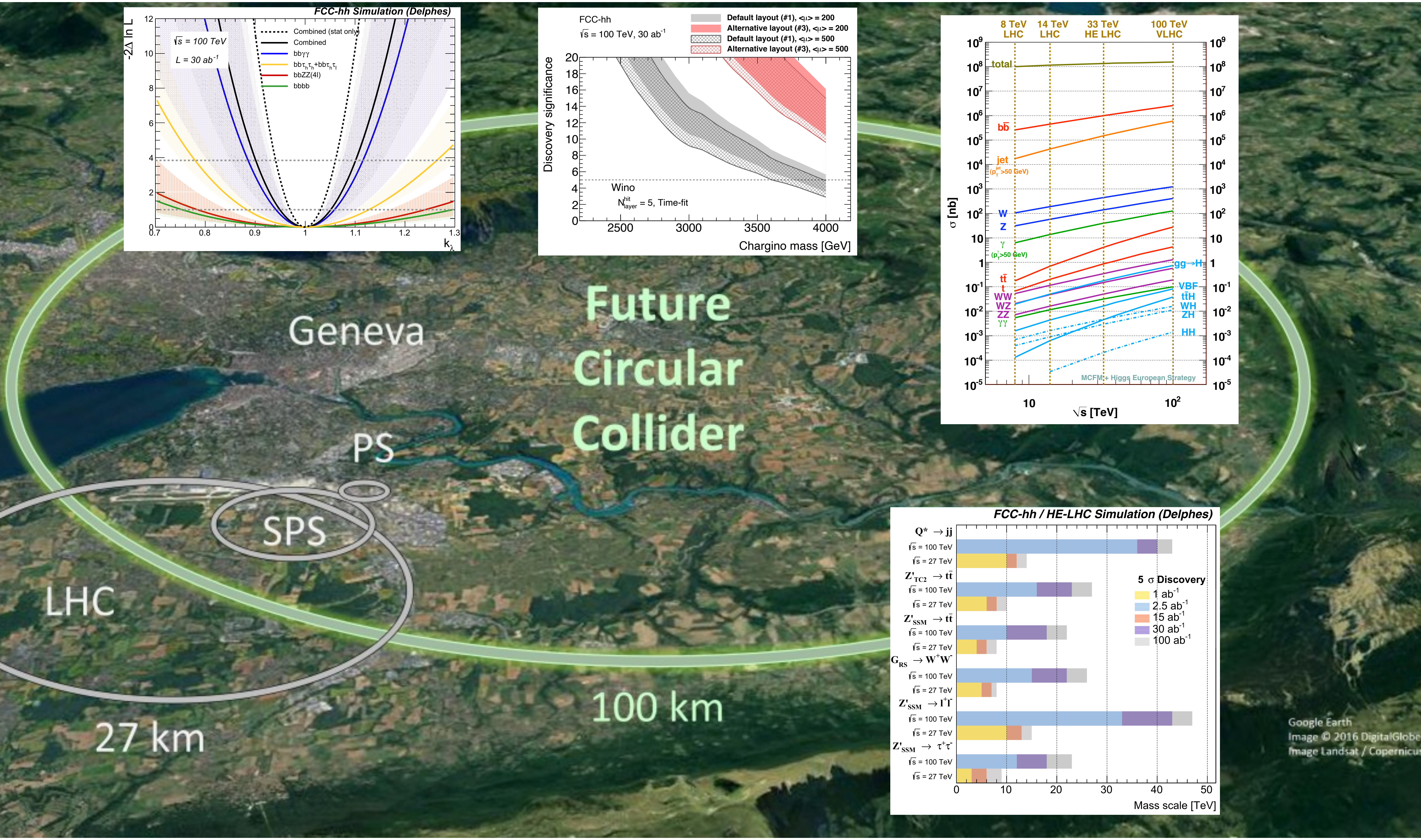
Physics at Future Hadron Colliders



Berkeley UNIVERSITY OF CALIFORNIA

Heather M. Gray, LHCP 2022

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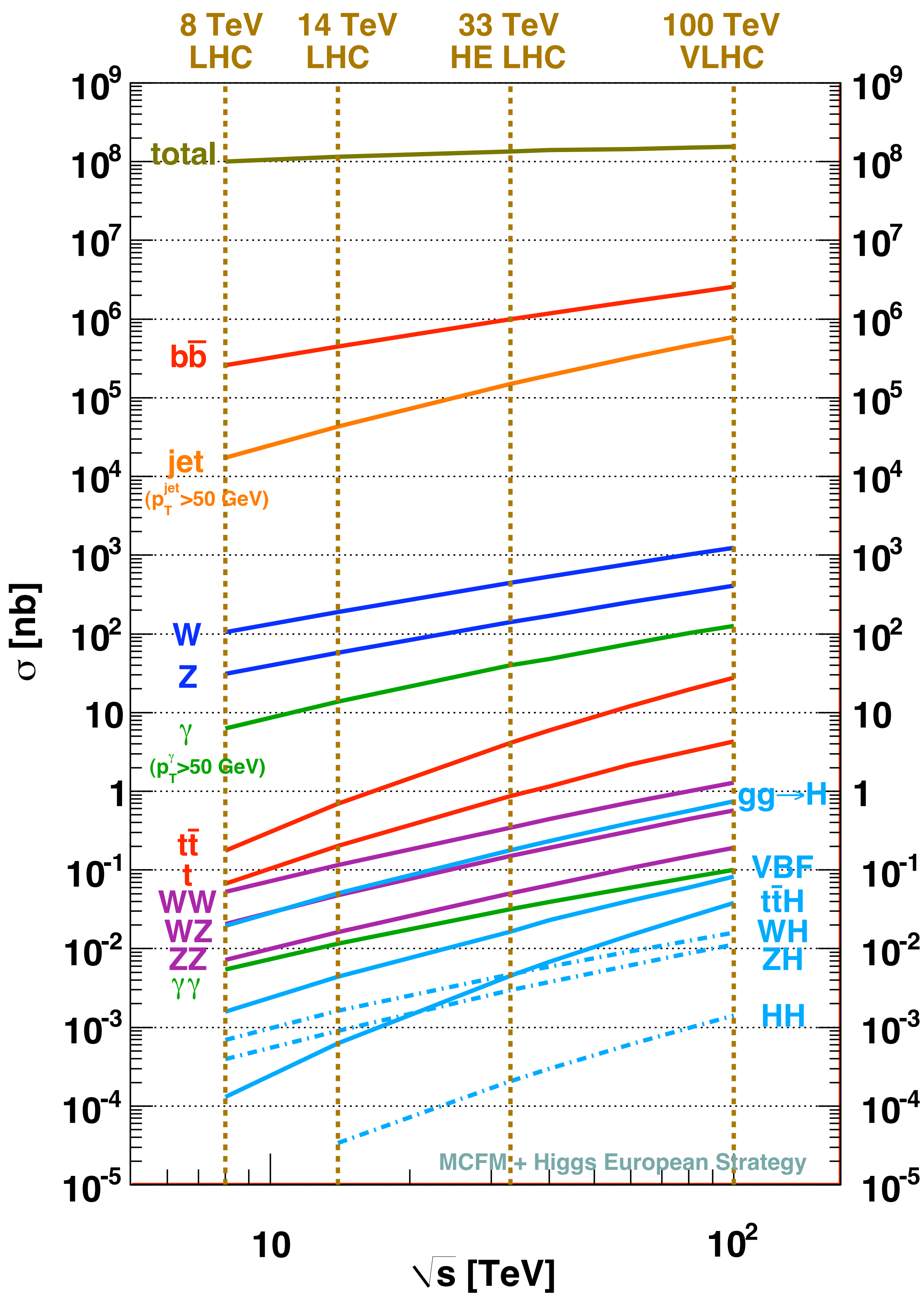
Introduction

- Hadron colliders are general purpose machines and, as such, capable of making a wide range of physics measurements including
  - **Precision measurements** of the Standard Model
    - Profiting from large cross-sections and high-luminosity
  - Direct searches for **new particles** and **new physics**
    - Unique capability in direct reach to high mass and high-energies
- This talk will cover **selected topics** from both and highlight the capabilities of hadron colliders
  - see talk by A. Zaborowska for details of the **machines and detectors**
- Physics capabilities of hadron colliders are **complementary** to those of e^+e^- colliders
  - see talk by F. Simon
- Will focus here on **physics studies** for the **FCC-hh**, but these also illustrate the potential for any **100 TeV collider**

Cross sections vs collider energy

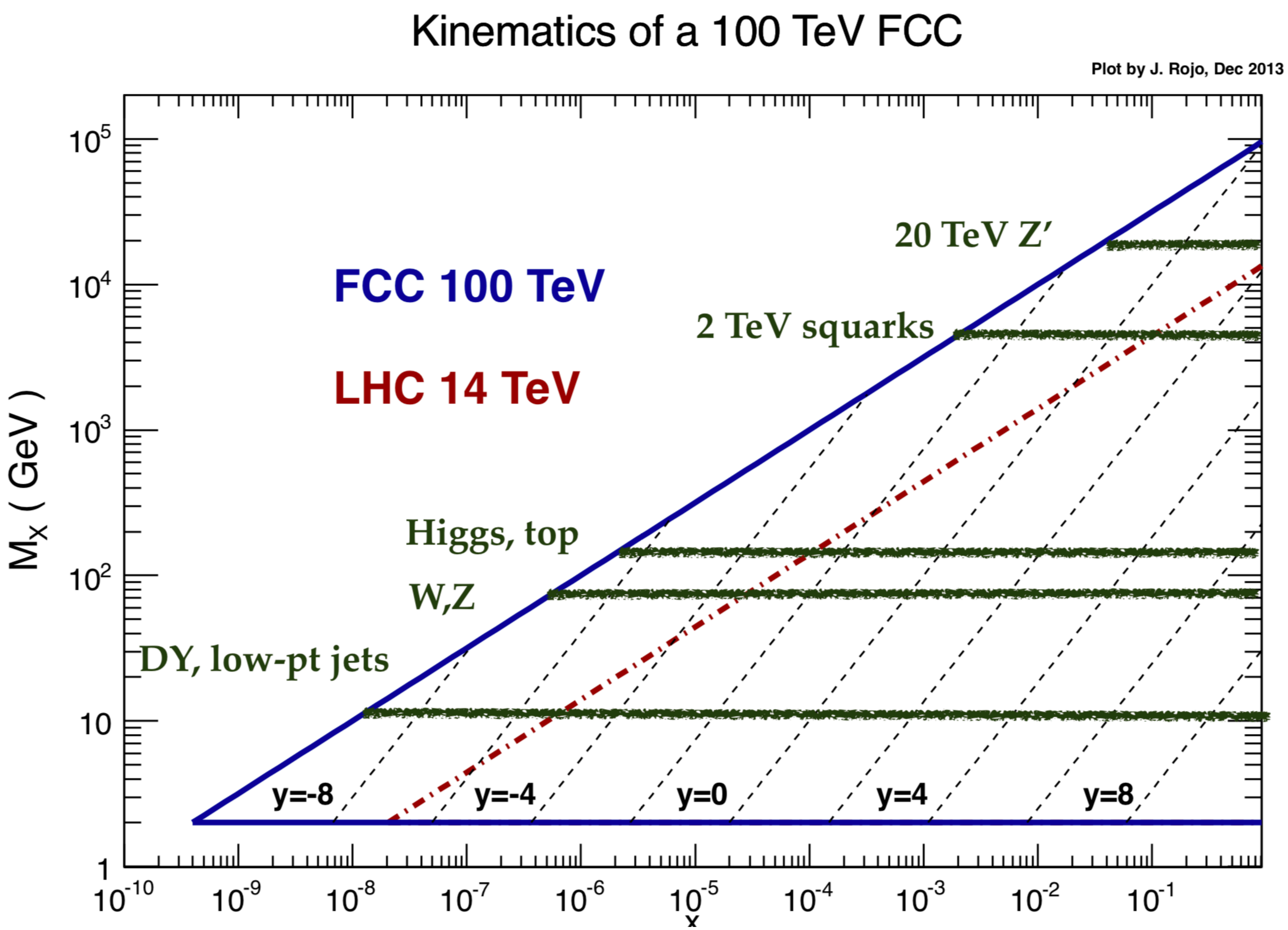


J. Campbell

Large increase in **cross sections** with collider energy

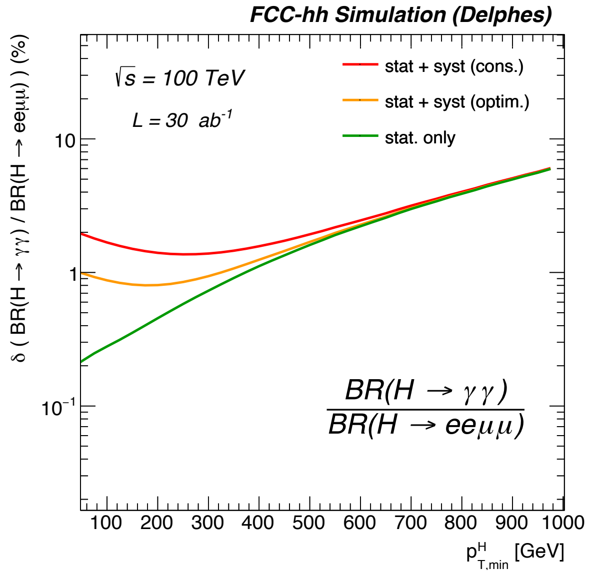
e.g. As increase is larger for heavier particles, ttH cross section becomes larger than WH/ ZH production at 100 TeV

