Future Hadron Colliders

If we live to see them

Elliot Lipeles

Outline

What is possibly on the horizon?

What physics can it do?

What do we need from the detector to do that?

Overview of the options

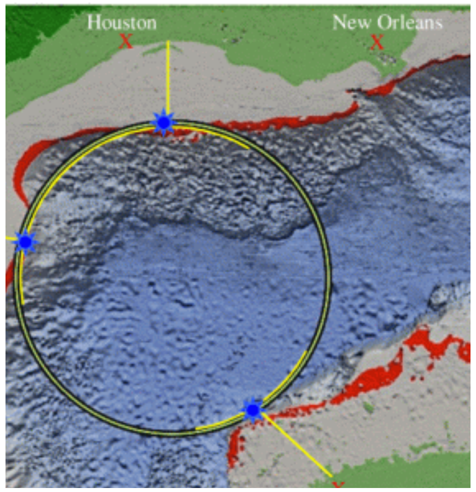
Preceded by ee machine

Must Remove FCC-ee first

Could be in tunnel simultaneously

From Snowmass "Implementation Task Force Report"

	CERN	China	Fermilab	Gulf of Mexico
	FCC-hh	SPPC	FNAL Site Filler	Coll. under sea
CM energy $\sqrt{s}$, TeV	100	125	24	100 - 500
Perimeter, km	91.2	100	16	1,900
Number of IP	4	2	2	2
Bending field, T	17	12 - 20	24.4	3.5
Peak lumi./IP (multipl.), $10^{34}cm^{-2}s^{-1}$	5-30 (1000)	10	3.5	50
Total power consumption, MW	560	400	200 - 300	200,000 !



Simple magnets, no tunnel, but needs to stay aligned floating in a ocean!

Advanced Superconductors (Nb3Sn)

Needs ~20 year R&D program

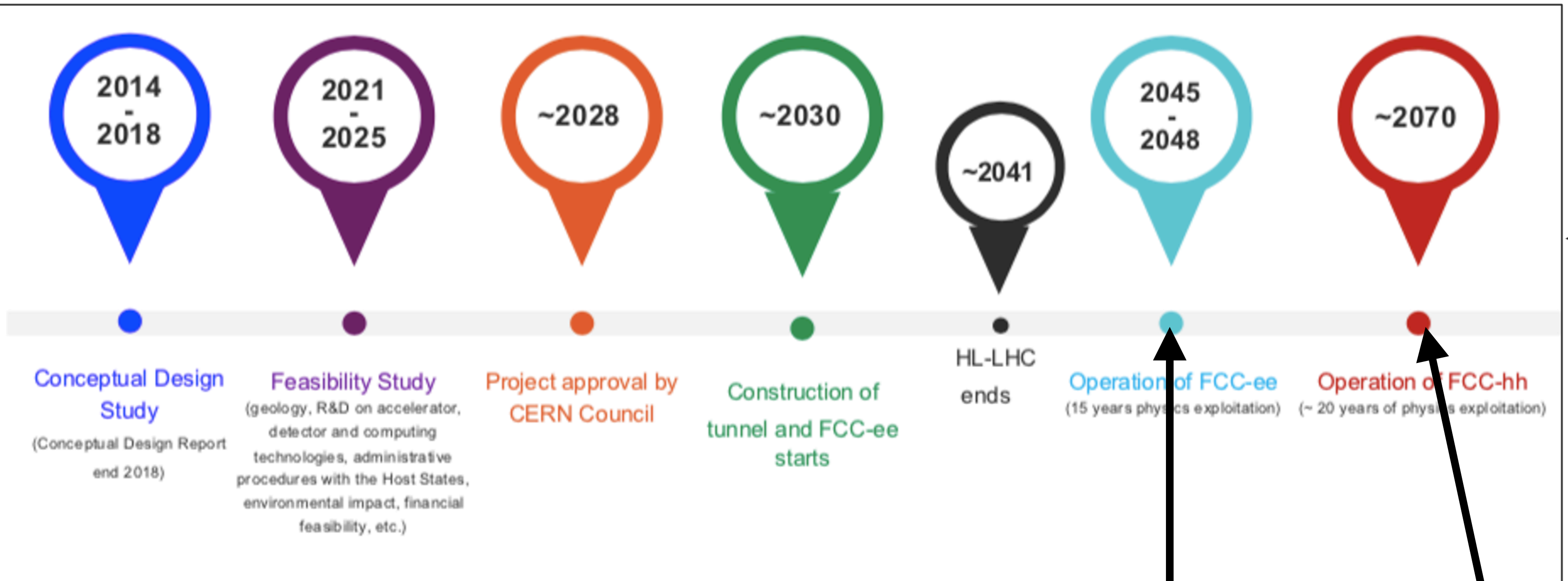
Iron + High-temperature

"Could be be easier to implement on a large scale the demanding Nb3Sn"

More speculative

Schedule :(

FCC-ee+FCC-hh Timeline



[From slides by Fabiola Gianotti]

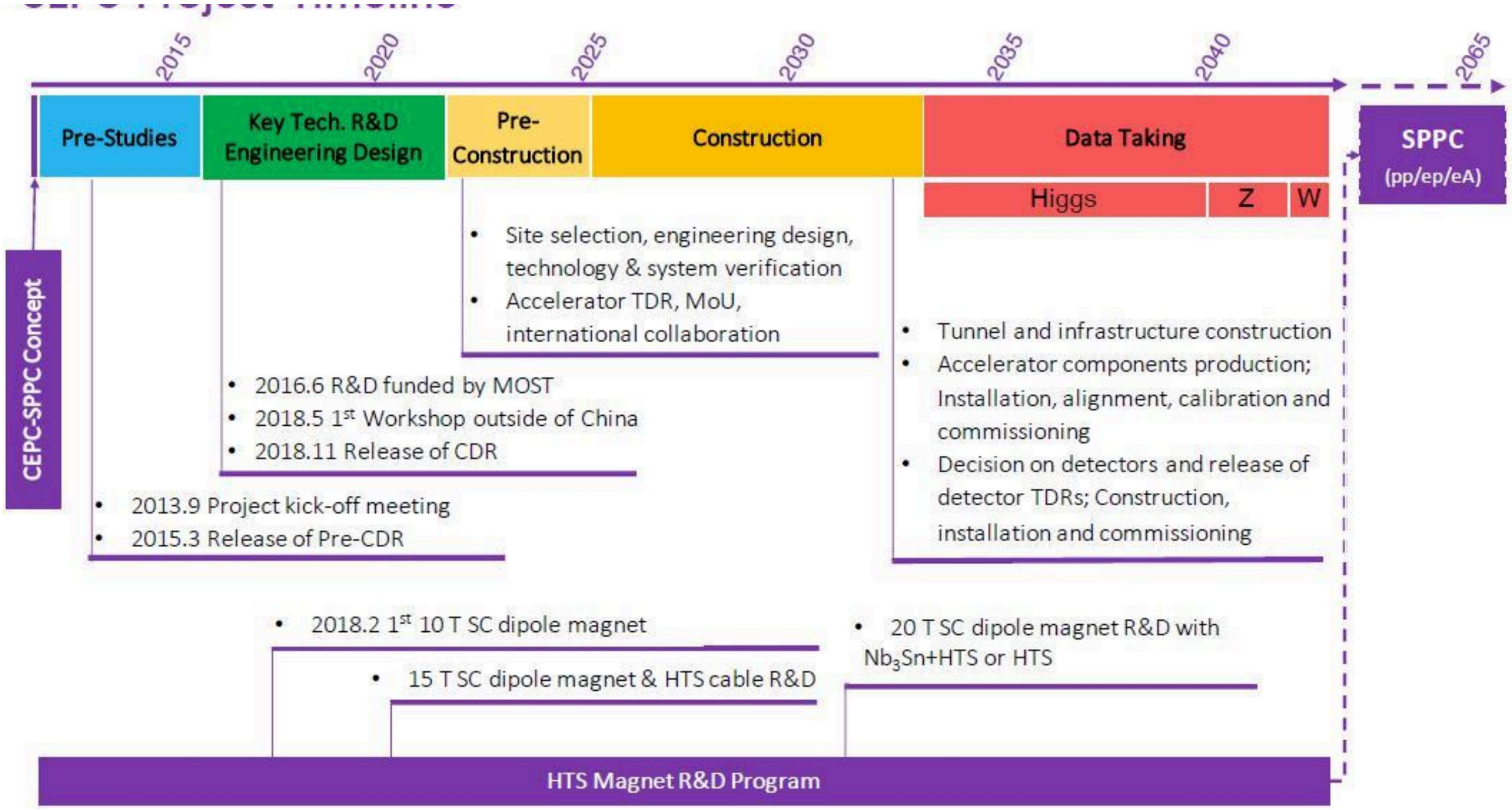
"Realistic" schedule takes into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that HL-LHC will run until ~ 2041
- → **ANY future collider at CERN cannot start physics operation before ~ 2045** (but construction will proceed in parallel to HL-LHC operation)

My retirement

My youngest graduate students retirement

CEPC+SPPC Timeline



Staged hadron machines has been discussed…

A low energy hadron machine instead of ee?

~100 TeV schedule driven by R&D and cost

- 16T+ magnets not ready
- Need to spread out tunnel cost from magnet cost (ee machines are cheaper)

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- E.g. a 6T magnets in a 91 km tunnel as a "Low energy" FCC-hh (~37 TeV)
- Issues:
  - Not cheap enough (I don't have numbers on this)
    - Let's not be too cheap with a generation of minds
  - Then you never do ee (where does 100 TeV not supersede ee?)
  - Maybe 100 TeV will be less appealing to build if already have 37 TeV

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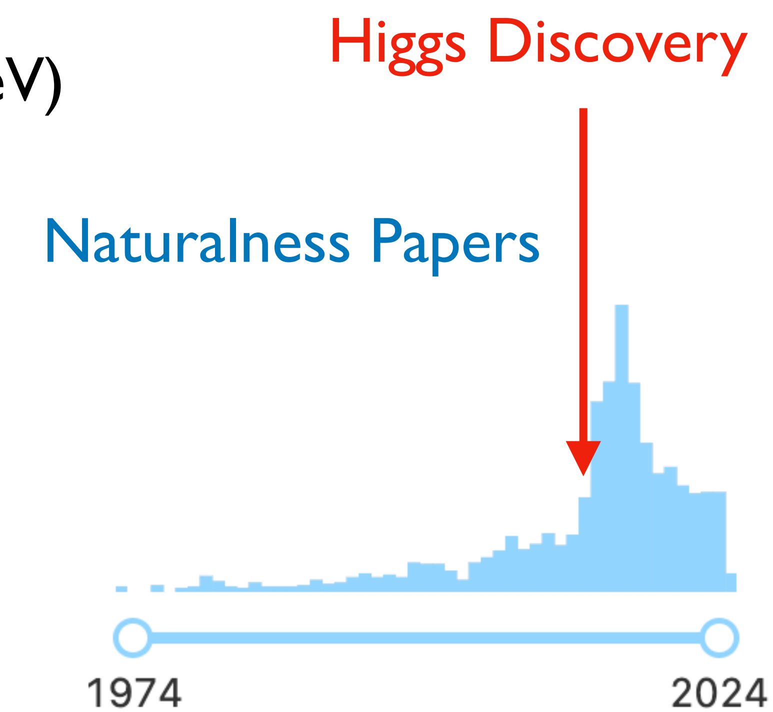

Constraints on Naturalness scale like E^2, so

- (30/14)~7 … a good step
- (100/30)~7 … another good step
- (100/14)~50 … no matter what your view of how unnatural things are now. At that point a "natural" explanation is pretty constrained

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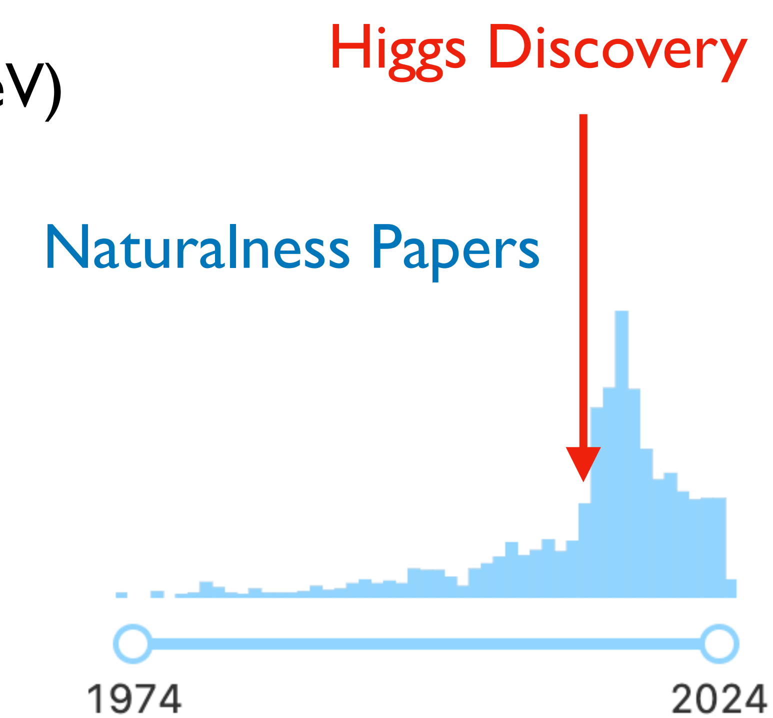

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HE-LHC was a 27 TeV option involved high-field magnets in LHC tunnel, but no longer consider feasible

- Magnet time scale is a problem
- Physics studies still give relevant intermediate point

