Two paths toward precision at a High Energy Lepton Collider

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

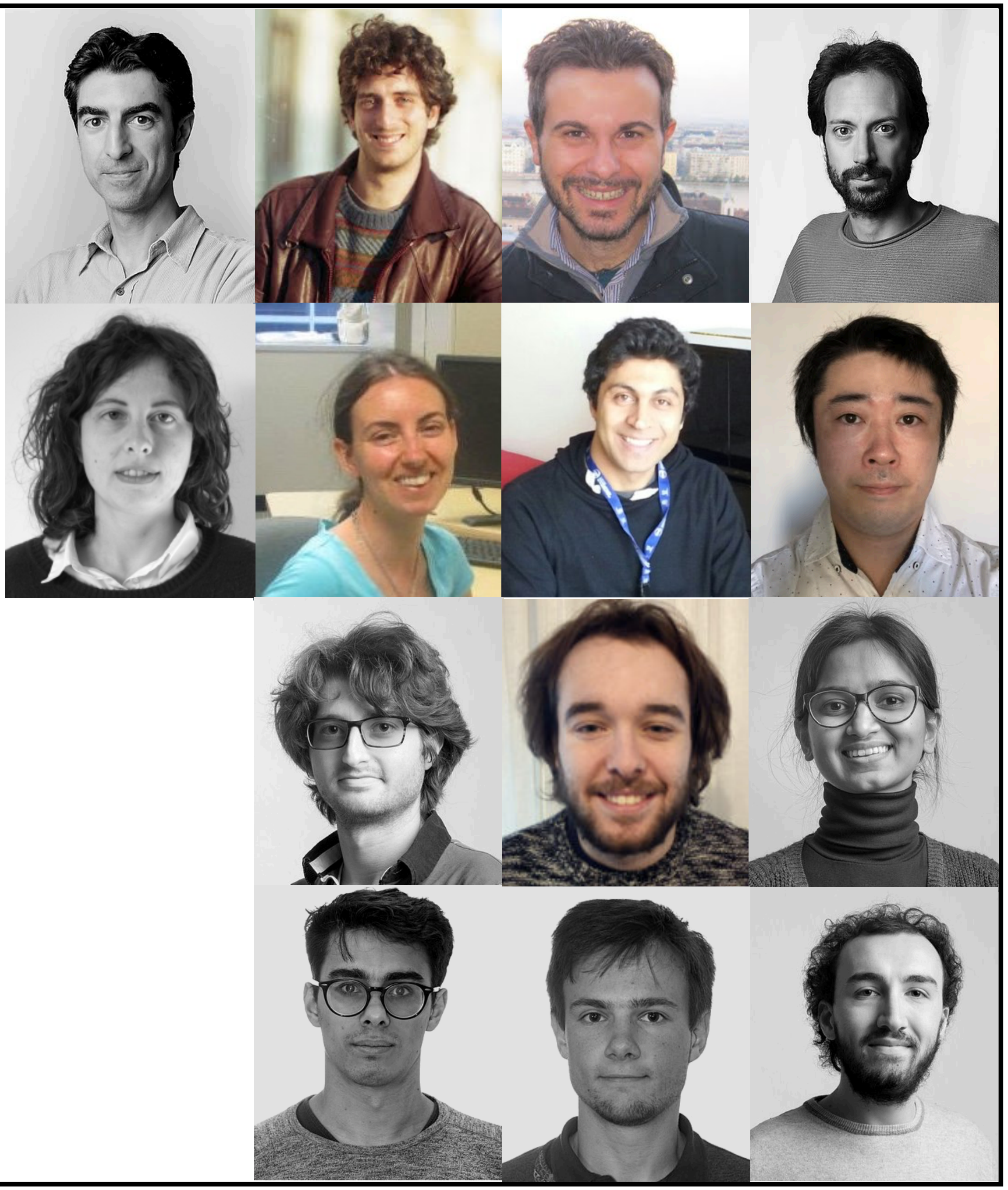
Istituto Nazionale di Fisica Nucleare

Dario Buttazzo

INFN Pisa — Seminario di Sezione — 12.5.2021

TPPC – Theoretical Particle Physics and Cosmology

Sezione di Pisa



Membri permanenti:

Roberto Contino (SNS), Dario Buttazzo (INFN), Paolo Panci (Unipi), Enrico Trincherini (SNS)

Postdoc:

Benedetta Belfatto (Unipi), Adrien Kuntz (SNS), Christian Gross (Unipi), Parsa Ghorbani (Unipi), Oleg Popov (SNS), Ryoutaro Watanabe (INFN), Natascia Vignaroli (Unipi)

Studenti Dottorato:

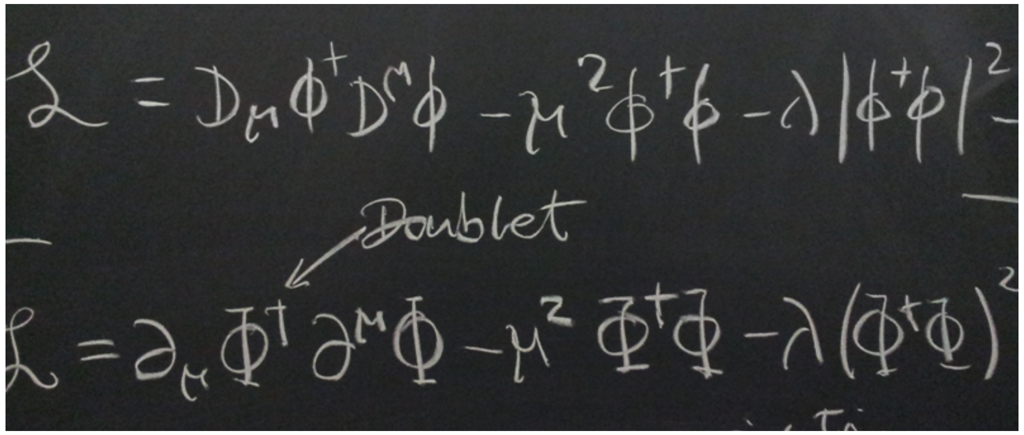
Salvatore Bottaro (SNS), Marco Costa (SNS), Giacomo Landini (Unipi), Francesco Serra (SNS), Sonali Verma (SNS), Ludovico Vittorio (SNS)

Sezione di Firenze

Membri permanenti: Michele Redi (INFN), Stefania De Curtis (INFN), Daniele Dominici (Unifi), Diego Redigolo (INFN), Andrea Tesi (INFN), Roberto Casalbuoni (Unifi)

Postdoc: Luigi Delle Rose, Rafael Delgado Lopez, Chen Zhang, Raghuveer Garani

Linee di ricerca

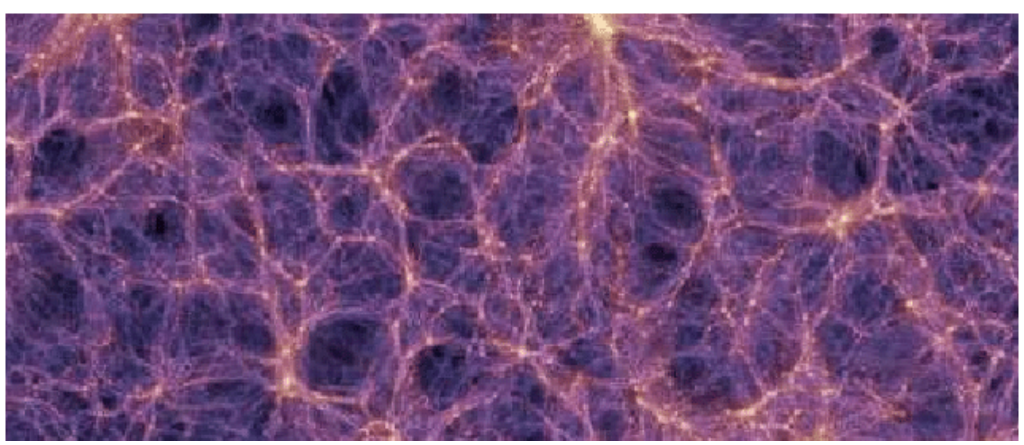


Beyond the Standard Model

- SM extensions at and above the TeV scale
- Experiments at intensity frontier and light new particles
- Flavour physics

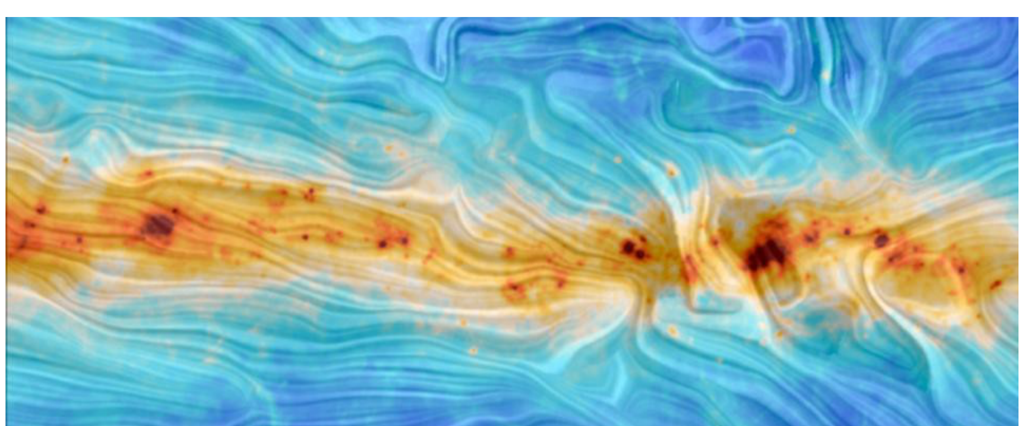
Collider Phenomenology

- LHC physics and future colliders
- Precision measurements and collider searches through machine learning



Dark Matter

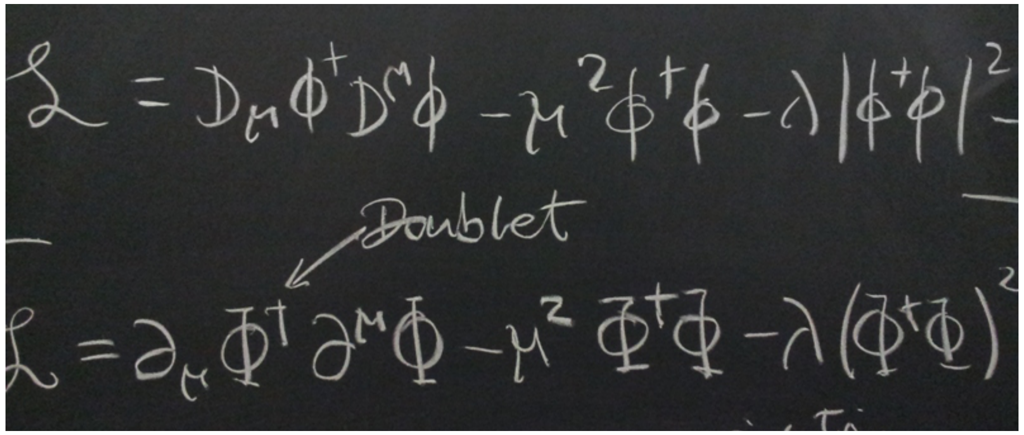
- DM models in gauge theories and beyond
- Indirect and direct detection experiments
- Light DM and axions



Gravity and Cosmology

- Gravitational waves from BSM physics
- Compact mergers and weakly coupled new physics

Linee di ricerca

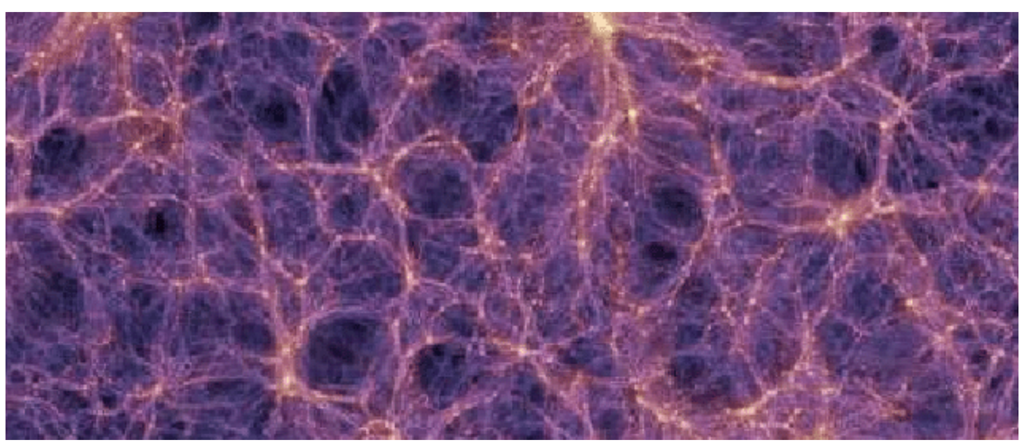


Beyond the Standard Model

- SM extensions at and above the TeV scale
- Experiments at intensity frontier and light new particles
- Flavour physics

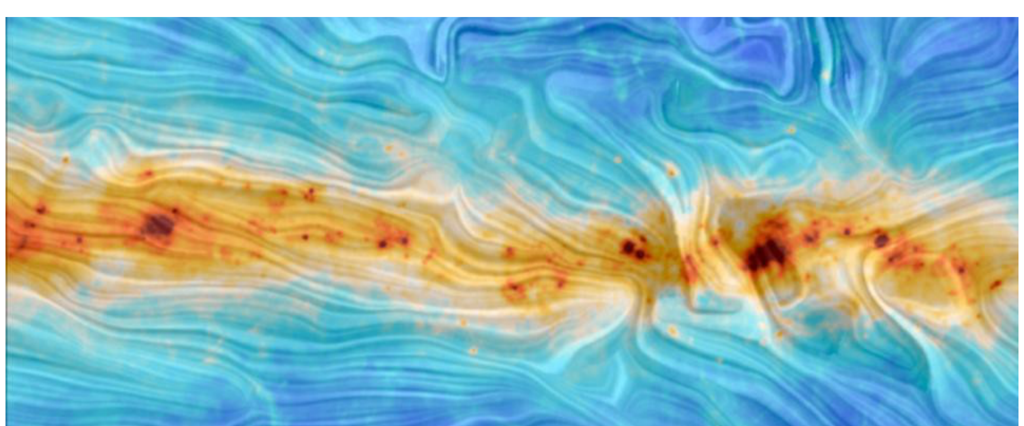
Collider Phenomenology

- LHC physics and future colliders
- Precision measurements and collider searches through machine learning



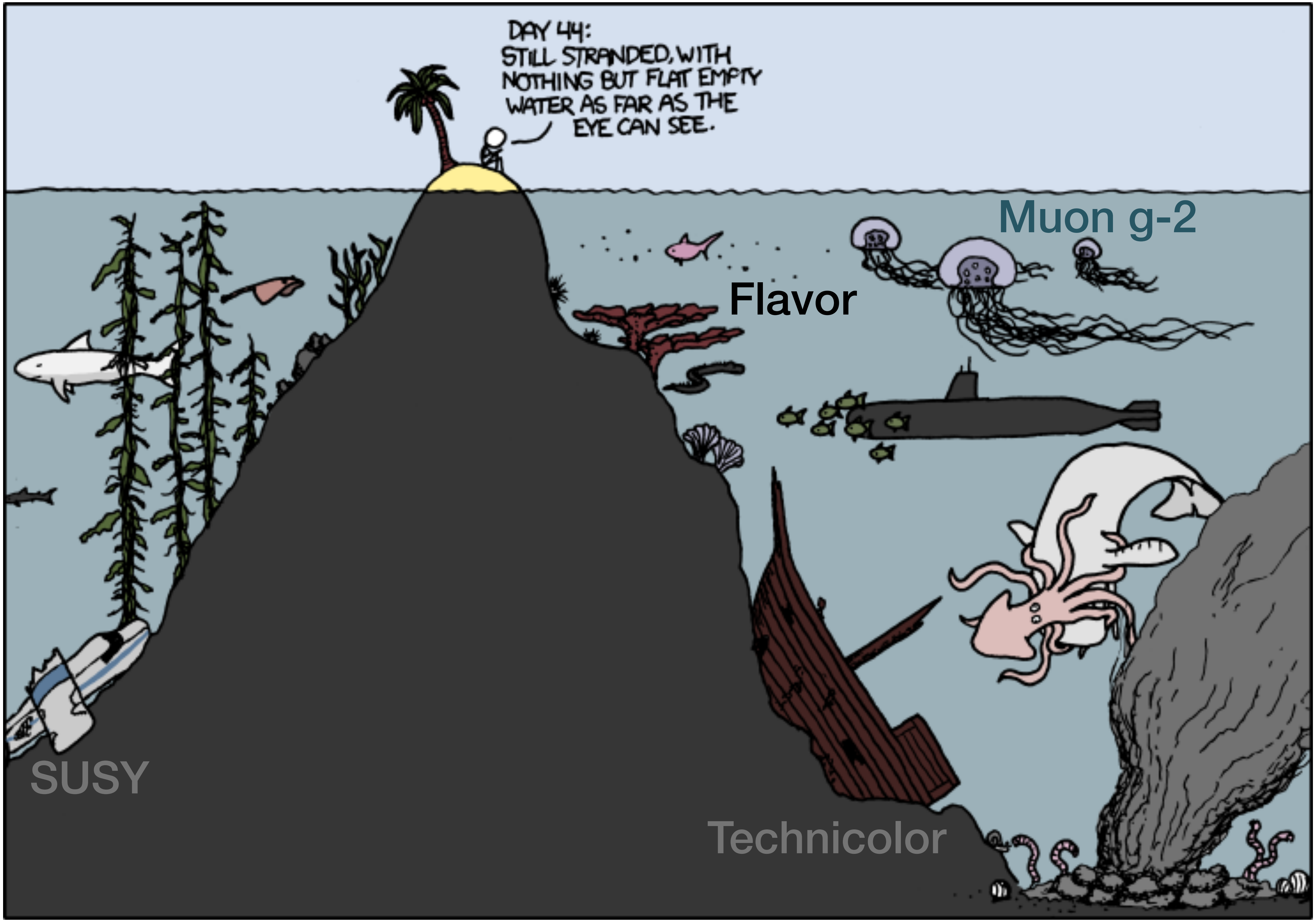
Dark Matter

- DM models in gauge theories and beyond
- Indirect and direct detection experiments
- Light DM and axions

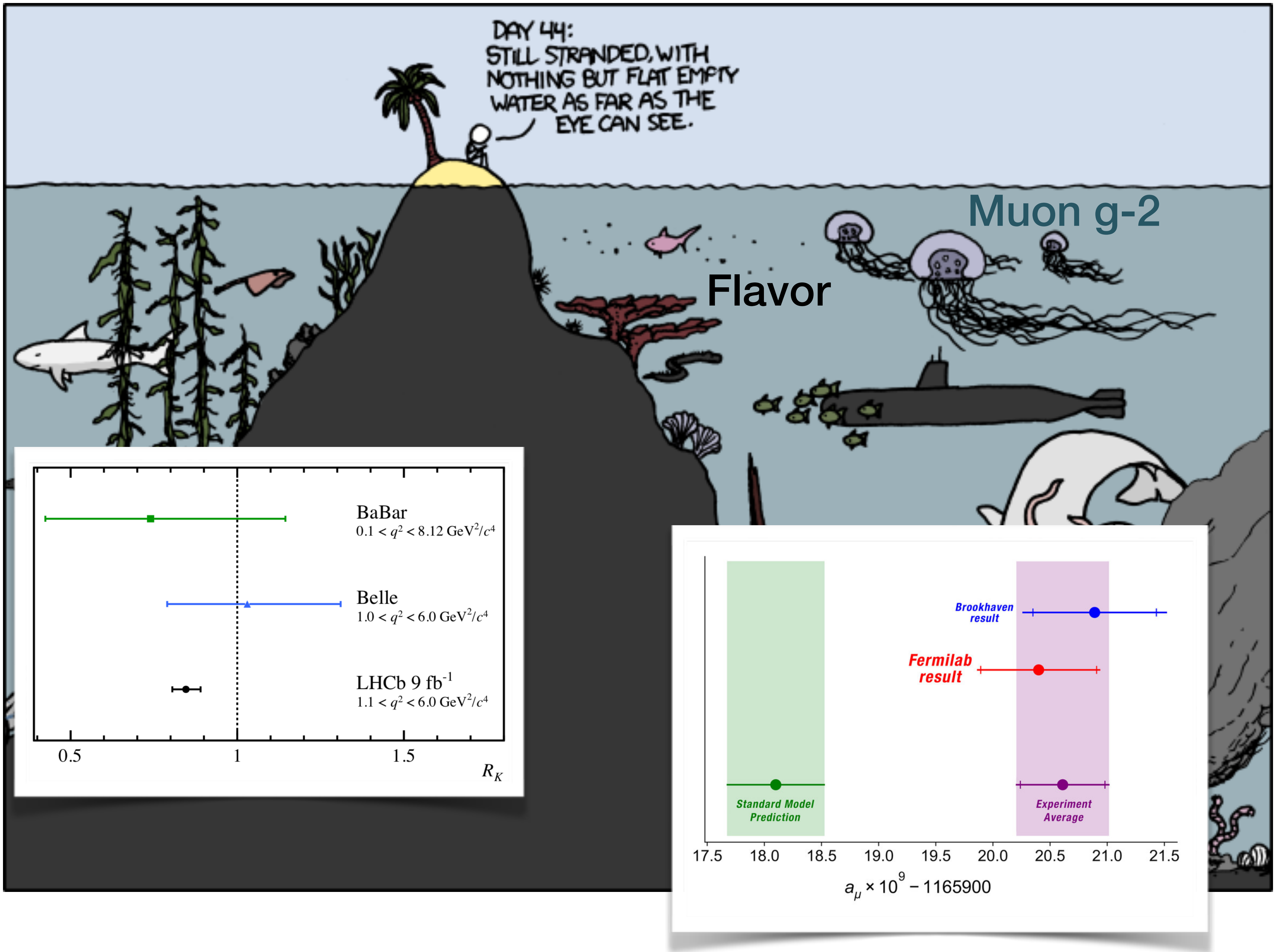


Gravity and Cosmology

- Gravitational waves from BSM physics
- Compact mergers and weakly coupled new physics


DAY 44:
STILL STRANDED, WITH NOTHING BUT FLAT EMPTY WATER AS FAR AS THE EYE CAN SEE.
Muon g-2
Flavor
SUSY
Technicolor

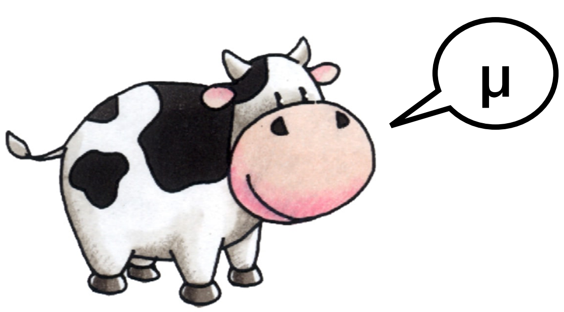
Collider physics in 2021: a theorist's view



Collider physics after 2021

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

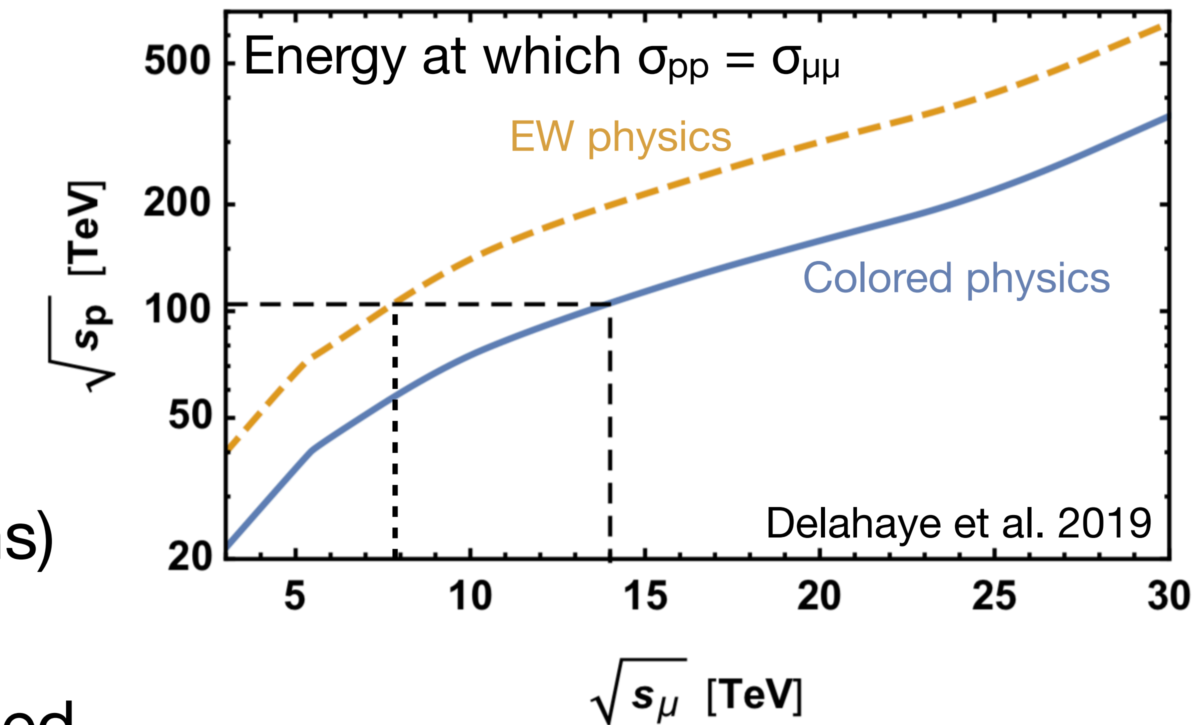
- ✦ No guaranteed discoveries: exploration of new domains
- ✦ No single experiment can explore all possible directions
- ✦ High-energy collider has guaranteed science output: possibility to perform physics measurements in unknown energy domain. Either validation of SM, or groundbreaking discovery.
- ✦ Expensive $\Longrightarrow$ need a big improvement in *as many as possible different directions* (bonus: could be built with new technology)



Muon collider is an interesting possibility!

Why muons?

- **Hadron colliders:** only small fraction of total energy available for hard scattering (hadrons are composite)



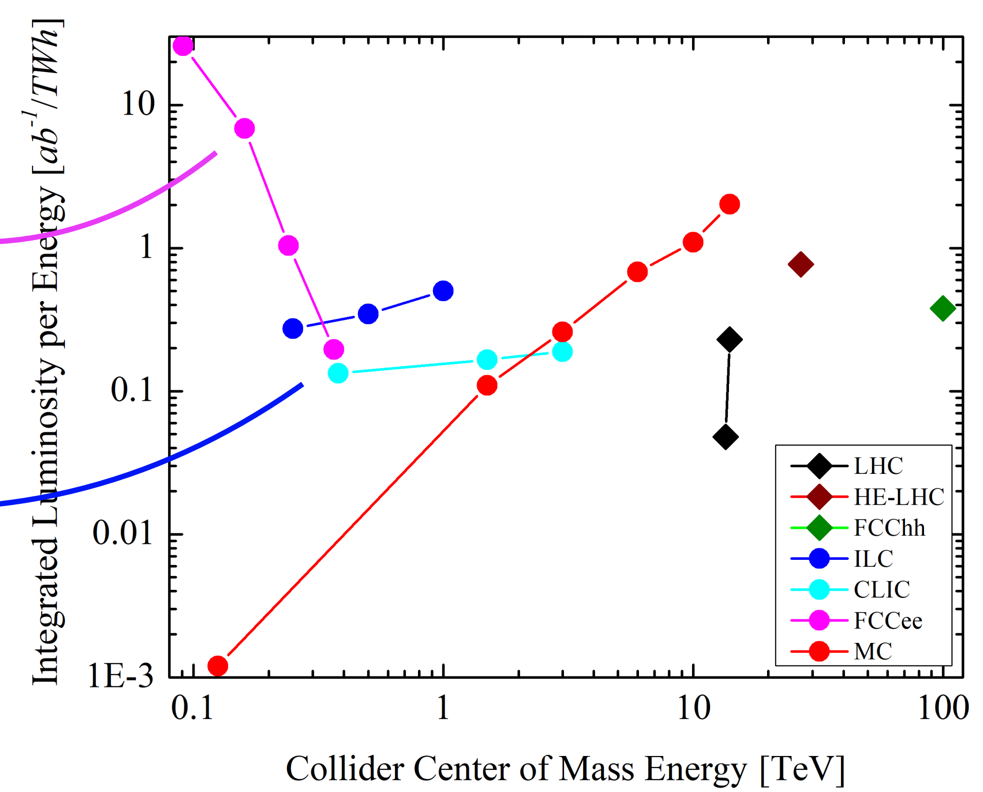
- **Lepton colliders:**
  - no energy lost in PDFs: ideal probes of short-distance physics
  - clean environment (no strong interactions)

- **Electrons** radiate too much when accelerated
  - Circular collider: energy limited by size & power consumption

$$\mathscr{L} \sim P_{\mathrm{rad}} E^{-3.5}$$

  - Linear collider: beam not recycled
    ⇒ low luminosity, high power consumption

$$\mathscr{L} \sim P_{\mathrm{RF}}$$



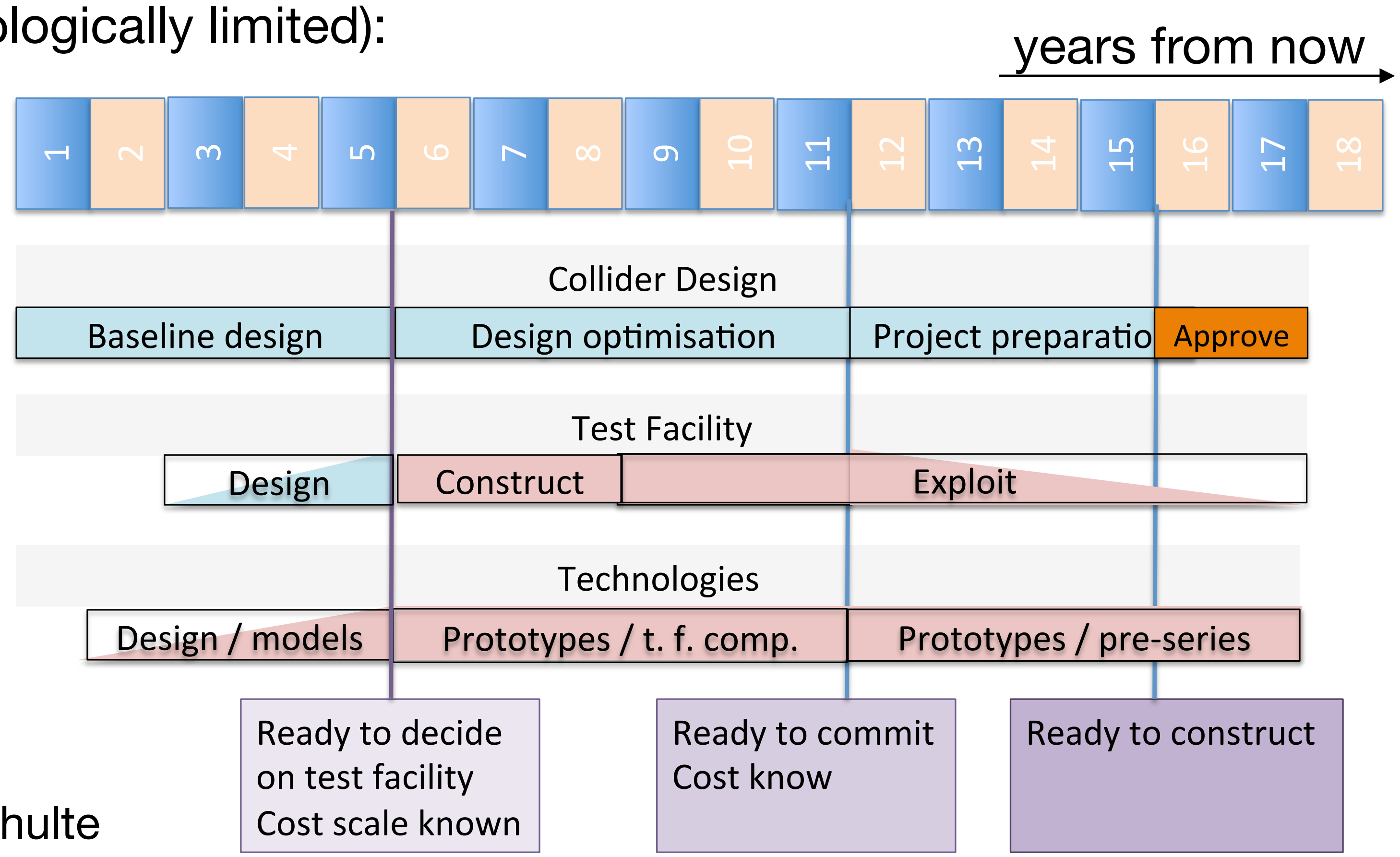
- **Muons:** elementary and heavy, perfect candidate!
But they decay…

$$\mathscr{L}/P \sim \gamma \sim E$$

Why now?

- Recent progress on muon acceleration & cooling:
  - MAP: muon collider feasibility design study — RAST **10**, No.01 (2019) 189
  - MICE: first demonstration of ionization muon cooling — Nature **578** (2020) 53
  - LEMMA: low-emittance beams from $e^+e^- \to \mu^+\mu^-$ (too low luminosity) — 1905.05747
- Muon Collider Collaboration @ CERN: assess whether the investment into full CDR and demonstrator is scientifically justified, in time for next ES update.

Timeline (technologically limited):



D. Schulte

Why now?

- Recent progress on muon acceleration & cooling:
  - MAP: muon collider feasibility design study — RAST **10**, No.01 (2019) 189
  - MICE: first demonstration of ionization muon cooling — Nature **578** (2020) 53
  - LEMMA: low-emittance beams from $e^+e^- \rightarrow \mu^+\mu^-$ (too low luminosity) — 1905.05747
- Muon Collider Collaboration @ CERN: assess whether the investment into full CDR and demonstrator is scientifically justified, in time for next ES update.

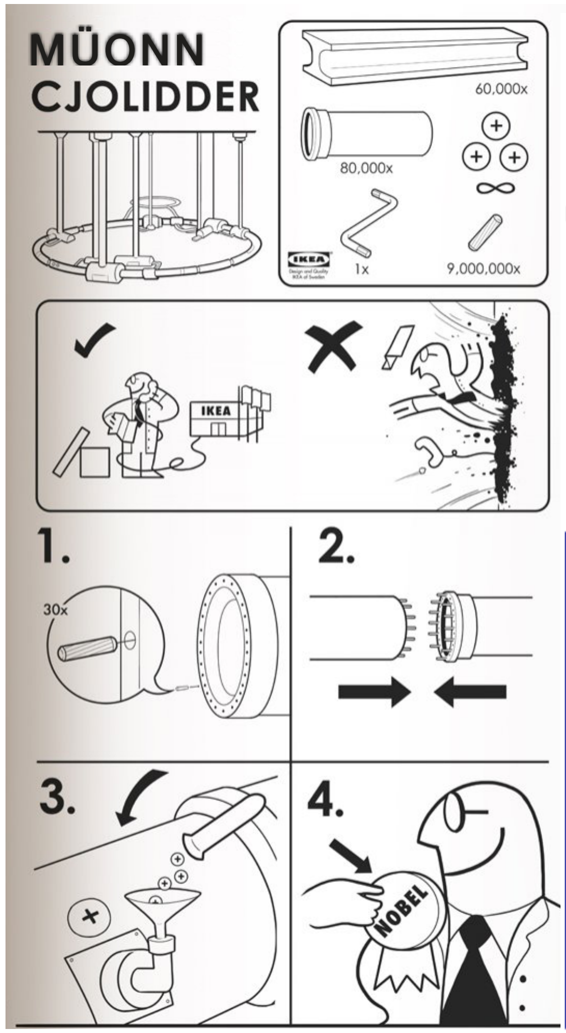
It's clearly the right time to start planning the next large collider!

