Physics at Hadron Colliders

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Outline

The ultimate goal is 10 TeV parton center of mass (pCM)

From P5: Theoretical and experimental studies indicate that a **comprehensive study of the electroweak scale requires colliders with energy of at least 10 TeV pCM**, larger than previously assumed.

What is it that 10 TeV pCM gives that an e^+e^- collider doesn't?

- Higgs Self Coupling
- Higgs Mass Stabilization/Naturalness : top partners, other SUSY, compositeness,...
- Dark Matter
- Massive array of less model driven searches: Z', LLP, axion-like, more Higgses, precision Higgs

What would we lose going to lower energy?

- E.g. if someone else builds e^+e^- somewhere else what would we lose by building the hadron collider we know how do to now

What would we lose if we skip e+e- and go straight to lower energy hadron collider?

- ***Can a hadron machine be the "Higgs Factory"™?***
- Important to separate physics from feasibility discussions
  - How does e^+e^- precision compare with hh direct reach and hh precision?

Higgs Self-Coupling Motivation

From P5: A precise measurement of the coupling of the Higgs boson to itself will tell us about the **shape of the Higgs potential**, which feeds into the behavior of the electroweak phase transition and has consequences related to the **matter-antimatter asymmetry and the ultimate fate of the universe**.

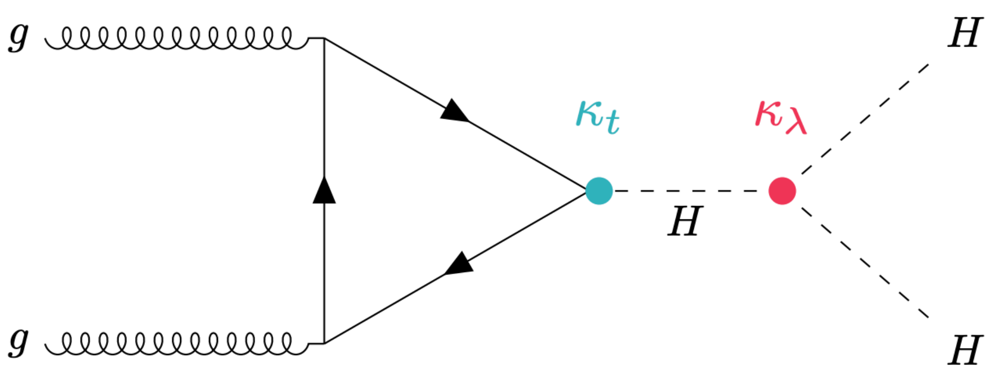
At the HL-LHC a measurement of the Higgs self-coupling with a precision of 50% should be possible. However, **a precision of 5%—an order of magnitude improvement—will dramatically enhance our knowledge of the potential and be sufficient to discover or rule out many models which could explain the matter-antimatter asymmetry.**

This can only be achieved with a collider with 10 TeV or greater pCM, due to the greatly enhanced rate of production of events with multiple Higgs bosons that are needed for measuring the Higgs self-coupling.

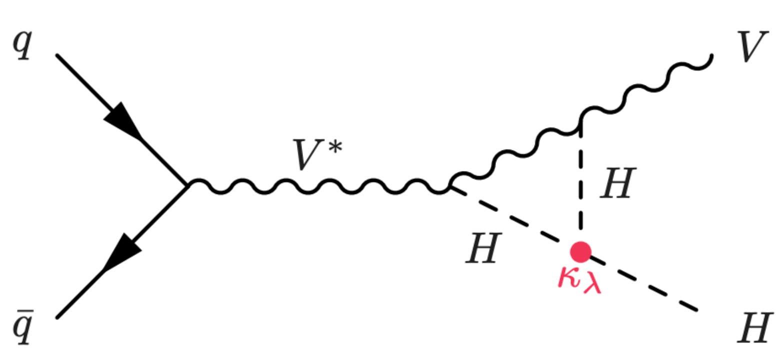
P5 puts a lot of emphasis on the self-coupling

Higgs Self-Coupling Predictions

Di-Higgs constraints



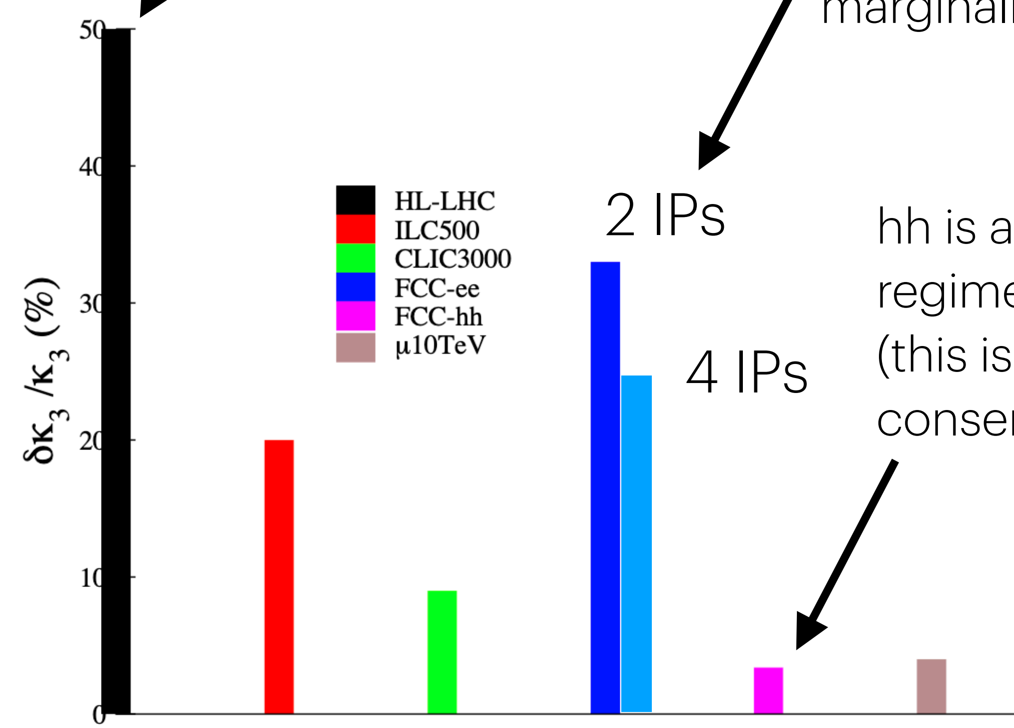
Single-Higgs constraints



ee only does the single-higgs constraints (these aren't even in the hadron collider estimates)

Estimate at Snowmass, ATLAS now expects 50% by itself! (also doesn't include lots of stuff)

ee is only marginally better



hh is a new regime (this is probably conservative)

10 TeV pCM gives qualitatively different constraints which are key science deliverable

Top Partners (stop squark ++)

Easiest way cancel top-loop contribution to Higgs mass is top partner

Current LHC limits for other top partners for comparison

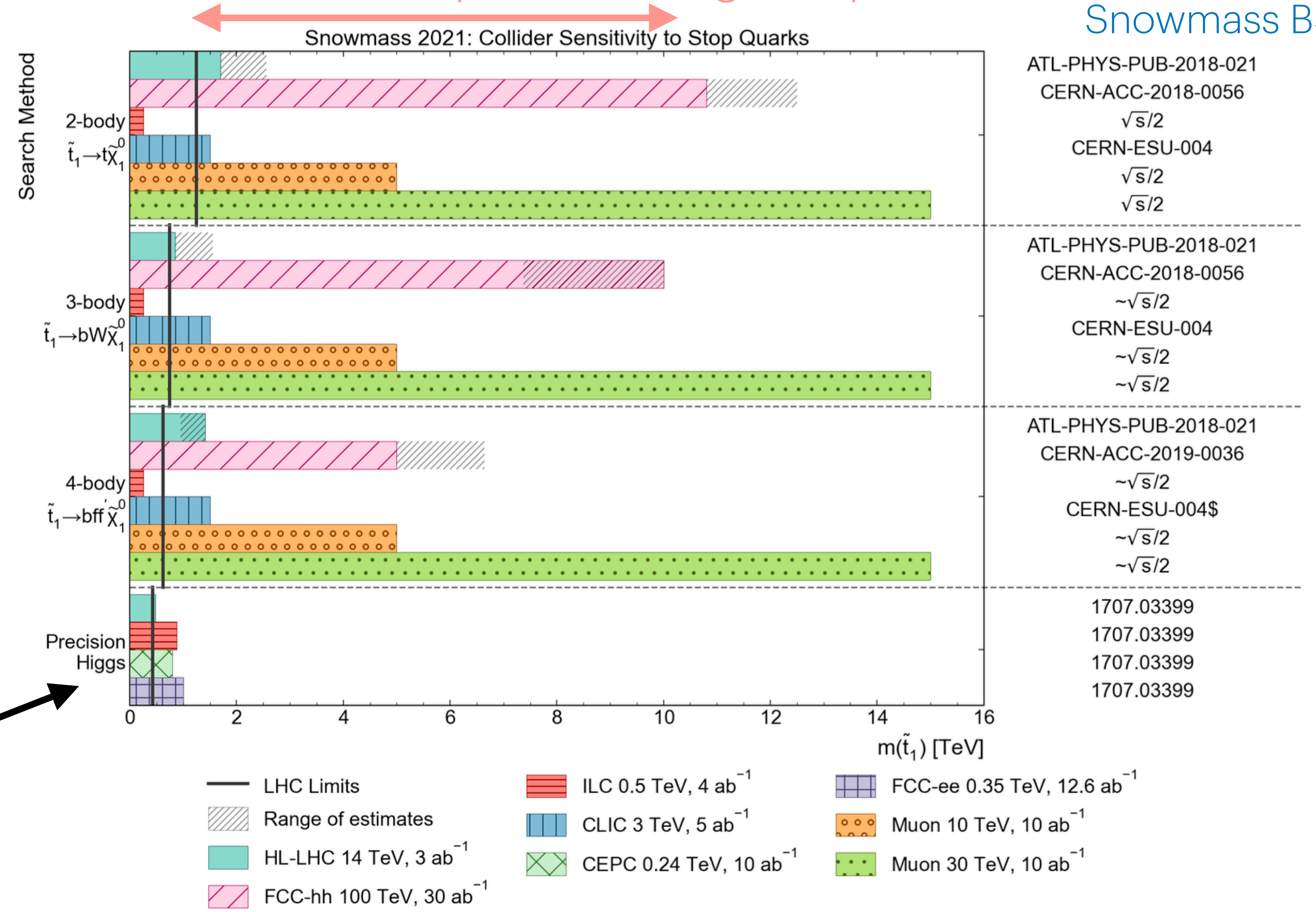
- Leptonic RPV
- Baryonic RPV
- Vector-like top

High Higgs mass is points to large stop mass

Snowmass BSM report

Easier to find

Harder to find



Indirect constraints from precision Higgs are not competitive for stop squarks

hh gives much greater reach on top partners (and many other things)... naturalness scales as E² so 5x energy is 25x naturalness constraint!

WIMPs are Alive and Well

≈ Simplest Model you can make…

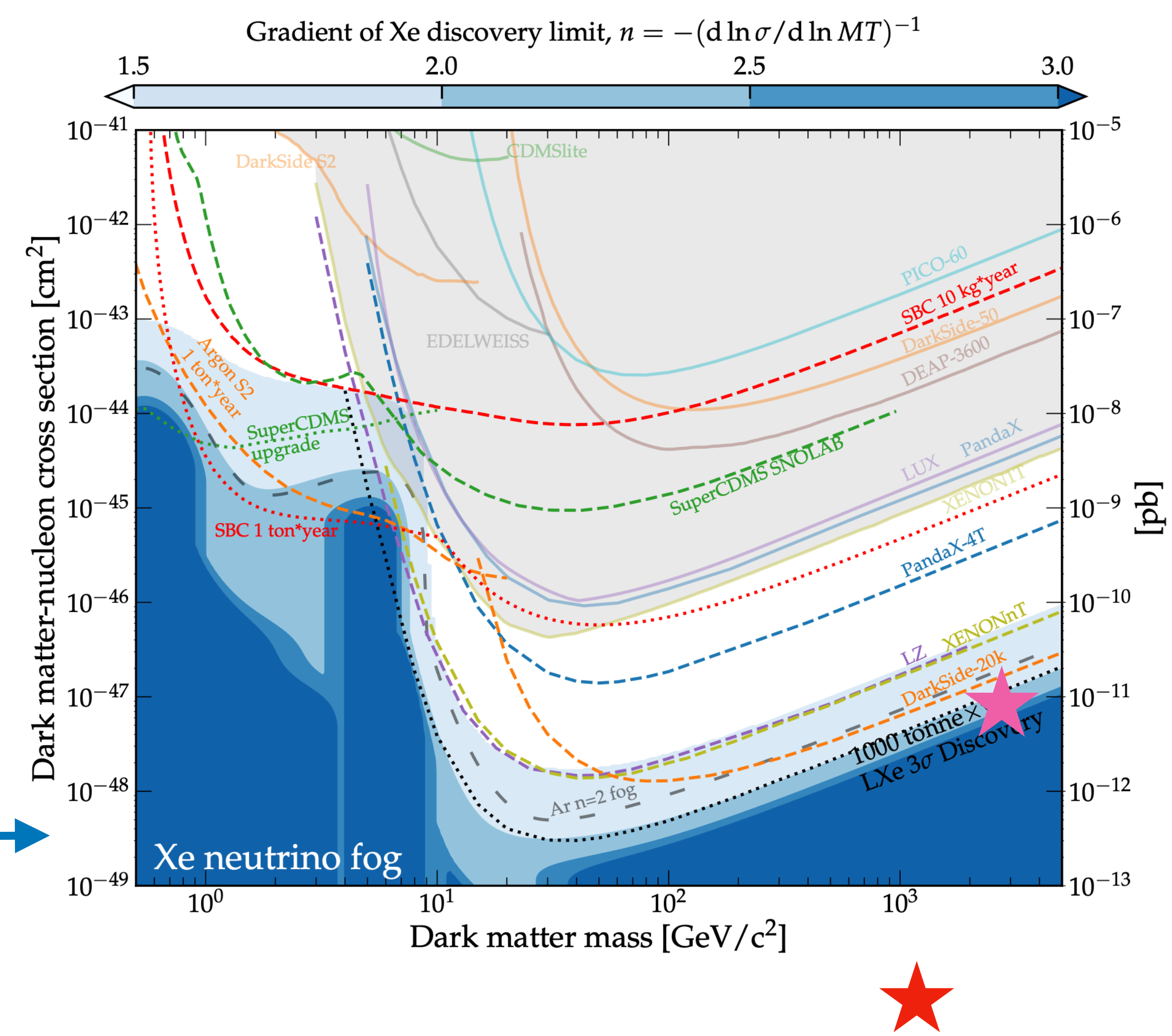
(=Minimal Dark Matter Nucl.Phys.B 753 (2006) 178)

- Add a new electroweak multiplet and couple to SM with by weak interactions
  - This is not quite the simplest models because it needs mass generation other than the Higgs
- For each representation the mass is then fixed by requiring saturation of the DM relic abundance

$SU(2)_L$ Multiplet	Mass	SUSY analog	Cross-sections
Doublet	1.1 TeV	Higgsino	★
Triplet	2.8 TeV	Wino	★

DM Cross-sections from Phys.Rev.D 108 (2023) 11, 116023

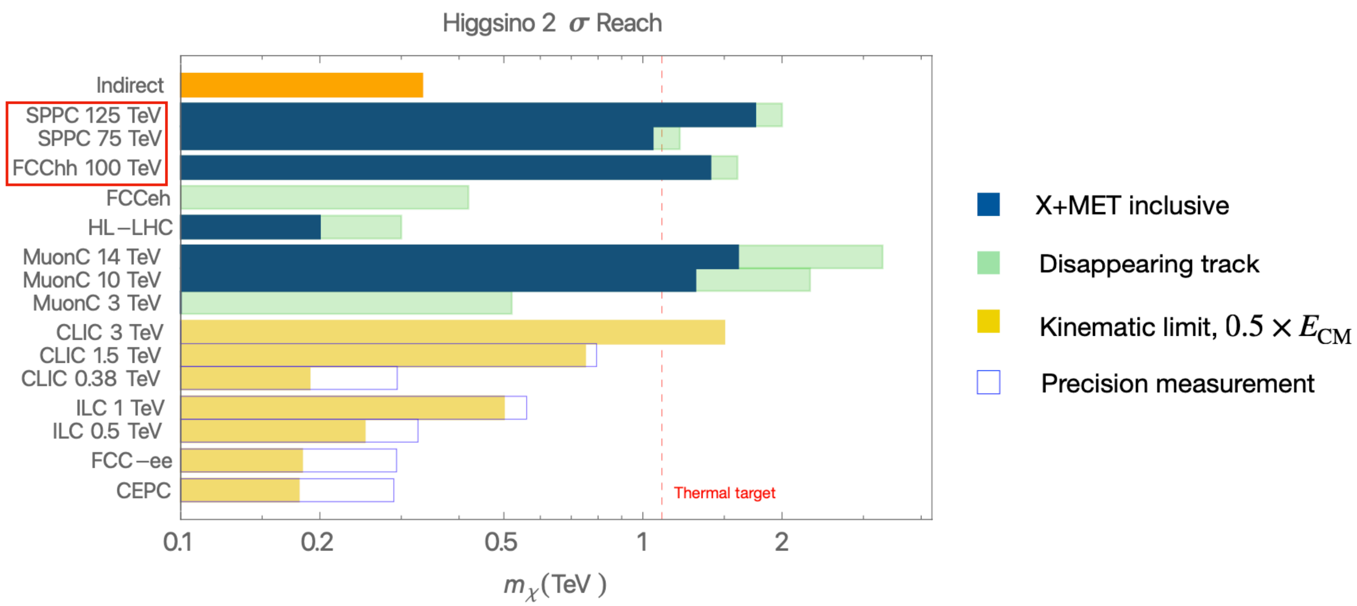
Snowmass Cosmic Frontier: https://arxiv.org/pdf/2203.08084

