Future of Particle Physics: Part 3

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Physics of the two infinities:
Ecole d'étFrance Excellence 2019

July 10, 2019

Outline

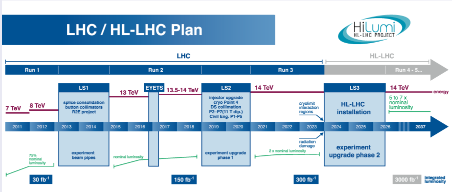
Introduction

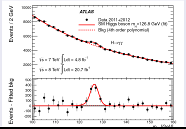
High Energy PHysics Current Context

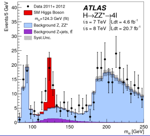
- The major recent and most important discovery was the Higgs boson in 2012
- The Higgs sector in the SM is thought as the most promising portal for possible Physics Beyond the SM (BSM)
- Therefore the priority at the LHC for short and medium terms is to search for BSM
  - Indirectly: through precision measurements, espcially of the Higgs boson properties
  - Directly: through production of new particles or phenomena

Where we stand & where we know we're heading to

- LHC: **Large Hadron Collider** (website)
  Circular tunnel of C=27 km, SC dipole magnets $B = 8.3T$ in $NbTi$,
  mainly pp collider at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 1 - 2 \times 10^{34} cm^{-2} s^{-1}$
- Ending date ("low lumi. LHC"): 2026 (after LS3) $\leftrightarrow \int \mathcal{L}dt = 300 fb^{-1}$
- HL-LHC: **High Luminosity – Large Hadron Collider** (website)
  mainly pp collider at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 5 - 20 \times 10^{34} cm^{-2} s^{-1}$
- Ending date: 2035 (after LS5) $\leftrightarrow \int \mathcal{L}dt = 3.000 fb^{-1}$

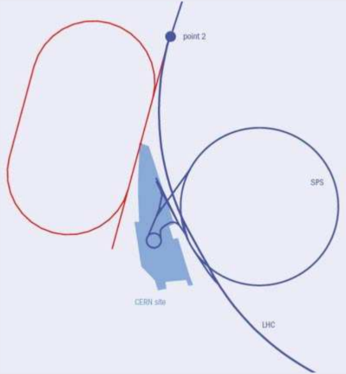


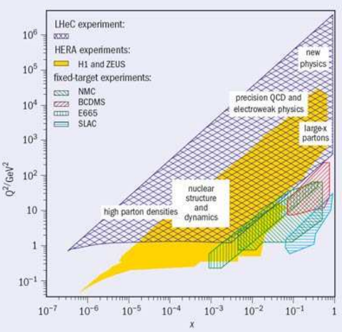




How we could go beyond ... through DIS

- LHeC: **Large Hadron Electron Collider** (website)
  LHC tunnel, $e^{\pm}p$ collider at $\sqrt{s} = \sqrt{4E_e E_p} = 1.3$ TeV, with $E_e = 60$ GeV, $E_p = 7$ TeV
- Polarization: $\mathcal{P}_{e^-} = 40\%$ & $\mathcal{P}_{e^+} = 40\%$
- $\mathcal{L} = 10^{33} cm^{-2} s^{-1} \leftrightarrow \int \mathcal{L}dt = 1.000 fb^{-1}$

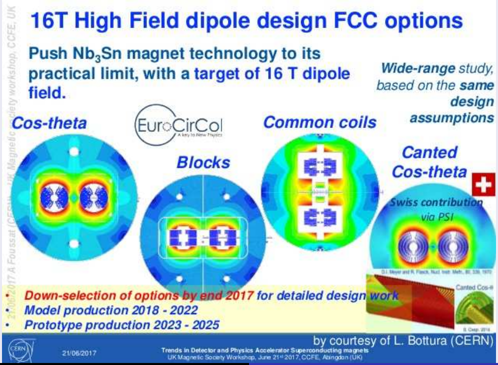




LHC & Its Immediate Extensions

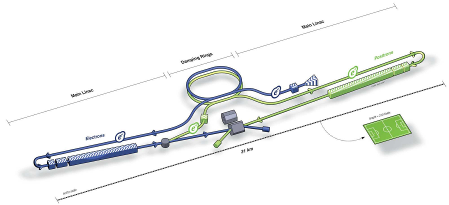
How we could go beyond ... breaking the Energy Frontier