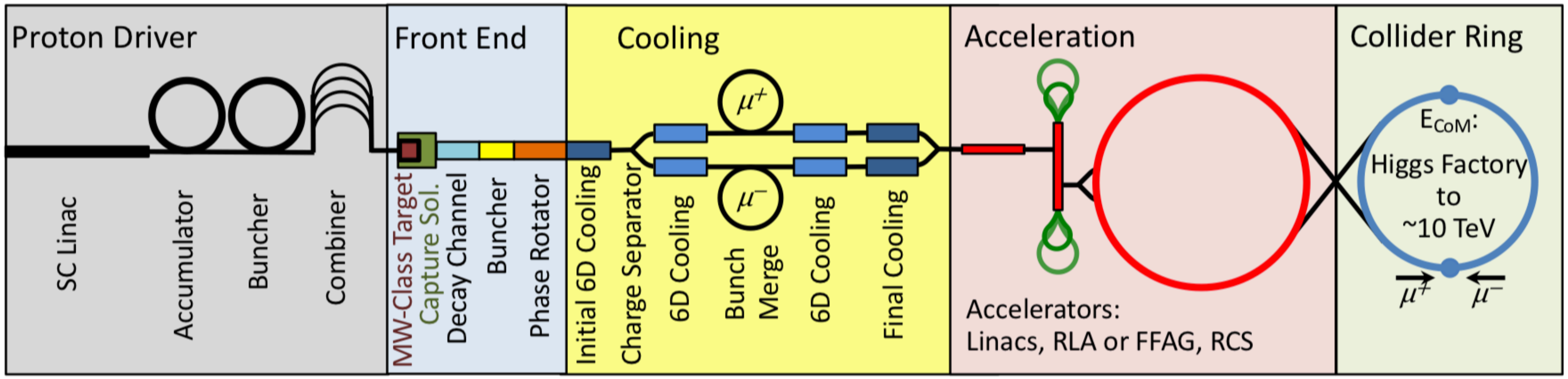
- European Strategy for Particle Physics
- Snowmass in the USA

- On the theory side: need for physics potential evaluation (to define energy, luminosity and detector performance goals).
  Strong interest in the theory community:

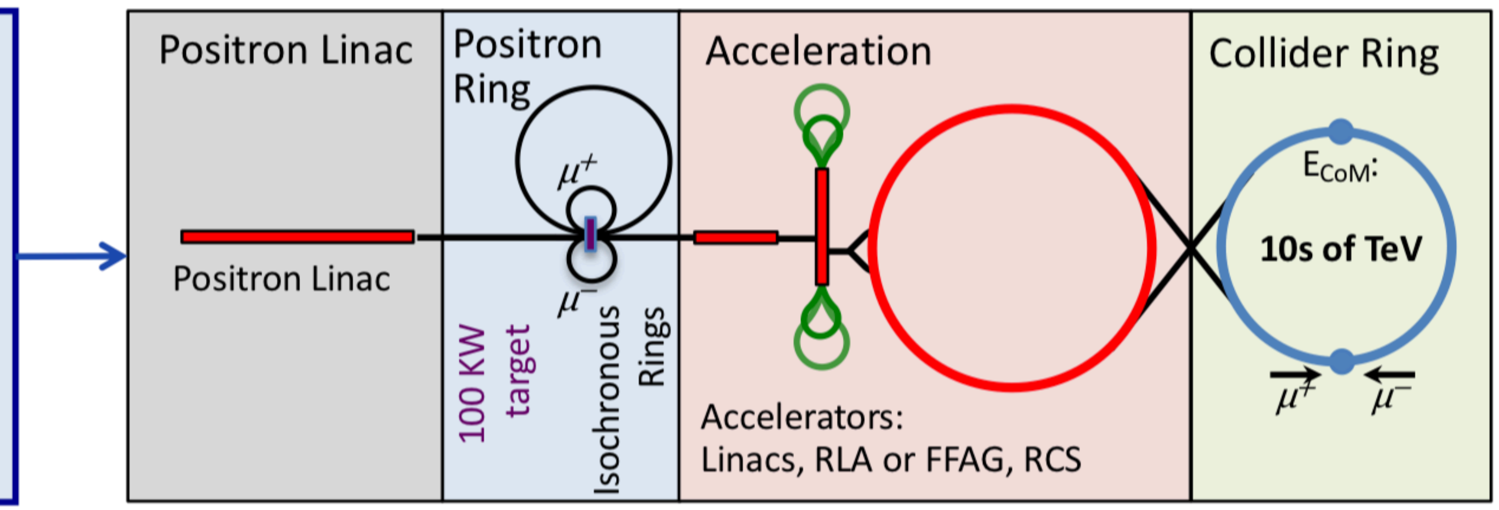
1807.04743 2005.10289 2009.11287 2101.10334
1901.06150 2006.16277 2012.02769 2102.08386
2003.13628 2007.14300 2012.11555 2103.14043
etc …

The muon collider in a nutshell

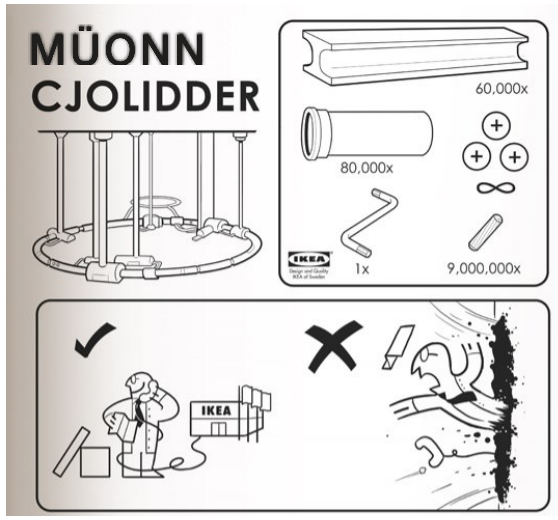


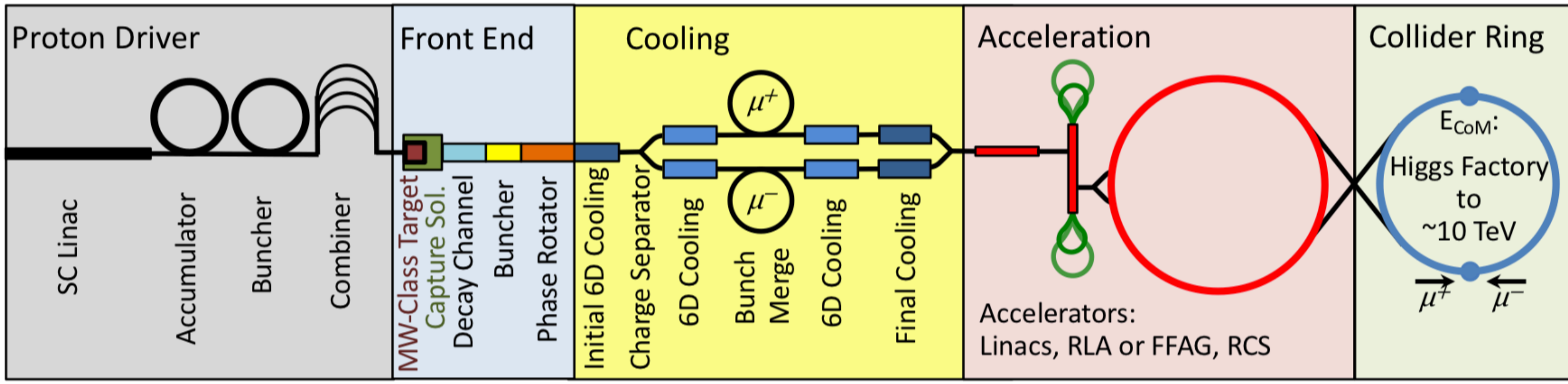


Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

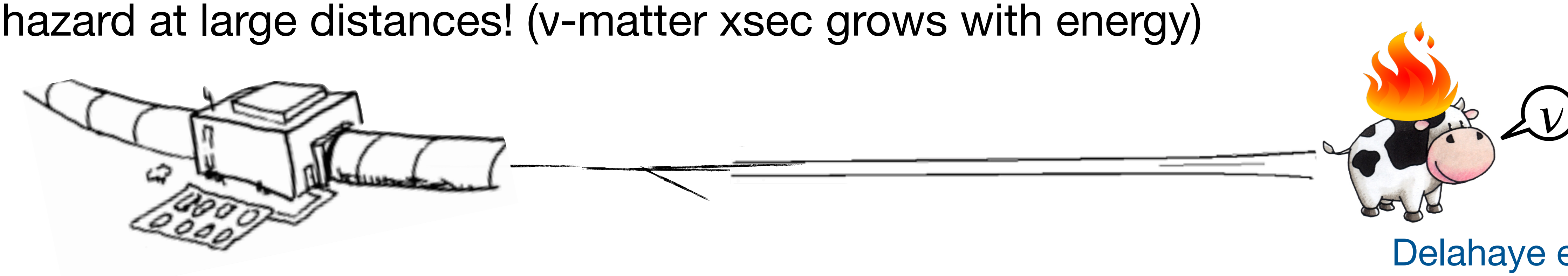


The muon collider in a nutshell





- Technological challenges: muon cooling, acceleration, …
- Detectors: large beam-induced bakground from decaying muons
- Neutrino radiation: ν flux from decaying muons so intense that can pose radiation hazard at large distances! (ν-matter xsec grows with energy)



Delahaye et al. 2019

- Luminosity $\gtrsim \dfrac{\text{5 years}}{\text{time}}\left(\dfrac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2 2\cdot 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \approx 10\,\mathrm{ab}^{-1}\left(\dfrac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2$

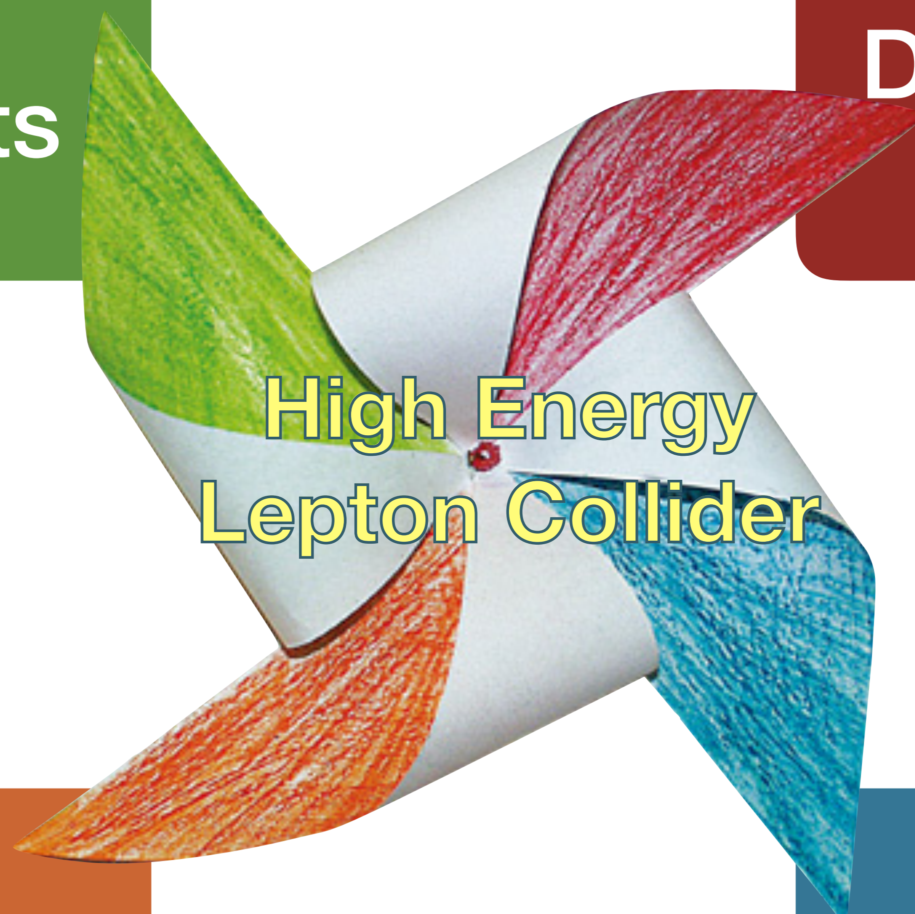
necessary to perform SM measurements with ~ % precision (10k events)

Physics cases for a High Energy Lepton Collider

From a theorist's point of view: Energy AND Precision!

High-rate measurements

Direct Searches



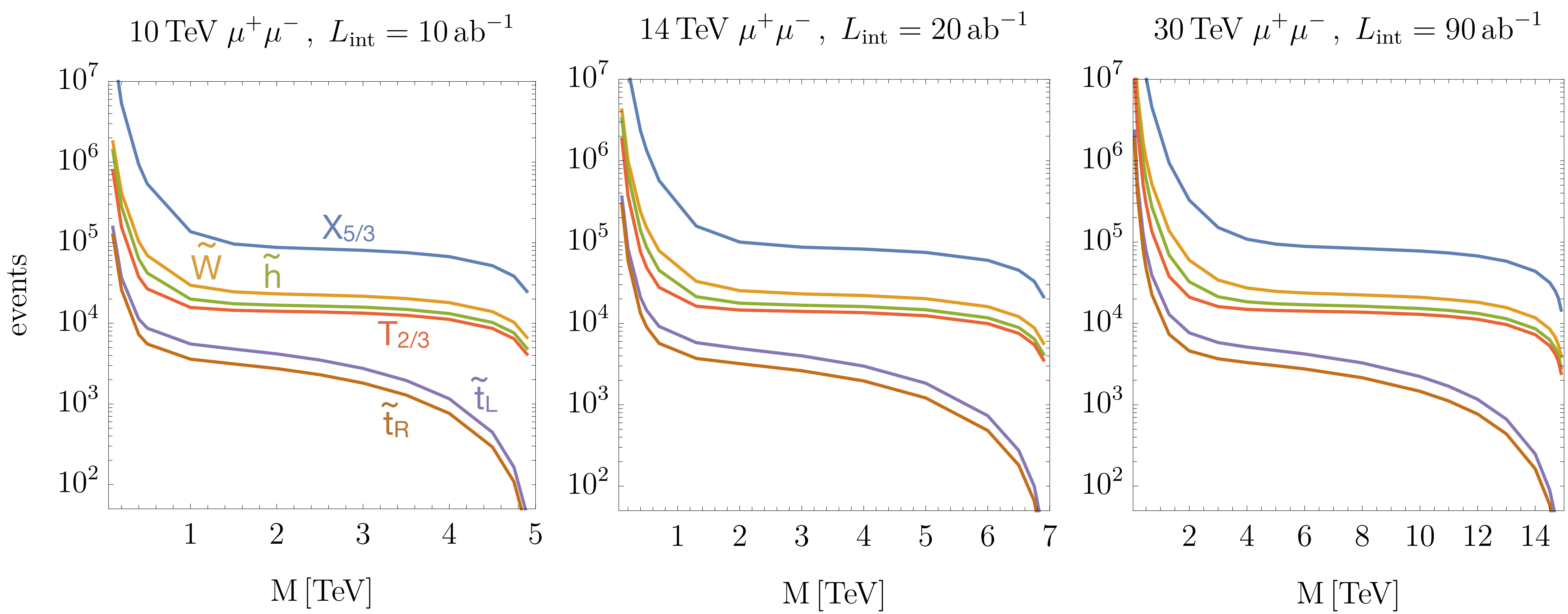
Muon-specific physics

High-energy probes

The most obvious physics case: direct searches

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

- EW pair-produced particles *up to kinematical threshold:*



Colored particles:
14 TeV μμ ~ 100 TeV pp

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

WIMP Dark Matter

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

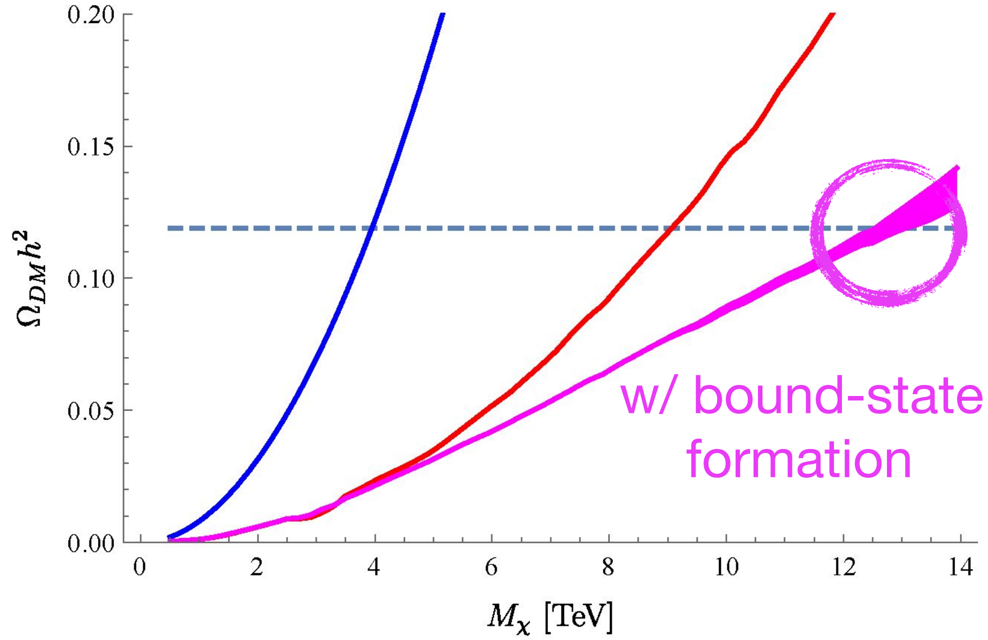
  (a) stable,

  (b) without coupling to Z & γ,

  (c) calculable (perturbative).

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

Fermion quintuplet



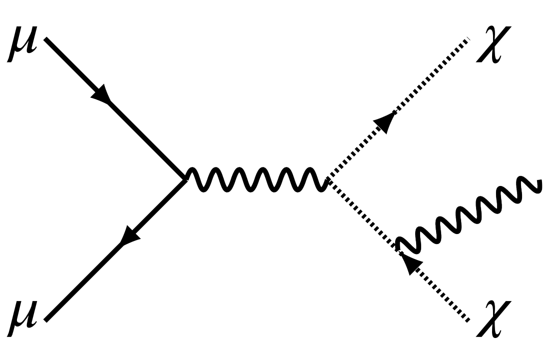
- Mass can be large: Muon-collider-energies crucial to probe some candidates!

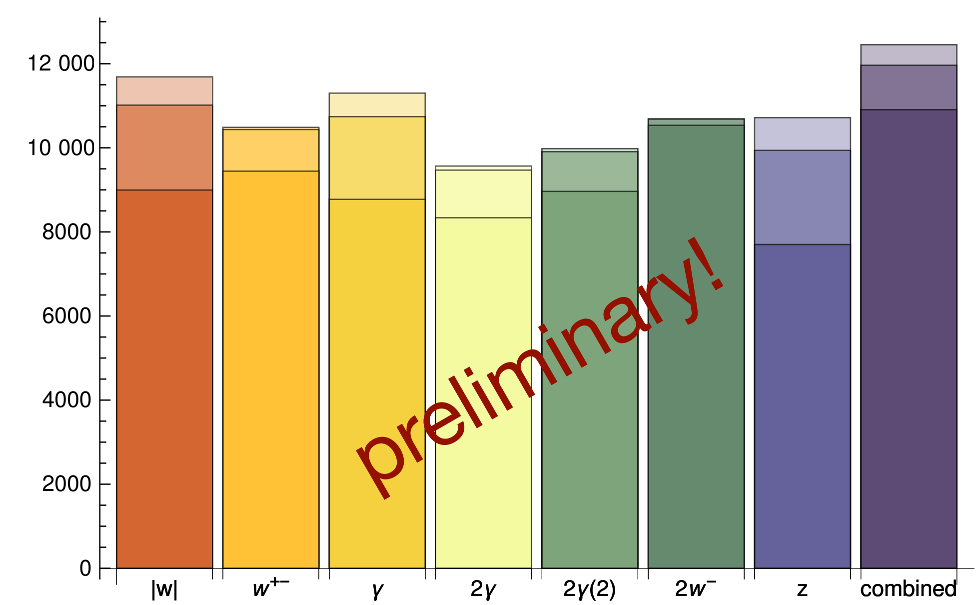
- Collider searches: mono-γ/W/Z signals

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

work in progress with
S. Bottaro, M. Costa, L. Vittorio
Franceschini, Panci, Redigolo

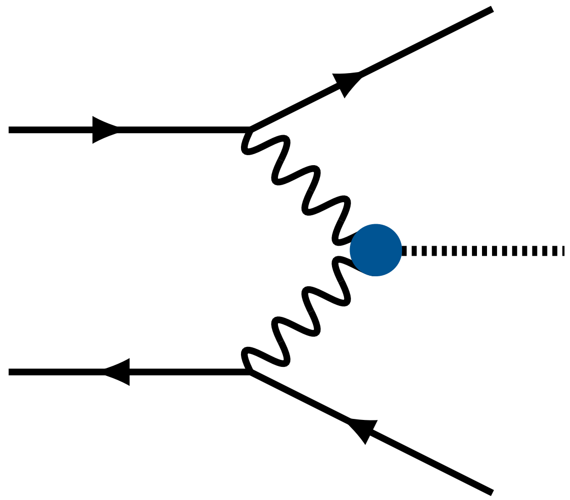
see also
Cirelli, Sala, Taoso 1407.7058
Han et al. 2009.11287



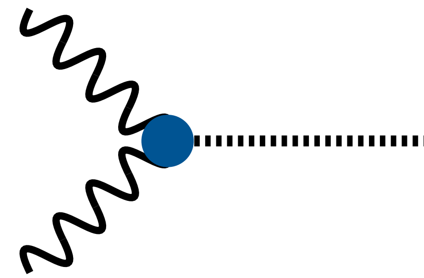


Resonances in VBF

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” $m_\phi \ll E$

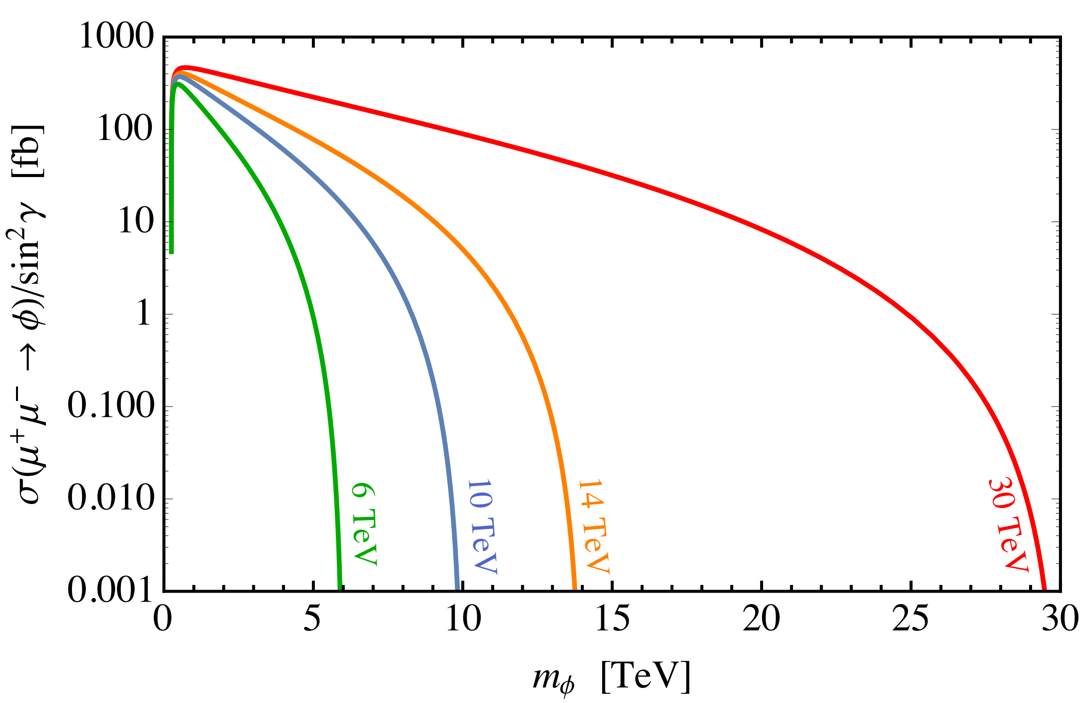
Dawson 1985

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

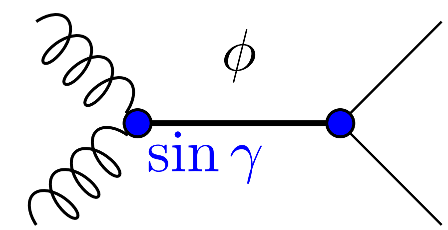
see also the “Muon Smasher’s guide”
Arkani-Hamed, Craig et al. 2103.14043

- Example: singlet scalar production $\mu^+\mu^- \to \phi\nu\nu, \quad \phi \to hh, W^+W^-, ZZ$

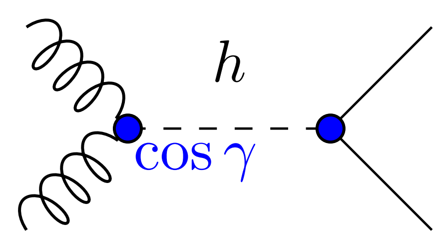
  It's like a heavy Higgs with narrow width + hh decay



$$\sigma_{\mu\mu\to\phi\nu\nu} \approx \frac{g^4 s_\gamma^2}{256\pi^3 v^2} \log \frac{s}{m_\phi^2}$$



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

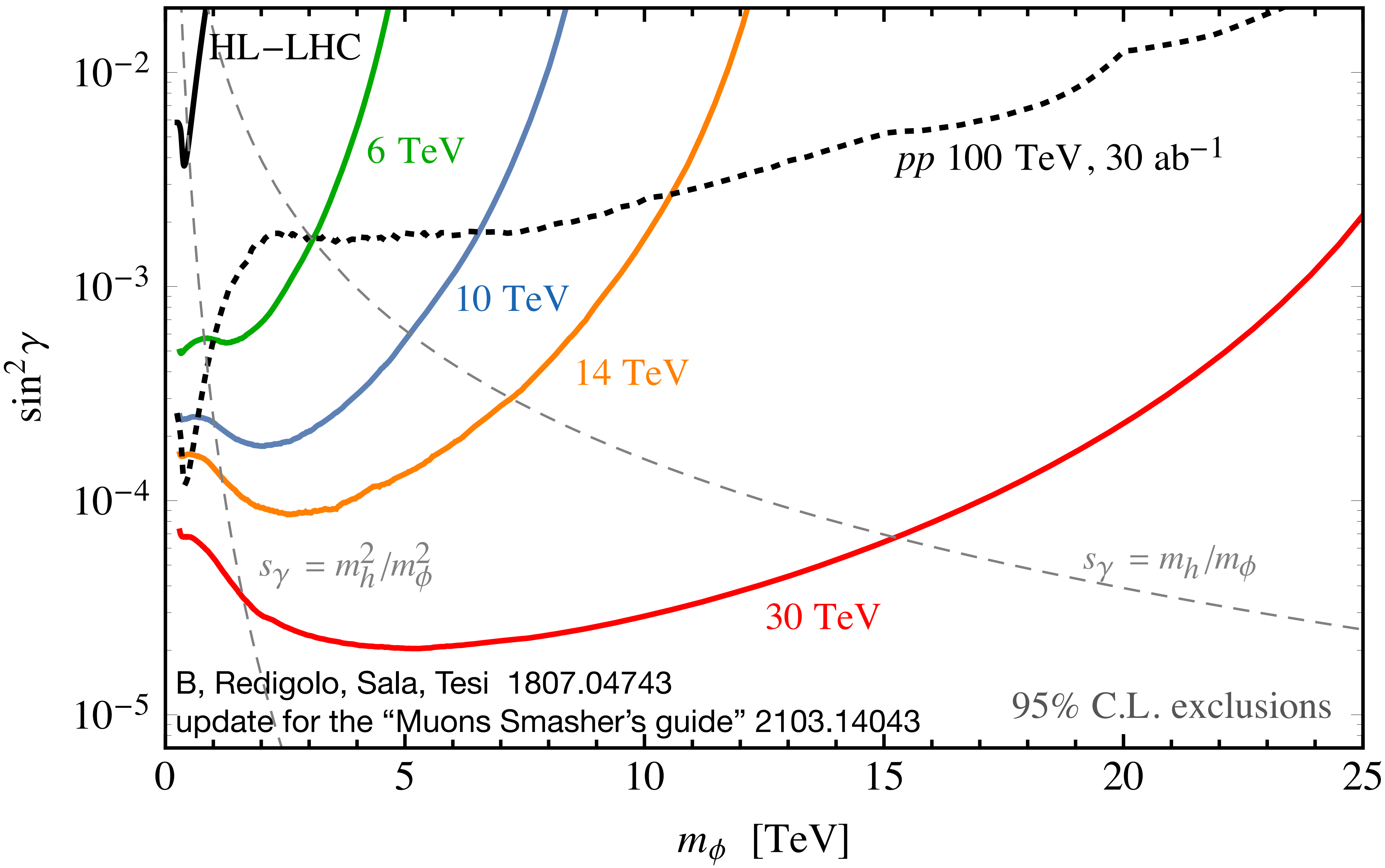


one parameter controls resonance production & Higgs couplings

Example: scalar singlet

Compare direct and indirect reach of different colliders

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

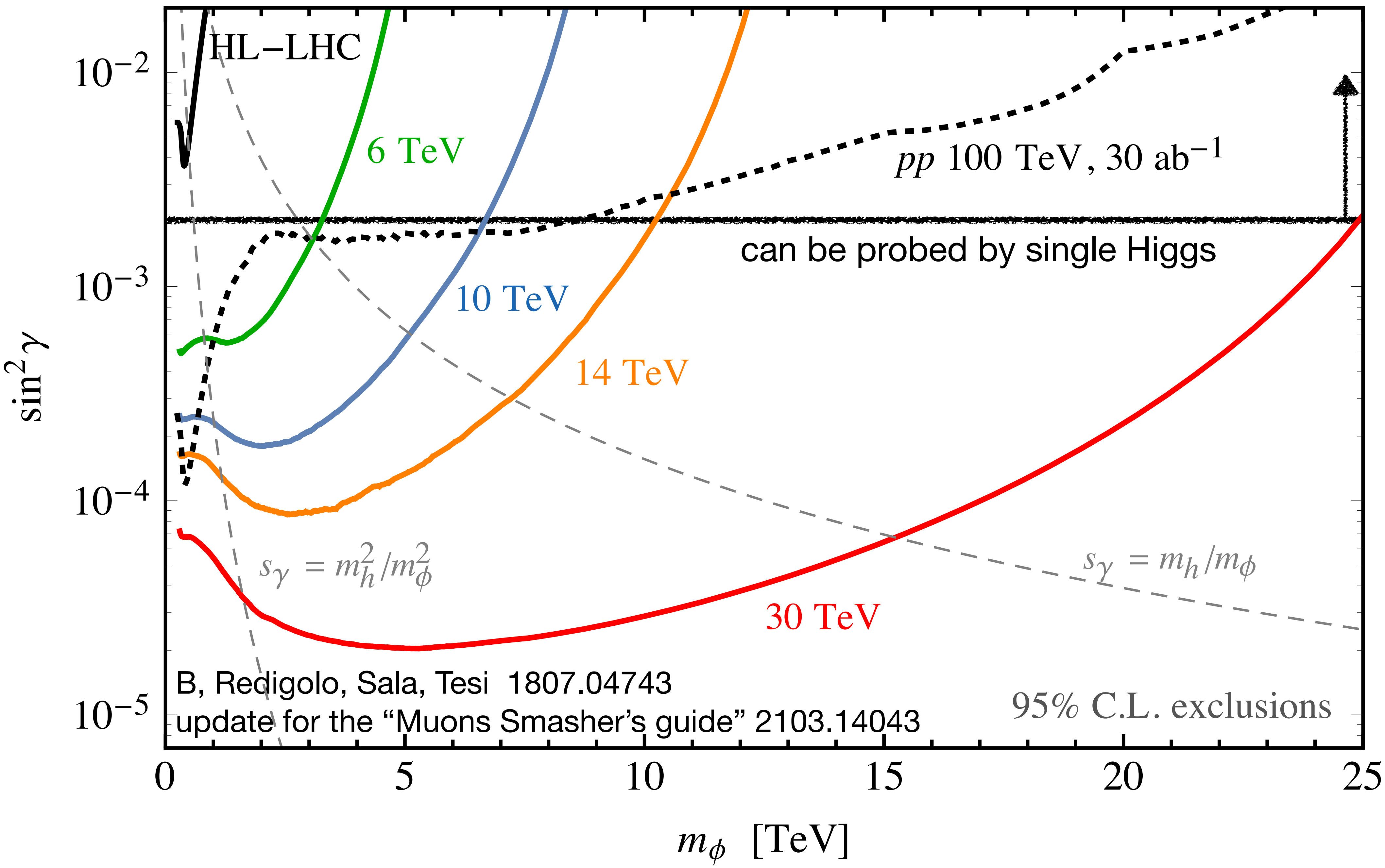


For this class of models, a high-energy $\mu^+\mu^-$ collider has an amazing reach if compared to single Higgs meas. or direct searches at a 100 TeV pp collider

Example: scalar singlet

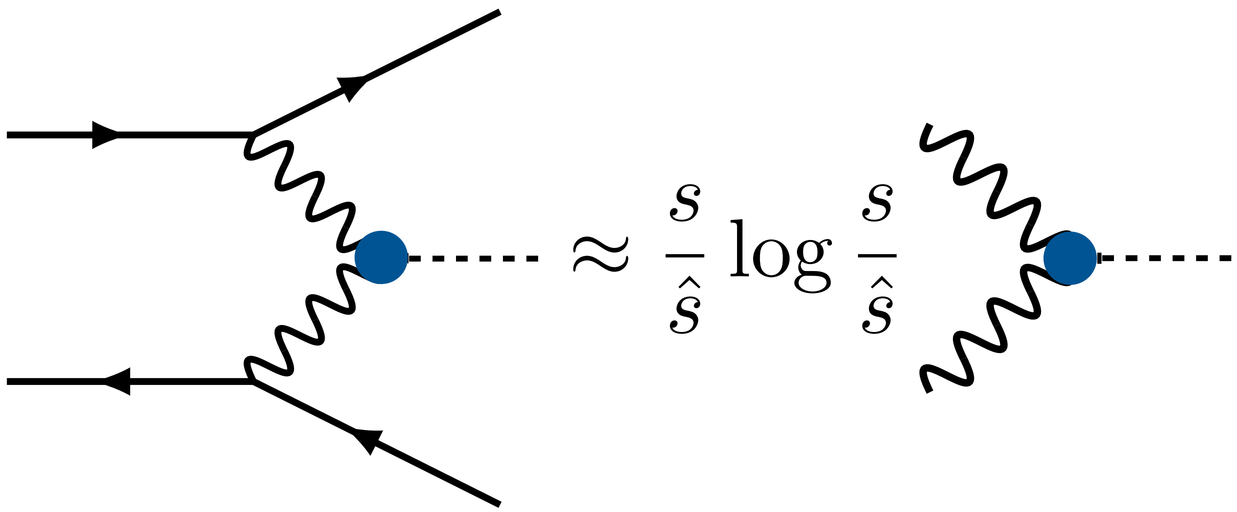
Compare direct and indirect reach of different colliders

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



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

High rate probes: Higgs physics

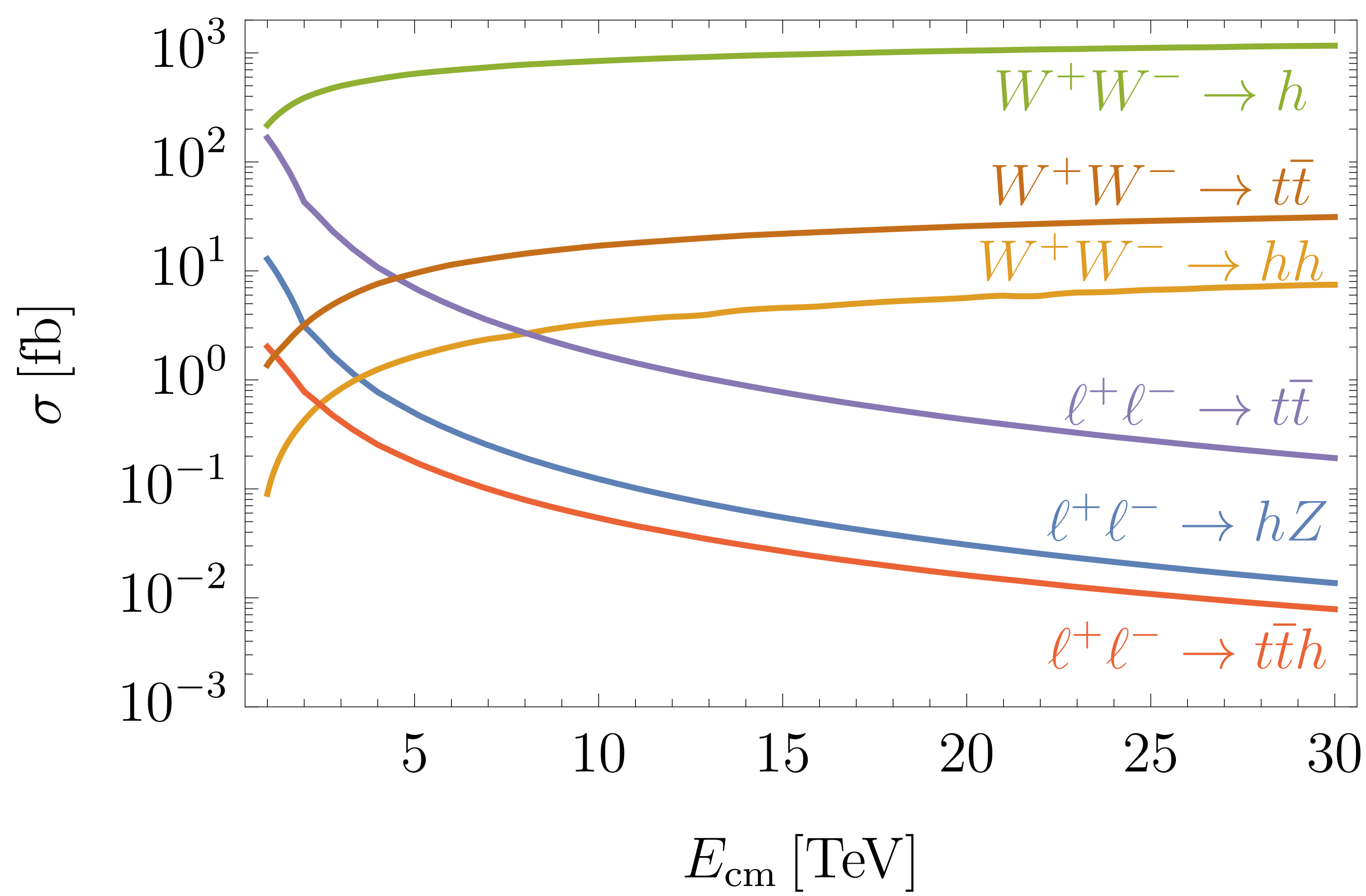


$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$

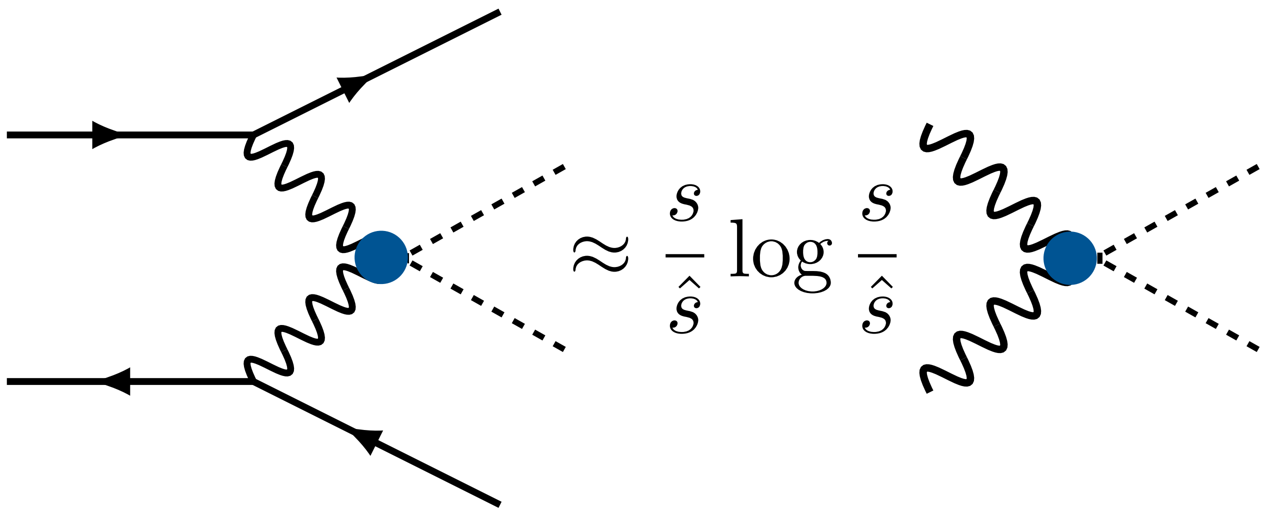
A High Energy Lepton Collider is a "vector boson collider"

