Muon colliders: a physics potential overview

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

Istituto Nazionale di Fisica Nucleare

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SUSY 2021 — 23 August 2021

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

Pair production,
Resonances, VBF,
Dark Matter, …

High-rate measurements

Single Higgs,
self coupling, rare and
exotic Higgs decays,
top quarks, …

High-energy probes

Di-boson, di-fermion,
tri-boson, EFT,
compositeness, …

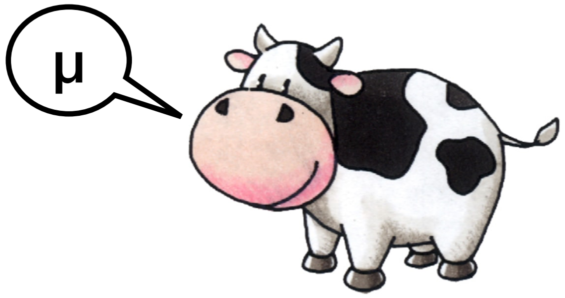
Muon physics

Lepton Flavor
Universality, b → sμμ,
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
1901.06150
2003.13628
2005.10289
2006.16277
2007.14300
2008.12204
2009.11287
2012.02769
2012.11555
2101.10334
2102.08386
2102.11292
2103.01617
2103.14043
2104.05720
2107.09688
etc …



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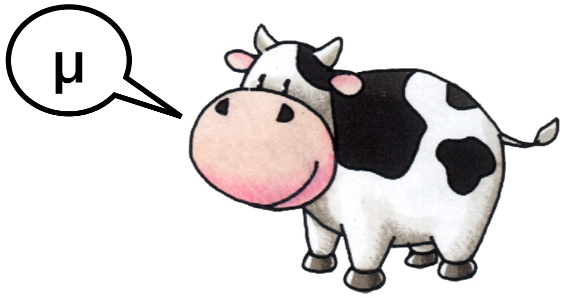
$$\mathscr{L}_{\text{int}} = 10\,\text{ab}^{-1} \times \left(\frac{E_{\text{cm}}}{10\,\text{TeV}}\right)^2$$

needed to be able to perform measurements with ~ % precision

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

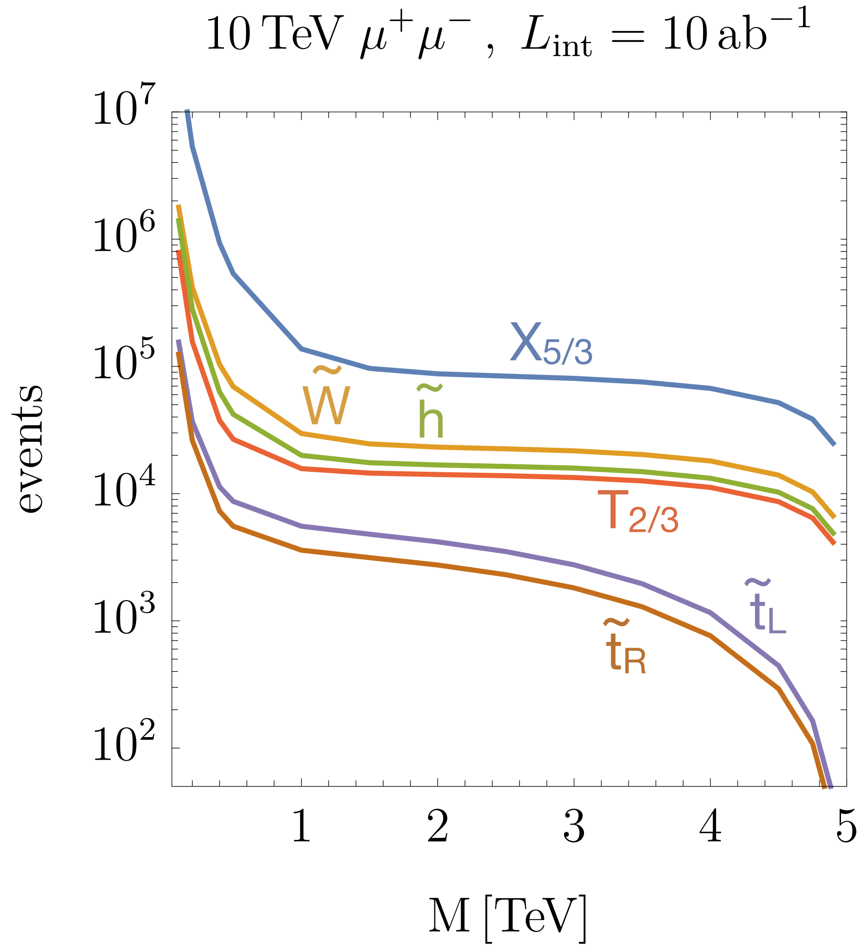


Synergy between physics, detector, and accelerator communities particularly important!

Direct searches

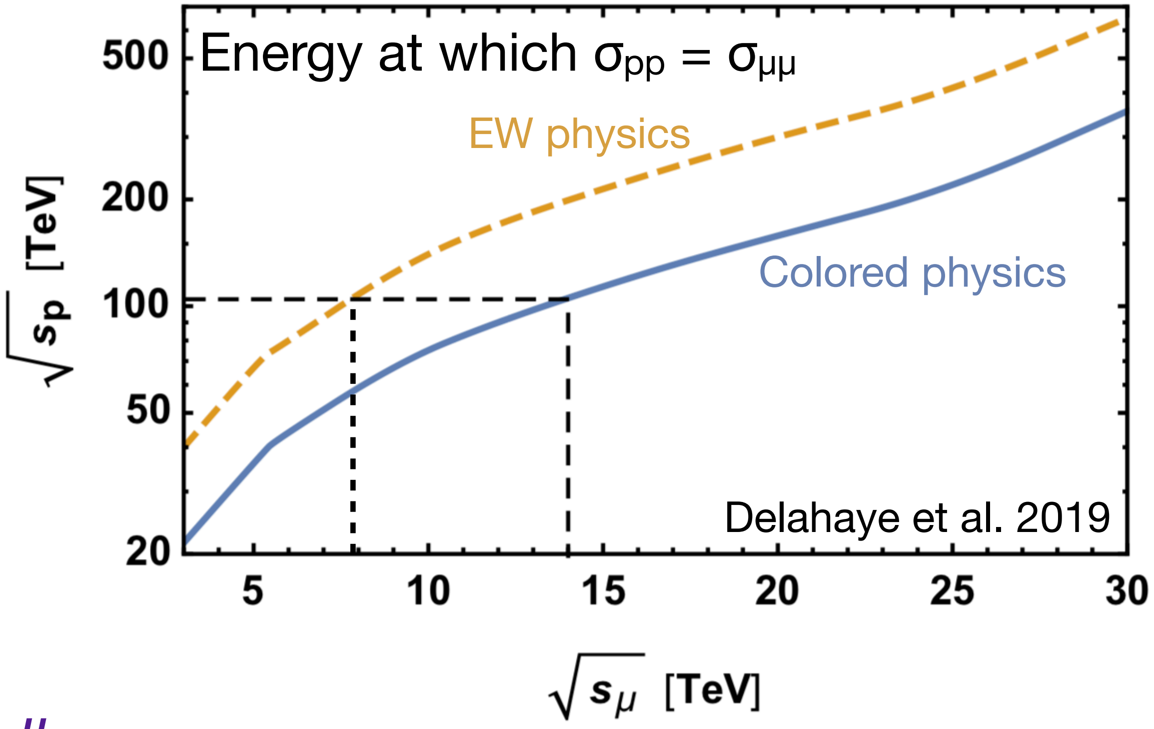
- The most striking advantage of a muon collider is the ability to collide elementary particles at very high center-of-mass energies
$\Longrightarrow$ **directly explore physics at 10+ TeV**

- 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

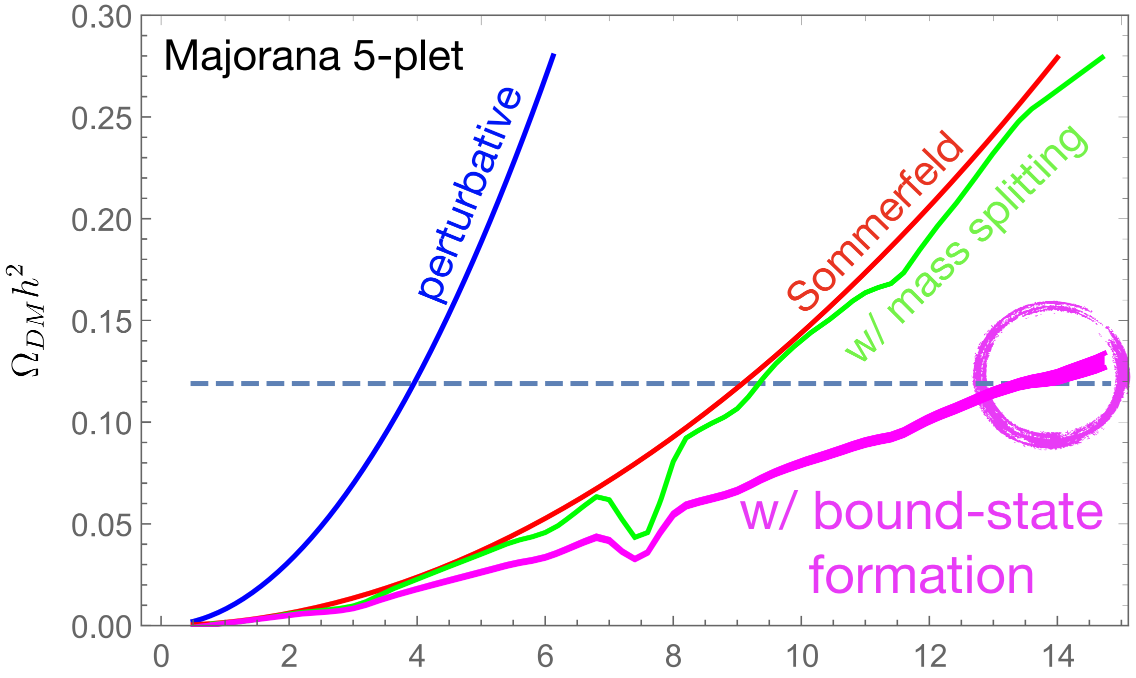


SUSY @μ-collider ☛ *see Nathaniel's talk*

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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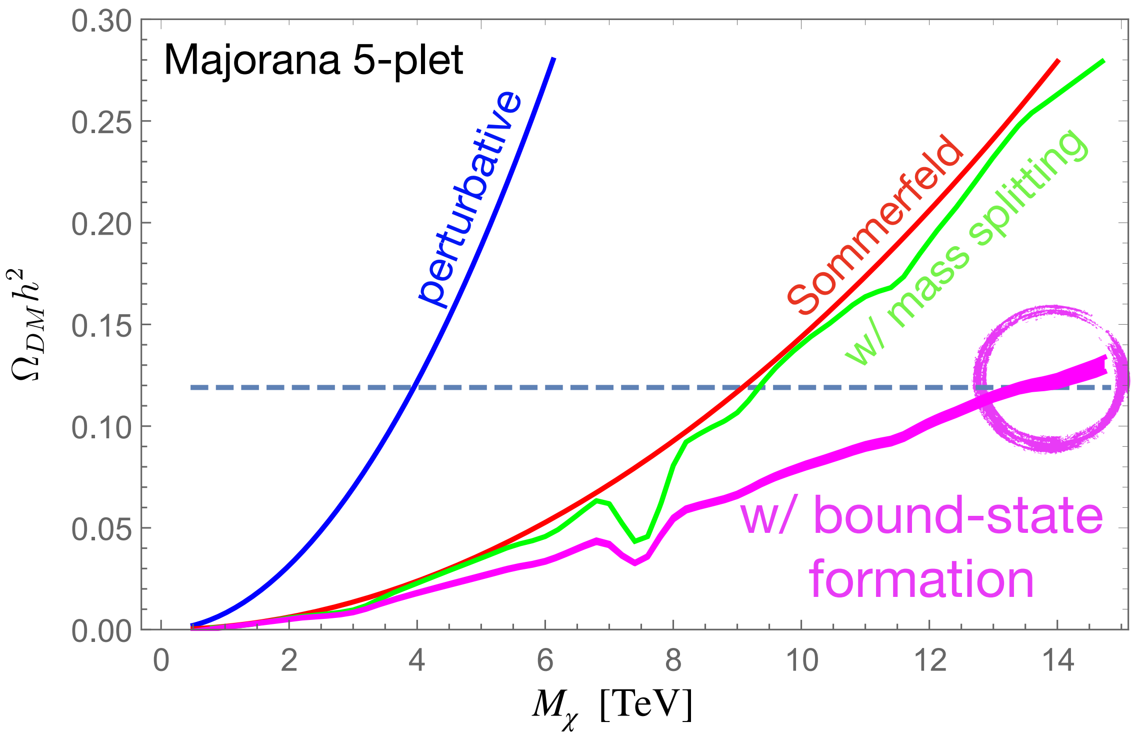
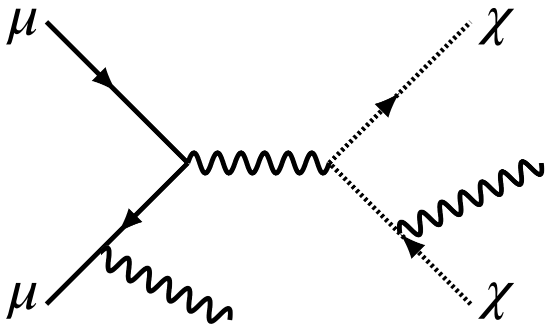


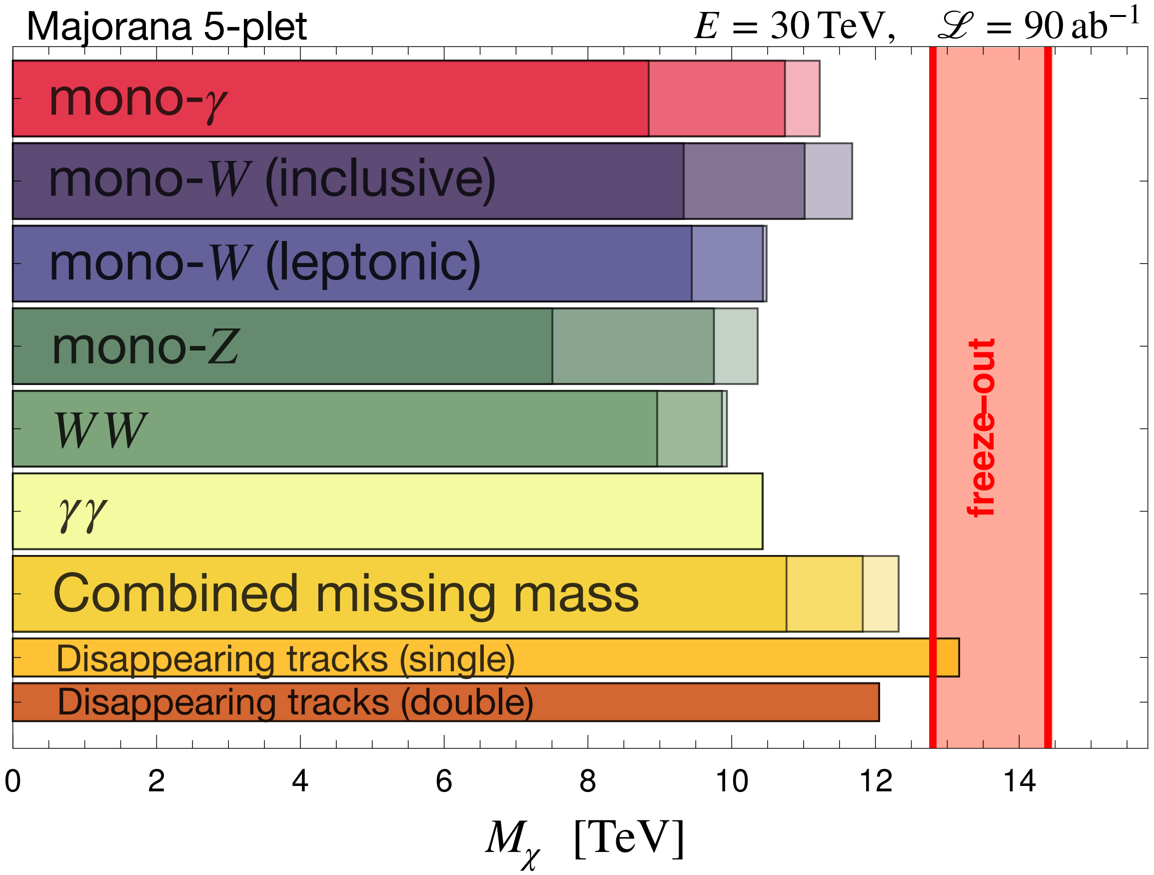
- ✦ **Mass can be large:** Muon-collider-energies crucial to probe some candidates!
- ✦ **Collider searches:** mono-γ/W/Z signals

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

Han et al. 2009.11287

S. Bottaro, M. Costa, L. Vittorio,
B, Franceschini, Panci, Redigolo 2107.09688





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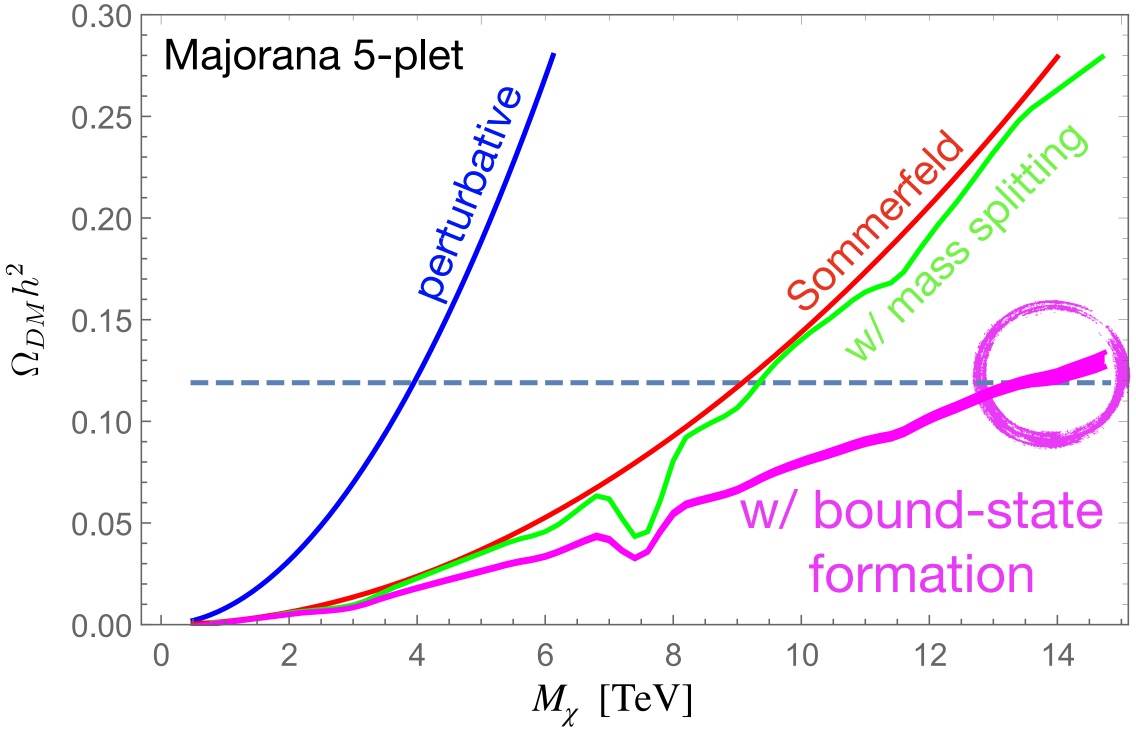

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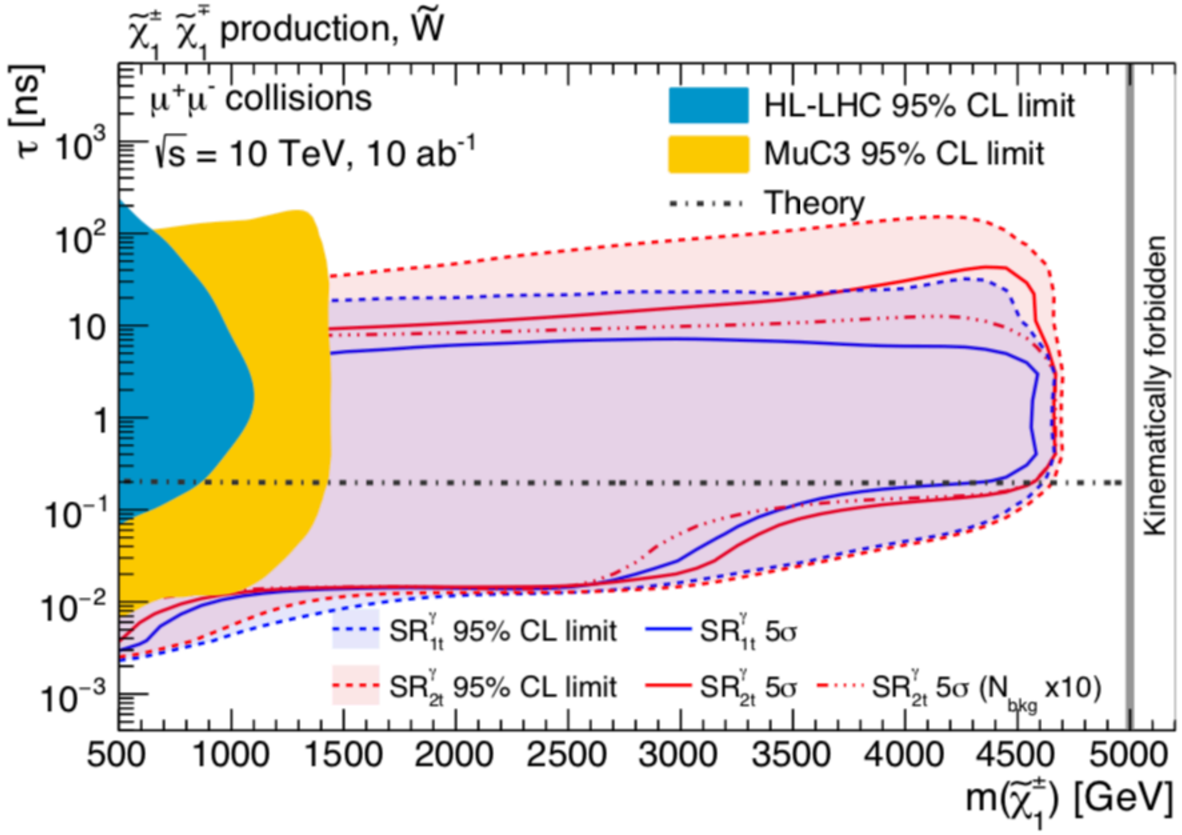
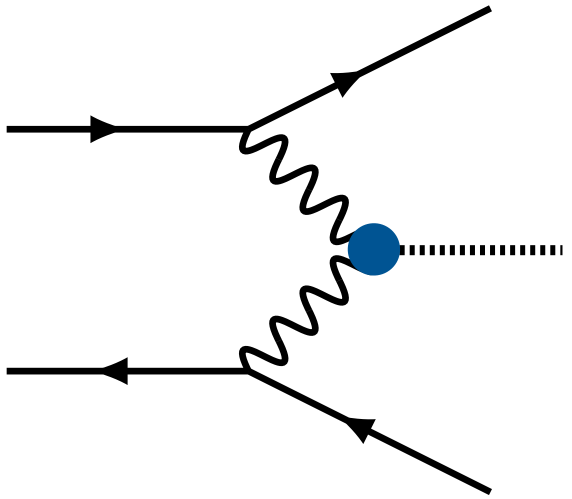
Charged components of multiplet are long-lived, can decay inside detector: disappearing tracks

Capdevilla et al. 2102.11292

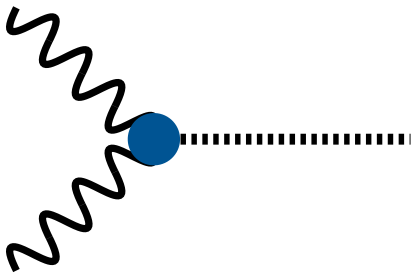


Resonances in VBF

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

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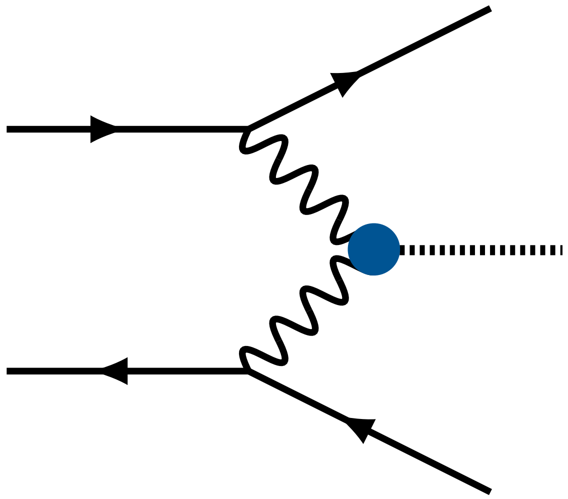

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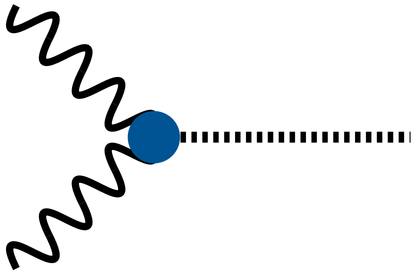

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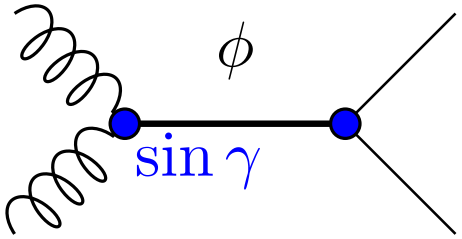
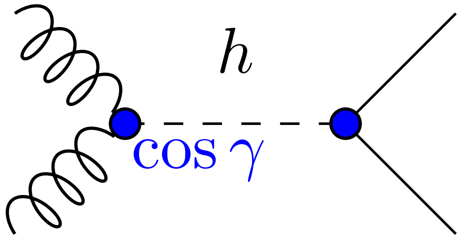
- Example: singlet scalar, $\mathscr{L}_{\rm int} \sim \phi |H|^2$ $\qquad \ell^+\ell^- \to \phi\nu\bar{\nu}$

