The BSM Physics Case for Future Hadron Colliders

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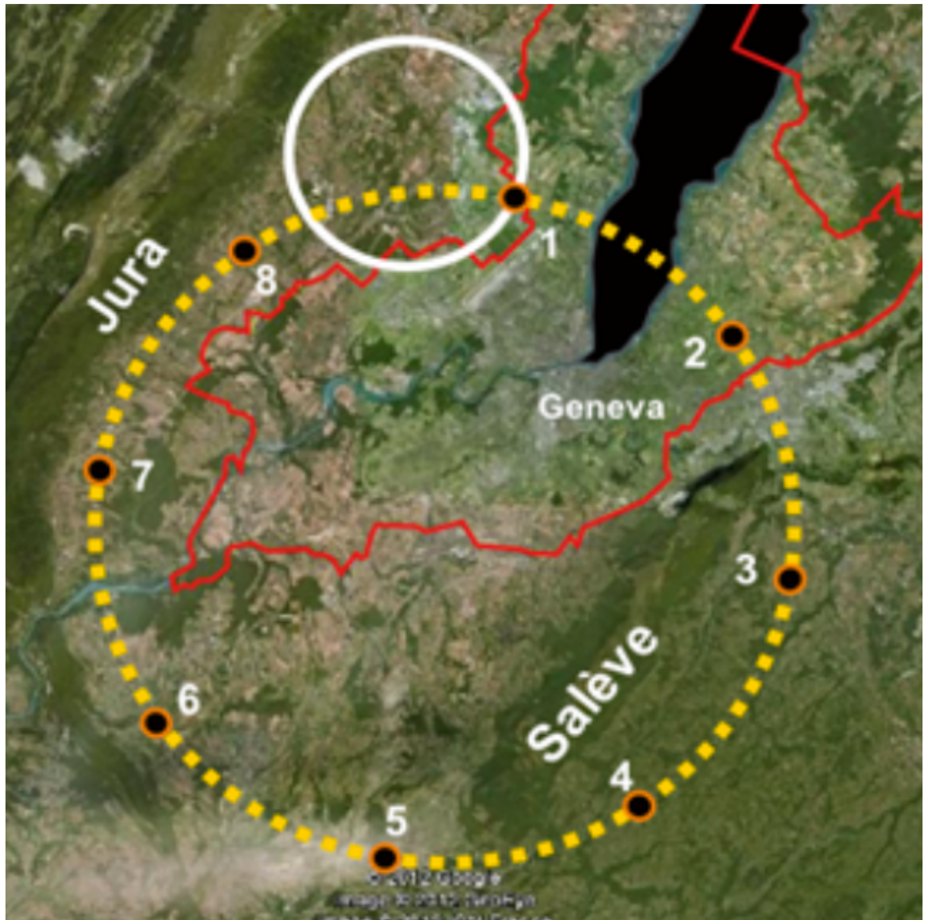
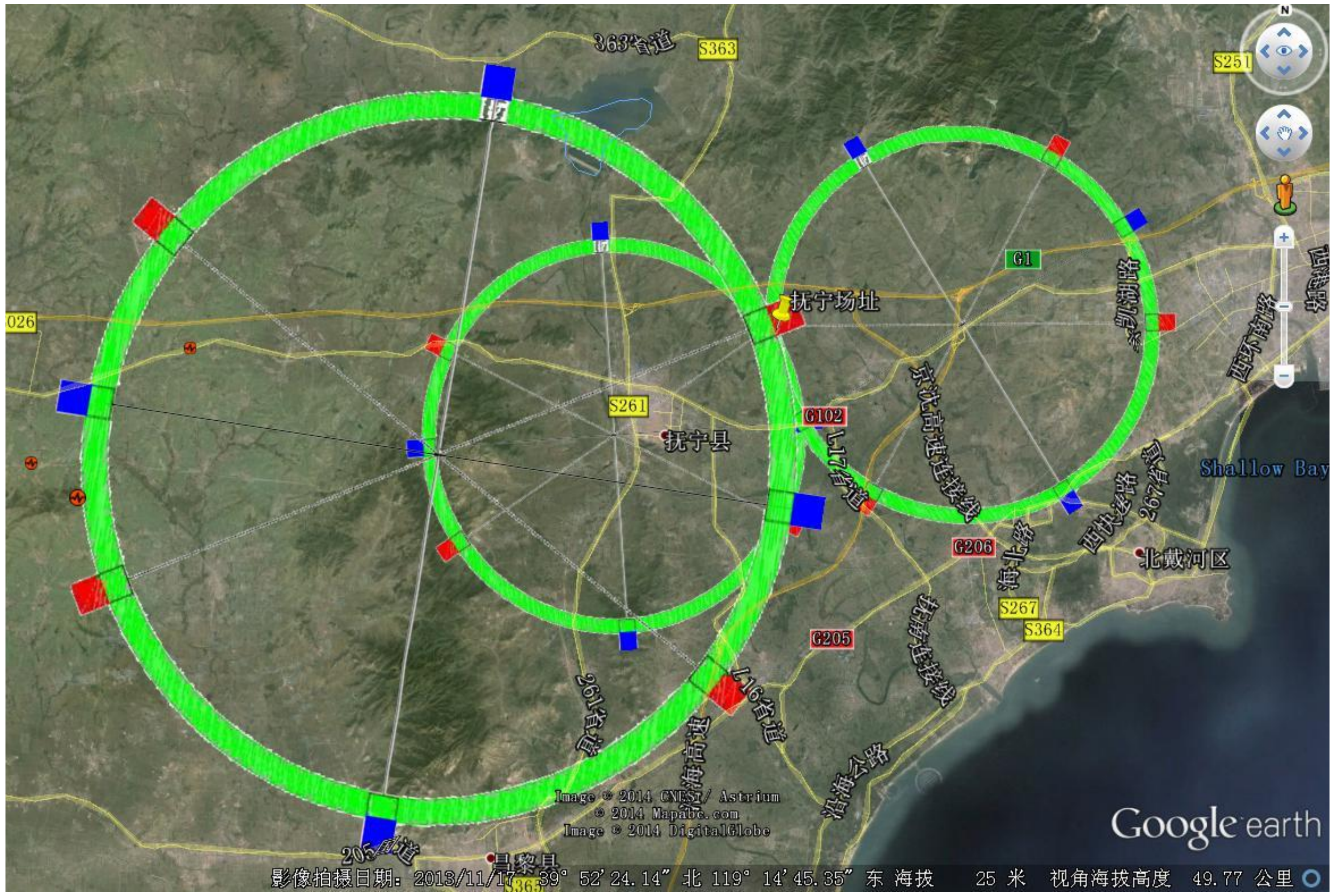
Harvard University
@ LHCP, June 9, 2021





Why Future Hadron Colliders?

There are plenty of good Standard Model answers, but this talk focuses on possibilities **beyond the Standard Model**.

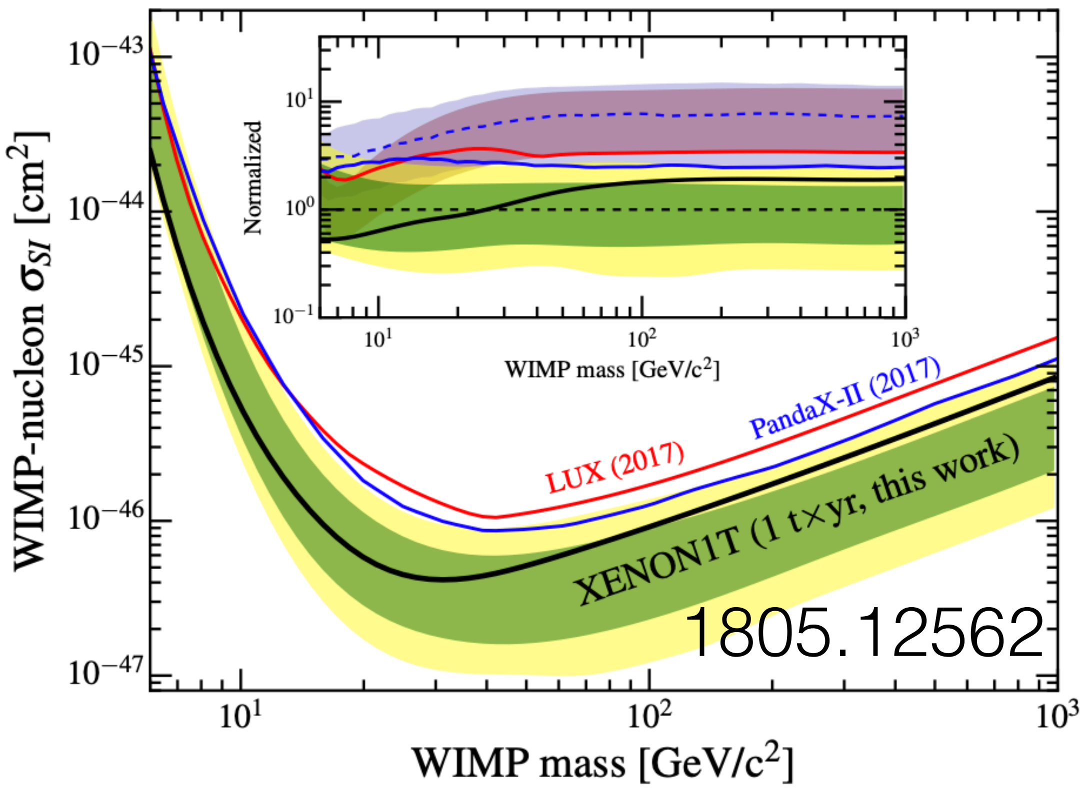
What are the new *qualitative insights* about nature we would obtain from a higher-energy hadron collider?

1. **Dark Matter**

2. Higgs Potential / Phase Transition

3. Deciphering New Physics

SU(2) Multiplet Dark Matter

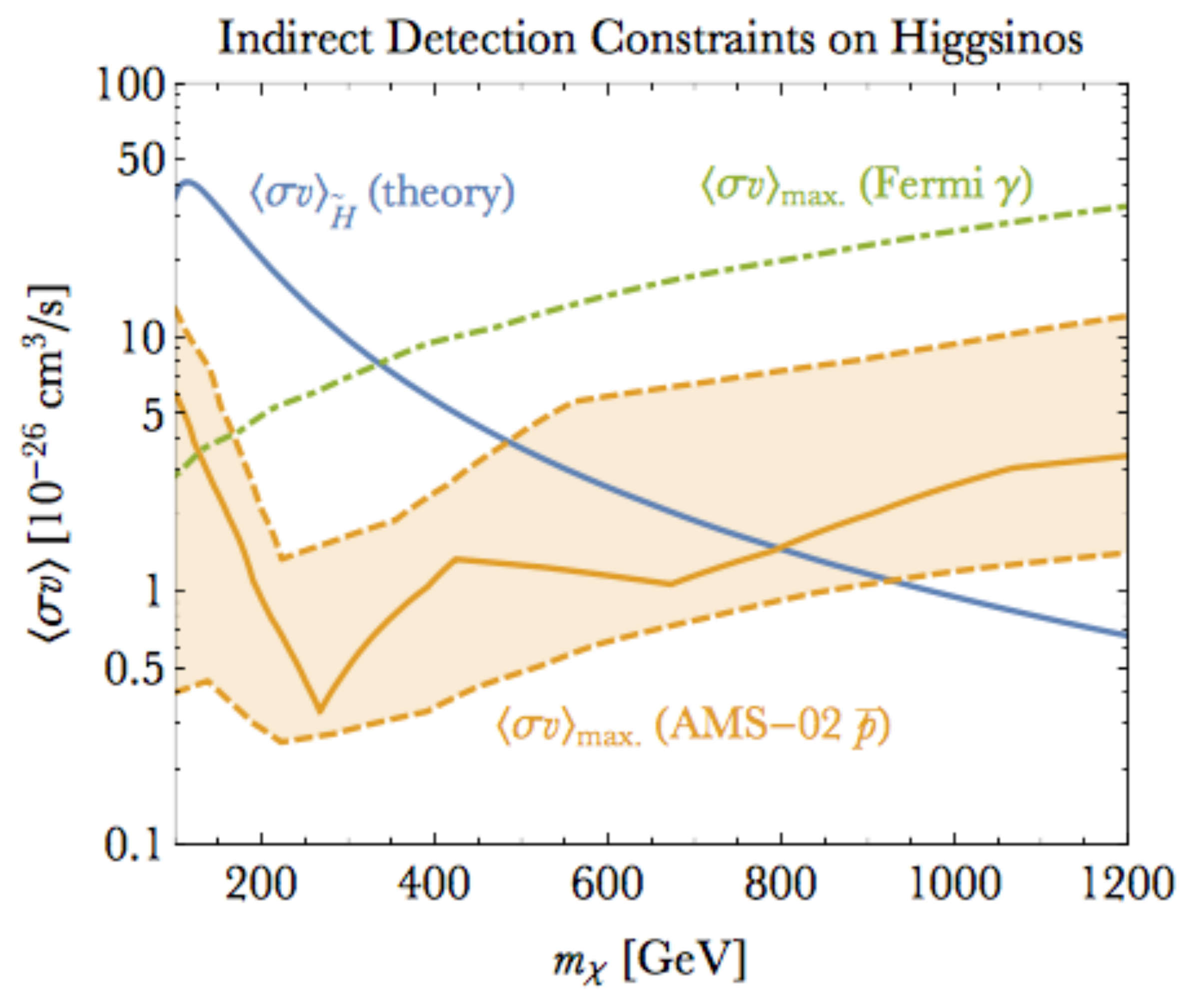


The xenon-based experiments have strongly constrained WIMPs coupling to the Higgs boson.

