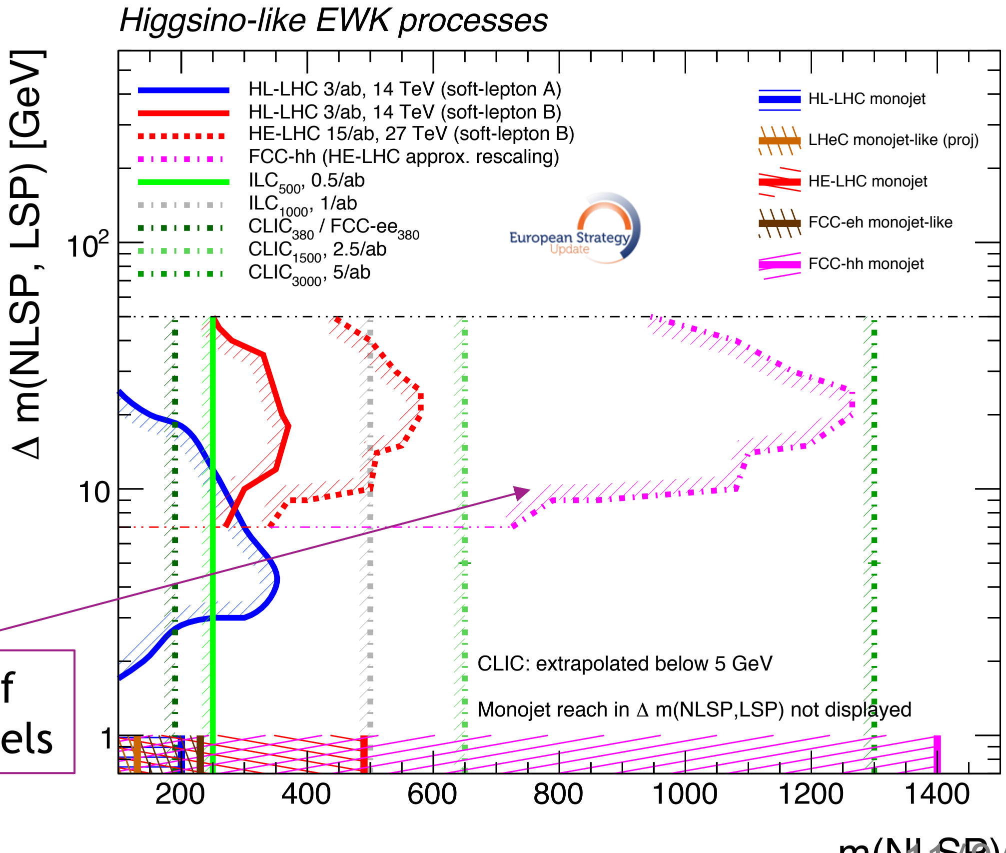


CERN-FCC-PHYS-2020-0004

pT min must be kept as low as possible

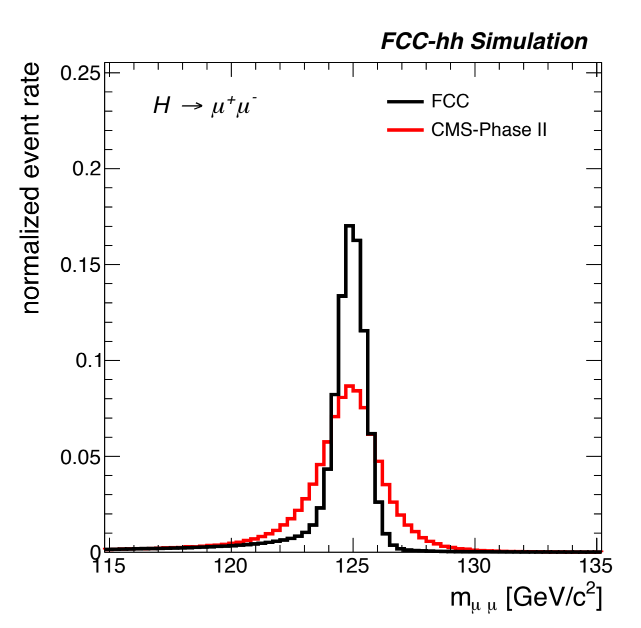
Target: ~ 4 GeV for electrons
~ 6-7 GeV for muons

Needed assumption for validity of projections for higgsino-like models

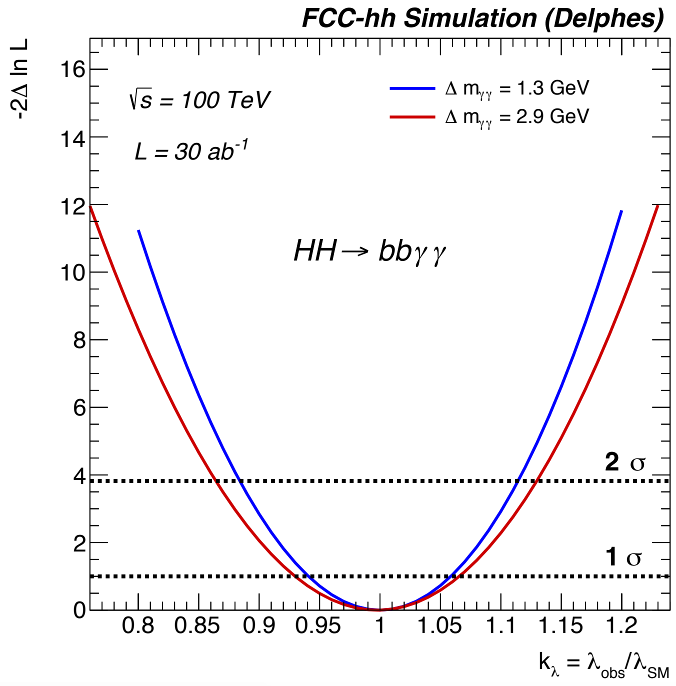


Impact of e/γ and μ resolutions: higgs

- For higgs rare decay processes (e.g. μμ, Zγ) or di-higgs studies, maximizing the performance requires minimizing the impact of multiple-scattering – i.e. minimizing material budget
  - Ideally, track momentum resolution should be $\sigma(p)/p \approx 0.5\%$ at $\eta \approx 0$, corresponding to about $0.2X_0$ radiation length of material for the entire tracking volume.
  - For the HH → $b\bar{b}\gamma\gamma$ decay mode, excellent energy photon resolution is needed in the E = 50 – 100 GeV energy range → translates into stringent requirements on stochastic and noise terms

