Precision physics

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Disclaimer

⚠ This talk is about **Physics** only.

⚠ I will consider colliders that

- exist today (LHC, SuperKEKB, SPS)
- could be built today (FCC-ee, CEPC, CLIC, ILC)
- could be built tomorrow, after technological R&D

  (Muon collider, pp colliders)

⚠ The physics potential of these machines is obviously very different.

The related ESPP decisions/considerations are also different…

Why a future collider?

Independently of LHC results, a future collider will be necessary to make advancements in fundamental high-energy physics.

Where should we go??

- No guaranteed discoveries: exploration of new domains
- High-energy collider has guaranteed science output: possibility to perform SM physics measurements in unknown energy domain.

  Either validation of SM, or groundbreaking discovery.
- Expensive $\Longrightarrow$ need a big improvement in *as many as possible different directions*

Why a future collider?

- What causes EWSB?

  i.e. *is it the SM up to accessible energy scales?*

- What's the origin of Flavor (including leptons)?

  and what's the origin of CP violation?

- What is Dark Matter?

- Unification
- Inflation
- Dark Energy
- Quantum gravity

Not clear if the solution lies at a scale accessible by colliders, and/or within particle physics…

Why a future collider?

- What causes EWSB?

  i.e. *is it the SM up to accessible energy scales?*

Clearly points to few TeV scale

- What's the origin of Flavor (including leptons)?

  and what's the origin of CP violation?

- What is Dark Matter?

Might point to few TeV scale, esp. if related to previous point

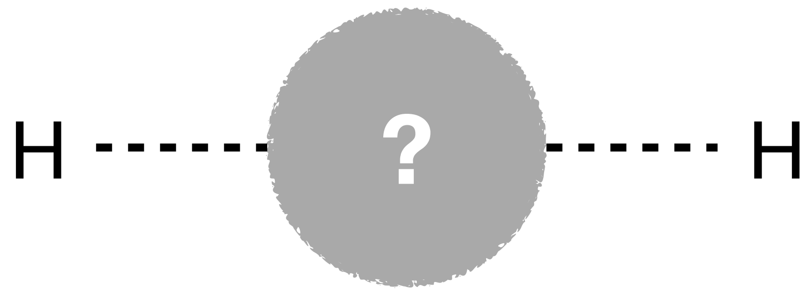
- Unification
- Inflation
- Dark Energy
- Quantum gravity

Not clear if the solution lies at a scale accessible by colliders, and/or within particle physics…

Why a few-TeV collider?

- Is it the SM up to the few TeV energy scale?

  i.e. what causes EWSB?



Loops of (weakly coupled) new particles:

$$\delta m_H^2 \approx \frac{g^2}{16\pi^2} M_{\rm NP}^2 \lesssim (gv)^2$$

Strong EWSB:

$$M_{\rm NP} \approx g_\star f \leq 4\pi f, \quad f \gtrsim v$$

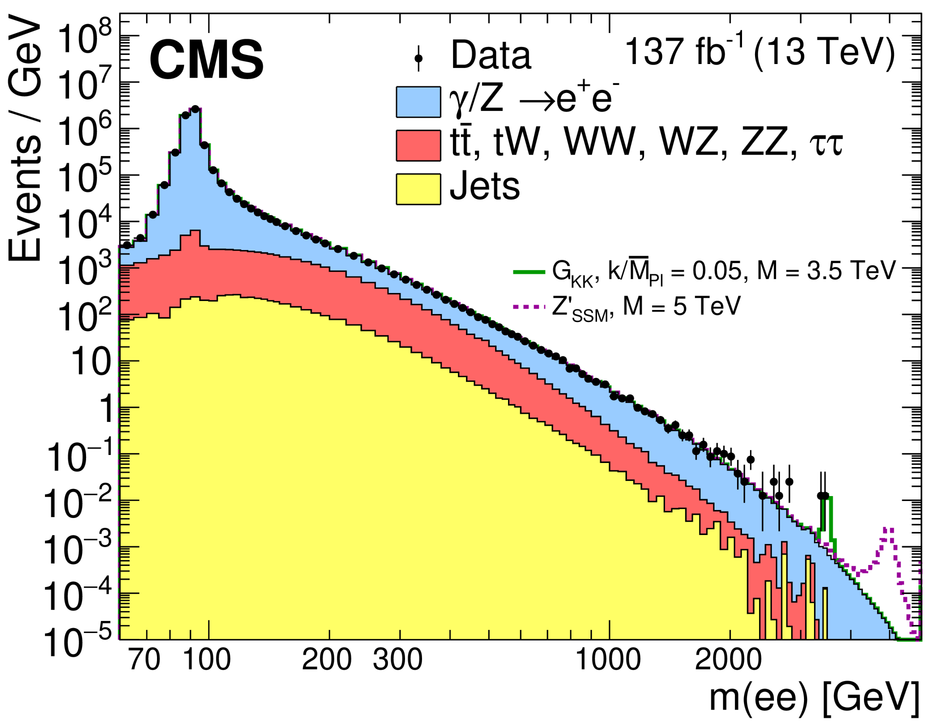
$$\Rightarrow \quad M_{\rm NP} \lesssim 4\pi v \approx 3\,\mathrm{TeV}$$

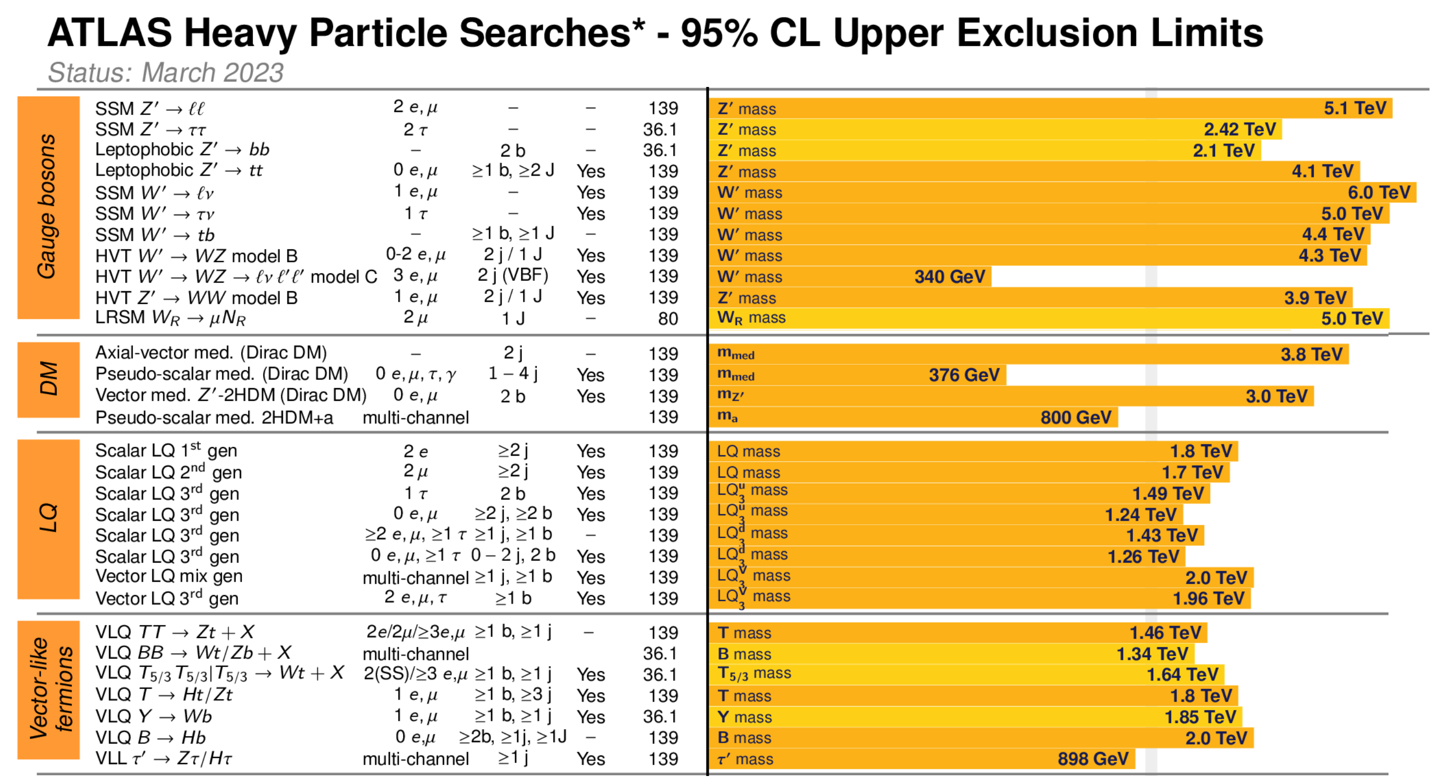
rough estimate! there can easily be some O(1) factor!

goal: explore physics at least up to $M_{\rm NP} \approx 10\,\mathrm{TeV}\,!$

Where do we stand?

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





☛ see talk by R. Franceschini

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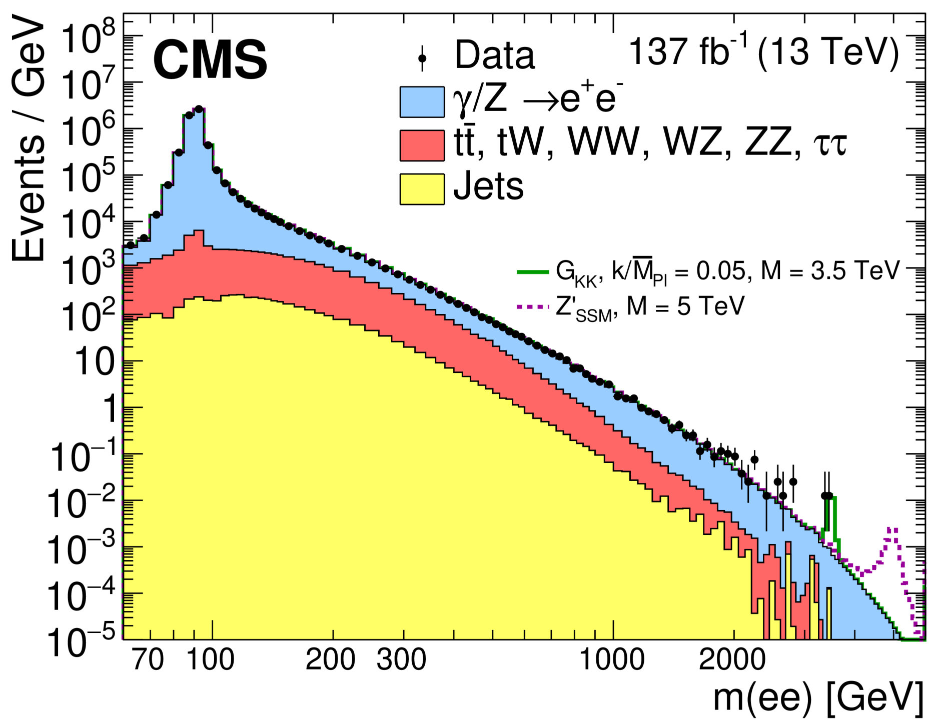
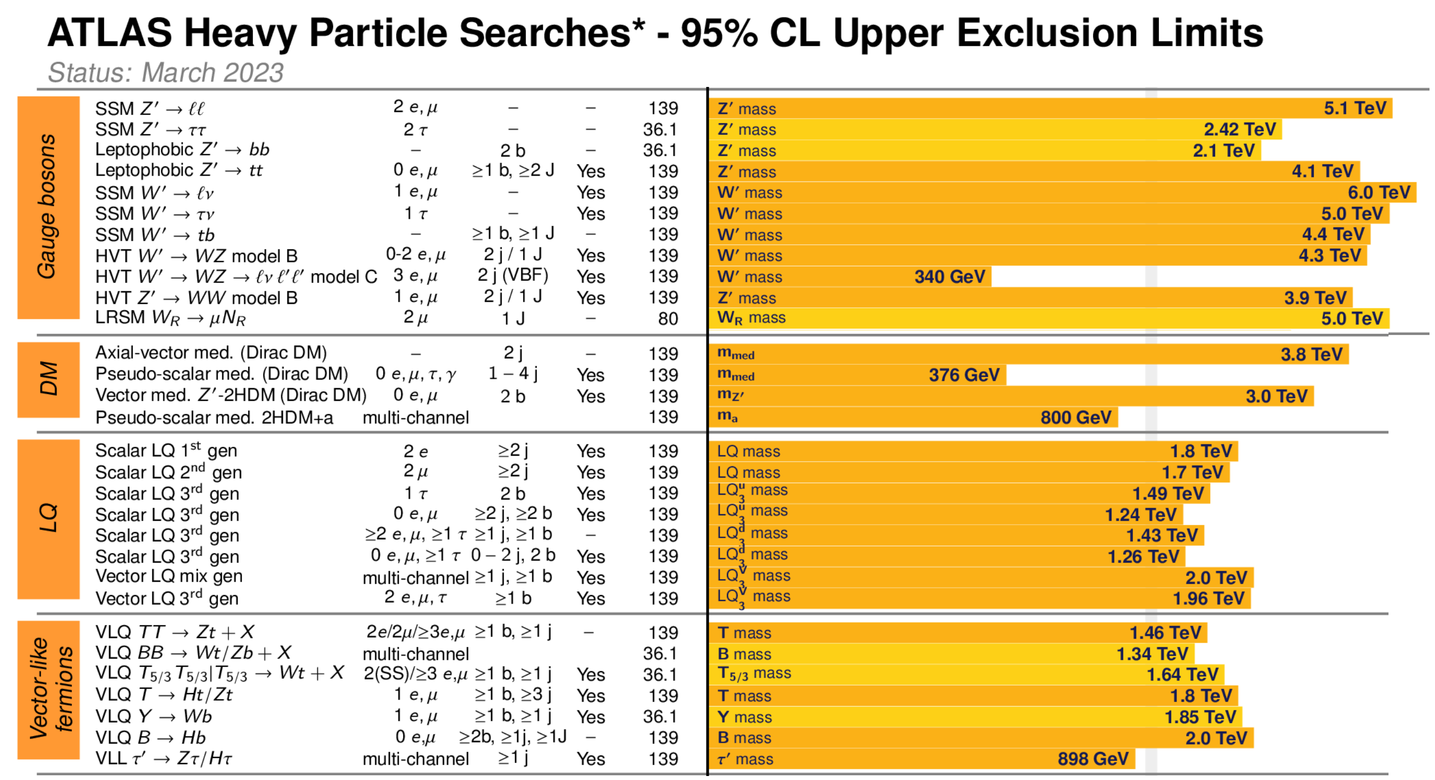


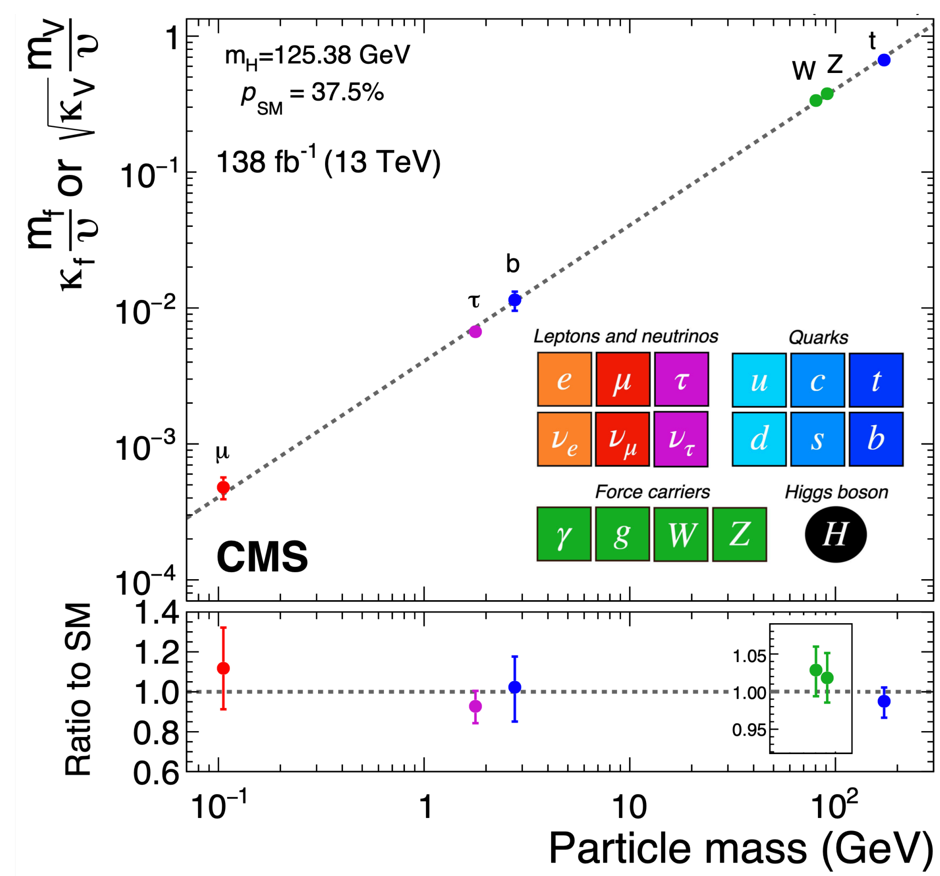


☛ see talk by R. Franceschini

- The Higgs boson is SM-like:

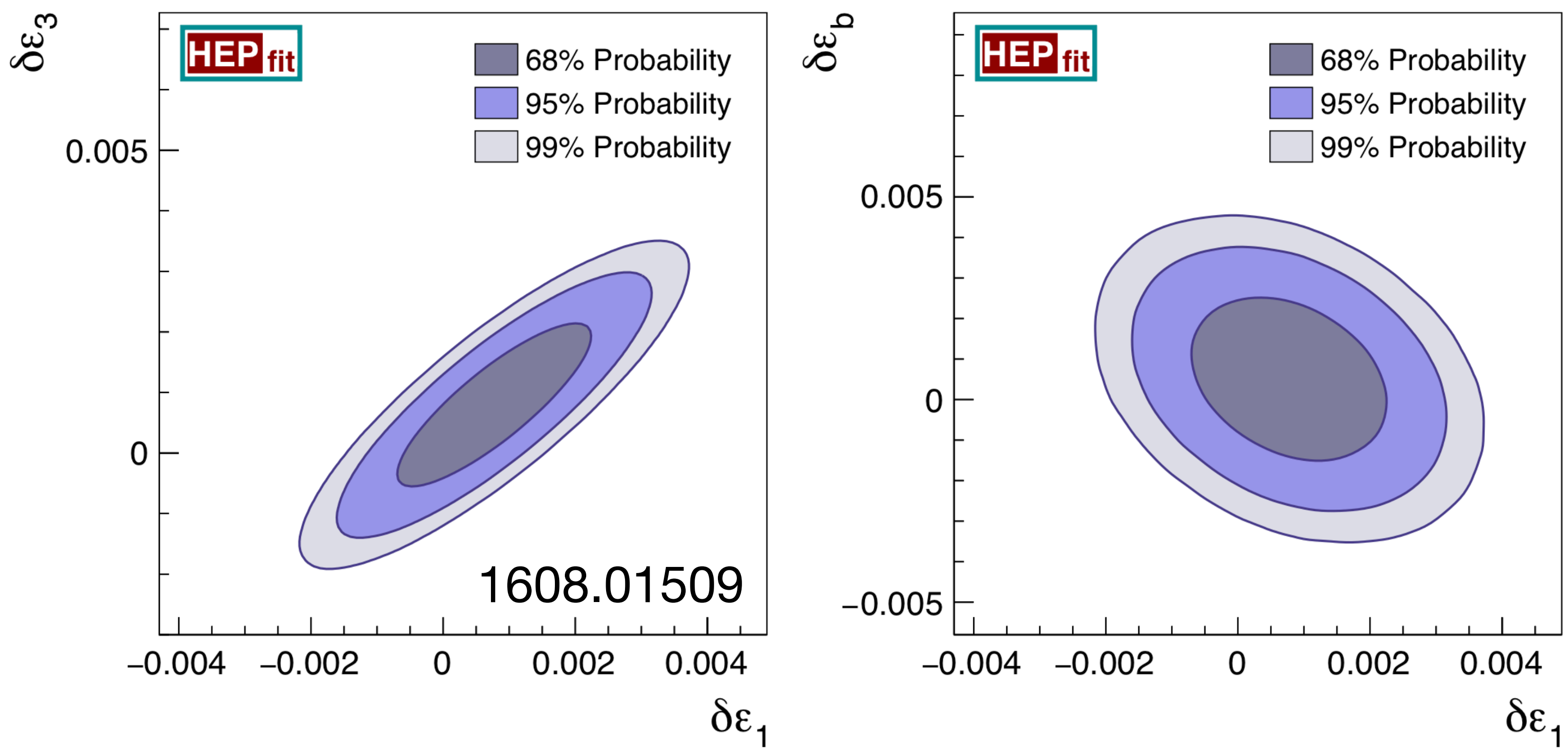
$$\delta\kappa \sim \frac{v^2}{M_{\rm NP}^2} g_\star^2 \lesssim 5\,\%$$

$$\longrightarrow \quad M_{\rm NP} \gtrsim g_\star \, {\rm TeV}$$



Where do we stand?

- The EW sector is SM-like: $M_{\rm NP} \gtrsim$ few TeV



$$\delta\varepsilon \sim \frac{m_W^2}{M_{\rm NP}^2} \lesssim \text{few} \times 10^{-3}$$

$$\rightarrow \quad M_{\rm NP} \gtrsim 2\,\text{TeV}$$

Where do we stand?

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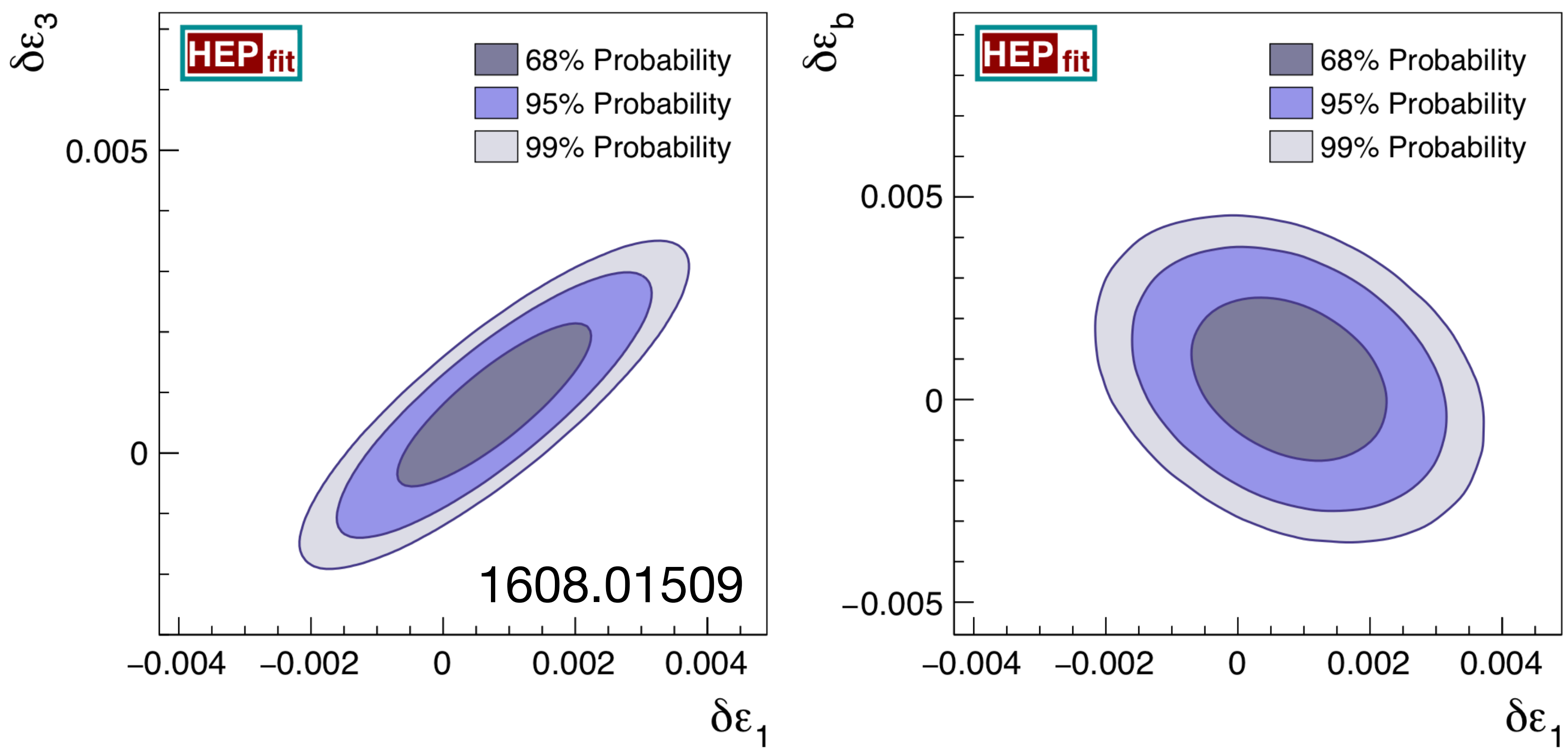


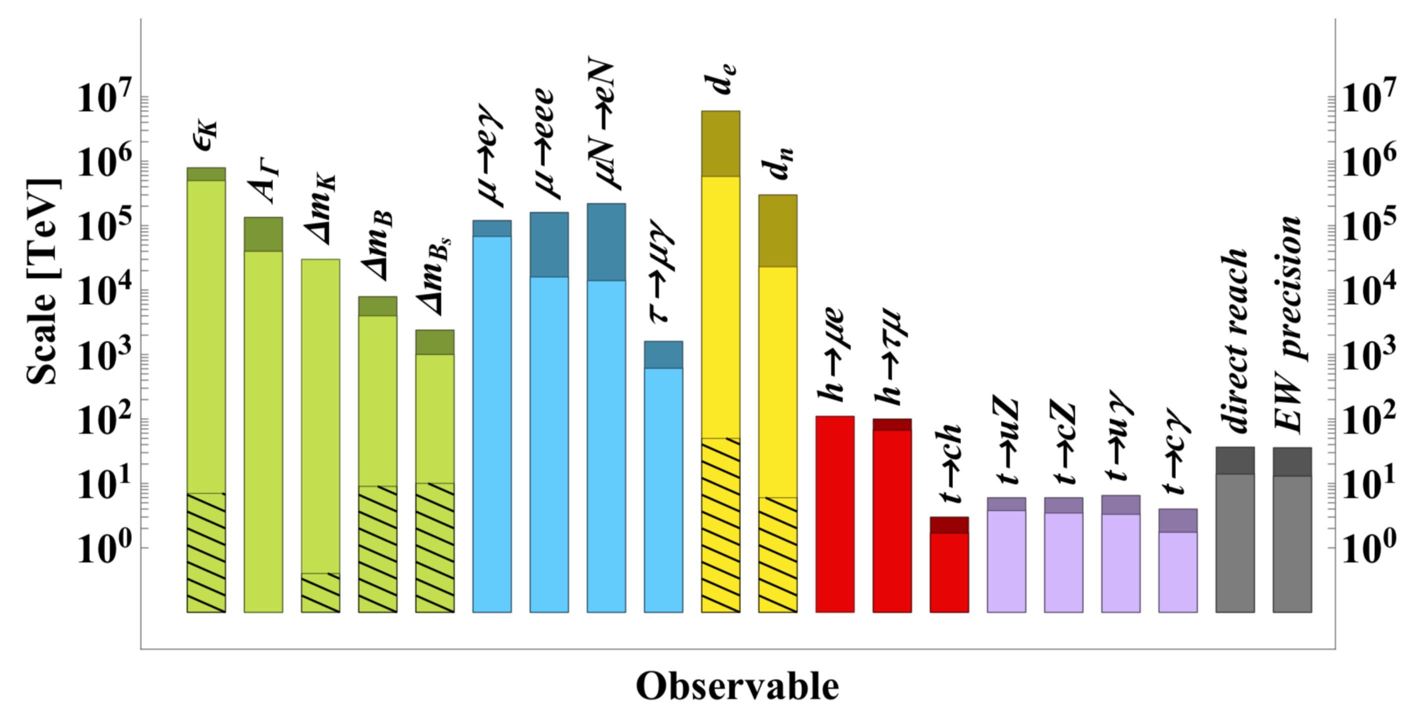
$$\delta\varepsilon \sim \frac{m_W^2}{M_{\rm NP}^2} \lesssim \text{few} \times 10^{-3}$$

$$\rightarrow \quad M_{\rm NP} \gtrsim 2\,\text{TeV}$$

- The CKM picture of flavor physics works well; lepton flavor is conserved; no CPV besides CKM phase

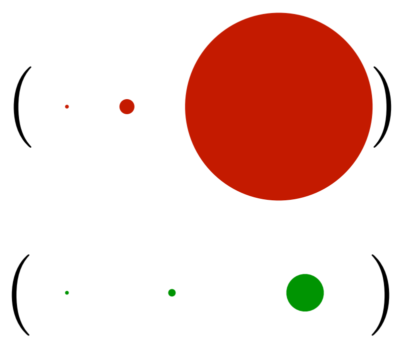
$$\frac{\delta\mathcal{O}}{\mathcal{O}_{\rm SM}} \sim \frac{v^2}{M_{\rm NP}^2}\frac{4\pi}{\alpha}\frac{1}{\xi_{ij}} \lesssim 10\,\%$$

$$\rightarrow \quad M_{\rm NP} \gtrsim 3\,\text{TeV}/\sqrt{\xi_{ij}}$$

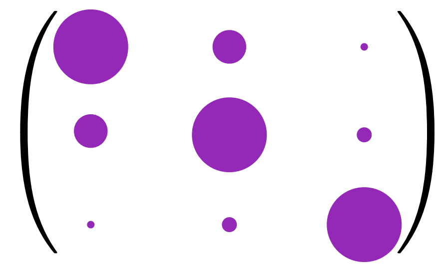


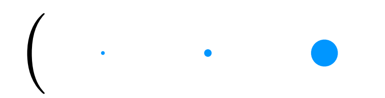
The flavor puzzle

- SM Yukawa couplings have an extremely hierarchical pattern

$m_u \sim$ 

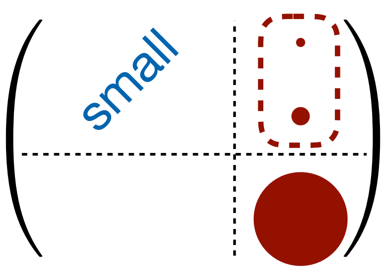
$m_d \sim$

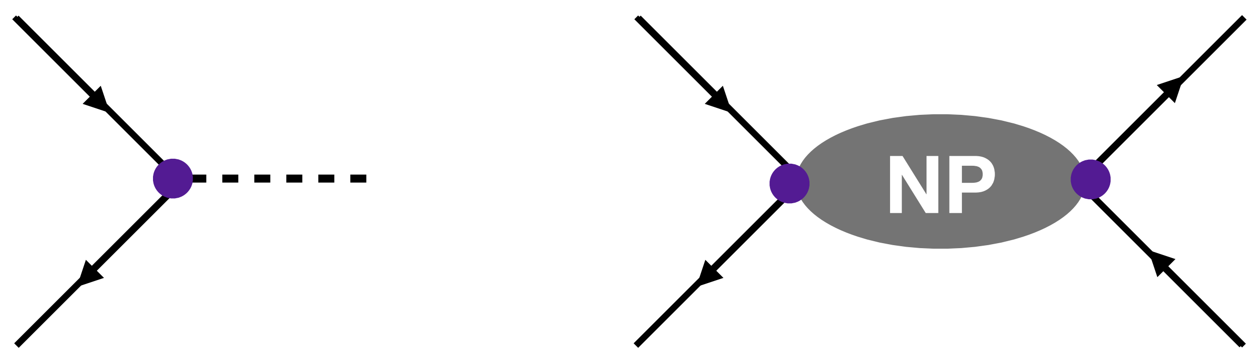
$V_{\rm CKM} \sim$ 

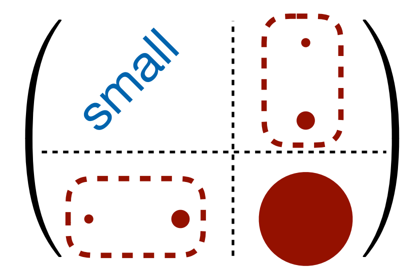
$m_\ell \sim$ 

☛ 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…

$Y_u \approx$ 



$\lambda_q \approx$ 

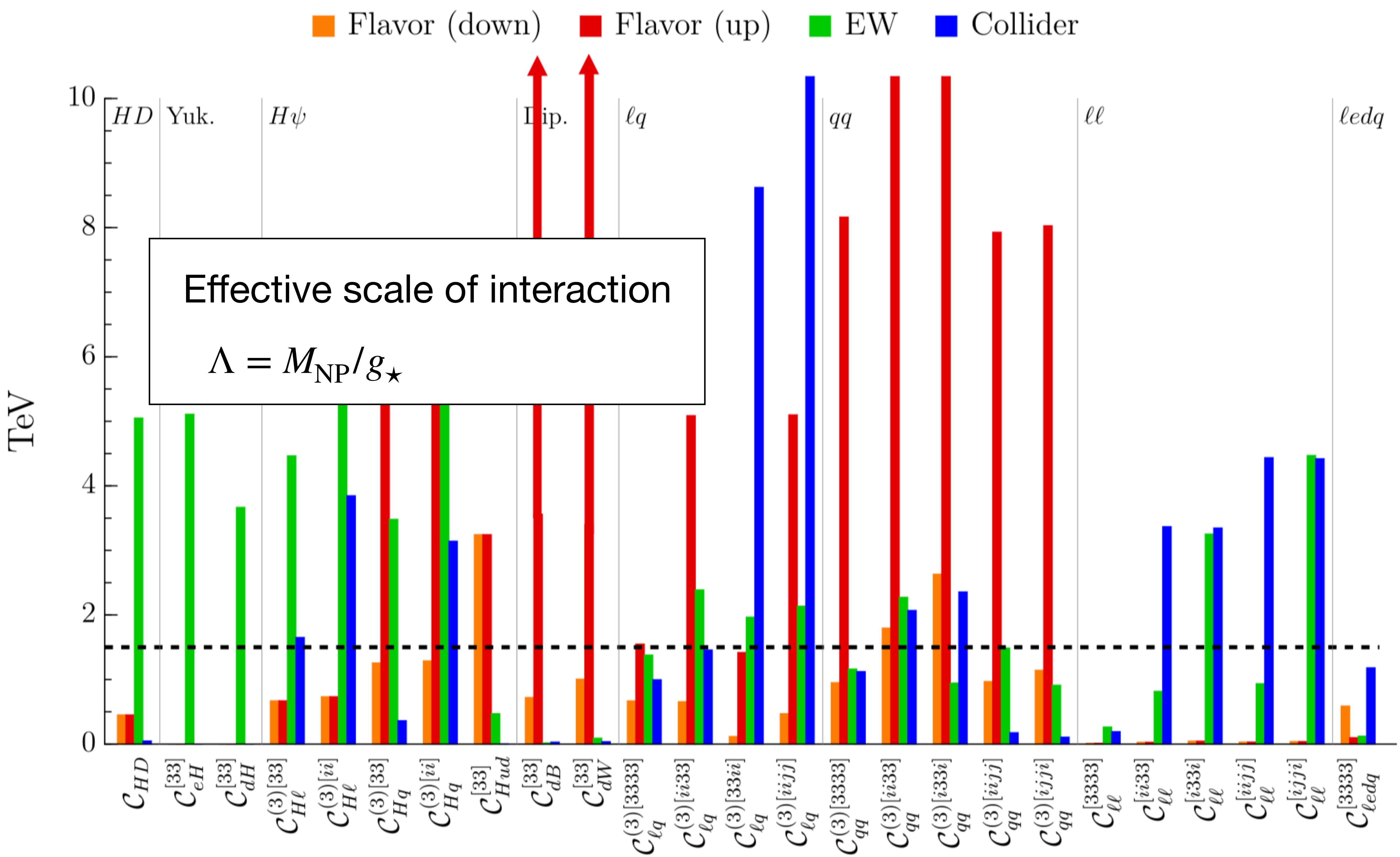
- Symmetries: e.g. MFV or U(2) models
  Barbieri et al. 2011; Isidori et al. 2017; …
- Dynamics: different NP scales for different families, related to Higgs
  Panico, Pomarol 2016; Bordone et al. 2017, etc…

→ $M_{\rm NP} \lesssim 3\,{\rm TeV}$

with O(1) couplings

Where do we stand?