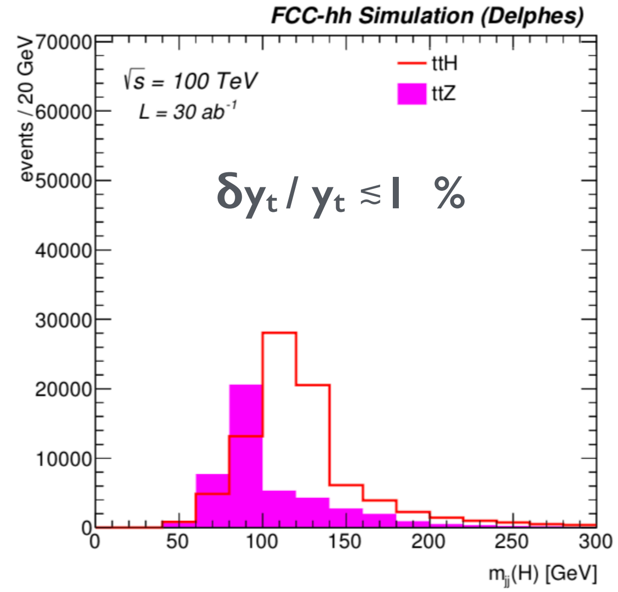
Kinematic Coverage

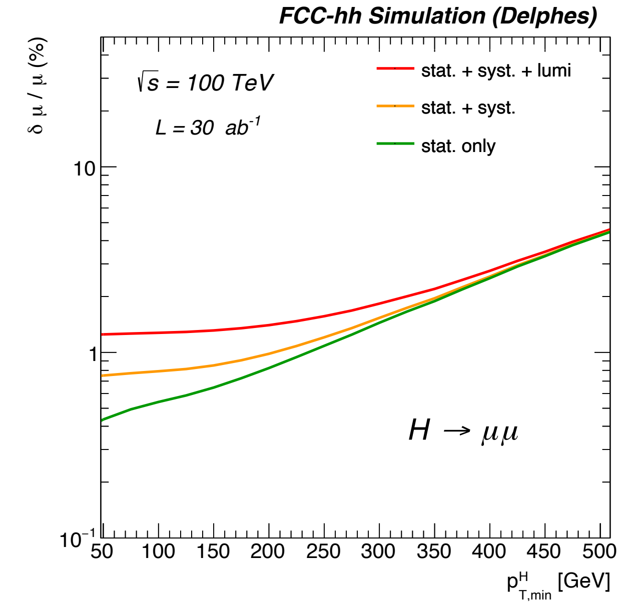


- Processes at FCC-hh will be produced at **higher rapidity** than at the LHC
  - Requirements on detector design and **acceptance**

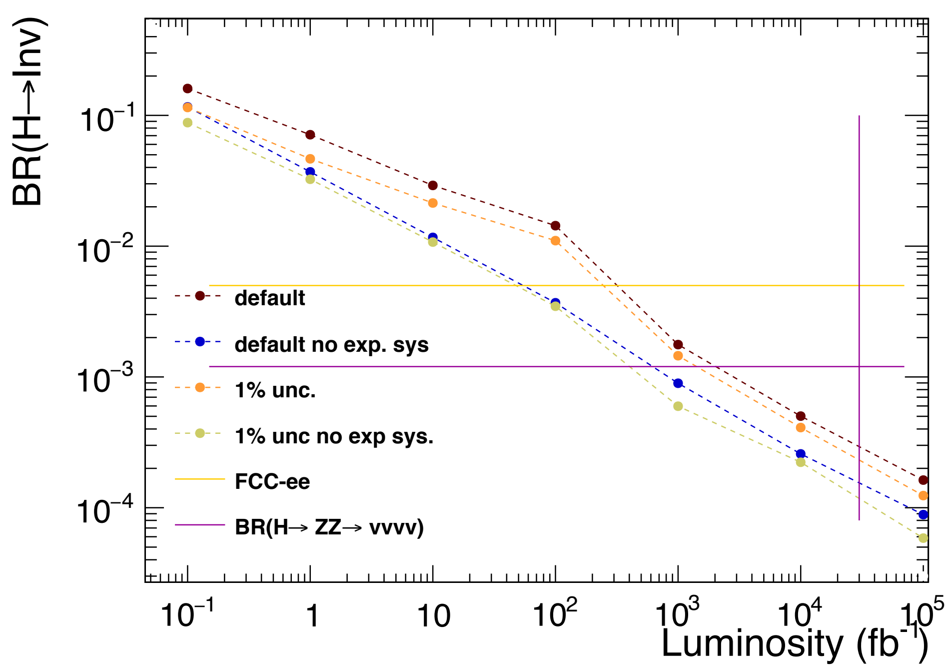
CERN-FCC-PHYS-2020-0004

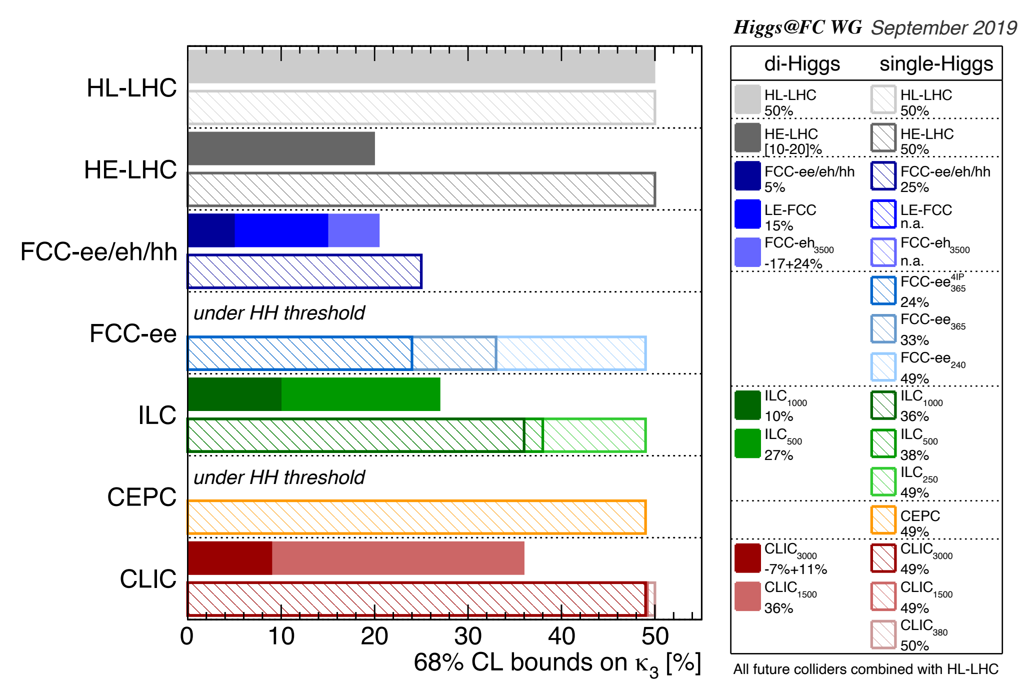






Precision Measurements: Higgs Physics

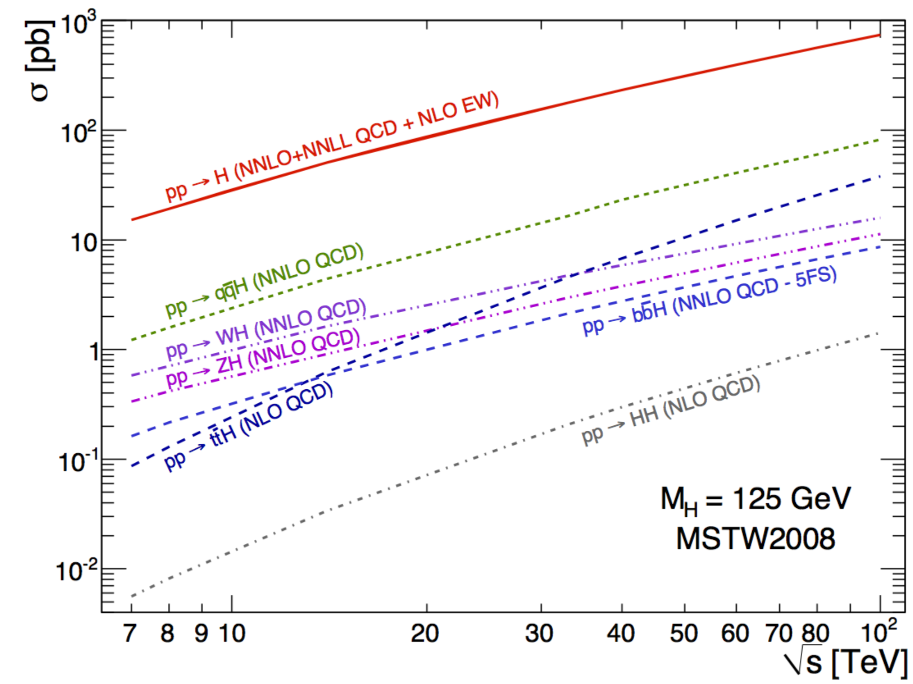




The Higgs Boson

- High precision measurements of all properties of Higgs boson are critical
- May prove to be a key to discovering physics beyond the Standard Model
- Hadron colliders are well-suited to provide
  - Higgs **coupling** measurements
    - **Rare** decays due to high luminosity
  - Higgs-**top** coupling
  - Higgs to **invisible**
  - Higgs **self-coupling**

Cross sections vs energy

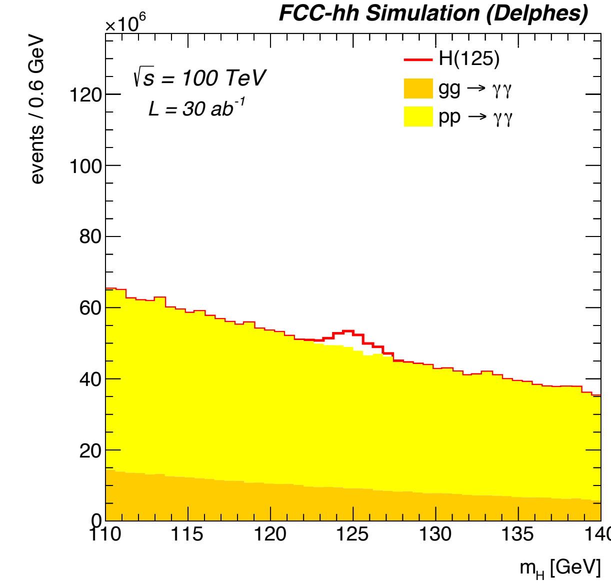


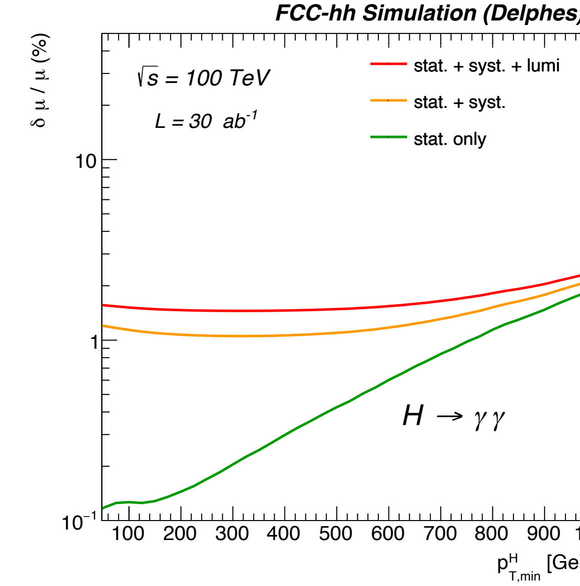
Many more Higgs bosons: large increase in cross sections

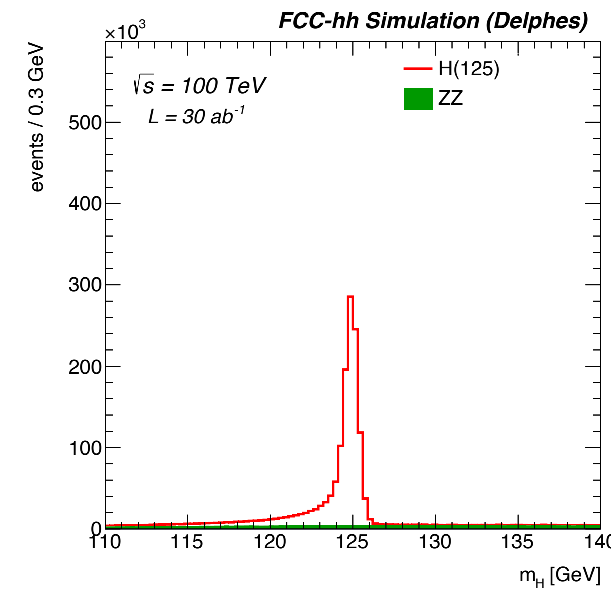
	σ(13 TeV)	σ(100 TeV)	σ(100)/σ(13)
ggH (N^3LO)	49 pb	803 pb	16
VBF (N^2LO)	3.8 pb	69 pb	16
VH (N^2LO)	2.3 pb	27 pb	11
ttH (N^2LO)	0.5 pb	34 pb	55

