Physics at lepton colliders

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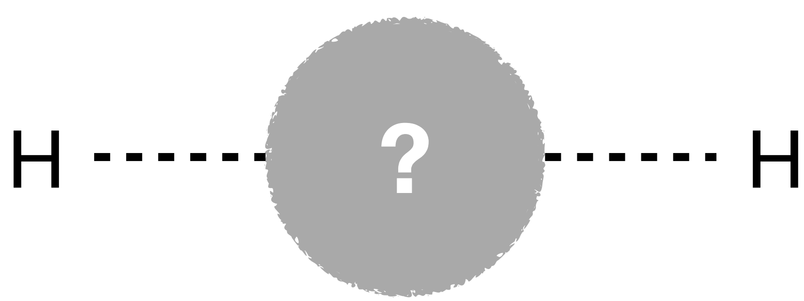
Why a future collider?

- Goal: explore physics at least up to $M_{\rm NP} \approx 10\,{\rm TeV}$

Direct searches	High-rate SM measurements	High-energy SM measurements
high energy to search for heavy new particles	high statistics for precise measurements	high energy to look for NP in SM processes

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



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

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

… and how is it related with the flavor problem?

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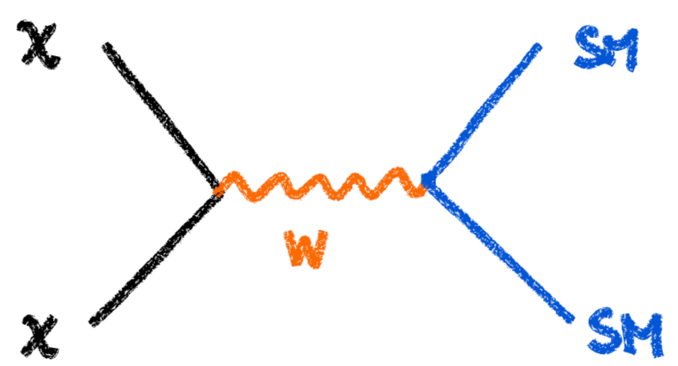

$$M_{\rm DM} \approx 1 - 15\,{\rm TeV}$$

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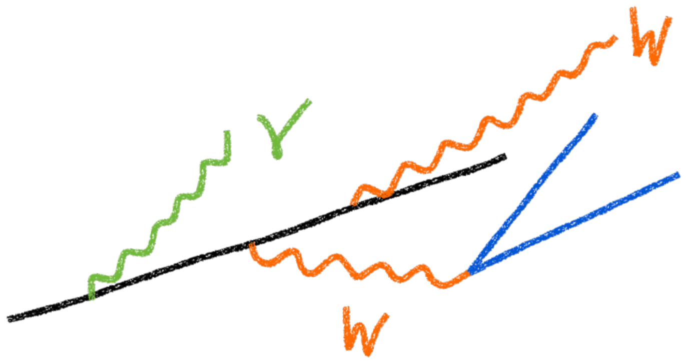
- What causes EWSB? i.e. does the SM hold up to few TeV?
- What is dark matter? Is it a WIMP?
- Observe restoration of EW symmetry (EW radiation)



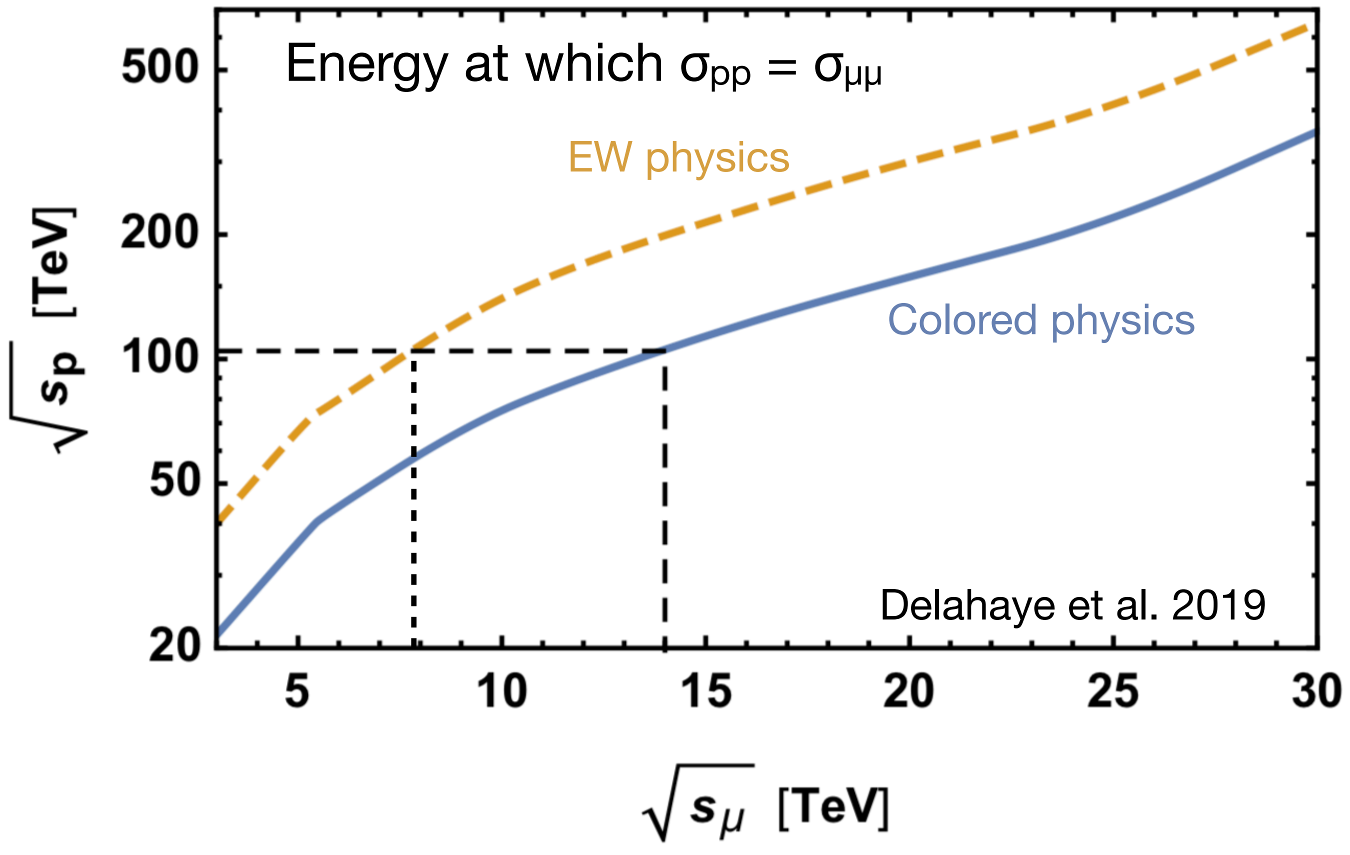
→ $E \approx 10\,\mathrm{TeV}$

Lepton colliders

- Lepton colliders are ideal probes of short-distance physics
  - elementary: no energy lost in PDFs,
    all beam energy is available for hard scattering

Colored particles:
14 TeV μμ ~ 100 TeV pp

EW particles:
14 TeV μμ ~ 200 TeV pp

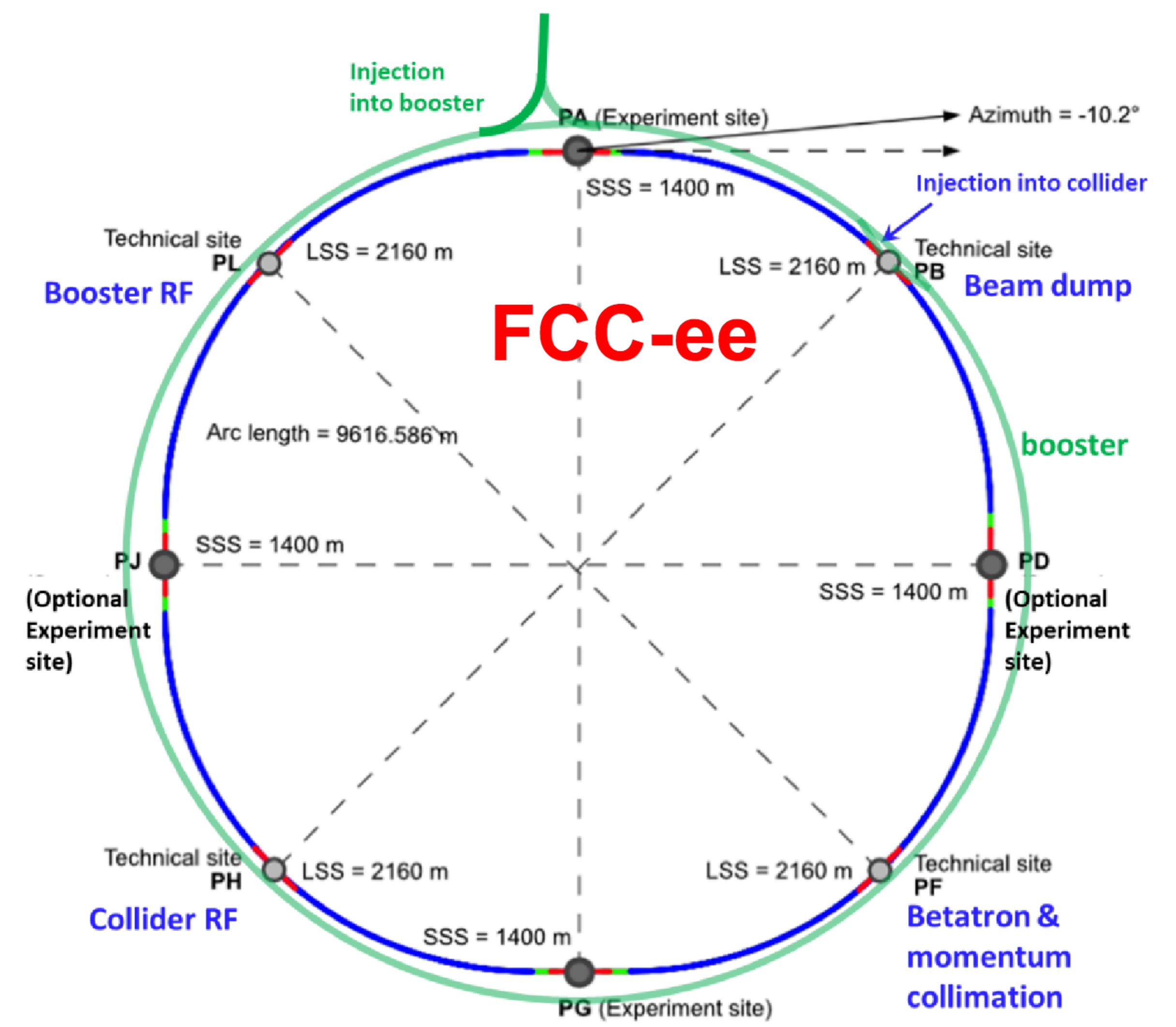


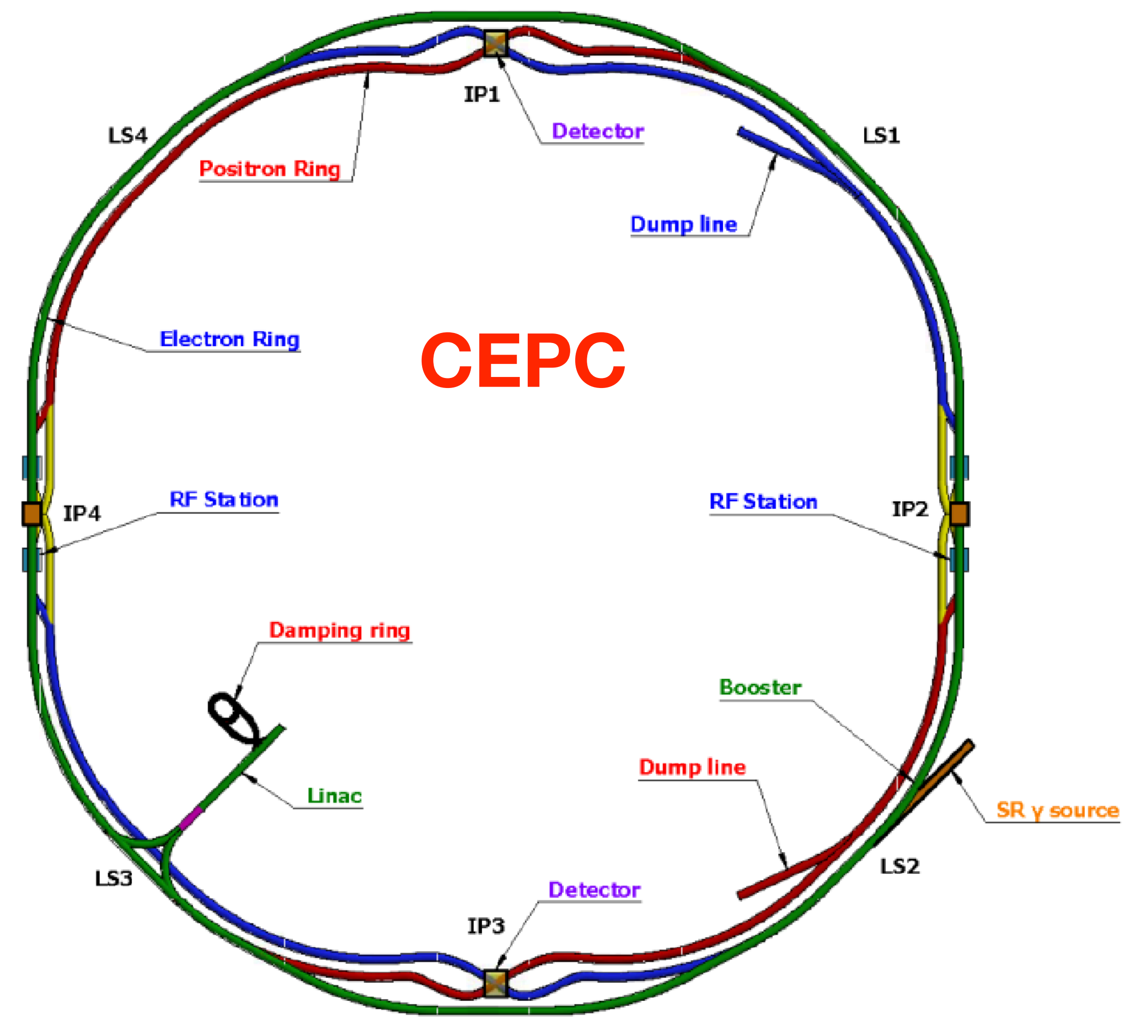
  - no strong interactions:
    no QCD background, high S/B

Electron-positron colliders

- They could be built today, if approved and funded.

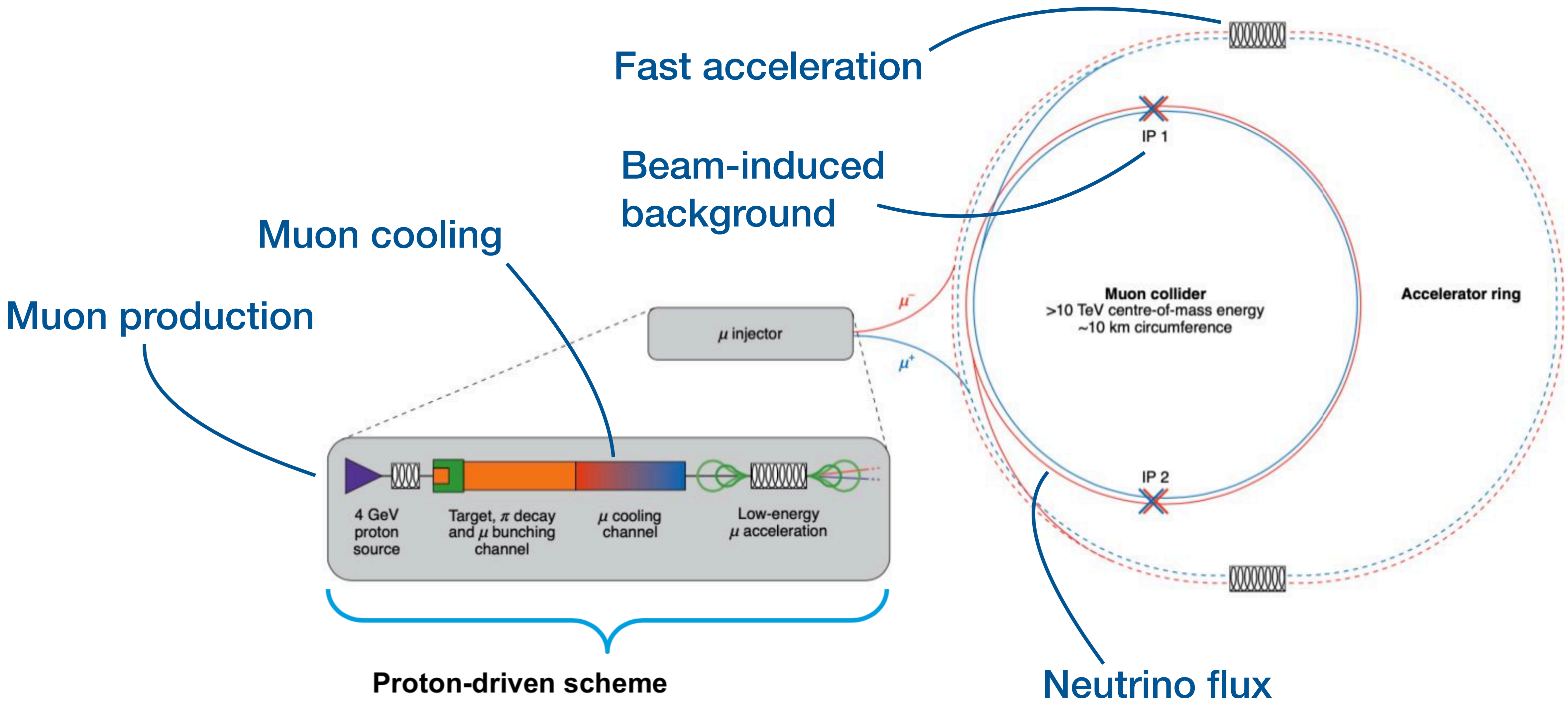
  Our quickest way to multi-TeV energies (indirectly).





Muon colliders?

- A muon collider is *not yet feasible* as of today!
- Several technical challenges that require major R&D effort

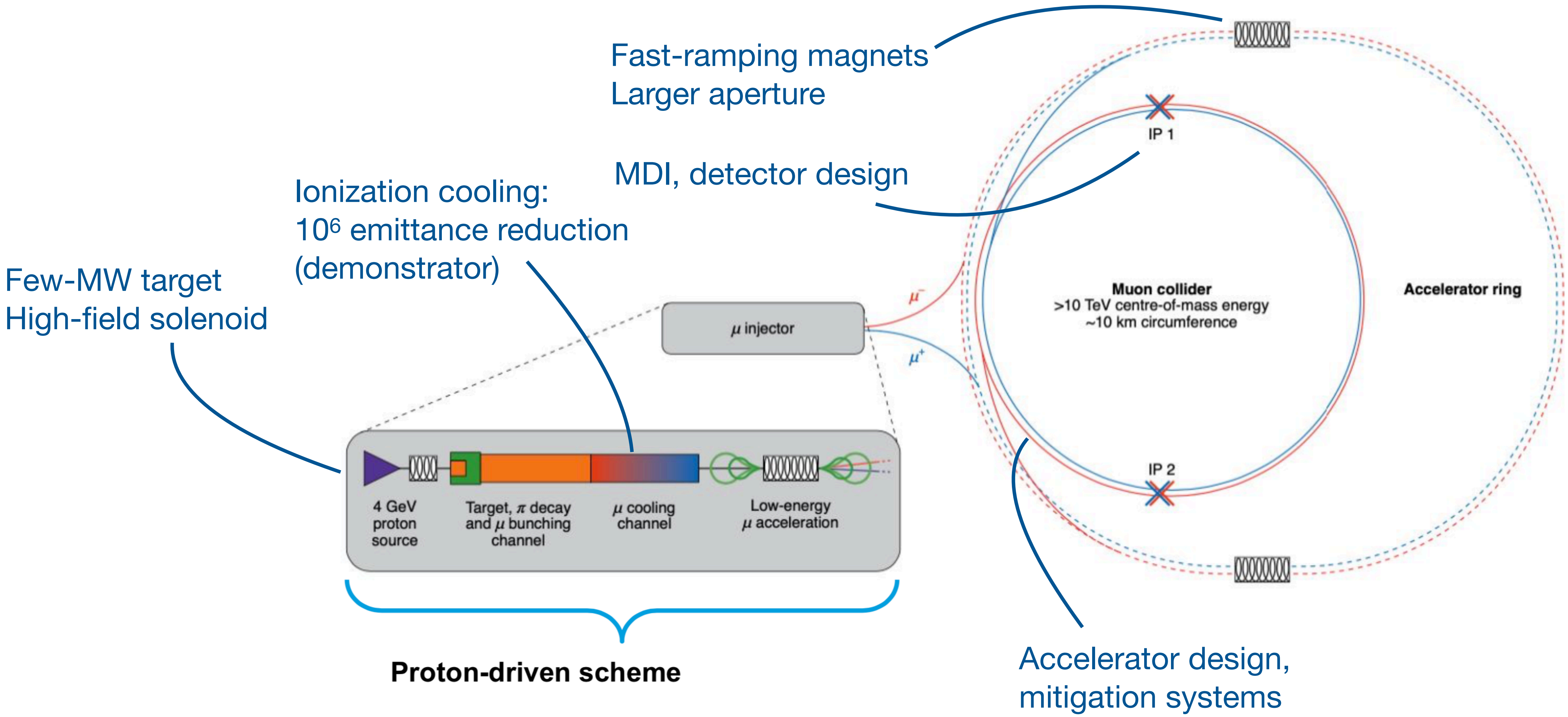


… it should not be compared with shovel-ready projects (like e+e- Higgs/EW factory)

Muon colliders!

- A muon collider is *not science-fiction* either!

- Several technical challenges that require major R&D effort



High energy lepton collider (10 TeV or more) is a dream for particle physics…

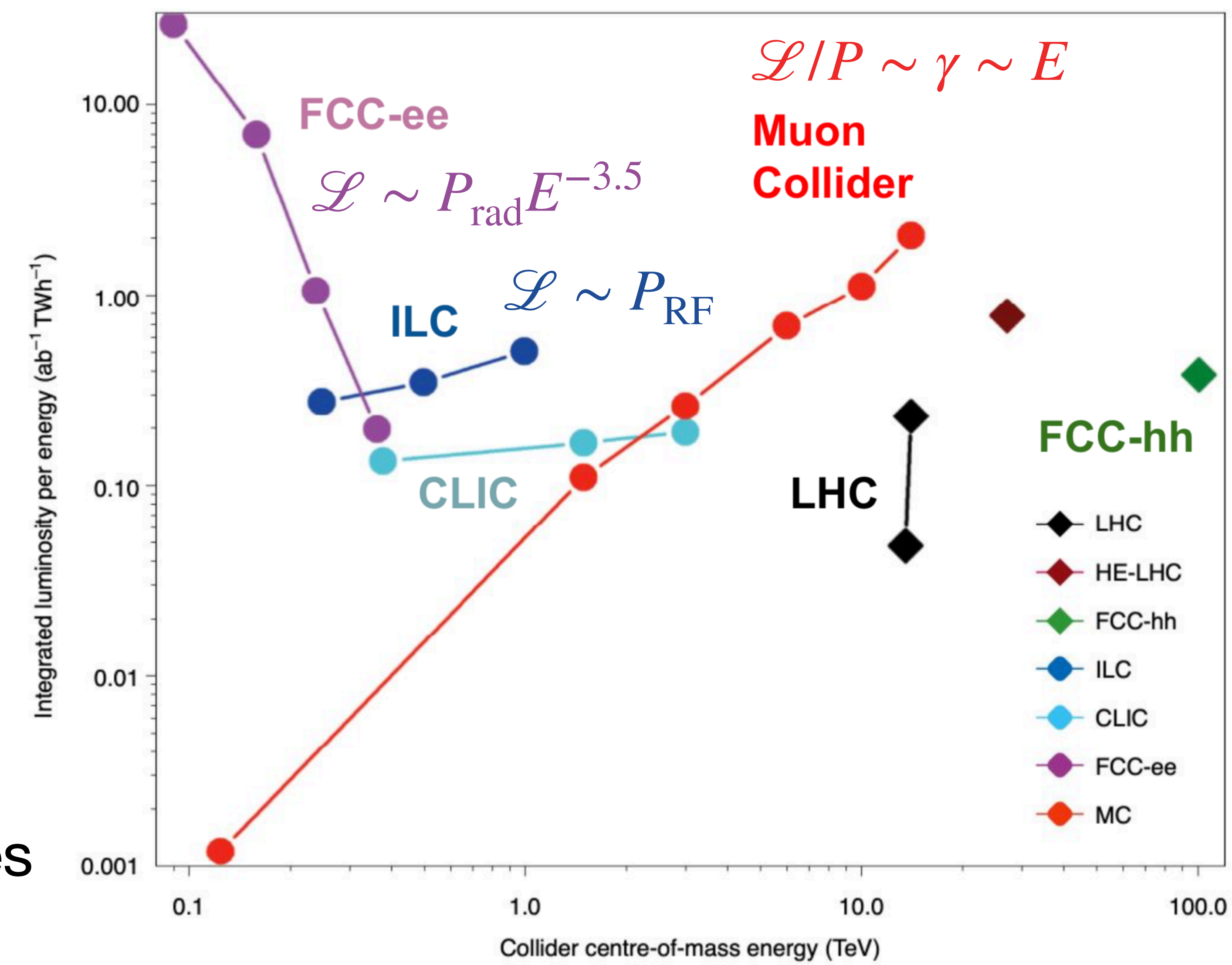
… dedicated R&D program crucial to establish feasibility in the next years!

Lepton colliders

- ✦ Lepton colliders are ideal probes of short-distance physics
- ✦ Muons are elementary and heavy (207 x electrons)
  - negligible energy loss in synchrotron radiation
  - negligible beamstrahlung

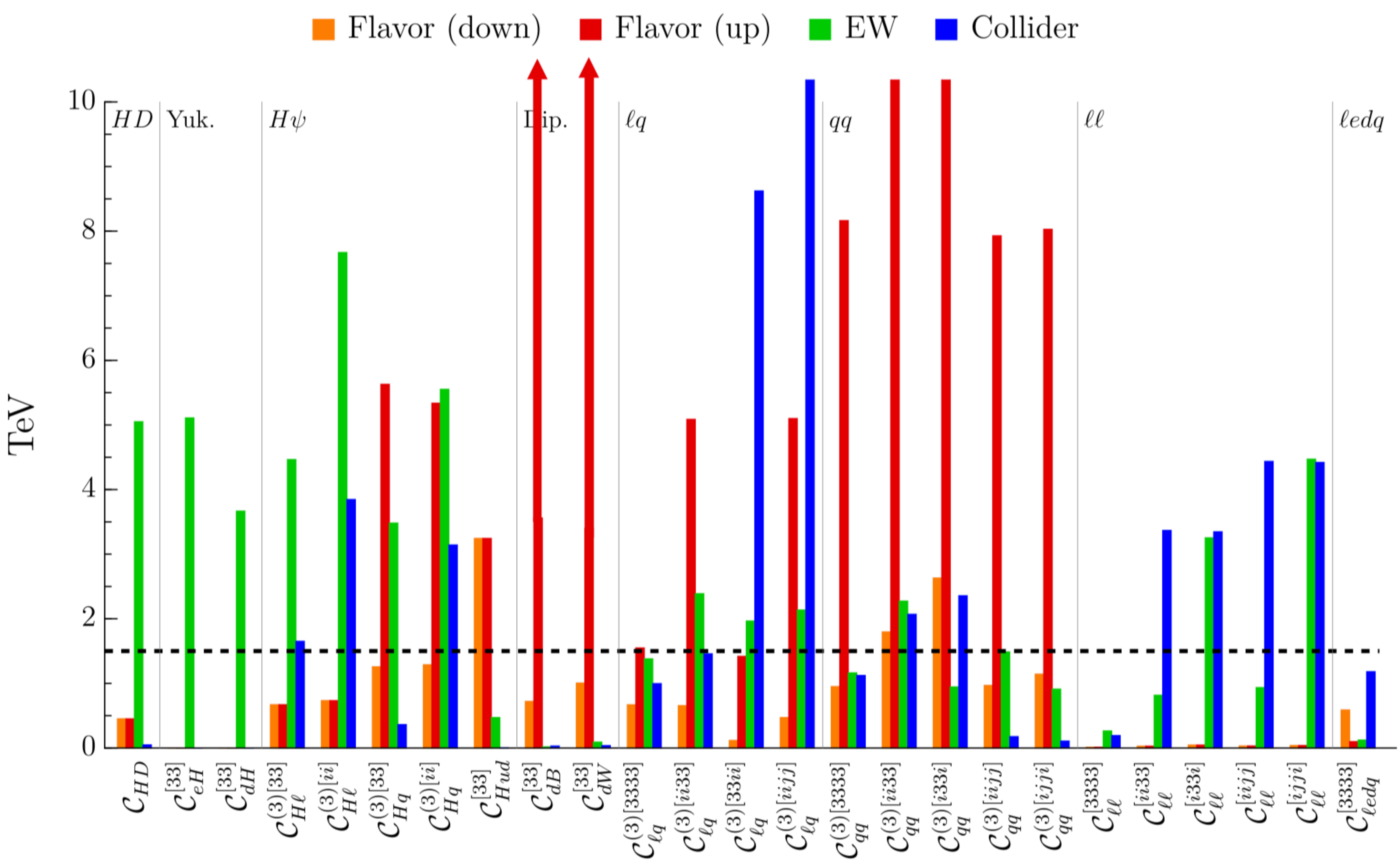
But they decay…

- ✦ Luminosity increases with the square of beam energy
  - muon lifetime increases
  - transverse emittance decreases



Where do we stand?

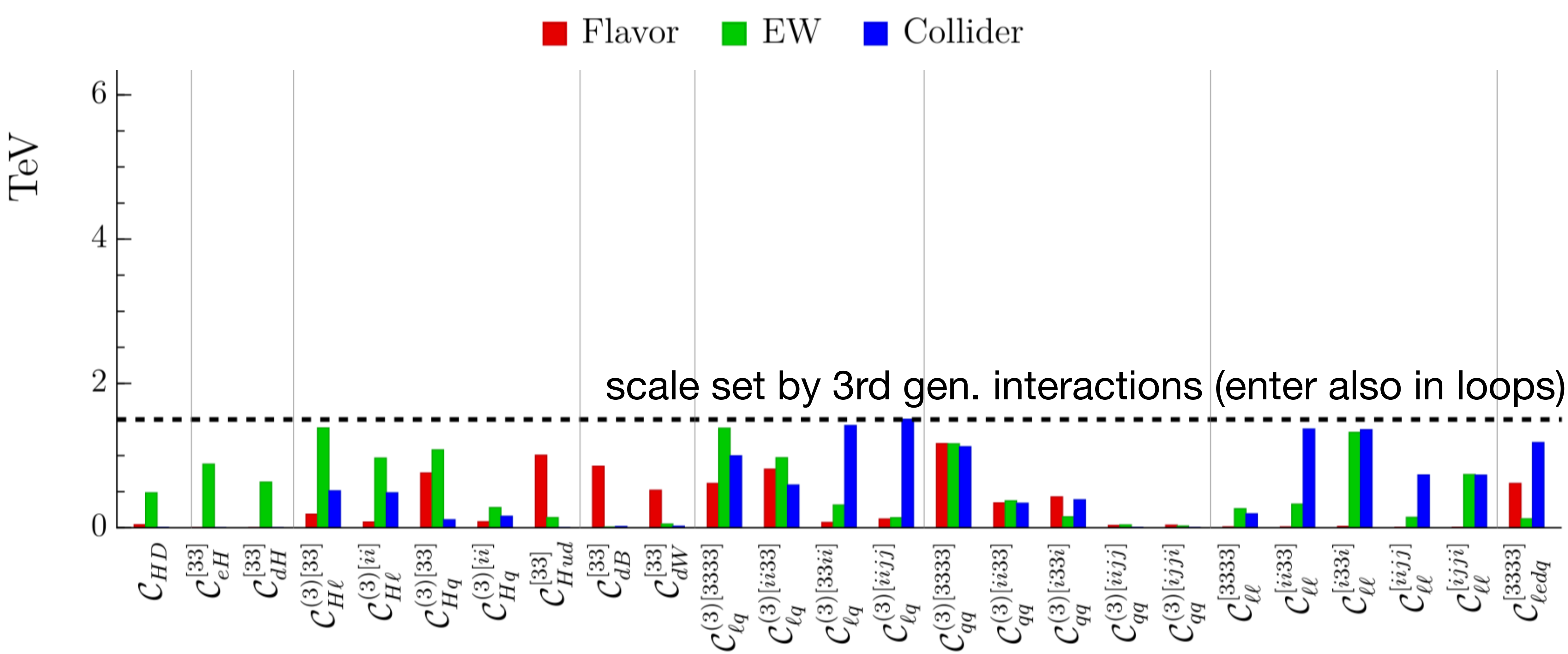
- With CKM-like suppression ($U(2)^3$ flavor symmetry):



Allwicher, Cornella, Isidori, Stefanek 2311.00020

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

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



Allwicher, Cornella, Isidori, Stefanek 2311.00020

see also talks by U. Haisch, P. Stangl

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

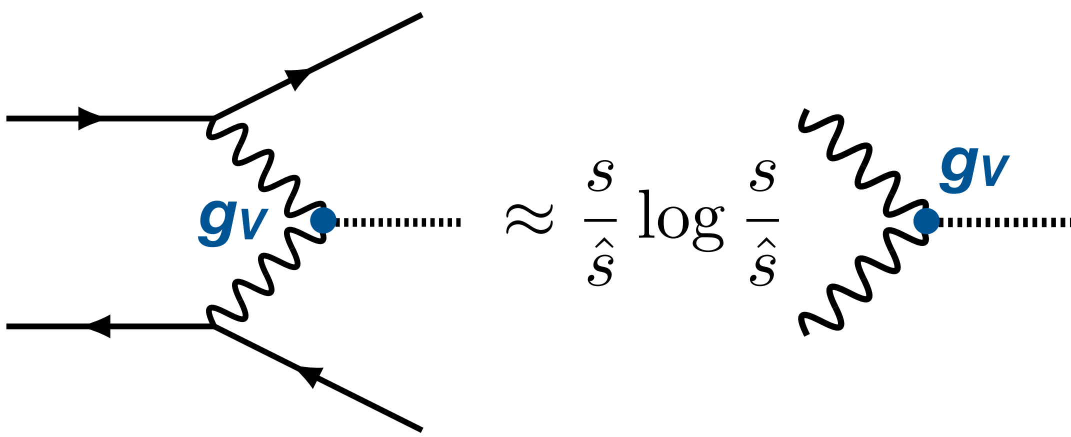
<u>large QCD backgrounds:</u>
only rare modes (BR < 10^{-3}) easily accessible

Higgs factories

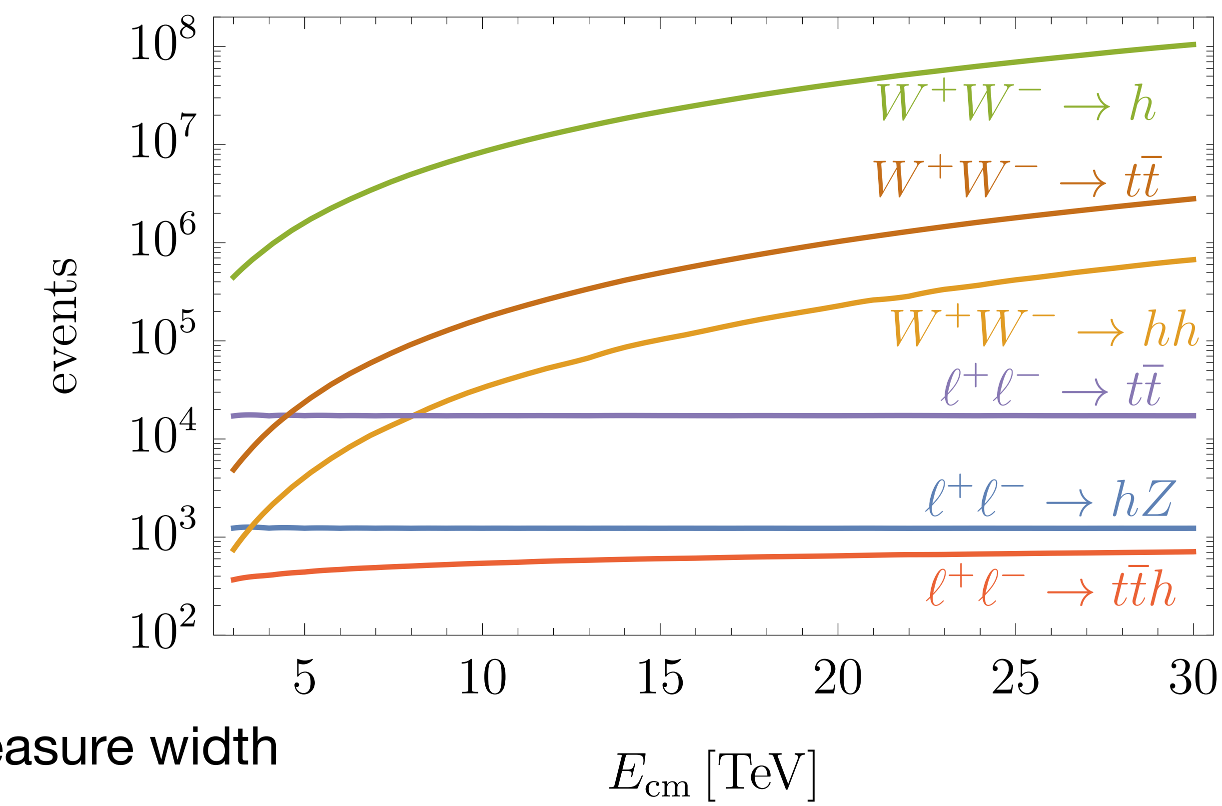
- Low-energy e+e- factories: $e^+e^- \to Zh$ @ 240 GeV

- 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”



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

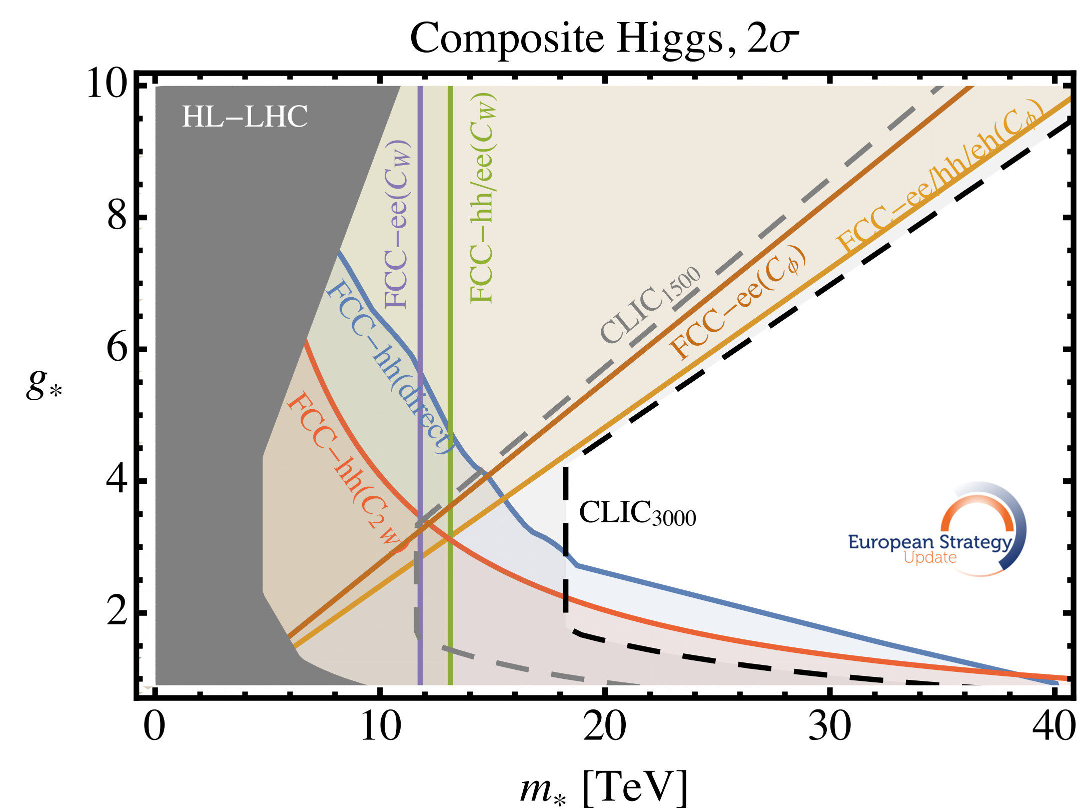
rare modes better (~ hadron collider)

2103.14043

What NP scales will we test with the Higgs?