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

- ✦ Very large single Higgs VBF rate (10^7–10^8 Higgs bosons)
  - Precision on Higgs couplings driven by systematics: ~ Higgs factory, maybe 1‰
  - Rare/Exotic Higgs decays!
- ✦ Large double Higgs VBF rate
  - Higgs 3-linear coupling



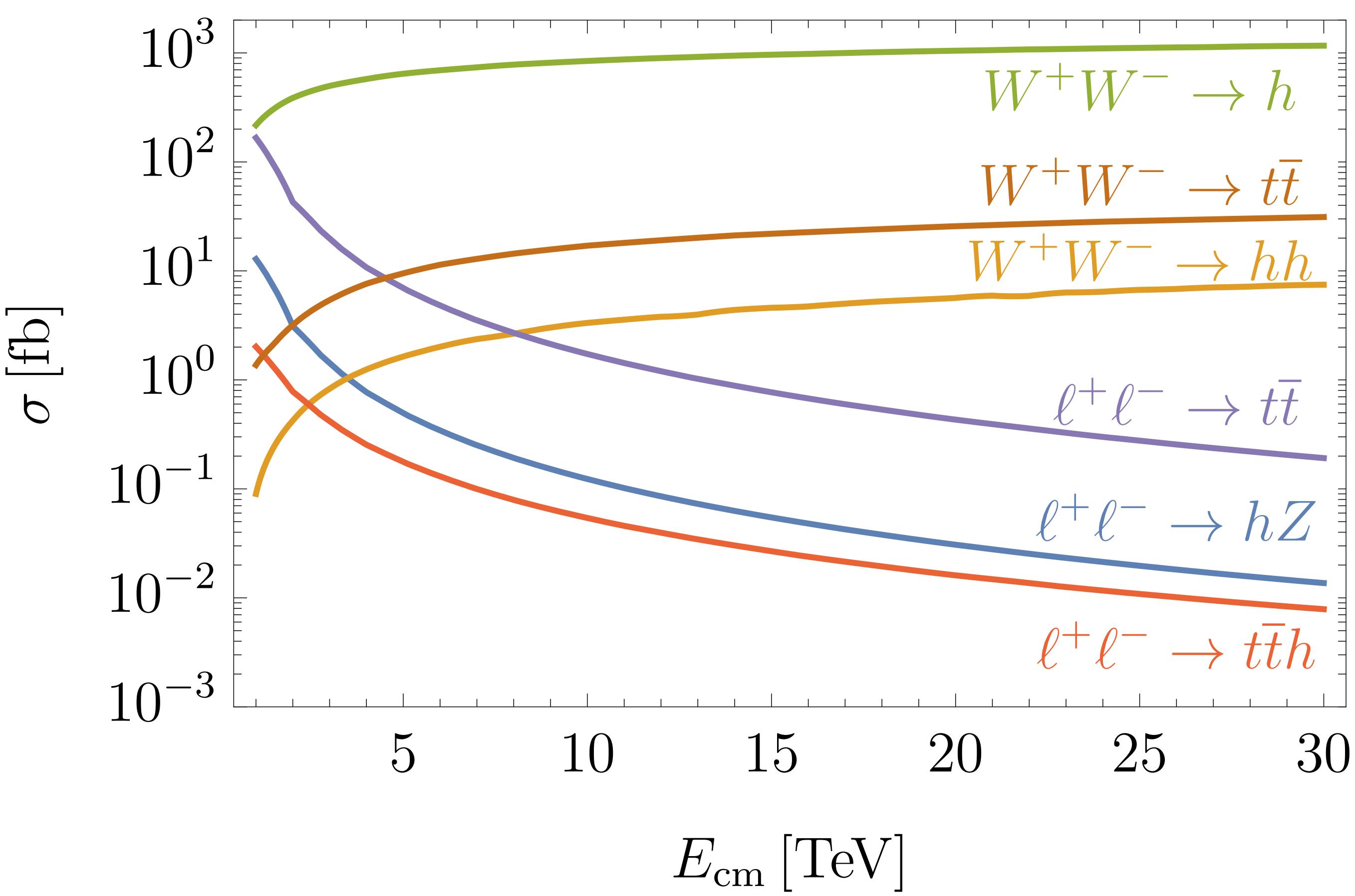
High rate probes: Higgs physics



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

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

- ✦ Very large single Higgs VBF rate (10^7–10^8 Higgs bosons)
    - Precision on Higgs couplings driven by systematics: ~ Higgs factory, maybe 1‰
    - Rare/Exotic Higgs decays!
- ✦ Large double Higgs VBF rate
    - Higgs 3-linear coupling



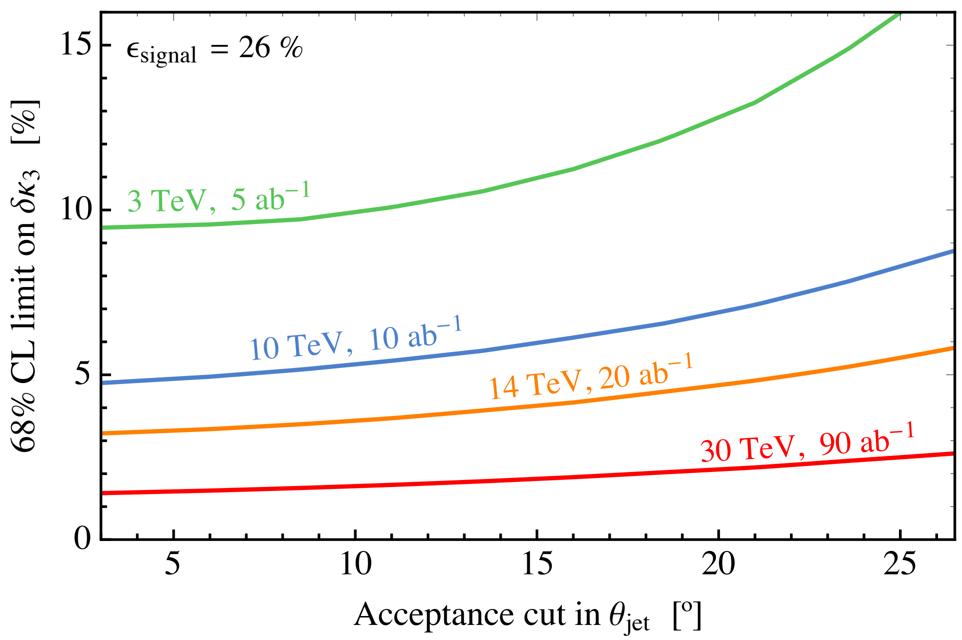
Double Higgs production

- Reach on Higgs trilinear coupling:

B, Franceschini, Wulzer 2012.11555

see also 2005.12204
2008.10289

E [TeV]	$\mathscr{L}$ [ab^{-1}]	N_{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%



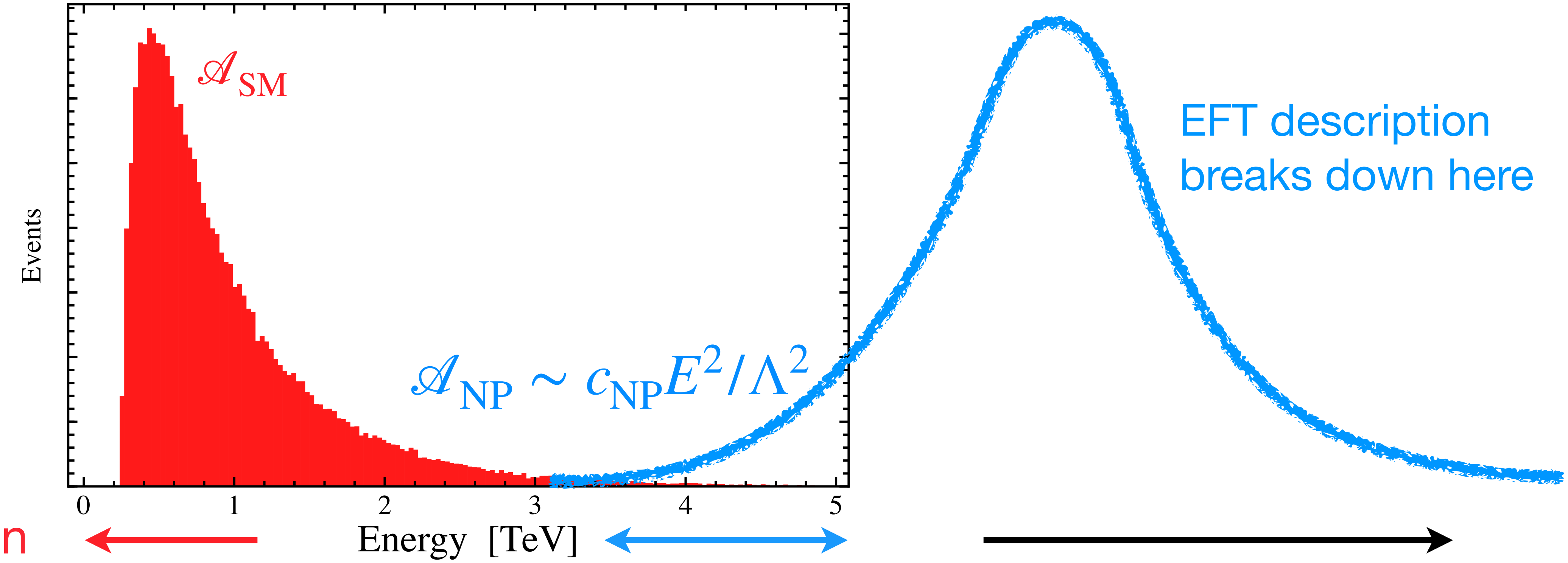
- Weak dependence on angular acceptance (signal is in the central region)
- Some dependence on detector resolution (to remove backgrounds)

see also CLIC study 1901.05897

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

High-energy probes

- NP effects are more important at high energies



Precision SM measurements

High energy (indirect) probes

direct searches

- Effective Field Theory description:

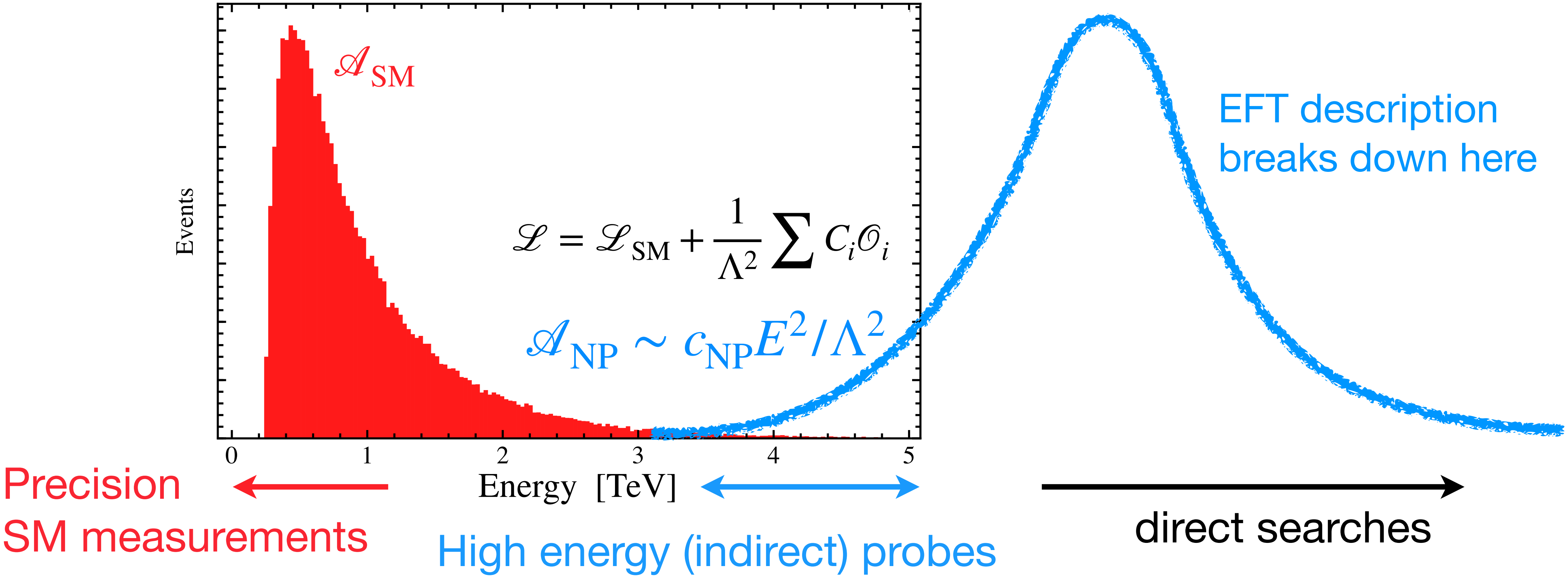
$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2} \sum C_i \mathscr{O}_i + \cdots$$

the "multipole expansion" of high-energy physics

$$V(\vec{R}) = \int \frac{\rho(\vec{r})}{|\vec{R} - \vec{r}|} d^3 r \xrightarrow{R \gg d} \frac{Q}{R} + \frac{\vec{Q}_1 \cdot \vec{R}}{R^3} + \frac{Q_2^{ij} R_i R_j}{R^5} + \cdots$$

High-energy probes

- NP effects are more important at high energies



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

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

1609.08157

1712.01310

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

High-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:

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

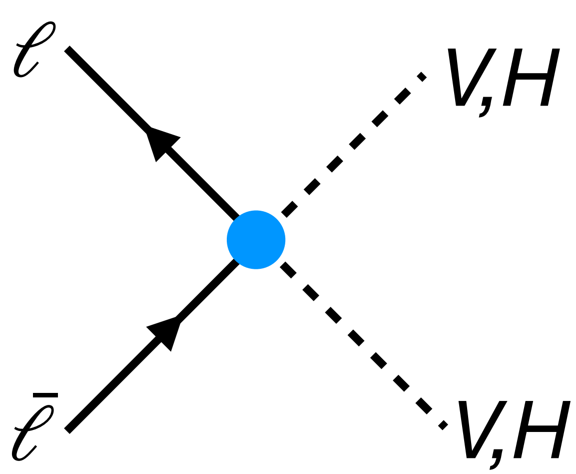
Determined by 3 fermion/scalar current-current interactions (Warsaw):

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

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

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

"high-energy primary effects"



High-energy di-bosons

- Longitudinal 2 → 2 scattering amplitudes at high energy:

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

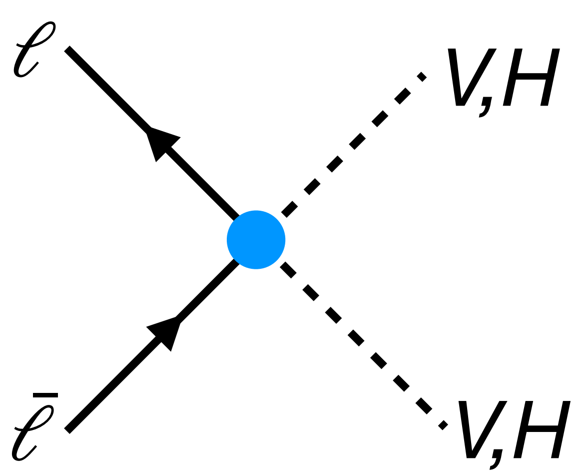
Determined by 3 fermion/scalar current-current interactions (Warsaw):

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

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

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

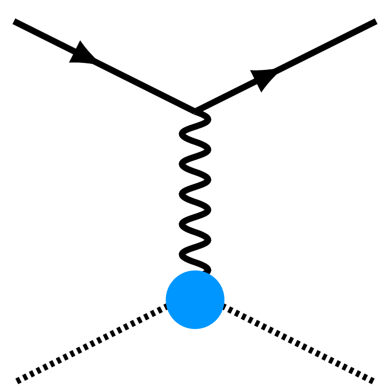
"high-energy primary effects"



$$G_{1L} = G_{lR}/2 = g'^2 C_B/4$$

$$G_{3L} = g^2 C_W/4$$

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



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

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

High-energy di-bosons

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

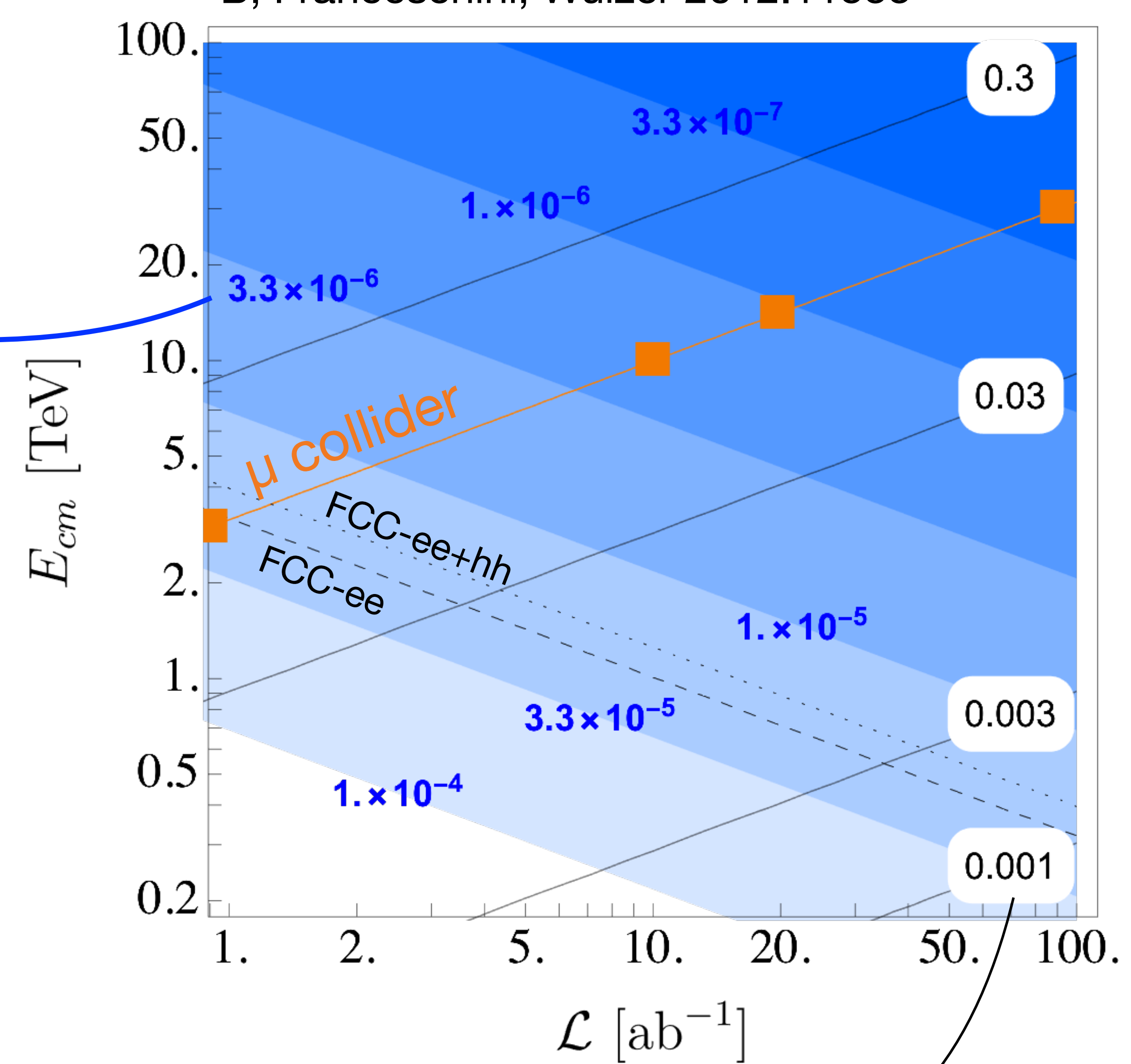
$$\sigma_{\mu\mu\to ZH} \approx 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\left[1 + \#\,E_{\text{cm}}^2 C_W + \#\,E_{\text{cm}}^4 C_W^2\right]$$

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

- In universal theories, $C_{W,B}$ 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

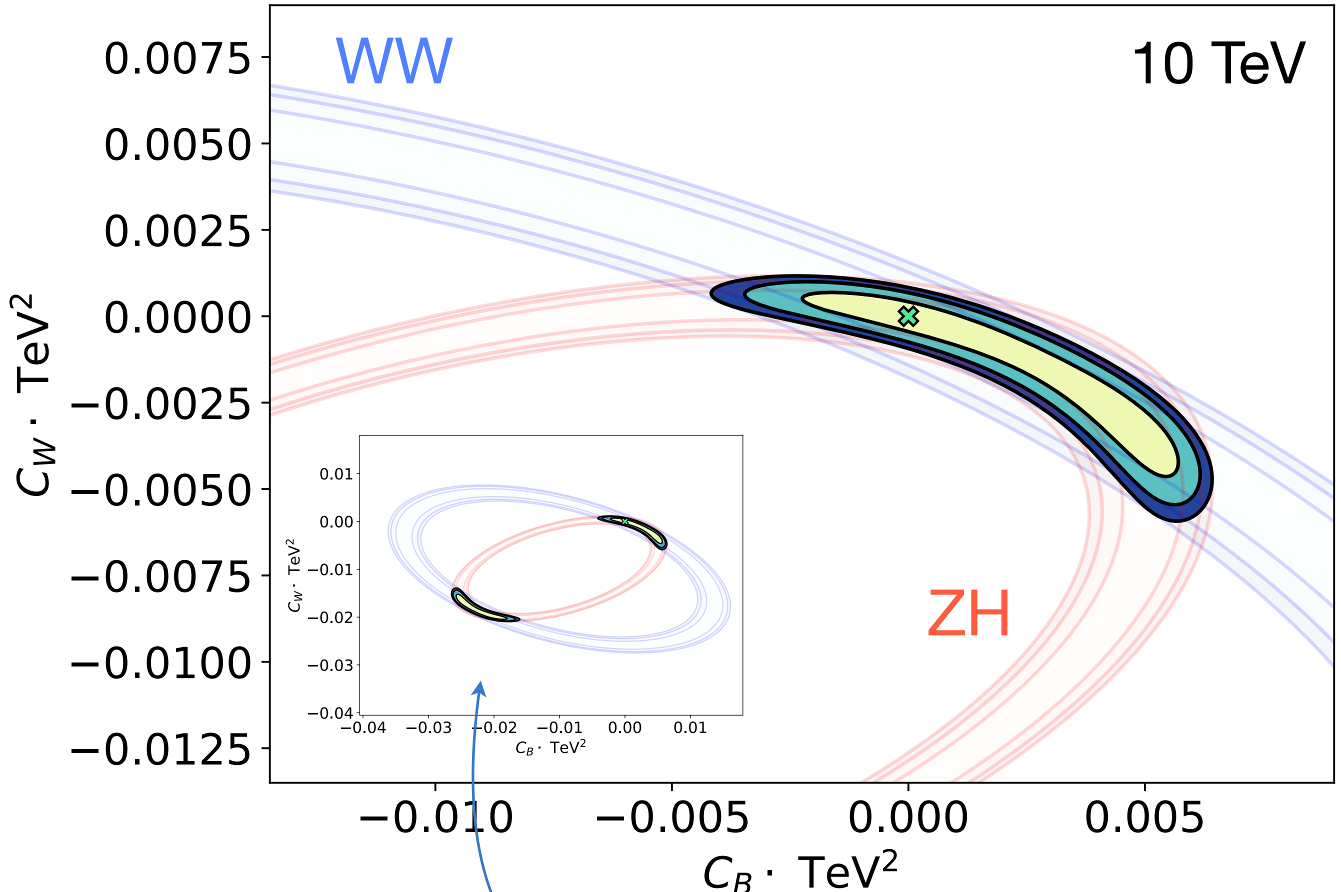
High-energy di-bosons

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

$$\sigma_{\mu\mu\to ZH} = 122\,\mathrm{ab}\left(\frac{10\,\mathrm{TeV}}{E_{\mathrm{cm}}}\right)^2\Big[1+\left(\frac{E_{\mathrm{cm}}}{0.78}\right)^2 C_W+\left(\frac{E_{\mathrm{cm}}}{1.64}\right)^2 C_B$$
$$+\left(\frac{E_{\mathrm{cm}}}{0.96}\right)^4 C_W^2+\left(\frac{E_{\mathrm{cm}}}{1.17}\right)^4 C_B^2-\left(\frac{E_{\mathrm{cm}}}{1.09}\right)^4 C_W C_B\Big]$$

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

B, Franceschini, Wulzer 2012.11555



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

SM cross-section
but large coupling

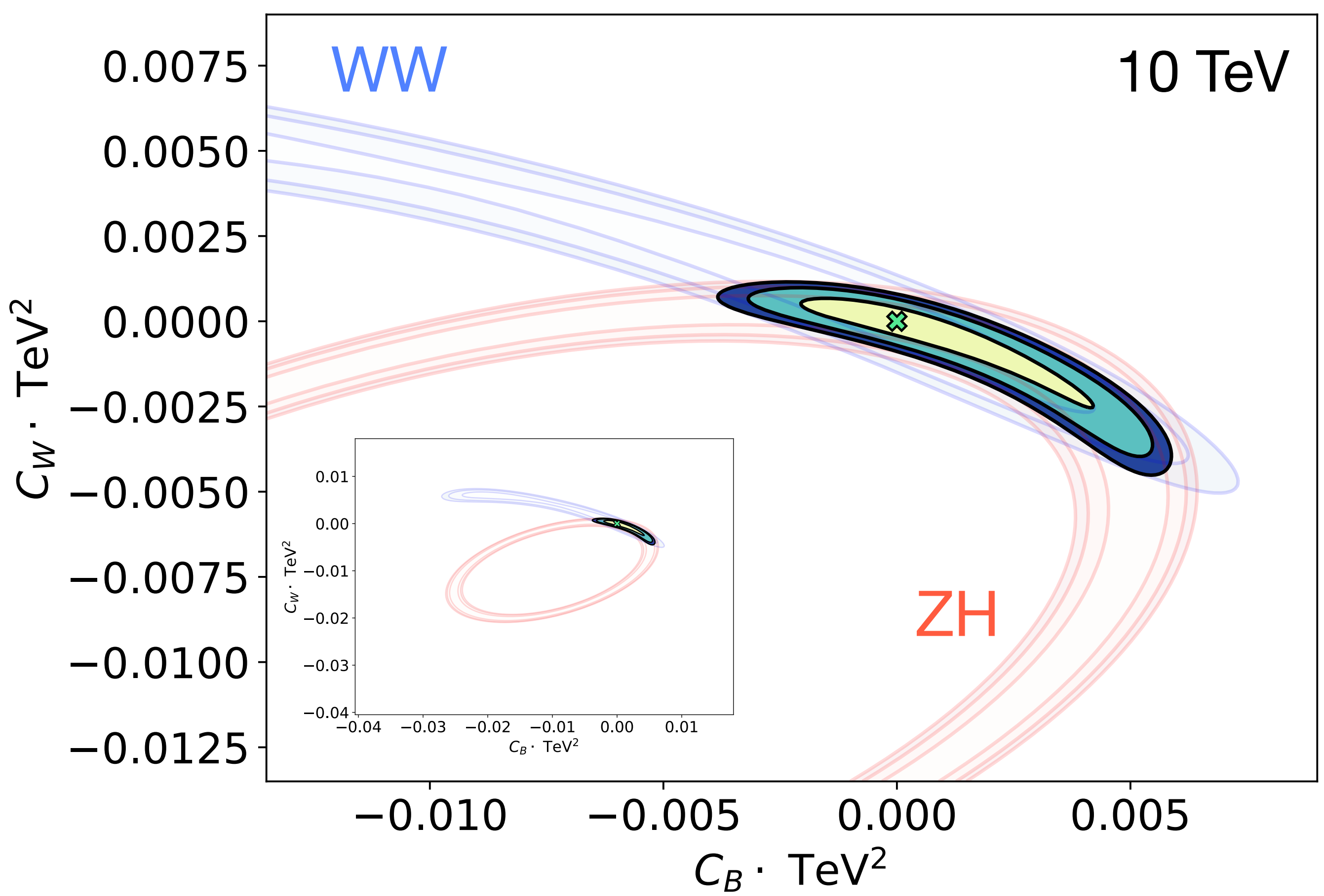
High-energy di-bosons

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

$$\sigma_{\mu\mu\to ZH} = 122\,\mathrm{ab}\left(\frac{10\,\mathrm{TeV}}{E_{\rm cm}}\right)^2\left[1+\left(\frac{E_{\rm cm}}{0.78}\right)^2 C_W+\left(\frac{E_{\rm cm}}{1.64}\right)^2 C_B + \left(\frac{E_{\rm cm}}{0.96}\right)^4 C_W^2+\left(\frac{E_{\rm cm}}{1.17}\right)^4 C_B^2-\left(\frac{E_{\rm cm}}{1.09}\right)^4 C_W C_B\right]$$

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

B, Franceschini, Wulzer 2012.11555



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

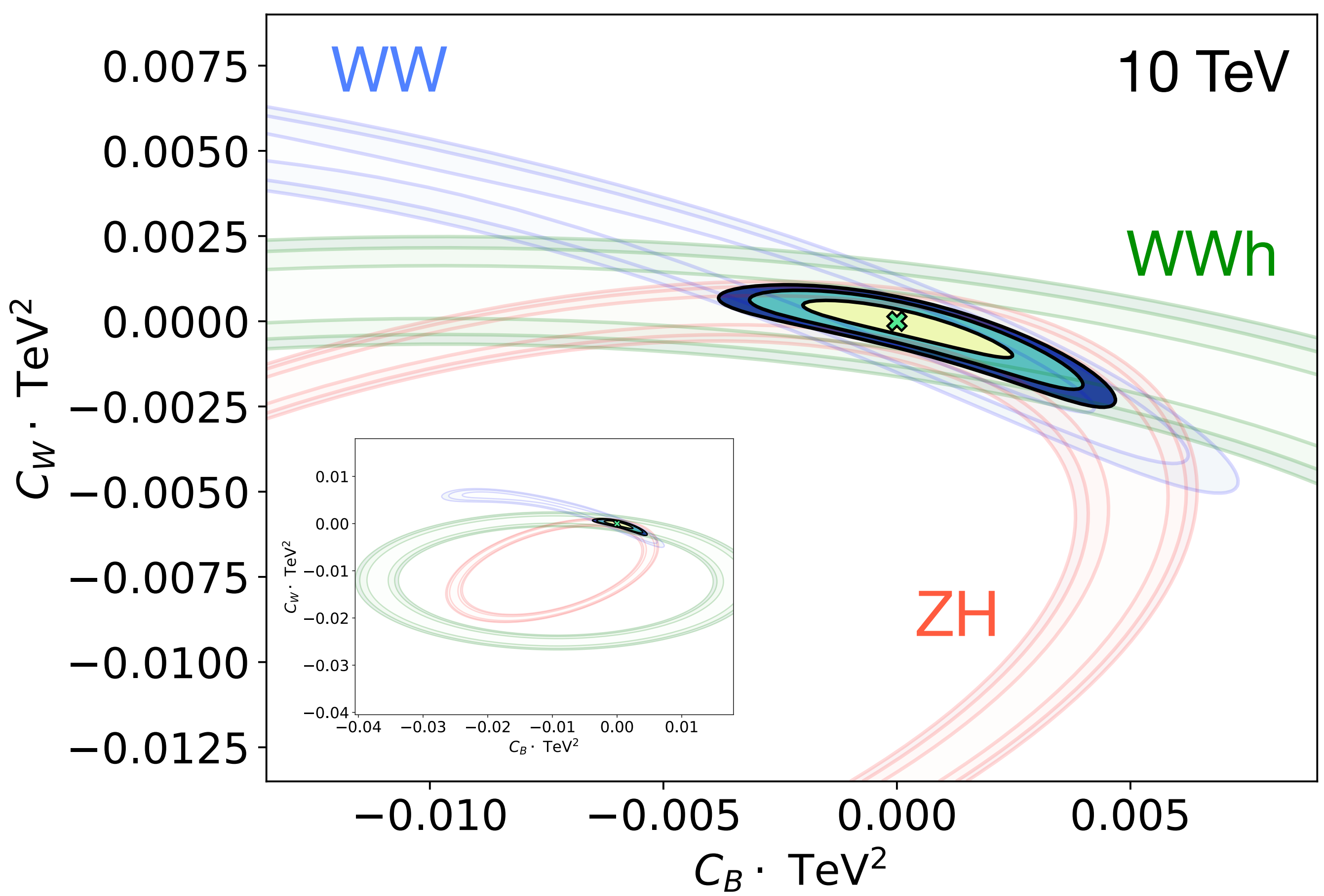
High-energy di-bosons

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

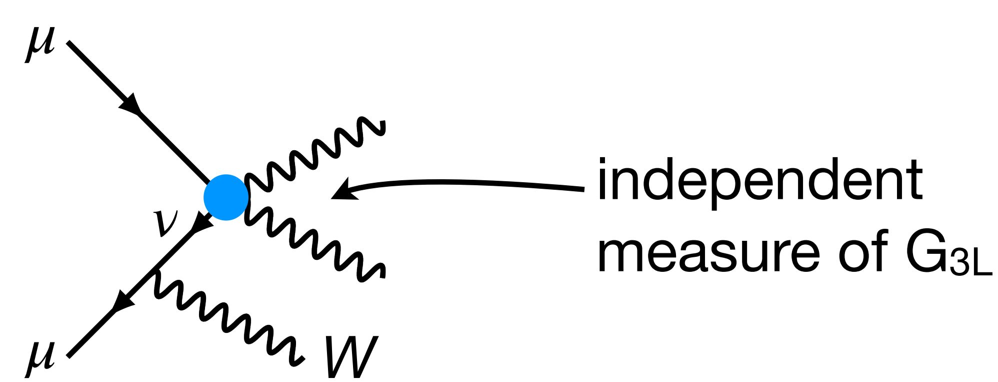
$$\sigma_{\mu\mu\to ZH} = 122\,\text{ab}\left(\frac{10\,\text{TeV}}{E_{\text{cm}}}\right)^2\Bigg[1+\left(\frac{E_{\text{cm}}}{0.78}\right)^2 C_W+\left(\frac{E_{\text{cm}}}{1.64}\right)^2 C_B$$
$$+\left(\frac{E_{\text{cm}}}{0.96}\right)^4 C_W^2+\left(\frac{E_{\text{cm}}}{1.17}\right)^4 C_B^2-\left(\frac{E_{\text{cm}}}{1.09}\right)^4 C_W C_B\Bigg]$$

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

B, Franceschini, Wulzer 2012.11555



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



"effective neutrino approximation"

