Near-future, Future and Futuristic Collider Physics

Fabio Maltoni

Université catholique de Louvain
Università di Bologna

2025 Near future 2050 Future 2075

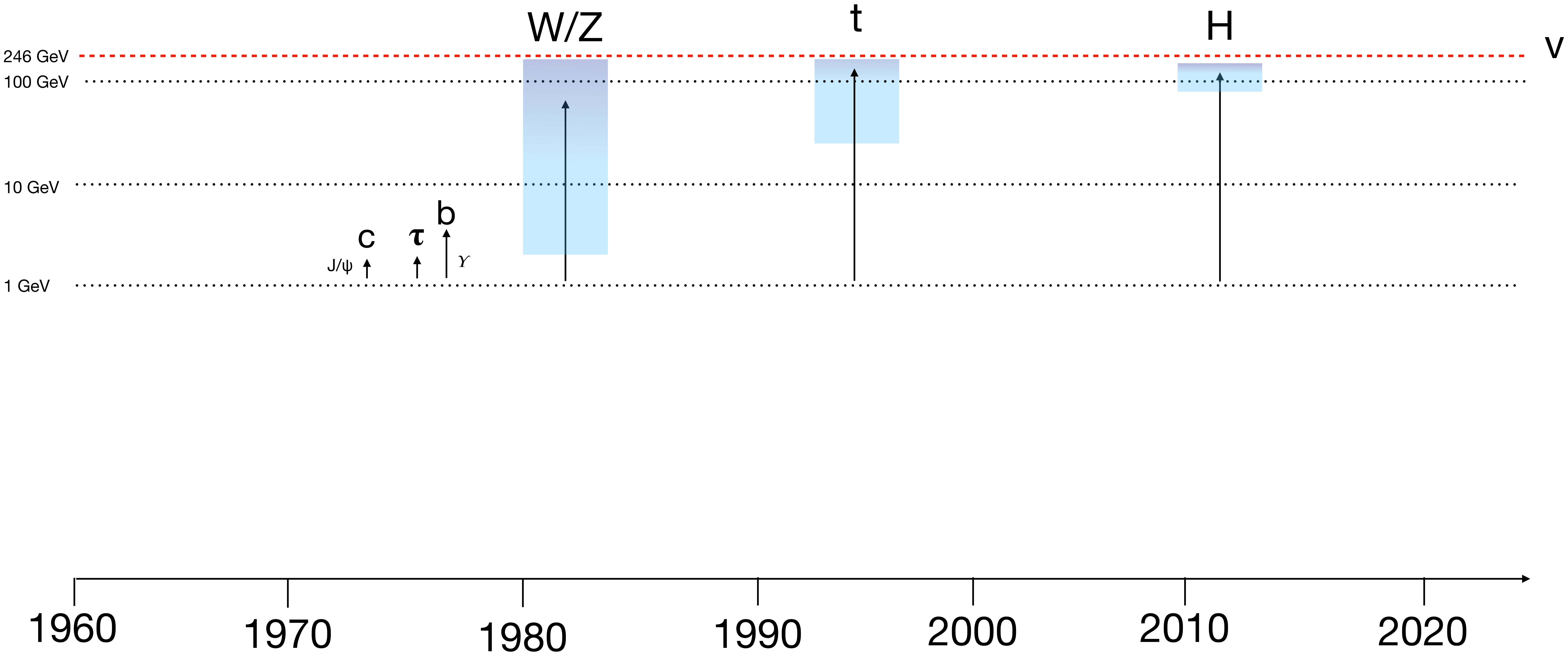
2025 → Trieste

2050 → Europe is the first climate neutral continent

2075 → 0% growth rate of human population

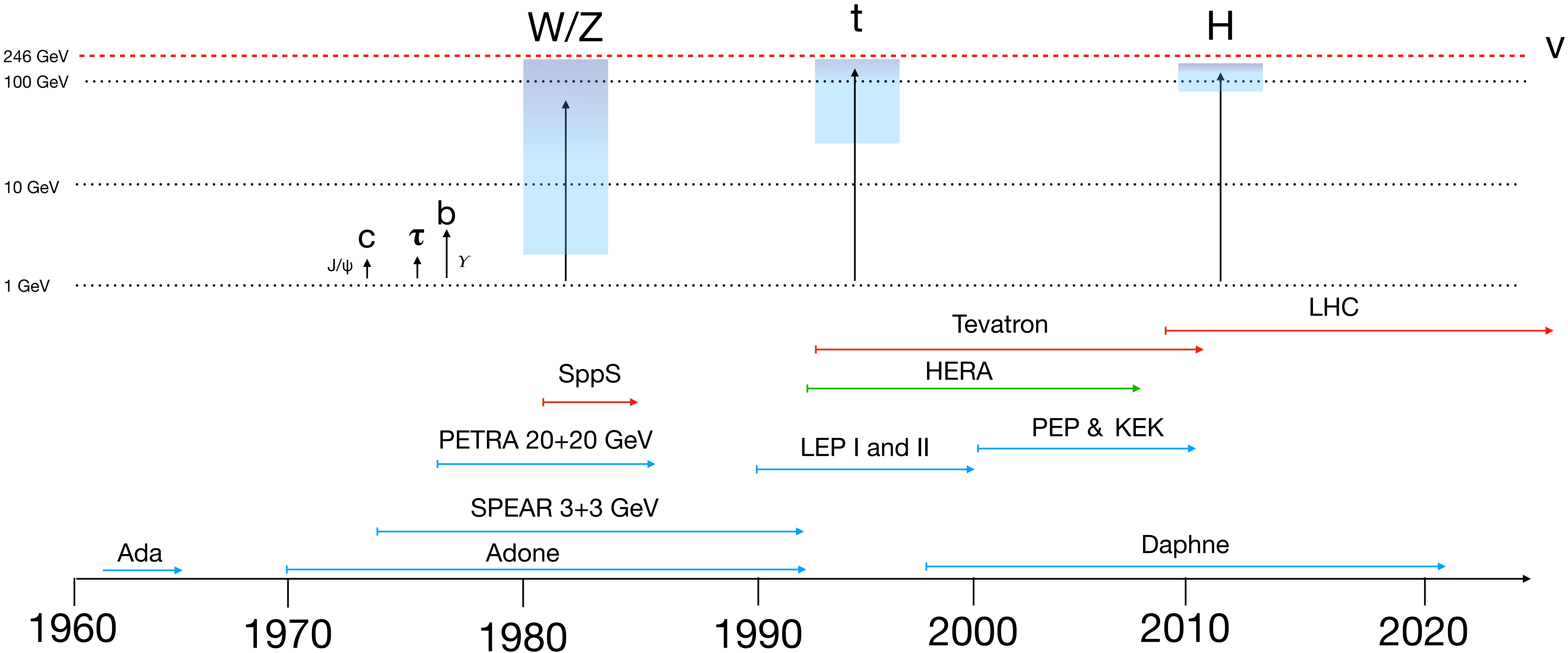
Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



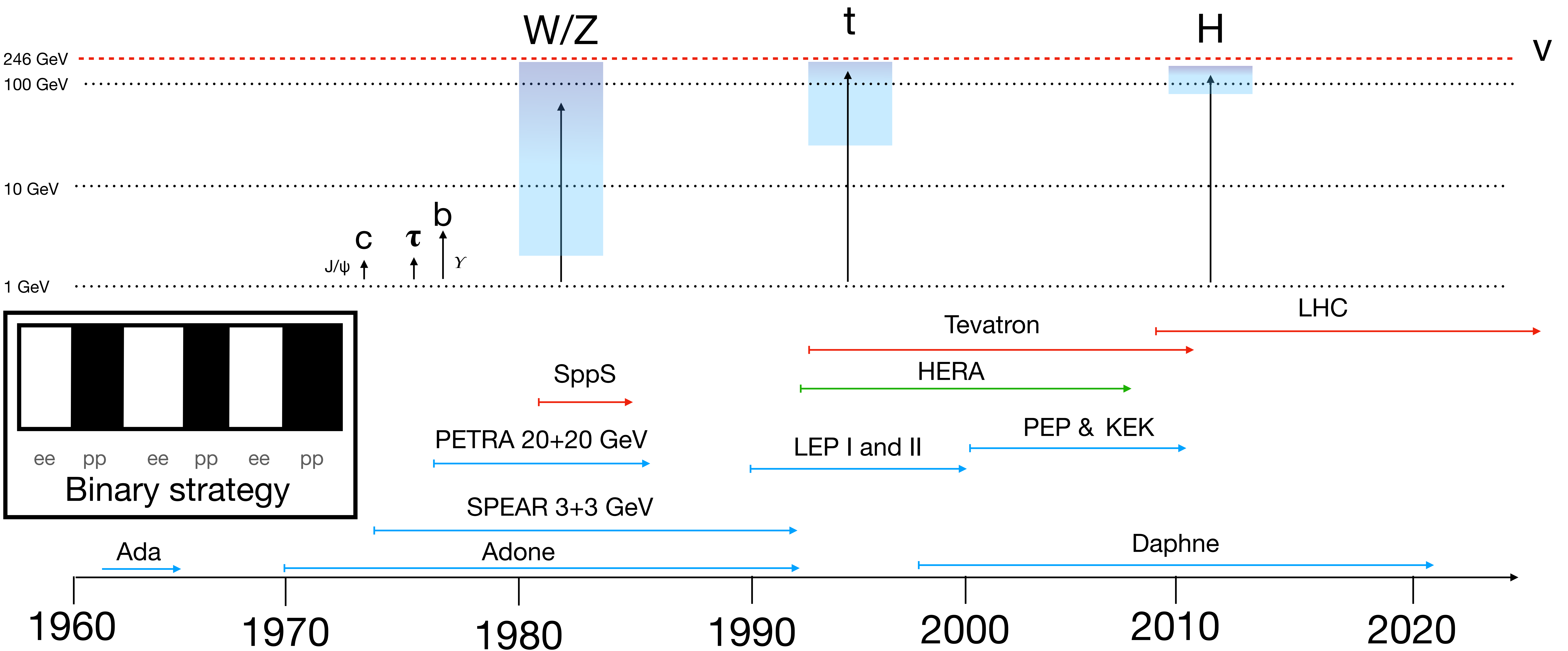
Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



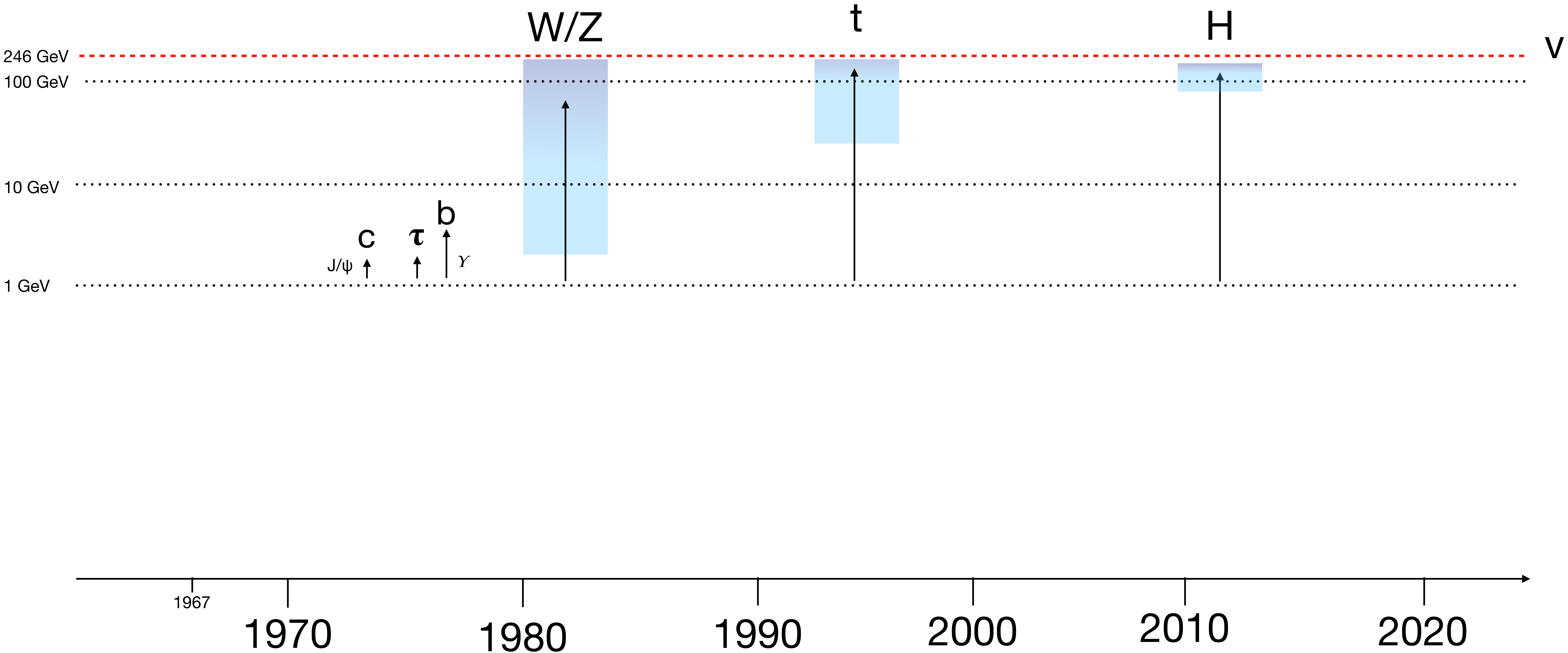
Experimental point of view

The story of collider physics in the last 60 years is marked by the accelerators eras and punctuated by key discoveries



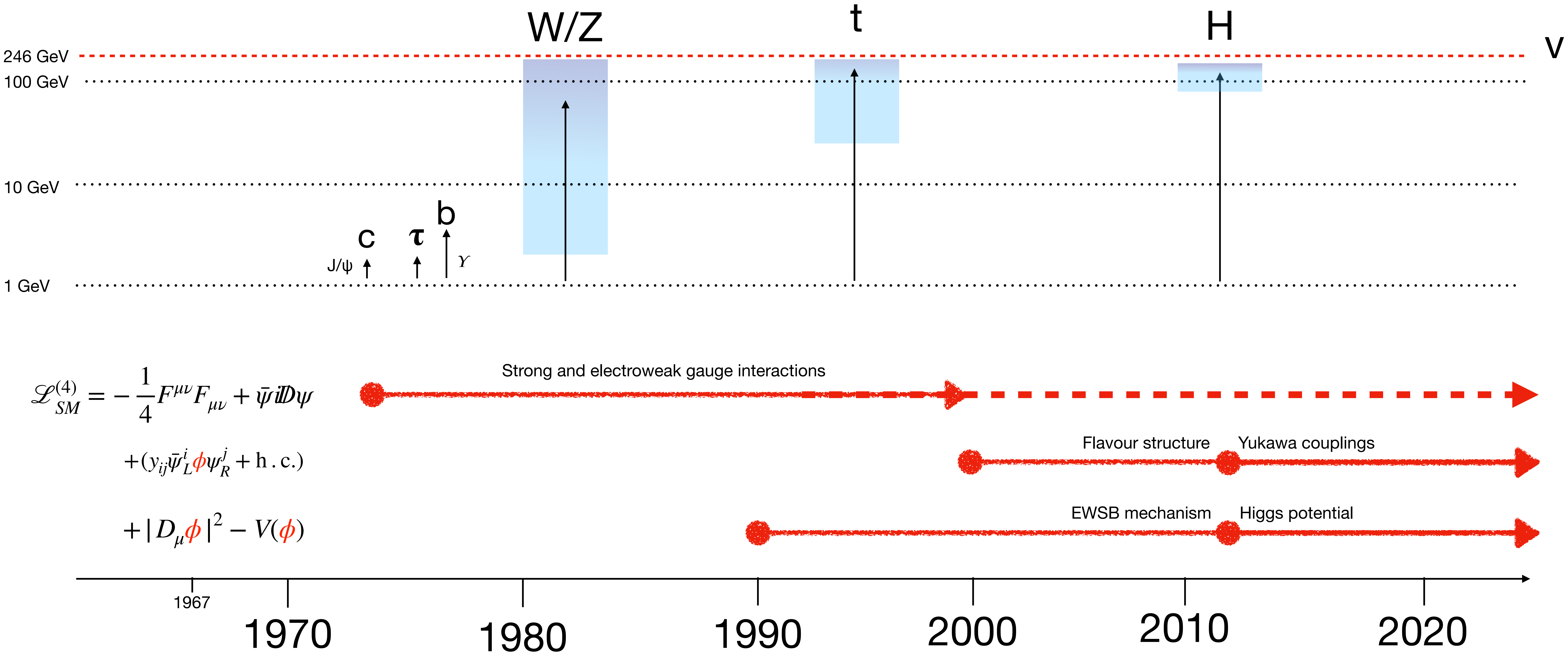
(A) theorist's point of view

The story of collider physics in the last 60 years is the slow yet steady turning of the Standard Model into a Standard Theory for Strong and EW interactions.



(A) theorist's point of view

The story of collider physics in the last 60 years is the slow yet steady turning of the Standard Model into a Standard Theory for Strong and EW interactions.



$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}i\not{D}\psi$$

$$+(y_{ij}\bar{\psi}^i_L\phi\psi^j_R + \mathrm{h.c.})$$

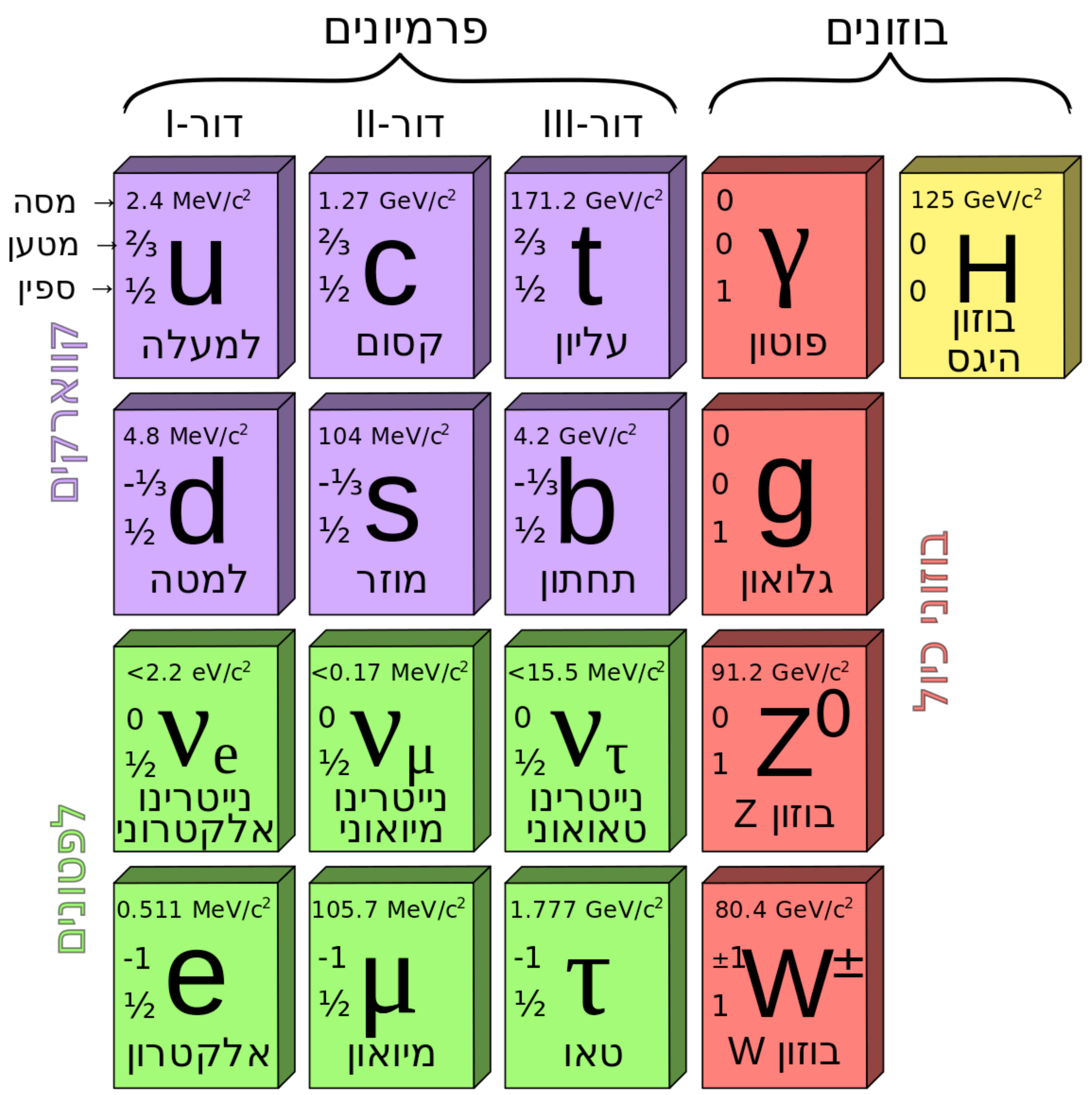
$$+|D_\mu\phi|^2 - V(\phi)$$

Where do we stand?

$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

3 gauge forces

1 scalar force



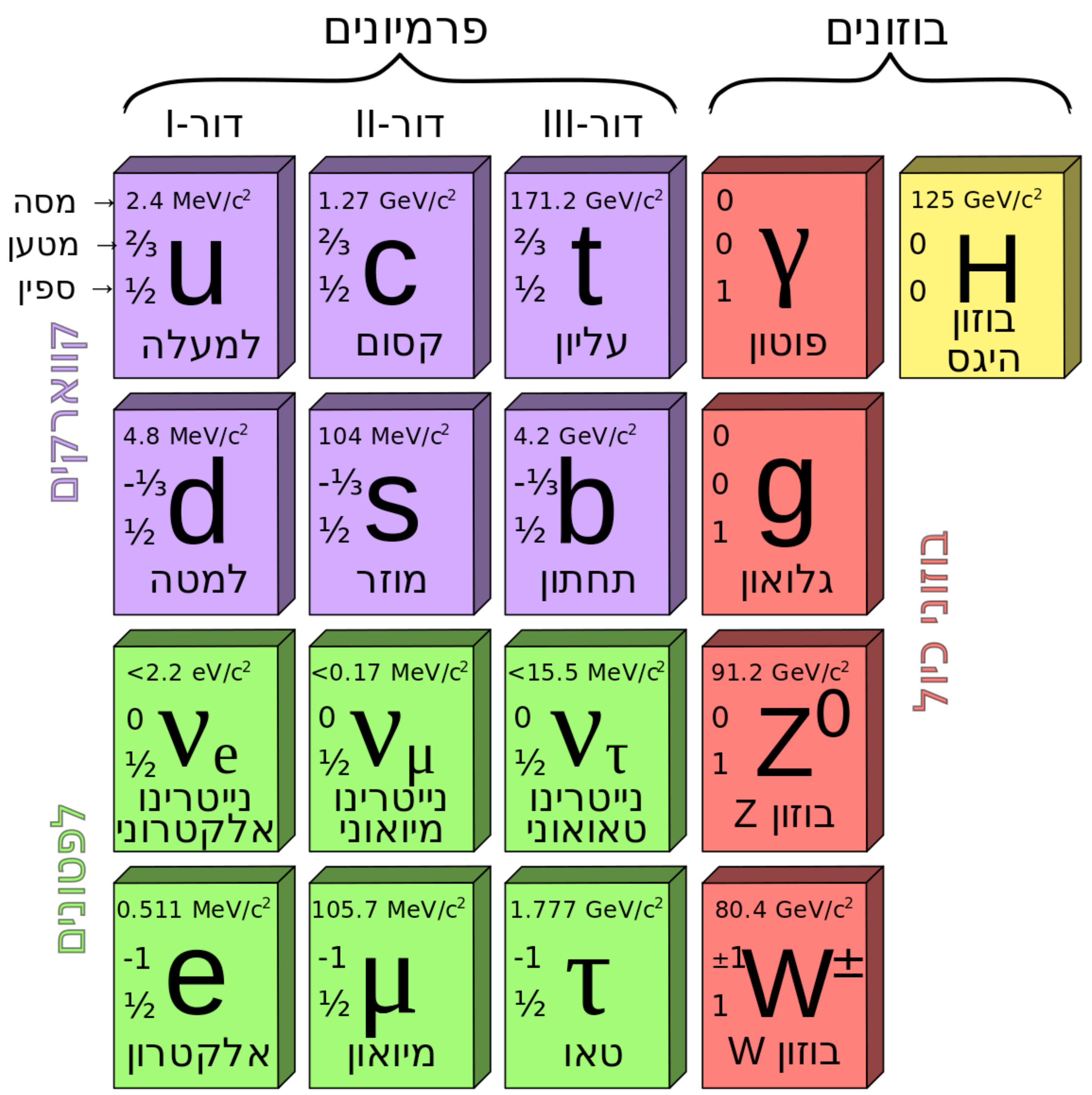
- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries
- Matter is organised in chiral multiplets of the fund. representation
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to $U(1)_{EM}$
- Yukawa interactions lead to fermion masses, mixing and CP violation
- Matter+gauge group => Anomaly free
- Neutrino masses can be accommodated in a natural way

Where do we stand?

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

3 gauge forces

1 scalar force

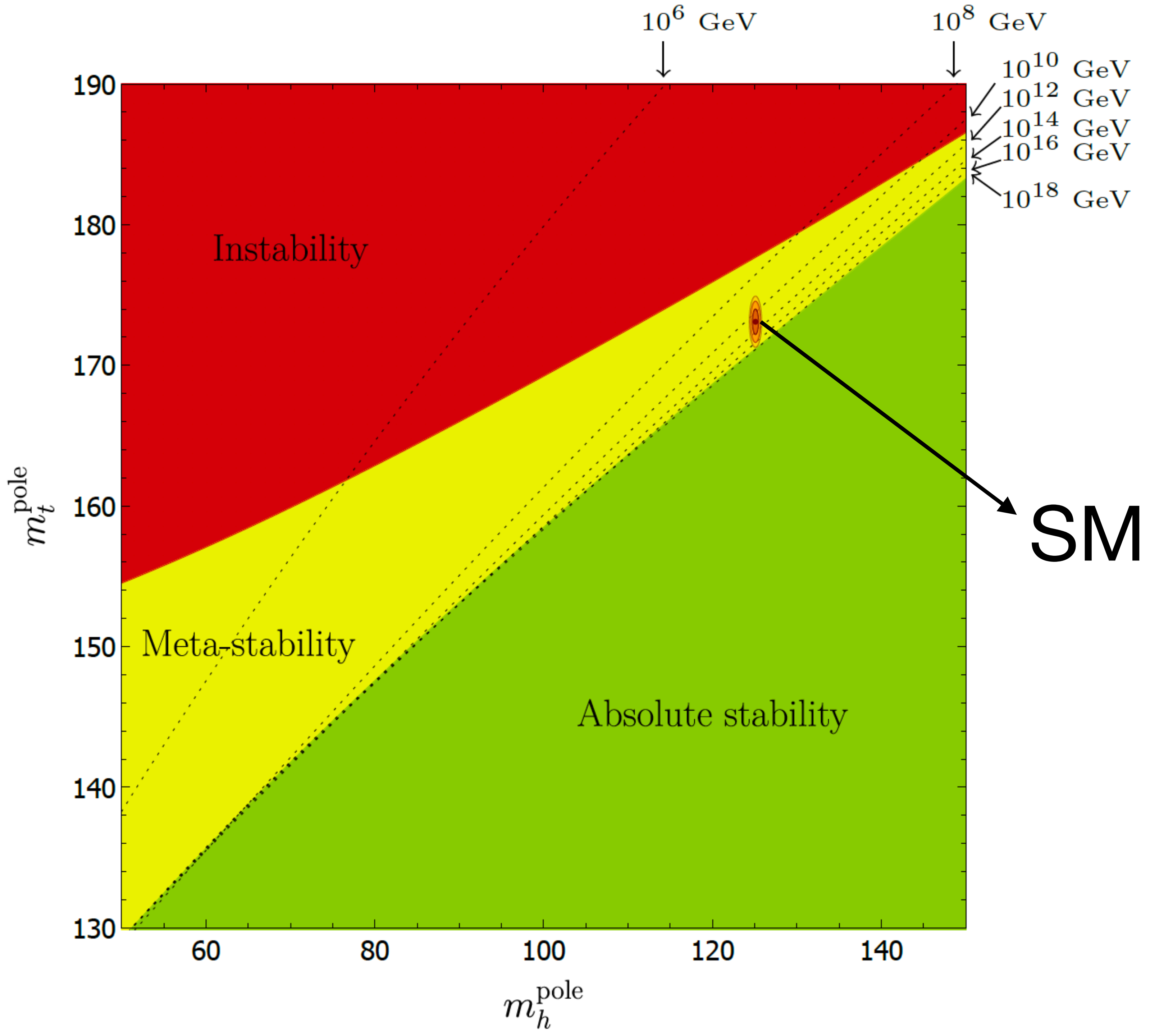


- SU(3)$_c$ x SU(2)$_L$ x U(1)$_Y$ gauge symmetries
- Matter is organised in chiral multiplets of the fund. representation
- The SU(2) x U(1) symmetry is spontaneously broken to U(1)$_{EM}$
- Yukawa interactions lead to fermion masses, mixing and CP violation
- Matter+gauge group => Anomaly free
- Neutrino masses can be accommodated in a natural way

Where do we stand?

$$\mathscr{L}^{(4)}_{SM} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D}\psi + (y_{ij}\bar{\psi}^i_L \phi \psi^j_R + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

MF, CPV, Flavour Custiodial, MV EWBG



[Andreassen et al. 1707.08124]

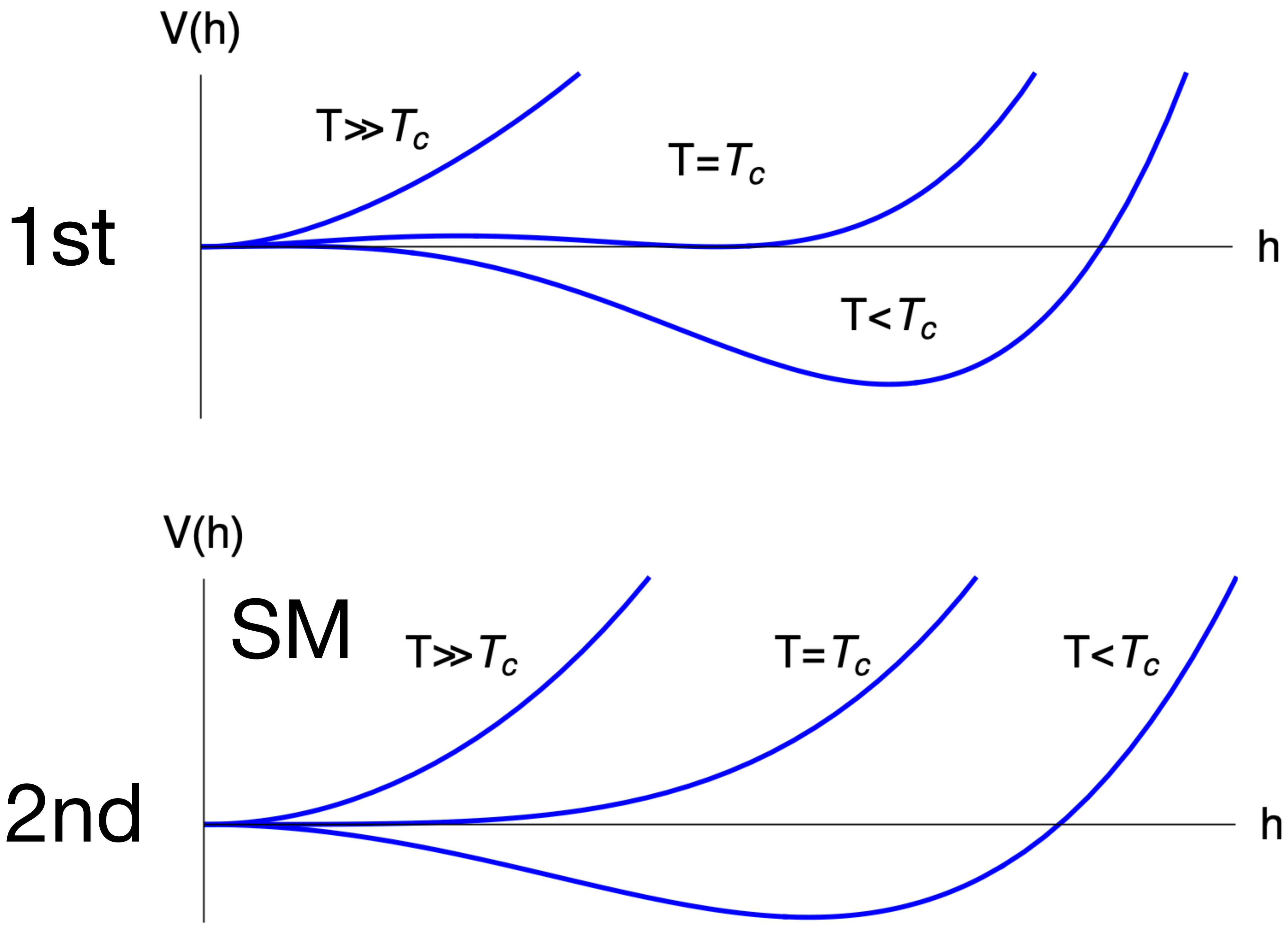
Apparently accidental, but key aspects for successful phenomenology:

- Lepton and Baryon number conservation
- Custodial symmetry
- Absence of FCN interactions
- Small and hierarchical mixing among quarks
- Collective suppression of CP violation
- IR values of the parameters do not indicate any problem at high scales, including vacuum stability

All these aspects are not only difficult to explain in one go, but are also typically not respected by extensions of the SM.

Where do we stand?

$$\mathscr{L}_{SM}^{(4)} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi} i \not{D} \psi + (y_{ij}\bar{\psi}_L^i \phi \psi_R^j + \mathrm{h.c.}) + |D_\mu \phi|^2 - V(\phi)$$

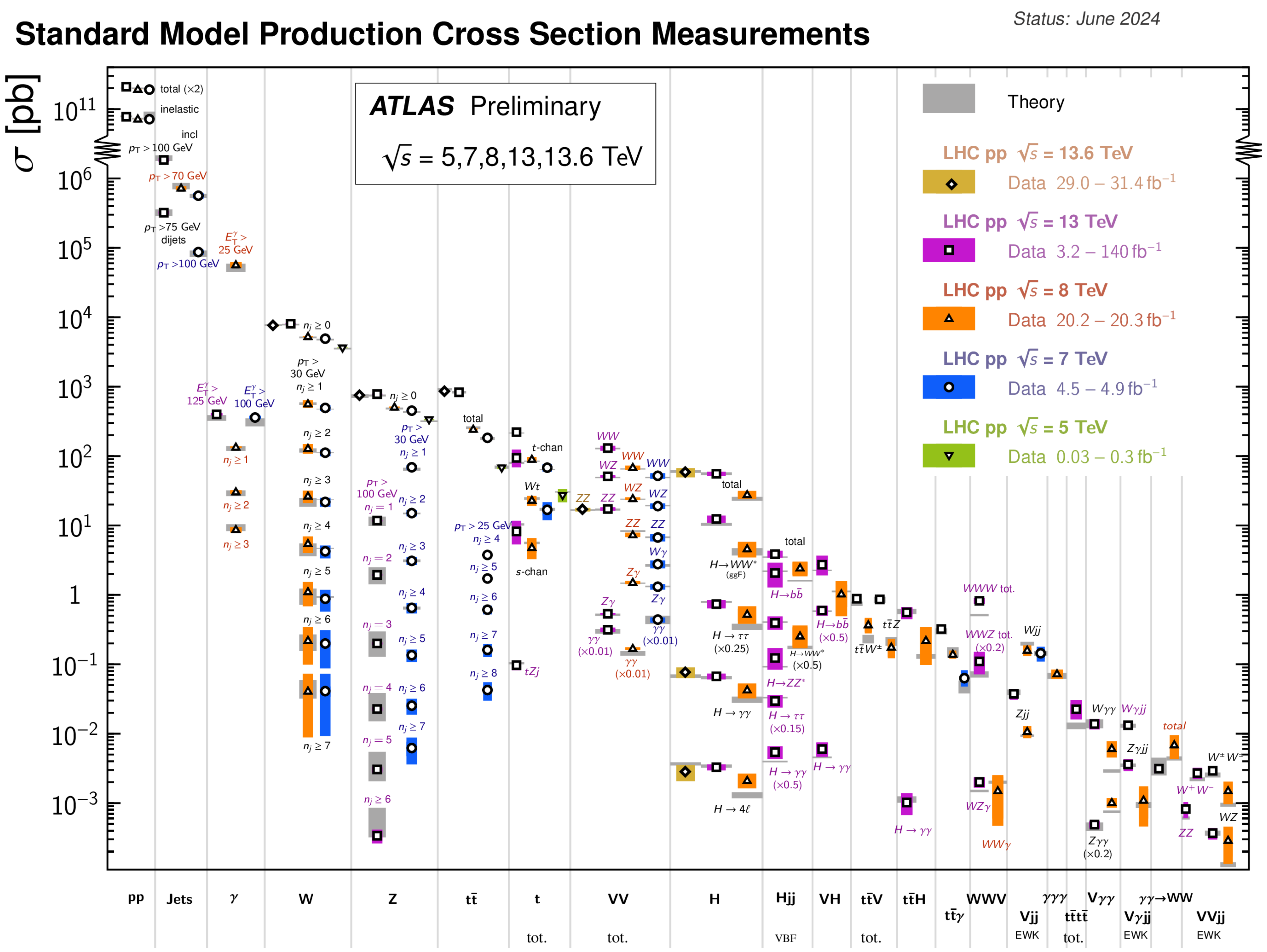


Yet many aspects of the SM are problematic vis-à-vis phenomenology:

- EWBG difficult because of smallness of CPV and no 1st order transition
- Nature of Dark Matter
- Unnaturally small Higgs mass and its origin
- Unnaturally small strong CP violation
- Fermion mass hierarchy and origin of CP violation

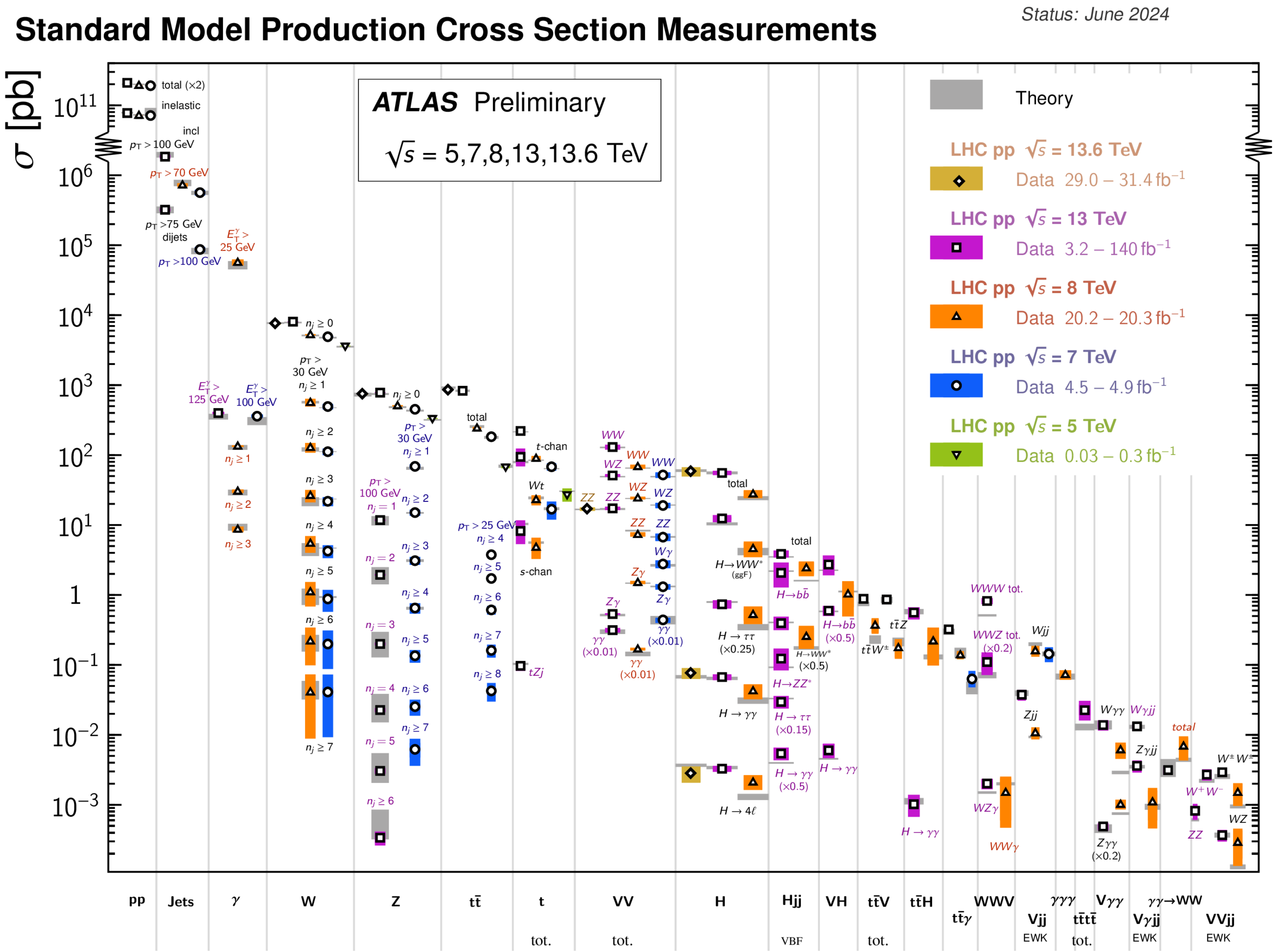
Beyond SM theories typically address one of the above problems at the time. We don't have a precise idea of where the scale of NP might reside.

Where do we stand?



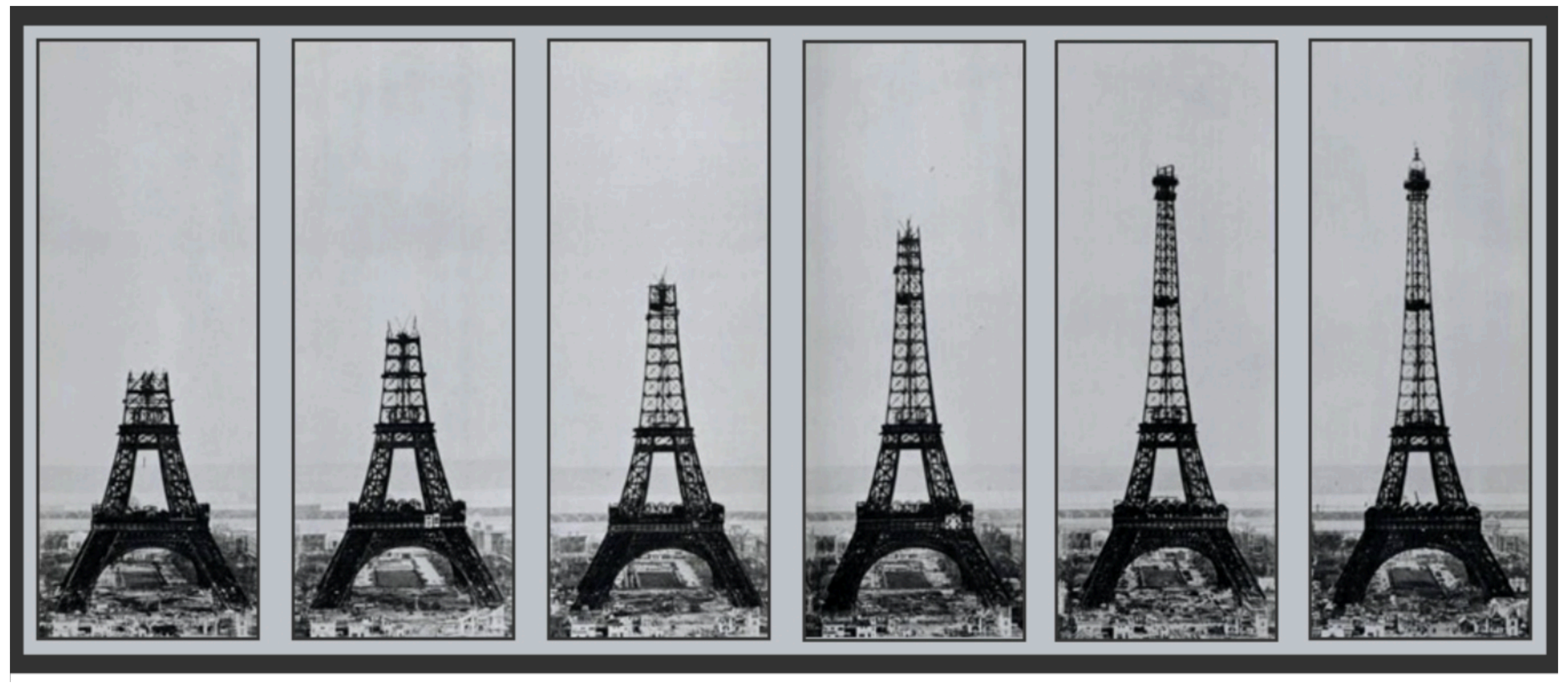
- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).

Where do we stand?

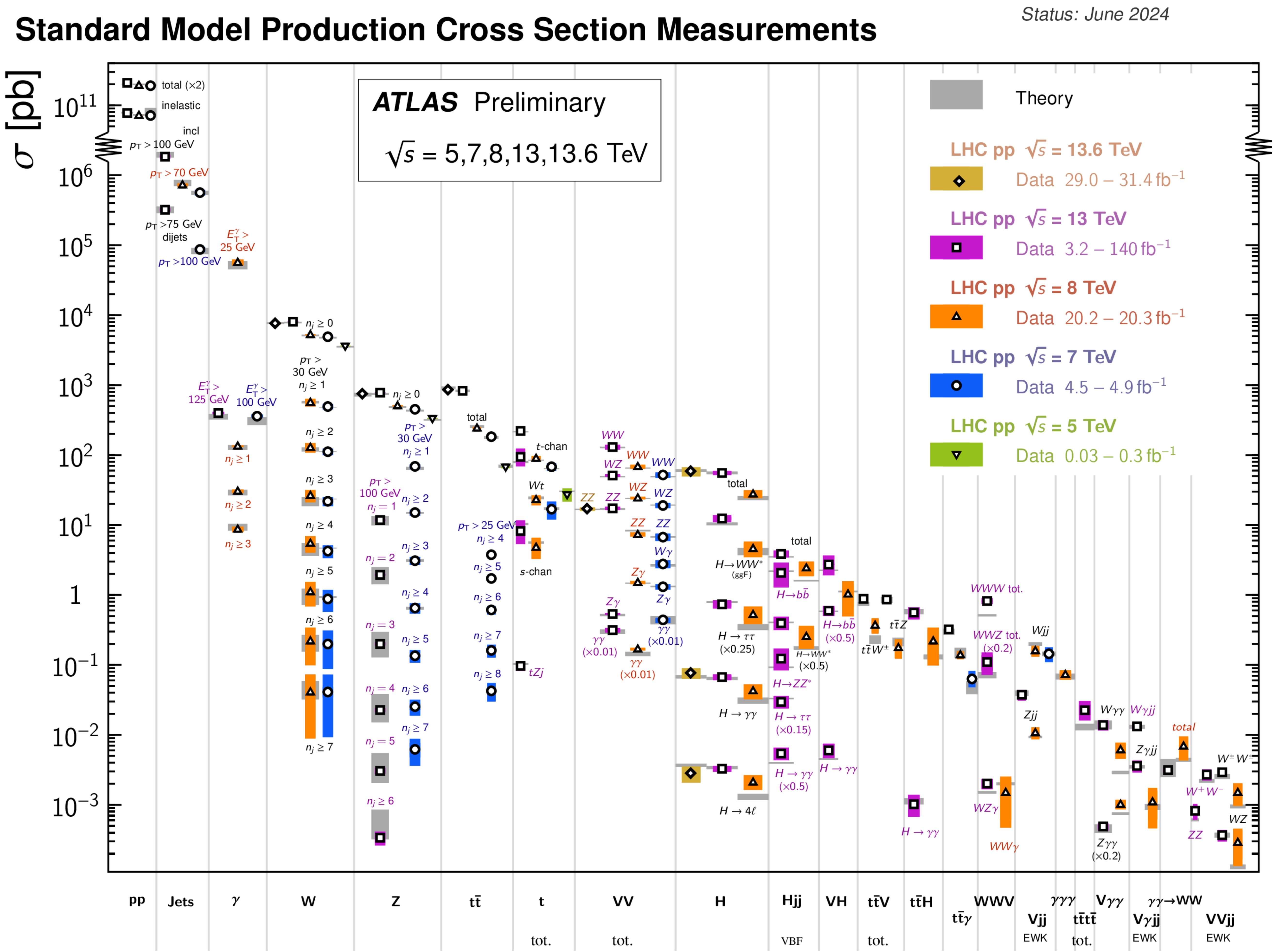

Standard Model Production Cross Section Measurements

Status: June 2024

- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.
- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).
- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



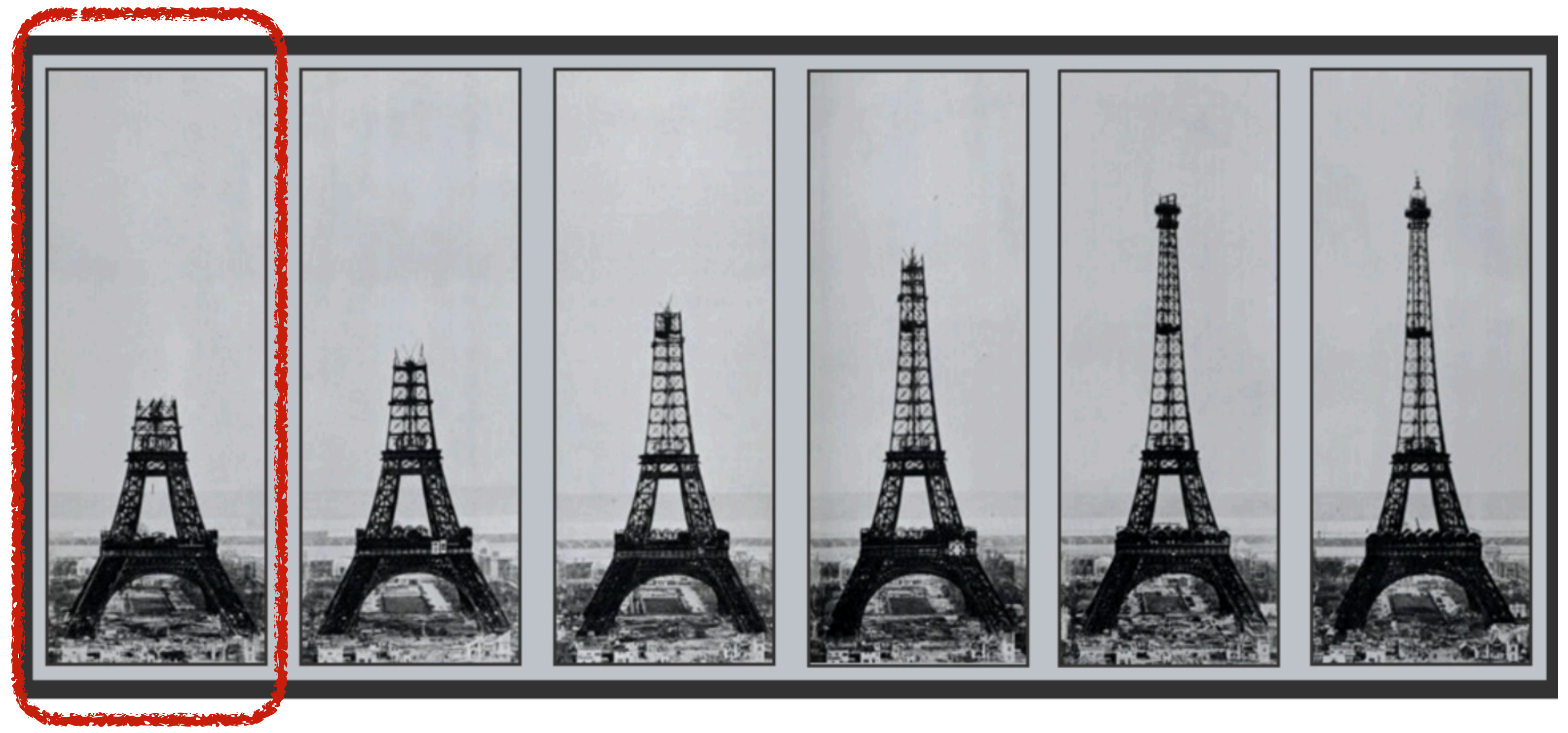
Where do we stand?



- Tangible results of an amazing experimental effort over a 10+ year span, accessing a wide range of final states, each with very different challenges.

- Theory predictions seem adeguate. (The key role of MCs is hidden in this plot).

- Comparison with SM predictions shows that we have the necessary theoretical and experimental control to move onto the next phase.



A quote

[S]He who knows the art of
the direct and the indirect approaches
will be victorious.

