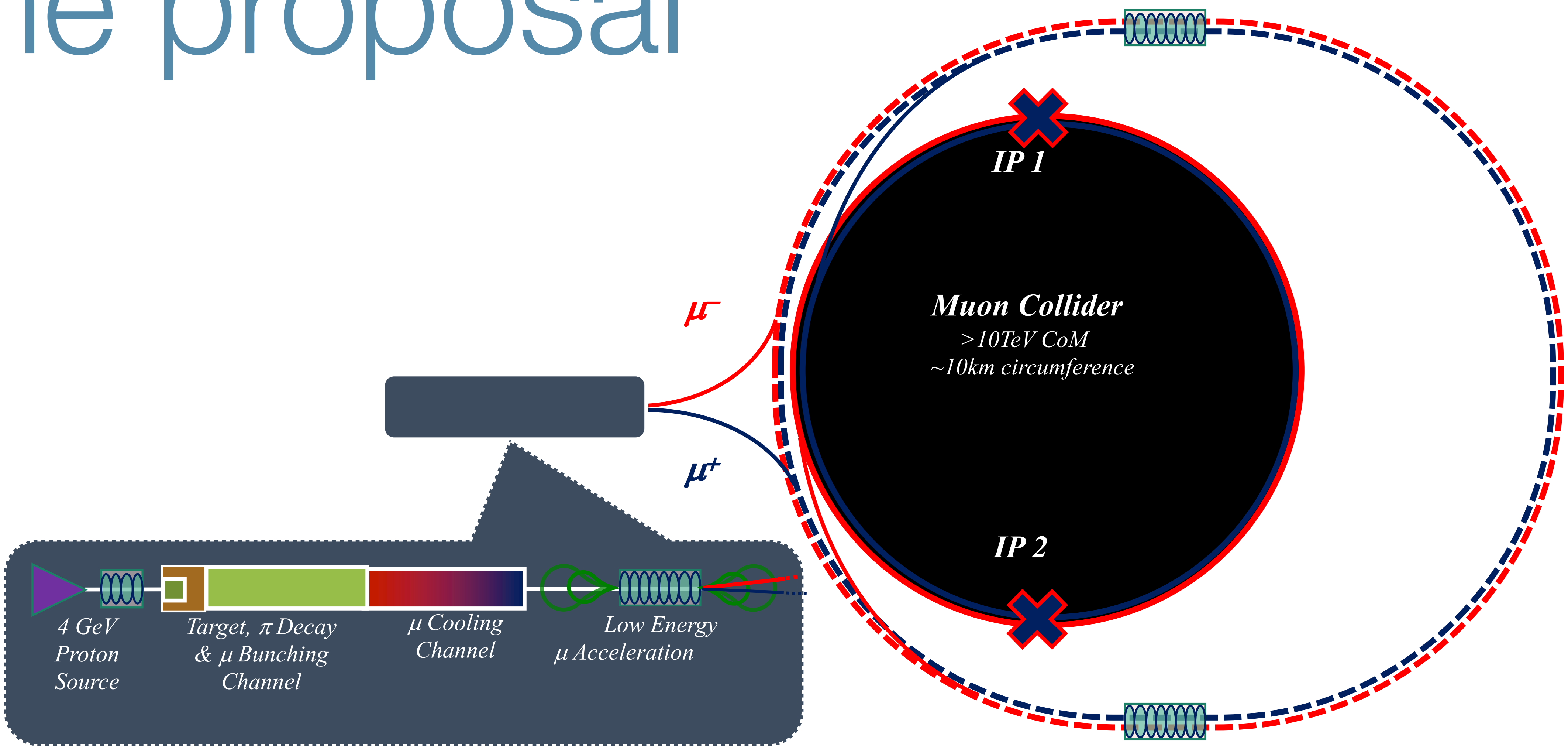
Physics potential of Muon Collider

LianTao Wang
University of Chicago

Muons in Minneapolis workshop, Dec 6, U. Minnesota

The proposal



Running scenarios

$$E_{\rm CM} = 3\ \text{TeV},\ \ \mathscr{L} = 1\ \text{ab}^{-1}$$
$$E_{\rm CM} = 10\ \text{TeV},\ \ \mathscr{L} = 10\ \text{ab}^{-1}$$

$$\mathscr{L} \propto E_{\rm CM}^2$$

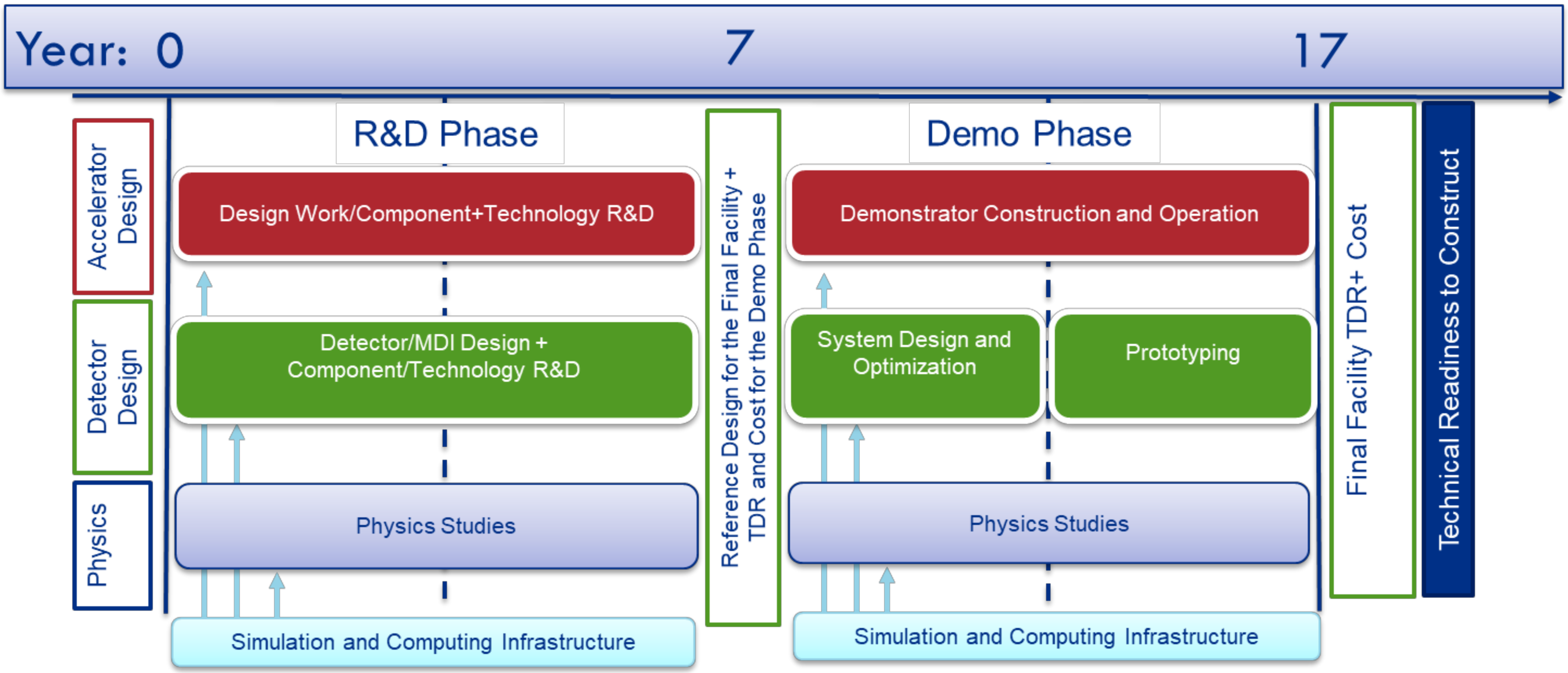
Ready to build?

Collider Concepts	Collider-in-Sea MuIC	WFA MuC ReLIC (≤3 TeV) Multi-TeV ILC (Nb_3Sn) CCC (TeV) SppC	FCC-hh FCC-eh CLIC TeV ILC (Nb)
Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

M. Palmer

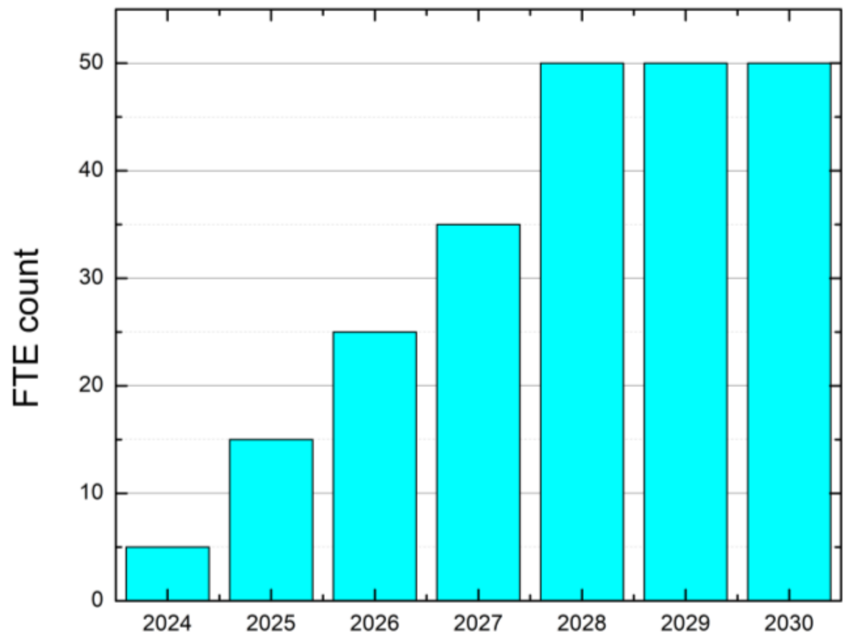
Before the decision to build it, needs more R&D.

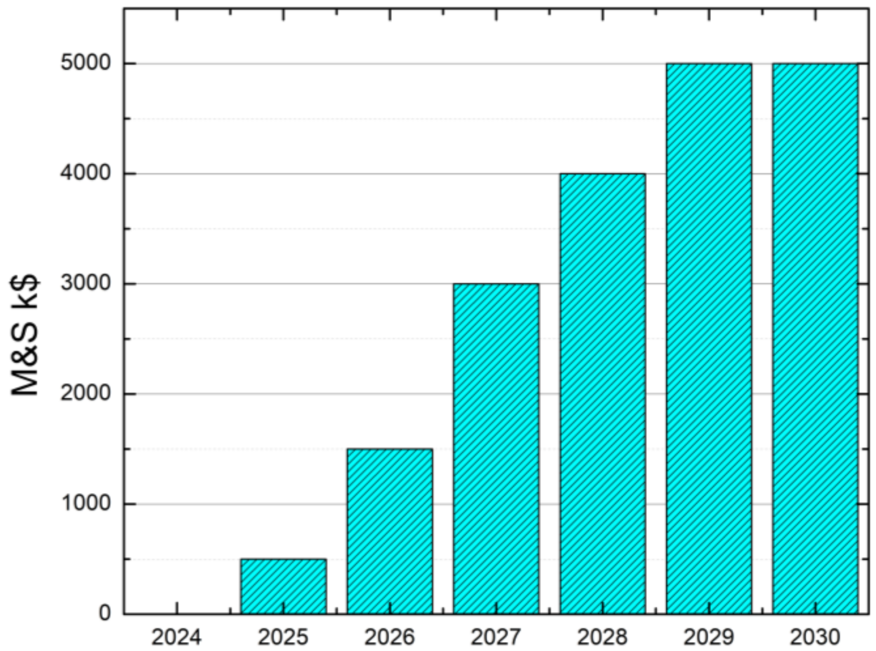
A plan.



Ready to build in early 2040s.

Need support





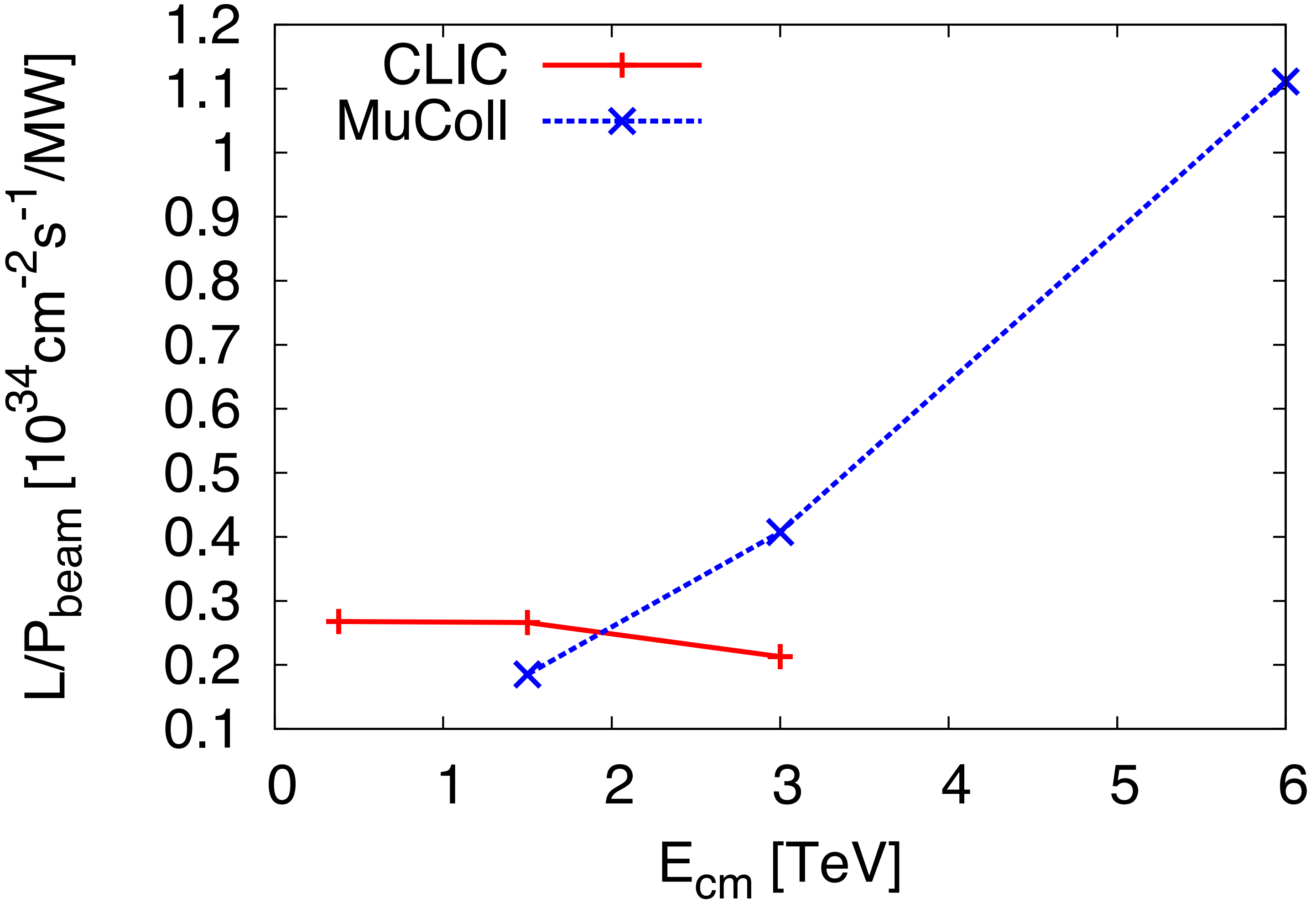
International Muon Collider Collaboration established after European strategy update in 2020.

US support (money, people) will be also crucial

A first step: P5 report (~ 24 hours from now)

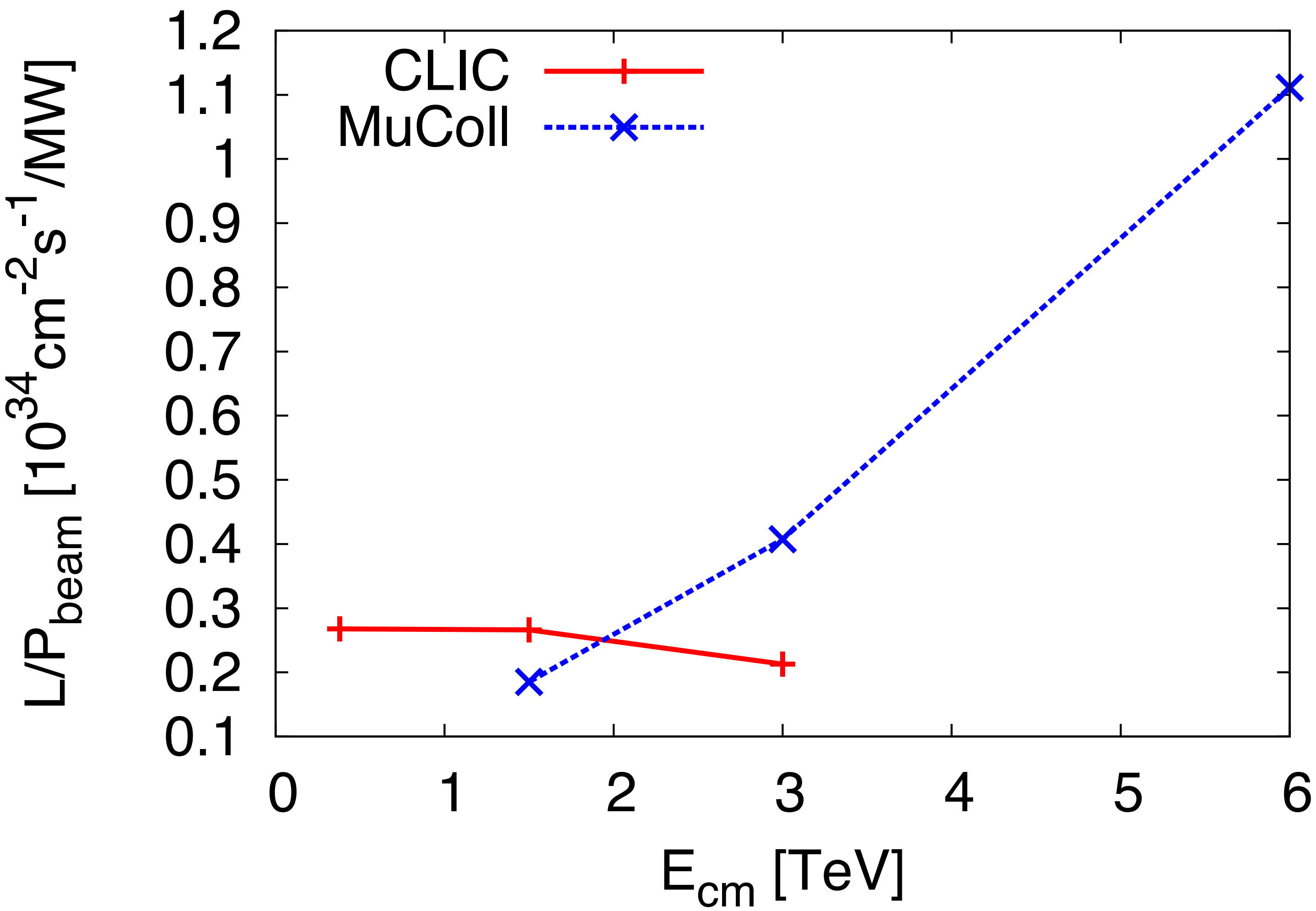
Why muon collider?

The obvious: higher energy, shorter distances



$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

The obvious: higher energy, shorter distances

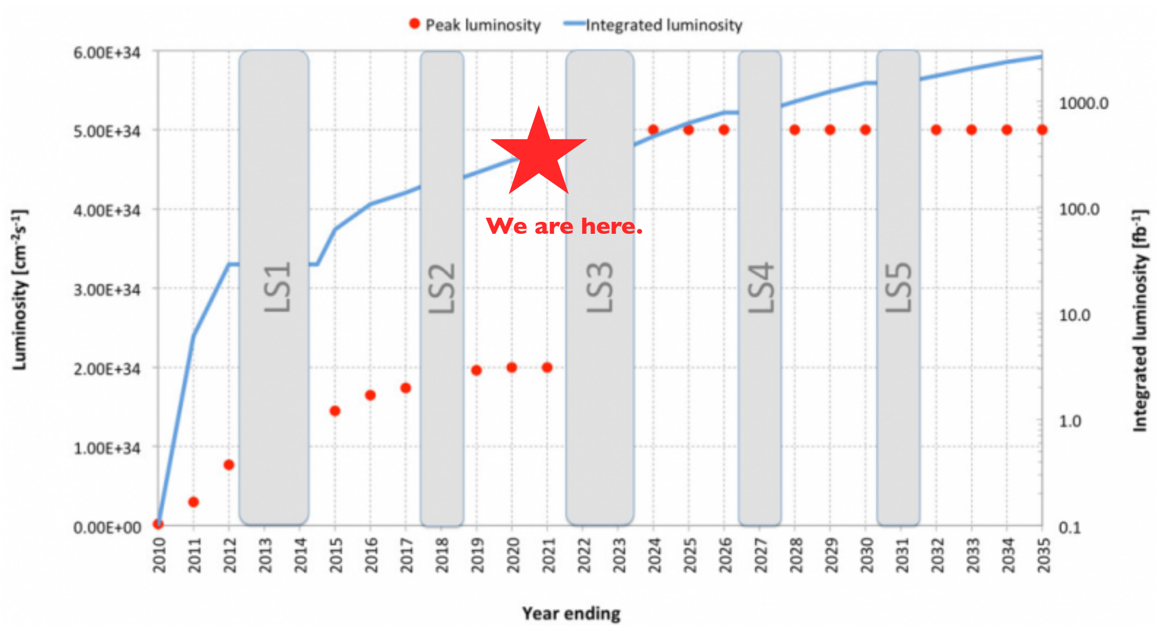


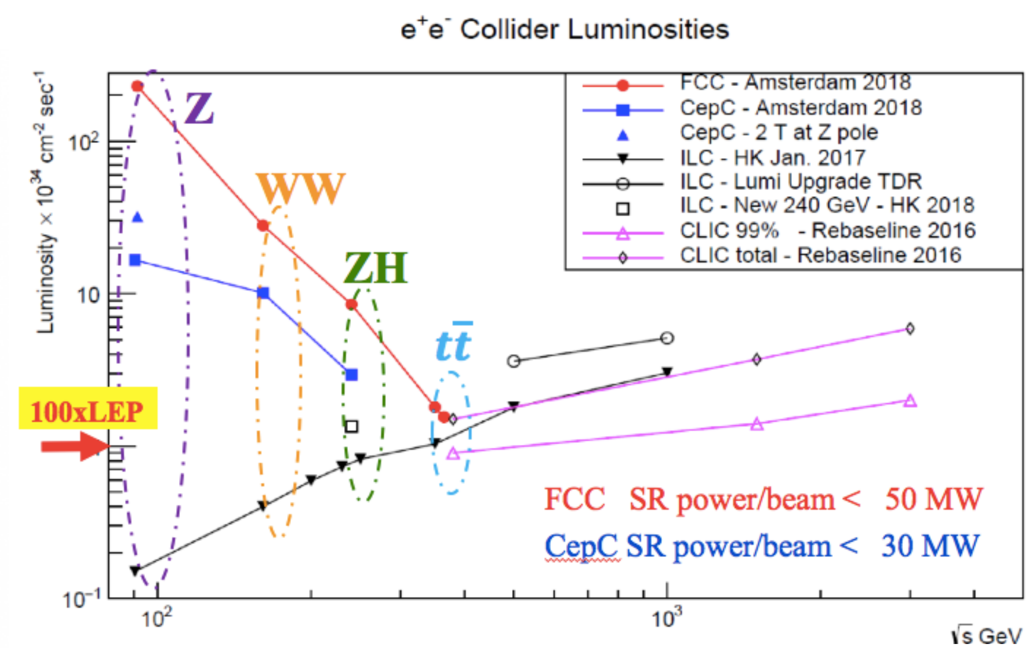
$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Good enough? Yes (for most of us).

