BSM from SM precision

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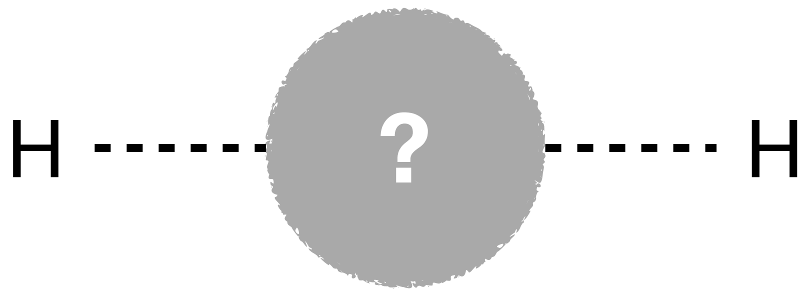
PASCOS 2024 — Rencontres du Vietnam — Quy Nhon, 8.7.2024

Why colliders?

Goal: explore physics at least up to $M \approx 10\,\mathrm{TeV}$

- ✦ What causes EWSB? i.e. does the SM hold up to few TeV?



$$M_{\mathrm{NP}} \lesssim 4\pi v \approx 3\,\mathrm{TeV}$$

rough estimate! there can easily be some O(1) factor

… and how is it related to the flavor problem?

Why colliders?

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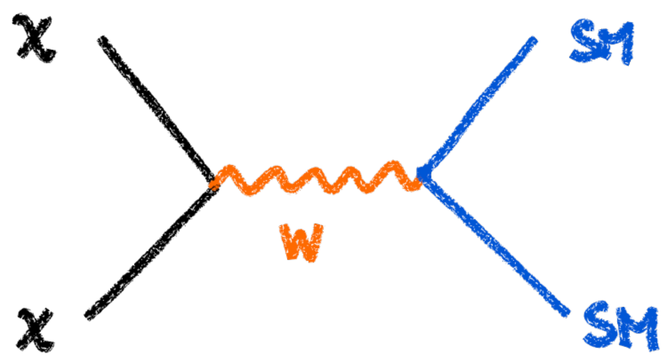
- ✦ What is dark matter? Is it a WIMP?



→ $M_{\mathrm{DM}} \approx 1 - 15\,\mathrm{TeV}$

Why colliders?

Goal: explore physics at least up to $M \approx 10\,\mathrm{TeV}$

- What causes EWSB? i.e. does the SM hold up to few TeV?

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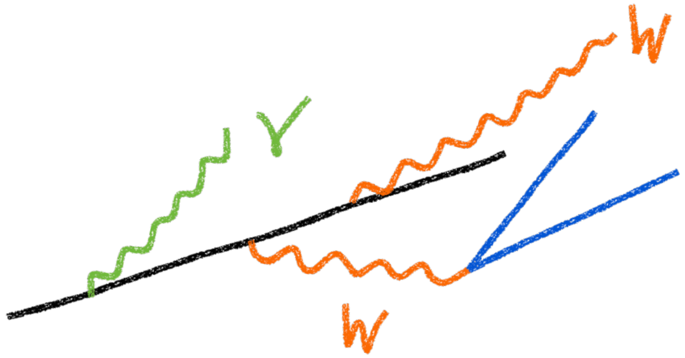
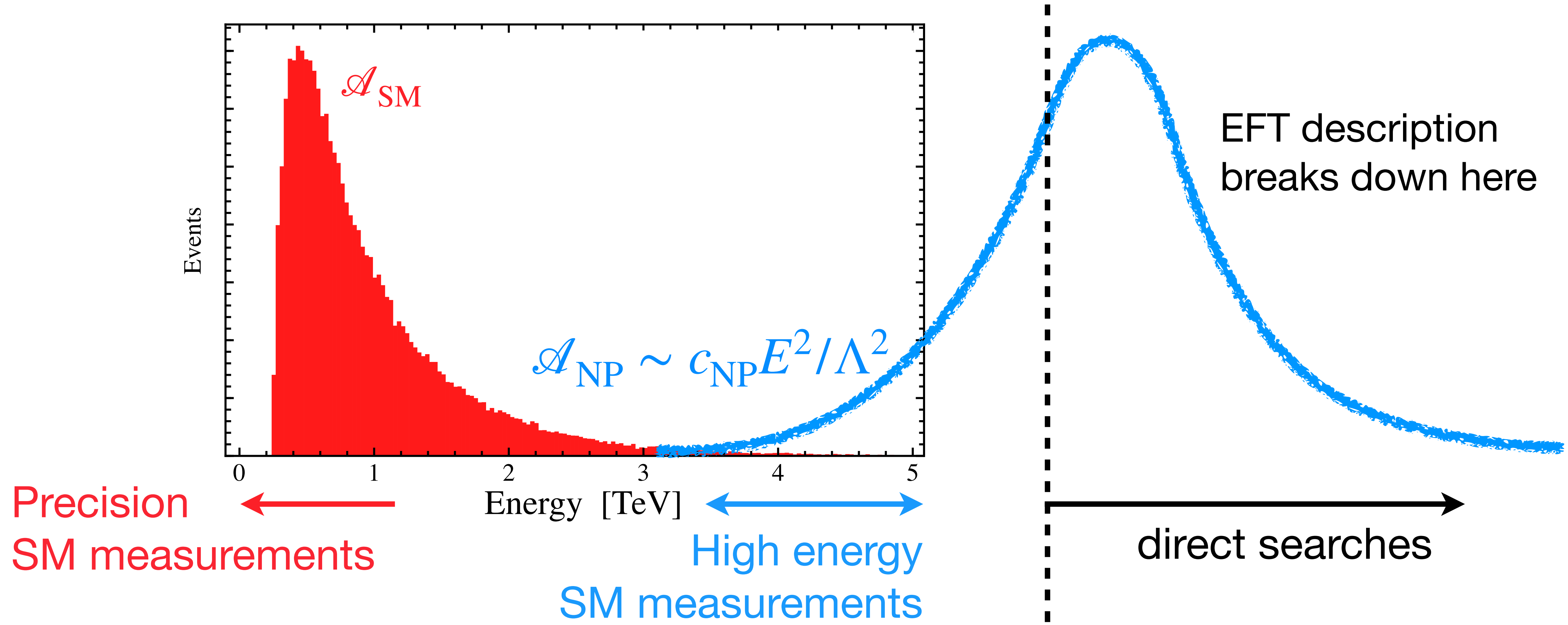
- Electroweak radiation: new phenomena *in the SM*

  Restoration of EW symmetry and radiation of “massless” EW bosons



$\Longrightarrow$ $E \approx 10\,\mathrm{TeV}$

Two paths to precision

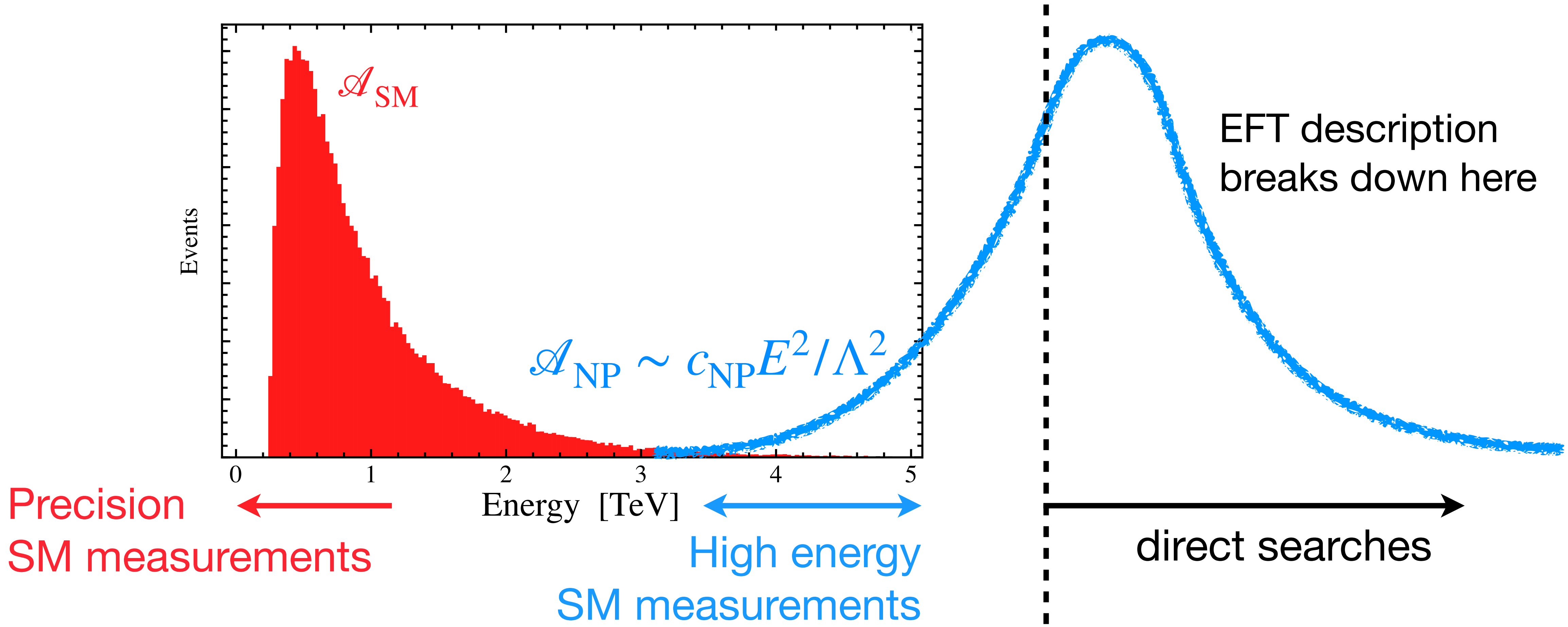


- The "multipole expansion" of particle physics: EFT

$$\mathscr{L} = \mathscr{L}_{\rm SM}^{d=4} + \frac{1}{\Lambda^2}\sum_i c_i \mathscr{O}_i^{d=6} + \frac{1}{\Lambda^4}\sum_i c_i \mathscr{O}_i^{d=8} + \cdots$$

  - Universal: particle content + Lorentz symmetry + SM internal symmetries
  - UV model encoded in values of Wilson coefficients c_i

Two paths to precision



Two ways to improve precision on coefficients (test higher scales Λ)

- **High rate:**

  More events = Better precision

- **High energy:**

  New physics effects grow ~ E^2

  Hard scattering $\sigma_{\rm SM} \sim 1/s$

Where do we stand?

- The SM works well at the TeV scale: → $M_{\mathrm{NP}} \gtrsim$ few TeV directly

- The Higgs boson is SM-like:

$$\delta\kappa \sim \frac{v^2}{M_{\mathrm{NP}}^2} g_\star^2 \lesssim 5\,\% \quad \longrightarrow \quad M_{\mathrm{NP}} \gtrsim g_\star\,\mathrm{TeV}$$

- The EW sector is SM-like:

$$\delta\varepsilon \sim \frac{m_W^2}{M_{\mathrm{NP}}^2} \lesssim \text{few} \times 10^{-3} \quad \longrightarrow \quad M_{\mathrm{NP}} \gtrsim 2\,\mathrm{TeV}$$

- The CKM picture of flavor and CP works well; lepton flavor is conserved

$$\frac{\delta\mathcal{O}_{ij}}{\mathcal{O}_{ij}^{\mathrm{SM}}} \sim \frac{v^2}{M_{\mathrm{NP}}^2}\frac{4\pi}{\alpha}\frac{c_{ij}}{\xi_{ij}} \lesssim 10\,\%$$

flavor suppression of the SM

$$\longrightarrow \quad M_{\mathrm{NP}} \gtrsim 3\,\mathrm{TeV}\left(\frac{c_{ij}}{\xi_{ij}}\right)^{1/2}$$

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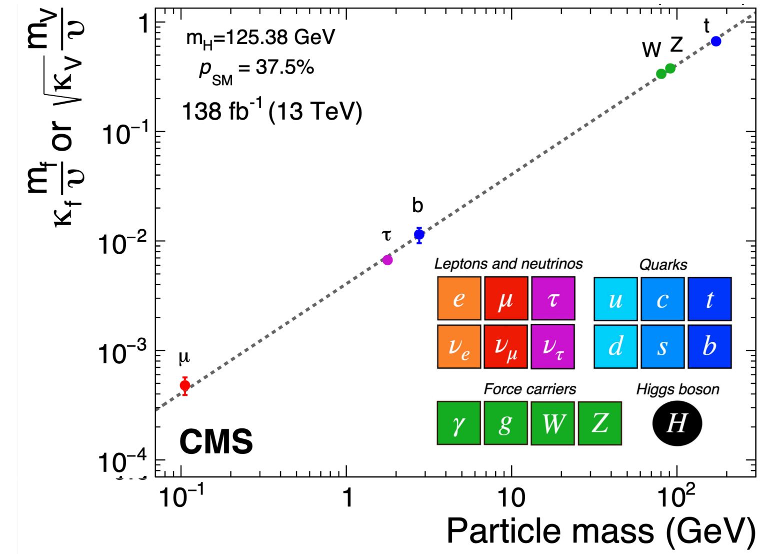

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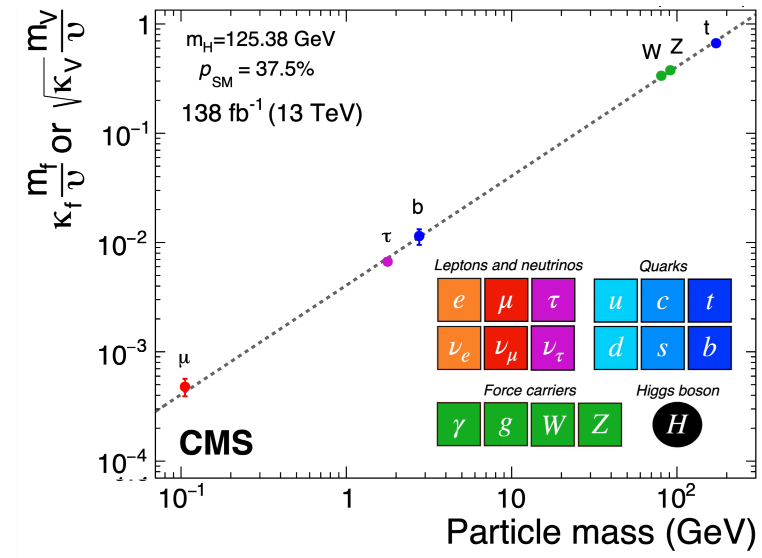

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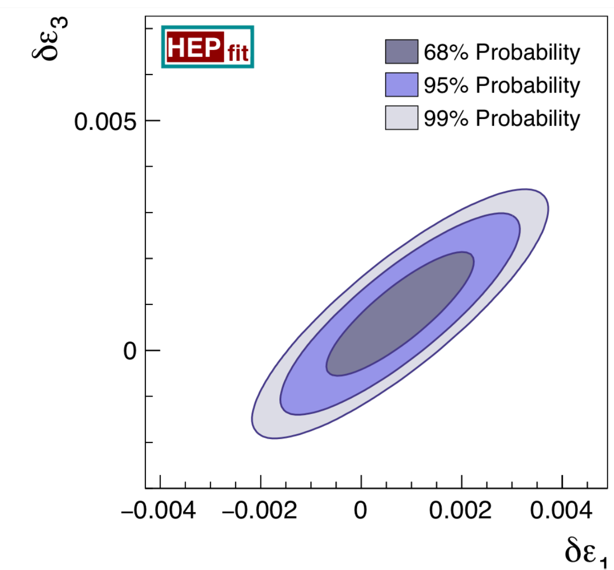

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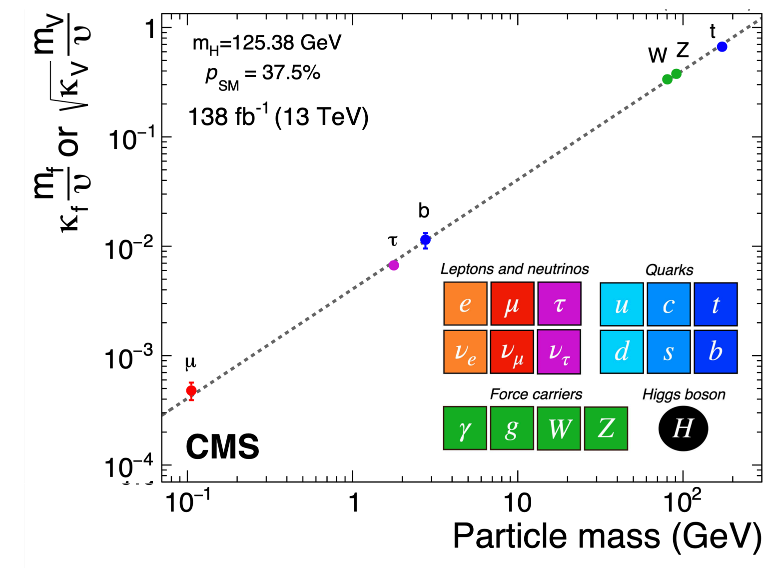