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

$$\Rightarrow \quad M_{\rm NP} \gtrsim g_\star \; 6\ \text{TeV}$$

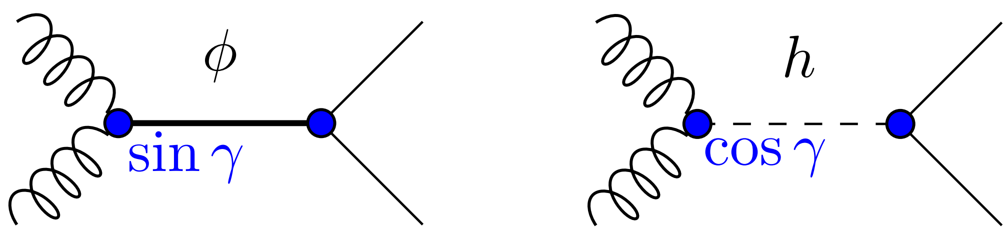


Direct vs indirect

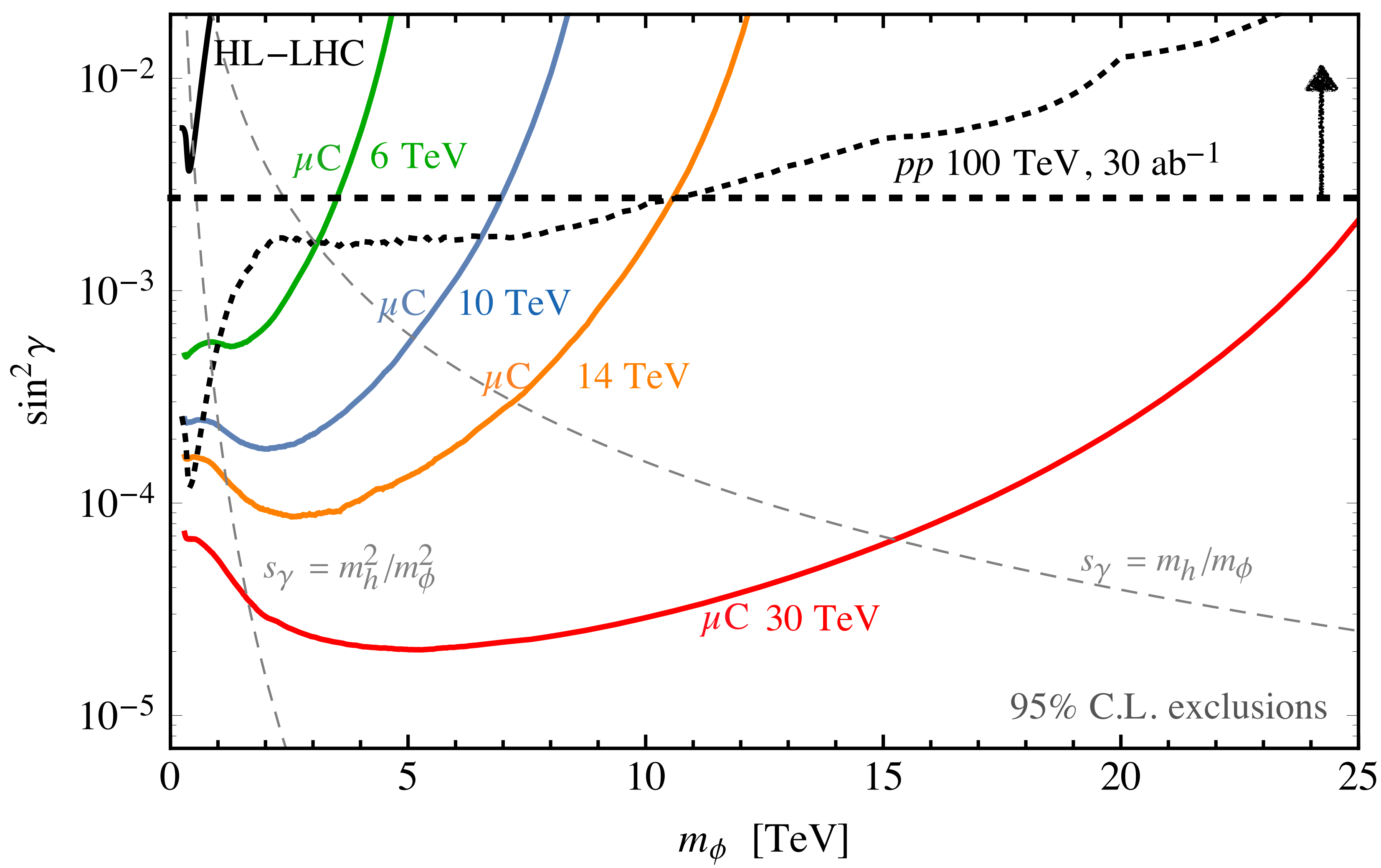
Compare single Higgs couplings measurements with reach of direct searches

- **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

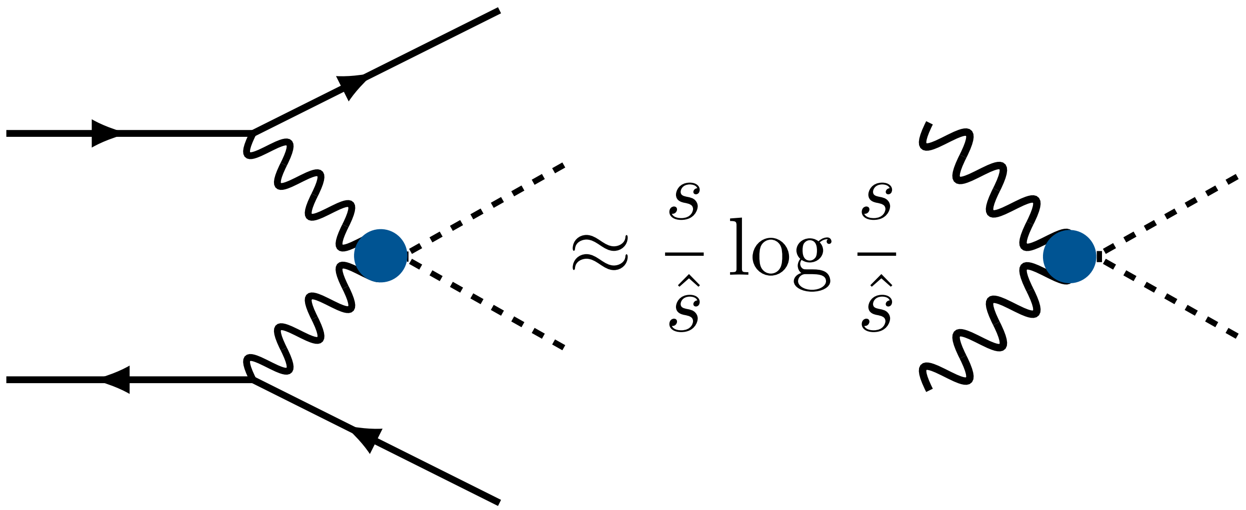


can be probed by single higgs

B, Redigolo, Sala, Tesi 1807.04743

High rate probes

- High rate: more events = better precision

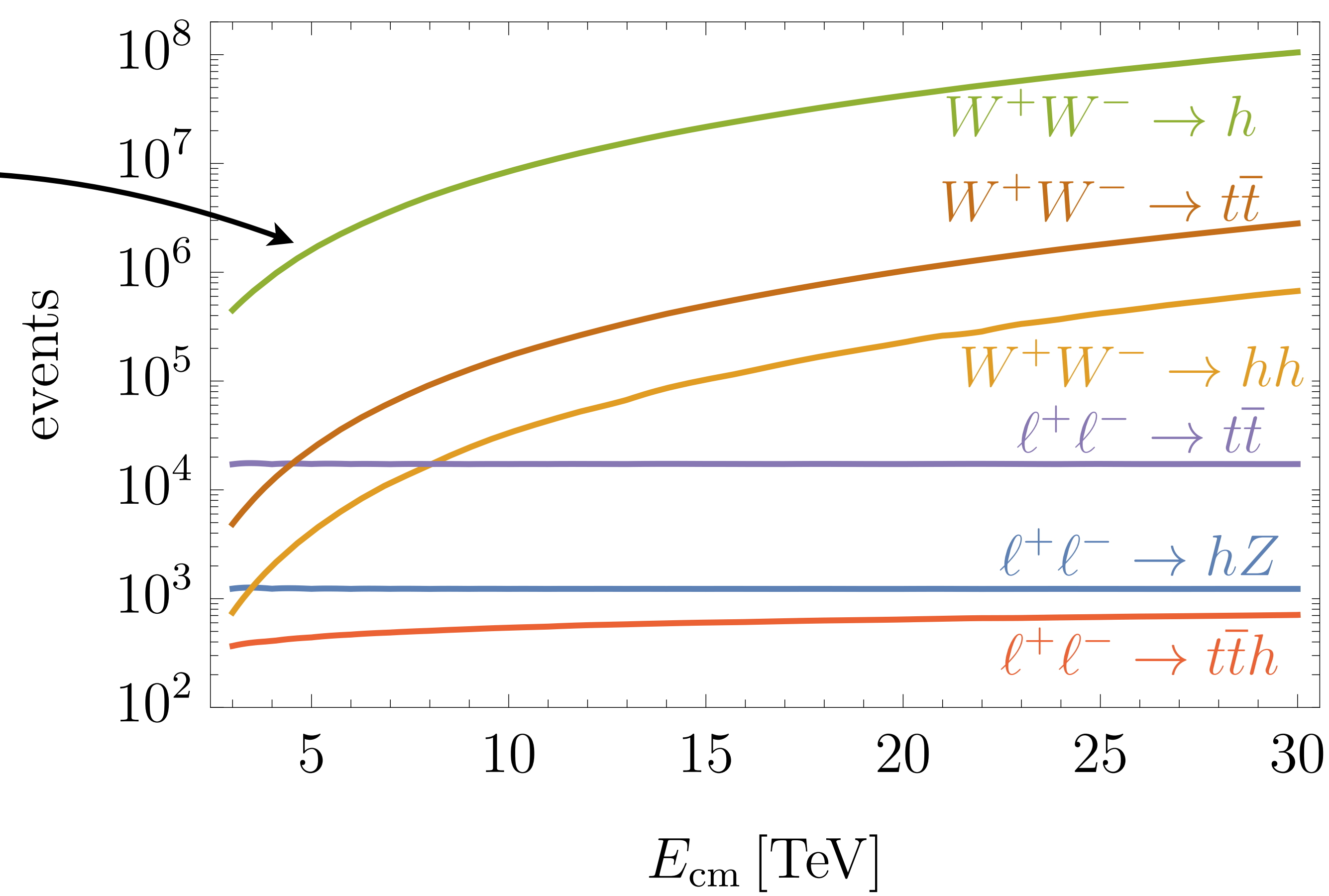


$$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$

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

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

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



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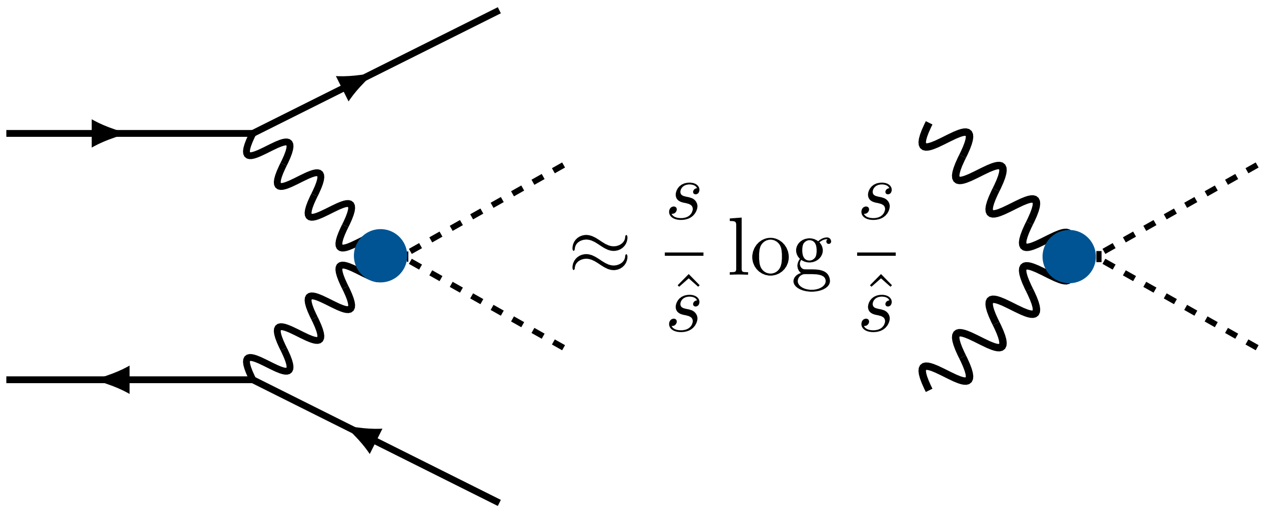
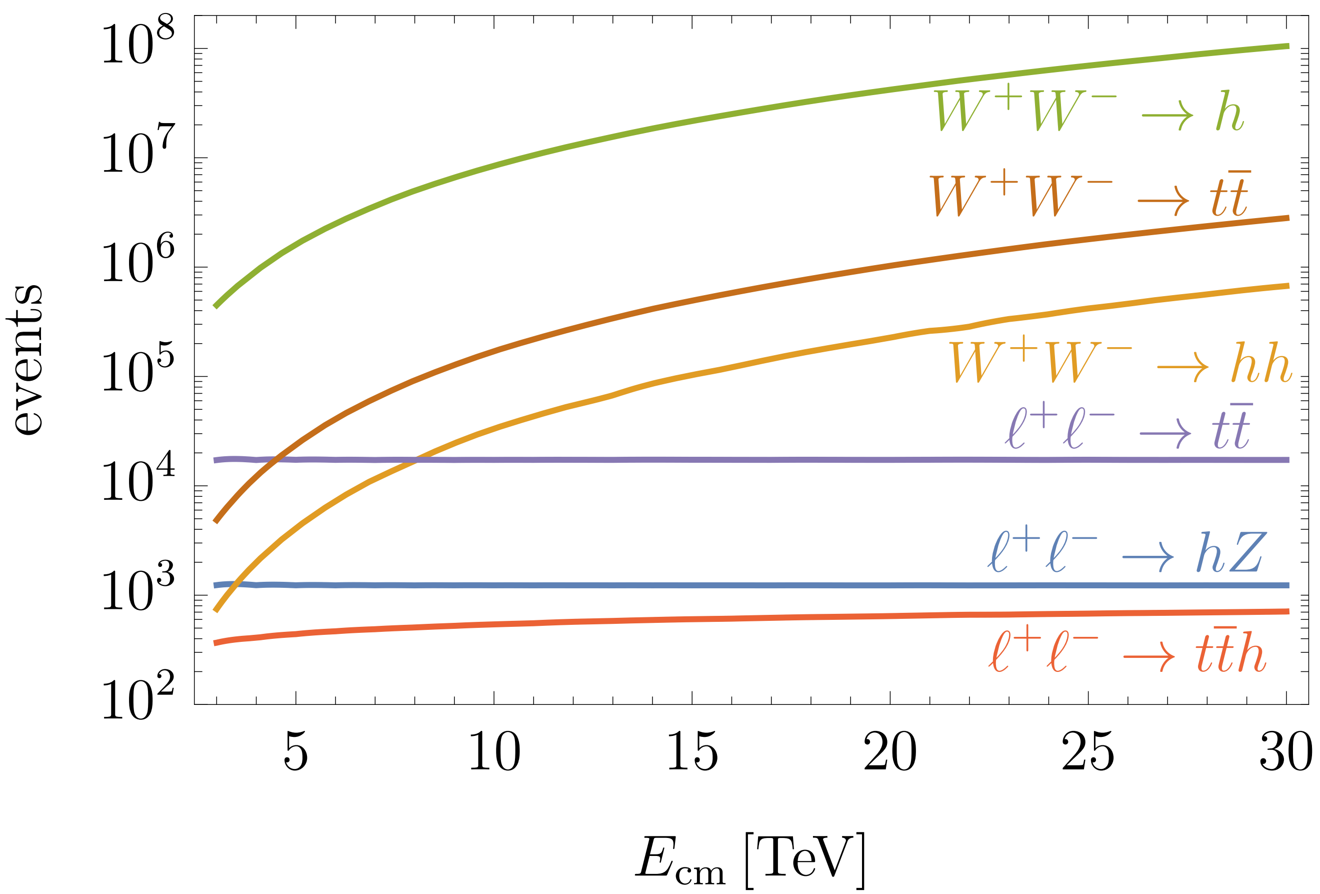


A High Energy Lepton Collider is a “vector boson collider”

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

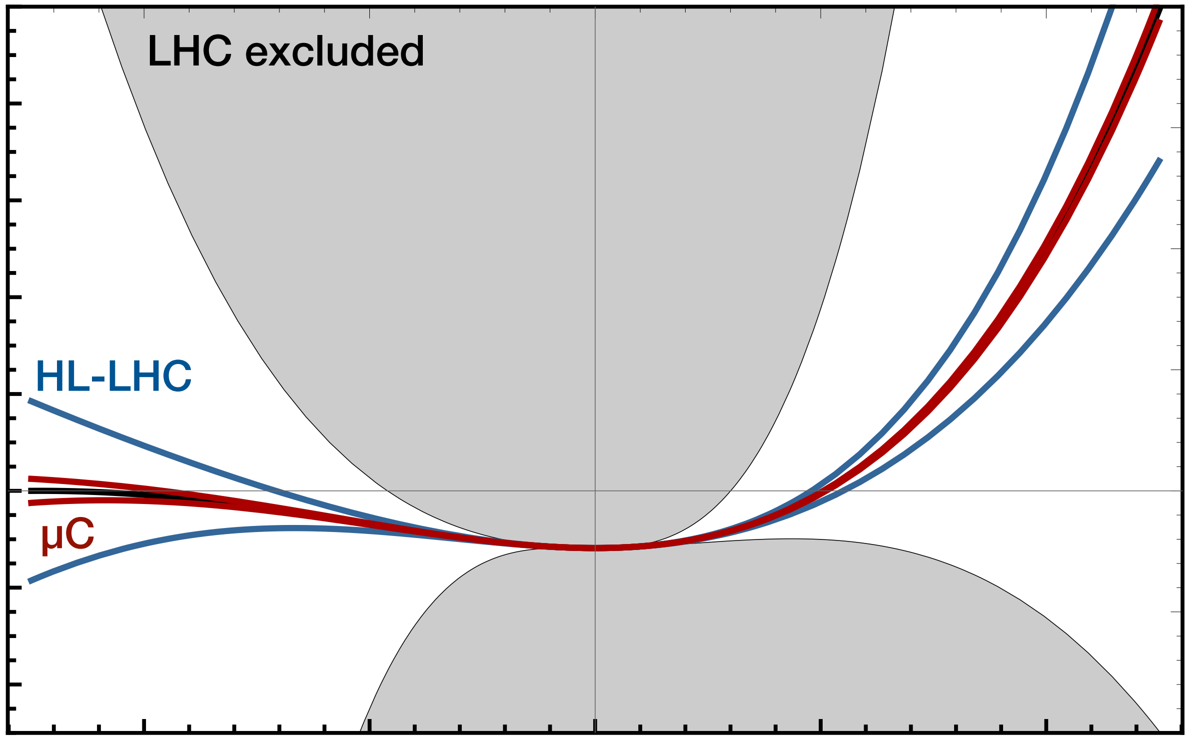
- Huge single Higgs rate in vector-boson-fusion: 10^7 Higgs bosons at 10 TeV
- Large double Higgs VBF rate
  - Higgs 3-linear coupling
- Triple Higgs production accessible
  - Higgs 4-linear coupling



Chiesa et al. 2003.13628

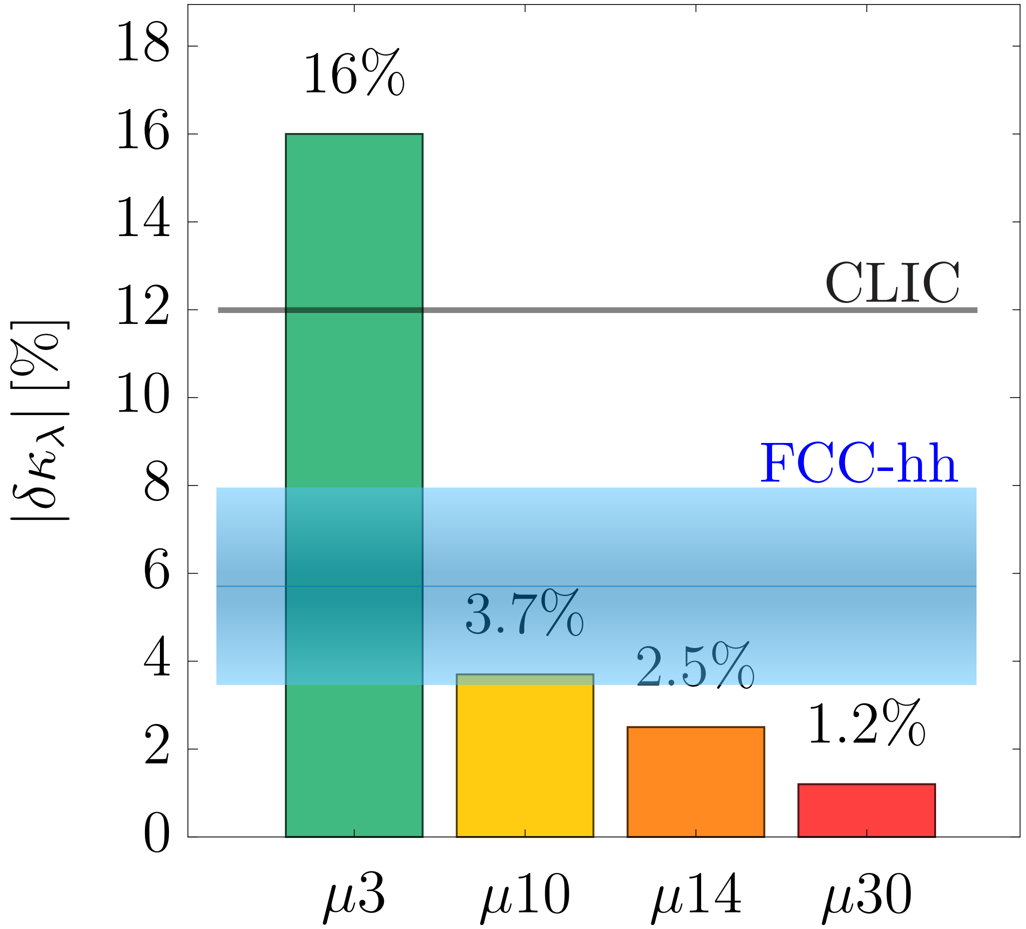
Double Higgs production

- 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



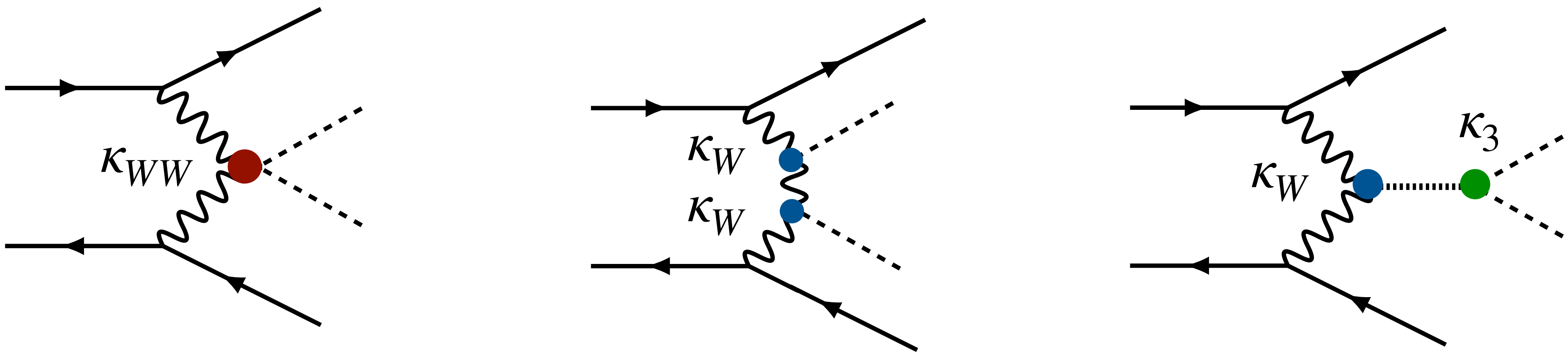
- Precise determination *only* possible at high-energy machines: FCC-hh or multi-TeV lepton collider

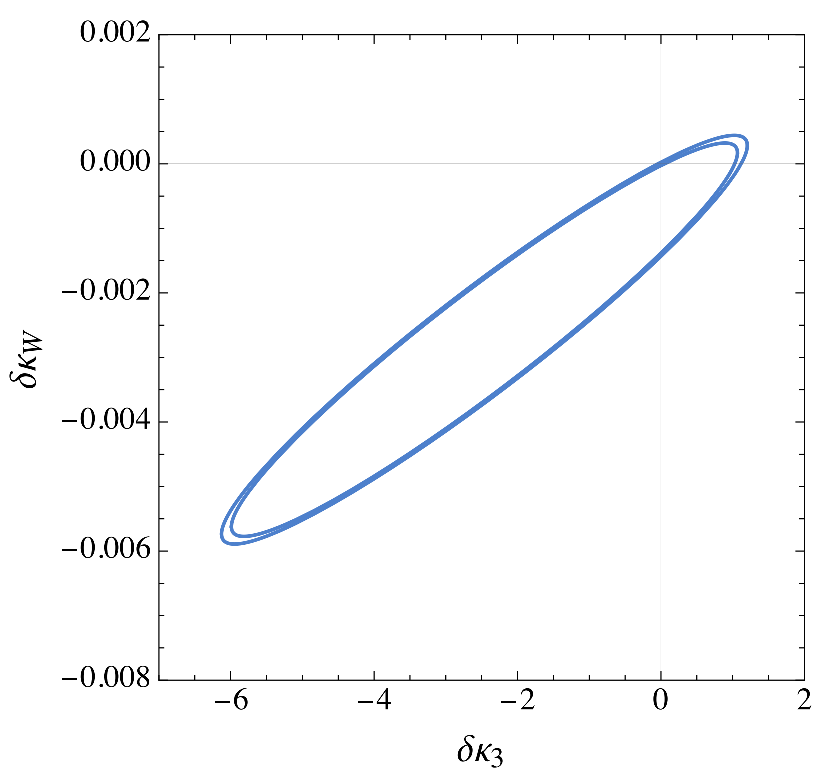
Mangano et al. 2004.03505
B, Franceschini, Wulzer 2012.11555
Costantini et al. 2005.10289

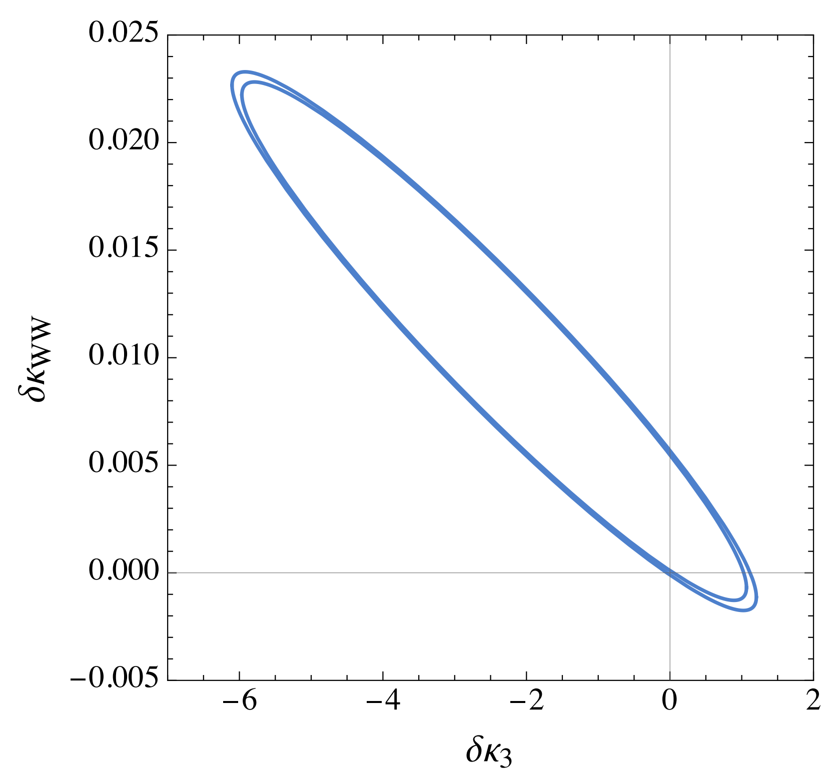
Han et al. 2008.12204
CLIC 1901.05897

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







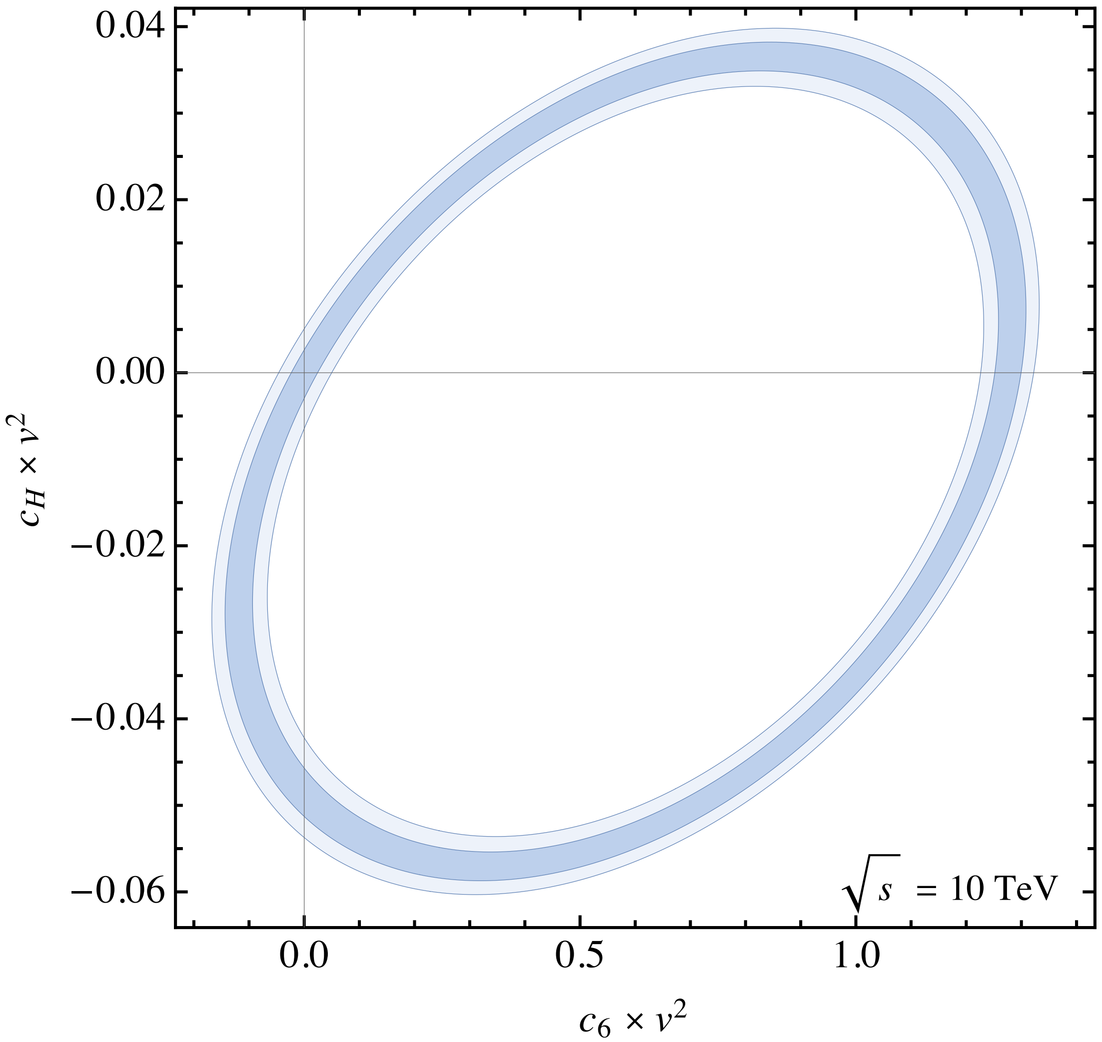
large degeneracy in total cross-section: coefficients not determined from *hh* production alone

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

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



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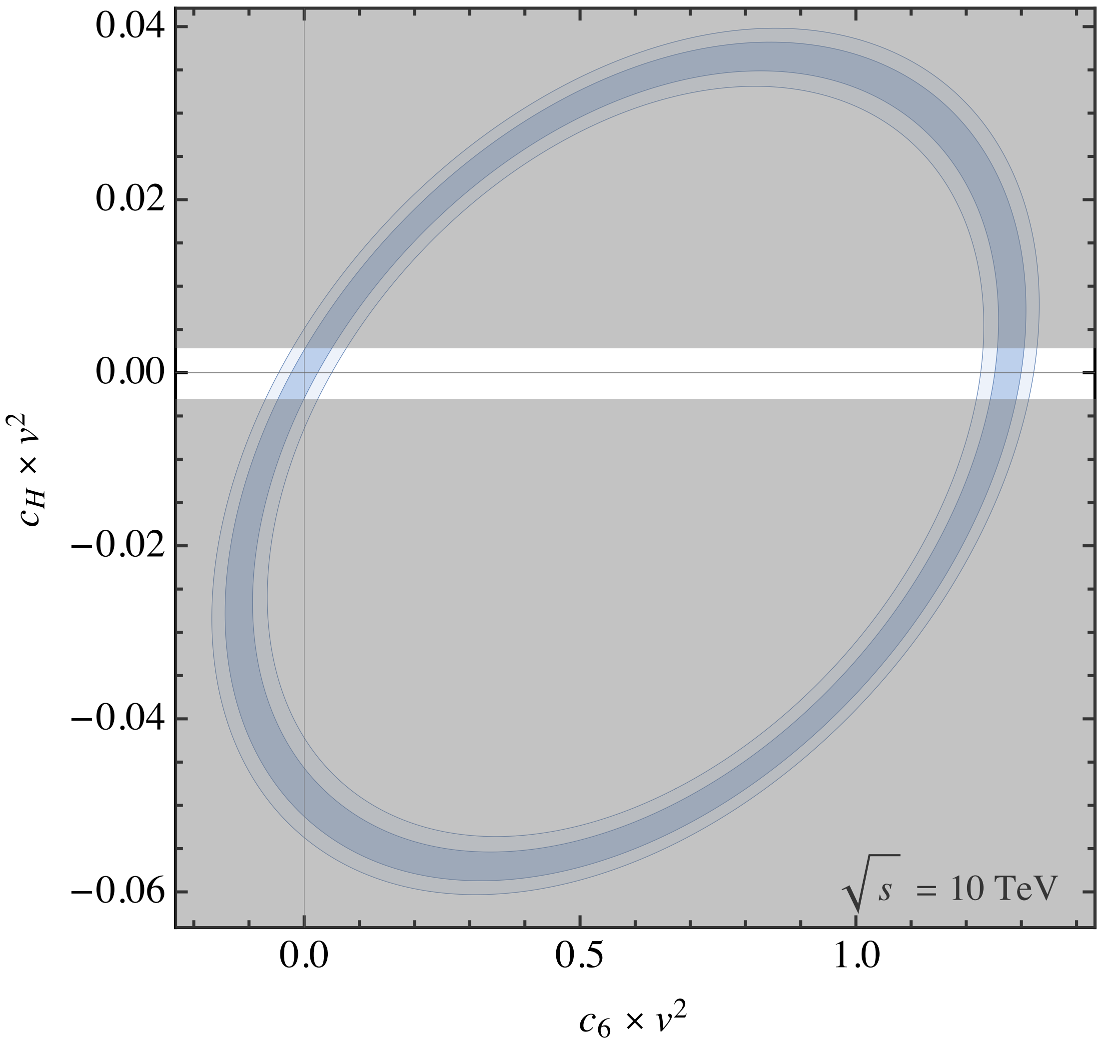


large degeneracy in total cross-section: coefficients not determined in general

O_H also affects all single Higgs couplings universally:

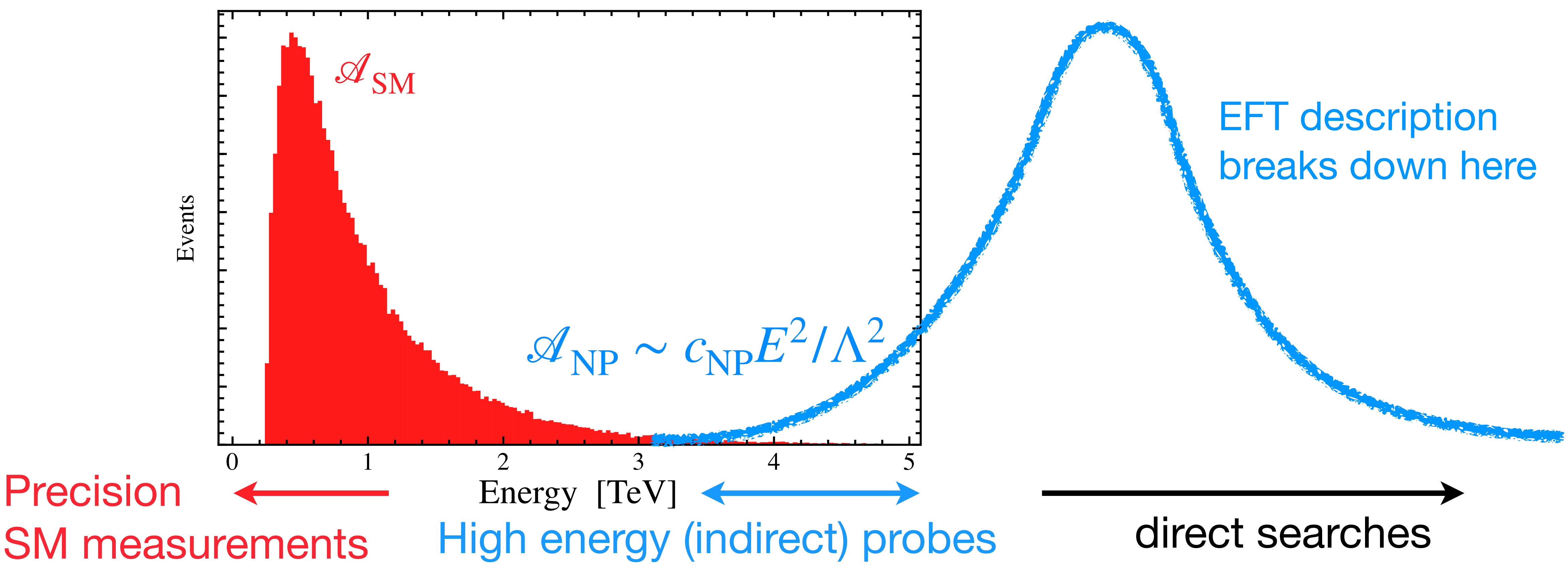
$$\kappa_{V,f} = 1 - v^2 C_H/2$$

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)