Still, why muon collider at these energies?

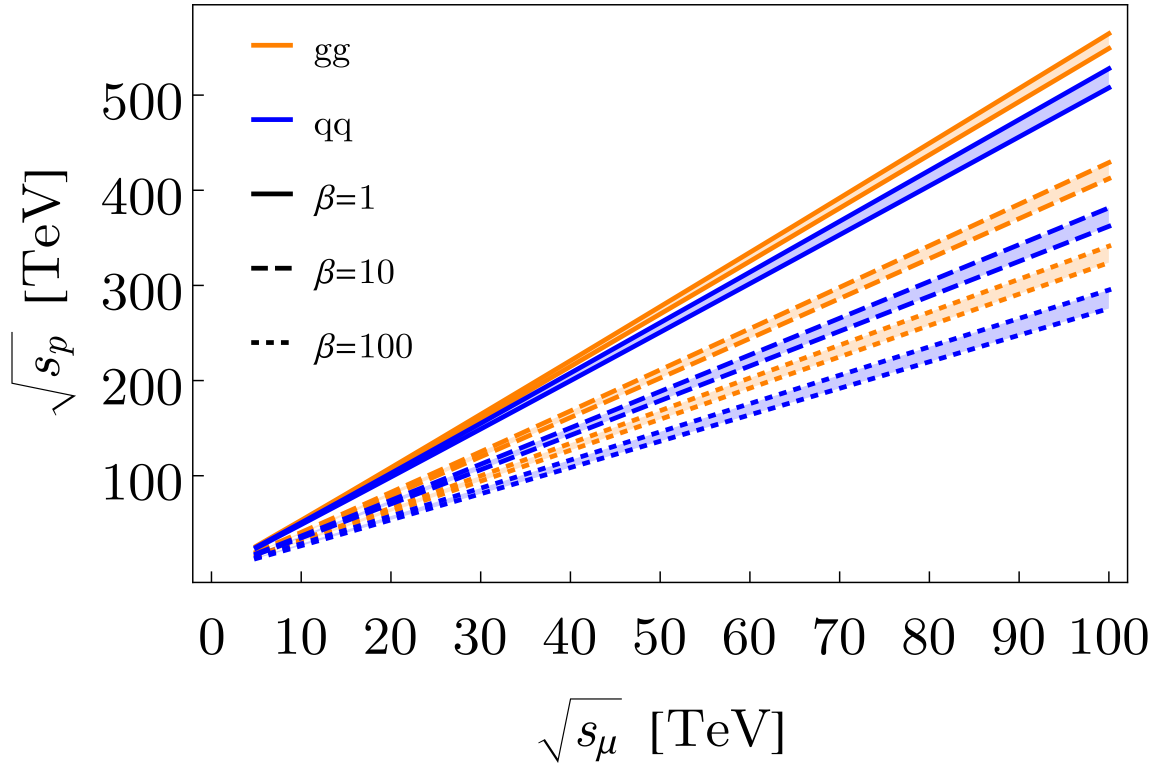
The coming decades



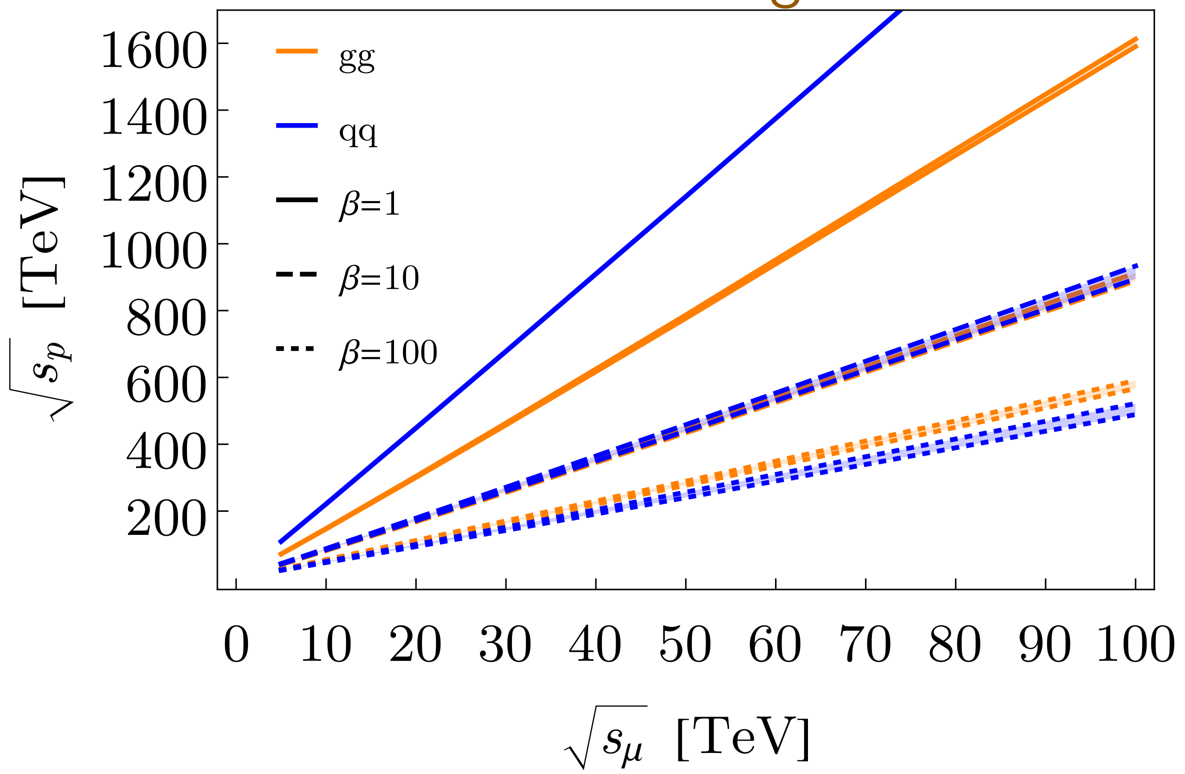


- Main “near term” targets: precision, rare processes.
- Muon collider, going beyond these options, such as LHC and the low energy Higgs factories.

Comparison with 100-ish TeV pp collider Such as FCC-hh or SPPC



“The muon smasher’s guide”



- Naively, 100 TeV pp ≈ 10+ TeV muon collider.
- Lepton collider “cleaner”. Good for precision, search in difficult channels.

Why ~10 TeV?

Why ~10 TeV?

- Are there guaranteed discoveries?
  - No.

Why ~10 TeV?

- Are there guaranteed discoveries?
  - No.
- It is a significant step beyond our current reach.
  - A lot of interesting physics to cover.

Why ~10 TeV?

- Are there guaranteed discoveries?
  - No.
- It is a significant step beyond our current reach.
  - A lot of interesting physics to cover.
- Higher energy is of course better for physics.
  - Limited by resource.

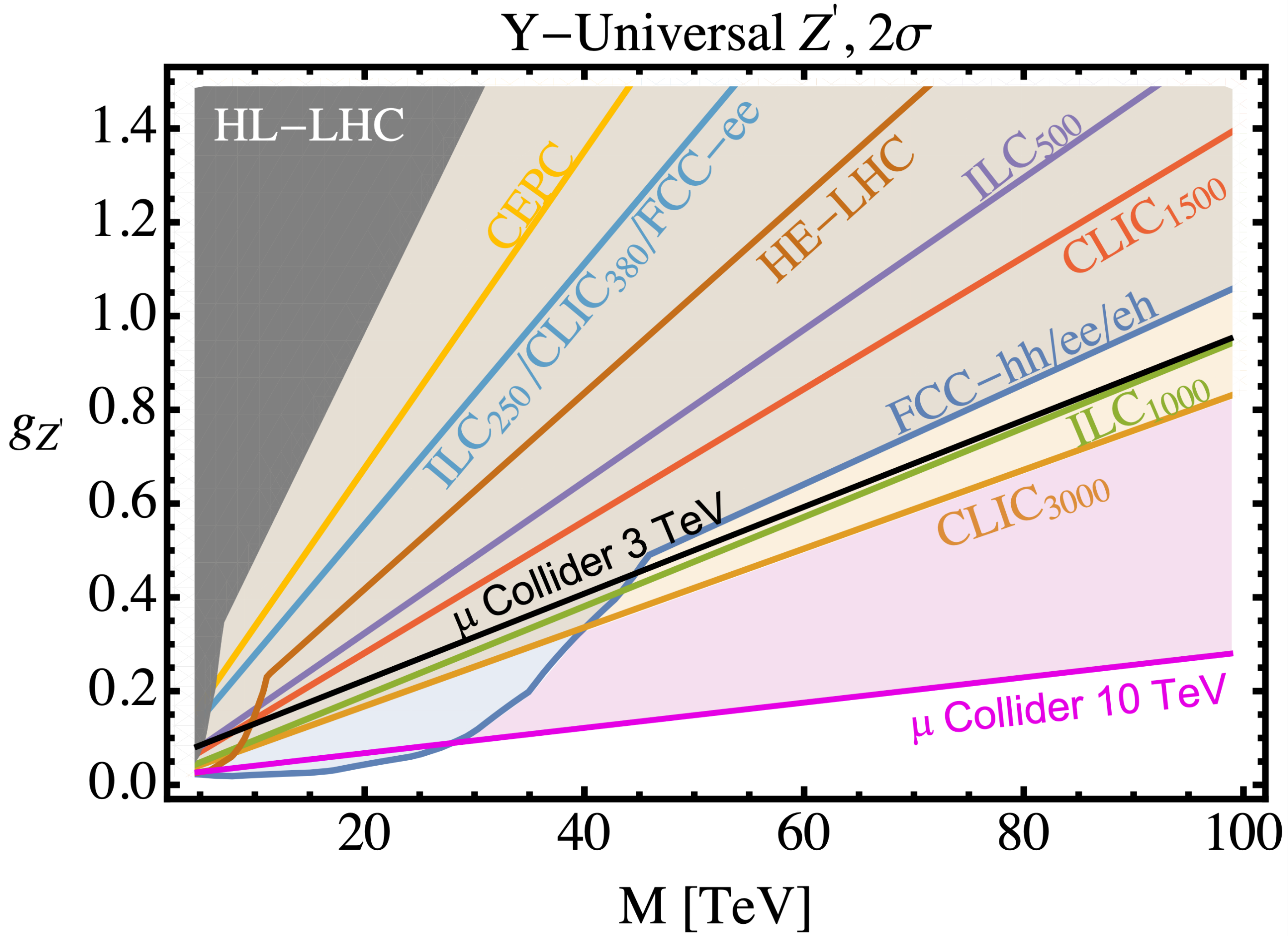
Why ~10 TeV?

- Are there guaranteed discoveries?
  - No.

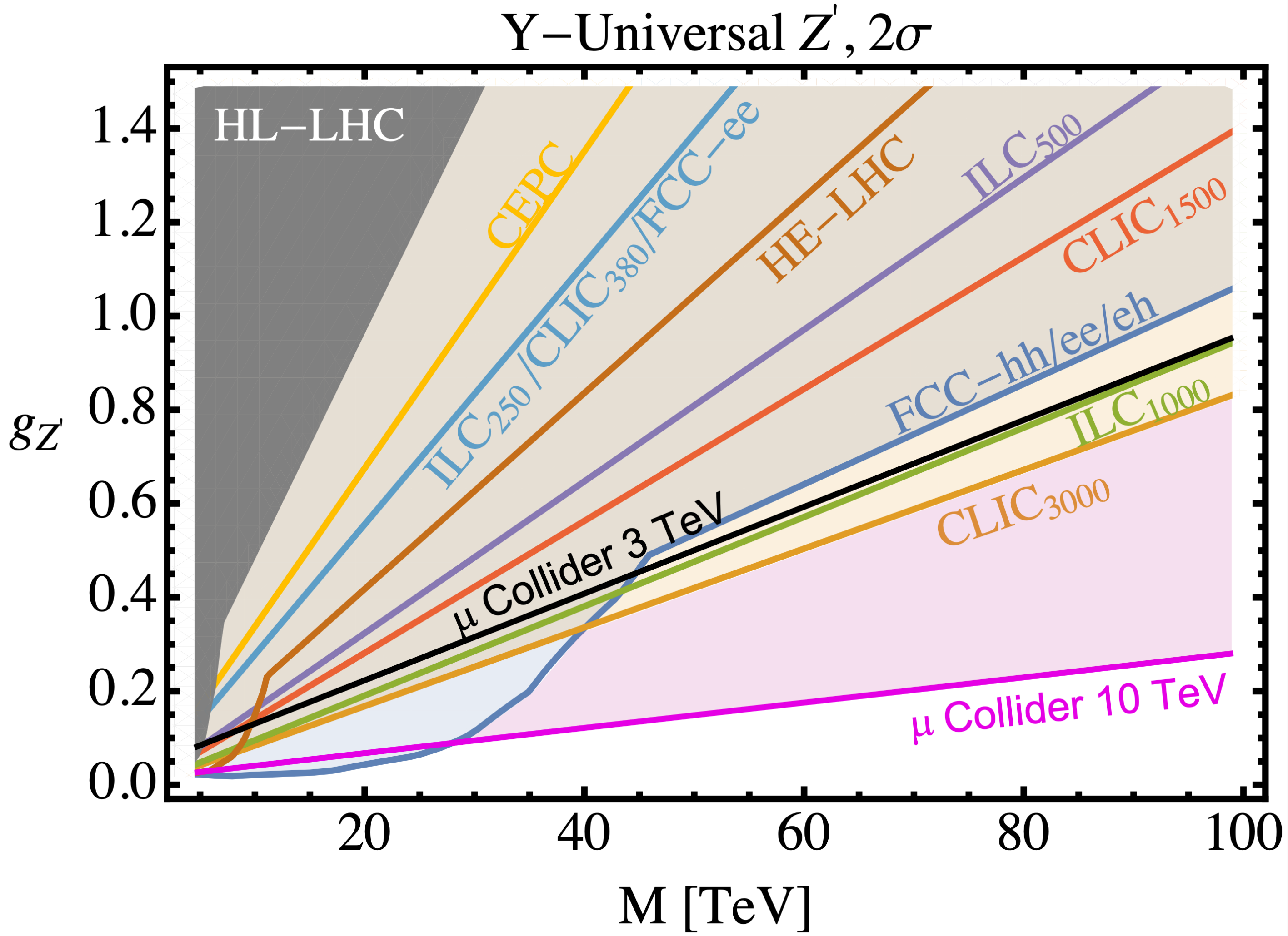
Rest of the talk

- It is a significant step beyond our current reach.
  - A lot of interesting physics to cover.
- Higher energy is of course better for physics.
  - Limited by resource.

Obvious: big step in NP searches

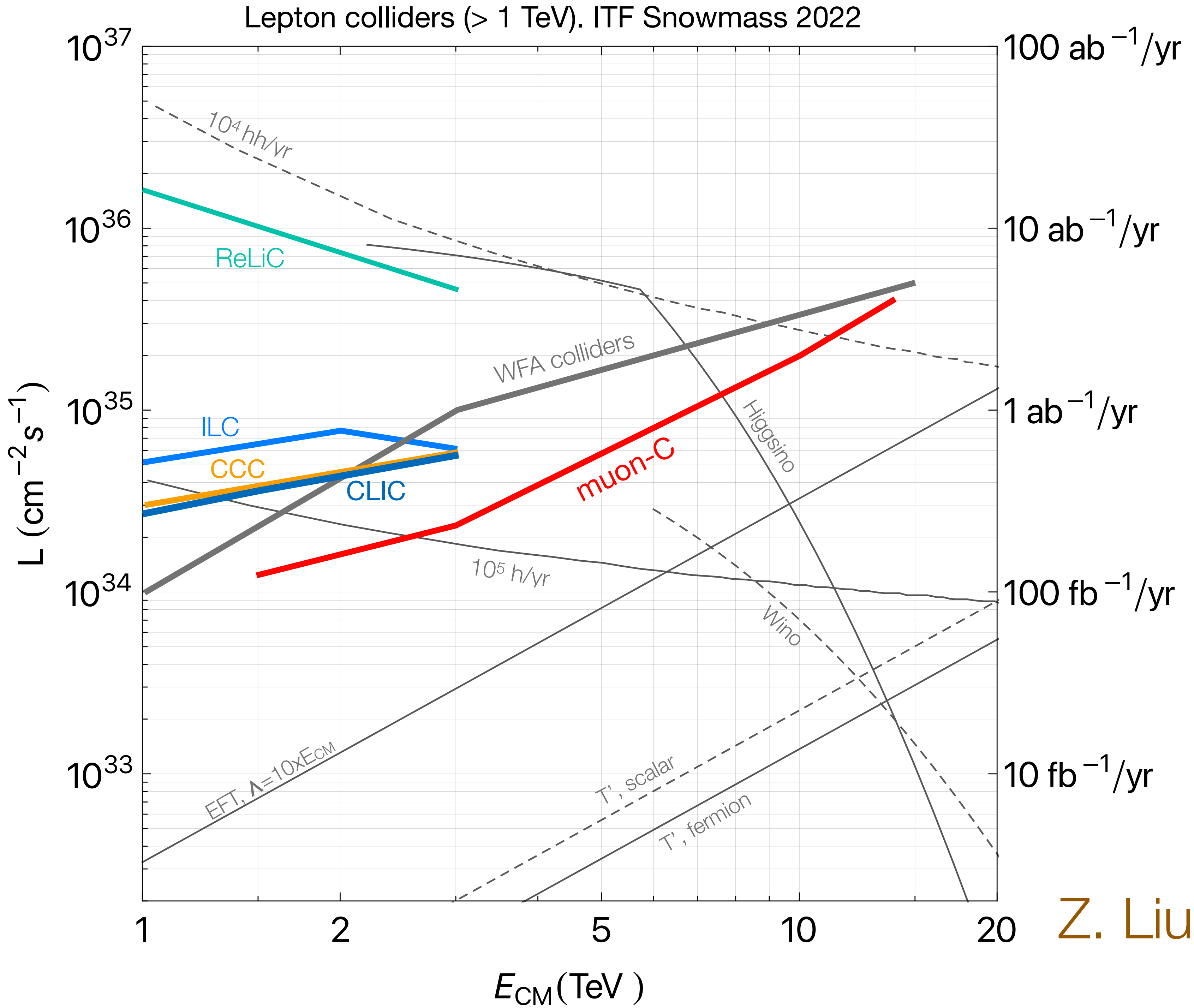


Obvious:
big step in NP searches



What are the interesting questions it can help answer?

Basic physics output



Z. Liu, LTW

Physics program at a muon collider

- Higgs and electroweak.
- New physics at higher energies.
  - Dark matter
  - Flavor, CP
  - …

References:
Muon smasher's guide, IMCC input to Snowmass, Muon collider forum report
Snowmass BSM working group report

Higgs and electroweak

- Obvious: important to understand the Higgs (more broadly, electroweak physics) better.

  - Origin of the weak scale.

  - Nature of EW symmetry breaking.