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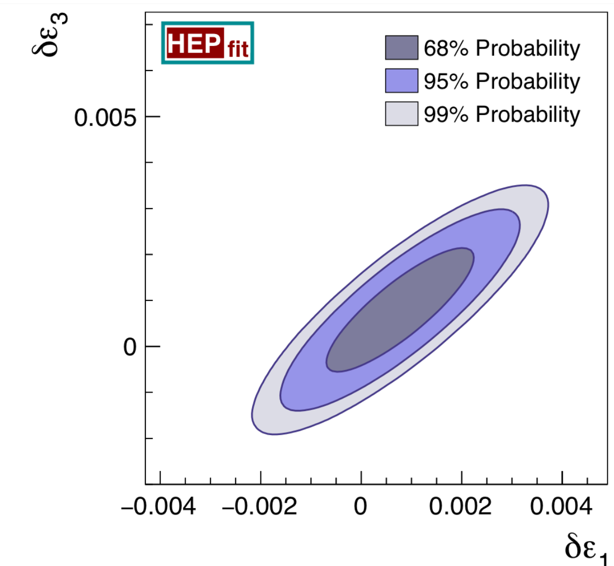

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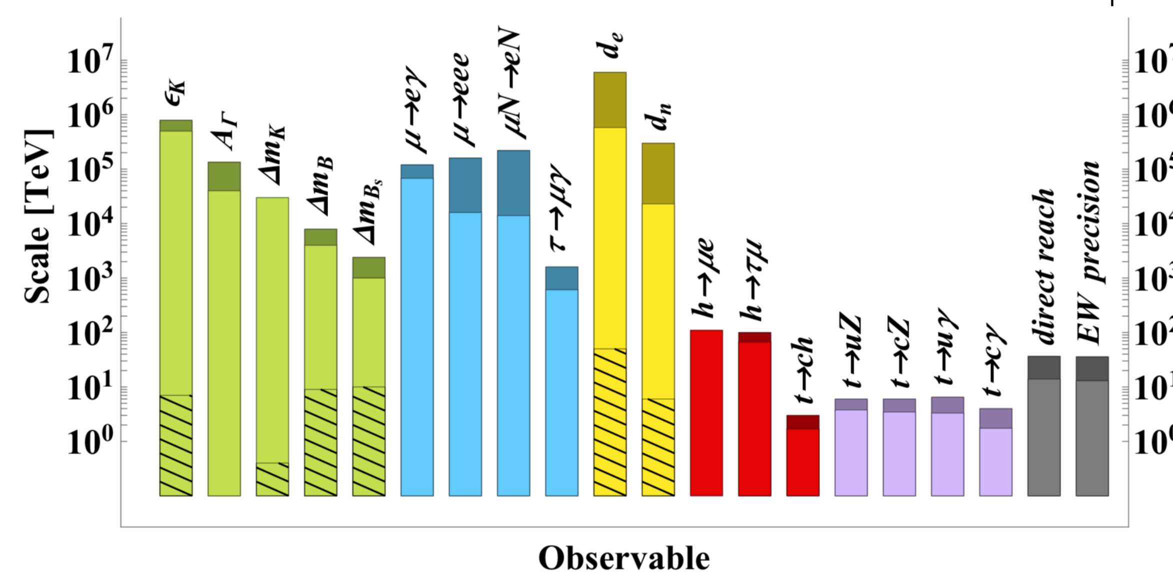
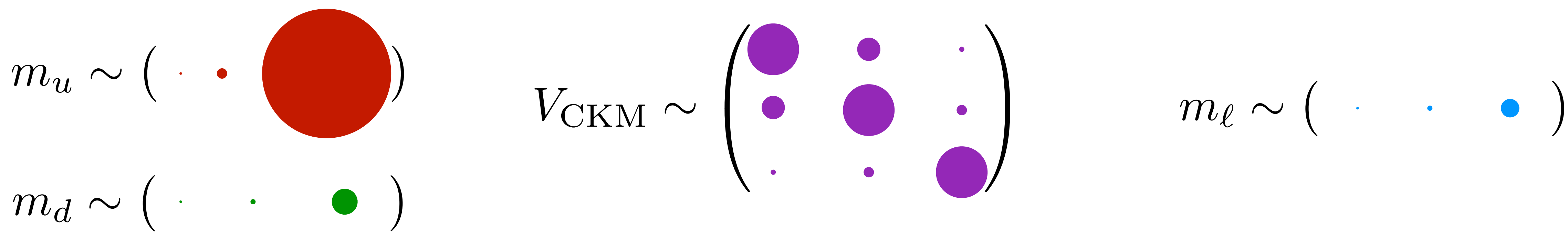


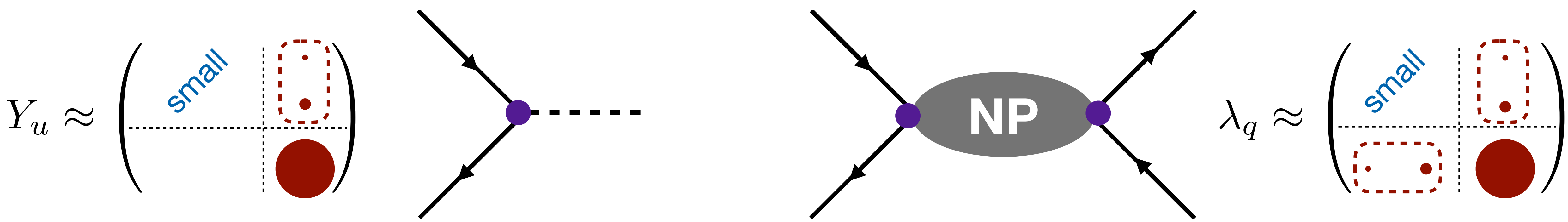
The flavor puzzle

✦ SM Yukawa couplings have an extremely hierarchical pattern



☛ What's the origin of this flavor structure? Why are there 3 families?

✦ Most likely NP in the Higgs sector couples to SM fermions in similar way…



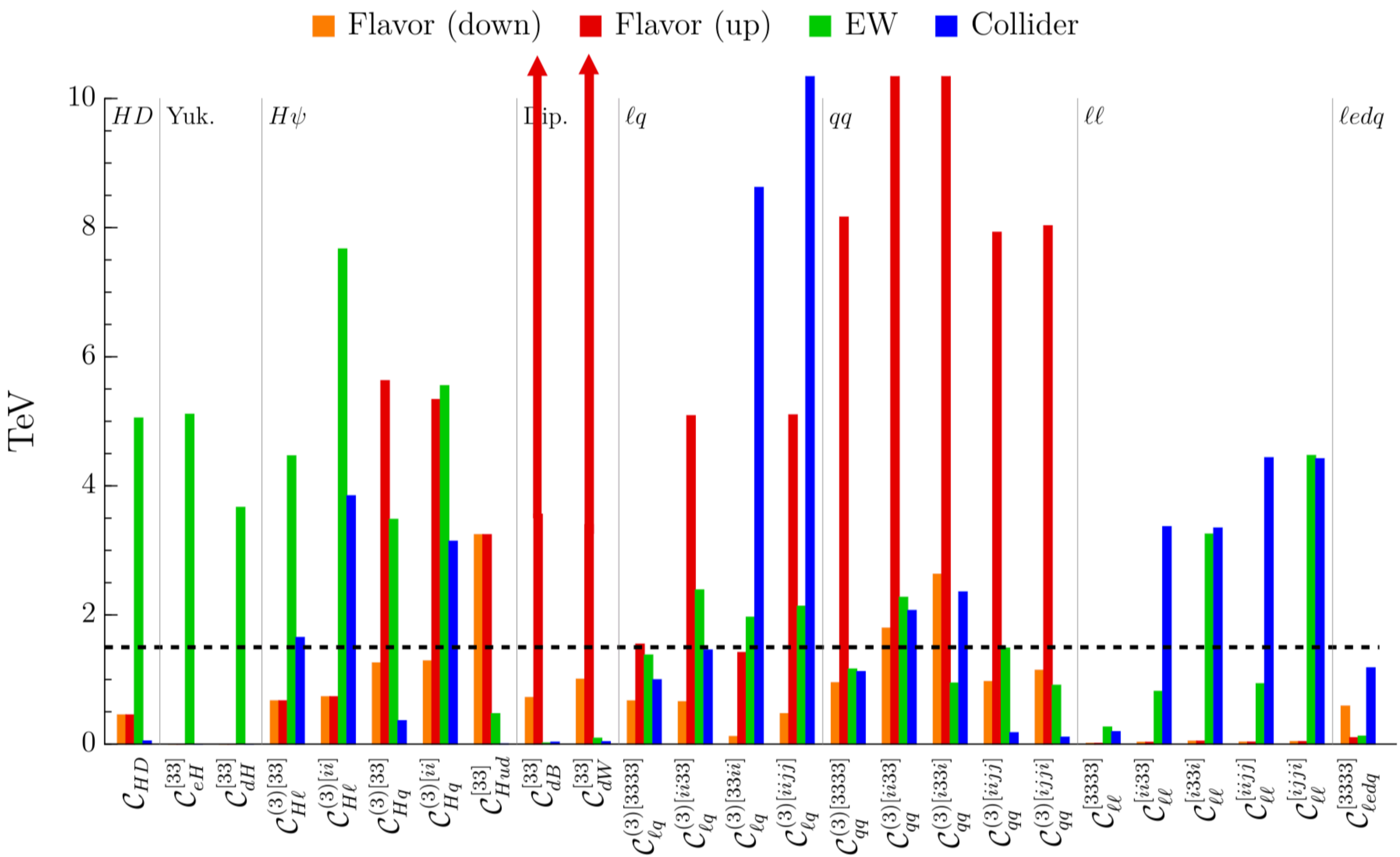
- Symmetries: e.g. MFV or U(2) models
  Barbieri et al. 2011; Isidori et al. 2017; …
- Dynamics: different NP scales for different families, related to Higgs
  Panico, Pomarol 2016; Bordone et al. 2017, etc…

→ $M_{\rm NP} \lesssim 3\,{\rm TeV}$

with O(1) couplings

Where do we stand?

- SMEFT with CKM-like suppression ($U(2)^3$ flavor symmetry):

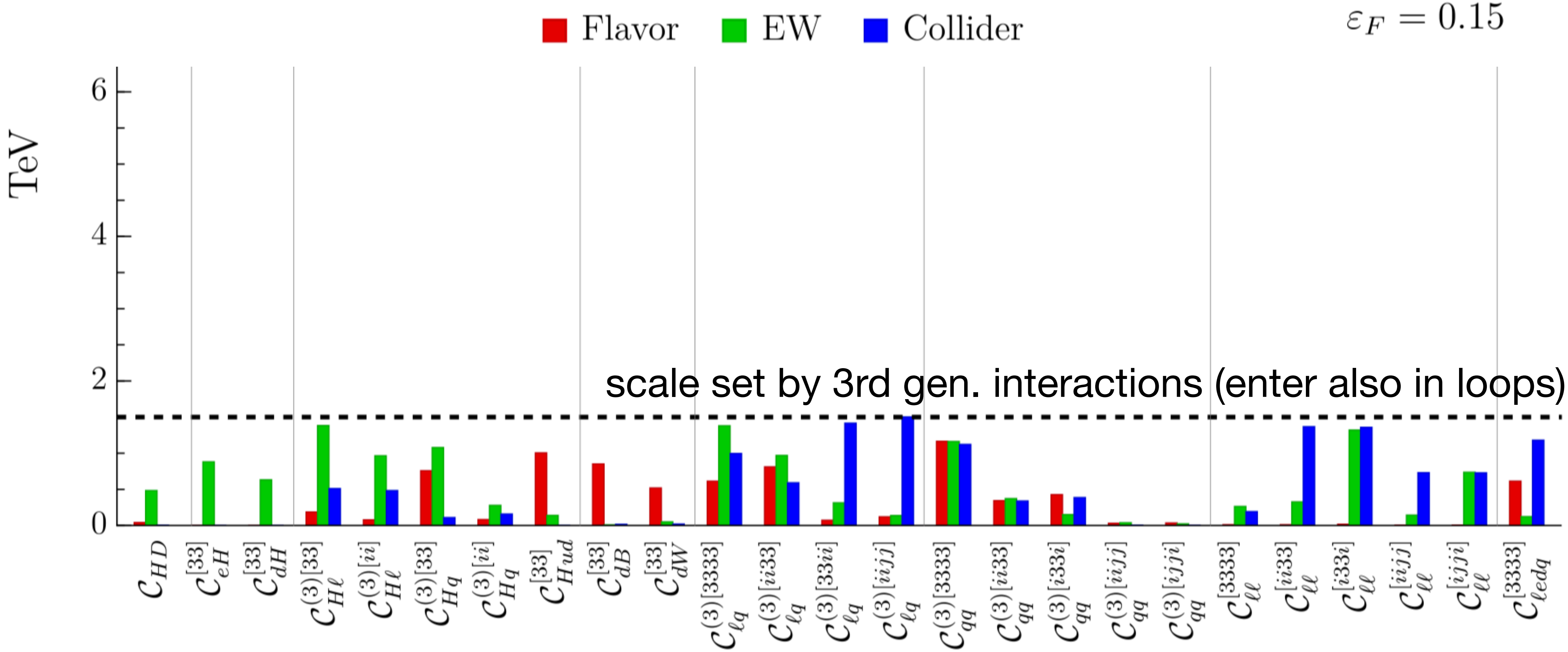


Allwicher, Cornella, Isidori, Stefanek 2311.00020

Where do we stand?

- SMEFT with CKM-like suppression (U(2)³ flavor symmetry):
- + mild suppression of light gen. interactions
- + some flavor alignment

$$\varepsilon_{\rm loop} = \frac{g_i}{16\pi^2}$$
$$\varepsilon_Q = 0.16$$
$$\varepsilon_L = 0.40$$
$$\varepsilon_H = 0.31$$
$$\varepsilon_F = 0.15$$



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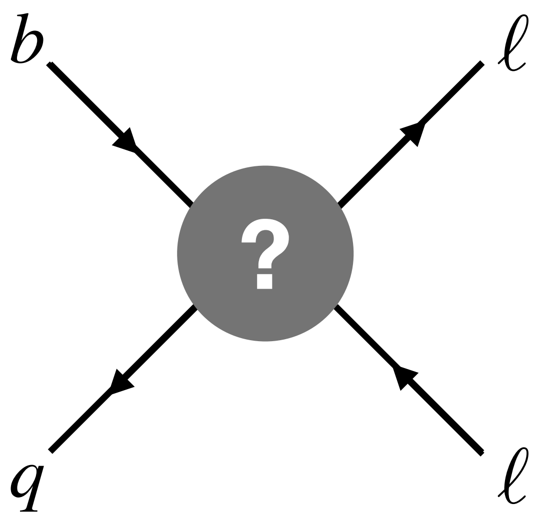
Third-generation flavor processes

- Semi-leptonic charged-current decays $b \to c\tau\nu$

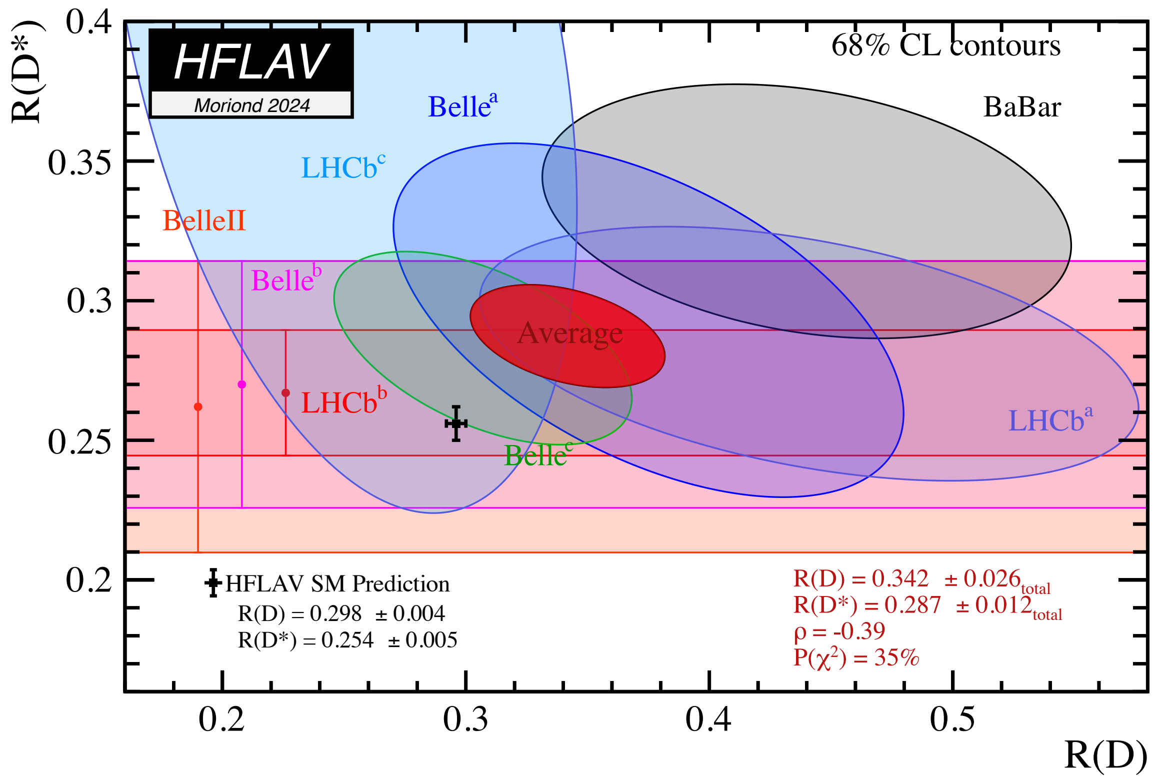


- Example: left-handed current, EW triplet

(scalar/tensor currents also possible, more constrained)