WIMPs in pure SU(2) multiplets have

$$\tilde{\chi}^0\tilde{\chi}^0 \to W^+W^-$$

annihilation. Indirect detection severely constrains winos*; constrains ***higgsinos*** mildly.



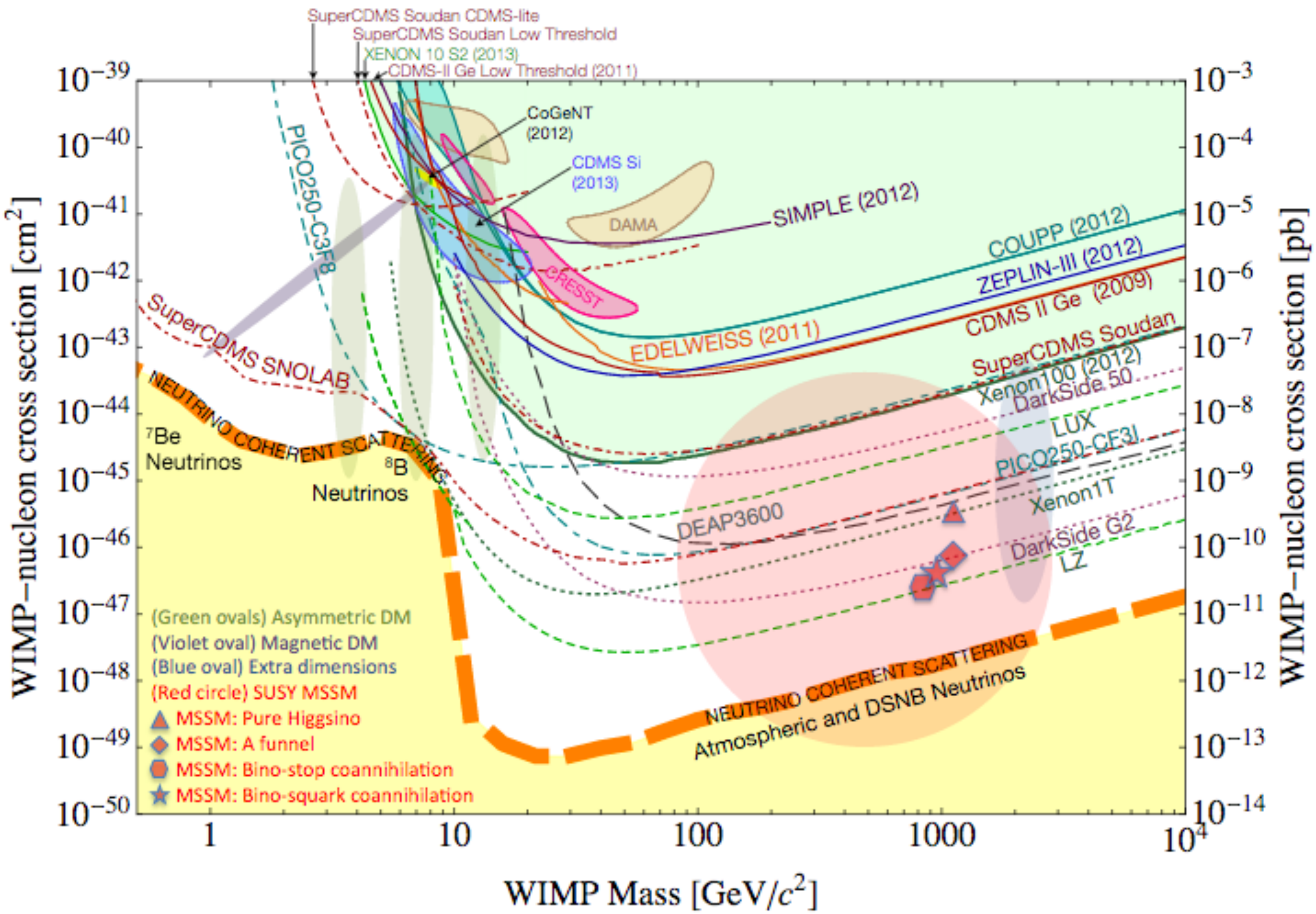
Krall, MR 1705.04843, using work of Cuoco, Krämer, Korsmeier 1610.03071

* Cohen, Lisanti, Pierce, Slatyer 1307.4082

* Fan, MR 1307.4400

Future Direct Detection

Snowmass: Cushman et al. 1310.8327



← Z exchange

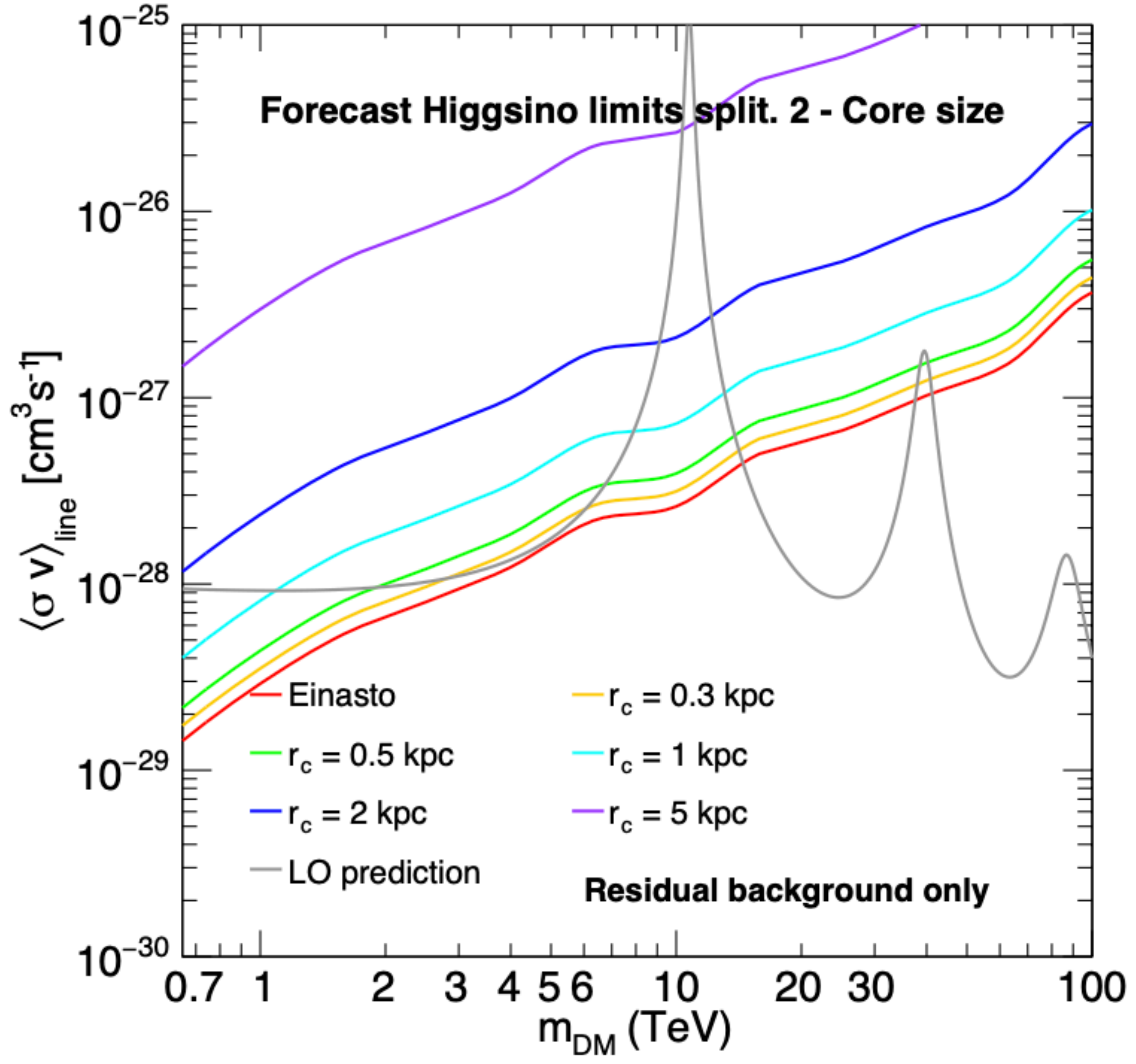
← *h* exchange

← *W* loop (wino)

← *W* loop (higgsino)

SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.

