Physics case of a 3 TeV muon collider

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thanks to D. Buttazzo, N. Craig, F. Maltoni, L. Sestini, A. Wulzer, X. Zhao

Open Questions on the "big picture" on fundamental physics circa 2020

	?	what is the dark matter in the Universe?
	(one parameter)	why QCD does not violate CP?
	(one parameter)	how have baryons originated in the early Universe?
	(several parameters)	what originates flavor mixing and fermions masses?
	(several parameters)	what gives mass to neutrinos?
~~EFT~~	(one parameter)	why gravity and weak interactions are so different?
~~EFT~~	(one parameter)	what fixes the cosmological constant?

- ? Need new matter (or even bigger modifications to the SM)
- (one parameter) Adjusting one SM parameter might do
- (several parameters) Adjusting several SM parameters might do
- ~~EFT~~ Separation of scales as an organizing principle might fail

EACH of these issues one day will teach us a lesson

Open Questions on the "big picture" on fundamental physics circa 2020

$\mu^+\mu^-$ sensitivity to weak interactions

WEAK INTERACTIONS

STRONG INTERACTIONS

- ? what is the dark matter in the Universe? ✓ (weak)
- why QCD does not violate CP? ✓ (weak) ✓ (strong)
- how have baryons originated in the early Universe? ✓ (weak)
- what originates flavor mixing and fermions masses? ✓ (weak)
- what gives mass to neutrinos? ✓ (weak)
- ~~EFT~~ why gravity and weak interactions are so different? ✓ (weak)
- ~~EFT~~ what fixes the cosmological constant? ✓ (weak)

Accelerators are excellent probes

Open Questions on the "big picture" on fundamental physics circa 2020

$\mu^+\mu^-$ sensitivity to weak interactions

- ? what is the dark matter in the Universe?
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- ~~EFT~~ what fixes the cosmological constant?

Question	WEAK INTERACTIONS	STRONG INTERACTIONS	ACCELERATORS
what is the dark matter in the Universe?	✓		✓
why QCD does not violate CP?	✓	✓	
how have baryons originated in the early Universe?	✓		✓
what originates flavor mixing and fermions masses?	✓		
what gives mass to neutrinos?	✓		
why gravity and weak interactions are so different?	✓		✓
what fixes the cosmological constant?	✓		

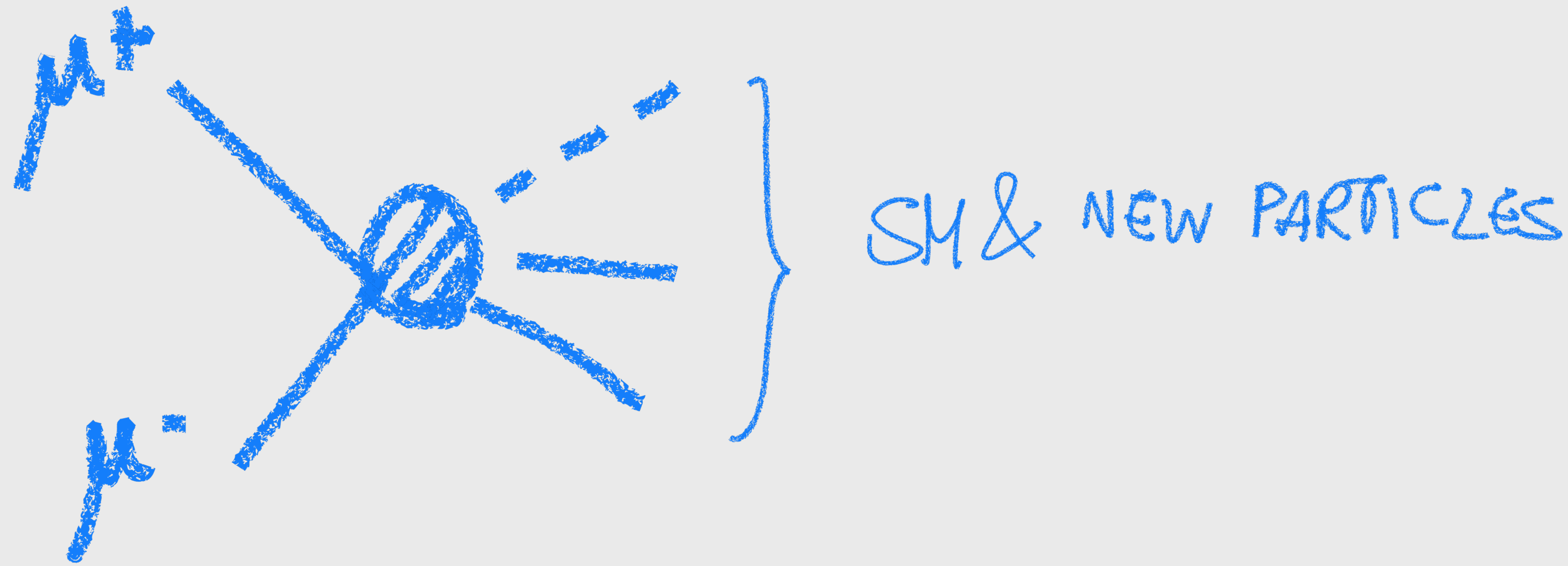
Accelerators are excellent probes

$\mu^+\mu^-$ collisions to probe fundamental physics

- production of SM and new physics in direct $\mu^+\mu^-$ annihilation
- production of SM and new physics using beam constituents (e.g. W bosons)
- indirect probes of new physics in direct $\mu^+\mu^-$ annihilation

3 TeV center of mass brings significant extension compared to HL-LHC

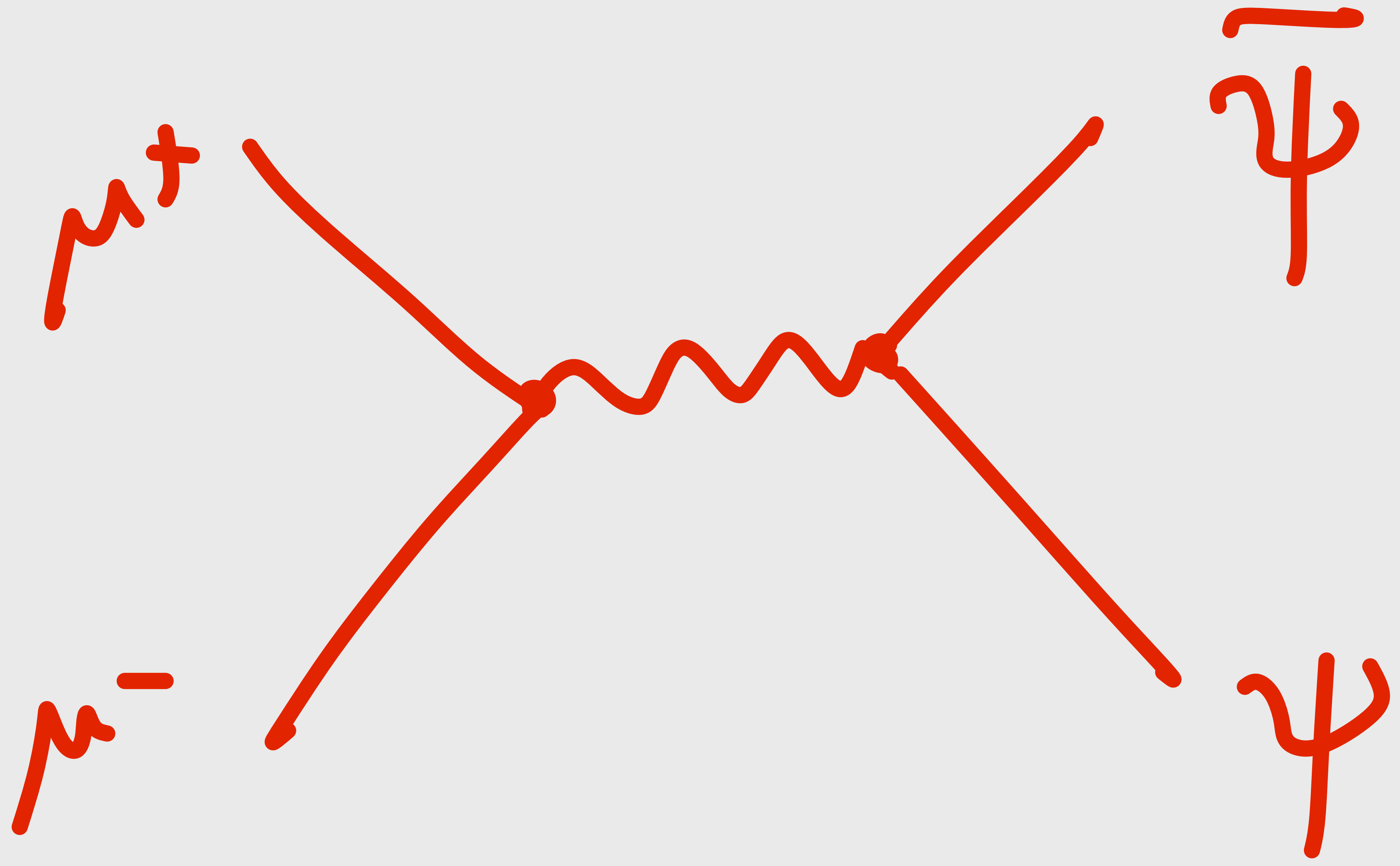
“Valence” Leptons



$\mu^+\mu^- \to$ new physics

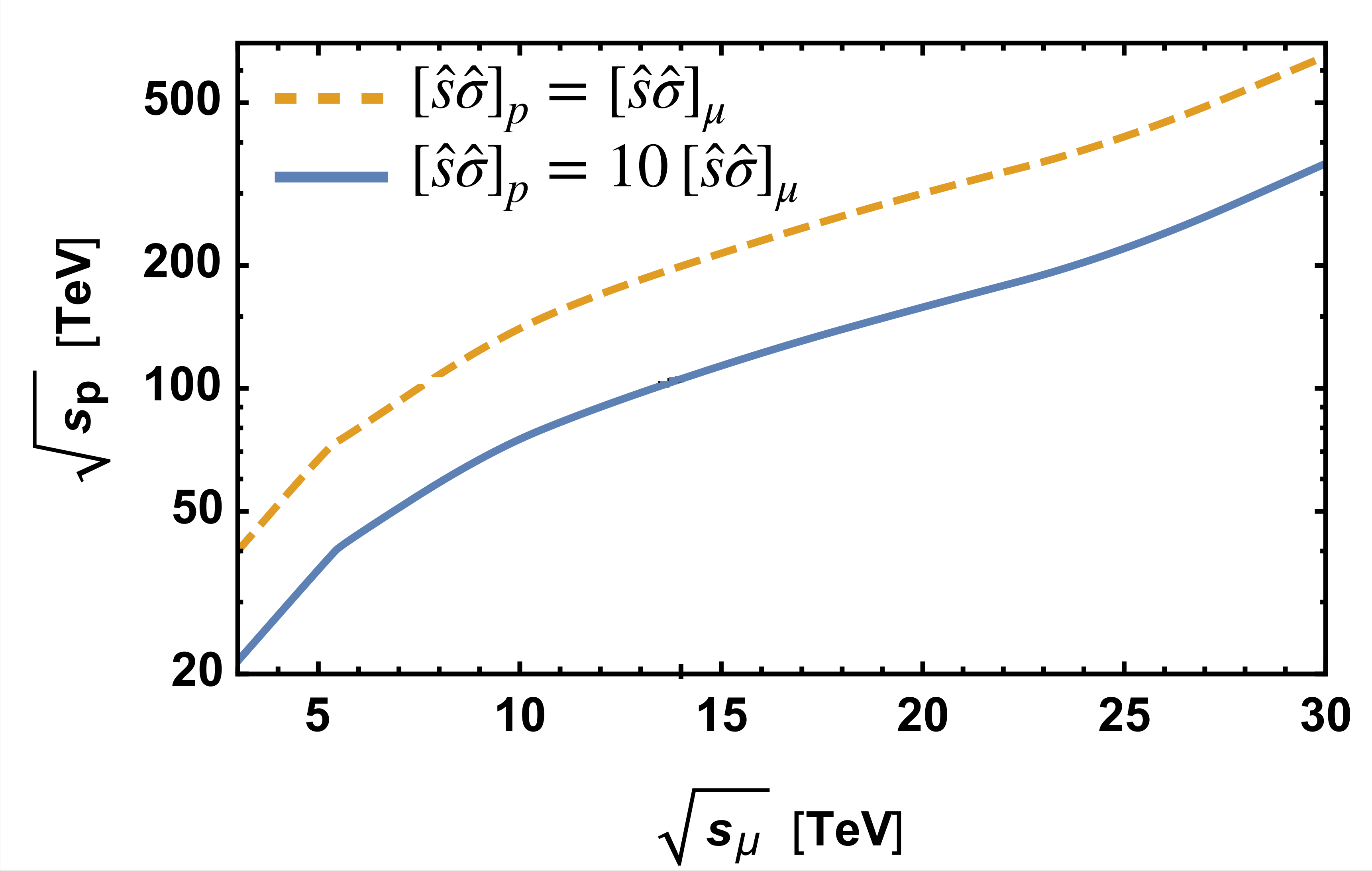
VALENCE MUONS

Can produce heavy new physics (colored or not)



in principle can probe directly new states at $\frac{\sqrt{s}}{2}$ scale!

Compares pretty well with a *pp* collider 2005.10289



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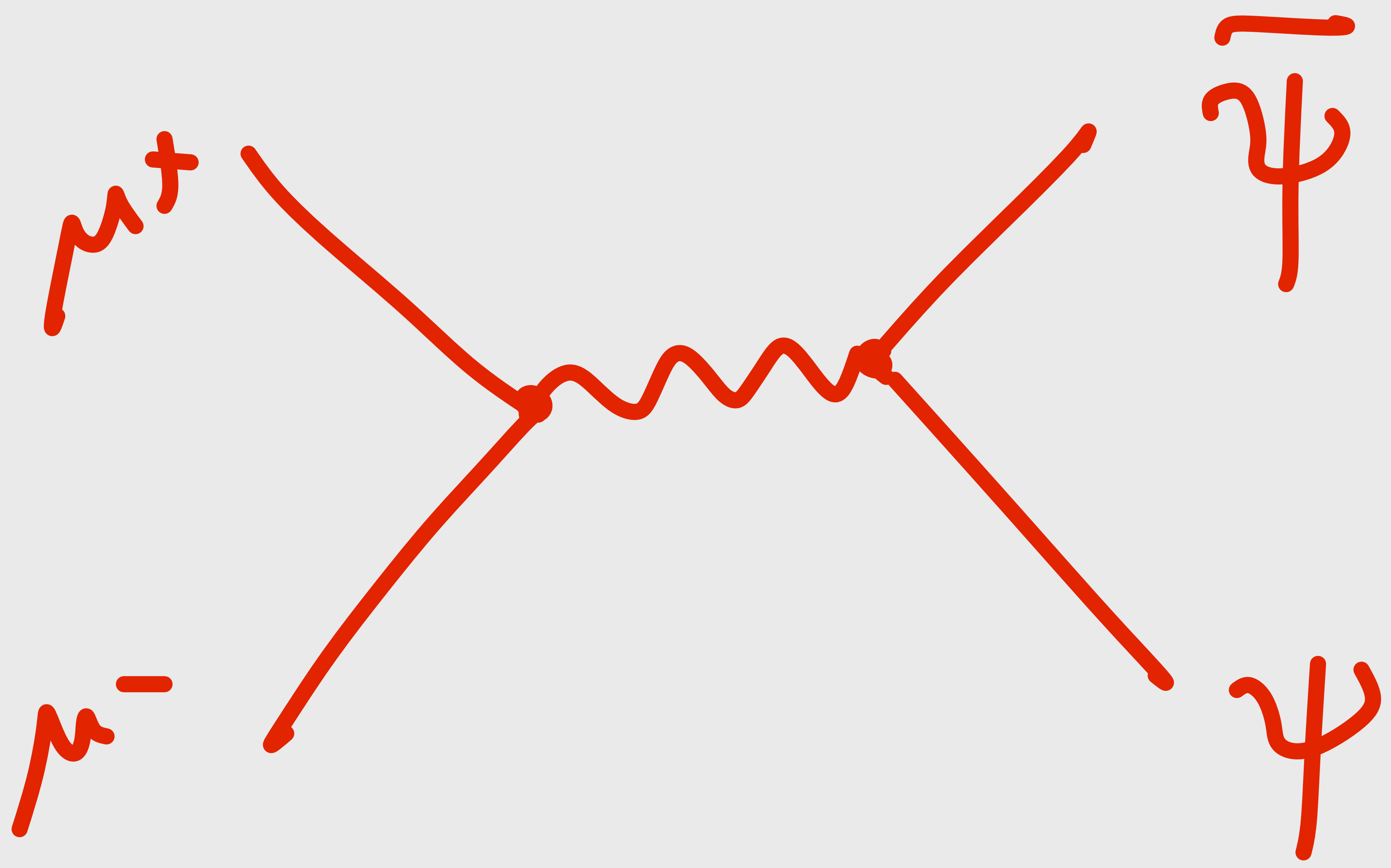

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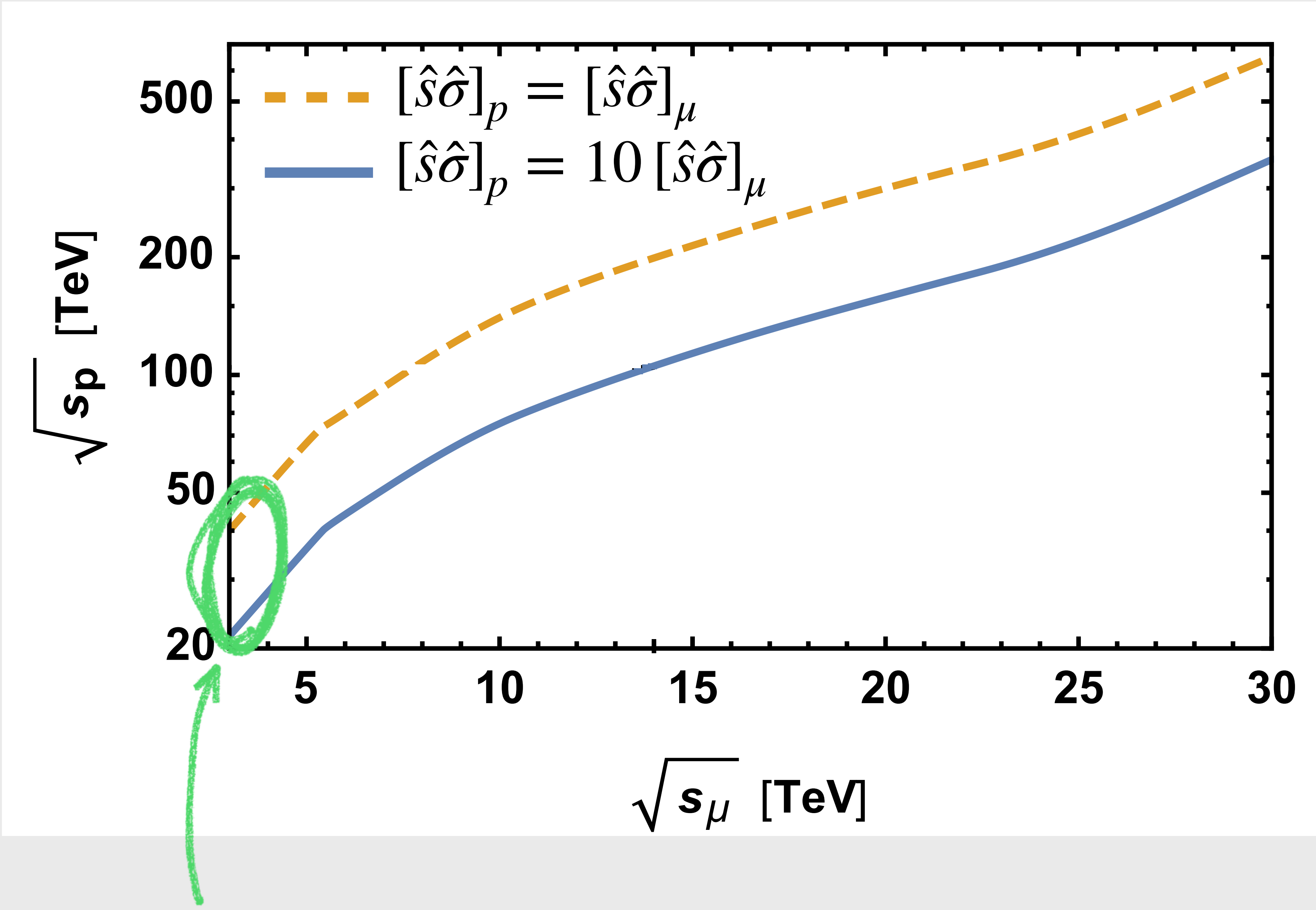
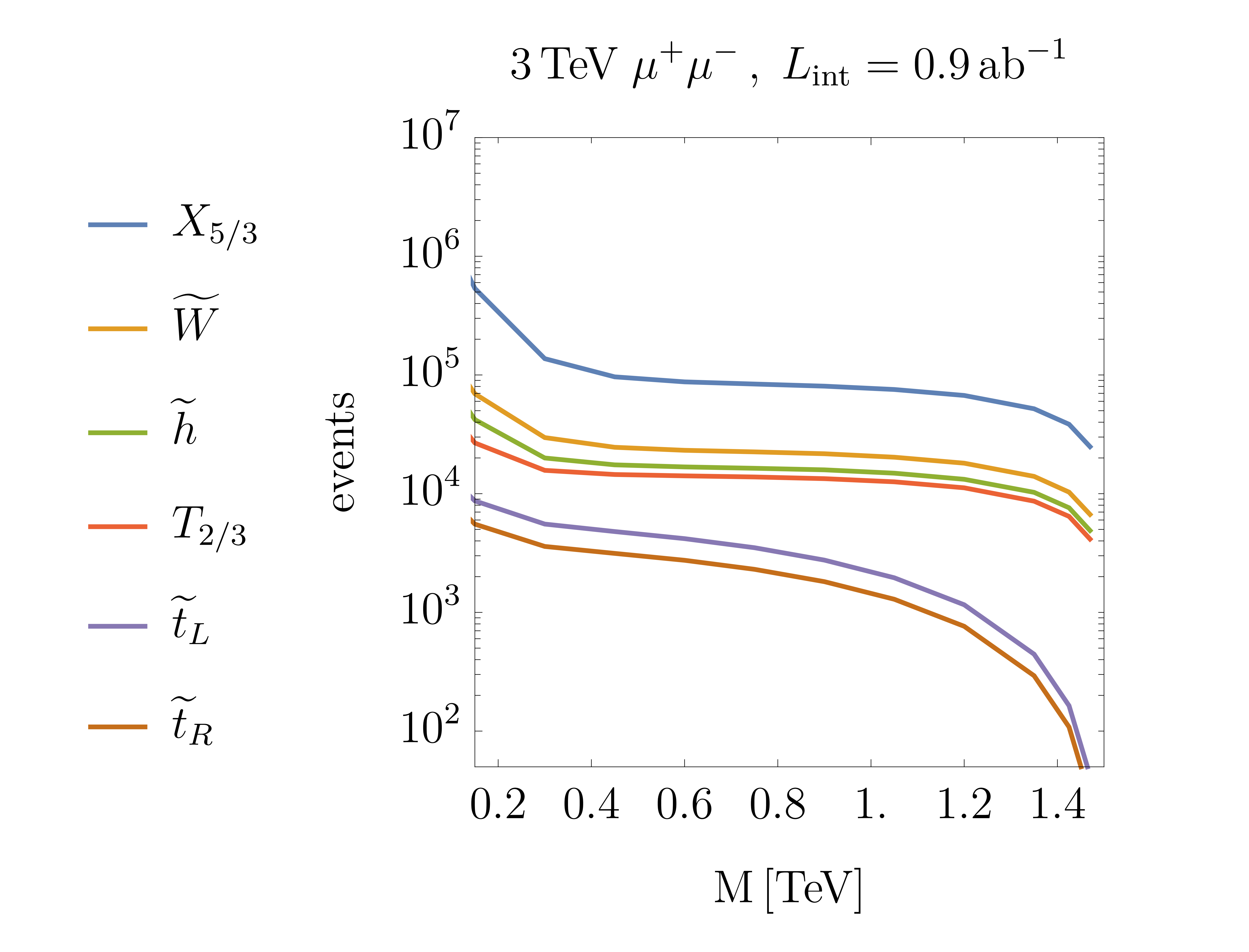


3 TeV $\mu^+\mu^-$ roughly equivalent to 20+ TeV *pp*

$\mu^+\mu^- \to$ new physics

VALENCE MUONS



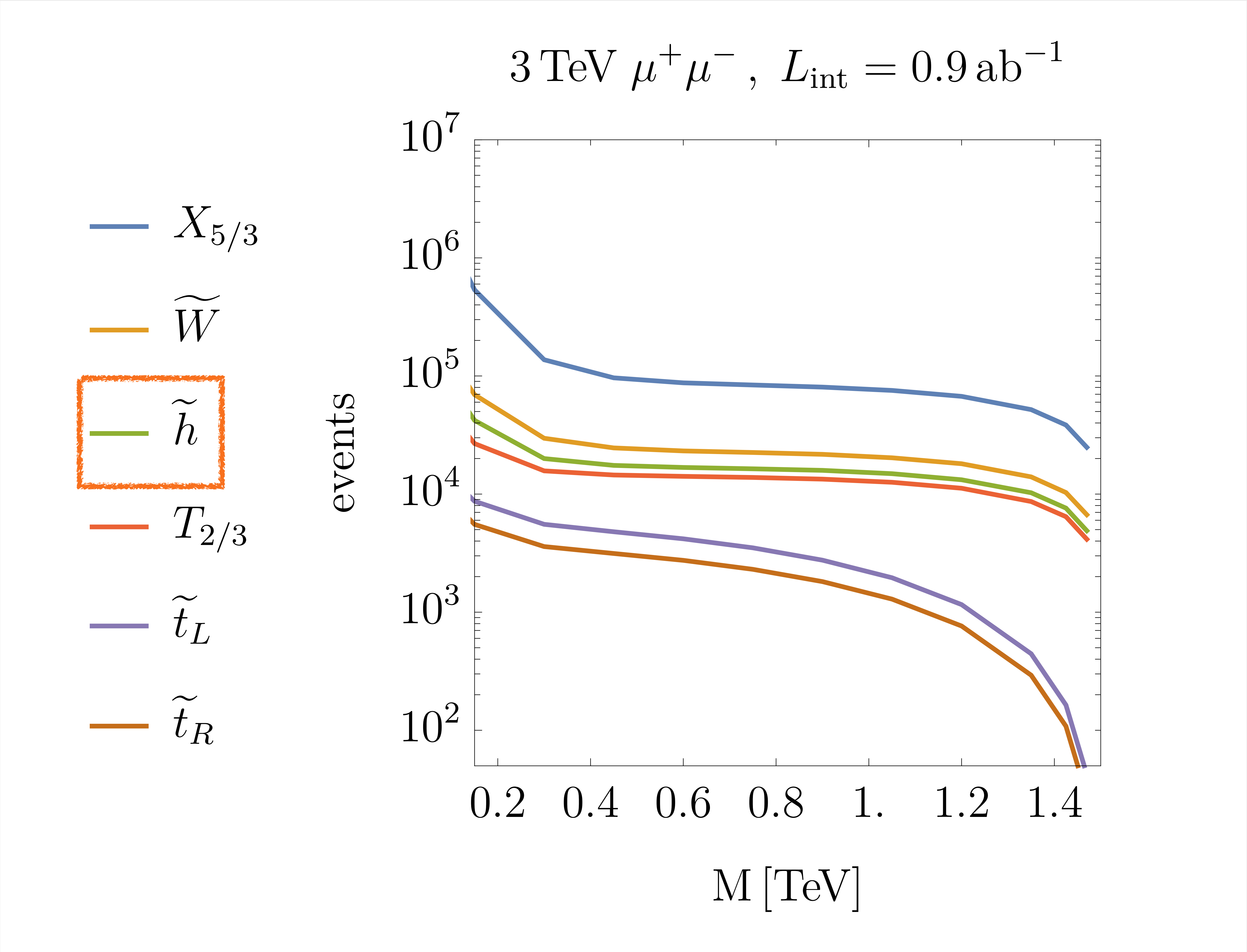
BEST POSITION TO OBSERVE ANY SIGN OF ELECTROWEAK NEW PHYSICS

(e.g. in the Higgs sector, or from new strong interactions at the TeV, fermions mass and mixing generation at the TeV)

Any sign of SUSY below the TeV will be observable, no matter if the sparticles are colored or not.

$\mu^+\mu^- \to$ new physics

VALENCE MUONS



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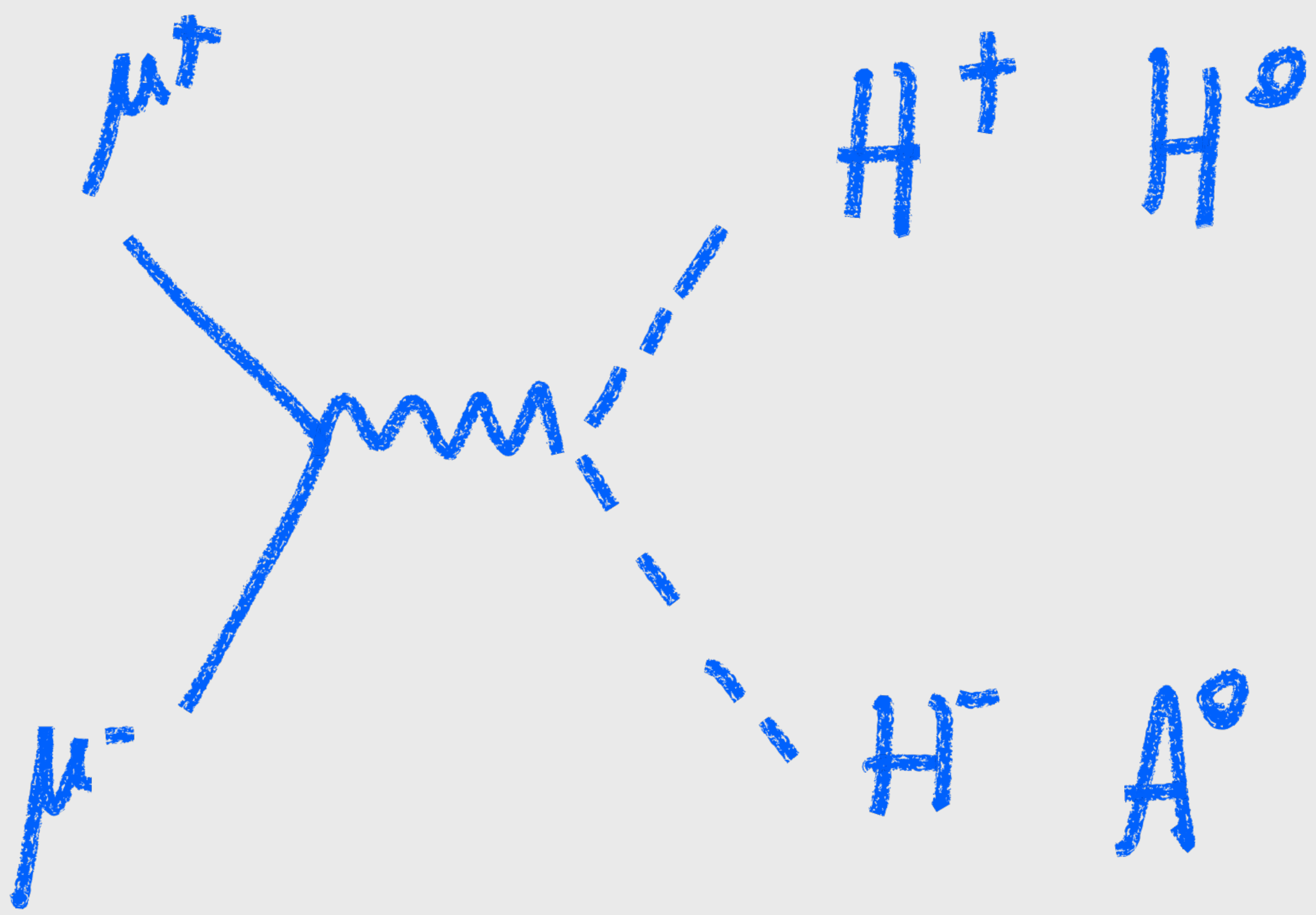
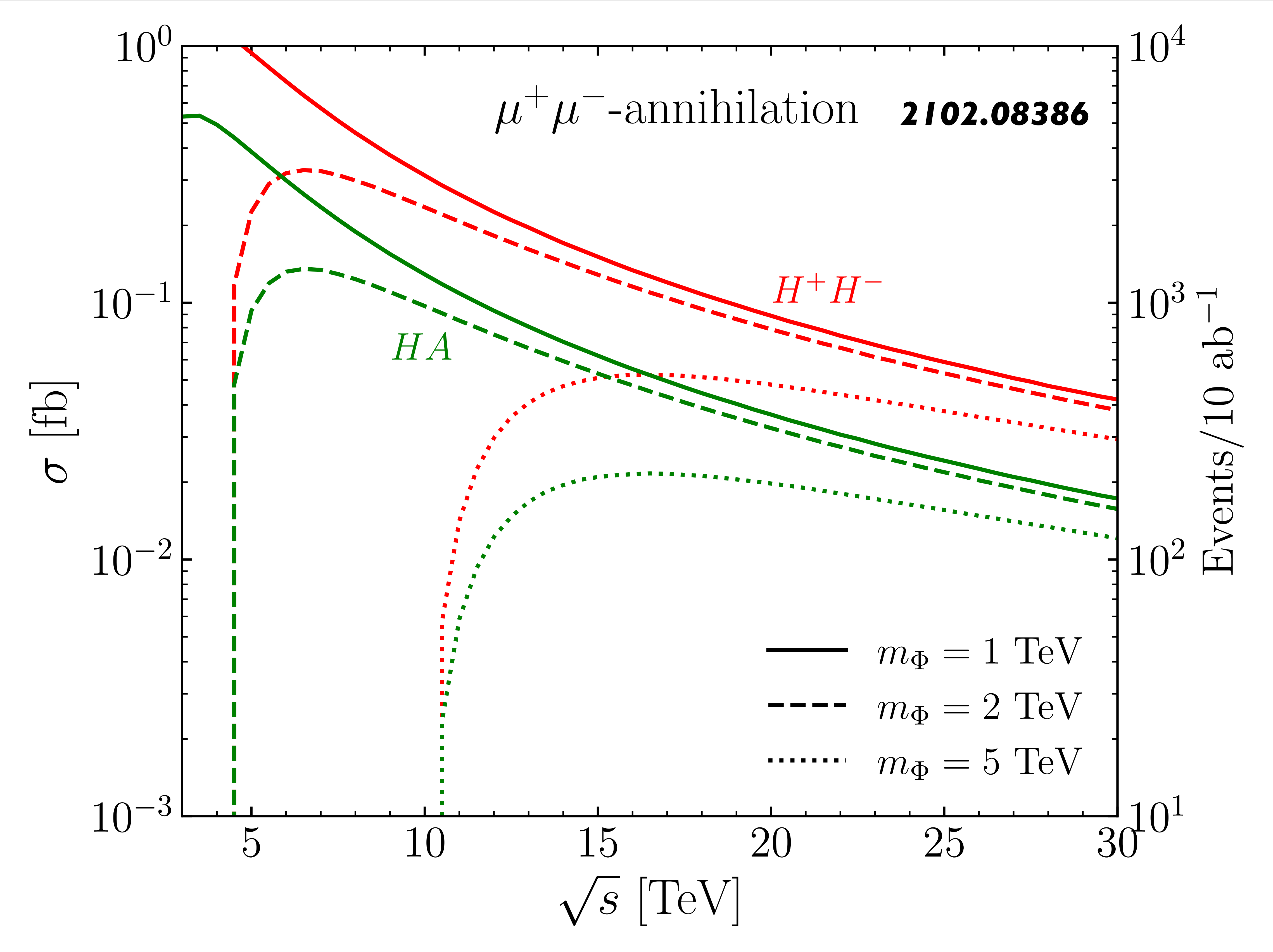
2HDM

VALENCE MUONS





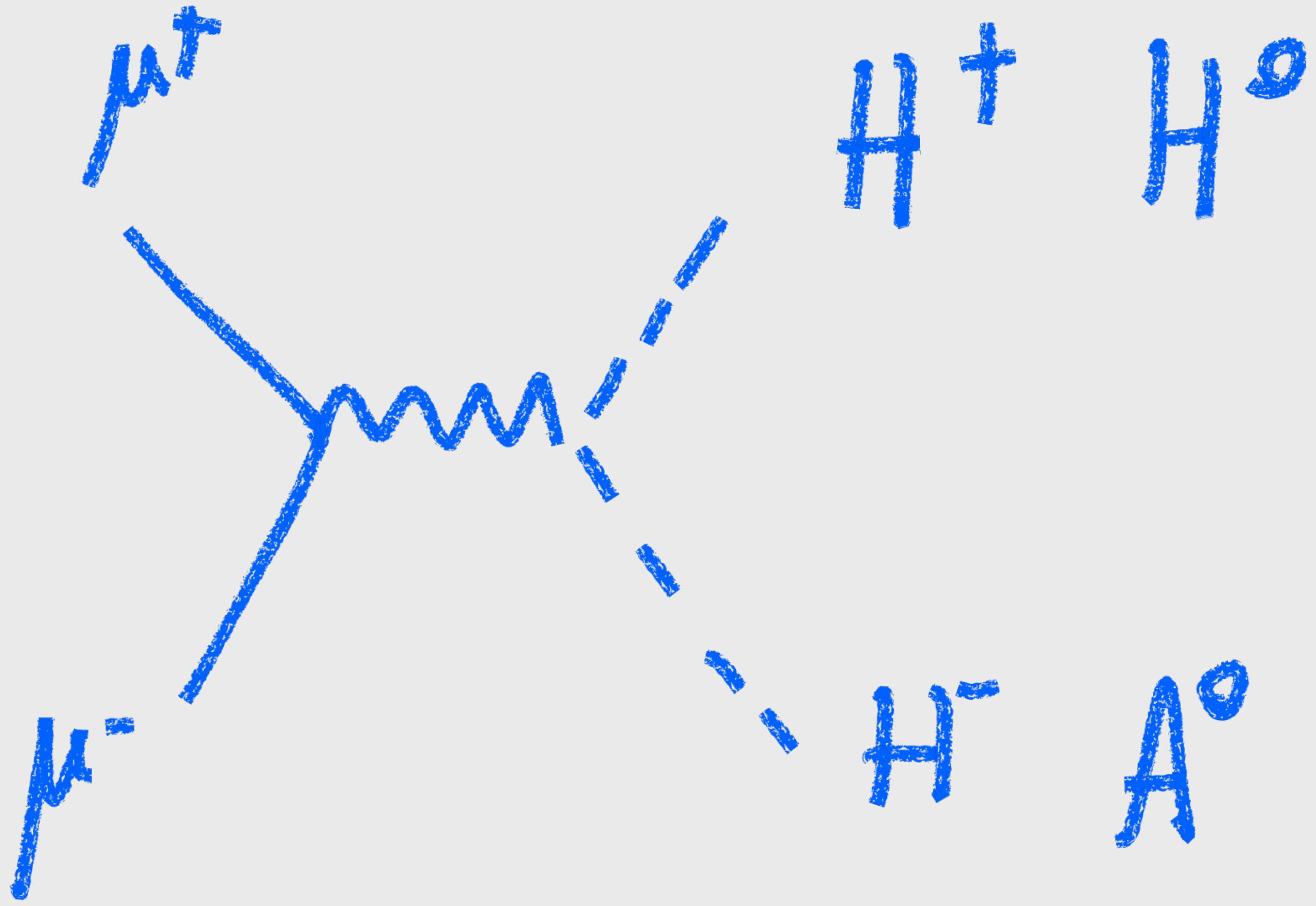
- HL-LHC coverage ends well below TeV
- detailed model analysis for 3 TeV desirable
- reach close to $\sqrt{s}/2$