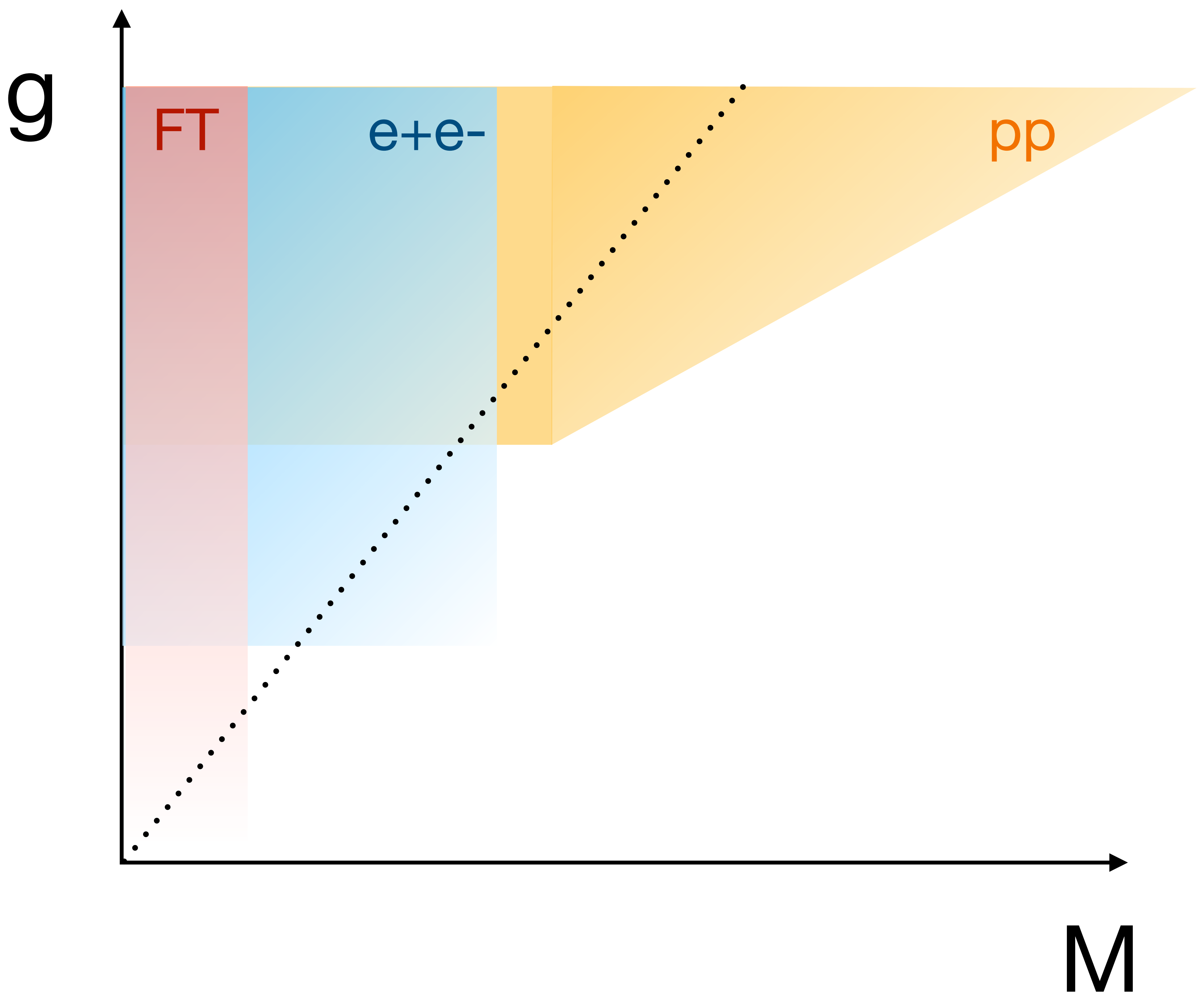
A quote

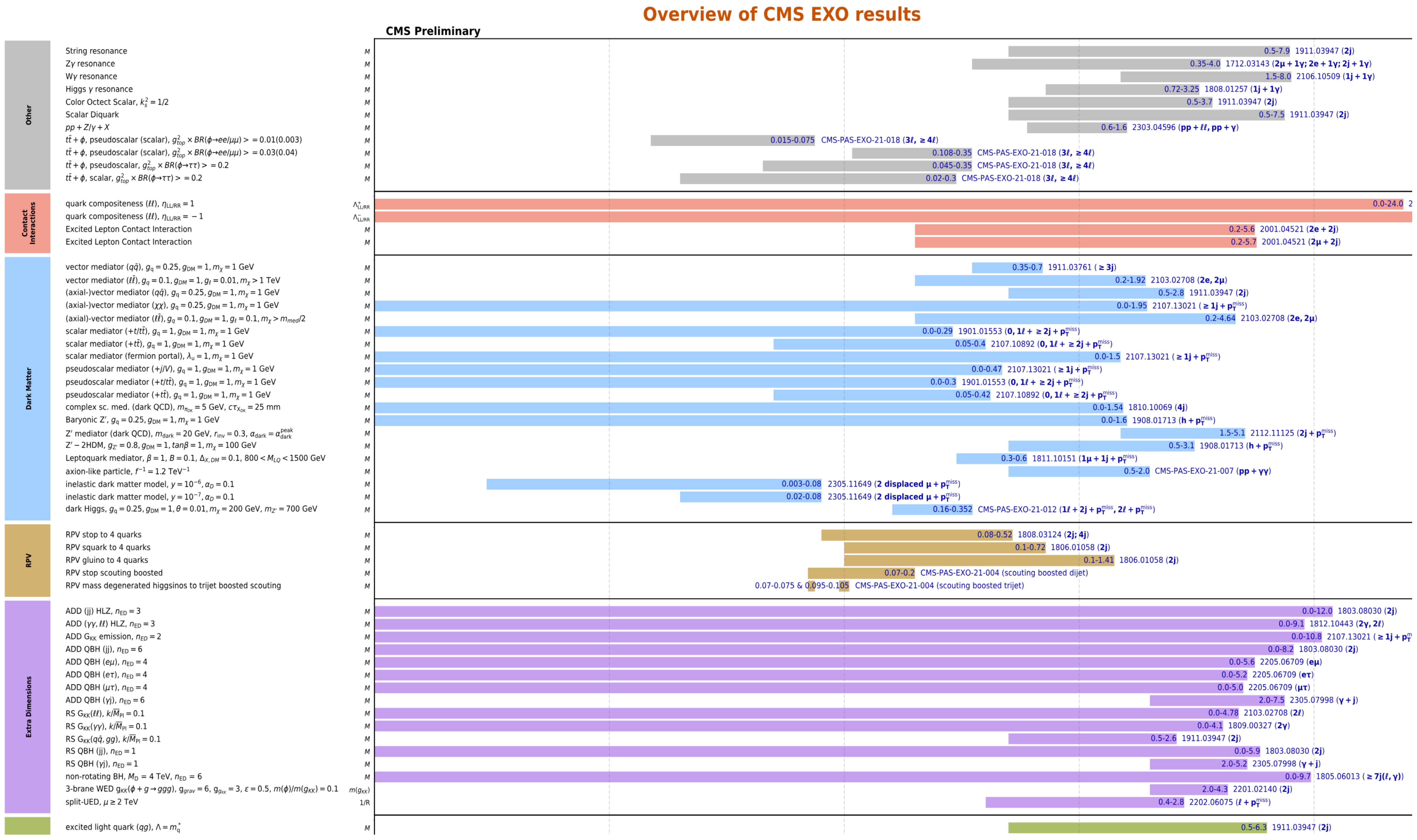
[S]He who knows the art of
the direct and the indirect approaches
will be victorious.

Sun Tzu, The Art of War

Λ_{BSM} is low

BSM direct searches





Λ_{BSM} is high

Effective field theory

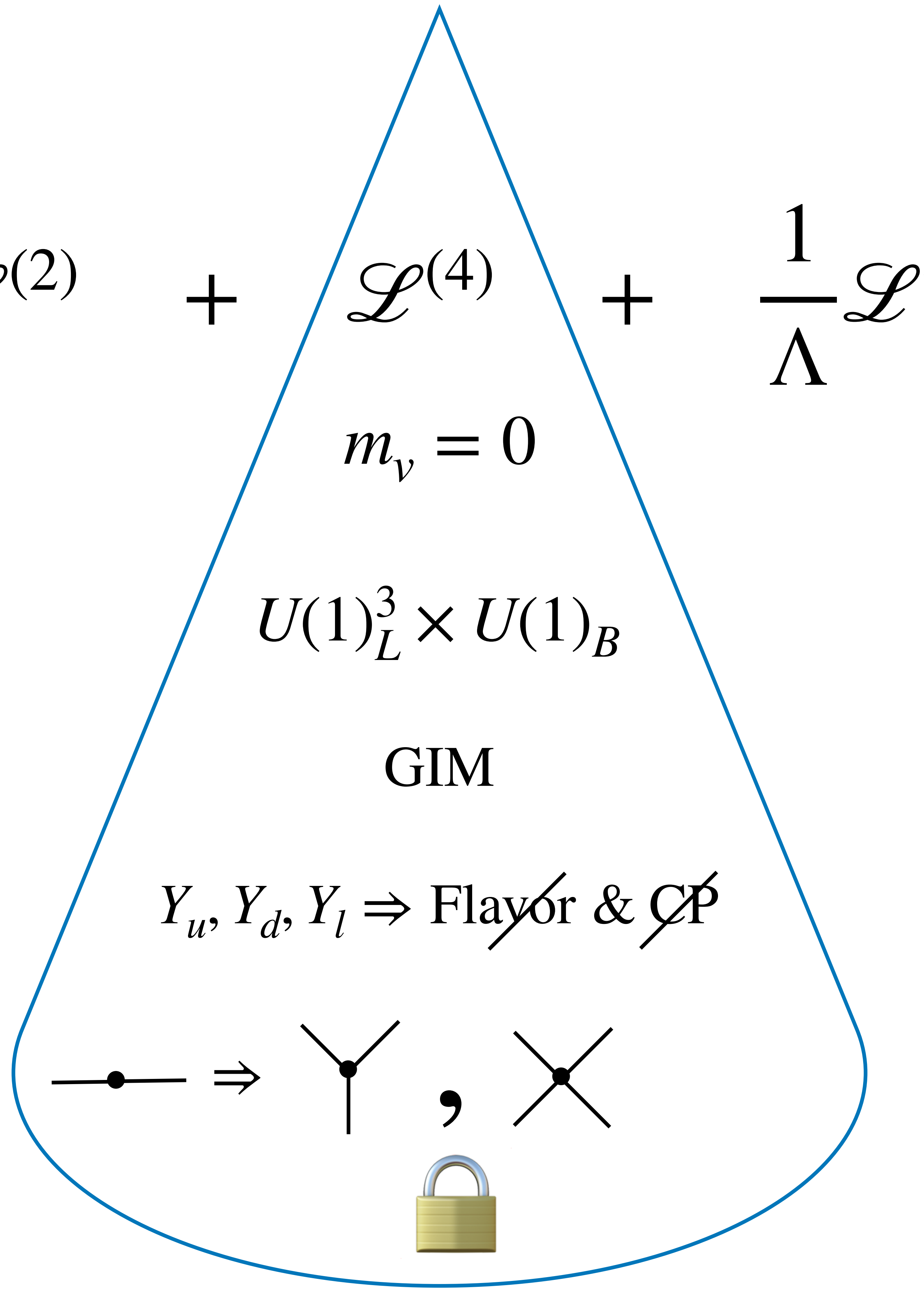
$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

Rattazzi®

Λ_{BSM} is high

Effective field theory

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$



$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

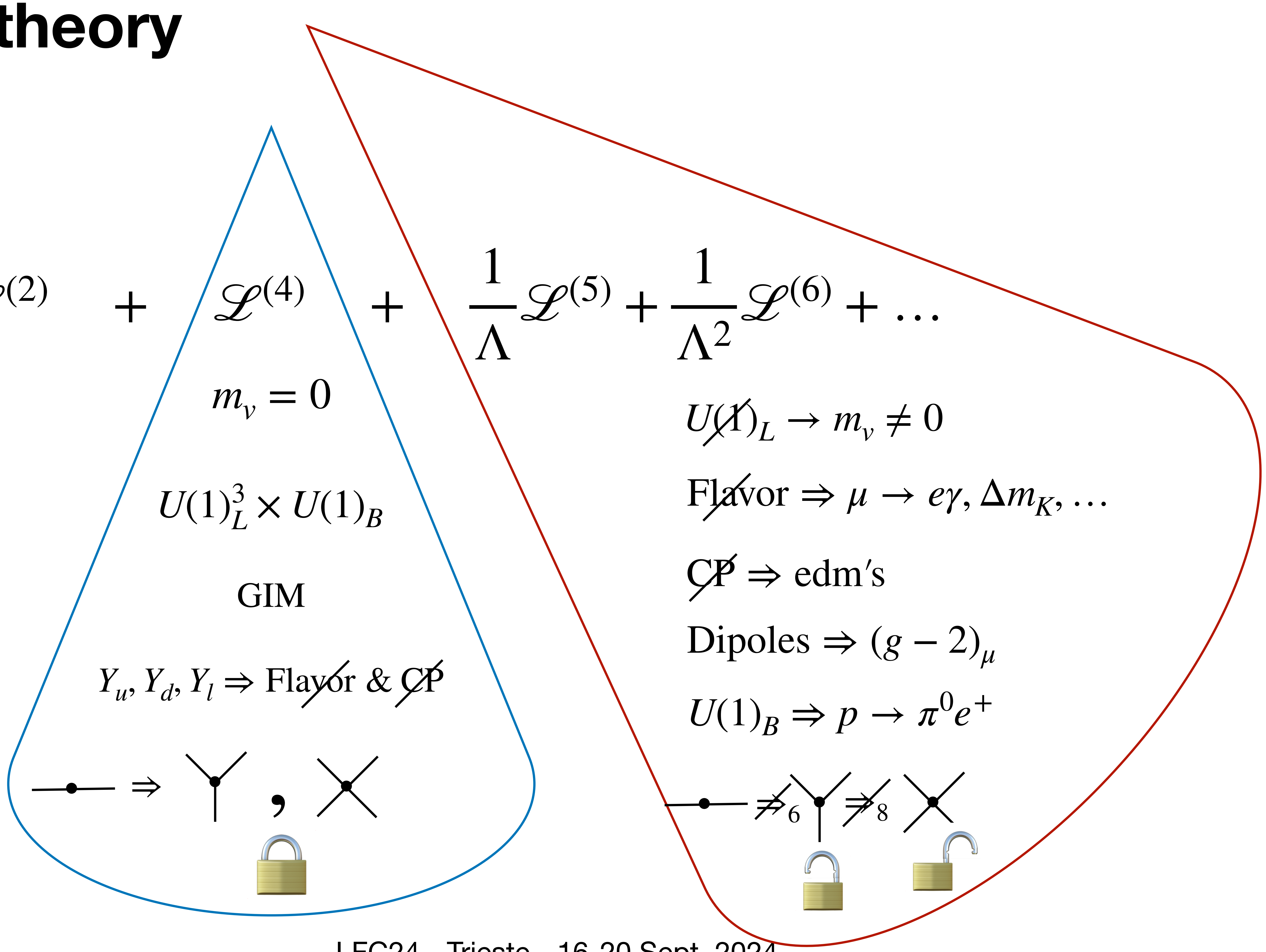
GIM

$Y_u, Y_d, Y_l \Rightarrow \text{Fla}\cancel{\text{vo}}\text{r} \;\&\; \cancel{\text{C}}\text{P}$

Rattazzi®

Λ_{BSM} is high

Effective field theory



$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_\nu = 0$

$U(1)^3_L \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}}$ & $\cancel{CP}$

$\Rightarrow$,

$U(\cancel{1})_L \rightarrow m_\nu \neq 0$

$\cancel{\text{Flavor}} \Rightarrow \mu \rightarrow e\gamma, \Delta m_K, \dots$

$\cancel{CP} \Rightarrow$ edm′s

Dipoles $\Rightarrow (g-2)_\mu$

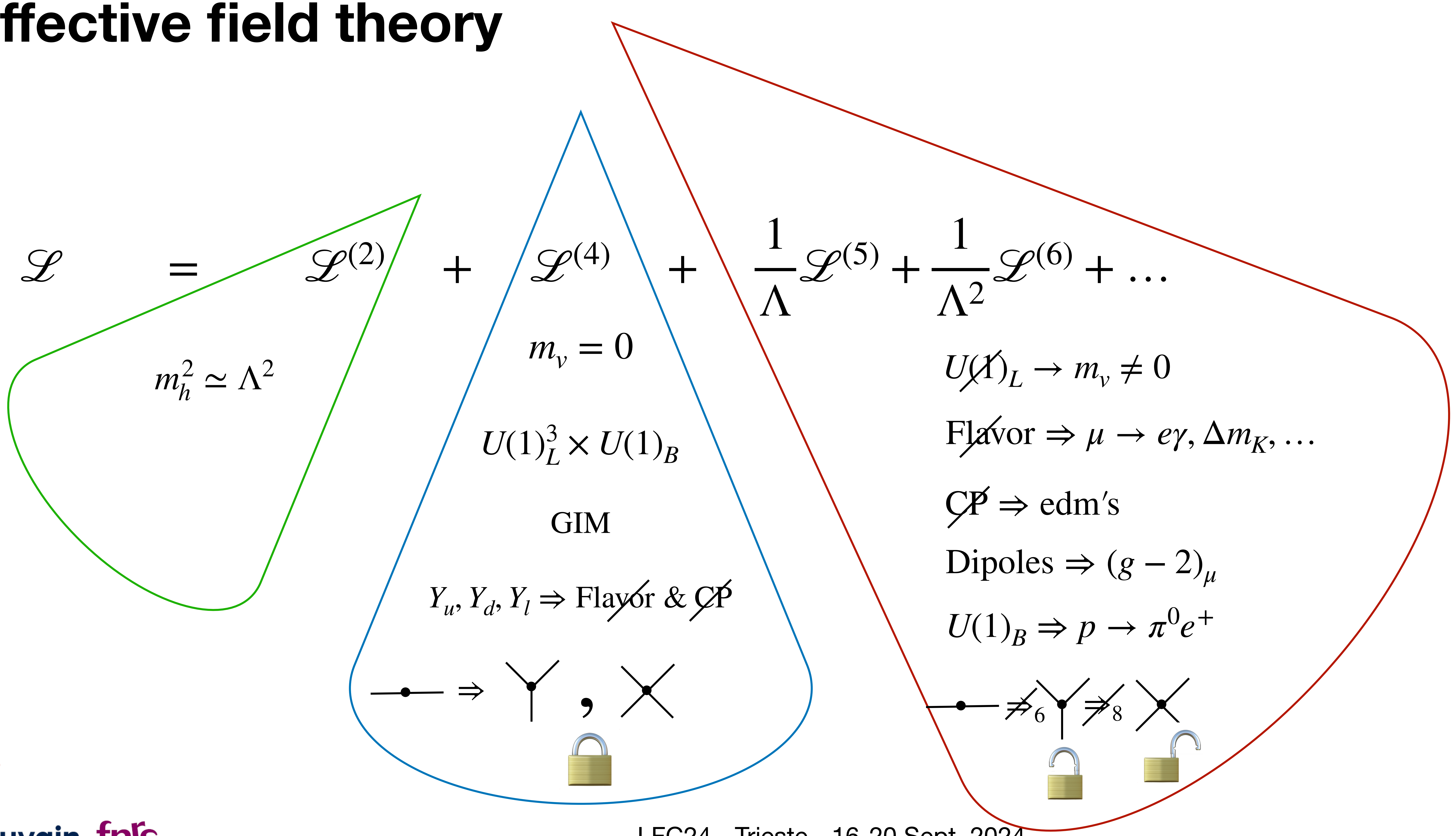
$U(1)_B \Rightarrow p \rightarrow \pi^0 e^+$

$\not\Rightarrow_6$ $\not\Rightarrow_8$

Rattazzi®

$\Lambda_{\rm BSM}$ is high

Effective field theory



$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ $\cancel{\text{Flavor}}$ & $\cancel{CP}$

$\Rightarrow$,

$\cancel{U(1)}_L \to m_\nu \neq 0$

$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \dots$

$\cancel{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

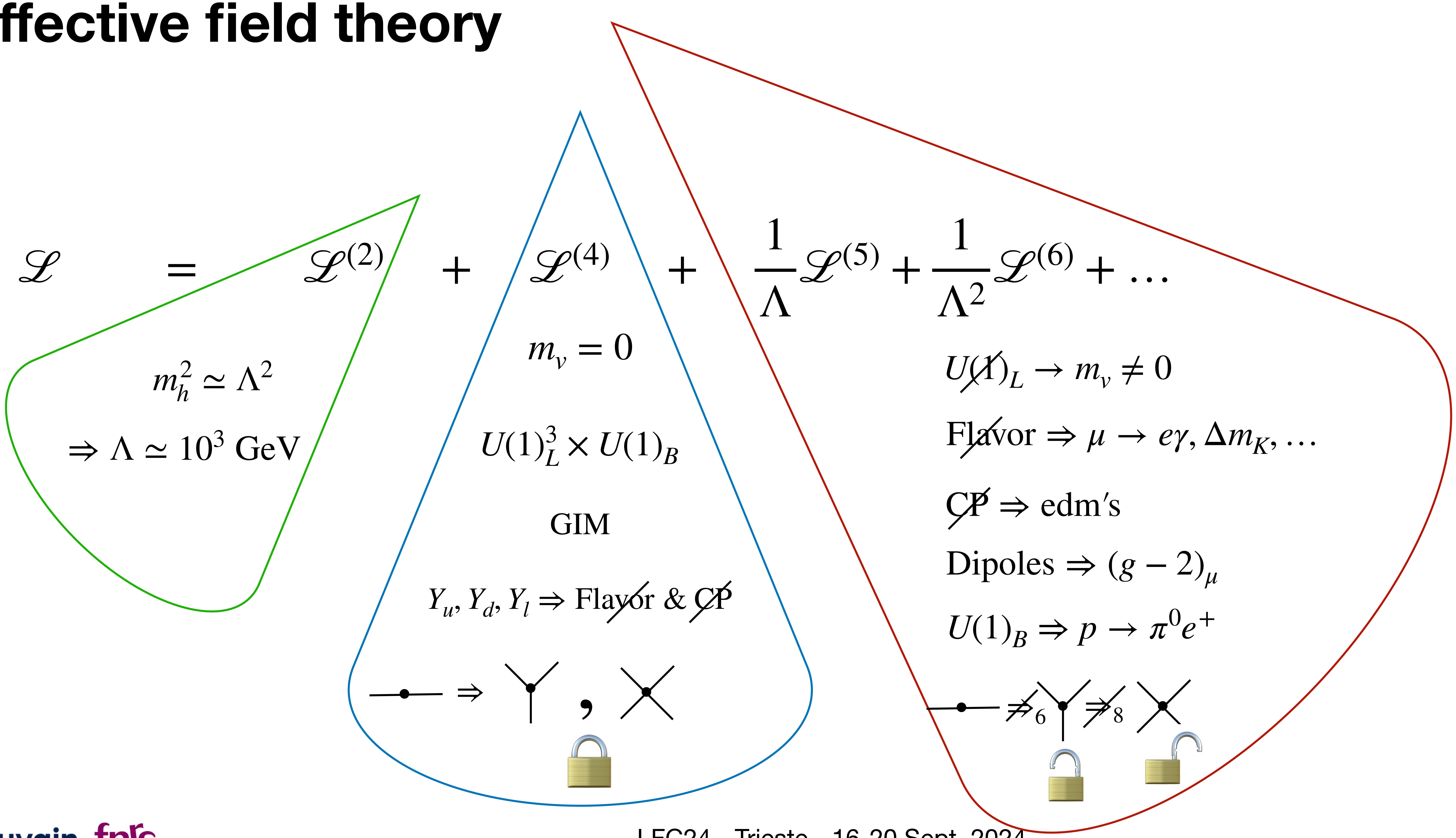
$U(1)_B \Rightarrow p \to \pi^0 e^+$

$\not\Rightarrow_6$ $\not\Rightarrow_8$

Rattazzi®

Λ_{BSM} is high

Effective field theory



$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow$ $\cancel{\text{Flavor}}$ & $\cancel{CP}$

$U(\cancel{1})_L \rightarrow m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

$\cancel{\text{Flavor}} \Rightarrow \mu \rightarrow e\gamma, \Delta m_K, \dots$ $\Rightarrow \Lambda \geq 10^6$ GeV

$\cancel{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

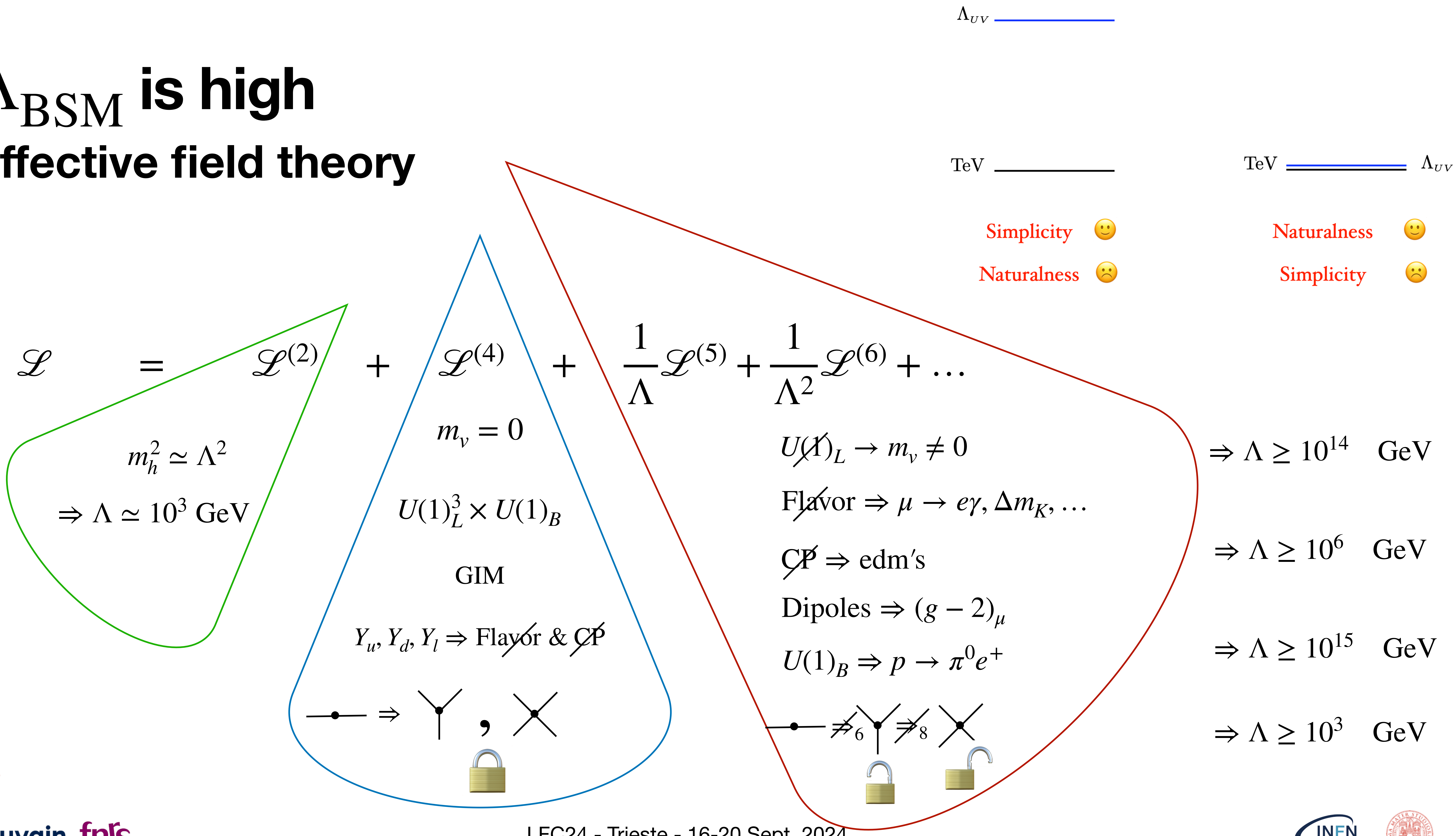
$U(1)_B \Rightarrow p \rightarrow \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

$\Rightarrow \Lambda \geq 10^3$ GeV

Rattazzi®

$\Lambda_{\rm BSM}$ is high

Effective field theory



Simplicity 🙂

Naturalness ☹️

Naturalness 🙂

Simplicity ☹️

$$\mathscr{L} = \mathscr{L}^{(2)} + \mathscr{L}^{(4)} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)} + \dots$$

$m_h^2 \simeq \Lambda^2$

$\Rightarrow \Lambda \simeq 10^3$ GeV

$m_\nu = 0$

$U(1)_L^3 \times U(1)_B$

GIM

$Y_u, Y_d, Y_l \Rightarrow \cancel{\text{Flavor}}\ \&\ \cancel{CP}$

$U(\cancel{1})_L \to m_\nu \neq 0$ $\Rightarrow \Lambda \geq 10^{14}$ GeV

$\cancel{\text{Flavor}} \Rightarrow \mu \to e\gamma, \Delta m_K, \dots$ $\Rightarrow \Lambda \geq 10^{6}$ GeV

$\cancel{CP} \Rightarrow$ edm's

Dipoles $\Rightarrow (g-2)_\mu$

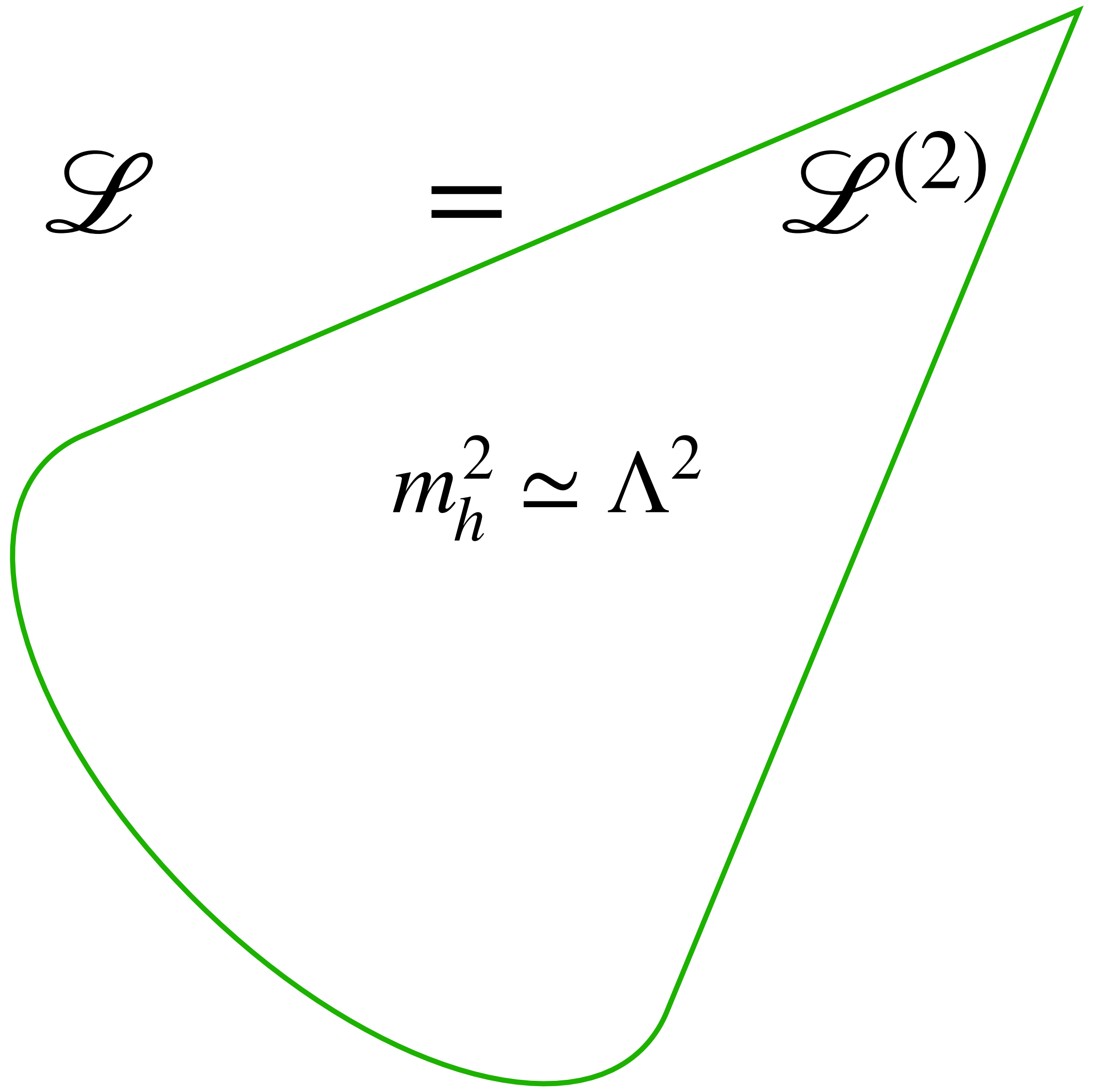
$U(1)_B \Rightarrow p \to \pi^0 e^+$ $\Rightarrow \Lambda \geq 10^{15}$ GeV

$\Rightarrow \Lambda \geq 10^{3}$ GeV

Rattazzi®

$\Lambda_{\rm BSM}$ is high

Effective field theory



$$\mathscr{L} = \mathscr{L}^{(2)}$$

$$m_h^2 \simeq \Lambda^2$$

Defining the amount of “tuning”

$$\varepsilon \equiv m_H^2/\Delta m_H^2$$

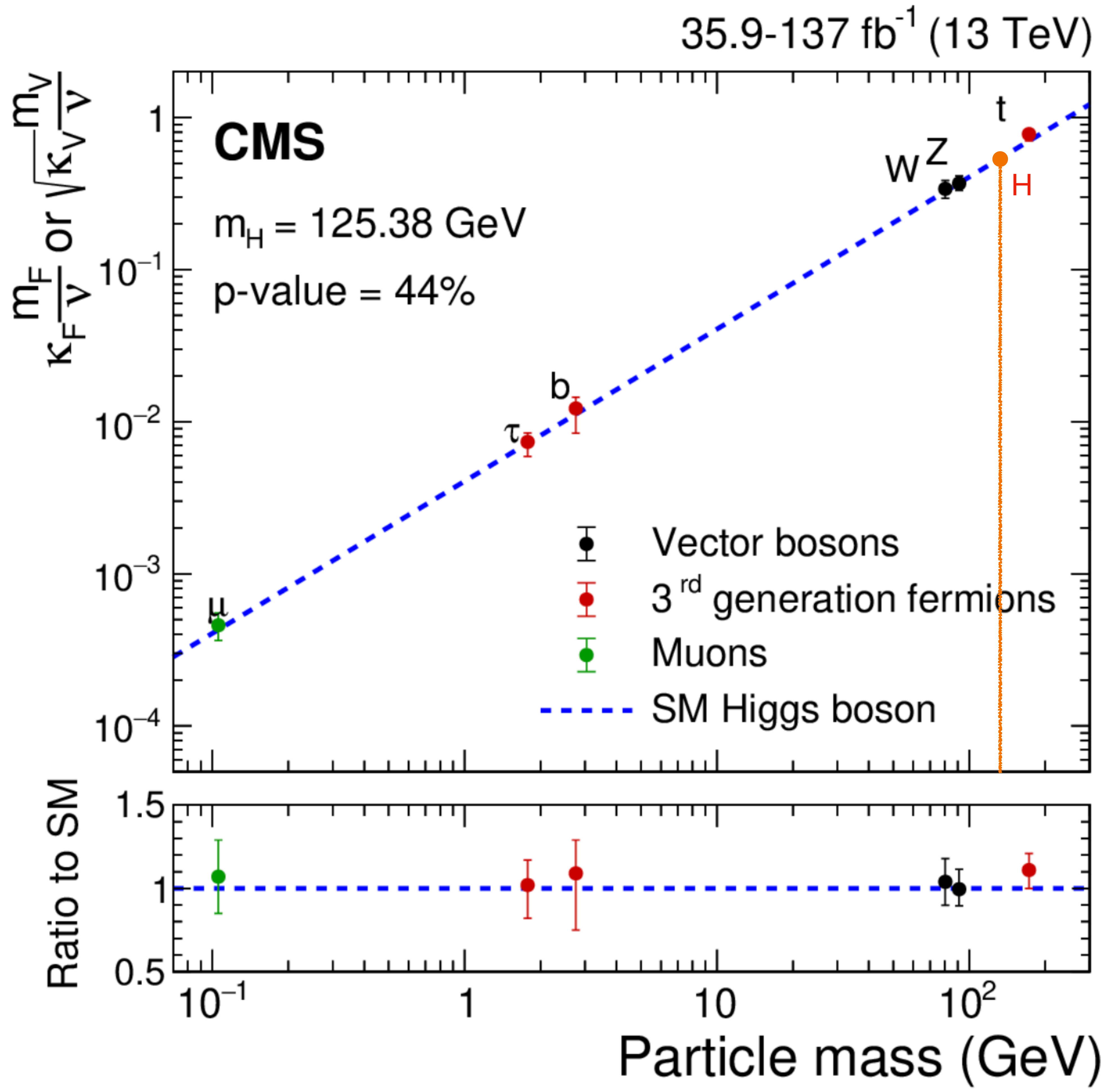
Consider the case of New Physics due to the presence of a top parter.
Different level of sensitivity can be realised:

- ***Soft:*** $\Delta m_H^2 \sim m_T^2$. This situation is realized in SUSY with soft terms generated at a high scale. In the absence of any tuning $m_T \sim m_H \sim 100\,\text{GeV}$, within the energy range of LEP and Tevatron.
- ***SuperSoft:*** $\Delta m_H^2 \sim (3y_t^2)/(4\pi^2)\, m_T^2$. This situation is realized in SUSY with low scale mediation and in CH. Without any tuning one expects $m_T \sim m_H/\sqrt{3y_t^2/4\pi^2} \sim 450\,\text{GeV}$, within the reach of the LHC.
- ***HyperSoft:*** $\Delta m_H^2 \sim (3\lambda_h)/(16\pi^2)\, m_T^2$. The mechanism of Neutral Naturalness is a prime example. The top partner mass is naturally pushed around 1.5 TeV.

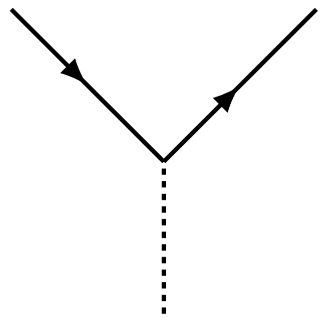
Rattazzi®GGI tea break

Present

Higgs couplings

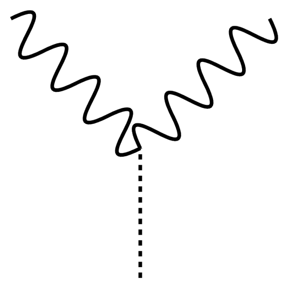


Unique mass generation mechanism for fermions/vectors and the scalar.

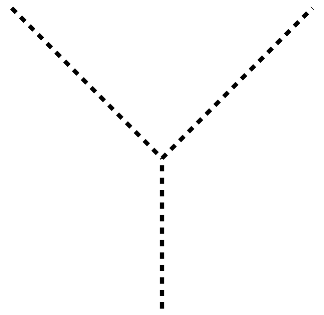


$$i\, m_f/v$$

$$igm_W g_{\mu\nu} = 2i\, v g_{\mu\nu} \cdot m_W^2/v^2$$



$$ig\frac{m_Z}{\cos\theta_W}g_{\mu\nu} = 2ivg_{\mu\nu} \cdot m_Z^2/v^2$$



$$-3\, iv \cdot m_h^2/v^2$$

+ 4 point interactions.

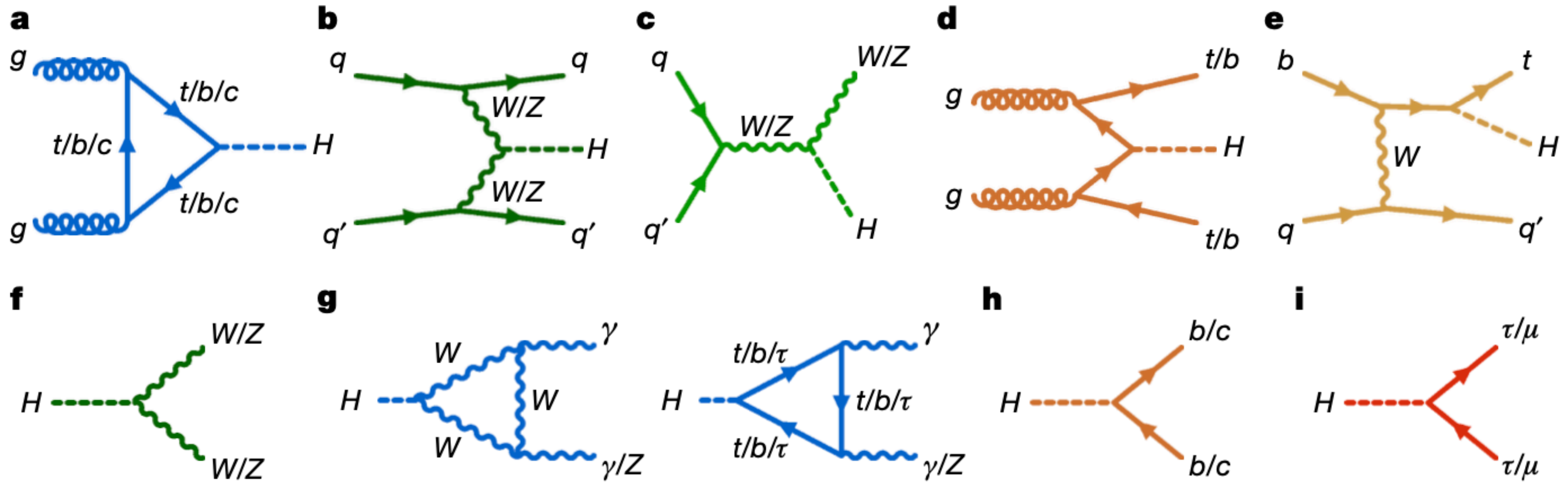
$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4 + \dots$$

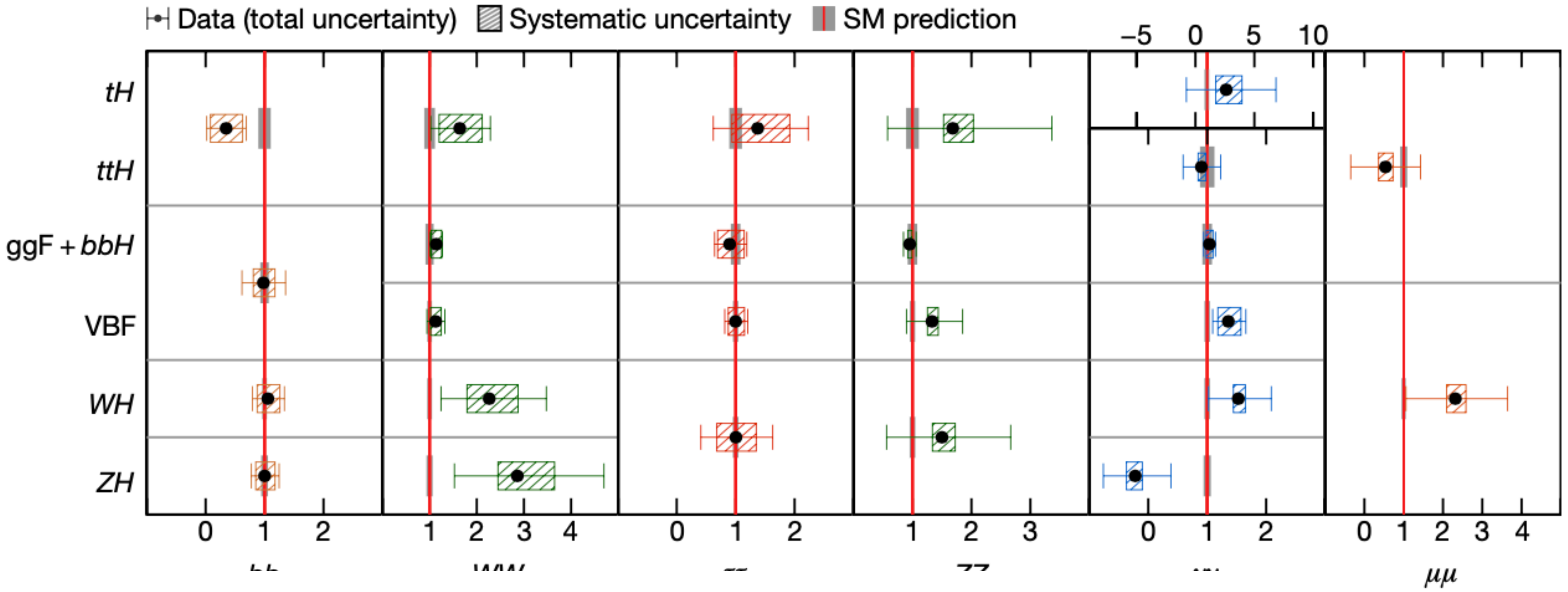
$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\rm SM} = \lambda \\ \lambda_4^{\rm SM} = \lambda \end{cases}$$

In the SM gauge invariance + SSB => constrained system. Two-point functions (propagators/masses) fix the 3-point and 4-point interactions!

Present

Higgs couplings





$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \ \pm 0.03\,(\text{exp.}) \ \pm 0.04\,(\text{sig. th.}) \ \pm 0.02\,(\text{bkg. th.}).$$

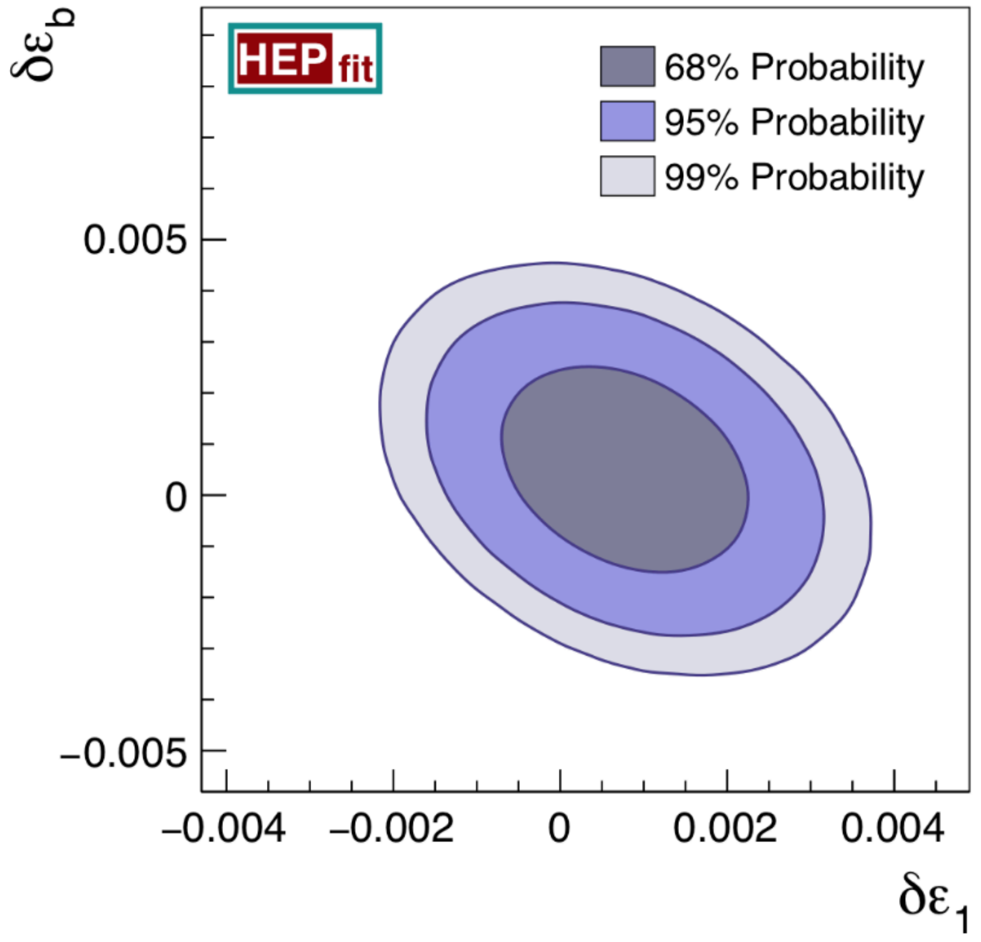
The deviations δg_H from the SM in single and multi-Higgs couplings satisfy

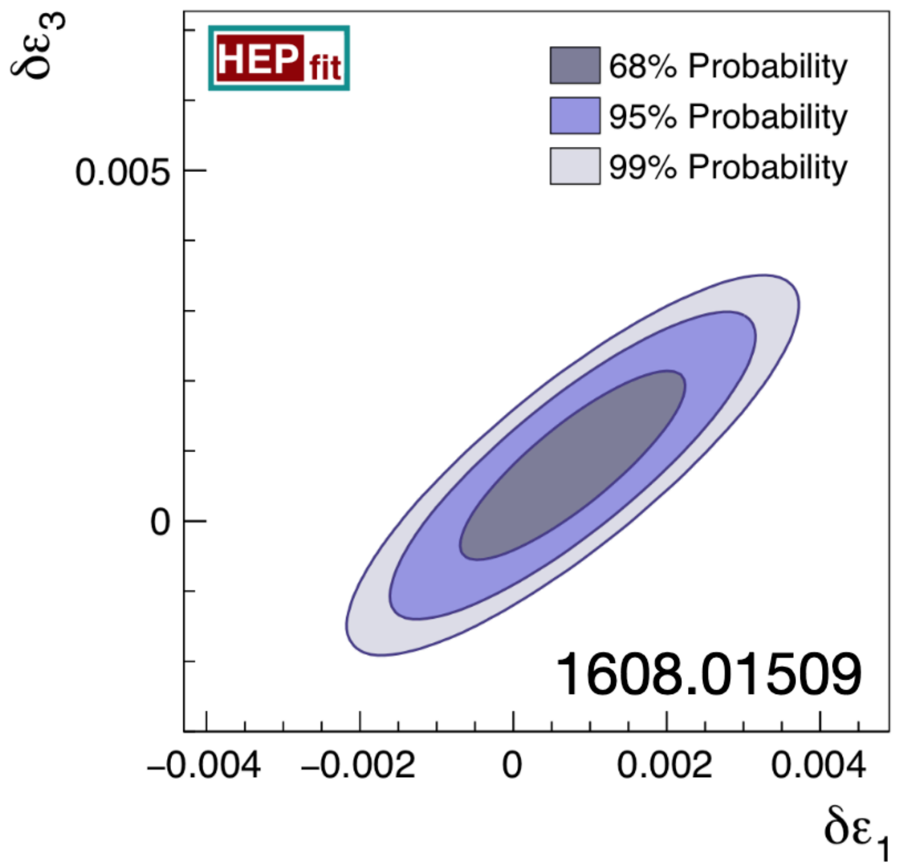
$$\delta g_H / g_H{}^{\text{SM}} \sim c\,\varepsilon$$

with *c* a coupling-dependent coefficient, and ε the Higgs mass correction. In basically all models, there always exists a set of couplings where *c* ~ *O*(1). The only exception is strictly supersoft SUSY, where one can cleverly go down to *c* ~ 0.1. Not surprisingly full Naturalness basically mandates *O*(1) deviations in Higgs couplings.

Present

EW precision





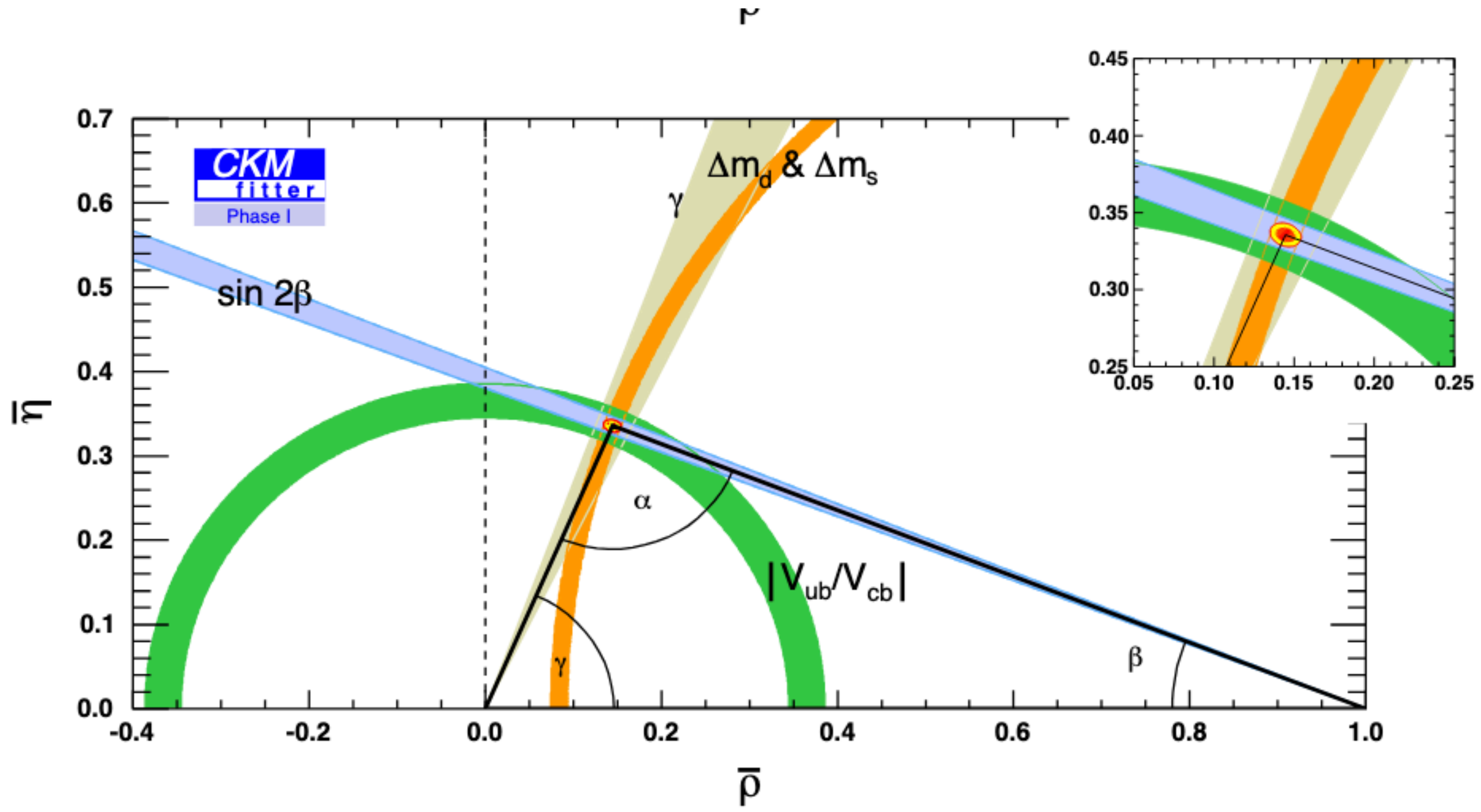
While Higgs couplings probe naturalness, EWPO sense the dynamics off EWSB indirectly via loops. Consider the S parameter,

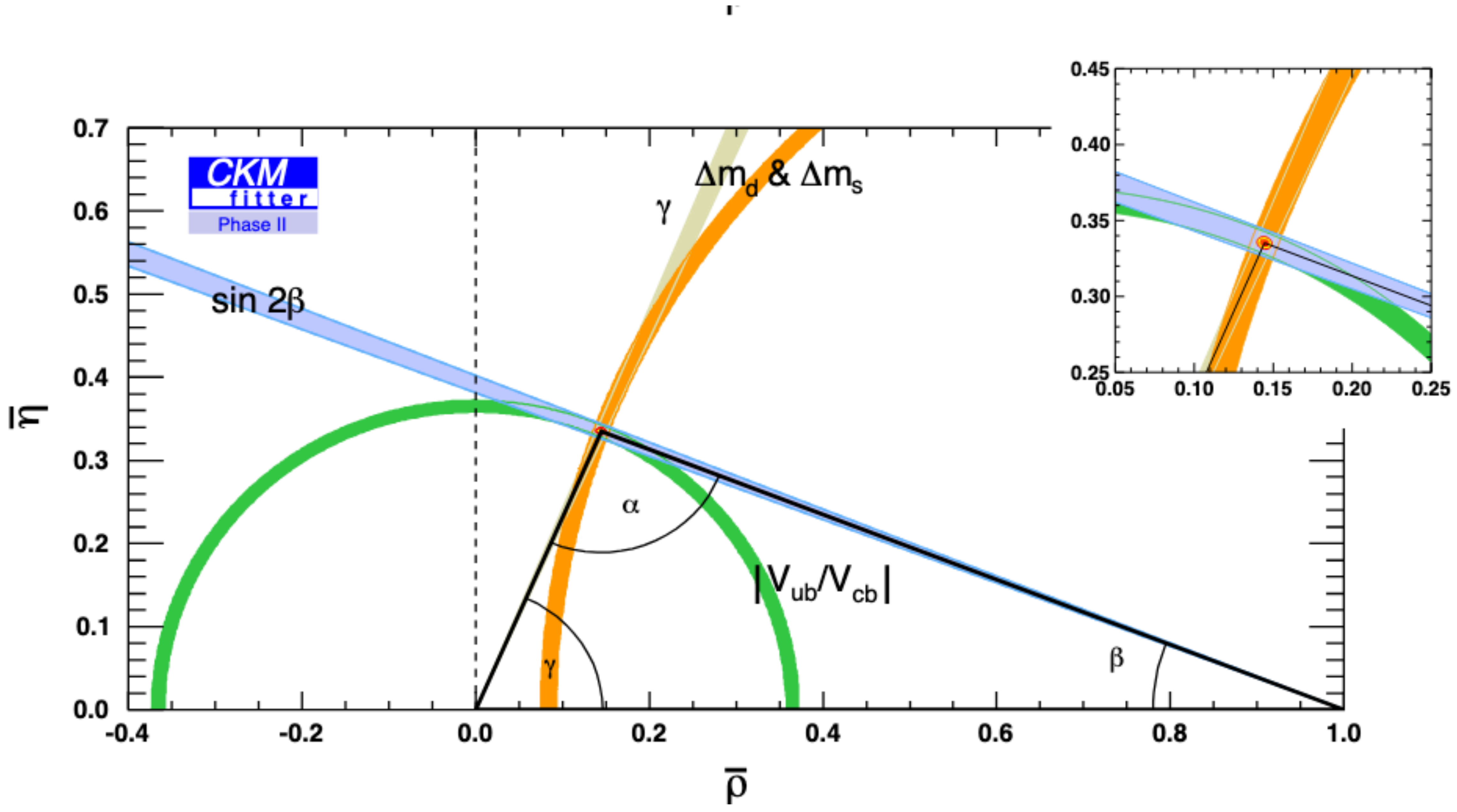
$$\widehat{S} \sim \frac{\alpha_W}{4\pi}\frac{g_*^2 v^2}{m_*^2} N \lesssim \frac{m_W^2}{m_*^2}$$

For CH one obtains $3 \cdot 10^{-2}\epsilon$,indicating a sensitivity of order 10^{-5} corresponds to 10^{-3} in the Higgs couplings. SUSY does not saturate the bound.