Future Indirect Detection: CTA



$$\delta m_N = 2\,\mathrm{GeV}$$

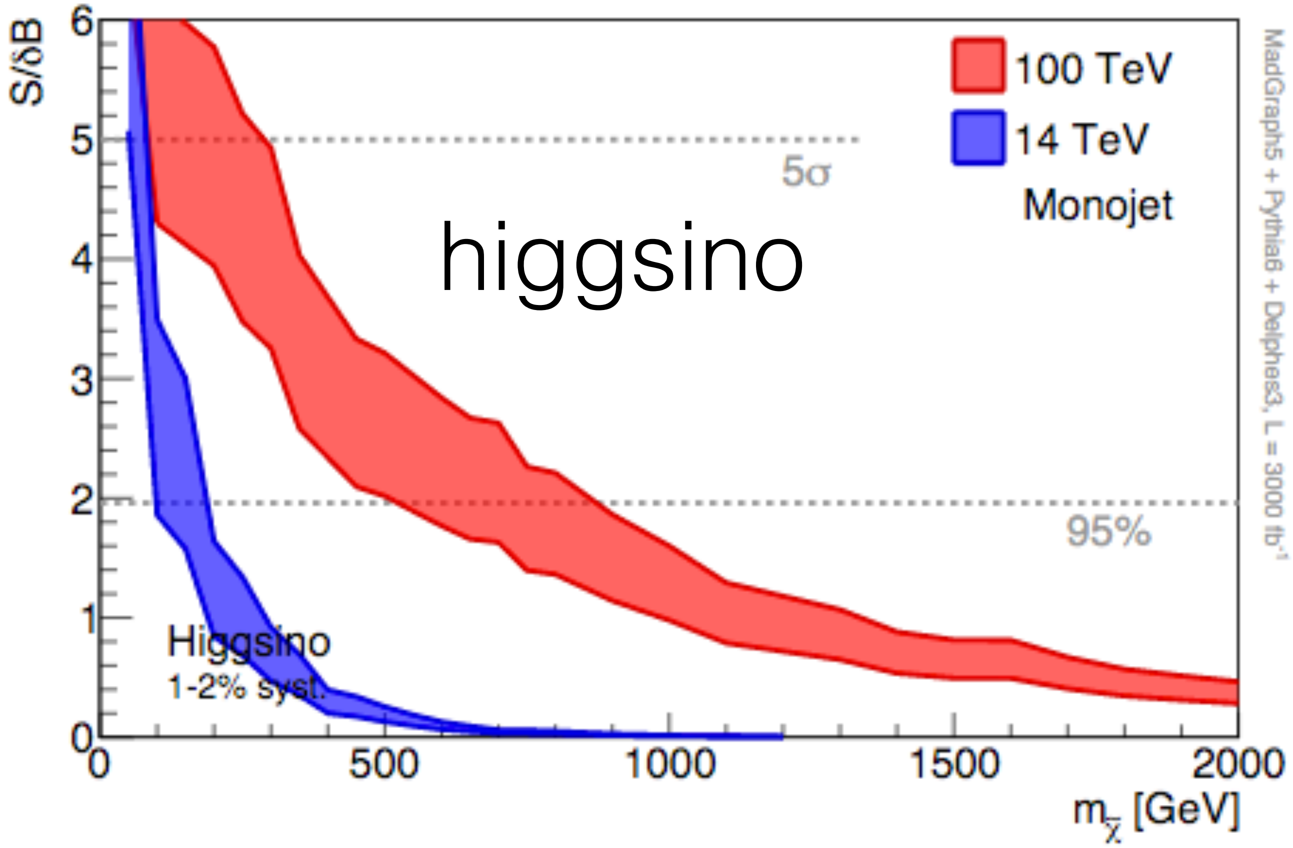
$$\delta m_+ = 480\,\mathrm{MeV}$$

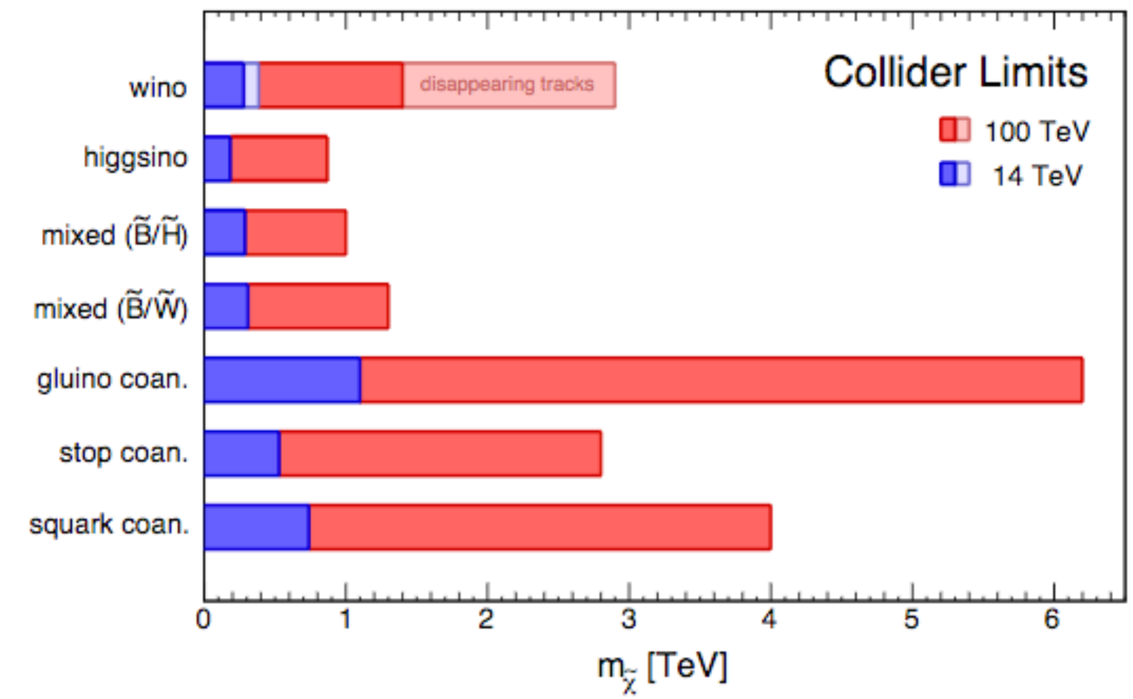
Sensitive to mass splittings, DM profile in galactic center.

Macias, Moulin, Rinchiuso, Rodd, Slatyer 2008.00692

SU(2) Multiplet DM at 100 TeV

M Low and L-T Wang: 1404.0682





Monojet searches cover much of the higgsino range.

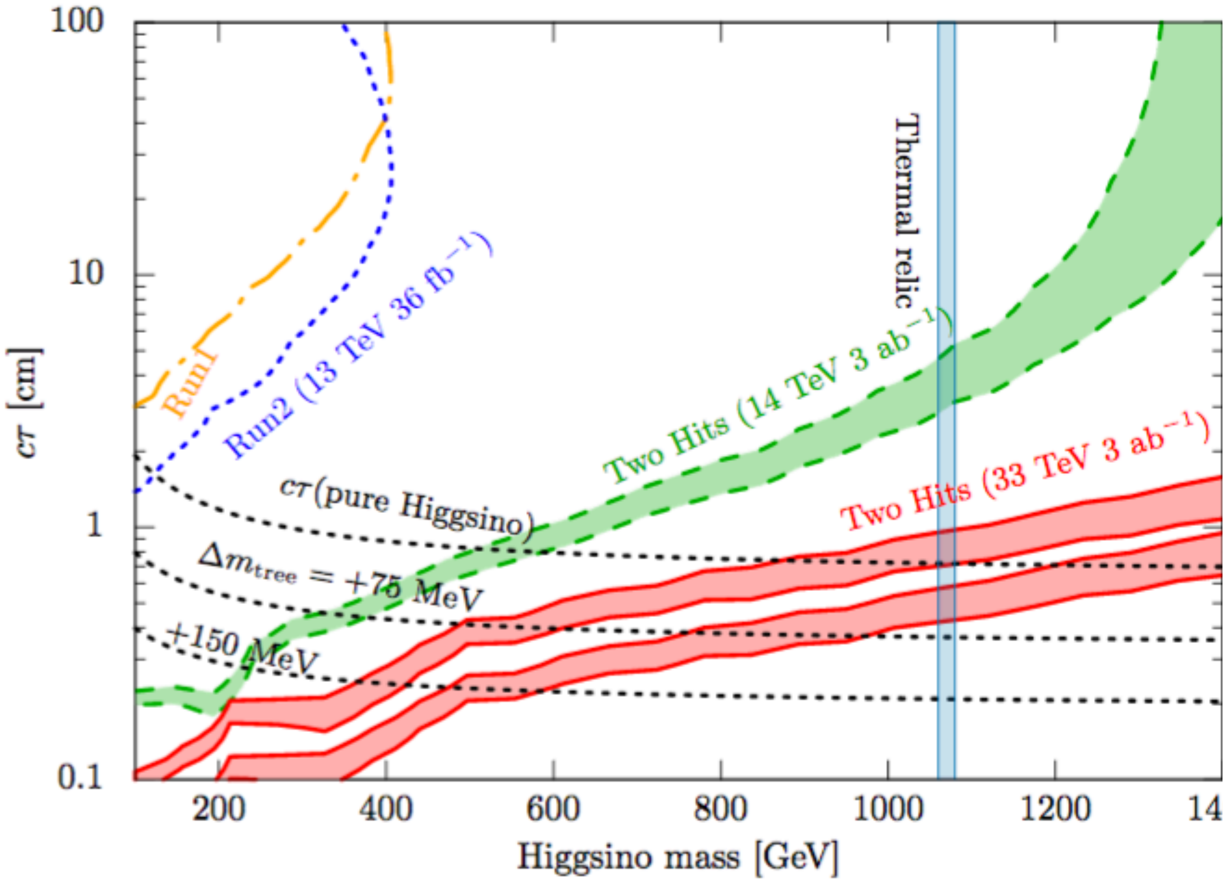
Notice **wide bands**: varying background systematics 1-2%. Big exp. challenge is well-characterized background!

some other 100 TeV SUSY DM studies: Cirelli, Sala, Taoso 1407.7058 (disappearing tracks for winos); Acharya, Bozek, Pongkitivanichkul, Sakurai 1410.1532 (wino->higgsino); Gori, Jung, Wang Wells 1410.6287 (multilepton, dilepton)

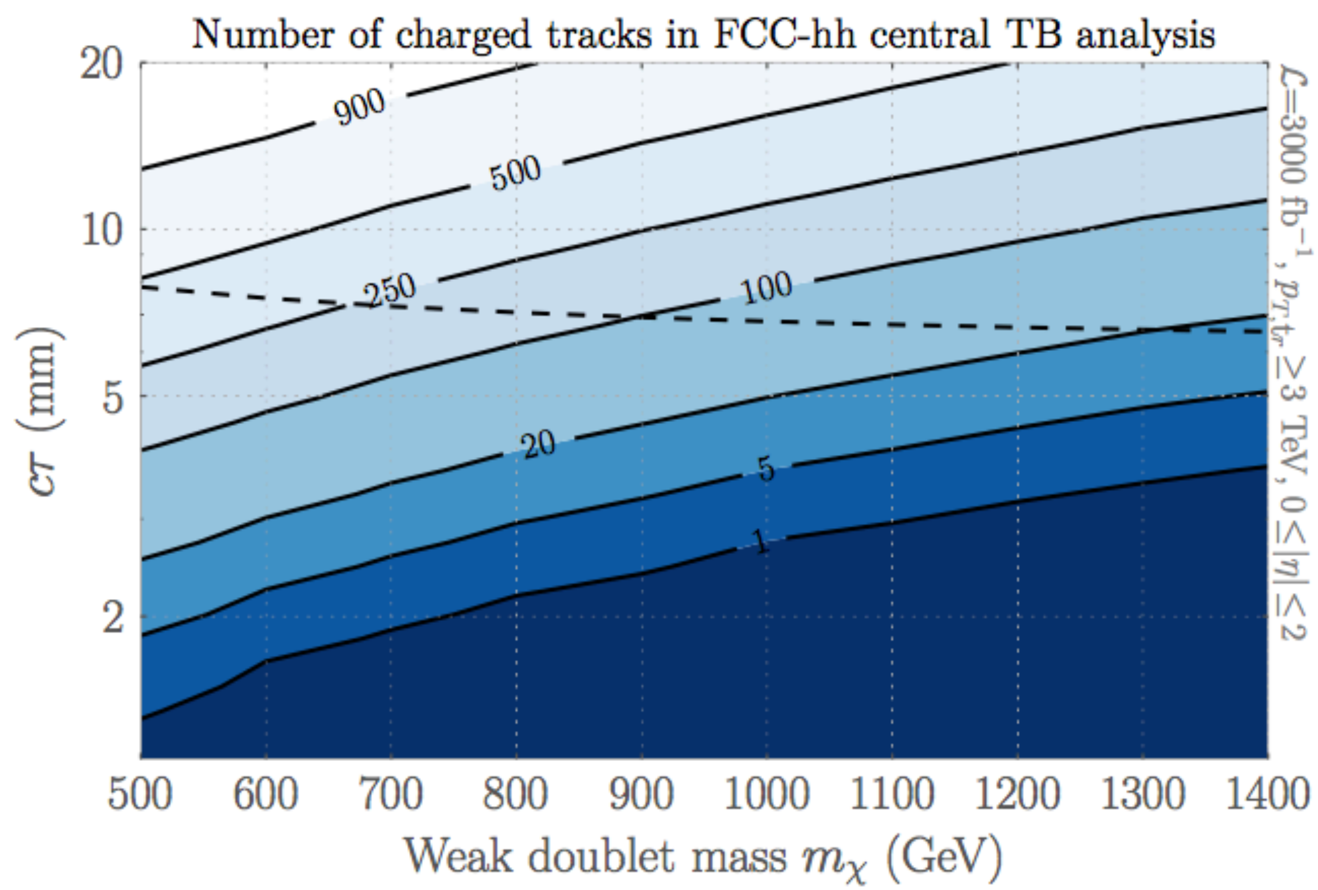
Higgsinos and Disappearing Tracks

The mildly long lifetime of a chargino can provide an additional handle on the very pure higgsino corner of parameter space:

Fukuda, Nagata, Otono, Shirai
1703.09675



Mahbubani, Schwaller, Zurita
1703.05327



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Hadron Colliders as Higgs Factories

Electron/positron colliders: $\sigma(e^+e^- \to hZ) \approx 200\ \mathrm{fb}$
(at the peak of the cross section, c.m. energy ~ 250 GeV)

So 5/ab of data (CEPC or FCC-ee) leads to 10^6 Higgses.
Very clean, so ~0.1% measurement of Higgs coupling to Z.