- With CKM-like suppression (U(2)³ flavor symmetry)



Allwicher, Cornella, Isidori, Stefanek 2311.00020

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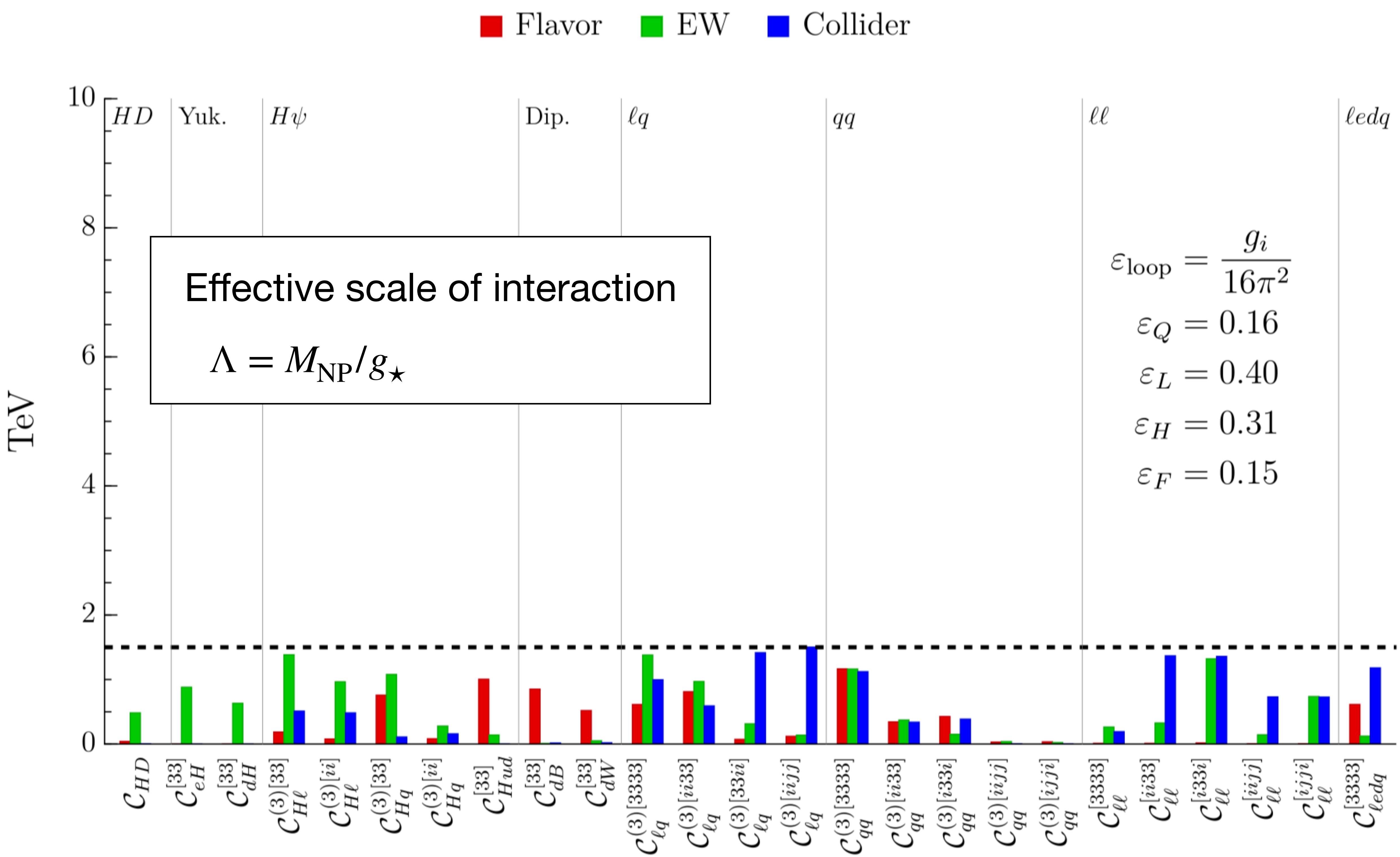

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The next 15 years: Flavor

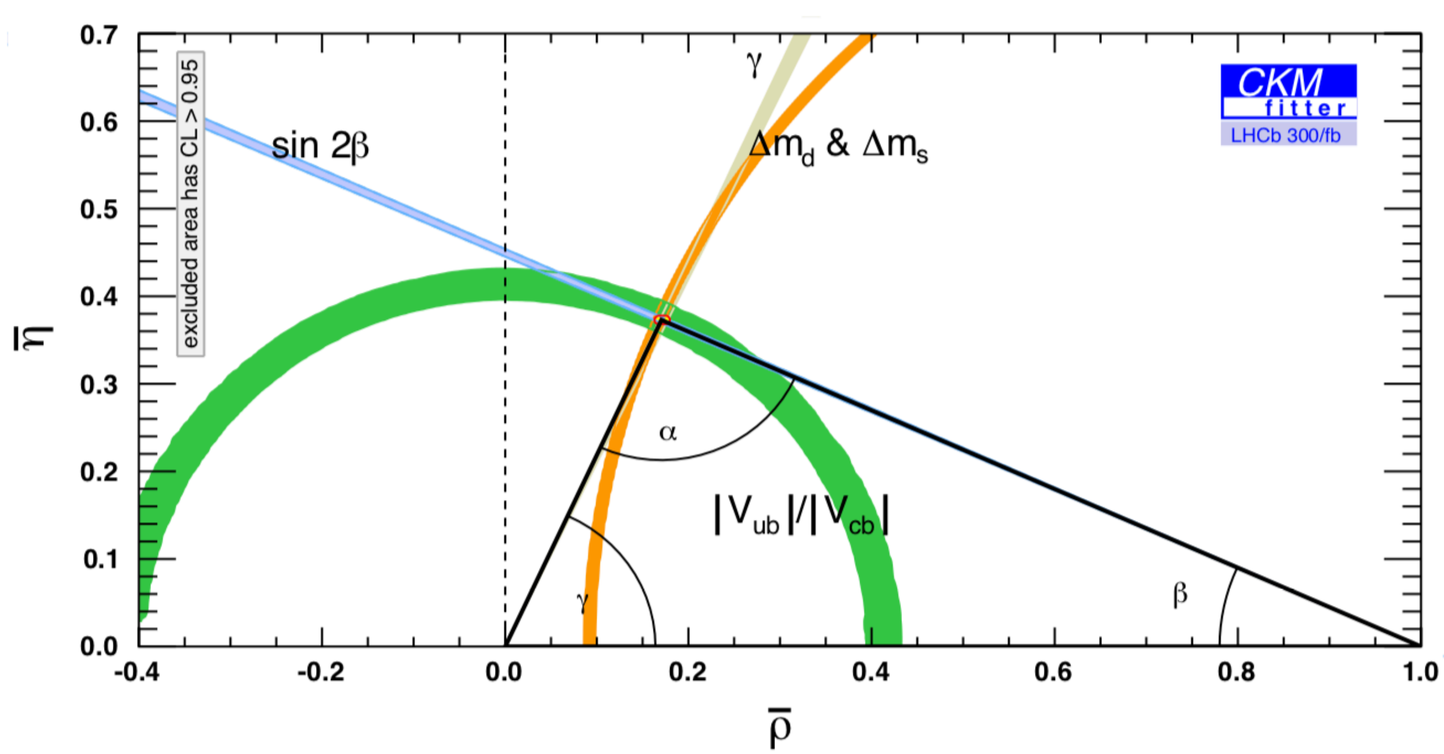
- **Significant improvement** in flavor measurements in the next (few) years!

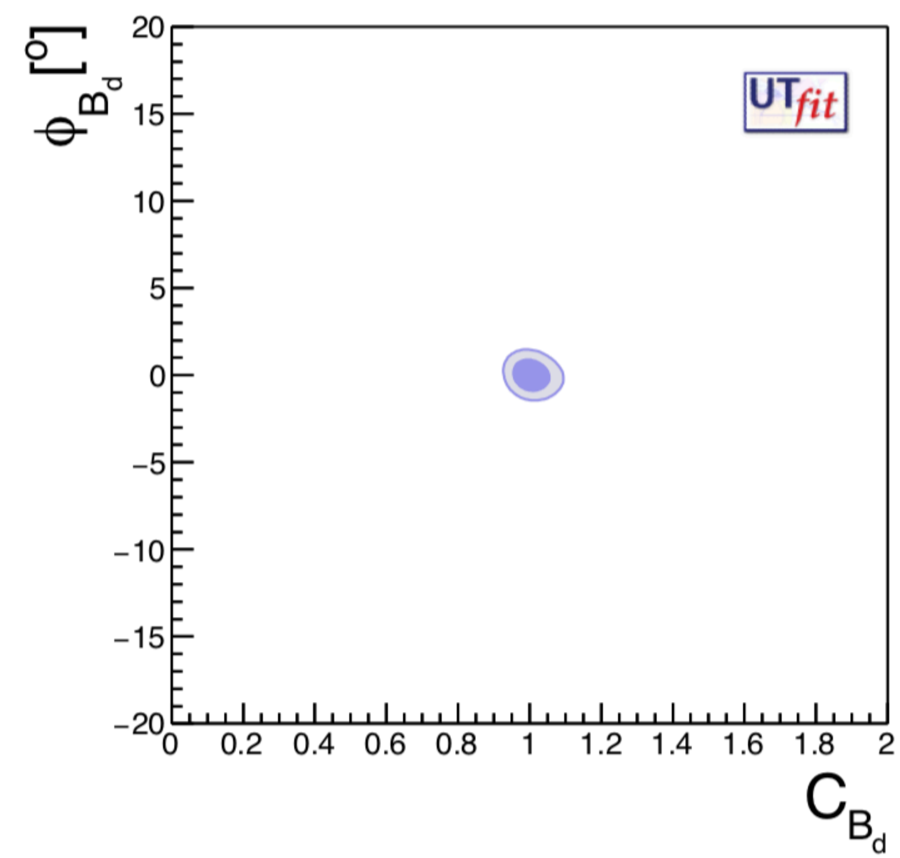
(upgrade 2)

- 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





O(15 y) timescale!

- Precision on CKM matrix elements < 1% (tree-level and loop)
  - Needed as input of SM predictions in all other observables!
- CPV in Bs system. CPV in charm with extreme precision.

The next 15 years: Flavor

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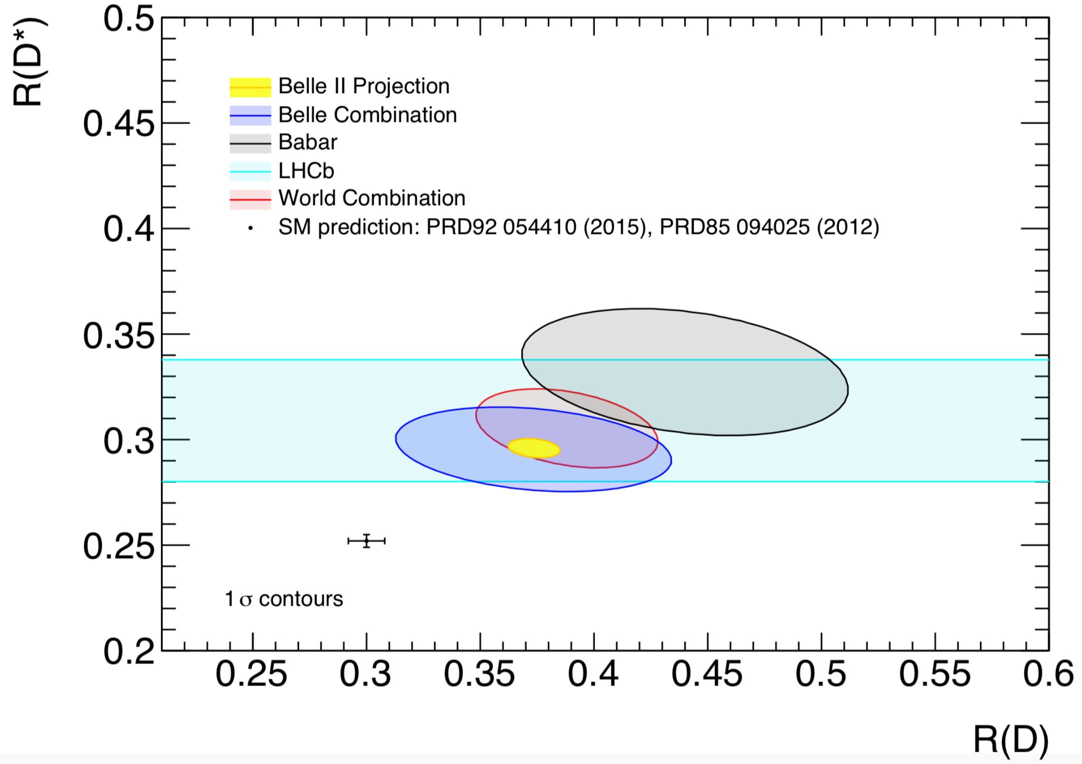


O(15 y) timescale!

- Semi-leptonic decays $b \to q\ell\nu$
- Semi-tauonic decays @ few %

$$\Rightarrow \quad M_{\rm NP} > 5\,\text{TeV} \times g_\star$$

(today below 1 TeV)

- Rare leptonic & semi-leptonic B decays
  - Access to b → dll transitions
  - LFU below 1% precision
- Rare tau decays and LFV

For the first time precise measurements of rare processes for different flavors:
$b \to s$ vs $b \to d$; τ vs μ, e; $\ell^\pm$ vs ν_ℓ

Ultimate precision on all 'visible' B and D decay modes

The next 15 years: Flavor

- Access to FCNC decays with neutrinos and taus for the first time!

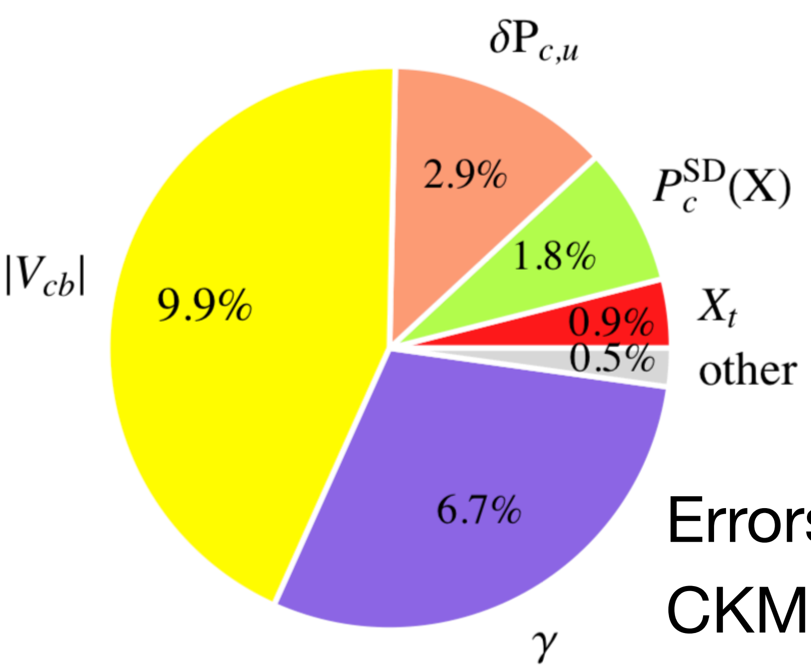
  crucial to determine up vs. down aligment of NP: can suppress only one!

- Belle II will measure $B \to K^{(*)}\nu\nu$ to 10%

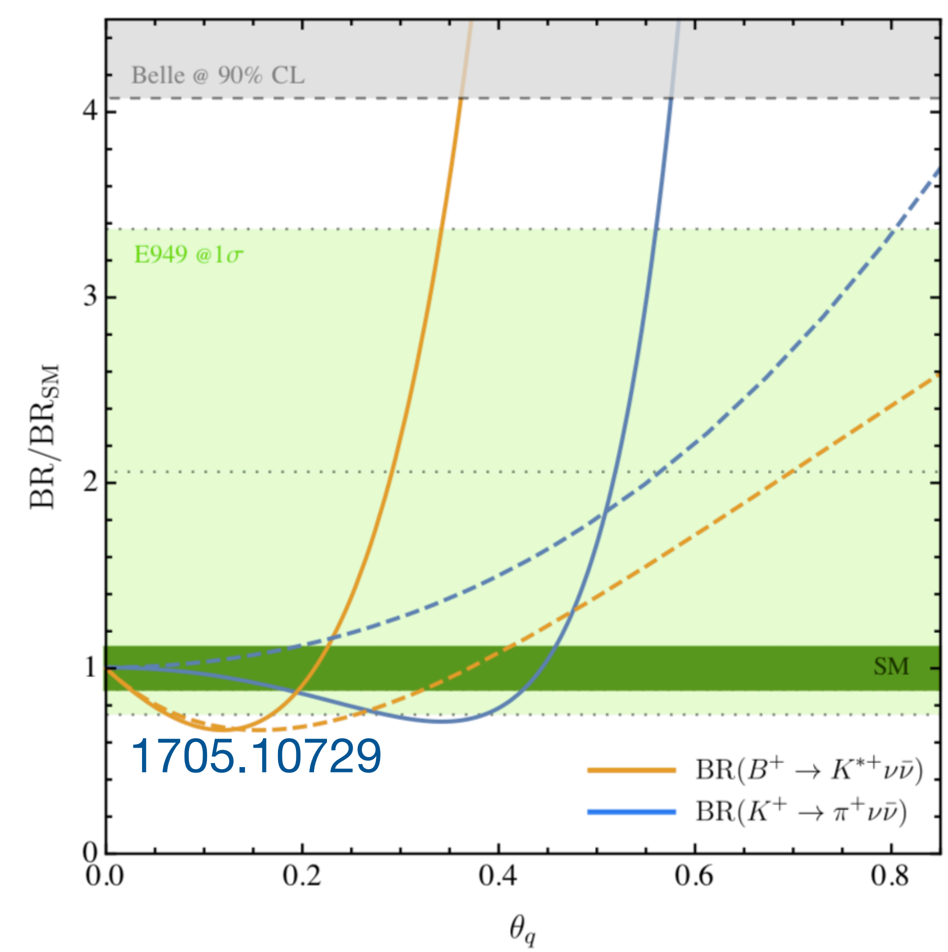
  O(10 y) timescale!

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%

- $K^+ \to \pi^+\nu\nu$ to 10% from NA62 and below 5% from HIKE



Errors dominated by CKM (will improve a lot!)



- $K_L \to \pi^0\nu\nu$ one of the few *very* clean modes (like $B_s \to \mu\mu$, or CP asymmetry in $B \to \psi K_S$).

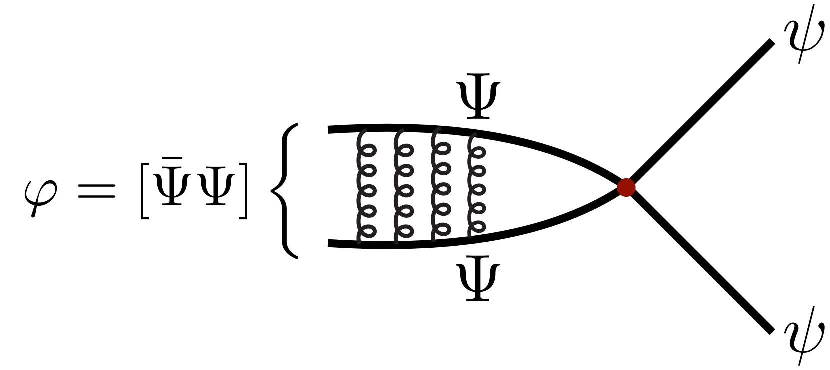
What NP scales will we test with flavor?

- <u>A natural example:</u> composite Higgs models.

  Higgs is a Goldstone boson (like the pion in QCD)

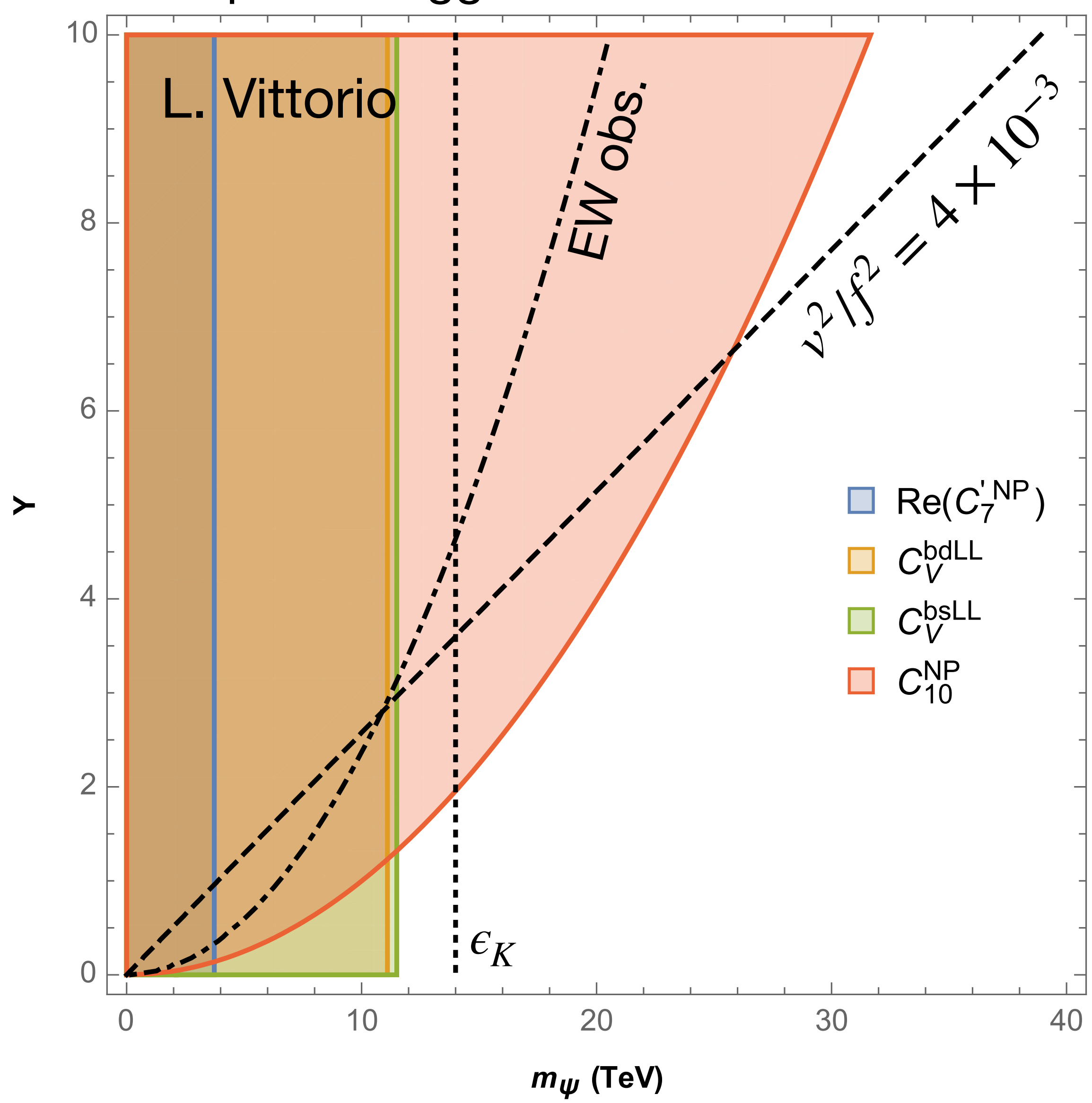
  composite at a scale $M_\star = g_\star f$

  Size of the Higgs — Decay constant of the Higgs



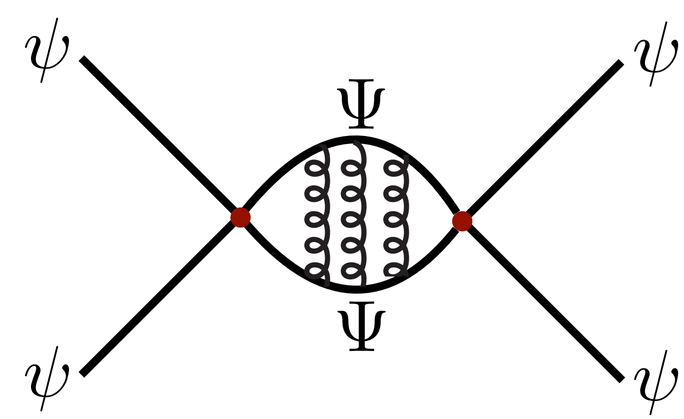
$\kappa_h \sim v^2/f^2$

Composite Higgs MCH5



Higgs couplings ~ 0.004, i.e. f > 4 TeV

Flavor effects known to be important



projections for
LHCb 300 fb^{-1} & Belle II
O(10 y) timescale!

Flavor @ FCC-ee

- Unique flavor physics program possible at FCC-ee!

2106.01259

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

~ LHCb ⊕ B-factory

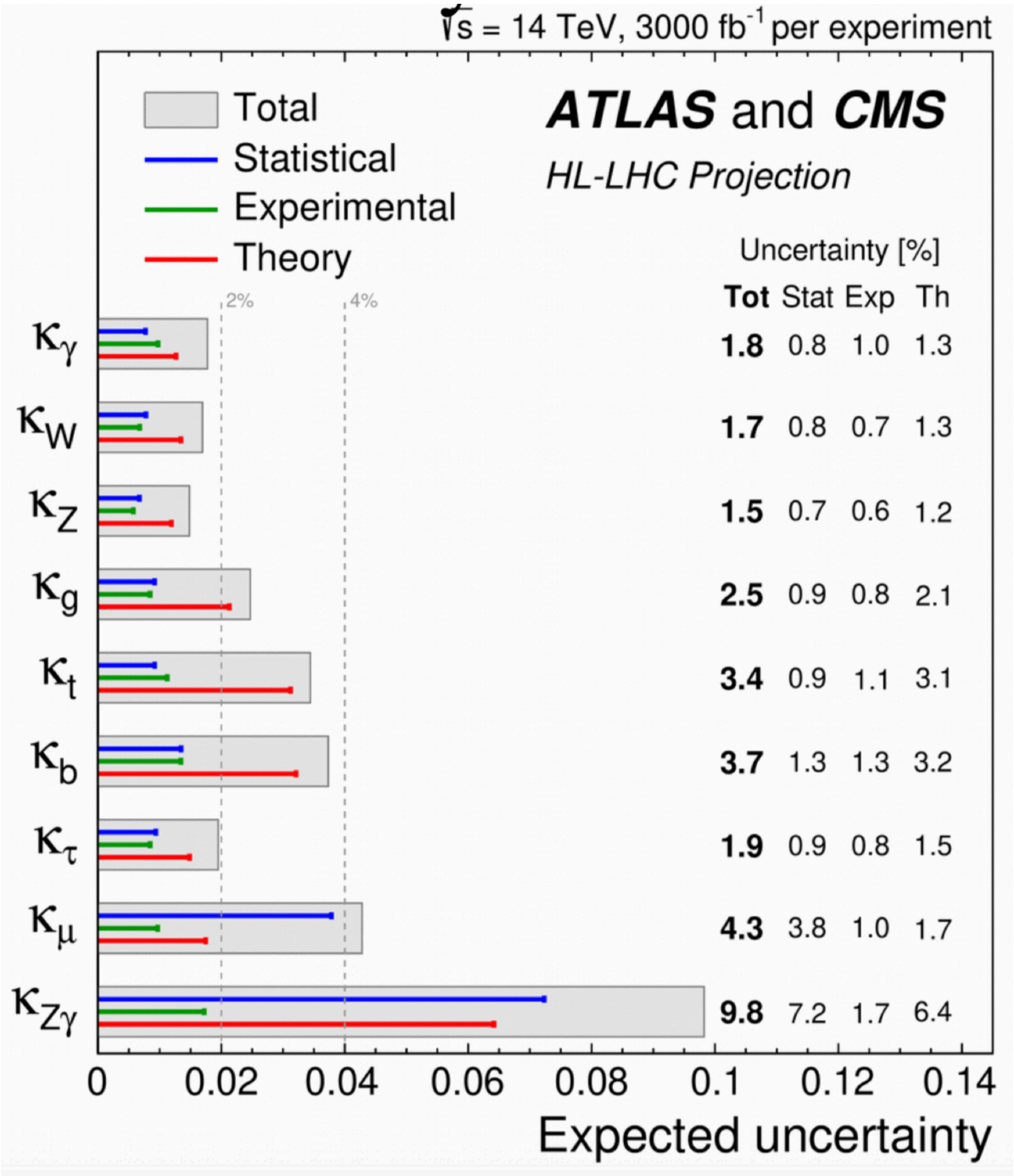
- ~ 10^{12} b quark pairs (and 10^{11} tau pairs) in a B-factory like environment from Z boson decays.

➡ can measure decay modes with missing energy (esp. τ's and ν's) with 100x more statistics than Belle II!

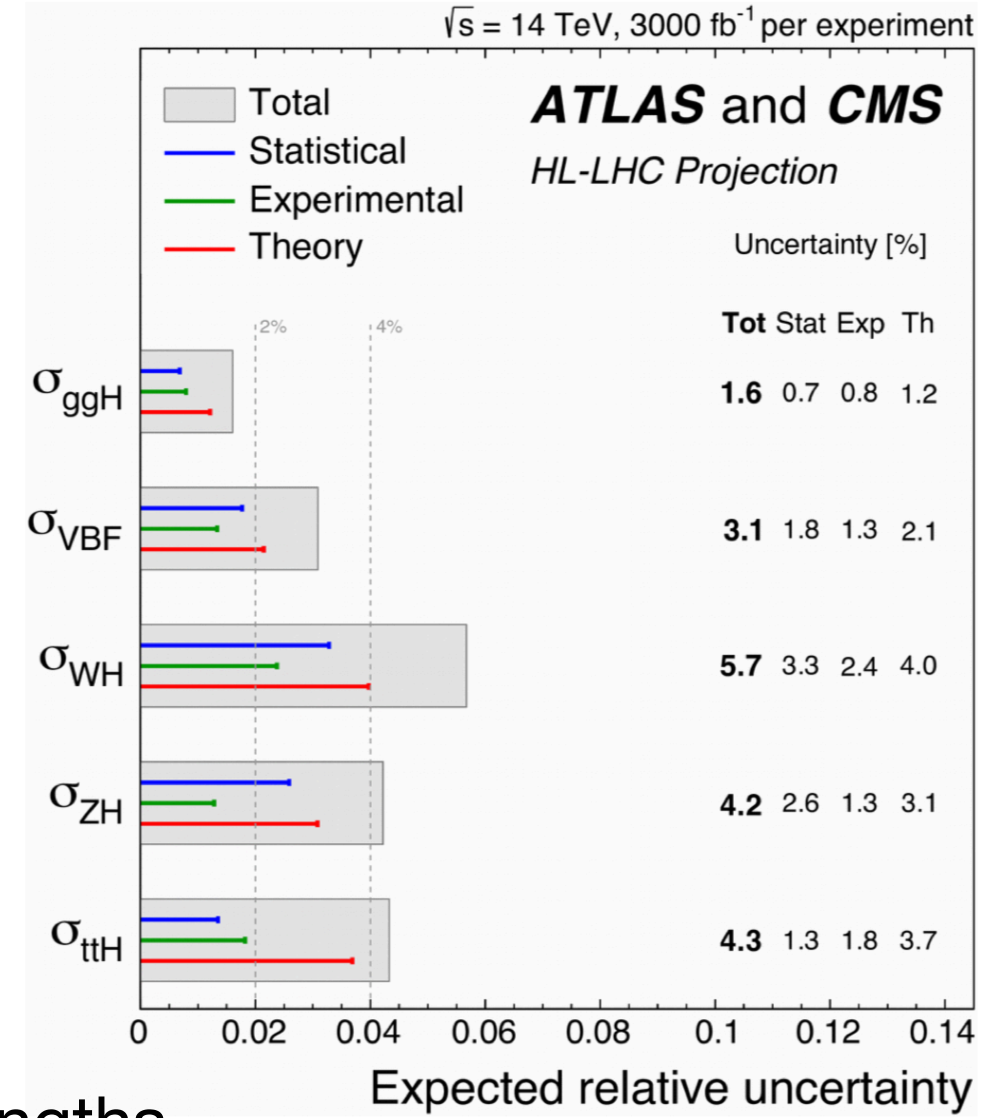
Example: 10^3 $B \to K^{(*)}\tau\tau$ events (vs. 10 @ Belle II). Few % precision!