Physics Program

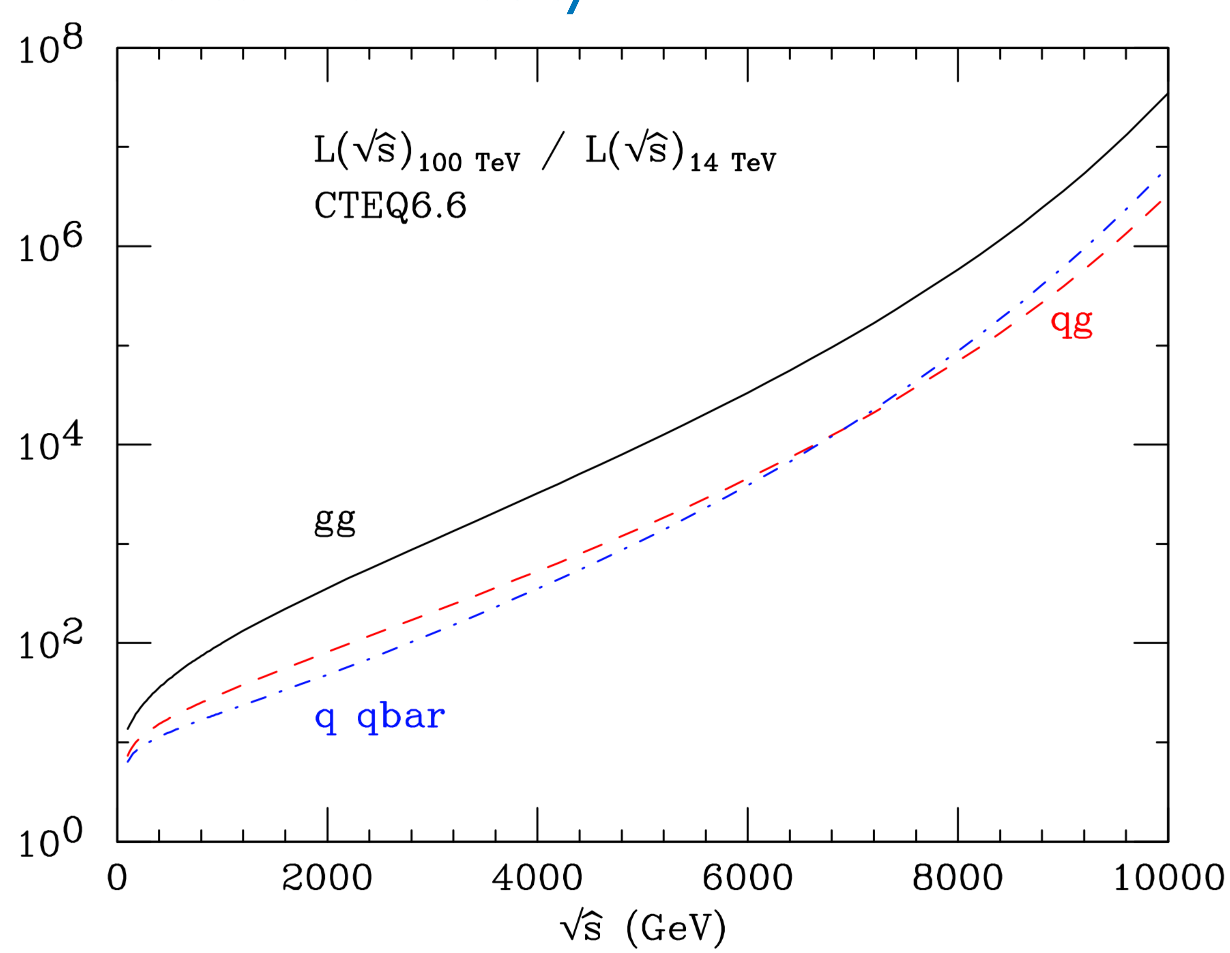
Direct Searches = New Particles

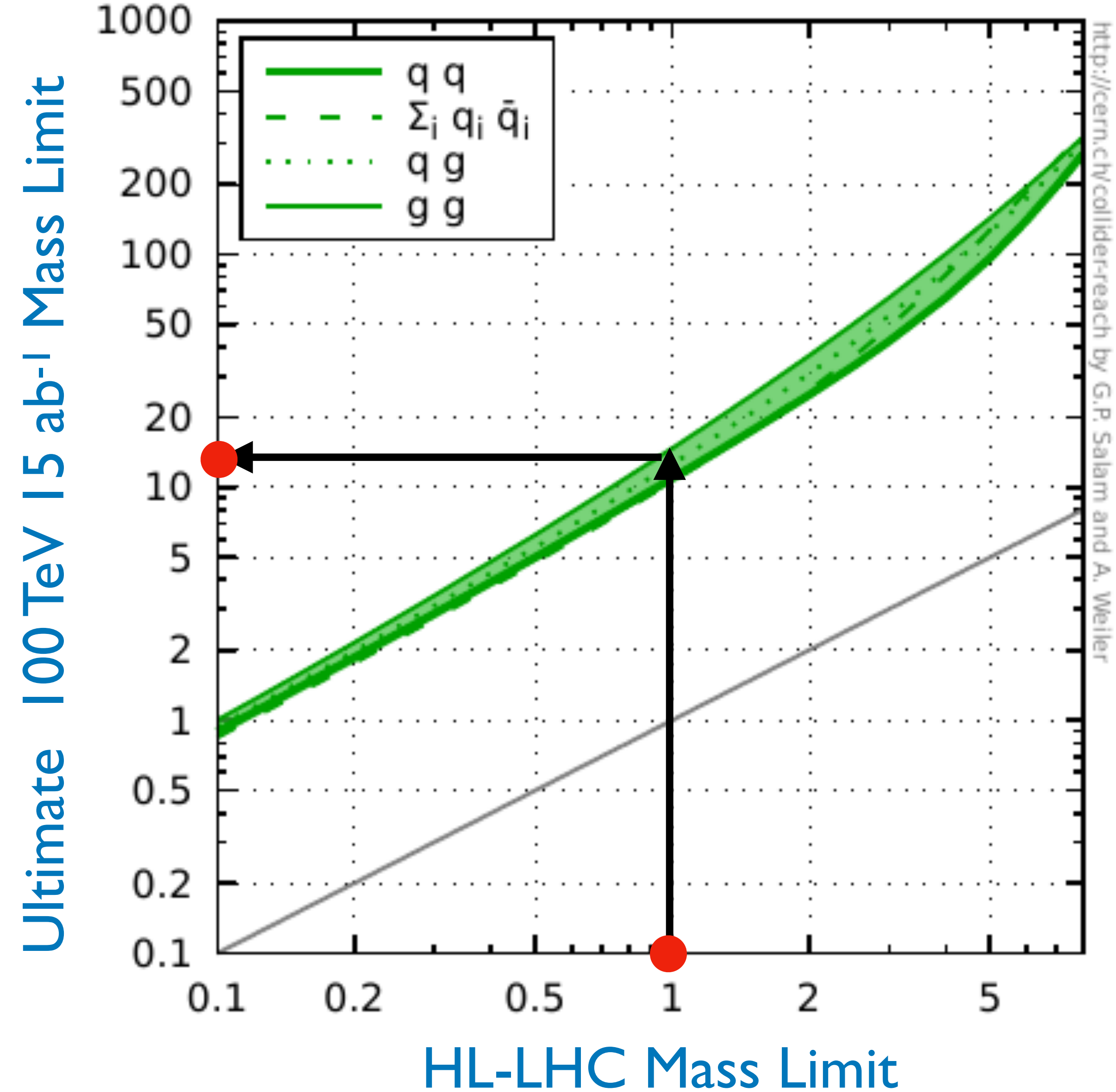
- SUSY
- Thermal Dark Matter

Coupling measurements

- Higgs-Self Coupling
- Energy = Precision

Parton Luminosity





"Collider Reach" extrapolator

http://collider-reach.web.cern.ch/

1 TeV limit @ HL-LHC → 10-14 TeV limit @ 100 TeV

Top Partners (stop squark ++)

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

Current LHC limits for other top partners for comparison

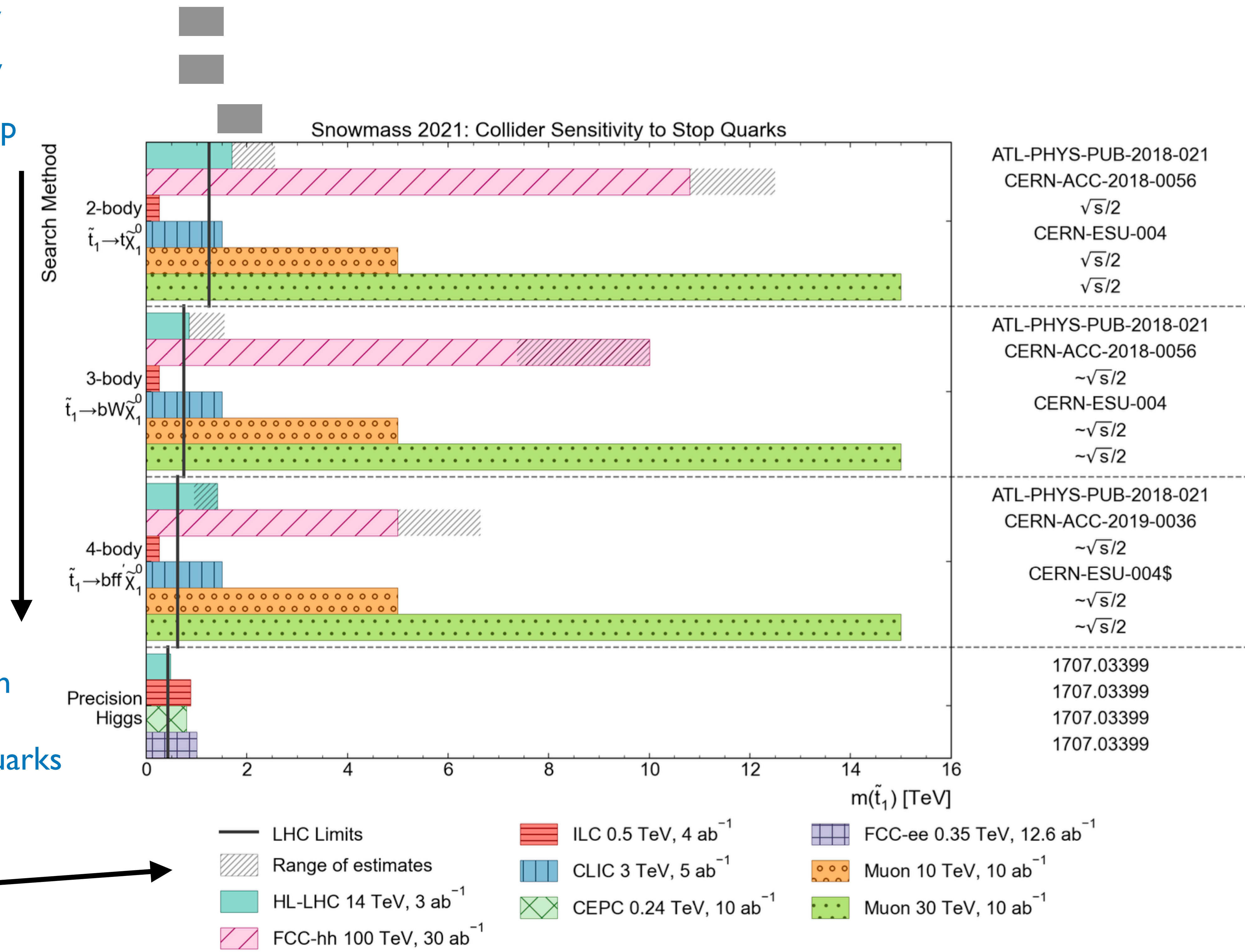
Leptonic RPV

Baryonic RPV

Vector-like top

Sensitivity varies with kinematics of decay

Decreasing q^2 of decay



Indirect constraints from precision Higgs are not competitive for stop squarks

Compares Collider Reach to Dedicated Study if available

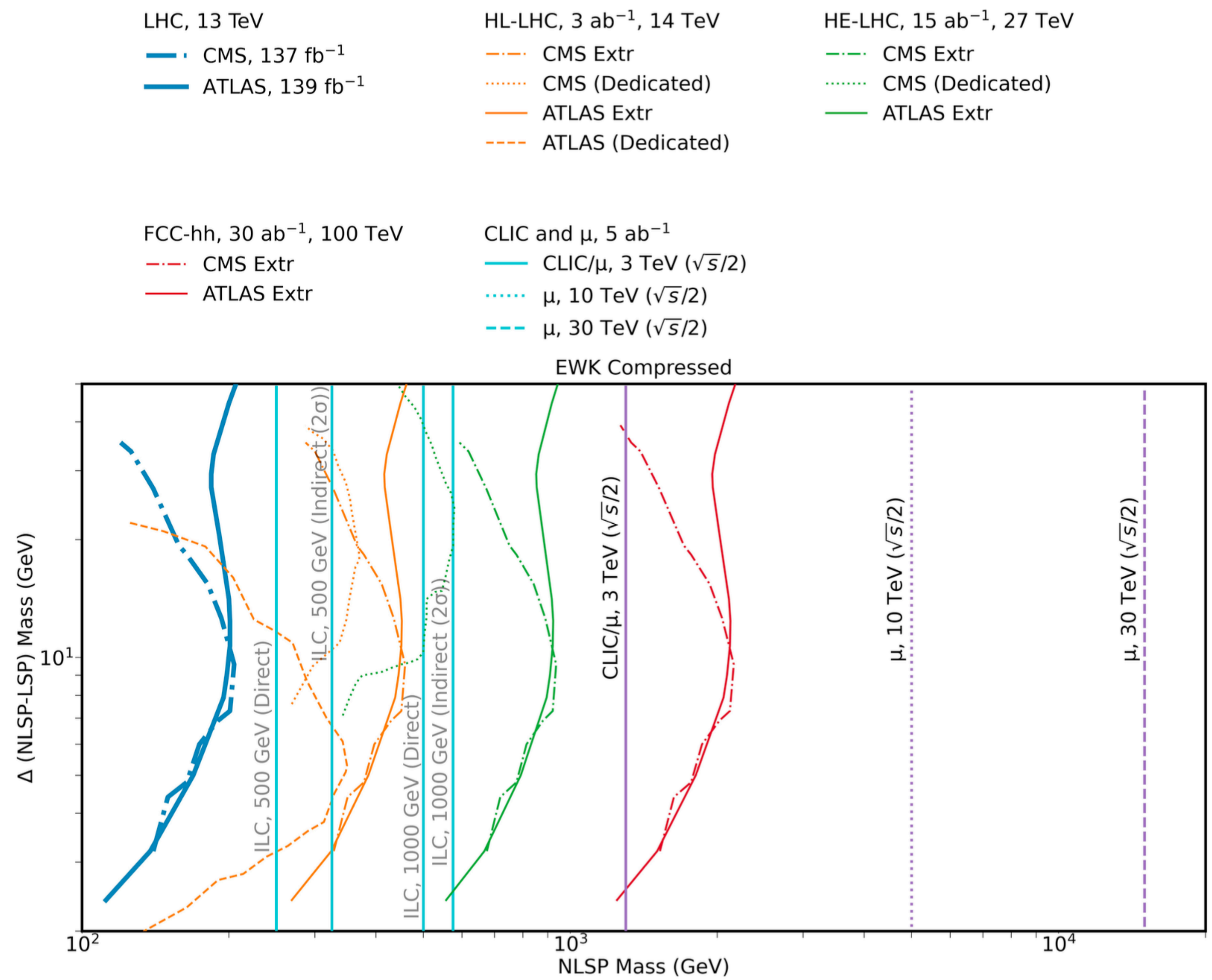
Compressed Higgsinos (difficult end of SUSY for hh machine)

