Muon colliders: a physics potential overview

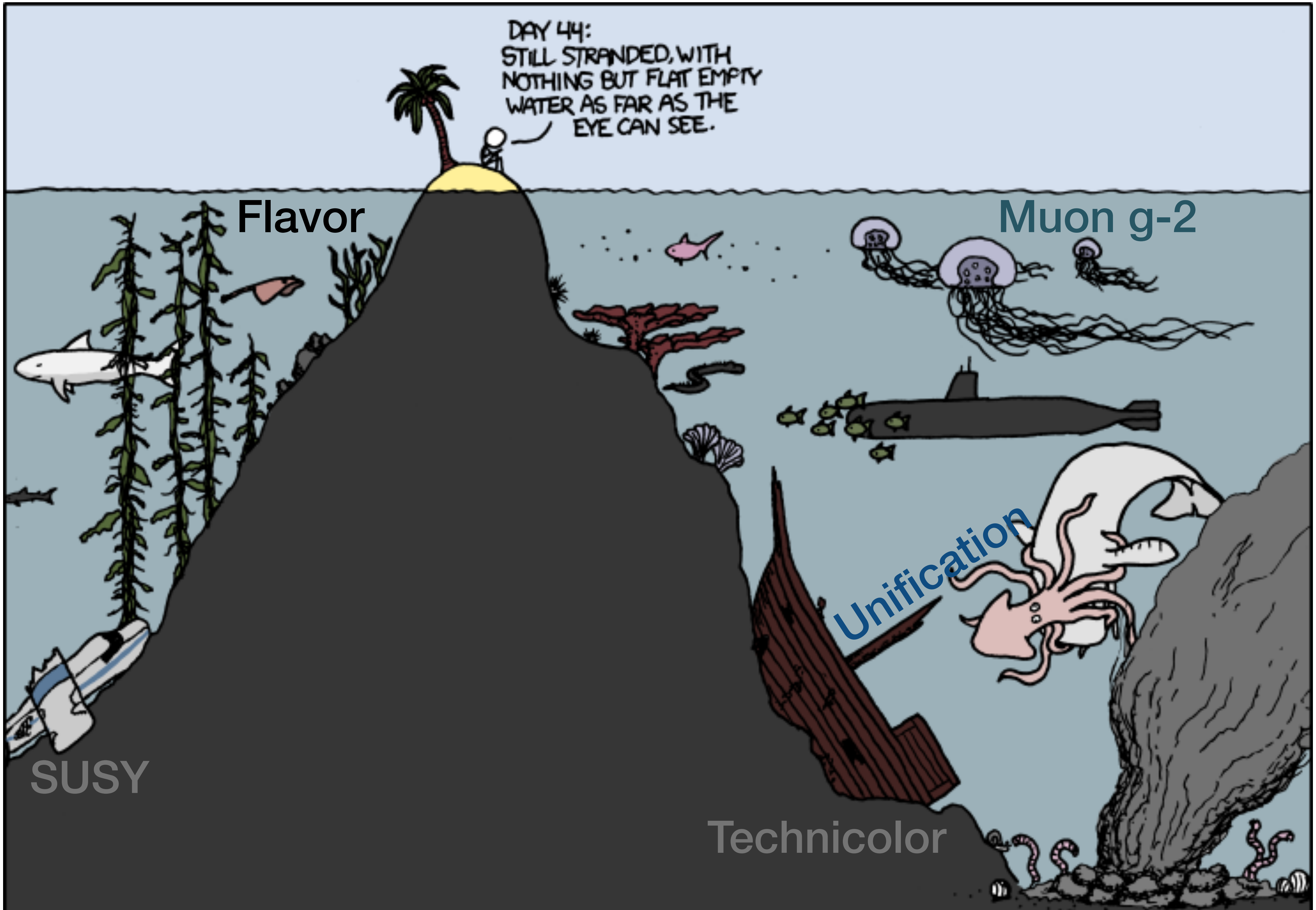
a.k.a. “Good reasons to build a Muon Collider”

Istituto Nazionale di Fisica Nucleare

Dario Buttazzo

Muon Collider Physics and Detector Workshop — 2 June 2021

Collider physics in 2021: a theorist's view



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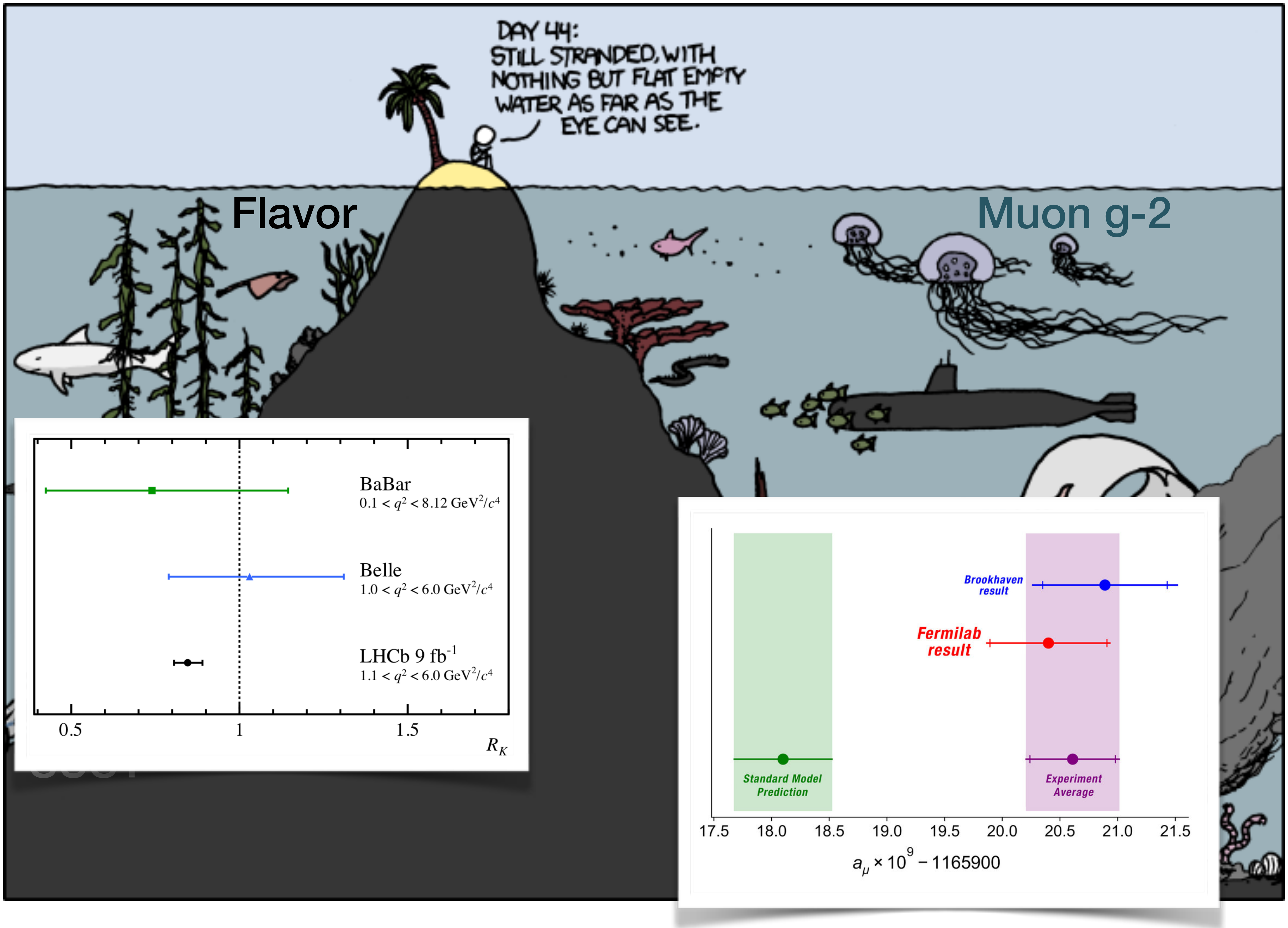


Muon collider physics potential

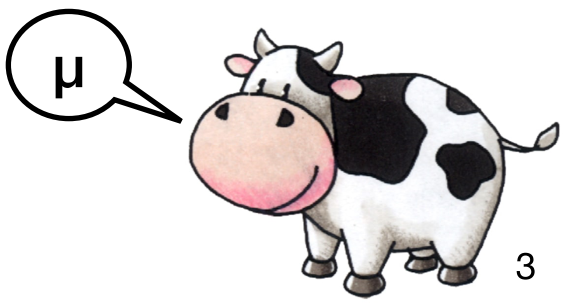
A high-energy muon collider is simply a **dream machine**: allows to probe unprecedented energy scales, exploring many different directions at once!

Direct searches	**High-rate measurements**	**High-energy probes**	**Muon physics**
Pair production, Resonances, VBF, Dark Matter, …	Single Higgs, self coupling, rare and exotic Higgs decays, top quarks, …	Di-boson, di-fermion, tri-boson, EFT, compositeness, …	Lepton Flavor Universality, $b \to s\mu\mu$, muon g-2, …

- ✦ Theory input needed: define energy, luminosity and detector performance goals — physics potential of a multi-TeV muon collider

- ✦ Great interest in the theory community:

1807.04743 2005.10289 2008.12204 2012.11555 2102.11292 2104.05720
1901.06150 2006.16277 2009.11287 2101.10334 2103.01617 etc …
2003.13628 2007.14300 2012.02769 2102.08386 2103.14043



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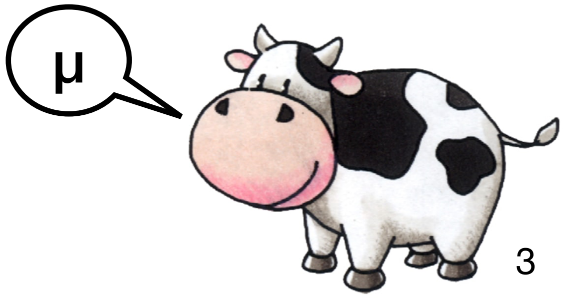
$$\mathscr{L}_{\mathrm{int}} = 10\,\mathrm{ab}^{-1} \times \left(\frac{E_{\mathrm{cm}}}{10\,\mathrm{TeV}}\right)^2$$

needed to be able to perform measurements with ~ % precision

everything else is still unknown:
will be determined by technological feasibility & physics goals

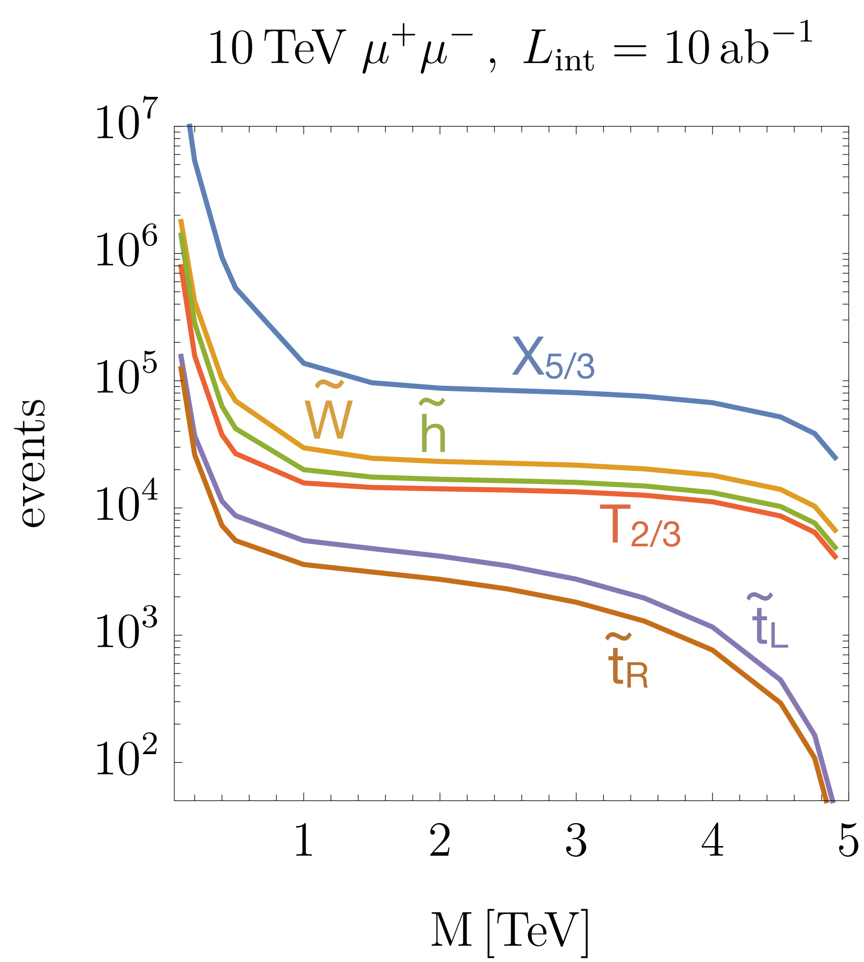
Synergy between physics, detector, and accelerator communities particularly important!

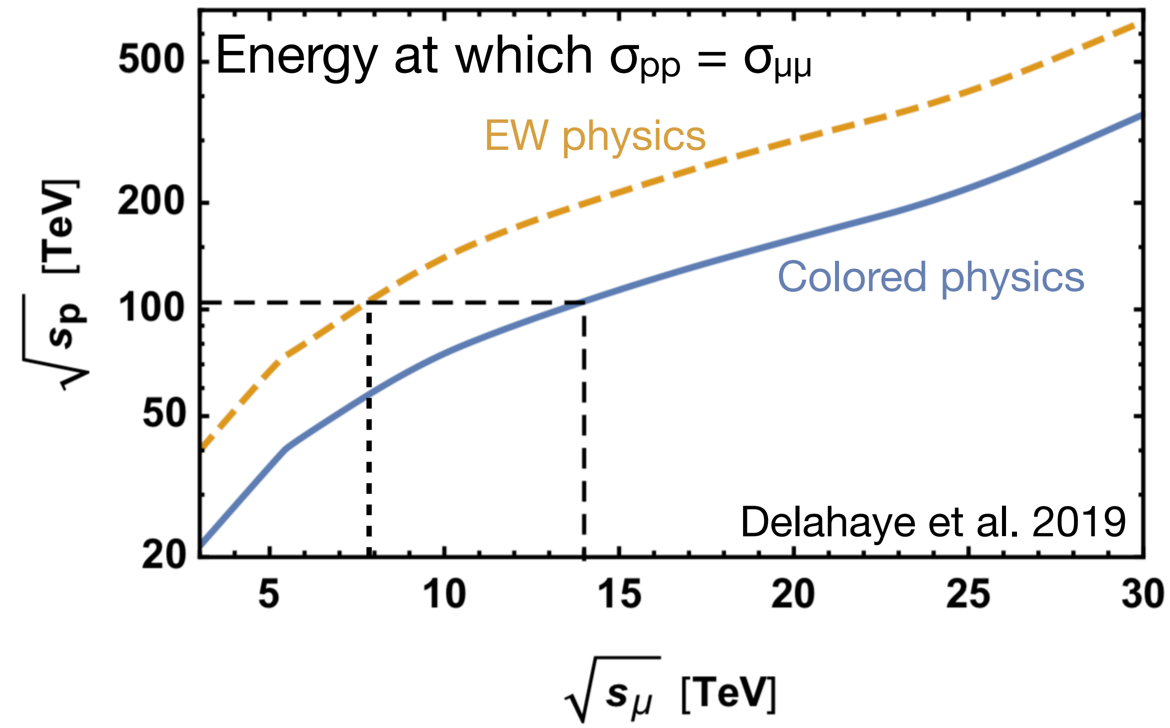


Direct searches

- The most striking advantage of a muon collider is the ability to collide elementary particles at very high center-of-mass 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!





Colored particles: 14 TeV μμ ~ 100 TeV pp

EW particles: 14 TeV μμ >>> 100 TeV pp

Example: WIMP Dark Matter

- Weakly Interacting Massive Particle in the purest sense: most general EW multiplet with DM candidate that is

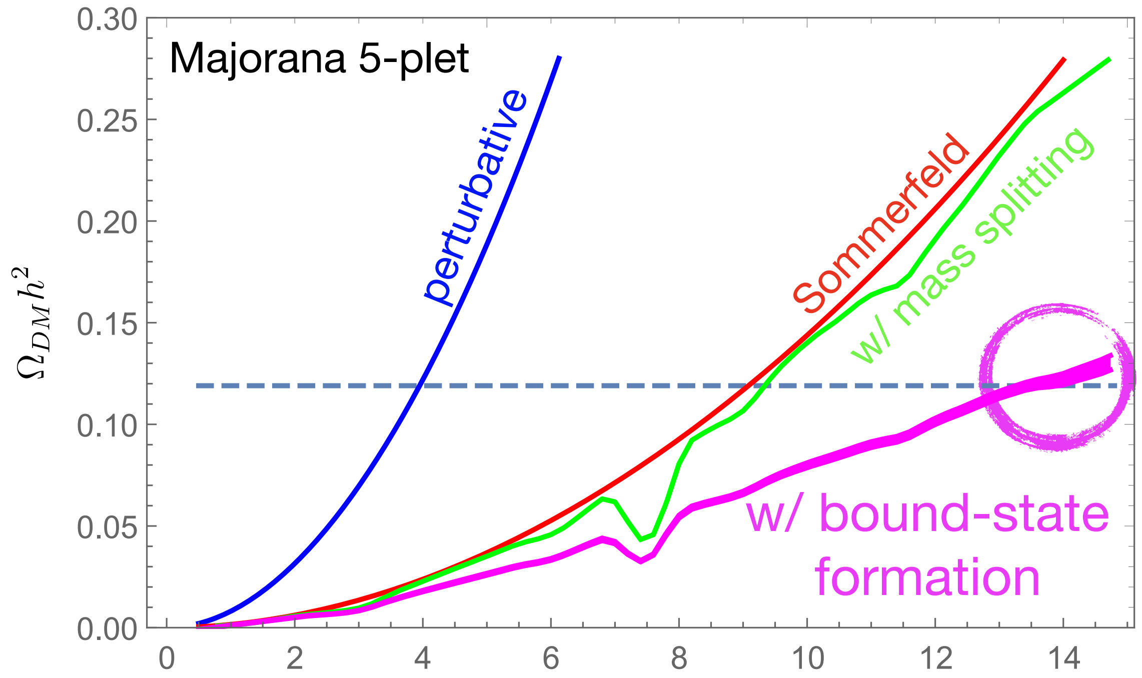
  (a) stable,

  (b) without coupling to γ & Z,

  (c) calculable (perturbative).

- Mass can be large: Muon-collider-energies crucial to probe some candidates!

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



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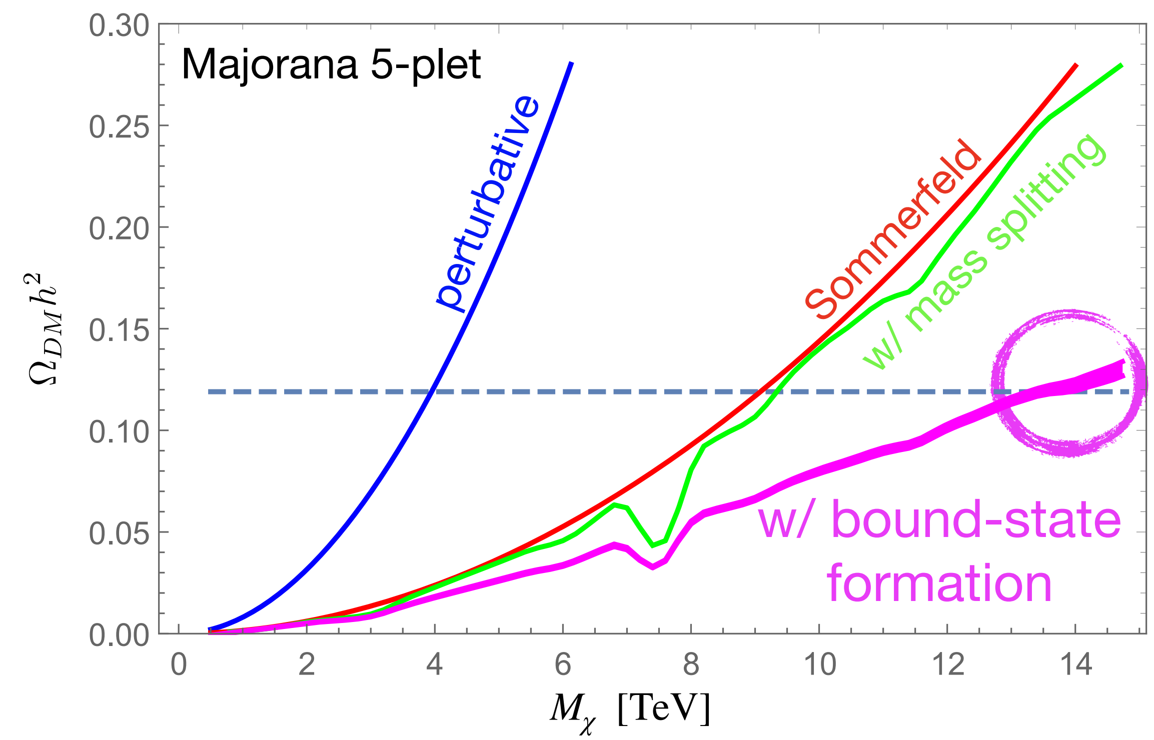

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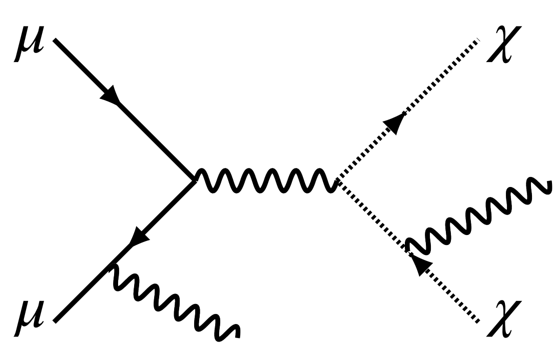
- Collider searches: mono-γ/W/Z signals

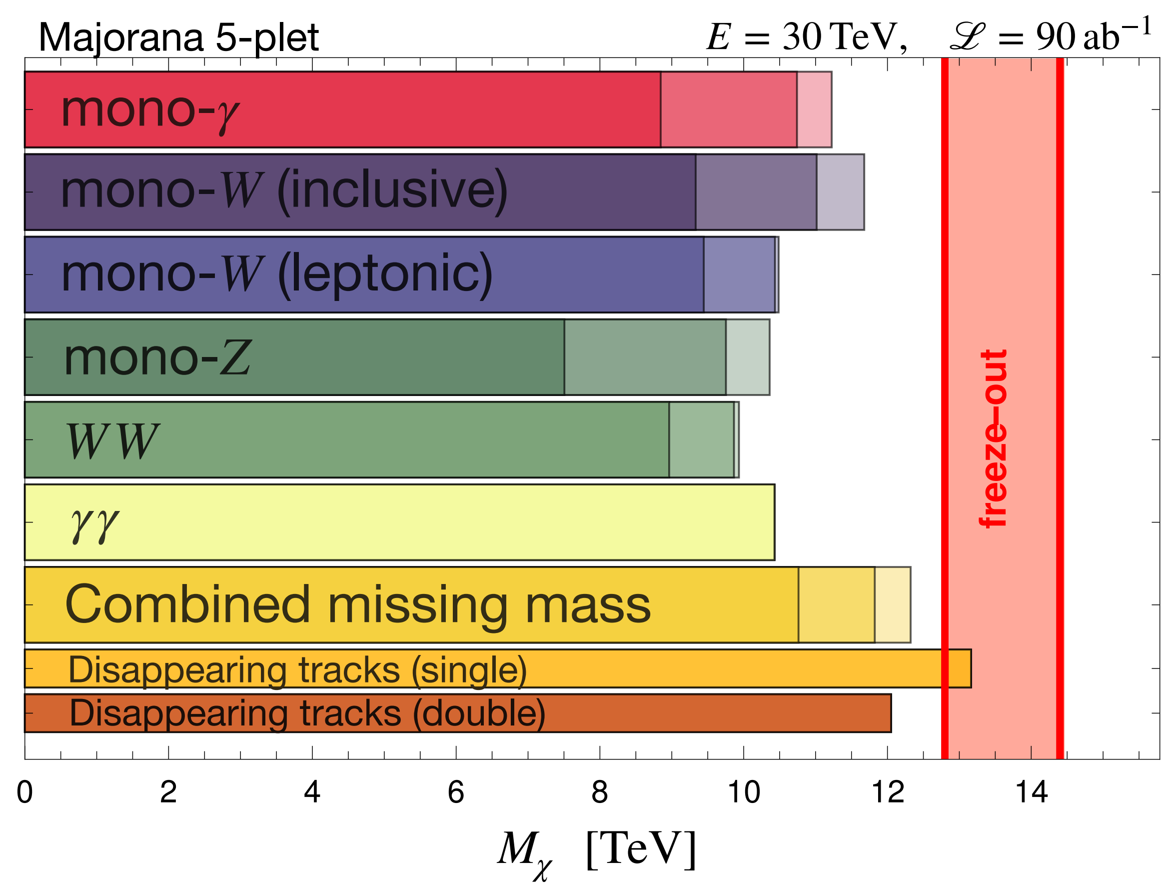
  double emission ($\gamma\gamma$, WW) also important

Han et al. 2009.11287

S. Bottaro, M. Costa, L. Vittorio,
B, Franceschini, Panci, Redigolo 2106.xxxxx

☛ talk by Lian-Tao





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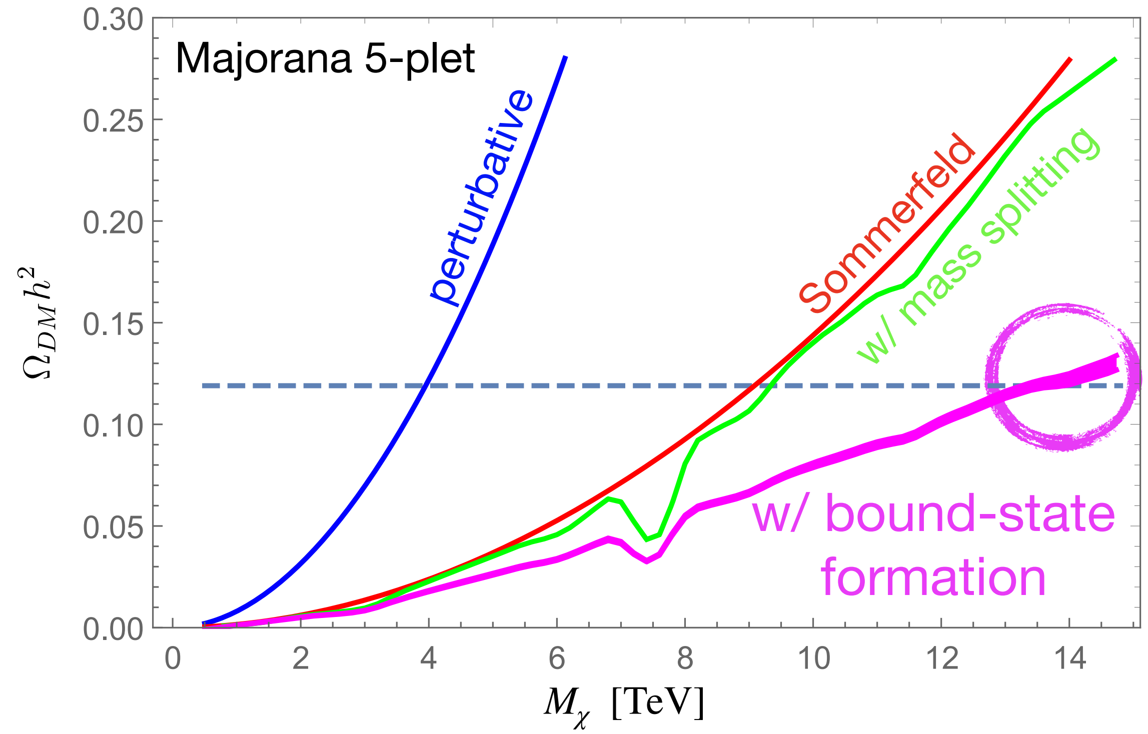

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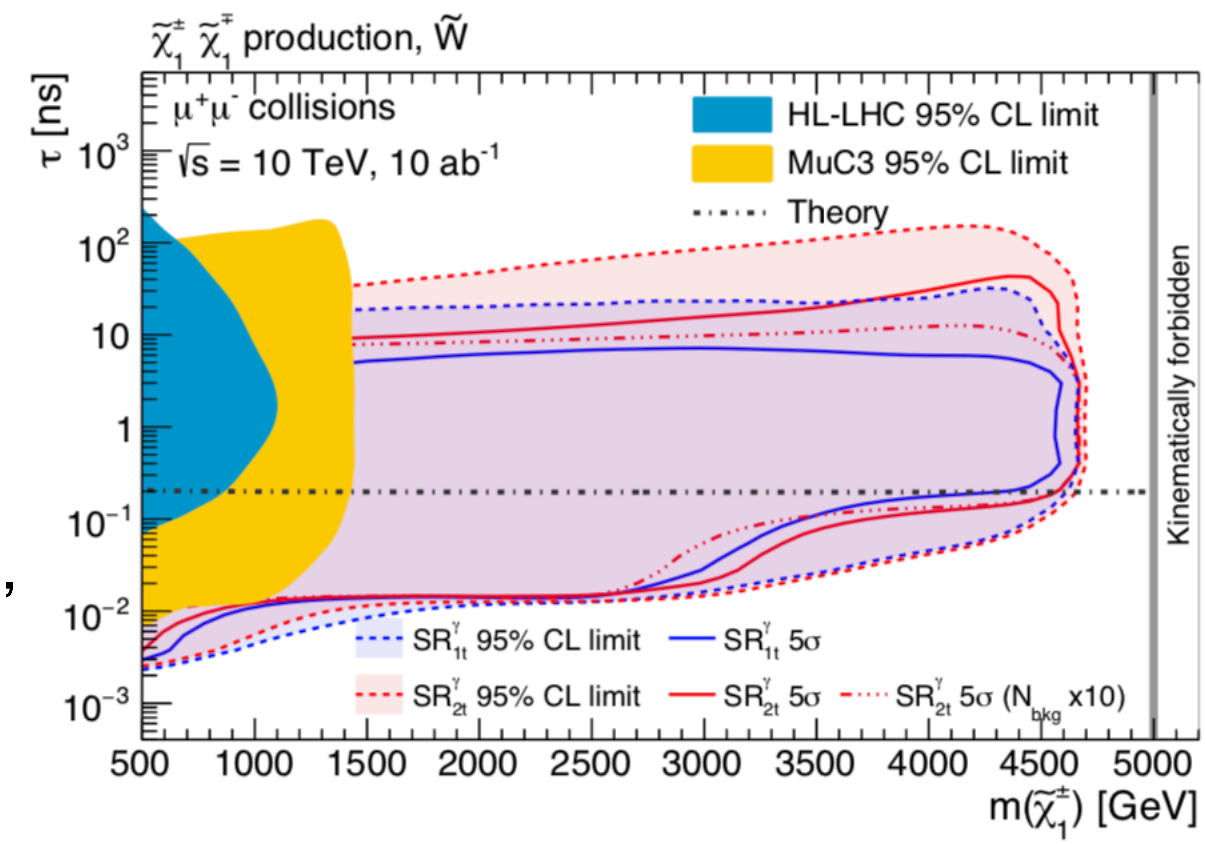
Charged components of multiplet are long-lived, can decay inside detector: disappearing tracks

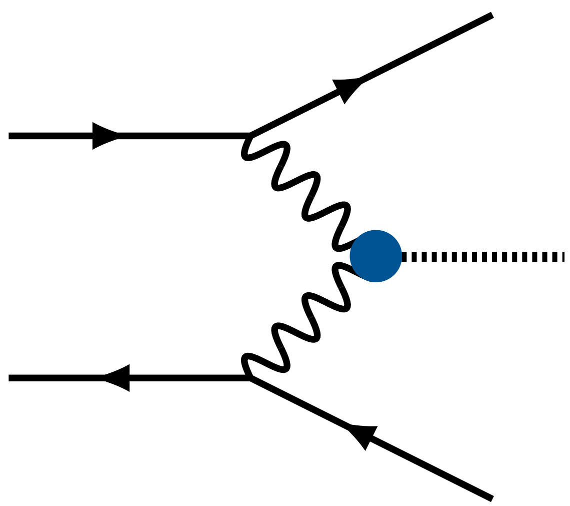
☛ talk by José

Capdevilla et al. 2102.11292

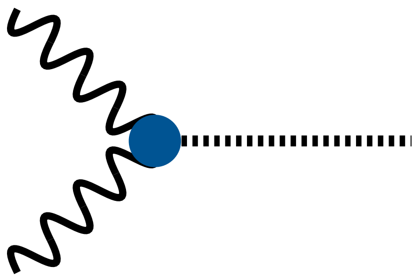


Resonances in VBF

The μ-collider is a “vector boson collider”



$$\approx \frac{E^2}{m_\phi^2} \log \frac{E^2}{m_\phi^2}$$



enhanced if the resonance is “light” $m_\phi \ll E$

Dawson 1985

B, Redigolo, Sala, Tesi 1807.04743
Costantini et al. 2005.10289

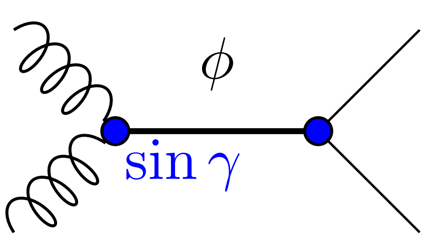
see also the “Muon Smasher’s guide”
Al Ali, Arkani-Hamed et al. 2103.14043

