# Theory Perspective

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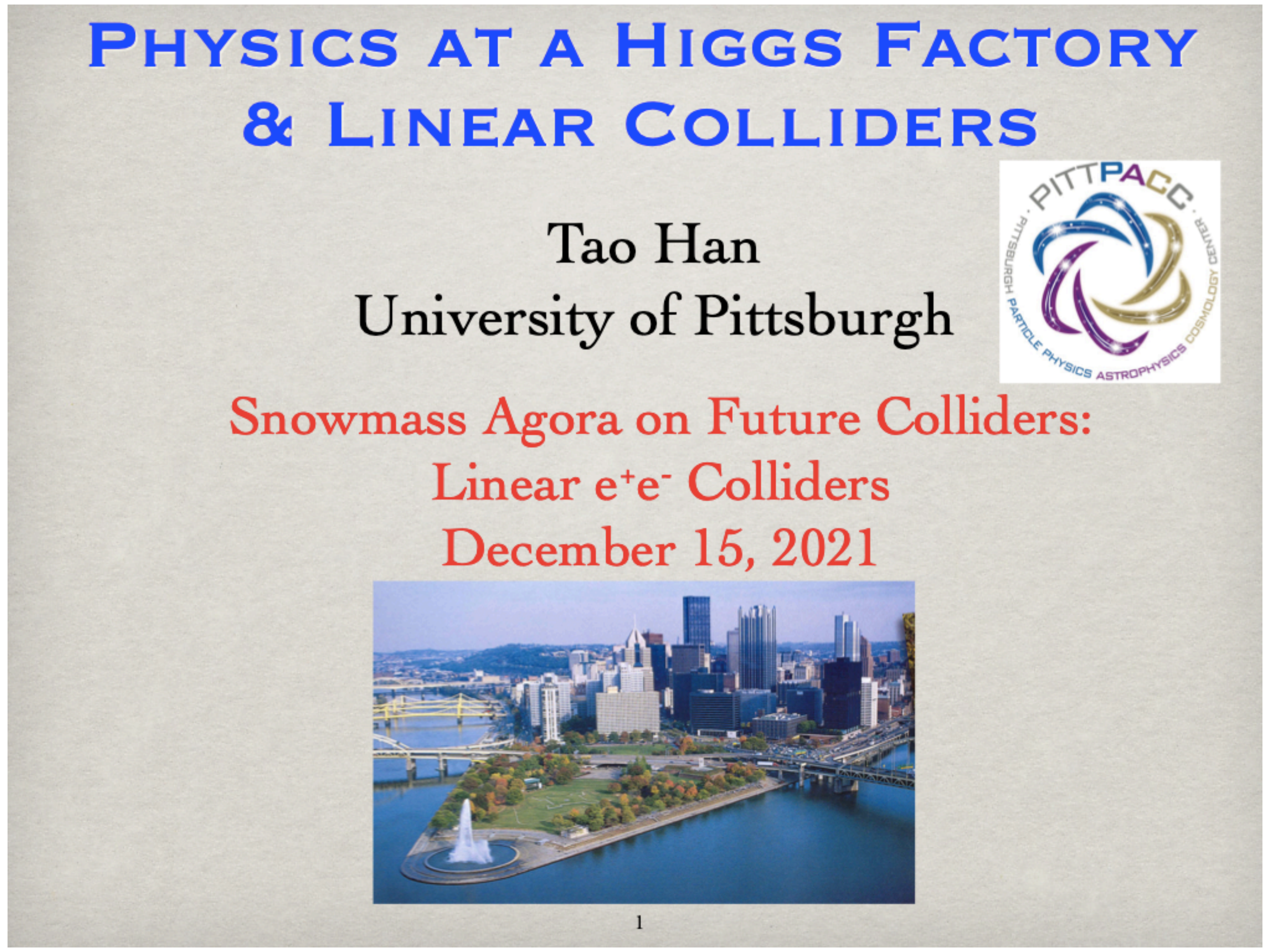
# Previous Agoras and the Physics Cases




FCC

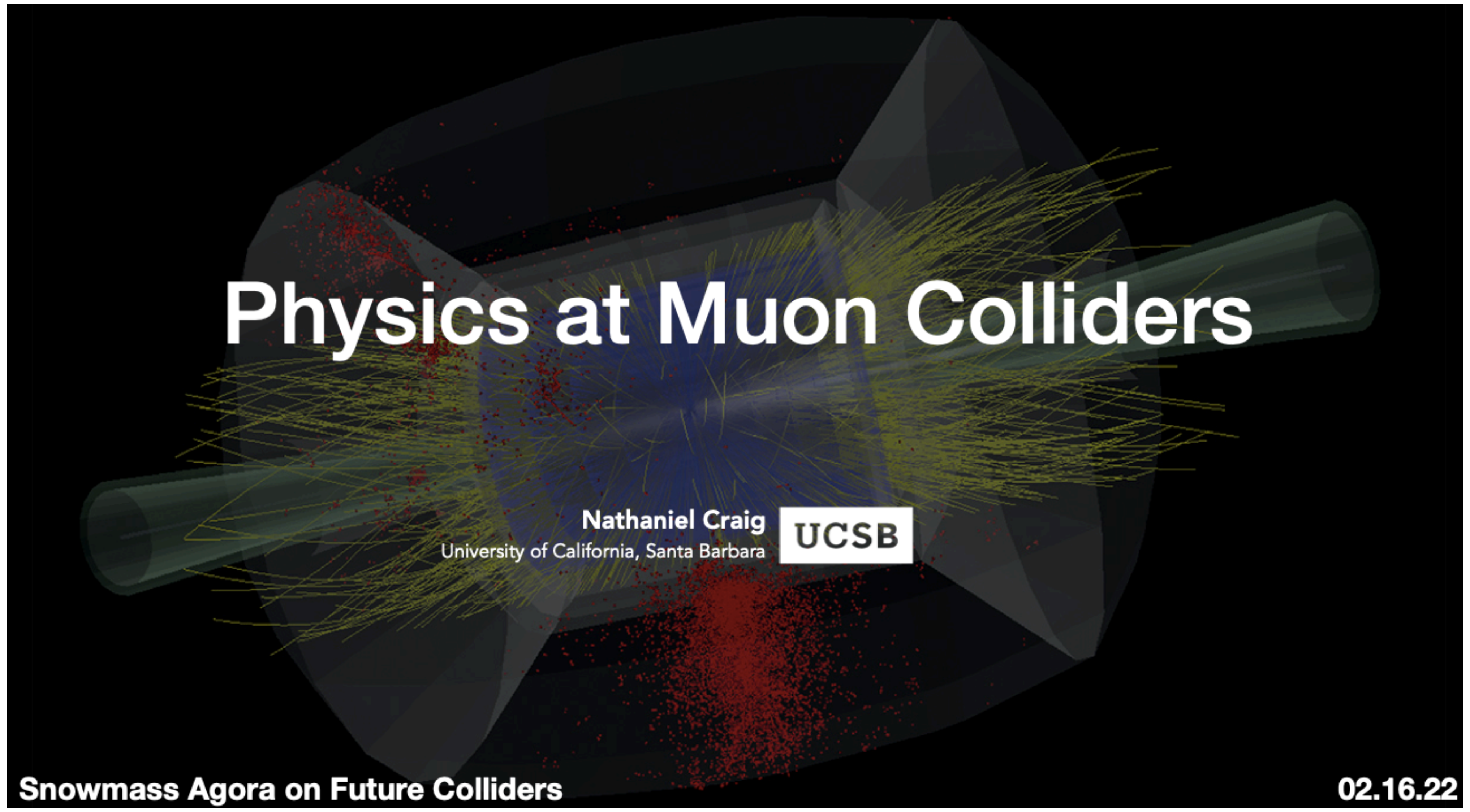
## Physics at FCC-ee

A great Higgs Factory and MUCH MORE!