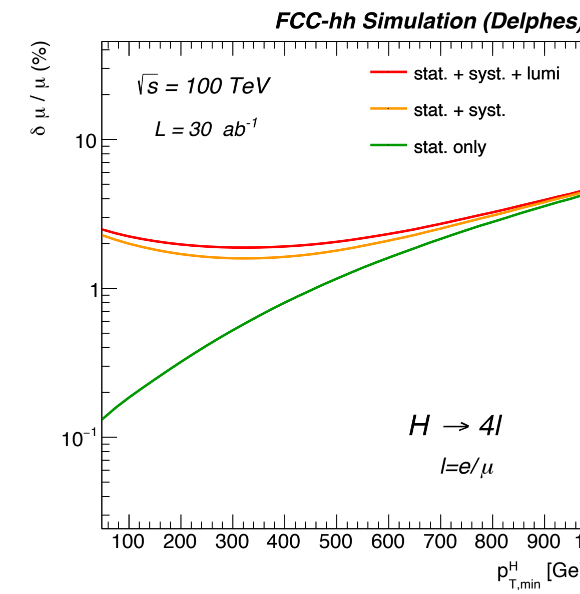
Higgs Coupling Measurements

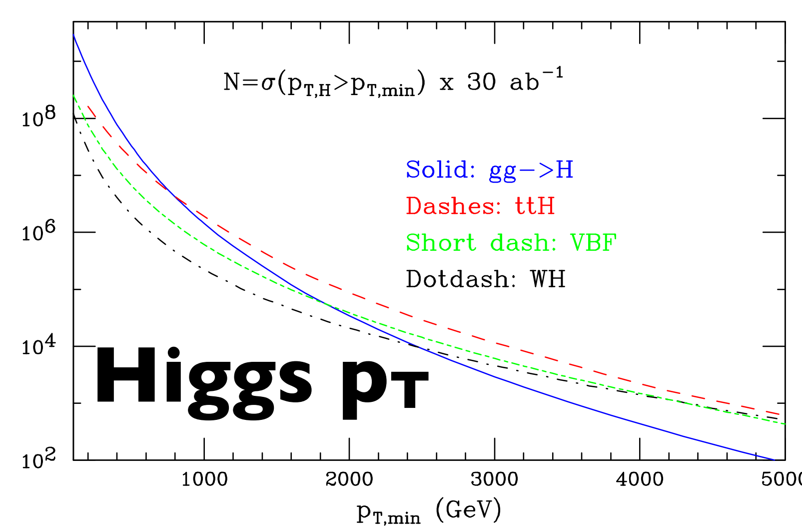
- Hadron colliders cannot make absolute measurements of Higgs couplings
- Either make **model dependent** measurements or measure coupling **ratios** wrt $H \to ZZ$ (and use precise ee measurement) with high statistics
- e.g. $H \to \gamma\gamma$
  - 0.1% stat
  - 1.45% stat + syst + lumi
- Can reduce systematics (incl. impact of pile up) by used boosted Higgs ($> 10^6$ with $p_T > 1$ TeV)
- Also measurements of Higgs p_T
  - Could probe new physics

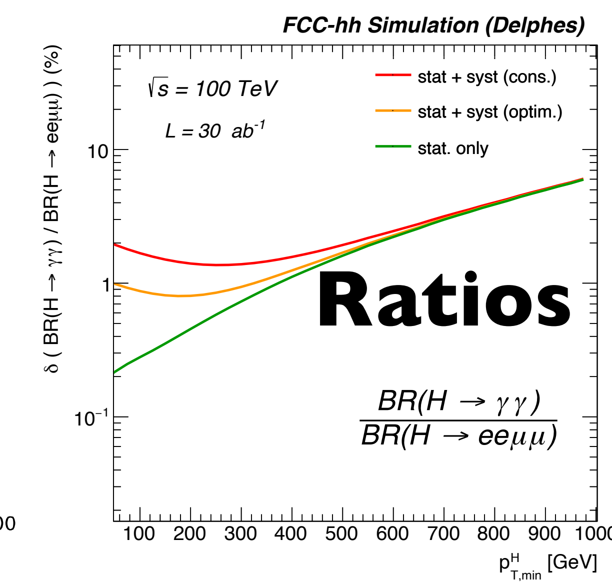








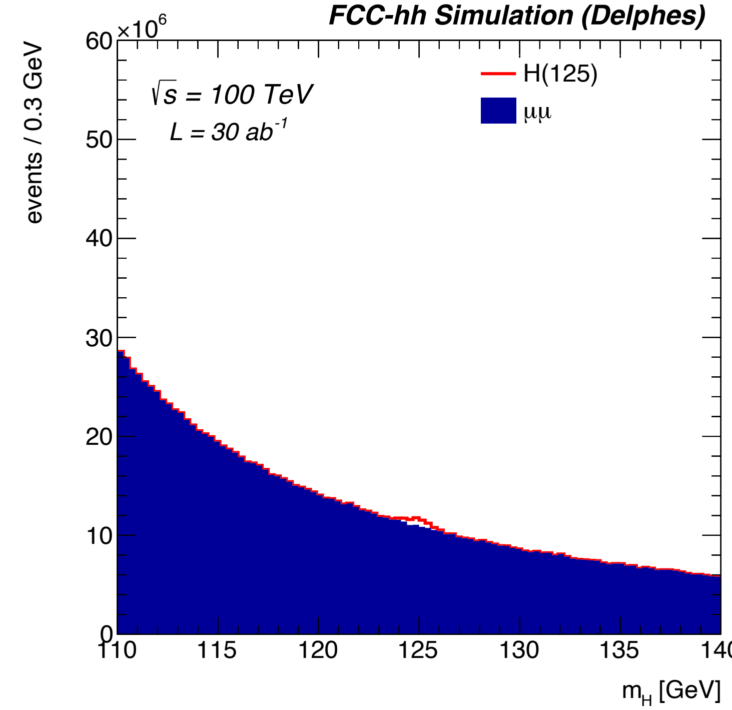


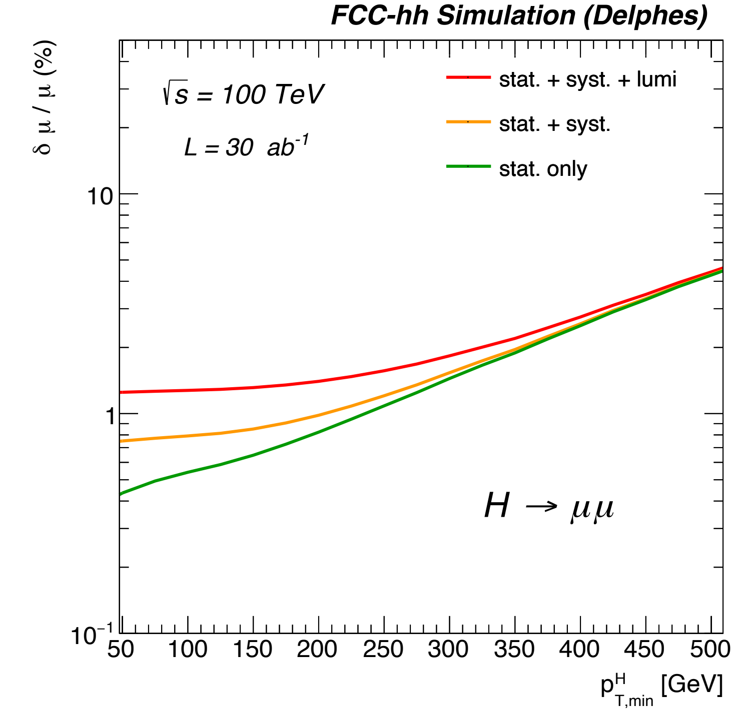


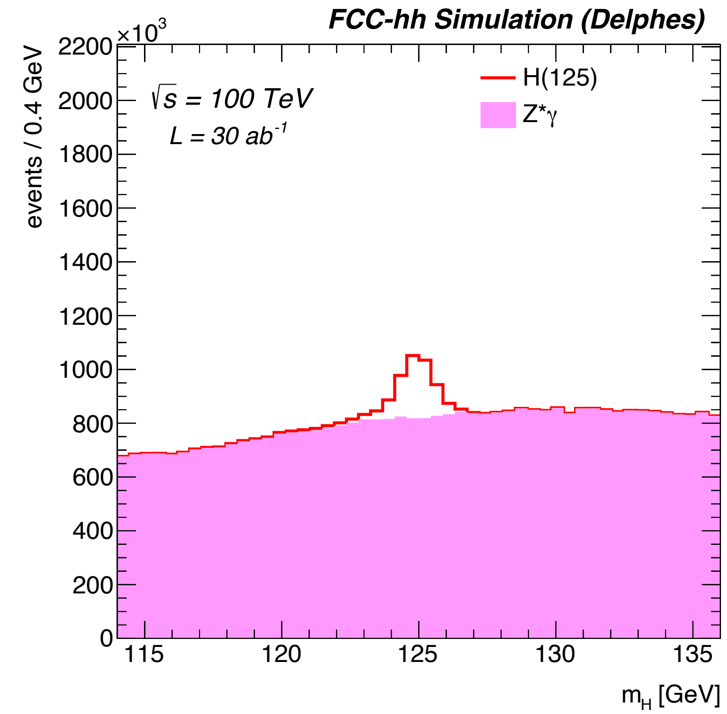
Rare Higgs Decays

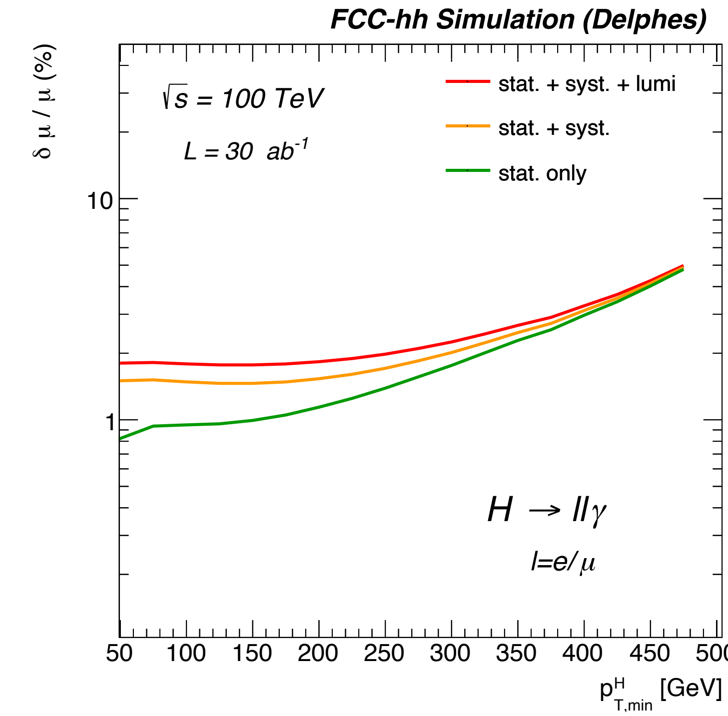
- Large production cross sections and high luminosity would allow precise measurements of rare Higgs decays
- $H \to \mu\mu$
  - 0.28% stat
  - 1.22% stat+syst+lumi
  - (8.2% @ HL-LHC)
- $H \to Z\gamma$
  - 0.55% stat
  - 1.61% stat+syst+lumi
  - (19.1% @ HL-LHC)