Higgs and electroweak

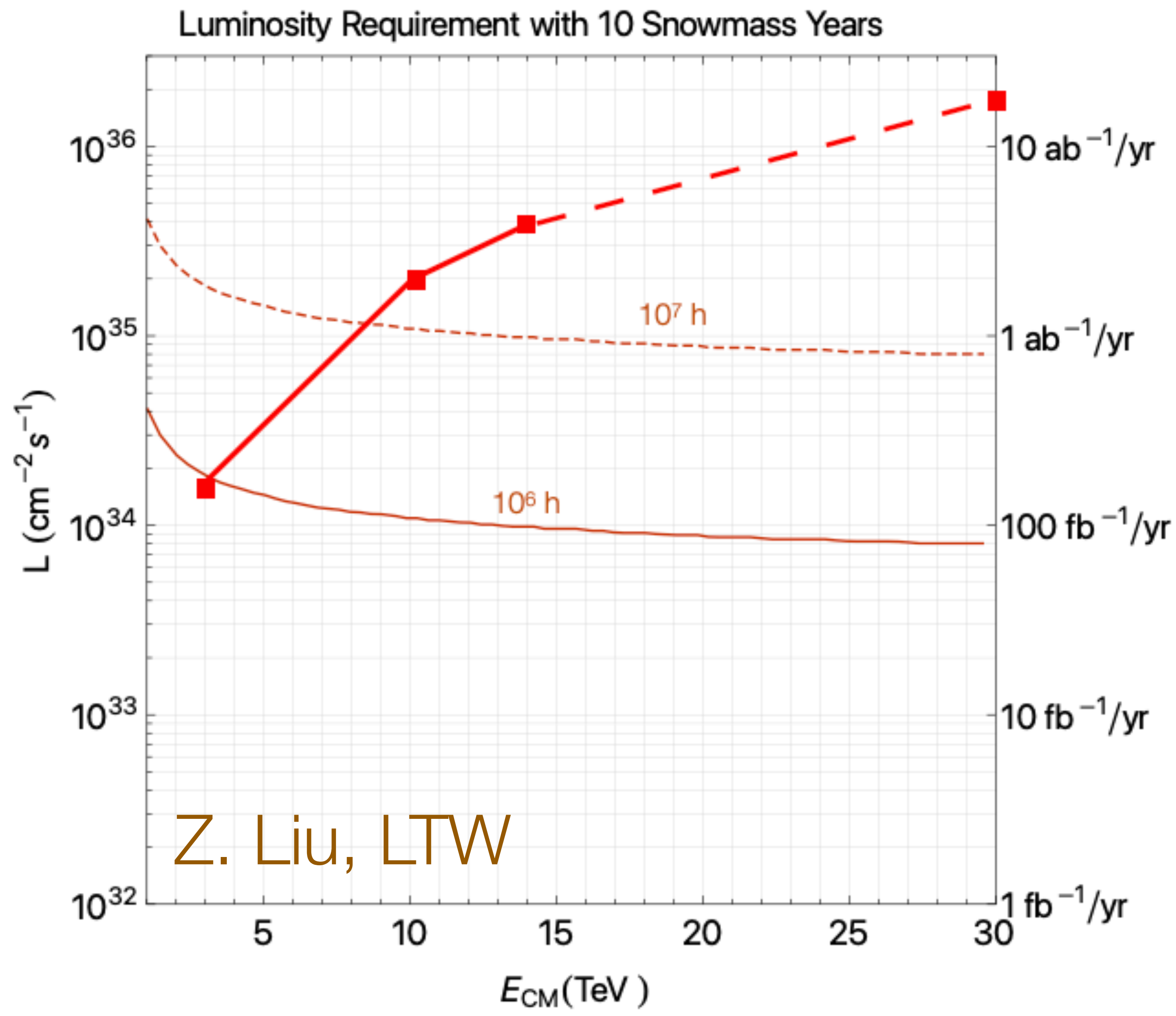
- Obvious: important to understand the Higgs (more broadly, electroweak physics) better.
    - Origin of the weak scale.
    - Nature of EW symmetry breaking.
- Not so obvious: what does muon collider bring to the table?

Higgs and electroweak

- Obvious: important to understand the Higgs (more broadly, electroweak physics) better.
    - Origin of the weak scale.
    - Nature of EW symmetry breaking.
- Not so obvious: what does muon collider bring to the table?

It will reach energies much beyond the electroweak scale!

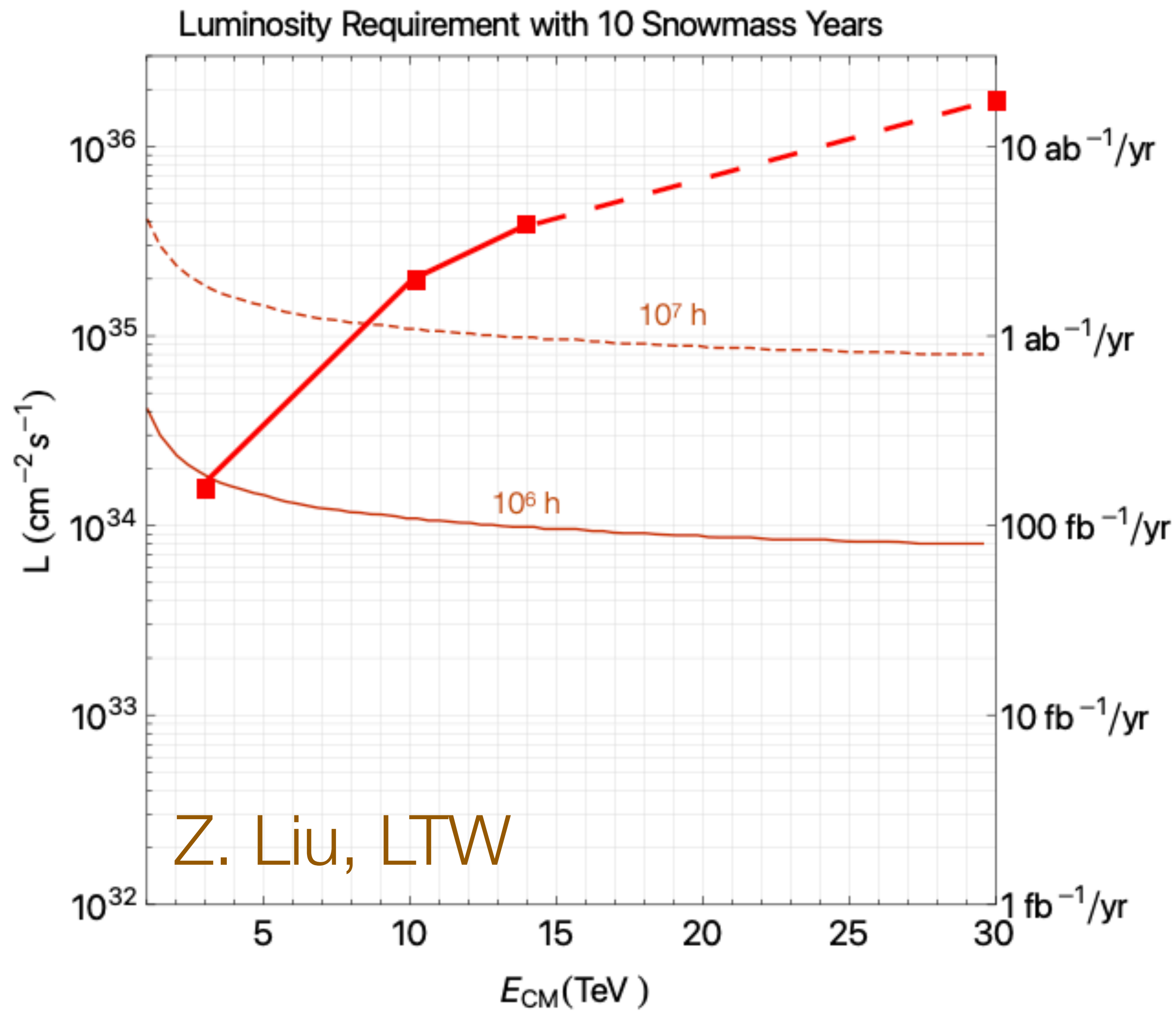
MC as Higgs factory



In comparison:

low(er) energy Higgs factories
~ 10^6 Higgses

MC as Higgs factory



In comparison:

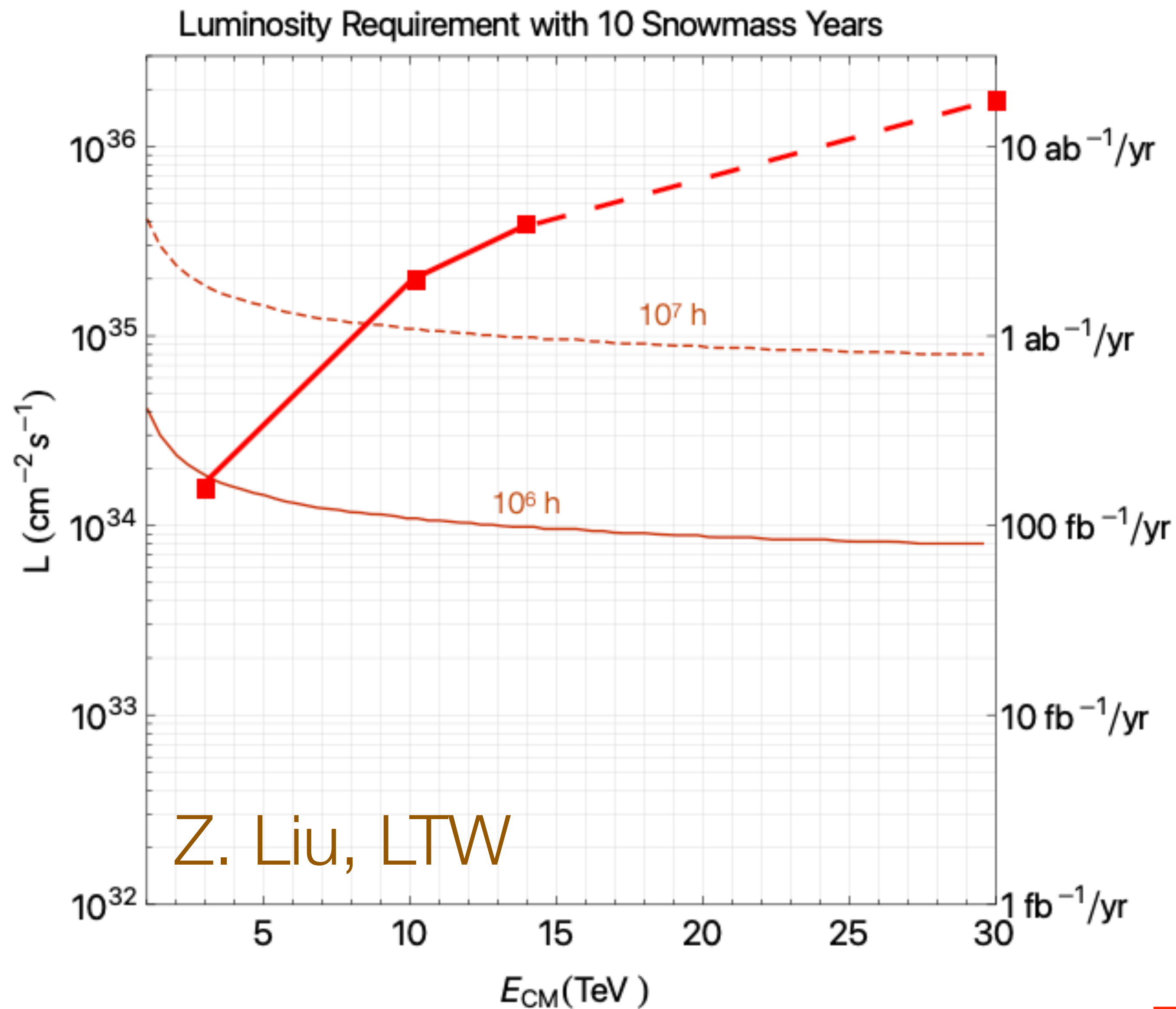
low(er) energy Higgs factories
~ 10^6 Higgses

Assuming:

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

E_{CM} :	125 GeV	1.5 TeV	3 TeV	6 TeV	10 TeV	30 TeV
# of Higgs/10^7s:	~$10^{4\text{-}5}$	~4×10^4	~2×10^5	10^6	10^7	10^8

MC as Higgs factory



In comparison:

low(er) energy Higgs factories
~ 10^6 Higgses

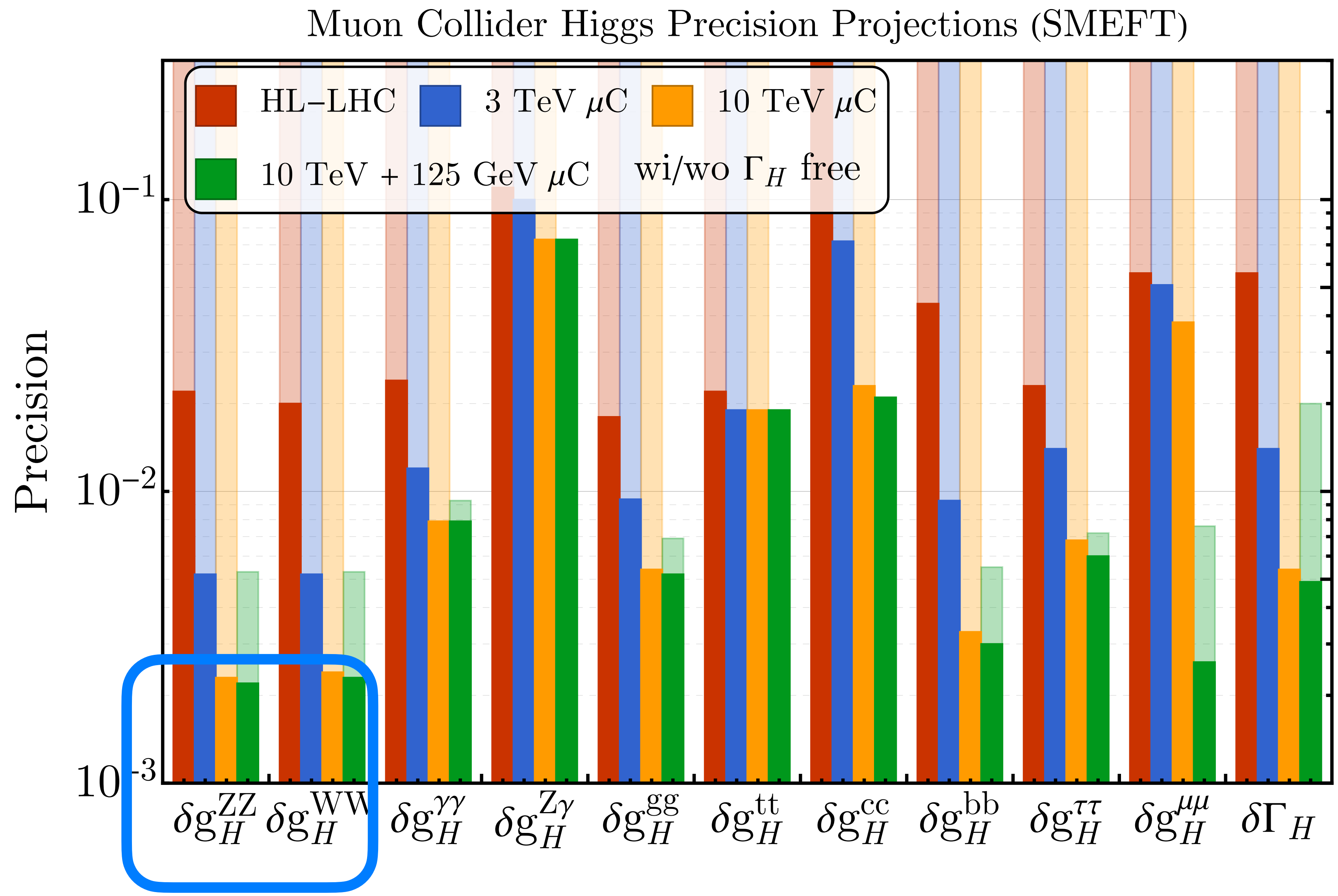
better than low E higgs factories

Assuming:

$$\mathscr{L} = \left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^2 \times 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$$

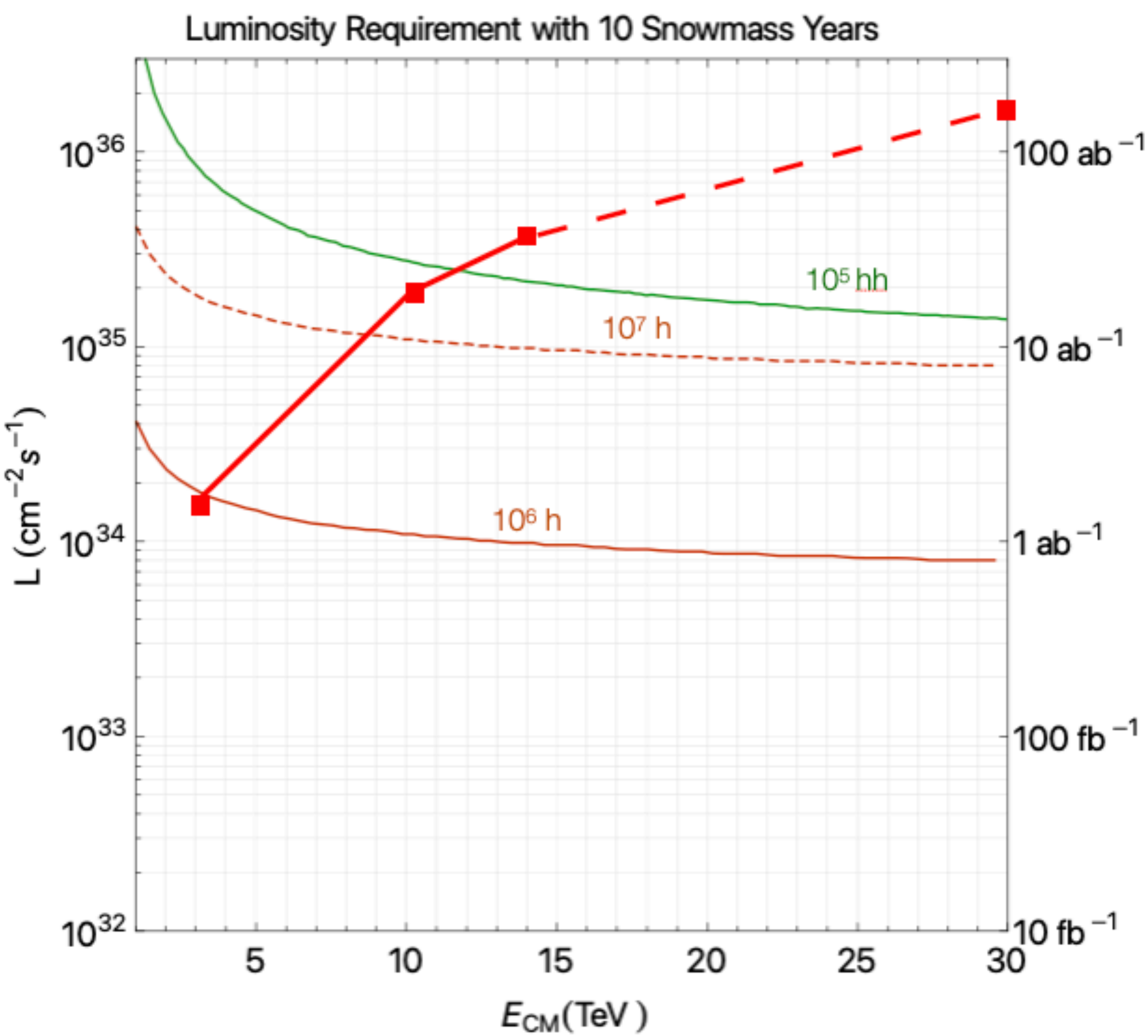
E_{CM} :	125 GeV	1.5 TeV	3 TeV	6 TeV	10 TeV	30 TeV
# of Higgs/10^7s:	~10^{4-5}	~4×10^4	~2×10^5	10^6	10^7	10^8

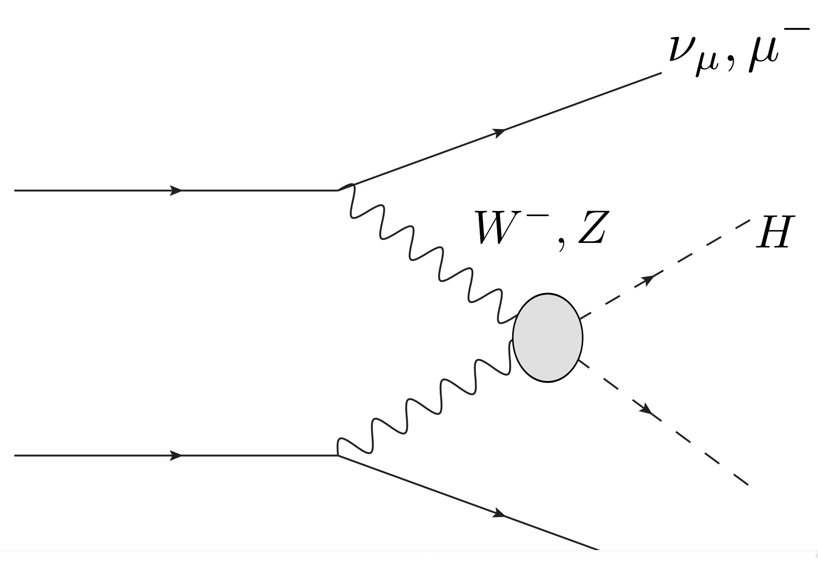
Higgs precision



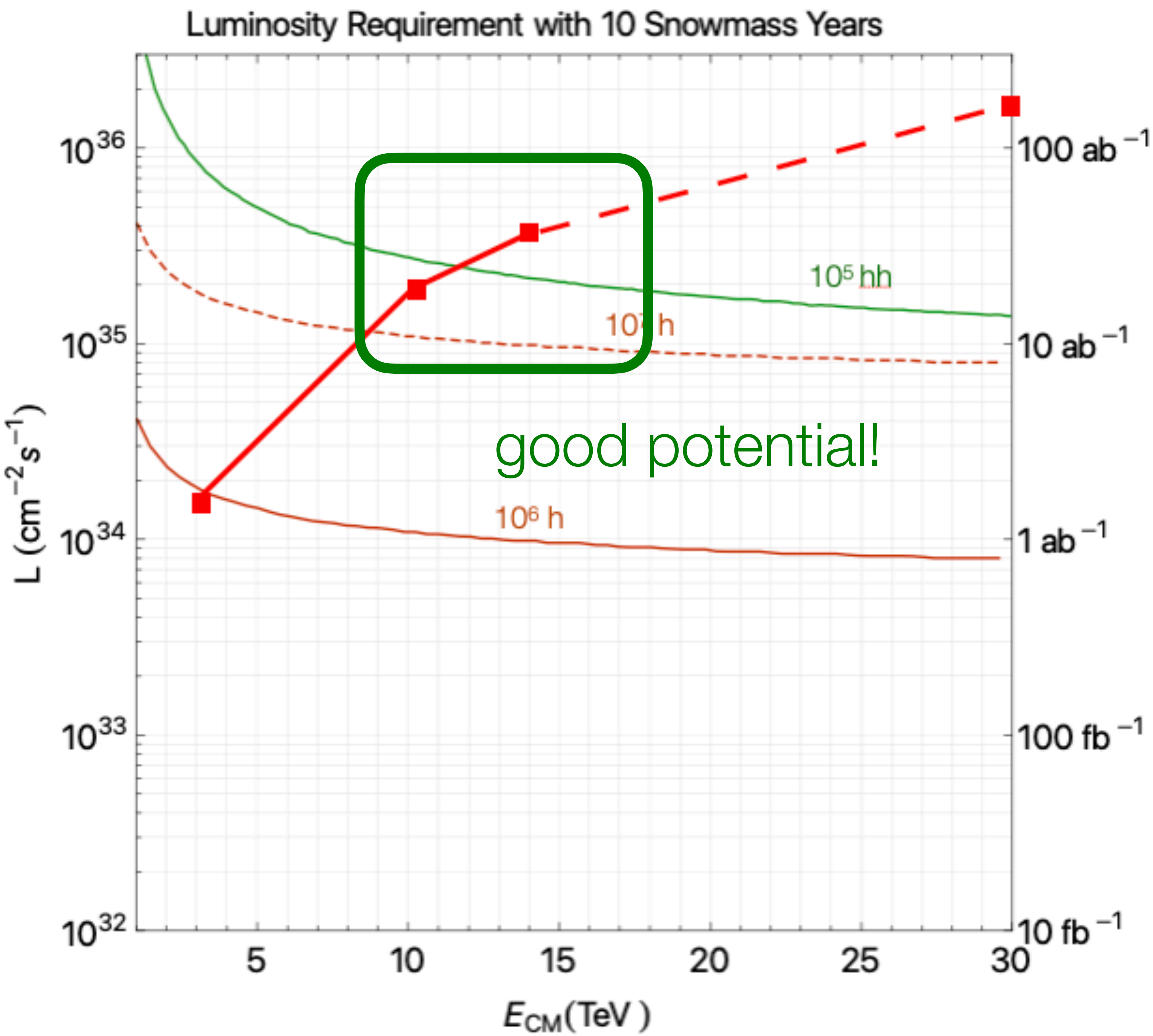
0.1% level or better measurement possible at higher energies.
A factor of 10 better than the HL-LHC
Comparable to e+e- Higgs factories