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

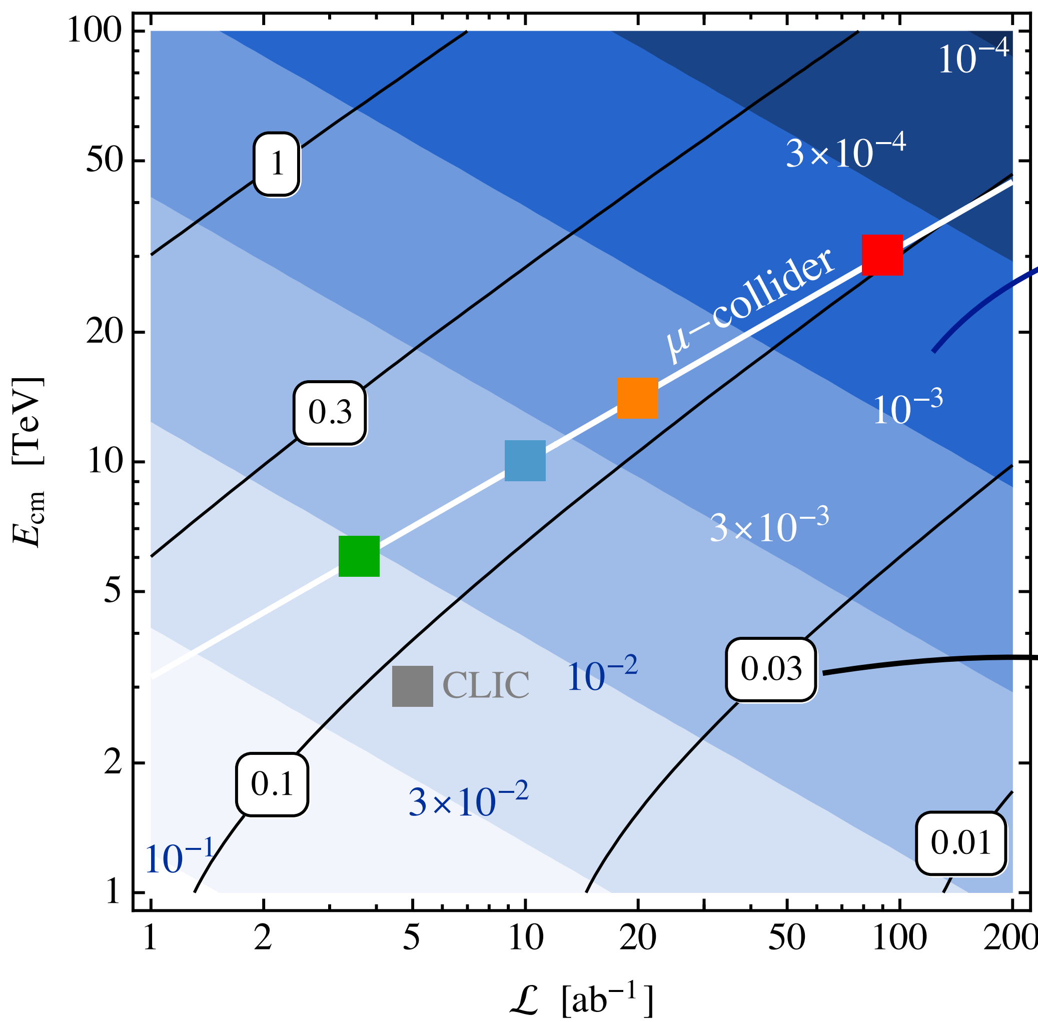
Double Higgs at high mass

- Double Higgs production is affected by two operators in SM EFT:

$$\mathcal{O}_6 = -\lambda |H|^6 \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \qquad \kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right)$$

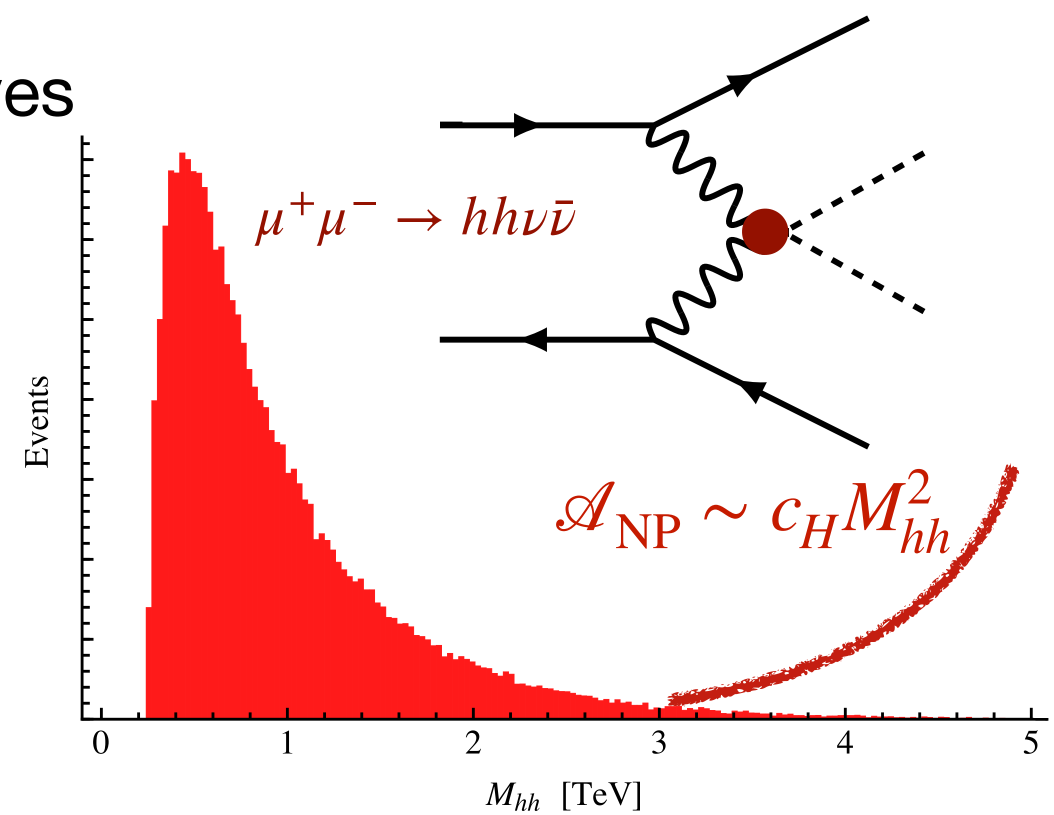
c_H can be constrained from Higgs couplings (but indirect measurement)

- 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 pole physics at energies ≳ 10 TeV

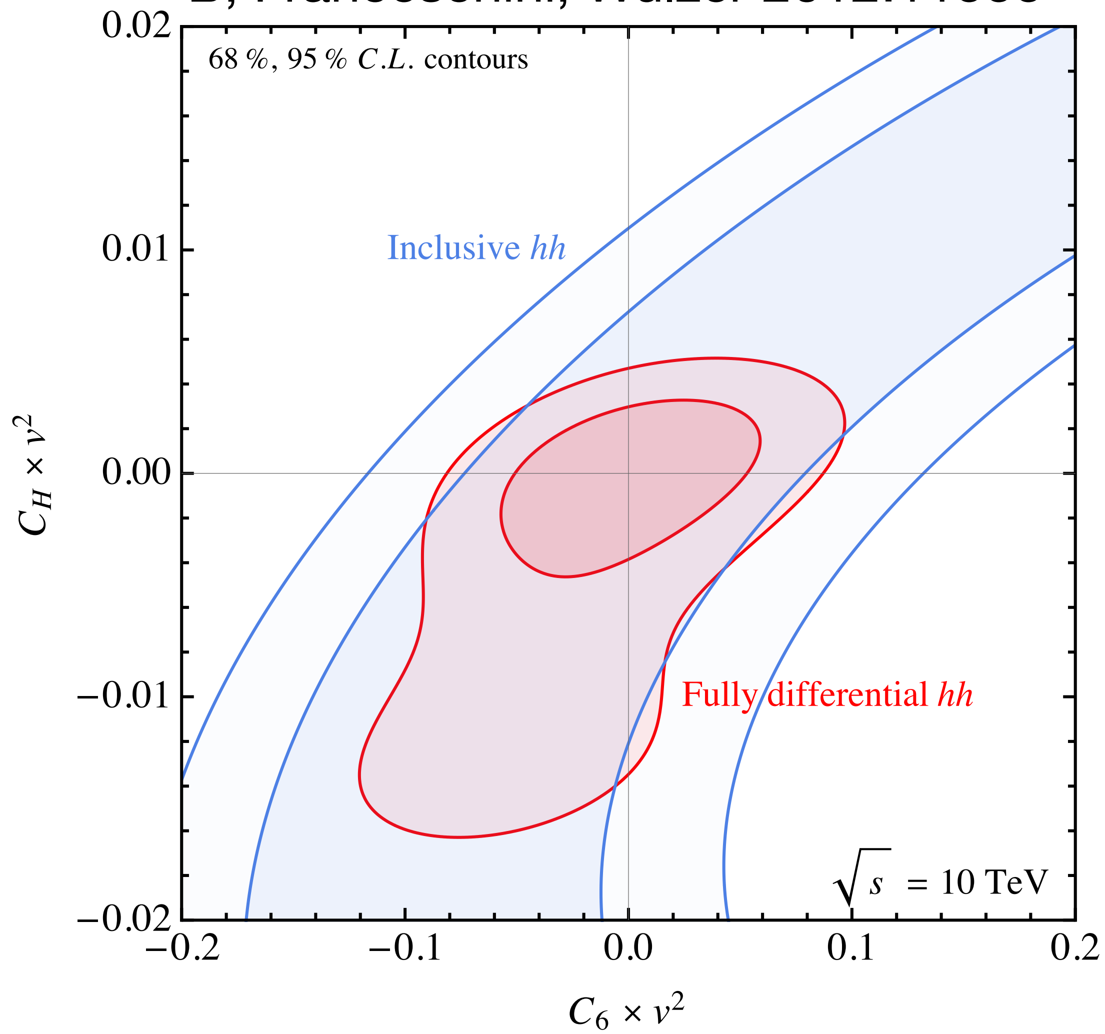
Double Higgs at high mass

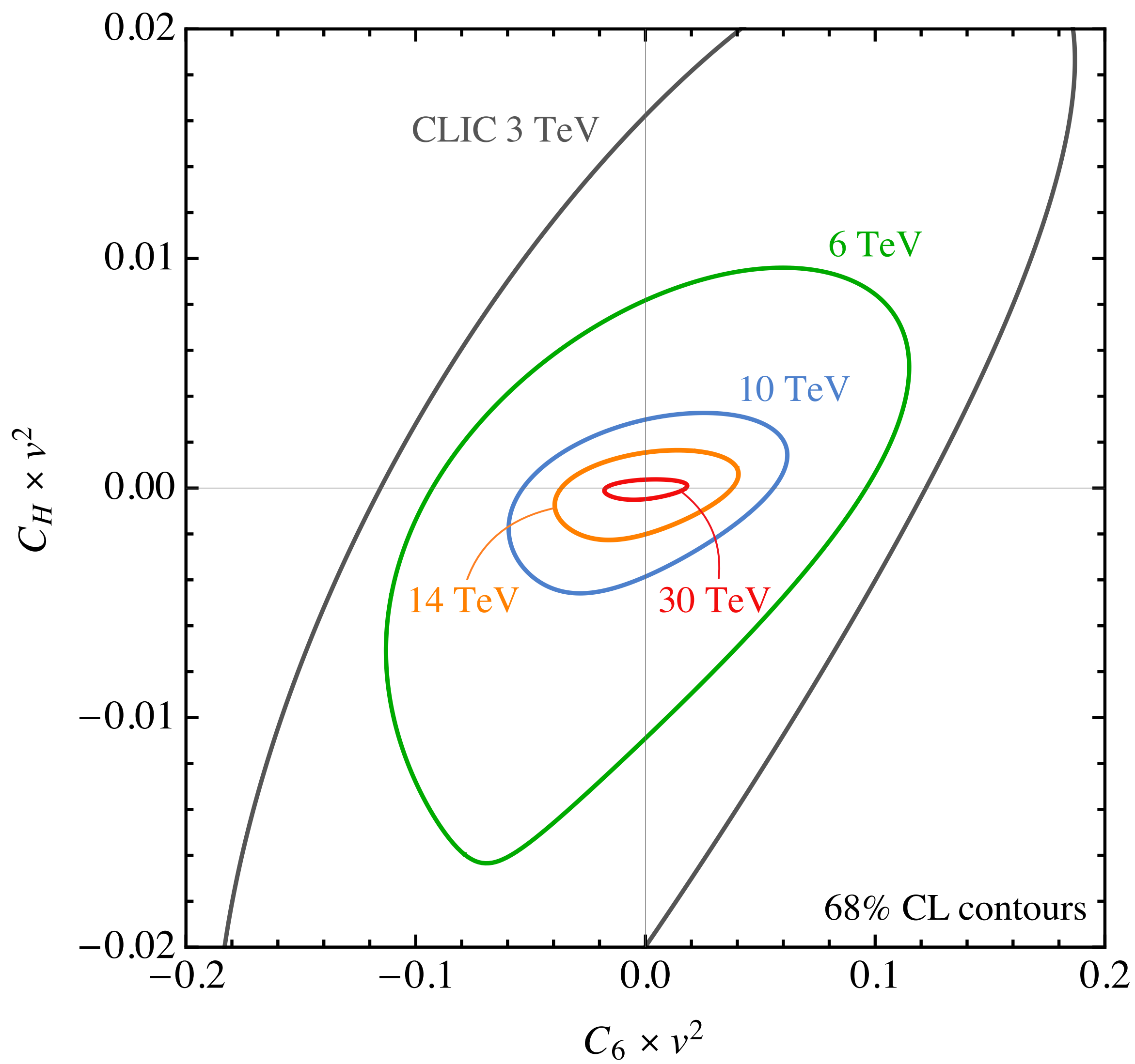
- Double Higgs production is affected by two operators in SM EFT:

$$\mathcal{O}_6 = -\lambda |H|^6 \qquad \mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \qquad \kappa_3 = 1 + v^2\left(C_6 - \frac{3}{2}C_H\right)$$

- Fully differential analysis in p_T and invariant mass to optimize combined sensitivity to C_H and C_6

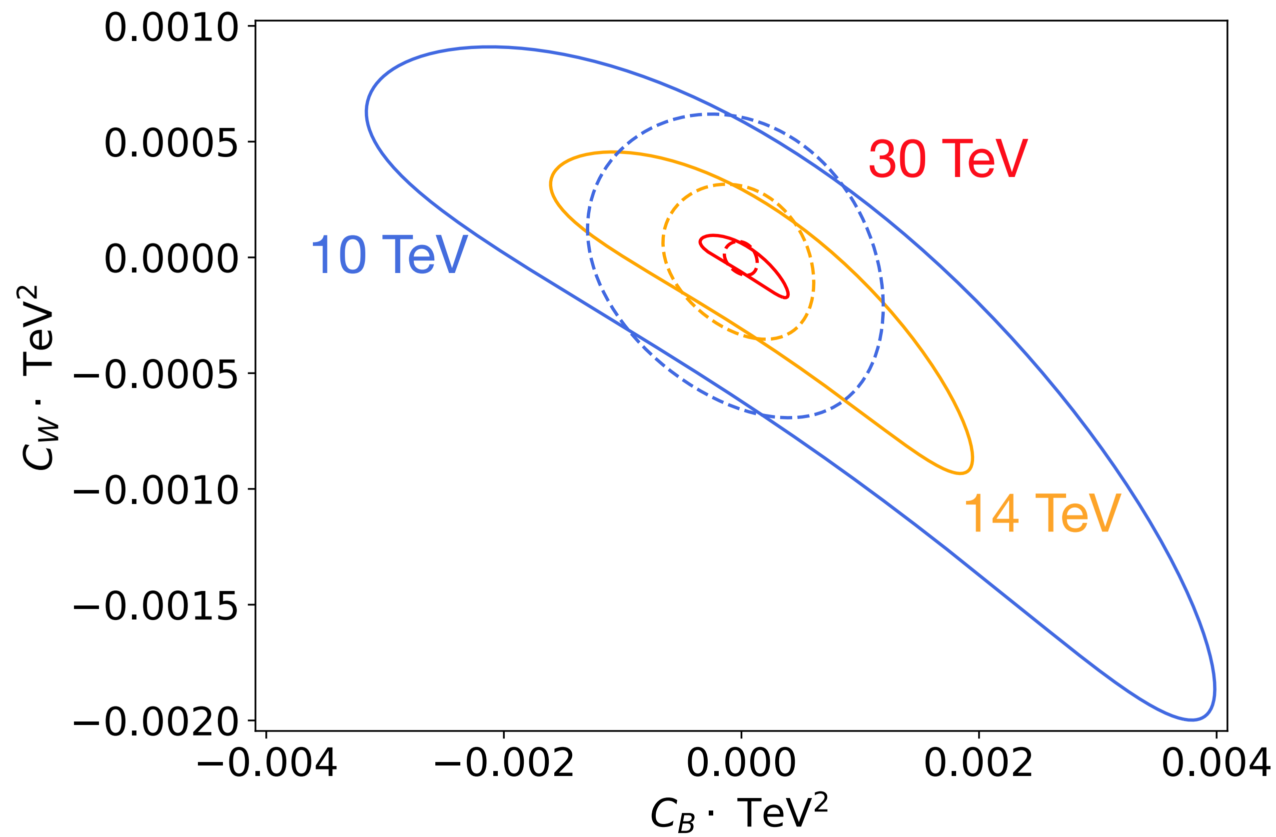
B, Franceschini, Wulzer 2012.11555

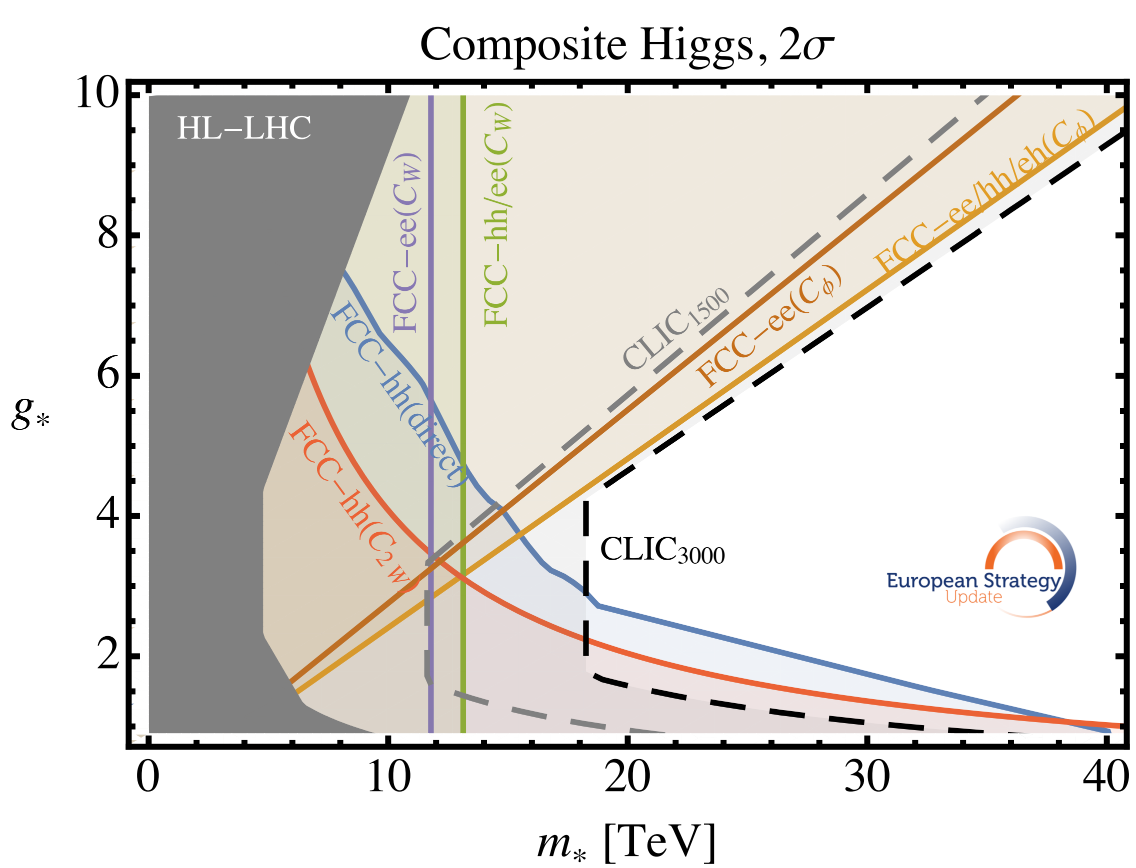


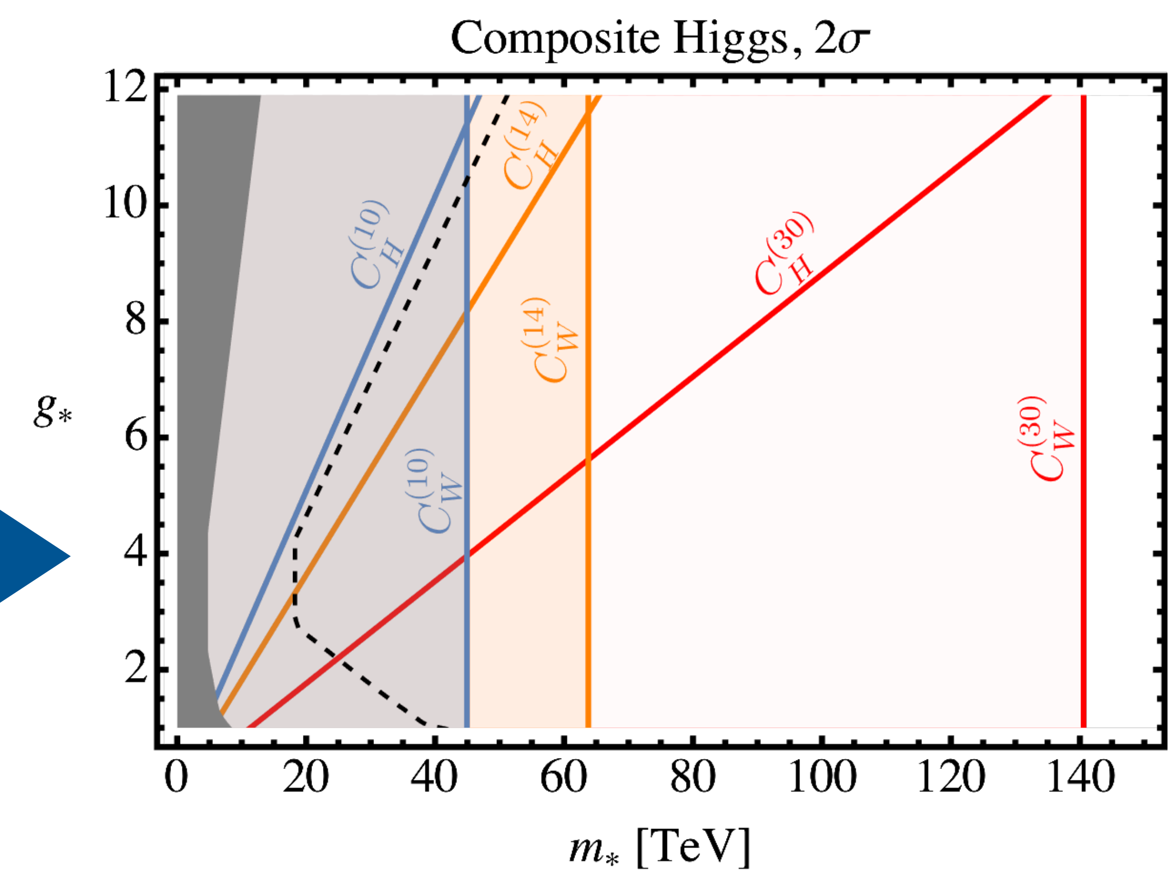


High-energy probes: EW & Higgs physics

- A muon collider is able to probe new physics scales > 100 TeV
  - $\ell^+\ell^- \to VV: \quad \hat{S} \sim m_W^2/m_\star^2 \lesssim 10^{-7}$
  - $VV \to HH: \quad \xi \sim v^2/f^2 \lesssim 10^{-3}$







Almost order of magnitude improvement w.r.t. FCC / CLIC!

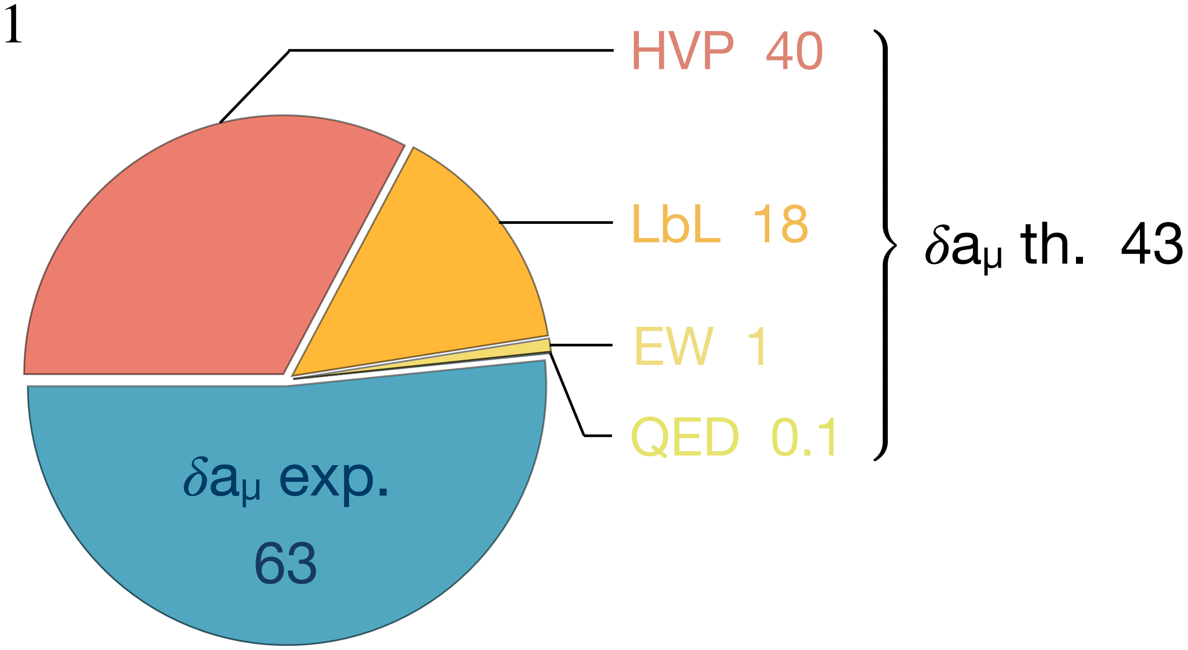
The muon g-2

- Status of the muon $a_\mu = (g-2)/2$ until April 2020:

$$a_\mu^{(\mathrm{exp})} = 116592089(63) \times 10^{-11} \qquad a_\mu^{(\mathrm{th})} = 116591810(43) \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{(\mathrm{exp})} - a_\mu^{(\mathrm{th})} = 279(76) \times 10^{-11}$$

3.7 σ discrepancy



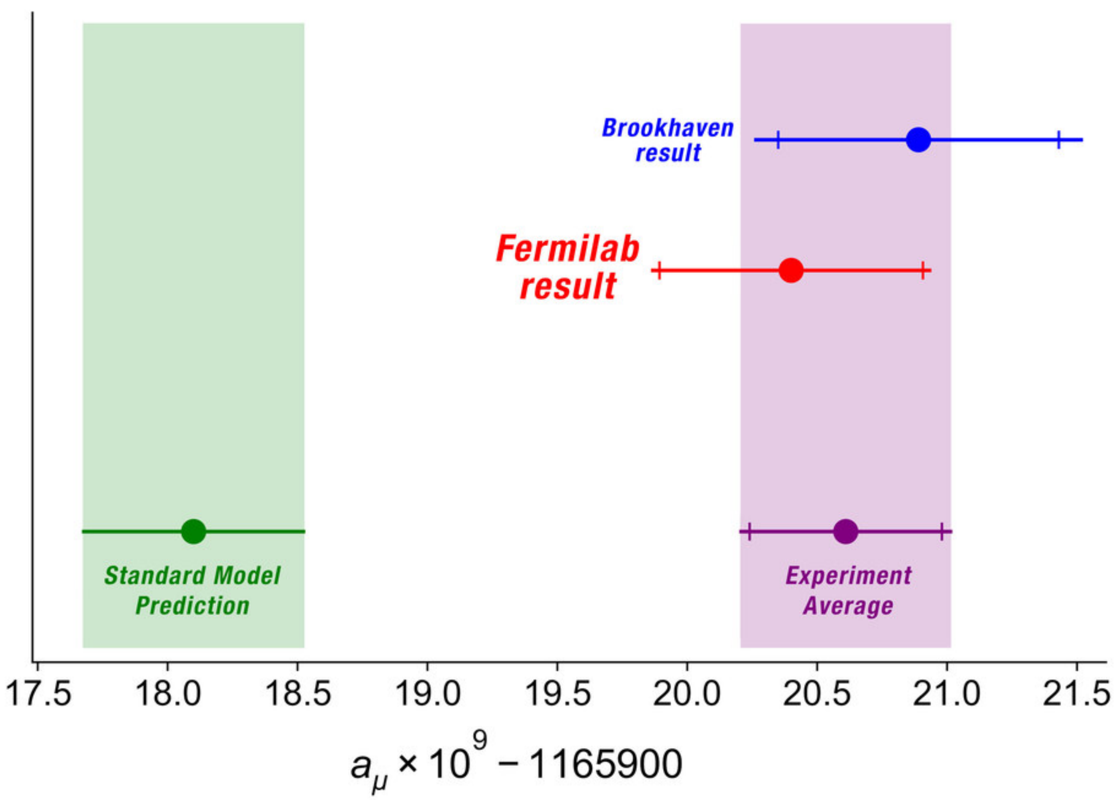
The muon g-2

- Status of the muon a_μ = (g-2)/2: exp. result confirmed by Fermilab!

$$a_\mu^{(\mathrm{exp})} = 116592061(41) \times 10^{-11} \qquad a_\mu^{(\mathrm{th})} = 116591810(43) \times 10^{-11}$$

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

4.2 σ discrepancy



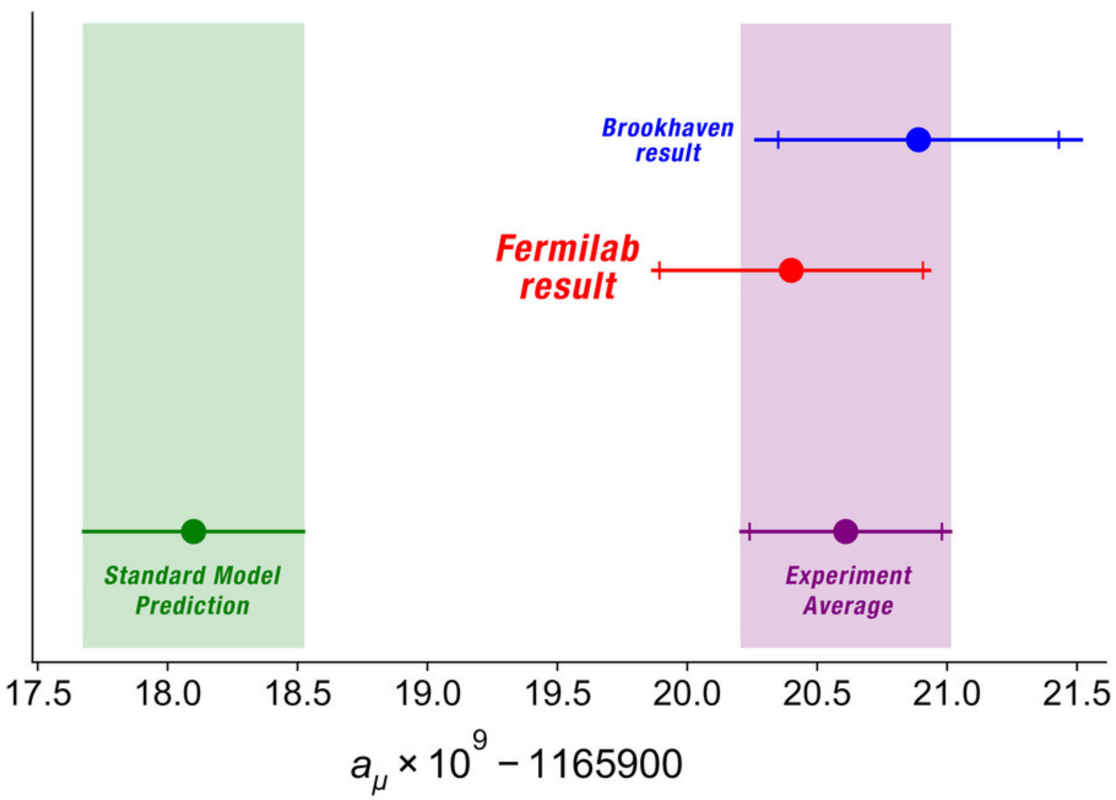
The muon g-2

- Status of the muon $a_\mu = (g-2)/2$: exp. result confirmed by Fermilab!

$$a_\mu^{(\mathrm{exp})} = 116592061(41) \times 10^{-11} \qquad a_\mu^{(\mathrm{th})} = 116591810(43) \times 10^{-11}$$

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

4.2 σ discrepancy



- Theoretical uncertainty can hardly be reduced further… lattice results?