➡ $M_{\rm NP} \gtrsim$ several TeV — for NP coupled to 3rd family, complementary with $b \to s\nu\nu$

The next 15 years: Higgs



- ✦ Various production modes (ttH @ few %) and differential cross-sections

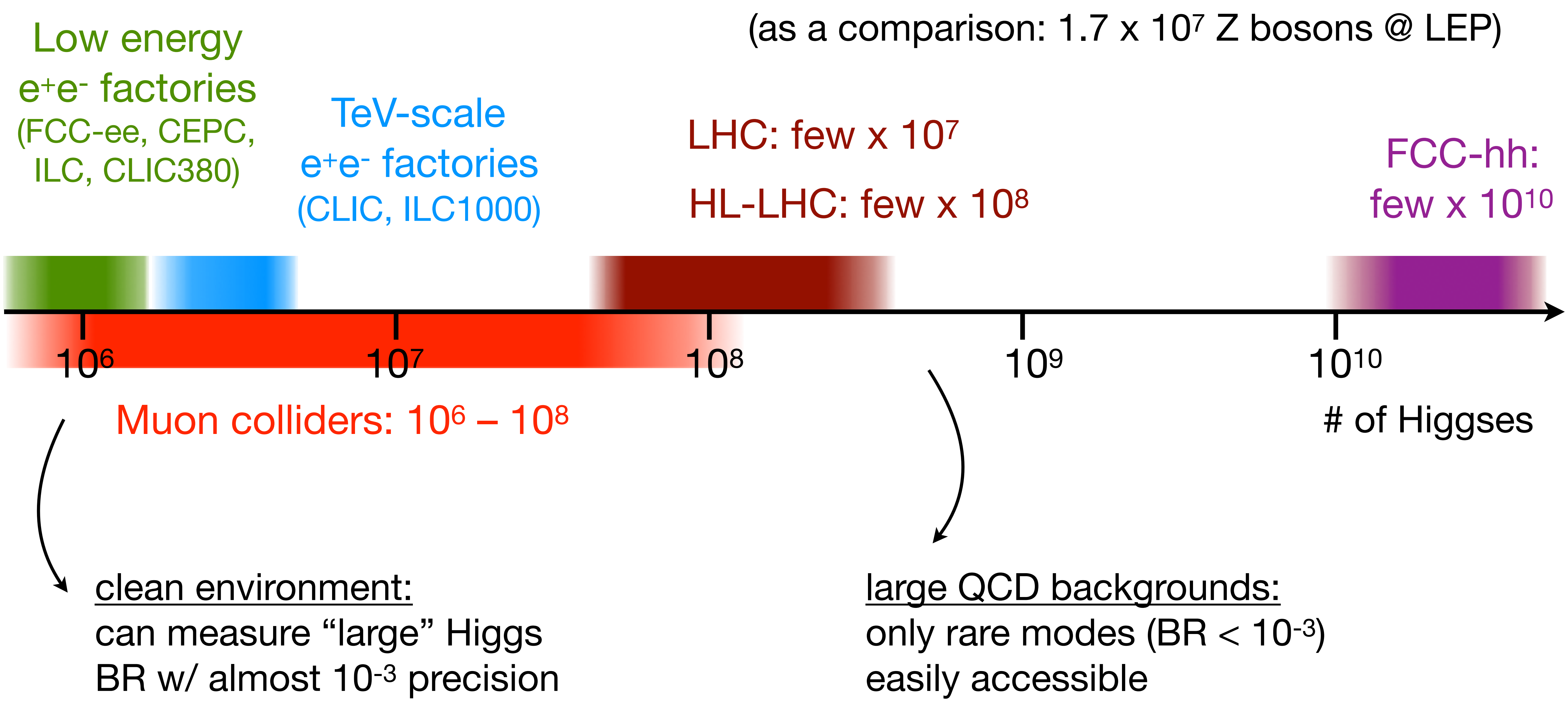


- ✦ Factor 2-3 improvement in Higgs signal strengths

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

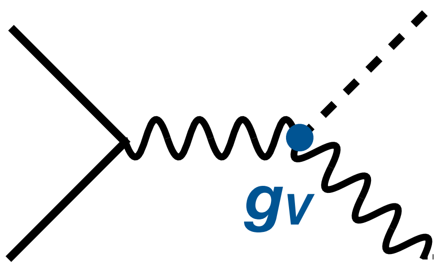
Higgs factories

- All proposed future colliders will be able to produce millions of Higgses
  → study single Higgs couplings with below percent precision!



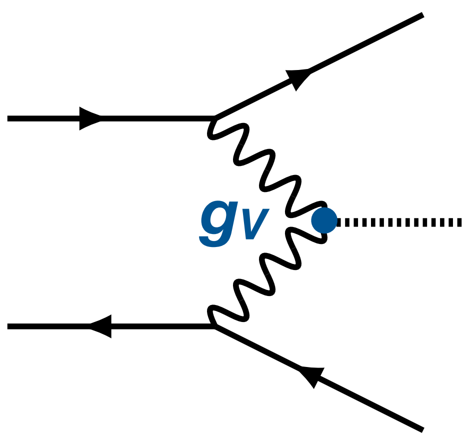
Higgs factories

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

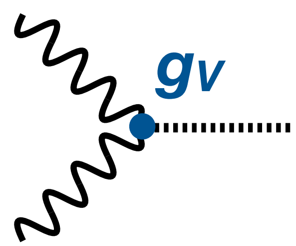


- measure the recoil (missing mass) of h against Z
- *direct* measurement of gV ⟶ other couplings + width

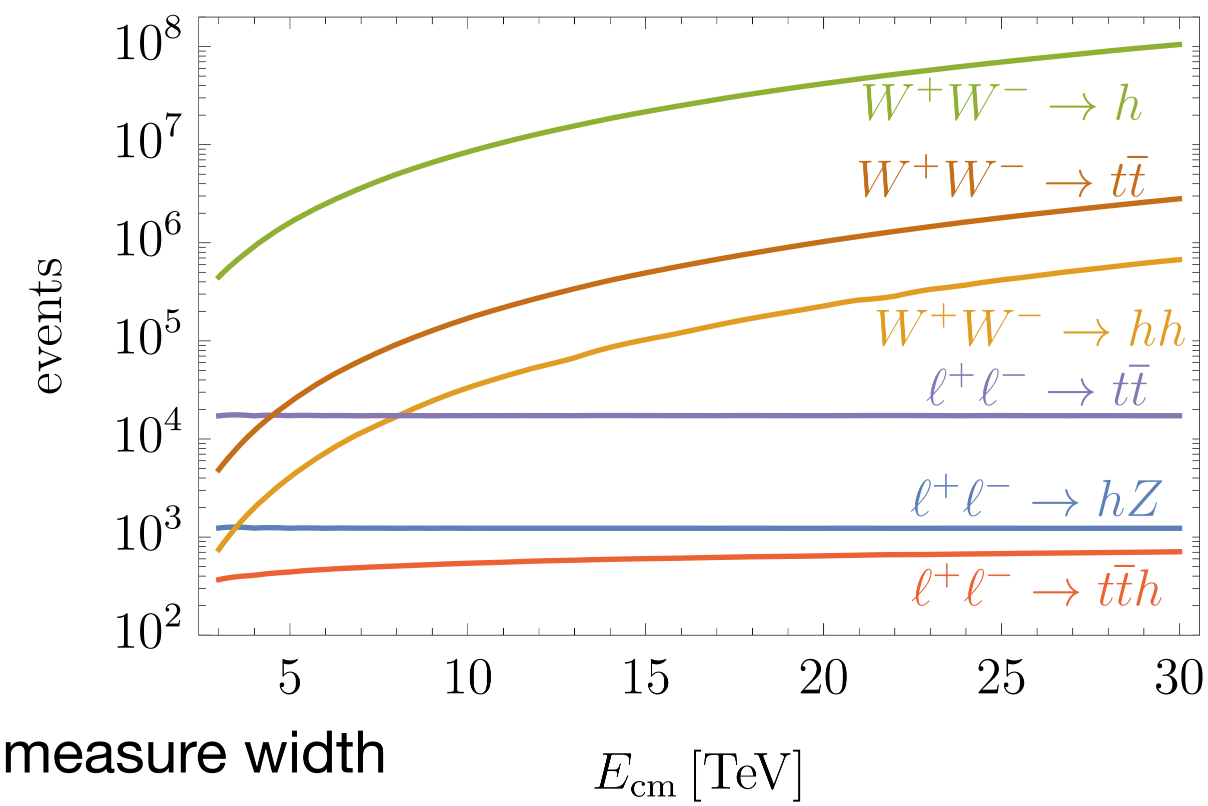
- A high-energy lepton collider is a “vector boson collider”



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



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 S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ 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

dominant channels ~ other Higgs factories

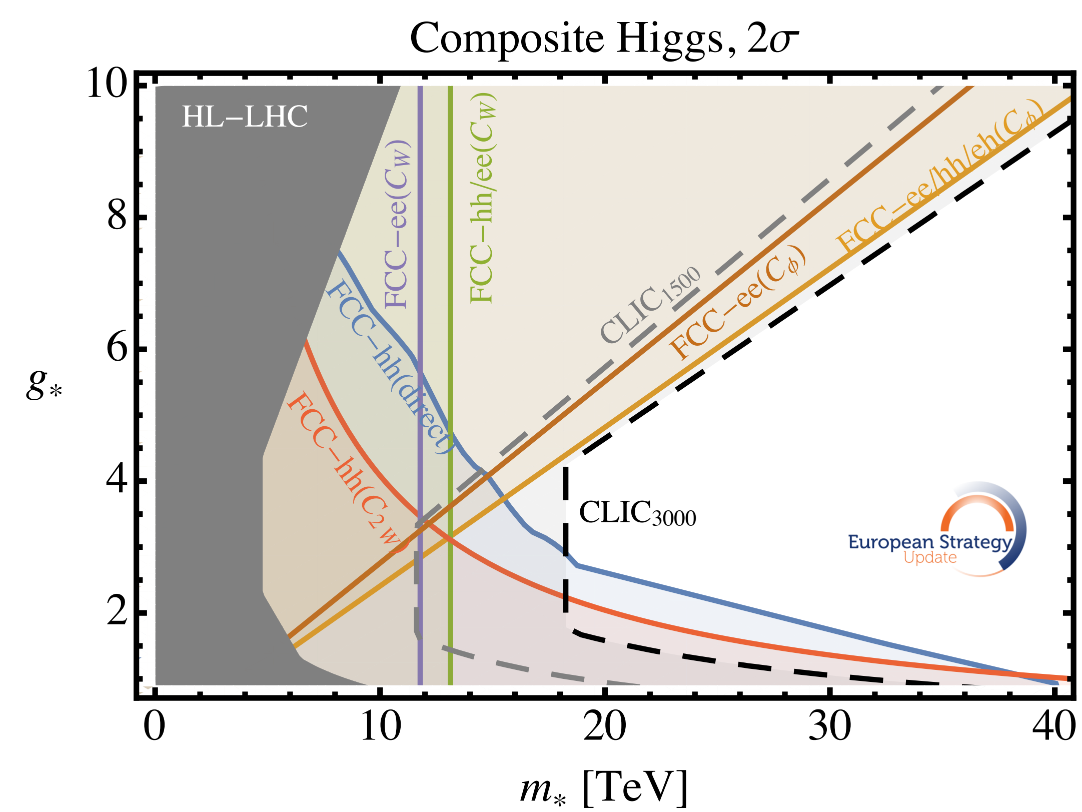
rare modes better (~ hadron collider)

2103.14043

What NP scales will we test with the Higgs?

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

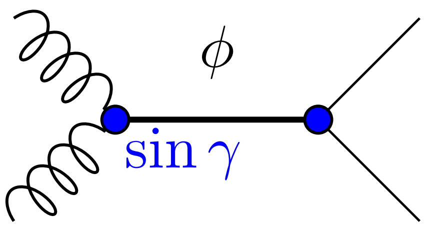
$$\longrightarrow \quad M_{\rm NP} \gtrsim g_\star \; \mathbf{6\ TeV}$$

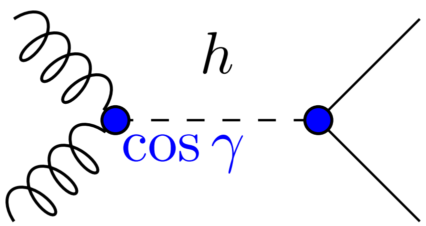


Compare single Higgs couplings measurements with reach of direct searches

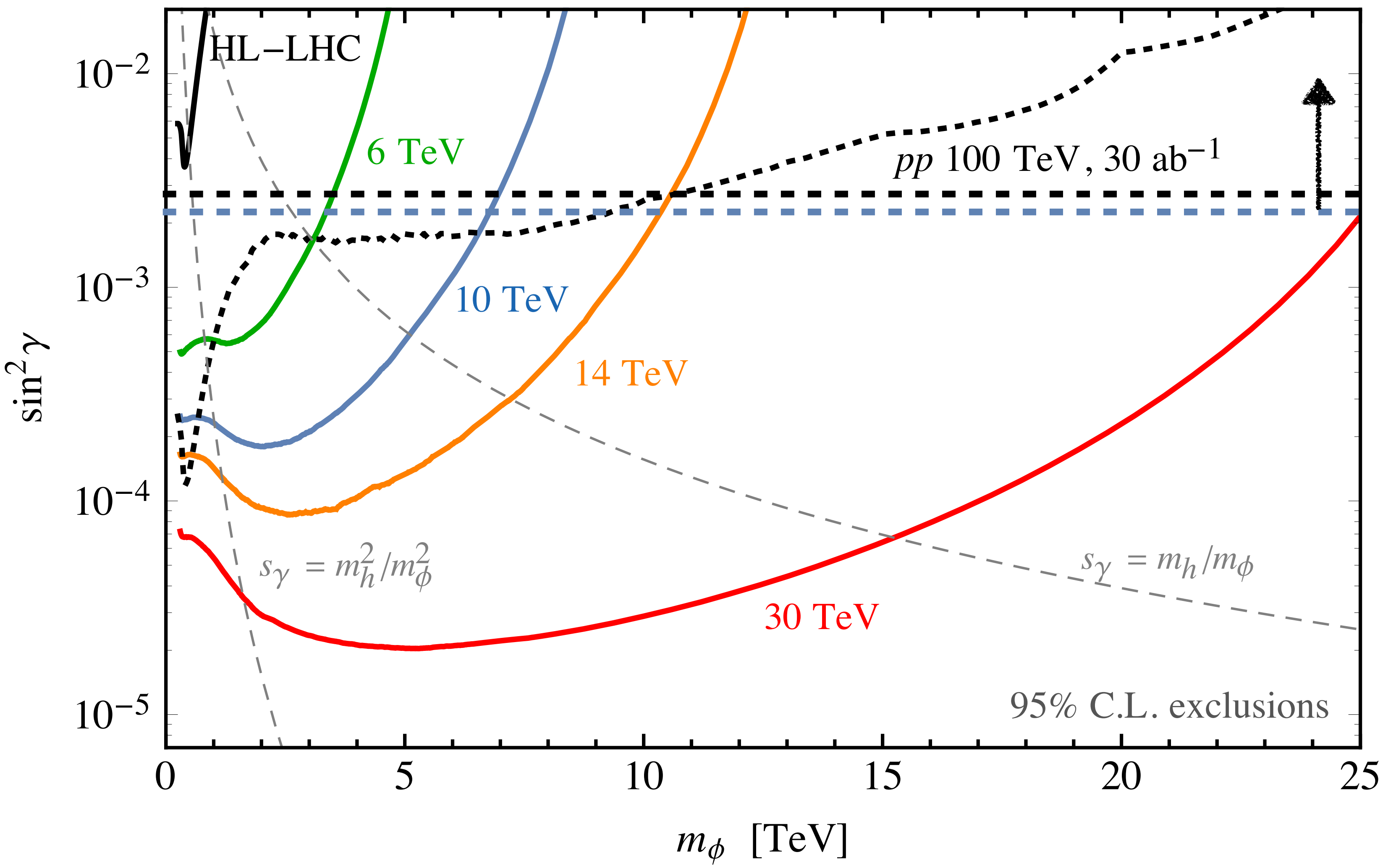
- **Example: singlet scalar** $\mathscr{L}_{\text{int}} \sim \phi |H|^2$

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





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



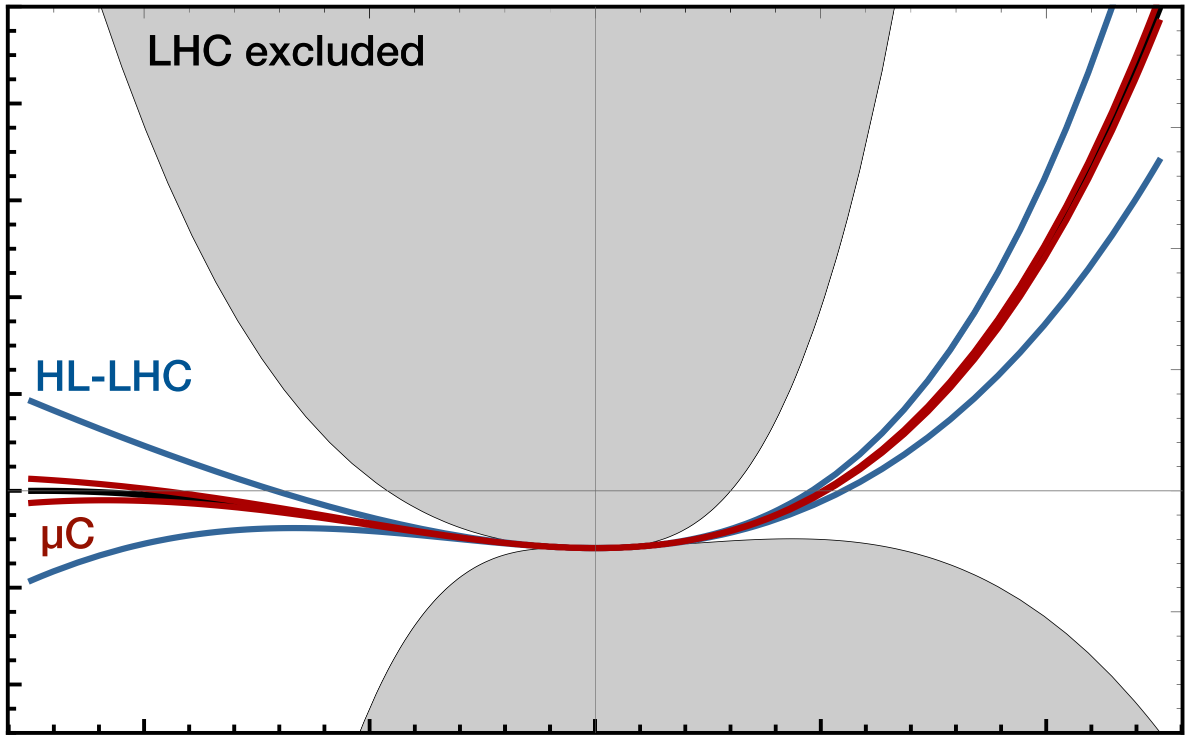
can be probed by single higgs

☛ see talk by R. Franceschini

B, Redigolo, Sala, Tesi 1807.04743

Double Higgs production

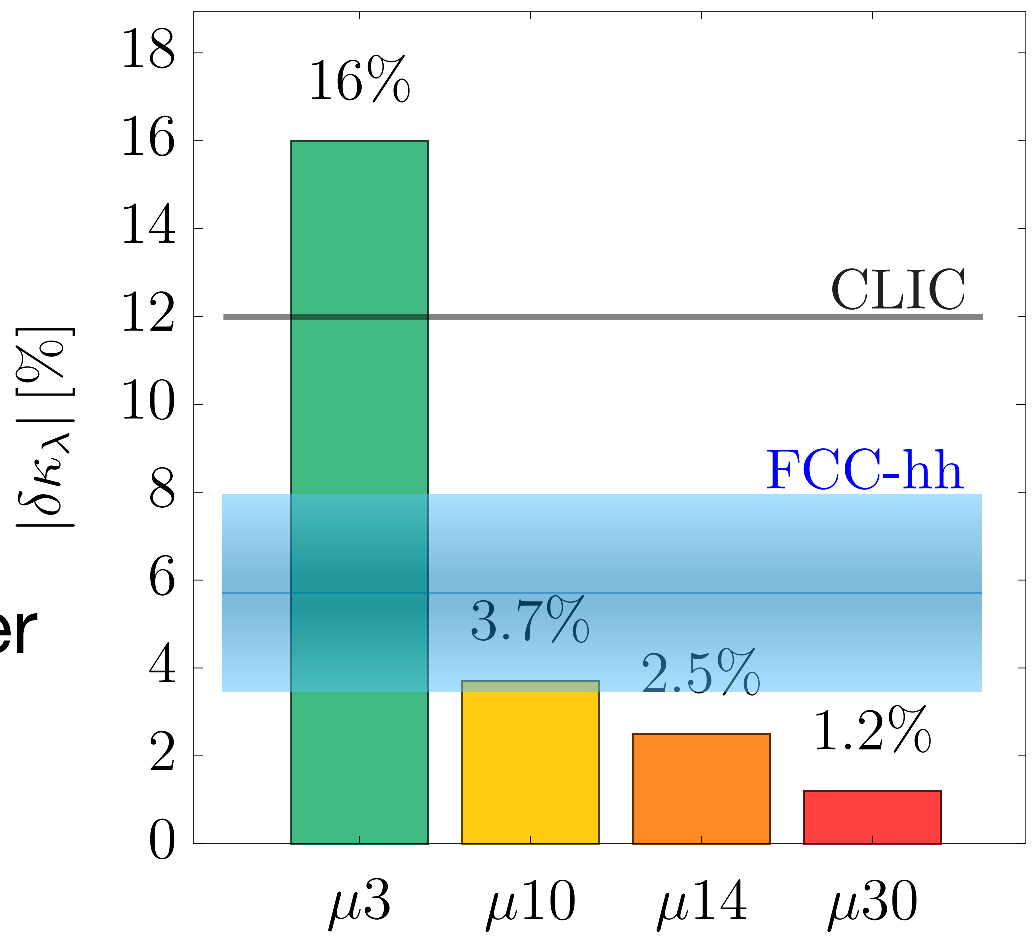
- Measurement of trilinear coupling: access to the Higgs potential



credits: Craig, Petrossian-Byrne

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

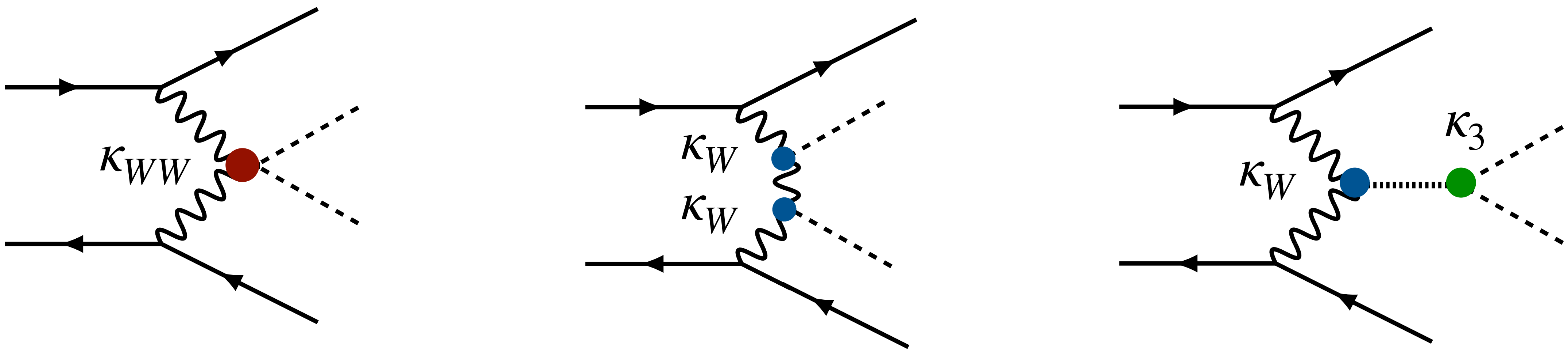
- Precise determination *only* possible at high-energy machines: 100 TeV FCC-hh or multi-TeV Muon collider



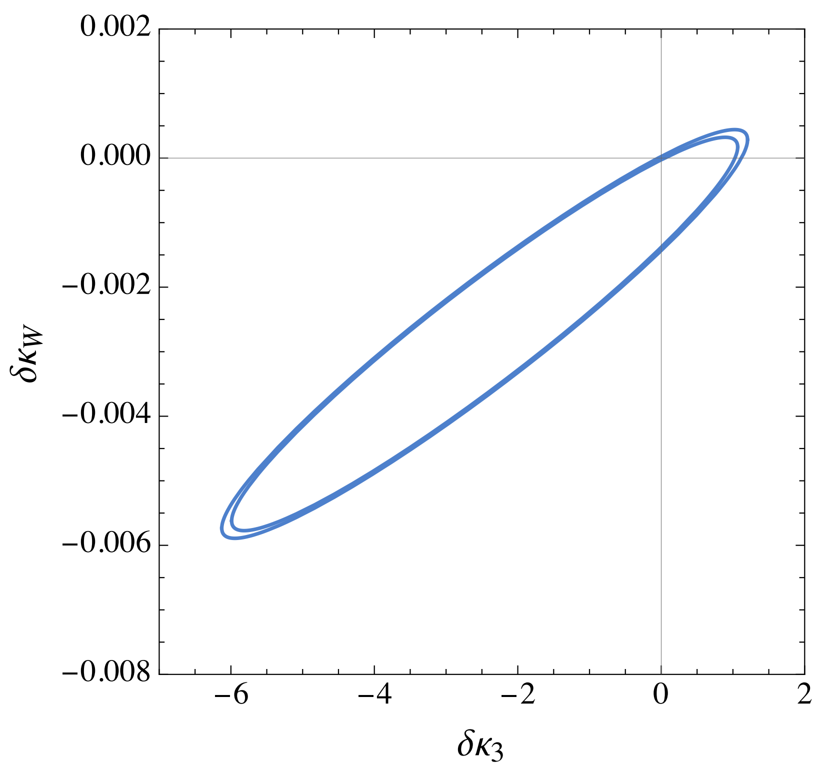
Mangano et al. 2004.03505
B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289
Han et al. 2008.12204
CLIC 1901.05897

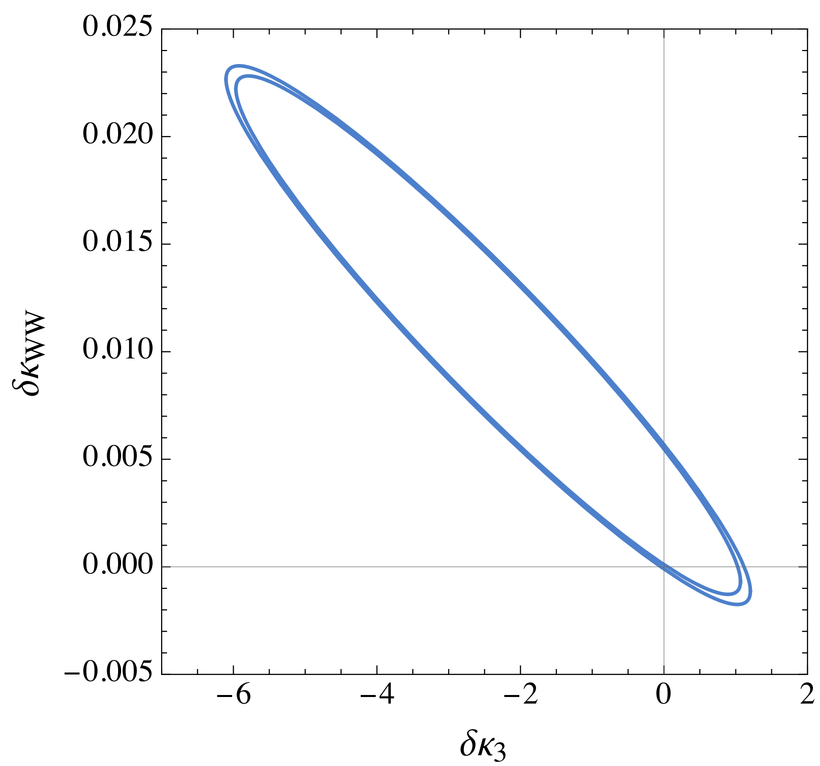
Double Higgs production

- Double Higgs production depends on trilinear coupling κ_3 but also on W-boson couplings κ_W, κ_{WW} that enter the production cross-section



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

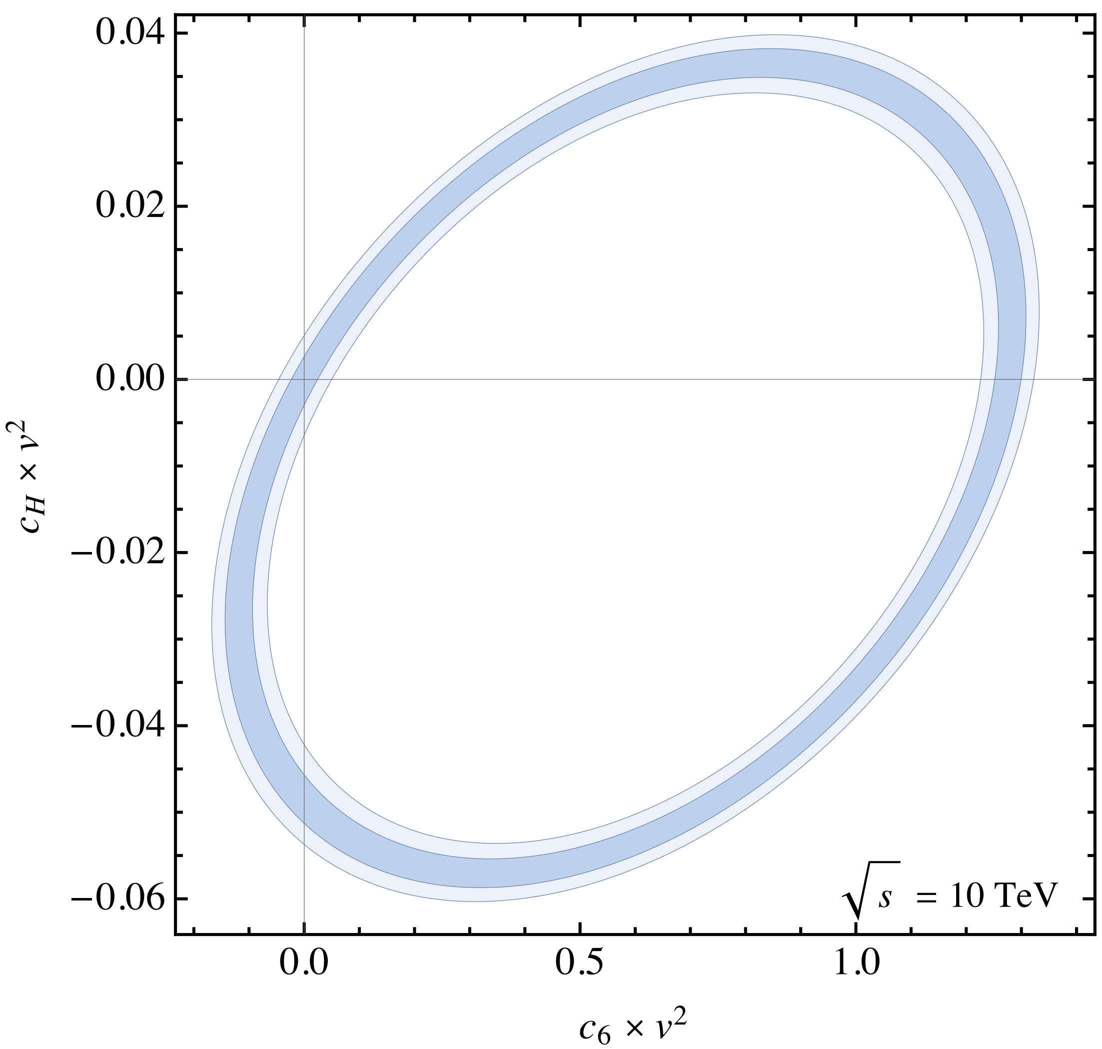




Double Higgs production

- Double Higgs production depends on trilinear coupling κ_3 but also on W-boson couplings κ_W, κ_{WW} that enter the production cross-section
- Two dim. 6 operators: $\mathcal{O}_6 = -\lambda |H|^6$ $\quad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$