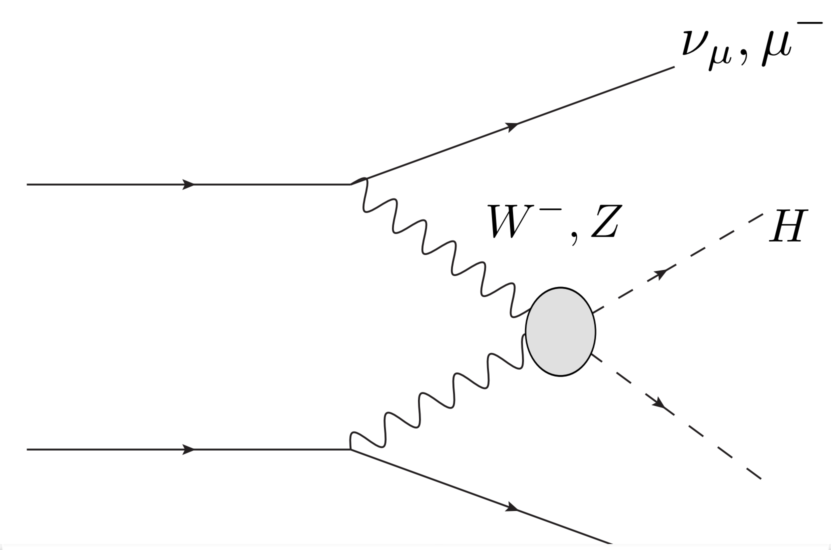
Double Higgs





Double Higgs

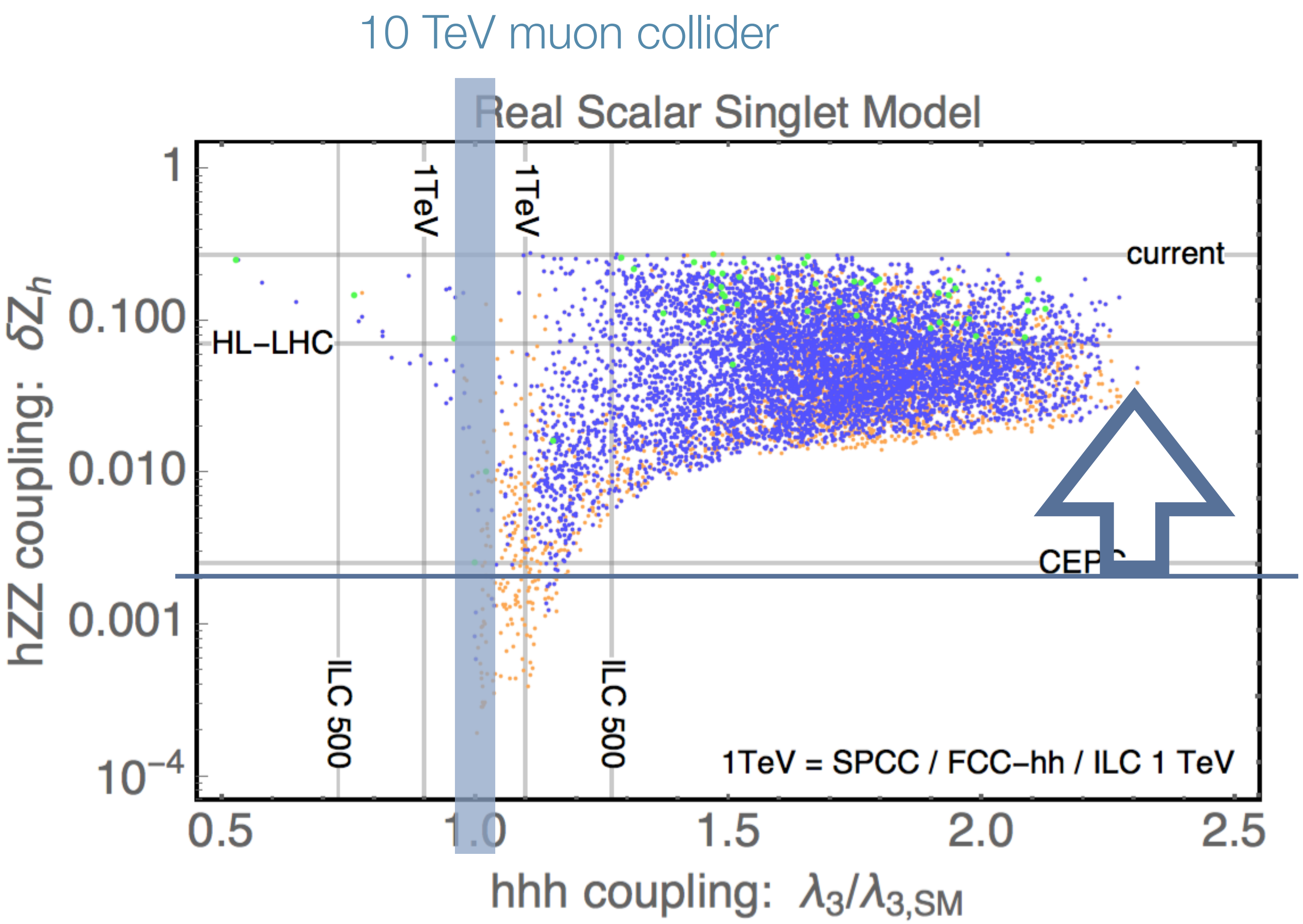


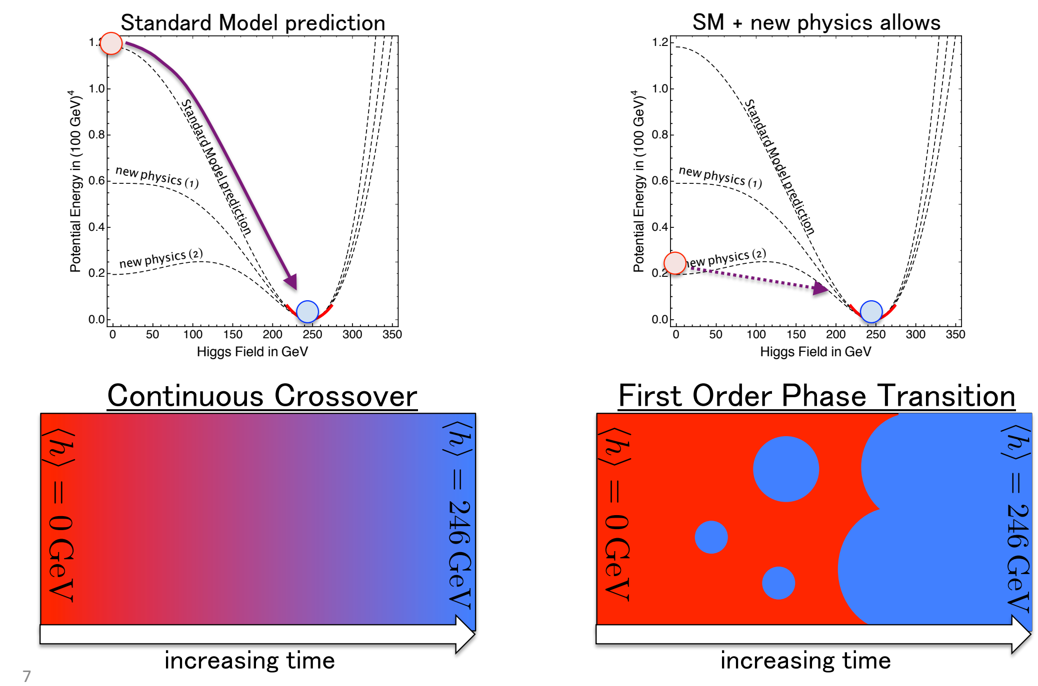


Crucial measurements such at the Higgs self-coupling.

Nature of EW phase transition

Which one is the right picture?

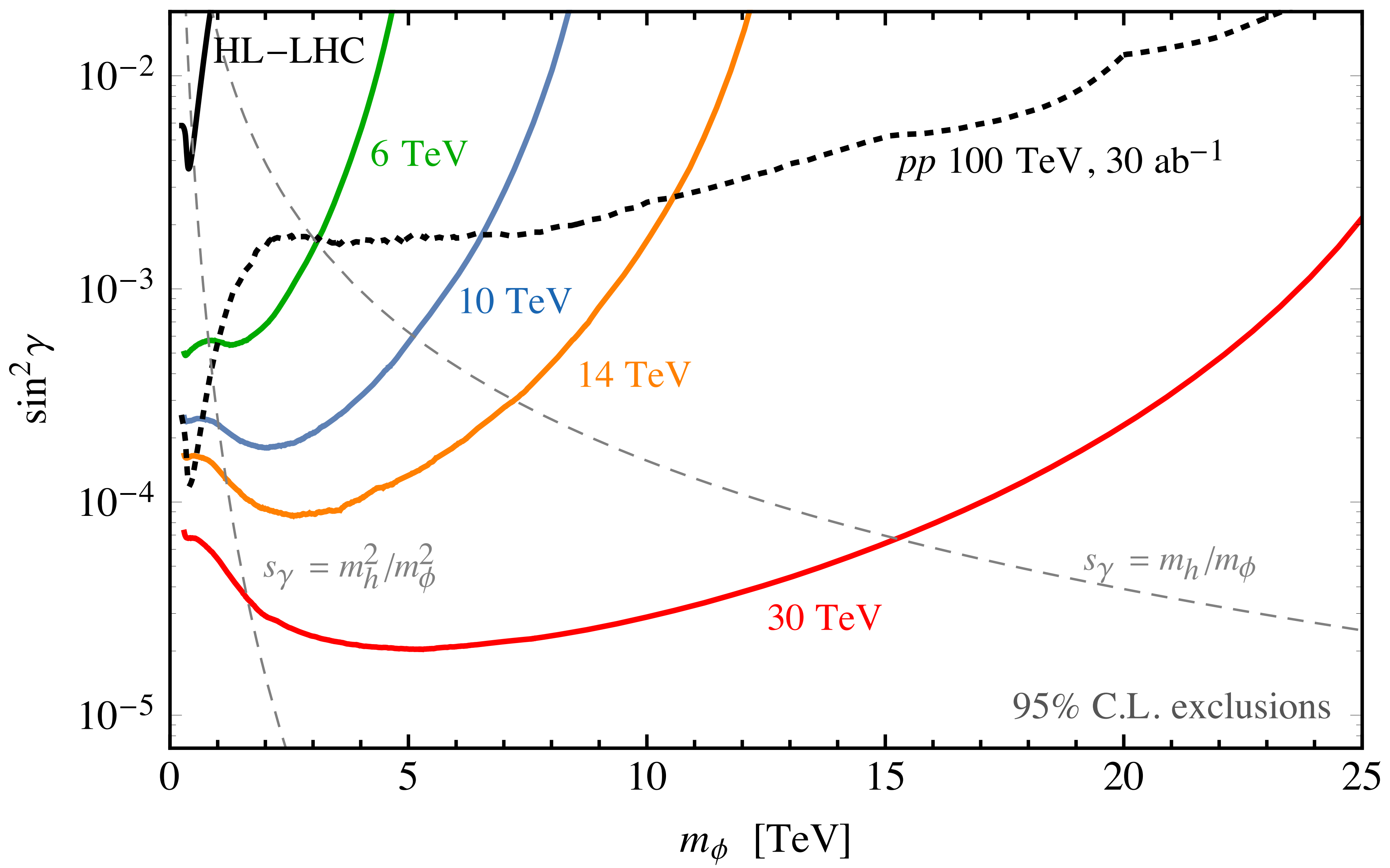




Precision Higgs measurements, self coupling and beyond, can reveal a lot.

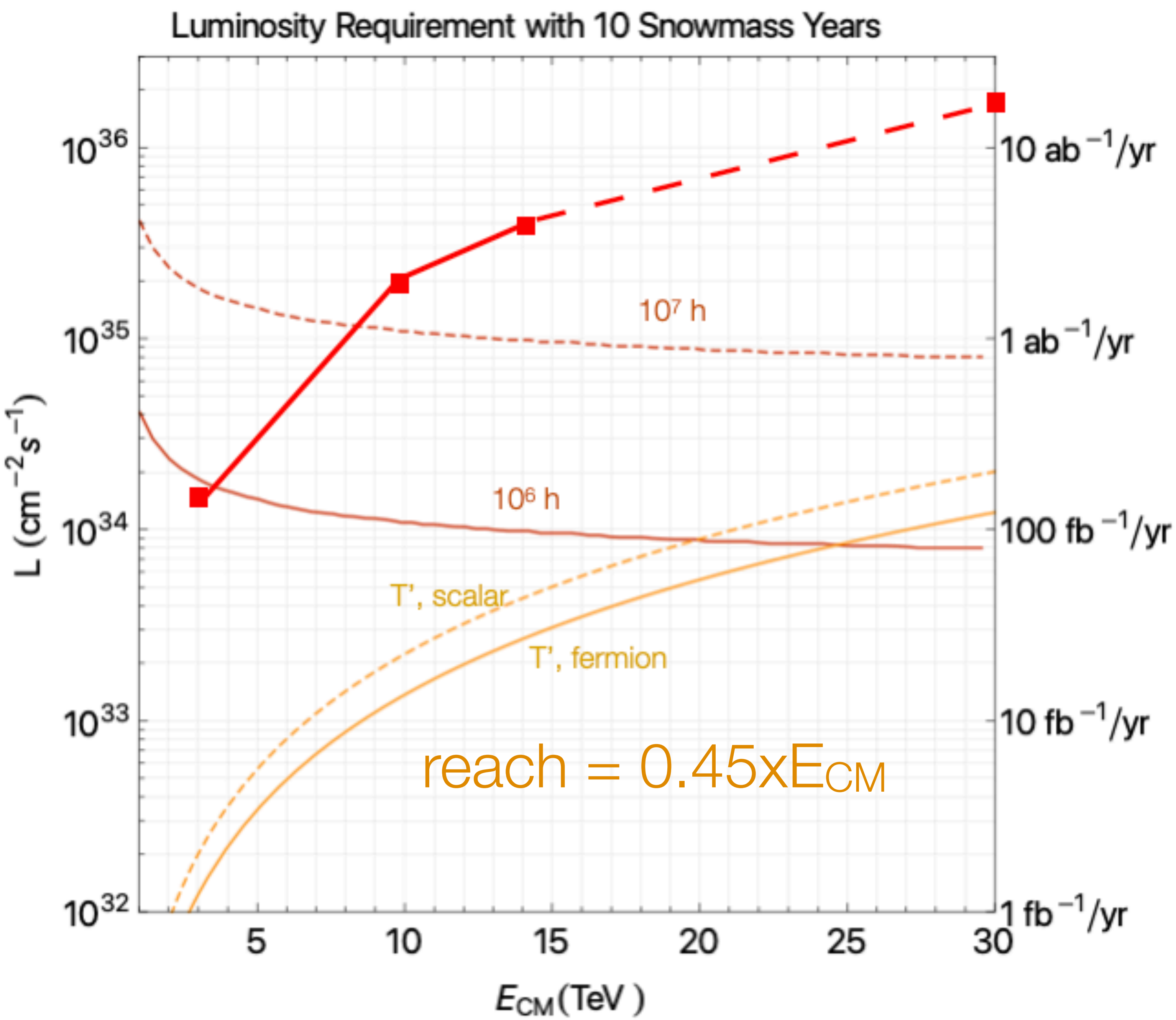
Higgs's friends

D. Buttazzo, D. Redigolo, F. Sala, A. Tesi, 1807.04743



Singlet scalar mixing with the Higgs.

Top partner



Pair production

$\mu^+\mu^- \to T'\tilde{T}'$

Examples:
SUSY stop
Composite T
…

Spectacular signal, 10s event needed for discovery

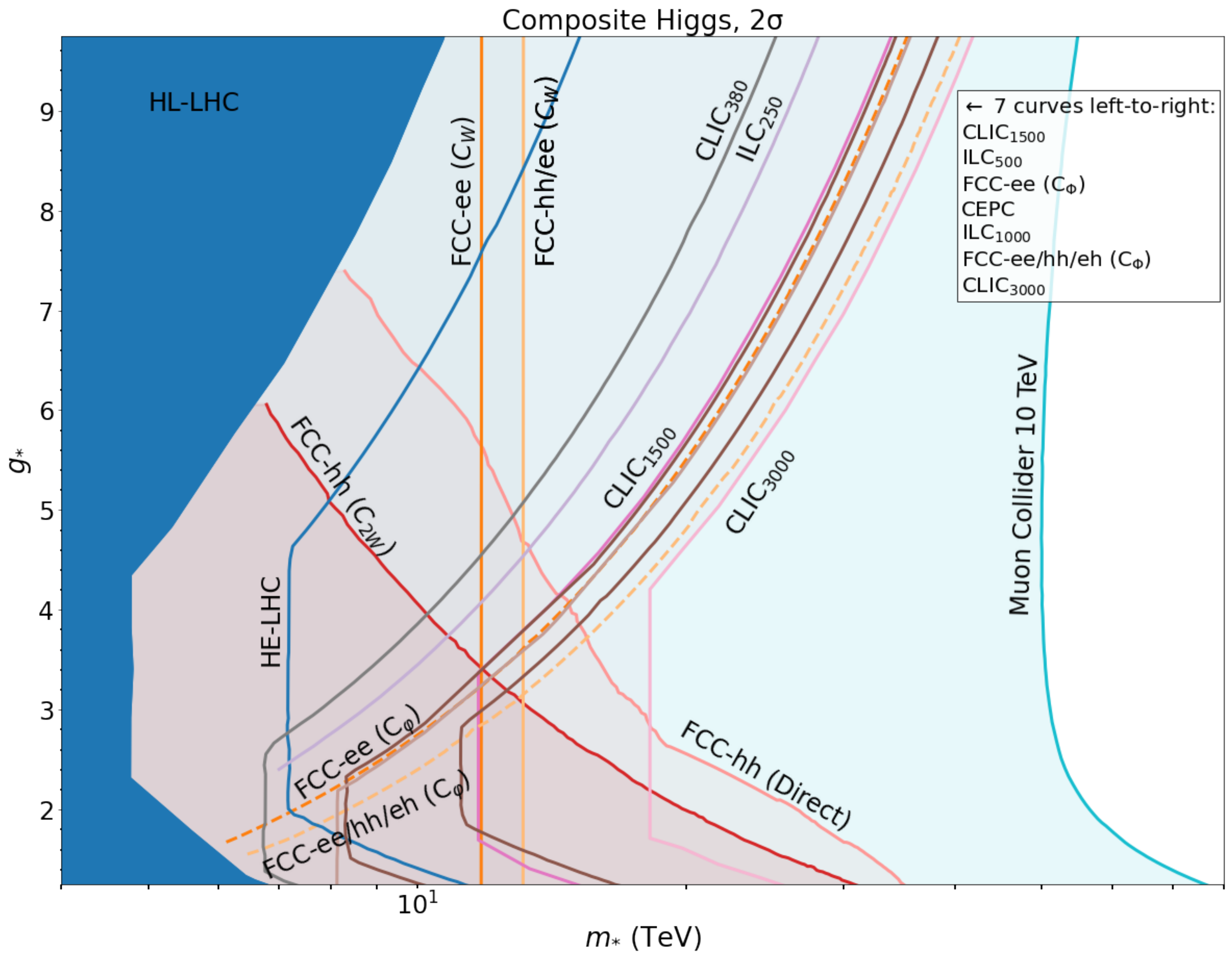
Energy⇒precision

- The effect of heavy new physics can be parameterized by higher dimensional (EFT) operators.
- Their effect grows at higher energies.
  - e.g. if new physics lead to dim-6 operators

$$\frac{\mathcal{O}^{(6)}}{\Lambda_{\mathrm{NP}}^2} \to d\sigma \propto E^2$$

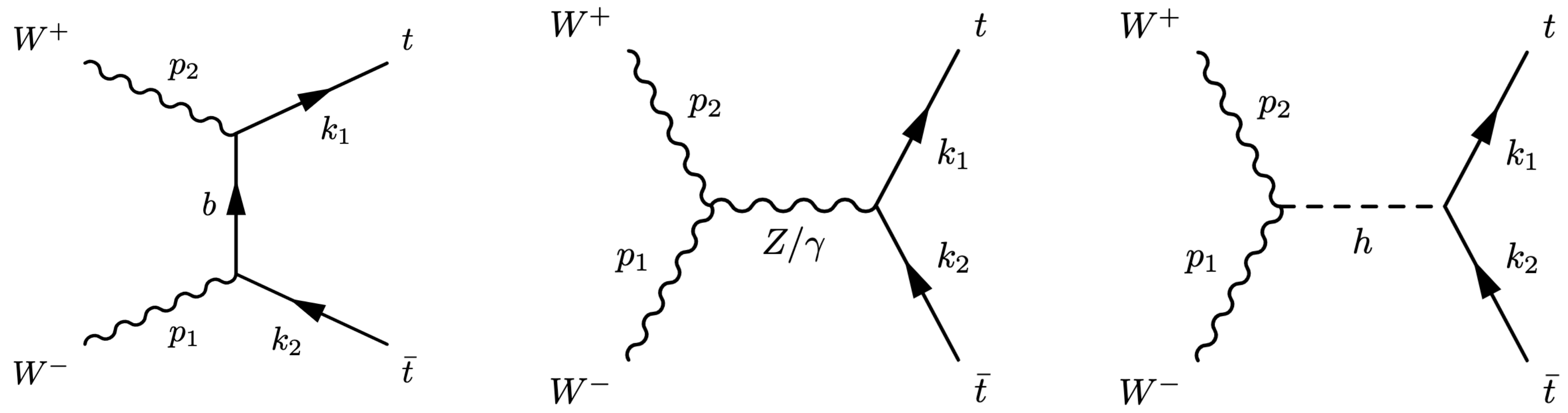
Higher energy ⇒ better precision

Composite Higgs



$$\frac{c_\phi}{\Lambda^2}\frac{1}{2}\partial_\mu\left(\phi^\dagger\phi\right)\partial^\mu\left(\phi^\dagger\phi\right)$$