"Natural" SUSY wants like Higgsinos

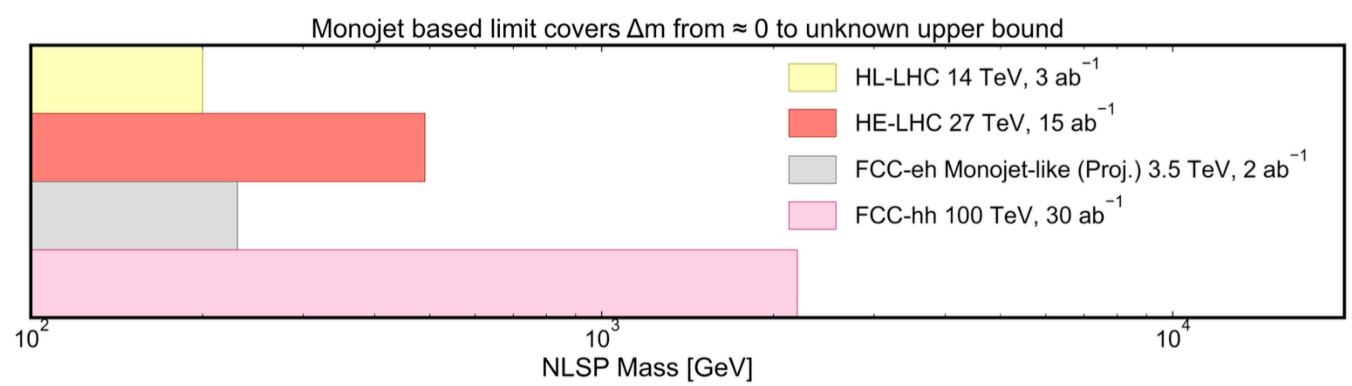
- Otherwise you start needing a fine-tuning to get a light Higgs even with SUSY

Constraints for ll+MET searches:

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



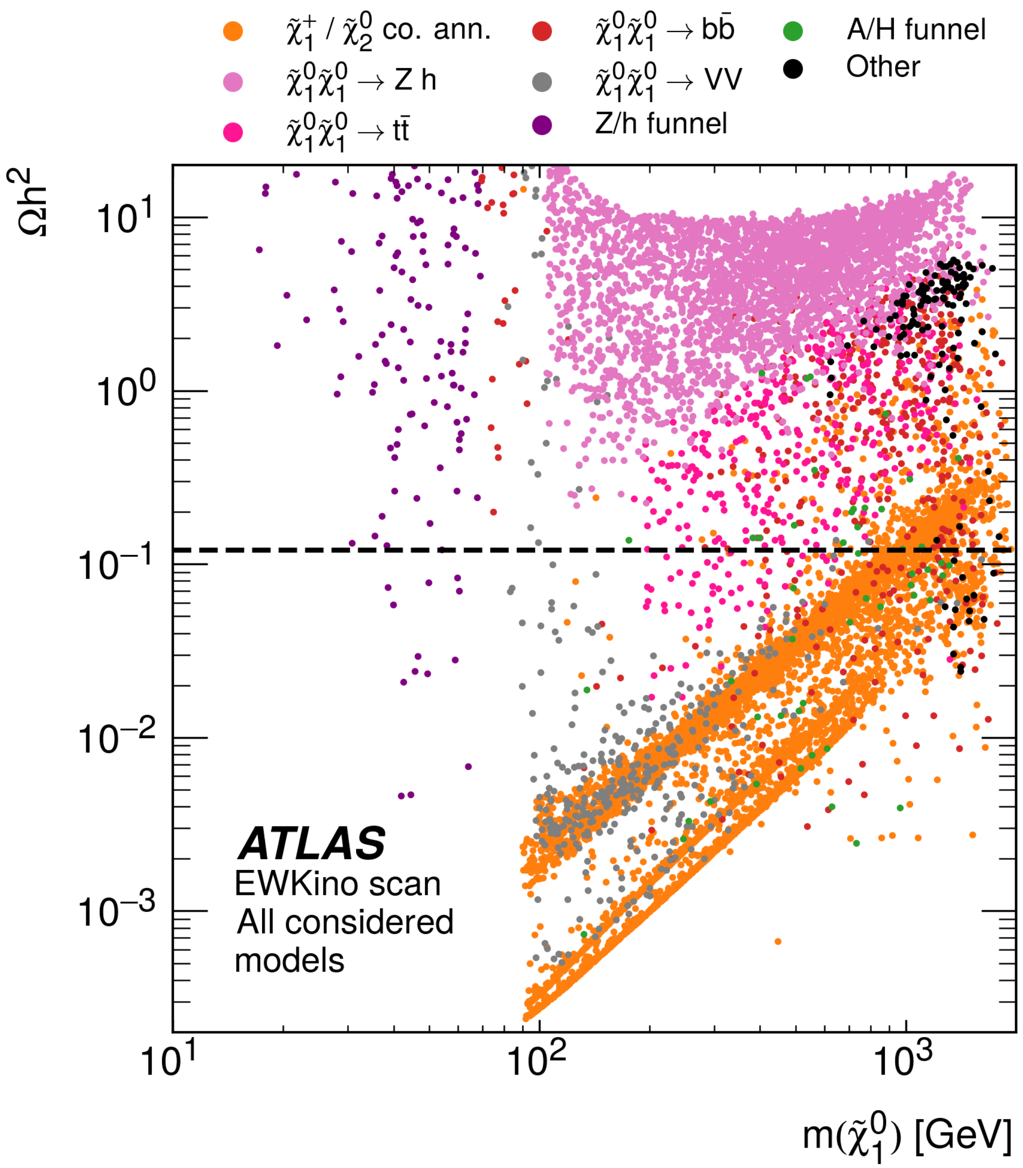
Just the shape of the Missing energy distribution = very generic constraint



Dark Matter

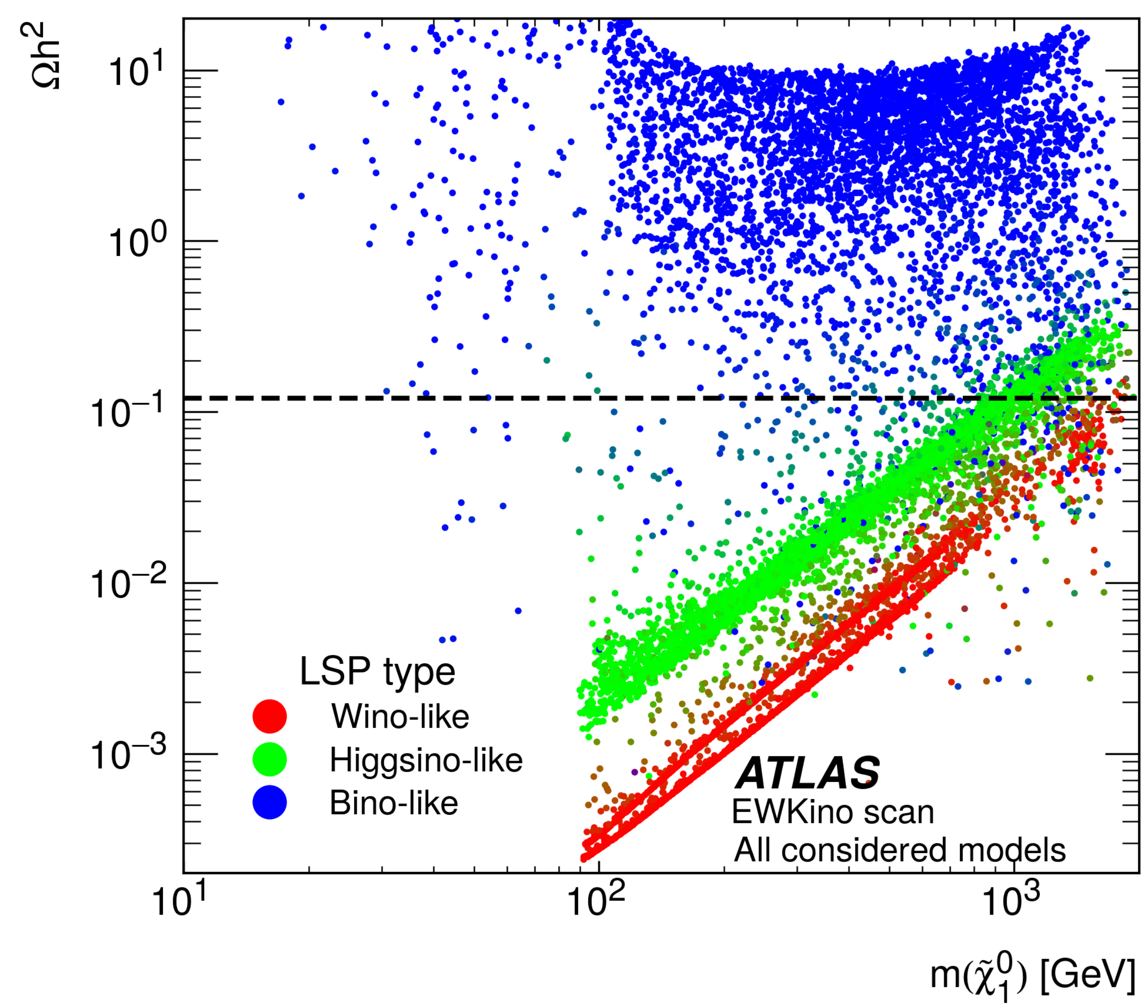
Minimal WIMPs:

- Electroweak multiplet coupled via SM gauge bosons
- Only free parameter in model is mass
- Requiring right thermal relic abundance gives specific mass target
  - Higgsino-like ~ 1.1 TeV
  - Wino-line ~ 2.8 TeV



Same points labelled by LSP type

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



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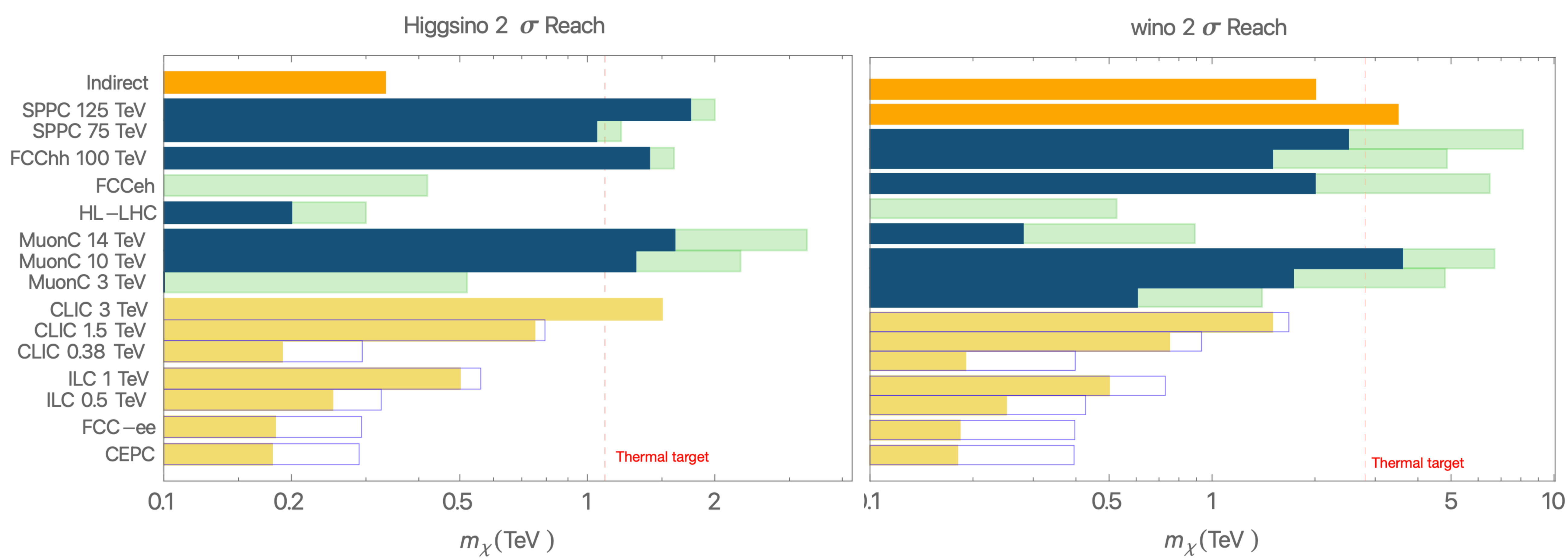
X+MET inclusive
Disappearing track
Kinematic limit, $0.5 \times E_{CM}$
Precision measurement

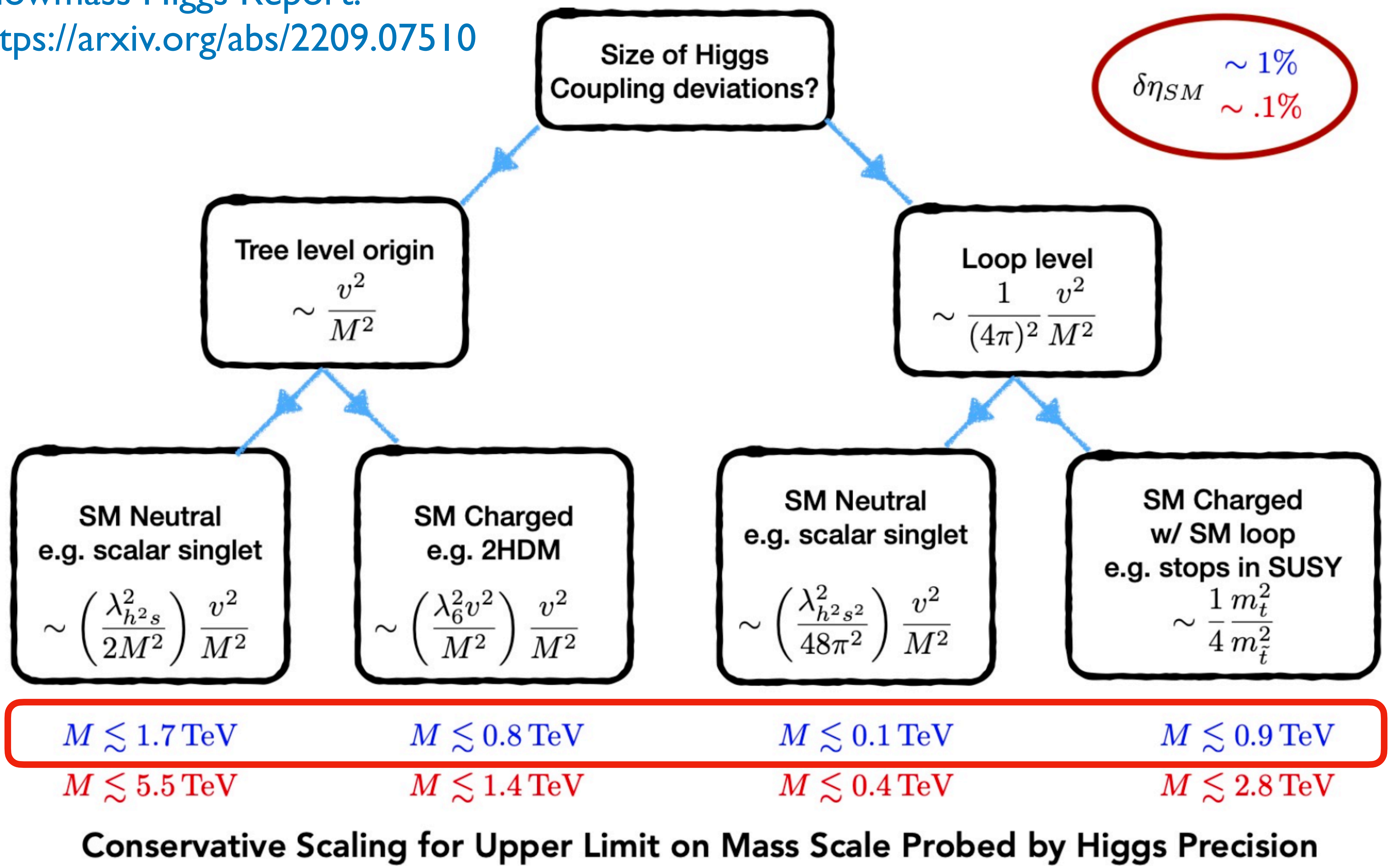


Beyond Minimal WIMPs:

- Huge variety of targets and methods
- Notably coupling DM with new mediator leads to many possible mediator searches

Precision Higgs Coupling vs hh reach

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

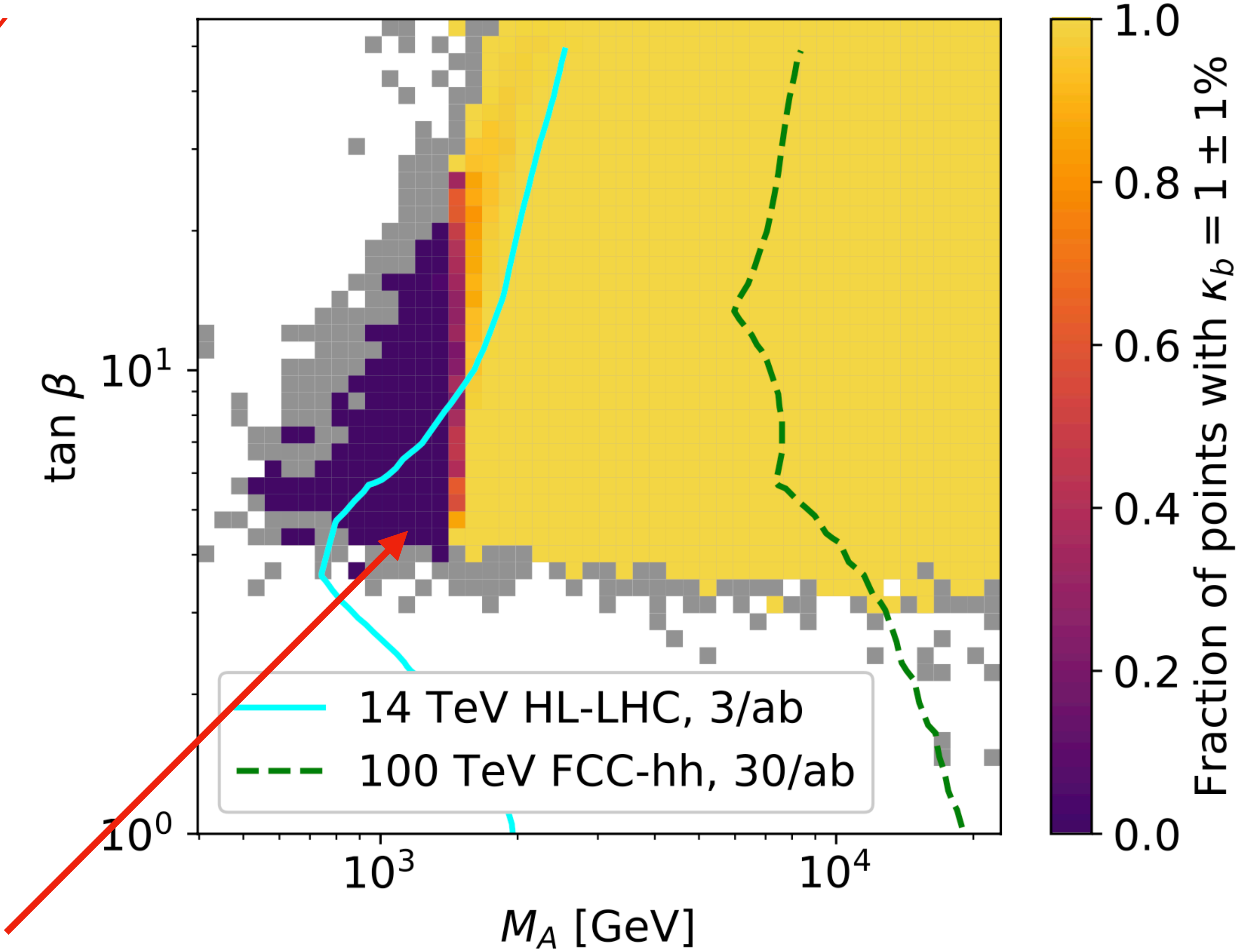


This is ~2-5 sigma at e+e- collider precision

Higgs Couplings vs Direct Searches

E.g. 2HDM in SUSY

Scan of currently possible pMSSM



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Region that would not already be found by LHC

https://arxiv.org/abs/2209.13128

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 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%
$B(\mathrm{H} \to \mathrm{invisible})$	B@95%CL	1×10^{-4}	2.5×10^{-4}

These are way beyond anything possible in a lepton collider for these rare modes

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

Maybe people will get smarter here

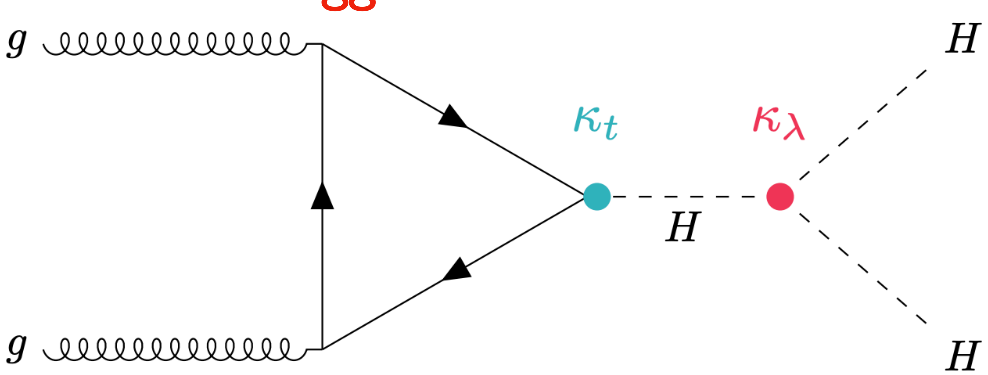
FCC-hh CDR: https://cds.cern.ch/record/2651300

Higgs Self-Coupling

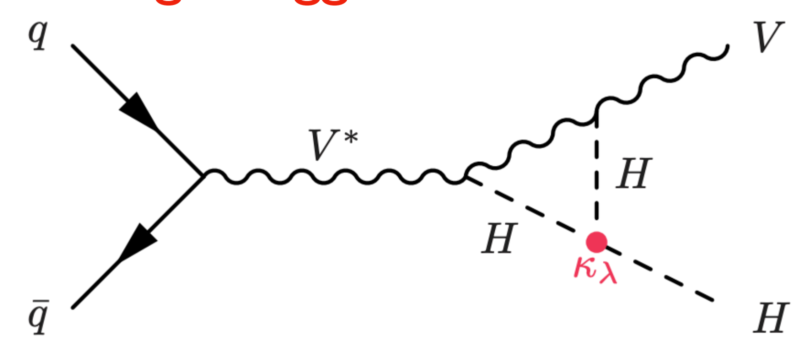
Connection to order of electroweak phase transition

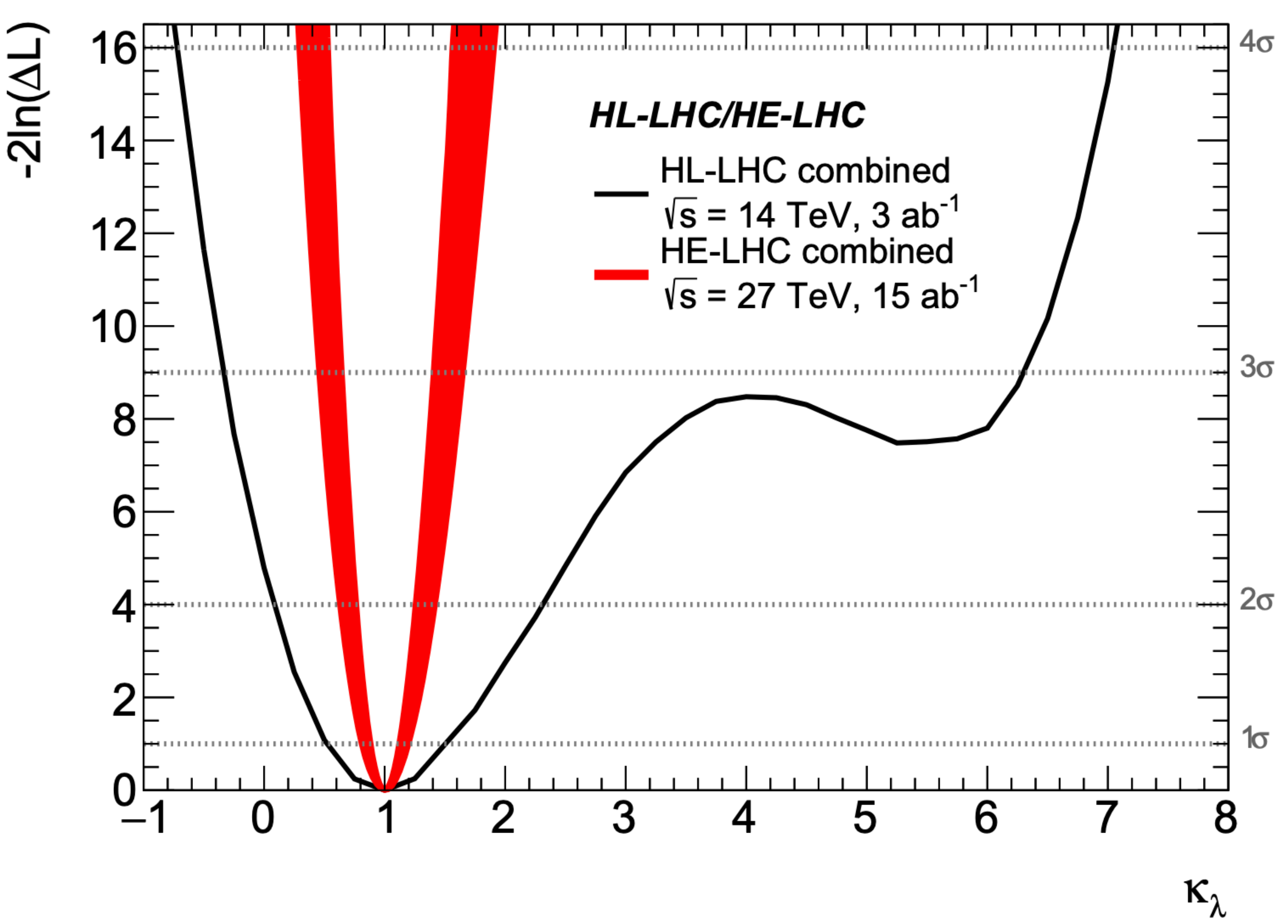
Need strongly 1st order transition to generate matter anti-matter asymmetry