**Mutatis mutandis, CEPC Physics is potentially the same**

Many thanks to the FCC collaboration members for the great efforts and ideas joining Theory, Experiment and Accelerator Physics.

01.04.22 Alain Blondel FCC-ee Physics

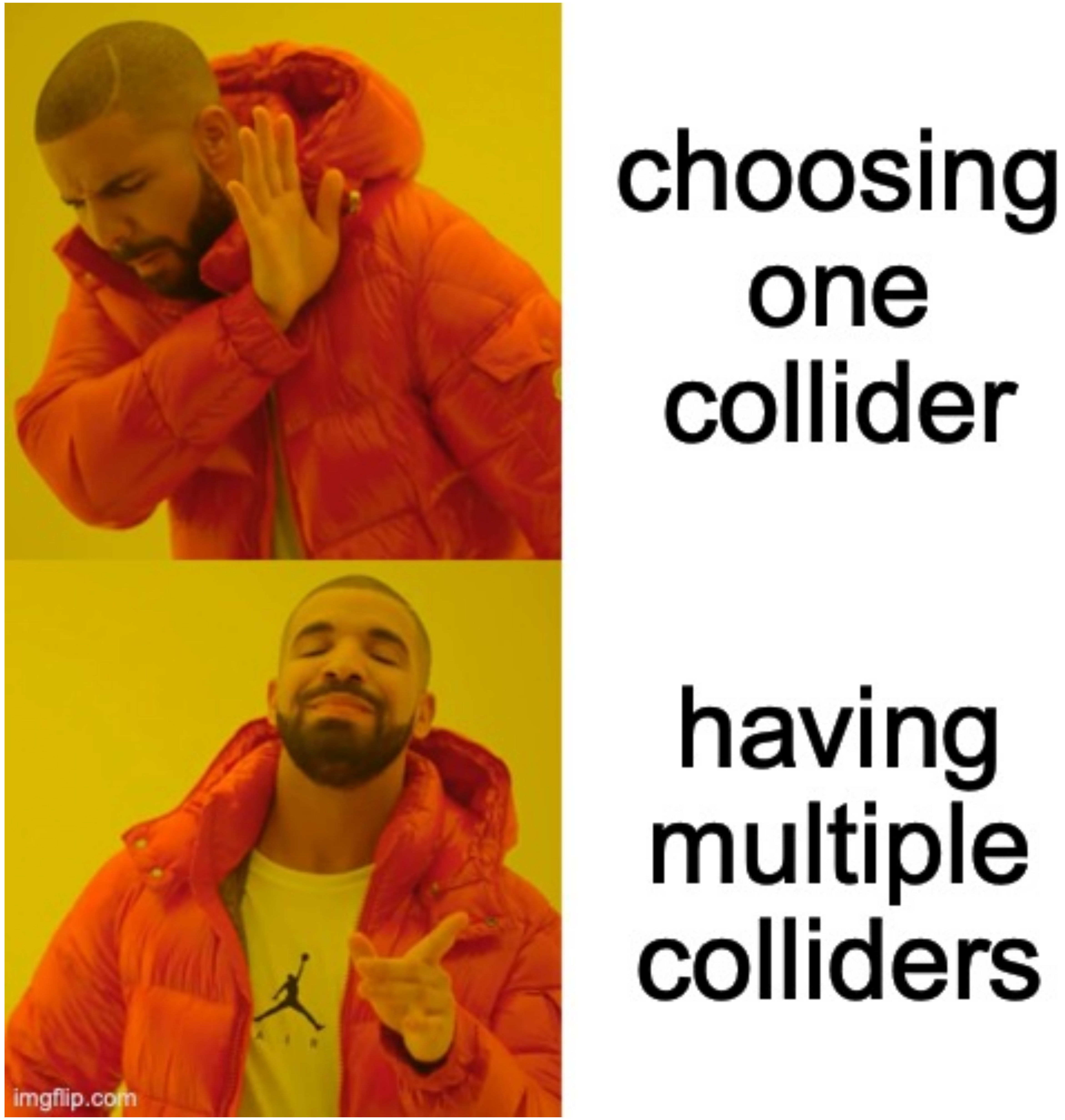



## Physics motivation for future hh-eh colliders

Michele Selvaggi

CERN

# Theory Perspective...



# Theory Perspective…

**I'd like more energy, more luminosity while maintaining precision at lowest energy scales possible and please do this all without a trigger**

# Theory Perspective...

First lesson... theorists will always over ask

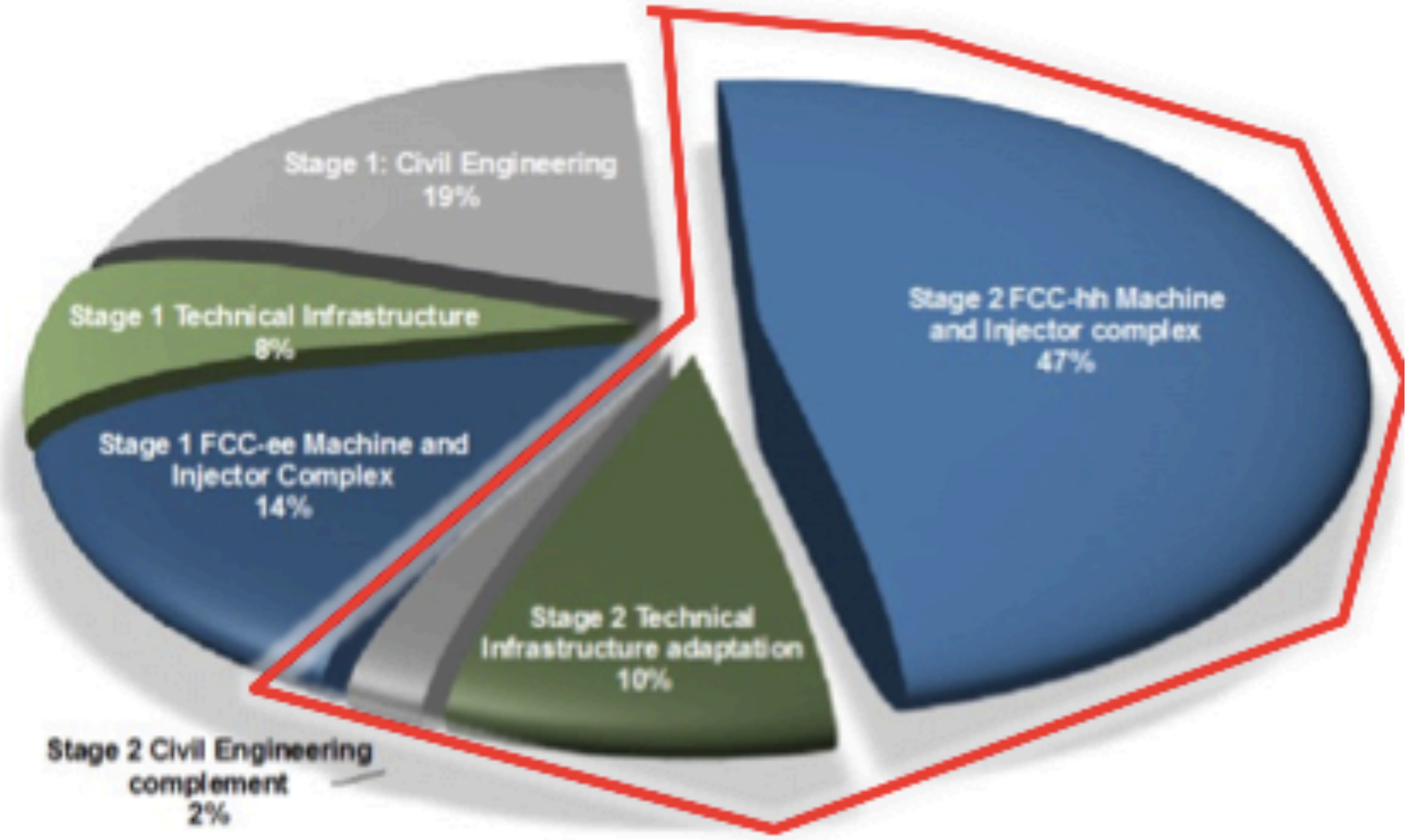
Then reality sets in (or a parent says no...)