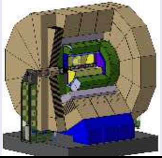
- HE-LHC: **High Energy – Large Hadron Collider** (workshop)
  LHC tunnel, mainly pp collider at $\sqrt{s} = 27$ TeV and
  $\mathcal{L} = 25 \times 10^{34} cm^{-2} s^{-1} \leftrightarrow \int \mathcal{L}dt = 10.000 fb^{-1}$
  - Key instrumental ingredients
    - B=16T dipole magnets using Nb_3Sn
    - New vacuum system
    - These R&D's are conducted in view of FCC-hh
    - Possible starting date: 2040

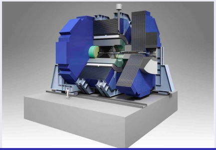


New Era of Precision Measurements (Higgs,...)

- ILC: **International Linear Collider** (website)
  - 31 km tunnel, including 2 Linacs of 11 km each
  - e^+e^- collider at $\sqrt{s} = 0.25 - 0.35 - 0.50 - 1$ TeV
    $\leftrightarrow \int \mathcal{L}dt = 500 - 200 - 5.000 - 1.000 fb^{-1}$
  - Polarization: $\mathcal{P}_{e^-} = 80\%$ & $\mathcal{P}_{e^+} = 30\%$
  - Possible starting date: 2030
  - Meetings: Recent Workshop in Strasbourg

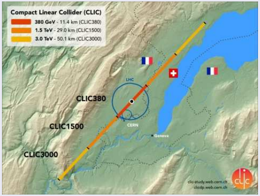


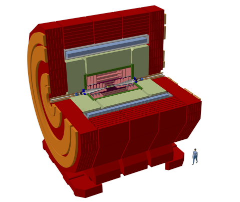




Extending Precision Measurements & Direct Discovery Potential (1)

- CLIC: **Compact Linear Collider** (website)
  - e^+e^- collider at $\sqrt{s} = 0.38 - 1.5 - 3$ TeV $\leftrightarrow \int \mathcal{L}dt = 500 - 1.500 - 2.000 fb^{-1}$
  - $\mathcal{L} = (1-2-5) \times 10^{34} cm^{-2}s^{-1}$
  - Polarization: $\mathcal{P}_{e^-} = 80\%$ & $\mathcal{P}_{e^+} = 0\%$
  - Document: CERN Yellow Report
  - Meetings: Next Workshop at CERN
  - Possible starting date: 2035

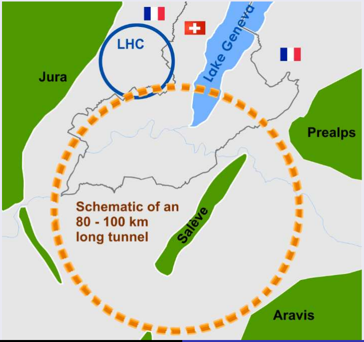




Circular Colliders

Extreme Statistics for Precision Measurements

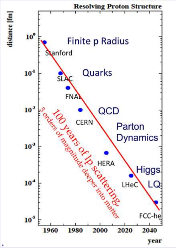
- FCC-ee: **Future Circular Collider-e^+e^-** (website)
  Circular tunnel of C=100 km,
  $\sqrt{s} = (91.2 - 160 - 240 - 365) GeV$
  $\mathcal{L} = (230 - 32 - 8 - 1.5) \times 10^{34} cm^{-2} s^{-1} \leftrightarrow \int \mathcal{L} dt = 88.000 - 15.000 - 1.000 fb^{-1}/y$
- Polarization: under study, $\mathcal{P}_{e^-} = 30\%$ achievable $\sqrt{s} = (91.2 - 160) GeV$
- Possible starting date: 2039
- Similar Project: CEPC (Circular Electron Positron Collider) in China (website)