Proton/proton collider: gluon fusion rate ~ **50 pb** @ 14 TeV and ~ **800 pb** @ 100 TeV.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy
1503.06056 Anastasiou, Duhr, Dulat, Herzog, Mistlberger N^{3}LO; CERN 100 TeV report

The true Higgs factories are hadron machines! Messier environment, but: LHC will measure $\mathrm{Br}(h \to \gamma\gamma)/\mathrm{Br}(h \to ZZ^*)$ better than any planned future e^+e^- collider.
Also great for rare decays. (Curtin et al. 1312.4992 Exotic Decays survey)

Precision Higgs Measurements

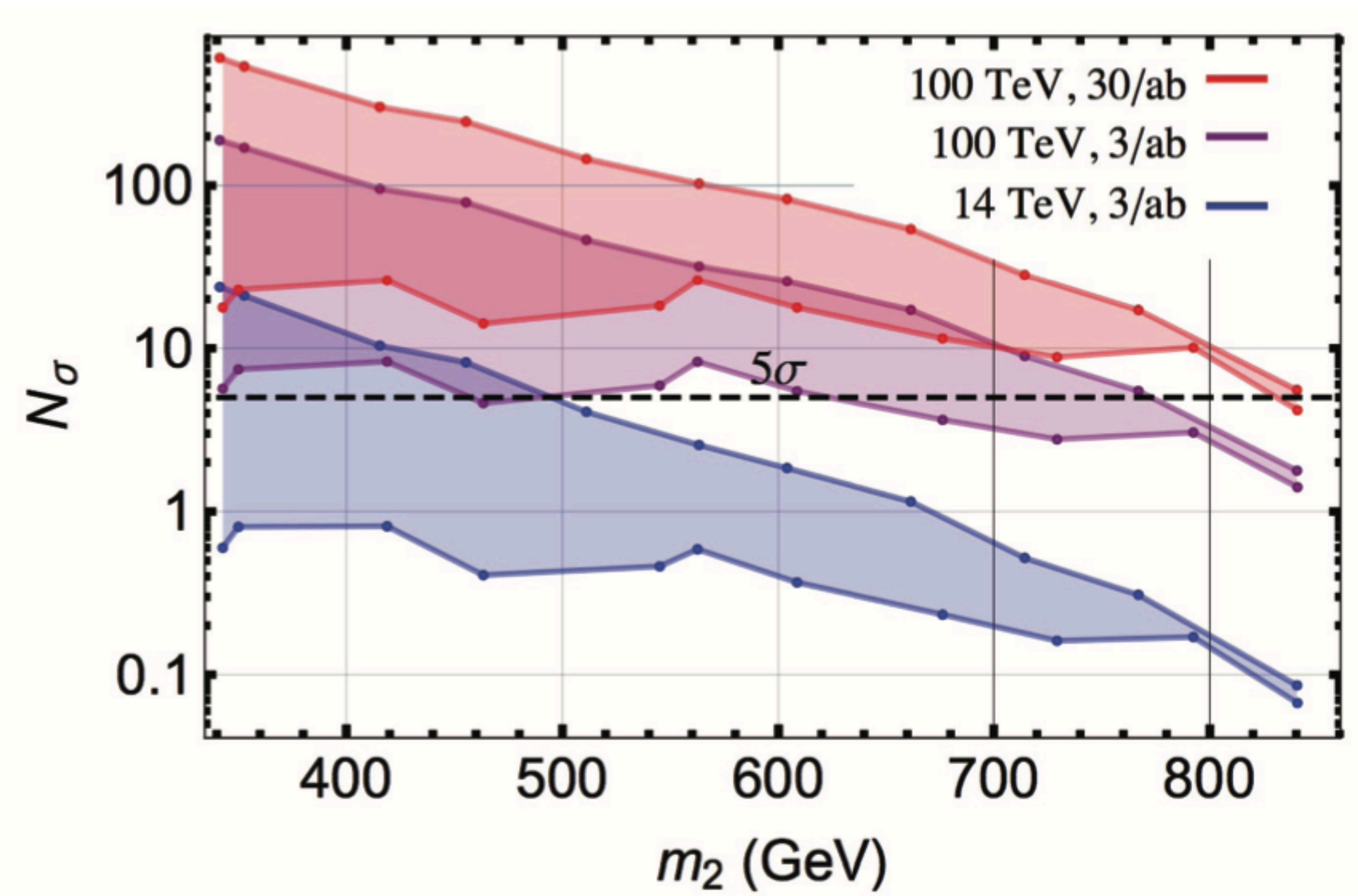
Table 1.2: Target precision for the parameters relative to the measurement of various Higgs decays, ratios thereof, and of the Higgs self-coupling λ. Notice that Lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.

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}

from: Future Circular Collider Study, Vol. 3 (FCC-hh CDR)

Singlet Scalar with Higgs Mixing

Resonant di-Higgs production: $h_2 \to 2h_1 \to 4\tau, b\bar{b}\gamma\gamma$



Parameter space with **strongly first-order phase transition** can be probed

Kotwal, No, Ramsey-Musolf, Winslow 1605.06123

(Also see 4b studies for HL-LHC by Li, Ramsey-Musolf, Willocq, 1906.05289)

Electroweak Phase Transition “Nightmare” Scenario

Singlet scalar with a $\mathbb{Z}_2$ symmetry $\phi \mapsto -\phi$

$$V(h,\phi) = V_{\rm SM}(h) + \frac{1}{2}M^2\phi^2 + c_\phi |H|^2 \phi^2$$

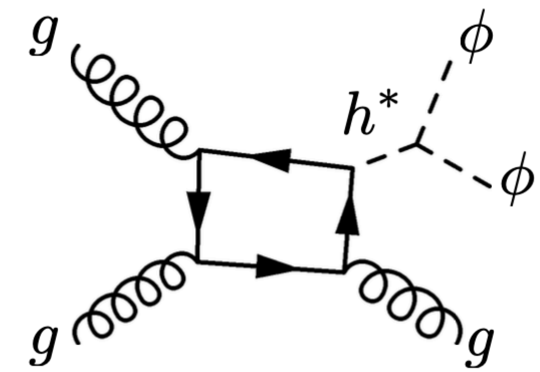
No *mixing* with the Higgs boson. **Stable, invisible.**

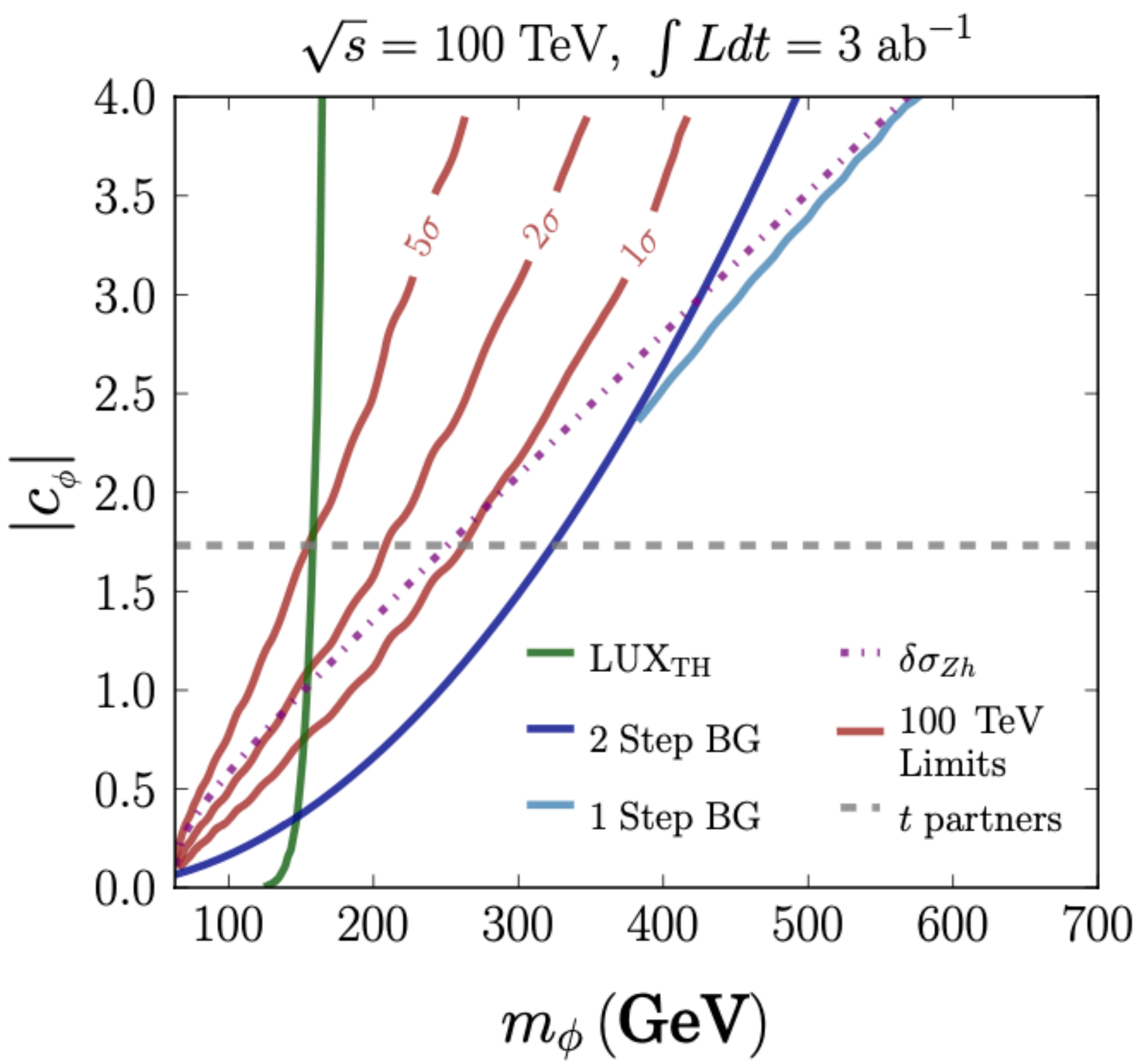
After EWSB: $h\phi^2$ vertex. Light ϕ: invisible width of Higgs.
$m_\phi > \frac{1}{2}m_h$: difficult!

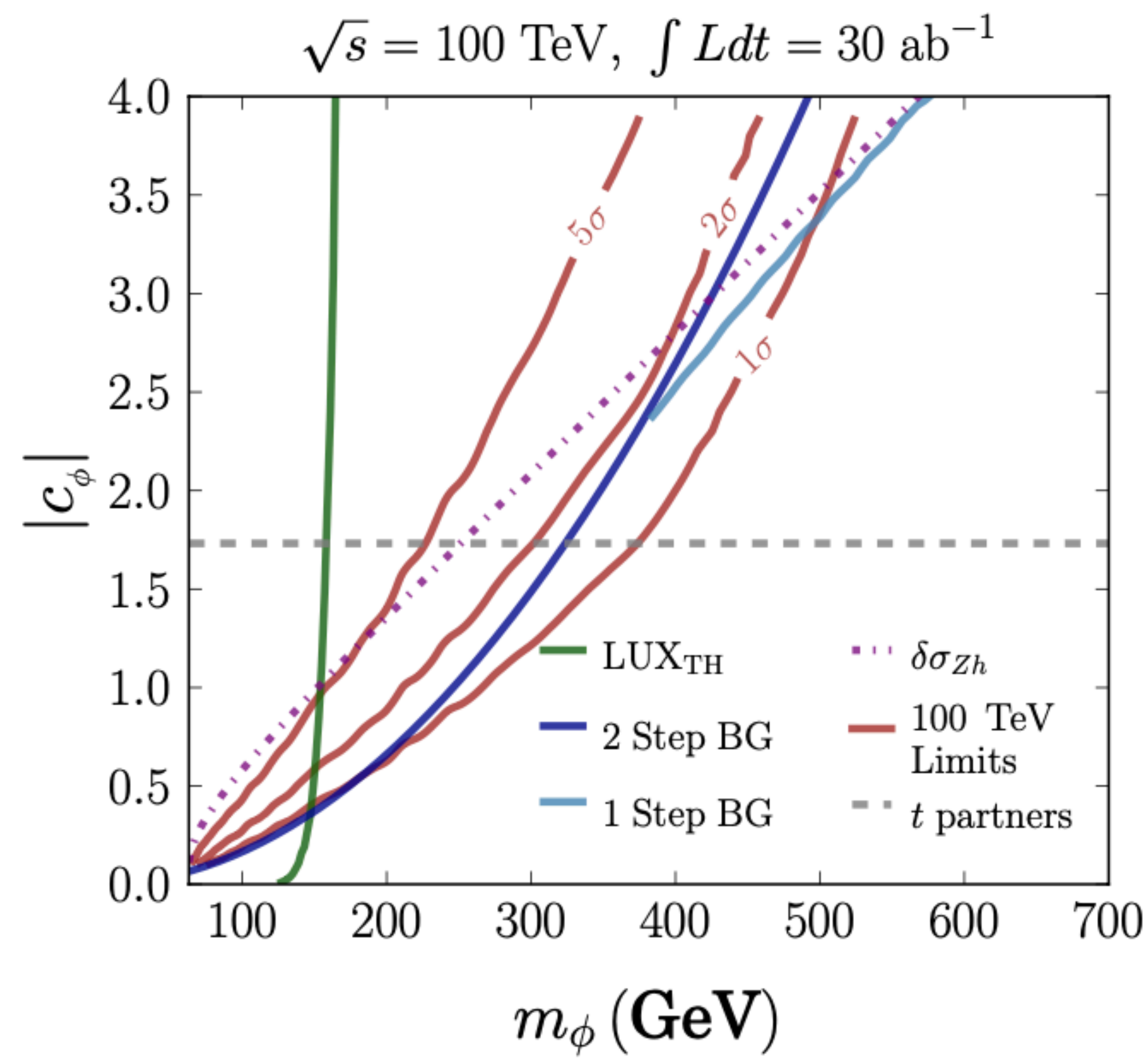
Curtin, Meade, Yu 1409.0005

The Higgs Portal Above Threshold

VBF $\phi\phi jj$ (forward jets) and gluon fusion







(Craig, Lou, McCullough, Thalapillil arXiv:1412.0258)

