Physics at the High Energy Muon Collider

APR. 25 2023

ROBERTO FRANCESCHINI (ROMA 3 UNIVERSITY)

ROMA TRE UNIVERSITÀ DEGLI STUDI

INFN Roma3

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

		Question	WEAK INTERACTIONS	STRONG INTERACTIONS
	?	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?	✓	
~~EFT~~		why gravity and weak interactions are so different?	✓	
~~EFT~~		what fixes the cosmological constant?	✓	

Accelerators are excellent probes

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

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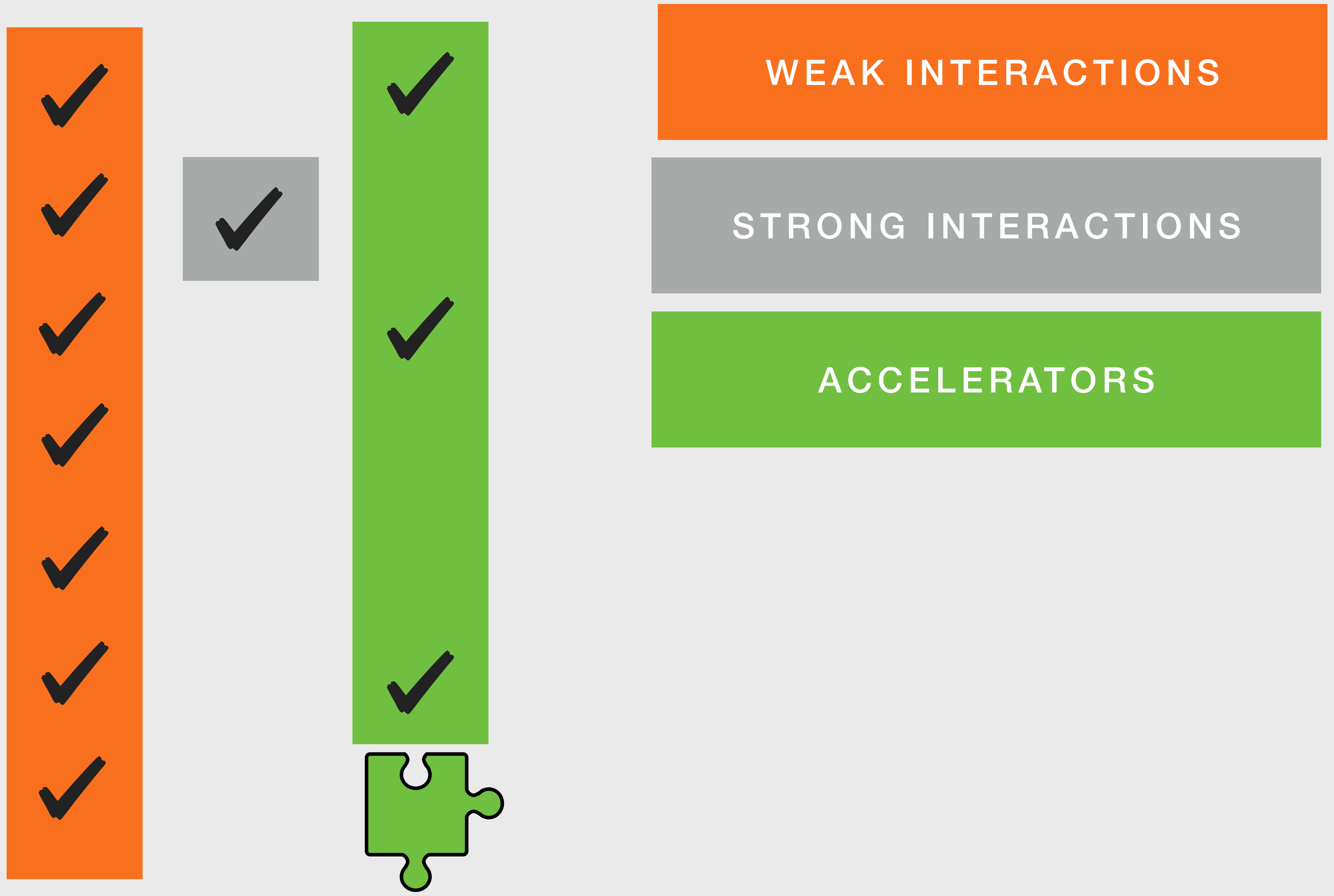

Accelerators are excellent probes

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

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

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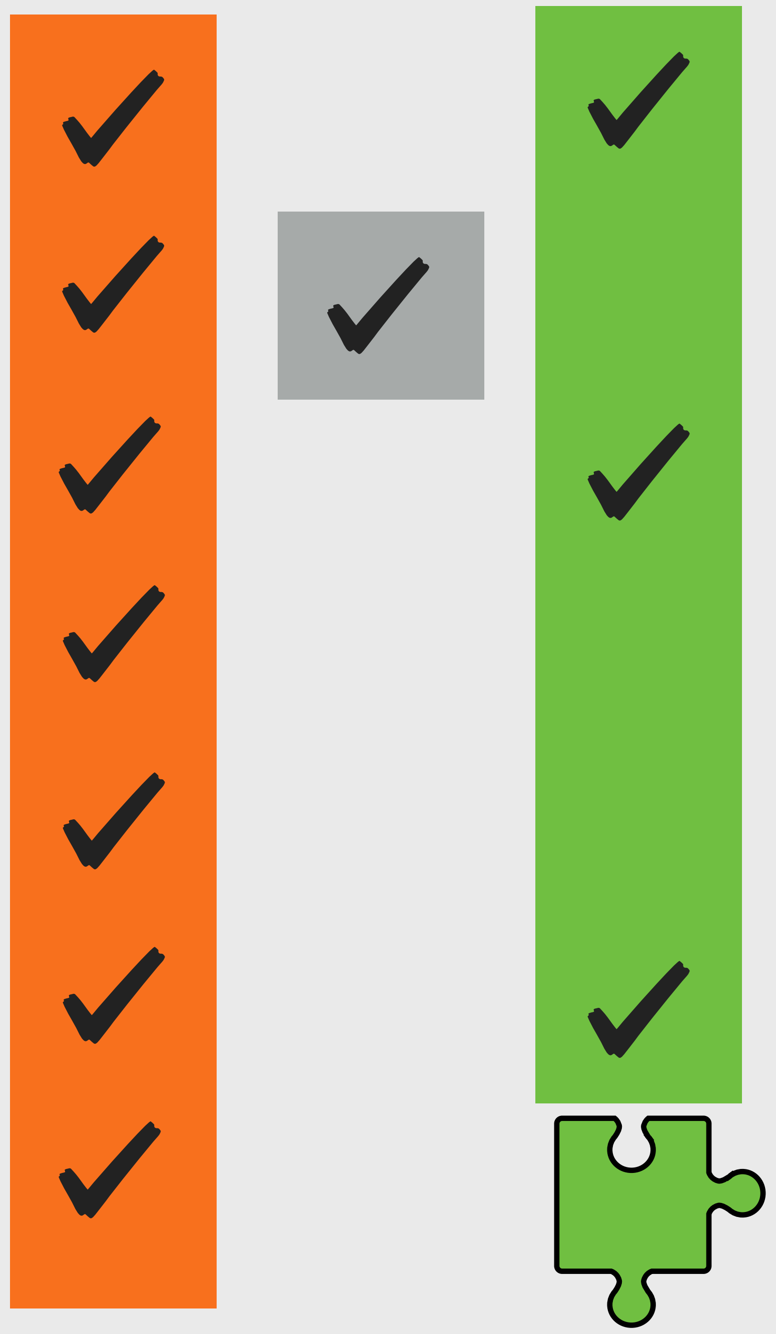


WEAK INTERACTIONS

STRONG INTERACTIONS

ACCELERATORS

Accelerators are excellent probes

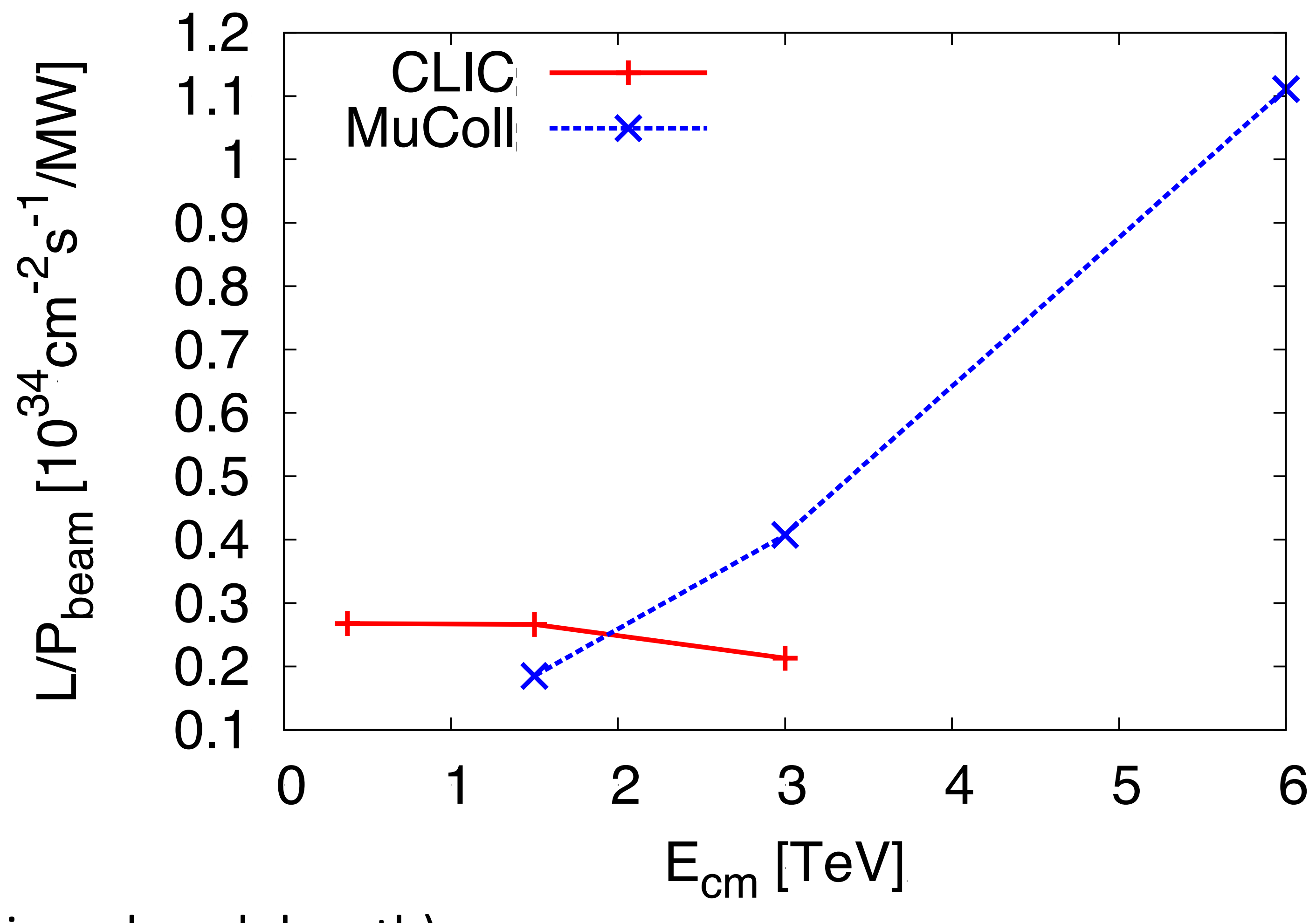
Muon colliders

HIGHLY EFFICIENT | **HIGH ENERGY COLLIDER**

Luminosity Comparison

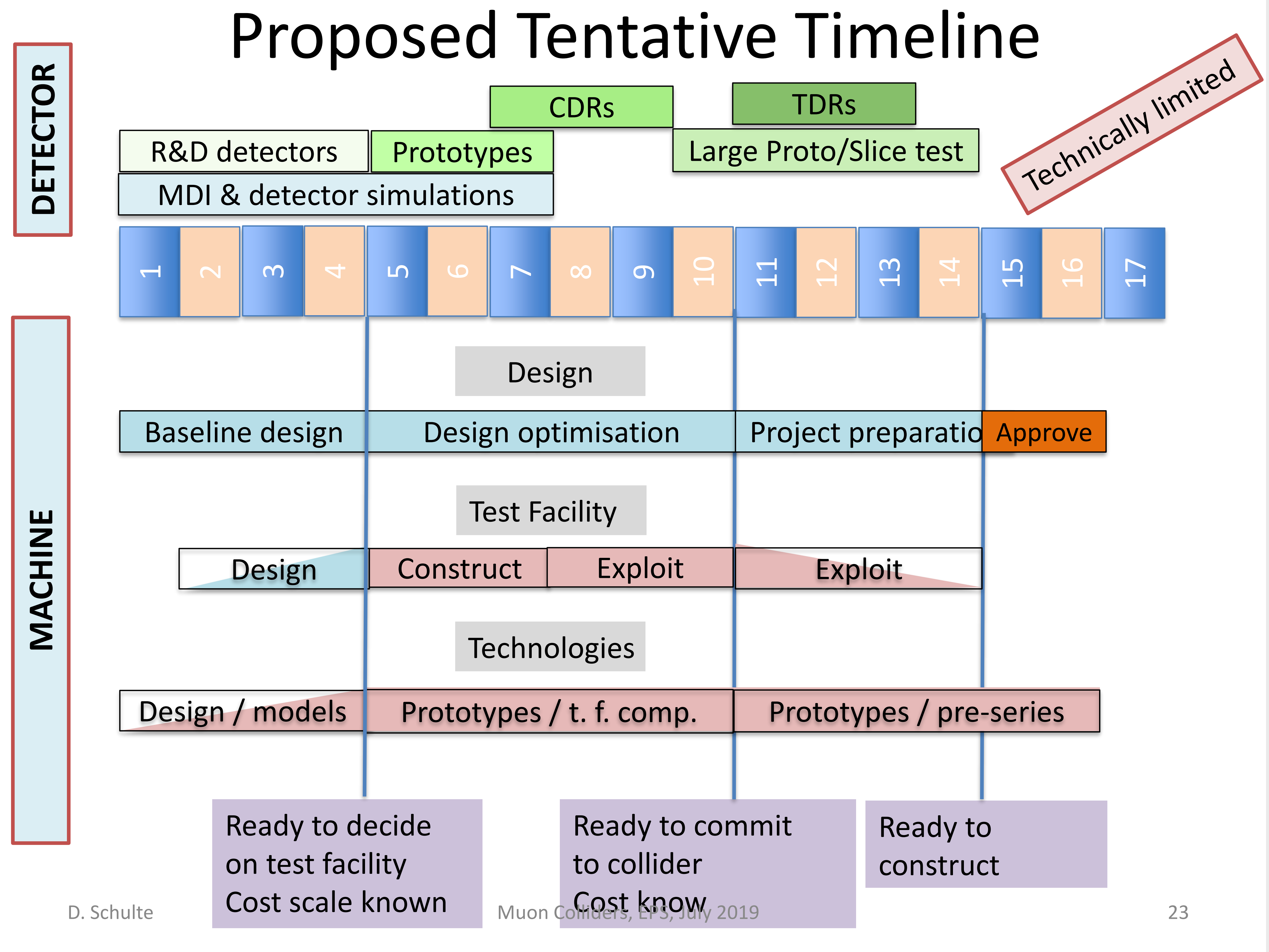
The luminosity per beam power is about constant in linear colliders

It can increase in proton-based muon colliders



Strategy CLIC:
Keep all parameters at IP constant
(charge, norm. emittances, betafunctions, bunch length)
⇒ Linear increase of luminosity with energy (beam size reduction)

Strategy muon collider:
Keep all parameters at IP constant
With exception of bunch length and betafunction
⇒ Quadratic increase of luminosity with energy (beam size reduction)



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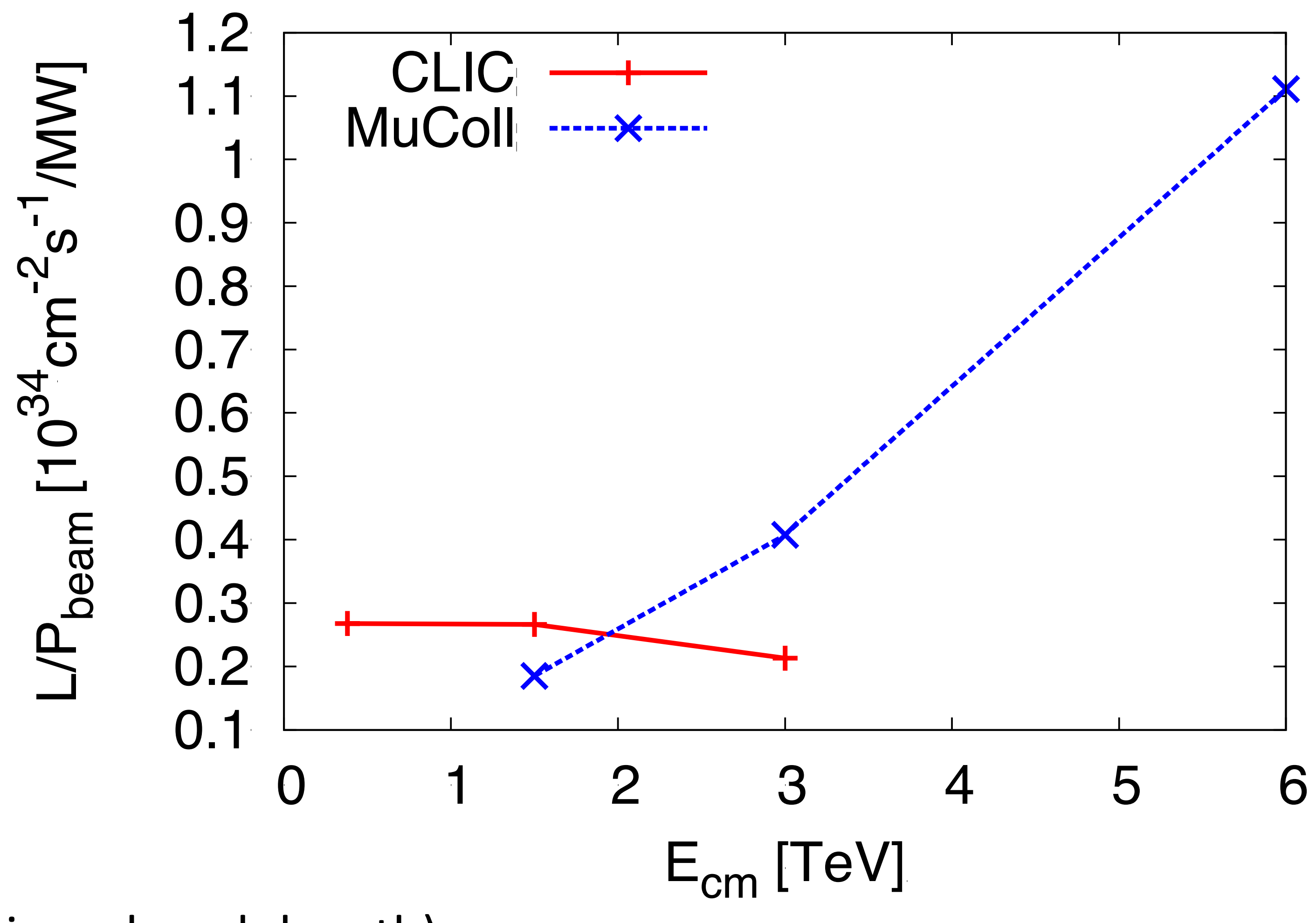

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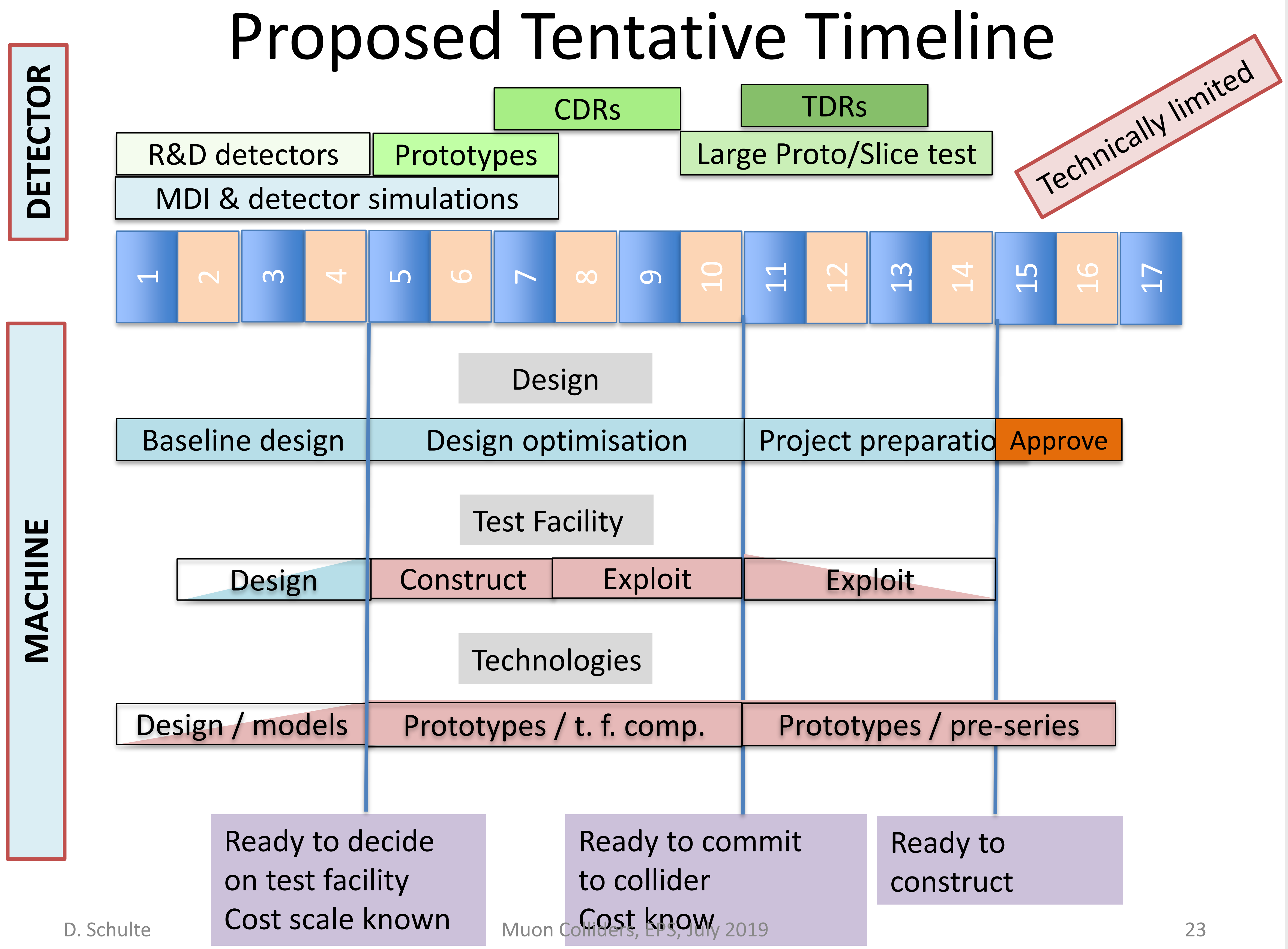
D. Schulte Muon Colliders, EPS, July 2019 7



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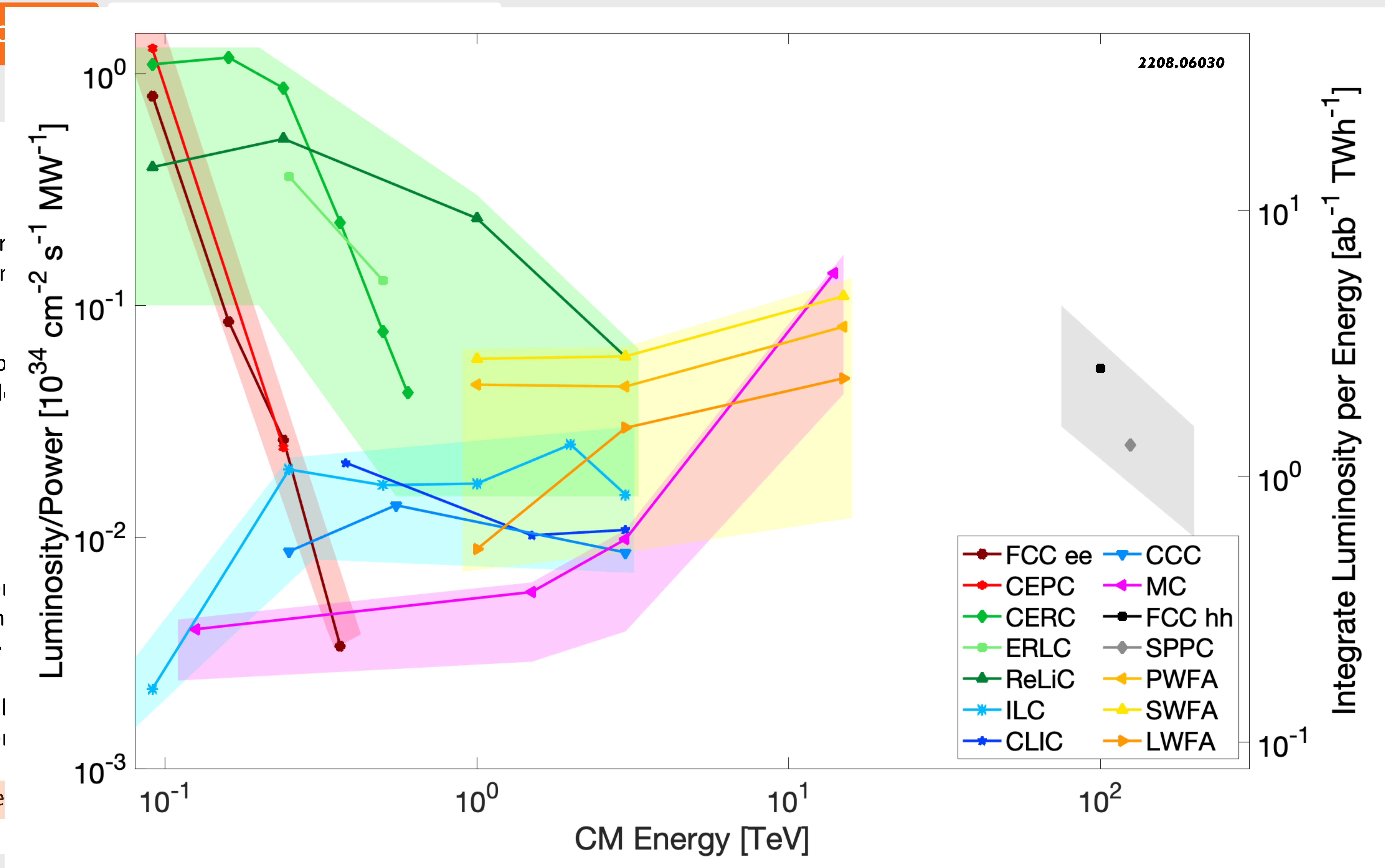
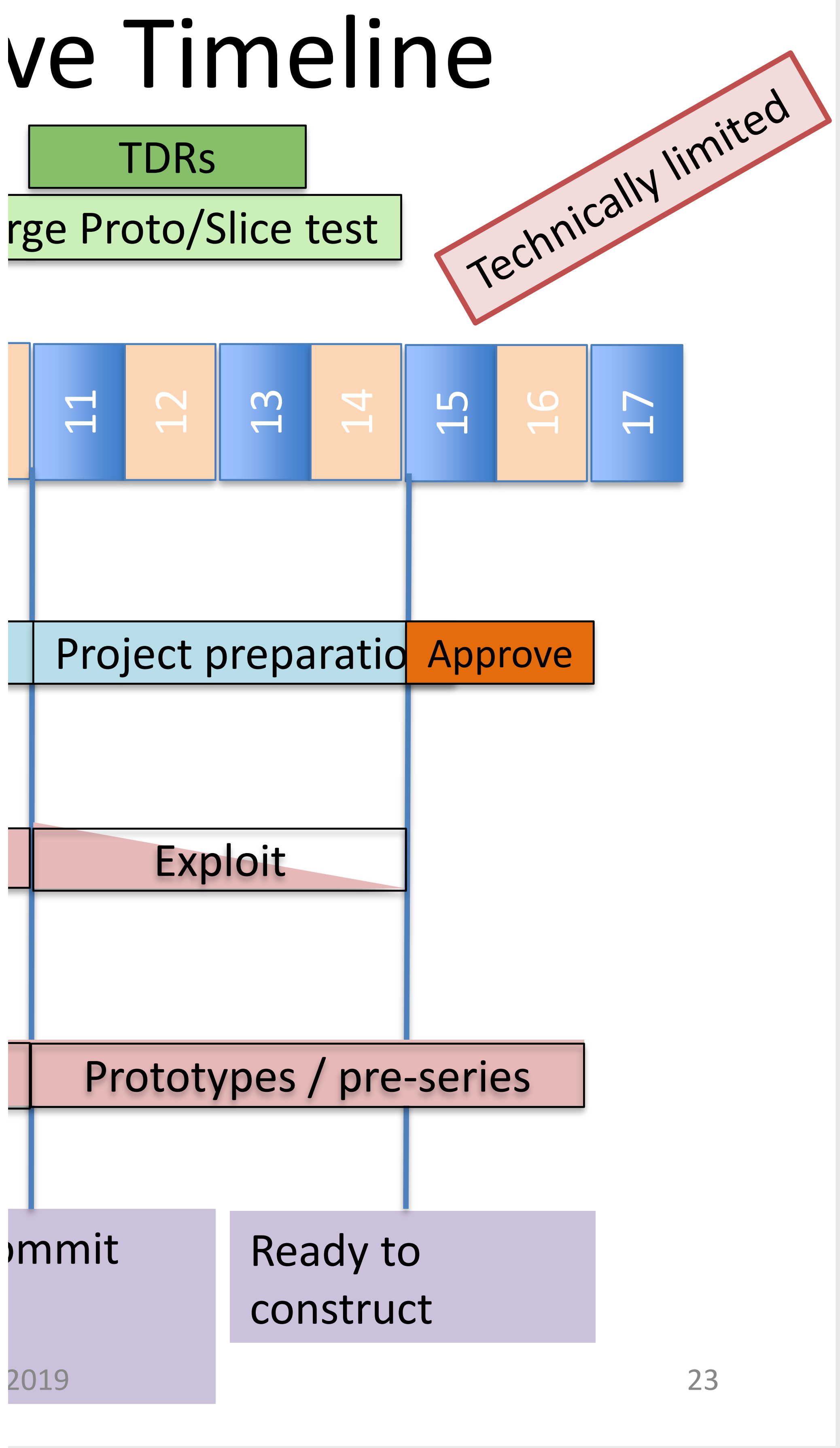
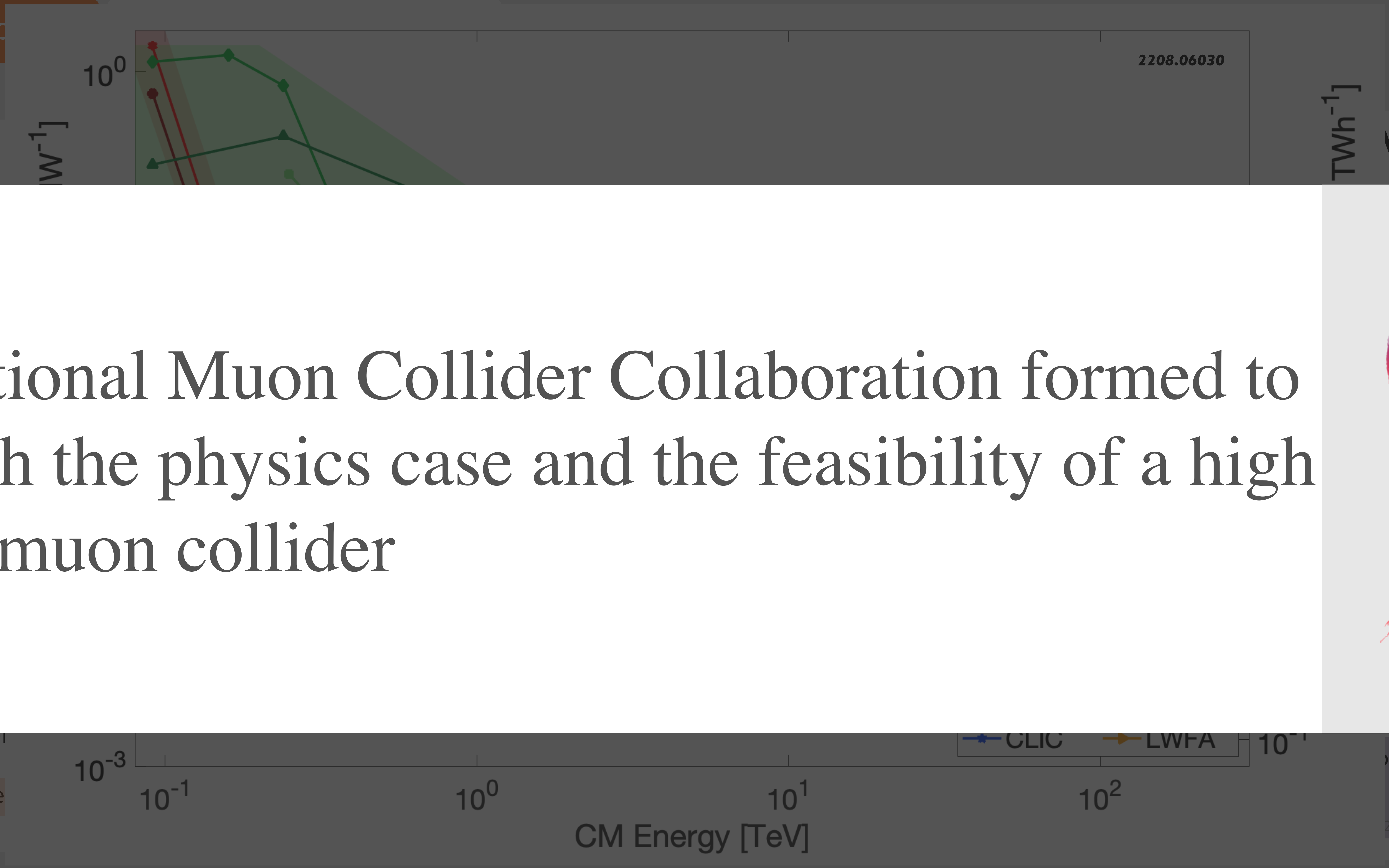




https://muoncollider.web.cern.ch/ 2203.07261 2203.07256 2203.07224 2203.08033 2203.07964

Muon colliders



- International Muon Collider Collaboration formed to establish the physics case and the feasibility of a high energy muon collider

A Muon Collider in the US?

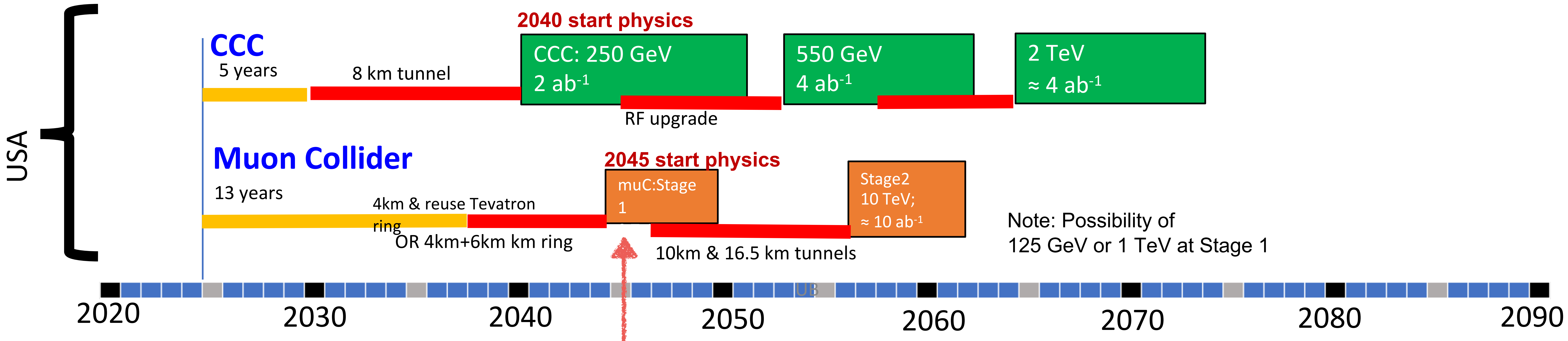
Possible scenarios of future colliders

Proton collider
Electron collider
Muon collider

Construction/Transformation
Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

2045^{10}_{0} first $\mu^+\mu^-$ collisions pushing both the intensity and energy frontier

VERY SIGNIFICANT INTEREST FROM US COMMUNITY IN RECENT YEARS CULMINATED AT SNOWMASS 2022

Muons collisions

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

DIRECT SEARCHES

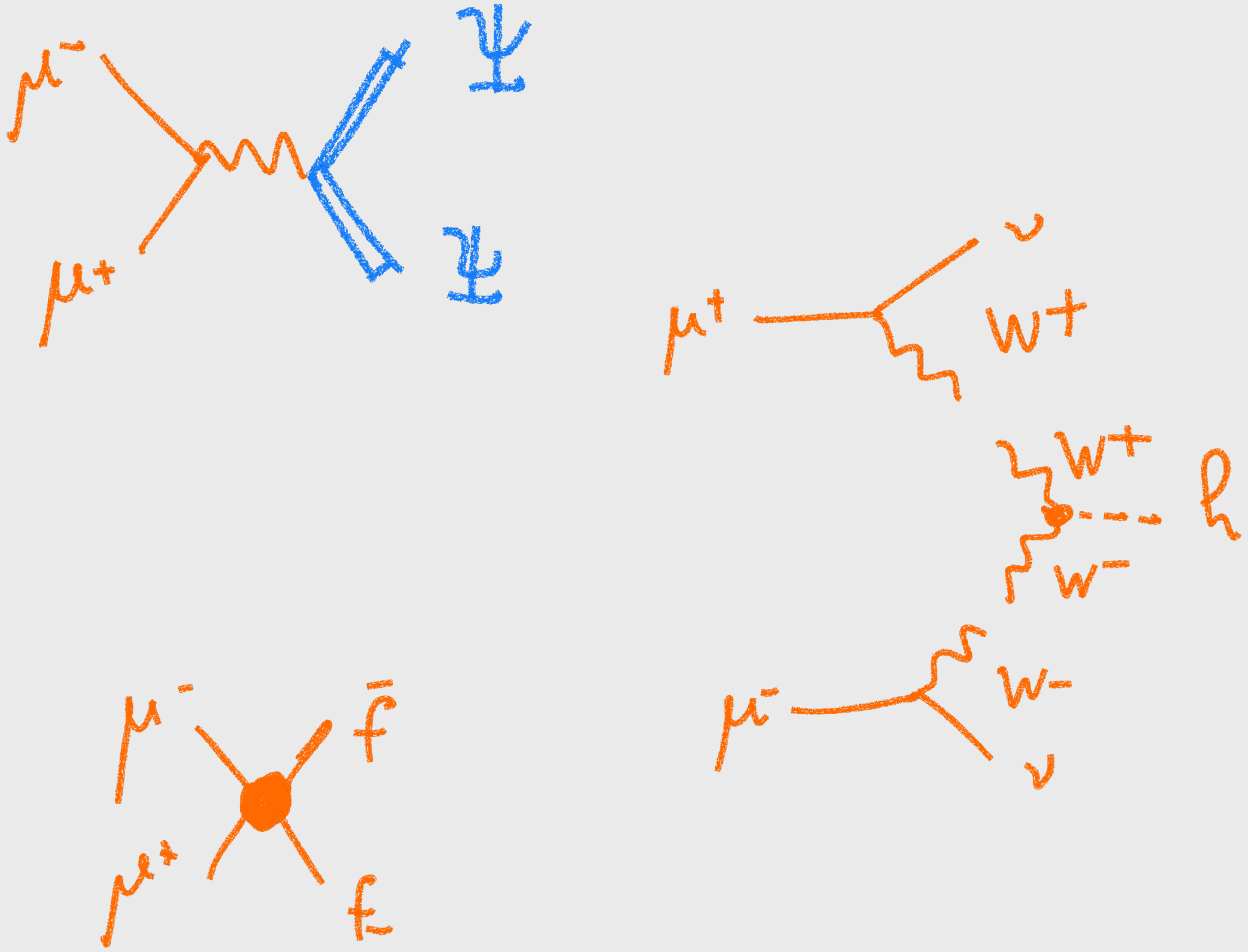
- production of SM and new physics in direct $\mu^+\mu^-$ annihilation

HIGH-INTENSITY PROBES

- production of SM and new physics using beam constituents (e.g. W bosons)

HIGH-ENERGY PROBES

- indirect probes of new physics in direct $\mu^+\mu^-$ annihilation



$\sqrt{s} \gtrsim 3$ TeV center of mass brings significant extension compared to HL-LHC

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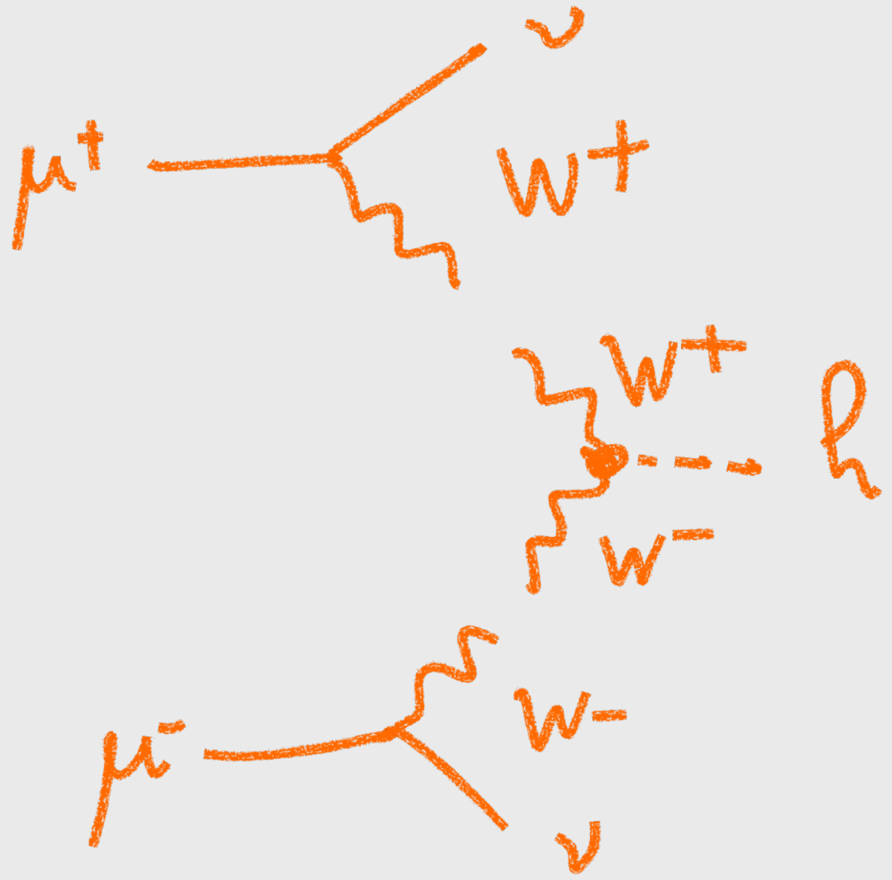

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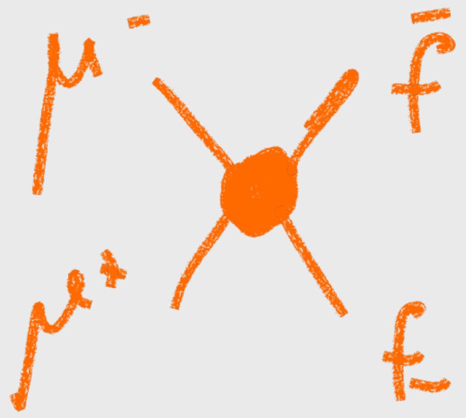

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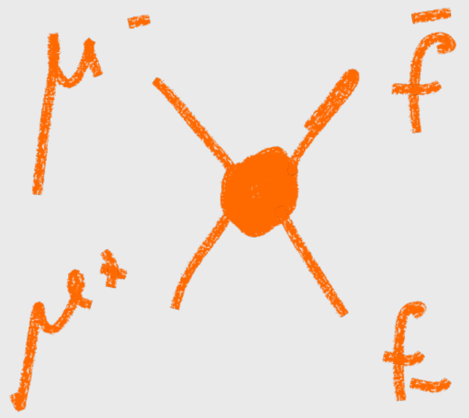

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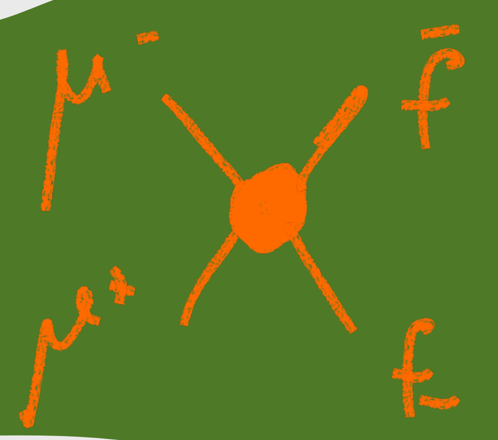

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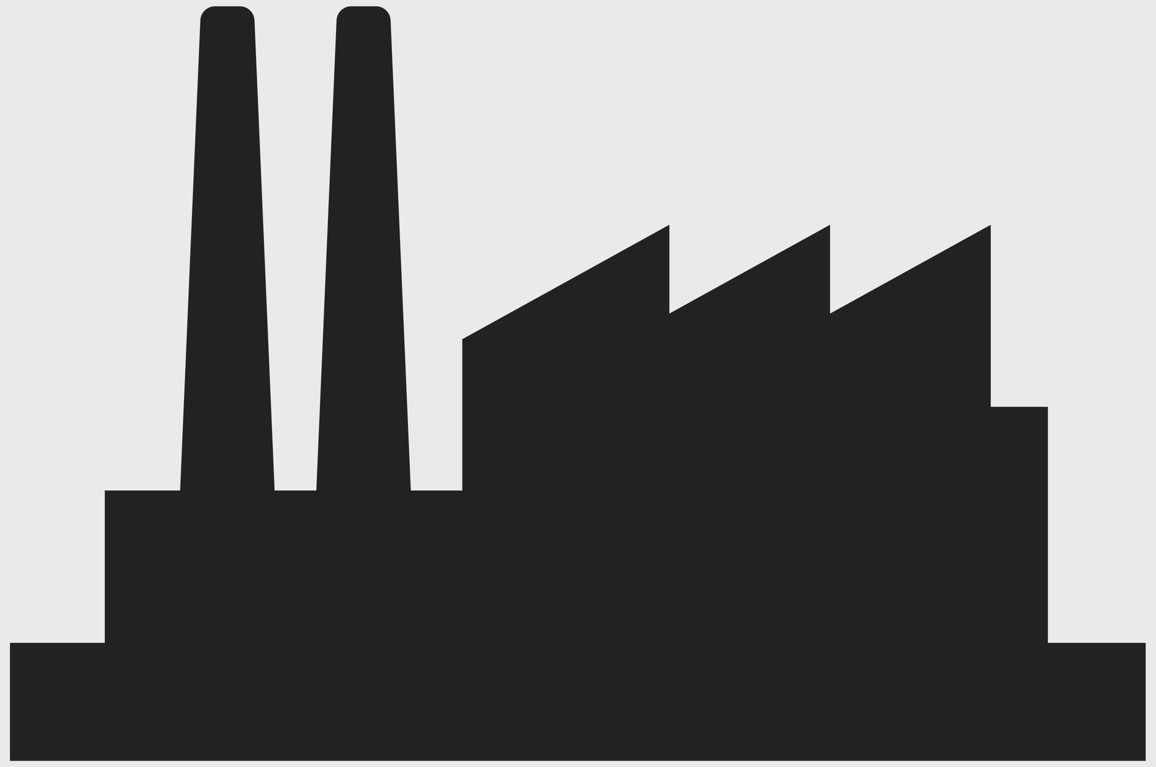
Microscope & Factory