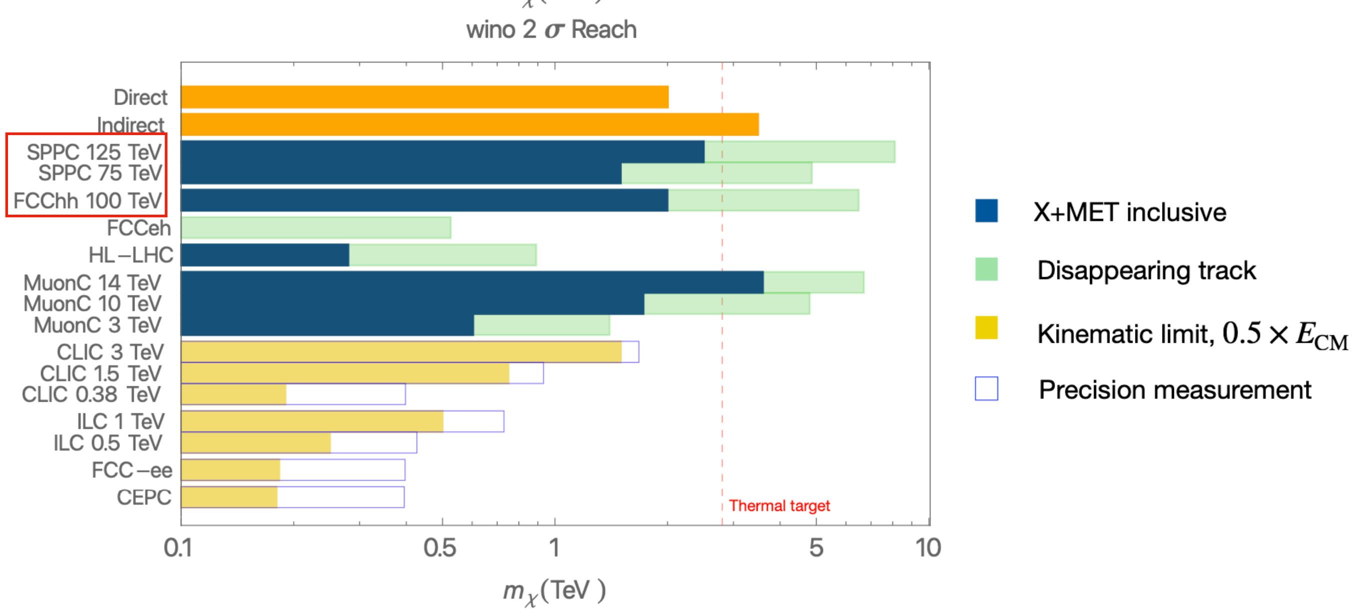


Some of the simplest models are not reachable by direct detection, colliders can give good inputs on this

SUSY Dark Matter and Naturalness

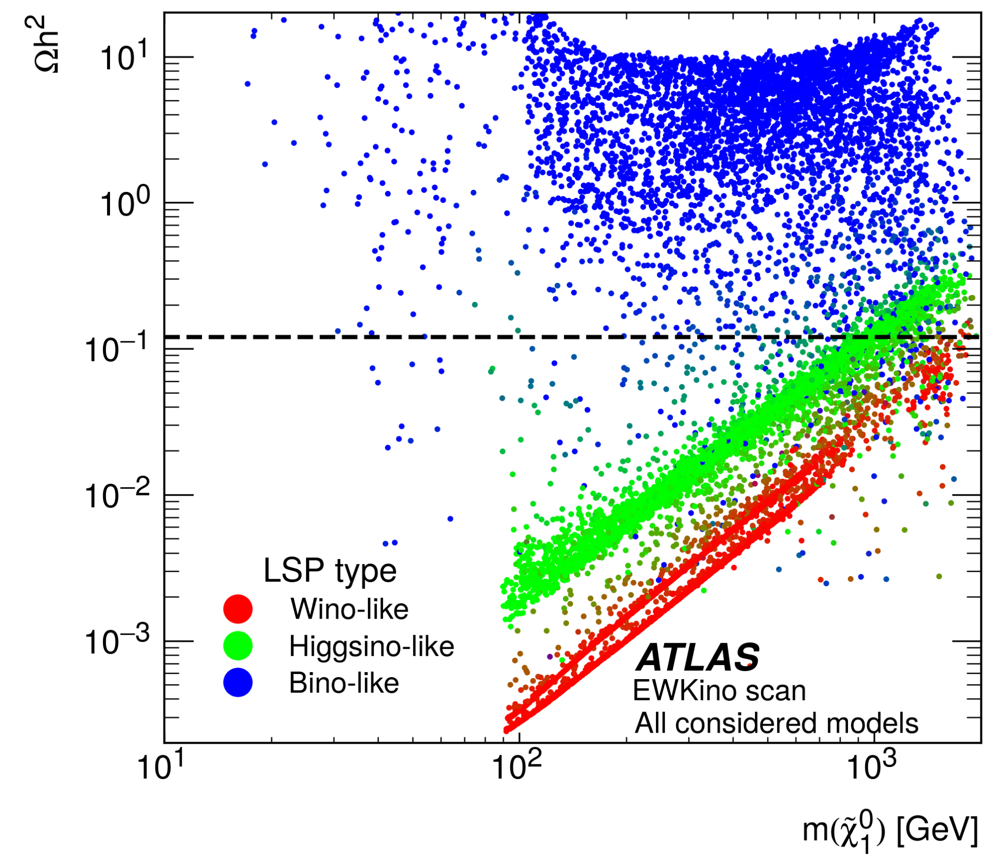
Snowmass BSM report





Understanding Thermal Target/ Connection to SUSY

https://cds.cern.ch/record/2888303/



Also, "Natural" SUSY wants light Higgsinos

- Otherwise you start needing a fine-tuning to get a light Higgs even with SUSY

Some of the simplest models (… and RPC SUSY) want DM mass in a range only reachable by 10 TeV pCM

Precision Higgs Couplings

Hadron machines make a lot of Higgs!

		$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
fcc-hh	N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
HL-LHC	N_{100}/N_{14}	180	170	100	110	530	390

FCC-hh CDR: https://cds.cern.ch/record/2651300

FCC coupling sensitivity estimates

Observable	Parameter	Precision (stat)	Precision (stat+syst+lumi)
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)$	$\delta\mu/\mu$	0.1%	1.45%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta\mu/\mu$	0.28%	1.22%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta\mu/\mu$	0.18%	1.85%
$\mu = \sigma(\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to \gamma\mu\mu)$	$\delta\mu/\mu$	0.55%	1.61%
$\mu = \sigma(\mathrm{HH}) \times \mathrm{B}(\mathrm{H} \to \gamma\gamma)\mathrm{B}(\mathrm{H} \to b\bar{b})$	$\delta\lambda/\lambda$	5%	7.0%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu)/\mathrm{B}(\mathrm{H} \to 4\mu)$	$\delta R/R$	0.33%	1.3%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2e2\mu)$	$\delta R/R$	0.17%	0.8%
$R = \mathrm{B}(\mathrm{H} \to \gamma\gamma)/\mathrm{B}(\mathrm{H} \to 2\mu)$	$\delta R/R$	0.29%	1.38%
$R = \mathrm{B}(\mathrm{H} \to \mu\mu\gamma)/\mathrm{B}(\mathrm{H} \to \mu\mu)$	$\delta R/R$	0.58%	1.82%
$R = \sigma(t\bar{t}\mathrm{H}) \times \mathrm{B}(\mathrm{H} \to b\bar{b})/\sigma(t\bar{t}\mathrm{Z}) \times \mathrm{B}(\mathrm{Z} \to b\bar{b})$	$\delta R/R$	1.05%	1.9%
$B(\mathrm{H} \to \text{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

Loop couplings can be a catch all for lower energy particles that were somehow missed

ttH is kinematically out of reach for e^+e^-

Maybe people will get smarter here

These are way beyond anything possible in a e^+e^- collider for these rare modes… we don't have that many studies for the modes ee can do

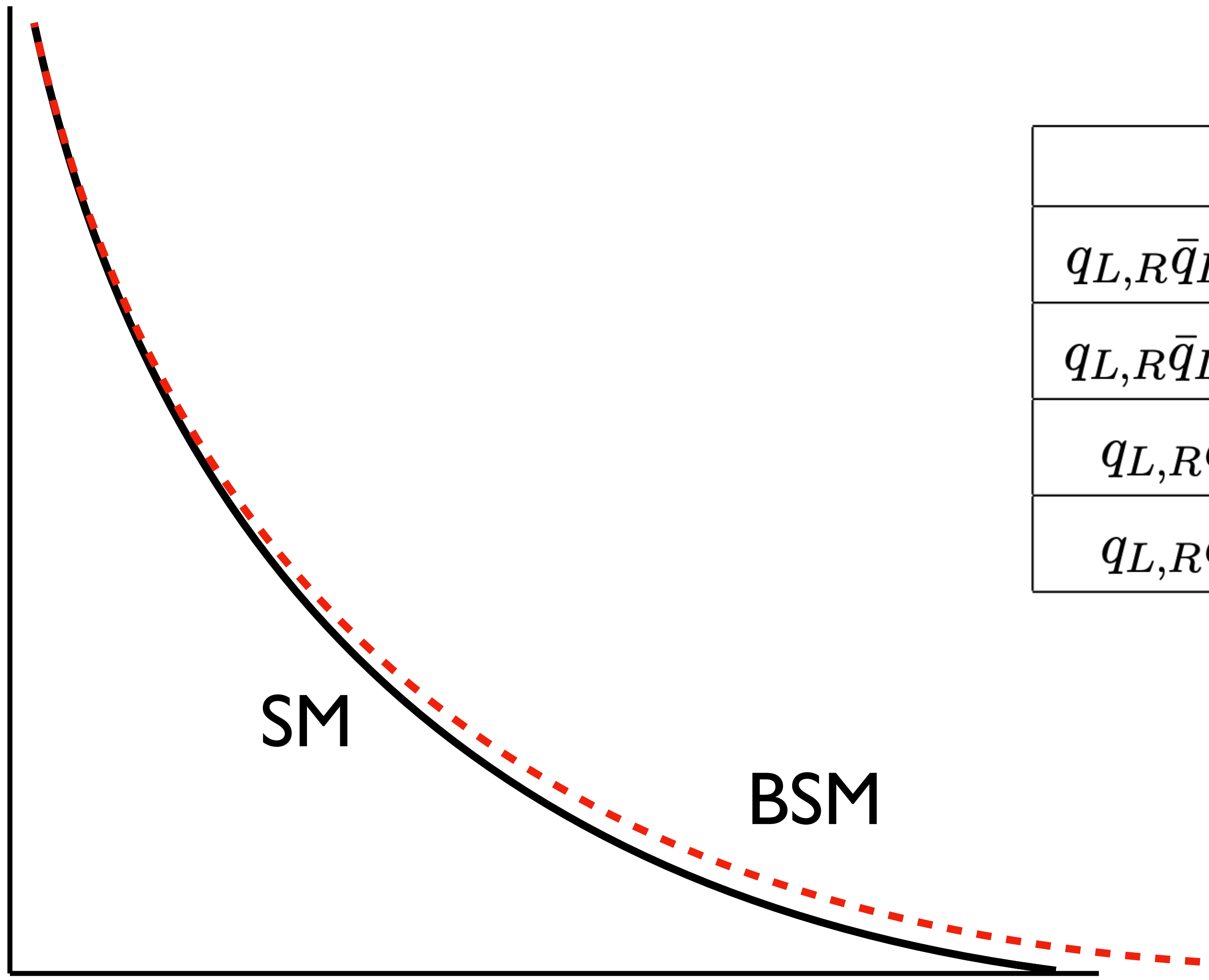
e.g. H→bb at ~5×10^{-3} level might be possible at FCC-hh

Energy = Precision

Effective Field Theory operator effects generally grow with energy

This leads to an energy = precision logic

Roughly 10% at 1 TeV ~ 0.1% at 100 GeV



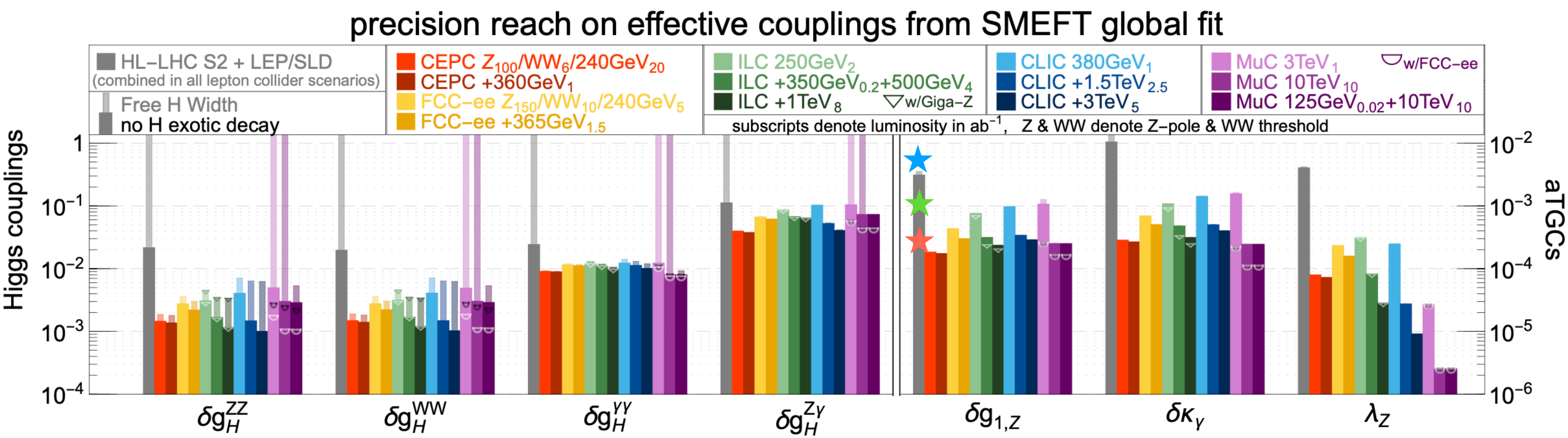
	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

https://arxiv.org/abs/1712.01310

Hadron colliders can get high precision by having high energy compared to e^+e^-

Precision EWK

Comment from Snowmass Precision Report: "At this point, not enough information was available to include pp colliders beyond the LHC (such as HE-LHC or a O(100)-TeV collider) in the global fit. It is likely that these machines have superior sensitivity to many energy-dependent operators, such as 4-fermion operators involving quarks and several operators that mediate multi-boson interactions."