Present and near future

Flavor





(upgrade 2)

- O(10^{14}) b and c hadrons
- O(10^{11}) τ leptons

- O(10^{10}) B mesons
- O(10^{10}) τ's

in clean environment

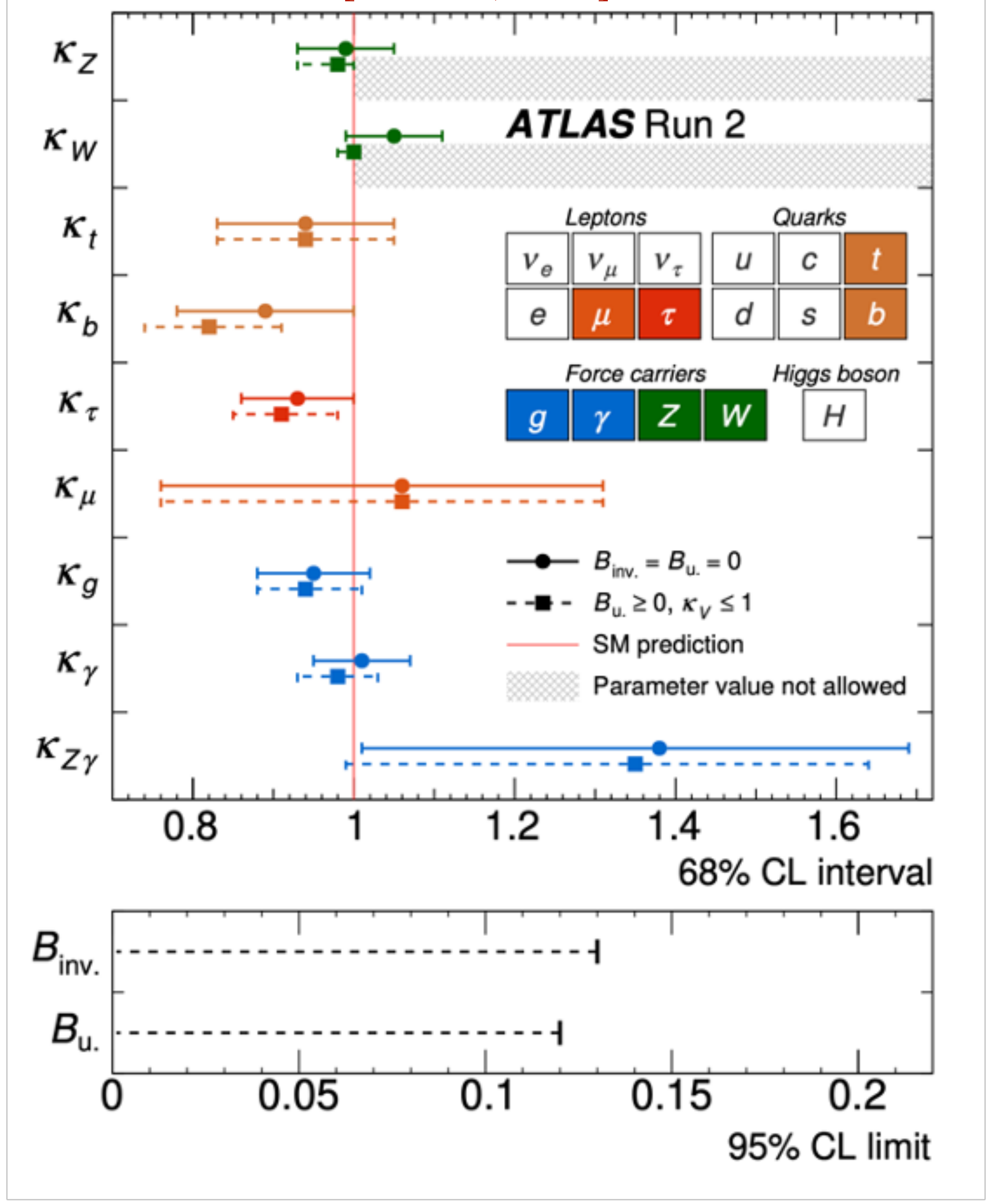
The Higgs near future

Couplings at HL-LHC

The Higgs near future

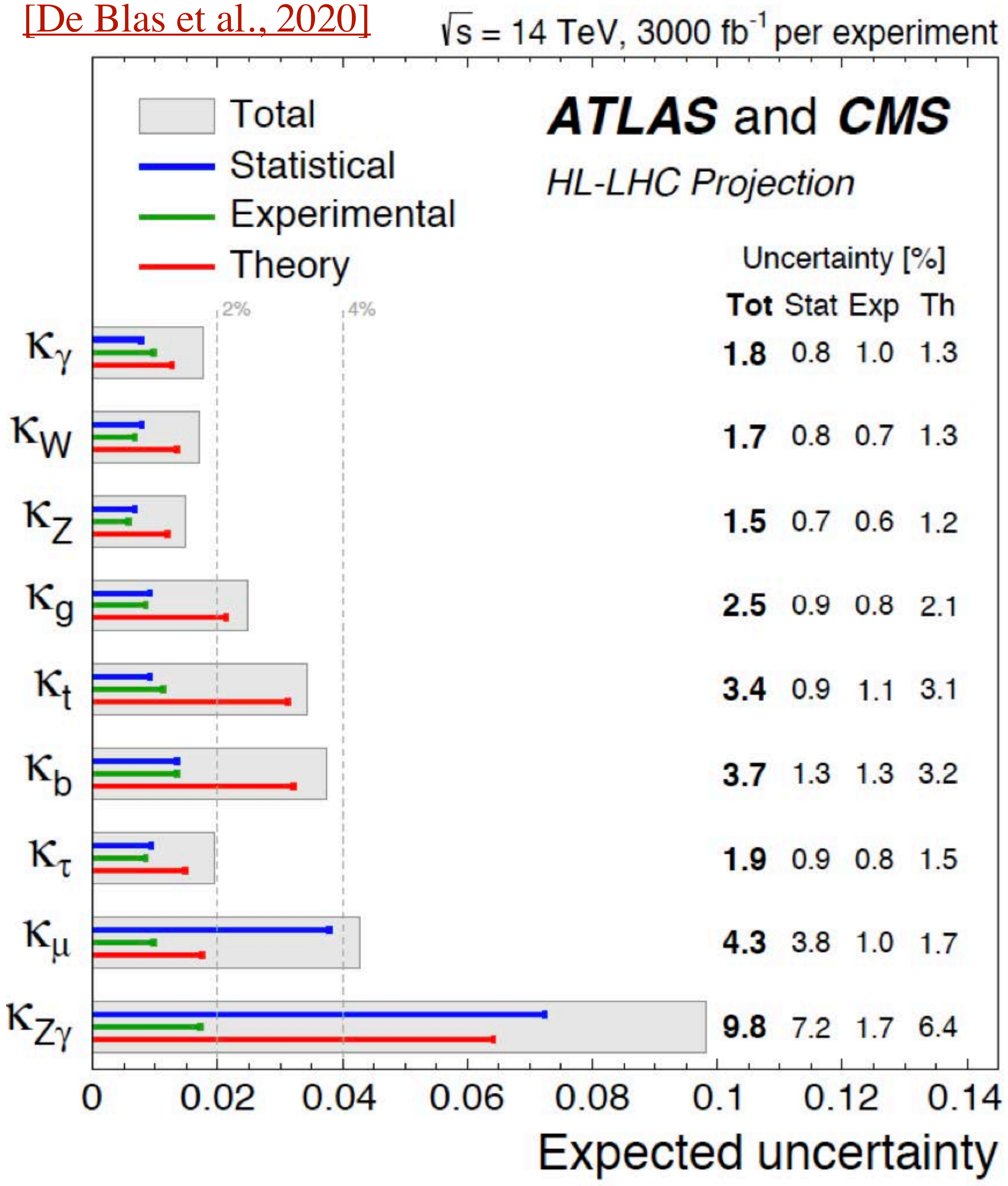
Couplings at HL-LHC

[ATLAS, 2024]



10-20% → 2-4%

[De Blas et al., 2020]

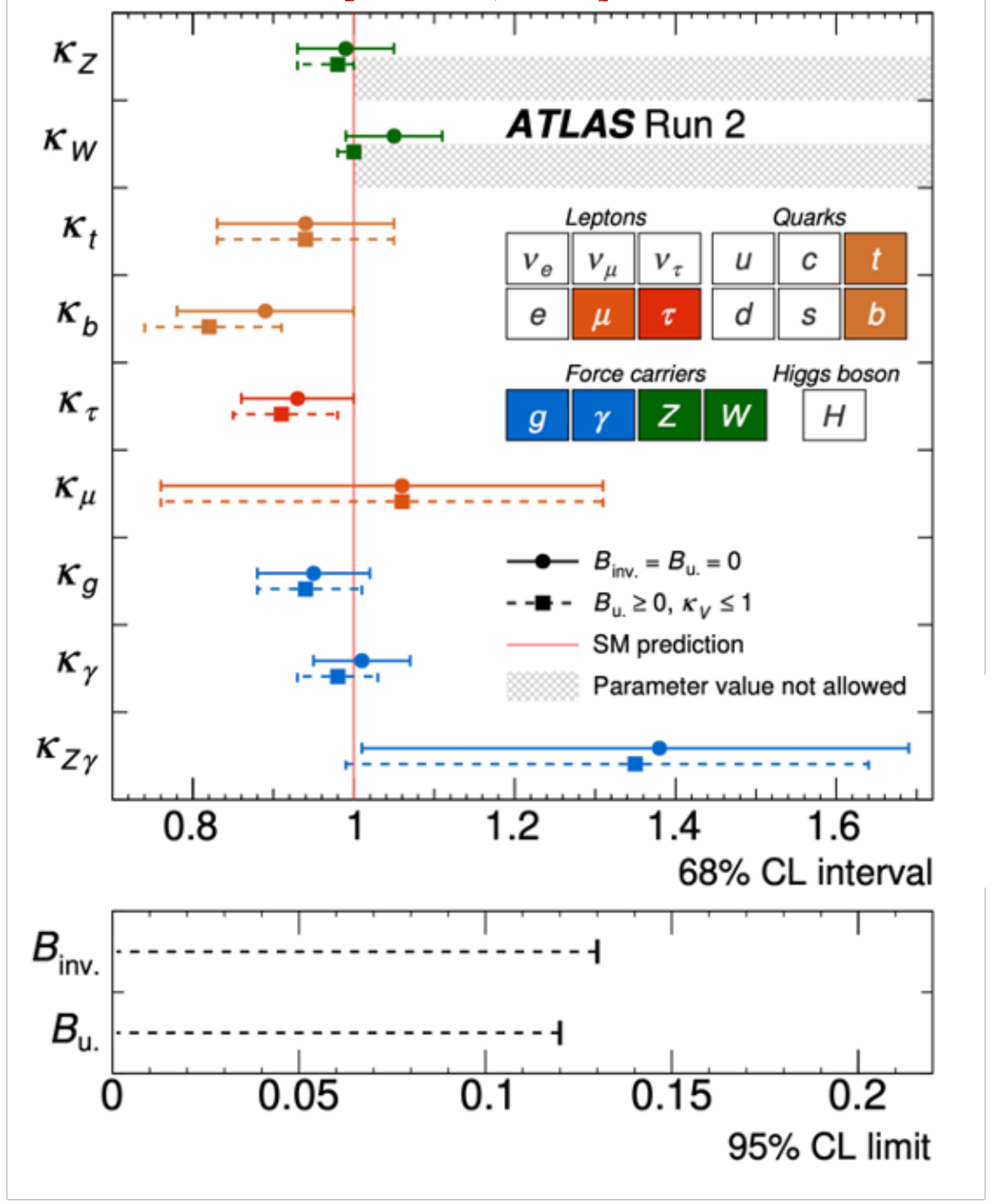


$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2 \cdot \Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad \to \quad \mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

The Higgs near future

Couplings at HL-LHC

[ATLAS, 2024]

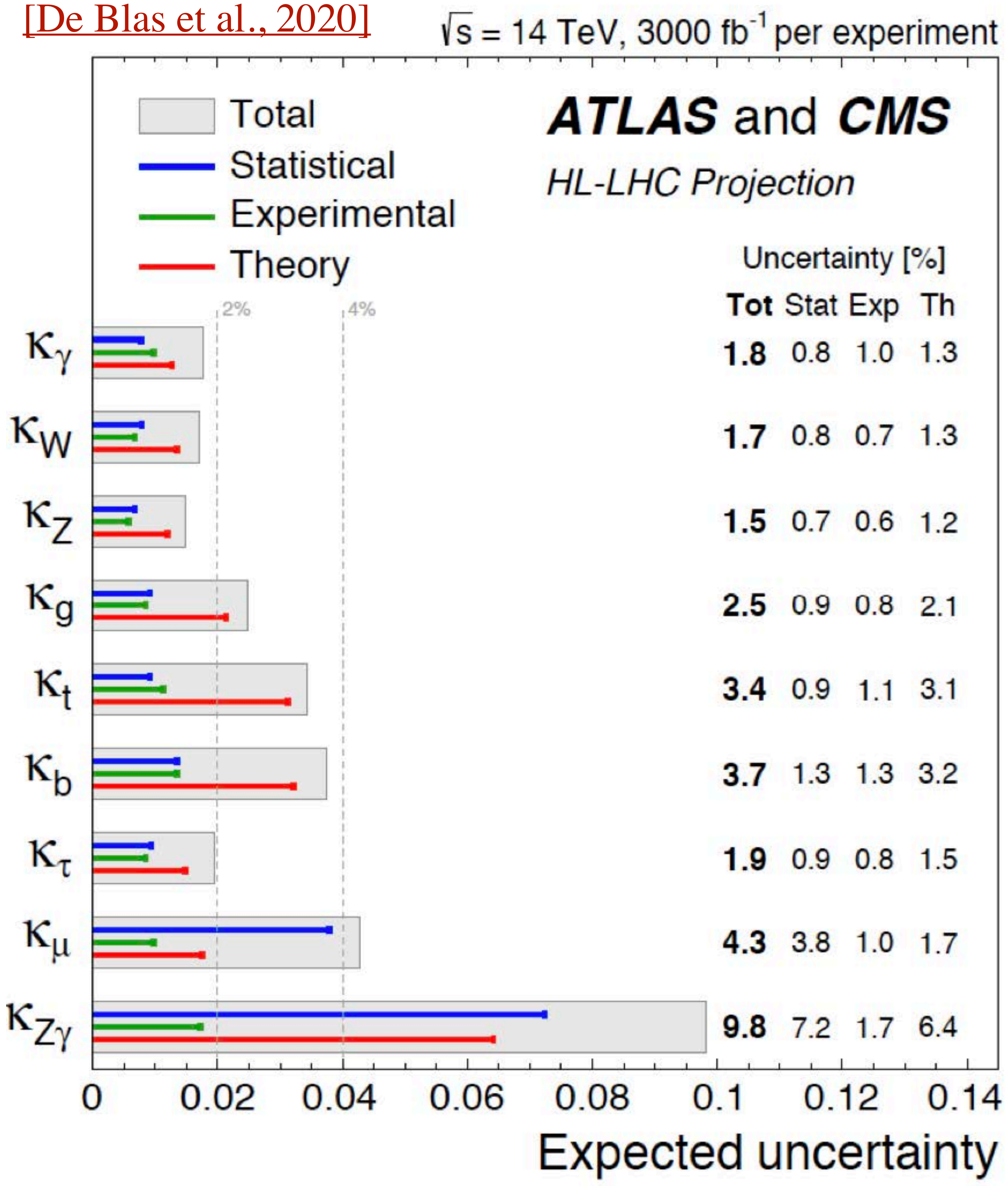


10-20% → 2-4%

$$\delta g_H / g_H{}^{\mathrm{SM}} \sim c\,\varepsilon$$

$$(\sigma\cdot\mathrm{BR})(i\to \mathrm{H} \to f) = \frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad\to\quad \mu_i^f \equiv \frac{\sigma\cdot\mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot\mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

[De Blas et al., 2020]



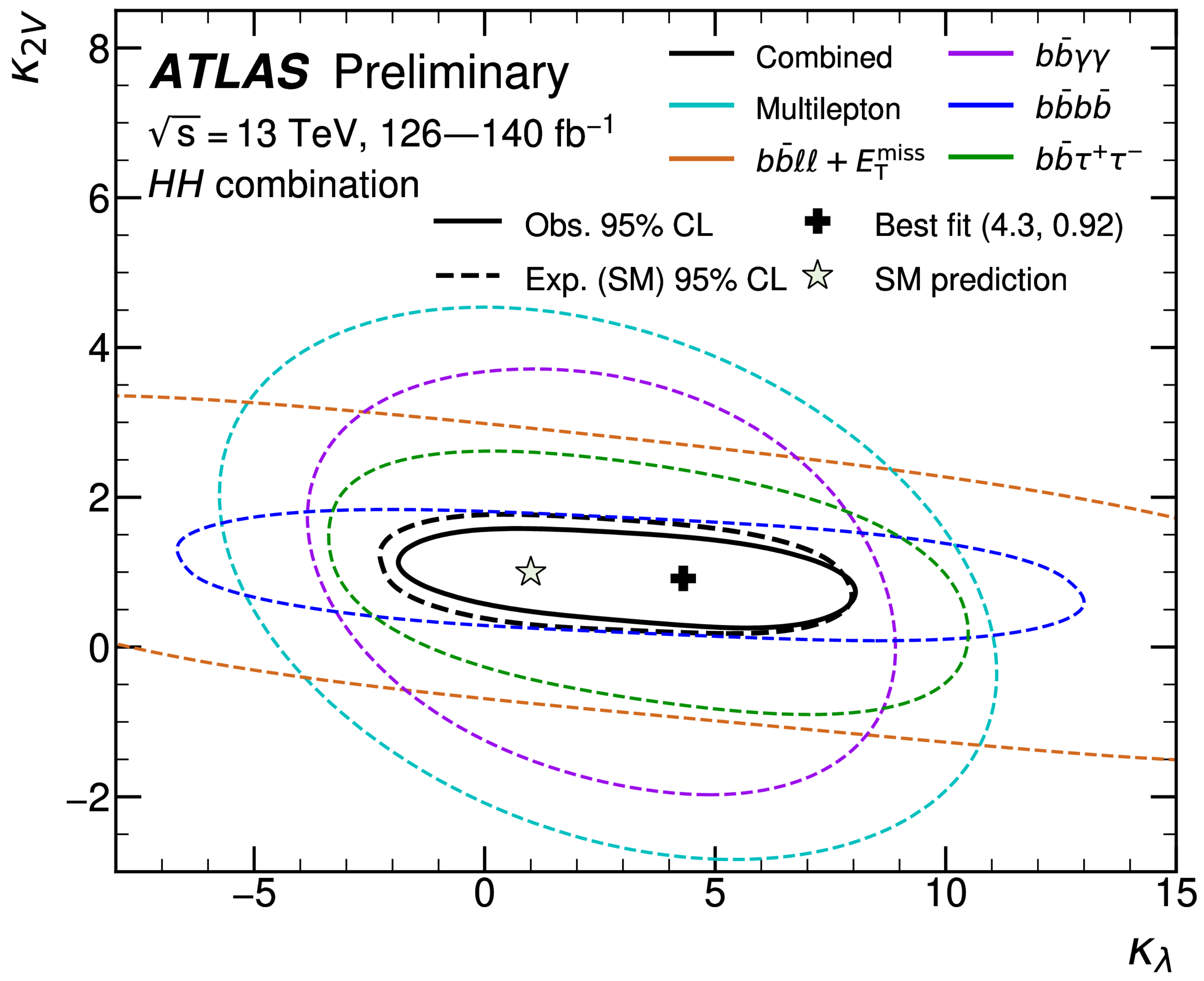
	Tot	Stat	Exp	Th
κ_γ	**1.8**	0.8	1.0	1.3
κ_W	**1.7**	0.8	0.7	1.3
κ_Z	**1.5**	0.7	0.6	1.2
κ_g	**2.5**	0.9	0.8	2.1
κ_t	**3.4**	0.9	1.1	3.1
κ_b	**3.7**	1.3	1.3	3.2
κ_τ	**1.9**	0.9	0.8	1.5
κ_μ	**4.3**	3.8	1.0	1.7
$\kappa_{Z\gamma}$	**9.8**	7.2	1.7	6.4

The Higgs near future

Higgs self-coupling

Now

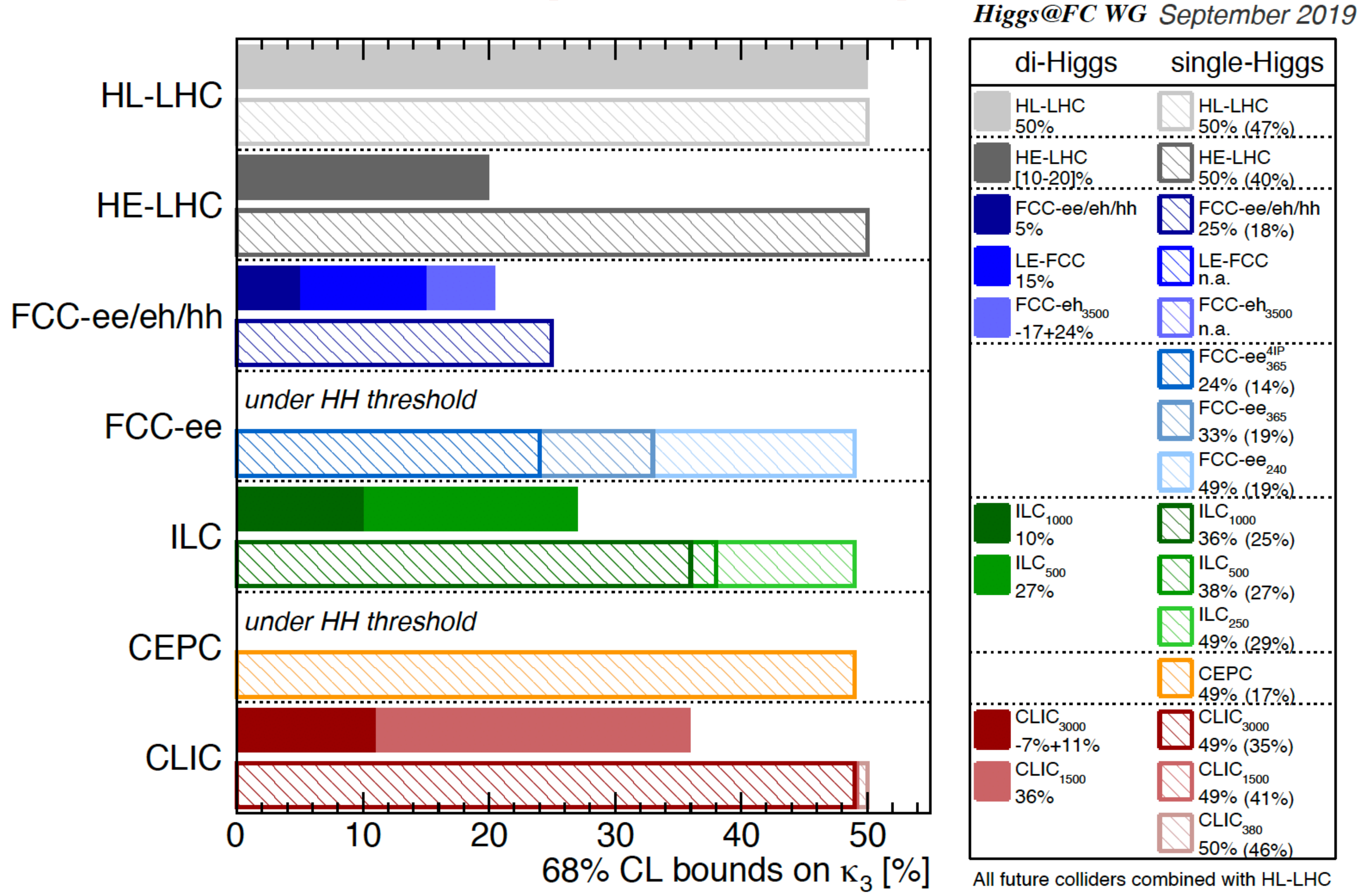
[ATLAS, 2024]



Current limits on k_λ and k_{2V}

Future

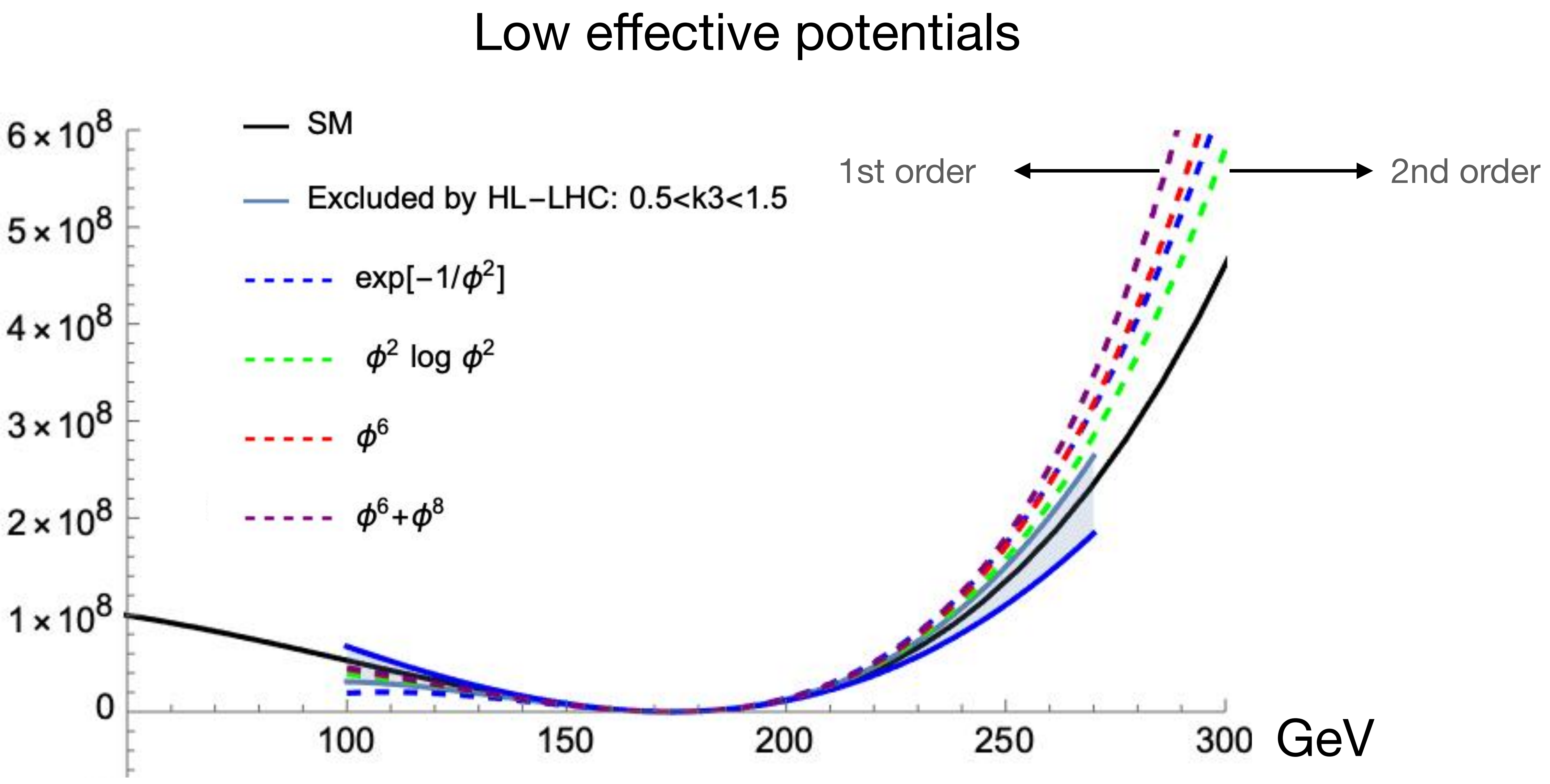
[De Blas et al., 2020]



Future limits on k_λ

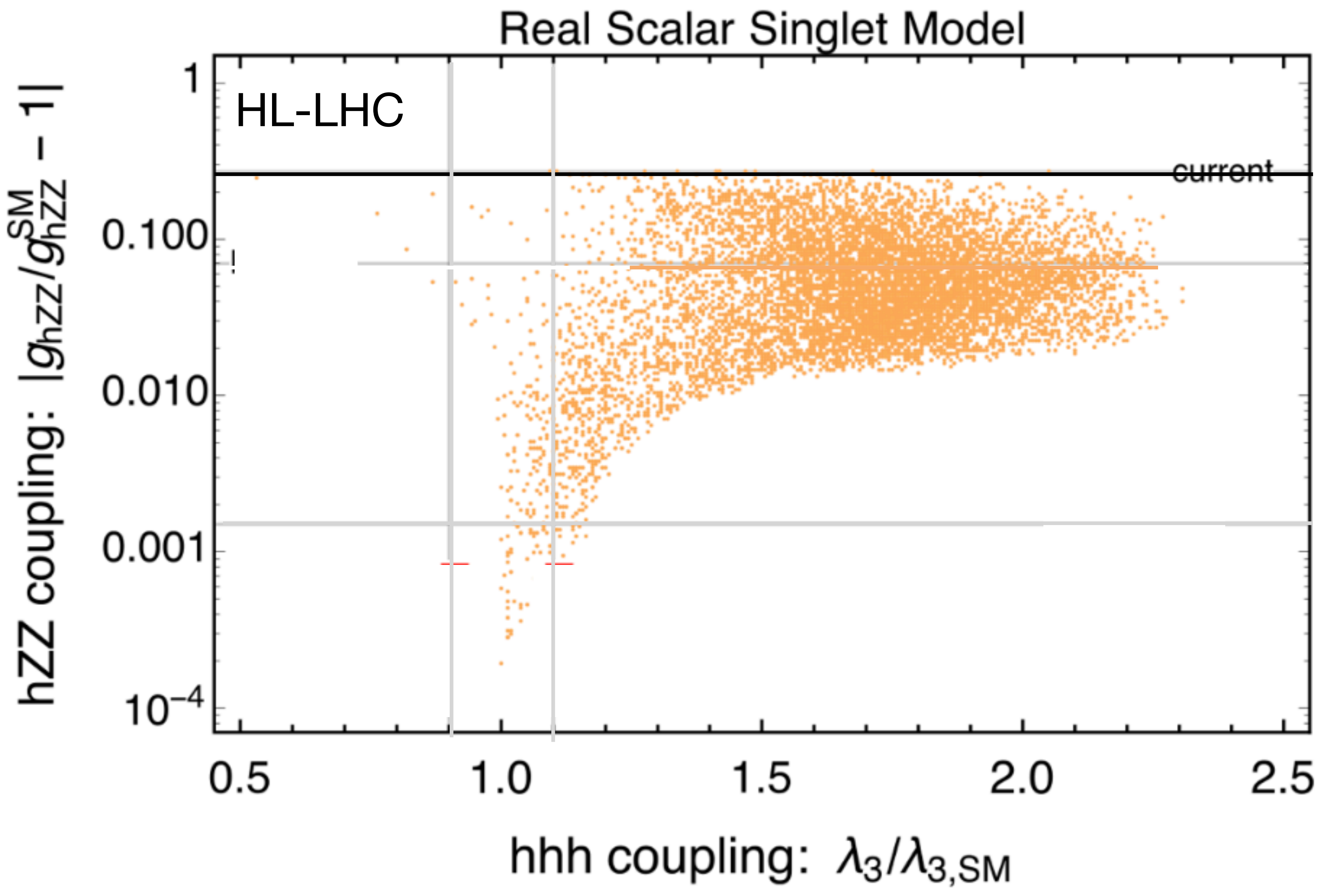
The Higgs near future

Higgs potential



Plot based on the results of 1711.00019 [hep-ph]

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

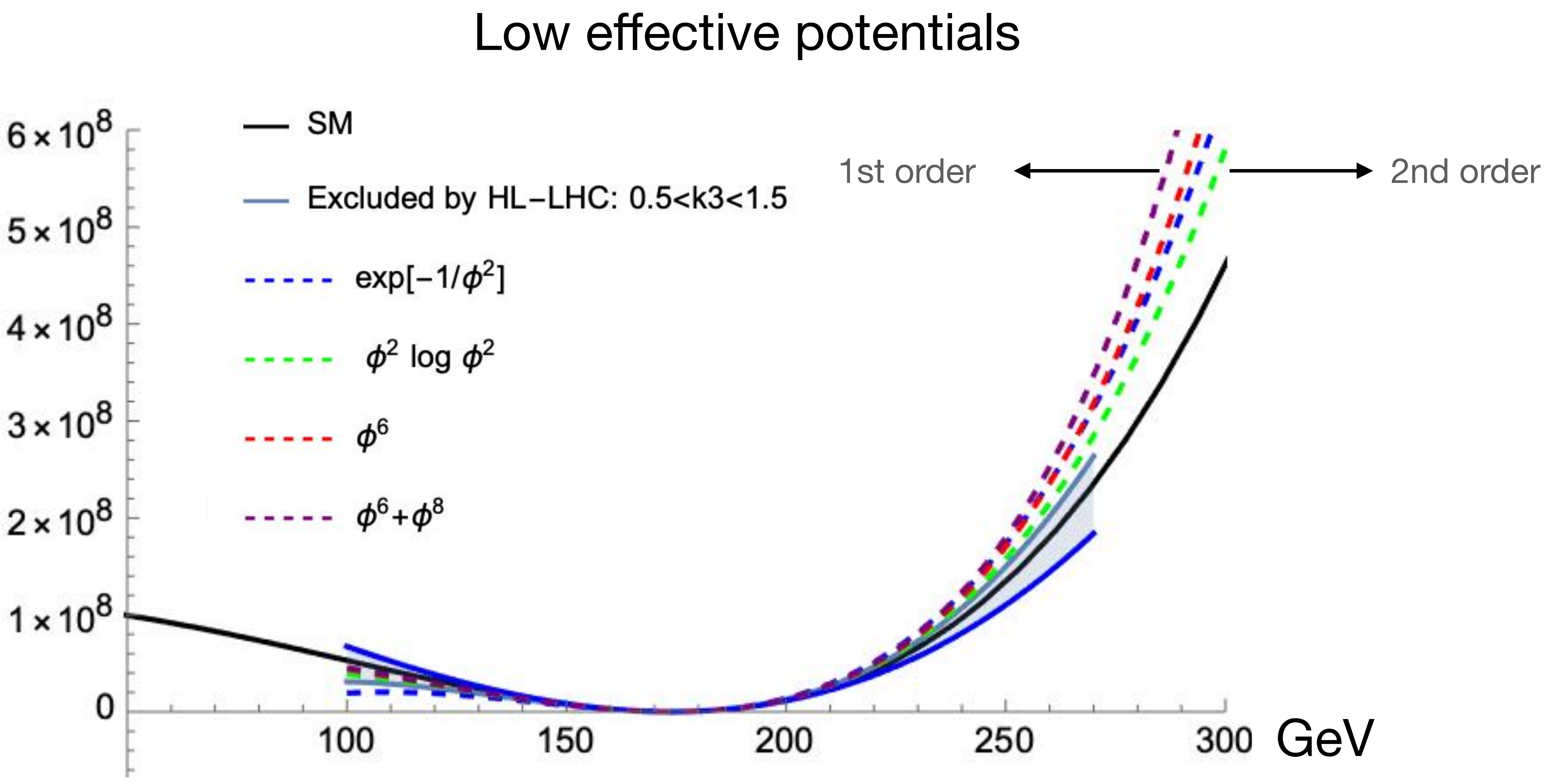


FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

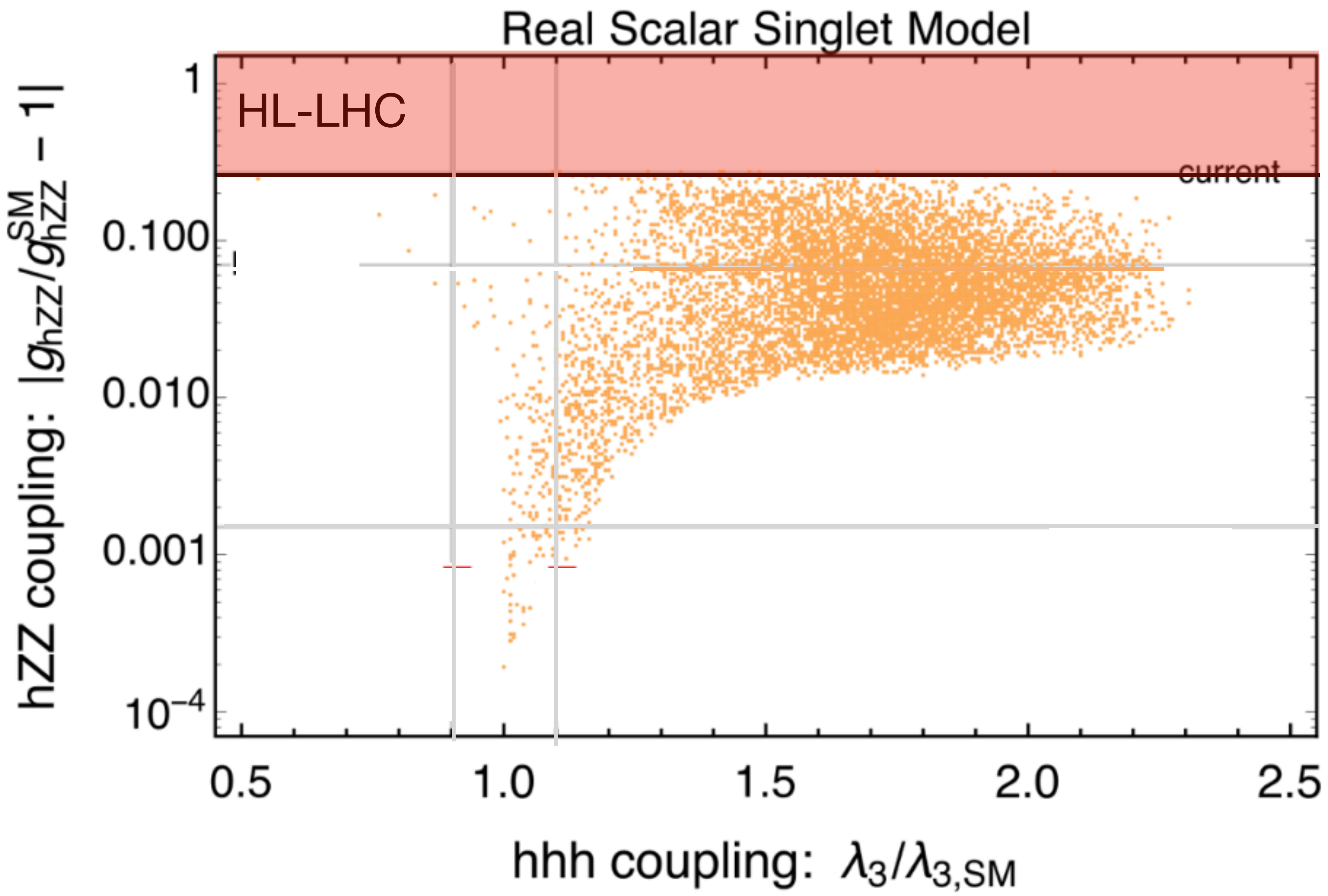
HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

The Higgs near future

Higgs potential



Plot based on the results of 1711.00019 [hep-ph]



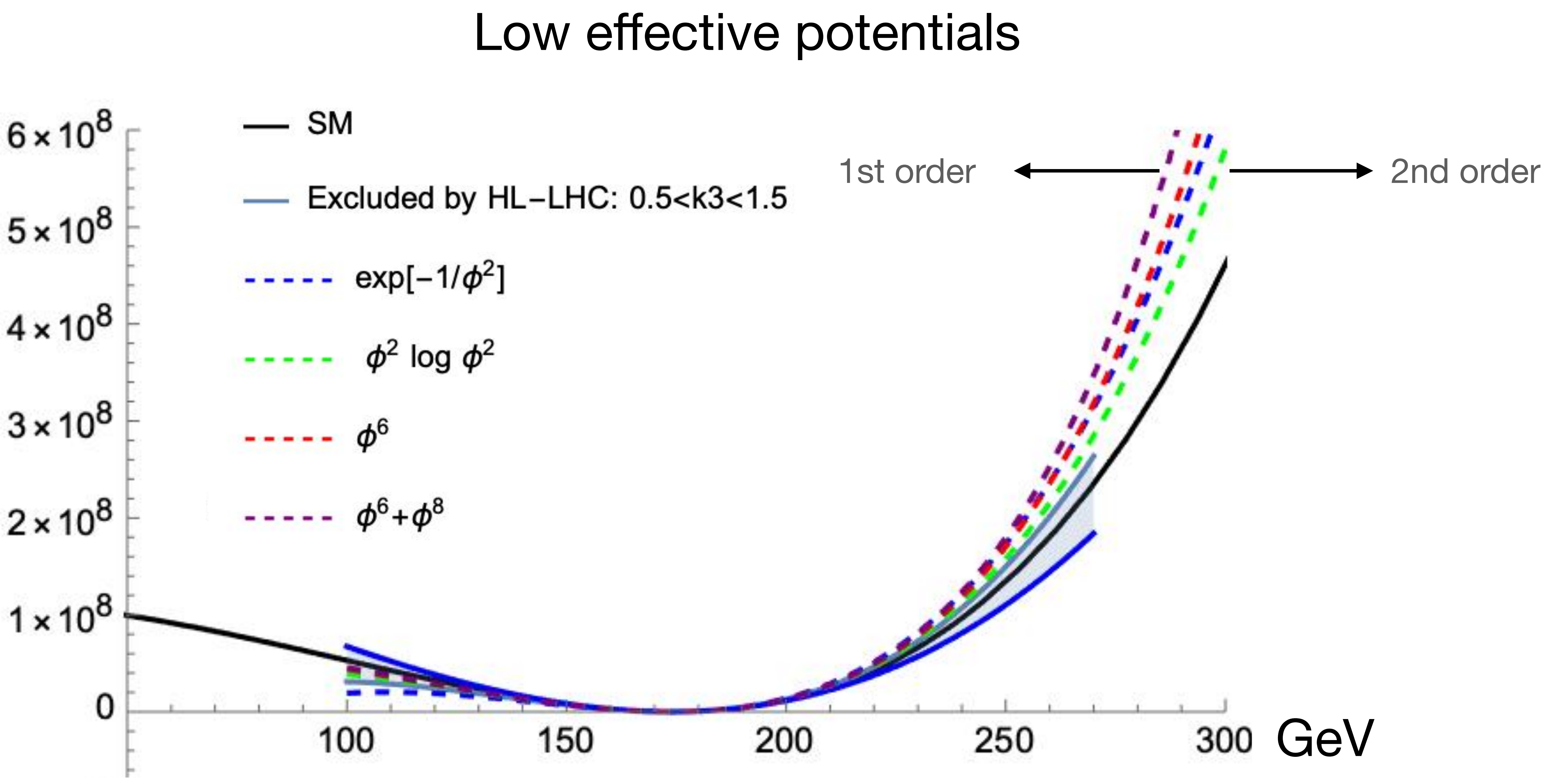
FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

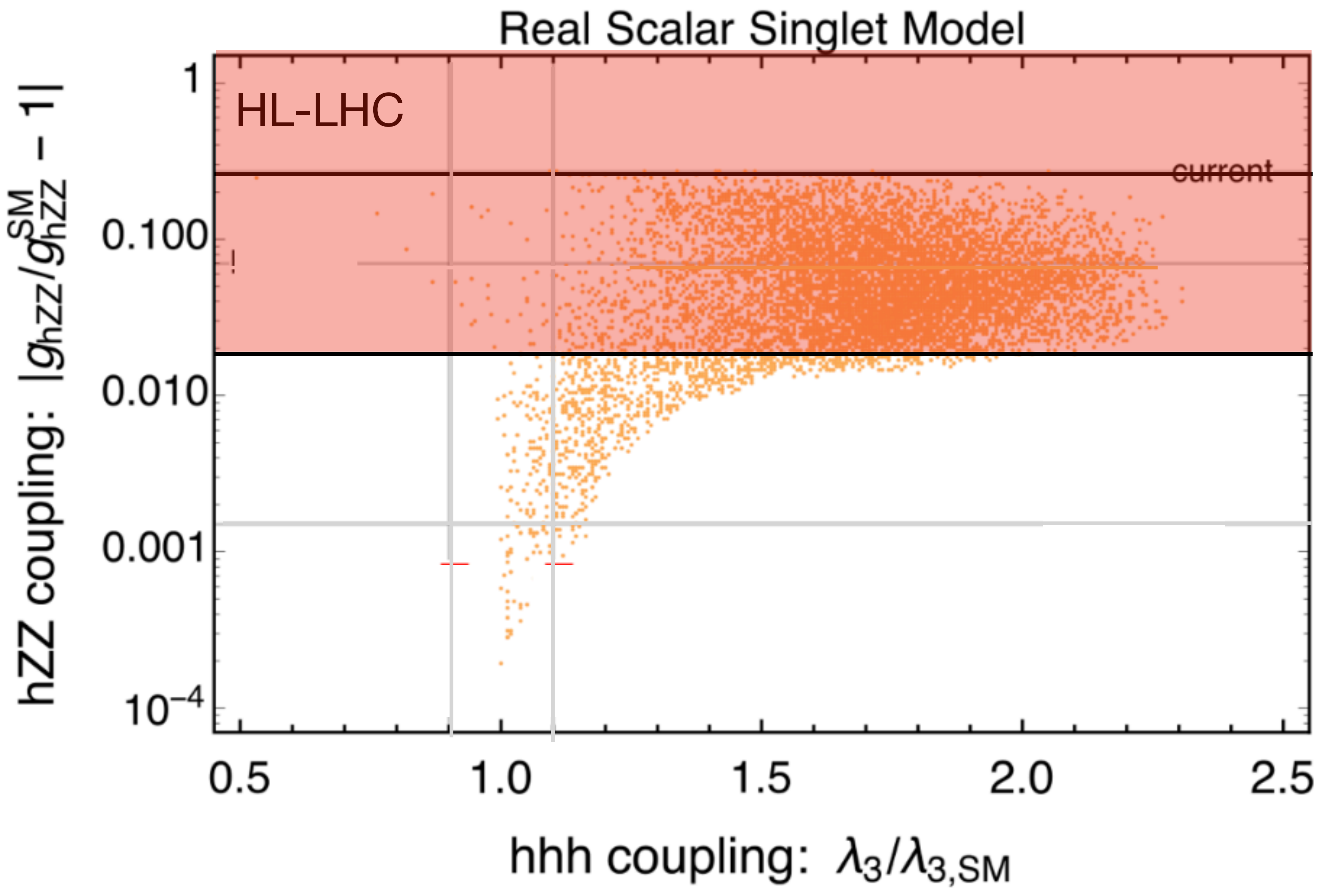
The Higgs near future

Higgs potential



Plot based on the results of [1711.00019 [hep-ph]]

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

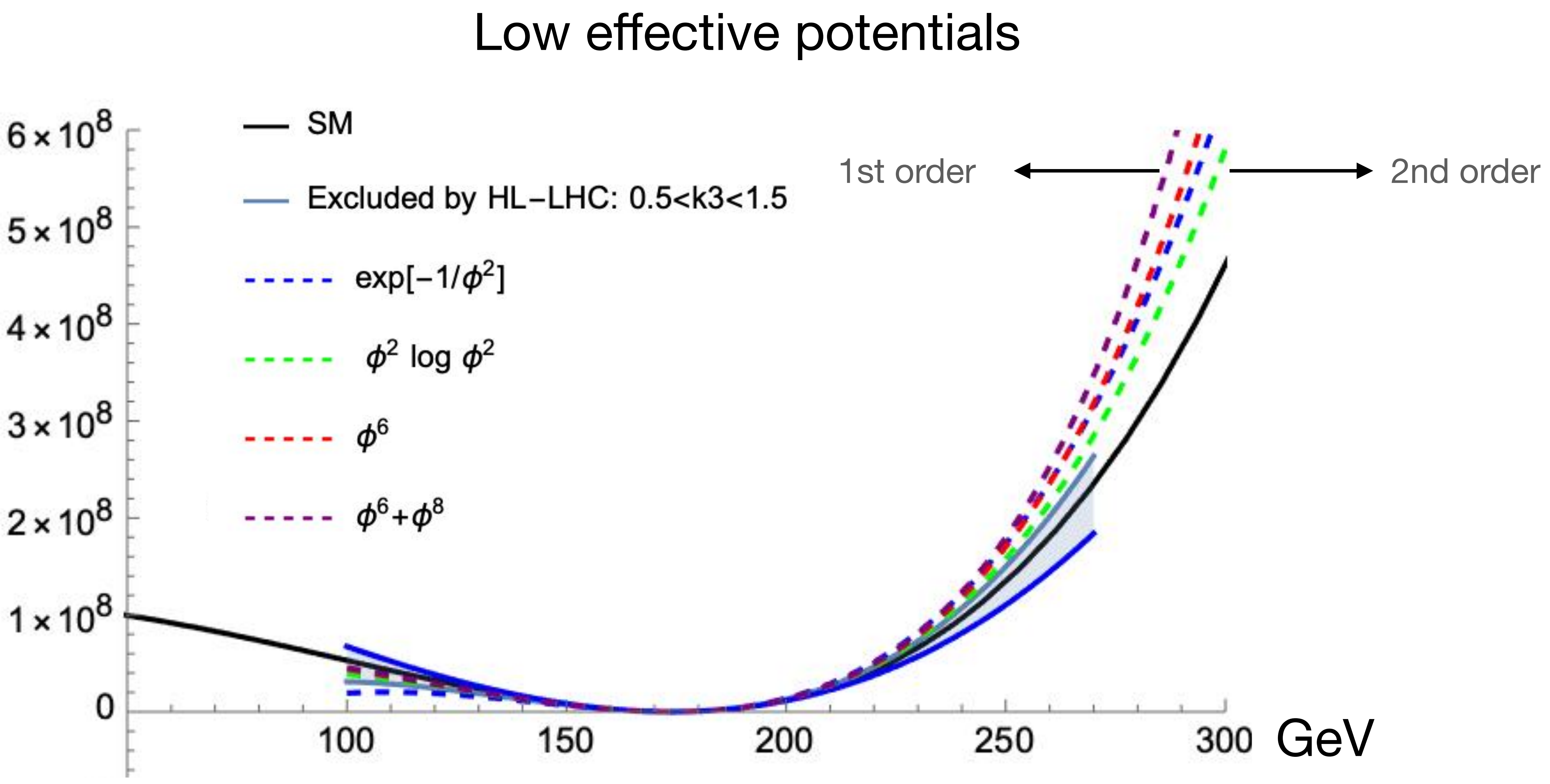


FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

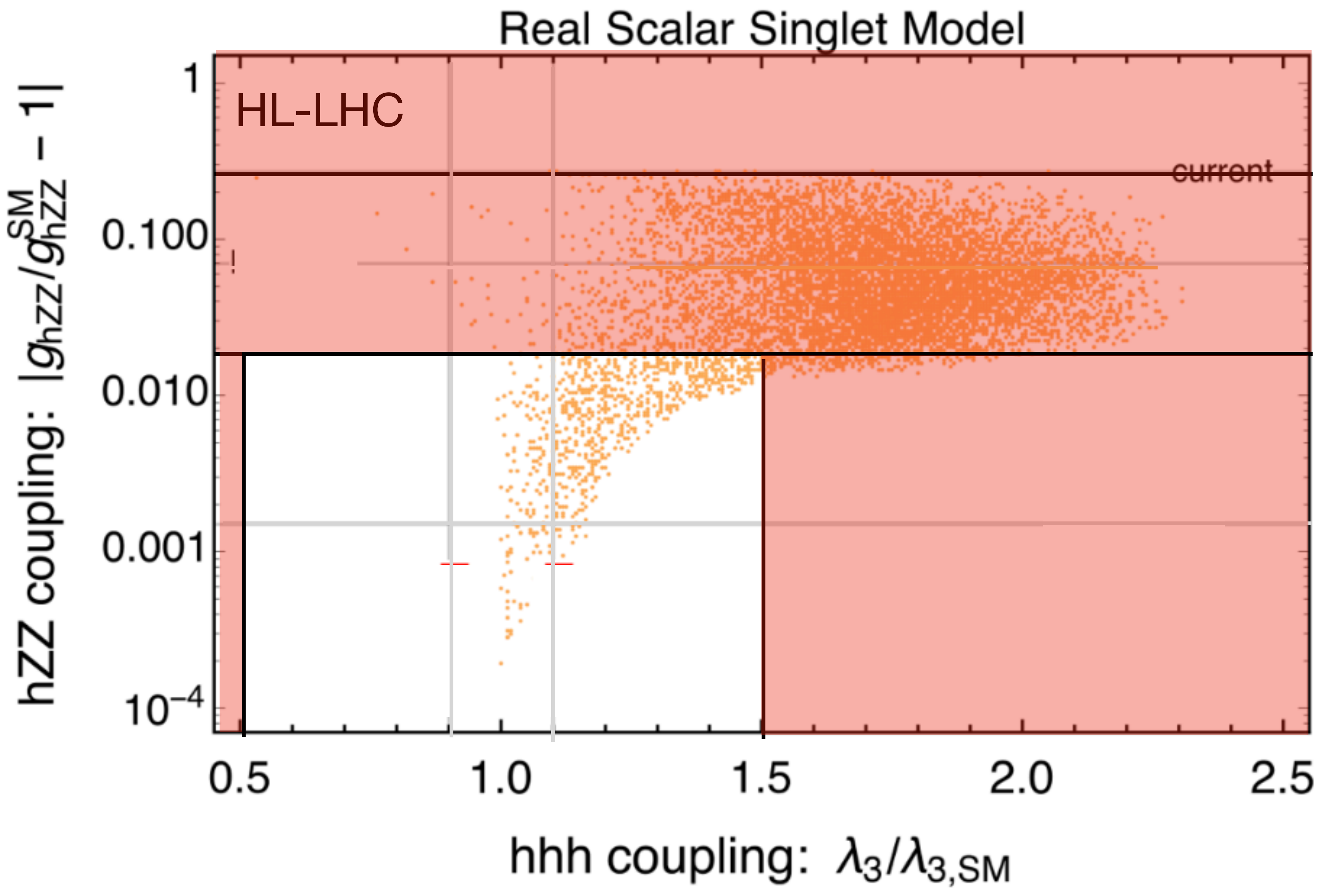
The Higgs near future

Higgs potential



Plot based on the results of 1711.00019 [hep-ph]

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**



FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

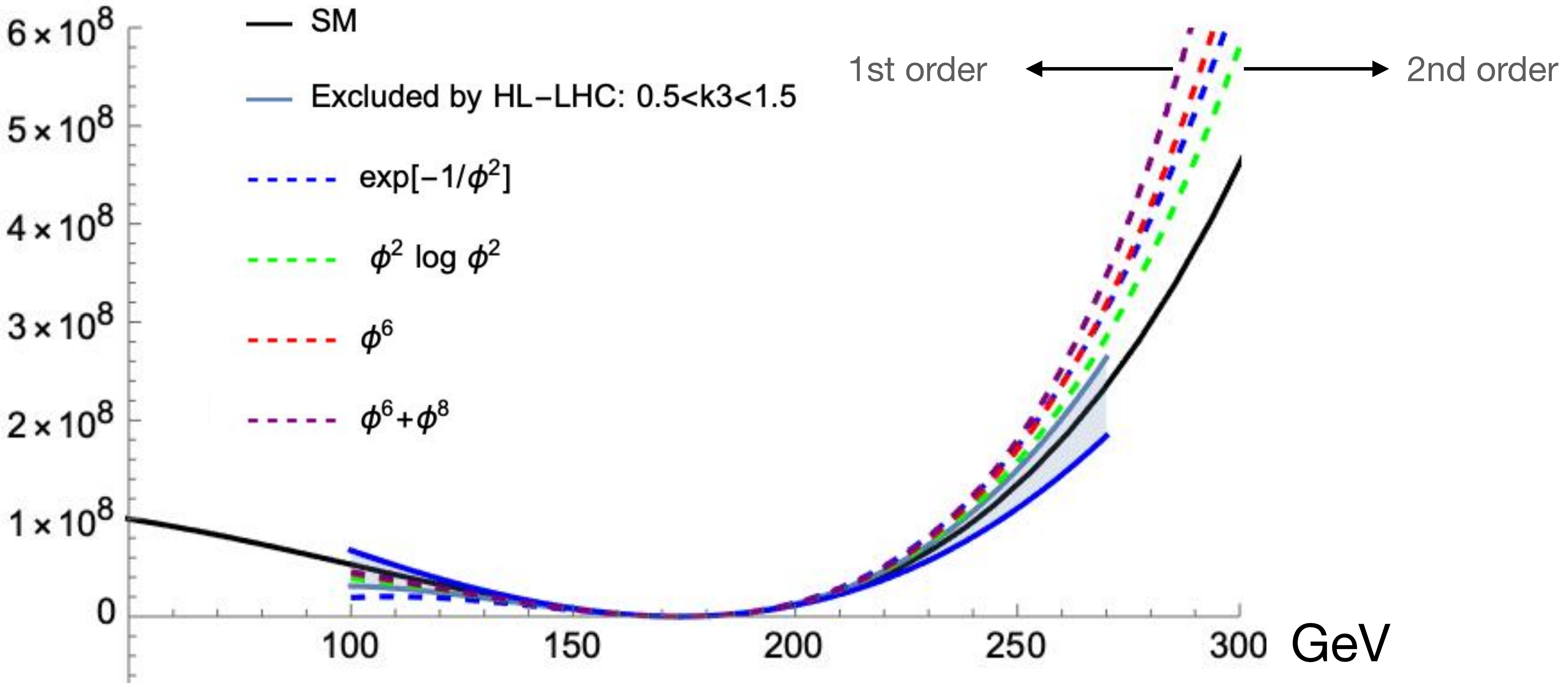
HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