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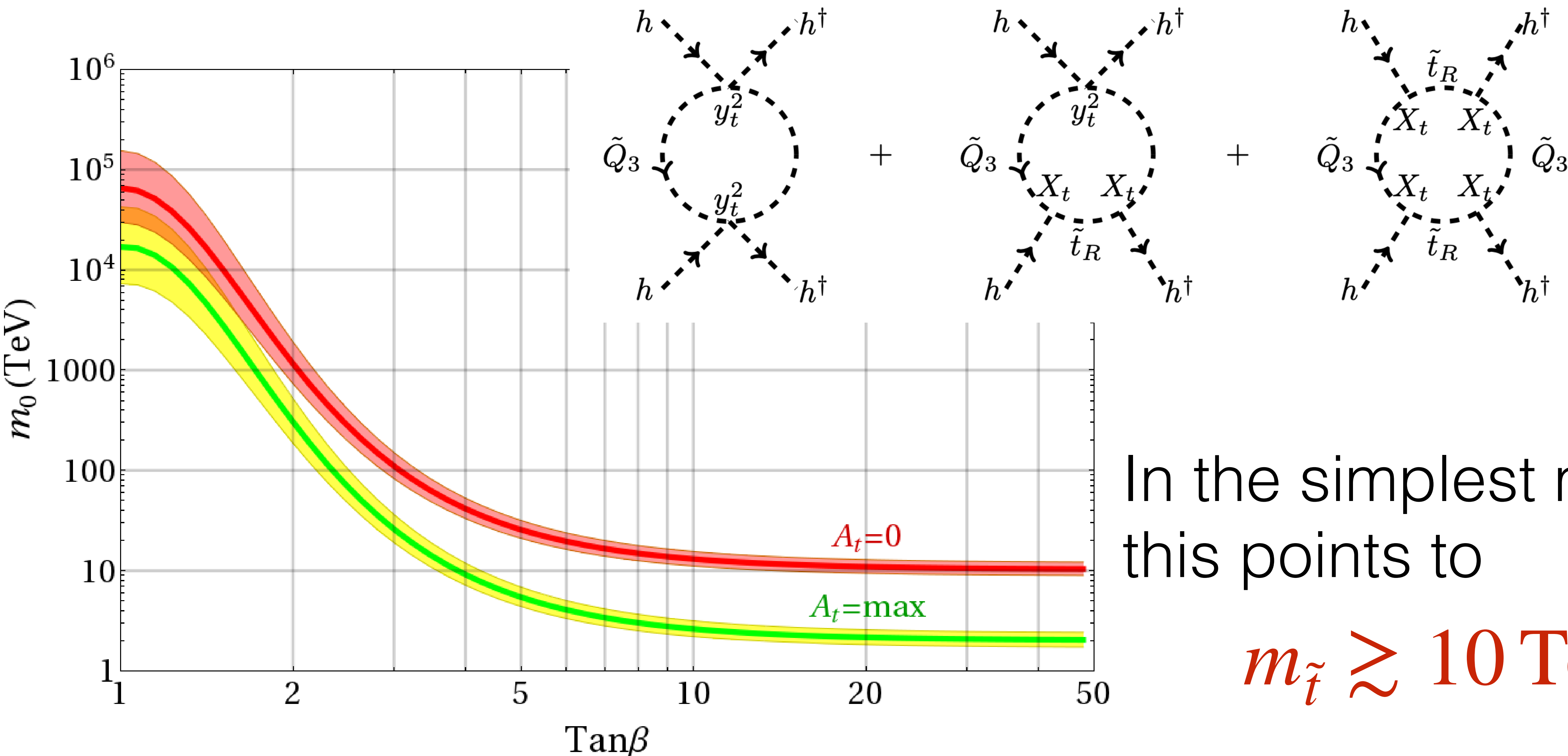
Why is the Higgs Mass 125 GeV?

In the MSSM, largely depends on the stop mass and $\tan\beta$.



In the simplest models, this points to

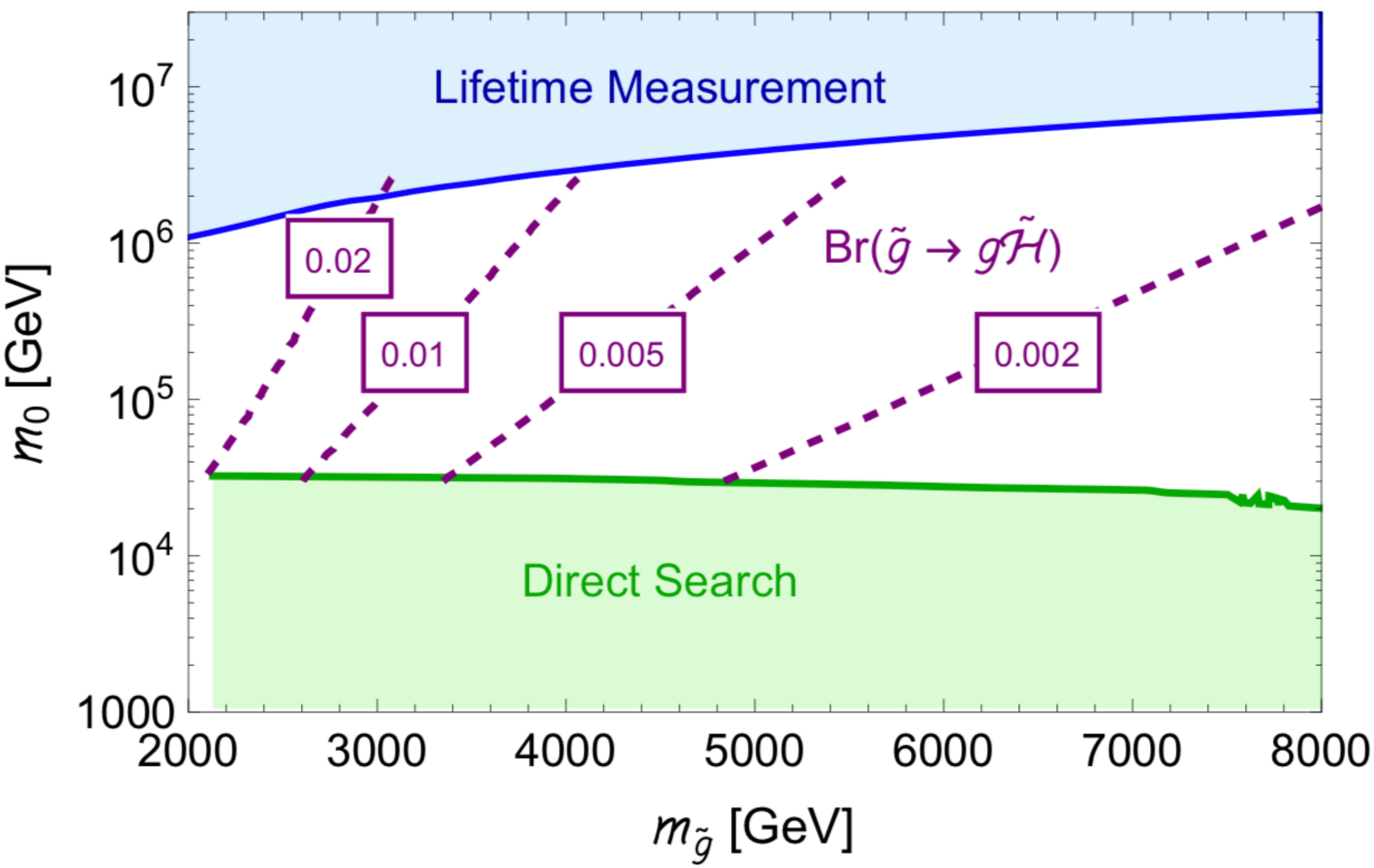
$$m_{\tilde{t}} \gtrsim 10\,\mathrm{TeV}$$

Can we test this?

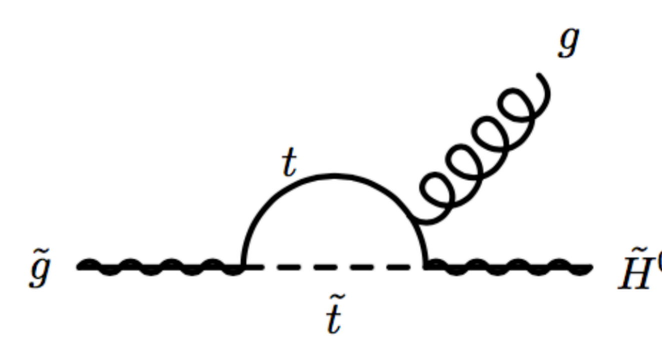
Arvanitaki, Craig, Dimopoulos, Villadoro
1210.0555

Partial discovery scenario

We may get only *part* of the spectrum. **Example: split SUSY**.
Scalars out of reach.
But the 100 TeV collider would be a **gluino factory:** $\sim 10^5$ to 10^7 gluinos



logs from loops



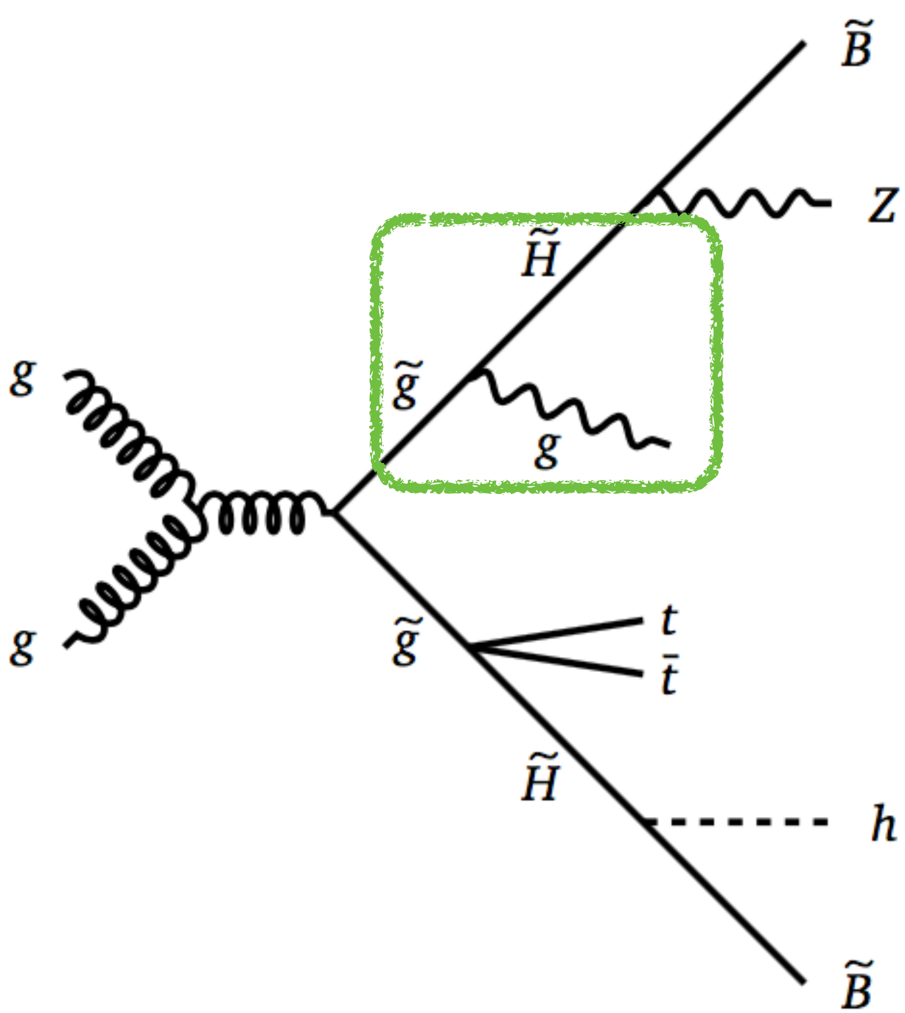
Can we learn where the scalars are?