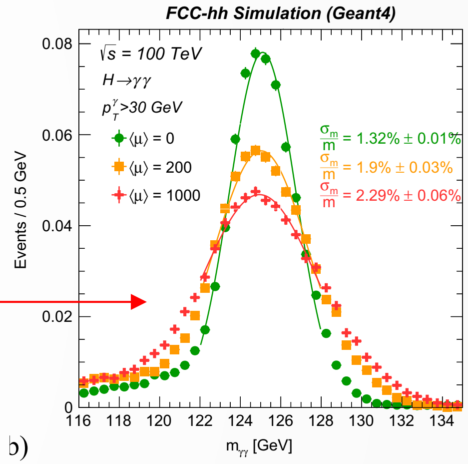


Use tilted module geometry



Should achieve 1% γγ

Pile-up might degrade this considerably



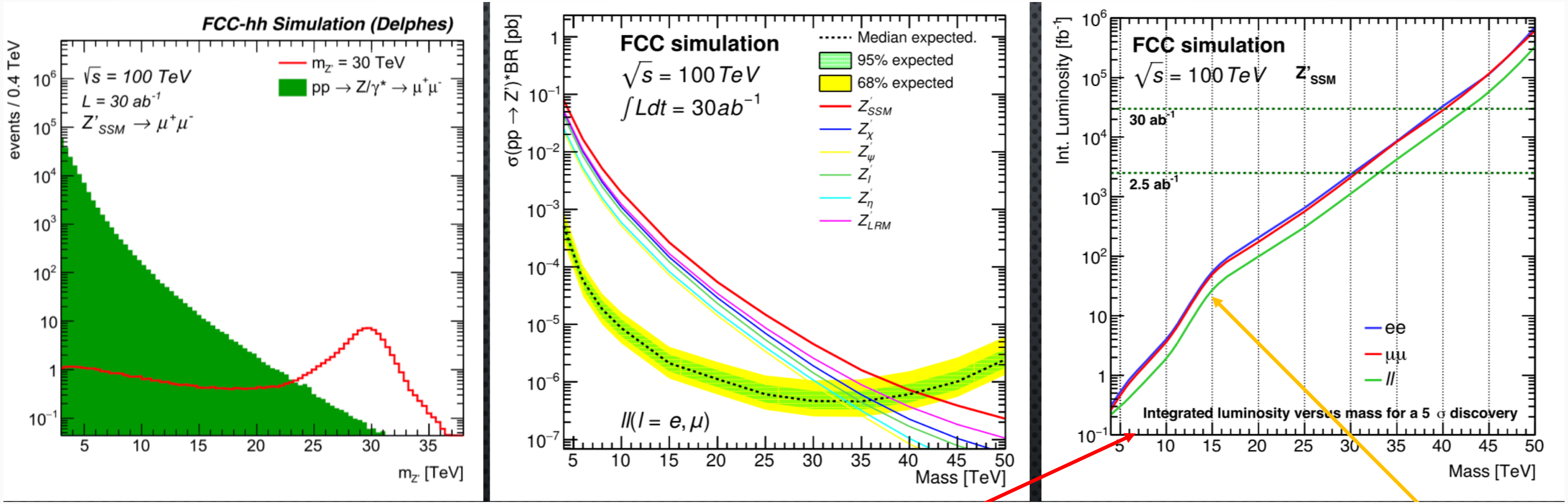
b)

	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 $|\eta| \approx 0$.

Impact of jets, e/γ, μ, τ at high pT: resonances

- For searches for heavy resonance, good reconstruction efficiency for high pT objects is fundamental
- **Dilepton (ee, μμ) resonance searches:**



HL-LHC reach @ 6.4 TeV

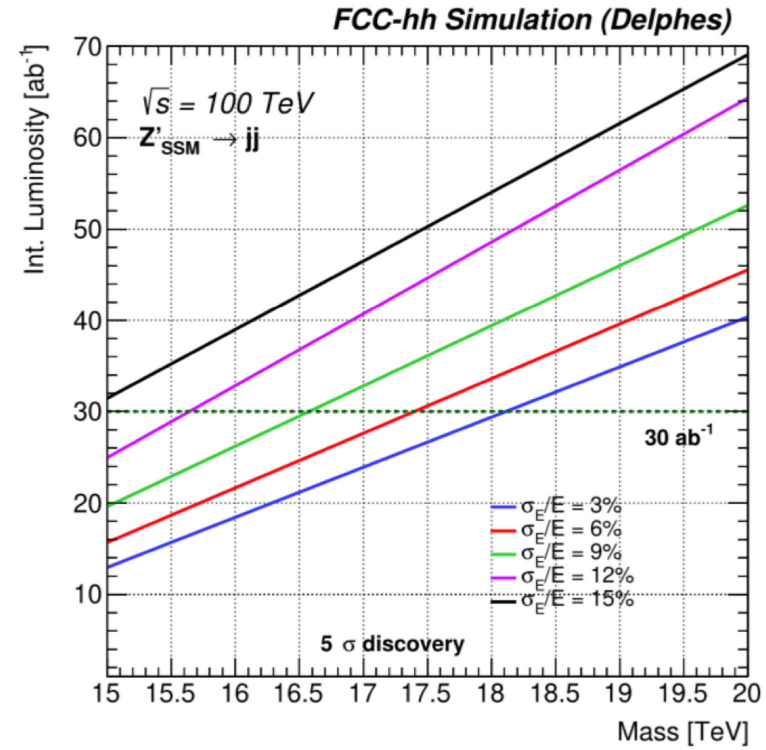
Slope changes as search becomes almost BG free