Third-family operator after CKM rotation $q_L^3 = \begin{pmatrix} V_{i3} u_L^i \\ b_L \end{pmatrix}$

$$(\bar{q}_L^3 \gamma_\mu \sigma^a q_L^3)(\bar{\ell}_L^3 \gamma^\mu \sigma^a \ell_L^3) = V_{cb} (\bar{b}_L \gamma_\mu c_L)(\bar{\nu}_\tau \gamma^\mu \tau_L) + \cdots$$



Today: effect ~ 10% of SM

$$M_{\rm NP} = \Lambda \times g_\star \gtrsim 1.2\,{\rm TeV} \times g_\star$$

Third-generation flavor processes

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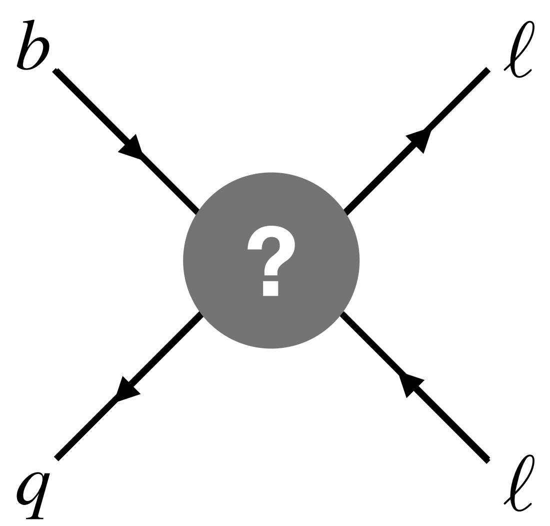

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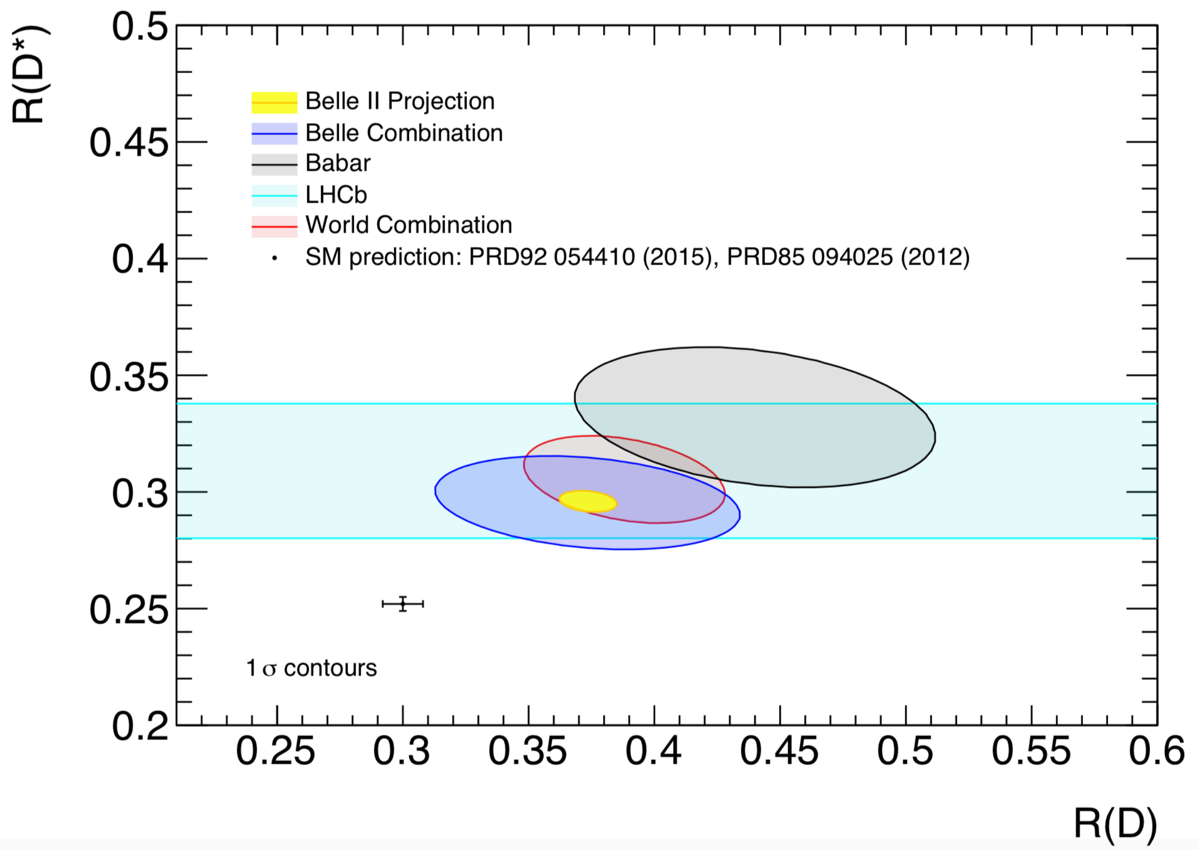
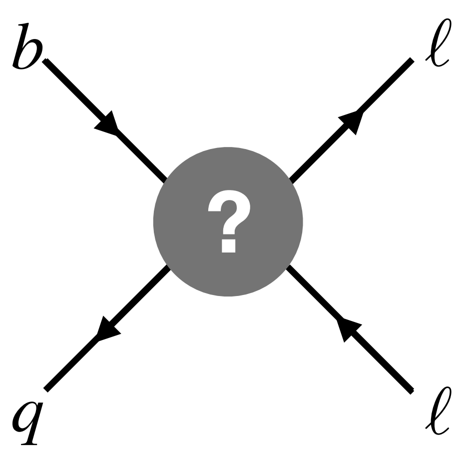


Belle II prospects: ~ 1% of SM

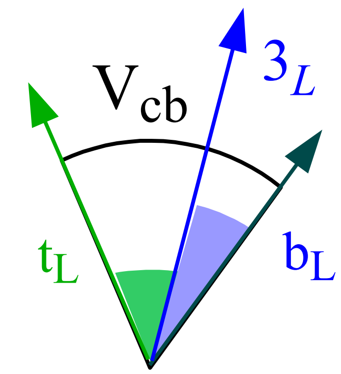
$$M_{\rm NP} = \Lambda \times g_\star \gtrsim 4\,{\rm TeV} \times g_\star$$

☛ talk by F. Forti on Wednesday

Correlations: neutral currents



- Flavor misalignment generates FCNC:



$$(\bar{q}^3_L\gamma_\mu\sigma^a q^3_L)(\bar{\ell}^3_L\gamma^\mu\sigma^a\ell^3_L) \;=\; V_{cb}(1-\theta)(\bar{b}_L\gamma_\mu c_L)(\bar{\nu}_\tau\gamma^\mu\tau_L)$$

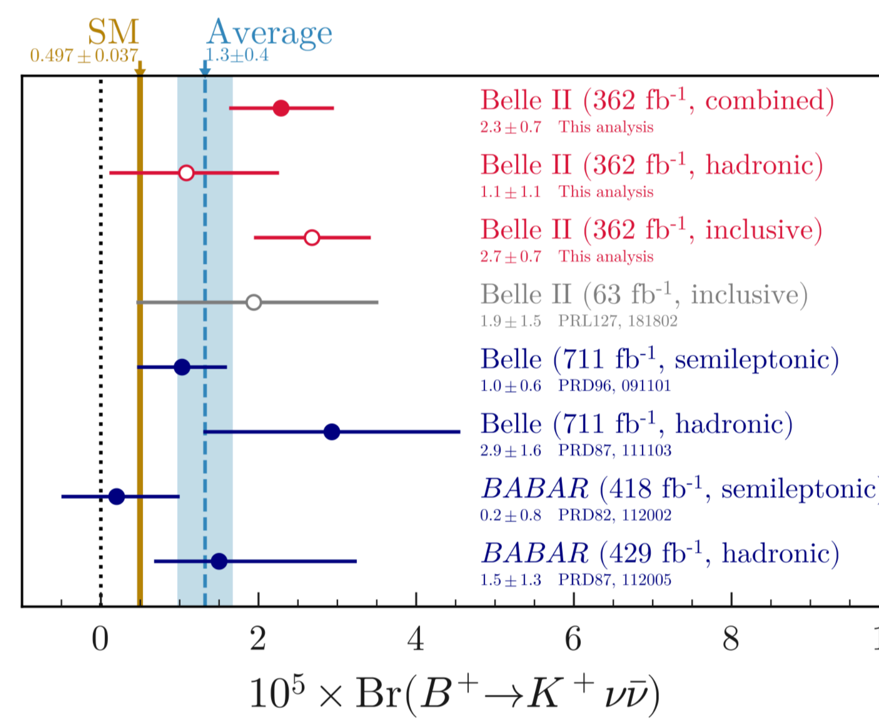
$$+V_{ts}\,\theta\left[(\bar{b}_L\gamma_\mu s_L)(\bar{\tau}_L\gamma^\mu\tau_L) - (\bar{b}_L\gamma_\mu s_L)(\bar{\nu}_\tau\gamma^\mu\nu_\tau)\right] + \cdots$$

related by SU(2)$_L$

related by SU(2)$_L$ + flavor

- $b \to s\nu\nu$ will be measured precisely by Belle II

Observables	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu}$	9.3%

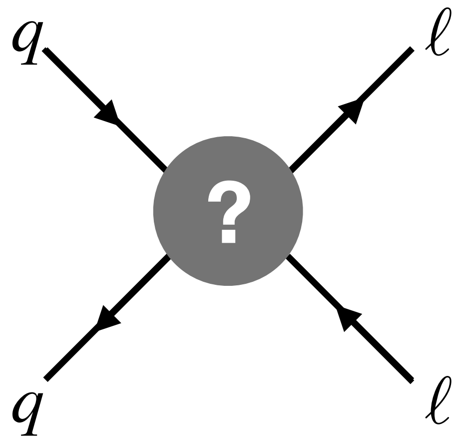


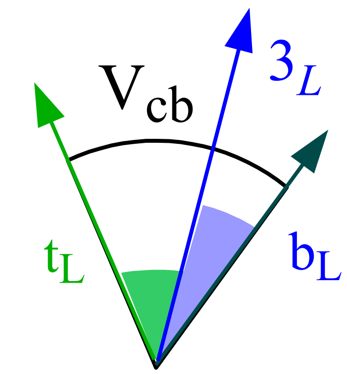
- $b \to s\tau\tau$ possible at FCC-ee!

Decay mode/Experiment	Belle II (50/ab)	LHCb Upgr. (50/fb)	FCC-*ee*
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 500	~ 800
$\mathcal{B}(B_s \to \tau^+\tau^-)$			
$B^+ \to \tau^+\nu$	7%	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	5%

S. Monteil

Correlations: second generation





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$$+V^*_{ts}\,\theta\left[(\bar{b}_L \gamma_\mu s_L)(\bar{\tau}_L \gamma^\mu \tau_L) - (\bar{b}_L \gamma_\mu s_L)(\bar{\nu}_\tau \gamma^\mu \nu_\tau)\right] + \cdots$$

related by SU(2)$_L$

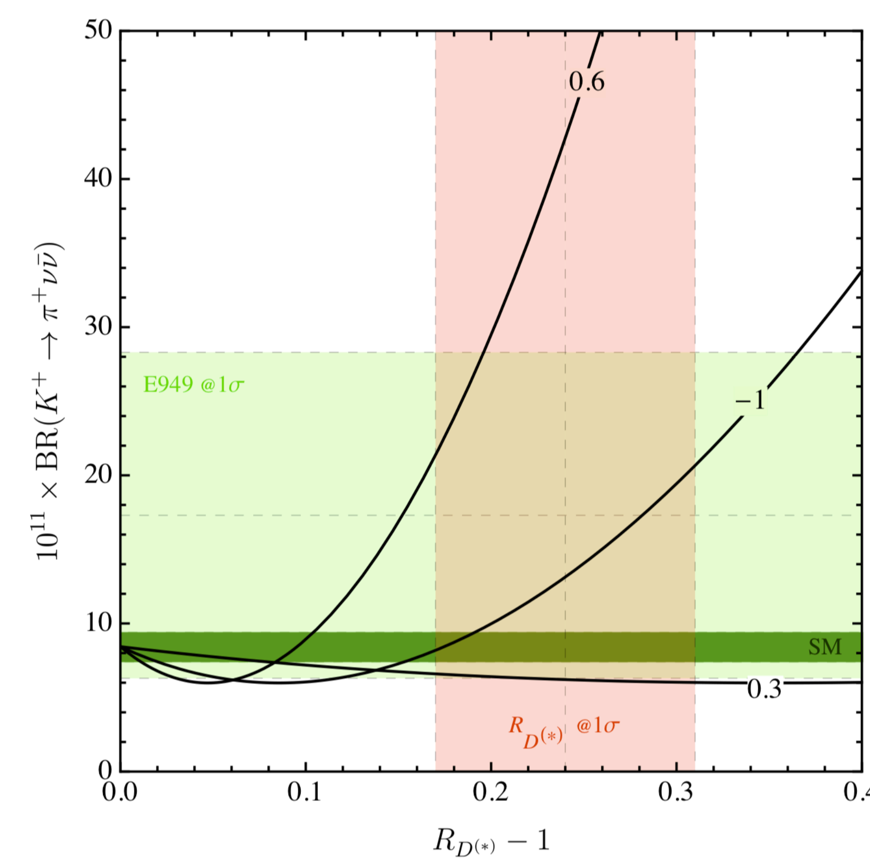
… and couplings to light quarks

$$+V^*_{ts} V_{td}\,\theta^2 (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_\tau \gamma_\mu \nu_\tau) + V_{cb} V^*_{ub} (1-\theta)^2 (\bar{c}_L \gamma_\mu u_L)(\bar{\nu}_\tau \gamma_\mu \nu_\tau)$$

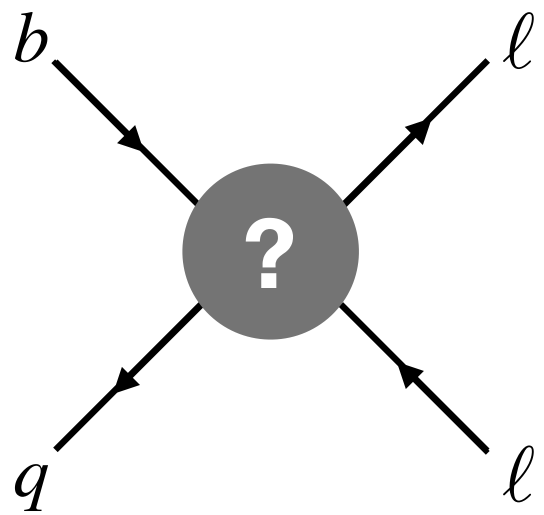
related by SU(2)$_L$ + flavor

- Kaon sector: $s \to d\nu\nu$ from NA62 and KOTO
- Charm sector: various clean $c \to u\nu\nu$ decays measurable!