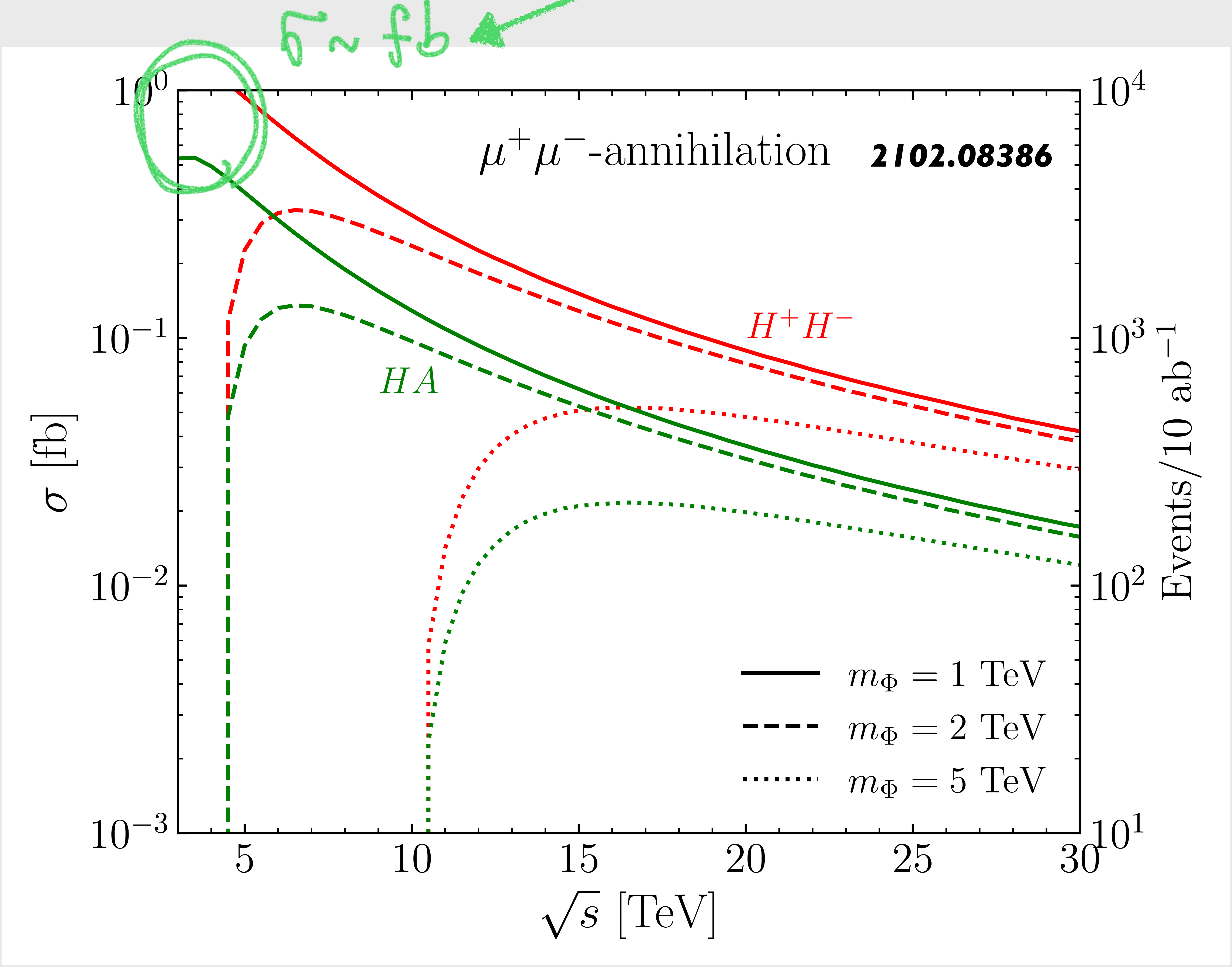
2HDM

VALENCE MUONS

thousands of events per ab^{-1}

$\mu\mu$ 3 TeV
$\sigma \simeq 1$ fb





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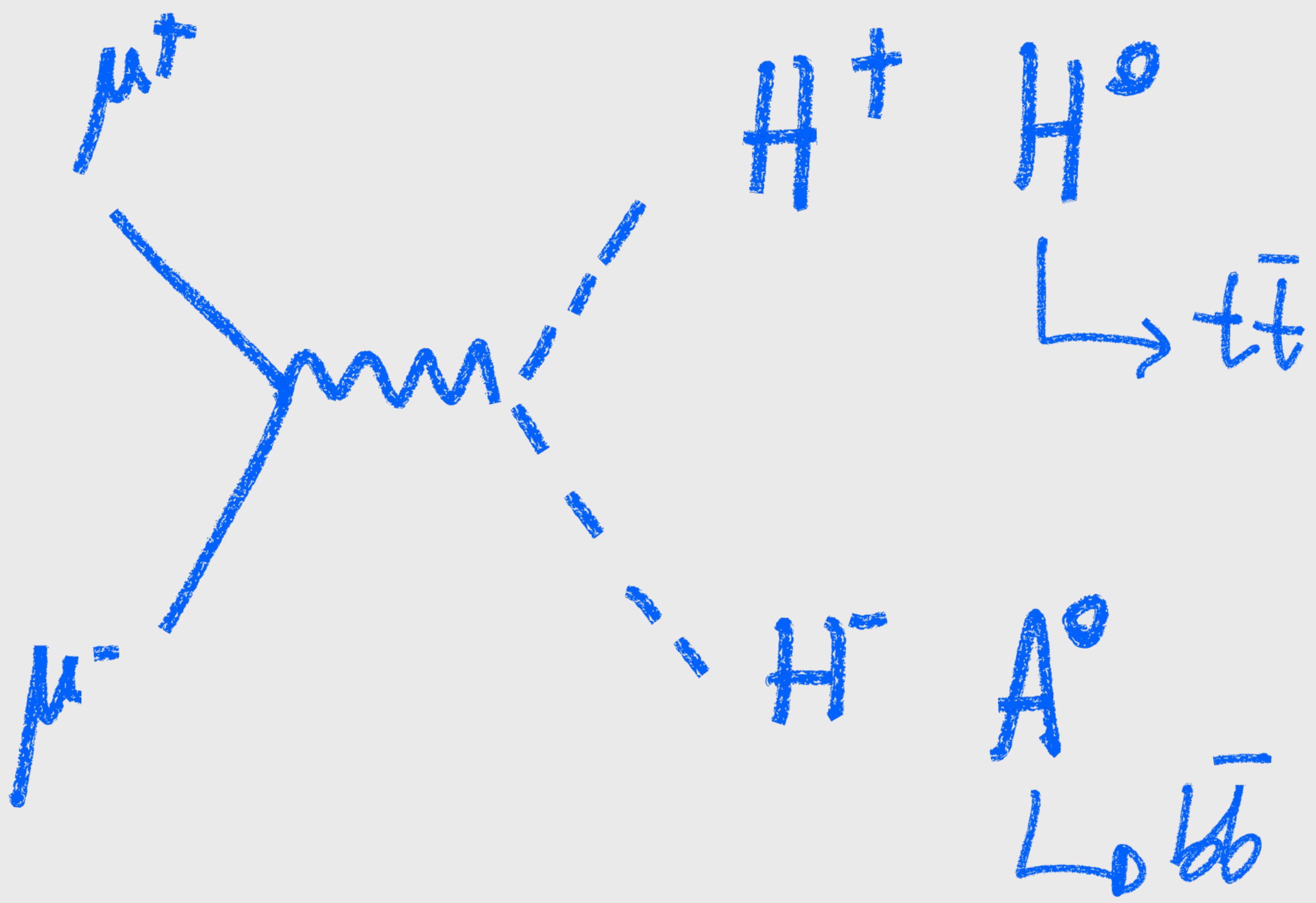

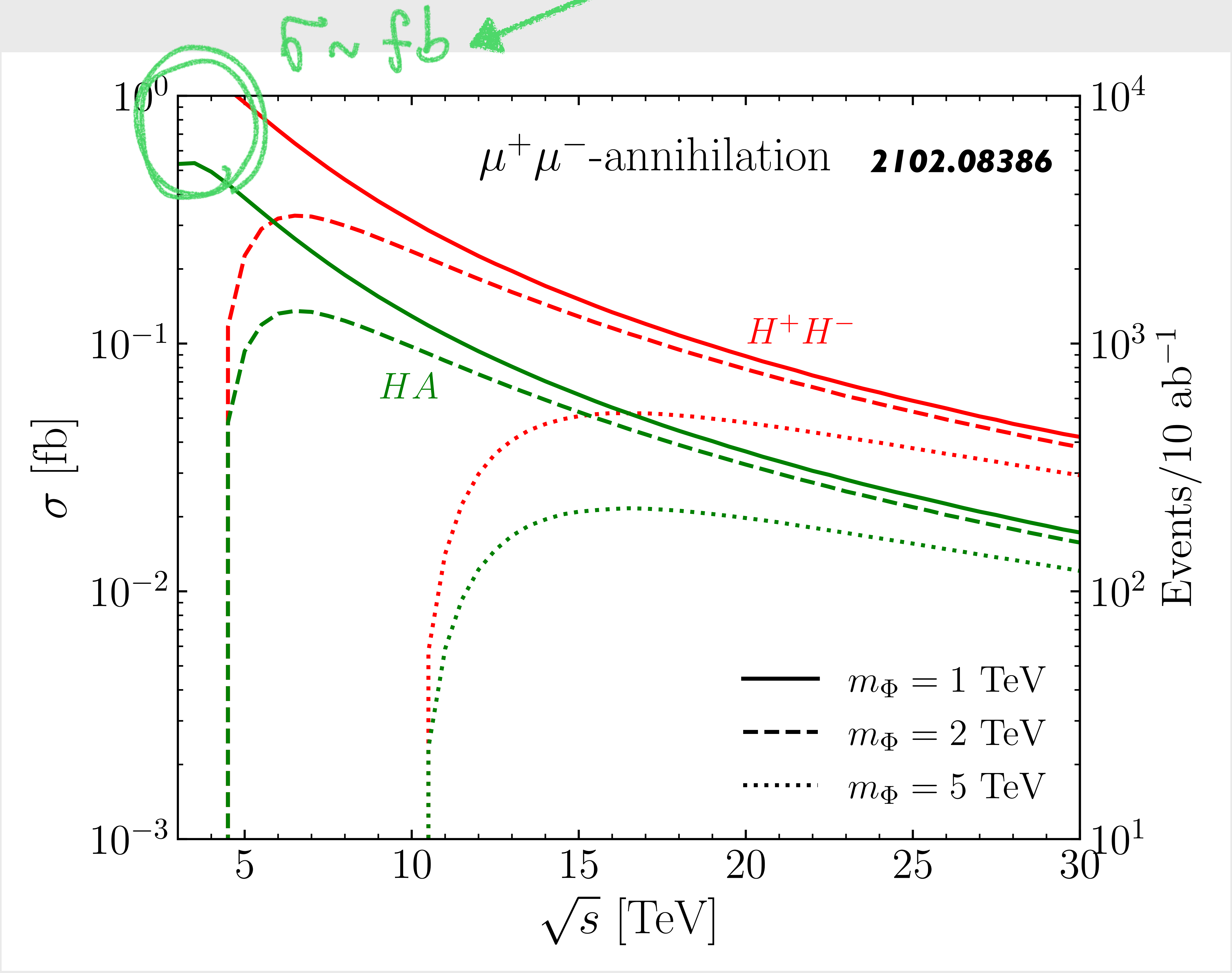

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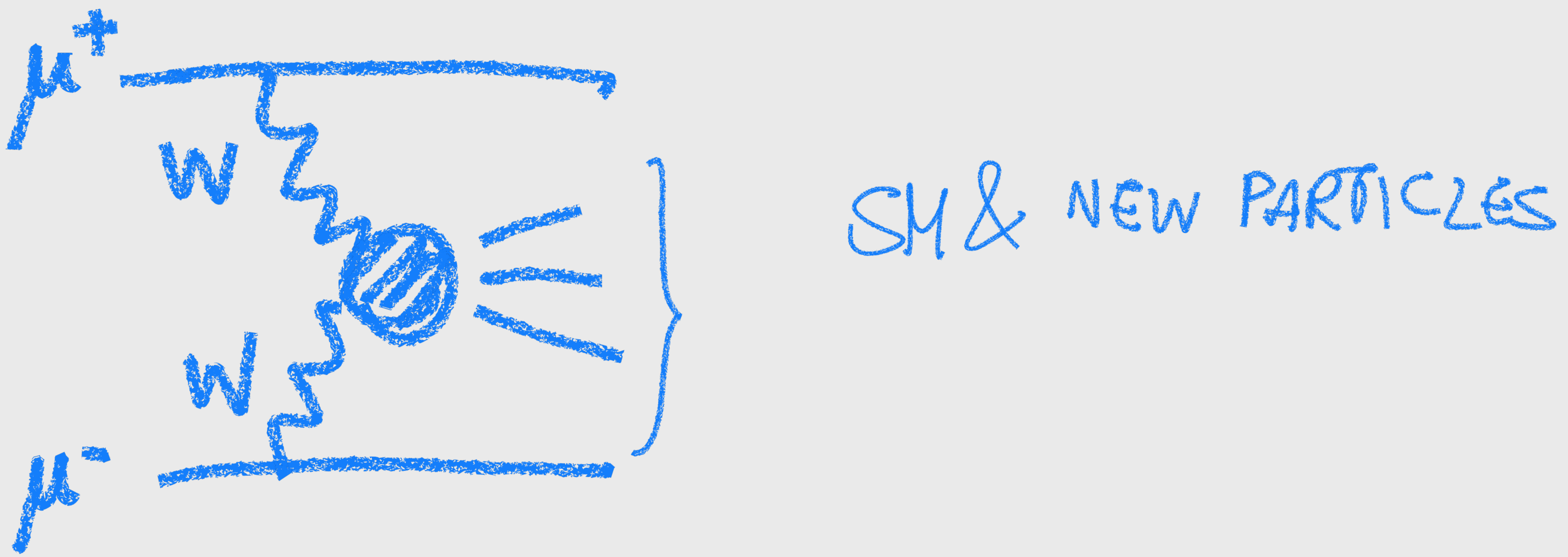
- detailed model analysis for 3 TeV desirable
- reach close to $\sqrt{s}/2$

at $\sqrt{s} \gg 100$ GeV

Weak Bosons collider

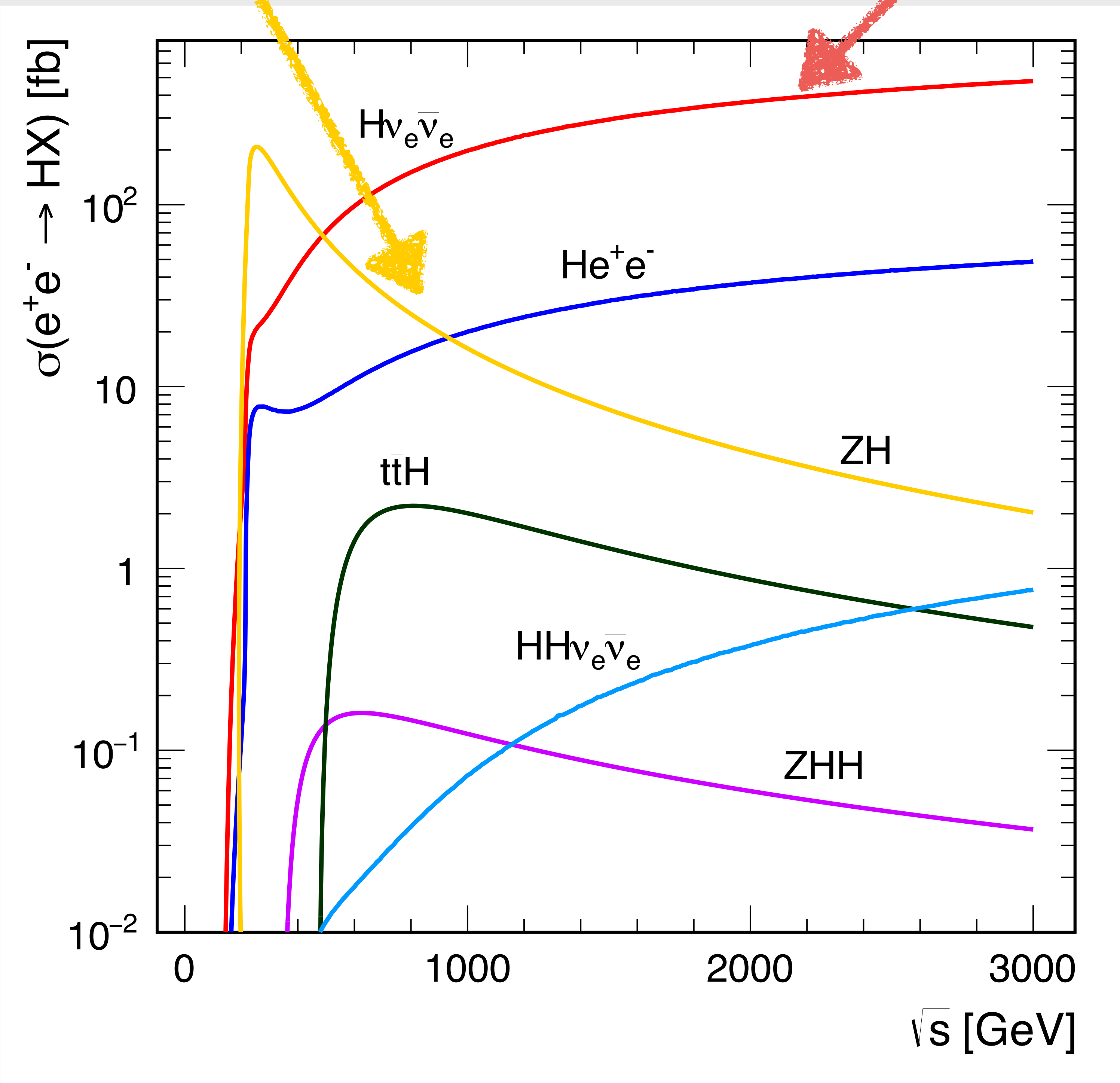


Higgs boson

$\mu^+\mu^- \to h\nu\bar{\nu}$

10^6 HIGGS BOSONS | **MEGA-HIGGS FACTORY**

$\sigma \sim 1/s$ $\sigma \sim log(s)$



At 3 TeV the weak bosons are sufficiently light that can be radiated very efficiently

$$\sqrt{s} = 3\,\text{TeV}$$
$$\sigma \cdot \mathscr{L} \Rightarrow O(10^6)\ \text{h}$$

- large number of Higgs bosons!

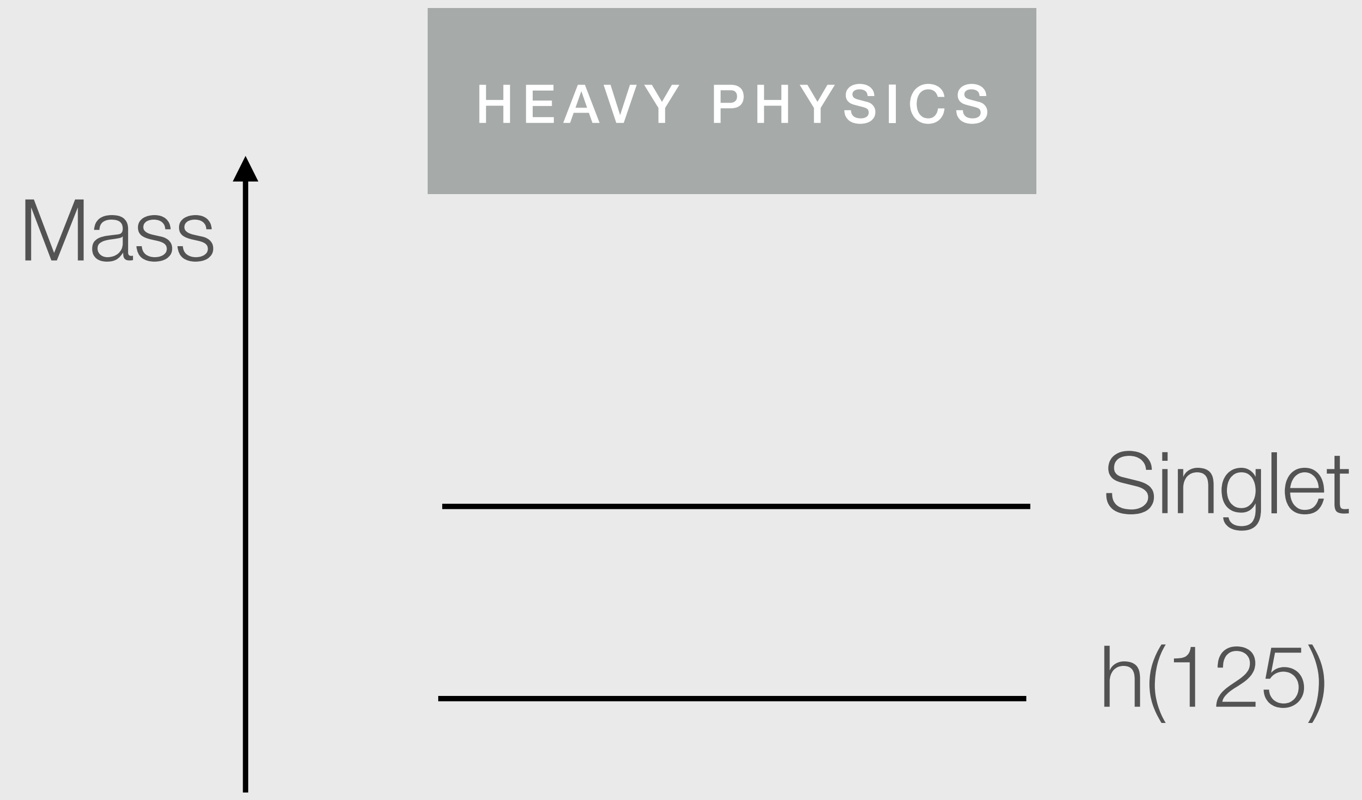
NEXT TALK BY L. SESTINI

FURTHER OPPORTUNITIES

- ultra-rare Higgs decays
- differential distribution
- off-shell Higgs bosons
- rare production modes

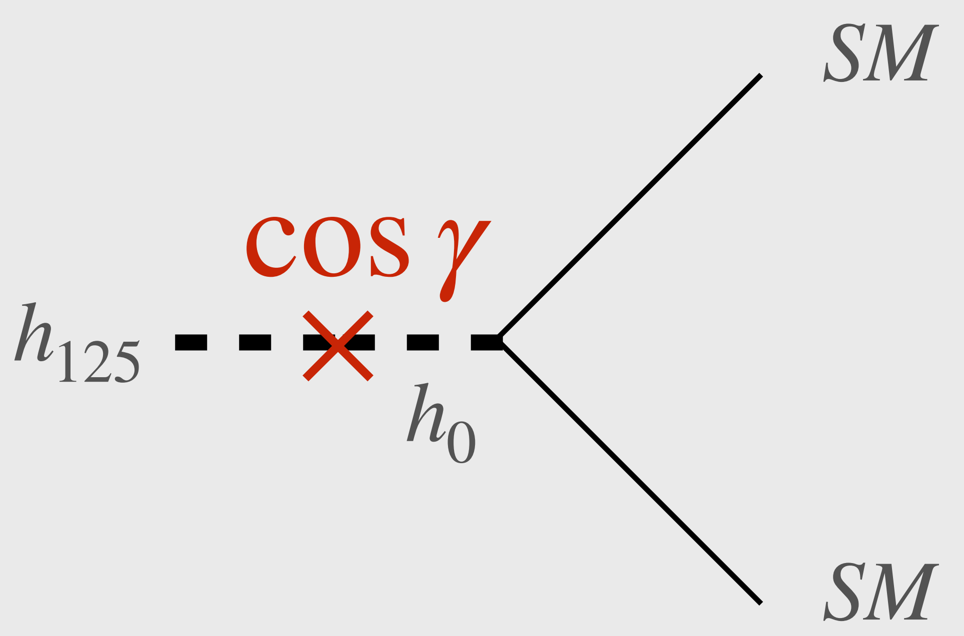
Impact on BSM

Higgs + Singlet

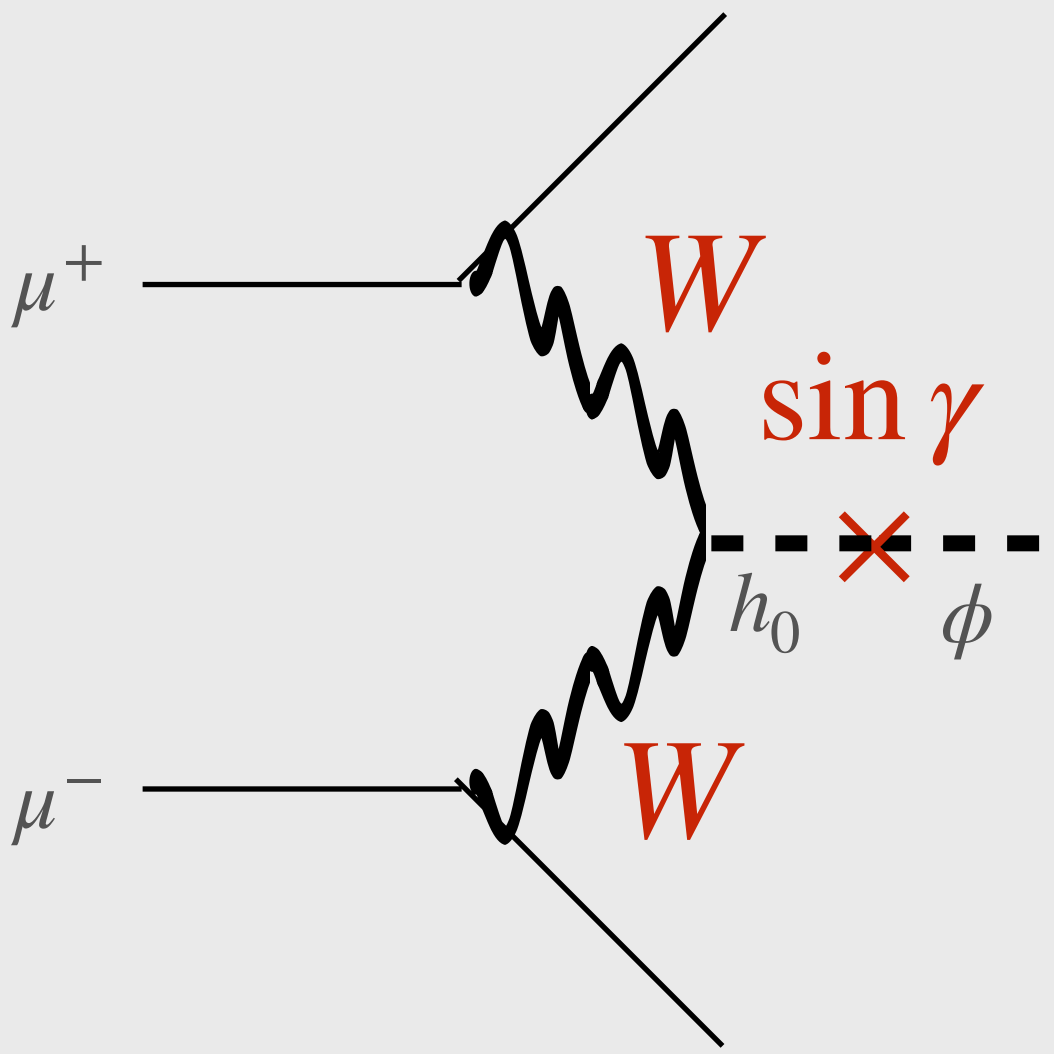


- Broad coverage of BSM scenarios: *(N)MSSM*, *Twin Higgs*, *Higgs portal*, *modified Higgs potential (Baryogenesis)*
- Phenomenology is also useful as “simplified model”

Higgs + Singlet



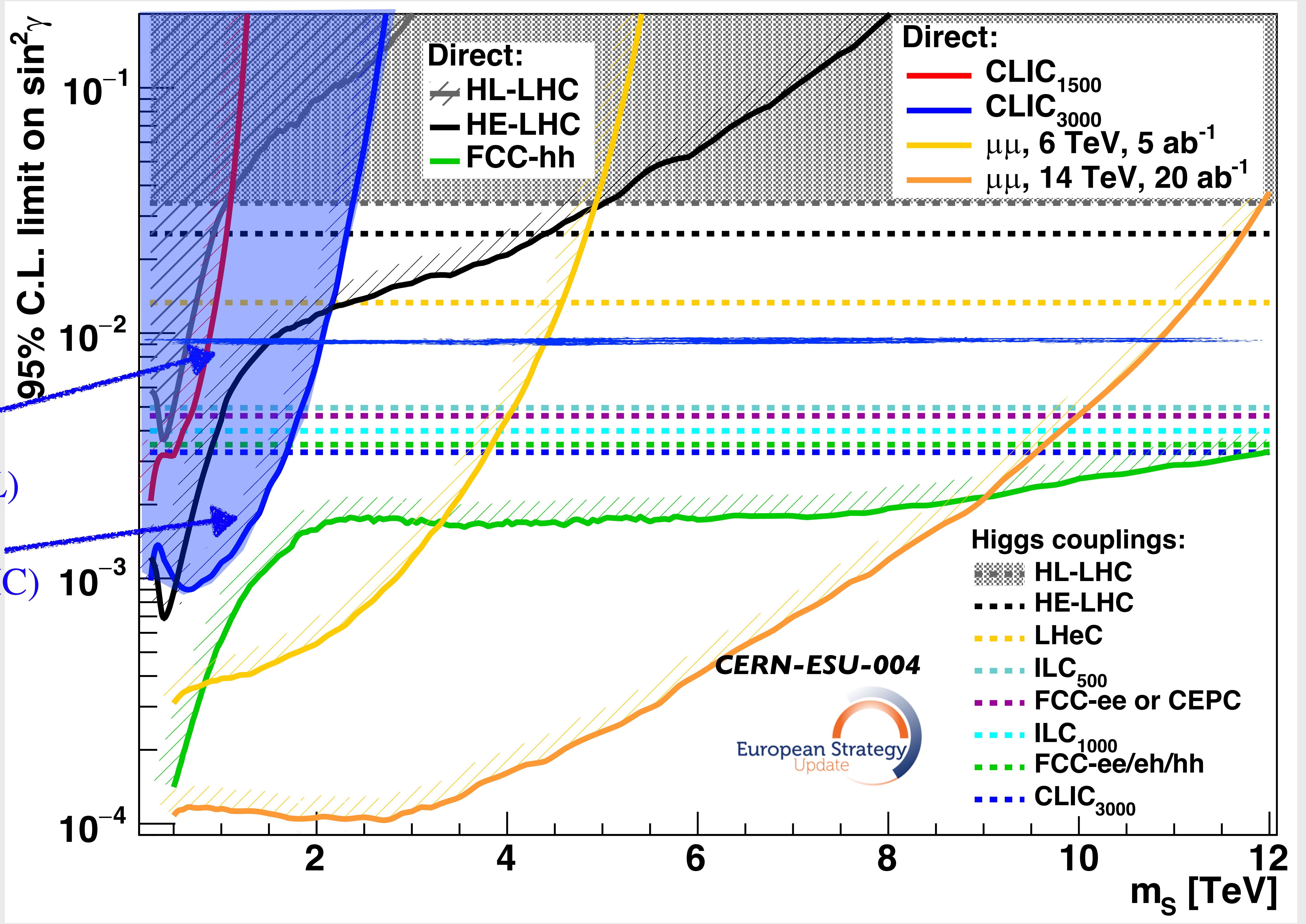
EXPLOIT ONCE MORE THE W BOSON LUMINOSITY



3 TeV

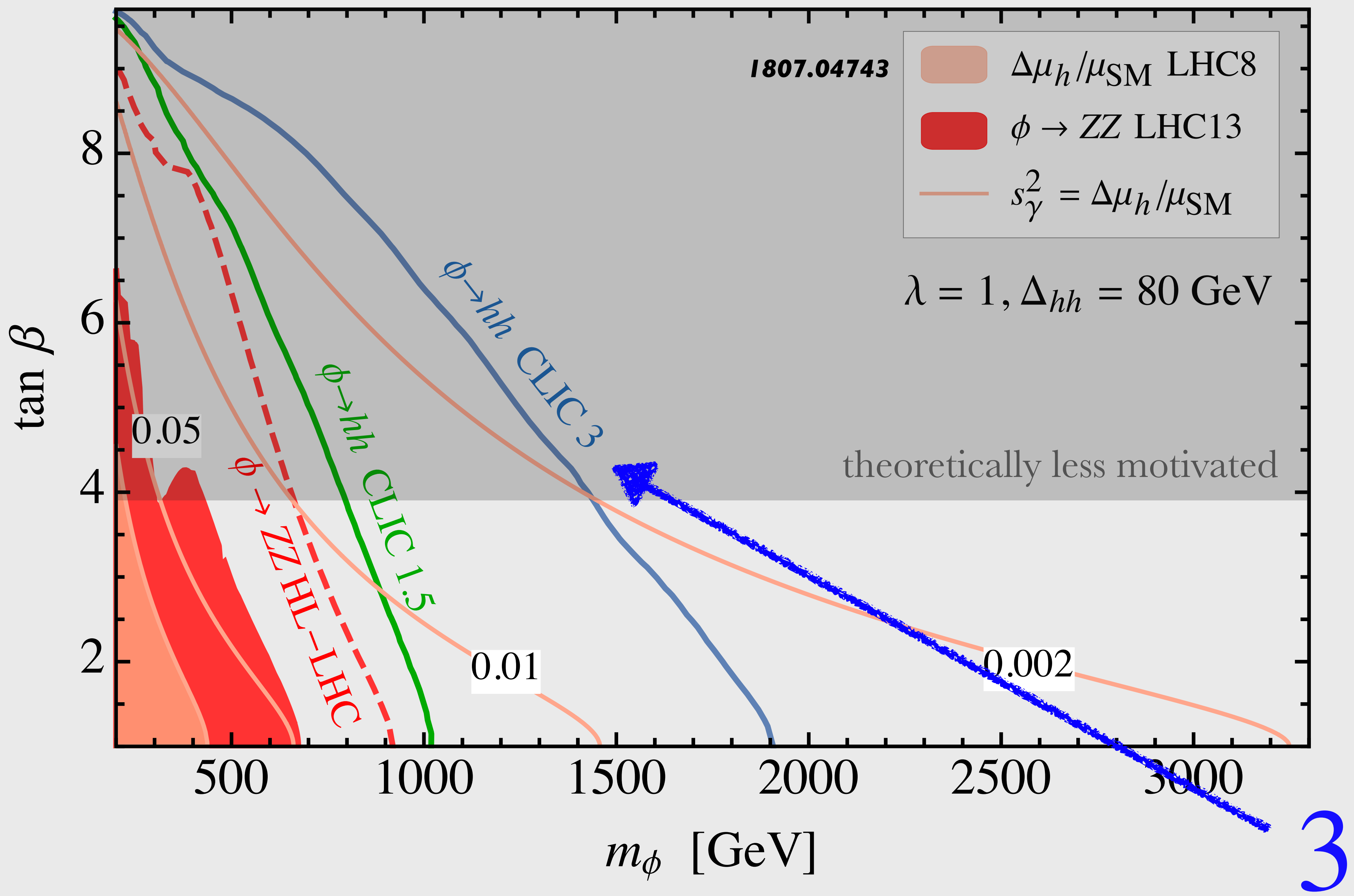
$\sigma_h \cdot BR_{bb} @ 1\,\% \; (95\,\%\, CL)$

3 TeV(CLIC)



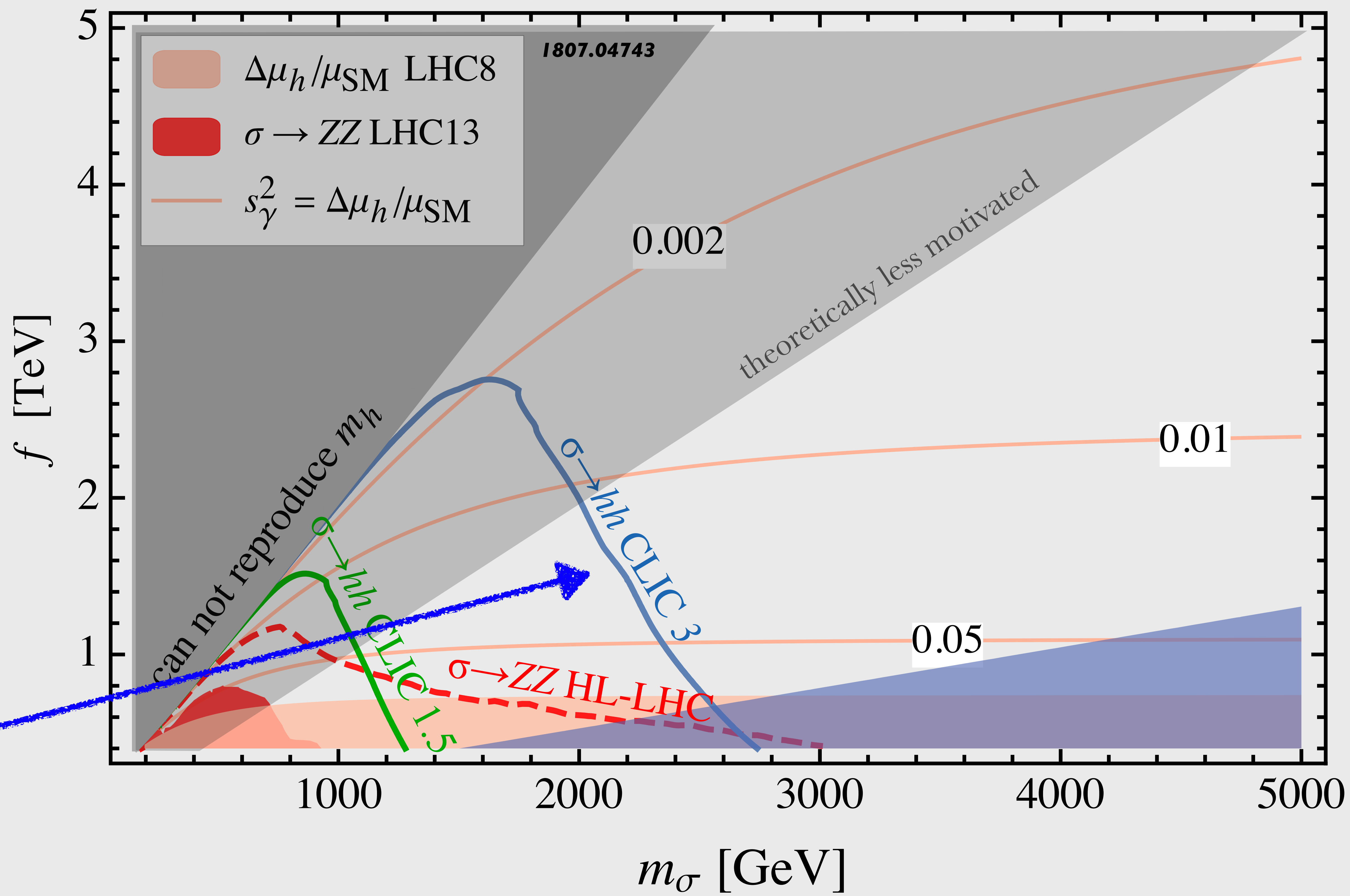
Higgs + Singlet: BSM interpretations

NMSSM



3 TeV(CLIC)

TWIN HIGGS

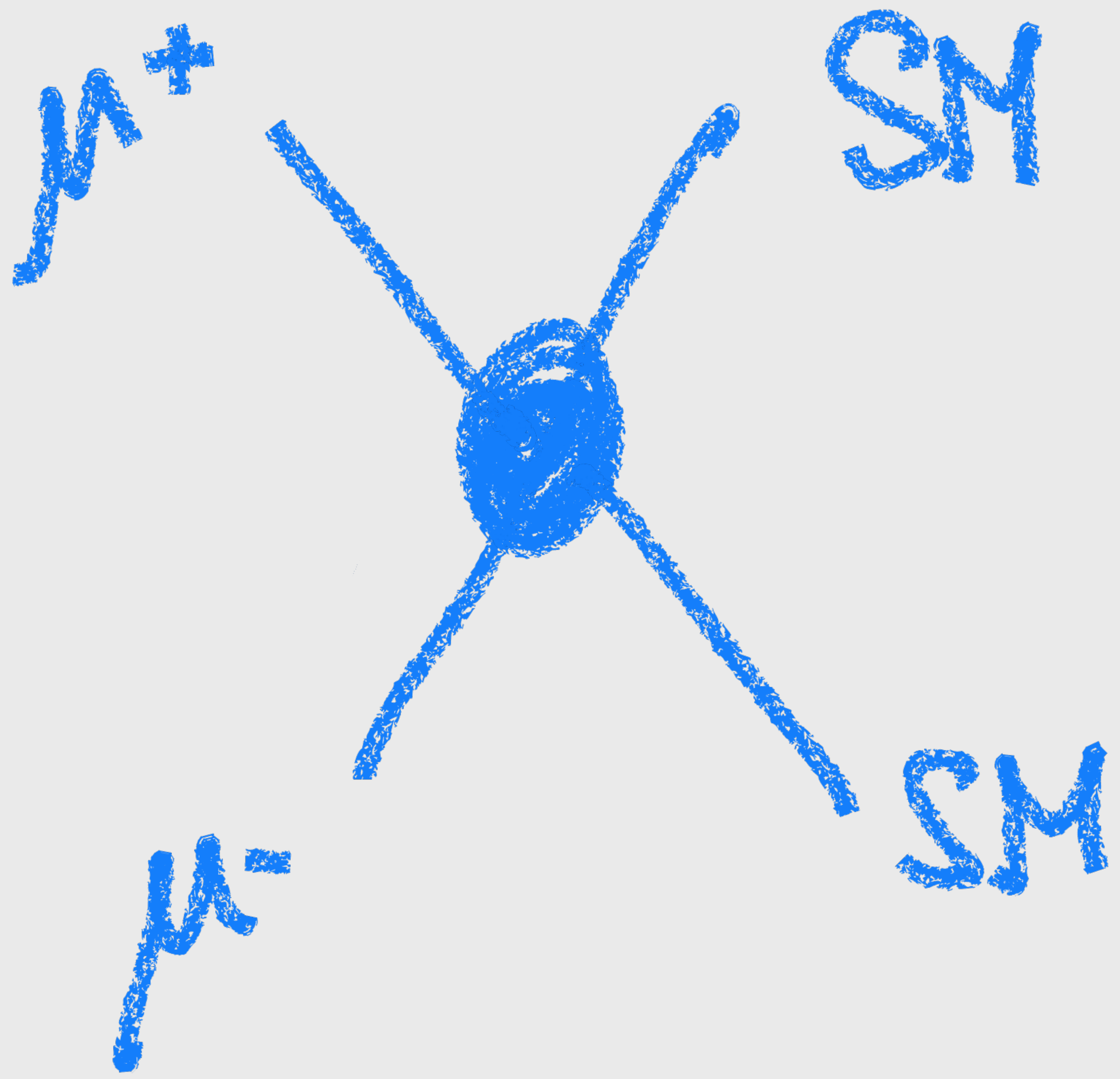


$m_\phi > 1.5$ TeV
for $\tan\beta < 4$ (most motivated range of the model)