Top quark - Higgs coupling



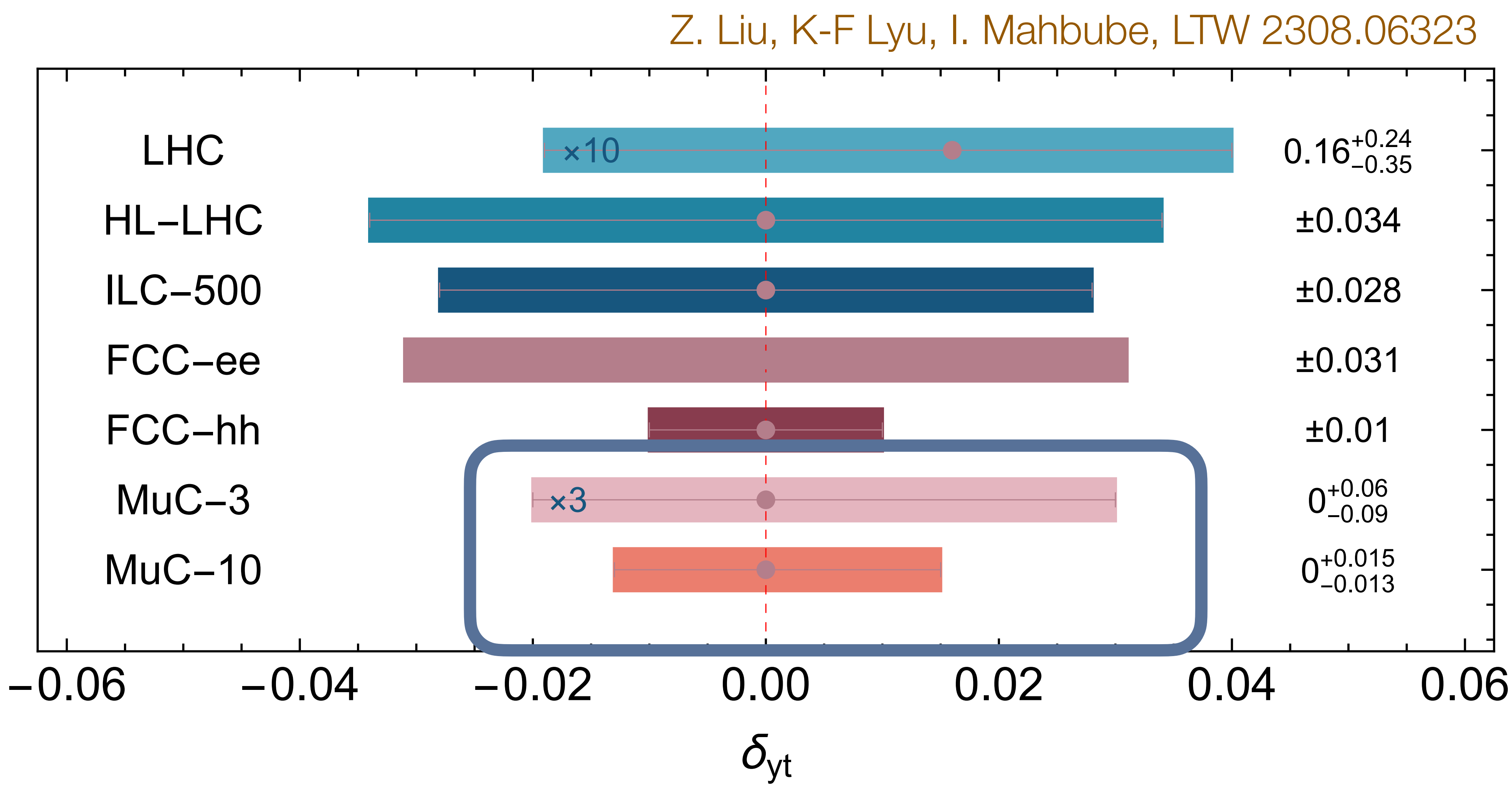
Largest Higgs coupling.

Plays an important role in weak scale dynamics. Sensitive to new physics.

e.g. NP effect = $\frac{1}{\Lambda^2} H^\dagger H H Q t \;\rightarrow\; \mathscr{M} \propto E$

Larger effect at high energies!

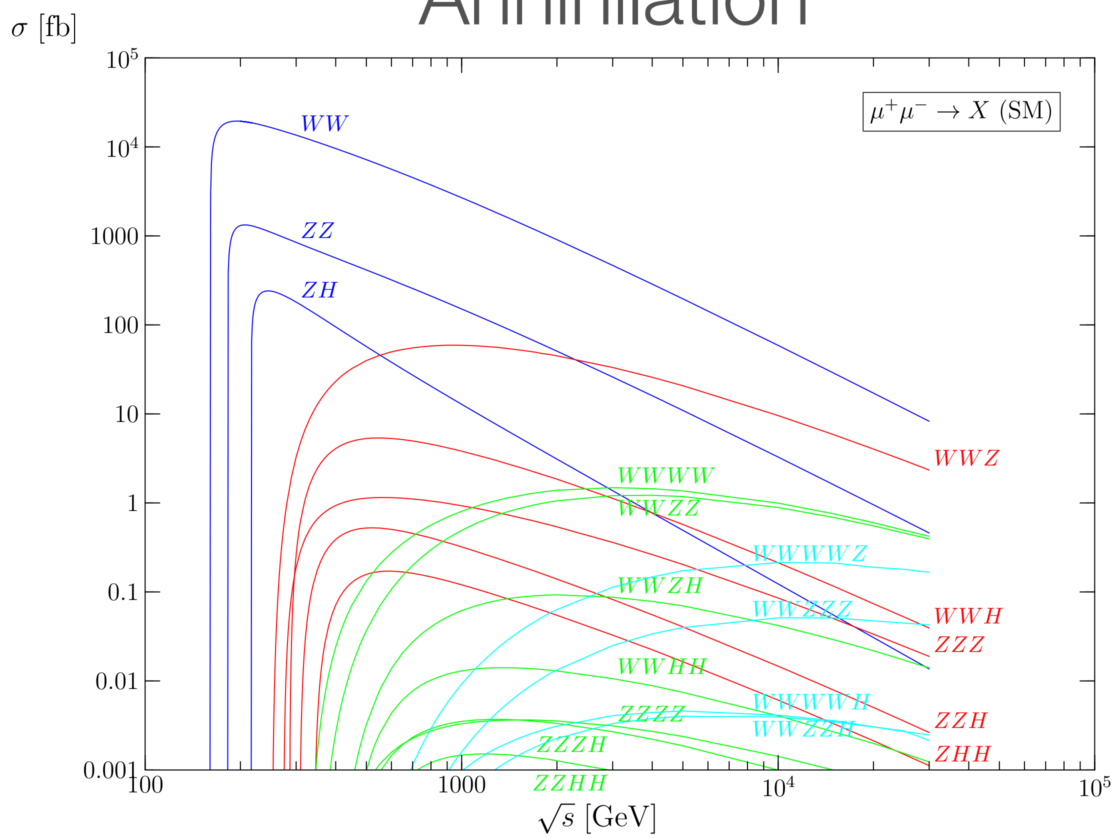
Top quark - Higgs coupling



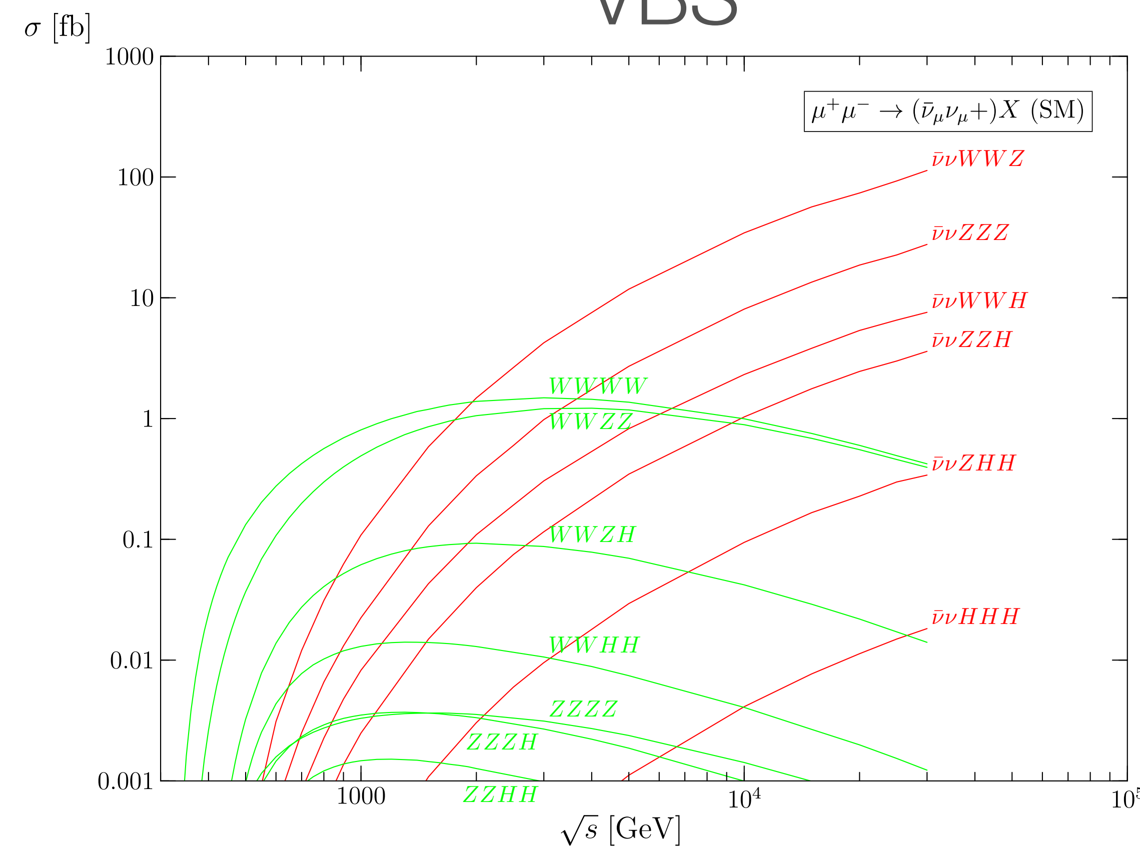
Higher energies at muon collider lead to better precision.

Multi-boson production

Annihilation



VBS



From W. Kilian, PittPACC workshop on muon Collider, 2020

Calculation: WHIZARD ($\Rightarrow$ from CLICdp studies, cf. CERN YR / arXiv:1812.02093.)

W, Z, h “massless”.

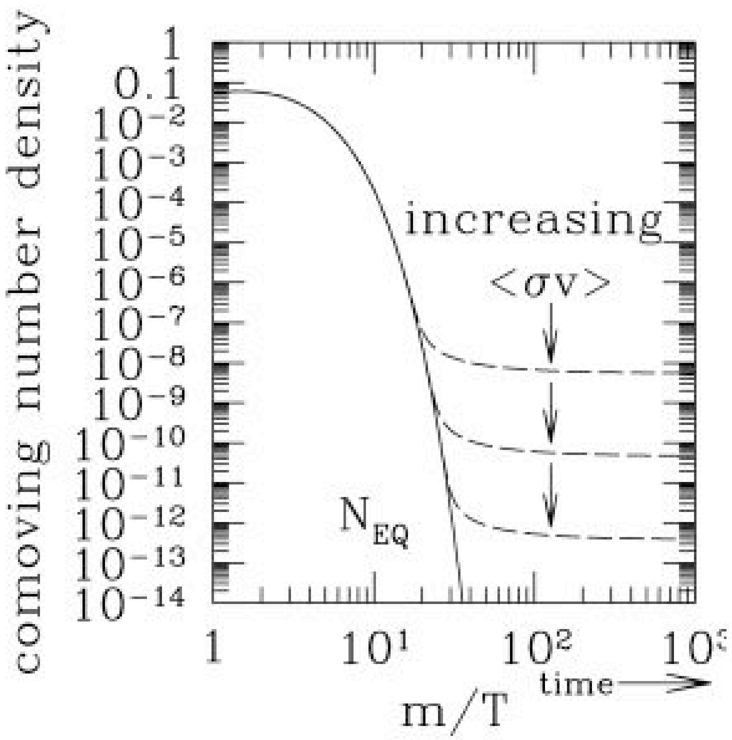
Can be sensitive to higher order NP effects.

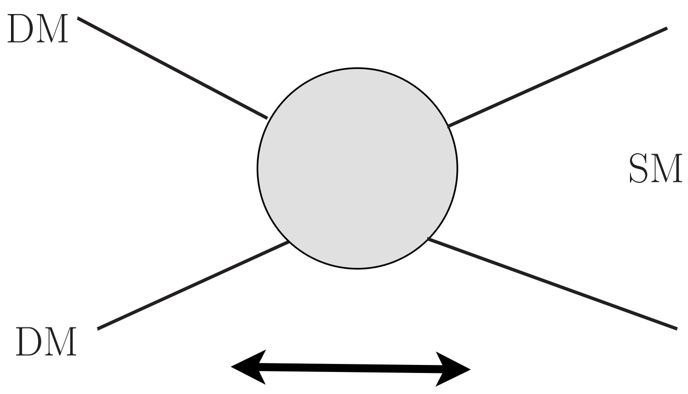
Physics program at a muon collider

- Higgs and electroweak.
- New physics at higher energies.
  - Dark matter
  - Flavor, CP
  - …

References:
Muon smasher's guide, IMCC input to Snowmass, Muon collider forum report
Snowmass BSM working group report

WIMP:



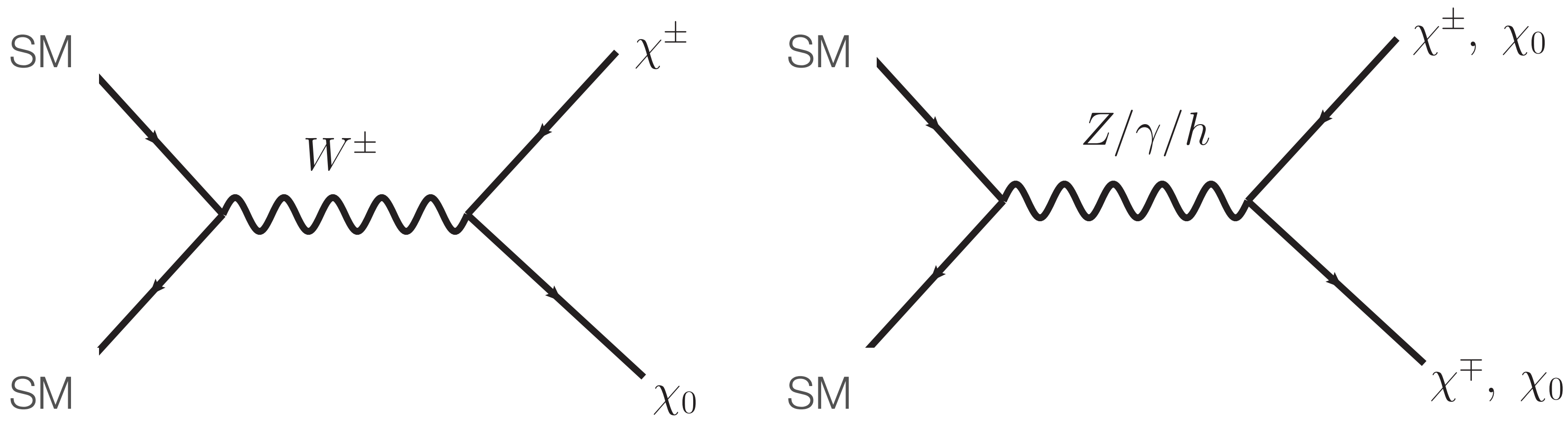


$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

- Simple assumption: DM in thermal eq. with the SM in early universe

Simplest model: part of an EW multiplet

"Minimal dark matter", Cirelli, Fornengo and Strumia, hep-ph/0512090, 0903.3381



- Simplicity: there is no additional new mediator.
    - Mediated by W/Z/h. Very predictive.
- In SUSY, there are two such examples
    - Higgsino: doublet. Wino: triplet.

Thermal targets

Model (color, n, Y)		Therm. target
(1,2,1/2)	Dirac	1.1 TeV
(1,3,0)	Majorana	2.8 TeV
$(1,3,\epsilon)$	Dirac	2.0 TeV
(1,5,0)	Majorana	14 TeV
$(1,5,\epsilon)$	Dirac	6.6 TeV
(1,7,0)	Majorana	48.8 TeV
$(1,7,\epsilon)$	Dirac	16 TeV

Correct relic abundance
$\Rightarrow$ Thermal targets

Reach up to thermal target
$\approx$
complete coverage for WIMP candidate

Way beyond LHC reach.

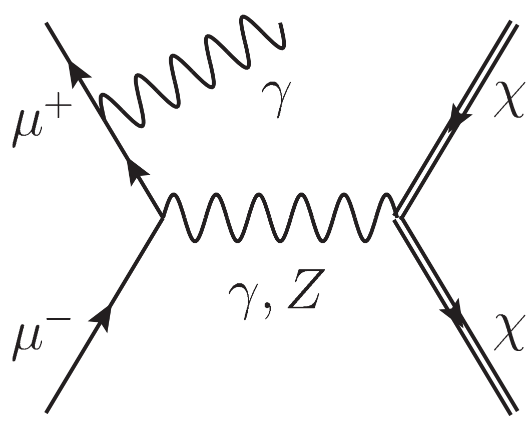
Mitridate, Redi, Smirnov, Strumia, 1702.01141

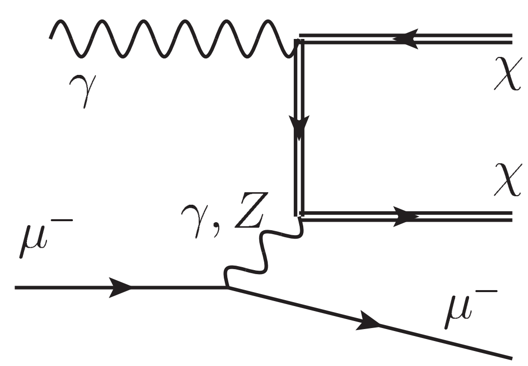
S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

Two classes of “direct” DM signals at colliders

- Production of dark matter particle.
  - Inclusive search for X+MET
    - similar to mono-jet at hadron colliders

Examples:

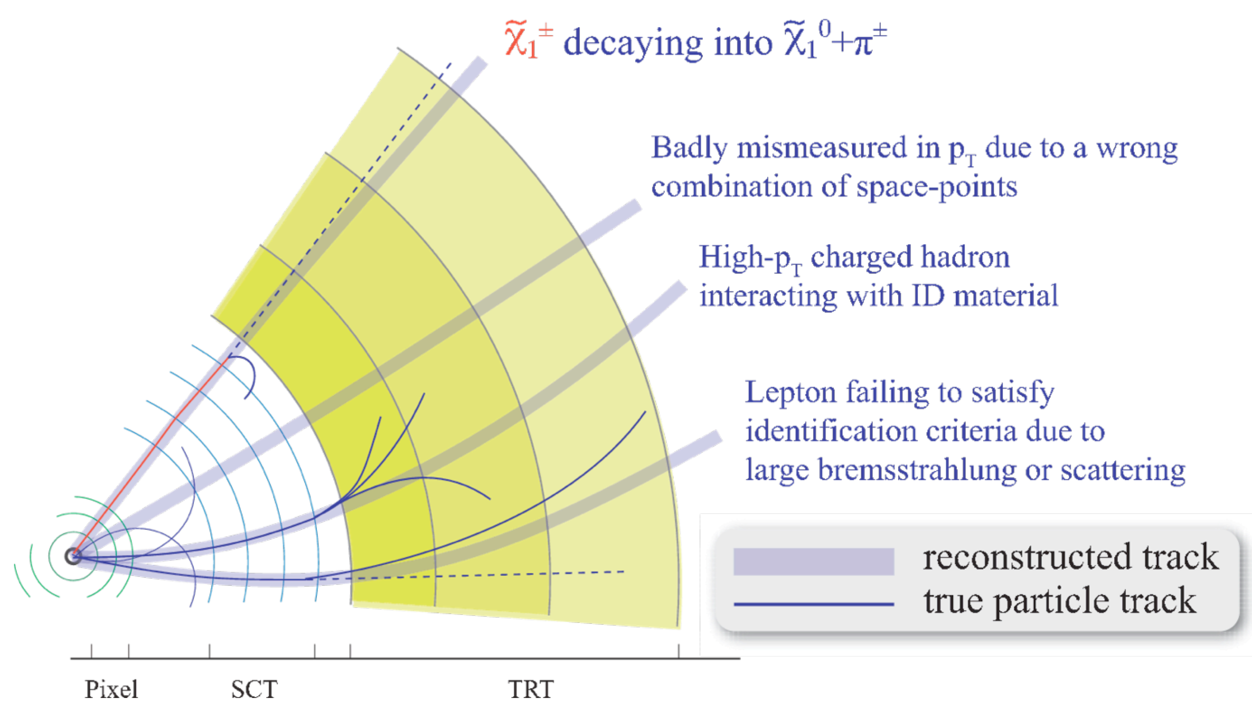




Challenges: sizable background, systematics

Two classes of “direct” DM signals at colliders

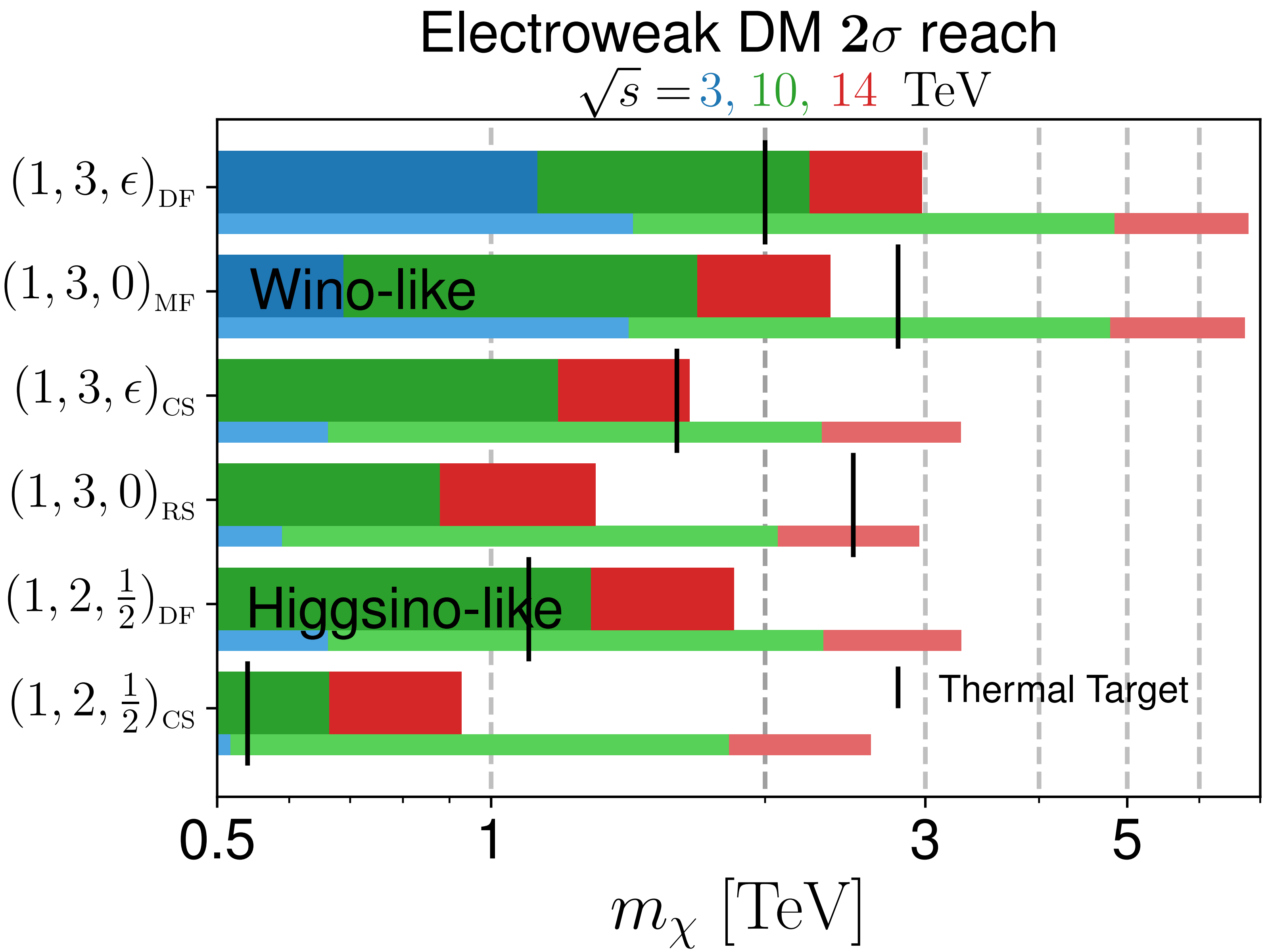
- Small EW induced mass splitting, charged member long-lived.
  - Disappearing track



Challenge: detector need to be close, beam induced background

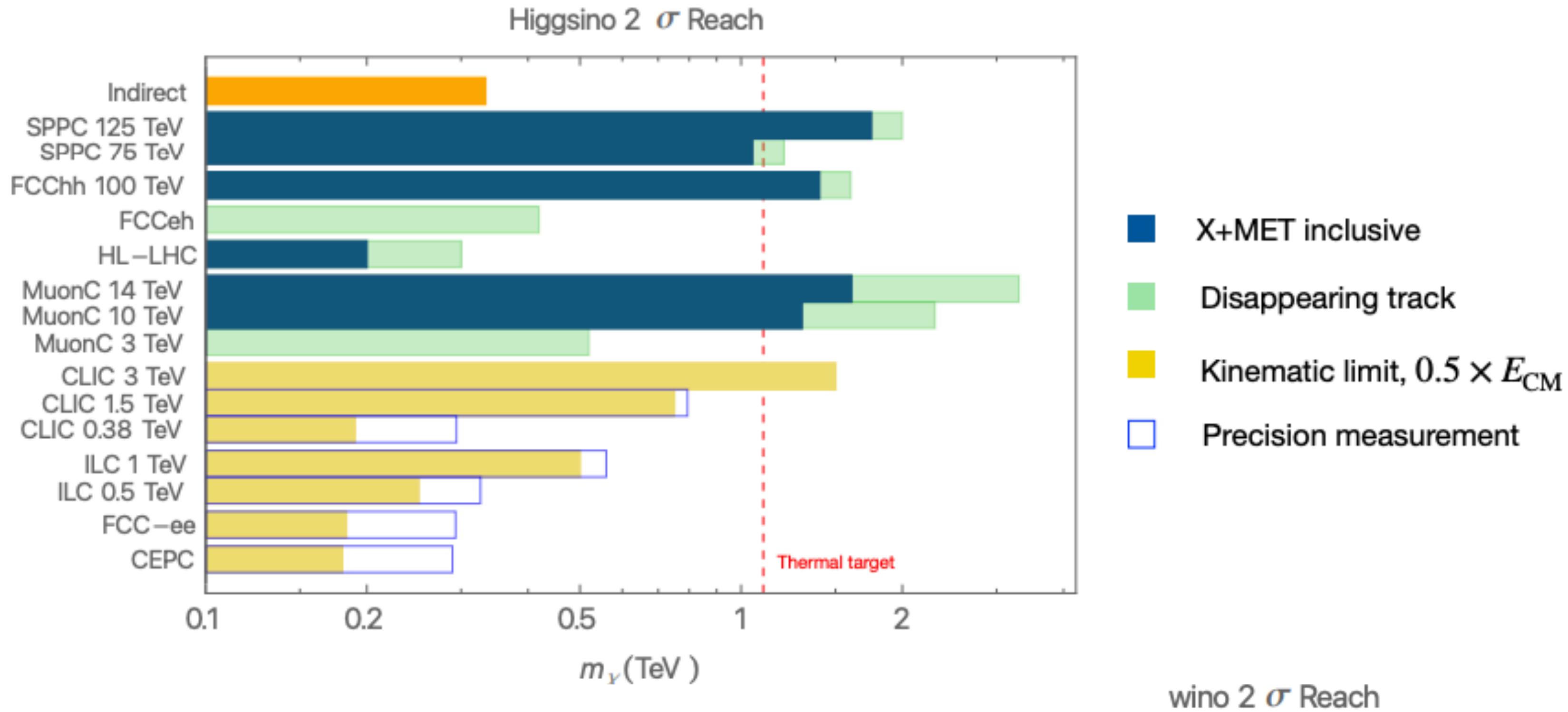
WIMP reach

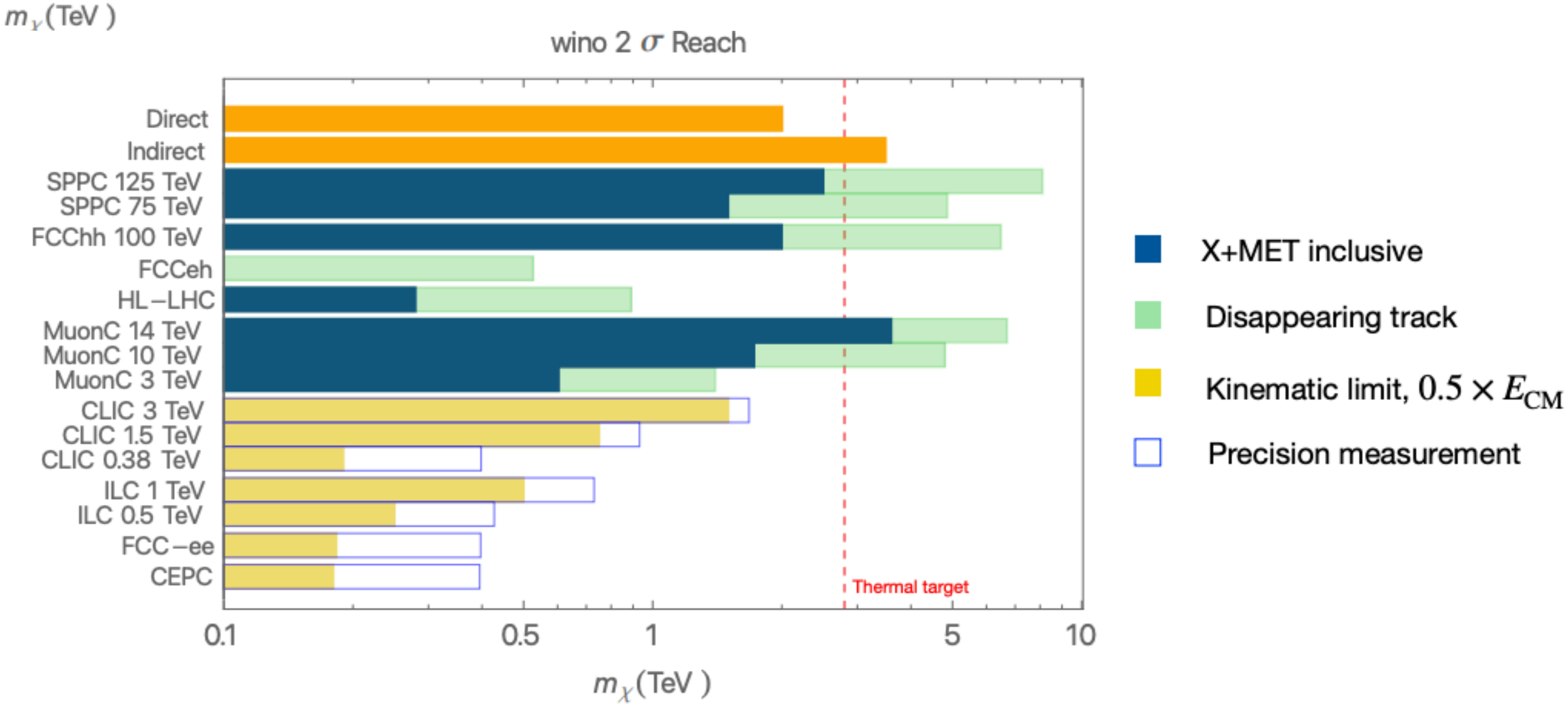
T. Han, Z. Liu, X. Wang, LTW, 2009.11287, 2203.07351



High energy muon collider can play a decisive role in probing WIMP dark matter!

Muon Collider vs others





Physics program at a muon collider

- Higgs and electroweak.
- New physics at higher energies.
  - Dark matter
  - Flavor, CP
  - …

References:
Muon smasher's guide, IMCC input to Snowmass, Muon collider forum report
Snowmass BSM working group report

Flavor (CP)

- What is the scale of new flavor/CP physics?
- Flavor (CP) measurements have consistently pushed this to be (far) beyond weak scale.
  - e. g. Lepton flavor violation
  - e. g. EDM
- High energy muon colliders offers new windows to probe them.

Lepton flavor violation

Exp limit: $\mathrm{BR}(\mu \to 3\mathrm{e}) < 10^{-12}$

Constraint: $\frac{c}{\Lambda^2}(e\Gamma\mu)(e\Gamma e), \ \ \Lambda > 2 \times 10^2 \ \mathrm{TeV}$

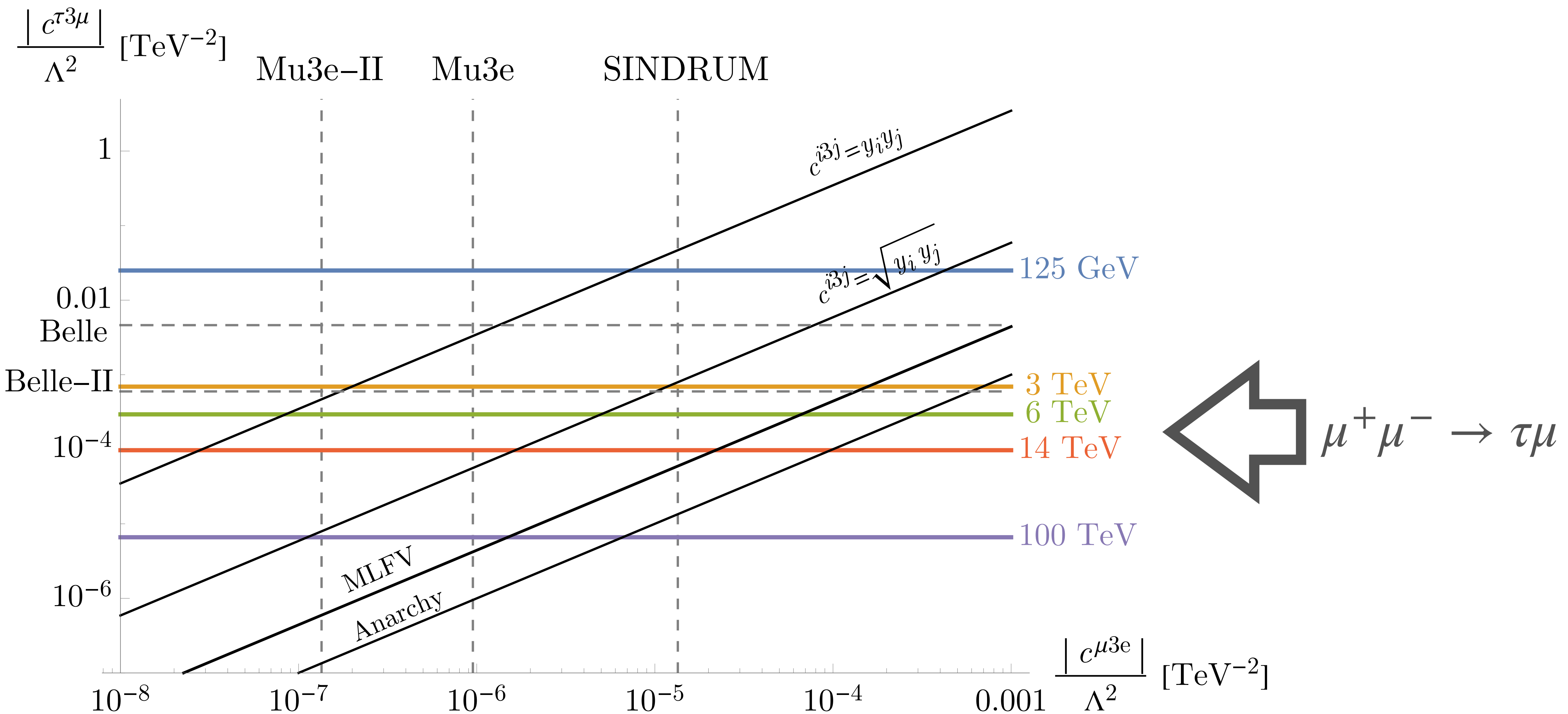
Exp limit: $\mathrm{BR}(\tau \to 3\mu) < 2.1 \times 10^{-8}$

Constraint: $\frac{c}{\Lambda^2}(\mu\Gamma\tau)(\mu\Gamma\mu), \ \ \Lambda > 10 \ \mathrm{TeV}$

Direct probe at muon colliders: $\mu^+\mu^- \to \ell_i \ell_j$

Probing lepton flavor violation

S. Homiller, Q. Lu, M. Reece, 2203.08825, Smasher's guide



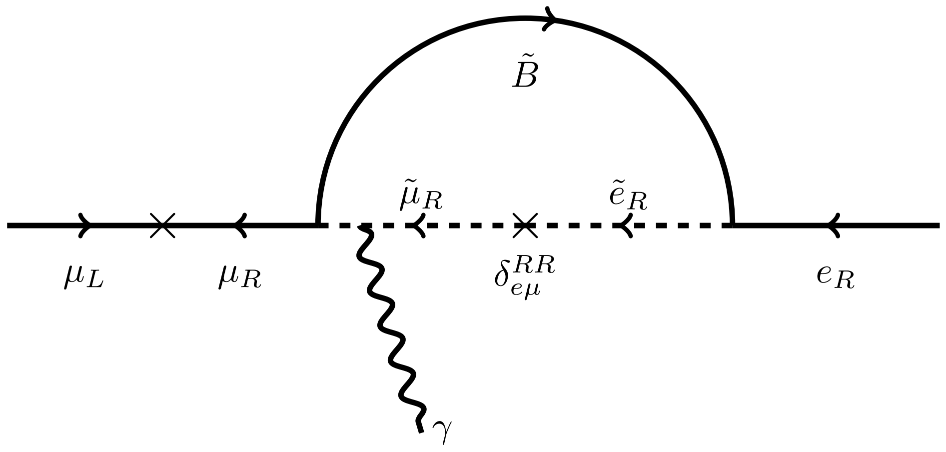
LFV at loop order

- At loop order, the NP masses is lower.
  - Opportunity to search for it directly at muon collider.

LFV at loop order

- Supersymmetry.
- Slepton flavor violation.

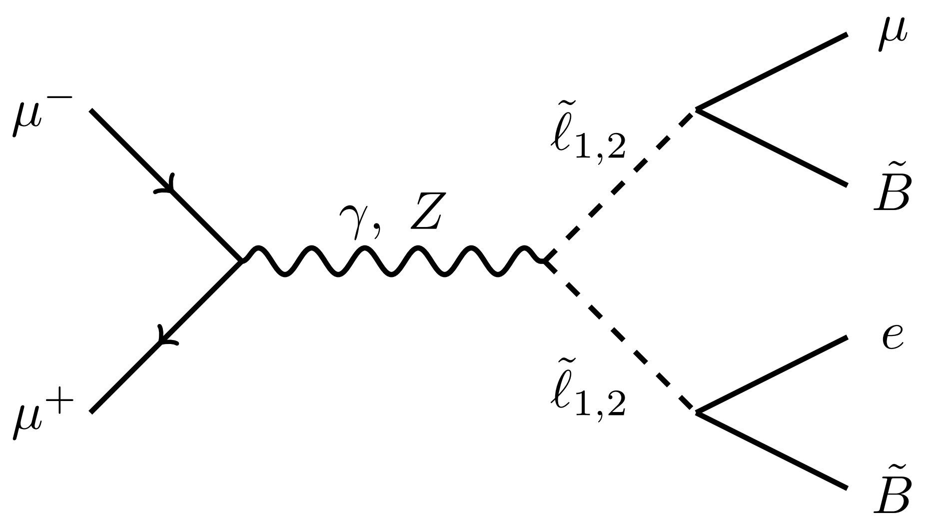
$$\begin{pmatrix} m_R^2 + \Delta_{ee}^{RR} & \Delta_{e\mu}^{RR} \\ \left(\Delta_{e\mu}^{RR}\right)^* & m_R^2 + \Delta_{\mu\mu}^{RR} \end{pmatrix}$$

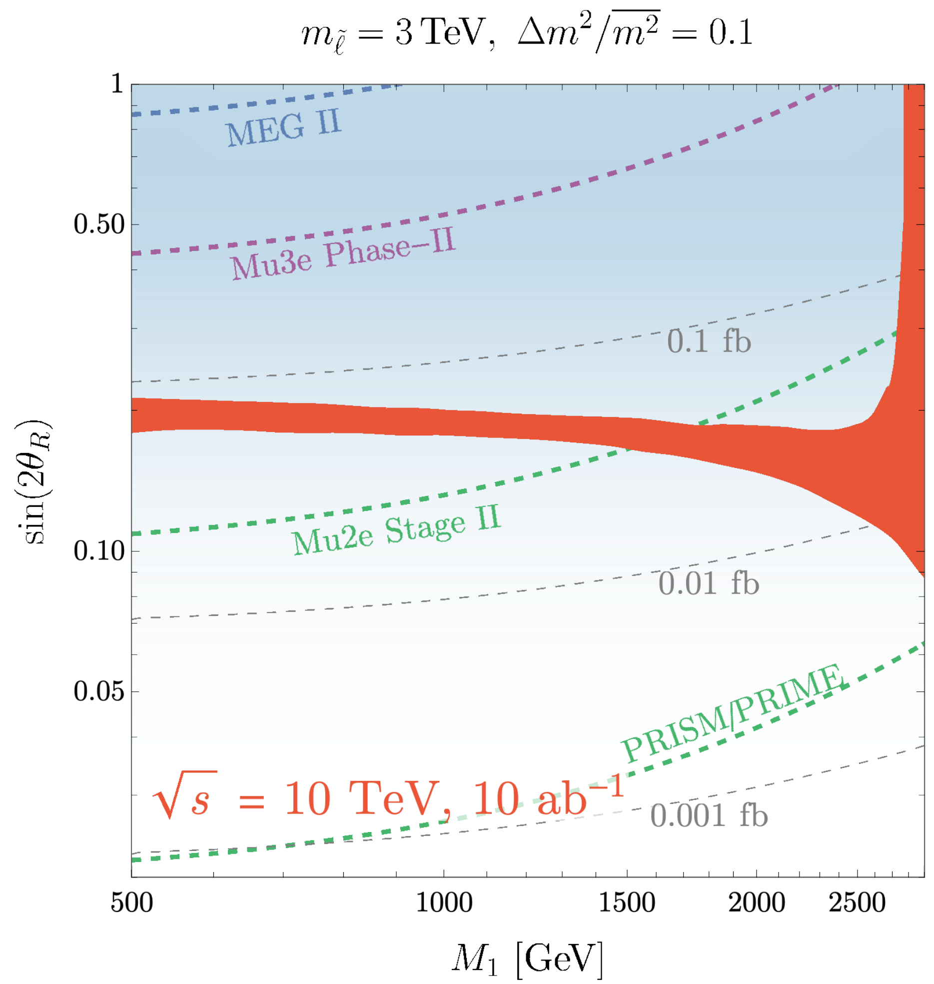


$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13} \;\to\; \mathrm{m_{SUSY}} > \mathrm{TeV}$$