- Example: singlet scalar, $\mathscr{L}_{\text{int}} \sim \phi |H|^2$ $\qquad \ell^+\ell^- \to \phi\nu\bar{\nu}$

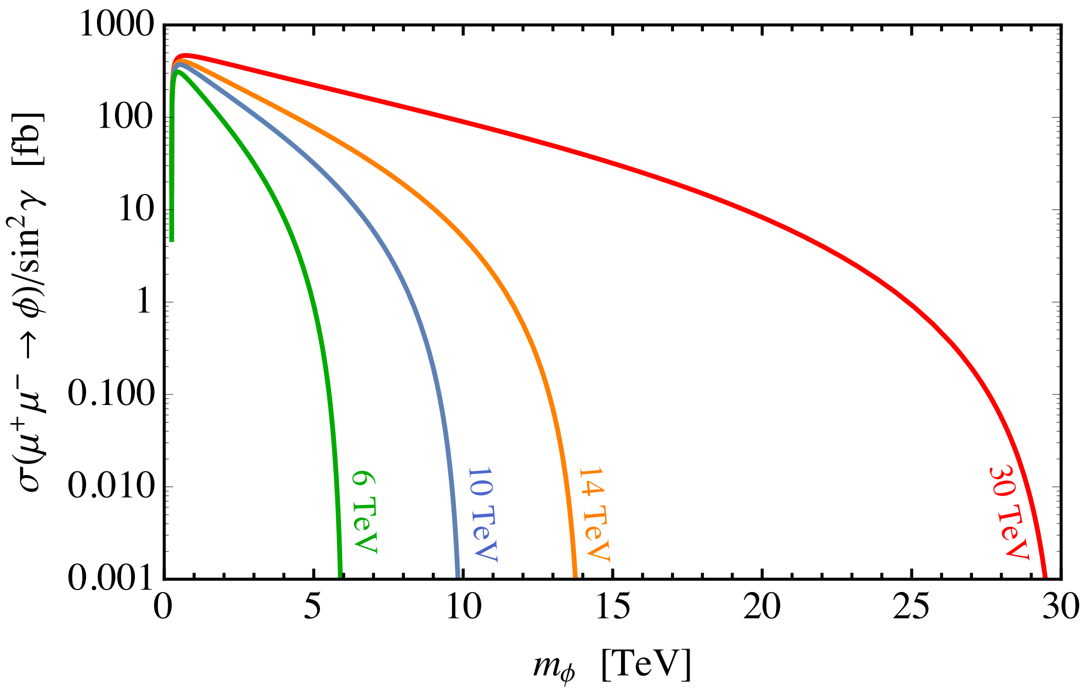
  ϕ is like a heavy Higgs with narrow width + hh decay $\qquad \phi \to hh, WW, ZZ$

cross-section grows at high energy due to longitudinal W-fusion

$$\sigma_{\ell\ell\to\phi\nu\nu} \approx \frac{g^2 \sin^2\gamma}{256\pi^3 v^2} \log \frac{s}{m_\phi^2}$$



γ mixing angle between SM Higgs h and singlet ϕ



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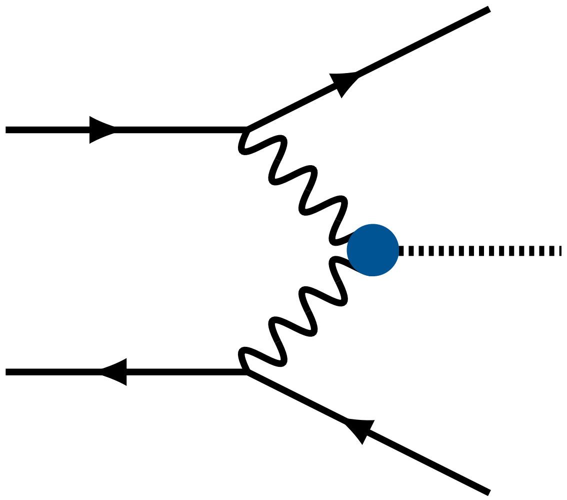

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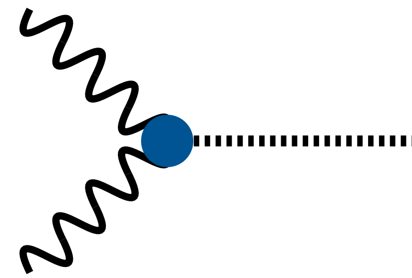

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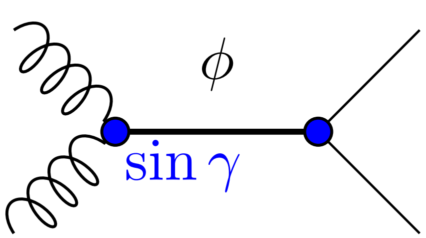
one single parameter controls resonance production, decay, & Higgs coupling modifications



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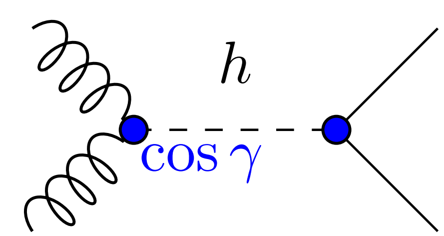

Example: scalar singlet

Compare direct and indirect reach of different colliders

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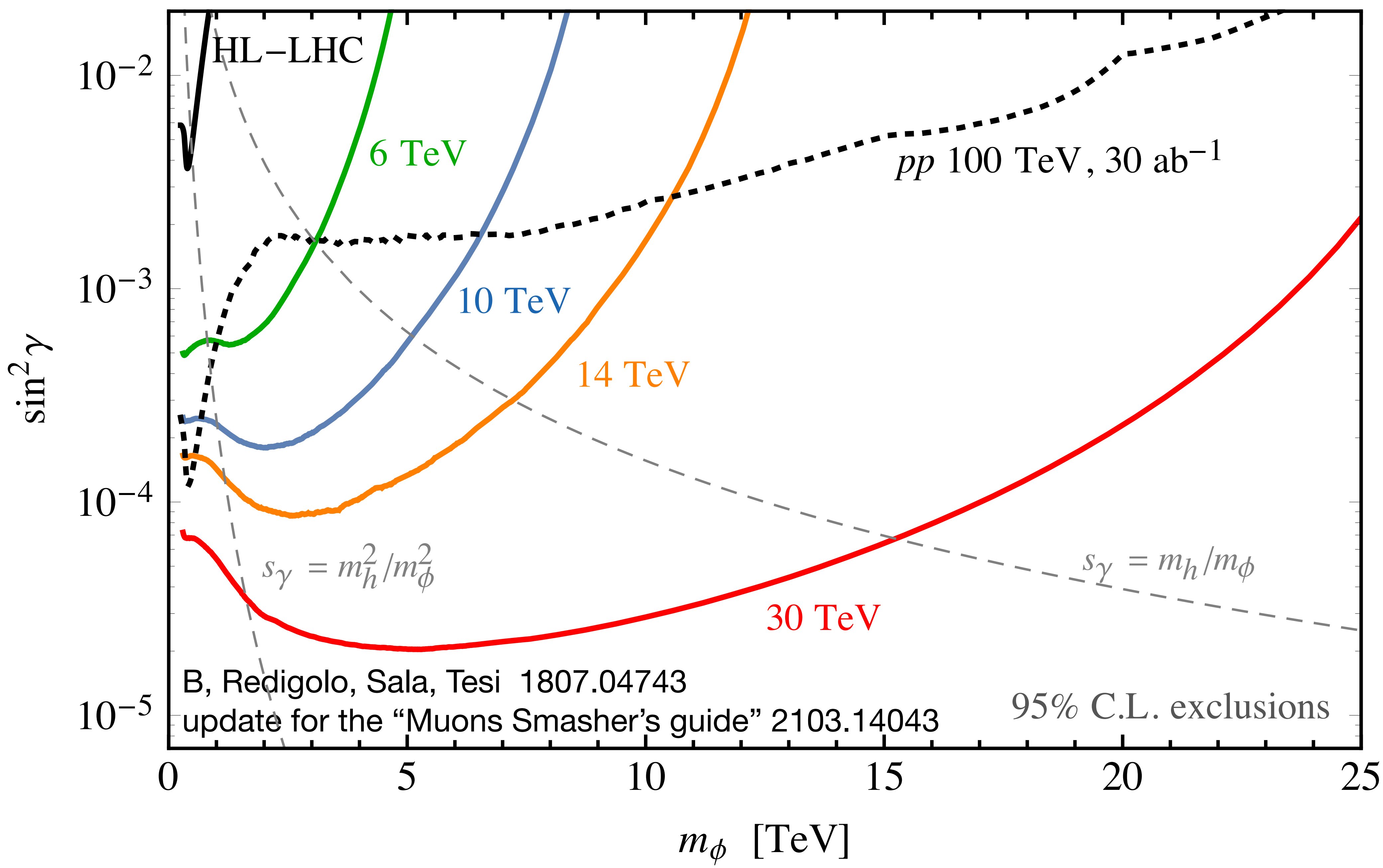

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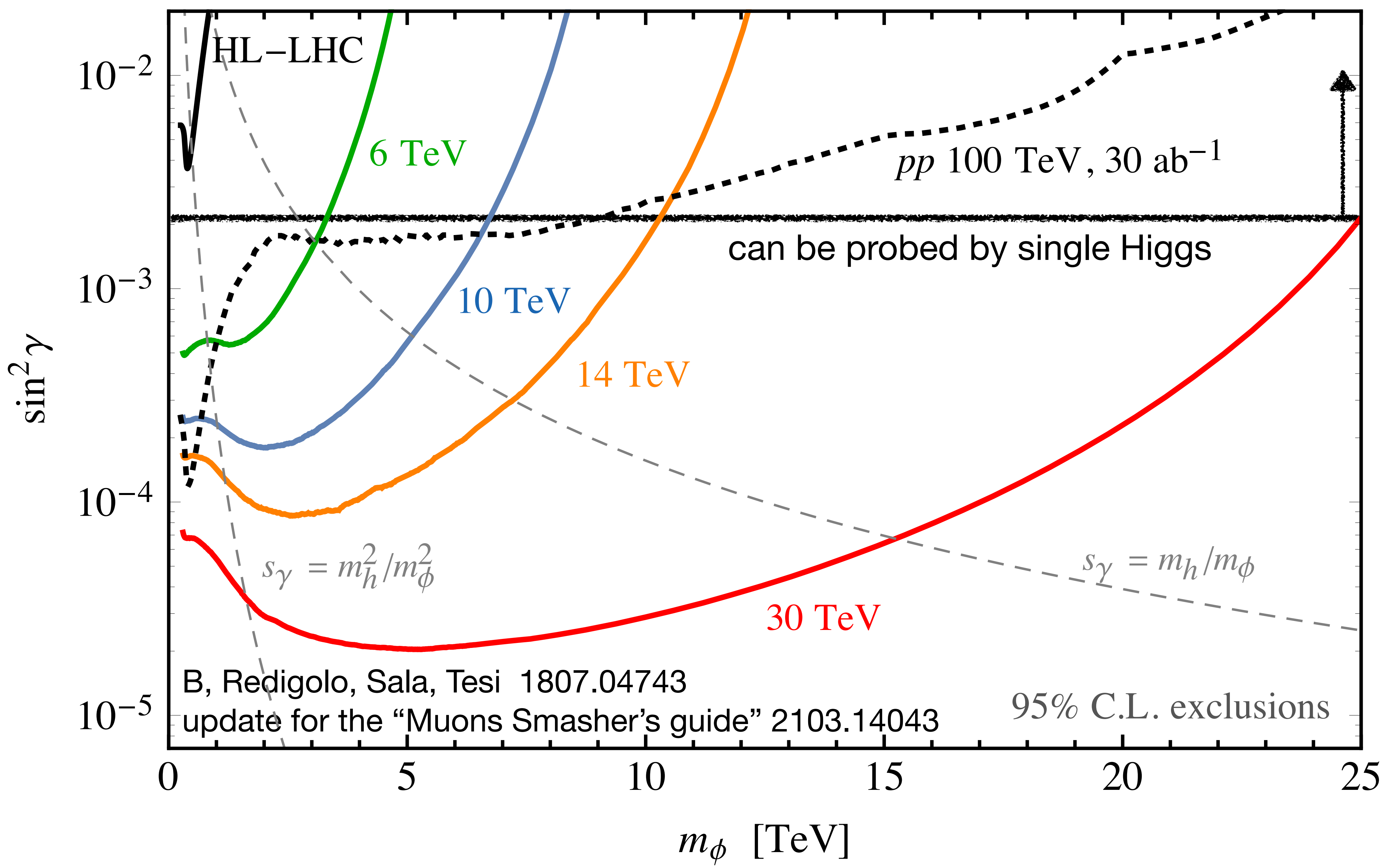

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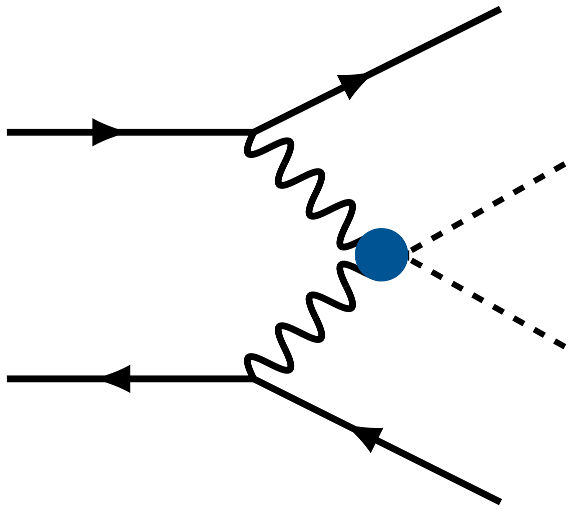
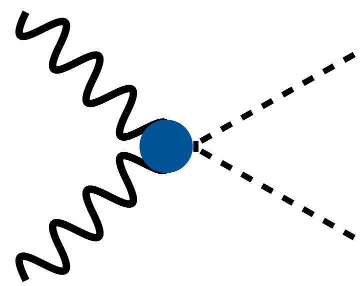
High rate probes: Higgs physics



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



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

B, Redigolo, Sala, Tesi 1807.04743

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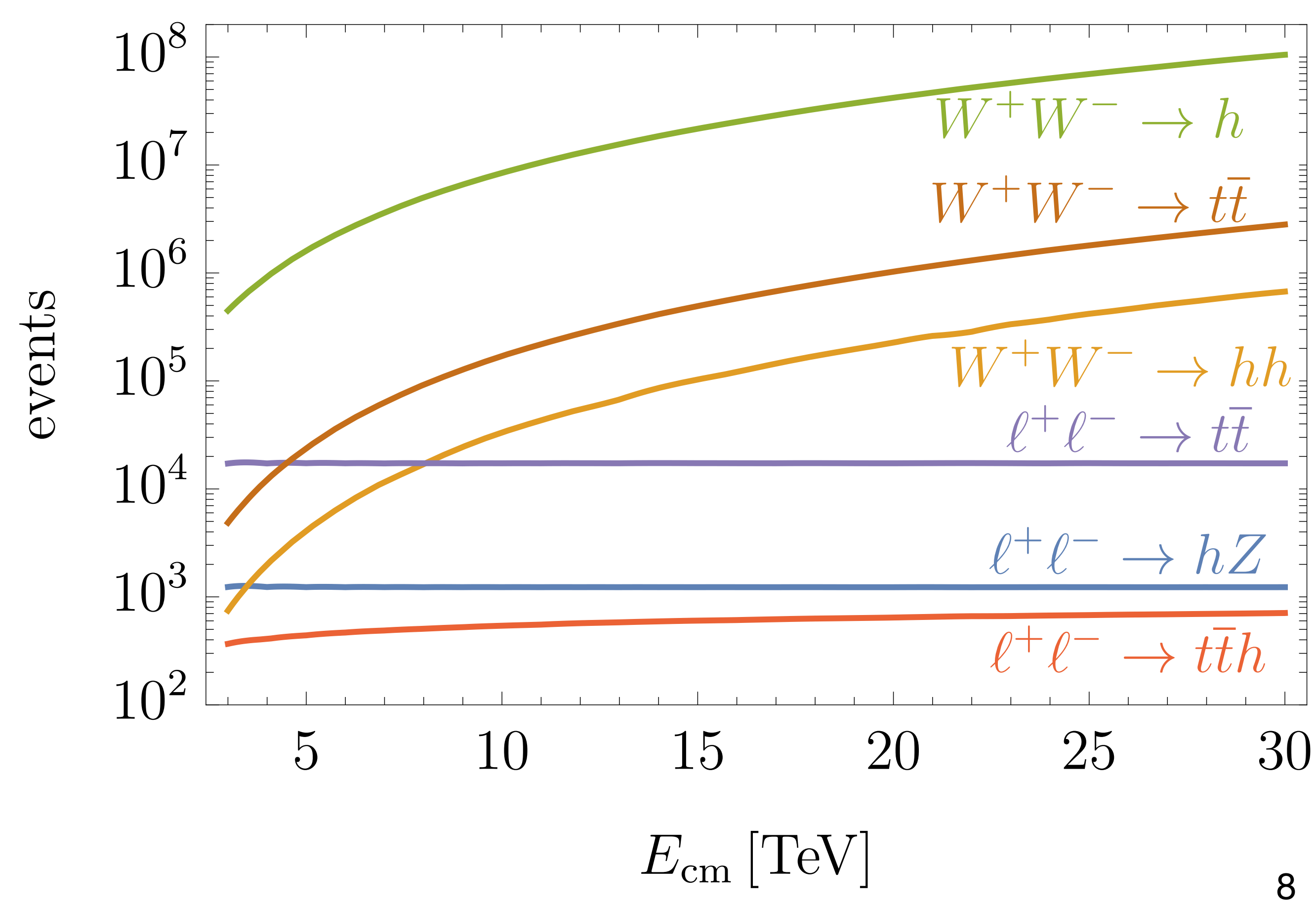
- ✦ Huge single Higgs VBF rate (10^7-10^8 Higgs bosons at 10-30 TeV)
  - Precision on Higgs couplings driven by systematic errors:

    probably 1‰ like H-factories

    ☛ *see Patrick’s talk tomorrow*
  - Statistical error small
  - Opportunity for Rare and Exotic Higgs decays!



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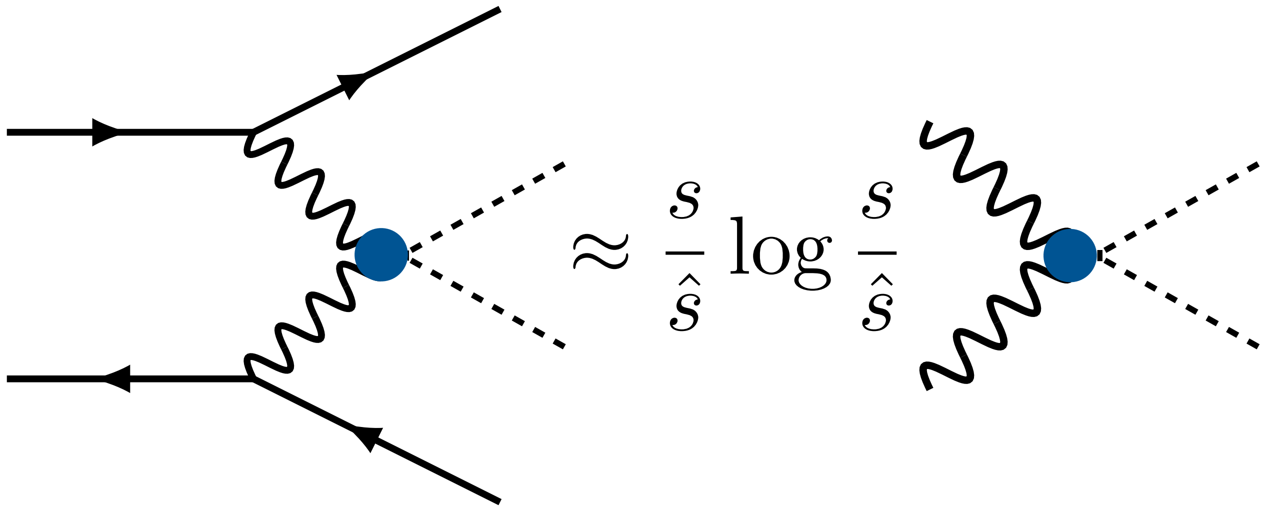

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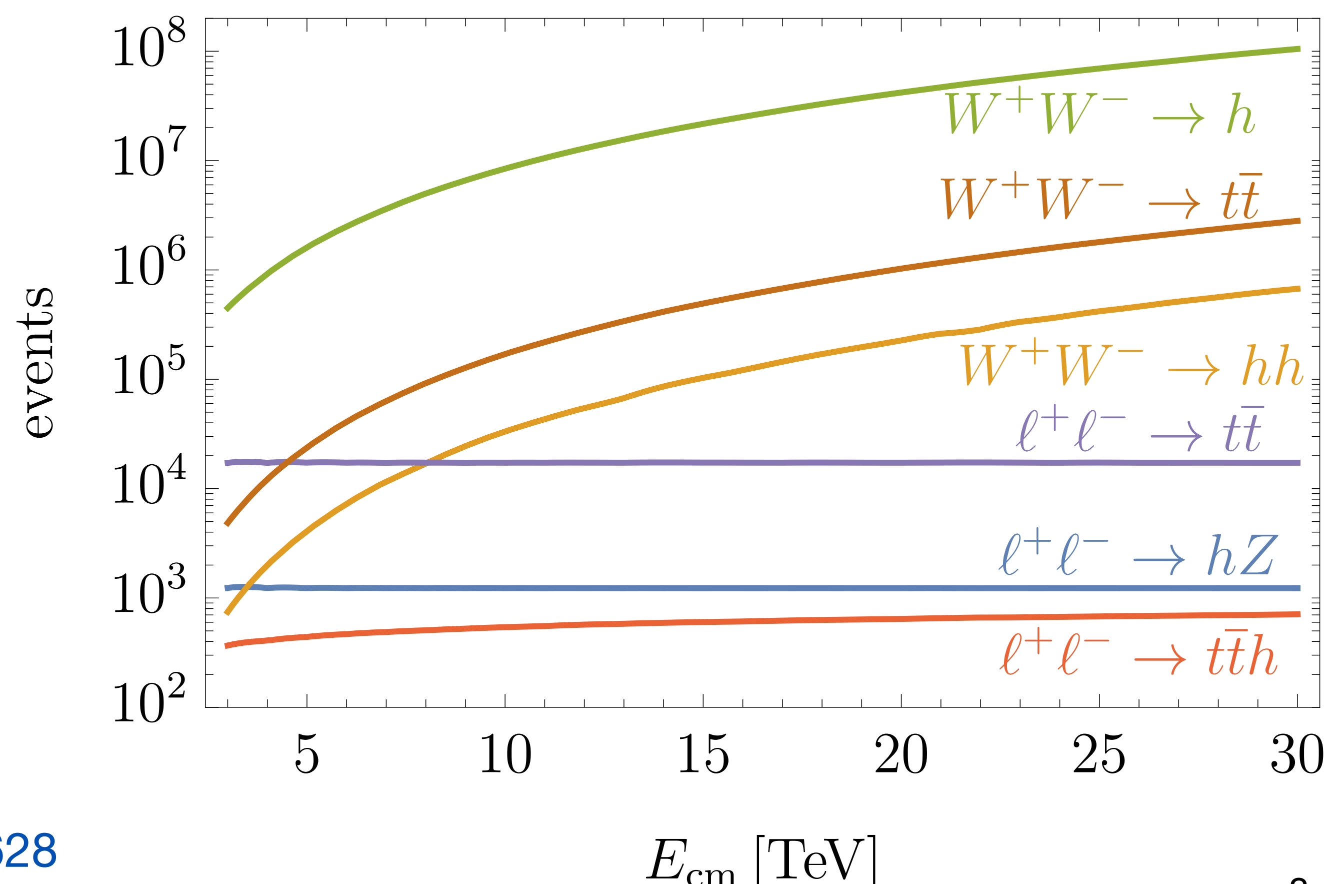
- ✦ Large double Higgs VBF rate
  - Higgs 3-linear coupling
- ✦ Triple Higgs production accessible
  - Higgs 4-linear coupling, dim. 8 operators

Chiesa et al. 2003.13628

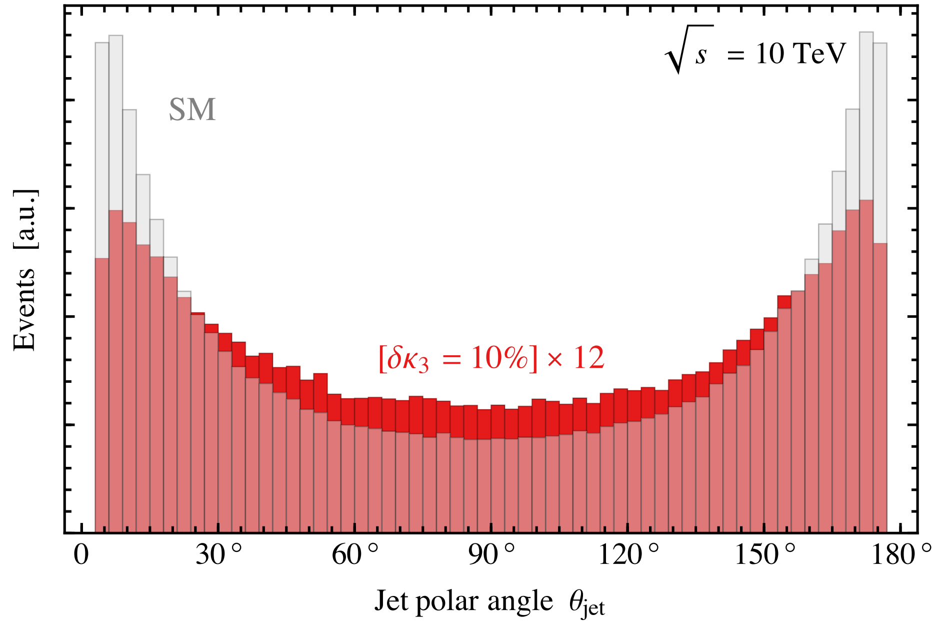


Double Higgs production

- Reach on Higgs trilinear coupling: $hh \to 4b$

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

E [TeV]	$\mathscr{L}$ [ab-1]	$N_{\rm rec}$	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\kappa_3$
3	5	170	~ 7.5%	~ 10%
10	10	620	~ 4%	~ 5%
14	20	1340	~ 2.7%	~ 3.5%
30	90	6'300	~ 1.2%	~ 1.5%



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

see also CLIC study 1901.05897

- For comparison, reach of FCC-hh is $\delta\kappa_3$ ~ 3.5% – 8% depending on systematics assumptions

Mangano et al. 2004.03505

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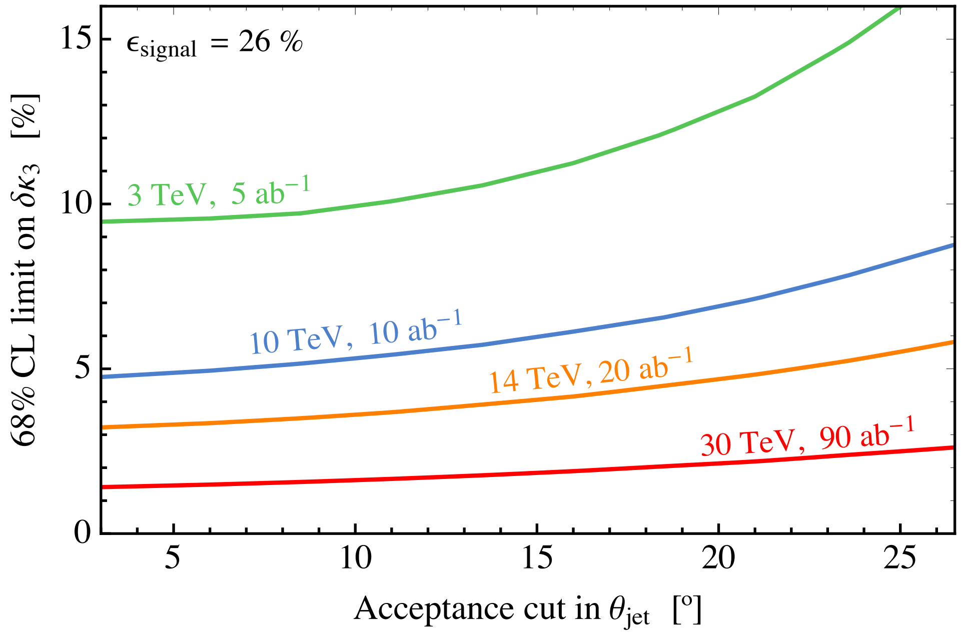

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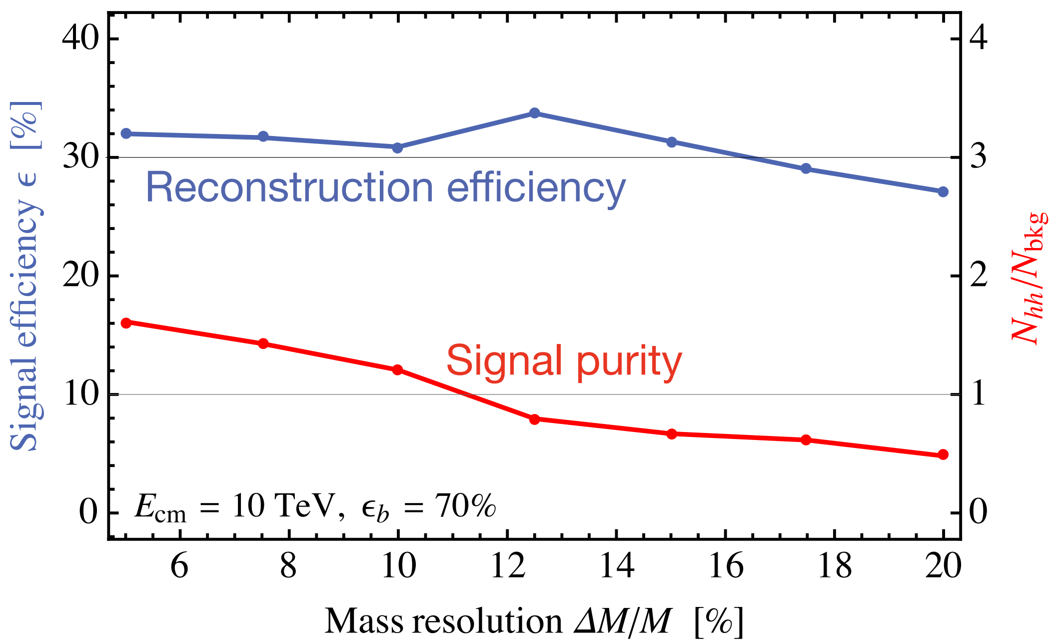