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



large degeneracy in total cross-section: coefficients not determined in general

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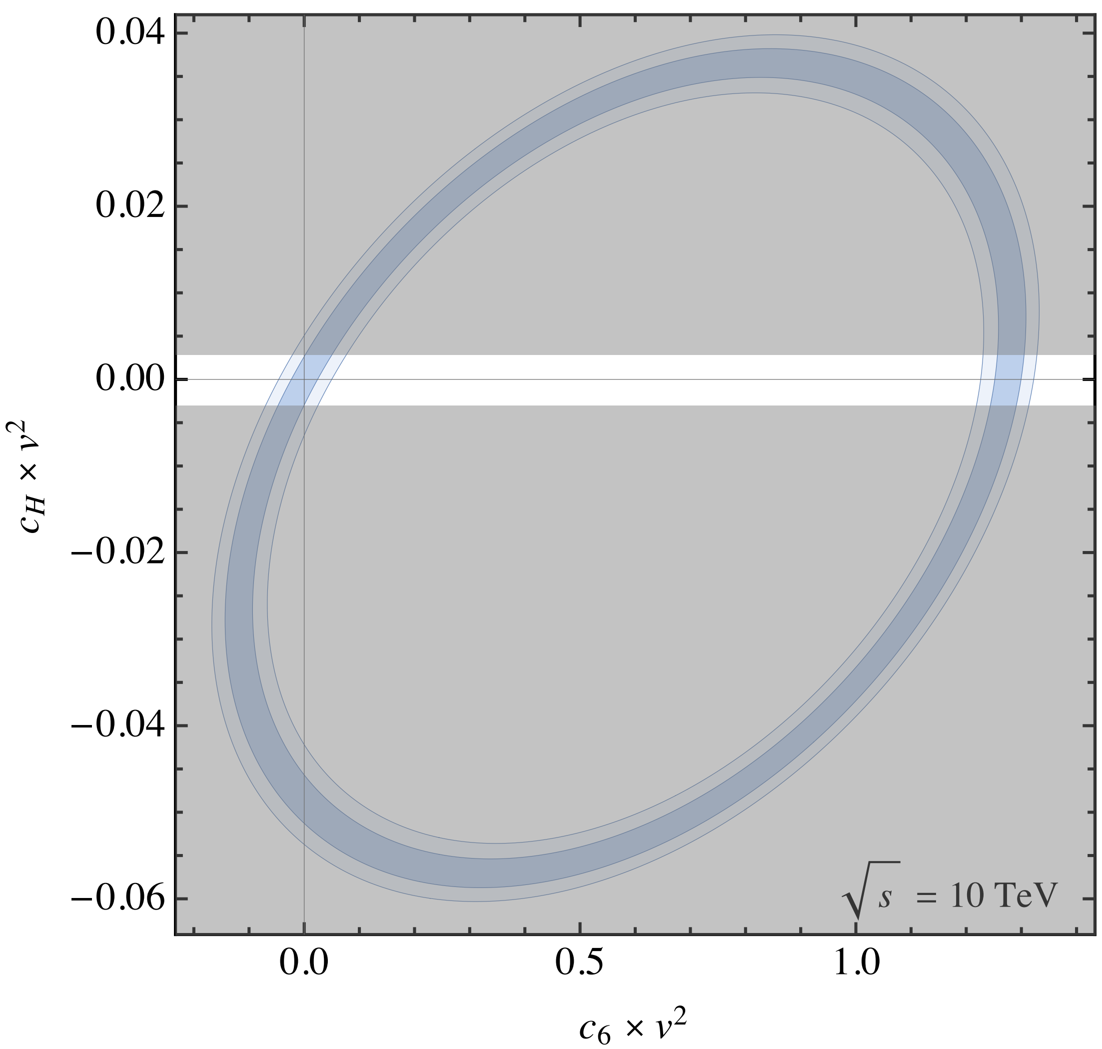


large degeneracy in total cross-section: coefficients not determined in general

O_H also affects all single Higgs couplings universally:

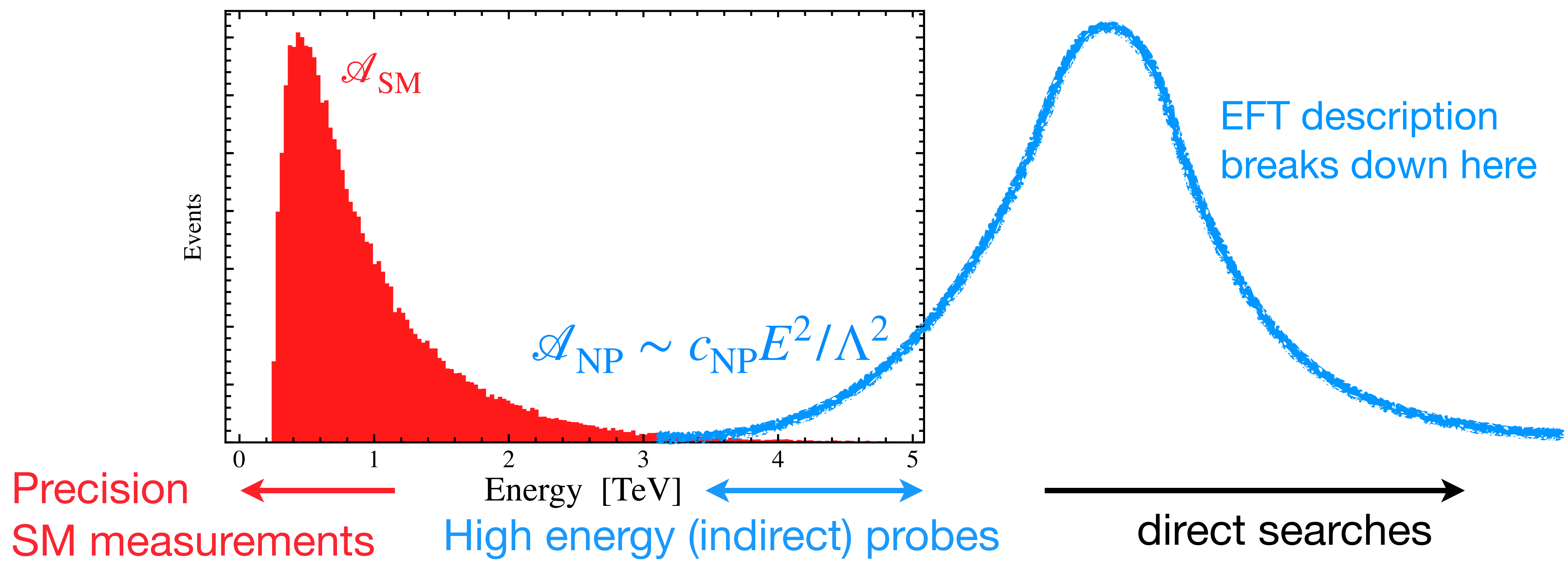
$$\kappa_{V,f} = 1 - v^2 C_H/2$$

C_H can be constrained from Higgs couplings $\Delta\kappa_V \sim C_H v^2 \lesssim \text{few} \times 10^{-3}$

Higgs at high-energy

- Higgs physics doesn't mean just couplings. There's much more information in the energy dependence of the interactions! (form factors)

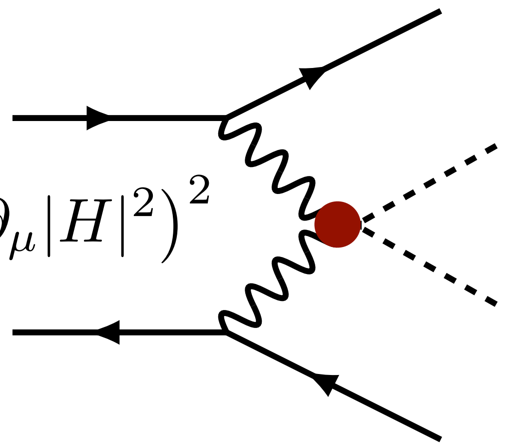
- NP effects are more important at high energies (≈ high-pT tails at LHC)



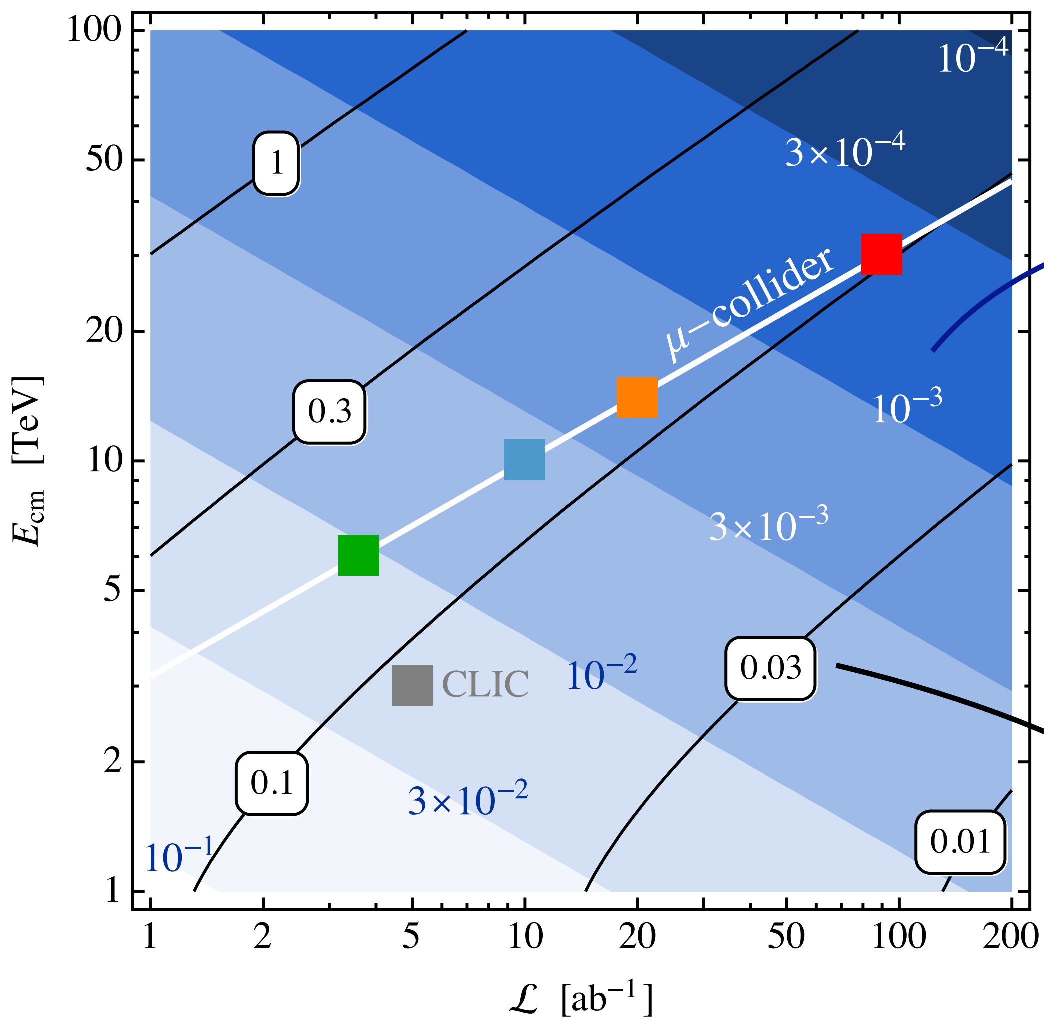
Double Higgs at high mass

- NP contribution from $\mathcal{O}_H$ (equivalently κ_W, κ_{WW}) grows as E^2: high mass tail gives a *direct* measurement of C_H

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

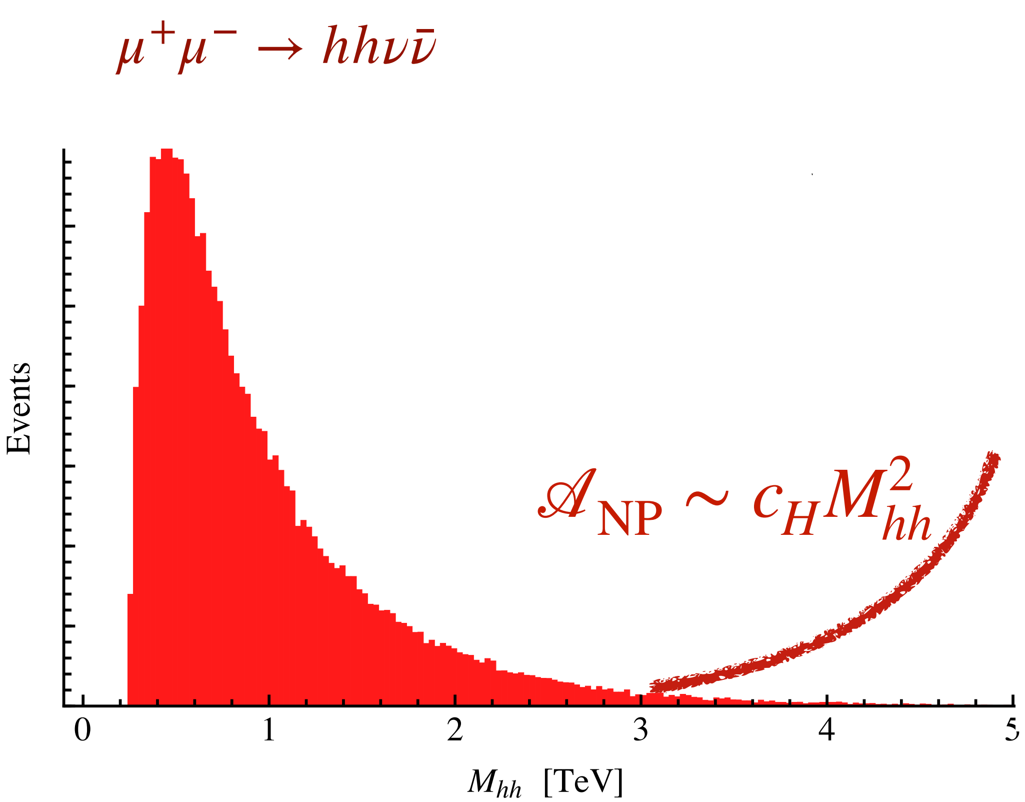


High-energy WW → *hh* more sensitive than Higgs pole physics at energies ≳ 10 TeV



$\xi \equiv C_H v^2$

S/B low-precision measurement



(see also Contino et al. 1309.7038)

EW precision

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

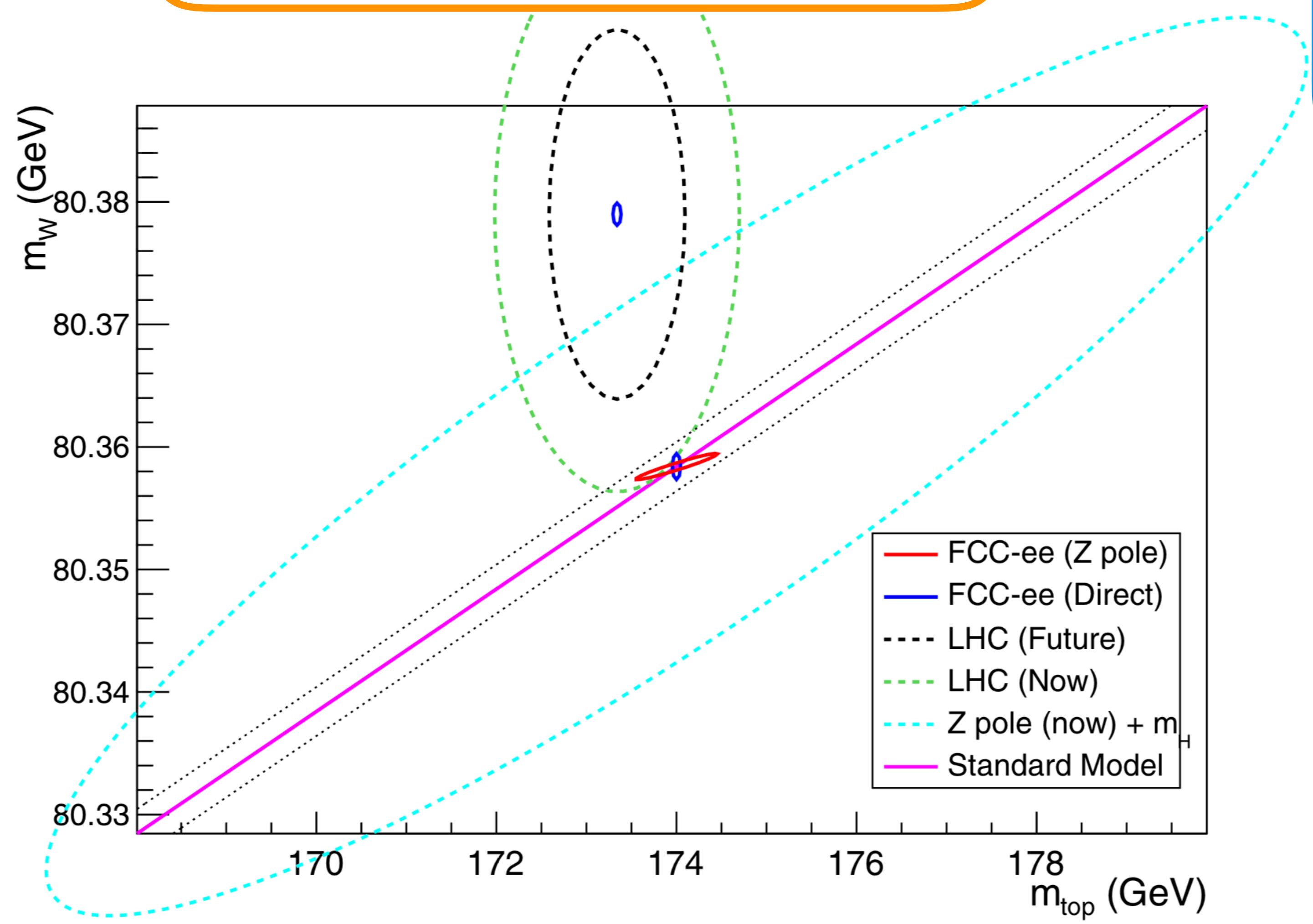
$$\mathcal{O}_T = \left(H^\dagger D^\mu H\right)^2$$

$\Delta\rho$

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

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

$\sin^2\theta_{\text{eff}}$



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

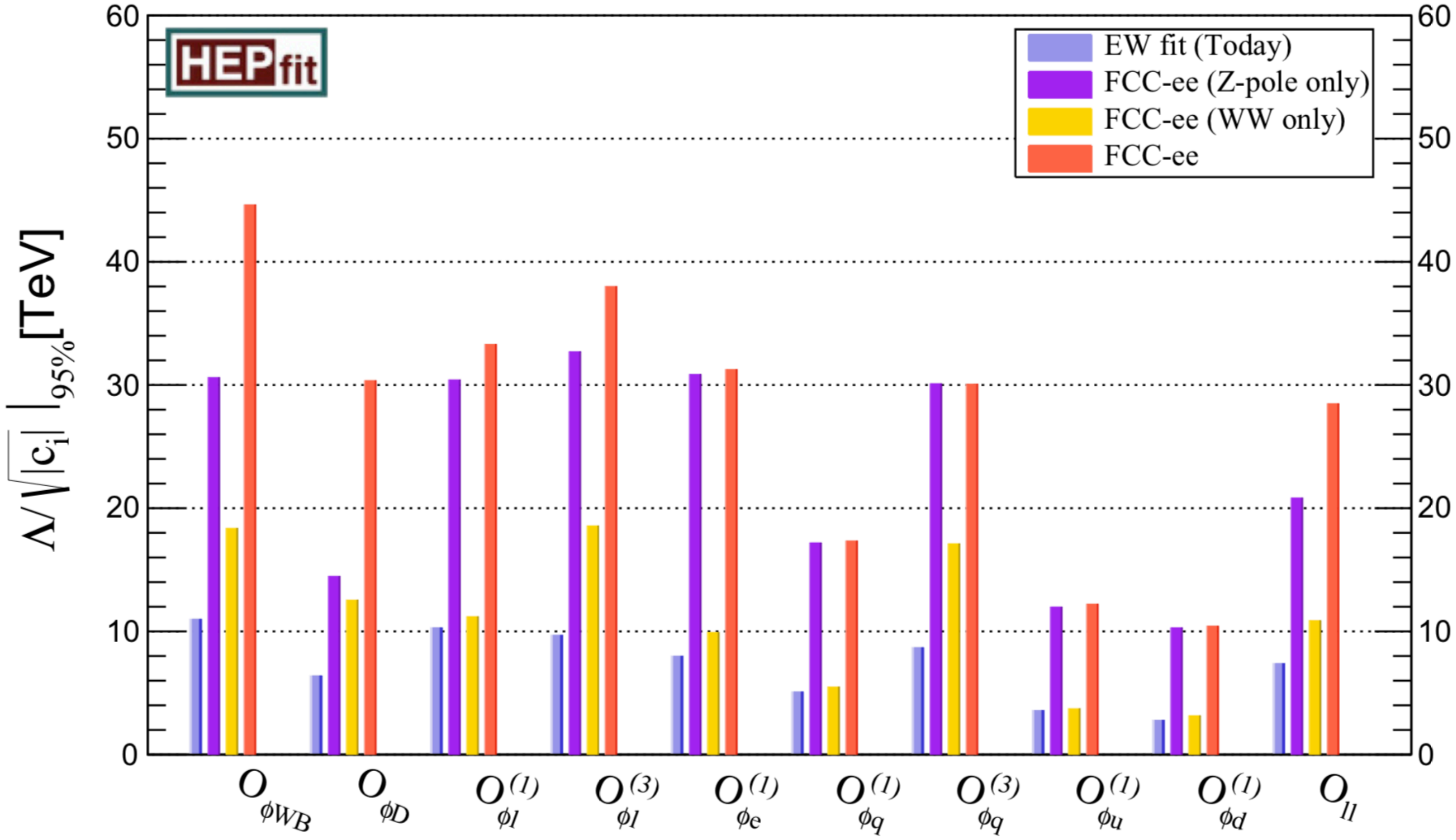
$$\Delta\hat{S} \sim \frac{m_W^2}{M_{\text{NP}}^2} \lesssim \text{few} \times 10^{-5}$$

$$\Rightarrow \quad M_{\text{NP}} \gtrsim 12\,\text{TeV}$$

	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

- In general, several more operators enter the EW fit

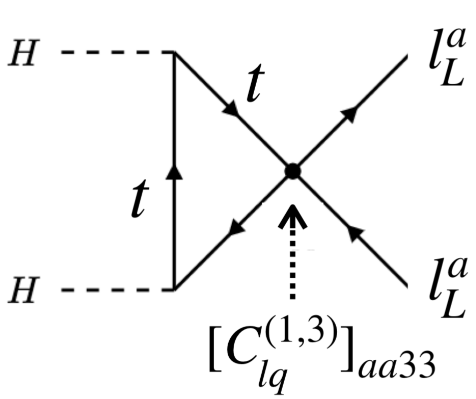


effective scales ~ 30 TeV

$$M_{\rm NP}^{\rm EW} = \Lambda \times g_\star \approx 12\,{\rm TeV}\left(\frac{g_\star}{g_2}\right)$$

Several 4-fermion interactions enter through one loop RGE

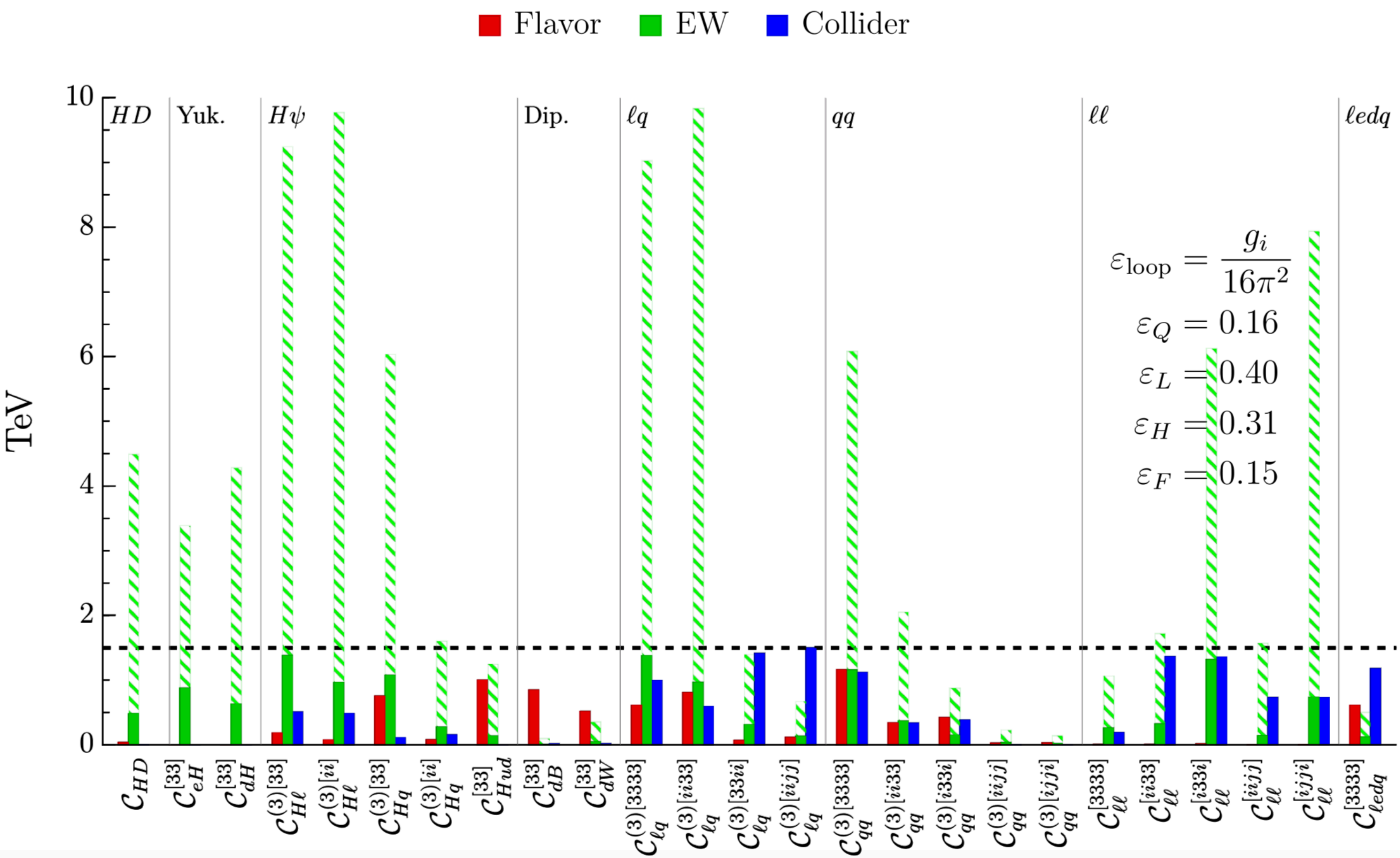
2311.00020, 1704.04504



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

$$M_{\rm NP}^{4f} \gtrsim 10\,{\rm TeV} \times g_\star$$

EW precision



Allwicher, Cornella, Isidori, Stefanek 2311.00020

Challenges

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

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

- 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, …)

- High rate measurements eventually limited by systematics

  - Why 10^{12} Z bosons?

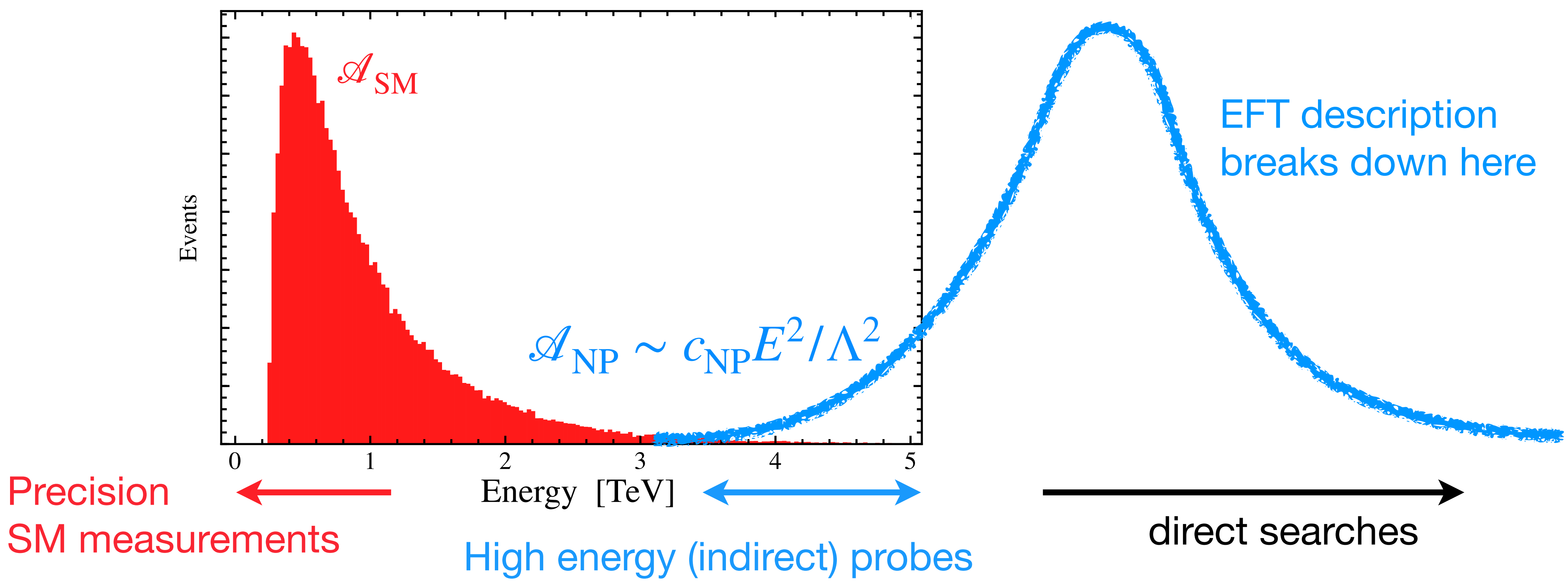
    Lepton asymmetries: $N_{\text{events}} = N_Z \times \text{BR}(Z \to \ell^+\ell^-) \times A_\ell \sim 3 \times 10^{-4}\, N_Z$

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

- *Eventually, we'll need to measure physics at higher energy to improve!*

EW precision at high-energy

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



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

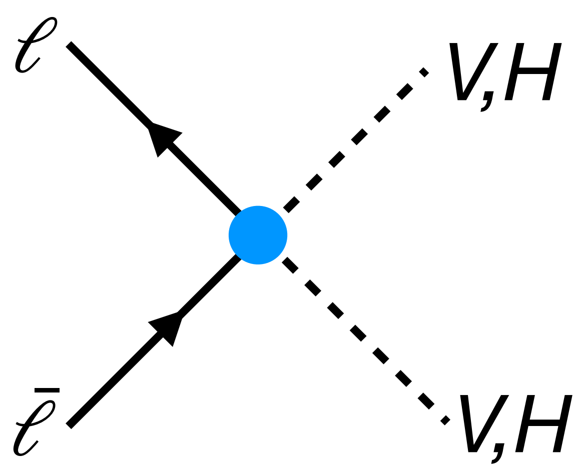
- Effective at LHC, FCC-hh, CLIC: “energy helps accuracy”…

Farina et al. 1609.08157, Franceschini et al. 1712.01310, …

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

Example: high-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:



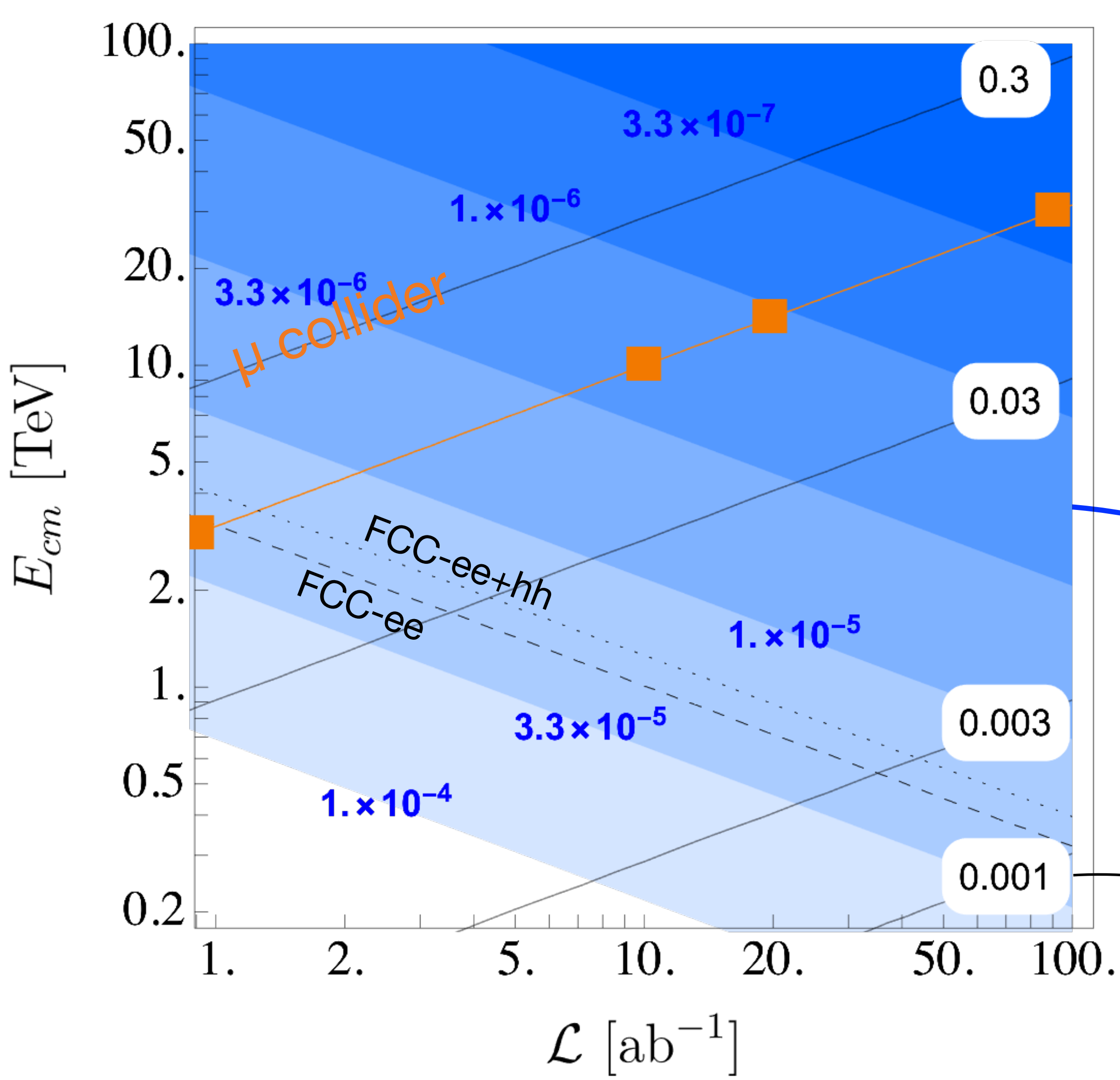
$$\ell^+\ell^- \to W_L^+ W_L^-$$

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

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

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$



related with Z-pole observables

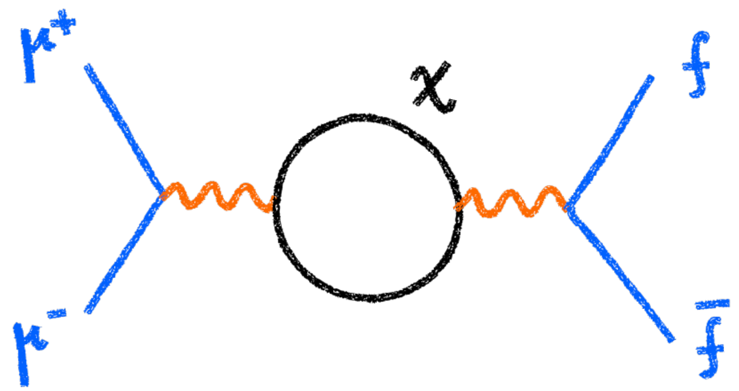
$$\hat{S} = m_W^2 (C_W + C_B)$$

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

precision of measurement

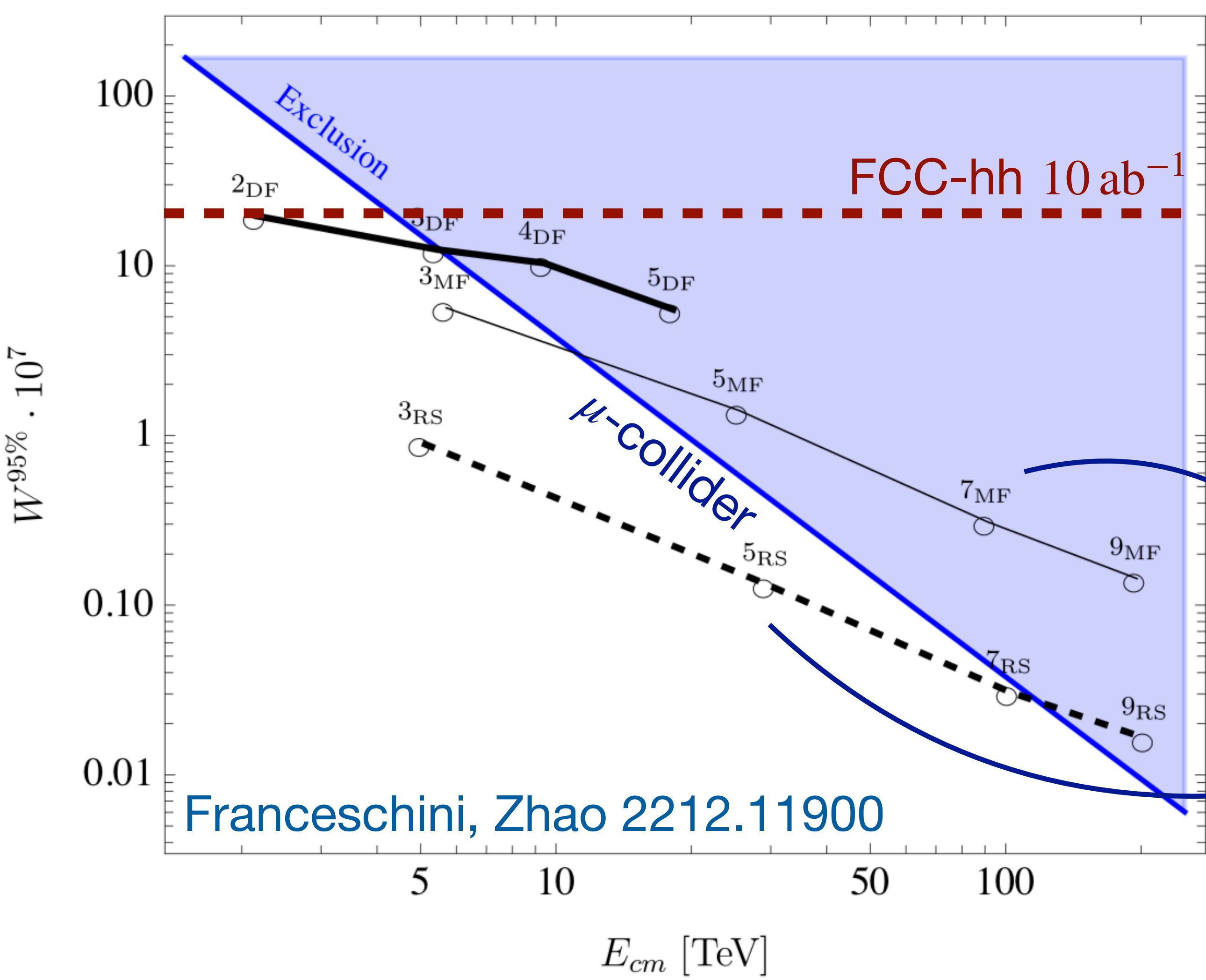
EW-charged matter

- 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

☛ see talk by R. Franceschini



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

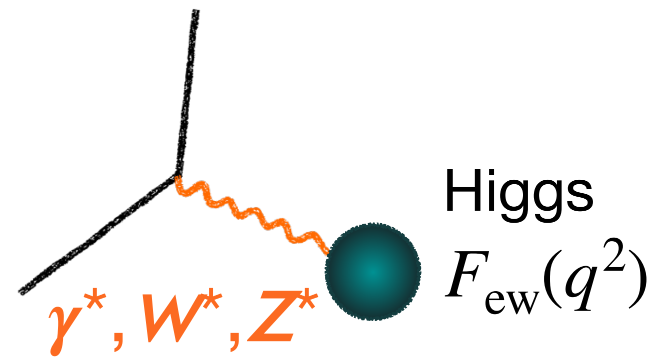
$$\hat{Y} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 Y^2 n \propto 1/n^4$$

right of blue line: can be tested indirectly

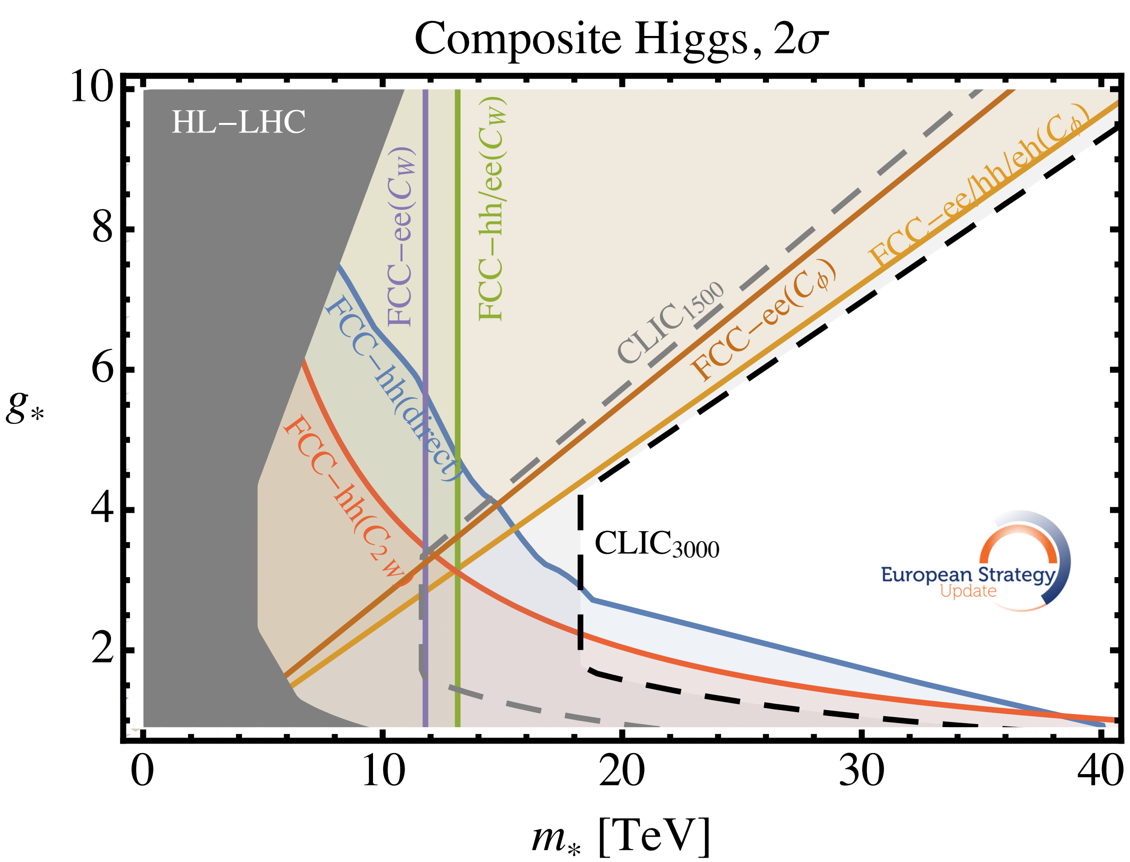
left of blue line: can be tested directly

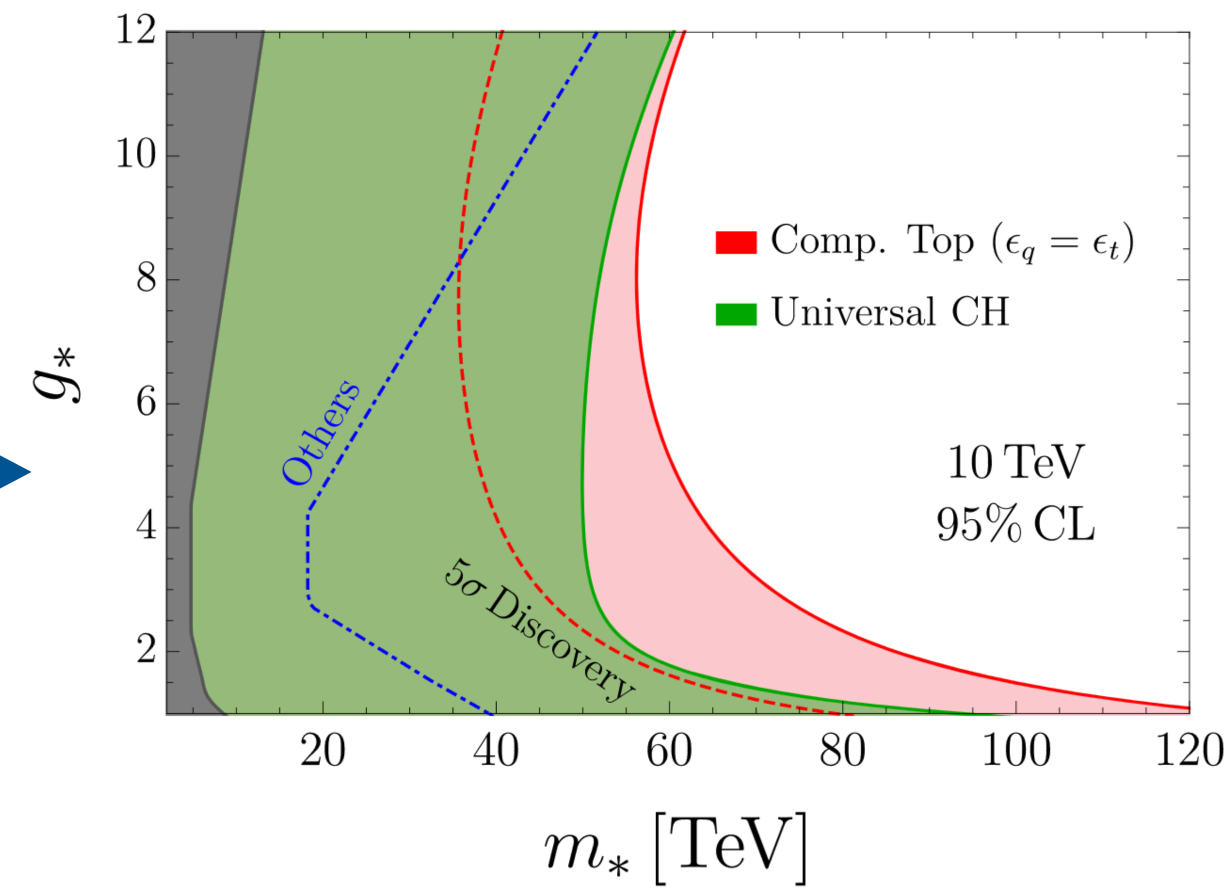
High-energy probes: EW & Higgs physics

- High-energy processes at a 10–30 TeV lepton collider are able to probe EW new physics scales of 100 TeV or more.
  - 10x higher than ultimate precision at Z pole



- Example: new physics with mass $m_\star$ and coupling $g_\star$



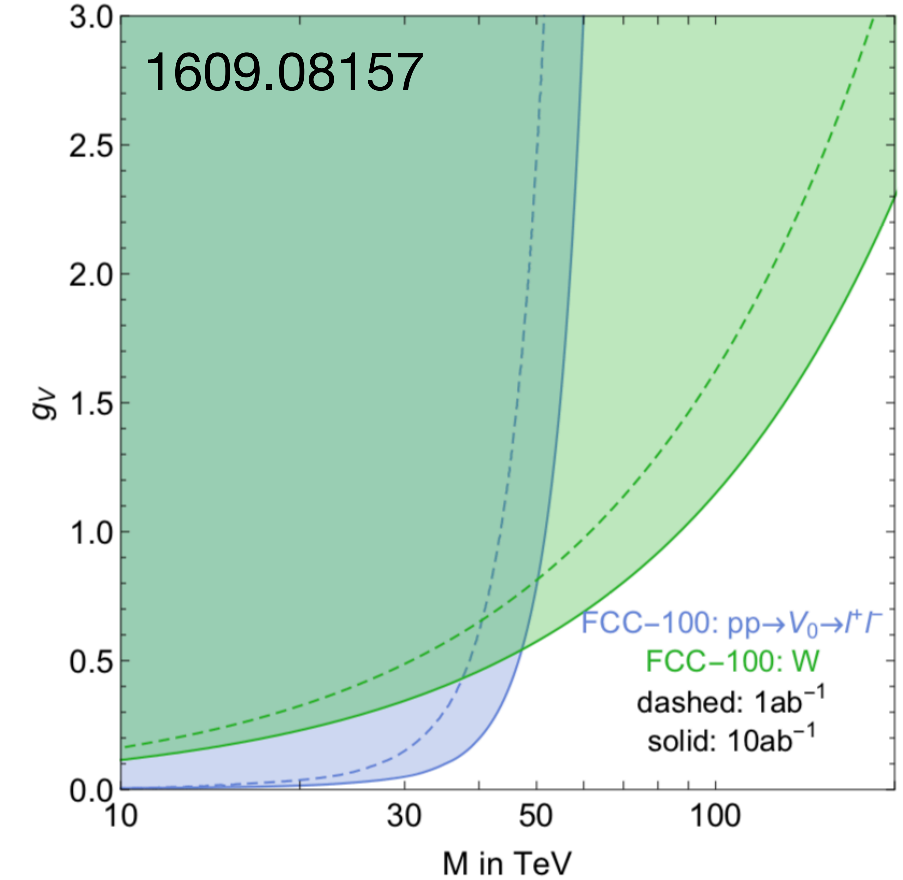


EW physics at hadron colliders

- A similar strategy can be used at a high-energy hadron collider
  - $pp \to \ell\ell, \ell\nu$ constrains W, Y parameters

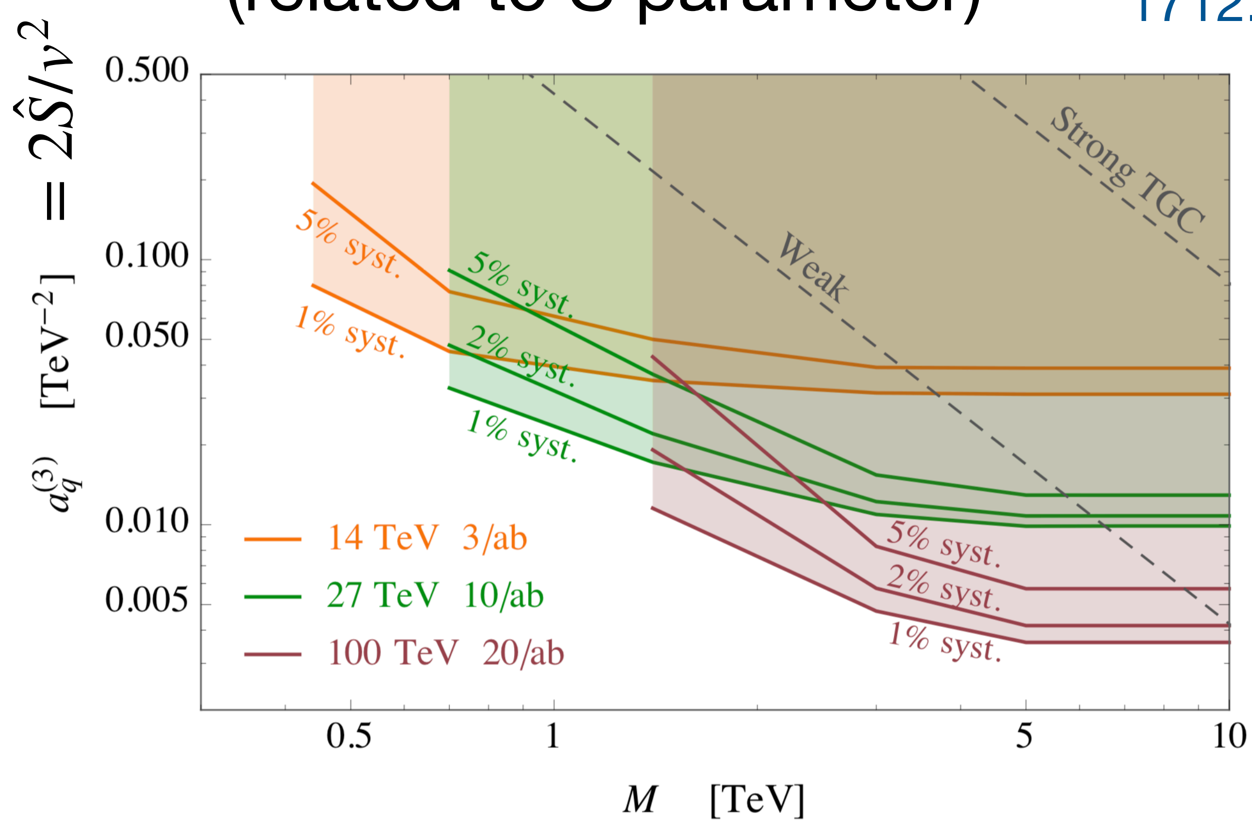
		LHC 13		100 TeV
luminosity		$0.3\,\text{ab}^{-1}$	$3\,\text{ab}^{-1}$	$10\,\text{ab}^{-1}$
NC	$W\times10^4$	±1.5	±0.8	±0.04
	$Y\times10^4$	±2.3	±1.2	±0.06
CC	$W\times10^4$	±0.7	±0.45	±0.02

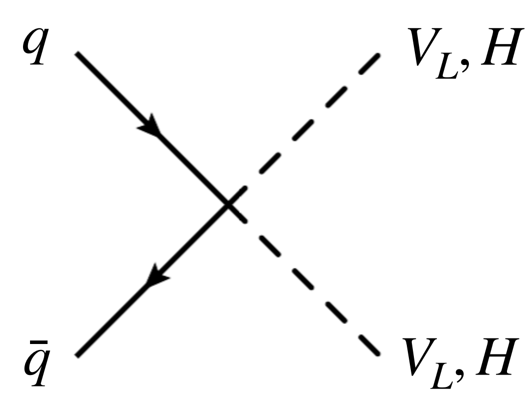
1609.08157



  - $pp \to Vh, VV$ constrains C_W, C_B (related to S parameter)

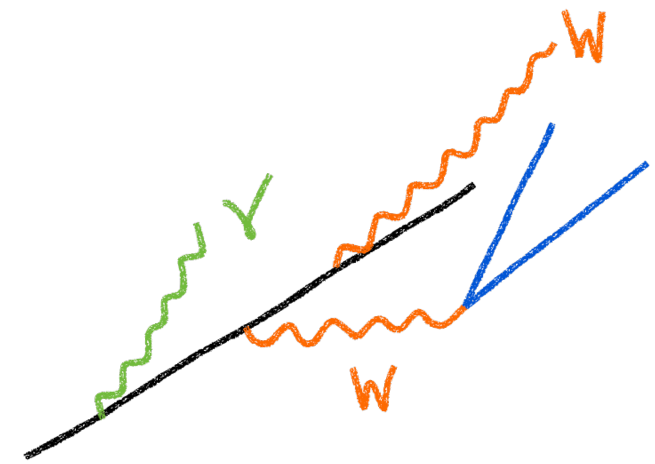
1712.01310





- Strong PDF suppression at high pT: lower reach

Challenges/opportunities



EW radiation becomes important at multi-TeV energies!

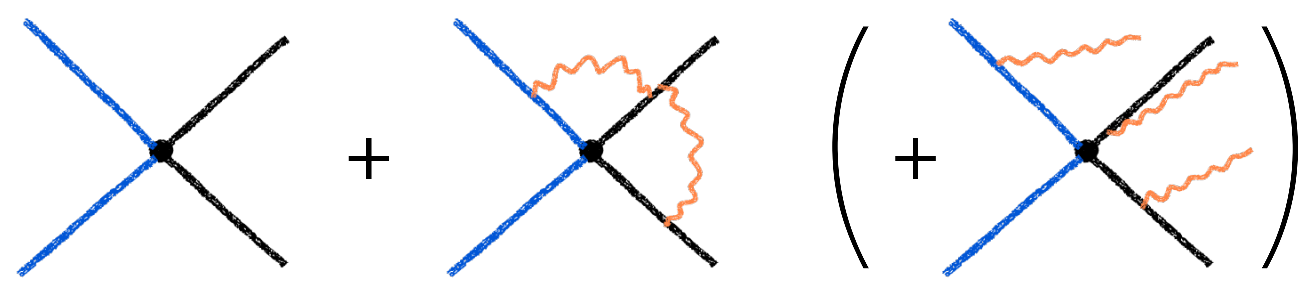
Especially relevant for muon collider, but also FCC-hh…

- ✦ $m_{W,Z} \ll E$: 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



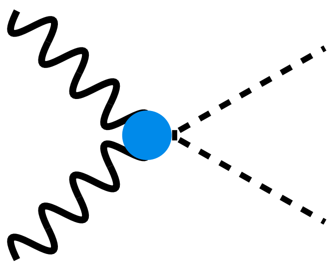
☛ Initial state is EW-charged:
(Precise) resummation of double logs needed. Goal: % or ‰ precision

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

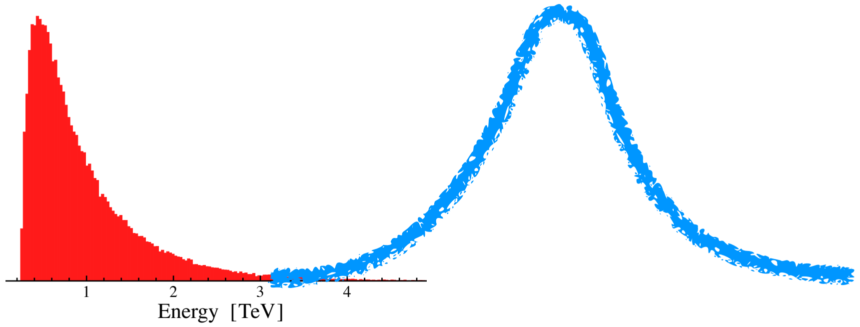
Summary

- One of the priorities for our field in the next decades will be to **explore the 10+ TeV scale.** Precision measurements might be the quickest way…

- Two complementary paths to precision measurements:



High rate



High energy

- **“Near” future:** flavor physics, Higgs physics at %, high-pT LHC.

  Scales of few TeV, EW particles below few 100 GeV

- **e+e- factory:** Higgs physics at 10^{-3}, EW physics at 10^{-5}, flavor.

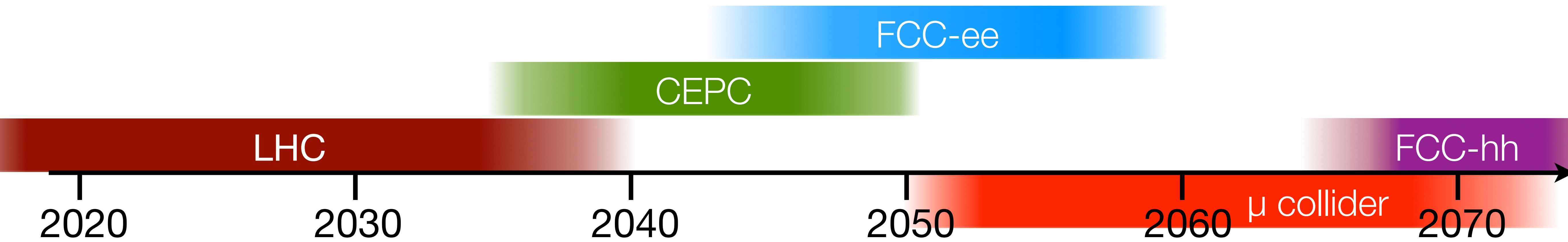
  Scales > 10 TeV, EW particles at few TeV

- **Ultimate goal:** collide elementary particles at the 10+ TeV energy frontier.

  WW factory: Higgs physics at 10^{-3}, Higgs self-coupling.

  High-energy: EWPT at 10^{-7}, i.e. scales > 100 TeV. EW particles at 10+ TeV

The importance of precision measurements



The next 25+ years of particle physics will (mostly) be precision physics!

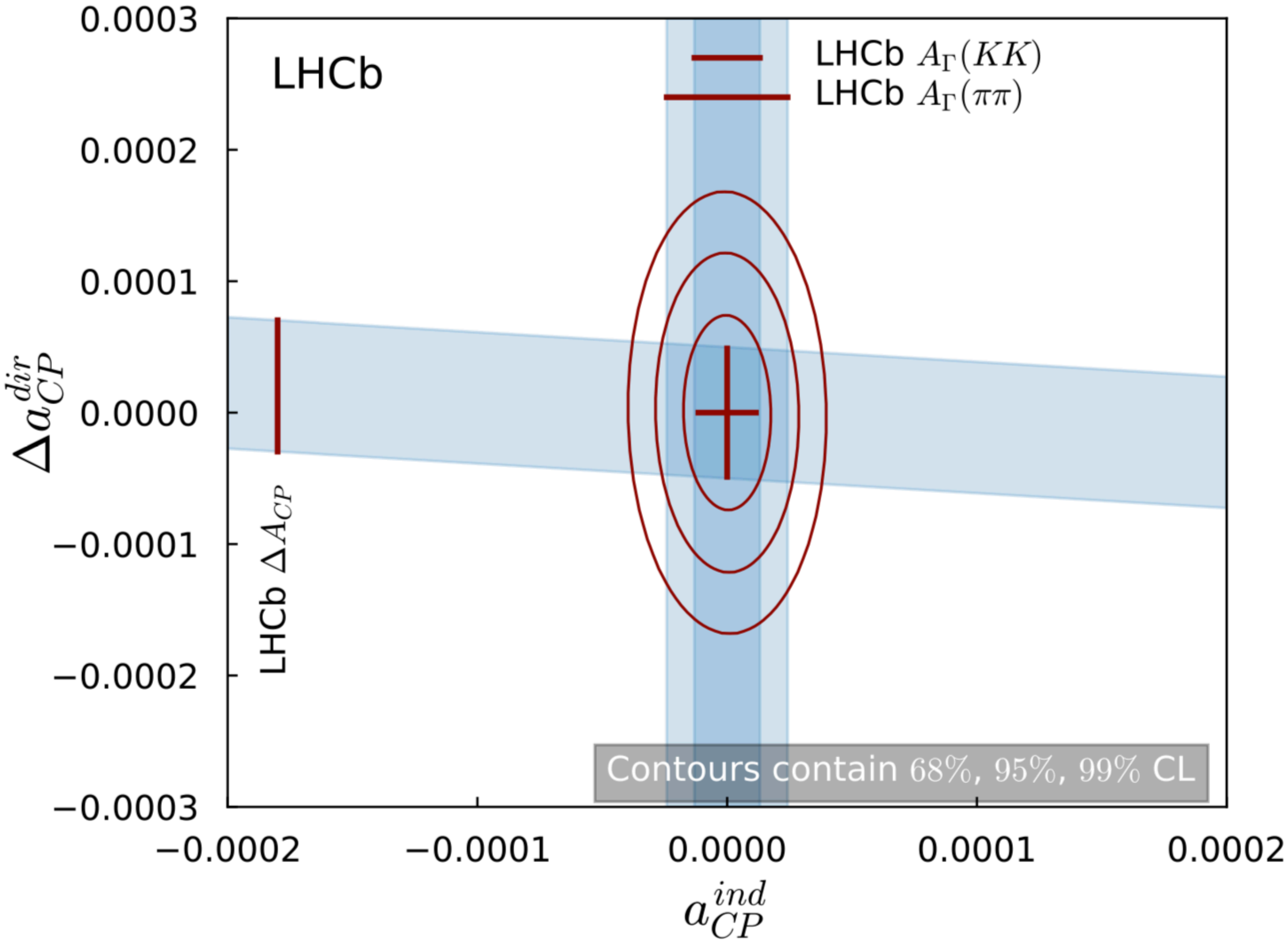
Several examples of great indirect discoveries in the past:

- $K_L \rightarrow \mu\mu$ branching ratio, K-K oscillations: prediction of charm mass
  Glashow, Iliopoulos, Maiani 1970 Lee, Gaillard 1974
- CPV in K system: existence of 3rd generation
  Kobayashi, Maskawa 1973
- e+e- scattering below the EW scale: prediction of W, Z masses
  early 1980's
- Frequency of B-B oscillations: prediction of large top mass
  late 1980's
- ElectroWeak Precision Tests: prediction of Higgs mass
  late 1990's

Backup

Charm physics @ LHCb

- Huge sample of charmed mesons, will allow first precise measurement of CPV in D system.
- Needs big advancement in theory understanding to extract NP limit (situation similar to $K \to \pi\pi$)



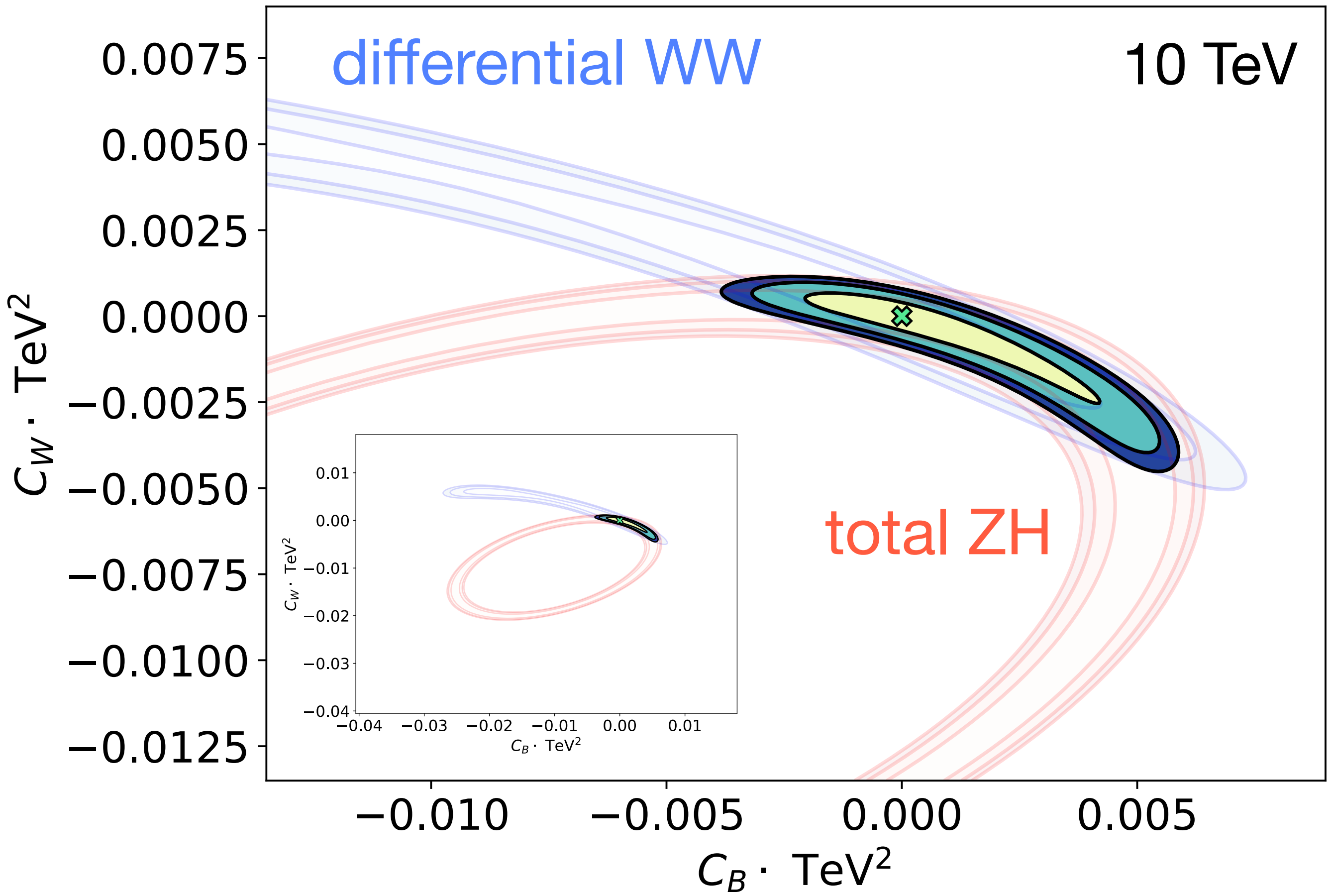
High-energy di-bosons

- C_W and C_B determined from high-energy $\mu^+\mu^- \to ZH, W^+W^-$ cross-sections

$$\sigma_{\mu\mu\to ZH} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\left[1 + \#\,E_{\text{cm}}^2 C_W + \#\,E_{\text{cm}}^4 C_W^2\right]$$

☛ Limits on $C_{W,B}$ scale as E^2

B, Franceschini, Wulzer 2012.11555



- Fully differential WW cross-section in scattering and decay angles: can exploit the interference with transverse polarization amplitude

High-energy di-bosons

- C_W and C_B determined from high-energy $\mu^+\mu^- \to ZH, W^+W^-$ cross-sections

$$\sigma_{\mu\mu\to ZH} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\left[1 + \#\,E_{\text{cm}}^2 C_W + \#\,E_{\text{cm}}^4 C_W^2\right]$$