  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

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

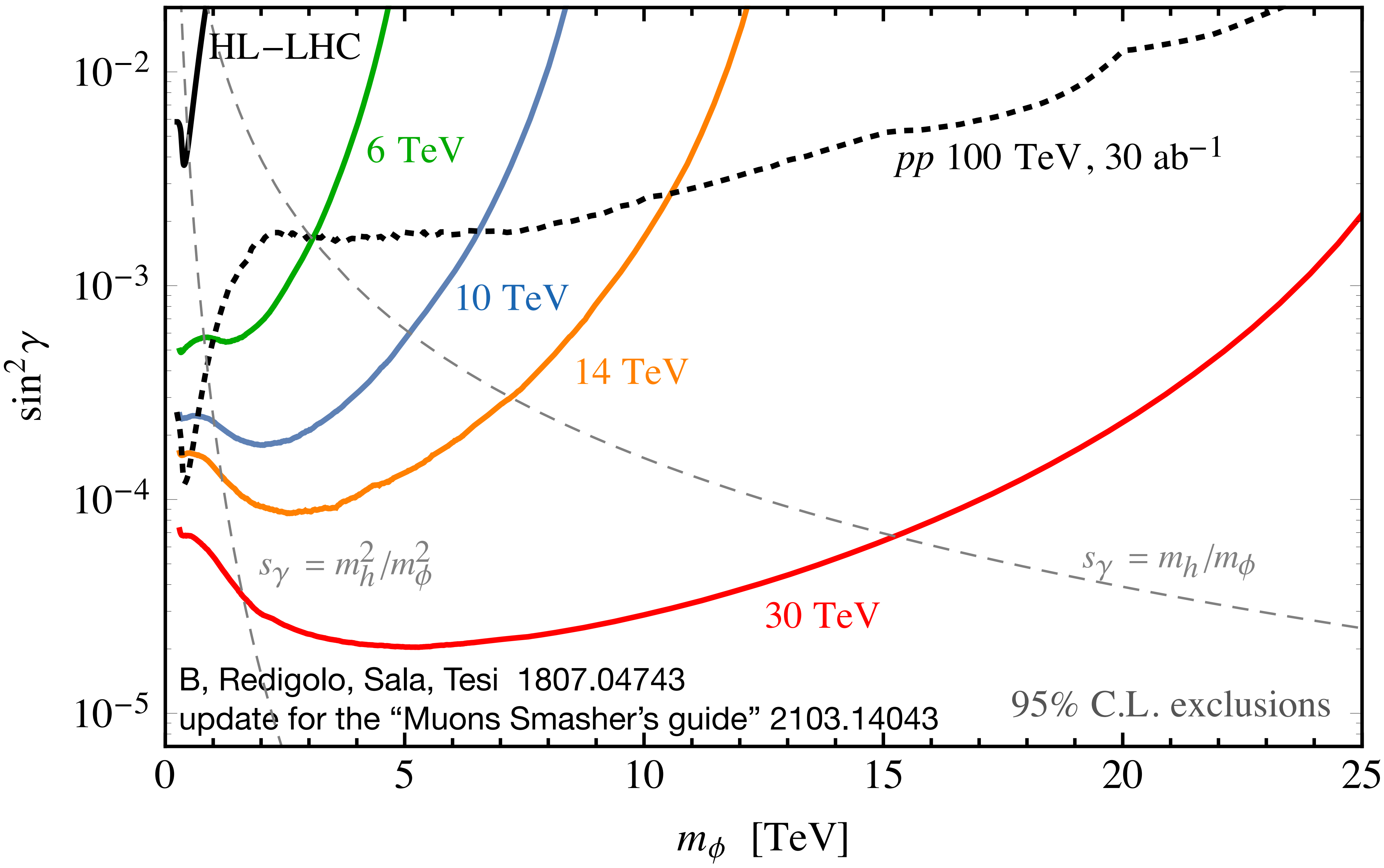


γ mixing angle between SM Higgs *h* and singlet ϕ

Example: scalar singlet

Compare direct and indirect reach of different colliders

$$\sin^2\gamma \approx \Delta\mu_h/\mu_h^{\mathrm{SM}} \approx \sigma_{VV\to\phi}/\sigma_{VV\to h}^{\mathrm{SM}}$$



B, Redigolo, Sala, Tesi 1807.04743
update for the “Muons Smasher’s guide” 2103.14043

For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

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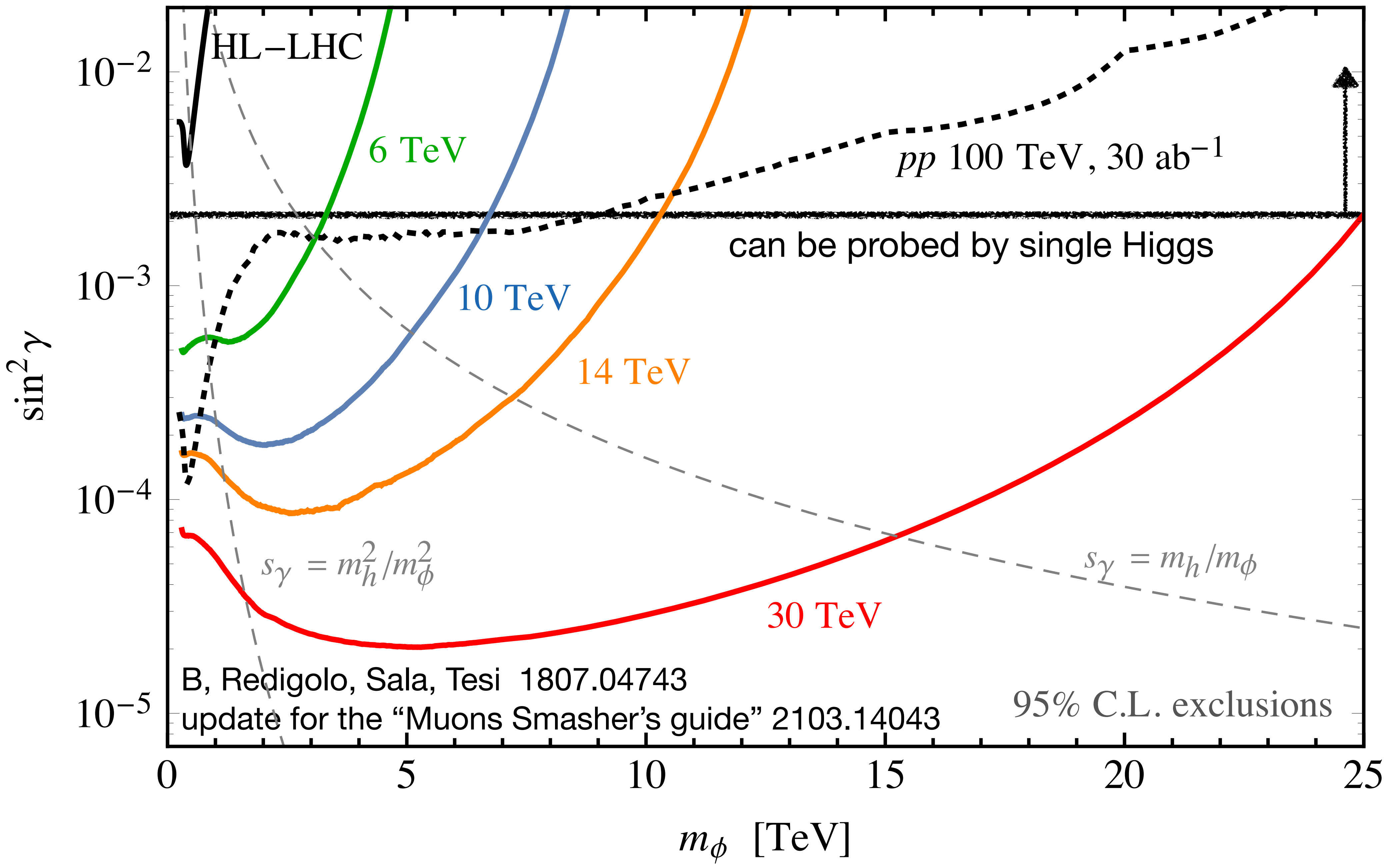

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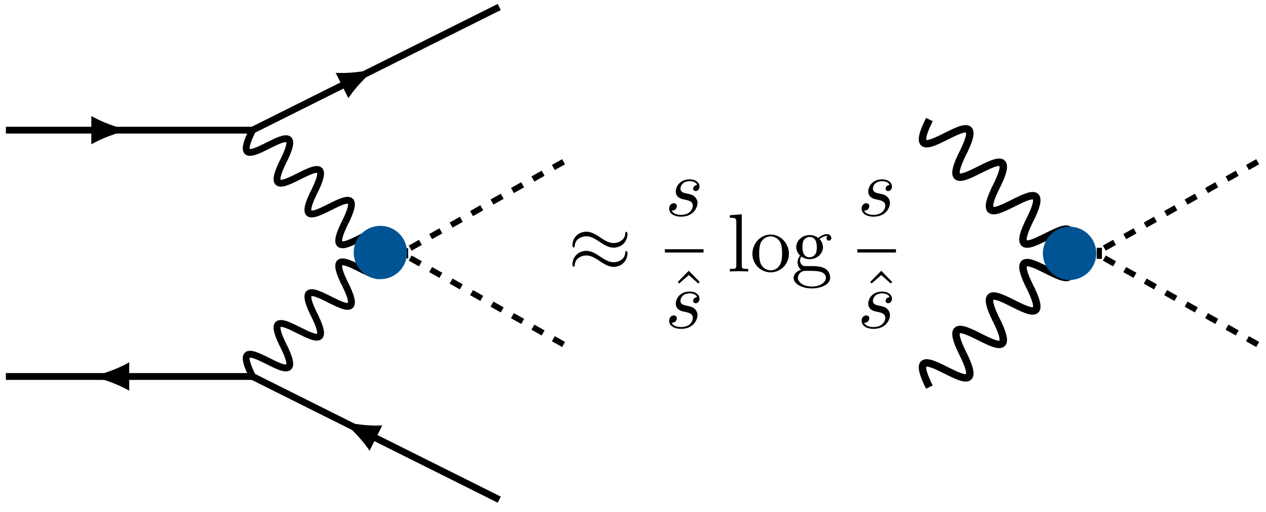
High rate probes: Higgs physics



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

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

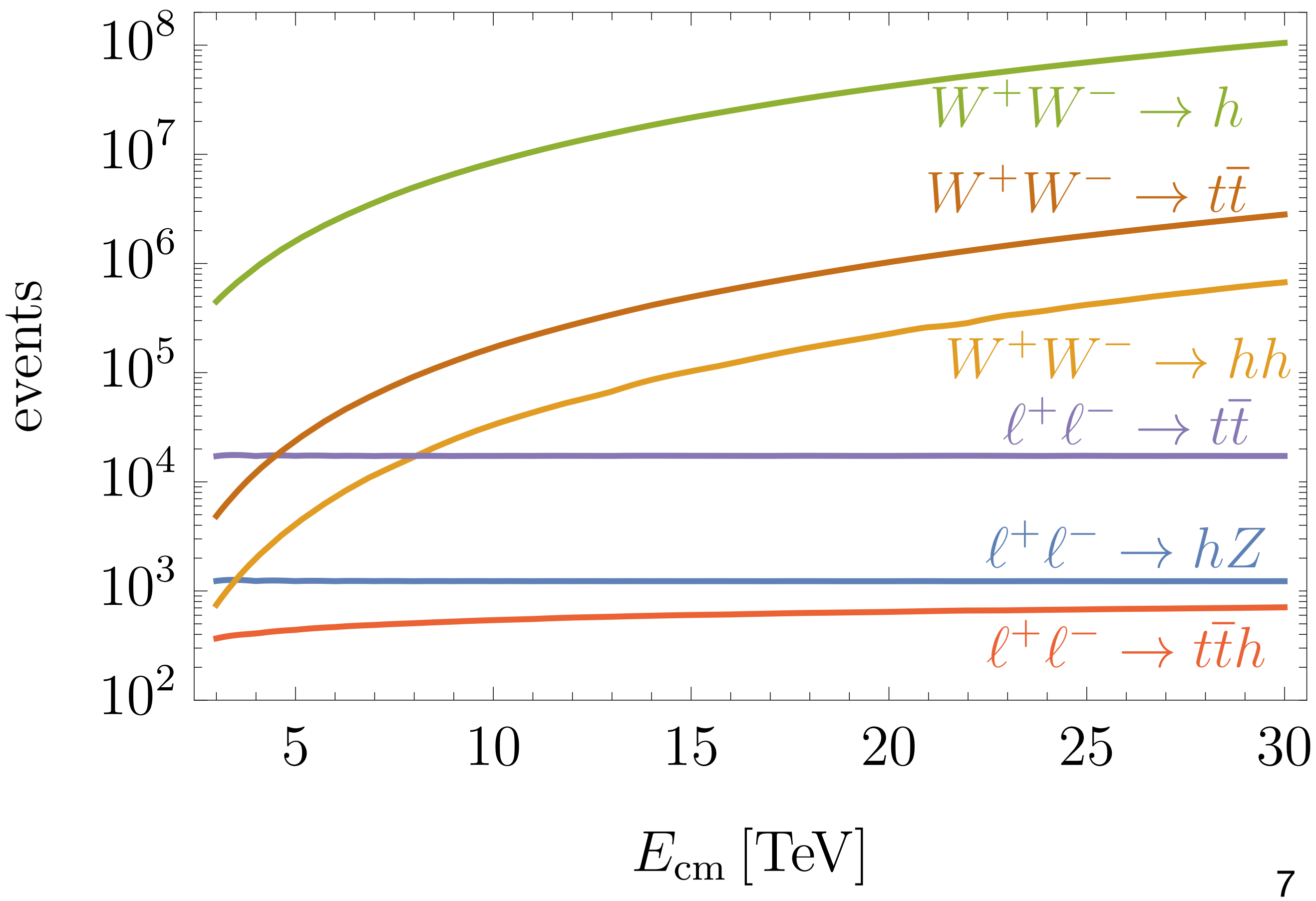
Costantini et al. 2005.10289

Al Ali, Arkani-Hamed et al. 2103.14043

- ✦ 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
  - Opportunity for Rare Higgs decays!
- ✦ Large double Higgs VBF rate
  - Higgs 3-linear coupling
- ✦ Triple Higgs production accessible
  - Higgs 4-linear coupling (dim. 8)

Chiesa et al. 2003.13628

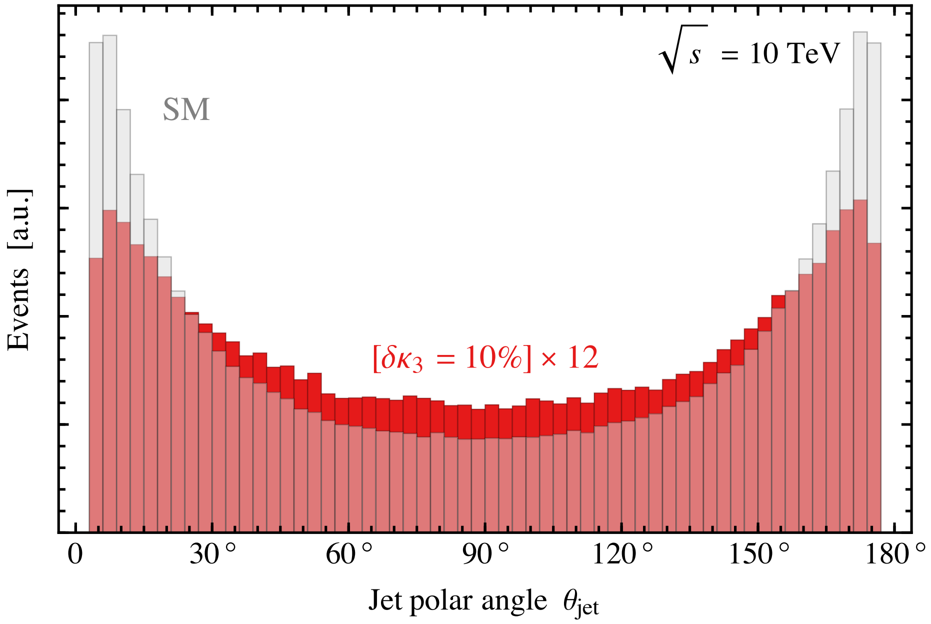


Double Higgs production

- Reach on Higgs trilinear coupling: hh → 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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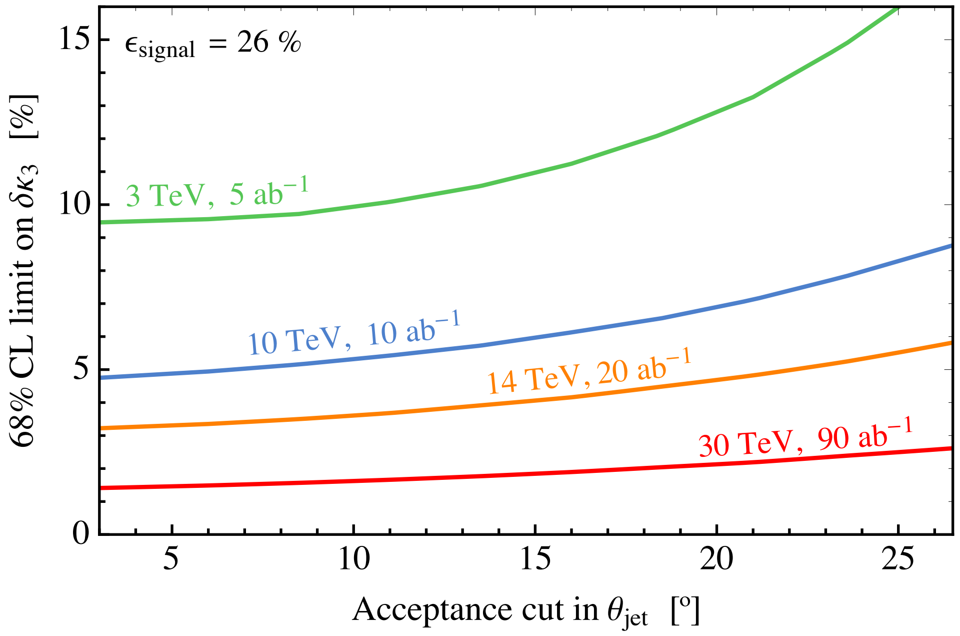

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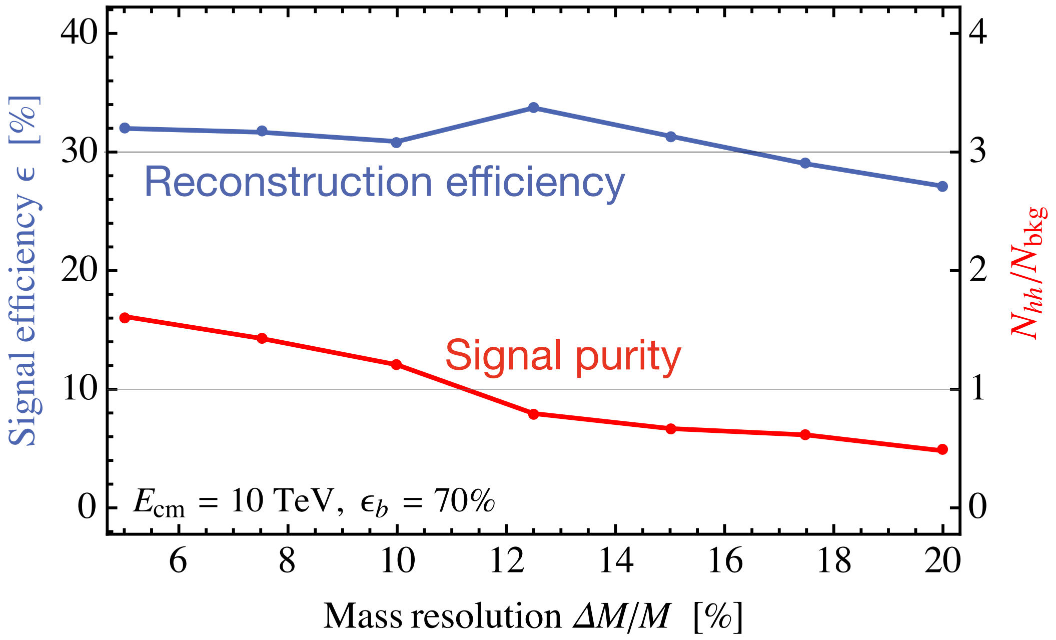

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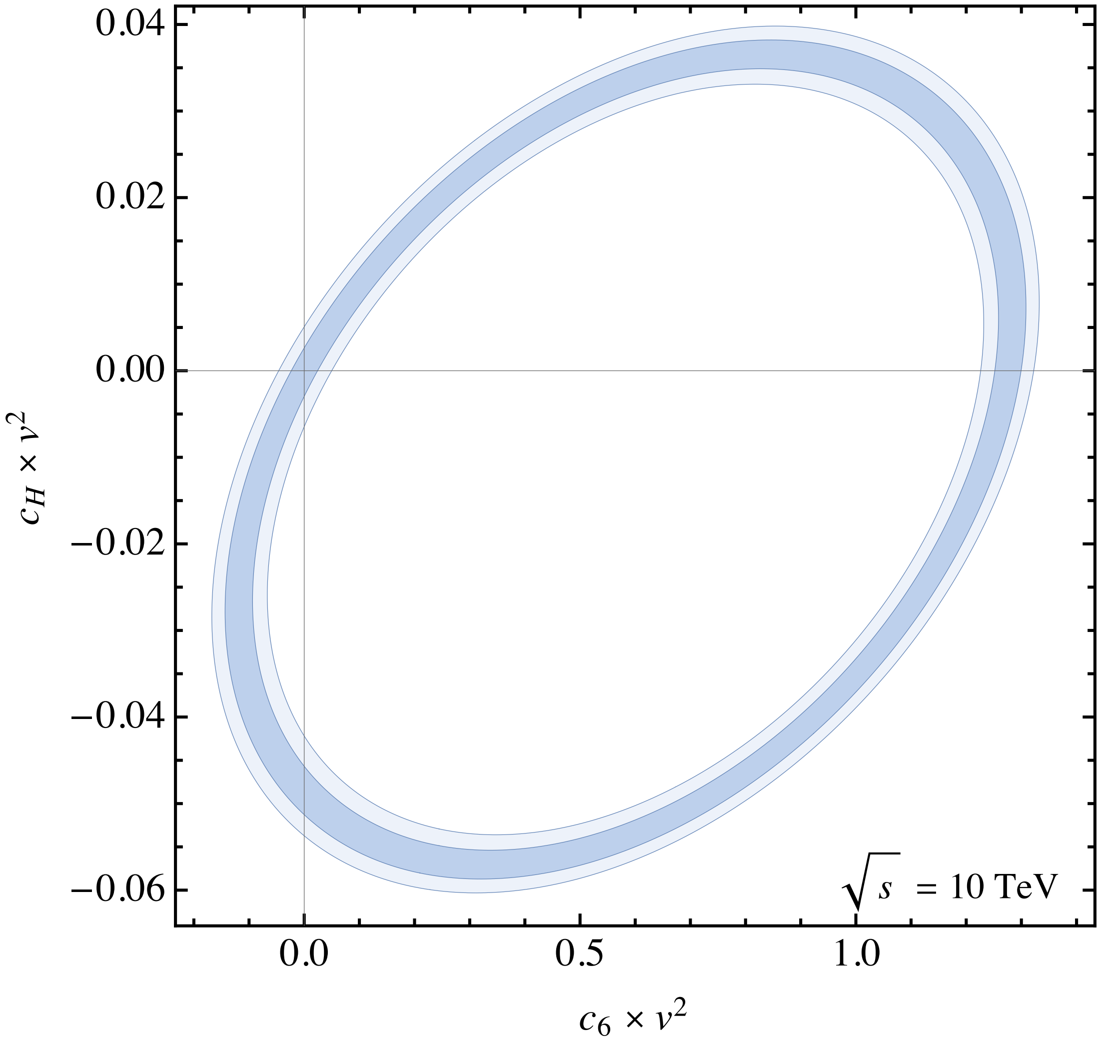
Double Higgs production

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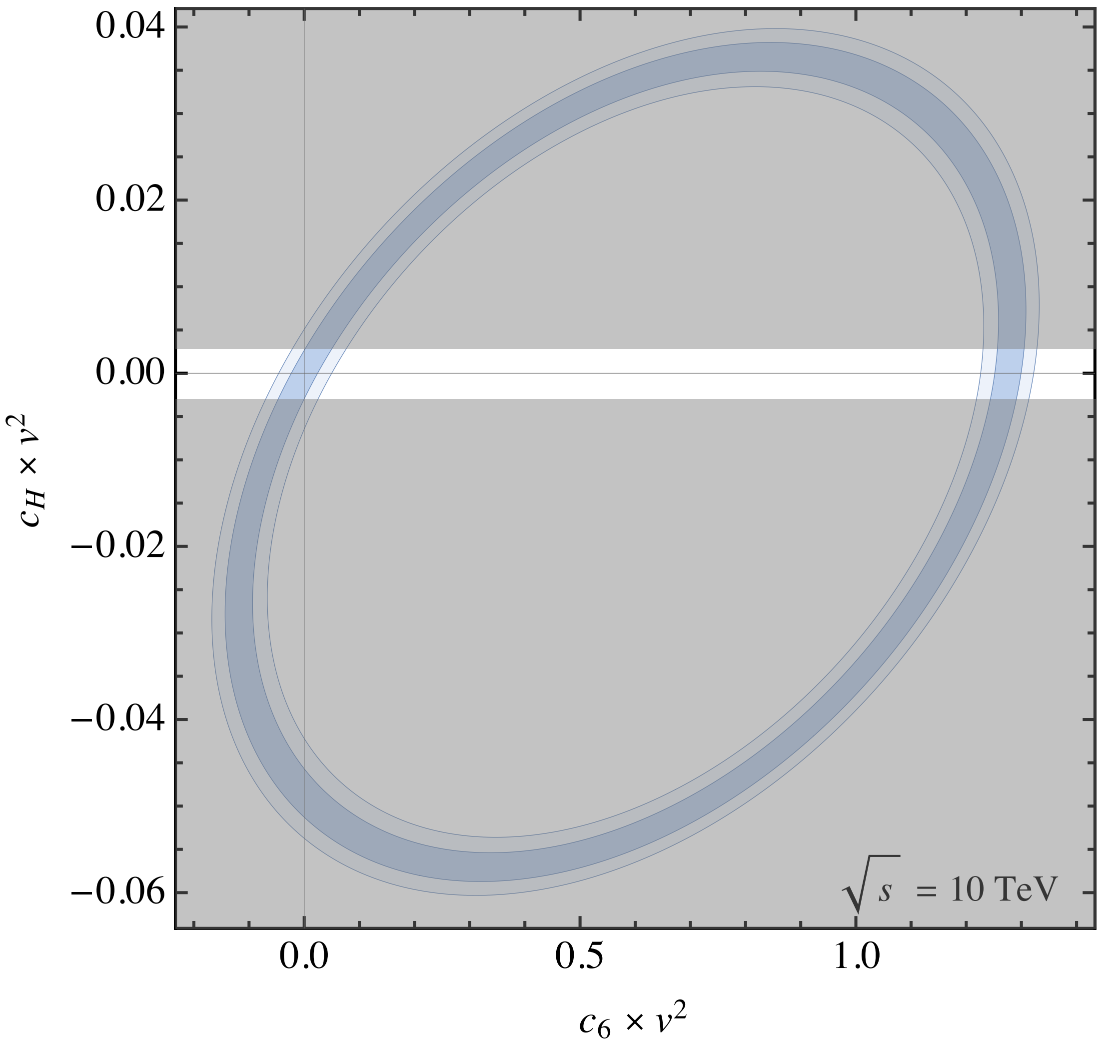