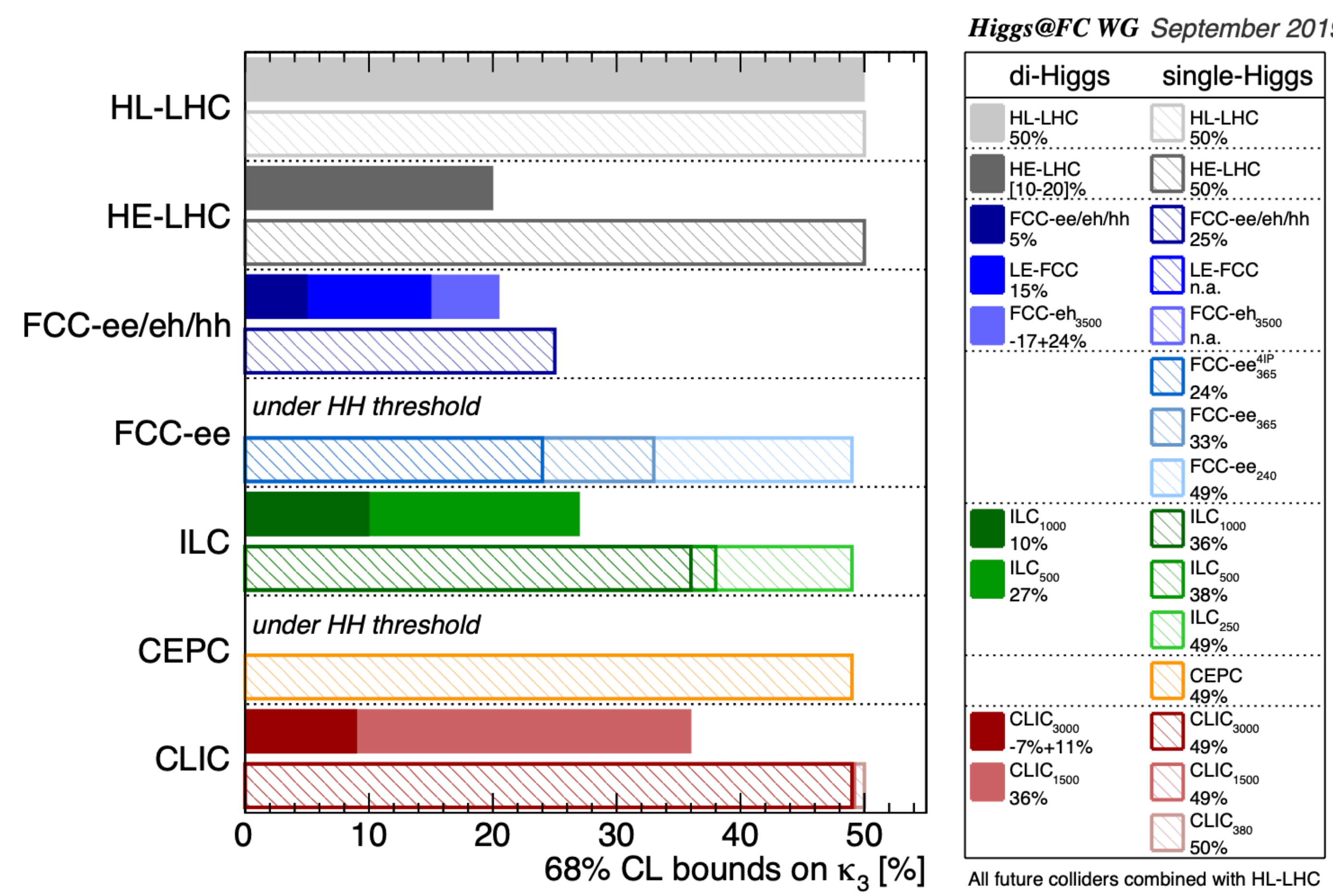
Di-higgs constraints



single-higgs constraints







Energy = Precision

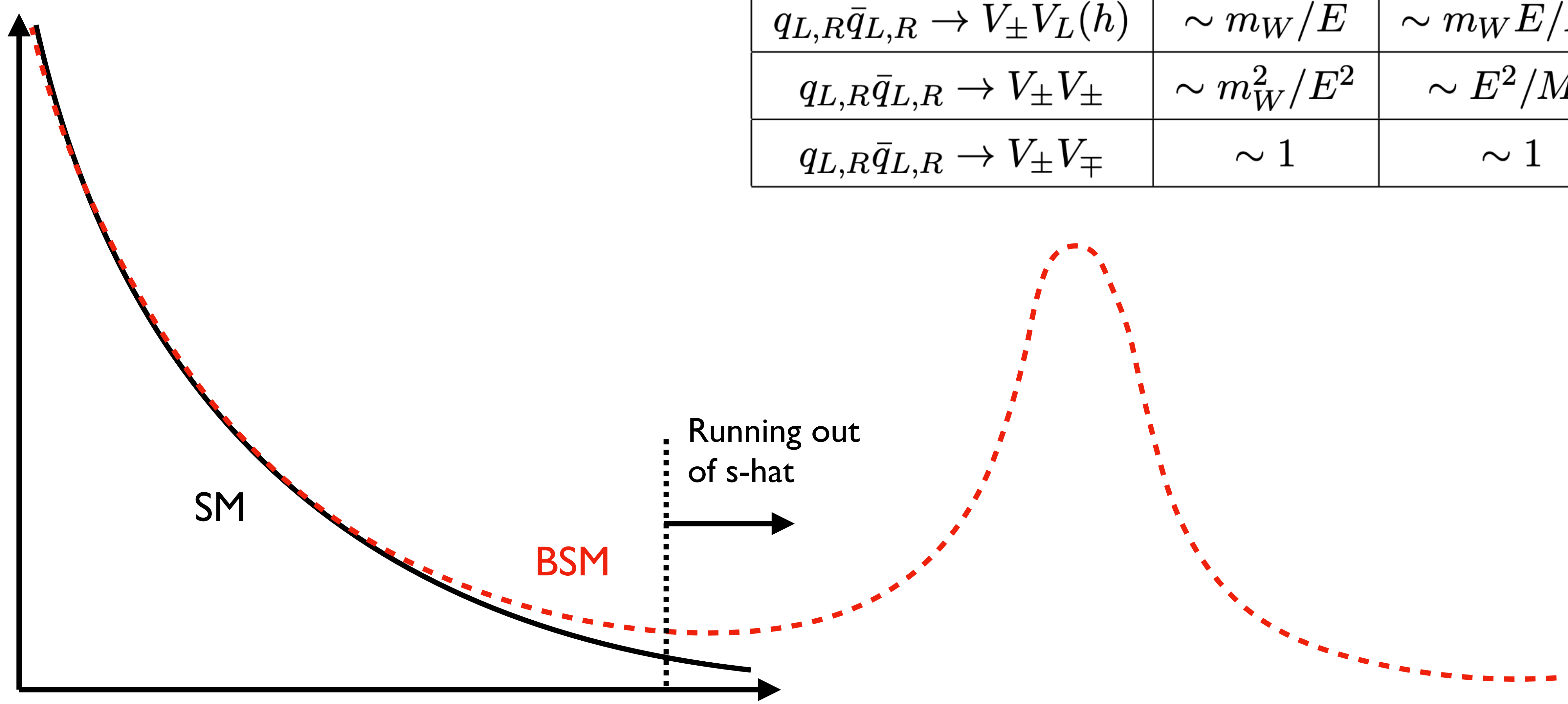
Effective Field Theory operator BSM effects generally grow with energy

This leads to an energy = precision logic

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

https://arxiv.org/abs/1712.01310

	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



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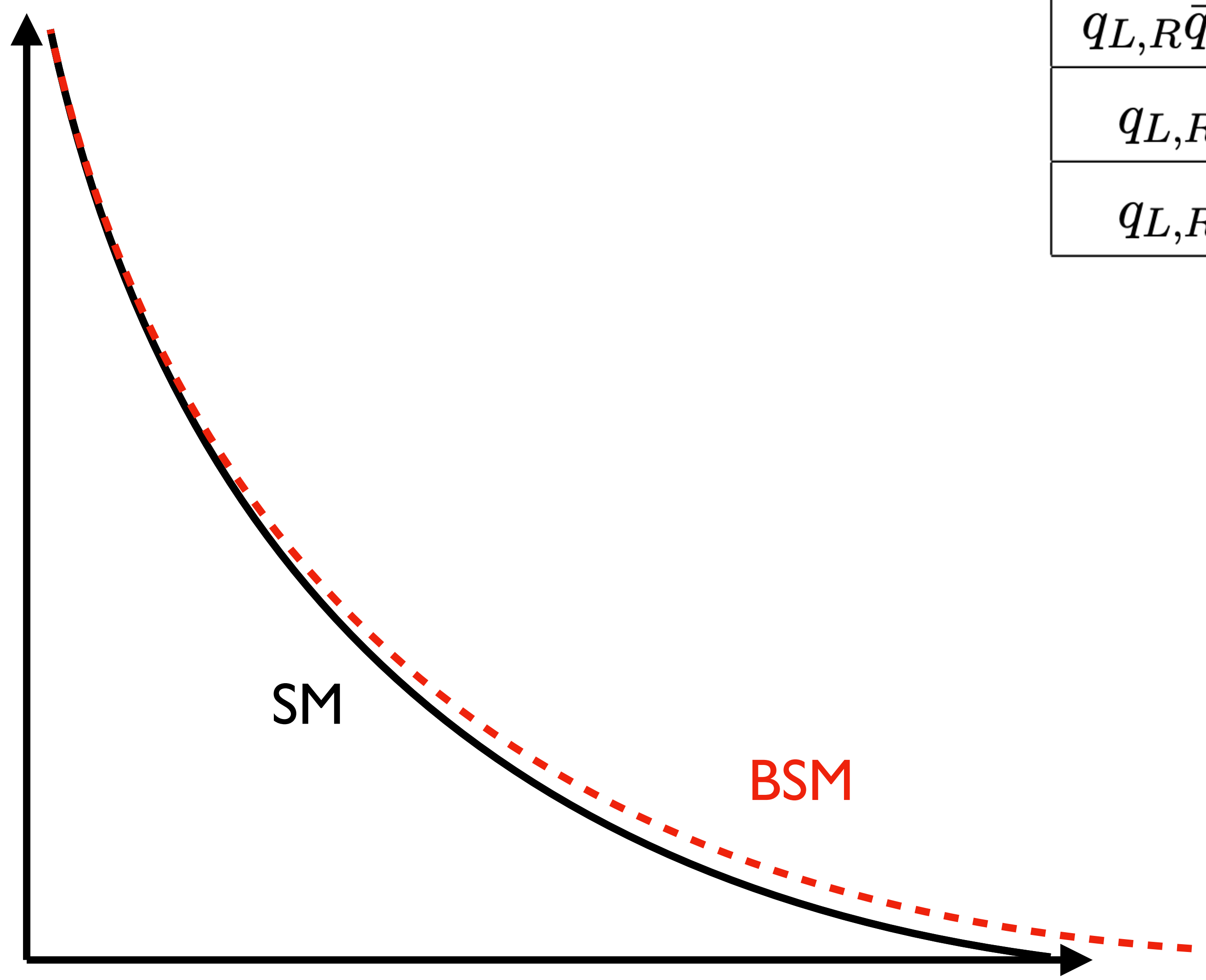
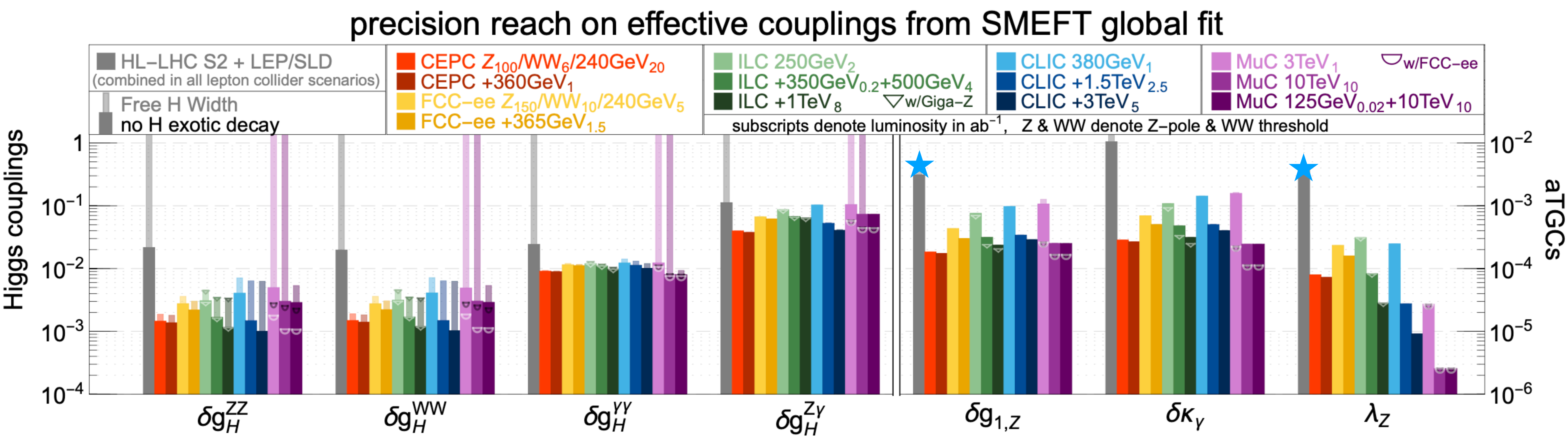


Precision EWK



Snowmass Precision Measurements Report (European Strategy very similar)

https://arxiv.org/abs/2209.08078

★ = CMS WV (lvJ): https://arxiv.org/pdf/1907.08354.pdf

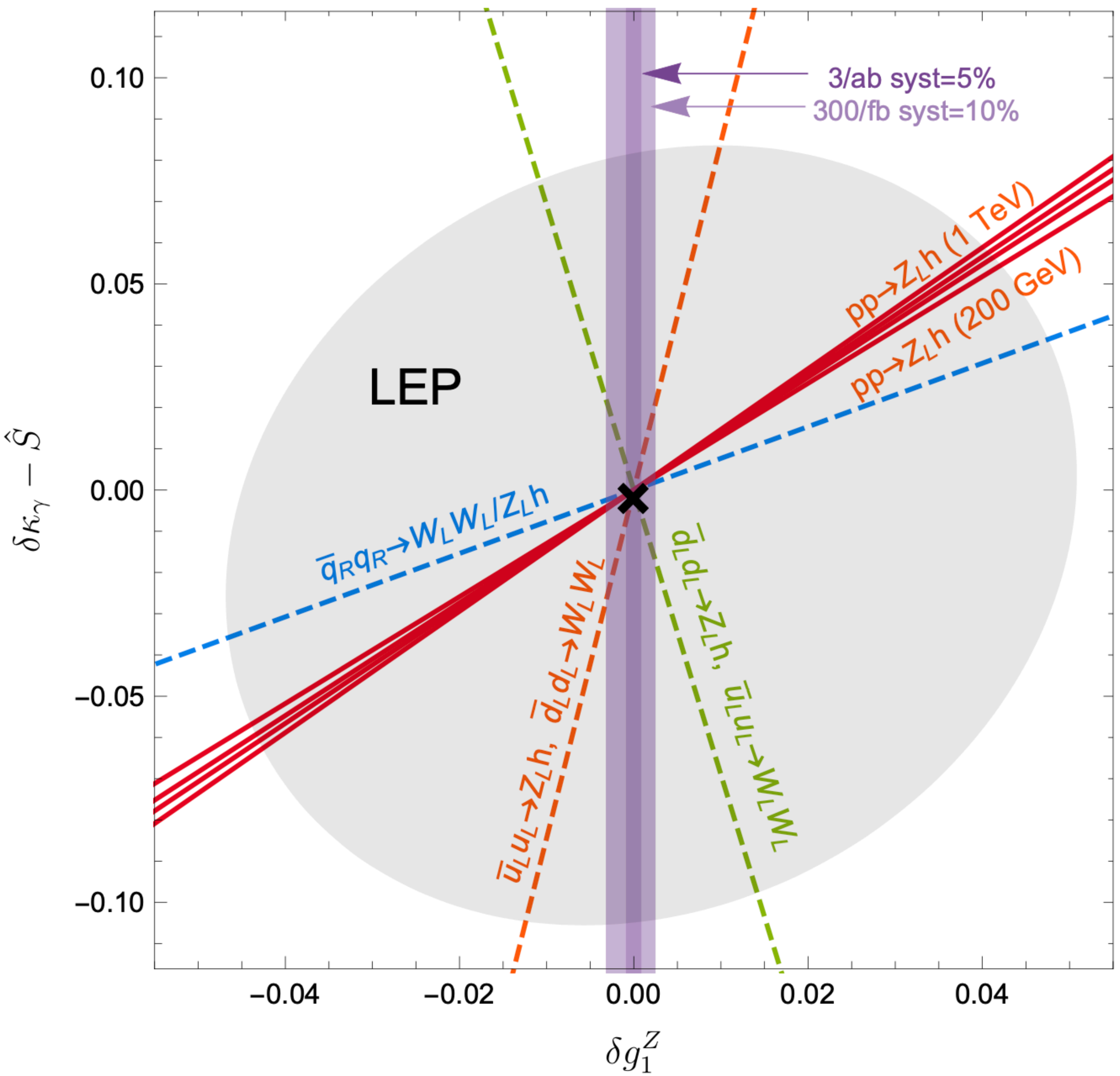
aTGC	Expected limit
λ_Z	[-0.0060, 0.0061]
Δg_1^Z	[-0.0070, 0.0061]
$\Delta \kappa_Z$	[-0.0074, 0.0078]

Issues:

1) HL-HLC limits are already met with CMS 35 fb^{-1} result
   - That's ~1/100th the final data
   - This probably due to projects based on leptonic instead of semileptonic measurement
2) No fcc-hh or other future hadron collider?
   - Sensitivity probably grows with E^2

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."