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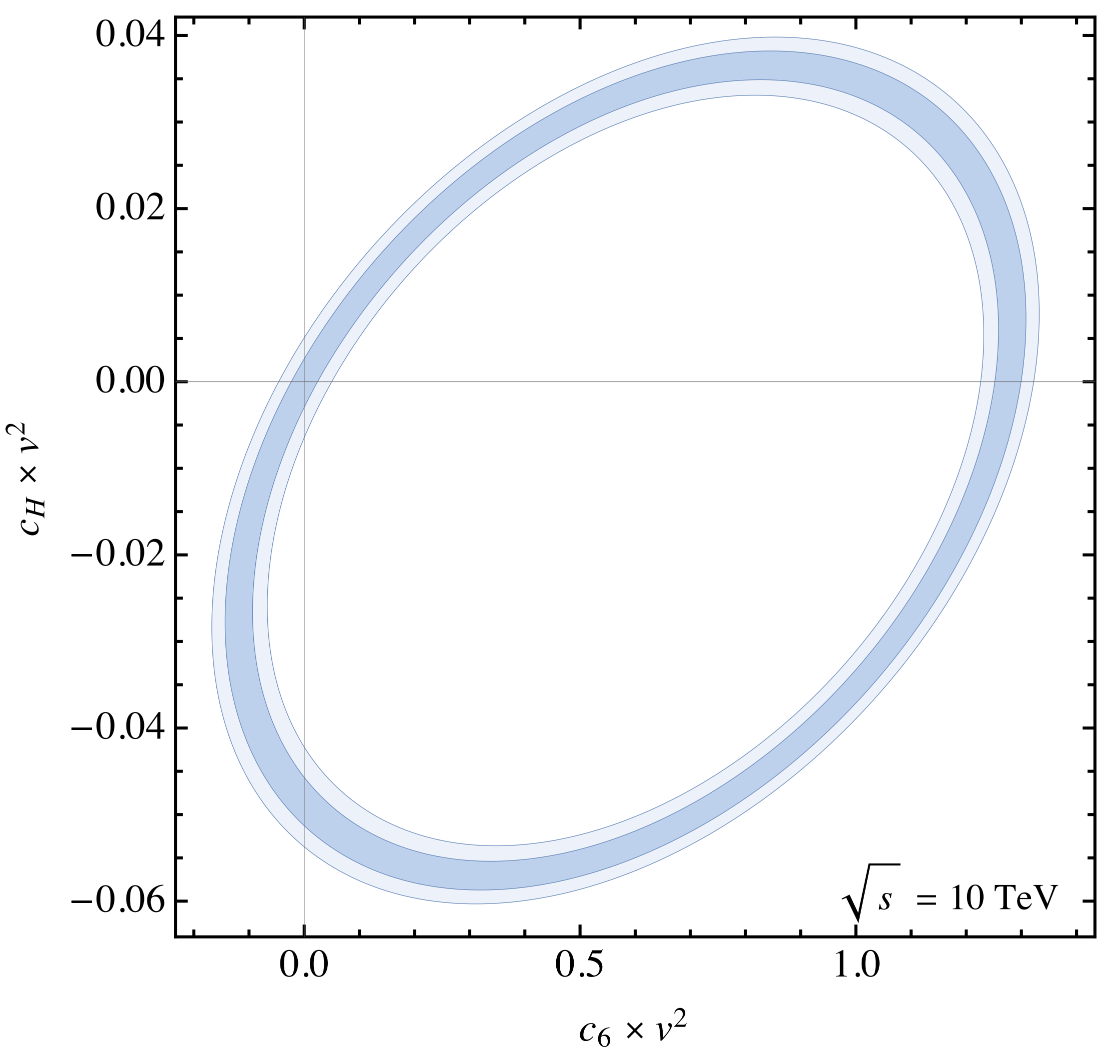
Double Higgs production

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

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



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

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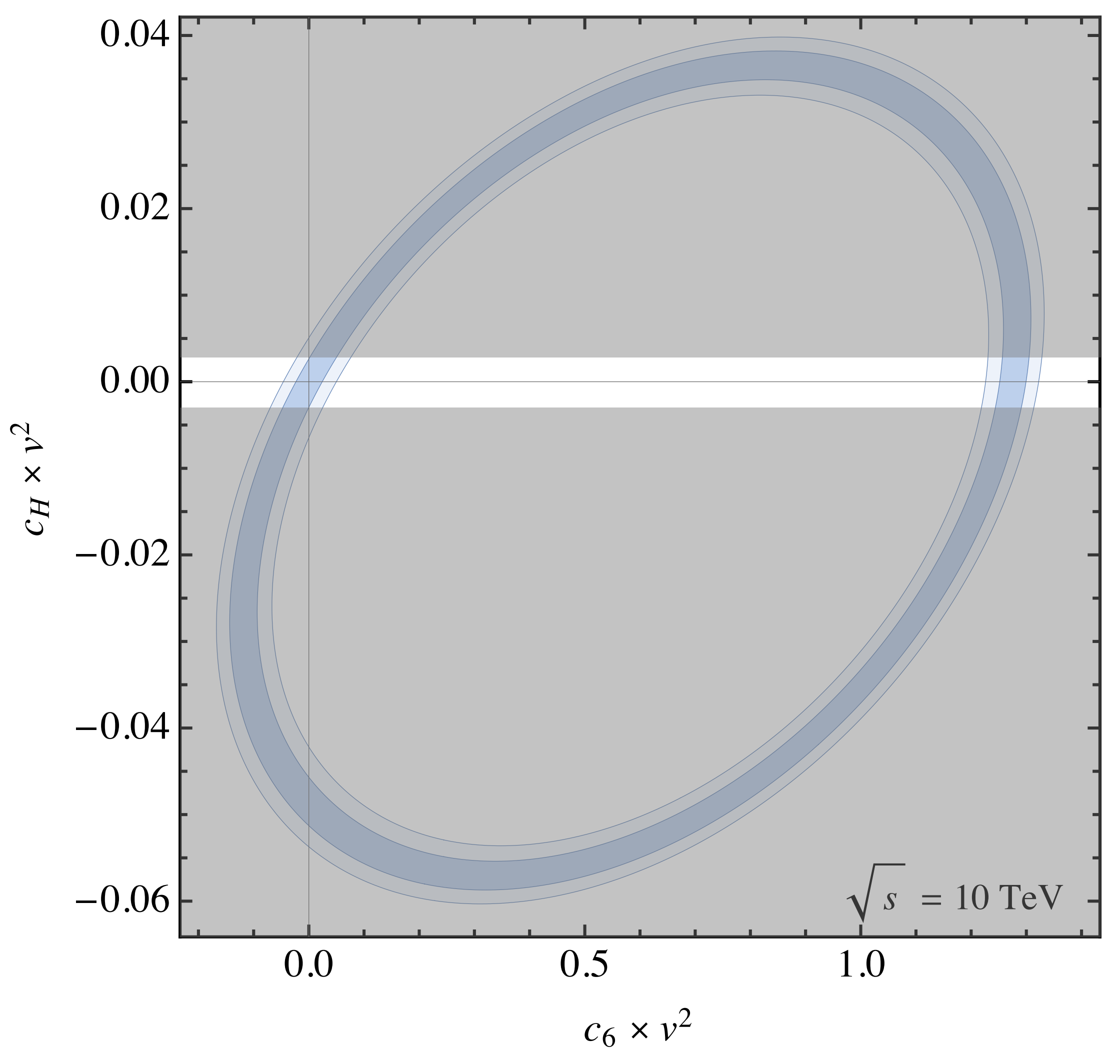

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O_H also affects all single Higgs couplings universally:

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

C_H can be constrained from Higgs couplings (but indirect measurement)

$$\Delta\kappa_V \sim C_H v^2 \lesssim \text{few} \times 10^{-3}$$

Double Higgs at high mass

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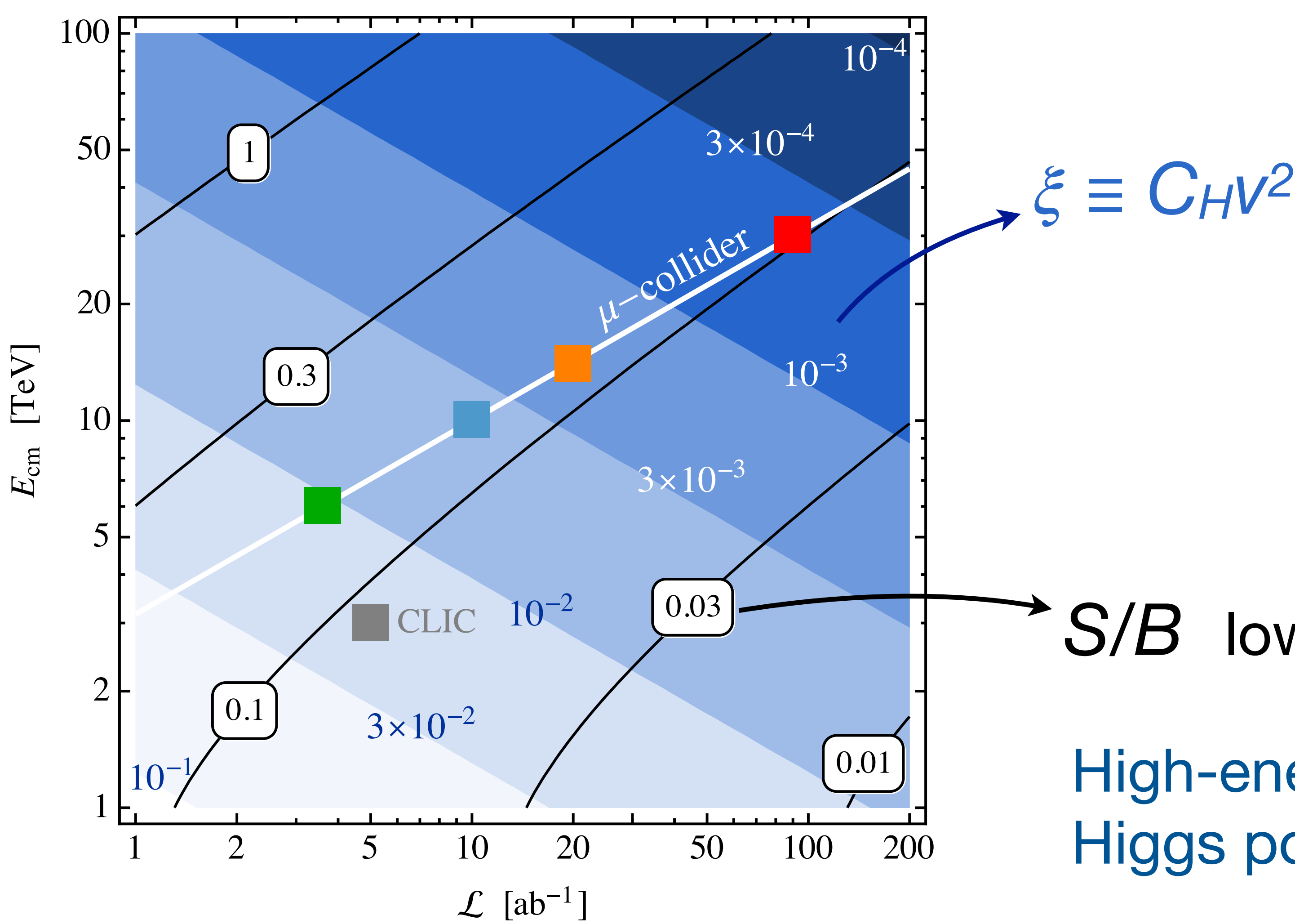
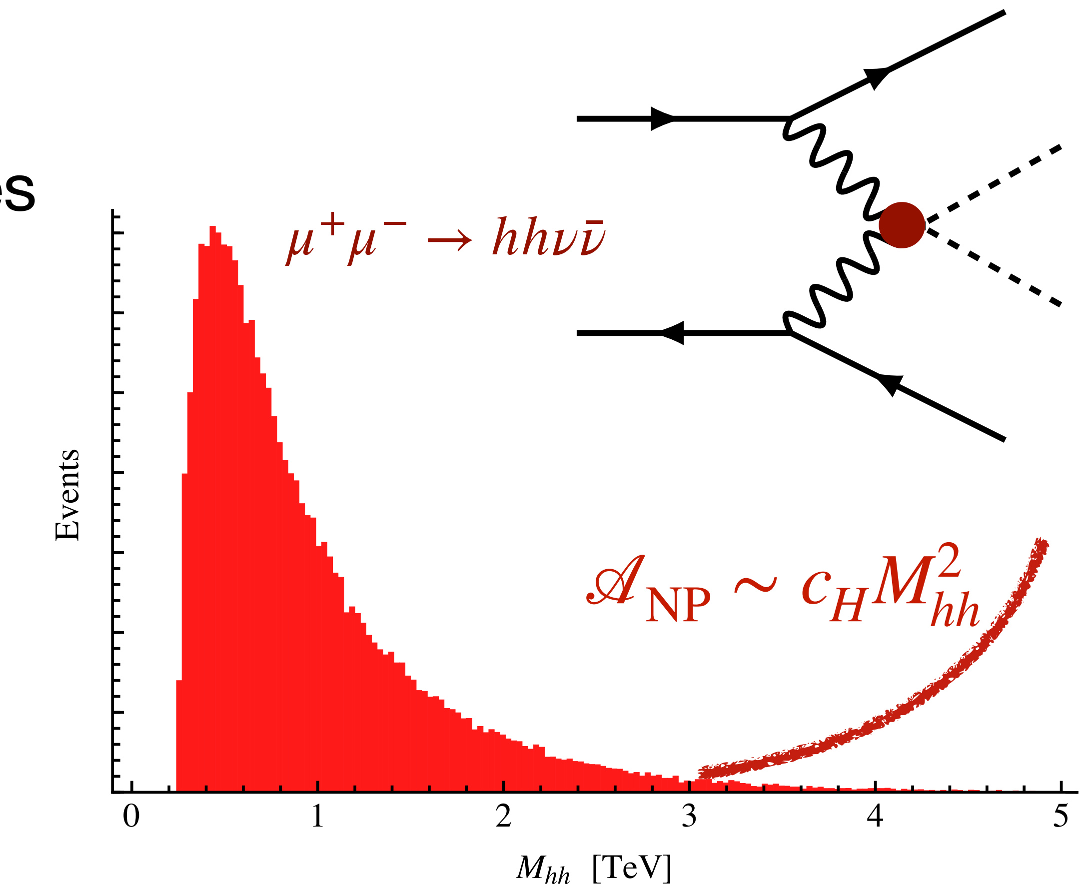
- O_H contribution grows as E^2: high mass tail gives a *direct* measurement of C_H (*WWhh* coupling)





(see also Contino et al. 1309.7038)

S/B low-precision measurement

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

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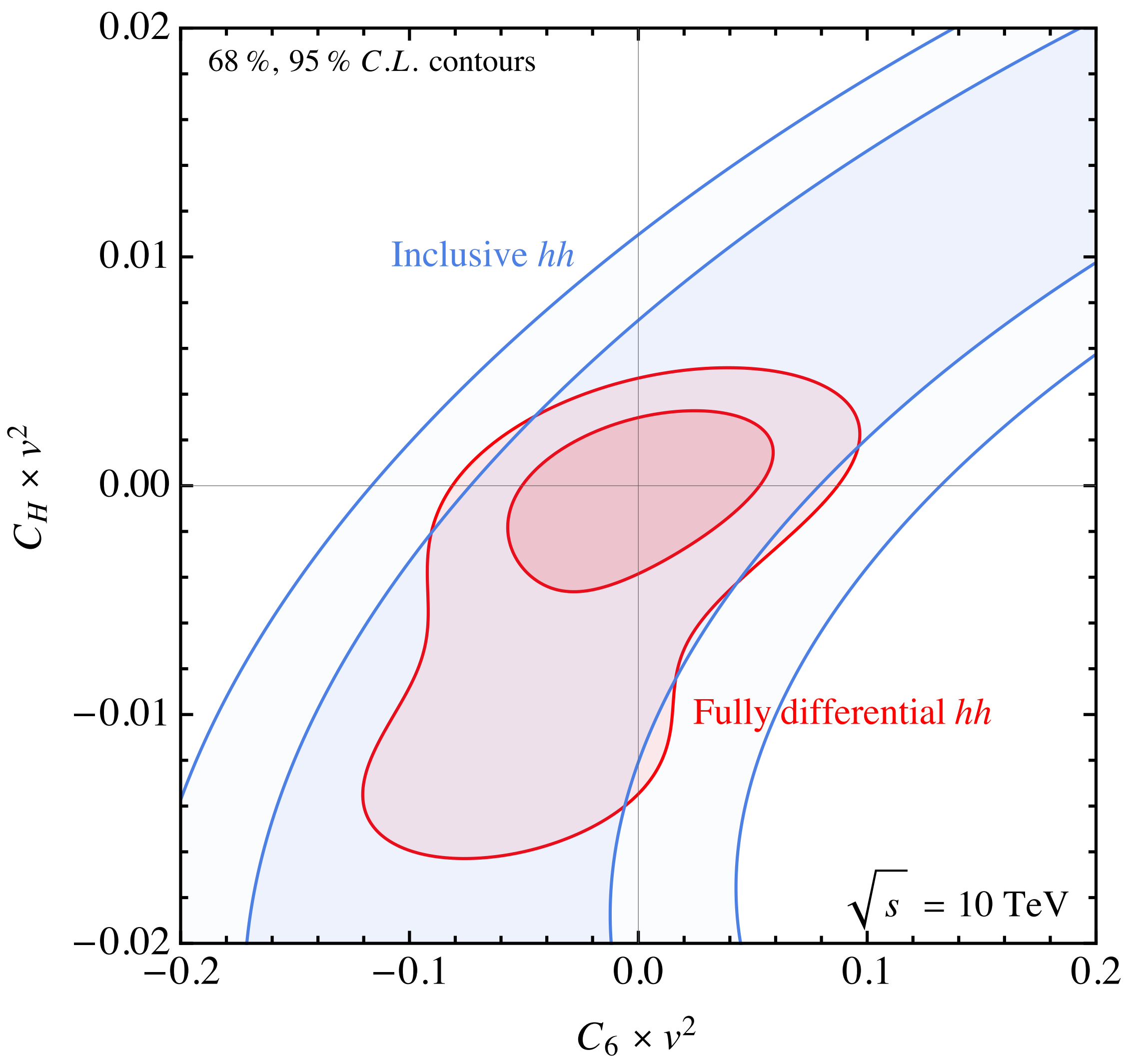
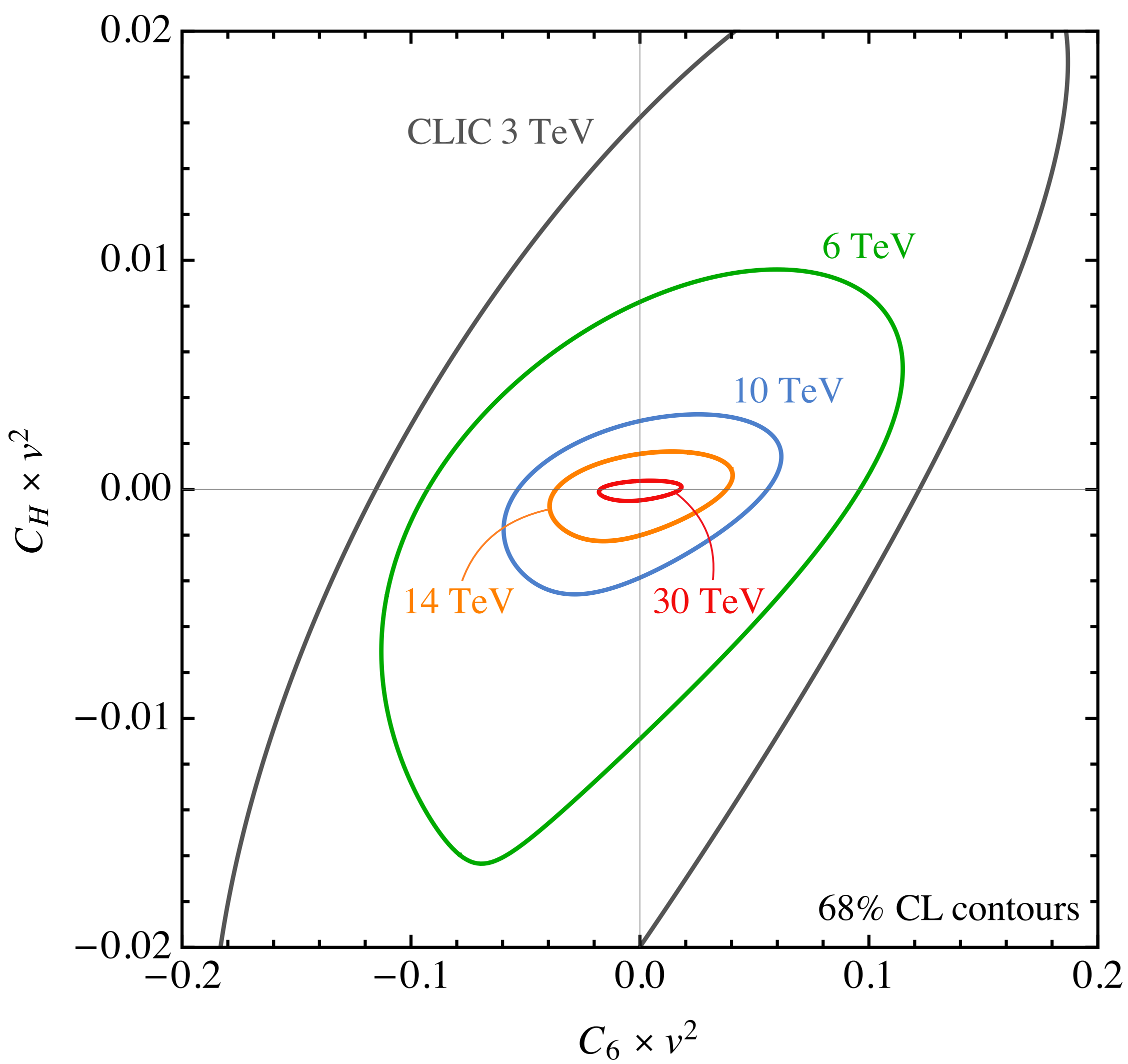
- Differential analysis in p_T and M_{hh} to optimize combined sensitivity to C_H and C_6

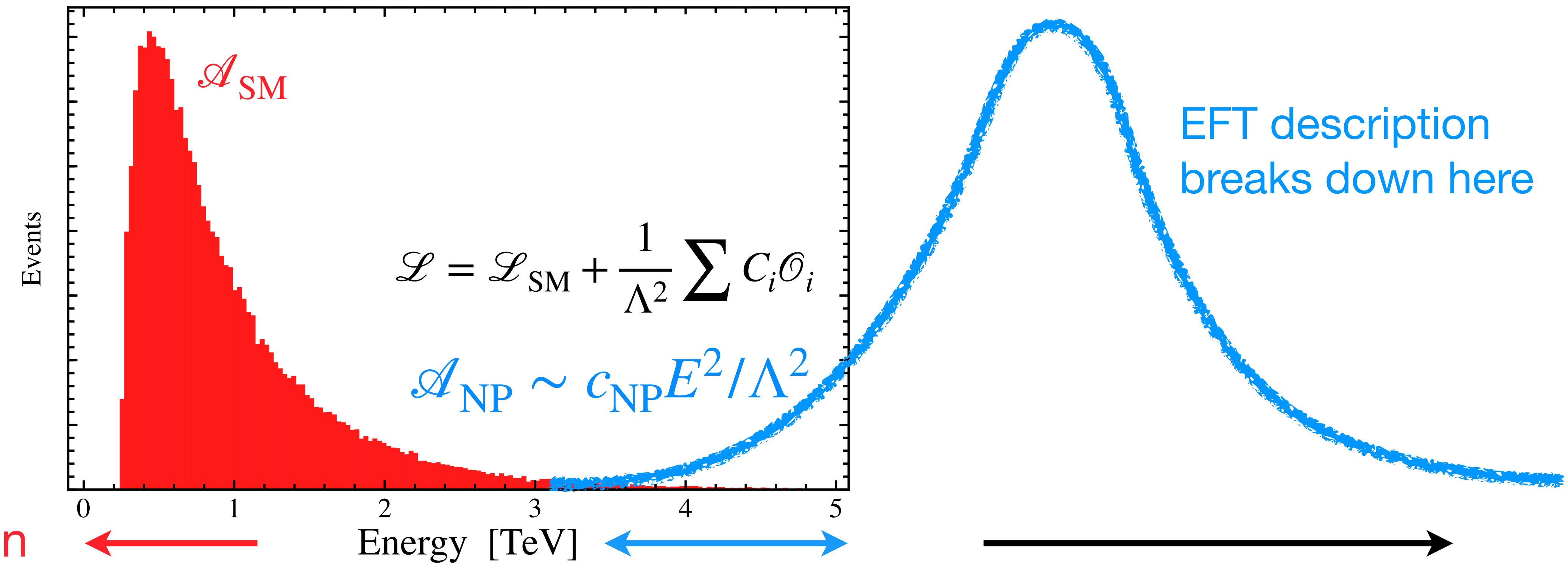
B, Franceschini, Wulzer 2012.11555





High-energy probes

- NP effects are more important at high energies



Precision SM measurements ← High energy (indirect) probes ↔ direct searches →

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

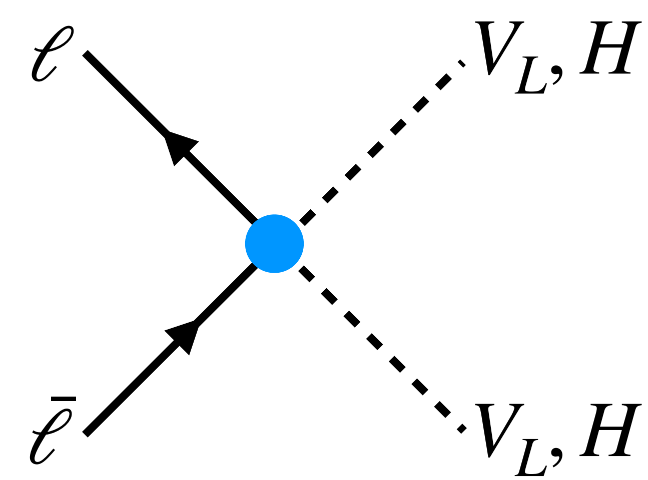
- Effective at LHC, FCC-hh, CLIC: “energy helps accuracy”…

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

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

High-energy di-bosons

- $2 \to 2$ scattering into longitudinal bosons at high energy: $\ell^+\ell^- \to W_L^+ W_L^-$ $\quad \ell^+\ell^- \to Z_L H$



In flavor-universal theories, two dim-6 operators:

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

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

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

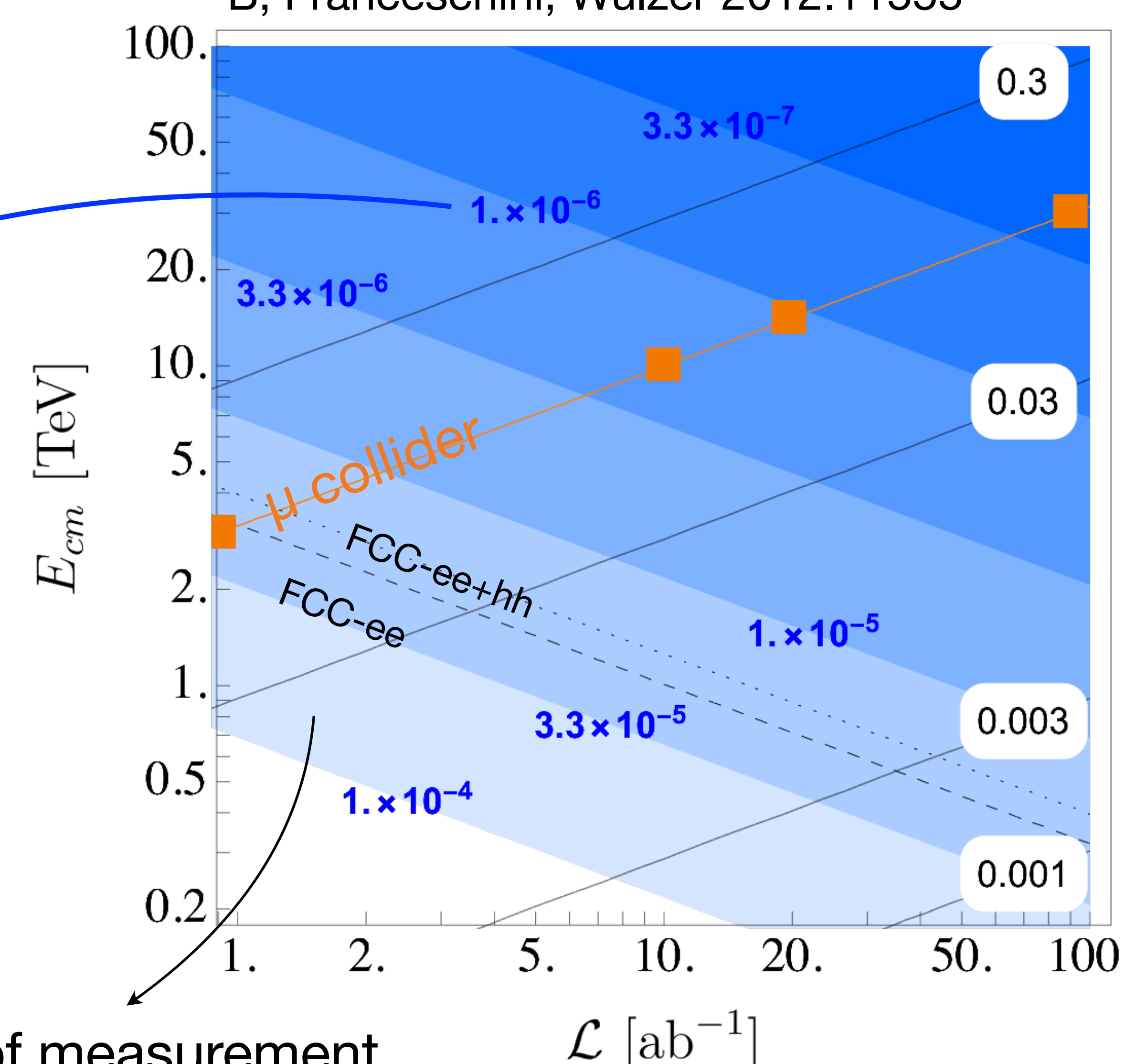
Muon collider:

$$10\,\text{TeV}: \quad C_W \lesssim (40\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-6}$$
$$30\,\text{TeV}: \quad C_W \lesssim (120\,\text{TeV})^{-2}, \quad \hat{S} \lesssim 10^{-7}$$

$$\text{LEP}: \quad \hat{S} \lesssim 10^{-3}$$
$$\text{FCC}: \quad \hat{S} \lesssim 10^{-5}$$

← ultimate precision at Z pole

B, Franceschini, Wulzer 2012.11555



precision of measurement

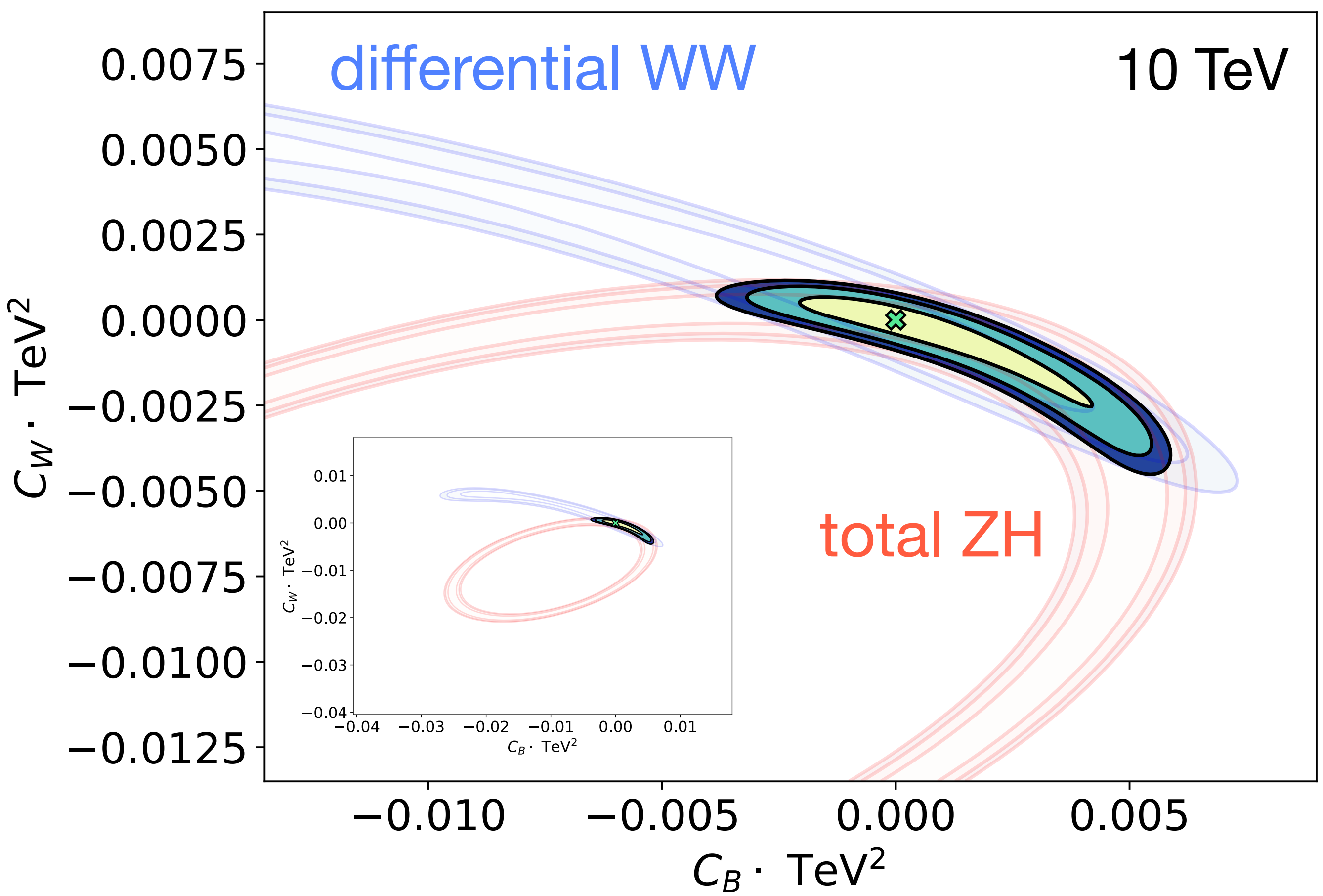
High-energy di-bosons

- C_W and C_B determined from high-energy $\mu^+\mu^-$ → *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