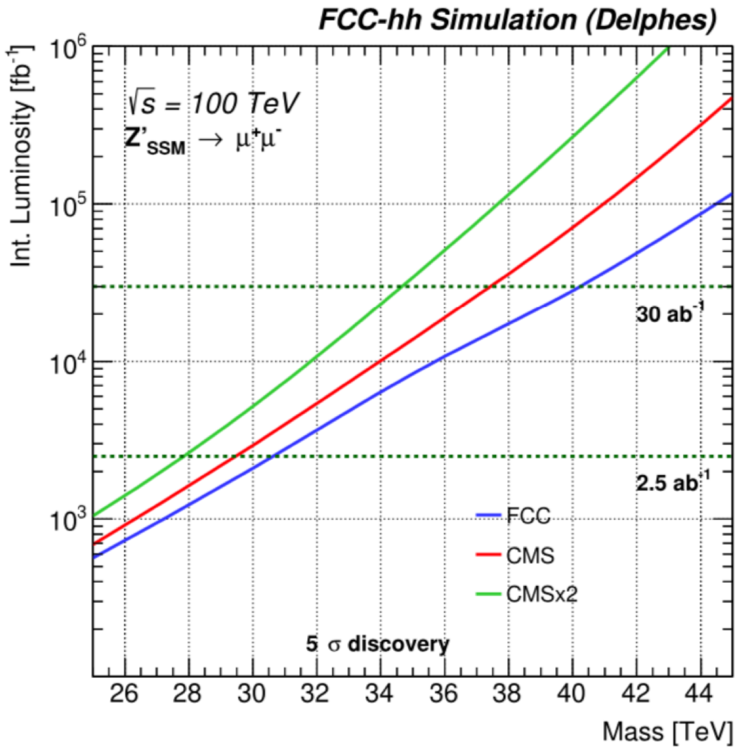
Eur. Phys. J. C (2019) 79:569

Effects of design on projections

- Efficiency assumptions for these studies

	Electrons (%)	Muons (%)	Photons (%)
FCC-hh	99	95	95
HE-LHC	95	95	95





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LAr technology envisaged **for ECAL**

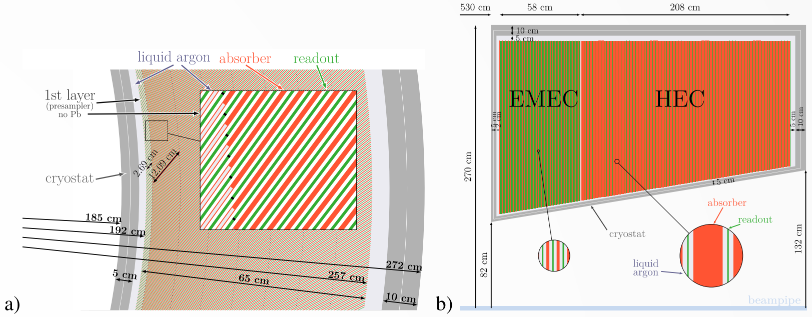


Fig. 7.16. (a) LAr barrel ECAL geometry and (b) LAr endcap calorimeter geometry.

Different assumption on calorimeter resolution and muon resolution have a huge impact on the discovery reach as expected. **Best assumptions:**

ECAL and HCAL:

$\sigma_E/E \approx 0.3\%$ and $\sigma_E/E \approx 3\%$

Muon resolution:

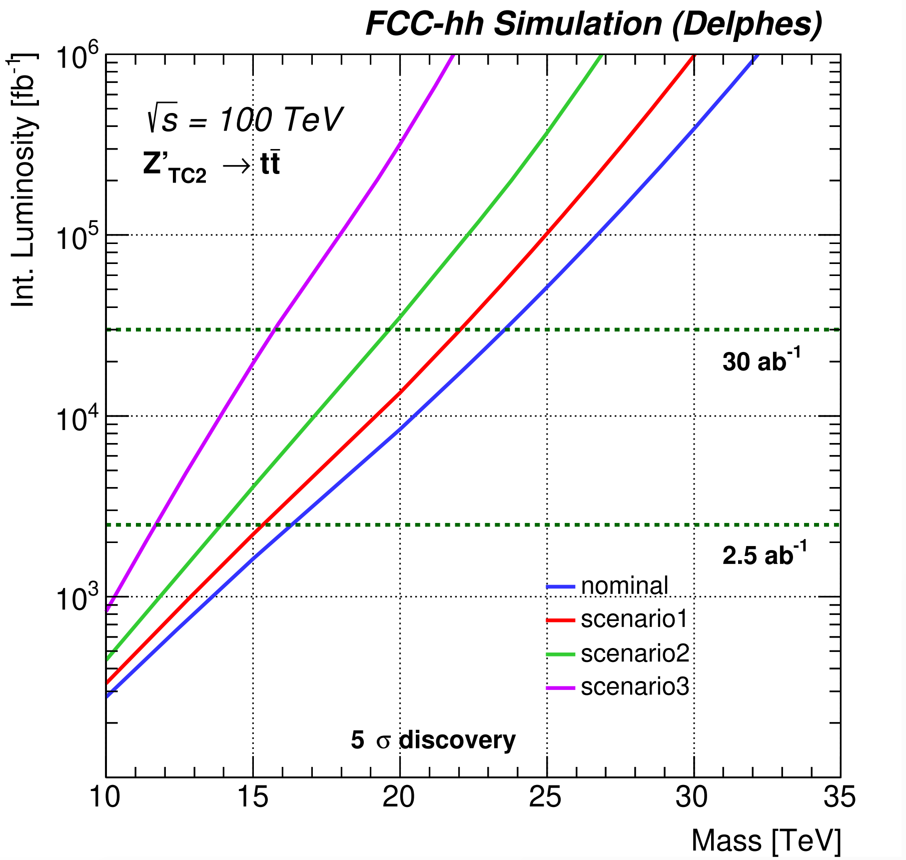
$\sigma_p/p \approx 5\%$ at $p_T = 20$ TeV

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 $(1 - p_T\ [\text{TeV}]/15)\cdot 85\%$
  - mis-identification efficiency:

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

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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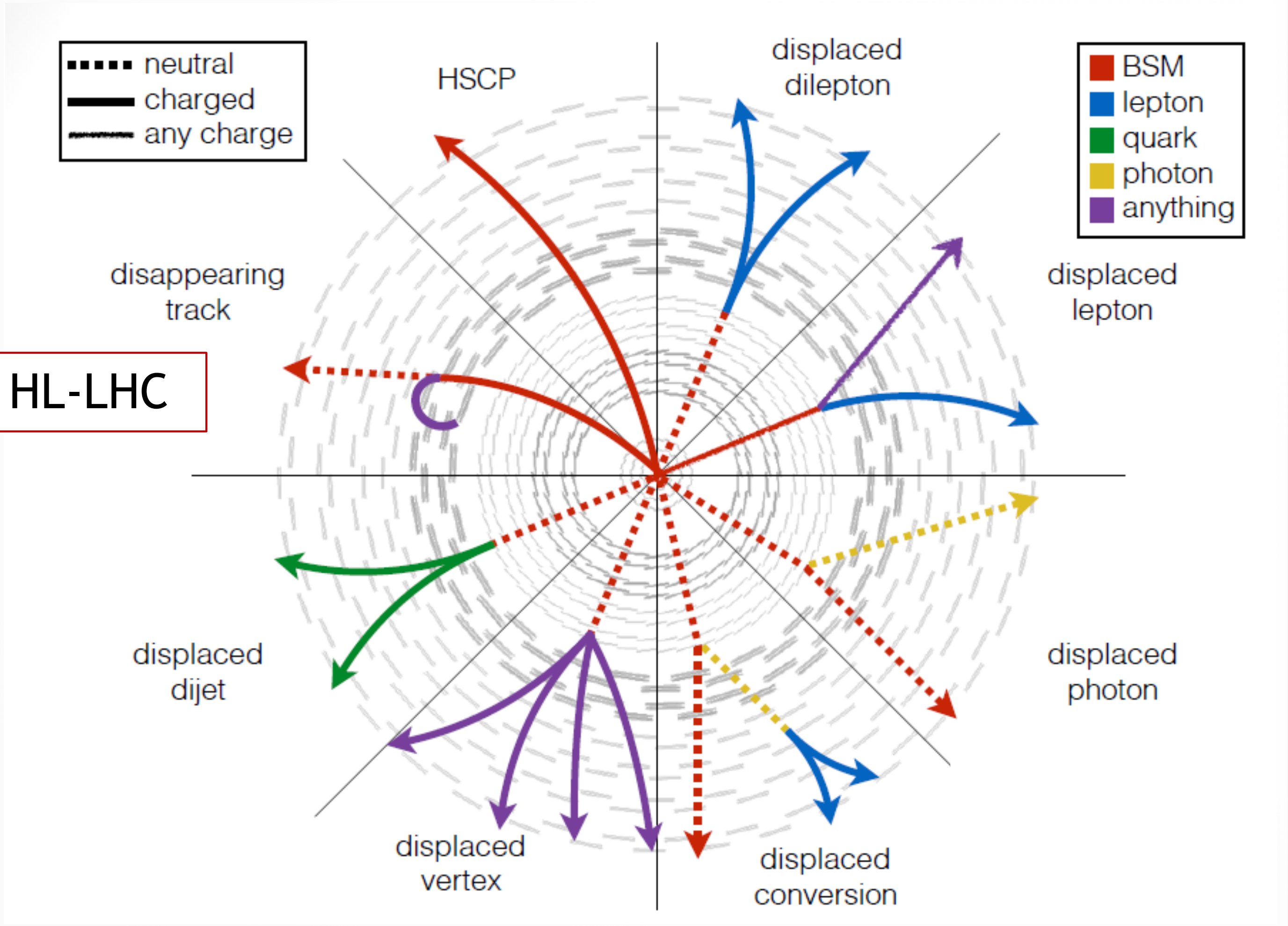
Long lived particles: a challenge

- 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)

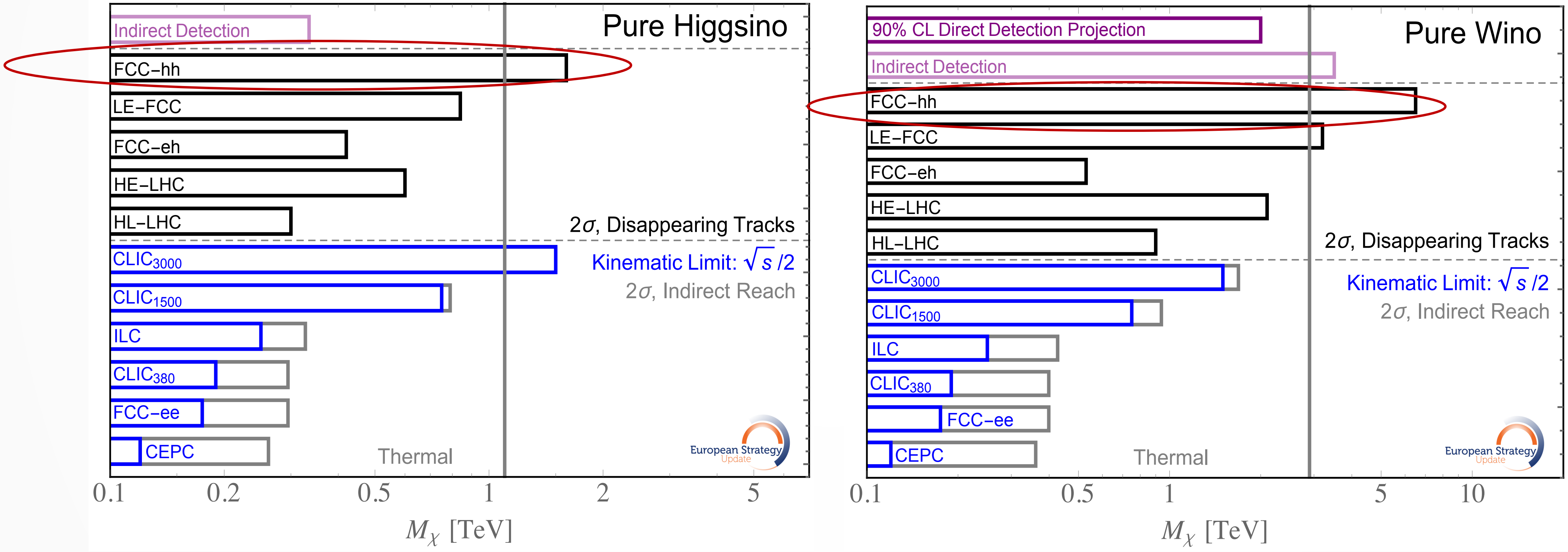
E.g. @ HL-LHC



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

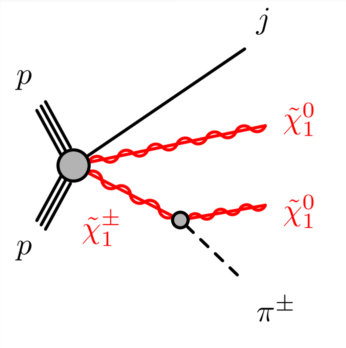


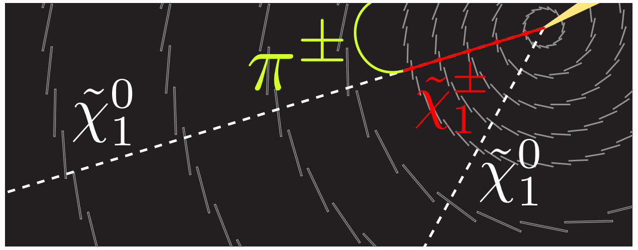
FCC-hh can conclusively test the hypothesis of thermal DM in both scenarios - but what are the assumptions?