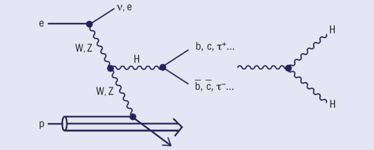


Circular Colliders

Playing the "Super-Hera"

- FCC-eh: **Future Circular Collider-$e^{\pm}p$**
  FCC-ee tunnel, $e^{\pm}p$ collider at $\sqrt{s} = \sqrt{4E_eE_p} = 3.5$ TeV, with $E_e = 60$ GeV, $E_p = 50$ TeV
- R&D in Common with LHeC: see recent workshop
- $\mathcal{L} = 1.1 \times 10^{34} cm^{-2}s^{-1} \leftrightarrow \int \mathcal{L}dt = 400 fb^{-1}/y$
- Possible starting date: 2045

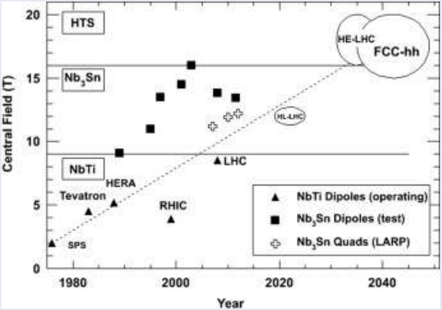




Circular Colliders

Ultimate Conceivable Energy Frontier

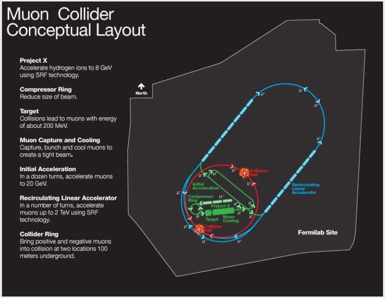
- FCC-hh: **Future Circular Collider-*pp*** (website)
  FCC-ee tunnel, $\sqrt{s} = 100$ TeV and $\mathcal{L} = 5 - 30 \times 10^{34} cm^{-2} s^{-1} \leftrightarrow \int \mathcal{L} dt = 17.500 fb^{-1}$
- Physics potential: see recent CERN Yellow Report
- Possible starting date: 2043
- Similar Project: SppC (Super pp Collider) in China (see recent workshop)



Circular Colliders

Extending Precision Measurements & Direct Discovery Potential (2)

- Muon Collider: **Future $\mu^+\mu^-$ Circular Collider** (website)
  L=2 km tunnel (LINACs+colliding rings) at FERMILAB, $\sqrt{s} = 1.5 - 3$ TeV
- $\mathcal{L} = 1.25 - 3 \times 10^{34} cm^{-2}s^{-1} \leftrightarrow \int \mathcal{L}dt = 400 - 1.000 fb^{-1}/y$
- Source of high energy neutrinos



Comparing Facilities (1/2)