High-energy di-bosons

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

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

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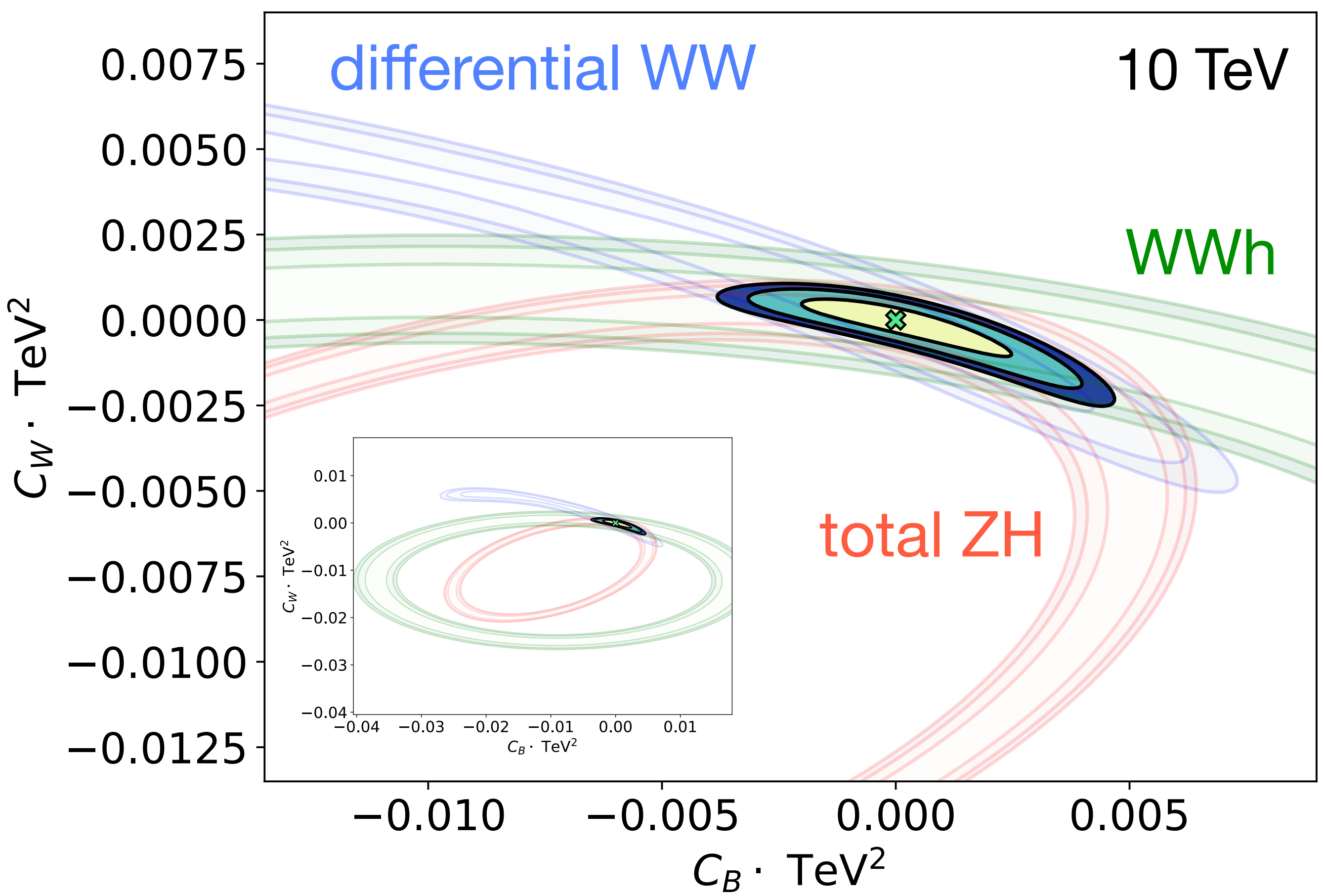
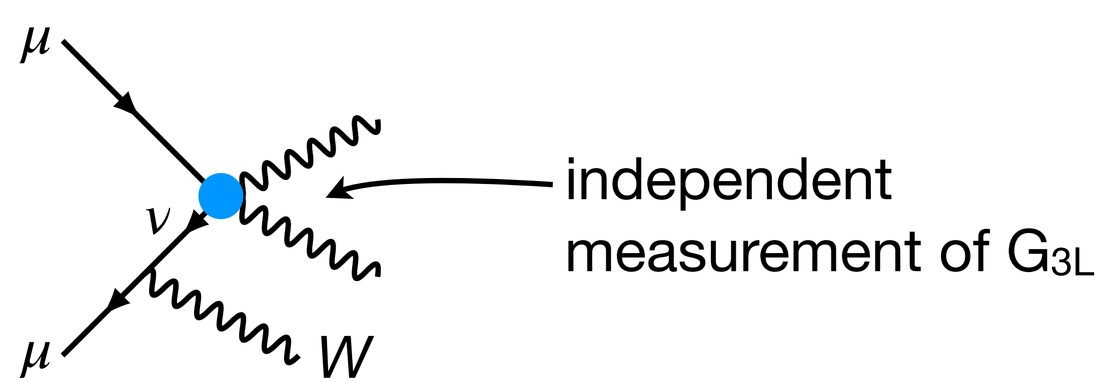


- Gauge boson radiation important at high energies: soft W emission allows to access the charged processes $\ell^\pm\nu \to W^\pm Z, W^\pm H$

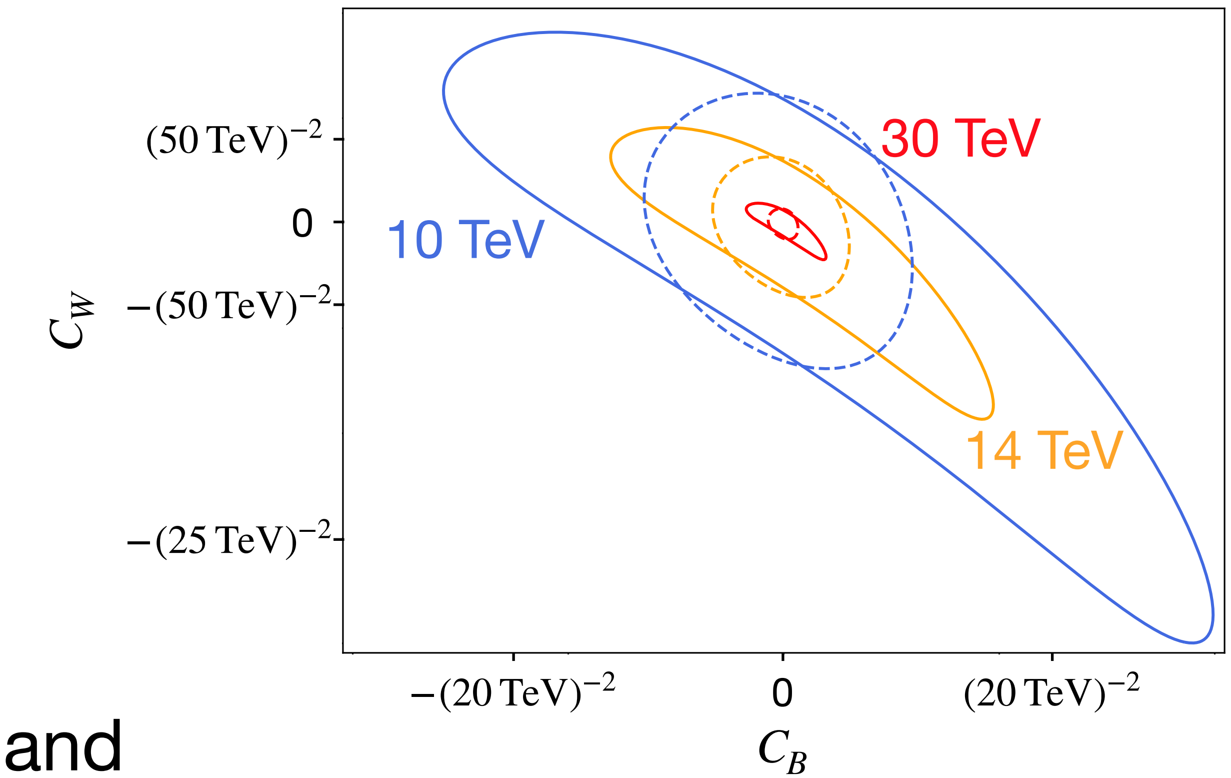


"effective neutrino approximation"

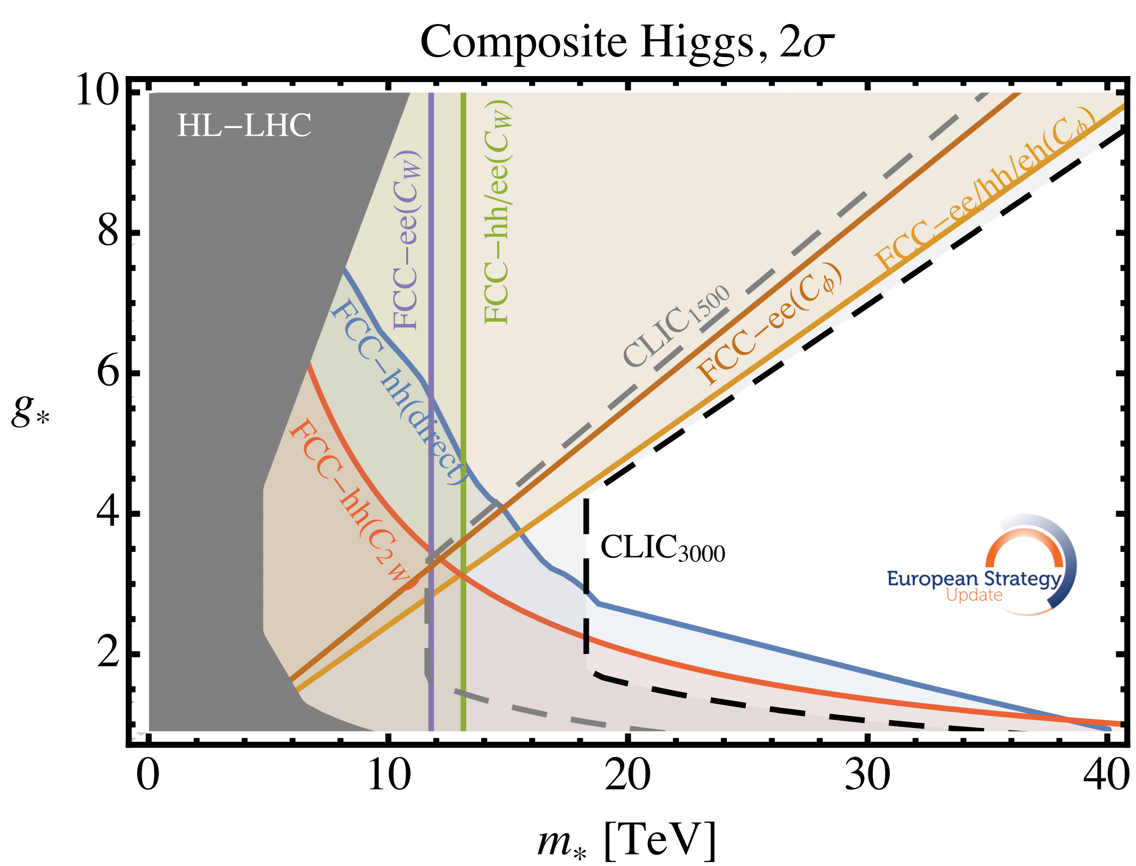
need to properly include higher-order effects inclusive observables, resummation, …

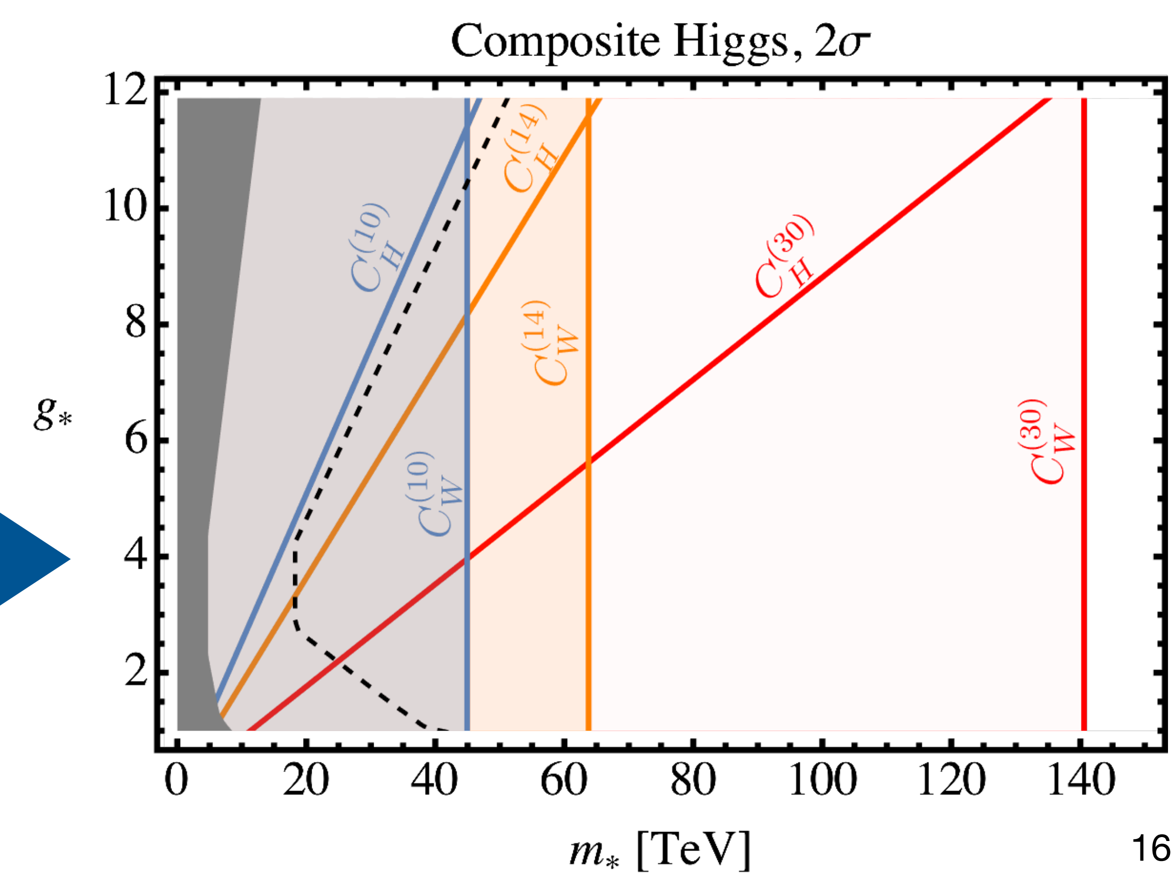
☛ see talks by Davide and Christian

- High-energy probes at a 10–30 TeV muon collider are able to probe new physics scales ~ 100 TeV
  - $\ell^+\ell^- \to VV: \quad \hat{S} \sim m_W^2/m_\star^2 \lesssim 10^{-7}$
  - $VV \to HH: \quad \xi \sim v^2/f^2 \lesssim 10^{-3}$



- Example: new physics with mass $m_\star$ and coupling $g_\star$ – *almost order of magnitude improvement w.r.t. FCC / CLIC!*





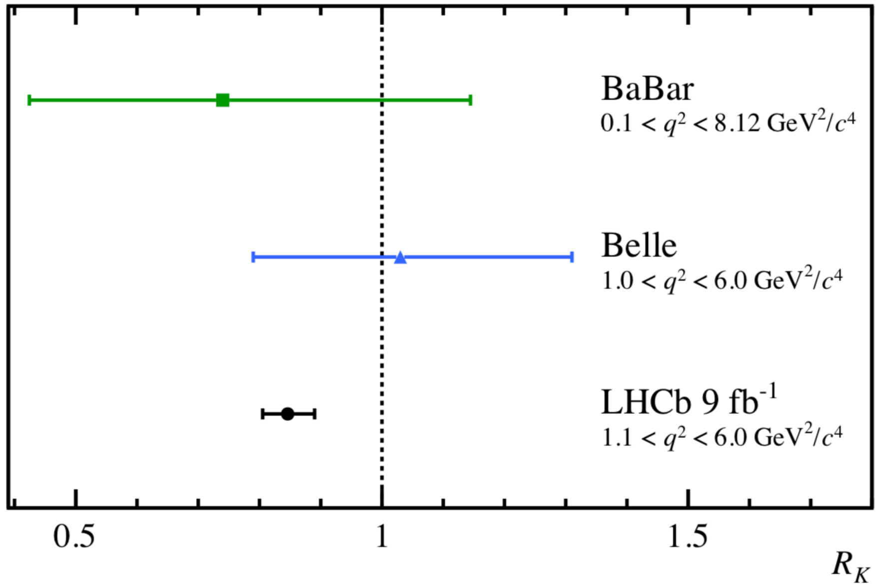
Non-universal physics: muons vs. electrons

Several experimental hints of New Physics *coupled dominantly to muons!*

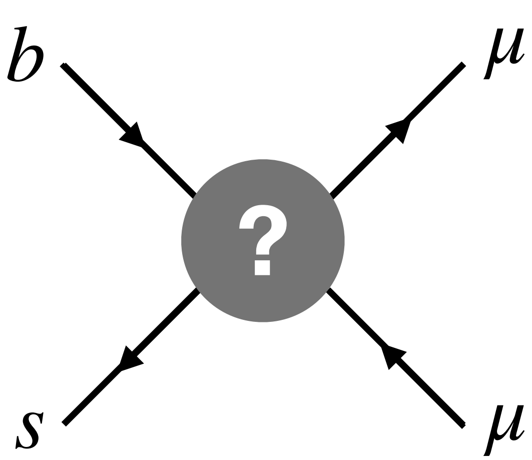
- ✦ "Flavor anomalies" in B meson decays:
  - Lepton Flavor Universality ratios (R_K, R_{K^*}, …)
  - $b \to s\mu\mu$ angular observables
  - several $b \to s\mu\mu$ branching ratios

5.9 σ discrepancy combined (2103.13370)

LHCb 2103.11769



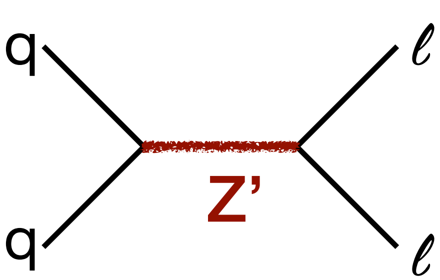
☛ *see Wolfgang's talk*

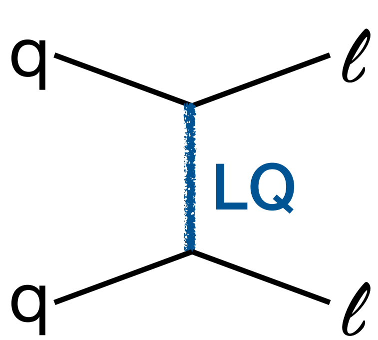


$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma_\nu s_L)(\bar{\mu}_L\gamma^\nu\mu_L)$$

$$\Lambda \approx 30\,\text{TeV} \approx 6\,\text{TeV} \cdot V_{cb}^{-1/2}$$

LHC will not be able to probe entire parameter space with high-pT searches!





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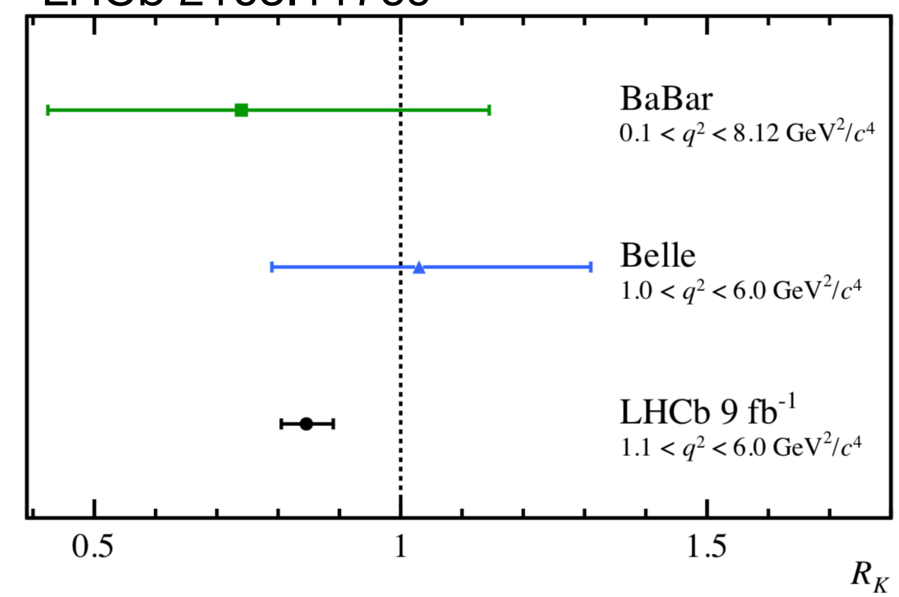
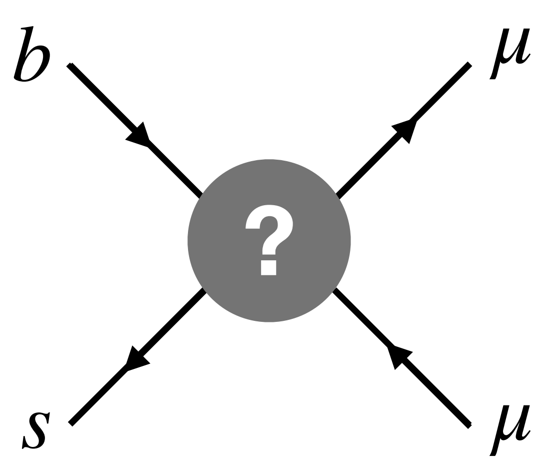


☛ *see Wolfgang's talk*



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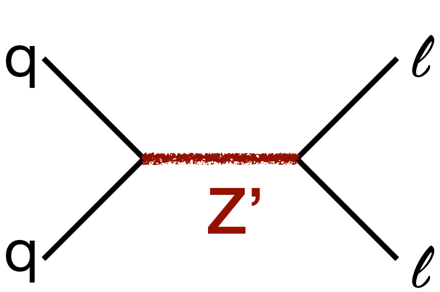

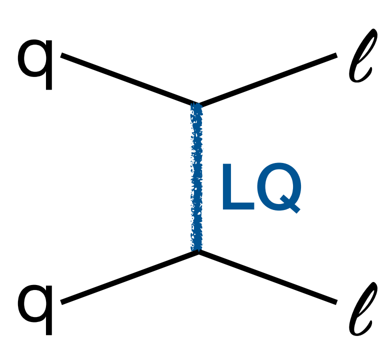

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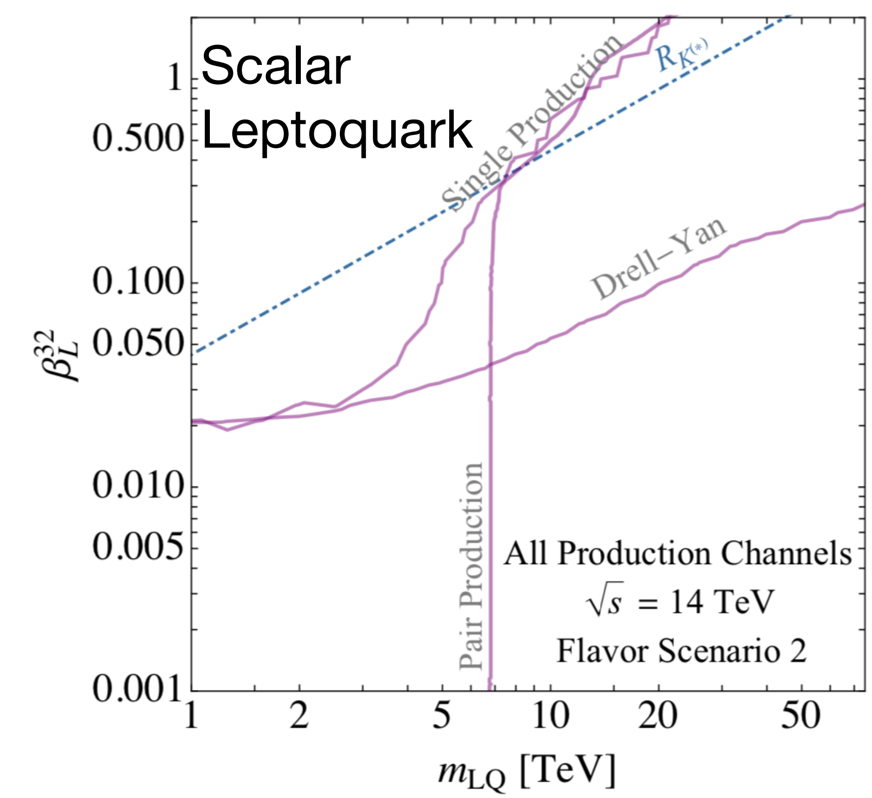

Muon collider reach:

Huang et al. 2103.01617,

Asadi et al. 2104.05720

Non-universal physics: muons vs. electrons

Several experimental hints of New Physics *coupled dominantly to muons!*

- “Flavor anomalies” in B meson decays

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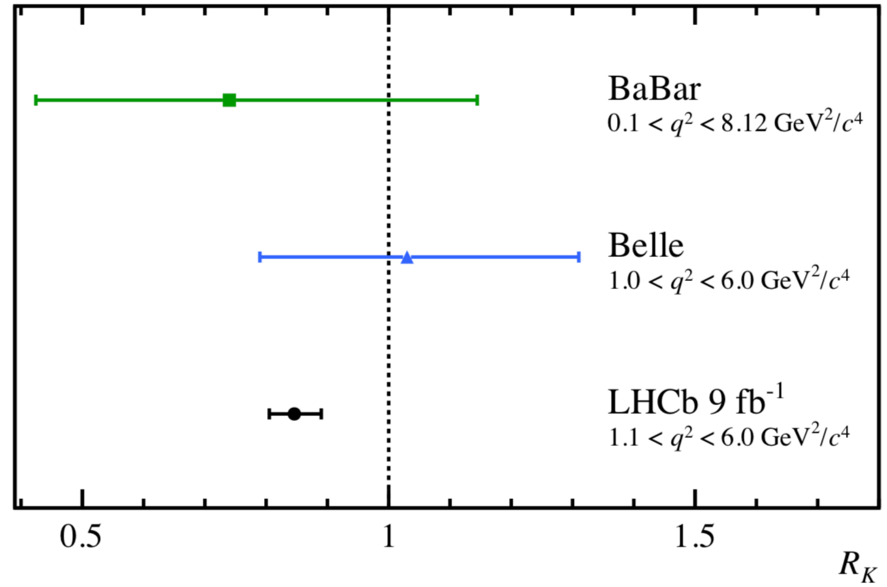
LHCb 2103.11769

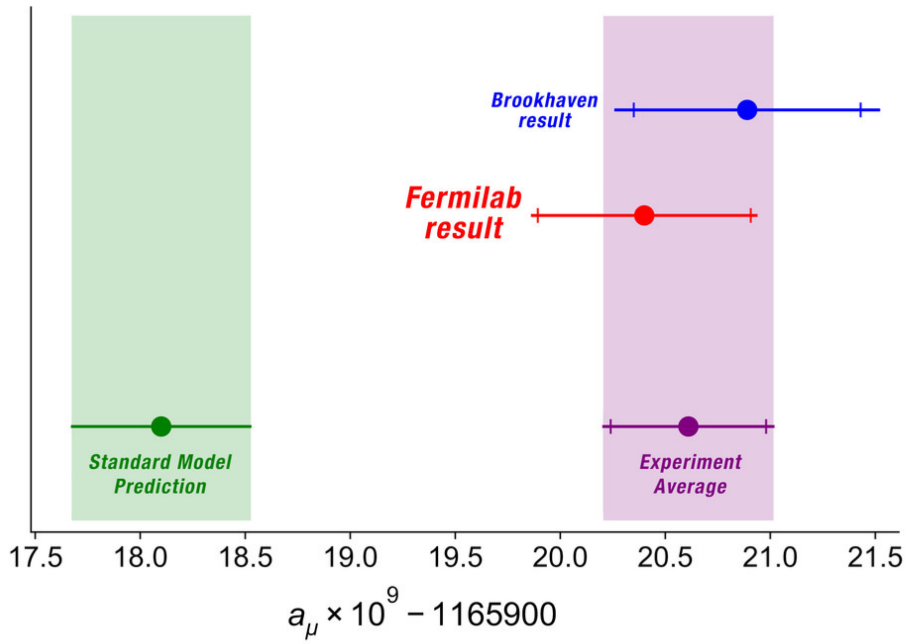


- Muon anomalous magnetic moment:

$$\Delta a_\mu = a_\mu^{(\mathrm{exp})} - a_\mu^{(\mathrm{th})} = 251(59) \times 10^{-11}$$

4.2 σ discrepancy!

2104.03281



- E989 experiment confirmed previous result, improvement expected in next years…
- Theoretical (and systematic) errors need to be controlled at the level of $\Delta a_\mu \sim 10^{-9}$

➡ Independent test of Δa_μ is desirable (ideally with different sys. & th. errors)

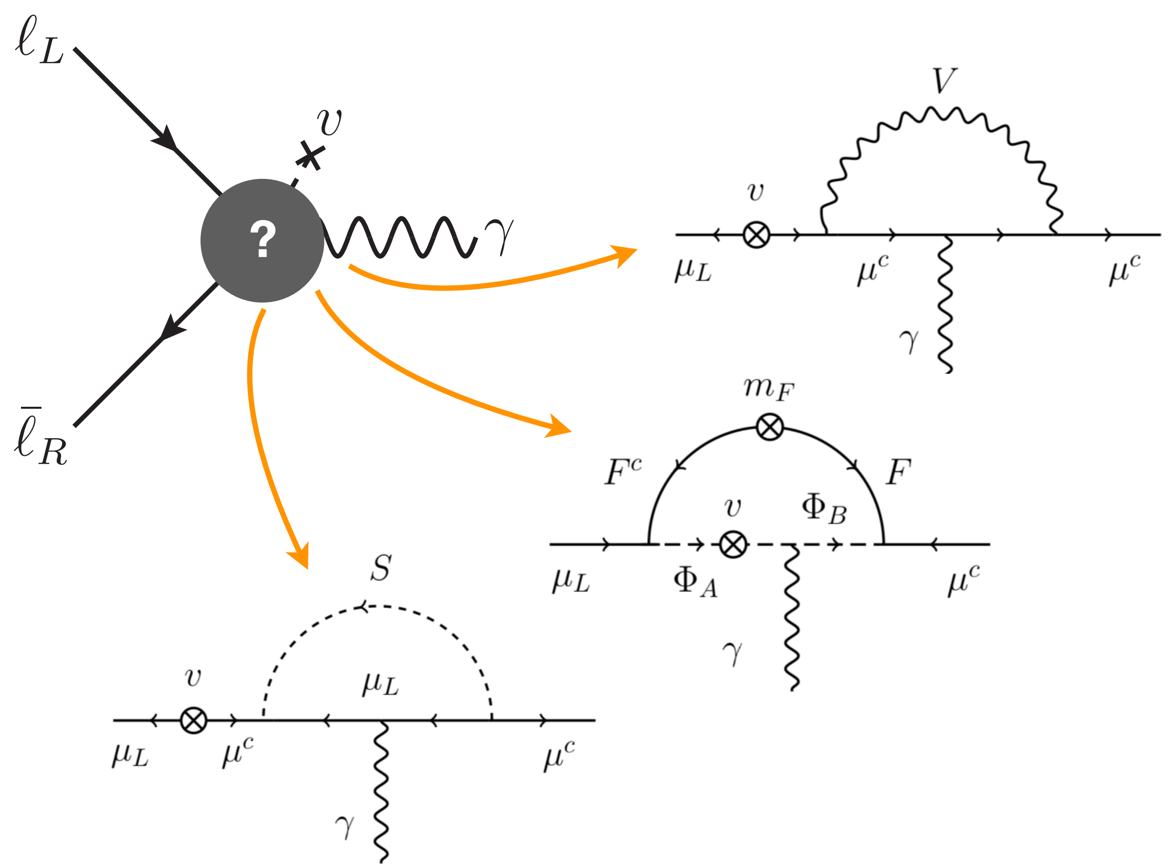
A muon collider can give the first model-independent, high-energy test of Δa_μ

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

Classify New Physics that can enter the loop, under reasonable assumptions:

- electroweak charges
- flavor structure
- naturalness
- number of particles



- A 20–30 TeV muon collider can test the most motivated, weakly coupled models

Capdevilla et al. 2006.16277, 2101.10334

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

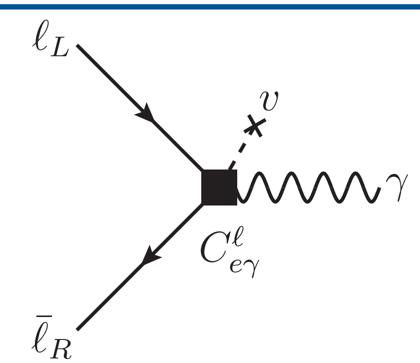
Capdevilla et al. 2006.16277

- If new physics is heavy: EFT!