Snowmass Precision Measurements Report https://arxiv.org/abs/2209.08078

But for $\delta g_{1,Z}$ there are **much** better limits than what is shown for HL-LHC…

★ HL-HLC limits are already ~met with early CMS 35 fb^{-1} result for using WW/WZ (https://arxiv.org/pdf/1907.08354.pdf)

- That's ~1/100th the final data
- This probably due to projects based on leptonic instead of semileptonic measurement

★ CMS EFT fit gives using H→γγ and Wγ (https://arxiv.org/pdf/1907.08354.pdf)

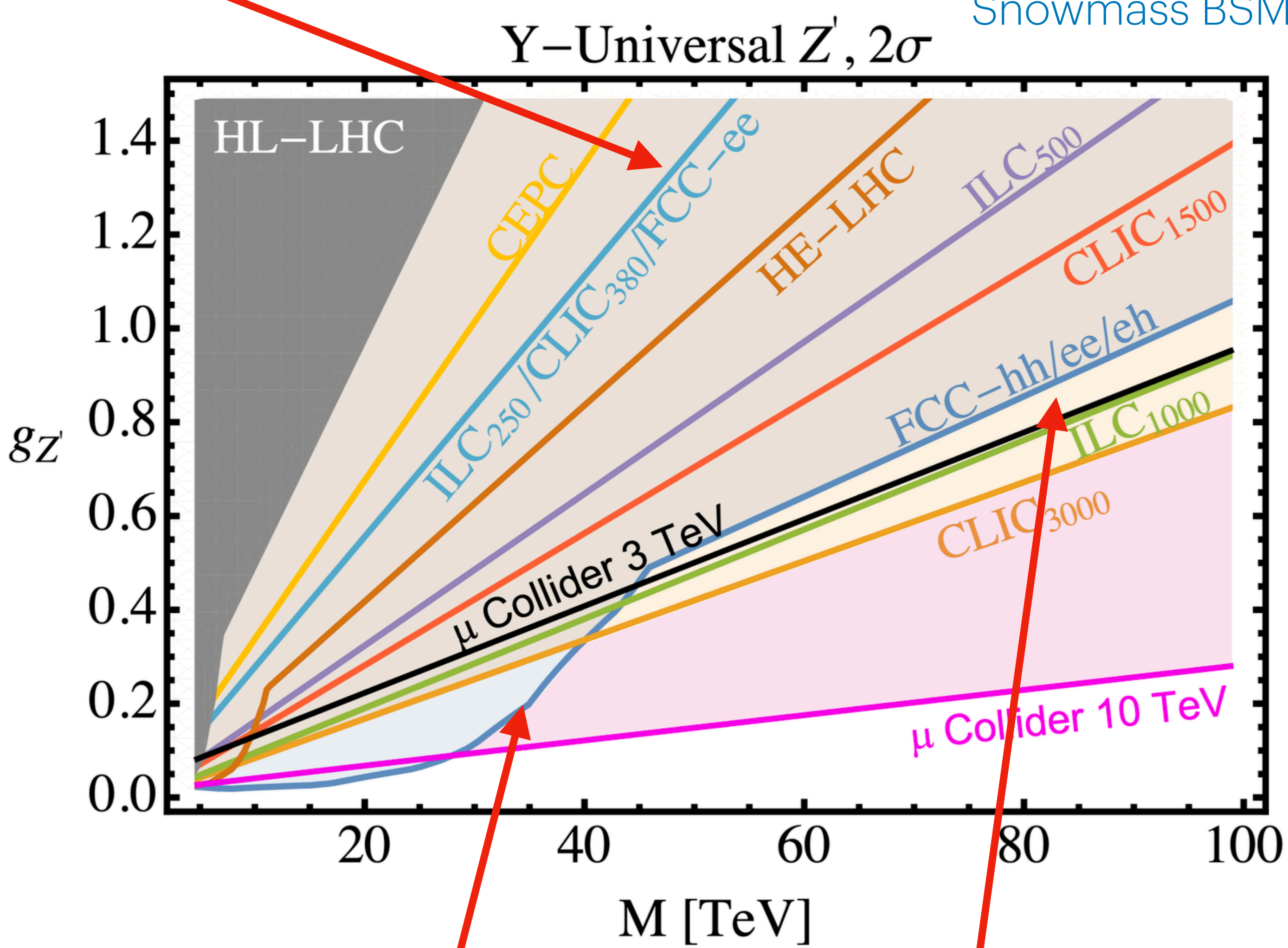
★ Theorist estimate for FCC-hh using ZH (https://arxiv.org/pdf/2208.11134)

We really don't know how "precise" hh can be but it's likely very good!

Z' as a benchmark

ee Higgs factory line
gets weak a low
coupling

Snowmass BSM report



hh direct searches are stronger at
low coupling AND indirect searches
with EFT at stranger at high coupling

hh here is using only
leptonic WZ!

Summary so far…

What is it that 10 TeV pCM gives that an e^+e^- collider doesn't?

- Much more self-coupling
- Much larger new physics reach
- Key Dark Matter targets
- Precision on specific interesting rare Higgs decays and $t\bar{t}H$ couplings
- Massive array of less model driven searches: Z', LLP, axion-like, more Higgses, precision Higgs

I didn't address rare Higgs and rare Z, some thoughts…

- Rare Higgs, the ~1000x larger Higgs production rate means most if not all signatures are better at hadron machine
- Rare Z… depends on signature
  - 30 ab^{-1} gives… 3.9×10^{13} W bosons and 1.2×10^{13} Z bosons
  - For distinctive signatures (e.g. LLPs) hh may exceed Tera Z, but not for that many

P5 said this for a reason : Comprehensive study of the electroweak scale requires colliders with energy of at least 10 TeV pCM!

What would we lose going to lower energy?

What can we (maybe) build now…

From Frank Zimmerman has provided a set of plausible targets (link to note)

Wait for his talk to here more

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
Centre-of-mass energy	TeV	72	72	72	84	102	120	14
Peak arc dipole field	T	12	12	12	14	17	20	8.33
Beam current	A	0.5	1.12	1.12	0.5	0.5	0.2	(1.12) 0.58
SR power / beam	kW	650	1450	1450	1200	2670	2020	(7.3) 3.6
Initial events / crossing		580	2820	955	590	732	141	(135) 27
Luminosity / yr	fb^{-1}	950	$\geq$2000	1300	920	920	370	(240) 55

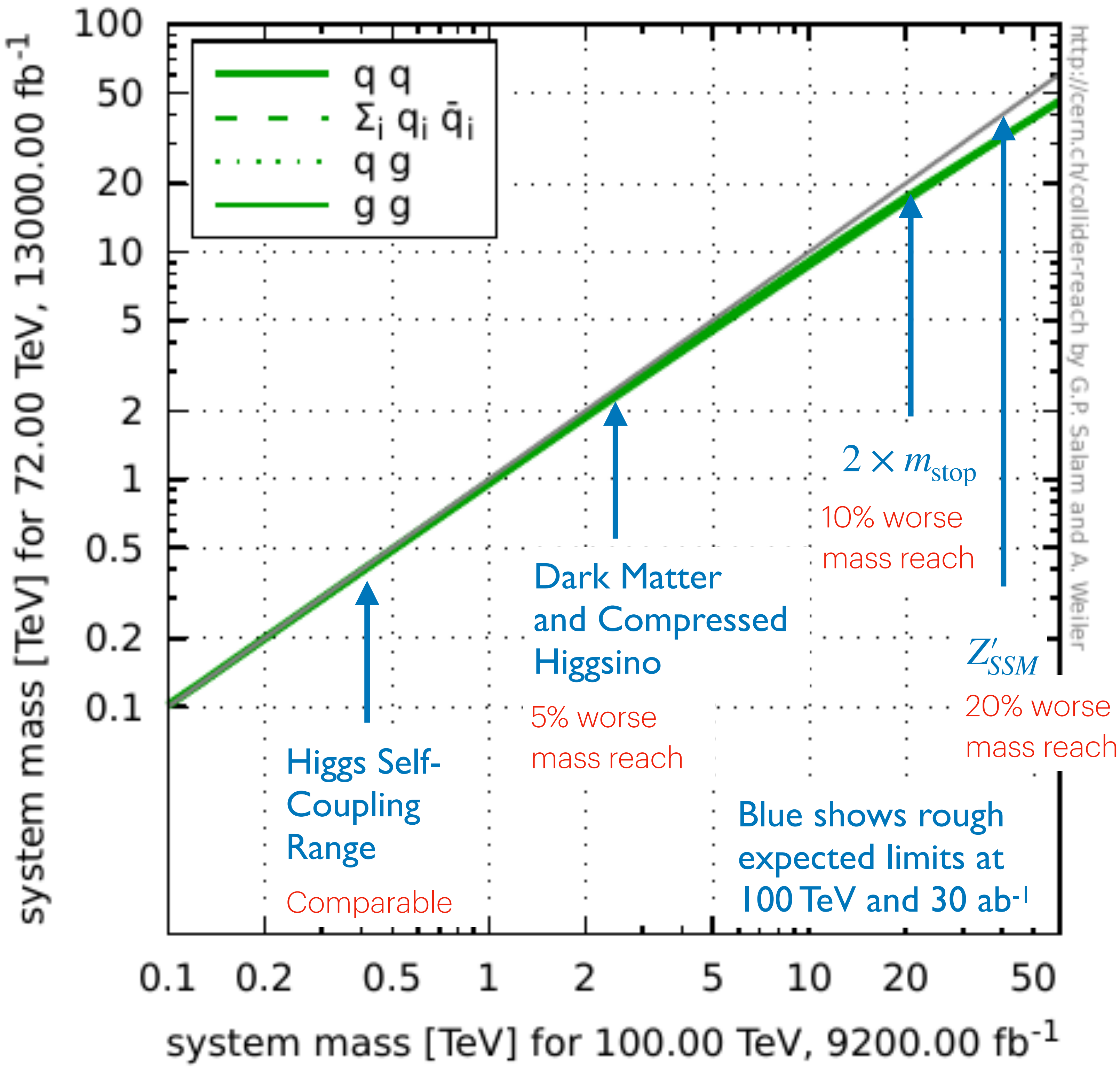
Luminosity limited by synchrotron radiation
so luminosities are not the same

LHC magnet technology in new tunnel could give 50 TeV

Compared 102 TeV with 920 fb^{-1}/year to 72 TeV with
1300 fb^{-1}/year luminosity leveled

Energy vs Luminosity

Compared 102 TeV with 920 fb^{-1}/year to 72 TeV with 1300 fb^{-1}/year luminosity leveled (F12PU)



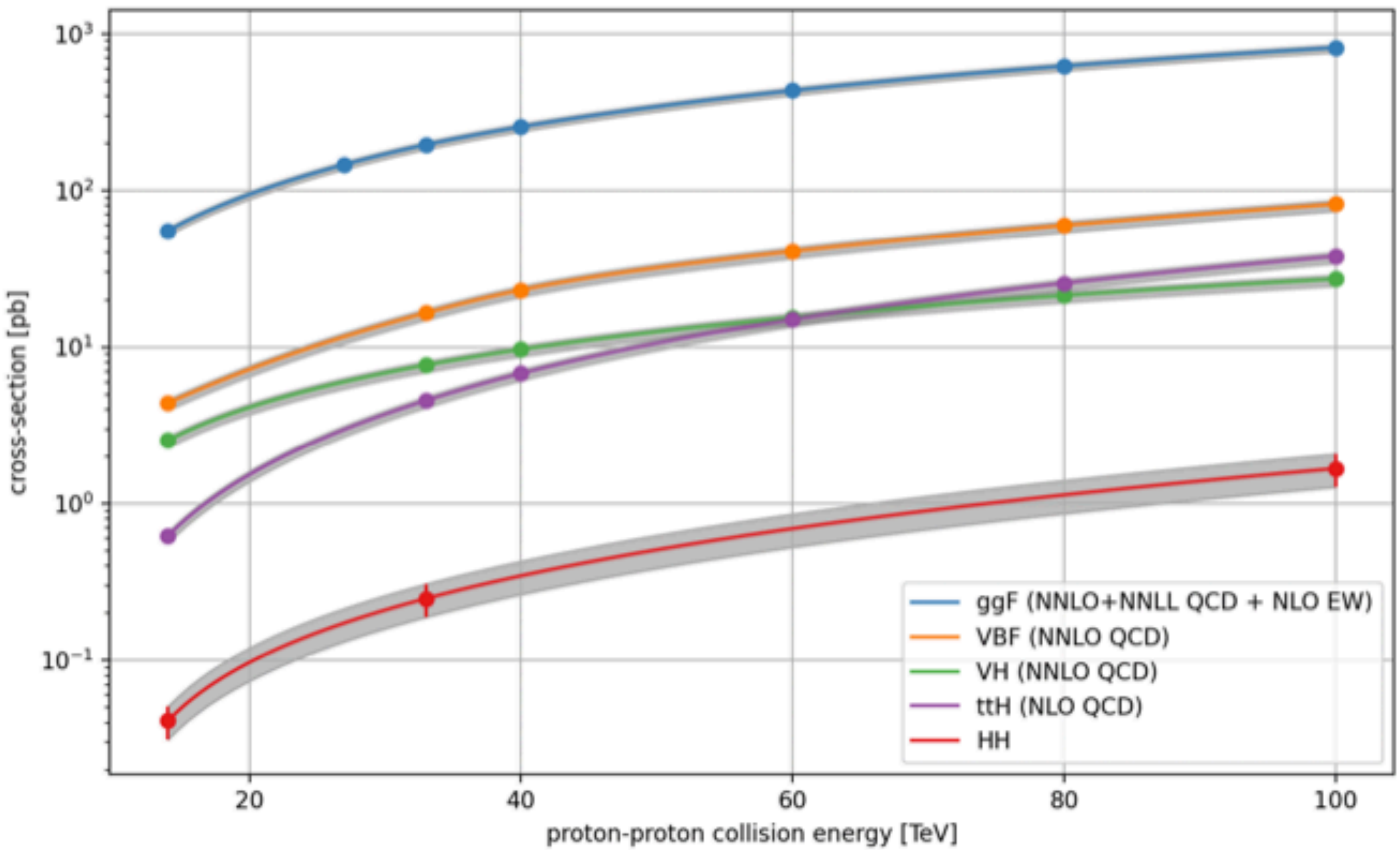
Using "Collider-Reach" tool from Salam and Weiler: http://collider-reach.web.cern.ch/

Finds mass where same number of signal events would be expected

If I guess at making the Synchrotron radiation levels the same 72 TeV is better than 102 TeV below 3 TeV CM!

Losses are not that large going to lower energy!

All that Higgs physics vs Energy



Notice the big gain is from 14 TeV to ~50 TeV, much slower above that

My last question…

What would we lose if we skip e+e- and go straight to lower energy hadron collider?

- ***Can a hadron machine be the "Higgs Factory"™?***

- Important to separate physics from feasibility discussions
  - Physics questions not adequately studied in my view
  - How does e^+e^- precision compare with hh direct reach and hh precision?

Hadron machines can give precision

We can compare measurements of specific quantities: e.g. Higgs branching fractions, W-mass, ...

- The list of studies is not very comprehensive

Or we can compare sensitivity to EFT parameters

- But again we need to think carefully about whether our inputs are truly representative

FCC-hh	
$\delta\mu_{ggF,4\mu}$	0.019
$\delta\mu_{ggF,\gamma\gamma}$	0.015
$\delta\mu_{ggF,Z\gamma}$	0.016
$\delta\mu_{ggF,\mu\mu}$	0.012
$\delta(\mathrm{BR}_{\mu\mu}/\mathrm{BR}_{4\mu})$	0.013
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{2e2\mu})$	0.008
$\delta(\mathrm{BR}_{\gamma\gamma}/\mathrm{BR}_{\mu\mu})$	0.014
$\delta(\mathrm{BR}_{\mu\mu\gamma}/\mathrm{BR}_{\gamma\gamma})$	0.018
$\delta(\sigma^{bb}_{ttH}/\sigma^{bb}_{ttZ})$	0.019
Invisible decays	
$\mathrm{BR}_{\mathrm{inv}}$	<0.00013
Direct constraint on Higgs self-interaction	
$\delta\kappa_3$	0.05