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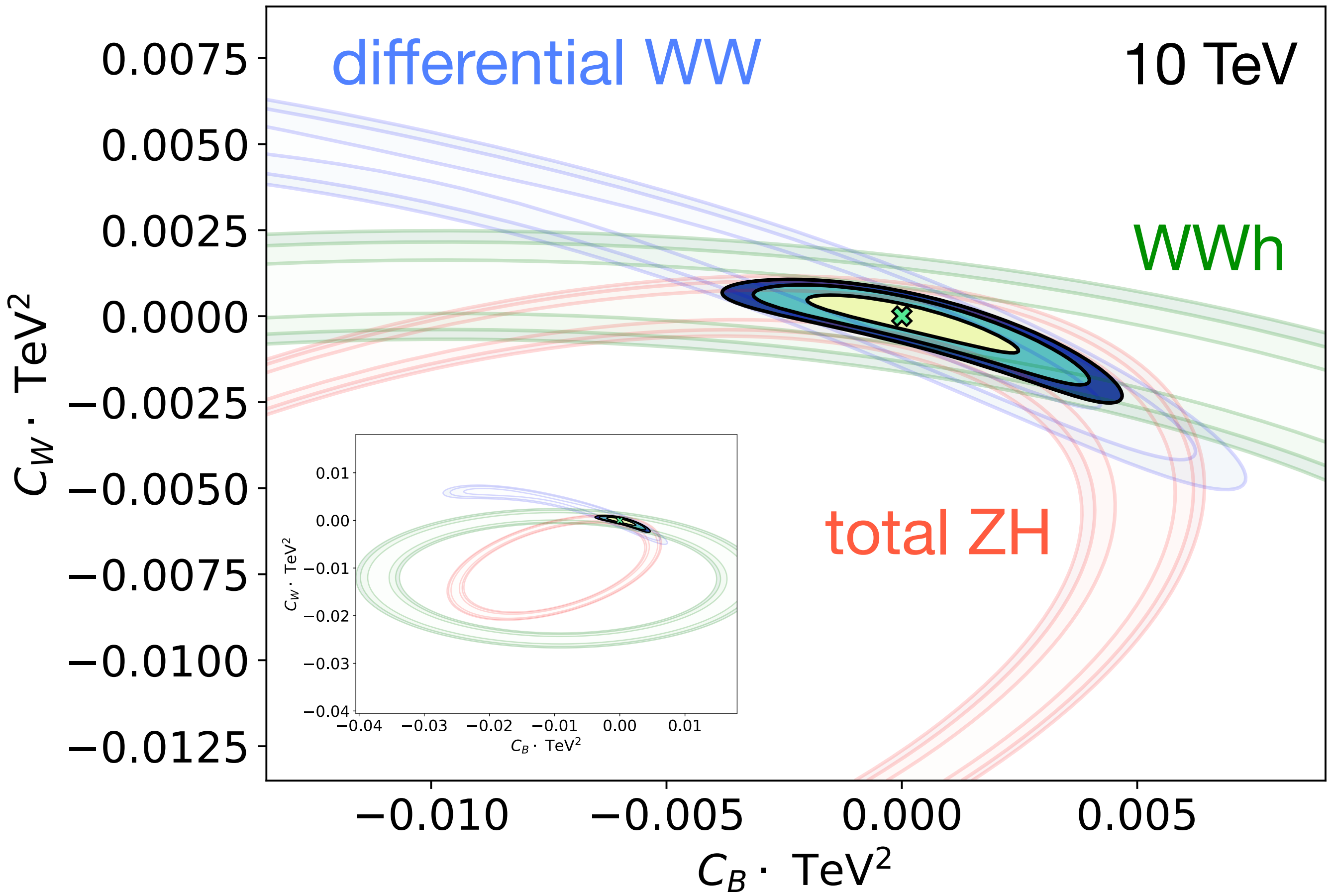
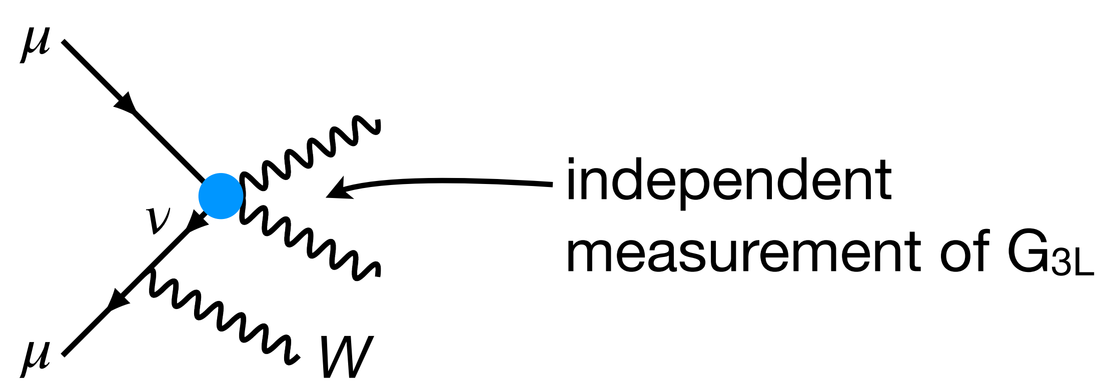


- Gauge boson radiation important at high energies: soft W emission allows to access the charged processes $\ell^\pm\nu \to W^\pm Z, W^\pm H$



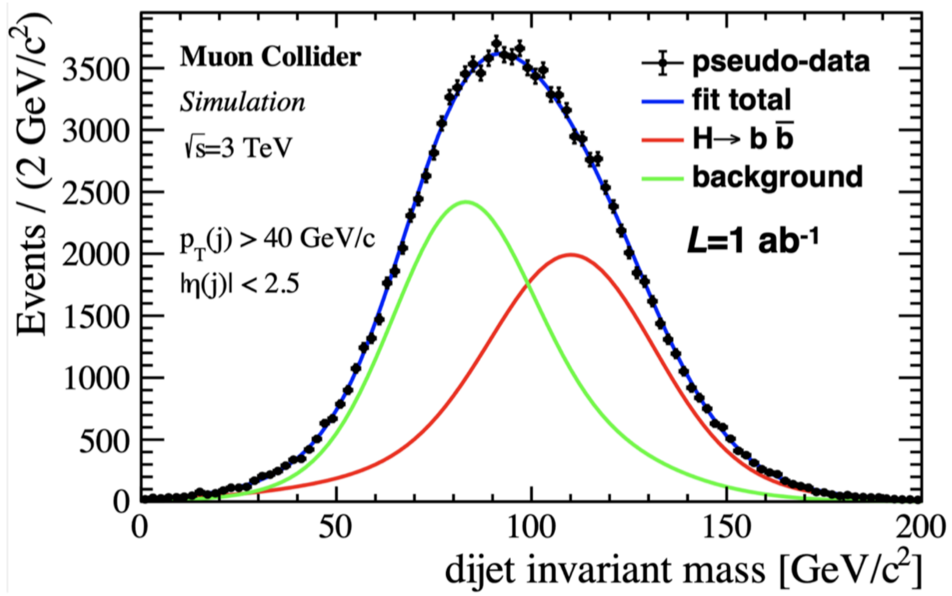
"effective neutrino approximation"

need to properly include higher-order effects
inclusive observables, resummation, …

Single Higgs: backgrounds

- Physics backgrounds (including the Higgs itself!)
- Beam-induced background

L. Sestini et al.



- Detector performance
  - "soft" and forward particles

Forslund, Meade
2203.09425

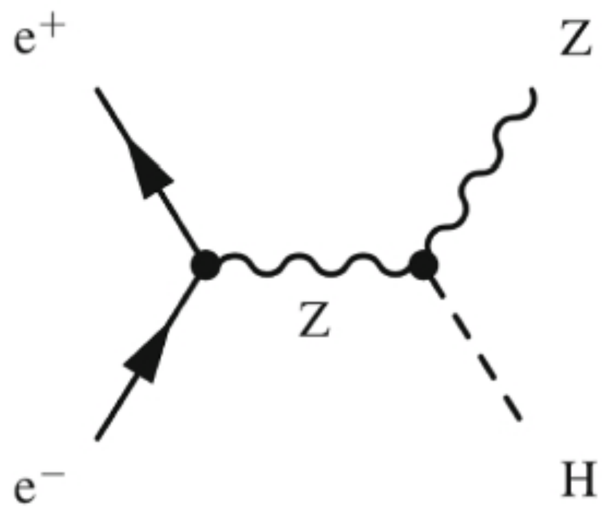
Production	Decay	$\Delta\sigma/\sigma$ (%)		Signal Only
		3 TeV	10 TeV	10 TeV
W^+W^- fusion	bb	0.80	0.22	0.17
	cc	12	3.6	1.7
	gg	2.8	0.79	0.19
	$\tau^+\tau^-$	3.8	1.1	0.54
	$WW^*(jj\ell\nu)$	1.6	0.42	0.30
	$WW^*(4j)$	5.4	1.2	0.49
	$ZZ^*(4\ell)$	48	13	12
	$ZZ^*(jj\ell\ell)$	12	3.4	2.3
	$ZZ^*(4j)$	65	15	1.4
	$\gamma\gamma$	6.4	1.7	1.3
	$Z(jj)\gamma$	45	12	2.0
	$\mu^+\mu^-$	28	5.7	3.9
ZZ fusion	bb	2.6	0.77	0.49
	cc	72	17	-
	gg	14	3.3	-
	$\tau^+\tau^-$	21	4.8	-
	$WW^*(jj\ell\nu)$	8.4	2.0	-
	$WW^*(4j)$	17	4.4	1.3
	$ZZ^*(jj\ell\ell)$	34	11	-
	$\gamma\gamma$	23	4.8	-
ttH	bb	61	53	12

Degeneracy: invisible Higgs search

- Caveat: single Higgs at μC can access only

$$\mu_f = \sigma_h \times \mathrm{BR}_{h\to f} \sim \frac{g_W^2 \times g_f^2}{\Gamma_h} \quad \text{(similar to LHC)}$$

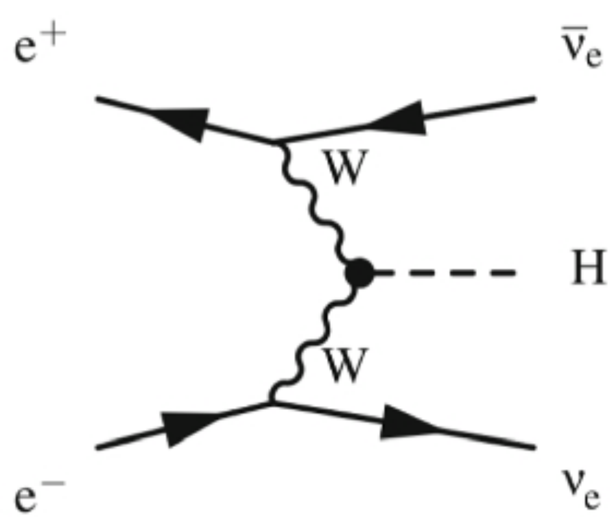
Higgsstrahlung



$s = (p_h + p_Z)^2$

Inclusive measurement, $\sigma_h \sim g_Z^2$

WW fusion



Hard neutrinos not seen,

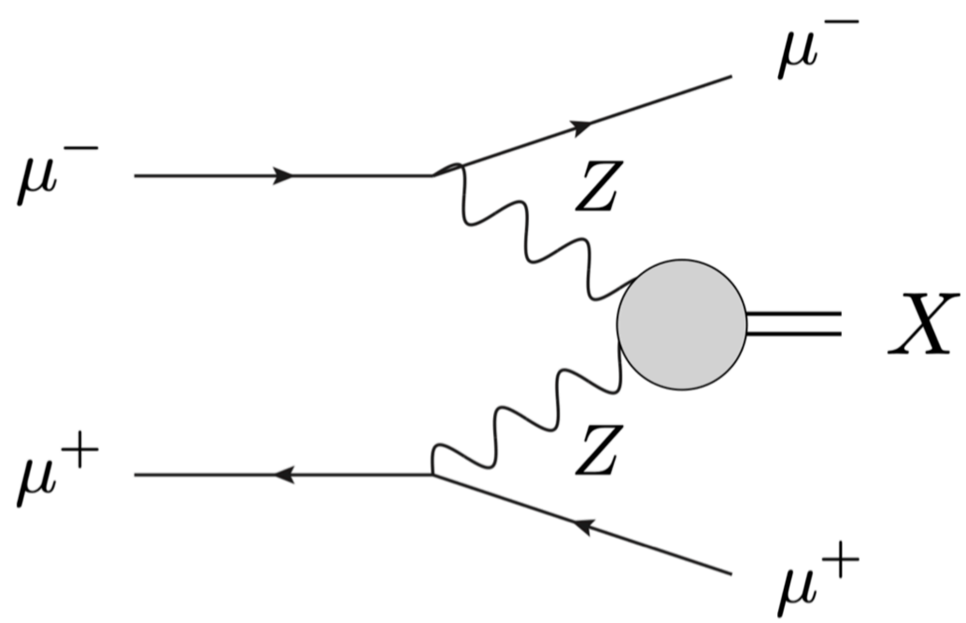
WW → h → WW depends on g_W and Γ

cannot disentangle deviations in the couplings from modifications of total width

Inclusive Higgs search

- Try to do an inclusive single Higgs measurement with ZZ → h

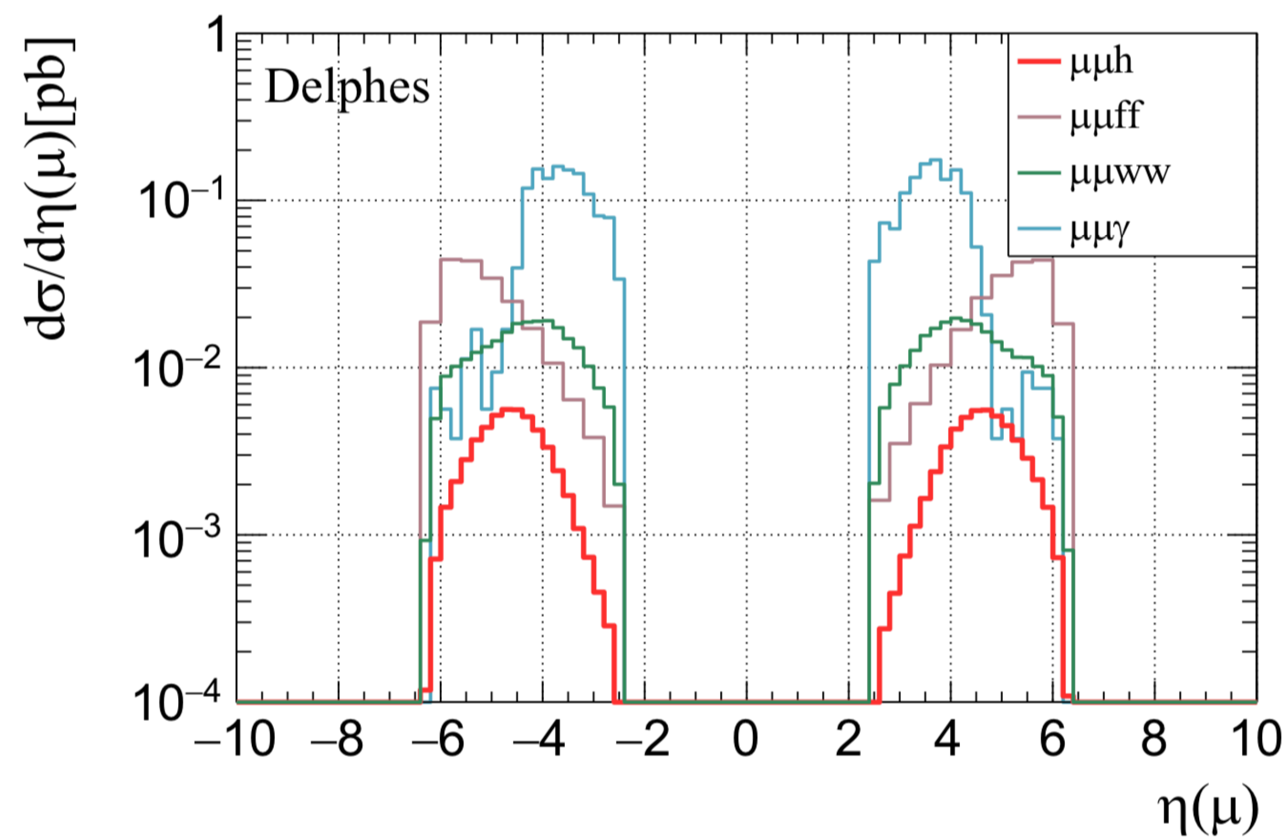
P. Li, Z. Liu, K. Lyu 2401.08756



- cross-section ~ 10x lower than WW
- **needs forward muon detection!**

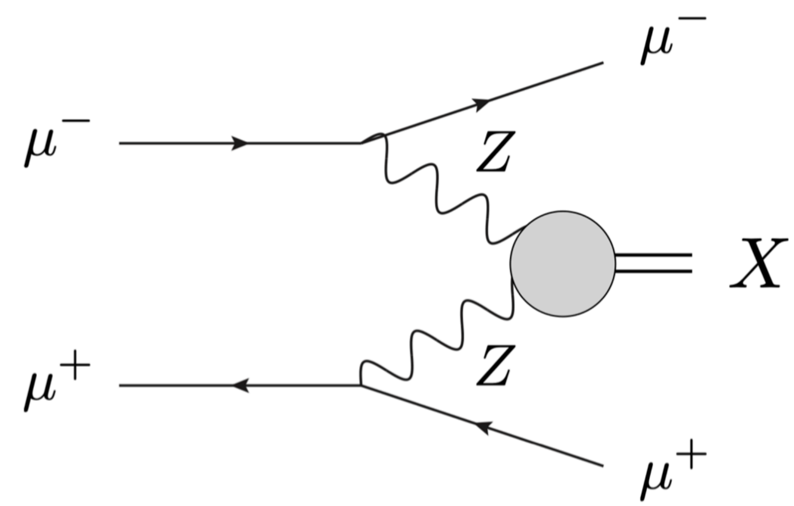
$$s = (p_h + p_{\mu 1} + p_{\mu 2})^2$$

	$\eta < 4$	$\eta < 6$
$\mathrm{Br}^{95\%}_{\mathrm{inv}}(\%)$	$^{+0.64}_{\;\;0}$	$^{+0.10}_{\;\;0}$
$\mathrm{Br}^{95\%}_{\mathrm{unt}}(\%)$	$^{+27}_{\;\;0}$	$^{+2.0}_{\;\;0}$
$\kappa_\Gamma(\%)$	$^{+34}_{-0.45}$	$^{+2.1}_{-0.41}$



Invisible Higgs @ muon collider

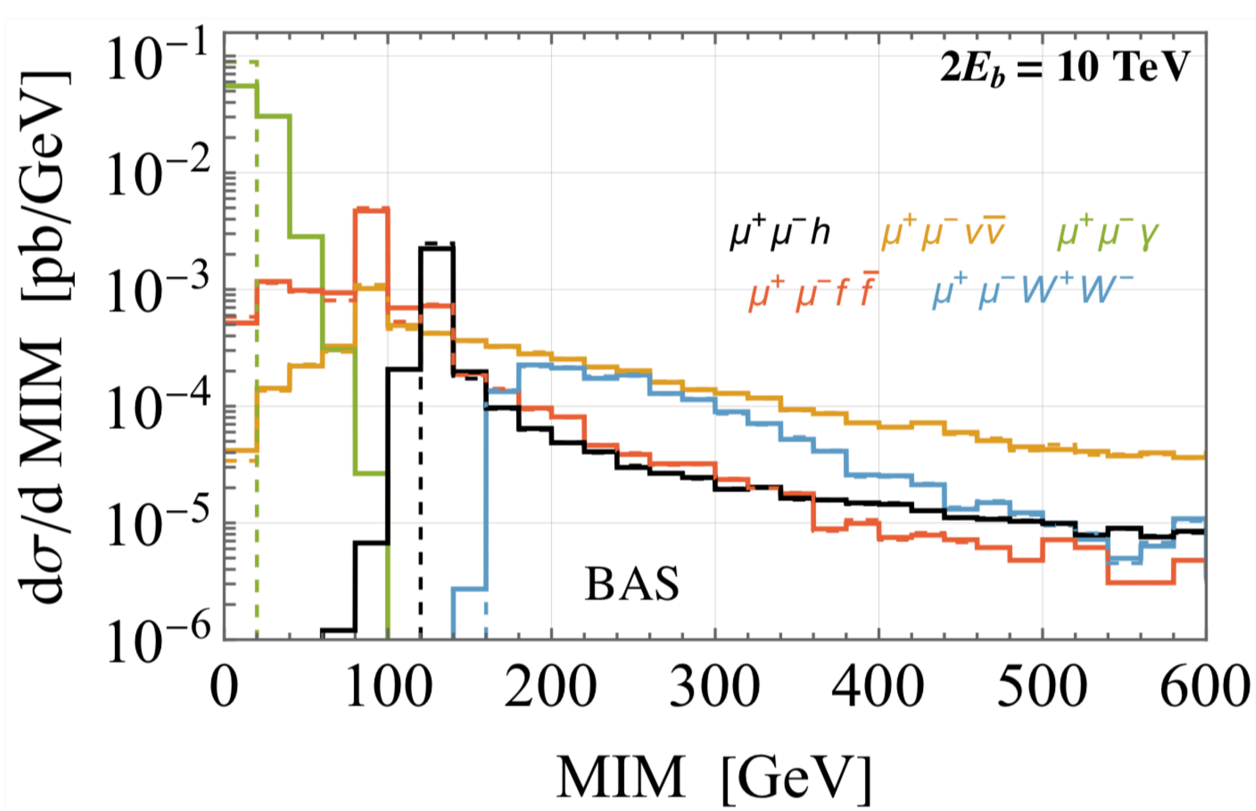
- Invisible BSM Higgs Branching Ratio can be one of the contributions to total width Γ.

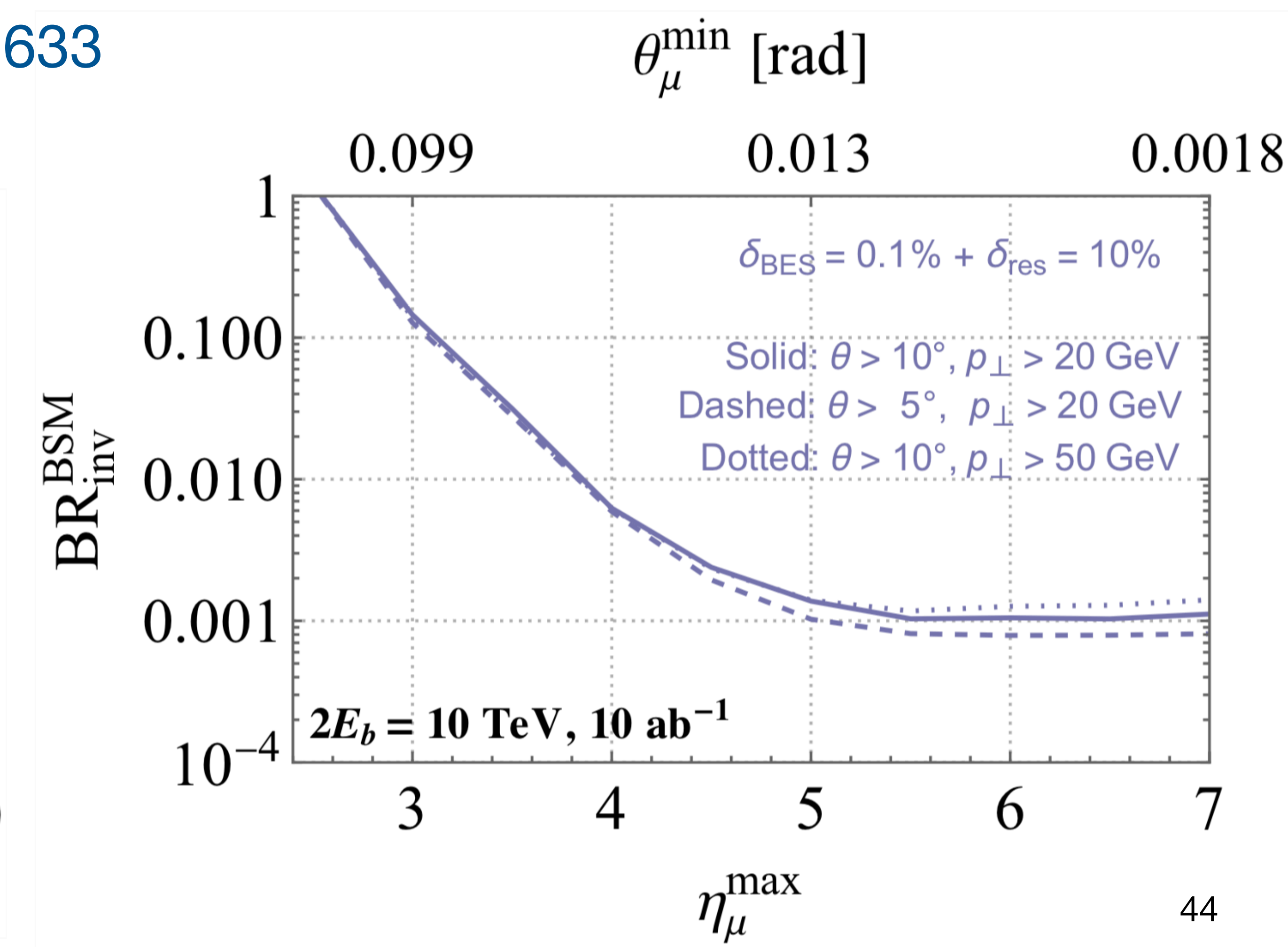


- Can also be studied in ZZ-fusion: 10^{-3} sensitivity *if we can detect muons at* $\eta \gtrsim 5$

Ruhdorfer, Salvioni, Wulzer 2303.14202

Forslund, Meade 2308.02633

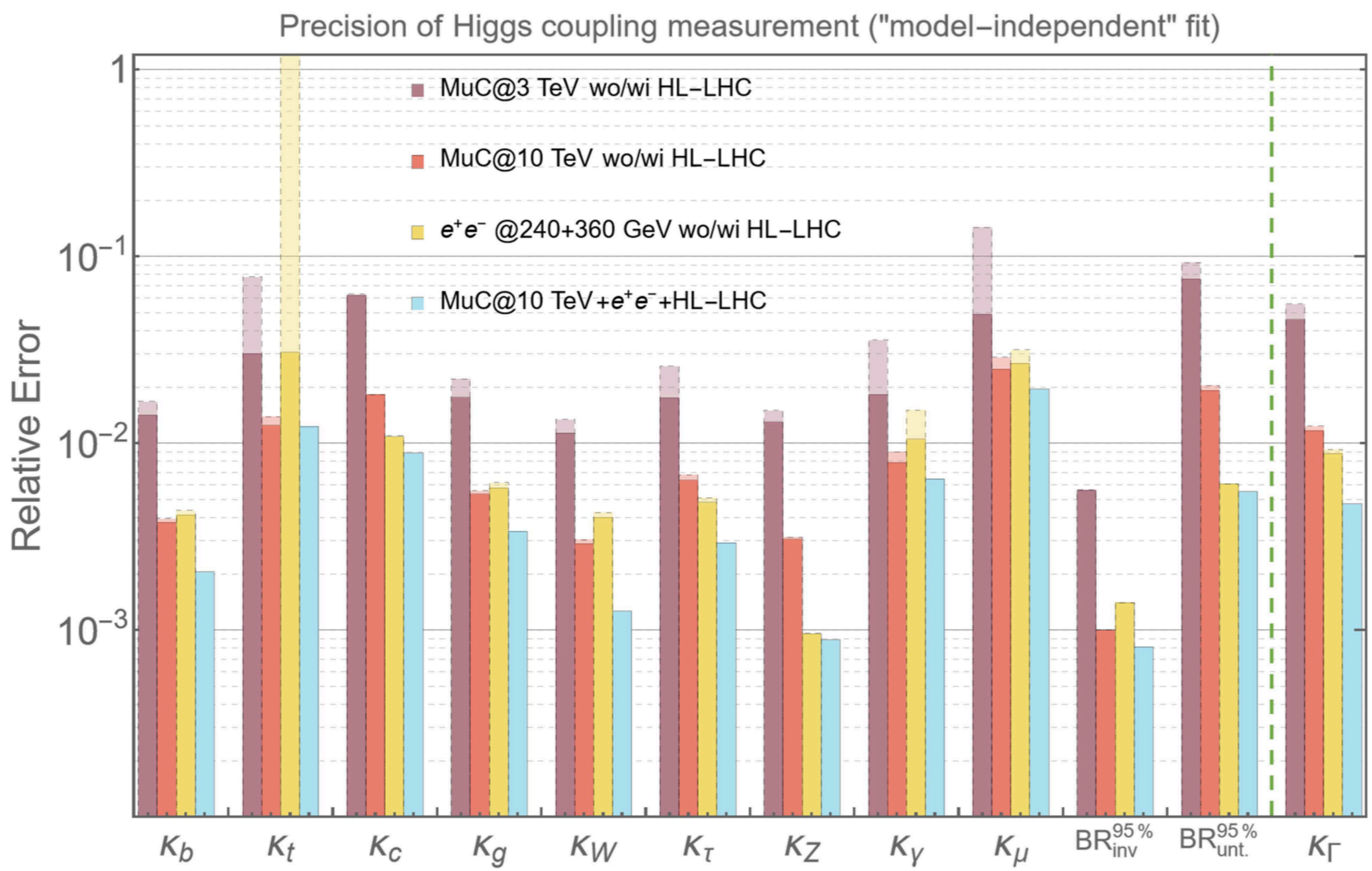




Higgs couplings at muon collider

- A full-fledged Higgs-physics program is possible at a μC

- Single Higgs couplings can more easily be studied at e^+e^- factory! *(most likely before a μC!)*



P. Li, Z. Liu, K. Lyu 2401.08756

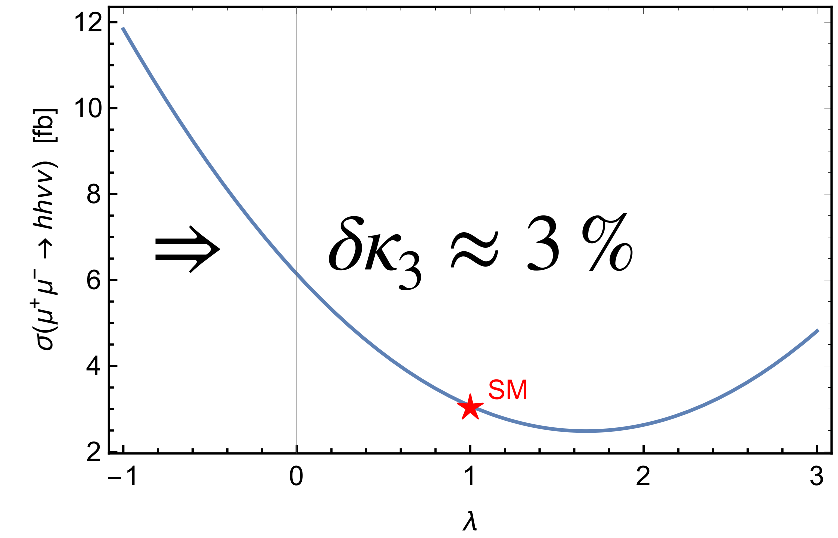
Double Higgs production

Number of events $\sim s \log(s/m_h^2) \approx 10^5$ at 14 TeV

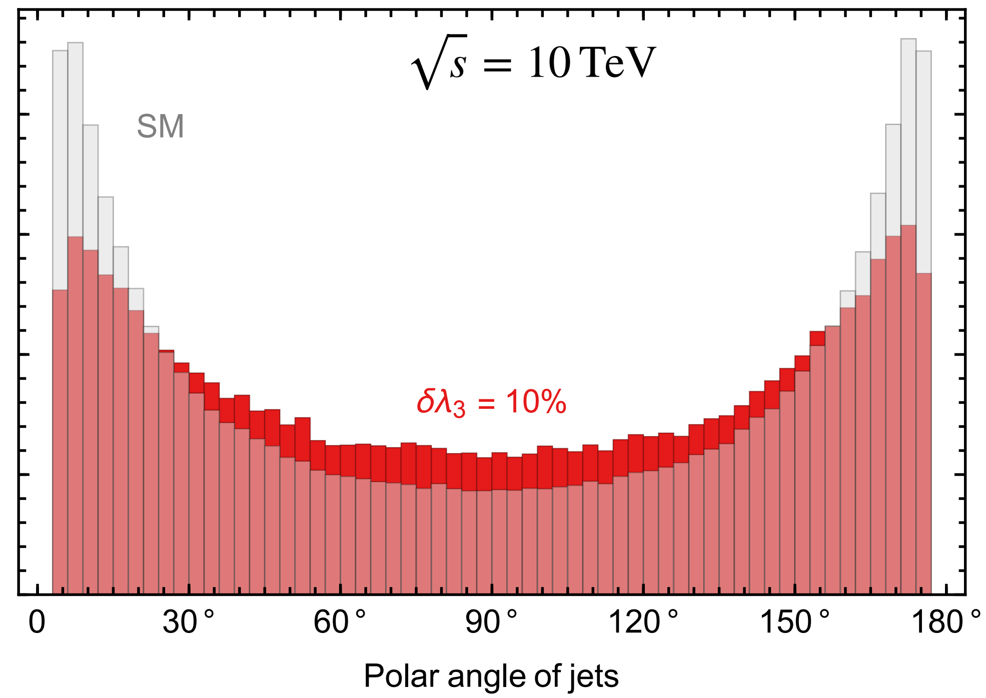
Naïve estimate of the reach: $\delta\sigma \sim (N \times \epsilon)^{-1/2} \approx 1\,\%$

$$\left.\begin{array}{r}\text{reconstruction eff.} \sim 30\,\% \\ \mathrm{BR}(hh \to 4b) = 34\,\%\end{array}\right\} \epsilon \sim 10\,\%$$