# Then reality sets in budgets...

## FCC-hh cost estimate as part of FCC-integrated project cost estimate

FUTURE CIRCULAR COLLIDER

| Domain | Cost in MCHF |
|---|---|
| Stage 1 - Civil Engineering | 5,400 |
| Stage 1 - Technical Infrastructure | 2,200 |
| Stage 1 - FCC-ee Machine and Injector Complex | 4,000 |
| Stage 2 - Civil Engineering complement | 600 |
| Stage 2 - Technical Infrastructure adaptation | 2,800 |
| Stage 2 - FCC-hh Machine and Injector complex | 13,600 |
| **TOTAL construction cost for integral FCC project** | **28,600** |




Total construction cost FCC-ee (Z, W, H) amounts to 10,500 MCHF & 1,100 MCHF (tt).

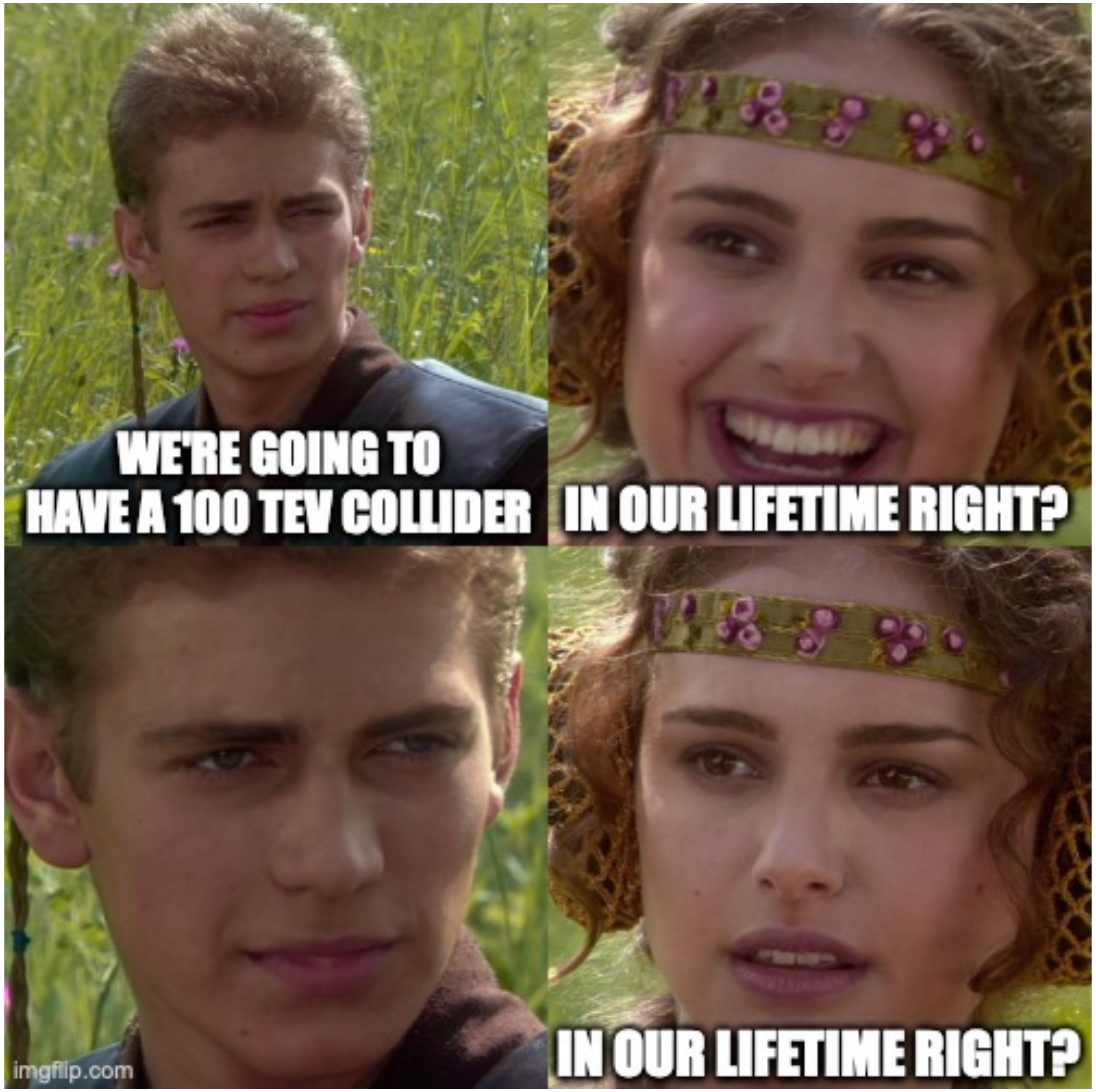
# Then reality sets in timelines...

**Realistic timeline matched to HL-LHC:**

- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

# And then we arrive here...



This is above my pay grade, but I'd like to give you a takeaway message that there are different physics potentials cases for all of them that are intriguing

# Complementarity

- **Measuring the same physics multiple ways** - that's what a lot of the focus is on and very important (energy vs precision etc)

- **Accessing different aspects of physics with different machines to get a complete picture** - fraught with sociological dangers but I personally think it's a stronger motivation to continue with R&D on multiple fronts


Not about greed of theorists, but about physics!