$m_\sigma > 2$ TeV
for $m_\sigma/f > 1$ (most motivated range of the model)

at $\sqrt{s} \gg 100$ GeV

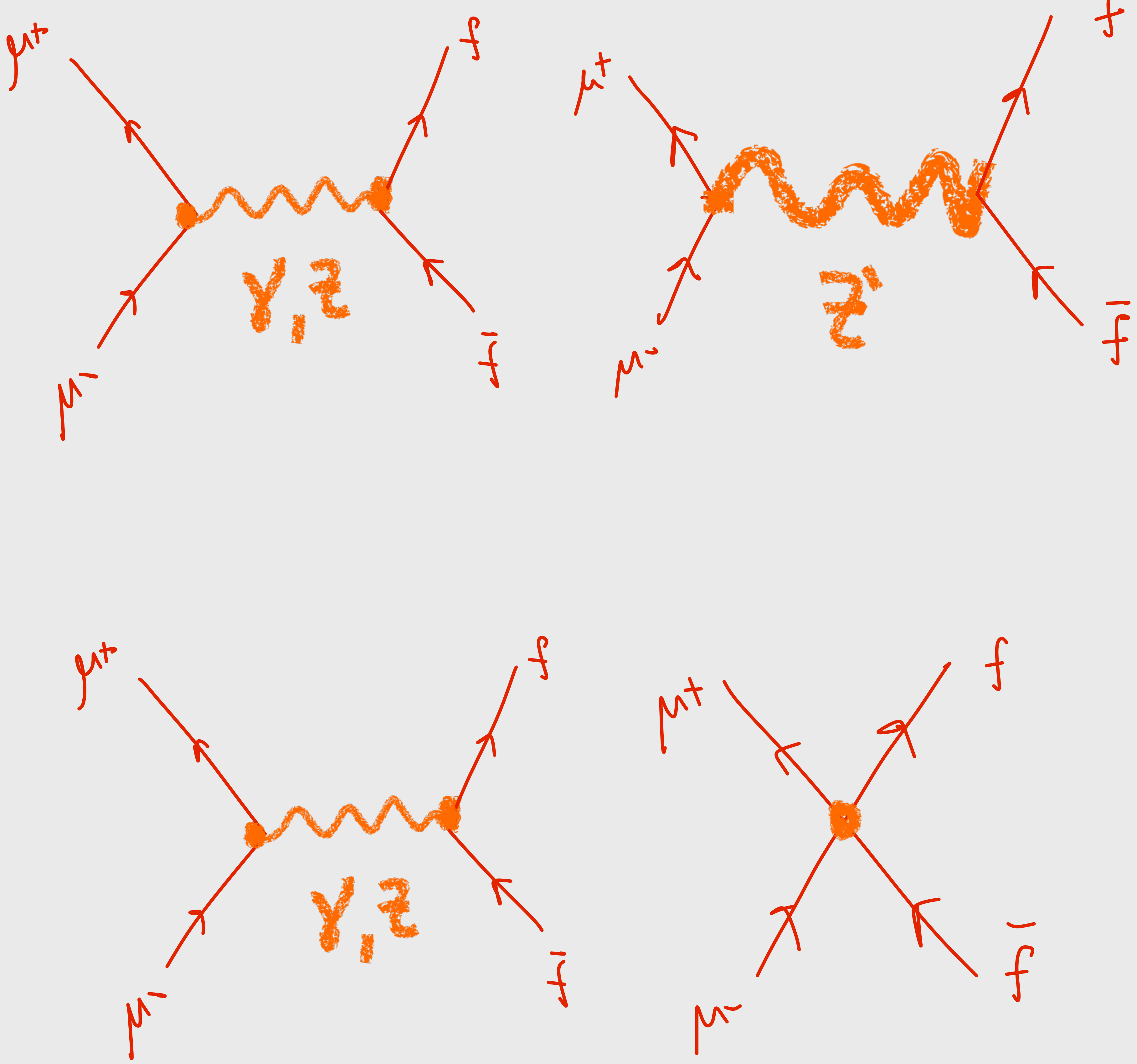
Indirect Effects

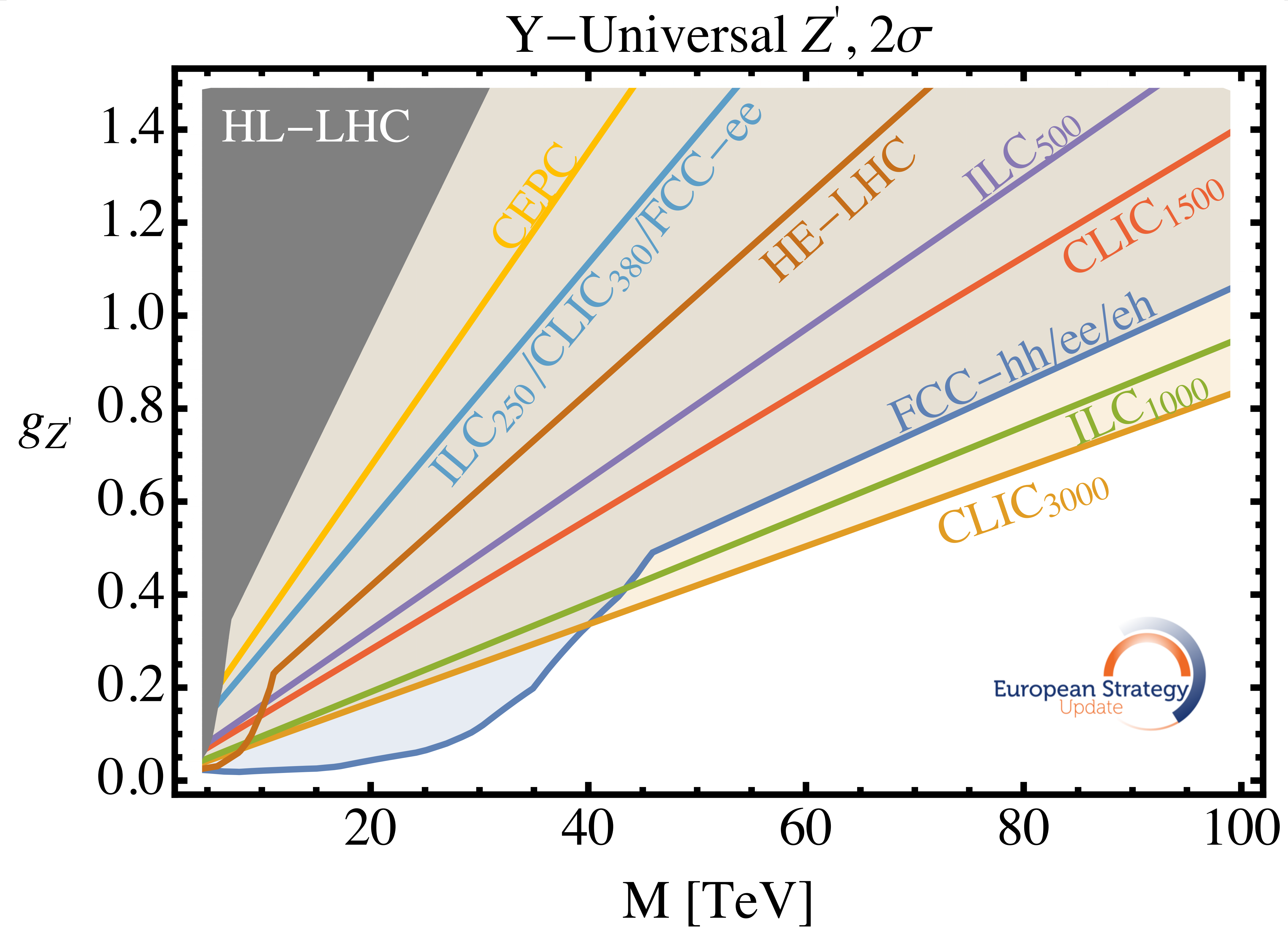


A heavy Z'

DRELL-YAN

RATES AND ANGULAR DISTRIBUTIONS





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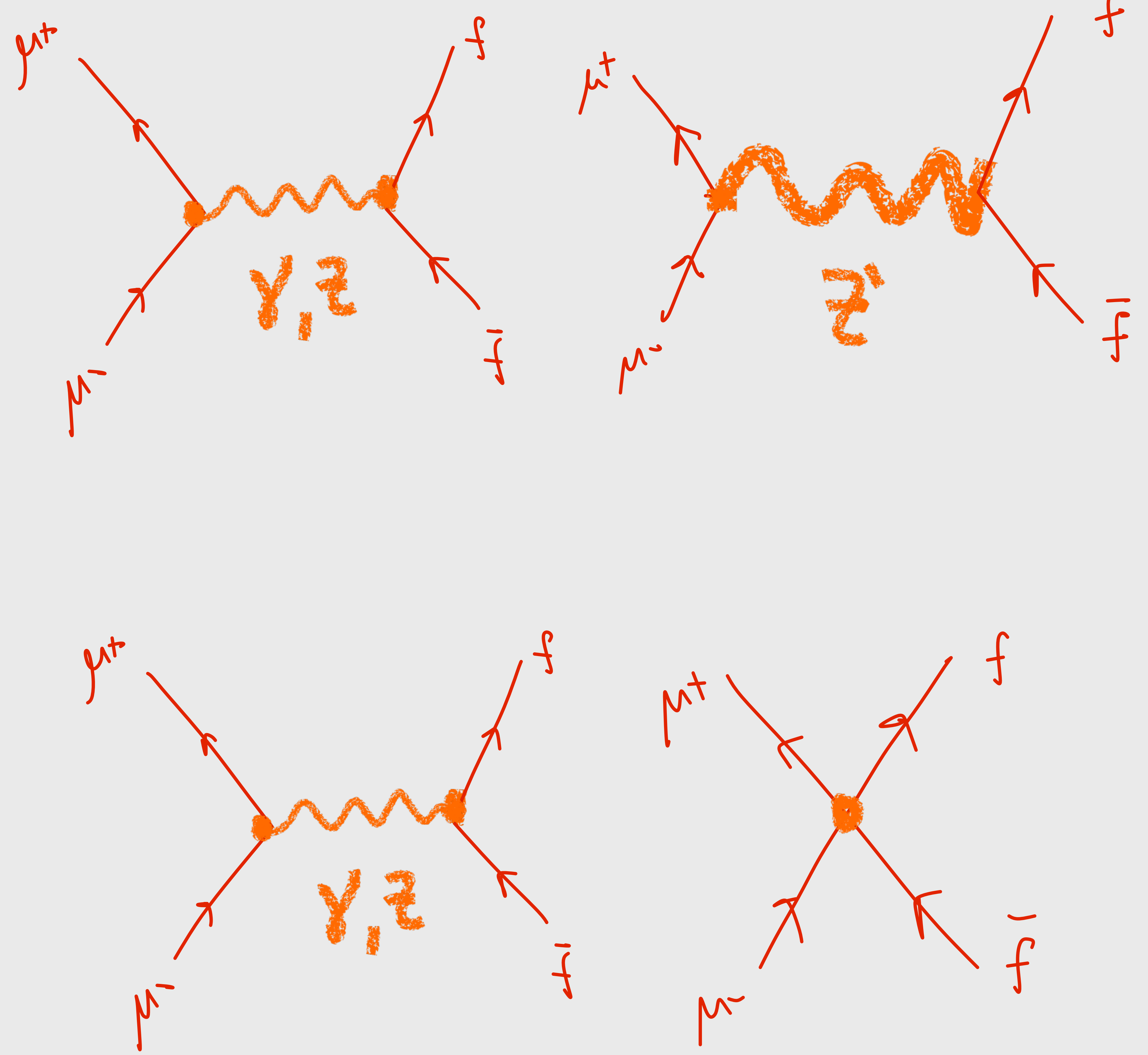

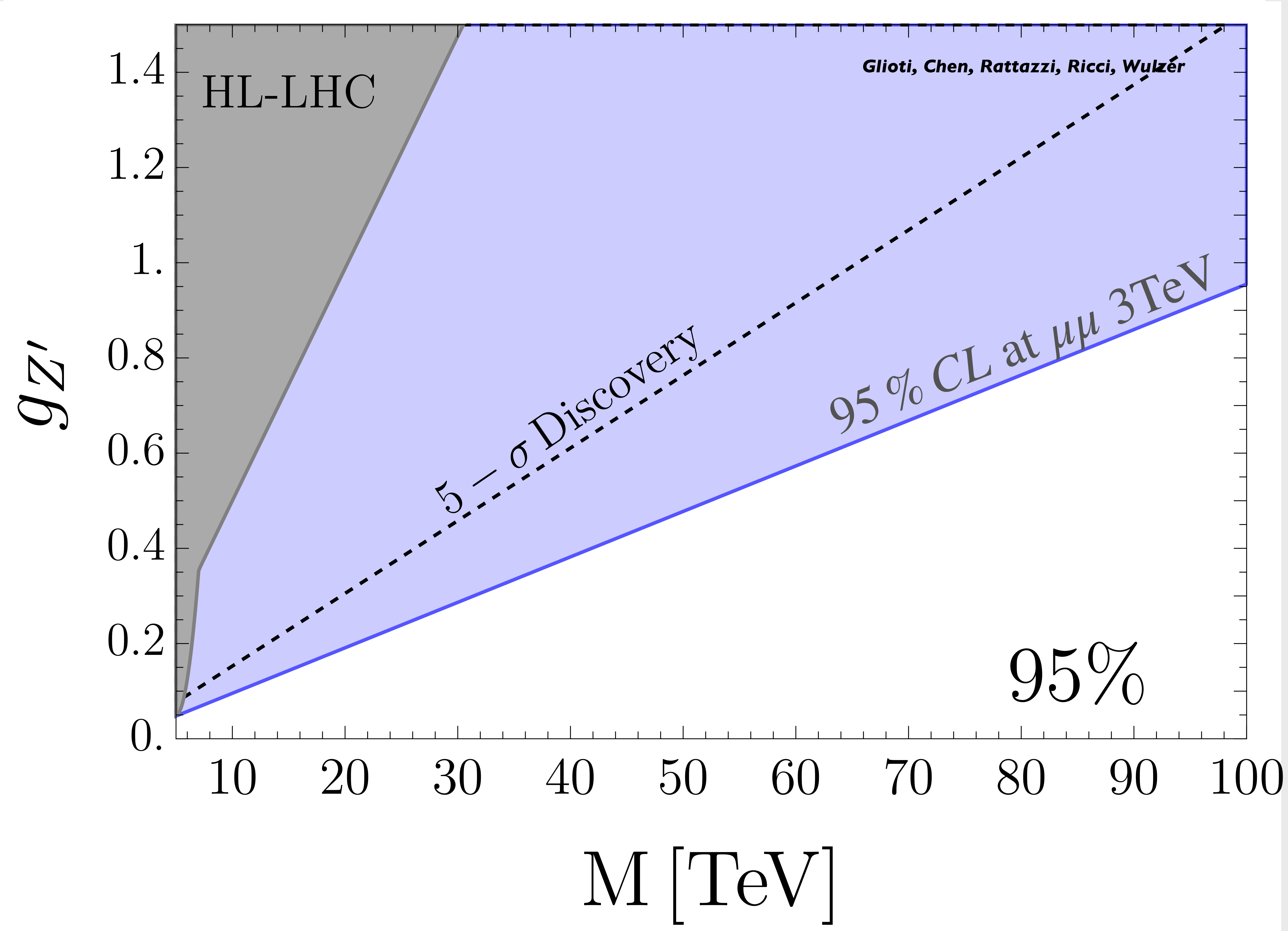

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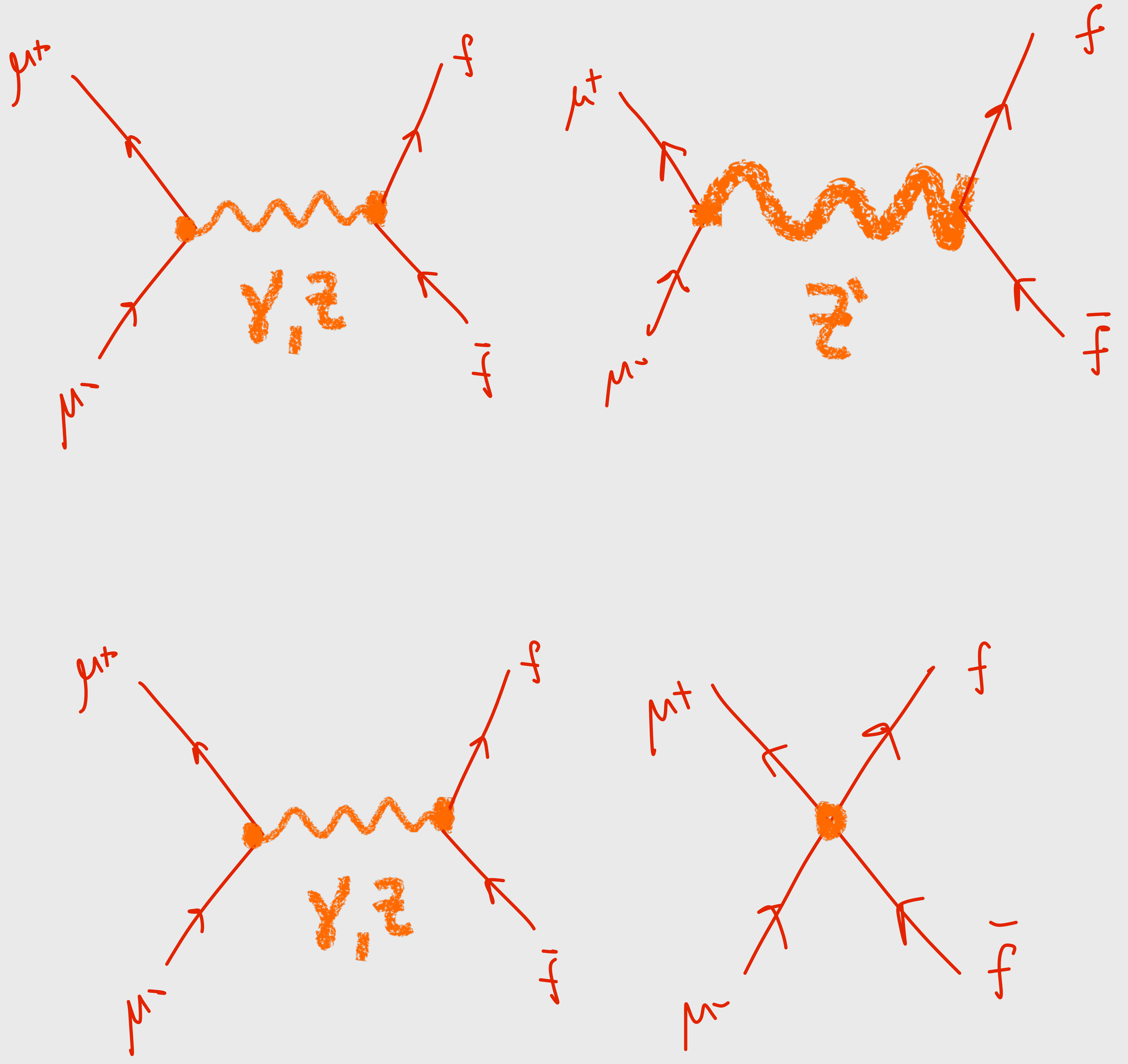
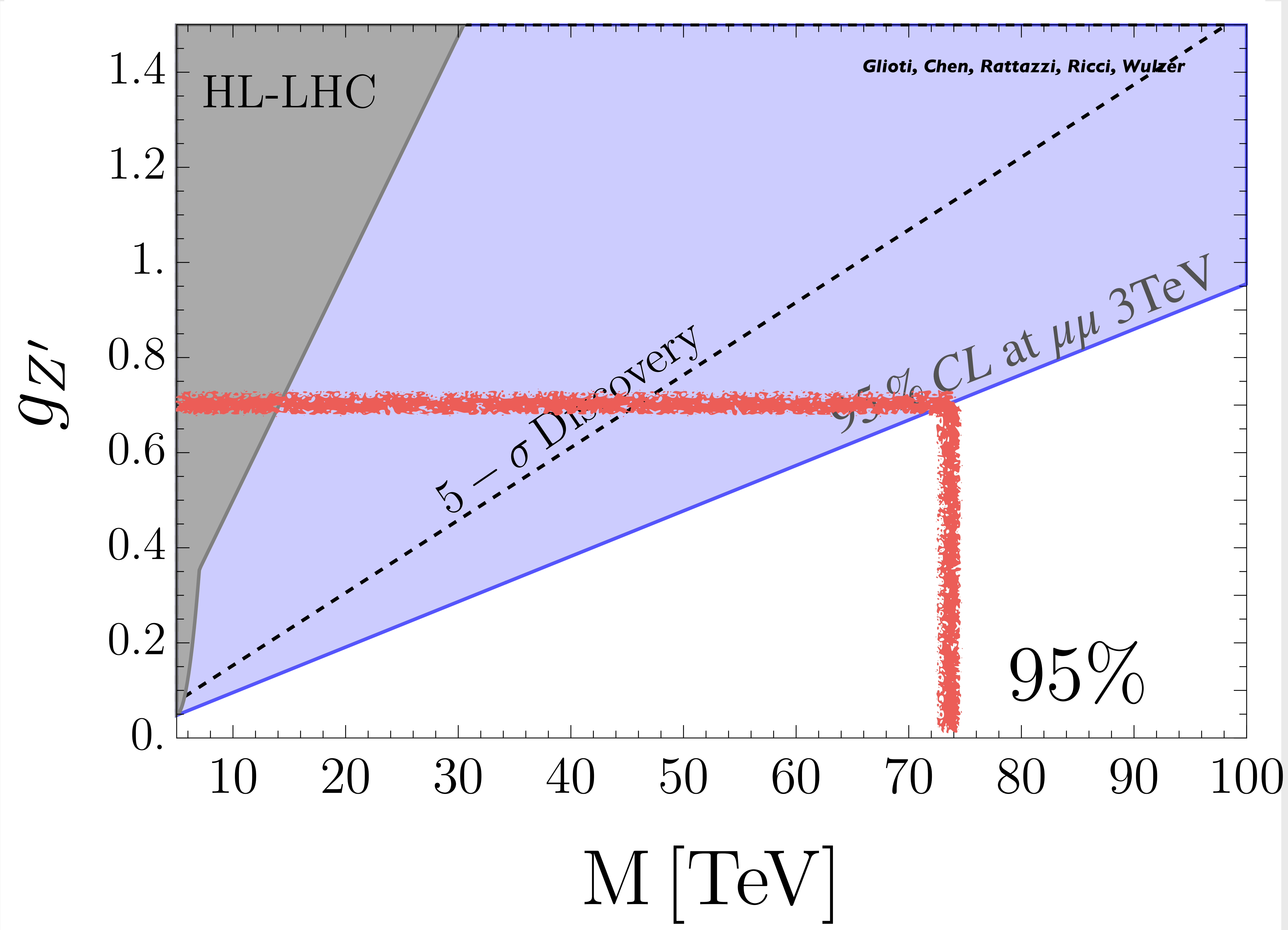


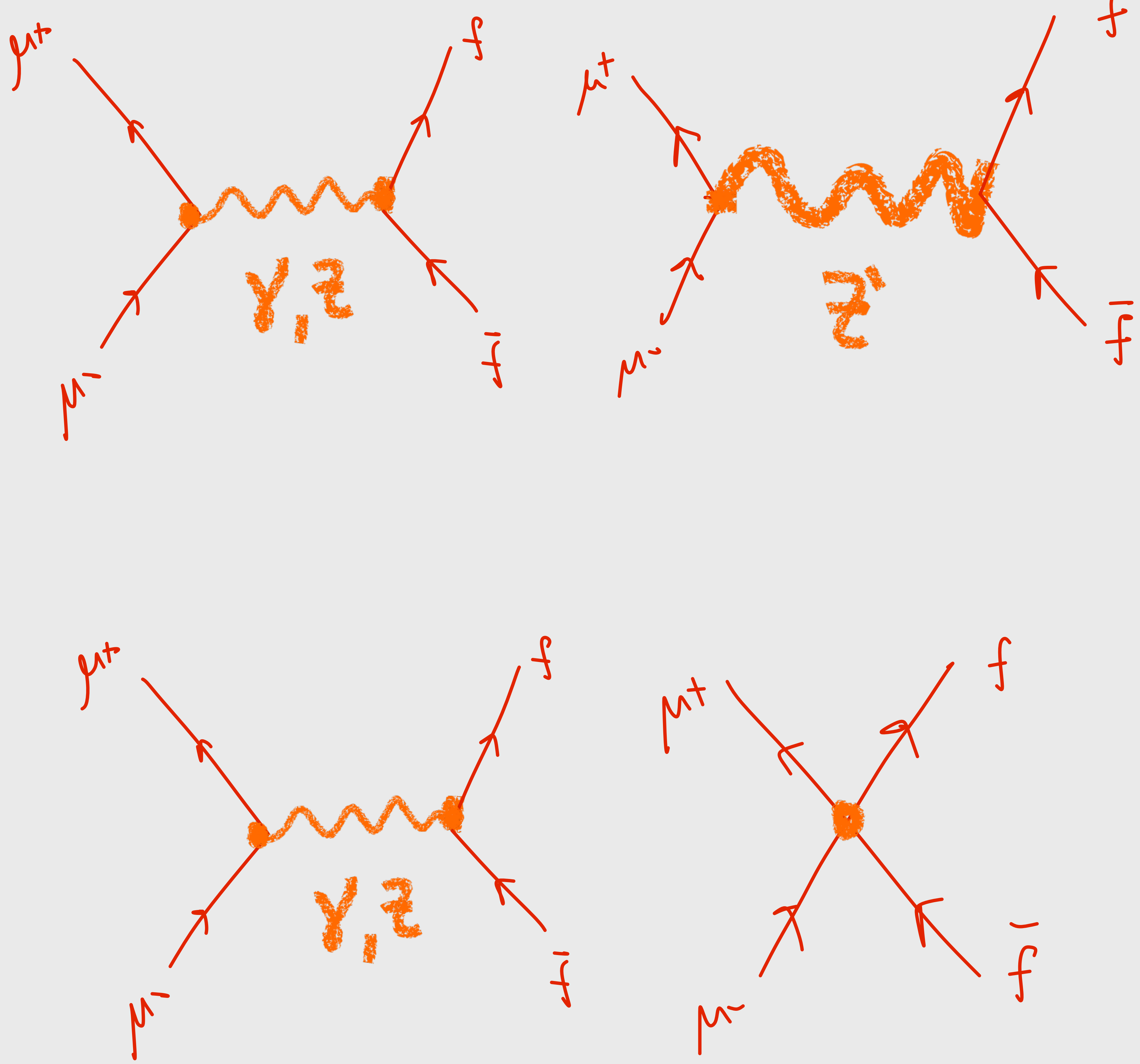


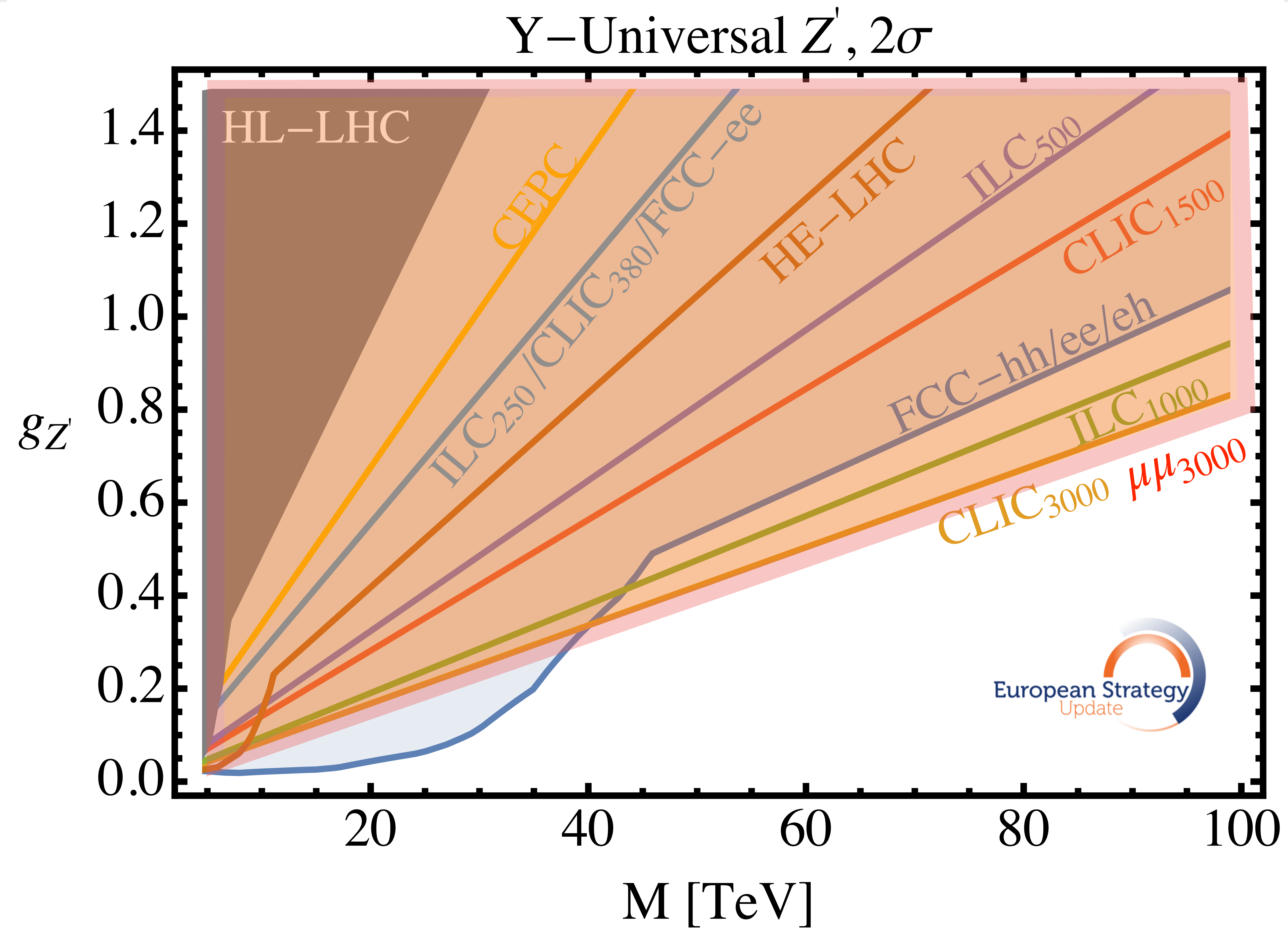
$\sqrt{s} \simeq 3$ TeV can probe 70+ TeV mass for $g_{Z'} \simeq g_{SM} \simeq 0.67$

A heavy Z'

DRELL-YAN

RATES AND ANGULAR DISTRIBUTIONS

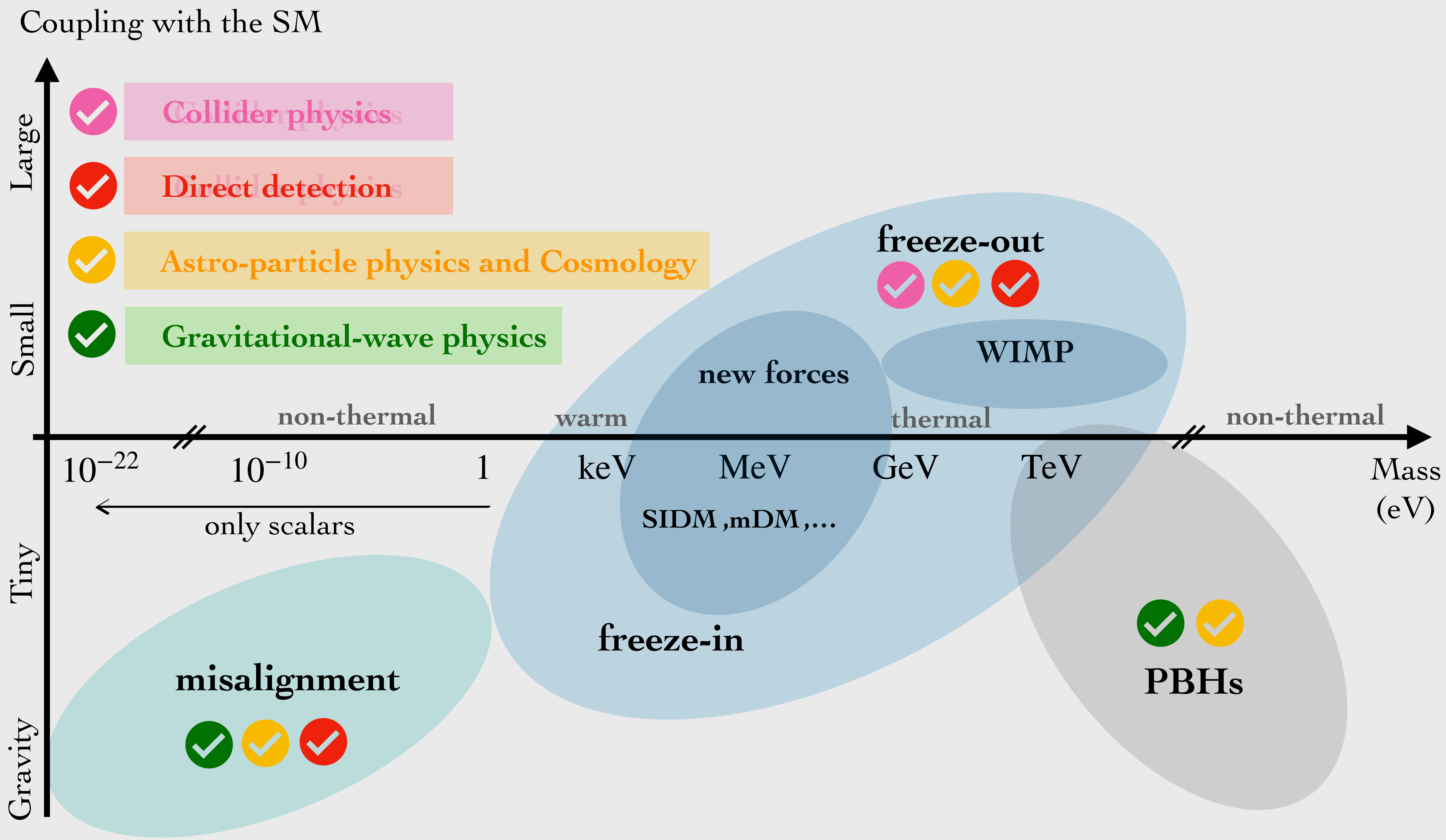


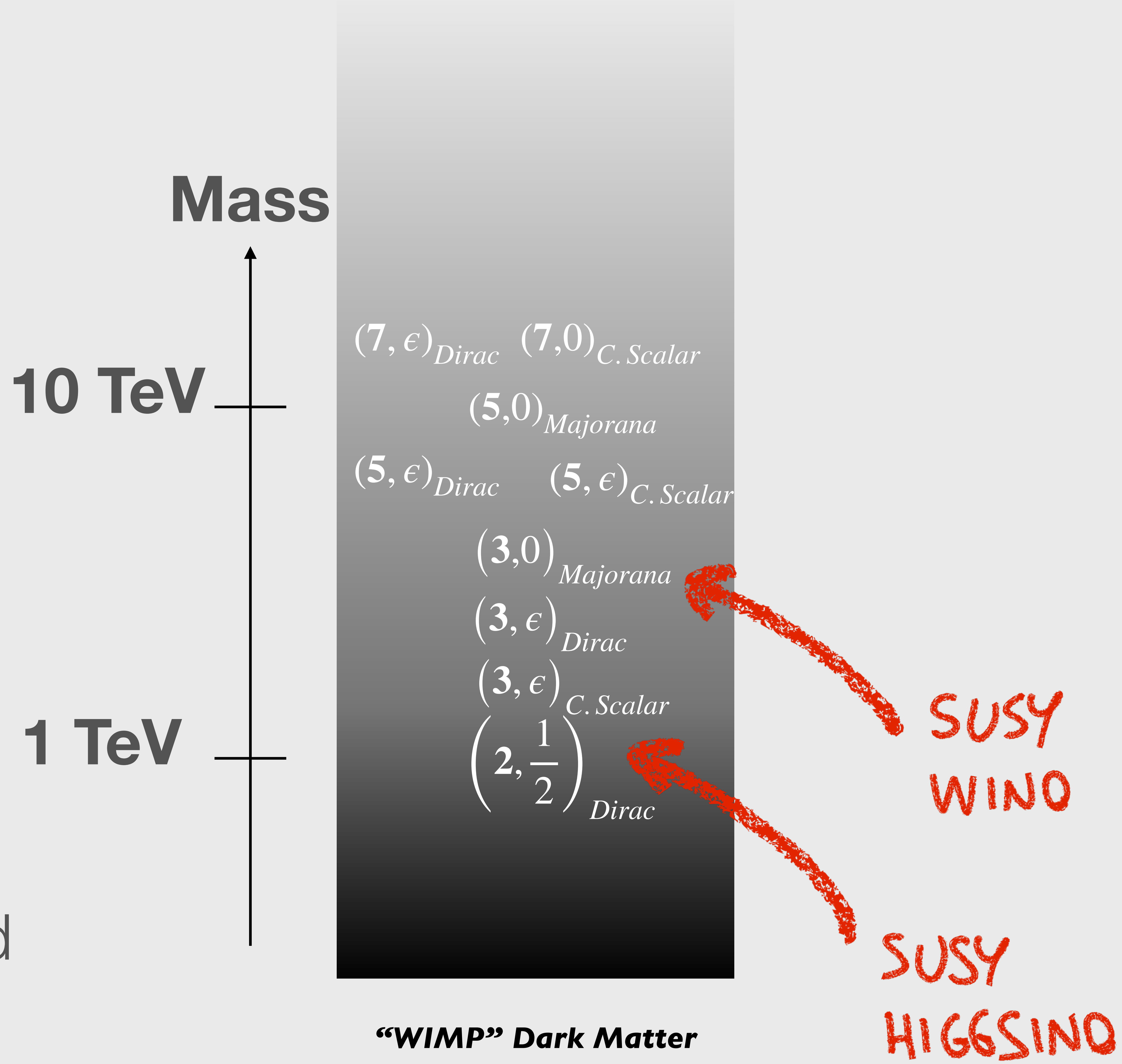


Dark Matter

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!





- High energy colliders are excellent and very robust probes of WIMPs!

Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra — Generic leptons+missing momentum

Co-annihilation — Soft-objects + missing momentum

GeV

WIMP-like multiplet
Accidental Dark Matter — Short (disappearing) tracks

DM SM singlet
$e^+e^- \rightarrow Z' \rightarrow \chi\,\chi$ — 0 — Mono-photon

Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet $e^+e^- \to Z' \to \chi\,\chi$	0	Mono-photon

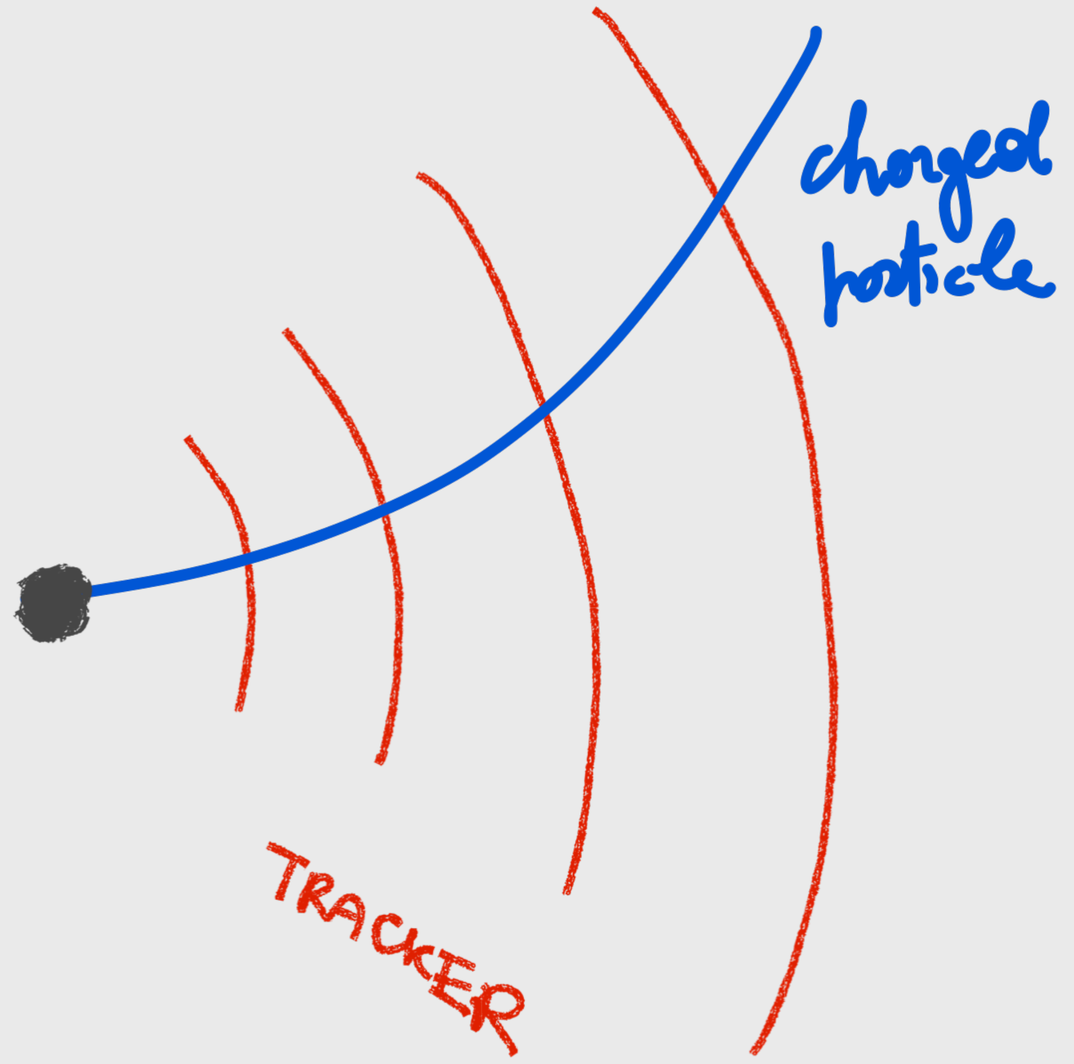
Precision Tests

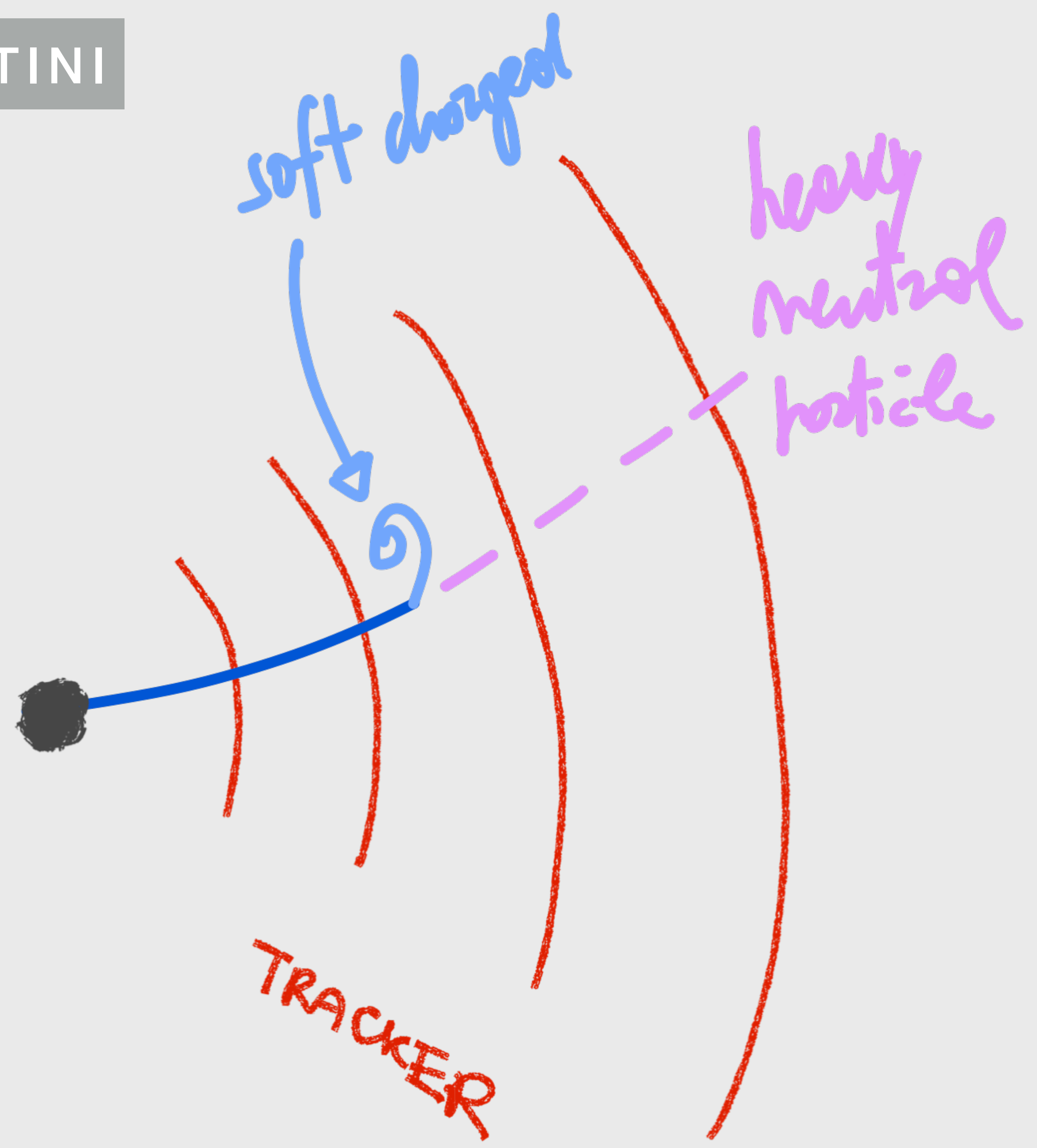
Higgsino DM

STUB-TRACKS

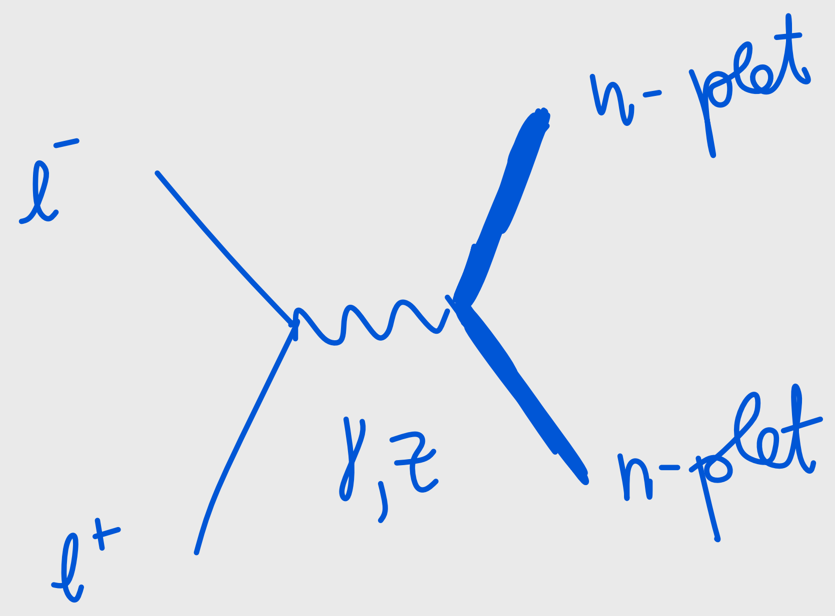
EXOTIC SIGNAL

NEXT TALK BY L. SESTINI

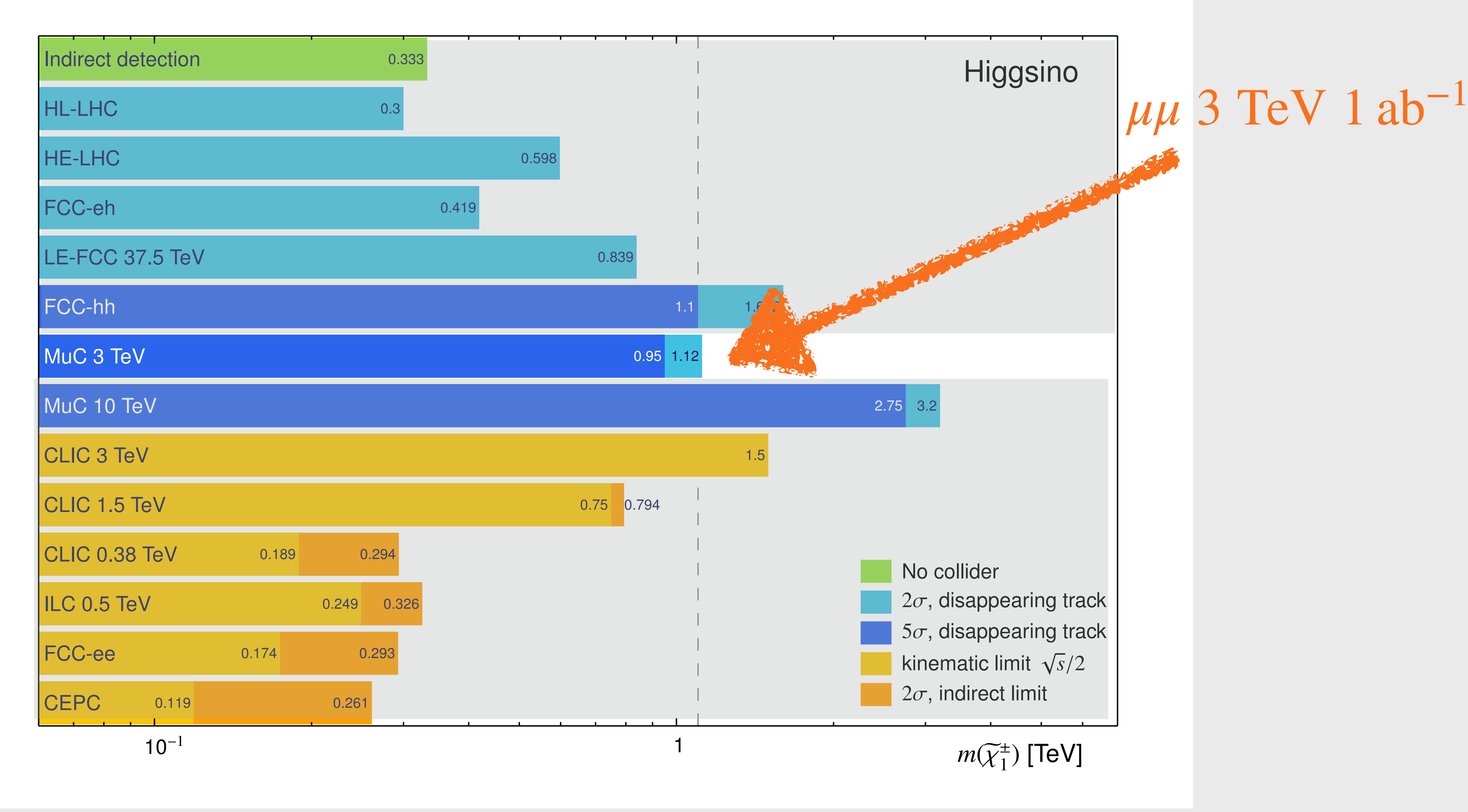




- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W m_W$ ~ 0.1 GeV - GeV



LARGE RATES, BUT NEEDS TO LIGHT UP THE DETECTOR IN A DISCERNIBLE WAY



Electroweak Dark Matter: LSP (+NLSP)