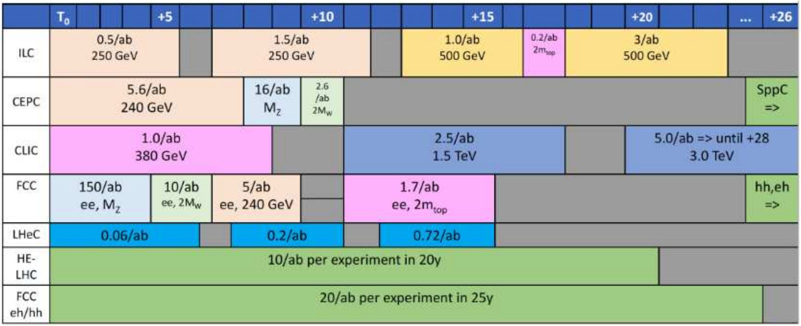
Features

Future Colliders in a chart

Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]\ \text{cm}^{-2}\text{s}^{-1}$	$\mathscr{L}$ $[\text{ab}^{-1}]$	Time [years]	Refs.	Abbreviation	
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC	pp
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC	
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh	
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]		ee
		$2M_W$	0/0	2	25	10	1-2			
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$	
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$	
							(+1)		(1y SD before $2m_{top}$ run)	
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$	
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$	
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$	
							(+1)		(1y SD after 250 GeV run)	
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC	
		$2M_W$	0/0	2	10	2.6	1			
		240 GeV	0/0	2	3	5.6	7			
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$	
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$	
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$	
							(+4)		(2y SDs between energy stages)	
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC	
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC	ep
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh	

Comparing Facilities (2/2)

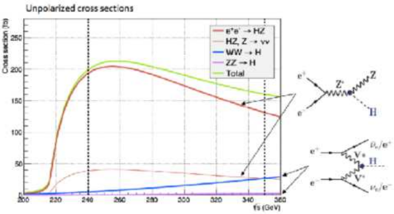
Timelines



Higgs Production at FCC-ee

➡ **Exploiting a very large Higgs boson sample, produced under clean experimental conditions, and collected with superb precision detectors**

working point	luminosity/IP [10^{34} cm^{-2}s^{-1}]	total luminosity (2 IPs)/ year	physics goal	run time [years]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	52 ab^{-1}/year		
W	30	7.8 ab^{-1}/year	10 ab^{-1}	~1
H	7.0	1.8 ab^{-1}/year	5 ab^{-1}	3
top	1.6	0.4 ab^{-1}/year	1.5 ab^{-1}	4



	FCC-ee 240 GeV	FCC-ee 350 GeV
Total Integrated Luminosity (ab-1)	5	1.5
Number of Higgs bosons from $e^+e^- \to HZ$	1,000,000	200,000
Number of Higgs bosons form fusion process	25,000	40,000

Higgs Coupling to Z

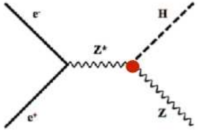
Higgs Properties

Higgs Coupling to Z

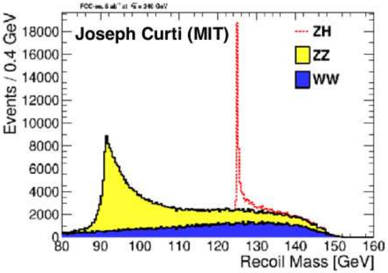
➡ **Recoil method provides unique opportunity for model independent measurement of HZ coupling**

- Higgs events are tagged Higgs decay mode independent
- expected precision **~0.5%** on ZH cross section
- using only leptonic Z decays and only measurement at 240 GeV so far

$$\boxed{\sigma(ee \to ZH) \propto g^2_{HZ}}$$



$$m_R^2 = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$



Higgs Properties

Higgs Production at FCC-ee

Higgs Total Decay Width

➡ **Total Higgs boson width can be extracted from a combination of measurements in a model independent way**

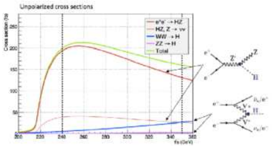
- **1) tagging Higgs final states**

$$\sigma(ee \to ZH) \cdot BR(H \to ZZ) \propto \frac{g_{HZ}^4}{\Gamma}$$

- **2) measurements of vector boson fusion production at 350 GeV**

$$\frac{\sigma(ee\to ZH)\cdot BR(H\to WW)\cdot\sigma(ee\to ZH)\cdot BR(H\to bb)}{\sigma(ee\to\nu\nu H)\cdot BR(H\to bb)}$$

$$\propto \frac{g_{HZ}^2\cdot \cancel{g_{HW}^2}}{\Gamma}\cdot\frac{g_{HZ}^2\cdot \cancel{g_{Hb}^2}}{\cancel{\Gamma}}\cdot\frac{\cancel{\Gamma}}{\cancel{g_{HW}^2}\cdot \cancel{g_{Hb}^2}} = \frac{g_{HZ}^4}{\Gamma}$$