Agrawal, Fan, MR, Xue ’17
(also see Sato, Shirai, Tobioka ’12)

Scalar mass: collider benchmark

$$M_2 > |\mu| > M_1$$

$$M_3 = 2\ \text{TeV}, \quad M_2 = 800\ \text{GeV}, \quad M_1 = 200\ \text{GeV}, \quad \text{and} \quad \mu = 400\ \text{GeV}.$$



Diagnostic of scalar mass: rate of 1-loop

$$\tilde{g} \to \widetilde{H} + g$$

so find a hard jet and Z on one side of event

$$H_T > 2\ \text{TeV}, \quad p_T^{\text{missing}} > 1\ \text{TeV}, \quad p_T(j_1) > 1\ \text{TeV},$$
$$N_{\text{jet}} < 5,\ \text{one leptonic } Z\ (80\ \text{GeV} < m_{\ell\ell} < 100\ \text{GeV}),$$
$$m_{j_1 Z} > m_{\text{all other jets}},\ M_{T2}^{\ell\ell} > 80\ \text{GeV}.$$

Scalar mass: collider benchmark

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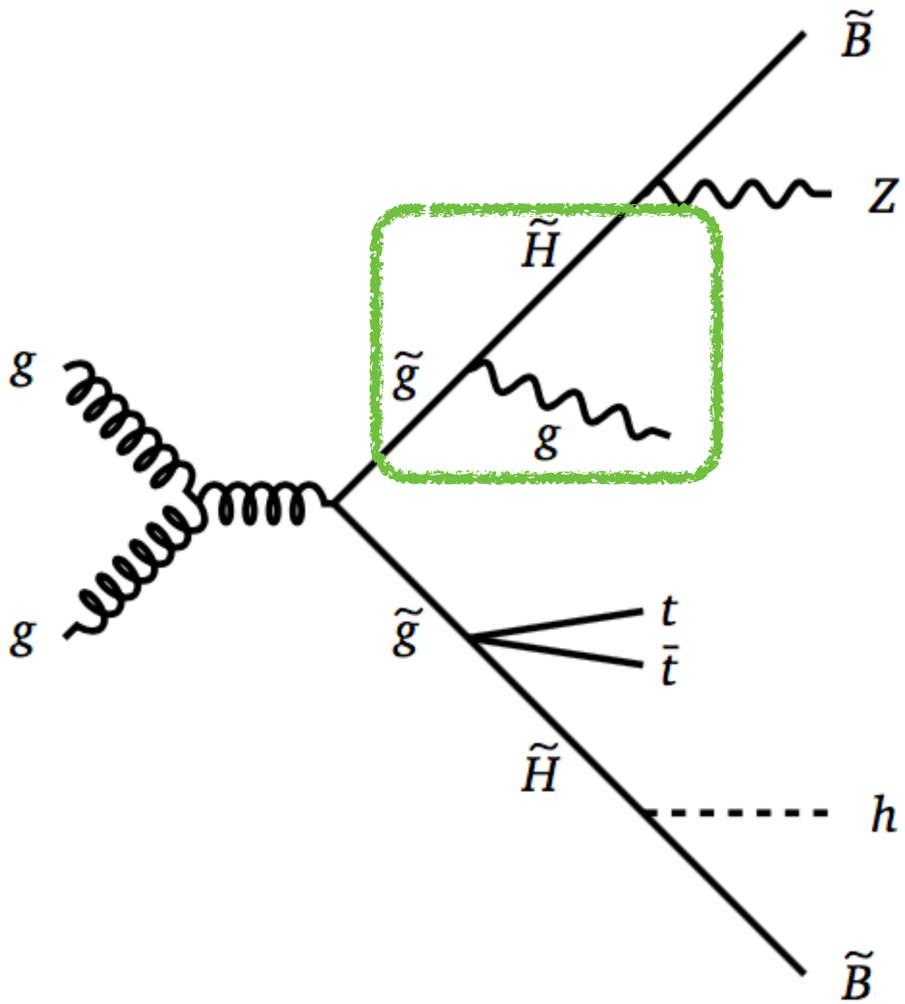
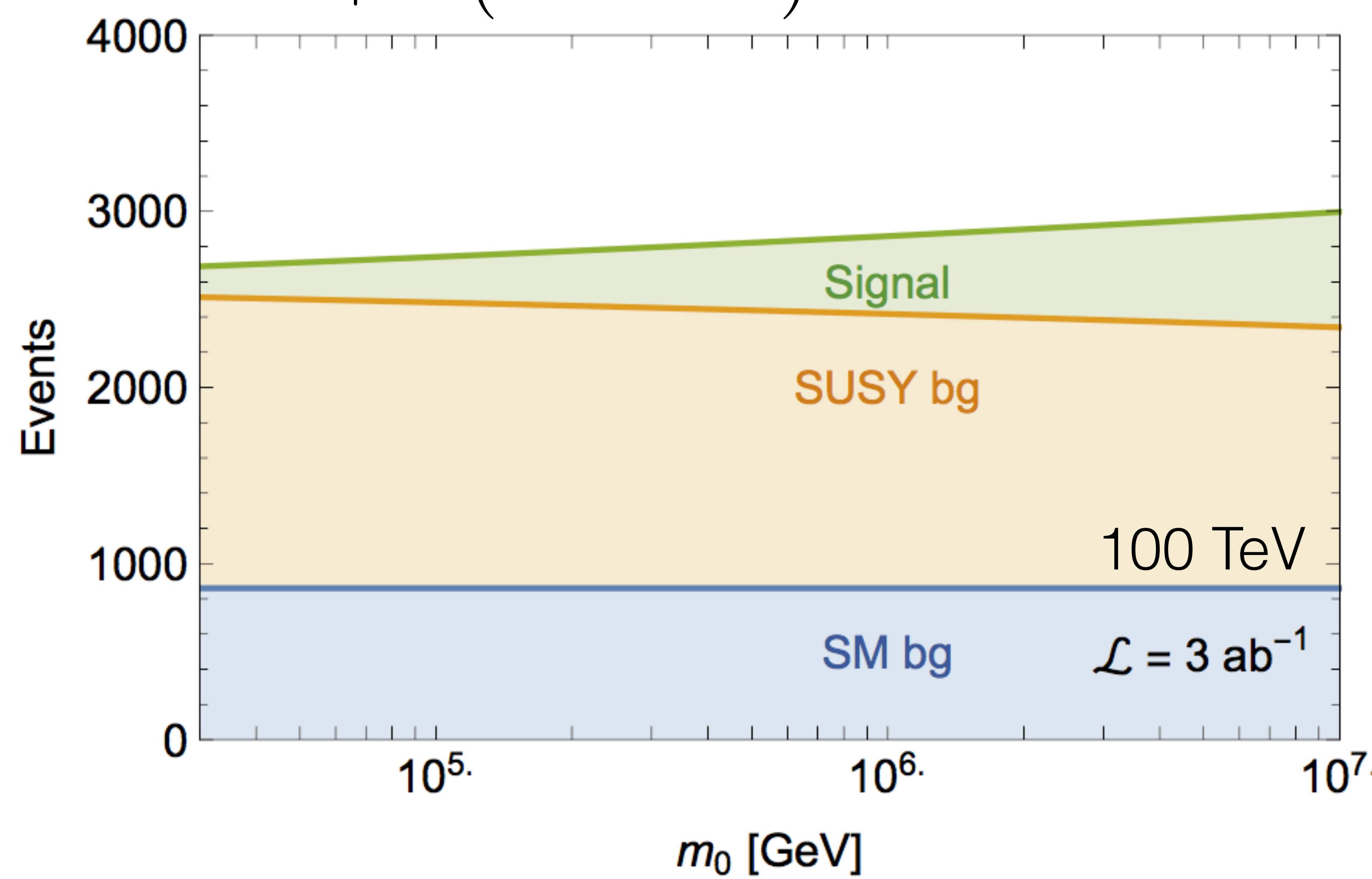


SM backgrounds:

$$Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu}) + \text{jets}$$
$$t\bar{t} + Z(\to \ell^+\ell^-)$$

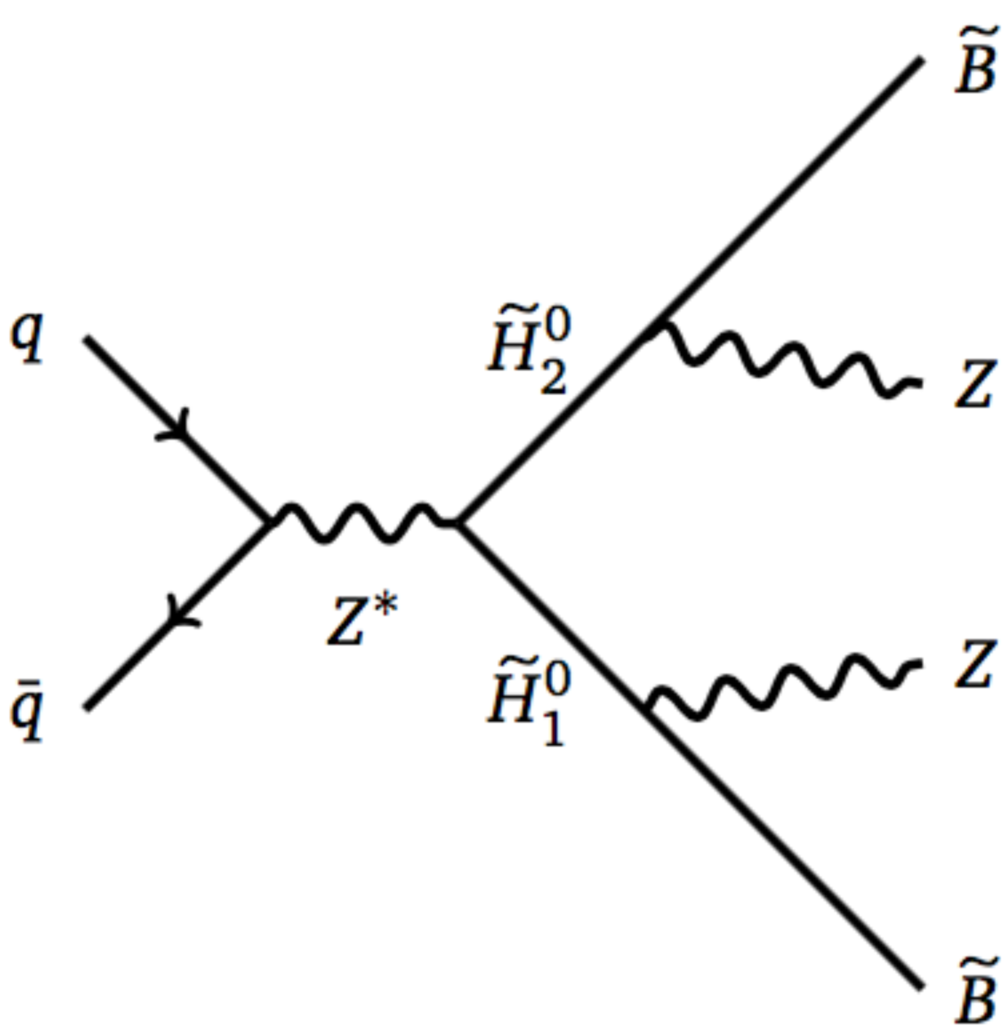


Tan beta: collider benchmark

$$\boldsymbol{M_2 > |\mu| > M_1}$$

$$M_3 = 2\text{ TeV}, \quad M_2 = 800\text{ GeV}, \quad M_1 = 200\text{ GeV}, \quad \text{and} \quad \mu = 400\text{ GeV}.$$

Off-diagonal Z boson coupling!