FCC-hh (Extra inputs used in κ fits)	
$\delta(\sigma^{H\to\gamma\gamma}_{WH}/\sigma^{Z\to e^+e^-}_{WZ})$	0.014
$\delta(\sigma^{H\to\tau\tau}_{WH}/\sigma^{Z\to\tau\tau}_{WZ})$	0.016
$\delta(\sigma^{H\to bb}_{WH}/\sigma^{Z\to bb}_{WZ})$	0.011
$\delta(\sigma^{H\to WW}_{WH}/\sigma^{H\to\gamma\gamma}_{WH})$	0.015

kappa framework ~ just dial the Higgs couplings

kappa-0-HL	HL+FCC-ee	HL+FCC-hh
$\kappa_W[\%]$	0.38	0.39
$\kappa_Z[\%]$	0.14	0.63
$\kappa_g[\%]$	0.88	0.74
$\kappa_\gamma[\%]$	1.2	0.56
$\kappa_{Z\gamma}[\%]$	10.	0.89
$\kappa_c[\%]$	1.3	–
$\kappa_t[\%]$	3.1	0.99
$\kappa_b[\%]$	0.59	0.99
$\kappa_\mu[\%]$	3.9	0.68
$\kappa_\tau[\%]$	0.61	0.9
$\Gamma_H[\%]$	0.87	1.3

https://arxiv.org/pdf/1905.03764

Using only a fraction of what hh can do and its competitive with ee

SMEFT = better framework

Penn
UNIVERSITY *of* PENNSYLVANIA

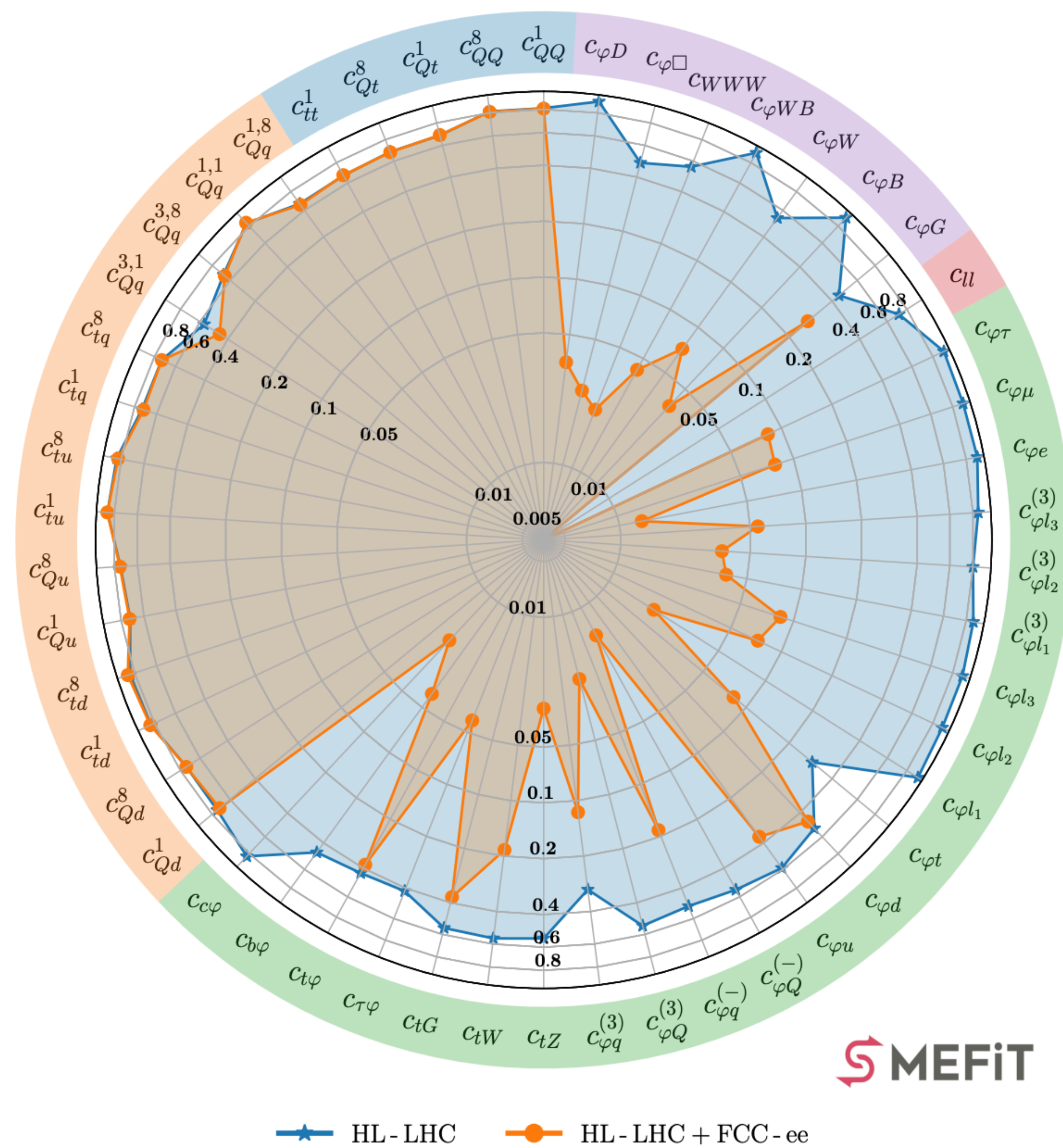
Coherent framework (with some theory assumptions)

This shows what ee does but what does hh do???

- This will tell us if hh can do the precision physics

Also…

- HL-LHC is very much a work in progress
  - many more methods to come not just repeat with more data
- Individual constraints from HL-LHC are much close to ee, implying there are just a few unconstrained combinations



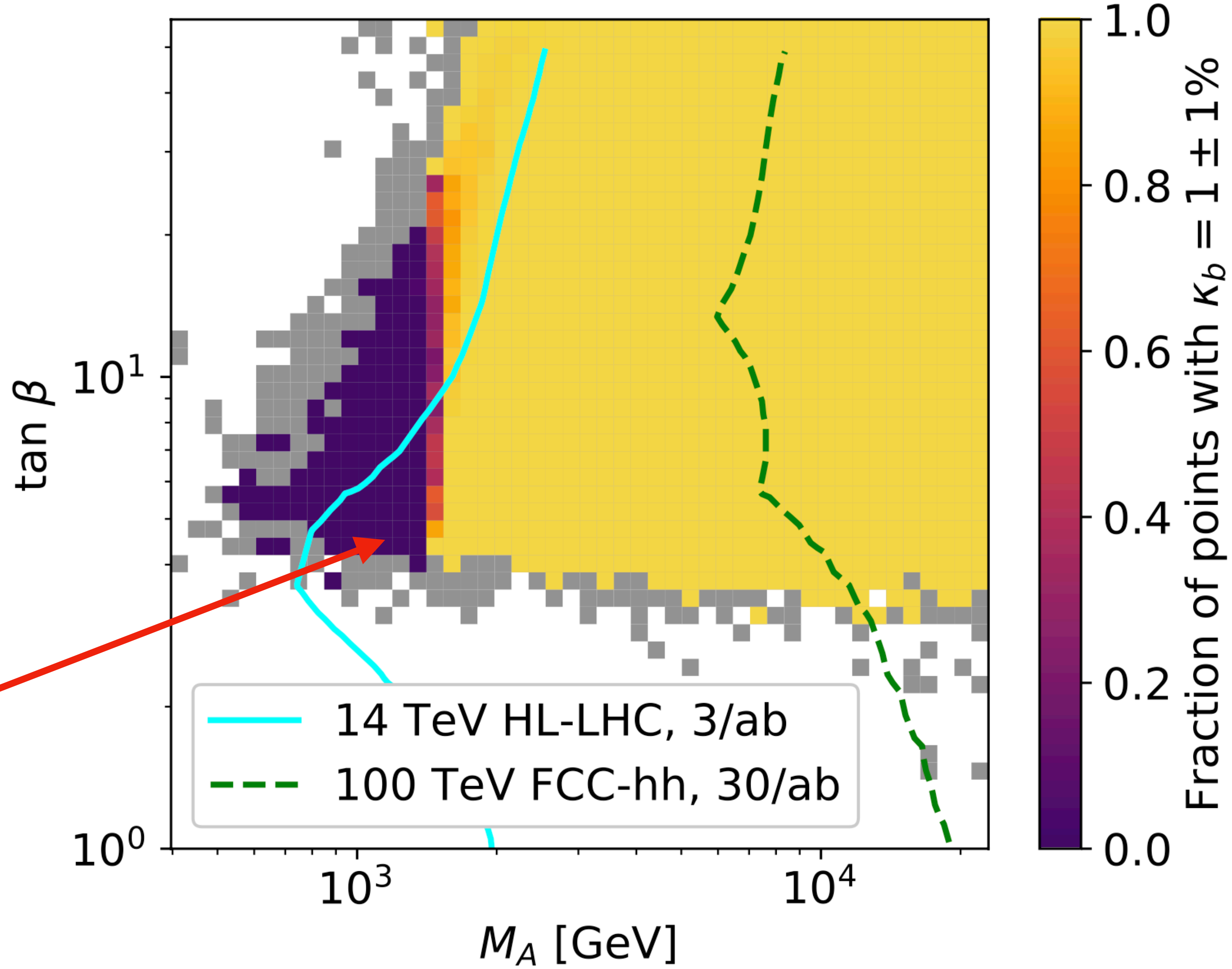
Precision versus direct reach

In many cases, the physics constrained by precision is directly accessible at an hadron machine

Snowmass BSM report

E.g. 2HDM in SUSY

Scan of currently possible pMSSM



Region that would not already be found by LHC

This is ~2 sigma at e+e- collider precision

Toward the European Strategy

- Think about what precision hh can do on on two fronts
  - Direct measurements of Higgs and other couplings (e.g. top mass)
  - EFT measurements that can be input into fit
- What do we lose with a lower energy (50 TeV, 70 TeV, ...)?
  - What can do to make this financially feasible?
- What about rare processes?
  - At least a few examples would be good...
- Learn from and incorporate ATLAS and CMS updates

Conclusion

FCC-hh is the ultimate goal

- P5 calls 10 TeV pCM the goal for good reason → driver of the combined FCC program
- hh gives dramatically better reach for self-coupling, new states (naturalness related and others), dark matter, and much more
- hh is likely competitive or better on the EFT/precision couplings
- ee may really only be better for very rare Z decays which do not have distinctive (e.g. LLP) signatures.

Linear colliders vs circular

- linear doesn't have a path to 10 TeV pCM
- linear doesn't have Tera Z which maybe only place where ee would not be exceeded

Lower energy doesn’t lose that that much

- Lowering energy can raise luminosity because of synchrotron radiation constraints
- Higher luminosity can compensate for lower energy, particularly for "~3 TeV" and below CM targets

hh has the potential to do the Higgs Factory program and should be evaluated for that role

- Means a much higher discovery potential in the careers of current graduate students
- Maybe the integrated cost is lower ???

Back-up

What do we want to know about the Higgs?

From P5 Section 3.2.1 Science Overview

Major Questions:

- Composite?
- How many Higgses?
- Naturalness?
- BSM decays?
- Origin of Higgs couplings? (Matter-Antimatter Asymmetry, Origin of Neutrino mass)
- Self-coupling and "electroweak" phase transition

Precision Higgs Coupling vs hh reach

Snowmass Higgs Report:
https://arxiv.org/abs/2209.07510

Size of Higgs Coupling deviations?

$\delta\eta_{SM}$ $\sim 1\%$ $\sim .1\%$

Tree level origin $\sim \frac{v^2}{M^2}$

Loop level $\sim \frac{1}{(4\pi)^2}\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2s}}{2M^2}\right)\frac{v^2}{M^2}$

SM Charged e.g. 2HDM $\sim \left(\frac{\lambda^2_6 v^2}{M^2}\right)\frac{v^2}{M^2}$

SM Neutral e.g. scalar singlet $\sim \left(\frac{\lambda^2_{h^2s^2}}{48\pi^2}\right)\frac{v^2}{M^2}$

SM Charged w/ SM loop e.g. stops in SUSY $\sim \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}}^2}$

$M \lesssim 1.7\,\mathrm{TeV}$	$M \lesssim 0.8\,\mathrm{TeV}$	$M \lesssim 0.1\,\mathrm{TeV}$	$M \lesssim 0.9\,\mathrm{TeV}$
$M \lesssim 5.5\,\mathrm{TeV}$	$M \lesssim 1.4\,\mathrm{TeV}$	$M \lesssim 0.4\,\mathrm{TeV}$	$M \lesssim 2.8\,\mathrm{TeV}$

This is ~2-5 sigma at e+e- collider precision

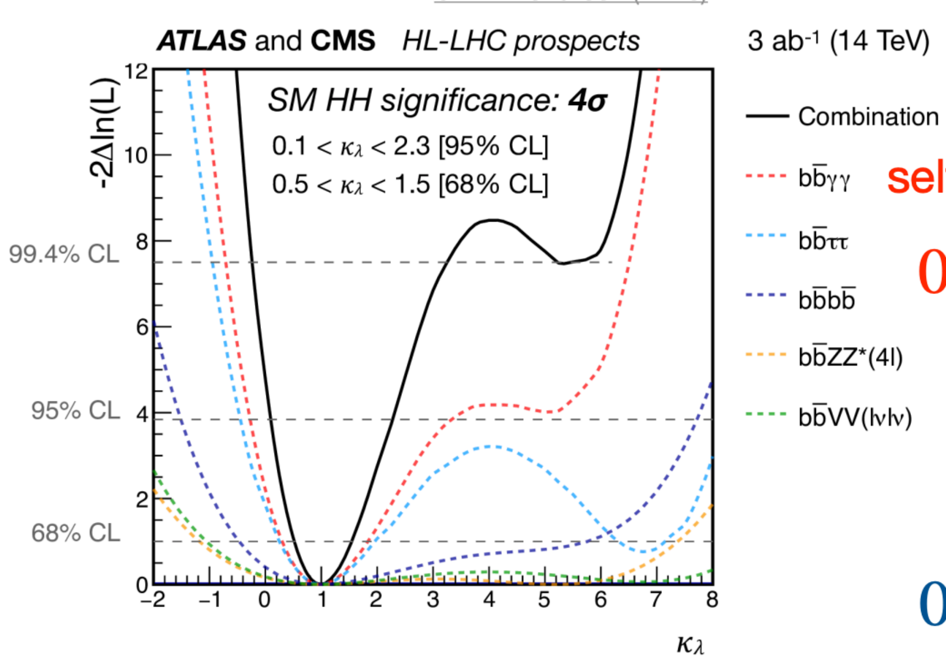
Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

ATLAS HH improvements

- **ATLAS+CMS Yellow Report 2018**

$pp \to HH$ significance = 4.0 σ (4.5 σ stat only)

CERN-2019-007 (YR18)



self-coupling modifier

$0.52 < \kappa_\lambda < 1.5$

(68% Cl)

ATLAS-PHYS-PUB-2018-053

ATLAS only

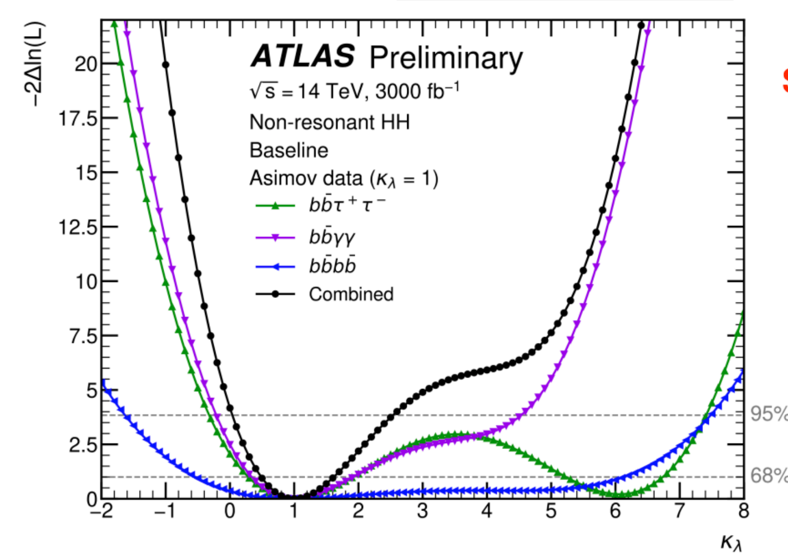
$0.25 < \kappa_\lambda < 1.9$

- **ATLAS update after Snowmass 2021**

Extrapolated from **full** Run 2 $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}b\bar{b}$

$pp \to HH$ significance = 3.4 σ (4.9 σ stat only)

ATLAS-PHYS-PUB-2022-053



self-coupling mod.

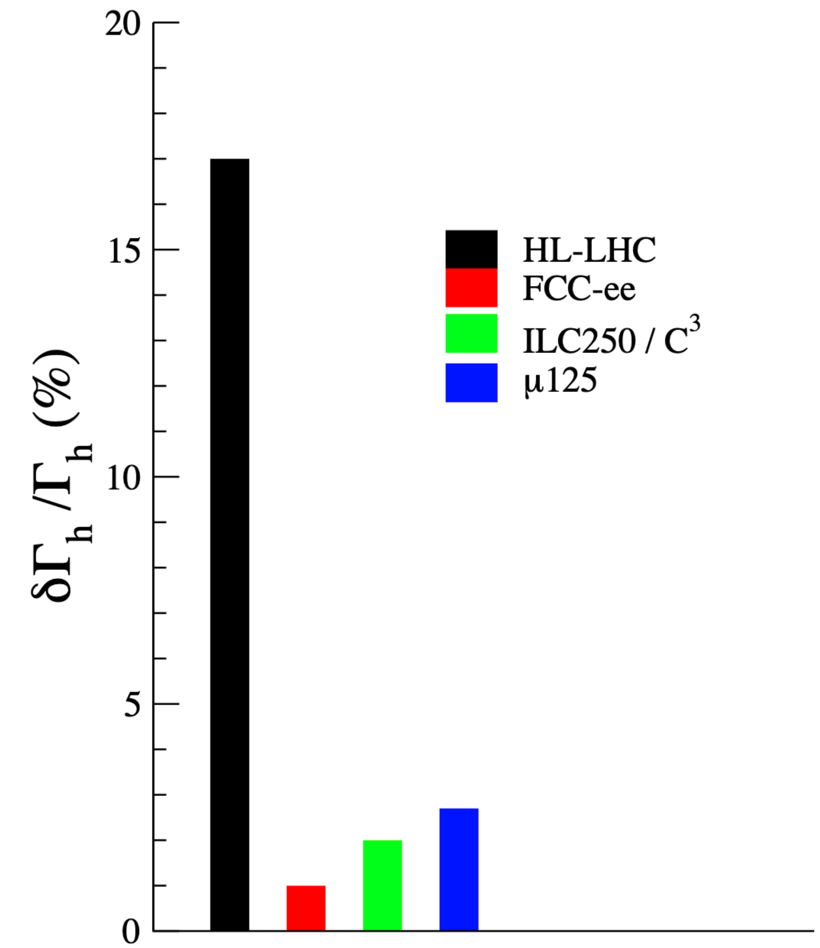
$0.5 < \kappa_\lambda < 1.6$

(68% Cl)

18

Higgs Width = Absolute Normalization

Does HL-LHC really reflect the best we can do?