- **3) combination of all measurements**

Higgs Properties

Higgs Production at FCC-ee

Higgs Coupling to Z

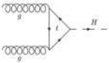
Precision on Higgs Coupling Measurements

Coupling	HL-LHC	FCC-ee $\sqrt{s} = 240$ GeV	FCC-ee $\sqrt{s} = 350$ GeV
g_{HZ}	2-4	0.21	0.21
g_{HW}	2-5	1.25	0.43
g_{Hb}	5-7	1.25	0.64
g_{Hc}	–	1.49	1.04
g_{Hg}	3-5	1.59	1.18
$g_{H\tau}$	5-8	1.34	0.81
$g_{H\mu}$	5	8.85	8.79
$g_{H\gamma}$	2-5	2.37	2.12
Γ_H	5-8	2.61	1.55

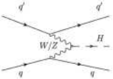
Table: Accuracy on Higgs couplings measurements in [%]

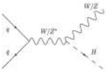
Higgs Production at FCC-hh

- Cross sections and expected statistics:

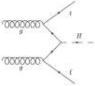


	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N³LO)	49 pb	803 pb	16
VBF (N²LO)	3.8 pb	69 pb	16
VH (N²LO)	2.3 pb	27 pb	11
ttH (N²LO)	0.5 pb	34 pb	55





	N_{100}	N_{100}/N_8	N_{100}/N_{14}
$gg \to H$	16×10^9	4×10^4	110
VBF	1.6×10^9	5×10^4	120
WH	3.2×10^8	2×10^4	65
ZH	2.2×10^8	3×10^4	85
$t\bar{t}H$	7.6×10^8	3×10^5	420



$N_{100} = \sigma_{100\,\mathrm{TeV}} \times 20\ \mathrm{ab}^{-1}$
$N_8 = \sigma_{8\,\mathrm{TeV}} \times 20\ \mathrm{fb}^{-1}$
$N_{14} = \sigma_{14\,\mathrm{TeV}} \times 3\ \mathrm{ab}^{-1}$

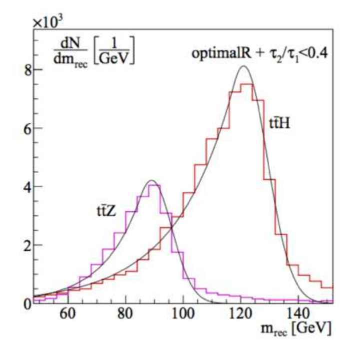
Factor: 1/100 1/10 reduction in stat. unc.

- **Large statistics** will allow to isolate **cleaner samples** in regions with:
  - higher S/B
  - smaller impact of systematics

Higgs Properties

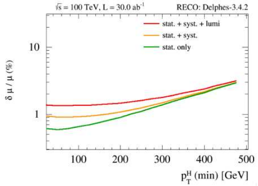
Top Yukawa Coupling

- Can be measured very accurately through $\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$: $\left[\frac{\delta y_t}{y_t}\right]_{Stat \oplus Syst_{TH}} \approx 1\%$
- Highest sensitivity in 1/2-leptonic boosted topology

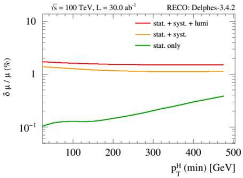


Higgs Properties

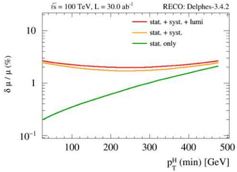
$H \to \mu^+\mu^-$



$H \to \gamma\gamma$



$H \to 4\ell^\pm$



Summary

- Very large stats for S, but also for B (assume $\approx$ infinite stat. in CRs)
- More accurate measurements of Higgs couplings than FCC-ee ($\mu^+\mu^-$, $\gamma\gamma$)
- Measurement of ratios of BR can break the "syst.$\oplus$ lumi. wall (2-3%)"