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.

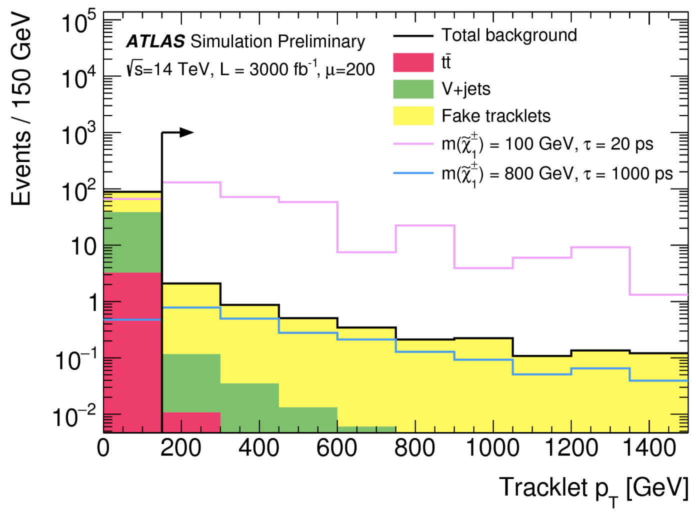
Variable	SR Selection
Lepton veto p_T [GeV]	>20
$\min\{\Delta\phi(\text{jet}_{1-4}, E_T^{miss})\}$	> 1
E_T^{miss} [GeV]	> 300
Leading jet p_T [GeV]	> 300
Leading tracklet p_T [GeV]	> 150
$\Delta\phi(E_T^{miss}, \text{trk})$	< 0.5

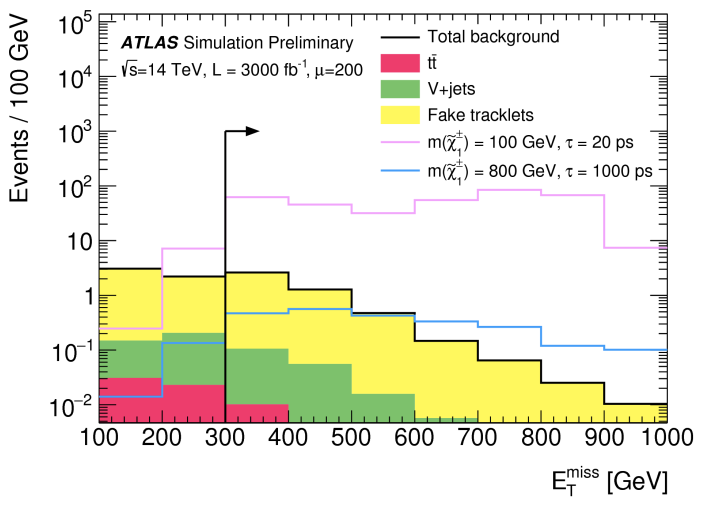
Tracklet reconstruction:

- “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

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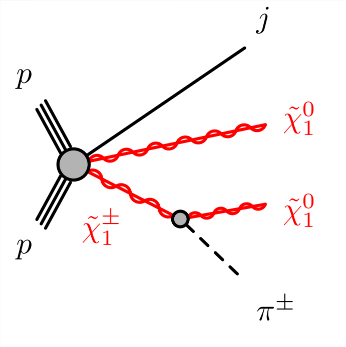
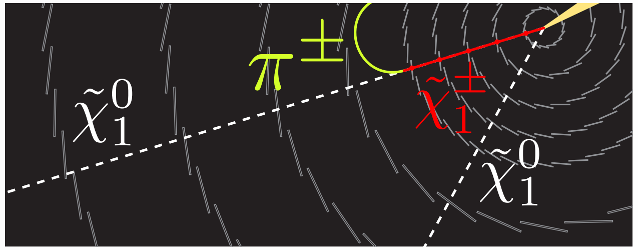




Very challenging with high pile-up → not shown in this sketch

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)

Results and FCC projections

- Results at HL-LHC …

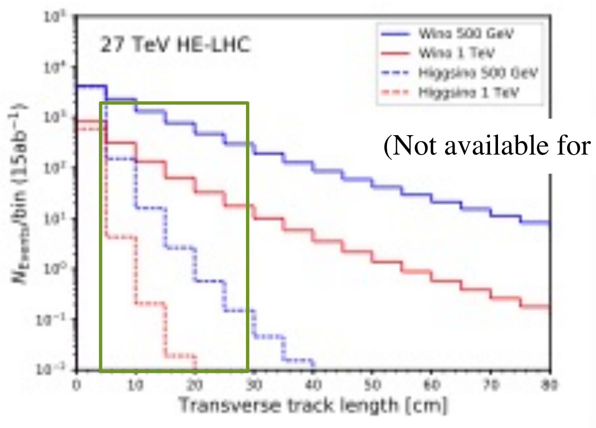
… and projections to FCC-hh

[extrapolated by theorists]

Section 4.1.2 of arxiv:1812.07831

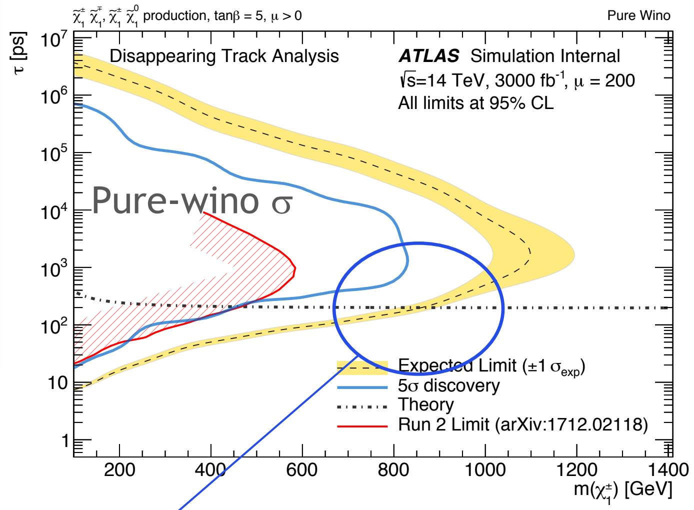
transverse charged track length must be in specific ranges to retain sensitivity