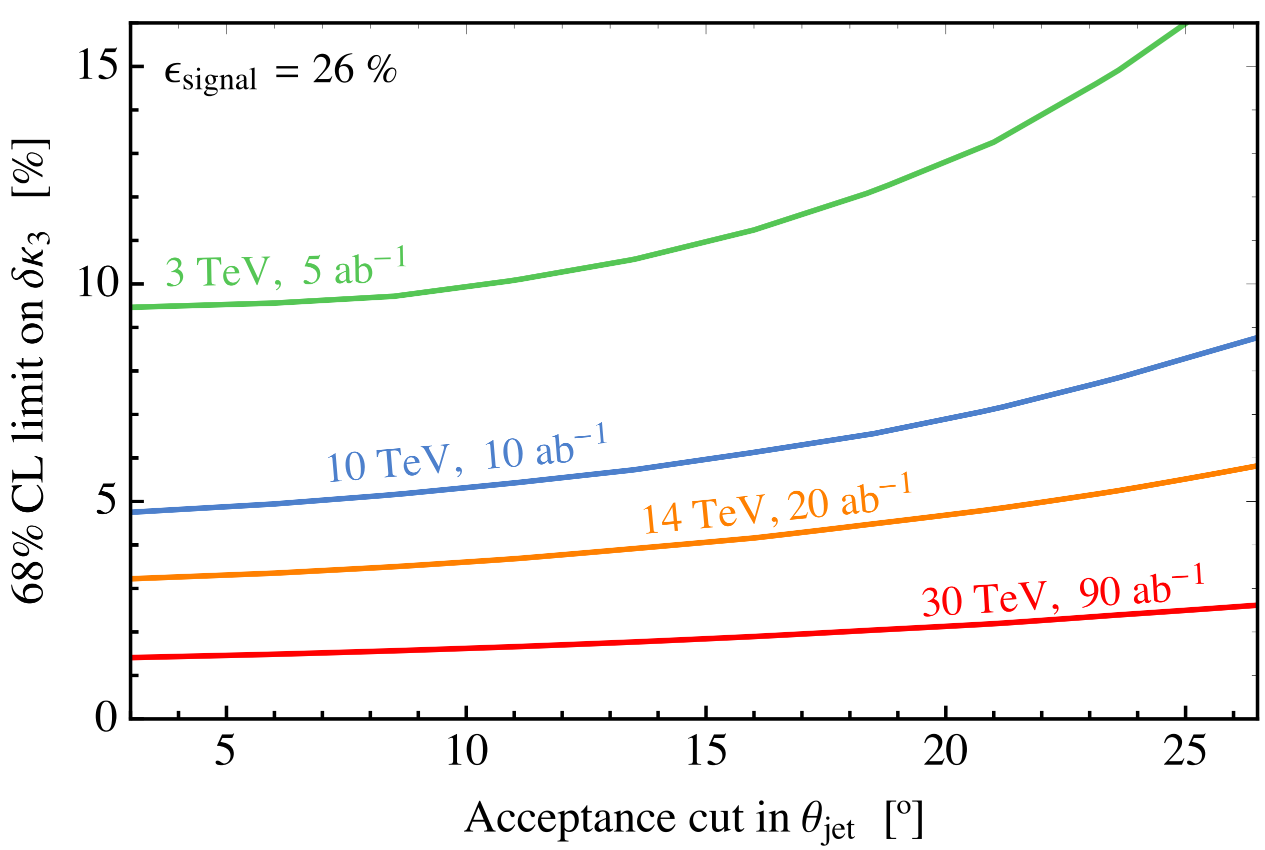
$\Rightarrow \delta\kappa_3 \approx 3\,\%$



- ✦ **Acceptance cuts** in polar angle θ and p_T of jets:
  - ‣ *hh* signal is strongly peaked in forward region



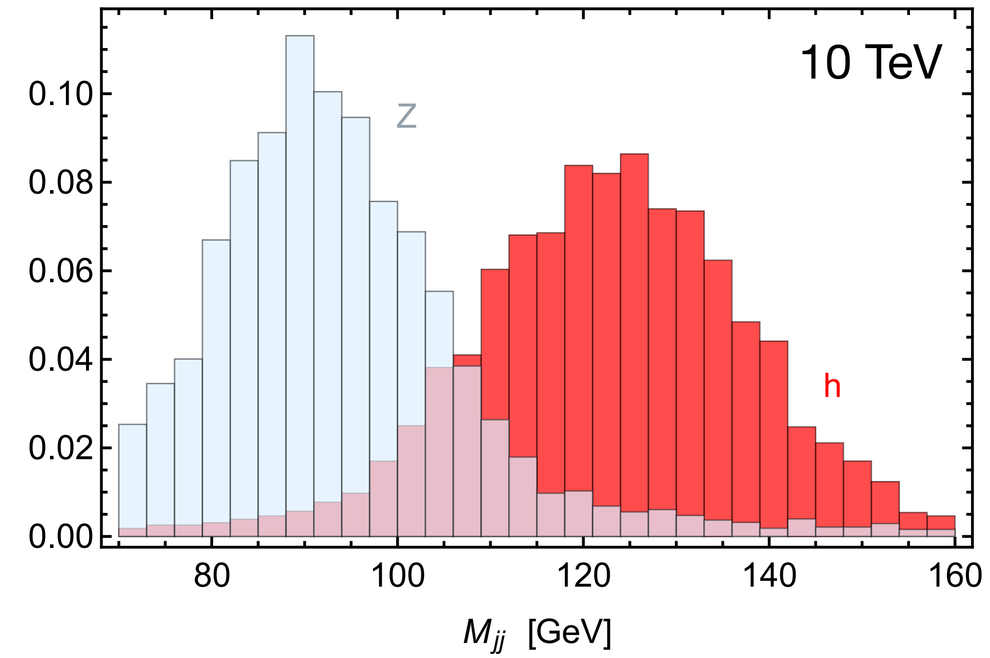
B, Franceschini, Wulzer 2012.11555

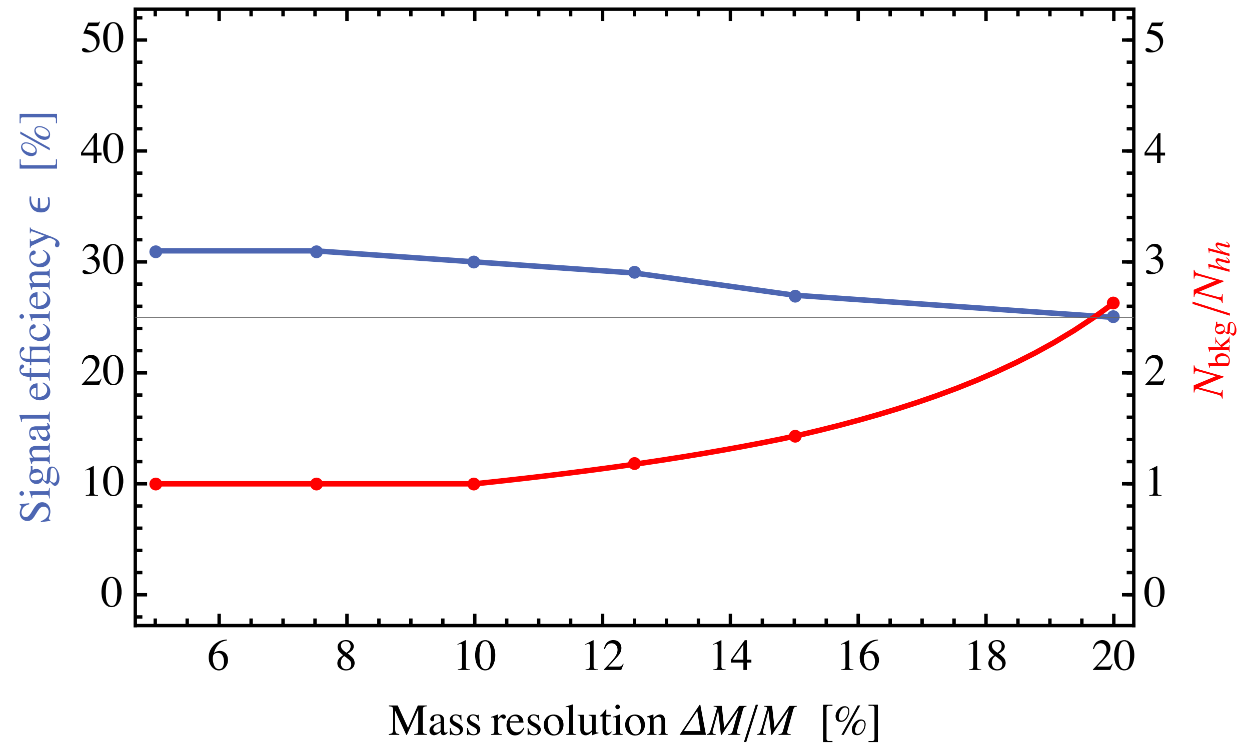


- ‣ Contribution from trilinear coupling is more central: loss due to angular cut is less important

Double Higgs production

- **Backgrounds are important** and cannot be neglected (see also CLIC study 1901.05897)
    - Mainly VBF di-boson production: Zh & ZZ, but also WW, Wh, WZ…
    - Precise invariant mass reconstruction is crucial to isolate signal





NB: (Very!) simplified background analysis *(at parton level!)*

All this should be done properly with a detector simulation

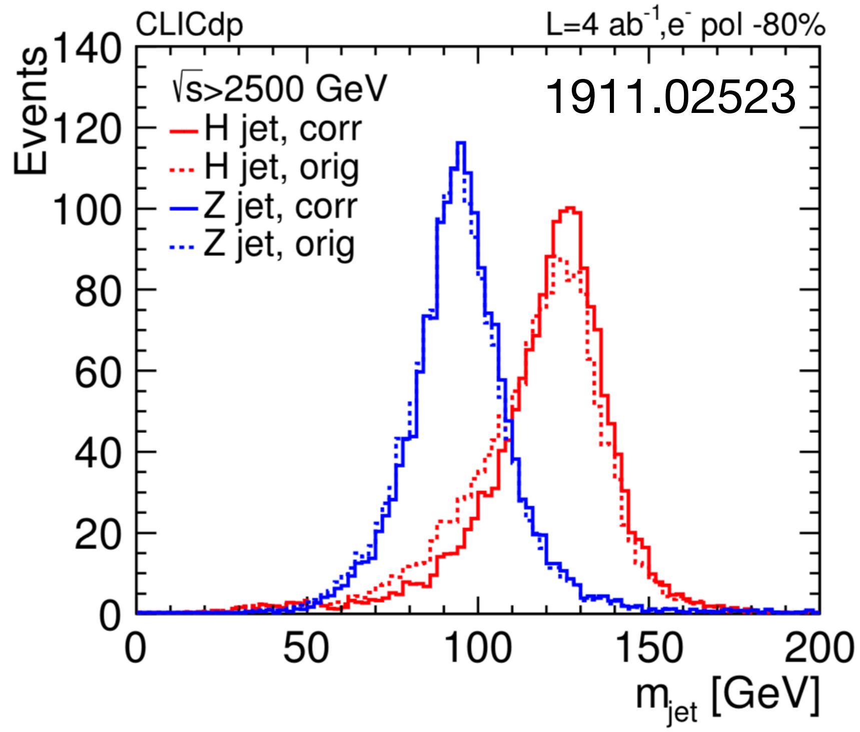
However, perfect agreement with 1901.05897! (3 TeV CLIC)

B, Franceschini, Wulzer 2012.11555

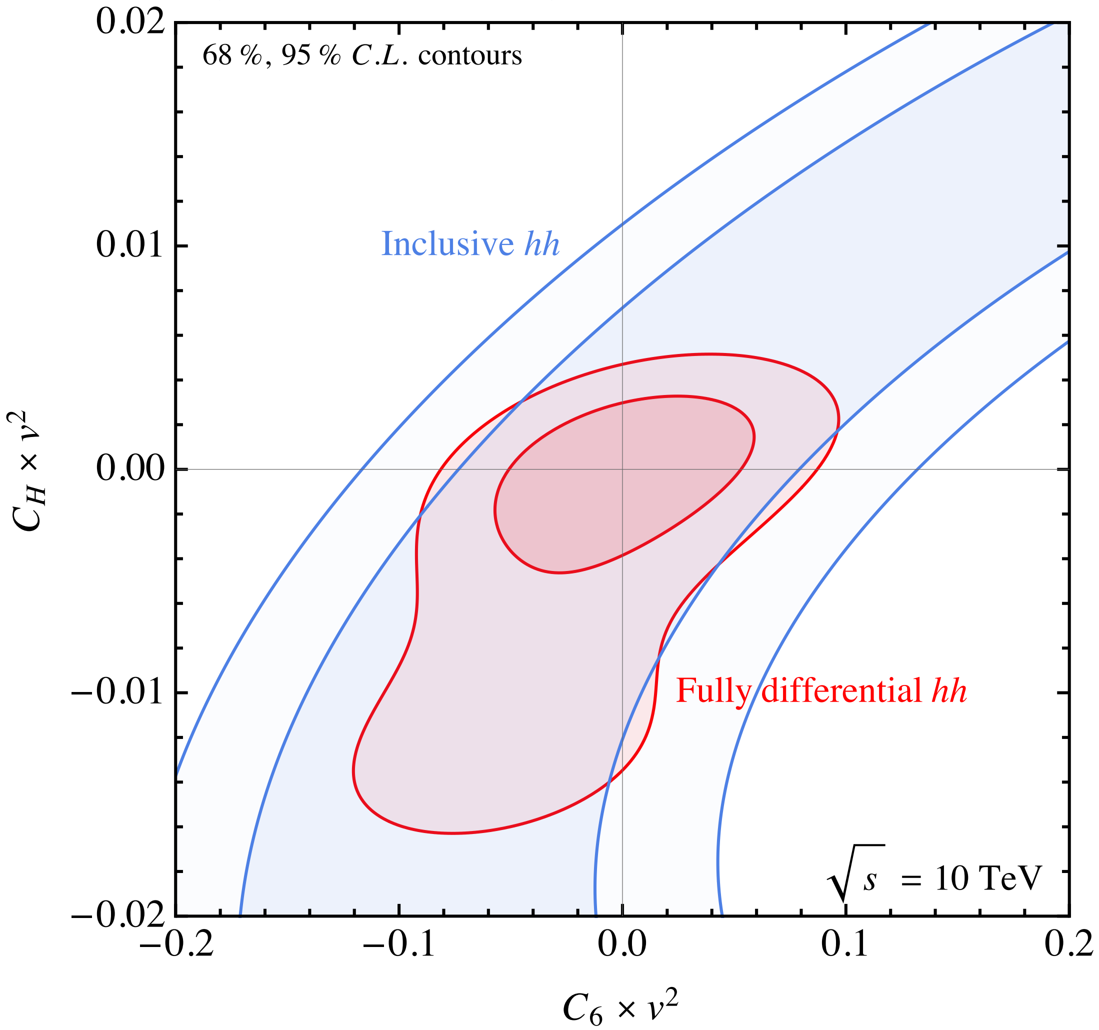
Double Higgs at high mass

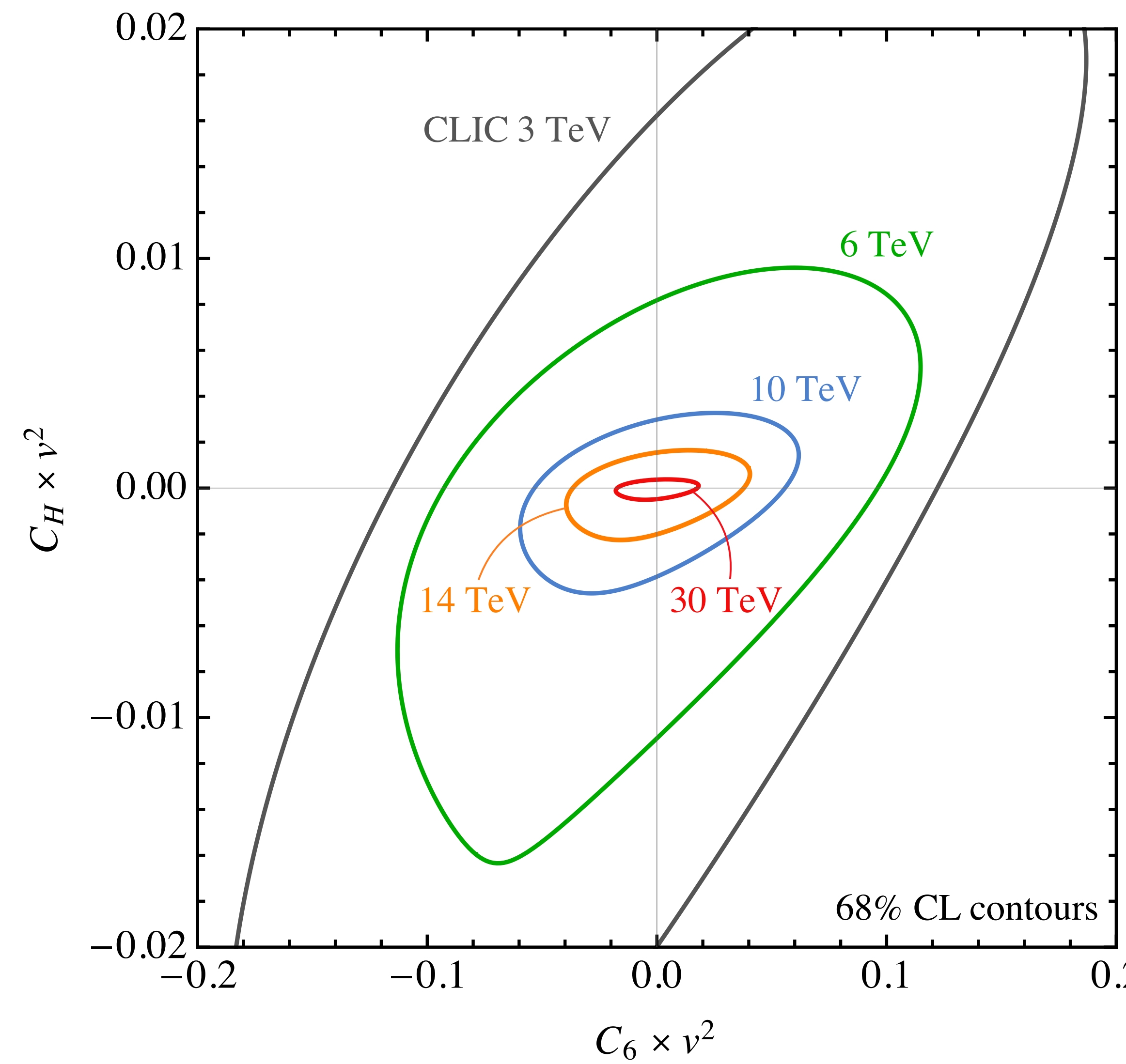
- Fully differential analysis in p_T and M_{hh} to optimize combined sensitivity to C_H and C_6
- Very boosted Higgs bosons: treat them as a single h-jet, without reconstructing the 4 b's.

  We assumed a boosted-H tagging efficiency ~ 50%



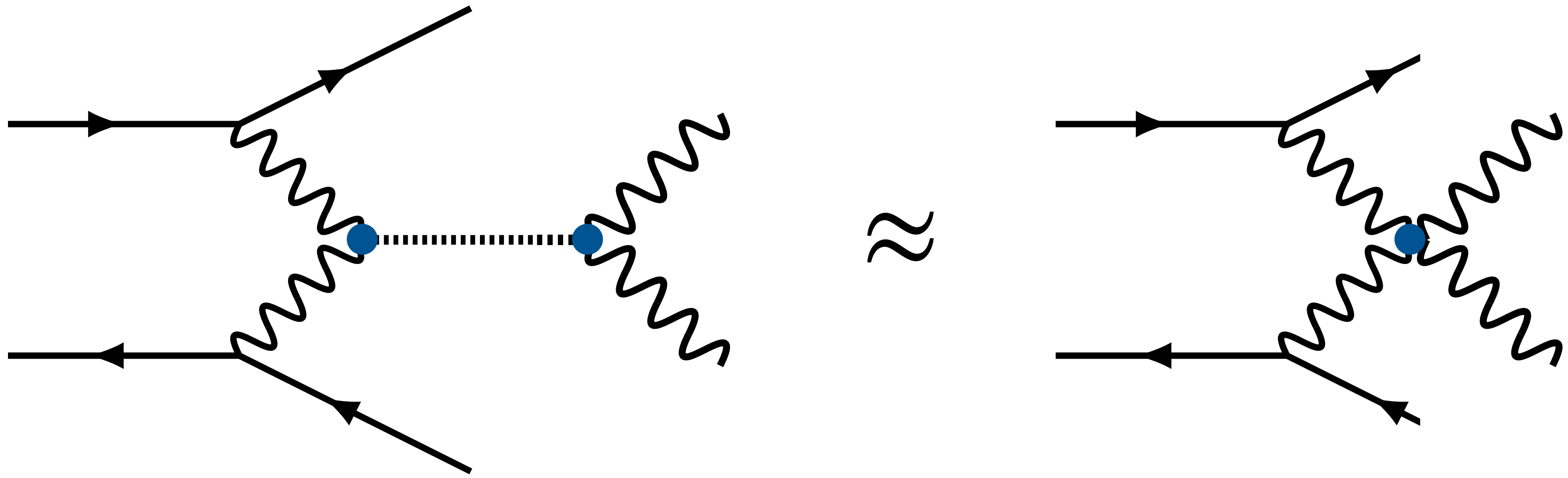
B, Franceschini, Wulzer 2012.11555





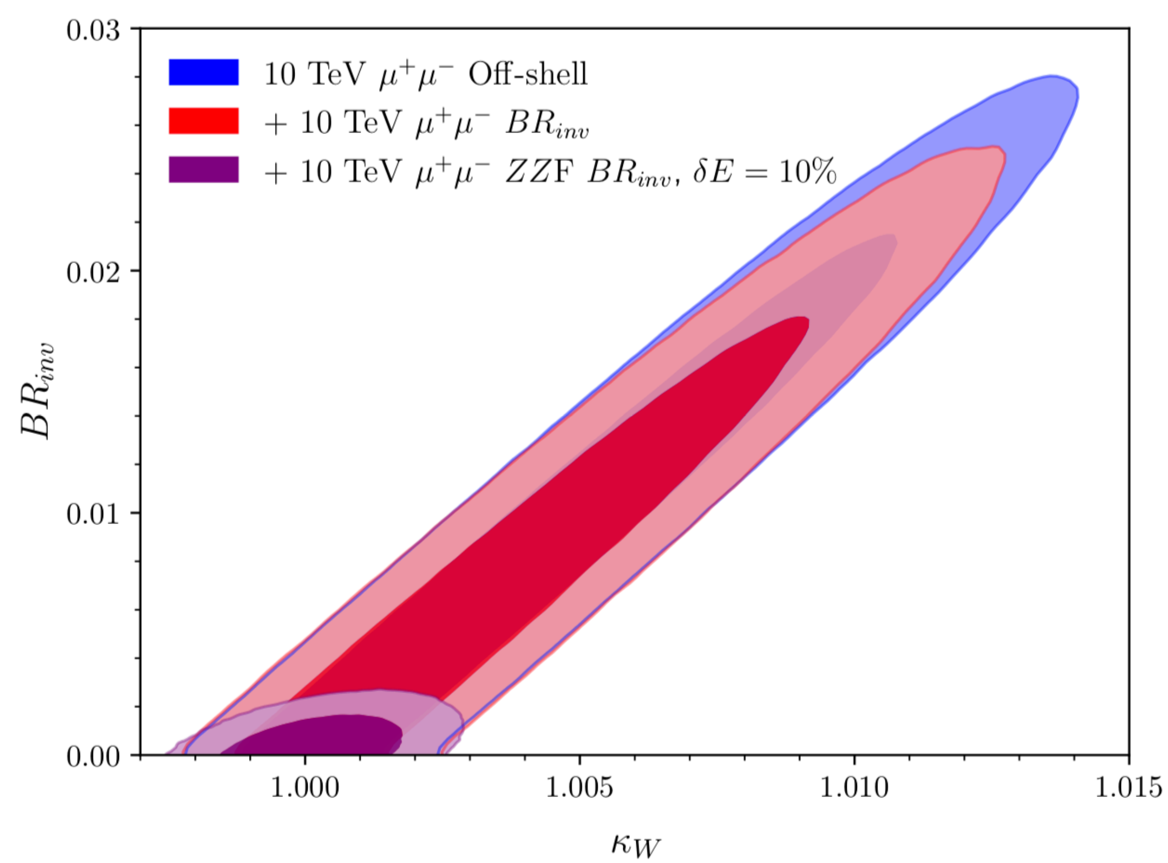
Single Higgs at high mass (off-shell)

- Off-shell single Higgs production: independent of width



$$\sim \frac{E^2}{\Lambda^4}$$

Forslund, Meade 2308.02633



precision limited (~ 3%) due to backgrounds: not possible to determine κ_W precisely through WW scattering

➔ correlation width vs. coupling

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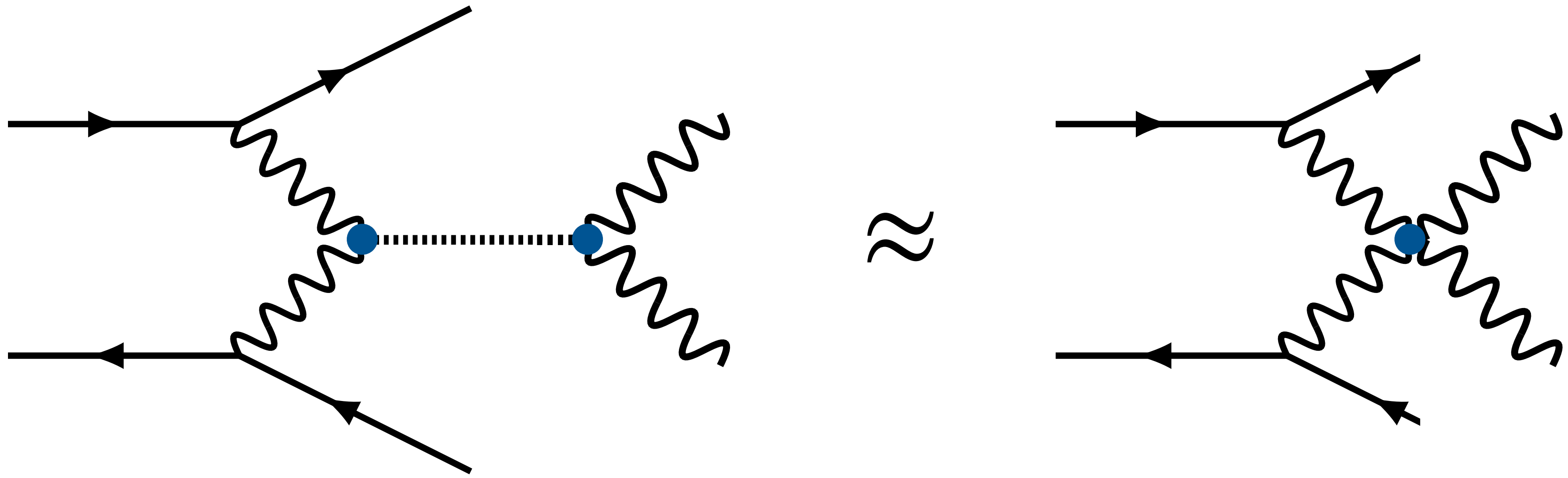
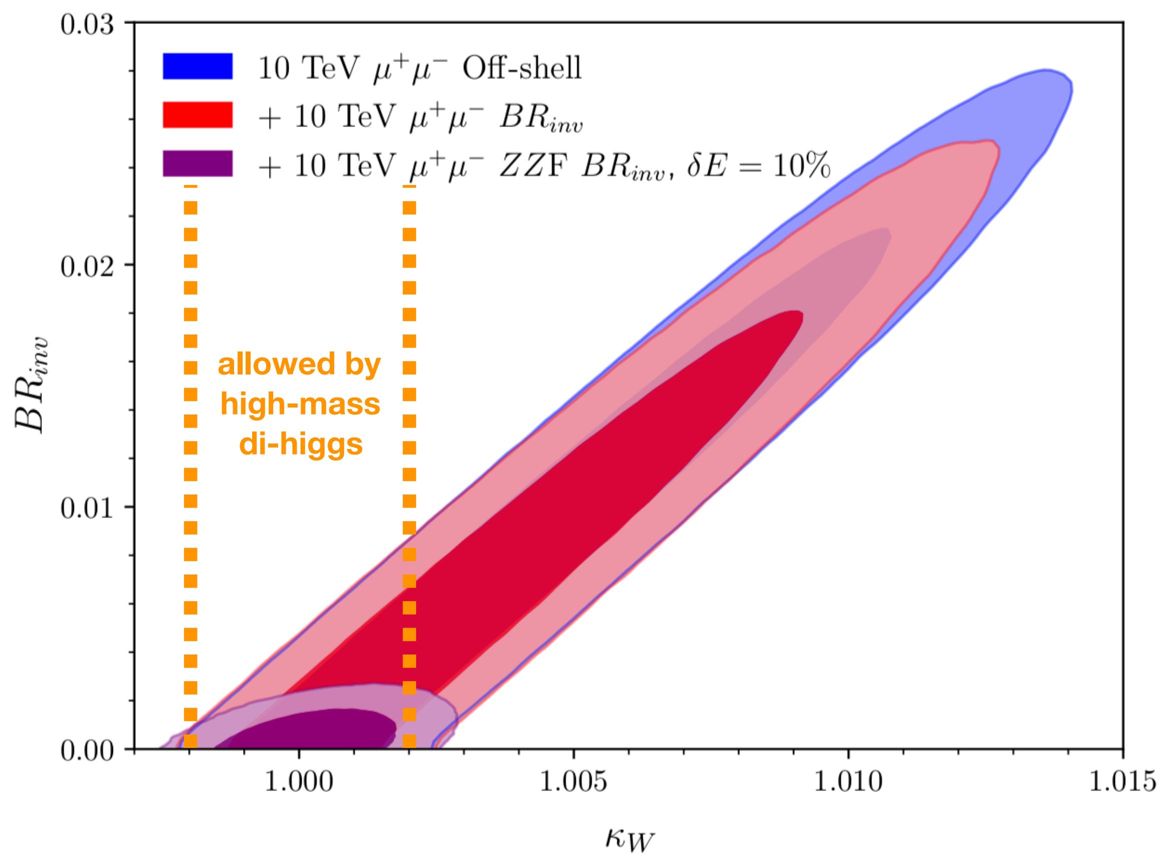


$$\approx \quad \sim \quad \frac{E^2}{\Lambda^4}$$

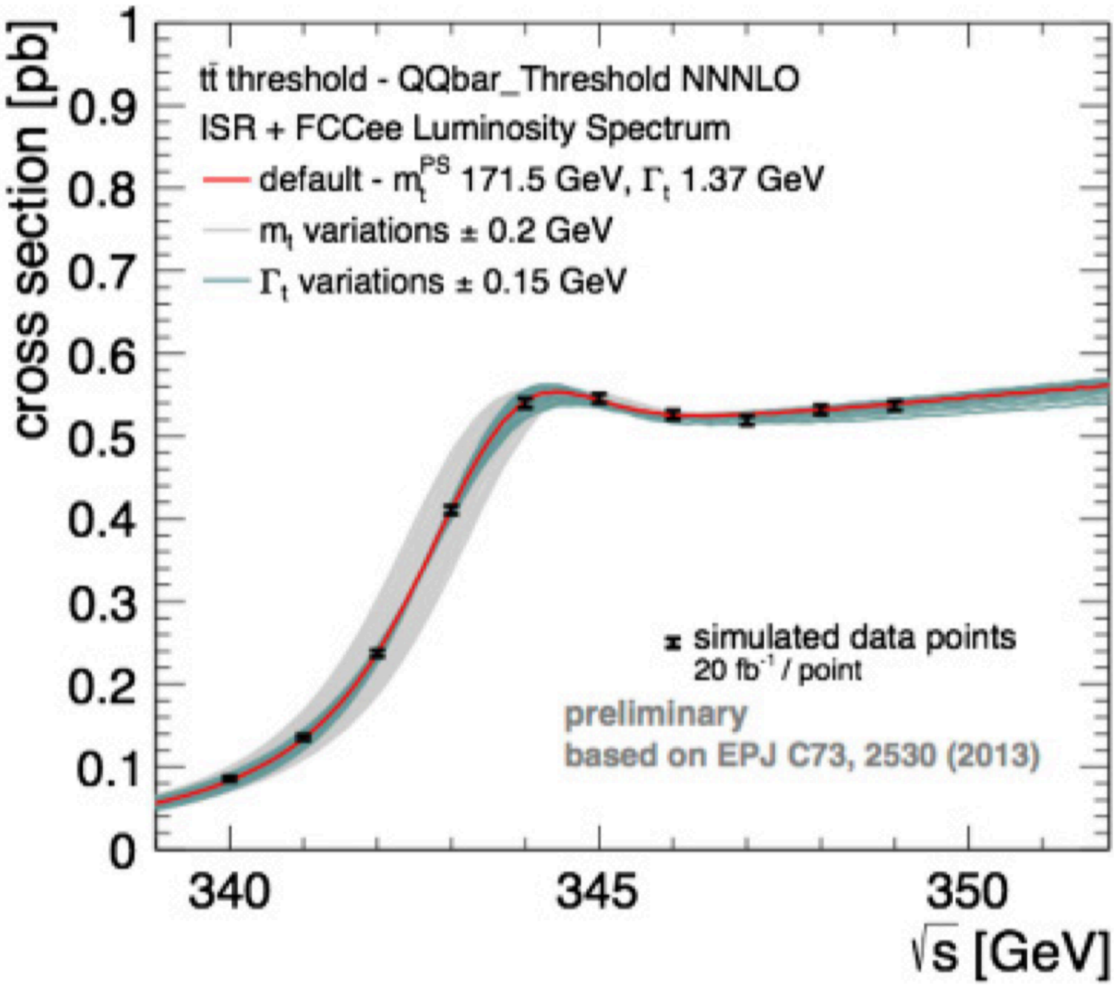
Forslund, Meade 2308.02633



precision limited (~ 3%) due to backgrounds: not possible to determine κ_W precisely through WW scattering

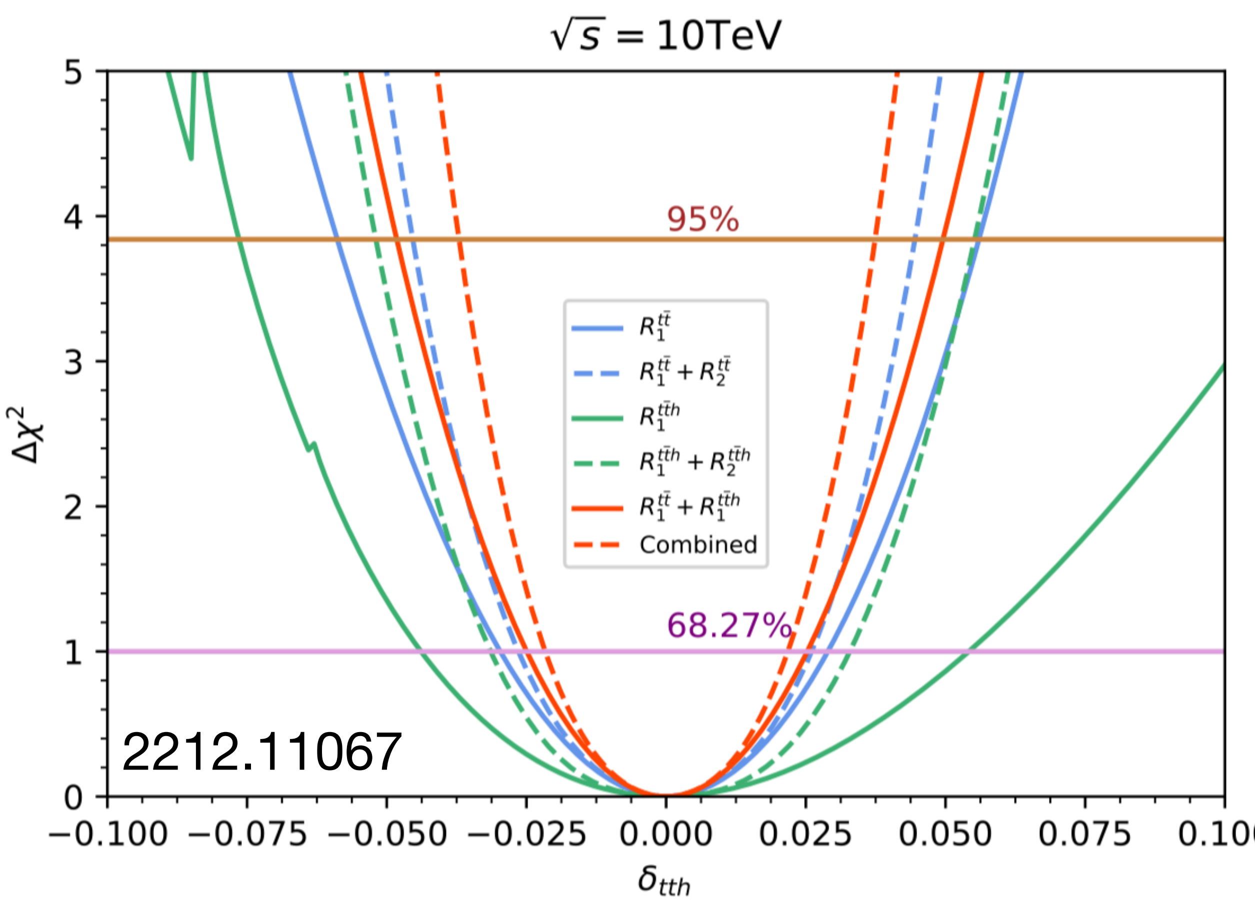
➔ correlation width vs. coupling

Top quark Yukawa



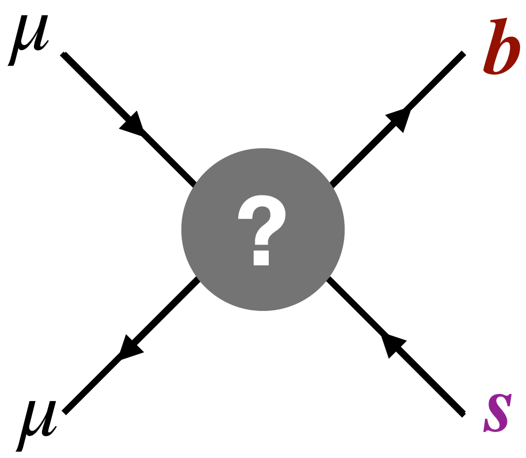
threshold scan @ FCC

tth @ muon collider



(a) $\mu^+\mu^- \to t\bar{t}\nu\bar{\nu}$ with $\sqrt{s} = 10$ TeV and $L = 10\,\text{ab}^{-1}$.