# Covering all physics possibilities is too hard...

## Long-Lived Particles

### LLP Matrix

| Signature | HL-LHC | Higgs factories | High energy hadron colliders | Muon colliders |
|---|---|---|---|---|
| Neutral LLP (including Higgs) | • Track-Based Triggers for Exotic Signatures, arXiv:2203.07314<br>• The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039<br>• Recent Progress and Next Steps for the MATHUSLA LLP Detector, arXiv:2203.08126<br>• Sensitivity to millicharged particles in future proton-proton collisions at the LHC, arXiv:2104.07151<br>• The road ahead for CODEX-b, arXiv:2203.07316<br>• The Forward Physics Facility, 2203.05090, 2109.10905<br>• Theory, phenomenology, and experimental avenues for dark showers, arxiv: 2203.09503<br>• Theory Meets the Lab, arxiv: 2203.10089<br>• LHCb future dark-sector sensitivity projections for Snowmass 2021, arxiv: 2203.07048<br>• Physics with the Phase-2 ATLAS and CMS Detectors | • Searches for Long-Lived Particles at the Future FCC-ee, arXiv:2203.05502<br>• The Future Circular Collider: a Summary for the US 2021 Snowmass Process, arXiv:2203.06520<br>• The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039<br>• Physics potential of timing layers in future collider detectors, arxiv: 2005.05221<br>• Sensitivity to decays of long-lived dark photons at the ILC, arxiv: 22<br>• The Internati Collider, arXi<br>• Belle II physi plans for the beyond | • The Present and Future Status of Heavy Neutral Leptons, arXiv:2203.08039<br>• Physics potential of timing layers in future collider detectors, arxiv: 2005.05221 | • Axion-Like Particles at High Energy Muon Colliders, arXiv:2203.05484 |
| Disappearing Tracks and HSCP | • Track-Based Triggers for Exotic Signatures, arXiv:2203.07314<br>• Physics with the Phase-2 ATLAS and CMS Detectors | • The Internati Collider, arXi | | |

Can we look for LLPs at

- HL-LHC? Yes
- Higgs factory? Yes
- High energy hadron machine? Probably
- Muon collider? Yes

Discussion: difficult to project sensitivities at future machines without real detectors / data, but still useful for design studies!

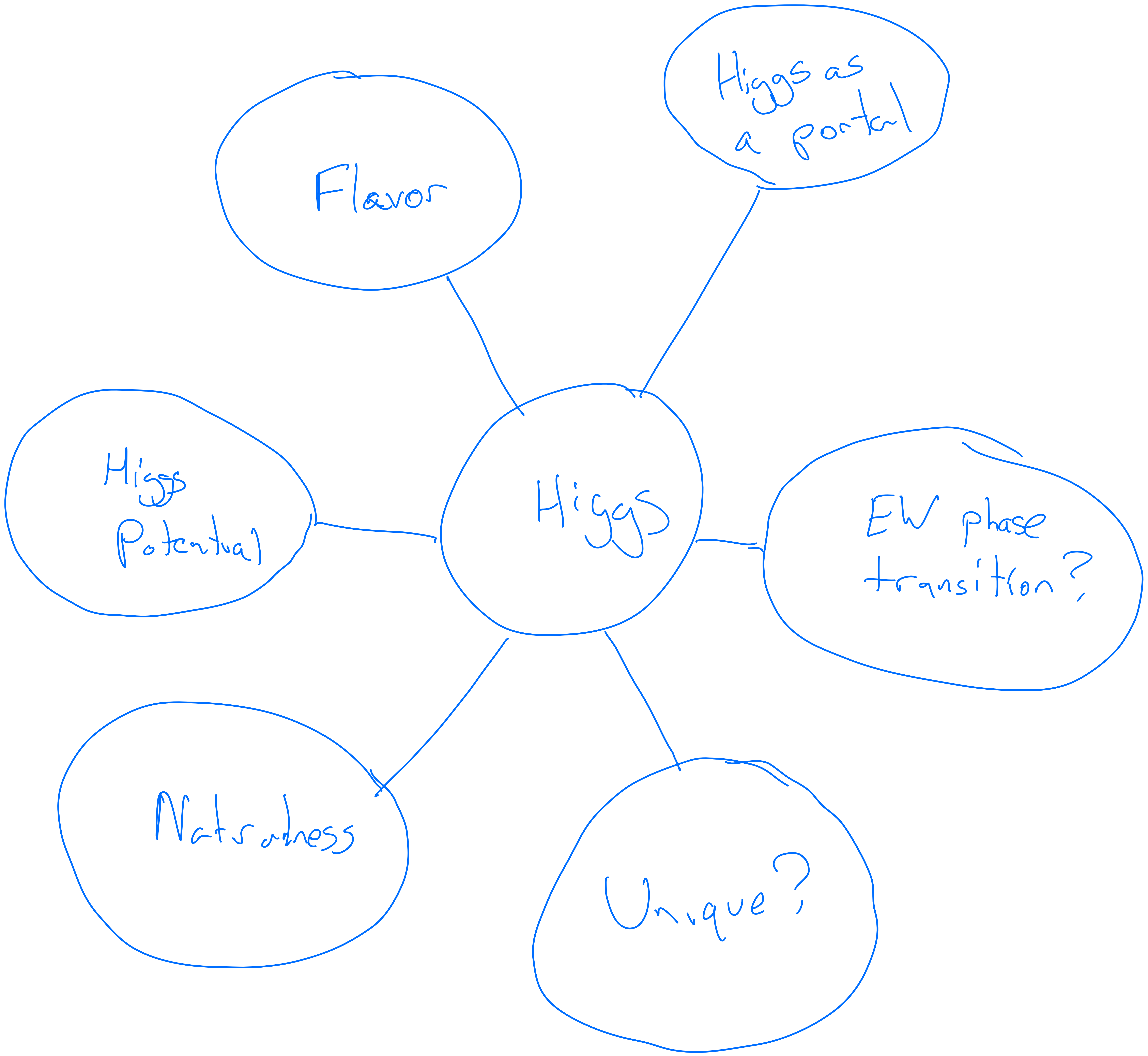


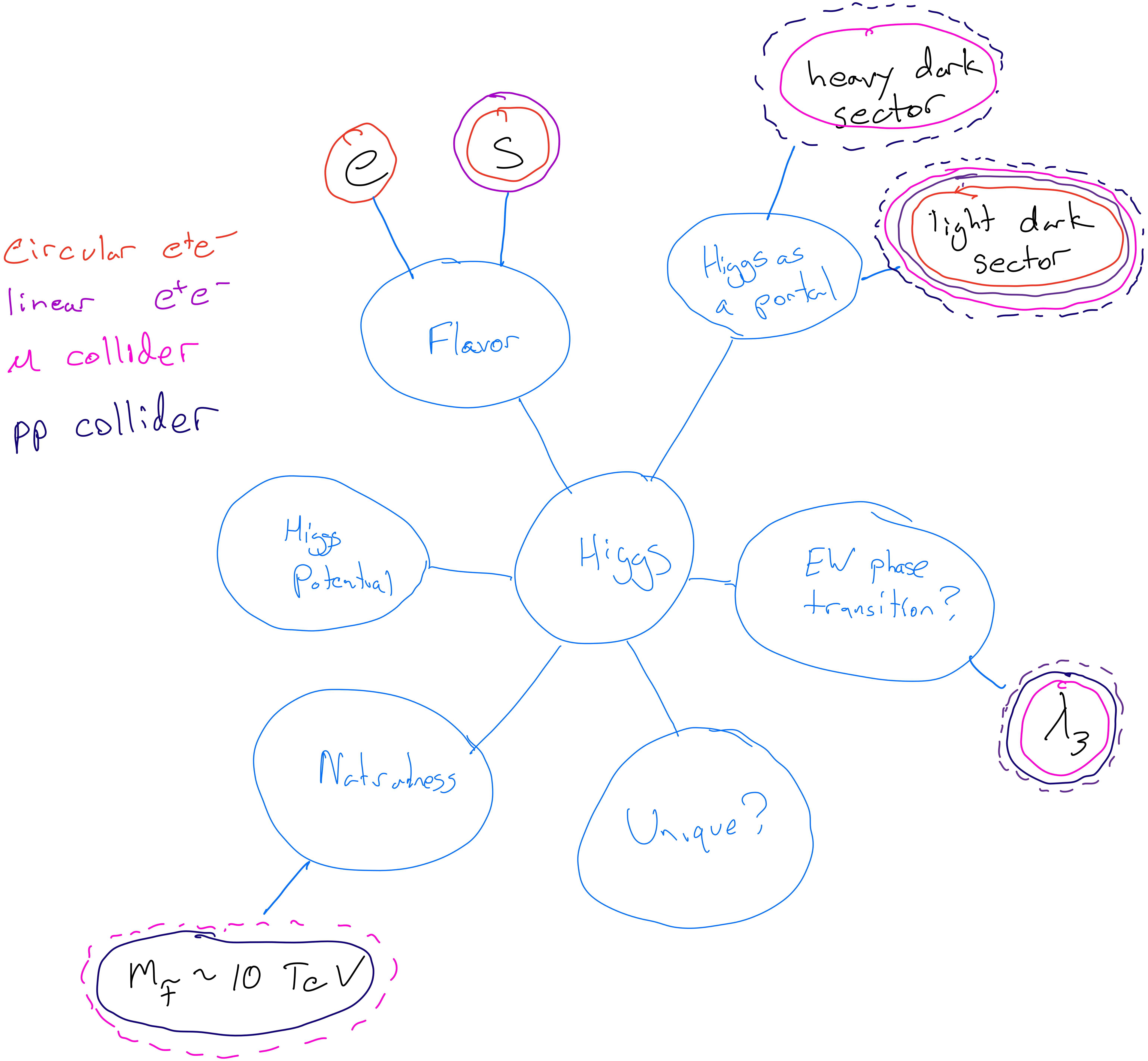
Even one very specific thing like LLPs has an enormous breadth to it