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

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 $\mu\mu \to h\gamma$

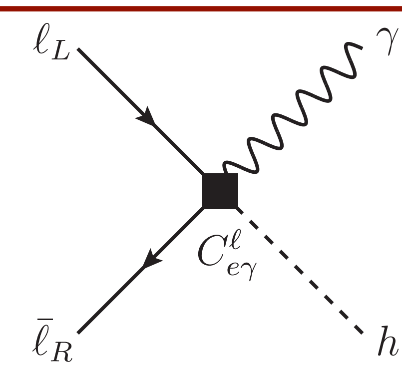
B, Paradisi 2012.02769

At high energy

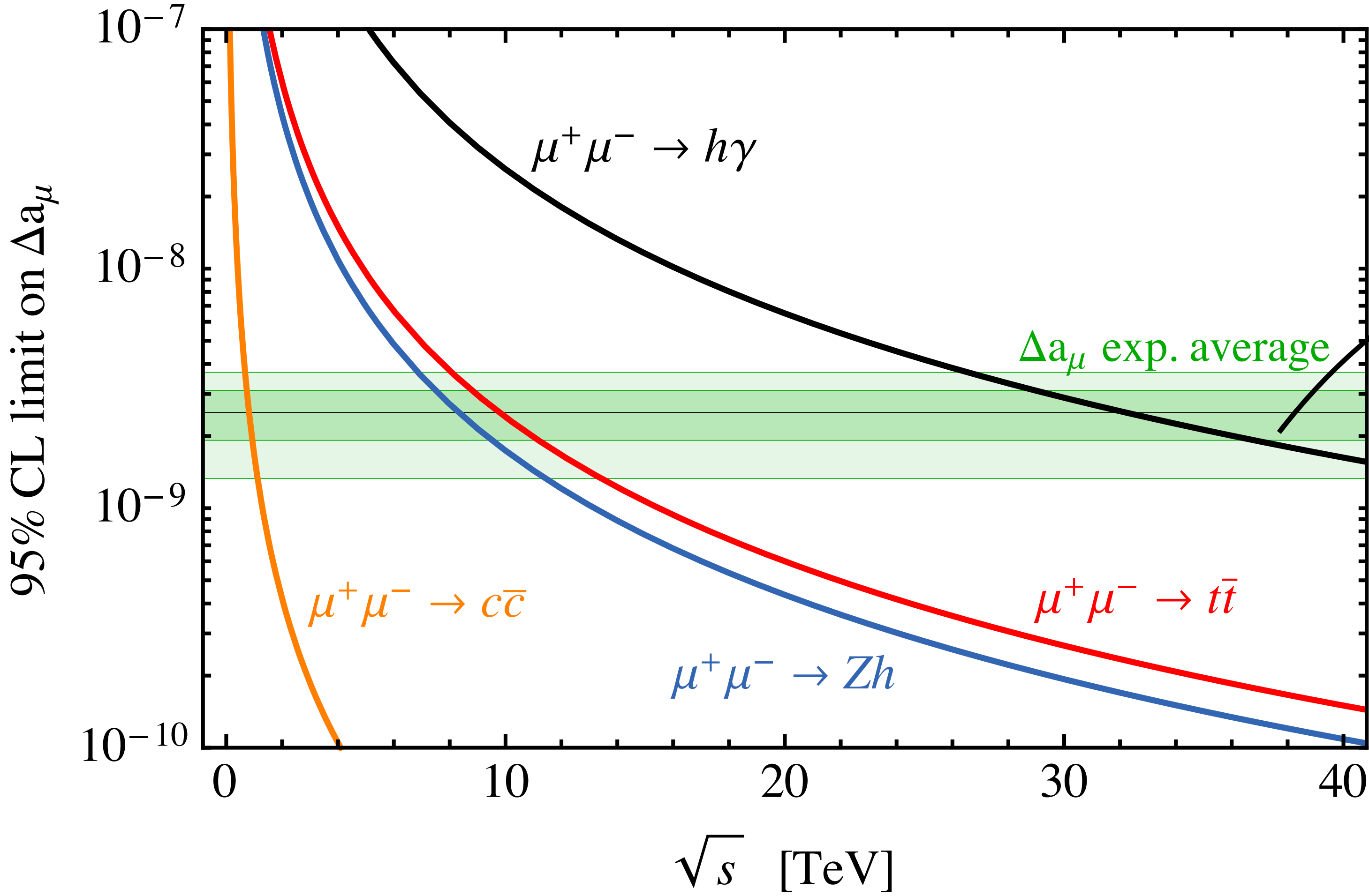
$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\text{ab} \left(\frac{\sqrt{s}}{30\,\text{TeV}} \right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right)^2$$

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

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)

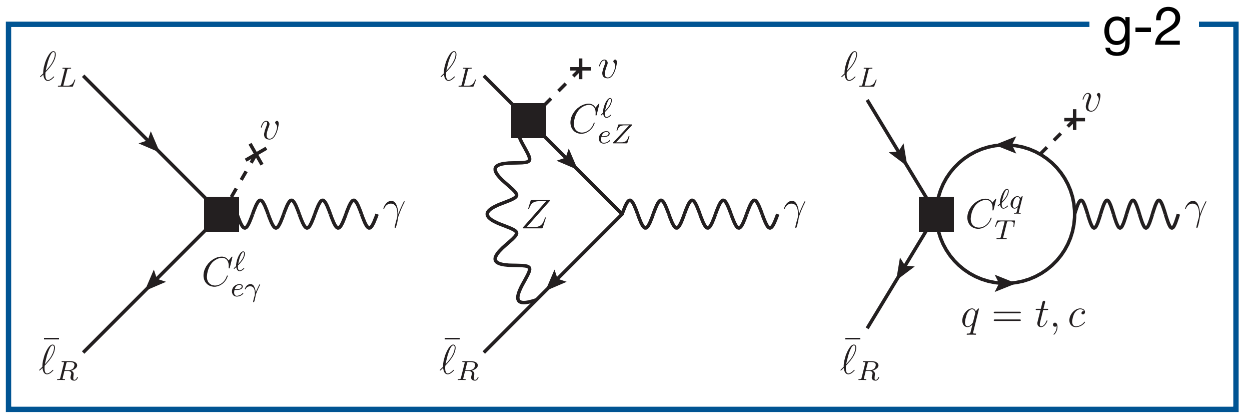
This result is completely model-independent!

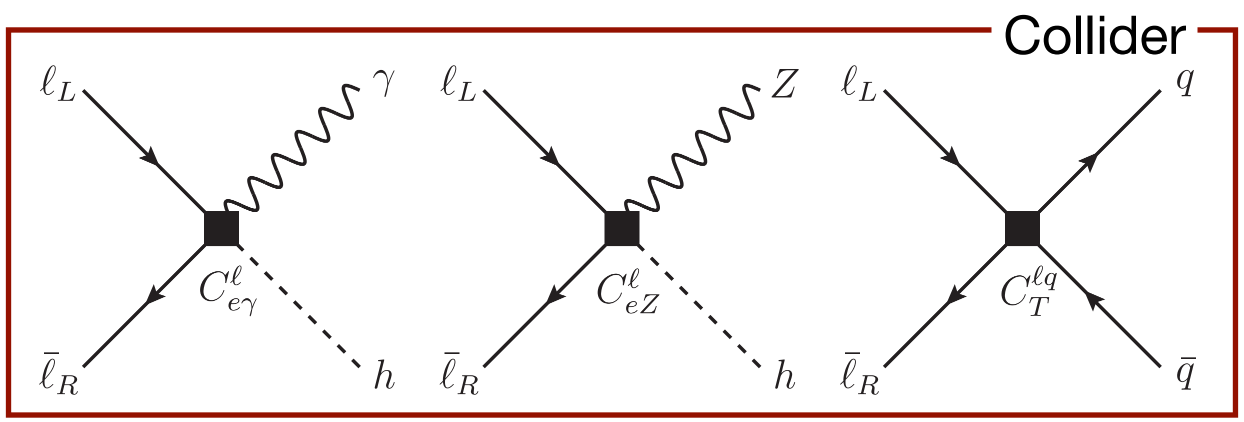
B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

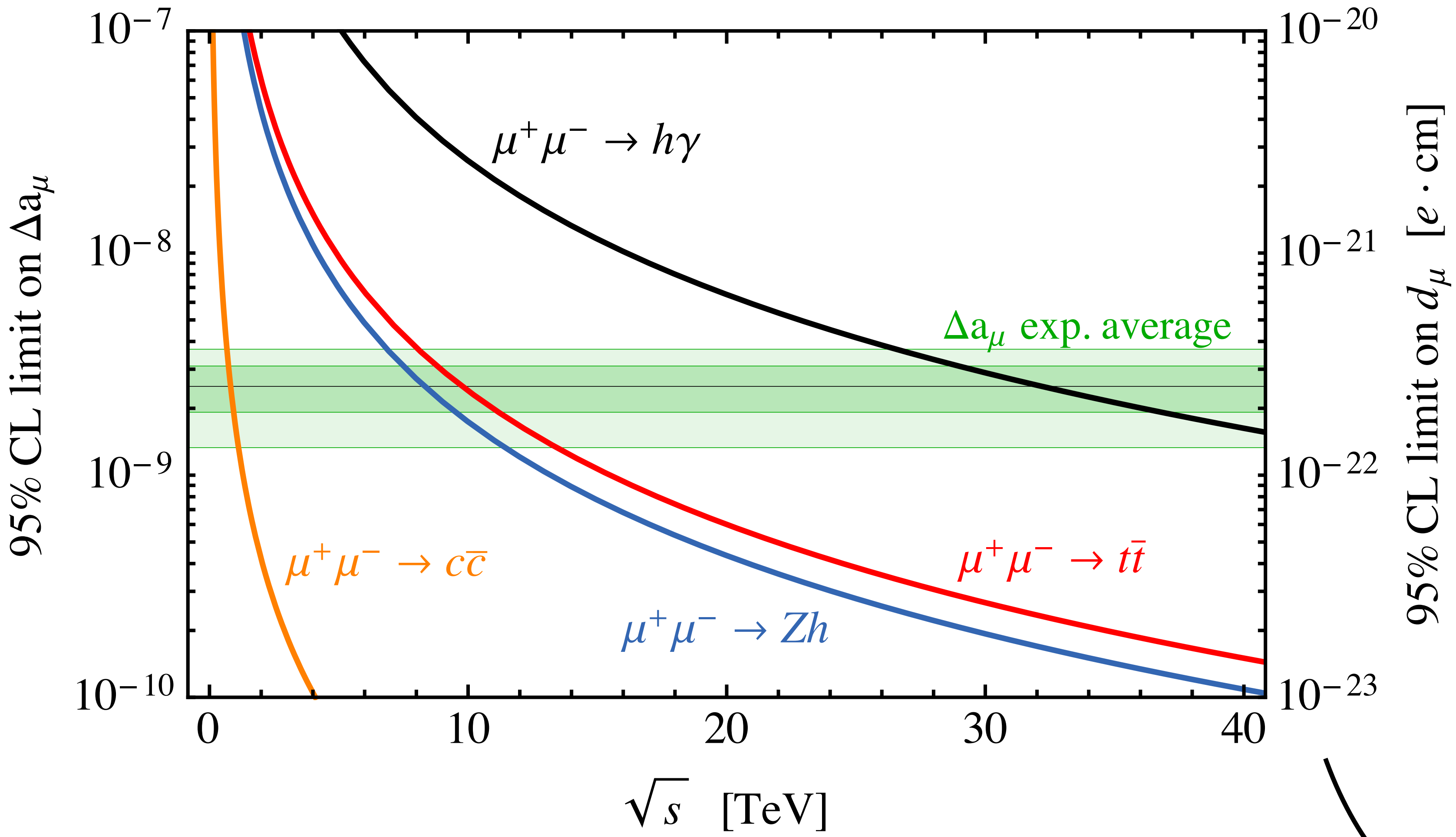
$$\Delta a_\mu \approx \left(\frac{250\,\text{TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

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





Muon g-2 @ muon collider



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

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

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

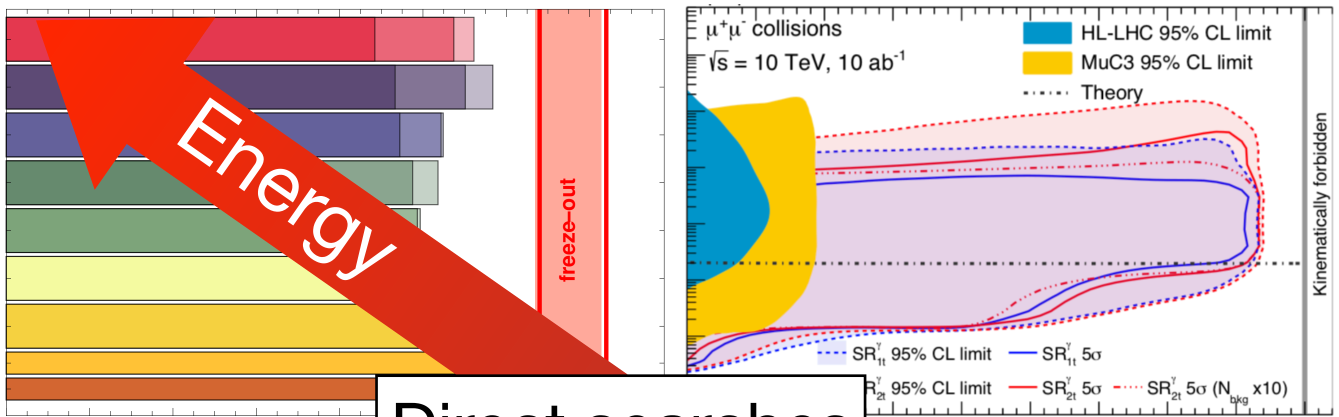
3 o.o.m. stronger than present bound!

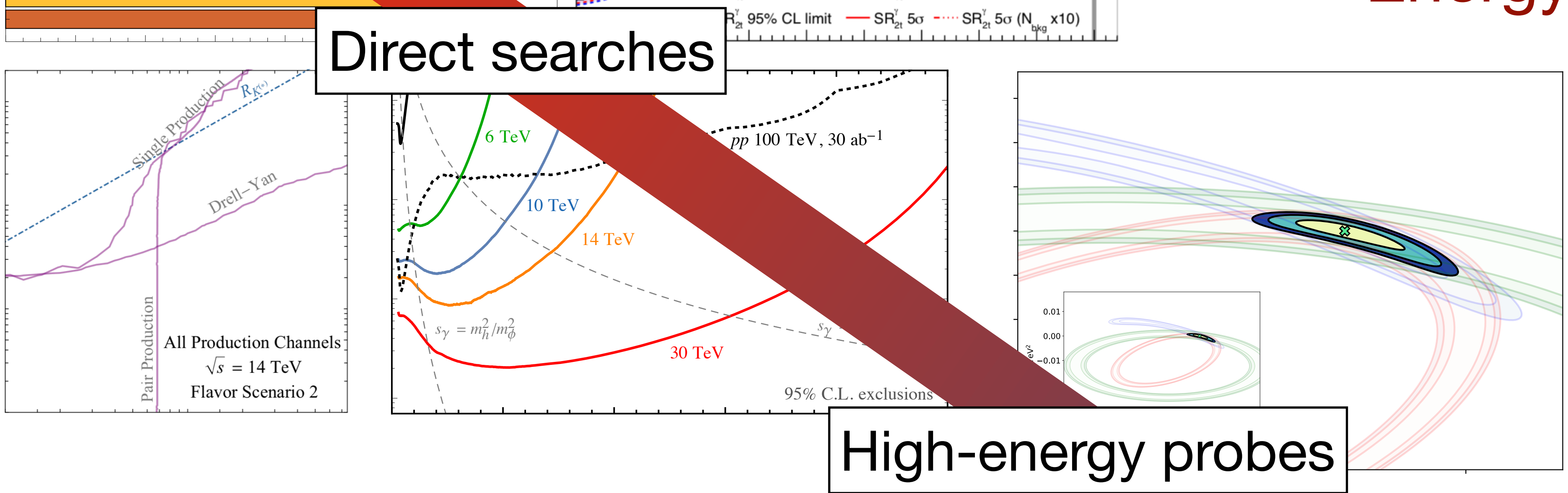
Summary

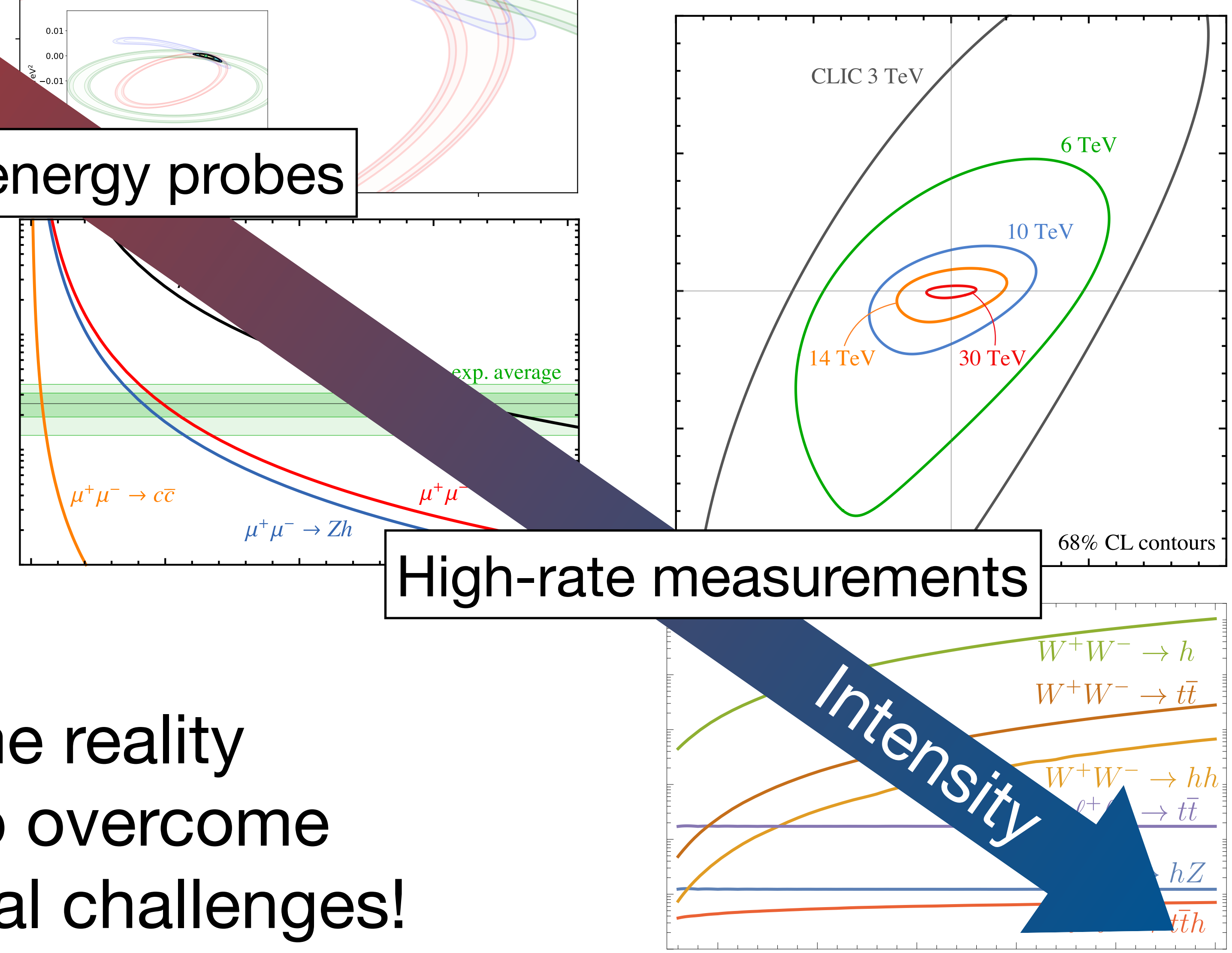
Two colliders at once

in a high-energy muon collider

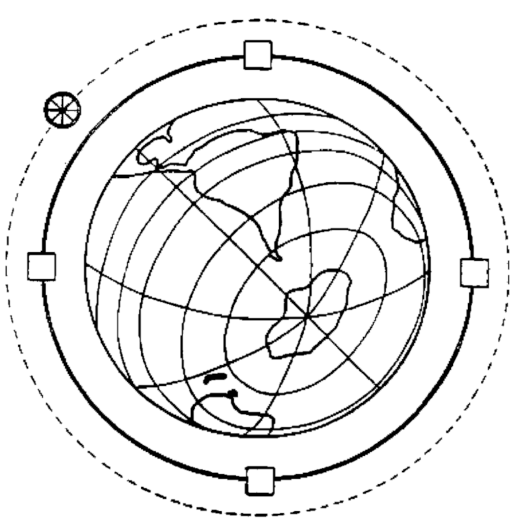
Energy AND Precision







A *dream machine*
able to explore a completely
new range of energies…



… could become reality
if we manage to overcome
the technological challenges!

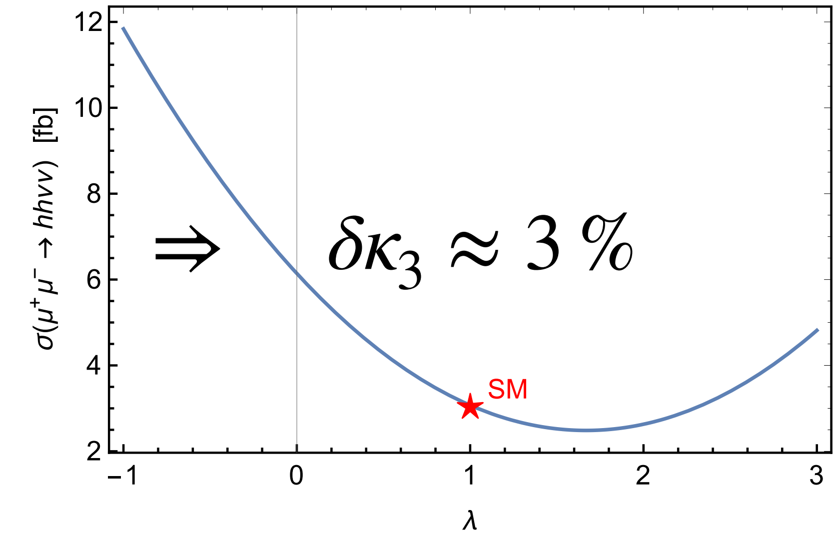
Backup

Double Higgs production

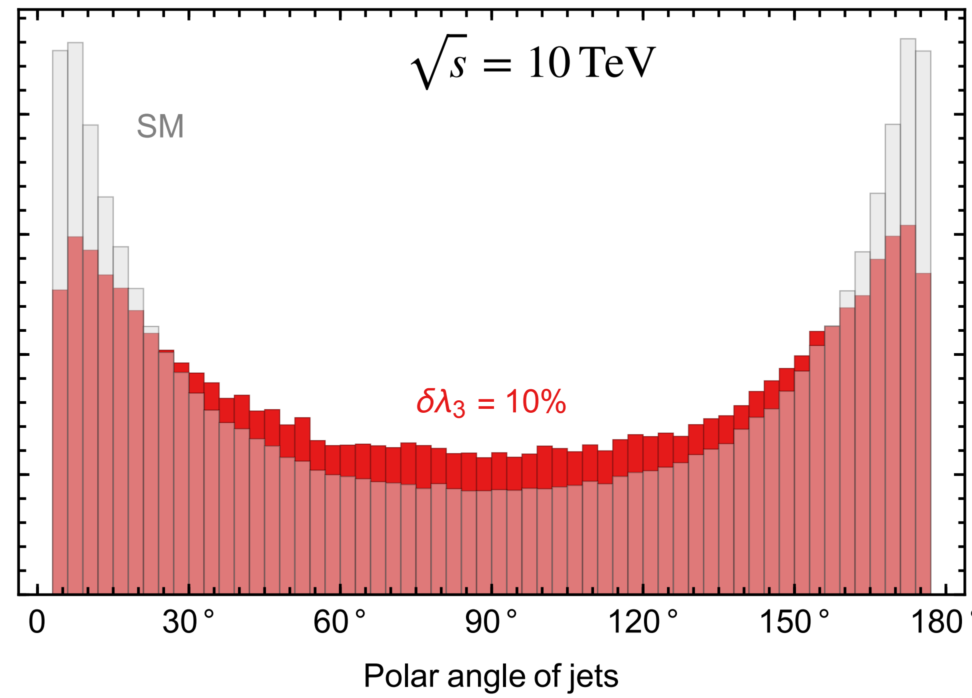
Number of events $\sim s \log(s/m_h^2) \approx 10^5$ at 14 TeV

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

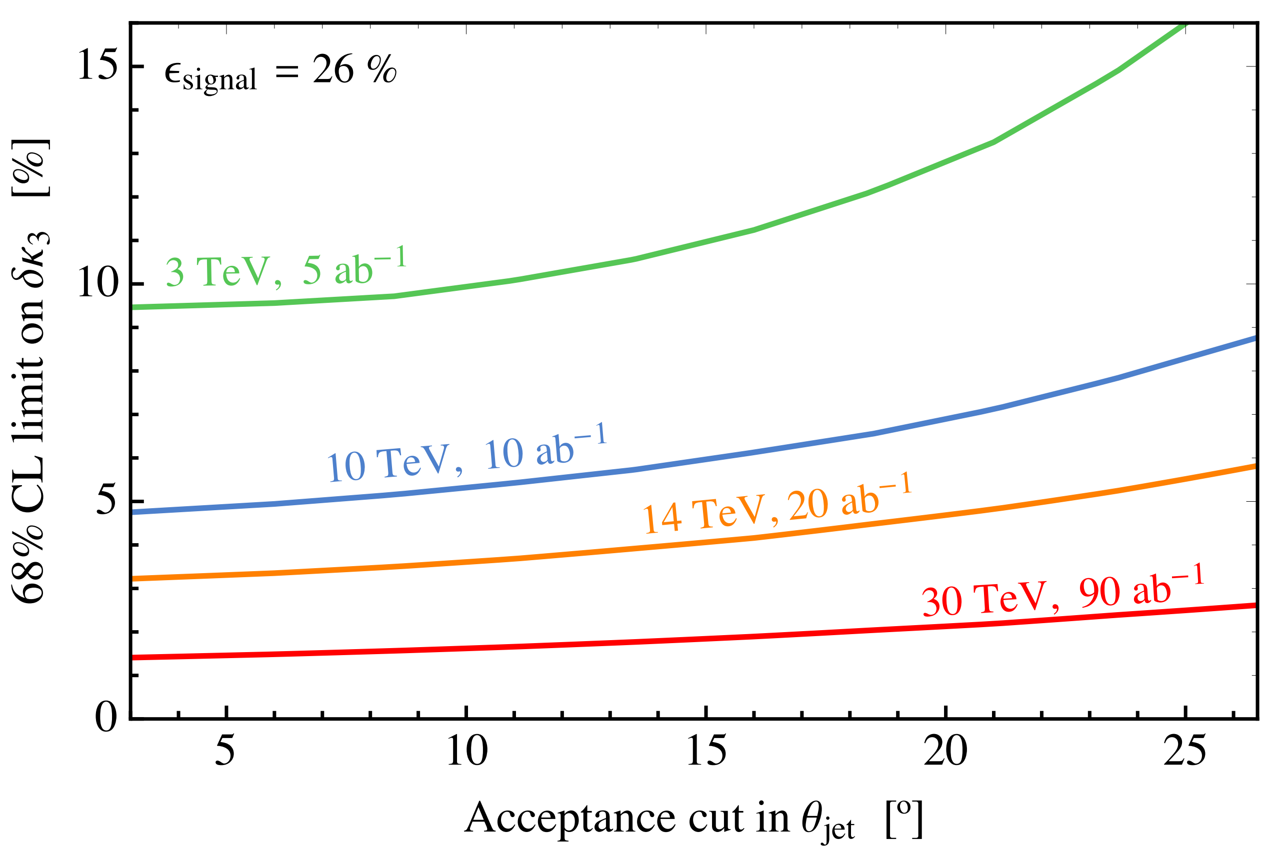
$$\left.\begin{array}{r}\text{reconstruction eff.} \sim 30\,\% \\ \mathrm{BR}(hh \to 4b) = 34\,\%\end{array}\right\} \epsilon \sim 10\,\%$$



- ✦ **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

$hh \to 4b$ signal

- **Acceptance cuts** in polar angle θ and p_T of b-jets.