&



Microscope & Factory

Towards a Muon Collider

118 pages

e-Print: 2303.08533 [physics.acc-ph]
Report number: FERMILAB-PUB-23-123-AD-PPD-T

https://arxiv.org/abs/2303.08533

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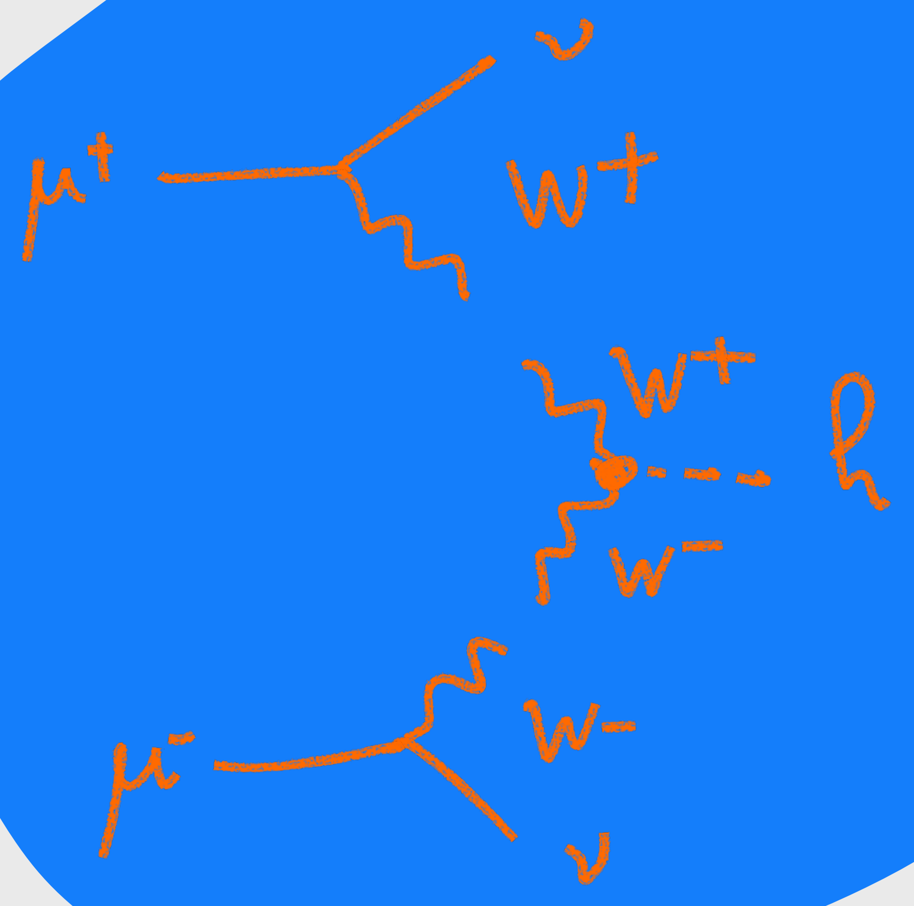

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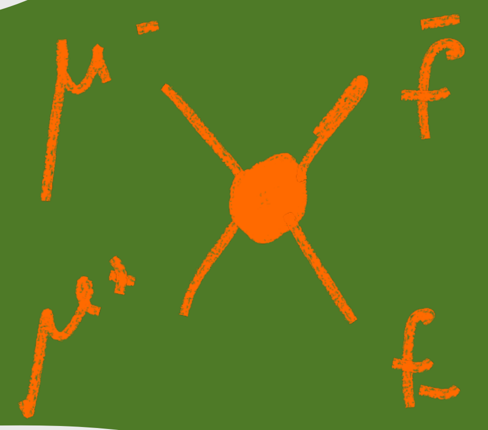

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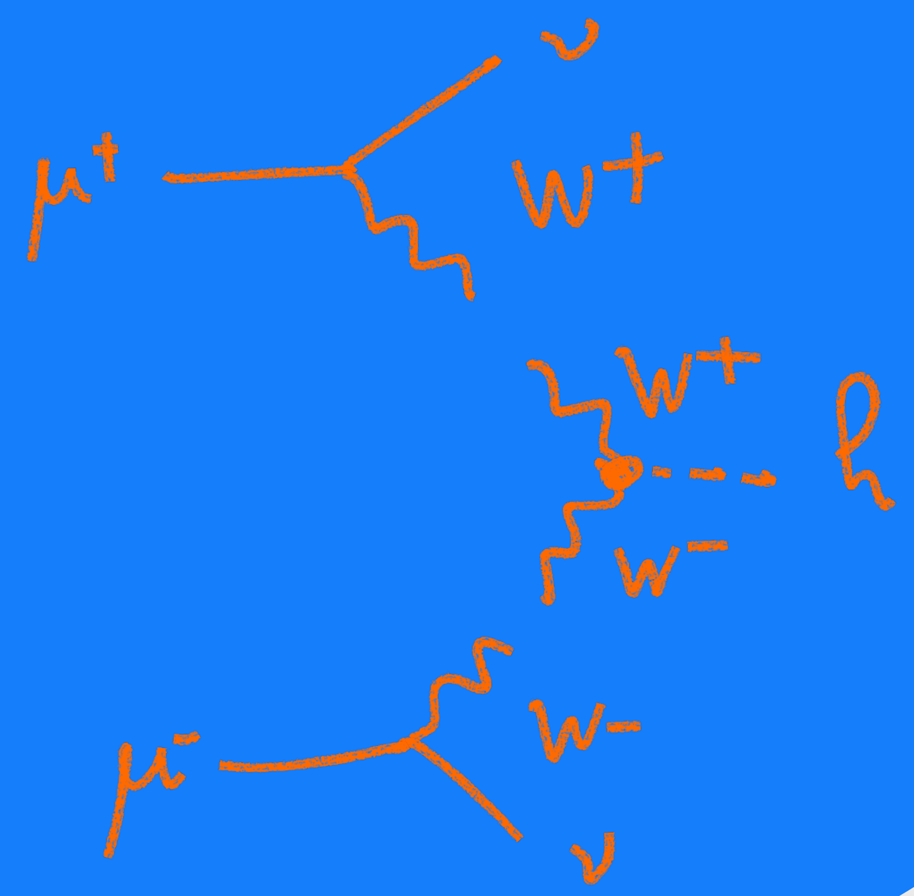

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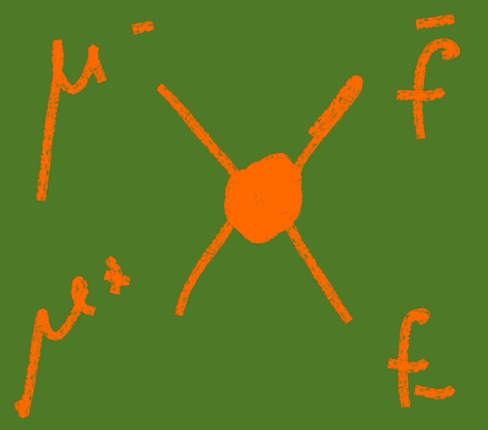

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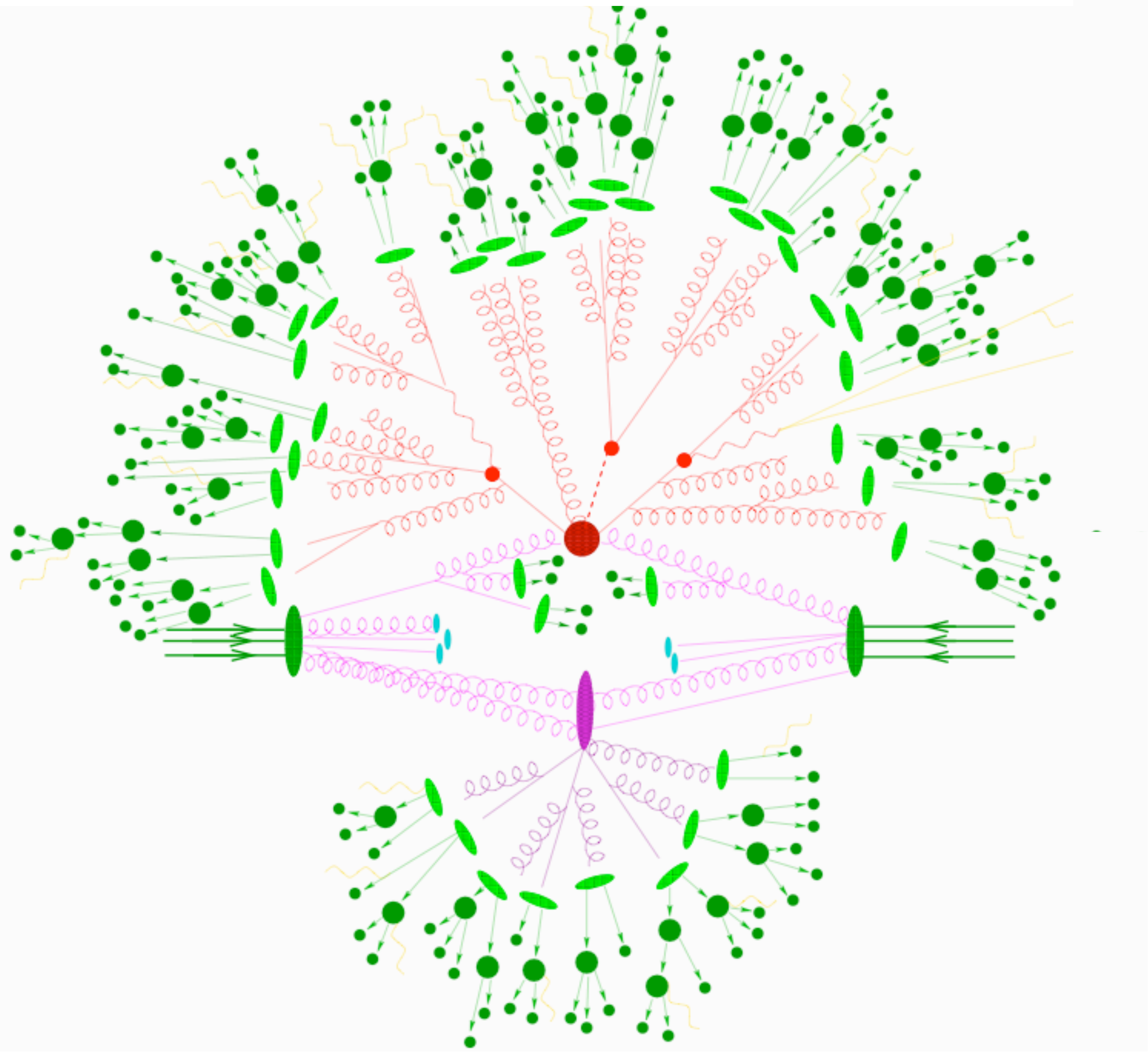
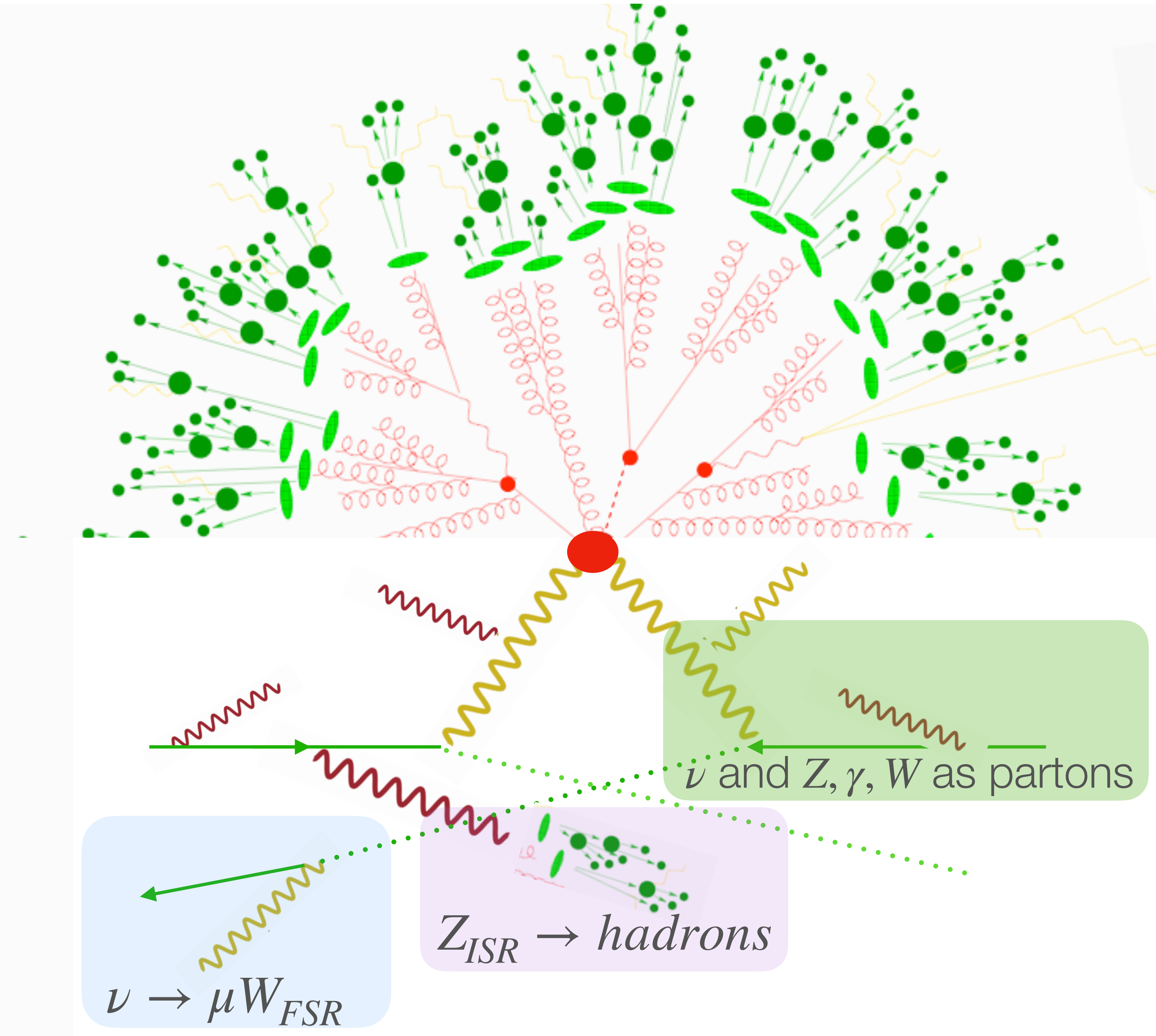
$\mu^+\mu^- \to SM\, SM\, \nu\bar{\nu}$

STANDARD MODEL | "FACTORY"

tth production at the LHC (Fully hadronic)



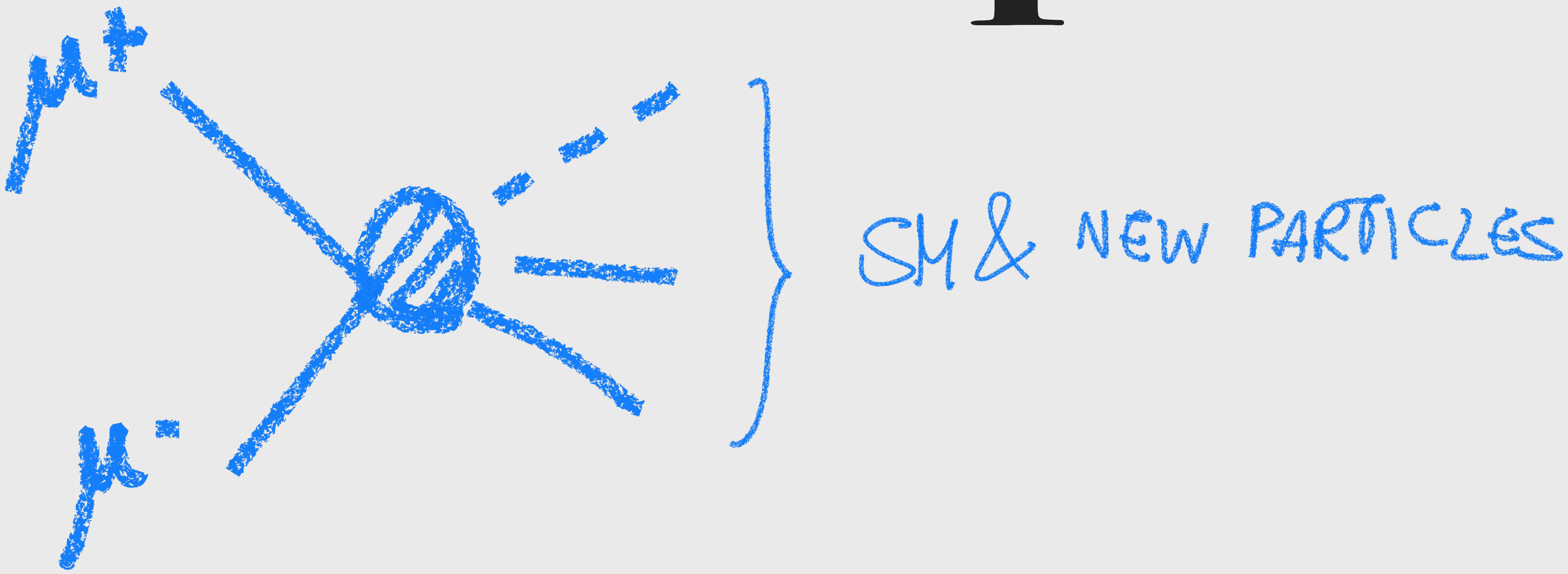
tth production at the muC 100 TeV (F. Maltoni)



NEW PHENOMENA AND NEW REGIMES IN pQFT

- weak corrections become "ordinary"
- weak "partons"
- large EW logarithms

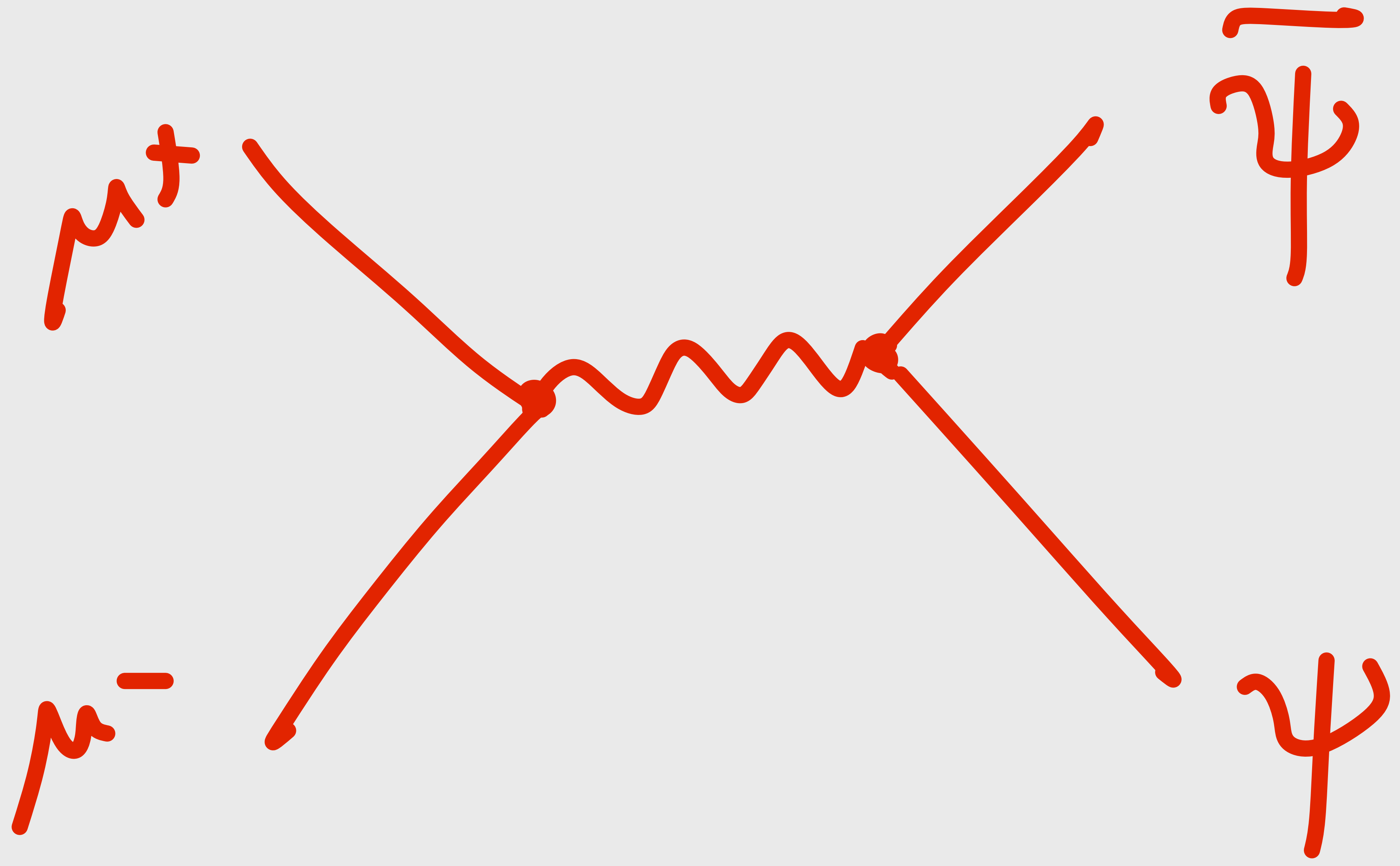
"Valence" Leptons



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

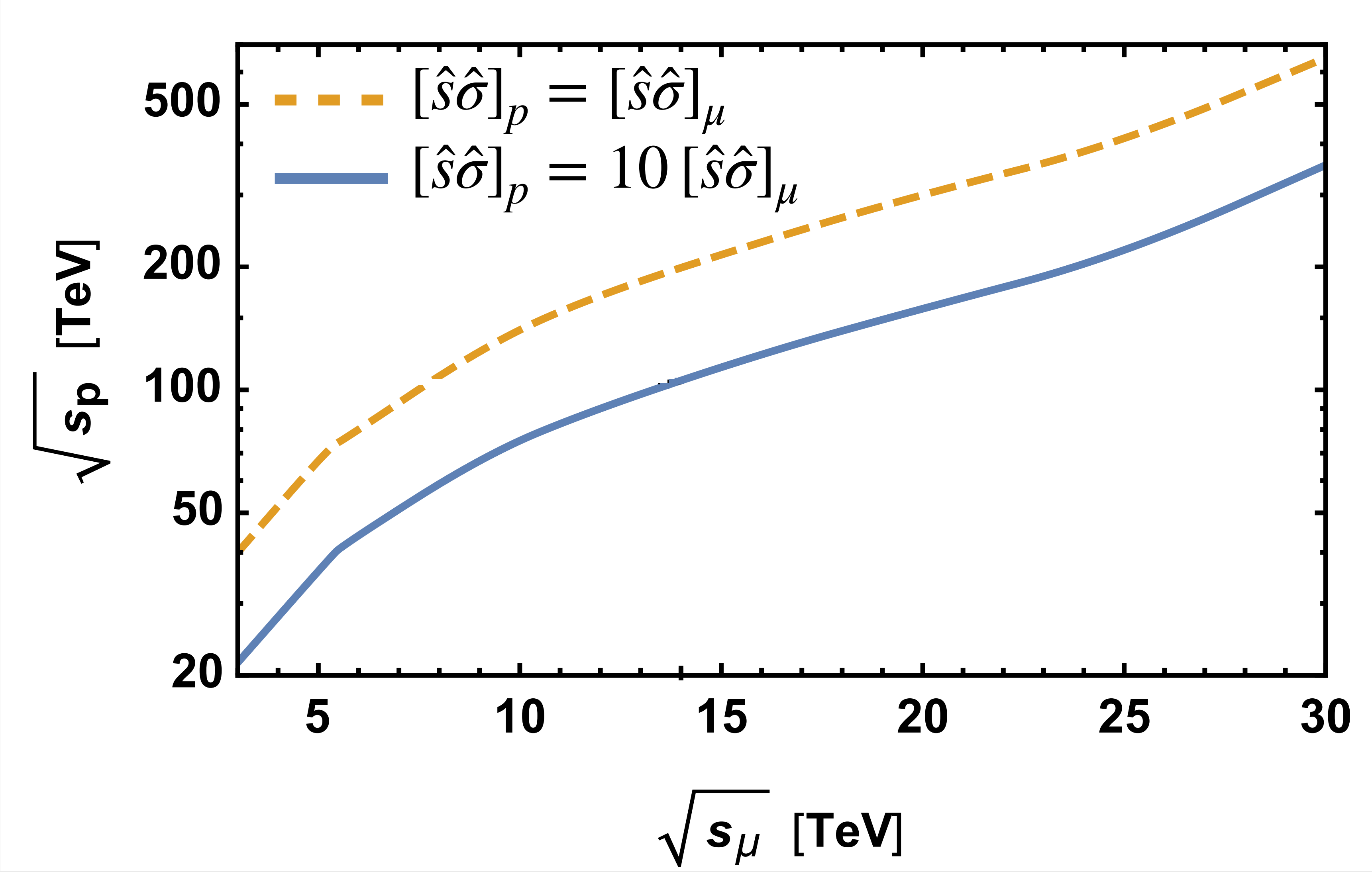
VALENCE MUONS

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 2209.01318



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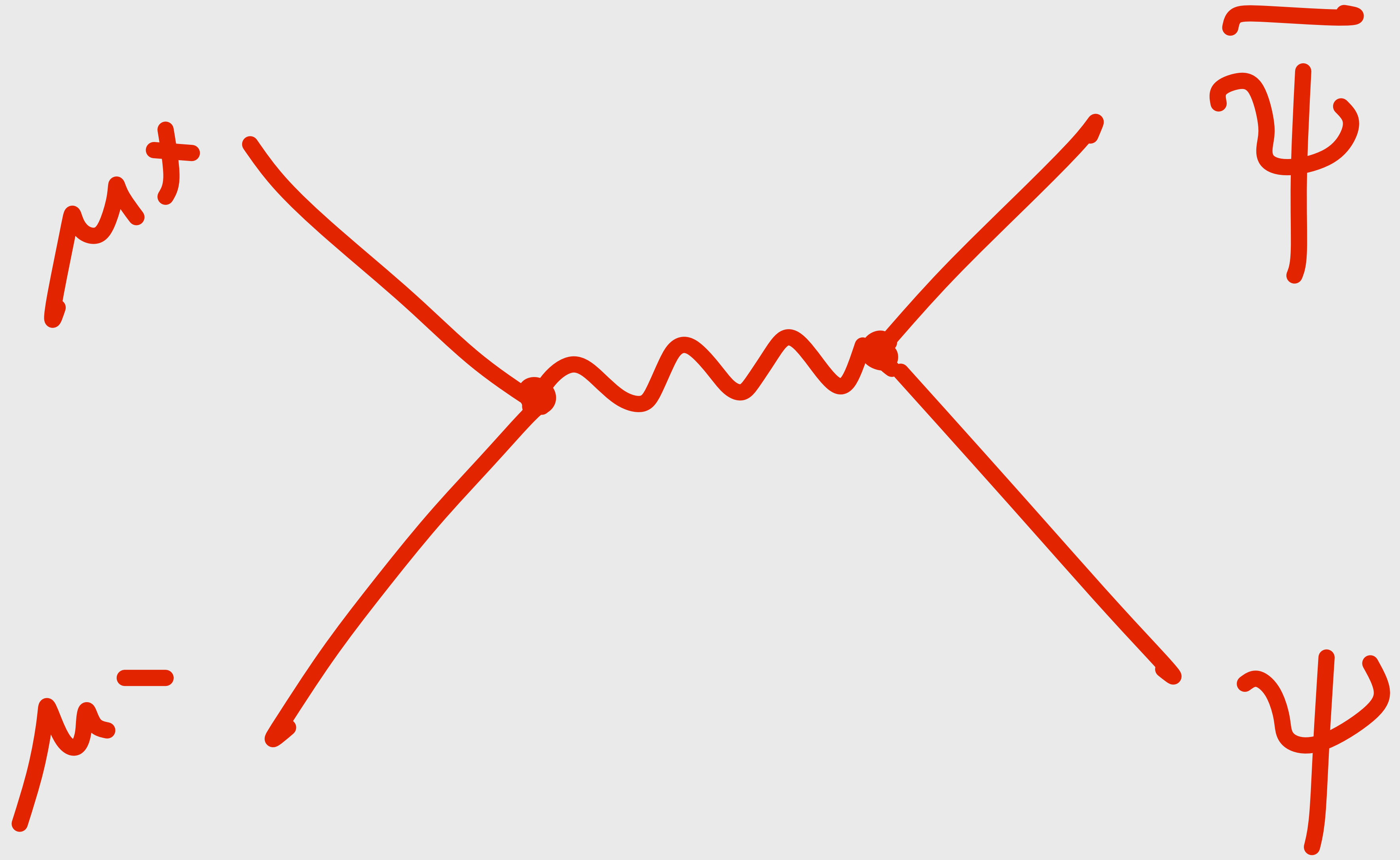

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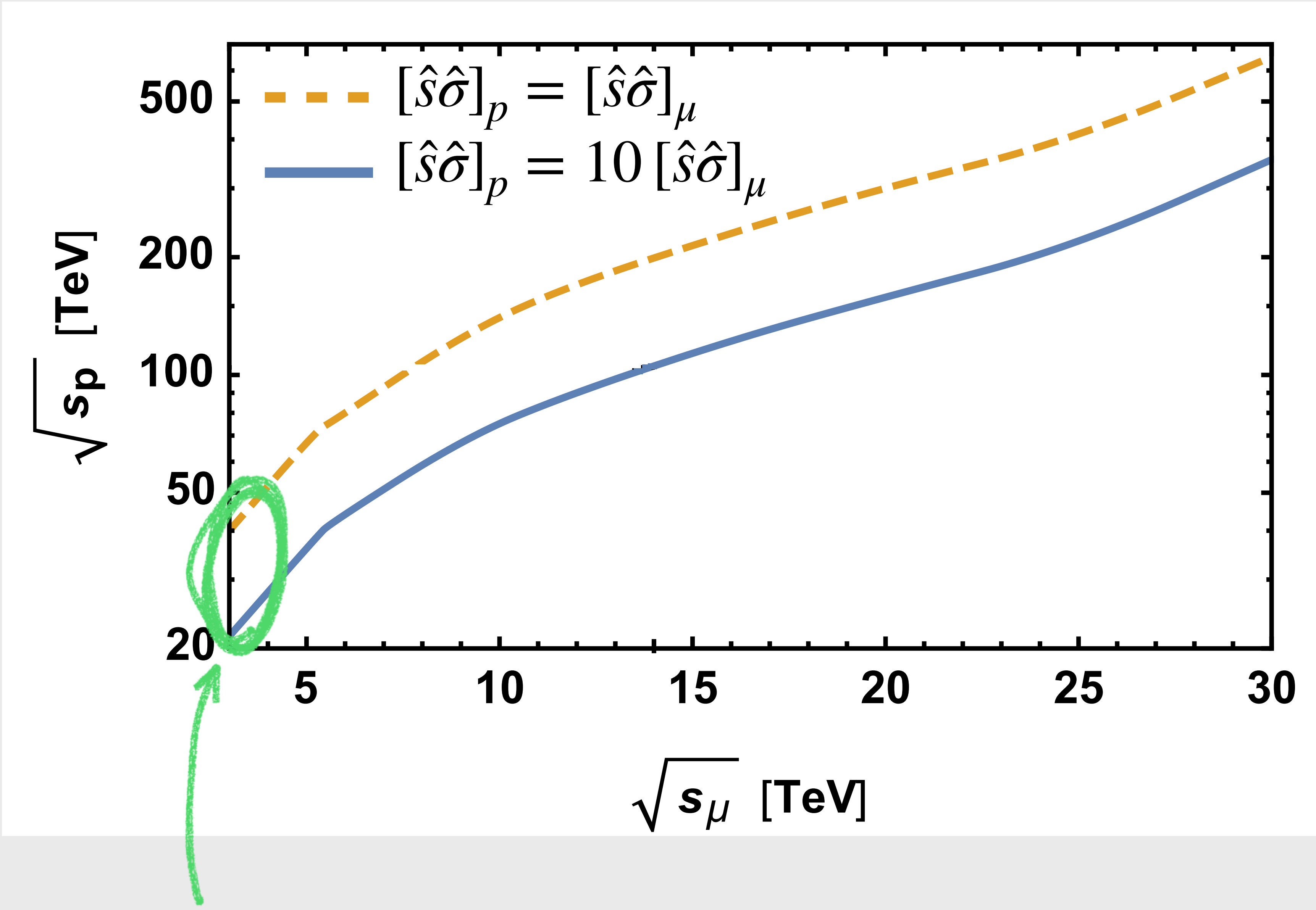
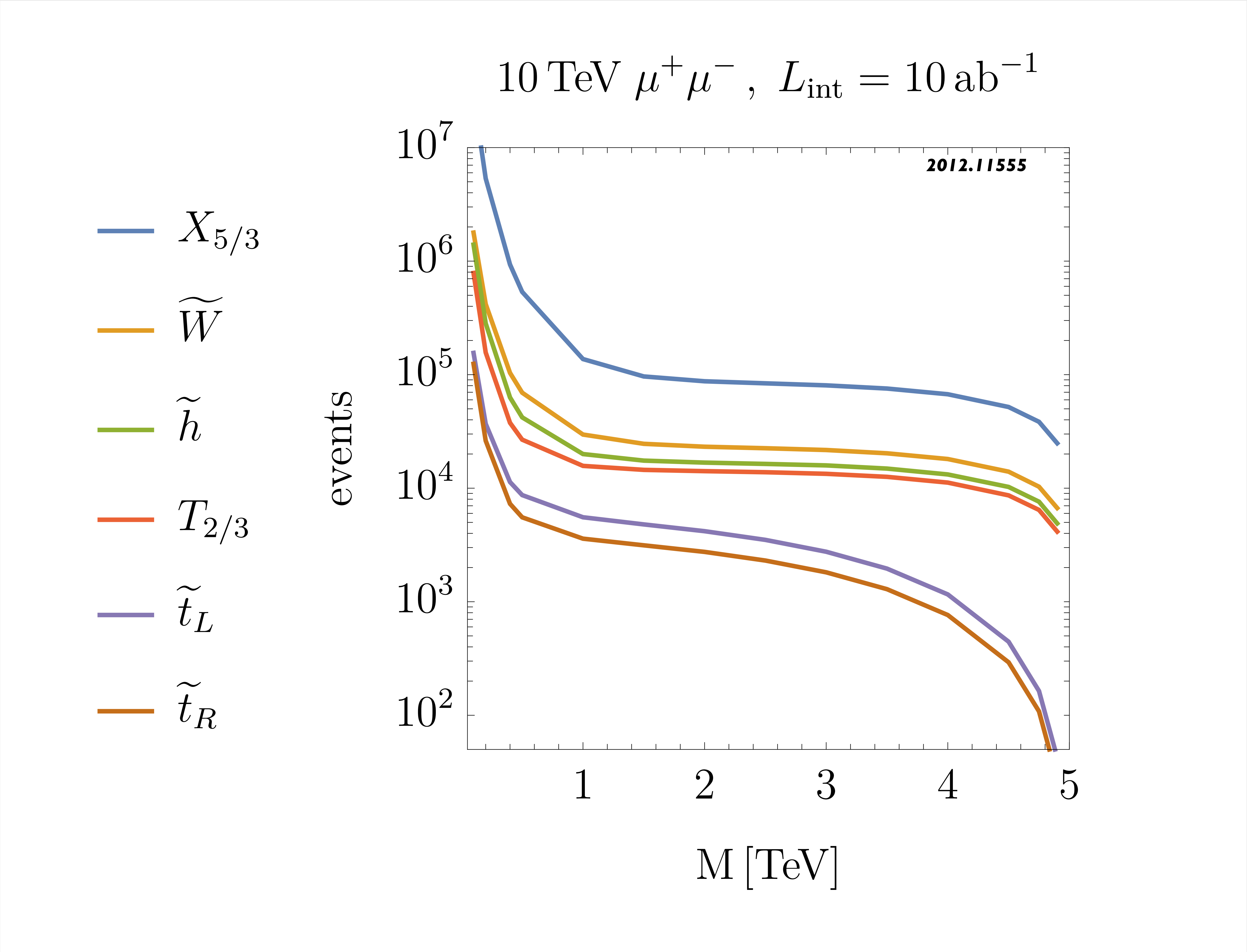


3 TeV $\mu^+\mu^-$ roughly equivalent to 20+ TeV *pp*

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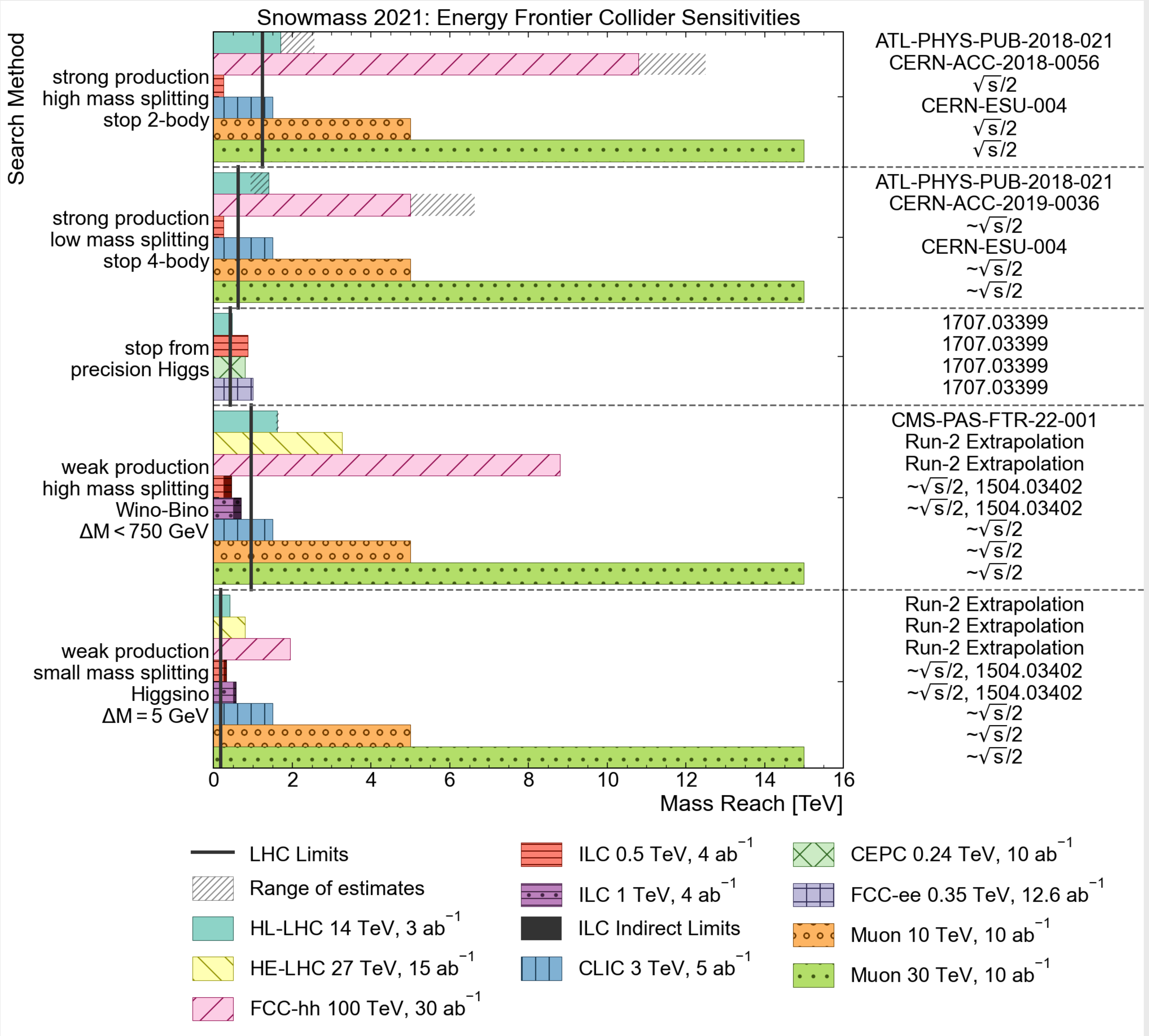

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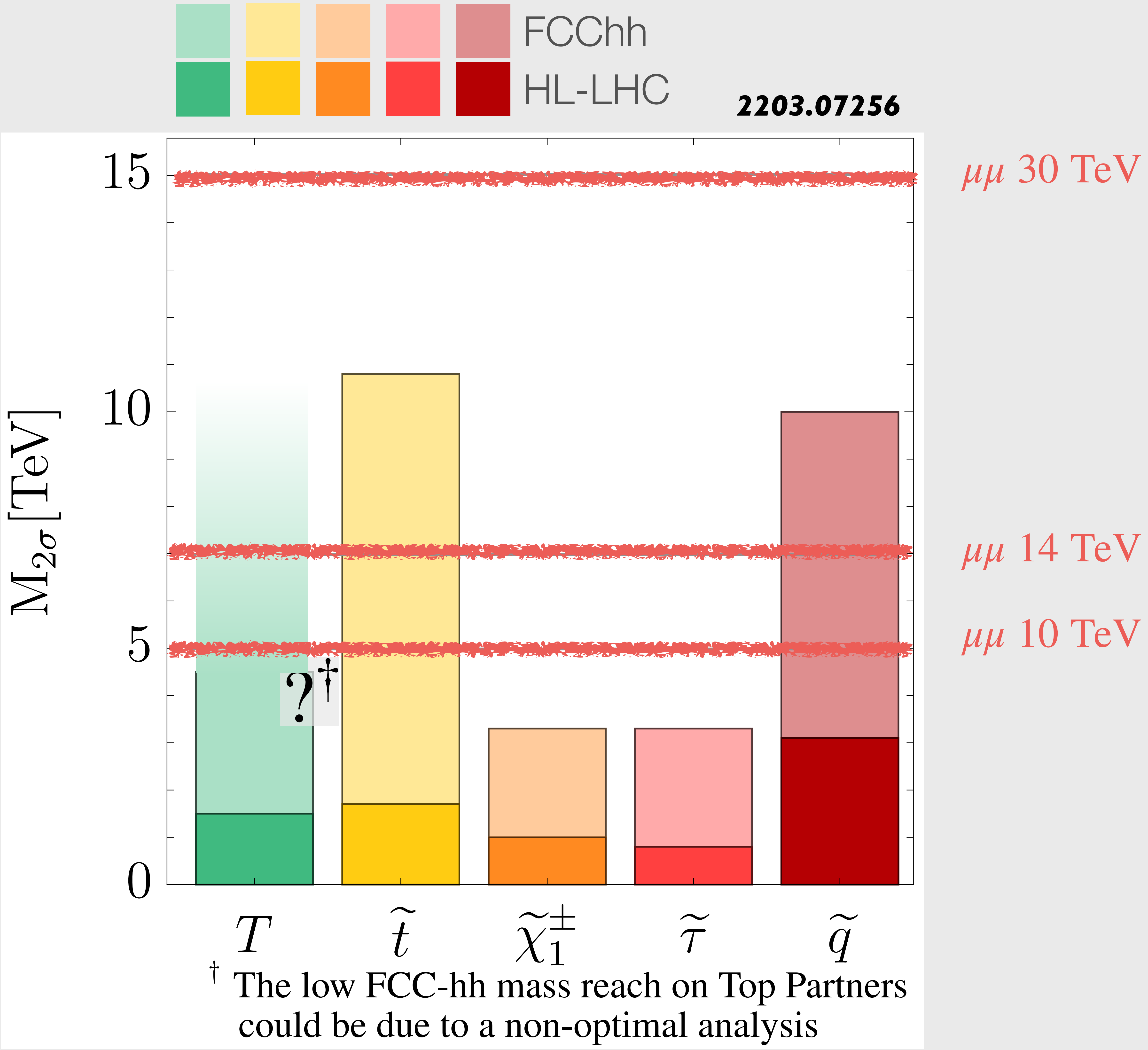

2HDM

DOUBLETS

BIG JUMP AT FUTURE COLLIDERS

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.