Example that has been done



https://arxiv.org/pdf/1712.01310.pdf

Purple band is (HL)-LHC

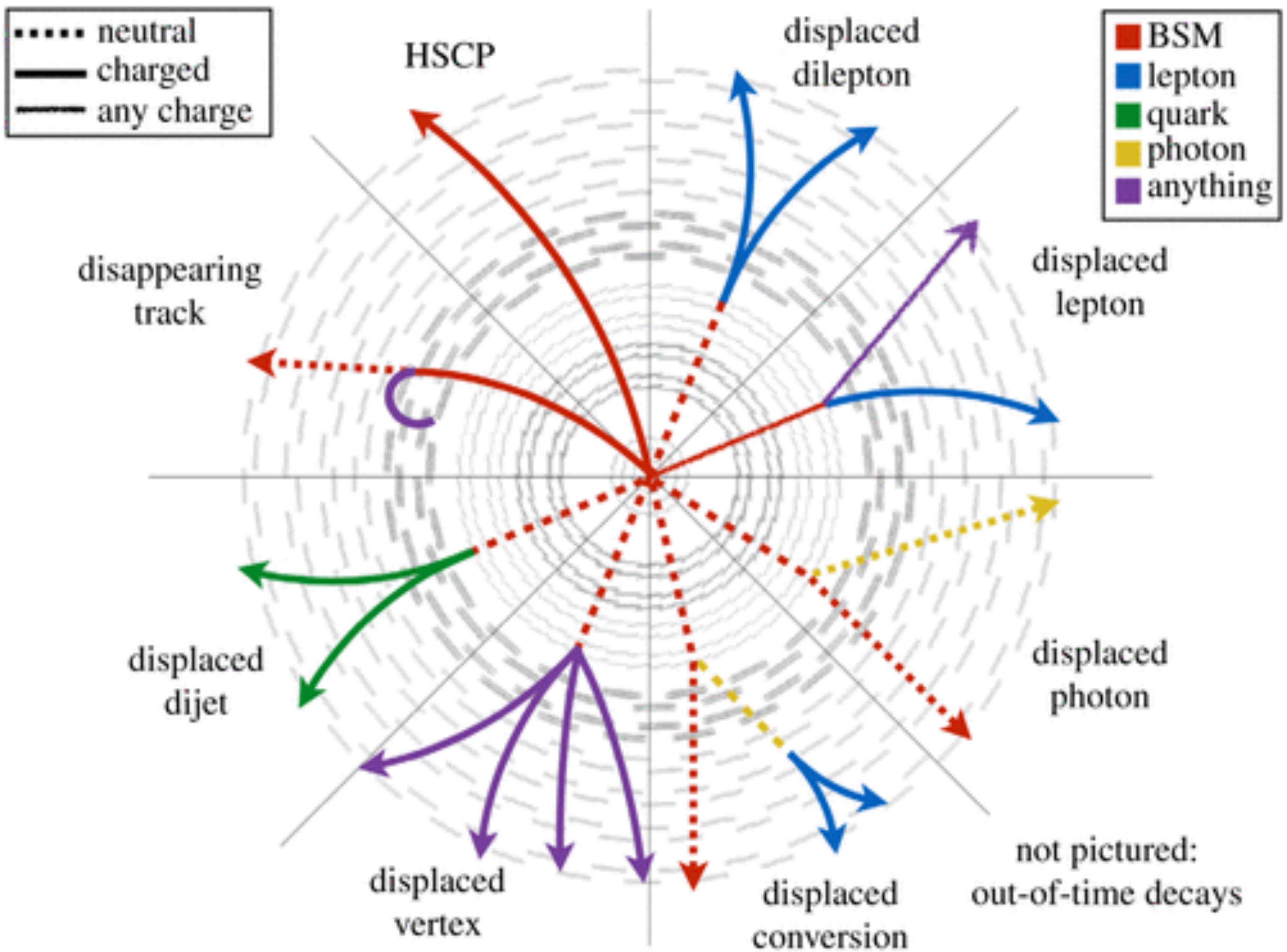
$$WZ \to \ell\nu\,\ell\ell$$

Details…

- This is much lower than limits on Snowmass plot!
- Analysis could certainly be more sophisticated.
- Semileptonic is likely more sensitive

Exotic Signatures

Exotic Signatures like Long-Lived Particles can be very clean



Detectors Challenges

Parameter	Unit	LHC	HL-LHC	HE-LHC	FCC-hh
E_{cm}	TeV	14	14	27	100
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950 (~175 for early phase)
Line PU density	mm^{-1}	0.2	1.0	3.2	8.1
Rate of charged tracks	GHz	59	297	1234	3942

Pile-up…

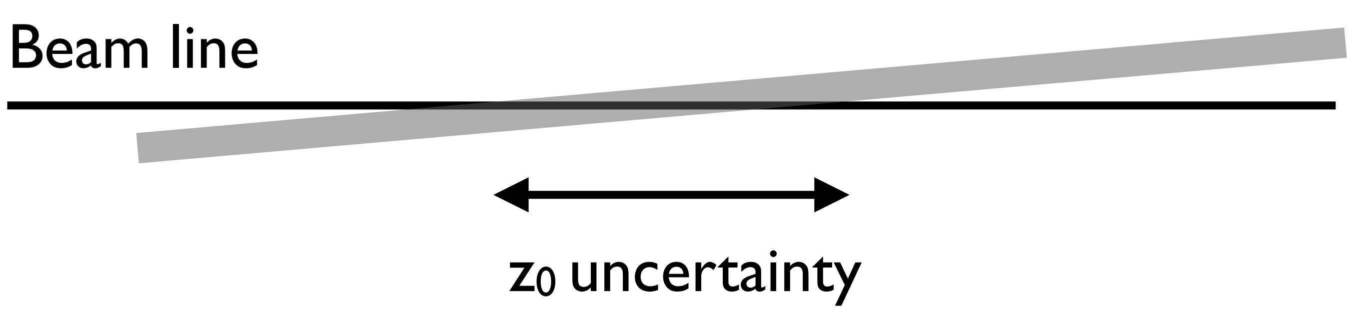
At most a few pile-up in neighborhood within z_0 resolution of a track

Order of magnitude worse (~double for early phase)

Pixel detectors should be able to deal with this

Timing detectors seem like the obvious solution

Especially in forward region where tracks nearly parallel to beam



Track trajectory with uncertainty band

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

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Charged part. flux at 2.5 cm, est. (FLUKA)	$\mathrm{GHz\,cm^{-2}}$	0.1	0.7	2.7	8.4 (10)
1 MeV-neq fluence at 2.5 cm, est. (FLUKA)	$10^{16}\,\mathrm{cm^{-2}}$	0.4	3.9	16.8	84.3 (60)
Total ionising dose at 2.5 cm, est. (FLUKA)	MGy	1.3	13	54	270 (300)

Detector Radiation Issues…

Already, HL-LHC innermost pixel layer might not make it past ~2 $\mathrm{ab^{-1}}$

From FCC-hh CDR: "Novel sensors and readout electronics have to be developed for the innermost parts of the tracker"

Radiation levels where we want inner pixel detectors are insane!

(Early phase ~5x less only slightly insane)

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

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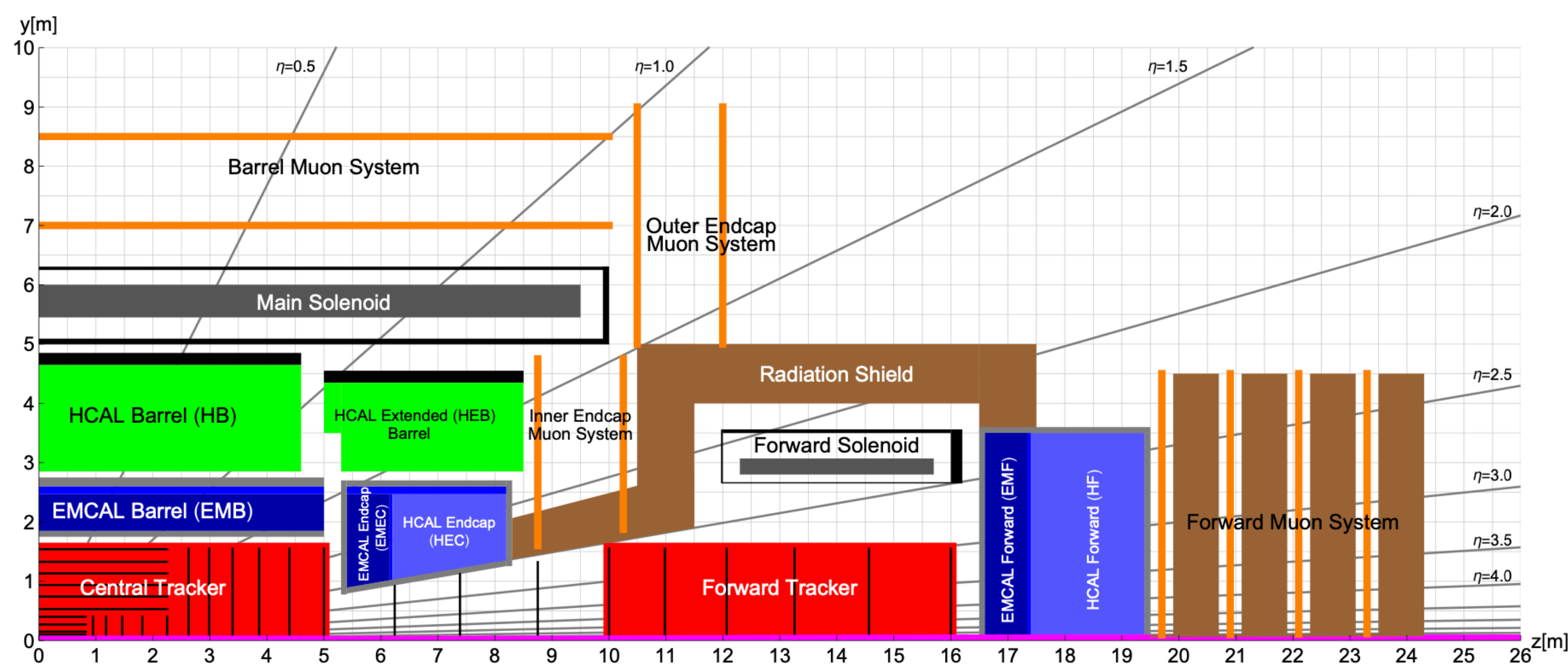
E_{cm}	TeV	14	14	27	100
Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950 (~175 for early phase)
90% $b\bar{b}$ $p_T^b > 30\,\text{GeV/c}$ [341]	$\|\eta\| <$	3	3	3.3	4.5
VBF jet peak [341]	$\|\eta\|$	3.4	3.4	3.7	4.4
90% VBF jets [341]	$\|\eta\| <$	4.5	4.5	5.0	6.0
90% $H \to 4l$ [341]	$\|\eta\| <$	3.8	3.8	4.1	4.8

Electroweak scale physics is at higher rapidity

Current LHC detectors only track to ~2.5, HL-LHC detectors plan tracking to go to 4

Would like another ~ 1-1.5 units of rapidity but its hard

FCC-hh CDR does have plan for this



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Peak av. PU events/BC, nominal (ultimate)		25 (50)	130 (200)	435	950 (~175 for early phase)
$b\bar{b}$ $p_T^b > 30\,\mathrm{GeV/c}$ rate	MHz	0.02	0.08	1	8
Jets $p_T^{\mathrm{jet}} > 50\,\mathrm{GeV/c}$ rate	MHz	0.2	1.1	14	90
$W^+ \rightarrow l + \nu$ rate	kHz	0.12	0.6	5.8	23
$W^- \rightarrow l + \nu$ rate	kHz	0.1	0.5	4.5	19
$Z \rightarrow ll$ rate	kHz	0.02	0.1	1	4.2

Rates of electroweak physics are close to the LHC first-level trigger rates

Trigger…

From FCC-hh CDR: "This essentially means that today's offline algorithms have to be migrated to the trigger"

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

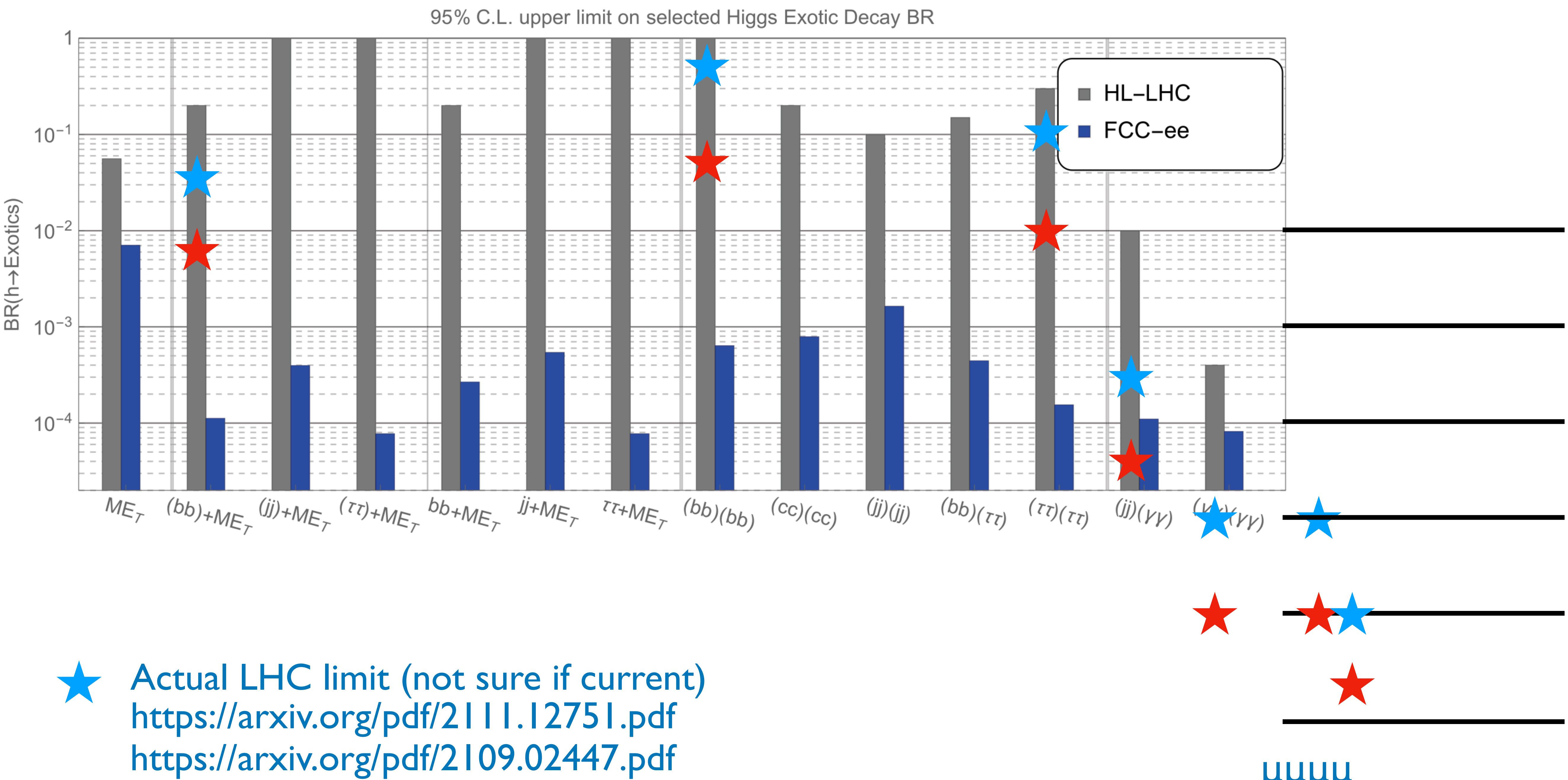
Hadron Colliders Provide Great Reach

Biggest Issue is that not only will I not be likely to see it, my junior graduates students may not either

- We know how to build a good step in energy now
  - This would advance:
    - Higgs Self-coupling / Electroweak Phase Transition
    - Dark Matter (and mediators)
    - Naturalness
- Comparison with precision are not complete…
- There are large detector challenges but at least to a lower luminosity (HL-LHC-like) phase no miracles have to happen