$H \to \mu\mu$





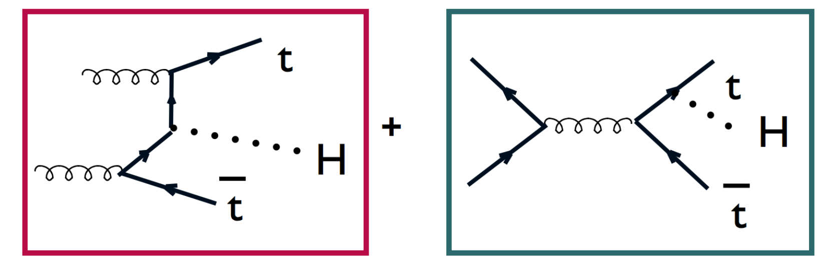




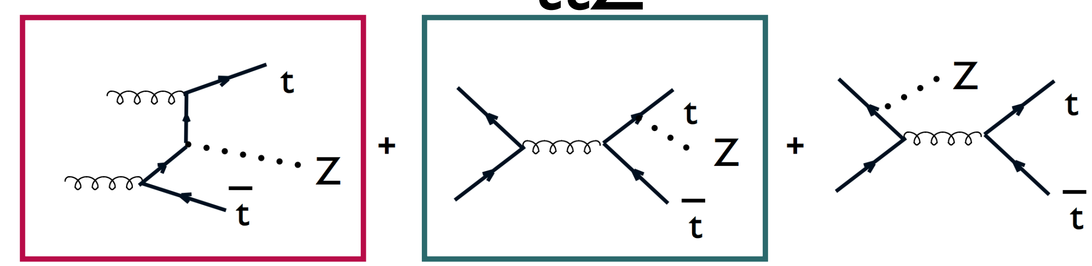
$H \to Z^*\gamma$

Higgs-Top Coupling

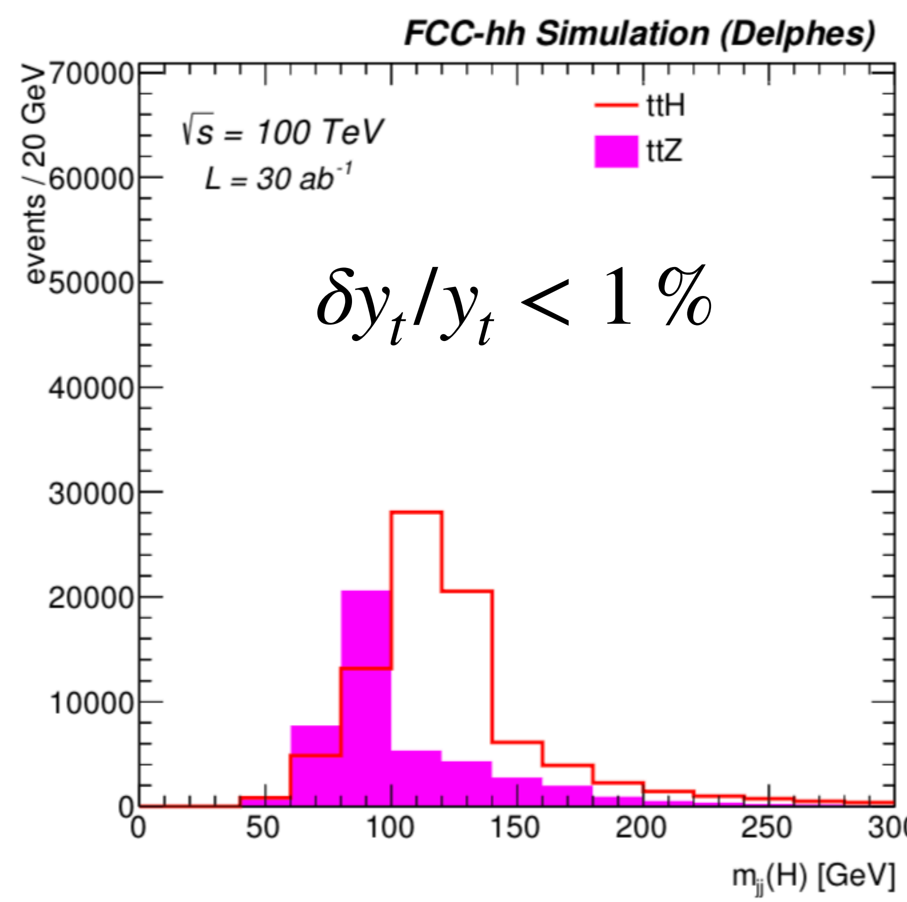
ttH



ttZ

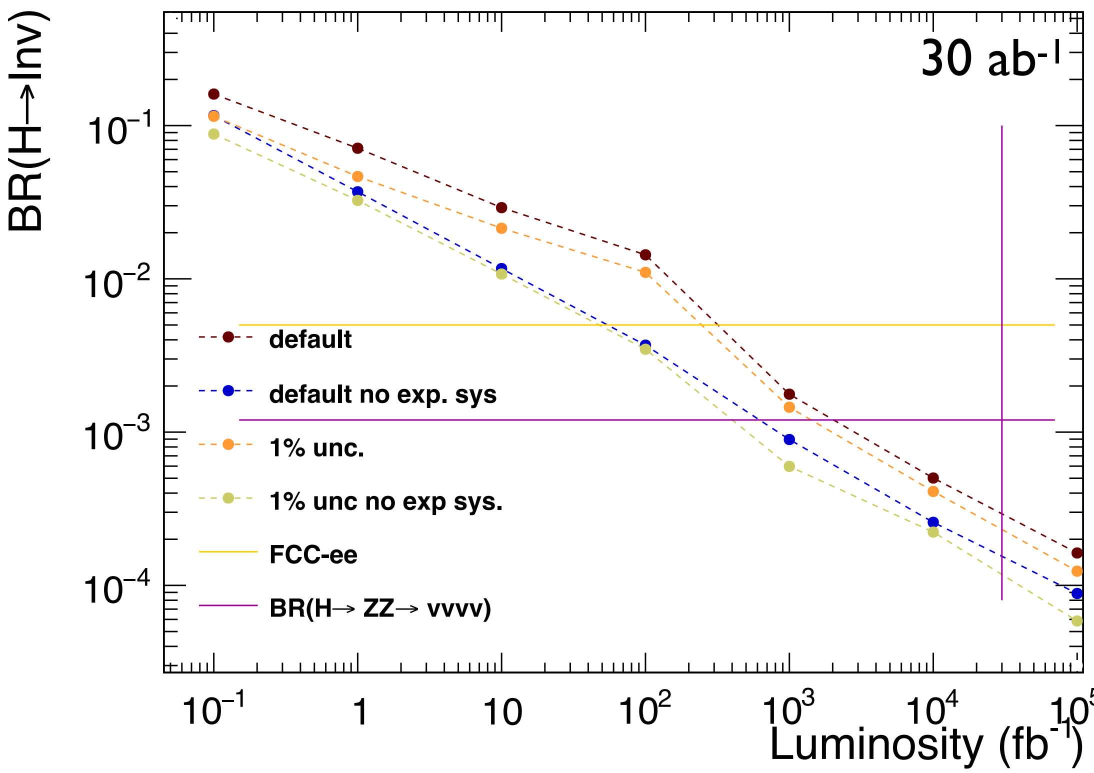


- Again due to the energy, 100 TeV colliders can make precise measurements of κ_t
  - ttH production cross section increases more rapidly than other production cross sections with energy
- Following Mangano et al. a precise measurement could be made by measuring the ratio ttH/ttZ
  - Cancellation of systematics including **luminosity**, **theory** & **experimental** systematics
- Expected precision of O(1%)
  - Assumes $\sigma(ttZ)$ is known, e.g. from FCC-ee



Higgs Decays to Invisible Particles

- Constraints on Higgs decays to invisible particles can be used as **generic searches** for (light) new particles coupling to the Higgs boson
- **Profile likelihood fit** to the E_T^{miss} in **boosted Higgs** events
  - Backgrounds **constrained** from Z and W control regions
- $BR(H \to inv) < 10^{-4}$
  - Depends on level to which backgrounds can be constrained
  - **Competitive at low mass** with direct detection experiments like LUX, PANDA, CDMS

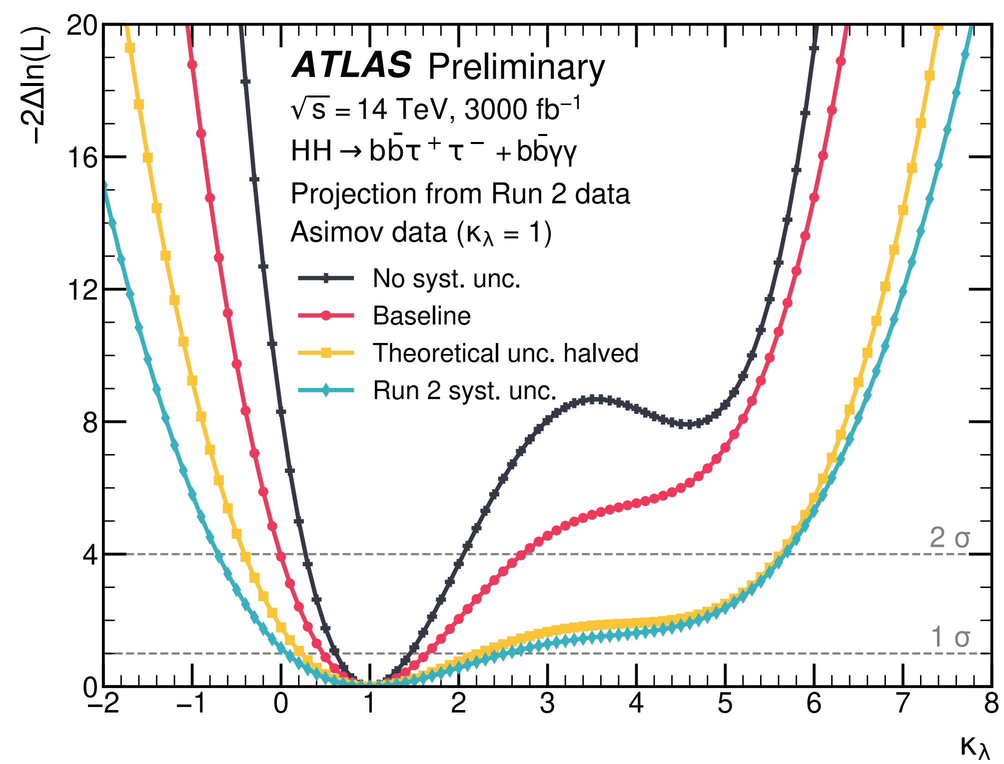


FCC-ee

$H \to ZZ \to \nu\nu$

Higgs Self-coupling

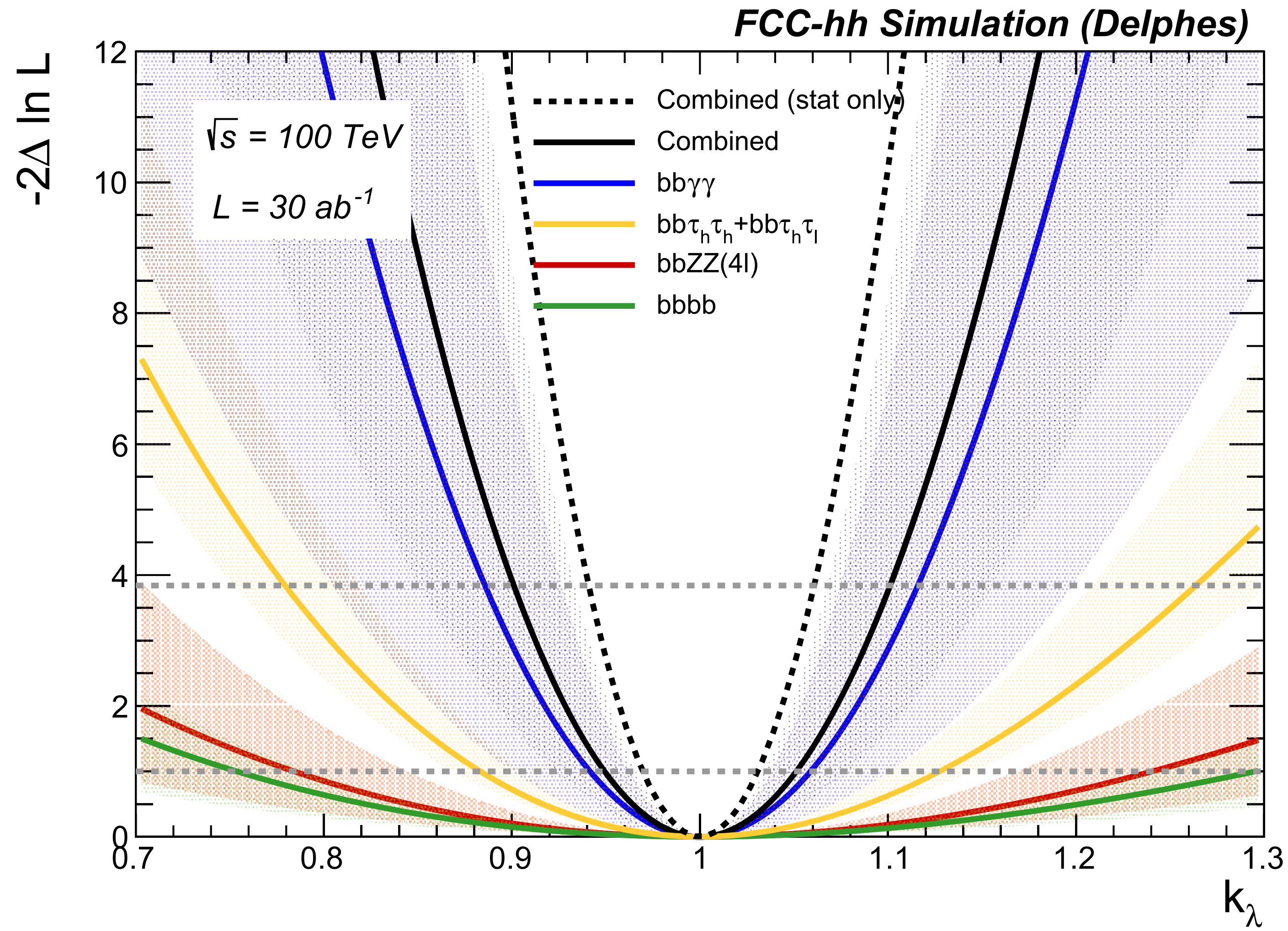
- Direct access to **Higgs potential**
  - Confirm mechanism of **electroweak symmetry** breaking
- Tiny cross section due to negative interference
- Key channels include
  - $bb\tau\tau$
  - $bb\gamma\gamma$
  - $bbbb$
- Expect to react a precision of ~50% by the end of HL-LHC
  - Depends strongly on assumptions about **systematics**