See talks on EW baryo/lepto-genesis on THU afternoon

The Higgs near future

Higgs potential

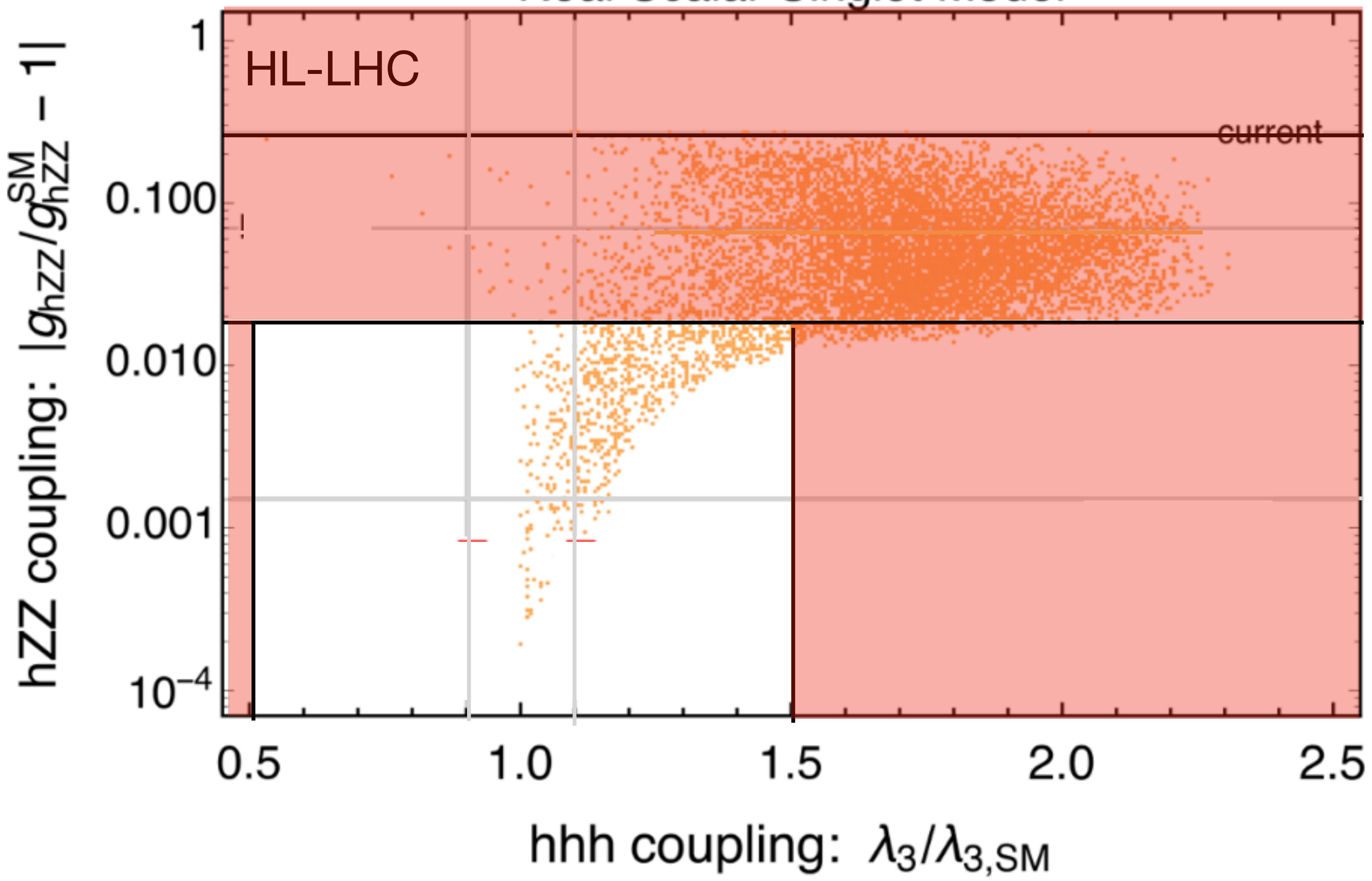
Low effective potentials



Plot based on the results of [1711.00019 [hep-ph]]

All plotted potentials are at the border of the first-second order transition. **HL-LHC will be able to probe (excluding) a 1st order phase transition in a generic EFT.**

Real Scalar Singlet Model



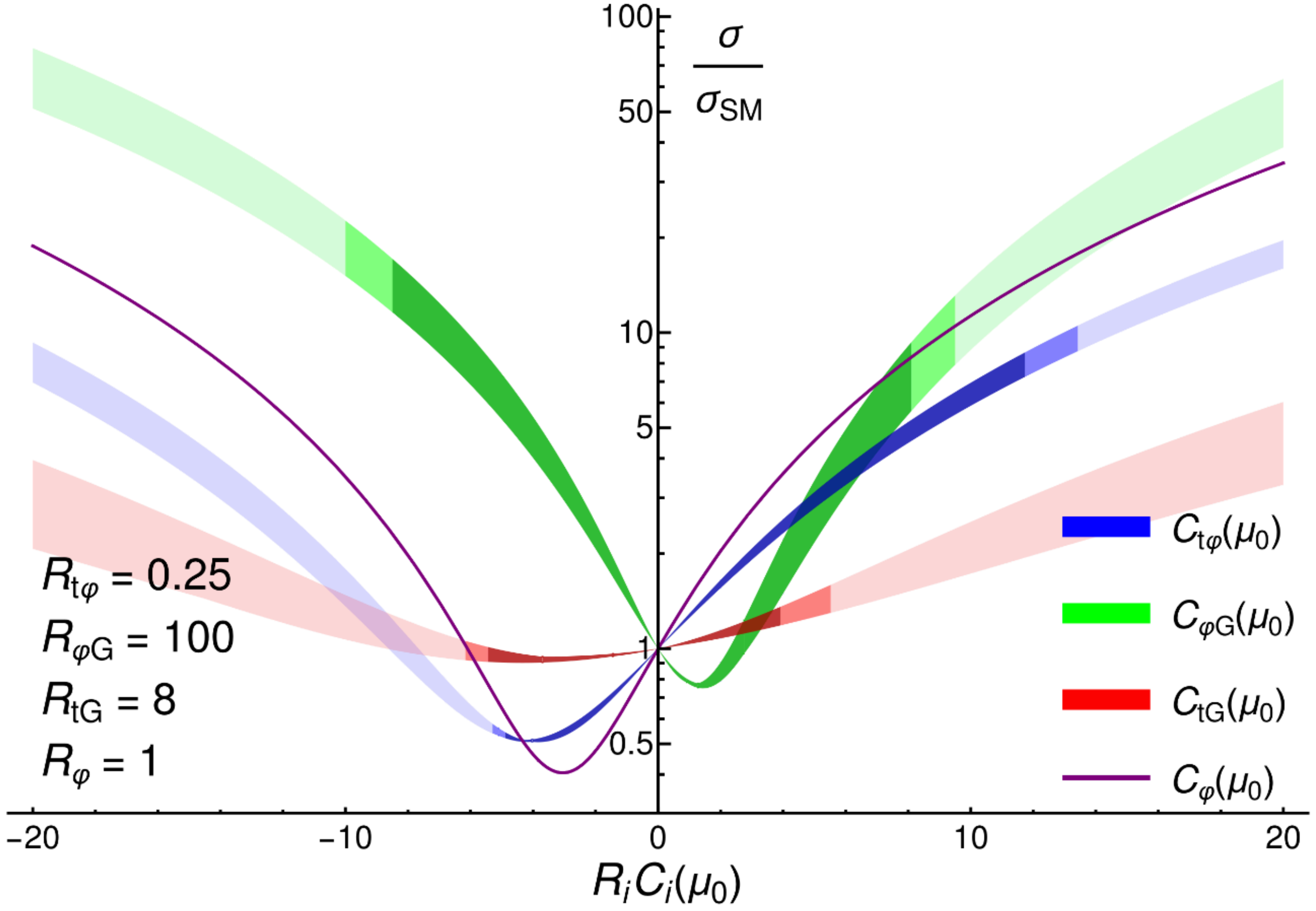
FCC Physics Opportunities Eur.Phys.J.C 79 (2019) 6, 474

HL-LHC will be able to exclude a large number of simple alternative BSM scenarios for 1st phase order transition.

The Higgs near future

Higgs potential

FM, Ventura, Vryonidou, 2406.06670 [hep-ph]



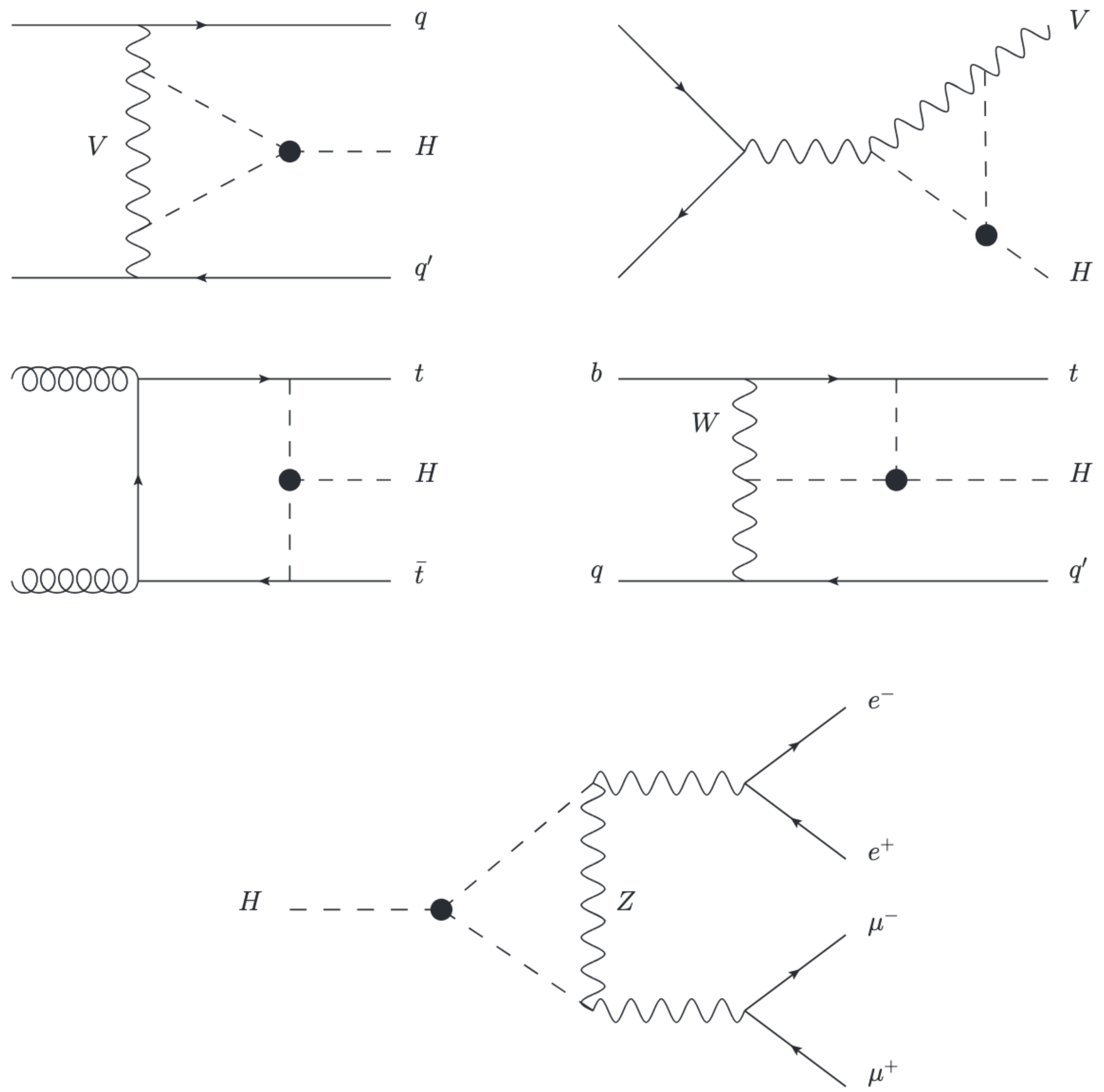
To learn about the Higgs self-coupling one needs to control several other couplings.

The Higgs near future

Indirect determinations

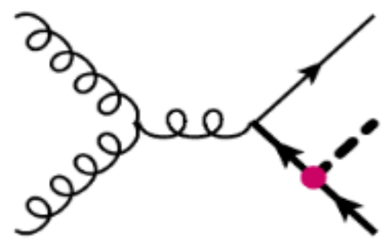
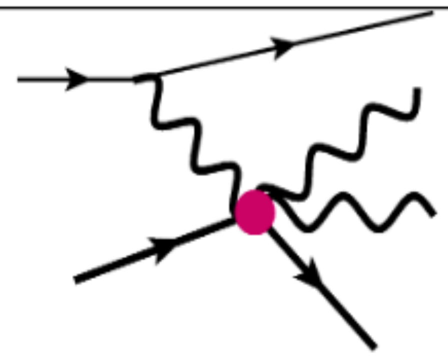
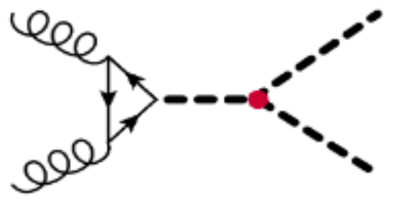
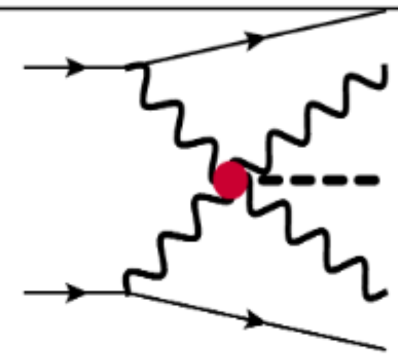
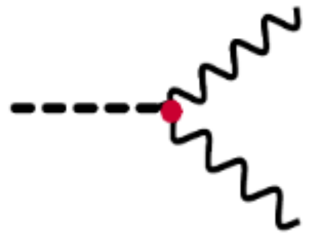
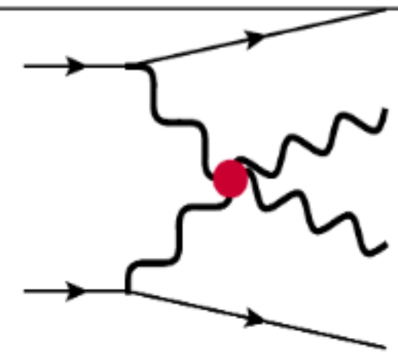
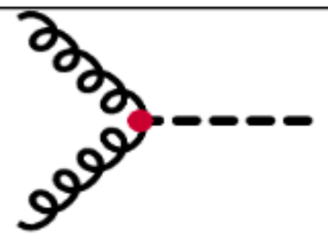
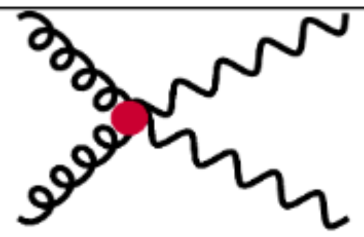
Precision (loops)

[Degrassi et al, 1607.04251 , 1709.08649]



Possibility to learn about Higgs couplings from processes with just one Higgs from loops.

[Henning et al. 2018]

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

Energy (More states)

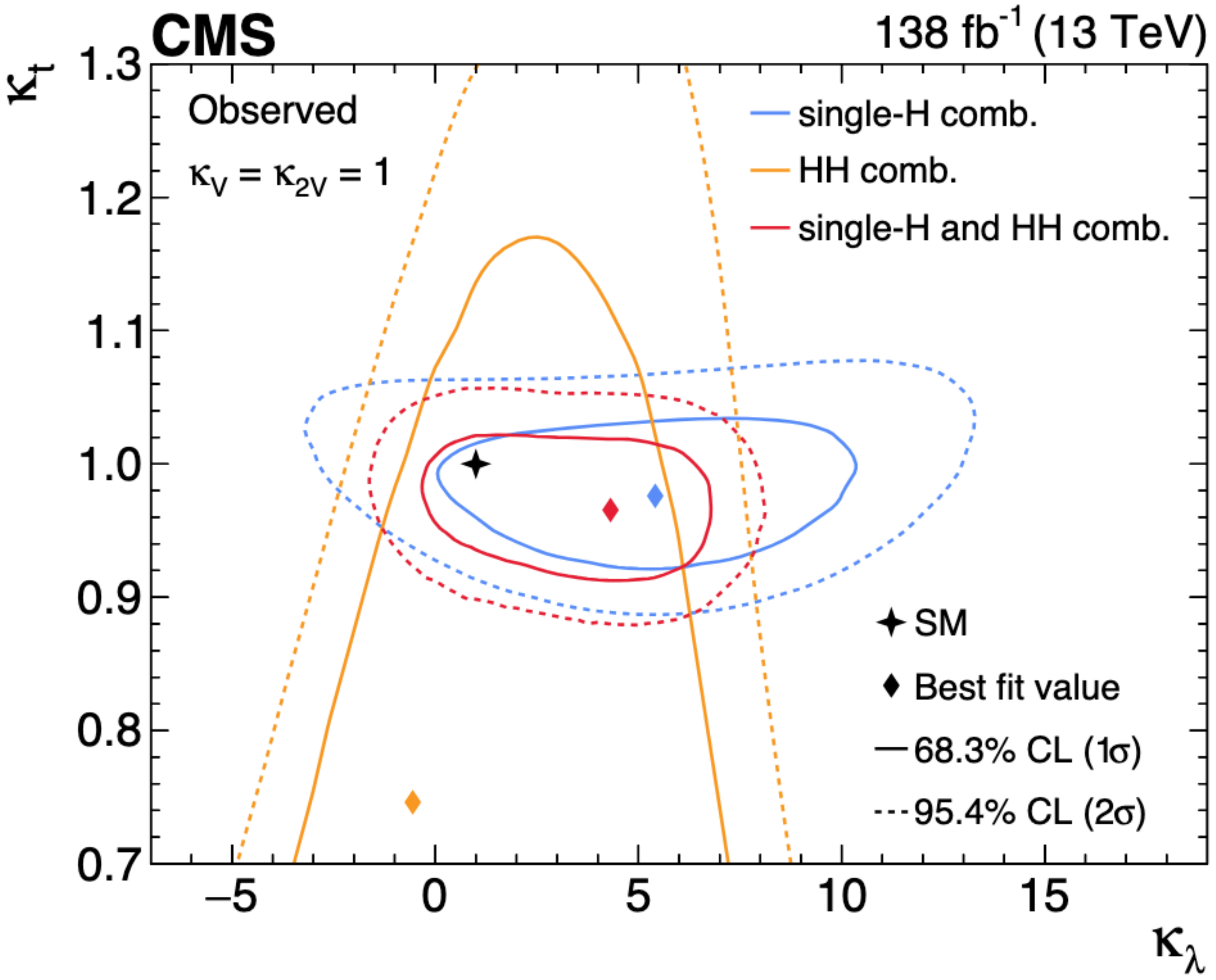
Possibility to learn about (trilinear) Higgs couplings from processes with no (one) Higgs.

The Higgs near future

Indirect determinations

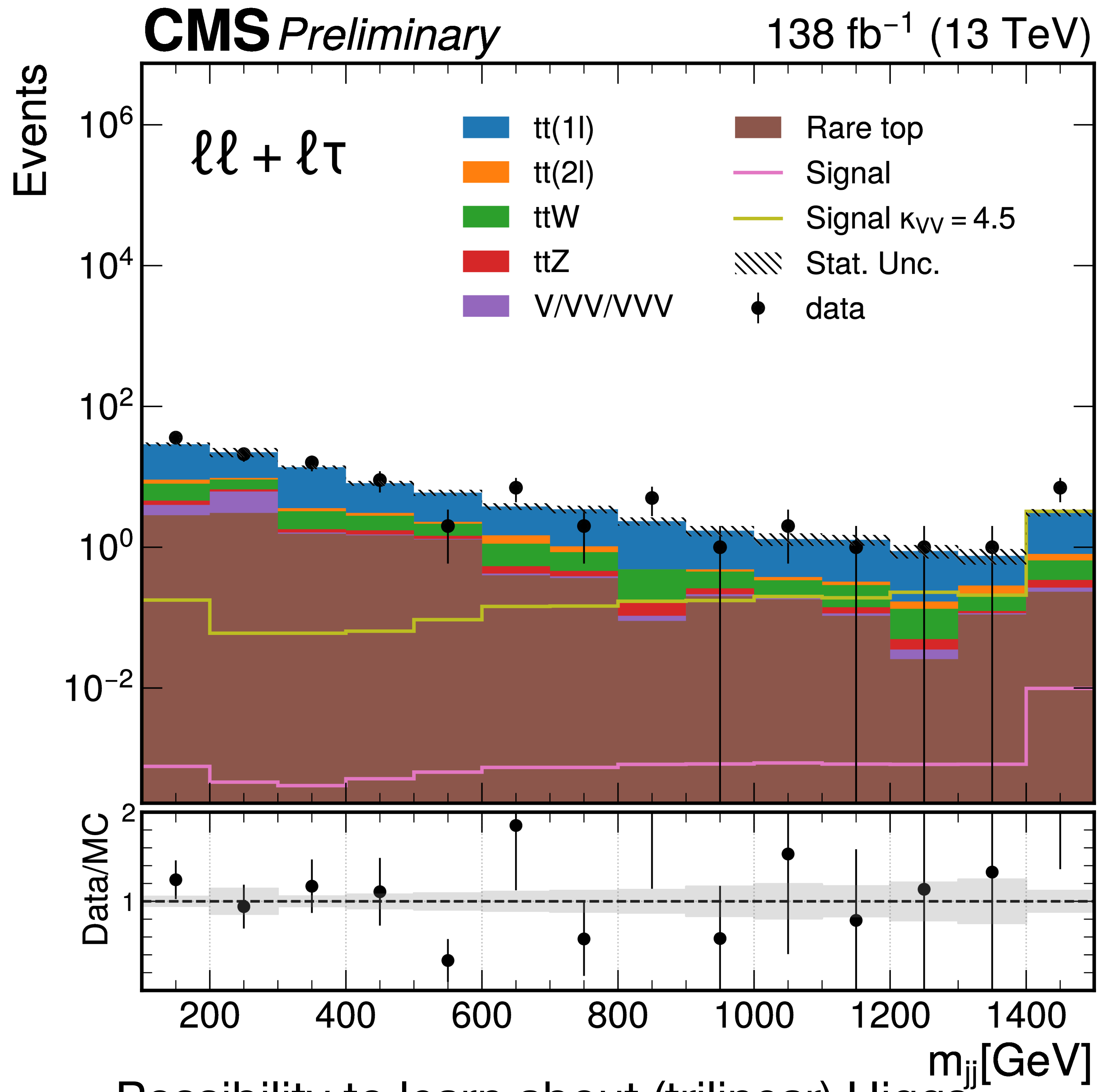
Precision (loops)

[Degrassi et al, 1607.04251 , 1709.08649]



Possibility to learn about Higgs couplings from processes with just one Higgs from loops.

[Henning et al. 2018]



Possibility to learn about (trilinear) Higgs couplings from processes with no (one) Higgs.

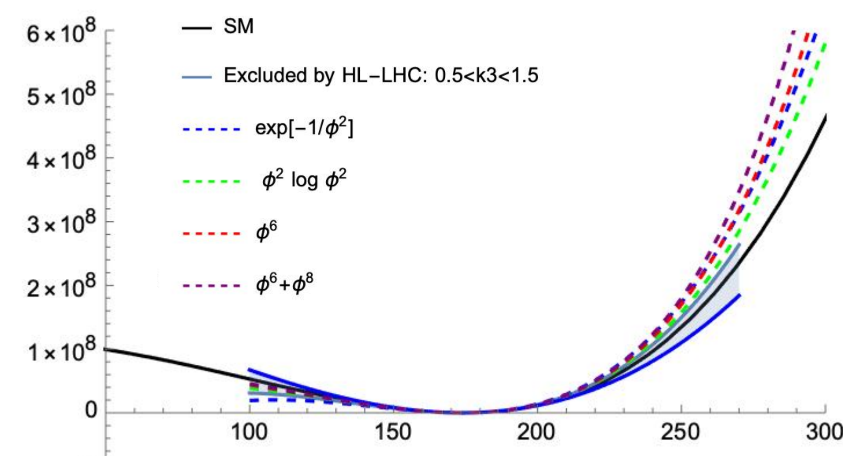
Energy (More states)

EW interactions are the new QCD

We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.

EW interactions are the new QCD

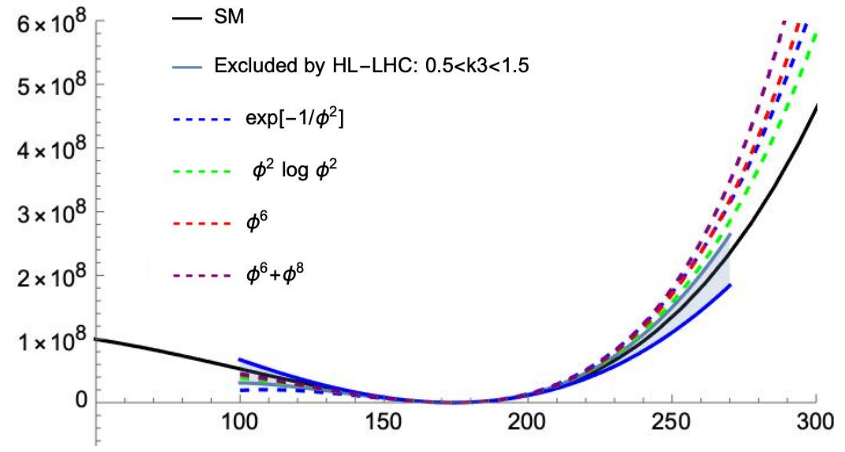
We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.



1st or 2nd order

EW interactions are the new QCD

We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.



1st or 2nd order

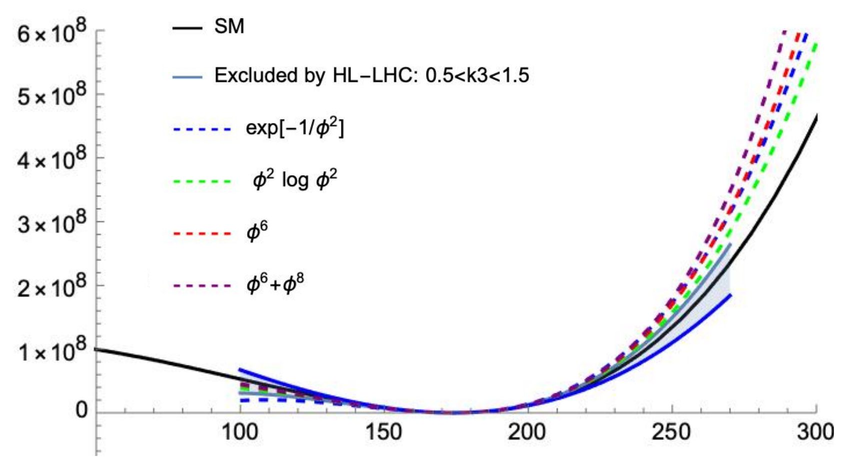
$$\phi^\pm = W_L^\pm$$

$$\phi^0 = Z_L^0$$

EW restoration

EW interactions are the new QCD

We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.

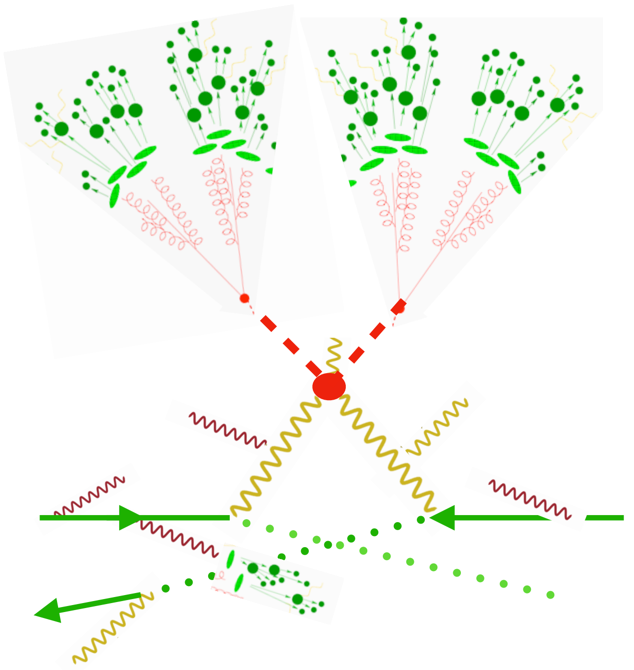


1st or 2nd order

$$\phi^\pm = W_L^\pm$$

$$\phi^0 = Z_L^0$$

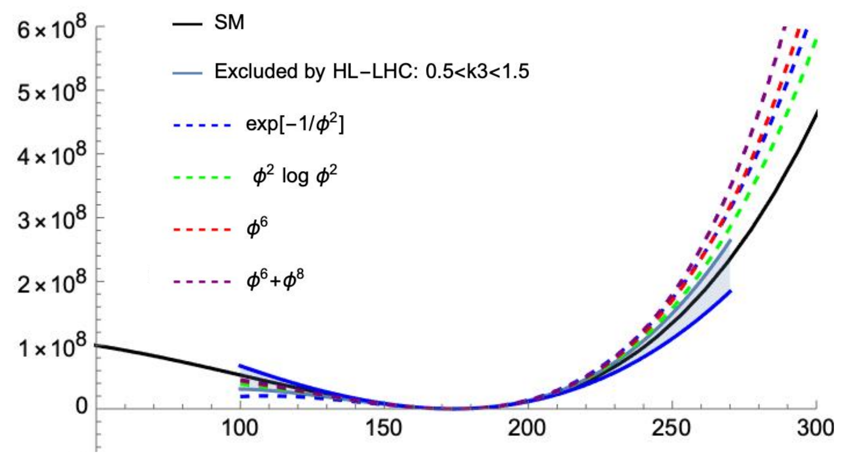
EW restoration



EW showers

EW interactions are the new QCD

We start only now to test EW interactions but only in a very low energy regime, i.e., in their broken phase.

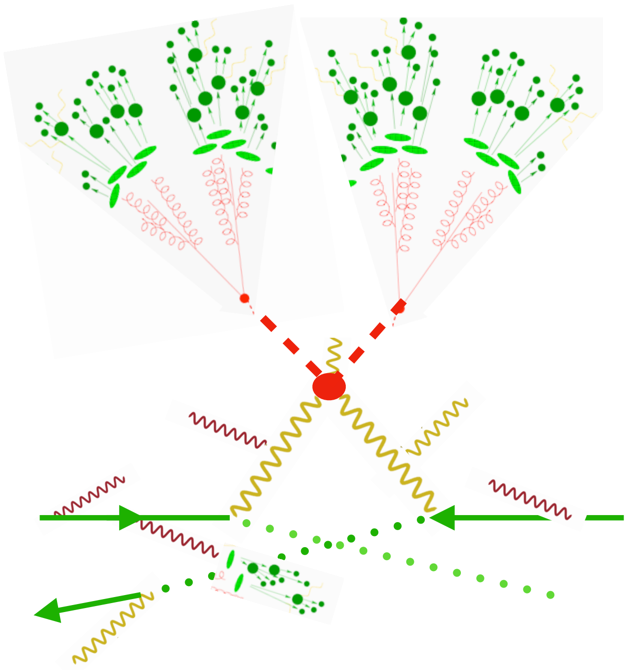


1st or 2nd order

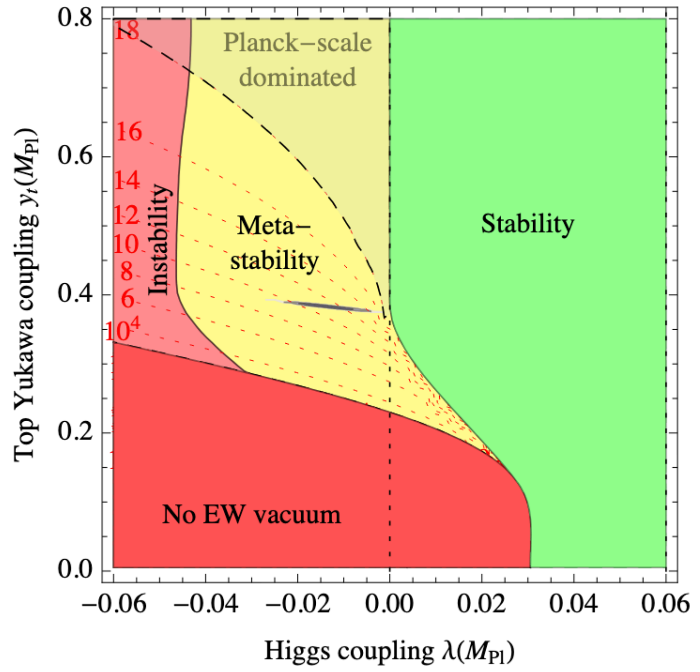
$$\phi^{\pm} = W_L^{\pm}$$

$$\phi^0 = Z_L^0$$

EW restoration



EW showers



Vacuum Stability

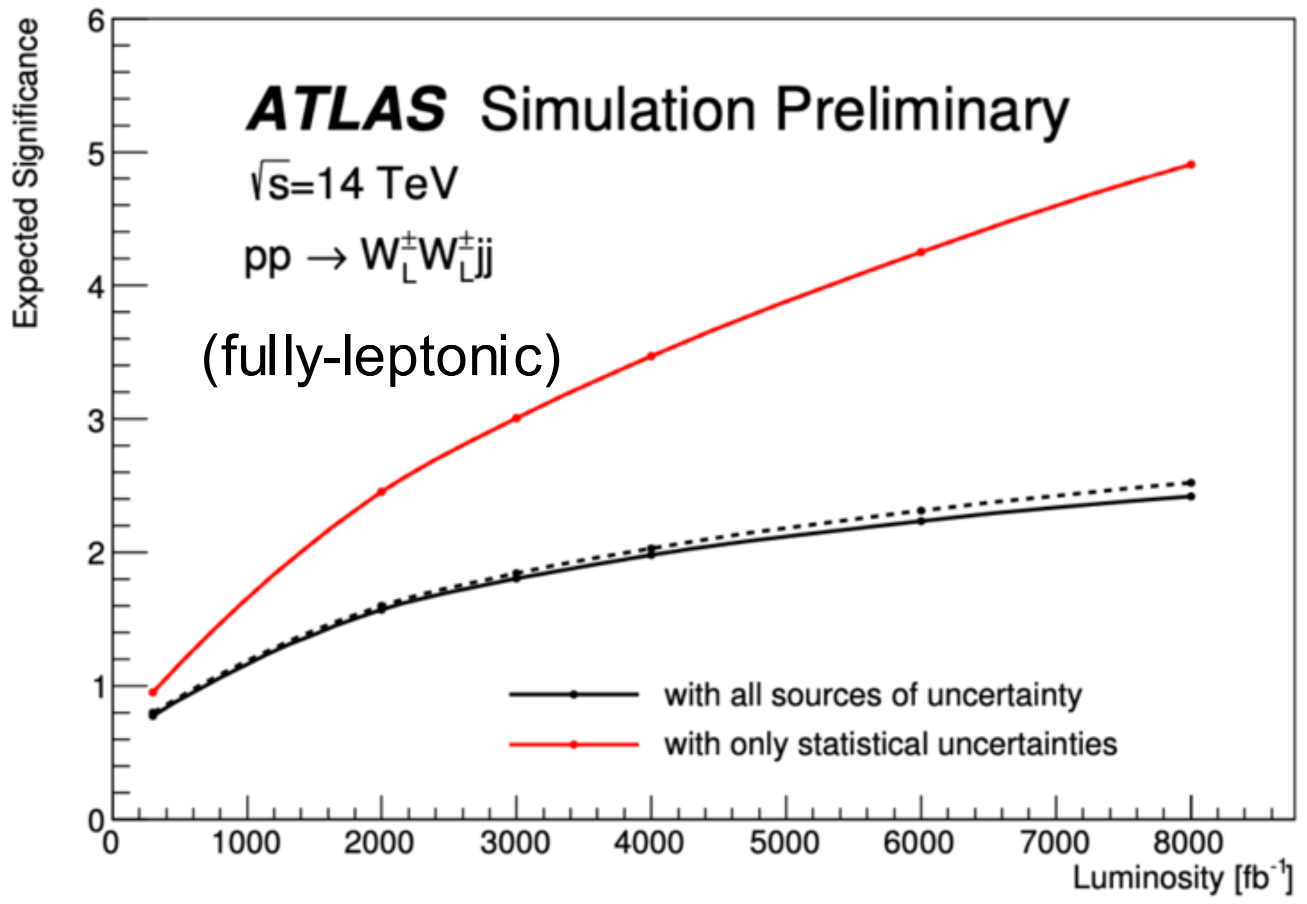
EW interactions are the new QCD

EW restoration

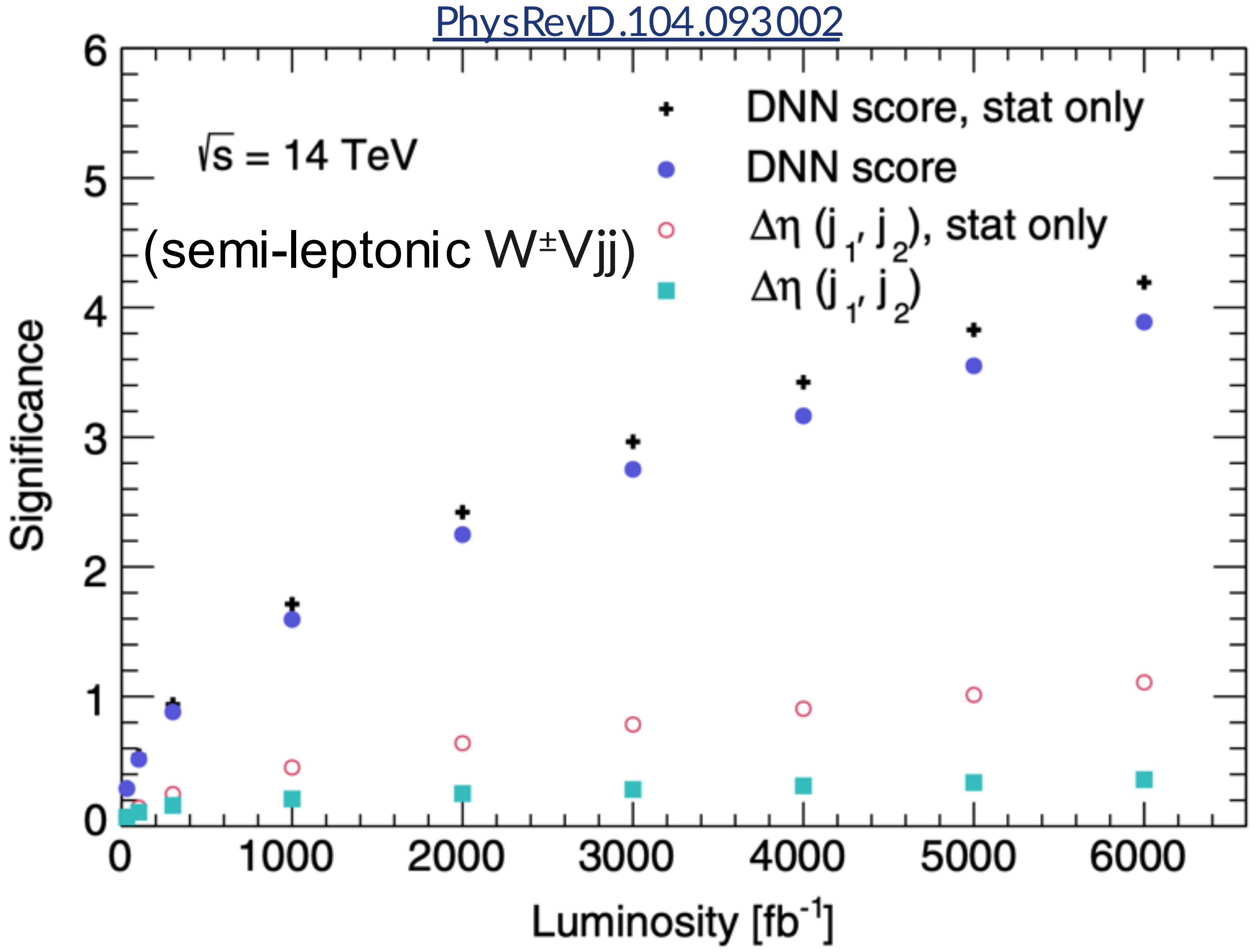
[Mwewa, FCC-hh kick-off meeting]

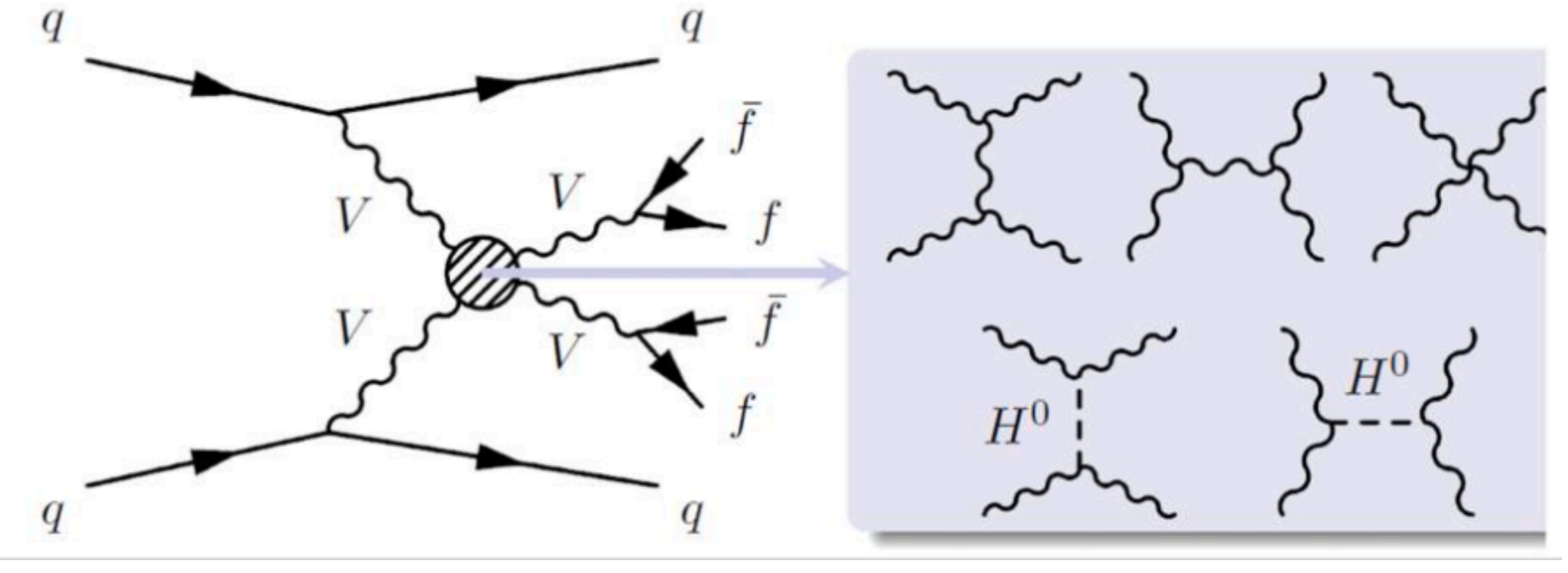
VBS, such as W+W+jj, gives access to longitudinally polarised vector bosons. However cross sections are very small (about 10% of the total) and significant only in the tails

ATL-PHYS-PUB-2018-052



PhysRevD.104.093002

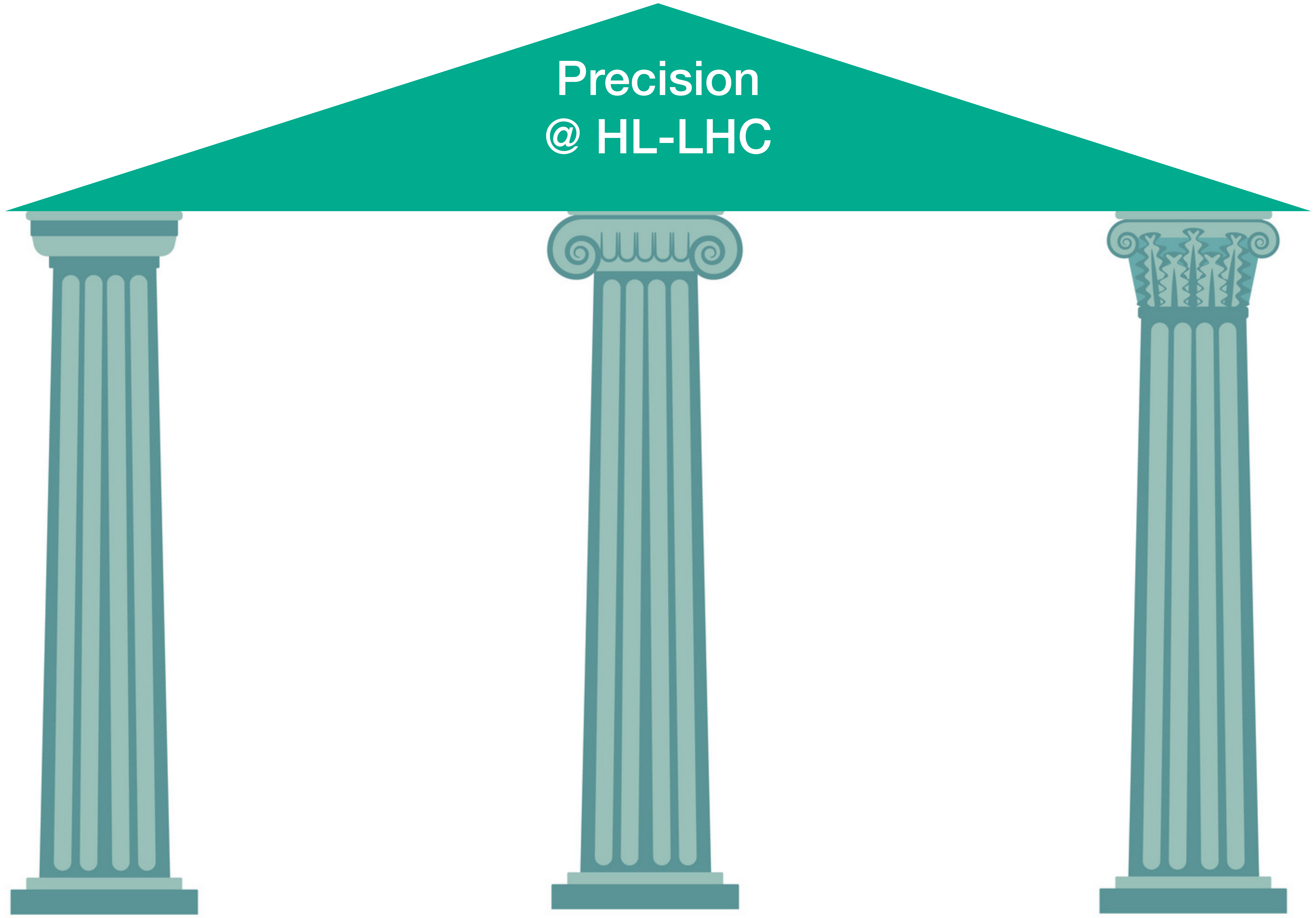




Considering all channels, and both experiments we could get at 5 sigma level for LL at 3 iab.

Theoretical challenges of the HL-LHC

Status



Precision
@ HL-LHC

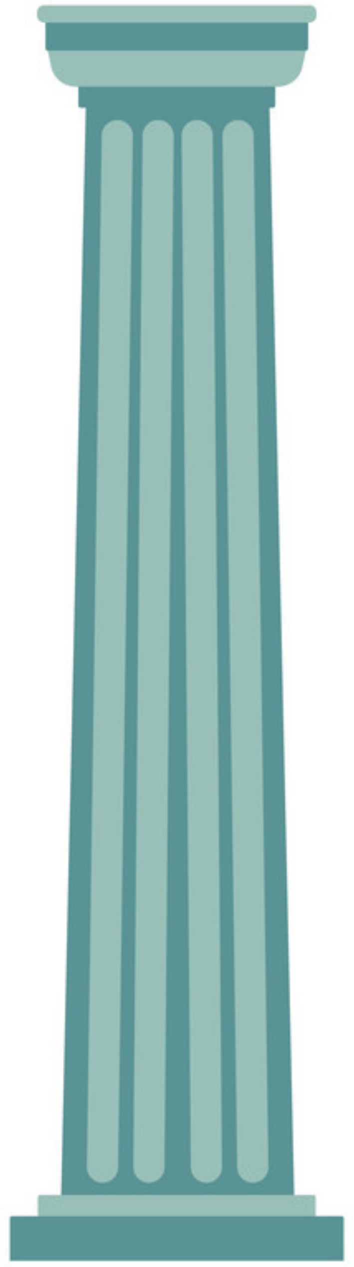
Fixed Order
LO, NLO,…
QCD EW

Resummation
LL, NLL,…
Parton Showers

PDF’s
LO,NLO,..Evolution
Fits

Theoretical challenges of the HL-LHC

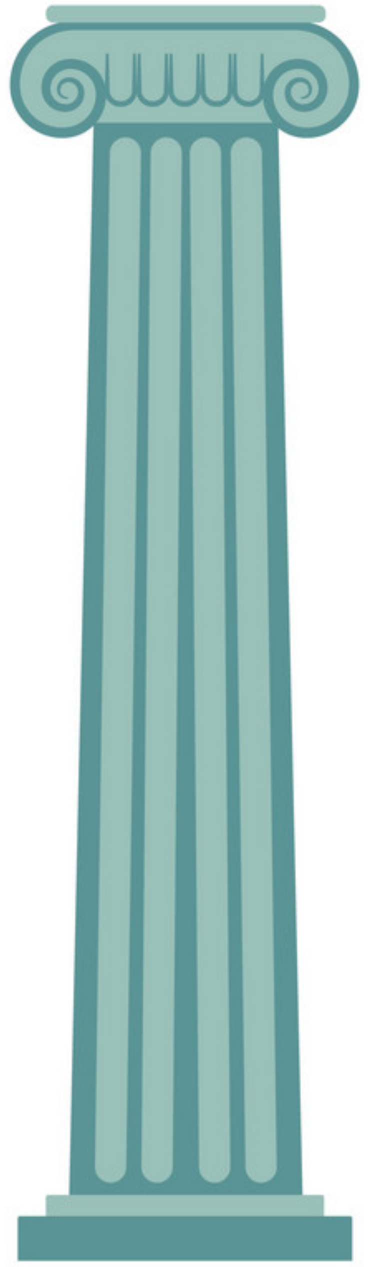
Reach the 1% goal for the HL-LHC



Fixed Order

LO, NLO,…

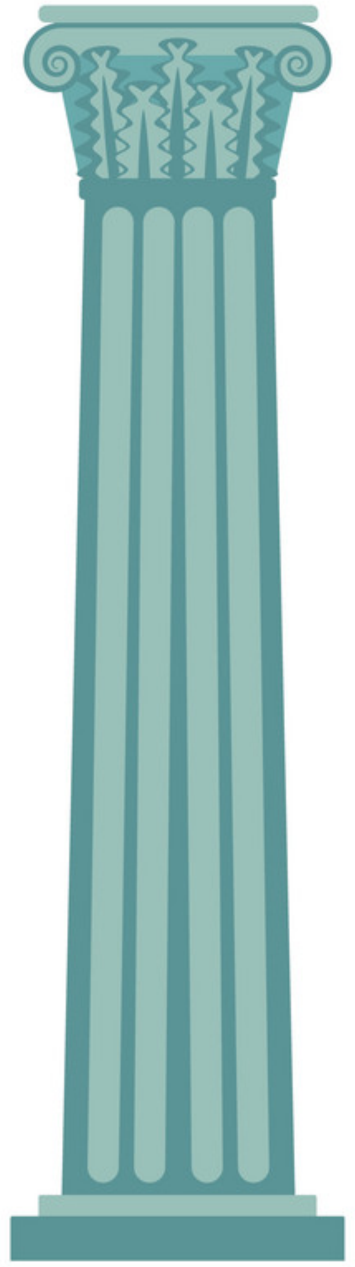
QCD/EW



Resum

LL, NLL,…

PS



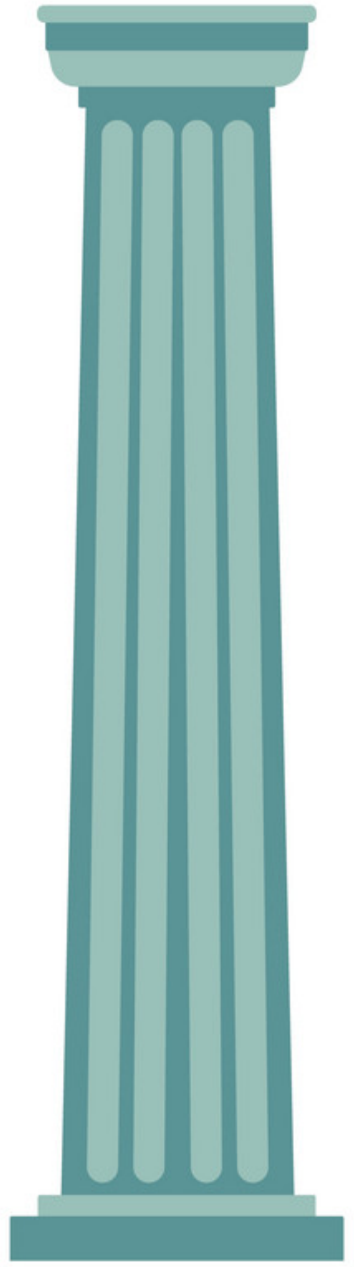
PDF's

LO,NLO,..

Fits

Theoretical challenges of the HL-LHC

Reach the 1% goal for the HL-LHC

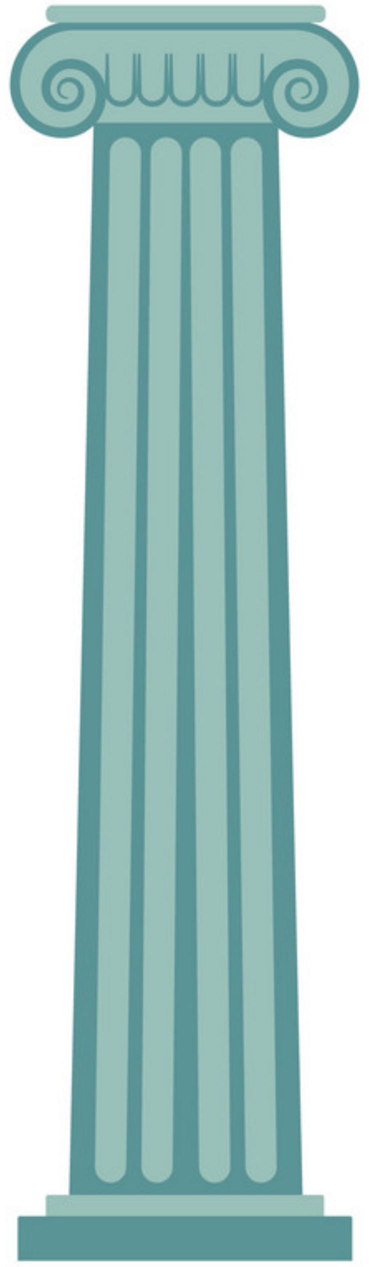


- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

Fixed Order

LO, NLO,…

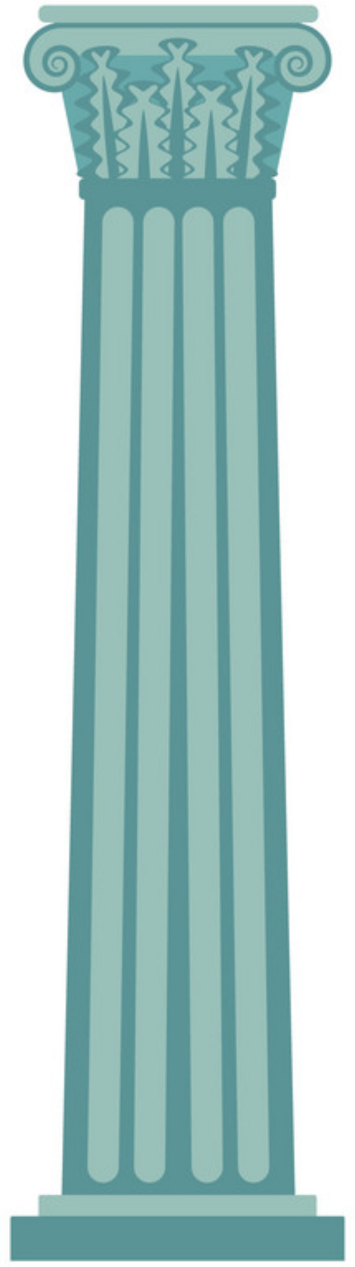
QCD/EW



Resum

LL, NLL,…

PS



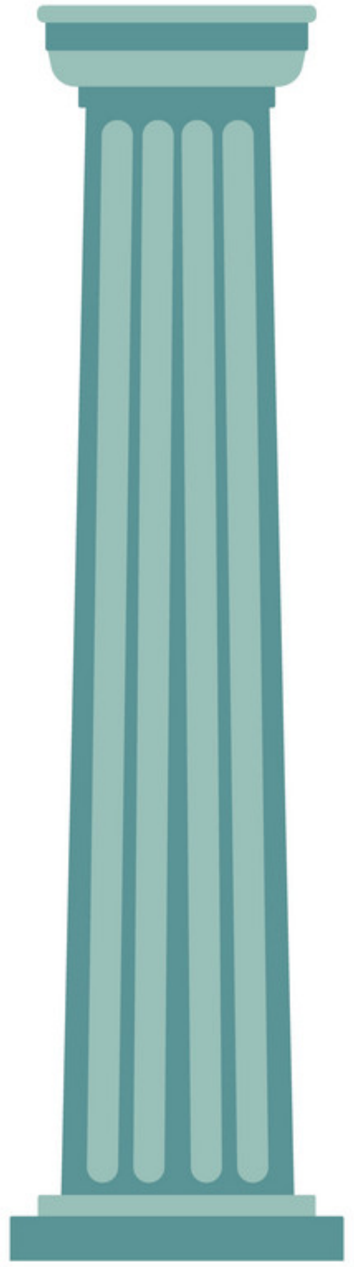
PDF's

LO,NLO,..