# One particular example: Higgs as a tool! (P5 once said something about this...)

I like this example since we know the Higgs exists, whereas many other particles I or others theorists have imagined I just really *hope* exist...

The Higgs discovery ***generated*** more questions than answers, that are inextricably connected to our fundamental understanding of the universe


Flavor
Higgs as a portal
Higgs Potential
Higgs
EW phase transition?
Naturalness
Unique?


circular e+e−
linear e+e−
μ collider
pp collider
e
S
heavy dark sector
light dark sector
Flavor
Higgs as a portal
Higgs Potential
Higgs
EW phase transition?
λ3
Naturalness
Unique?
M~T ~ 10 TeV

For a vibrant Higgs program we see that circular e+e-, linear e+e-, pp, muon colliders all have access to different fundamental questions concerning the Higgs

In turn from the *theory* perspective it strongly motivates R&D on all directions to enable a vision for a future HEP collider program in the US

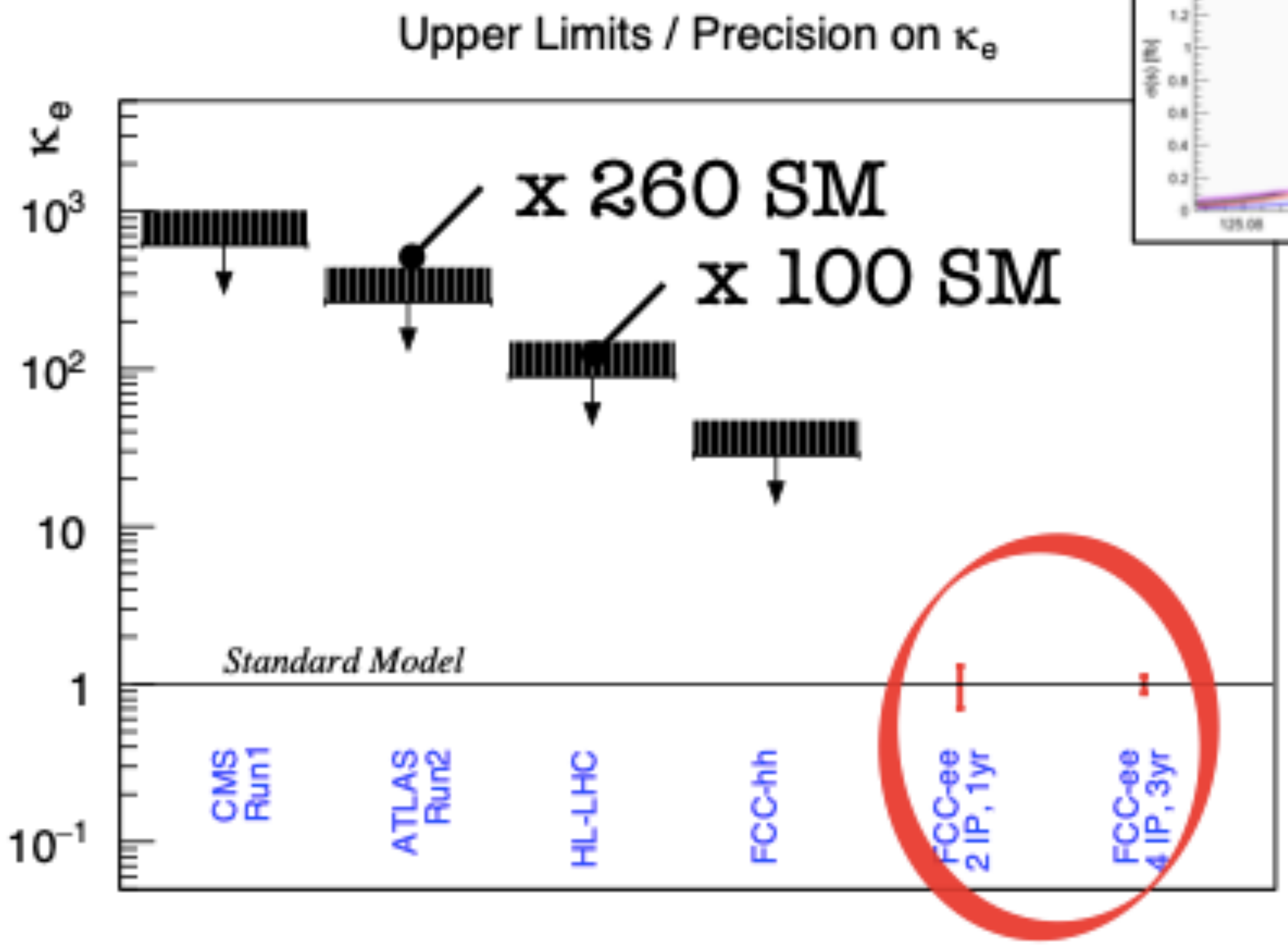

choosing just one collider

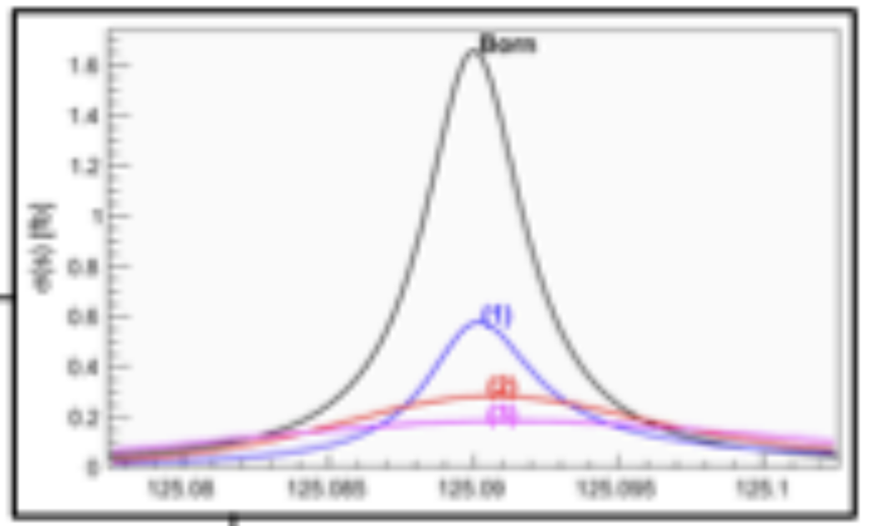
having R&D for multiple colliders

# Thanks!

# Backup

- **20 ab$^{-1}$ / year at $\sqrt{s}$ = 125 GeV** *(not in baseline FCC-ee)*
- **Monochromatization $\sigma_{\sqrt{s}} \sim$ 1-2 × $\Gamma_H \sim$ 6 to 10 MeV**
  - **Resonant ee → H production**