Backup

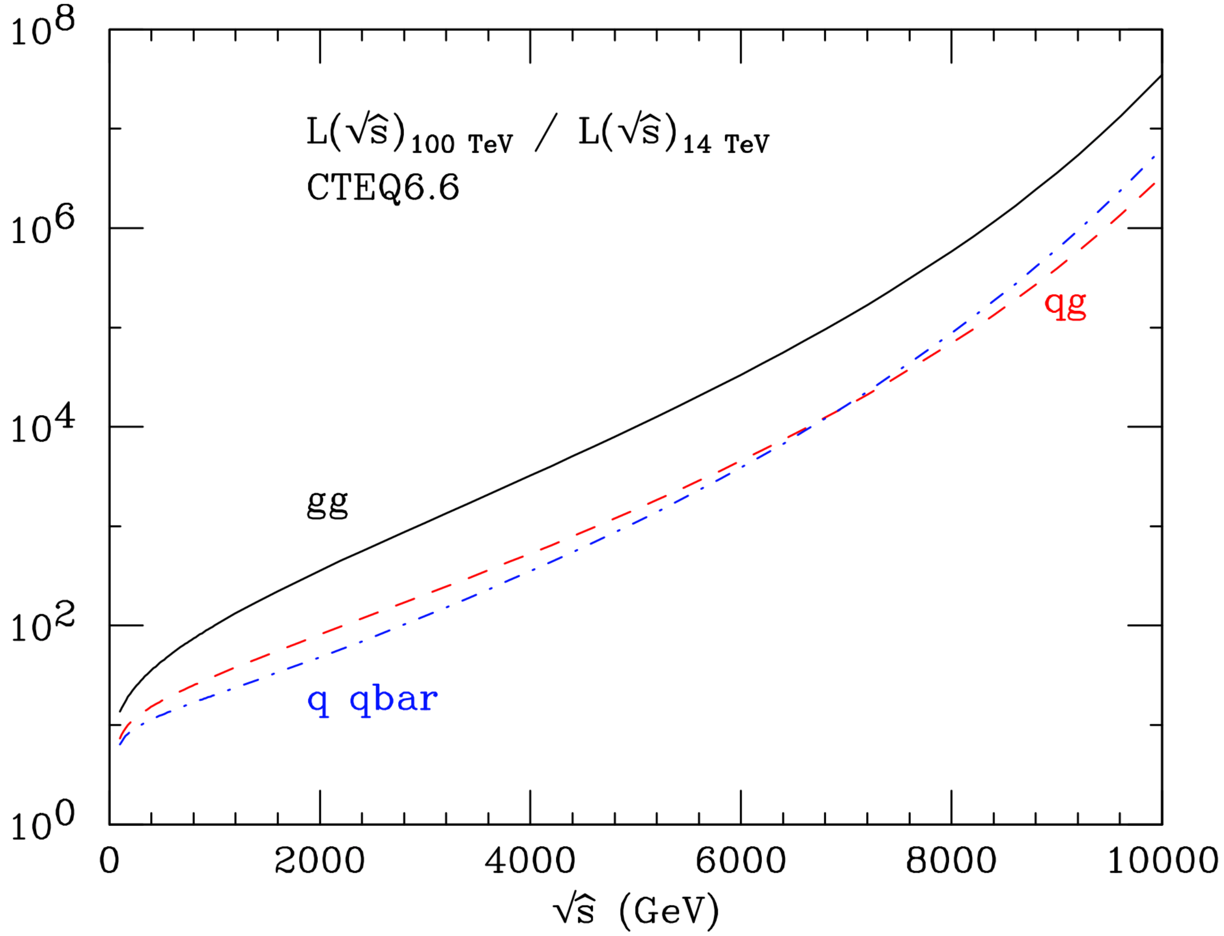
Exotic Higgs…

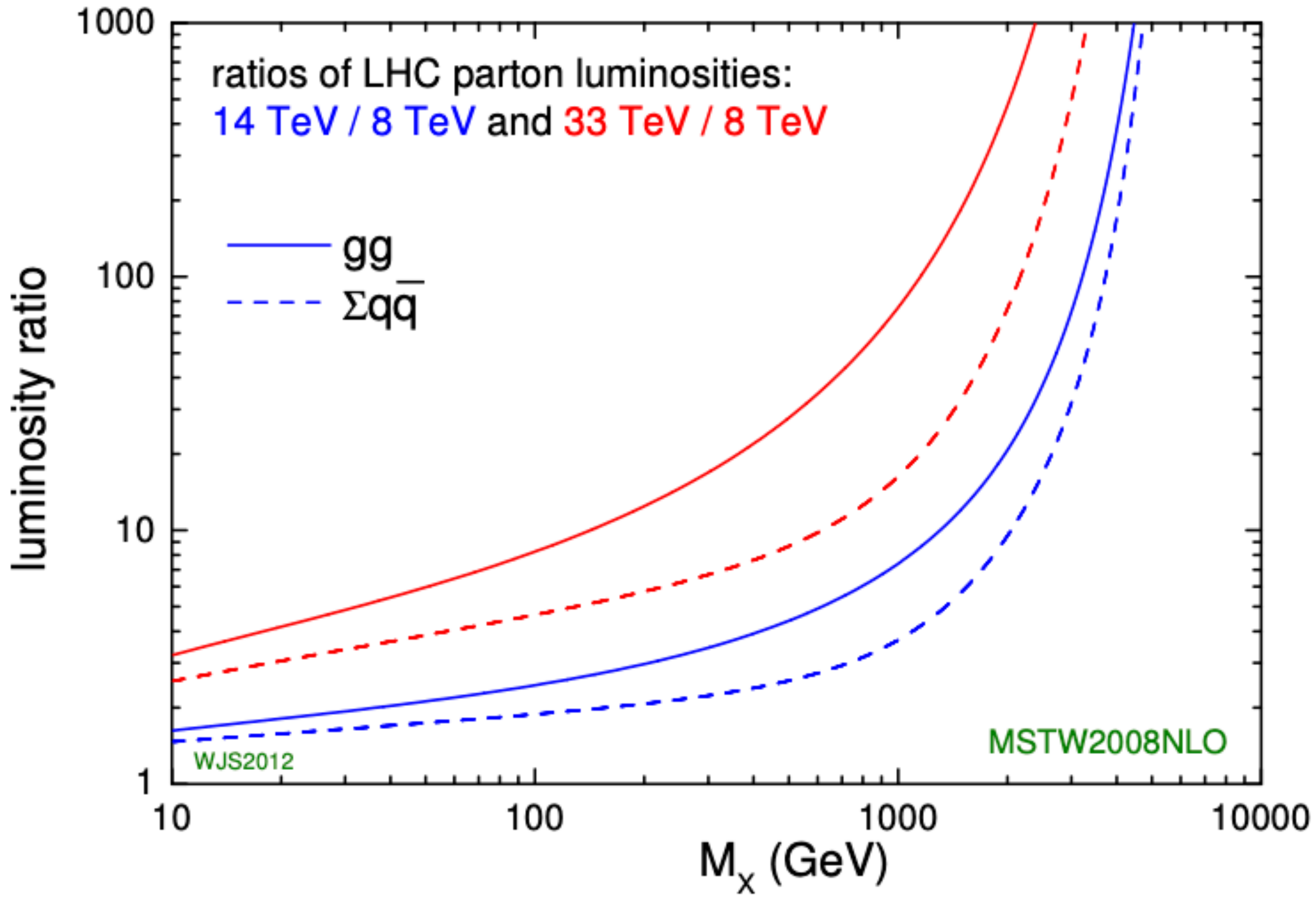


Actual LHC limit (not sure if current)
https://arxiv.org/pdf/2111.12751.pdf
https://arxiv.org/pdf/2109.02447.pdf

Extrapolated assuming sqrt(Lumi)