large degeneracy in total cross-section: coefficients not determined in general

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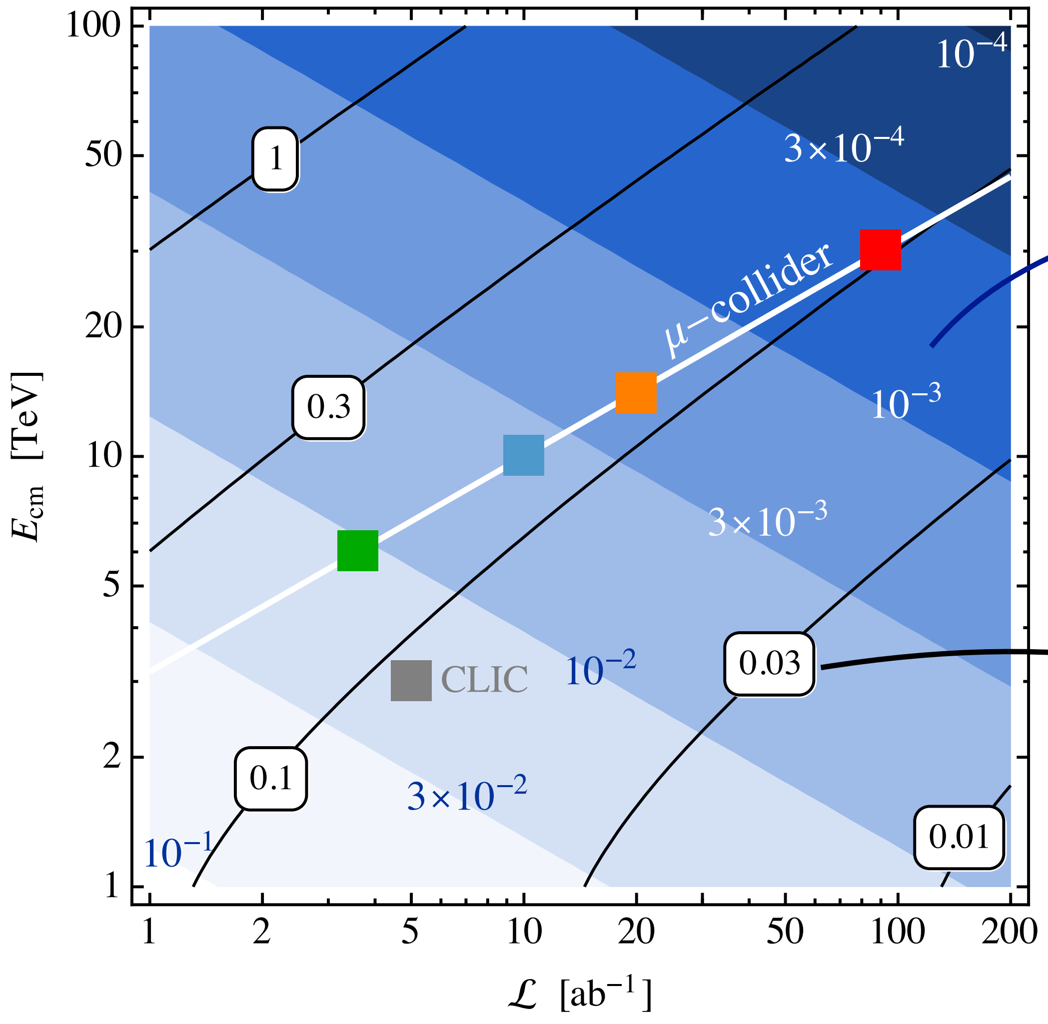
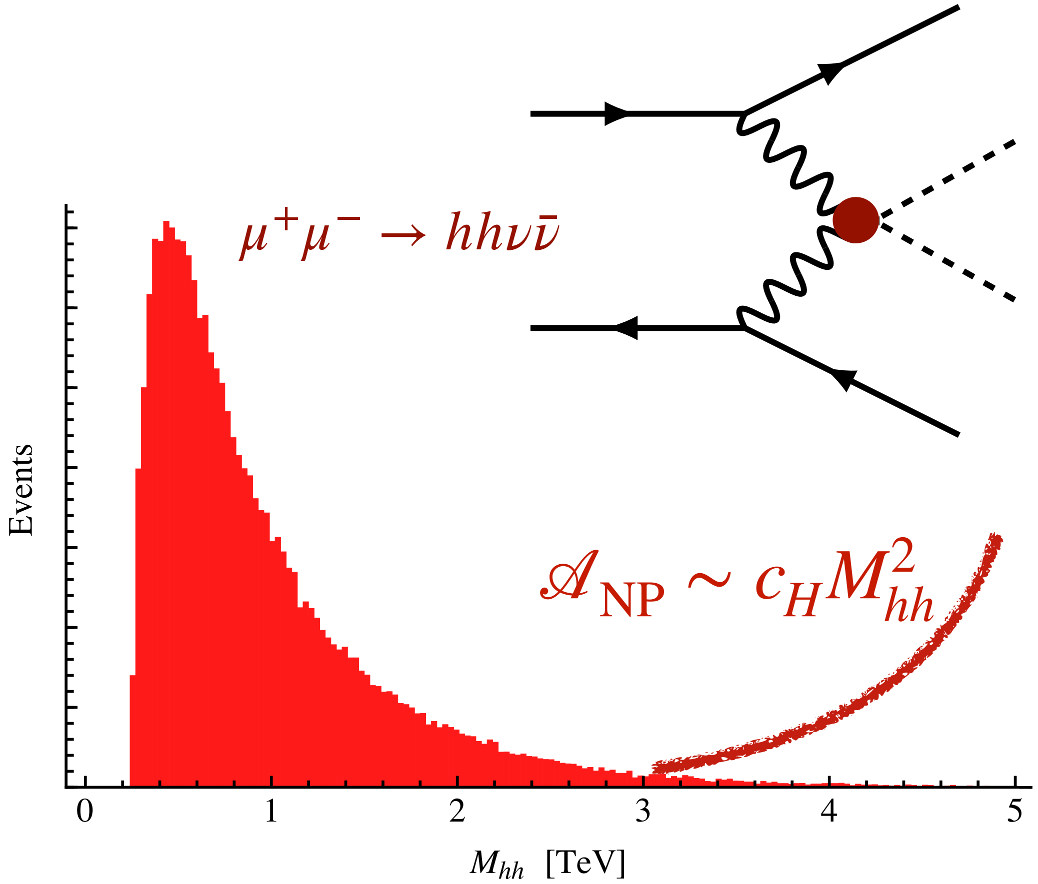
- O_H contribution grows as E^2: high mass tail gives a *direct* measurement of C_H (*WWhh* coupling)



$\xi \equiv C_H v^2$

S/B low-precision measurement



(see also Contino et al. 1309.7038)

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

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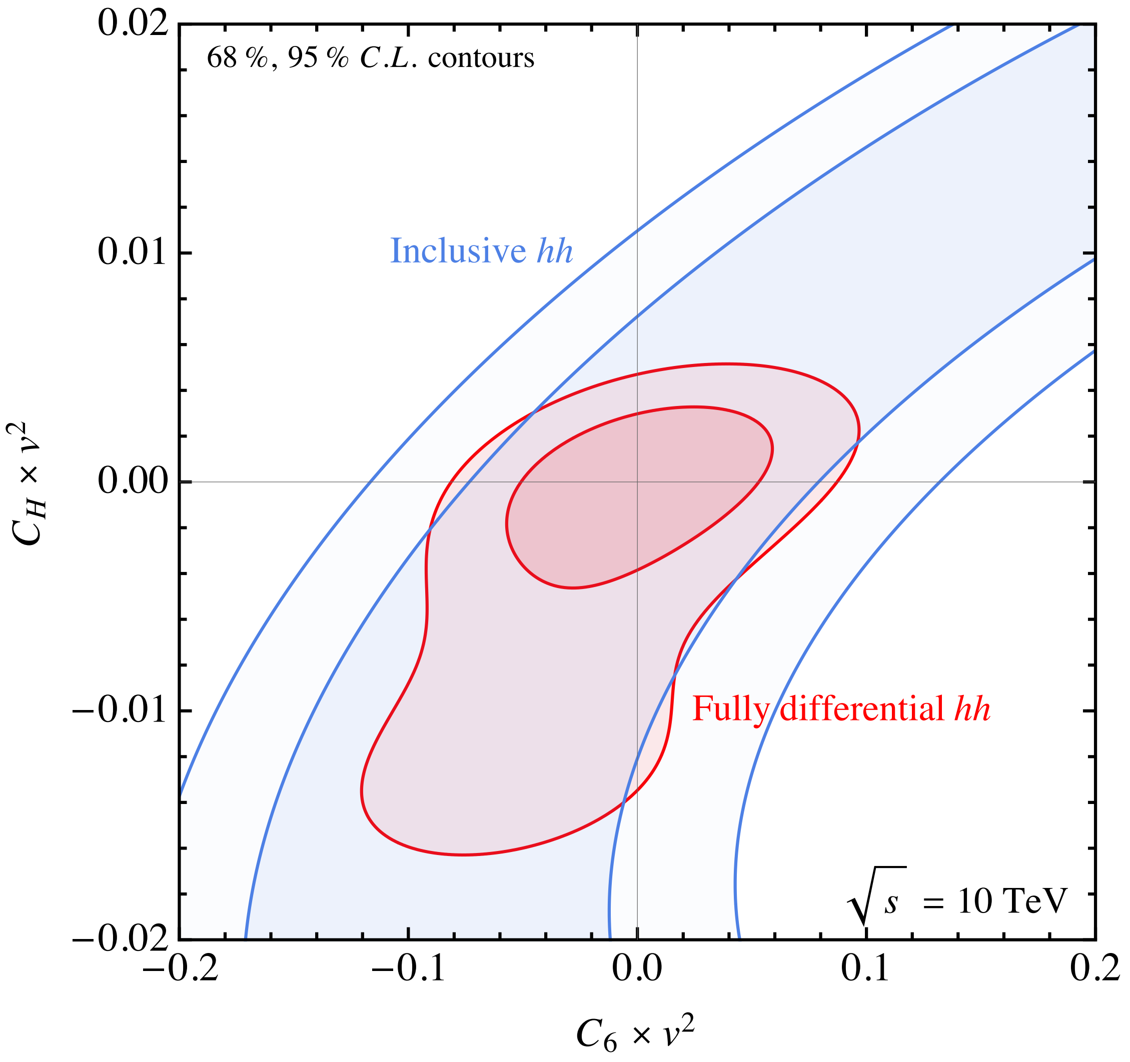
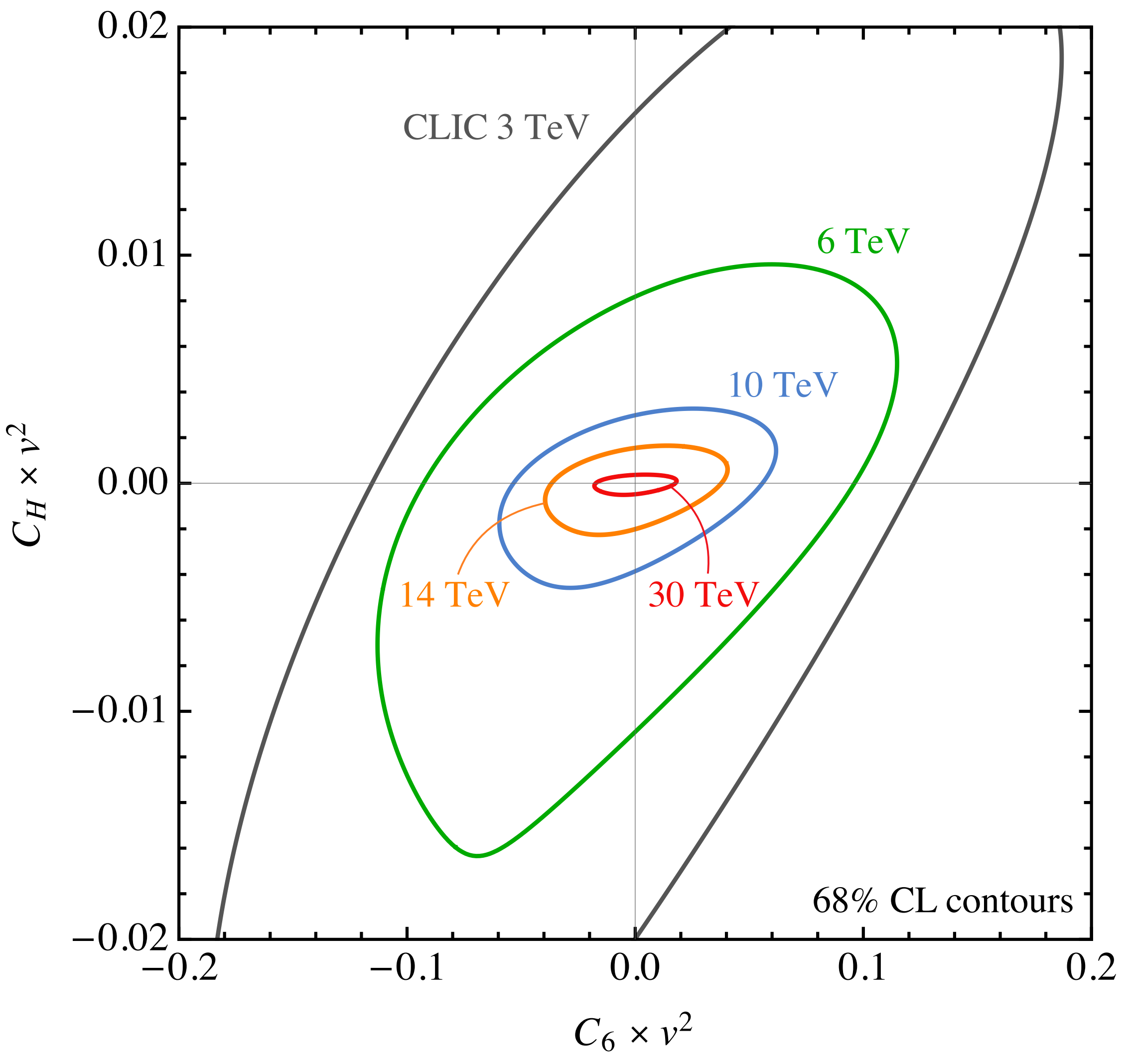
- Differential analysis in p_T and M_{hh} to optimize combined sensitivity to C_H and C_6

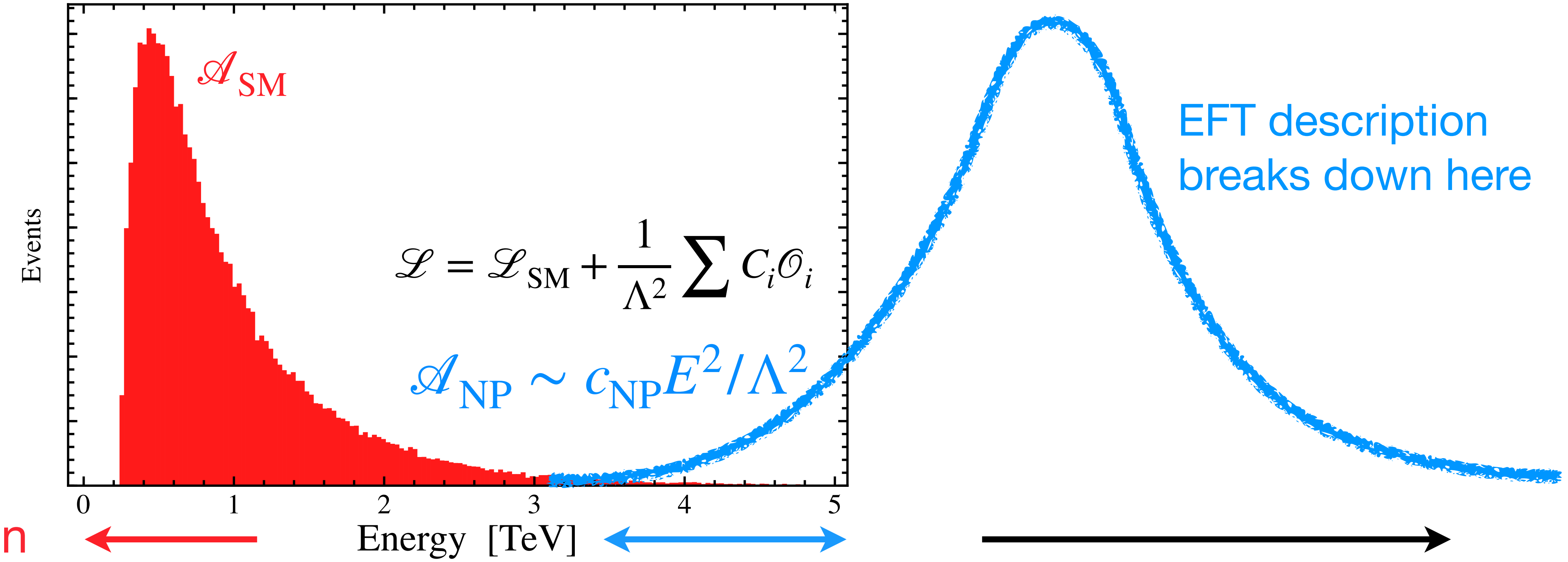
B, Franceschini, Wulzer 2012.11555





High-energy probes

- NP effects are more important at high energies



EFT description breaks down here

Precision SM measurements

High energy (indirect) probes

direct searches

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

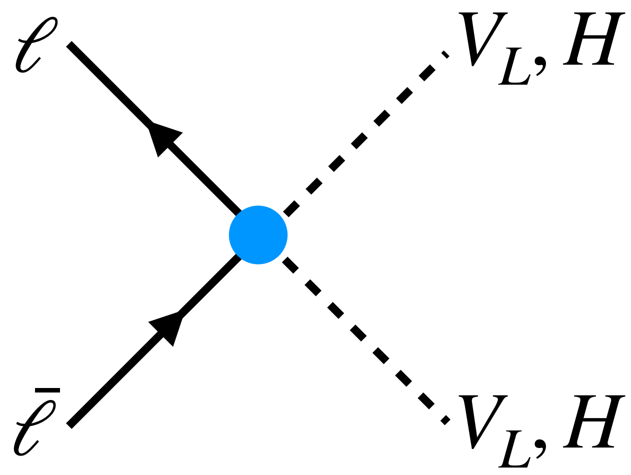
- Effective at LHC, FCC-hh, CLIC: “energy helps accuracy”…

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



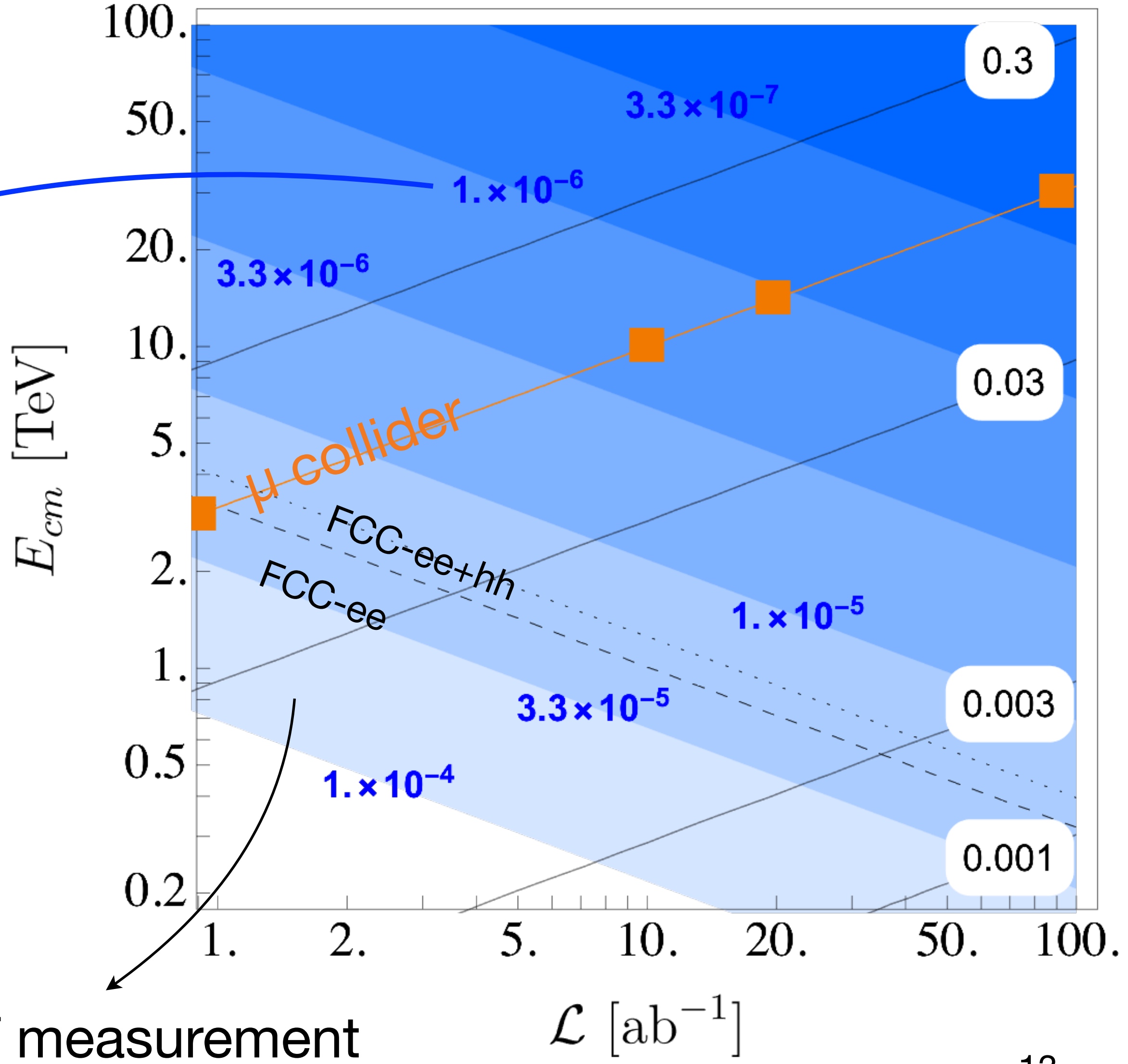
In flavor-universal theories, two dim-6 operators:

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

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

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

B, Franceschini, Wulzer 2012.11555



precision of measurement

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 di-bosons

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

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

☛ Limits on $C_{W,B}$ scale as E^2

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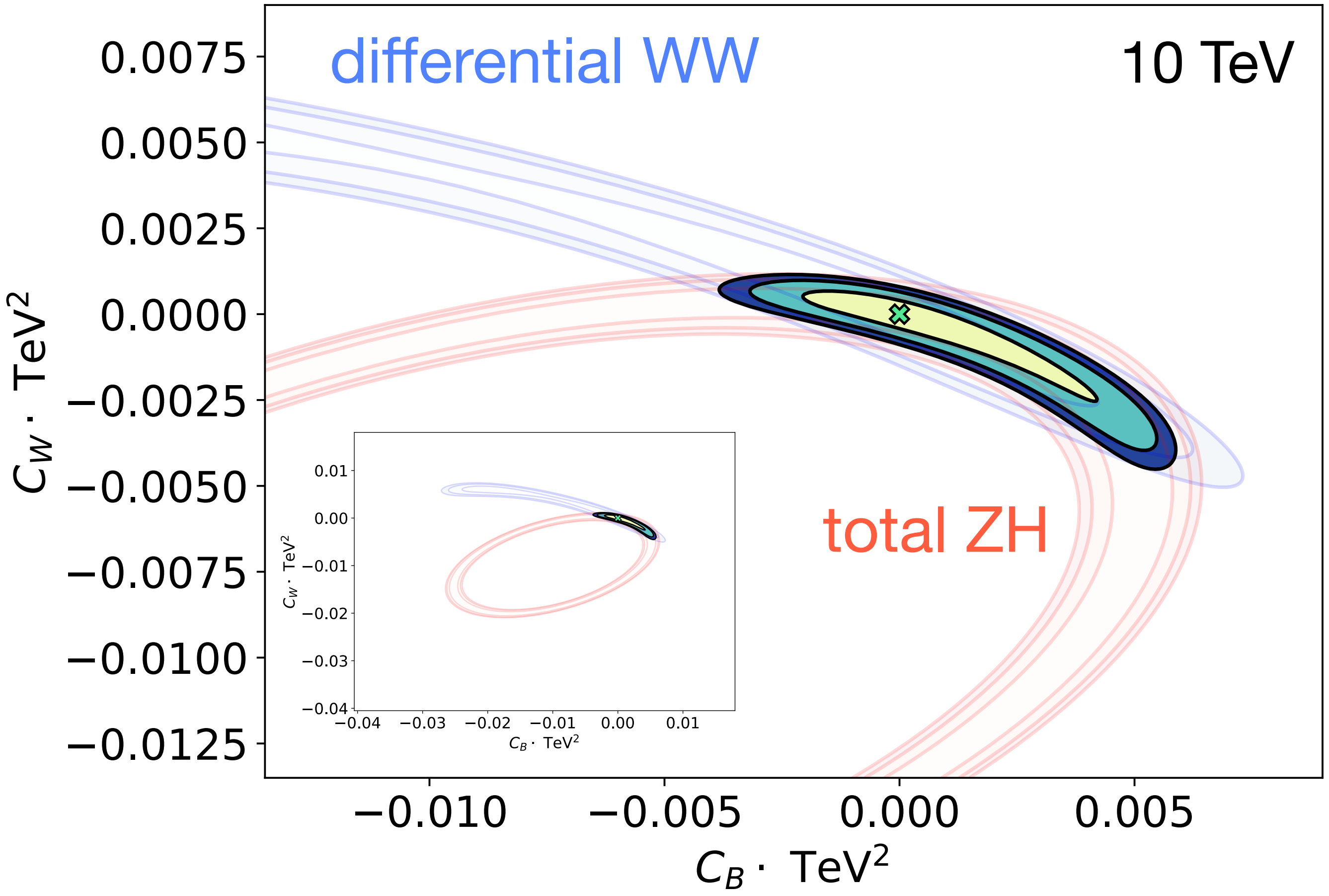

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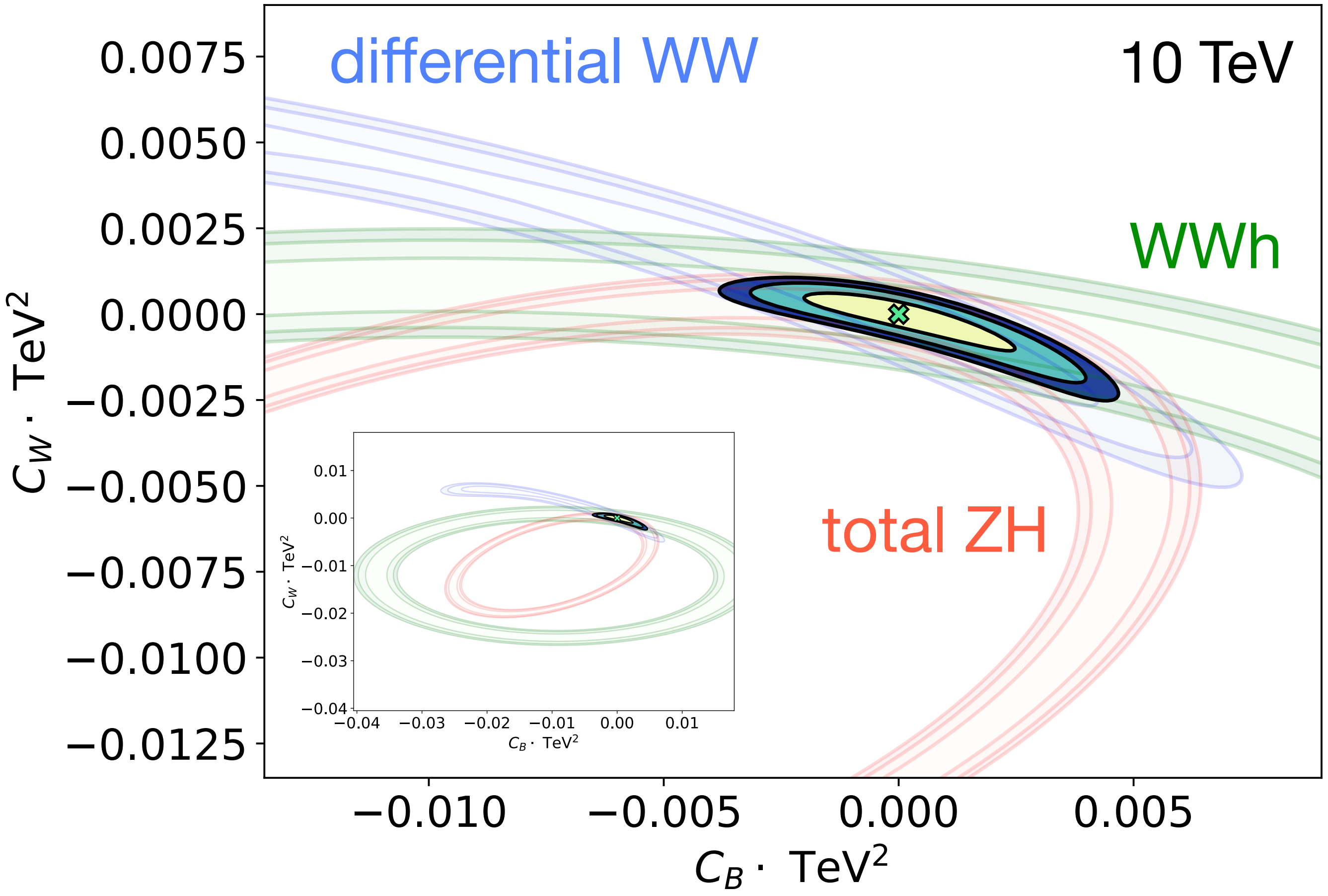
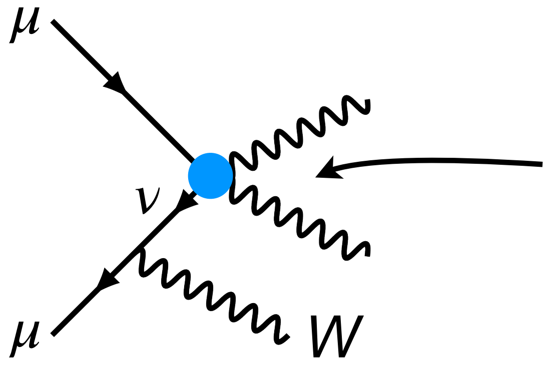
☛ Limits on $C_{W,B}$ scale as E^2