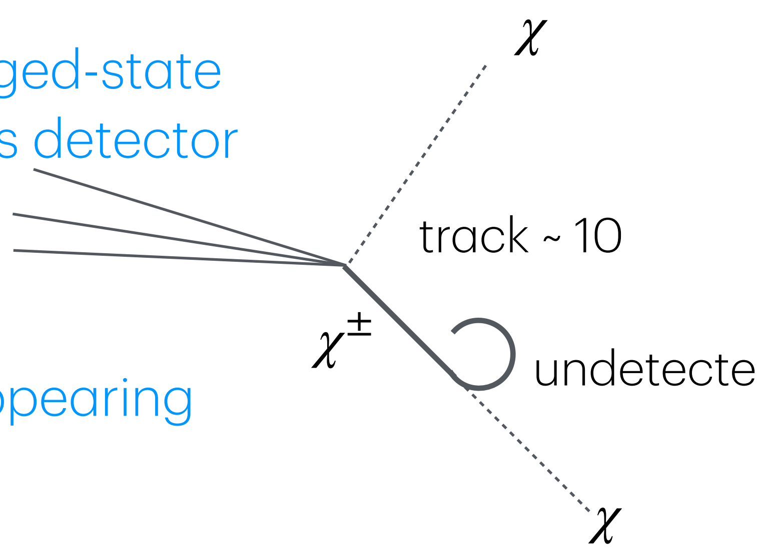


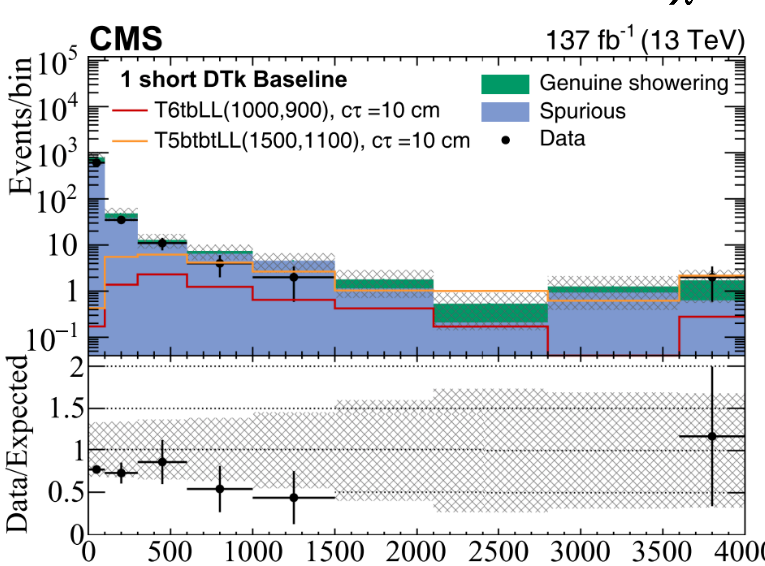
Minimal: Just at an SU(2) Multiplet at LHC

Multiplet of states means nearby (small ΔM) to another state

Charged-state enters detector

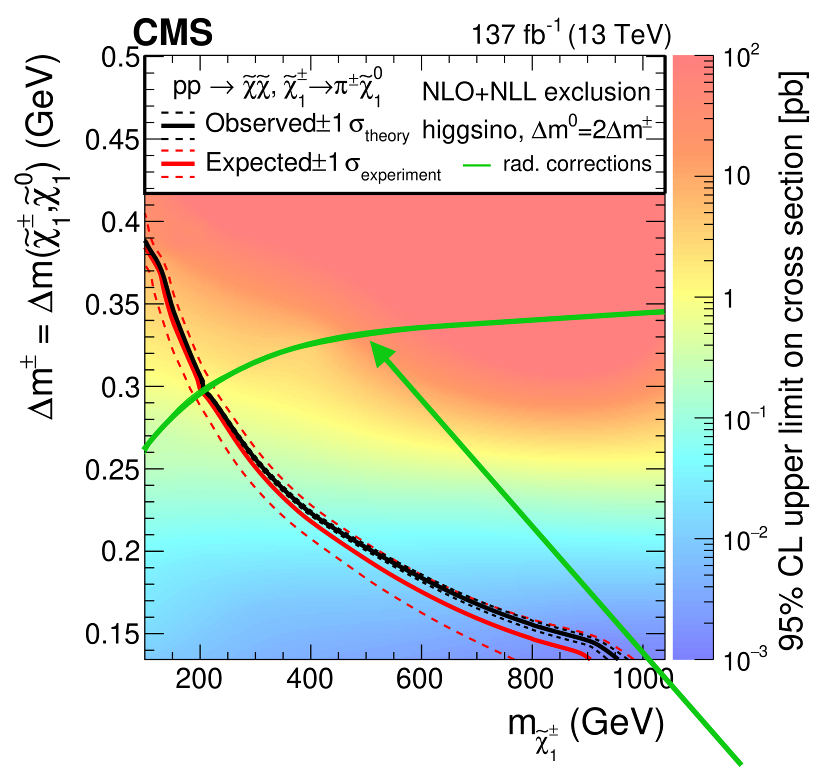
Disappearing Track



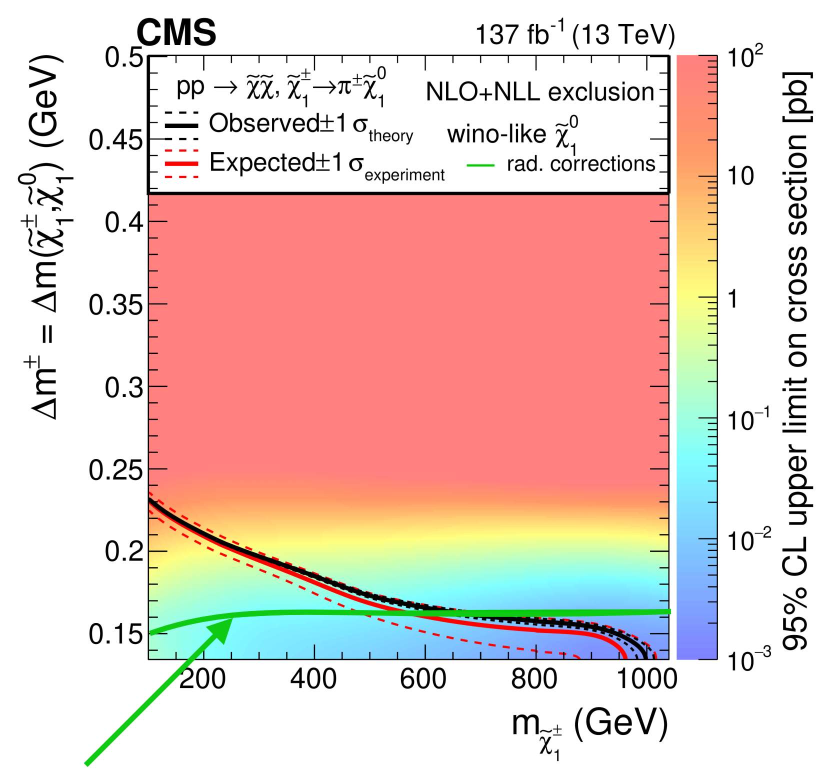


Mass from dE/dx + momentum

Doublet = Higgsino



Triplet = Wino



No other states means ΔM is fixed by radiative corrections

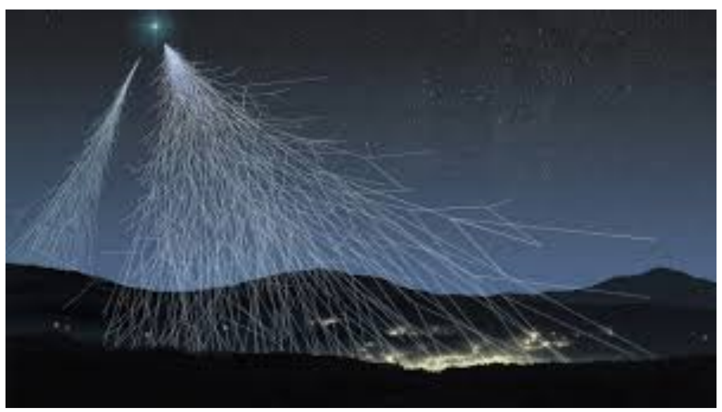
Full SUSY (more states) huge range of ΔM is allowed

Phys.Rev.D 109 (2024) 7, 072007

Indirect Detection

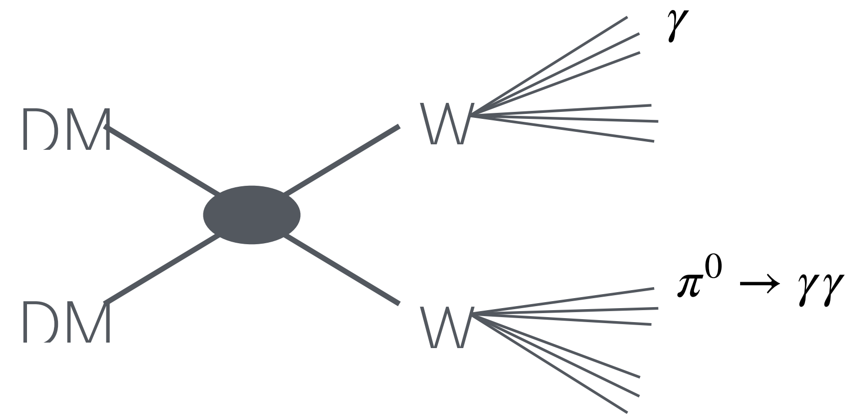
H.E.S.S results

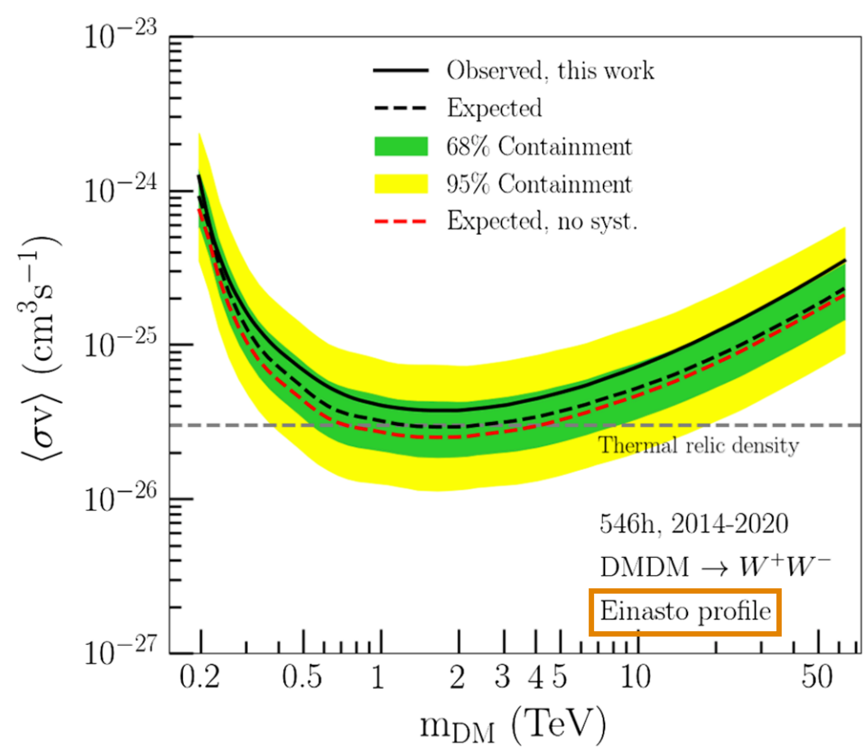
Air shower from gamma makes Cherenkov Radiation

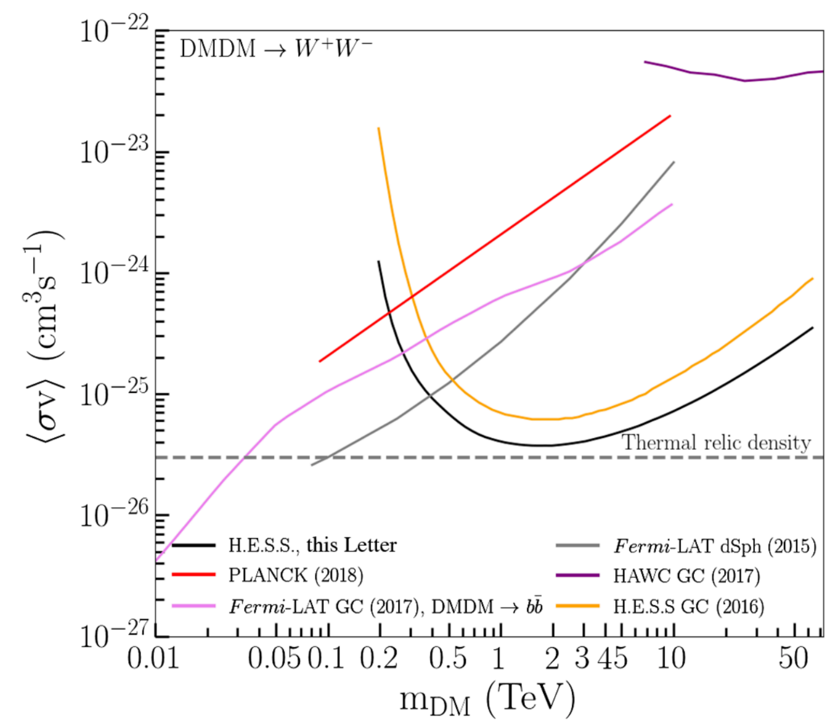


Array of five ground-based Cherenkov telescopes

DM DM → WW applies
(... more general)







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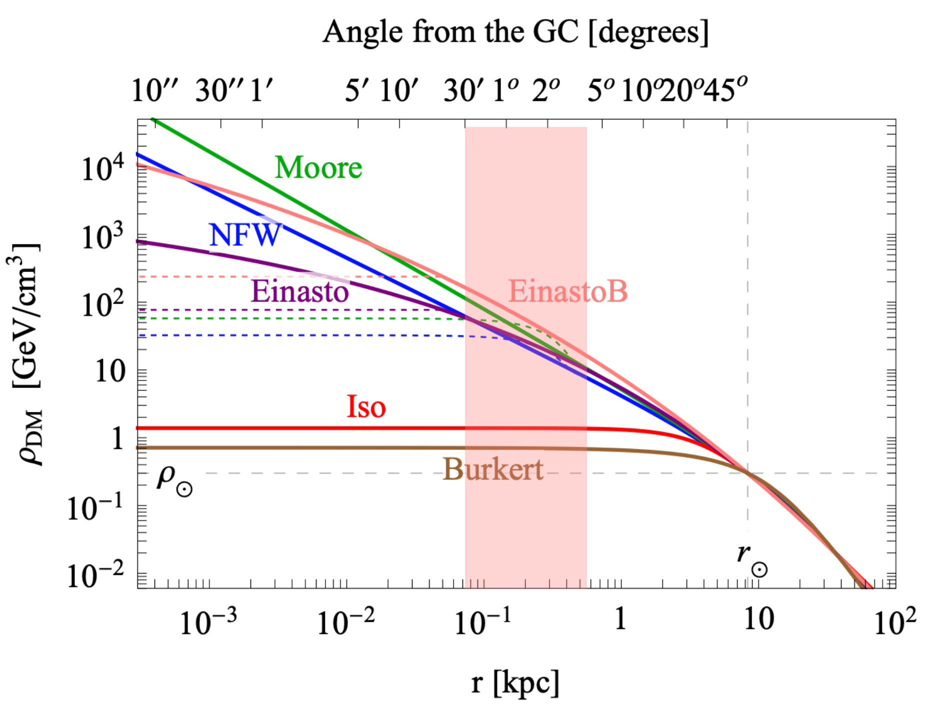
Dark Matter Galactic Profile

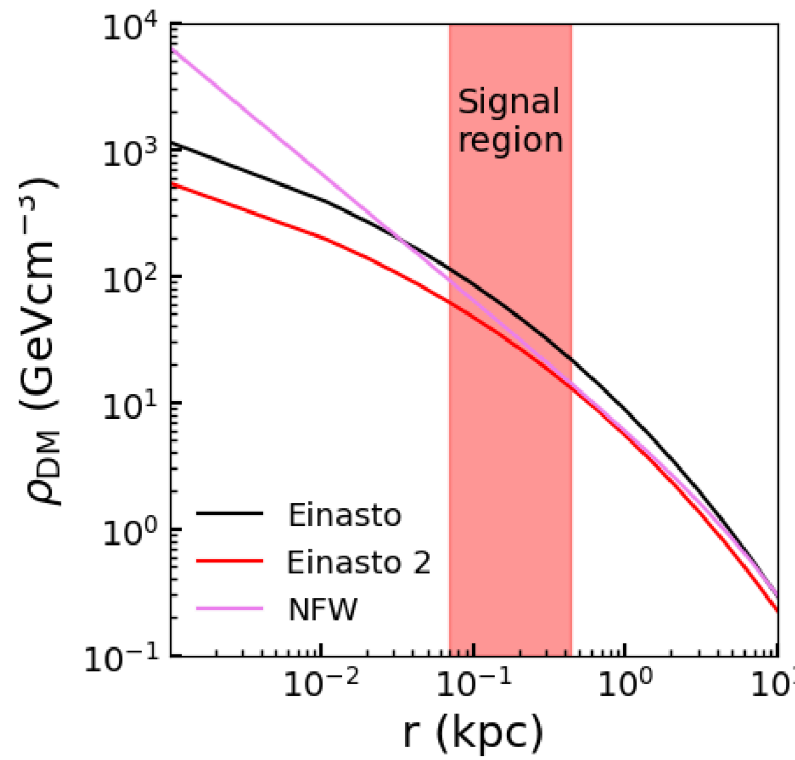
We don't actually know the galactic dark matter density very well