At tan β = 1, get h+Z+MET but no Z+Z+MET, so measure the Z+Z+MET rate in 4 leptons.

$$2\text{ pairs}, \ |m_{\ell\ell} - m_Z| < 10\text{ GeV}$$

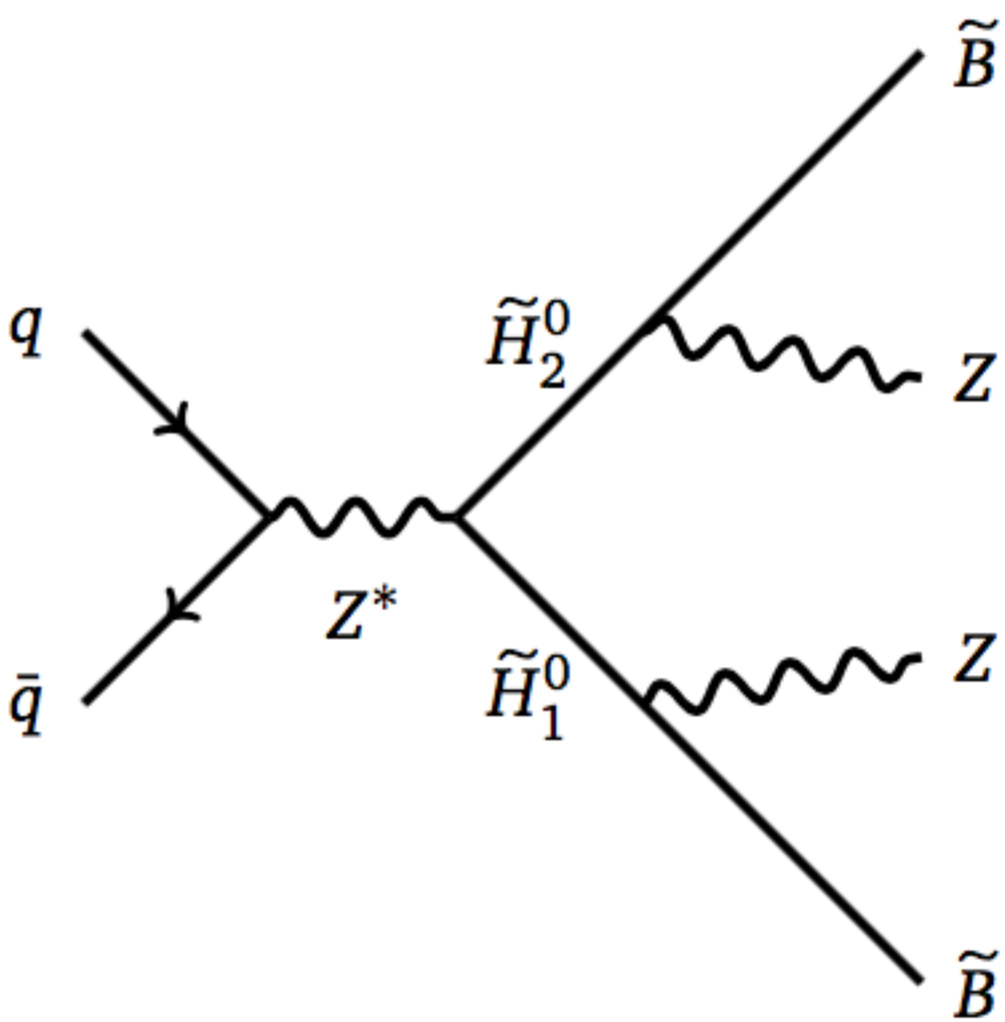
$$p_T^{\text{missing}} > 150\text{ GeV}$$

$$\sum_{\text{visible}} |p_T| < 600\text{ GeV}$$

Tan beta: collider benchmark

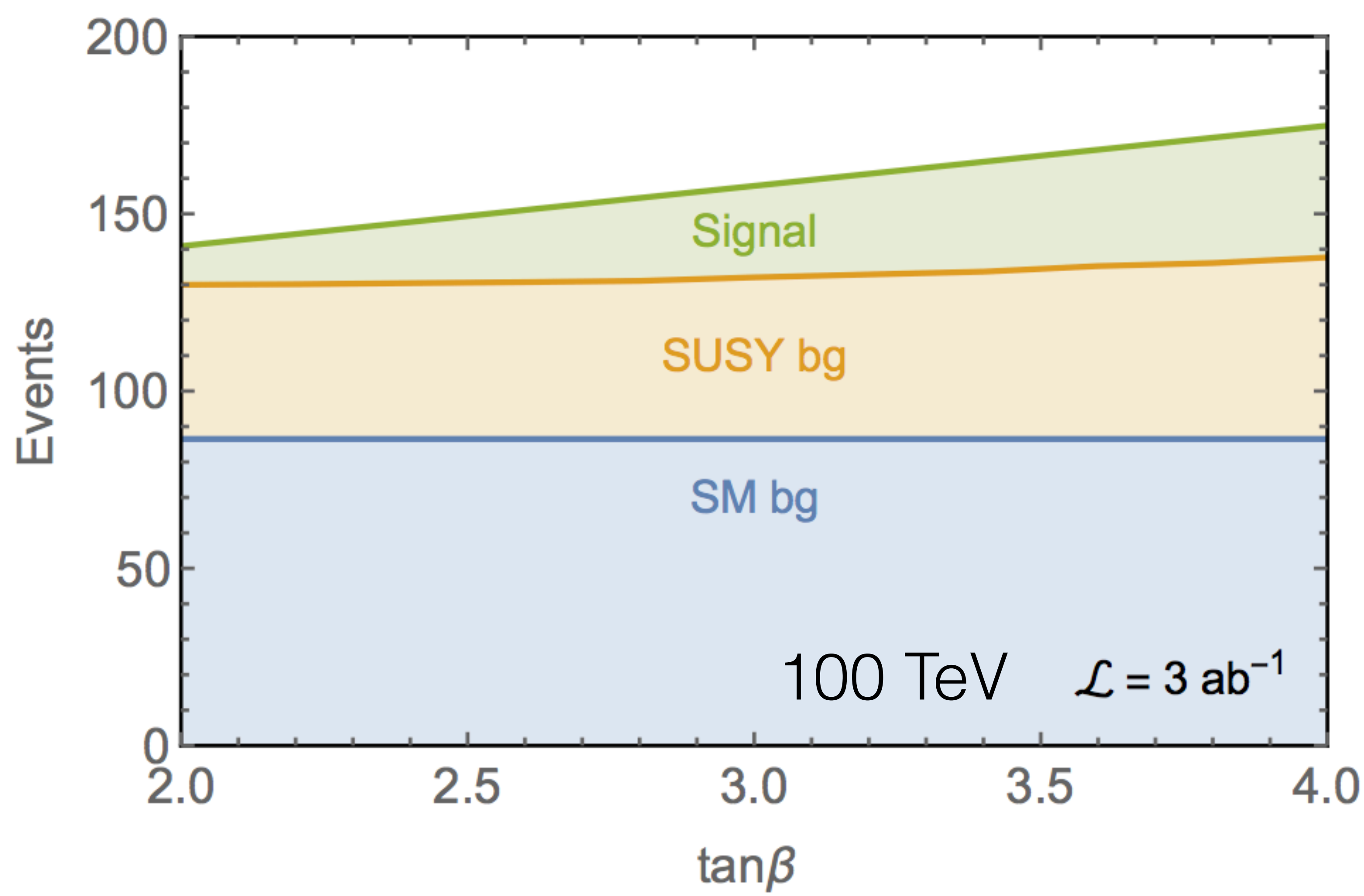
$$M_2 > |\mu| > M_1$$

$$M_3 = 2\ \text{TeV}, \quad M_2 = 800\ \text{GeV}, \quad M_1 = 200\ \text{GeV}, \quad \text{and} \quad \mu = 400\ \text{GeV}.$$

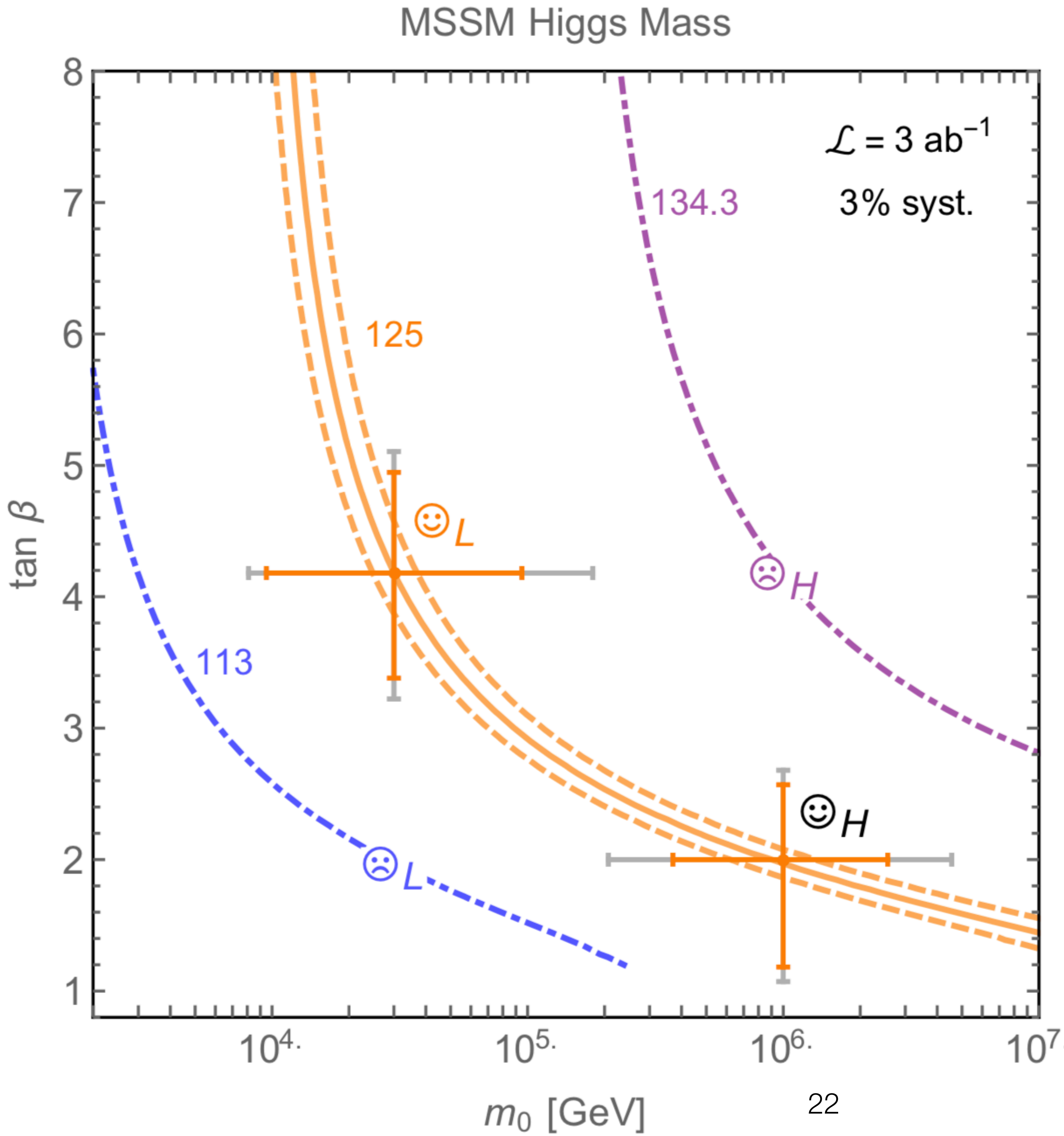


SM background:

$$Z(\to \ell^+\ell^-) + Z(\to \ell^+\ell^-) + Z(\to \nu\bar{\nu})$$



Testing the MSSM Higgs mass hypothesis



Precision physics @ future hadron collider could answer **big question**: where does the Higgs mass come from?

Would open up **new big question**: where does the SUSY breaking scale come from?