Fits

Theoretical challenges of the HL-LHC

Reach the 1% goal for the HL-LHC

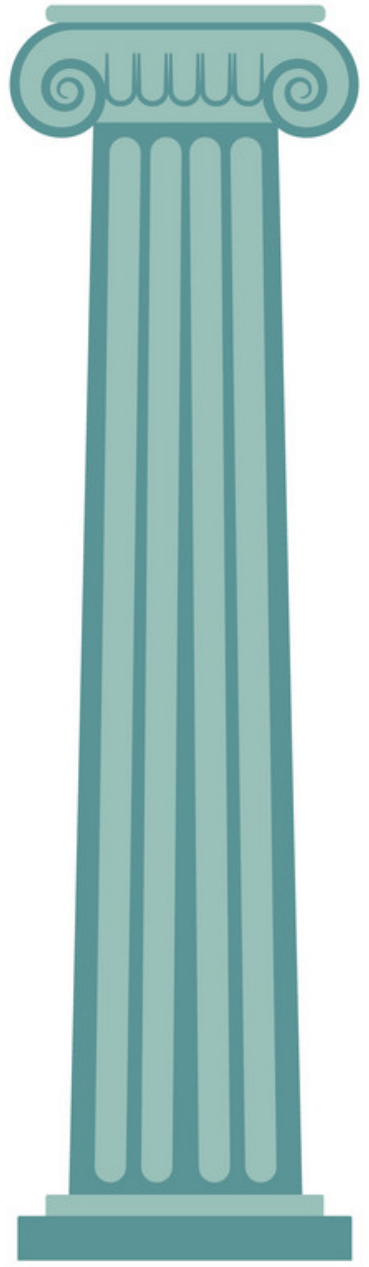


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

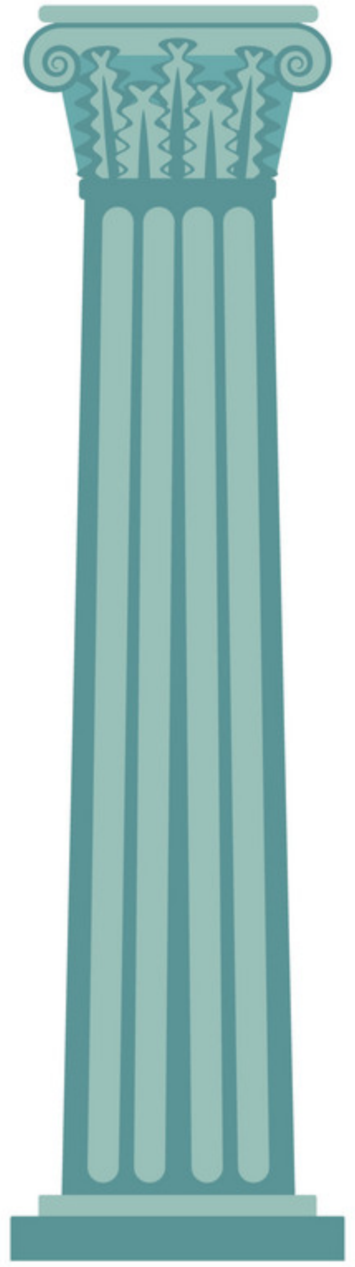


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



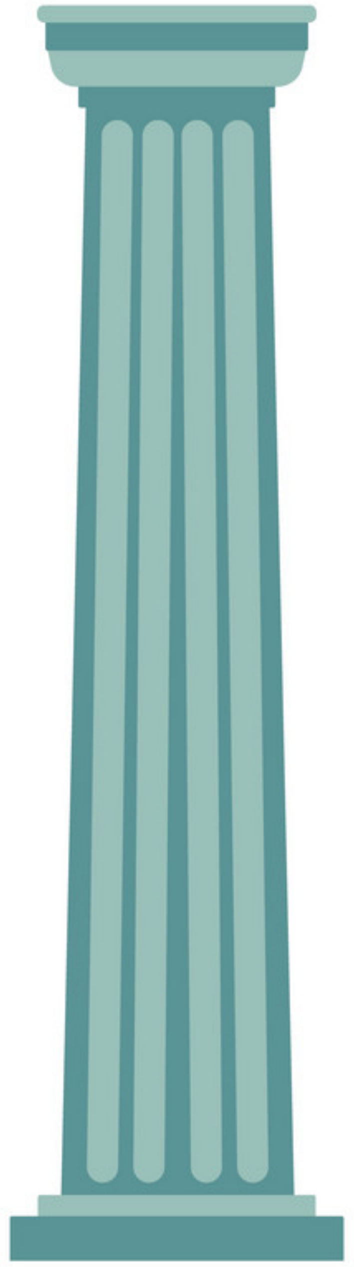
PDF's

LO,NLO,..

Fits

Theoretical challenges of the HL-LHC

Reach the 1% goal for the HL-LHC

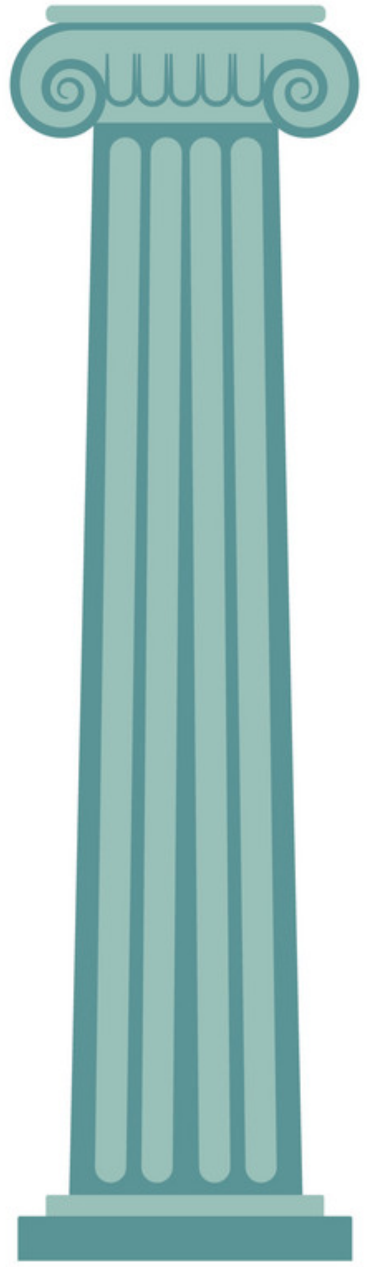


Fixed Order

LO, NLO,…

QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.

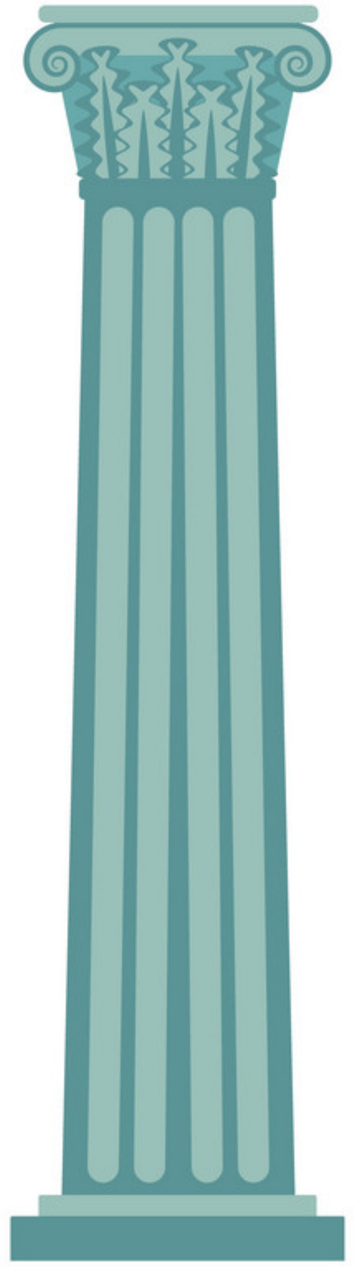


Resum

LL, NLL,…

PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF's

LO,NLO,..

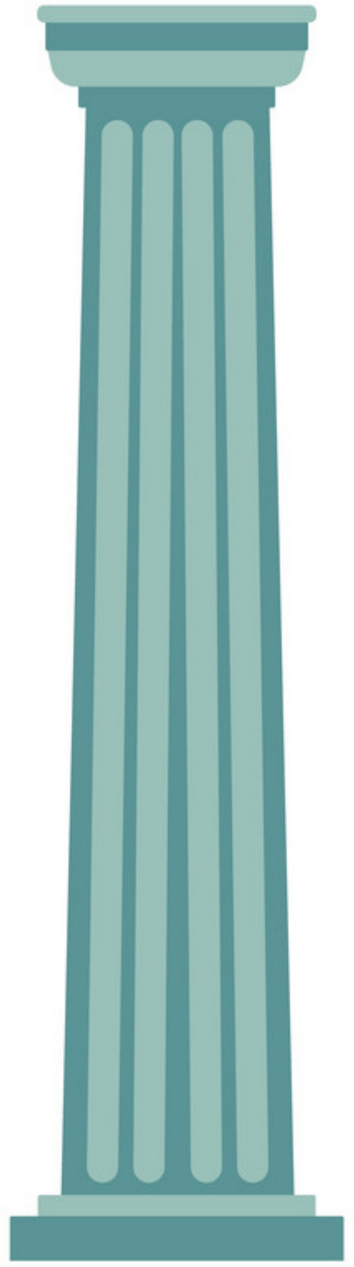
Fits

- Complete N3LO PDF's evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

See talks in the QCD session on Tue afternoon!

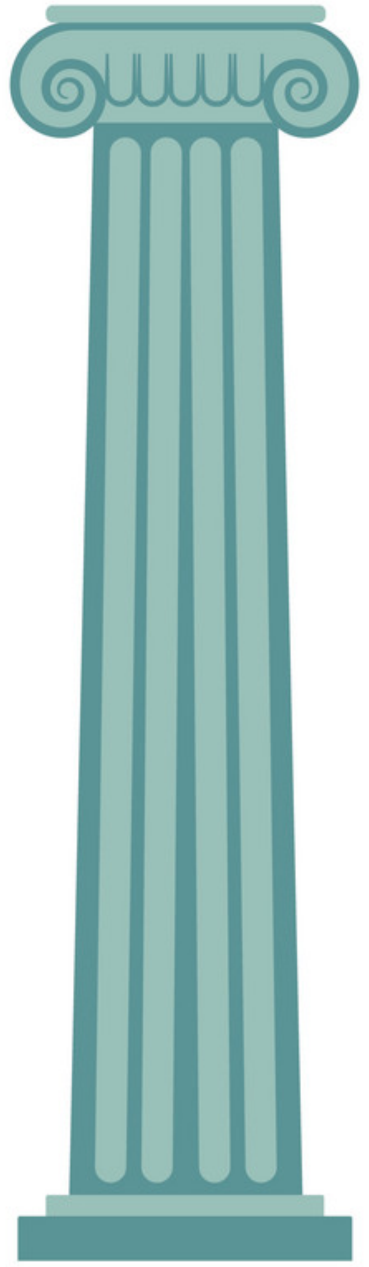
Theoretical challenges of the HL-LHC

Reach the 1% goal for the HL-LHC



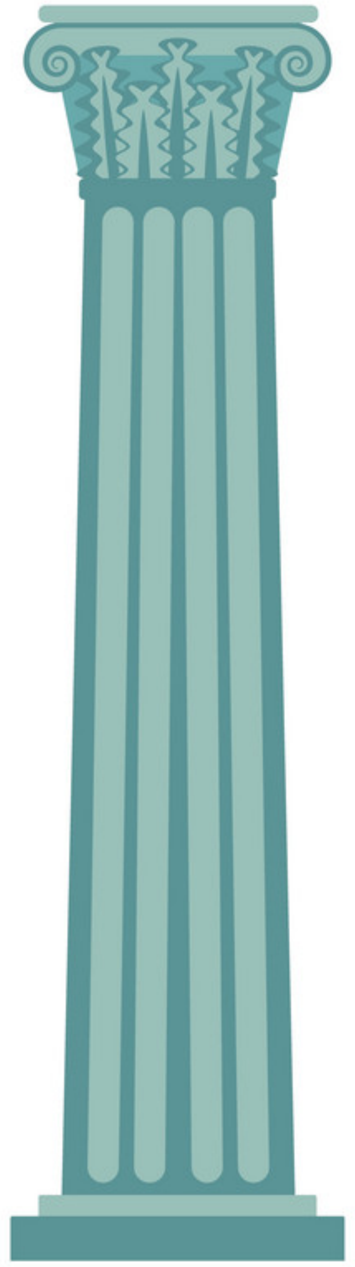
Fixed Order
LO, NLO,…
QCD/EW

- Very fast progress in conceptual as well as technical aspects.
- Tight and consolidated community, with high momentum.
- Considering the status of 20 years ago seems clear that NNLO will be completed and N3LO will start to become available for 2→2 (see 3-loop $q\bar{q} \to \gamma\gamma$ results)
- Mixed QCD-EW being included.



Resum
LL, NLL,…
PS

- A variety of approaches available, both analytical and numerical.
- Analytically historically matching the FO accuracy.
- NNLO+PS will be the new standard. (N3LO+PS already being explored)
- Having a NLL and beyond PS, is being explored now. To be seen.
- Not clear whether one can reach 1%.



PDF’s
LO,NLO,..
Fits

- Complete N3LO PDF’s evolution not available yet.
- PDF determination from fitting large set of data. Final quality depends on measurements.
- Error budget with many sources. MHO uncertainties yet to be included in the final assessment.
- Reaching 1% will be very challenging.
- Room for a breakthrough from lattice.

Timeline(s)

To be taken cum grano salis

SuperKEKB

LHC

HL-LHC

2025

Near future

2050

Future

2075

Timeline(s)

To be taken cum grano salis

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

e+e- ILC 250

e+e- ILC 500

e+e- ILC 1000

e+e- FCC-ee : 91,240,365 GeV

A

LHC

HL-LHC

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

2025

Near future

2050

Future

2075

Timeline(s)

To be taken cum grano salis


SuperKEKB

e+e- CEPC

ppPC

e+e- ILC 250

e+e- ILC 500

e+e- ILC 1000

A

e+e- FCC-ee : 91,240,365 GeV

FCC-hh

LHC

HL-LHC

FCC-hh at 80 TeV with 14T magnets

B's

LEP3 with Lumi=1/5 Lumi FCC-ee

2025

Near future

2050

Future

2075

Timeline(s)

To be taken cum grano salis

Timeline(s)

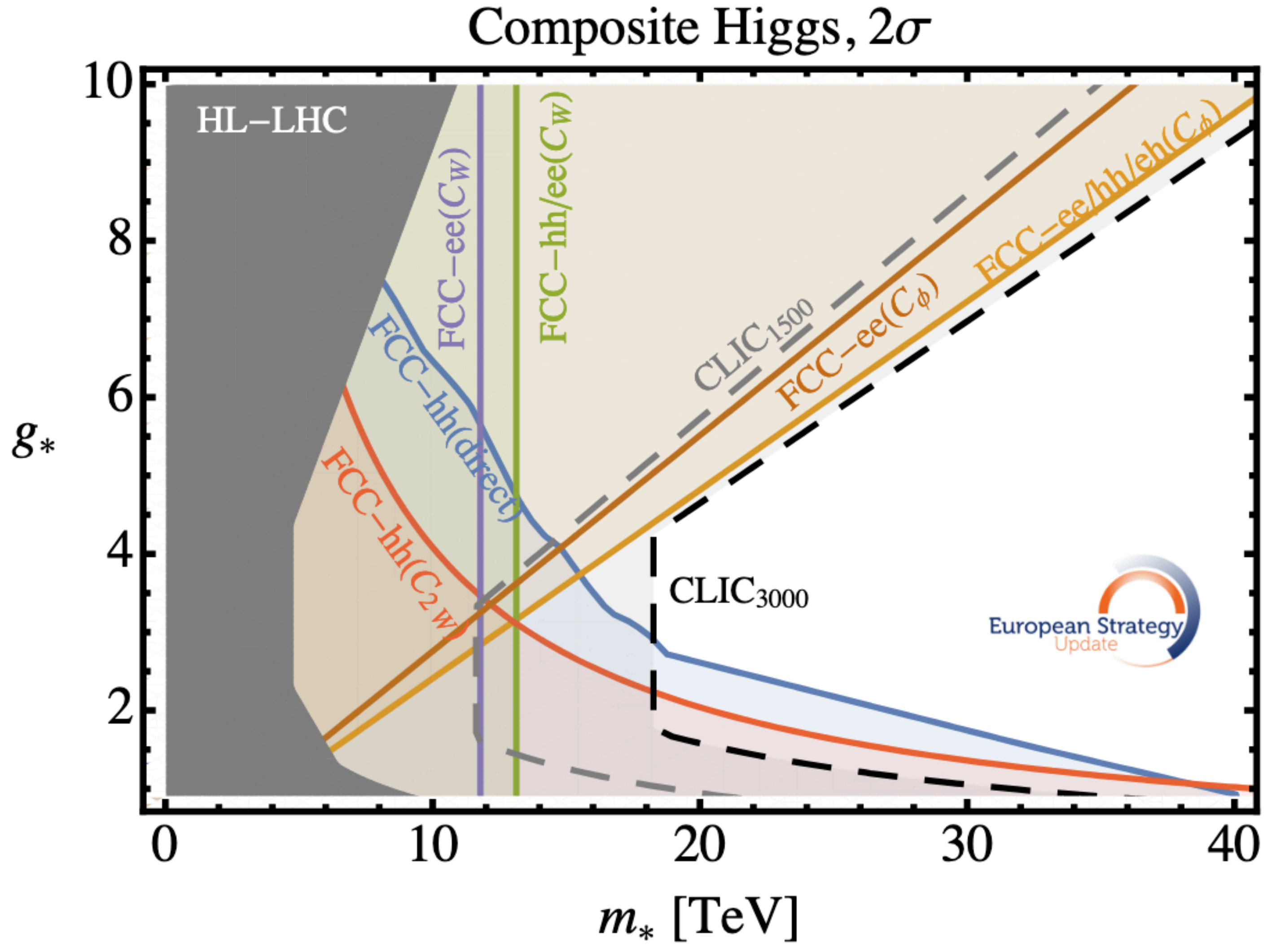
To be taken cum grano salis

Future colliders

Reach in Higgs couplings

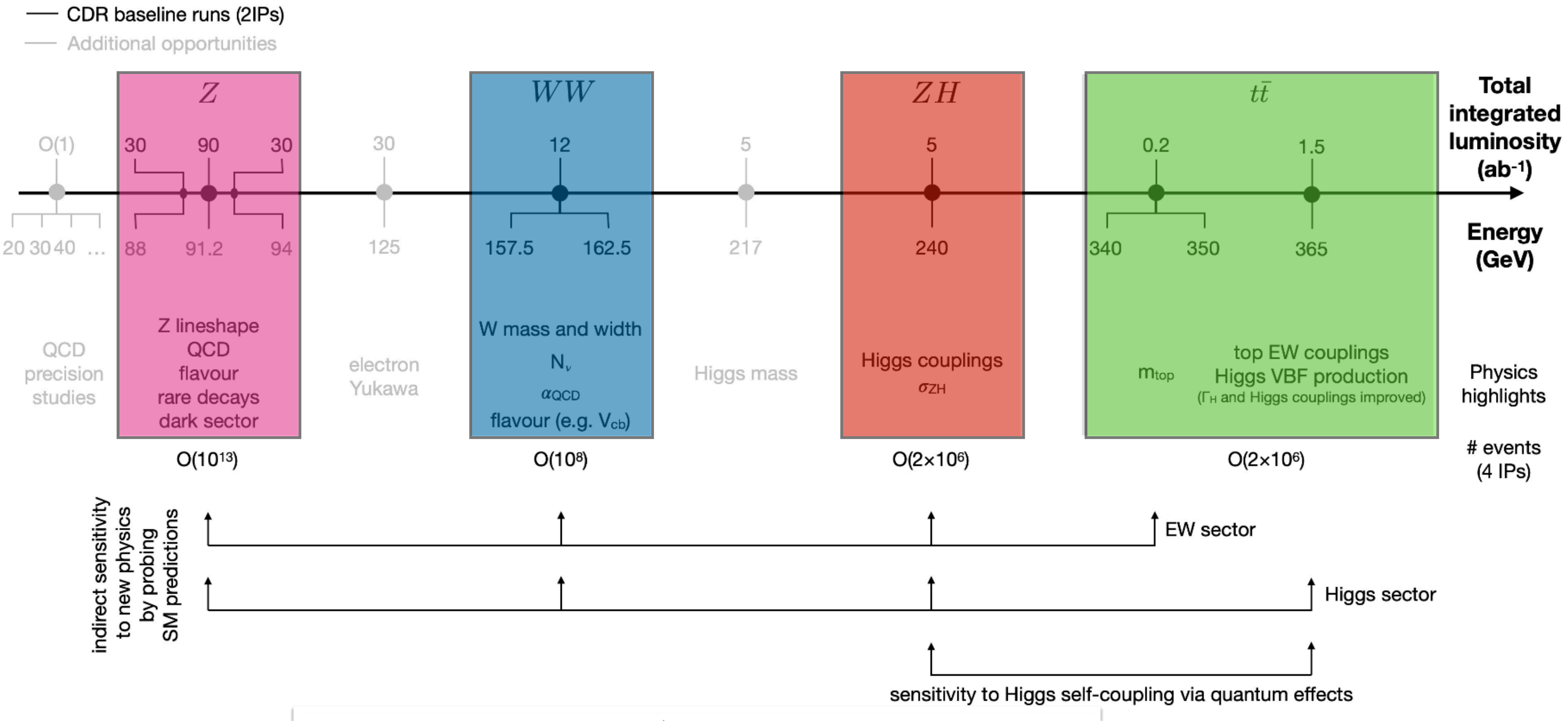
[De Blas et al., 2020]

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44



Improvements by factors of 5-10 ⇒ same on the scale on NP $\delta g_H / g_H{}^{\mathrm{SM}} \sim c\,\varepsilon$

FCC-ee runs



CDR baseline runs (2IPs)

Additional opportunities

Total integrated luminosity (ab^{-1})

Energy (GeV)

Physics highlights

events (4 IPs)

O(1)

20 30 40 …

QCD precision studies

Z

30 90 30

88 91.2 94

Z lineshape
QCD
flavour
rare decays
dark sector

$O(10^{13})$

30

125

electron Yukawa

WW

12

157.5 162.5

W mass and width
N_ν
α_{QCD}
flavour (e.g. V_{cb})

$O(10^{8})$

5

217

Higgs mass

ZH

5

240

Higgs couplings
σ_{ZH}

$O(2\times10^{6})$

$t\bar{t}$

0.2 1.5

340 350 365

m_{top}

top EW couplings
Higgs VBF production
(Γ_H and Higgs couplings improved)

$O(2\times10^{6})$

indirect sensitivity to new physics by probing SM predictions

EW sector

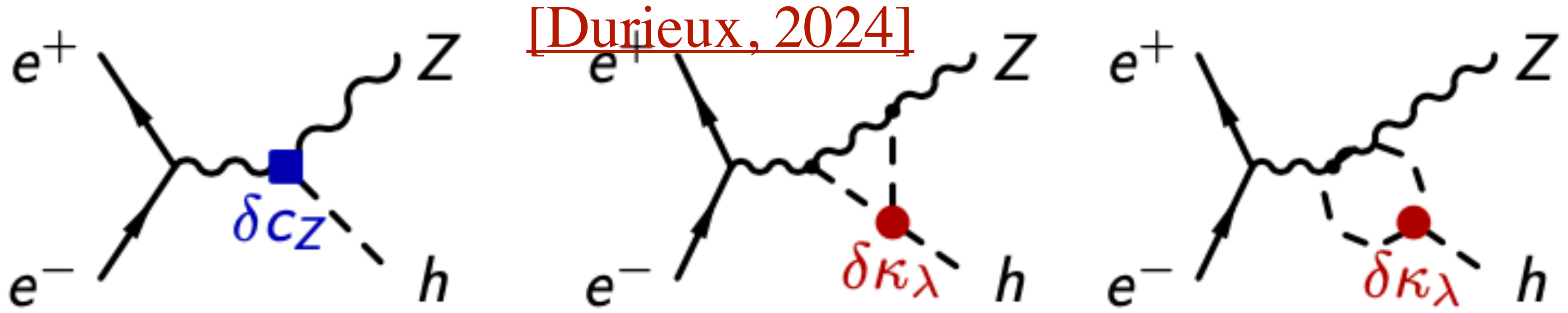
Higgs sector

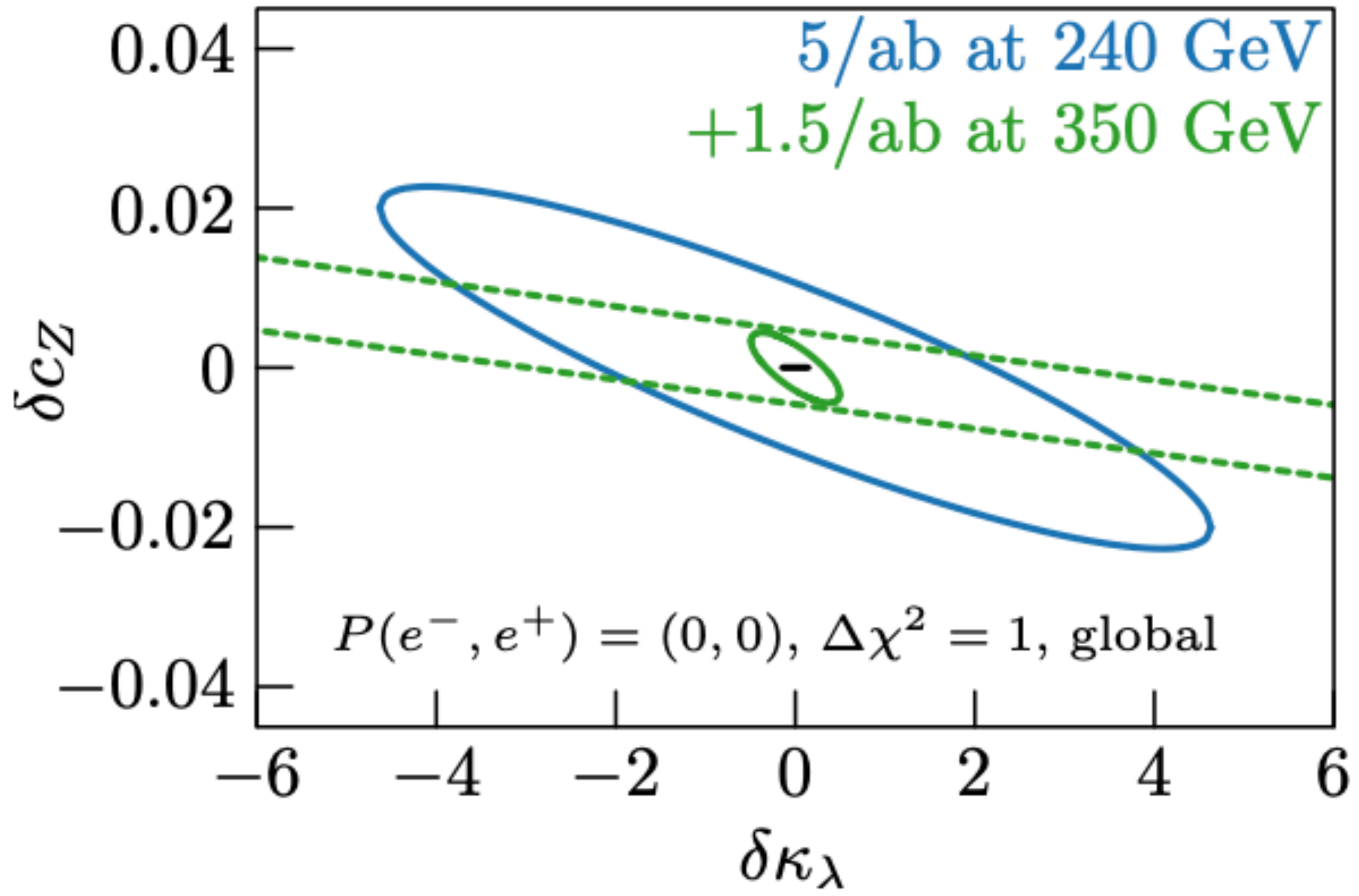
sensitivity to Higgs self-coupling via quantum effects

Higgs self-coupling

FCC-ee (and FCC-hh)

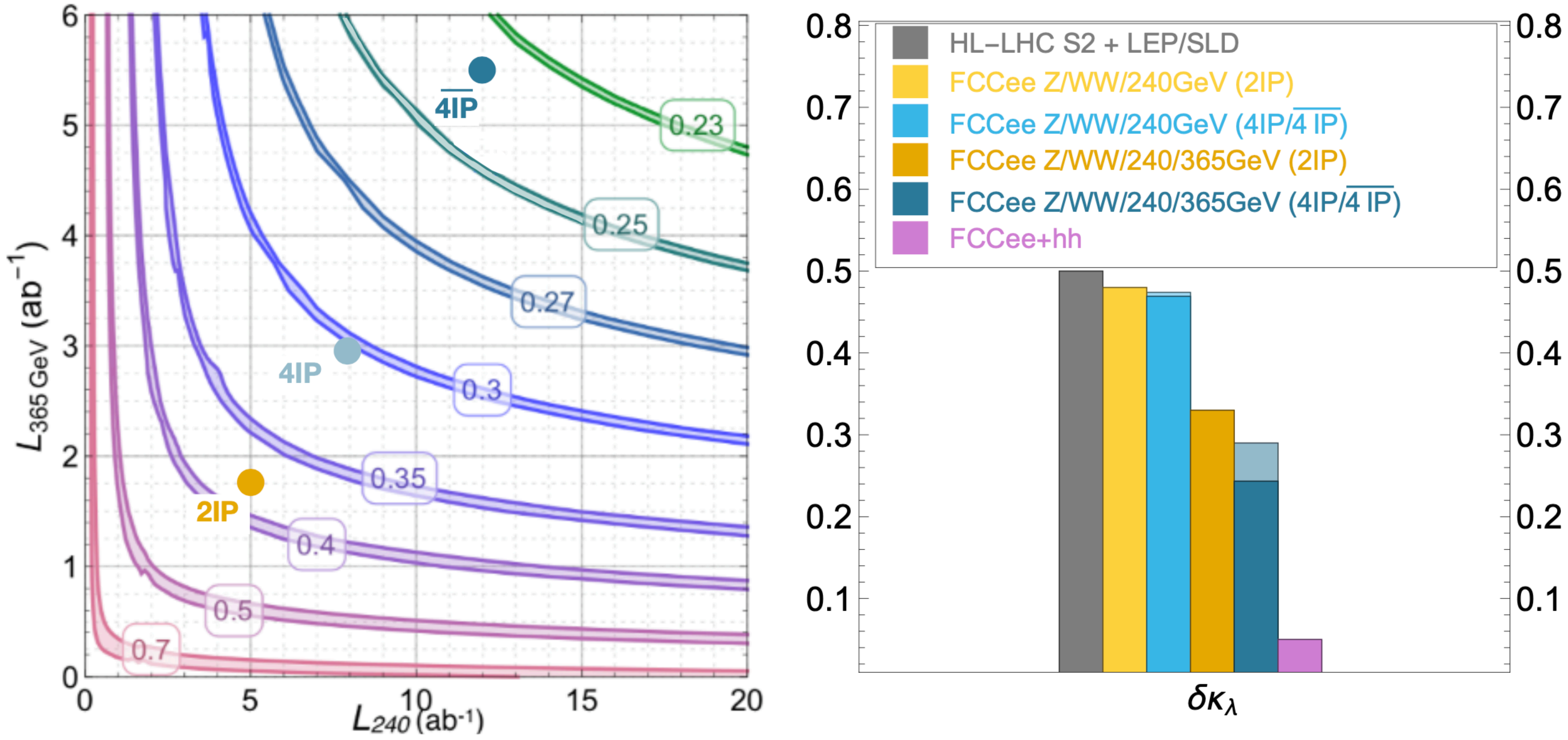
[Durieux, 2024]





[Interim FCC feasibility report, 2024]

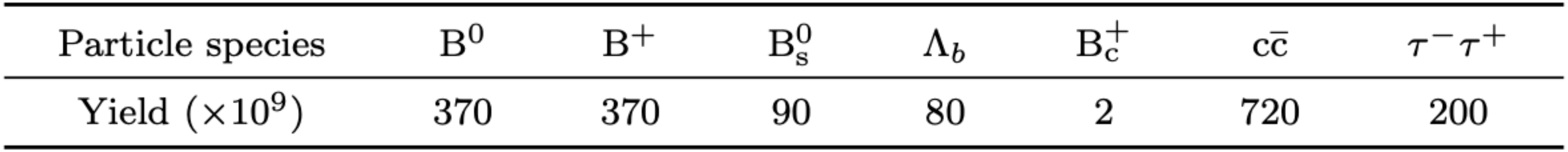
Precision of $\delta\kappa_\lambda$ from EFT global fit (FCC-ee + HL-LHC)



k_λ can be constrained by two measurements and provide competitive info.

Flavour at the Z-pole

Physics potential



Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

Clean environment, with precise momentum of the pair-produced b's, c's and τ from Z decays (as in B-factories), with ~ 10 times more $b\bar{b}$ and $\bar{c}c$ pairs compared to the final Belle-II statistics.

Boosted b's and τ's, leading to significantly higher efficiency (compared to B fac- tories) for modes with missing energy (especially multiple-ν modes) and inclusive modes, and smaller error in lepton ID efficiencies.

1. Rare b-hadron decays with $\tau\bar{\tau}$ pairs in the final state (about 3 orders of magnitude between SM predictions and data).
2. Charged-current b-hadrons decays with a τν pair in the final state.
3. Lepton flavour violating τ decays.
4. Lepton-universality tests in τ decays.

See talks of flavour session on Wed morning

Flavour at the Z-pole

Physics potential

Particle species	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	370	370	90	80	2	720	200

Clean environment, with precise momentum of the pair-produced b's, c's and τ from Z decays (as in B-factories), with ~ 10 times more $b\bar{b}$ and $\bar{c}c$ pairs compared to the final Belle-II statistics.

Boosted b's and τ's, leading to significantly higher efficiency (compared to B fac- tories) for modes with missing energy (especially multiple-ν modes) and inclusive modes, and smaller error in lepton ID efficiencies.

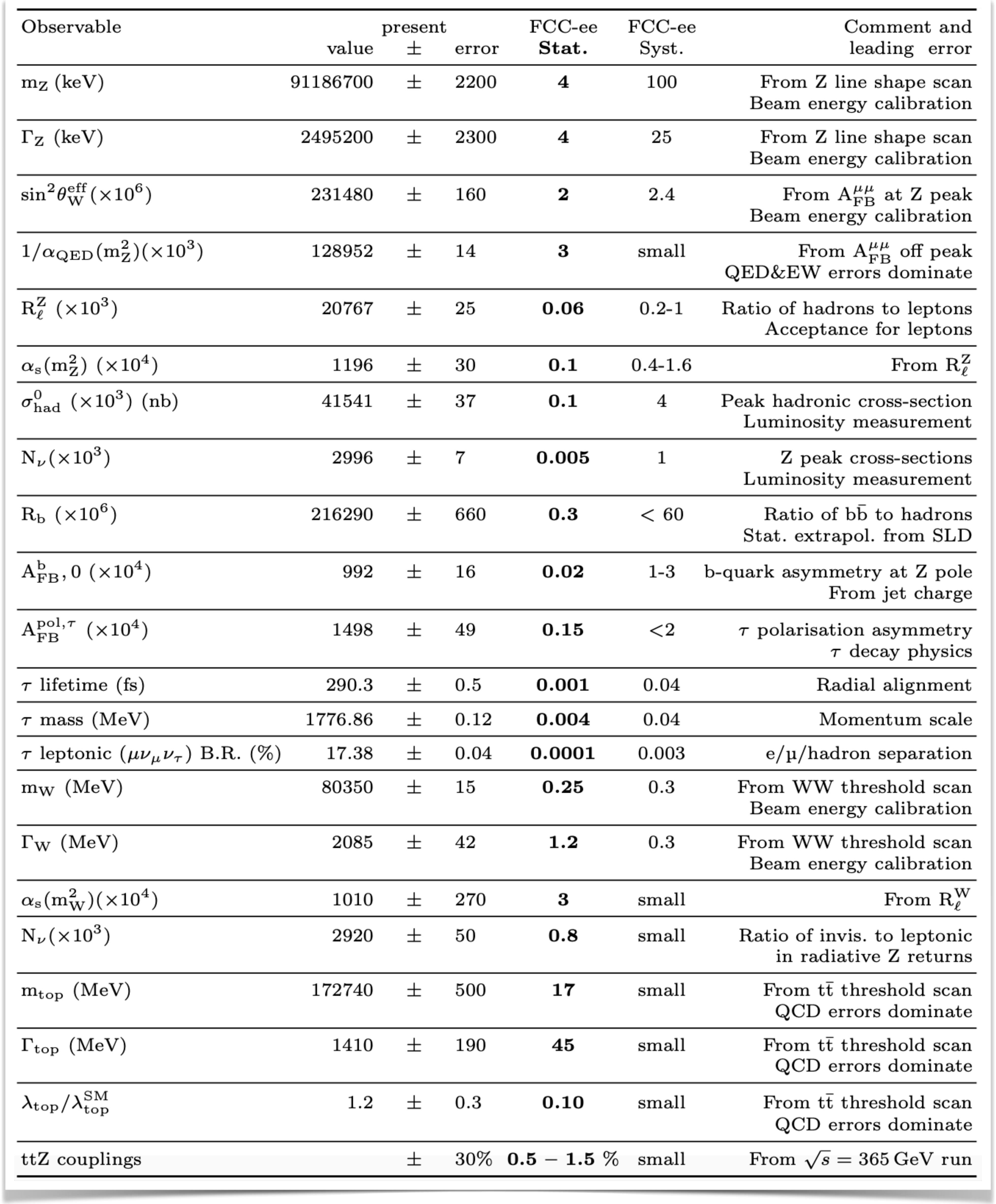
1. Rare b-hadron decays with $\tau\bar{\tau}$ pairs in the final state (about 3 orders of magnitude between SM predictions and data).
2. Charged-current b-hadrons decays with a τν pair in the final state.
3. Lepton flavour violating τ decays.
4. Lepton-universality tests in τ decays.

EWPO

FCC-ee

- Experimental precision of the typical EWPO attainable at FCC-ee runs.
- Improvements in precision typically at level of 2-3 orders of magnitude.
- Sensitivity to NP goes up to10-100 TeV scale
- $5 \cdot 10^{12}$ Z bosons would allow the electroweak precision tests, the KM consistency checks and flavour physics in general, including the study of rare decays, and the search for feebly-interacting particles.
- $5 \cdot 10^{9}$ Z bosons would enough to meet the needs for the HZ run.

[Interim FCC feasibility report, 2024]



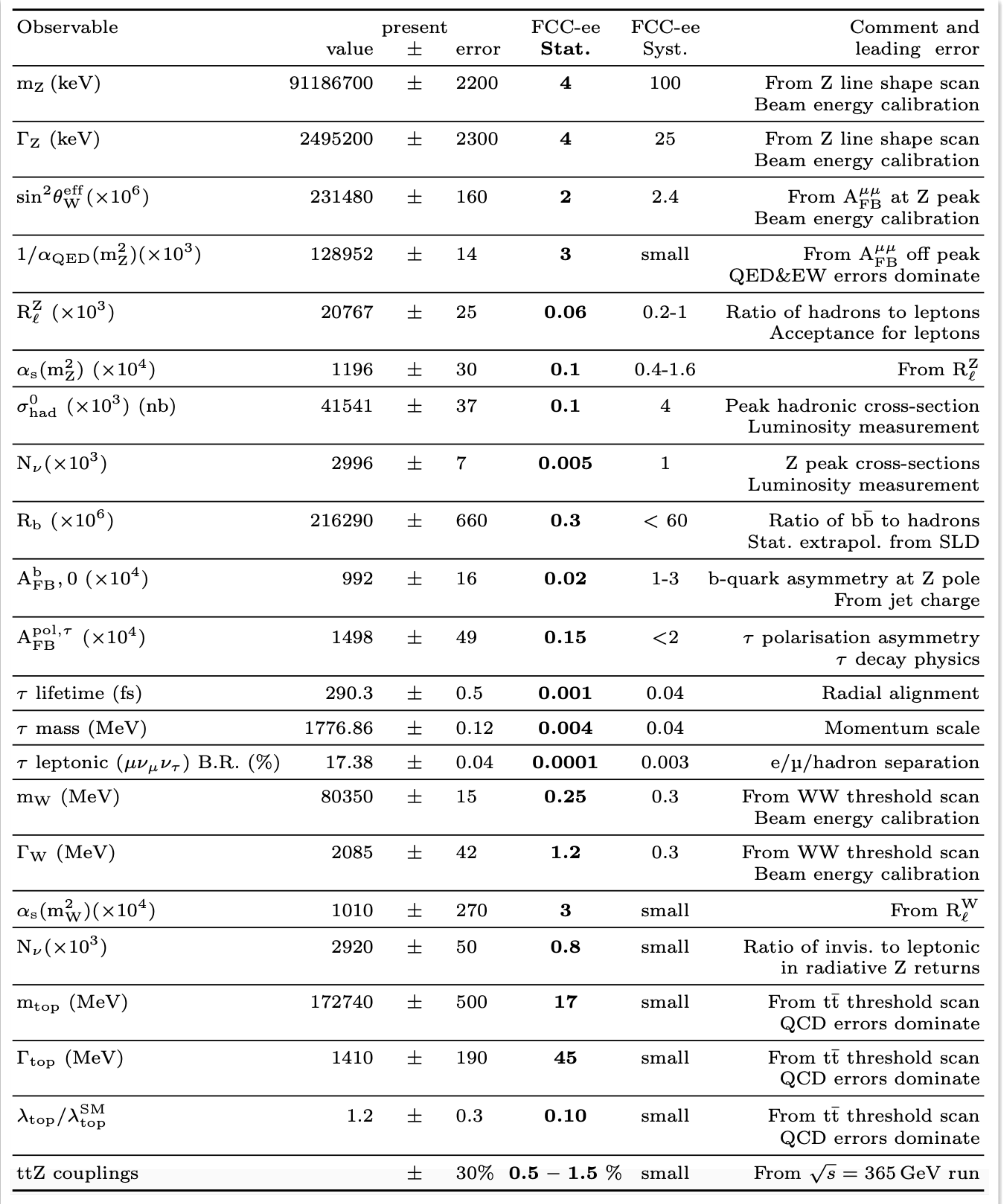
Observable		present		FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\mathrm{eff}}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\mathrm{QED}}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{\mathrm{pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\mathrm{top}}/\lambda_{\mathrm{top}}^{\mathrm{SM}}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5** %	small	From $\sqrt{s} = 365\,\mathrm{GeV}$ run

See talks on precision on TUE morning

EWPO

FCC-ee

- Experimental precision of the typical EWPO attainable at FCC-ee runs.
- Improvements in precision typically at level of 2-3 orders of magnitude.
- Sensitivity to NP goes up to10-100 TeV scale
- $5 \cdot 10^{12}$ Z bosons would allow the electroweak precision tests, the KM consistency checks and flavour physics in general, including the study of rare decays, and the search for feebly-interacting particles.
- $5 \cdot 10^{9}$ Z bosons would enough to meet the needs for the HZ run.



Observable	present			FCC-ee	FCC-ee	Comment and
	value	±	error	**Stat.**	Syst.	leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
σ_{had}^0 $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross-section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross-sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

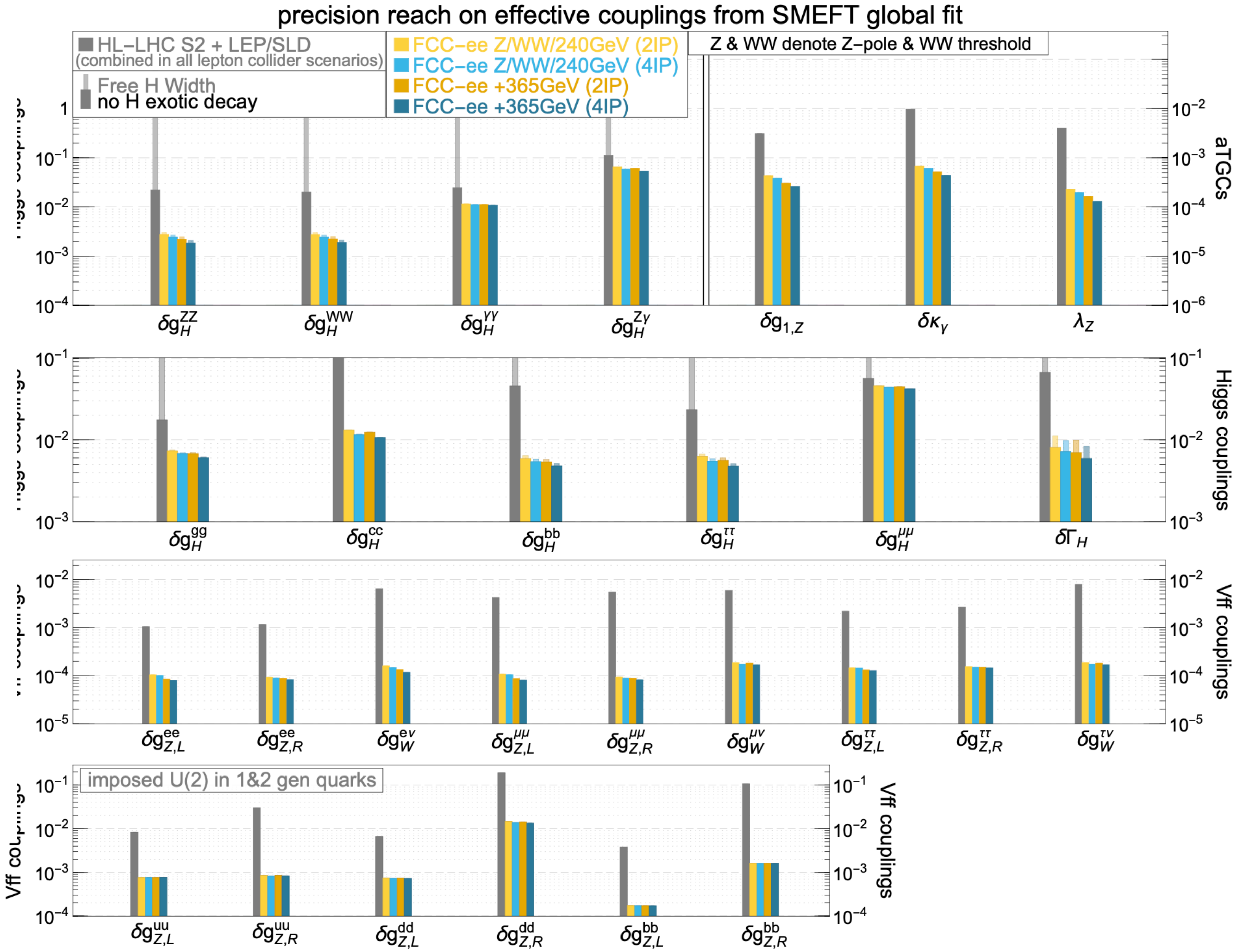
[Interim FCC feasibility report, 2024]

Global fits

FCC-ee

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR}_{\mathrm{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR}_{\mathrm{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

[Interim FCC feasibility report, 2024]


precision reach on effective couplings from SMEFT global fit

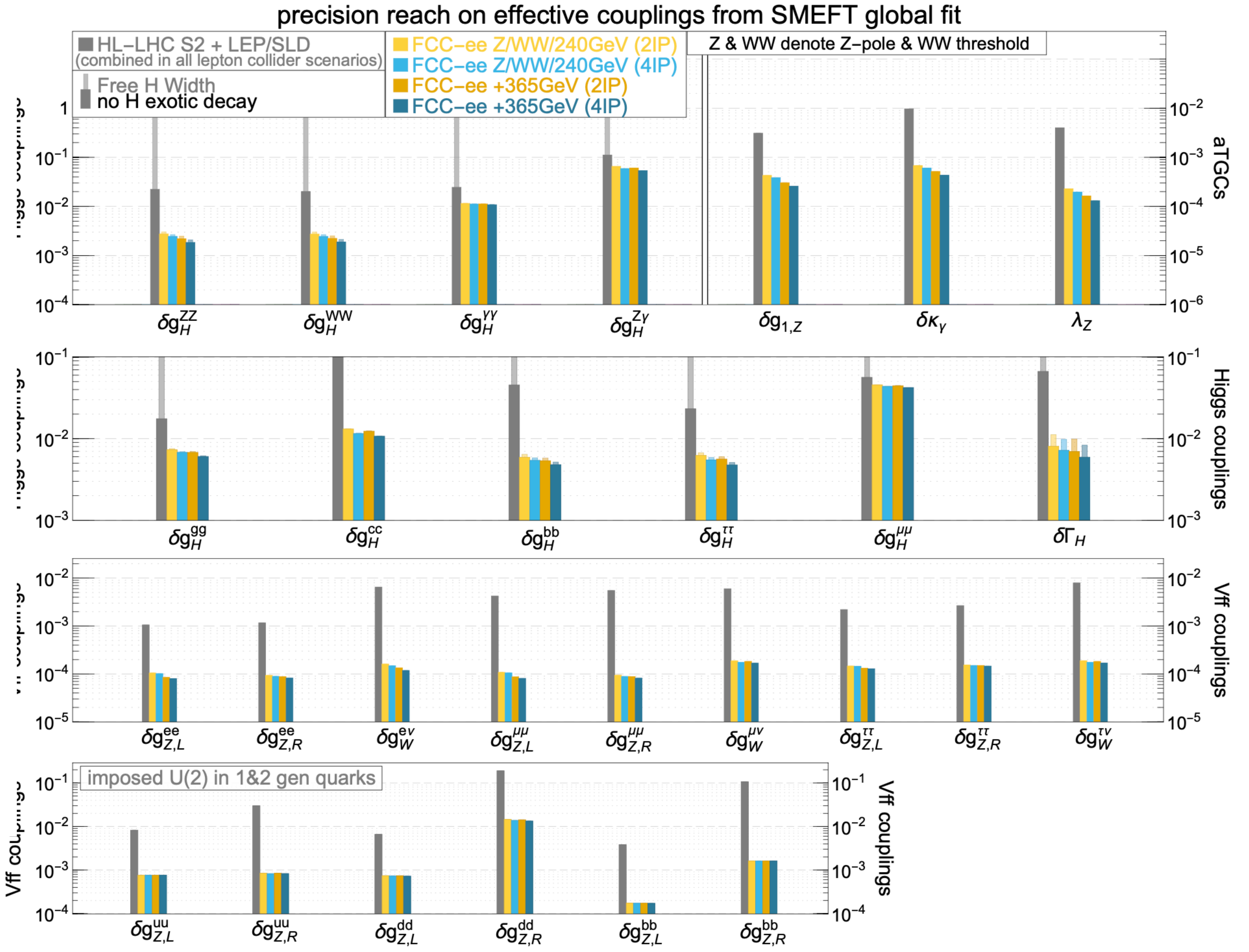
See talks on TUE morning

Global fits

FCC-ee

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

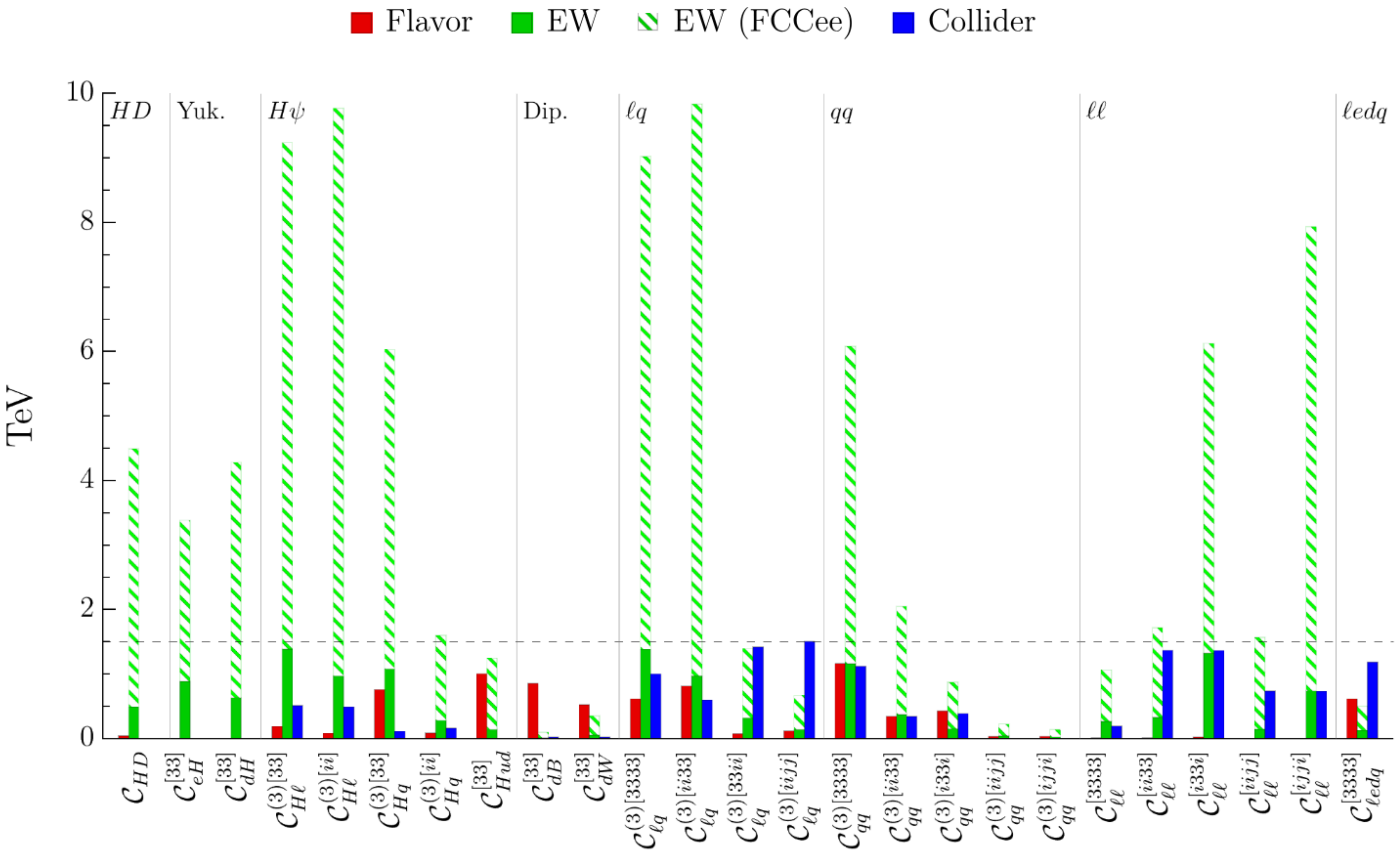
[Interim FCC feasibility report, 2024]