Δm

Wide open spectra	Generic leptons+missing momentum	Precision Tests
Co-annihilation	Soft-objects + missing momentum	
GeV		
WIMP-like multiplet Accidental Dark Matter	Short (disappearing) tracks	
DM SM singlet $e^+e^- \to Z' \to \chi\,\chi$	Mono-photon	
0		

Electroweak Dark Matter: LSP (+NLSP)

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	GeV	
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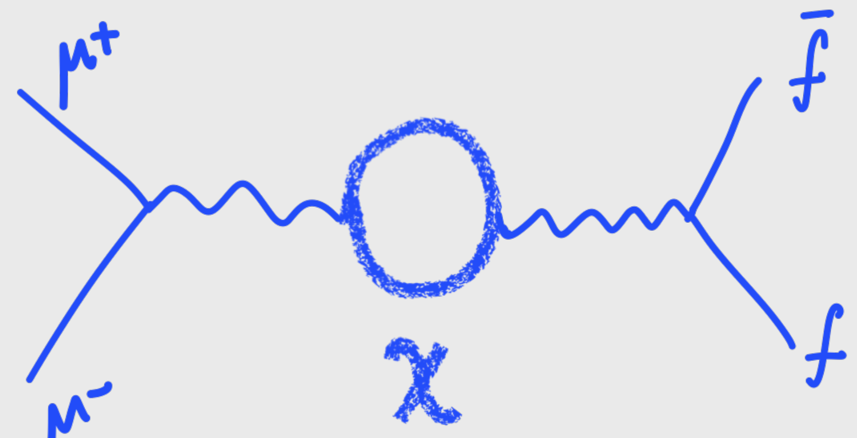
DM SM singlet $e^+e^- \to Z' \to \chi\,\chi$	0	Mono-photon

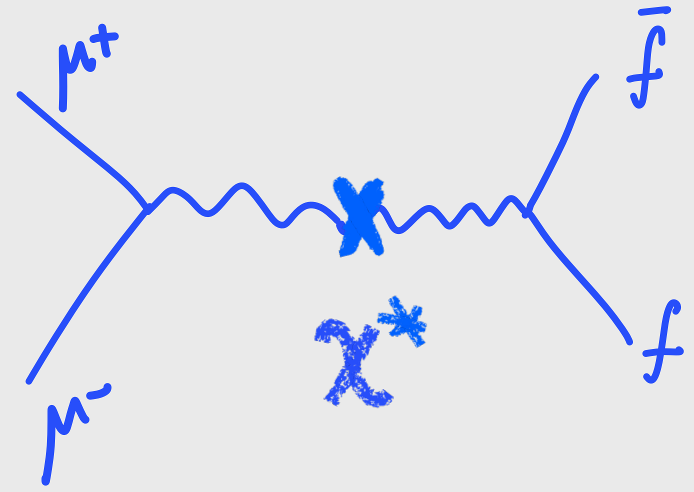
} Precision Tests

$\mu^+\mu^- \to f\bar{f}, W^+W^-$

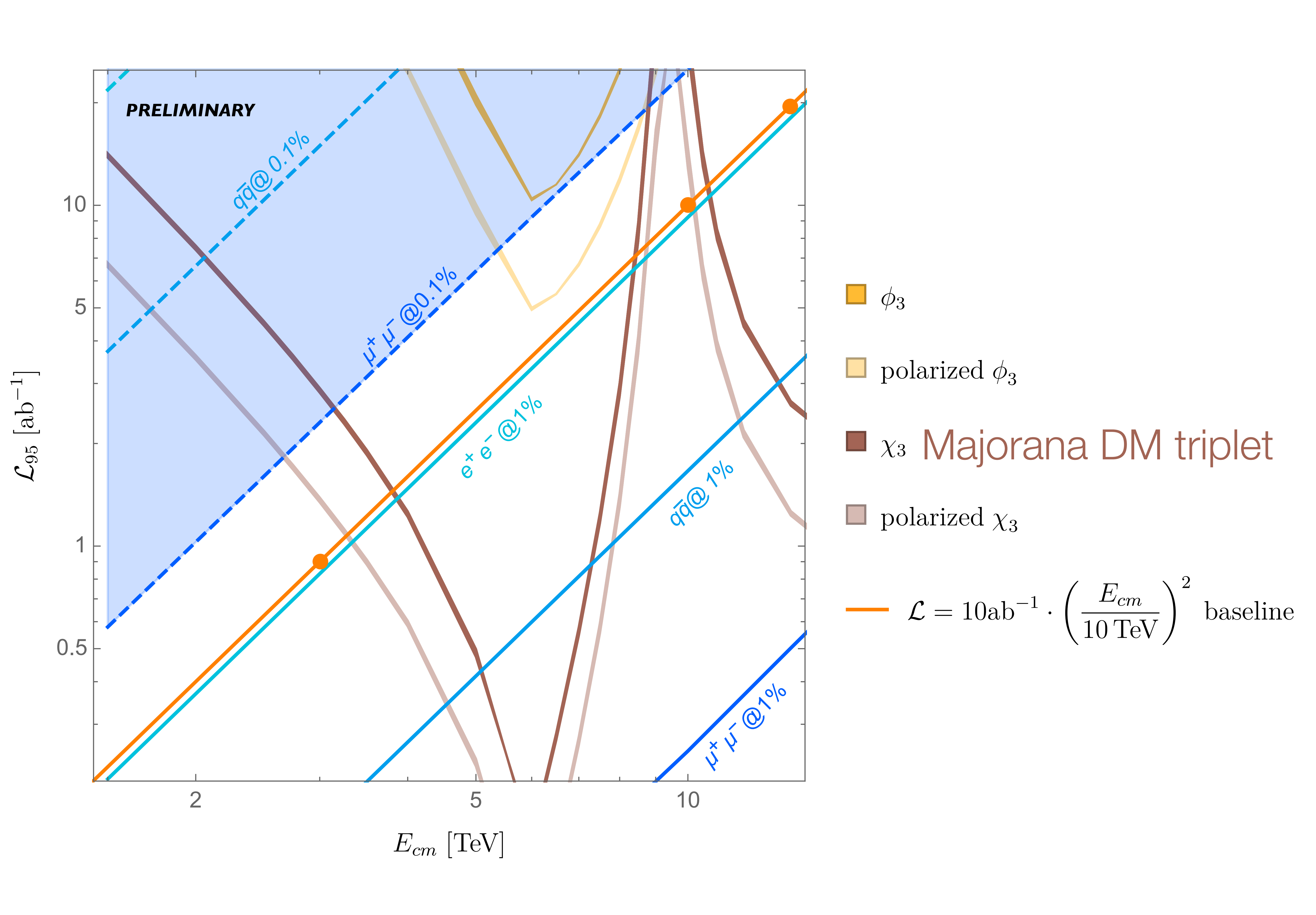
PRECISION TOTAL CROSS-SECTION



χ is heavy/light new physics

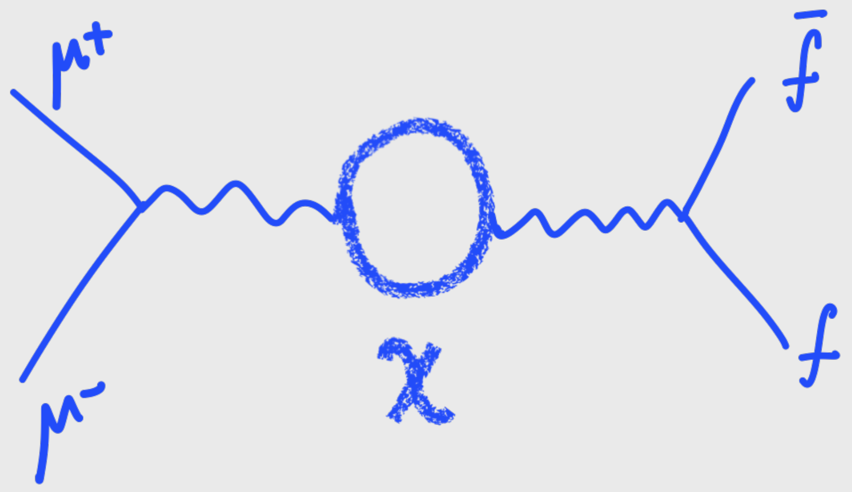


- fiducial cross-sections are significantly affected by off-shell new physics heavier than the collider kinematic reach



$\mu^+\mu^- \to f\bar{f}, W^+W^-$

PRECISION **TOTAL CROSS-SECTION**



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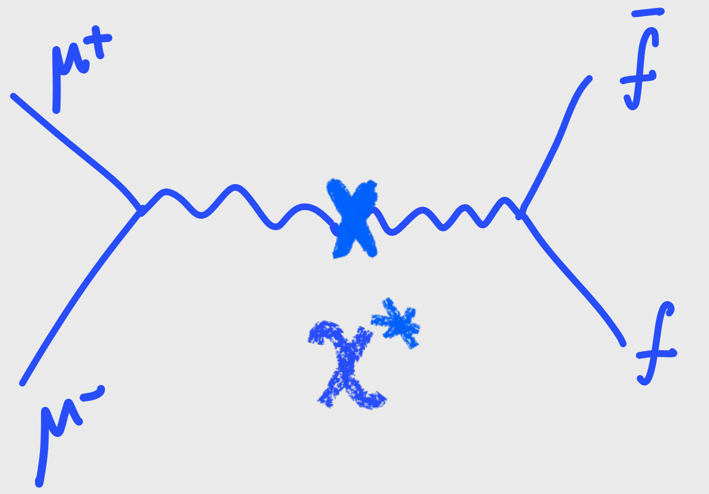

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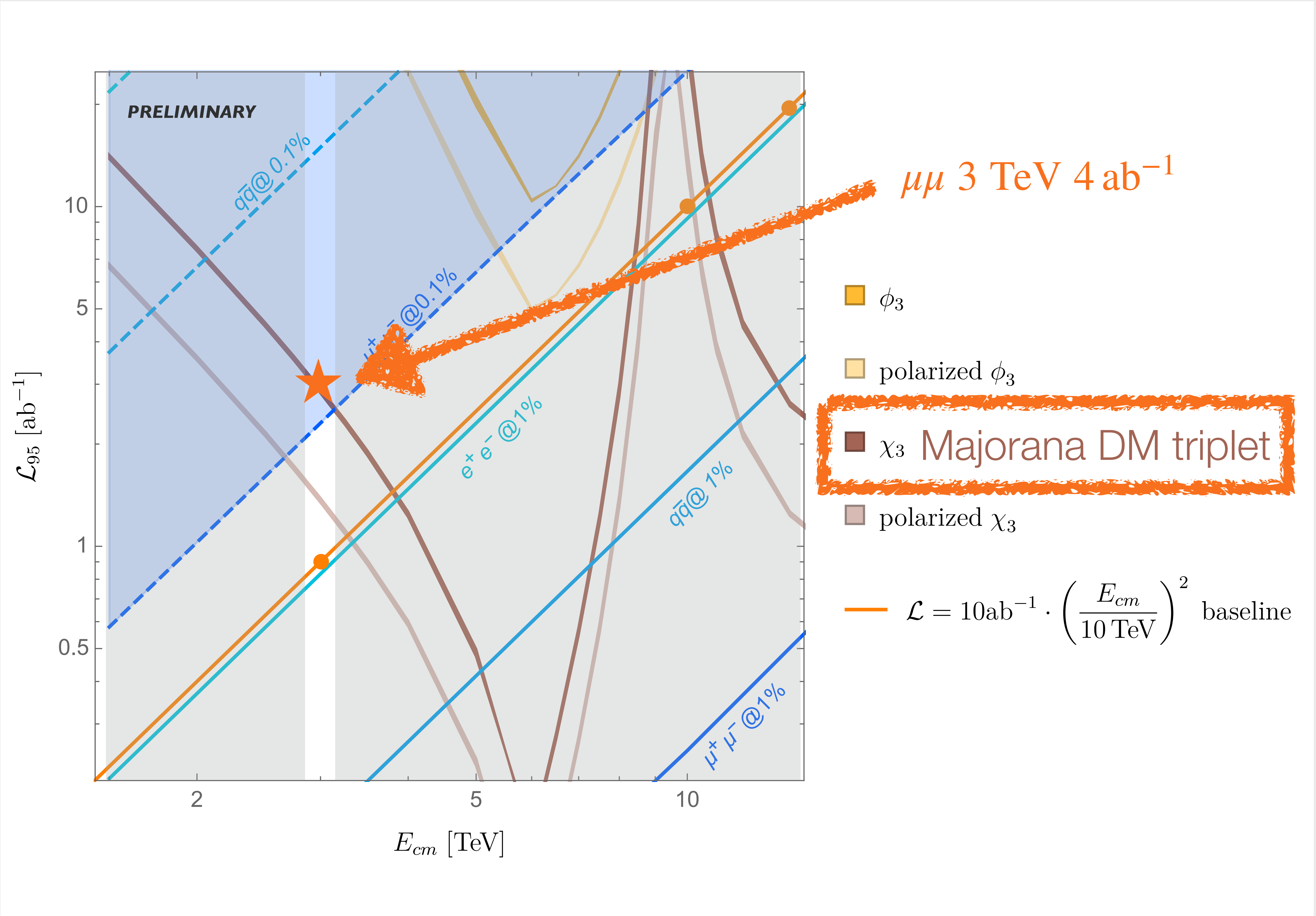
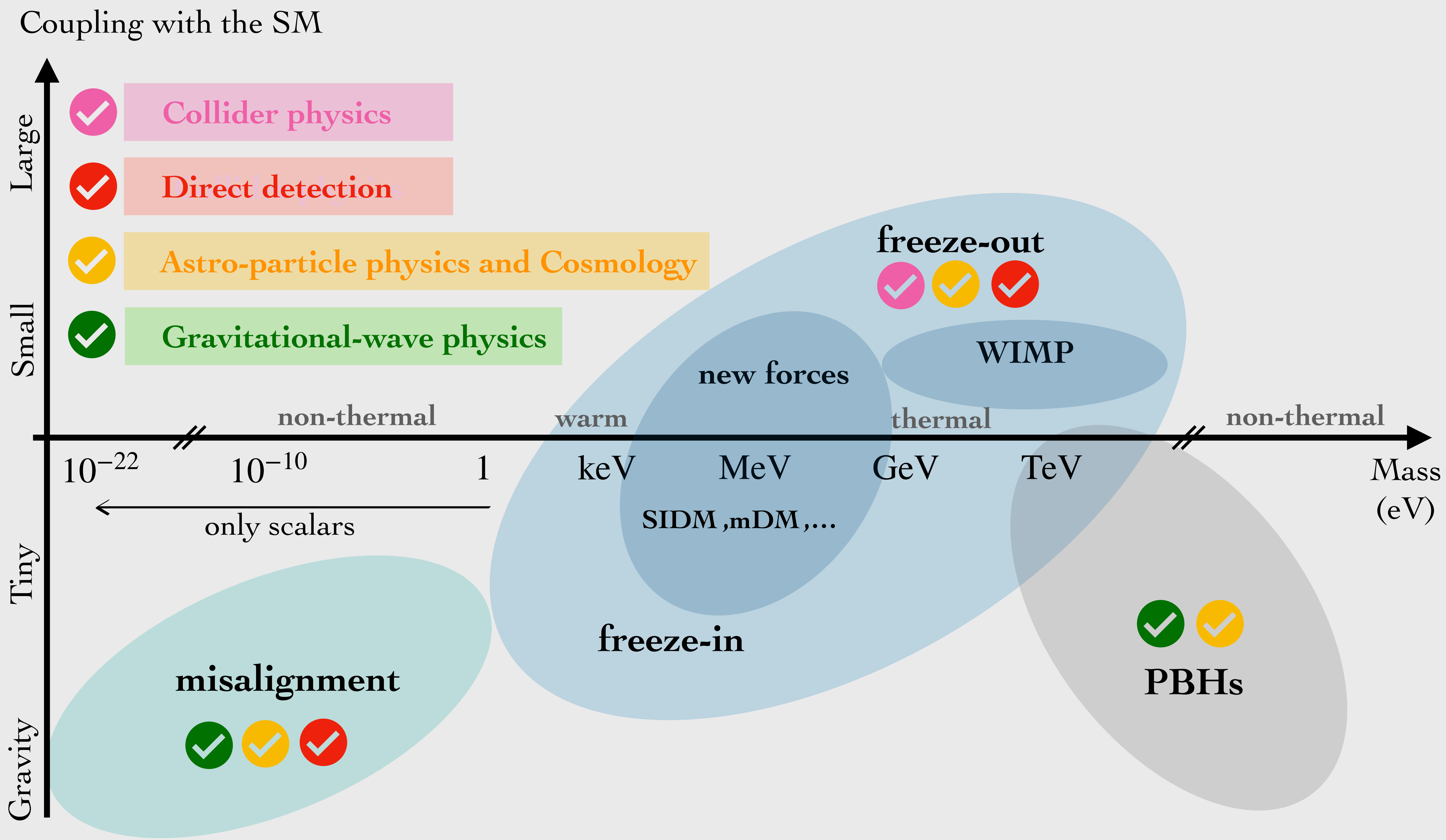
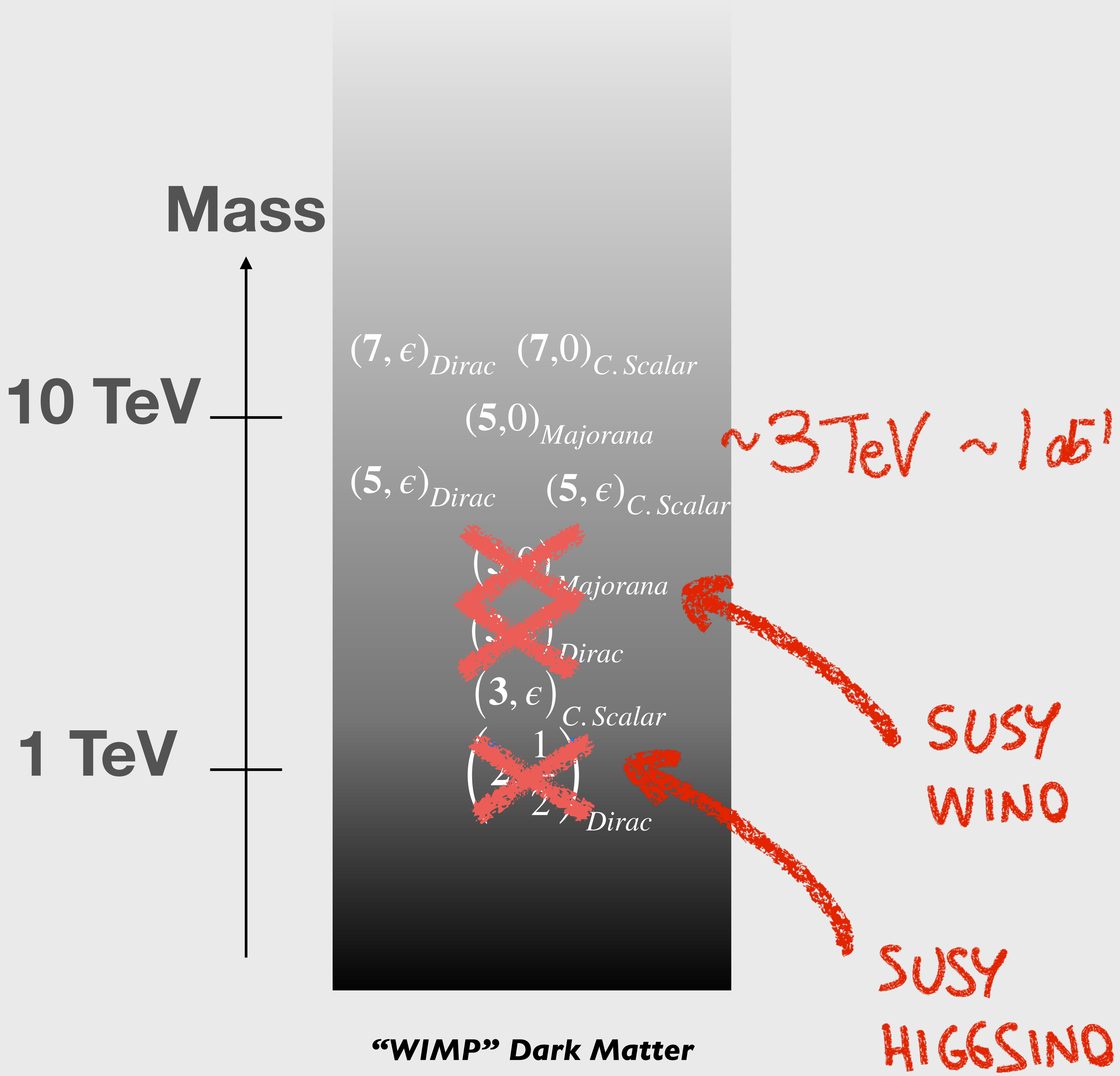


Electroweak Dark Matter: LSP (+NLSP)





Electroweak symmetry breaking

Big picture questions:

- Extended Higgs Sector
  back to “valence” muon collisions
  and direct production of new physics

- Higgs compositeness

Electroweak symmetry breaking

Big picture questions:

- Extended Higgs Sector

  back to "valence" muon collisions
  and direct production of new physics

- Higgs compositeness

“The size of the Higgs boson”

it matters because being “point-like” is the source of all the theoretical questions on the Higgs boson and weak scale

… and if it is not … well, that is physics beyond the Standard Model!

Effects of the size of the Higgs boson

h ~ π STRONGLY INTERACTING LIGHT HIGGS

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$

$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star / m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

Effects of the size of the Higgs boson

h ~ π

STRONGLY INTERACTING LIGHT HIGGS

$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$
$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$
$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$
$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

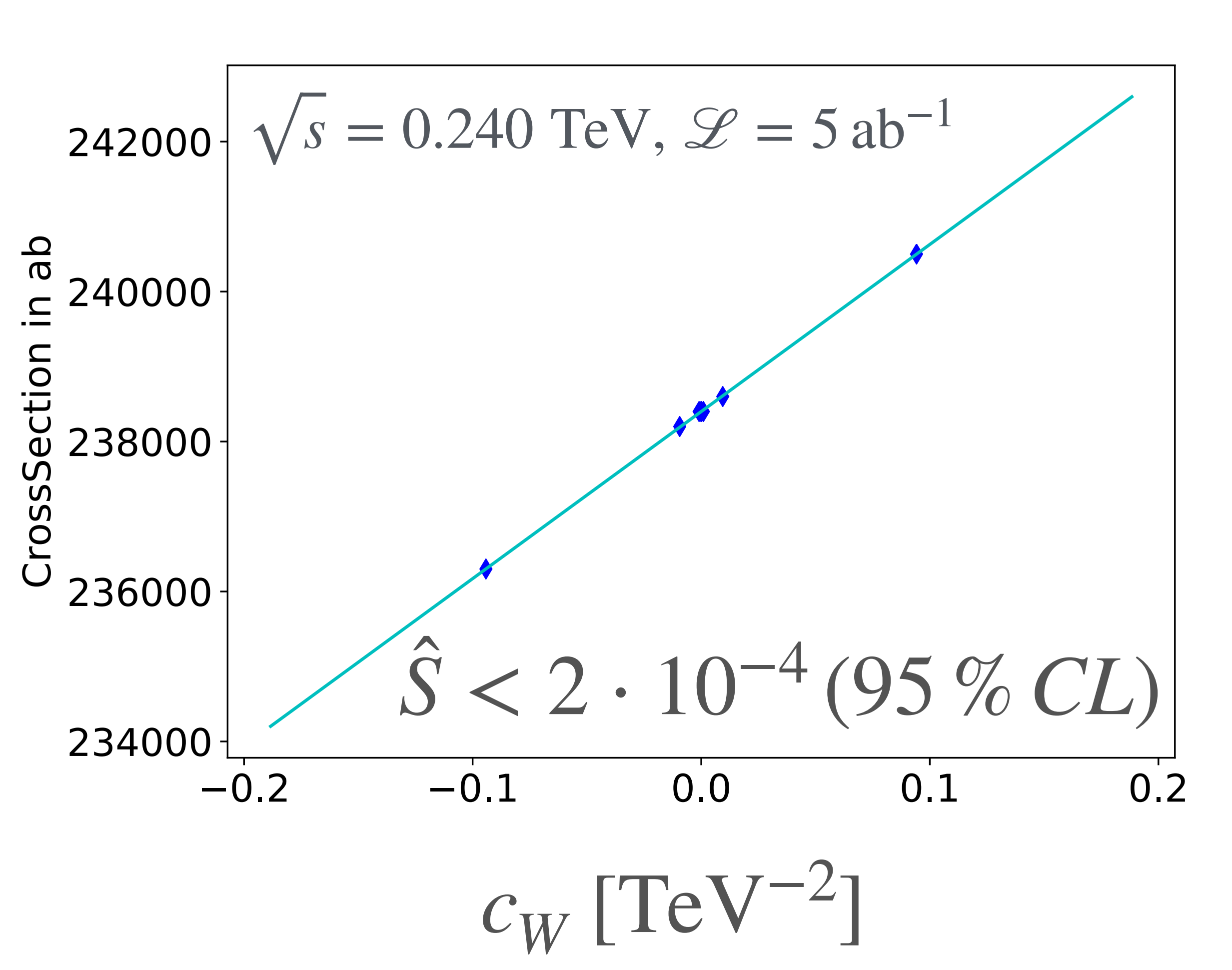
$\ell_{Higgs} \sim 1/m_\star$

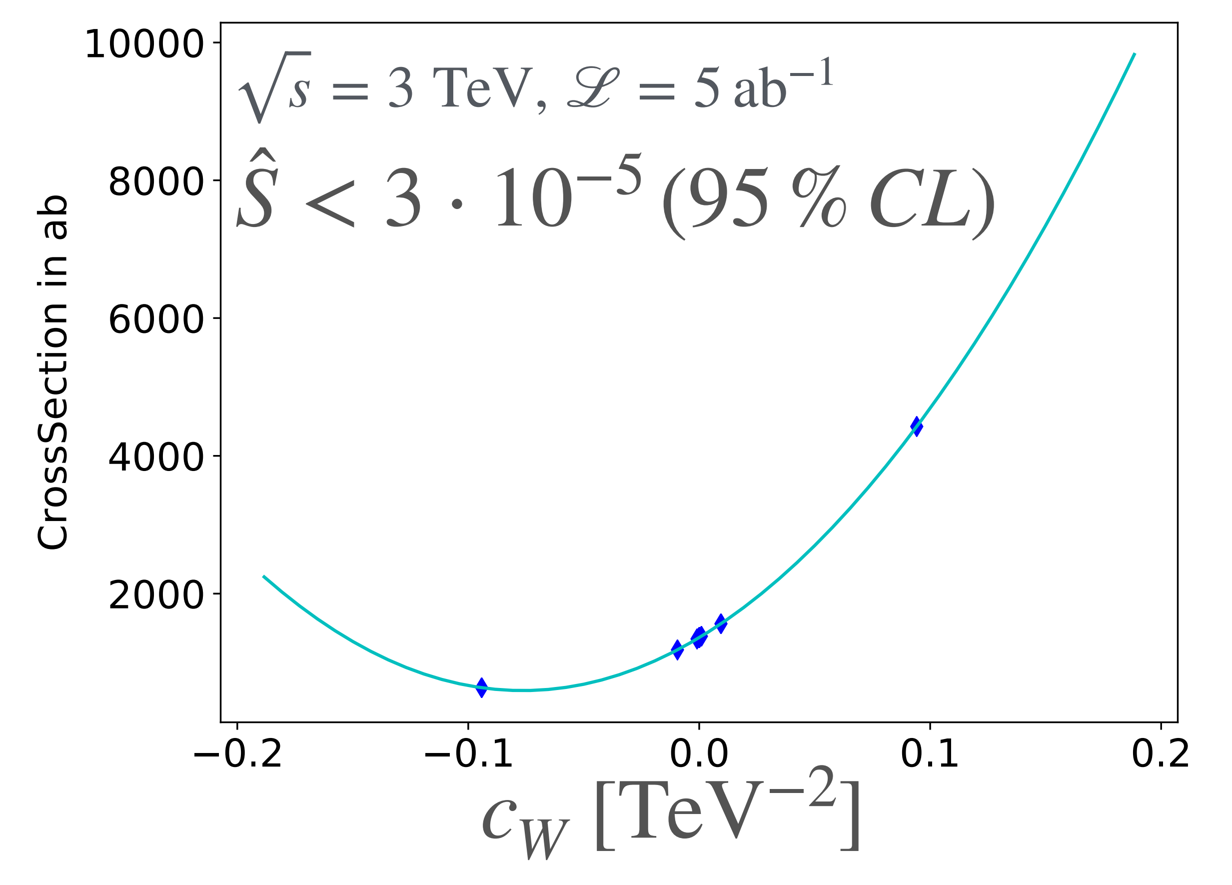
$\mu^+\mu^- \to Zh$

TOTAL RATE

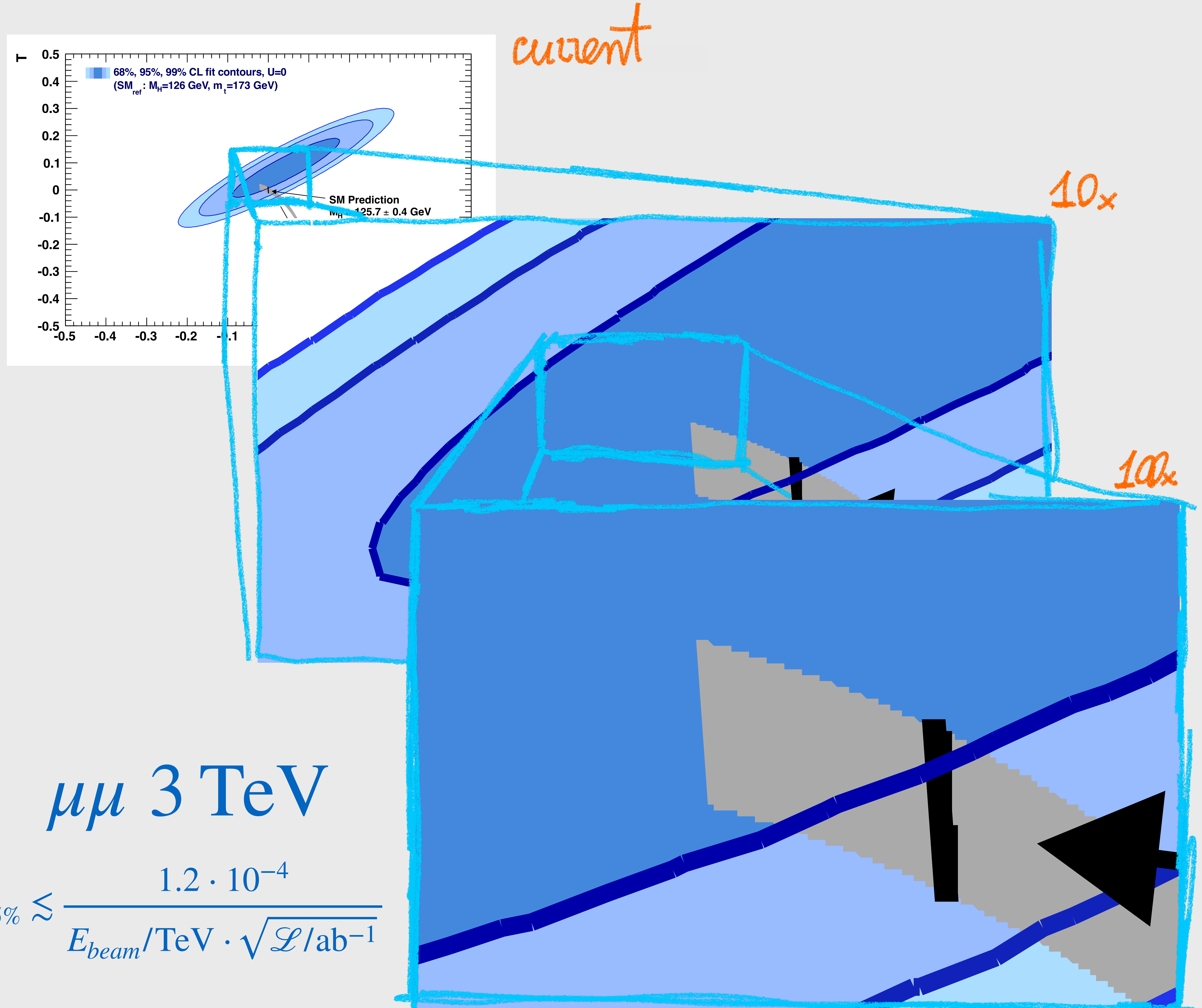
$$\sigma_{Zh} = \left|A_{SM}^{(00)}\right|^2 + A_{SM}^{00}\cdot A_{BSM}^{00} + \ldots$$

$c_W = \hat{S}/m_W^2$





LEP



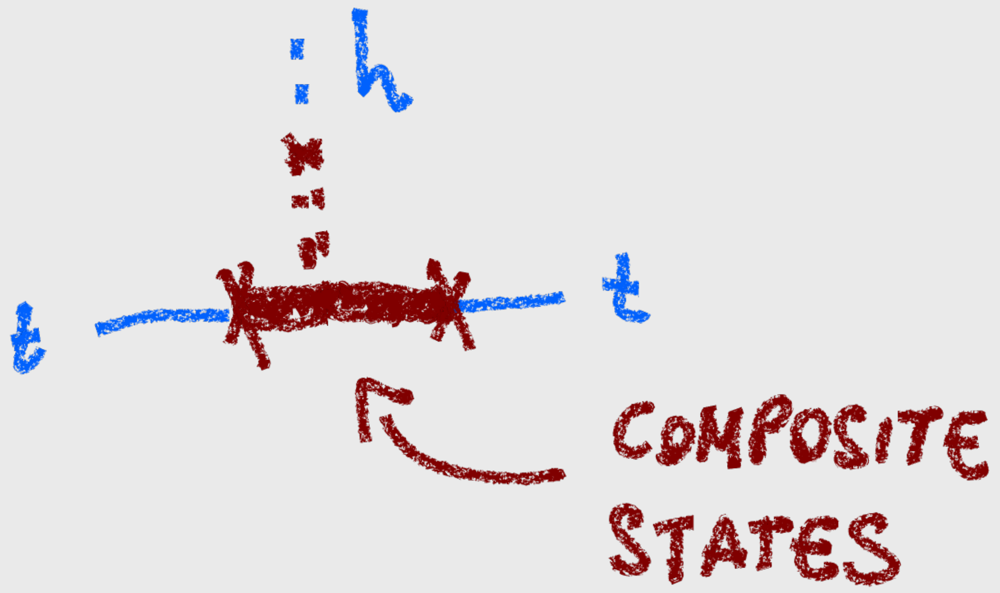
$\mu\mu$ 3 TeV

$$\hat{S}_{95\%} \lesssim \frac{1.2\cdot 10^{-4}}{E_{beam}/\text{TeV}\cdot\sqrt{\mathscr{L}/ab^{-1}}}$$

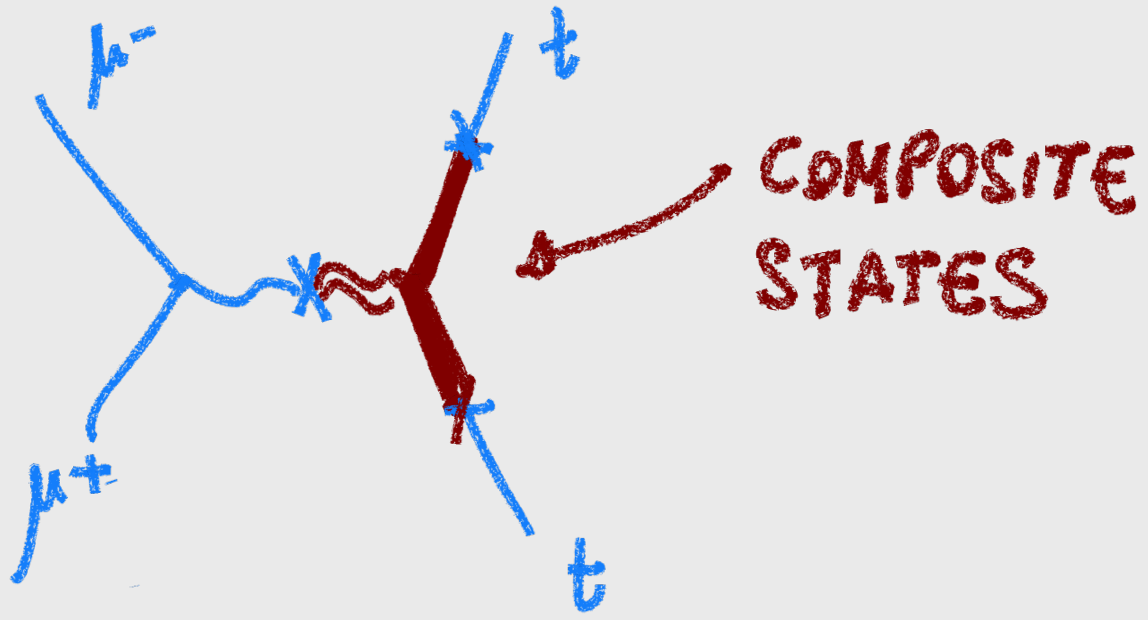
Effects of the size of the top quark

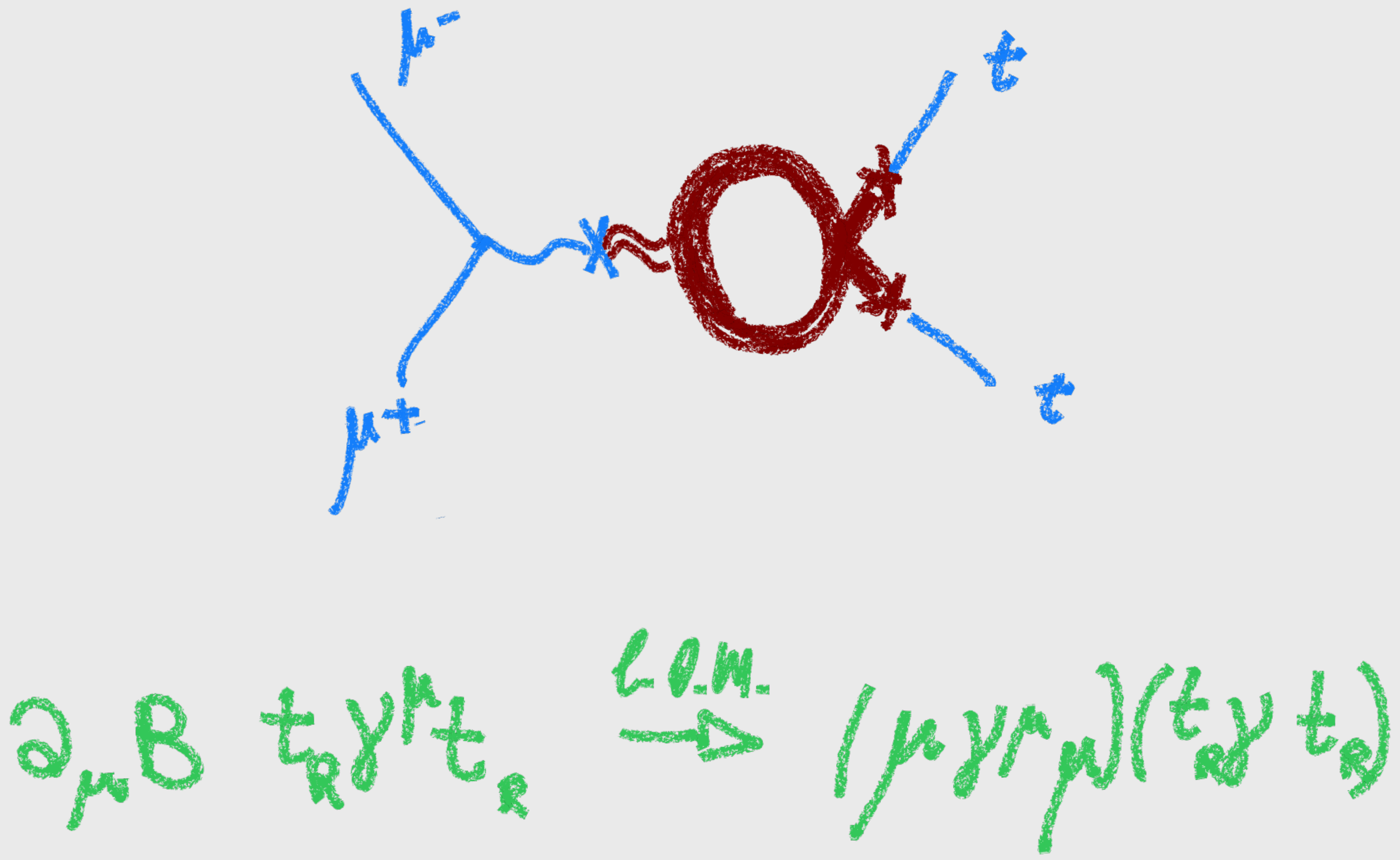
STRONGLY INTERACTING TOP AND HIGGS

- Top quarks are naturally involved in a composite Higgs sector.