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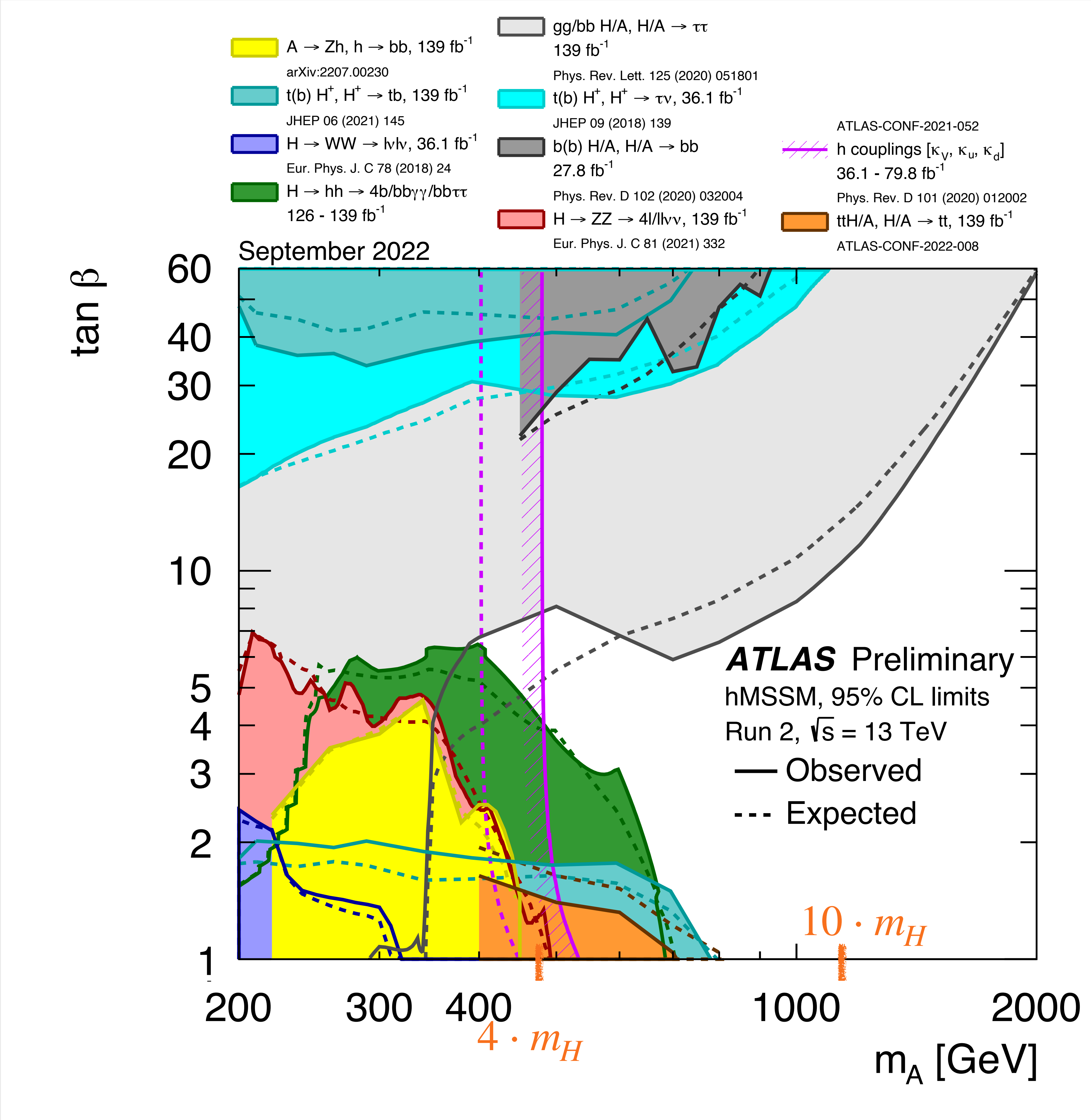

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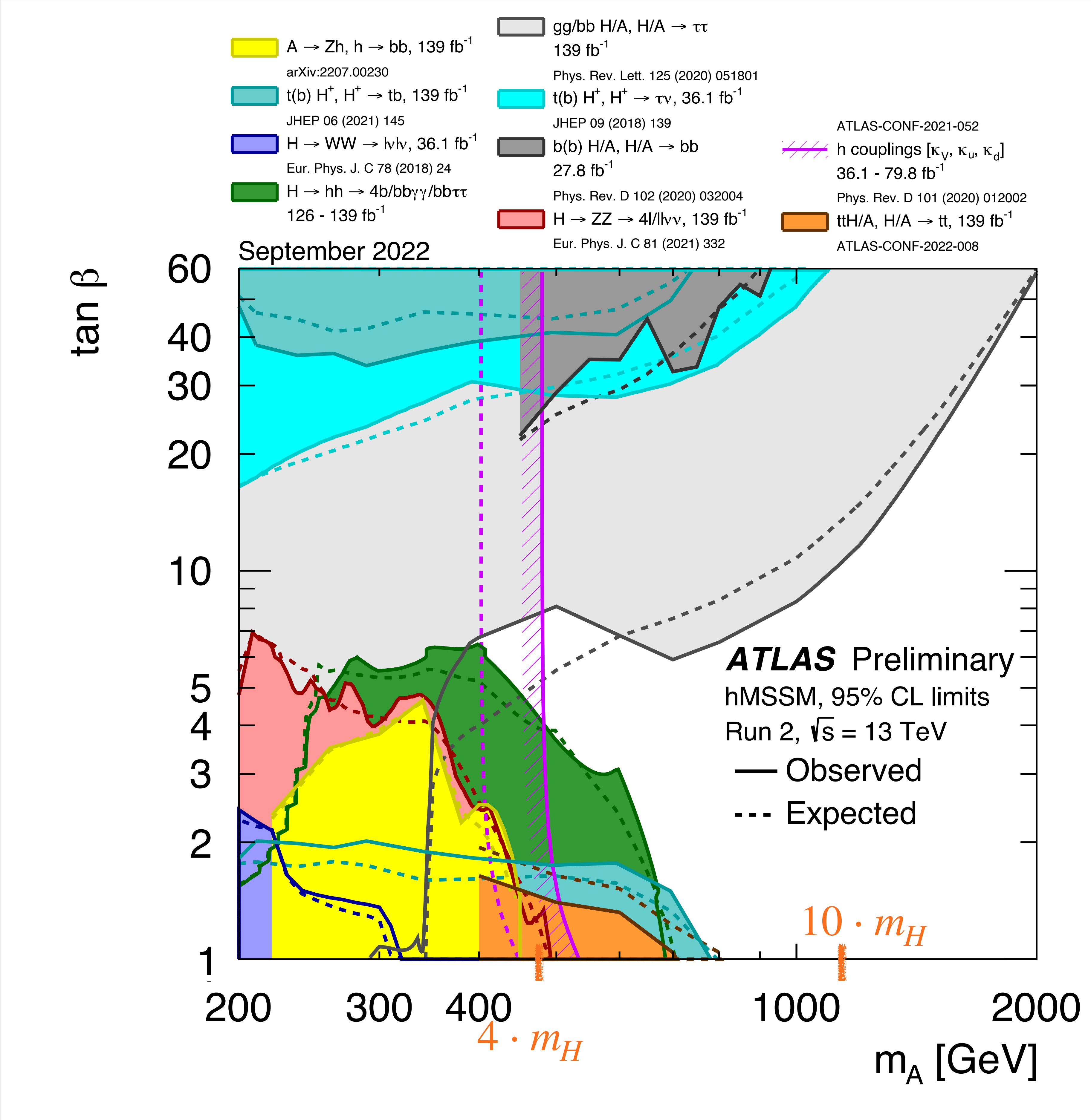

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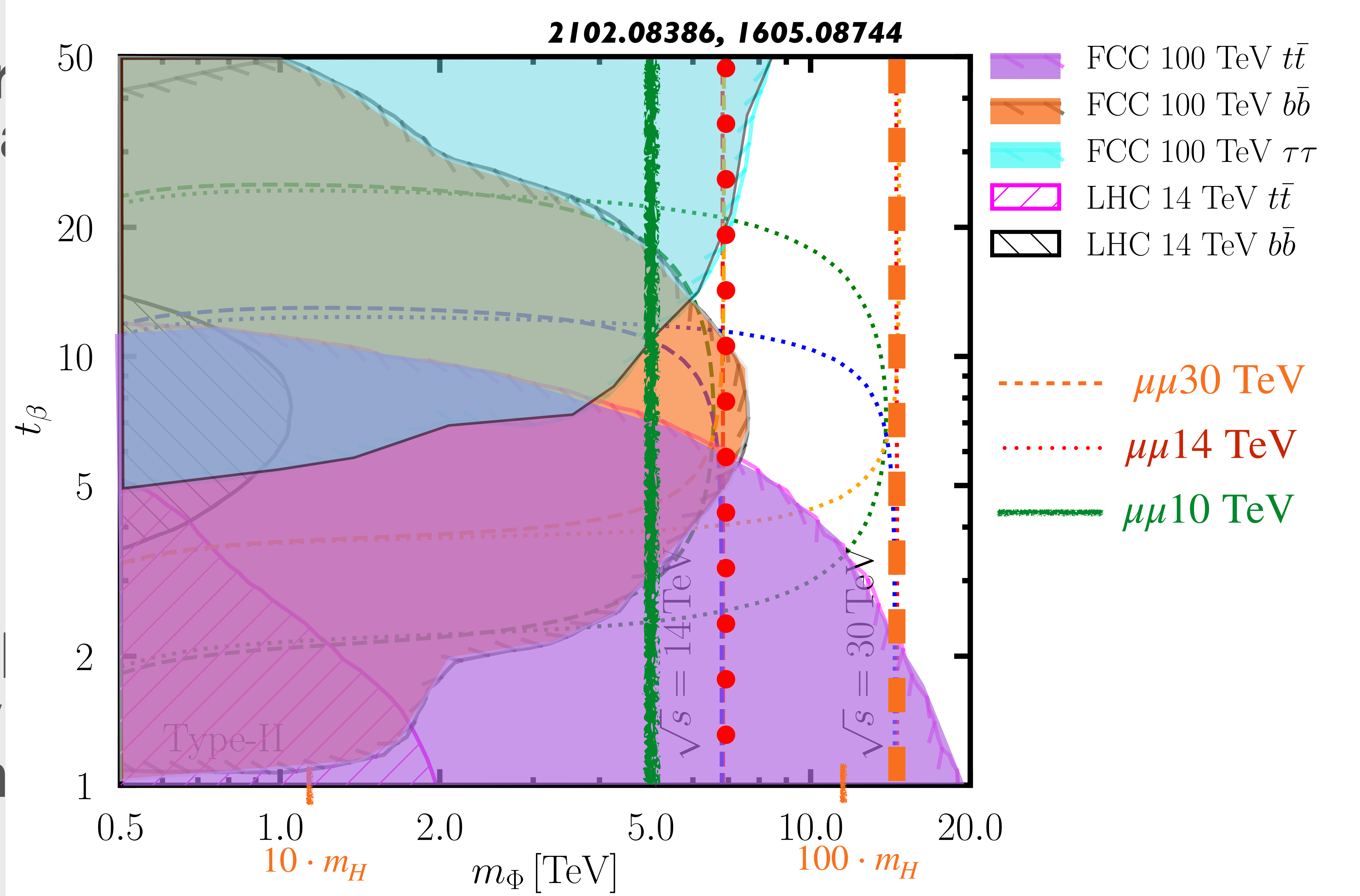

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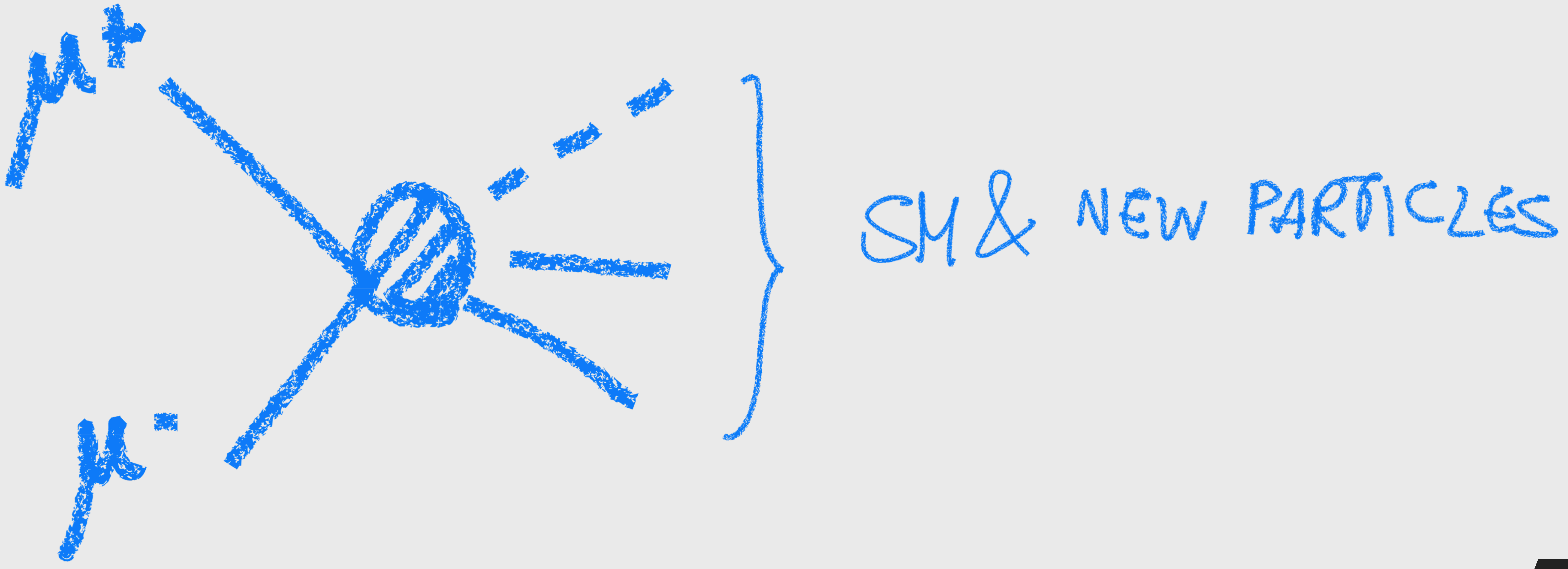
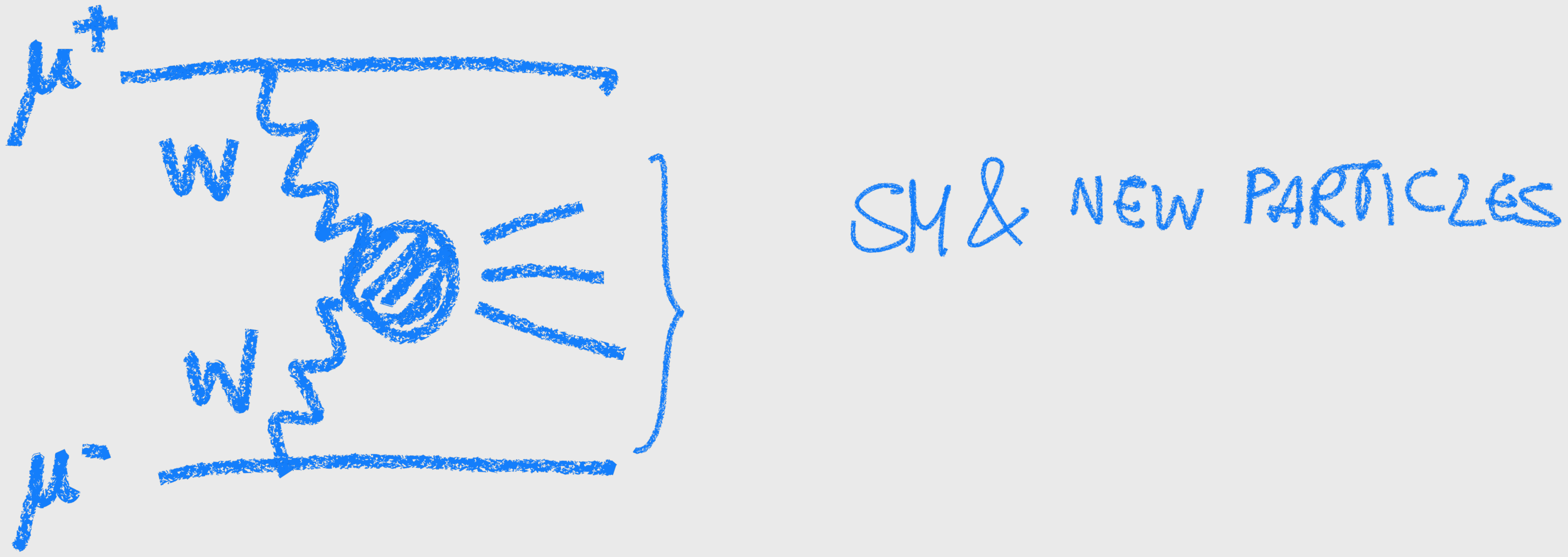


reach for new physics at $\sqrt{s}/2$

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

Weak Bosons collider

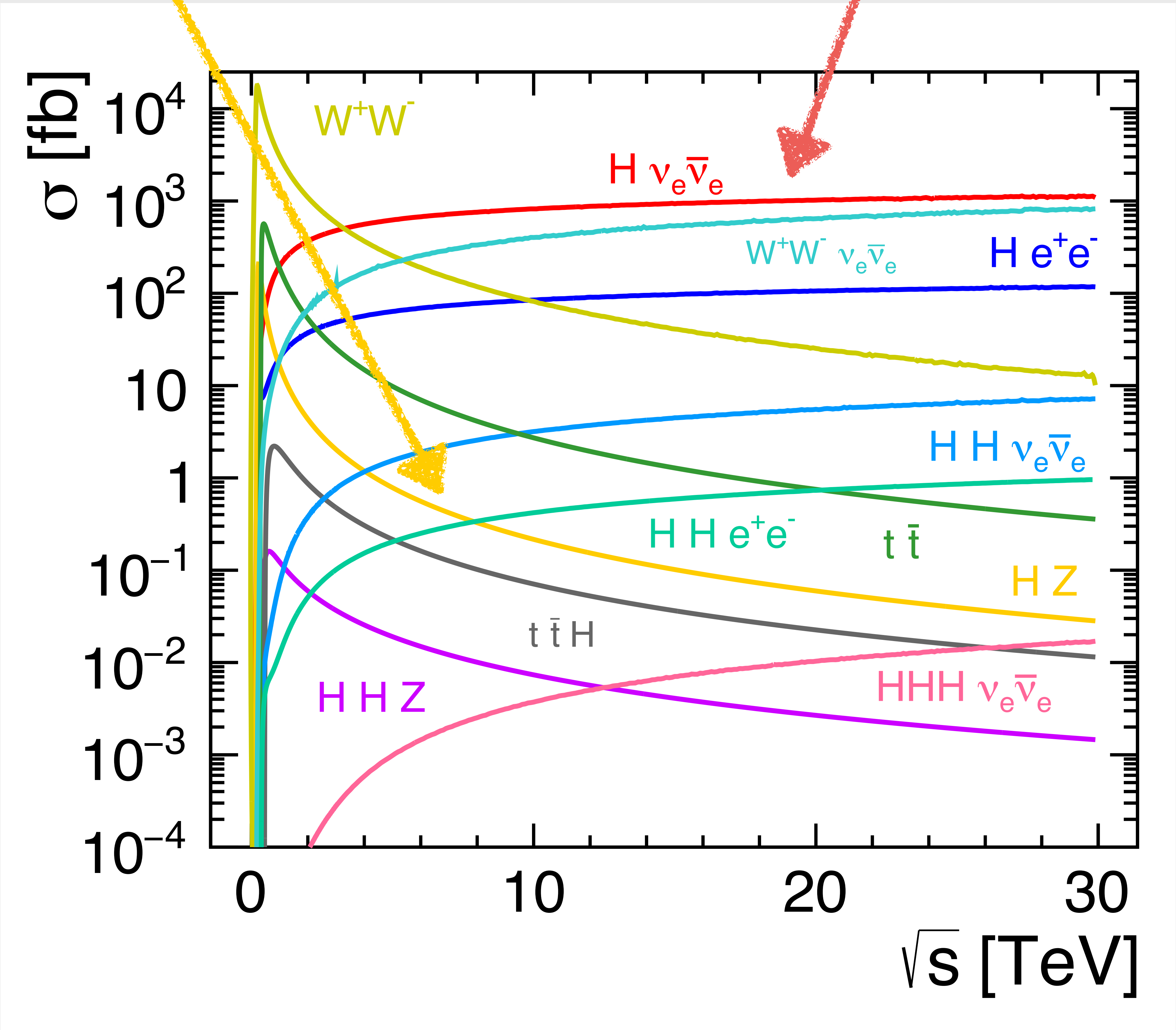


Higgs boson

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

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!

FURTHER OPPORTUNITIES

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

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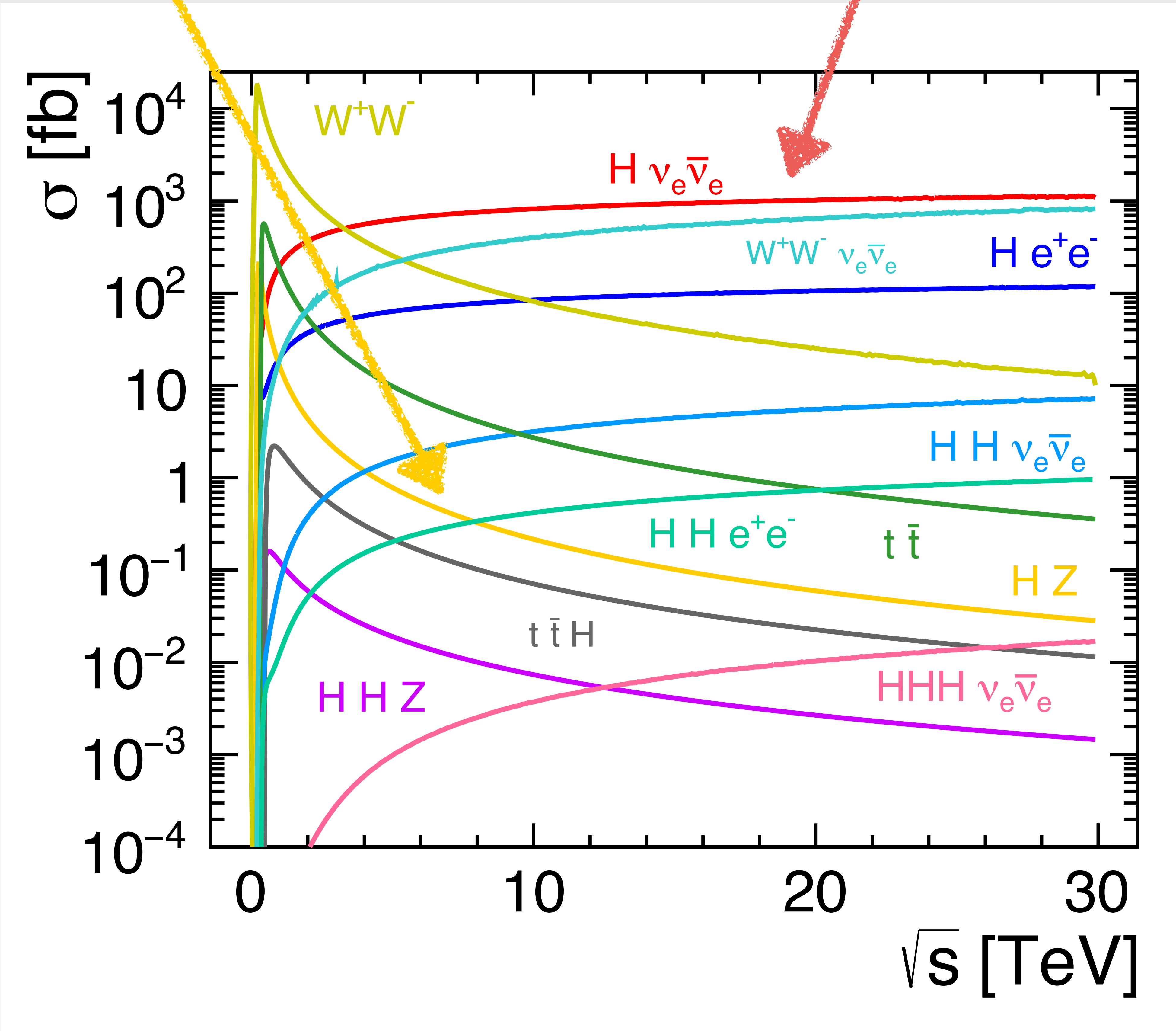

At 30 TeV the weak bosons are sufficiently light that can be radiated very efficiently

$$\sqrt{s} = 30\,\text{TeV}$$
$$\sigma \cdot \mathscr{L} \Rightarrow O(10^8)\ \text{h}$$

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10⁶ HIGGS BOSONS | MEGA-HIGGS FACTORY

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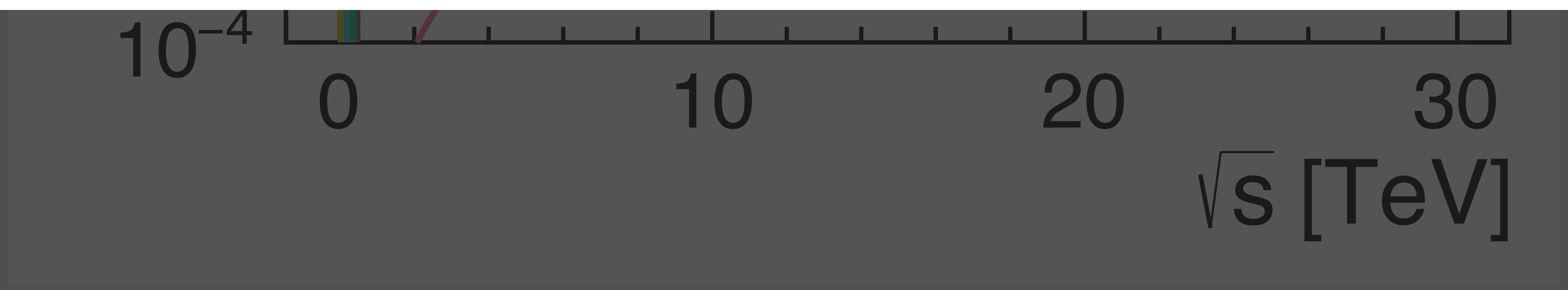
At 30 TeV the weak bosons are sufficiently light that can be radiated very efficiently

- Higgs factory at 3 TeV
- $10\times$ Higgs factory at 10 TeV
- $100\times$ Higgs factory at 30 TeV

International MUON Collider Collaboration



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- off-shell Higgs bosons
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Summary: Higgs@FC (by couplings)

0.1% coupling precision, sensitivity to new physics at $10\ \mathrm{TeV} \simeq 100 \cdot m_h$

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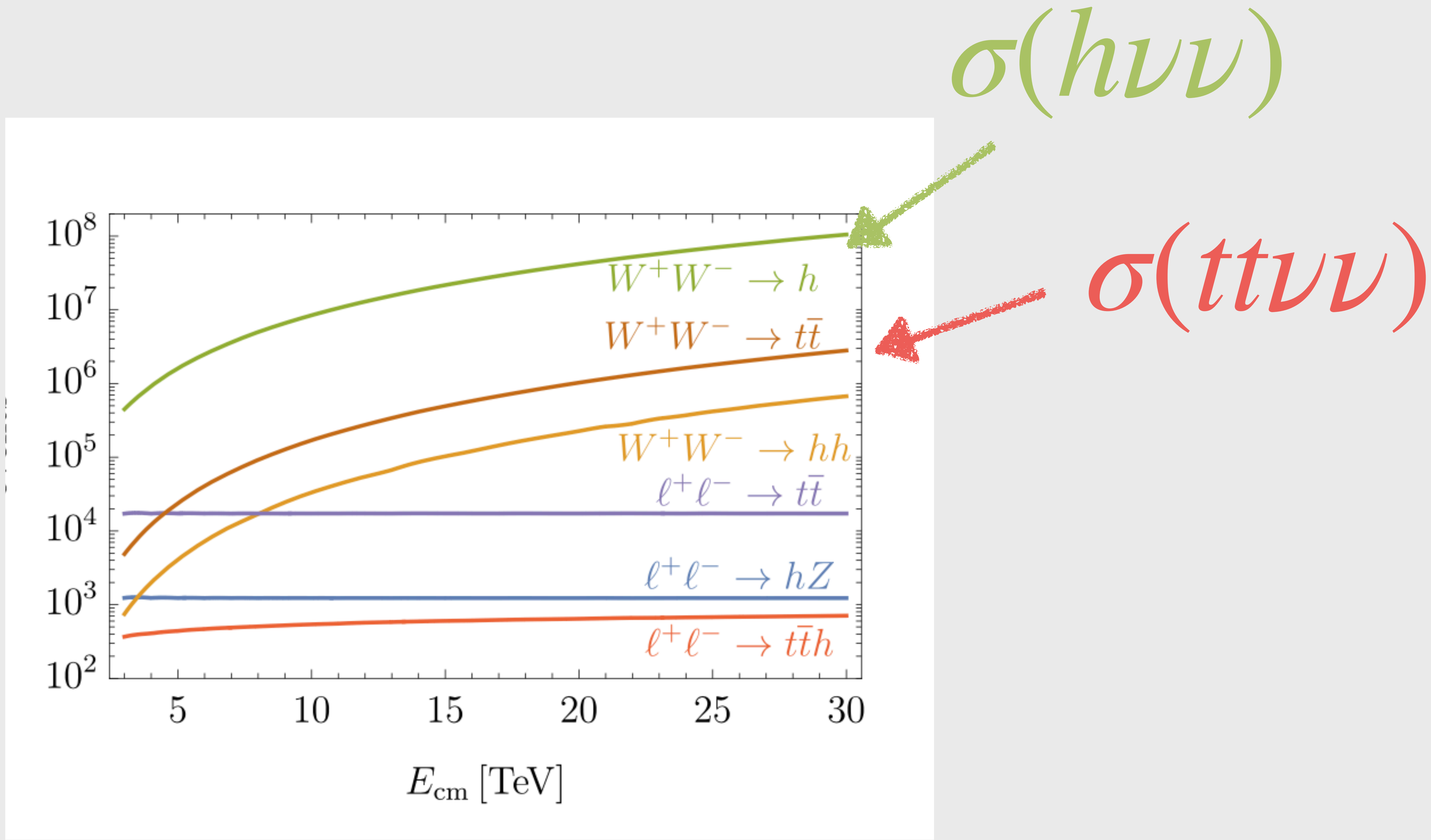

- large number of top quarks!
  - rare top decays
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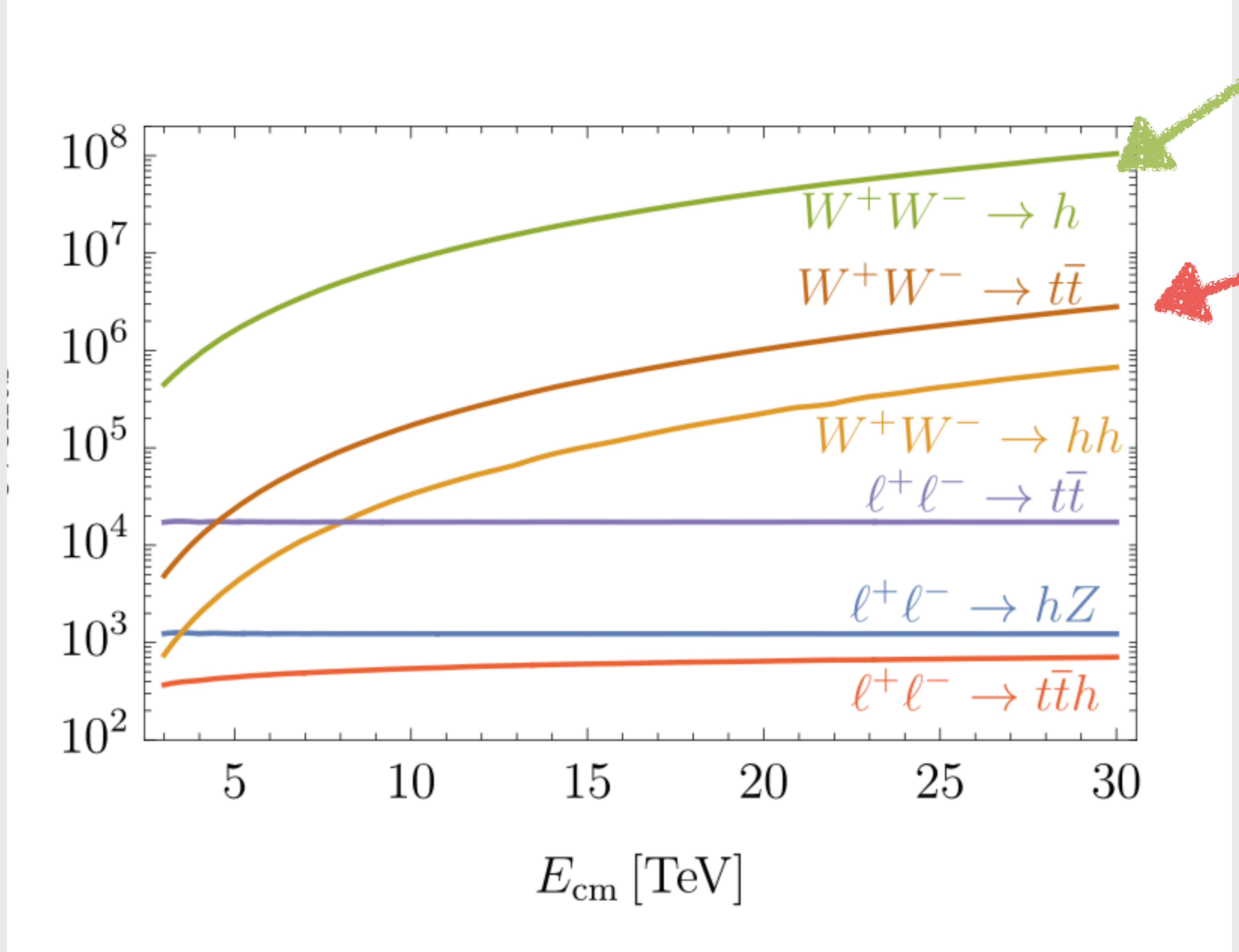
STANDARD MODEL "FACTORY"



$\sigma(h\nu\nu)$

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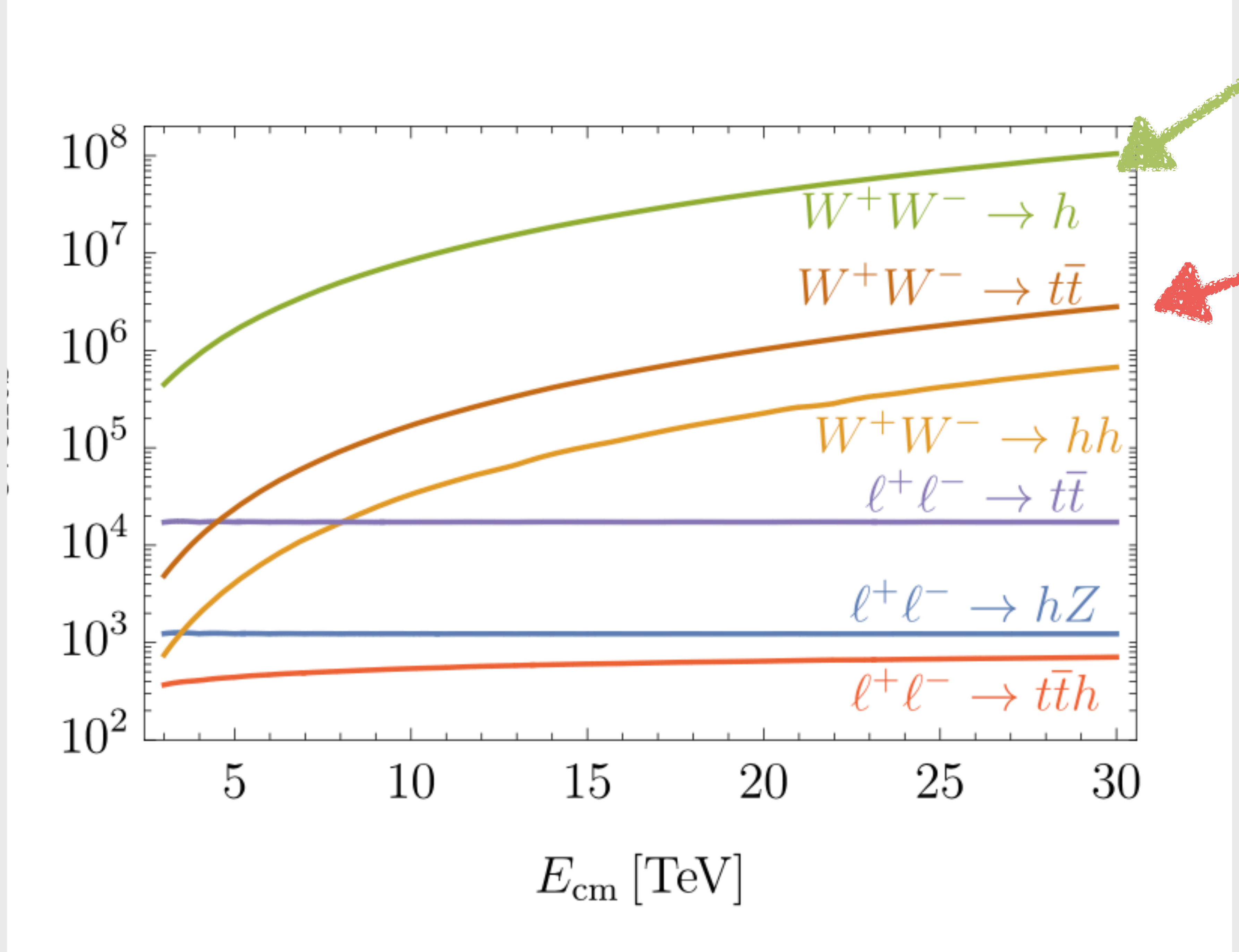

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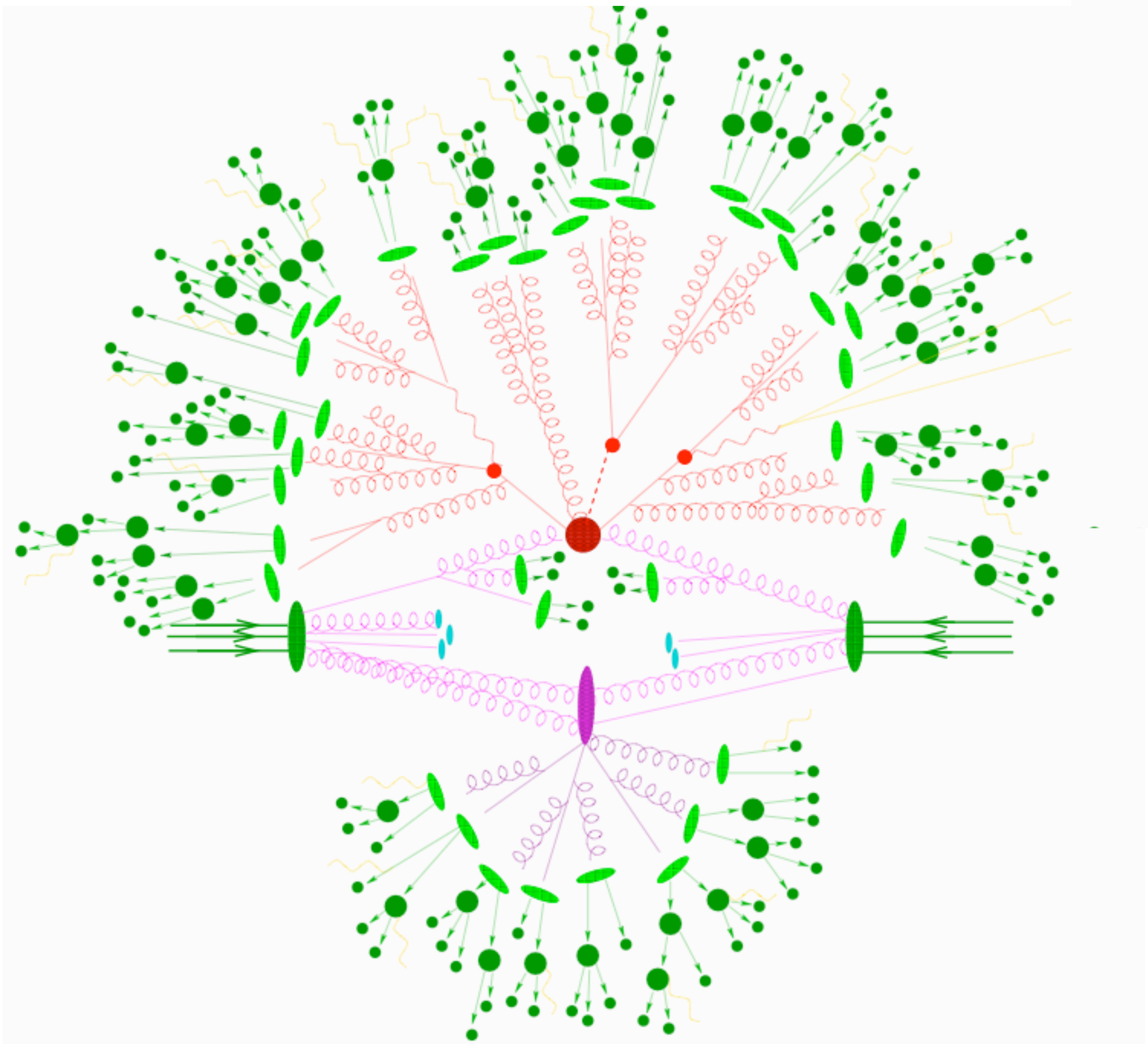

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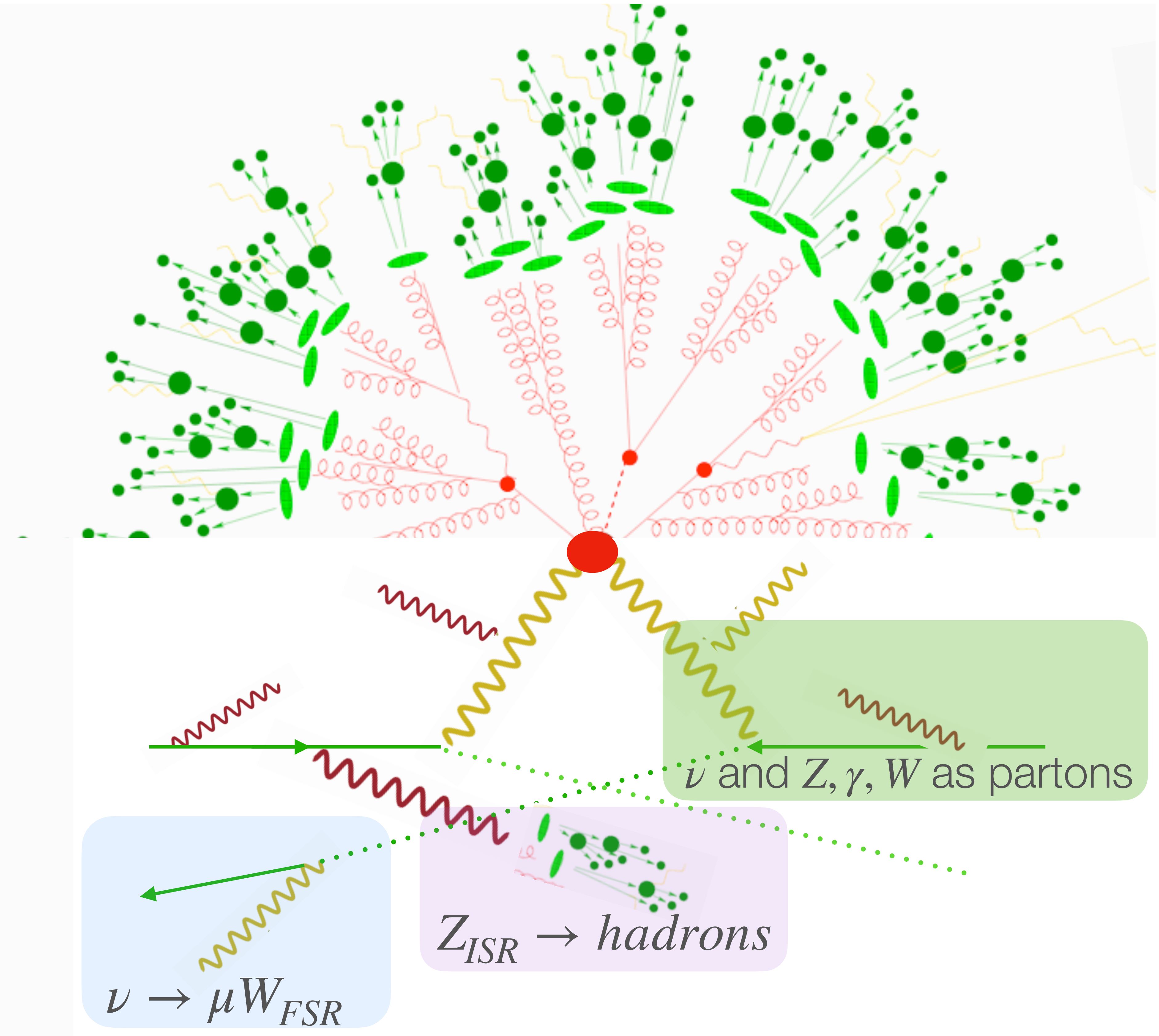

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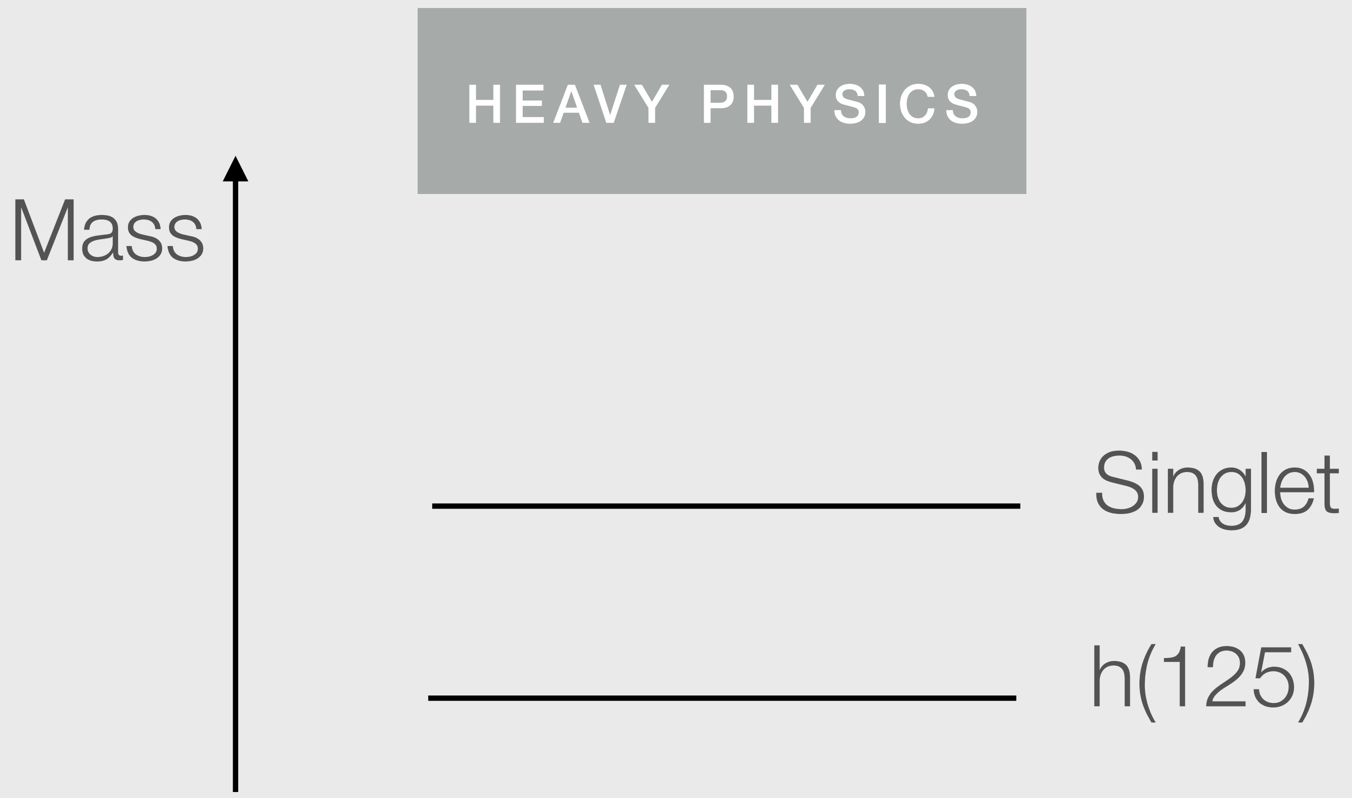
- large EW logarithms

Higgs + Singlet

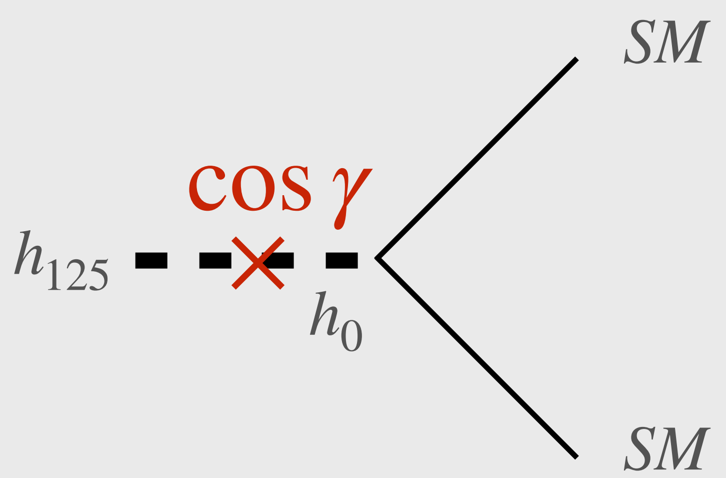


- Broad coverage of BSM scenarios: *(N)MSSM*, *Twin Higgs*, *Higgs portal*, *modified Higgs potential (Baryogenesis)*
- Phenomenology is also useful as "simplified model"