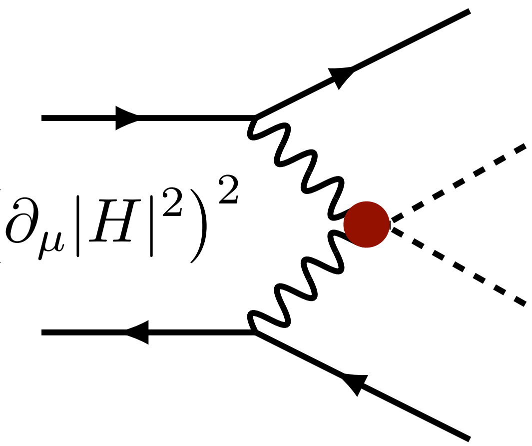
- NP effects are more important at high energies (≈ high-pT tails at LHC)



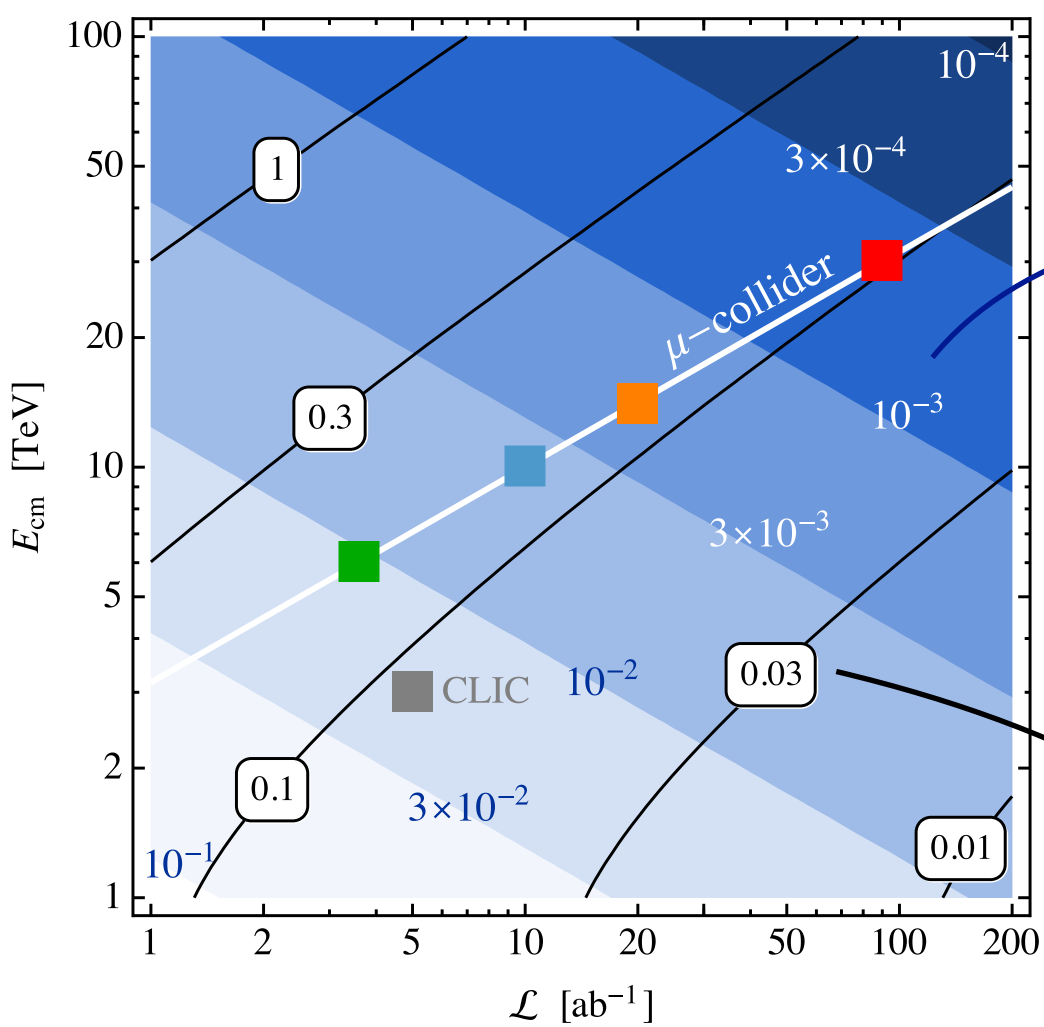
Double Higgs at high mass

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

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

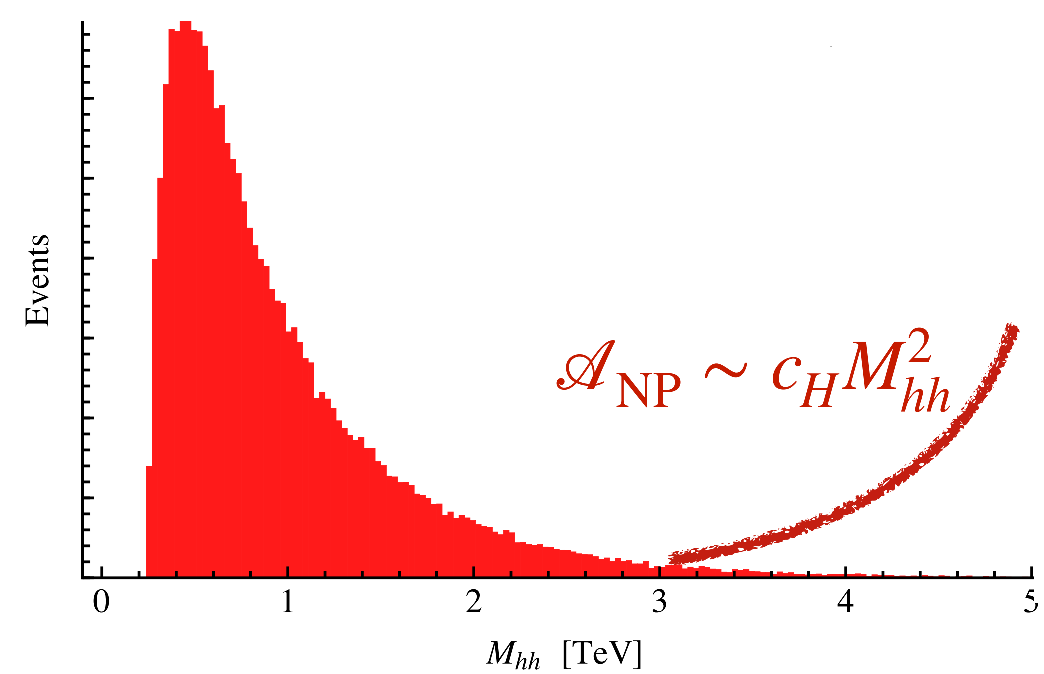


High-energy WW → *hh* more sensitive than Higgs pole physics at energies ≳ 10 TeV



$\xi \equiv C_H v^2$

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



(see also Contino et al. 1309.7038)

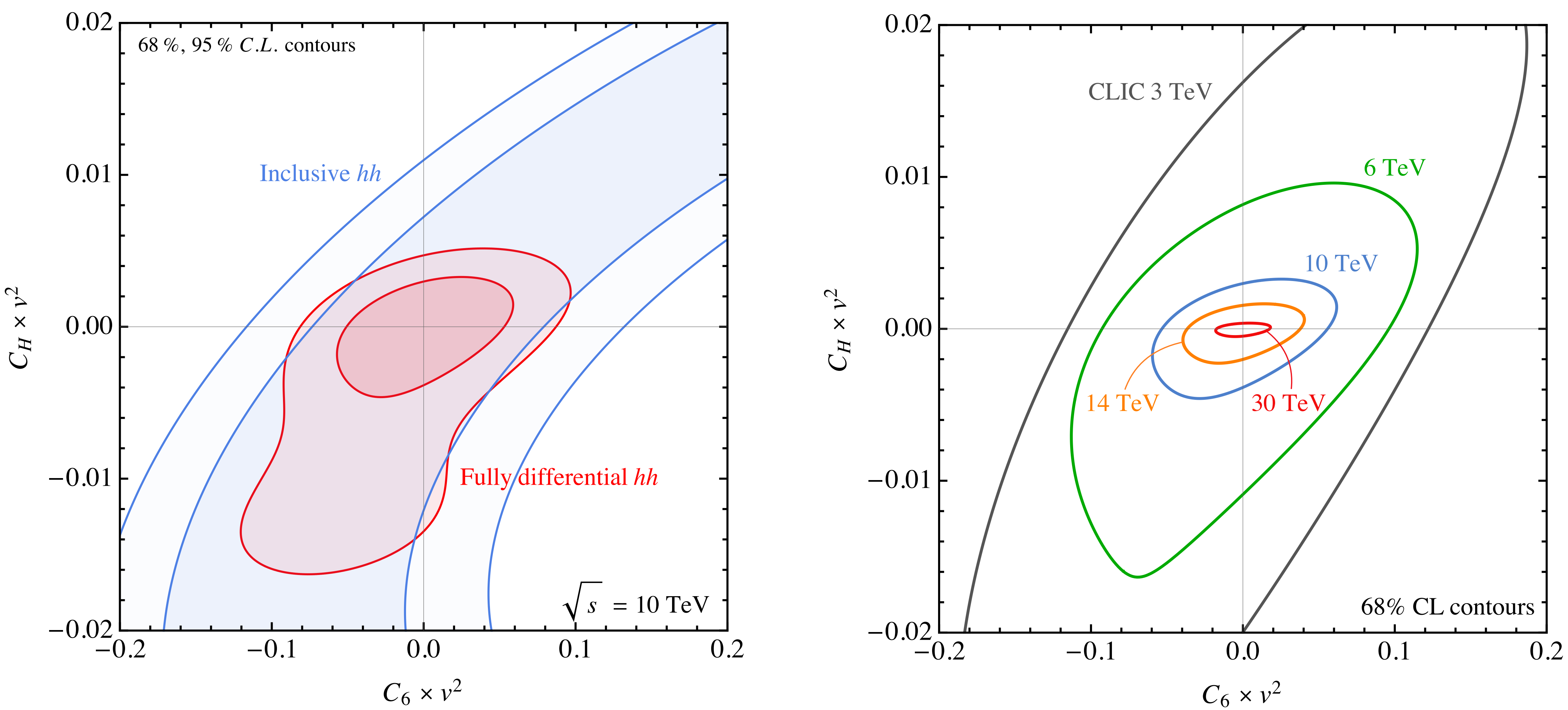
S/B low-precision measurement

Double Higgs at high mass

- SM Effective Theory: $\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i C_i \mathcal{O}_i^{(6)} + \cdots$
- 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}:



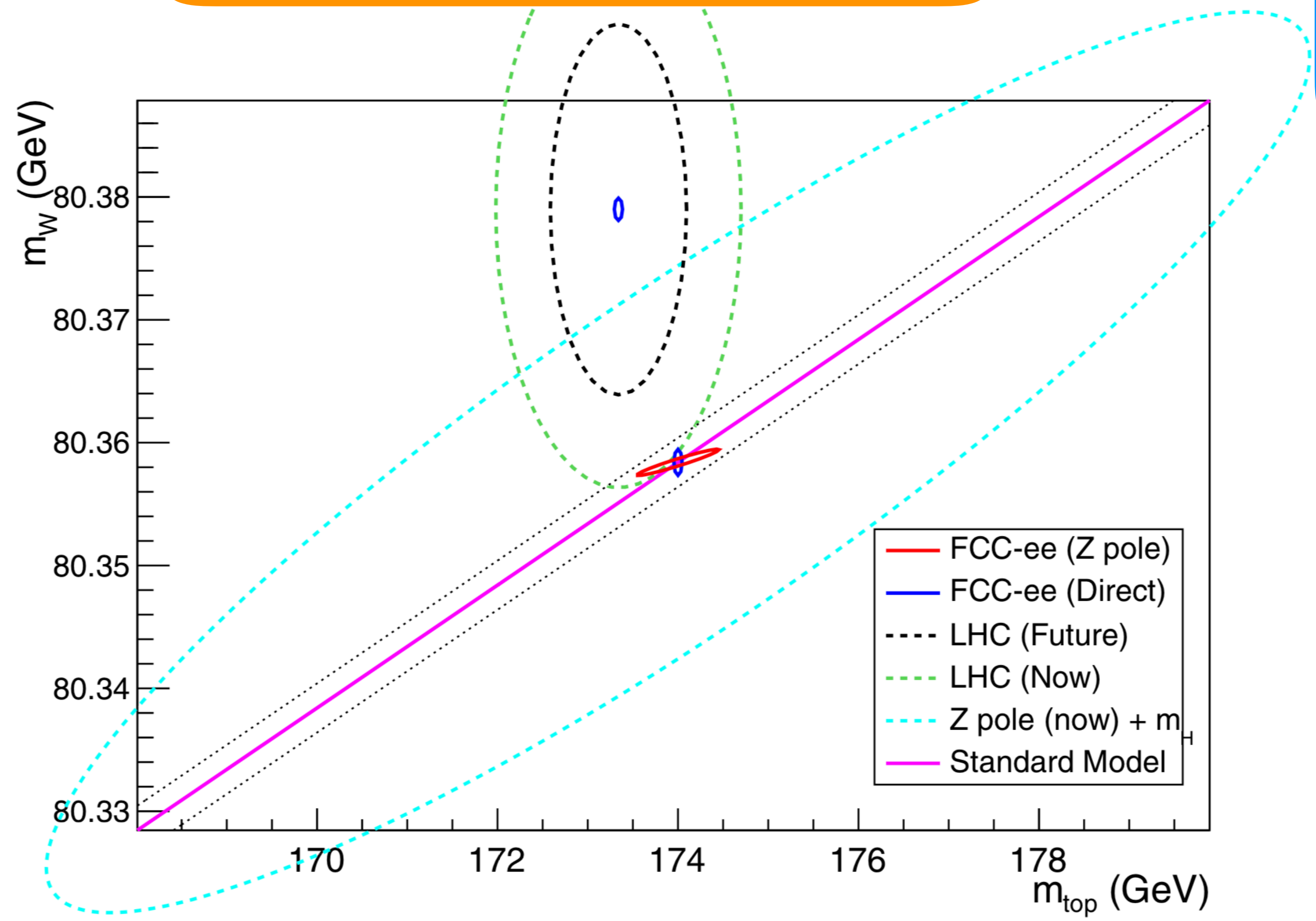
EW precision

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

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

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

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



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

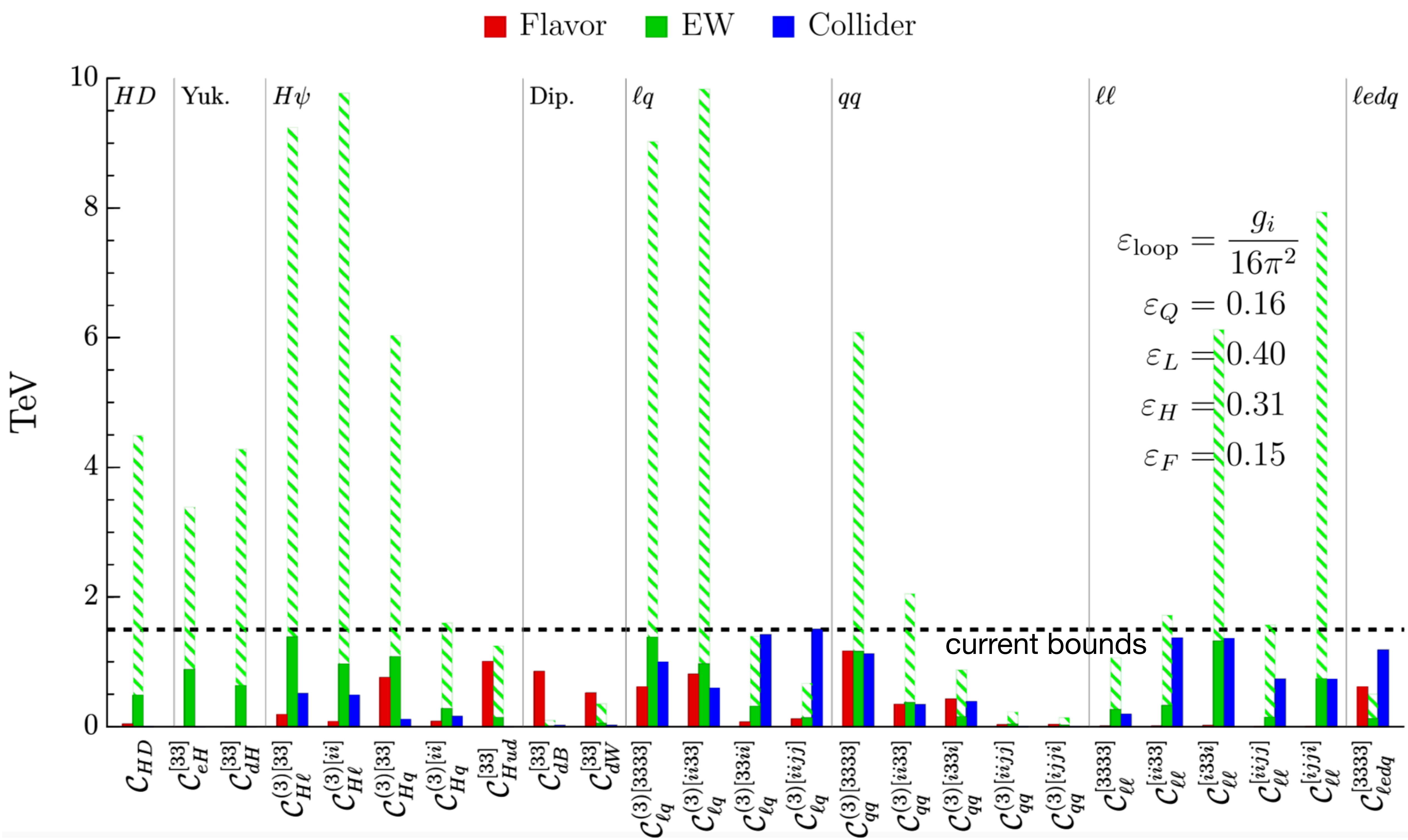
$$\Delta\hat{S} \sim \frac{m_W^2}{M_{\rm NP}^2} \lesssim \text{few} \times 10^{-5}$$

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

	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

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



Allwicher, Cornella, Isidori, Stefanek 2311.00020

Flavor @ FCC-ee

- Unique flavor physics program possible at FCC-ee!
  - ~ 10^{12} b quark pairs (and 10^{11} tau pairs) in a B-factory-like environment from Z boson decays

Decay mode/Experiment	Belle II (50/ab)	LHCb Run I	LHCb Upgr. (50/fb)	FCC-*ee*
EW/H penguins				
$B^0 \to K^*(892)e^+e^-$	~ 2000	~ 150	~ 5000	~ 200000
$\mathcal{B}(B^0 \to K^*(892)\tau^+\tau^-)$	~ 10	–	–	~ 1000
$B_s \to \mu^+\mu^-$	n/a	~ 15	~ 500	~ 800
$B^0 \to \mu^+\mu^-$	~ 5	–	~ 50	~ 100
$\mathcal{B}(B_s \to \tau^+\tau^-)$				
Leptonic decays				
$B^+ \to \mu^+\nu$	5%	–	–	3%
$B^+ \to \tau^+\nu$	7%	–	–	2%
$B_c^+ \to \tau^+\nu$	n/a	–	–	5%

[Table from S. Monteil]

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

→ $M_{\rm NP} \gtrsim$ several TeV, for NP coupled to 3rd family

complementary to other flavor probes

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?

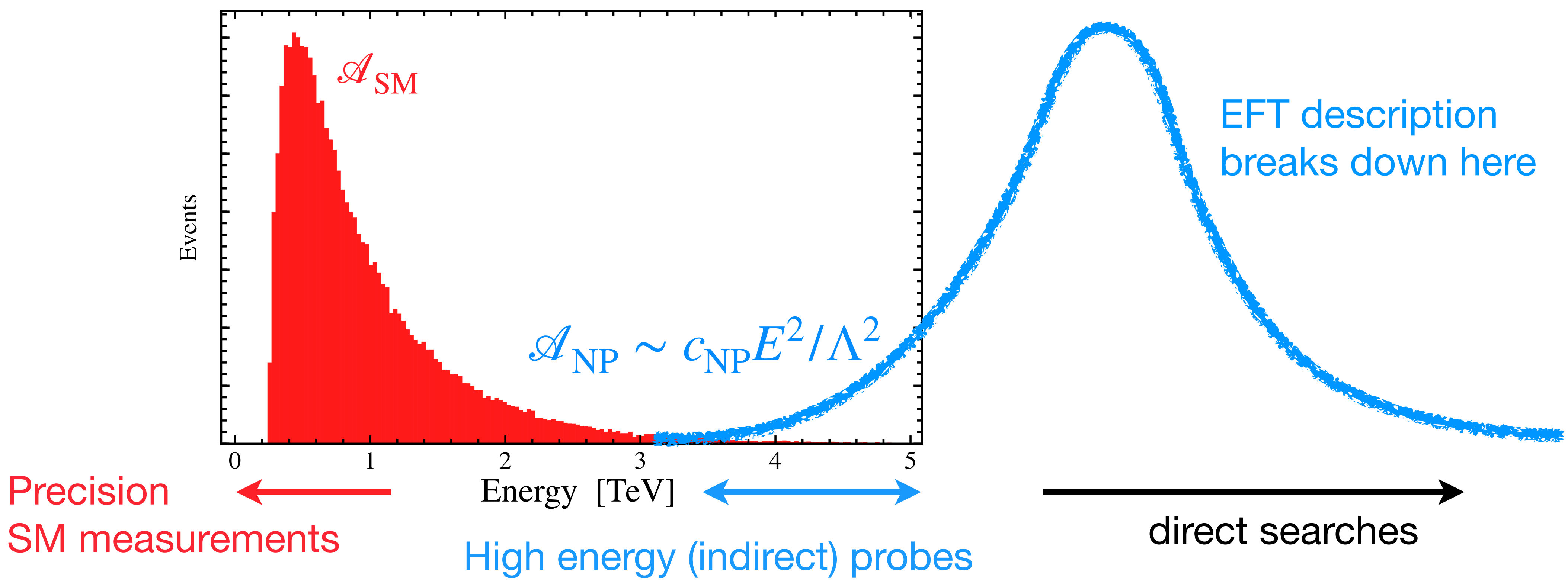
    Lepton asymmetries: $N_{\text{events}} = N_Z \times \text{BR}(Z \to \ell^+\ell^-) \times A_\ell \sim 3 \times 10^{-4}\, N_Z$

    $\implies N_Z \approx 10^{12}$ 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 $\mathscr{L} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2} \sum C_i \mathcal{O}_i$



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

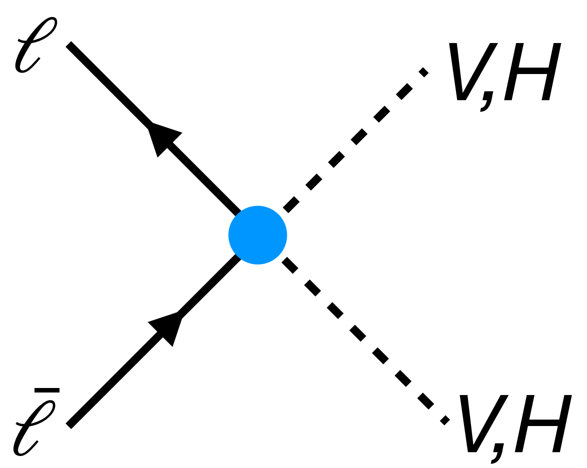
- Effective at LHC, FCC-hh, CLIC: “energy helps accuracy”…

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

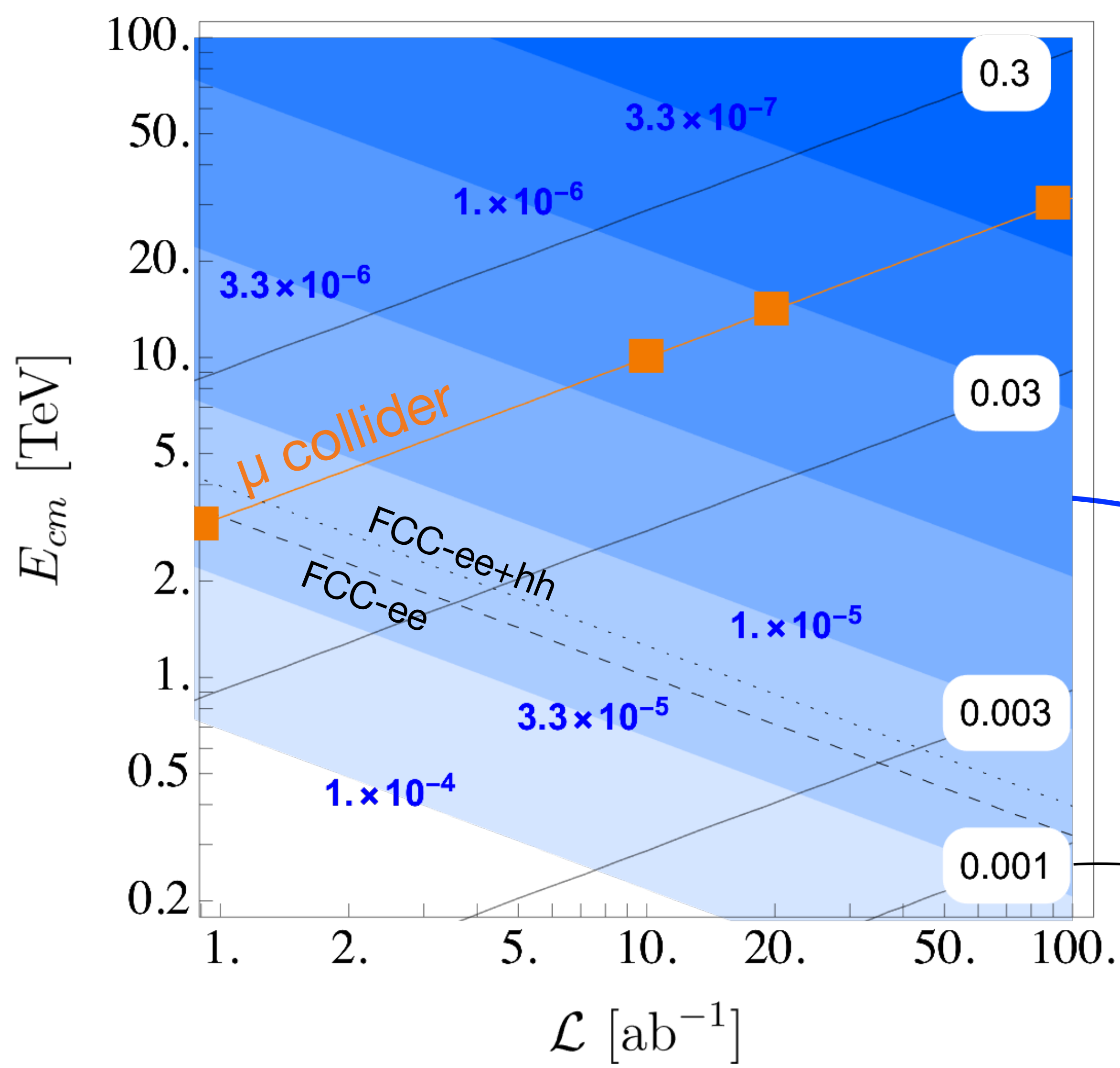
- Longitudinal 2 → 2 scattering amplitudes at high energy:



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

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

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



related with Z-pole observables

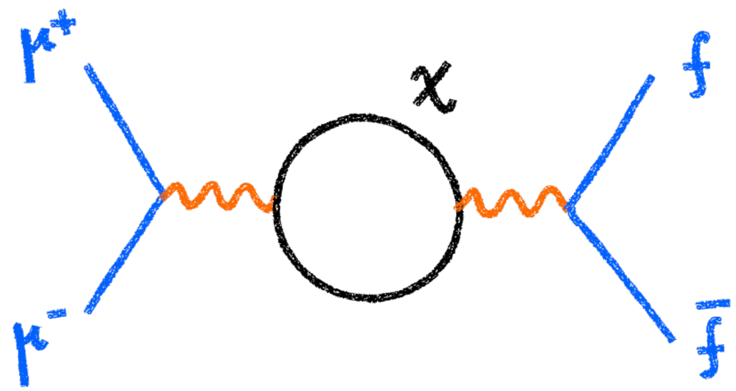
$$\hat{S} = m_W^2 (C_W + C_B)$$

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

precision of measurement

EW-charged matter

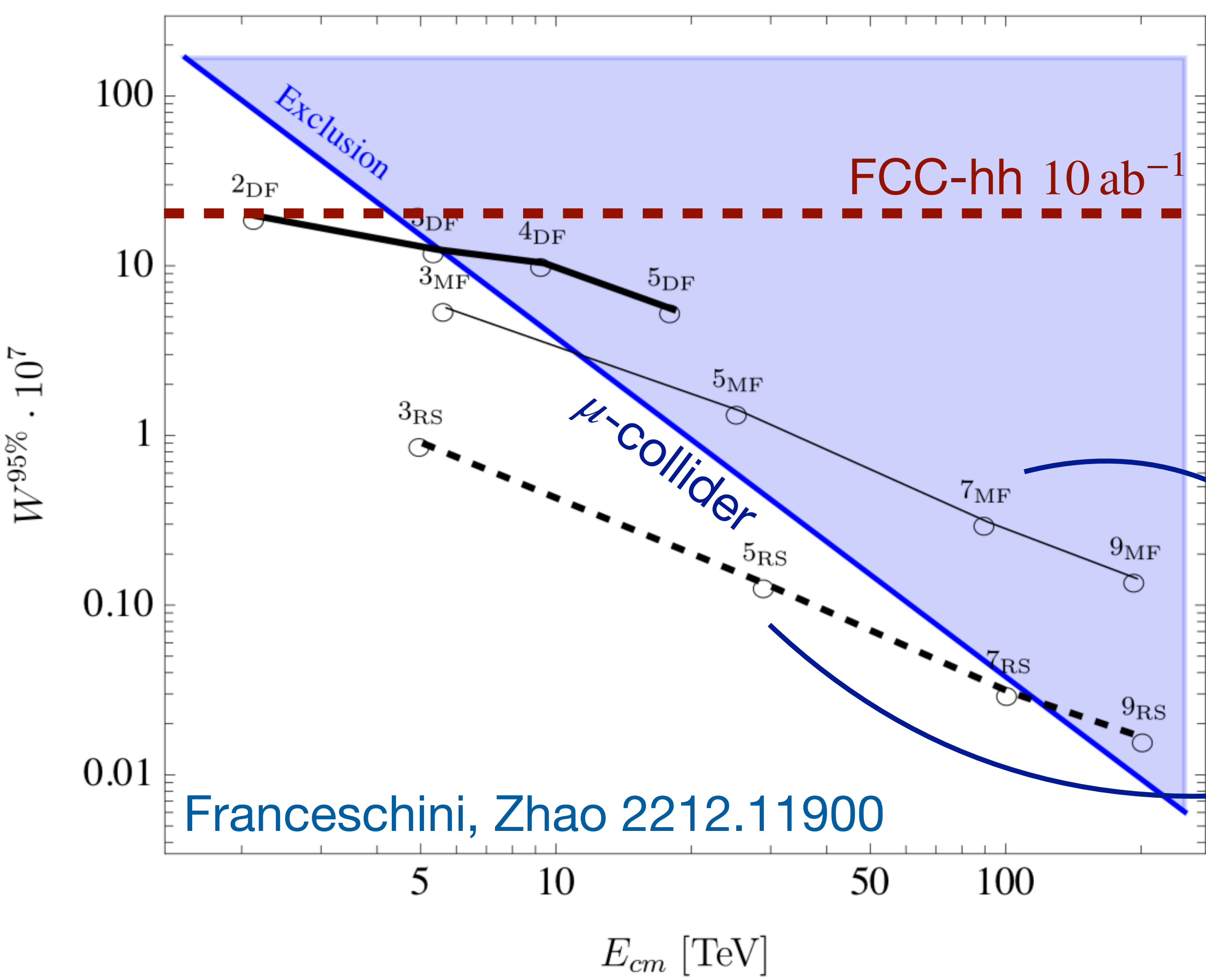
- All EW multiplets contribute to high-energy 2 → 2 fermion scattering: effects that grow with energy, can be tested at μ collider



can be WIMP dark matter if M ~ few TeV

Cirelli, Fornengo, Strumia hep-ph/0512090

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



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

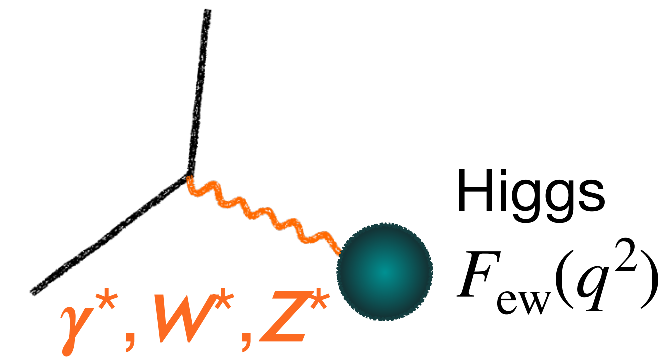
$$\hat{Y} \approx 10^{-7} \times \left(\frac{1\,\text{TeV}}{M_{\text{DM}}}\right)^2 Y^2 n \propto 1/n^4$$

right of blue line: can be tested indirectly

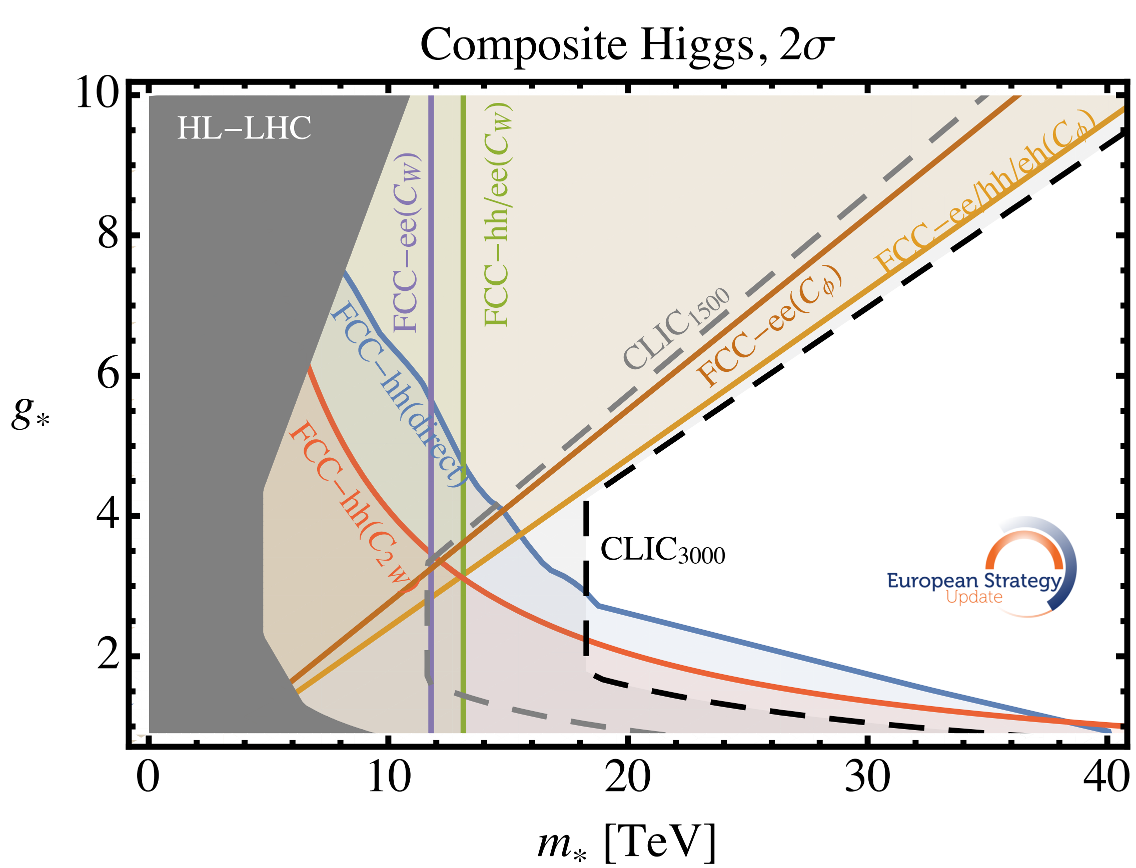
left of blue line: can be tested directly