- $t\bar{t}$ final states contain new information not present in generic $f\bar{f}$ Drell-Yan

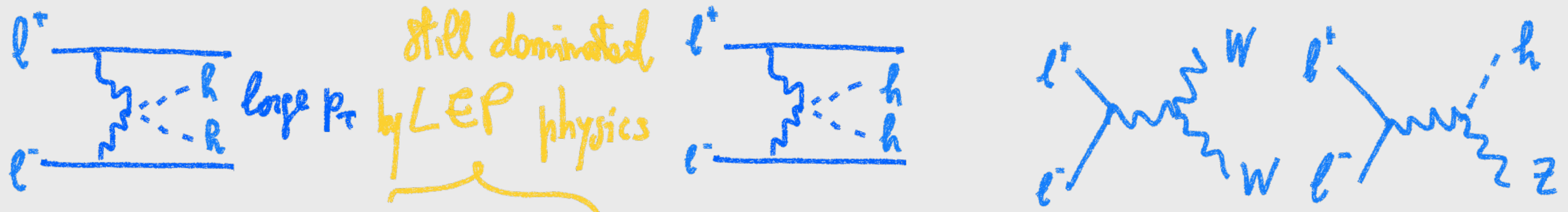




- enhanced $\mu\bar{\mu}t\bar{t}$ contact interaction!

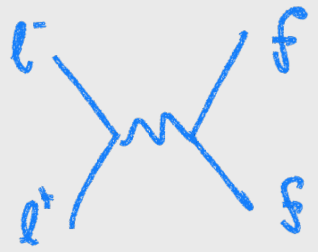
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W\mathcal{O}_W + c_B\mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW}+c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB}+c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3!\, g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$

$1/f \sim g_\star/m_\star$

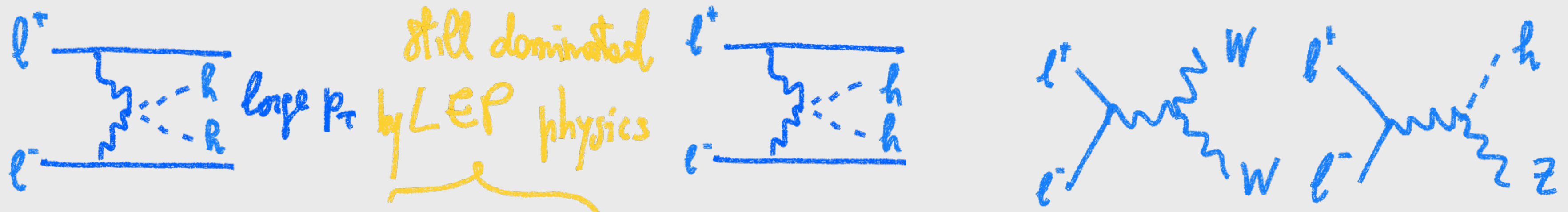
$1/(g_\star f) \sim 1/m_\star$

$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

$\ell_{top} \sim 1/m_\star \sim \ell_{Higgs}$

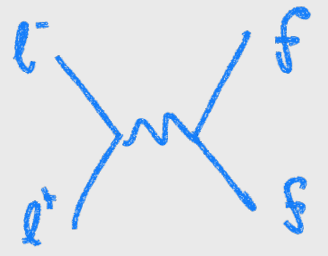
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



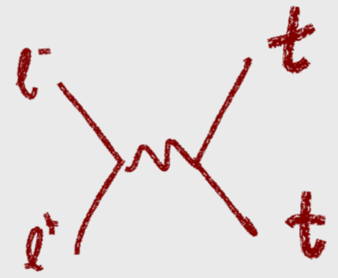
$$\mathcal{L}^{d=6}_{universal} = c_H \frac{g_*^2}{m_*^2}\mathcal{O}_H + c_T \frac{N_c \epsilon_q^4 g_*^4}{(4\pi)^2 m_*^2}\mathcal{O}_T + c_6 \lambda \frac{g_*^2}{m_*^2}\mathcal{O}_6 + \frac{1}{m_*^2}\left[c_W \mathcal{O}_W + c_B \mathcal{O}_B\right]$$

$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



$$+ \frac{1}{g_*^2 m_*^2}\left[c_{2W} g^2 \mathcal{O}_{2W} + c_{2B} g'^2 \mathcal{O}_{2B}\right] + c_{3W}\frac{3! g^2}{(4\pi)^2 m_*^2}\mathcal{O}_{3W}$$

$$+ c_{y_t}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_t} + c_{y_b}\frac{g_*^2}{m_*^2}\mathcal{O}_{y_b}$$



$$+ c_{tD}\frac{g_*^2}{m_*^2}\mathcal{O}_{tD}$$

$1/f \sim g_\star/m_\star$

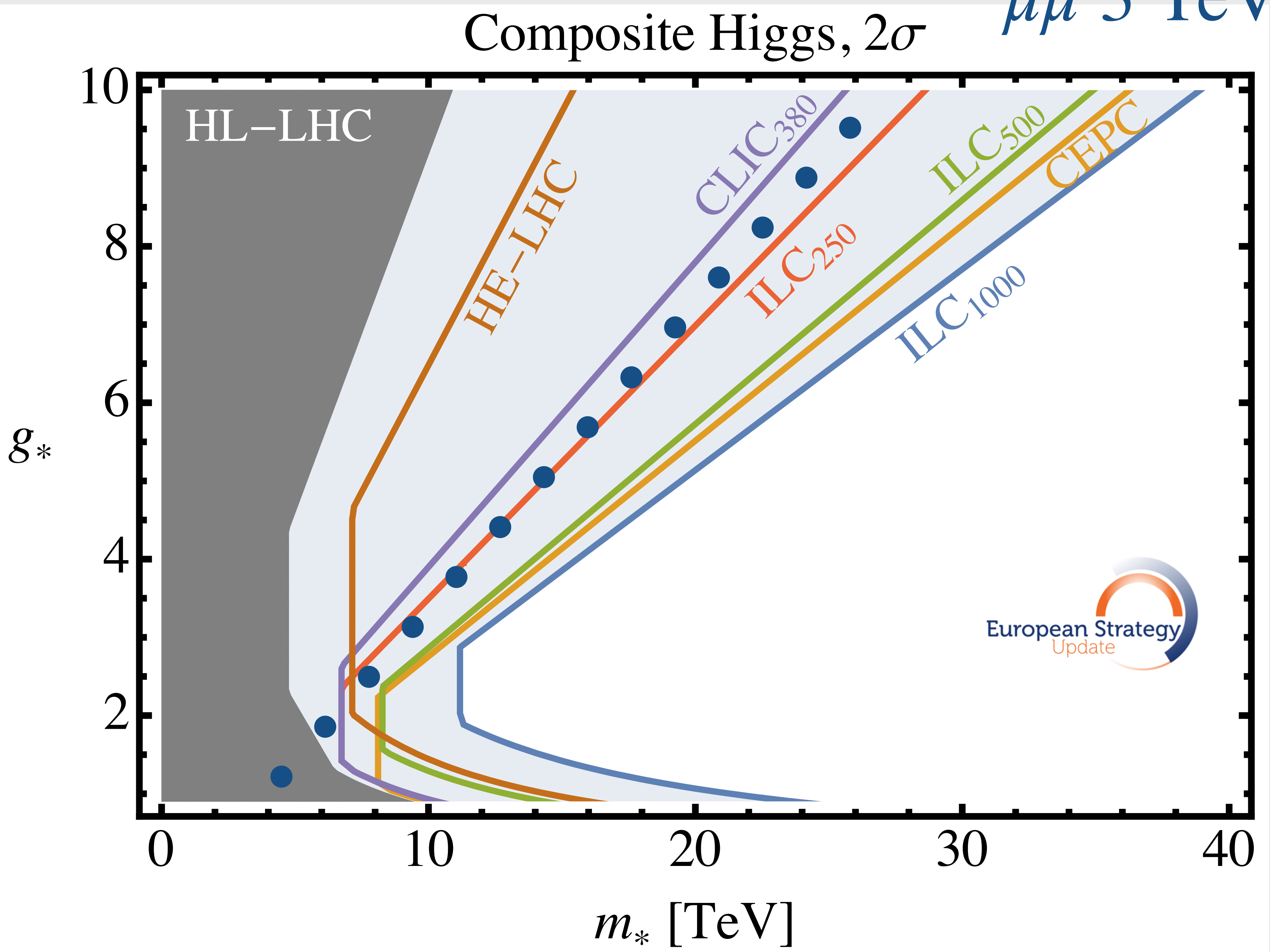
$1/(g_\star f) \sim 1/m_\star$

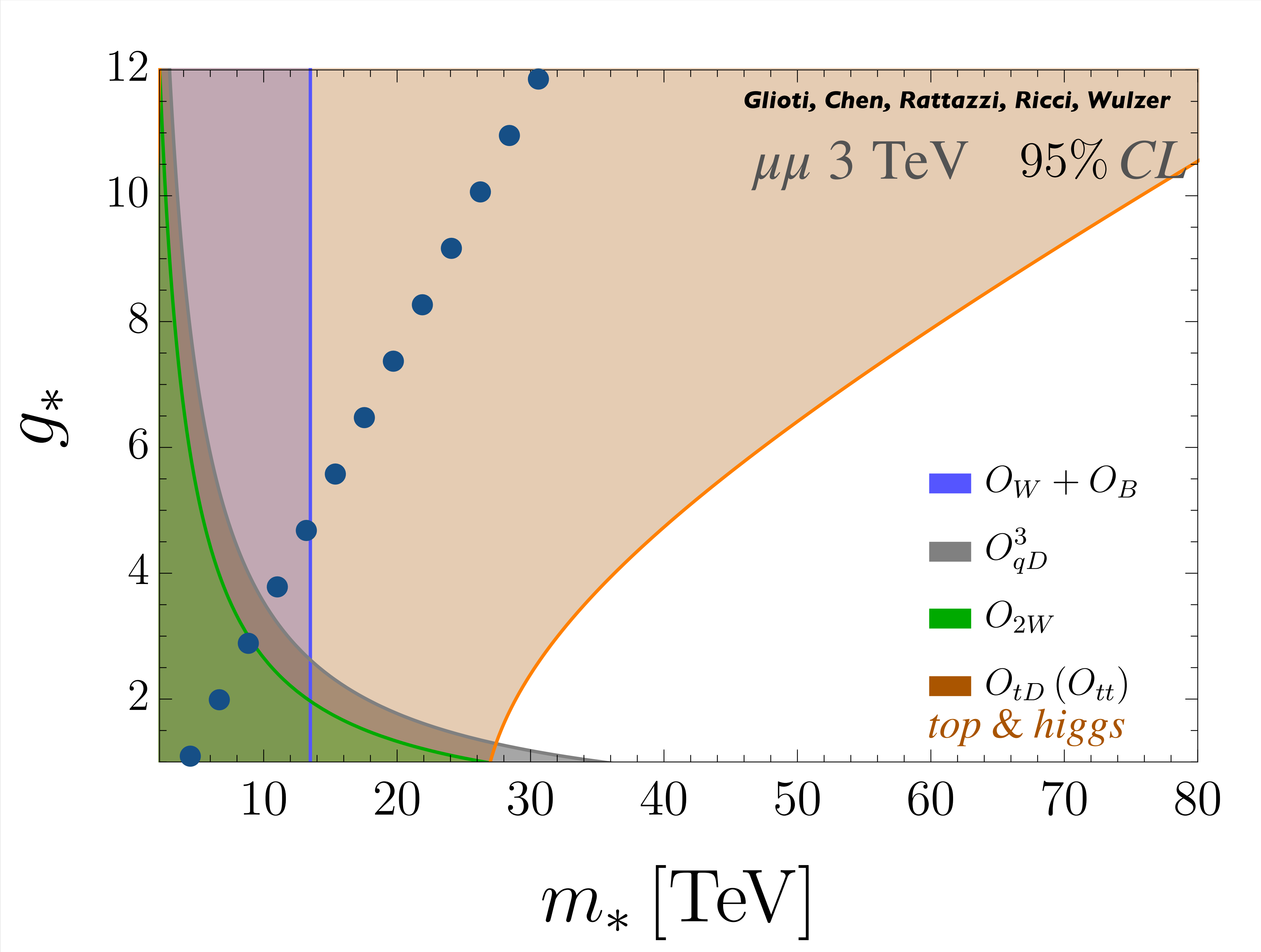
$g_{SM}/(g_\star f) \sim g_{SM}/m_\star$

$\ell_{top} \sim 1/m_\star \sim \ell_{Higgs}$

Looking ahead

single Higgs
$\mu\mu$ 3 TeV





compositeness at few TeV @ HL-LHC

compositeness at few 10 TeV

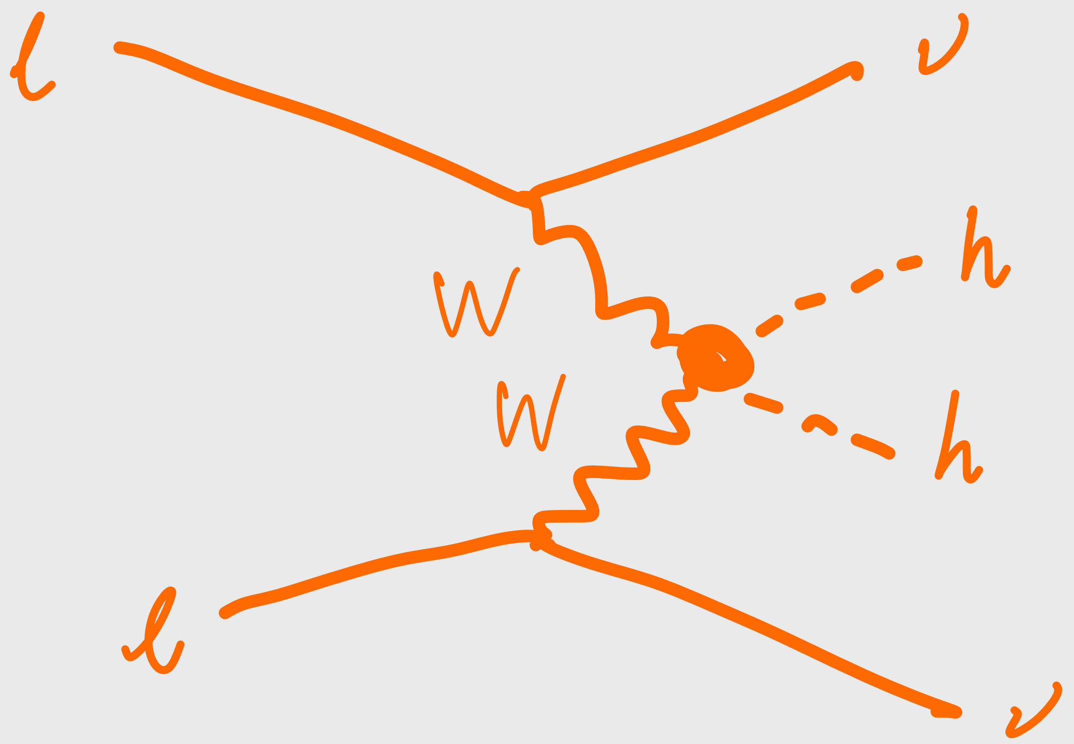
$\mu^+\mu^- \to hh$

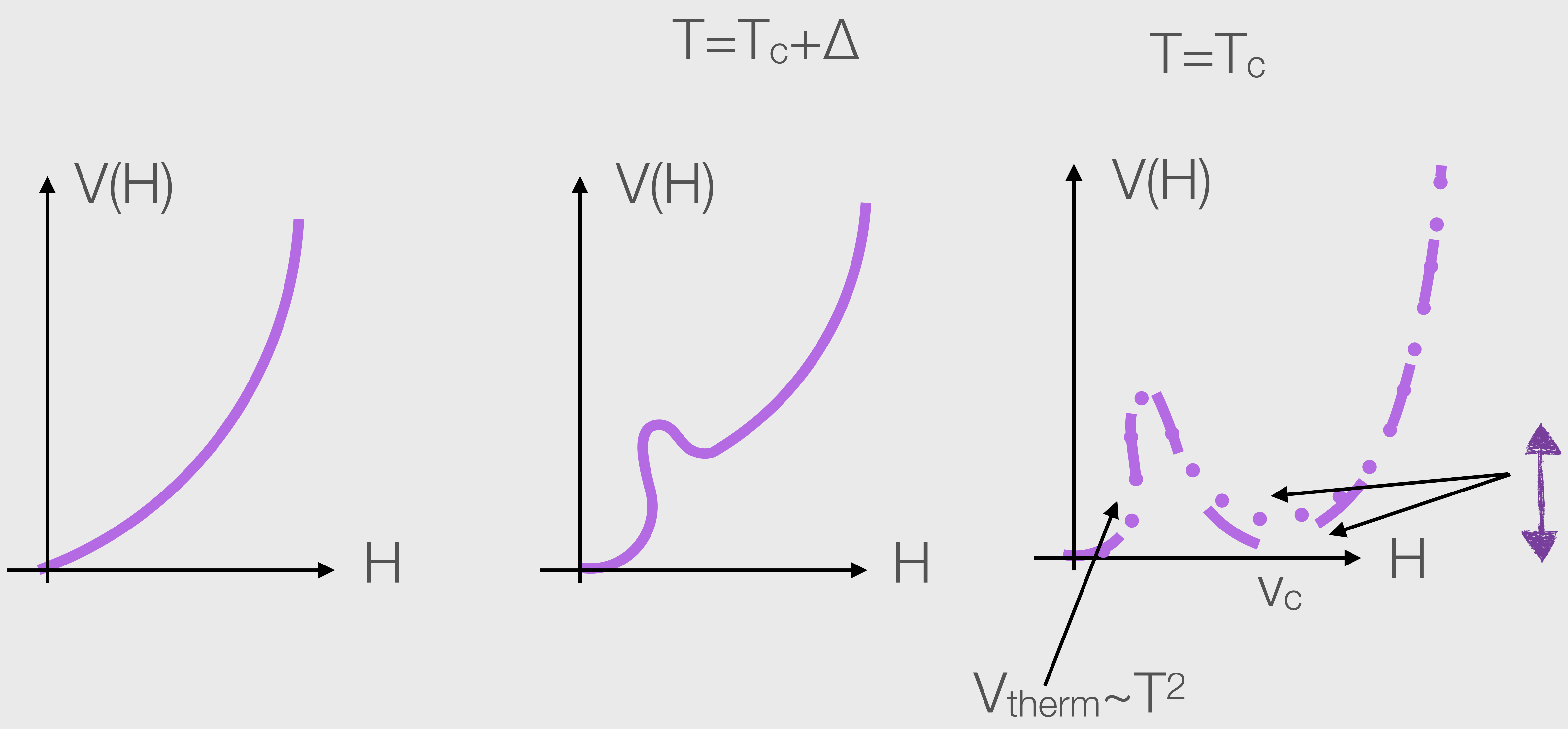
W BOSON COLLIDER

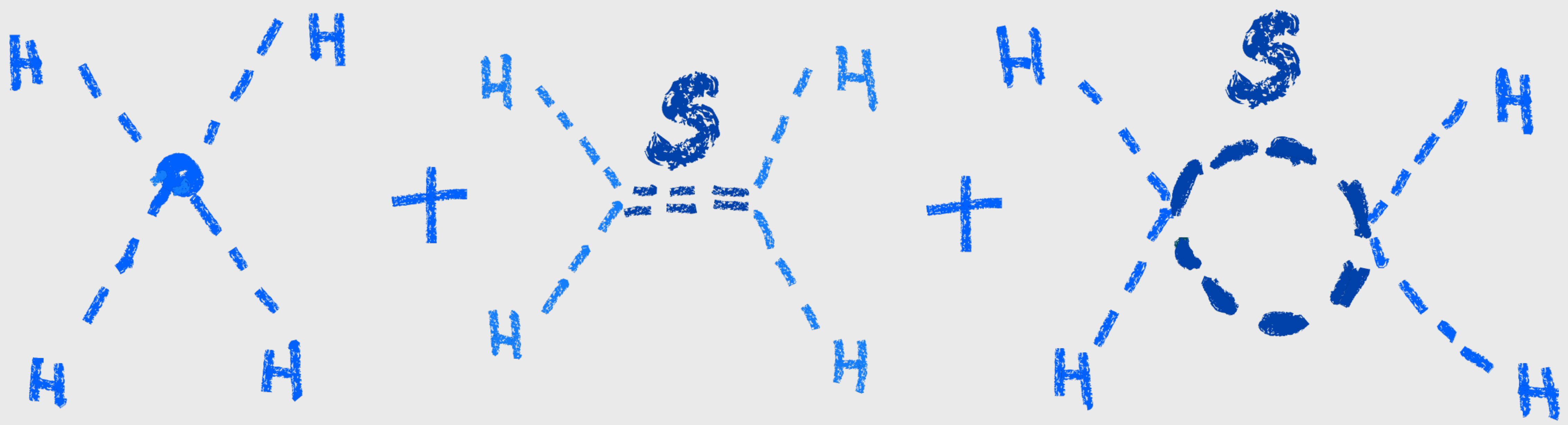
Electroweak phase transition

NEXT TALK BY L. SESTINI

- High-Energy lepton collider has large flux of “partonic” W bosons







Singlet tree and loop makes V(0,v) deeper

EW phase transition

DIRECT & INDIRECT | INTERPLAY

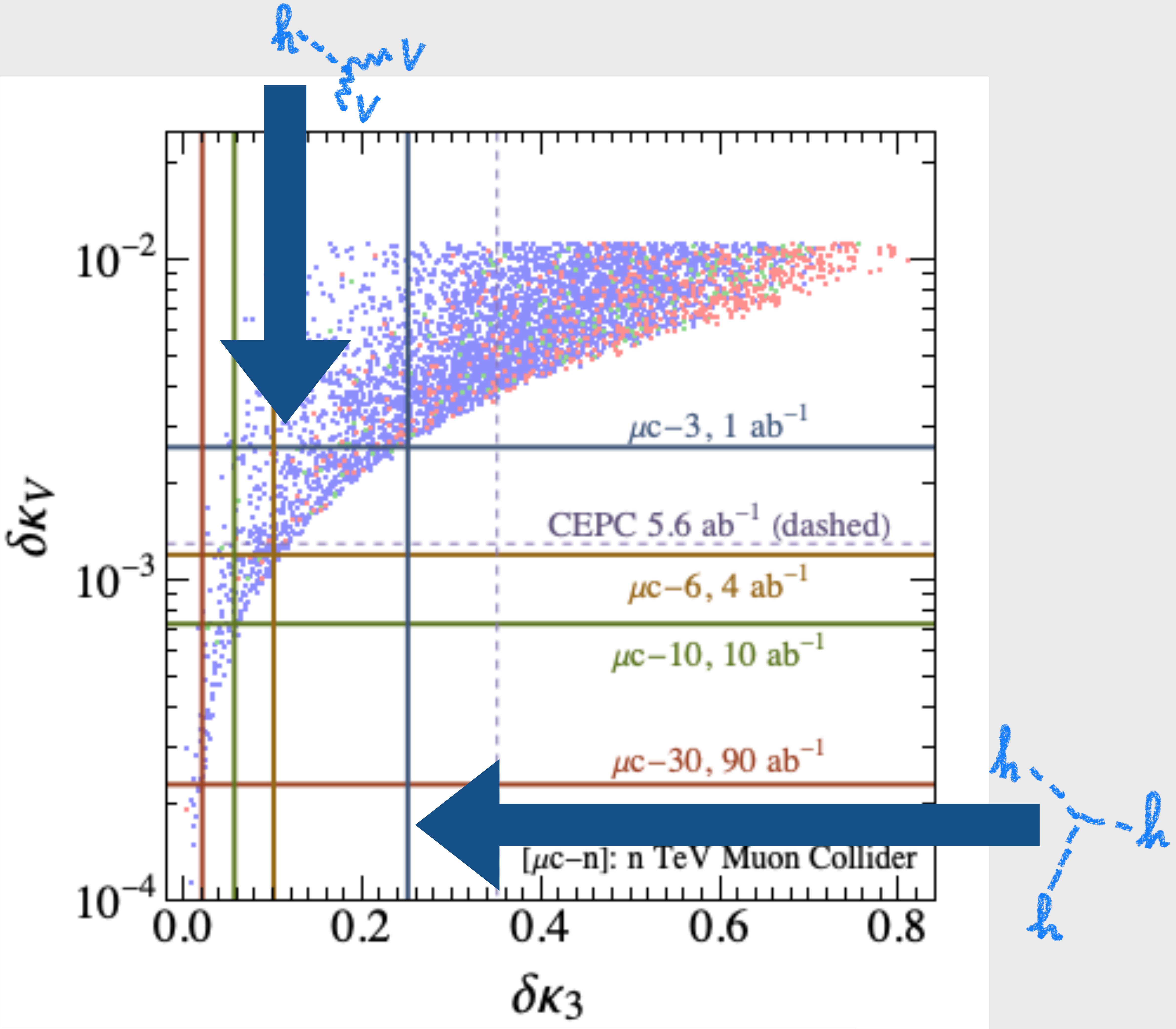
$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

strong First Order EW phase transition on all points

Gravity Wave SNR



EW phase transition

DIRECT & INDIRECT INTERPLAY

$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

independent parameters

$$\{M_{h_2}, \theta, v_s, b_3, b_4\}$$

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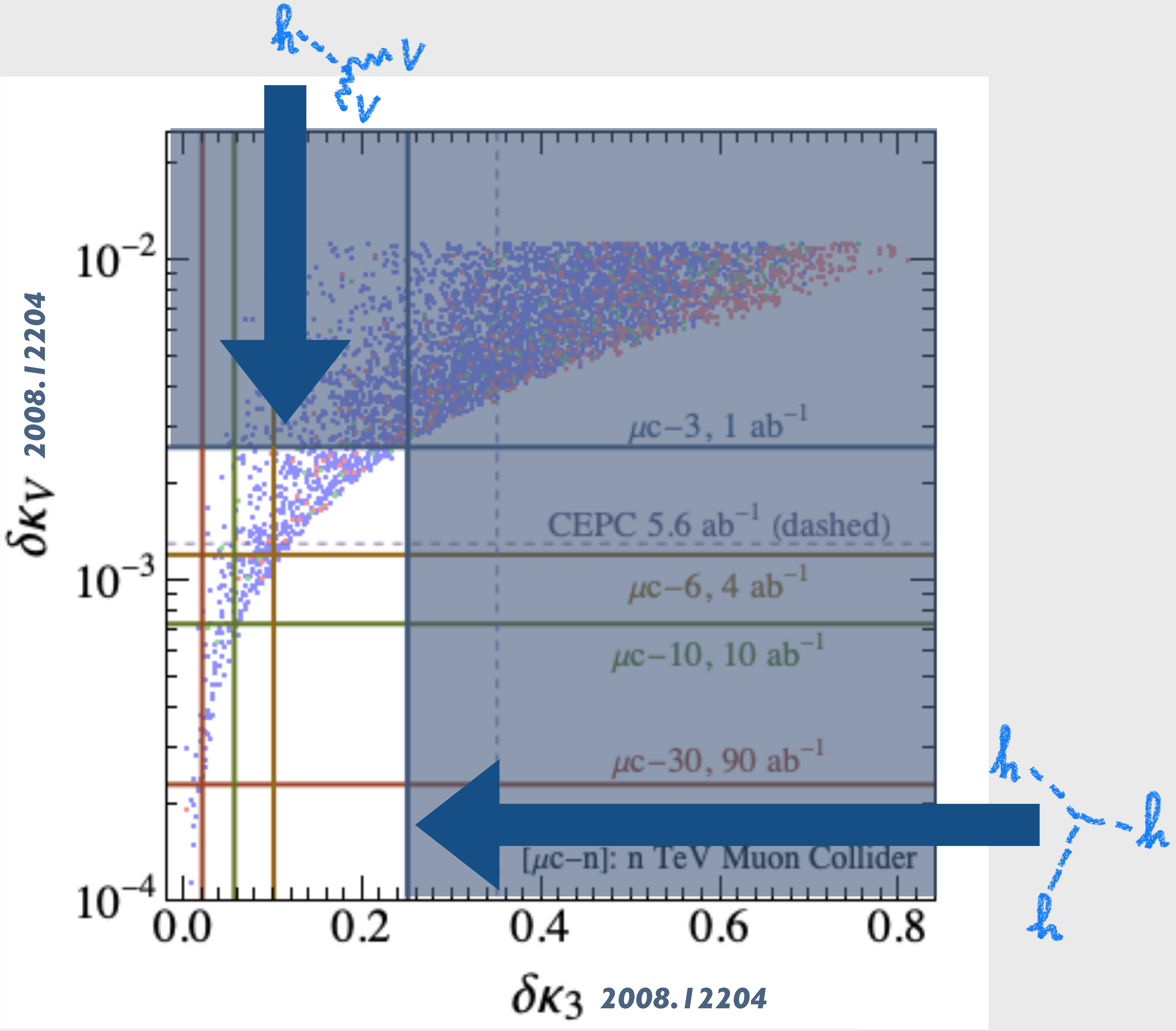


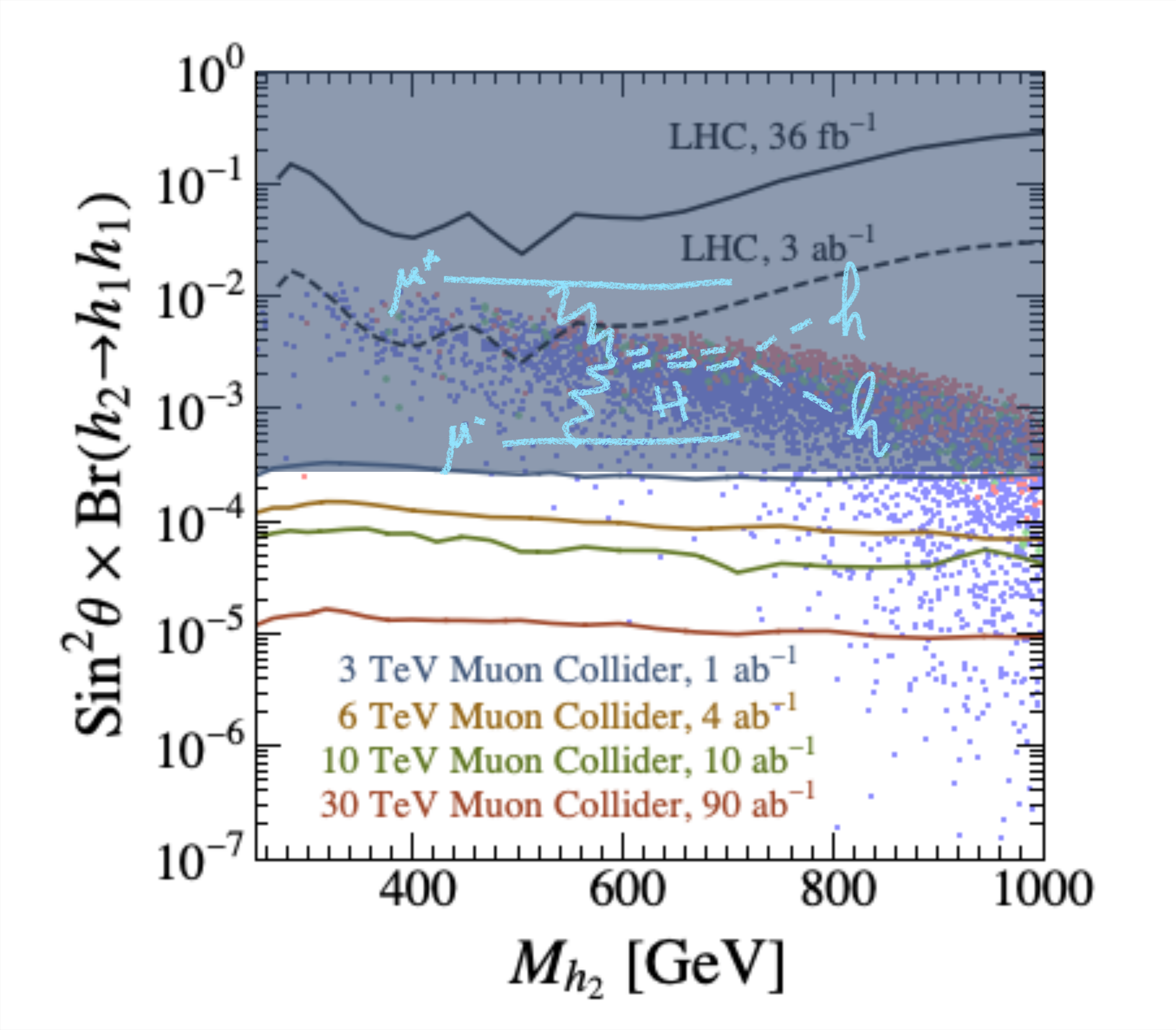
EW phase transition

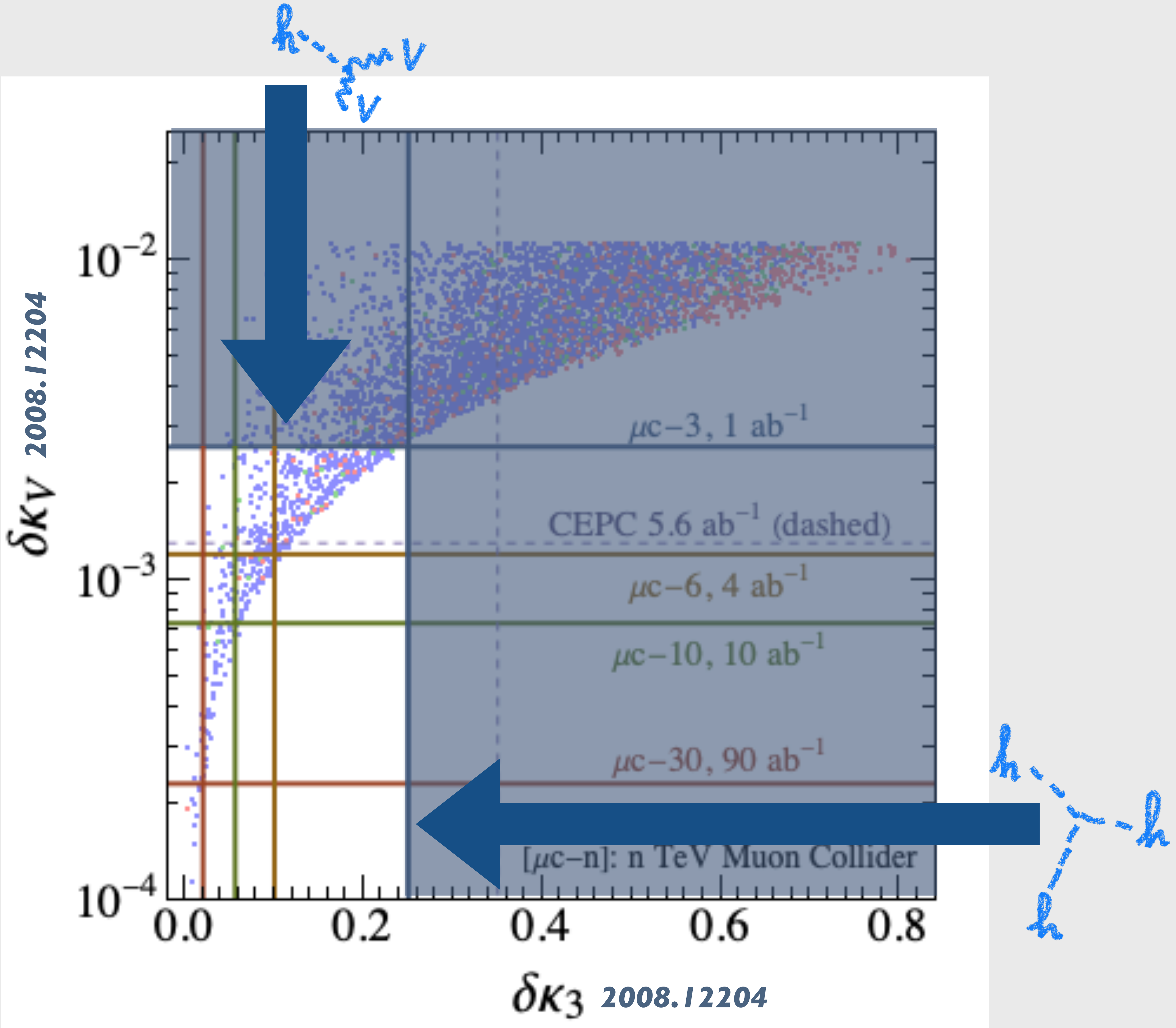
DIRECT & INDIRECT

INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR





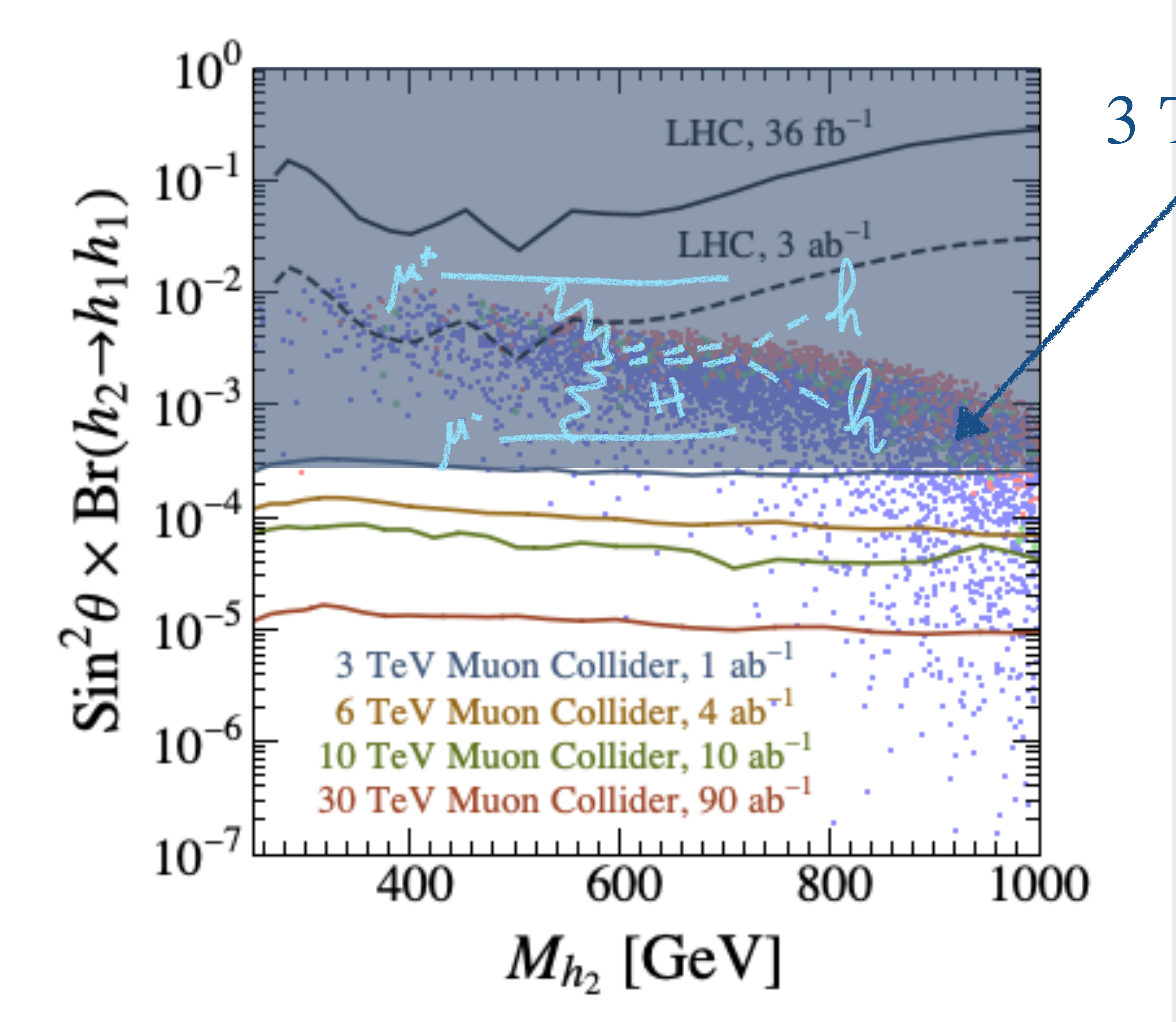
EW phase transition

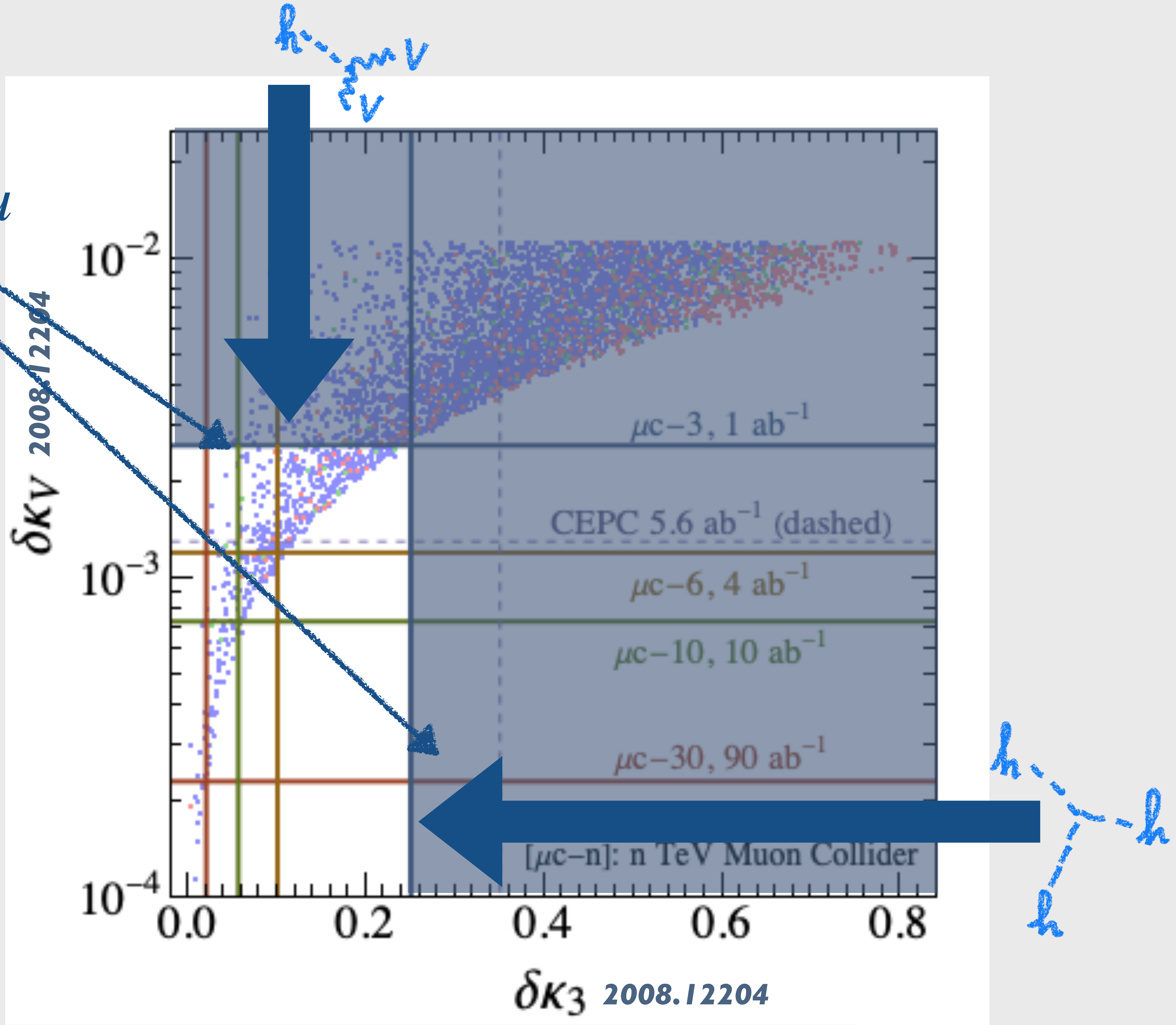
DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