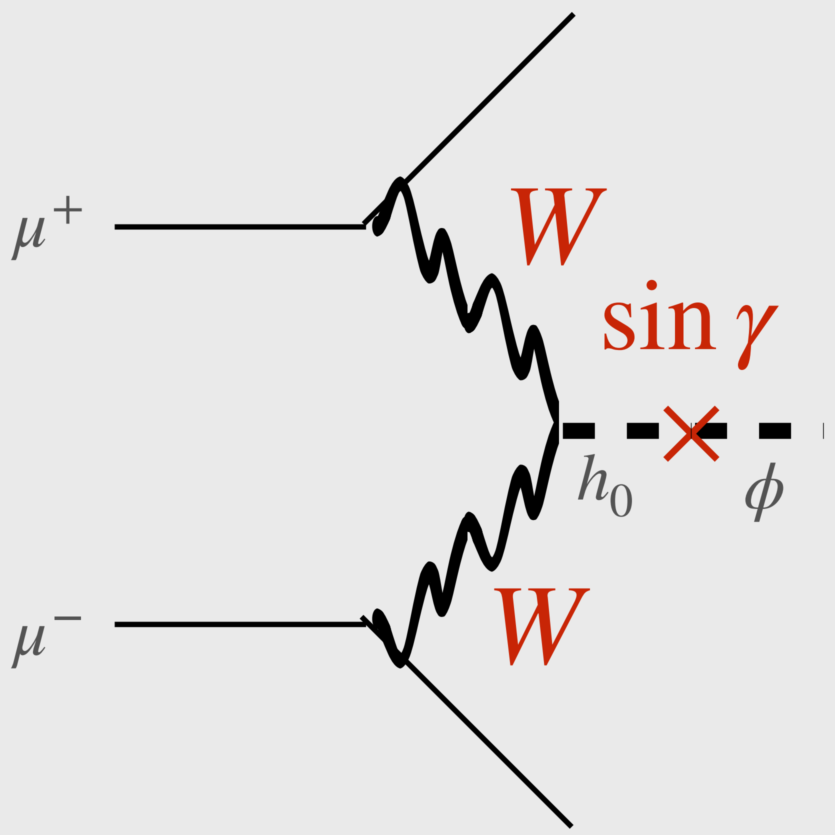
Higgs + Singlet

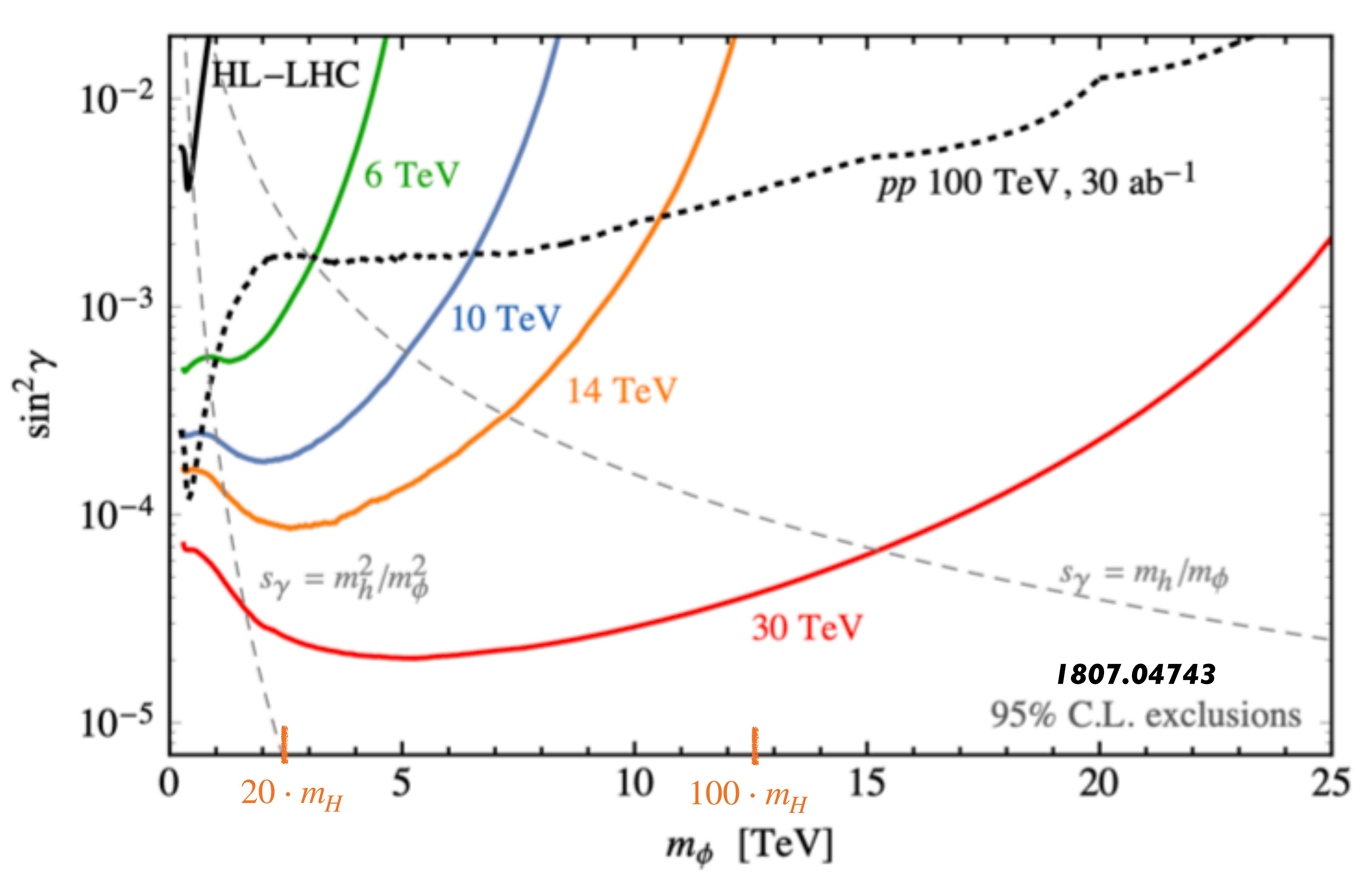
SINGELTS

BIG JUMP AT FUTURE COLLIDERS



EXPLOIT ONCE MORE THE W BOSON LUMINOSITY

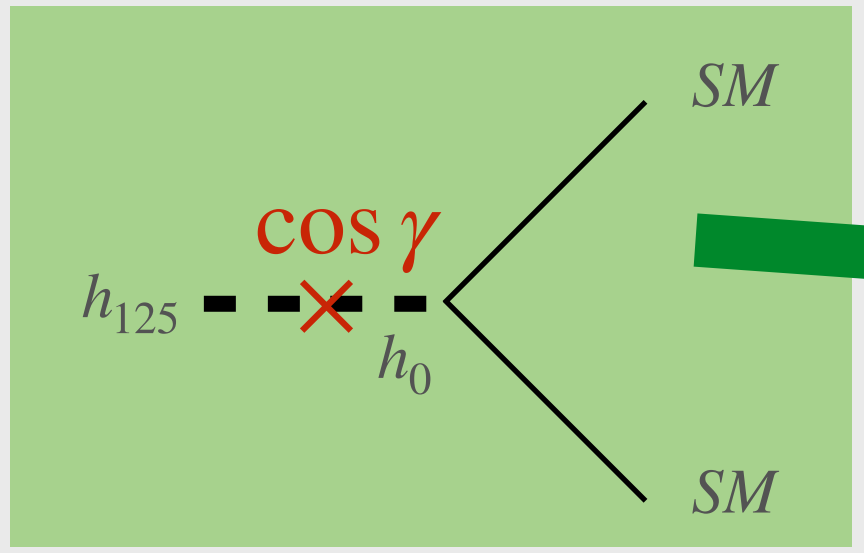




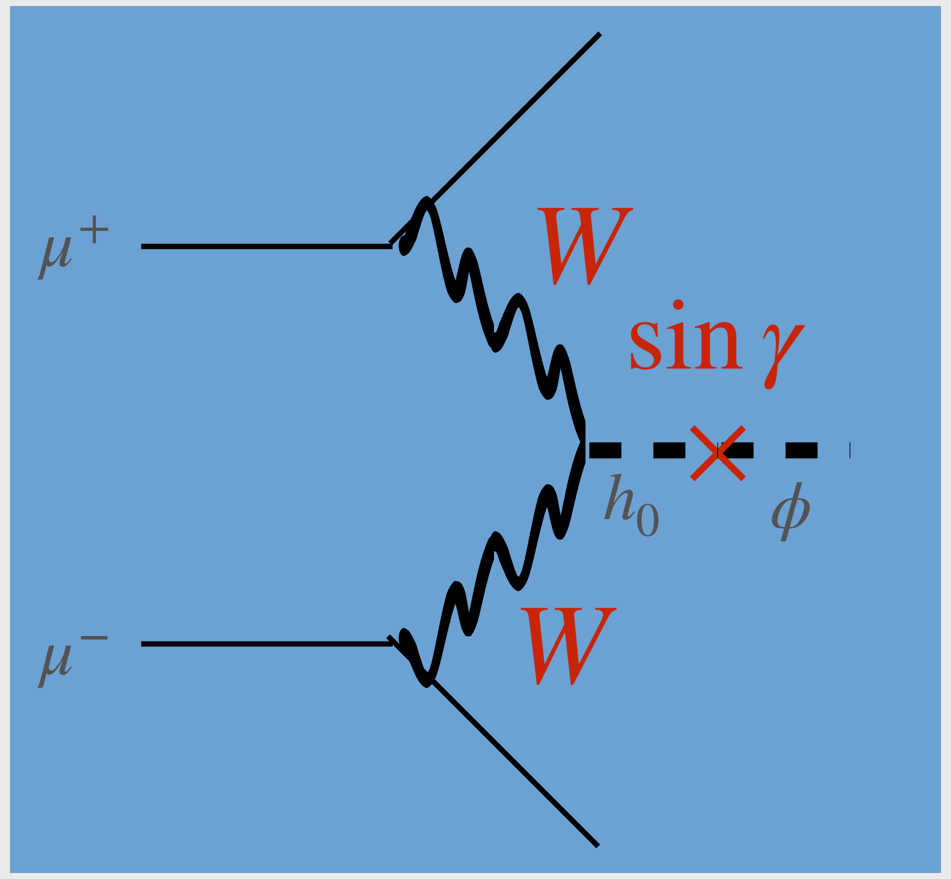
Higgs + Singlet

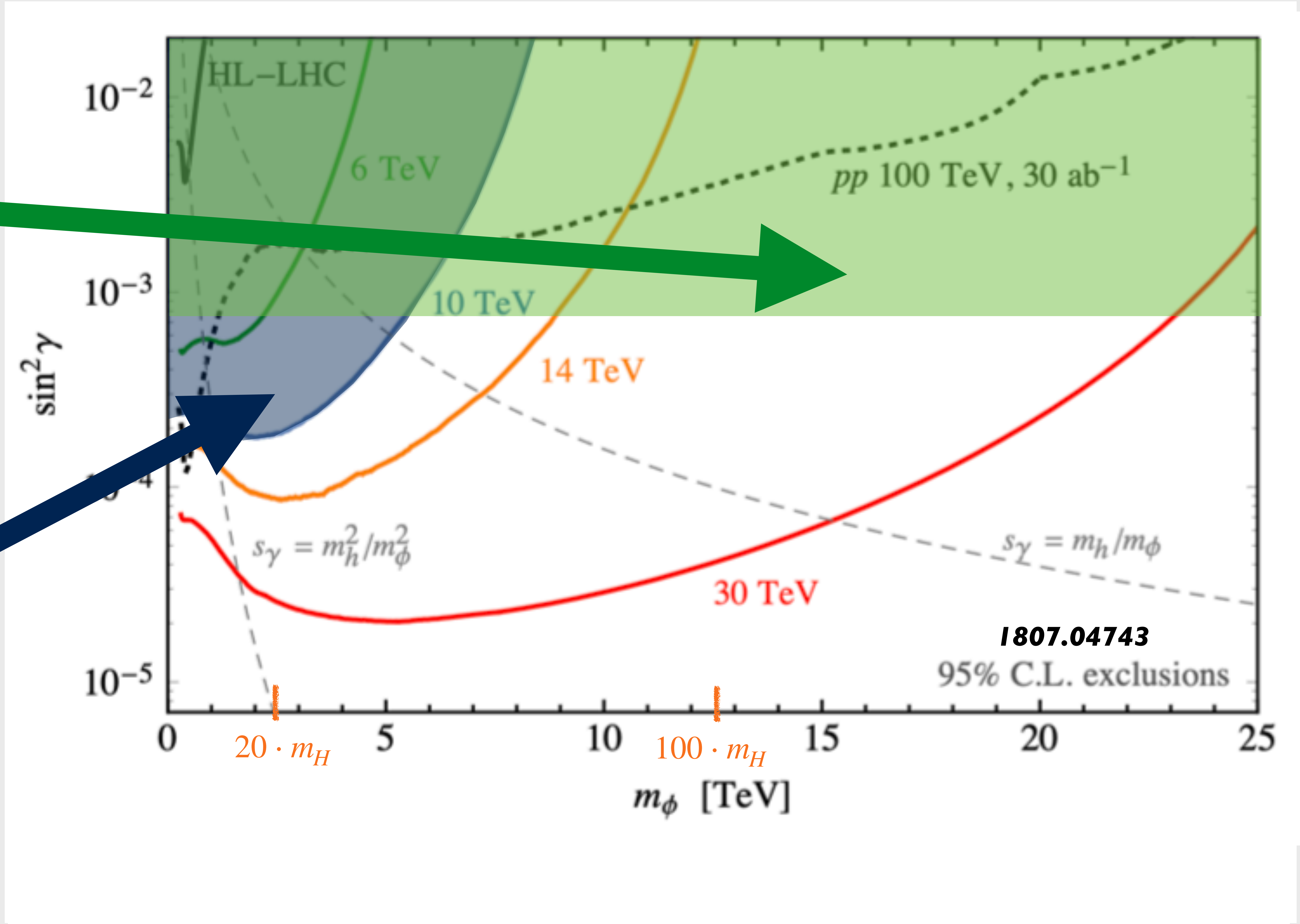
SINGELTS

BIG JUMP AT FUTURE COLLIDERS



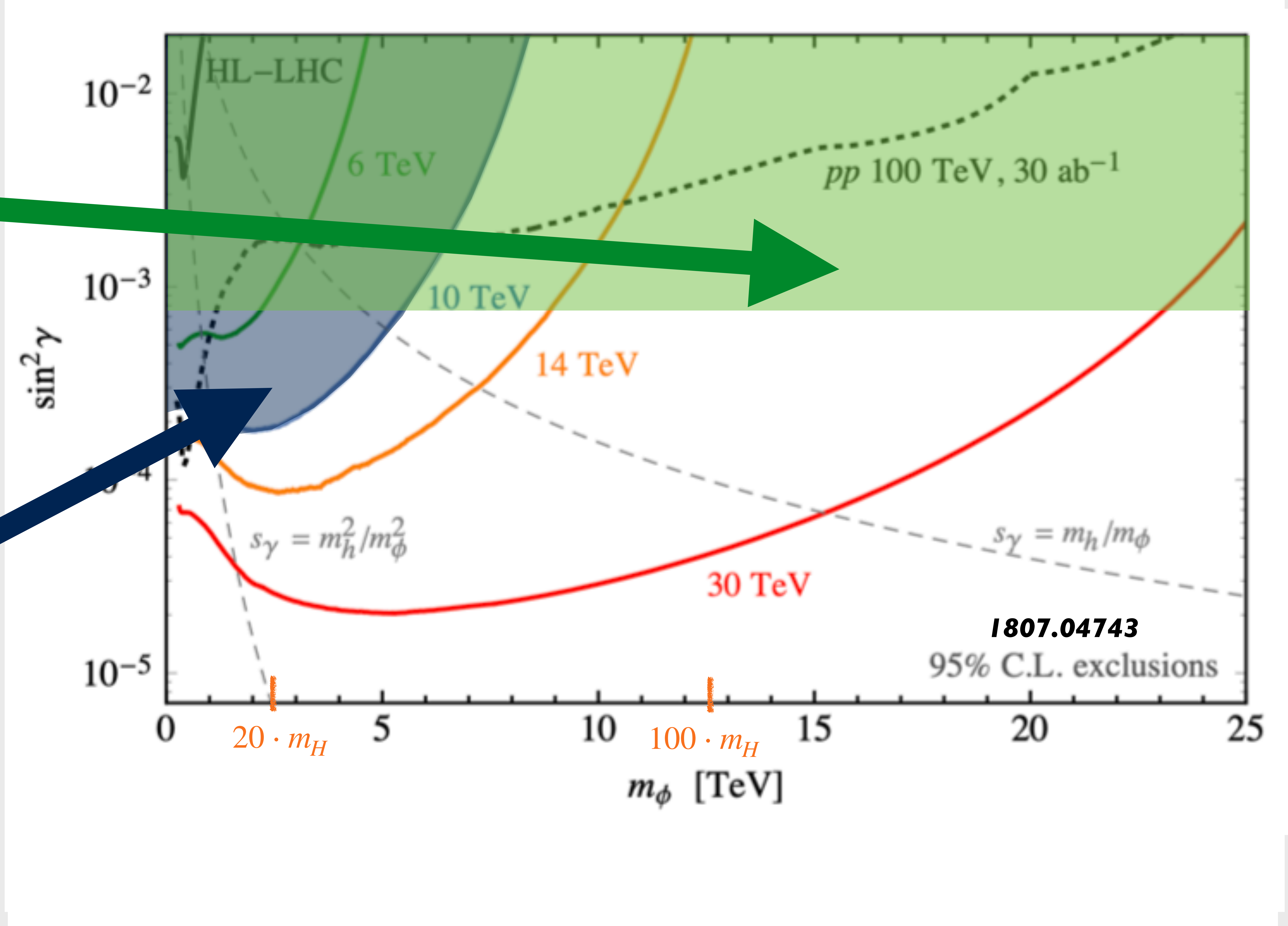
EXPLOIT ONCE MORE THE W BOSON LUMINOSITY



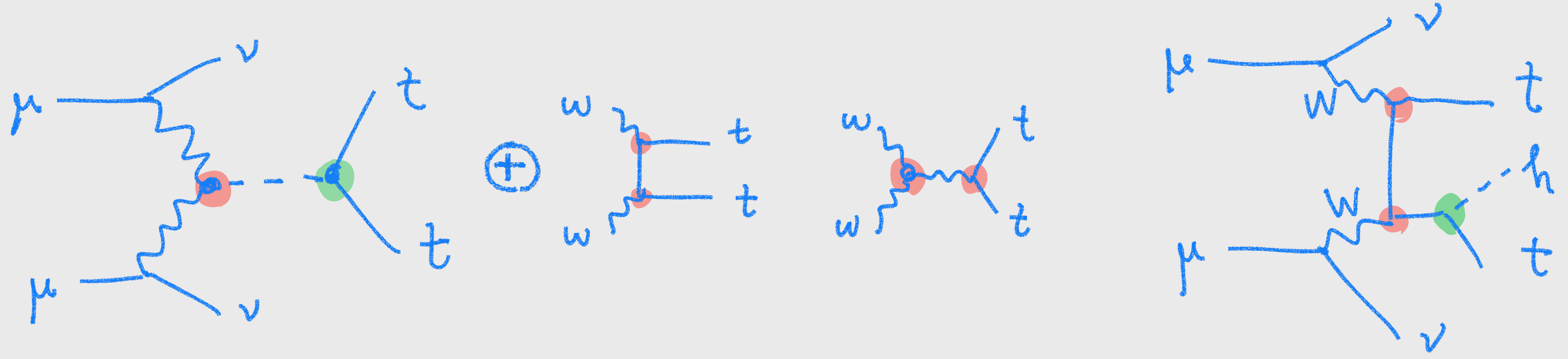


Higgs + Singlet

SINGELTS | BIG JUMP AT FUTURE COLLIDERS

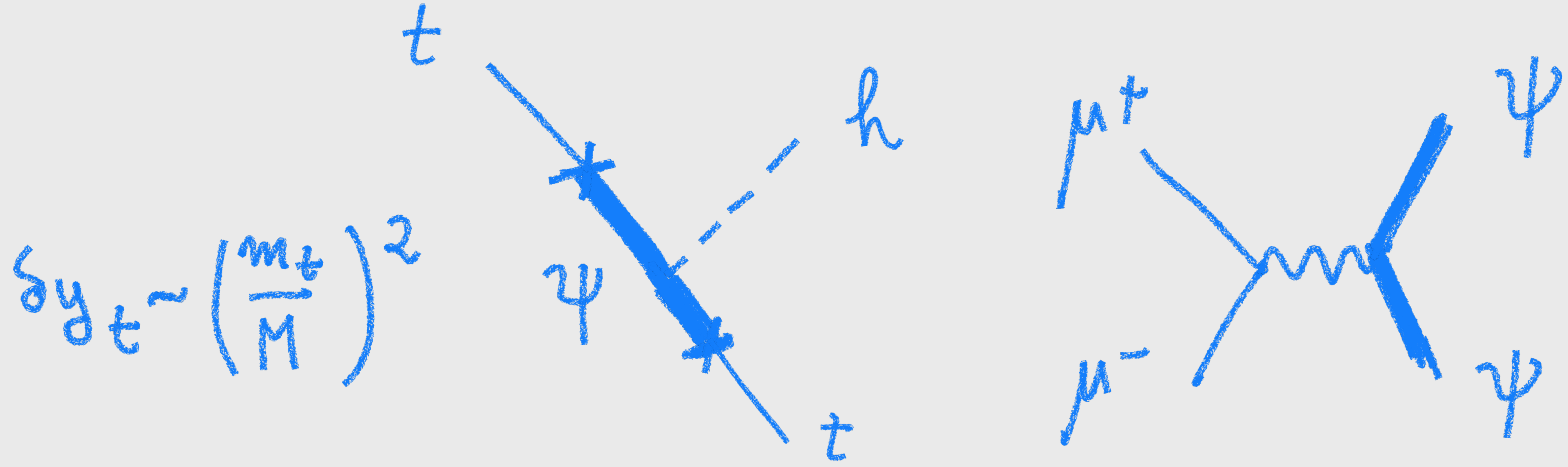


Joint-ventures on the Yukawa of the top quark



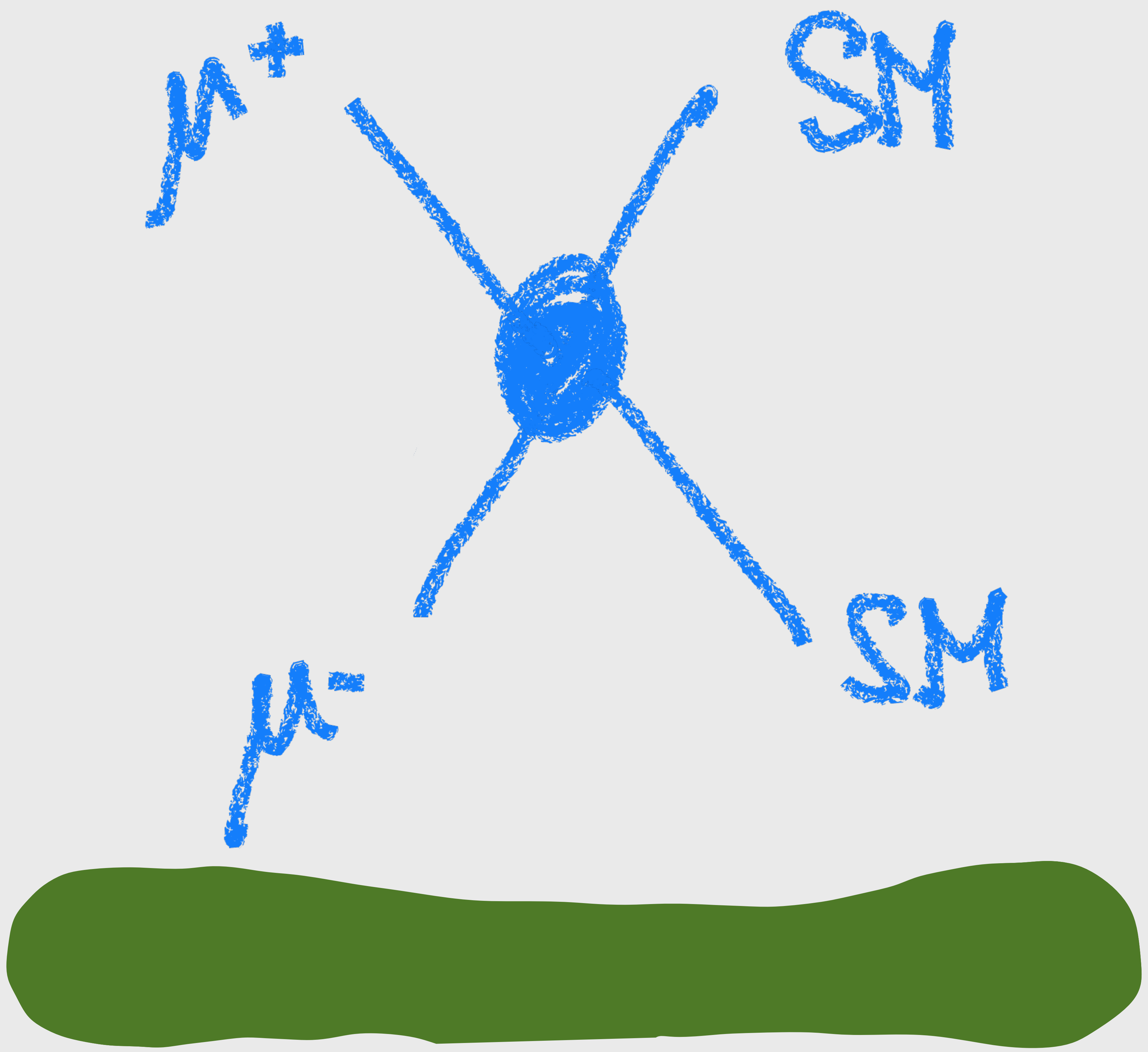
A global fit of “top ⊂ SM” to search for couplings deviations in $\mu\mu$ collider top factory”

The same muon collider that acts as “top factory” can also test directly the existence of new states responsible for the deviations in the couplings



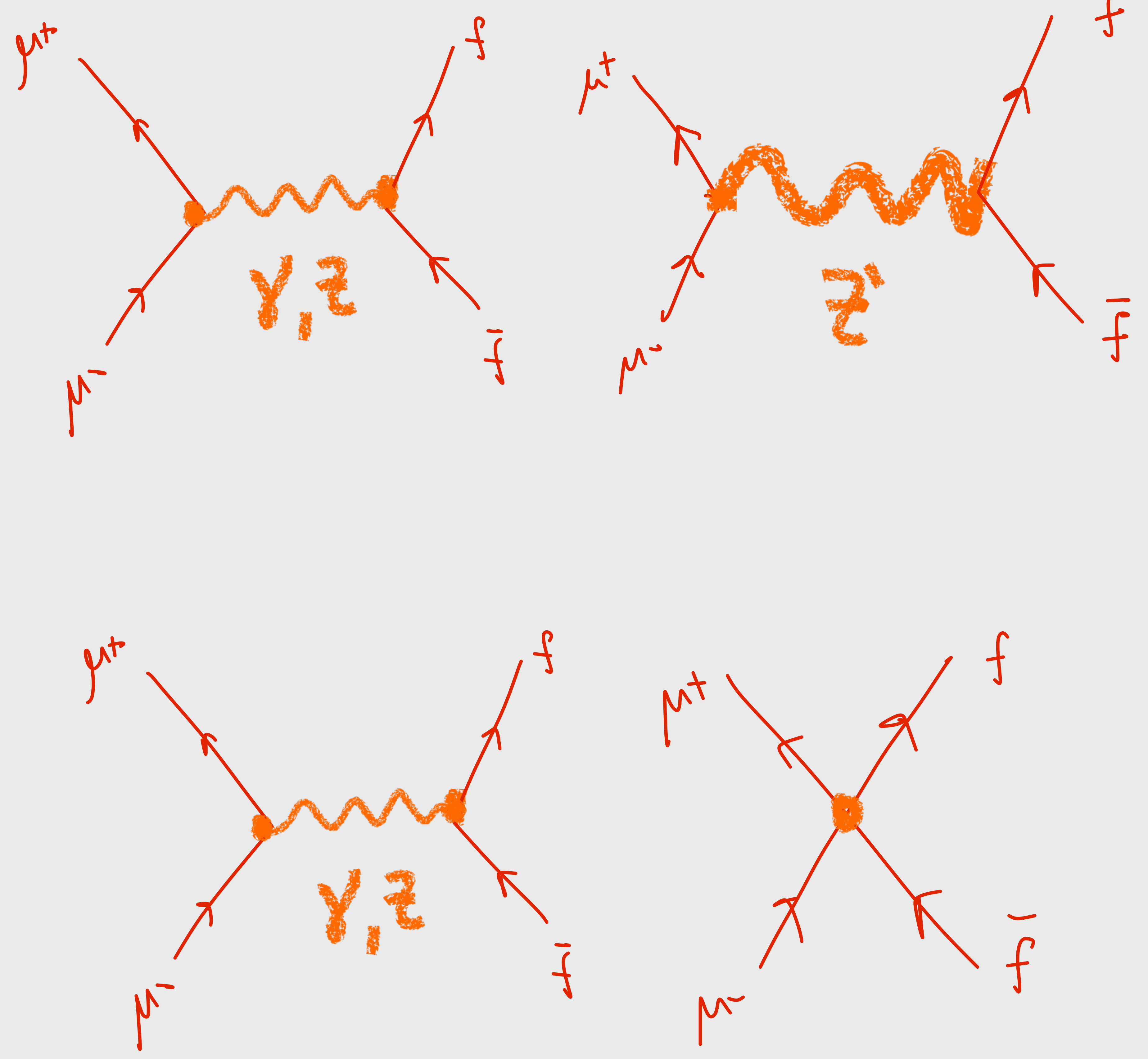
same machine can perform complementary direct and indirect tests of BSM at $\sqrt{s} \gg 100$ GeV

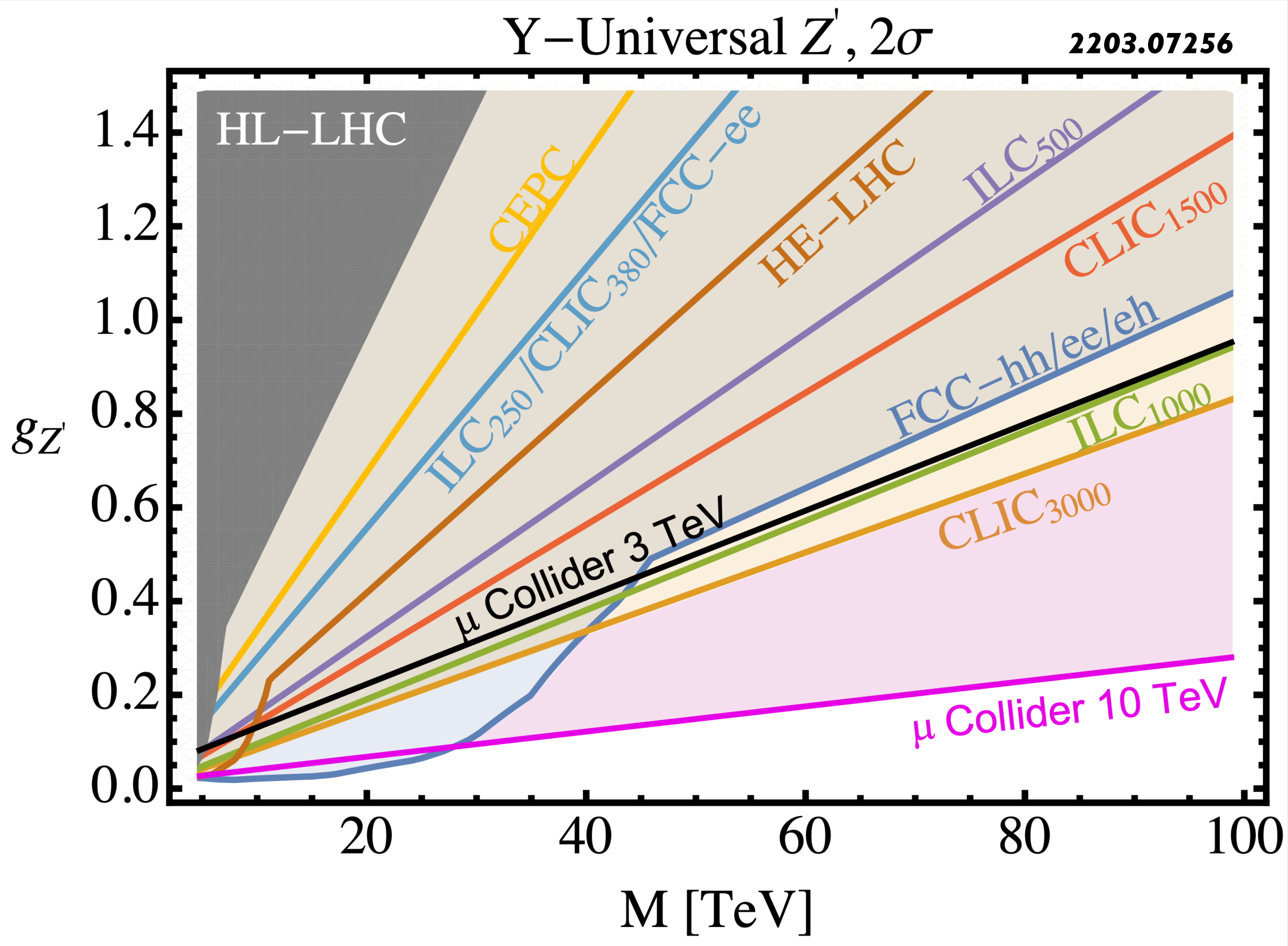
Indirect Effects



A heavy Z'

DRELL-YAN RATES AND ANGULAR DISTRIBUTIONS

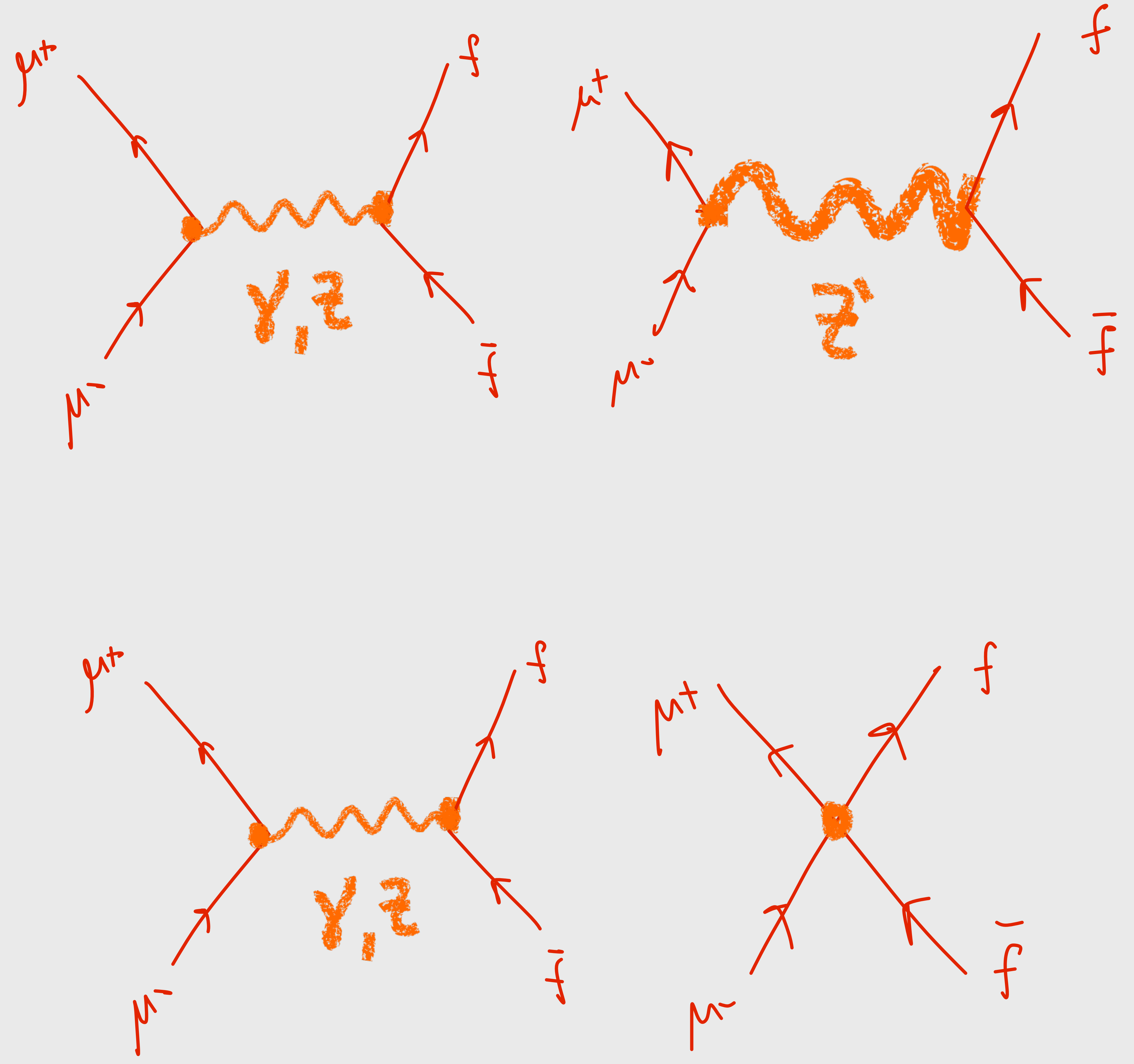


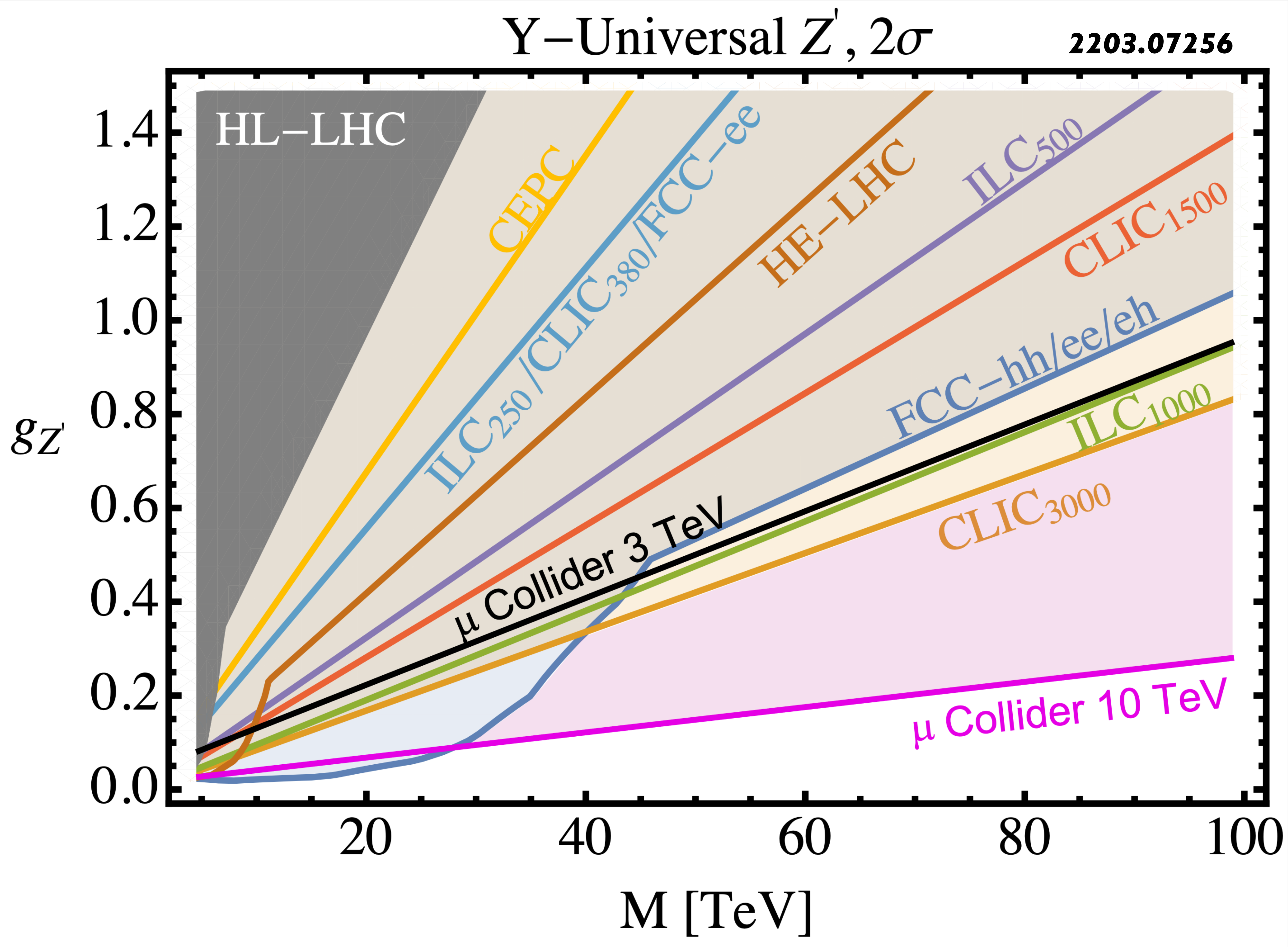


$\sqrt{s} \simeq 3$ TeV can probe 70+ TeV mass for $g_{Z'} \simeq g_{SM} \simeq 0.67$

A heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

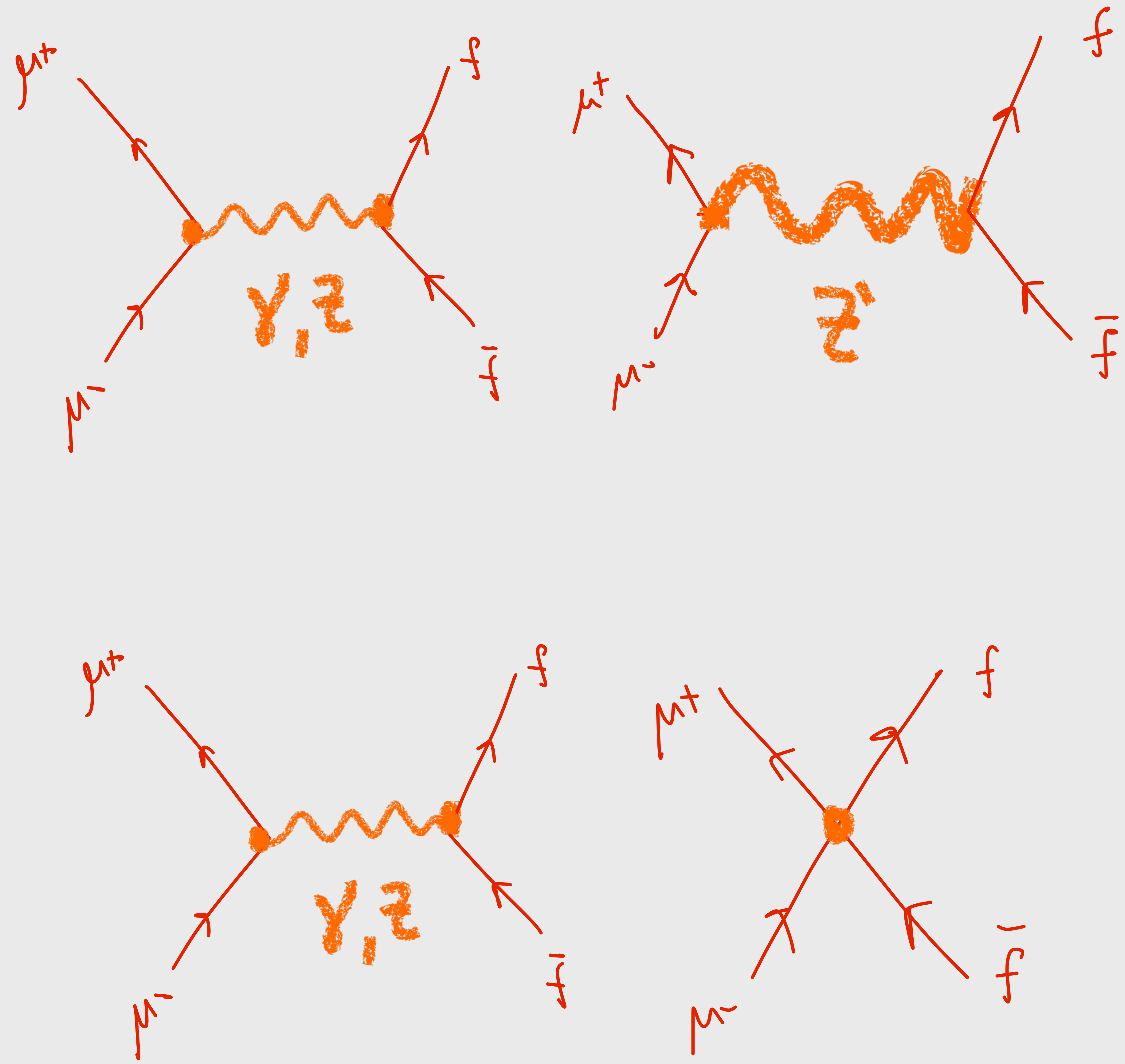




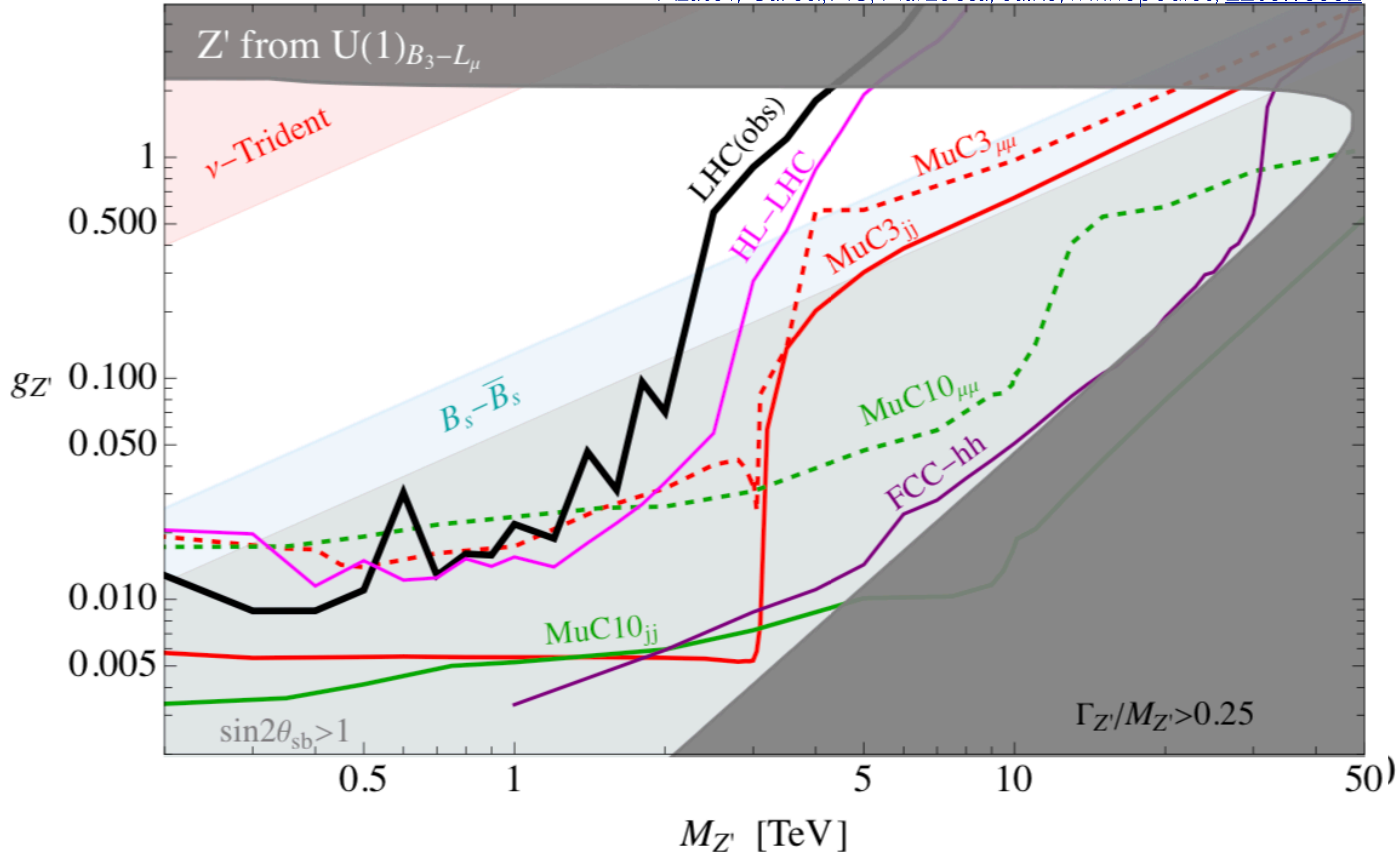
Another heavy Z'

DRELL-YAN | RATES AND ANGULAR DISTRIBUTIONS

$$bs\mu\mu: \quad \epsilon_{sb} = -1.7 \times 10^{-3} \left(\frac{M_{Z'}}{g_{Z'}\,\mathrm{TeV}}\right)^2$$



Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; 2205.13552

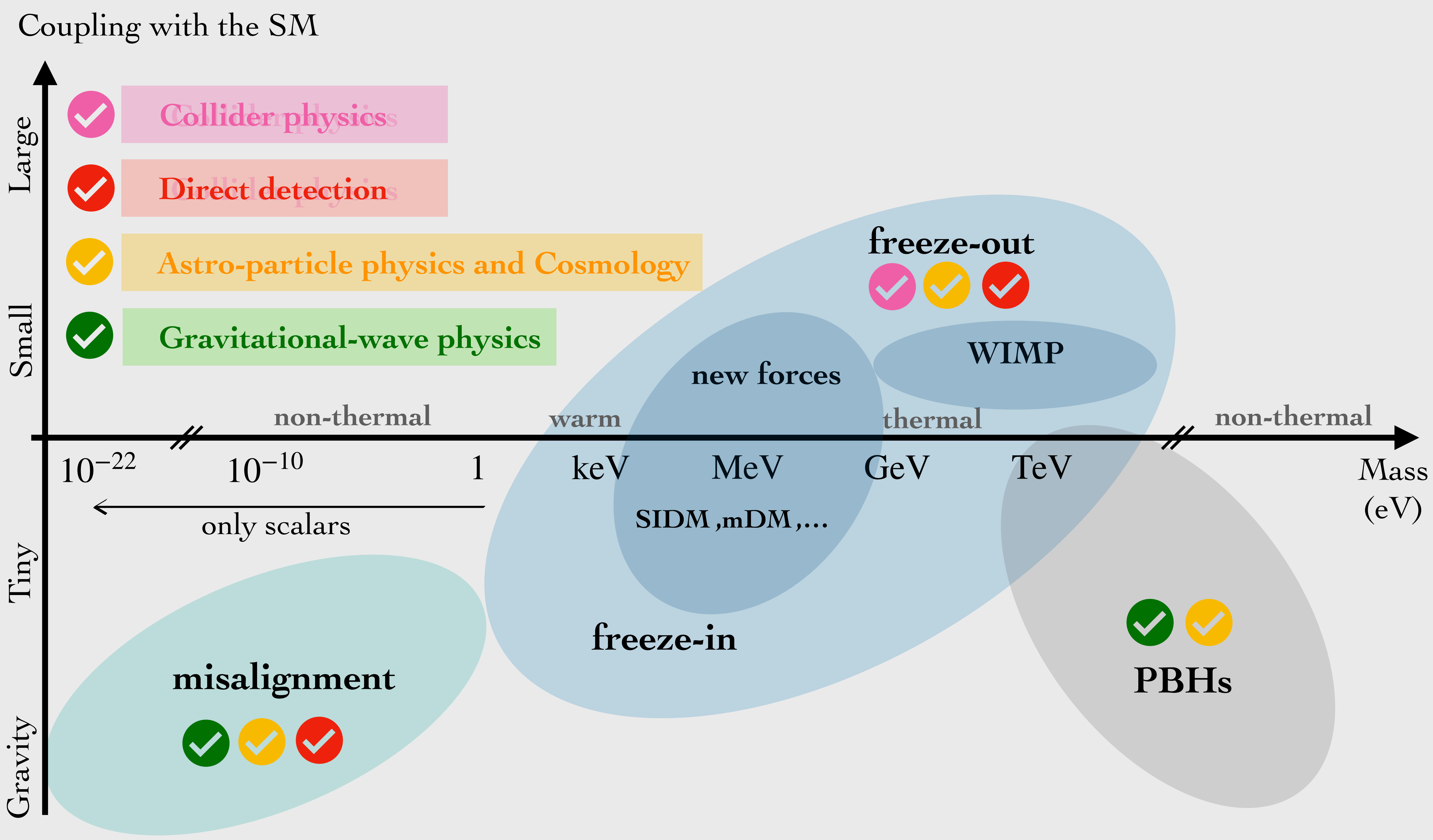


flashing concrete results for

Dark Matter at the weak scale

Electroweak Dark Matter: LSP (+NLSP)

- The chessboard of DM is very large!