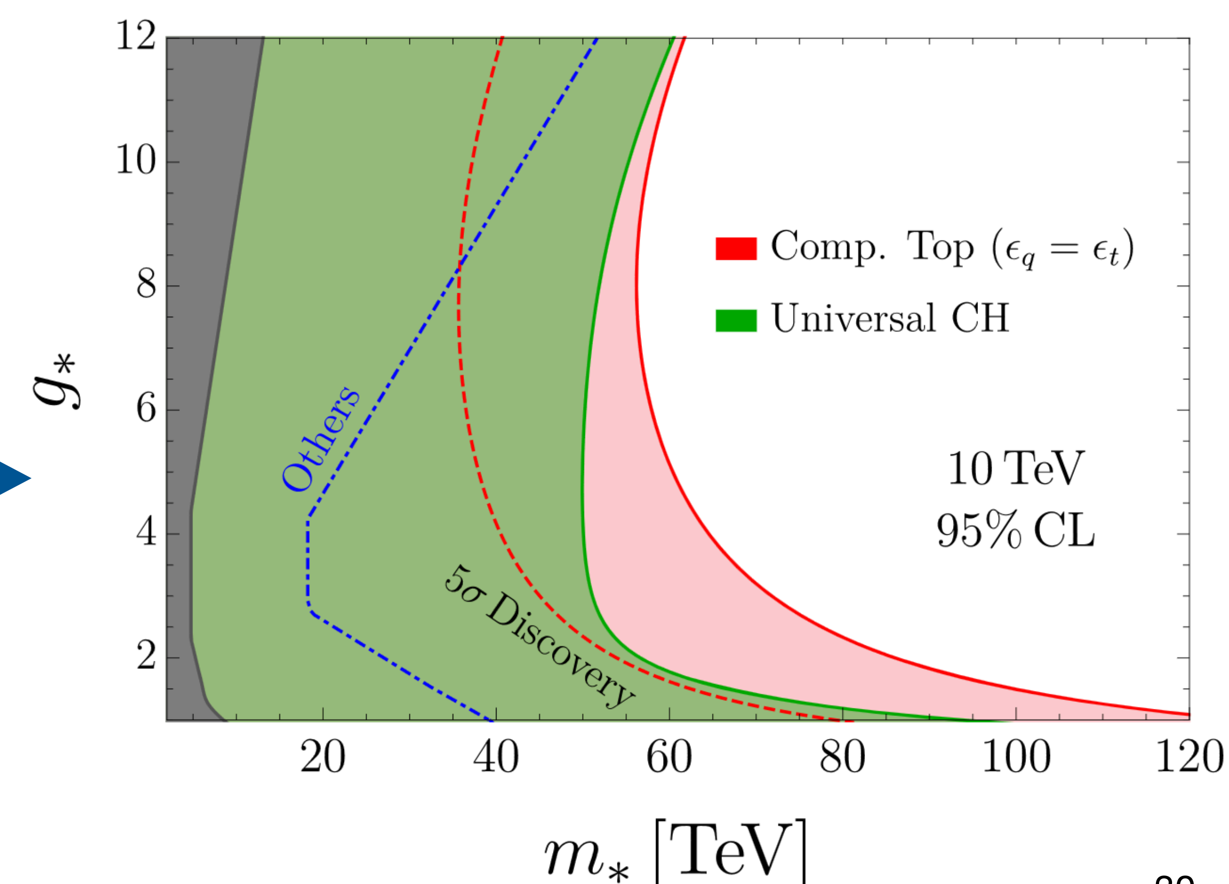
High-energy probes: EW & Higgs physics

- 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



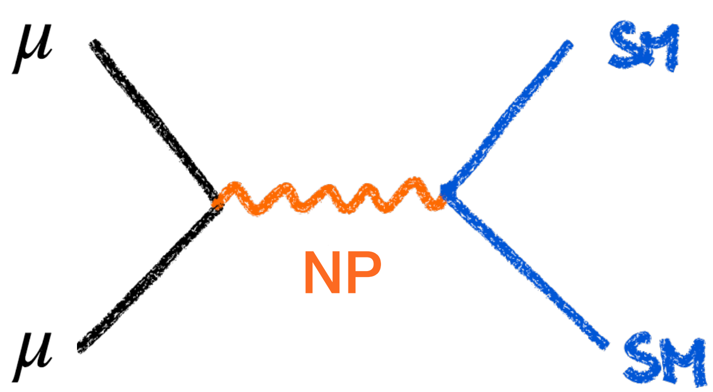
- Example: new physics with mass $m_\star$ and coupling $g_\star$ to Higgs



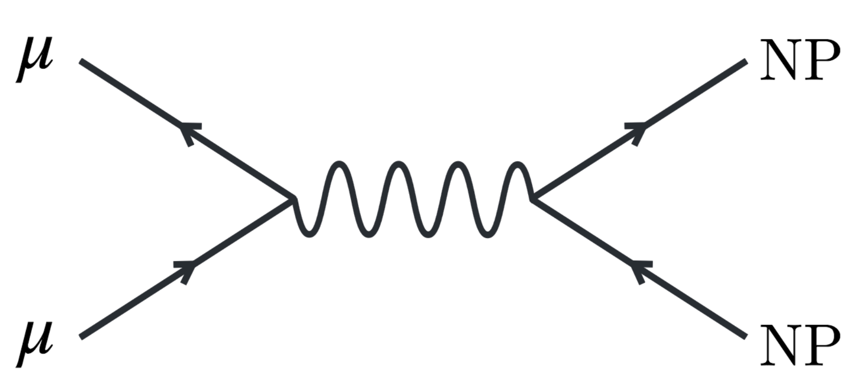


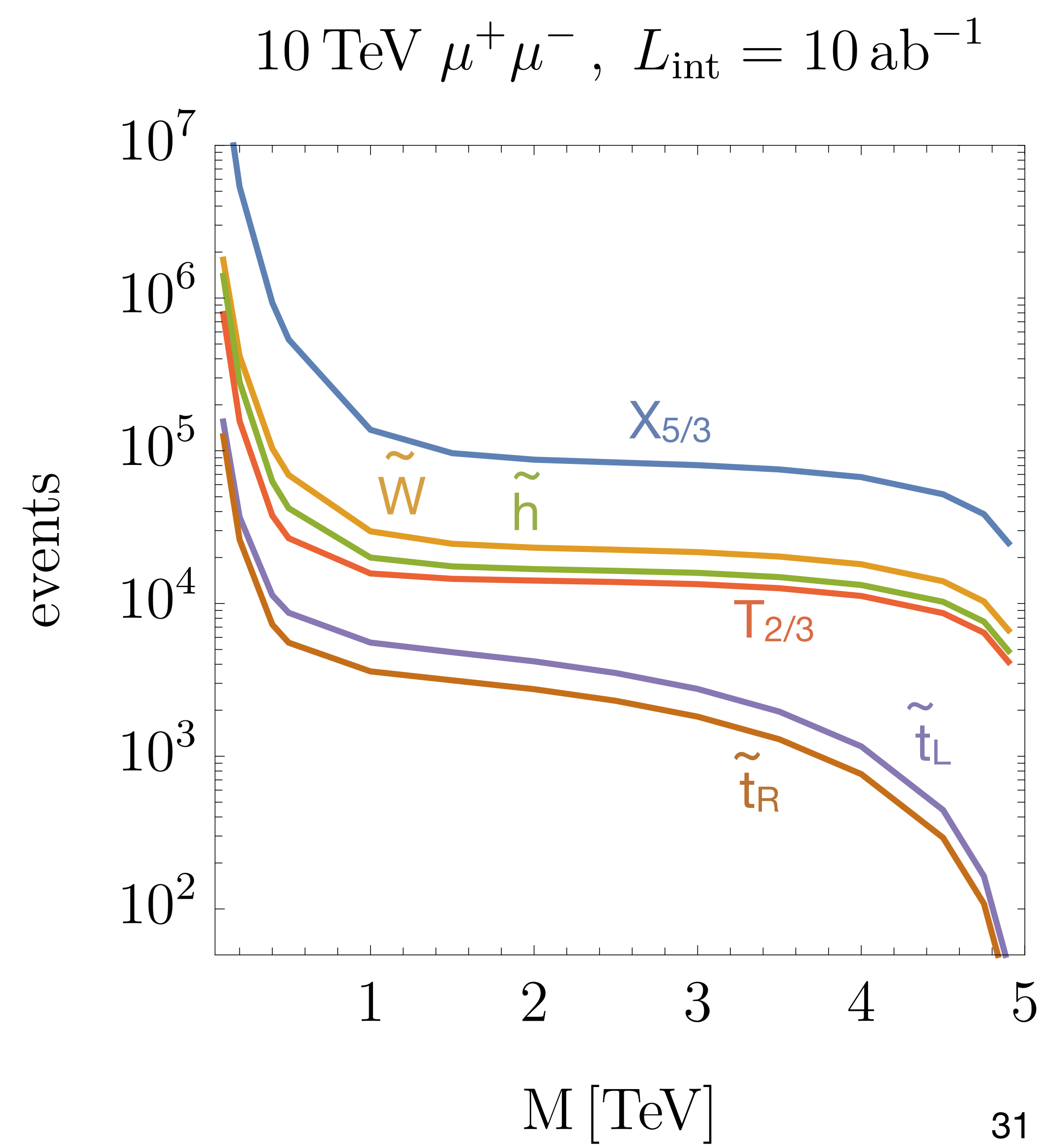
Direct searches

- Main motivation for a muon collider: ability to collide elementary particles at very high energies $\Longrightarrow$ **directly explore physics at 10+ TeV**



- Produce pairs of EW particles *up to kinematical threshold:* no loss of energy due to parton distribution functions!

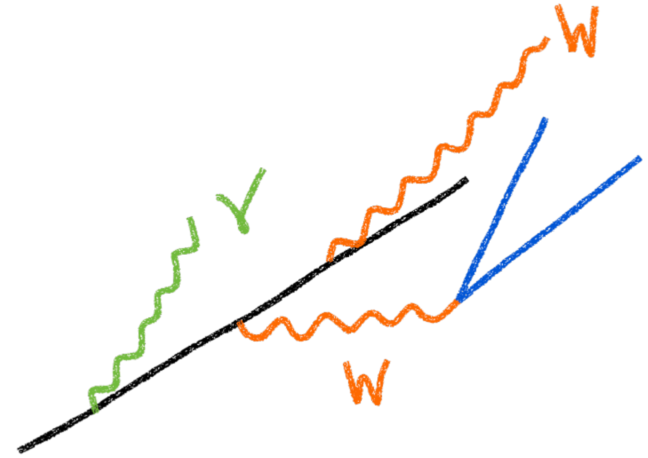




EW radiation

EW radiation becomes important at multi-TeV energies!

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

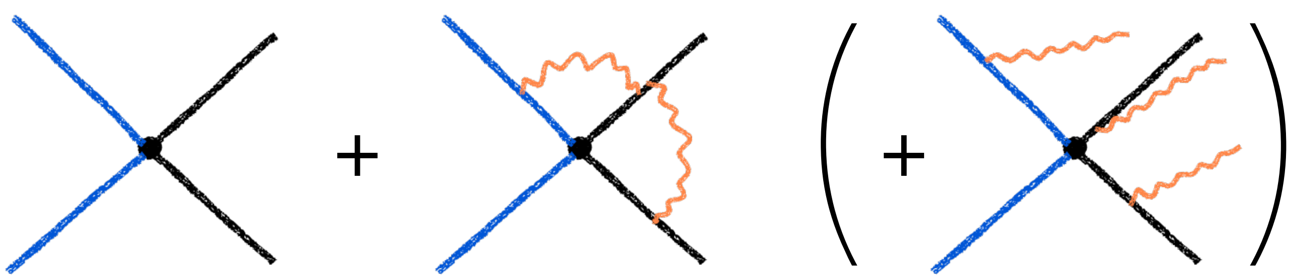


- ✦ $m_{W,Z} \ll E$: γ, W, Z are all similar!
- ✦ Multiple gauge boson emission is not suppressed

Sudakov factor $\frac{\alpha}{4\pi}\log^2\left(\frac{E^2}{m_W^2}\right)$ × 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

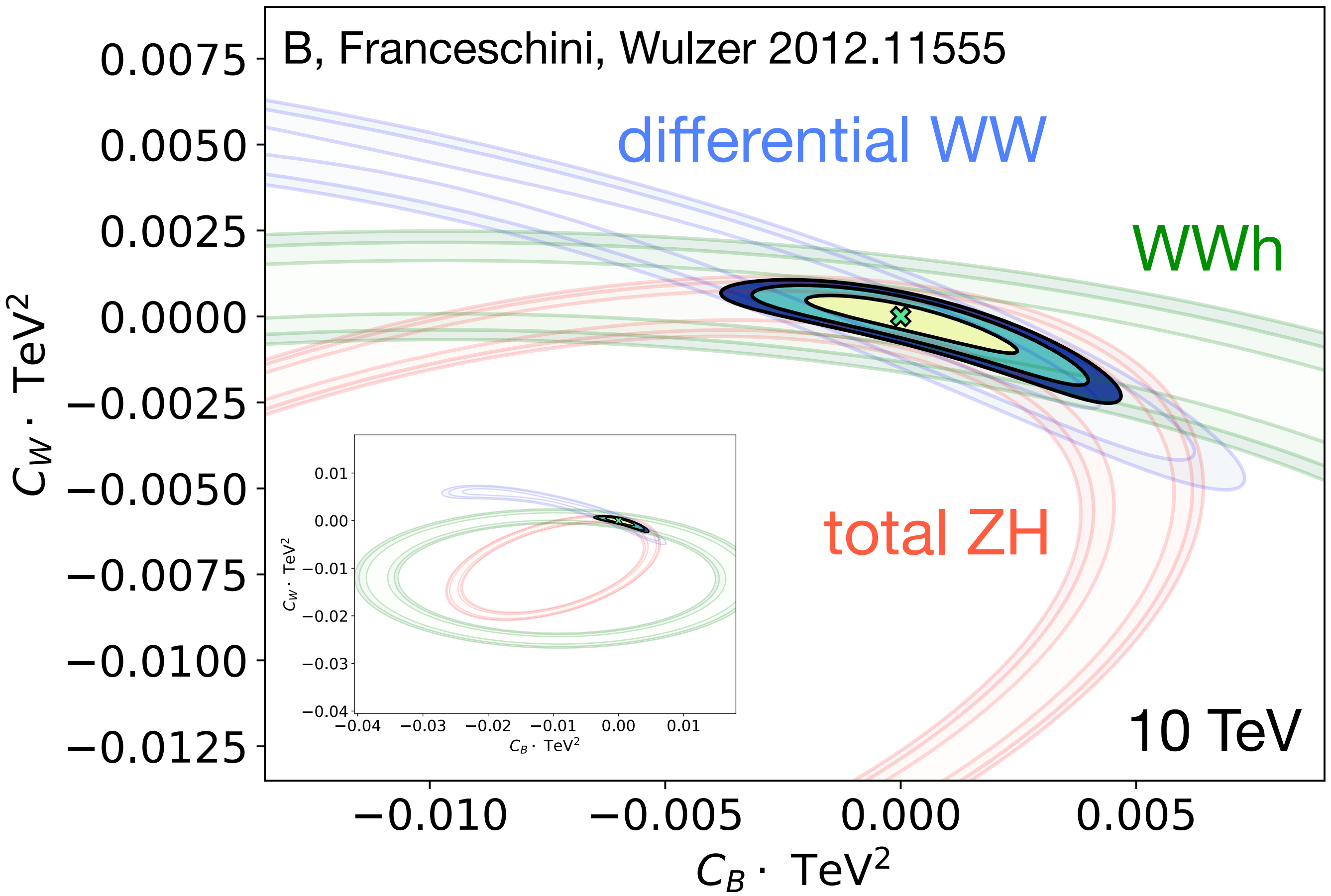


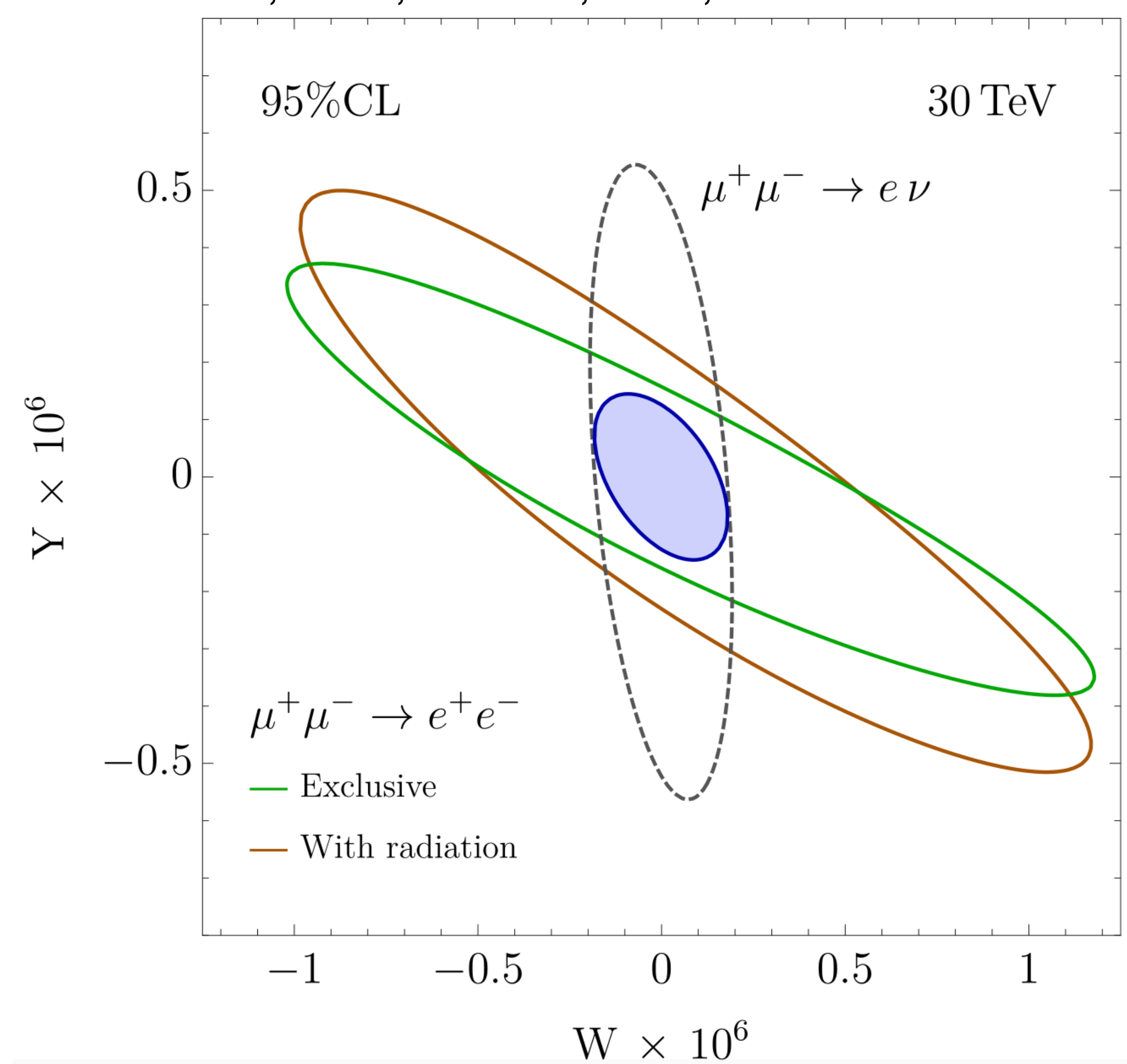
☛ Initial state is EW-charged:

(Precise) resummation of double logs needed. Goal: % or ‰ precision

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

EW radiation

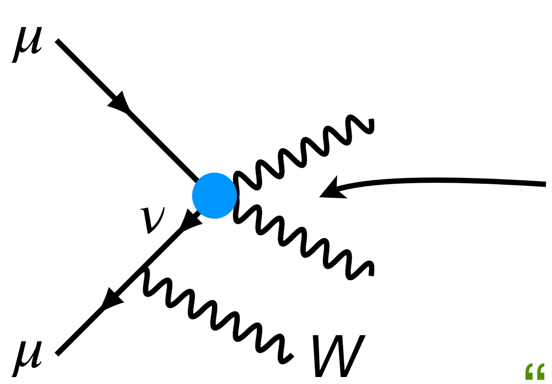




Gauge boson radiation important:

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, …

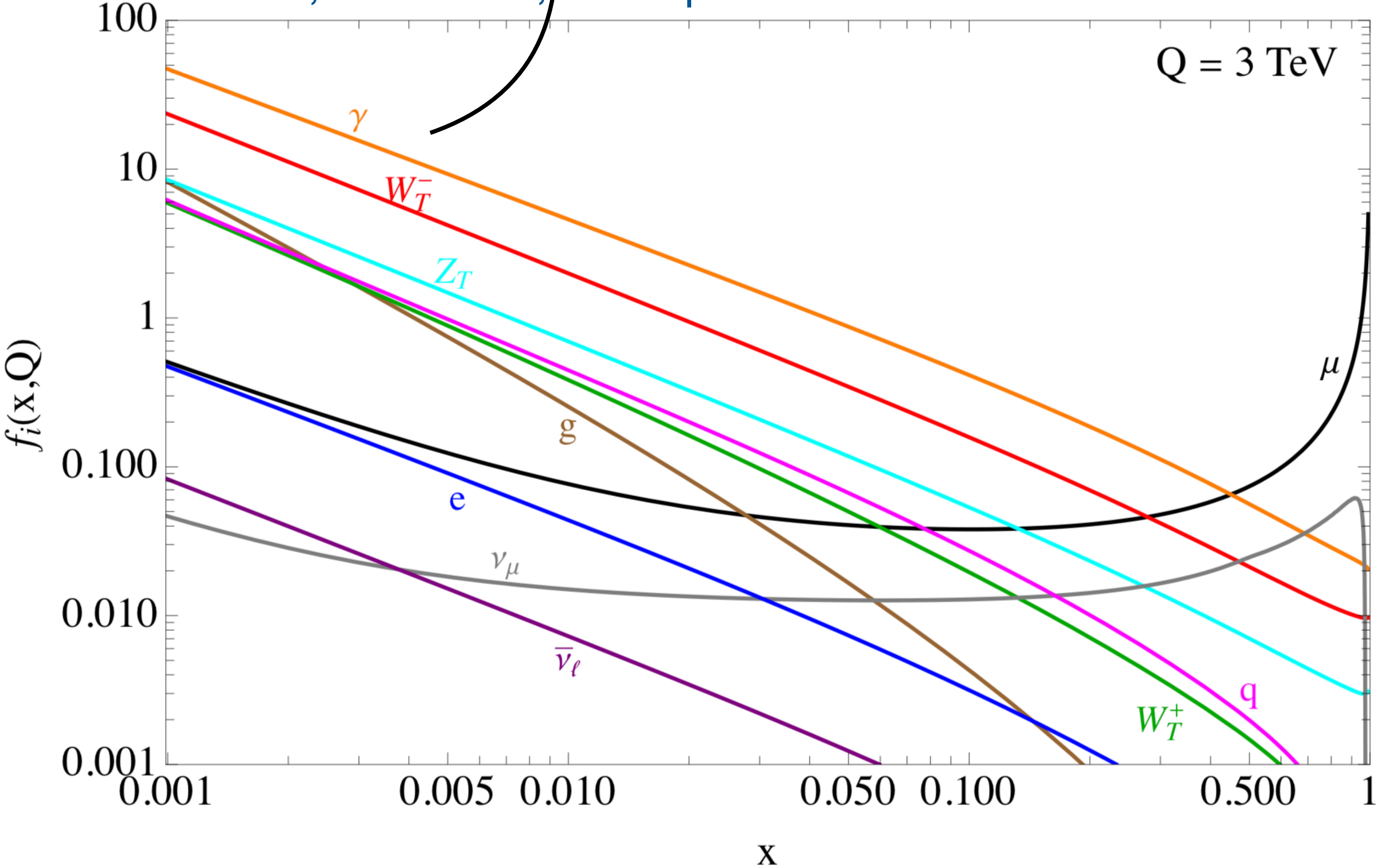
EW radiation

- Resummation of large logarithms: lepton PDF

Soft + collinear radiation: VBF

Elementary leptons: hard 2 → 2 scattering

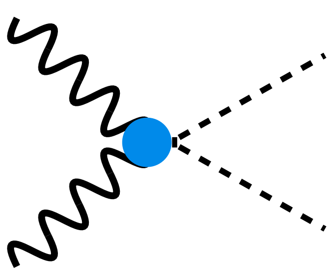
Garosi, Marzocca, Trifinopoulos 2303.16964



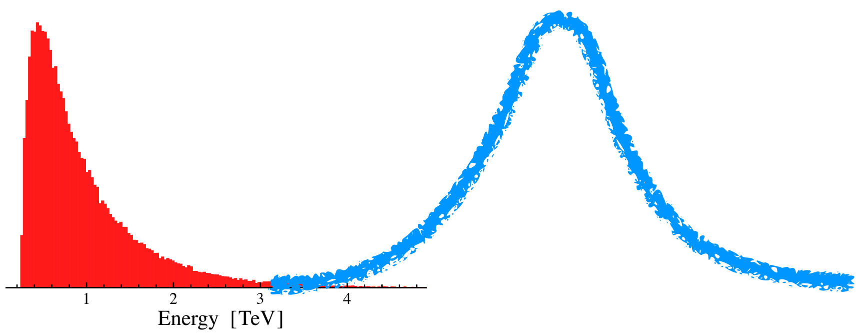
Summary

- 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

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

    The easiest way to reach 10 TeV (indirectly)

  - **High-energy $\mu^+\mu^-$ collider:** collide elementary particles at the energy frontier.

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

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

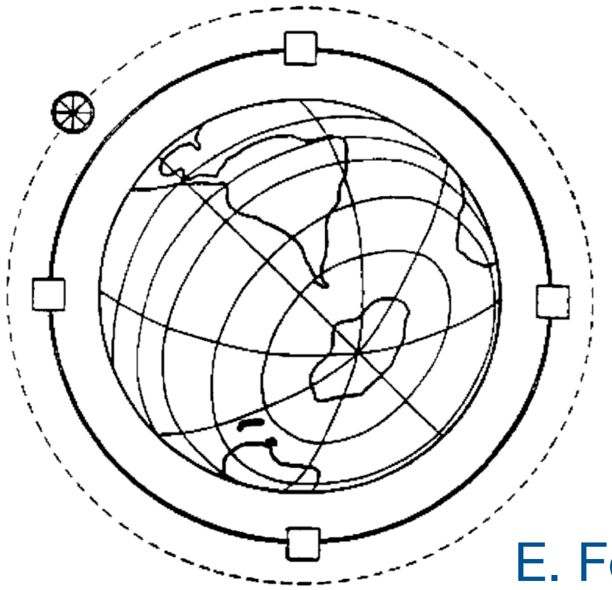
Summary

- 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…

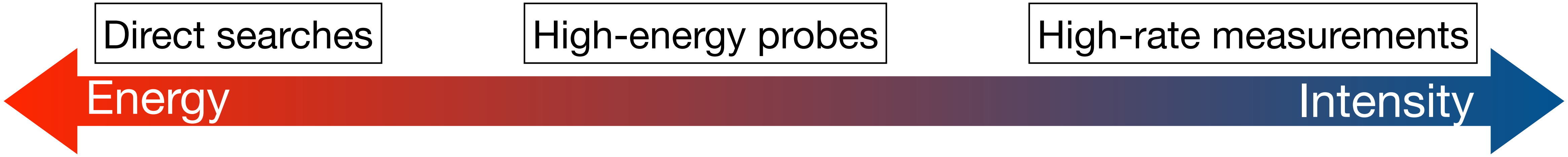
- We need to start planning the next collider now, to ensure a physics program after LHC. Today e^+e^- EW & Higgs factory is the only option.

- New technologies will be crucial to progress in high-energy physics!

  Feasibility of a high-energy muon collider will be a game changer: both energy and precision



E. Fermi, 1954

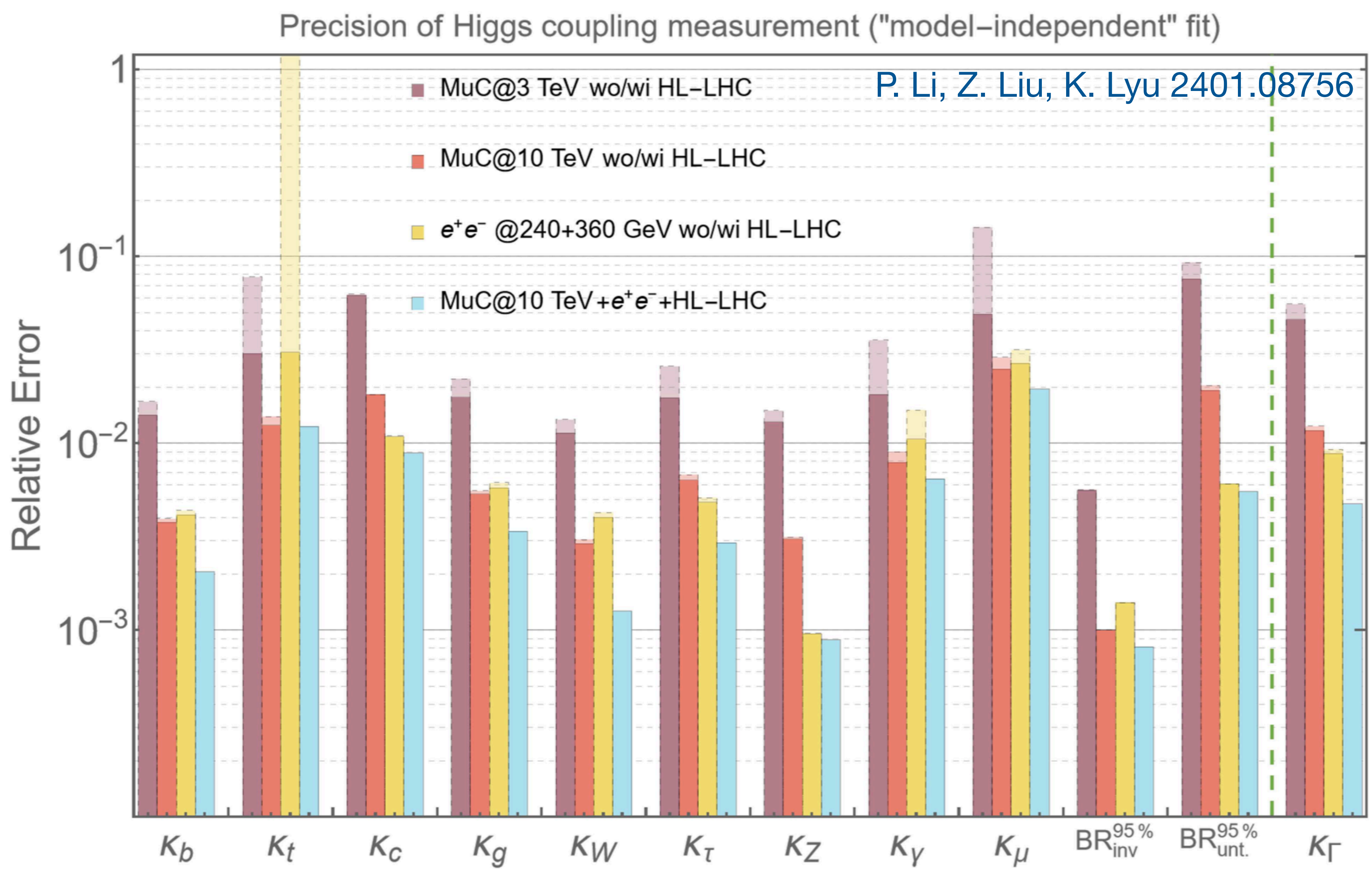


Backup

Higgs couplings at muon collider

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

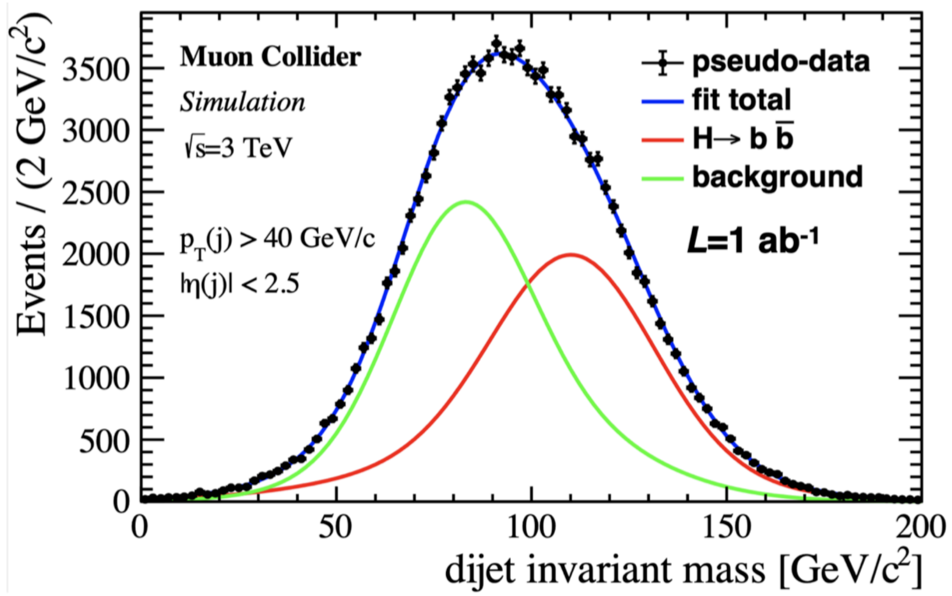
- Single Higgs couplings can more easily be studied at e^+e^- factory! *(most likely before a μC!)*



Single Higgs: backgrounds

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

L. Sestini et al.



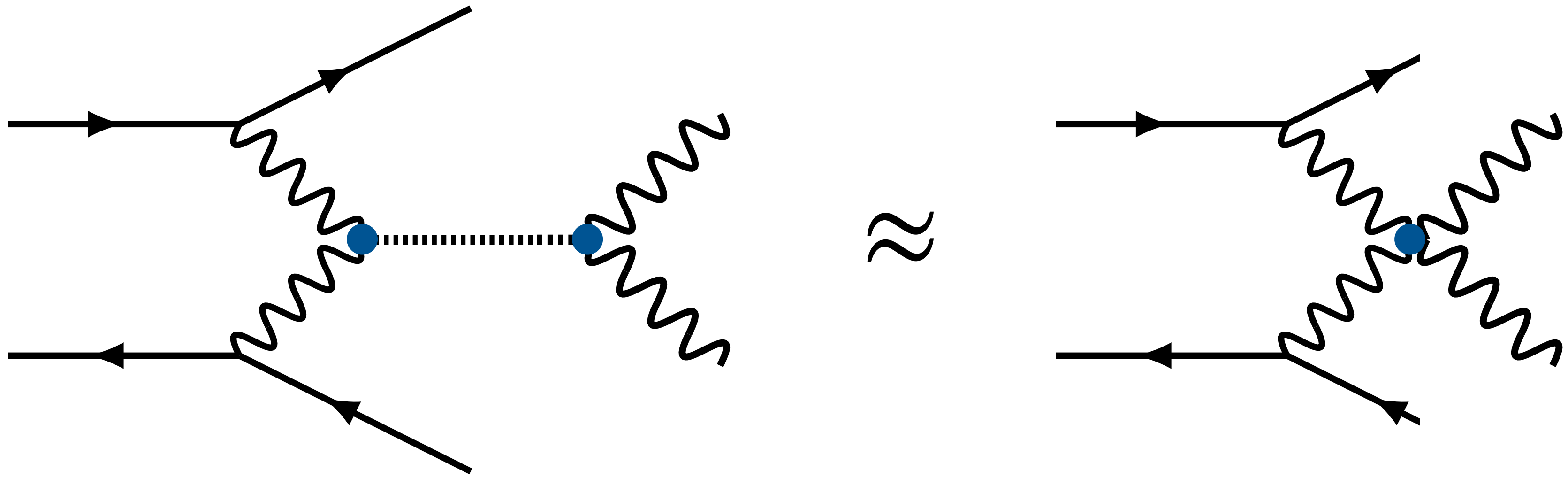
- Detector performance
  - “soft” and forward particles

Production	Decay	$\Delta\sigma/\sigma$ (%) 3 TeV	$\Delta\sigma/\sigma$ (%) 10 TeV	Signal Only 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

Forslund, Meade
2203.09425

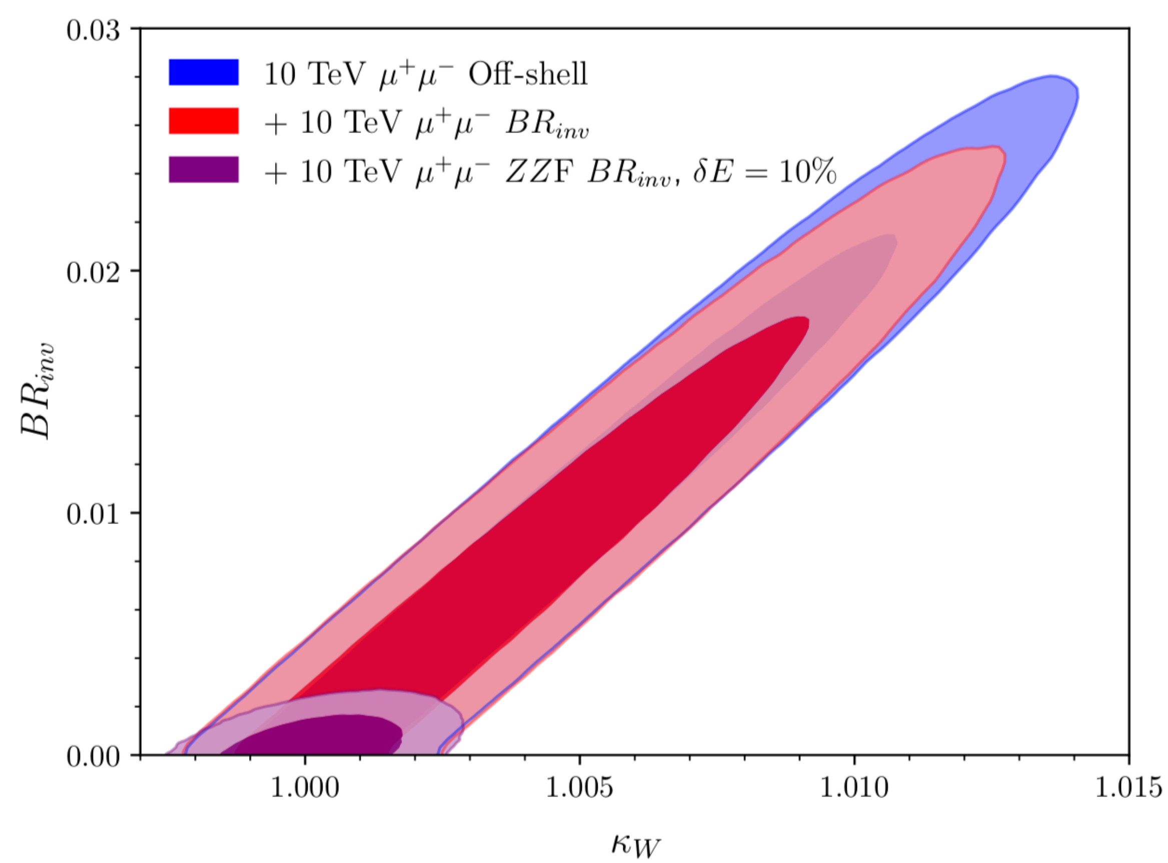
Single Higgs at high mass (off-shell)

- Off-shell single Higgs production: independent of width



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

Forslund, Meade 2308.02633

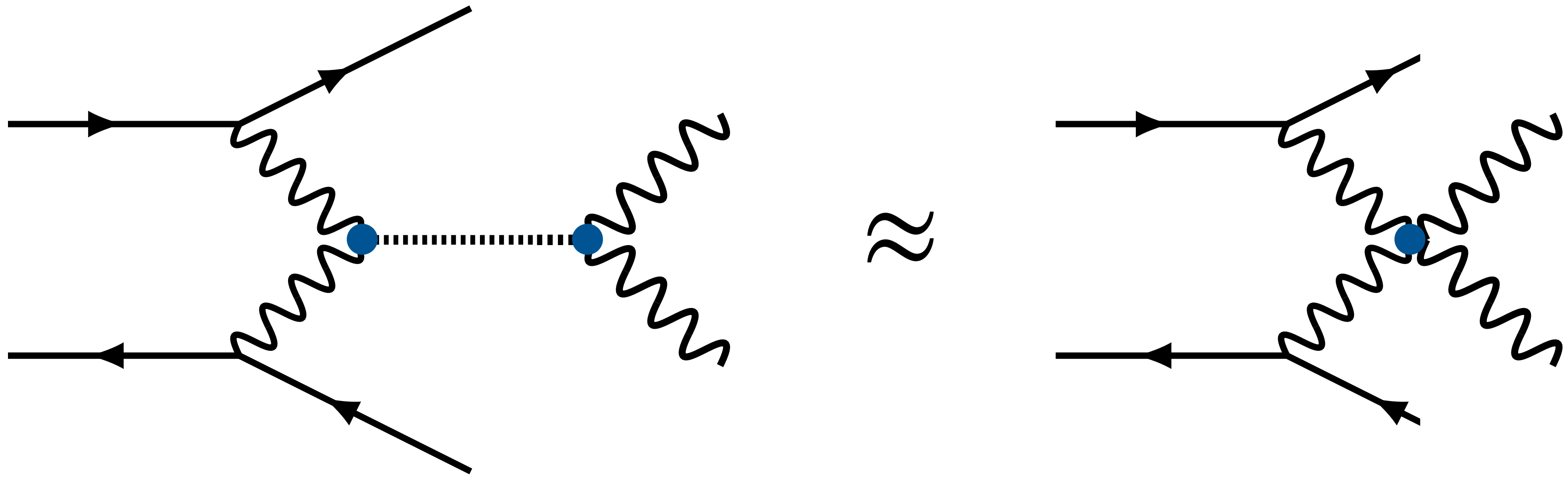


precision limited (~ 3%) due to backgrounds: not possible to determine κ_W precisely through WW scattering