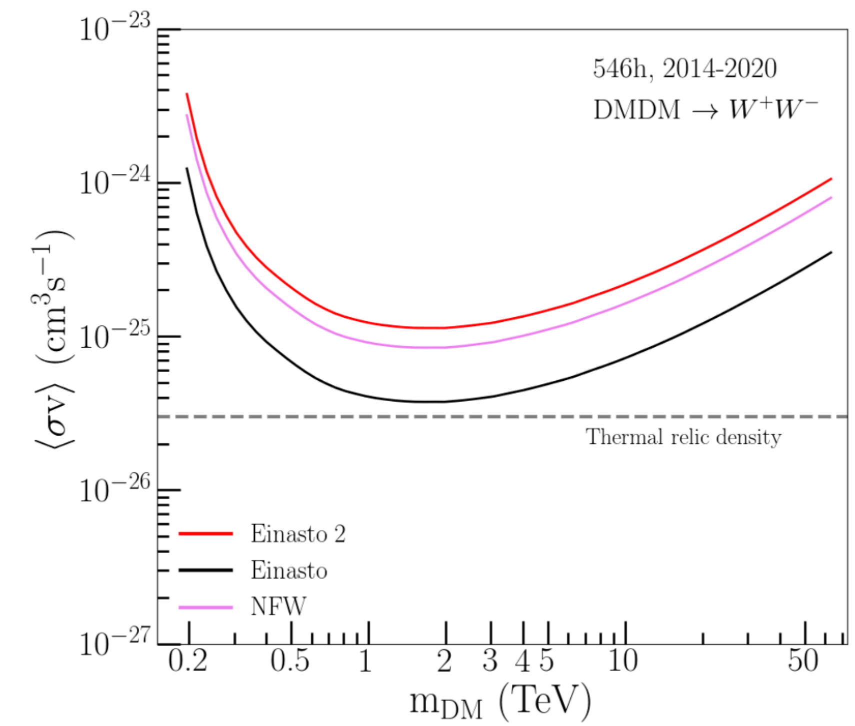
Plausible Dark Matter Densities



https://arxiv.org/pdf/1012.4515.pdf

H.E.S.S. Results Sensitivity to Profile





From HESS paper: "cored profiles such as the Burkert one are not studied here, since they need dedicated observations and analysis procedure"

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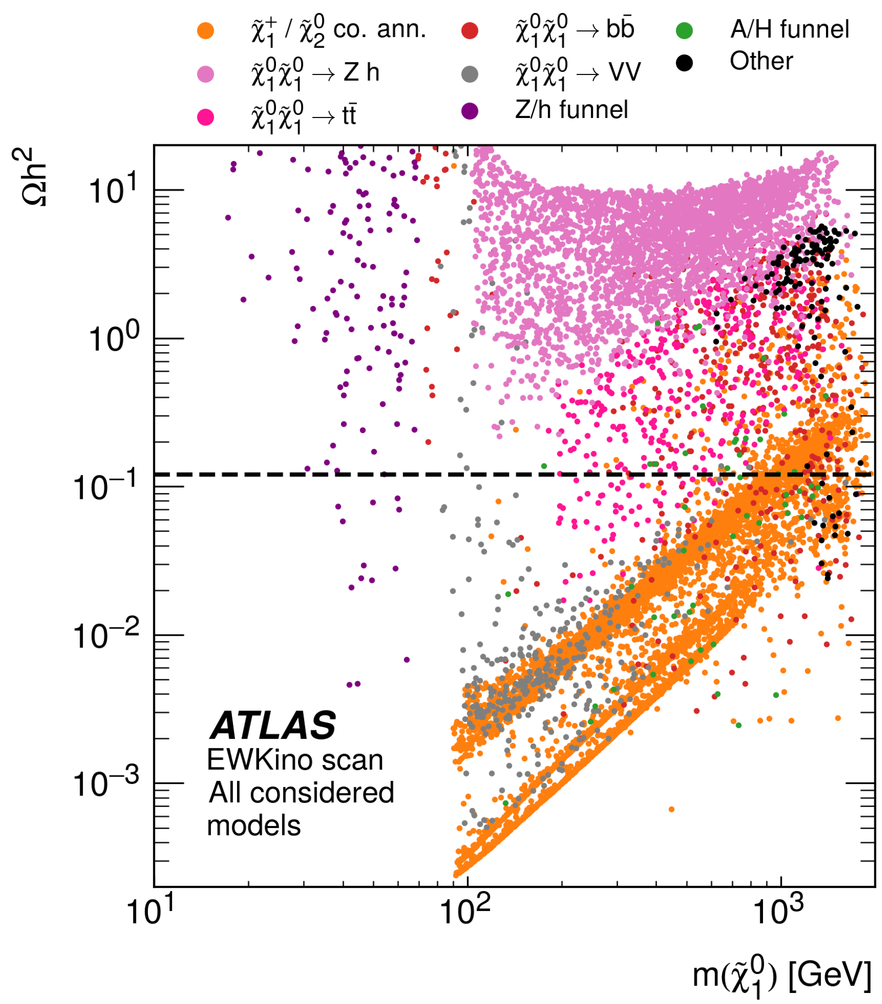
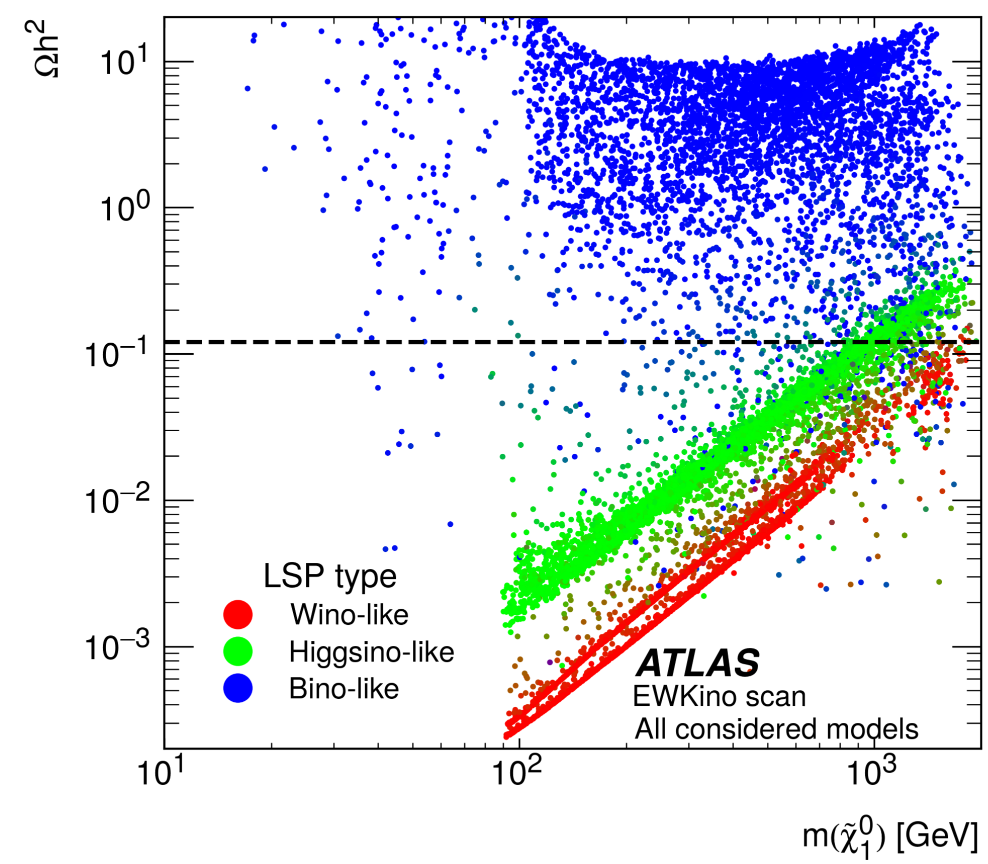
SUSY and relic abundance

https://cds.cern.ch/record/2888303/



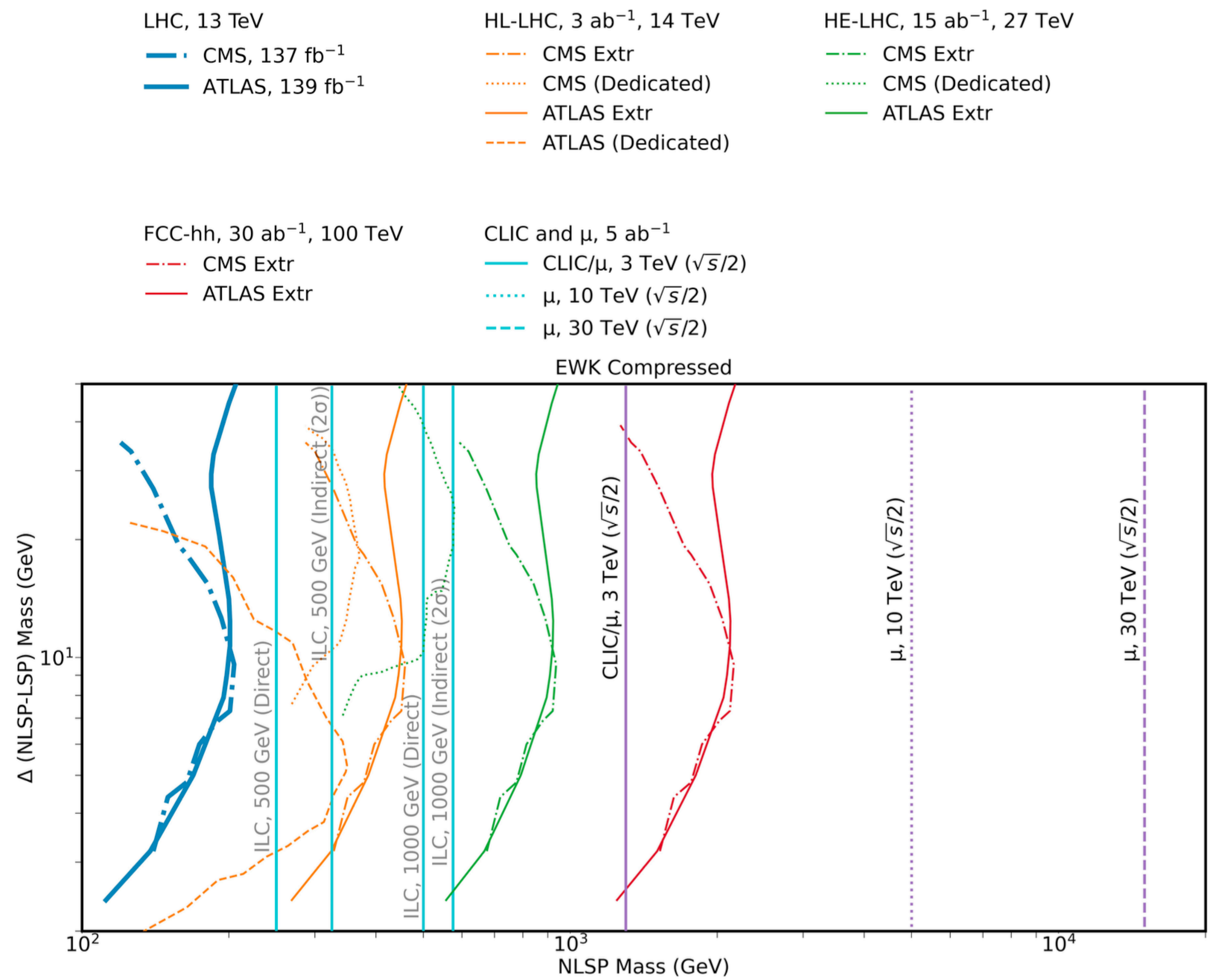
Same points labelled by LSP type



Compressed Higgsinos (difficult end of SUSY for hh machine)

"Natural" SUSY wants like Higgsinos

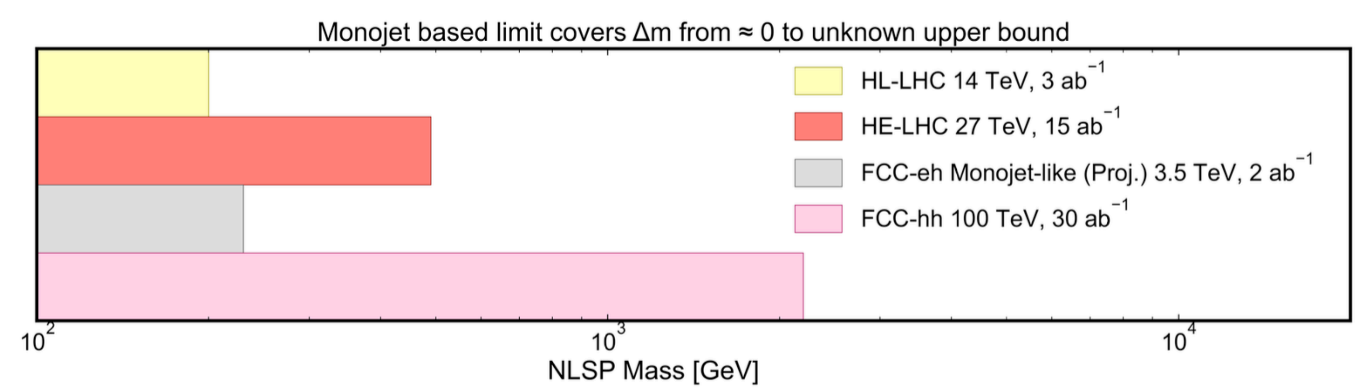
- Otherwise you start needing a fine-tuning to get a light Higgs even with SUSY



Constraints for ll+MET searches:

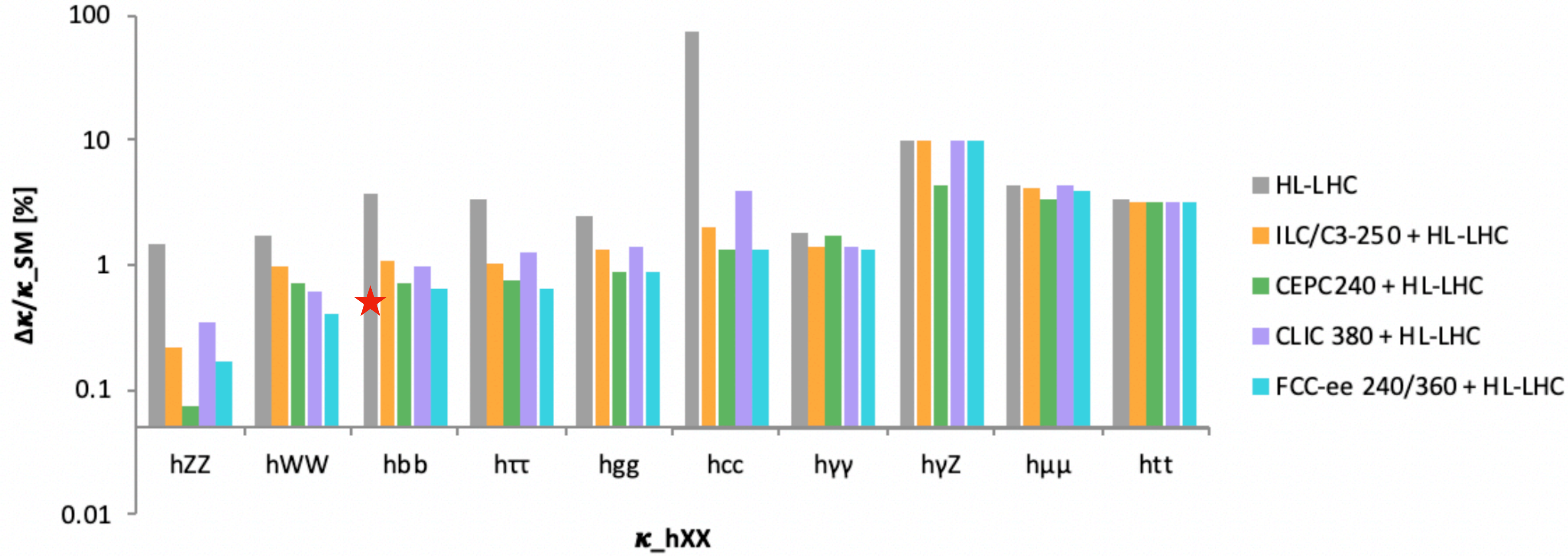
$$\chi_2^0 \to \chi_1^0 + \ell\ell$$

Just the shape of the Missing energy distribution = very generic constraint



H→bb at FCC-hh?