- E989 Muon g-2 experiment:

$$\delta a_\mu^{(\mathrm{exp})} < 20 \times 10^{-11}$$ in a few years

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

  ➡ An independent test of Δa_μ is desirable (possibly with different systematic & theoretical errors)

Muon collider can give the first model-independent high-energy test of Δa_μ

New physics in the muon g-2

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

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

tiny effect: not directly testable at colliders until now

  - Λ ~ TeV, weak coupling

    (favored by naturalness arguments, but challenged by LEP, LHC…)

  - Λ ≲ TeV, NP is light and feebly coupled to the SM

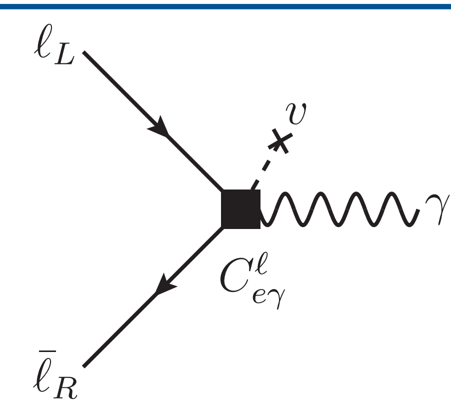
    (e.g. axion-like particles, dark sectors, light scalars, …)

  - Λ ≫ TeV, heavy NP with O(1) couplings to the SM

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

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

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



Muon g-2 @ muon collider

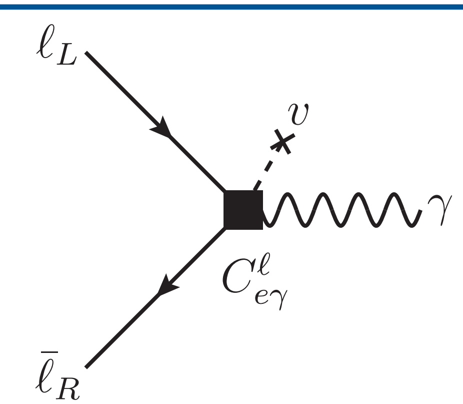
- If new physics is light enough (i.e. weakly coupled, $m_\star \sim \Lambda \cdot g_\star / 4\pi$), a Muon Collider can directly produce the new particles
  - ☛ direct searches: model-dependent — Curtin et al. 2006.16277

- If new physics is heavy: EFT — Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

B, Paradisi 2012.02769

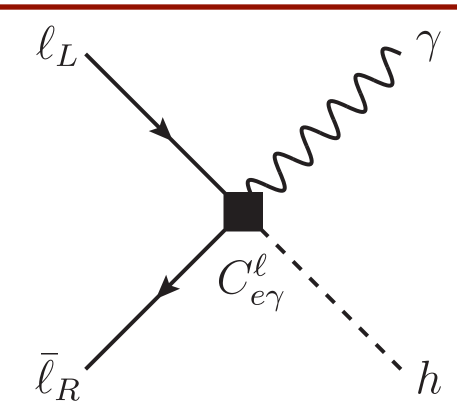
At low energy

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



At high energy

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



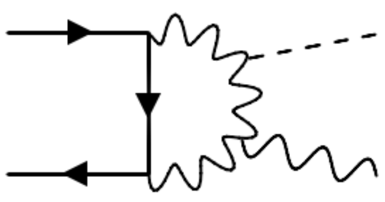
$$N_{h\gamma} = \sigma \cdot \mathscr{L} \approx \left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^4 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

need E > 10 TeV

Muon g-2 @ muon collider

- SM irreducible 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

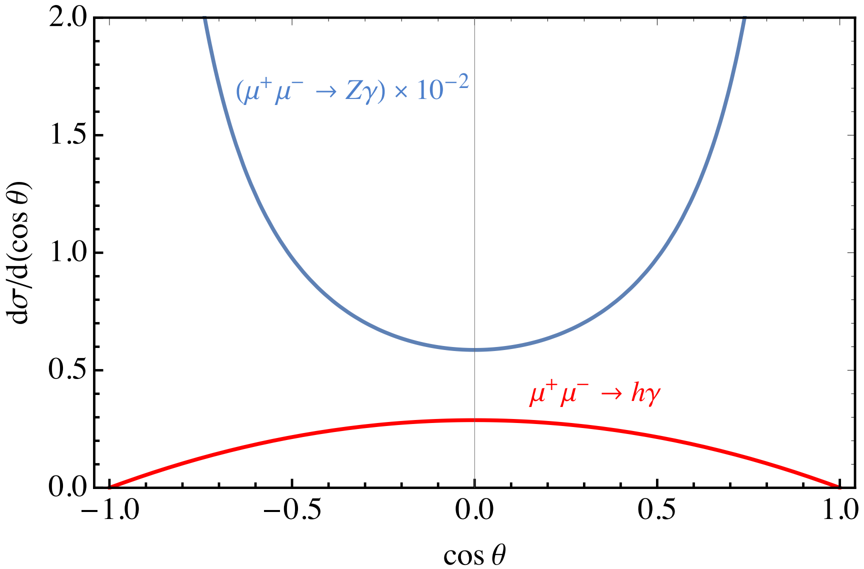


- Main background from $\mu\mu \to Z\gamma$ (where Z is mistaken for H)

  (large due to transverse Z polarizations)

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

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



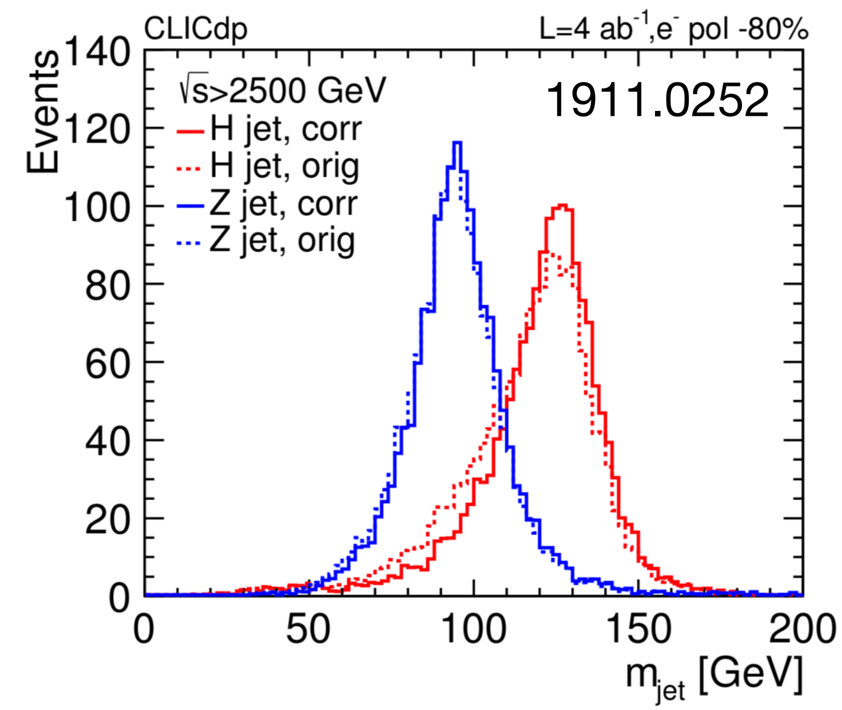
Search in h → bb channel:

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

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%

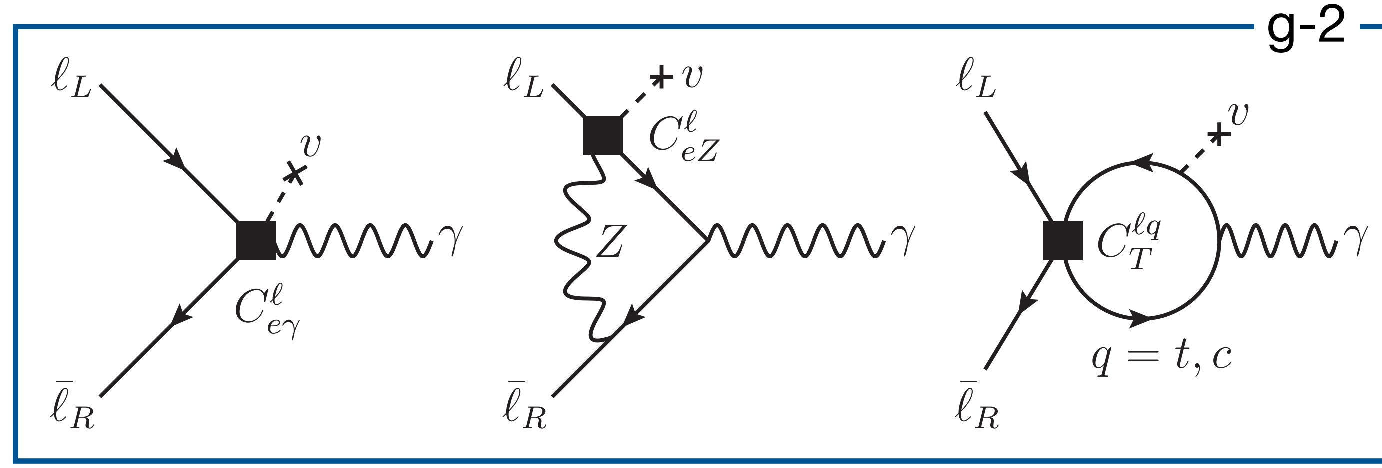


Beyond tree-level

- Other operators contribute to g-2 at one loop:

$$\mathscr{L} = \frac{C_{eB}}{\Lambda^2}(\bar{\ell}_L \sigma^{\mu\nu} e_R)\, H\, B_{\mu\nu} + \frac{C_{eW}}{\Lambda^2}(\bar{\ell}_L \sigma^{\mu\nu} e_R)\tau^I\, H\, W^I_{\mu\nu} + \frac{C_{qT}}{\Lambda^2}(\bar{\ell}_L \sigma^{\mu\nu} e_R)\, \epsilon\, (\bar{q}_L \sigma_{\mu\nu} u_R)$$

(+ other effects suppressed by y_μ)



Including 1-loop running:

$$\Delta a_\mu \simeq \frac{4 m_\mu v}{e \Lambda^2}\left(C_{e\gamma}(m_\mu) - \frac{3\alpha}{2\pi}\frac{c_W^2 - s_W^2}{s_W c_W} C_{eZ} \log\frac{\Lambda}{m_Z}\right) - \sum_{q=c,t} \frac{4 m_\mu m_q}{\pi^2}\frac{C_{Tq}}{\Lambda^2}\log\frac{\Lambda}{m_q}$$

$$\approx \left(\frac{250\ \mathrm{TeV}}{\Lambda^2}\right)^2 (C_{e\gamma} - 0.2 C_{Tt} - 0.001 C_{Tc} - 0.05 C_{eZ})$$

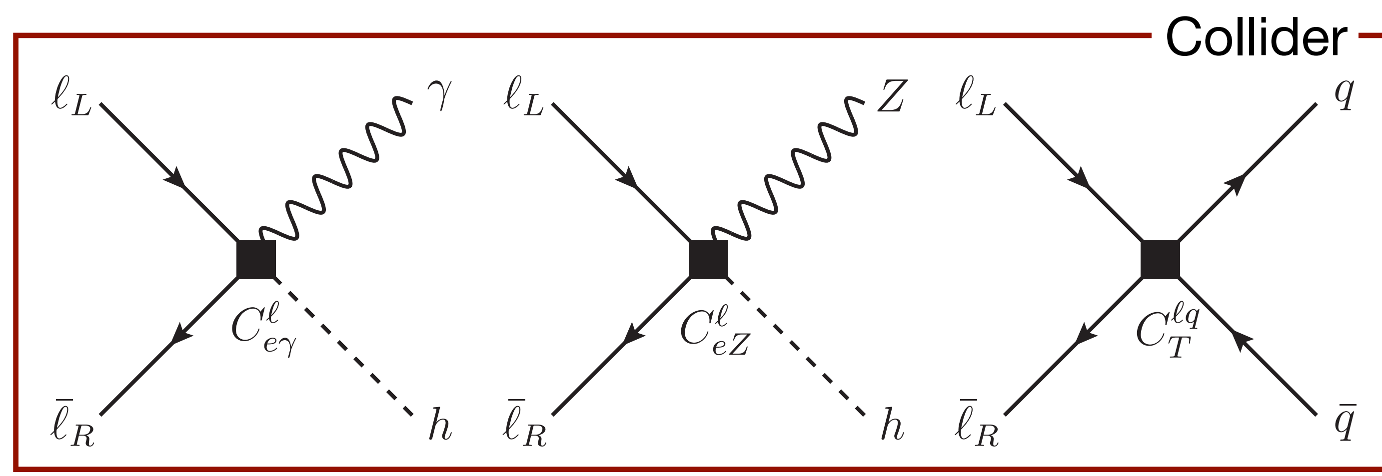
B, Paradisi 2012.02769

Full set of operators can be probed at high energy

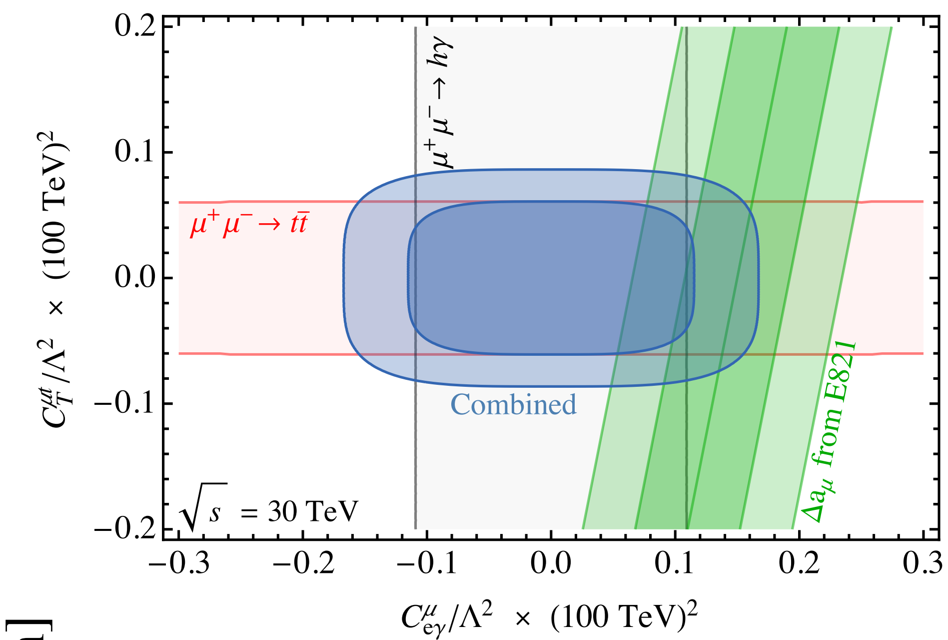
$\mu^+\mu^- \to h\gamma$

$\mu^+\mu^- \to hZ$

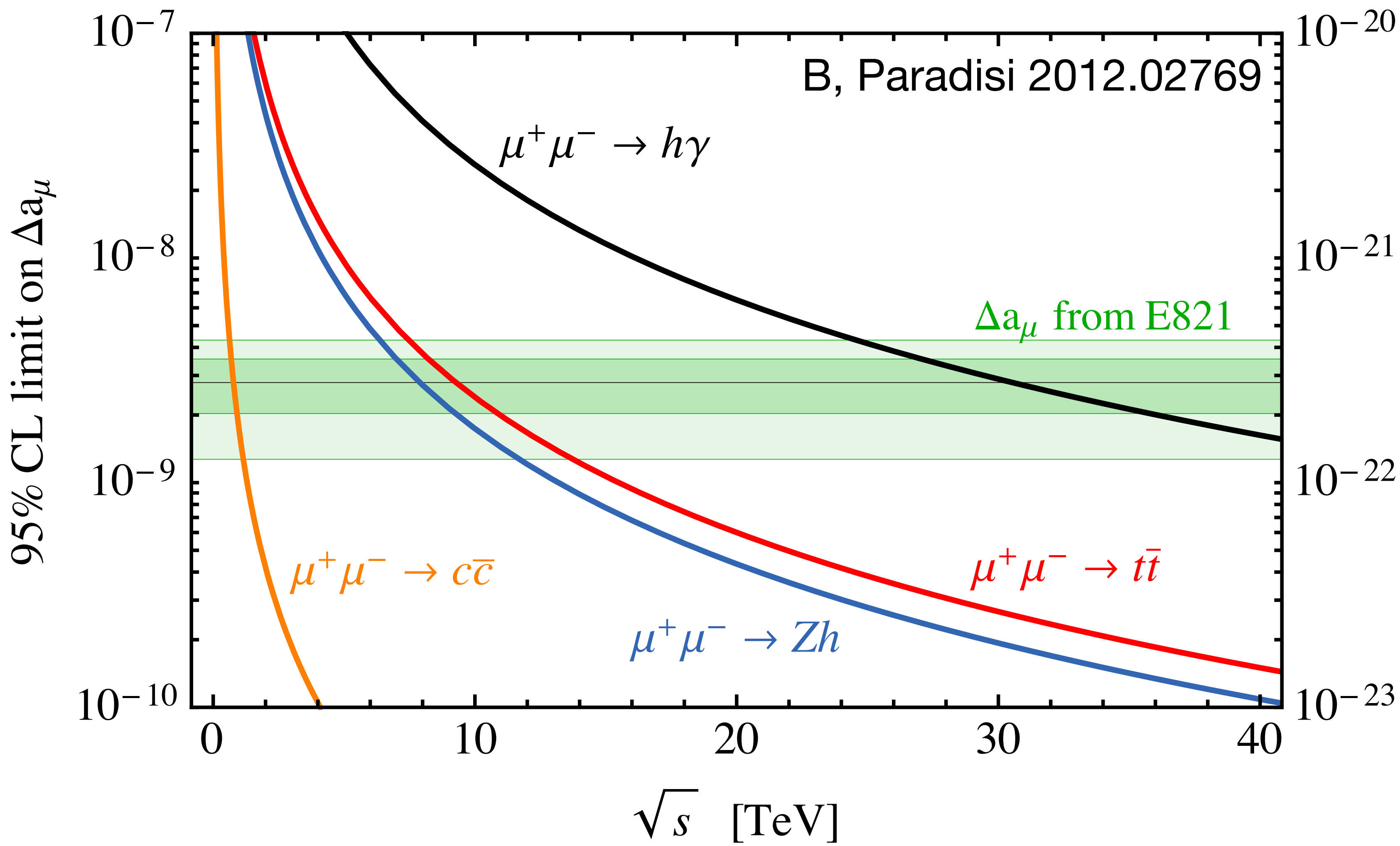
$\mu^+\mu^- \to q\bar{q}$



Muon g-2 @ muon collider



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



Muon EDM for free!

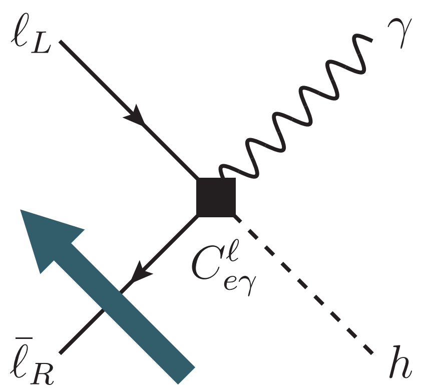
$$d_\mu = \frac{\Delta a_\mu \tan\phi_\mu}{2m_\mu} e = \frac{2v\,\text{Im}(C_{e\gamma})}{\Lambda^2}$$

Collider constrains $|C_{e\gamma}|^2 \Rightarrow d_\mu \lesssim 10^{-22}\, e\cdot\text{cm}$

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

Lepton g-2 from rare Higgs decays

- Dipole operator contributes also to h $\to \ell\ell\gamma$ 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:

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

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

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

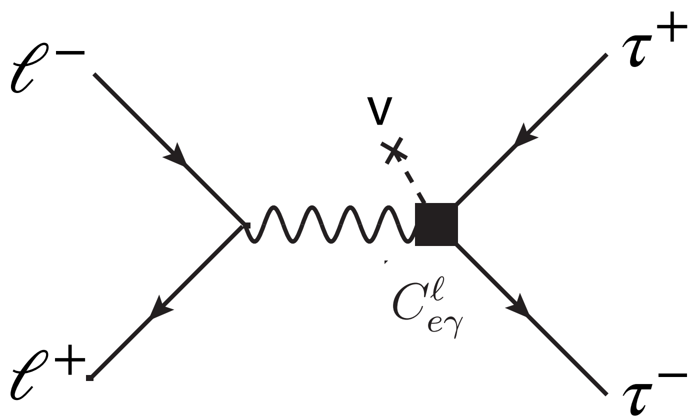
3 o.o.m. improvement!

Lepton g-2 from rare Higgs decays

Further possibilities to measure Δa_τ precisely from high-energy probes

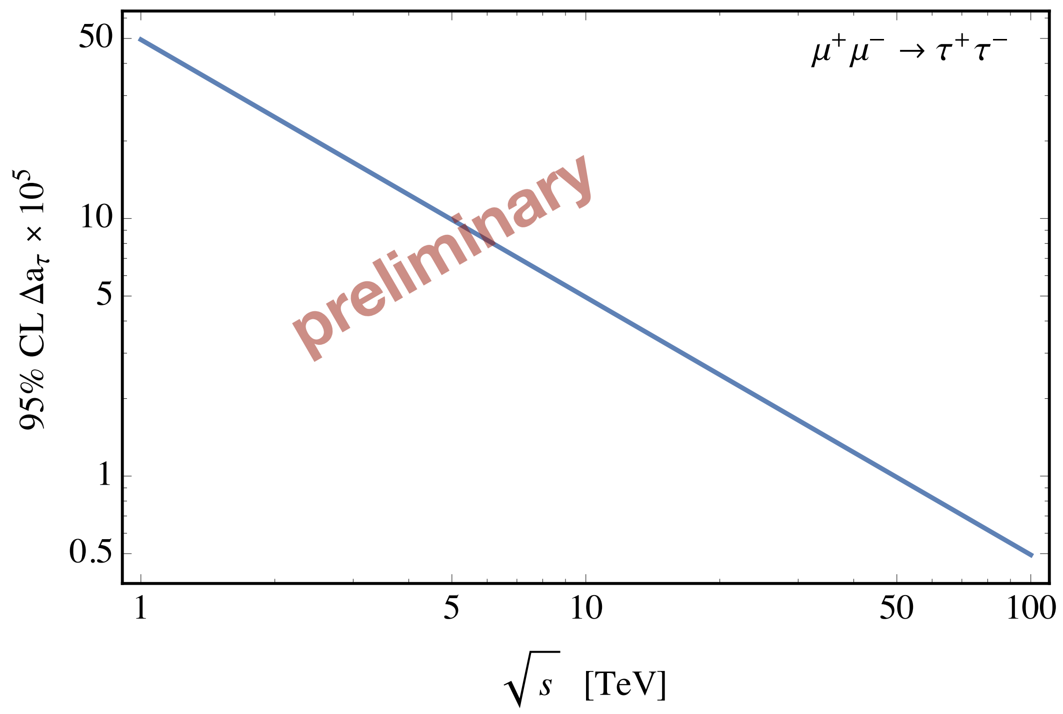
- Pair production

work in progress with P. Paradisi



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

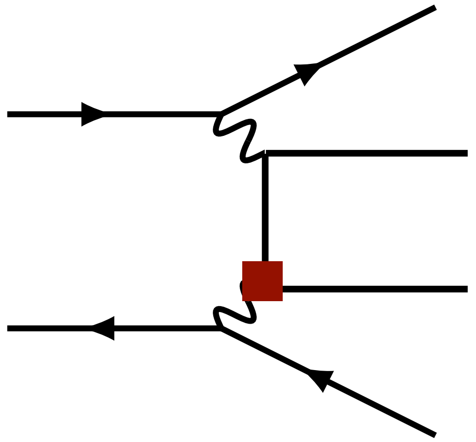
$$\sigma_{\rm NP} = \frac{4\pi\alpha^2}{3}\frac{|C^\ell_{e\gamma}|^2 v^2}{\Lambda^4} \sim \frac{\pi\alpha^2\Delta a_\ell^2}{6m_\ell^2}$$



Could probe Δa_τ ~ few 10^{-5}

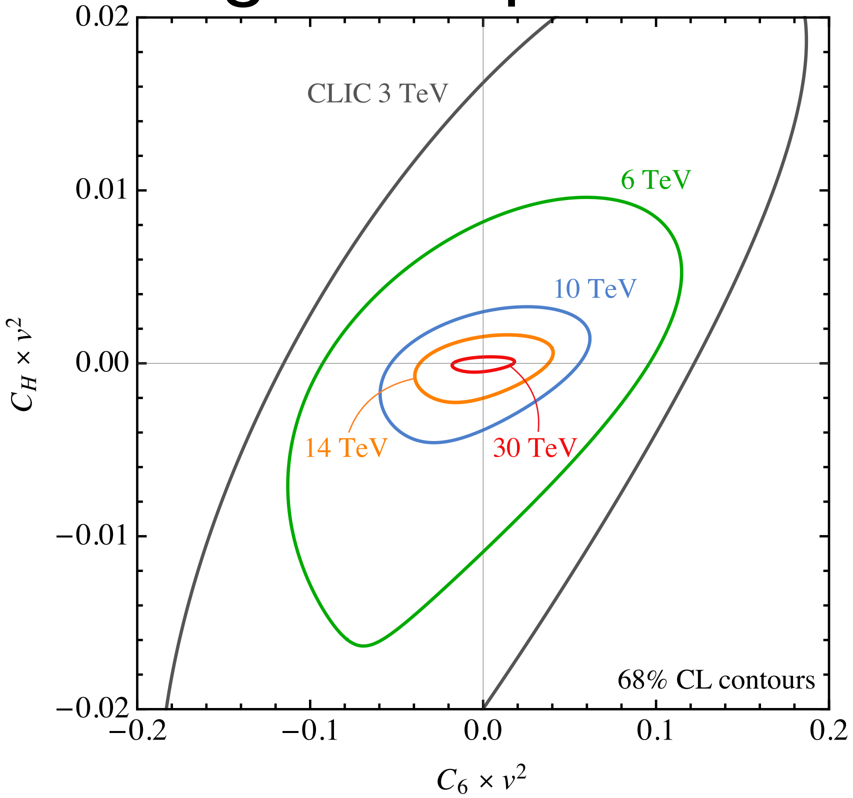
- Vector boson fusion: $\ell^+\ell^- \to \ell^+\ell^-\tau^+\tau^-,\ \nu\bar{\nu}\tau^+\tau^-$

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

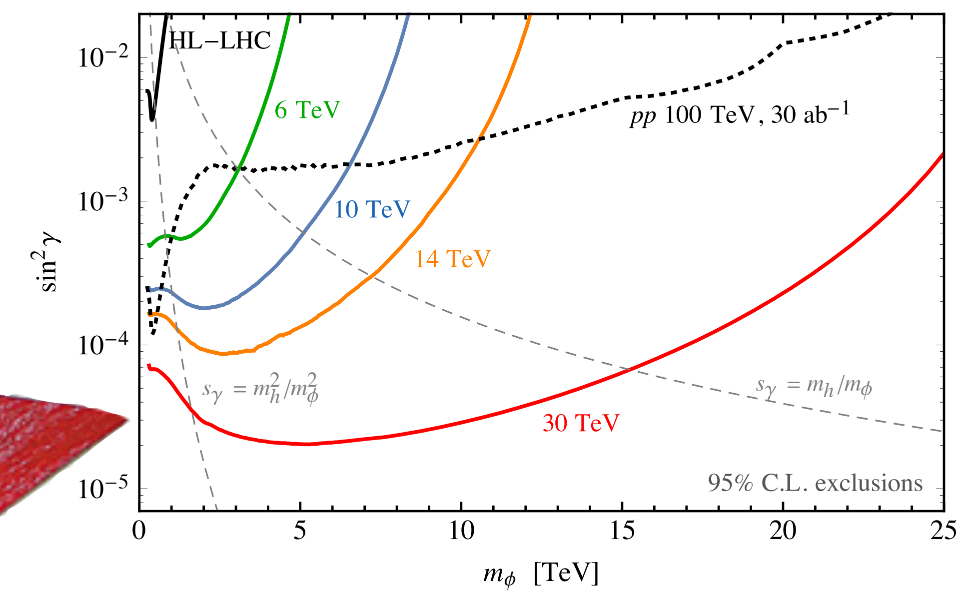


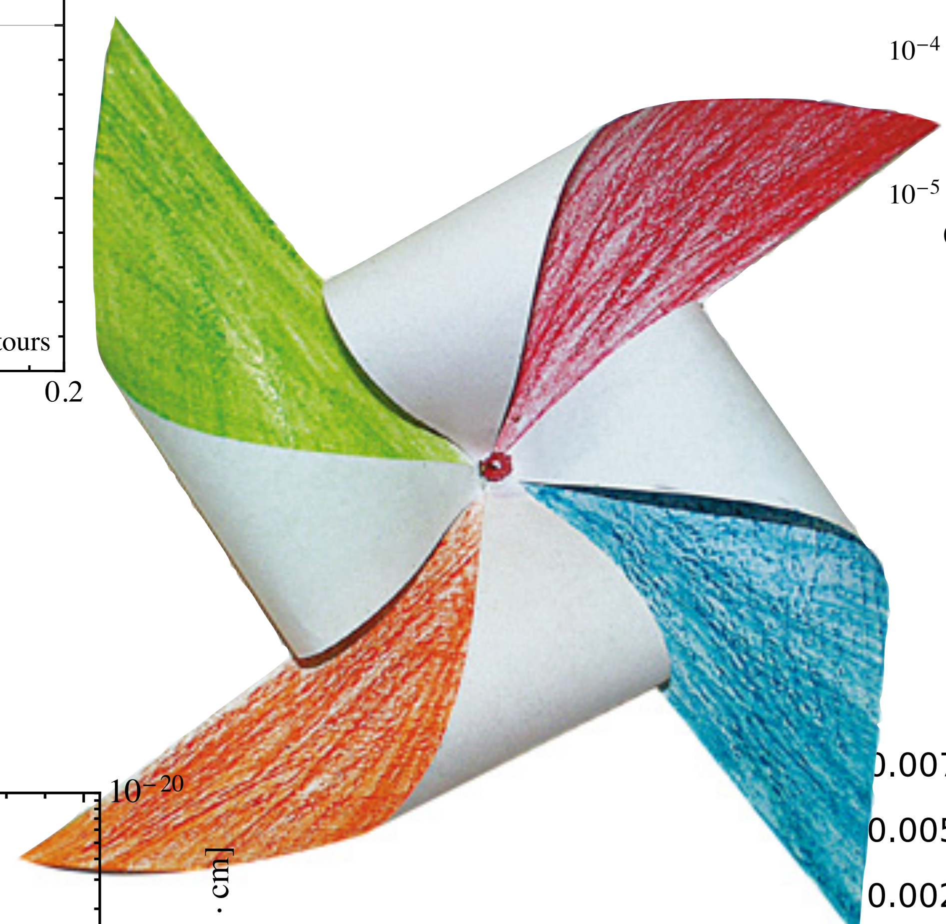
Summary

High-rate precision

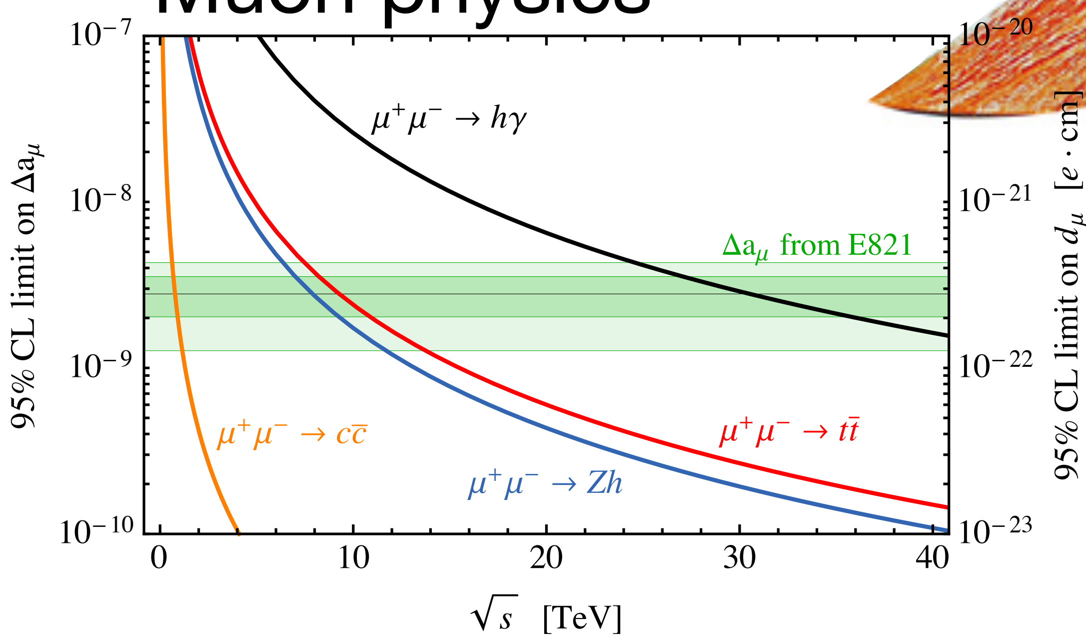


Direct searches

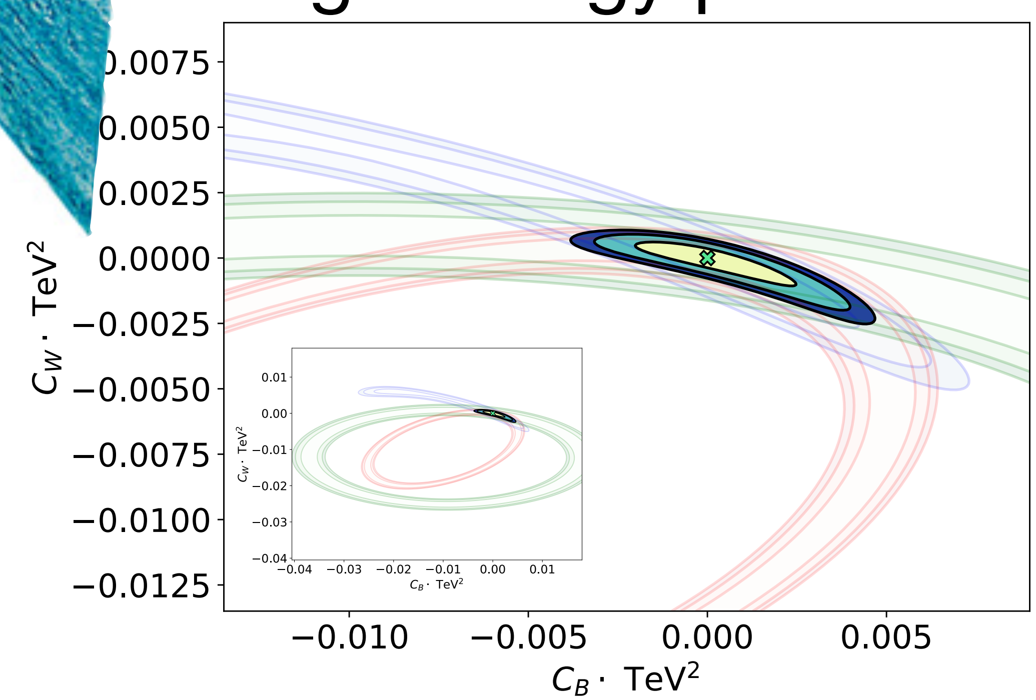


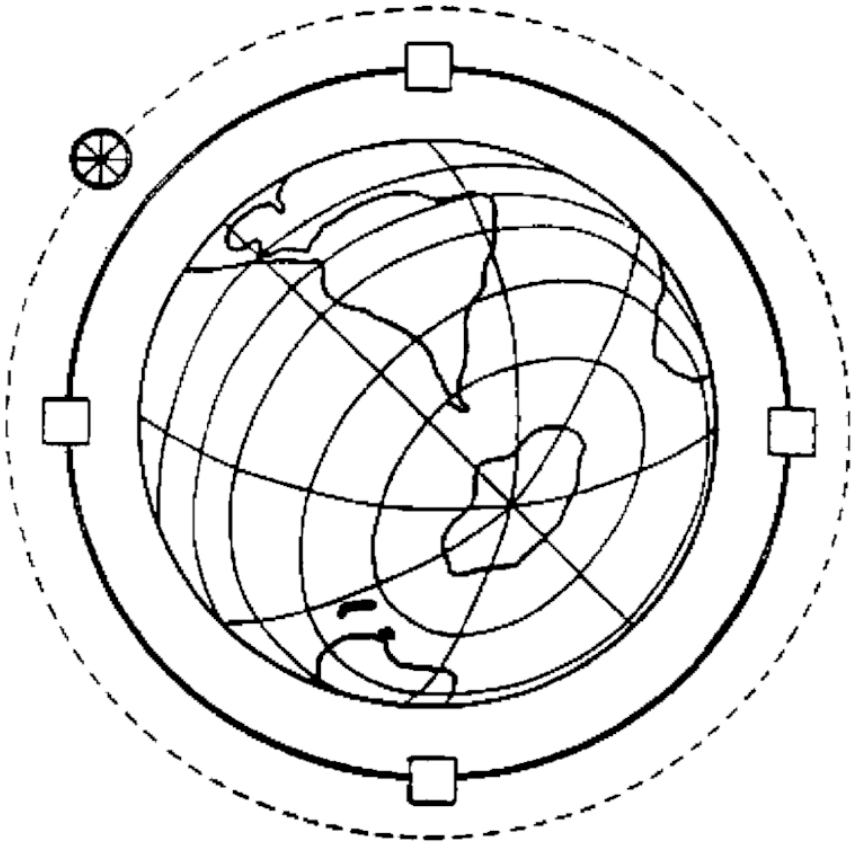


Muon physics

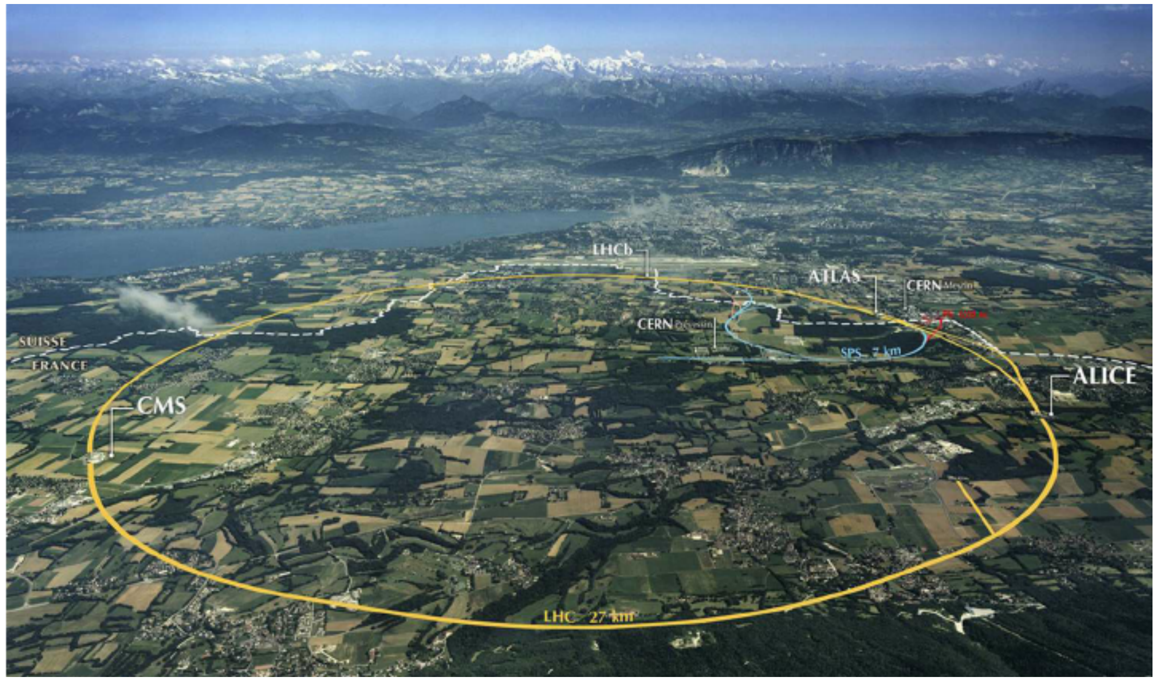


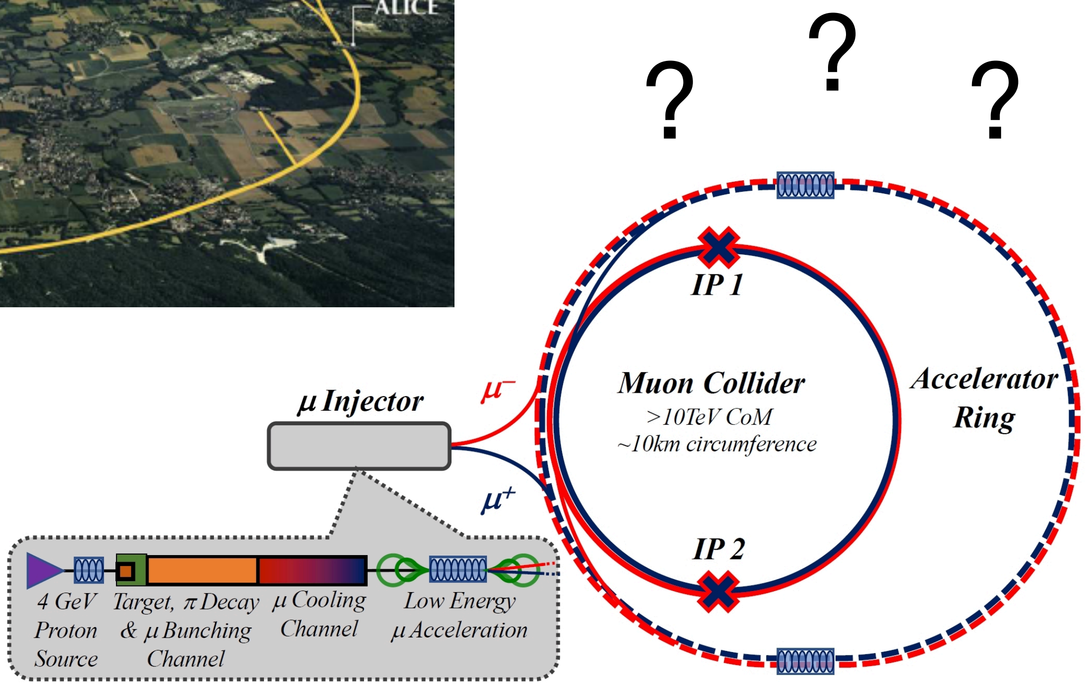
High-energy probes





Fermi, 1954
3 TeV center-of-mass





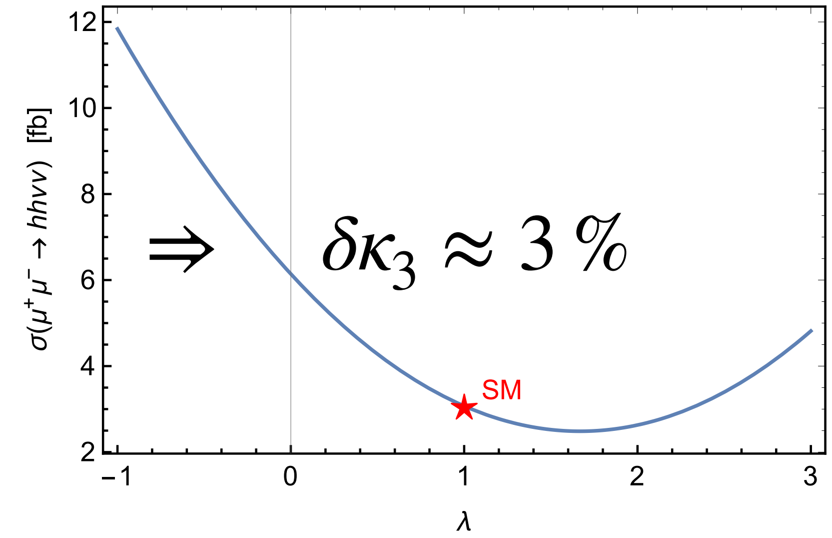
Backup

Double Higgs production

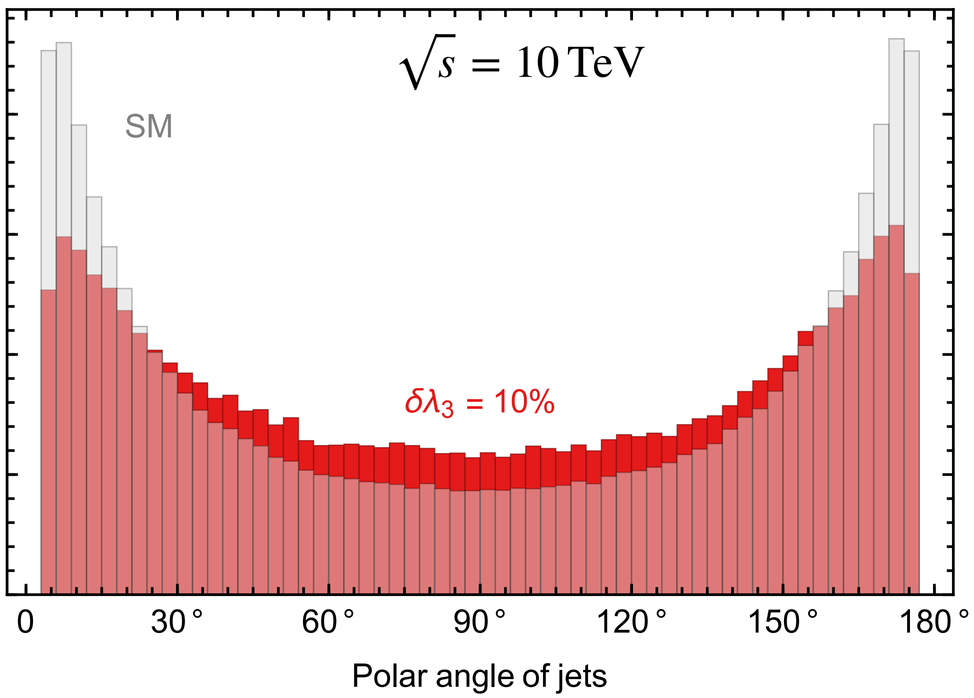
Number of events $\sim s\log(s/m_h^2) \approx 10^5$ at 14 TeV