➔ correlation width vs. coupling

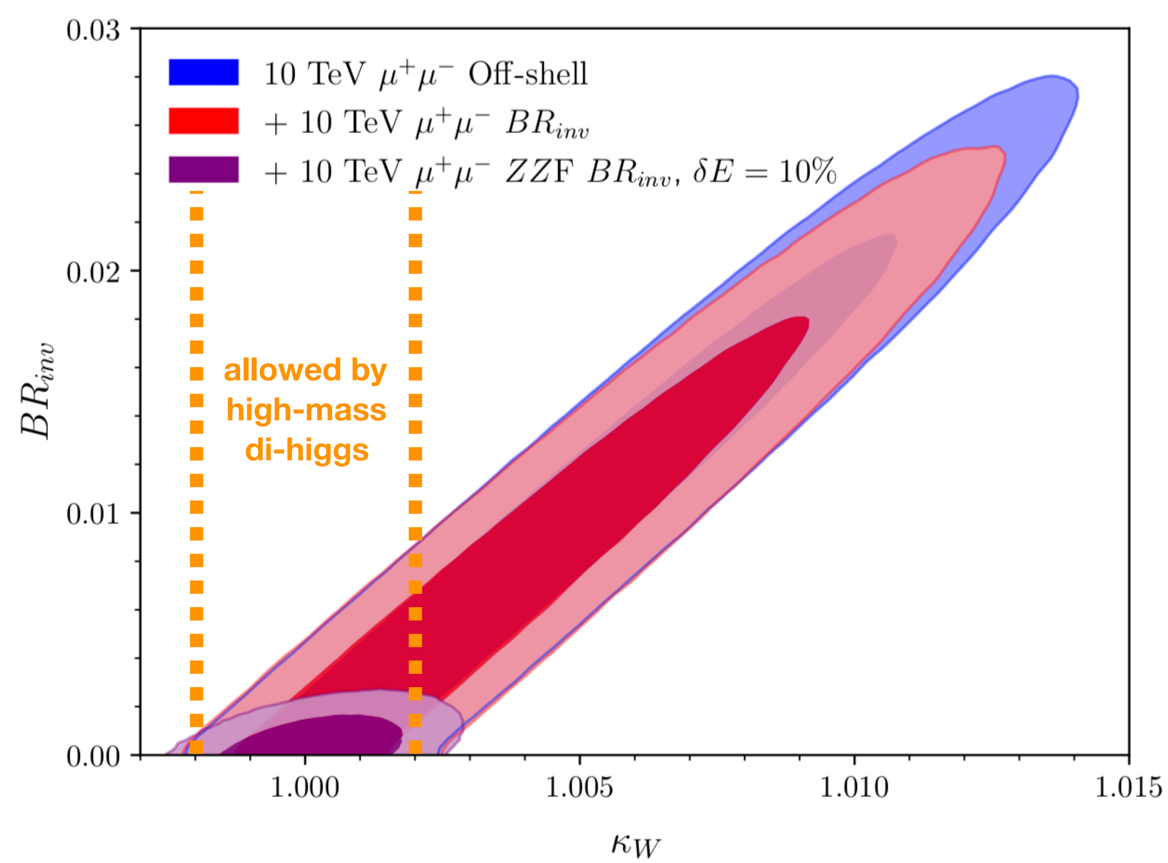
Single Higgs at high mass (off-shell)

- Off-shell single Higgs production: independent of width



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

Forslund, Meade 2308.02633



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

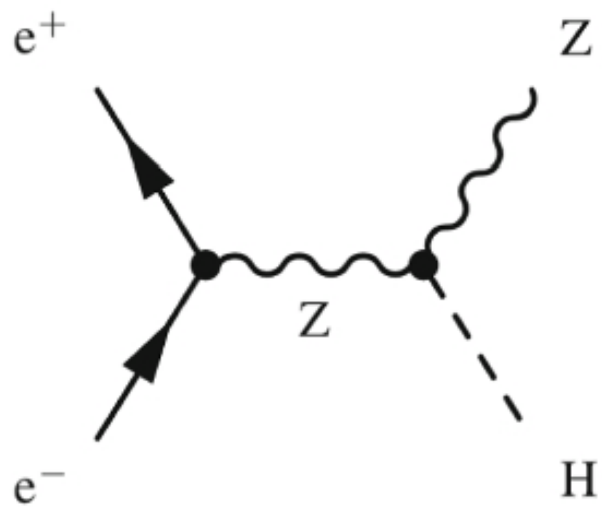
➔ correlation width vs. coupling

Inclusive Higgs search

- Caveat: single Higgs at μC can access only

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

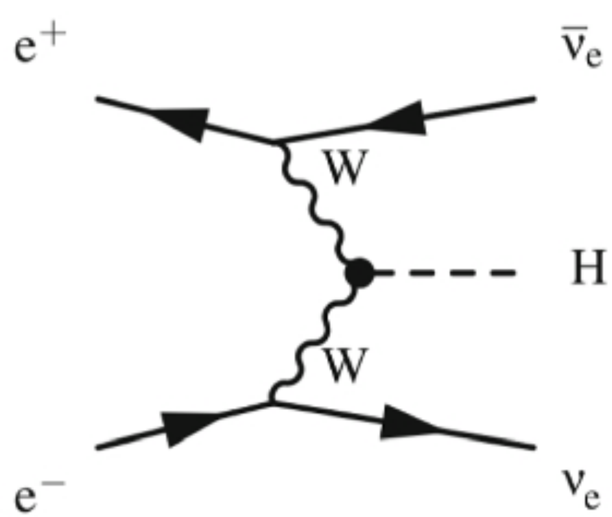
Higgsstrahlung



$s = (p_h + p_Z)^2$

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

WW fusion



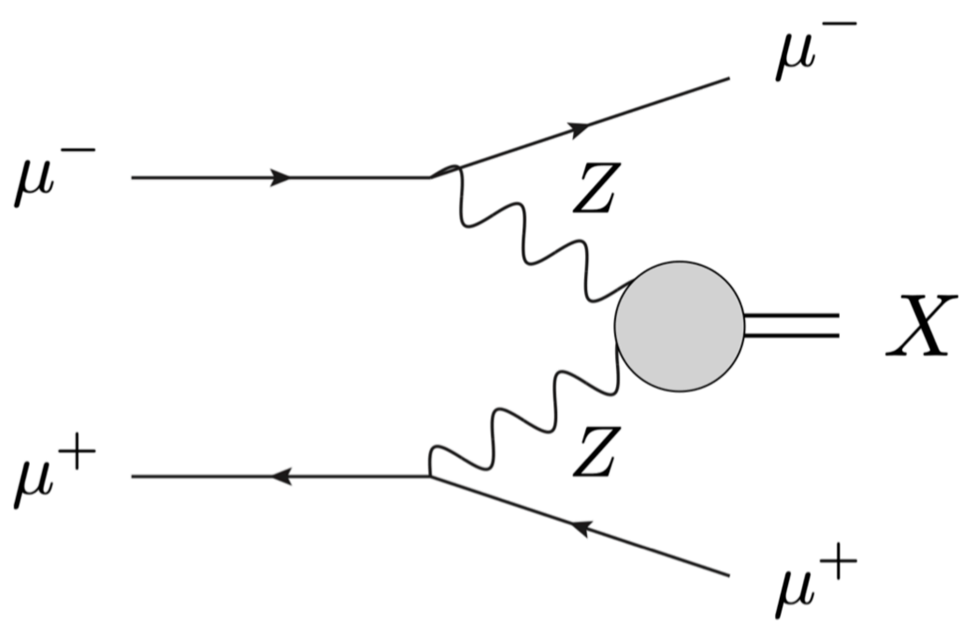
Hard neutrinos not seen,

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



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

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

- Untagged: % sensitivity

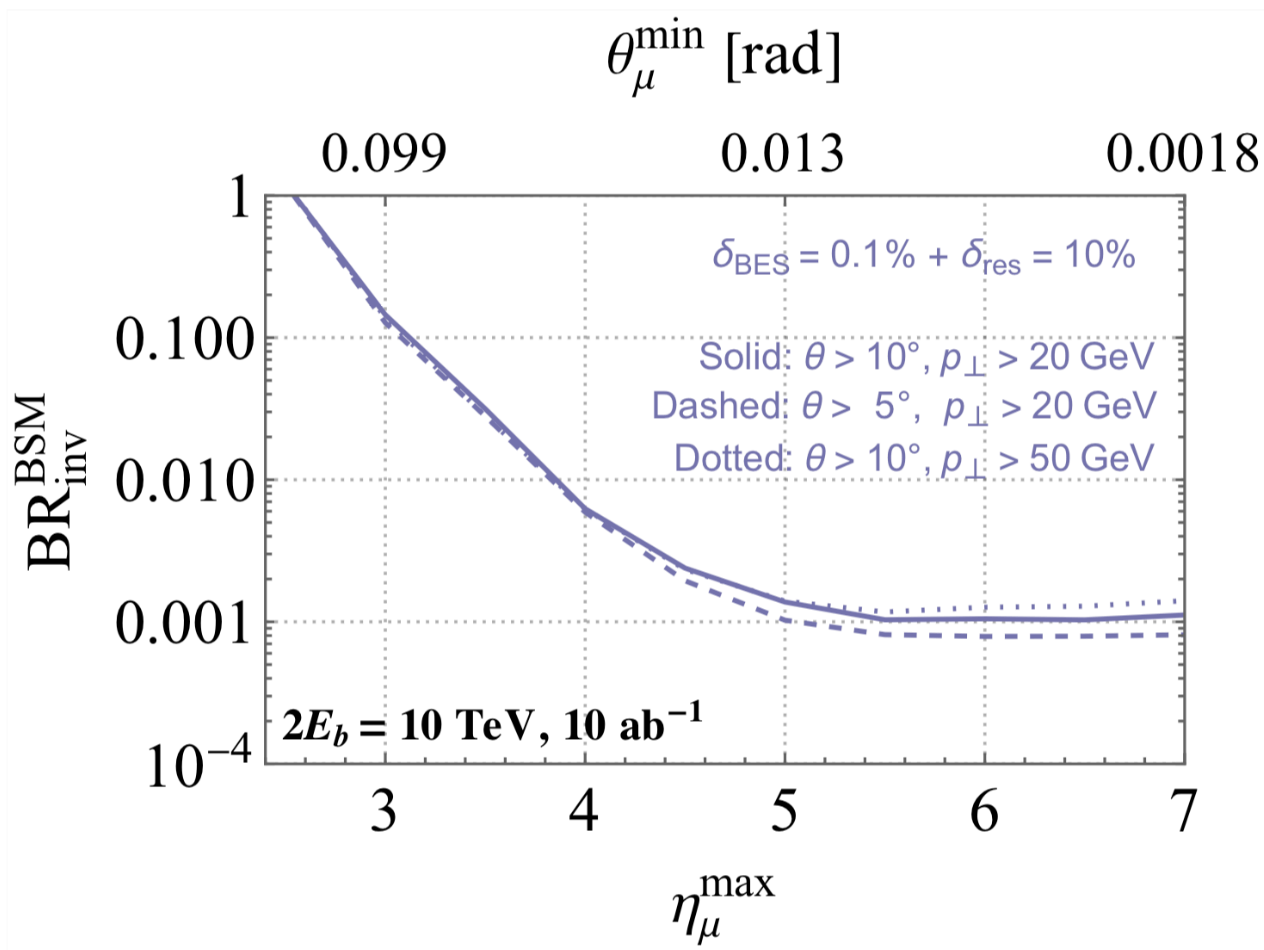
  if muons detected at $\eta \gtrsim 6$

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

- Invisible: 10^{-3} sensitivity

  if muons detected at $\eta \gtrsim 5$

  Ruhdorfer, Salvioni, Wulzer 2303.14202
  Forslund, Meade 2308.02633

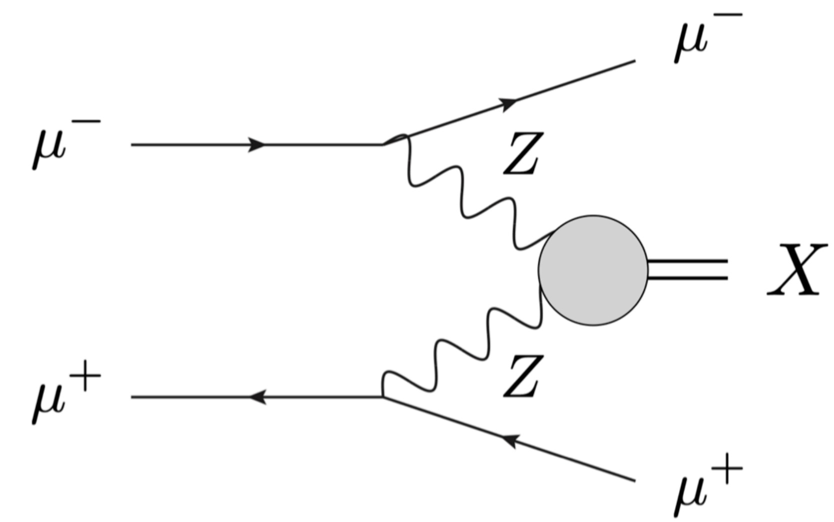


Invisible Higgs @ muon collider

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

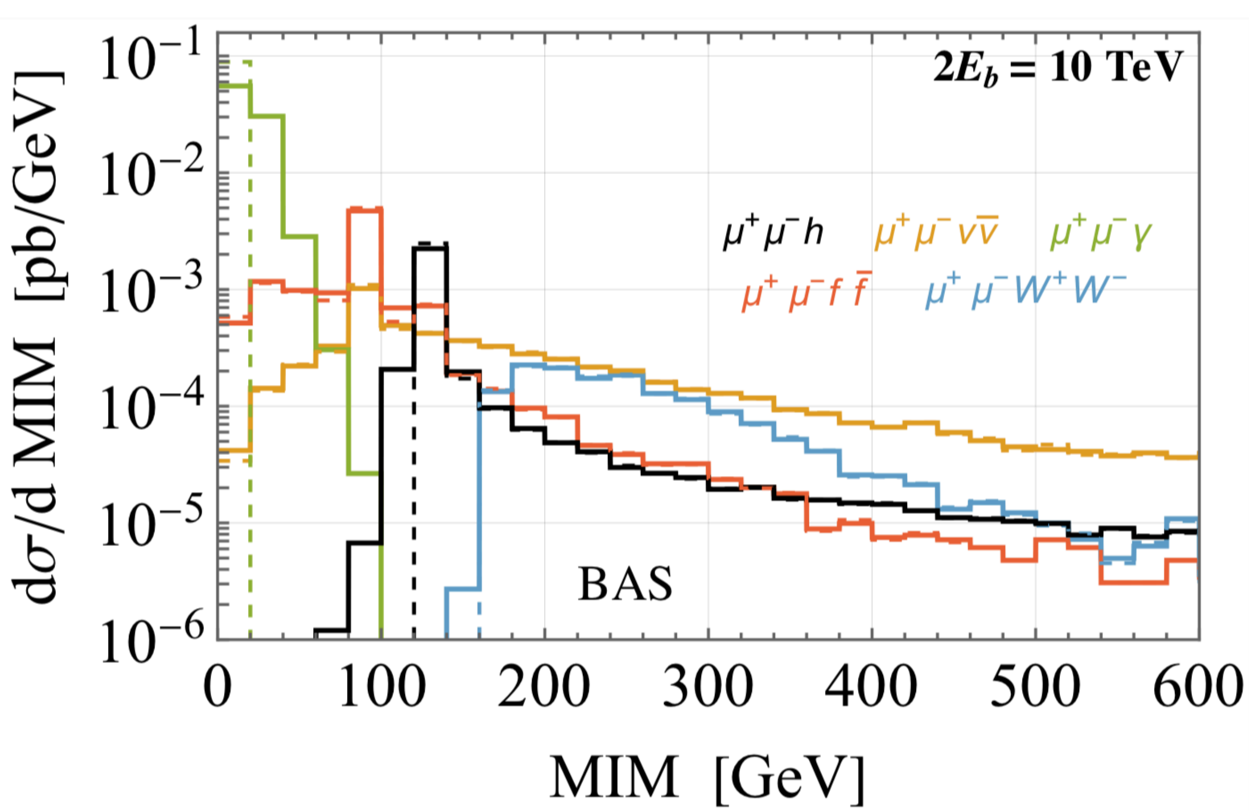
- Can also be studied in ZZ-fusion:

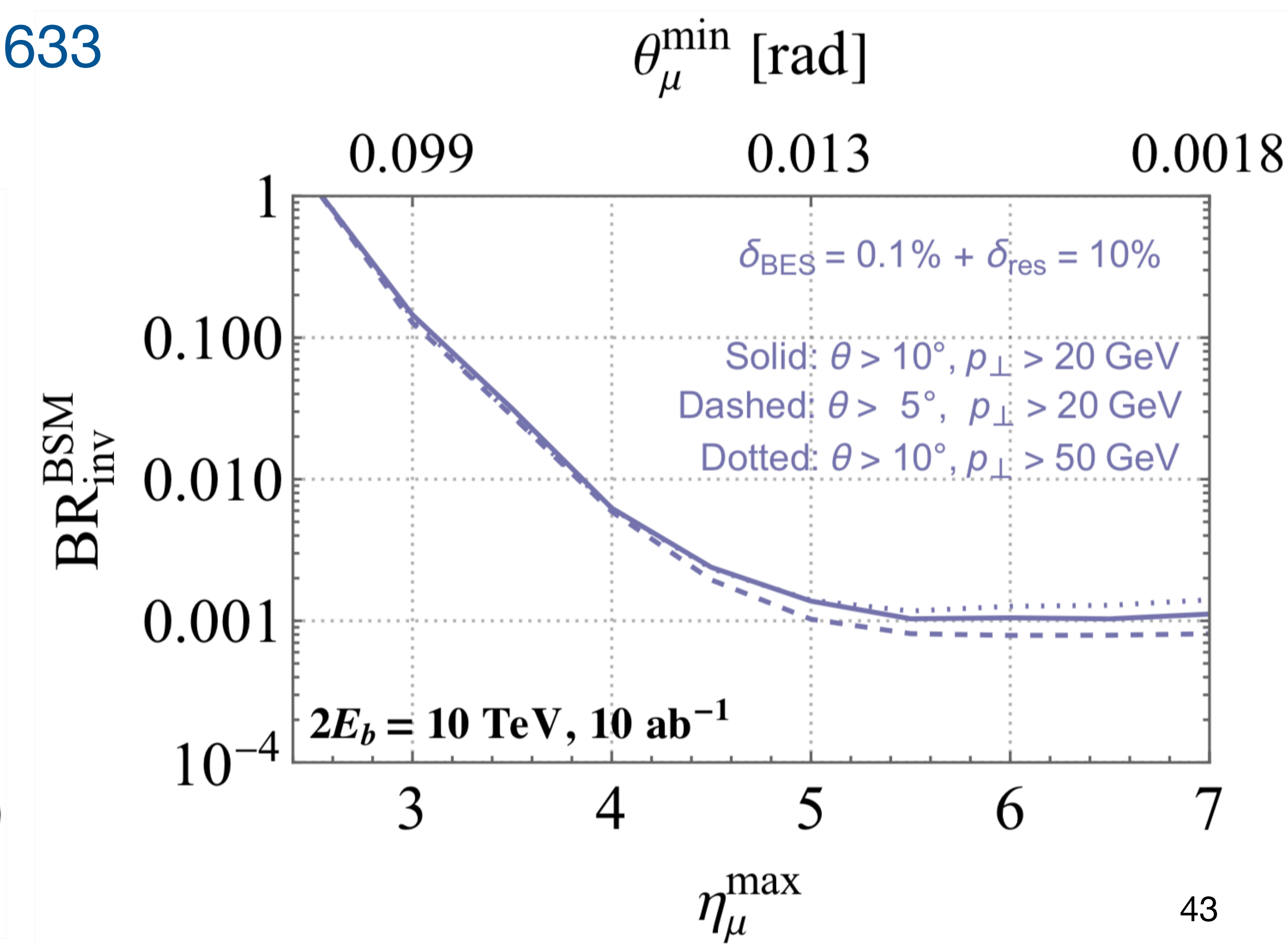
  10^{-3} sensitivity *if muons detected at* $\eta \gtrsim 5$



Ruhdorfer, Salvioni, Wulzer 2303.14202

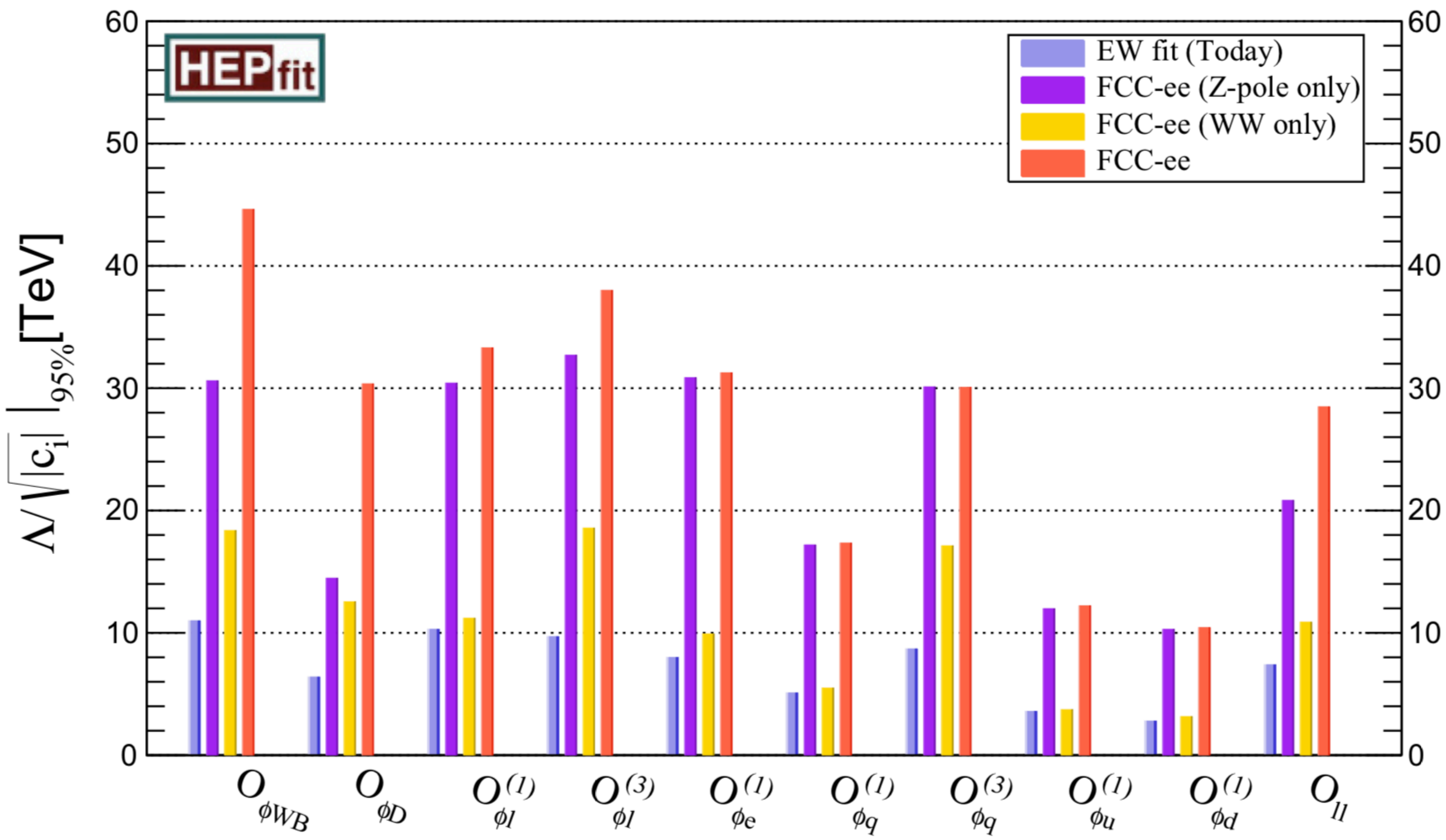
Forslund, Meade 2308.02633





EW precision

- In general, several more operators enter the EW fit

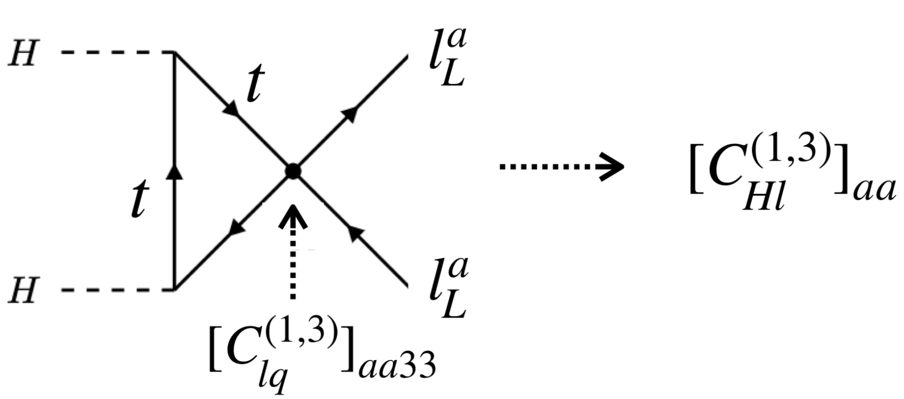


effective scales ~ 30 TeV

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

Several 4-fermion interactions enter through one loop RGE

2311.00020, 1704.04504



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

Example: WIMP Dark Matter

- Weakly Interacting Massive Particle: most general EW multiplet with DM candidate that is

  (a) stable,

  (b) without coupling to γ & Z,

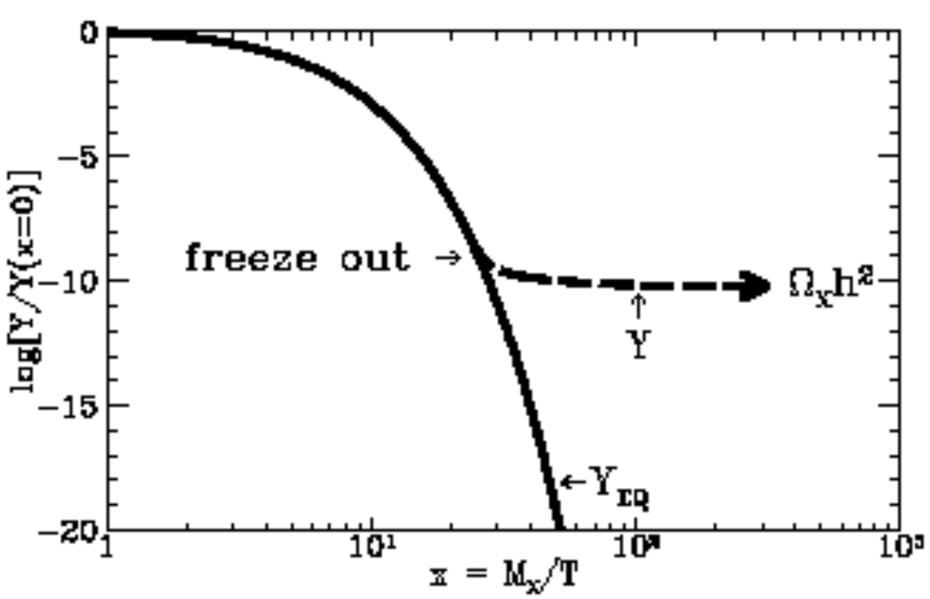
  (c) calculable (perturbative).

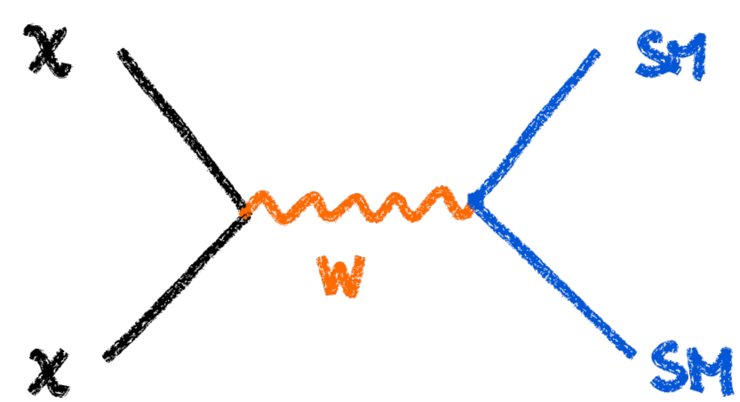
similar to Minimal DM:
Cirelli, Fornengo, Strumia hep-ph/0512090

$$\chi_n = (\cdots, \chi^-, \chi^0, \chi^+, \cdots)$$

- Mass fixed by freeze-out DM abundance

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





EW n-plet	Mass [TeV]
$2_{1/2}$	1.08
3_0	2.86
$4_{1/2}$	4.8
5_0	13.6
5_1	9.9
$6_{1/2}$	31.8
7_0	48.8
9_0	113

☛ talks by Raki and Paolo

Energies of several TeV crucial to probe these WIMP candidates!

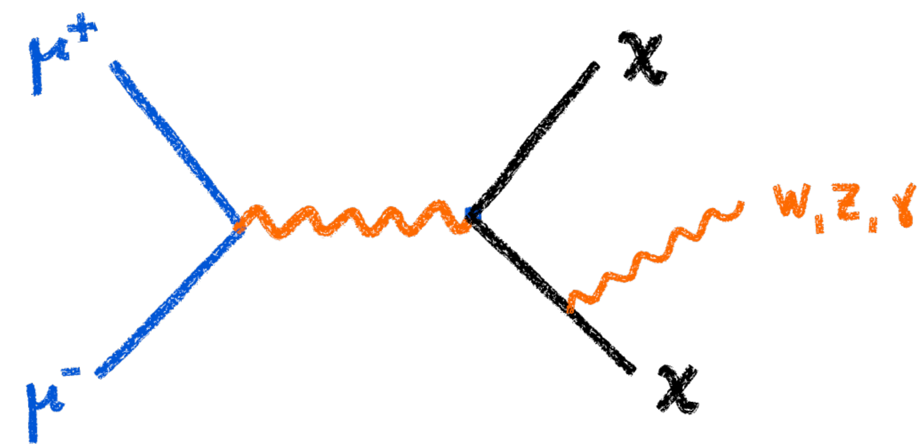
Example: WIMP Dark Matter

- Mono-γ/W/Z signals: $\mu\bar{\mu} \to \chi\bar{\chi} + X$

  DM pair production + EW radiation

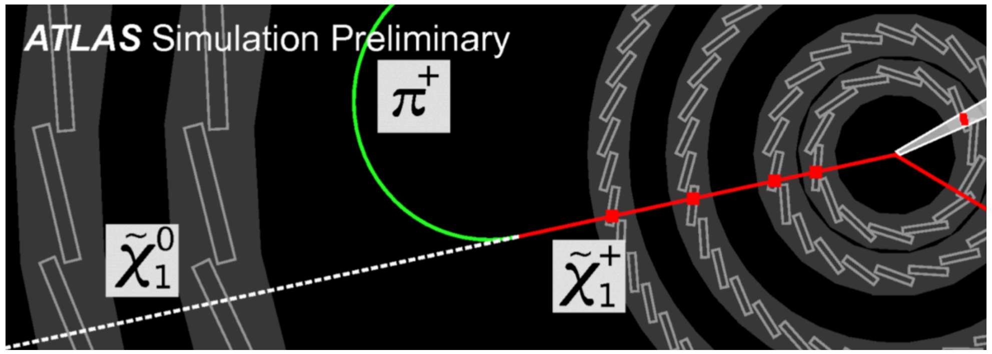
  Han et al. 2009.11287

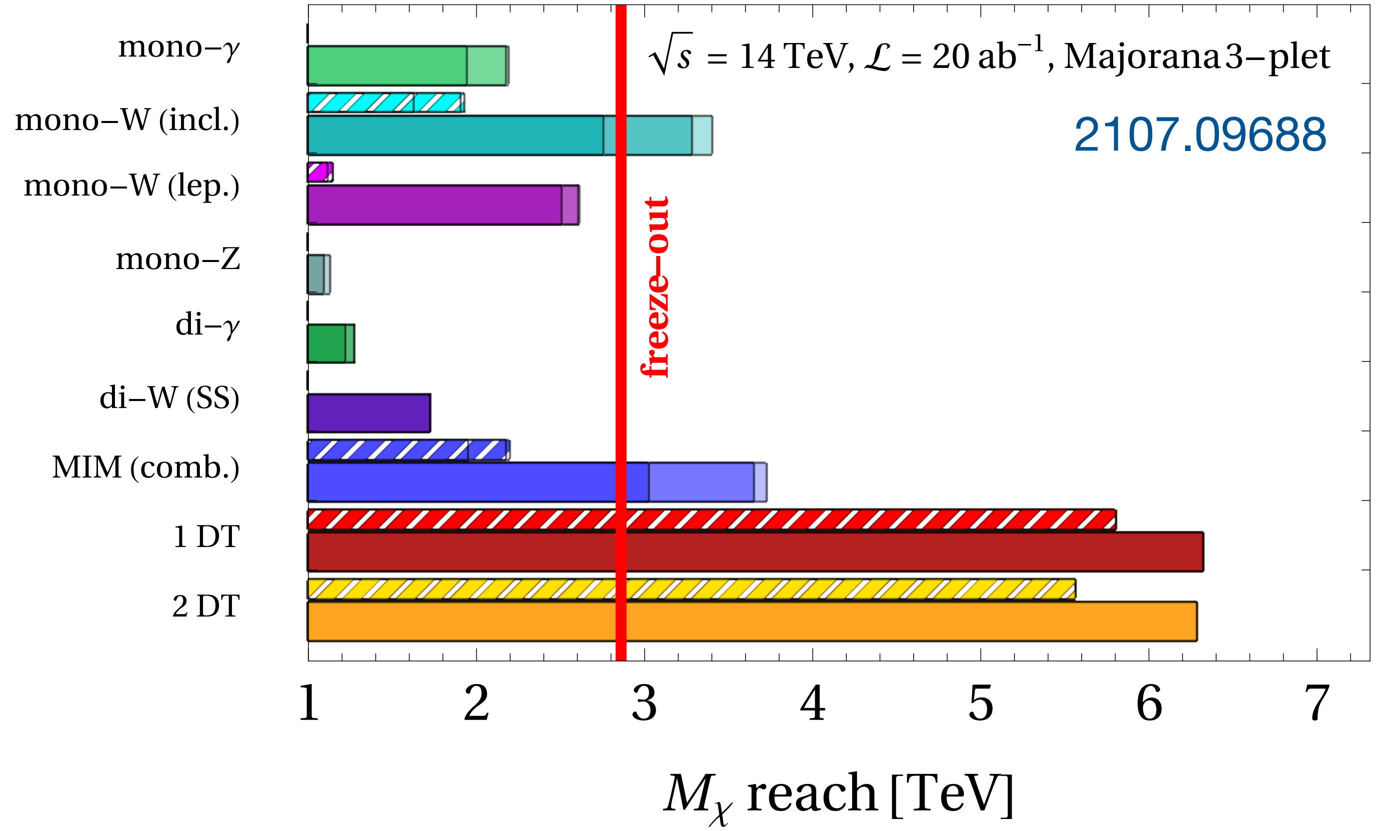
  Bottaro et al. 2107.09688, 2205.04486



- Disappearing tracks: charged components of χ can be long-lived $\chi^{\pm} \to \chi^0 \pi^{\pm}$

  Capdevilla et al. 2102.11292





μC can probe all relevant WIMP candidates!

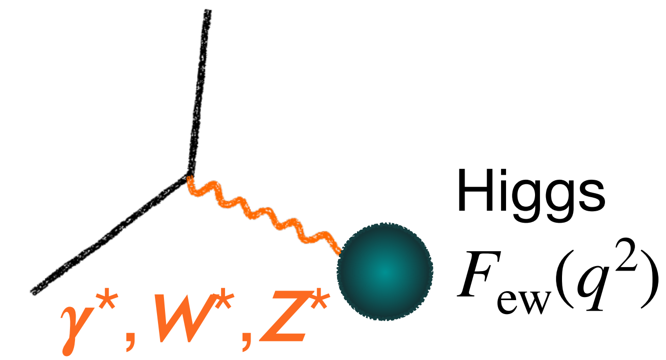
More difficult at hadron colliders, due to PDF suppression

FCC physics study

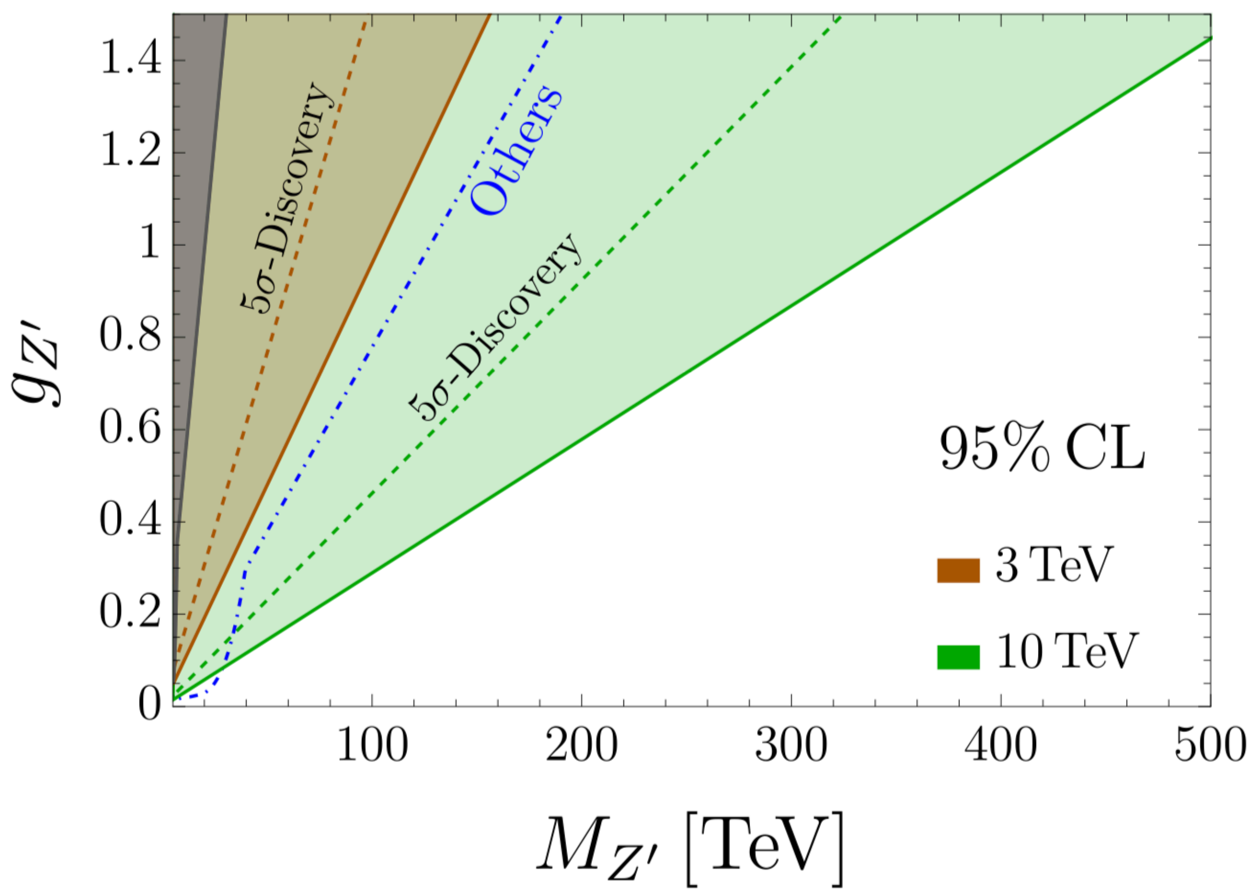
Cirelli, Sala, Taoso 1407.7058

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: heavy resonance with mass $m_{Z'}$ and coupling $g_{Z'}$ to fermions

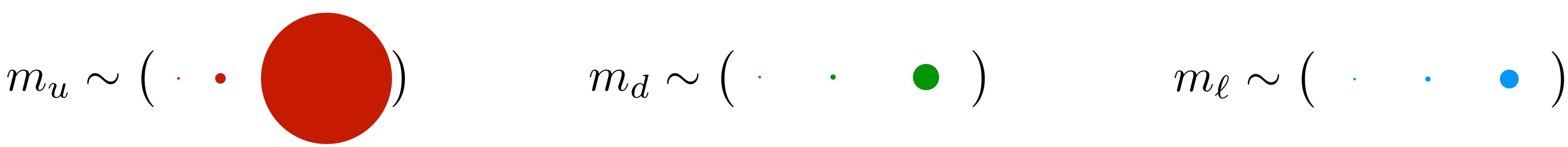


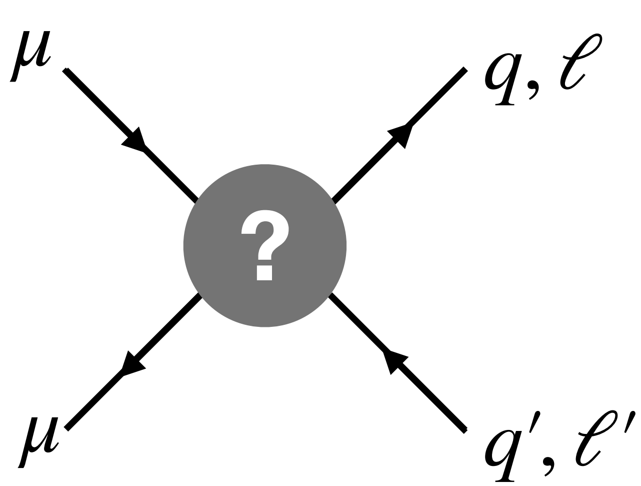
Flavour: muons vs. electrons

- New Physics (especially if related to the Higgs sector) could distinguish the different families of fermions.