→ Gravity Wave SNR

3 TeV $\mu\mu$





parameters space of 1st order phase transition accessible by **several measurements available at the 3 TeV $\mu\mu$ collider**

Physics at 3 TeV $\mu^+\mu^-$ collider

- A 3 TeV muon collider can bring excellent progress over HL-LHC about key questions on fundamental interactions (nature of the Higgs bosons, nature of Dark Matter, nature of the EW phase transition)

- 3 TeV is a sufficiently high energy to enable both modes of exploration as
  - high energy machine (e.g. Dark Matter direct production, Higgs and top compositeness, …)
  - high intensity machine (e.g. SM Higgs boson production)

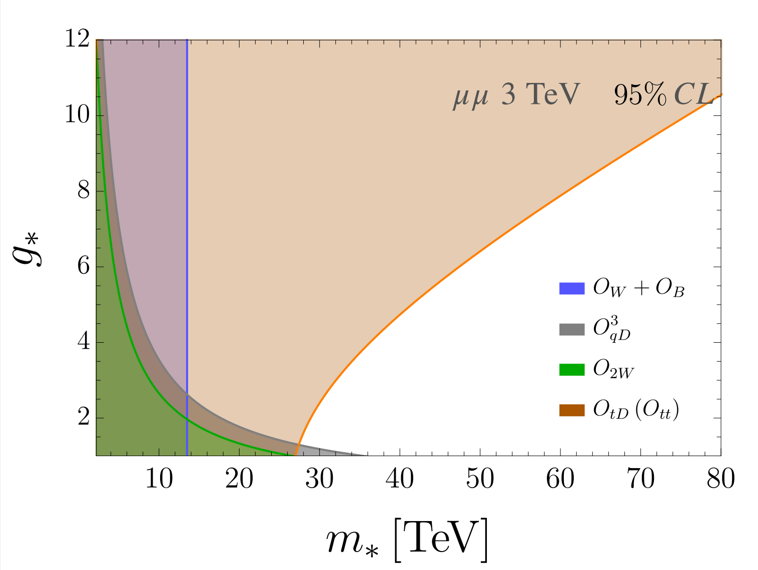
- These two modes complement each other very nicely (e.g. EW phase transition, extended Higgs sector)

- The relatively clean environment makes it suitable for searches of subtle exotic signals (e.g. tracklets from Dark Matter)

Physics at 3 TeV $\mu^+\mu^-$ collider

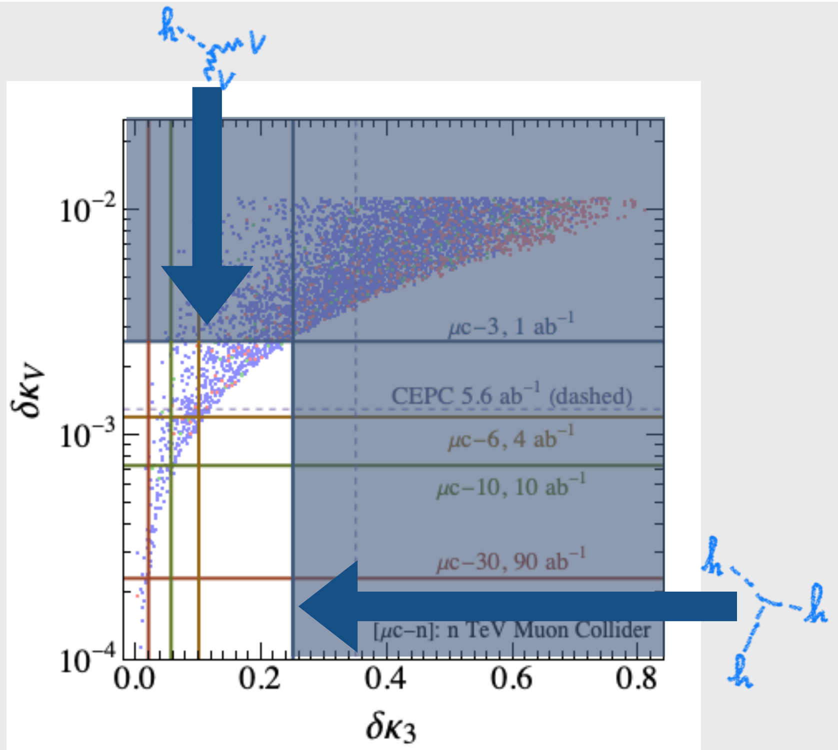
COMPOSITENESS

WELL ABOVE THE WEAK SCALE



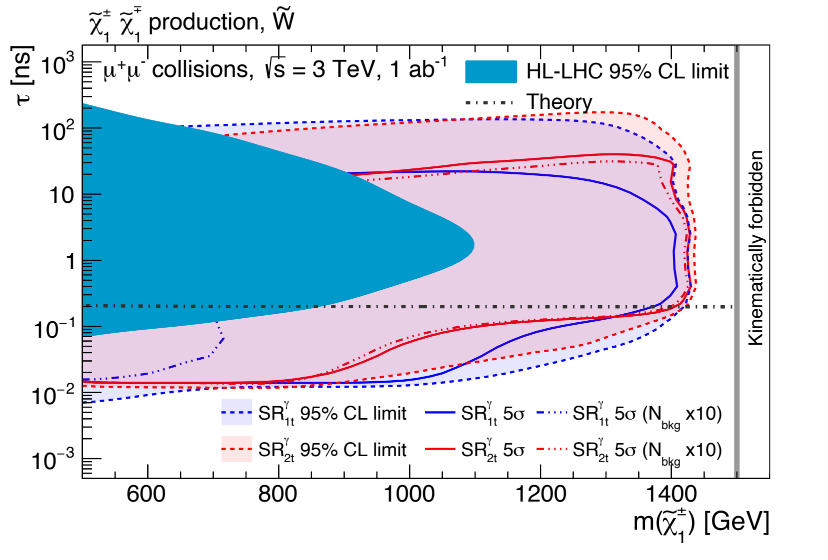
EW PHASE TRANSITION

SINGLETS AND EW CHARGED



DARK MATTER

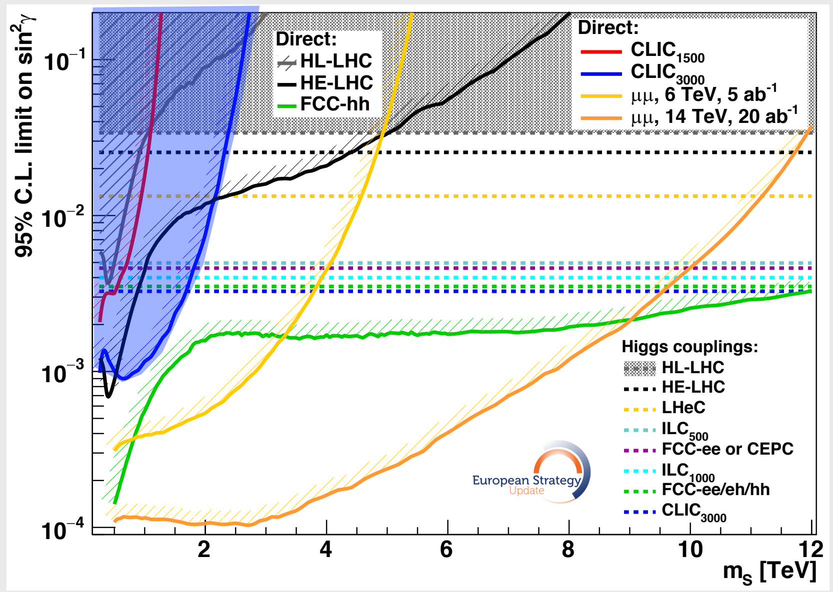
WIMP CANDIDATES including HIGGSINO and WINO



$\mu\mu$ 3 TeV

NEW SCALARS

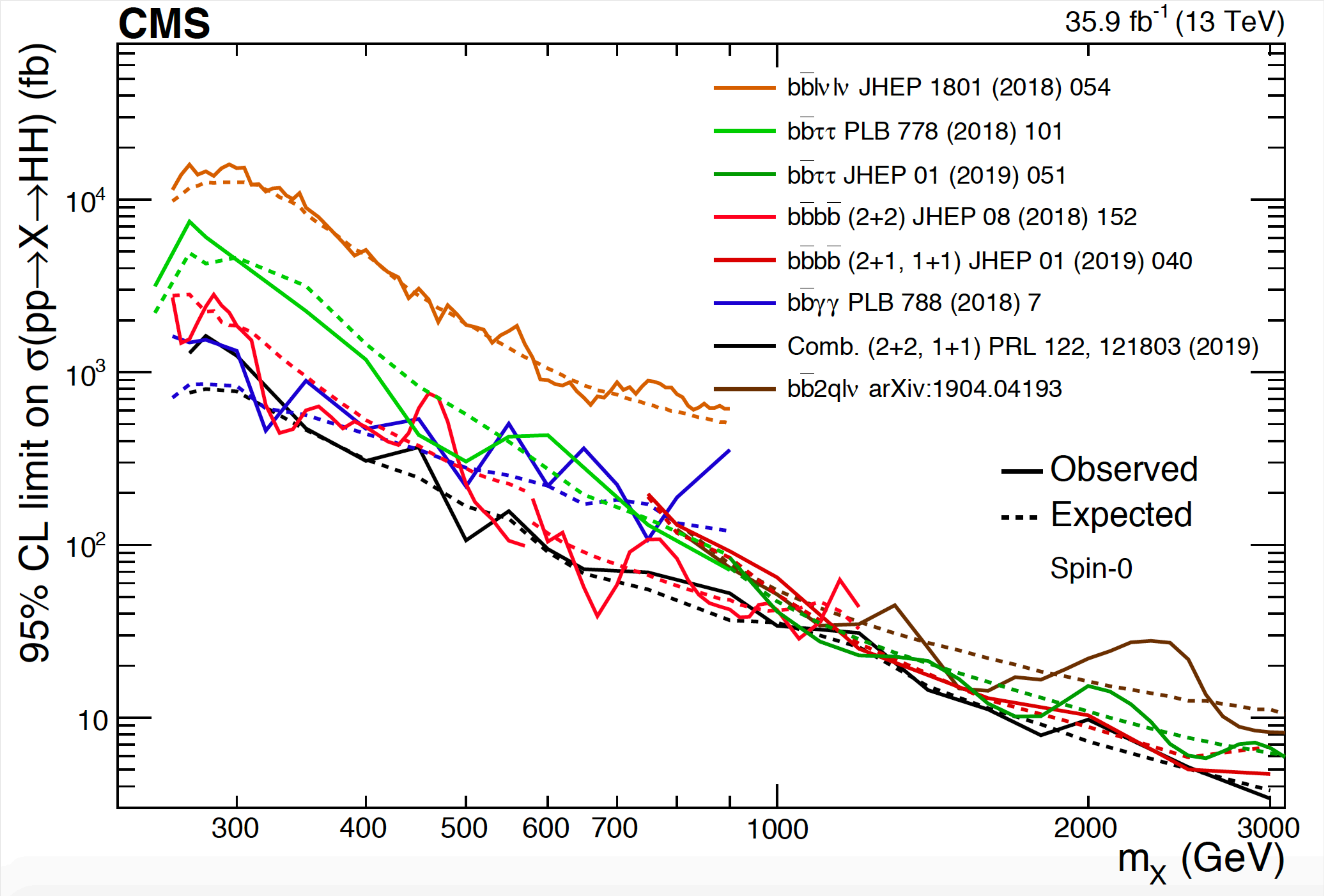
SINGLETS AND EW CHARGED



Thank you!

What about electroweak scalars?

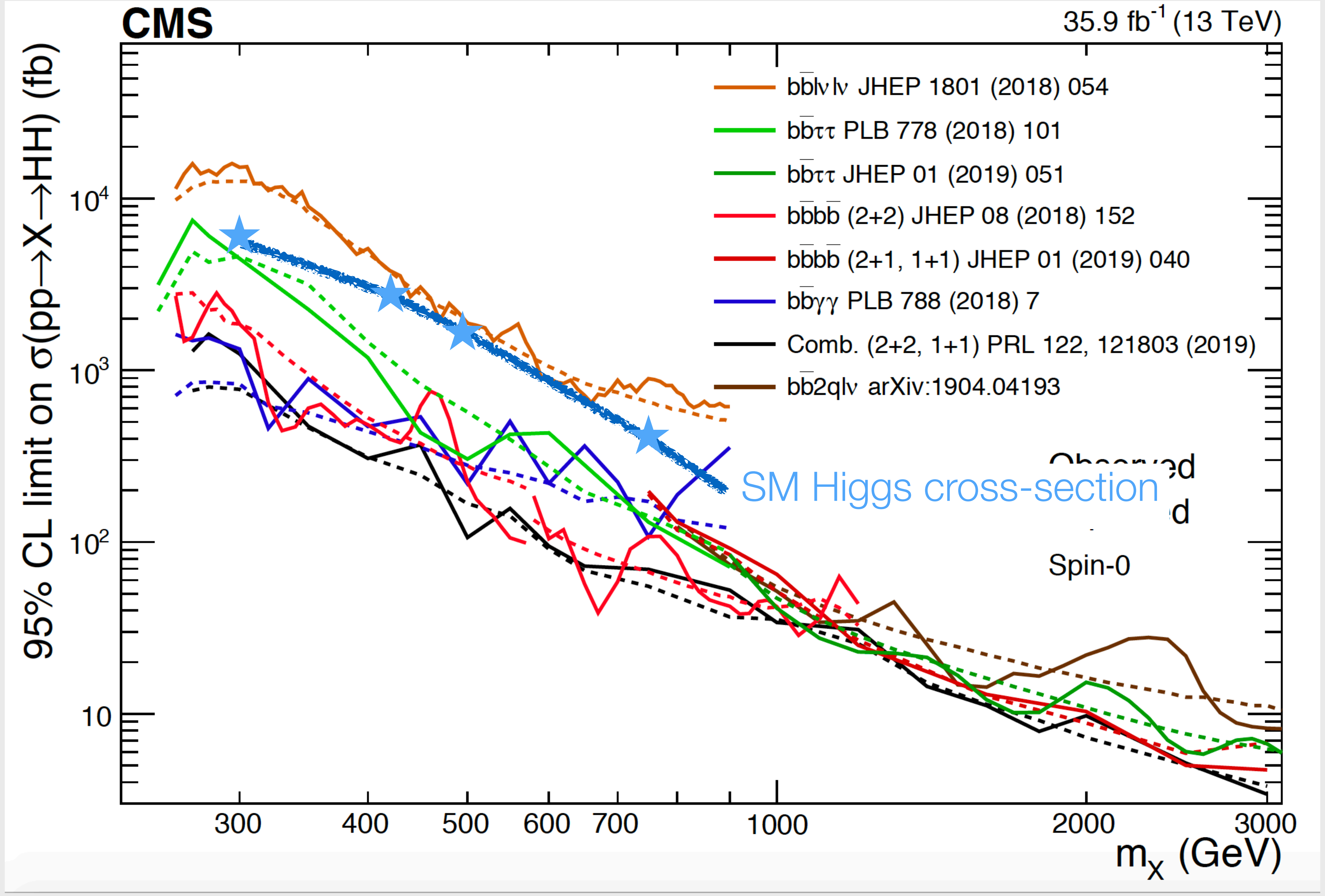
SINGLETS ARE ELUSIVE



Roberto Franceschini EOS meeting https://indico.iihe.ac.be/event/1341/

What about electroweak scalars?

SINGLETS ARE ELUSIVE



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What about electroweak scalars?

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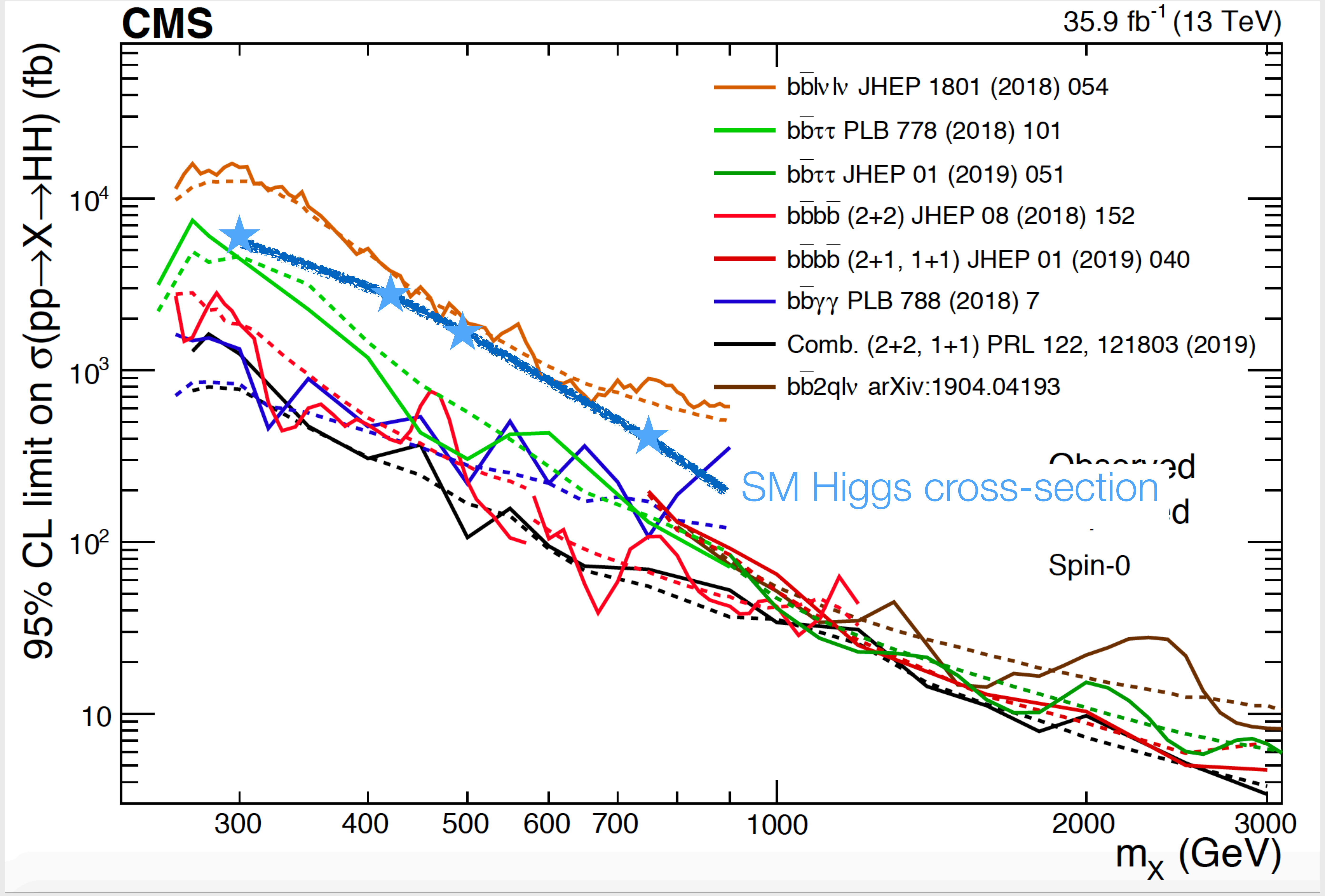
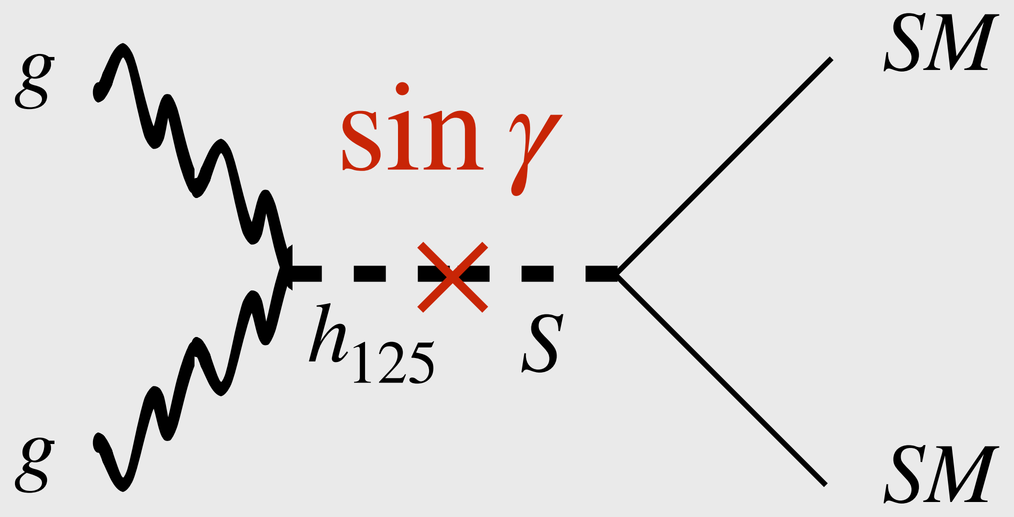


$$\sigma(\phi) \sim \sin^2\theta_{h\phi} \cdot \sigma(h_{SM} \text{ with } m_\phi)$$

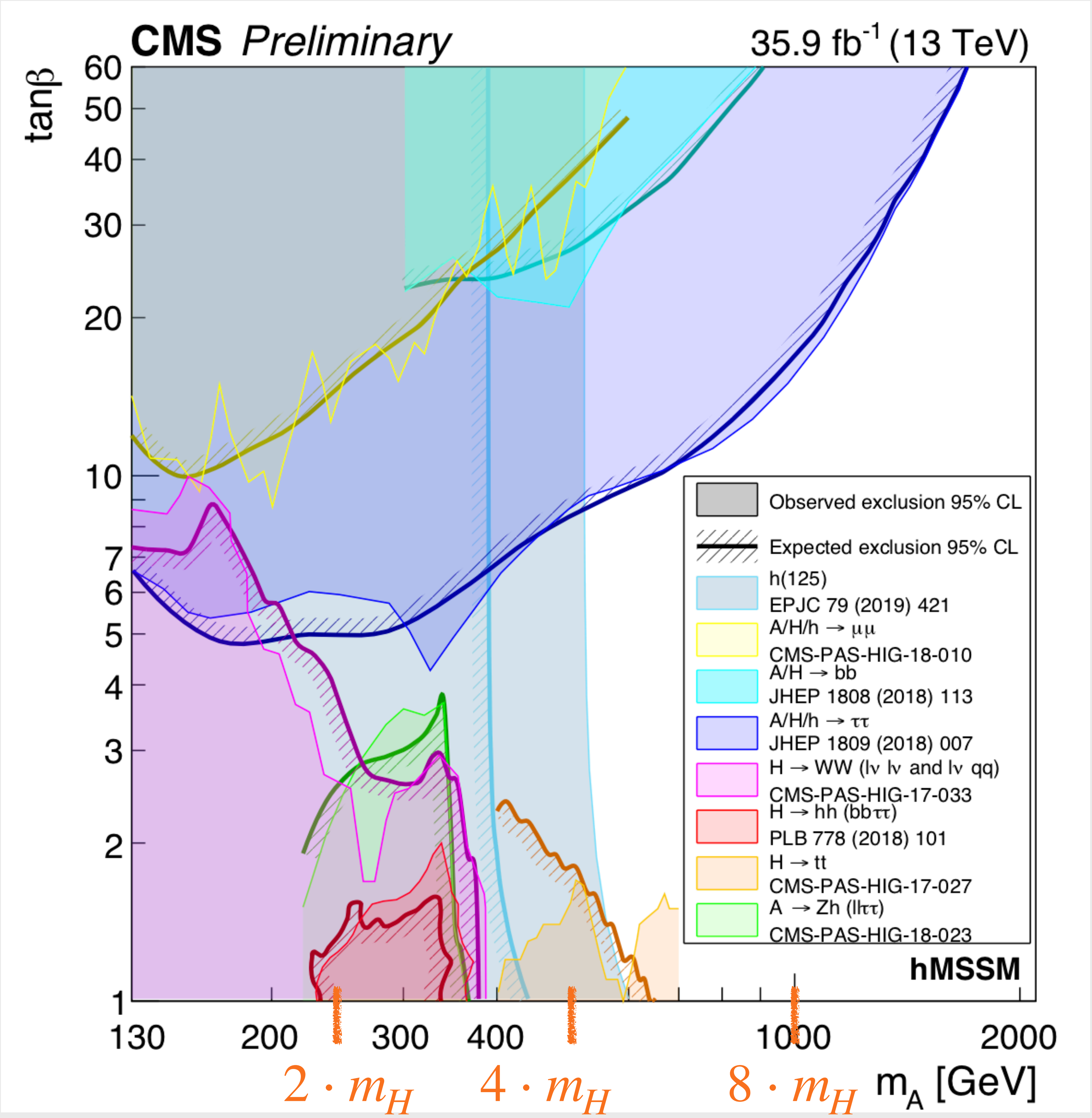


$$\Rightarrow \sin\theta \lesssim 0.3$$

$$\sin\theta \simeq \left(\frac{m_h}{m_H}\right)^{\alpha} \quad \Rightarrow m_H \simeq 2 \div 3 \cdot m_h$$

What about electroweak scalars?

DOUBLETS ARE ABOUT AS TOUGH TO CATCH



There is in general a weak sensitivity to new scalars, because of:

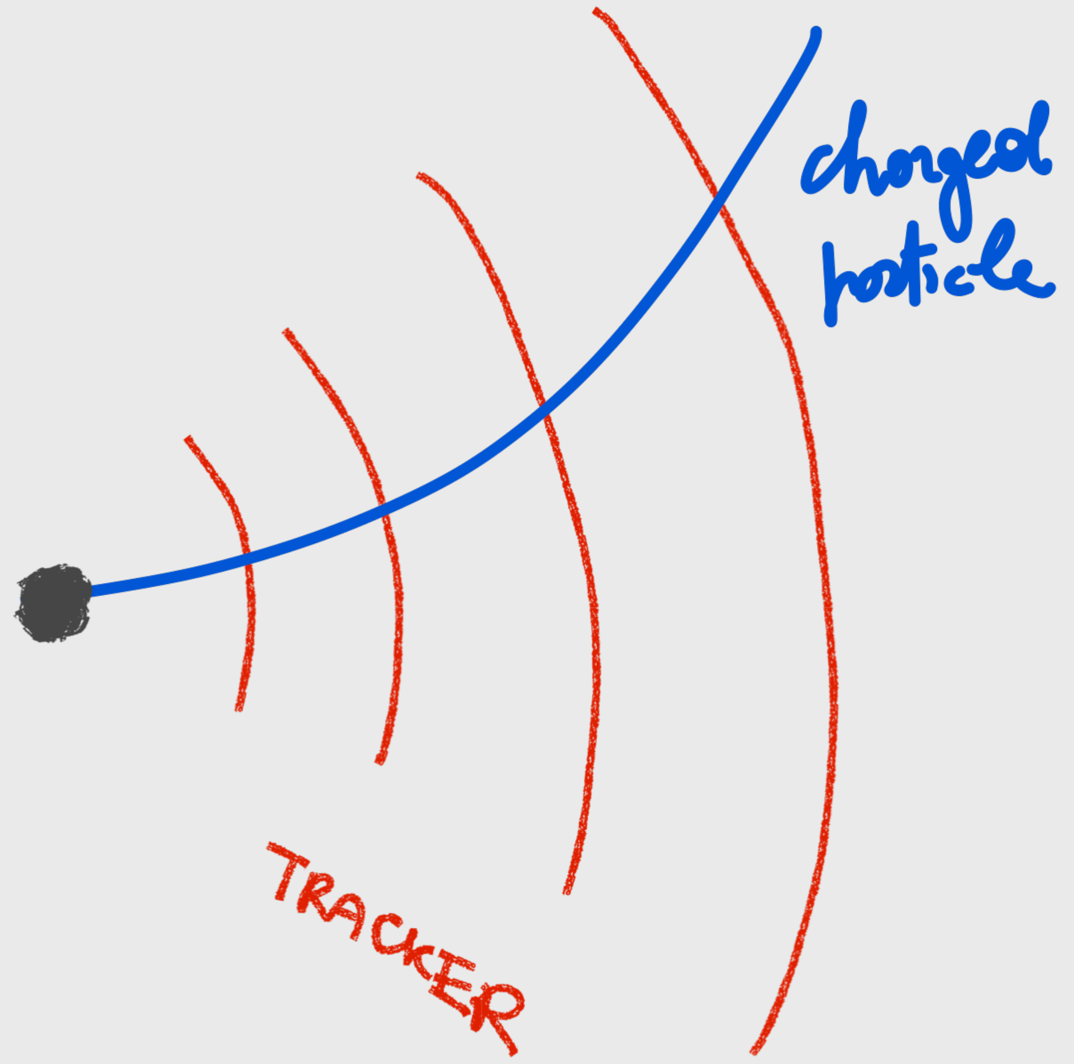
- **“small” cross-sections**
- **large backgrounds**

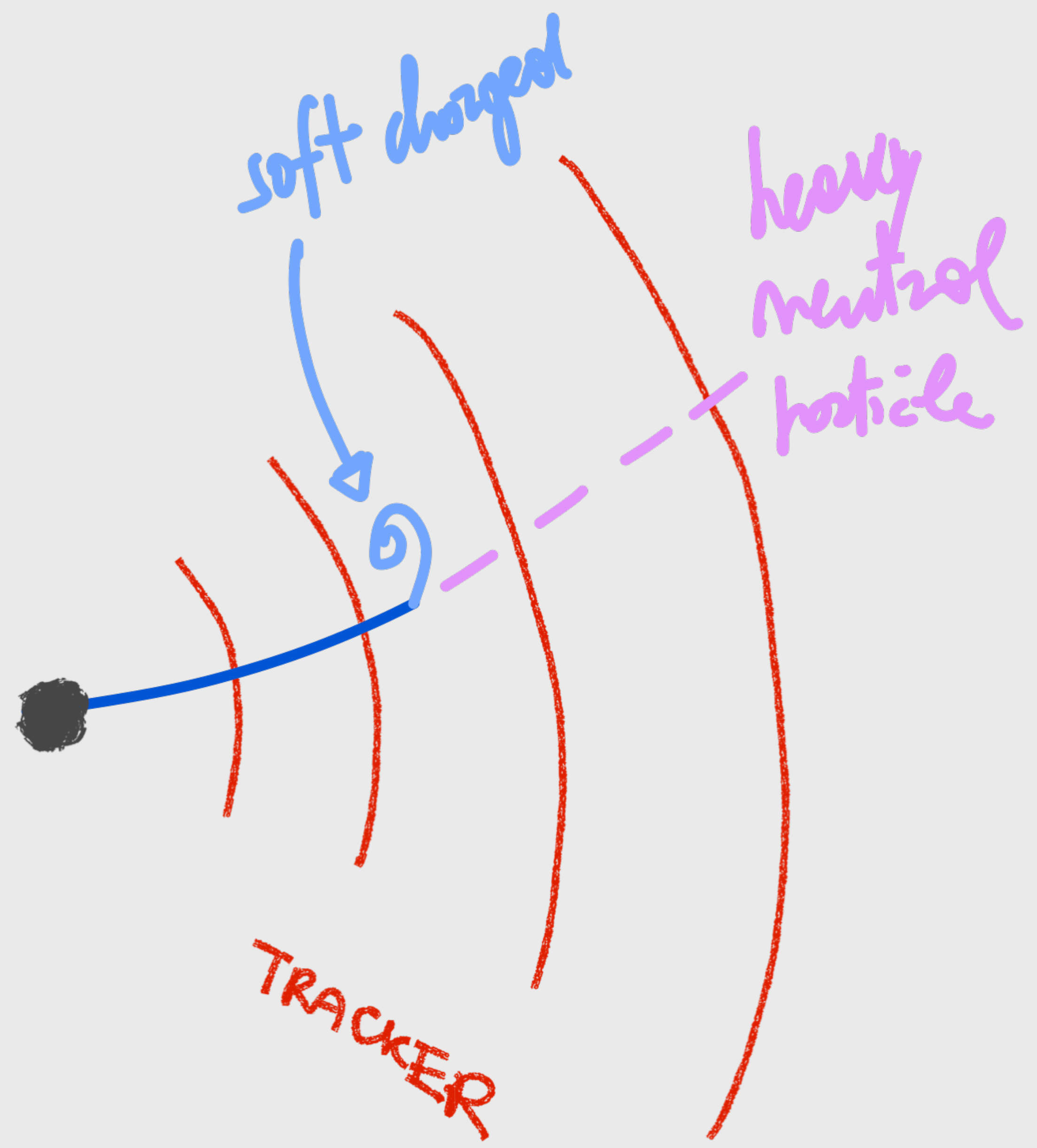
it is hard to explore the scalar sector and the only big discovery of the LHC may be left unmatched … even if light scalars may exist.