ATL-PHYS-PUB-2022-005

Higgs self-coupling at FCC-hh

- Highest precision channel: $bb\gamma\gamma$
- Expected combined precision on κ_λ of 3-8%
- Depends on detector performance and systematic assumptions
  - Studied for 3 different detector performance and systematic scenarios



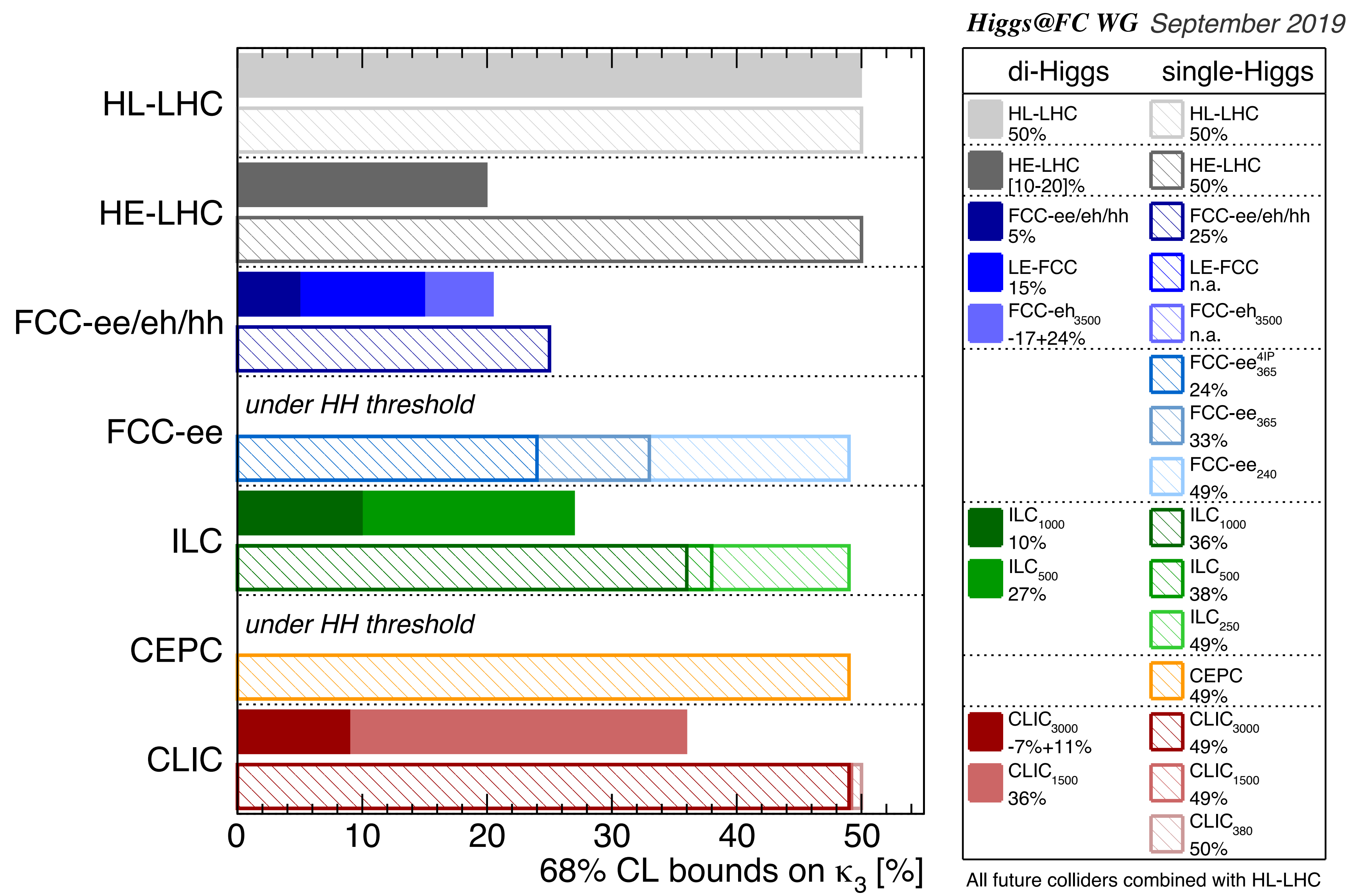
@68% CL	Scenario I	Scenario II	Scenario III
Stat only	3.0	4.1	5.6
Stat + syst	3.4	5.1	7.8

Detector performance/systematic assumptions

- Scenario I: Optimistic – target detector performance, similar to Run 2 LHC conditions.
- Scenario II: Realistic – intermediate detector performance.
- Scenario III: Conservative – pessimistic detector performance, assuming extrapolated HL-LHC performance using present-day algorithms.

https://link.springer.com/content/pdf/10.1140/epjc/s10052-020-08595-3.pdf

Summary of Higgs Self-Coupling Measurements



http://cds.cern.ch/record/2691414

FCC-hh can make the **most precise measurement** of the Higgs self-couplin of future colliders under consideration

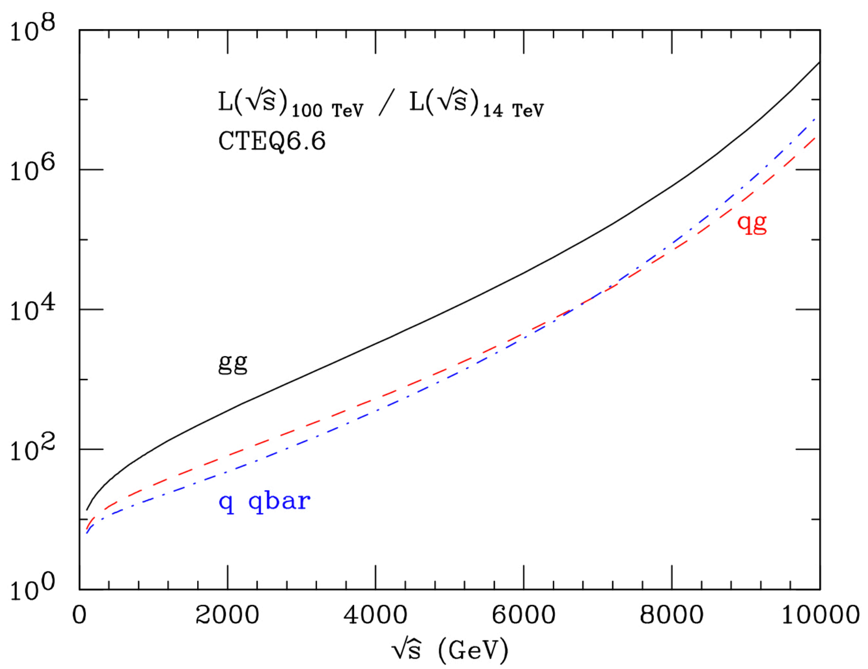
Summary of Higgs Measurements

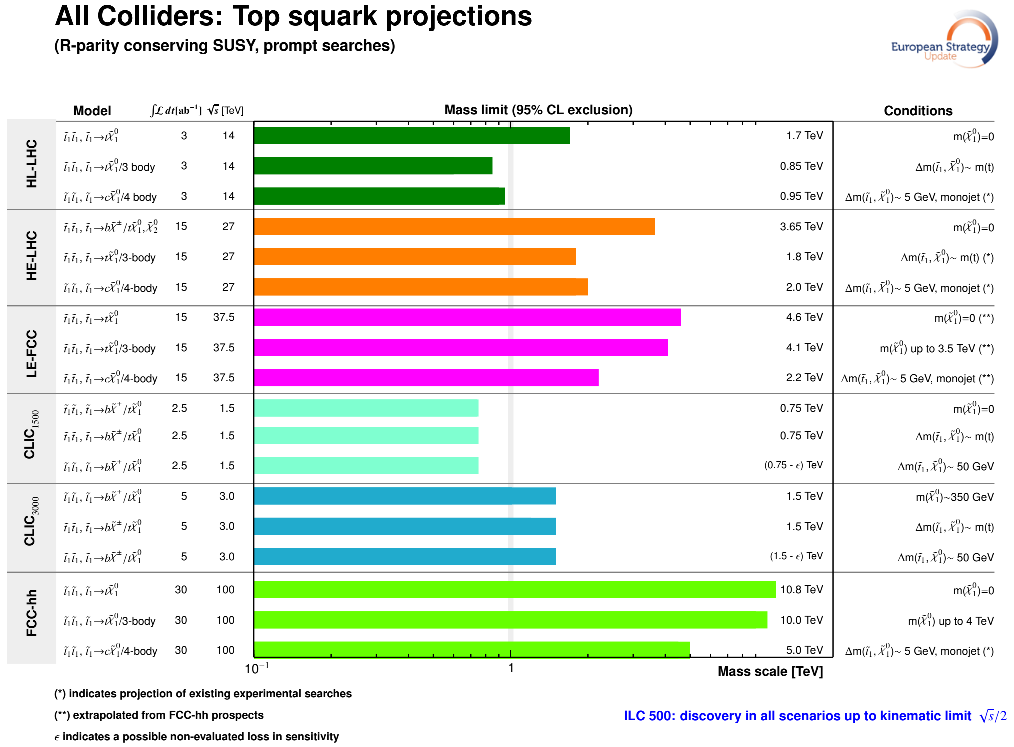
- Highlights include
  - Higgs **coupling** measurements
    - **Rare** decays due to high luminosity
  - Higgs-**top** coupling
  - Higgs to **invisible**
  - Higgs **self-coupling**

Comparison to other hadron colliders

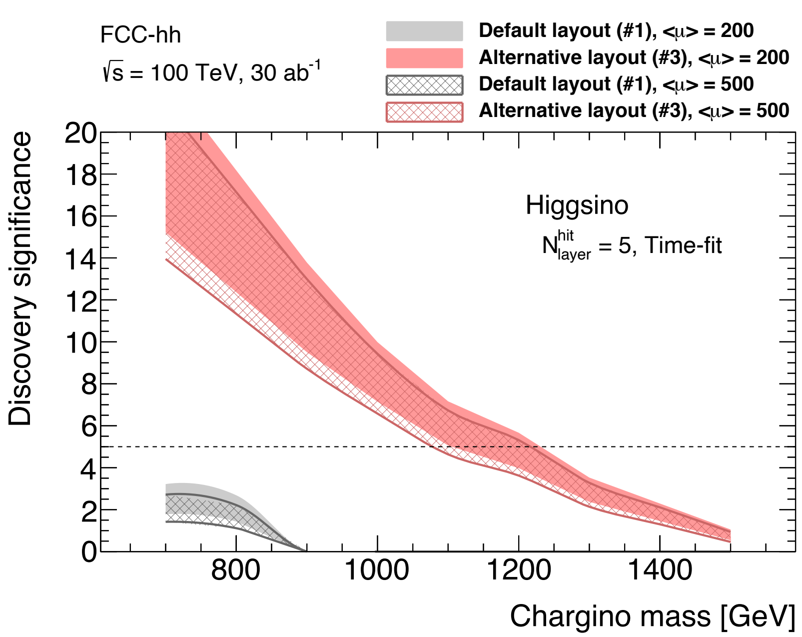
$\delta R/R$	HE-LHC	LE-FCC	FCC-hh
$R = B(H\to\gamma\gamma)/B(H\to 2e2\mu)$	1.7%	1.5%	0.8%
$R = B(H\to\mu\mu)/B(H\to 4\mu)$	3.6%	2.9%	1.3%
$R = B(H\to\mu\mu\gamma)/B(H\to\mu\mu)$	8.4%	6%	1.8%
$R = B(H\to\gamma\gamma)/B(H\to 2\mu)$	3.5 %	2.8%	1.4%