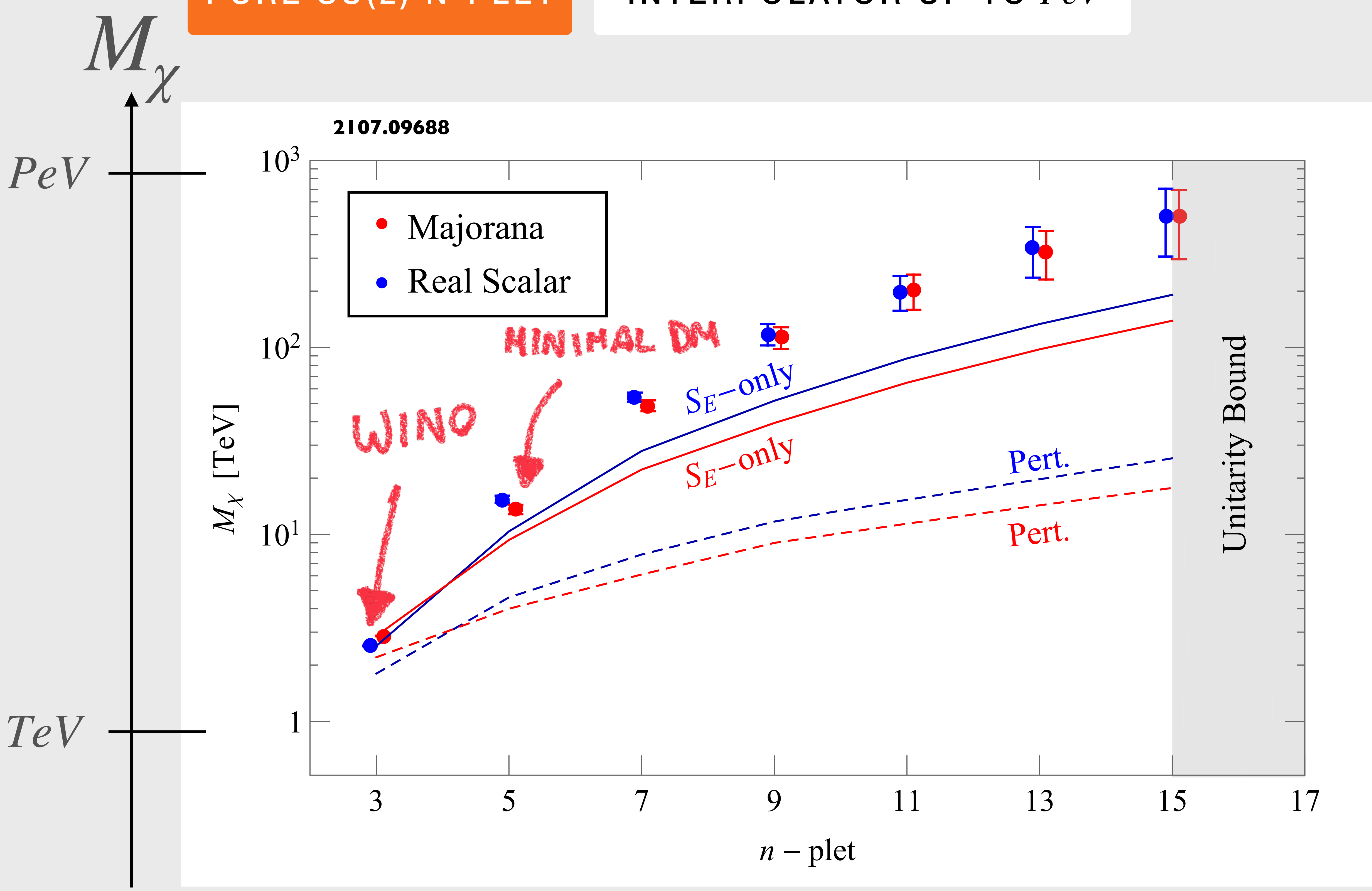


- High energy colliders are excellent and very robust probes of WIMPs!

WIMP Dark Matter as $SU(2)$ $n-$plet

PURE SU(2) N-PLET

INTERPOLATOR UP TO PeV

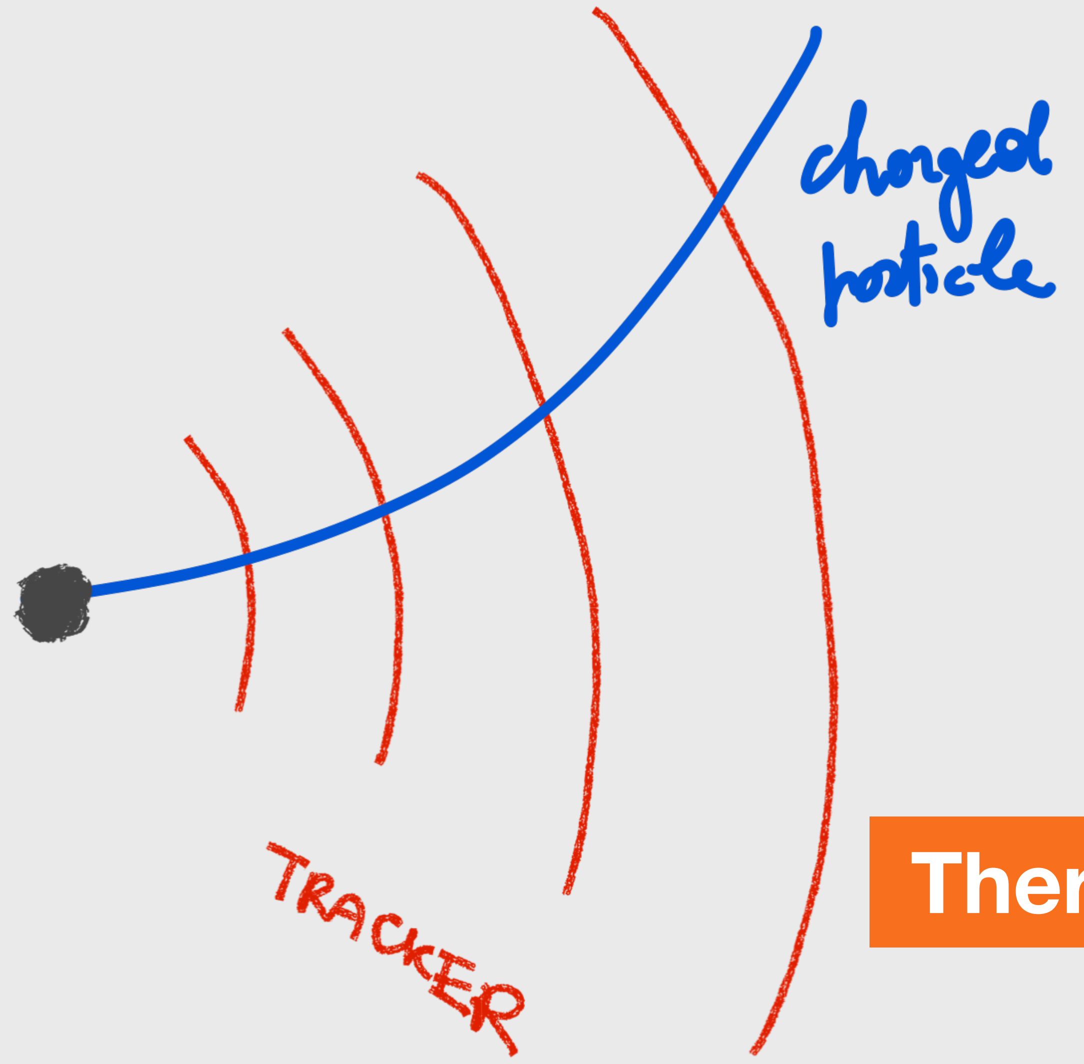


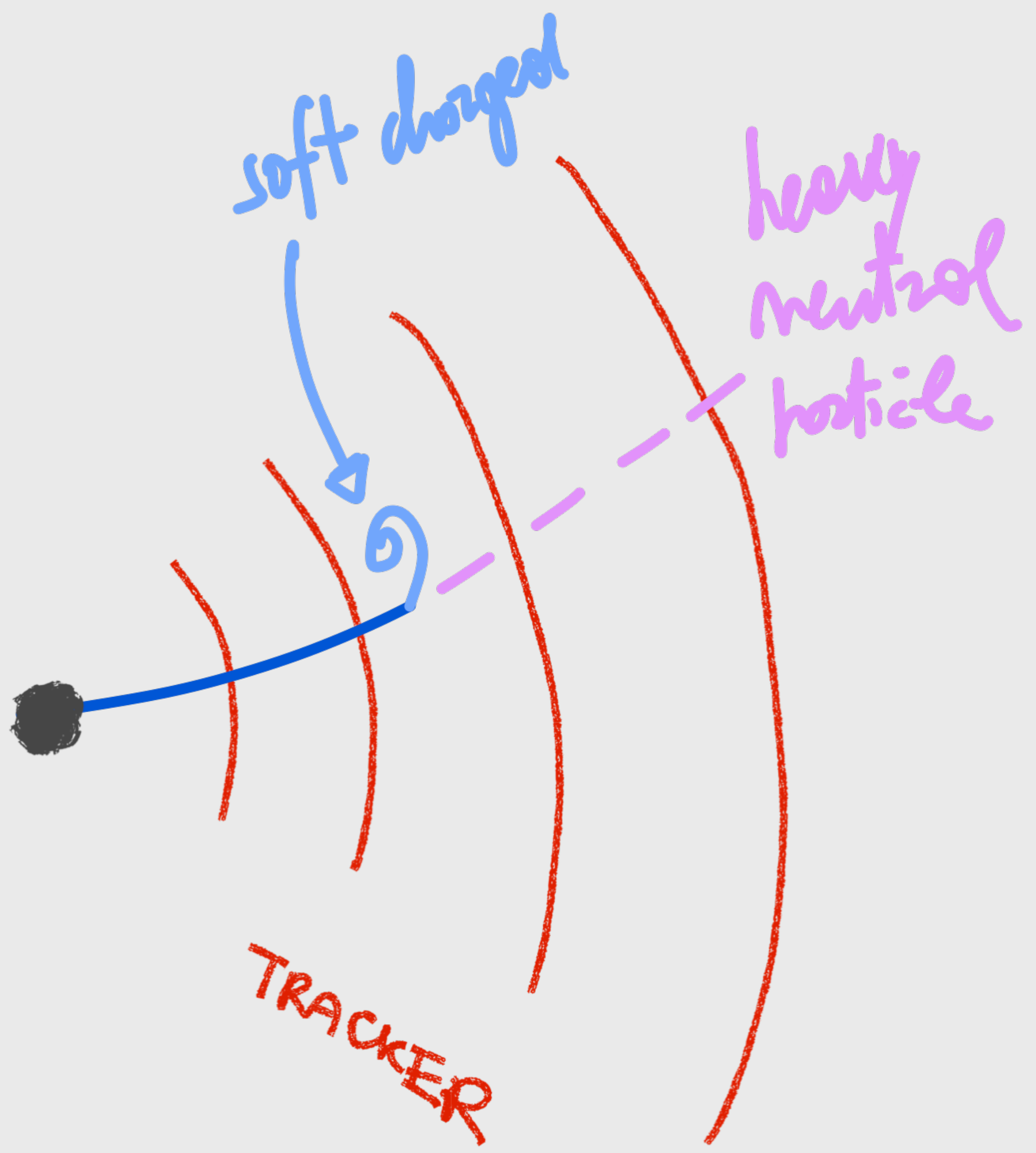
DM spin	EW n-plet	M_χ (TeV)	$(\sigma v)^{J=0}_{\text{tot}}/(\sigma v)^{J=0}_{\text{max}}$	$\Lambda_{\text{Landau}}/M_{\text{DM}}$	$\Lambda_{\text{UV}}/M_{\text{DM}}$
Real scalar	3	2.53 ± 0.01	–	3×10^{37}	$4 \times 10^{24}*$
	5	15.4 ± 0.7	0.002	5×10^{36}	2×10^{24}
	7	54.2 ± 3.1	0.022	2×10^{19}	2×10^{24}
	9	117.8 ± 15.4	0.088	3×10^{3}	2×10^{24}
	11	199 ± 42	0.25	20	3×10^{24}
	13	338 ± 102	0.6	3.5	3×10^{24}
Majorana fermion	3	2.86 ± 0.01	–	3×10^{37}	$8 \times 10^{12}*$
	5	13.6 ± 0.8	0.003	3×10^{17}	5×10^{12}
	7	48.8 ± 3.3	0.019	1×10^{4}	4×10^{7}
	9	113 ± 15	0.07	30	3×10^{7}
	11	202 ± 43	0.2	6	3×10^{7}
	13	324.6 ± 94	0.5	2.6	3×10^{7}

a "collection" of Dark Matter candidates with thermal mass from 1 TeV to fraction of PeV

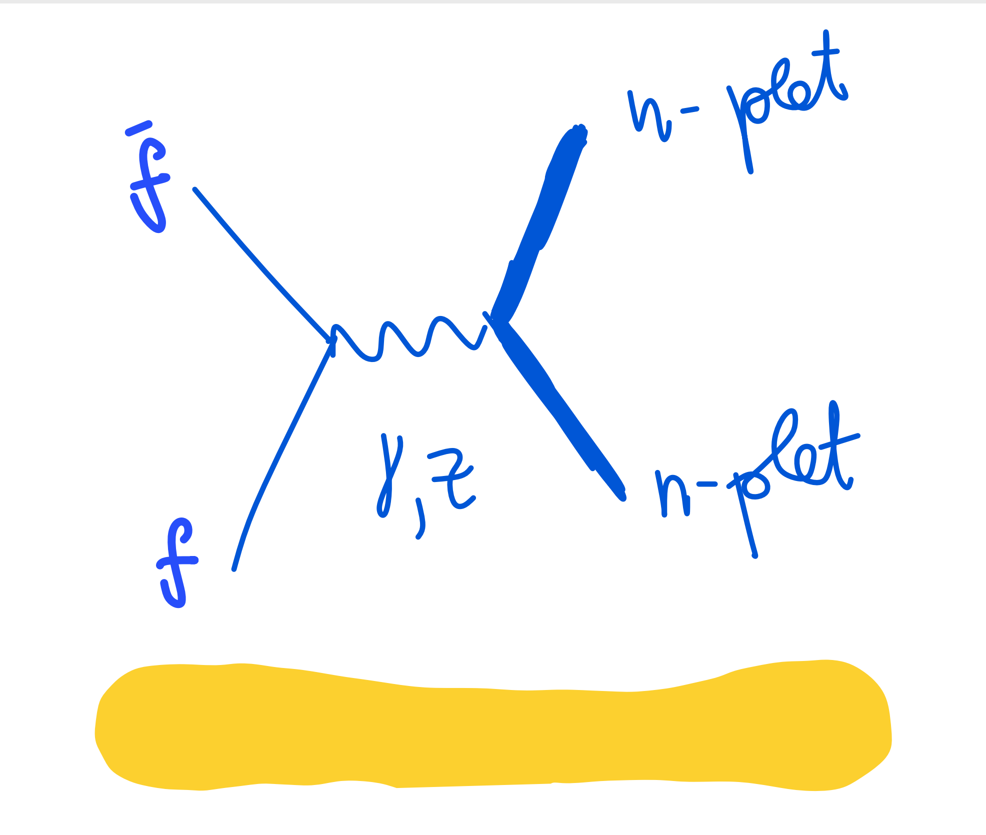
Higgsino DM

STUB-TRACKS | EXOTIC SIGNAL



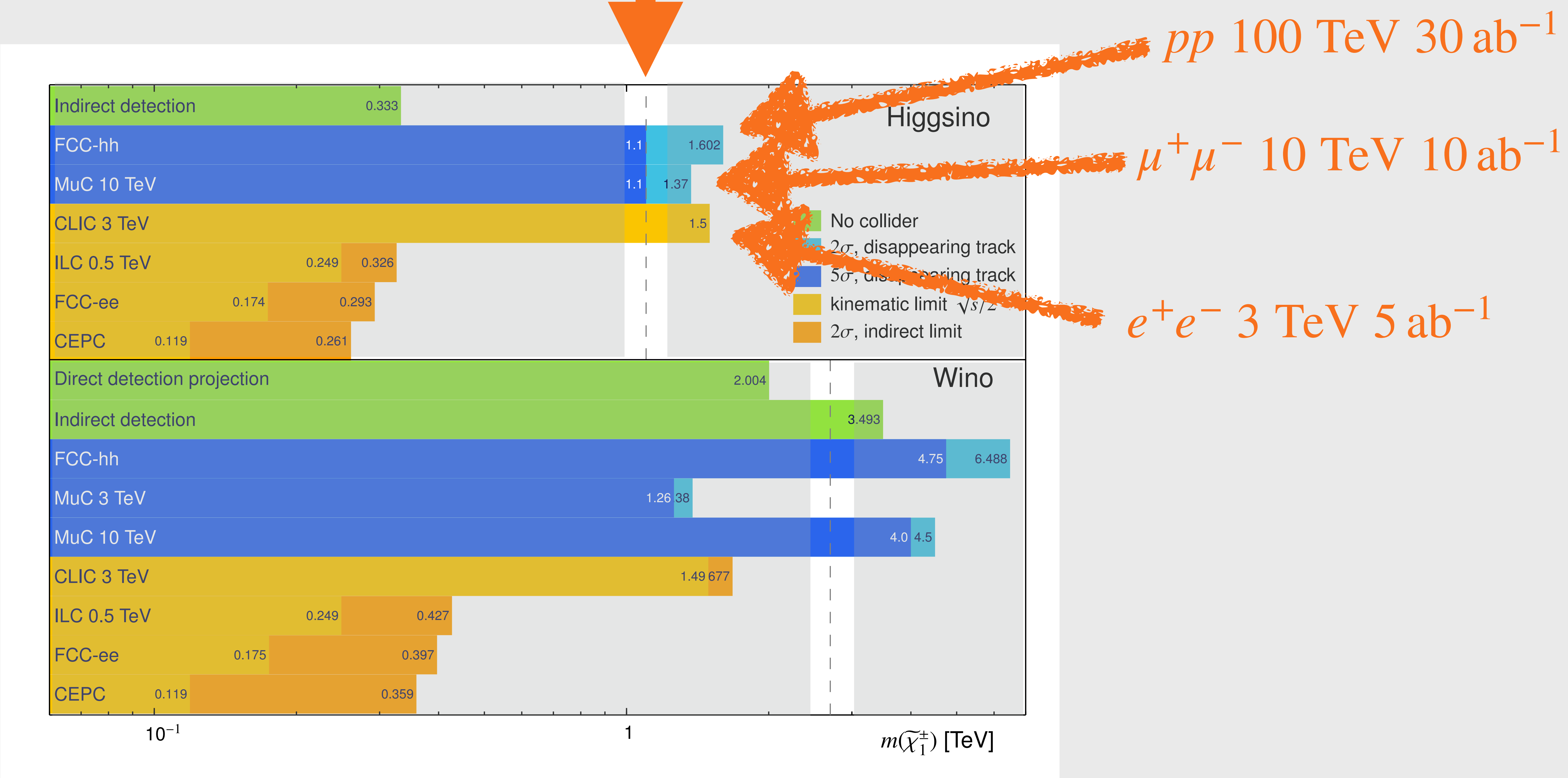


- Heavy n-plet of SU(2)
- Mass splitting ~ $\alpha_W m_W$ ~ 0.1 GeV - GeV



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

Thermal Higgsino



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 pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

Δm

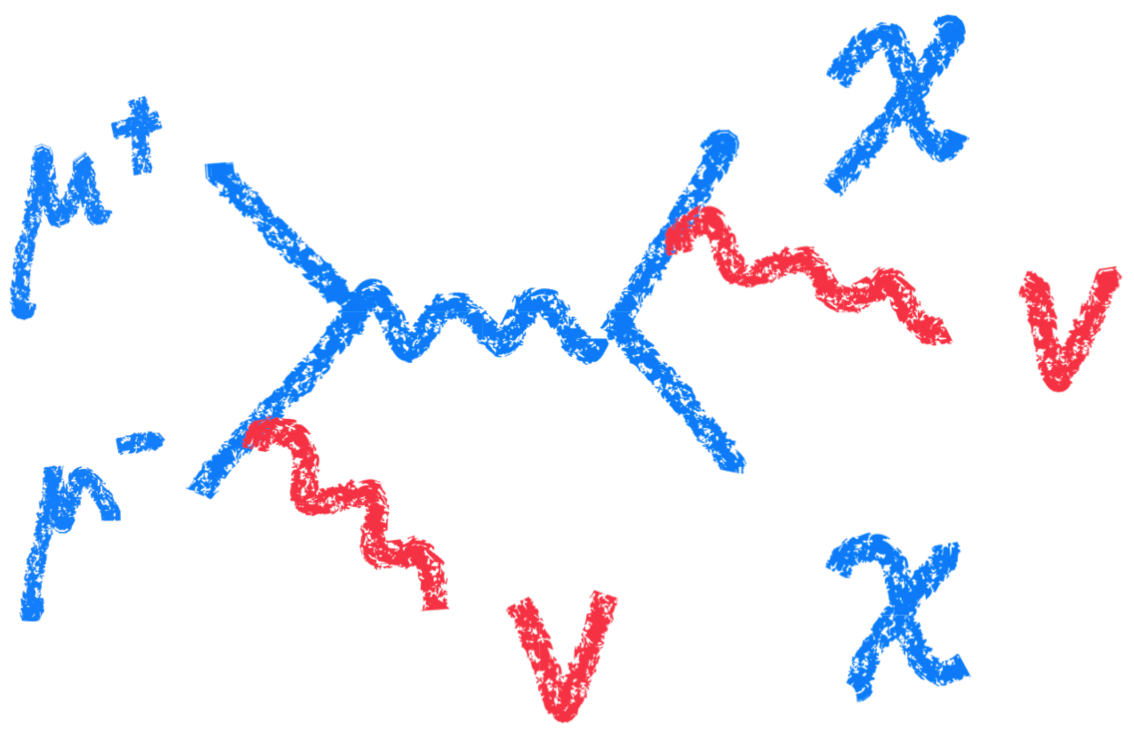
Wide open spectra		Generic leptons+missing momentum
Co-annihilation		Soft-objects + missing momentum
	GeV	
WIMP-like multiplet Accidental Dark Matter		Short (disappearing) tracks
DM SM singlet pp or $\ell^+\ell^- \to Z' \to \chi\,\chi$	0	Mono-X

Precision Tests

$$\mu^+\mu^- \to \chi\chi + X$$

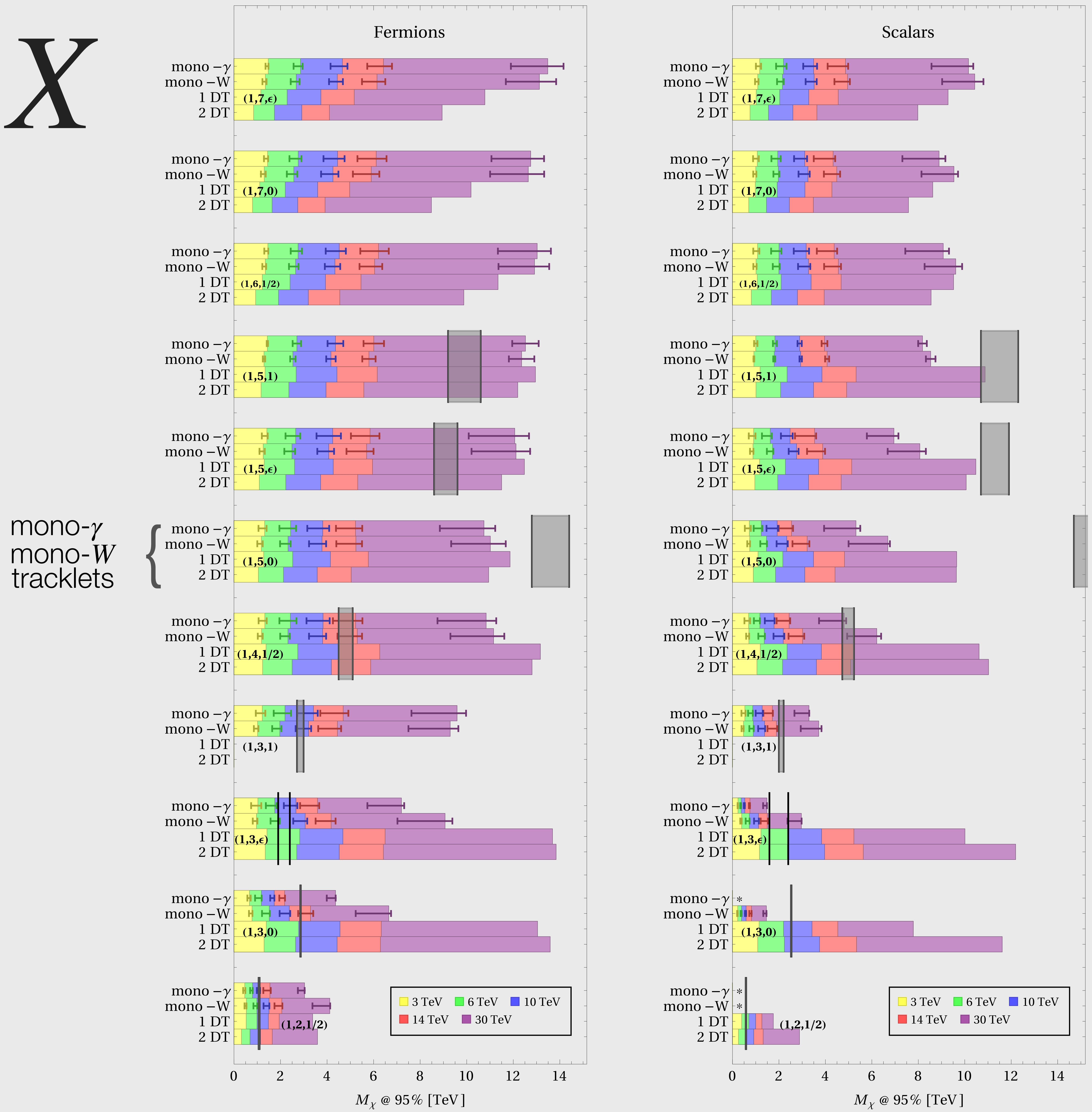
MONO-X

X $=\gamma, W, \ldots$



Large χ mass requires CoM energy!

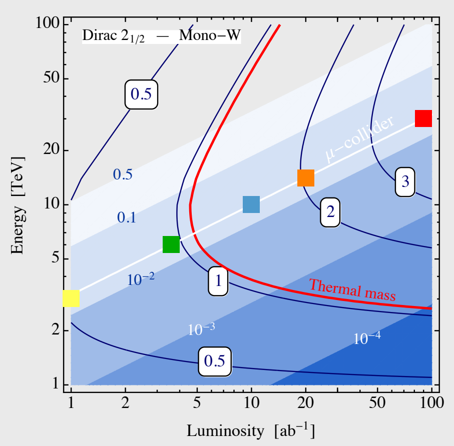
Weak radiation yield the most constraining channel "mono-W"

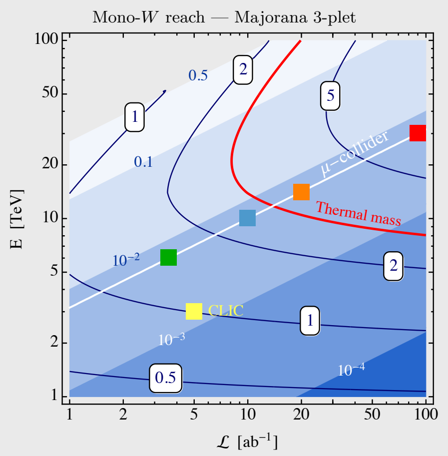


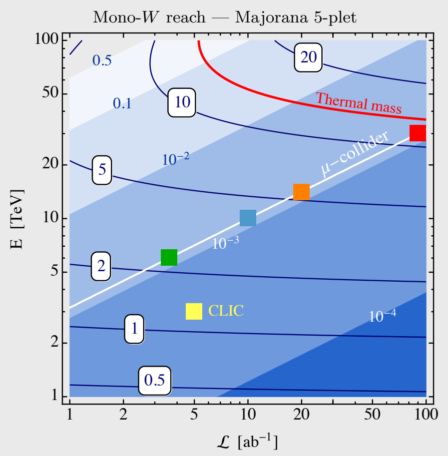
$$\mu^+\mu^- \rightarrow \chi\chi + X$$

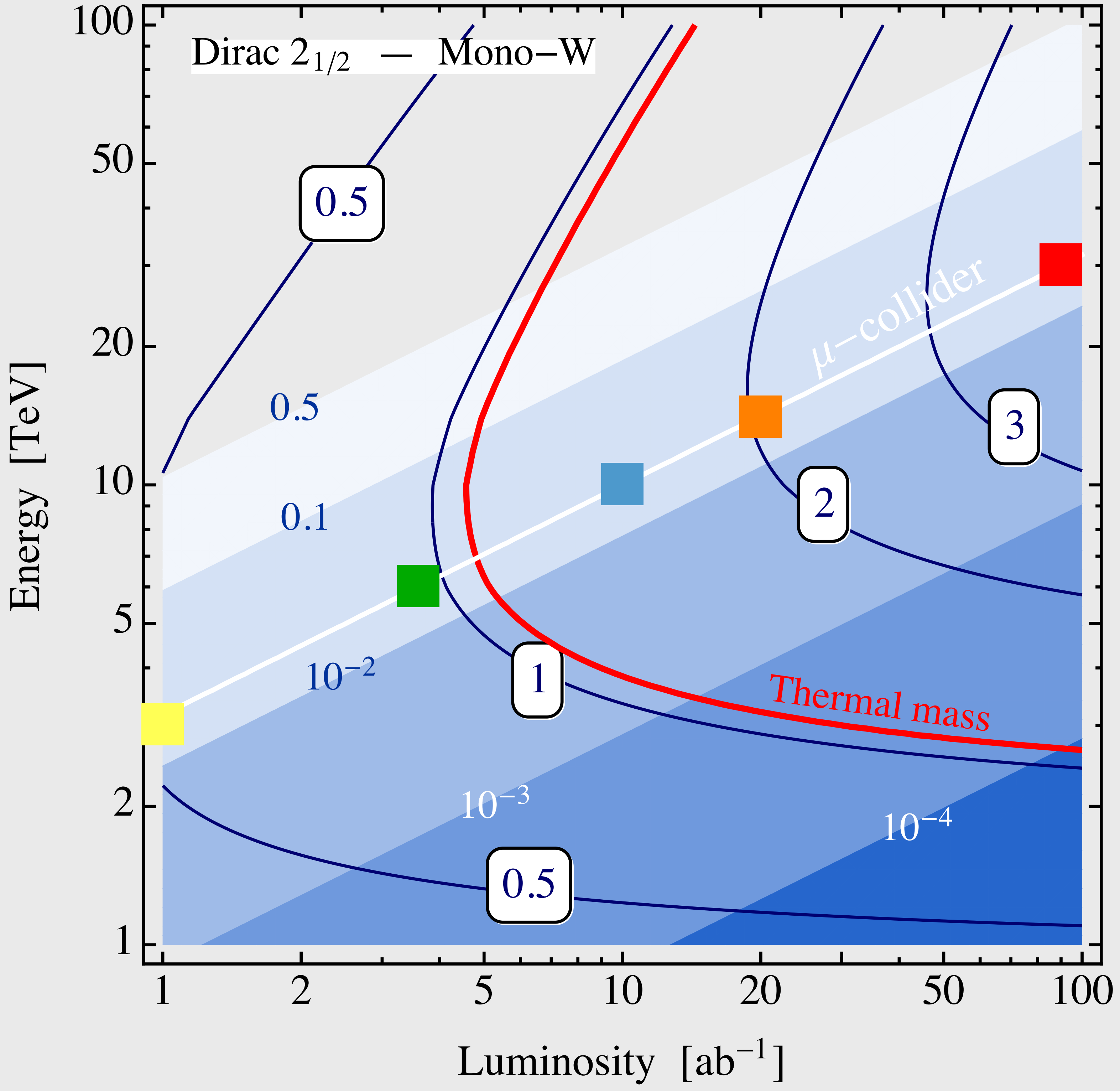
MONO-X

X=$\gamma, W, \ldots$

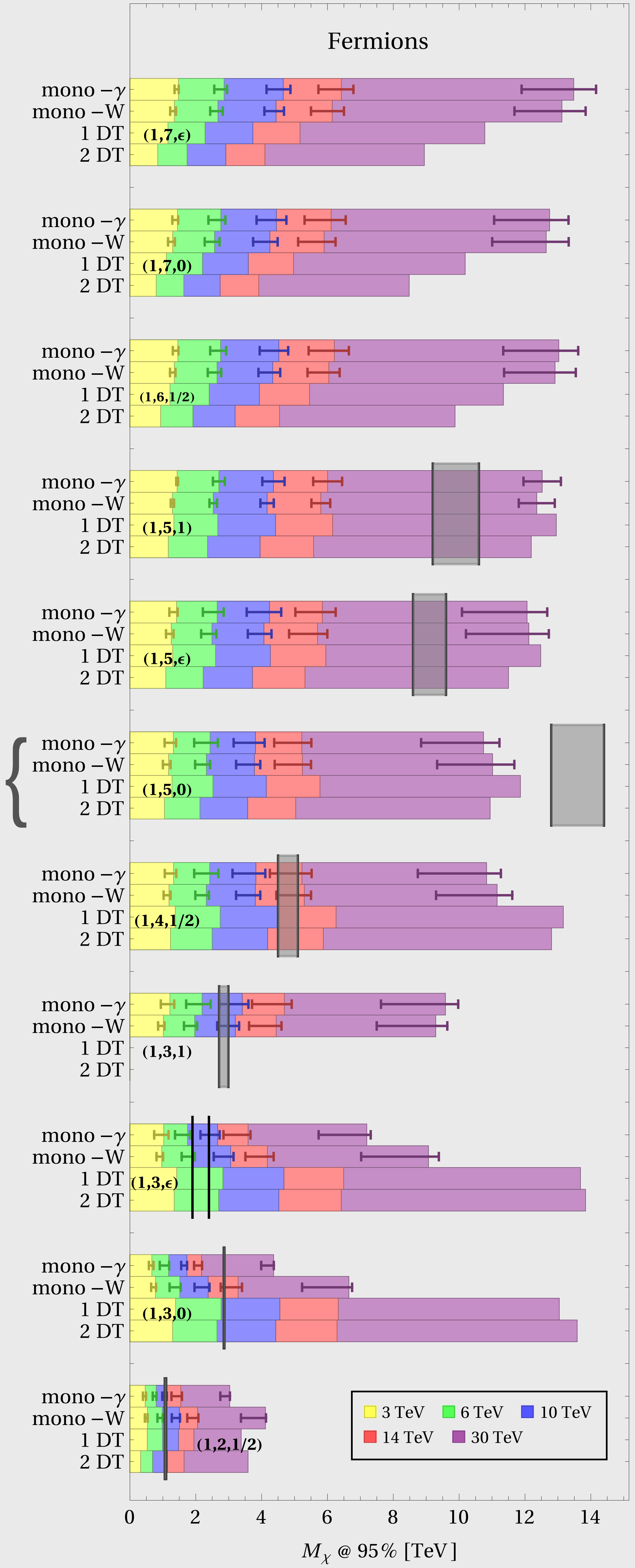


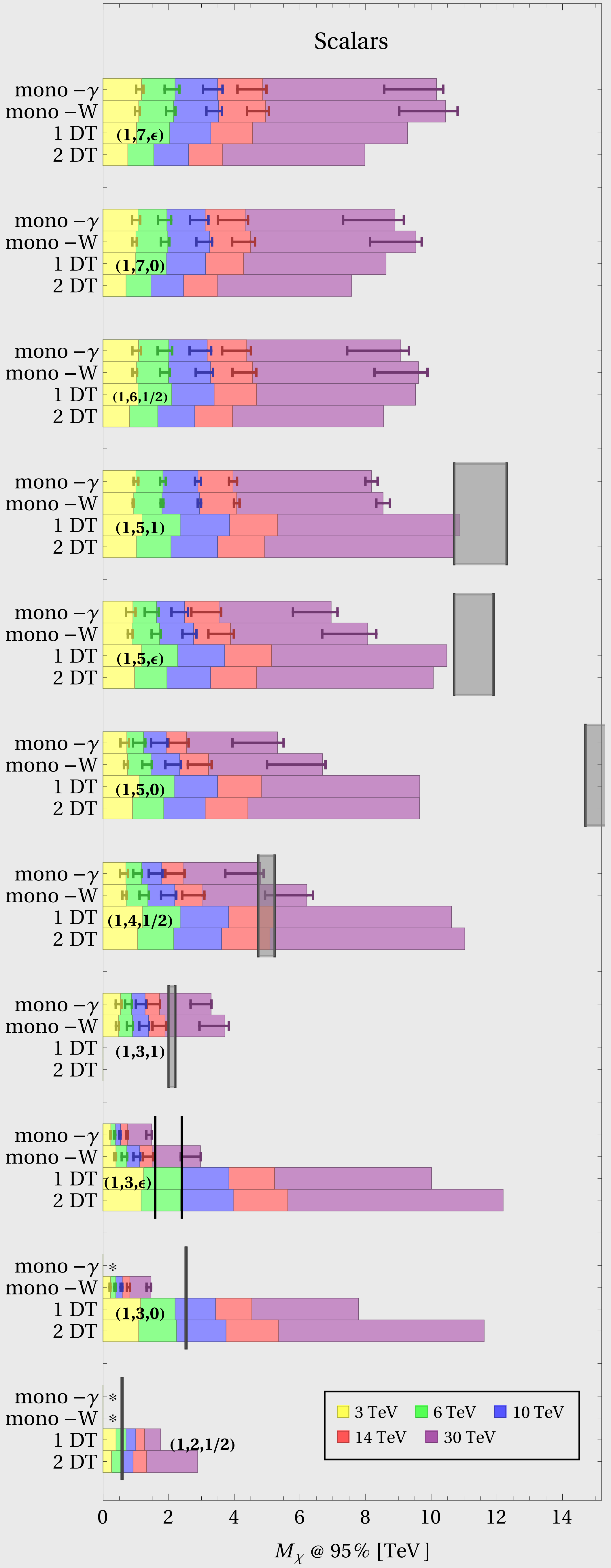






mono-γ
mono-W
tracklets





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 pp or $\ell^+\ell^- \to Z' \to \chi\chi$	0	Mono-X

} Precision Tests

Electroweak Dark Matter: LSP (+NLSP)

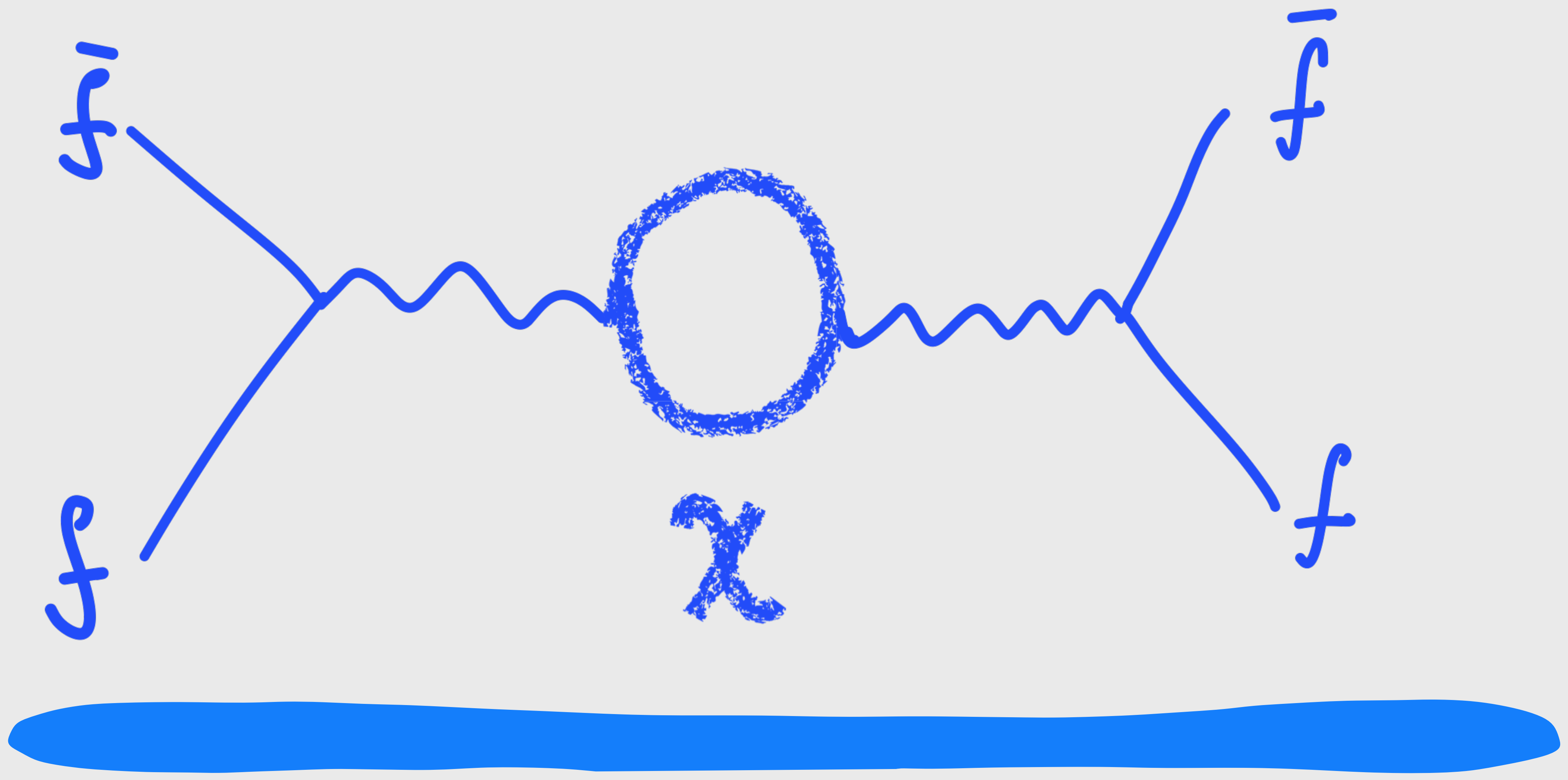
Δm

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 *pp* or $\ell^+\ell^- \to$ Z' $\to \chi\,\chi$	0	Mono-X