Quark flavor violation



Four-fermion interactions: muon current coupled to flavor-violating bilinear

$$\frac{c_{bs}}{\Lambda^2}(\bar{b}_{L,R}\gamma^\rho s_{L,R})(\bar{\mu}_{L,R}\gamma_\rho \mu_{L,R})$$

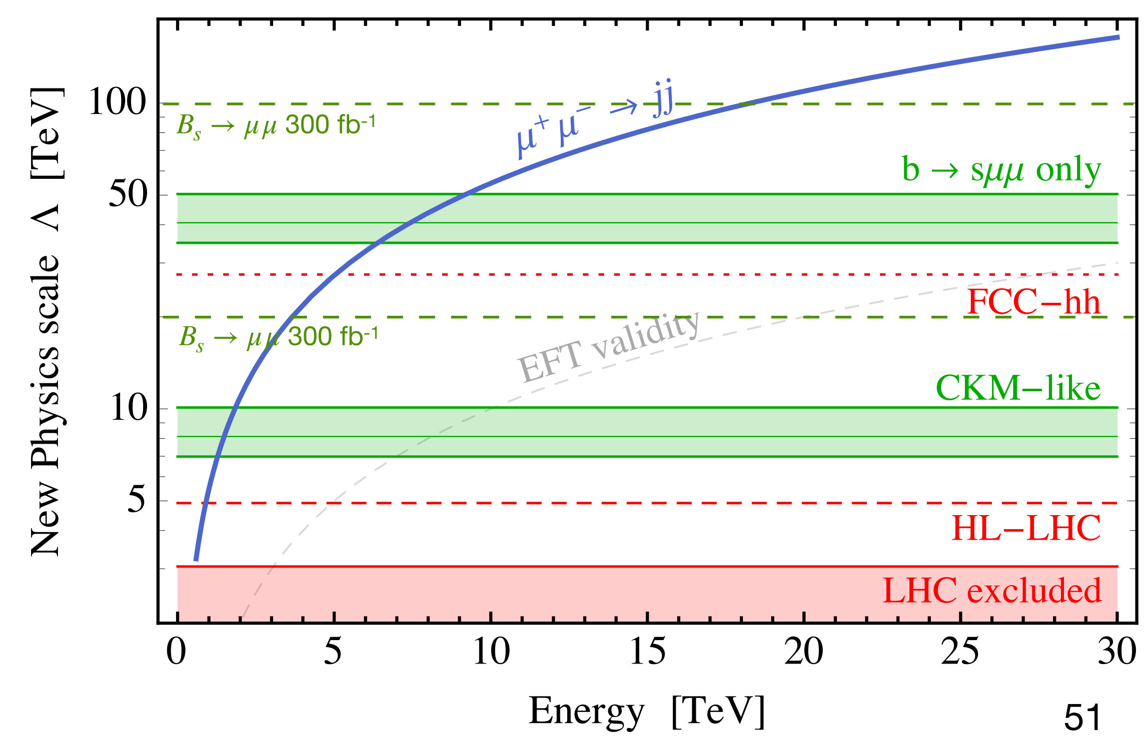
- Contributes to (semi-)leptonic rare B decays $b \to s\mu\mu$: branching ratios & angular observables of various hadronic processes

$$B_s \to \mu\mu, \qquad B \to K^{(*)}\mu\mu, \qquad B_s \to \phi\mu\mu, \qquad \Lambda_b \to \Lambda\mu\mu$$

- Theory uncertainties: cannot improve indefinitely with rare decays

$$\mathrm{BR}(B \to K\mu\mu) \sim \frac{m_W^4}{\Lambda^4}, \quad \sigma(\mu\bar{\mu} \to jj) \sim \frac{E^2}{\Lambda^4}$$

Azatov, Garosi, Greljo, Marzocca, Salko, Trifinopoulos 2205.13552



Muon g-2 @ muon collider

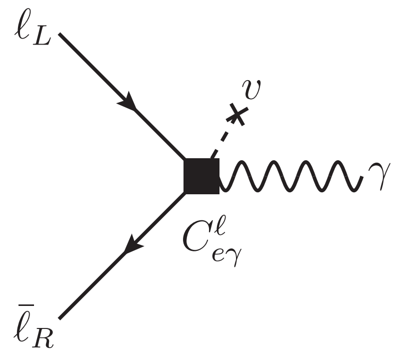
- If new physics is light enough (i.e. weakly coupled), a Muon Collider can directly produce the new particles ☛ direct searches: model-dependent

Capdevilla et al. 2006.16277

- If new physics is heavy: EFT!
  One dim. 6 operator contributes at tree-level: $\mathscr{L}_{g-2} = \frac{C_{e\gamma}}{\Lambda^2} H(\bar{\ell}_L \sigma_{\mu\nu} e_R)\, eF^{\mu\nu} + \text{h.c.}$

At low energy

$$\Delta a_\mu = \frac{4 m_\mu v}{\Lambda^2} C_{e\gamma} \approx 3 \times 10^{-9} \times \left(\frac{140\,\text{TeV}}{\Lambda}\right)^2 C_{e\gamma}$$



Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

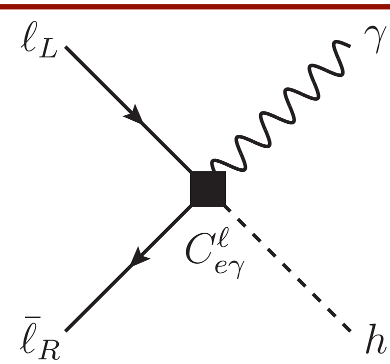
B, Paradisi 2012.02769

At high energy

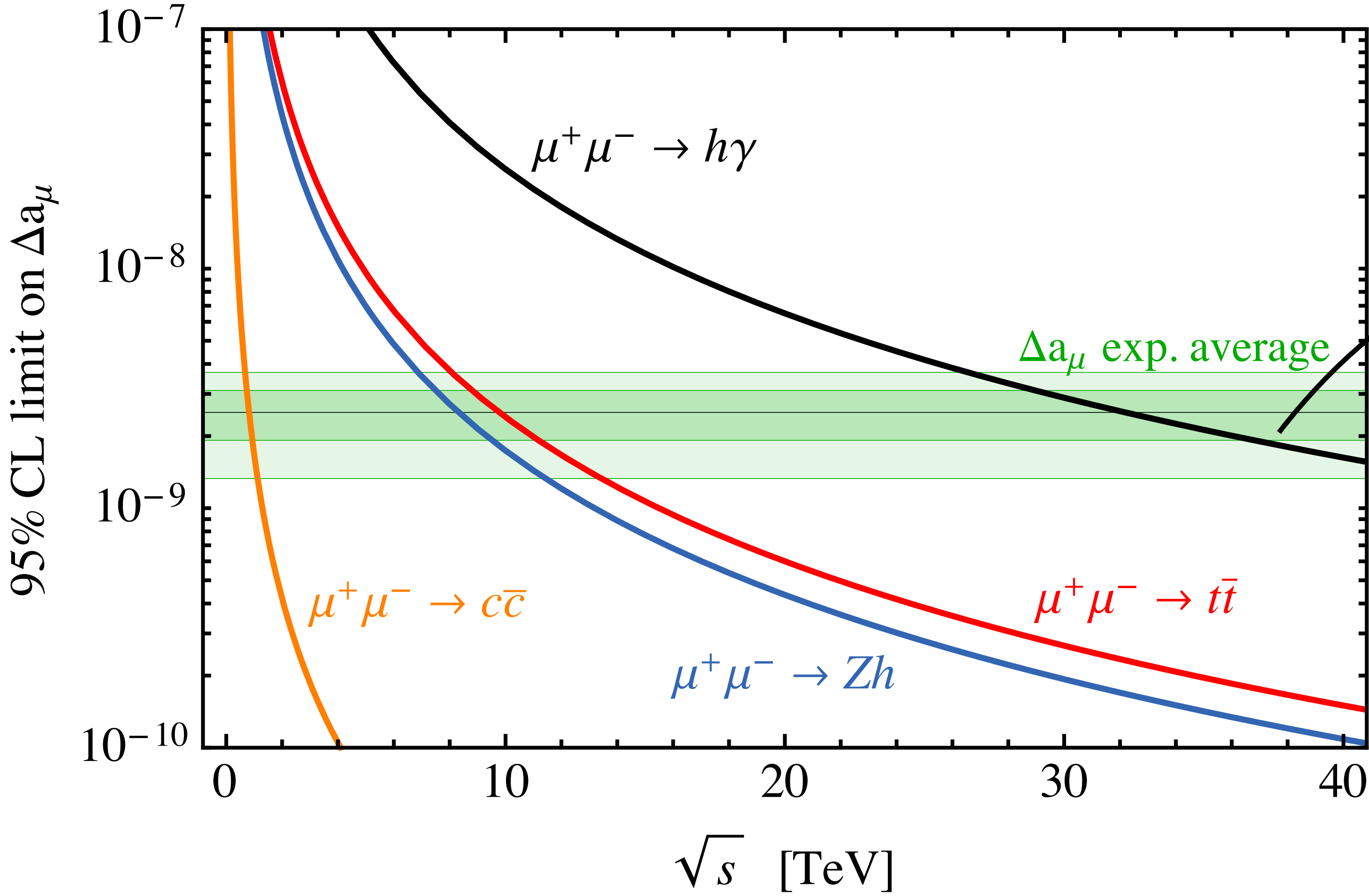
$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\text{ab} \left(\frac{\sqrt{s}}{30\,\text{TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

$$N_{h\gamma} = \sigma \cdot \mathscr{L} \approx \left(\frac{\sqrt{s}}{10\,\text{TeV}}\right)^4 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

need E > 10 TeV



Muon g-2 @ muon collider



Exp. value of Δa_μ can be tested at 95% CL at a 30 TeV collider!

(with reasonable assumptions on detector performance)

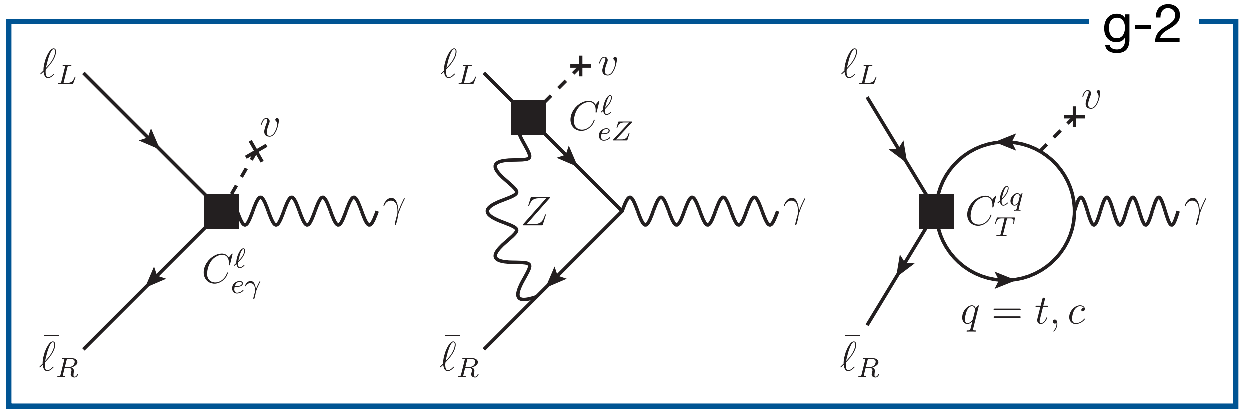
This result is completely model-independent!

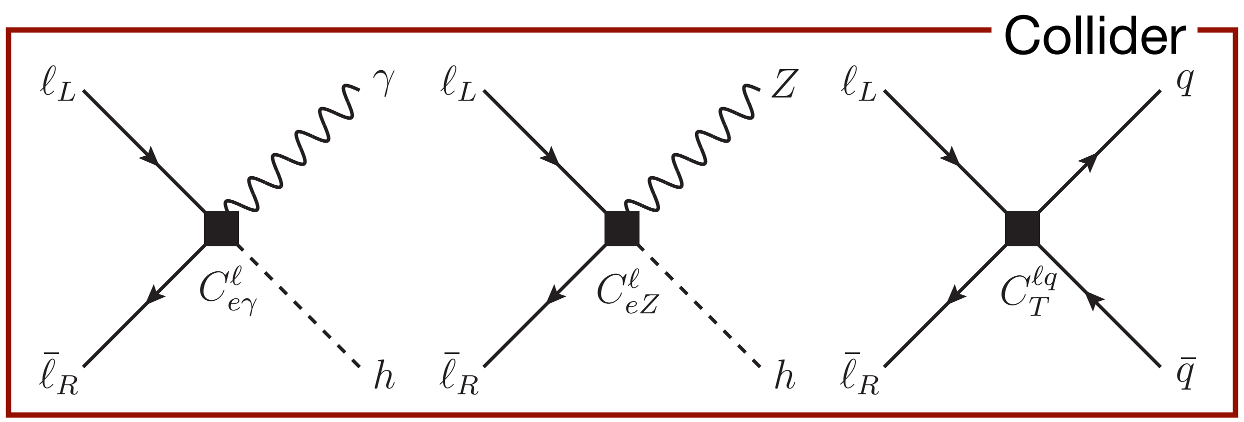
B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

$$\Delta a_\mu \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

- Full set of operators with $\Lambda \gtrsim 100$ TeV can be probed at a high-energy muon collider





Lepton g-2 from rare Higgs decays

- Tau magnetic dipole moment: enhanced due to the larger mass

$$\Delta a_\tau = \frac{4v\, m_\tau}{\Lambda^2} C_{e\gamma}^{\tau} \approx \Delta a_\mu \frac{m_\tau^2}{m_\mu^2} \approx 10^{-6}$$

if $C_{e\gamma}^{\ell}$ scales as y_ℓ

Present bound: $\Delta a_\tau \lesssim 10^{-2}$

from LEP $e^+e^- \to e^+e^-\tau^+\tau^-$

hep-ex/0406010

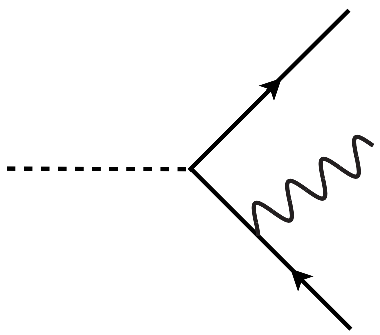
Can be improved to few 10-3

at HL-LHC 1908.05180

- Contribution to h $\to \tau\tau\gamma$ decays:

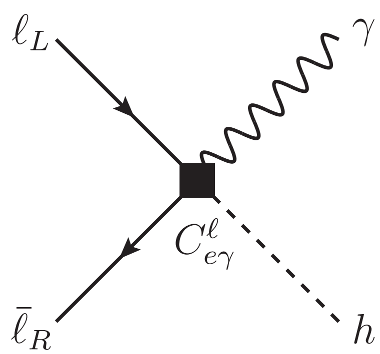
$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5 \times 10^{-4}$$

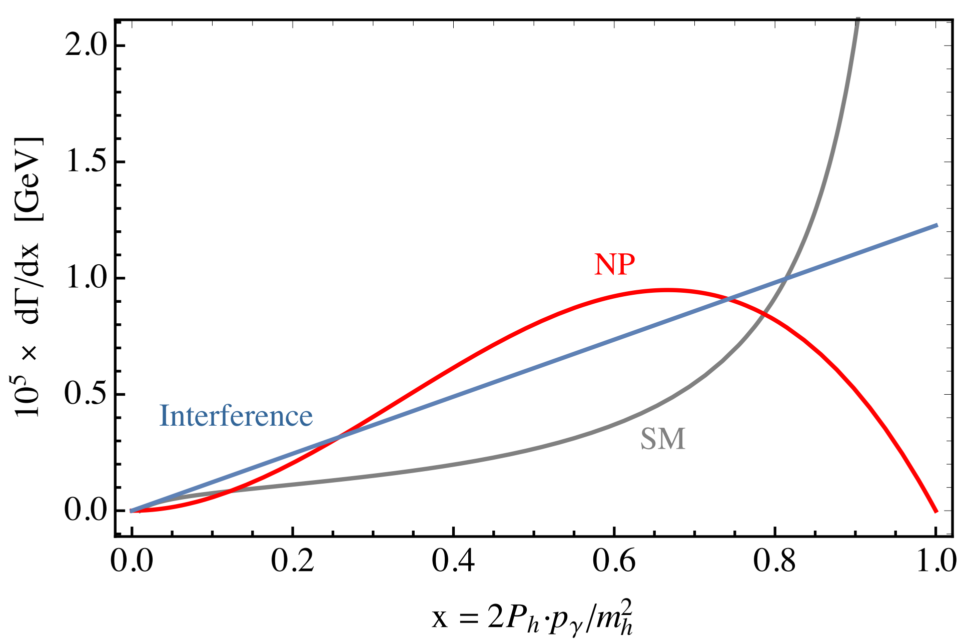
(with cut on soft collinear photon)



could be measured at few % level by Higgs factory

$$\mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2 \times \Delta a_\tau$$



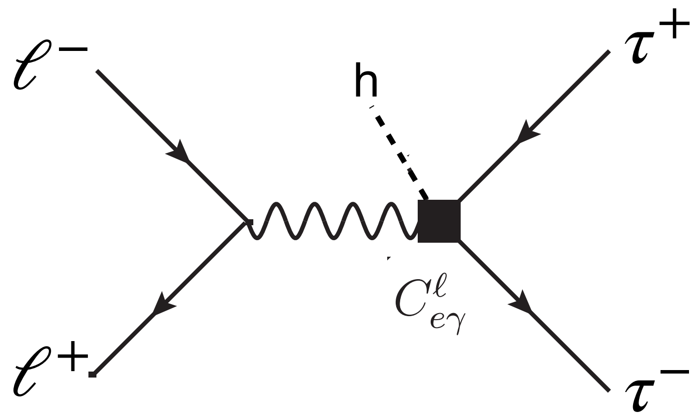


Tau g-2 from high-energy probes

Further possibilities to measure Δa_τ precisely from high-energy probes

- $H\tau\tau$ associated production

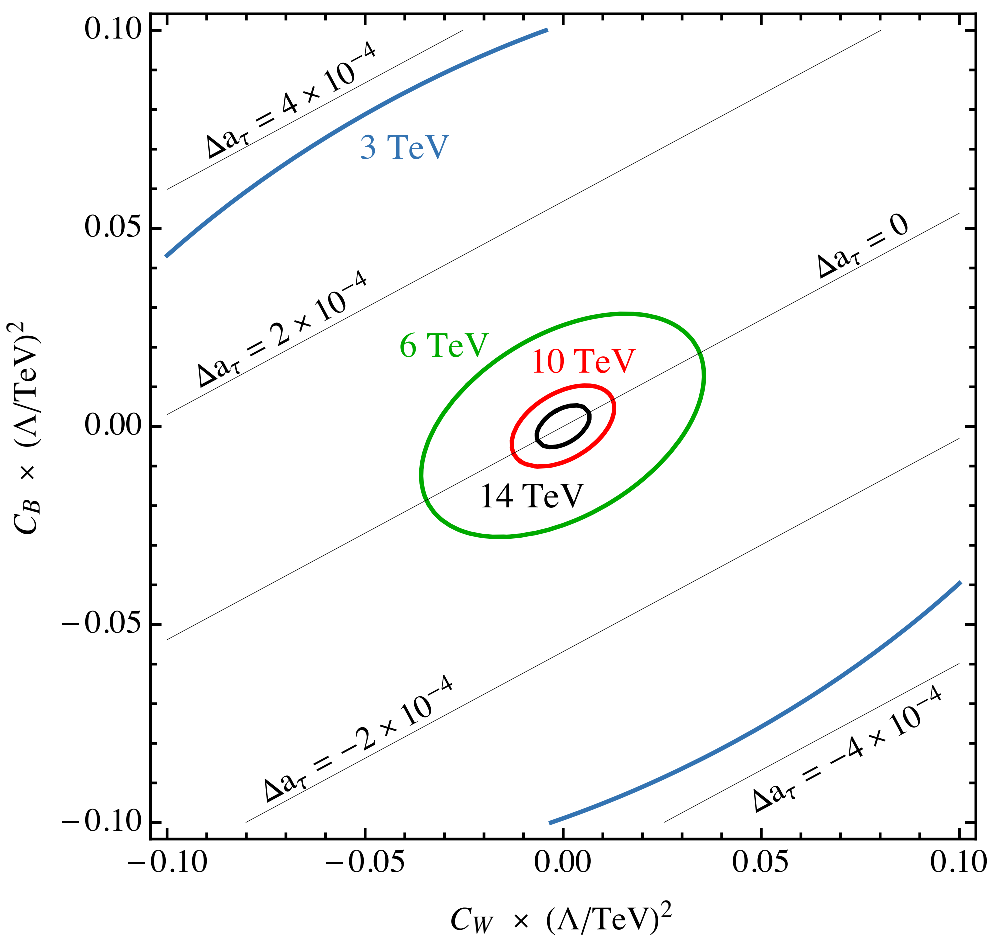
work in progress with Levati, Paradisi, Maltoni, Wang

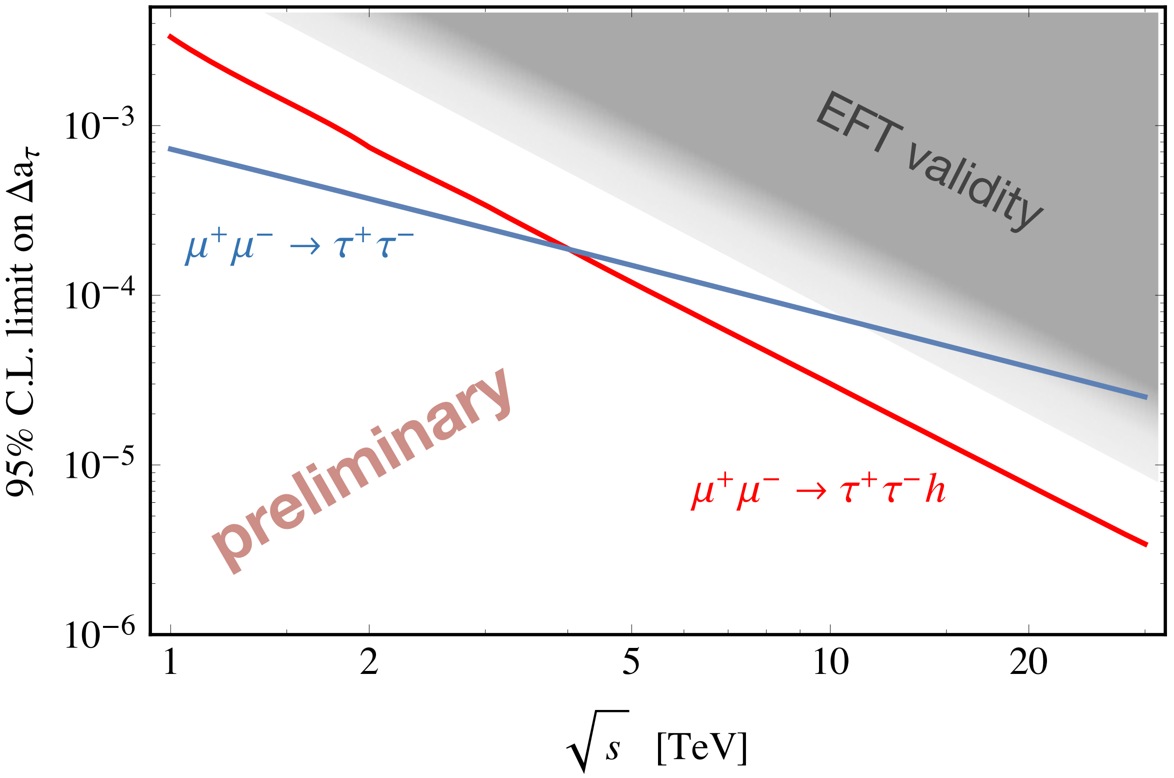


- Main background from μμ → $Z\gamma$

(where Z is mistaken for H)

Could probe $\Delta a_\tau \sim 10^{-5}$ @ 10 TeV





also a bound on tau EDM!

Tau g-2 from high-energy probes

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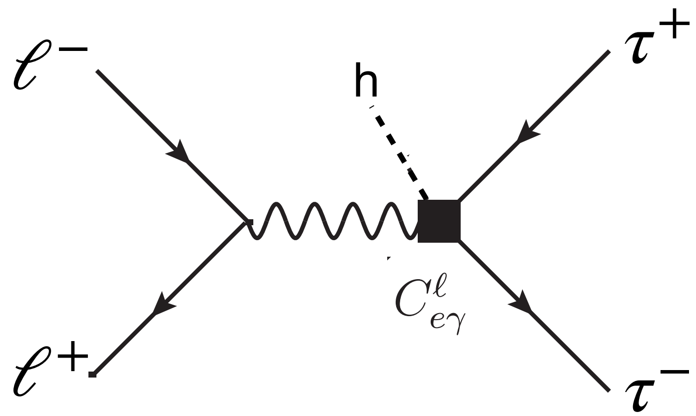

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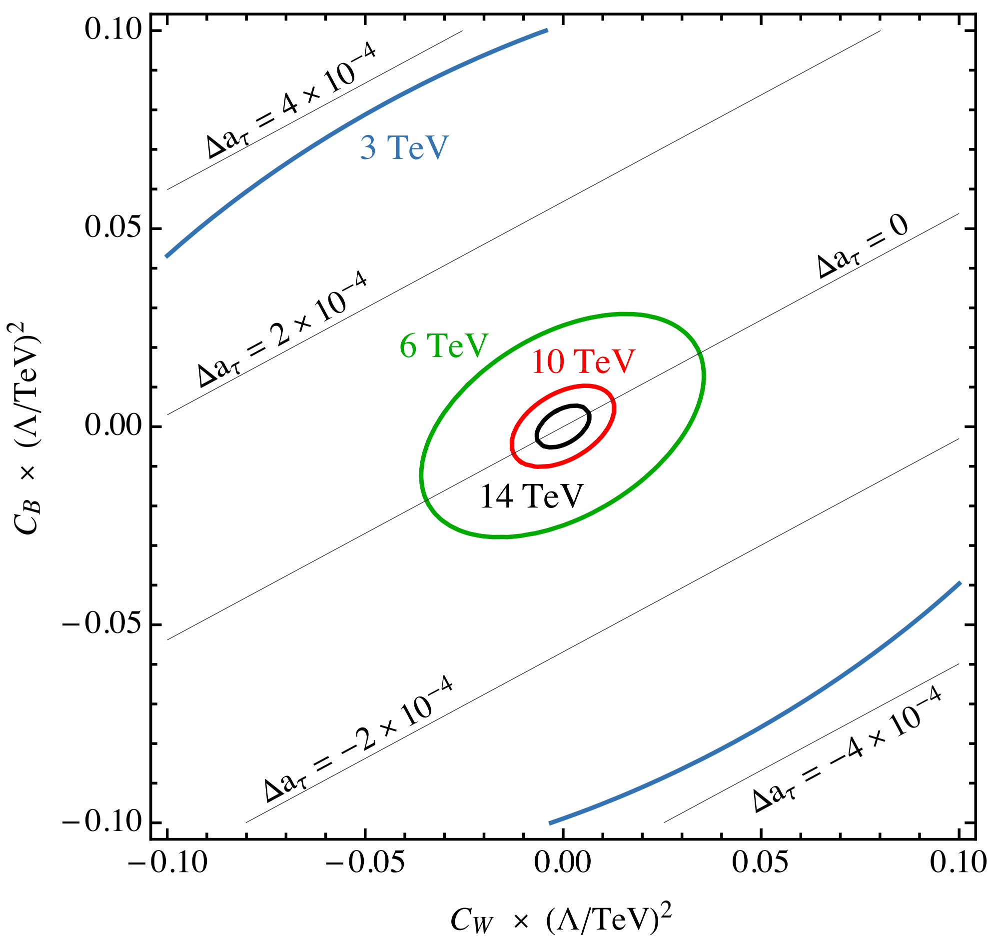

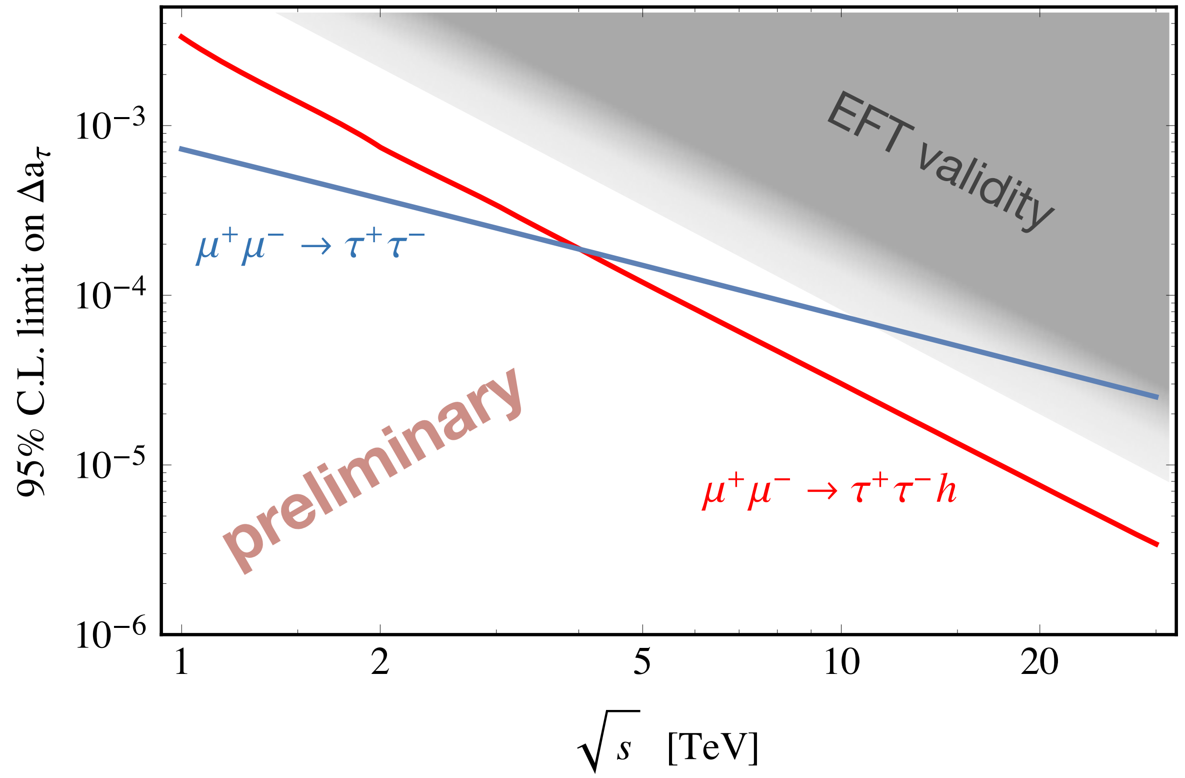

also a bound on tau EDM!