LFV at loop order

At muon collider

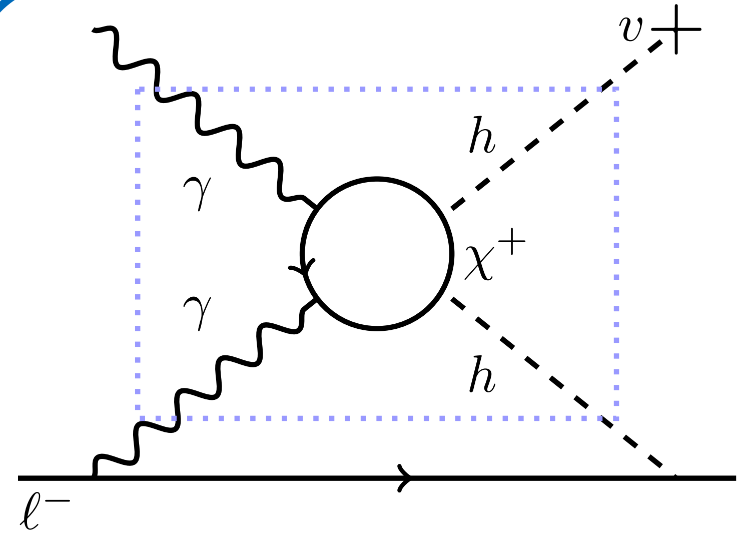


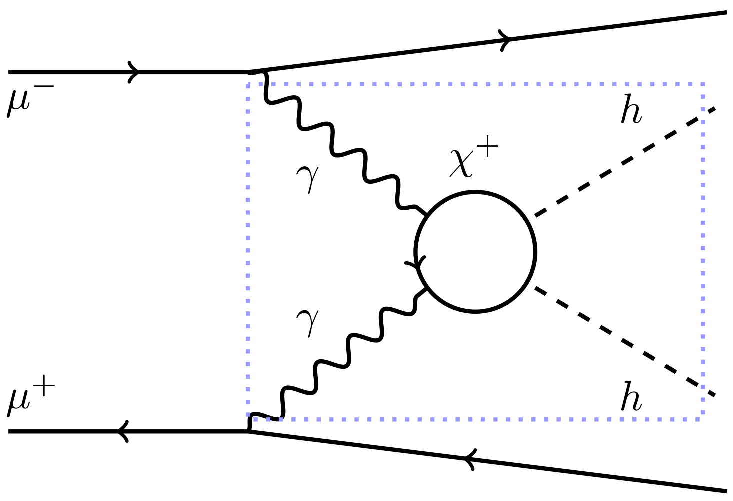


S. Homiller, Q. Lu, M. Reece, 2203.08825

10 TeV muon collider can have interesting reaches.
Complementary to low energy measurement.

EDM (Barr-Zee)



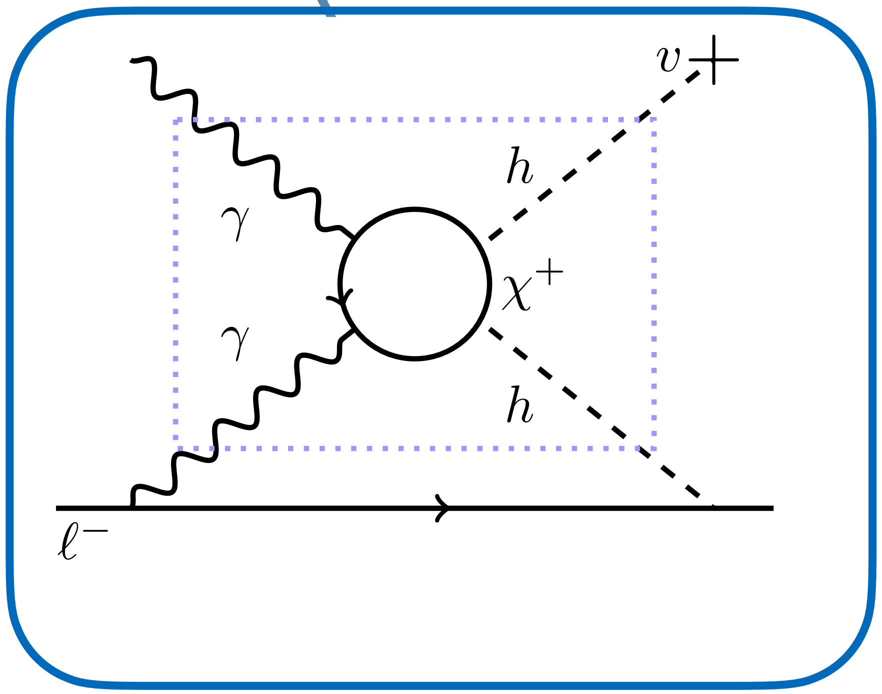


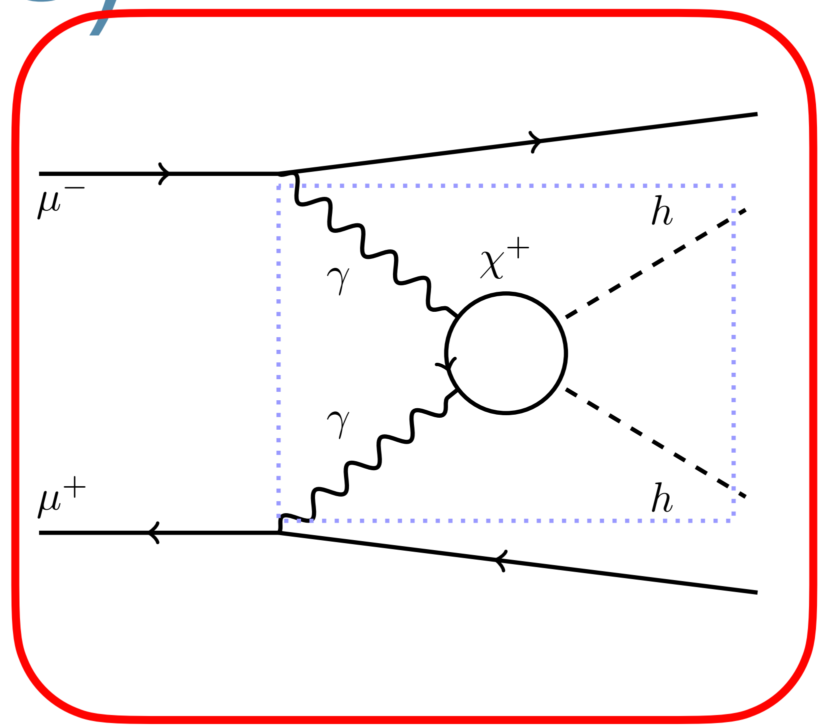
$$d_e \sim \sin(\delta_{\rm CP})\frac{e\,m_e}{M^2}\left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\,e\,{\rm cm}\,\sin(\delta_{\rm CP}) \times \begin{cases} (1\ {\rm PeV}/M)^2 & \text{for } k=1 \\ (20\ {\rm TeV}/M)^2 & \text{for } k=2 \end{cases}$$

2-loop Barr-Zee

Potential sensitivity of next generation exp.

EDM (Barr-Zee)





$$d_e \sim \sin(\delta_{\rm CP}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\, e\,{\rm cm}\, \sin(\delta_{\rm CP}) \times \begin{cases} (1\ {\rm PeV}/M)^2 & \text{for } k=1 \\ (20\ {\rm TeV}/M)^2 & \text{for } k=2 \end{cases}$$

2-loop Barr-Zee

Potential sensitivity of next generation exp.

Same process probed by 10(s) TeV muon collider!

Conclusion

- High energy muon collider holds promise of getting the next (10 TeV) high energy frontier.
- A lot of interesting physics to cover.
- My hope: we will do solid R&D in the coming decades to make it into a mature project.

DM part of a EW multiplet

$$\text{DM} \in (1, n, Y) \text{ of } SU(3)_C \times SU(2)_L \times U(1)_Y$$

- n odd. Fermionic.
  - n>7, Landau pole close to M_{DM} .
  - After EWSB, mass splitting (minimally) generated at 1-loop.
  - Choose Y=0. Lightest member electric neutral. Potential DM candidate.

DM part of a EW multiplet

$$\text{DM} \in (1,\, n,\, \text{Y}) \text{ of } \text{SU(3)}_\text{C} \times \text{SU(2)}_\text{L} \times \text{U(1)}_\text{Y}$$

- n even. Fermionic
  - Choose Y=(n-1)/2 ensures lightest member is neutral.
  - Direct detection rules out the minimal case due to tree level Z exchange.
    - Can be avoided to introduce a small splitting, $\delta m > 10^2$ keV, of the neutral states (for example, from a dim-5 operator). Not quite minimal (additional model dependence).
  - Famous example: Higgsino $(1,2)_{1/2}$

DM part of a EW multiplet

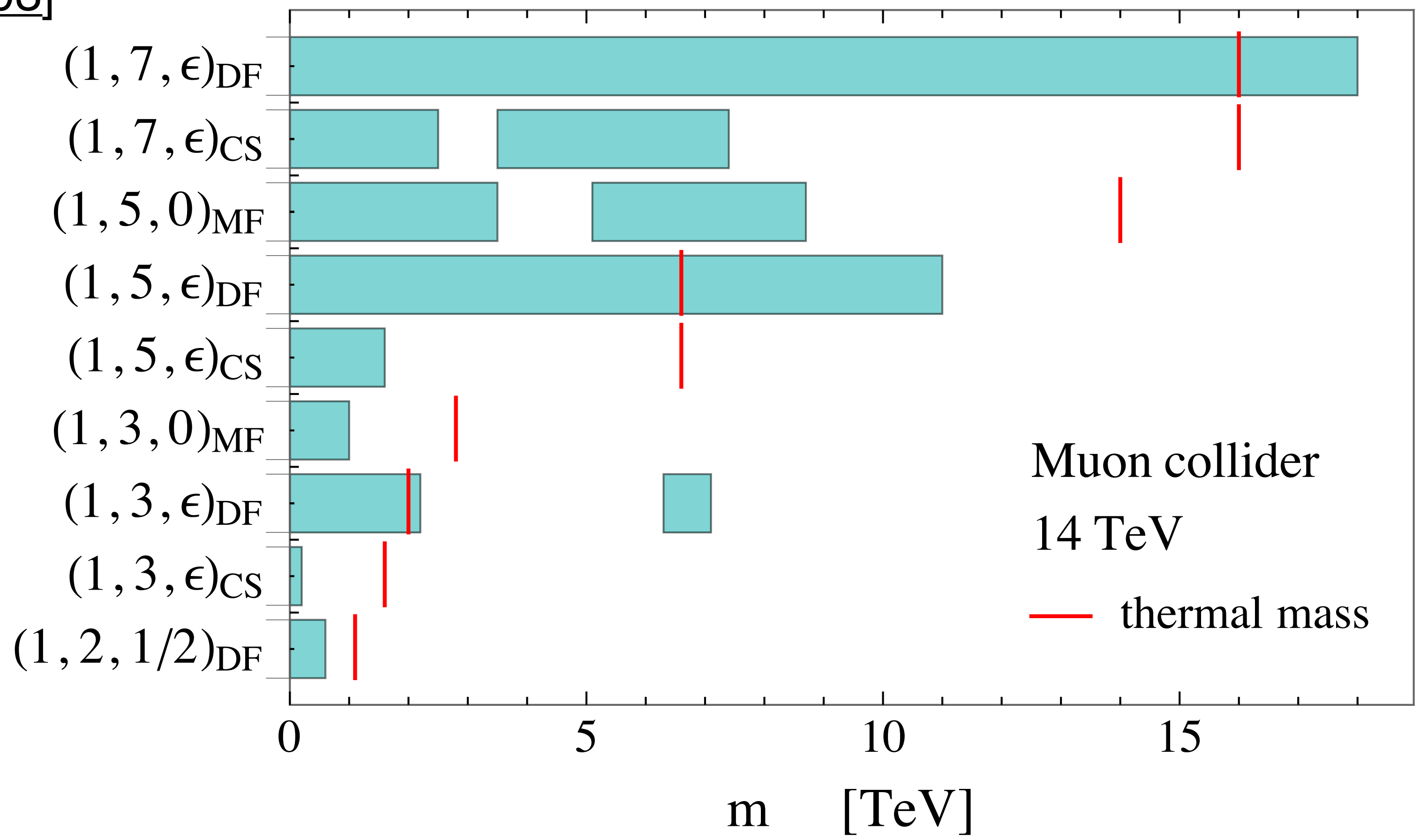
$$\text{DM} \in (1, n, \text{Y}) \;\; \text{of} \;\; \text{SU}(3)_\text{C} \times \text{SU}(2)_\text{L} \times \text{U}(1)_\text{Y}$$

- Scalar (real and complex)
    - Minimal case: mass splitting, stability discussion parallel to that of the fermionic multiplets.
    - Addition couplings of the form $H^\dagger H X^\dagger X$. More parameters involved in a full analysis.
- More focus on the fermion case (so far).

“indirect”, from precision measurement

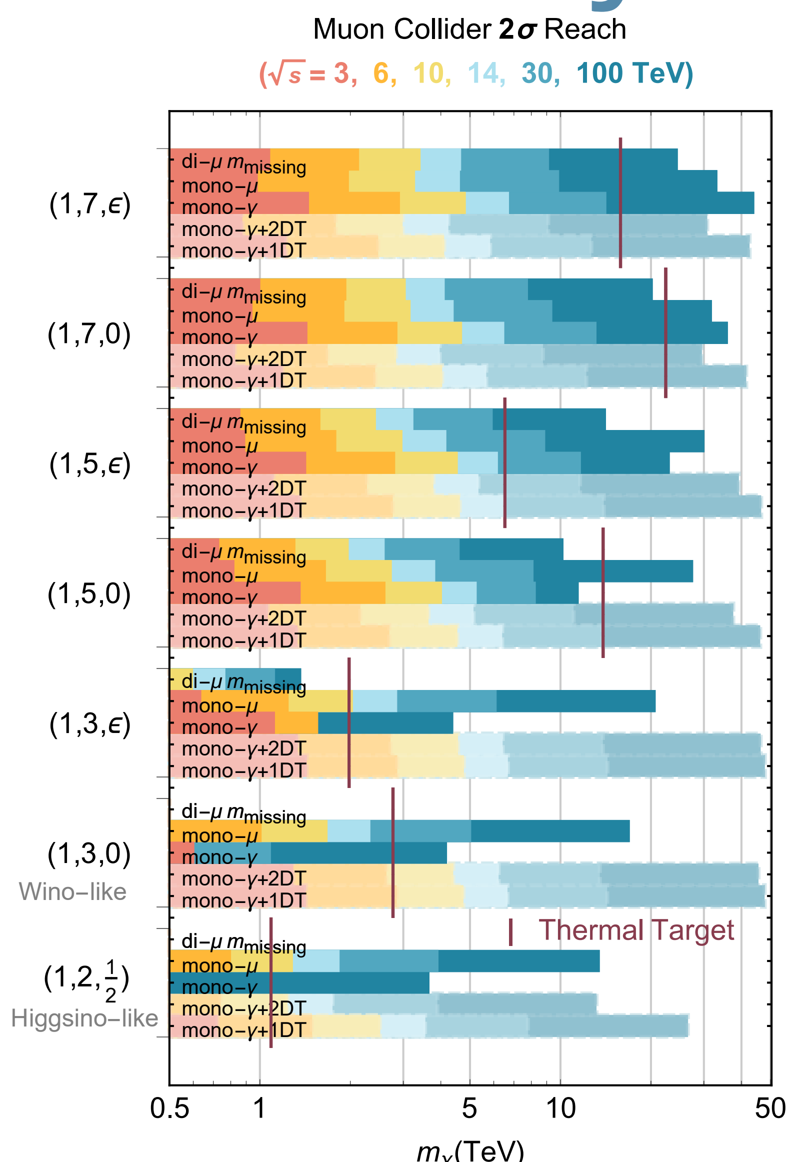
indirectly [1810.10993]

Di Luzio, Grober, Panico, 1810.10993

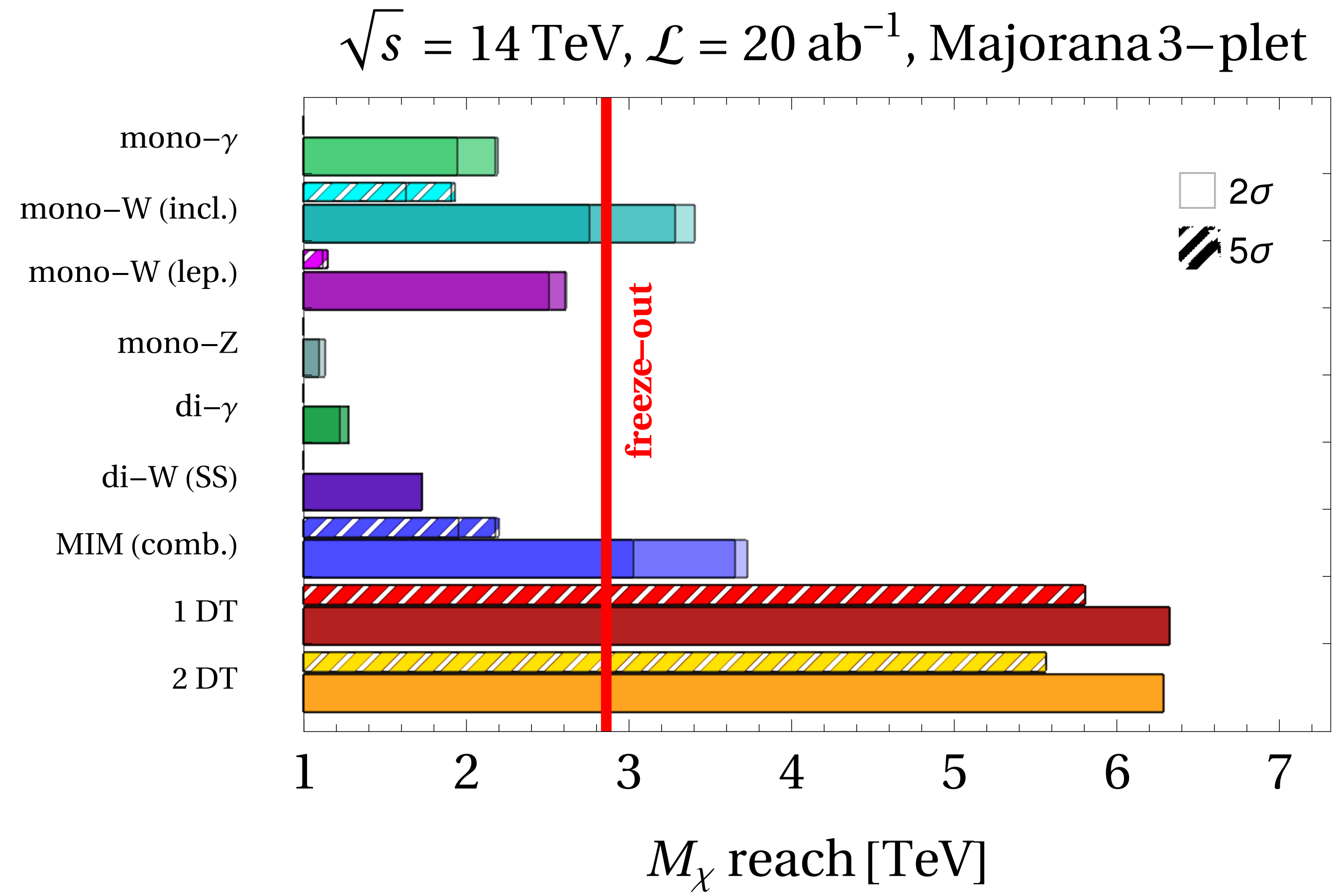


At loop level, modifying the $q\bar{q}($ or $\ell^+\ell^-) \to f\bar{f}$ amplitude