B, Franceschini, Wulzer 2012.11555



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



independent measurement of G_{3L}

“effective neutrino approximation”

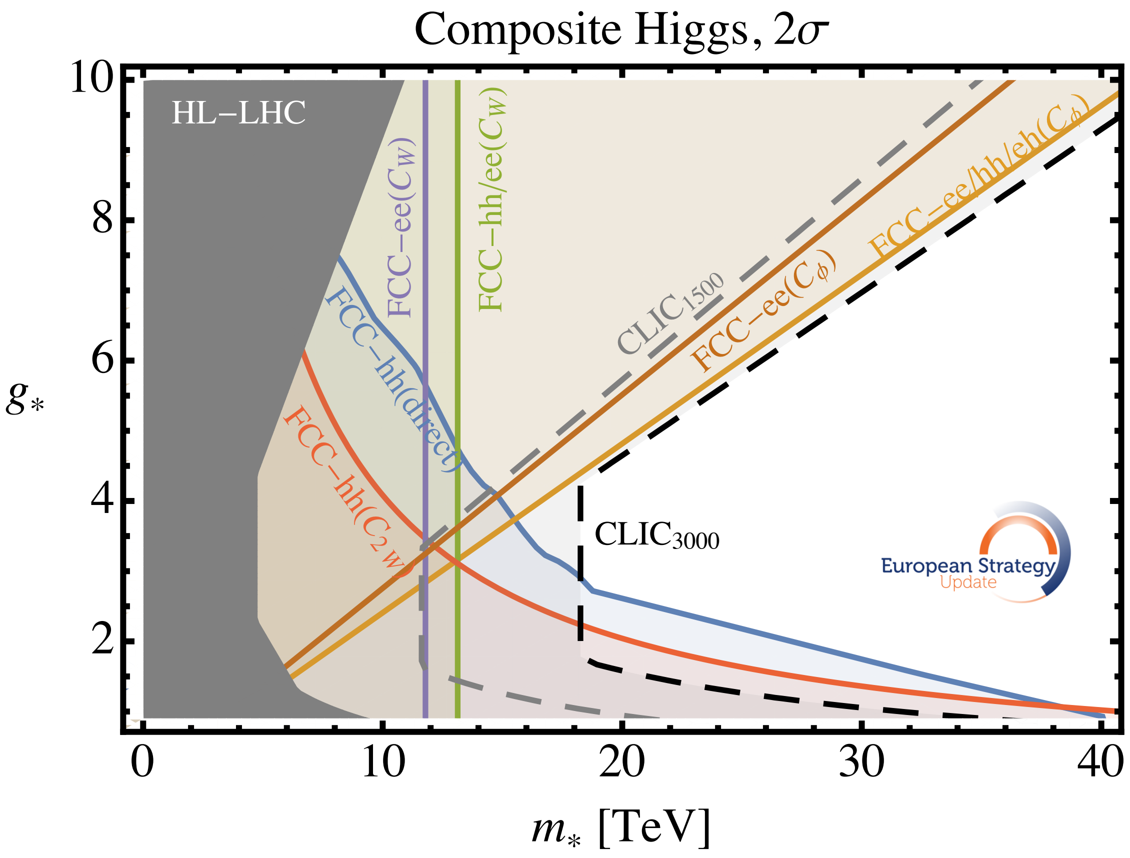
need to properly include higher-order effects inclusive observables, resummation, …

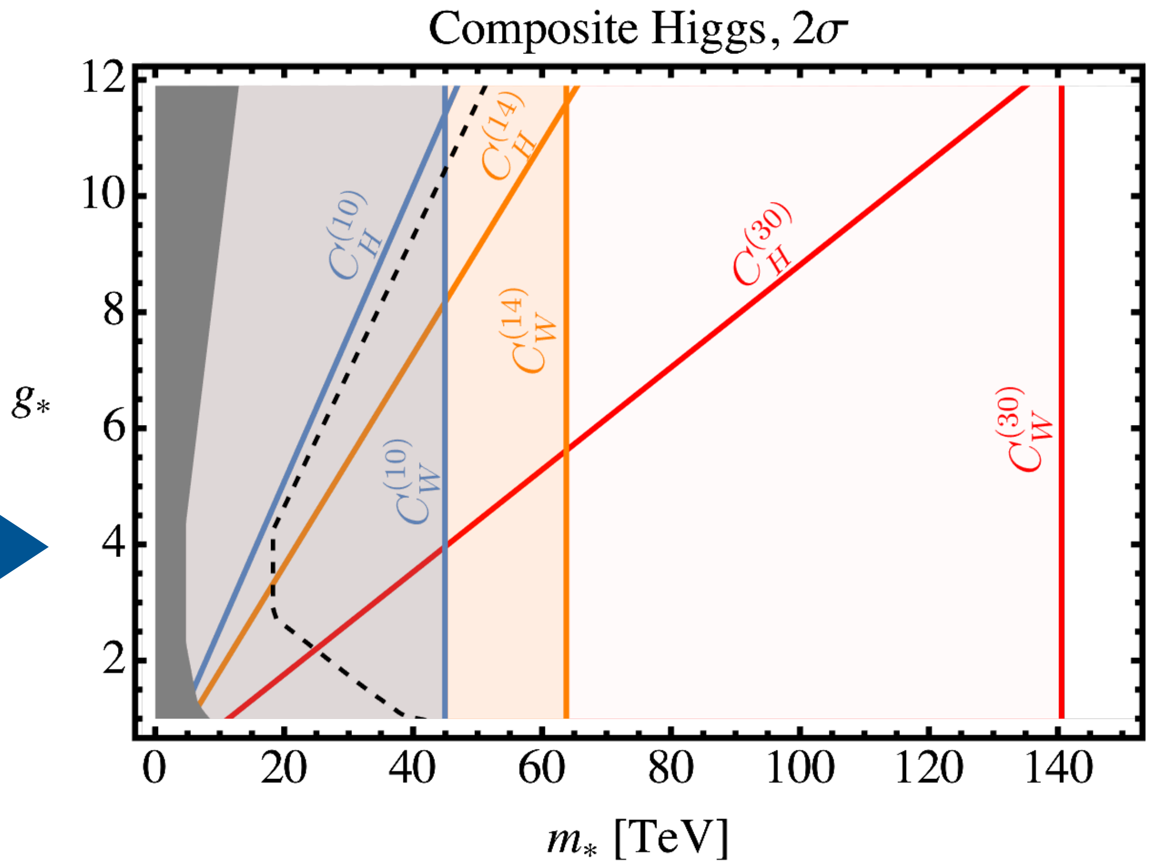
High-energy probes: EW & Higgs physics

- High-energy probes at a 10–30 TeV muon collider are able to test 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!*





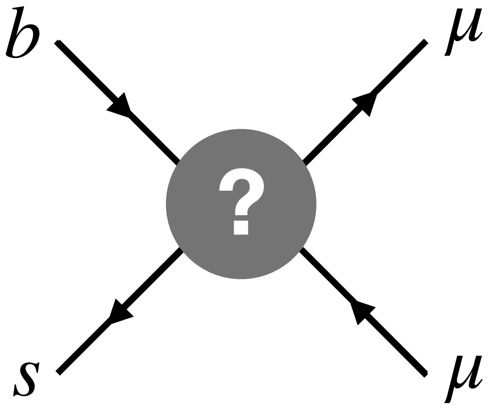
Non-universal physics: muons vs. electrons

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

- "Flavor anomalies" in $b \to s\mu\mu$ decays

  5.9 σ discrepancy combined (2103.13370)

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



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

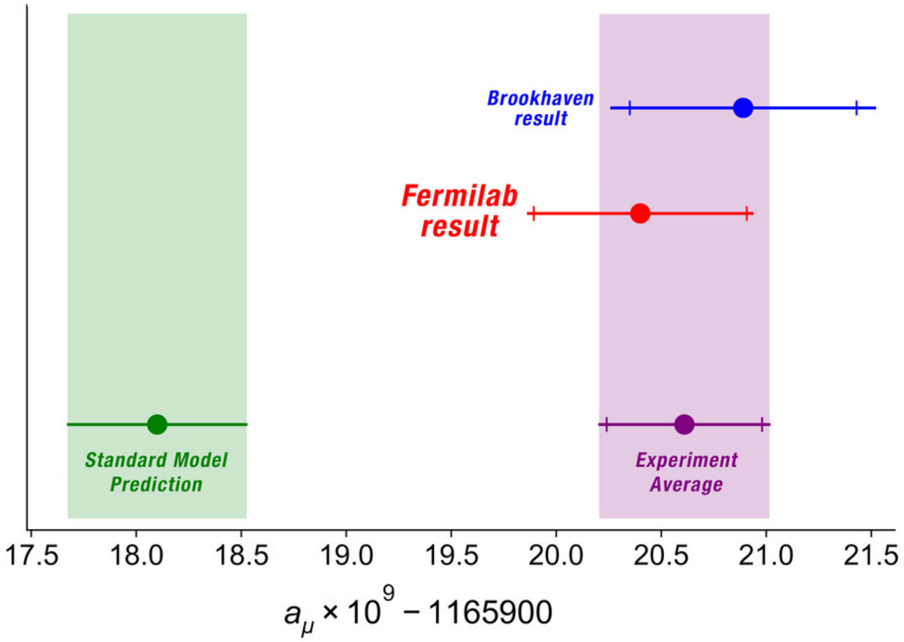
LHC will not be able to probe entire parameter space with high-pT searches!

Muon collider reach: Huang et al. 2103.01617, Asadi et al. 2104.05720

- 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



Theoretical (and systematic) errors need to be controlled at the level of $\Delta a_\mu \sim 10^{-9}$

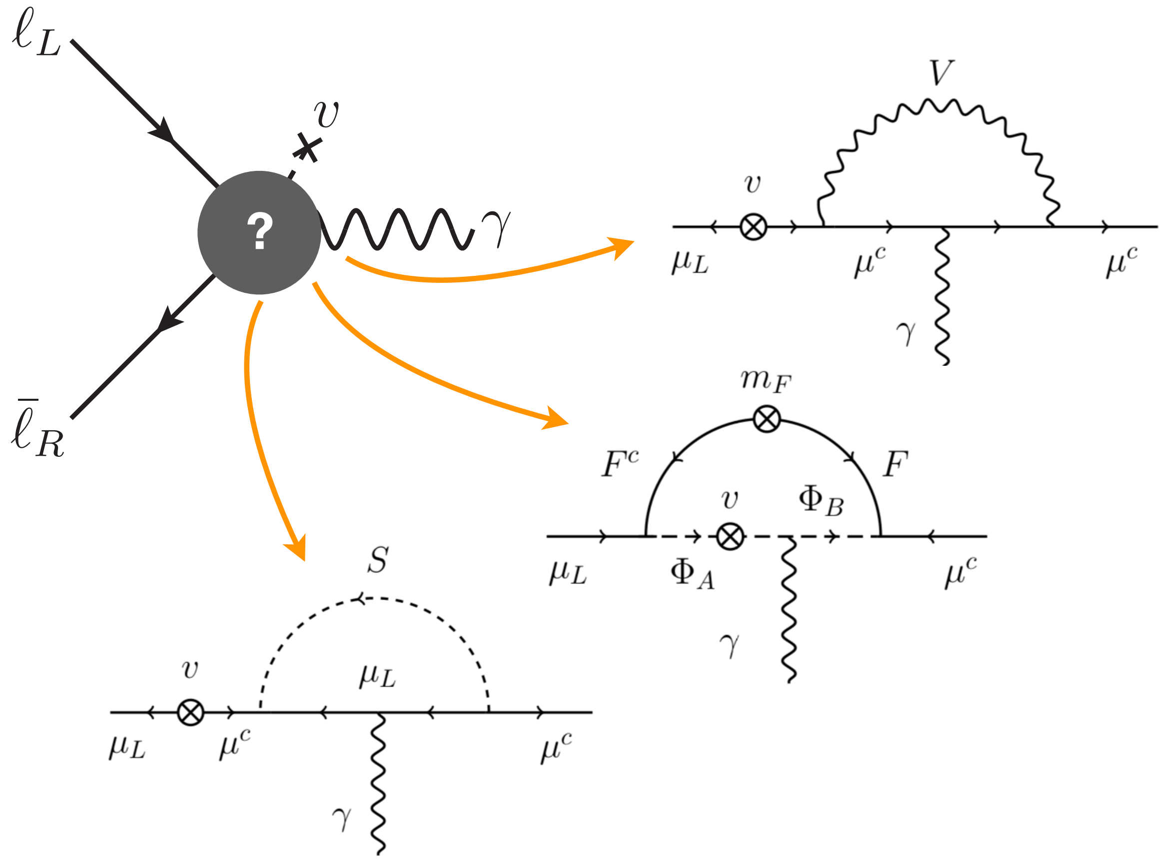
➡ Muon collider can provide a model-independent high-energy test of Δa_μ

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

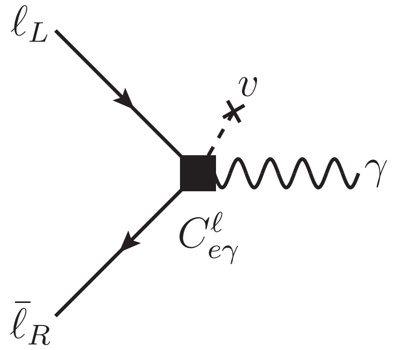
- If new physics is light enough (i.e. weakly coupled), a Muon Collider can directly produce the new particles ☛ direct searches: model-dependent

Capdevilla et al. 2006.16277

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

At low energy

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

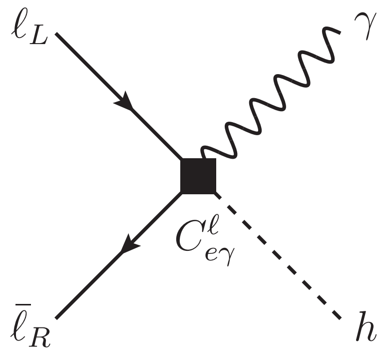


Dipole operator generates both Δa$_\mu$ and μμ → hγ

B, Paradisi 2012.02769

At high energy

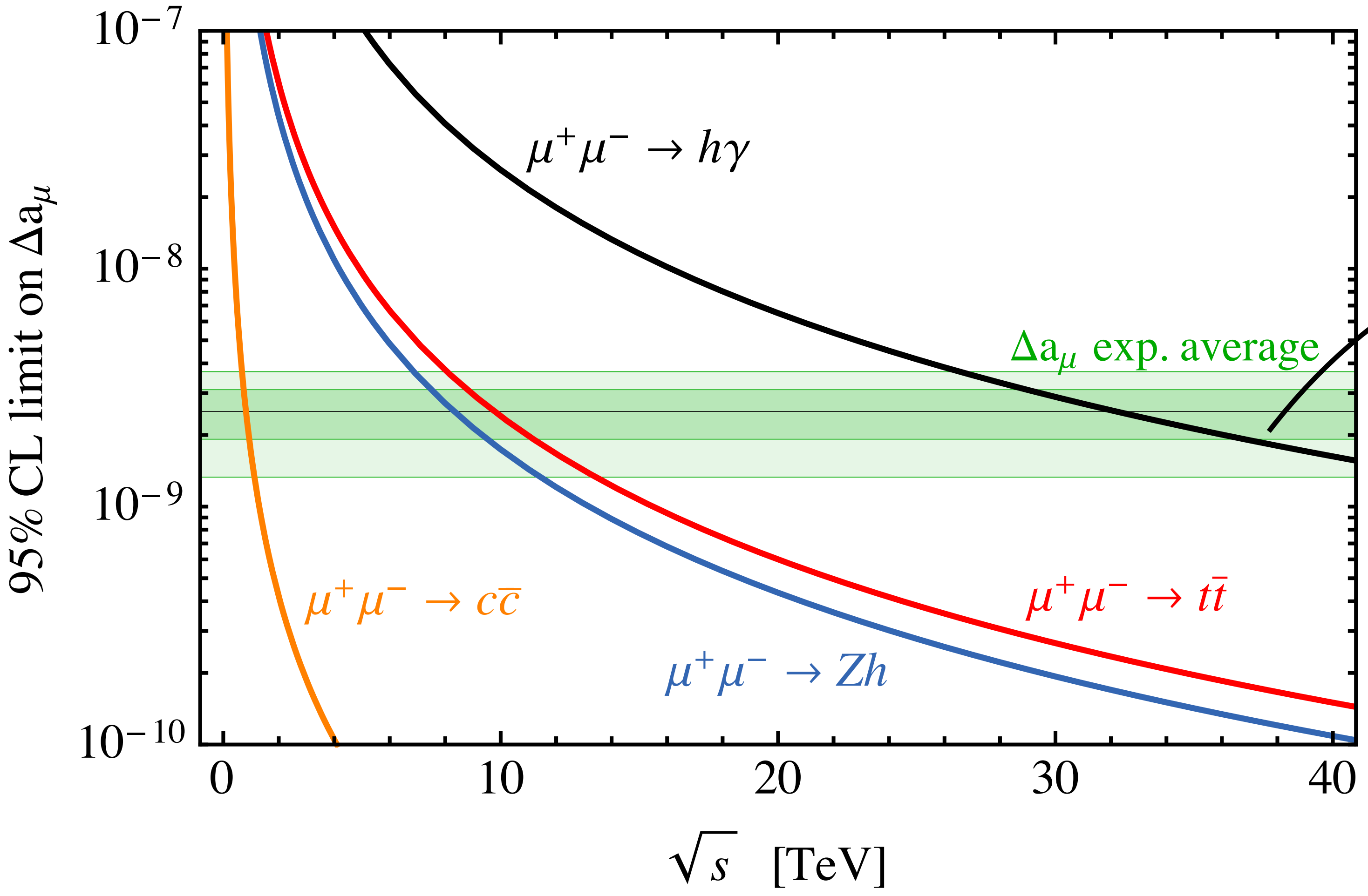
$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\mathrm{ab} \left(\frac{\sqrt{s}}{30\,\mathrm{TeV}} \right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}} \right)^2$$



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

need E > 10 TeV

Muon g-2 @ muon collider



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

(with reasonable assumptions on detector performance)

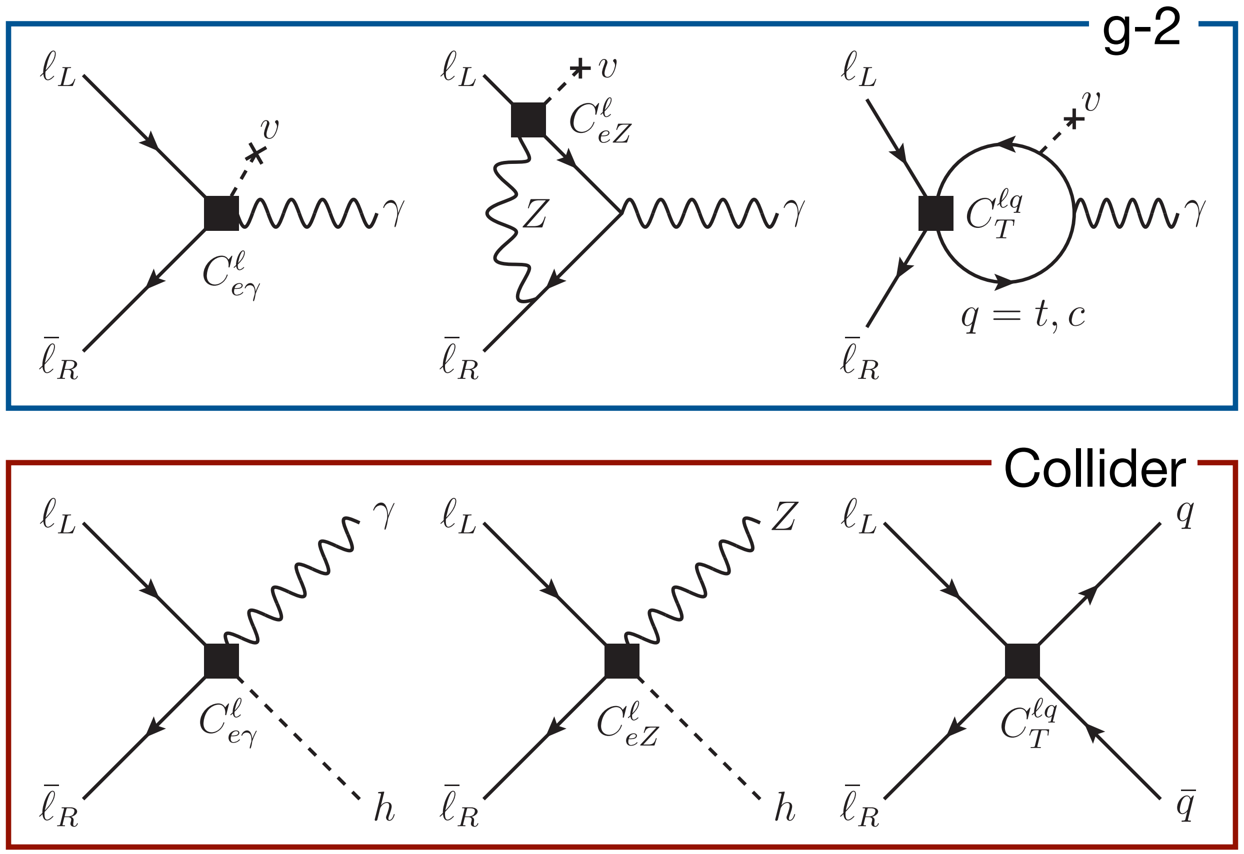
This result is completely model-independent!

B, Paradisi 2012.02769

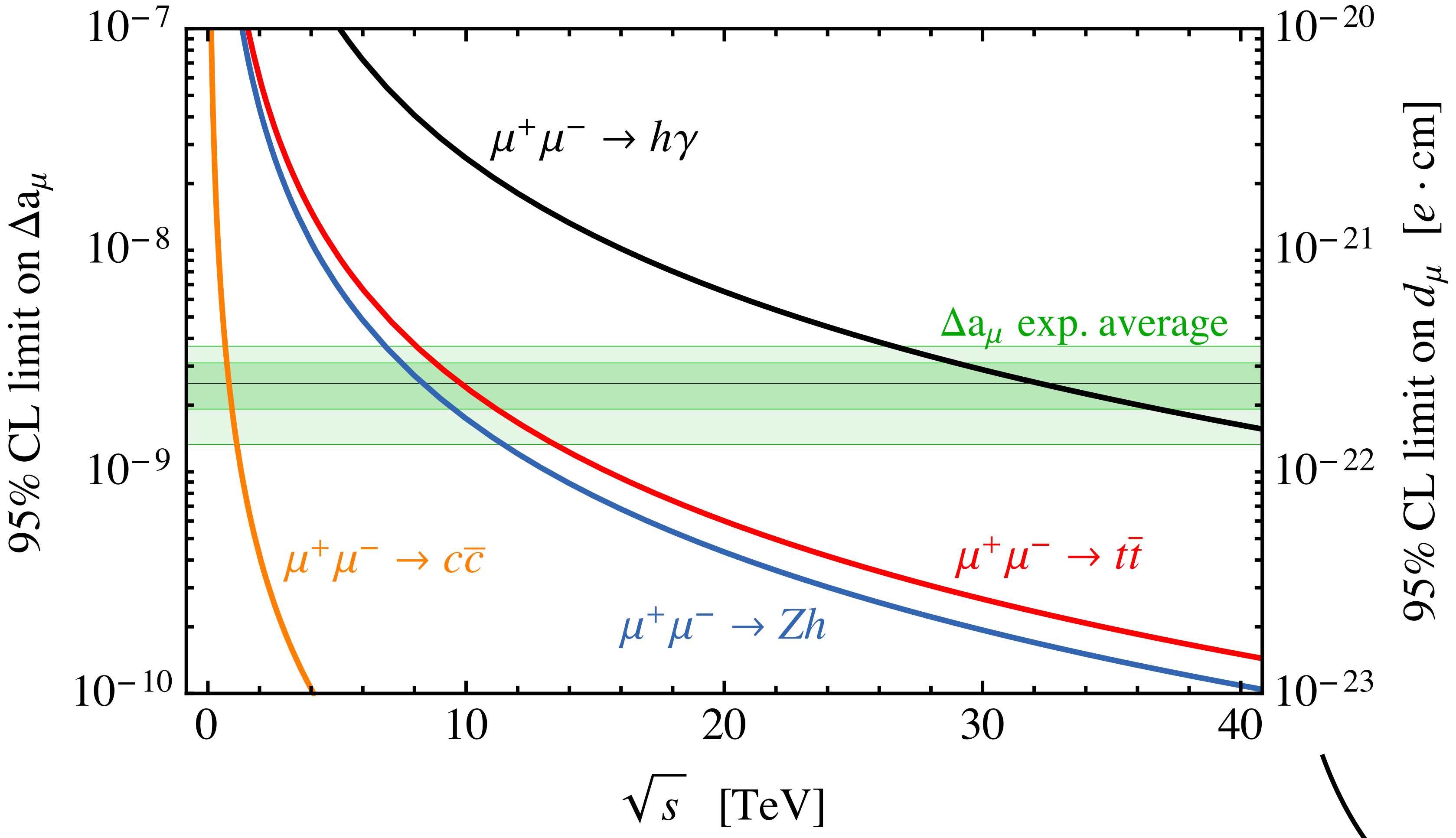
- Other operators enter g-2 at 1 loop:

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

- Full set of operators with Λ ≳ 100 TeV can be probed at a high-energy muon collider



Muon g-2 @ muon collider



Exp. value of Δa$_\mu$ can be tested at 95% CL at a 30 TeV collider!

This result is completely model-independent!

B, Paradisi 2012.02769

Muon EDM for free!