  E.g. for pT > 10 GeV, θ > 10º:

$$\sigma_{\rm cut}(3\,{\rm TeV}) = 0.13\left[1 - 0.87(\delta\lambda) + 0.74(\delta\lambda)^2\right]\ {\rm fb},$$
$$\sigma_{\rm cut}(10\,{\rm TeV}) = 0.24\left[1 - 0.81(\delta\lambda) + 0.71(\delta\lambda)^2\right]\ {\rm fb},$$
$$\sigma_{\rm cut}(30\,{\rm TeV}) = 0.27\left[1 - 0.79(\delta\lambda) + 0.78(\delta\lambda)^2\right]\ {\rm fb}.$$

BR($hh \to 4b$) = 34%

factor 10 loss
in xsec at 30 TeV

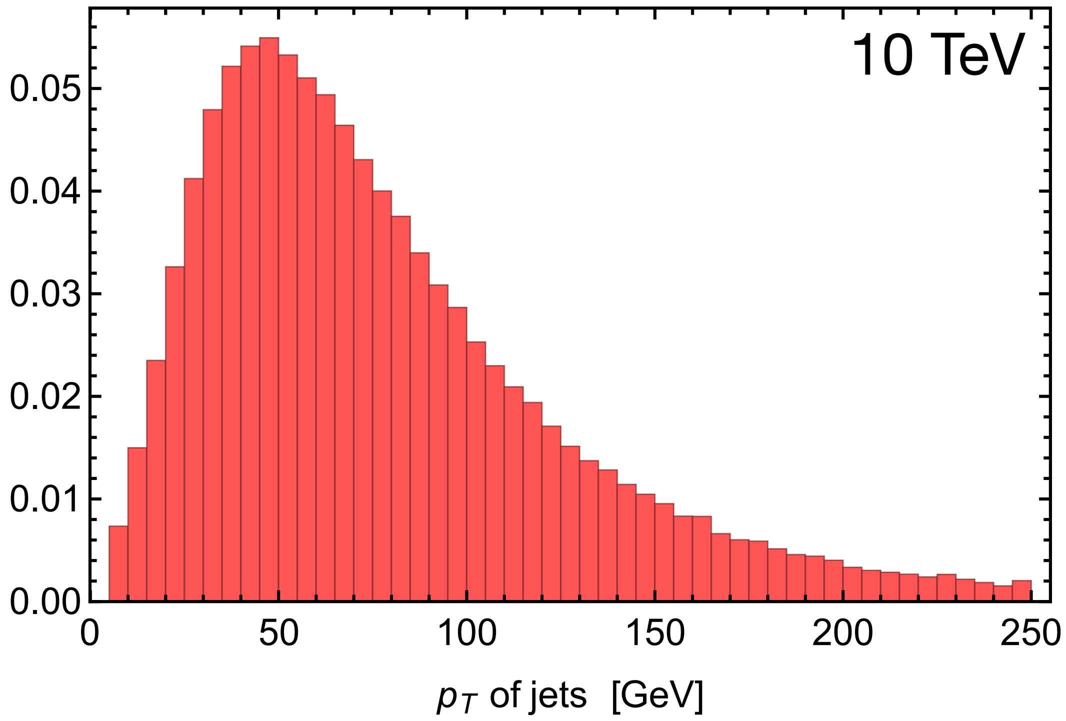
- **Neglect backgrounds** (for the moment)

- Assume signal **reconstruction efficiency** ε ~ 25% as CLIC [1901.05897]:
  mainly from invariant-mass cuts and b-tag

$\sqrt{s}$ [TeV]	L [ab^{-1}]	σ [fb]	N_{rec}	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\lambda$
3	5	0.13	170	~ 7.5%	~ 10%
10	10	0.24	630	~ 4%	~ 5%
30	90	0.74	6'300	~ 1.2%	~ 1.5%

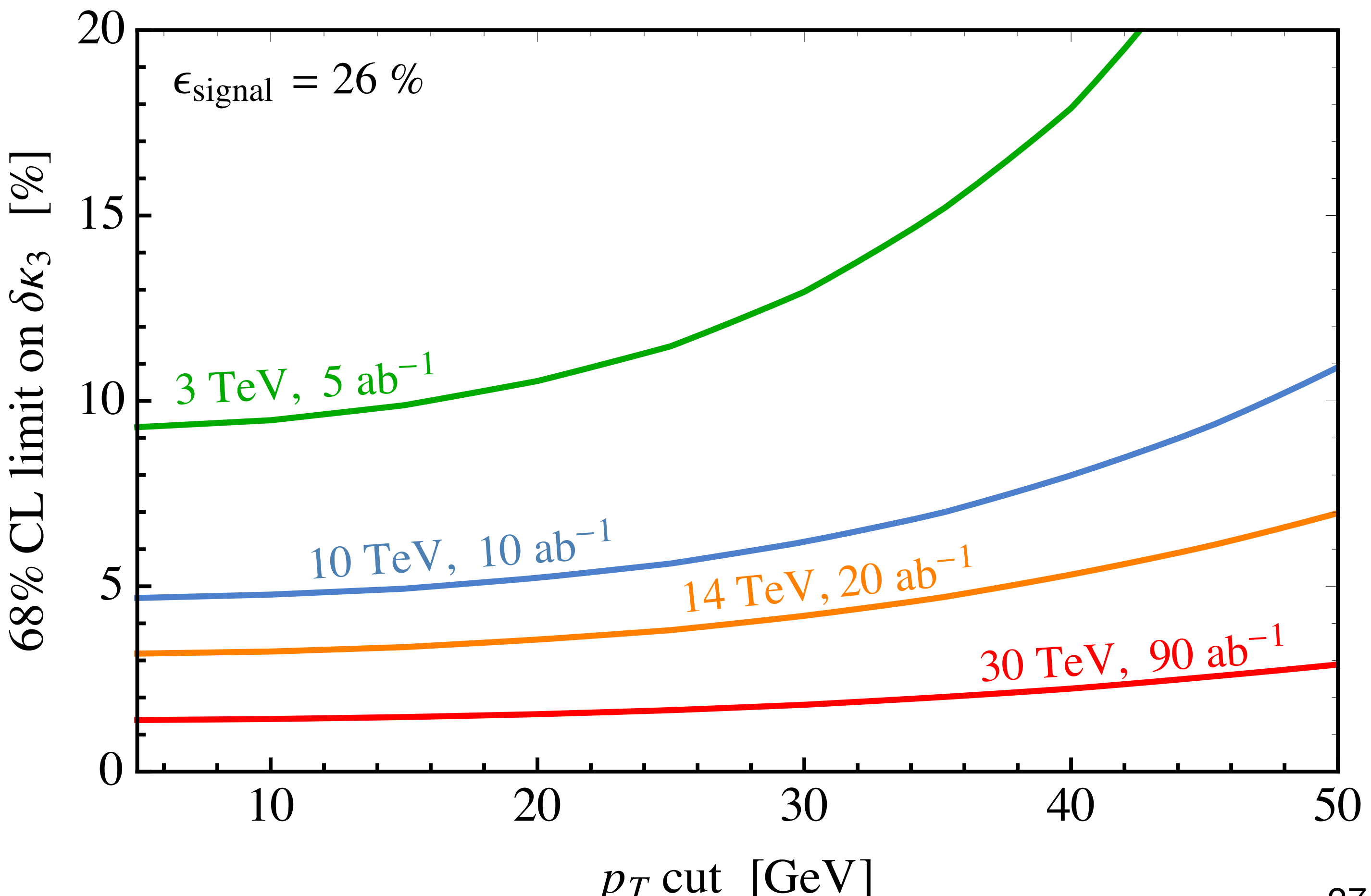
Sensitivity to jet p_T threshold

- Jets come from Higgs decays: typical momentum ~ $m_h/2$



- No significant impact if $pT_{min} \lesssim$ 40–50 GeV

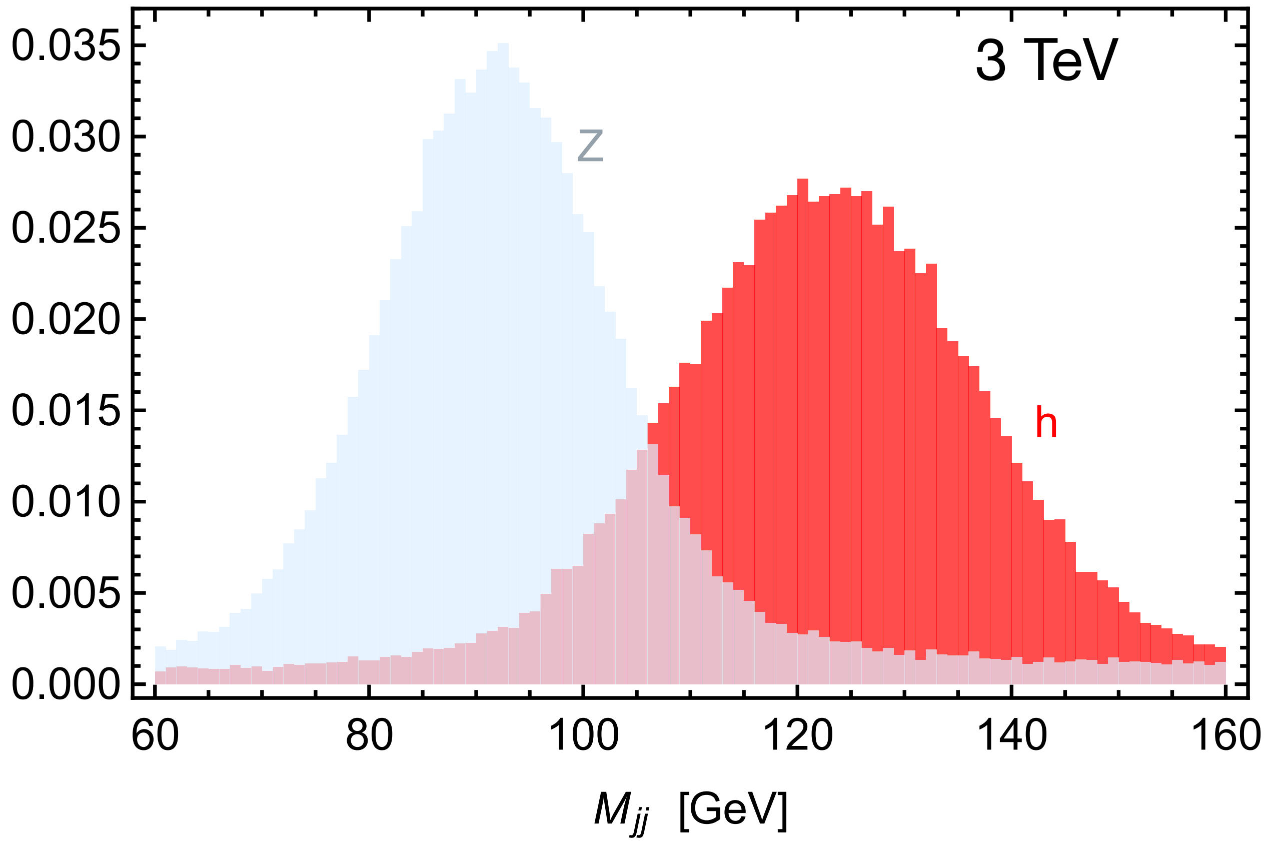
  higher thresholds start to reduce the sensitivity



Backgrounds

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

- Include all VV → VV processes (Zhνν, ZZνν, WWνν, Whν, WZν)
- Apply gaussian smearing to jets, assuming 15% energy resolution
- Reconstruct bosons by pairing jets with minimal $|m(j_1 j_2) - m(j_3 j_4)|$



- Optimize cuts to reject bkg: dijet inv. mass, n. of b-tags

  $M_{hh} > 105$ GeV,

  $n_b = 3.2$

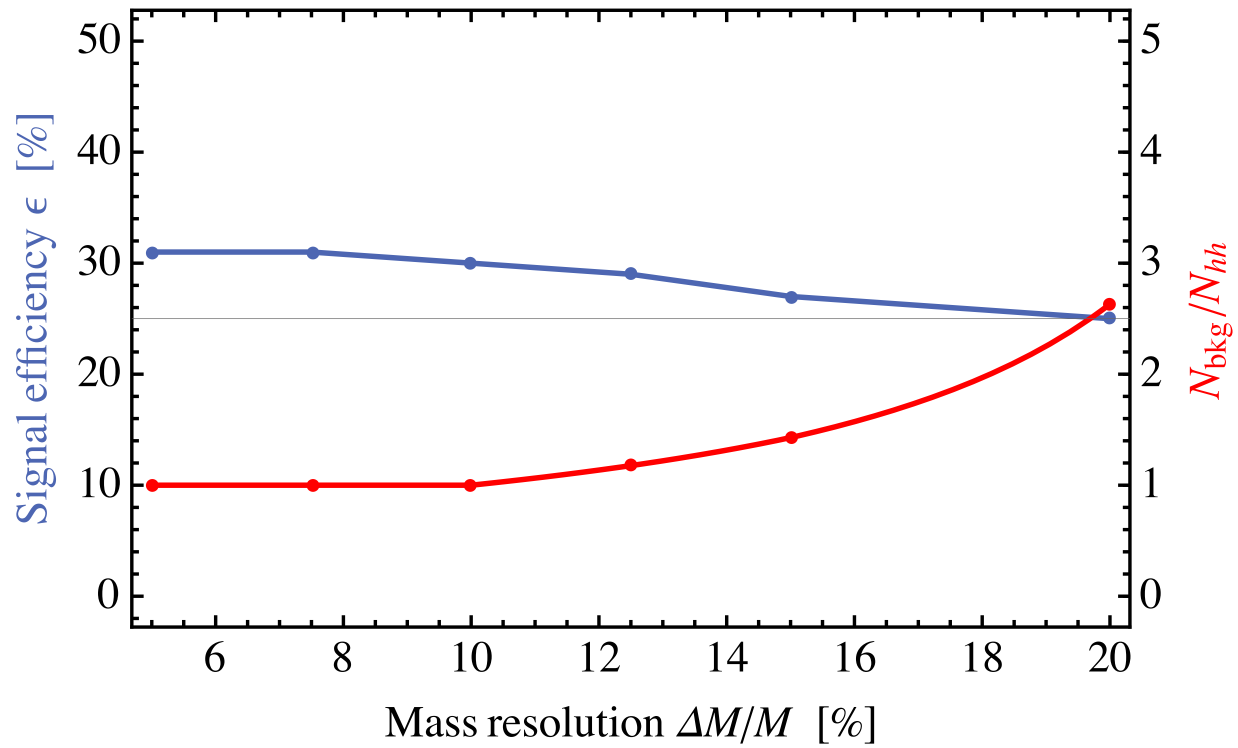
  $\varepsilon_{sig} = 27\%$

NB: all this should be done properly (and has been done, for CLIC), with a detector simulation

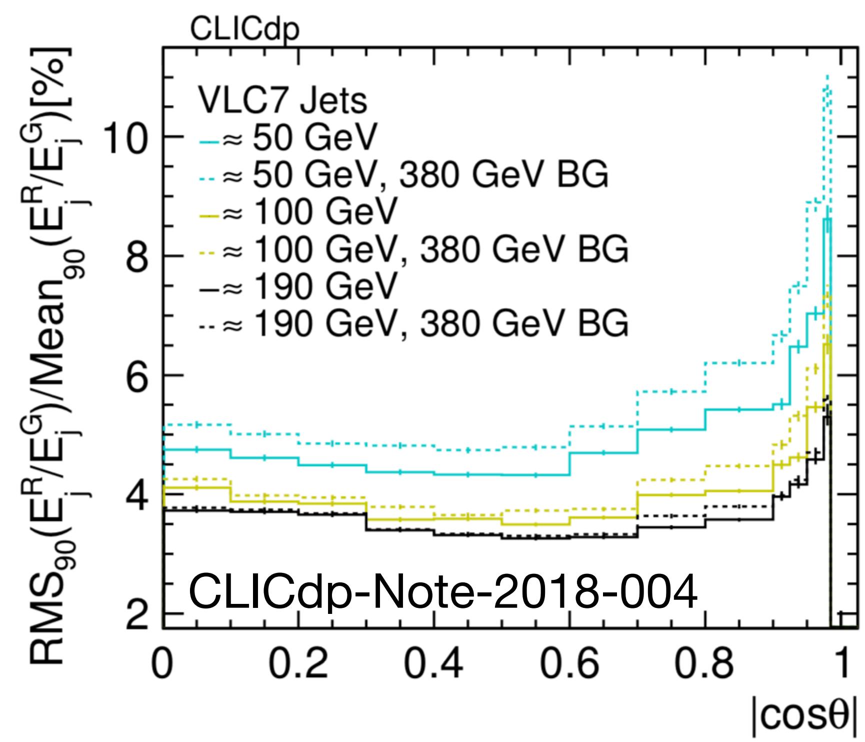
However, perfect agreement with 1901.05897!

Backgrounds

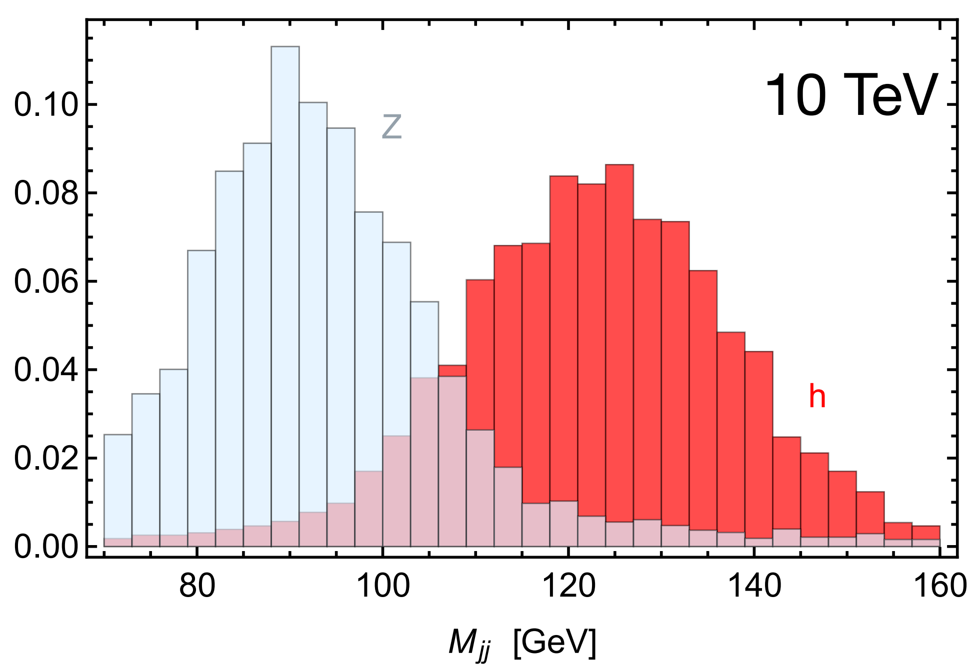
One can now repeat the analysis for different jet energy resolutions:



no real gain using only central events…



… and different energies:



- Optimize cuts to reject bkg:

  $M_{hh} > 105$ GeV,

  $n_b = 2.8$

  $\varepsilon_{sig} = 32\%$

result very similar to 3 TeV

High-energy di-bosons

- Longitudinal $2 \to 2$ 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:

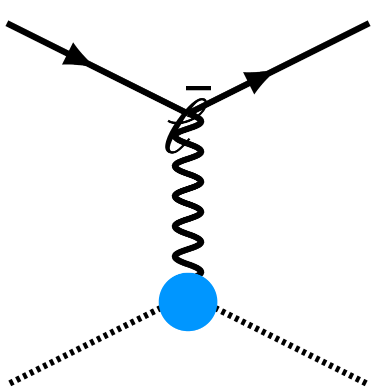
$$\mathcal{O}_{3L} = \left(\bar{\mathrm{L}}_L \gamma^\mu \sigma^a \mathrm{L}_L\right)\left(i H^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right),$$

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

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

“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 WW: angular analysis

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

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

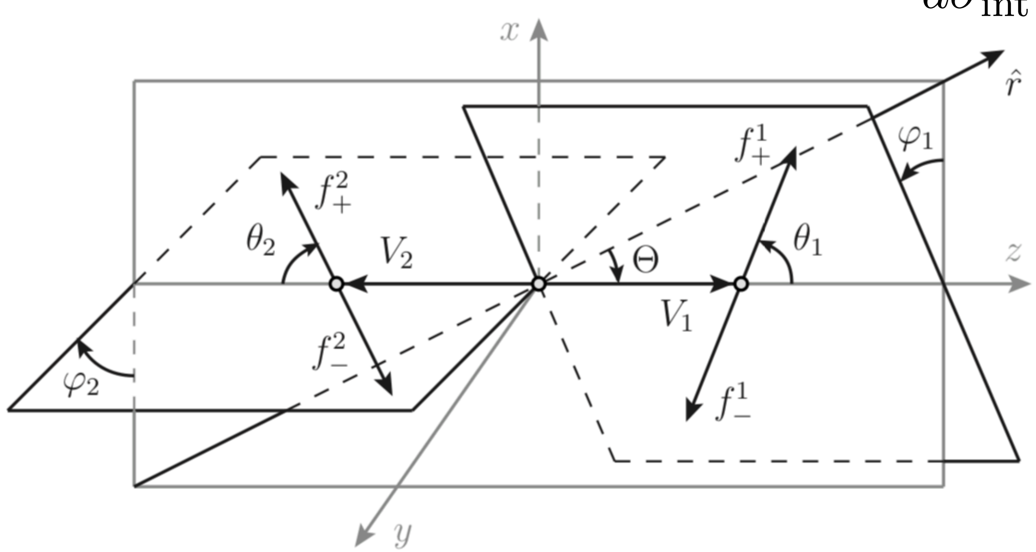
- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

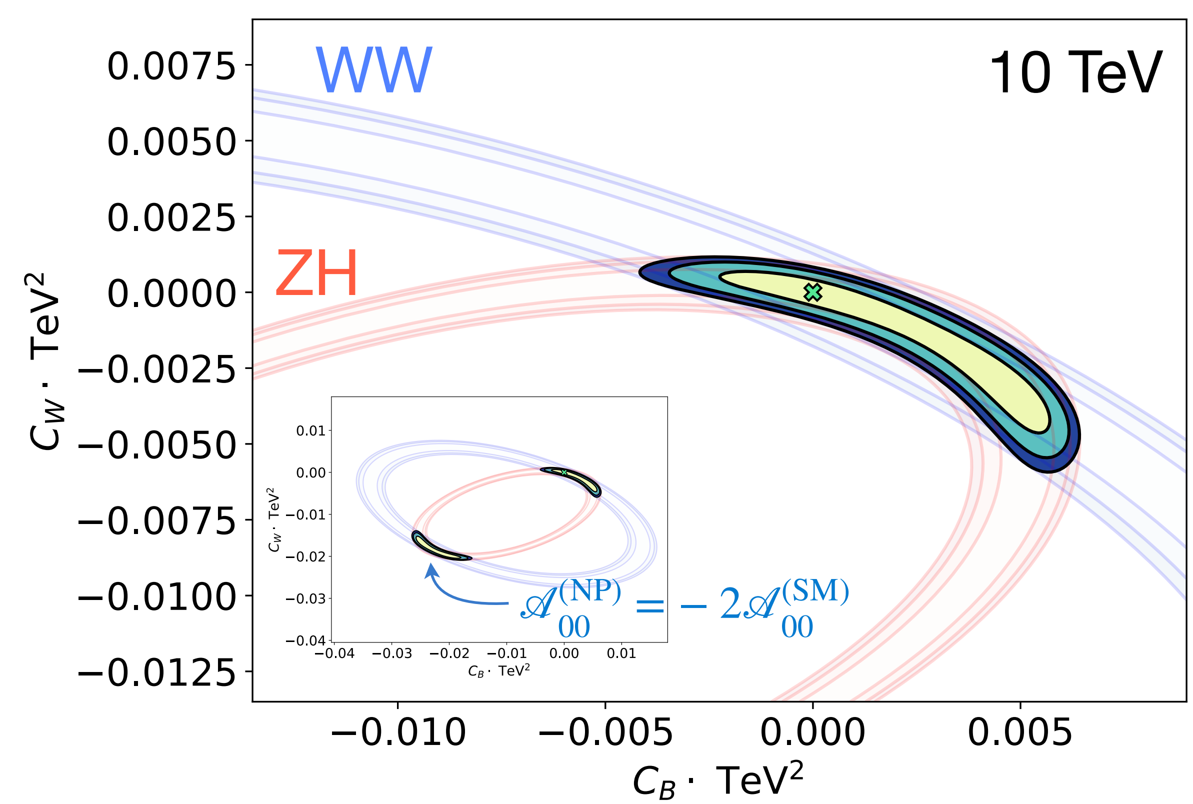
Interference between ±∓ and 00 helicity amplitudes cancels in the total cross-section ⇒ signal suppressed!

see also Panico et al. 1708.07823, 2007.10356

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

($\theta_\pm, \varphi_\pm$ 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!

B, Franceschini, Wulzer 2012.11555

A simple example: scalar singlet

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - a_{HS}|H|^2 S - \frac{\lambda_{HS}}{2}|H|^2 S^2 - V(S)$$

controls Higgs-singlet mixing ~ **sin γ**

portal coupling

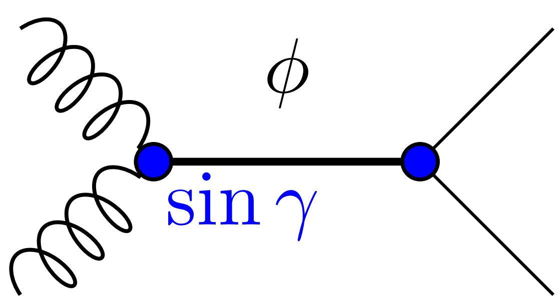
triple couplings: **BR(*ϕ* → *hh*)**, g_{hhh}

$$\sin\gamma \sim \frac{a_{HS} v}{m_S^2}$$

mass eigenstates:

$$h = \cos\gamma\, H^0 + \sin\gamma\, S$$
$$\phi = -\sin\gamma\, H^0 + \cos\gamma\, S$$

- ϕ can be singly produced:

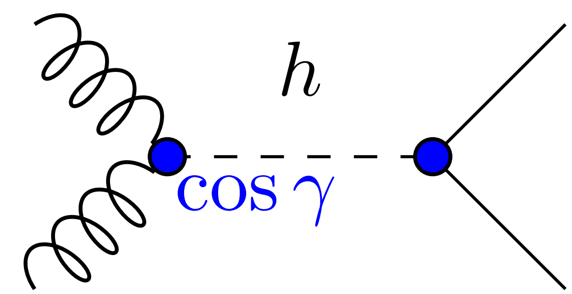


$$\sigma_\phi = \sigma_{\rm SM}(m_\phi) \times \sin^2\gamma$$

- ϕ decays to SM:

$$\mathrm{BR}_{\phi\to VV,ff} = \mathrm{BR}_{\rm SM}(m_\phi)\left[1 - \mathrm{BR}_{\phi\to hh}\right]$$

- Higgs signal strengths:

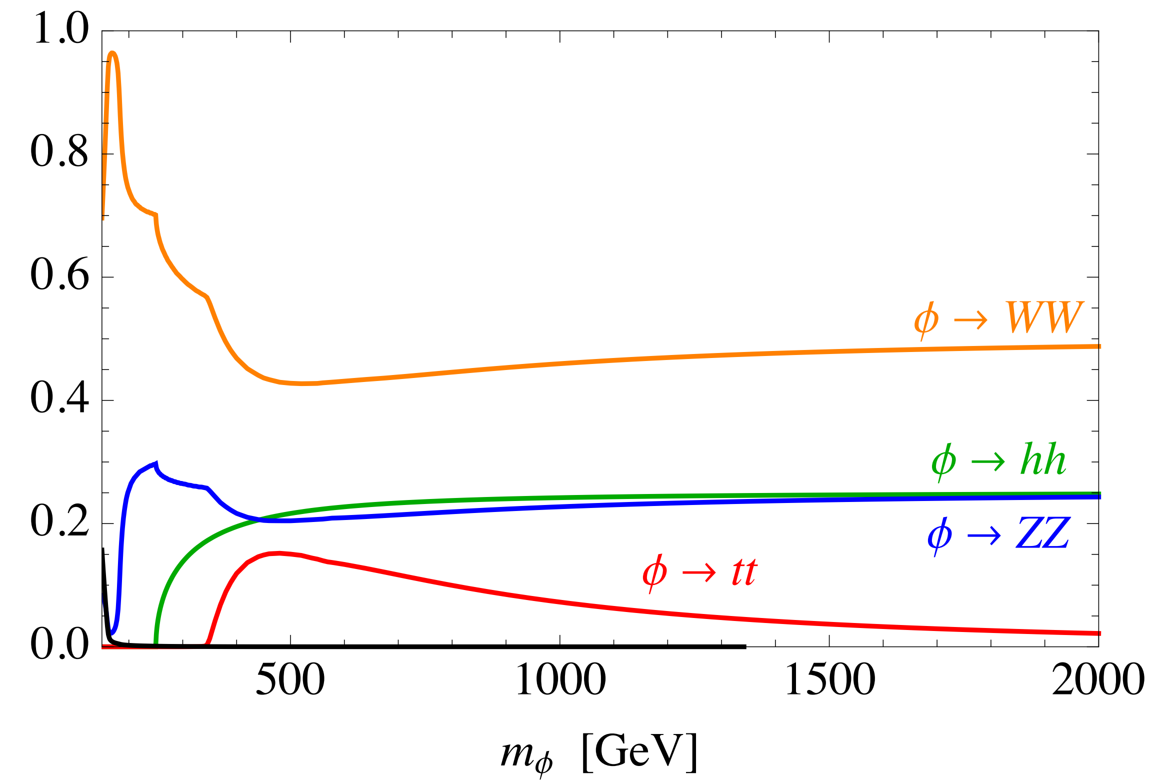


$$\mu_h = \mu_{\rm SM} \times \cos^2\gamma$$

ϕ is like a heavy SM Higgs with narrow width + *hh* channel

Scalar singlets at a HELC

- ϕ is like a heavy SM Higgs with narrow width: Dominant decay modes are into (longitudinal) bosons.

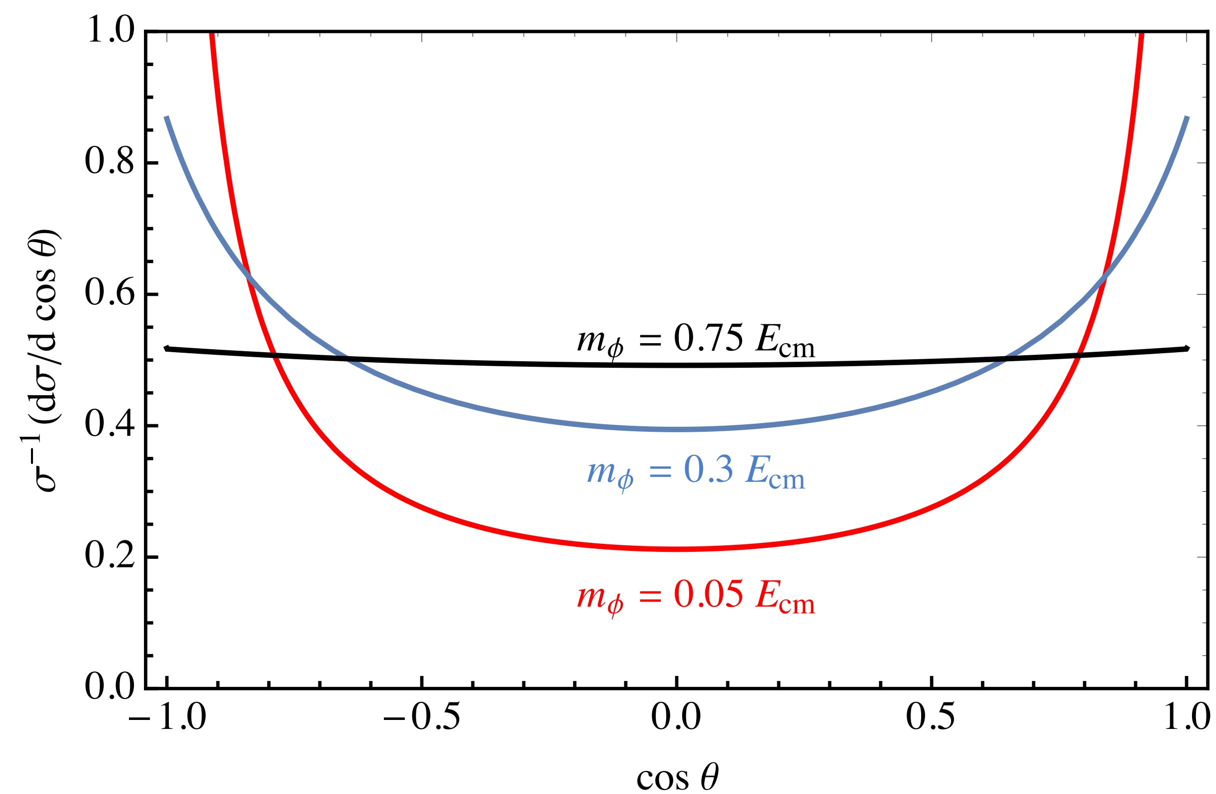


Goldstone boson equivalence theorem:

$$\mathrm{BR}_{\phi\to hh} = \mathrm{BR}_{\phi\to ZZ} = \frac{1}{2}\mathrm{BR}_{\phi\to WW} \simeq \frac{1}{4}$$

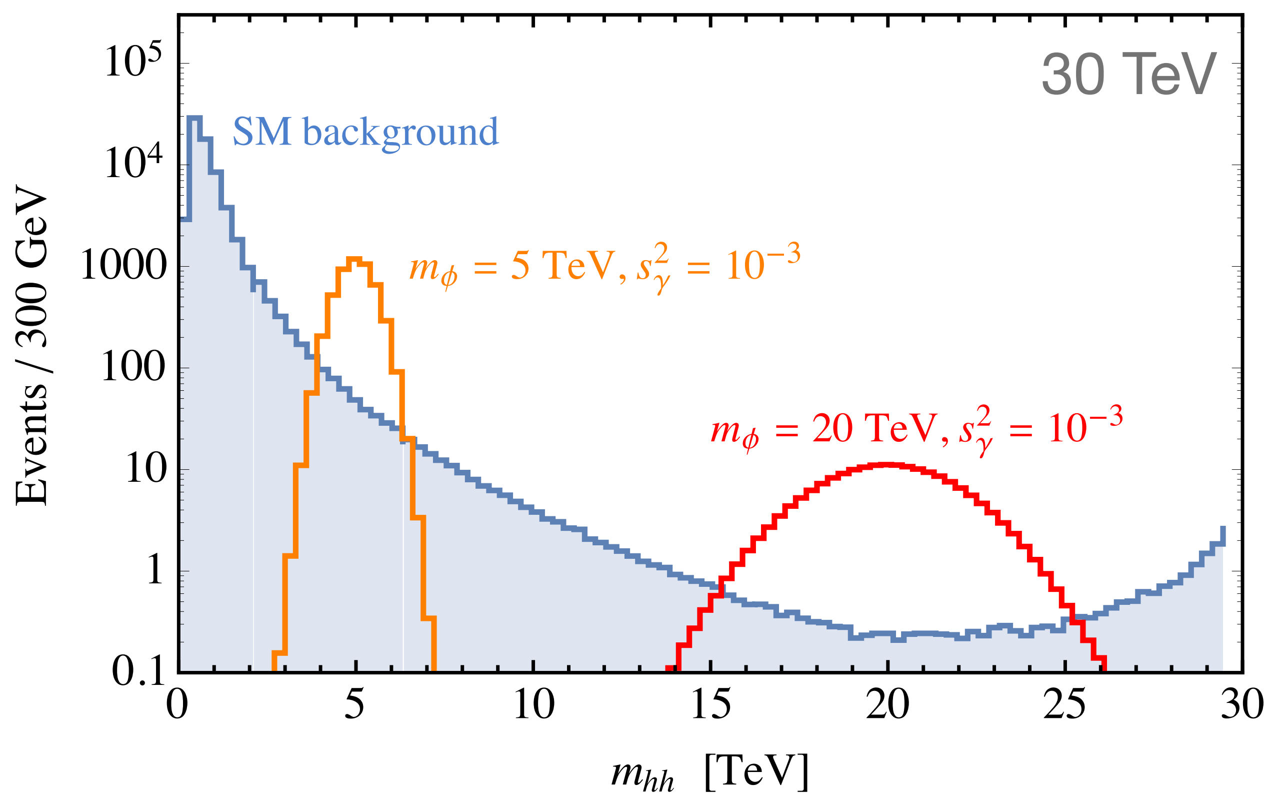
$$m_\phi \gg m_h$$

- Golden channels:
  - ***$\phi \to ZZ(4l,2l2j)$*:** very clean, some EW background; most sensitive channel at LHC.
  - ***$\phi \to hh(4b)$*:** also clean and very sensitive at l^+l^- collider; more challenging at LHC due to QCD background



hh(4*b*) decay channel

Cut & count experiment around the resonance peak:

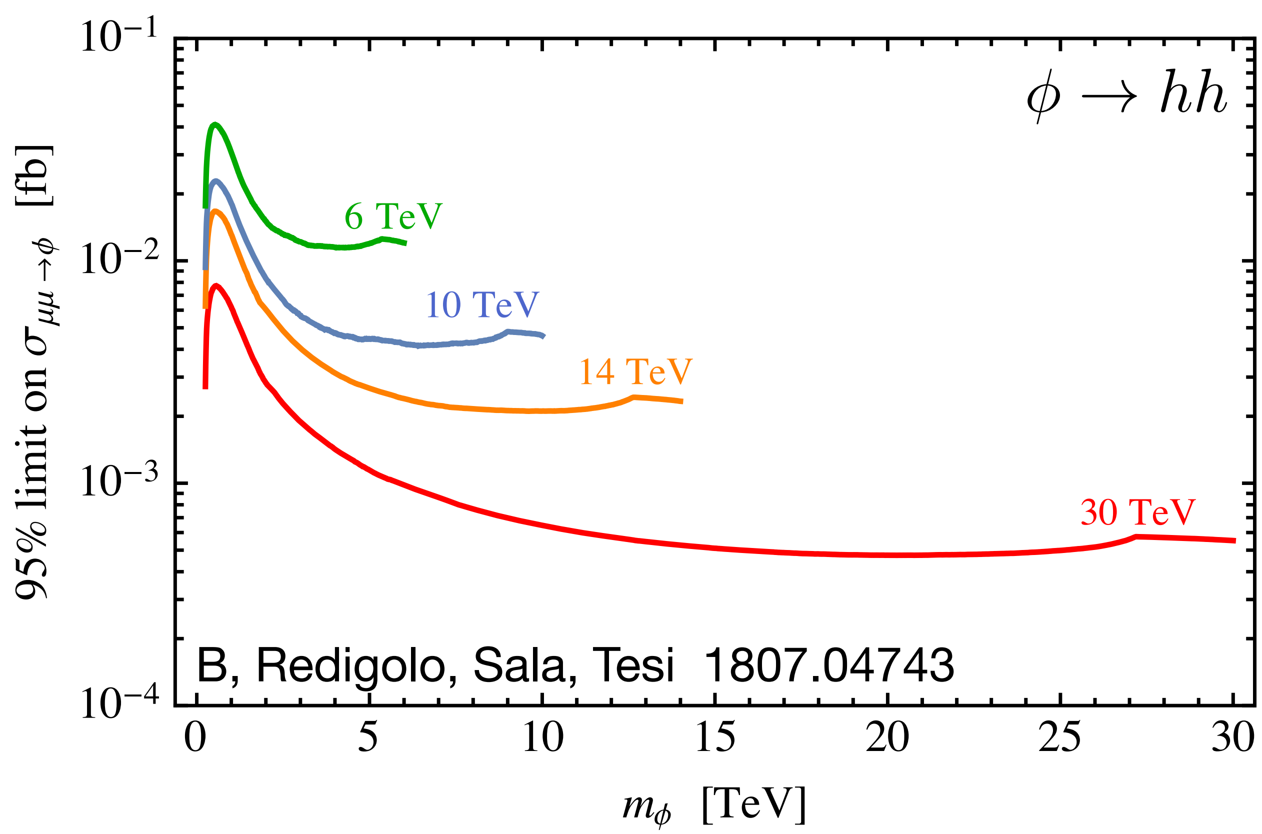


$$\text{significance} = \frac{N_{\text{sig}}}{\sqrt{(N_{\text{sig}} + N_{\text{bkg}}) + \alpha_{\text{sys}}^2 N_{\text{bkg}}^2}}$$

$\alpha_{\text{sys}} = 2\%$ (but it has no impact)

- Small background at high invariant-mass:
  - error is dominated by statistics
  - limits depend weakly on *ϕ* mass and collider energy

$$\sigma(e^+e^- \to \phi\nu\bar{\nu}) \times \text{BR}(\phi \to f) \simeq 3/L,$$



- For BR(ϕ → *hh*) ~ 0.25, most sensitive channel is *ϕ* → *hh(4b)*
  - *ϕ* → *VV* less sensitive, but complementary if BR(ϕ → *hh*) small

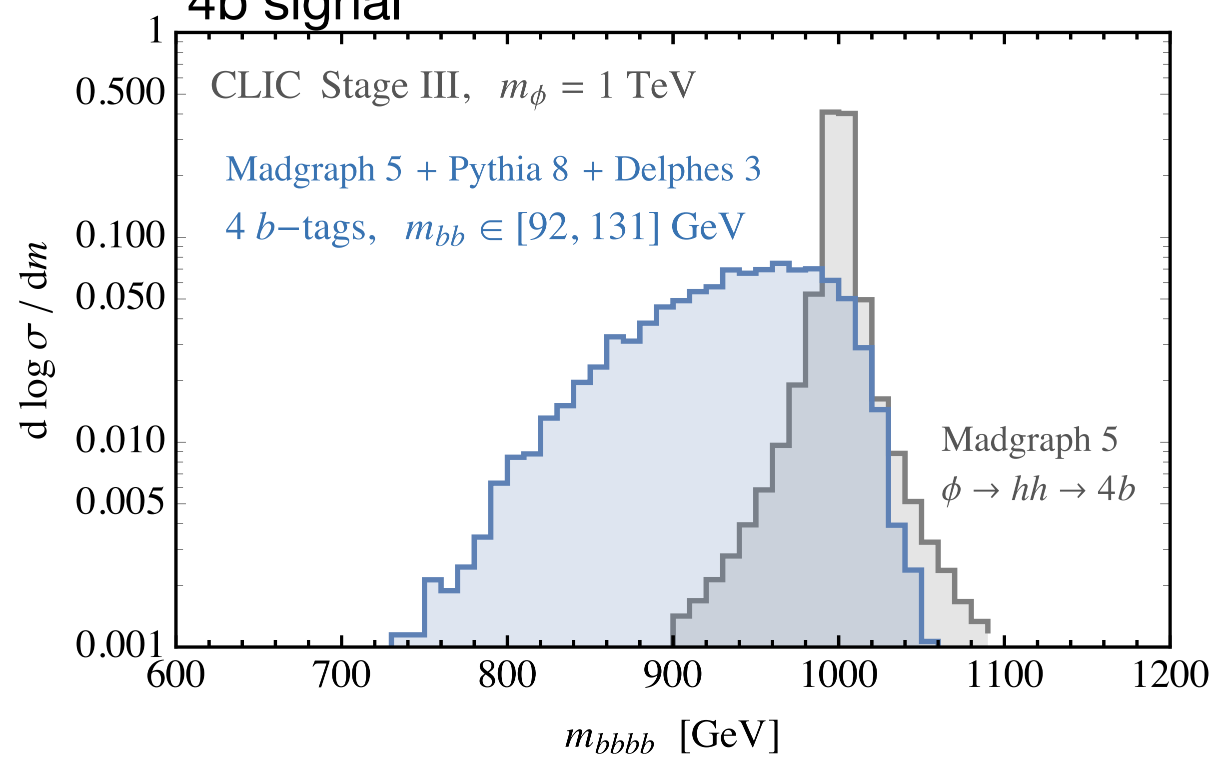
$hh(4b)$ decay channel

Main backgrounds: *hh*, *Zh, ZZ*. We simulate the full process $e^+e^- \to 4b + 2\nu$

1807.04743 — 3 TeV CLIC

- Detector simulation with CLICdp Delphes card
- VLC exclusive jet reconstruction, N = 4, R = 0.7 + 4 b-tags (loose tagging algorithm)
- h reconstruction: select the b pairs that give the best fit to two 125 GeV Higgs bosons, 90 GeV < m_{bb} < 130 GeV
- ϕ reconstruction: $0.75\, m_\phi < m_{4b} < 1.05\, m_\phi$
- Other cuts: $p_T > 20$ GeV, $|\cos\theta_h| < 0.9$

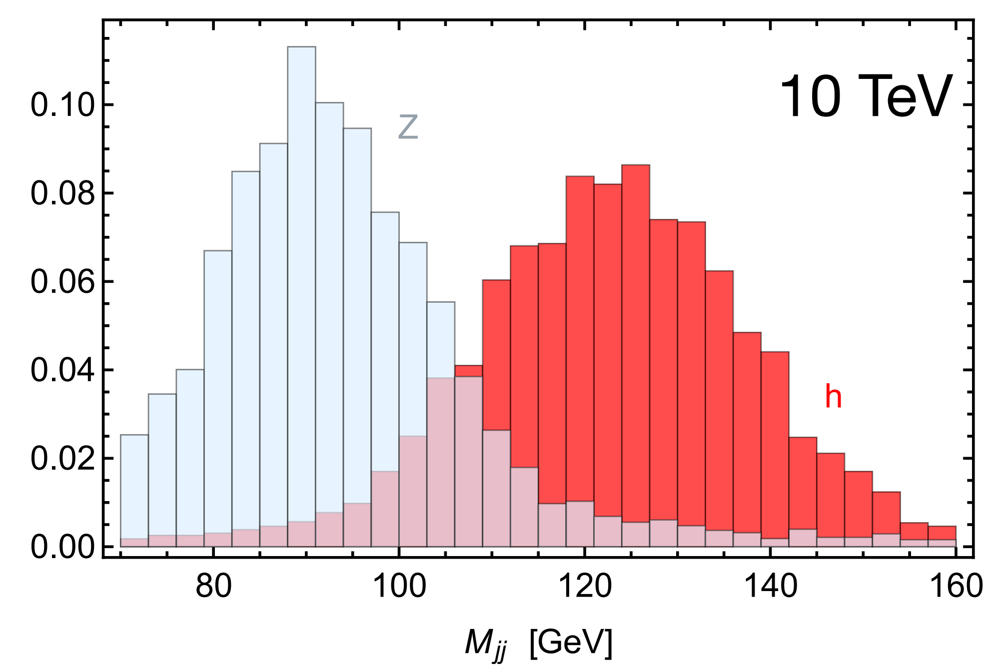
4b signal



Signal efficiency $\varepsilon_{sig} \sim 25 - 30\%$

Background reduced by $\varepsilon_{bkg} \sim 10^{-3} - 10^{-4}$

Checked (at parton level) that results still hold at 10 TeV: $\varepsilon_{sig} \sim 30\%$ assuming similar detector performance



(see also my talk of last month)

Goldstone bosons (Twin Higgs)

- Higgs mass is protected from radiative corrections without new light colored states

- Two copies of the SM, with approximate Z_2 symmetry, coupled through Higgs portal

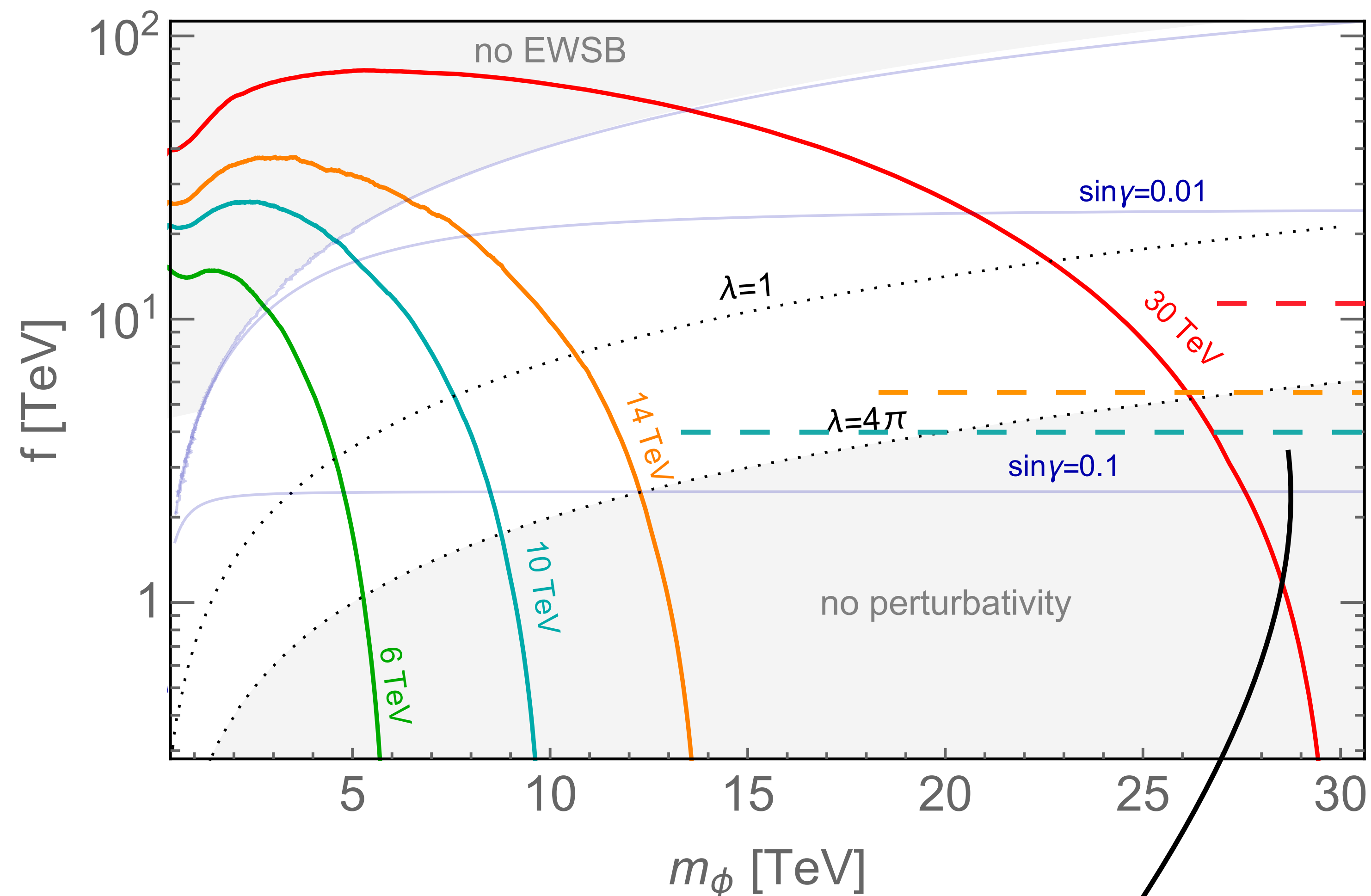
- Higgs is a pseudo-Goldstone

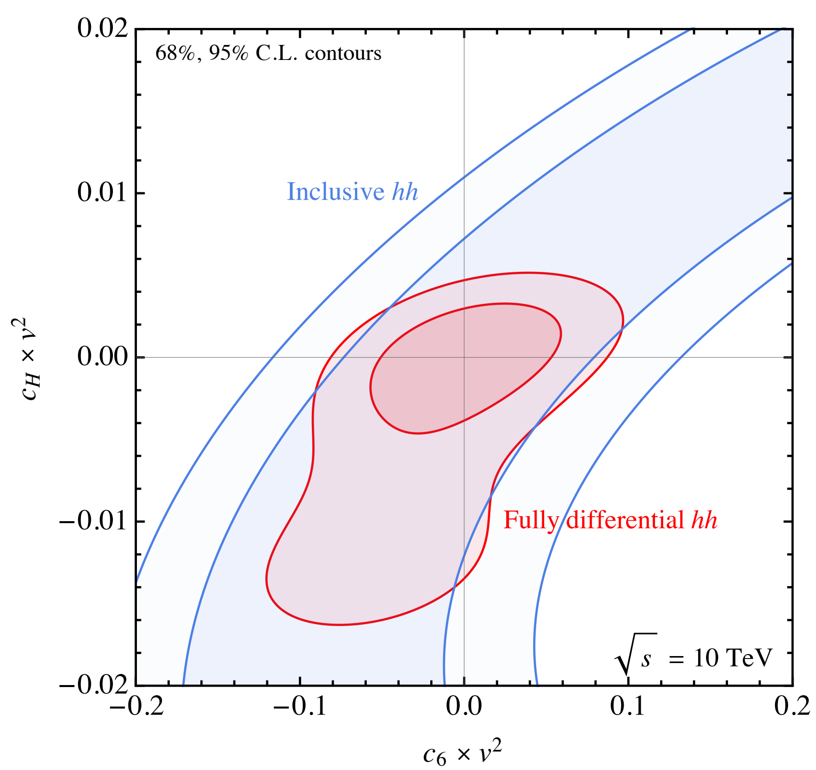
$$\sin^2\gamma \sim v^2/f^2$$

- Model-independent tests:

  ✓ Higgs couplings

  ✓ Search for the singlet





If ϕ heavy, no resonance search but EFT applies

μμ → hh still useful

B, Franceschini, Wulzer, 2012.xxxxx

Applications: SUSY (the NMSSM)

Three Higgs fields: H_u, H_d doublets + S singlet $\quad \mathcal{W} = \mathcal{W}_{\rm MSSM} + \lambda S H_u H_d + f(S)$

- ◇ Extra tree-level contribution to the Higgs mass
- ◇ Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

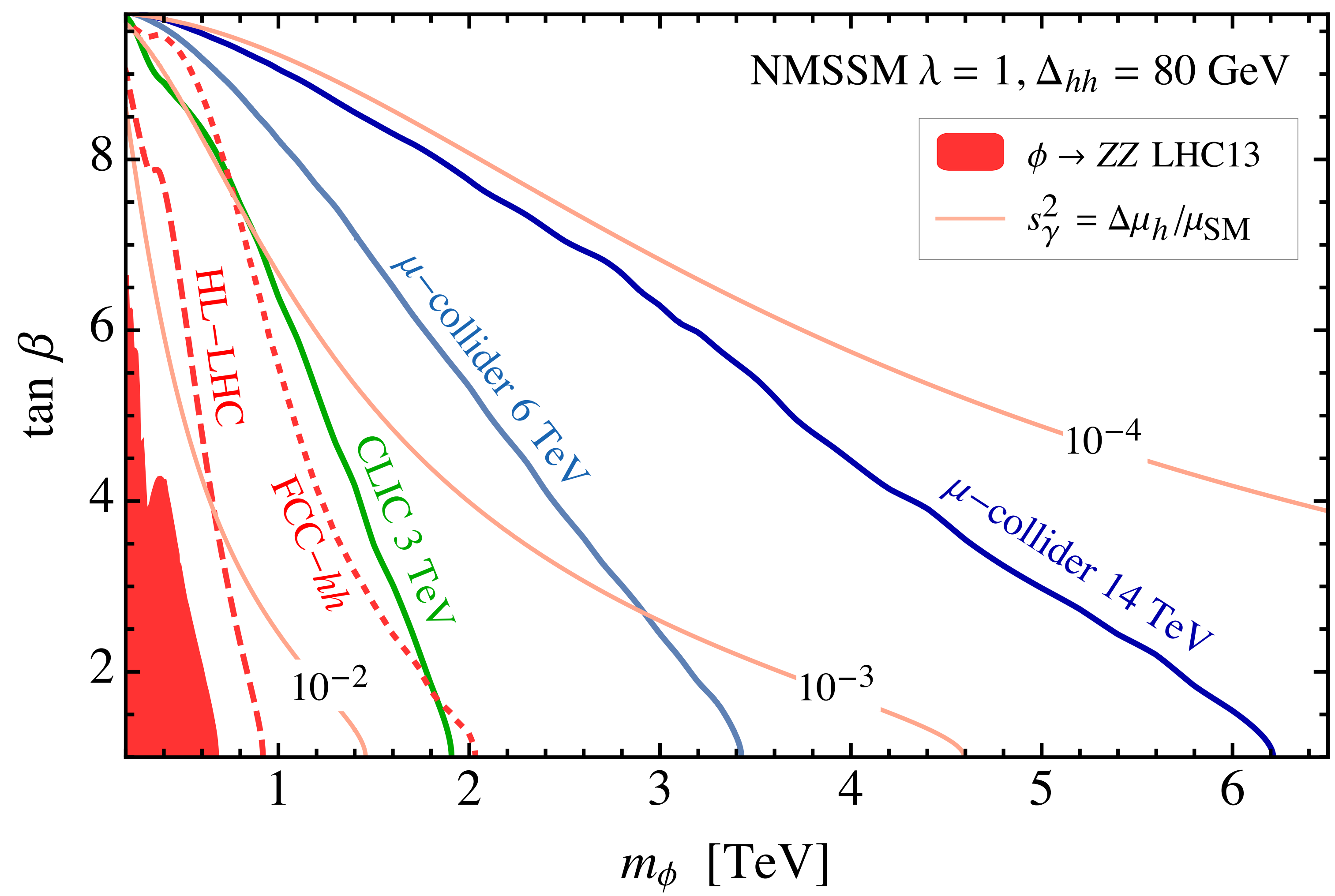
The singlet can be the lightest new state of the Higgs sector

Recast the previous bounds:

$$\sin^2\gamma = \frac{M_{hh}^2 - m_h^2}{m_\phi^2 - m_h^2}$$

$$M_{hh}^2 = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \Delta^2$$

loop correction to Higgs mass from top-stop

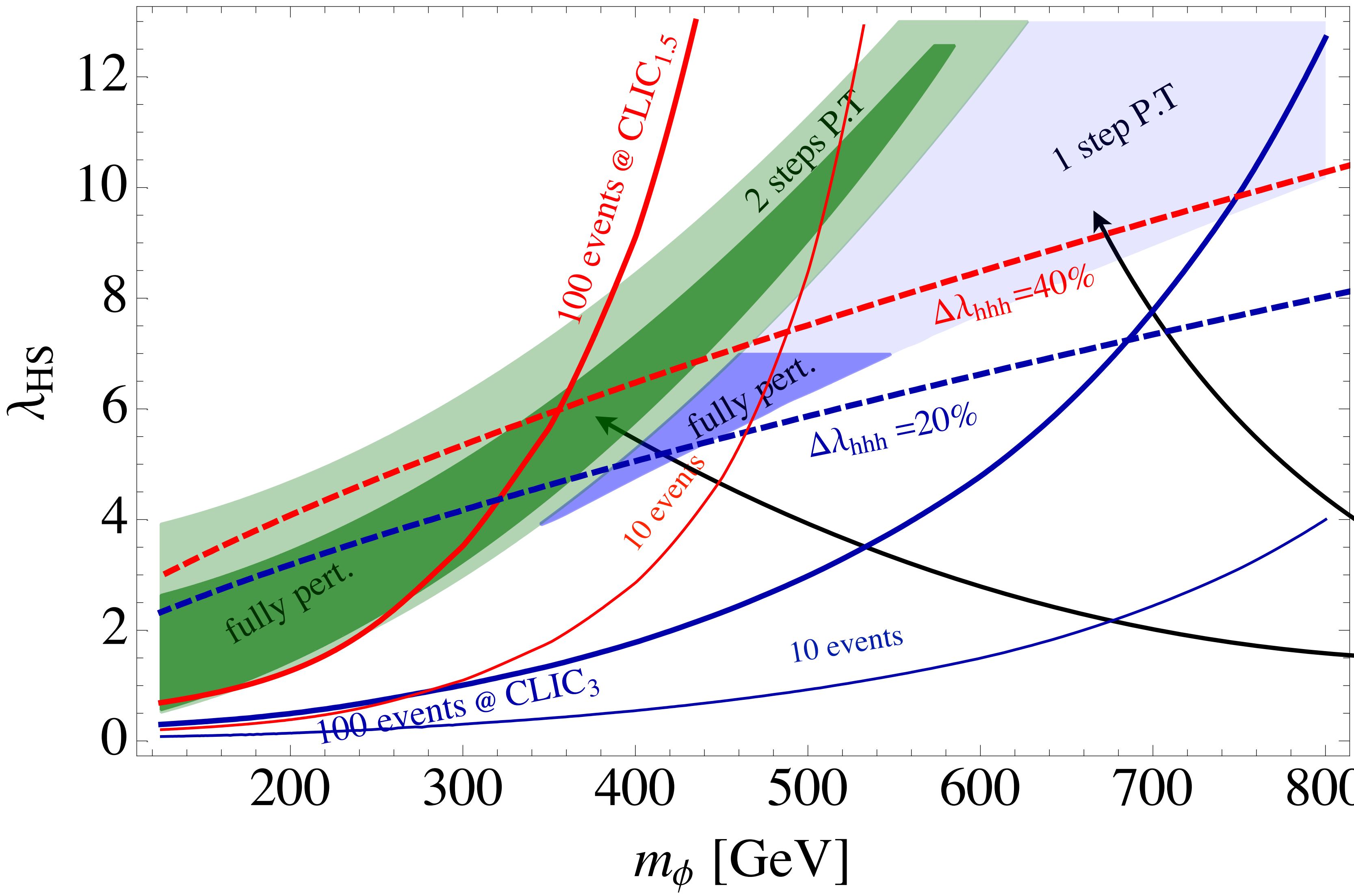


Weakly coupled & low mass: direct searches very powerful!

➡ see Andrea's talk for sparticle production!

Pair production: results

- Final states with 4 Higgs or vector bosons (e.g. $e^+e^- \to 8b + E_{miss}$): very small backgrounds, few events are needed to test the model at CLIC
- Even more stringent bounds in the case of displaced decays (smaller mixing): virtually all the ϕ can be identified, no background



λ_{HS} also induces modifications of the triple-Higgs coupling

➡ see talk by G. Panico

regions where 1st order EW phase transition can happen

CLIC can fully test the region where singlet gives 1st order phase transition!

New physics in the muon g-2

- The g-2 is generated by the dipole operator $\frac{c_\mu}{\Lambda_\mu} e(\bar{\mu}_L \sigma_{\mu\nu} \mu_R) F^{\mu\nu}$

$$\Delta a_\mu \approx a_\mu^{(\mathrm{EW})} \approx \frac{m_\mu^2}{16\pi^2 v^2} \approx 2 \times 10^{-9}$$

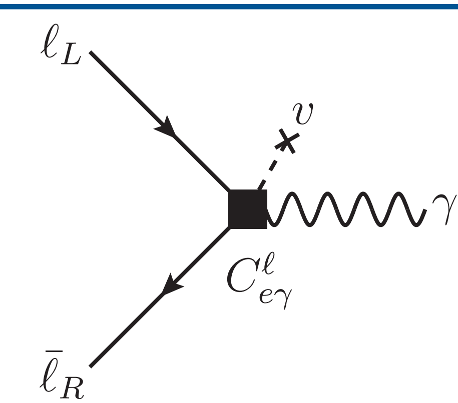
tiny effect: not directly testable at colliders until now

  - $\Lambda \sim$ TeV, weak coupling
    (favored by naturalness arguments, but challenged by LEP, LHC…)
  - $\Lambda \lesssim$ TeV, NP is light and feebly coupled to the SM
    (e.g. axion-like particles, dark sectors, light scalars, …)
  - $\Lambda \gg$ TeV, heavy NP with O(1) couplings to the SM

In the SM EFT one dim. 6 operator contributes at tree-level:

$$\mathscr{L}_{g-2} = \frac{C_{e\gamma}}{\Lambda^2} H (\bar{\ell}_L \sigma_{\mu\nu} e_R) \, e F^{\mu\nu} + \mathrm{h.c.}$$

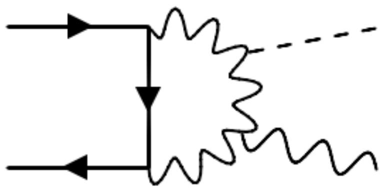
$$\Delta a_\mu = \frac{4 m_\mu v}{\Lambda^2} C_{e\gamma} \approx 3 \times 10^{-9} \times \left(\frac{140\,\mathrm{TeV}}{\Lambda} \right)^2 C_{e\gamma}$$



Muon g-2 @ muon collider

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

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

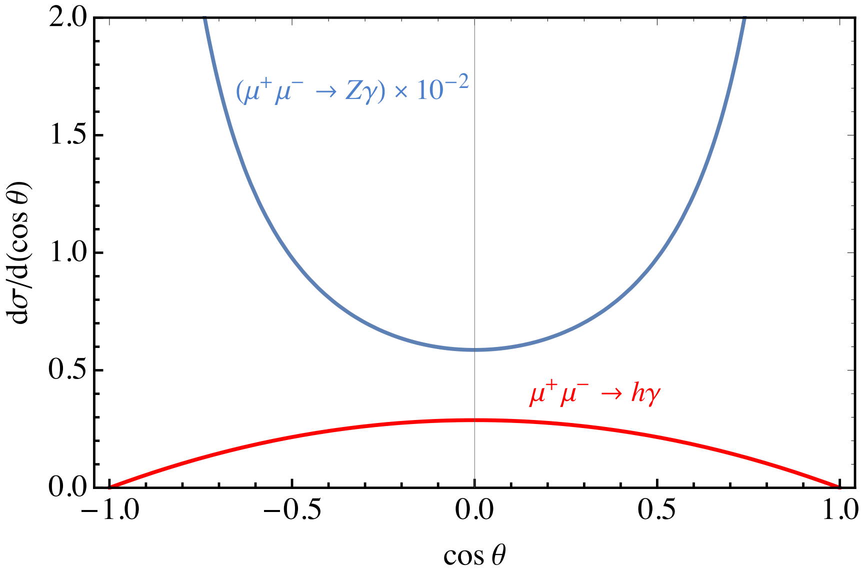


- Main background from $\mu\mu \to Z\gamma$ (where Z is mistaken for H)

  (large due to transverse Z polarizations)

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

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



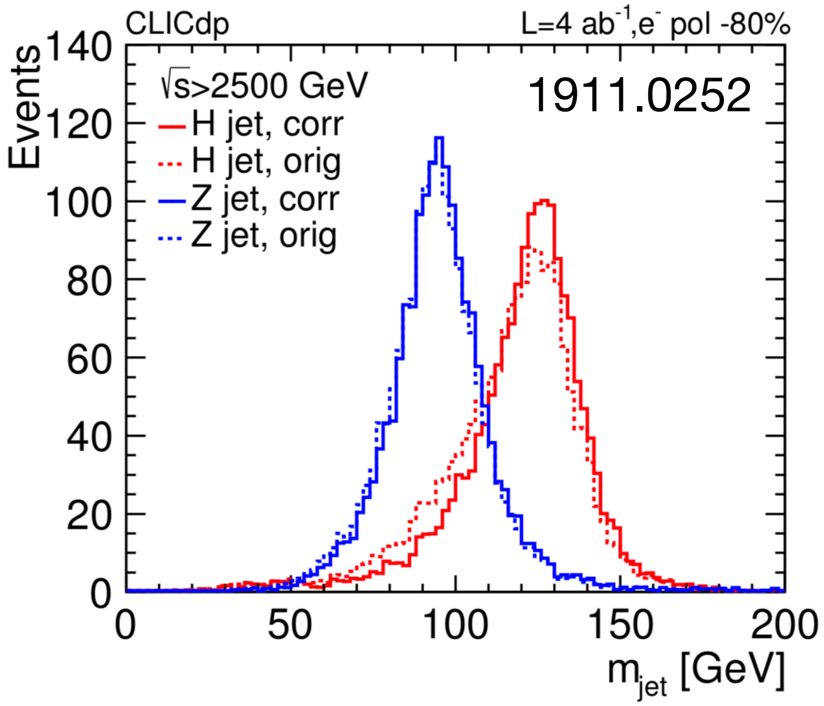
Search in h → bb channel:

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

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

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

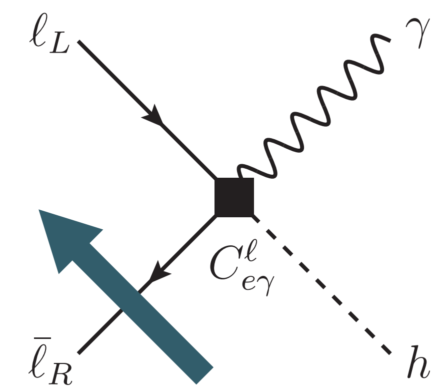
Δa_μ can be tested at 95% CL at a 30 TeV collider if Z→h mistag probability < 10-15%



Lepton g-2 from rare Higgs decays

- Dipole operator contributes also to h $\to \ell\ell\gamma$ decays!

$$\Gamma^{(\mathrm{int})}_{h\to\ell^+\ell^-\gamma} = \frac{\alpha m_\ell \mathrm{Re}(C_{e\gamma}) m_h^3}{16\pi^2 v} \qquad \Gamma^{(\mathrm{NP})}_{h\to\ell^+\ell^-\gamma} = \frac{\alpha |C_{e\gamma}|^2 m_h^5}{192\pi^2}$$



$$\Gamma^{(\mathrm{SM})}_{h\to\ell^+\ell^-\gamma} = \Gamma^{(\mathrm{SM})}_{\mathrm{tree}} + \Gamma^{(\mathrm{SM})}_{\mathrm{loop}}$$

(tree-level is suppressed by lepton mass)

- Very large single Higgs VBF rate @ μ-collider (10^7–10^8 Higgs bosons)

  - Muon:

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

1704.00790

$$\mathrm{BR}^{(\mathrm{NP})}_{h\to\mu^+\mu^-\gamma} \approx 5\times 10^{-10}\left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)$$

too small :(

  - Tau:

$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 10^{-3}$$

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

$$\Rightarrow \quad \Delta a_\tau \lesssim \text{few} \times 10^{-5}$$

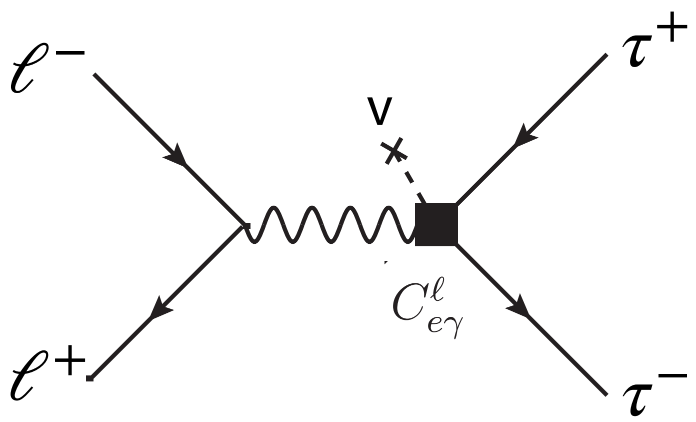
3 o.o.m. improvement!