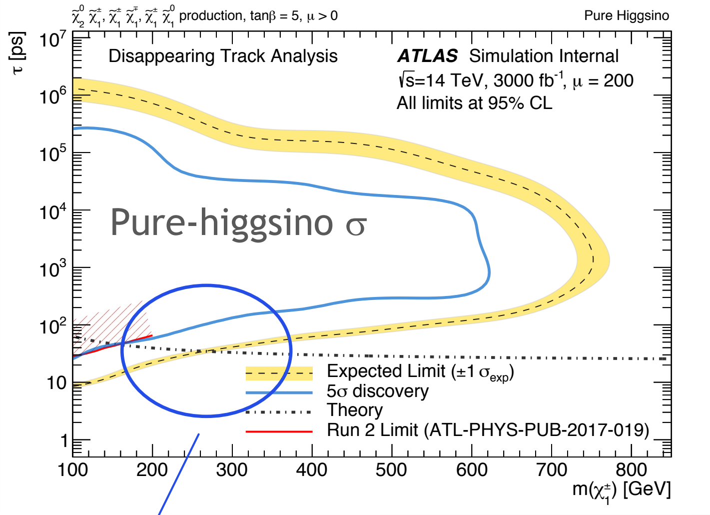
12 < d < 30 cm
@ FCC: p_T track in 1-1.4 TeV range



(Not available for FCC-hh)

HL-LHC





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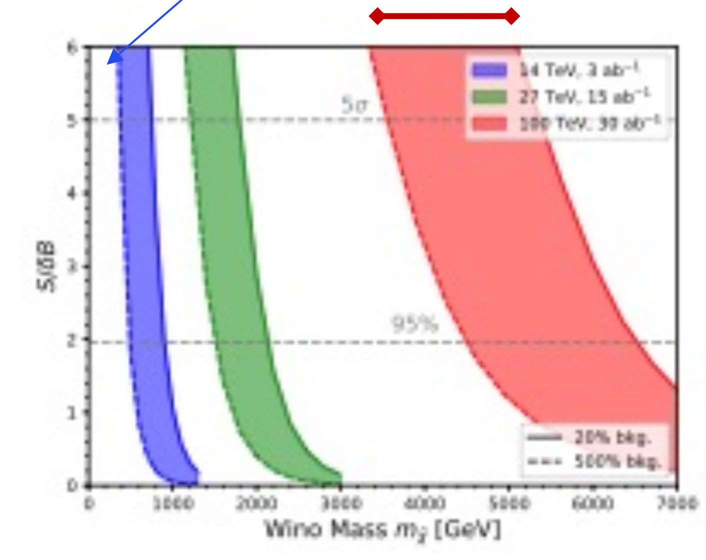
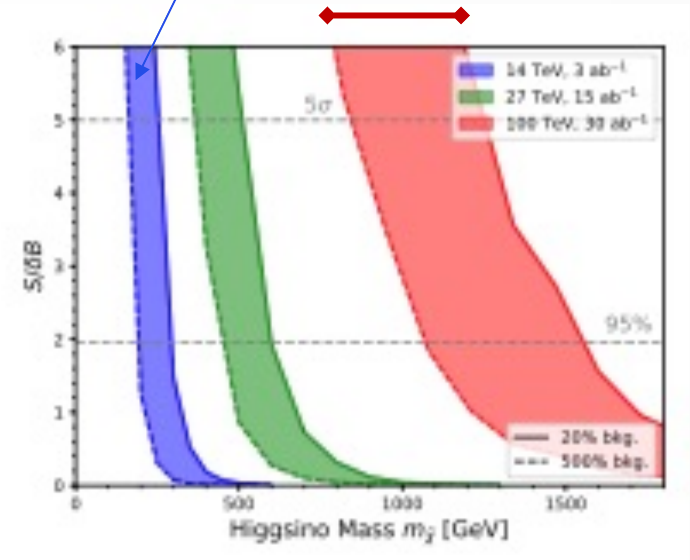
HL-LHC/HE-LHC/FCC-hh

Variation of bkg by factor 5



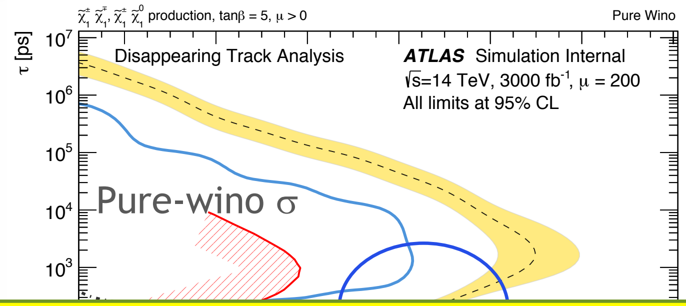


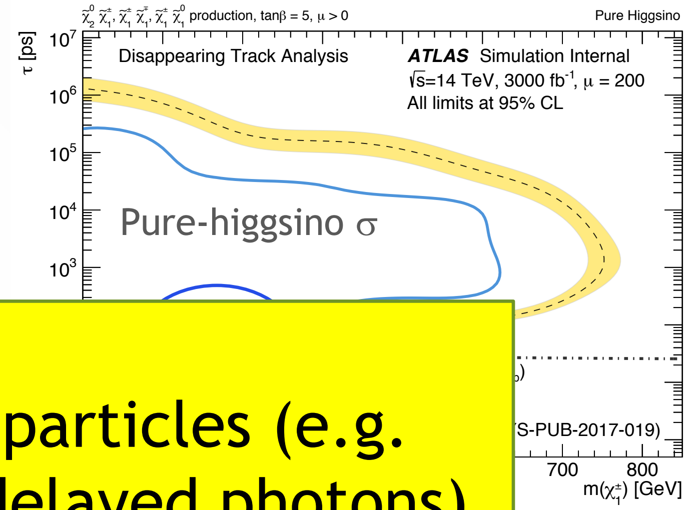
Assumptions on tracking capability and background are crucial