Bause, Gisbert, Golz, Hiller 2010.02225, 2007.05001



High-pT searches at LHC



- The same operators can be probed with high-pT processes at LHC, e.g. $bb \to \tau\tau, \;\; bc \to \tau\nu$

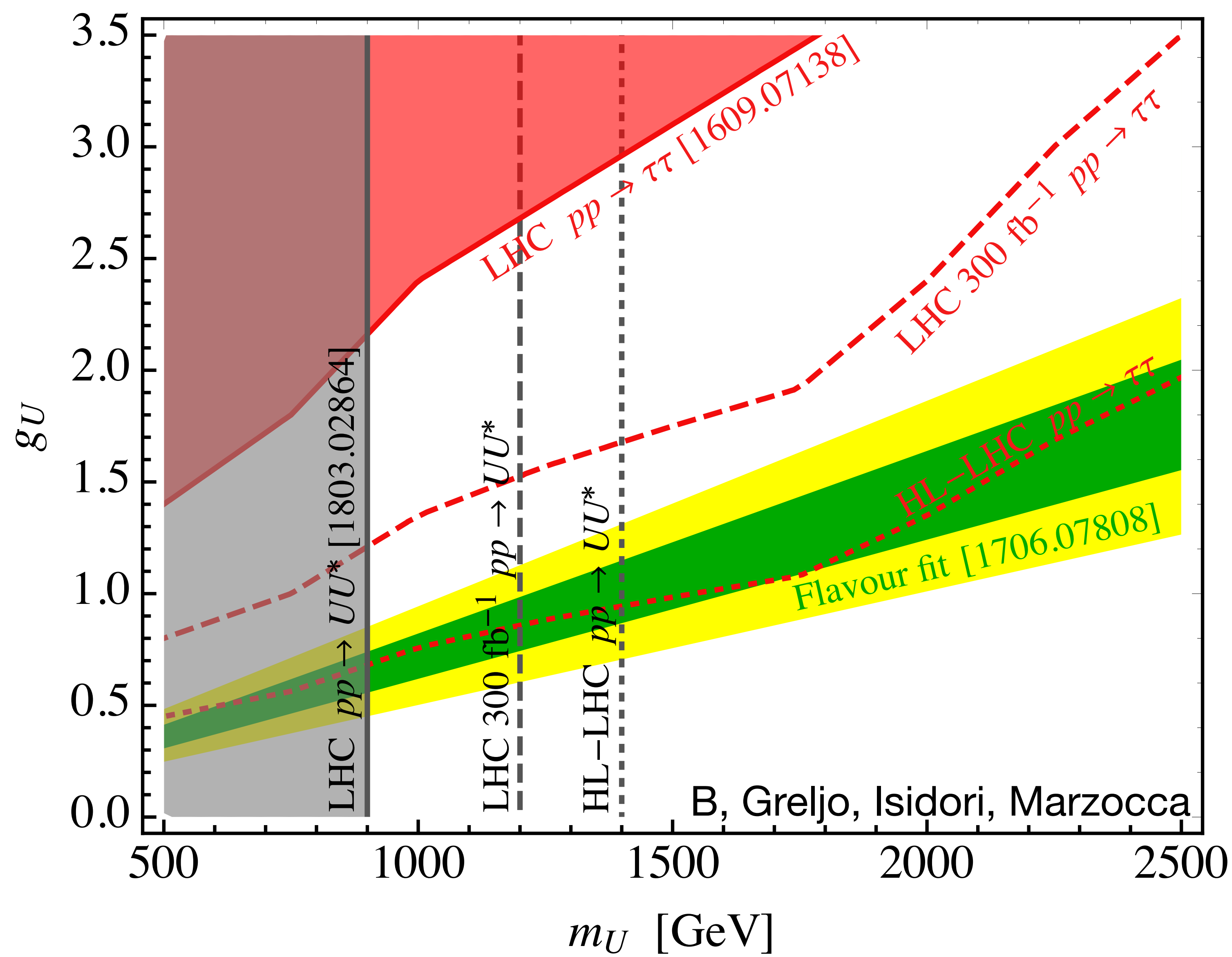
Faroughy, Greljo, Kamenik 2016

Greljo, Camalich, Ruiz 2018

- Strong suppression at high invariant masses due to proton PDF

- Flavor suppression

HL-LHC will not probe the full parameter space testable by rare decays

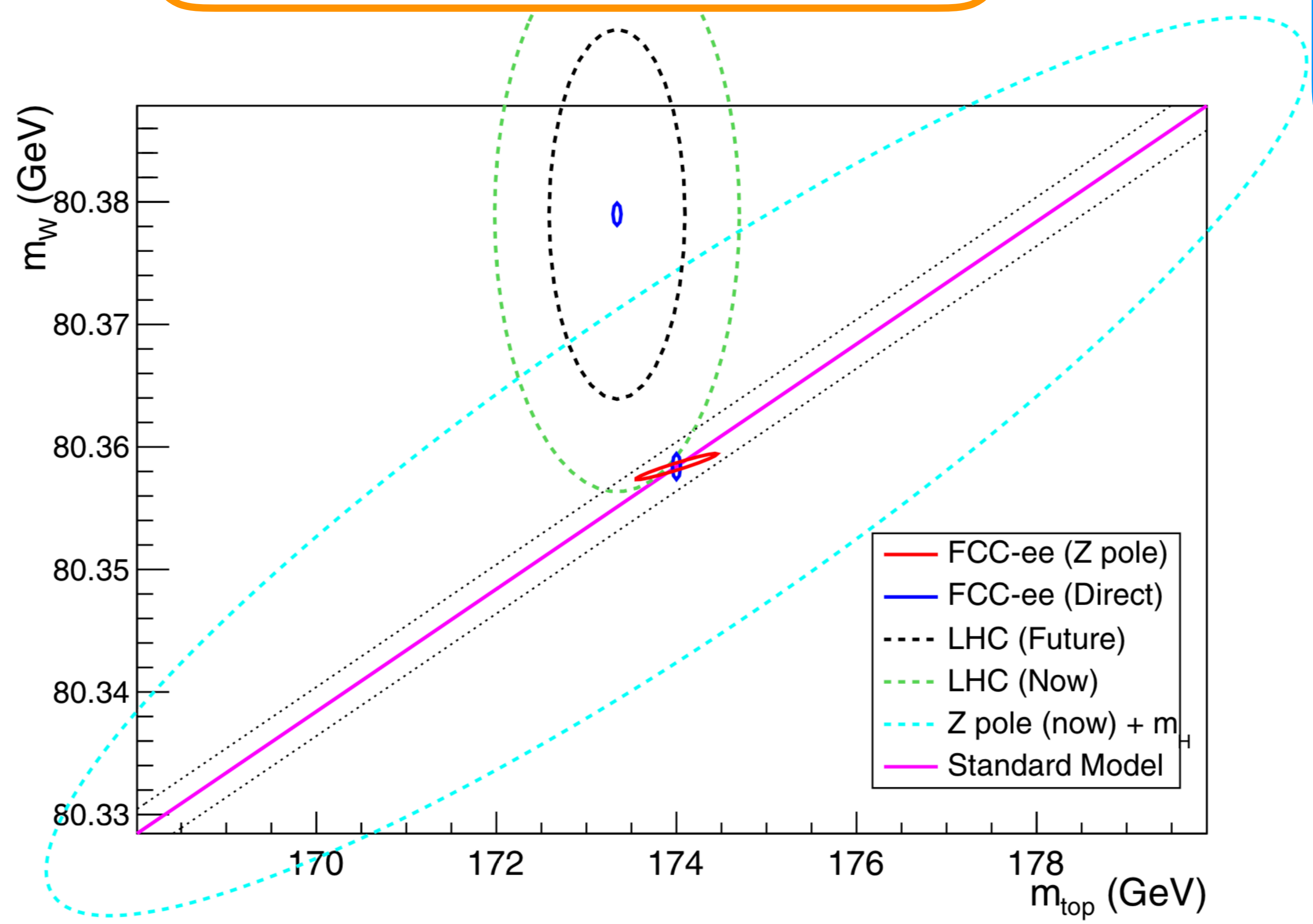


EW precision

- Higgs & EWSB physics $\longleftrightarrow$ EW precision measurements

$$\mathcal{O}_T = \left(H^\dagger D^\mu H\right)^2$$ $\Delta\rho$

$$\mathcal{O}_W = \left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$$
$\sin^2\theta_{\rm eff}$



- FCC-ee: 6 x 10[12] Z bosons ultimate precision at the Z pole, limited by syst. and th. errors

$$\Delta\hat{S} \sim \frac{m_W^2}{M_{\rm NP}^2} \lesssim \text{few} \times 10^{-5}$$

$\rightarrow$ $M_{\rm NP} \gtrsim 12\,\text{TeV}$

	Current	HL-LHC	ILC$_{250}$ (& ILC$_{91}$)		CEPC	FCC-ee	CLIC$_{380}$ (& CLIC$_{91}$)	
S	0.13	0.053	0.012	0.009	0.0068	0.0038	0.032	0.011
T	0.08	0.041	0.014	0.013	0.0072	0.0022	0.023	0.012

EW precision

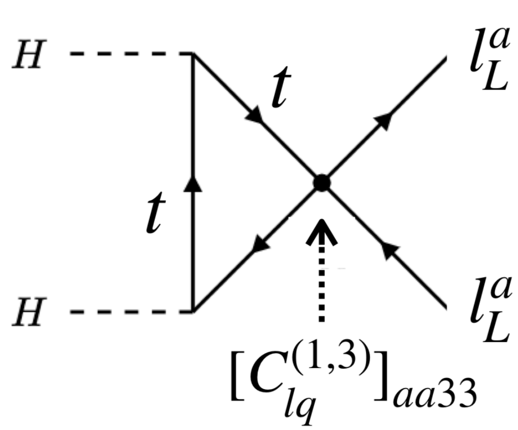
Why 10^{12} Z bosons?

- Lepton asymmetries are small: $N_{\text{events}} = N_Z \times \text{BR}(Z \to \ell^+\ell^-) \times A_\ell \sim 3 \times 10^{-4}\, N_Z$

$\Longrightarrow \;\; N_Z \approx 10^{12}$ for 10^{-4} precision.

- In general, several more operators enter the EW fit

4-fermion interactions affect EW observables through one loop RGE



$\longrightarrow$ $[C_{Hl}^{(1,3)}]_{aa}$

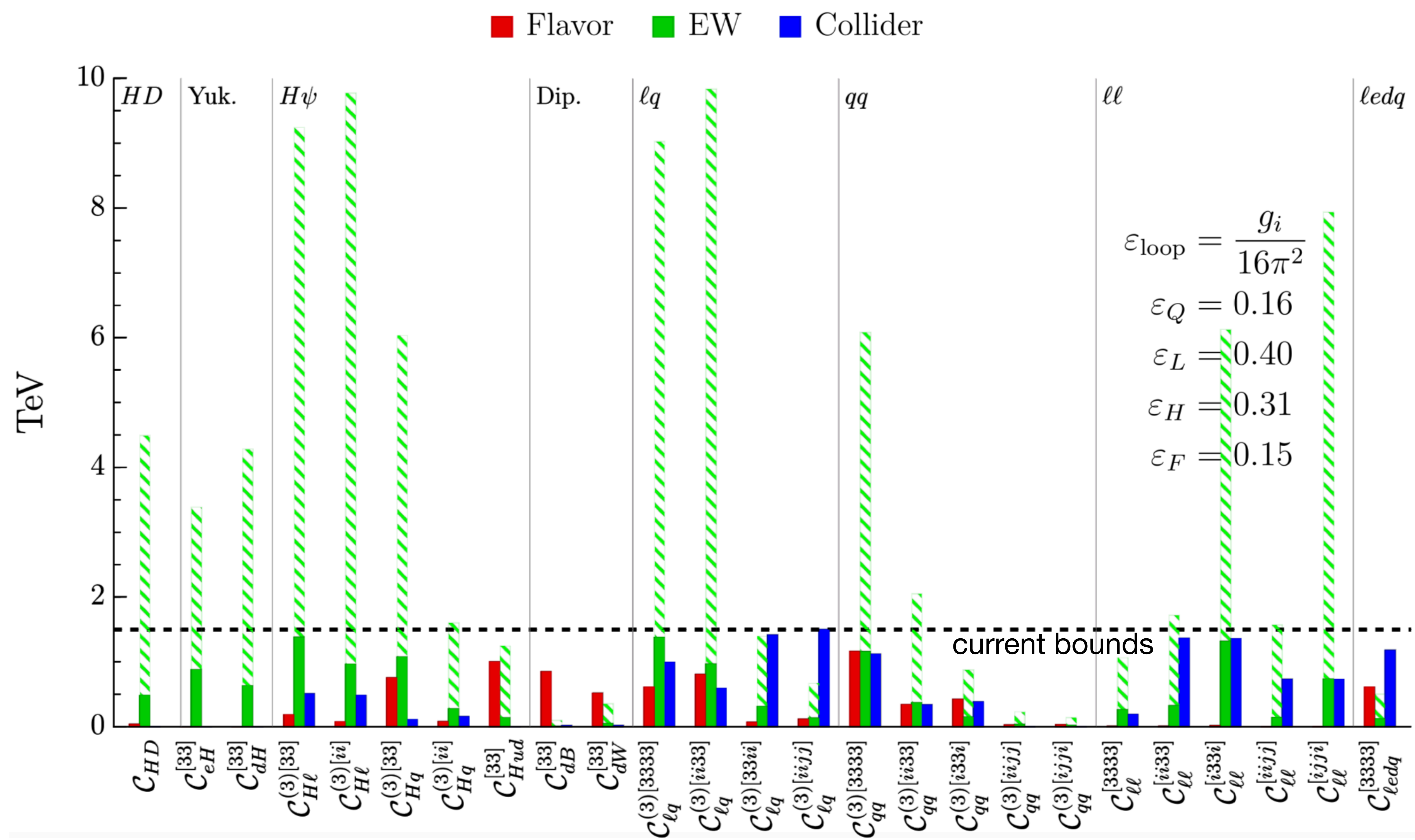
2311.00020, 1704.04504

rates and asymmetries in $Z \to \ell\ell$

$b \to c\ell\nu$ decays, LH current

EW precision

- $U(2)^3$ flavor symmetry + suppression of light gen. + some flavor alignment



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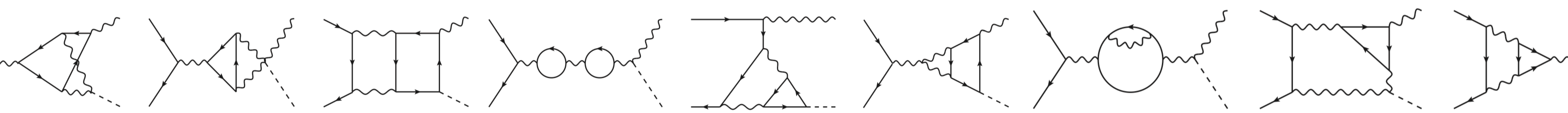
Challenges

- Precision measurements need to be matched with SM theory predictions of comparable precision

- Already now, huge rates of b, c hadrons at LHC not always reflected in improvement of physics reach, due to QCD
(e.g. hadronic channels, V_{cb} puzzle in semi-leptonic decays, K and D mixing, …)

$\Delta\hat{S} \lesssim 10^{-5} \quad \longrightarrow$ NNLO EW corrections required

Freytas, Song, Kie

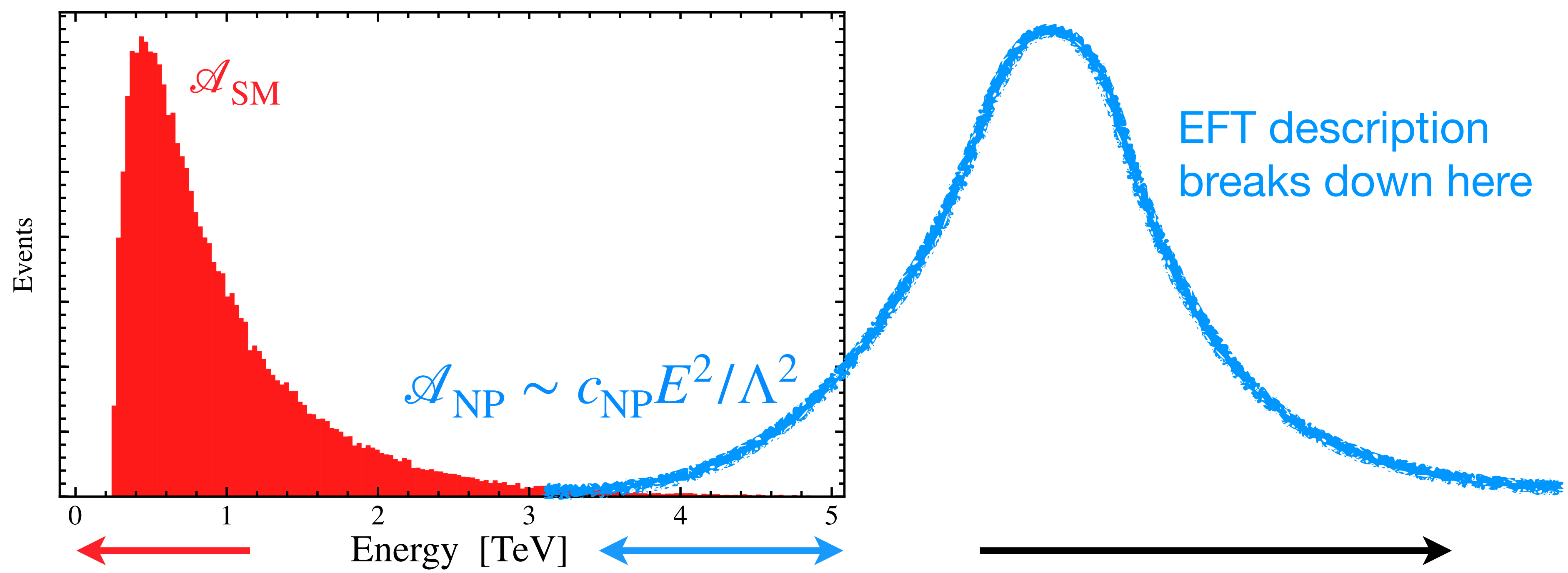


- High rate measurements eventually limited by systematics

We'll need to measure physics at higher energy to improve!

EW precision at high-energy

- NP effects are more important at high energies $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum C_i \mathcal{O}_i$



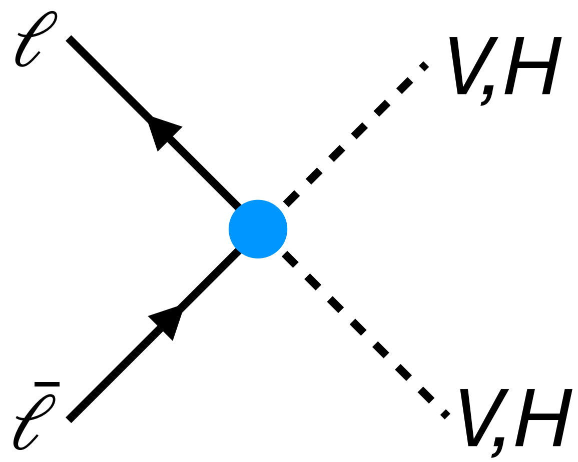
$$\frac{\Delta\sigma(E)}{\sigma_{SM}(E)} \propto \frac{E^2}{\Lambda^2_{BSM}} \approx \begin{cases} 10^{-6}, & E \sim 100\,\text{GeV} \\ 10^{-2}, & E \sim 10\,\text{TeV} \end{cases}$$

… taken to the extreme at a μ-collider with 10's of TeV!