[Allwicher et al. 2311.00020]

Global fit w/ flavour

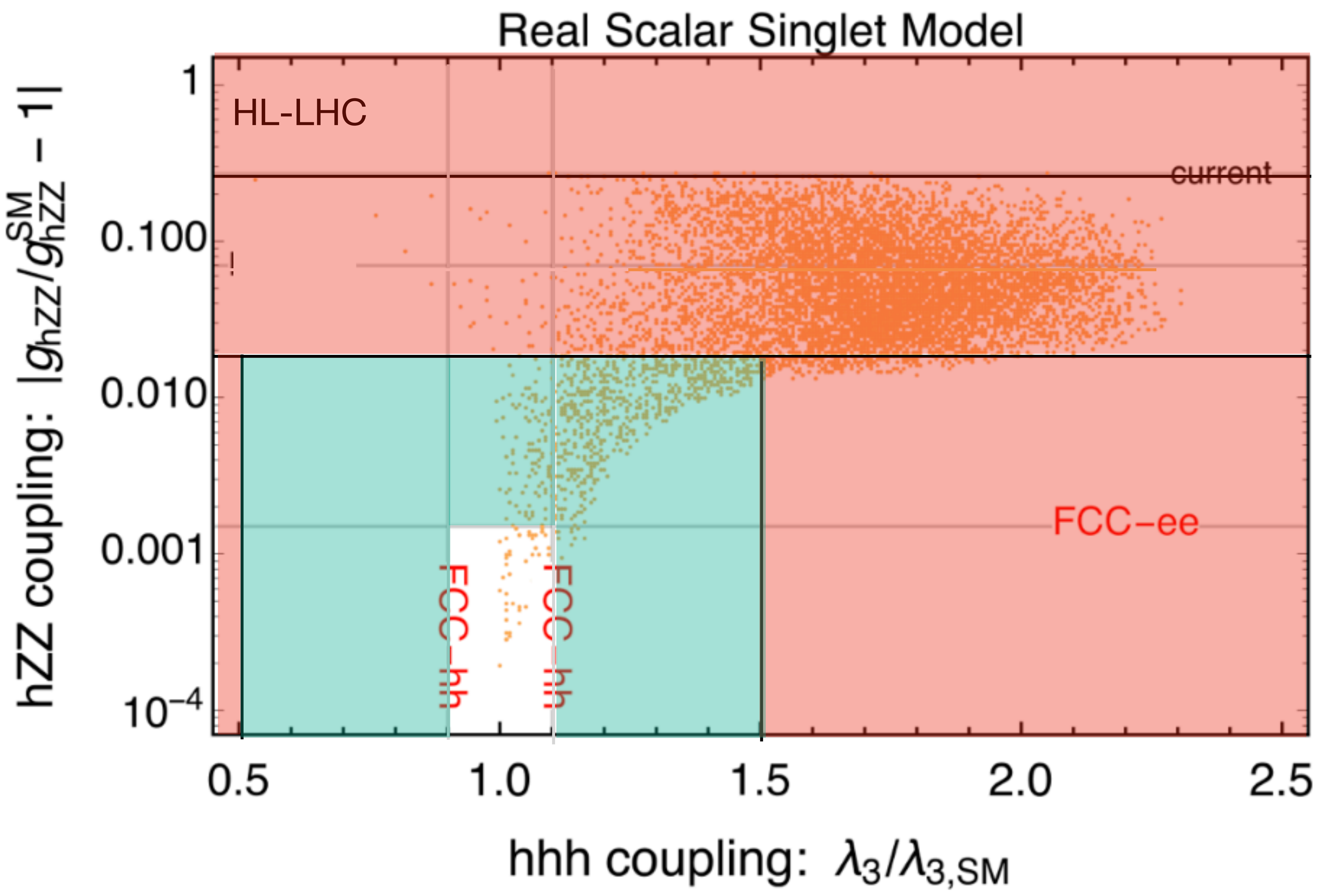
FCC-ee



[Interim FCC feasibility report, 2024]

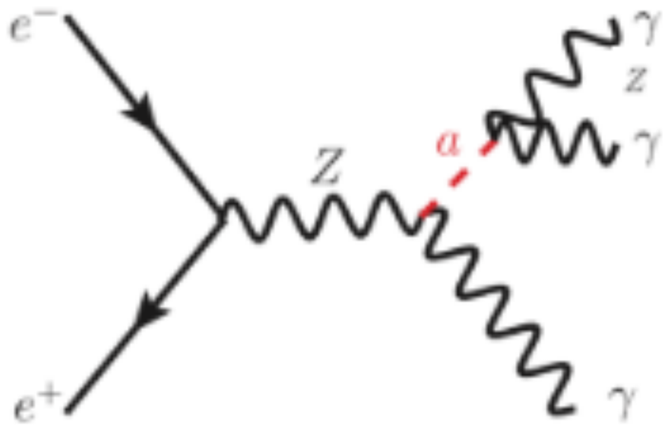
Scalar singlet

FCC-ee (and FCC-hh)

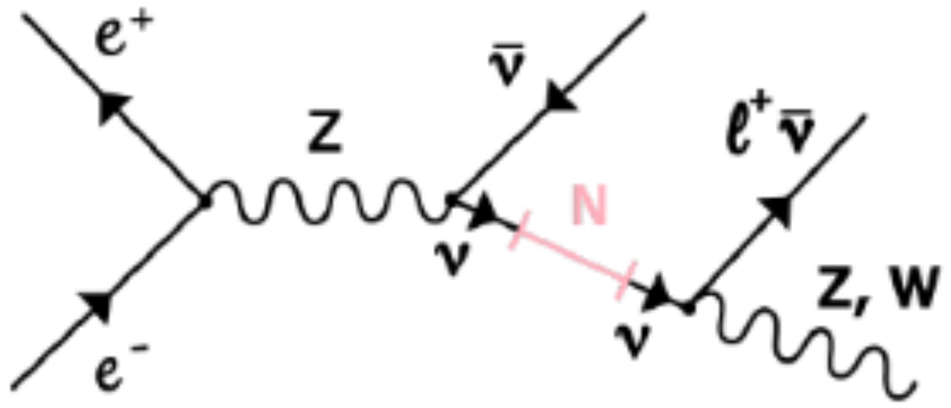


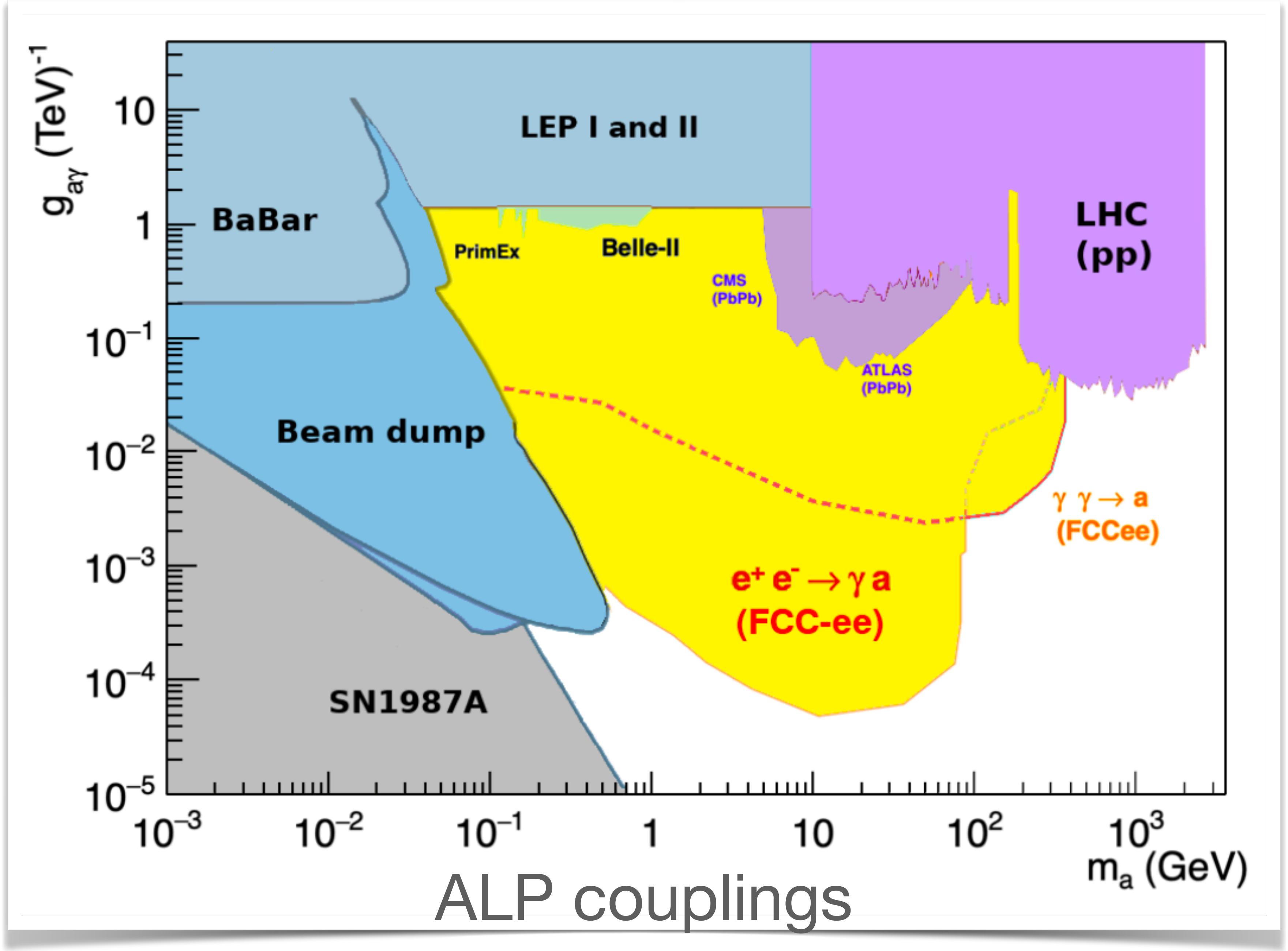
Alps and ν_R's

FCC-ee

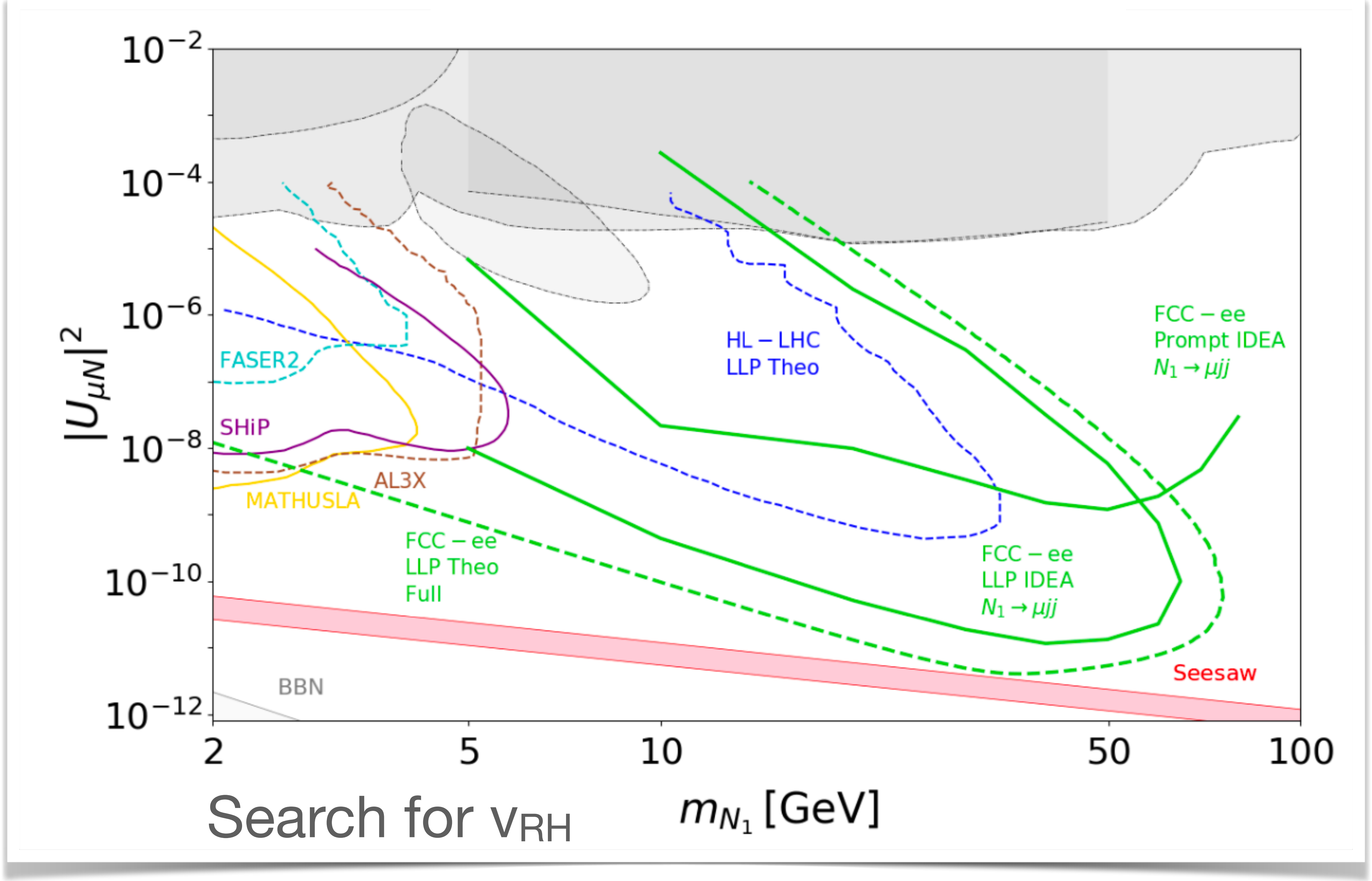


[Interim FCC feasibility report, 2024]





ALP couplings

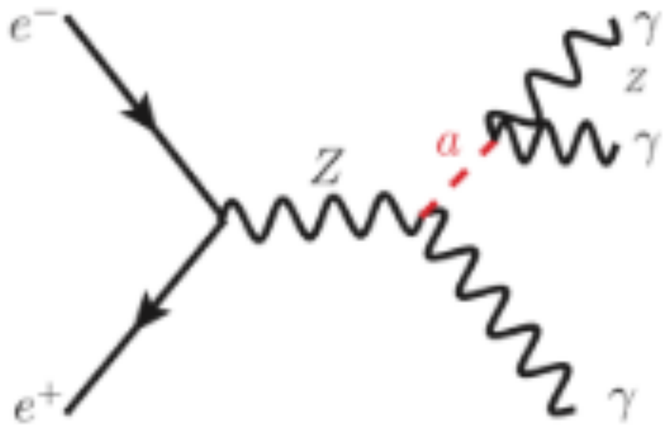


Search for ν_{RH}

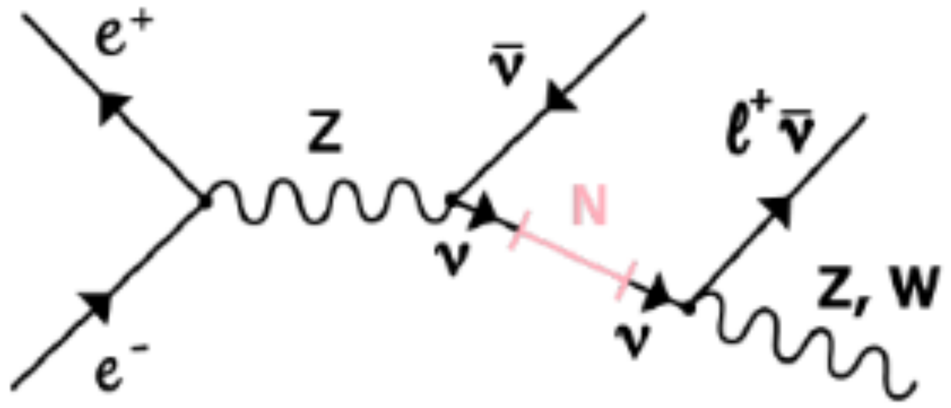
See talks in the BSM section on WED afternoon

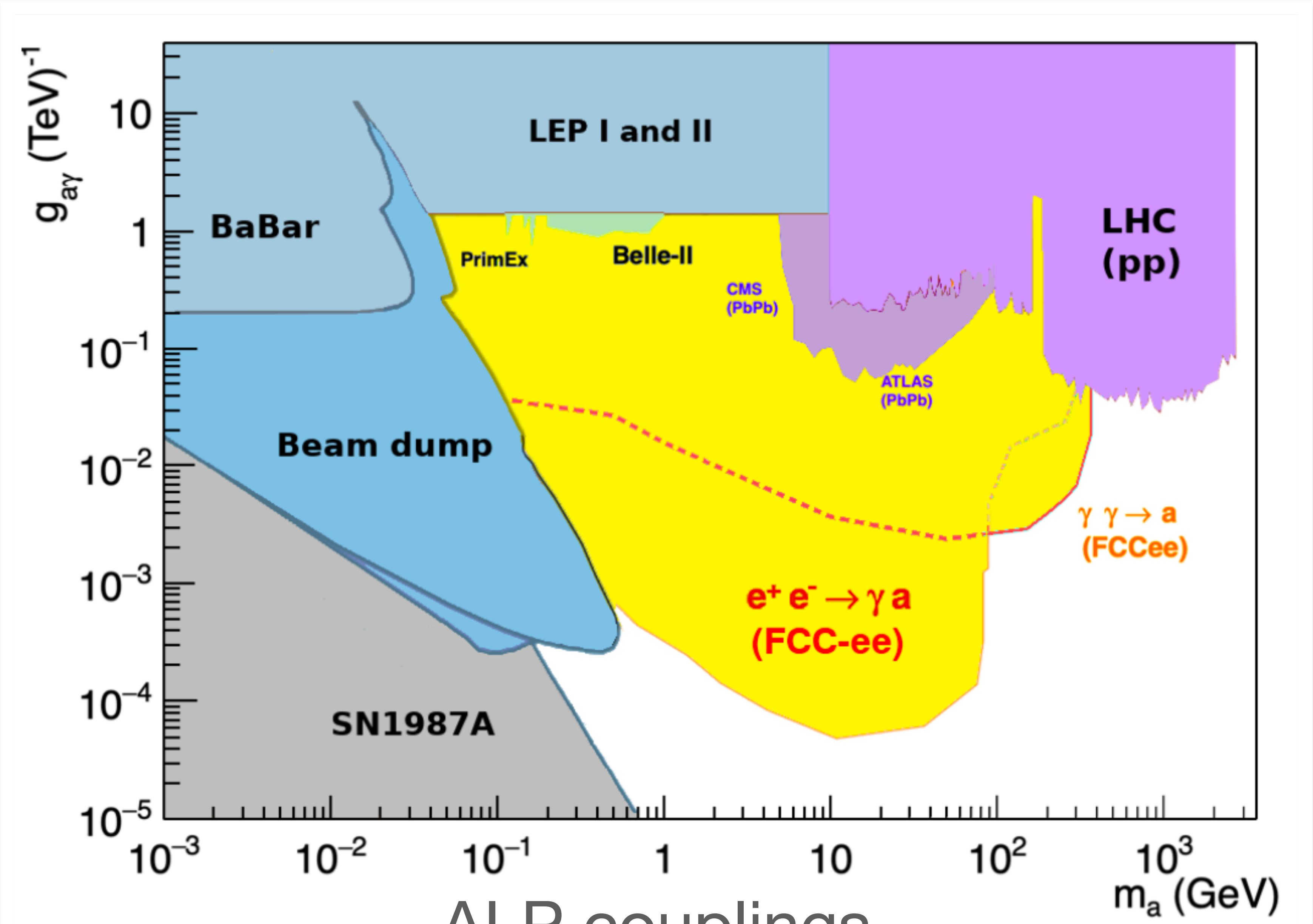
Alps and $\nu'_R s$

FCC-ee

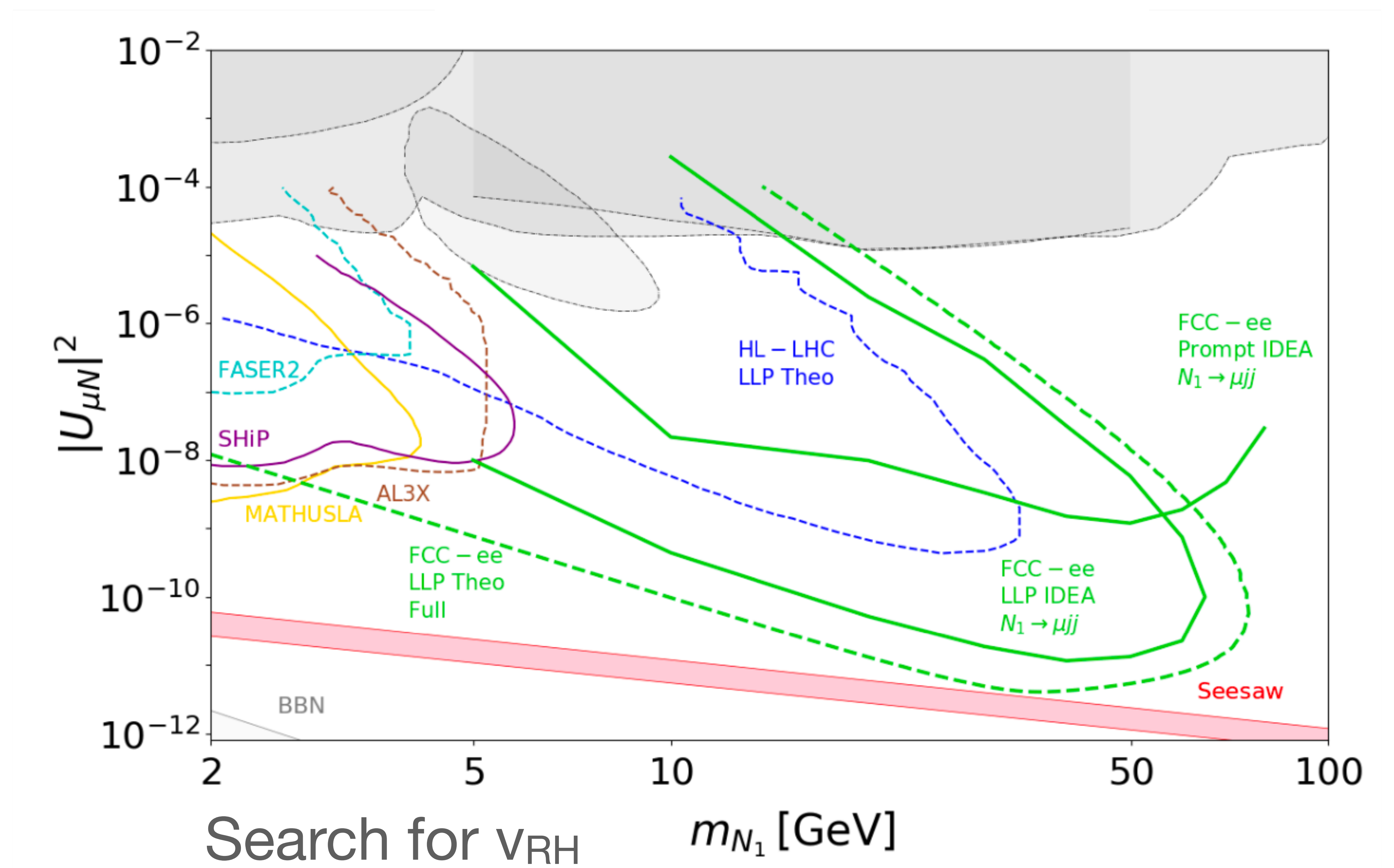


[Interim FCC feasibility report, 2024]





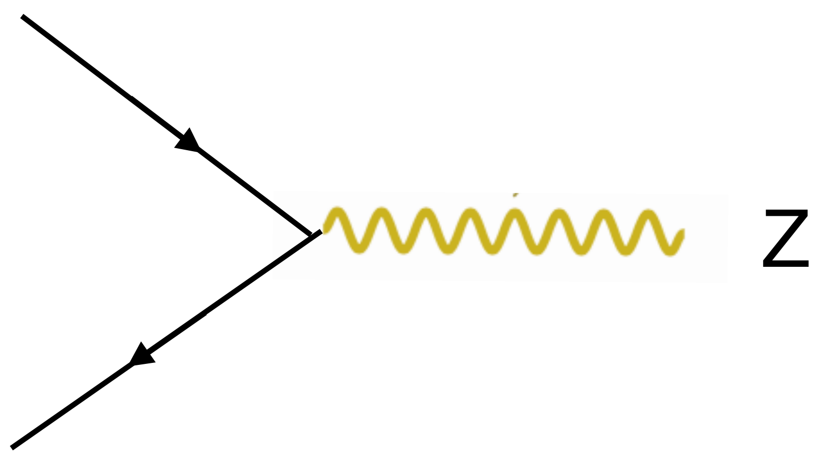
ALP couplings

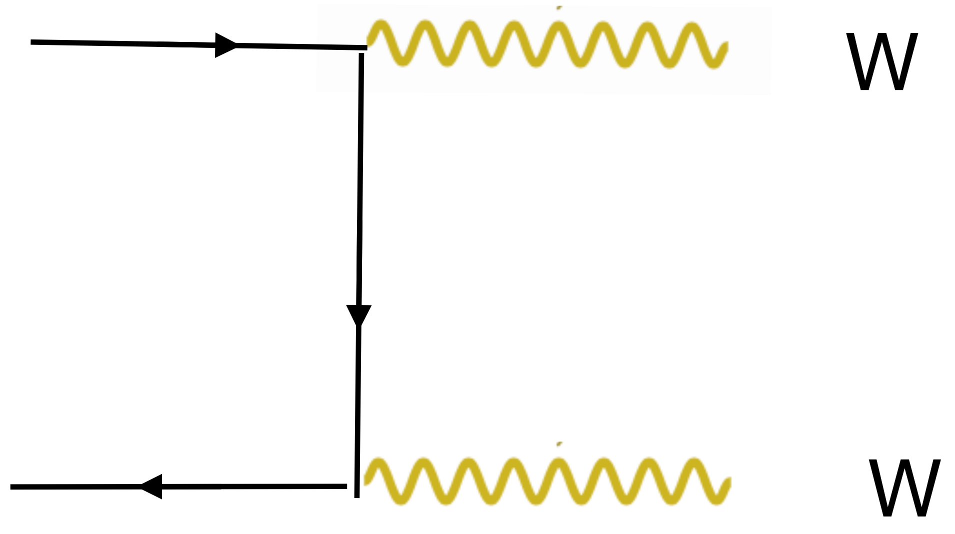


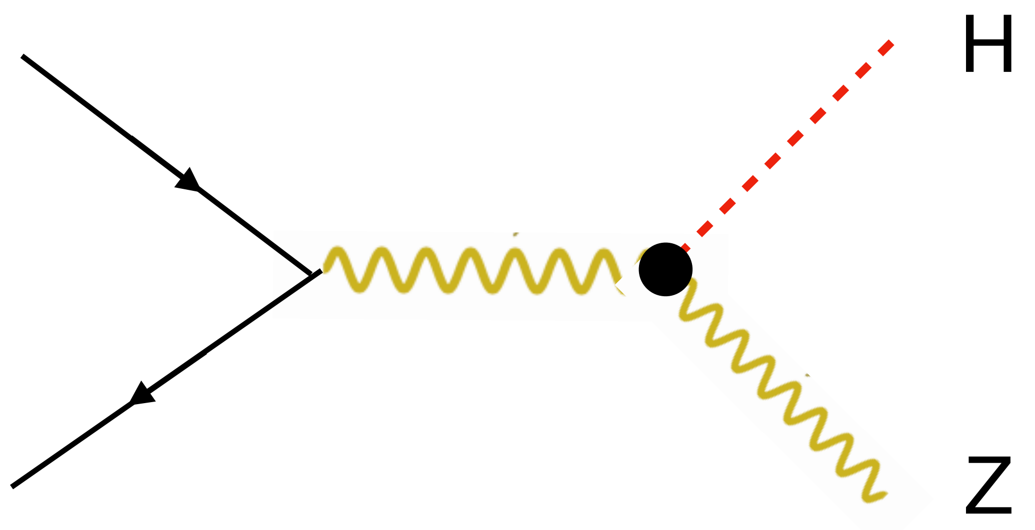
Search for ν_{RH}

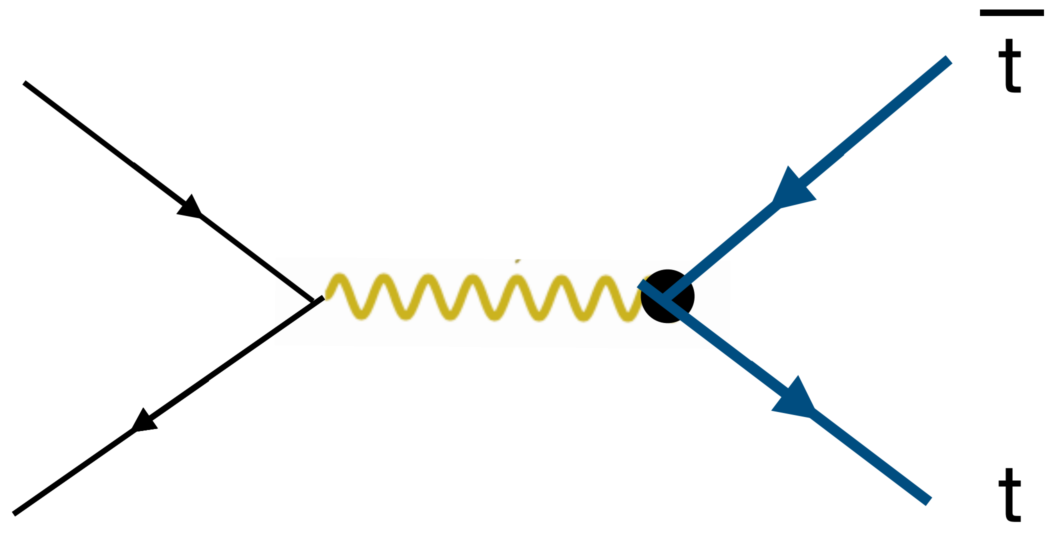
Precision calculations for weak scale factories

The workhorses









Z-pole observables. Need for NNLO EW in $2 \to 2$ scatterings and N3LO for $2 \to 1$. The current use and definition of PO's will need to be reconsidered.

Known at NLO in EW with W decays. In order to determine mW at 1 MeV needs to be known at the subpermill level. NNLO EW computation involves many scales. In addition an EFT treatment of the W threshold is necessary.

Workhorse for H studies. Known at NLO in EW with Z decays. NNLO correct. Gives access to trilinear and top-Yukawa at one loop and quadrilinear Higgs self-couplings and others at two loops.

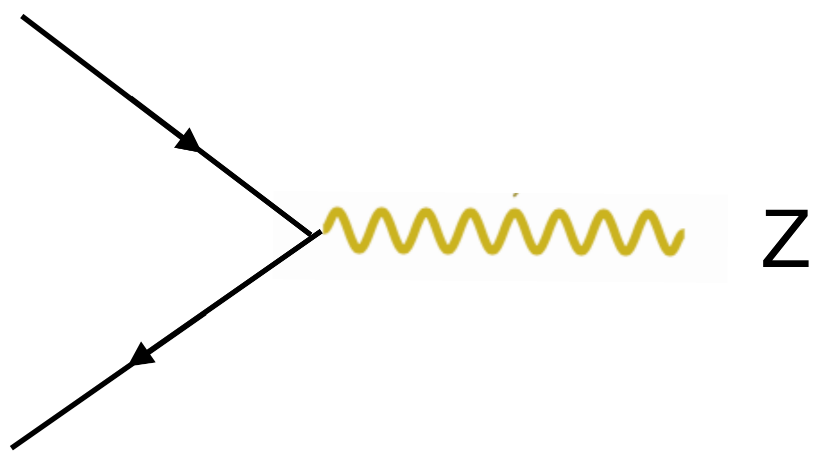
Known at N3LO in the NRQCD EFT approach at threshold for top mass and width determination. NLO QCD corrections for the 2->6 known. NNLO EW corrections are not known.

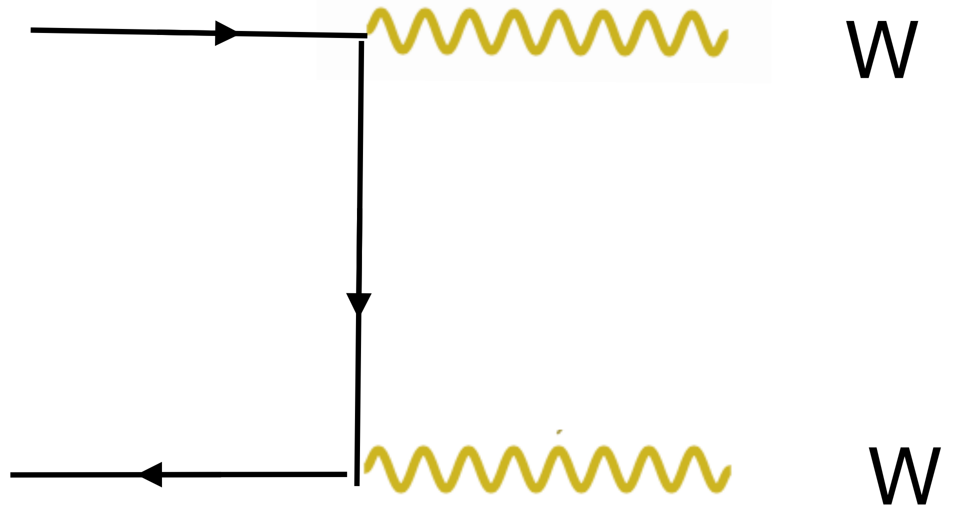
In addition ISR effects, collinear and soft need to be included.

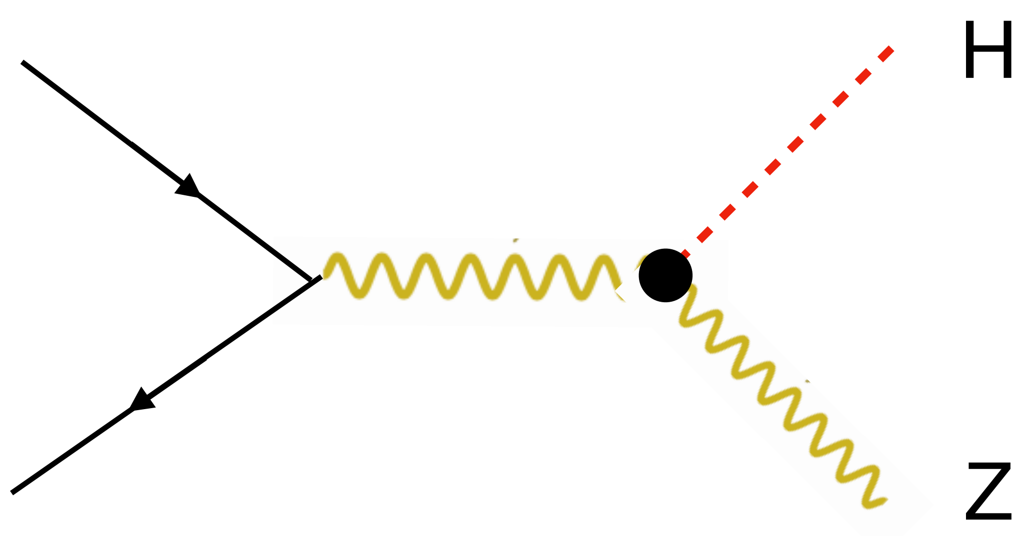
See TUE morning session

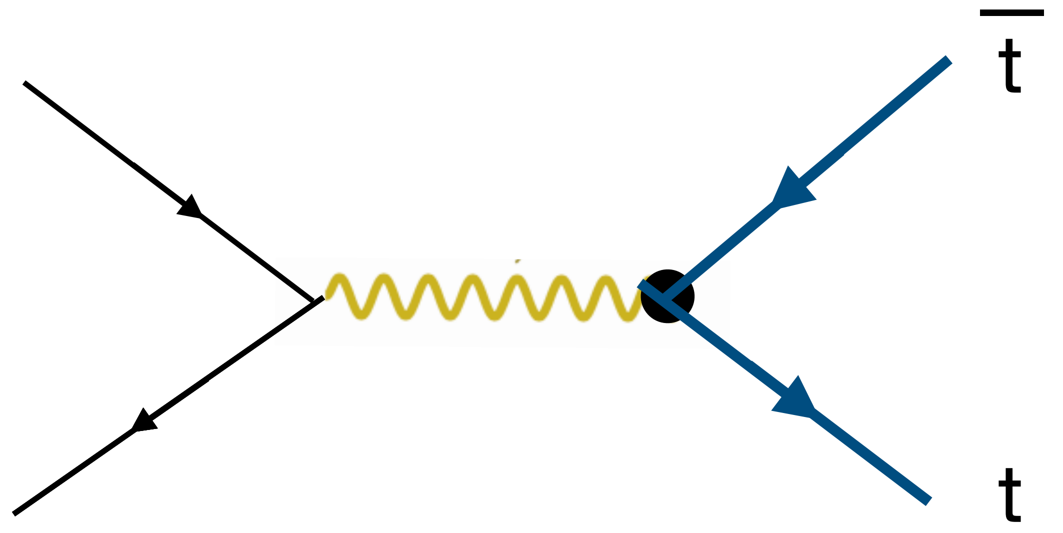
Precision calculations for weak scale factories

The workhorses









Z-pole observables. Need for NNLO EW in $2 \to 2$ scatterings and N3LO for $2 \to 1$. The current use and definition of PO's will need to be reconsidered.

Known at NLO in EW with W decays. In order to determine mW at 1 MeV needs to be known at the subpermill level. NNLO EW computation involves many scales. In addition an EFT treatment of the W threshold is necessary.

Workhorse for H studies. Known at NLO in EW with Z decays. NNLO correct. Gives access to trilinear and top-Yukawa at one loop and quadrilinear Higgs self-couplings and others at two loops.

Known at N3LO in the NRQCD EFT approach at threshold for top mass and width determination. NLO QCD corrections for the 2->6 known. NNLO EW corrections are not known.

In addition ISR effects, collinear and soft need to be included.

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e+e- ILC 250

e+e- ILC 500

e+e- ILC 1000

A

e+e- FCC-ee : 91,240,365 GeV

FCC-hh

FCC-eh with ERL

LHC

HL-LHC

FCC-hh at 80 TeV with 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

2025

Near future

2050

Future

2075

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e

C 1000

A

LHC

HL-LHC

GeV

FCC-hh

-eh with ERL

h 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

ee pp ee pp ee pp

The binary strategy

2025 Near future 2050 Future 2075

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e

C 1000

A

GeV

FCC-hh

-eh with ERL

LHC

HL-LHC

h 14T magnets

B’s

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

ee pp ee pp ee pp ee pp

The binary strategy

2025 Near future 2050 Future 2075

Timeline(s)

To be taken cum grano salis

SuperKEKB

e+e- CEPC

pp CEPC

e

C 1000

CERN

A

GeV

FCC-hh

-eh with ERL

LHC

HL-LHC

h 14T magnets

B's

LEP3 with Lumi=1/5 Lumi FCC-ee

LHeC with ERL

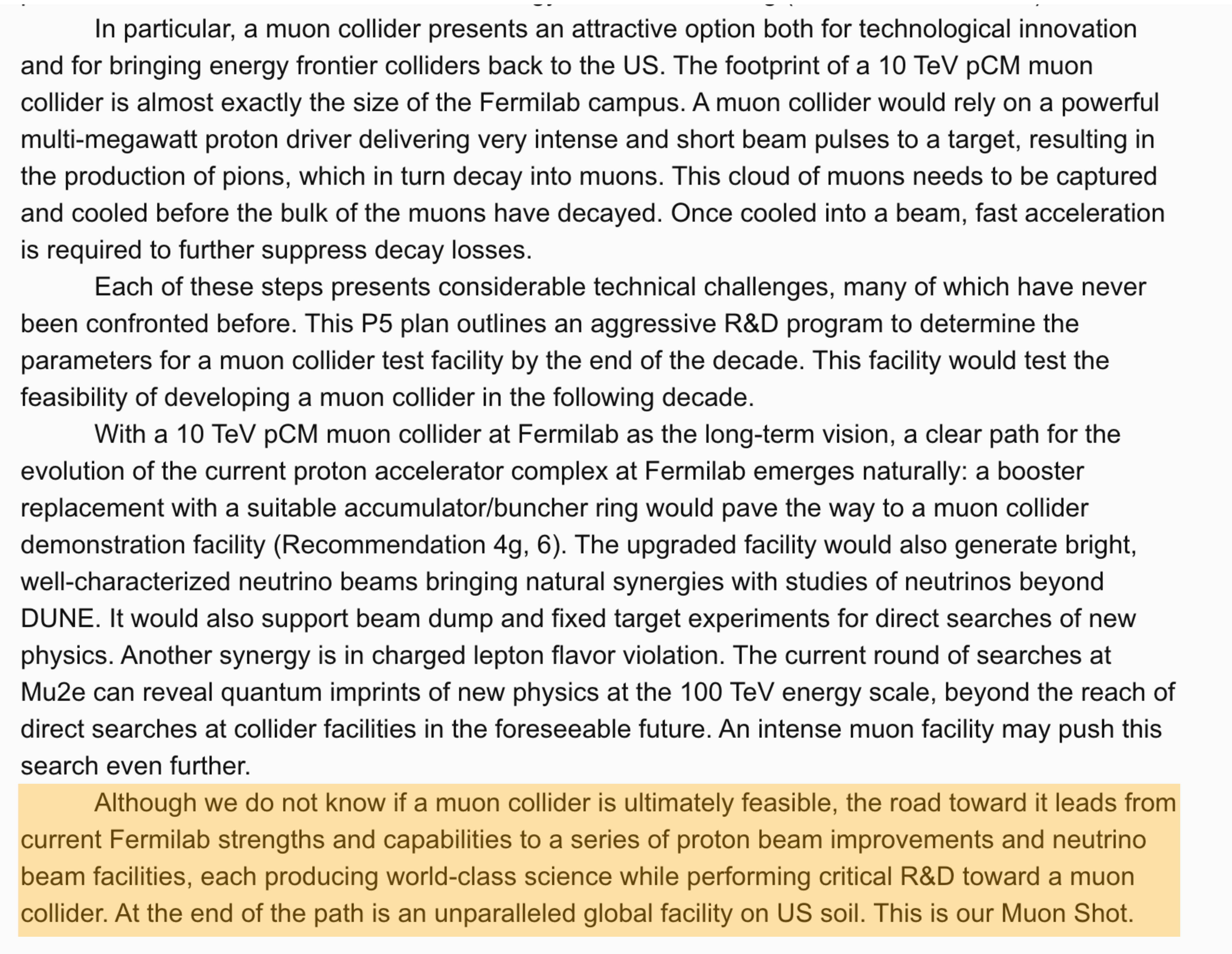
ee pp ee pp ee pp μC

The non-binary strategy

2025 Near future 2050 Future 2075

The muon shot

P5:

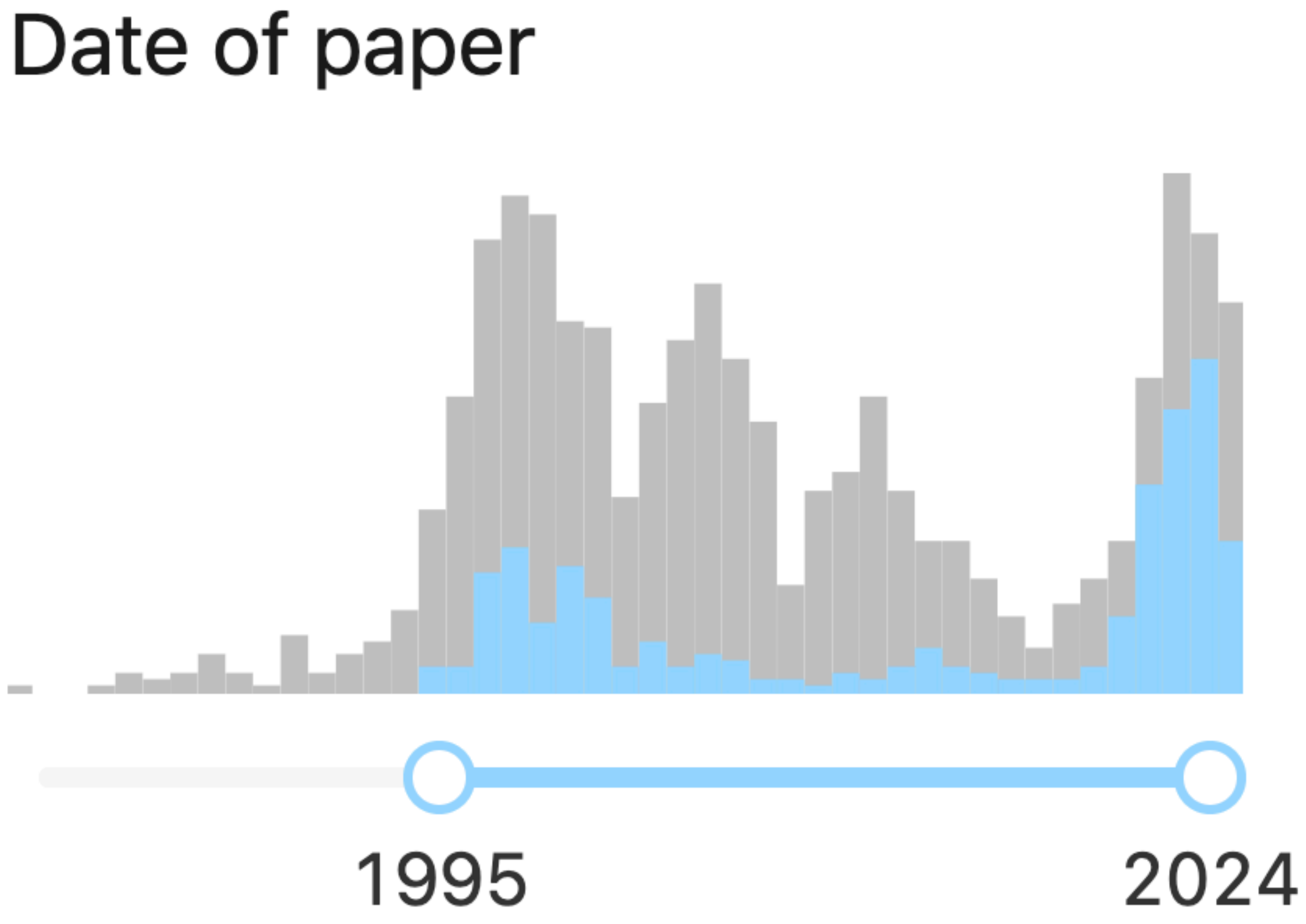


In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

Each of these steps presents considerable technical challenges, many of which have never been confronted before. This P5 plan outlines an aggressive R&D program to determine the parameters for a muon collider test facility by the end of the decade. This facility would test the feasibility of developing a muon collider in the following decade.

With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal quantum imprints of new physics at the 100 TeV energy scale, beyond the reach of direct searches at collider facilities in the foreseeable future. An intense muon facility may push this search even further.

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.

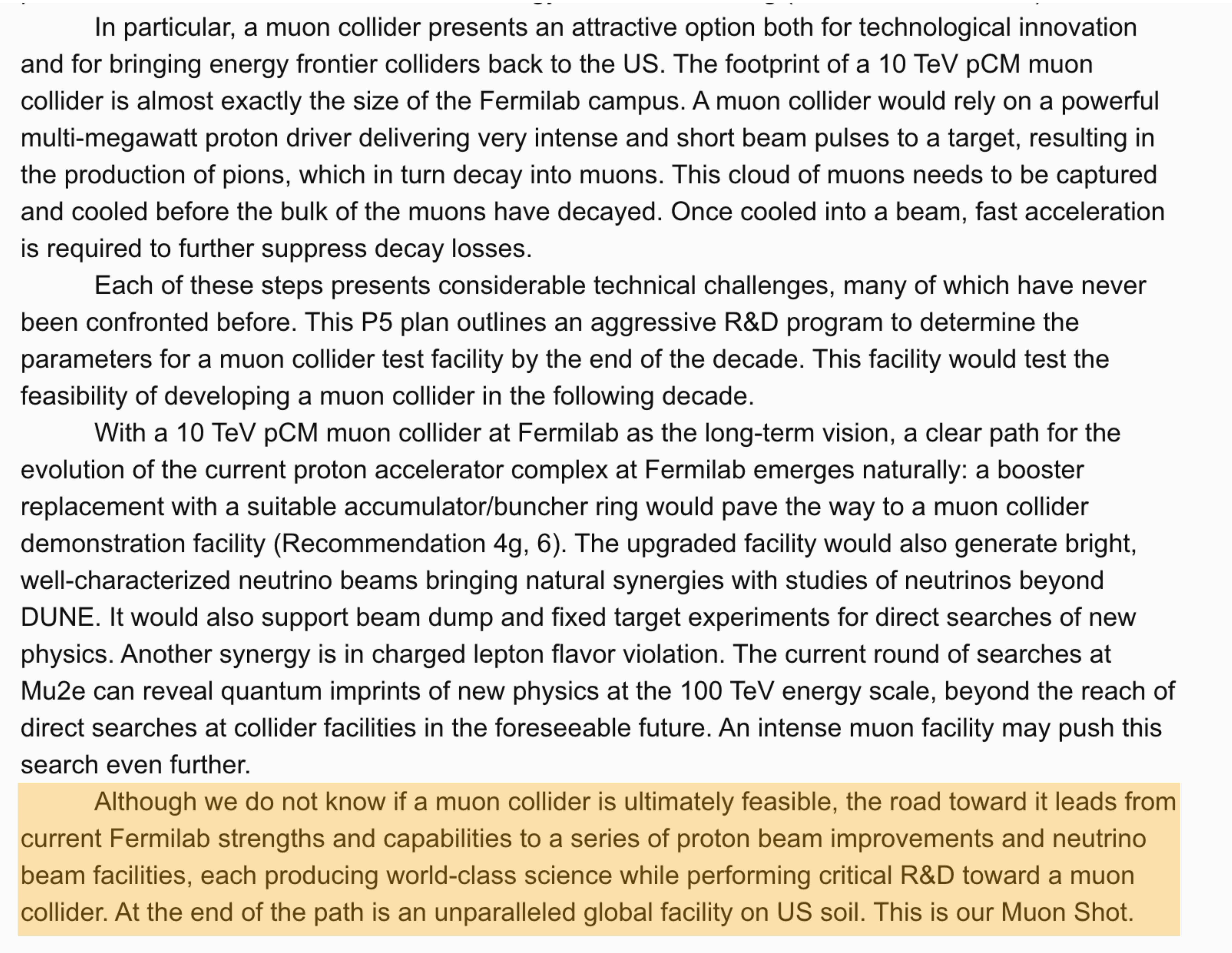


122 pheno papers in the last 5 years

See THU afternoon session

The muon shot

P5:

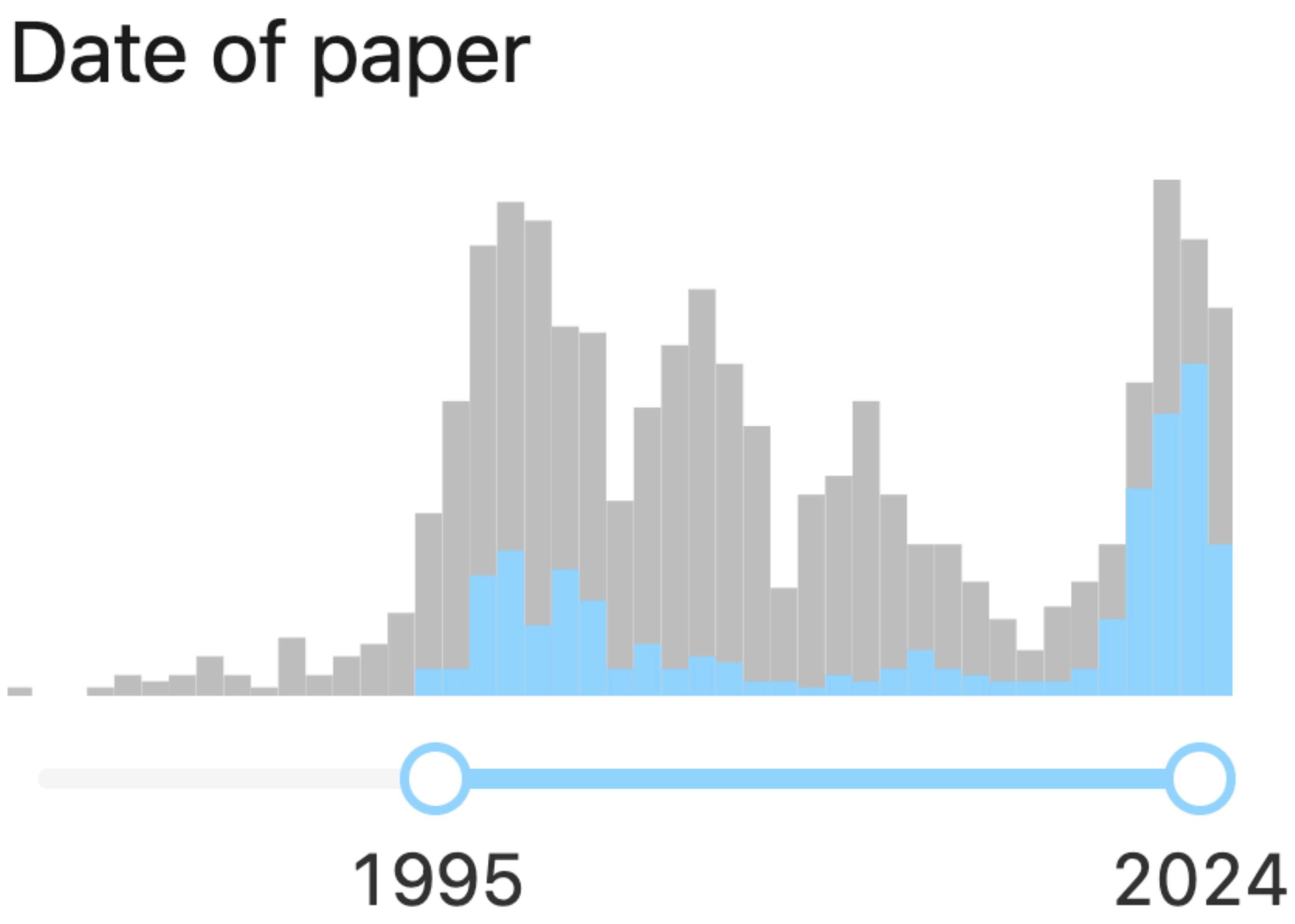


In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

Each of these steps presents considerable technical challenges, many of which have never been confronted before. This P5 plan outlines an aggressive R&D program to determine the parameters for a muon collider test facility by the end of the decade. This facility would test the feasibility of developing a muon collider in the following decade.

With a 10 TeV pCM muon collider at Fermilab as the long-term vision, a clear path for the evolution of the current proton accelerator complex at Fermilab emerges naturally: a booster replacement with a suitable accumulator/buncher ring would pave the way to a muon collider demonstration facility (Recommendation 4g, 6). The upgraded facility would also generate bright, well-characterized neutrino beams bringing natural synergies with studies of neutrinos beyond DUNE. It would also support beam dump and fixed target experiments for direct searches of new physics. Another synergy is in charged lepton flavor violation. The current round of searches at Mu2e can reveal quantum imprints of new physics at the 100 TeV energy scale, beyond the reach of direct searches at collider facilities in the foreseeable future. An intense muon facility may push this search even further.

Although we do not know if a muon collider is ultimately feasible, the road toward it leads from current Fermilab strengths and capabilities to a series of proton beam improvements and neutrino beam facilities, each producing world-class science while performing critical R&D toward a muon collider. At the end of the path is an unparalleled global facility on US soil. This is our Muon Shot.