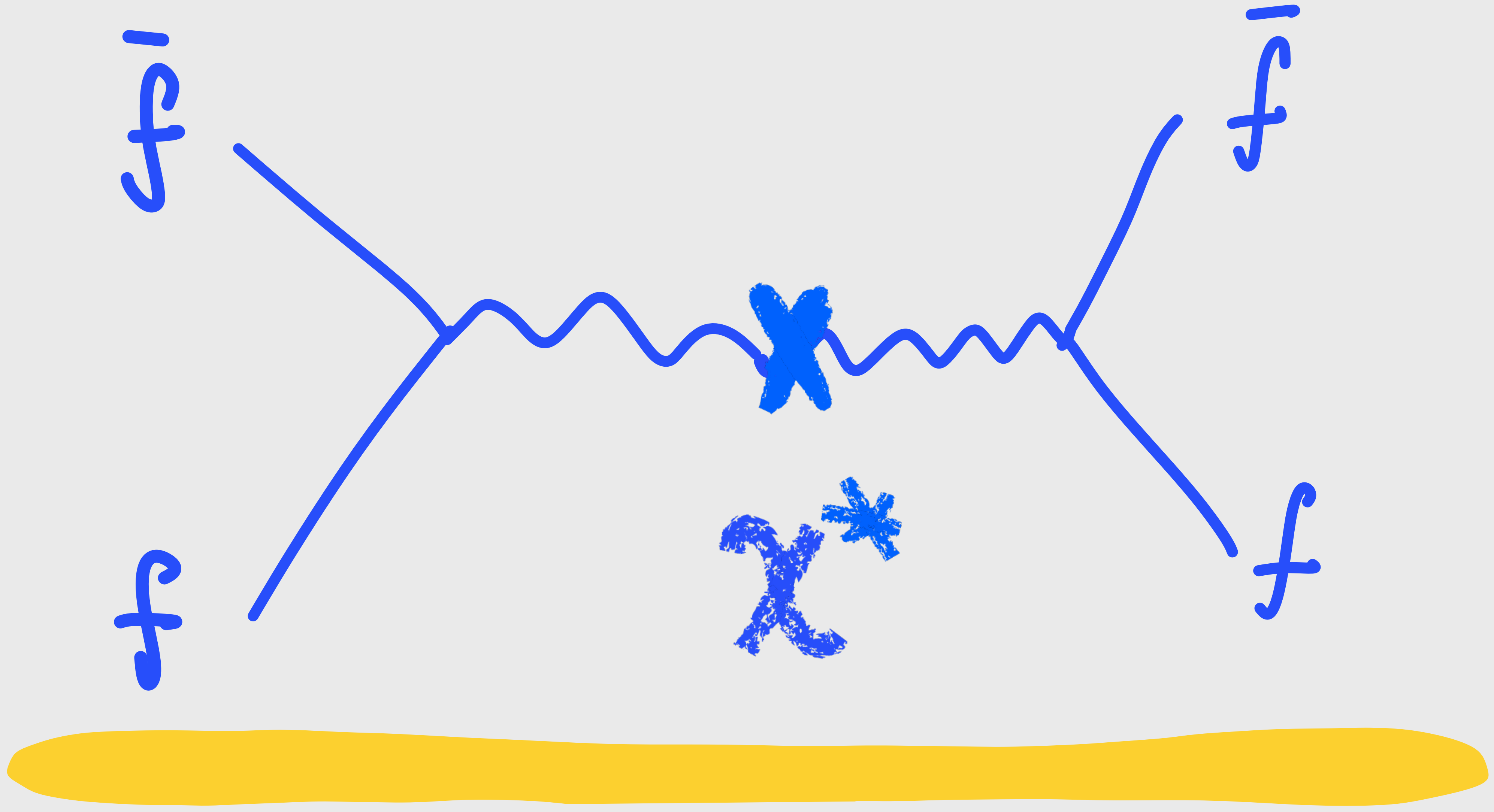
Precision Tests

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

PRECISION | TOTAL CROSS-SECTION

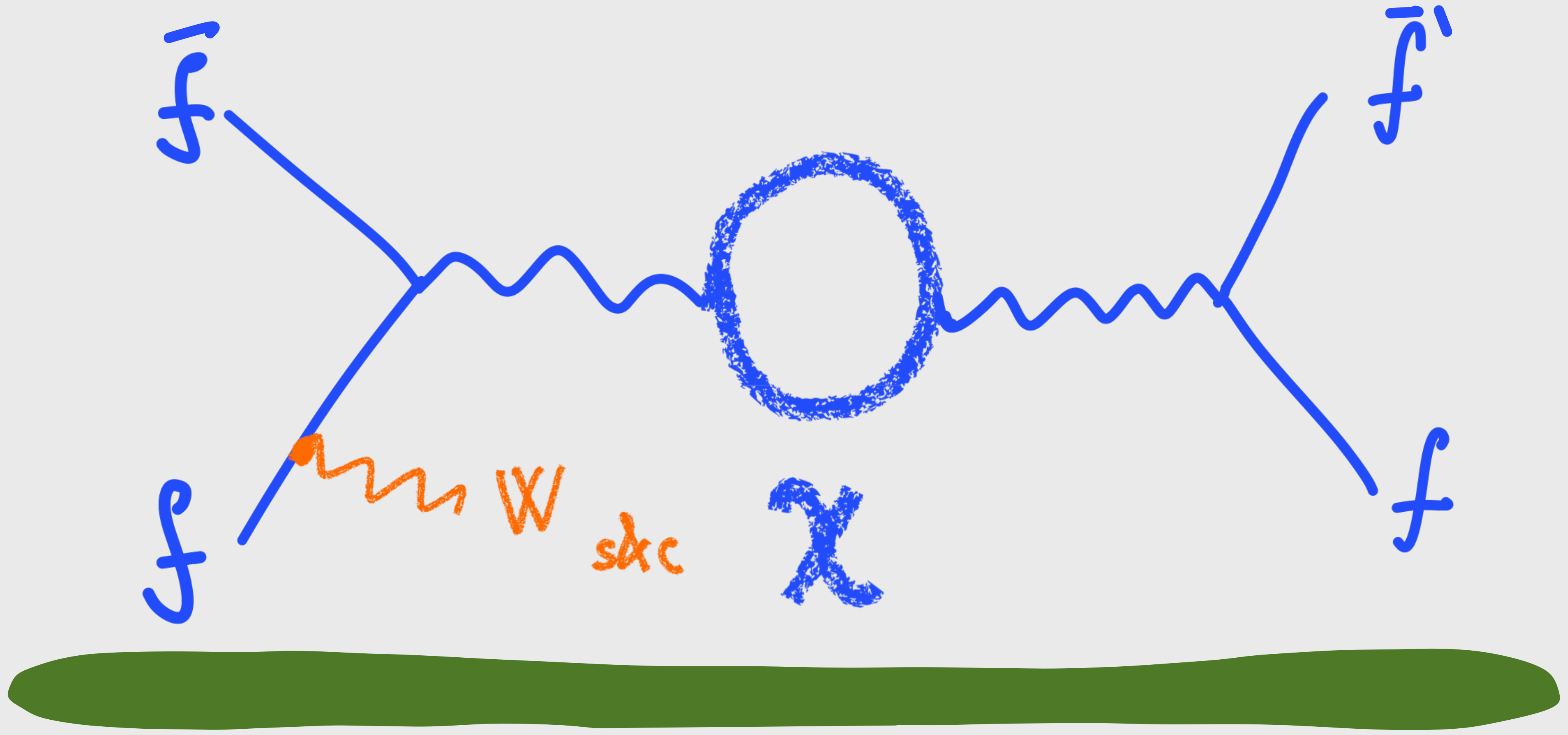


$m_\chi \gg E_{cm}$ →

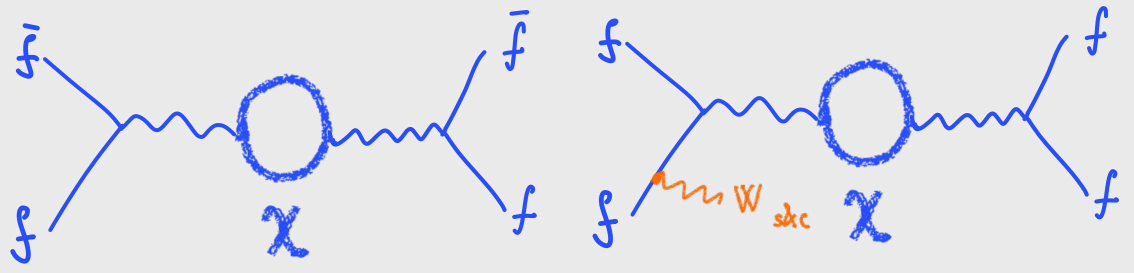


$$O_{2W} \propto (D_\mu W^{\mu\nu})^2$$

↓ $E_{cm} \gg m_W$

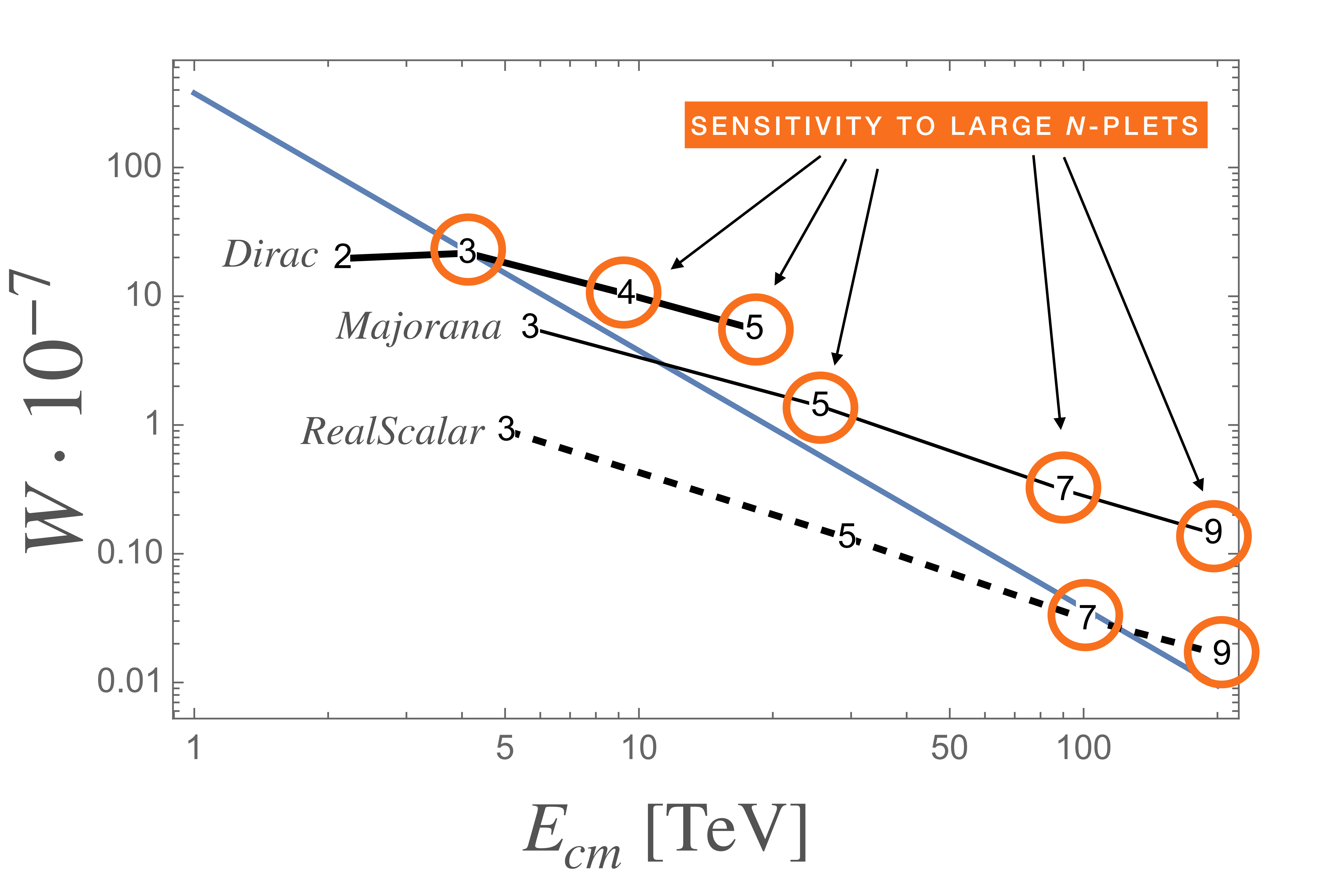


$\ell^+\ell^- \to f\bar{f}, Zh, W^+W^-, Wff'$



PRECISION

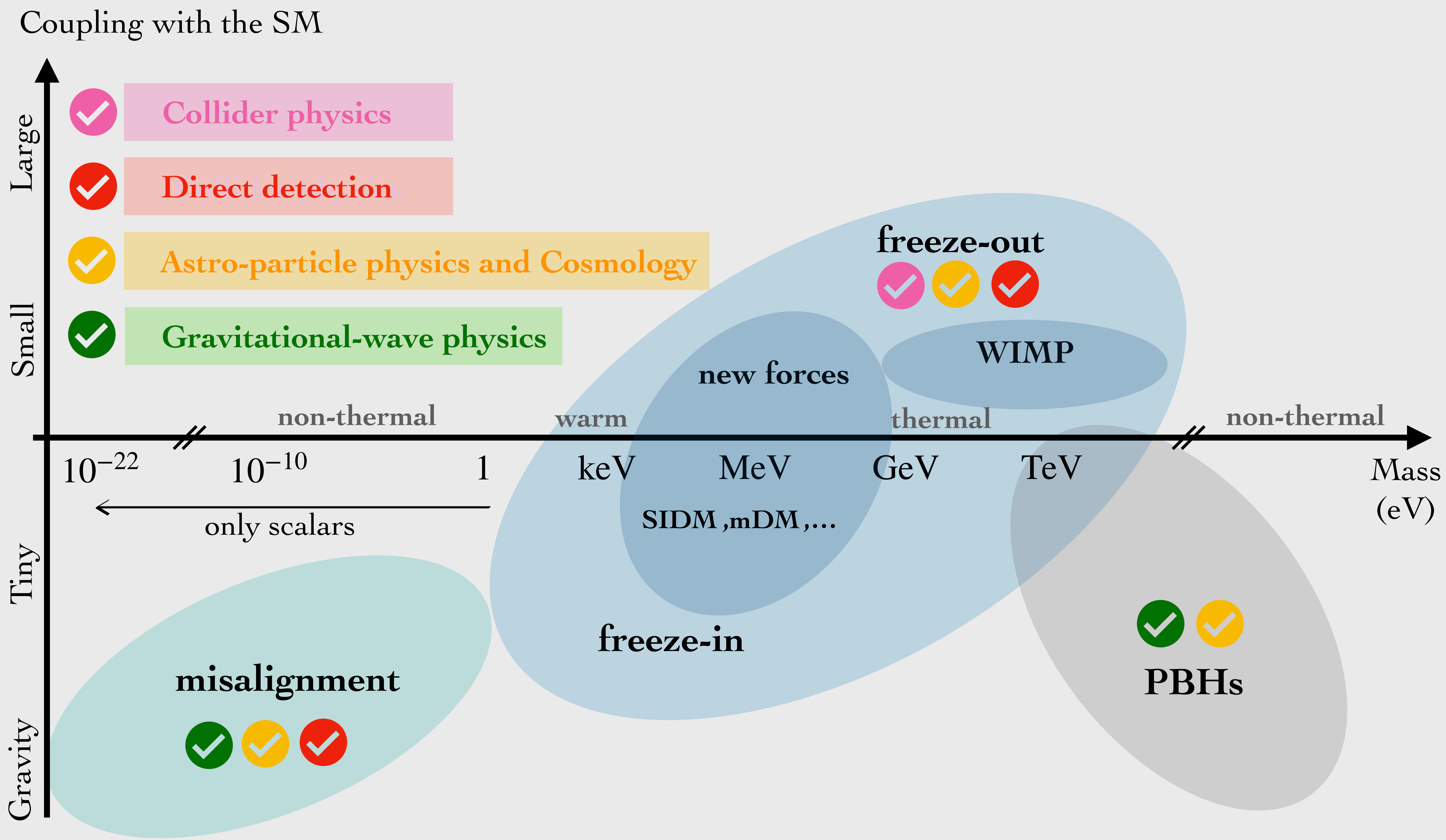
TOTAL CROSS-SECTION

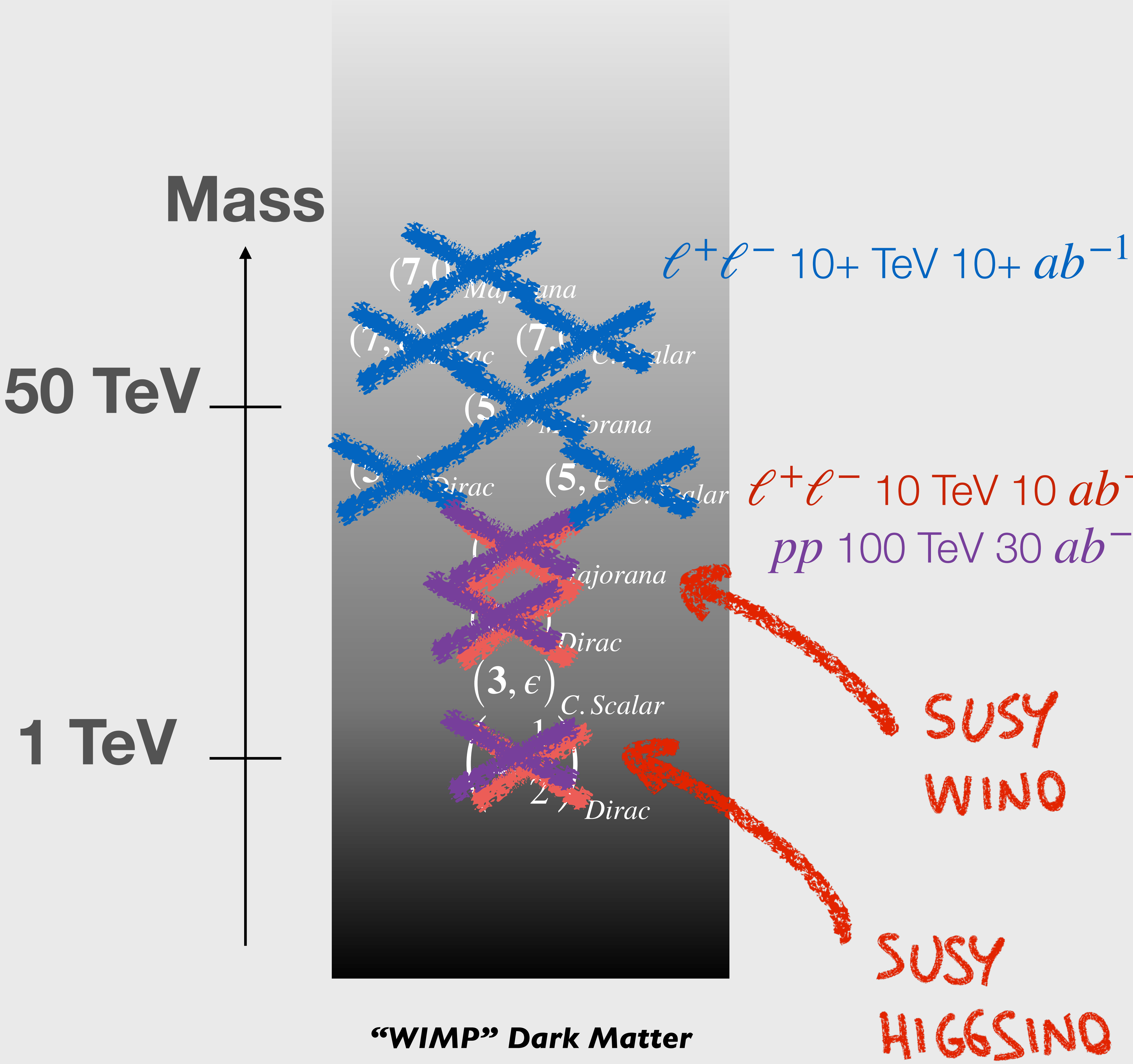


2202.10509	exclusive $W\times10^7$	inclusive $W\times10^7$
3 TeV	$[-53, 53]$	$[-41, 41]$
10 TeV	$[-5.71, 5.71]$	$[-3.71, 3.71]$
14 TeV	$[-3.11, 3.11]$	$[-1.90, 1.90]$
30 TeV	$[-0.80, 0.80]$	$[-0.42, 0.42]$

10 TeV	DL	$e^{DL}-1$	$SL(\frac{\pi}{2})$
$\ell_L \to \ell'_L$	-0.82	-0.56	0.33
$\ell_L \to q_L$	-0.78	-0.54	0.34
$\ell_L \to e_R$	-0.56	-0.43	0.17
$\ell_L \to u_R$	-0.48	-0.38	0.15
$\ell_L \to d_R$	-0.43	-0.35	0.13
$\ell_R \to \ell'_L$	-0.56	-0.43	0.17
$\ell_R \to q_L$	-0.53	-0.41	0.16
$\ell_R \to \ell'_R$	-0.30	-0.26	0.09
$\ell_R \to u_R$	-0.22	-0.20	0.07
$\ell_R \to d_R$	-0.17	-0.16	0.05

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

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

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

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

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

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

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

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

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

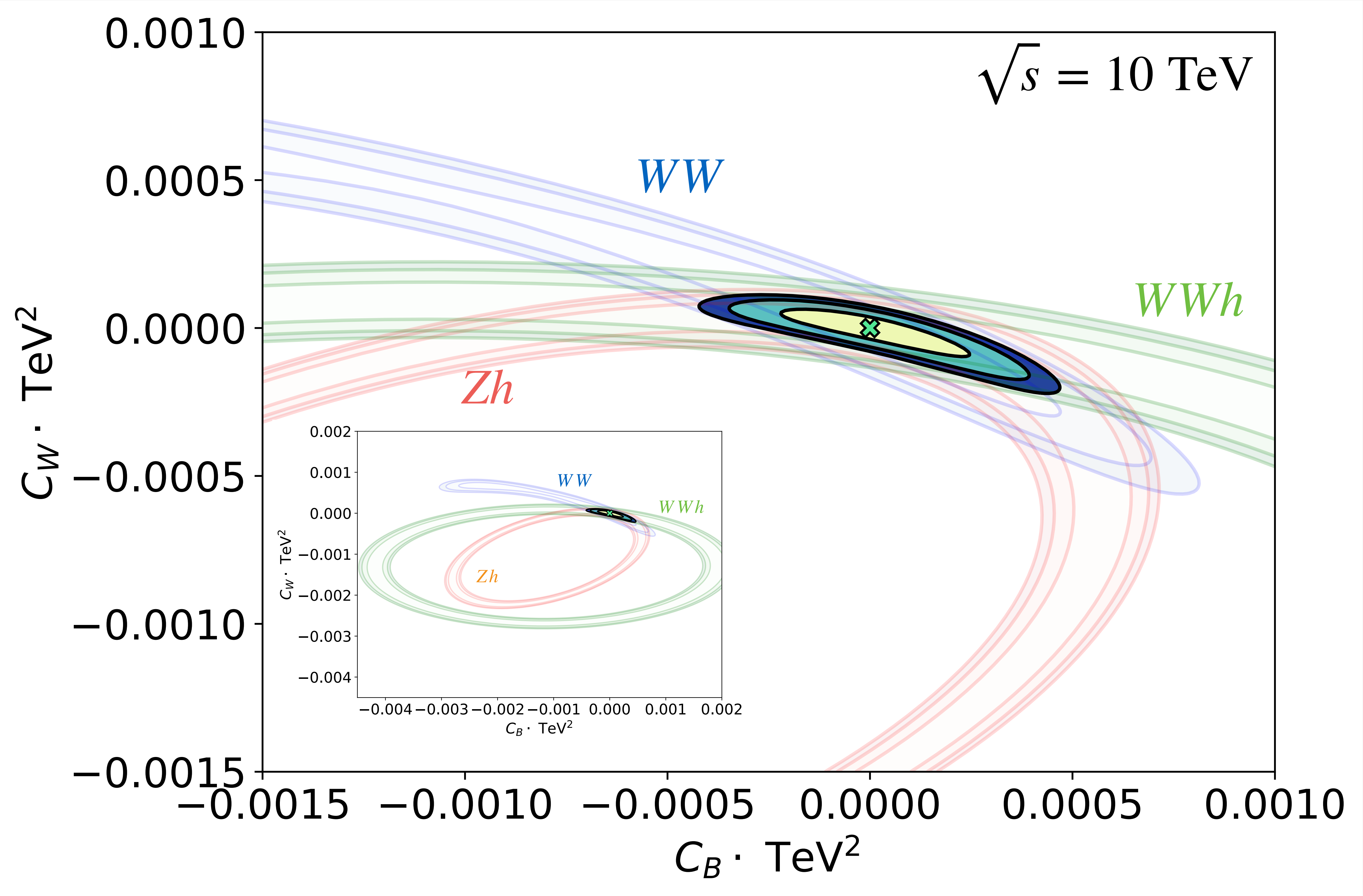
$\ell^+\ell^- \to$ VV+X

DI-BOSON ⊕ MULTI-BOSON

ZH: BSM and SM amplitudes have the same angular dependences, so the most powerful analysis is a simple cut-and-count.

WW: BSM and SM amplitudes **do not** have the same angular dependences, so the most powerful analysis is differential!

multi-body can contain hard sub-scattering with net electric charge, e.g. $e\nu \to Wh, WZ$ with new BSM couplings dependence



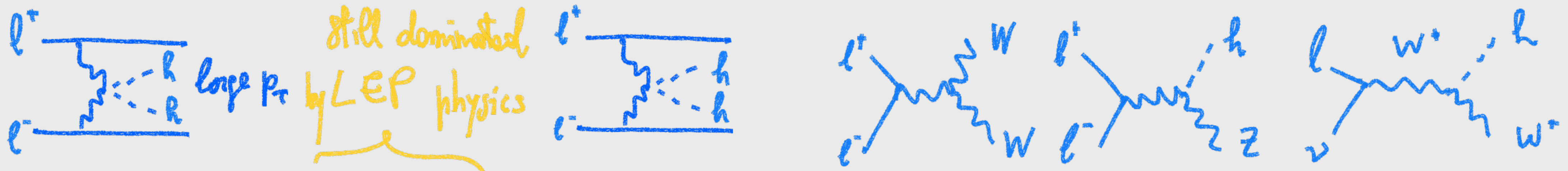
ZH: elliptical belt in 2D BSM coupling space

WW: basin in 2D BSM coupling space

WWh: elliptical belt in 2D BSM coupling space

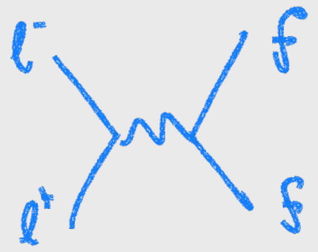
Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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

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



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

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

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

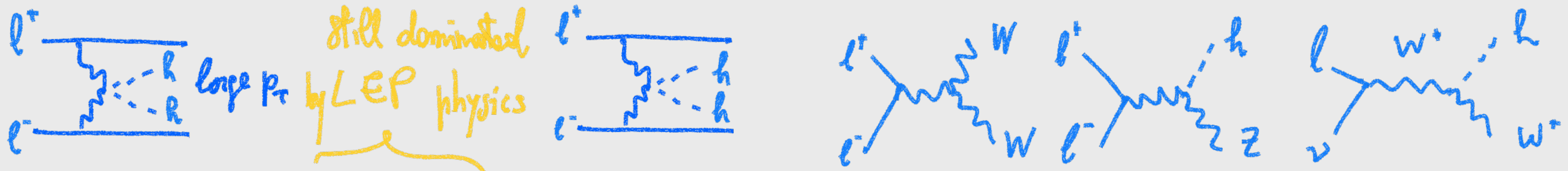
$1/(g_\star f) \sim 1/m_\star$

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

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

Effects of the size of the Higgs boson

STRONGLY INTERACTING TOP AND HIGGS



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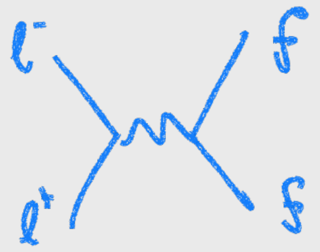
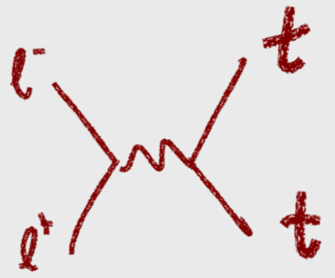
$$+ \frac{g_*^2}{(4\pi)^2 m_*^2}\left[c_{HW}\mathcal{O}_{HW} + c_{HB}\mathcal{O}_{HB}\right] + \frac{y_t^2}{(4\pi)^2 m_*^2}\left[c_{BB}\mathcal{O}_{BB} + c_{GG}\mathcal{O}_{GG}\right]$$