Lepton g-2 at high energy

Further possibilities to measure Δa_τ precisely from high-energy probes

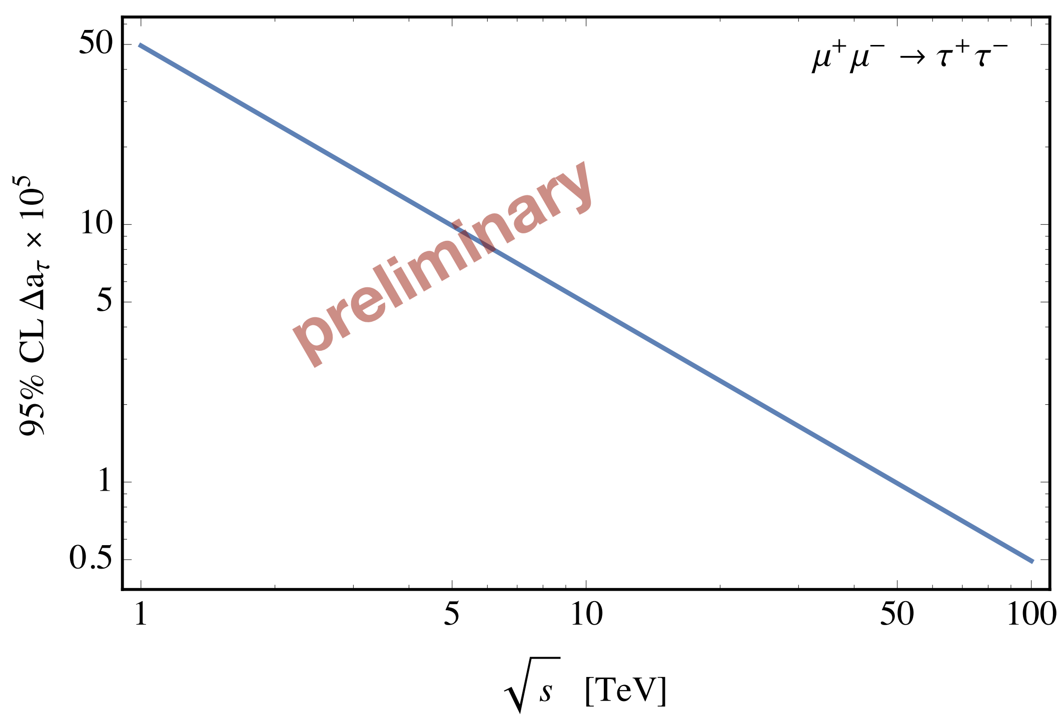
- Pair production

work in progress with P. Paradisi



$$\sigma_{\rm SM} \sim \frac{4\pi\alpha^2}{3s}$$

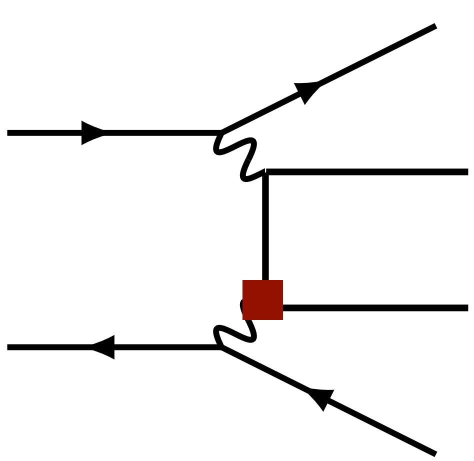
$$\sigma_{\rm NP} = \frac{4\pi\alpha^2}{3}\frac{|C^\ell_{e\gamma}|^2 v^2}{\Lambda^4} \sim \frac{\pi\alpha^2 \Delta a_\ell^2}{6 m_\ell^2}$$



Could probe Δa_τ ~ few 10^{-5}

- Vector boson fusion: $\ell^+\ell^- \to \ell^+\ell^-\tau^+\tau^-, \, \nu\bar{\nu}\tau^+\tau^-$

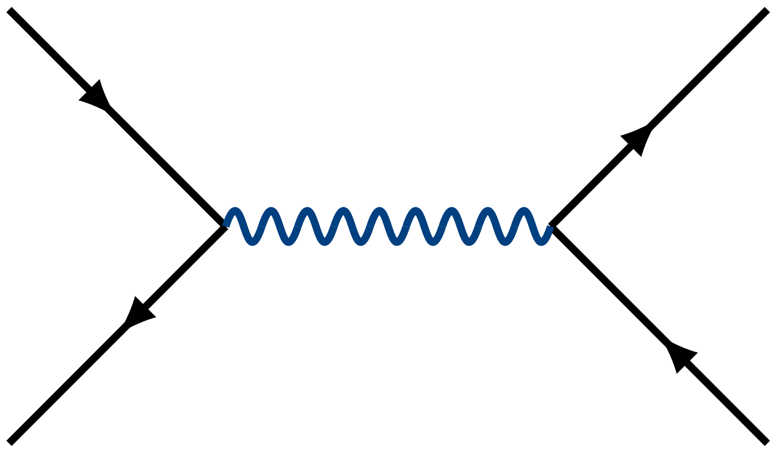
charged and neutral channel can constrain C_{eB} and C_{eW}



More resonances: Z'

Most typical example of direct search:

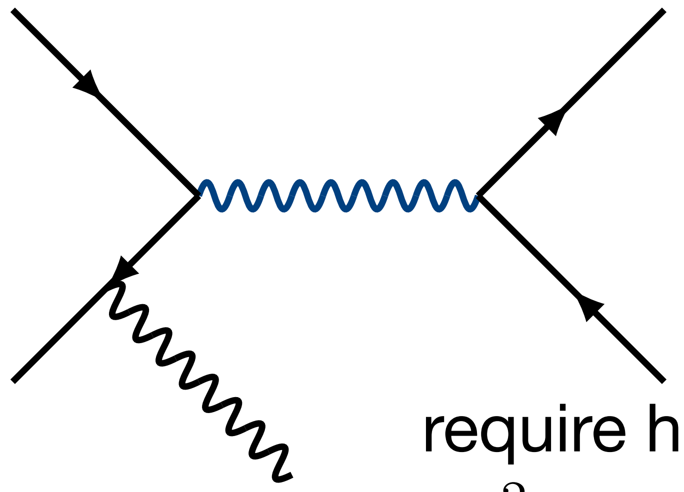
heavy s-channel resonance produced in Drell-Yan



If Z' produced on-shell, very large cross-section

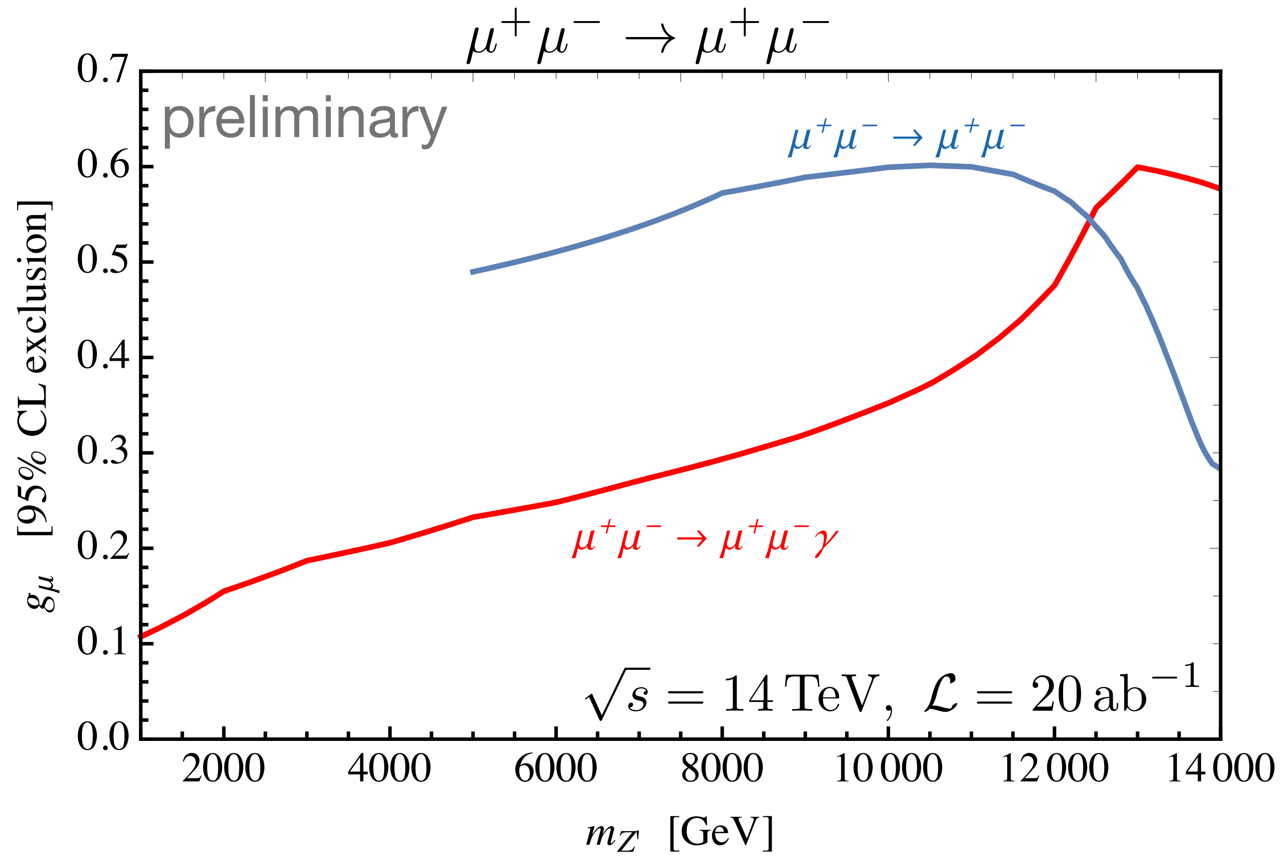
Problem: how do we look for resonances of unknown mass at fixed √s?

I. "Radiative return": produce resonance on-shell with ISR



require hard photon

$$M^2 = m_{\ell\ell}^2 = s - 2\sqrt{s}E_\gamma$$



II. Off-shell Z' exchange

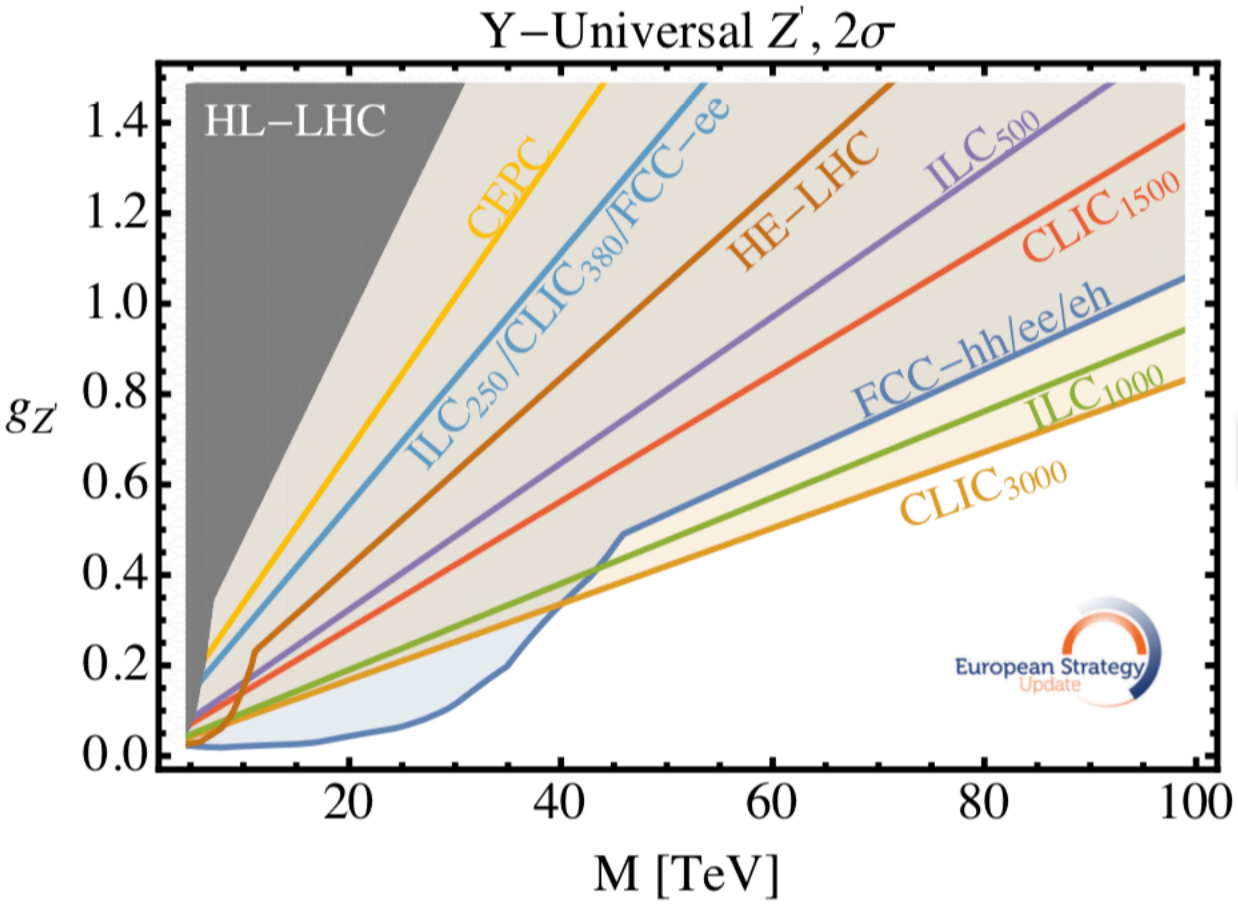
($\mu\mu \to ff$ cross-section)

kinematical cuts: $p_T > 20\,\mathrm{GeV}, \quad |\theta| > 5^\circ$

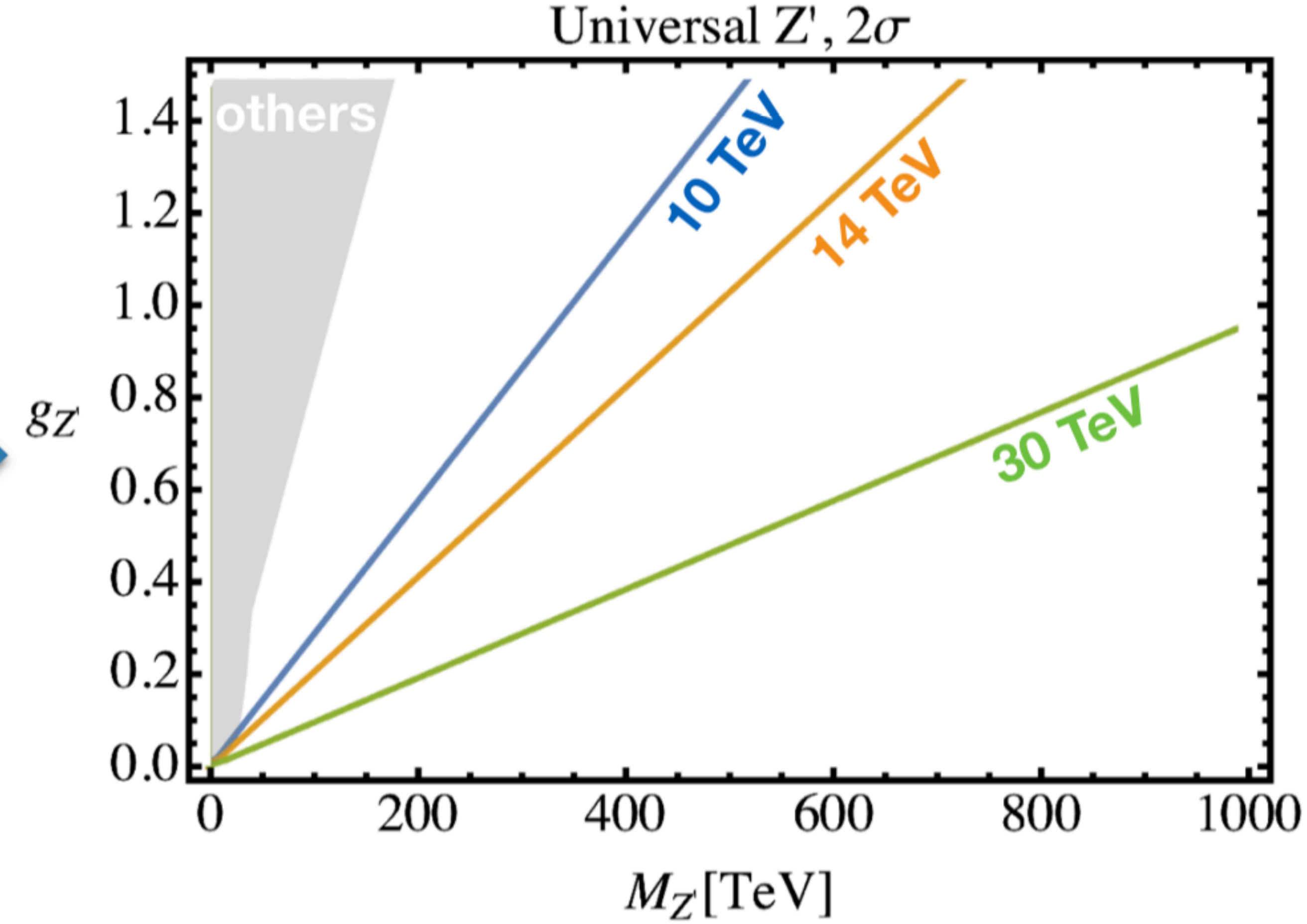
QED corrections $\approx \frac{2\alpha}{\pi}\log\frac{s}{m_\mu^2} \lesssim 10\%$

Direct searches: Z’

“Standard” Future Colliders



Muon Collider

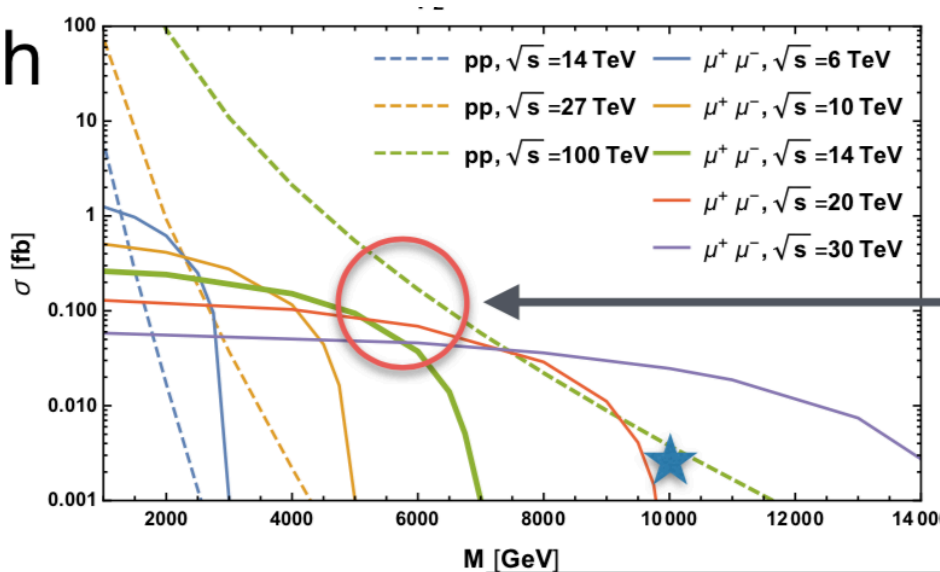


Direct searches

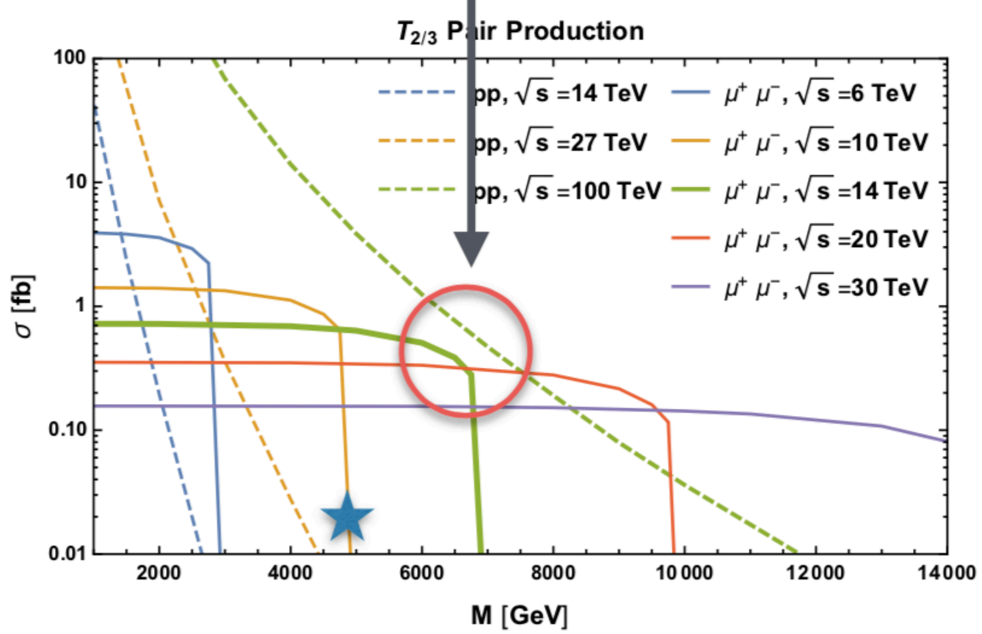
★ = FCC reach

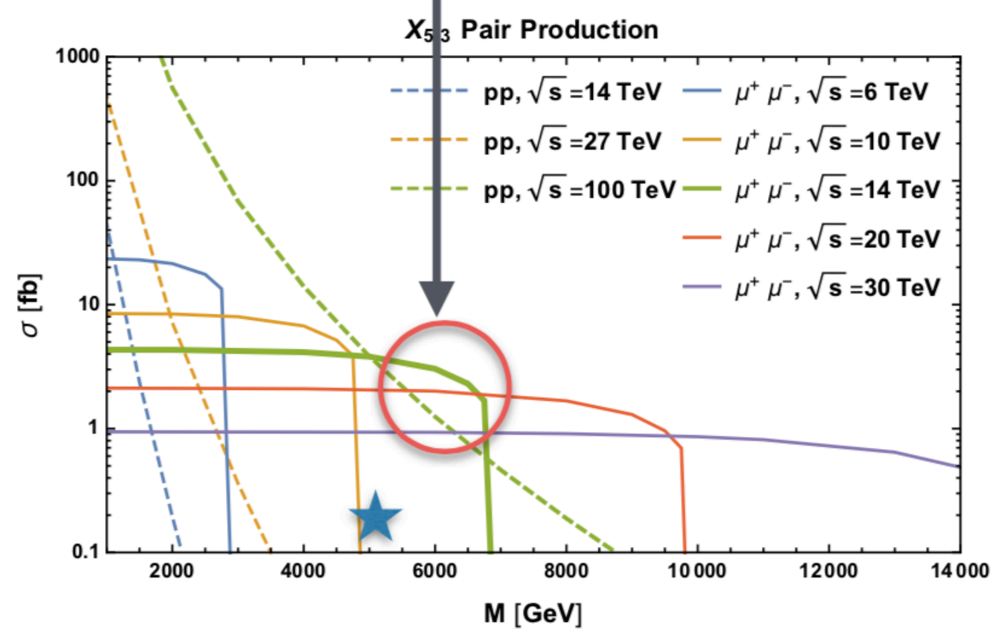
14 TeV μ-collider ~ FCC@100 TeV

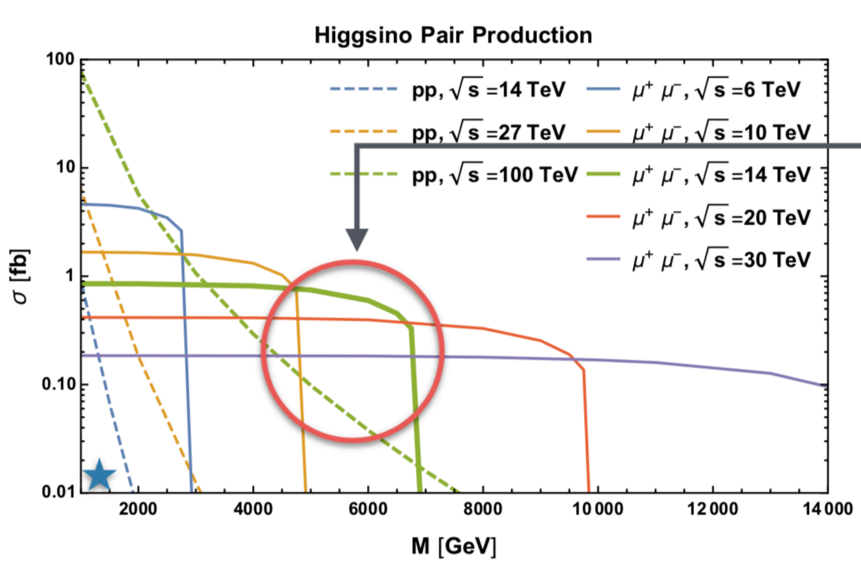
Stop

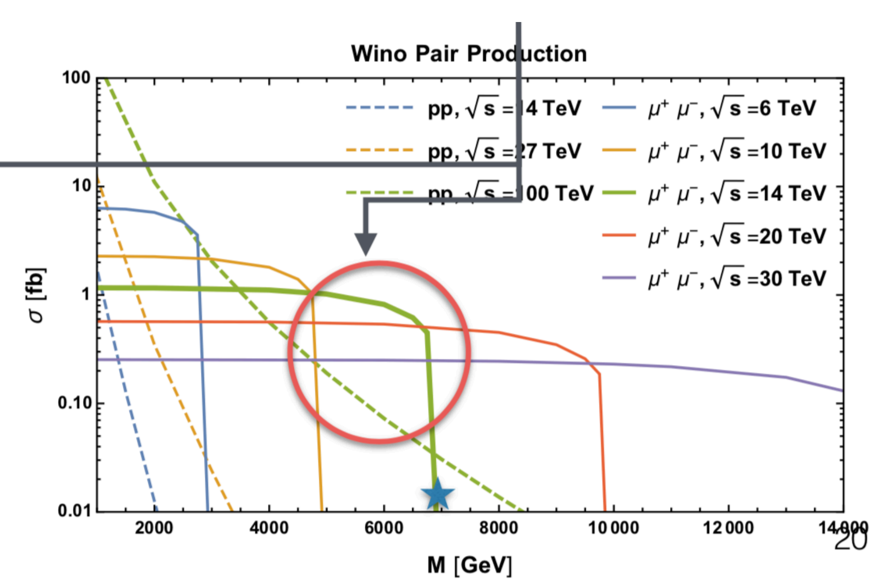


Top-Partners

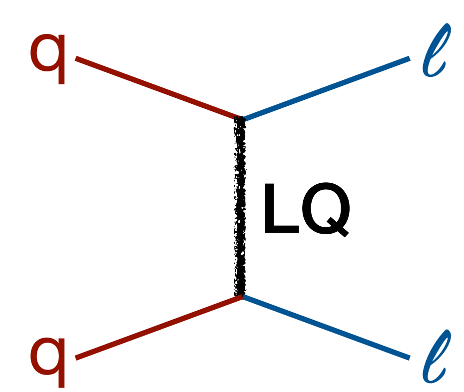








Coloured resonances: 3rd generation leptoquarks



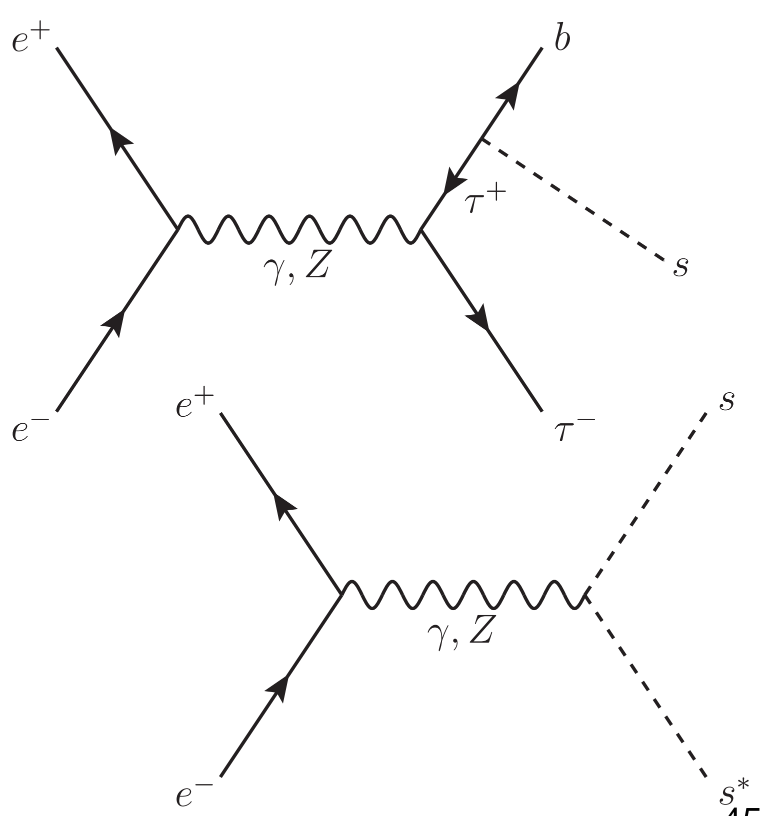
- Different signature compared to more "standard" BSM
- Interesting: NP coupled to 3rd generation fermions (*B physics anomalies!*)
- Can be either scalar or vector
- Difficult searches at LHC: High Lumi reach ~ 1.5 TeV

➡ $\sqrt{s}$ > 3 TeV interesting range for lepton colliders

3rd generation LQ production at a lepton collider:

- Pair production: large cross-section when allowed, does not depend on coupling to fermions
- Single production: radiation from bb or ττ pair

➡ bbττ final state, with $m_{b\tau} \sim M_{LQ}$



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