Higgs Properties

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Summary

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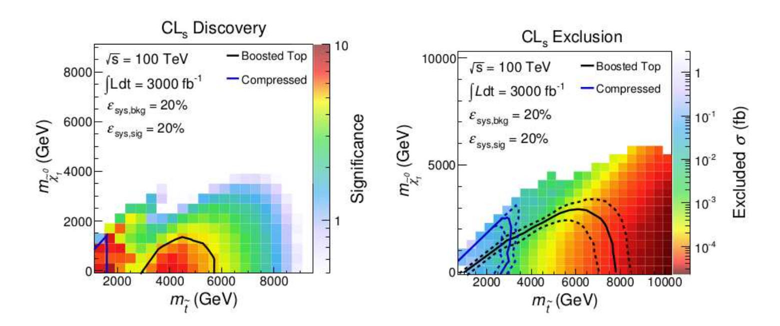
SUSY

Stop pairs HL-LHC vs FCC-hh

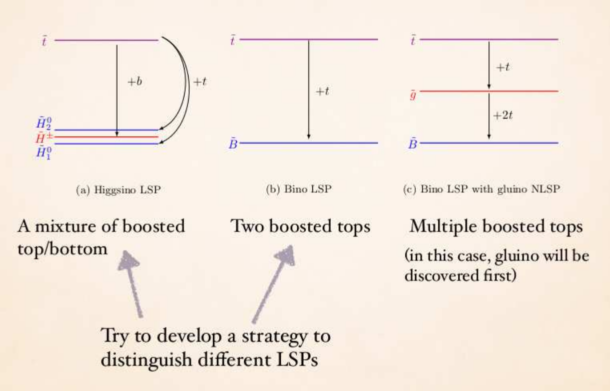
- SM objects boosted into a single calo cell: std tagging techniques bound to fail
- Ex: Simpl. Model $BR(\tilde{t} \to t + \tilde{B}) = 100\%$, choose a semi-muonic event topology
- Event selection: $p_T(\mu^\pm) > 200$ GeV, $\Delta R(\mu^\pm, jet) < 0.5$, $E^T_{miss} > 3 - 4$ TeV



- Result: discovery reach 6 TeV, exclusion 8 TeV

Stop pairs HL-LHC vs FCC-hh

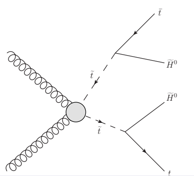
- Drawbacks:
  - $\mu^{\pm}$ does not distinguish between b- or top-jet
  - semi-muonic topology applies for short DK chains, not for long DK cascades
  - hence efforts to also tag hadronic top-jets
- Stop Simplified Models:

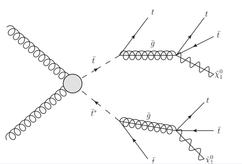


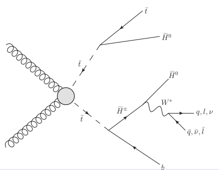
SUSY

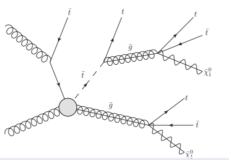
Stop pairs HL-LHC vs FCC-hh

- Processes w/ multiple boosted t's (b's) in the FS:





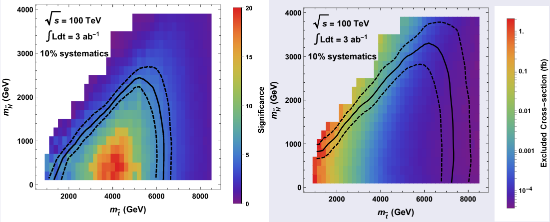




SUSY

Stop pairs HL-LHC vs FCC-hh

- Sensitivity to stop-higgsino signal:



SUSY

Stop pairs HL-LHC vs FCC-hh

- Distinguishing the associated LSP: $r_- = \frac{N_b - N_t}{N_b + N_t}$