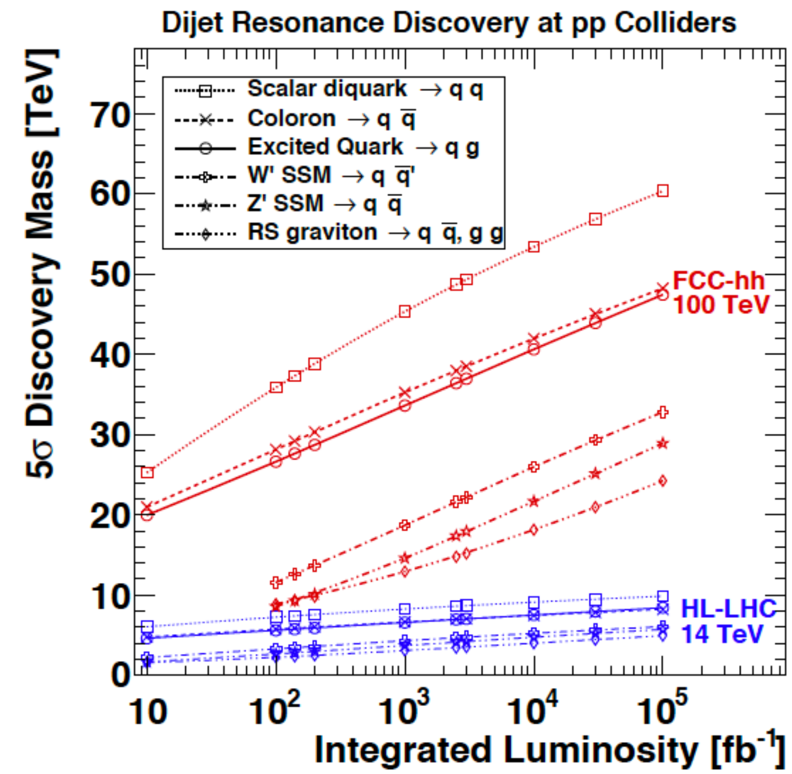
Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(H)\times B(H\to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(H)\times B(H\to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(H)\times B(H\to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(H)\times B(H\to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$R = B(H\to \mu\mu)/B(H\to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = B(H\to \gamma\gamma)/B(H\to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = B(H\to \gamma\gamma)/B(H\to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = B(H\to \mu\mu\gamma)/B(H\to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}H)\times B(H\to b\bar{b})/\sigma(t\bar{t}Z)\times B(Z\to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(H\to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}
HH production	$\delta\lambda/\lambda$	3.0–5.6%	3.4–7.8%





Searches for New Physics

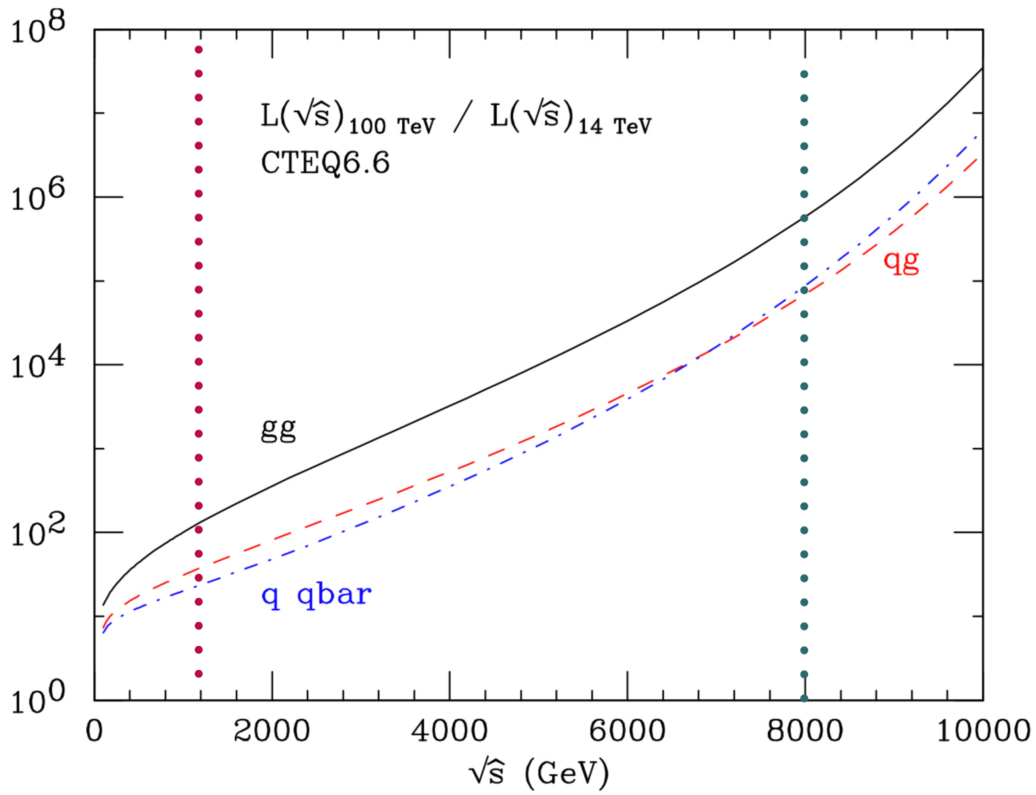


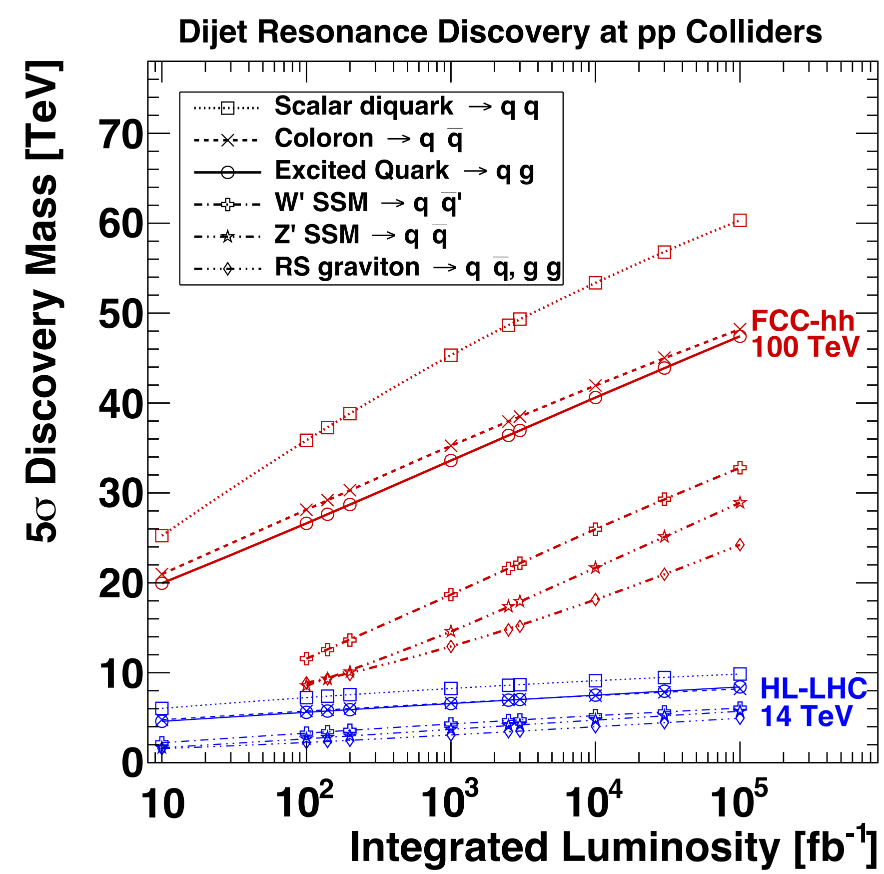


New physics prospects at 100 TeV

- 100 TeV colliders can directly probe new physics at very high energies
- PDF luminosity ratio increasing strongly as a function of the mass of the new particle
  - e.g. 100 @ 1 TeV
  - 10^6 @ 8 TeV
- Translates into discovery potential for high mass particles

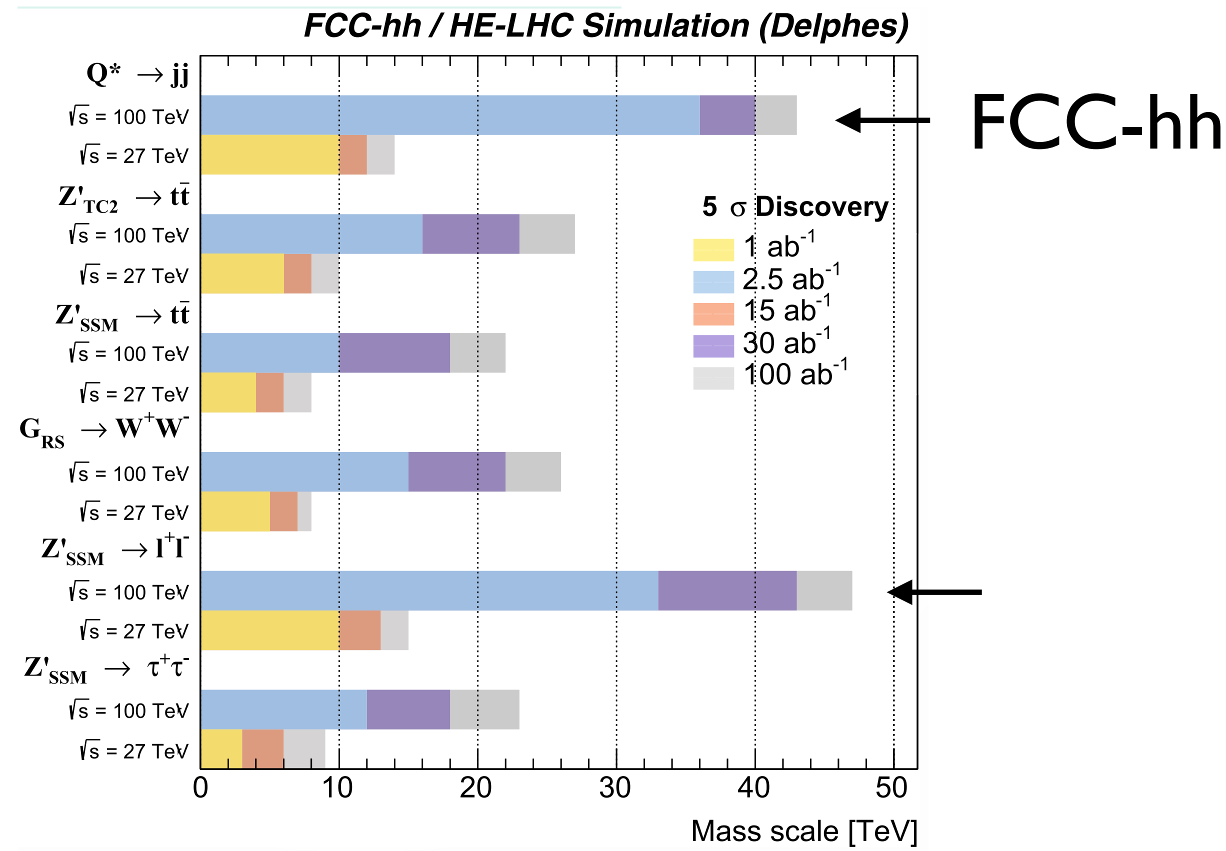
PDF Luminosity Ratio

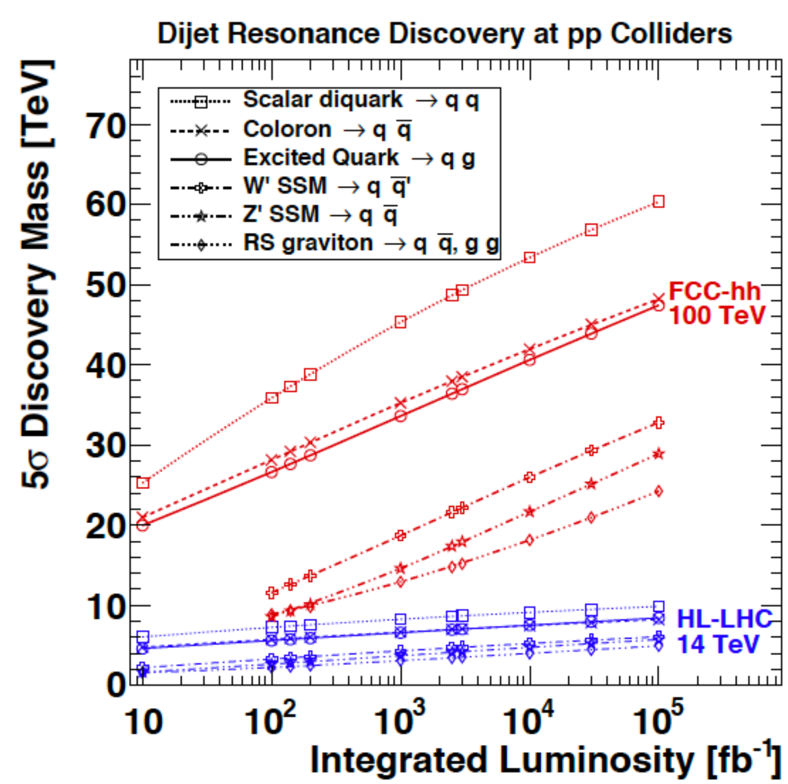




High mass new particles

- FCC-hh would probe the multi-TeV range for a wide variety of **generic models**
- Dijet resonances, $Z' \to ll$: up 40 TeV with 30 ab-1
- For other decay channels ($t\bar{t}$, $W^+W^-, \ell^+\ell-, \tau^+\tau^-$), reach is typically 10-20 TeV
- Reach is larger for **strongly** produced dijet resonances than **weakly** produced
- Mass reach is typically **7x** higher than for HL-LHC