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

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

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

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

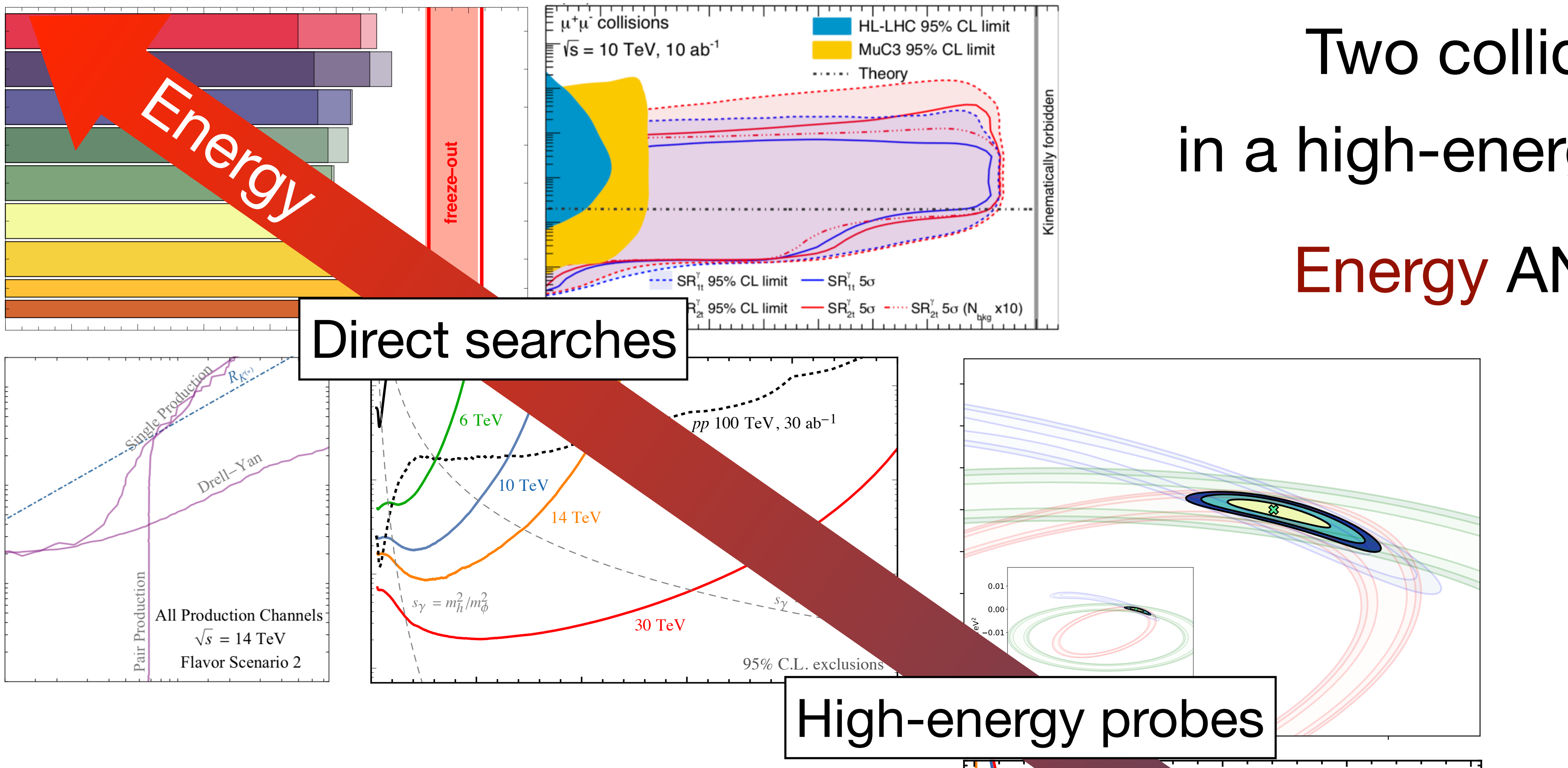
3 o.o.m. stronger than present bound!

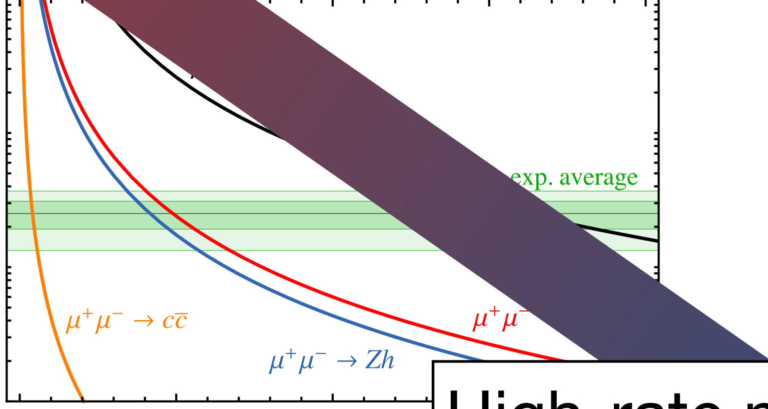
Summary

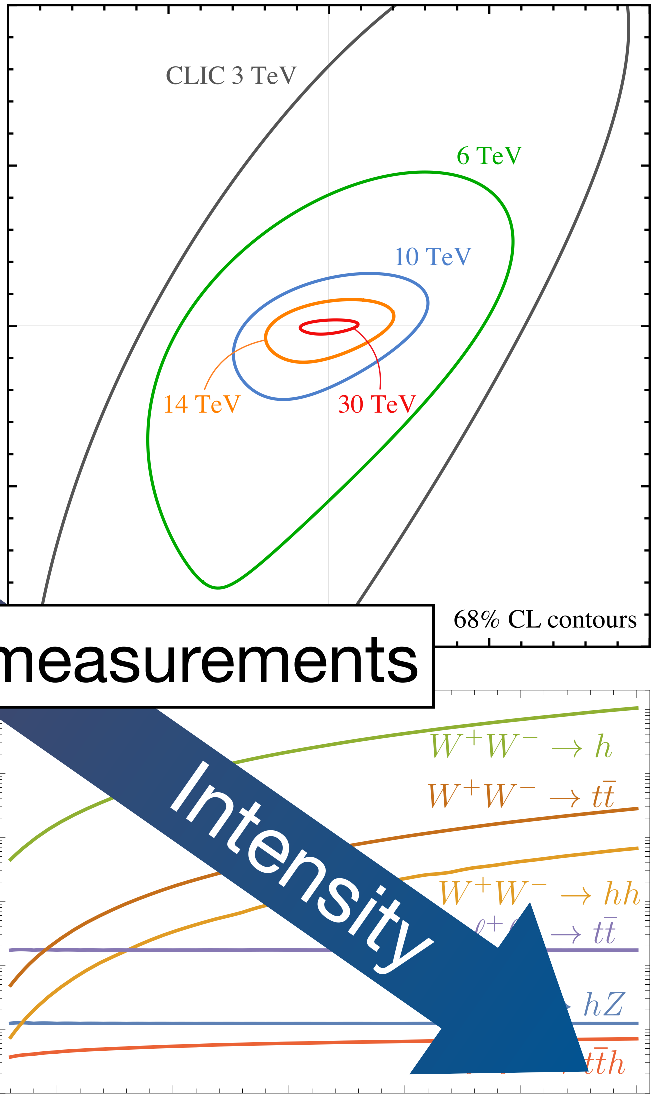
Two colliders at once

in a high-energy muon collider

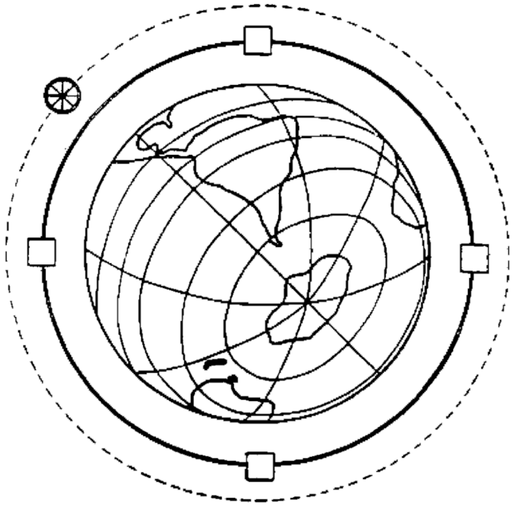
Energy AND Precision







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



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

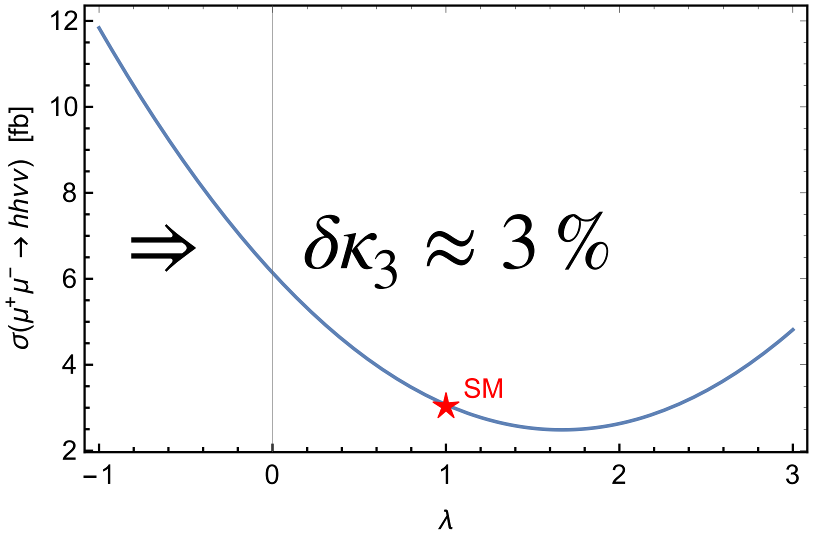
Backup

Double Higgs production

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

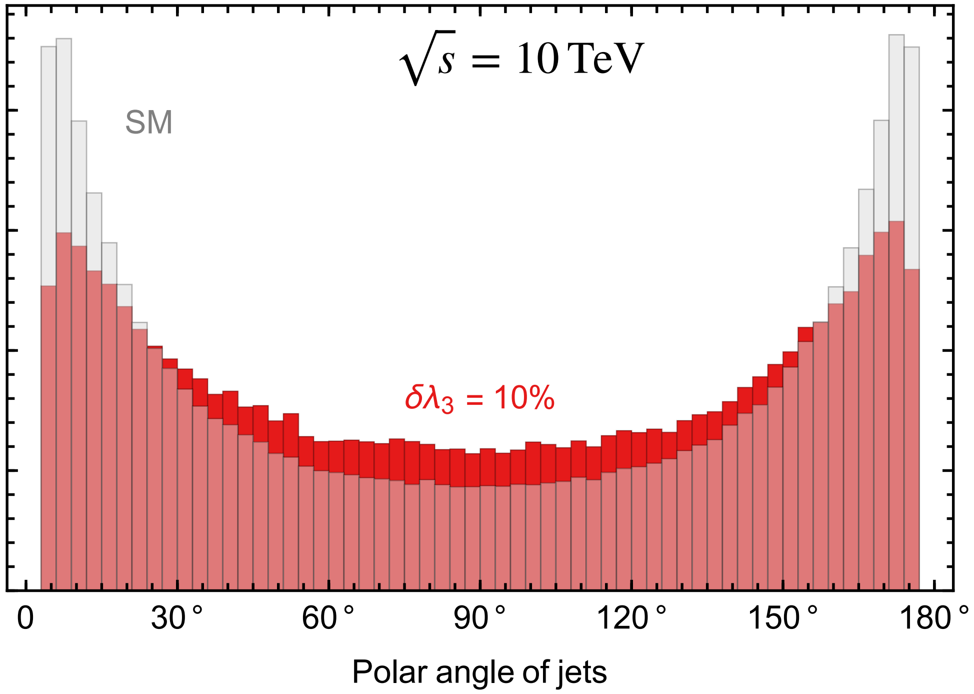
Naïve estimate of the reach: $\delta\sigma \sim (N \times \epsilon)^{-1/2} \approx 1\,\%$

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

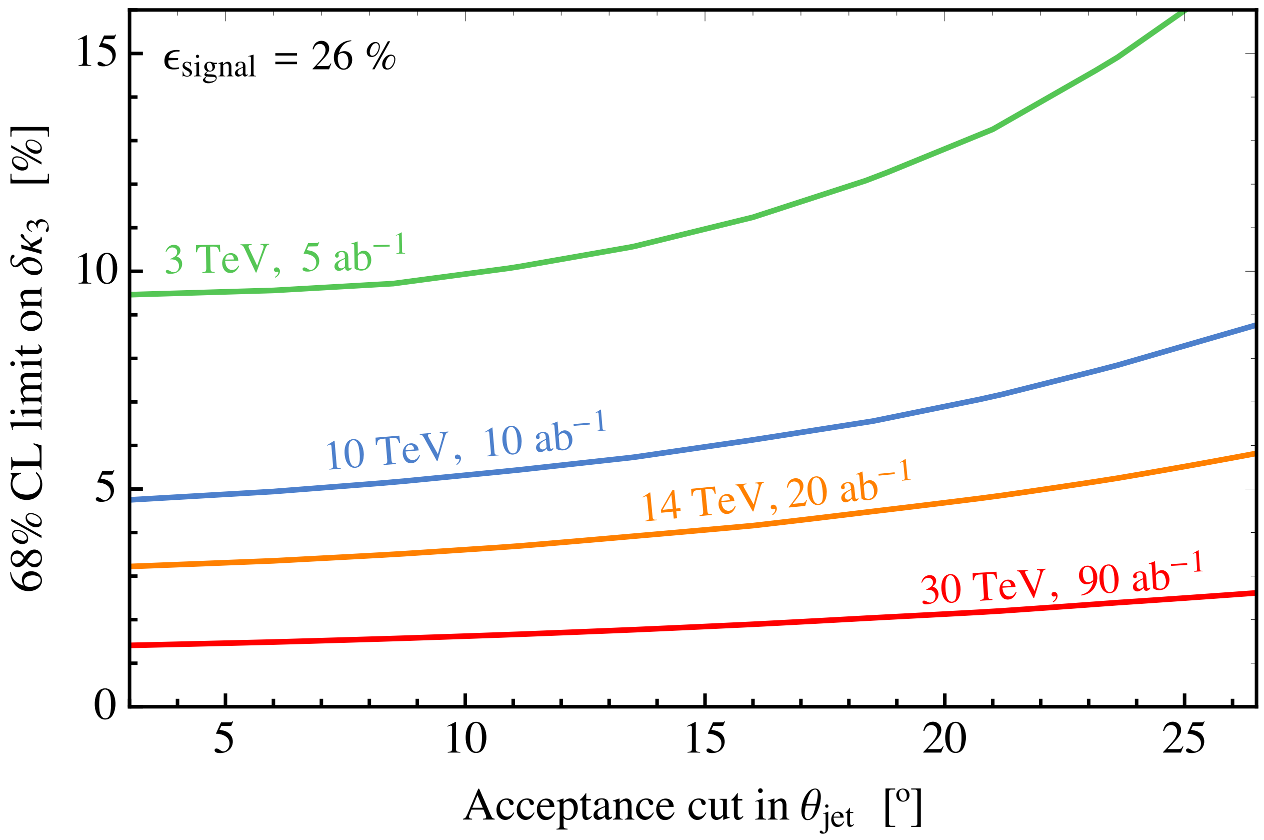


$\Rightarrow \quad \delta\kappa_3 \approx 3\,\%$

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



B, Franceschini, Wulzer 2012.11555



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

$hh \to 4b$ signal

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

  E.g. for pT > 10 GeV, $\theta > 10^\circ$:

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

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

factor 10 loss
in xsec at 30 TeV

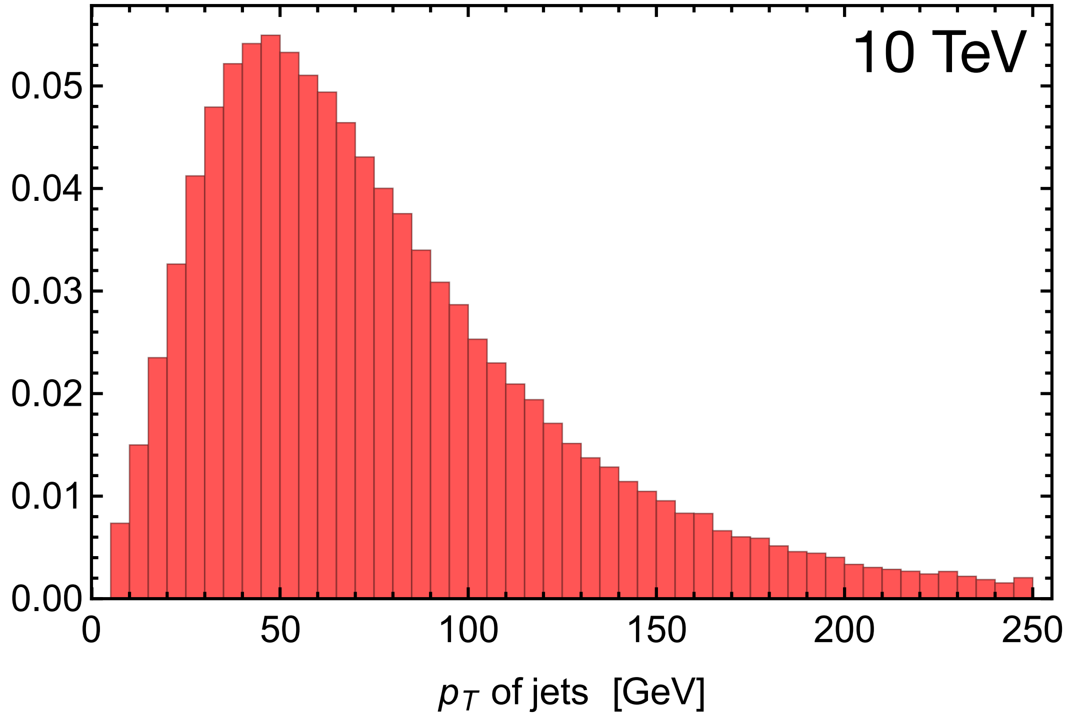
- **Neglect backgrounds** (for the moment)

- 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]	$N_{\rm rec}$	$\delta\sigma \sim N_{\rm rec}^{-1/2}$	$\delta\lambda$
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%

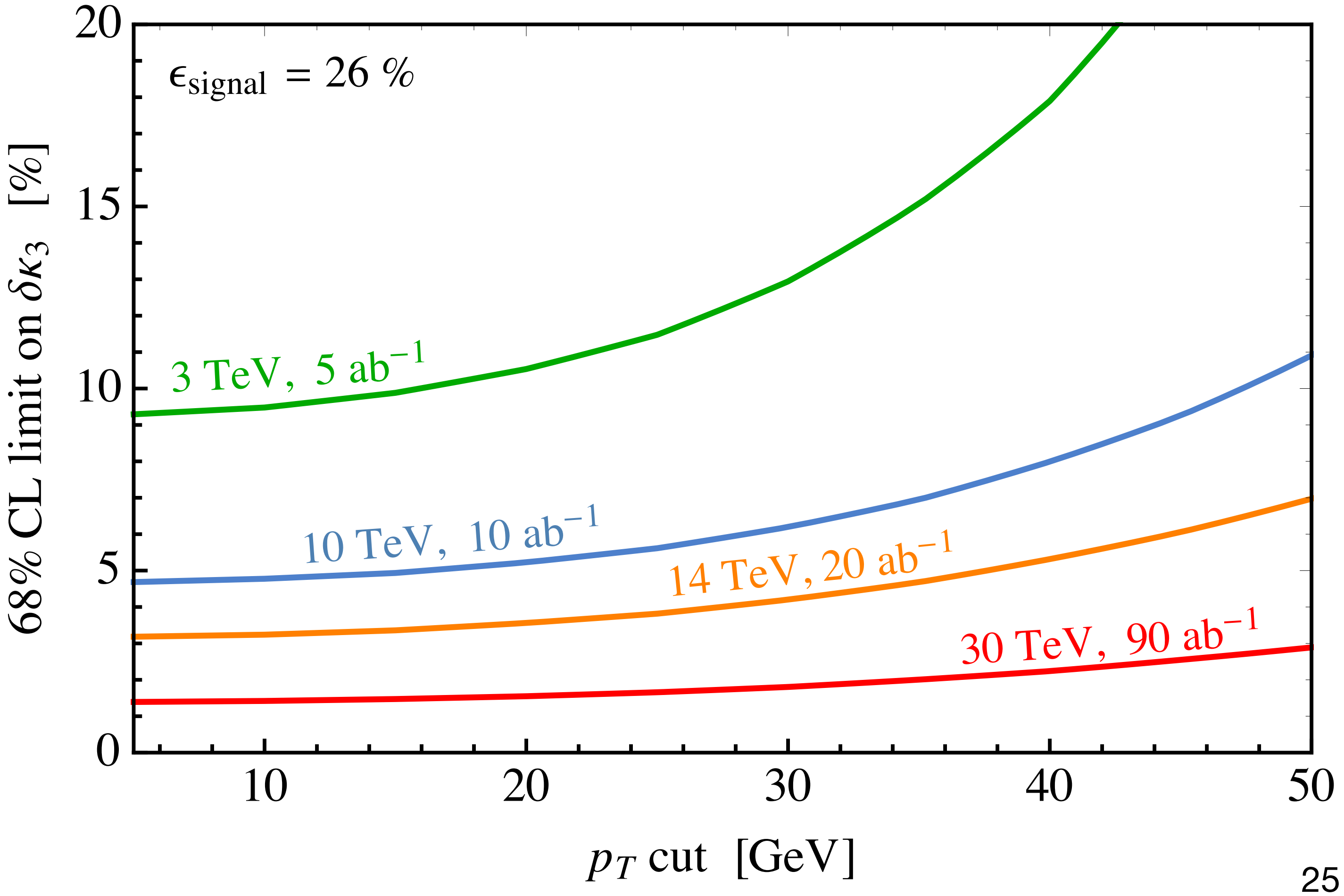
Sensitivity to jet p_T threshold

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



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

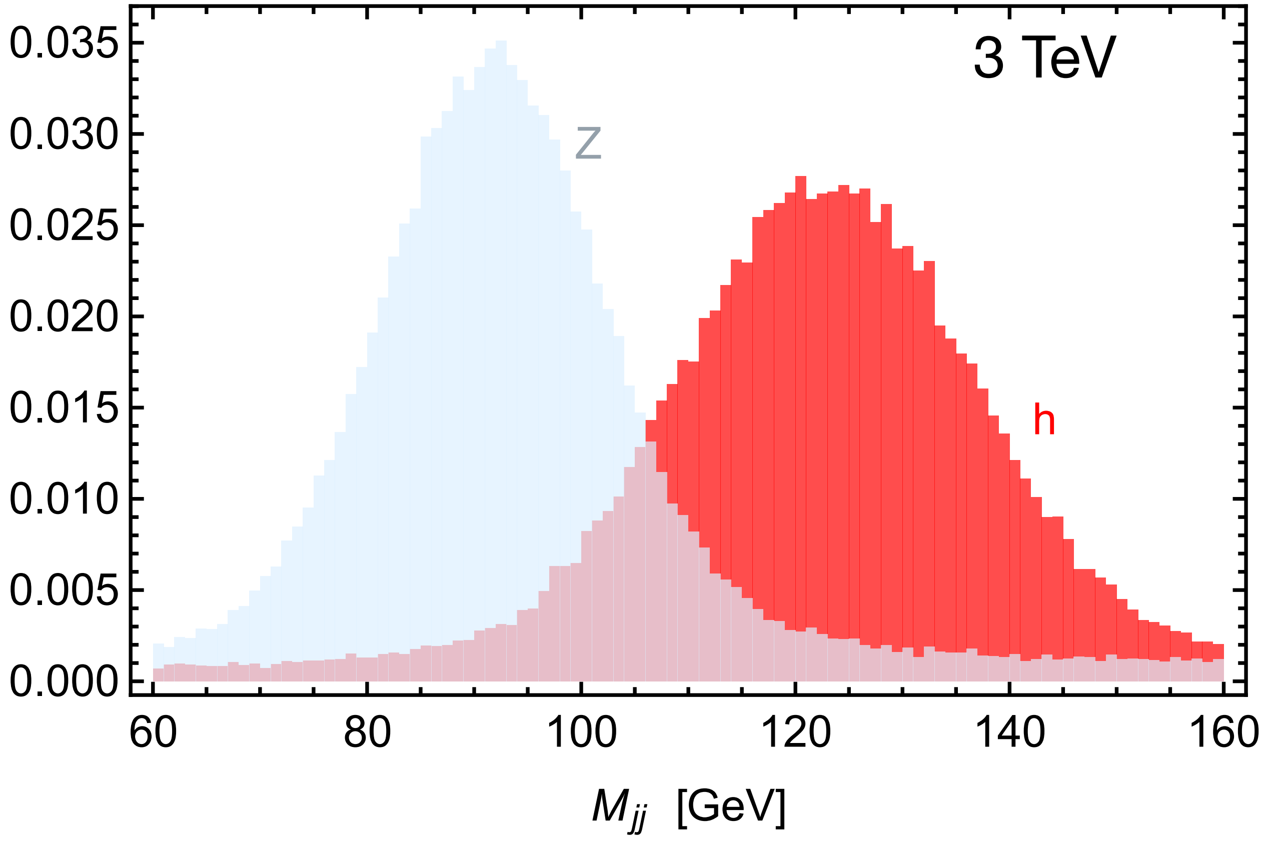
higher thresholds start to reduce the sensitivity



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 $|m(j_1j_2) - m(j_3j_4)|$



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

$M_{hh} > 105$ GeV,

$n_b = 3.2$

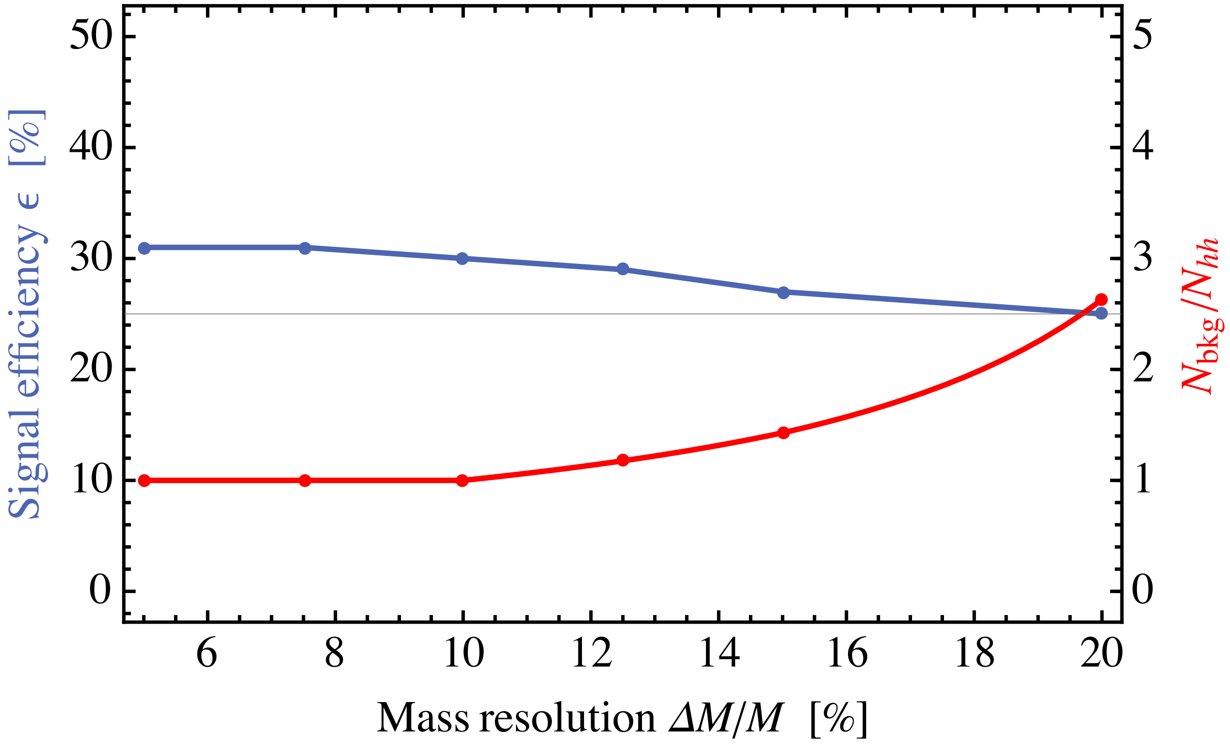
$\varepsilon_{sig} = 27\%$

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

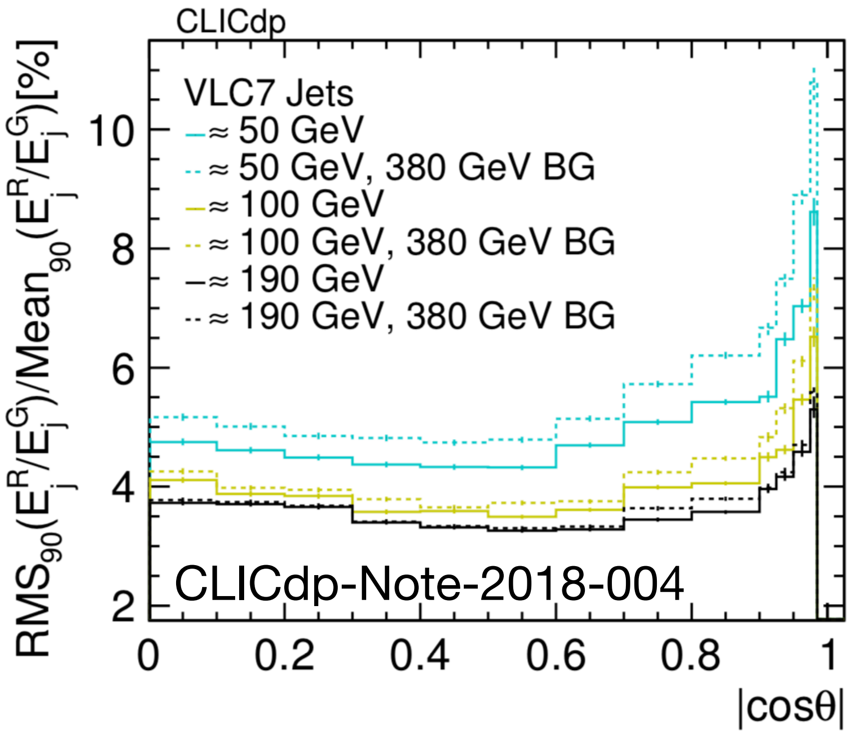
However, perfect agreement with 1901.05897!