Results and FCC projections

HL-LHC

- Results at HL-LHC …





… and projecti

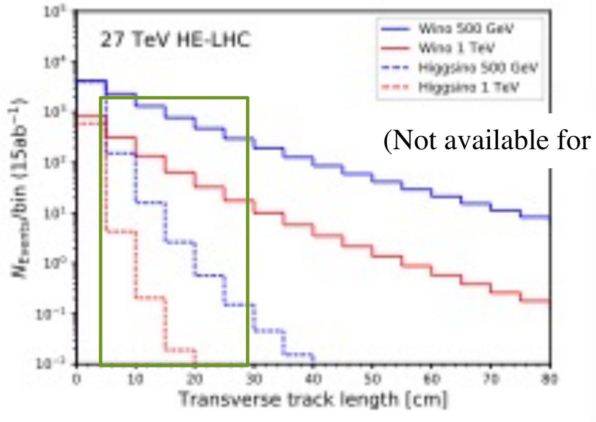
[extrapolated b

Section 4.1.2 of arx

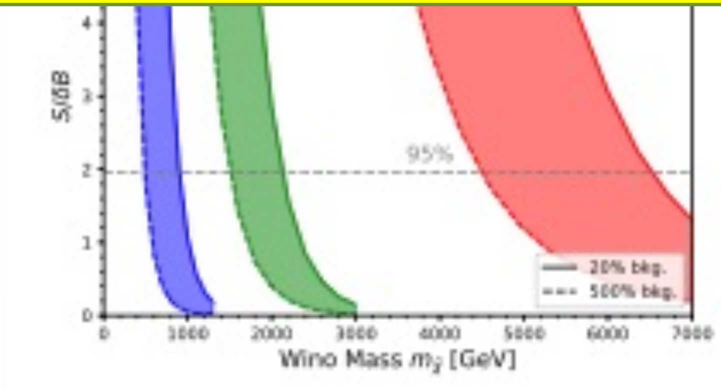
transverse charge
specific ranges to

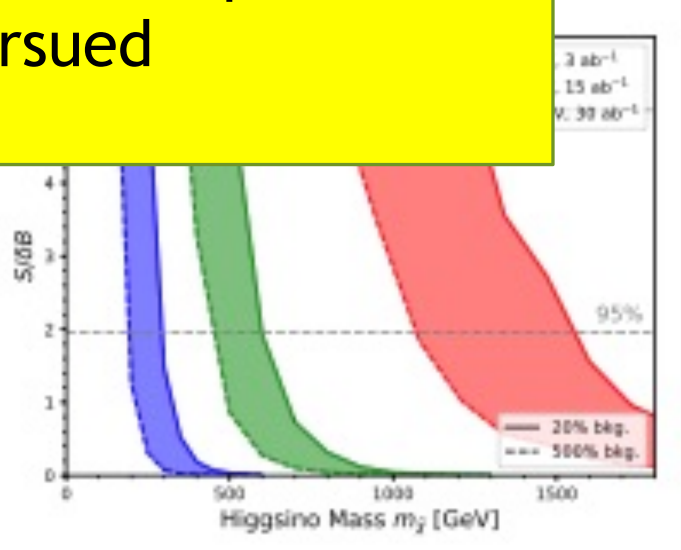
12 < d < 30 cm
@ FCC: p_T track in

This as other analyses targeting long-lived particles (e.g. exploiting displaced vertex, displaced jets, delayed photons) could be used as benchmarks to evaluate the impact of choices on techniques to be pursued



(Not available for FCC-hh)

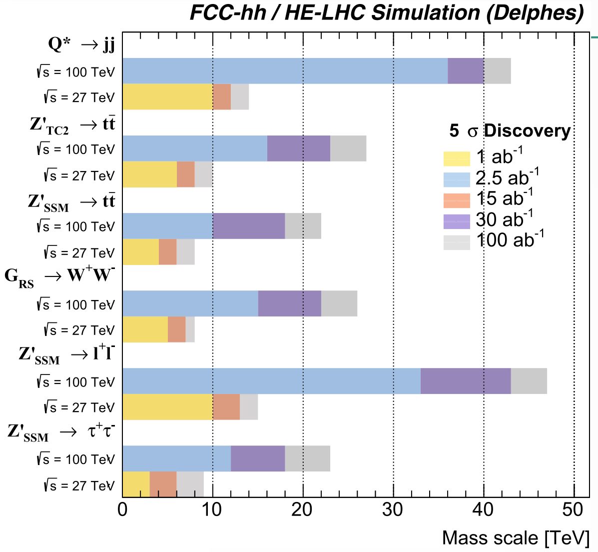


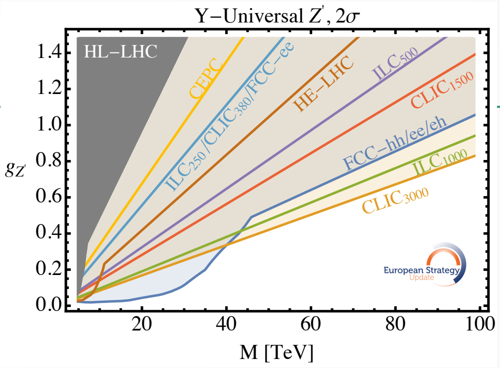


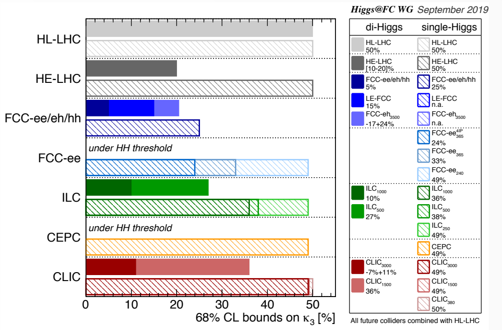
(Section 4.1 of arxiv:1812.07831)

Conclusions

- **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 in both scenarios







- Extreme granularity, excellent energy-momentum resolution beyond the LHC detectors, together with novel algorithms [see also back-up] will be needed to achieve optimal object reconstruction and identification
- Comparative studies considering different hypotheses for detector performance have been made using some searches (especially for high mass resonances) as benchmarks
  - more should/could be done for interesting and challenging scenarios → useful exercise to inform about detector layout and techniques to be considered and further developed.
  - Obviously, developments on other fronts such as theoretical calculations, modeling of backgrounds, PDFs, would also be fundamental - and **have not been discussed here**.
- Additional documents prepared by FCC experts are available with links to software repositories including benchmark analyses, DELPHES cards etc – on-going work in preparation for more realistic detector response.