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

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



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

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

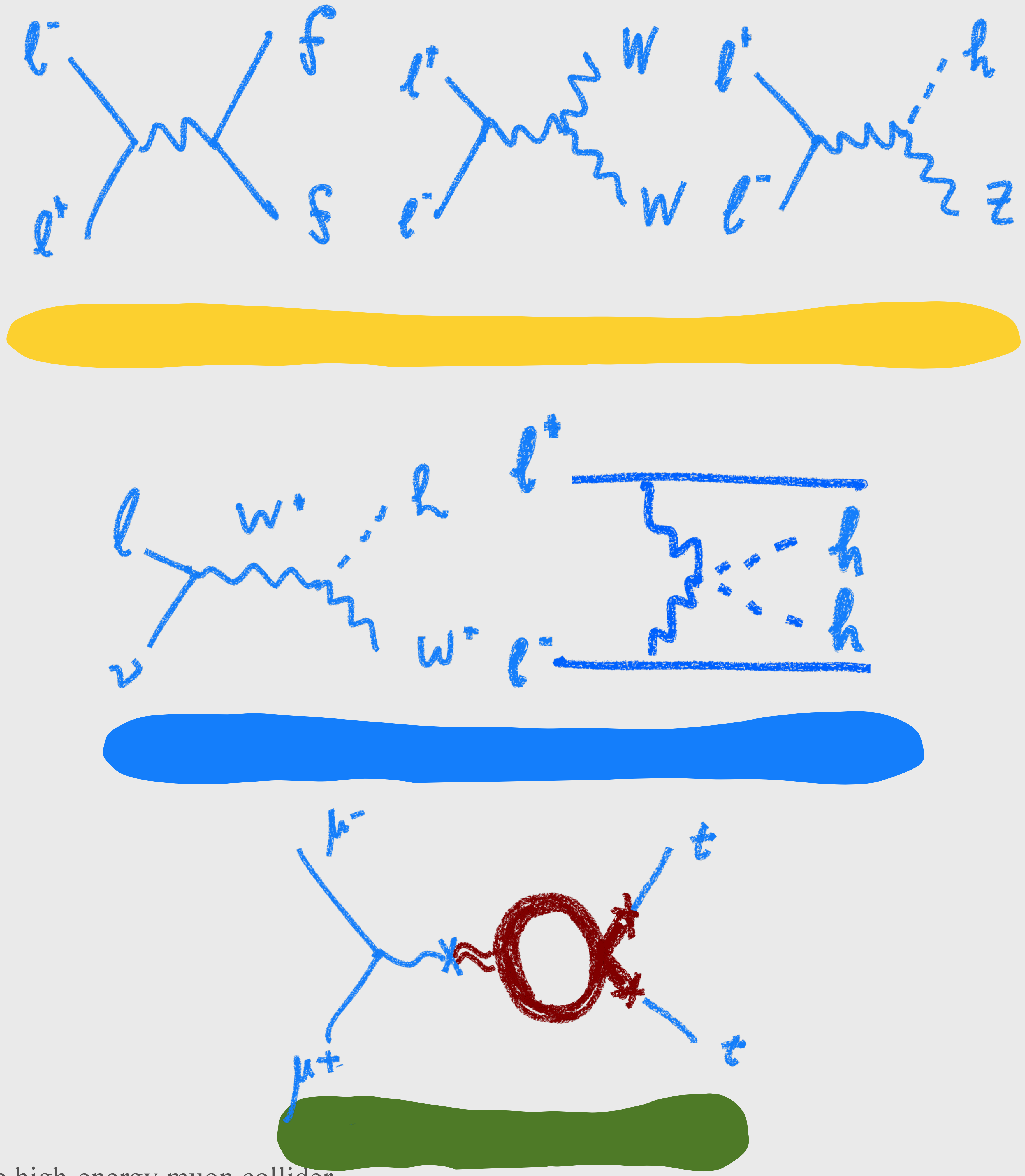
$1/(g_\star f) \sim 1/m_\star$

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

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

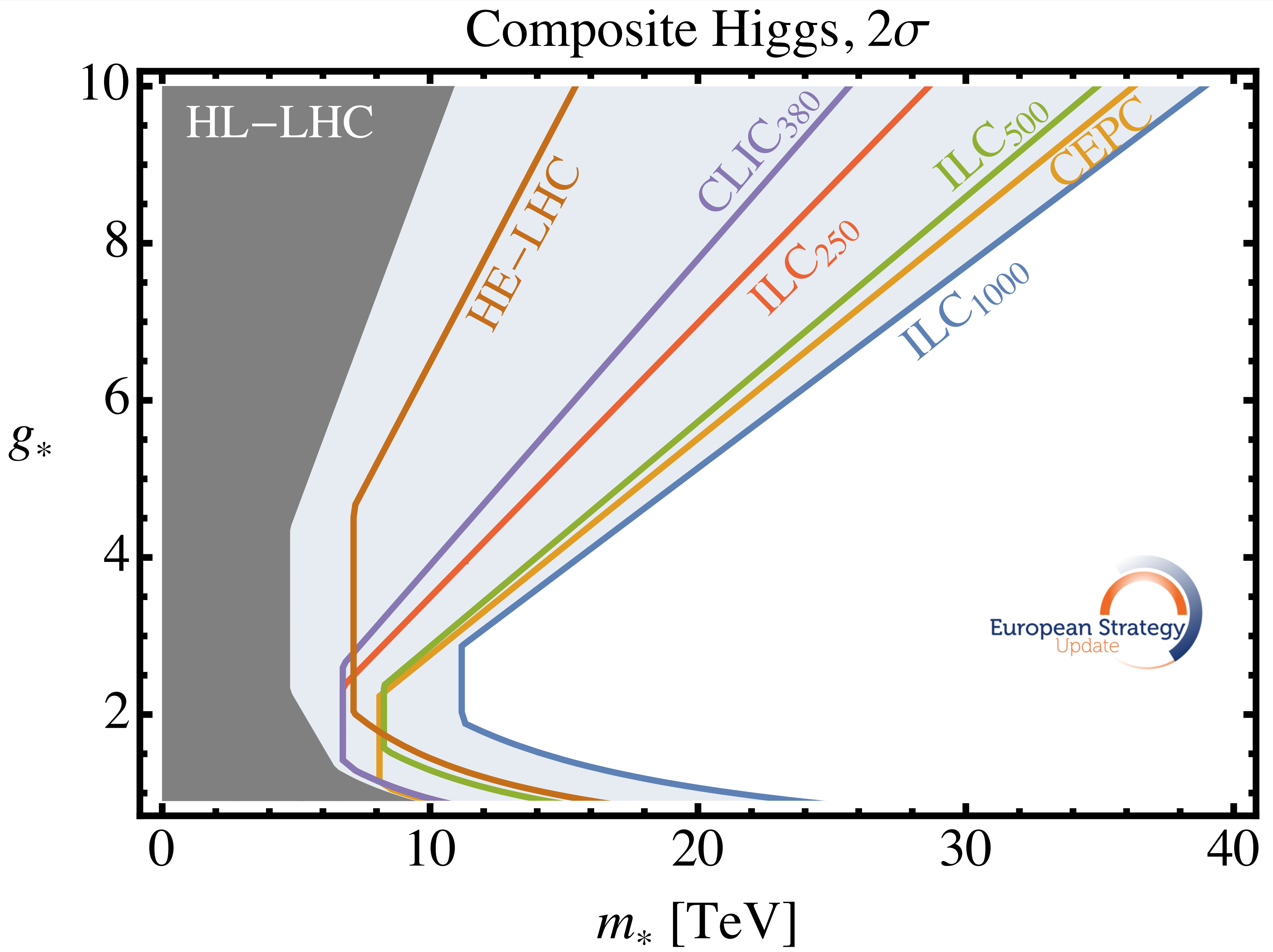
Effects of the size of the Higgs boson

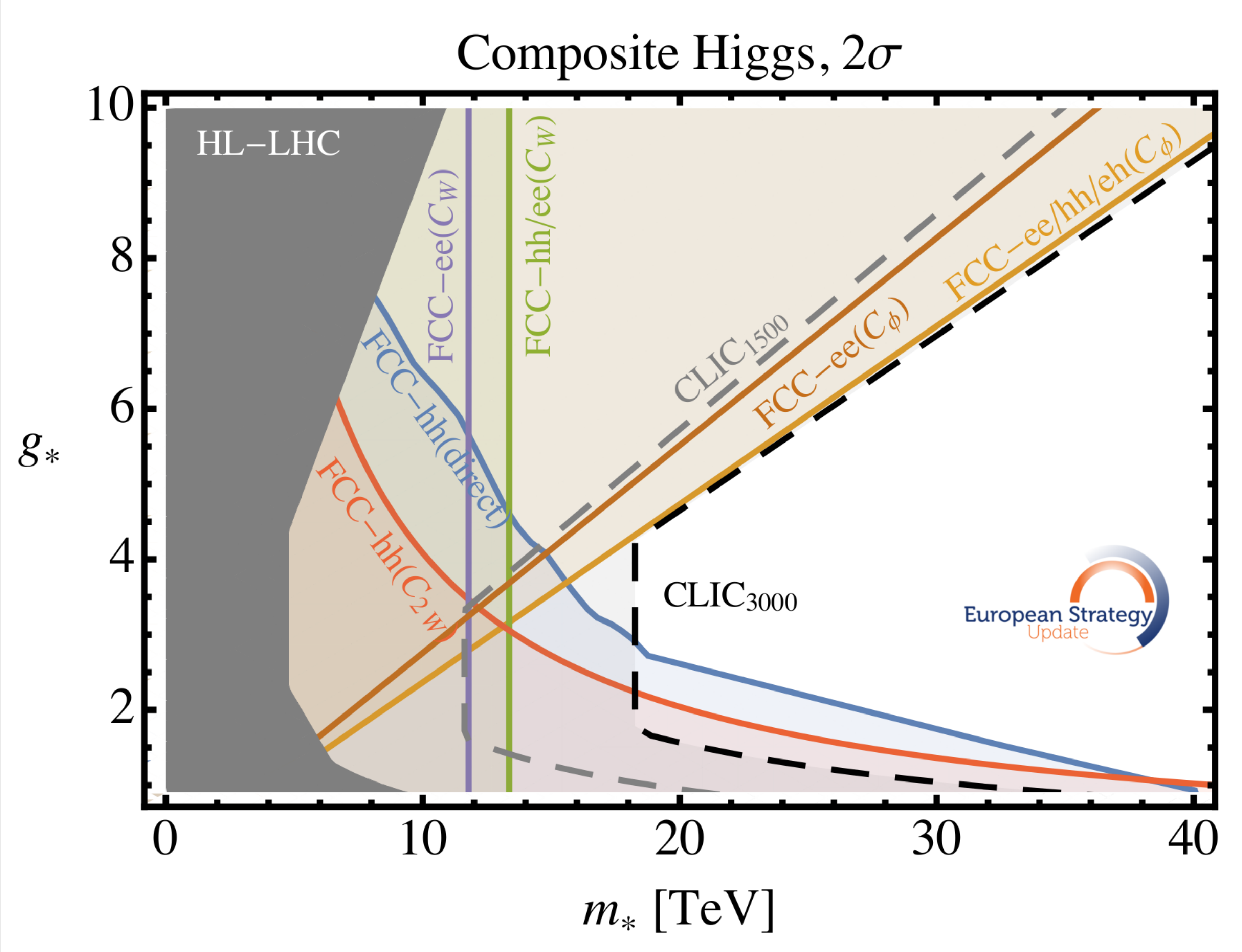
STRONGLY INTERACTING TOP AND HIGGS



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

Looking ahead

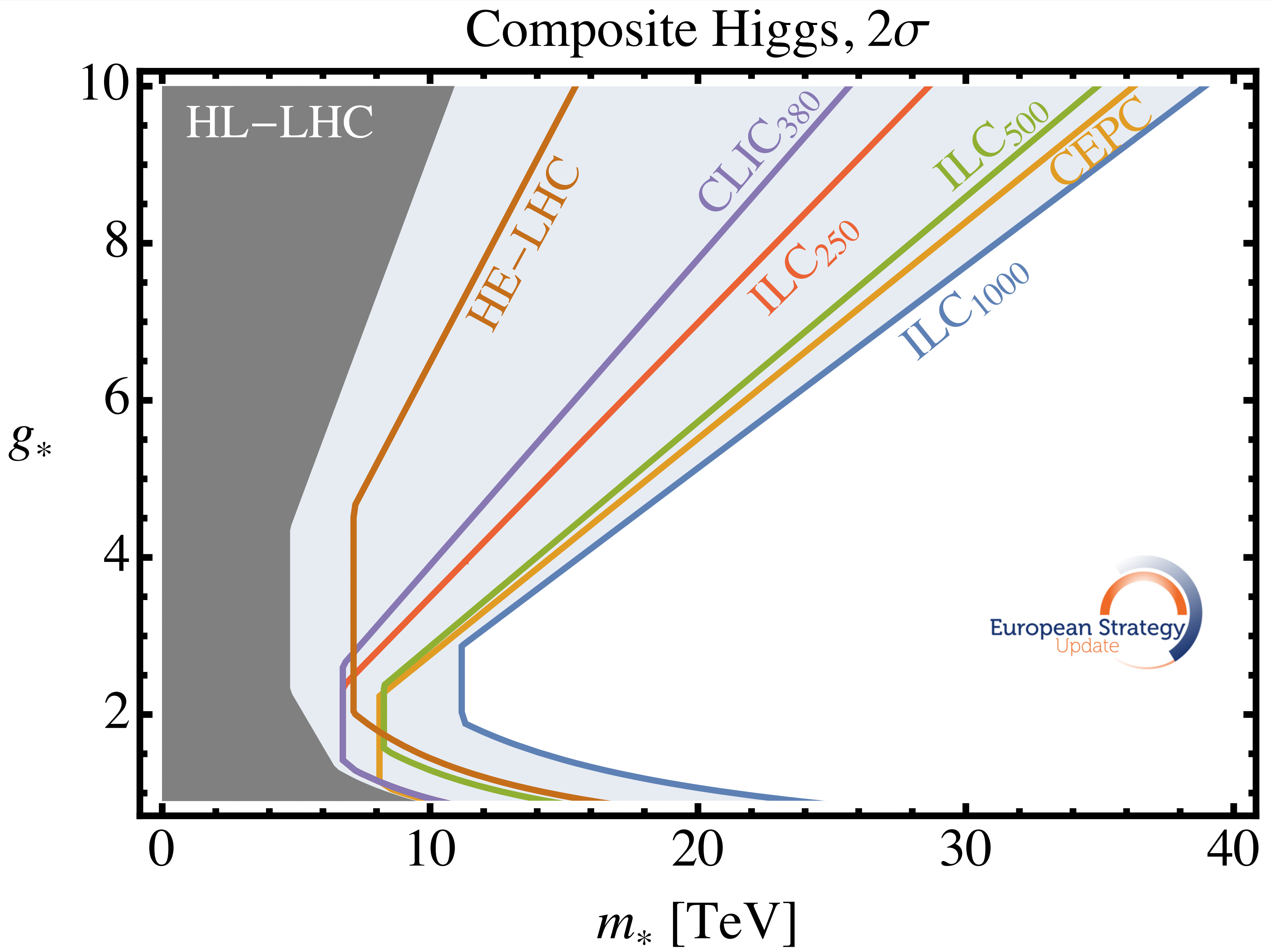




compositeness at few TeV @ HL-LHC

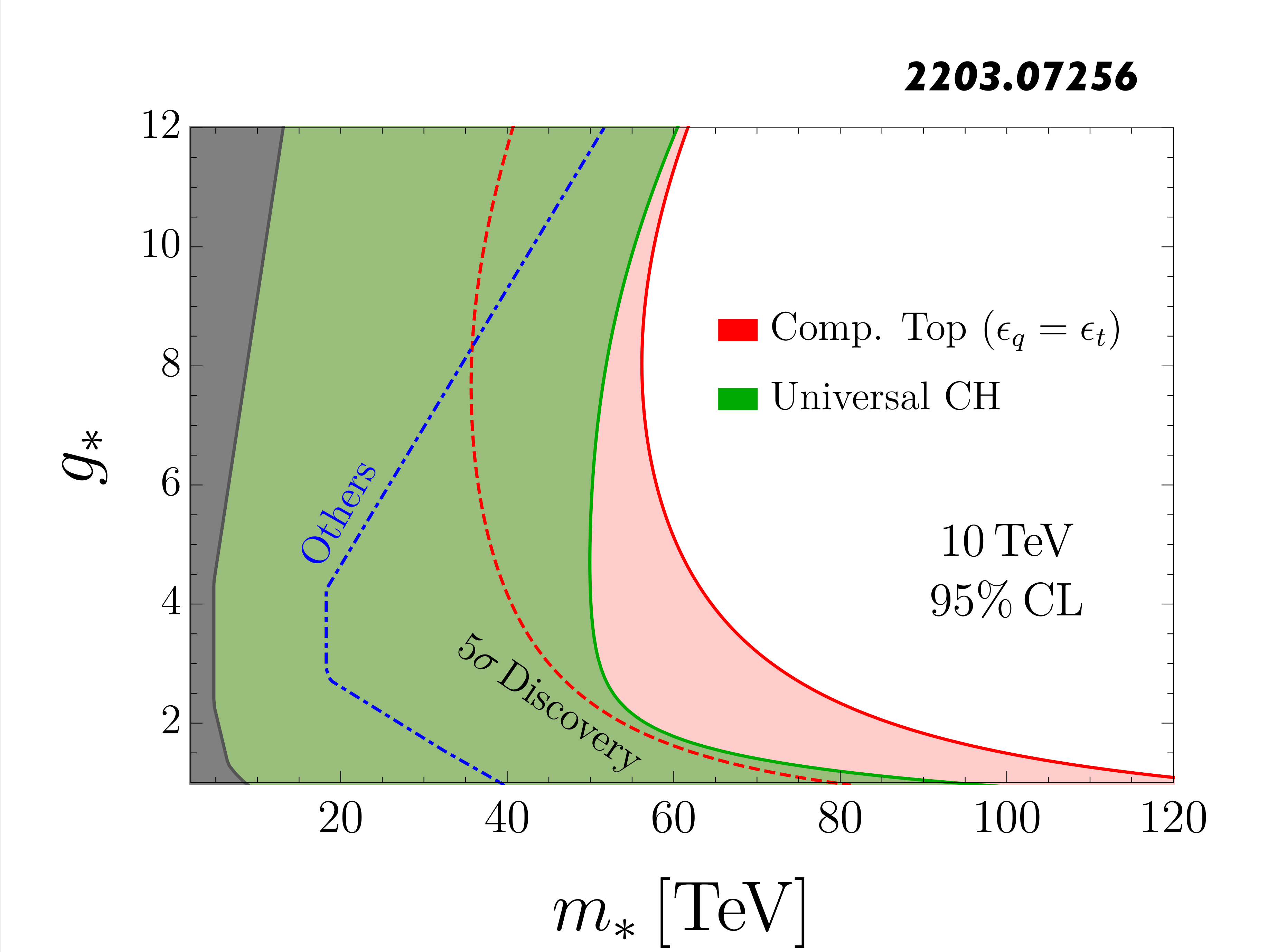
compositeness at few 10 TeV

Looking ahead



compositeness at few TeV @ HL-LHC

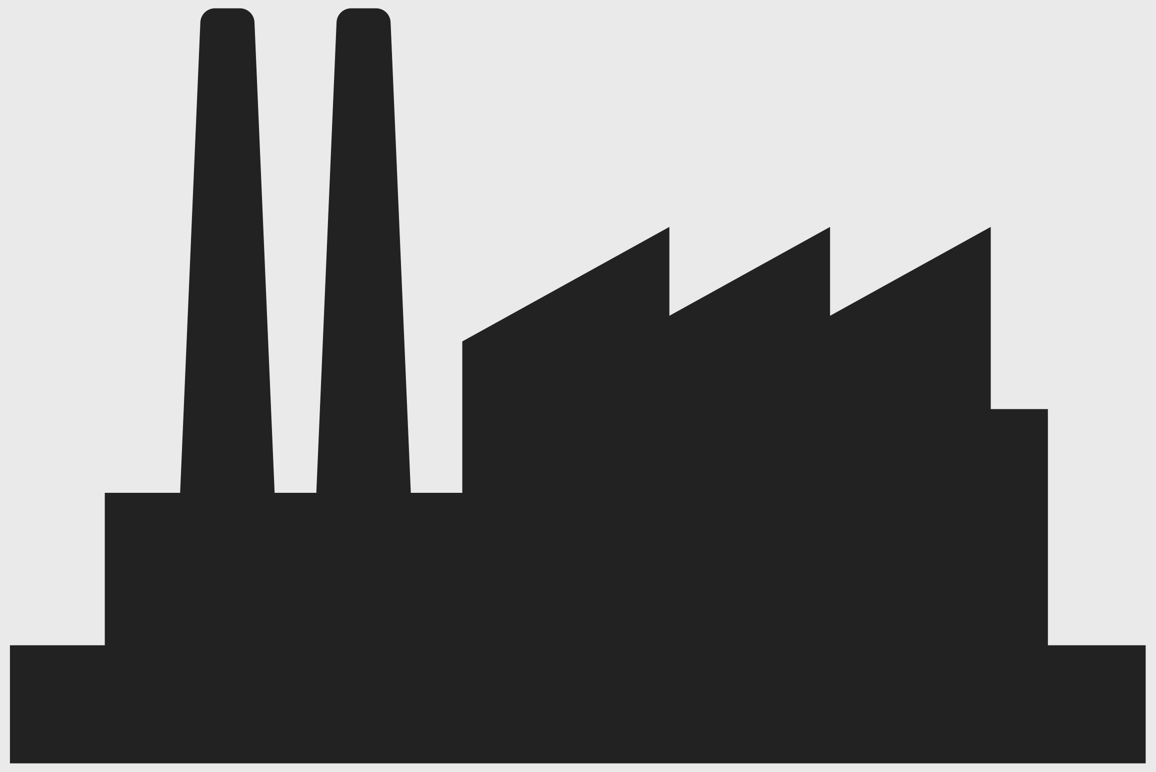
UNIQUE AVENUE TO EXPLORE WEAK INTERACTIONS FAR OFFSHORE FROM THE WEAK SCALE



compositeness at few 100 TeV

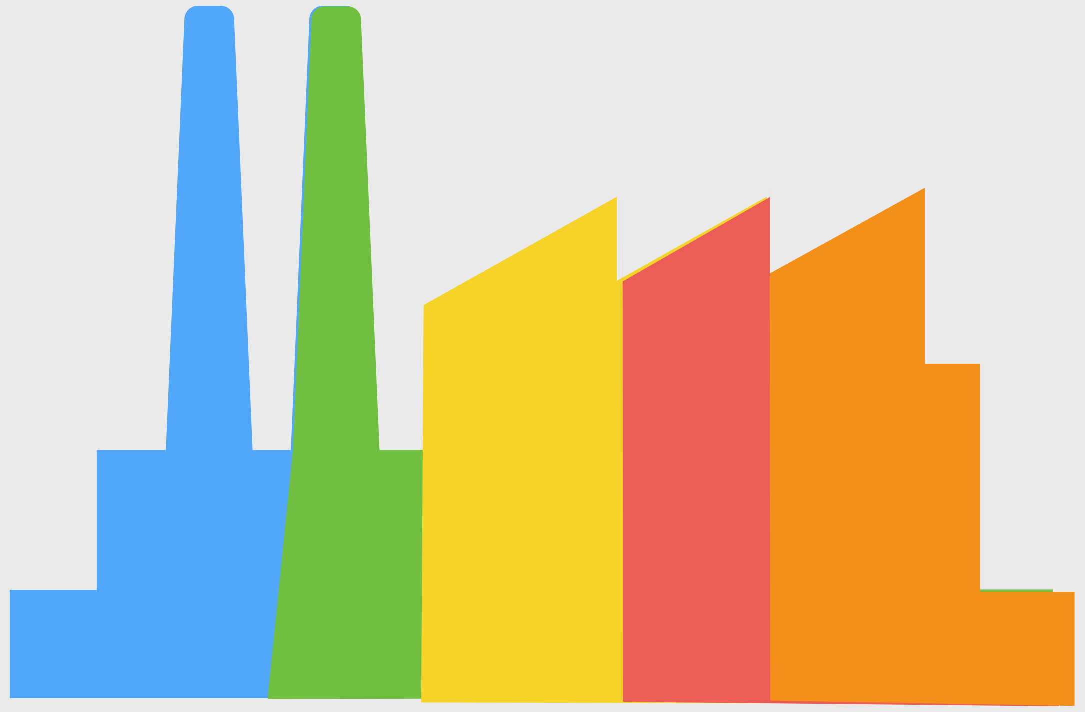
Microscope & Factory

&



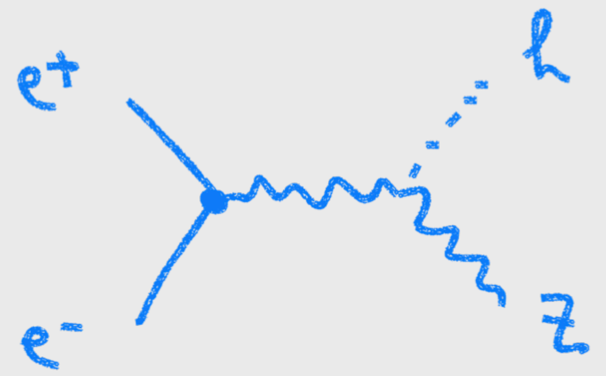
Microscope & Factory

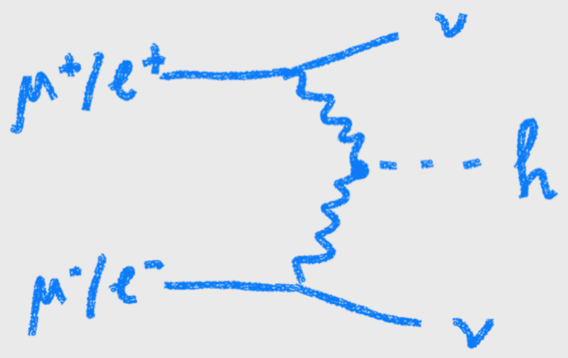
&

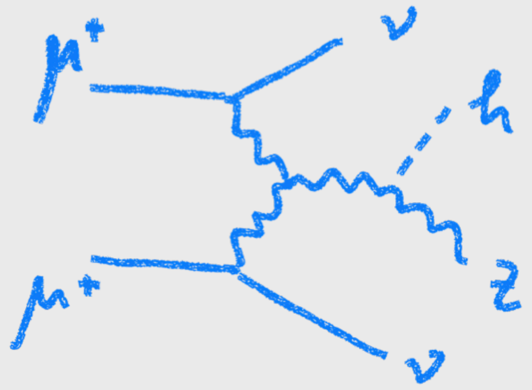


Summary and outlook: Higgs boson

- We have ambitious plans to thoroughly probe the Higgs boson

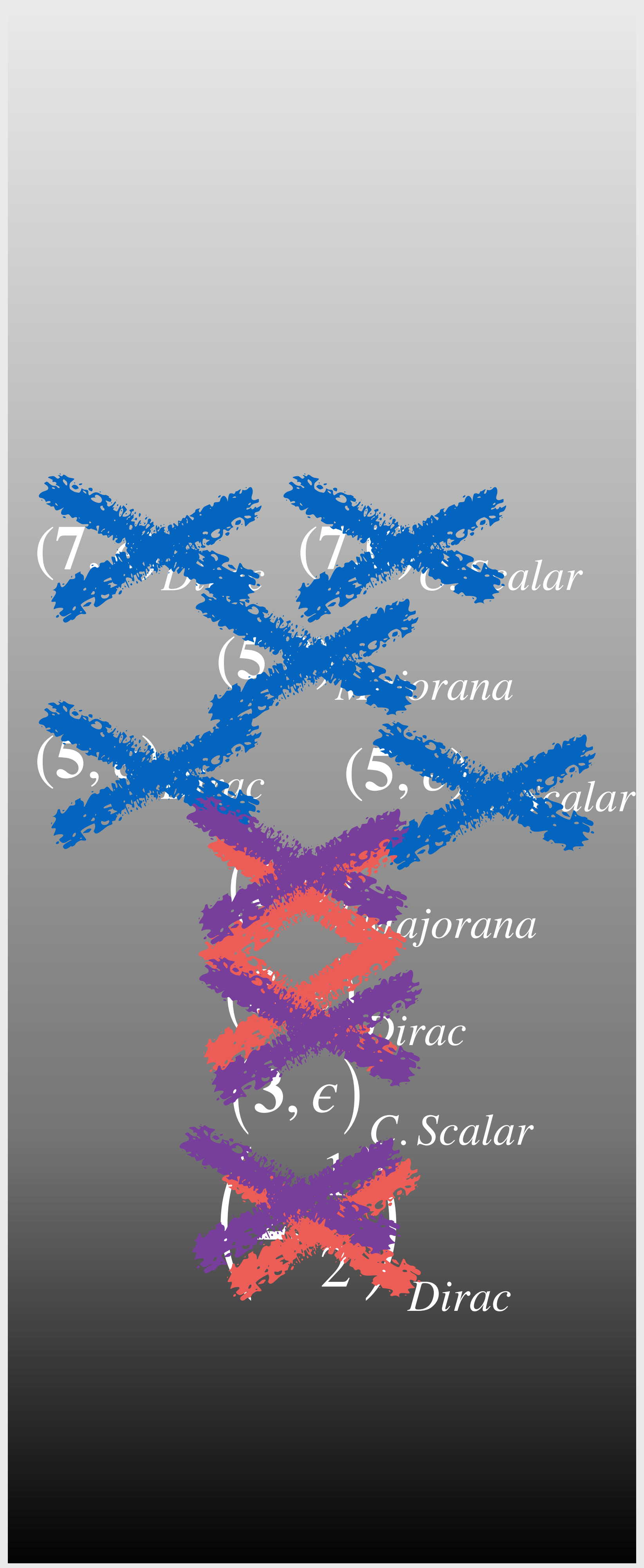


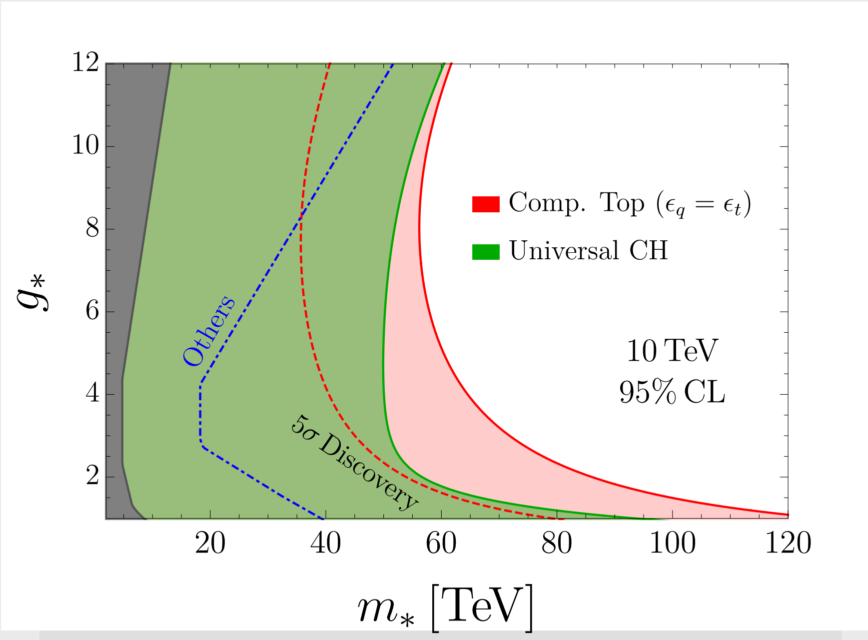


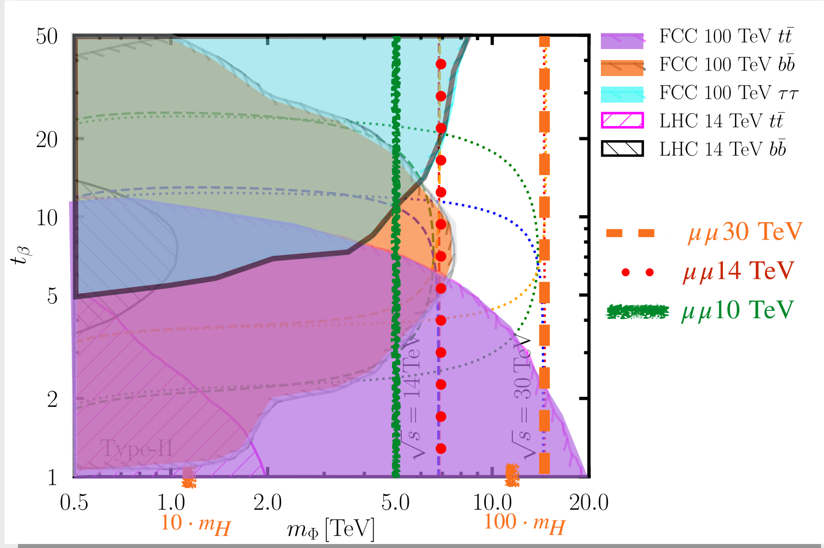


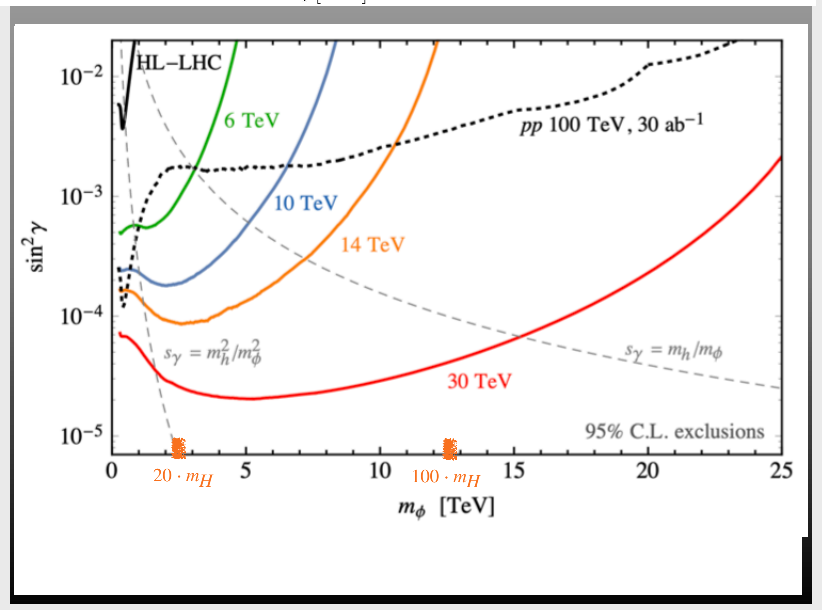
$$\frac{\delta g_h}{g_h} \simeq 10^{-3} \;\Rightarrow\; \Lambda_{NP} \simeq 100 \cdot m_h$$

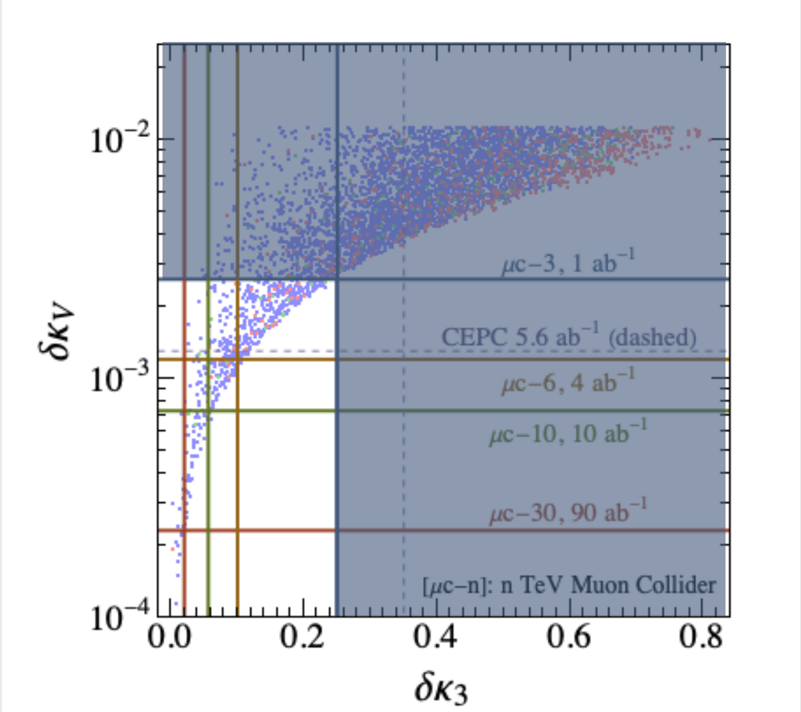
Summary and outlook: BSM

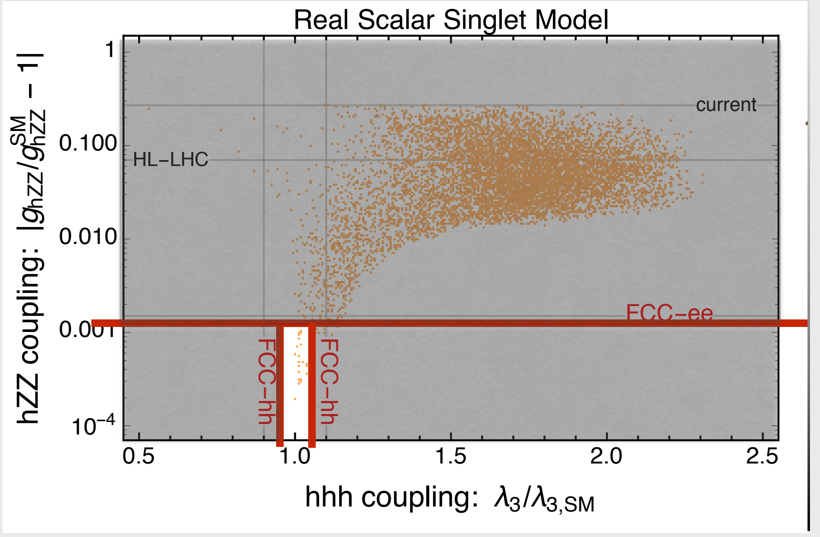












"WIMP" Dark Matter | ***EW symmetry breaking*** | ***EW phase transition***

see backup

effective c.o.m. energy

100 TeV

10+ TEV

Extraordinary probes of Higgs boson, electroweak new physics and Dark Matter

International MUON Collider Collaboration

SppC

3 TEV

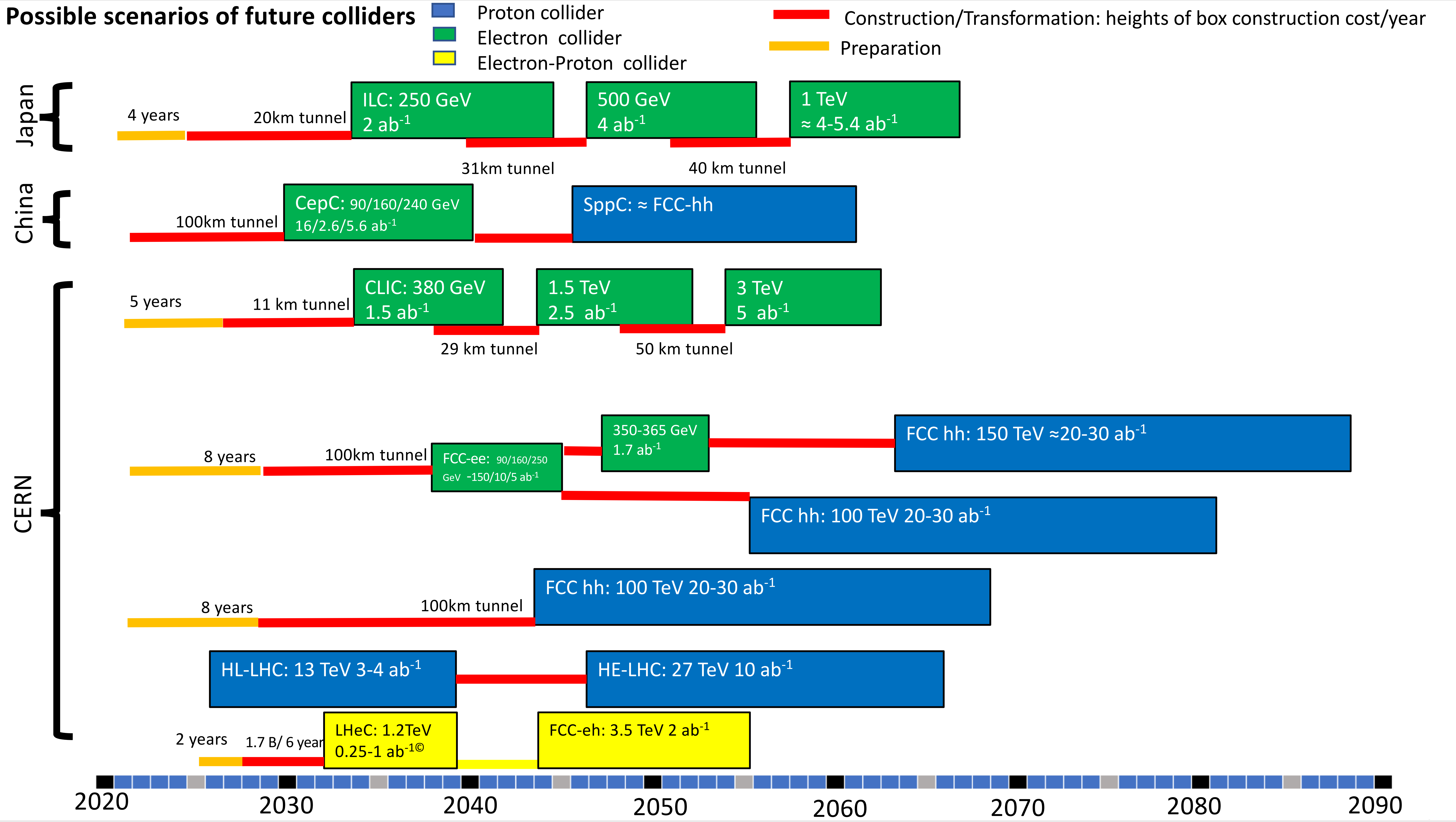
Several important milestones: **full exploration of TeV EW states, EW phase transition, TeV Dark Matter**

1 TeV

200-300 GeV

Precision study of the Higgs boson

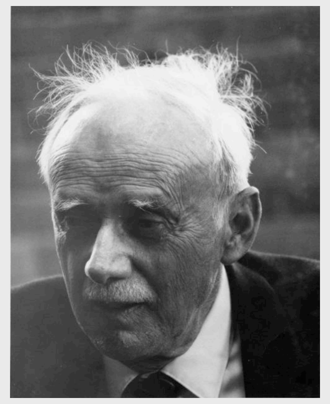
Are we ready?

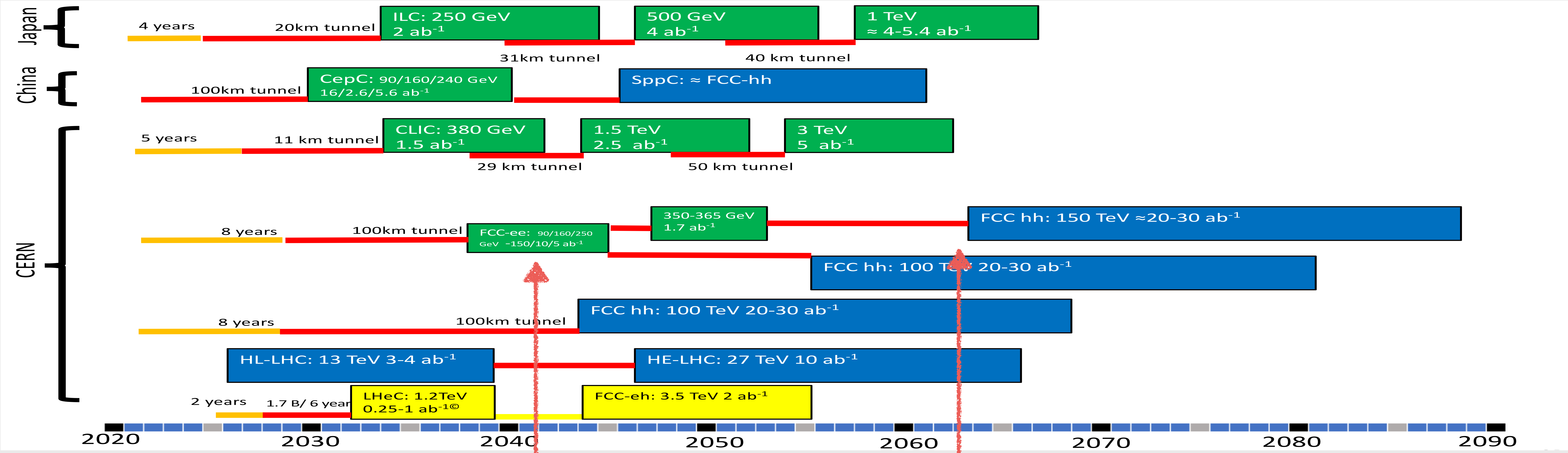


Possible scenarios of future colliders
Proton collider
Electron collider
Electron-Proton collider
Construction/Transformation: heights of box construction cost/year
Preparation
Japan
4 years
20km tunnel
ILC: 250 GeV 2 ab-1
31km tunnel
500 GeV 4 ab-1
40 km tunnel
1 TeV ≈ 4-5.4 ab-1
China
100km tunnel
CepC: 90/160/240 GeV 16/2.6/5.6 ab-1
SppC: ≈ FCC-hh
CERN
5 years
11 km tunnel
CLIC: 380 GeV 1.5 ab-1
29 km tunnel
1.5 TeV 2.5 ab-1
50 km tunnel
3 TeV 5 ab-1
8 years
100km tunnel
FCC-ee: 90/160/250 GeV -150/10/5 ab-1
350-365 GeV 1.7 ab-1
FCC hh: 150 TeV ≈20-30 ab-1
FCC hh: 100 TeV 20-30 ab-1
8 years
100km tunnel
FCC hh: 100 TeV 20-30 ab-1
HL-LHC: 13 TeV 3-4 ab-1
HE-LHC: 27 TeV 10 ab-1
2 years
1.7 B/ 6 year
LHeC: 1.2TeV 0.25-1 ab-1©
FCC-eh: 3.5 TeV 2 ab-1
2020
2030
2040
2050
2060
2070
2080
2090

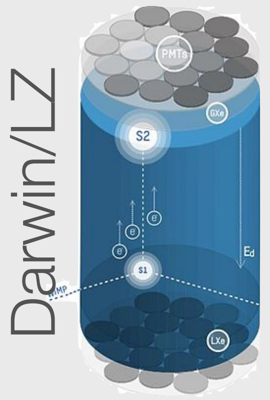
Are we ready?

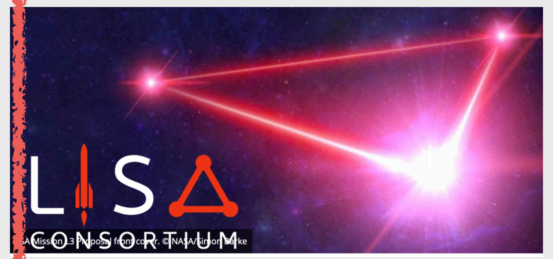
$$n_i = \frac{1}{e^{(\epsilon_i-\mu)/k_B T}+1}$$



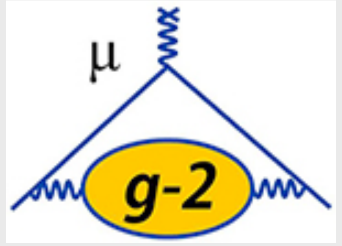


Belle II





HiLumi HL-LHC PROJECT



2045 ± 5 first e^+e^- collisions pushing the intensity frontier

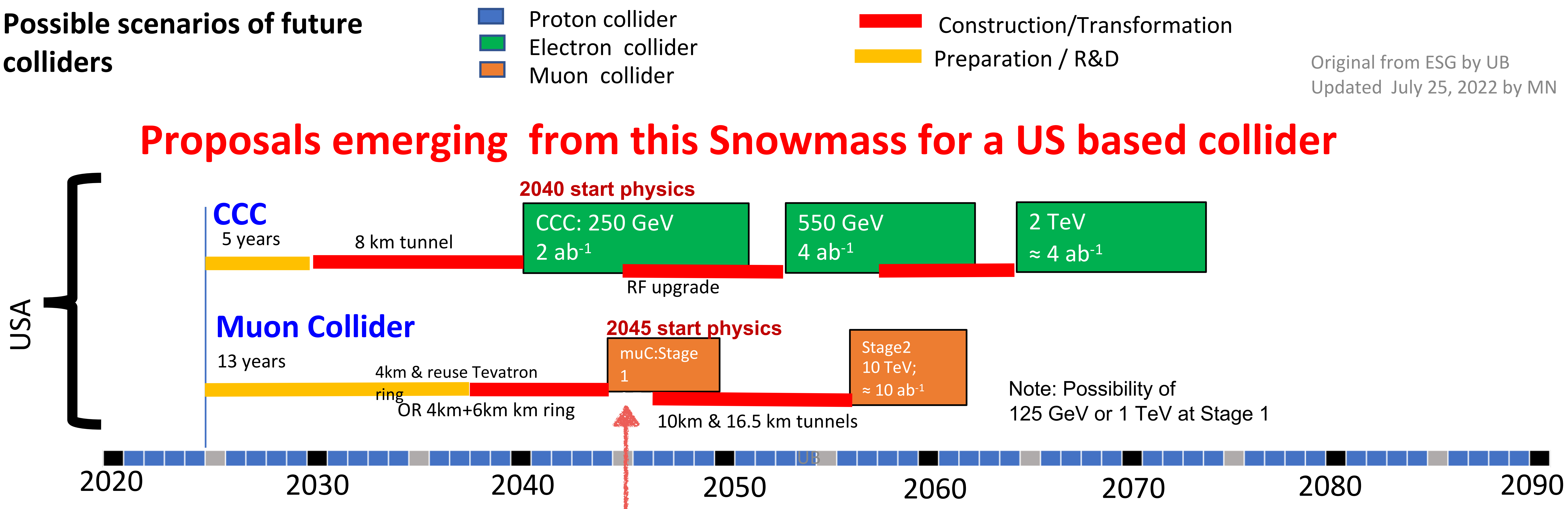
2060_0^{10} first pp collisions pushing the energy frontier

Are we ready?

Possible scenarios of future colliders

Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - International Cost Sharing

2045^{10}_{0} first $\mu^+\mu^-$ collisions pushing both the intensity and energy frontier

VERY SIGNIFICANT INTEREST FROM US COMMUNITY IN RECENT YEARS CULMINATED AT SNOWMASS 2022

TIME TO WORK ON MUON COLLIDER PHYSICS IS NOW!

Thank you!

TIME TO WORK ON MUON COLLIDER PHYSICS IS NOW!

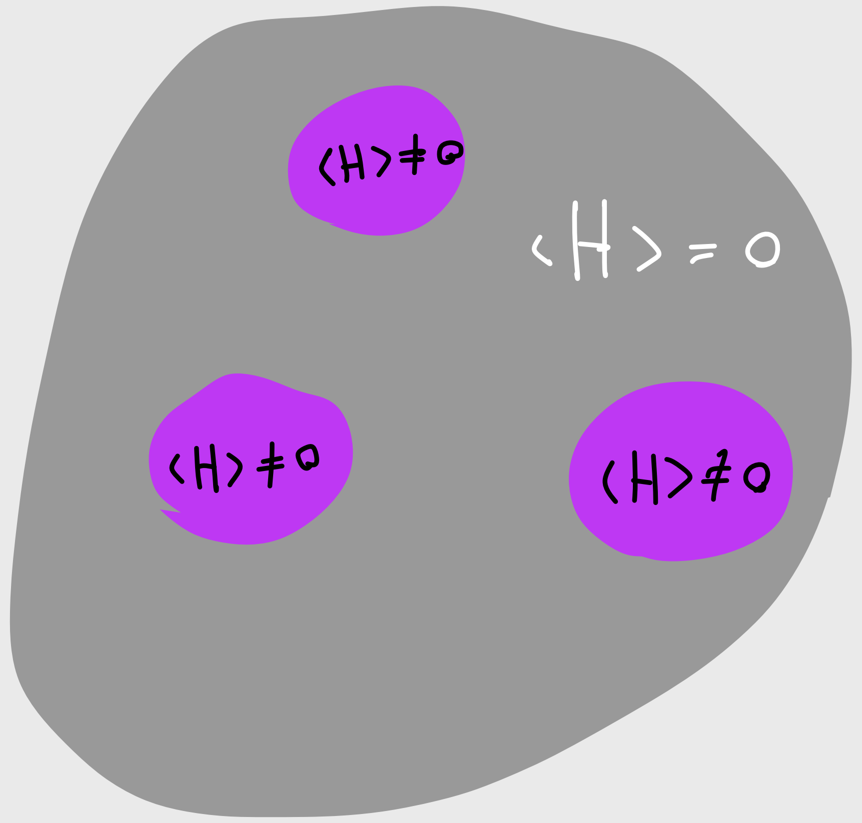
TALK TO YOU AT DINNER!

Thank you!

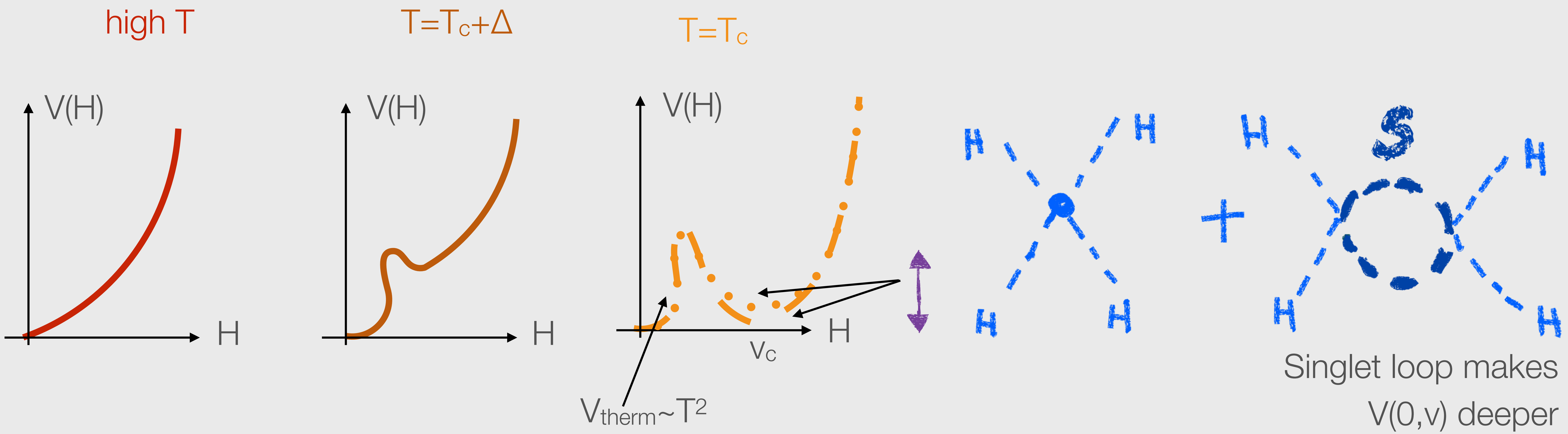
flashing concrete results for

Electroweak phase transition

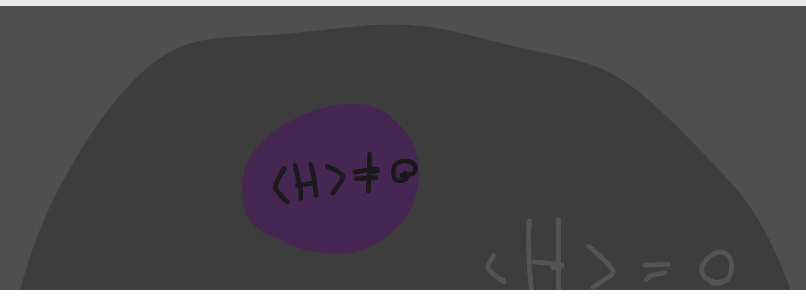
Electroweak phase transition



- Modifications of the Higgs potential ⇒ Out of Equilibrium transition from one vacuum to a new energetically favorable one



Electroweak phase transition



- We need to study all possible new states that induce a change in the Higgs boson potential.
- For these new state to have sizable effects in the early Universe they must be light, around 1 TeV at most.
- All searches for new Higgs bosons (or general electroweak particles) probe such fundamental issue of the origin of matter in the early Universe!

$V_{therm} \sim T^2$

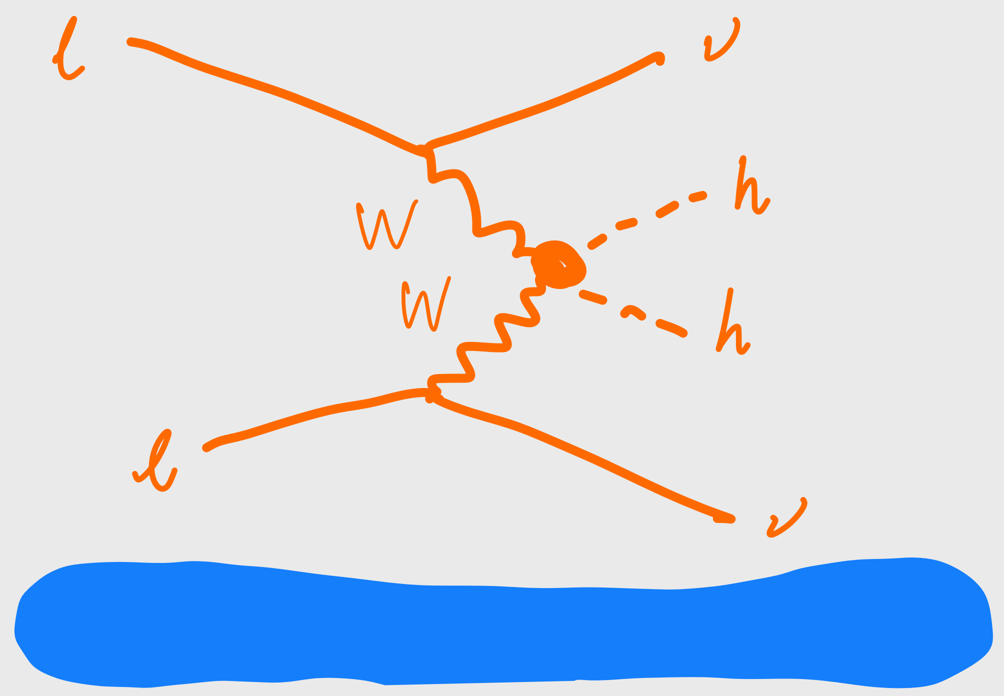
$V(0,v)$ deeper

pp or $\ell^+\ell^- \to hh$

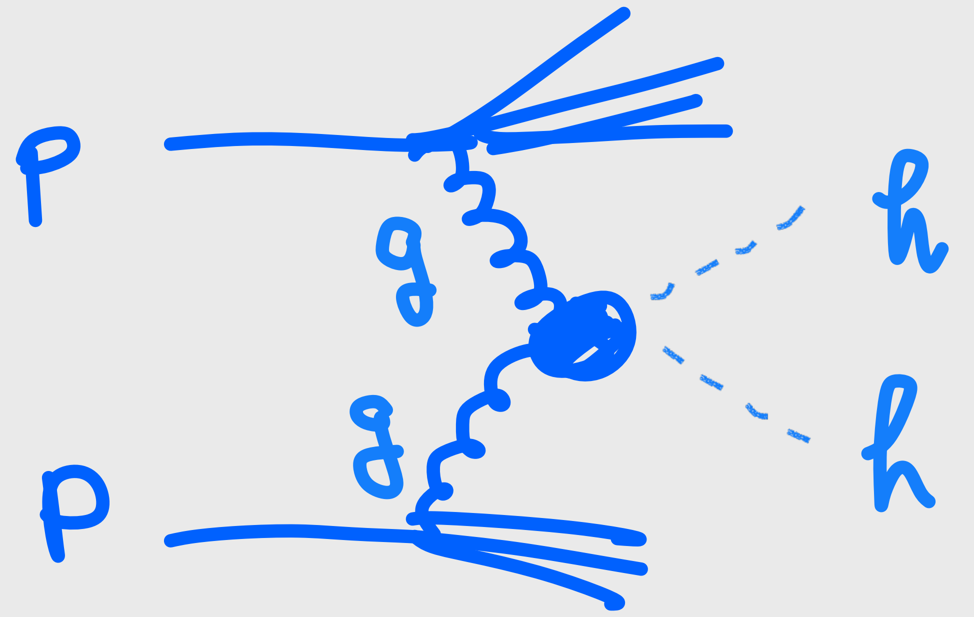
Electroweak phase transition

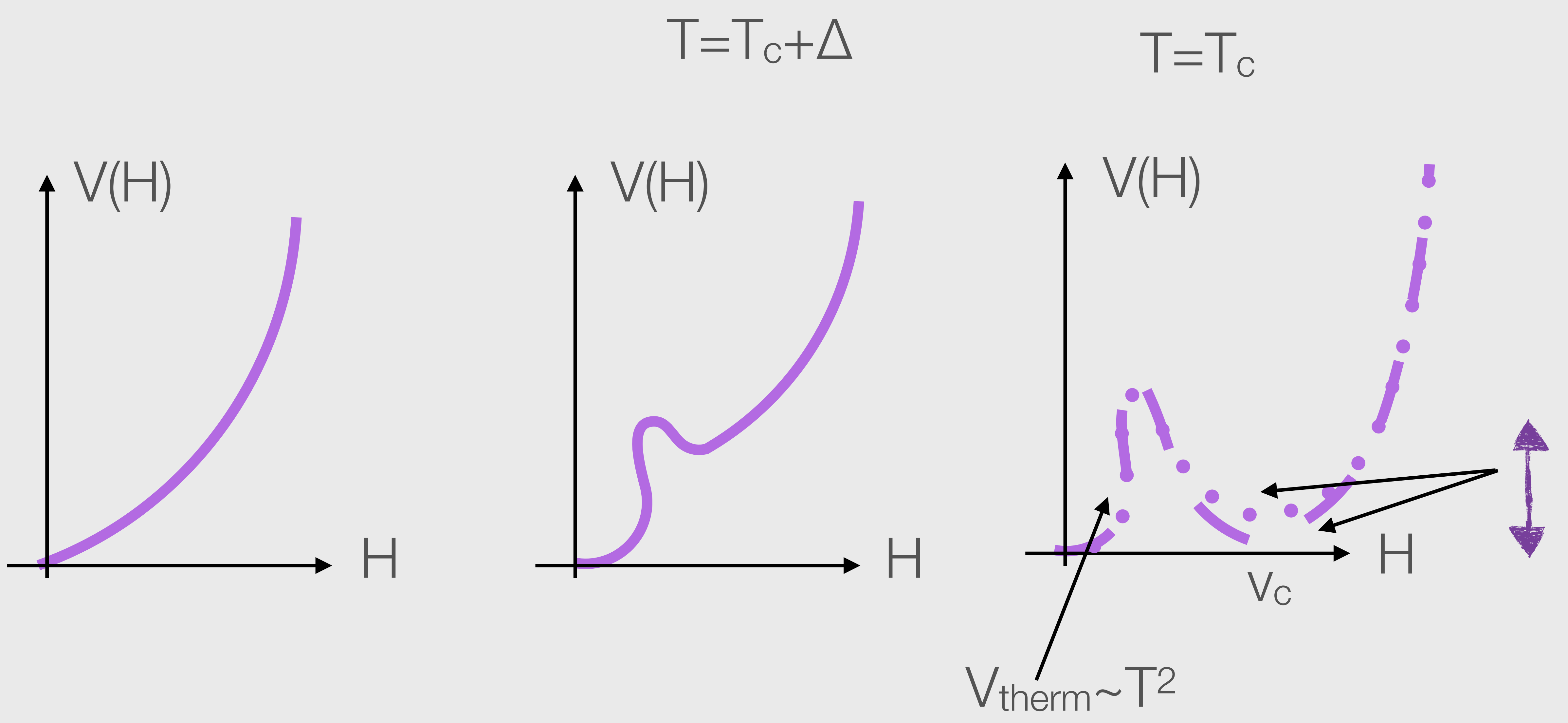
W BOSON COLLIDER

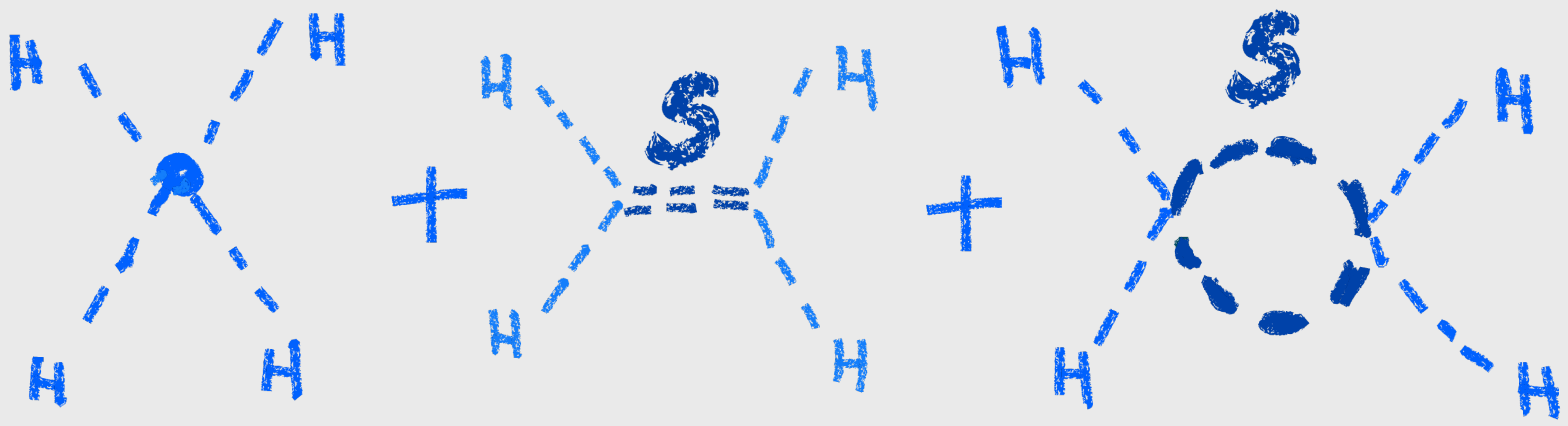
- High-Energy lepton collider has large flux of “partonic” W bosons