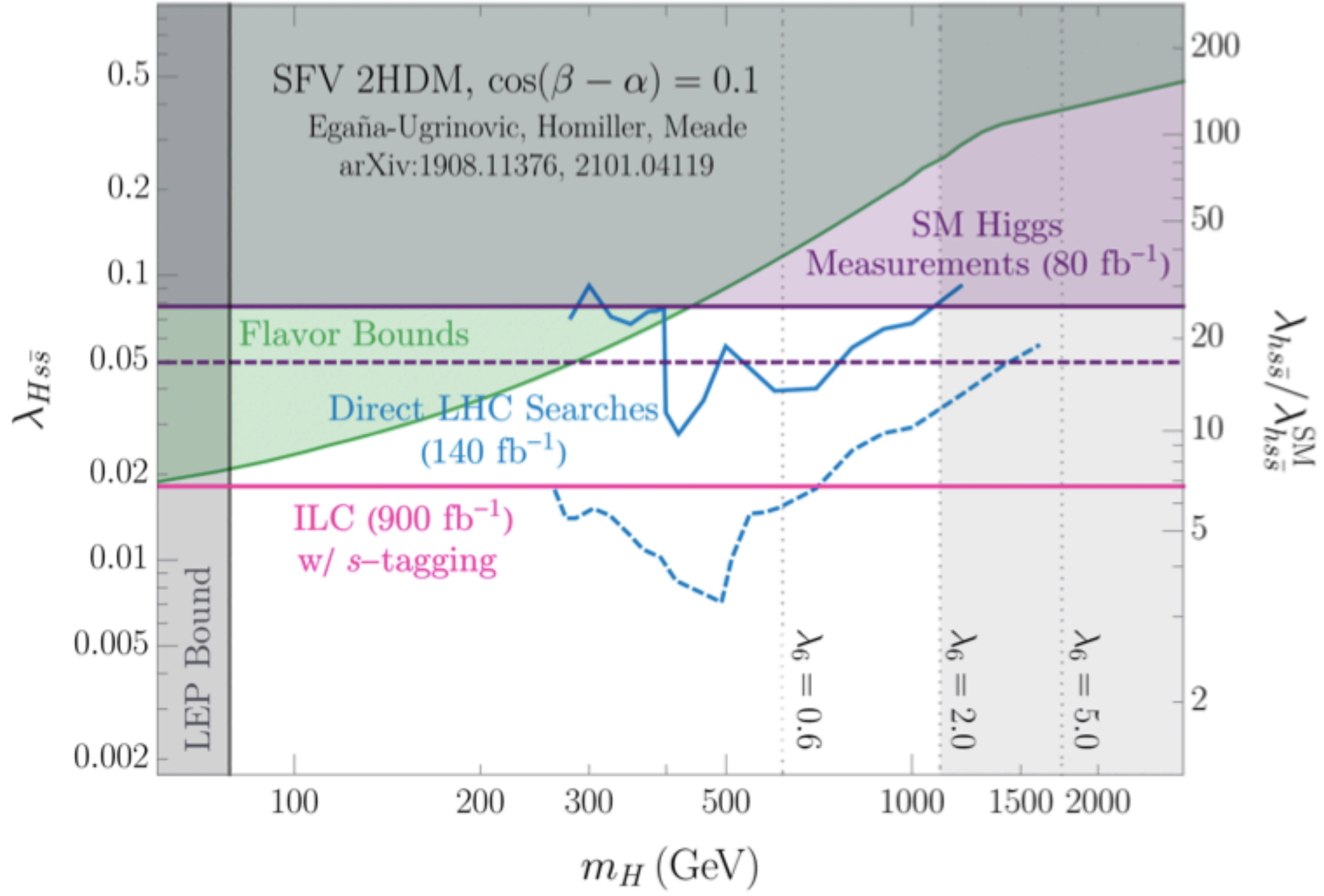


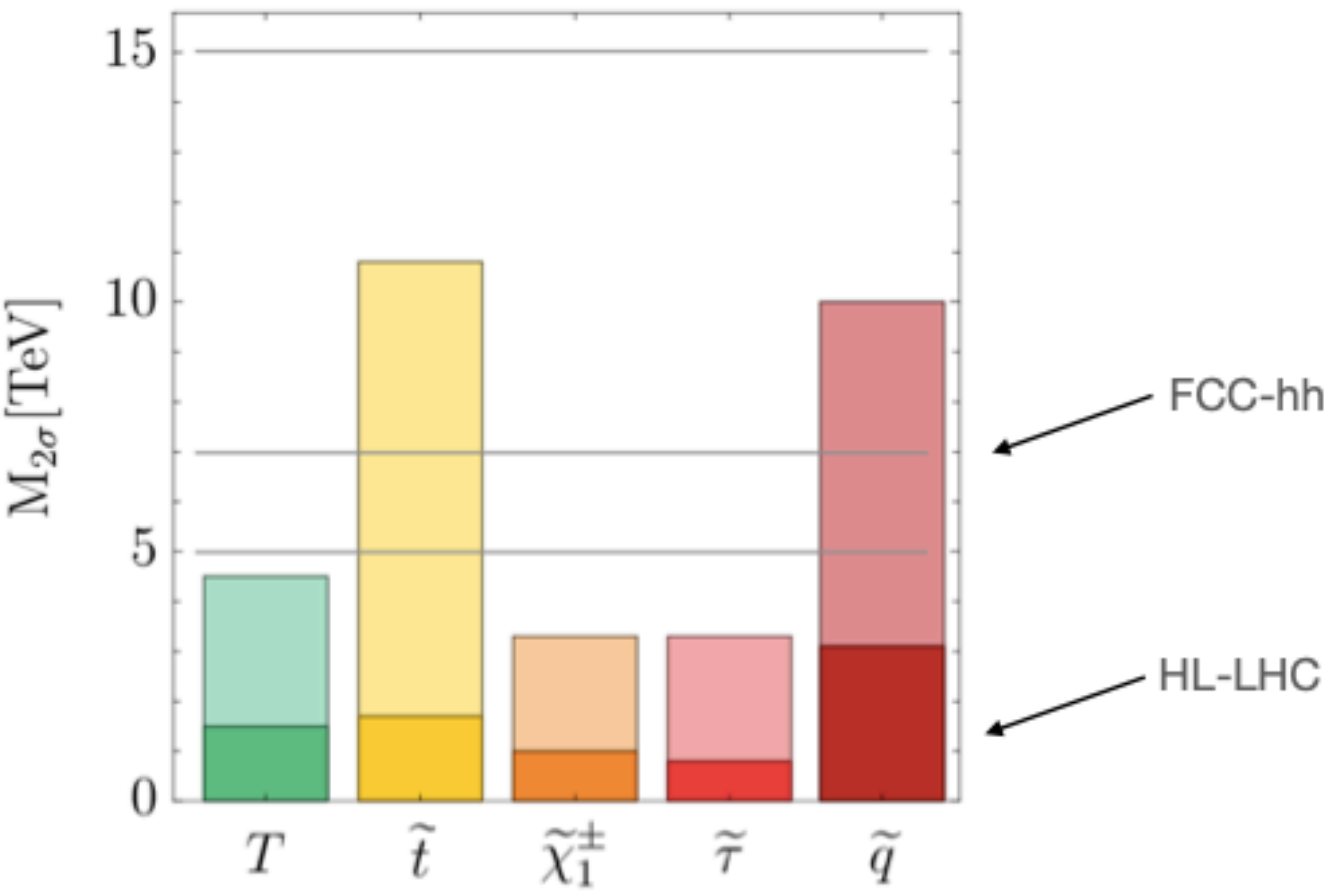
better

  - **2σ excess in one year with 2 IP**
  - **±15% precion on $\kappa_e$ in 3 years with 4 IP**