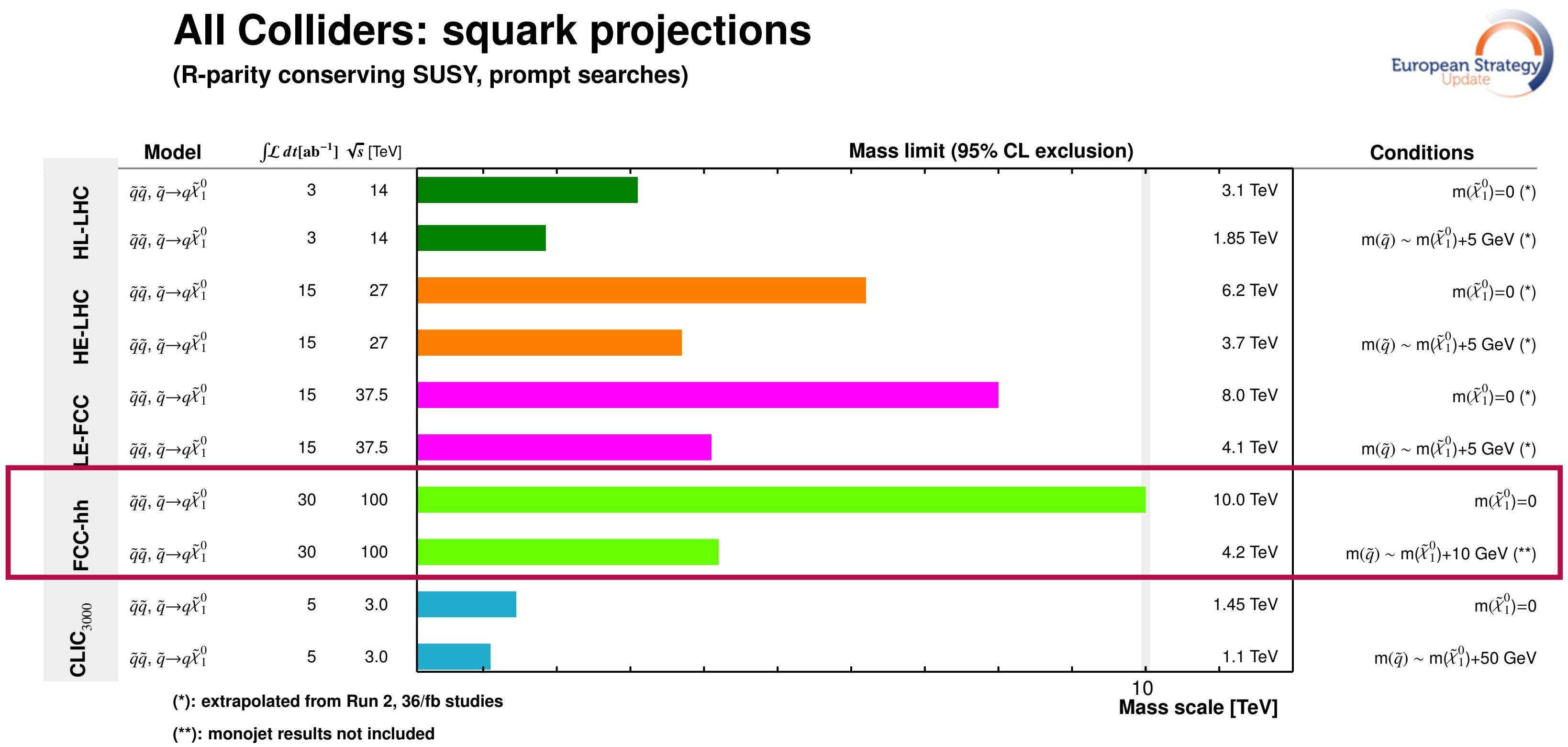




Model	HL-LHC √s = 14 TeV, ∫Ldt = 3 ab-1 5σ [TeV]	95% CL [TeV]	FCC-hh √s = 100 TeV, ∫Ldt = 30 ab-1 5σ [TeV]	95% CL [TeV]
Strongly Produced Dijet Resonances				
Diquark	8.7	9.4	57	63
Coloron	7.1	7.8	45	51
q*	7.0	7.9	44	50
Weakly Produced Dijet Resonances				
W'	4.8	5.6	29	36
Z'	4.2	5.2	25	32
RS grav.	3.5	4.4	21	27
Top Squark $\tilde{t}_1\tilde{t}_1 \to (t\,\tilde{\chi}^0_1)(t\,\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1) = 0$				
$\tilde{t}_1$	1.3	1.7	9.6	10.8

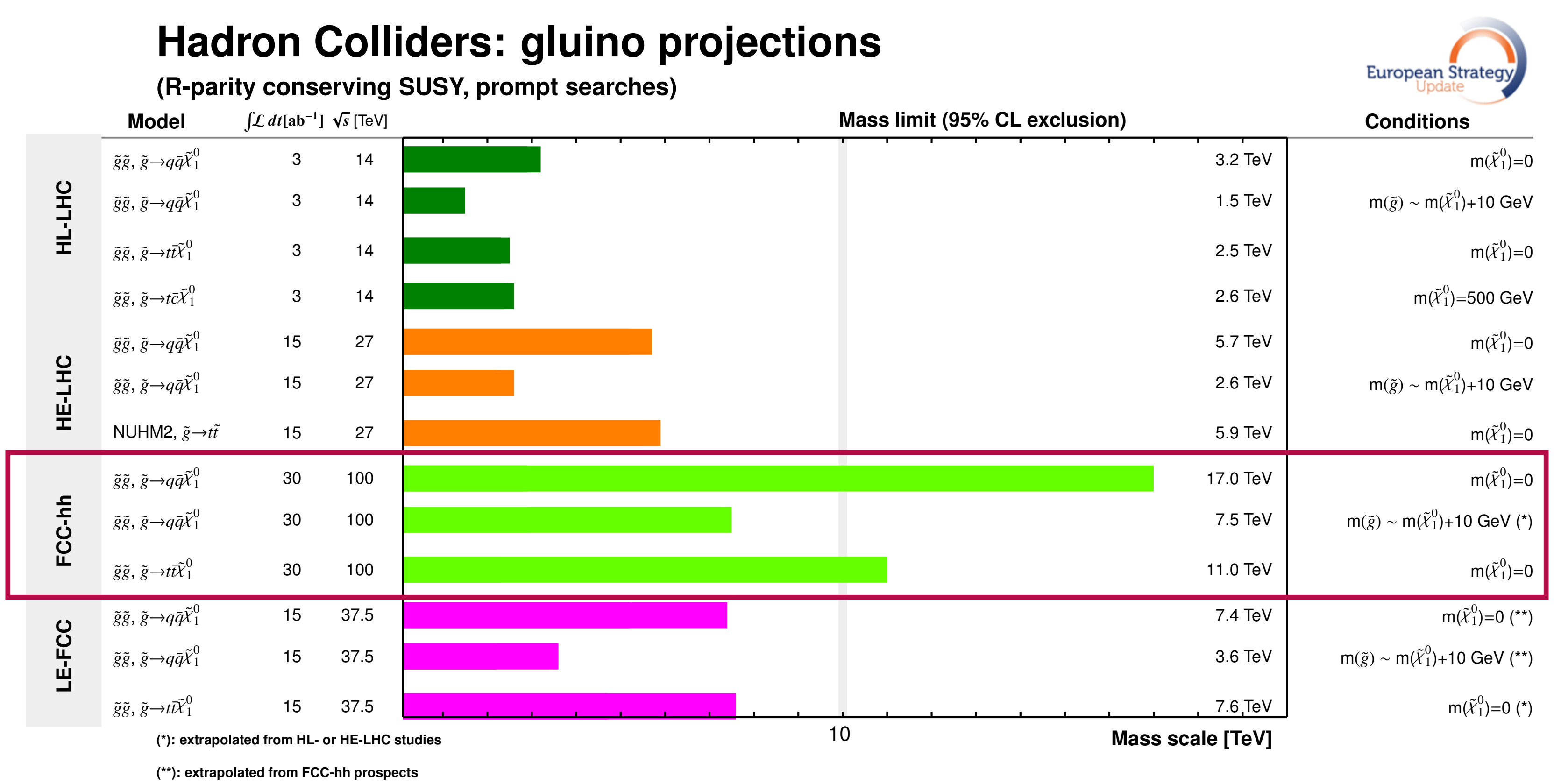
https://arxiv.org/abs/2202.03389

Supersymmetry: Squarks and Gluinos



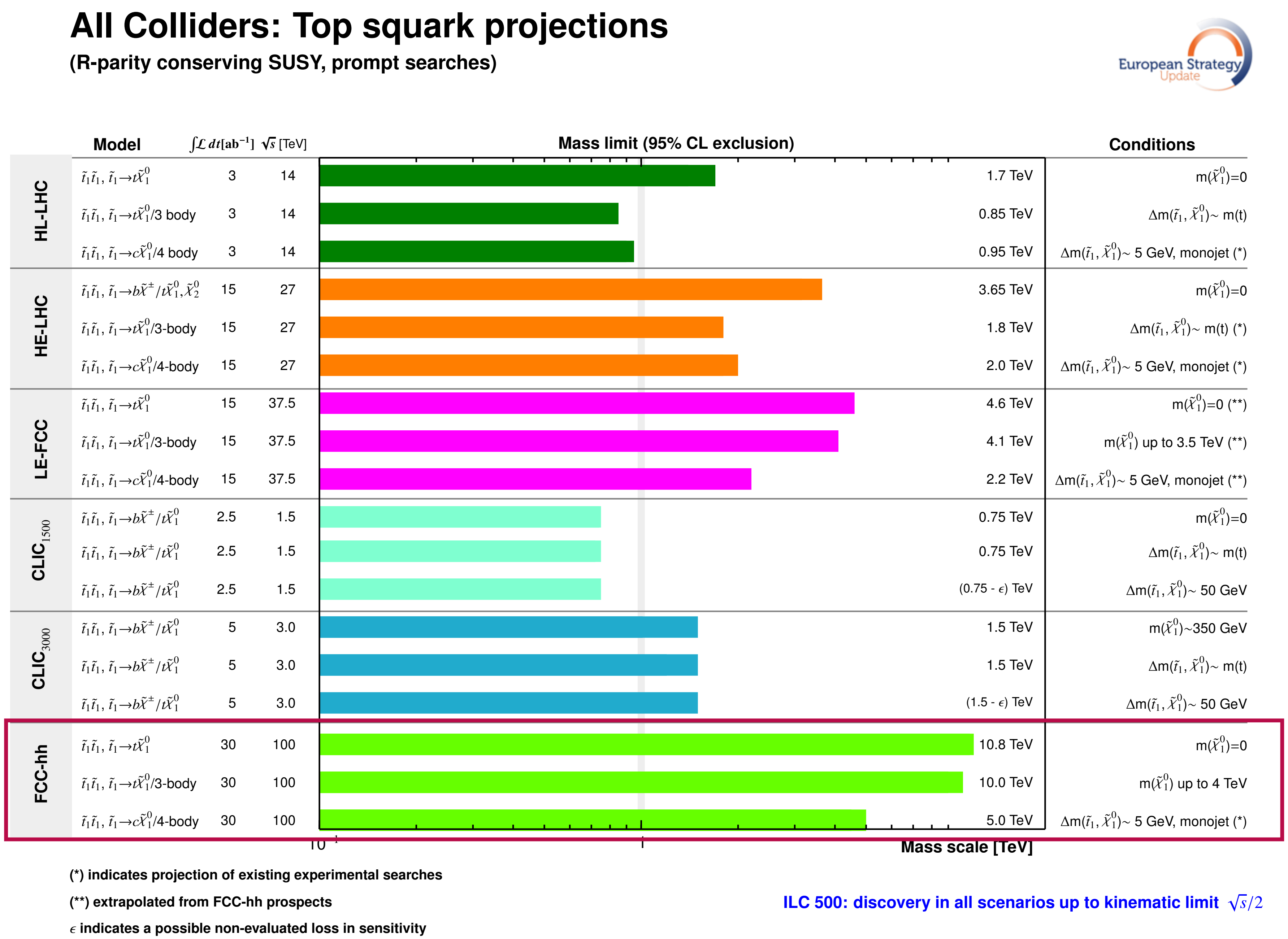
Large extension in reach of SUSY models with FCC-hh

FCC-hh probes **squarks** up to **10 TeV** extends HL-LHC mass reach by a factor of **2-3**



FCC-hh probes **gluinos** up to **17 TeV** extends HL-LHC mass reach by a factor of **4-5**