Tracklets

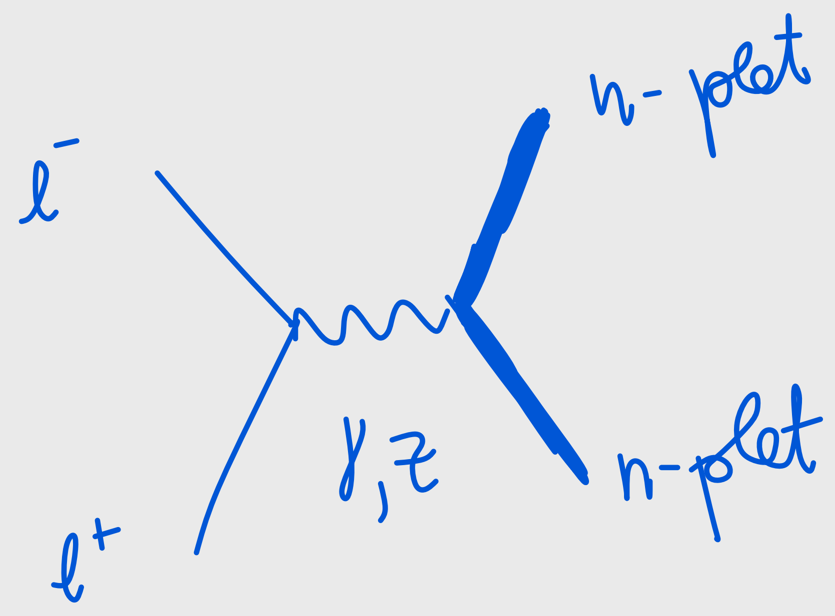
STUB-TRACKS

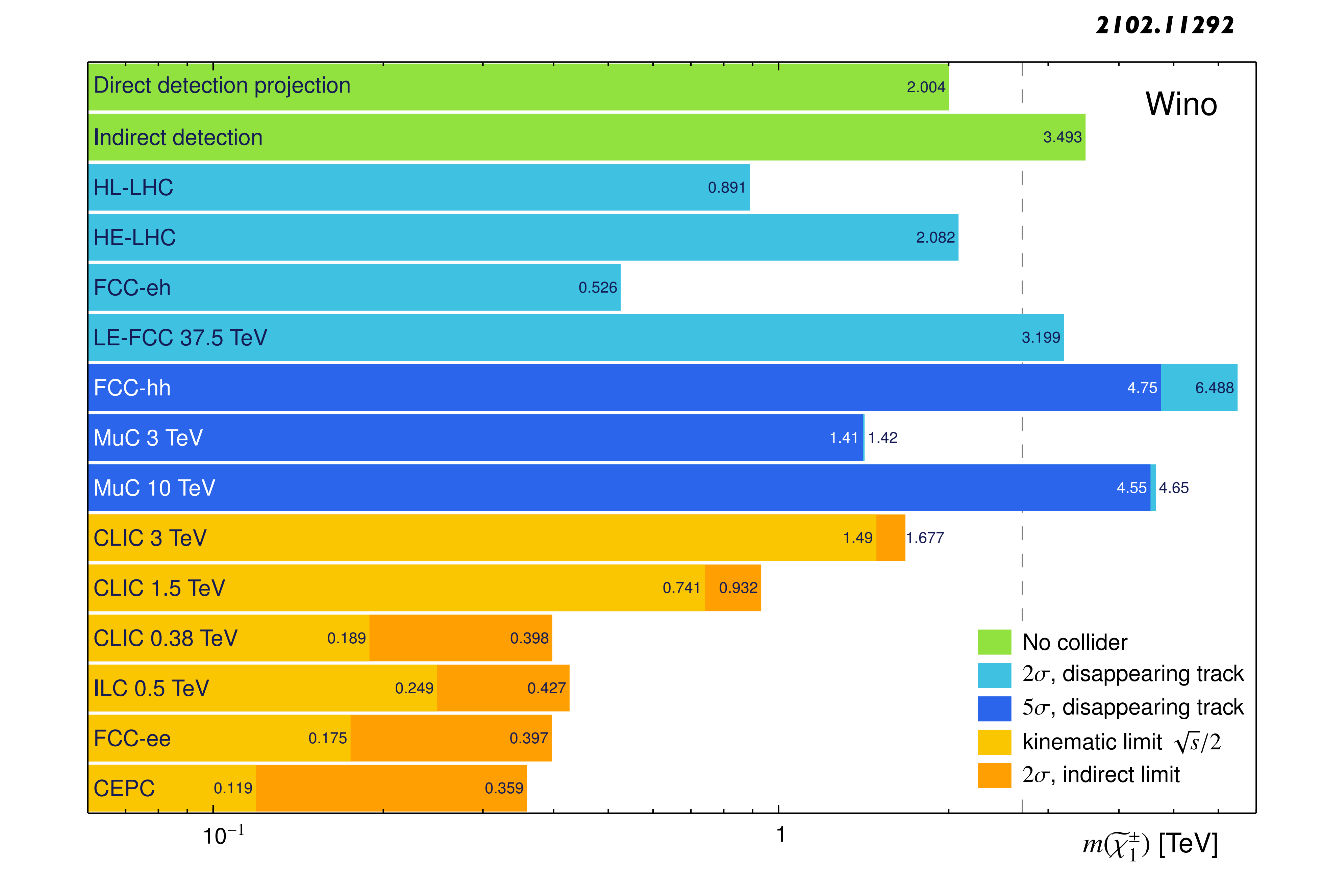
EXTRAPOLATION FROM CLIC





- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W m_W$ ~ 0.1 GeV - GeV

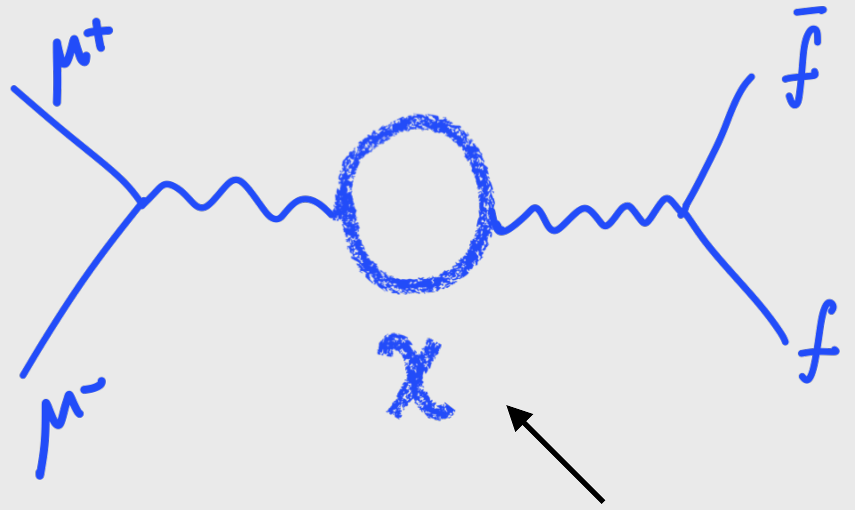




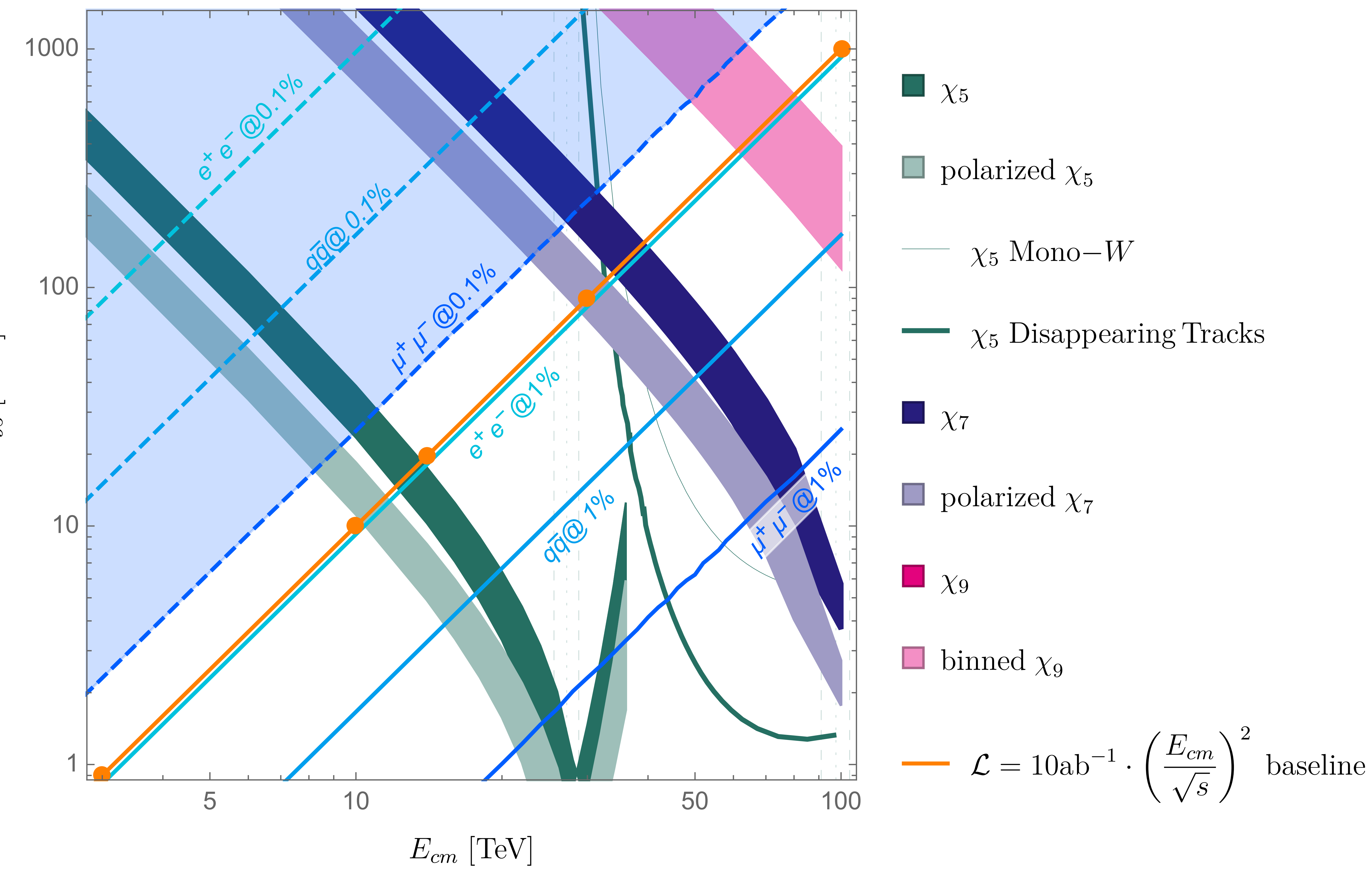
LARGE RATES, BUT NEEDS TO LIGHT UP THE DETECTOR IN A DISCERNIBLE WAY

$\mu^+\mu^- \to f\bar{f}, W^+W^-$

PRECISION **TOTAL CROSS-SECTION**

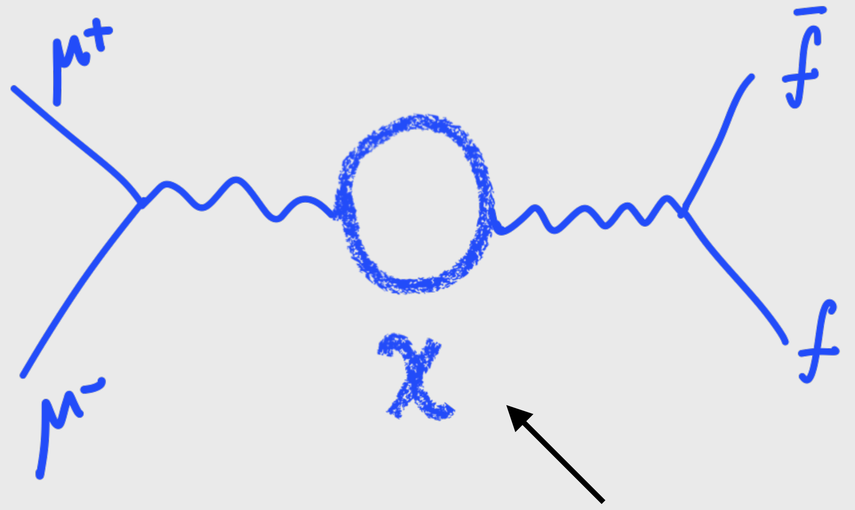


χ is heavy/light new physics



$\mu^+\mu^- \to f\bar{f}, W^+W^-$

PRECISION | **TOTAL CROSS-SECTION**



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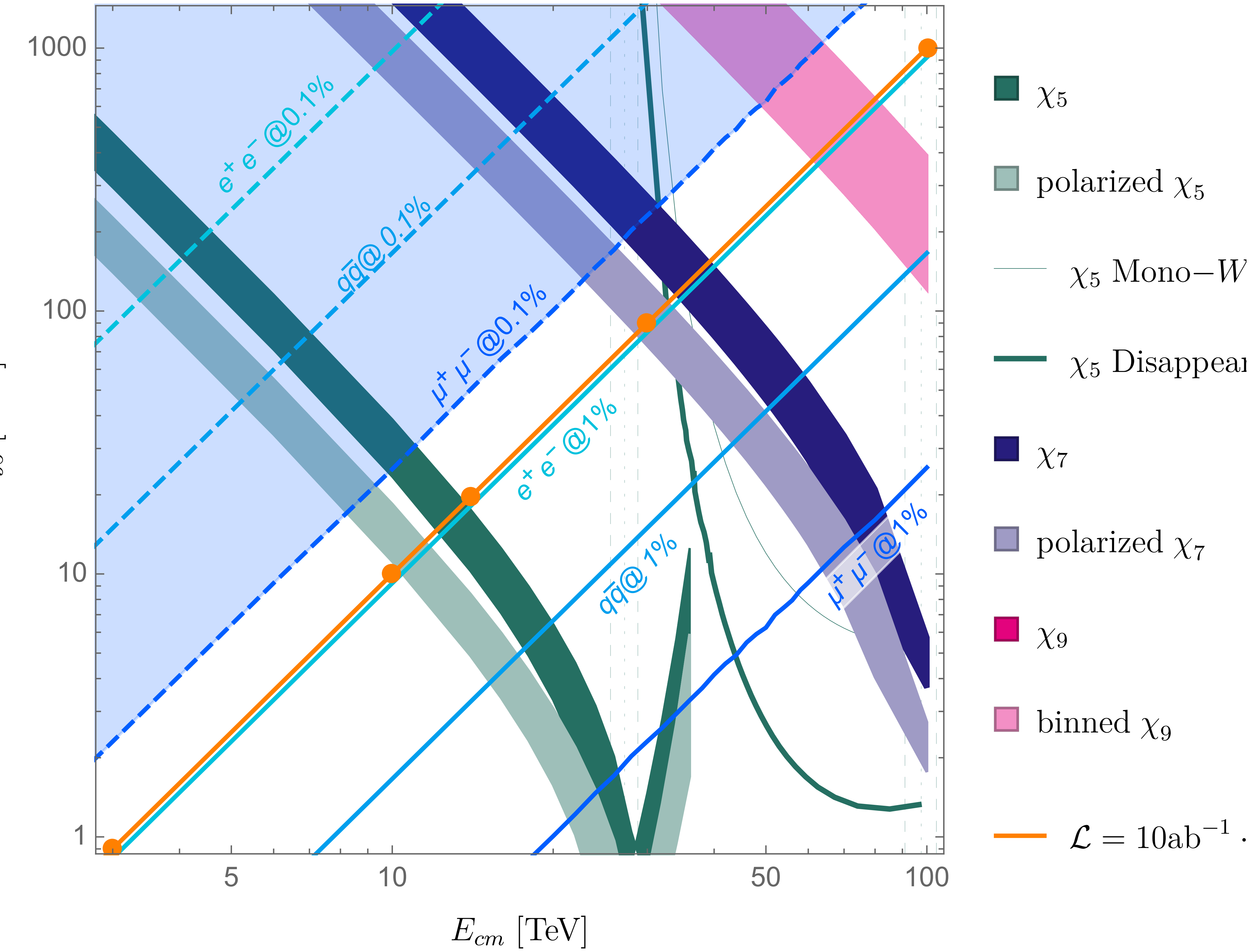
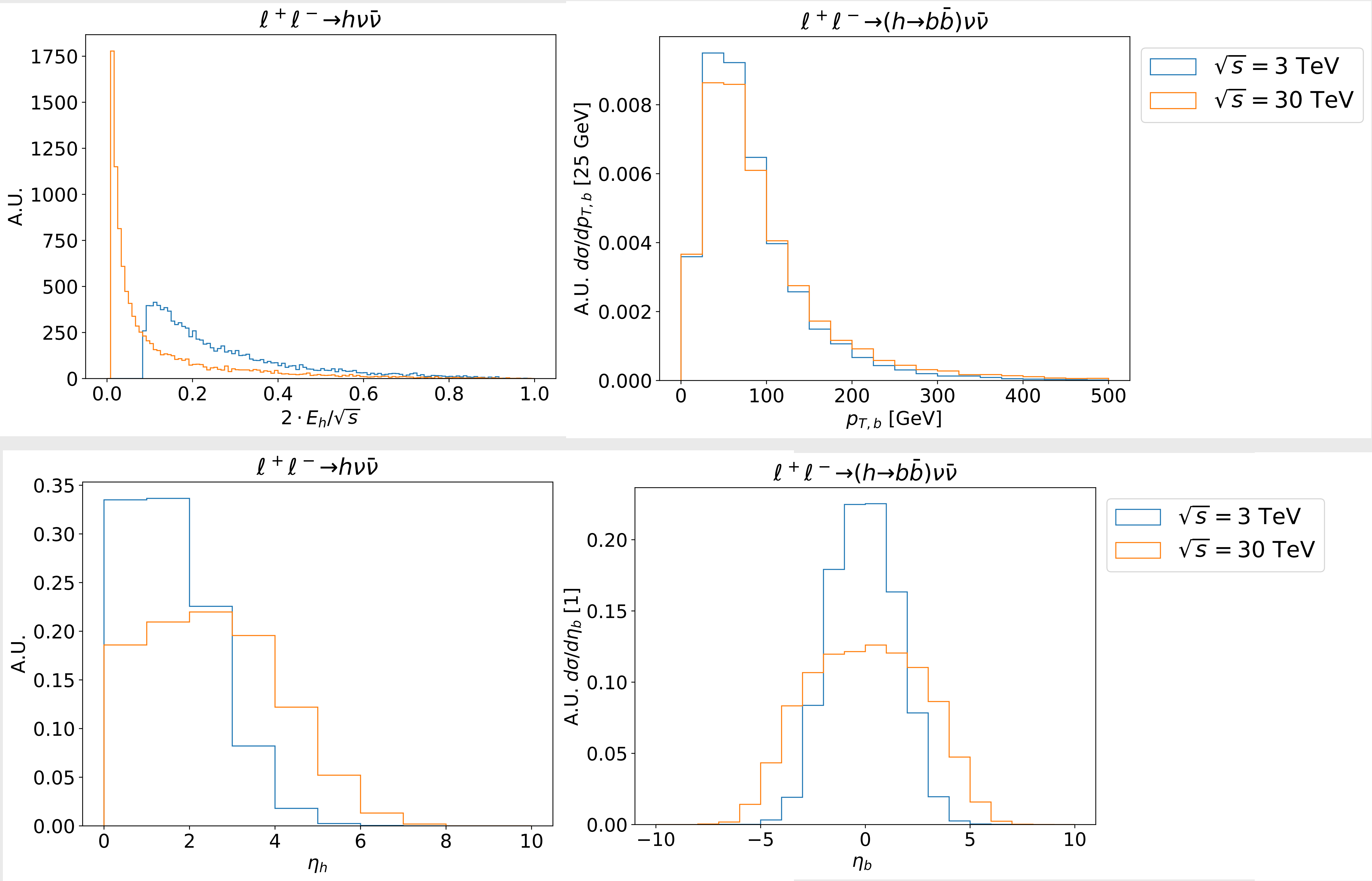


χ / m_χ [TeV]	DM	HL-LHC	HE-LHC	FCC-100	CLIC-3	Muon-14
$(1,2,1/2)_{\rm DF}$	1.1	–	–	–	0.4	0.6
$(1,3,\epsilon)_{\rm CS}$	1.6	–	–	–	0.2	0.2
$(1,3,\epsilon)_{\rm DF}$	2.0	–	0.6	1.5	0.8 & [1.0, 2.0]	2.2 & [6.3, 7.1]
$(1,3,0)_{\rm MF}$	2.8	–	–	0.4	0.6 & [1.2, 1.6]	1.0
$(1,5,\epsilon)_{\rm CS}$	6.6	0.2	0.4	1.0	0.5 & [0.7,1.6]	1.6
$(1,5,\epsilon)_{\rm DF}$	6.6	1.5	2.8	7.1	3.9	11
$(1,5,0)_{\rm MF}$	14	0.9	1.8	4.4	2.9	3.5 & [5.1, 8.7]
$(1,7,\epsilon)_{\rm CS}$	16	0.6	1.3	3.2	2.4	2.5 & [3.5, 7.4]
$(1,7,\epsilon)_{\rm DF}$	16	2.1	4.0	11	6.4	18

- Comprehensive tool to explore new electroweak particles
- Can probe valid dark matter candidates!

$\ell^+\ell^- \to h\nu\nu$

10^8 HIGGS BOSONS | **100×MEGA-HIGGS FACTORY**



$$\mathscr{L} \simeq 90 \cdot \left(\frac{\sqrt{s}}{30\,\mathrm{TeV}}\right)^2 \mathrm{ab}^{-1}$$

$\sigma(\ell^+\ell^- \to \nu\nu(h \to bb)) = 1\,\mathrm{pb}$ at 30 TeV

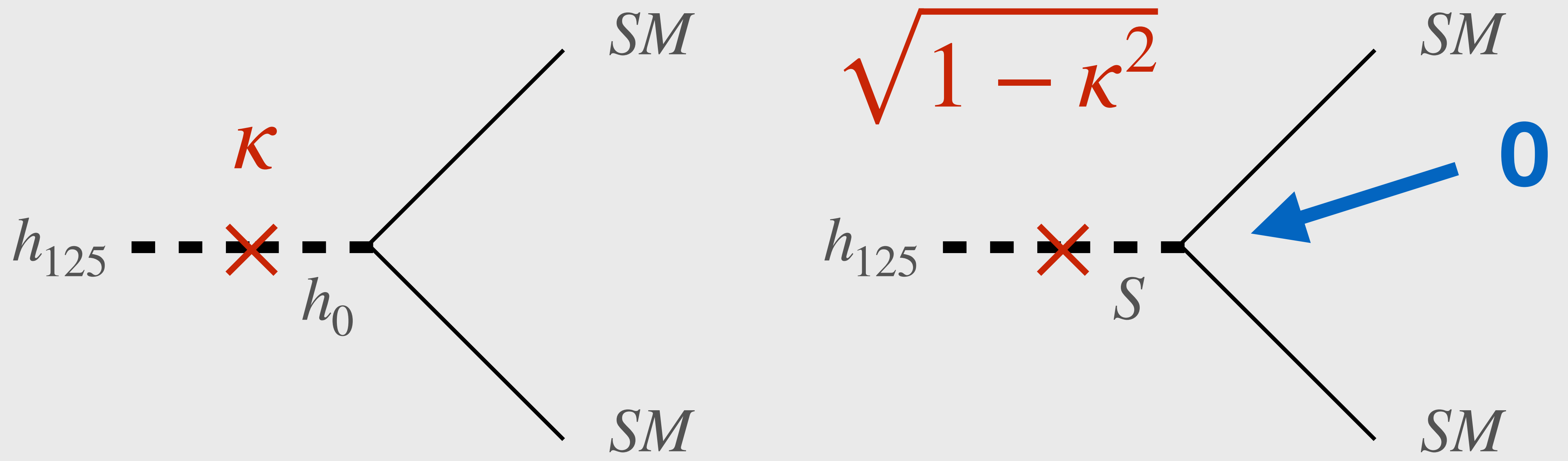
- most Higgs decays in acceptance ***2001.04431***
- $O(10^4)$ $H \to \mu^+\mu^-$ decays!
- clean decays where systematic may be small will be a key. E.g. 4ℓ, $\ell\ell Z$, $\gamma\gamma$, $Z\gamma$

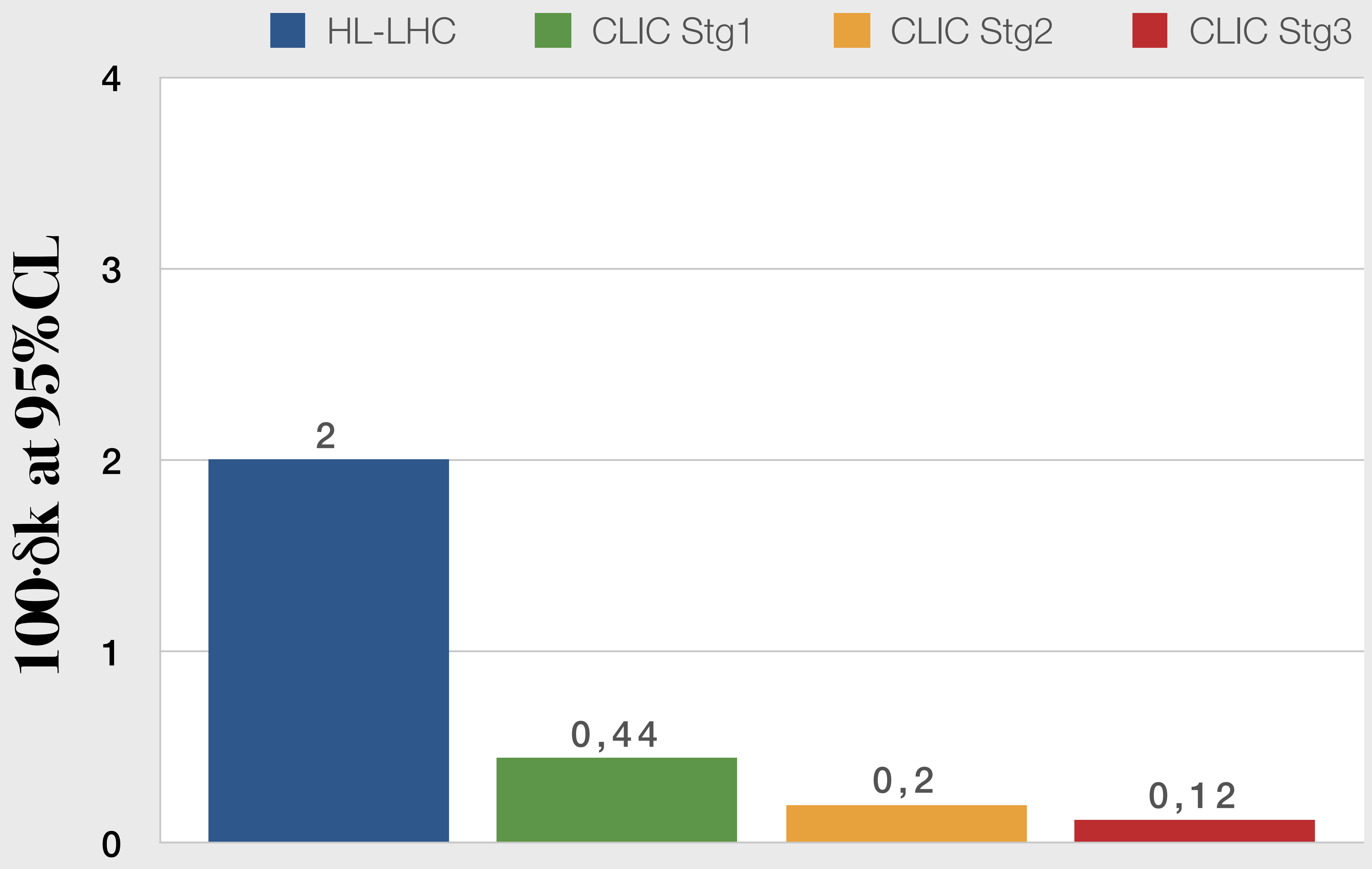
EFT

NEW SCALAR

SM+HEAVY SINGLET

$$h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1-\kappa^2}$$

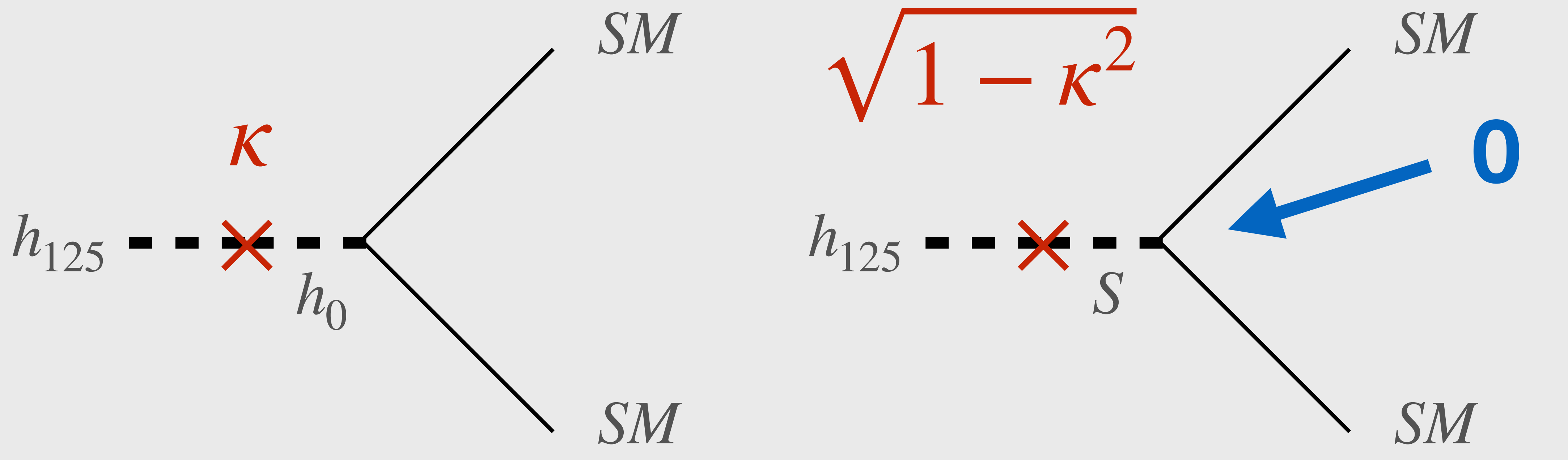




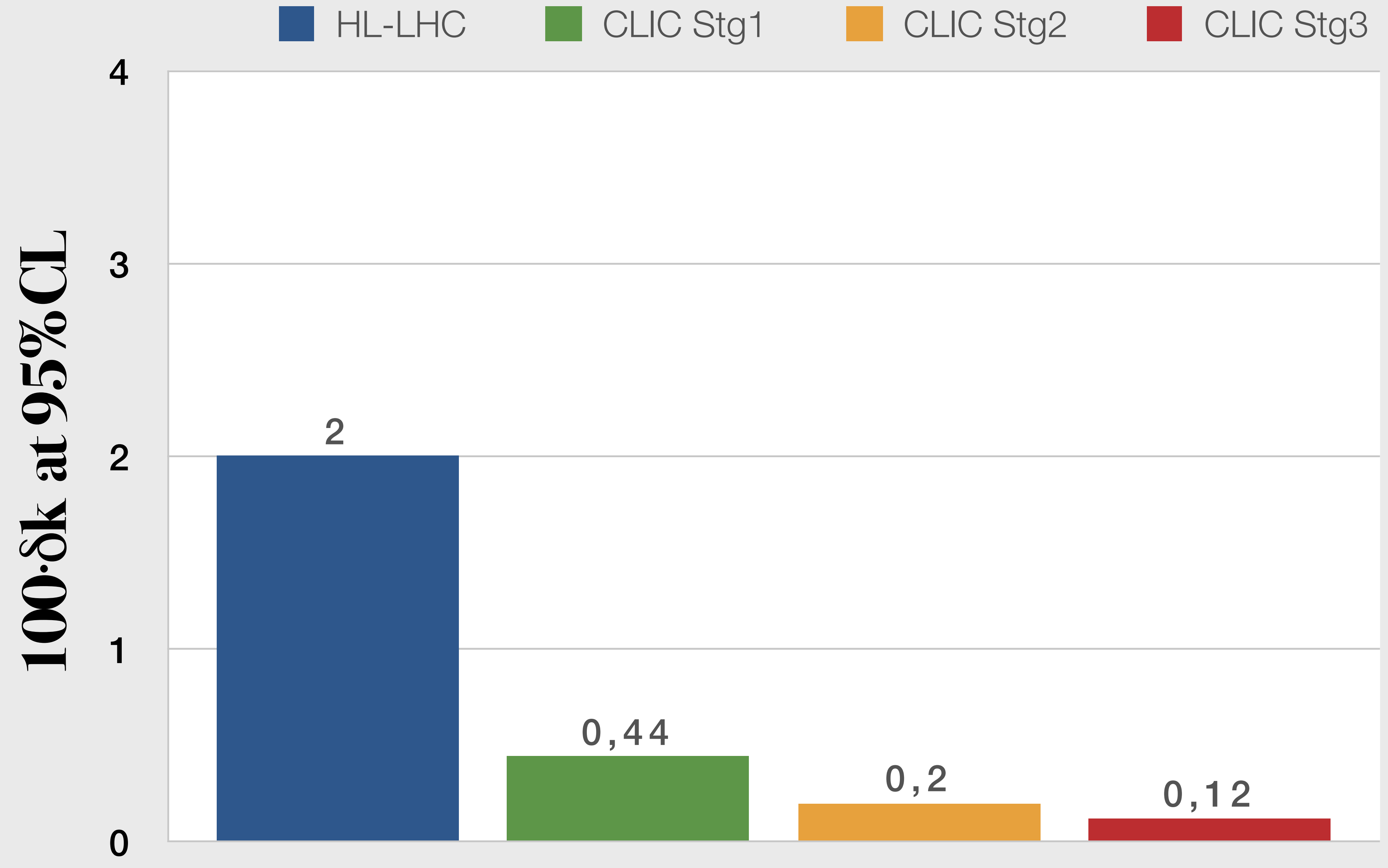
EFT

NEW SCALAR

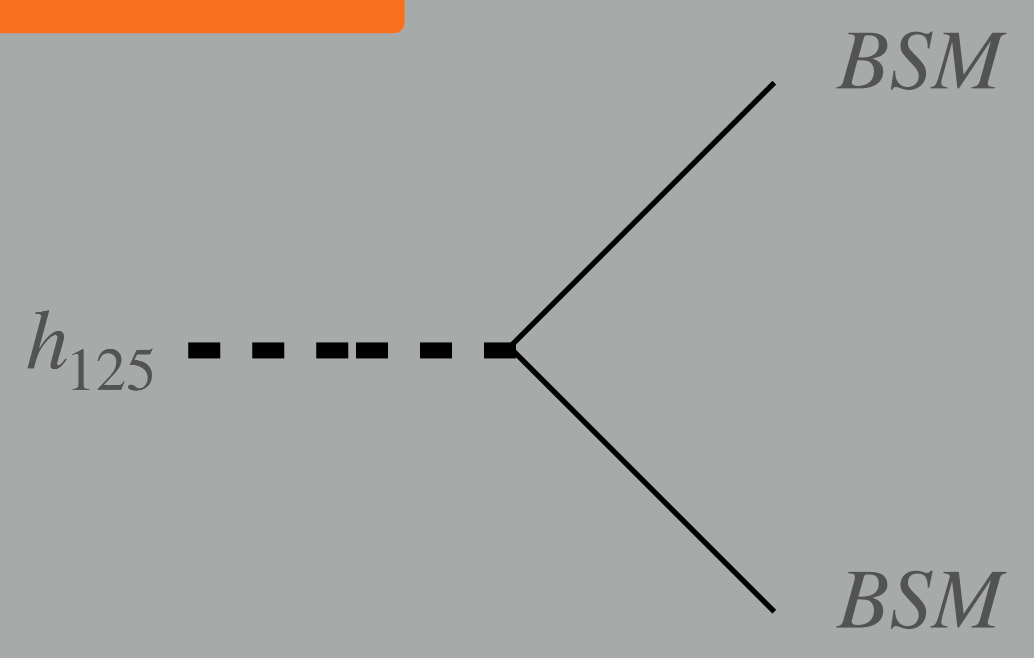
SM+HEAVY SINGLET



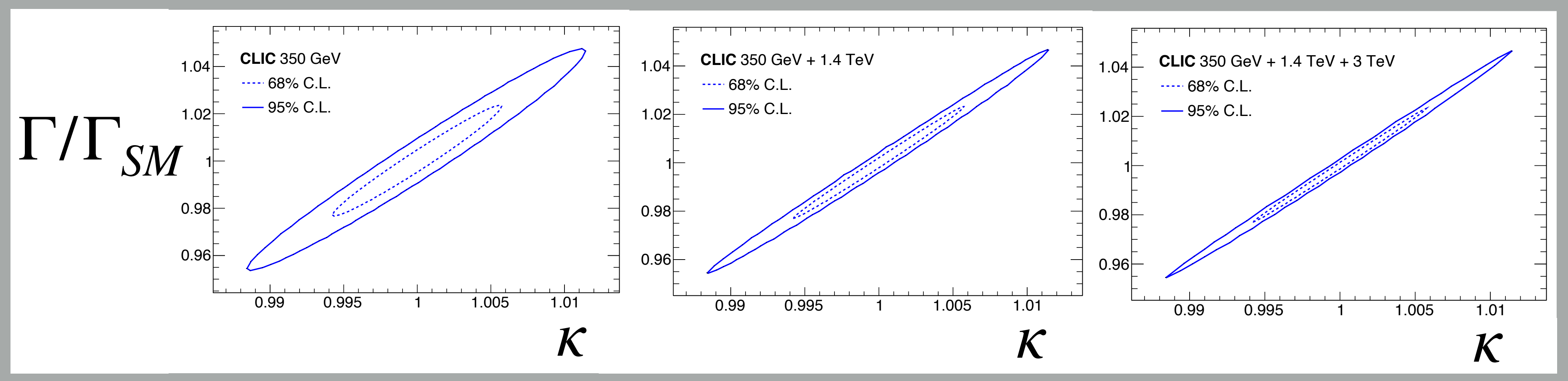
$$h_{125} = h_0 \cdot \kappa + S \cdot \sqrt{1-\kappa^2}$$



... BEYOND EFT

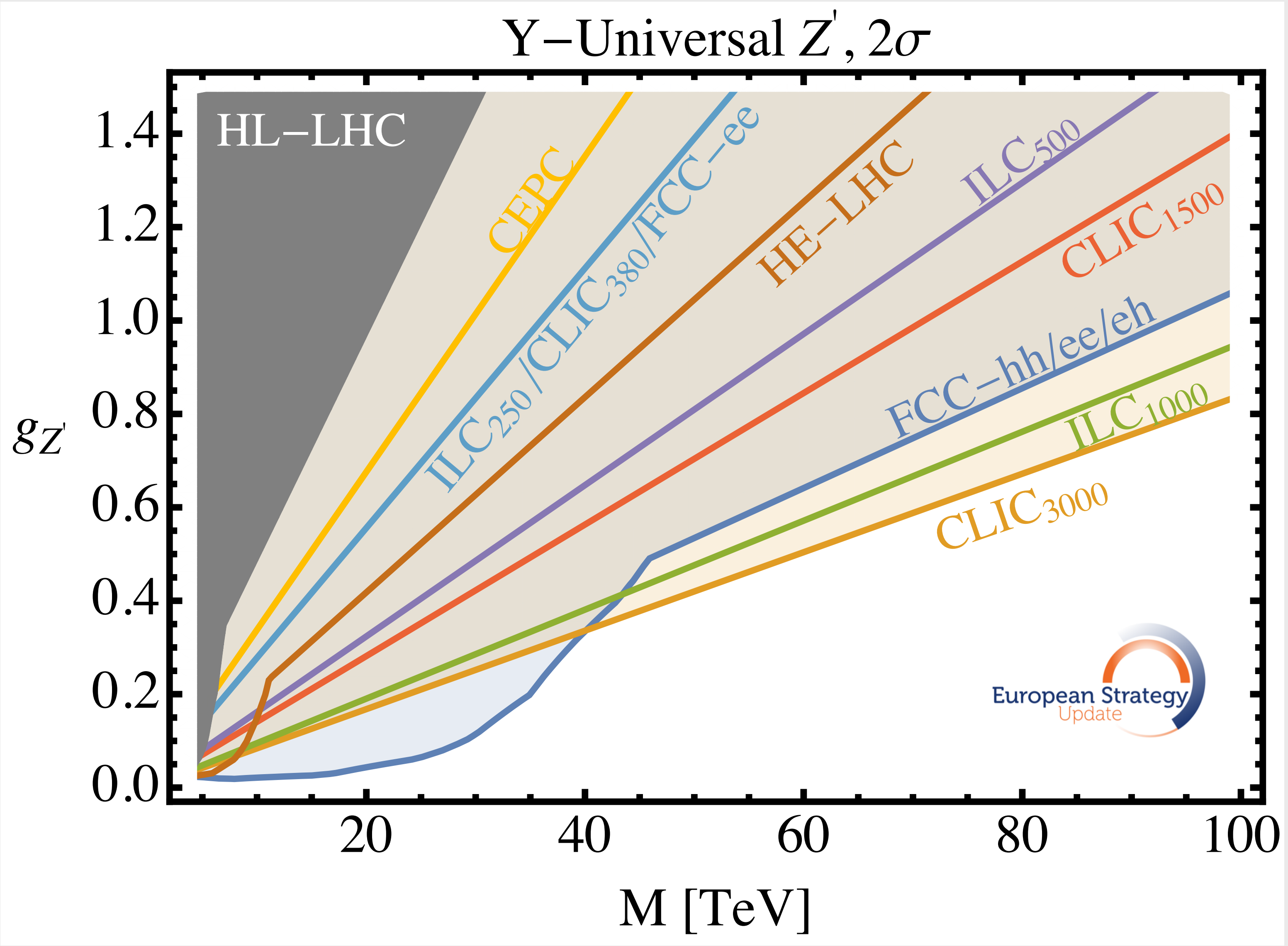


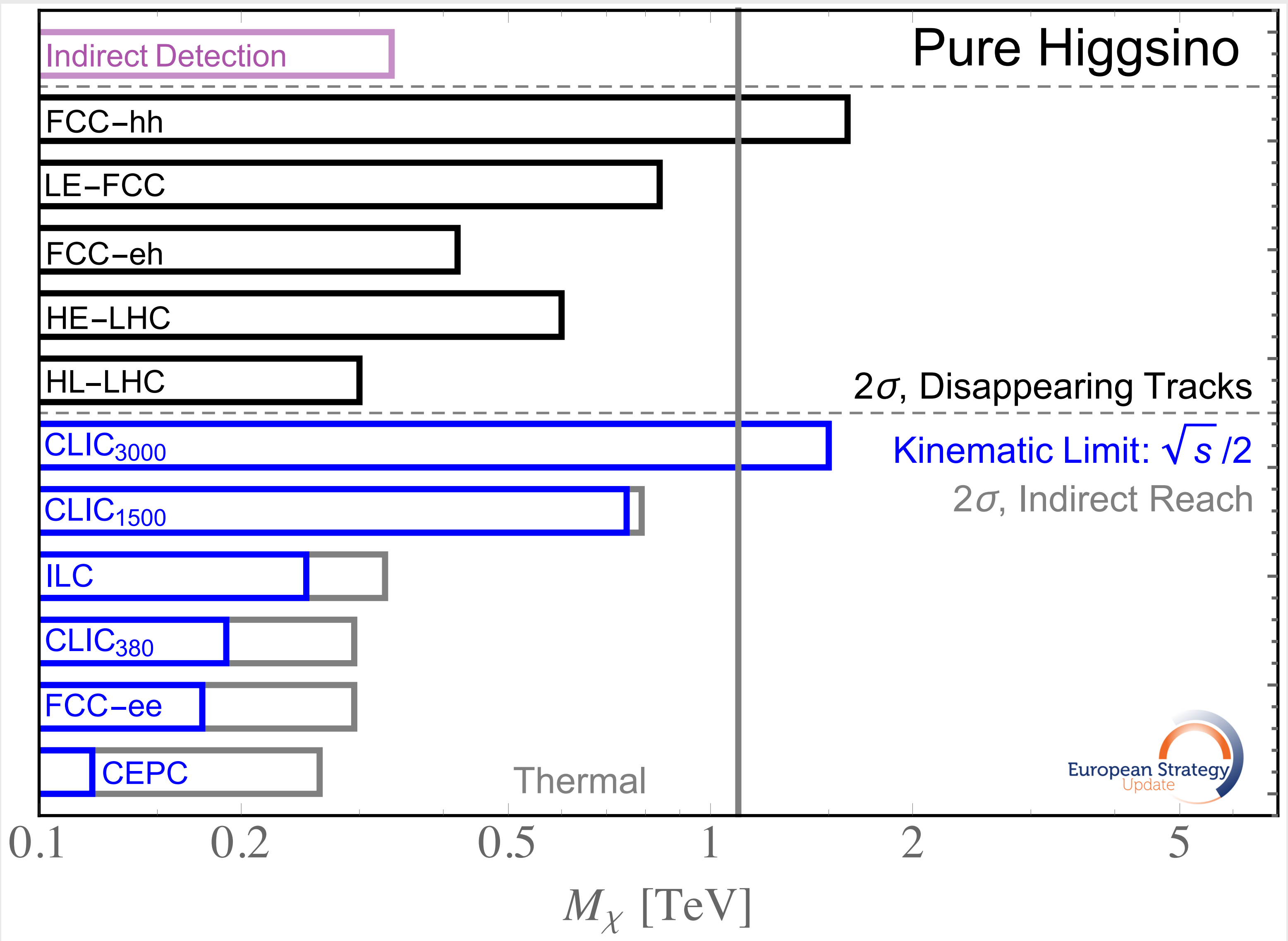
$$\Gamma_H = k^2 \Gamma_{SM} + \Gamma_{BSM}$$