- "Towards a muon collider" Accettura et al. 2303.08533
- talk by Karri on Thursday

Example: high-energy di-bosons

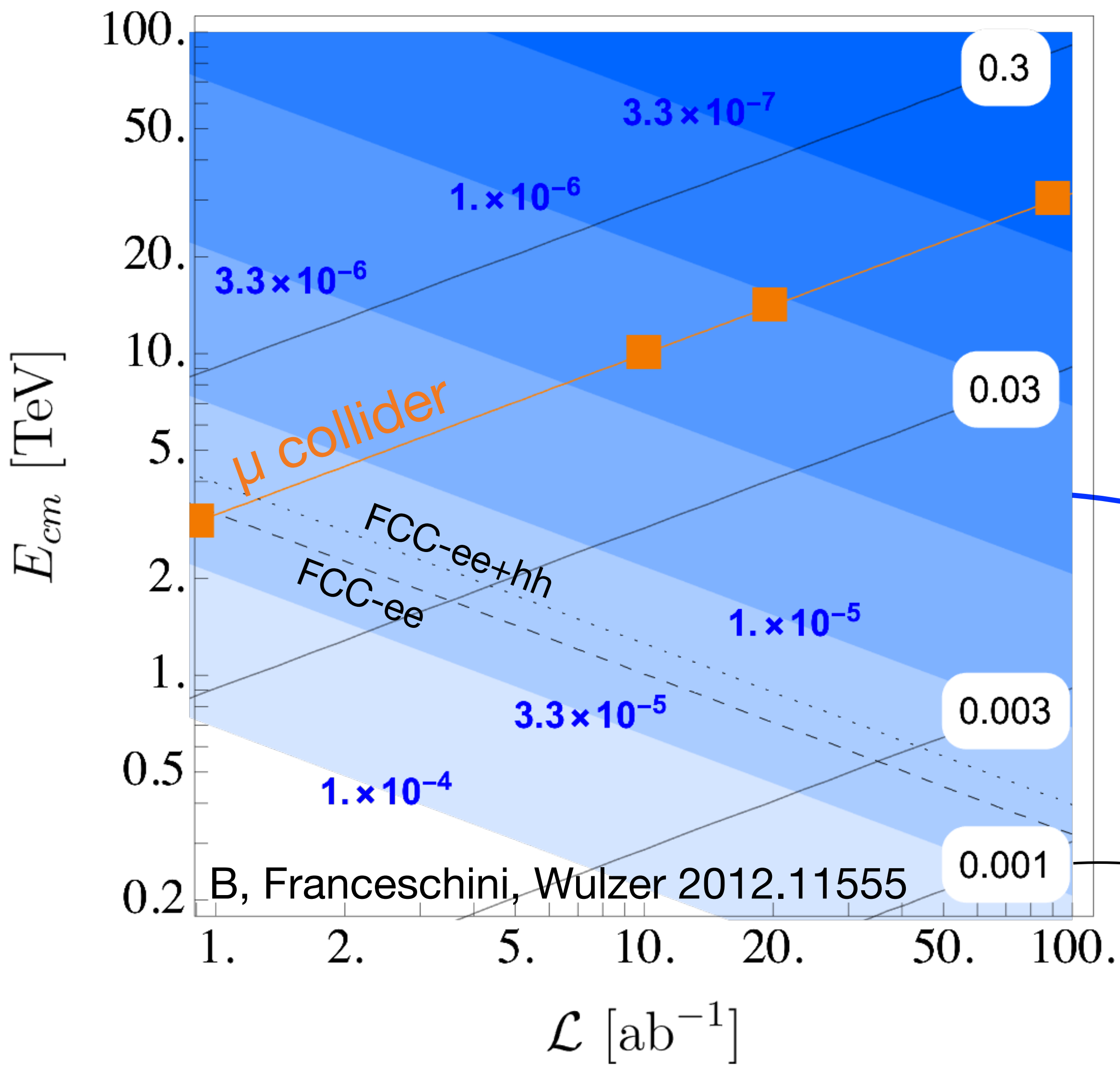
- Longitudinal $2 \to 2$ scattering amplitudes at high energy:



$$\ell^+\ell^- \to W_L^+ W_L^-$$
$$\ell^+\ell^- \to Z_L H$$

Determined by the same two operators that affect also EWPT (in flavor-universal theories):

$$\mathcal{O}_W = \left(H^\dagger \sigma^a D^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \left(H^\dagger D^\mu H\right) \partial^\nu B_{\mu\nu}$$



related with Z-pole observables

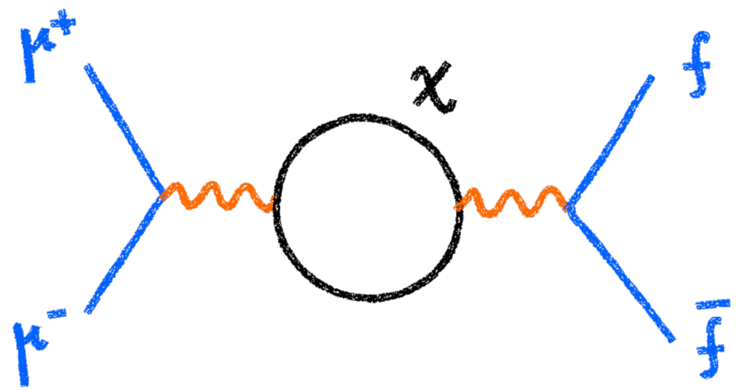
$$\hat{S} = m_W^2 (C_W + C_B)$$

LEP: 10^{-3}, FCC: few 10^{-5} **MuC:** 10^{-6}

precision of measurement

EW-charged matter

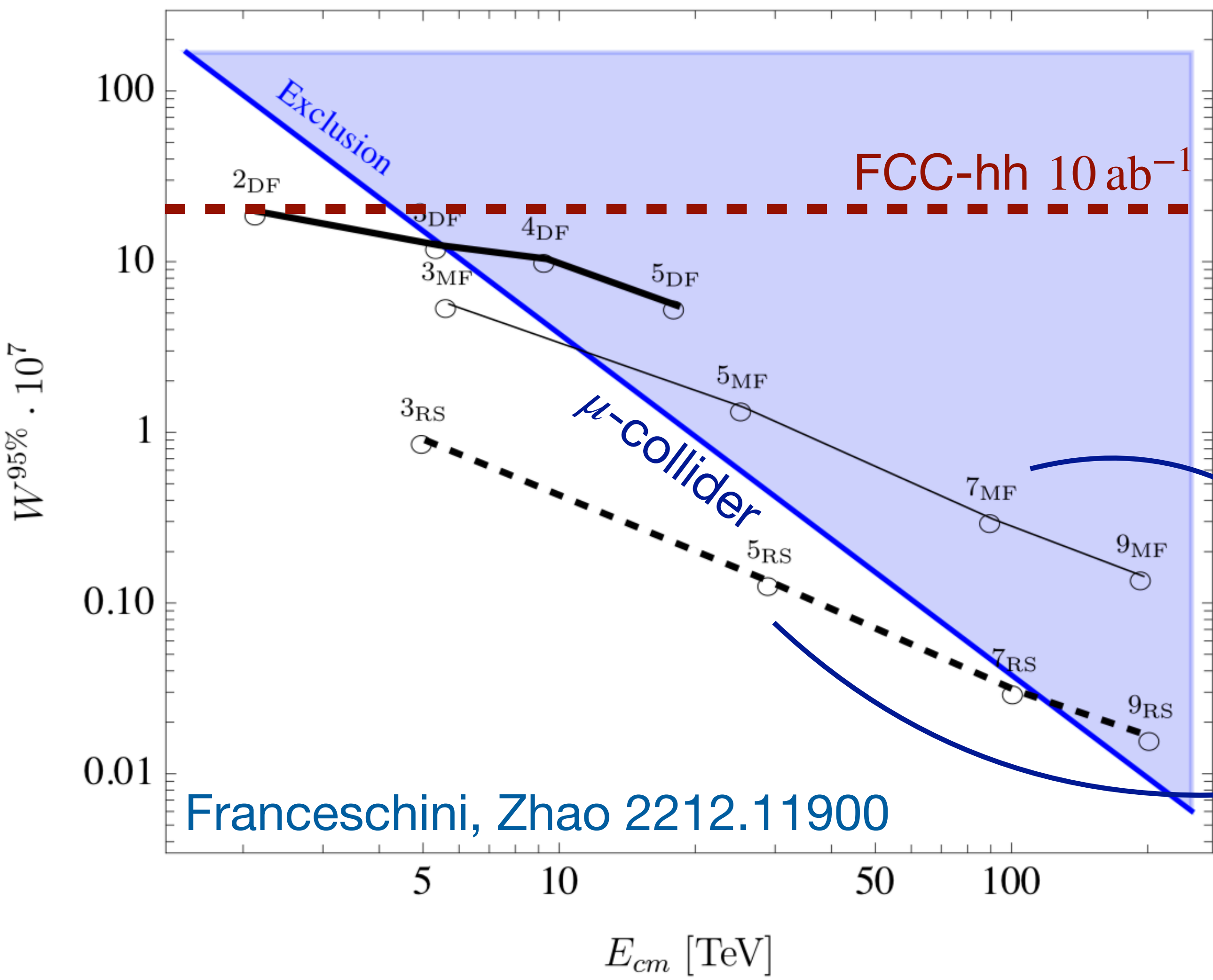
- All EW multiplets contribute to high-energy 2 → 2 fermion scattering: effects that grow with energy, can be tested at μ collider



can be WIMP dark matter if M ~ few TeV

Cirelli, Fornengo, Strumia hep-ph/0512090

Bottaro, B, Costa, Franceschini, Panci, Redigolo, Vittorio 2107.09688, 2205.04486



$$\hat{W} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 n^3 \propto 1/n^2$$

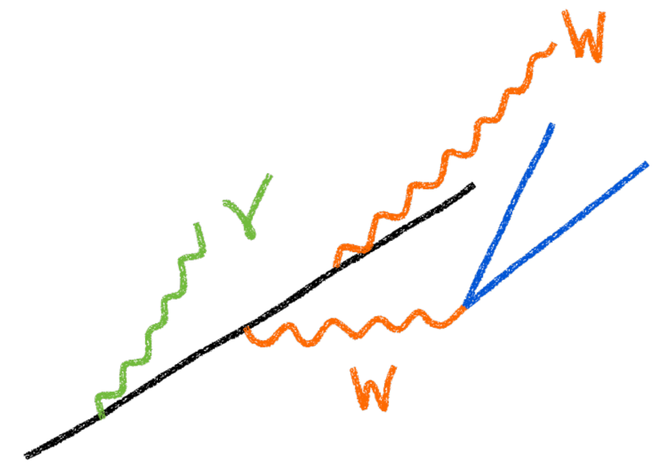
$$\hat{Y} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 Y^2 n \propto 1/n^4$$

right of blue line: can be tested indirectly

left of blue line: can be tested directly

EW radiation

EW radiation becomes important at multi-TeV energies!



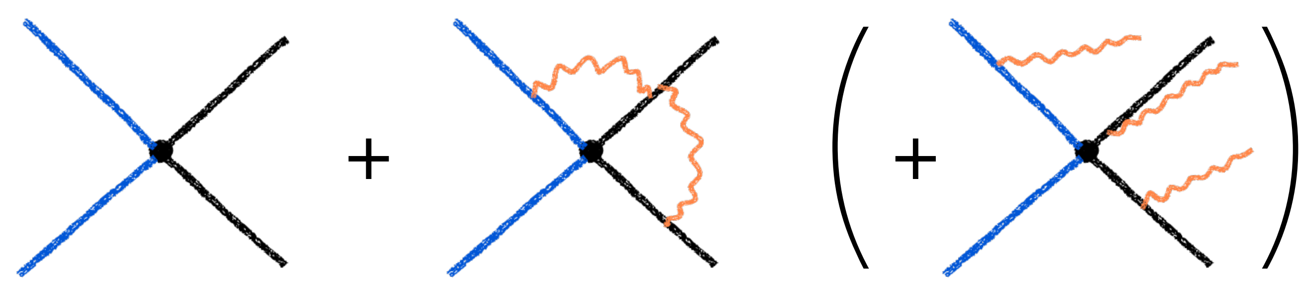
Especially relevant for muon collider, but also FCC-hh…

- $m_{W,Z} \ll E$: γ, W, Z are all similar!
- Multiple gauge boson emission is not suppressed

Sudakov factor $\frac{\alpha}{4\pi}\log^2\left(\frac{E^2}{m_W^2}\right) \times$ Casimir ≈ 1 for E ~ 10 TeV

- ☛ Which cross-section? Exclusive, (semi-)inclusive, depending on amount of radiation included

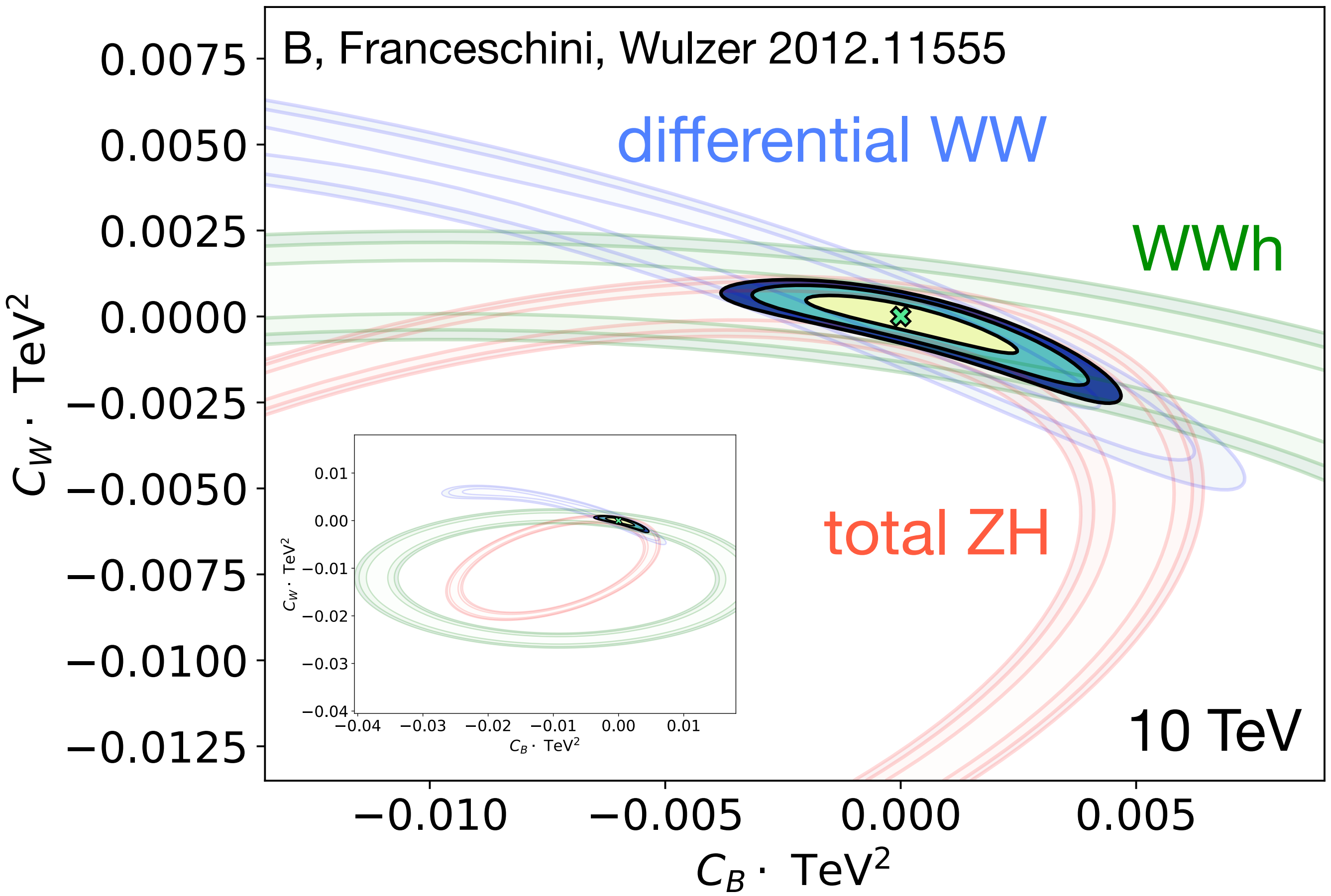
see Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509