Agrawal, Fan, MR, Xue '17

Conclusions

Powerful physics motivations for a high-energy hadron collider at ~100 TeV:

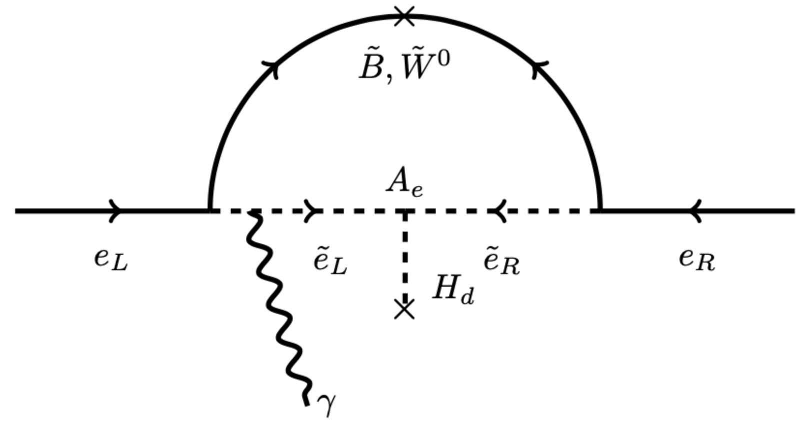
- Decisive study of SU(2) multiplet **dark matter**
- Measure **Higgs self-coupling**
- Explore parameter space for strong first-order **electroweak phase transition**
- Very high **mass reach** for new particles

But also: **factory for new particles at ~few TeV**. Explore their properties in detail: not just hints, but really **decipher the structure of new physics!**

Could CP and Flavor Lead the Way?

EDM, 1-loop

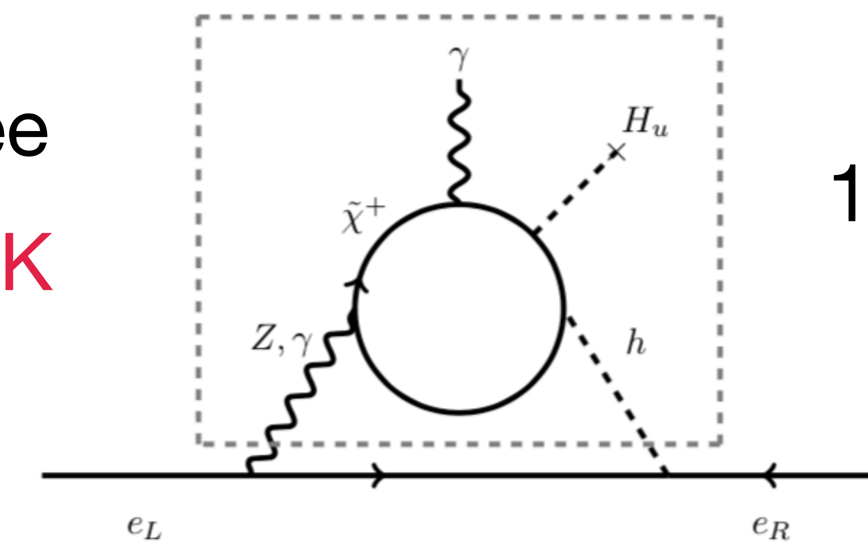
electron-flavored



10^{-32} *e* cm $\Longrightarrow$ ~ **1 PeV (!)**

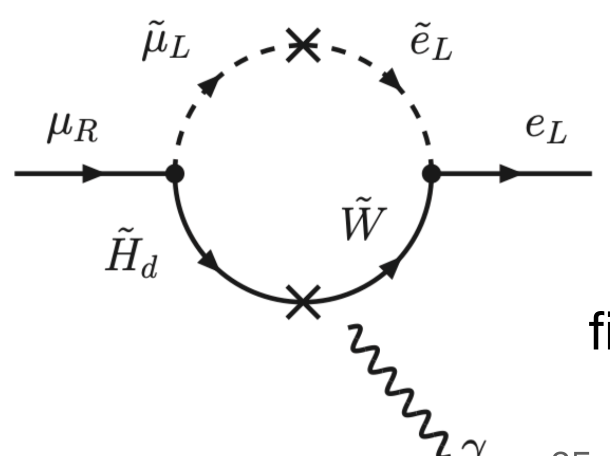
EDM, 2-loop Barr-Zee

Anything Higgs+EWK



10^{-32} *e* cm $\Longrightarrow$ ~ **50 TeV (!)**

μ→e, 1-loop,
flavor violating



10^{-19} on Al $\Longrightarrow$ ~ **50+ TeV (!)**

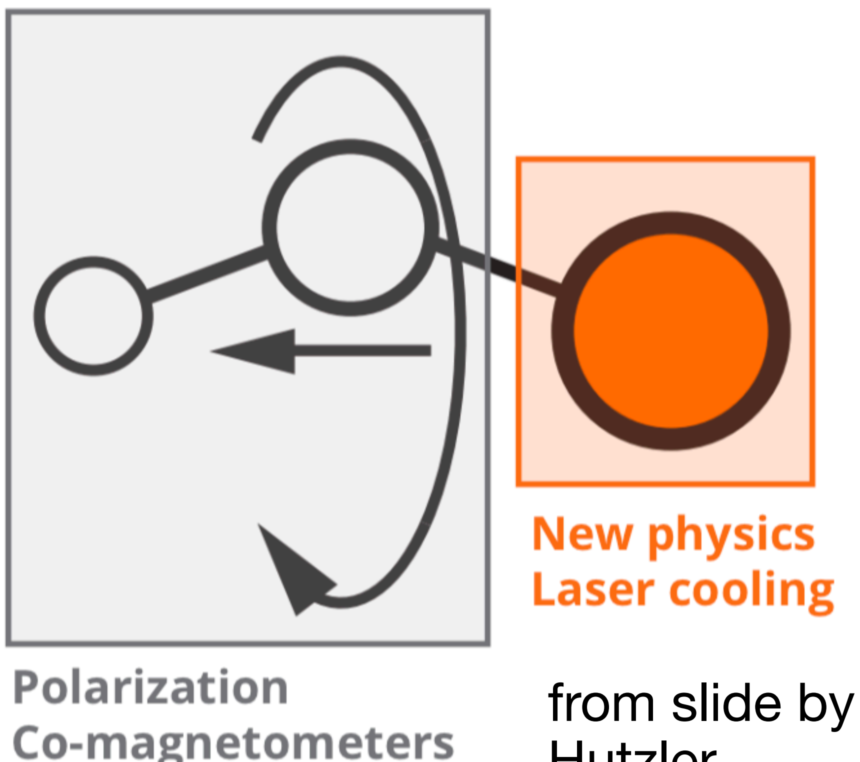
fig. from 1308.3653: Altmannshofer, Harnik, Zupan

(w/ electron Yukawa spurions on all diagrams)

EDM Precision on the Horizon

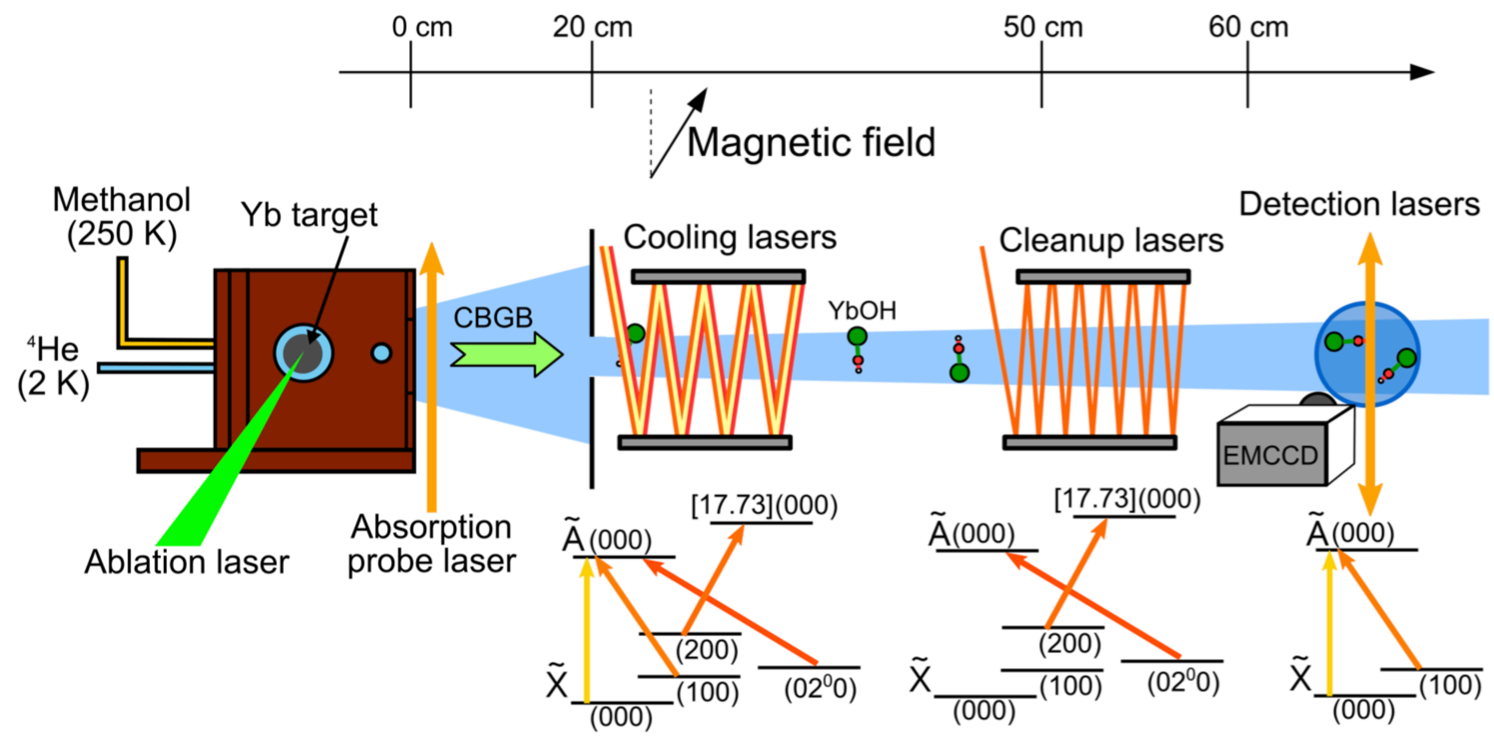
One of several parallel approaches:

Polyatomic Molecules (e.g., YbOH)



from slide by N. Hutzler

Hutzler, Kozyryev 1705.11020

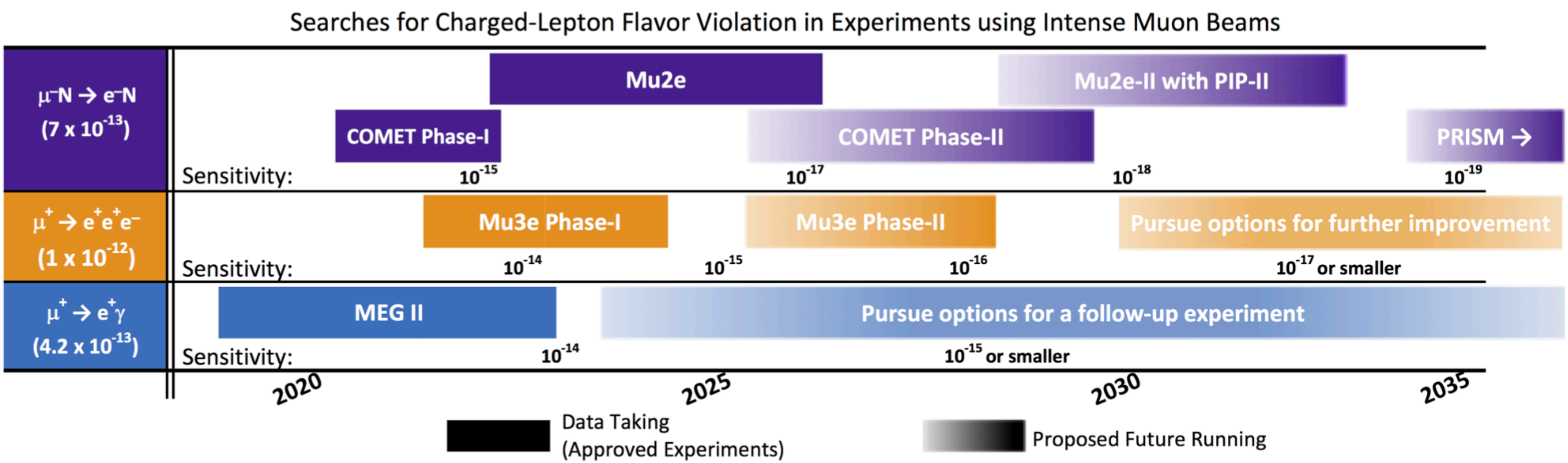


Laser cooling achieved

(Augenbraun et al., 1910.11318)

Electron EDM: $10^{-29} e\,\mathrm{cm} \longrightarrow 10^{-32} e\,\mathrm{cm}$ **!**

Charged Lepton Flavor Violation



Source: Baldini et al., 1812.06540, submission to 2020 European Strategy from COMET, MEG, Mu2e and Mu3e collaborations