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

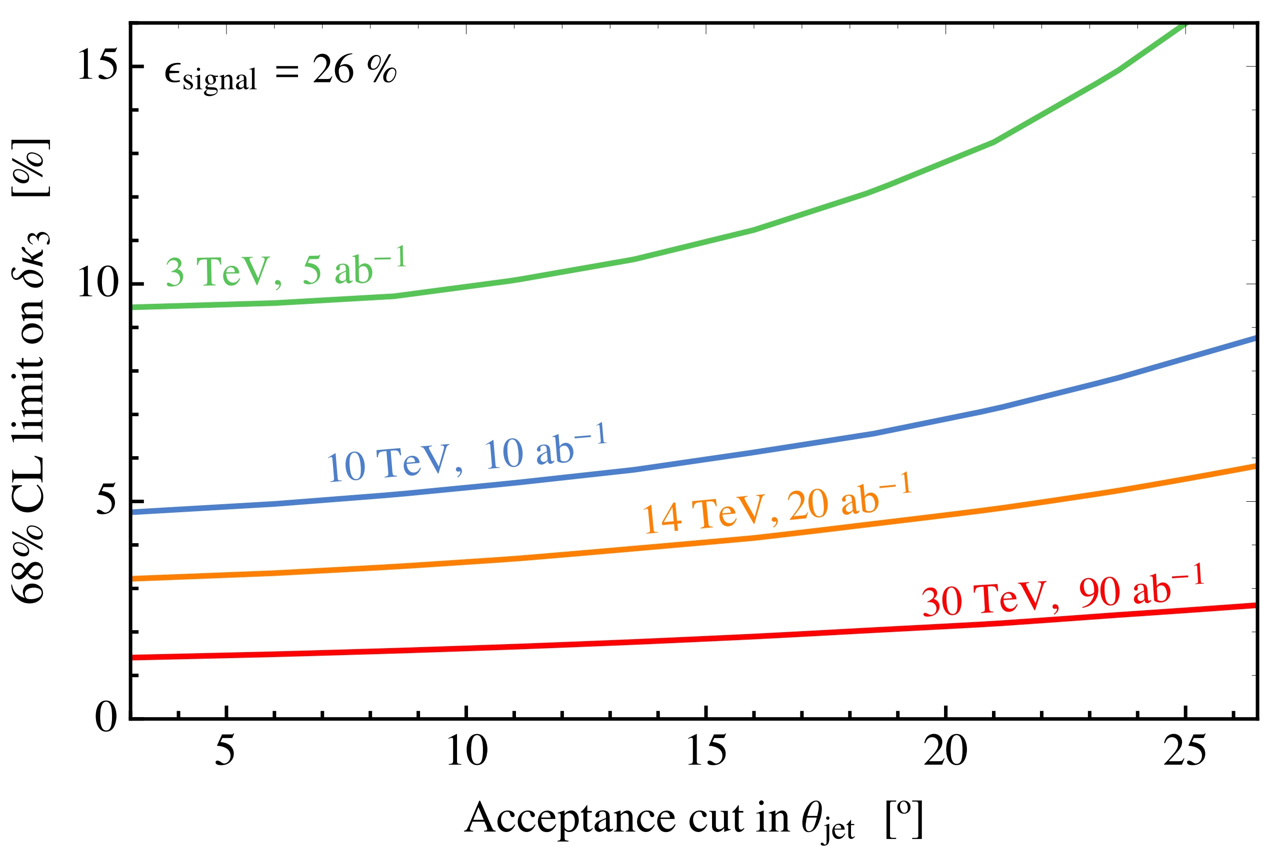
$$\left.\begin{array}{r}\text{reconstruction eff.} \sim 30\,\% \\ \mathrm{BR}(hh \to 4b) = 34\,\%\end{array}\right\} \epsilon \sim 10\,\%$$



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



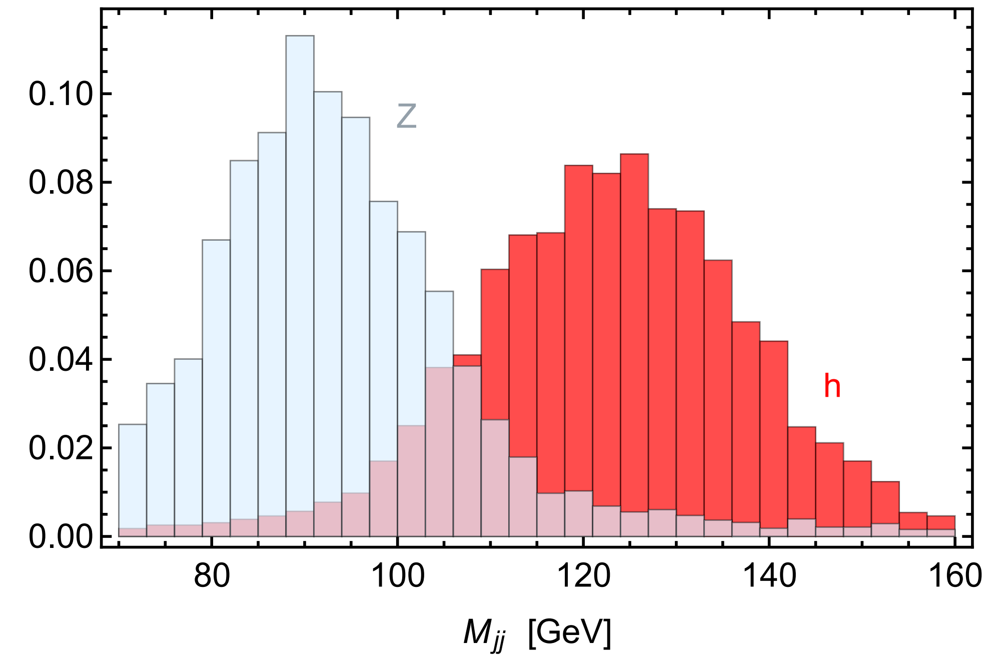
B, Franceschini, Wulzer 2012.11555

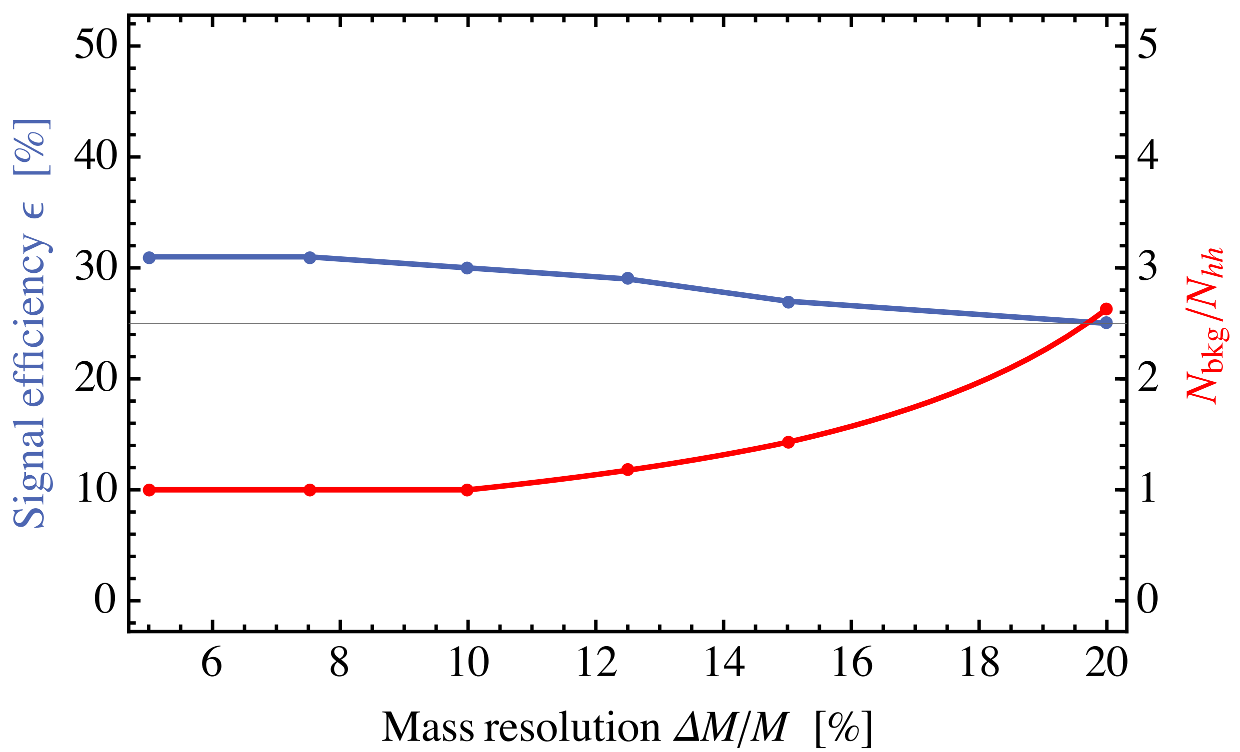


- Contribution from trilinear coupling is more central: loss due to angular cut is less important

Double Higgs production

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





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

All this should be done properly with a detector simulation (as has been done for CLIC).

However, perfect agreement with 1901.05897!

B, Franceschini, Wulzer 2012.11555

Double Higgs production

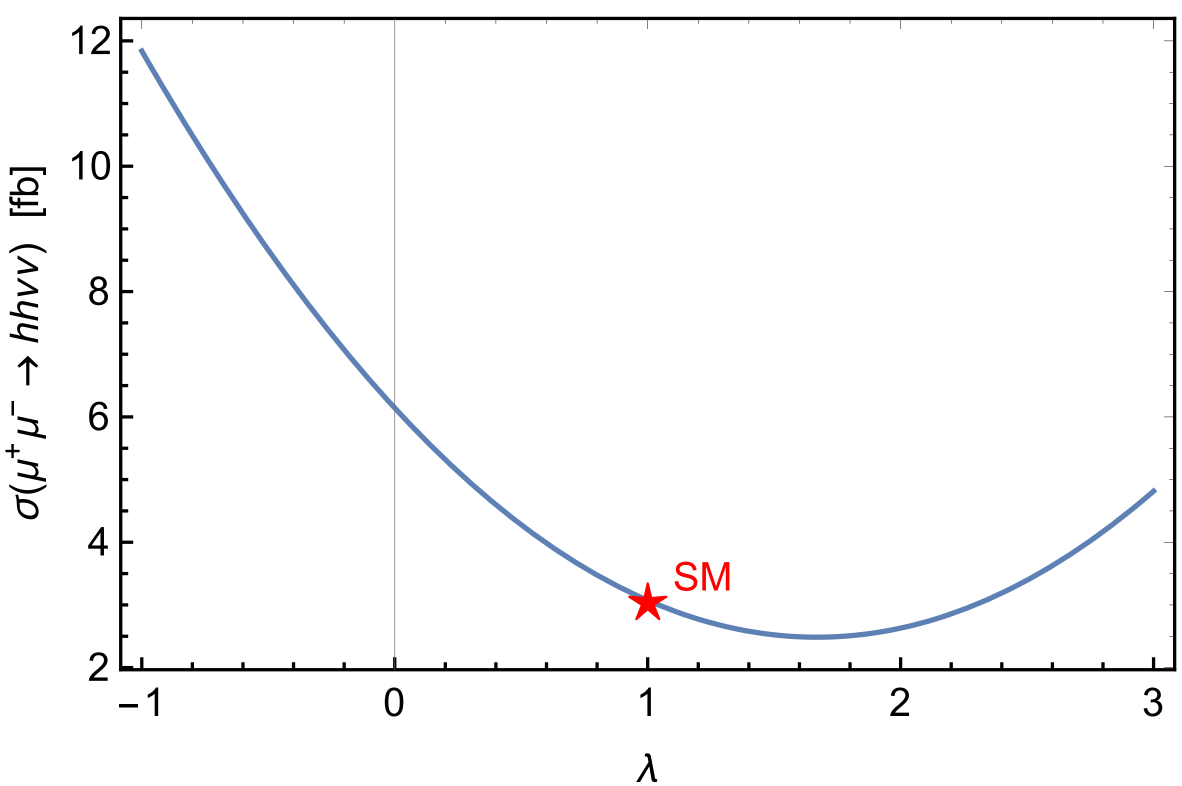
Number of events: N ~ s log(s/m_h^2)

$$N \sim s \log(s/m_h^2) \approx 10^{5 \div 6}$$

assume overall efficiency ~ 10%

Naïve estimate of the reach:

$\sqrt{s}$ [TeV]	L [ab^{-1}]	σ [fb]	N_{SM}	$\delta\sigma \sim (N_{SM} * \text{eff})^{-1/2}$	$\delta\lambda$
3	1	0.82	800	~ 10%	~ 15%
10	10	3.1	31,000	~ 1.8%	~ 4%
14	20	4.4	88,000	~ 1%	~ 3%
30	90	7.4	660,000	~ 0.4%	~ 1.5%



Cross-section dependence on δλ

$$\sigma = \sigma_{\rm SM} + a_1(\delta\lambda) + a_2(\delta\lambda)^2$$

$hh \to 4b$ signal

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

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

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

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

factor 10 loss
in xsec at 30 TeV

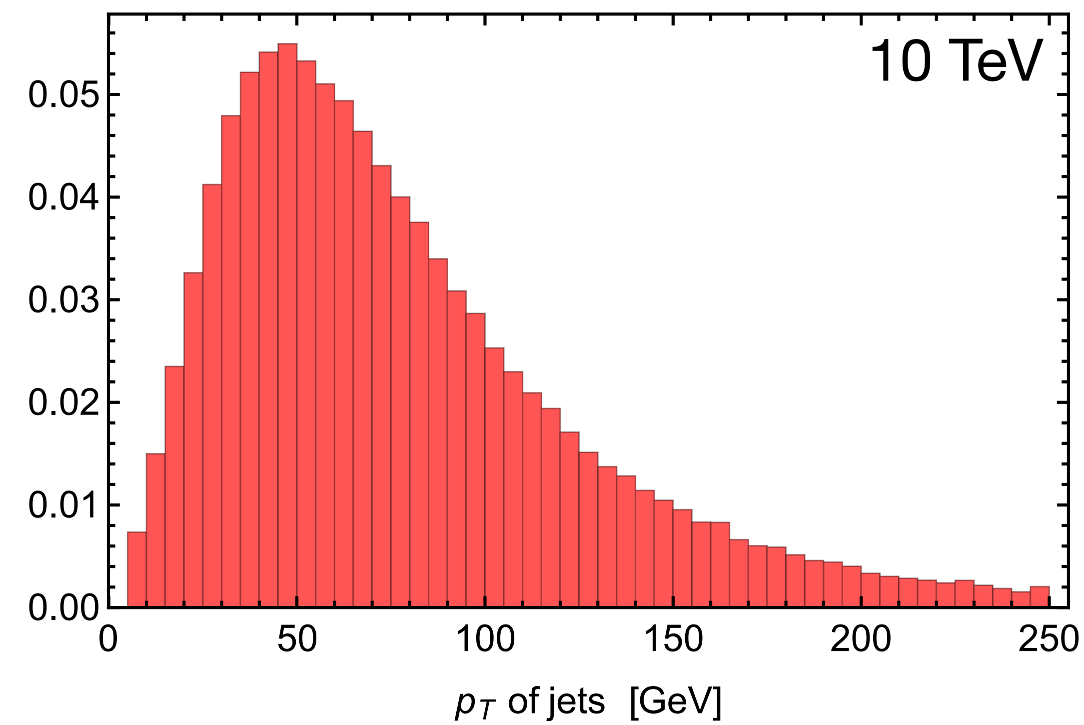
- **Neglect backgrounds** (for the moment)

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

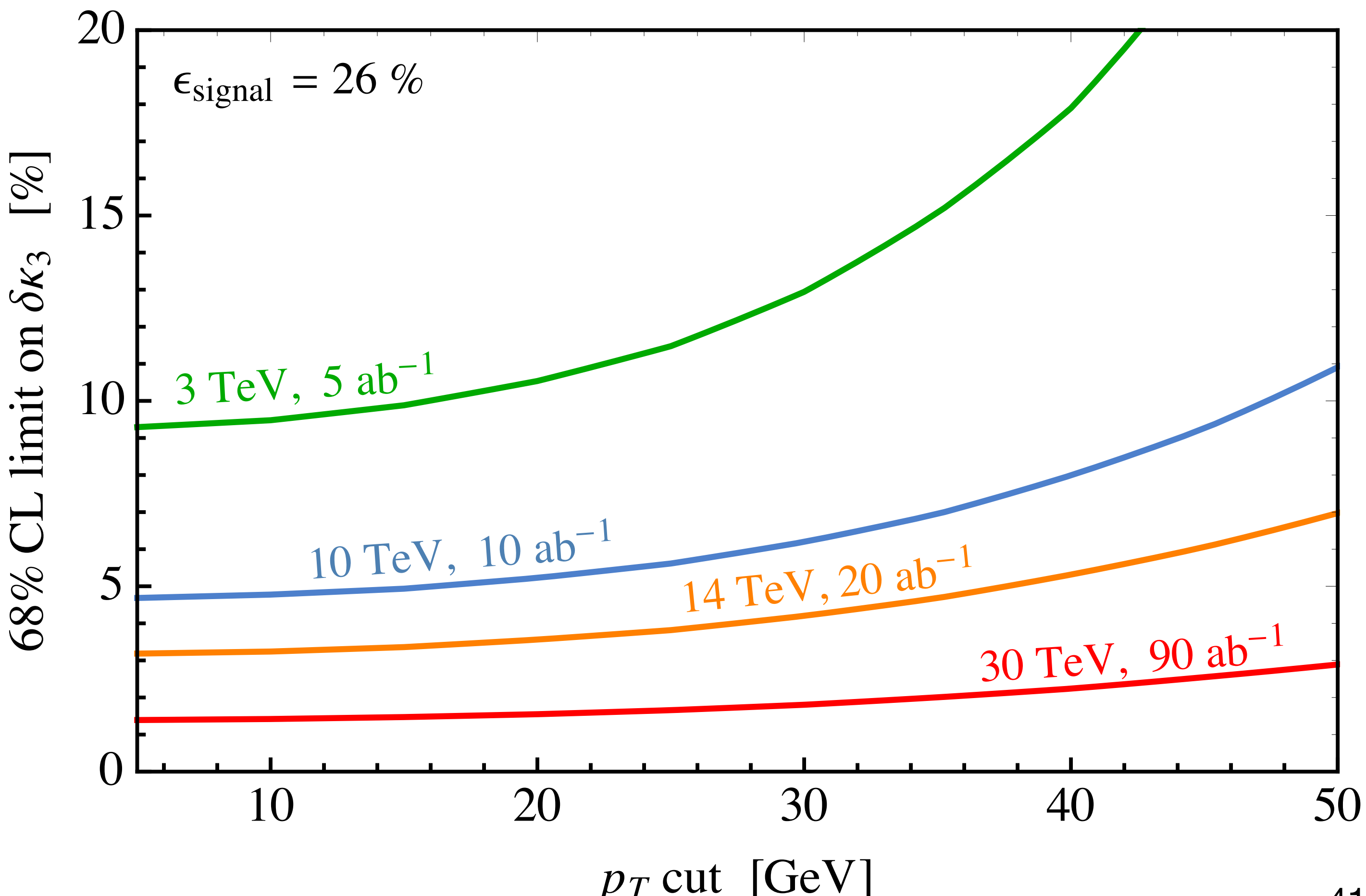
Sensitivity to jet p_T threshold

- 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

- Backgrounds are important and cannot be neglected (see also CLIC study [1901.05897])

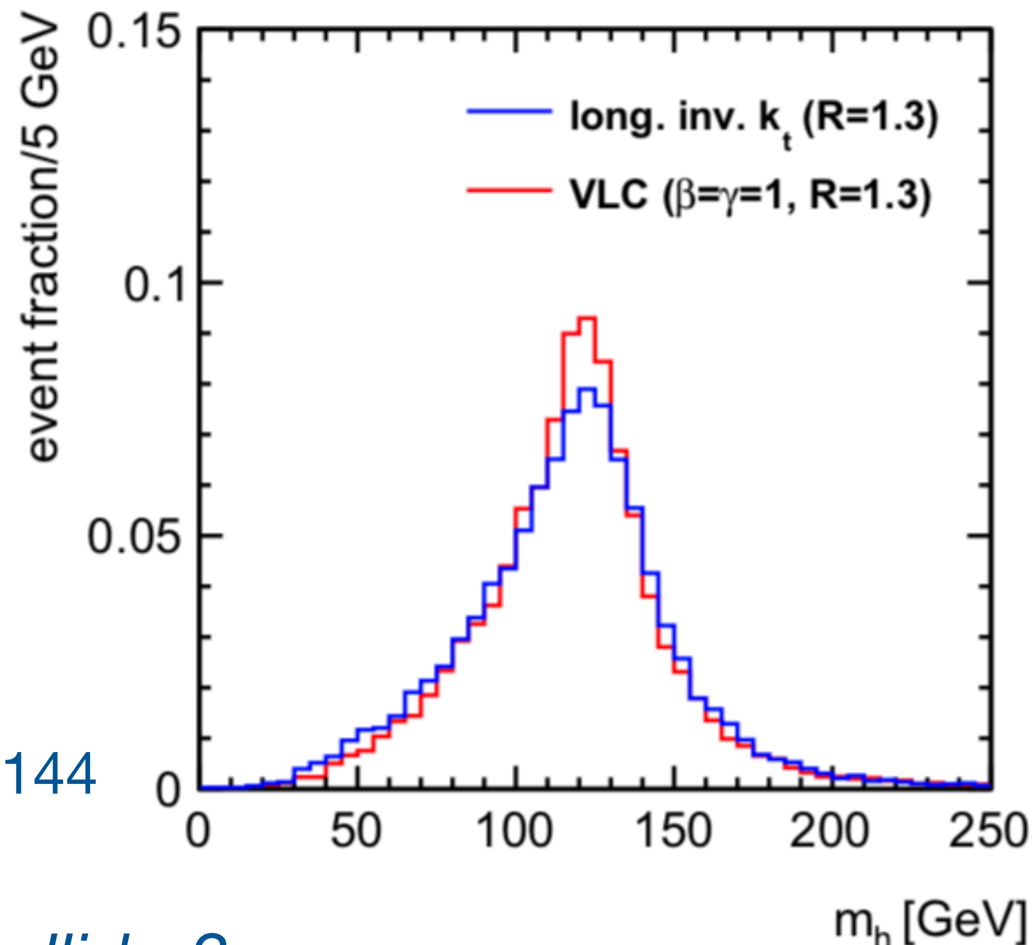
- Mainly VBF di-boson production: Zh & ZZ, but also WW, Wh, WZ…

  other backgrounds are easily rejected with cut on tot. inv. mass

- Precise invariant mass reconstruction is crucial to isolate signal

  - resolution on Z inv. mass ~ 6–7% at 3 TeV [CLICdp-Note-2018-004]

  - for Higgs energy resolution is worse: 10% on jet energy, ~ 15% on inv. mass (neutrinos in semi-leptonic b decay, too forward tracks missed)



thanks to Philipp
for discussion

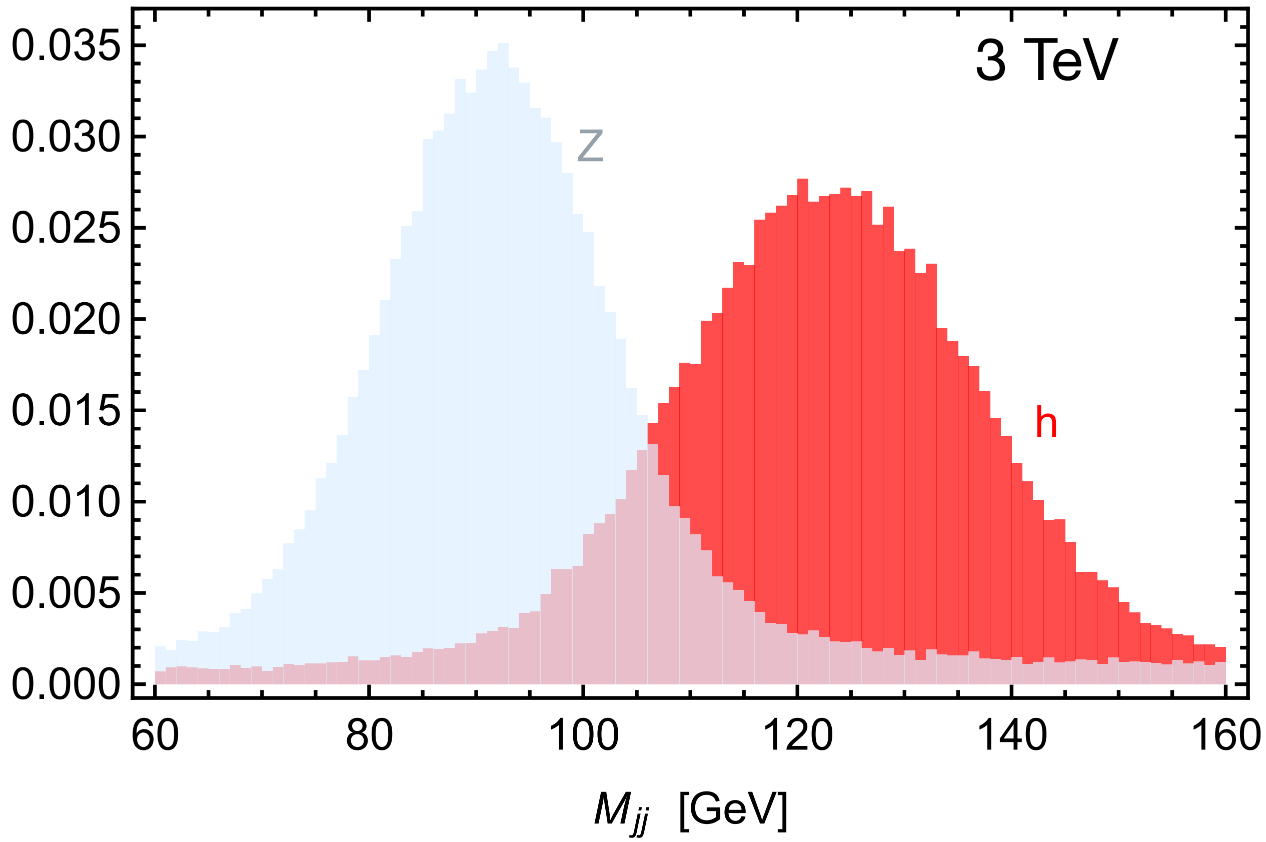
Eur. Phys. J. C (2018) 78:144

what happens at muon collider?

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,

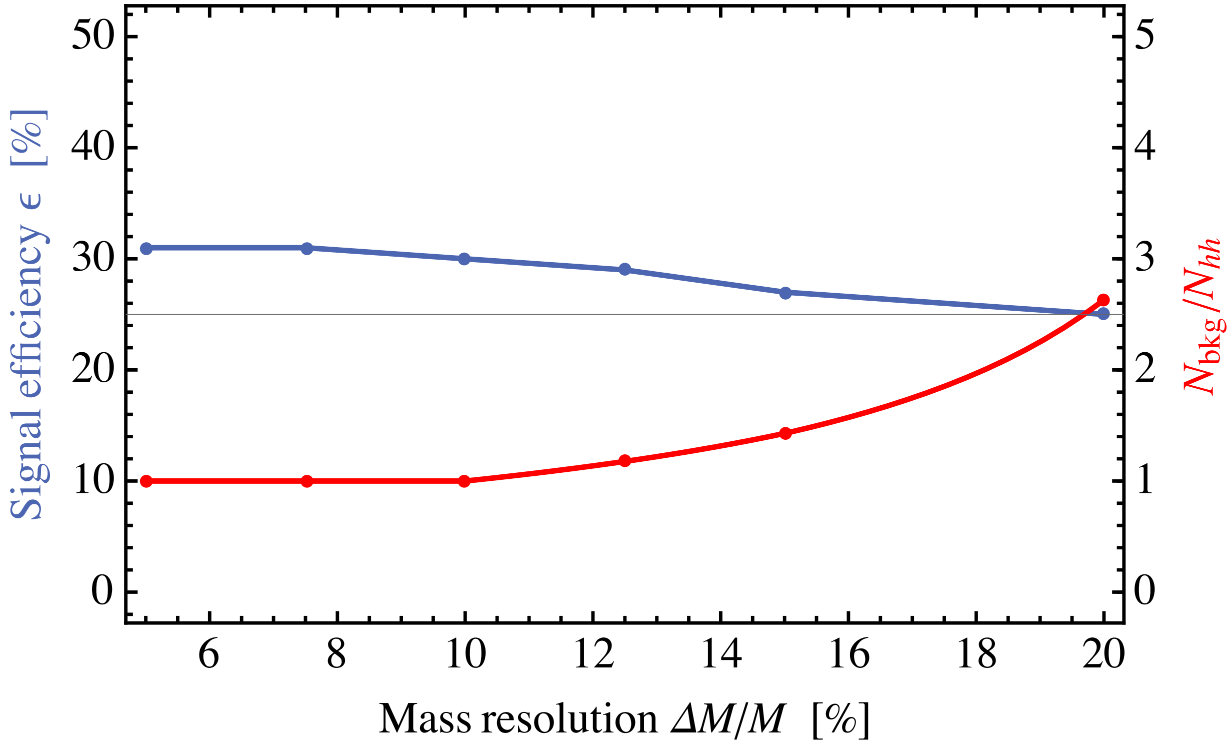
  n_b = 3.2

  ε_{sig} = 27%

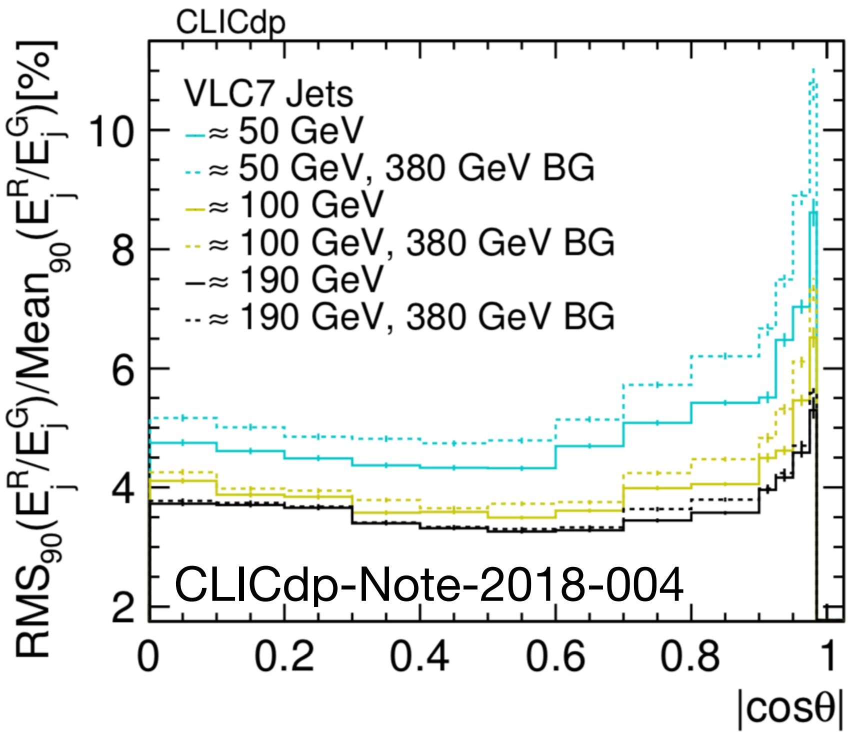
NB: all this should be done properly (and has been done, for CLIC), with a detector simulation