- EW interactions are flavour-universal: an accidental property of the gauge lagrangian, *not* a fundamental symmetry of nature!

  - Example: Yukawa couplings, the only non-gauge interactions in the SM, violate flavour universality maximally!





A muon collider collides 2nd generation particles: could test flavour structure

➡ High-energy probes can be even more powerful in this case: enhancement wrt. low energy observables can be as large as $(E/m_\mu)^2$

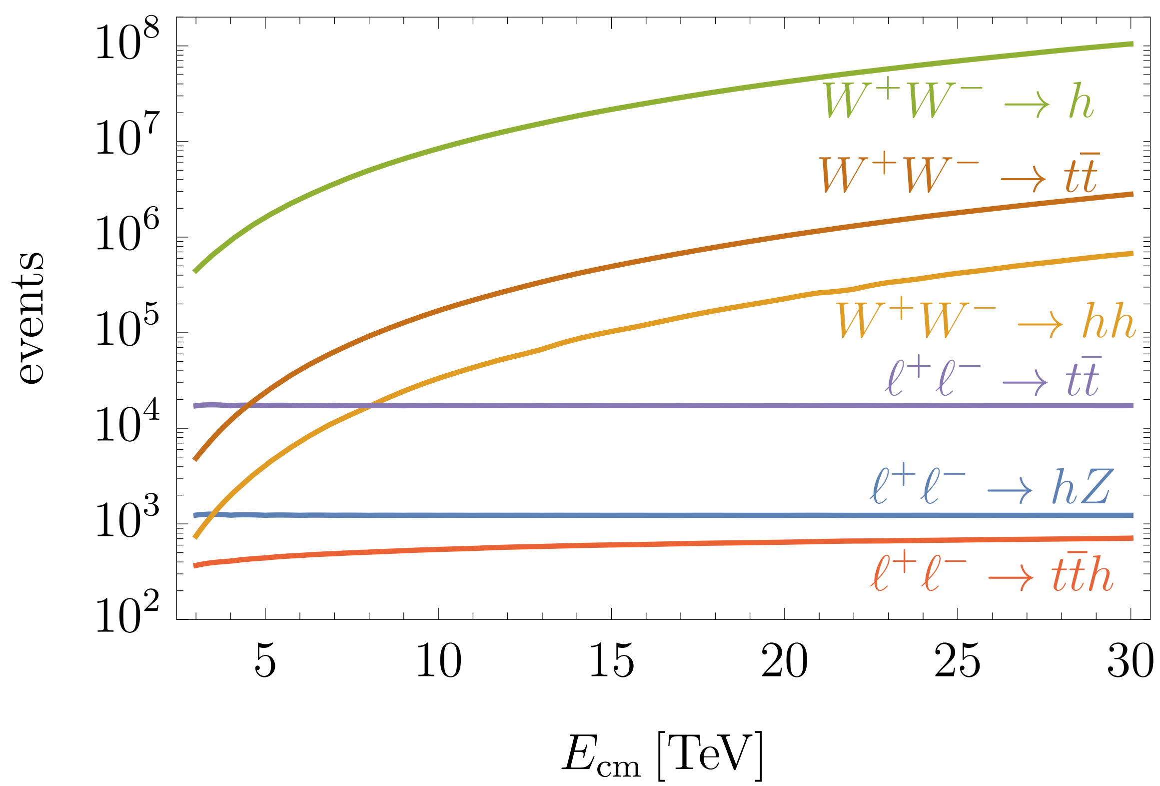
Flavor and precision

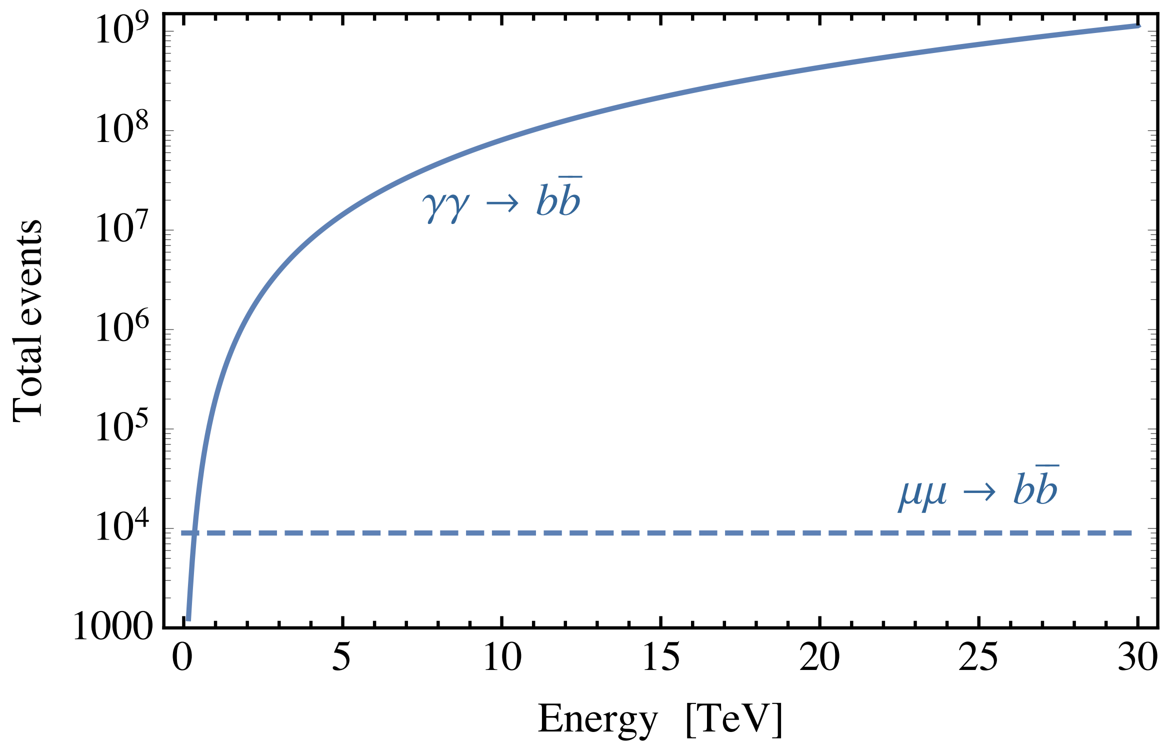
- Flavor processes: rare decays & tiny effects

$$\mathrm{BR}(B_s \to \mu\mu) \sim 10^{-9}, \qquad \mathrm{BR}(\tau \to 3\mu) \lesssim 10^{-8}, \qquad \Delta a_\mu \approx 10^{-9}$$

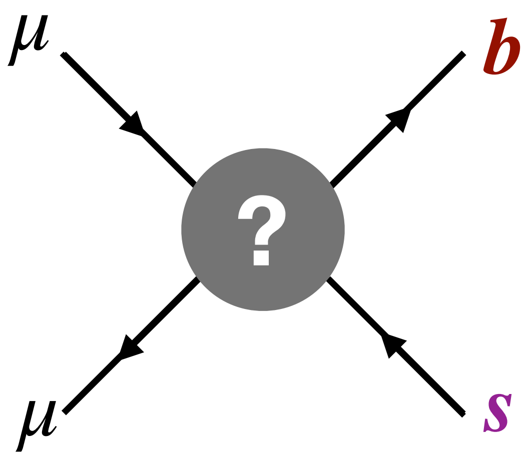
  ➡ need billions of events, usually probed by means of high-intensity experiments

- Muon-collider: very large number of (clean) EW particles, but overall event rate not comparable to flavor factories





Quark flavor violation



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

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

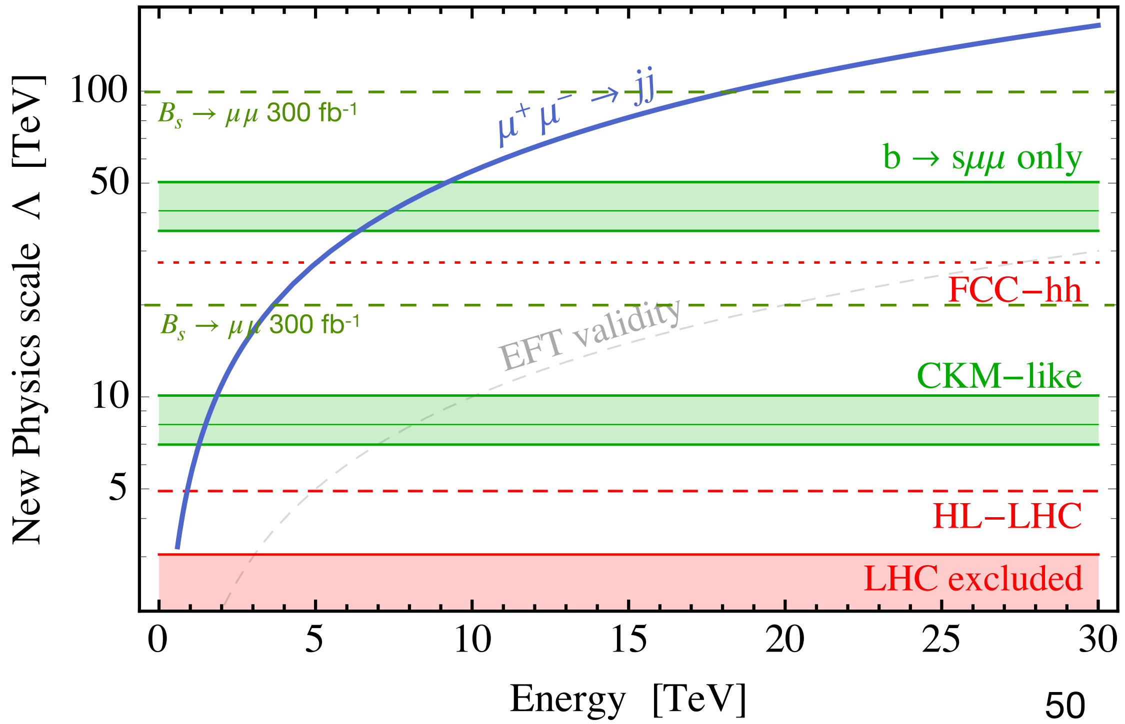
- Contributes to (semi-)leptonic rare B decays $b \to s\mu\mu$: branching ratios & angular observables of various hadronic processes

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

- Theory uncertainties: cannot improve indefinitely with rare decays

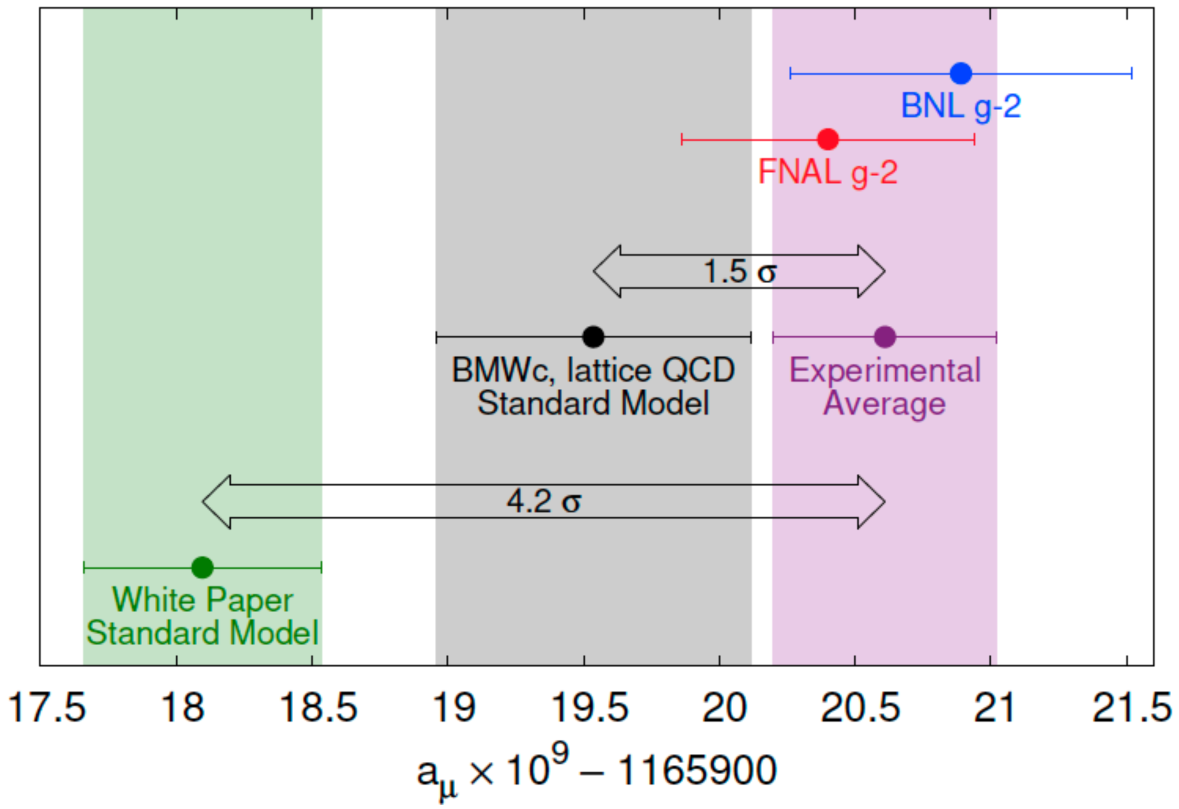
$$\mathrm{BR}(B \to K\mu\mu) \sim \frac{m_W^4}{\Lambda^4}, \quad \sigma(\mu\bar{\mu} \to jj) \sim \frac{E^2}{\Lambda^4}$$

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



Flavour @ muon collider: the muon g-2

- Example: muon g-2. Can it be tested at high energies at a muon collider?



$$\Delta a_\mu = ???$$

Flavour @ muon collider: the muon g-2

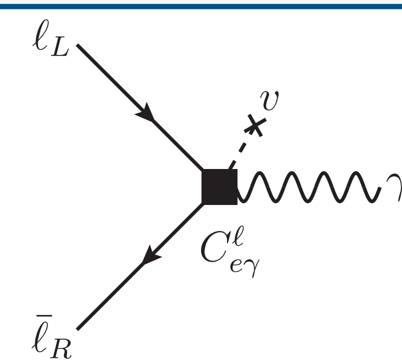
- Example: muon g-2. Can it be tested at high energies at a muon collider?

- If new physics is heavy: EFT!

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

At low energy

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

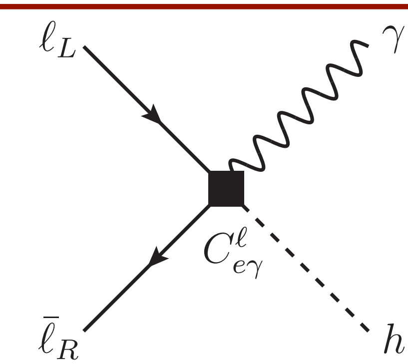


Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

B, Paradisi 2012.02769

At high energy

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



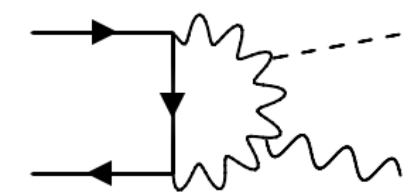
$$N_{h\gamma} = \sigma \cdot \mathscr{L} \approx \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}} \right)^4 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right)^2$$

need E > 10 TeV

Muon g-2 @ muon collider

- SM irreducible bakground is small: $\sigma^{(\mathrm{SM})}_{\mu^+\mu^-\to h\gamma} \approx 10^{-2}\,\mathrm{ab}\left(\dfrac{30\,\mathrm{TeV}}{\sqrt{s}}\right)^2$

  tree-level is suppressed by muon mass; loop contribution dominant

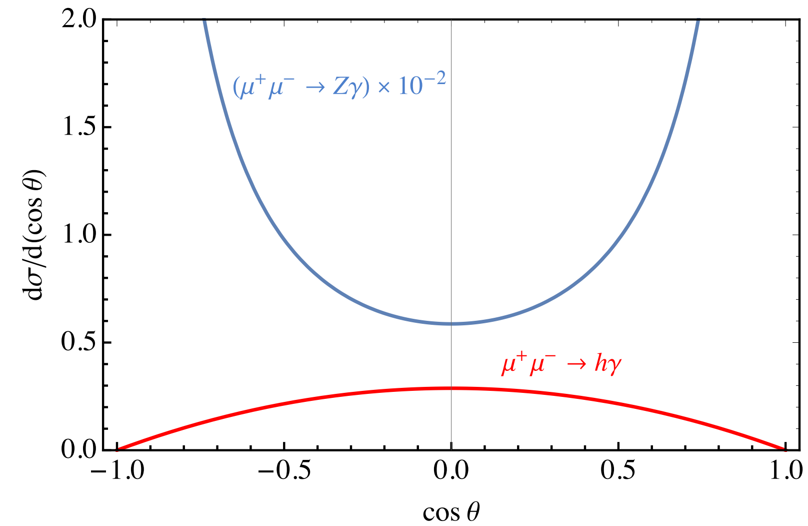


- Main background from $\mu\mu \to Z\gamma$ (where Z is mistaken for H)

  (large due to transverse Z polarizations)

$$\frac{d\sigma_{\mu\mu\to h\gamma}}{d\cos\theta} = \frac{|C^{\mu}_{e\gamma}(\Lambda)|^2}{\Lambda^4}\frac{s}{64\pi}(1-\cos^2\theta)$$

$$\frac{d\sigma_{\mu\mu\to Z\gamma}}{d\cos\theta} = \frac{\pi\alpha^2}{4s}\frac{1+\cos^2\theta}{\sin^2\theta}\frac{1-4s_W^2+8s_W^4}{s_W^2 c_W^2}$$



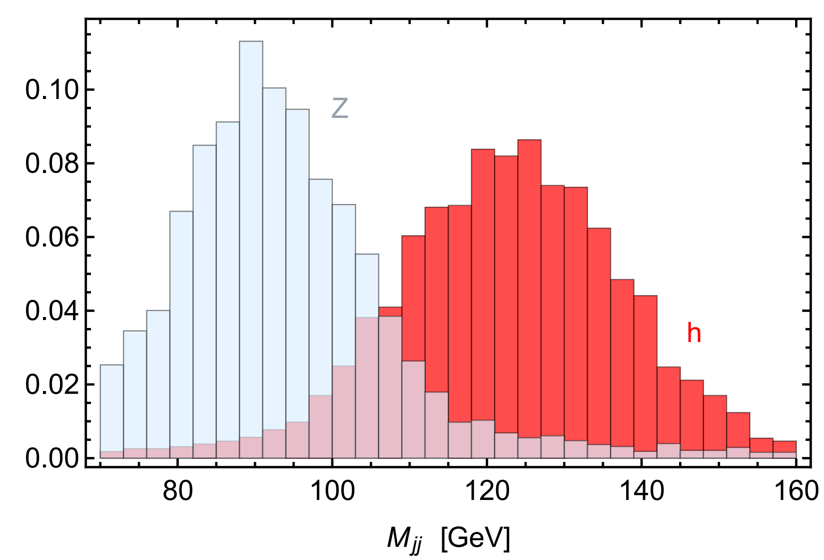
Search in h → bb channel:

$\epsilon_b \approx 80\,\%$ $\quad |\cos\theta_{\mathrm{cut}}| < 0.6$ $\quad \mathrm{BR}_{h\to b\bar{b}} = 58\,\%$

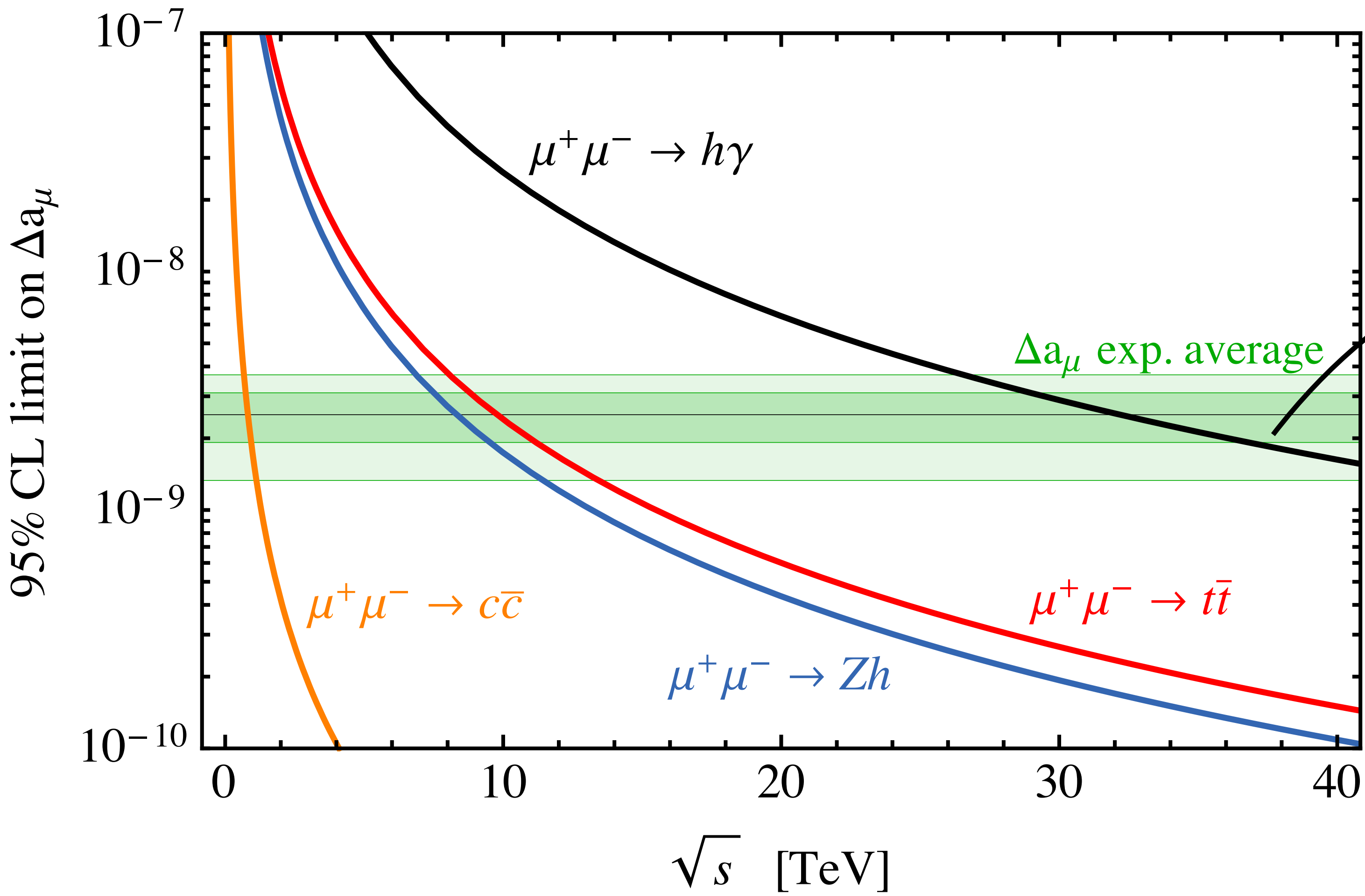
At 30 TeV, 90 ab^{-1}, for $\Delta a_\mu = 3\times 10^{-9}$:

$$N_S = 22, \quad N_B = 886 \times p_{Z\to h}$$

Δa$_\mu$ can be tested at 95% CL at a 30 TeV collider if Z→h mistag probability < 10-15%



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)

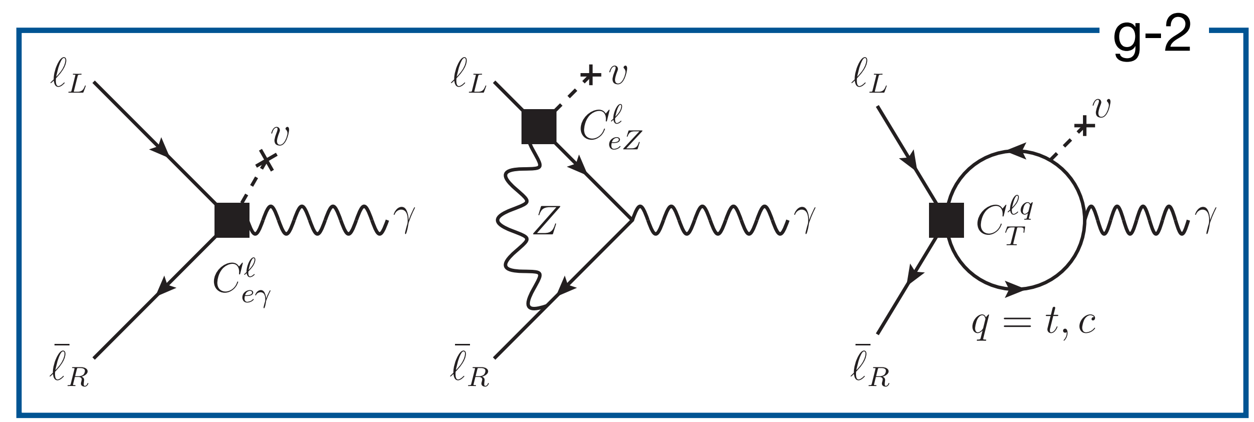
This result is completely model-independent!

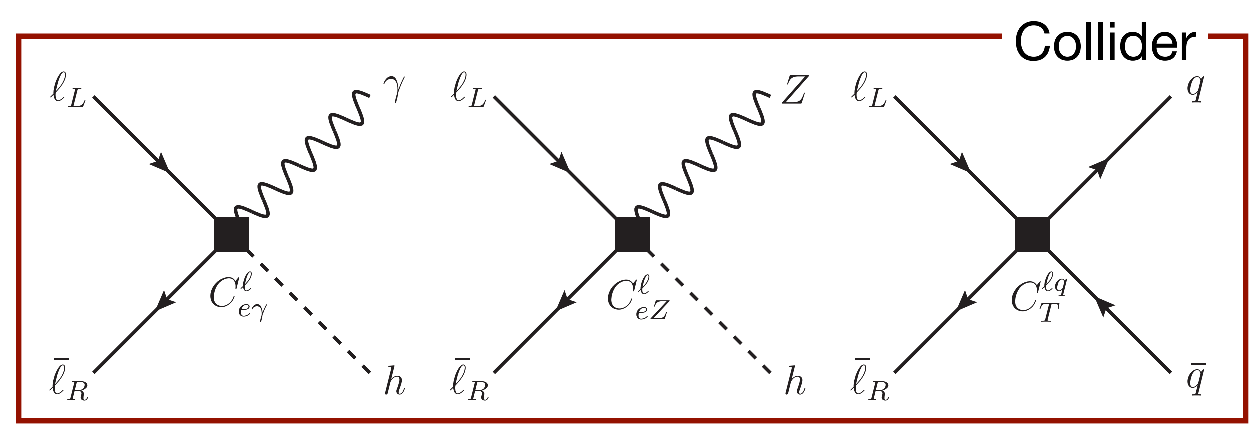
B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

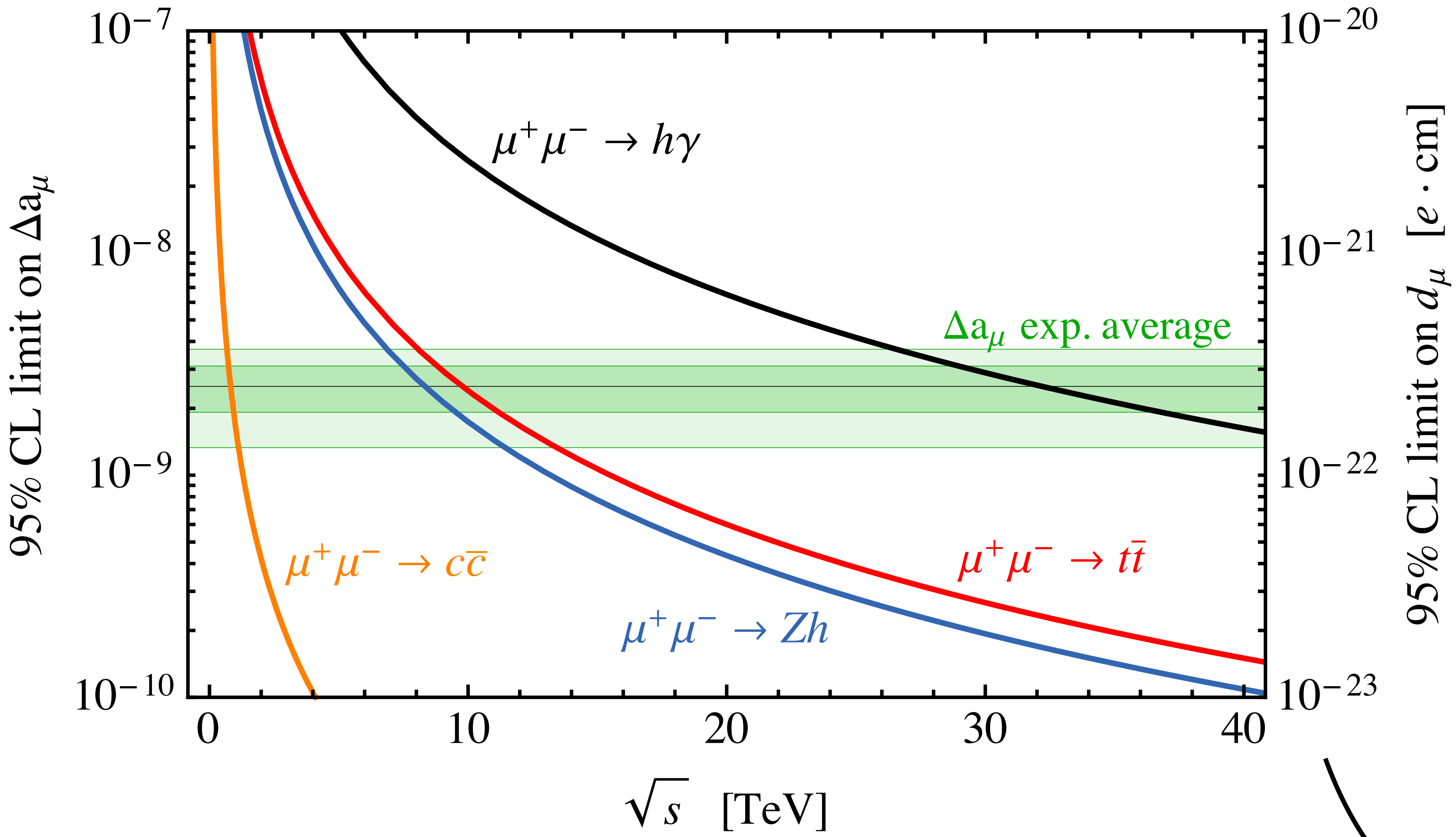
$$\Delta a_\mu \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

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





Muon g-2 @ muon collider



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This result is completely model-independent!

B, Paradisi 2012.02769

Muon EDM for free!

$$\Delta a_\mu = \frac{4 v m_\mu \mathrm{Re}(C_{e\gamma})}{\Lambda^2}$$

$$d_\mu = \frac{2v\,\mathrm{Im}(C_{e\gamma})}{\Lambda^2} = \frac{\Delta a_\mu}{2 m_\mu} \tan\phi_\mu\, e$$

Collider constrains $|C_{e\gamma}|^2$

$$\Rightarrow \quad d_\mu \lesssim 10^{-22}\, e \cdot \mathrm{cm}$$

3 o.o.m. stronger than present bound!

Lepton g-2 from rare Higgs decays

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

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

if $C^\ell_{e\gamma}$ scales as y_ℓ

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

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

hep-ex/0406010

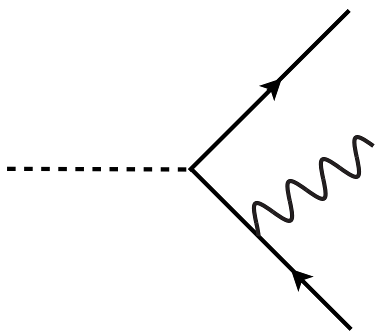
Can be improved to few 10-3

at HL-LHC 1908.05180

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

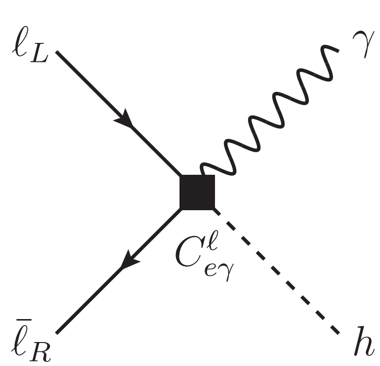
$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4}$$

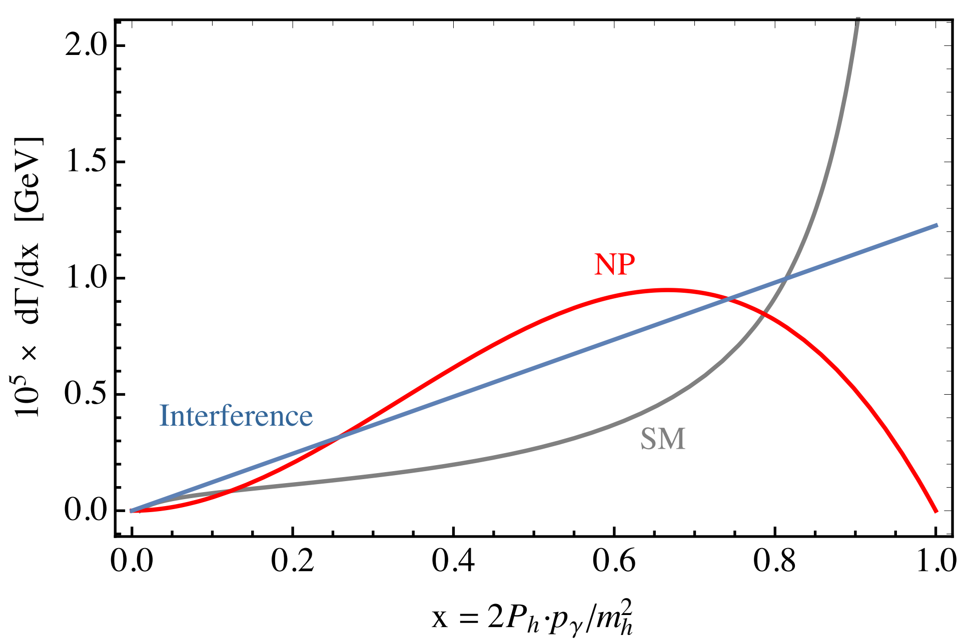
(with cut on soft collinear photon)



could be measured at few % level by Higgs factory

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



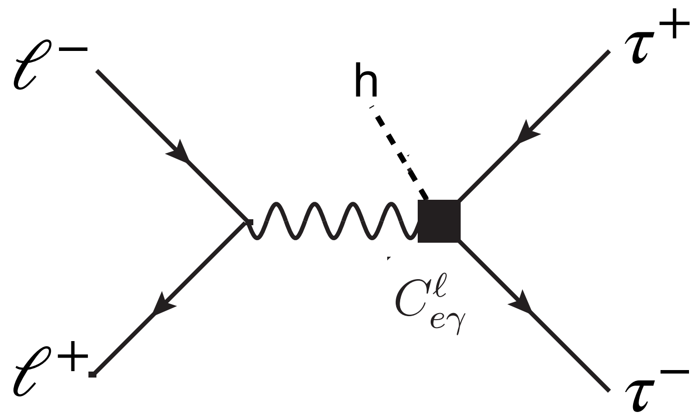


Tau g-2 from high-energy probes

Further possibilities to measure Δa_τ precisely from high-energy probes

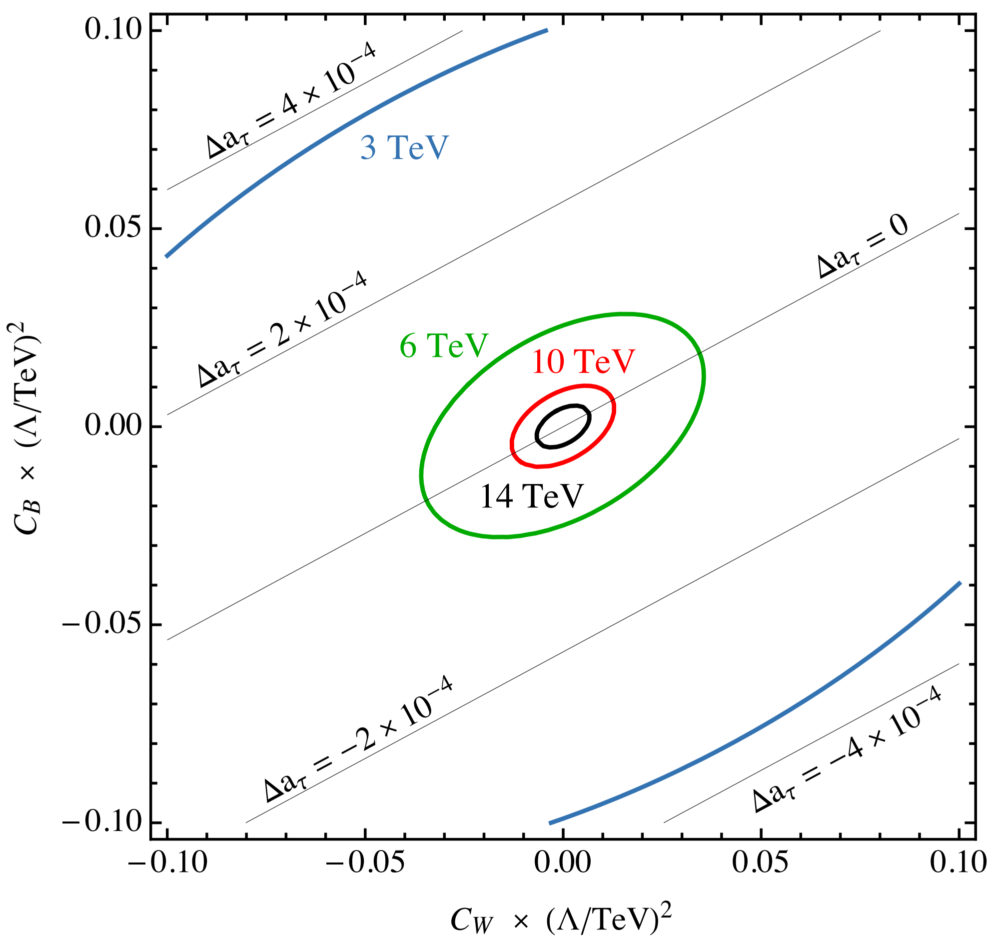
- ✦ $H\tau\tau$ associated production

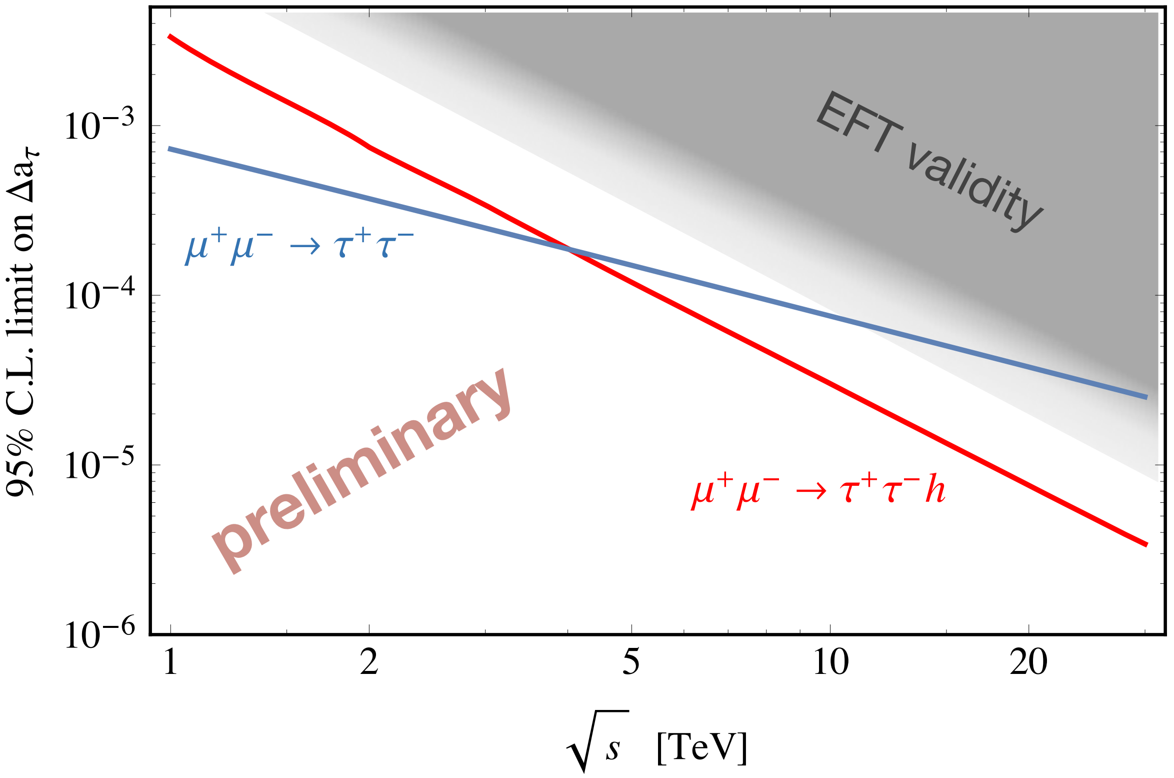
work in progress with Levati, Paradisi, Maltoni, Wang



- 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!