Backgrounds

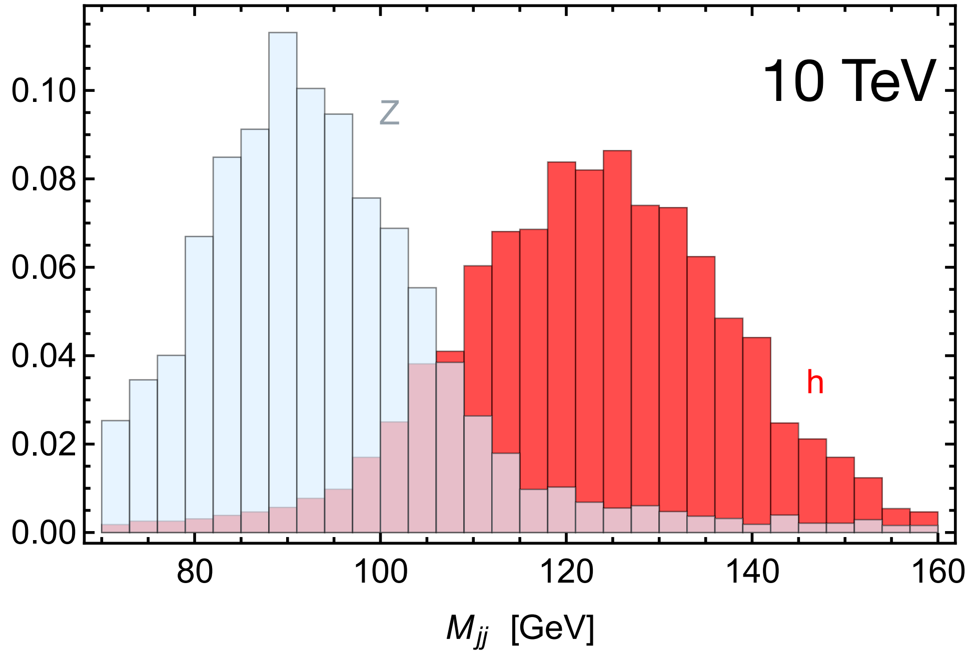
One can now repeat the analysis for different jet energy resolutions:



no real gain using only central events…



… and different energies:



- Optimize cuts to reject bkg:

  $M_{hh} > 105$ GeV,

  $n_b = 2.8$

  $\varepsilon_{\rm sig} = 32\%$

result very similar to 3 TeV

High-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:

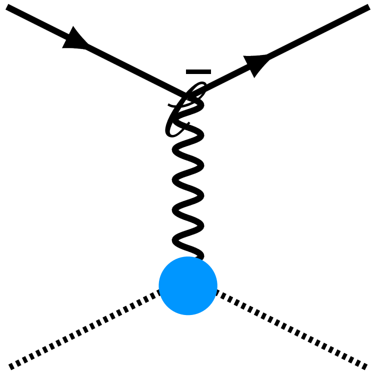
Process	BSM Amplitude
$\boxed{\ell^+_L\ell^-_L \to Z_0 h}$ $\bar\nu_L\nu_L \to W_0^+W_0^-$	$s\,(G_{3L}+G_{1L})\sin\theta_\star$
$\boxed{\ell^+_L\ell^-_L \to W_0^+W_0^-}$ $\bar\nu_L\nu_L \to Z_0 h$	$s\,(G_{3L}-G_{1L})\sin\theta_\star$
$\boxed{\ell^+_R\ell^-_R \to W_0^+W_0^-\,, Z_0 h}$	$s\,G_{lR}\sin\theta_\star$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

Determined by 3 fermion/scalar current-current interactions:

$$\boxed{\begin{aligned}\mathcal{O}_{3L} &= \left(\bar{\mathrm{L}}_L\gamma^\mu\sigma^a\mathrm{L}_L\right)\left(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H\right),\\ \mathcal{O}_{1L} &= \left(\bar{\mathrm{L}}_L\gamma^\mu\mathrm{L}_L\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right),\\ \mathcal{O}_{lR} &= \left(\bar{l}_R\gamma^\mu l_R\right)\left(iH^\dagger\overleftrightarrow{D}_\mu H\right).\end{aligned}}$$

“high-energy primary effects”

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



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

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

$$\boxed{\begin{aligned}\mathcal{O}_W &= \frac{ig}{2}\left(H^\dagger\sigma^a\overleftrightarrow{D}^\mu H\right)D^\nu W^a_{\mu\nu}\\ \mathcal{O}_B &= \frac{ig'}{2}\left(H^\dagger\overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}\\ \mathcal{O}_{HW} &= ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}\\ \mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}\end{aligned}}$$

High-energy WW: angular analysis

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

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

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

$$\mathscr{A}_{-+} = -\frac{g^2}{2}\sin\theta_\star$$

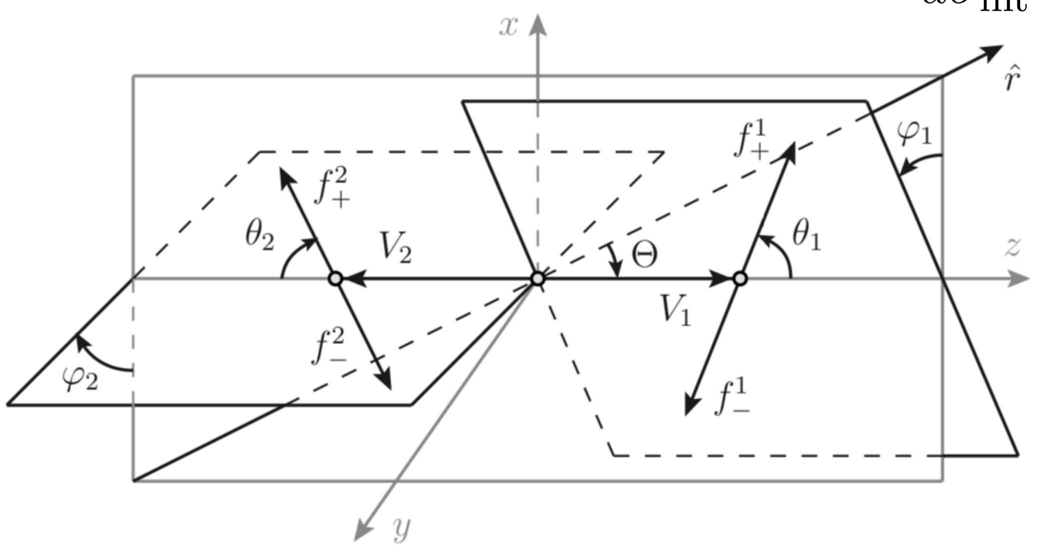
$$\mathscr{A}_{+-} = g^2\cos^2\frac{\theta_\star}{2}\cot^2\frac{\theta_\star}{2}$$

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

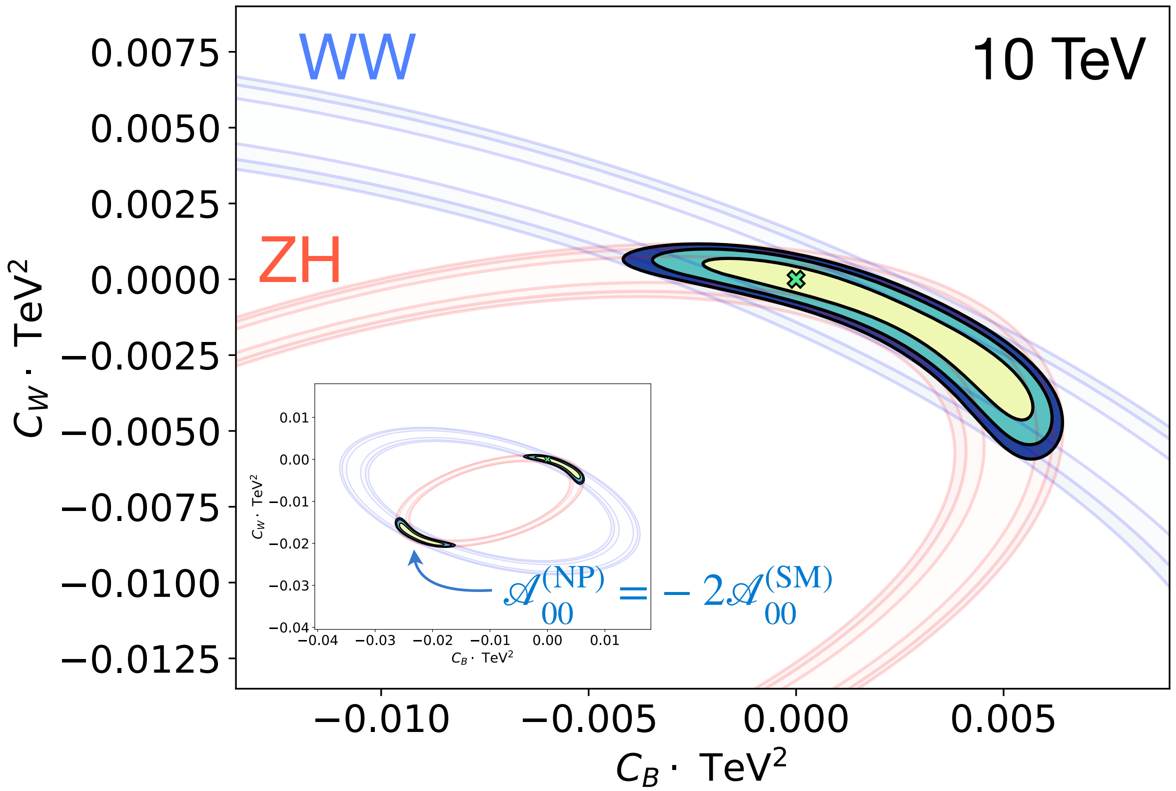
see also Panico et al. 1708.07823, 2007.10356

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

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



$\mathscr{A}_{00}^{(\mathrm{NP})} = -2\mathscr{A}_{00}^{(\mathrm{SM})}$

B, Franceschini, Wulzer 2012.11555

A simple example: scalar singlet

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

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

portal coupling

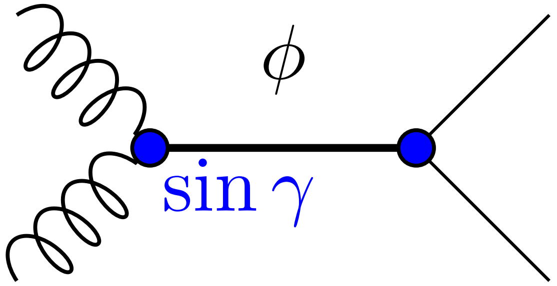
triple couplings:
BR(*ϕ* → *hh*), *g*

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

mass eigenstates: $h = \cos\gamma\, H^0 + \sin\gamma\, S$

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

- ϕ can be singly produced:

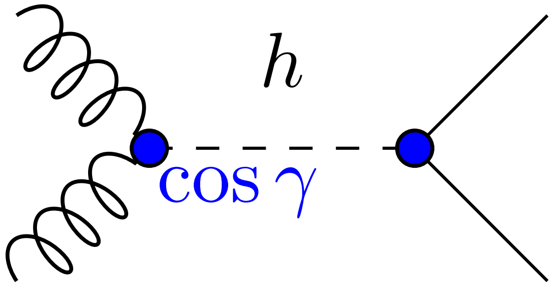


$$\sigma_\phi = \sigma_{\rm SM}(m_\phi) \times \sin^2\gamma$$

- 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:

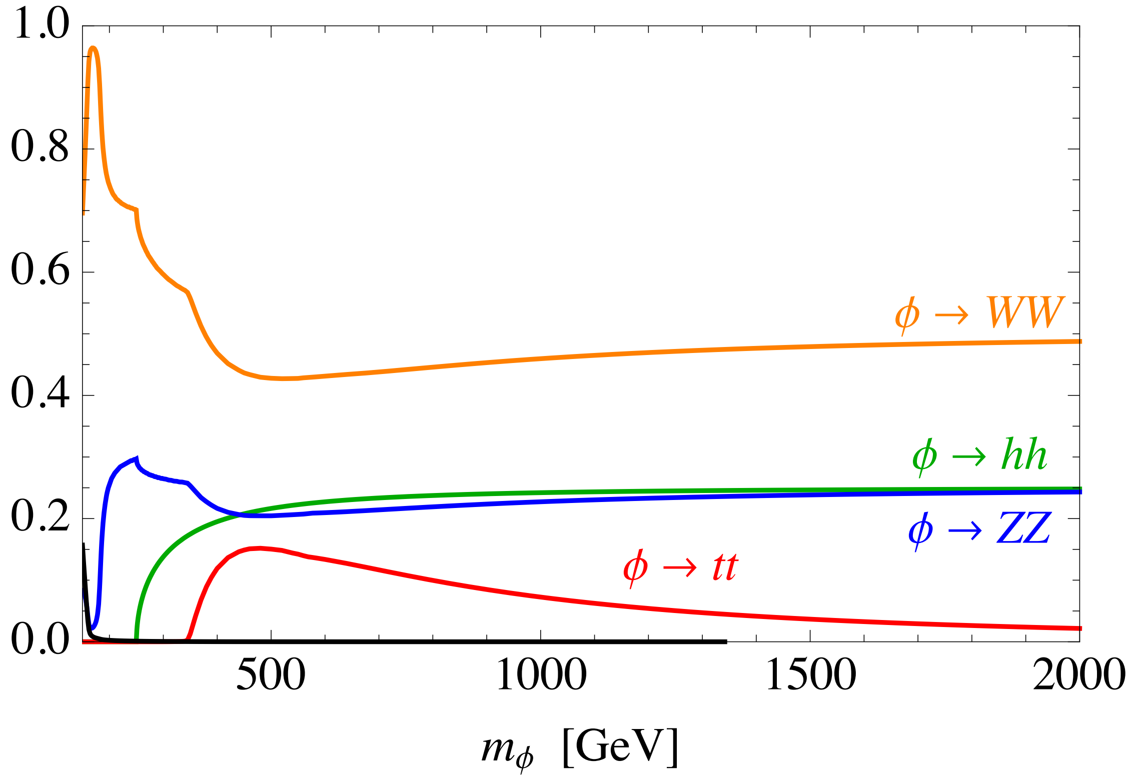


$$\mu_h = \mu_{\rm SM} \times \cos^2\gamma$$

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.

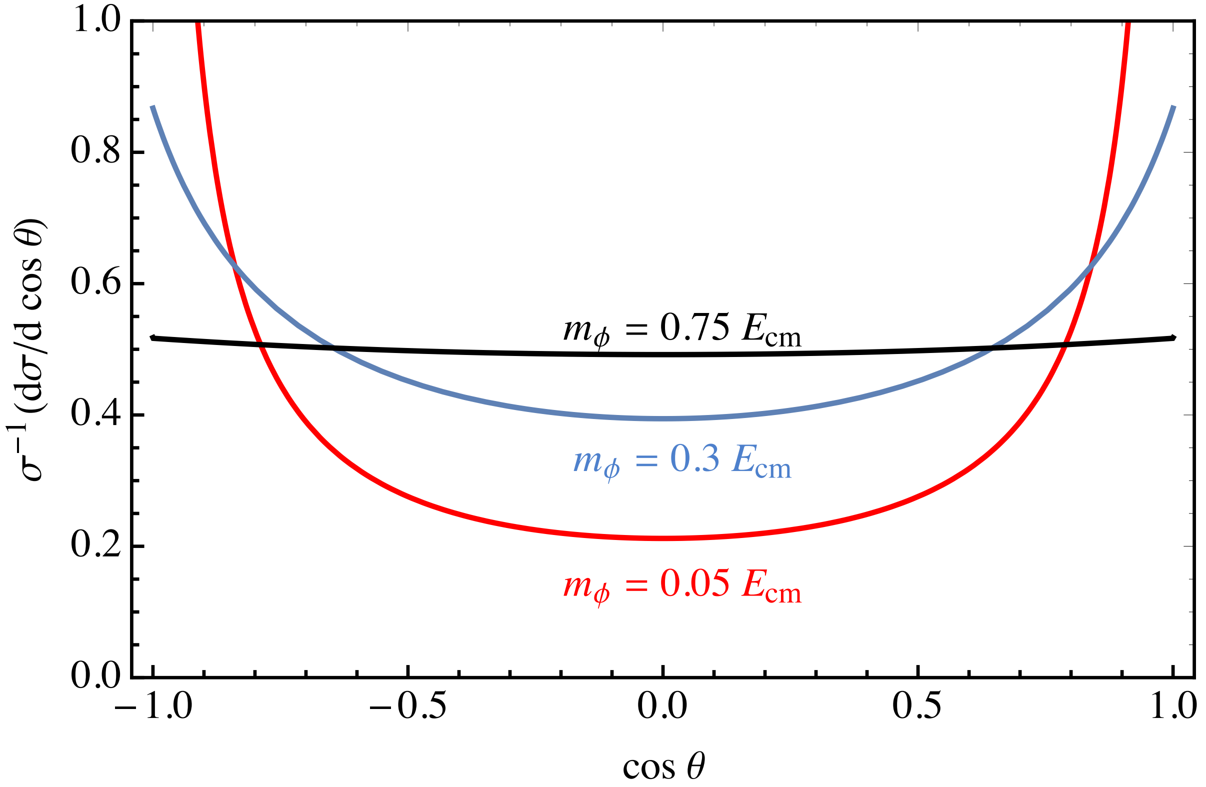


Goldstone boson equivalence theorem:

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

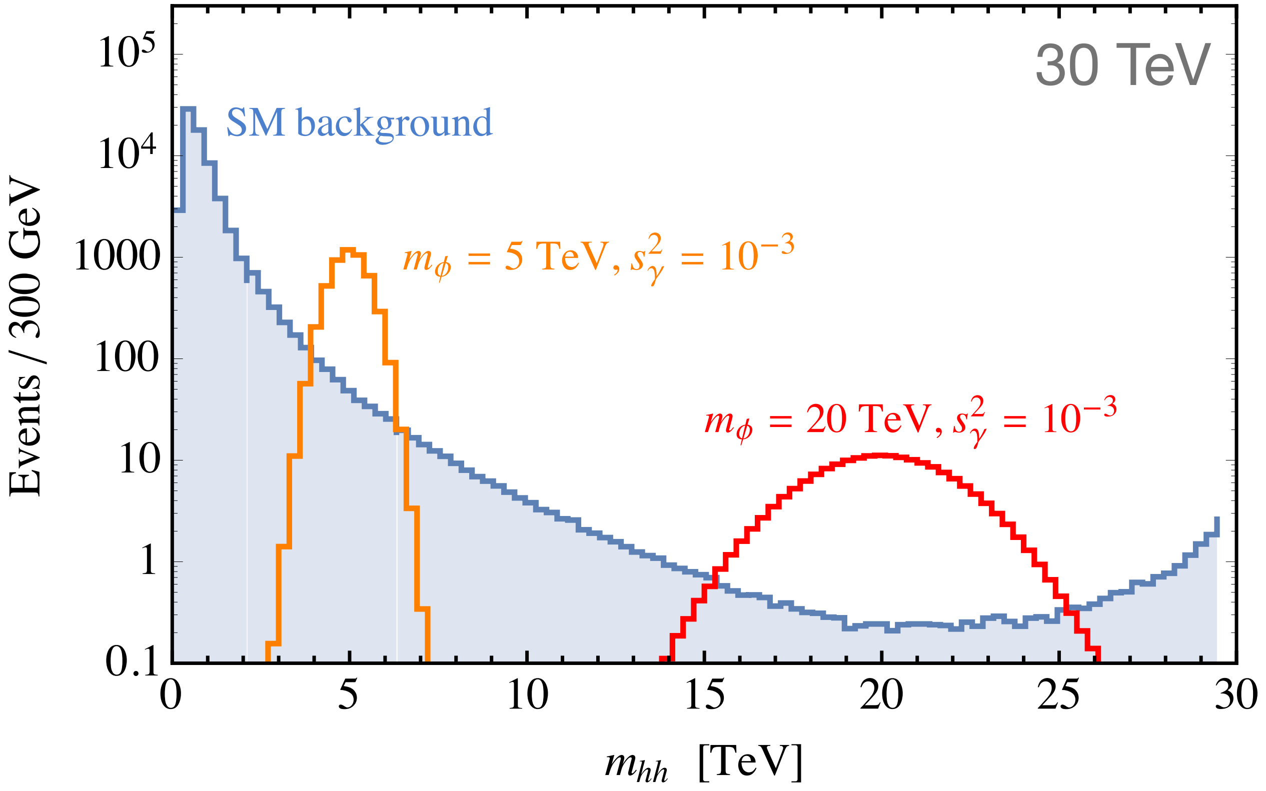
$$m_\phi \gg m_h$$

- Golden channels:
  - ***φ → ZZ(4l,2l2j)*:** very clean, some EW background; most sensitive channel at LHC.
  - ***φ → 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:

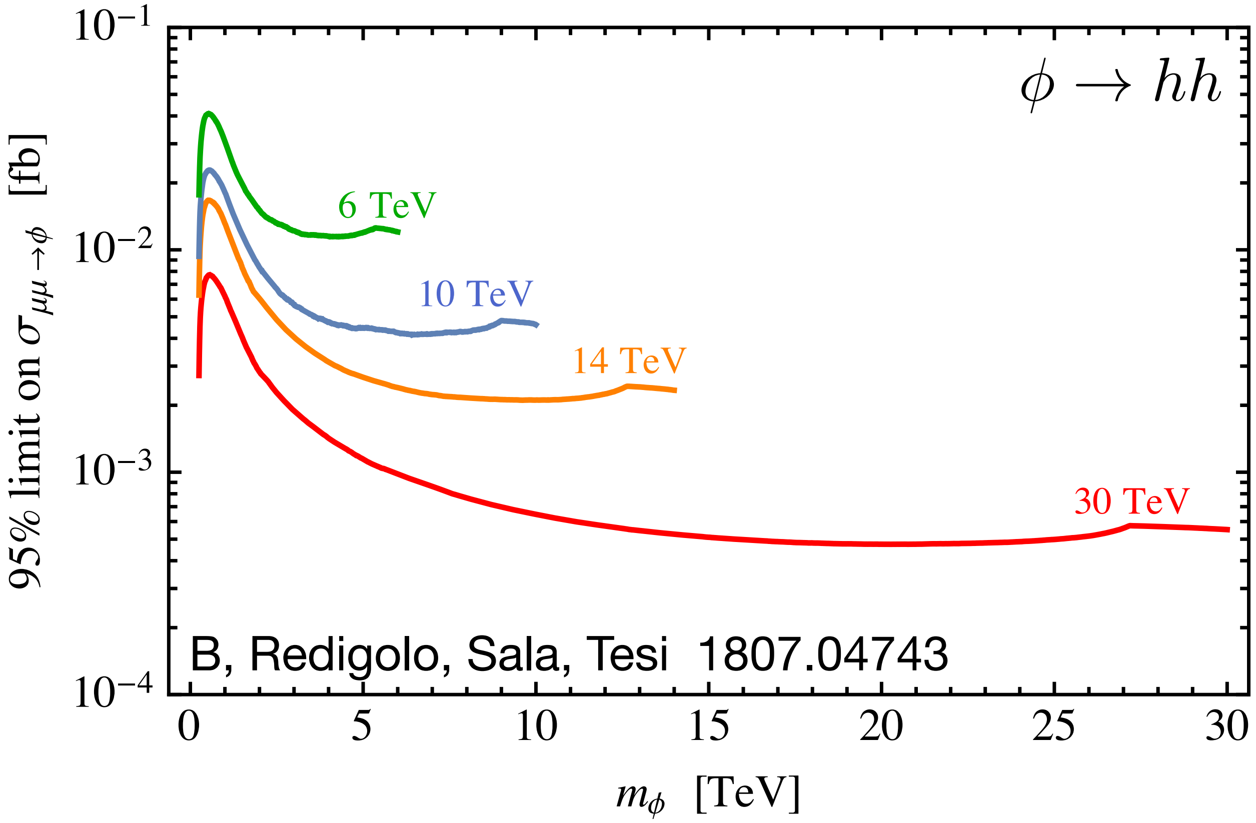


$$\text{significance} = \frac{N_{\text{sig}}}{\sqrt{(N_{\text{sig}} + N_{\text{bkg}}) + \alpha_{\text{sys}}^2 N_{\text{bkg}}^2}}$$

$\alpha_{\text{sys}} = 2\%$ (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

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



B, Redigolo, Sala, Tesi 1807.04743

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

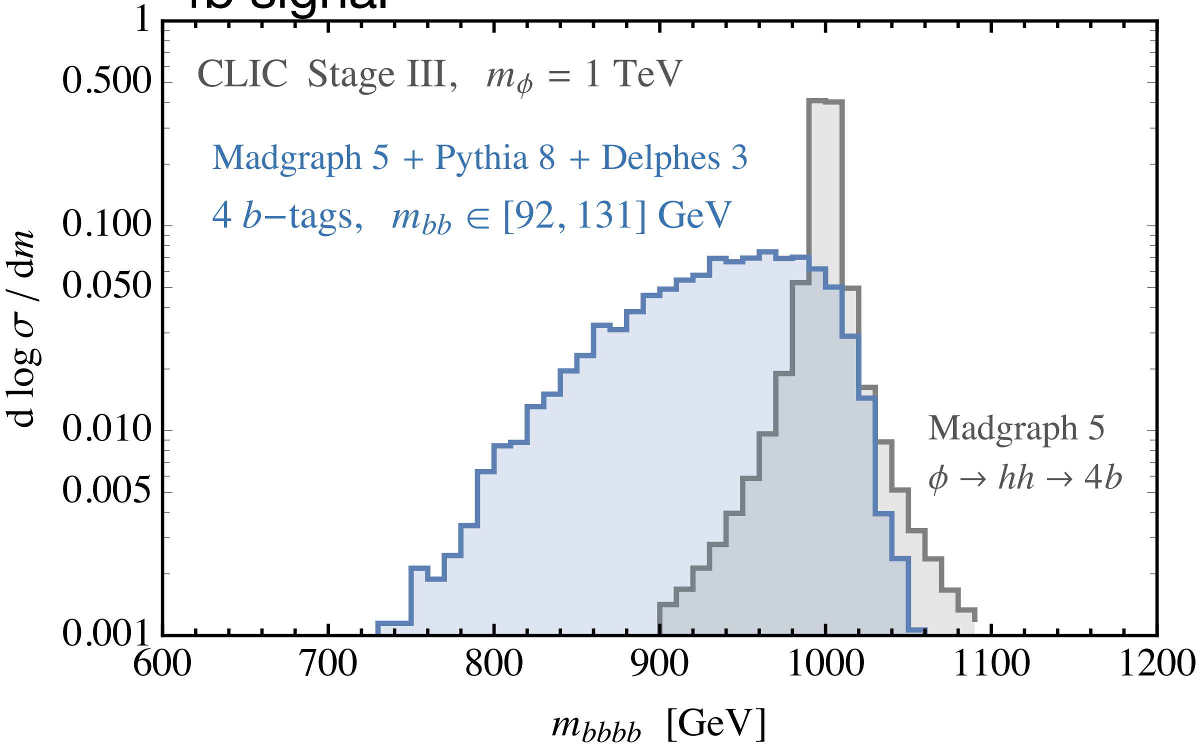
$hh(4b)$ decay channel

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_ϕ
- Other cuts: p_T > 20 GeV, $|\cos\theta_h|$ < 0.9