Backgrounds

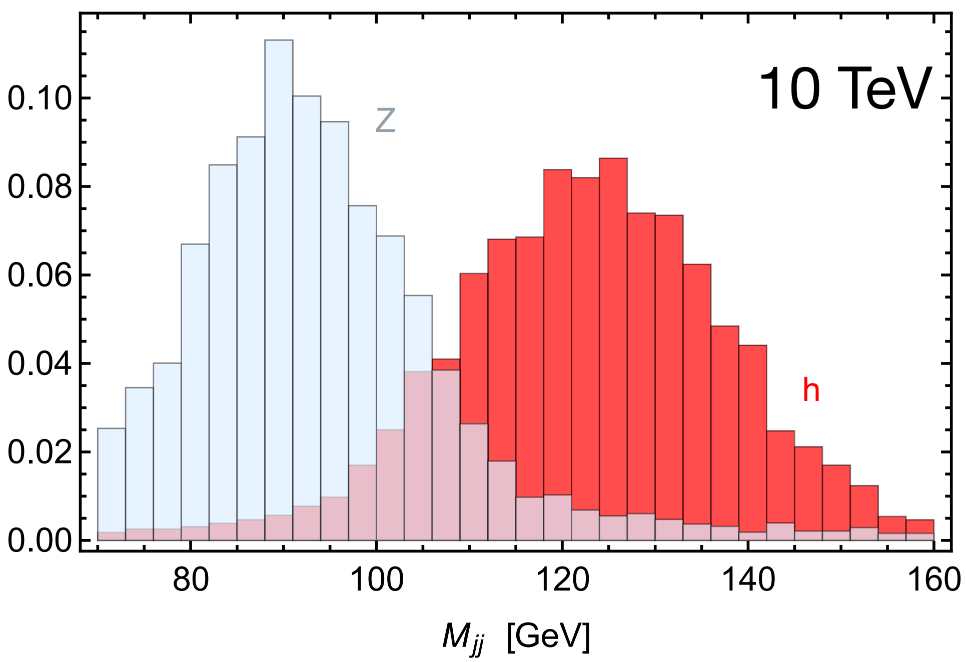
One can now repeat the analysis for different jet energy resolutions:



no real gain using only central events…



… and different energies:



- Optimize cuts to reject bkg:

  $M_{hh} > 105$ GeV,

  $n_b = 2.8$

  $\varepsilon_{sig} = 32\%$

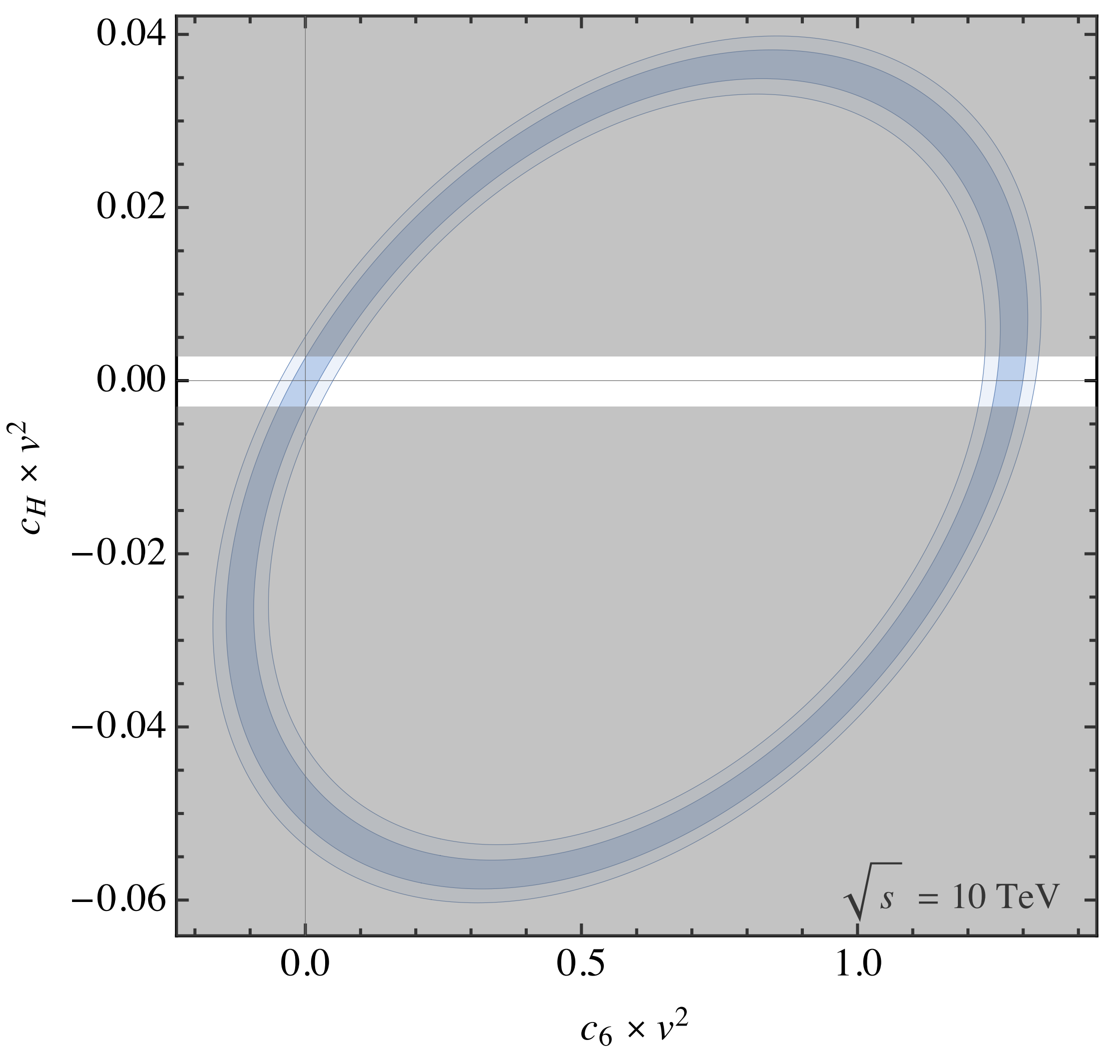
result very similar to 3 TeV

Double Higgs production: EFT fit

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

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

O_H also affects single Higgs couplings universally: $$\kappa_{V,f} = 1 - v^2 C_H/2$$



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

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

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

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:

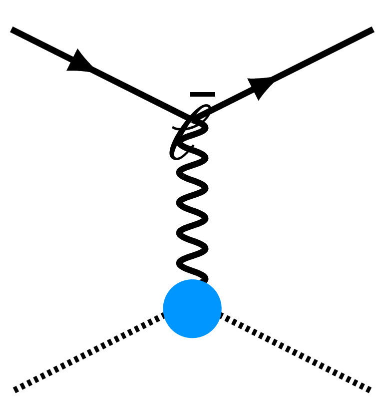
$$\mathcal{O}_{3L} = \left(\bar{\mathrm{L}}_L\gamma^\mu\sigma^a\mathrm{L}_L\right)\left(iH^\dagger\sigma^a\overleftrightarrow{D}_\mu H\right),$$

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

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

"high-energy primary effects"

- 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:

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

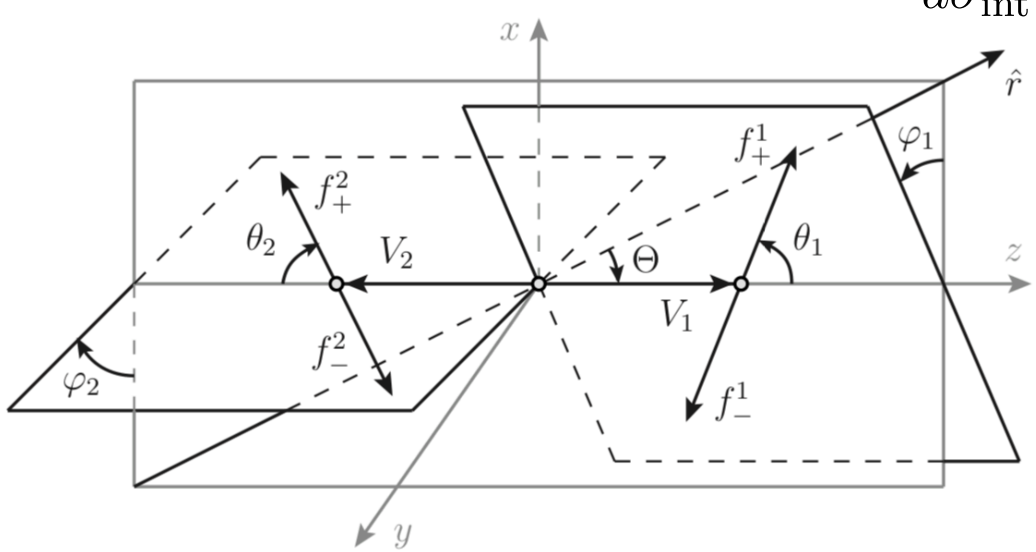
- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

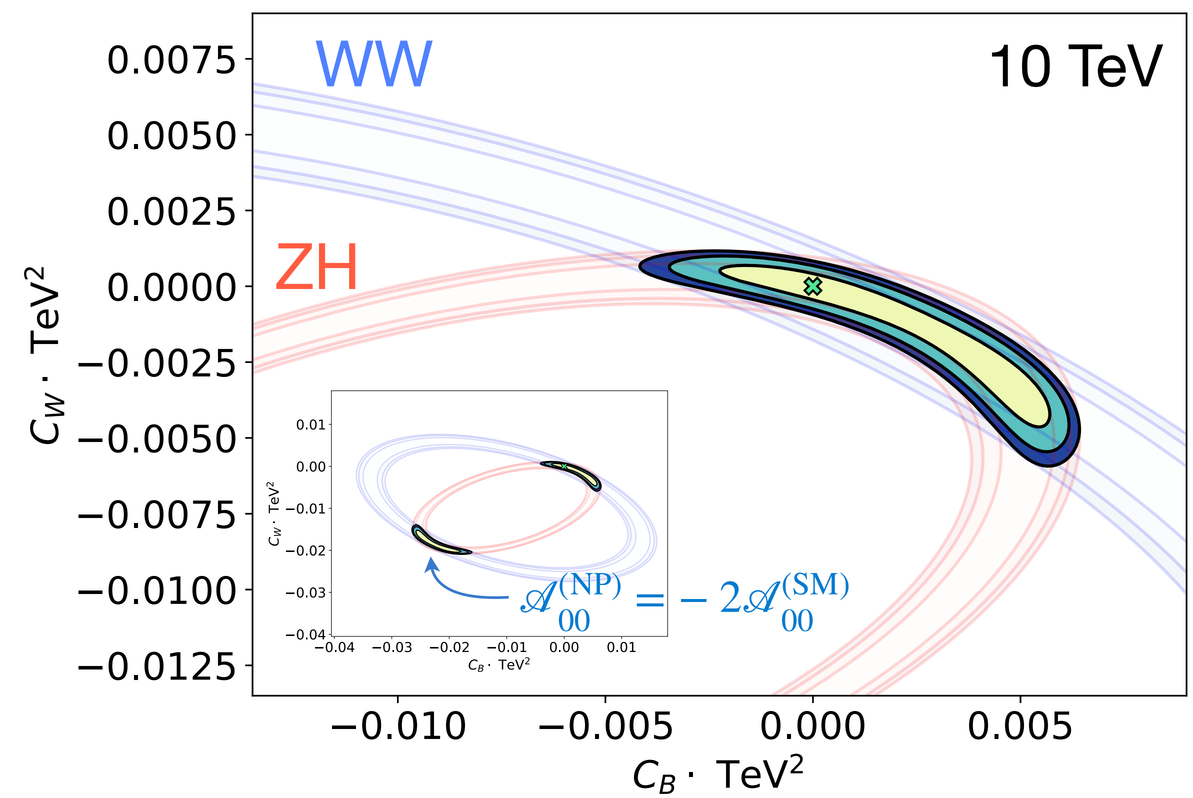
Interference between ±∓ and 00 helicity amplitudes cancels in the total cross-section ⇒ signal suppressed!

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

High-energy WW: angular analysis

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

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

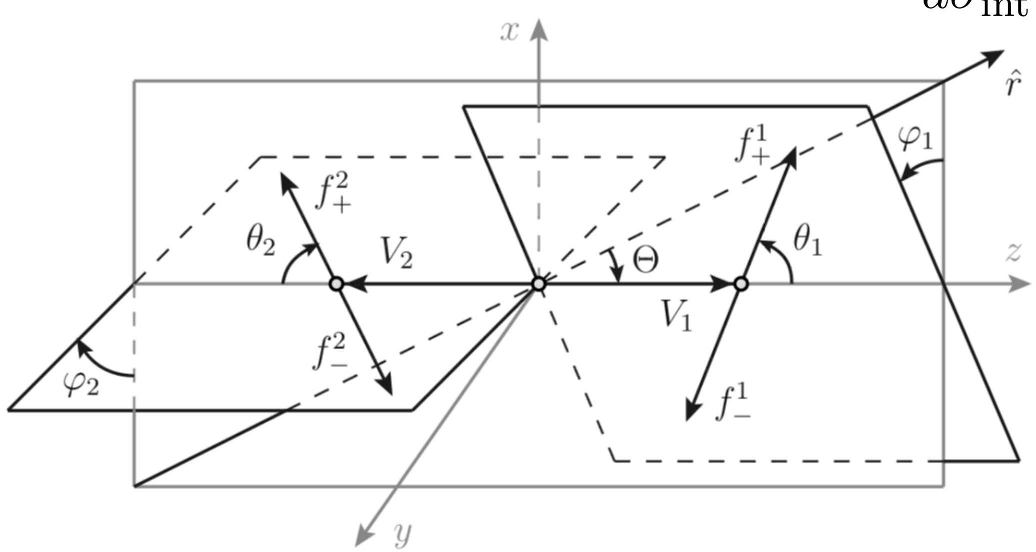
- In the SM, large contribution to $\mu^+\mu^- \to W^+W^-$ from transverse polarizations.

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

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

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

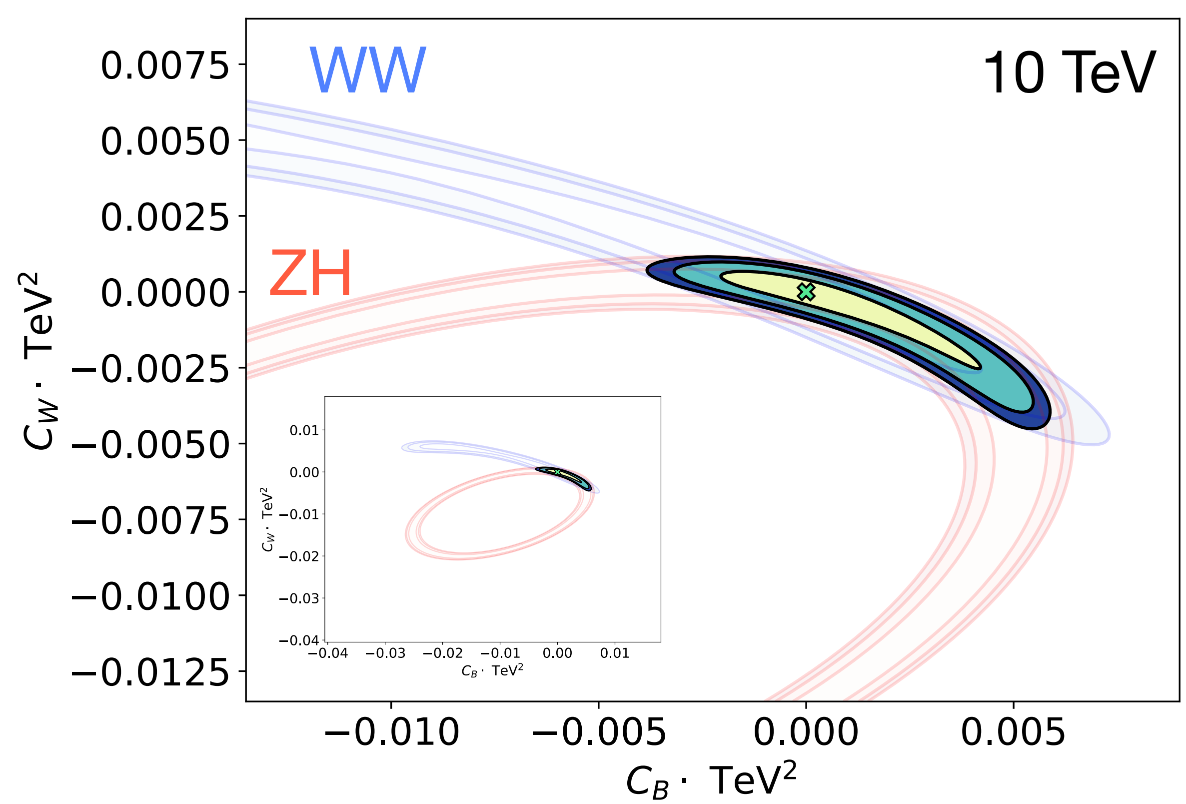
see also Panico et al. 1708.07823, 2007.10356



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

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

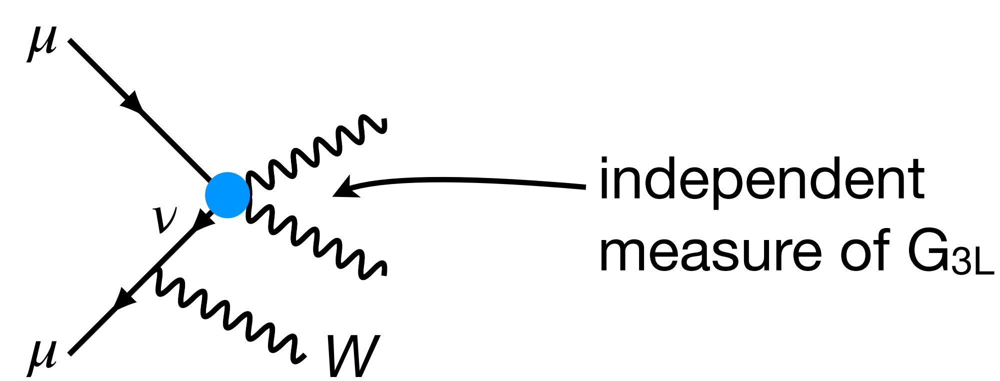
High-energy tri-bosons

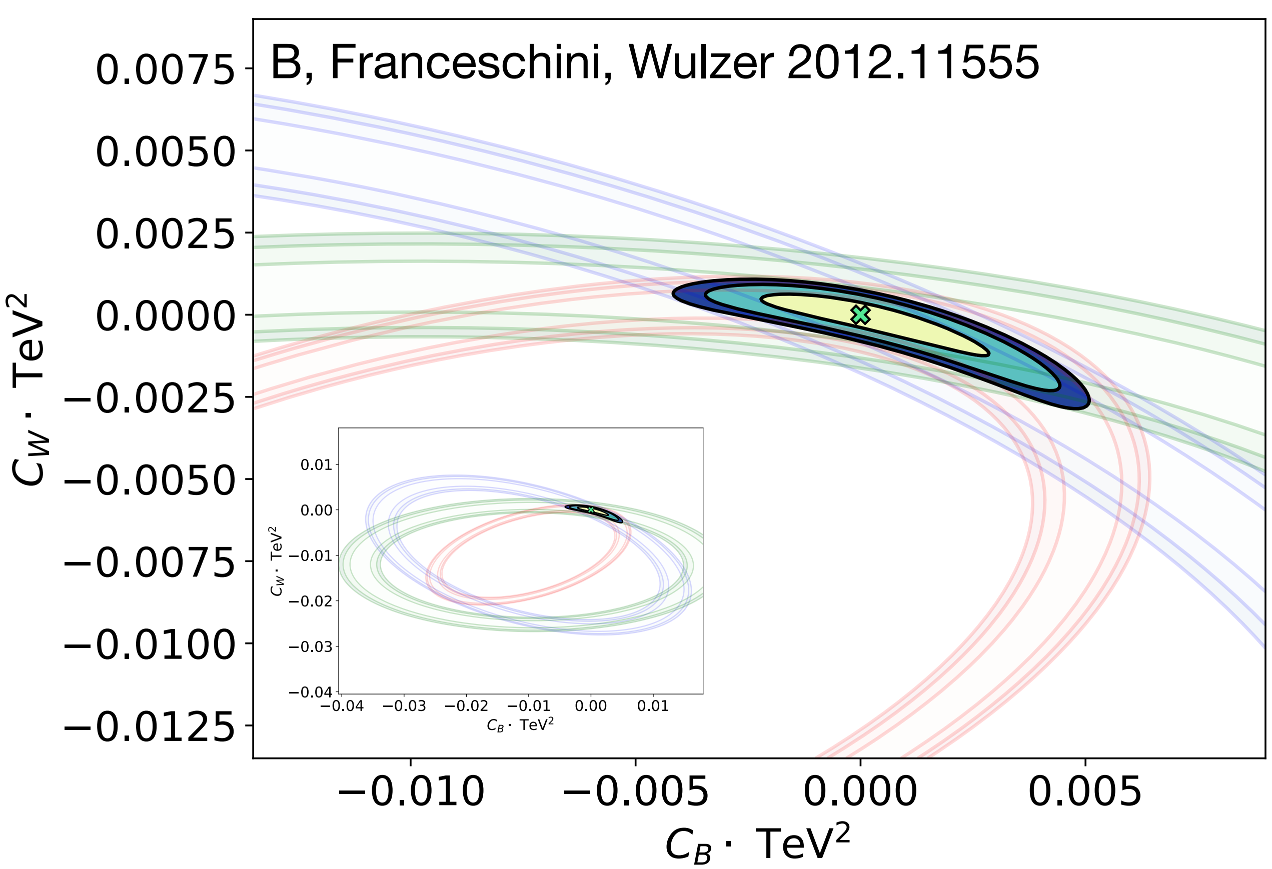
- Gauge boson radiation becomes important at high energies *(Sudakov double-log enhancement of soft-collinear emissions)*

$\mu^+\mu^- \to VV$ not much suppressed w.r.t. $\mu^+\mu^- \to VVV$ ($V = W^\pm, Z, H$)

- This allows to access the charged processes $\ell^\pm\nu \to W^\pm Z, W^\pm H$

"effective neutrino approximation"



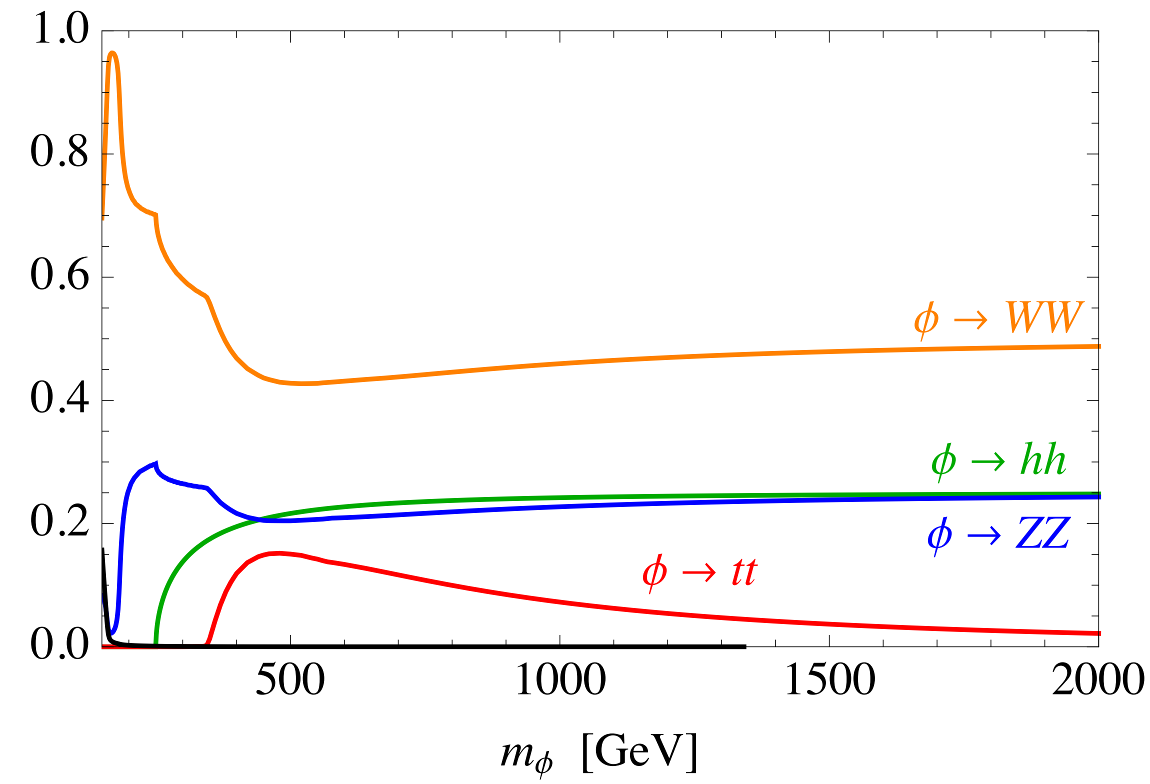


- NB: also 2 → 2 scatterings receive large radiative corrections: "soft" EW radiation must be taken into account properly…

➡ Inclusive NLO study of VV and VVV

Scalar singlets at a HELC

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

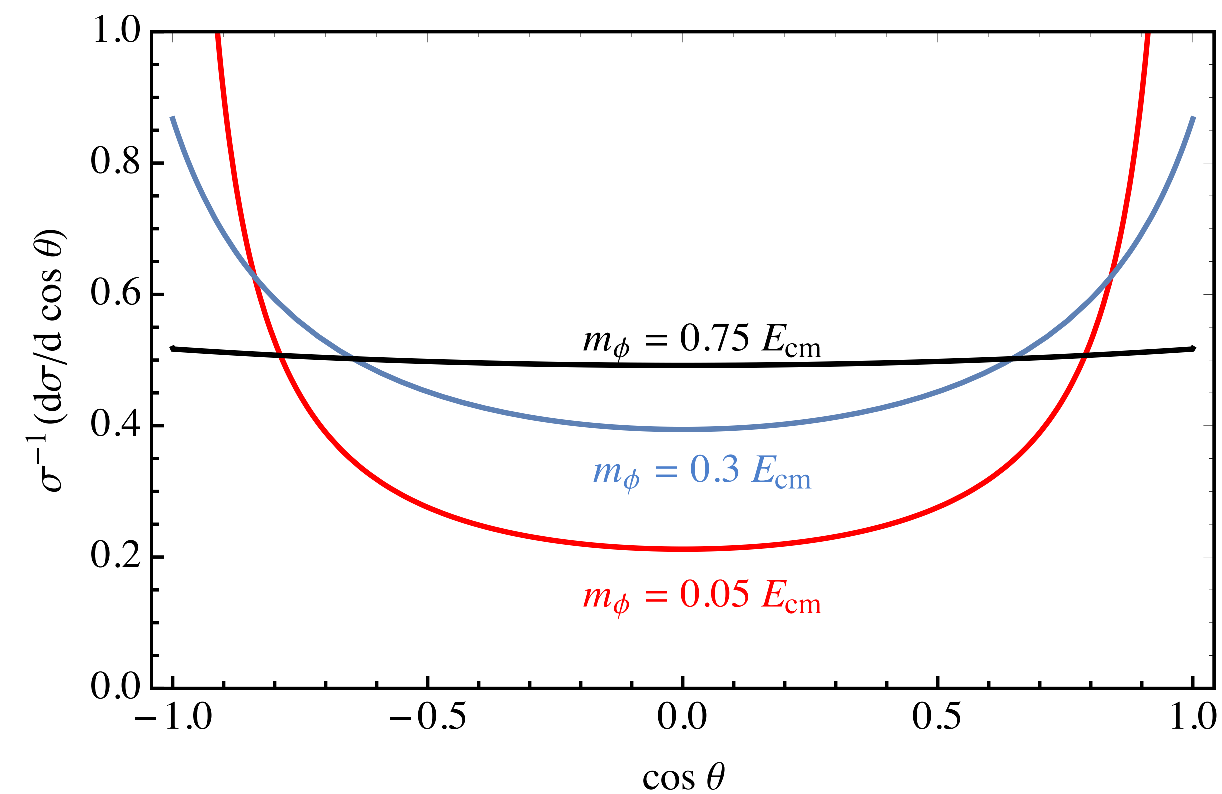


Goldstone boson equivalence theorem:

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

$$m_\phi \gg m_h$$

- 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



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:

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

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

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

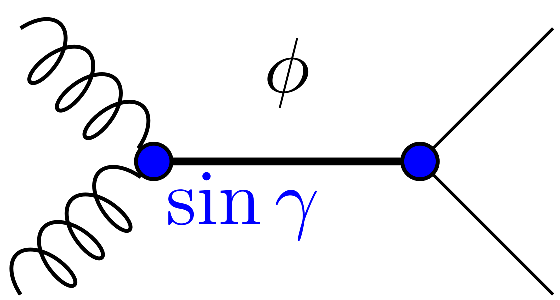
triple couplings: **BR(*ϕ* → *hh*)**, *g*$_{hhh}$

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

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

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

- ϕ can be singly produced:

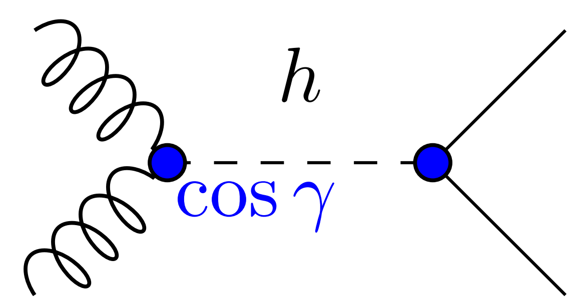


$$\sigma_\phi = \sigma_{\rm SM}(m_\phi) \times \sin^2\gamma$$

- 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:

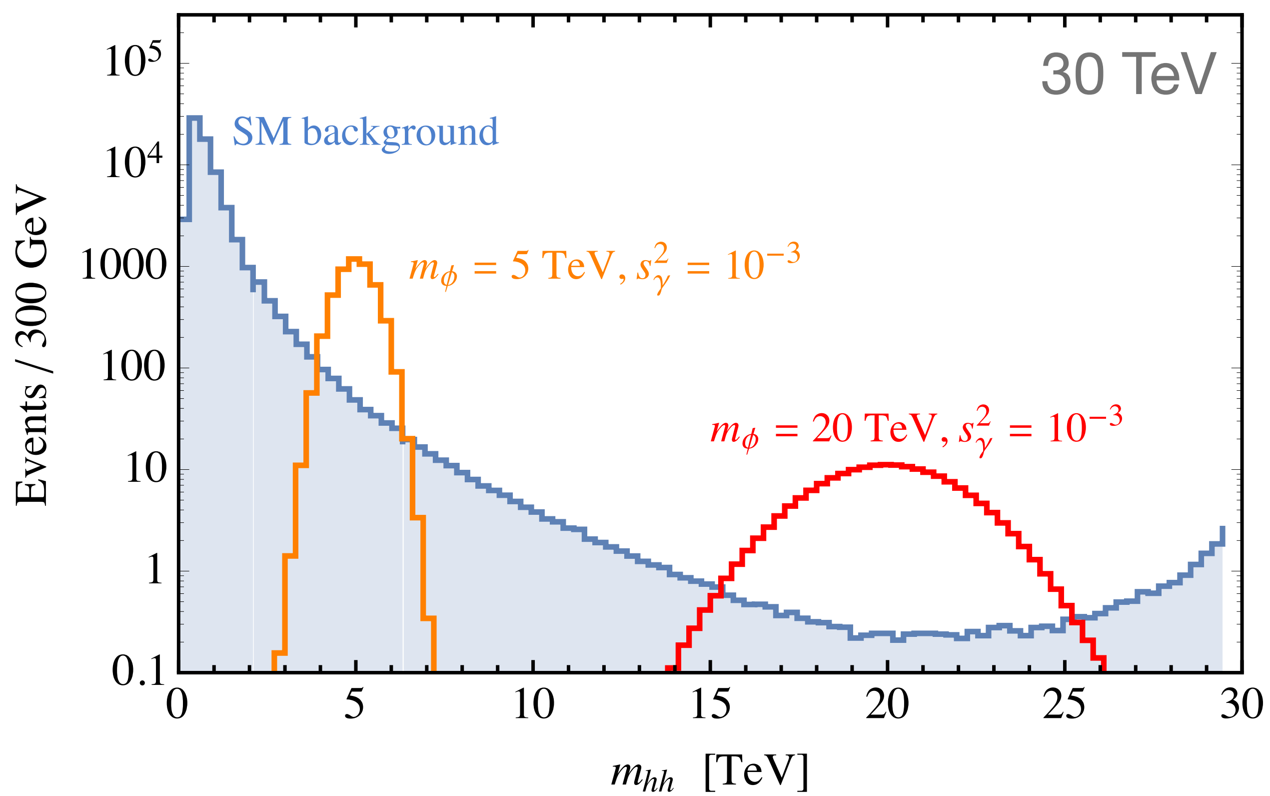


$$\mu_h = \mu_{\rm SM} \times \cos^2\gamma$$

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

hh(4*b*) decay channel

Cut & count experiment around the resonance peak:

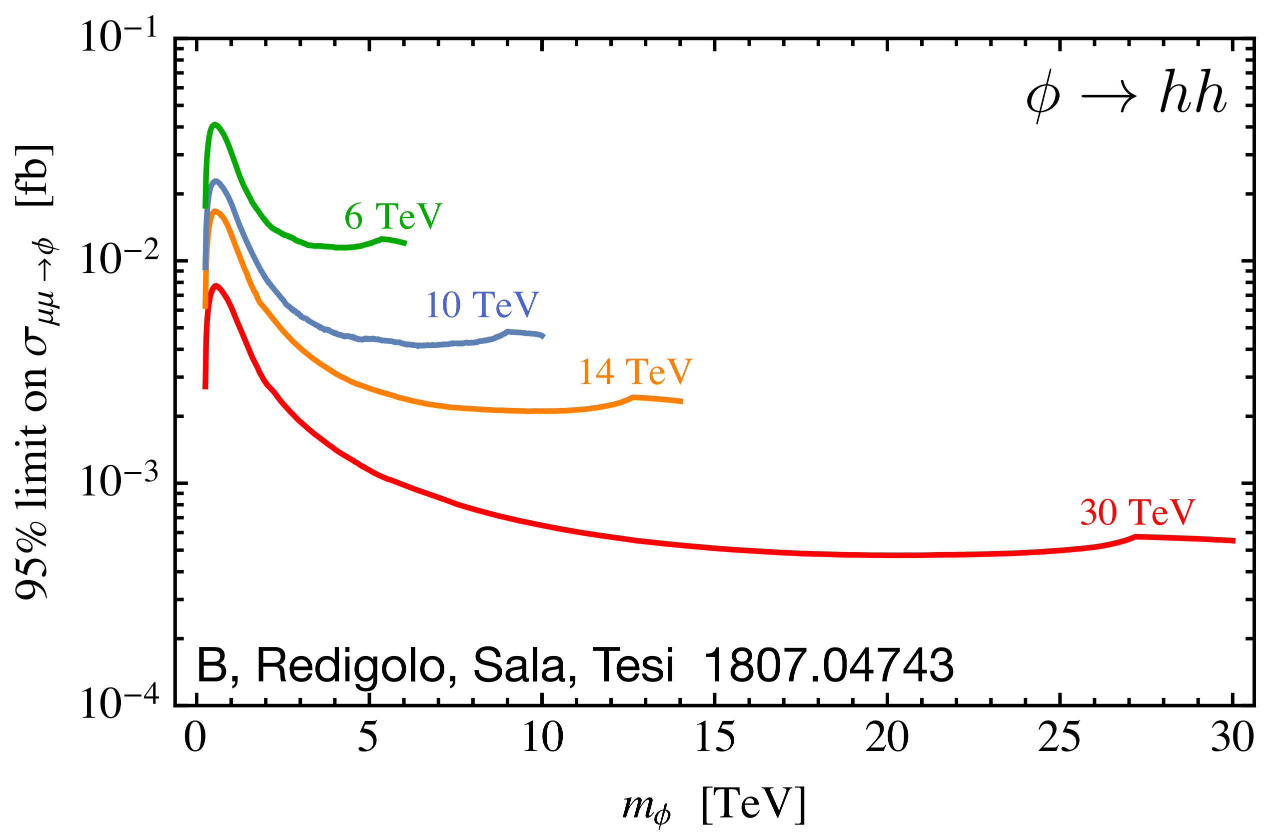


$$\text{significance} = \frac{N_{\text{sig}}}{\sqrt{(N_{\text{sig}} + N_{\text{bkg}}) + \alpha_{\text{sys}}^2 N_{\text{bkg}}^2}}$$