Snowmass Higgs report



Evidence H→bb might at the ~5x10^{-3} level might be possible at FCC-hh...

p_T^{min} (GeV)	W[e]+bb (pb)	W[e]Z[bb] (pb)	W[e]+bb (pb)	W[e]H (pb)	W[ℓ] bb $\times\varepsilon_b$ L	W[ℓ]Z[bb] $\times\varepsilon_b$ L	W[ℓ] bb $\times\varepsilon_b$ L	W[ℓ]H[bb] $\times\varepsilon_b$ L	$\delta R/R$
	$m[bb] \in m_Z$		$m[bb] \in m_H$		$m[bb] \in m_Z$		$m[bb] \in m_H$		
200	3.3E−2	2.5E−2	2.3E−2	3.8E−2	9.9E5	7.5E4	6.9E5	6.6E5	2.5E−3
300	1.2E−2	9.2E−3	8.8E−3	1.6E−2	3.6E5	5.5E4	2.6E5	2.8E5	3.2E−3
400	5.5E−3	4.3E−3	4.1E−3	7.9E−3	1.7E5	2.6E5	1.2E5	1.4E5	4.5E−3
600	1.7E−3	1.4E−3	1.3E−3	2.6E−3	5.1E4	8.4E4	3.9E4	4.5E4	7.8E−3
800	6.8E−4	6.2E−4	5.0E−4	1.2E−3	2.0E4	3.7E4	1.5E4	2.1E4	1.1E−2

https://cds.cern.ch/record/2681378/files/CERN-FCC-PHYS-2019-0002.pdf

Higgs mass implications for Stop mass

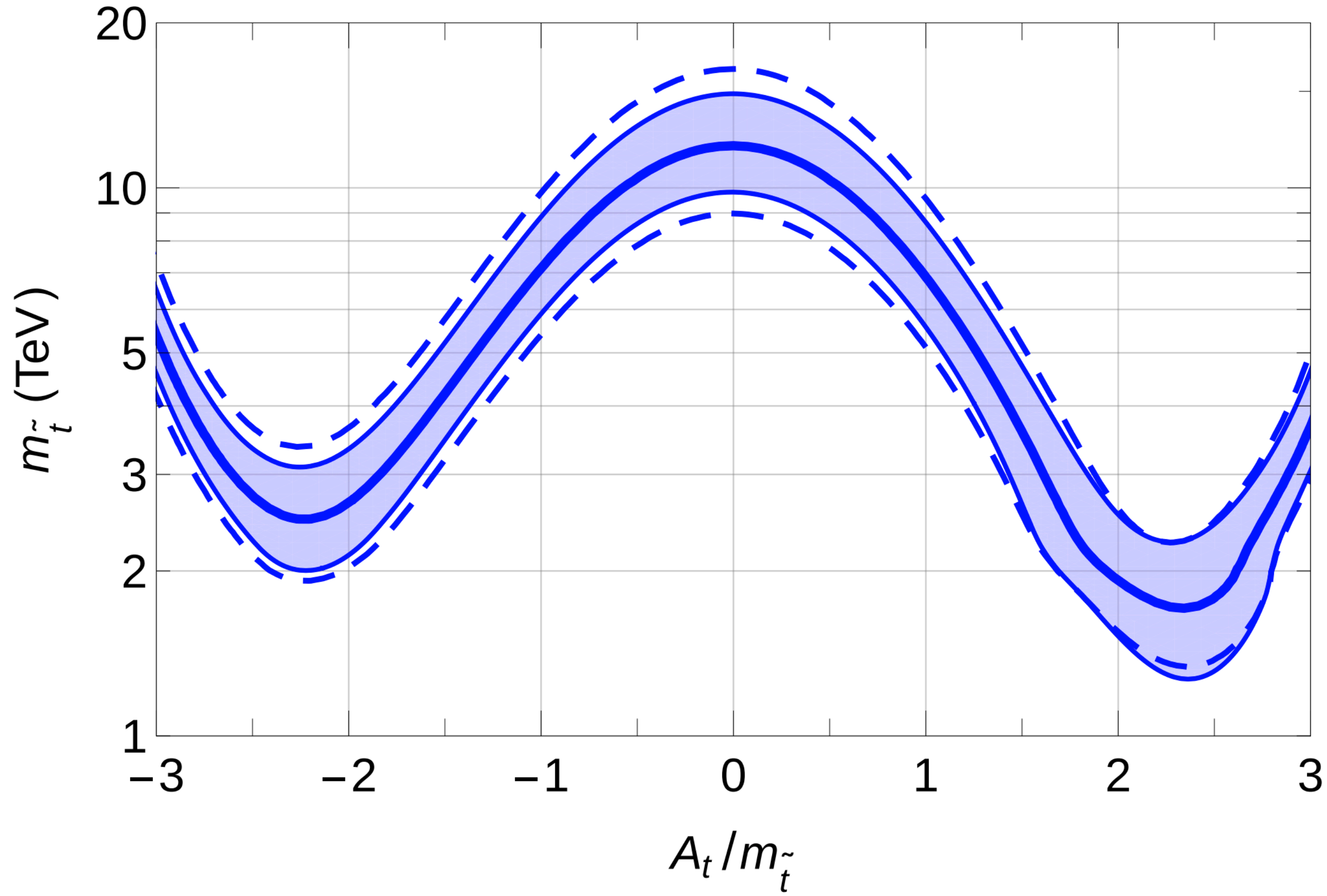


Figure 5: *Allowed values of the OS stop mass reproducing $m_h = 125$ GeV as a function of the stop mixing, with $\tan\beta = 20$, $\mu = 300$ GeV and all the other sparticles at 2 TeV. The band reproduce the theoretical uncertainties while the dashed line the 2σ experimental uncertainty from the top mass. The wiggle around the positive maximal mixing point is due to the physical threshold when $m_{\tilde{t}}$ crosses $M_3 + m_t$.*

Huge Production Rates

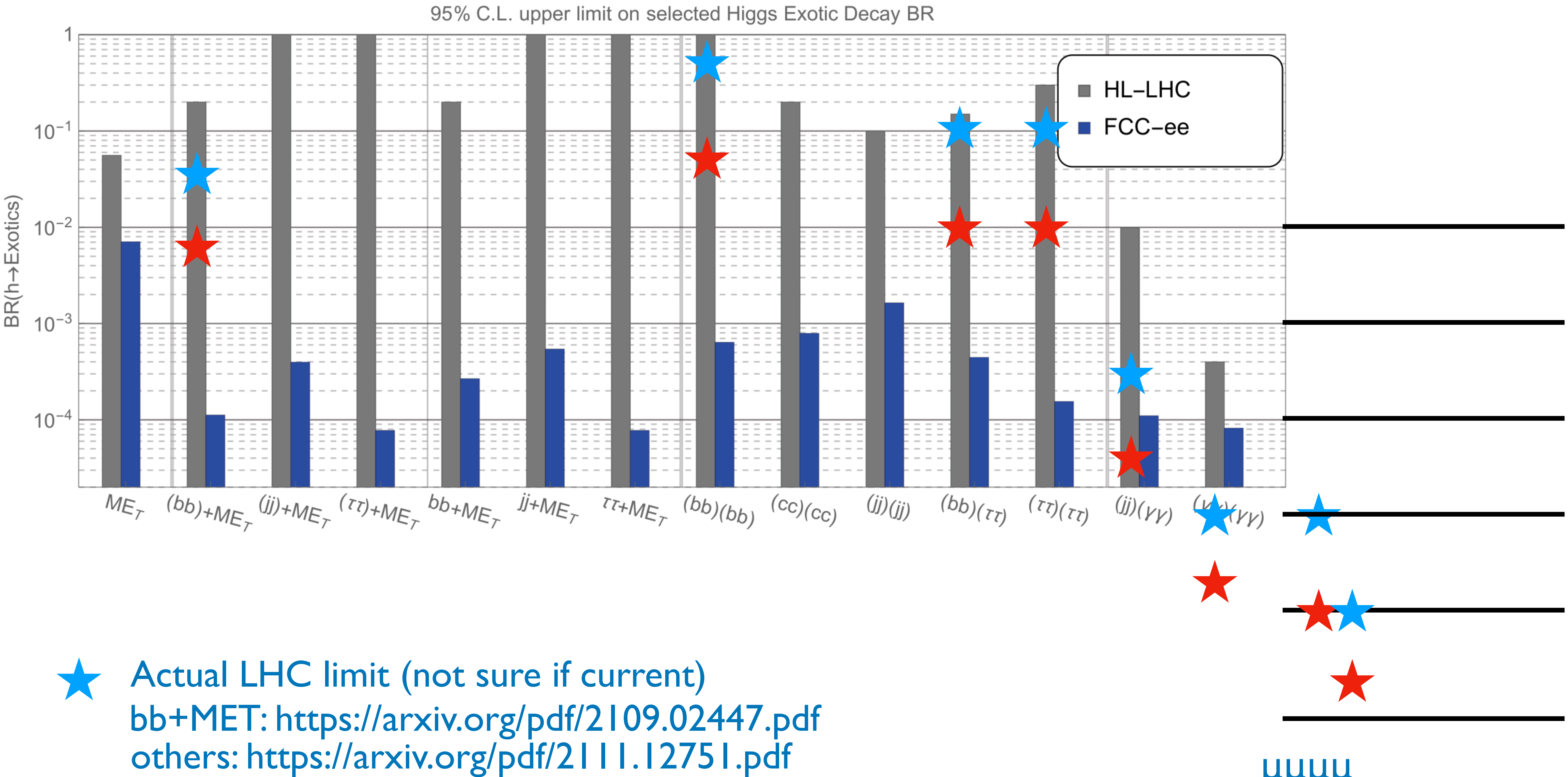
30 ab-1 gives…

- 3.9×10^{13} W bosons and 1.2×10^{13} Z bosons (beyond a TeraZ!)
- This gives great rare decay sensitivity if you can find the decay
  - LLPs are very strong signatures
- ~6-20% are leptonic decays which can be used for precision measurements

	$gg \to H$	VBF	WH	ZH	$t\bar{t}H$	HH
N_{100}	24×10^9	2.1×10^9	4.6×10^8	3.3×10^8	9.6×10^8	3.6×10^7
N_{100}/N_{14}	180	170	100	110	530	390

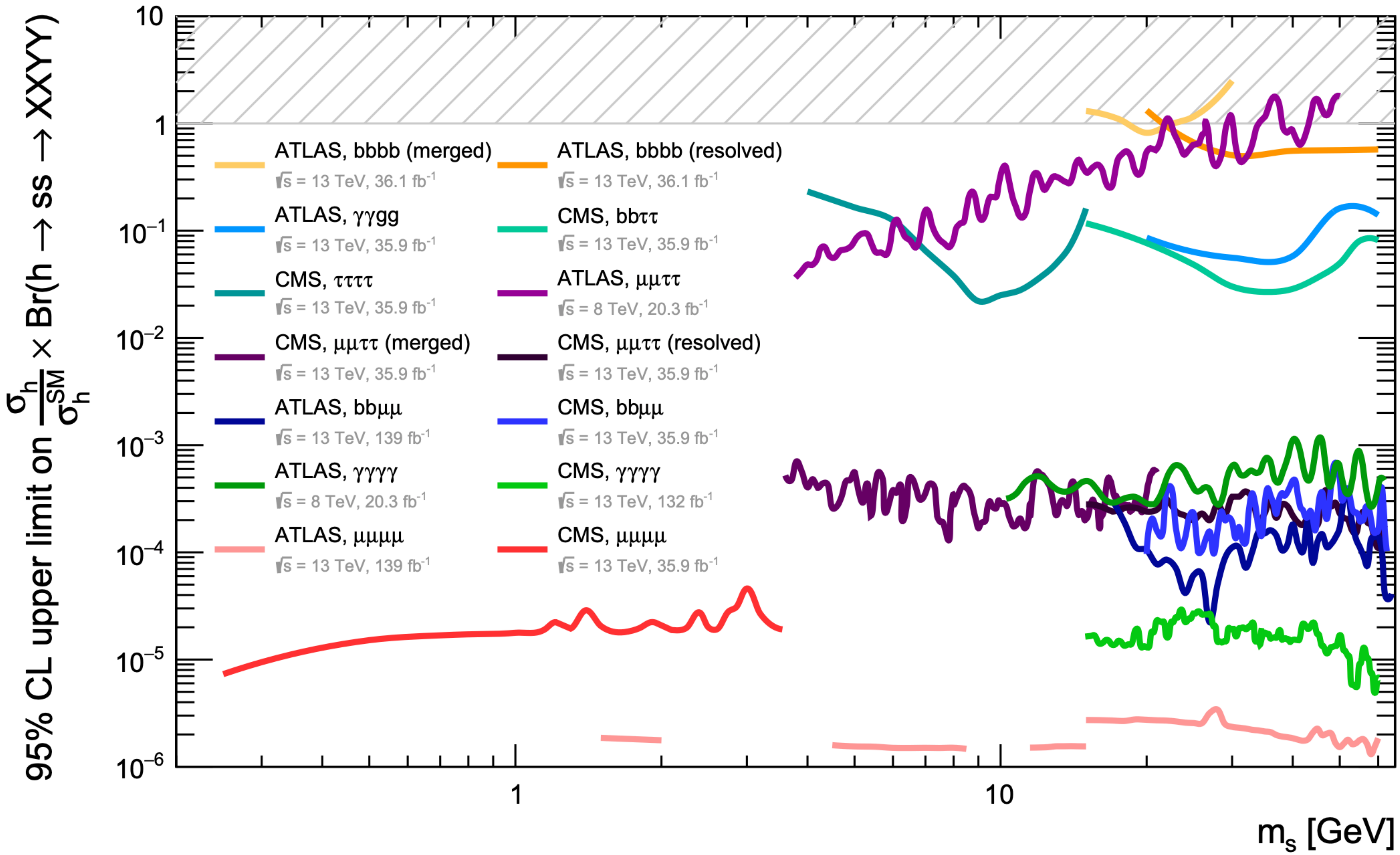
Exotic Higgs...

HL-LHC sensitivity underestimated
FCC-hh has order 100-1000x more Higgs



★ Actual LHC limit (not sure if current)
bb+MET: https://arxiv.org/pdf/2109.02447.pdf
others: https://arxiv.org/pdf/2111.12751.pdf
★ Extrapolated assuming sqrt(Lumi) for HL-LHC

Higgs to ss to XXYY



https://arxiv.org/pdf/2111.12751

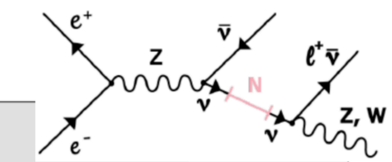
Can hadron collider not do these?