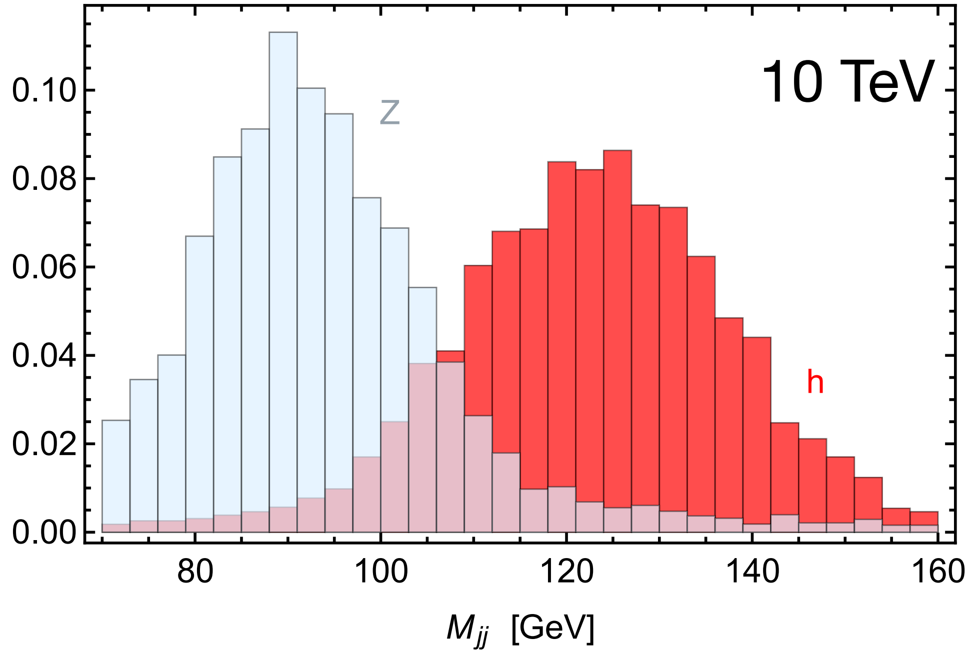
4b signal



Signal efficiency ε_{sig} ~ 25 – 30%

Background reduced by ε_{bkg} ~ 10^{-3} – 10^{-4}

Checked (at parton level) that results still hold at 10 TeV: ε_{sig} ~ 30% assuming similar detector performance



(see also my talk of last month)

Goldstone bosons (Twin Higgs)

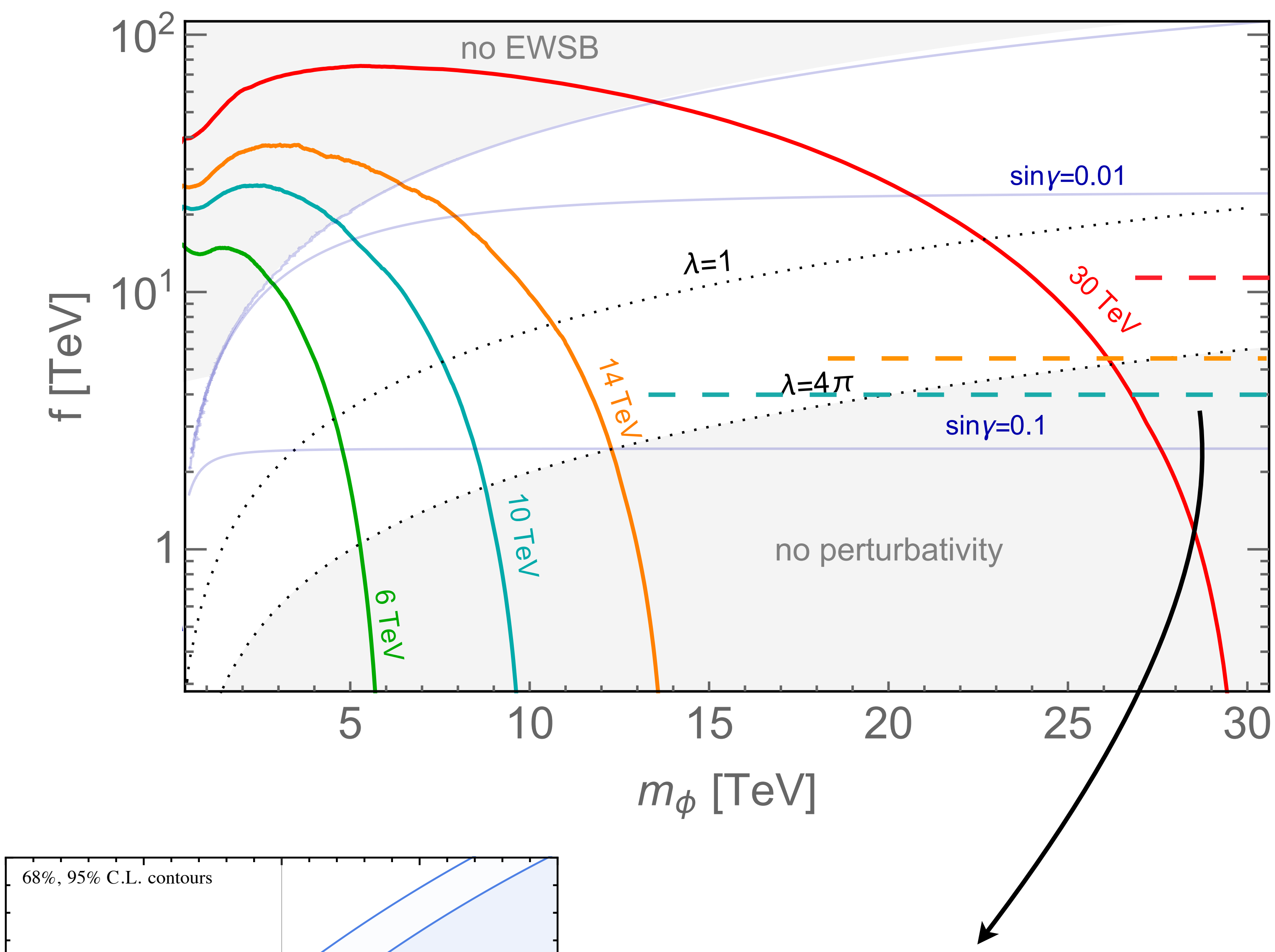
- Higgs mass is protected from radiative corrections without new light colored states

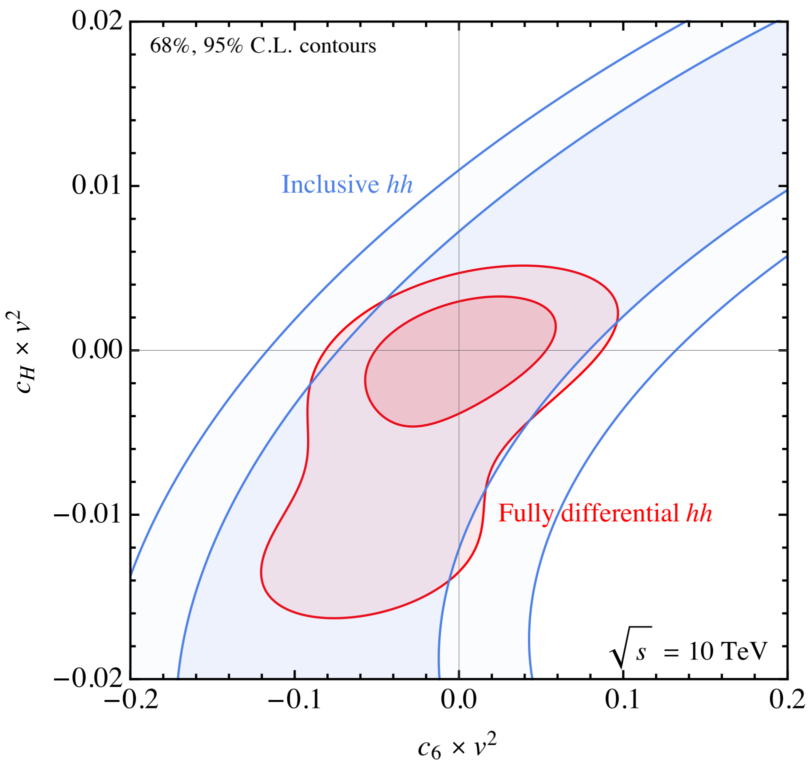
- Two copies of the SM, with approximate Z_2 symmetry, coupled through Higgs portal

- 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

$$\mathcal{W} = \mathcal{W}_{\rm MSSM} + \lambda S H_u H_d + f(S)$$

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

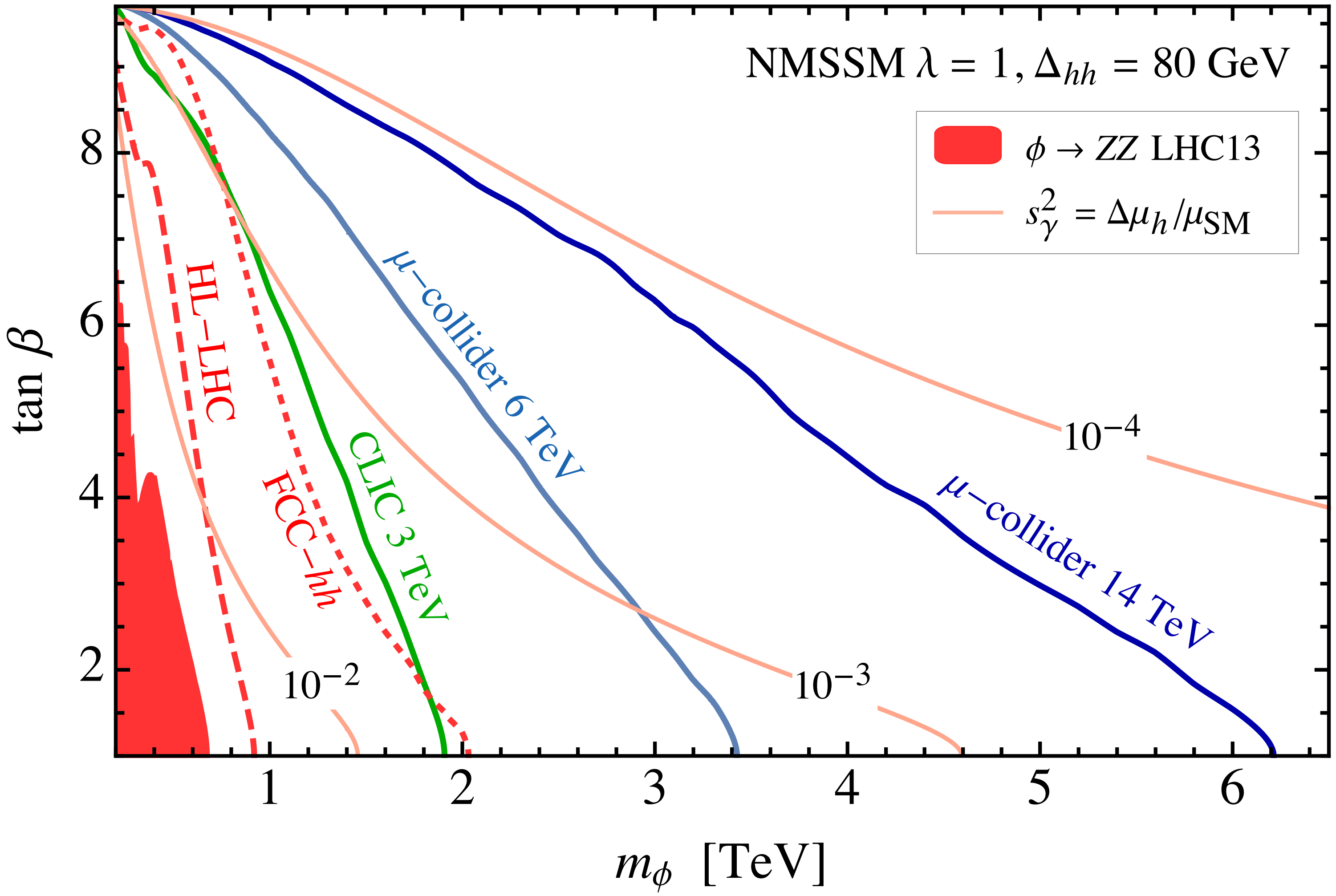
The singlet can be the lightest new state of the Higgs sector

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

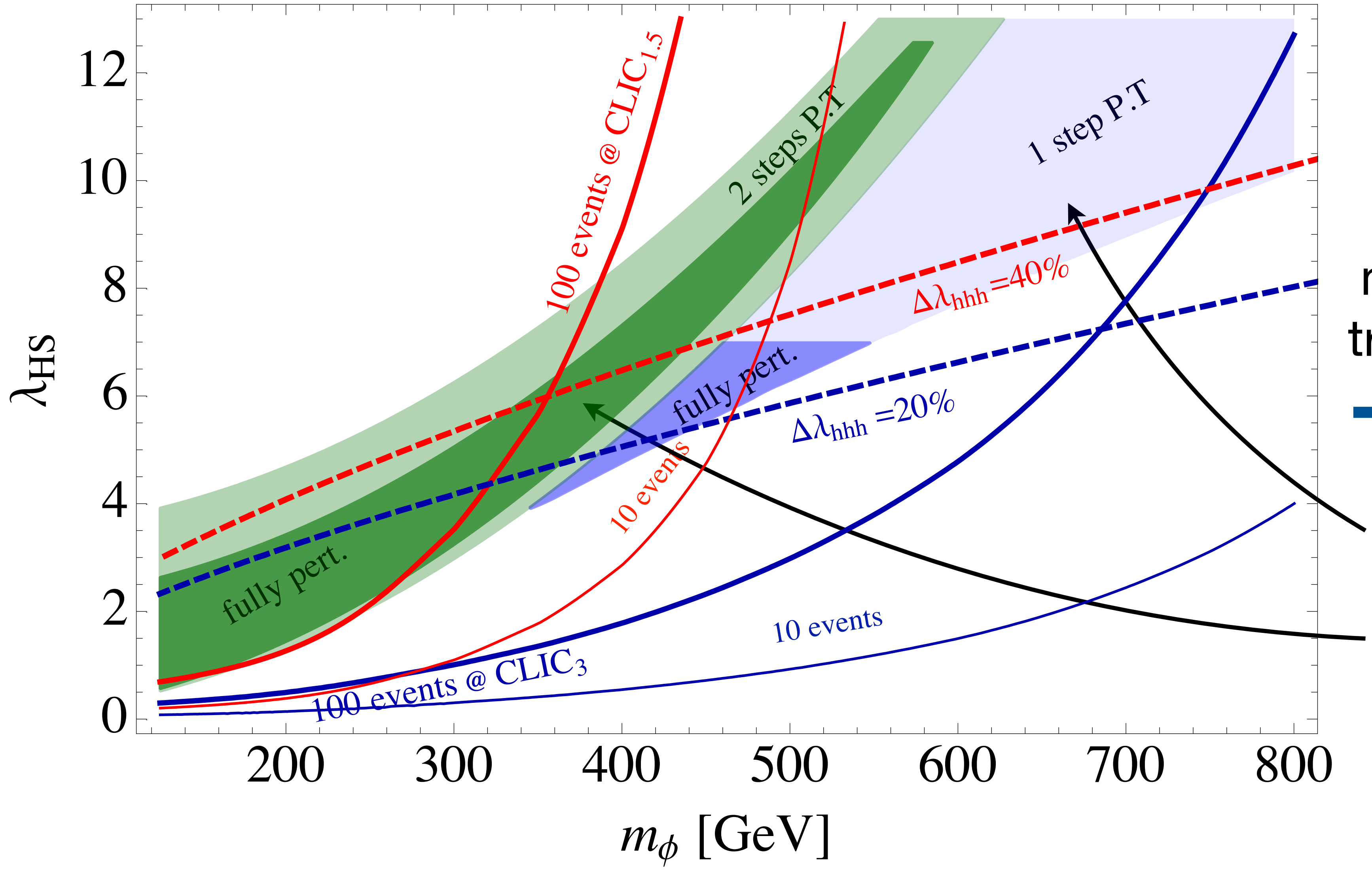


Weakly coupled & low mass:
direct searches very powerful!

→ see Andrea's talk for sparticle production!

Pair production: results

- Final states with 4 Higgs or vector bosons (e.g. $e^+e^- \rightarrow 8b + E_{miss}$): 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

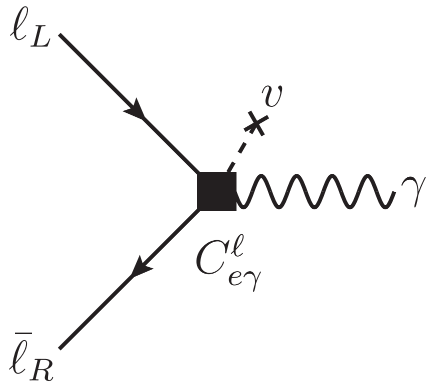
    (e.g. axion-like particles, dark sectors, light scalars, …)

  - $\Lambda \gg$ TeV, heavy NP with O(1) couplings to the SM ☚

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

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

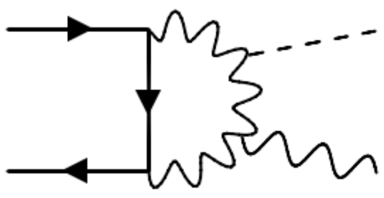
$$\Delta a_\mu = \frac{4 m_\mu v}{\Lambda^2} C_{e\gamma} \approx 3 \times 10^{-9} \times \left(\frac{140\,\mathrm{TeV}}{\Lambda}\right)^2 C_{e\gamma}$$



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

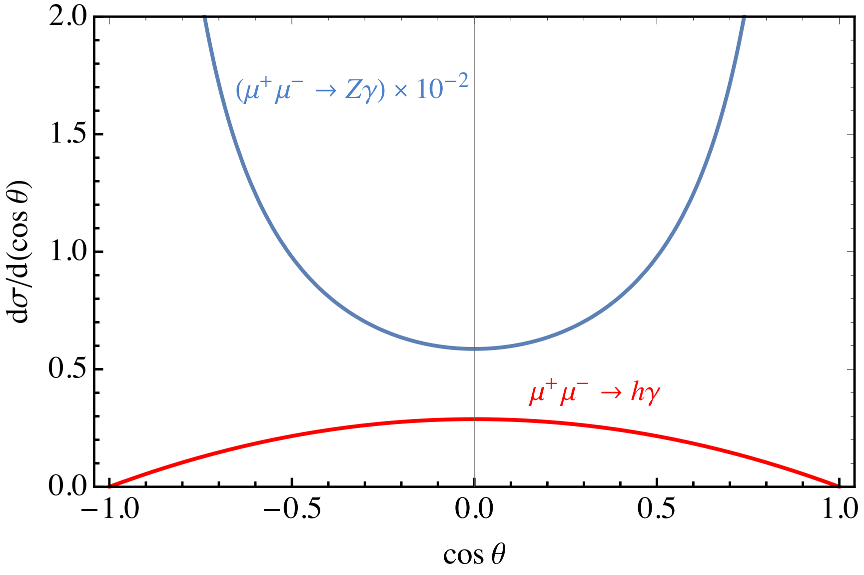


- Main background from $\mu\mu \to Z\gamma$ (where Z is mistaken for H)

  (large due to transverse Z polarizations)

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

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



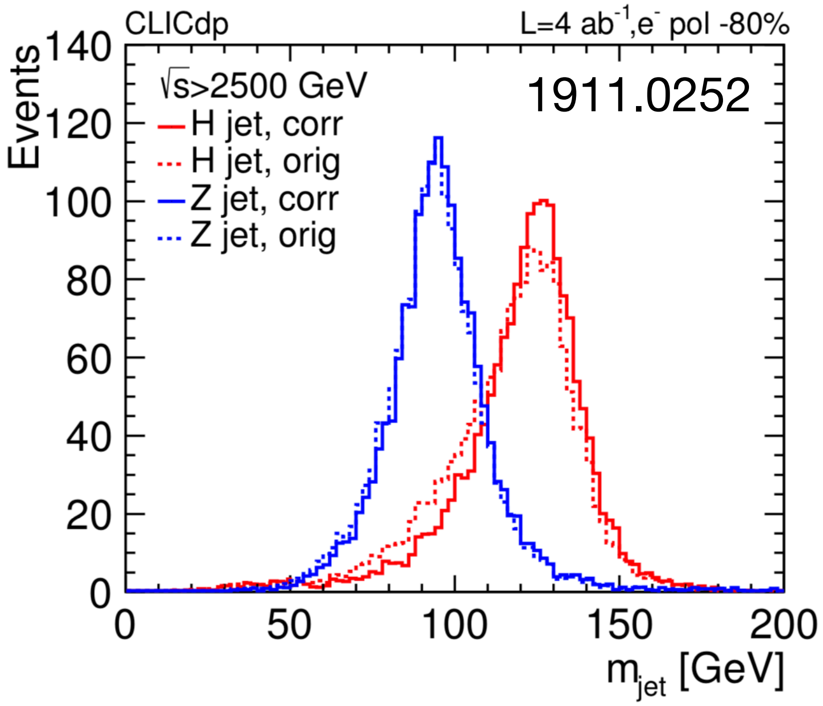
Search in h → bb channel:

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

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

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

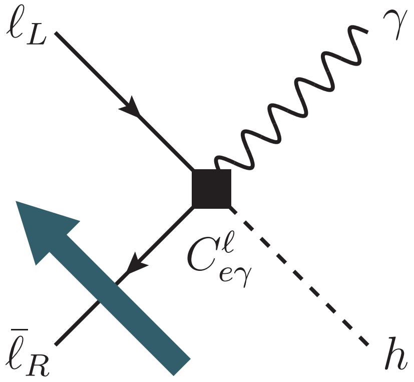
Δaμ can be tested at 95% CL at a 30 TeV collider if Z→h mistag probability < 10-15%



Lepton g-2 from rare Higgs decays

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

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



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

(tree-level is suppressed by lepton mass)

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

  - Muon:

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

1704.00790

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

too small :(

  - Tau:

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

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

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

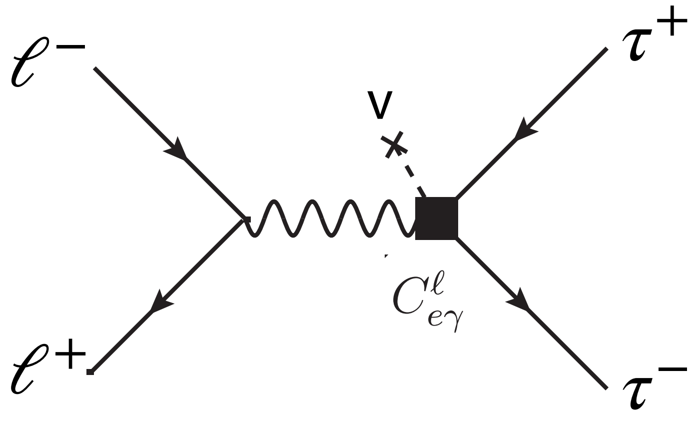
3 o.o.m. improvement!