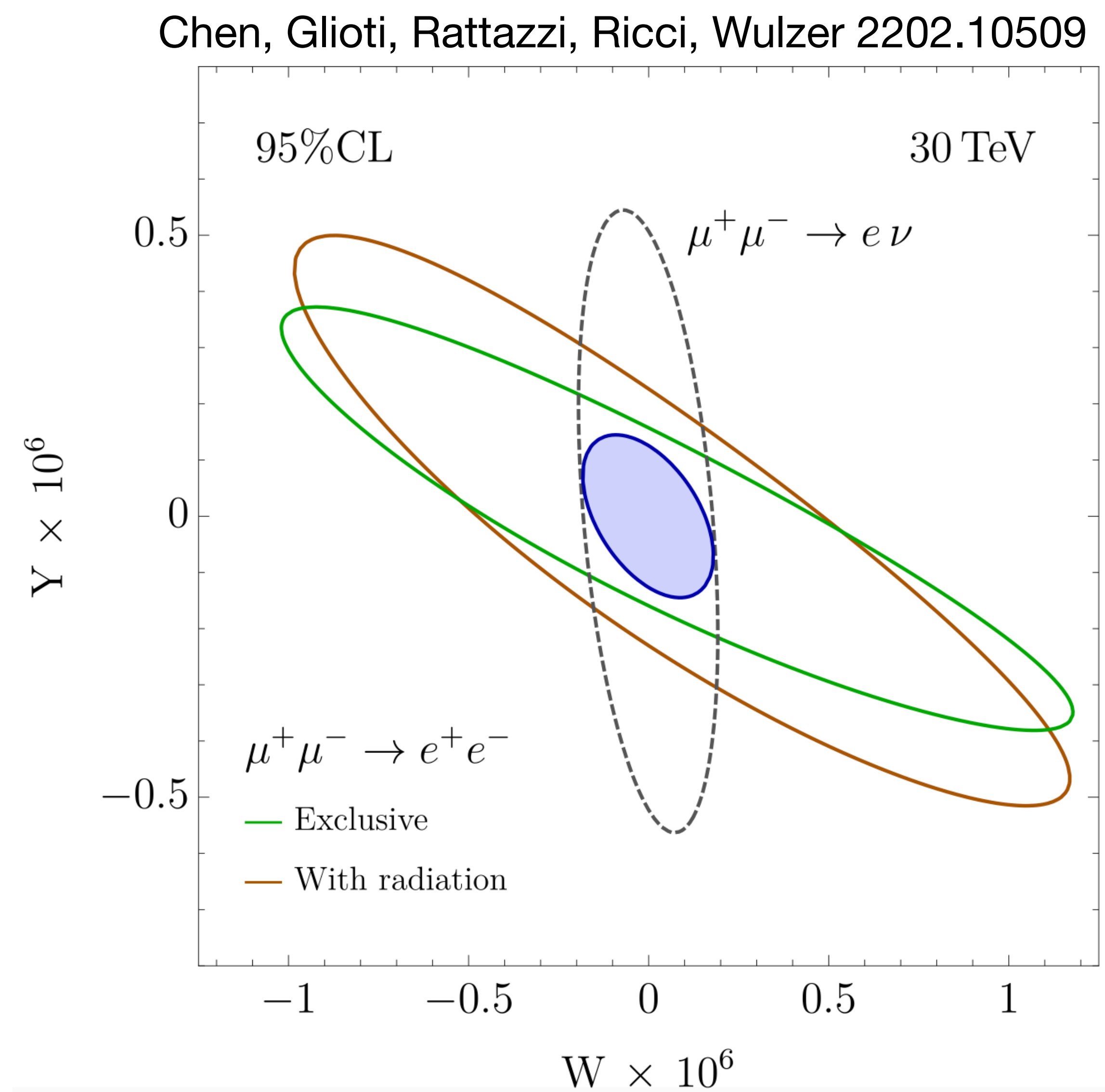


- ☛ Initial state is EW-charged:
  (Precise) resummation of double logs needed. Goal: % or ‰ precision

- ☛ Could one define EW jets? Neutrino “jet tagging”?

EW radiation

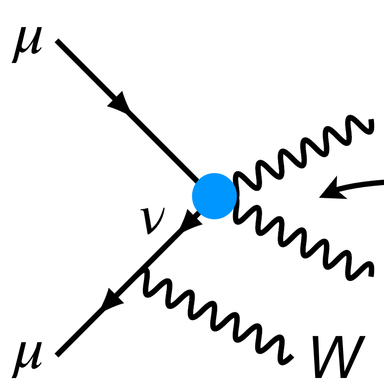




Gauge boson radiation important:

soft W emission allows to access

charged processes $\ell\nu \to W^{\pm}Z, W^{\pm}H$



independent measurement of C_W

“effective neutrino approximation”

- contains new physical information!
- need to properly define inclusive observables, resummation of logs, …

Higgs factories

- ✦ All proposed future colliders will be able to produce millions of Higgses

  ➔ study single Higgs couplings with below percent precision!

(as a comparison: 1.7 x 10^7 Z bosons @ LEP)

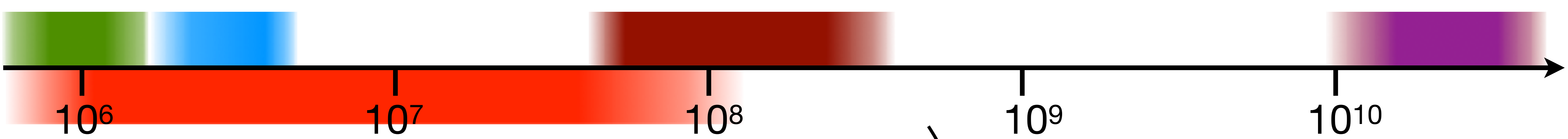
Low energy e^+e^- factories (FCC-ee, CEPC, ILC, CLIC380)

TeV-scale e^+e^- factories (CLIC, ILC1000)

LHC: few x 10^7

HL-LHC: few x 10^8

FCC-hh: few x 10^{10}



Muon colliders: 10^6 – 10^8

\# of Higgses

<u>clean environment:</u>
can measure “large” Higgs BR w/ almost 10^{-3} precision

<u>large QCD backgrounds:</u>
only rare modes (BR < 10^{-3}) easily accessible

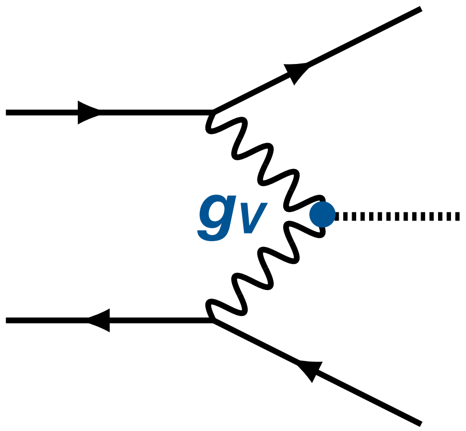
☛ talk by Paolo on Thursday

Higgs factories

- Low-energy e+e- factories: $e^+e^- \to Zh$ @ 240 GeV

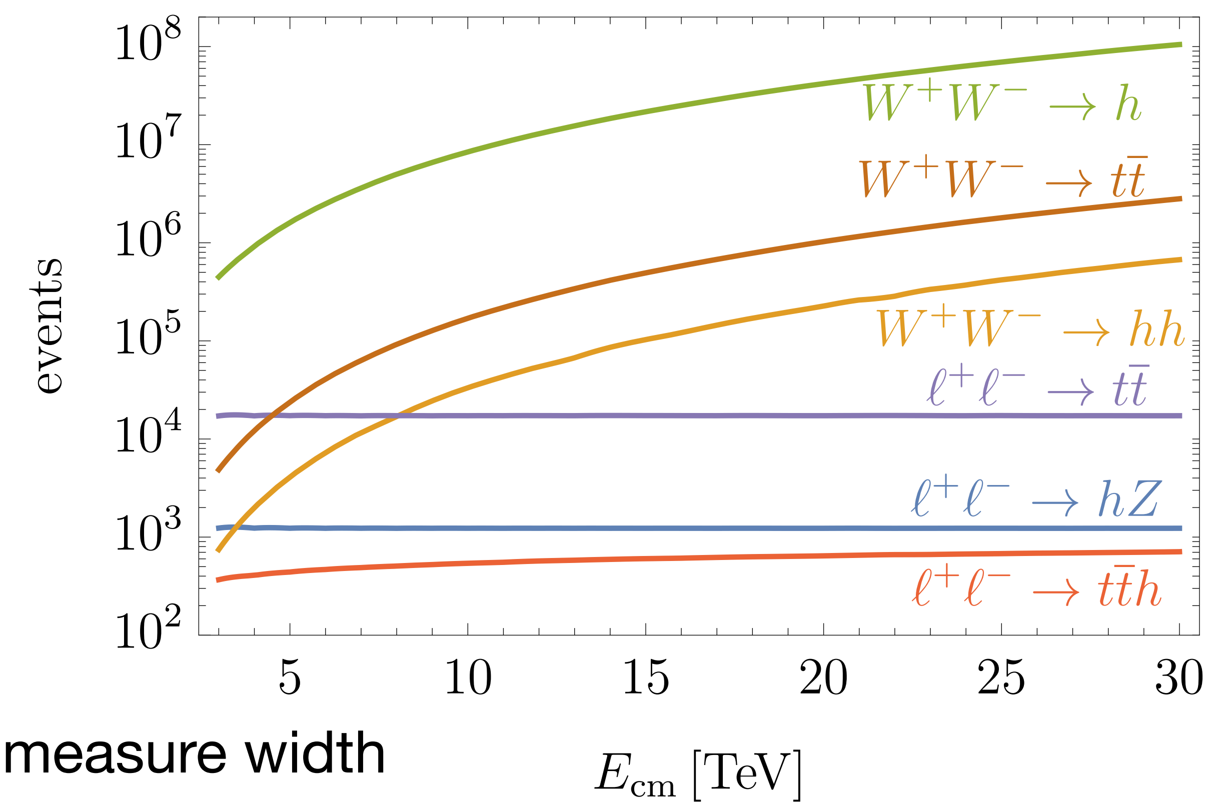
- measure the recoil (missing mass) of h against Z
- *direct* measurement of gV ⟶ other couplings + width

- A high-energy lepton collider is a "vector boson collider"



$$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$

For "soft" SM final state $\hat{s} \sim m_{\rm EW}^2$ cross-section is enhanced



- potentially huge single H production (10^7-10^8 at 10-30 TeV)
- hard neutrinos from W-fusion not seen
  ZZ fusion (forward lepton tagging) could still measure width

Higgs factories

κ-0 fit	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/	$\mu^+\mu^-$
			S2	S2′	250	500	1000	380	1500	3000		240	365	eh/hh	**10000**
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	0.1
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	0.4
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	0.7
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	0.8
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	7.2
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	2.3
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0	3.1
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	0.4
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	3.4
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	0.6

2103.14043

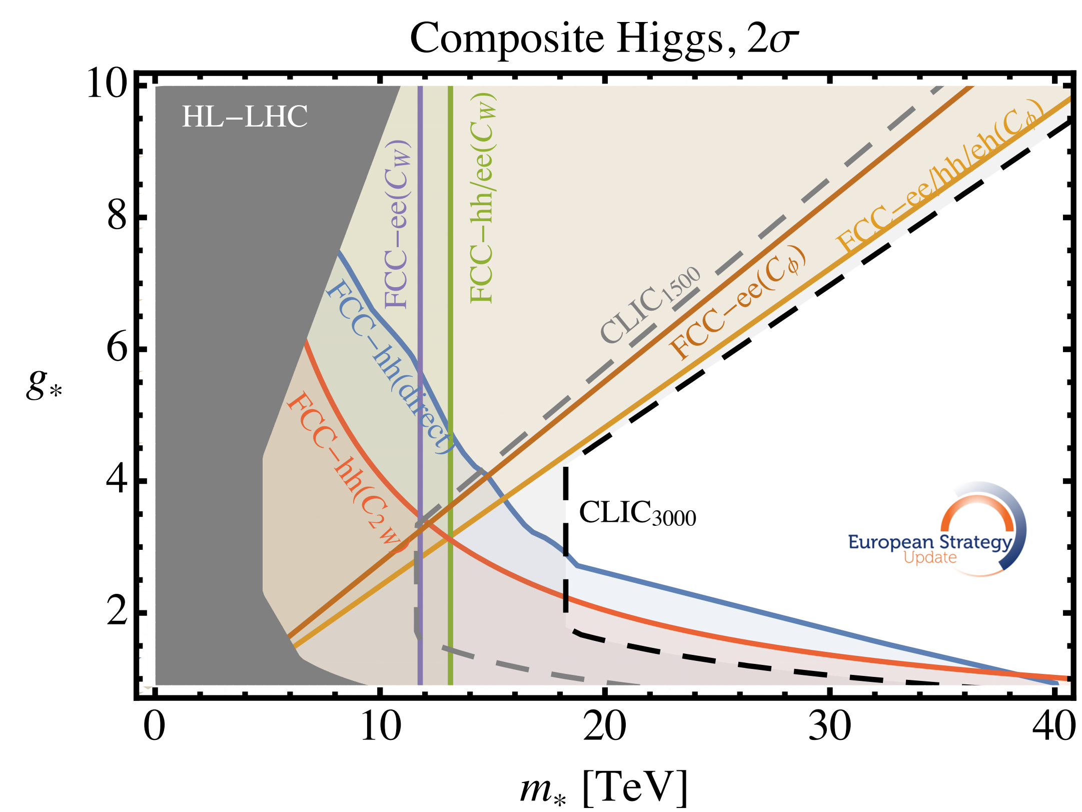
dominant channels: ~ few ‰

rare modes: high rate helps!

What NP scales will we test with the Higgs?

$$\delta\kappa \sim \frac{v^2}{M_{\rm NP}^2} g_\star^2 \lesssim \mathbf{0.2\%}$$

$$\rightarrow \quad M_{\rm NP} \gtrsim g_\star \ \mathbf{6\ TeV}$$

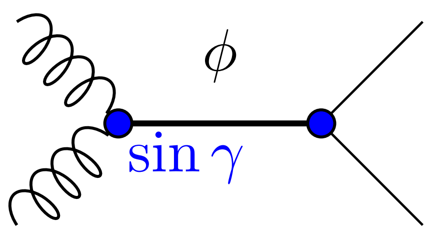


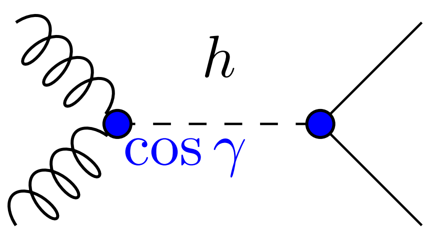
Direct vs indirect

Compare single Higgs couplings measurements with reach of direct searches

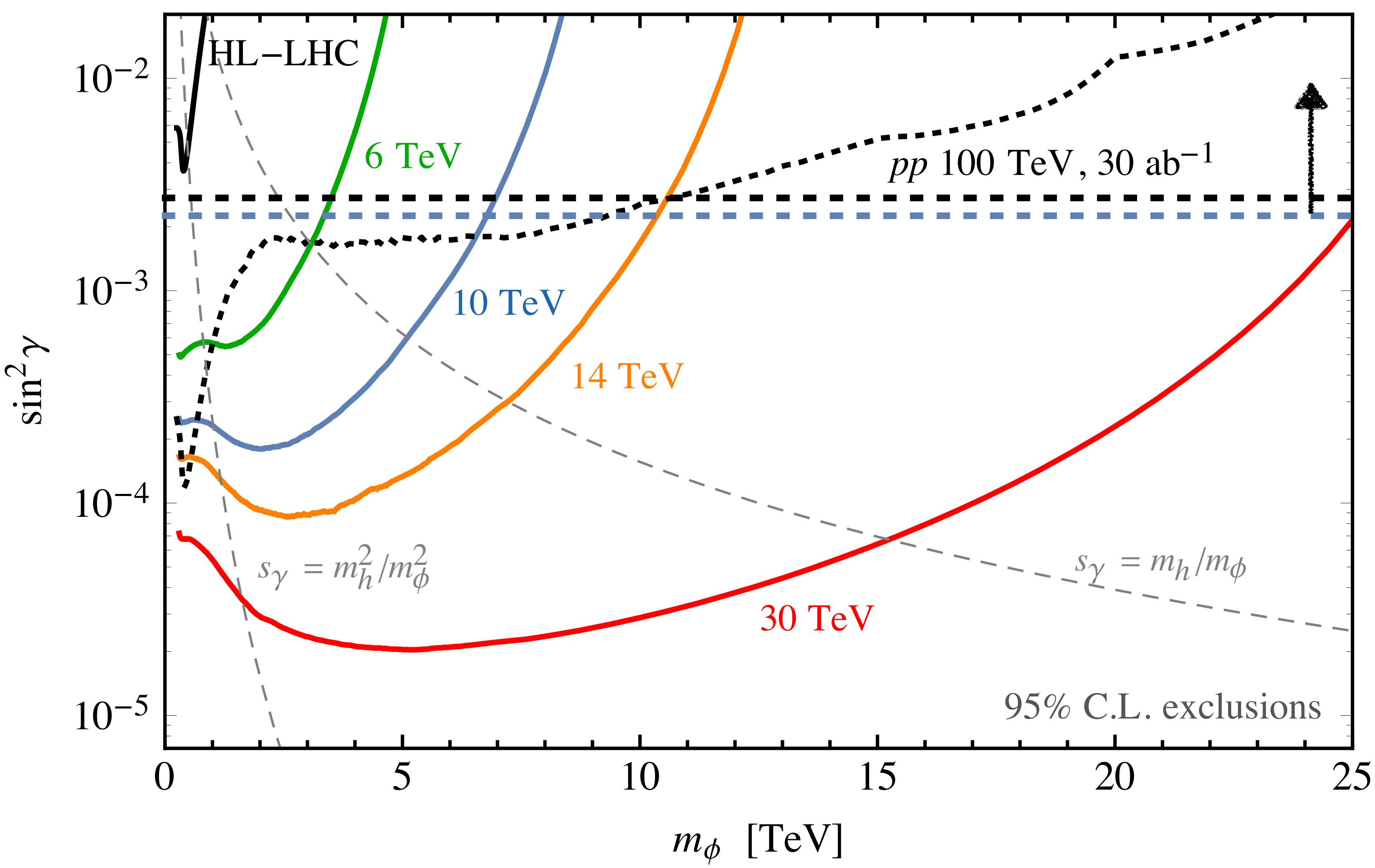
- **Example: singlet scalar** $\mathscr{L}_{\text{int}} \sim \phi |H|^2$