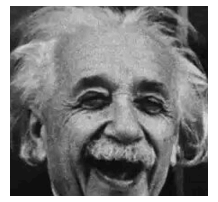
122 pheno papers in the last 5 years

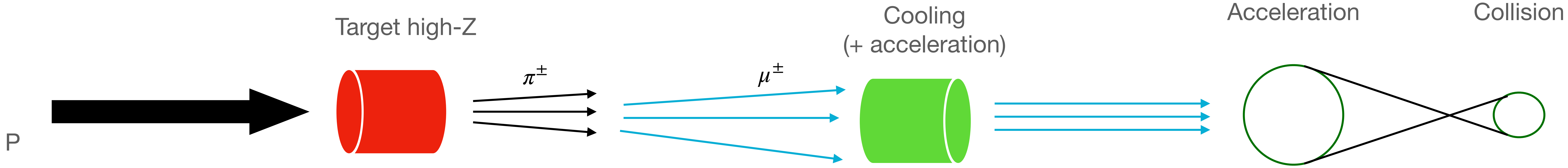
Basic elements

1. m_μ = 105 MeV $\Rightarrow P_\mu = \left(\frac{m_e}{m_\mu}\right)^4 P_e \Rightarrow$ up to 10-14 TeV syncrotron radiation is not a problem 🙂

2. $\tau_\mu = 2.2 \cdot 10^{-6} s \Rightarrow$ it decays very fast

3. $\gamma = 10^4 \Rightarrow t_\mu = 2.2 \cdot 10^{-2} s \Rightarrow$ $6.6 \cdot 10^3\,\mathrm{Km} = 660$ turns

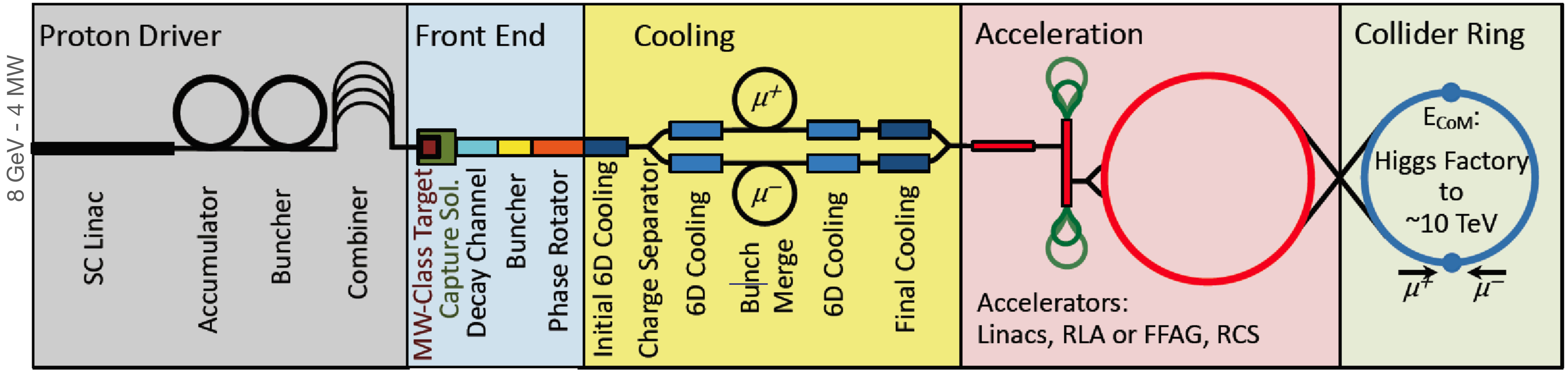




A new interest in a multi-TeV muon collider

Why?

Technology: new generation of accelerator technologies.
No known showstoppers.



Short, intense proton bunch

Protons produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

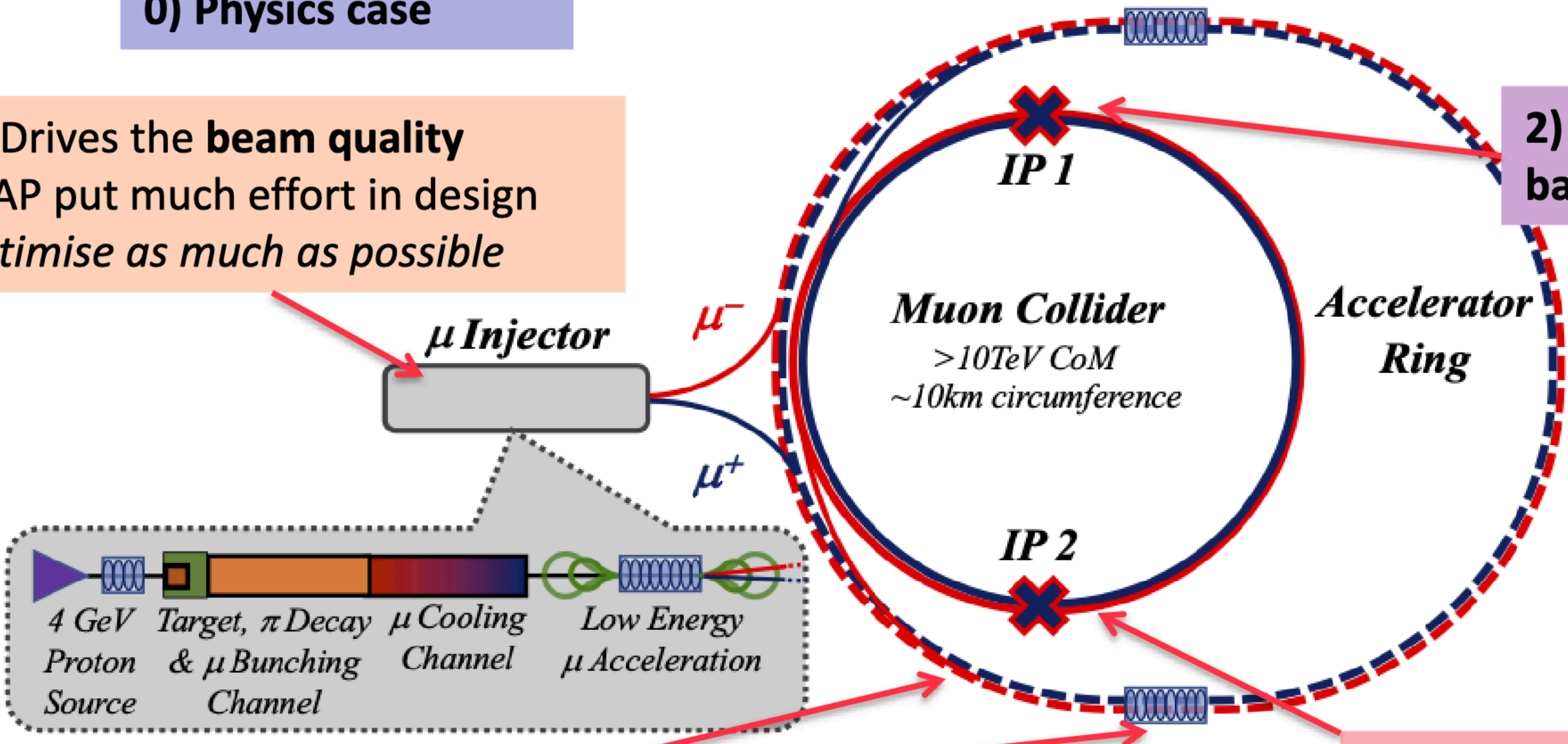
Collision

2407.12450 Muon Collider Interim Report

Key Challenges

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background

1) Dense neutrino flux
mitigated by mover system and site selection

3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

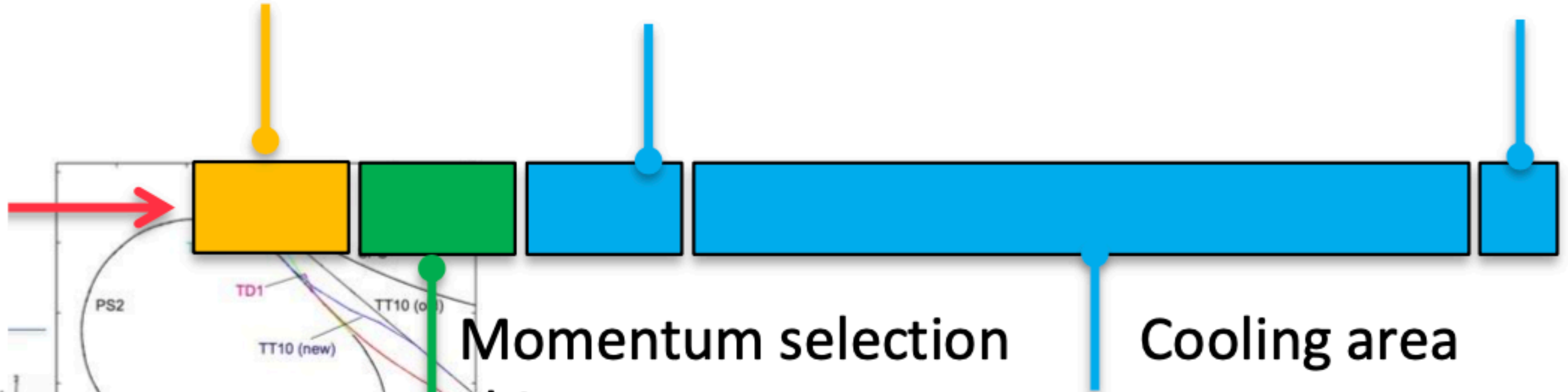
Demonstrator

Planning **demonstrator** facility with muon production target and cooling stations

Suitable **site exists** on CERN land and can use **PS proton beam**

- could combine with **NuStorm** or other option

Other sites should be explored (FNAL?)



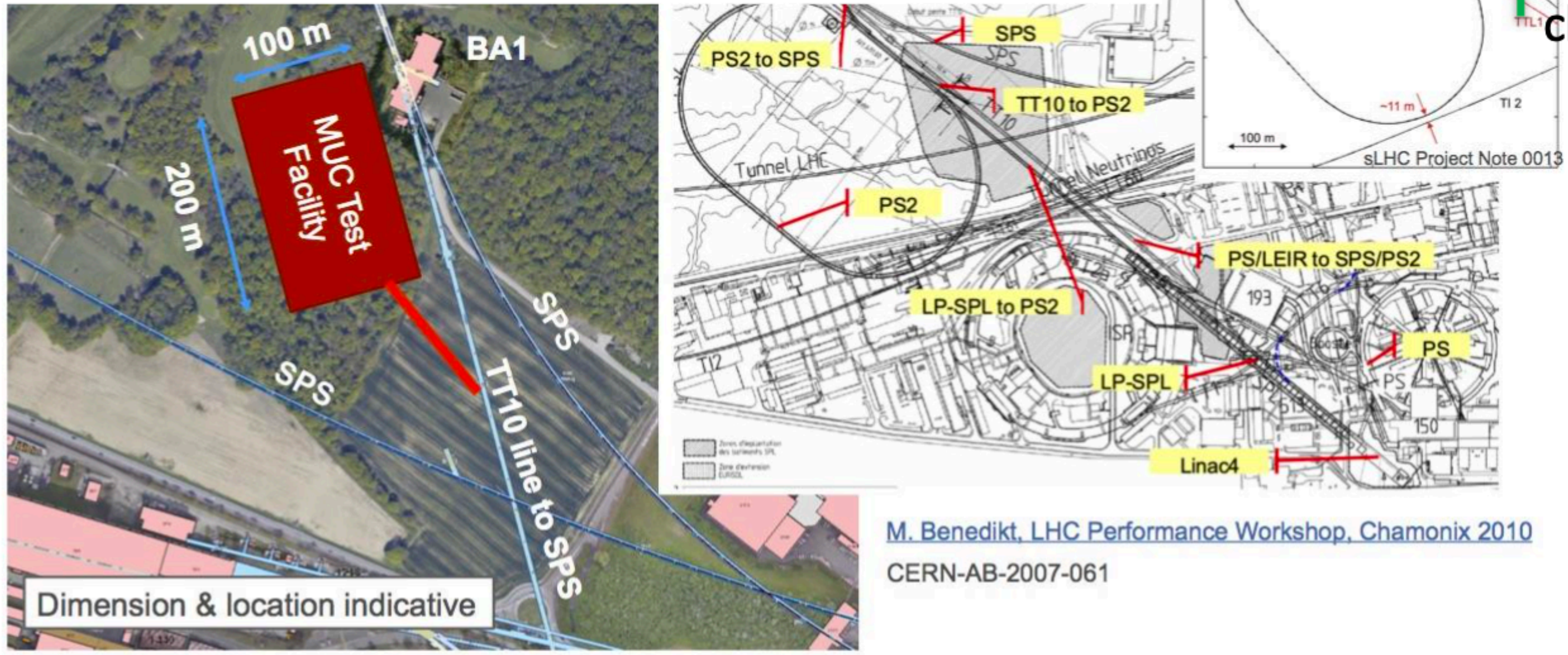
Target
+ horn (1st phase) /
+ superconducting solenoid (2nd phase)

Collimation and upstream diagnostics area

Downstream diagnostics area

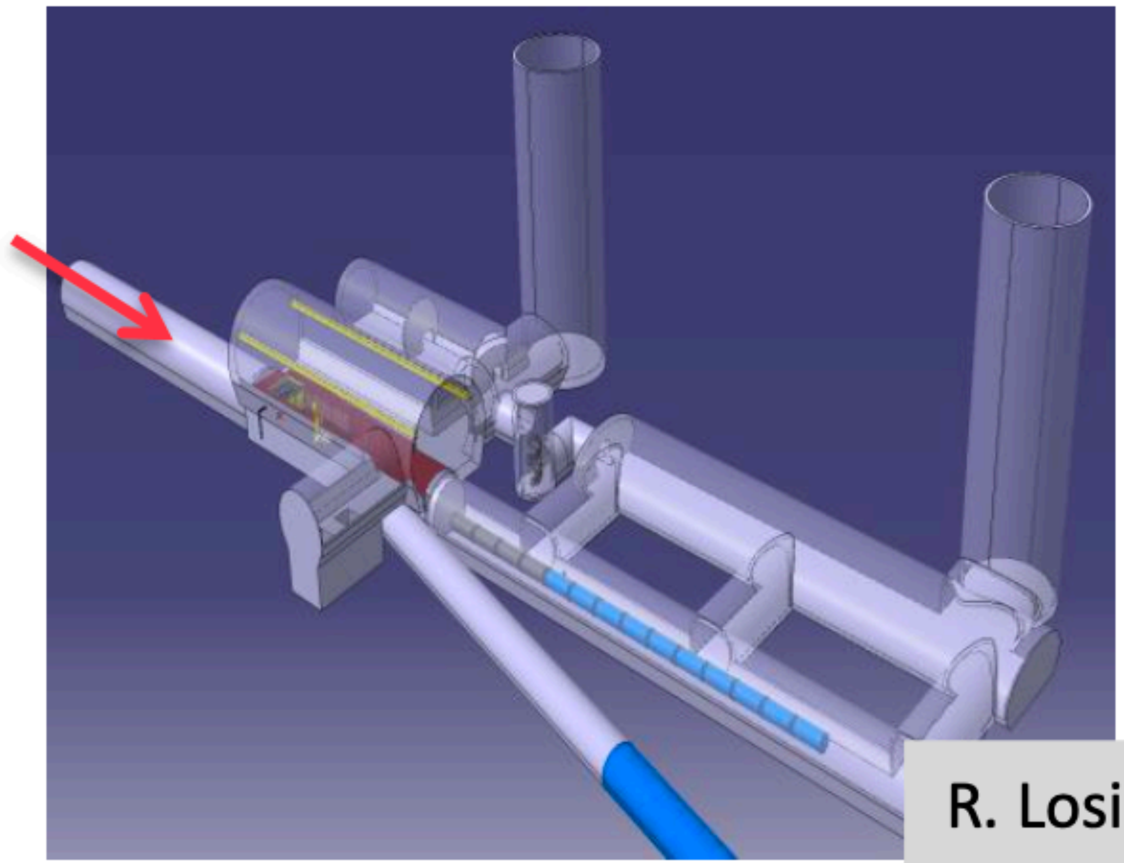
Momentum selection chicane

Cooling area



M. Benedikt, LHC Performance Workshop, Chamonix 2010

CERN-AB-2007-061



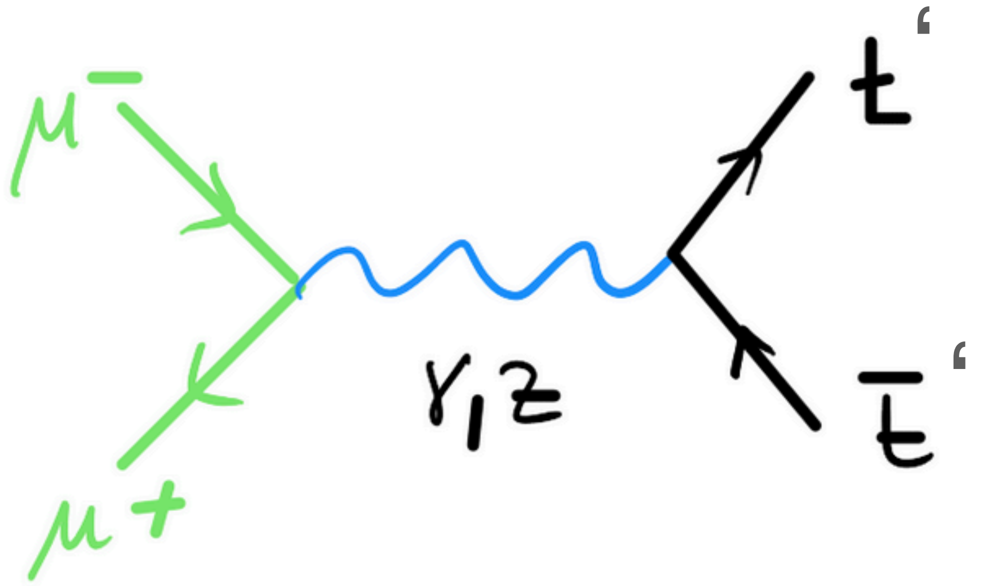
R. Losito, C. Rogers et al.

D. Schulte

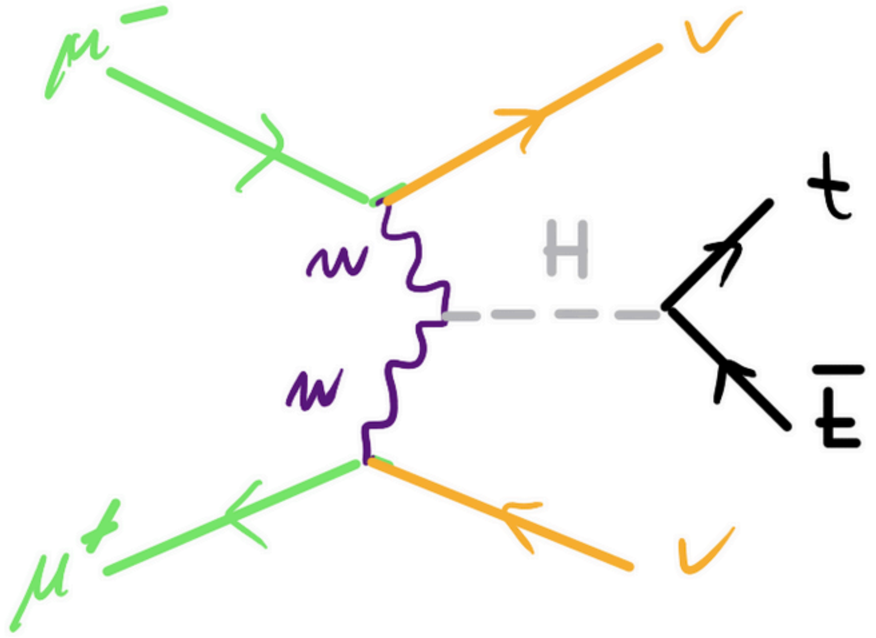
Muon collider physics

The essentials #1 : two colliders in one

O(10) TeV muon collider energy allows to have two colliders in one:



$$\sigma_s \sim \frac{1}{s} \quad \Longleftrightarrow \quad \sigma_s \sim \frac{1}{M^2} \log^n \frac{s}{M}$$



Energetic final states
(either heavy or very boosted)

Large production rates,
SM coupling measurements
Discovery light and weakly interacting

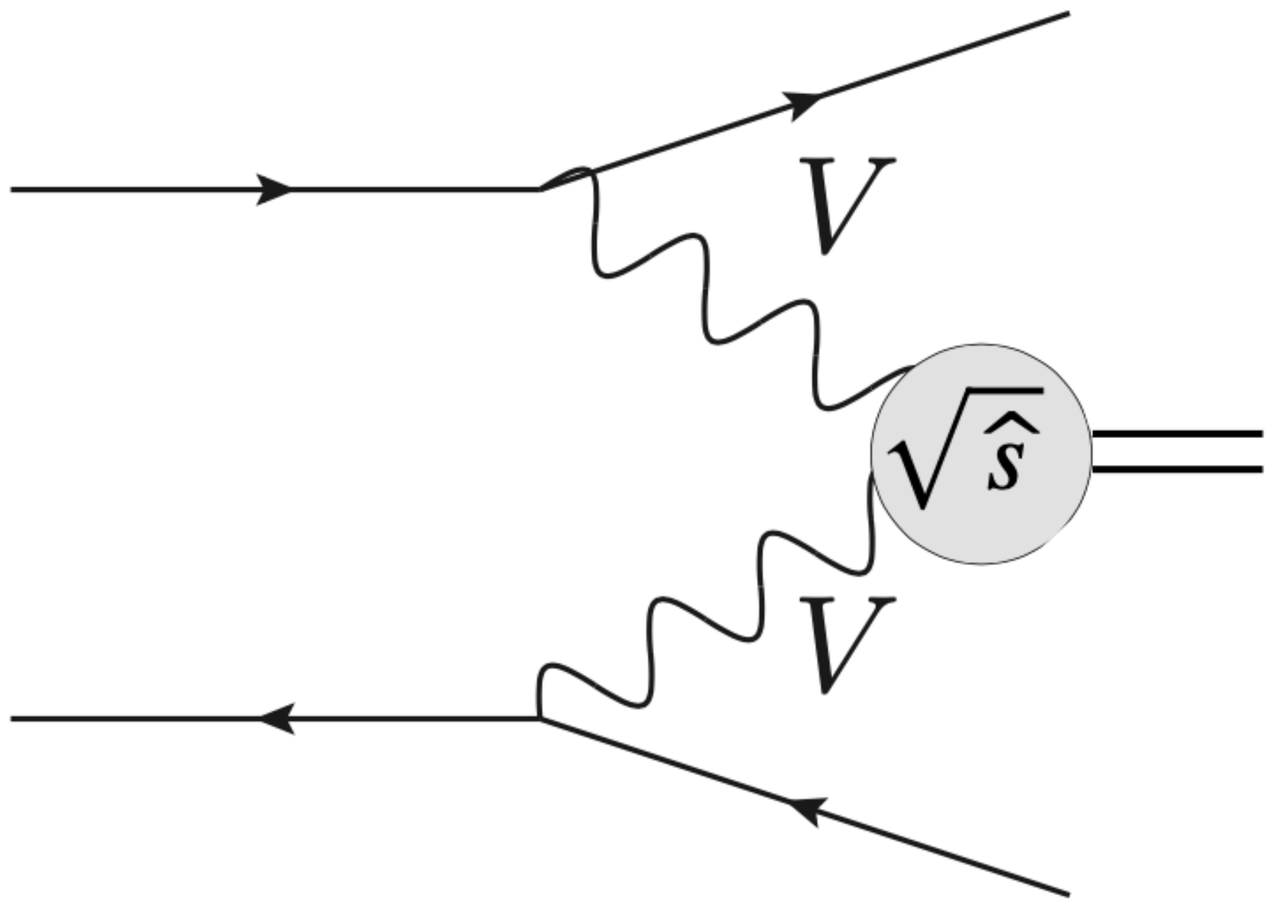
A completely new regime opening for a multi-TeV muon collider

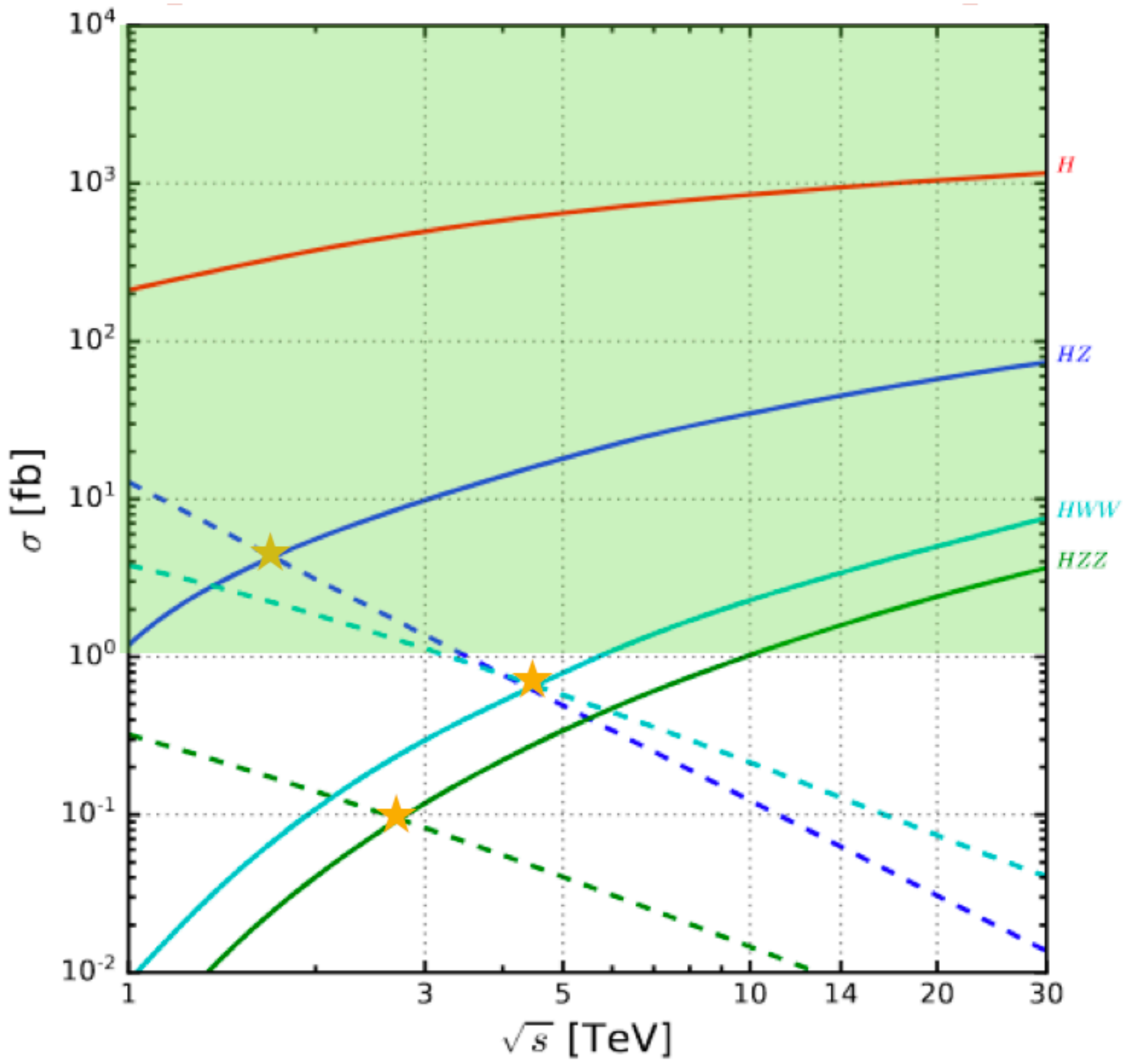
Different physics being probed in the two channels

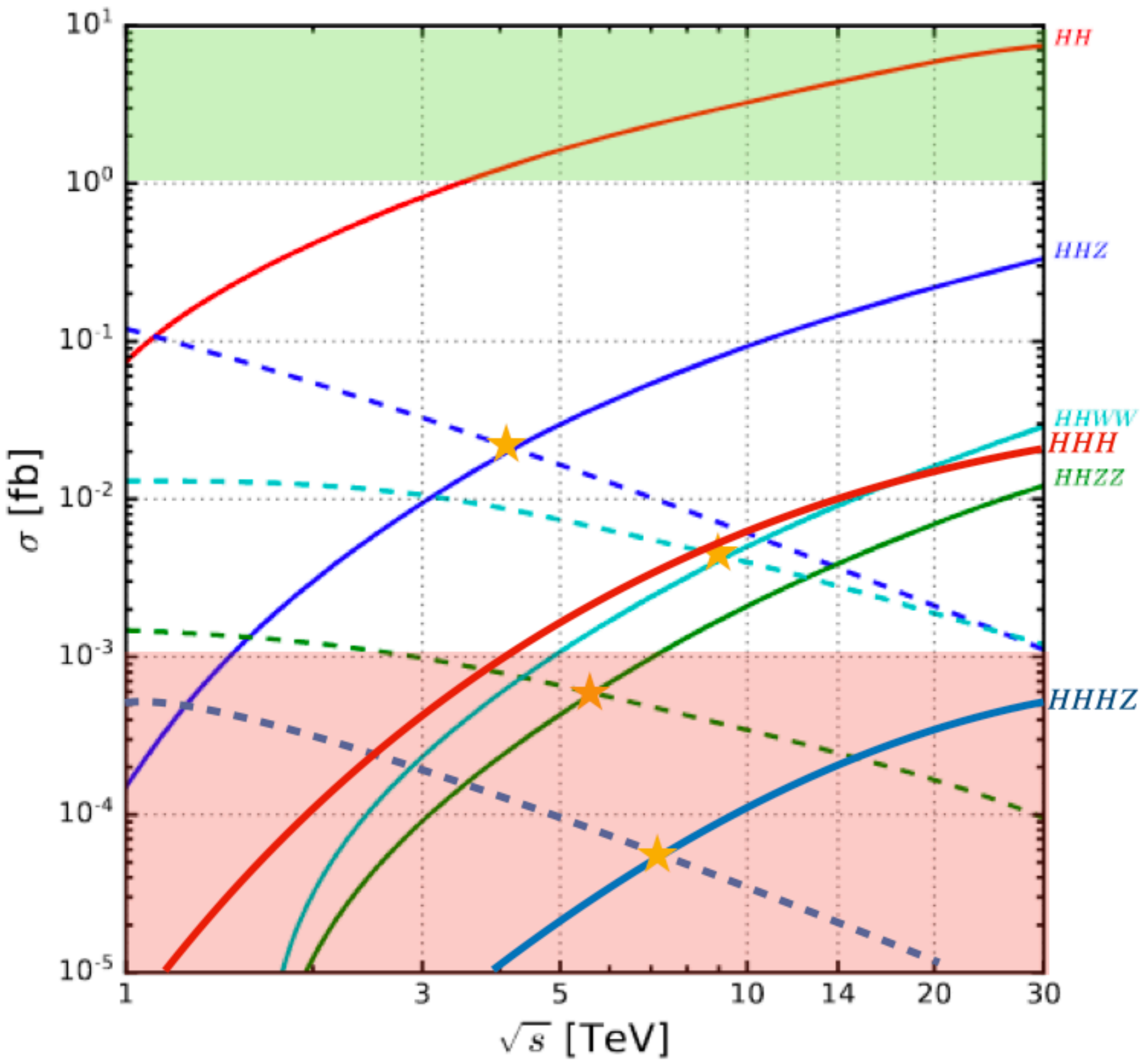
arXiv:2203.07256v1 Muon Collider Physics Summary

Muon collider physics

The essentials #1 : two colliders in one





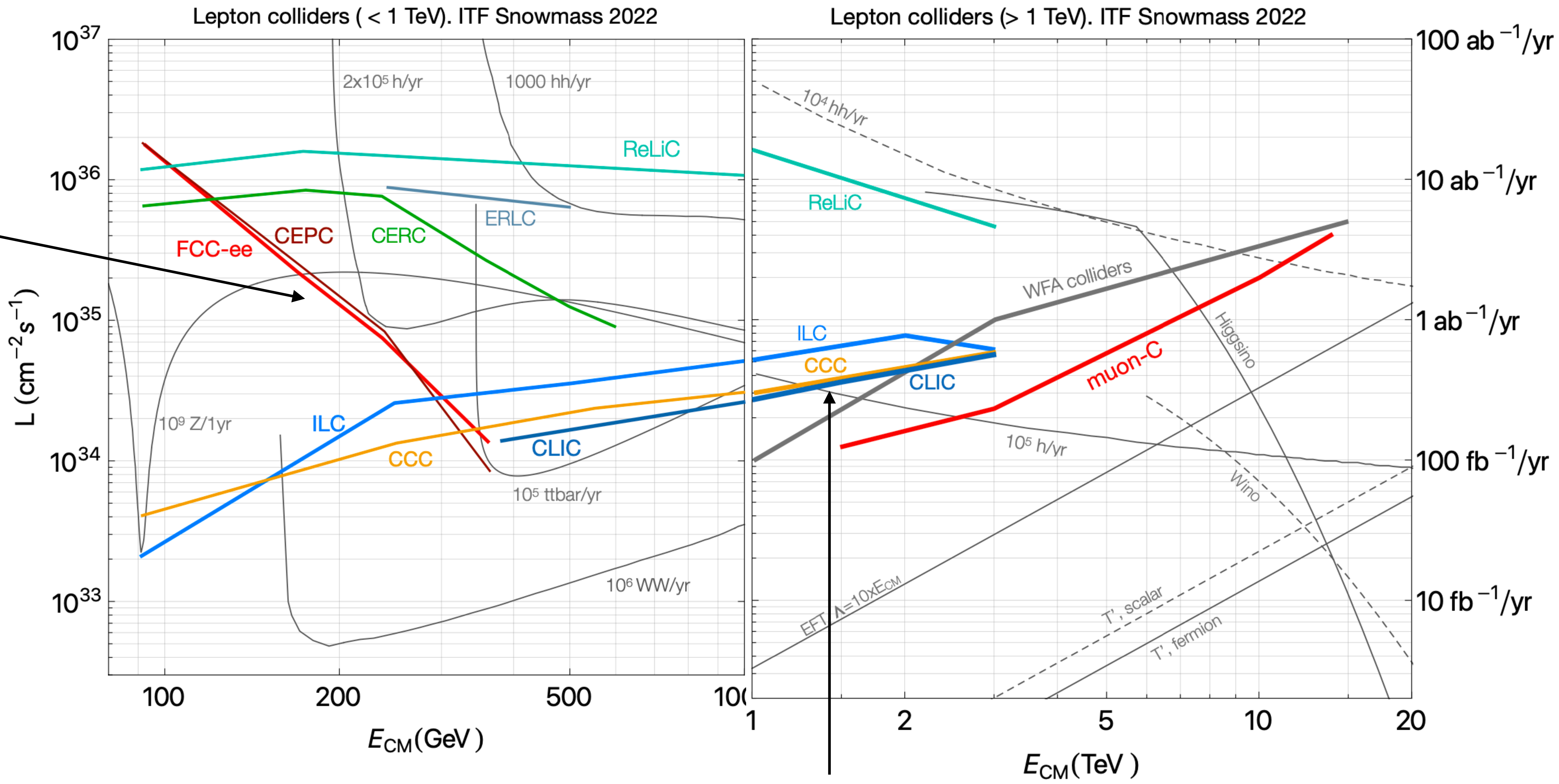


arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #2 : luminosity with energy

$L = P_{\text{synrad}} E_{\text{cm}}^{-3.5}$

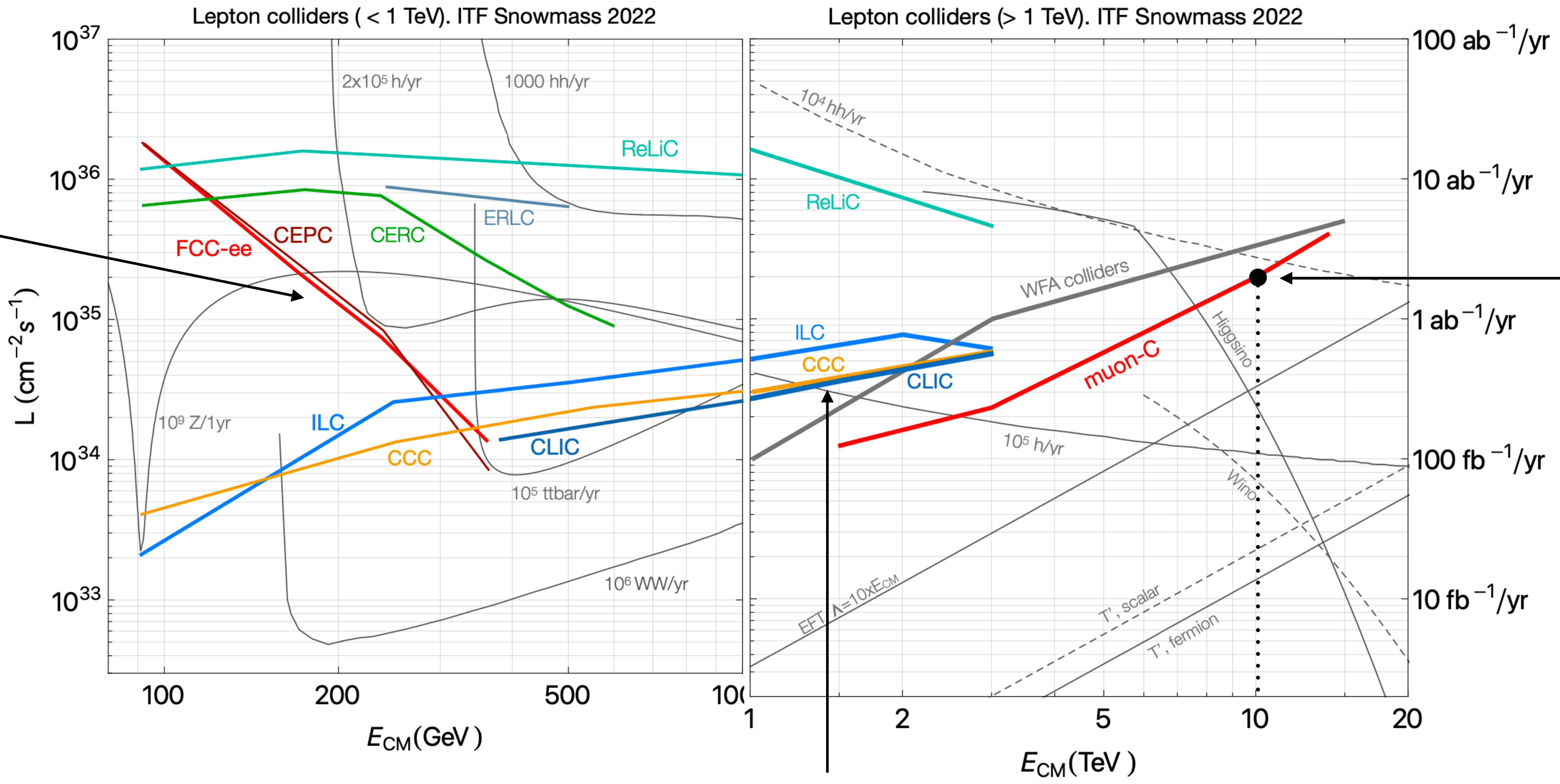


$L = P_{\text{RF}}$

Muon collider physics

The essentials #2 : luminosity with energy

$L = P_{\mathrm{synrad}} E_{\mathrm{cm}}^{-3.5}$



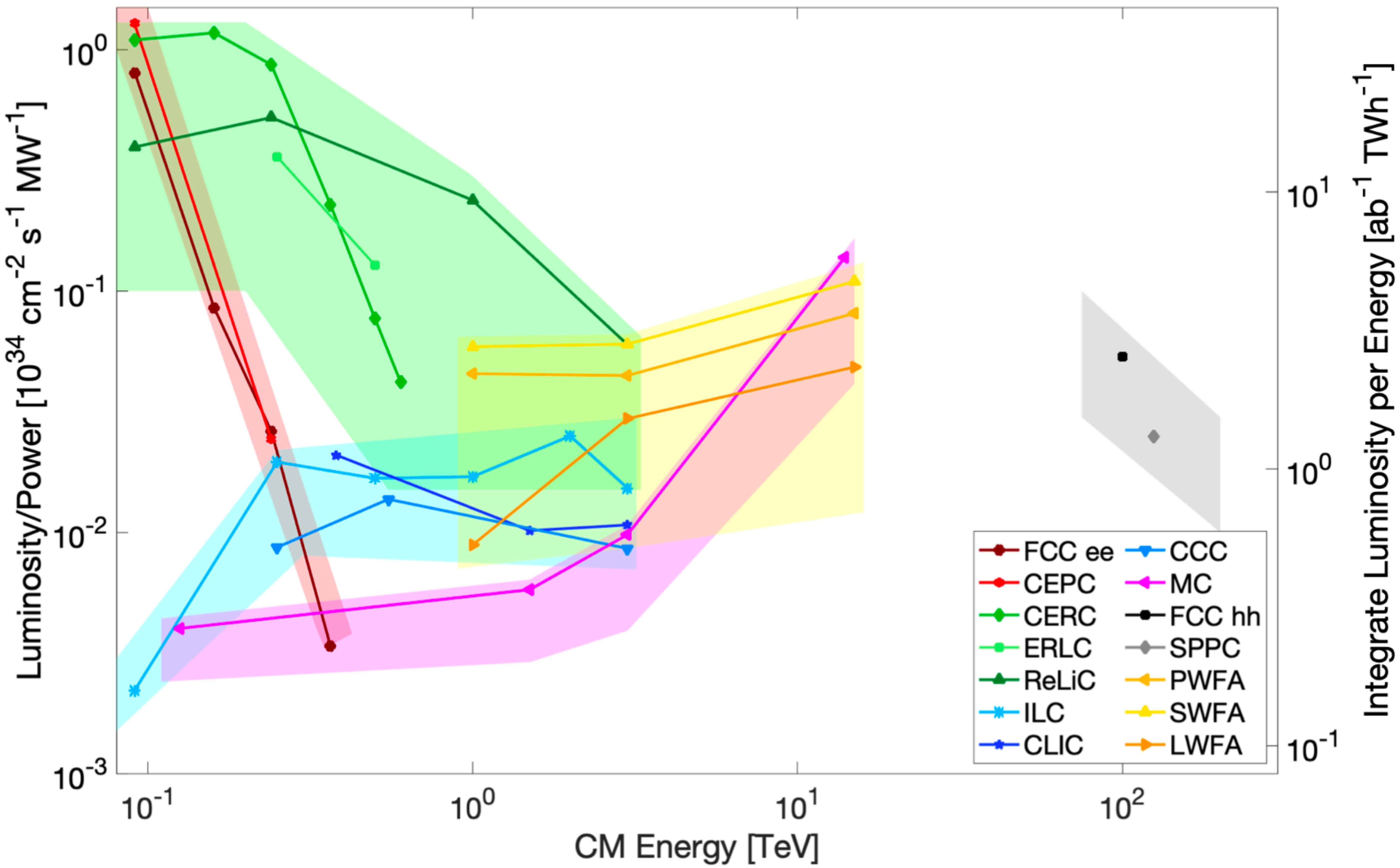
10 ab^{-1} in 5 years

$L = P_{\mathrm{RF}}$

arXiv:2208.06030 Collider Implementation Task Force

Muon collider physics

The essentials #3 : the green side

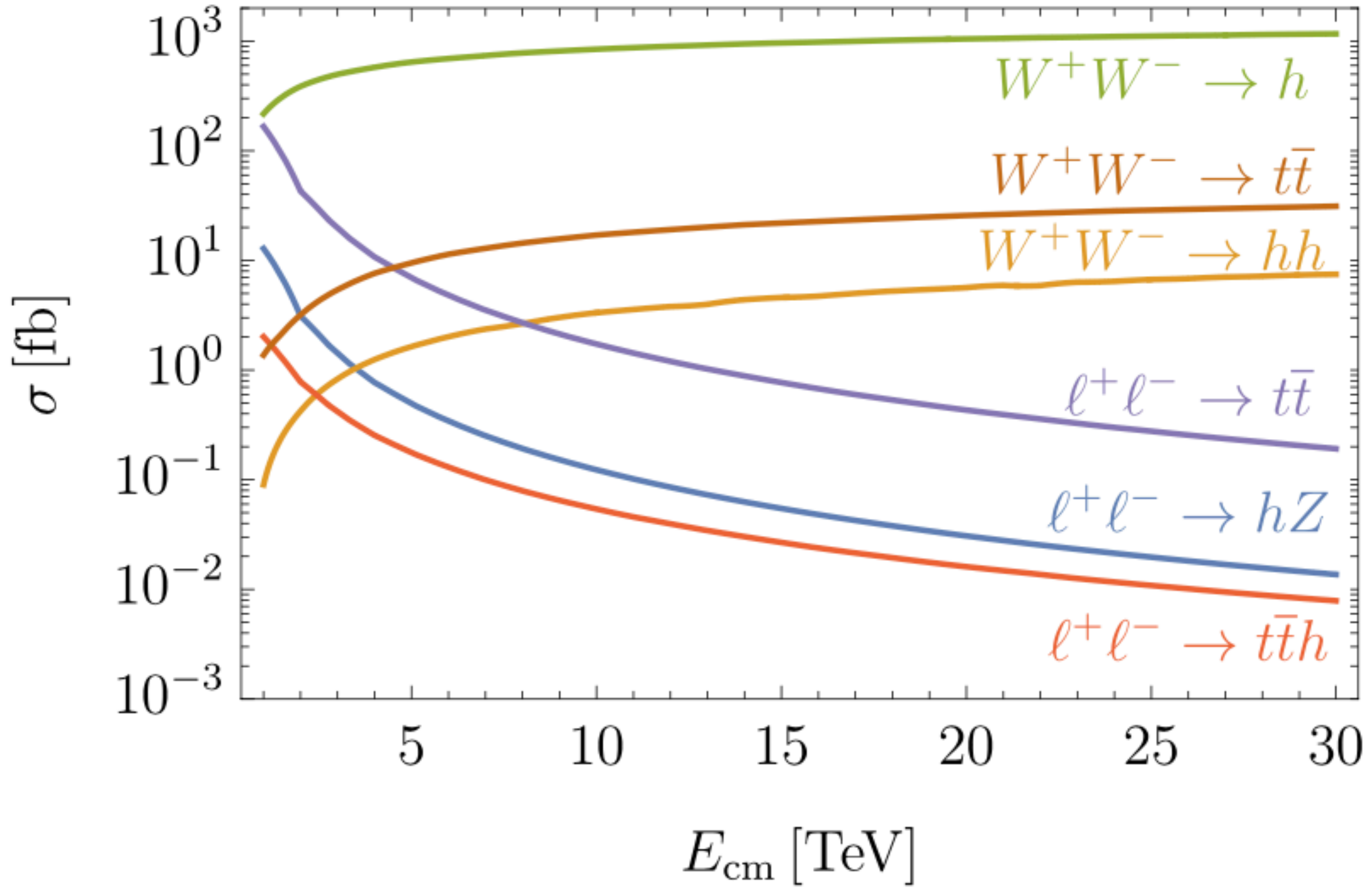


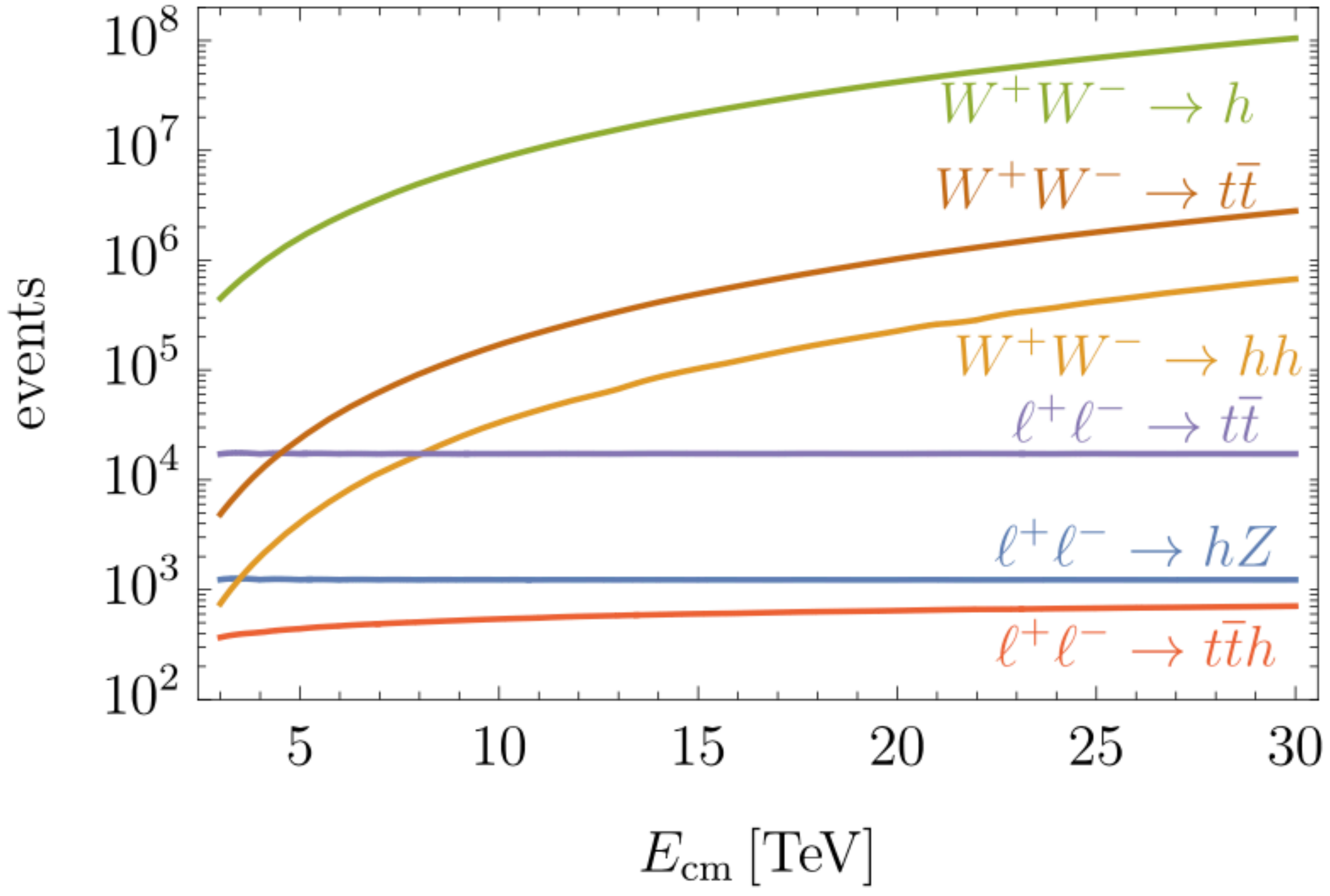
[Buttazzo, Franceschini, Wulzer 2012.11555]

Muon collider physics

The essentials #4 : luminosity with energy

$$L \gtrsim \frac{5\,\text{years}}{\text{time}}\left(\frac{\sqrt{s}_\mu}{10\,\text{TeV}}\right)^2 2\cdot 10^{35}\text{cm}^{-2}\text{s}^{-1}$$





$$\widehat{\mathcal{L}} = 10\,\text{ab}^{-1}\left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

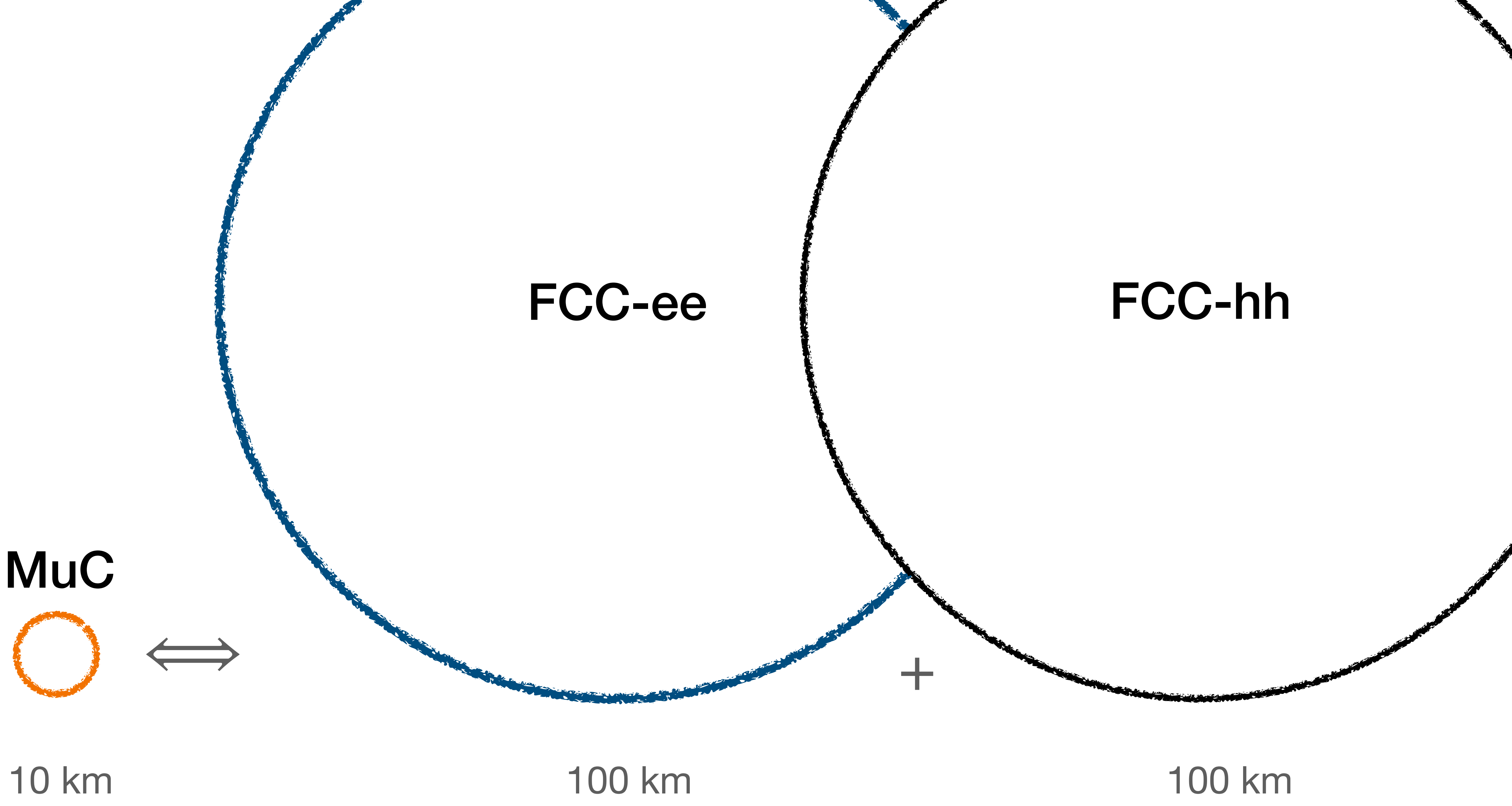
Muon collider physics

The essentials #5: compactness

Muon collider physics

The essentials #5: compactness

1] O(10) TeV Energy small hybrid collider:



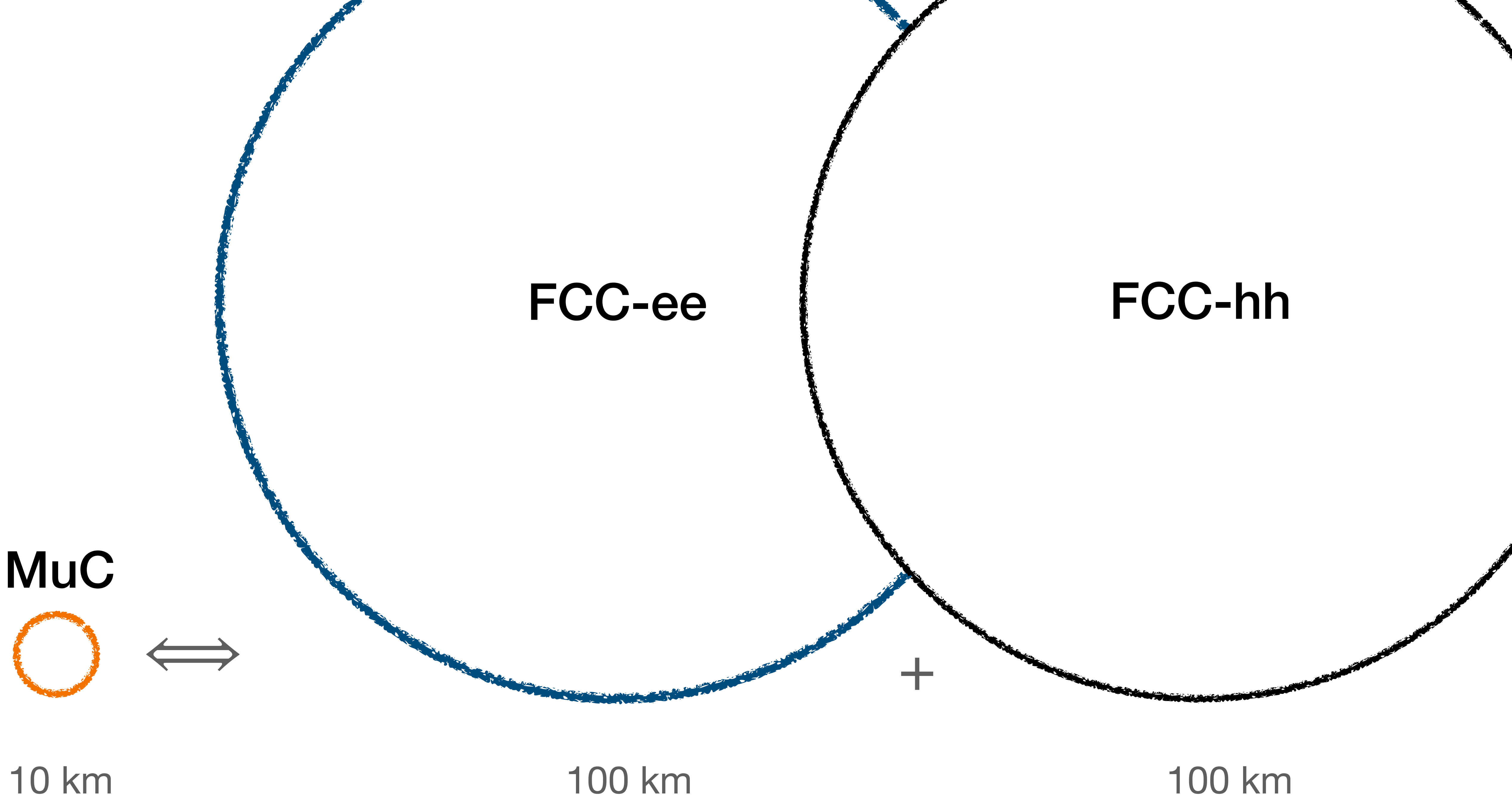
x

t

Muon collider physics

The essentials #5: compactness

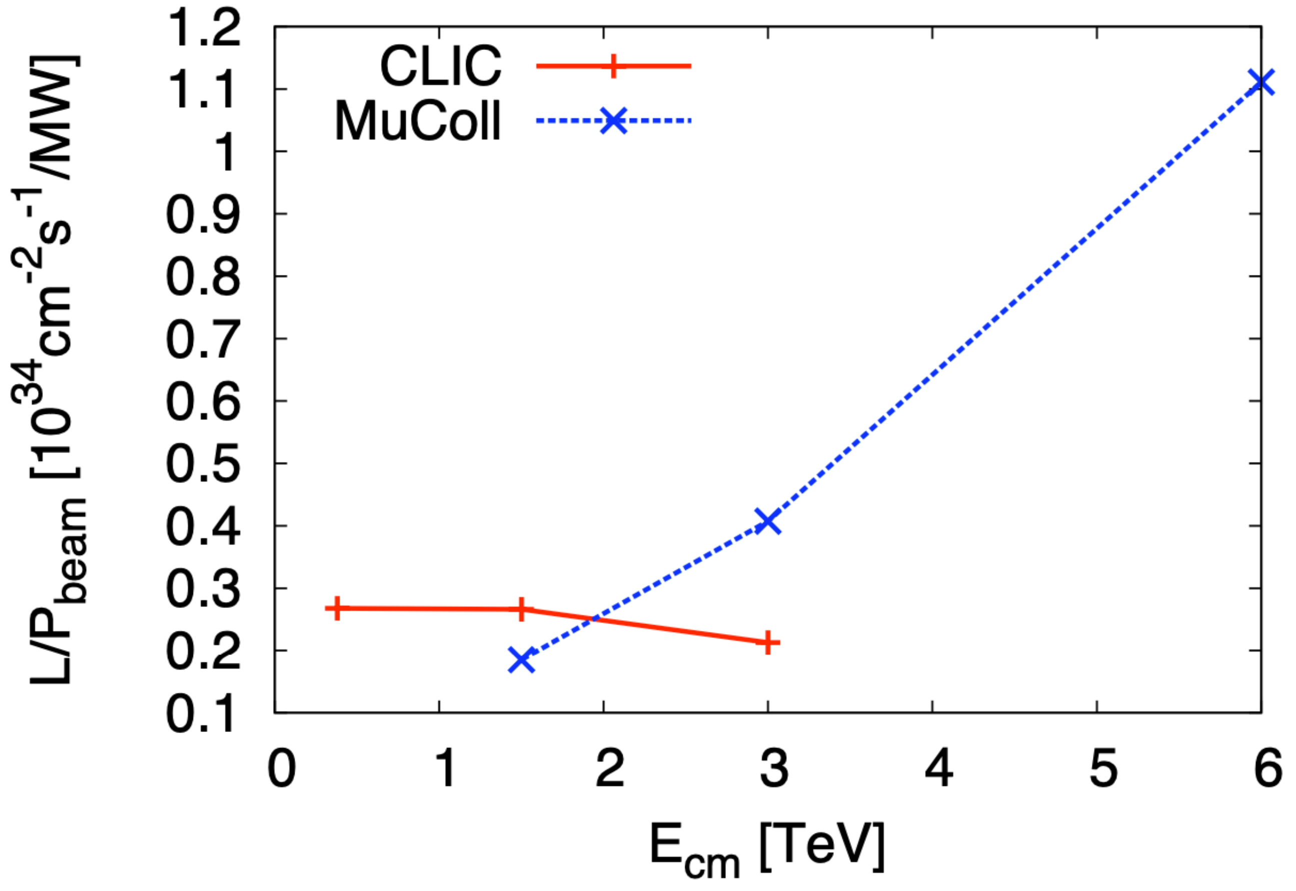
1] O(10) TeV Energy small hybrid collider:



x

t

2] Luminosity growing with energy:



⇒MuC is an STCC = Space-Time-Compact Collider

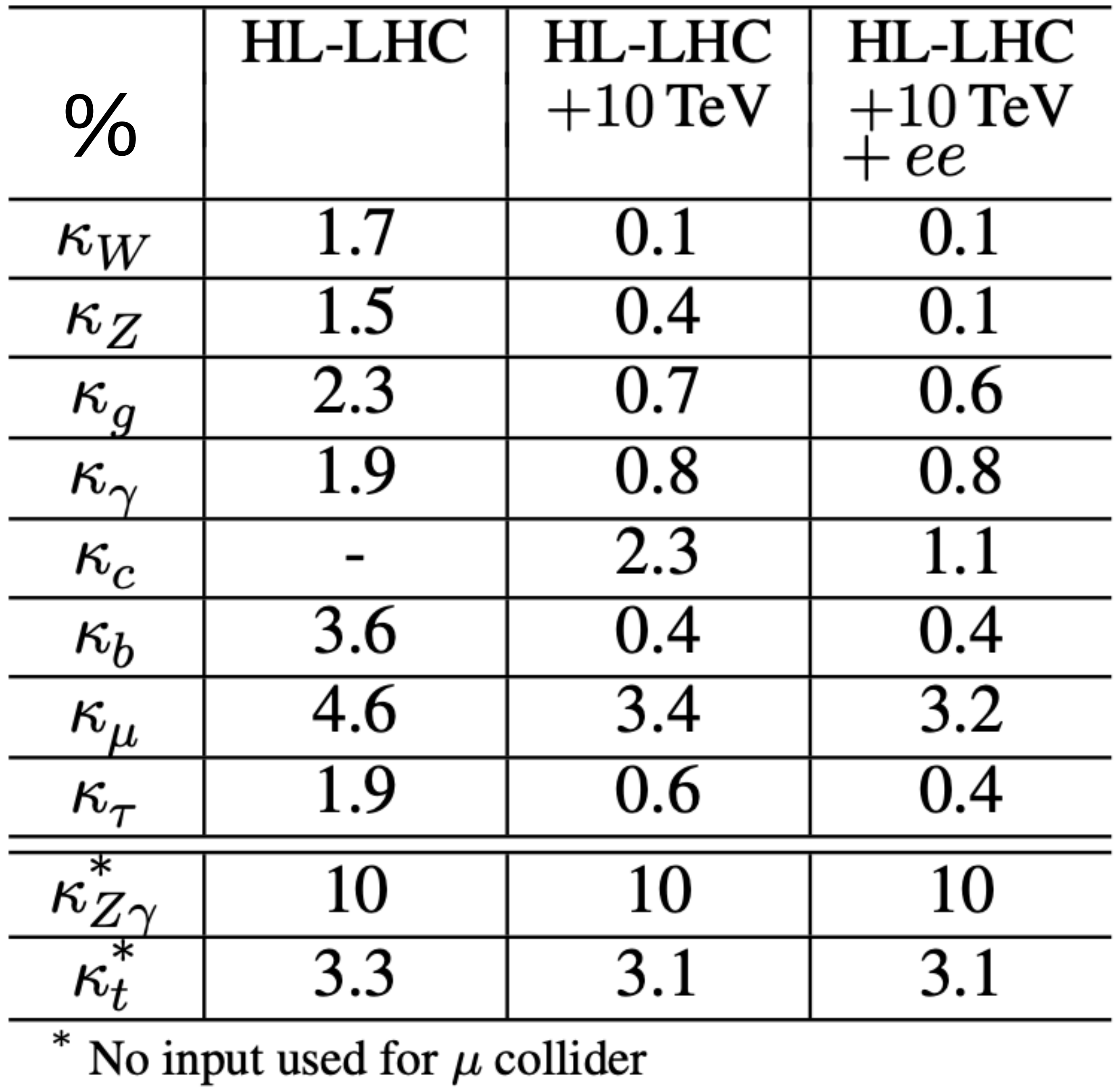
⇒ Goal of the tens:

10 TeV , 10 iab, 10 x smaller and O(10) x faster than the FCC

arXiv:2203.07256v1 Muon Collider Physics Summary

Higgs precision physics

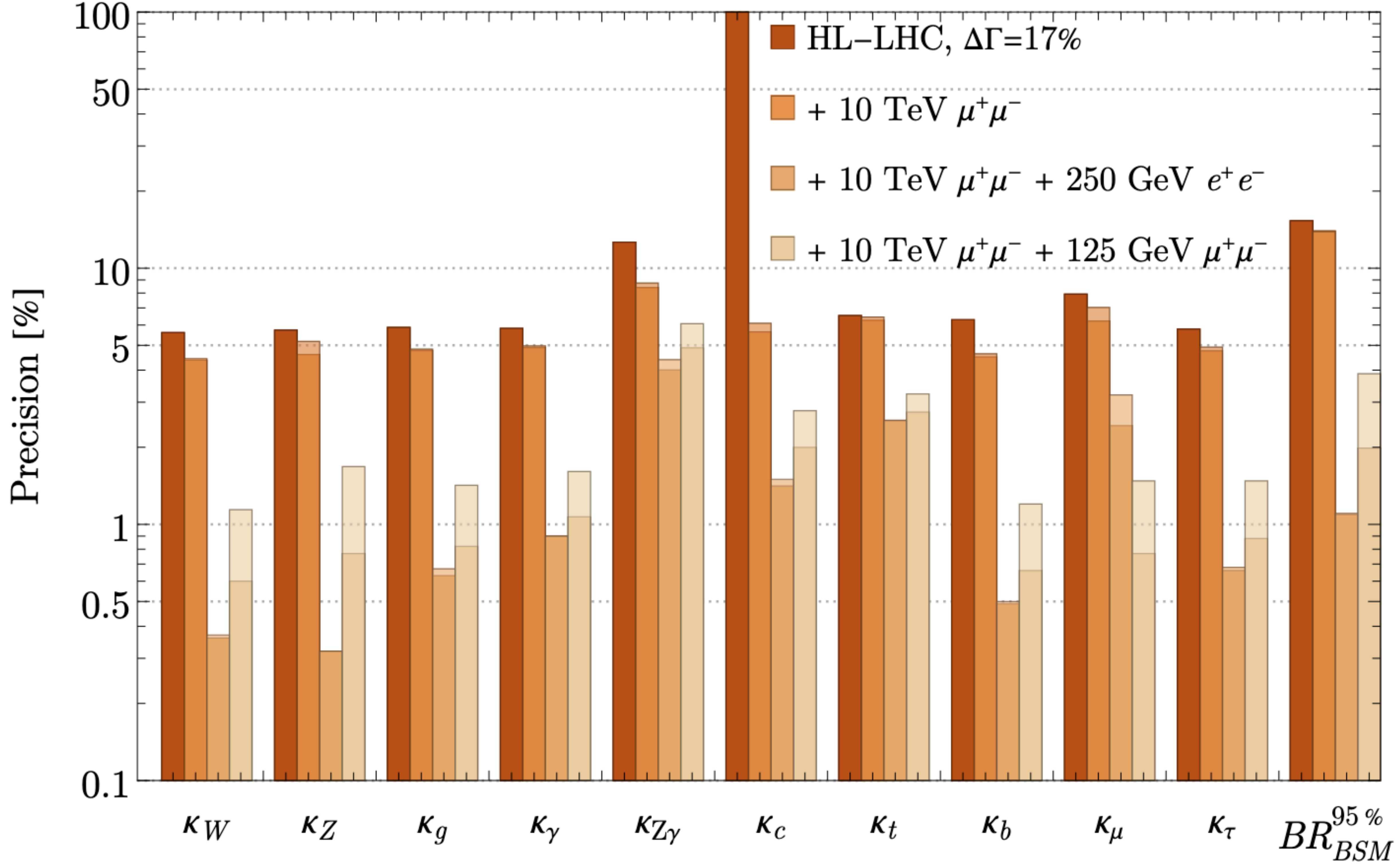
Higgs coupling sensitivities



%	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

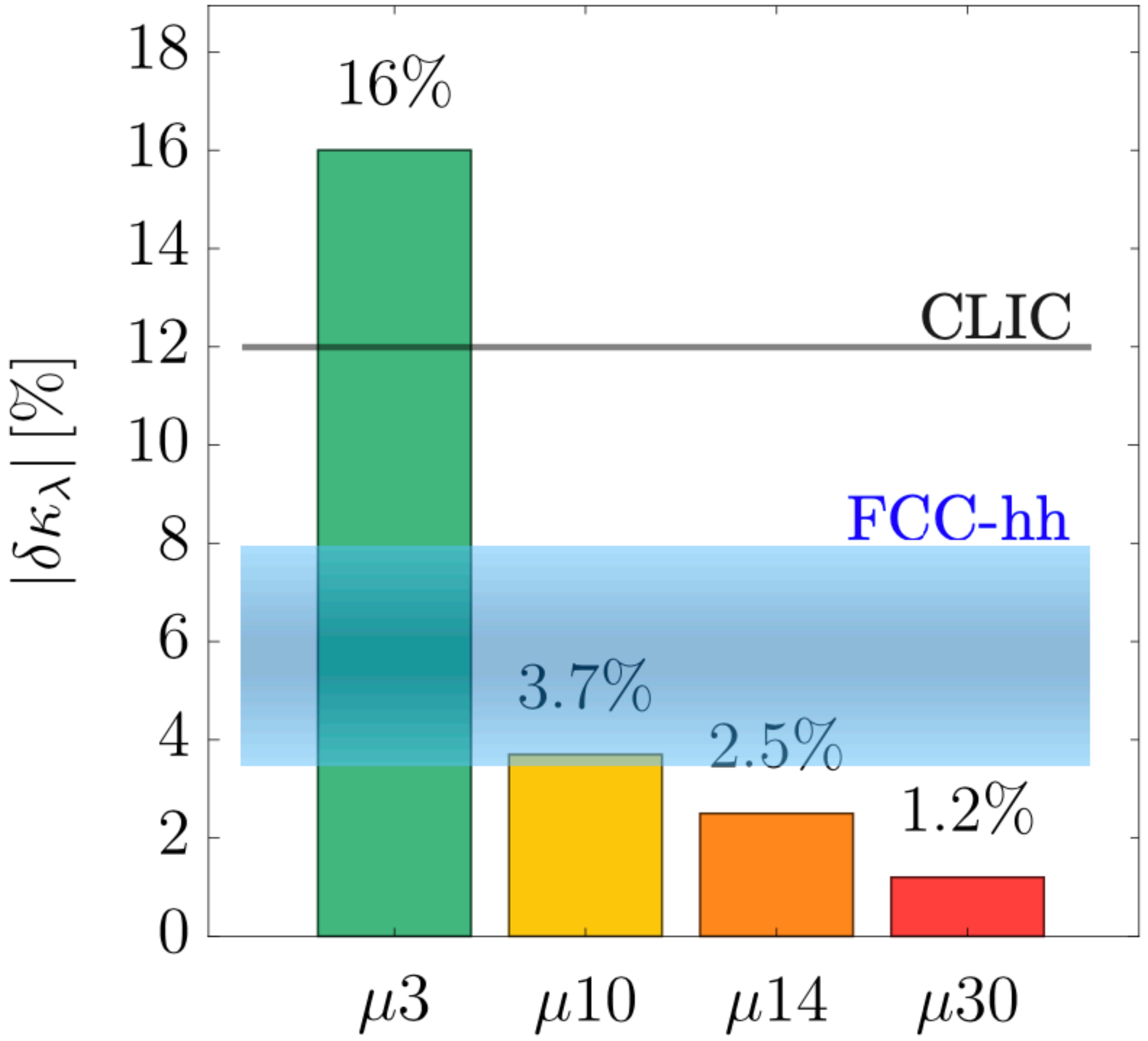
* No input used for μ collider

arXiv:2308.02633

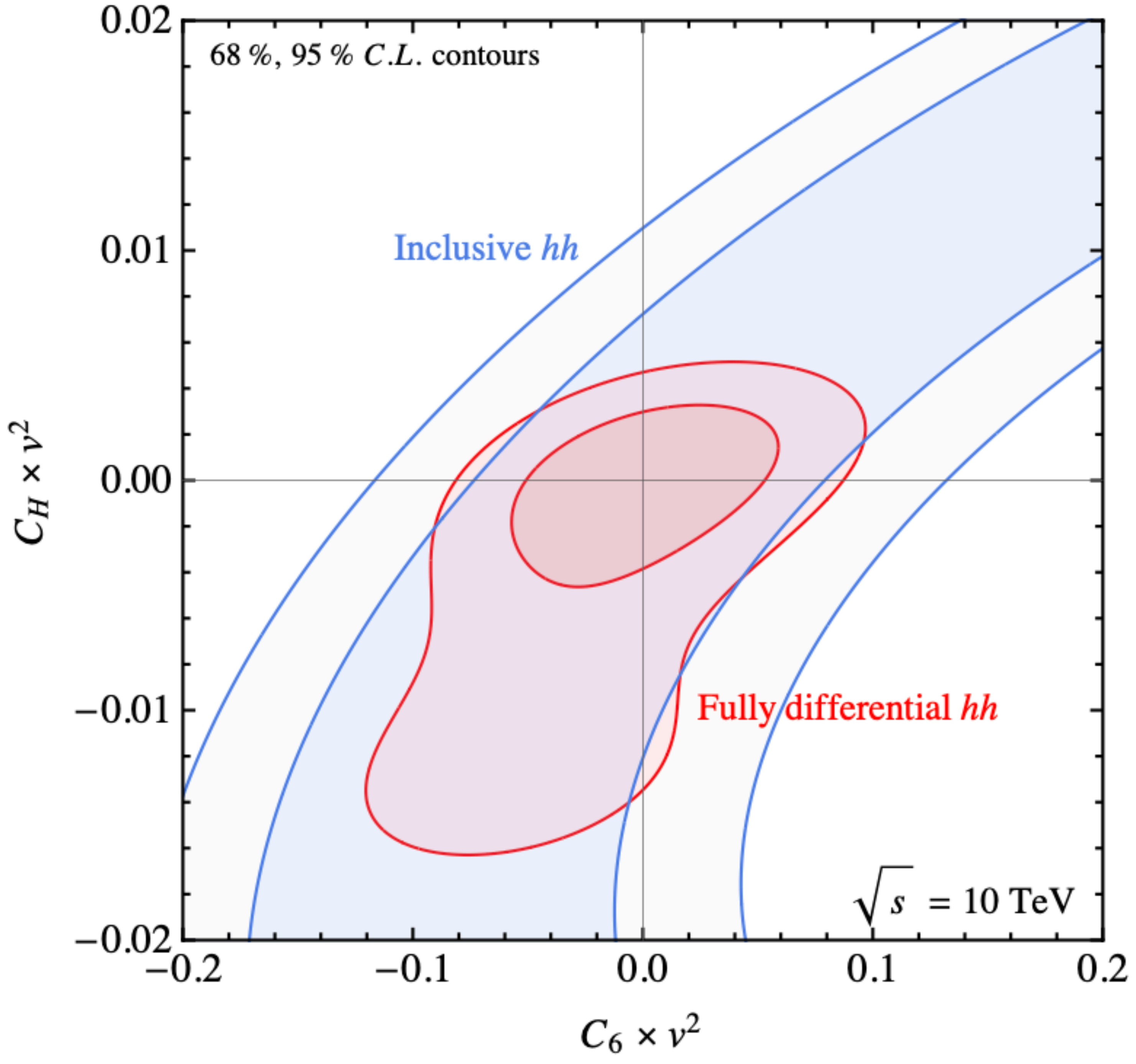


Higgs precision physics

The shape of the H potential: HH production



arXiv:2203.07256v1



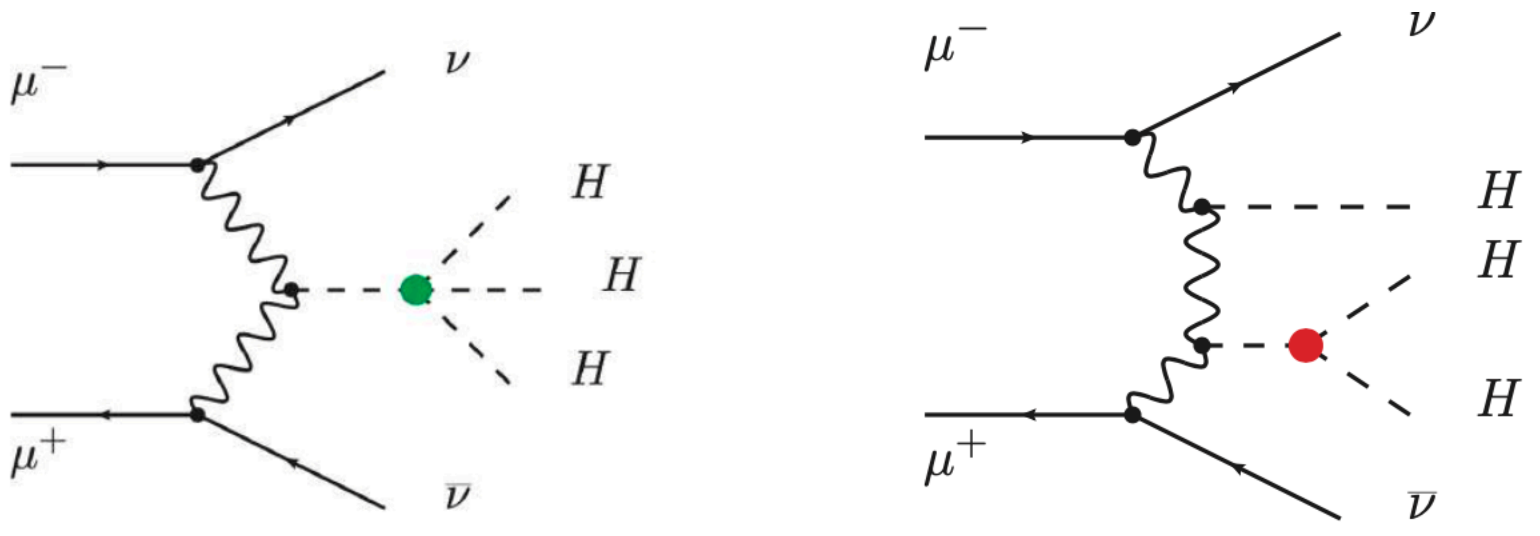
[Buttazzo et al. 2012.11555]

Reach on the trilinear coupling (and more) extremely competitive.

Higgs precision physics

The shape of the H potential : HHH production

3 Higgs final state



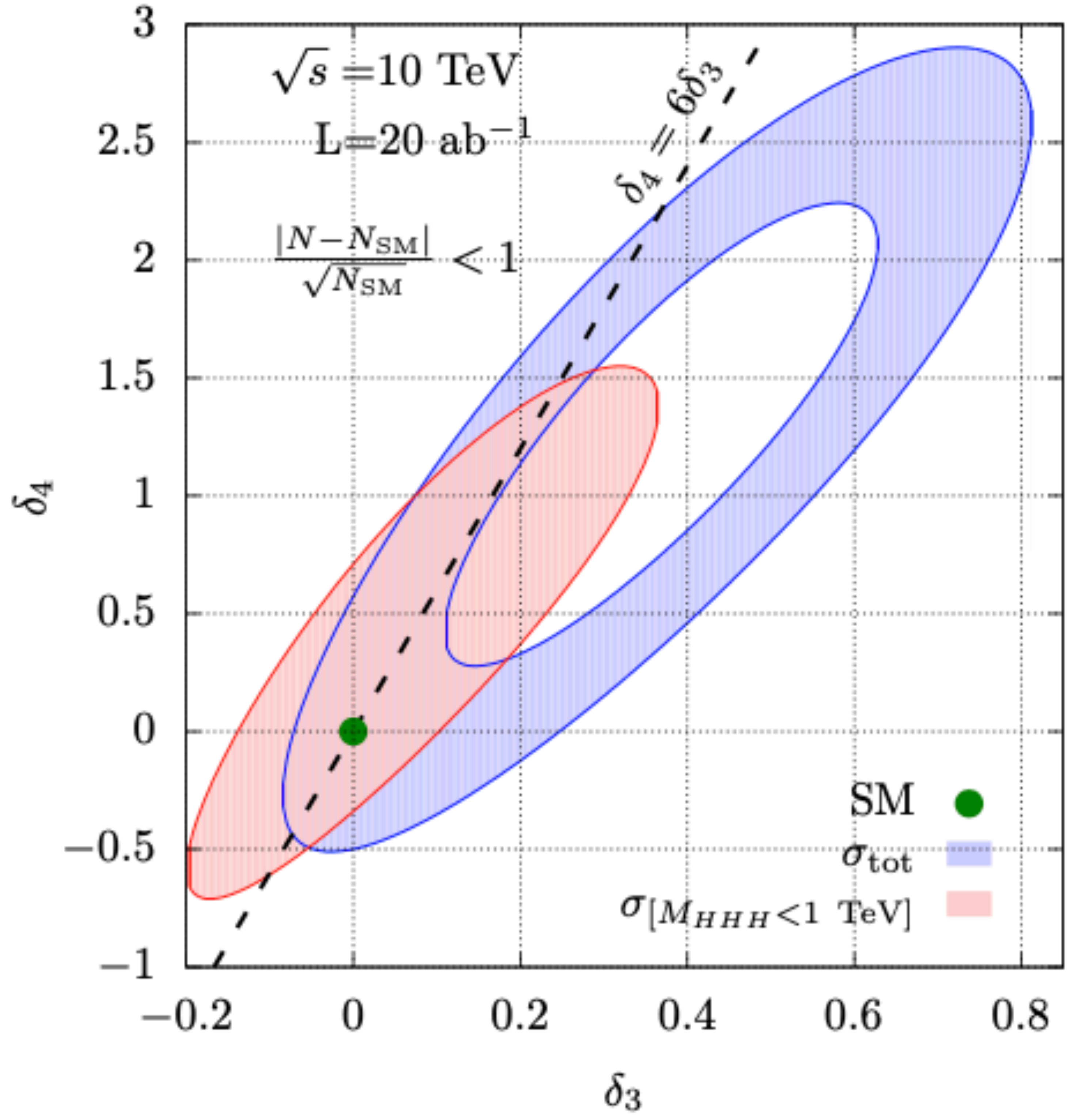
Quadrilinear determination extremely challenging at any collider, due to limited sensitivity.

$$\text{ILC} \sim [-10, 10]$$

$$\text{CLIC} \sim [-5, 5]$$

$$\text{FCC} \sim [-2, 4]$$

Very preliminary study points to the possibility of setting competitive bounds at a muon collider.



[Chiesa et al. 2003.13268]

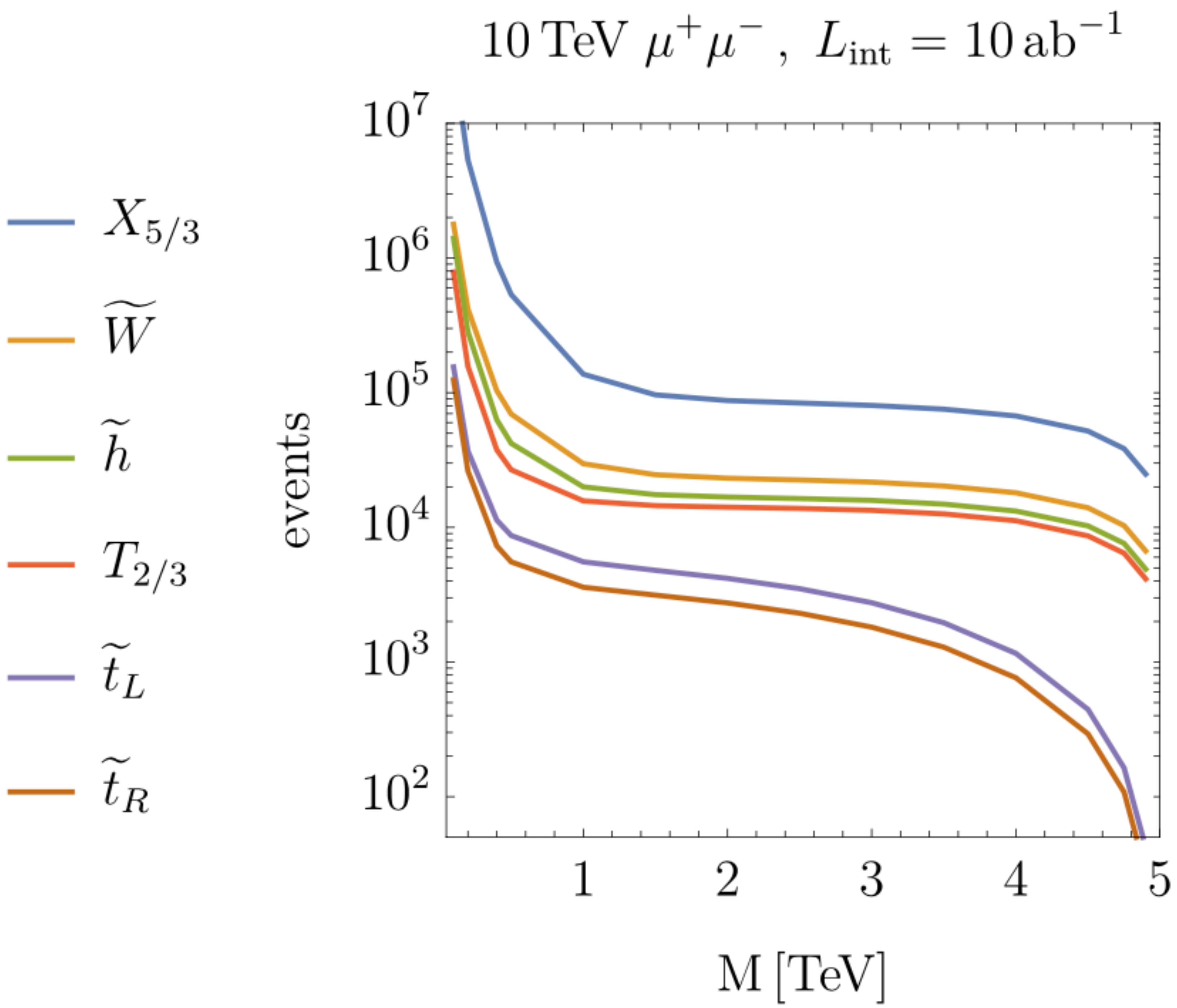
$$10\ \text{TeV} \quad \delta_4 \sim [-0.4, 0.7]$$

[arXiv:2203.07256 Muon Collider Physics Summary](arXiv:2203.07256)

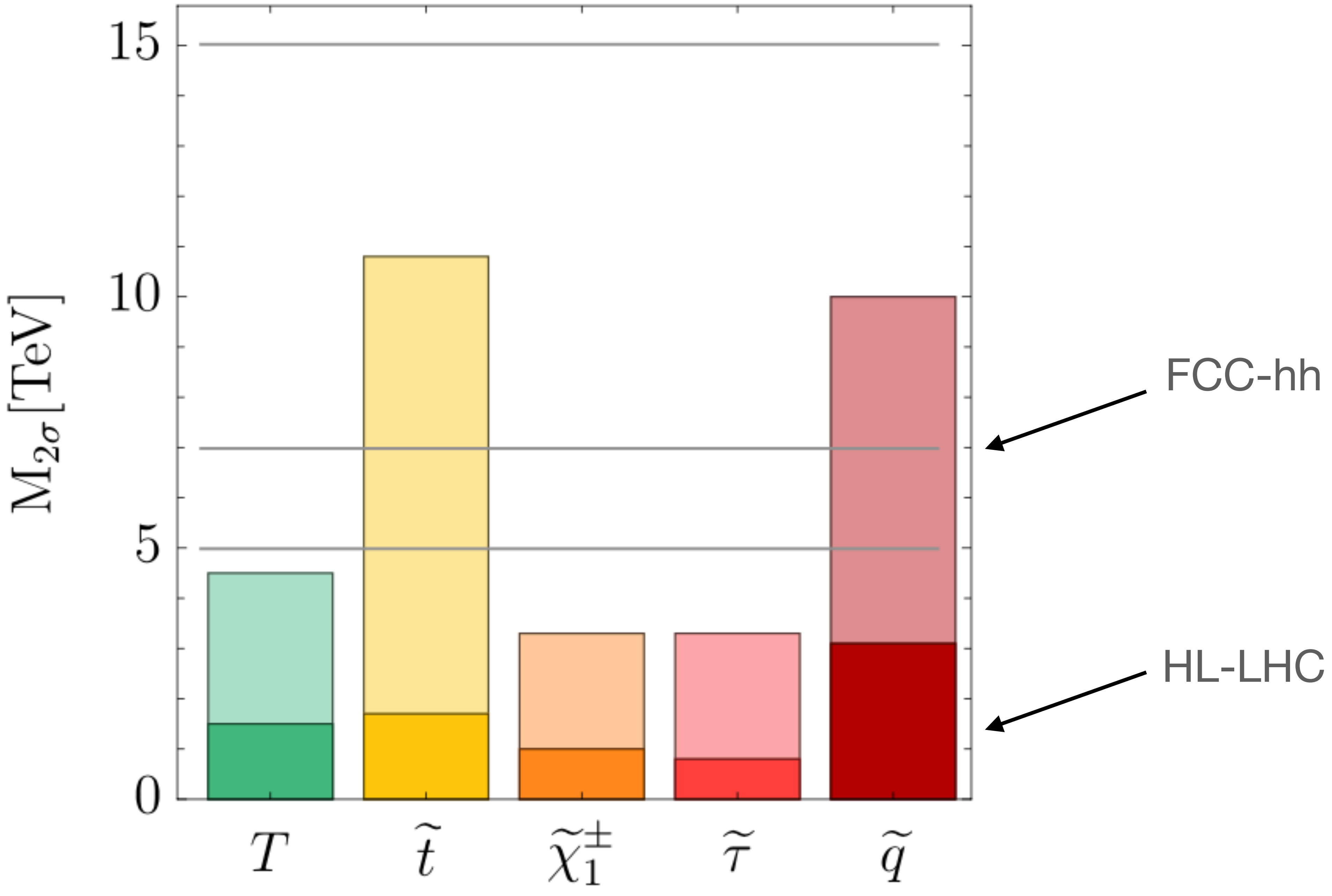
[arXiv:2209.01318 Muon Collider Forum Report](arXiv:2209.01318)

Direct reach

s-channel pair production



A few months of run could be sufficient for a discovery.



$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m^2}+\frac{m_t^2}{m^2}-\frac{m_t^2X_t^2}{m^2\,m^2}\right)$$

Matching Higgs precision:

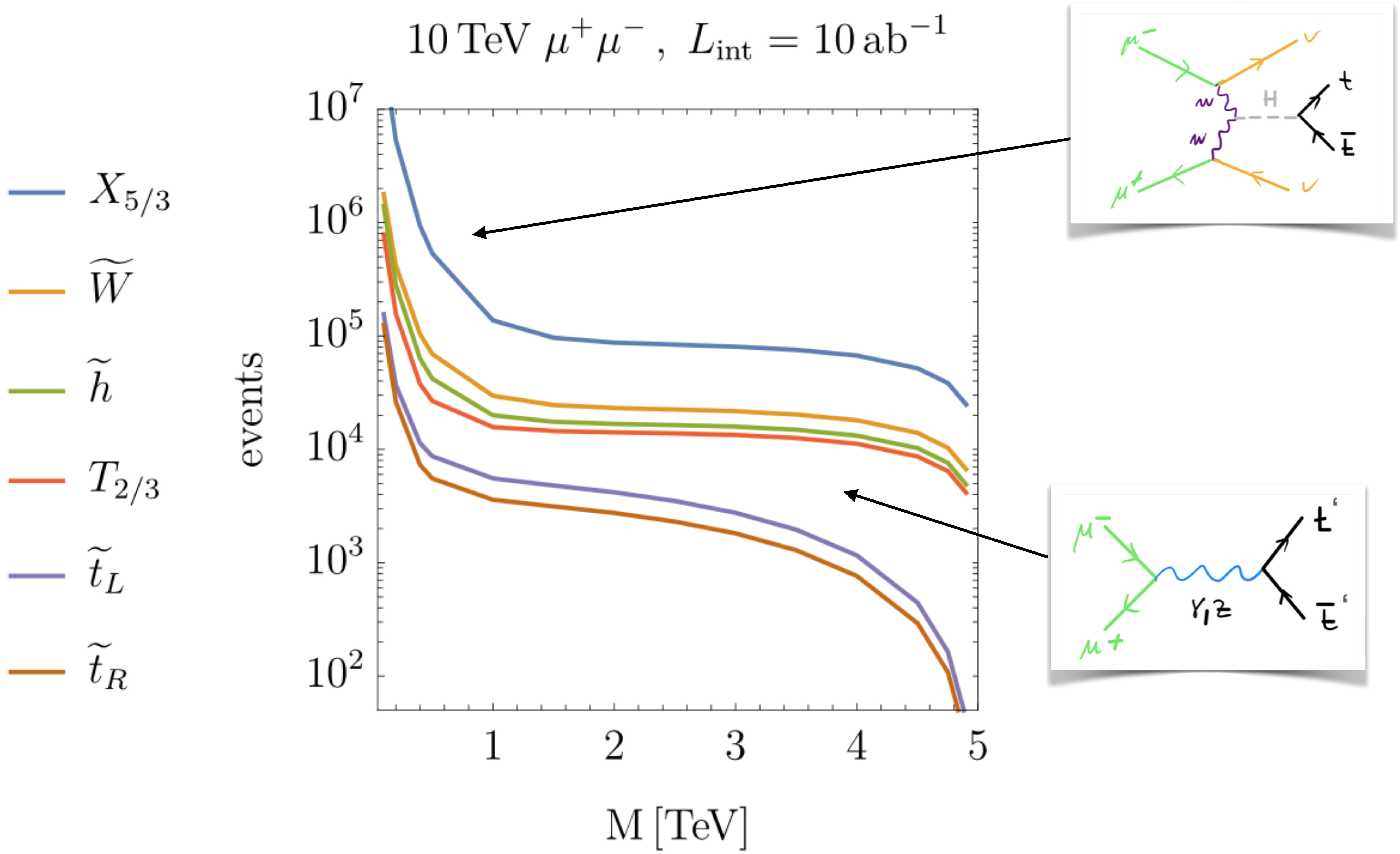
$$m_{\tilde{t}} \gtrsim 1.5\,\text{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\max}}}.$$

arXiv:2203.07256 Muon Collider Physics Summary

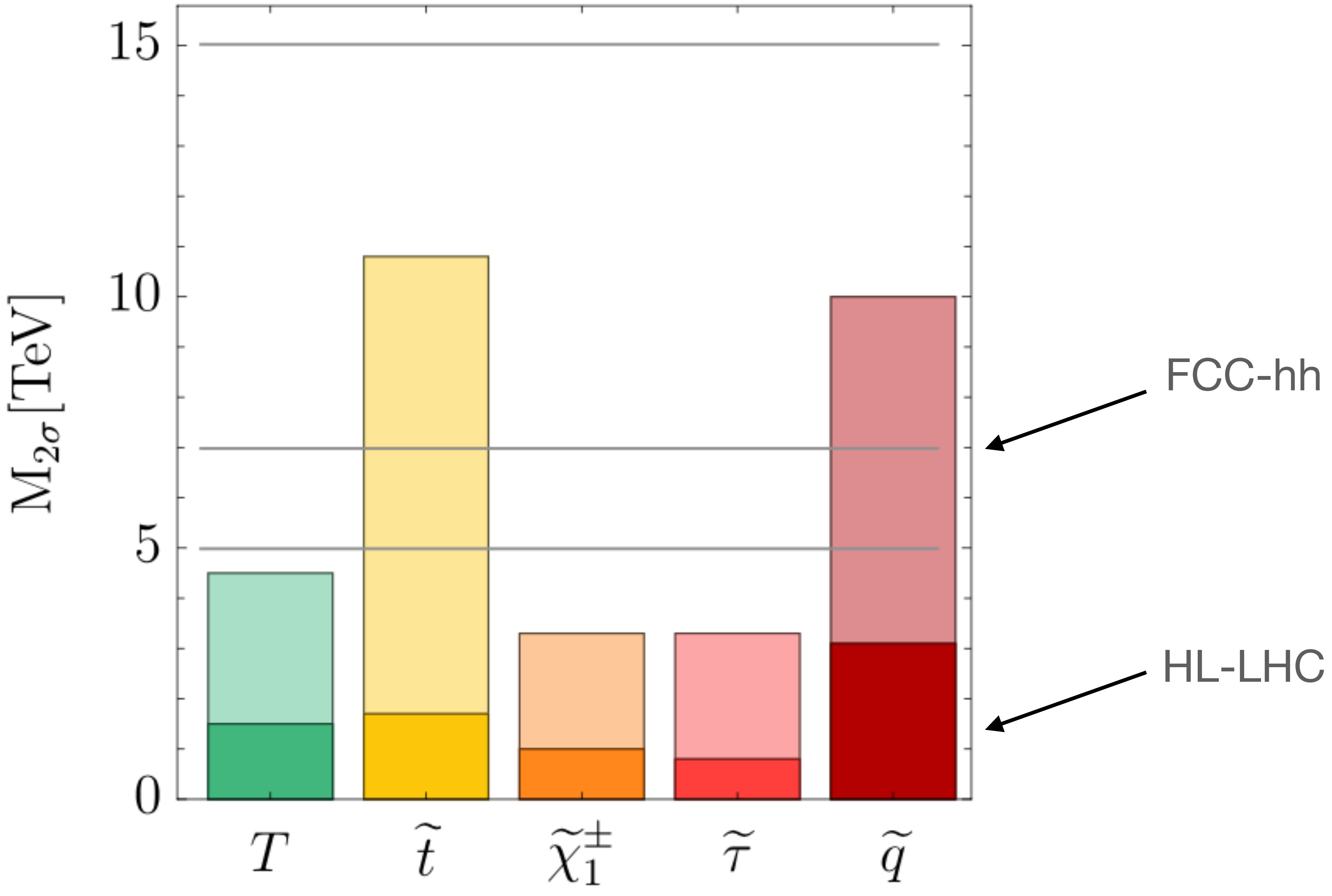
arXiv:2209.01318 Muon Collider Forum Report

Direct reach

s-channel pair production



A few months of run could be sufficient for a discovery.



$$\delta\kappa_g = \frac{1}{4}\left(\frac{m_t^2}{m^2} + \frac{m_t^2}{m^2} - \frac{m_t^2 X_t^2}{m^2\, m^2}\right)$$

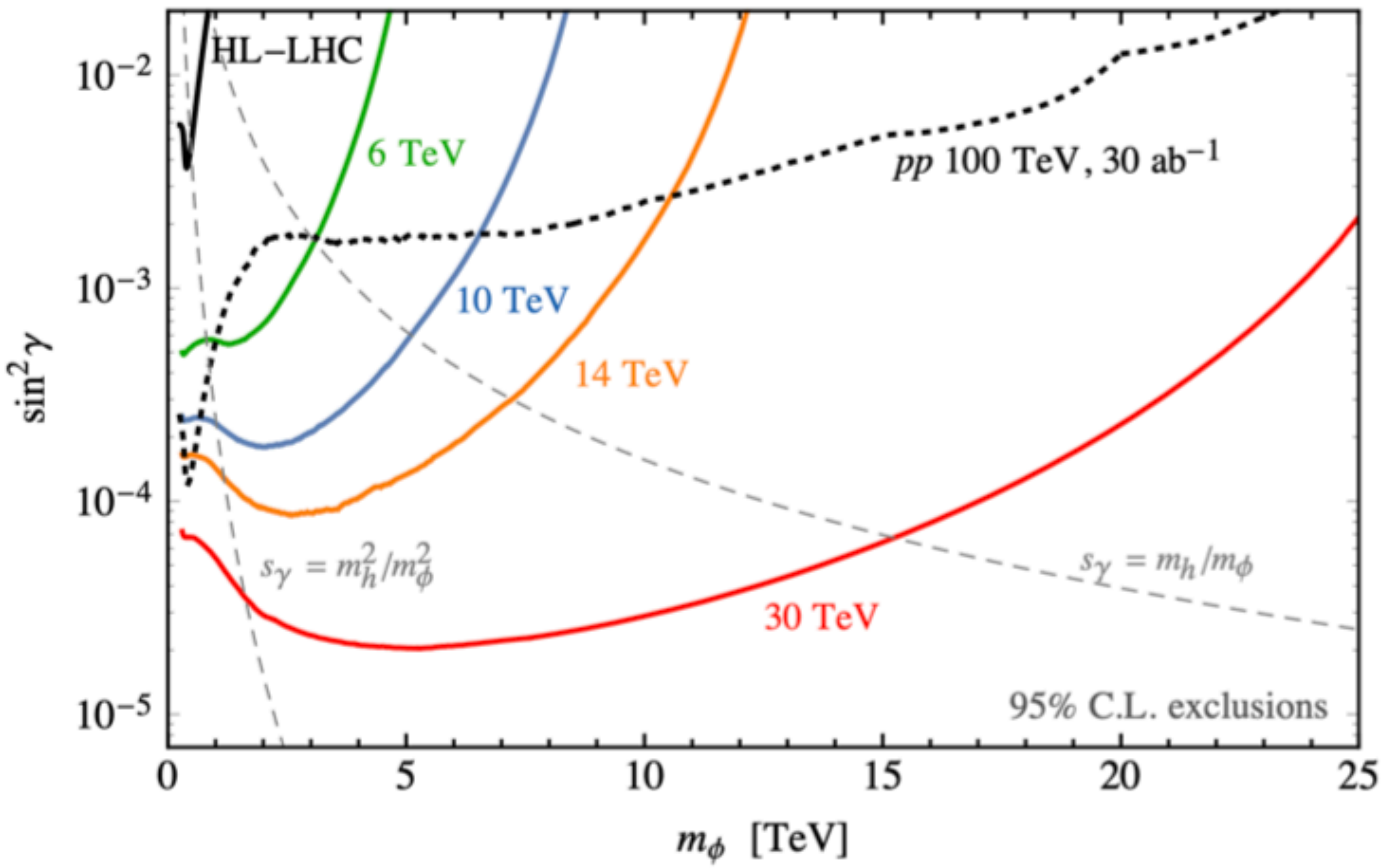
Matching Higgs precision:

$$m_{\tilde{t}} \gtrsim 1.5\,\text{TeV}\sqrt{\frac{0.67\%}{\delta\kappa_g^{\text{max}}}}.$$

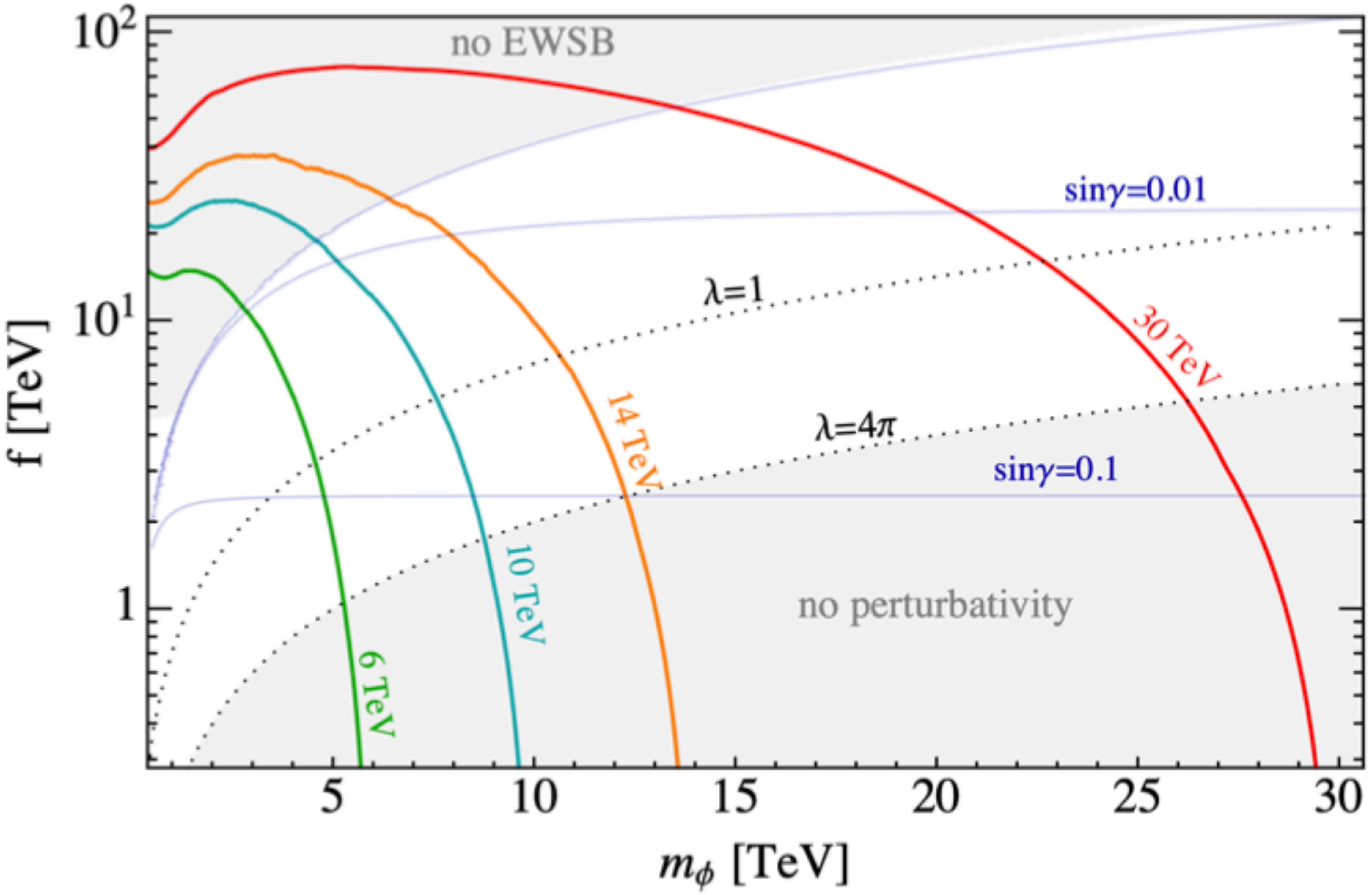
arXiv:2203.07256v1 Muon Collider Physics Summary
arXiv:2209.01318 Muon Collider Forum Report

Direct reach vs indirect

VBF scalar singlet production



mixed with the Higgs boson with strength sin γ.



Reach in terms of the scale f in the Twin Higgs model

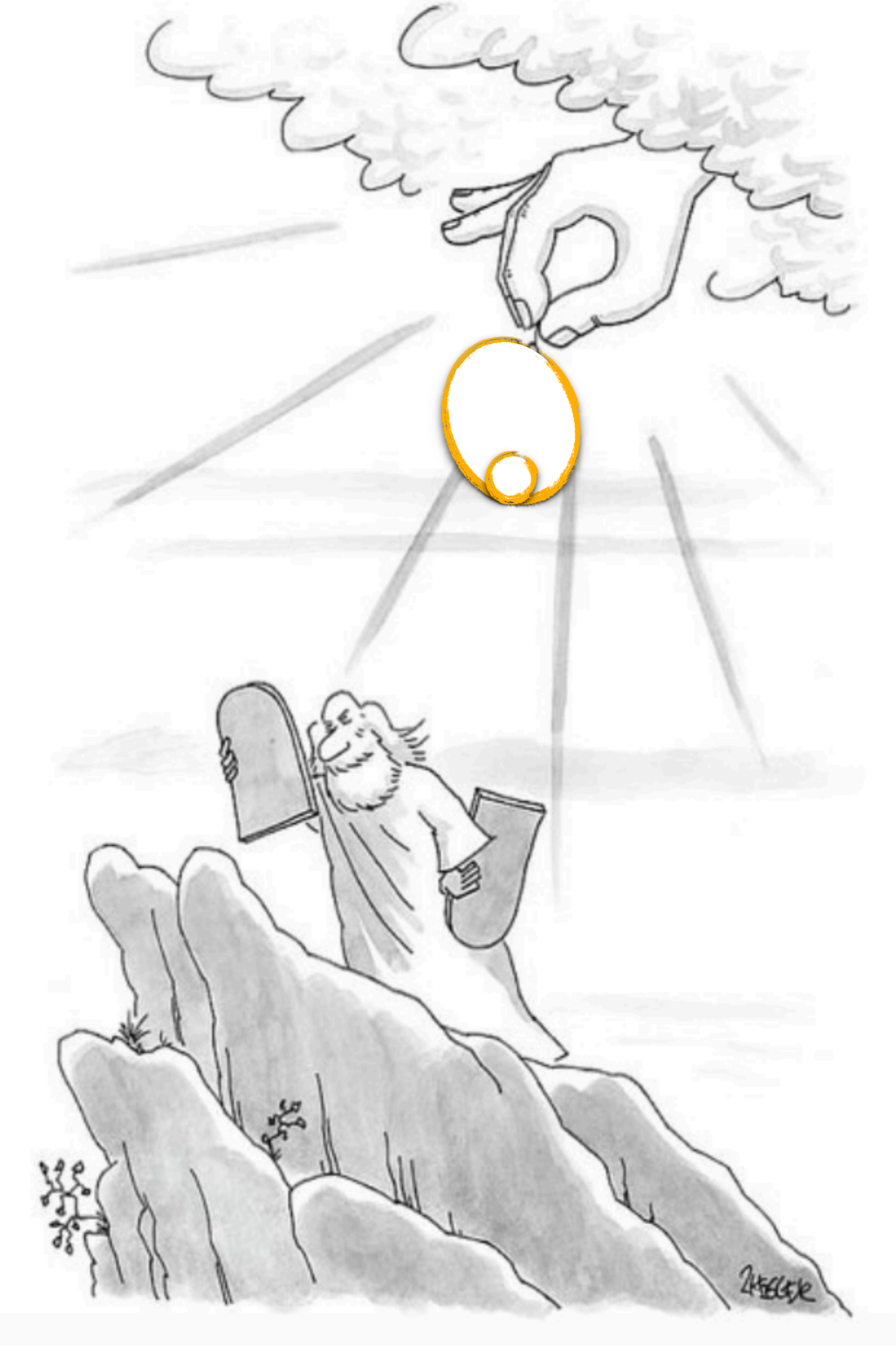
[Buttazzo et al. 1807.04743]

Summary

- In the **near future**, i.e. for the next 25 years the LHC will be THE machine to explore Higgs physics and the TeV scale through a compelling program of challenging measurements.

- For the **future**, i.e. after 2050, we are evaluating the options. The most mature and feasible project for CERN is an e+e- “weak-scale factory” in a new 91 Km circular tunnel and then the pp option in the 70’s.

- A **futuristic** collider based on accelerating muons could open a new era in HEP experiments, with an exciting physics case. The technology needs to and should be demonstrated.



Credits

For more details and information see the excellent talks by

Dario Buttazzo and Roberto Franceschini

last May at the INFN strategy meeting in Rome.