Lepton g-2 at high energy

Further possibilities to measure Δa_τ precisely from high-energy probes

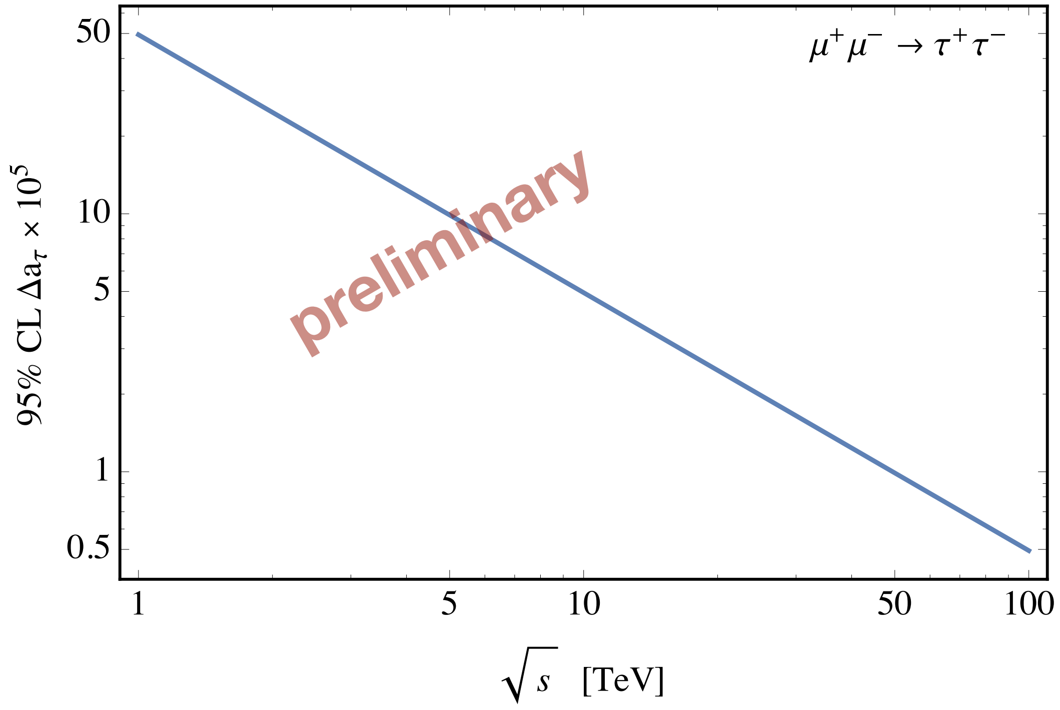
- Pair production

work in progress with P. Paradisi



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

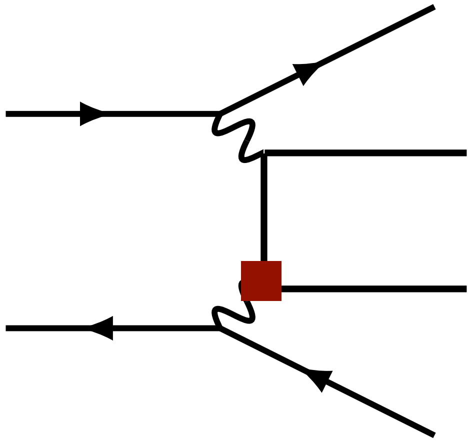
$$\sigma_{\rm NP} = \frac{4\pi\alpha^2}{3}\,\frac{|C^{\ell}_{e\gamma}|^2 v^2}{\Lambda^4} \sim \frac{\pi\alpha^2\Delta a_\ell^2}{6m_\ell^2}$$



Could probe Δa_τ ~ few 10^{-5}

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

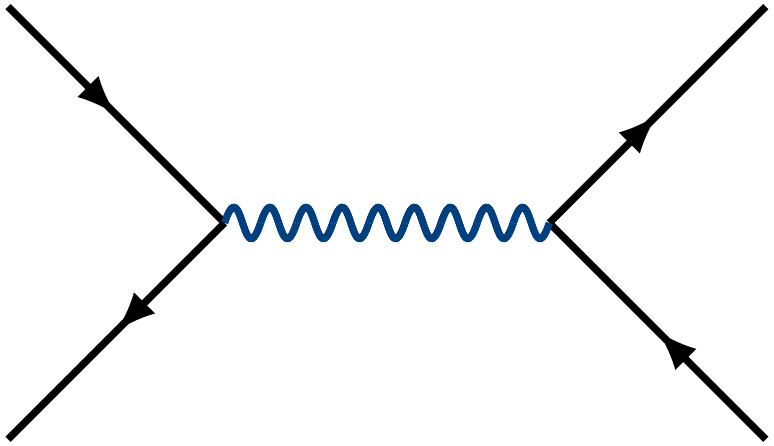
charged and neutral channel can constrain C_{eB} and C_{eW}



More resonances: Z’

Most typical example of direct search:

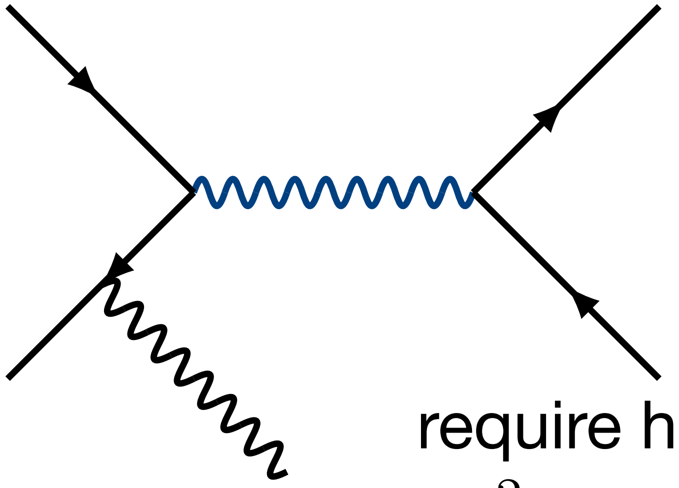
heavy s-channel resonance produced in Drell-Yan



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

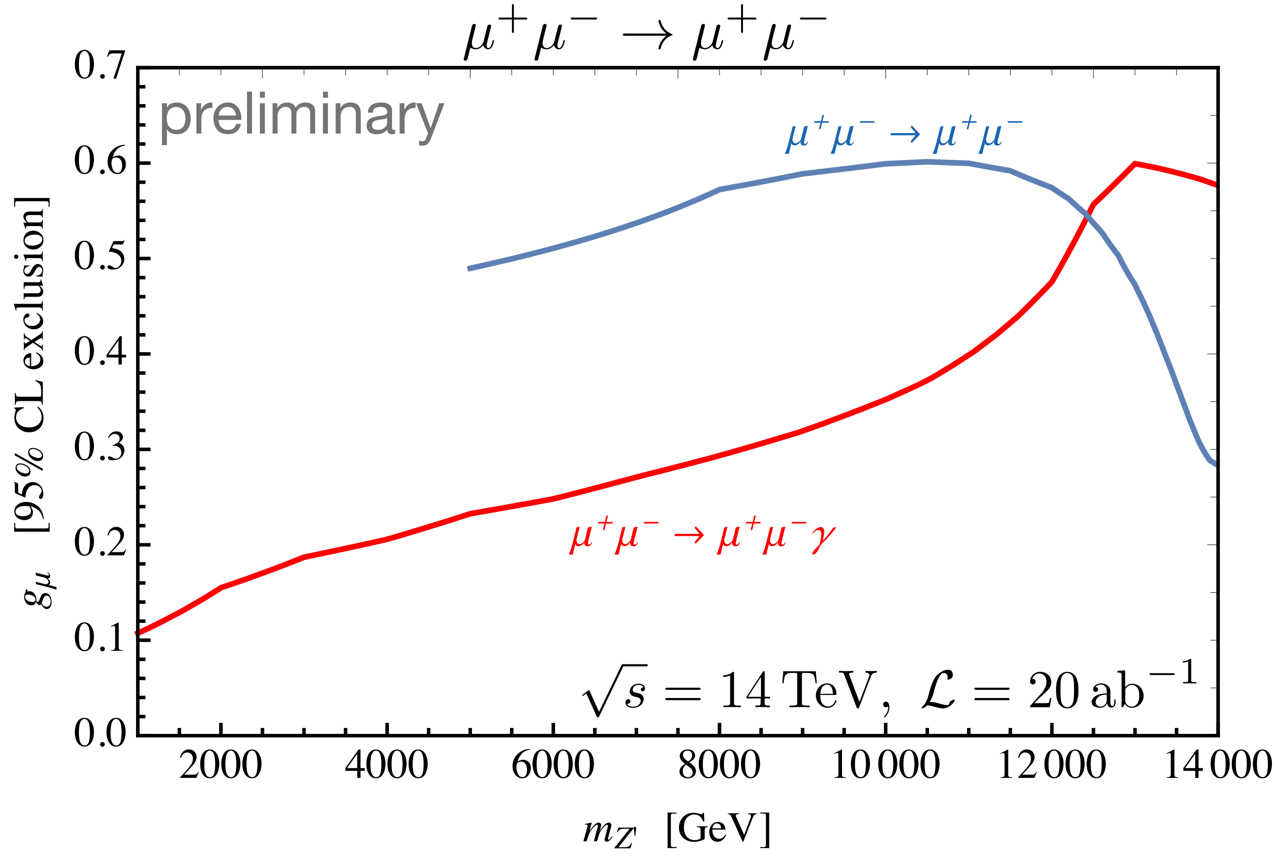
Problem: how do we look for resonances of unknown mass at fixed √s?

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

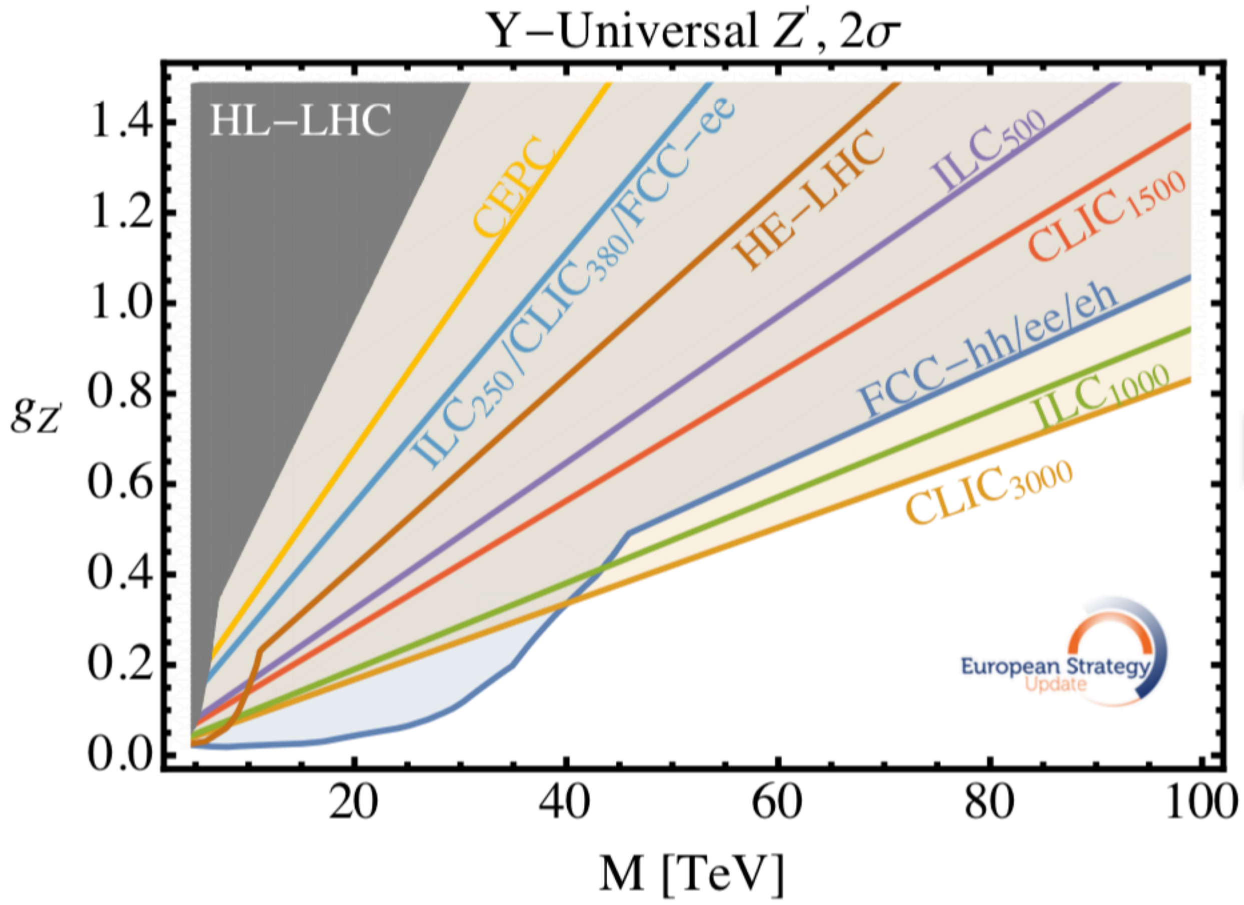
(μμ → ff cross-section)

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

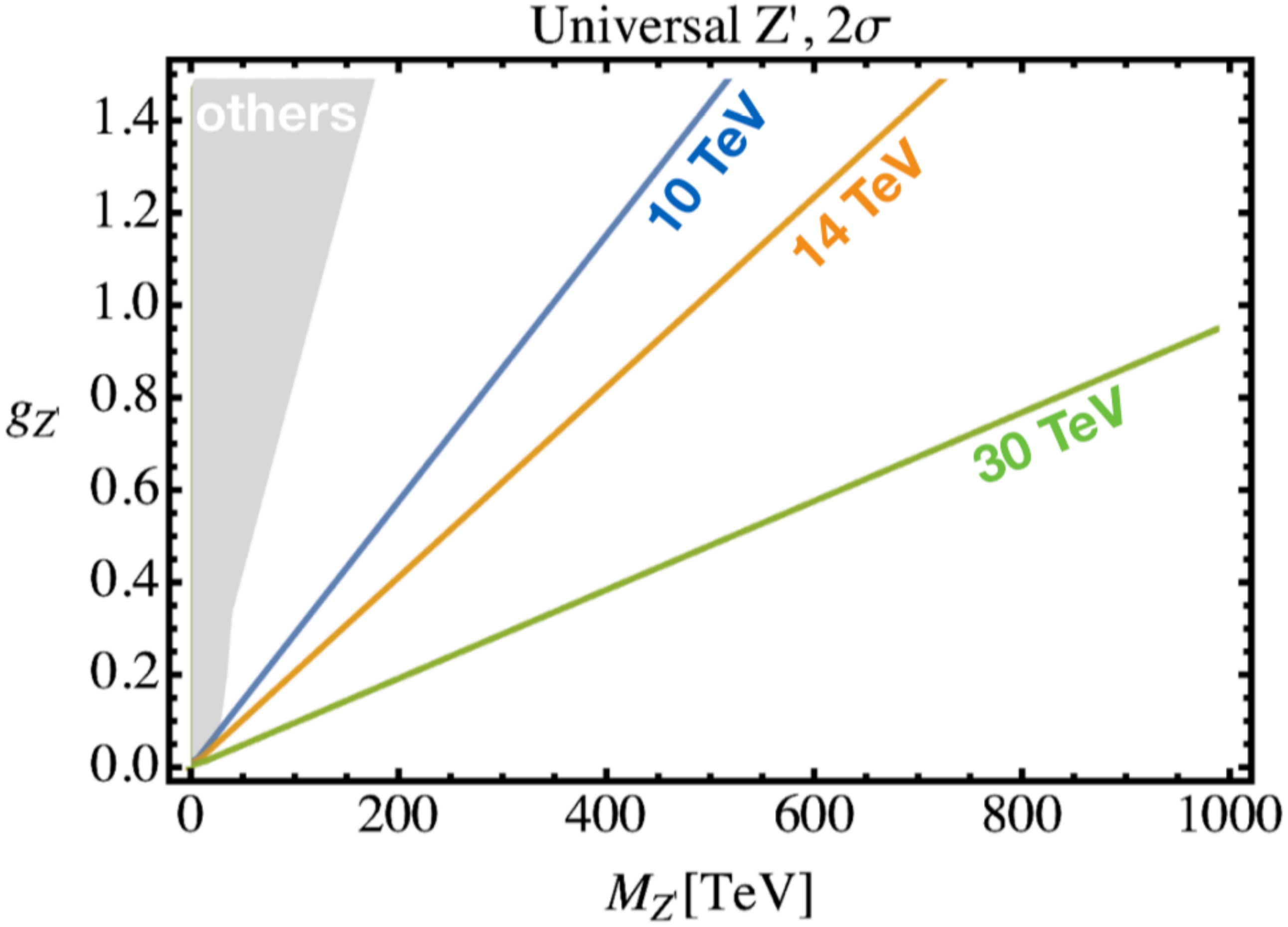
QED corrections $\approx \dfrac{2\alpha}{\pi}\log\dfrac{s}{m_\mu^2} \lesssim 10\%$

Direct searches: Z’

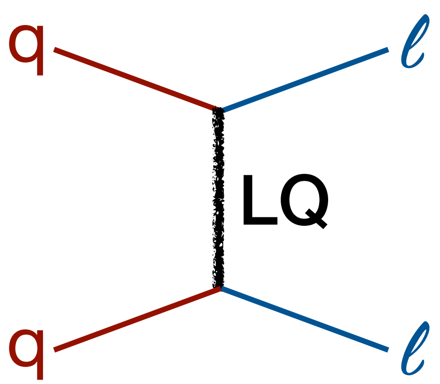
“Standard” Future Colliders



Muon Collider



Coloured resonances: 3rd generation leptoquarks



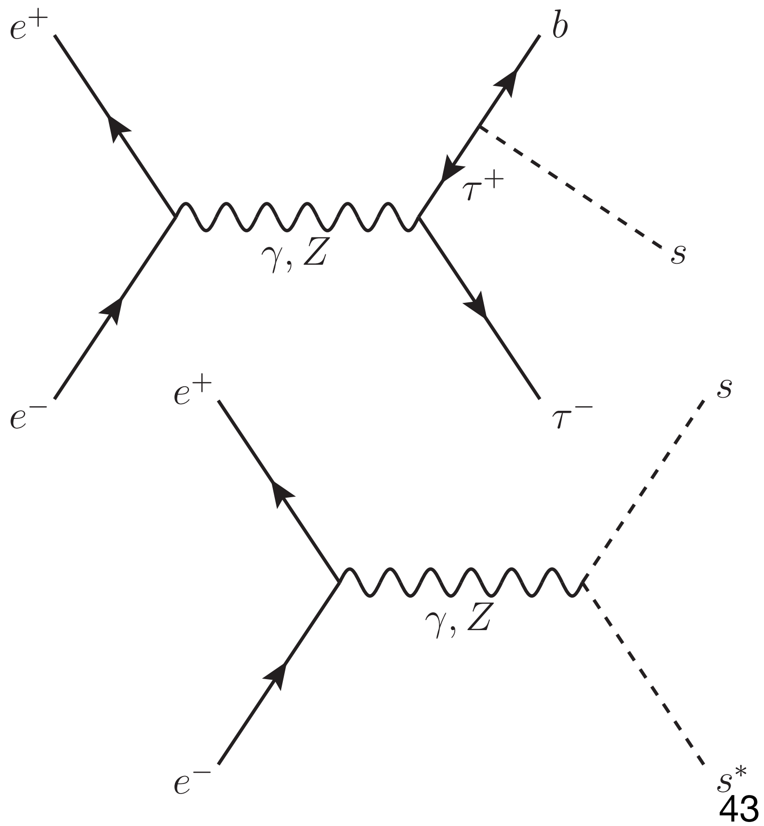
- Different signature compared to more "standard" BSM
- Interesting: NP coupled to 3rd generation fermions (*B physics anomalies!*)
- Can be either scalar or vector
- Difficult searches at LHC: High Lumi reach ~ 1.5 TeV

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

3rd generation LQ production at a lepton collider:

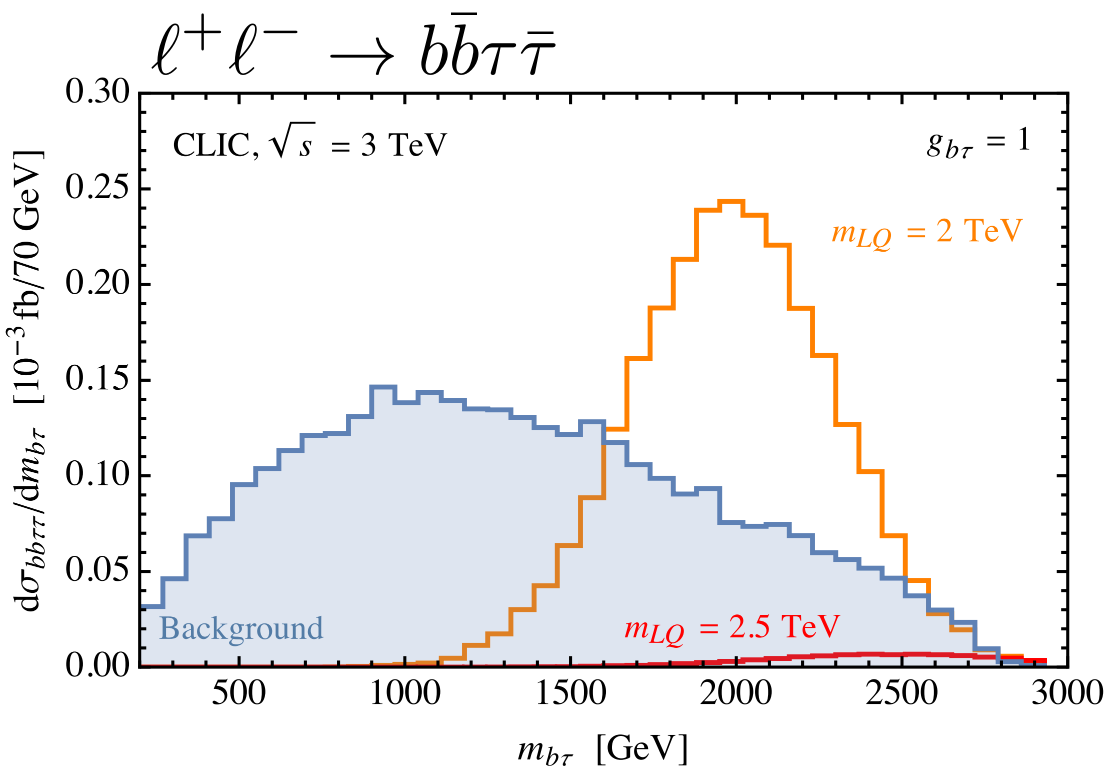
- Pair production: large cross-section when allowed, does not depend on coupling to fermions
- Single production: radiation from bb or ττ pair

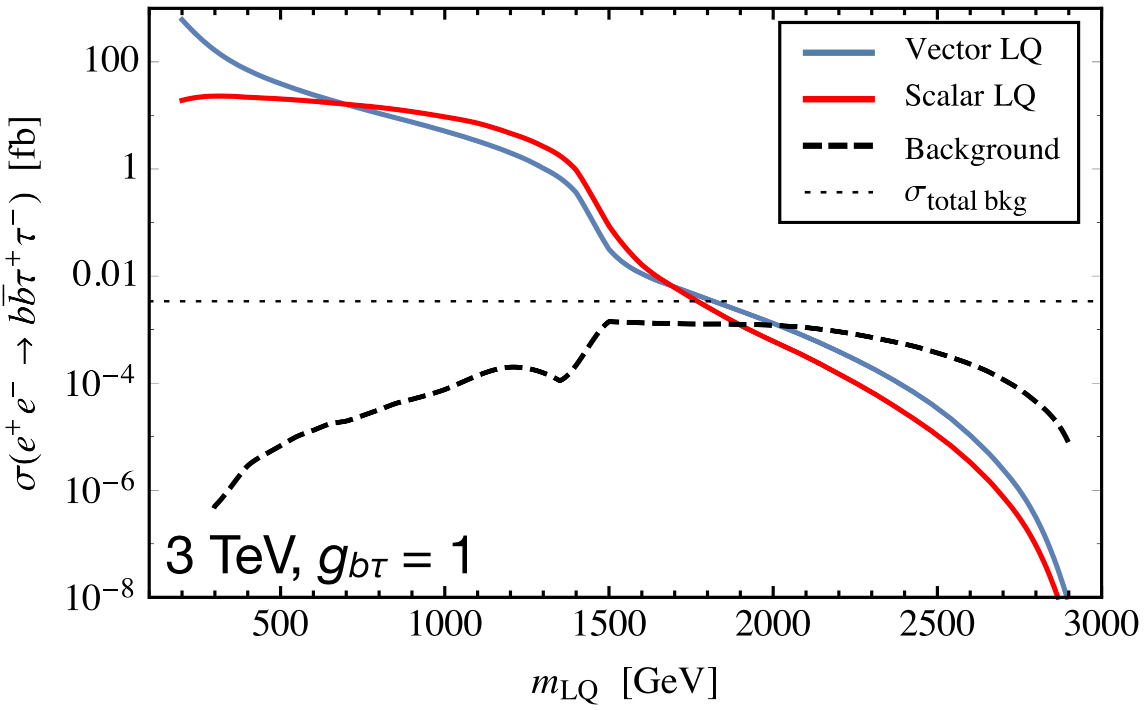
➡ bbττ final state, with $m_{b\tau} \sim M_{LQ}$



B, Greljo, Marzocca, Nardecchia 2018

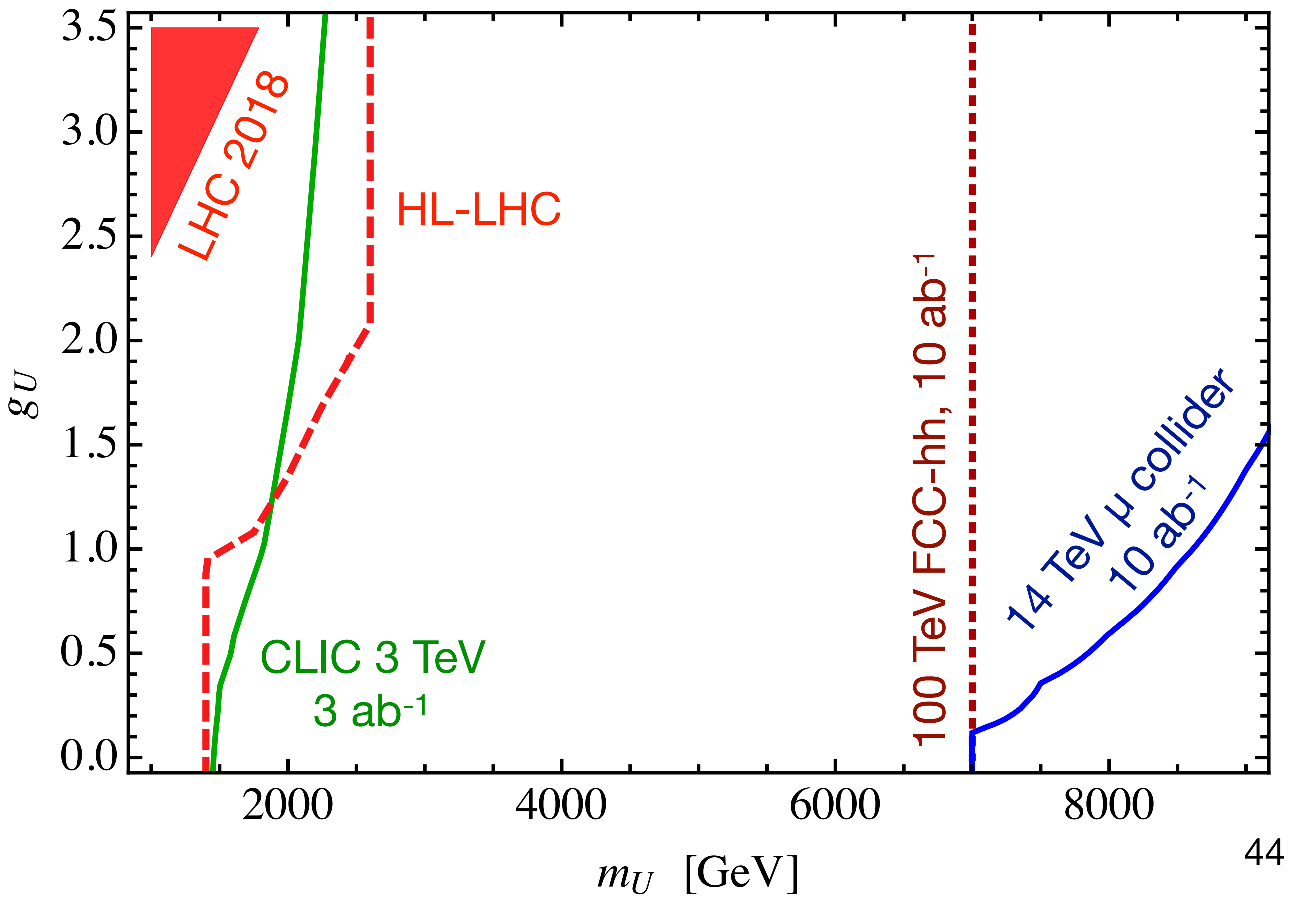
Coloured resonances: Leptoquarks





- Search is almost background-free: We set a bound simply by requiring 10 signal events

- The main limitation for CLIC is the c.o.m. energy: room for huge improvement at a μ-collider

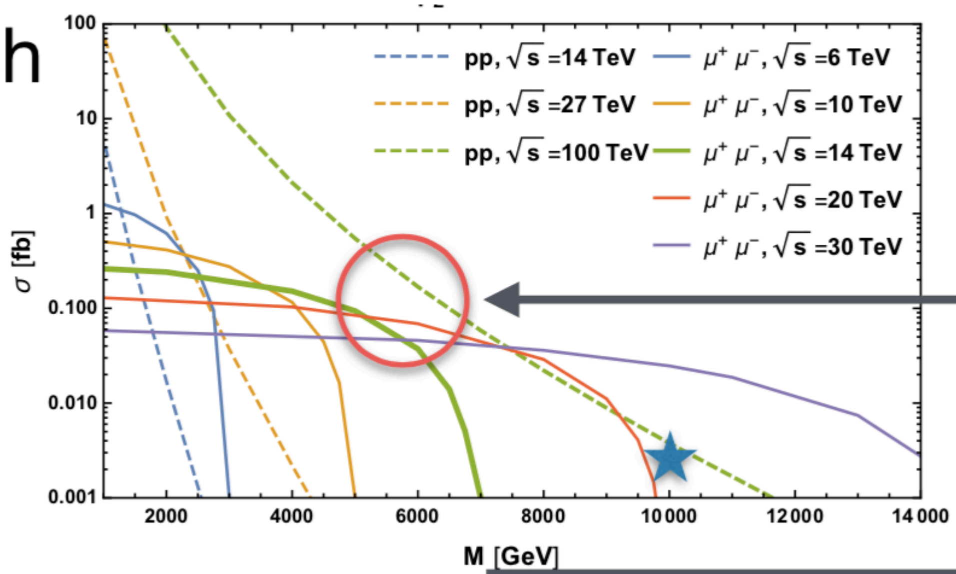


Direct searches

★ = FCC reach

14 TeV μ-collider ~ FCC@100 TeV

Stop



Top-Partners