Back up

Parameters and cross-sections

- Parameters

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$E_{\rm cm}$	TeV	14	14	27	100
Circumference	km	26.7	26.7	26.7	97.8
Peak $\mathcal{L}$, nominal (ultimate)	$10^{34}\,{\rm cm}^{-2}\,{\rm s}^{-1}$	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
$\sigma_{\rm inel}$[340]	mb	80	80	86	103
$\sigma_{\rm tot}$[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

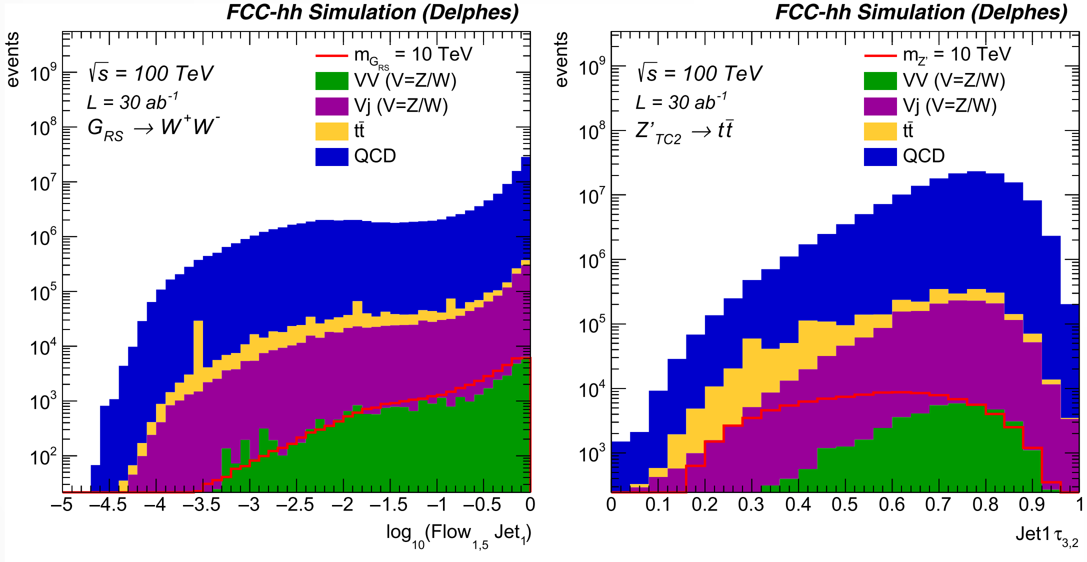
Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
$b\bar{b}$ cross-section	mb	0.5	0.5	1	2.5
$b\bar{b}$ rate	MHz	5	25	250	750
$b\bar{b}$ $p_T^{\rm b} > 30\,{\rm GeV/c}$ cross-section	μb	1.6	1.6	4.3	28
$b\bar{b}$ $p_T^{\rm b} > 30\,{\rm GeV/c}$ rate	MHz	0.02	0.08	1	8
Jets $p_T^{\rm jet} > 50\,{\rm GeV/c}$ cross-section [340]	μb	21	21	56	300
Jets $p_T^{\rm jet} > 50\,{\rm GeV/c}$ 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

High pT jets and boosted objects

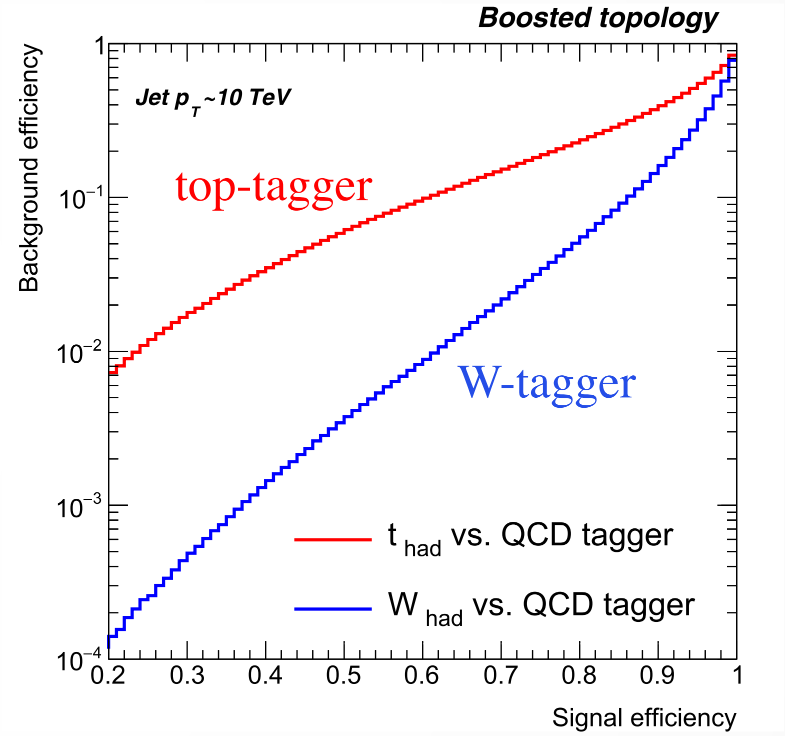
- Hadronic resonance with sub-structures used to study taggers for boosted objects:

Heavy particles can decay into highly boosted top/W/Z
→ collimated jets - @ 10 TeV, R = 0.02 for W boson!

Considering jets from tracks only:
→ Build taggers from jet sub-structure observables:
- Soft-dropped jet mass and N-subjettiness variable for top
- Isolation-like variables for W



Example of variables used in taggers



Expected capabilities with nominal assumptions on tracking resolution

Repository

Branch: master ▾ FCCAnalyses / FCChhAnalyses / FCChh /

Create new file | Find file | History

This branch is 3 commits ahead of clementhelsens:master.

Pull request | Compare

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