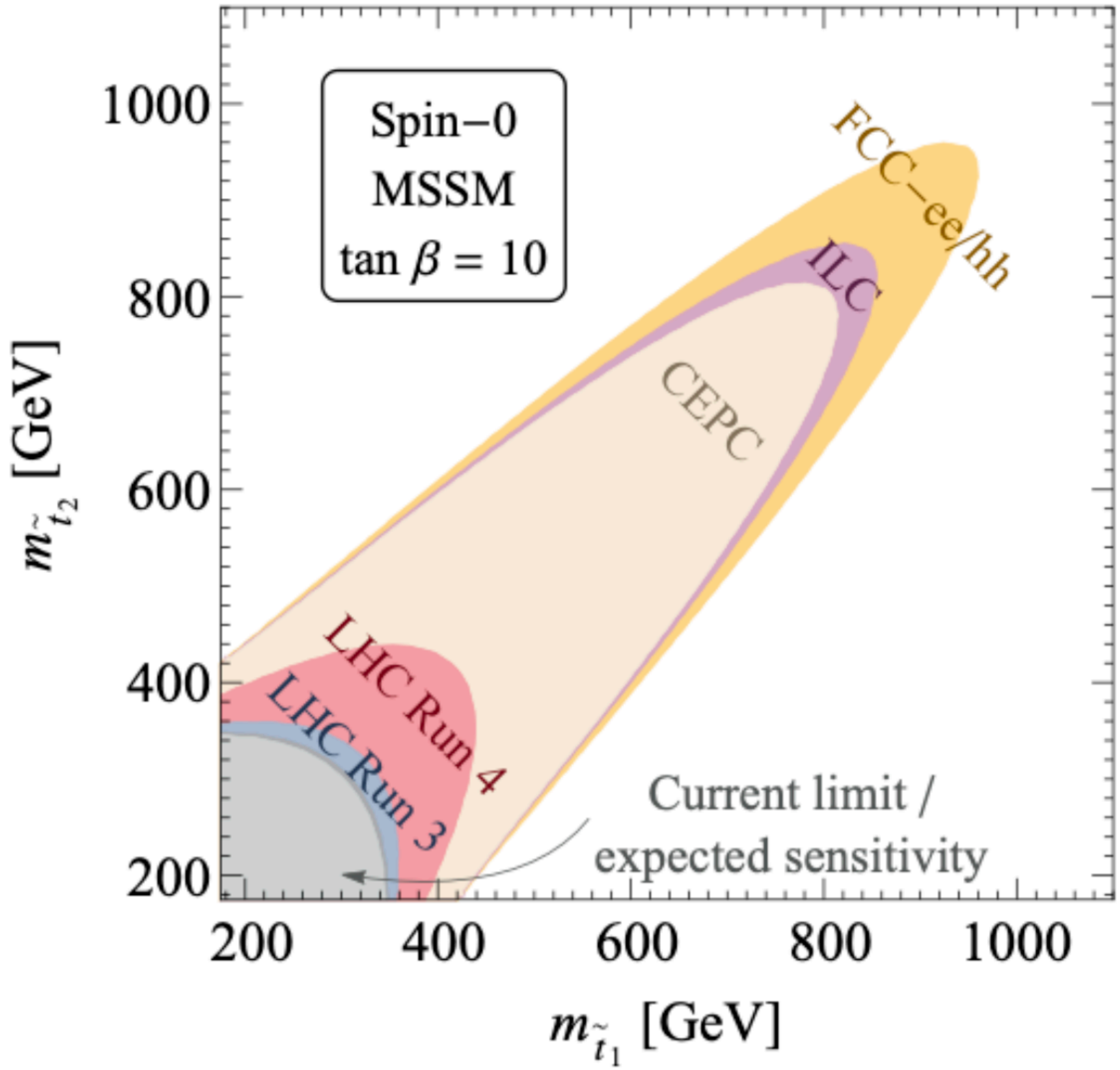
Parton Luminosity Ratios





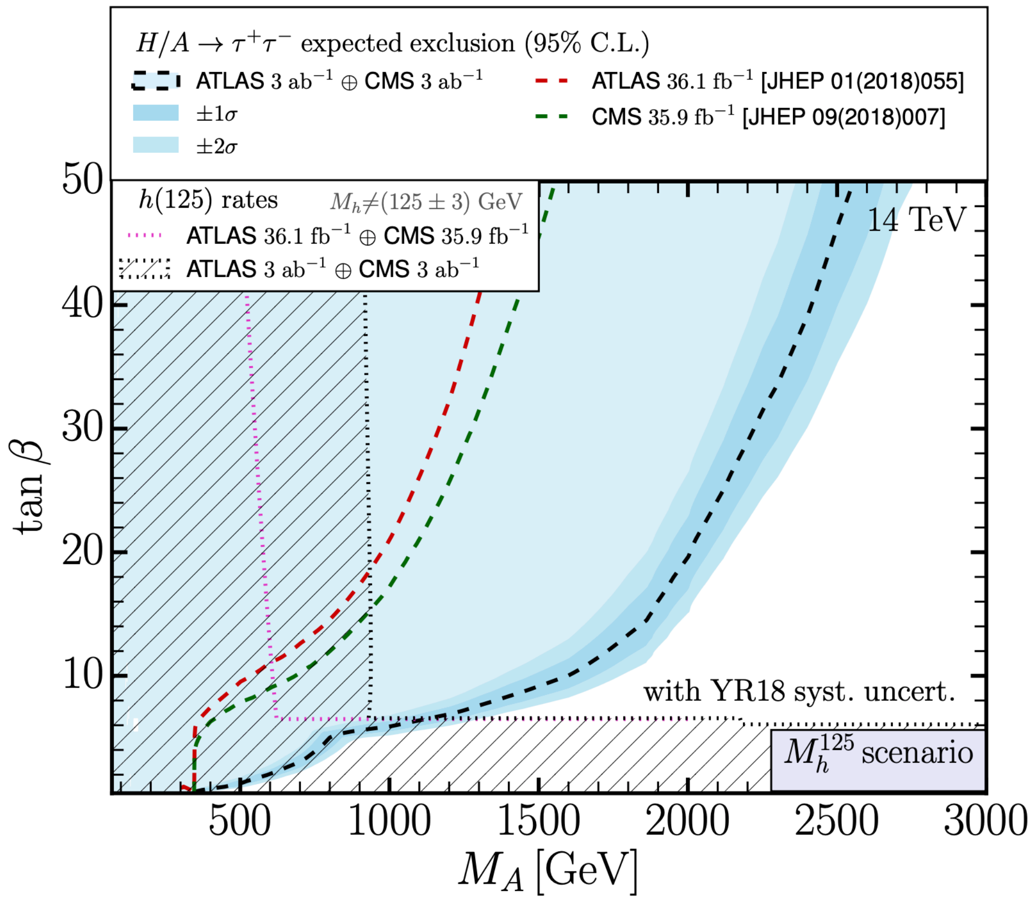
https://arxiv.org/pdf/1504.06108.pdf

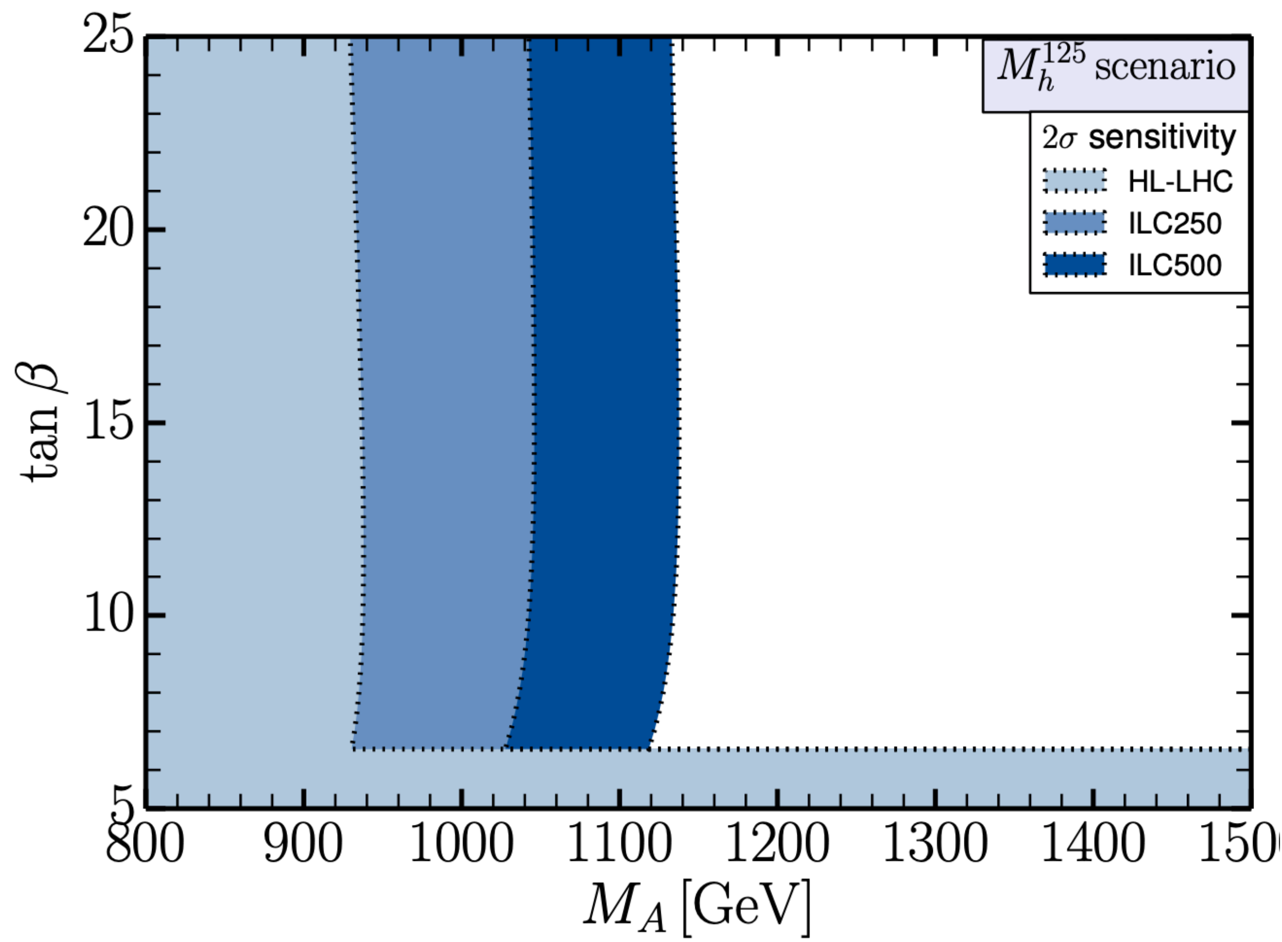
Indirect Stop Constraints



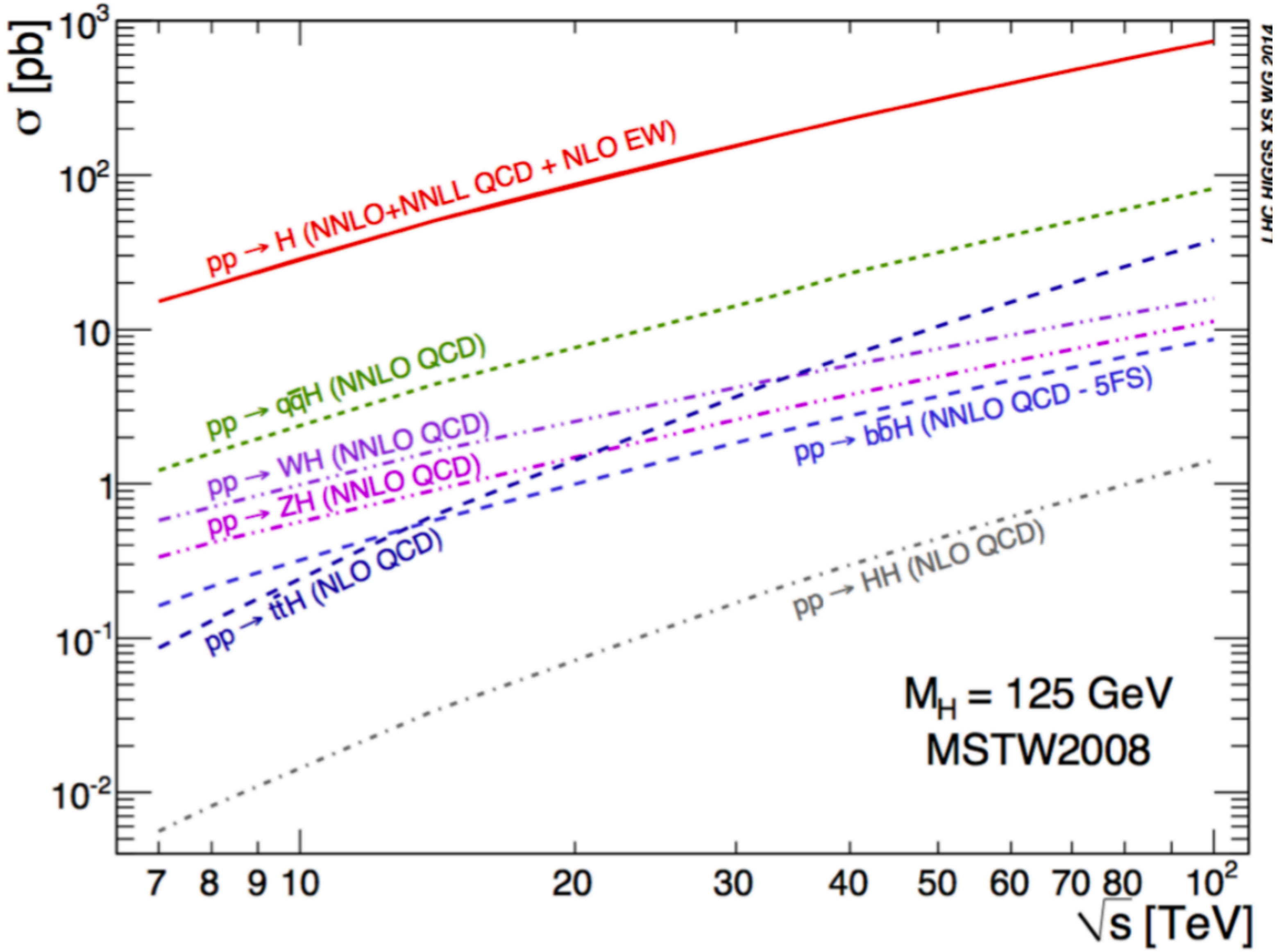
https://arxiv.org/pdf/1707.03399.pdf

Higgs Couplings vs Direct Searches

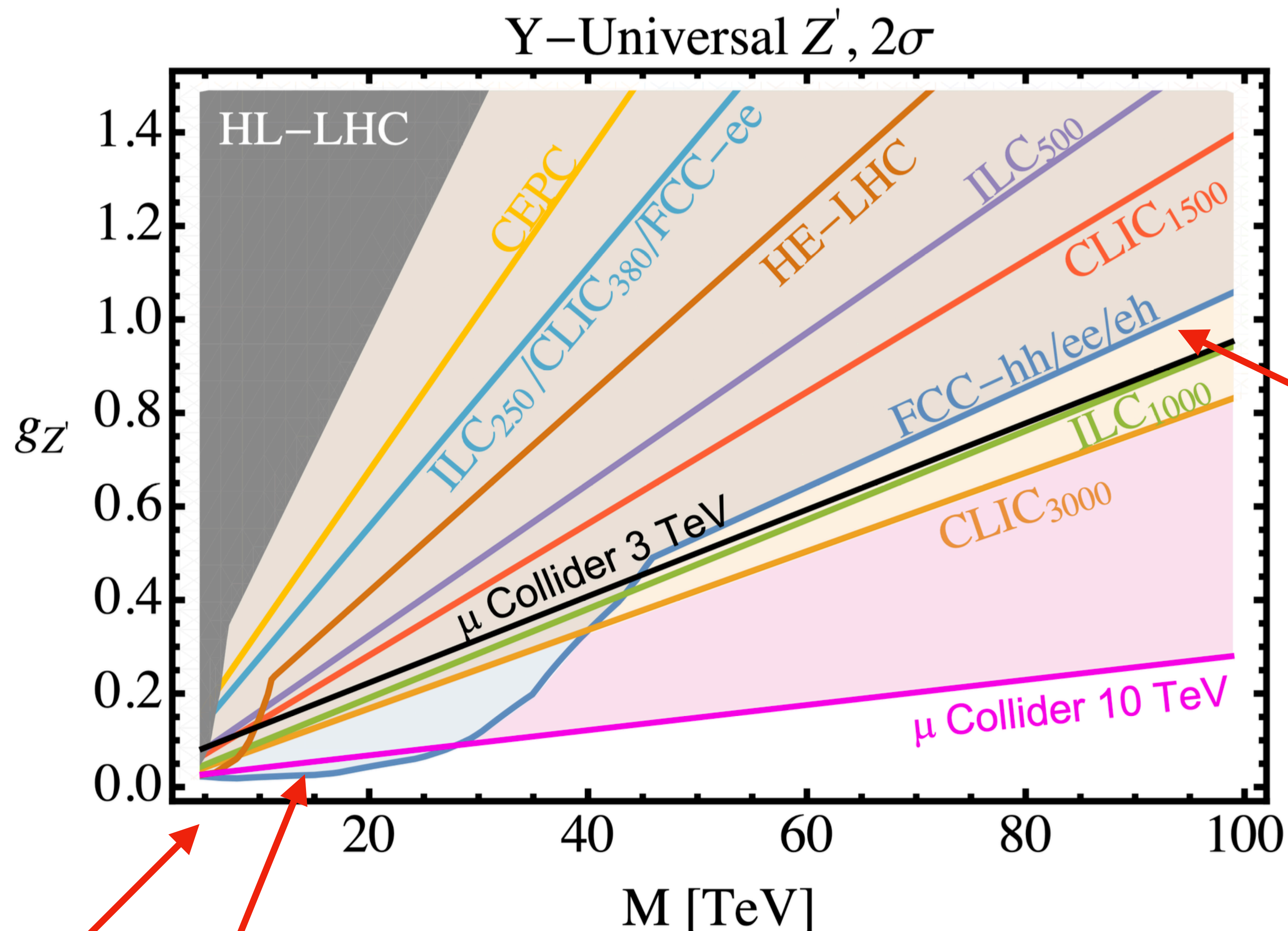




Higgs Cross-section vs sqrt(s)



Precision Physics Constraints

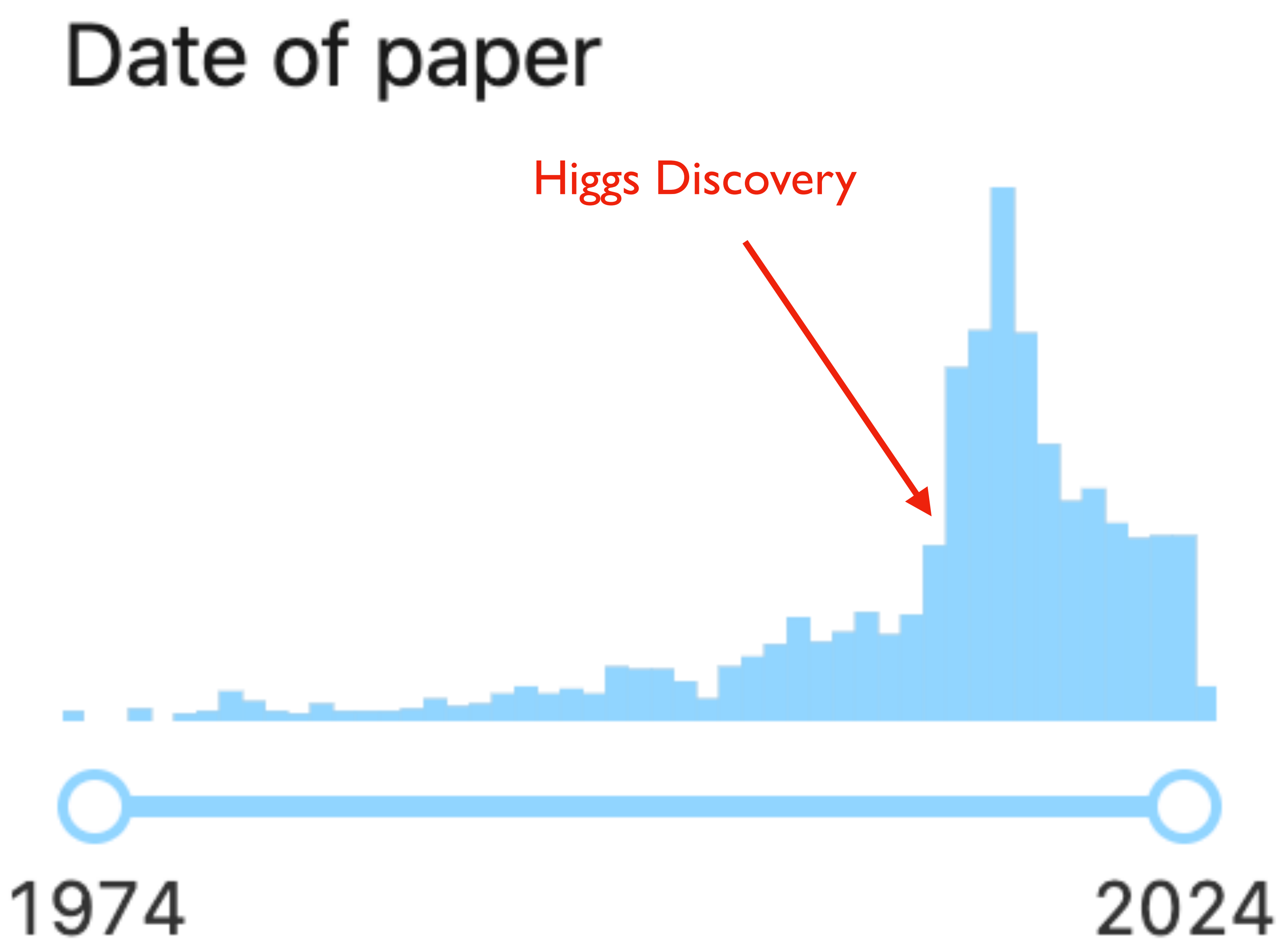


Indirect Constraints

5 TeV !

Direct Production Constraints

Naturalness Papers vs Time



Stop mass in light of 125 GeV