  ϕ is like a heavy Higgs with narrow width + hh decay





one single parameter controls resonance production, decay, & Higgs coupling modifications

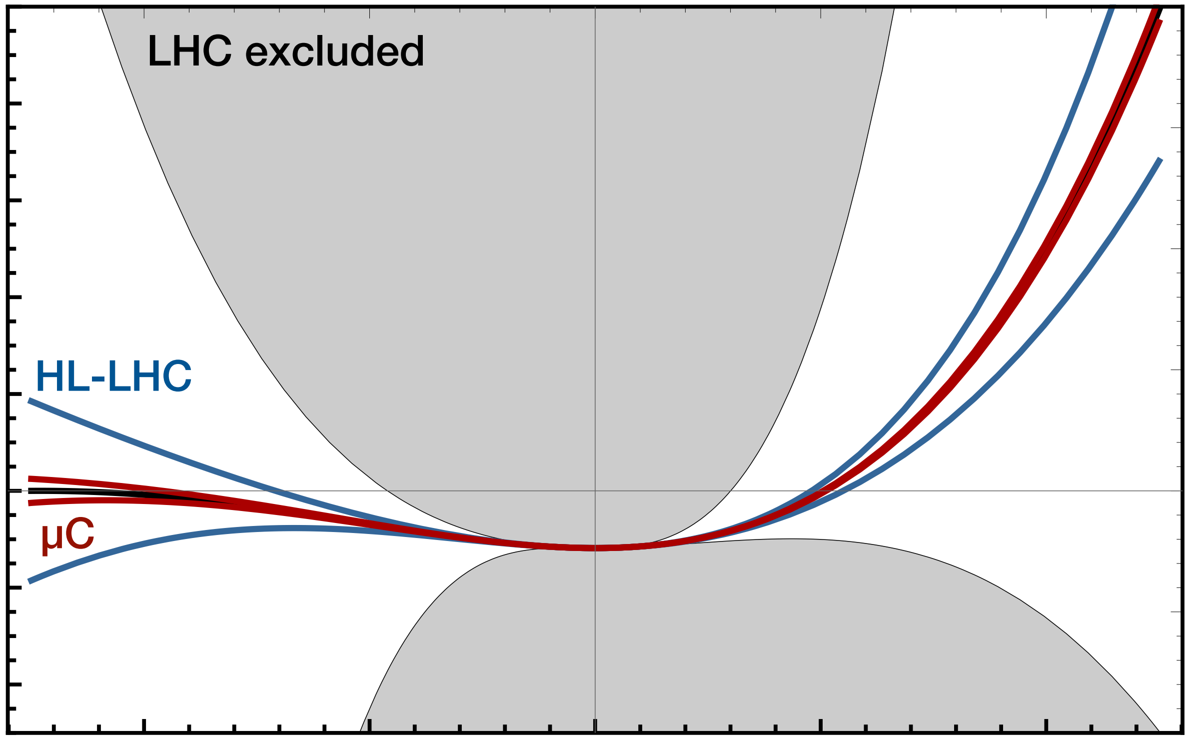


can be probed by single higgs

B, Redigolo, Sala, Tesi 1807.04743

Double Higgs production

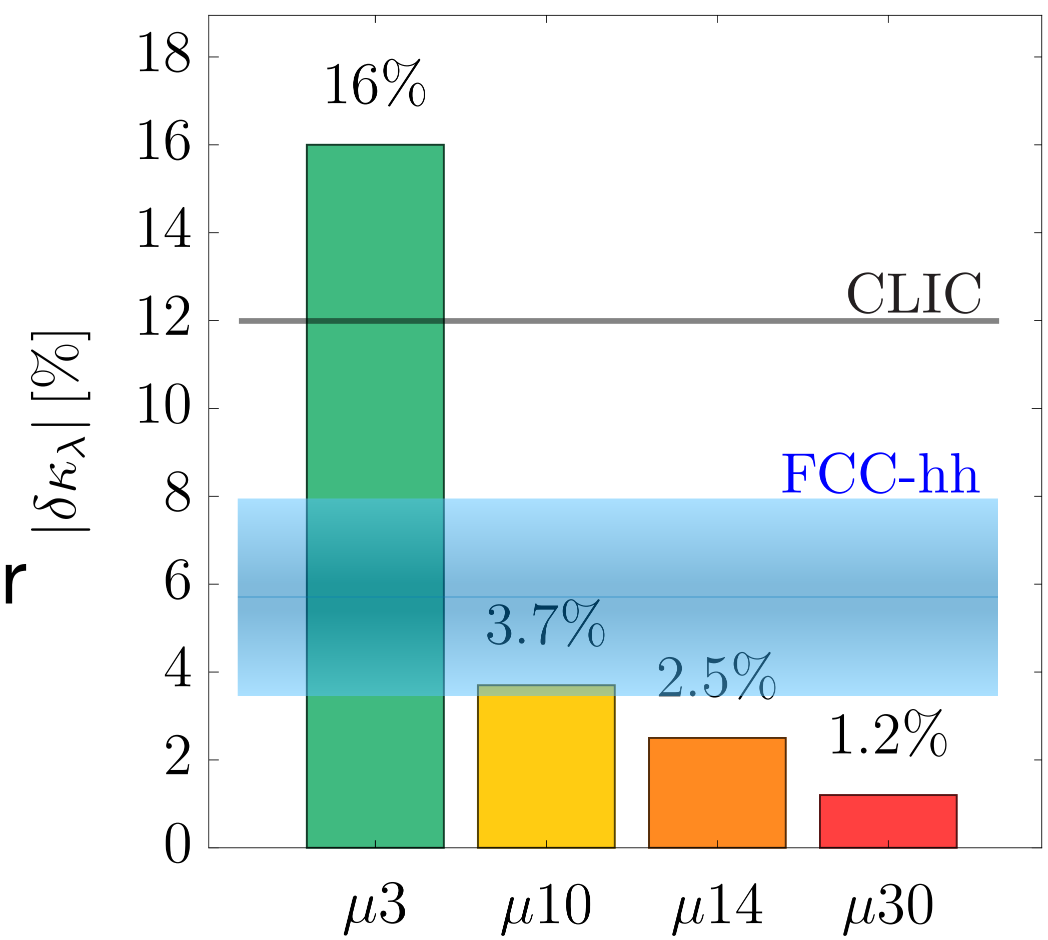
- Measurement of trilinear coupling: access to the Higgs potential



credits: Craig, Petrossian-Byrne

- very poorly known today!
- HL-LHC will only reach 50% precision on SM value

- Precise determination *only* possible at high-energy machines: need high rate! 100 TeV FCC-hh or multi-TeV Muon collider

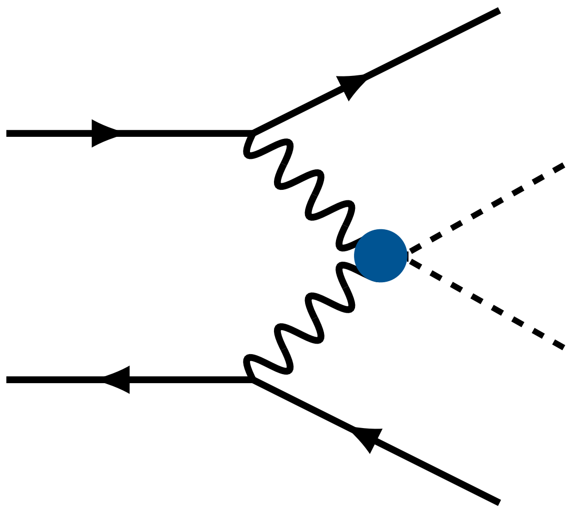


Mangano et al. 2004.03505
B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289

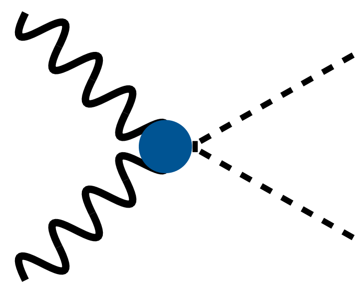
Han et al. 2008.12204
CLIC 1901.05897

High rate probes

- High rate: more events = better precision



$$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$

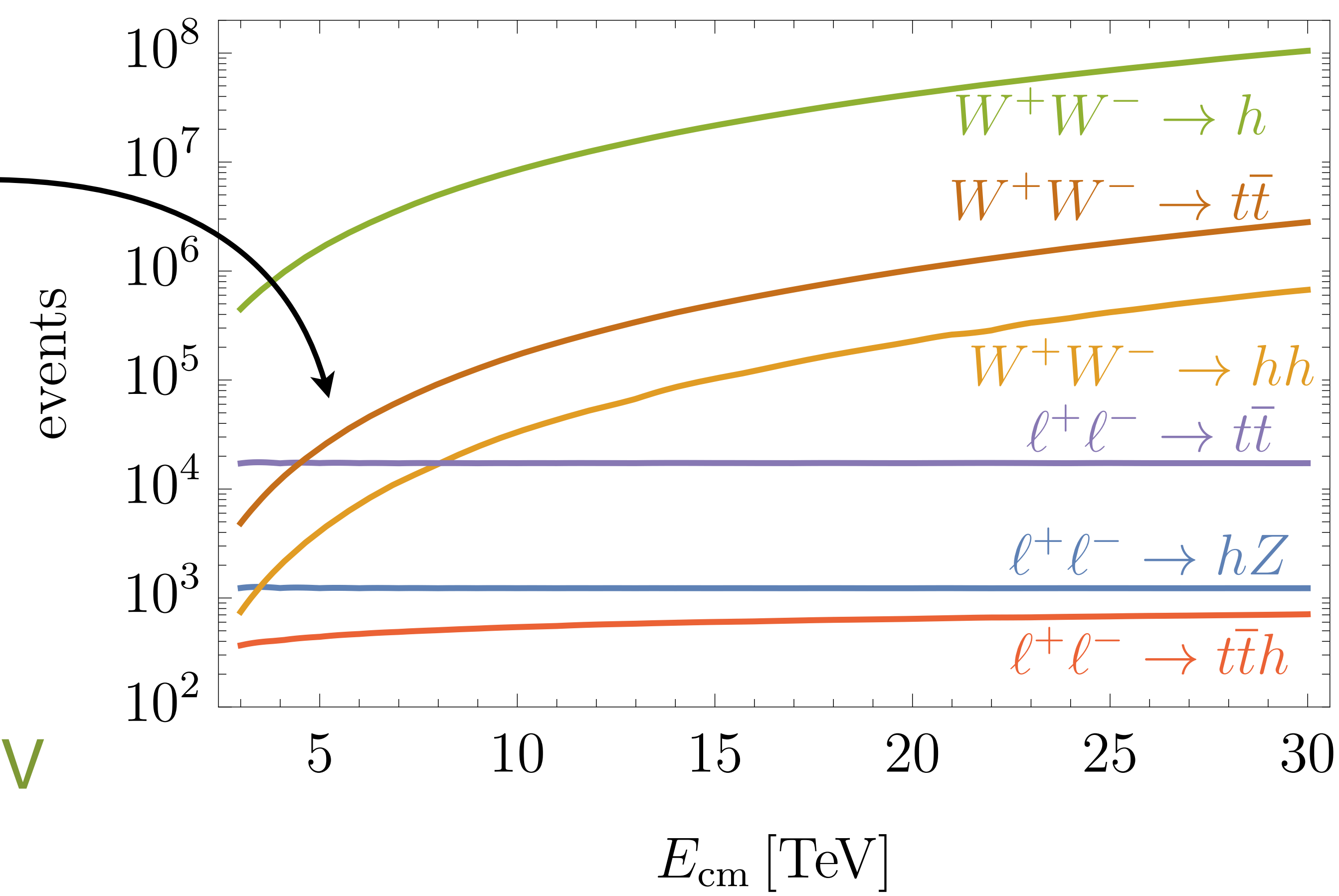


A High Energy Lepton Collider is a "vector boson collider"

For "soft" SM final state $\hat{s} \sim m_{\mathrm{EW}}^2$ cross-section is enhanced

Dawson 1985

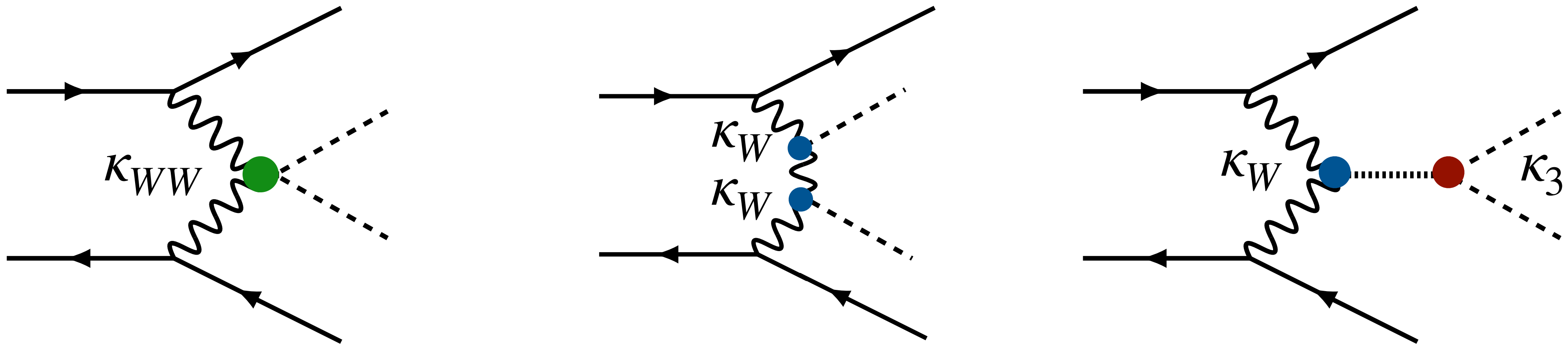
Above few TeV the VBF cross-section dominates over the hard 2 → 2



- Huge single Higgs rate in vector-boson-fusion: 10^7-10^8 Higgs bosons at 10-30 TeV

Double Higgs production

- Depends on h[3] coupling κ_3 but also on W-boson couplings κ_W, κ_{WW}:



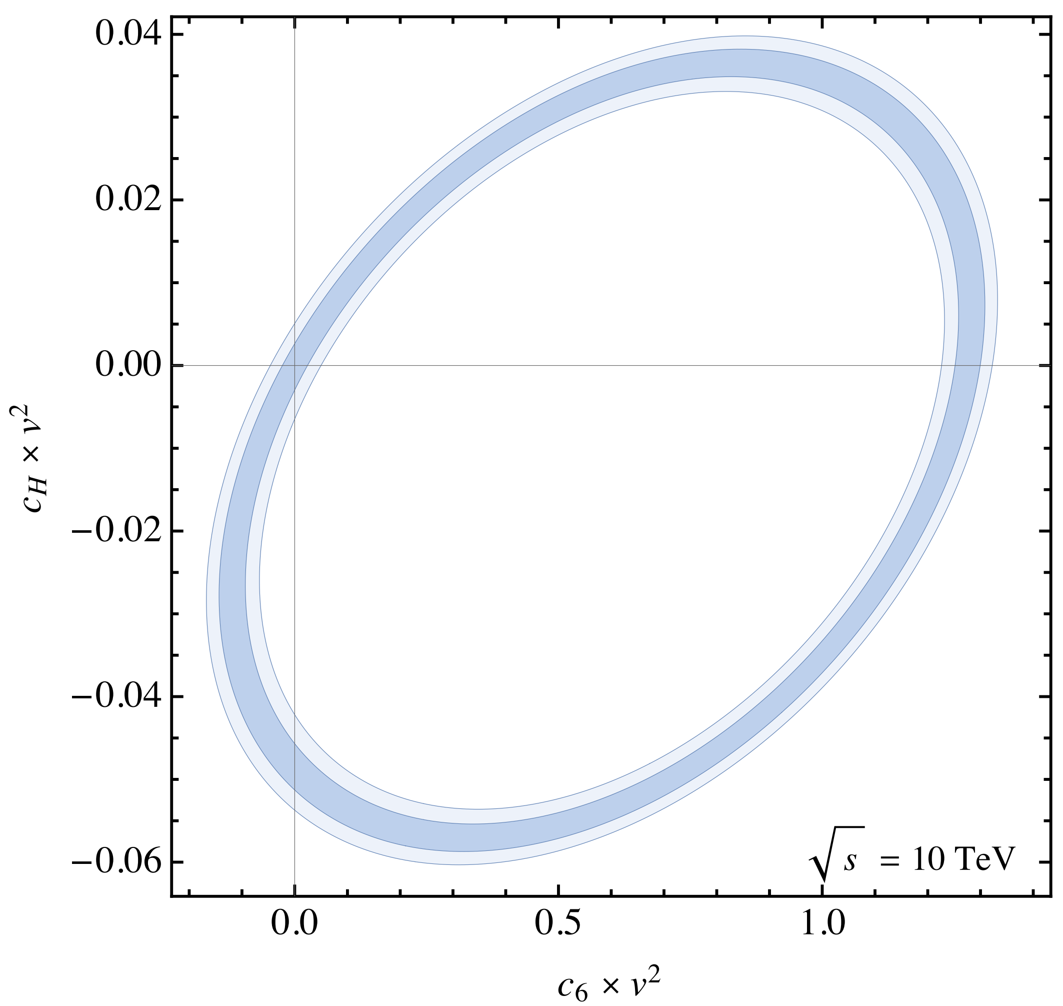
large degeneracy in total cross-section:
coefficients not determined
from *hh* production alone