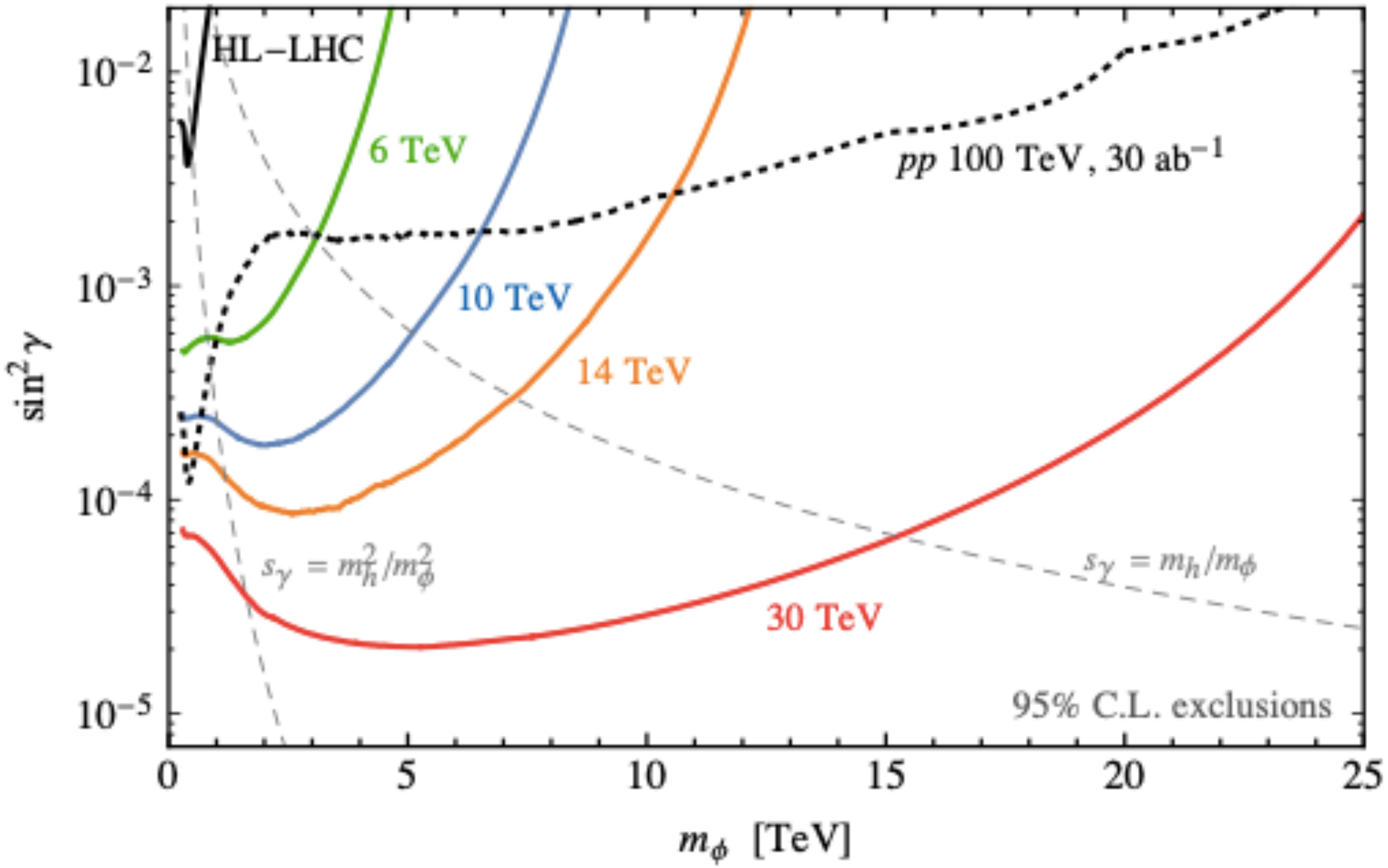
    ➔ **Not feasible at ILC or CLIC**

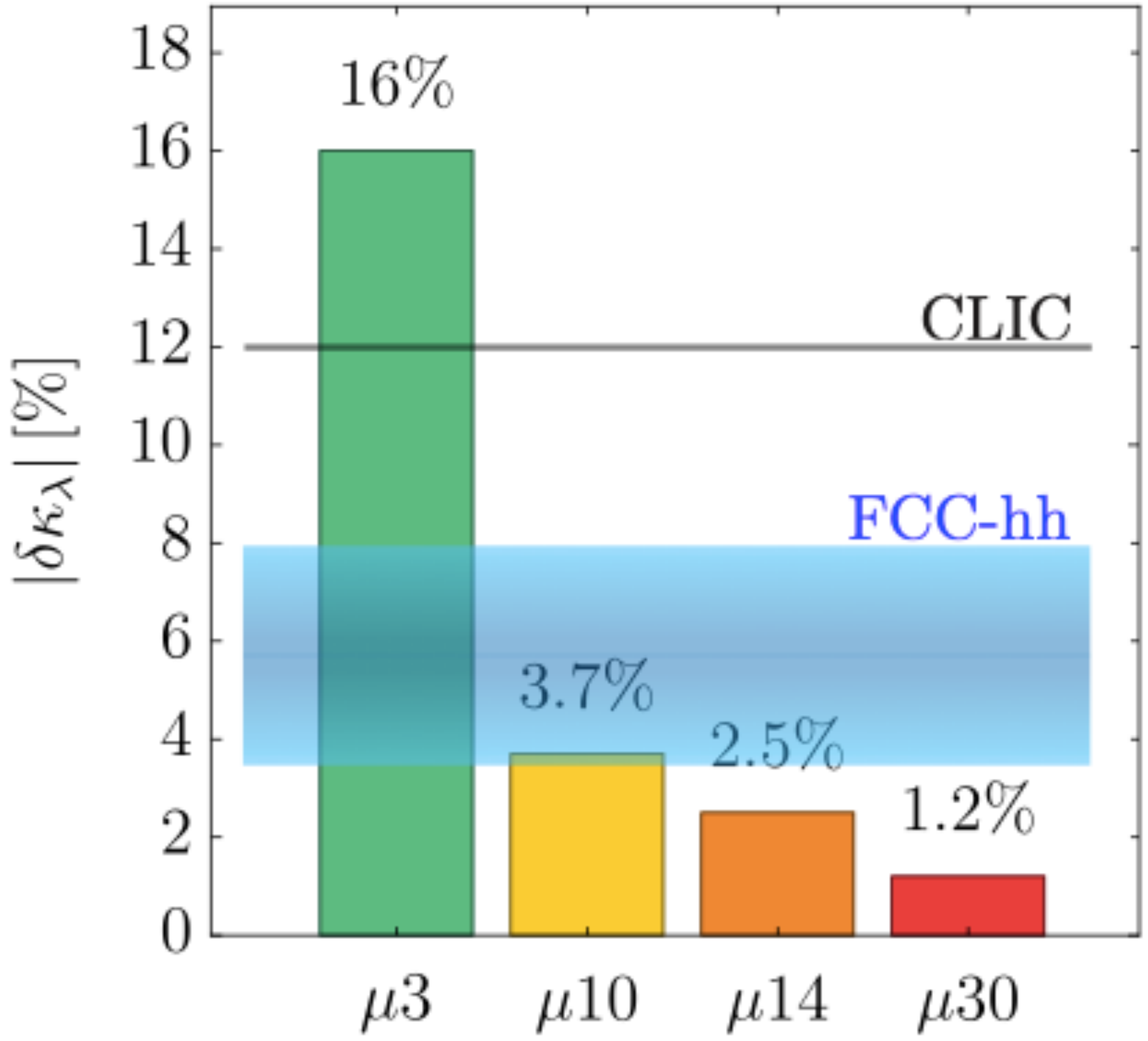


SFV 2HDM, $\cos(\beta - \alpha) = 0.1$
Egaña-Ugrinovic, Homiller, Meade
arXiv:1908.11376, 2101.04119
SM Higgs
Measurements (80 fb$^{-1}$)
Flavor Bounds
Direct LHC Searches
(140 fb$^{-1}$)
ILC (900 fb$^{-1}$)
w/ $s$–tagging
LEP Bound
$\lambda_6 = 0.6$
$\lambda_6 = 2.0$
$\lambda_6 = 5.0$
$\lambda_{Hs\bar{s}}$
$\lambda_{hs\bar{s}}/\lambda_{hs\bar{s}}^{SM}$
$m_H$ (GeV)
0.5
0.2
0.1
0.05
0.02
0.01
0.005
0.002
200
100
50
20
10
5
2
100
200
300
500
1000
1500
2000



15
10
5
0
$M_{2\sigma}$[TeV]
$T$
$\tilde{t}$
$\tilde{\chi}_1^{\pm}$
$\tilde{\tau}$
$\tilde{q}$