Reach by channel



T. Han, Z. Liu, X. Wang, LTW 2009.11287

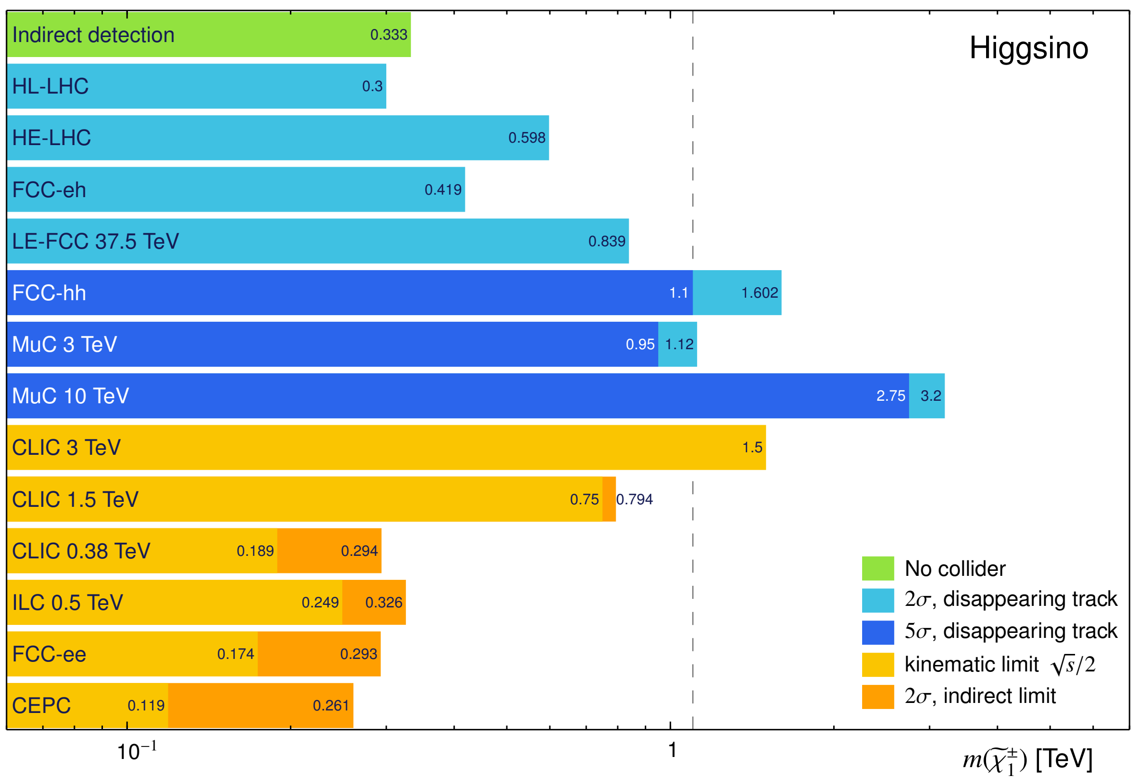


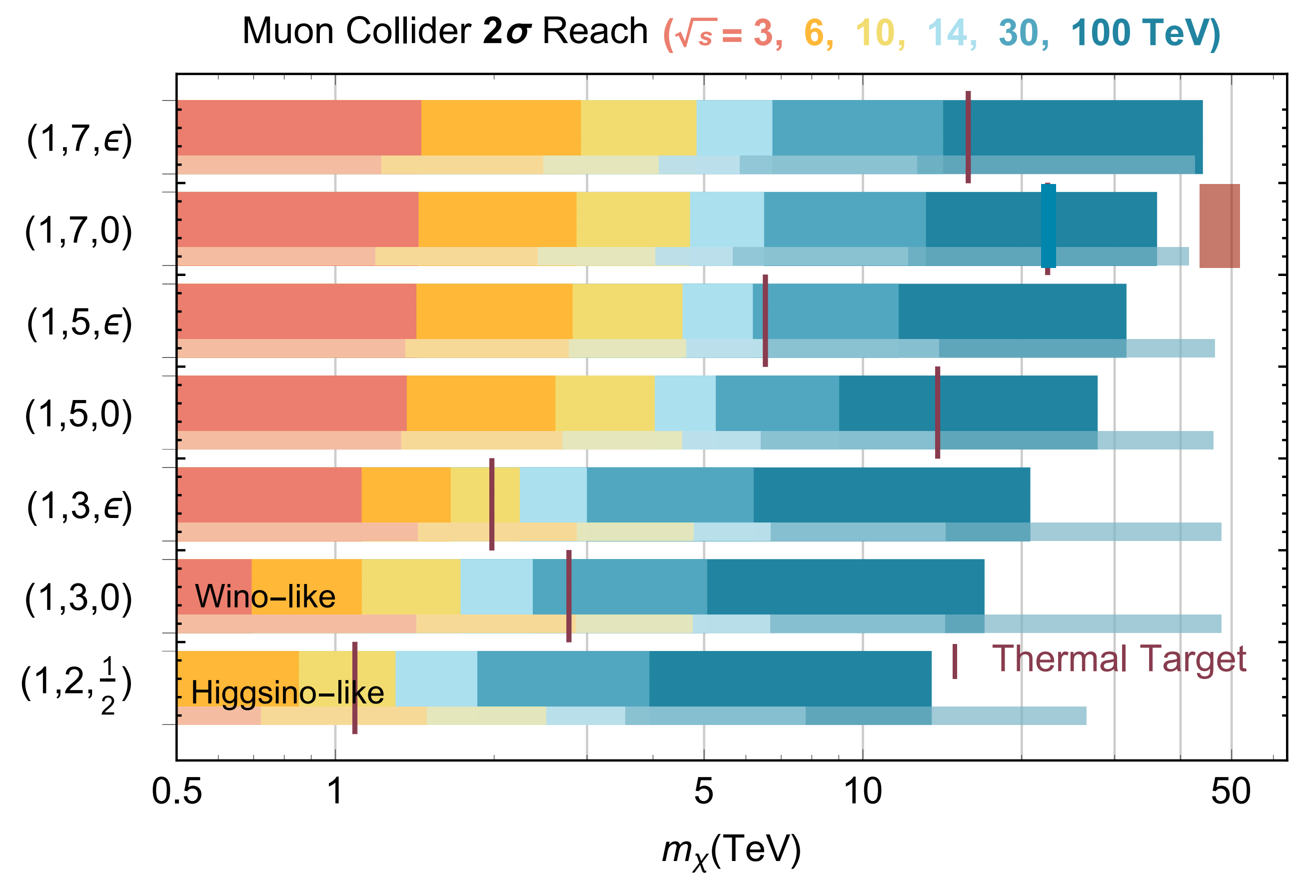
S. Bottaro, D. Buttazzo, M. Costa, R. Franceschini, P. Panci, D. Redigolo, L. Vittorio, 2107.09688

mono-X, more generic model independent. Interesting channels: muon-mu, mono-W.

Disappearing track. Some model dependence. Important to have the right BIB estimates.

Reach





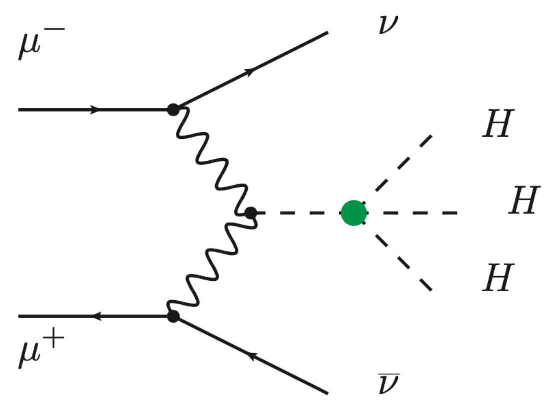
R. Capdevilla F. Meloni, J. Zurita, 2102.11292 T. Han, Z. Liu, X. Wang, LTW 2009.11287

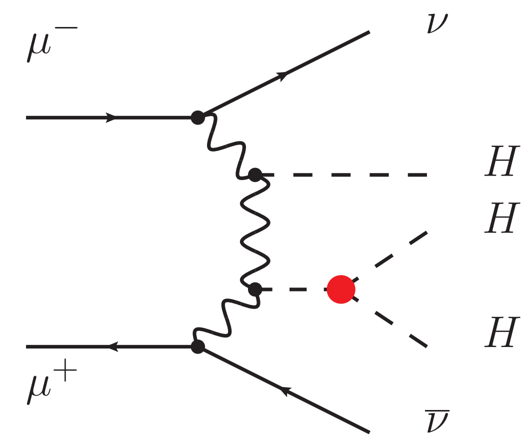
With inclusive signal: $E_{CM} \approx 14$ TeV enough to cover n≤3 multiplets.
Higher energy needed to cover higher multiplets.

If we have disappearing track: potential to reach almost $m_\chi \approx 1/2\ E_{CM}$

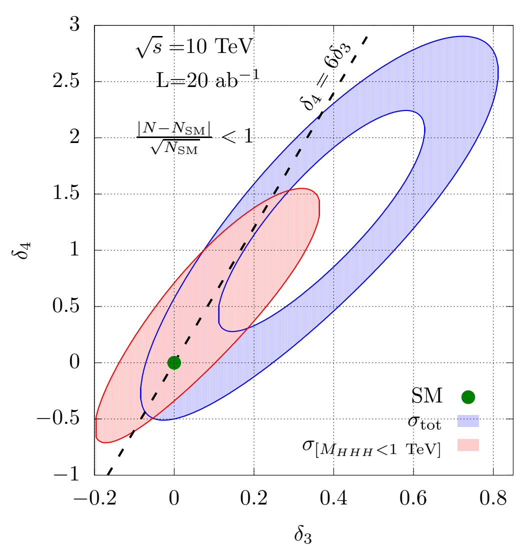
Higgs quartic coupling

3 Higgs final state

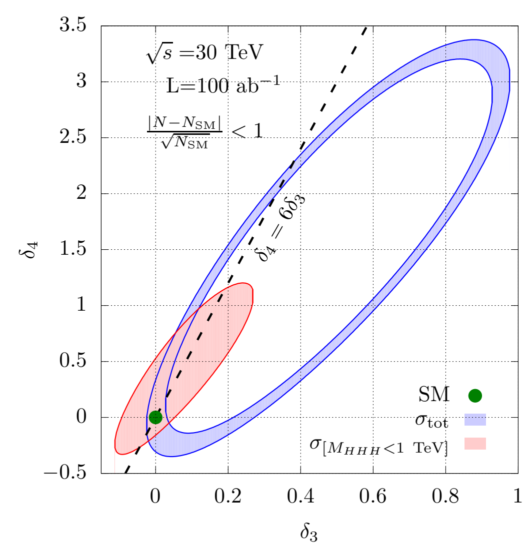




$$\frac{S}{\sqrt{B}} = \frac{|\mathcal{L} \cdot (\sigma - \sigma_{SM})|}{\sqrt{\mathcal{L} \cdot \sigma_{SM}}} \leq 1$$



10 TeV $\delta_4 \sim [-0.4, 0.7]$



30 TeV $\delta_4 \sim [-0.2, 0.5]$

Other colliders:

$$\text{ILC} \sim [-10, 10]$$
$$\text{CLIC} \sim [-5, 5]$$
$$\text{FCC} \sim [-2, 4]$$

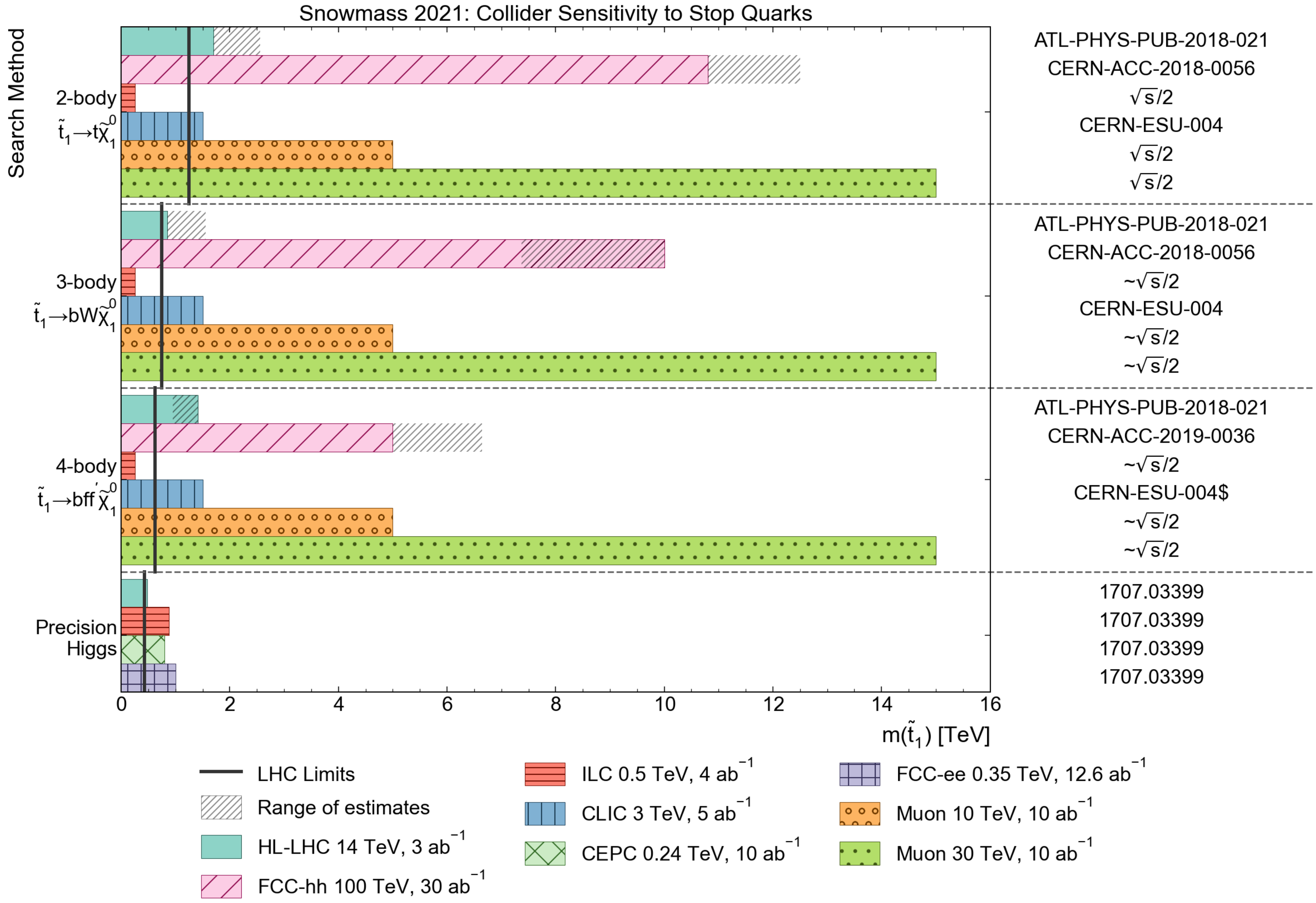
A 10 TeV muon collider would do better than FCC

Slide of E. Vryonidou

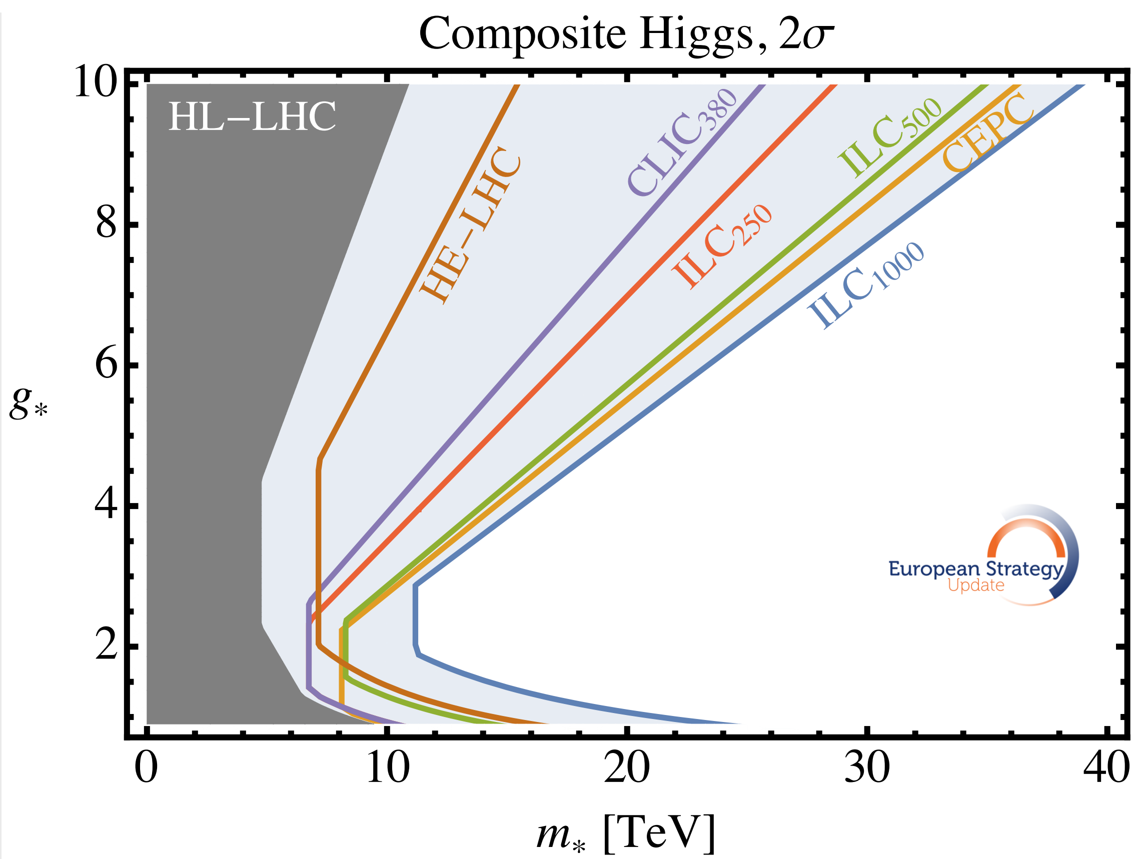
$$\lambda_3 = \lambda_{SM}(1 + \delta_3) = \kappa_3 \lambda_{SM}$$

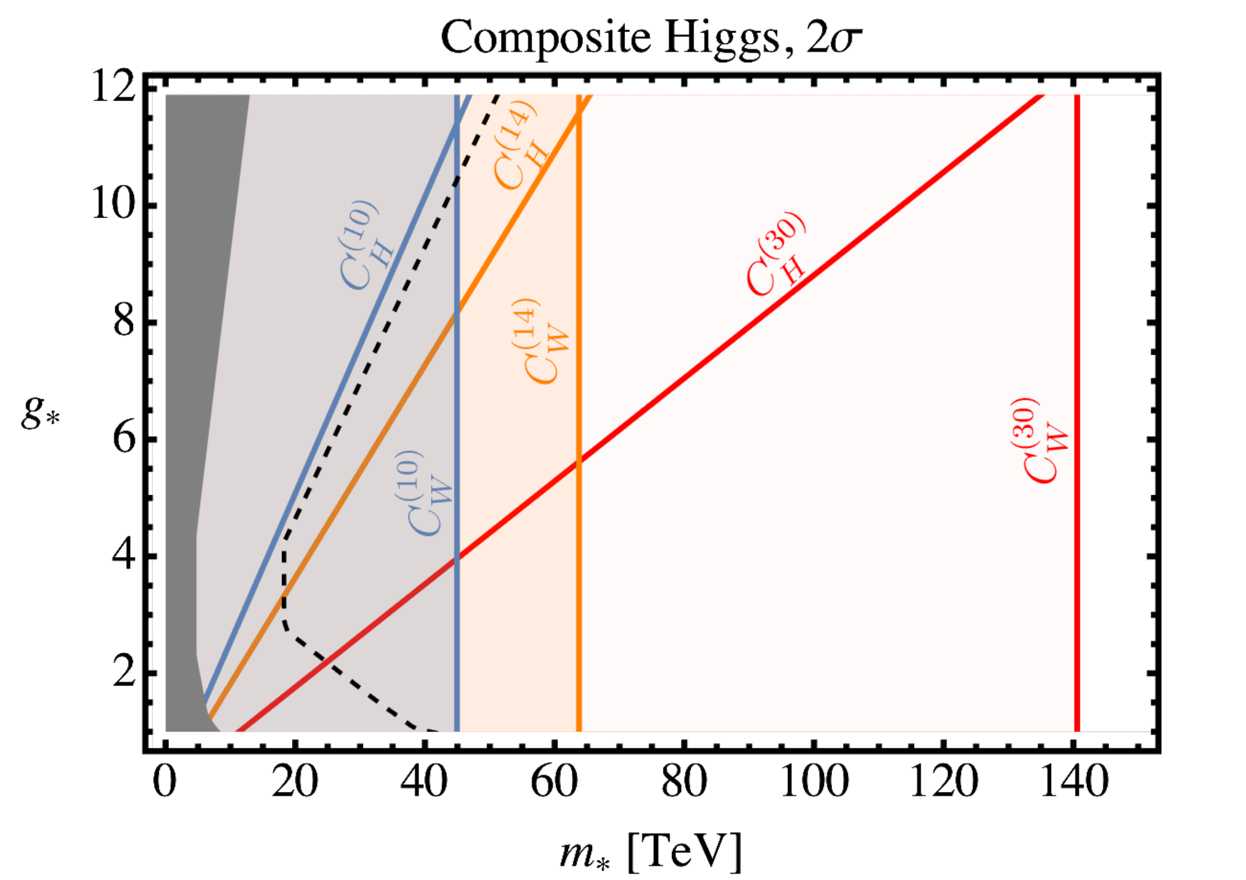
$$\lambda_4 = \lambda_{SM}(1 + \delta_4) = \kappa_4 \lambda_{SM}$$

Chiesa, Maltoni, Mantani, Mele, Piccinini, Zhao, 2003.13628


Snowmass 2021: Collider Sensitivity to Stop Quarks
Search Method
2-body
$\tilde{t}_1 \to t\tilde{\chi}_1^0$
3-body
$\tilde{t}_1 \to bW\tilde{\chi}_1^0$
4-body
$\tilde{t}_1 \to bff'\tilde{\chi}_1^0$
Precision
Higgs
0
2
4
6
8
10
12
14
16
$m(\tilde{t}_1)$ [TeV]
ATL-PHYS-PUB-2018-021
CERN-ACC-2018-0056
$\sqrt{s}/2$
CERN-ESU-004
$\sqrt{s}/2$
$\sqrt{s}/2$
ATL-PHYS-PUB-2018-021
CERN-ACC-2018-0056
$\sim\sqrt{s}/2$
CERN-ESU-004
$\sim\sqrt{s}/2$
$\sim\sqrt{s}/2$
ATL-PHYS-PUB-2018-021
CERN-ACC-2019-0036
$\sim\sqrt{s}/2$
CERN-ESU-004$
$\sim\sqrt{s}/2$
$\sim\sqrt{s}/2$
1707.03399
1707.03399
1707.03399
1707.03399
LHC Limits
Range of estimates
HL-LHC 14 TeV, 3 ab^{-1}
FCC-hh 100 TeV, 30 ab^{-1}
ILC 0.5 TeV, 4 ab^{-1}
CLIC 3 TeV, 5 ab^{-1}
CEPC 0.24 TeV, 10 ab^{-1}
FCC-ee 0.35 TeV, 12.6 ab^{-1}
Muon 10 TeV, 10 ab^{-1}
Muon 30 TeV, 10 ab^{-1}

Composite





Through precision measurement at high energies.

Blind spot for muon collider?

- New physics only charged under color.
  - e.g. Gluino
- Muon blind flavor specific coupling.