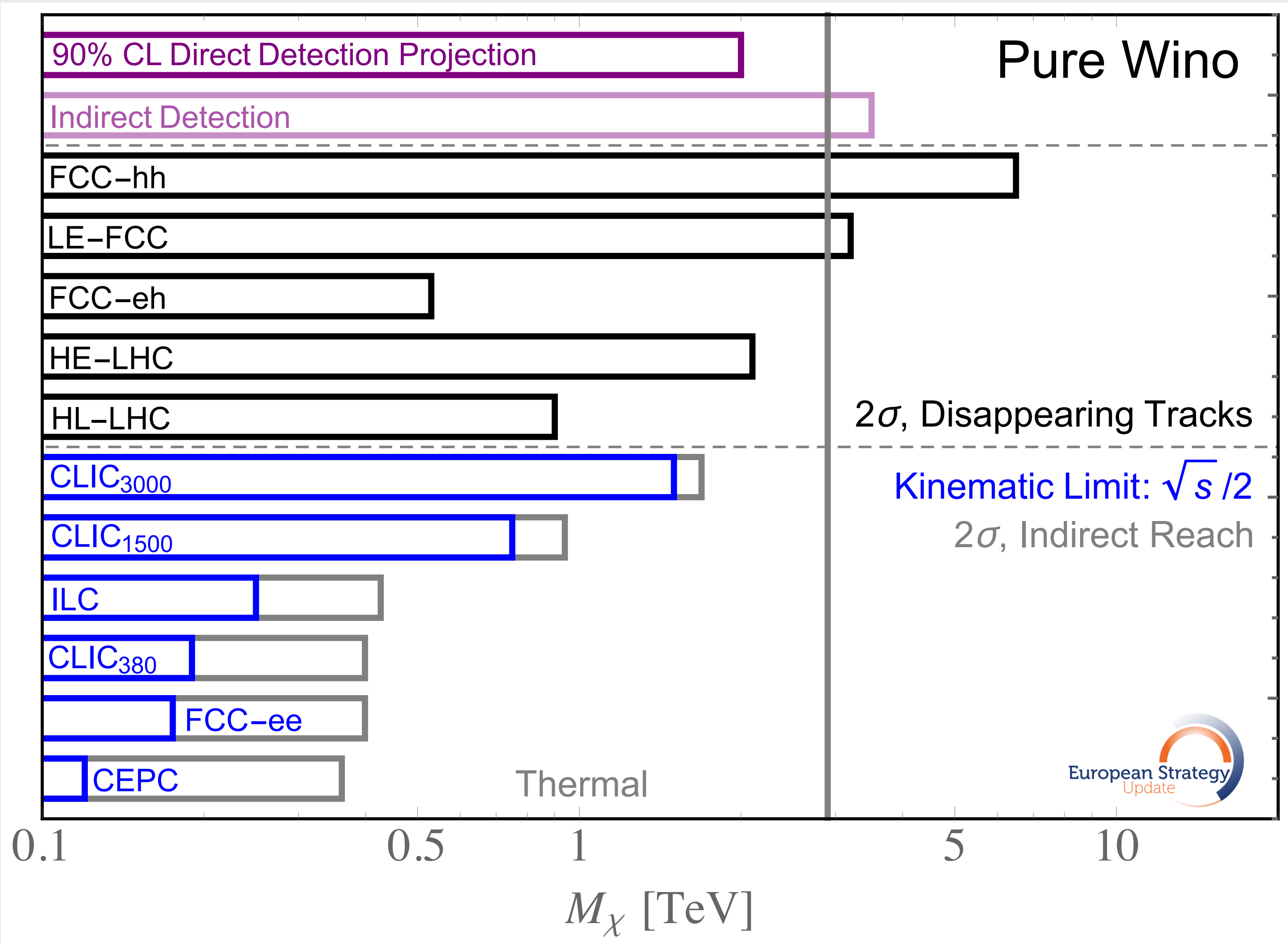


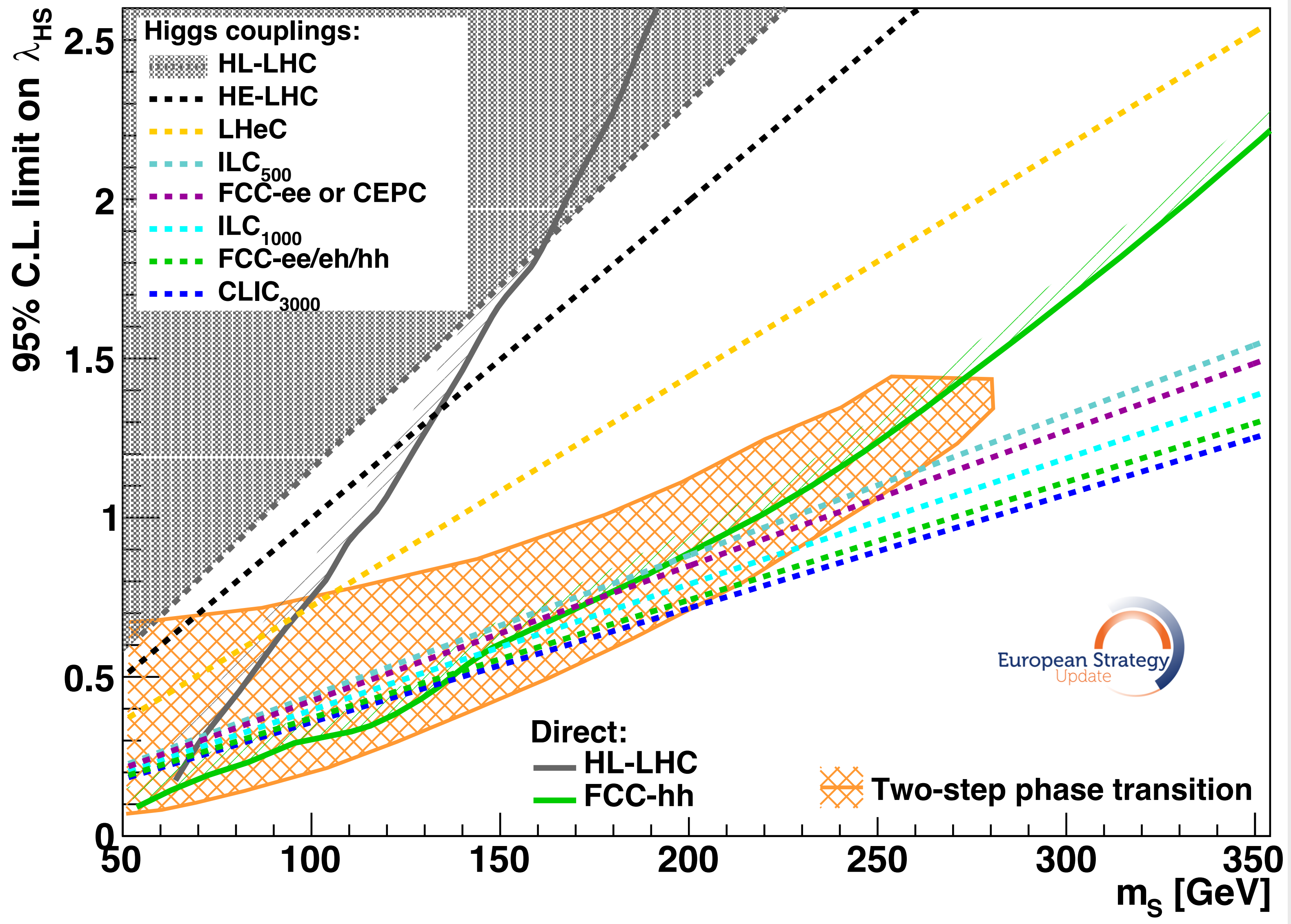
	Δg	$\Delta\Gamma_H$
Stage 1	0.58%	2.3%
Stage 1+2	0.57%	2.3%
Stage 1+2+3	0.57%	2.3%

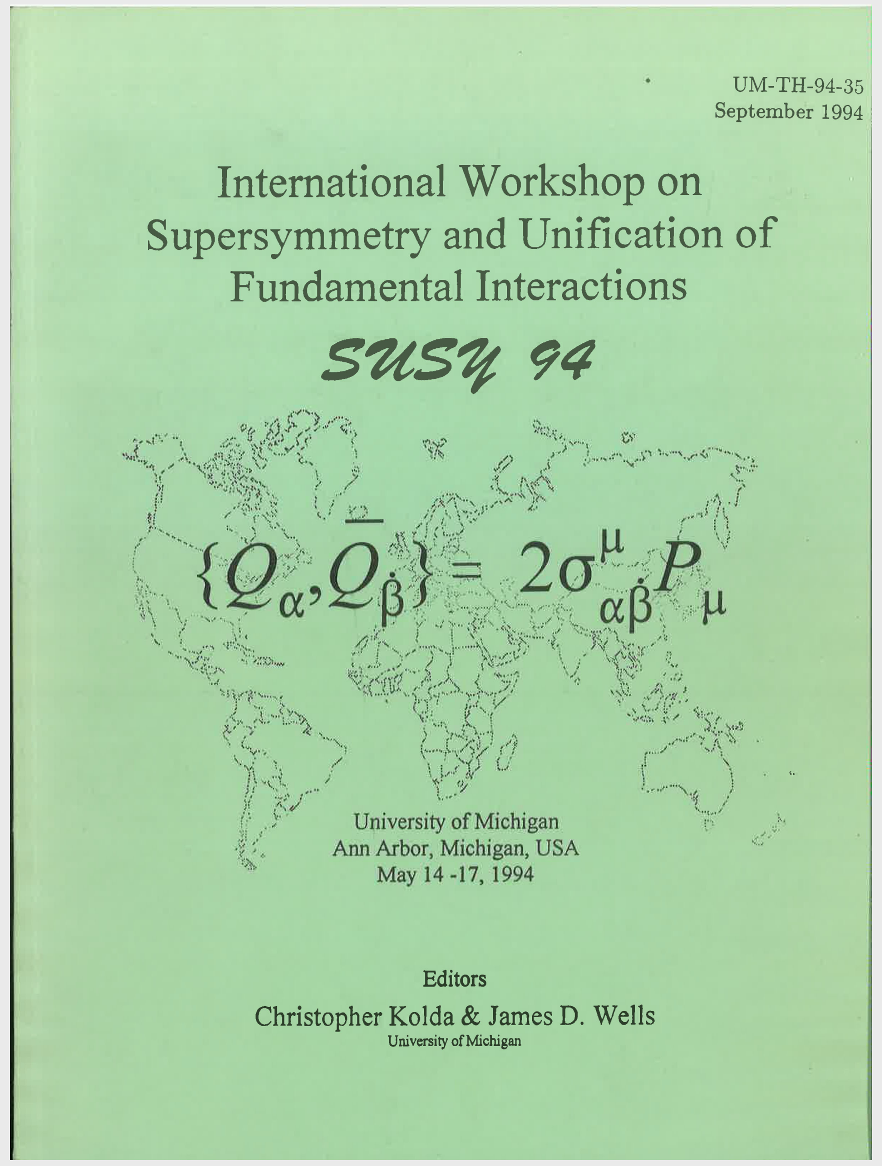
	$\Delta\Gamma_H$
Stage 1	0.47%
Stage 1+2	0.20%
Stage 1+2+3	0.13%










UM-TH-94-35
September 1994

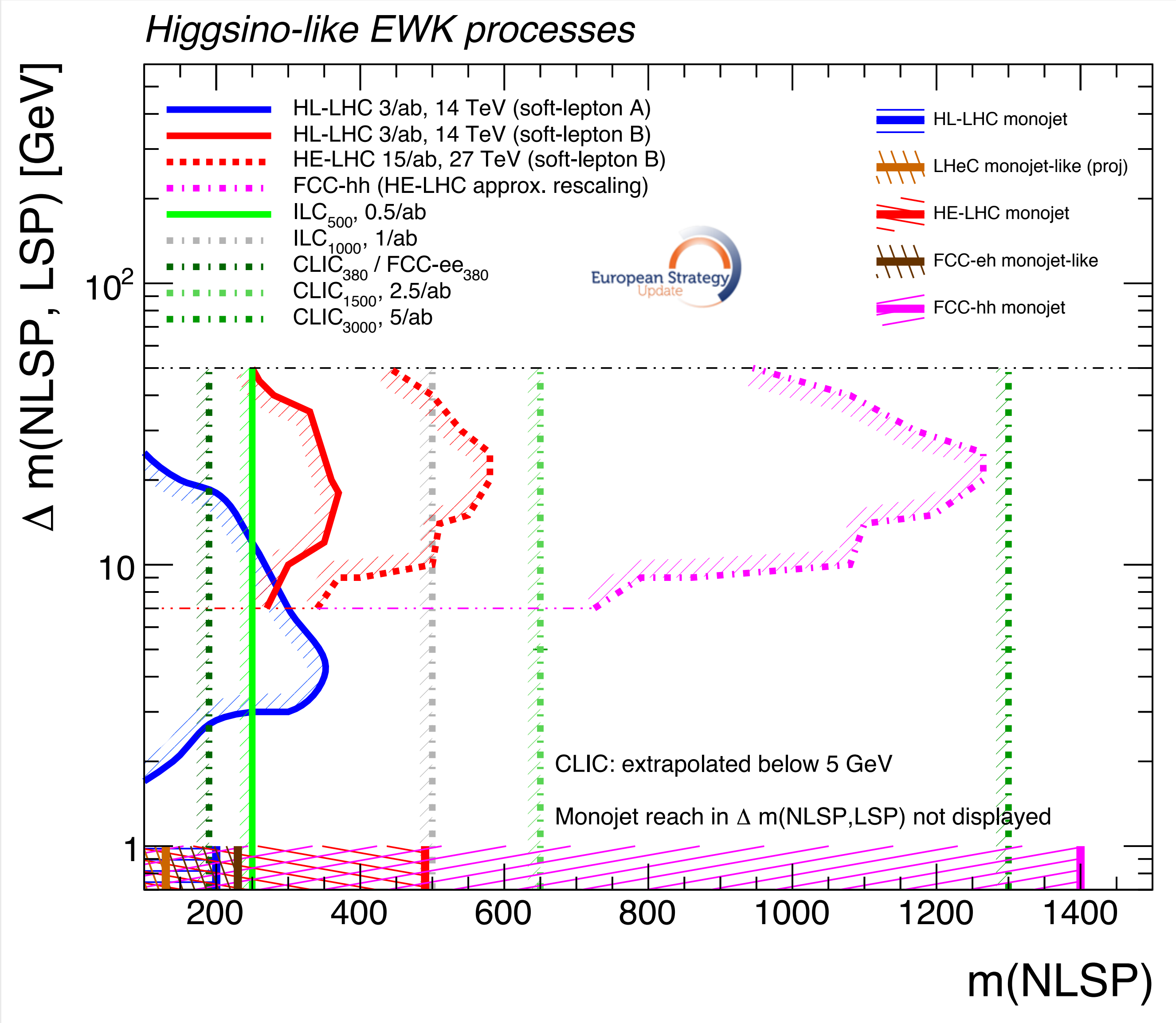
International Workshop on
Supersymmetry and Unification of
Fundamental Interactions

SUSY 94

$\{Q_\alpha, \bar{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$

University of Michigan
Ann Arbor, Michigan, USA
May 14 -17, 1994

Editors
Christopher Kolda & James D. Wells
University of Michigan



$e^+e^- \to f\bar{f}$

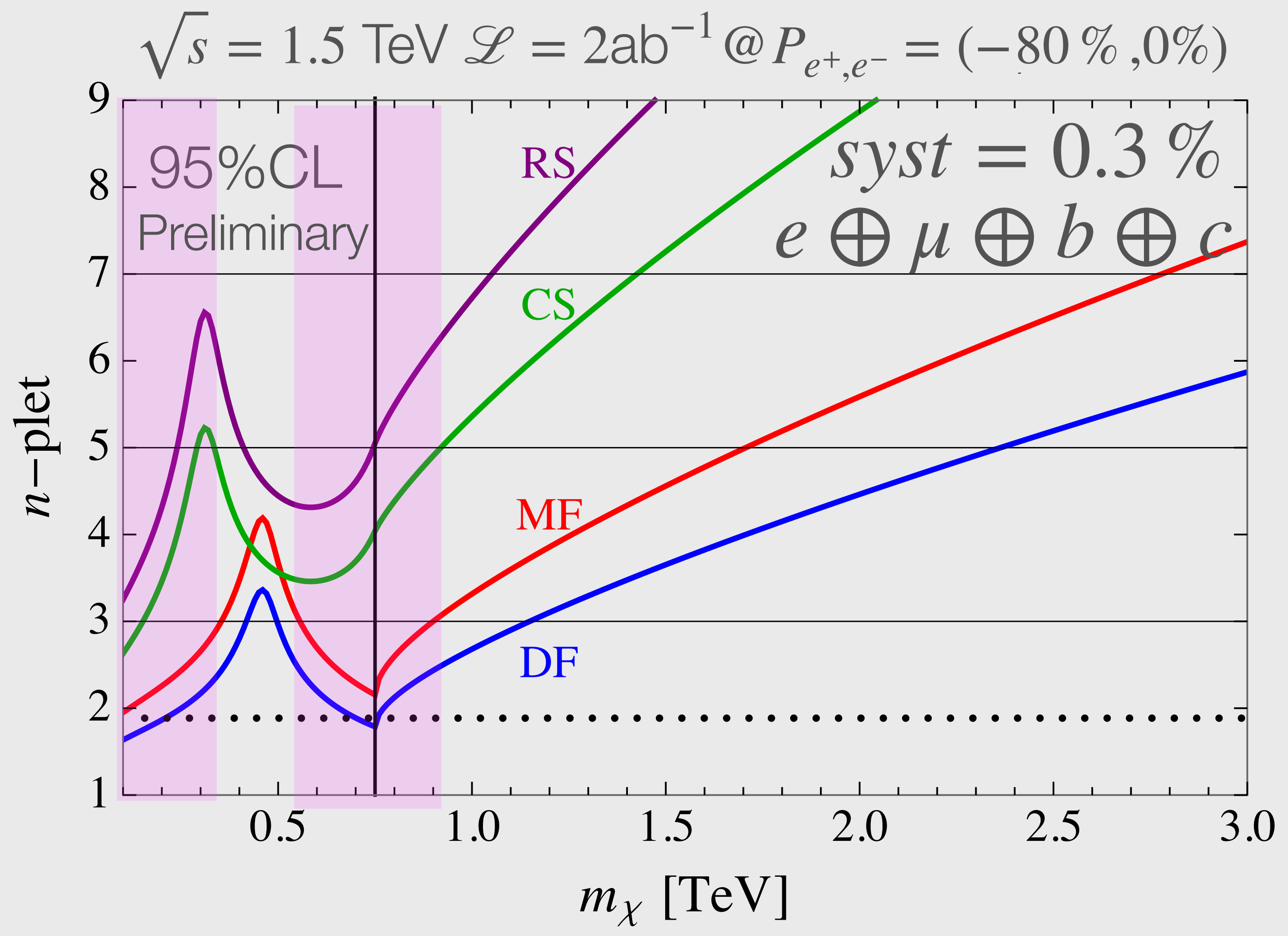
PRECISION | ANGULAR DISTRIBUTION

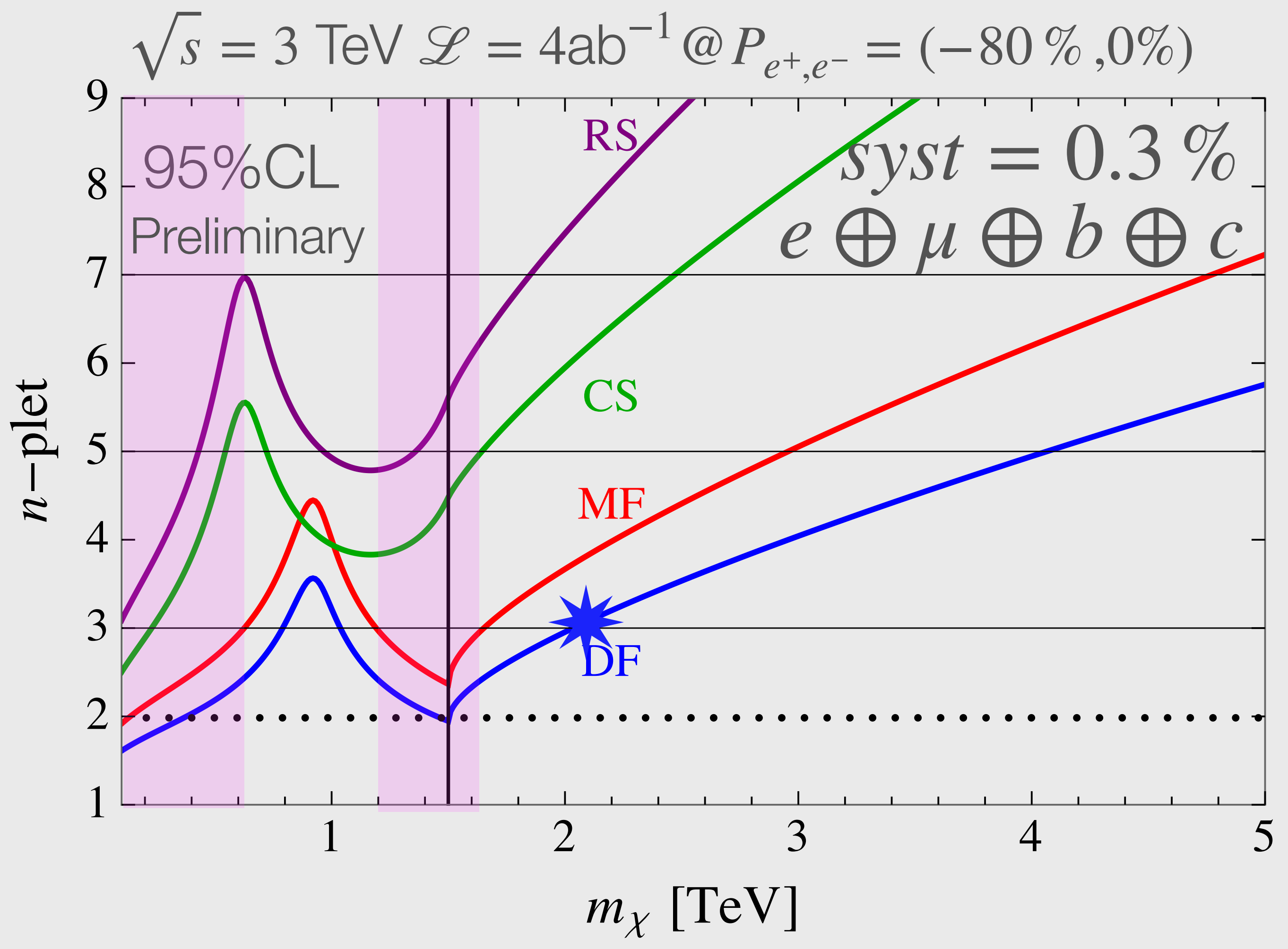
χ	$m_\chi^{(\mathrm{DM})}$ [TeV]	$m_\chi^{(\mathrm{CLIC-3})}$ [TeV]
$(1,2,1/2)_{\mathrm{DF}}$	1.1	1.5
$(1,3,\epsilon)_{\mathrm{CS}}$	1.55	-
$(1,3,\epsilon)_{\mathrm{DF}}$	2.0	2.1 ✶
$(1,3,0)_{\mathrm{MF}}$	2.8	1.7
$(1,5,\epsilon)_{\mathrm{CS}}$	6.6	1.7
$(1,5,\epsilon)_{\mathrm{DF}}$	6.6	4.1
$(1,5,0)_{\mathrm{MF}}$	11	3.0
$(1,7,\epsilon)_{\mathrm{CS}}$	16	2.5
$(1,7,\epsilon)_{\mathrm{DF}}$	16	6.8

Higgsino of split-SUSY (heavy sfermions)

Wino of split-SUSY (heavy sfermions)

Accidental Dark Matter 3-plet Dirac Fermion





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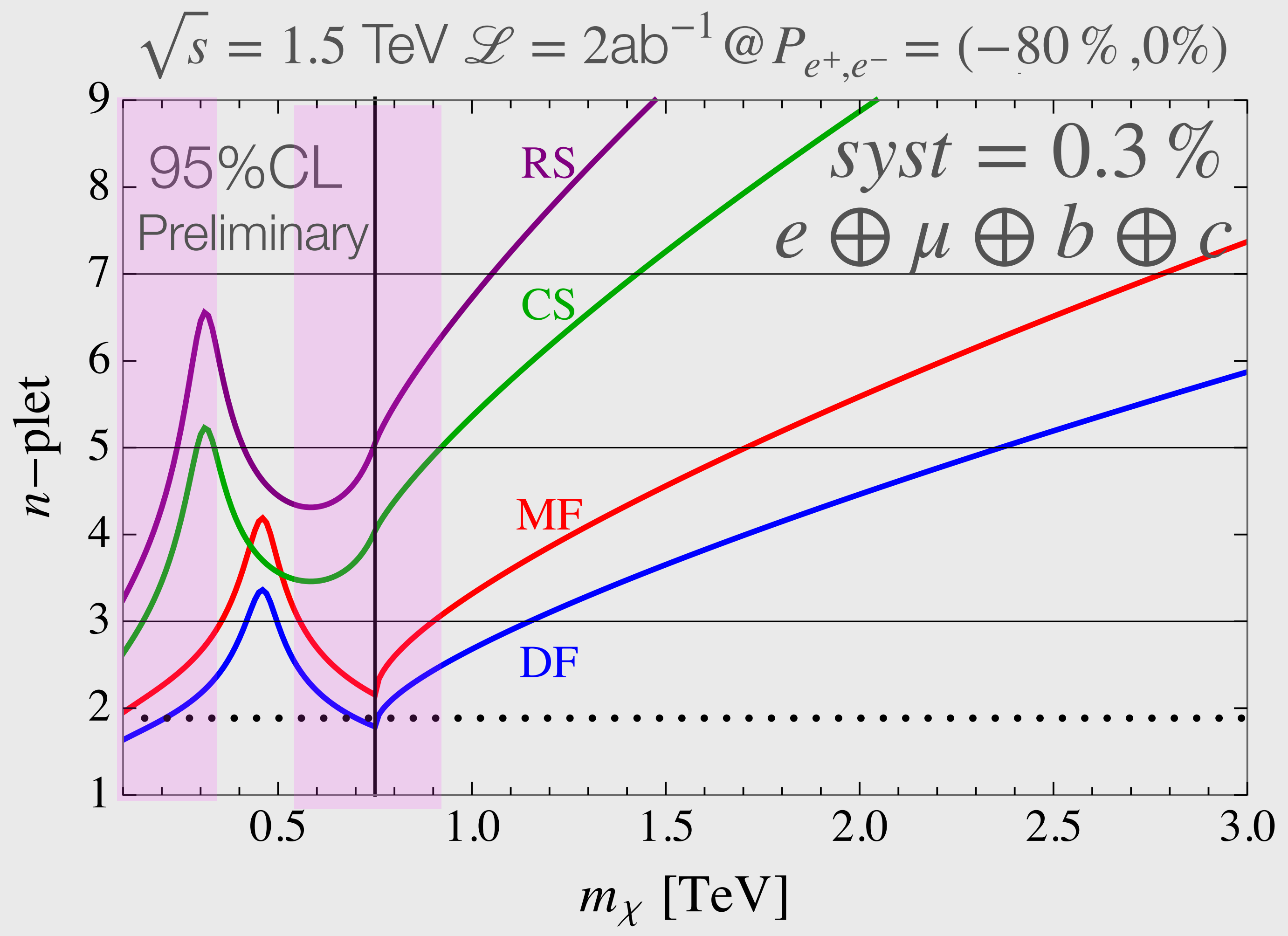

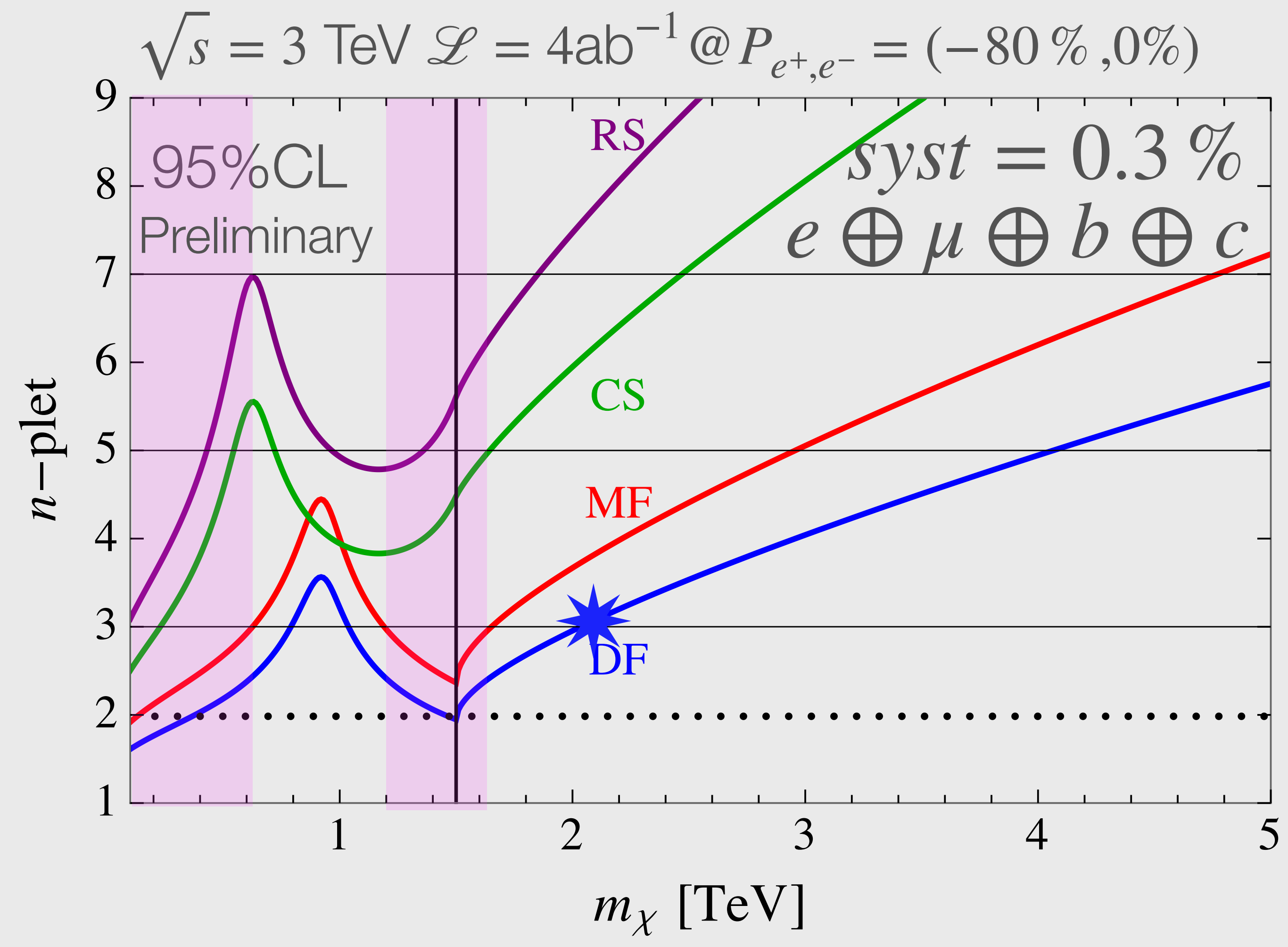

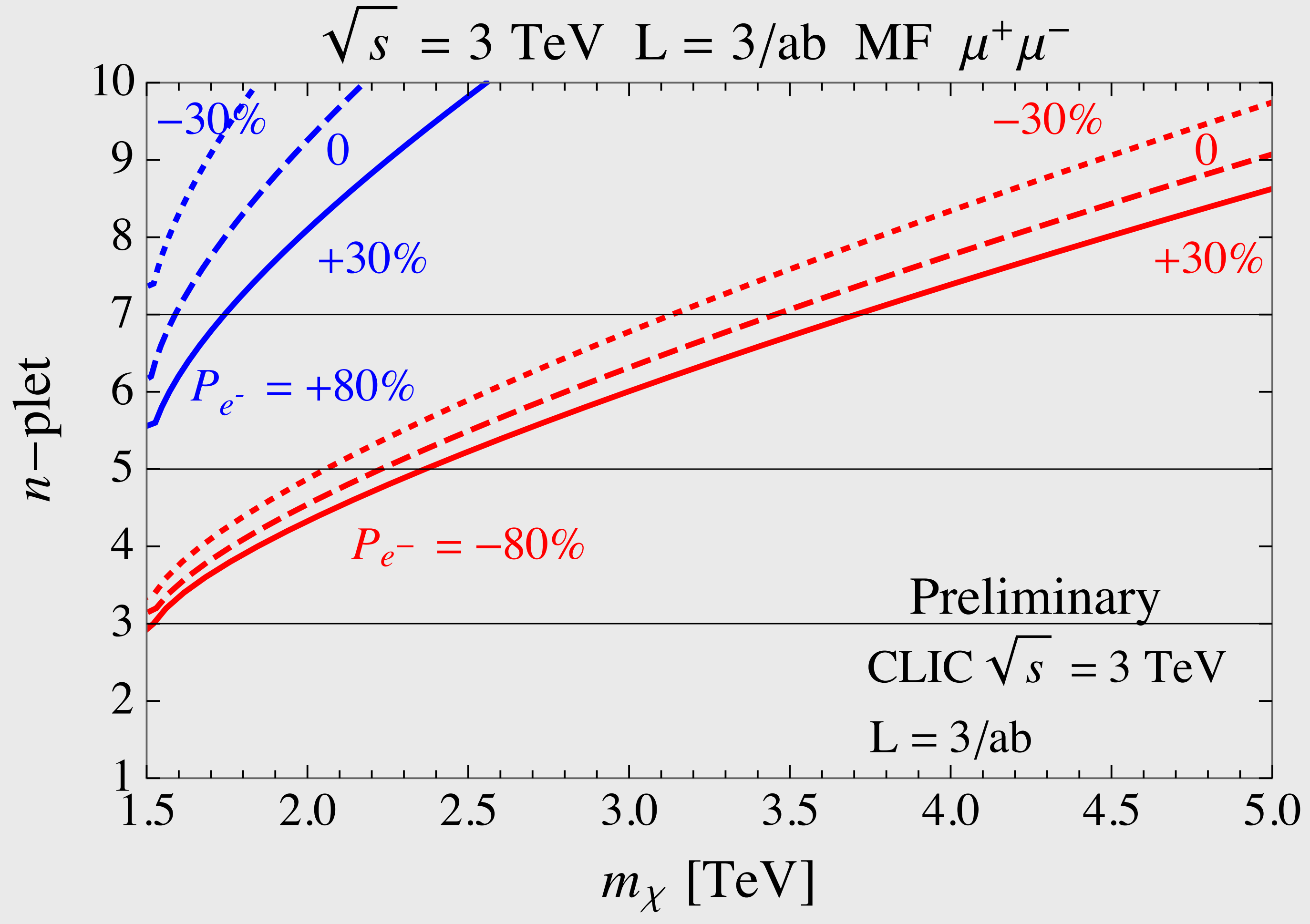

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PRECISION ANGULAR DISTRIBUTION

Polarization is very advantageous

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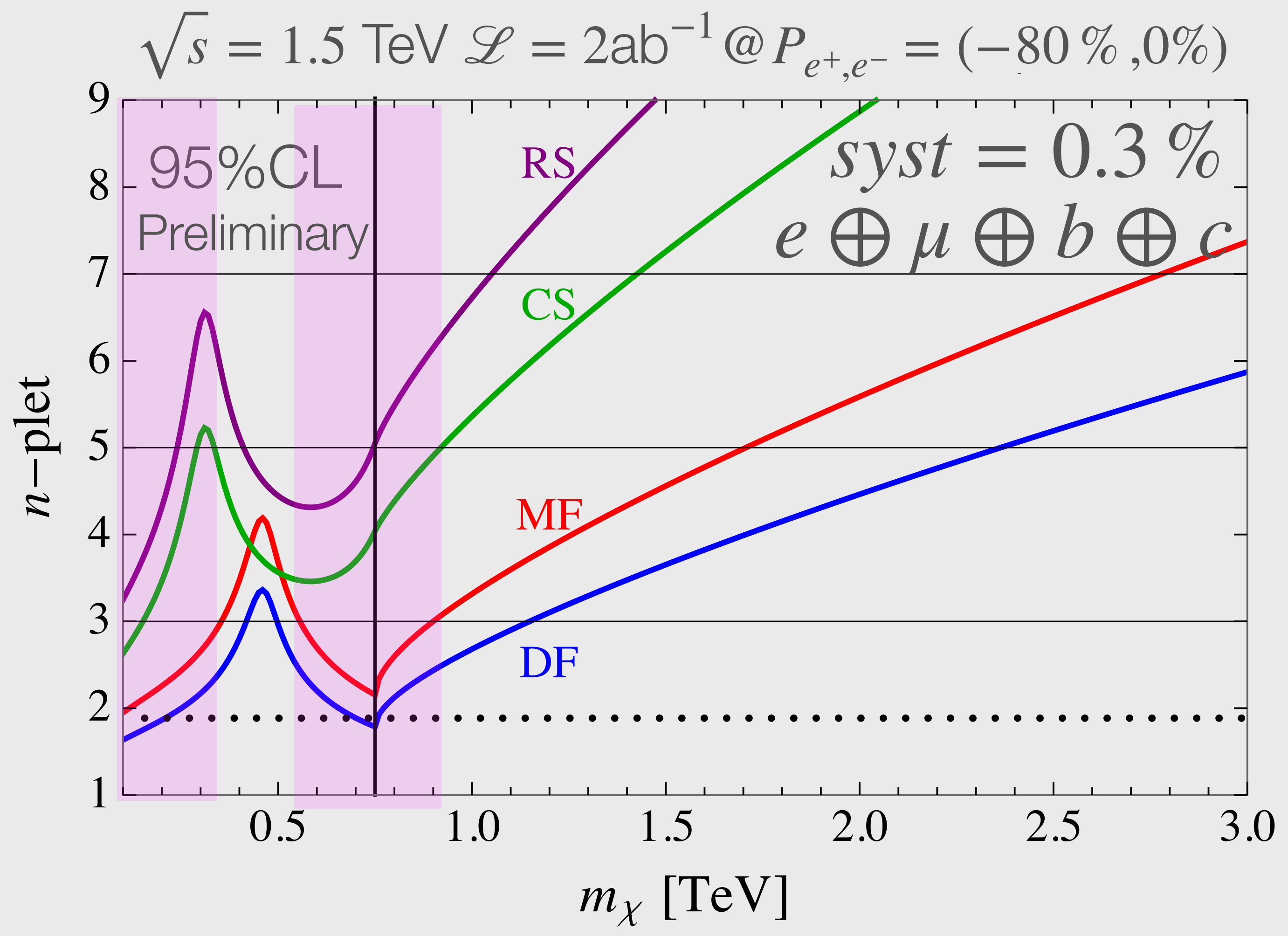

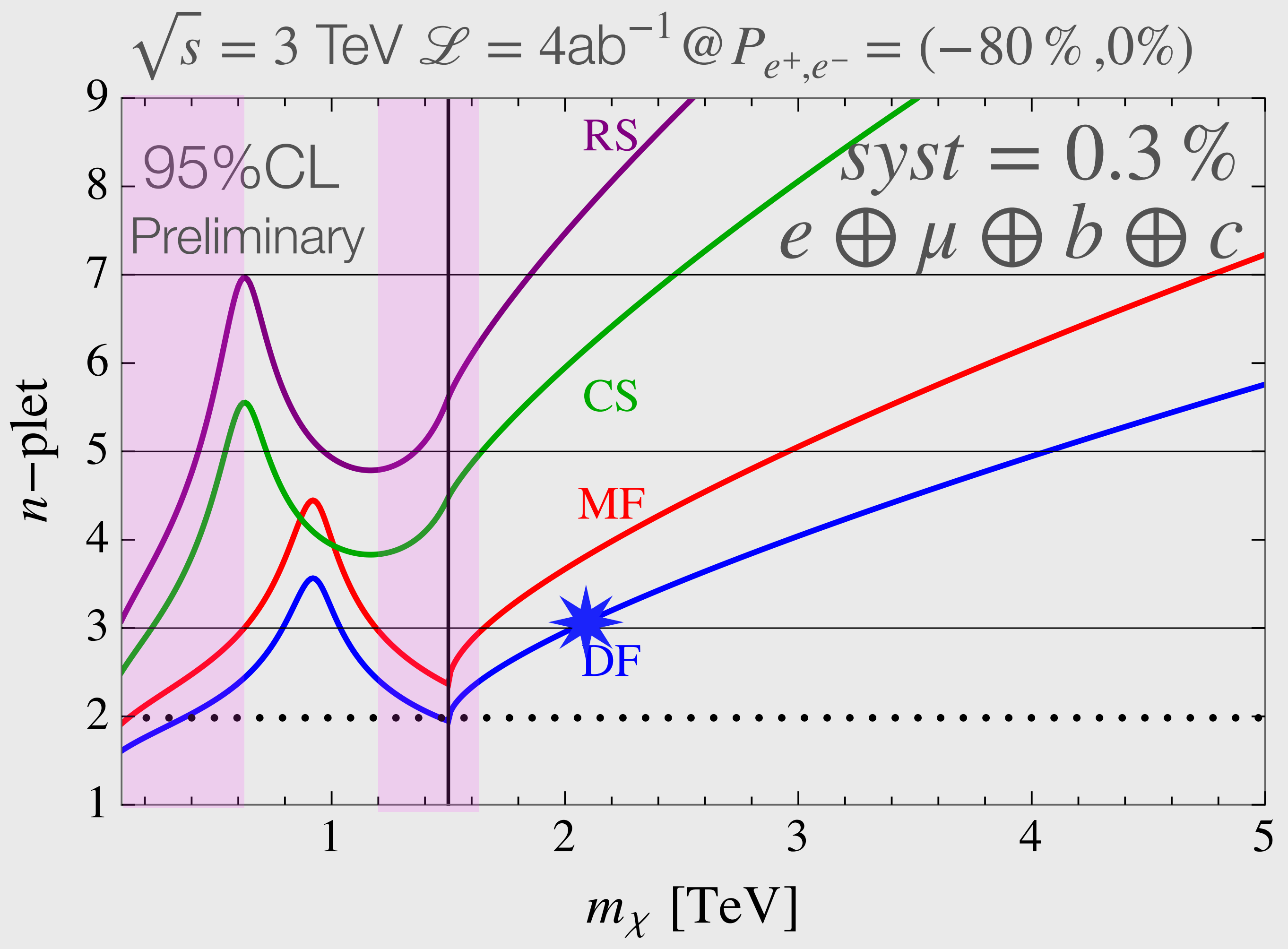

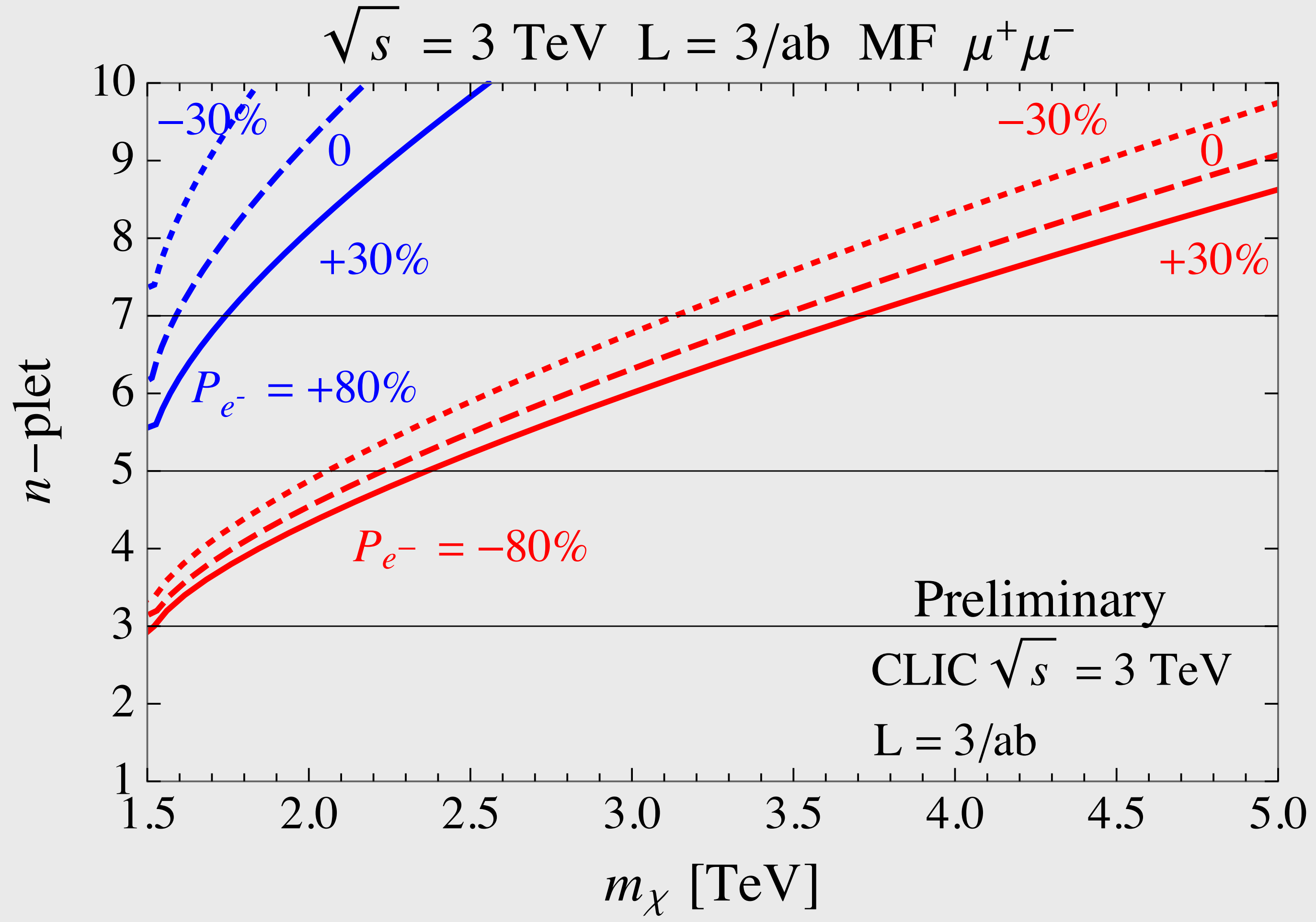

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