Double Higgs production

- Depends on h³ coupling κ_3 but also on W-boson couplings κ_W, κ_{WW}:

- Two dim. 6 operators: $\mathcal{O}_6 = -\lambda|H|^6$ $\quad$ $\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu|H|^2\right)^2$

$\kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right)$ $\quad$ $\kappa_W = 1 - v^2 C_H/2$ $\quad$ $\kappa_{WW} = 1 - 2v^2 C_H$



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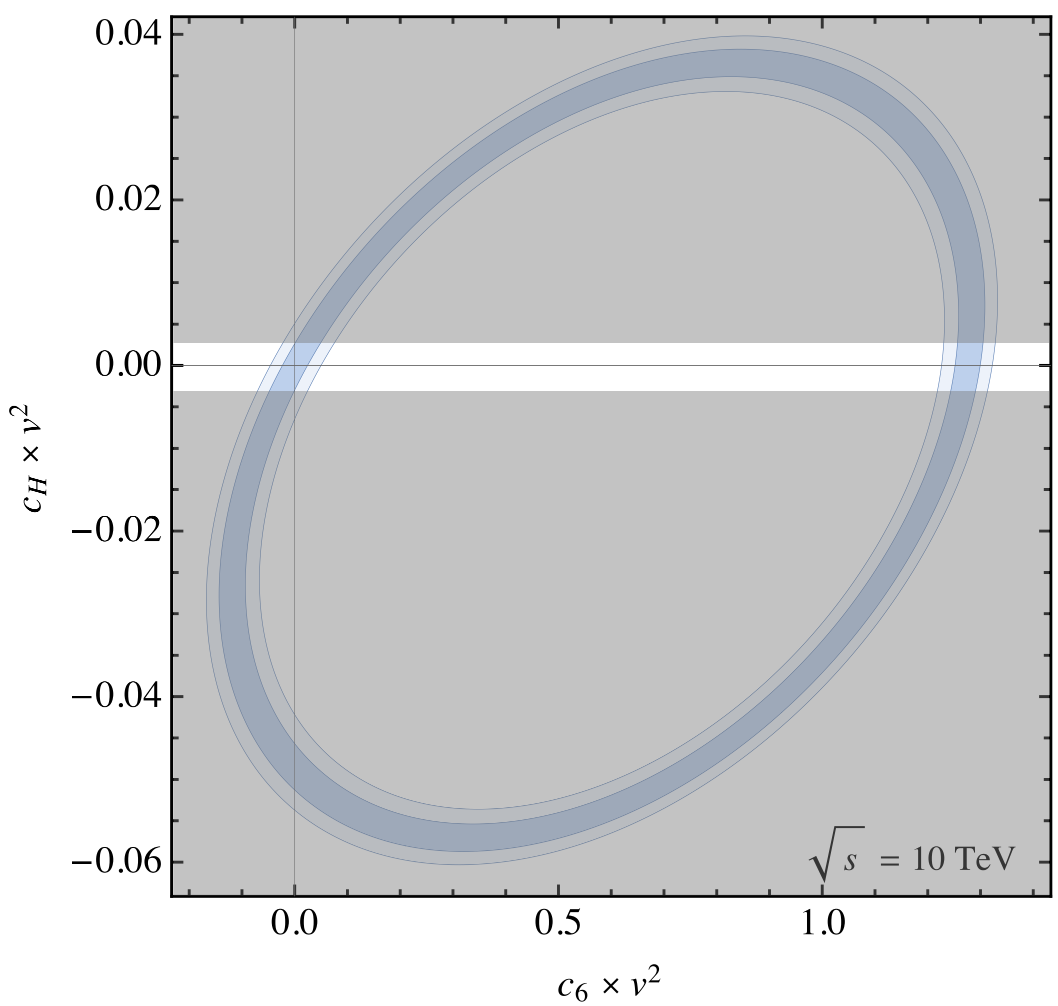

large degeneracy in total cross-section:
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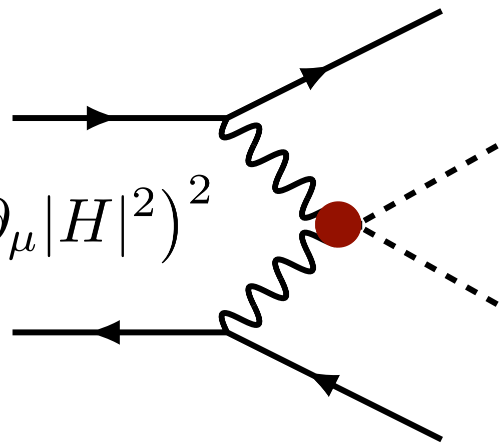
O_H can also be constrained from single Higgs couplings:

$$\Delta\kappa_{V,f} = v^2 C_H/2 \lesssim \text{few} \times 10^{-3}$$

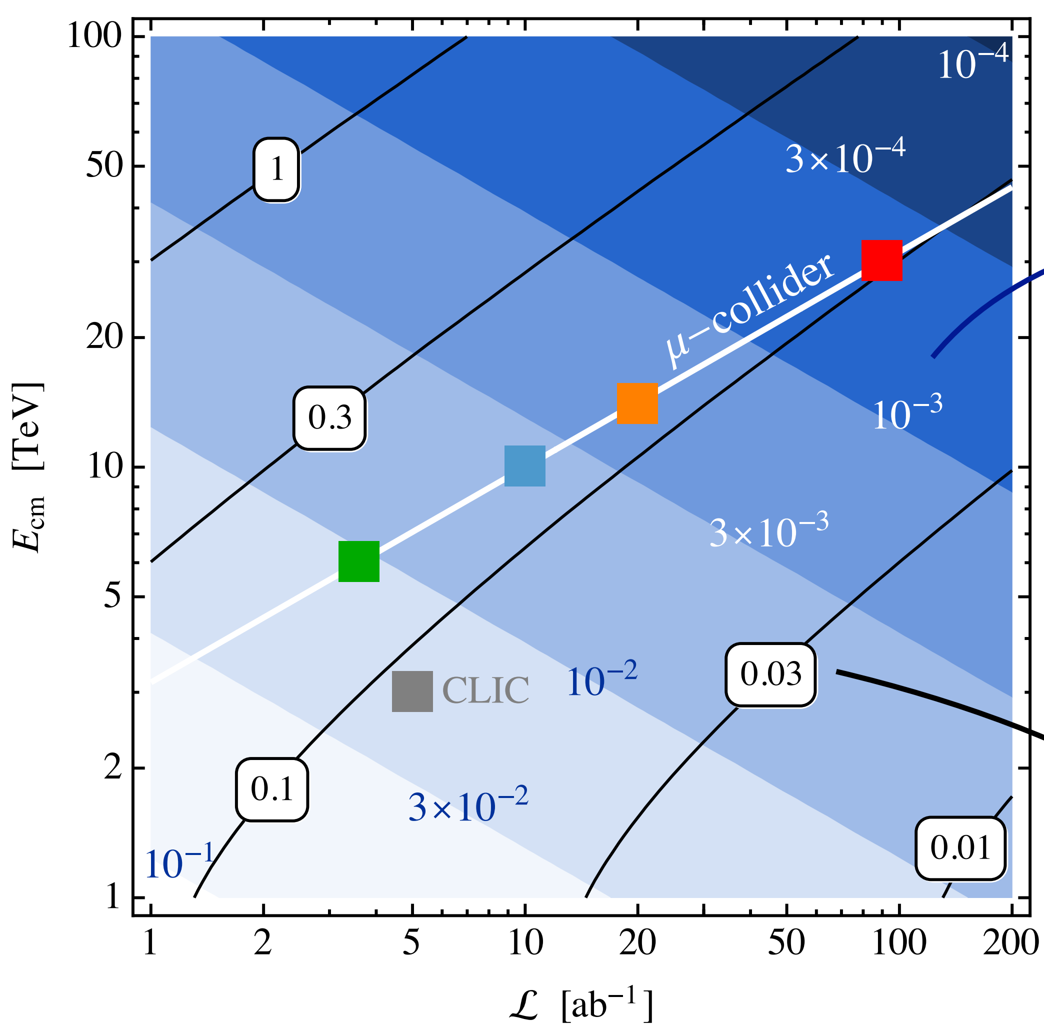
Double Higgs at high mass

- NP contribution from $\mathcal{O}_H$ (equivalently κ_W, κ_{WW}) grows as E²: high mass tail gives a *direct* measurement of C_H

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$



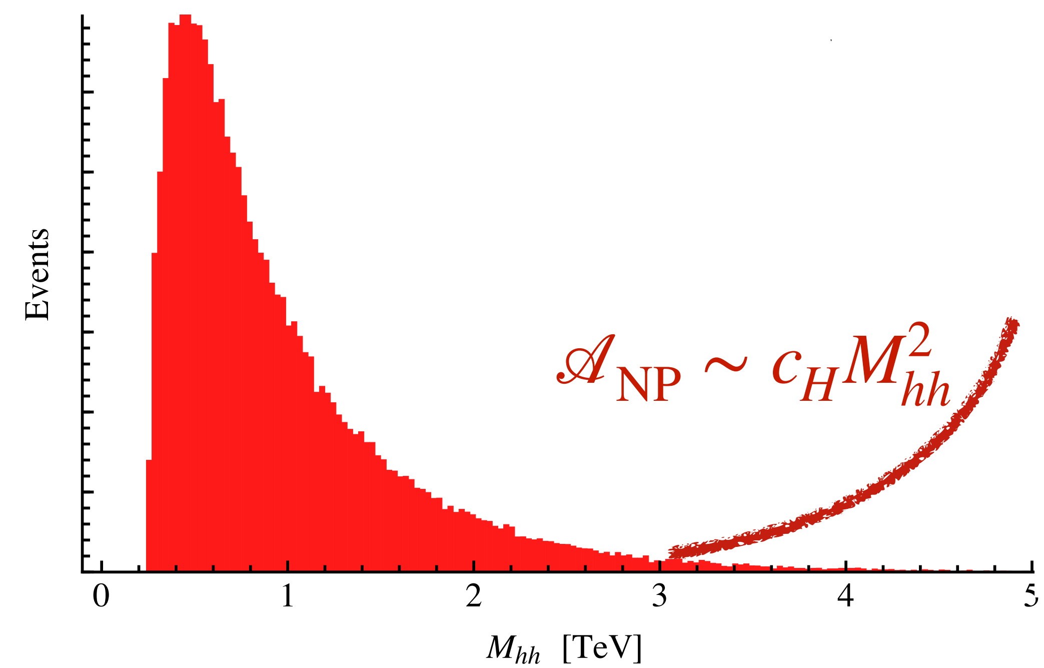
High-energy WW → *hh* more sensitive than Higgs pole physics at energies ≳ 10 TeV



$\xi \equiv C_H v^2$

S/B low-precision measurement

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



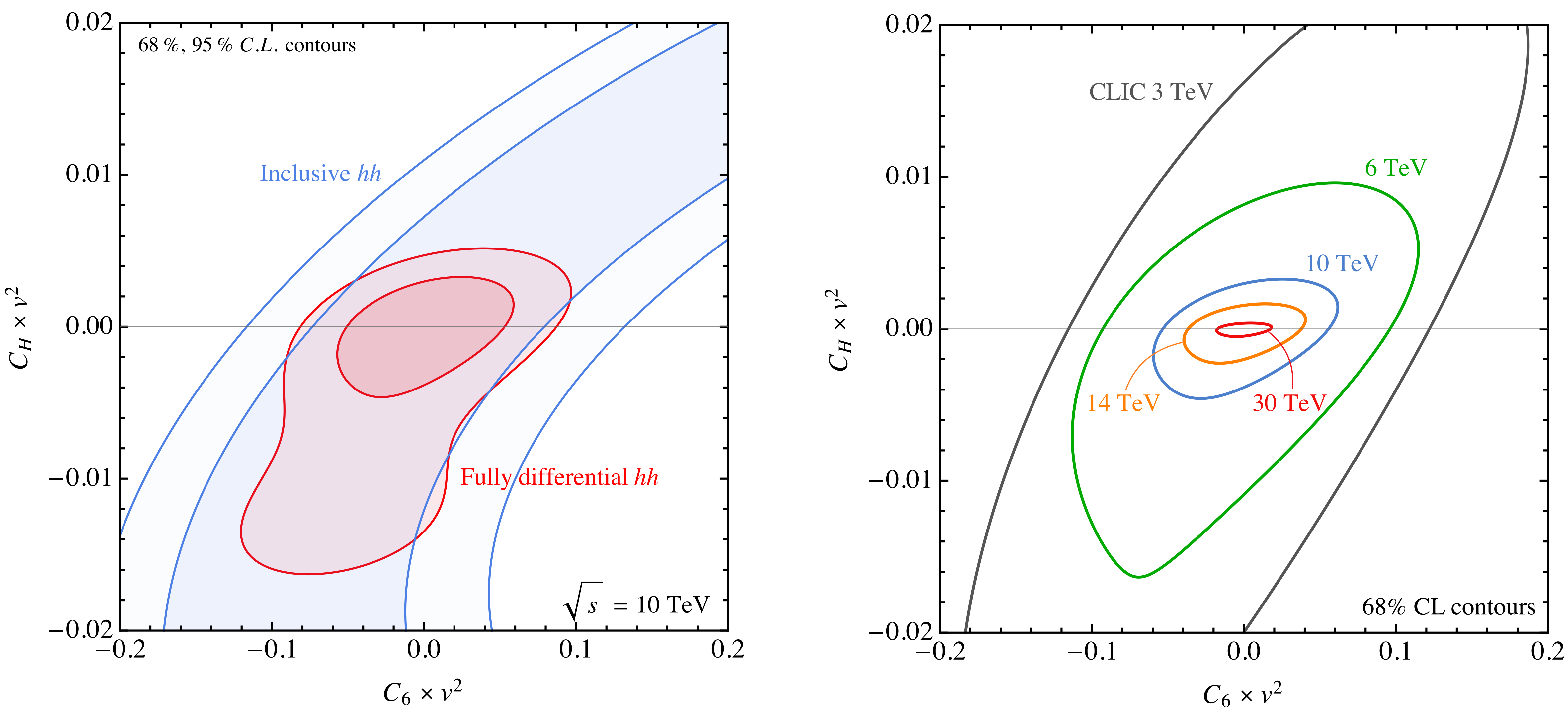
(see also Contino et al. 1309.7038)

Double Higgs at high mass

- SM Effective Theory: $\mathscr{L}_{\text{EFT}} = \mathscr{L}_{\text{SM}} + \sum_i C_i \mathcal{O}_i^{(6)} + \cdots$
- Trilinear coupling is affected by two operators: $\kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right)$

$$\mathcal{O}_6 = -\lambda |H|^6 \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

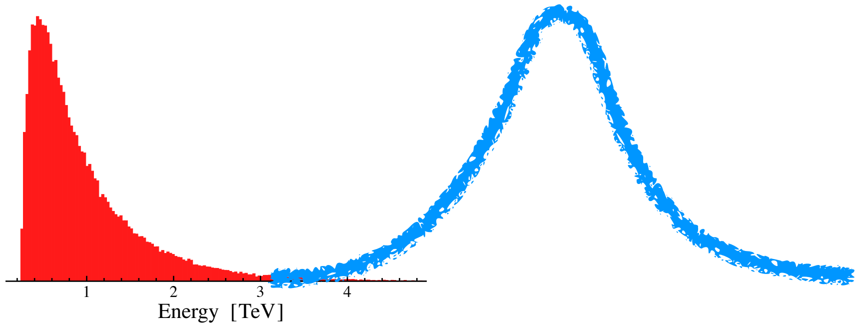
Differential analysis in p_T and M_{hh}:



Summary

- Long-term goal of particle physics: **explore the 10+ TeV scale.**
- Precision SM measurements might be the quickest way…
- Two complementary paths to precision:

High rate



High energy

Flavor: rare decays w/ 3rd family, neutrino modes

Electroweak: Z-pole precision, high-energy probes, radiation

Higgs: couplings, self-interaction, high-pT probes

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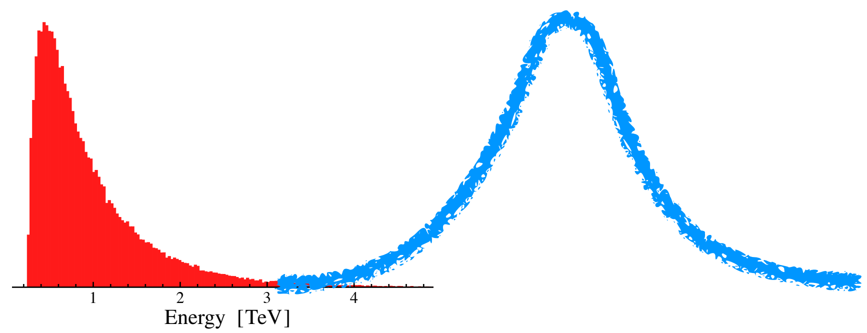

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Xin cảm ơn!