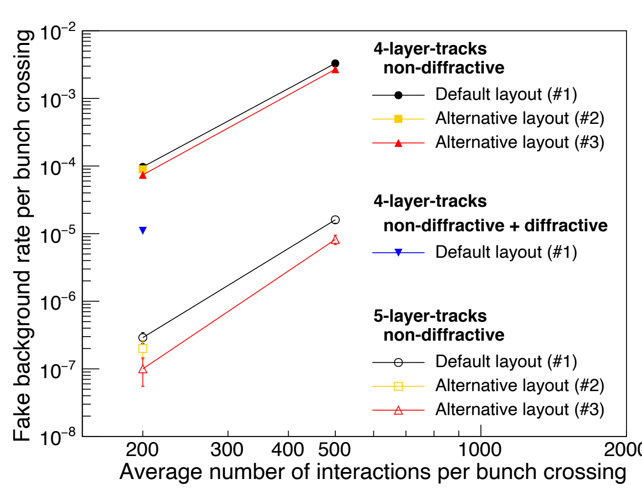
Supersymmetry: Top squarks



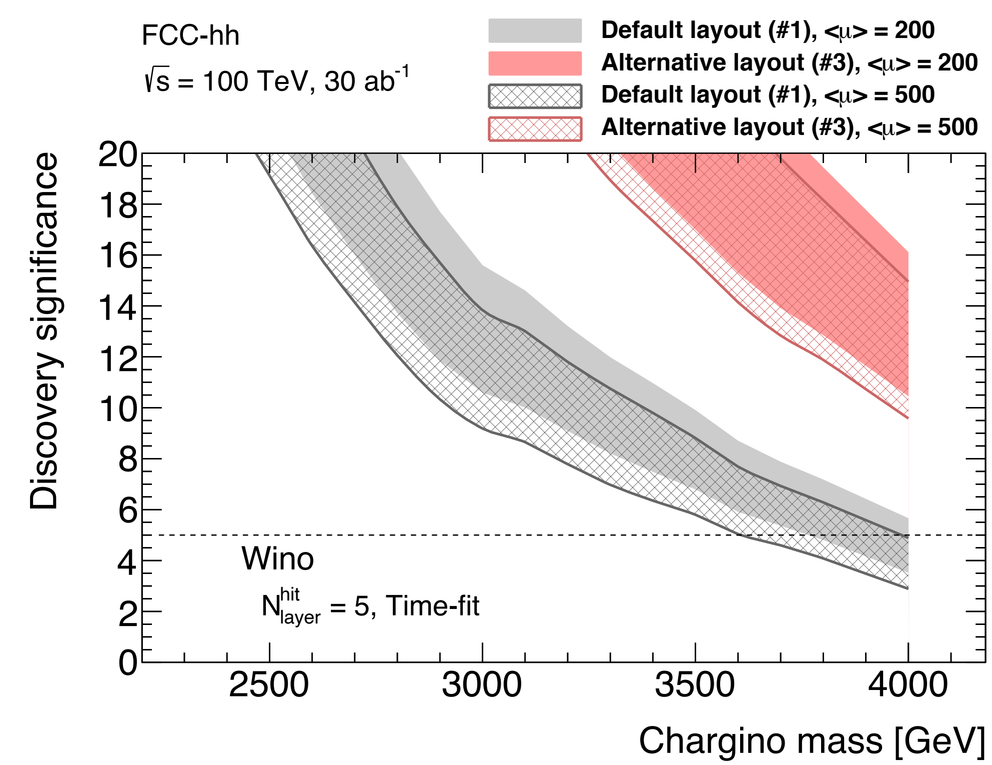
FCC-hh probes stops up to 11 TeV, relevant range for naturalness
extends HL-LHC mass reach by a factor of 5-12

Disappearing Tracks

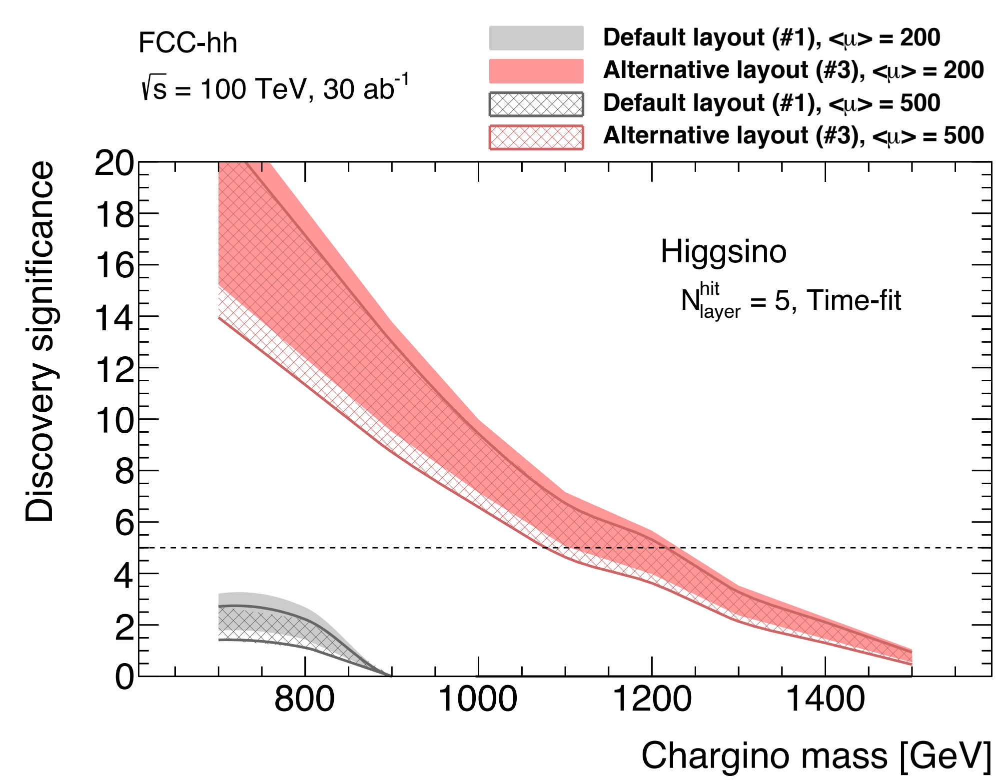
- Generic WIMP dark matter models predict **long-lived DM candidates**
  - Wino (2-3 TeV region)
  - Higgsino (1-1.2 TeV region)
- Can be probed using **disappearing track** analyses
- Sensitivity depends strongly on **detector design** (layers, timing information) and the amount of **pile up**
- Most optimistic scenario: FCC-hh could probe the entire predicted region



Wino



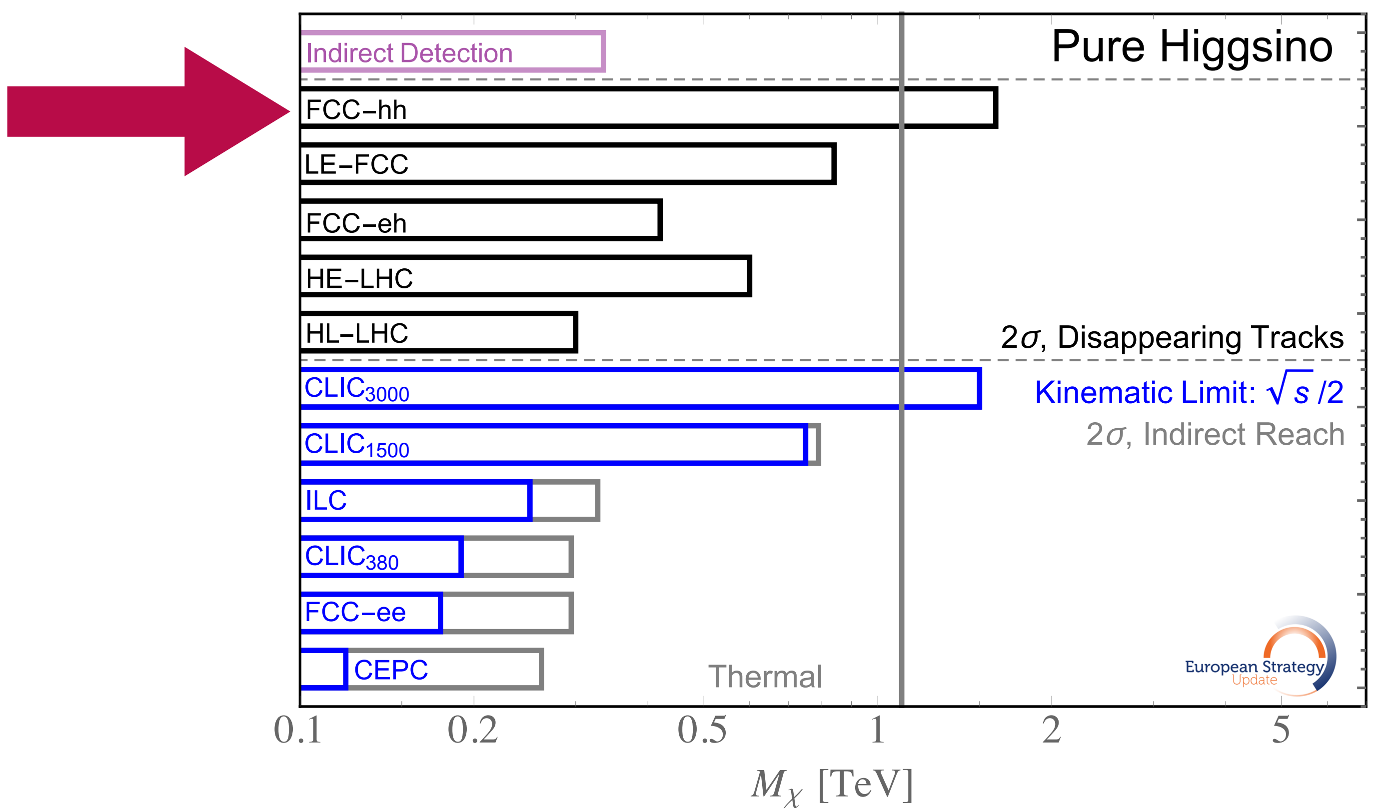
Higgsino



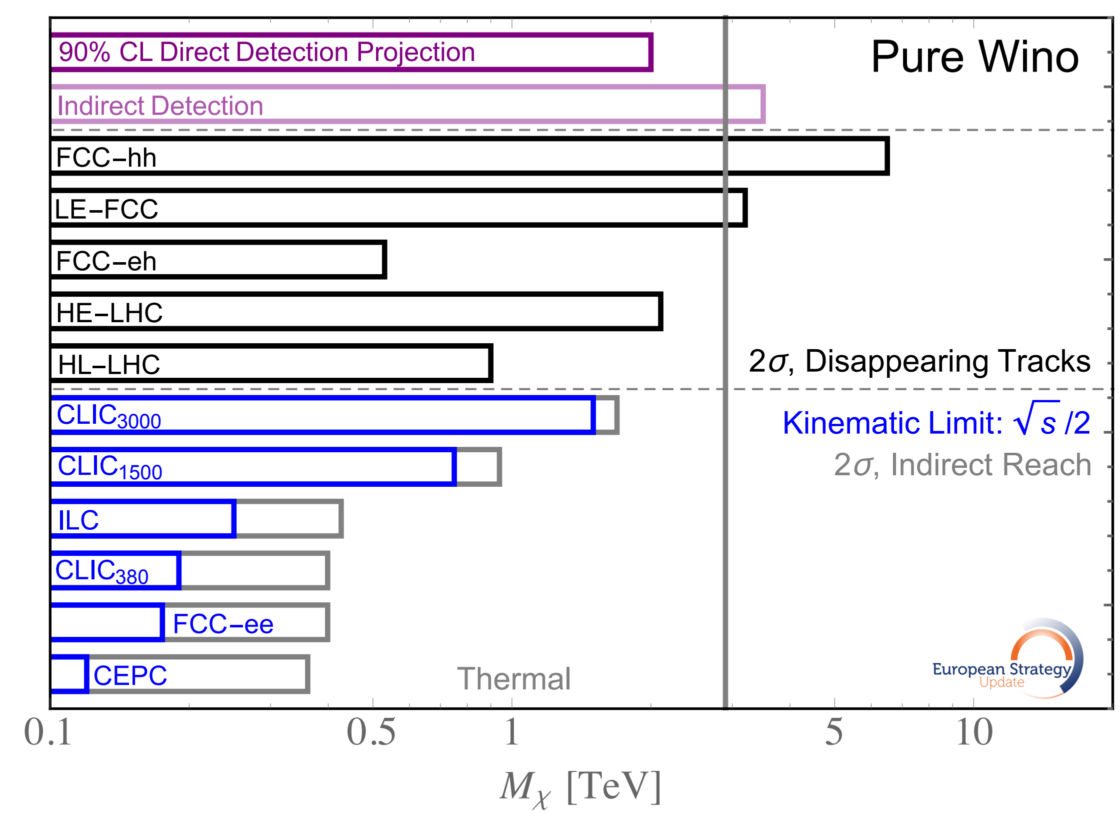
Assumes 50 ps timing resolution

Dark Matter Summary

Higgsino



Wino



Largest reach from FCC-hh; covers theoretically interesting range
Complemented by indirect reach from lepton colliders

Conclusion

- A 100 TeV proton-proton collider would provide us with a number of **unique opportunities**
  - Probe the **multi-TeV** range for **new particles** and **new interactions** (including generic models and supersymmetry)
  - Search for **dark matte**r candidates
  - Precision measurements of **Higgs boson** properties, including **rare decays**, **Higgs-top** coupling and the Higgs **self-coupling**
- It would be capable of a **broad spectrum** of physics studies, including many not discussed here
  - vector boson scattering, FCNC neutral currents, rare decays, multi-boson production, etc.
- Key challenges for physics measurements would be the large amount of **pile up** (perhaps up to 1000 interactions per collisions)
  - Will require detailed studies of detectors and mitigation techniques

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