- gg collisions as usual







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

EW phase transition

DIRECT & INDIRECT | INTERPLAY

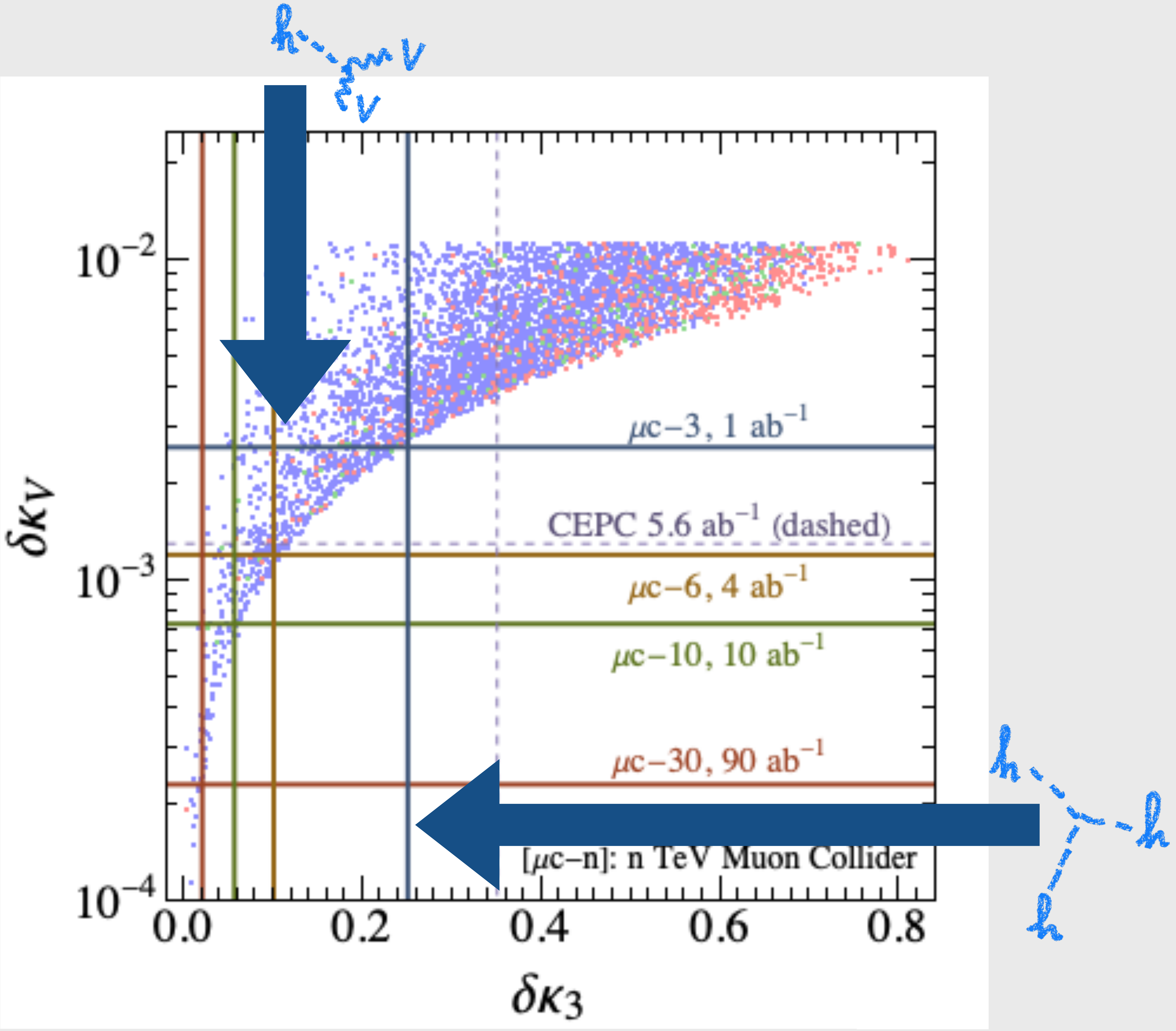
$$V(\Phi,S) = -\mu^2\left(\Phi^\dagger\Phi\right) + \lambda\left(\Phi^\dagger\Phi\right)^2 + \frac{a_1}{2}\left(\Phi^\dagger\Phi\right)S + \frac{a_2}{2}\left(\Phi^\dagger\Phi\right)S^2 + b_1 S + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4.$$

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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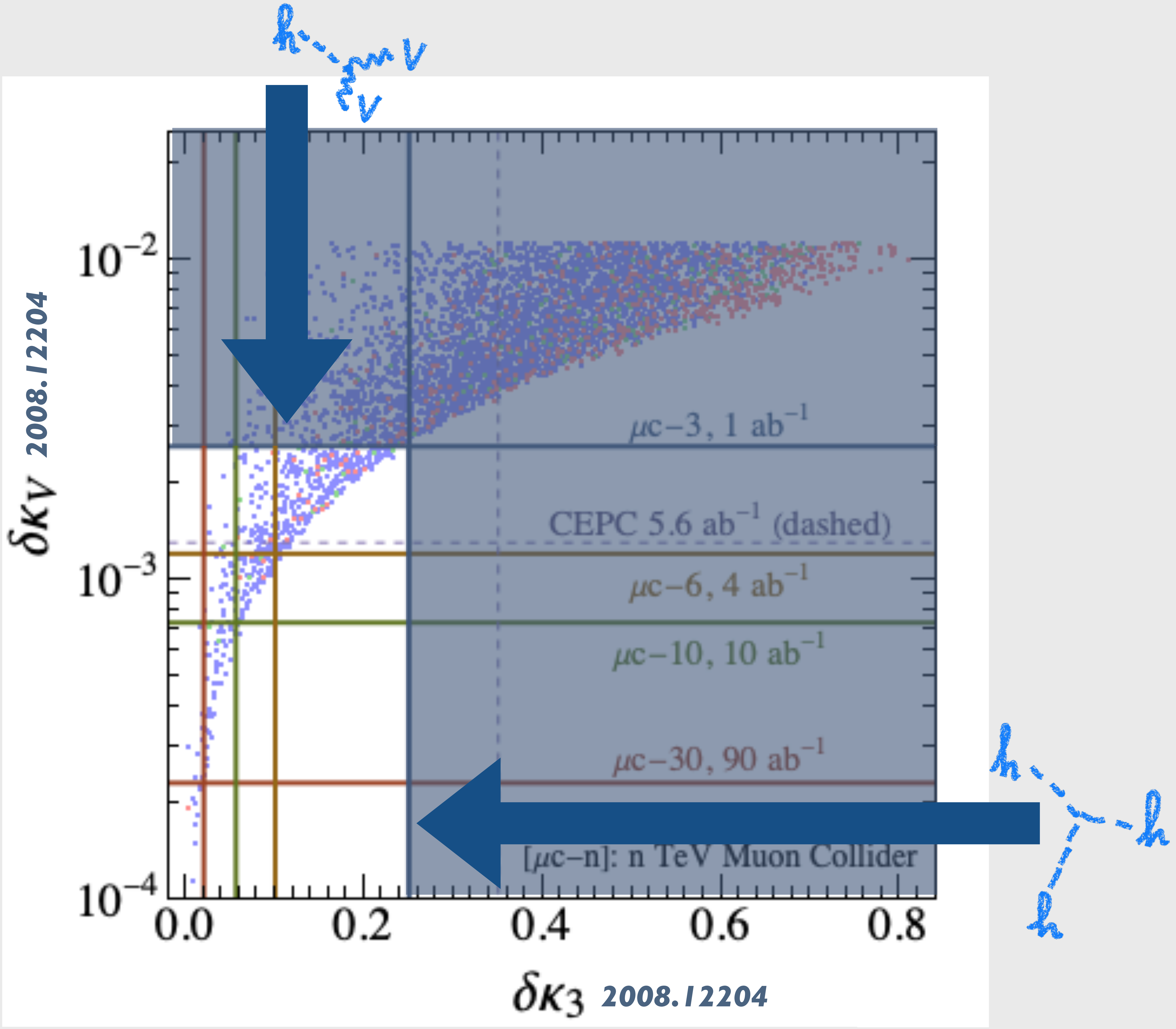
Gravity Wave SNR

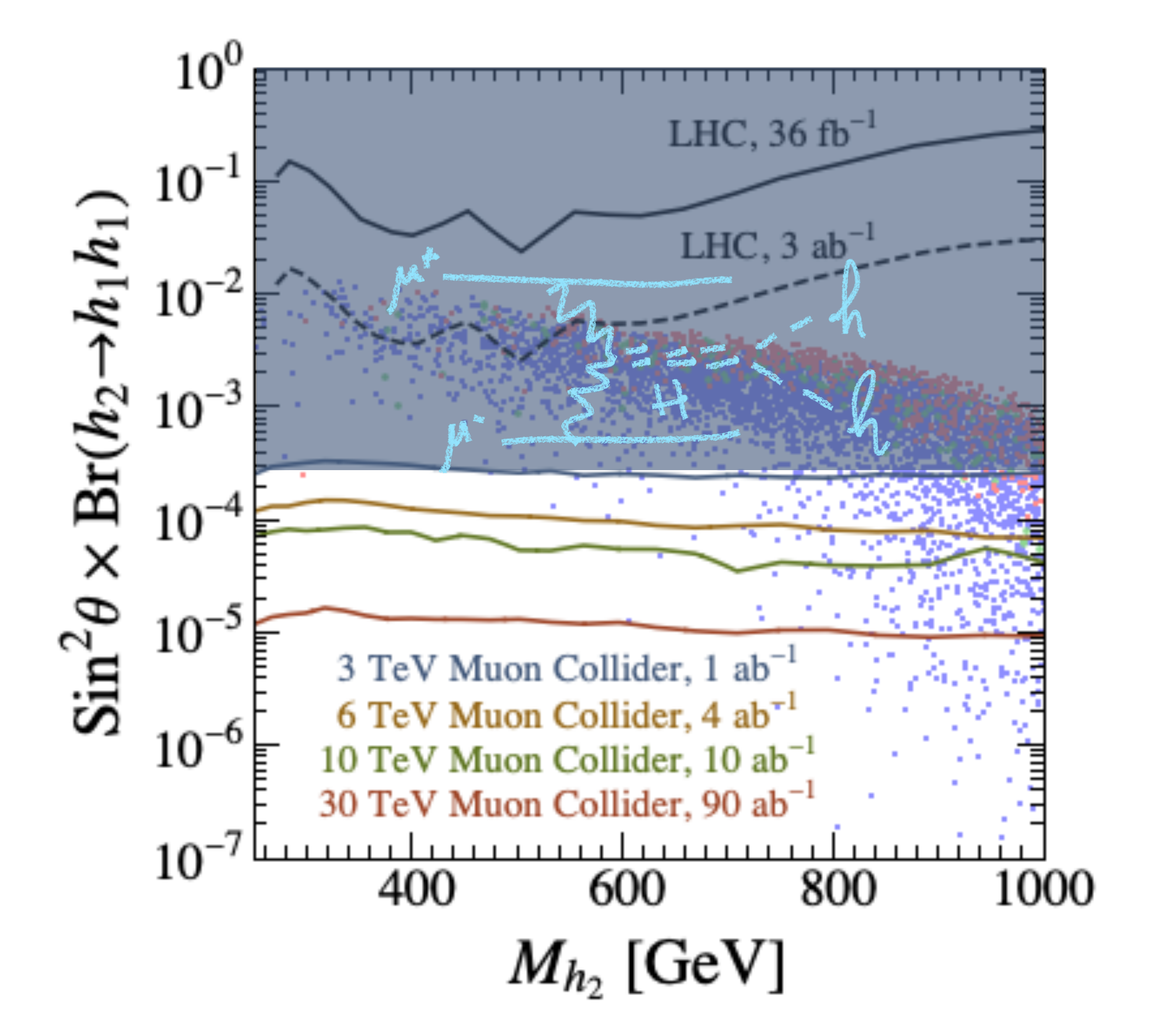


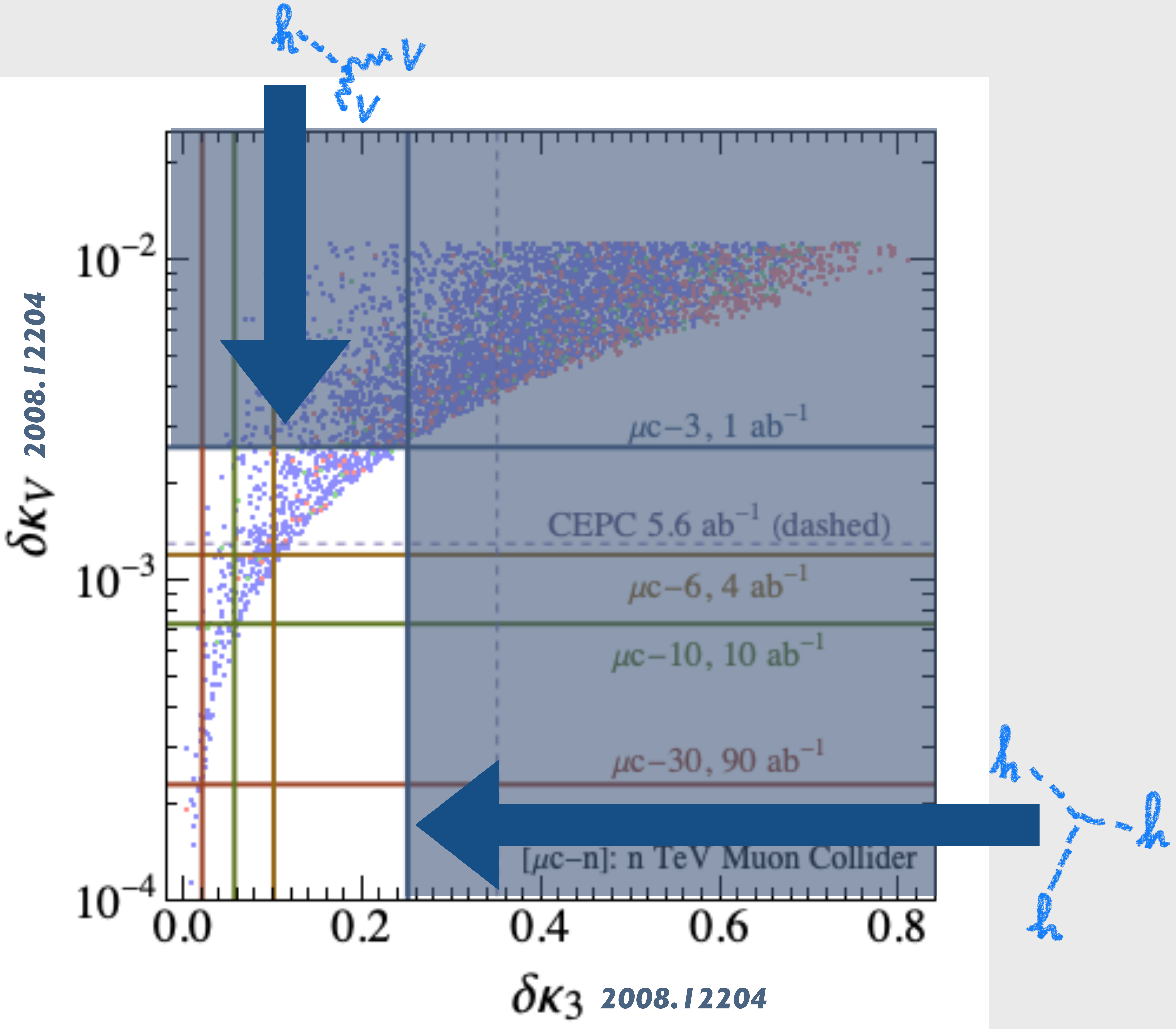
EW phase transition

DIRECT & INDIRECT | INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



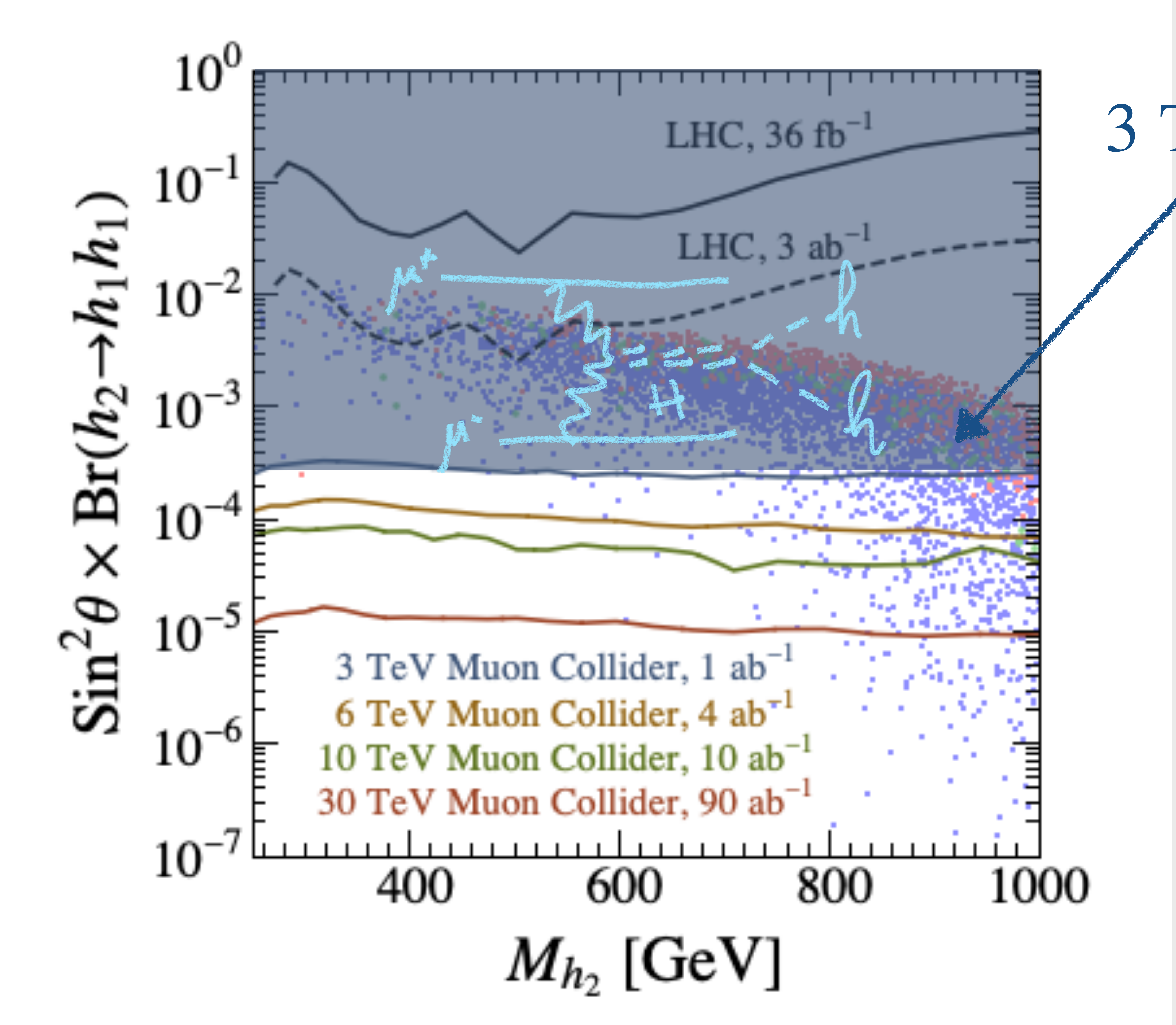


EW phase transition

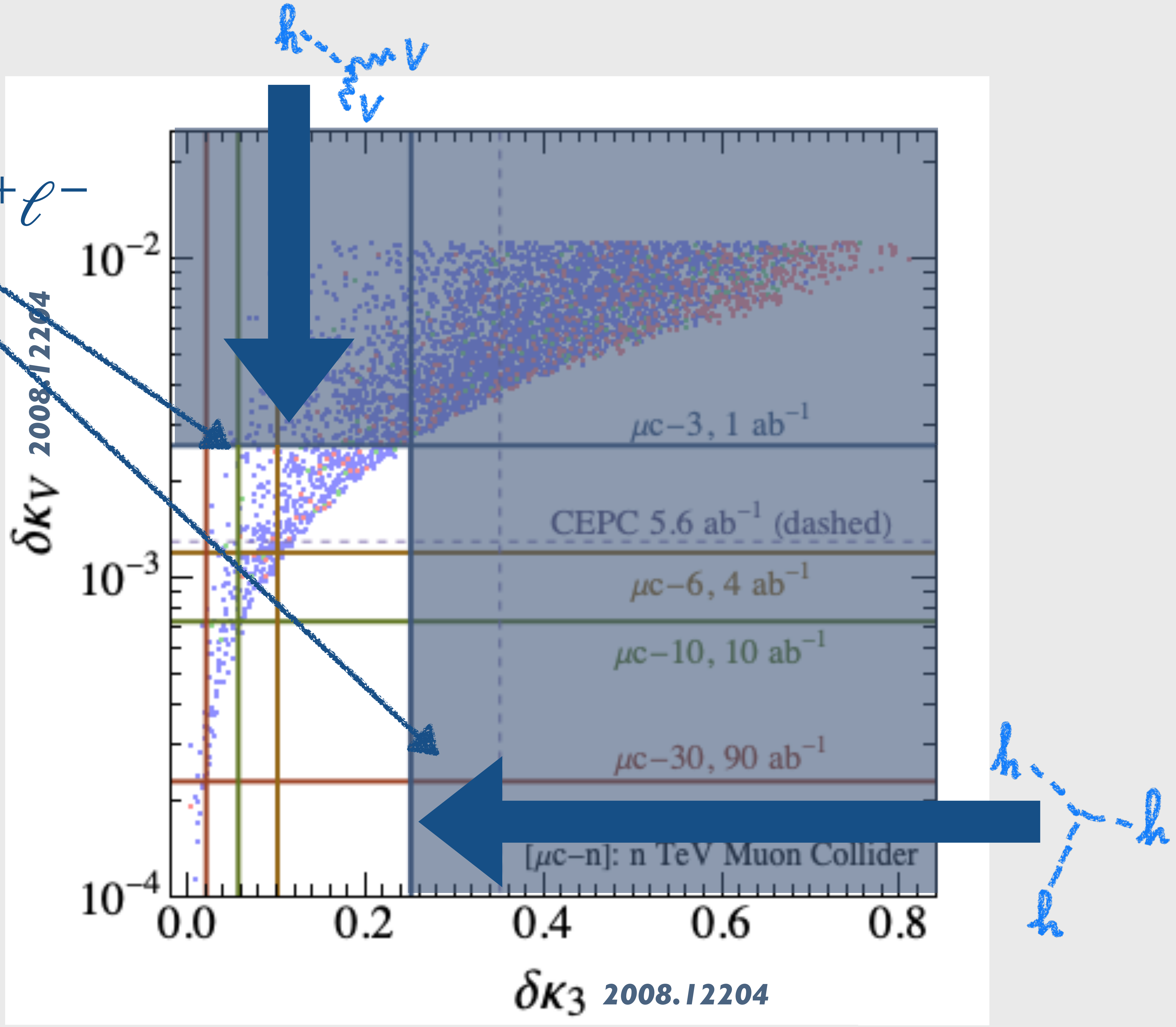
DIRECT & INDIRECT INTERPLAY

strong First Order EW phase transition on all points

Gravity Wave SNR



3 TeV $\ell^+\ell^-$

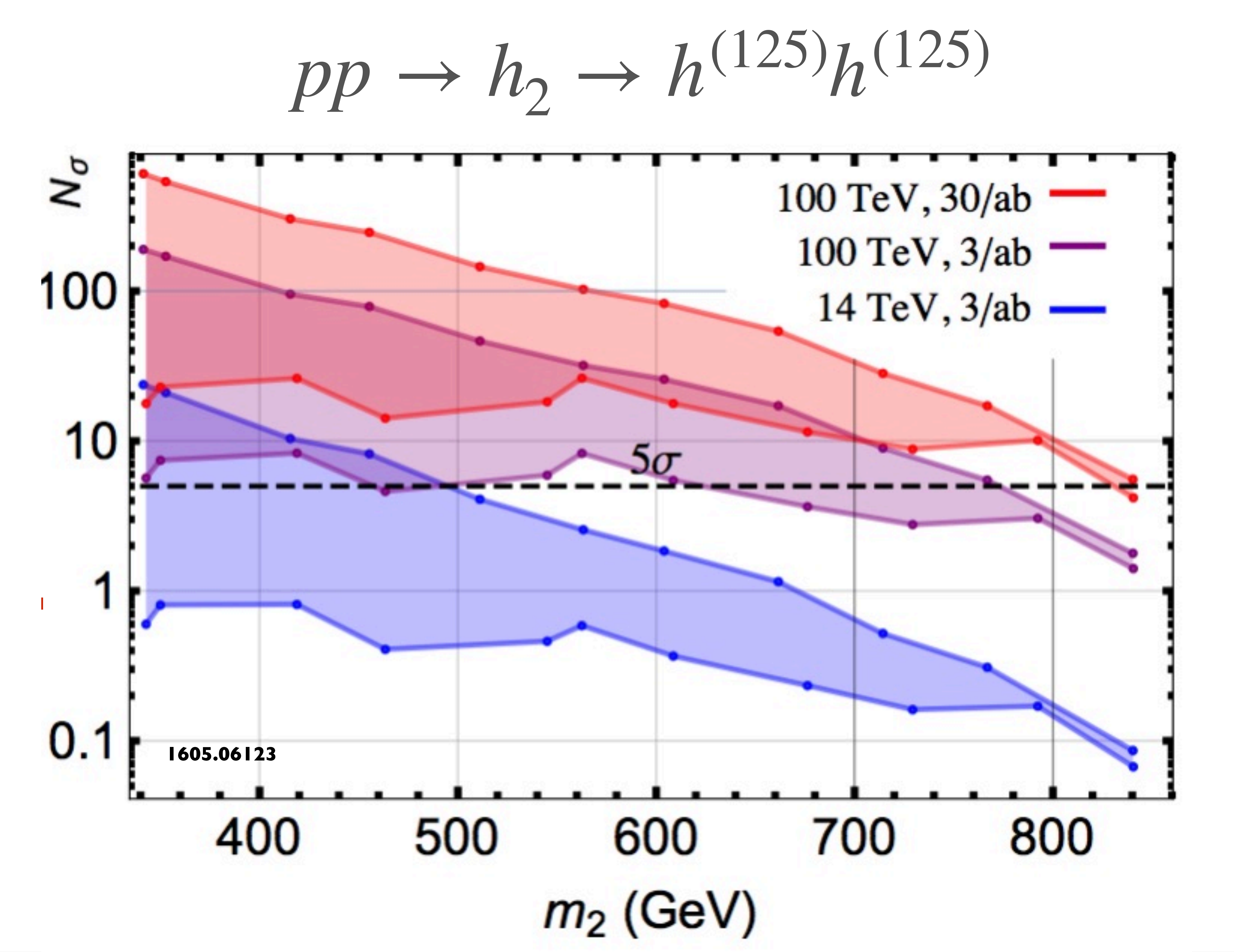


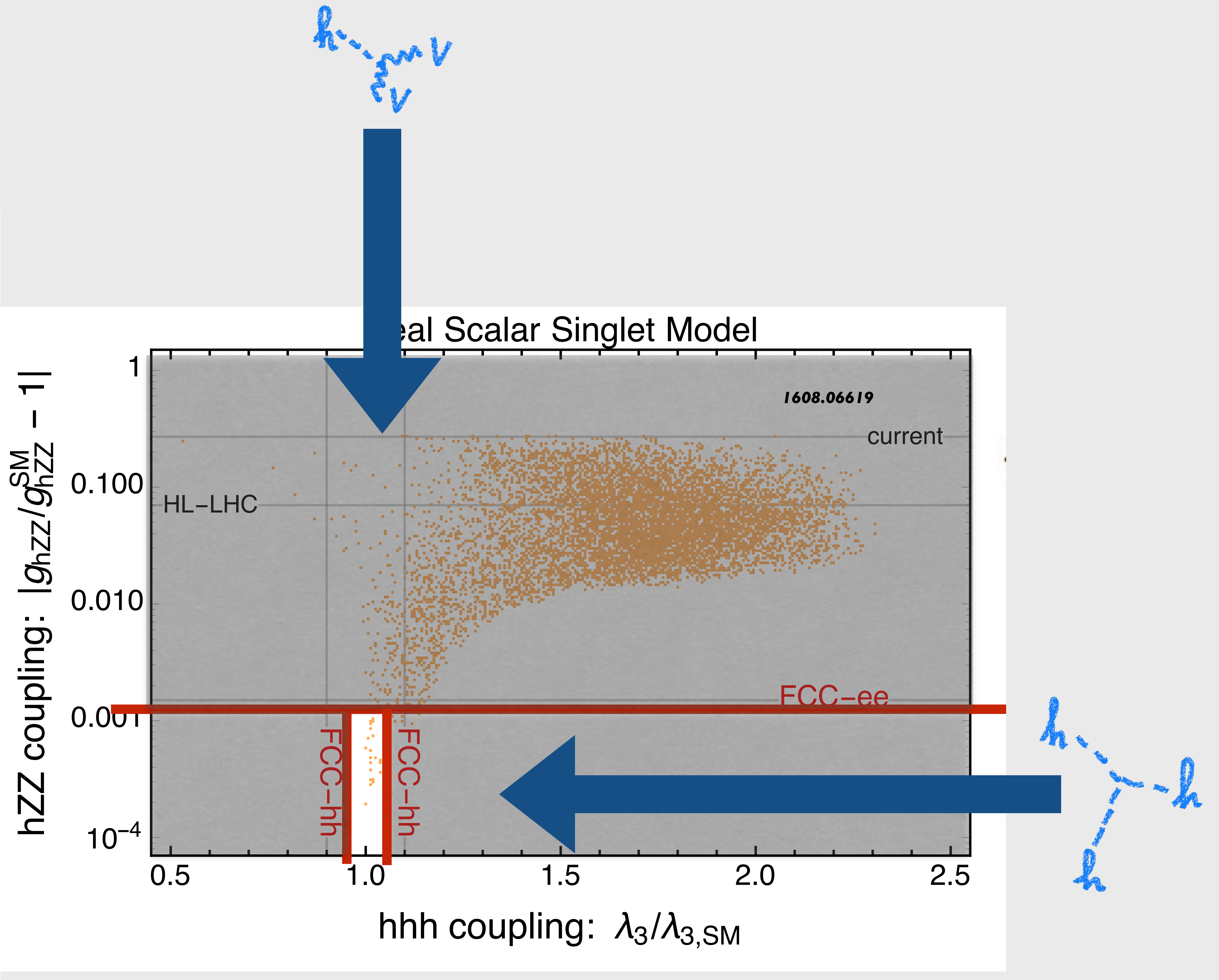
parameters space of 1st order phase transition accessible by **several measurements available at the** 3 TeV $\ell^+\ell^-$ **collider**

EW phase transition

DIRECT & INDIRECT

INTERPLAY

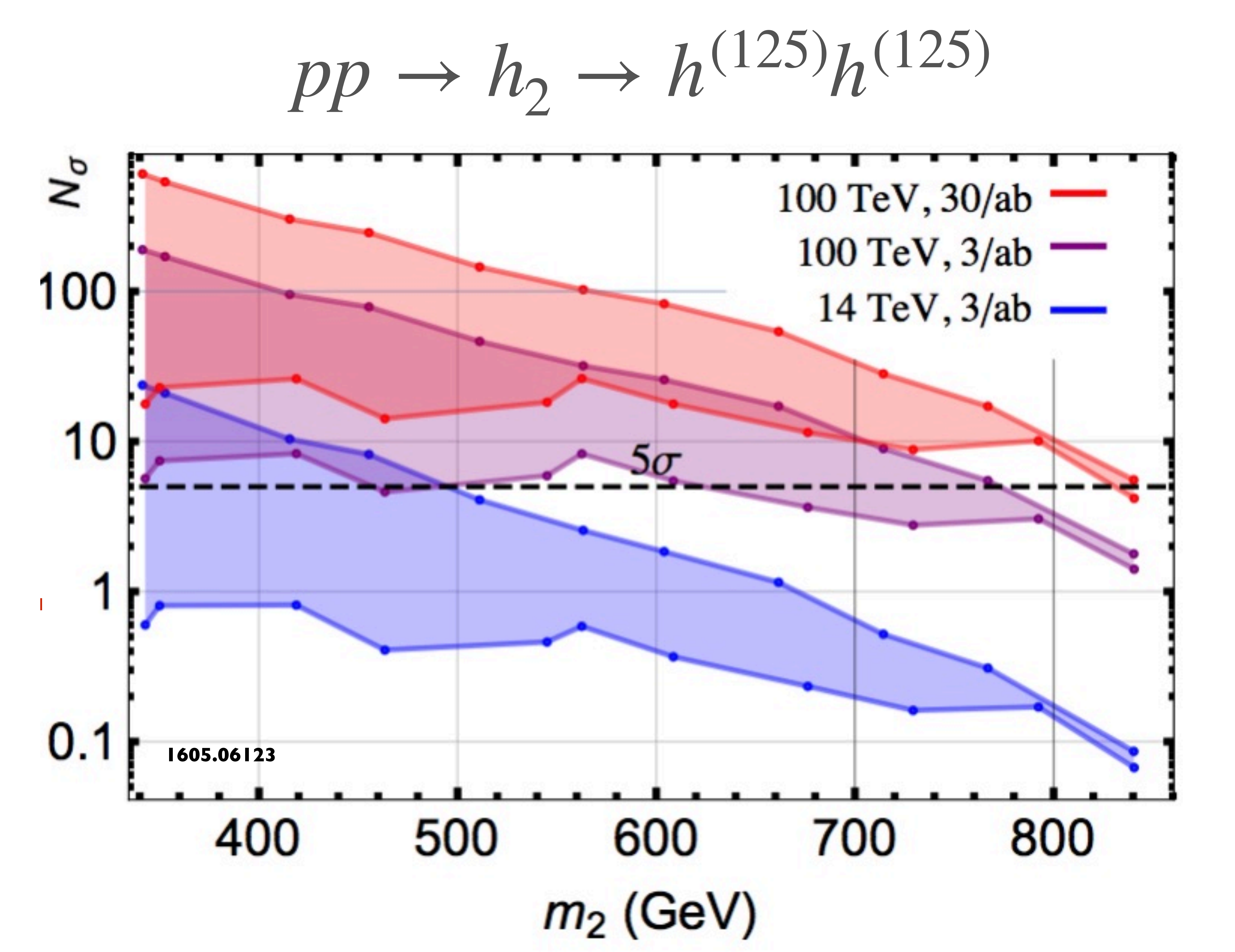


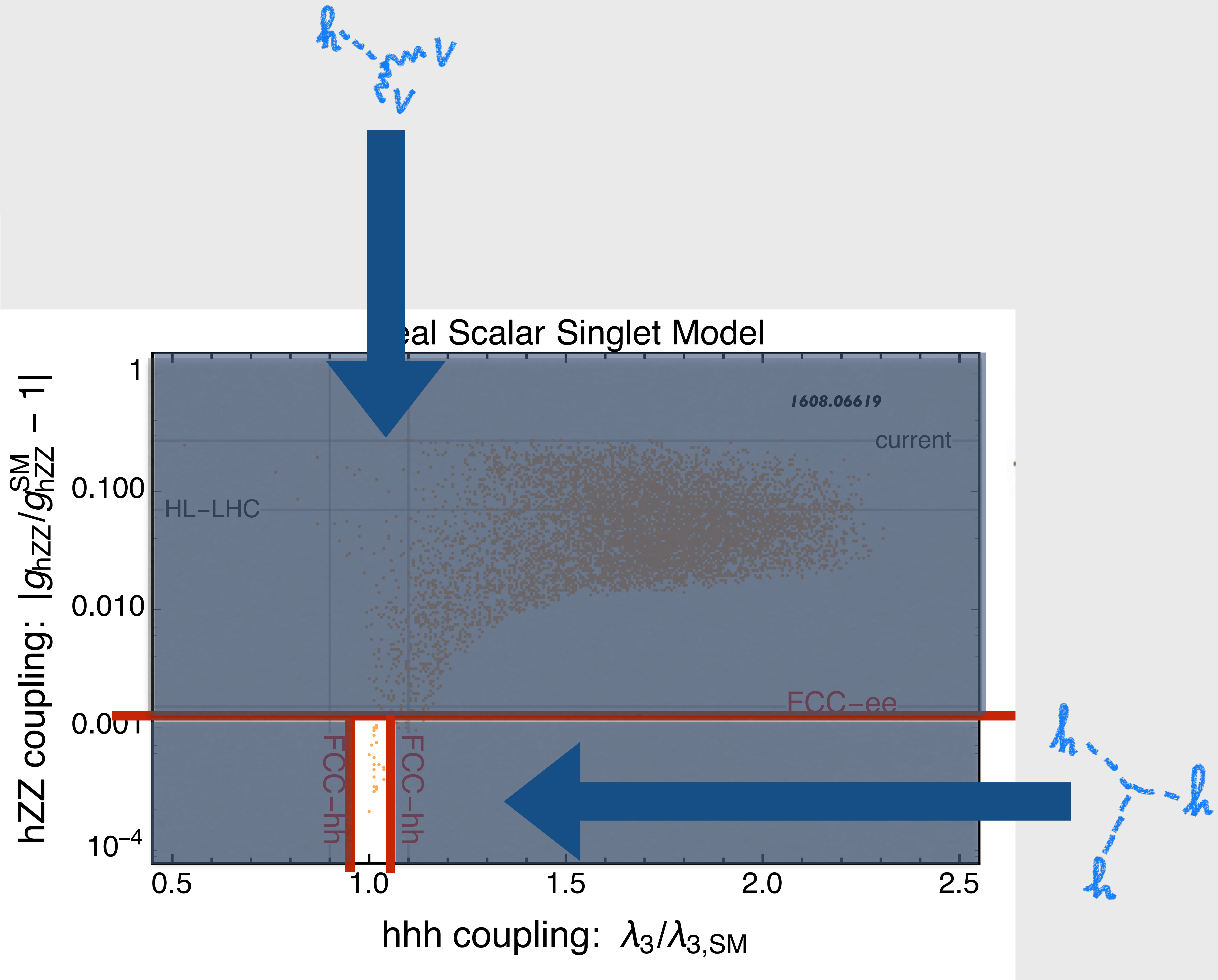


EW phase transition

DIRECT & INDIRECT

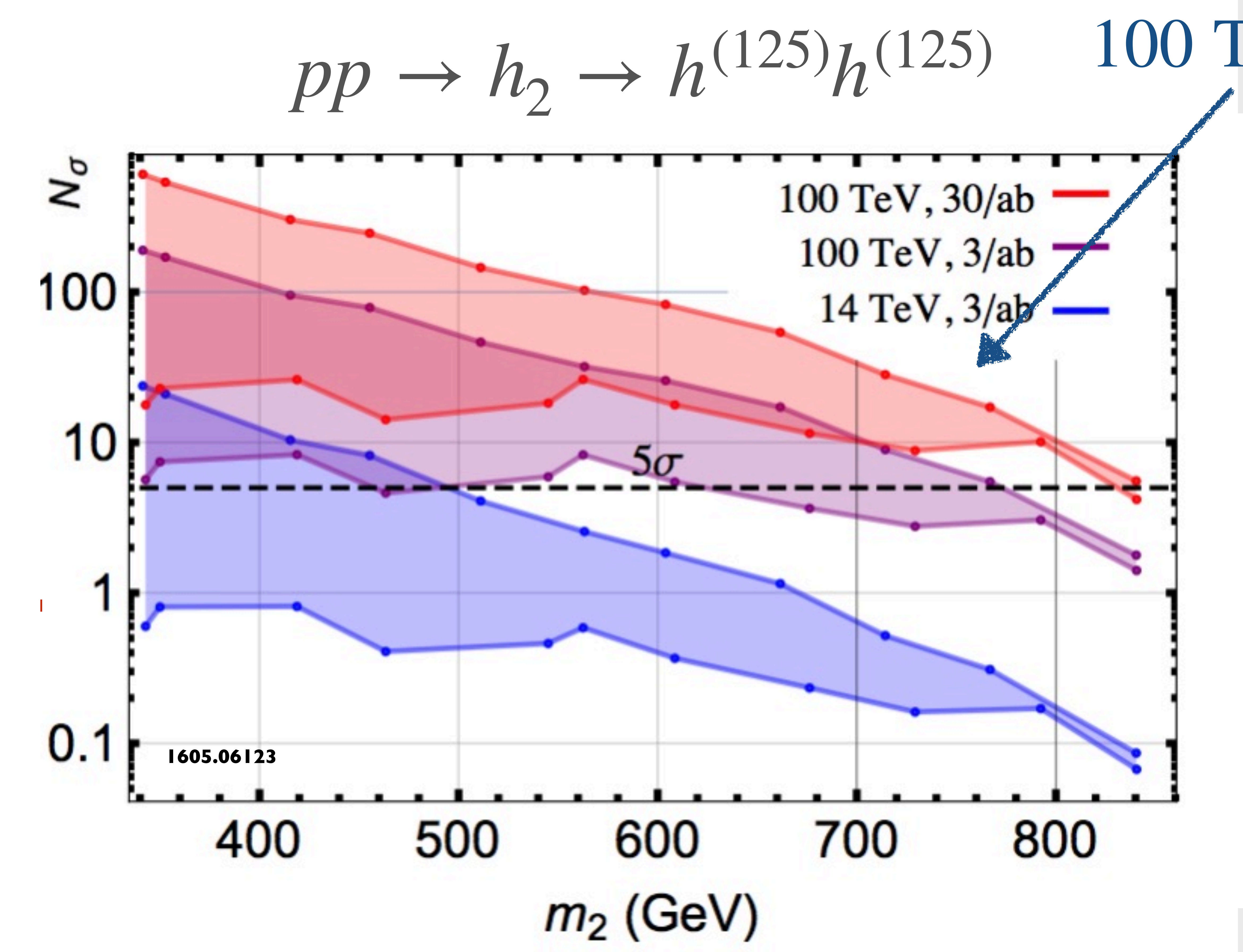
INTERPLAY

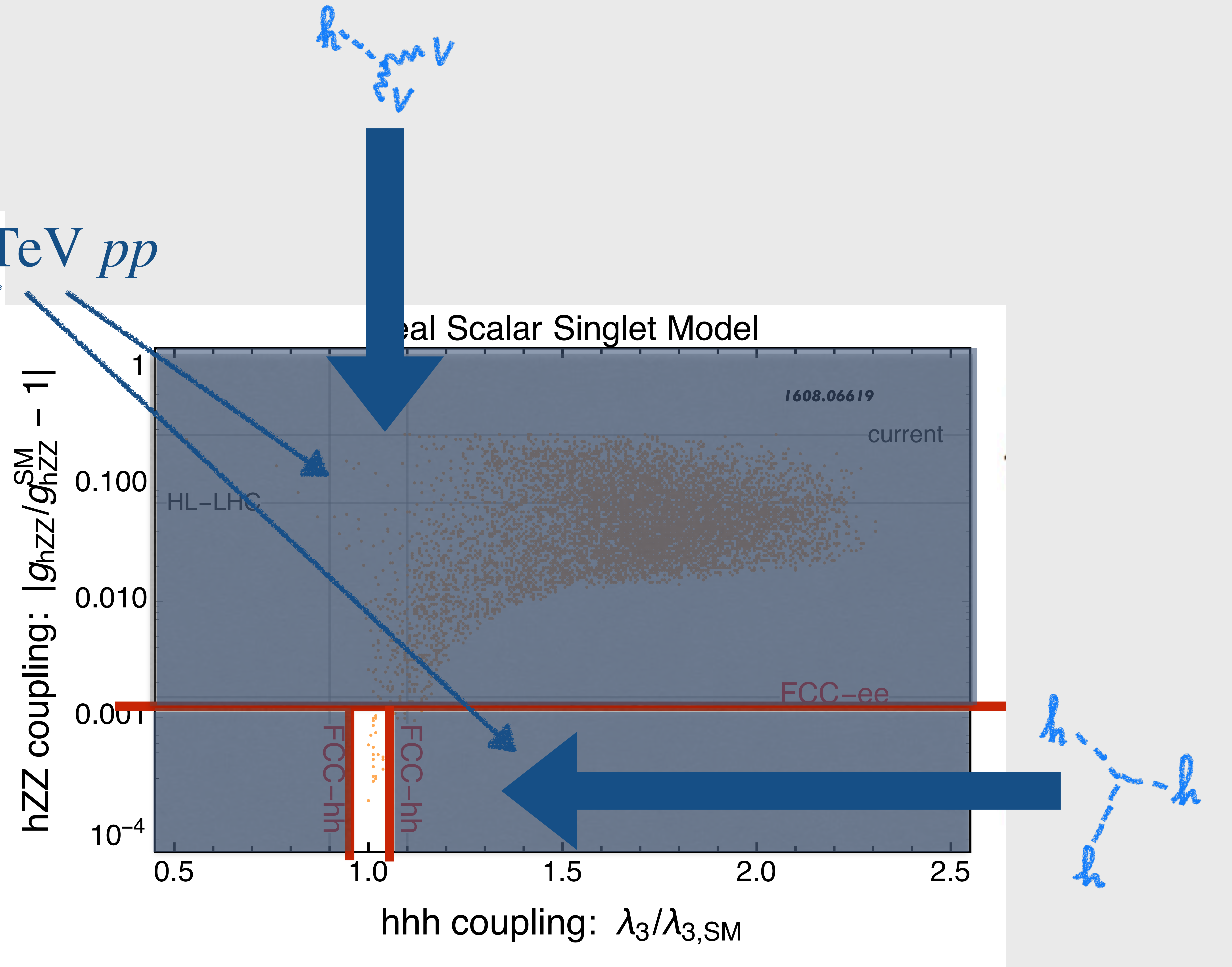




EW phase transition

DIRECT & INDIRECT | INTERPLAY





parameters space of 1st order phase transition accessible by **several measurements available at the 100 TeV pp collider**