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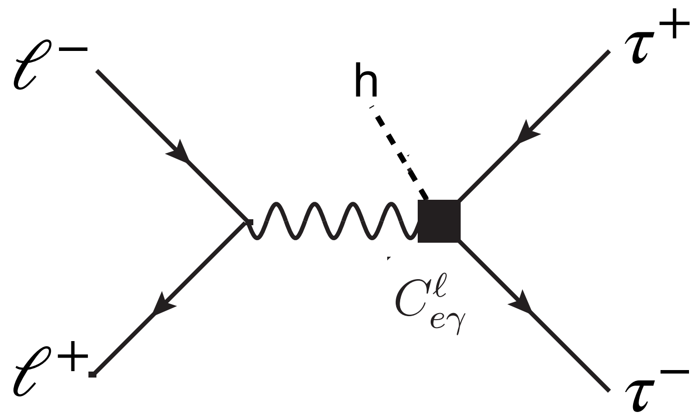

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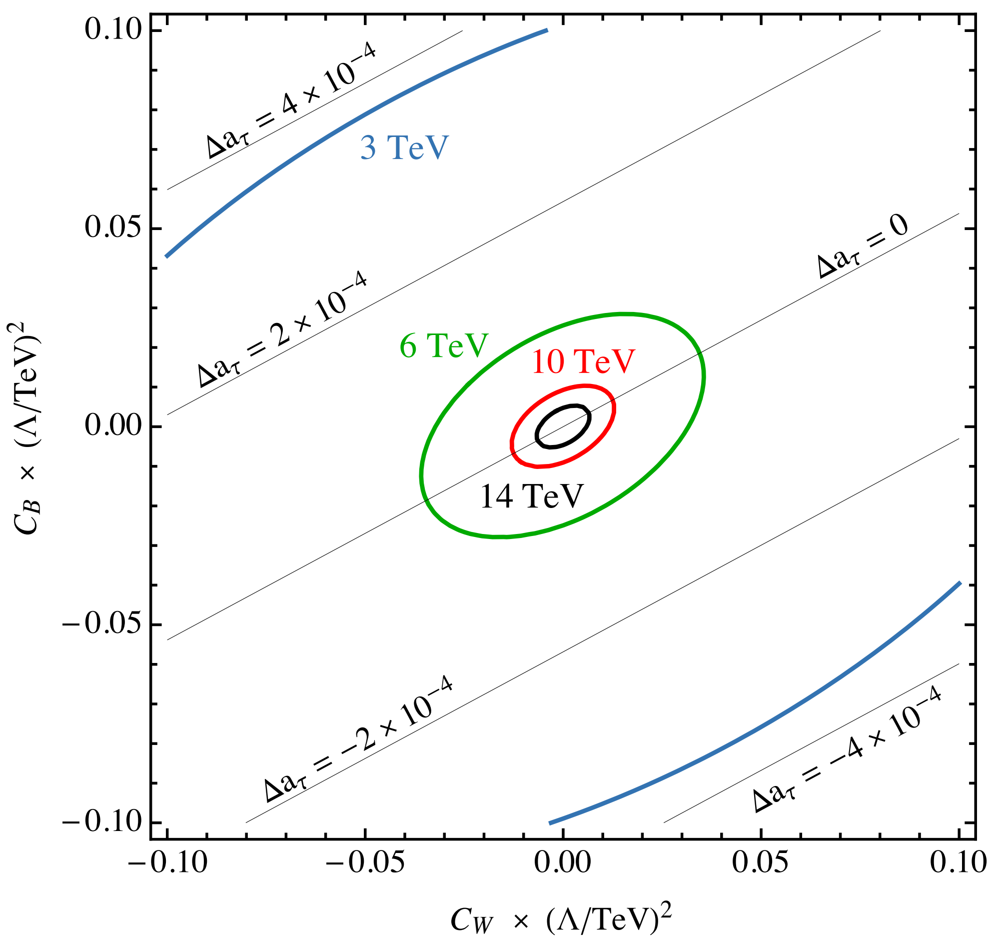

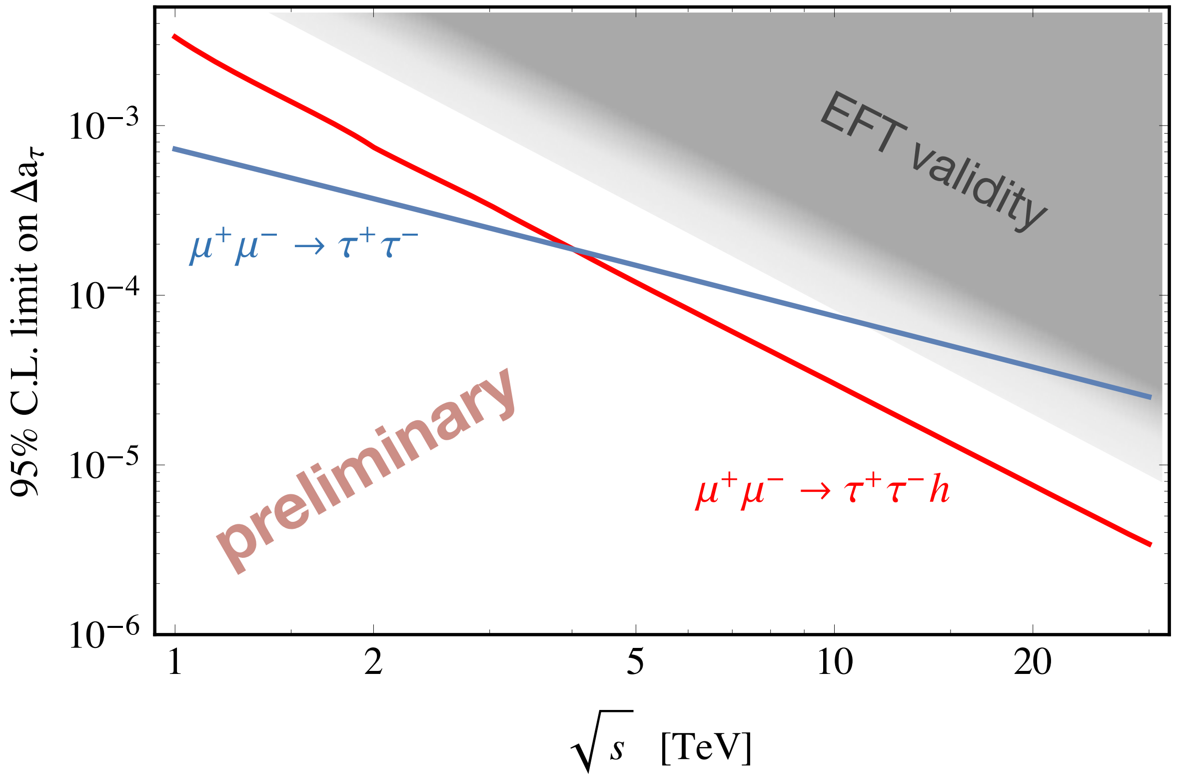

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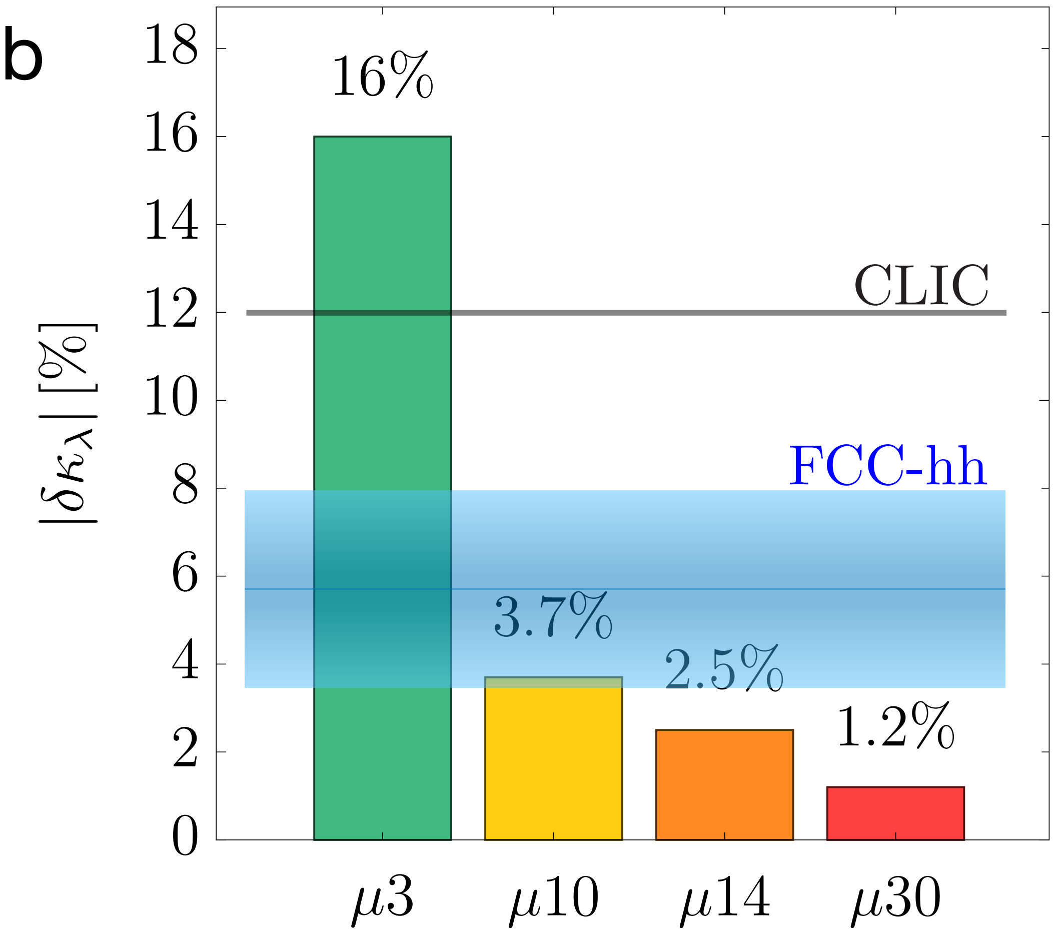
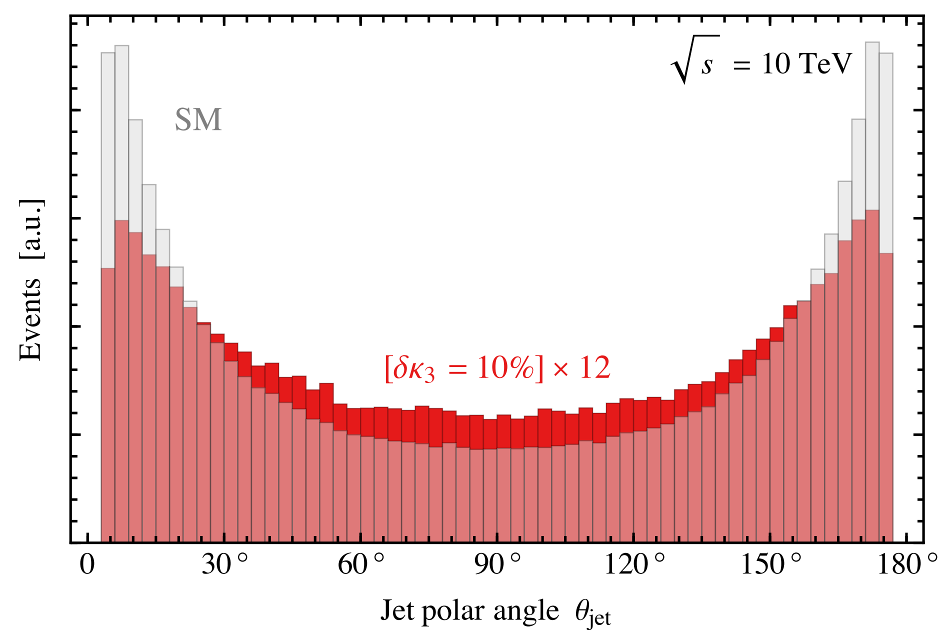
Double Higgs production

- Reach on Higgs trilinear coupling: hh ⟶ 4b

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{rec}	$\delta\kappa_3$
3	5	170	~ 10%
10	10	620	~ 4%
14	20	1340	~ 2.5%
30	90	6'300	~ 1.2%

B, Franceschini, Wulzer 2012.11555,
Han et al. 2008.12204, Costantini et al. 2005.10289





- Weak dependence on angular acceptance (signal is in the central region)
- Some dependence on detector resolution (to remove backgrounds)

B, Franceschini, Wulzer 2012.11555
see also CLIC study 1901.05897

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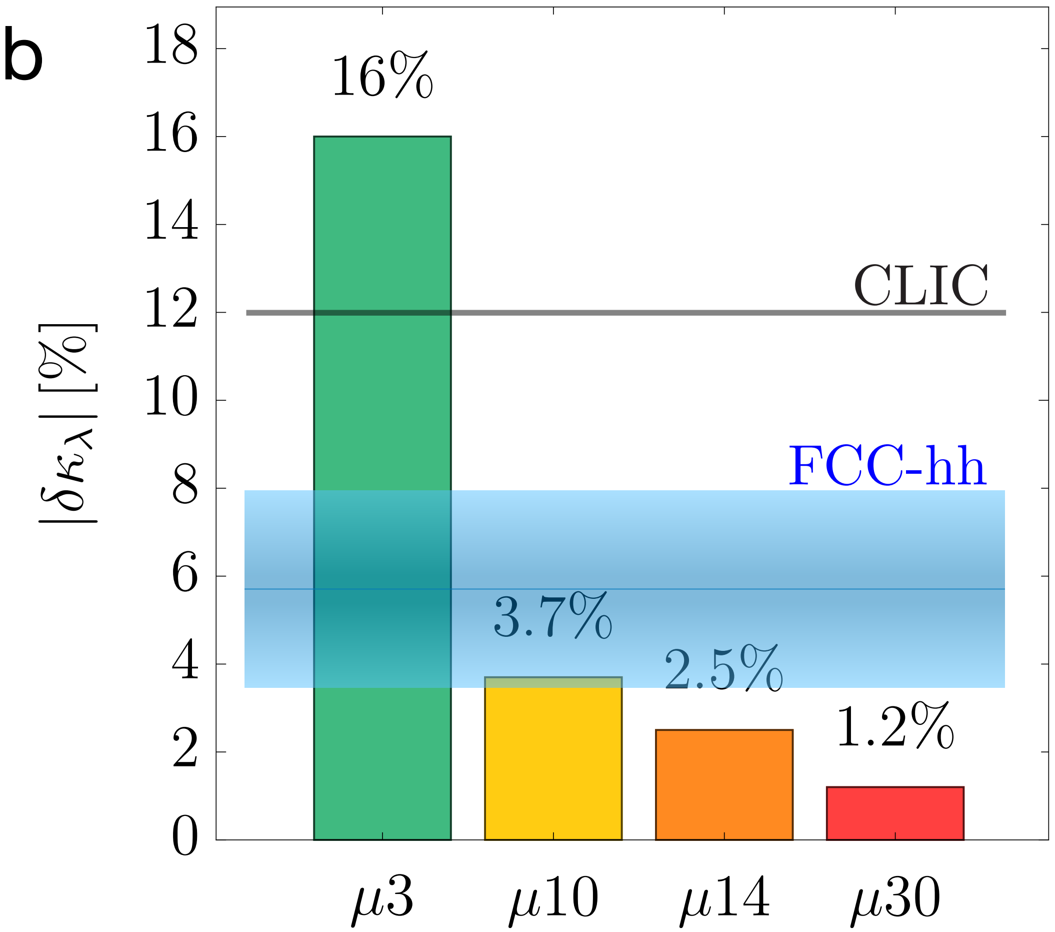

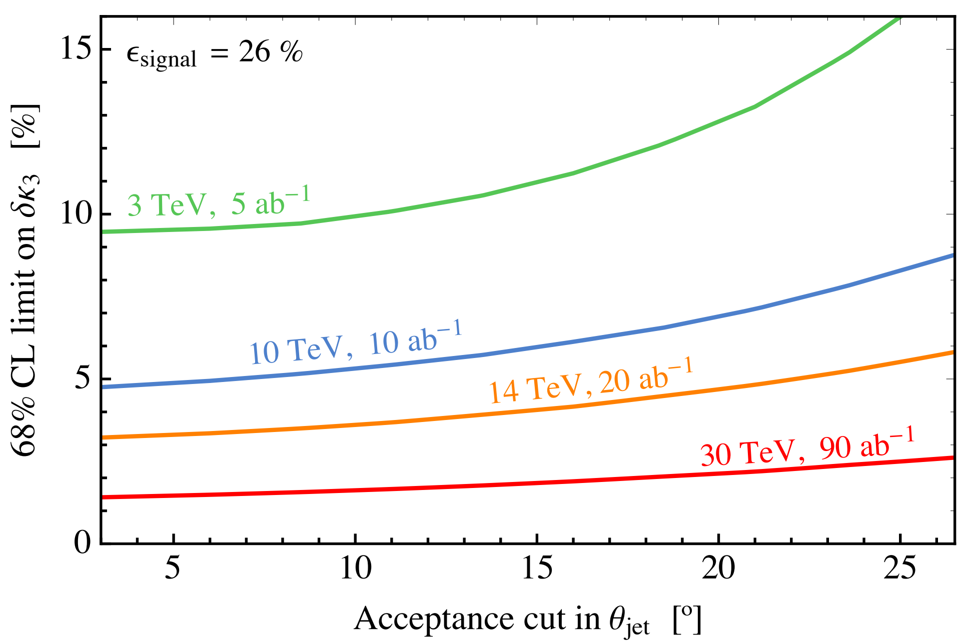

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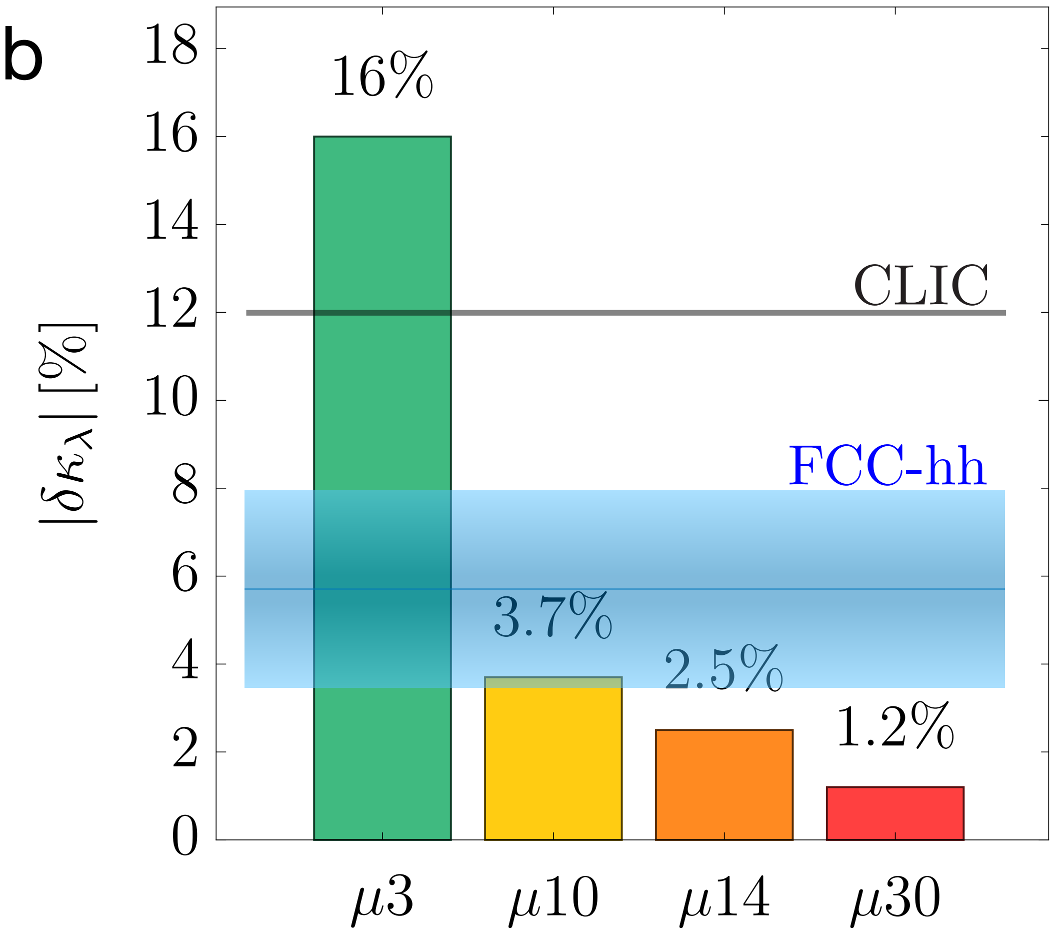

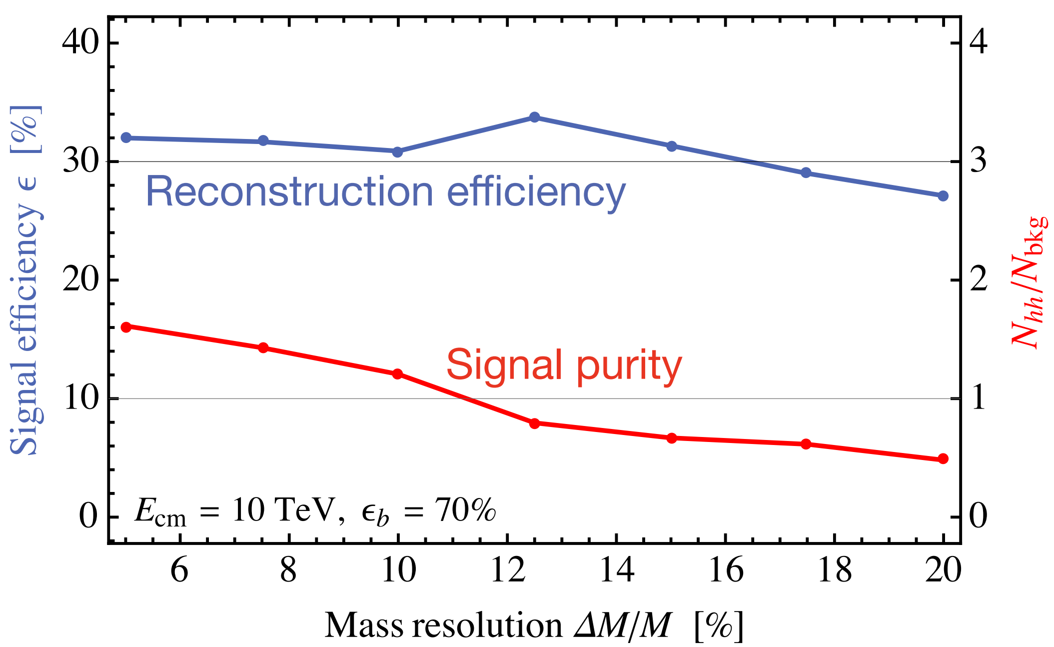

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- Some dependence on detector resolution (to remove backgrounds)

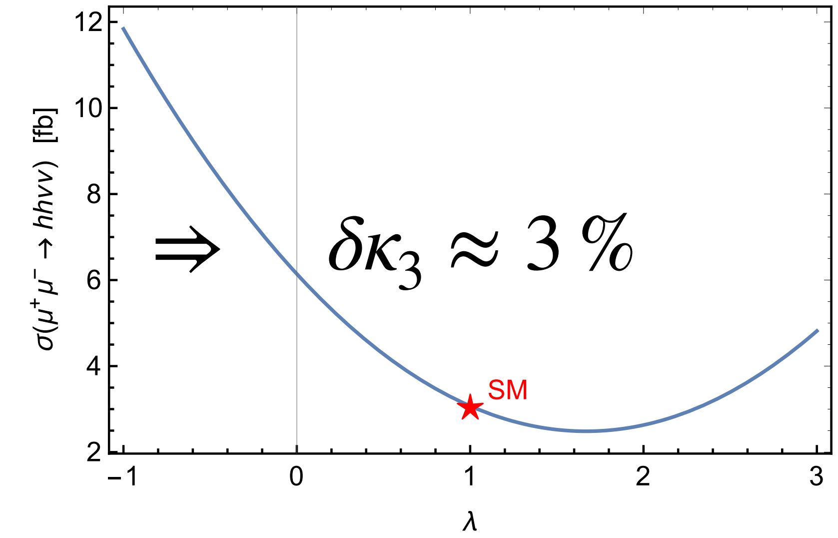
B, Franceschini, Wulzer 2012.11555
see also CLIC study 1901.05897

Double Higgs production

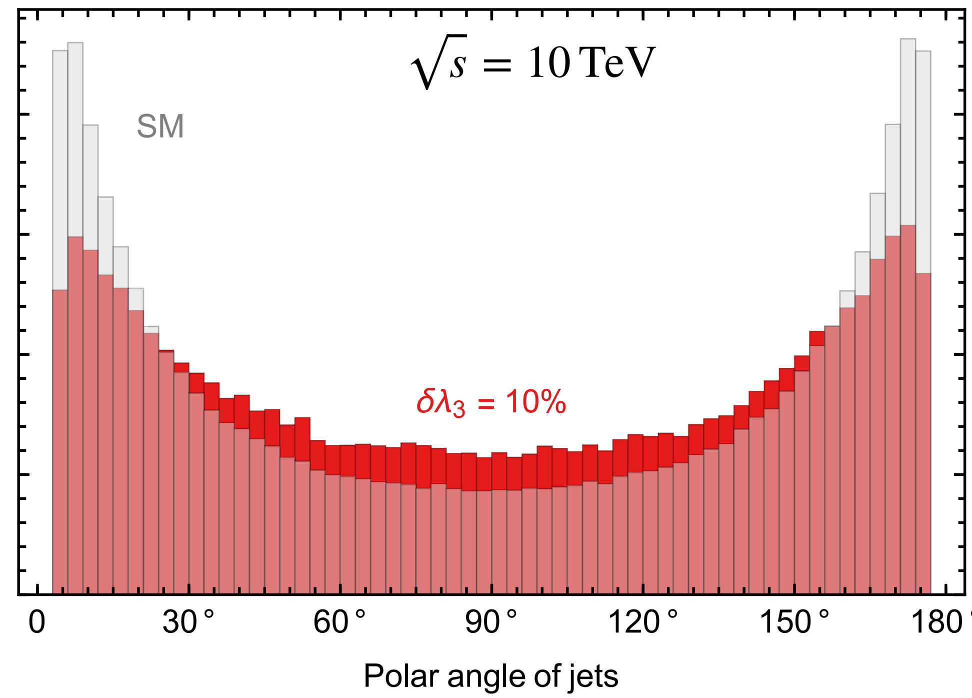
Number of events $\sim\ s\log(s/m_h^2)\ \approx 10^5$ at 14 TeV

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

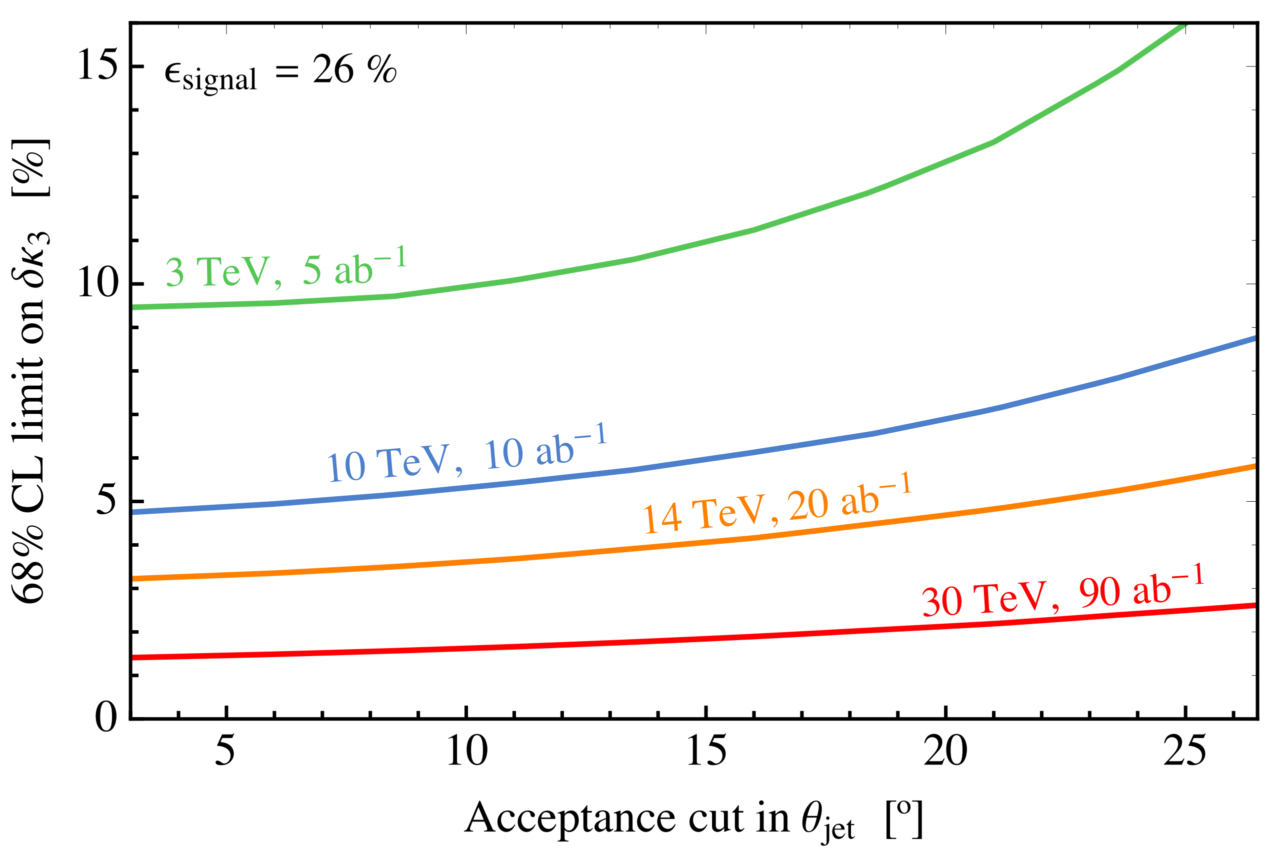
$$\left.\begin{array}{r}\text{reconstruction eff.} \sim 30\,\% \\ \mathrm{BR}(hh \to 4b) = 34\,\%\end{array}\right\} \epsilon \sim 10\,\%$$



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



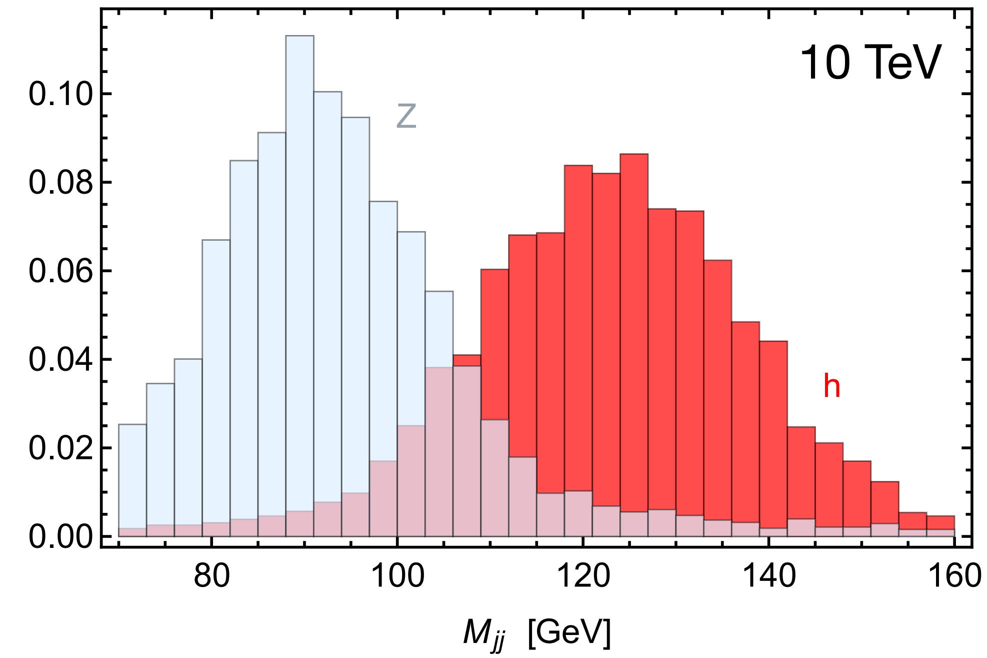
B, Franceschini, Wulzer 2012.11555

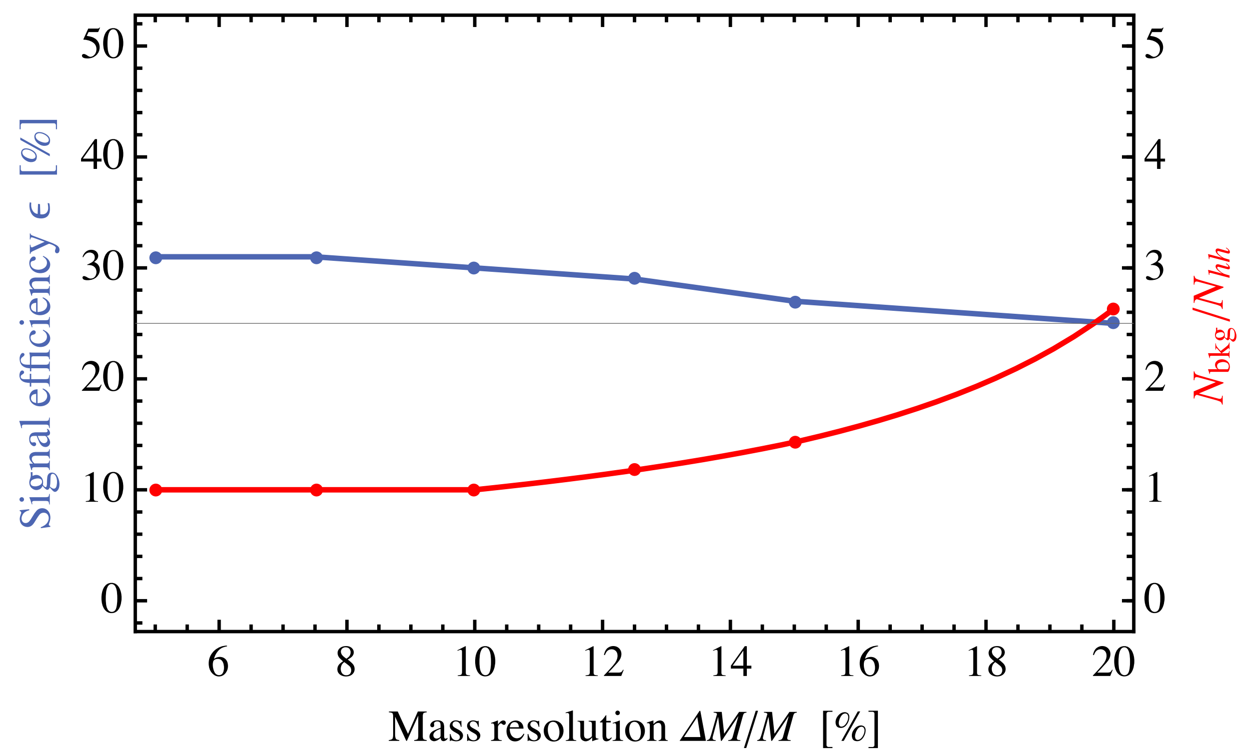


  - Contribution from trilinear coupling is more central: loss due to angular cut is less important