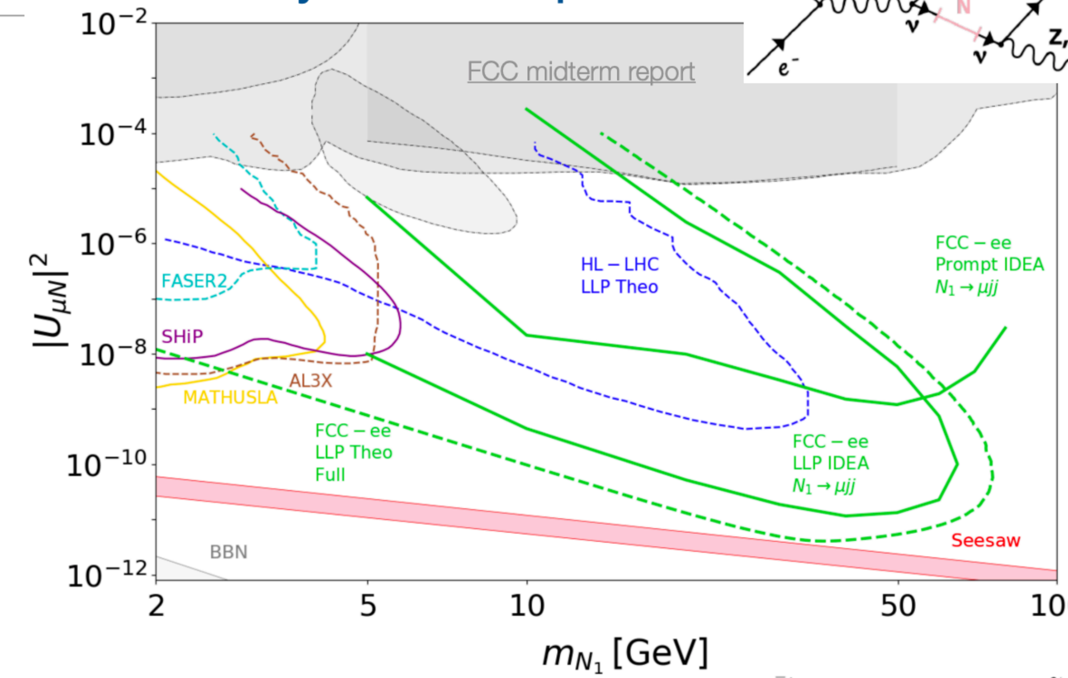
Slide from Willocq at LHCP

e+e− : Beyond the SM

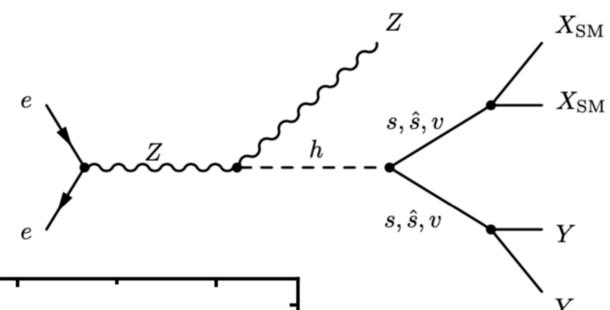
- Direct searches exploiting vast samples of Z and H bosons
  - **Origin of neutrino mass**: HNL reach down to $U^2 \simeq 10^{-11}$
  - **Dark sector**: ALP mediators reach to $g_{a\gamma} \simeq 10^{-4}\ \mathrm{TeV}^{-1}$
  - **Higgs portal**: BF reach down to 5×10^{-5}

Heavy neutral leptons

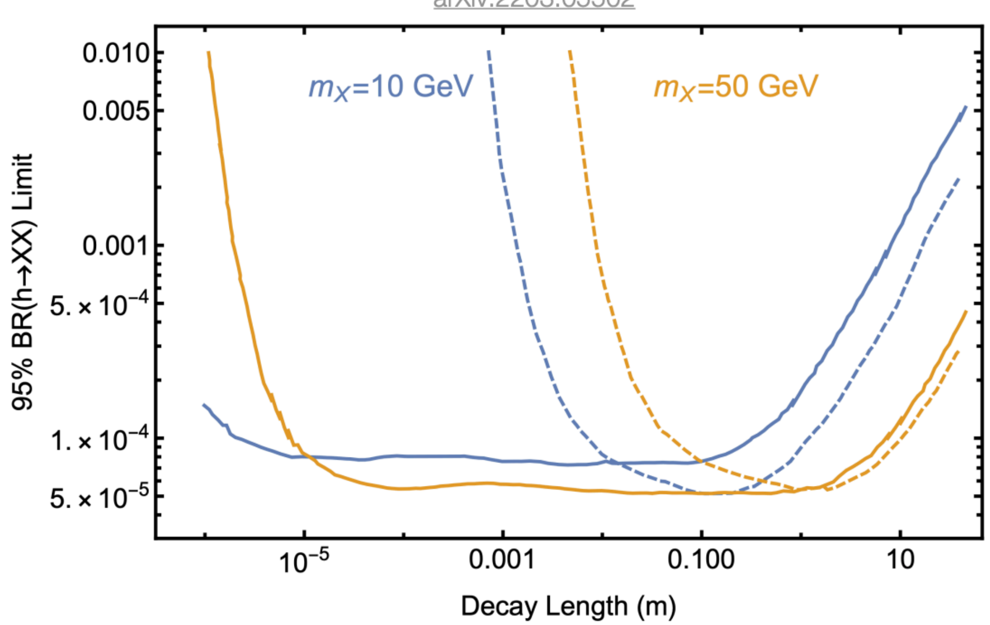




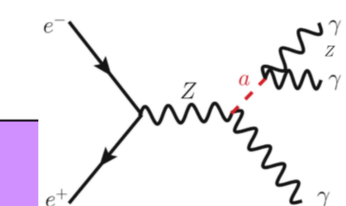
Higgs decay to LLP

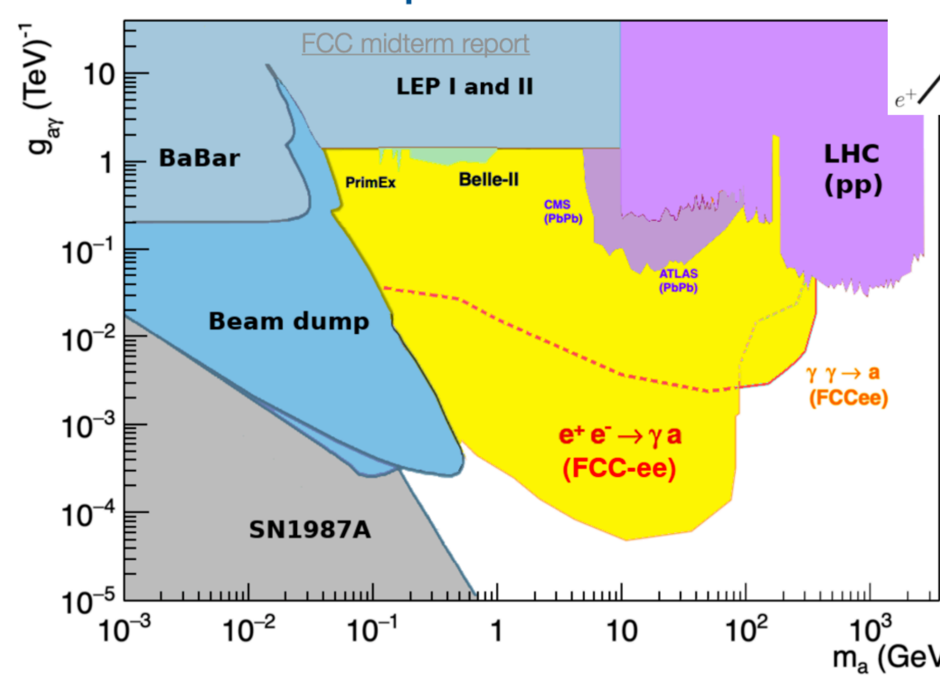


arXiv:2203.05502



Axion-like particles



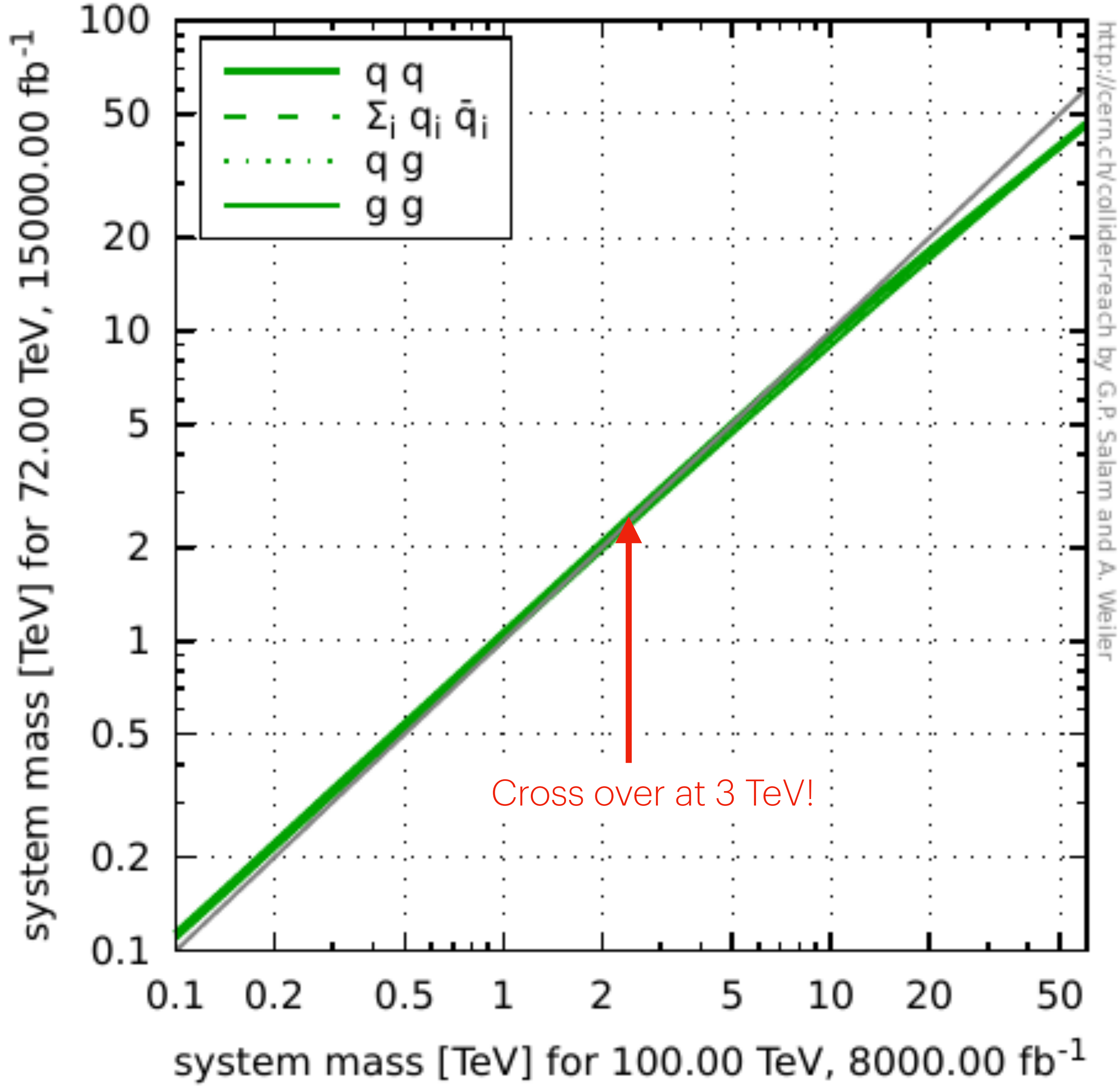


similar expectations for CEPC

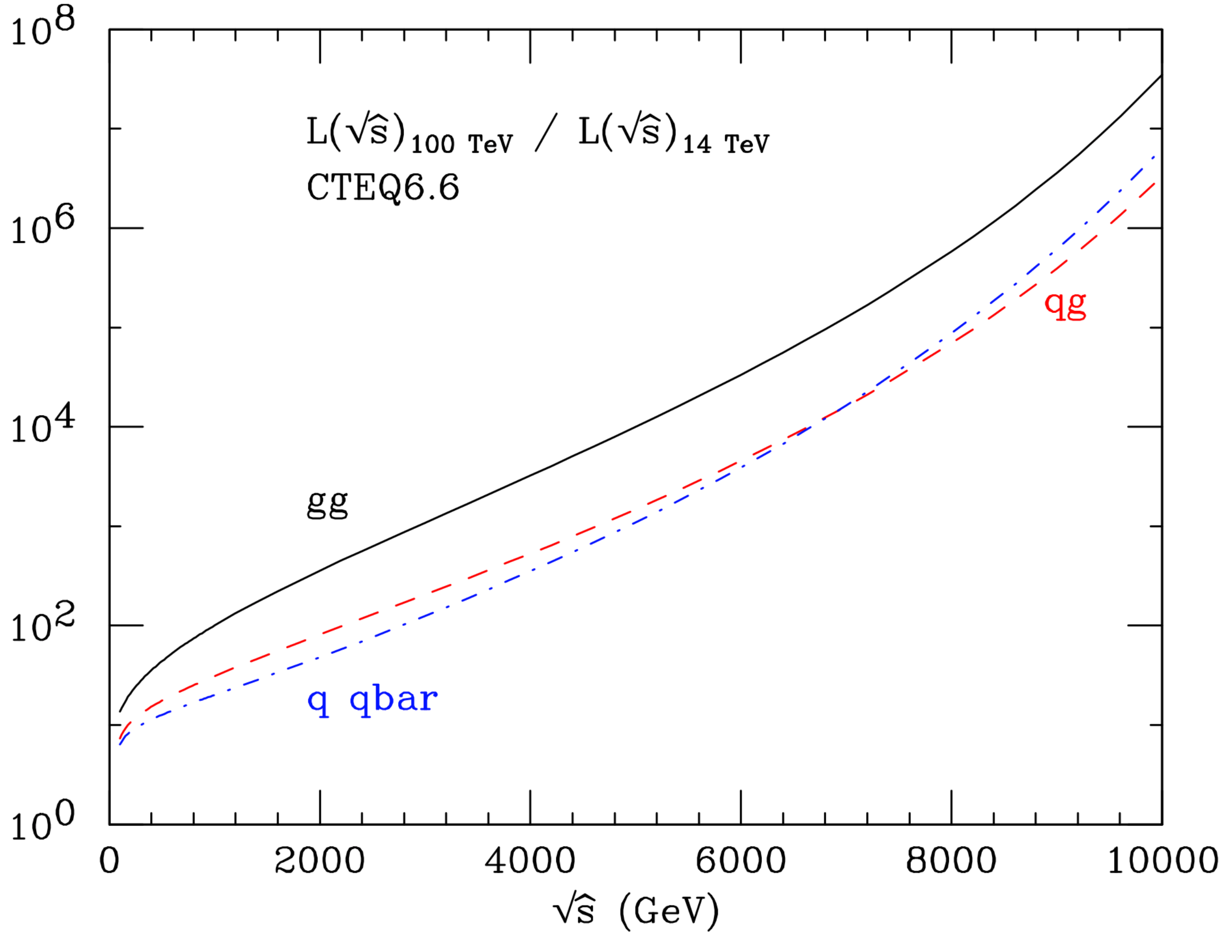
31

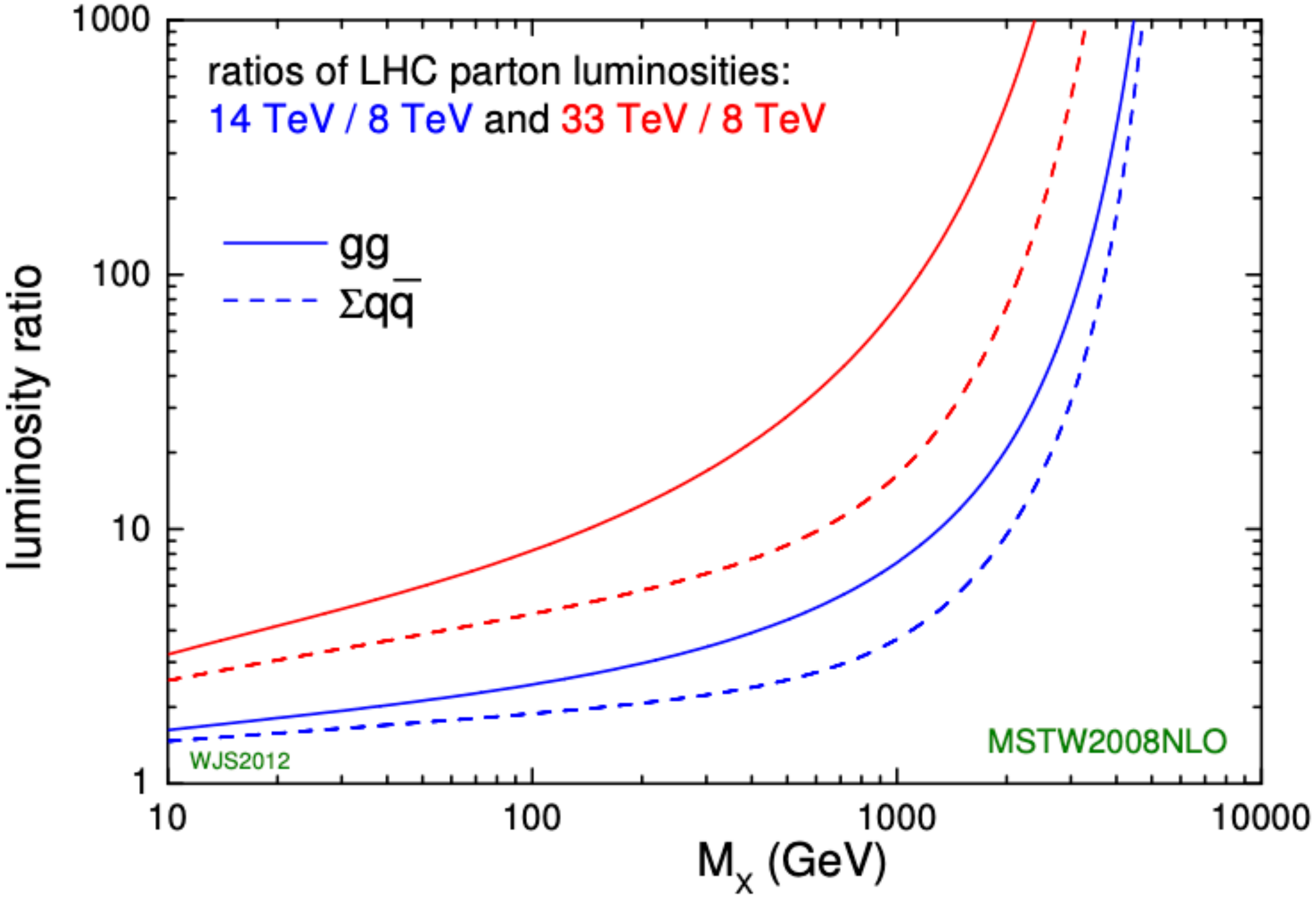
All above search channels involve displaced vertices

Guess at Same Synchrotron Dose



Parton Luminosity Ratios





https://arxiv.org/pdf/1504.06108.pdf

Exotic Signatures

Exotic Signatures like Long-Lived Particles can be very clean