FCC-hh
HL-LHC


HL−LHC
6 TeV
10 TeV
14 TeV
30 TeV
$pp$ 100 TeV, 30 ab$^{-1}$
$s_\gamma = m_h^2/m_\phi^2$
$s_\gamma = m_h/m_\phi$
95% C.L. exclusions
$\sin^2\gamma$
$m_\phi$ [TeV]
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
0
5
10
15
20
25



$|\delta\kappa_\lambda|$ [%]
16%
CLIC
FCC-hh
3.7%
2.5%
1.2%
$\mu 3$
$\mu 10$
$\mu 14$
$\mu 30$

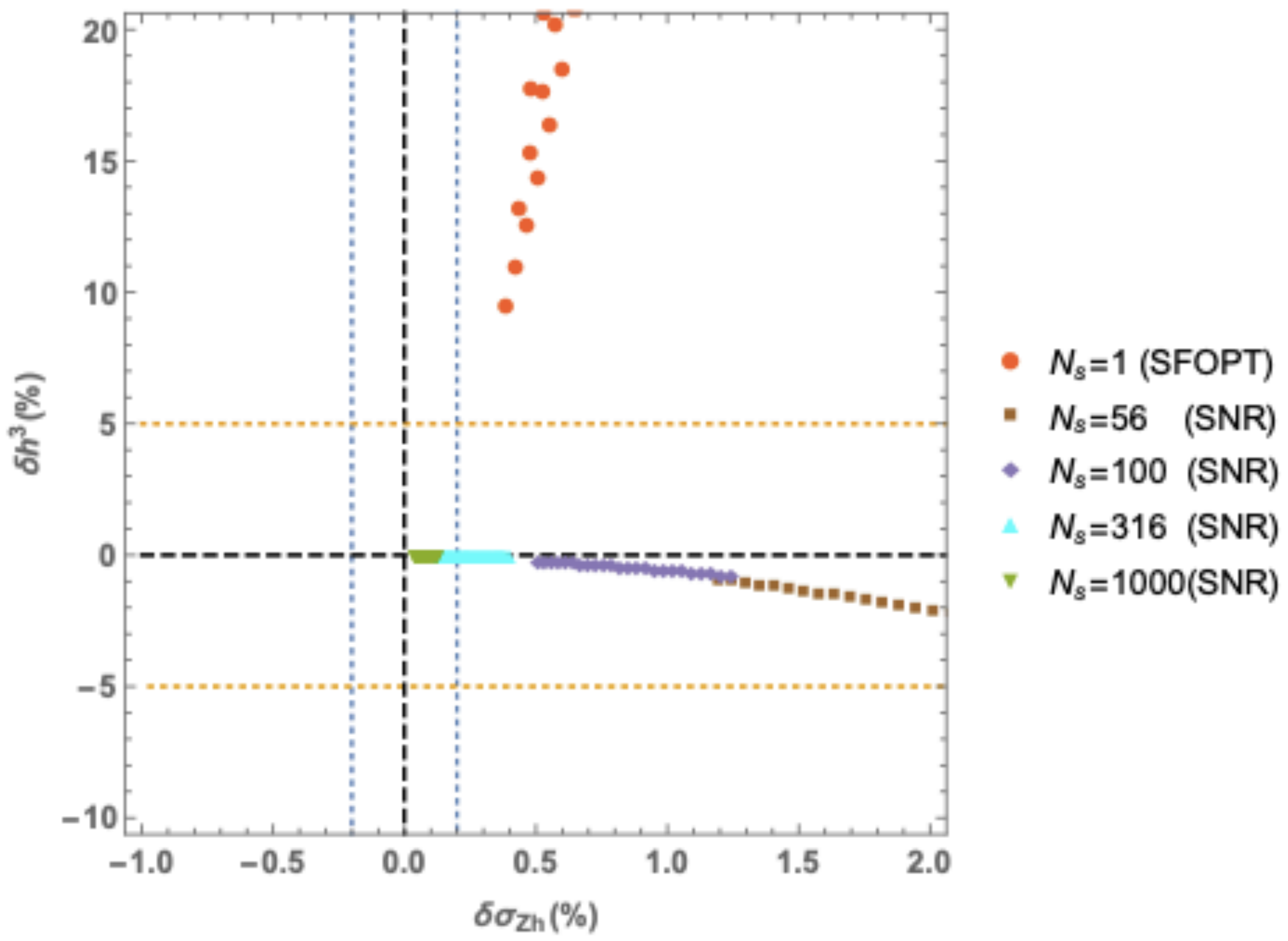



FIG. 3. Comparison between different SNR points and a SFOPT in the space of $\delta_{Zh}$ and $\delta_{h^3}$, for the onset of SNR and $v_c/T_c = 0.6$. The dashed lines represent projected sensitivities that can be found in [7, 8]; $\delta\sigma_{Zh} = 0.2\%$ and $\delta h^3 = 5\%$