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

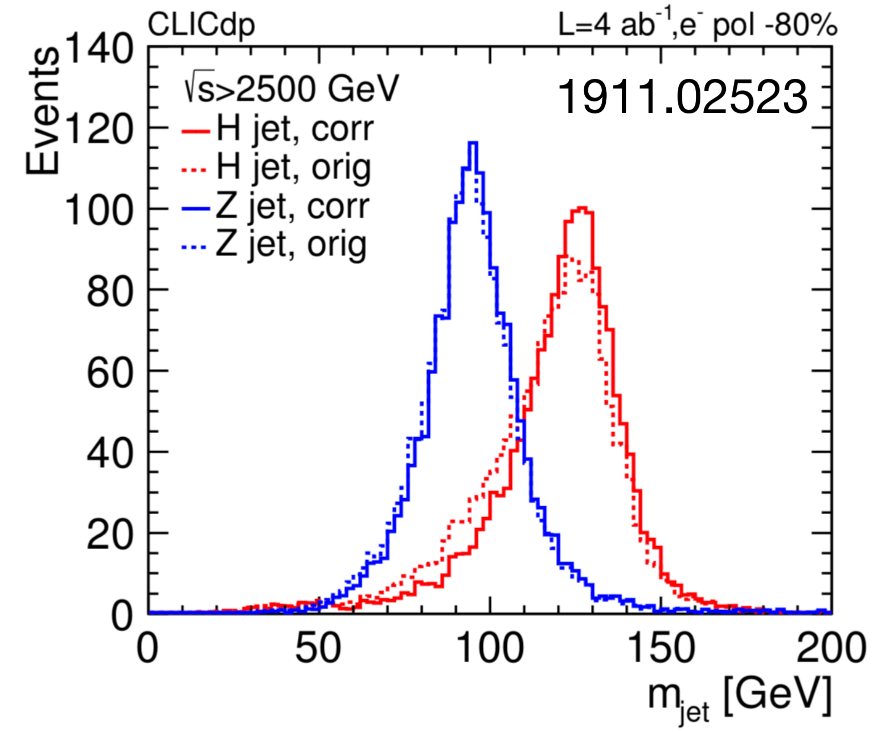
However, perfect agreement with 1901.05897! (3 TeV CLIC)

B, Franceschini, Wulzer 2012.11555

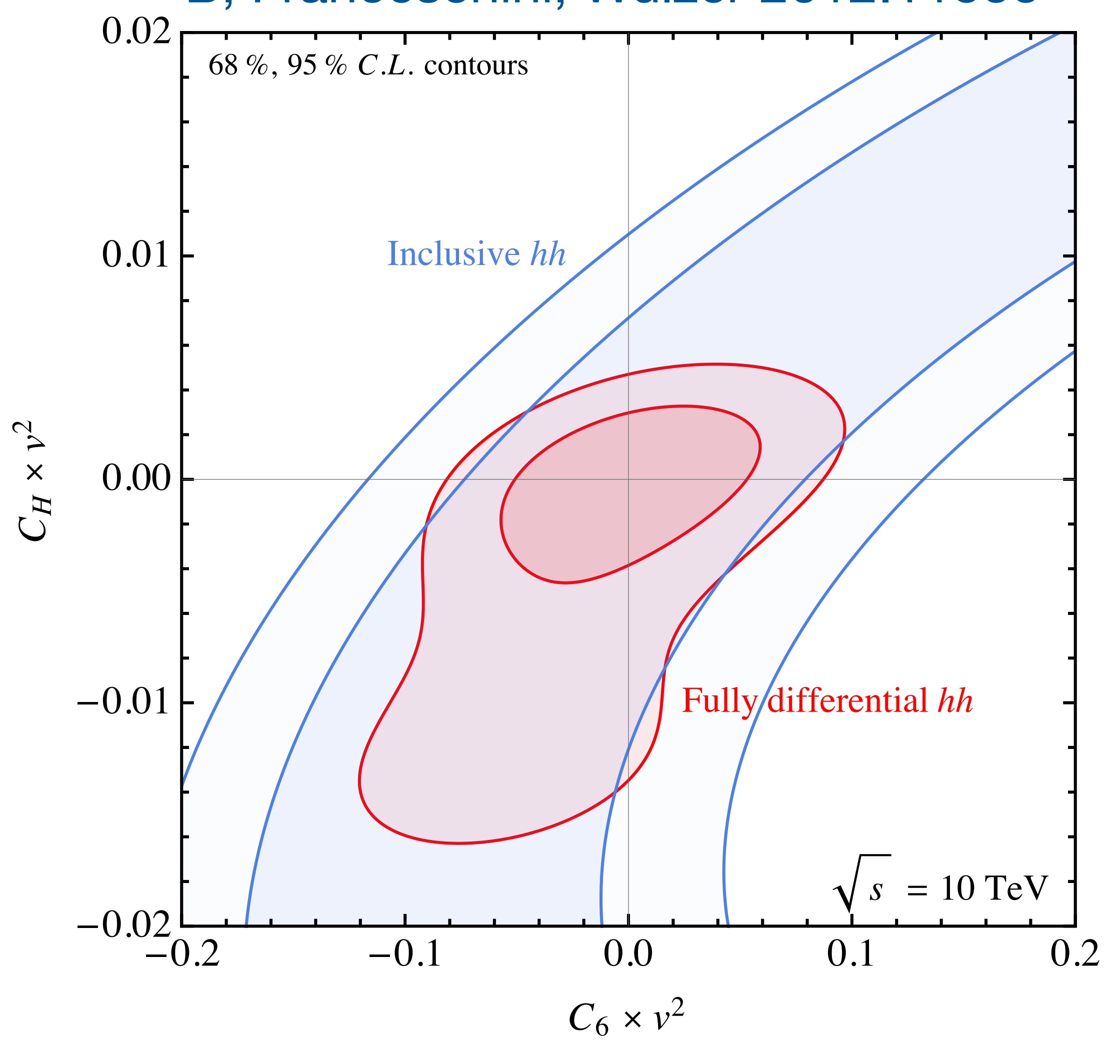
Double Higgs at high mass

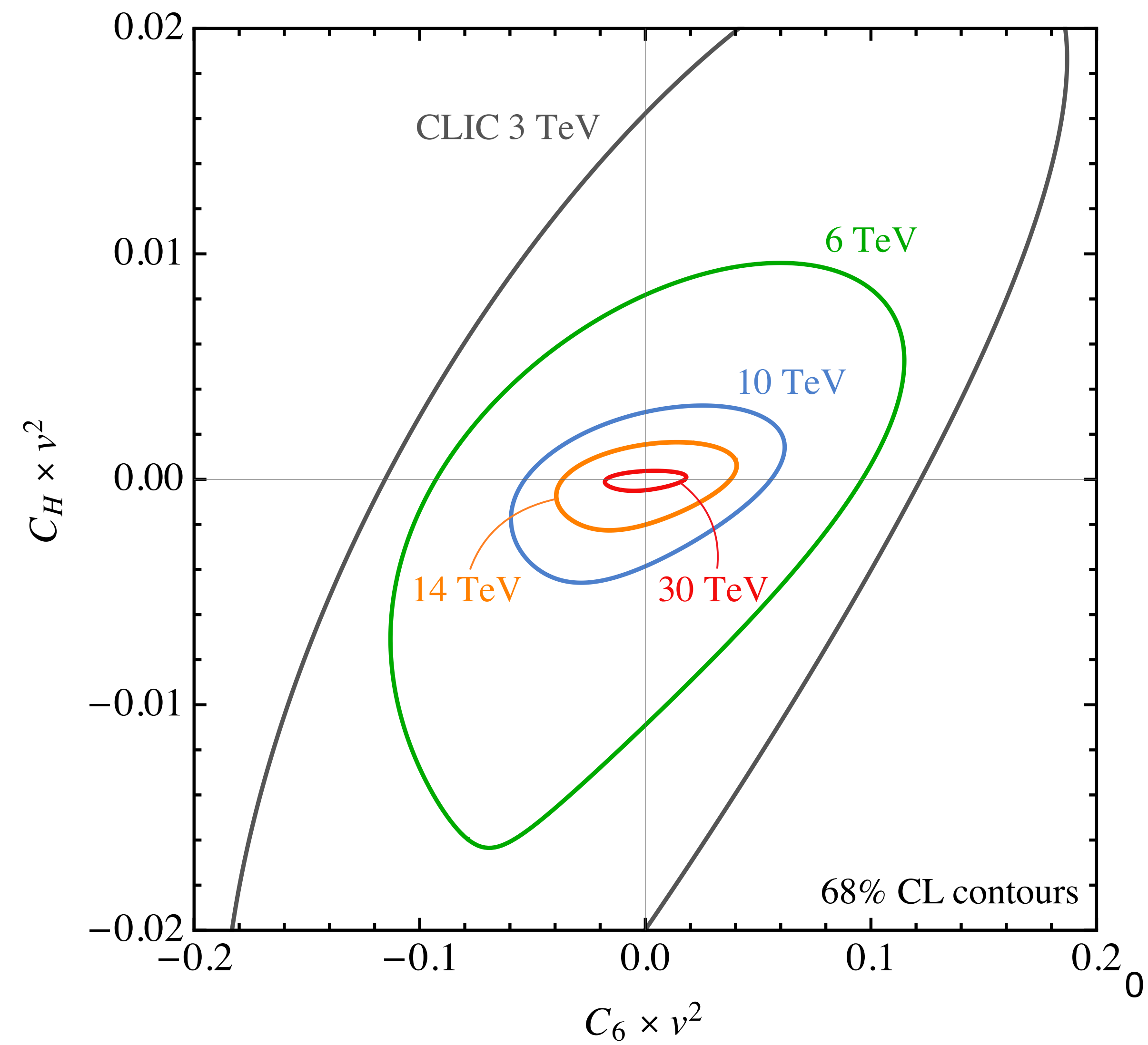
- Fully differential analysis in p_T and M_{hh} to optimize combined sensitivity to C_H and C_6
- Very boosted Higgs bosons: treat them as a single h-jet, without reconstructing the 4 b's.

  We assumed a boosted-H tagging efficiency ~ 50%



B, Franceschini, Wulzer 2012.11555





High-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:

Process	BSM Amplitude
$\ell_L^+\ell_L^- \to Z_0 h$ $\bar{\nu}_L\nu_L \to W_0^+W_0^-$	$s\,(G_{3L}+G_{1L})\sin\theta_\star$
$\ell_L^+\ell_L^- \to W_0^+W_0^-$ $\bar{\nu}_L\nu_L \to Z_0 h$	$s\,(G_{3L}-G_{1L})\sin\theta_\star$
$\ell_R^+\ell_R^- \to W_0^+W_0^-\,,Z_0 h$	$s\,G_{lR}\sin\theta_\star$
$\bar{\nu}_L\ell_L^- \to W_0^-Z_0\,/\,W_0^-h$ $\nu_L\ell_L^+ \to W_0^+Z_0\,/\,W_0^+h$	$\sqrt{2}\,s\,G_{3L}\sin\theta_\star$

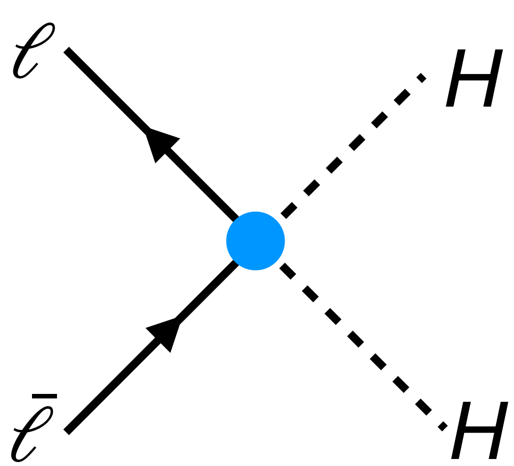
Determined by 3 fermion/scalar current-current interactions (Warsaw):

$$\mathcal{O}_{3L} = \left(\bar{\mathrm{L}}_L\gamma^\mu\sigma^a\mathrm{L}_L\right)\left(iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H\right),$$

$$\mathcal{O}_{1L} = \left(\bar{\mathrm{L}}_L\gamma^\mu\mathrm{L}_L\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right),$$

$$\mathcal{O}_{lR} = \left(\bar{l}_R\gamma^\mu l_R\right)\left(iH^\dagger \overleftrightarrow{D}_\mu H\right).$$

"high-energy primary effects"



High-energy di-bosons

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$\ell^+_L \ell^-_L \to W_0^+ W_0^-$ $\bar{\nu}_L \nu_L \to Z_0 h$	$s\,(G_{3L} - G_{1L}) \sin\theta_\star$
$\ell^+_R \ell^-_R \to W_0^+ W_0^-\,, Z_0 h$	$s\, G_{lR} \sin\theta_\star$
$\bar{\nu}_L \ell^-_L \to W_0^- Z_0 \,/\, W_0^- h$ $\nu_L \ell^+_L \to W_0^+ Z_0 \,/\, W_0^+ h$	$\sqrt{2}\, s\, G_{3L} \sin\theta_\star$

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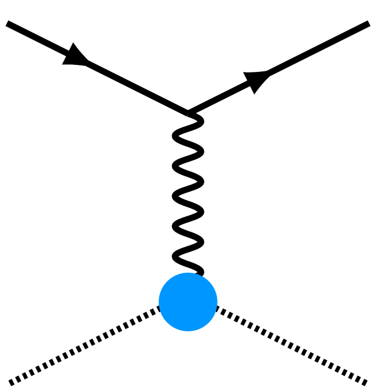
"high-energy primary effects"

✦ In flavor-universal theories, they are generated by SILH operators (via e.o.m.):



$$G_{1L} = \frac{1}{2} G_{lR} = \frac{g'^2}{4}(C_B + C_{HB})$$

$$G_{3L} = \frac{g^2}{4}(C_W + C_{HW})$$

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

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

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

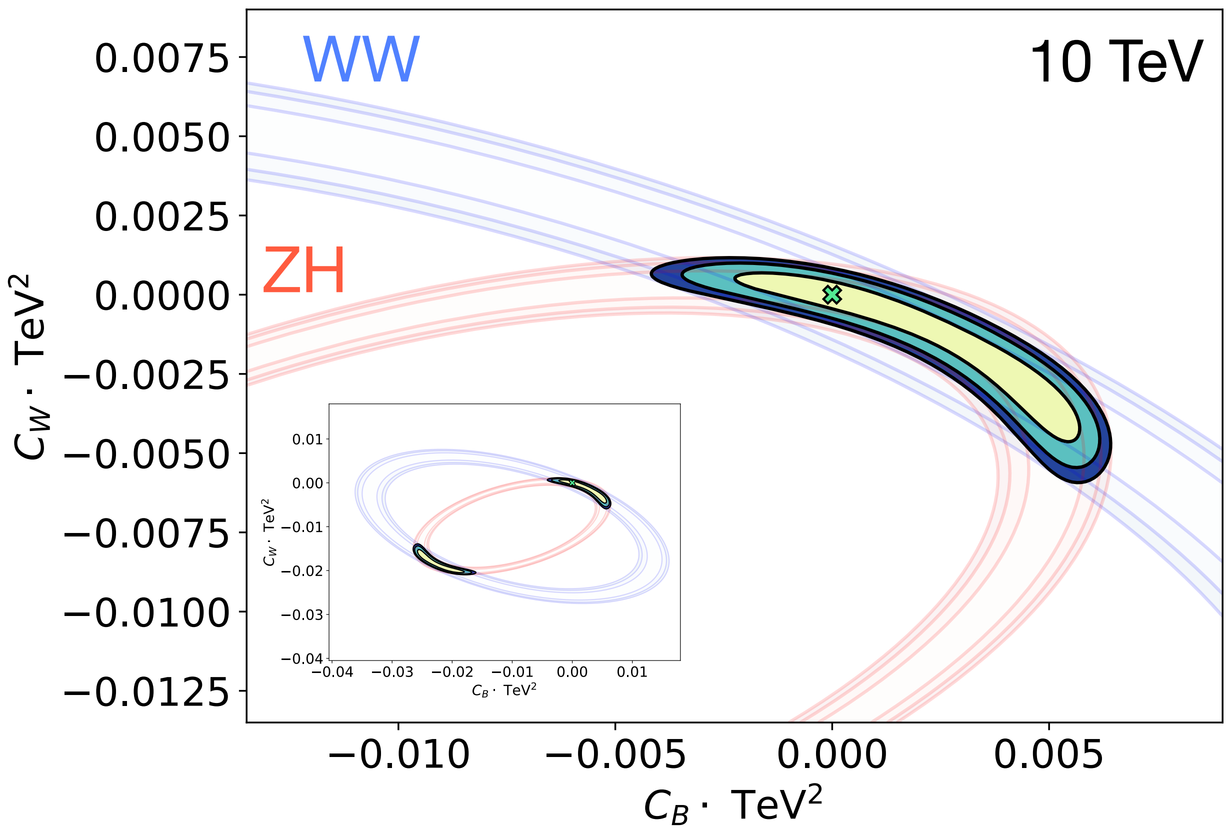
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

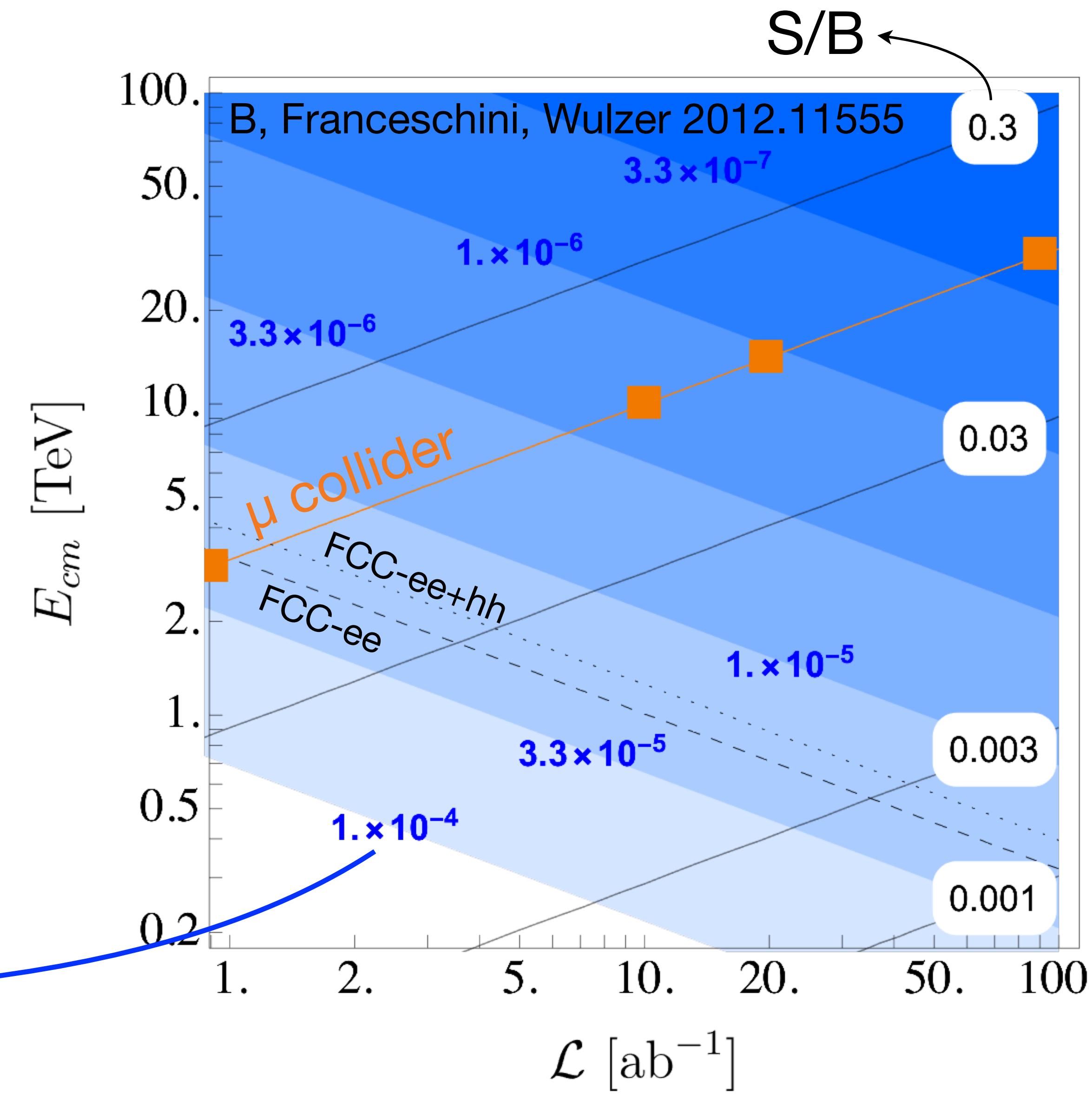
High-energy di-bosons

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

Limits on $C_{W,B}$ scale as E^2

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





- In universal theories, $C_{W,B}$ related with Z-pole and other EW observables

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

Muon collider:

$$10\,\text{TeV}: \quad C_W \lesssim (40\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-6}$$

$$30\,\text{TeV}: \quad C_W \lesssim (120\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-7}$$

LEP : $\hat{S} \lesssim 10^{-3}$

FCC : $\hat{S} \lesssim 10^{-5}$ ← ultimate precision at Z pole

High-energy WW: angular analysis

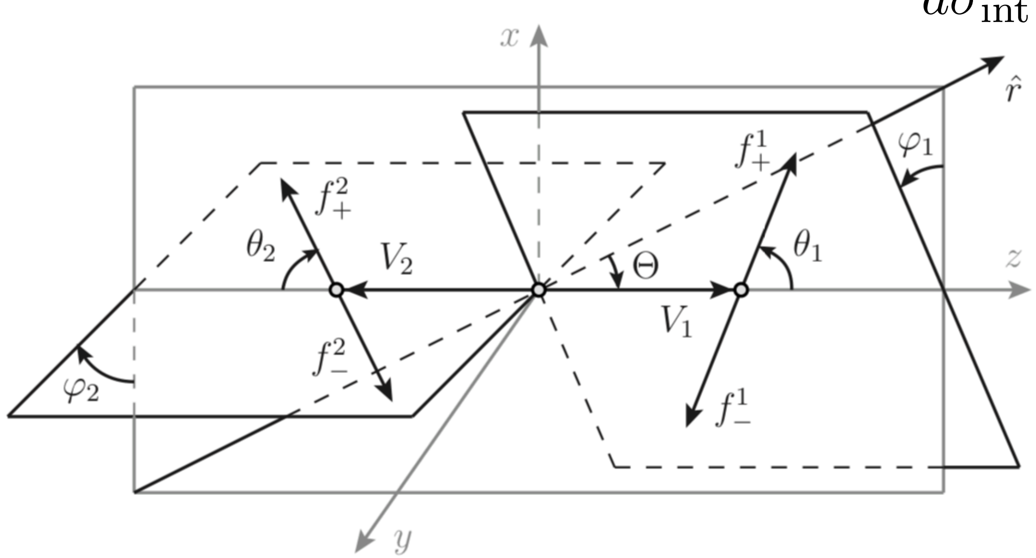
- $O_{W,B}$ contribute to longitudinal scattering amplitudes:

$$\mathscr{A}^{(NP)}_{00} = s\,(G_{1L} - G_{3L})\,\sin\theta_\star$$
$$\mathscr{A}_{-+} = -\frac{g^2}{2}\sin\theta_\star$$
$$\mathscr{A}_{+-} = g^2\cos^2\frac{\theta_\star}{2}\cot^2\frac{\theta_\star}{2}$$

- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

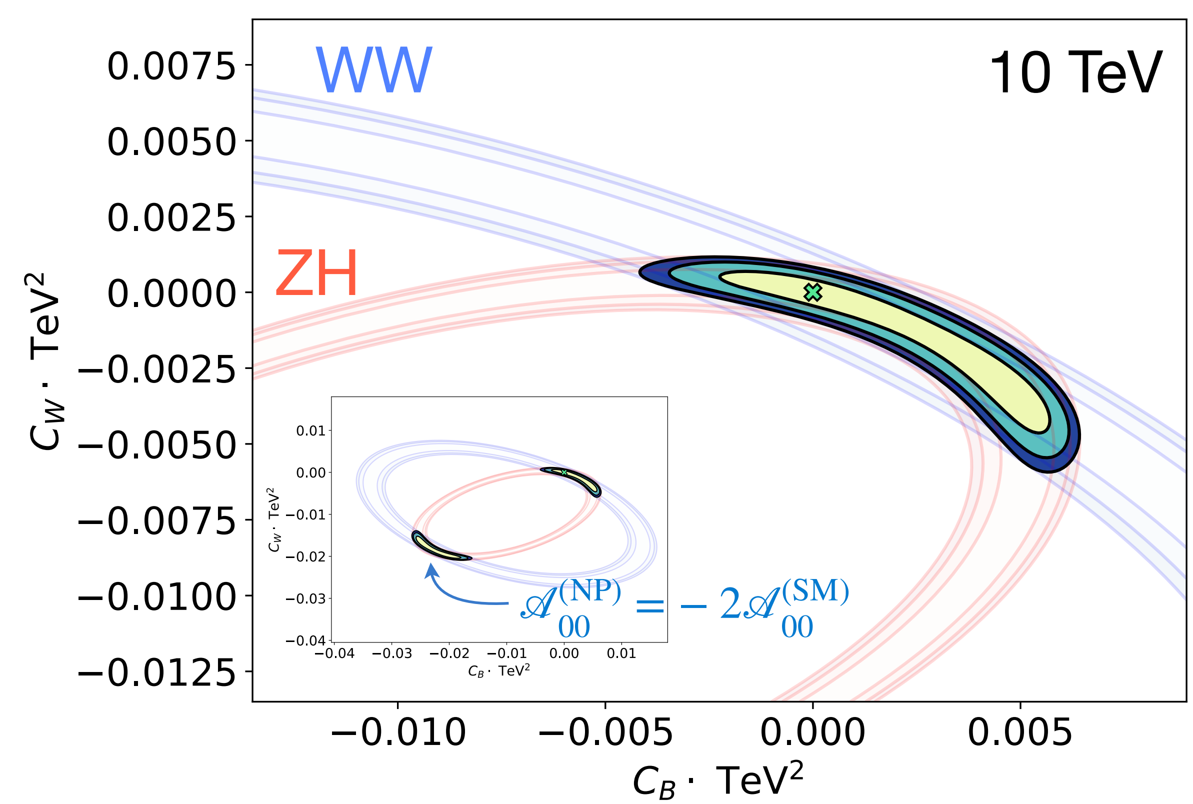
Interference between ±∓ and 00 helicity amplitudes cancels in the total cross-section ⇒ signal suppressed!

see also Panico et al. 1708.07823, 2007.10356



$$d\sigma_{\text{int}} \propto \mathcal{M}_{00}\mathcal{M}_{+-}\cos(\varphi_+ - \varphi_-)\sin\theta_+(1+\cos\theta_+)\sin\theta_-(1-\cos\theta_-)$$
$$+\mathcal{M}_{00}\mathcal{M}_{-+}\cos(\varphi_+ - \varphi_-)\sin\theta_+(1-\cos\theta_+)\sin\theta_-(1+\cos\theta_-)$$

($\theta_\pm, \varphi_\pm$ polar and azimuthal angle of $W^\pm$ decay products)



- Can exploit the SM/BSM interference by looking at fully differential WW cross-section in scattering and decay angles!

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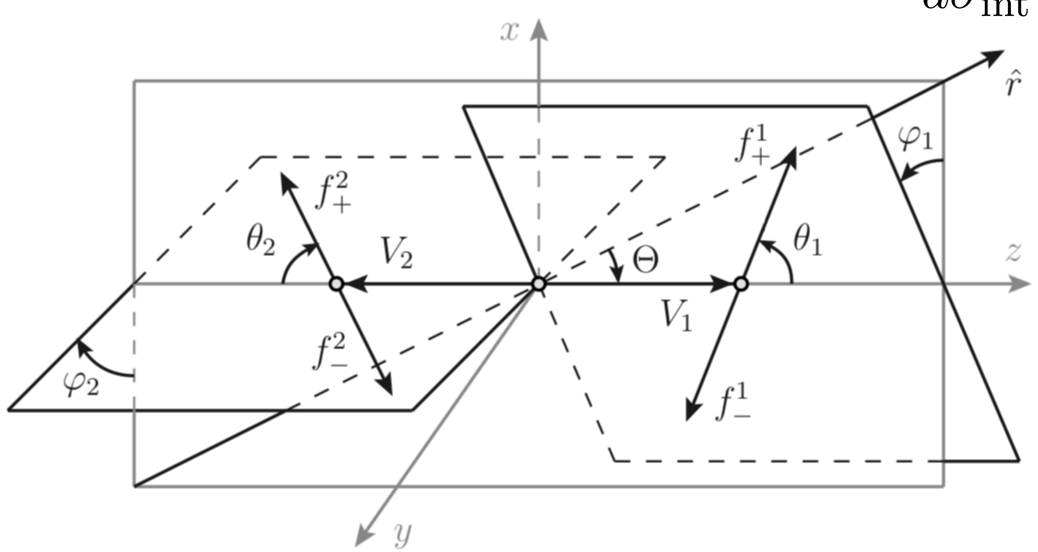

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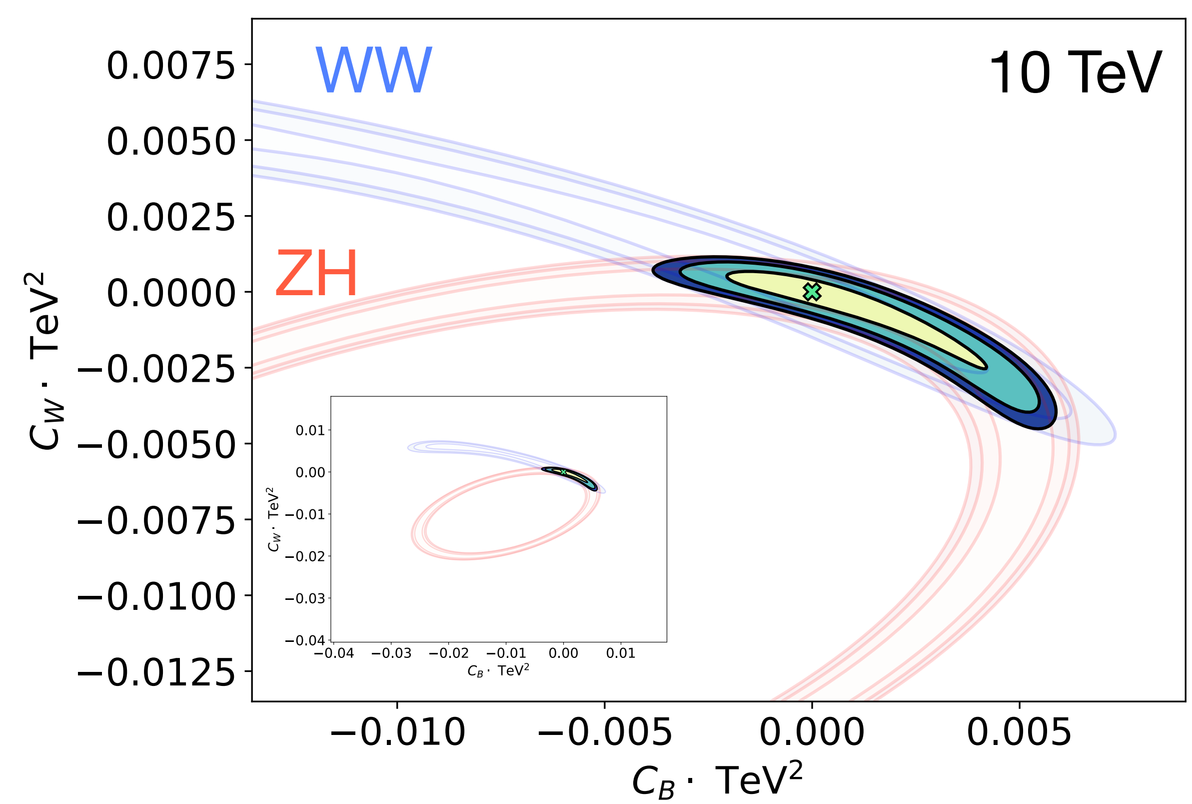

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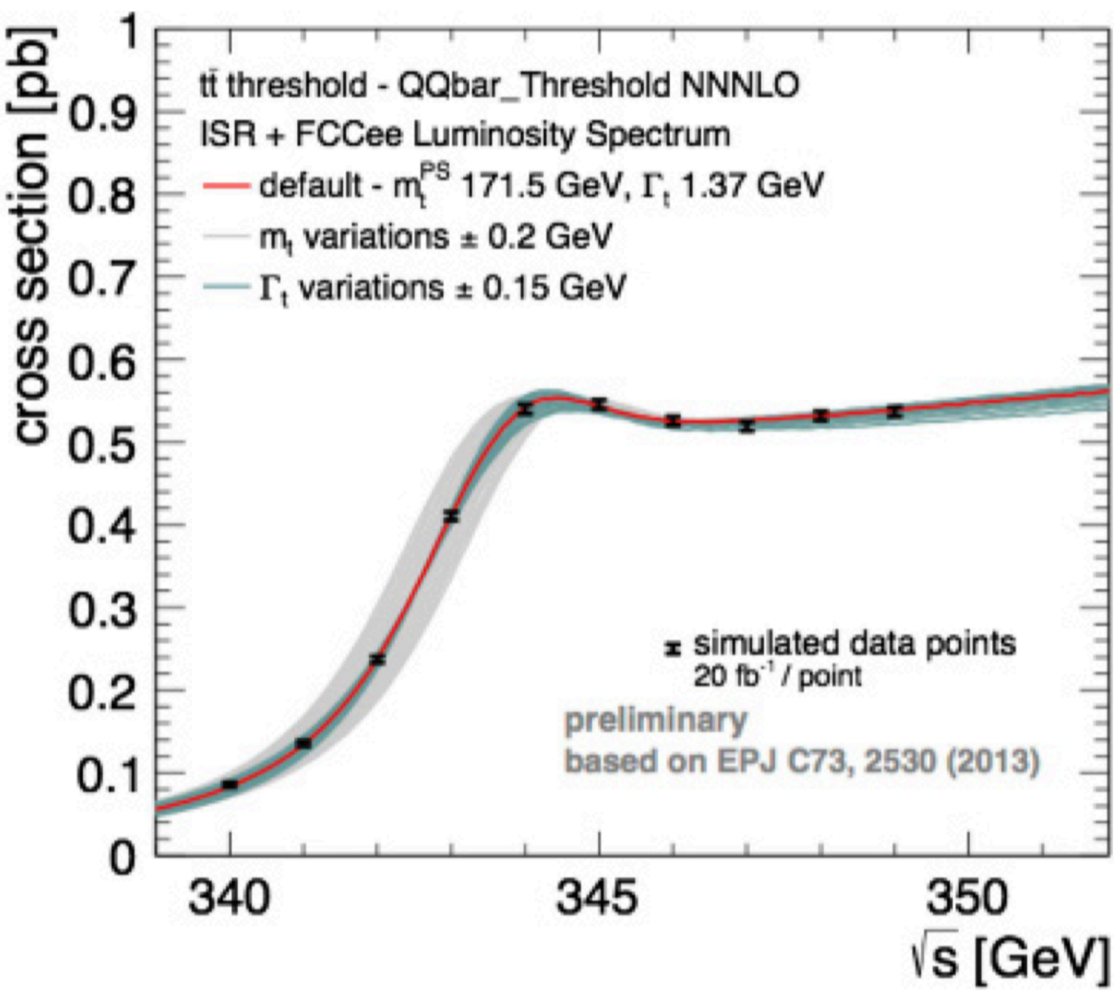
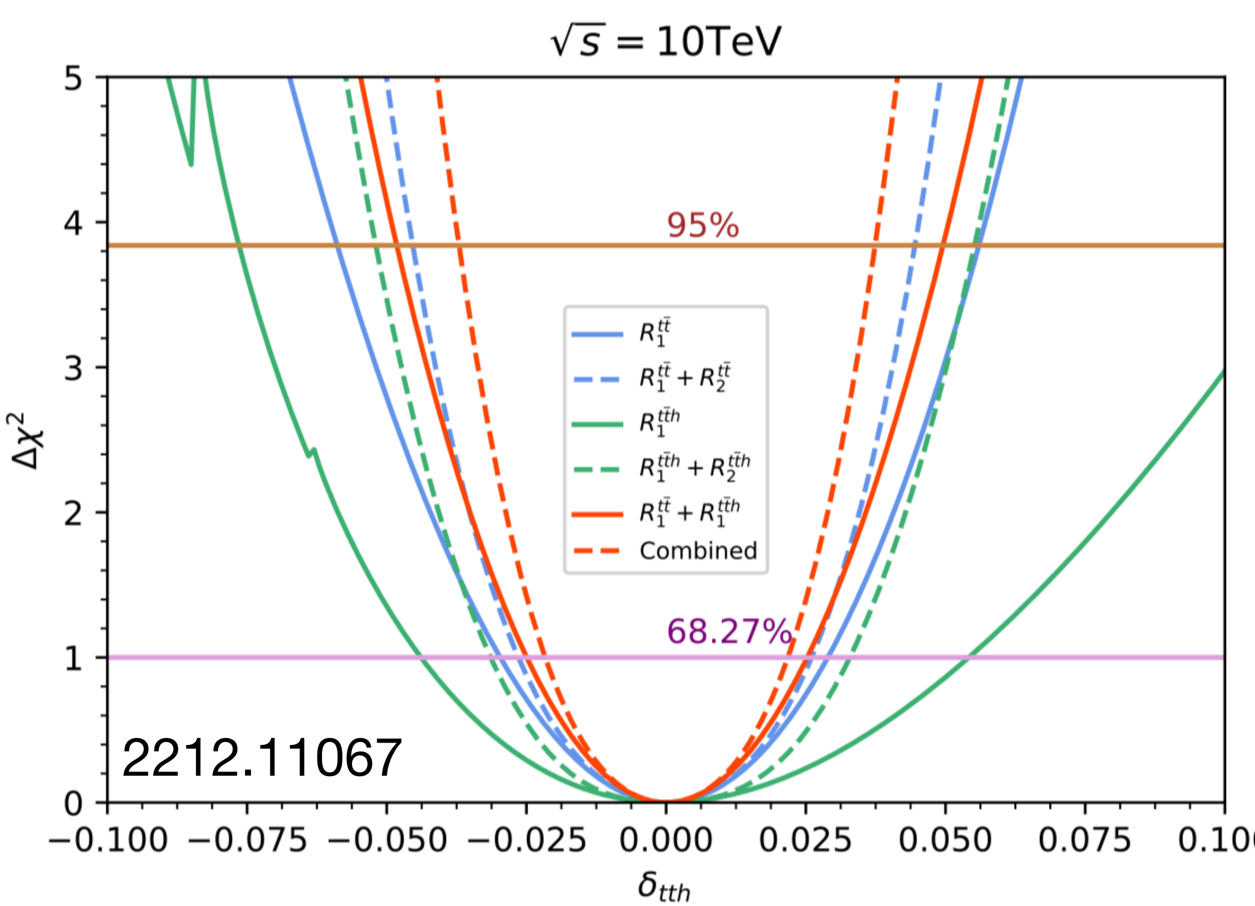
Top quark Yukawa



threshold scan @ FCC

tth @ muon collider



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