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

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

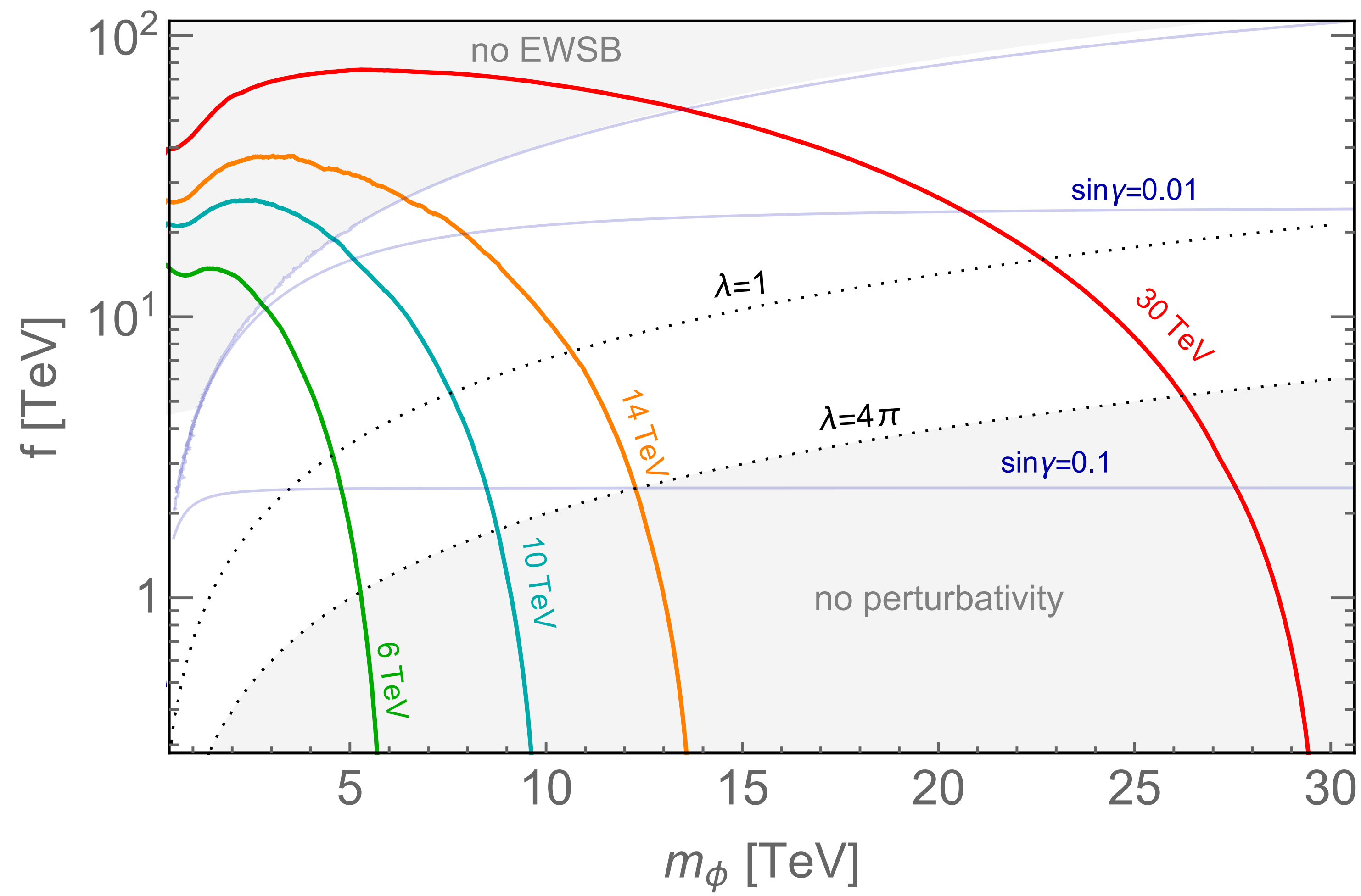
- Higgs is a pseudo-Goldstone

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

- Model-independent tests:

  ✓ Higgs couplings

  ✓ Search for the singlet



Goldstone bosons (Twin Higgs)

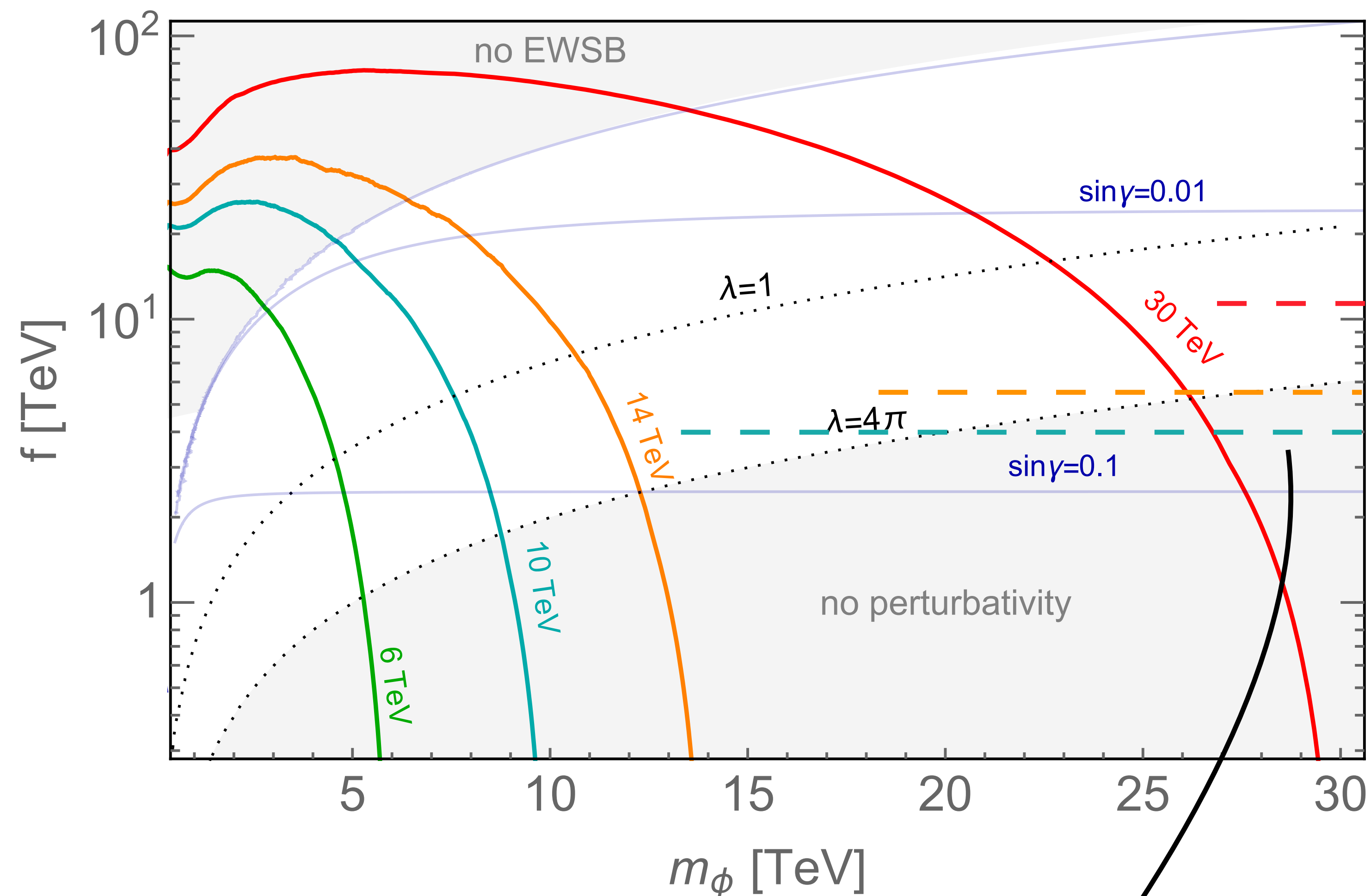
- Higgs mass is protected from radiative corrections without new light colored states

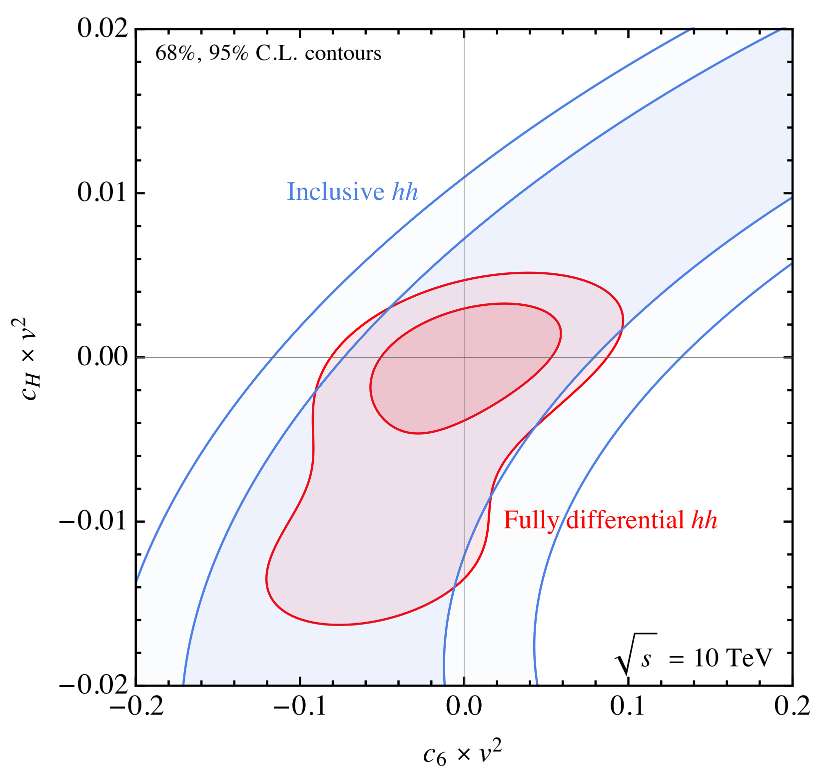
- Two copies of the SM, with approximate Z_2 symmetry, coupled through Higgs portal

- 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

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

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

- ◇ Alleviates fine-tuning in v for $\lambda \gtrsim 1$ and moderate $\tan\beta$

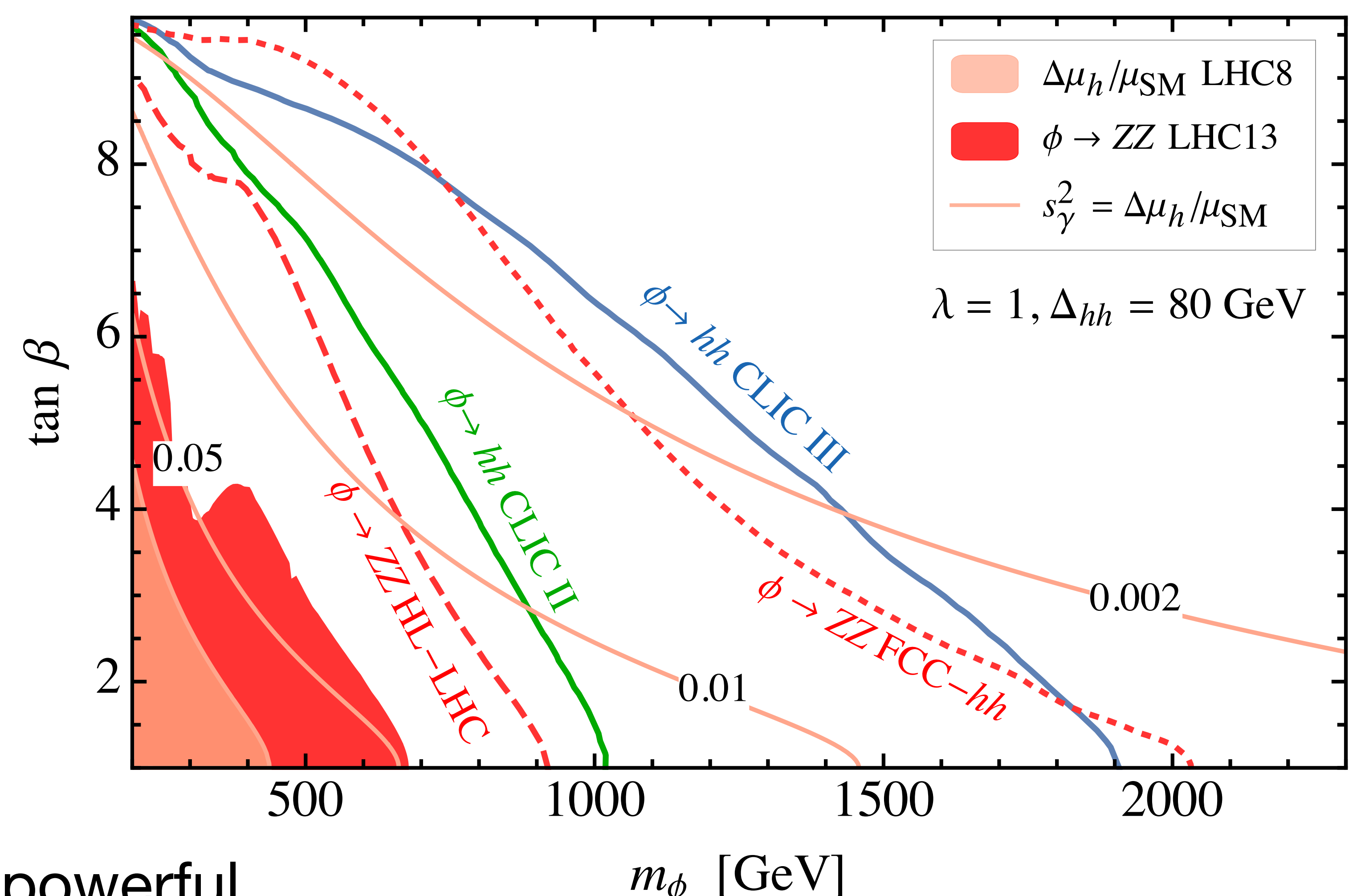
The singlet can be the lightest new state of the Higgs sector

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

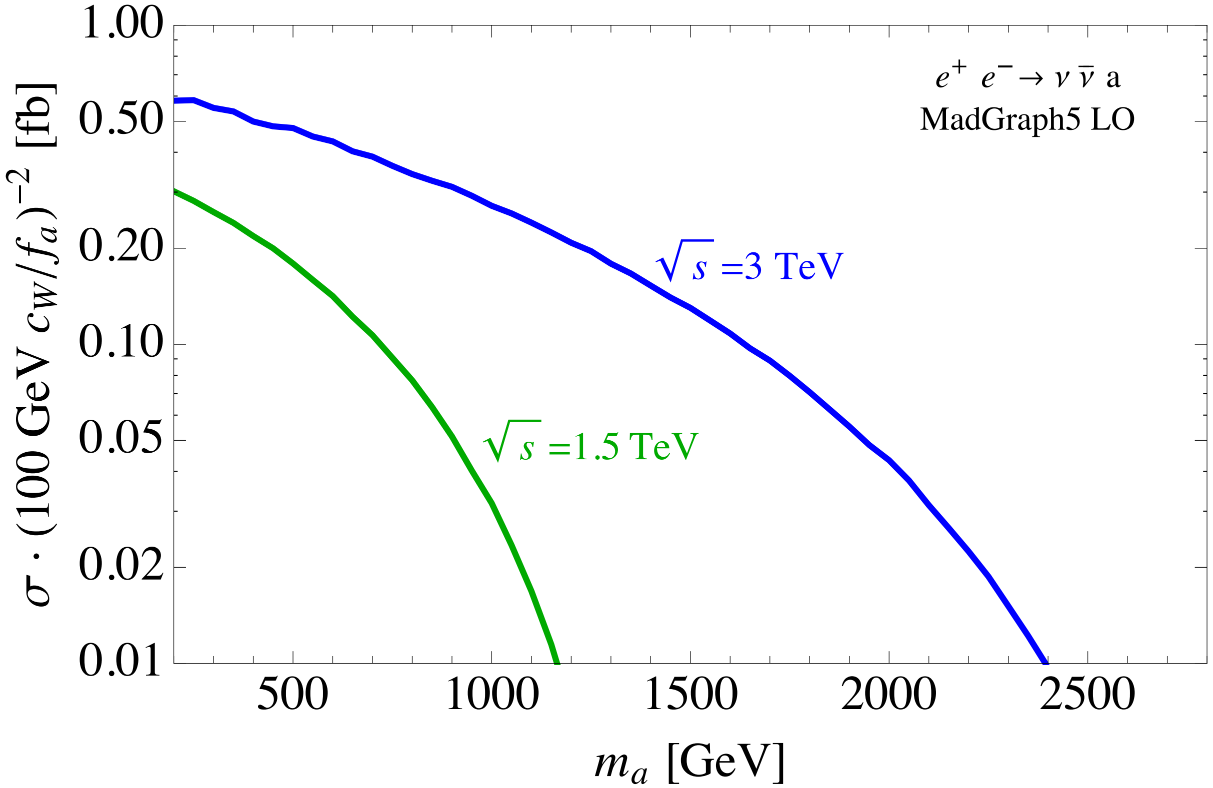


Weakly coupled: direct searches powerful

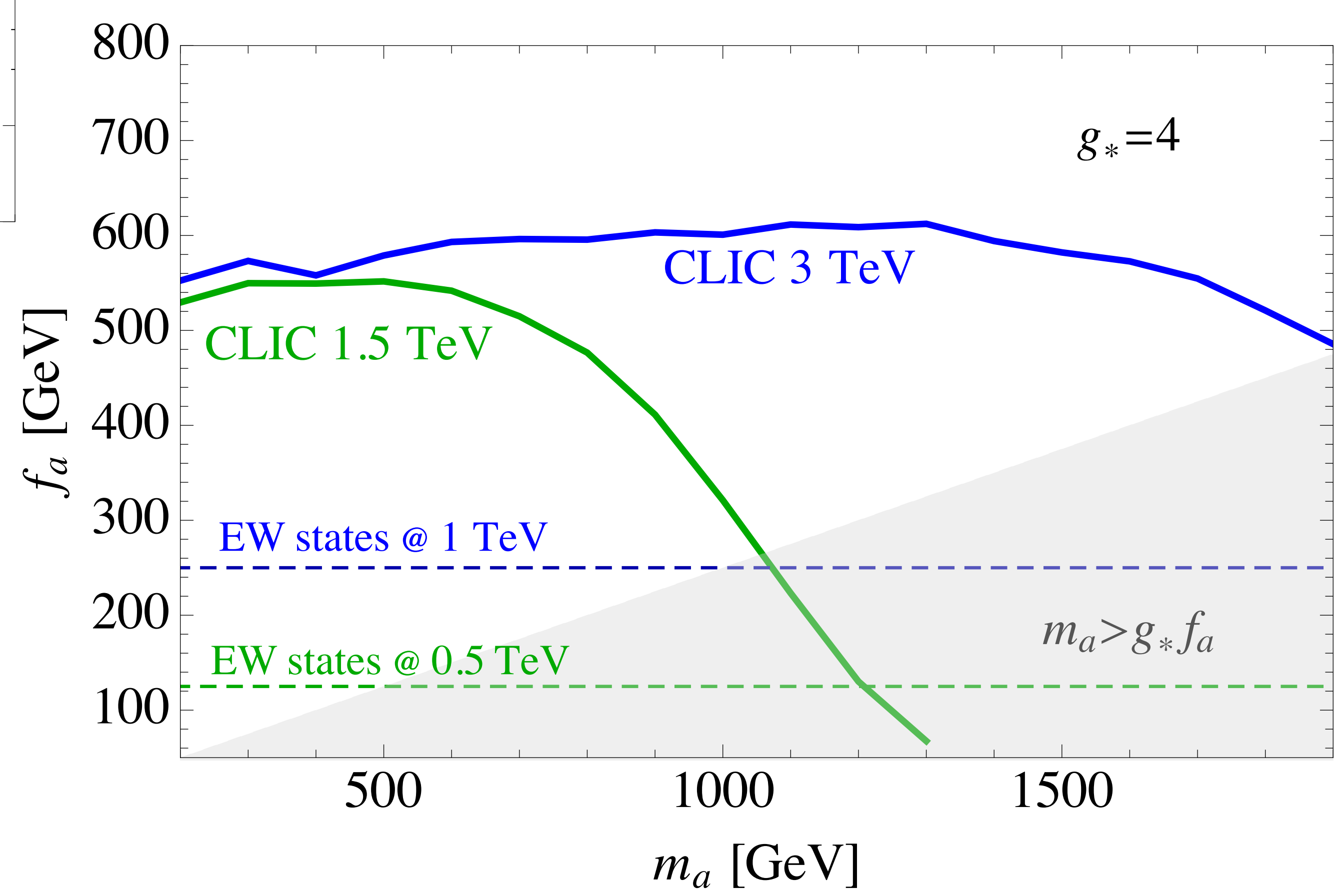
Axion-like particles (ALPs)

- EW ALP: $$\mathscr{L}_{\rm ALP} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{c_1\alpha_1}{4\pi}\frac{a}{f_a}B\tilde{B} + \frac{c_2\alpha_2}{4\pi}\frac{a}{f_a}W\tilde{W}$$

  SSB of a U(1) at scale f_a (**not** the QCD axion), physical cut-off at $g_* f_a$



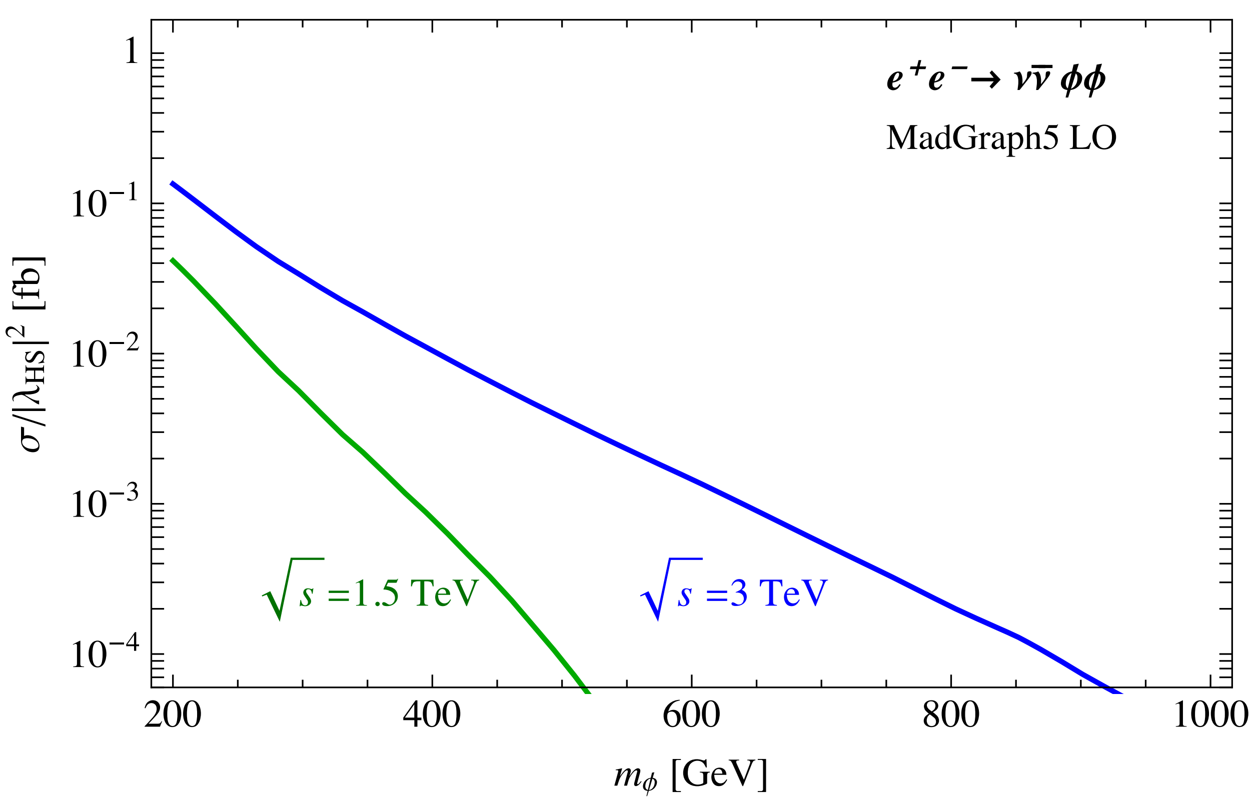
- Produced in W-fusion (but couple to transverse W's), and decay to vectors

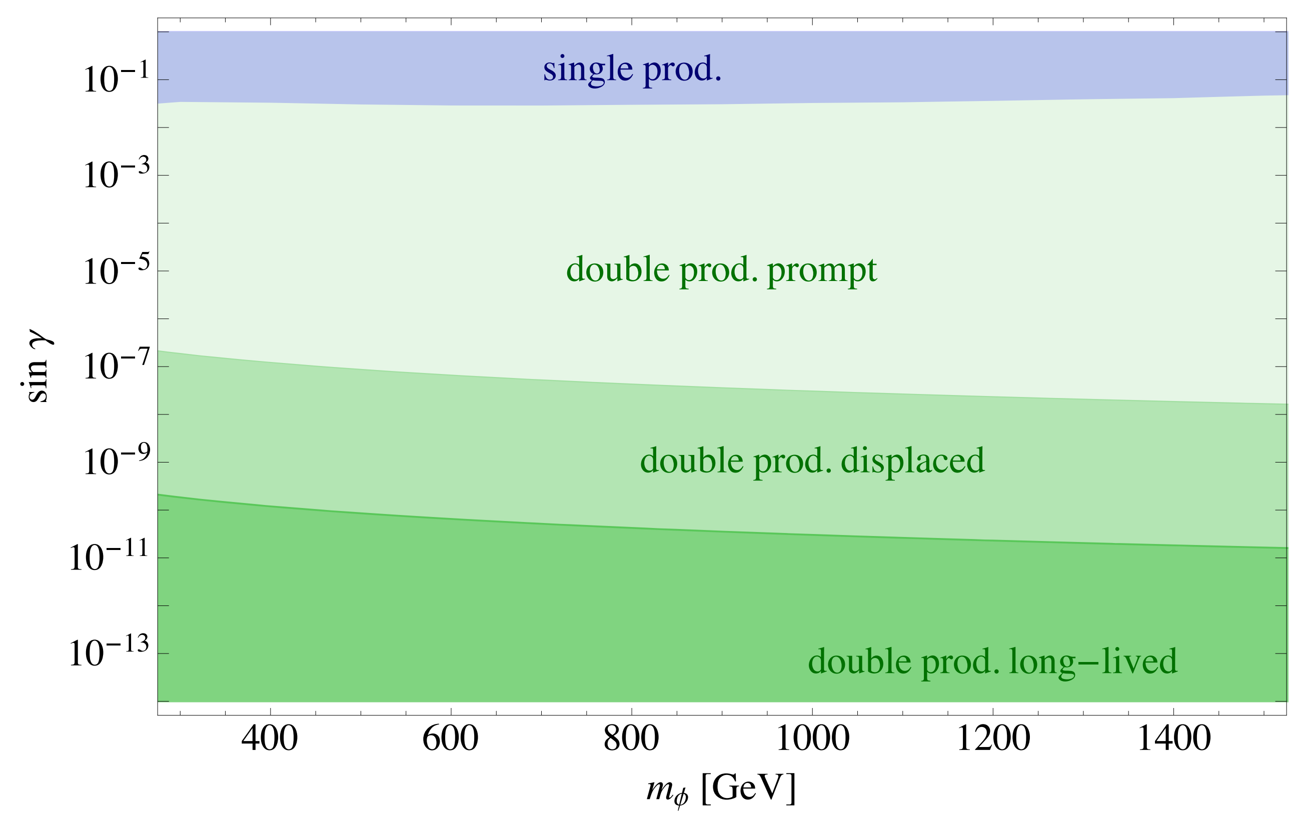


- In general, a → γγ is a golden channel, but could be suppressed for particular values of c_1, c_2 (photophobic ALP)

Pair production

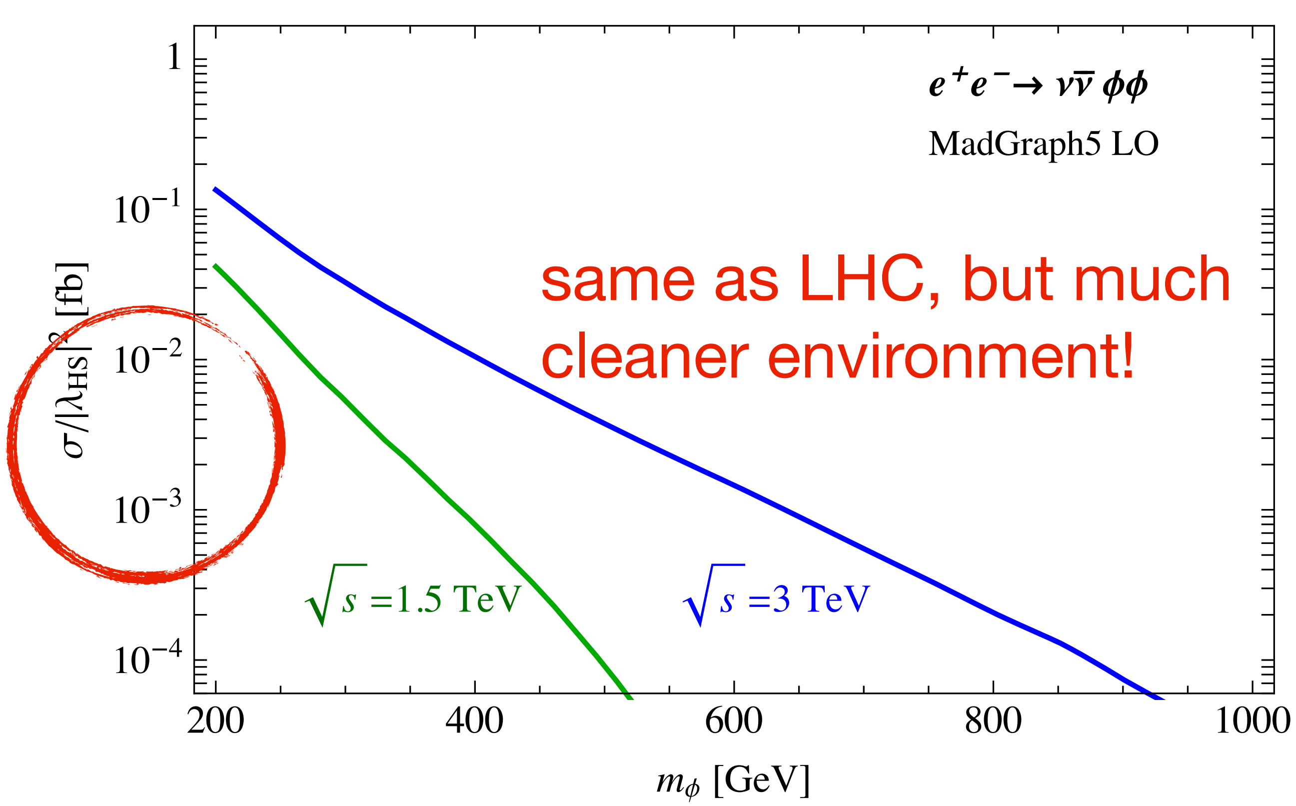
- In the limit of small mixing angle, the single production rate of ϕ vanishes
  - the Lagrangian has an approximate Z_2 symmetry $\phi \to -\phi$ $\cancel{a_{HS}|H|^2 S}$
- Double production rate does not depend on the mixing: controlled by the portal coupling $\lambda_{HS}\, S^2|H|^2$

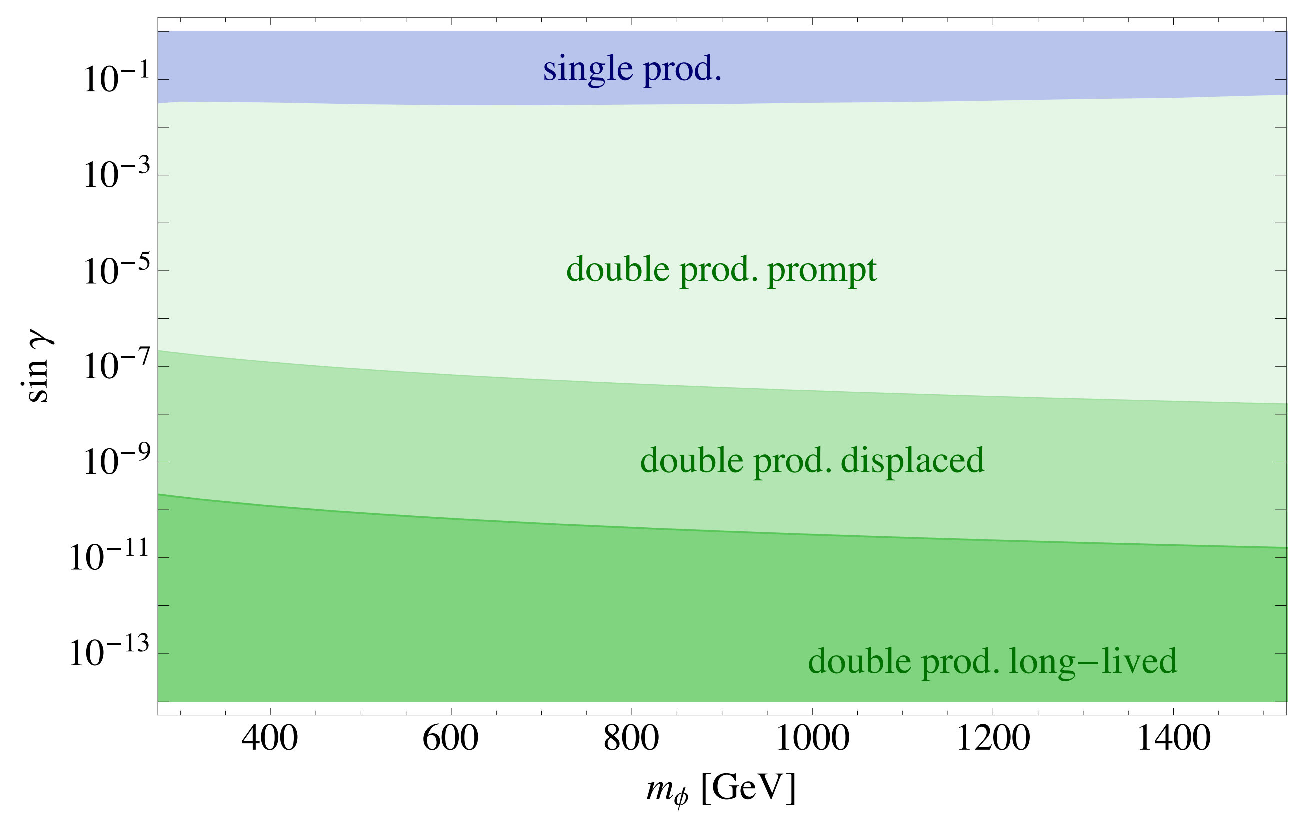




Pair production

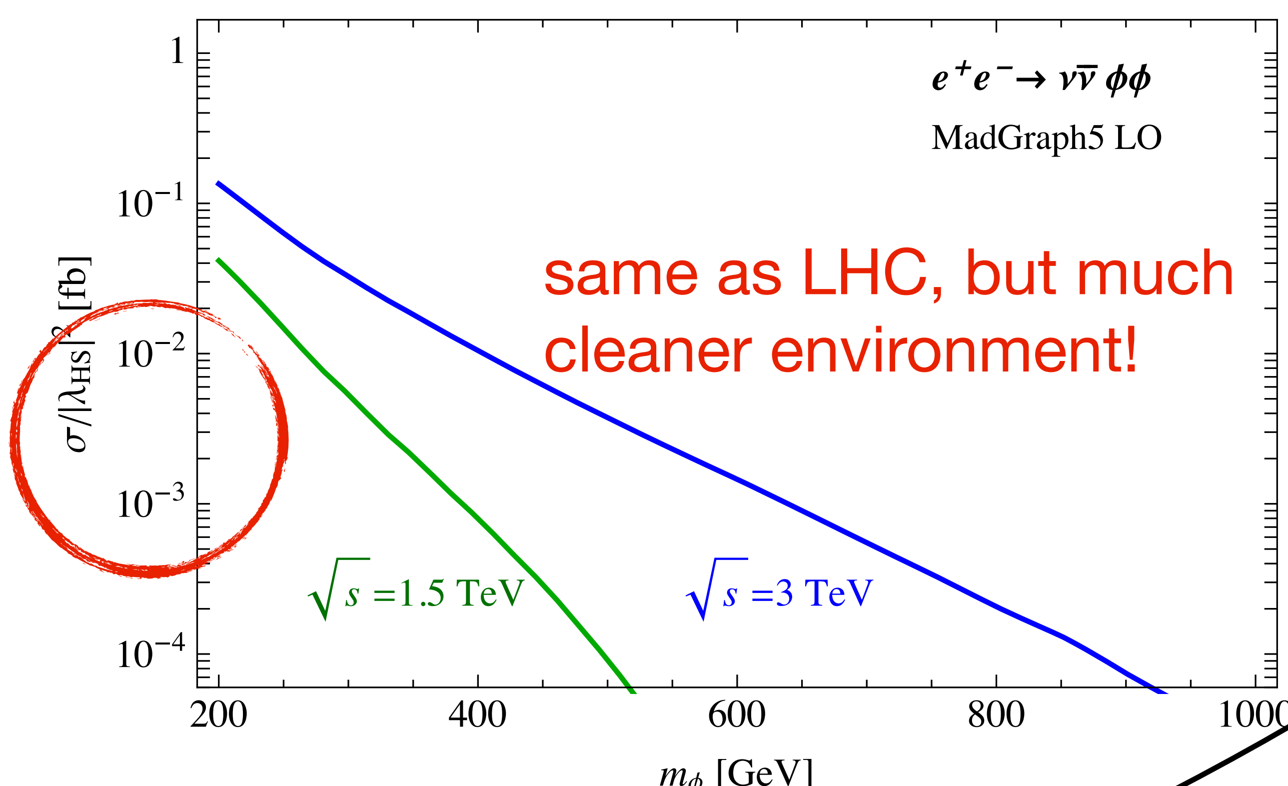
- In the limit of small mixing angle, the single production rate of ϕ vanishes
  - the Lagrangian has an approximate Z_2 symmetry $\phi \to -\phi$ $\cancel{a_{HS}|H|^2 S}$
- Double production rate does not depend on the mixing: controlled by the portal coupling $\lambda_{HS} S^2|H|^2$

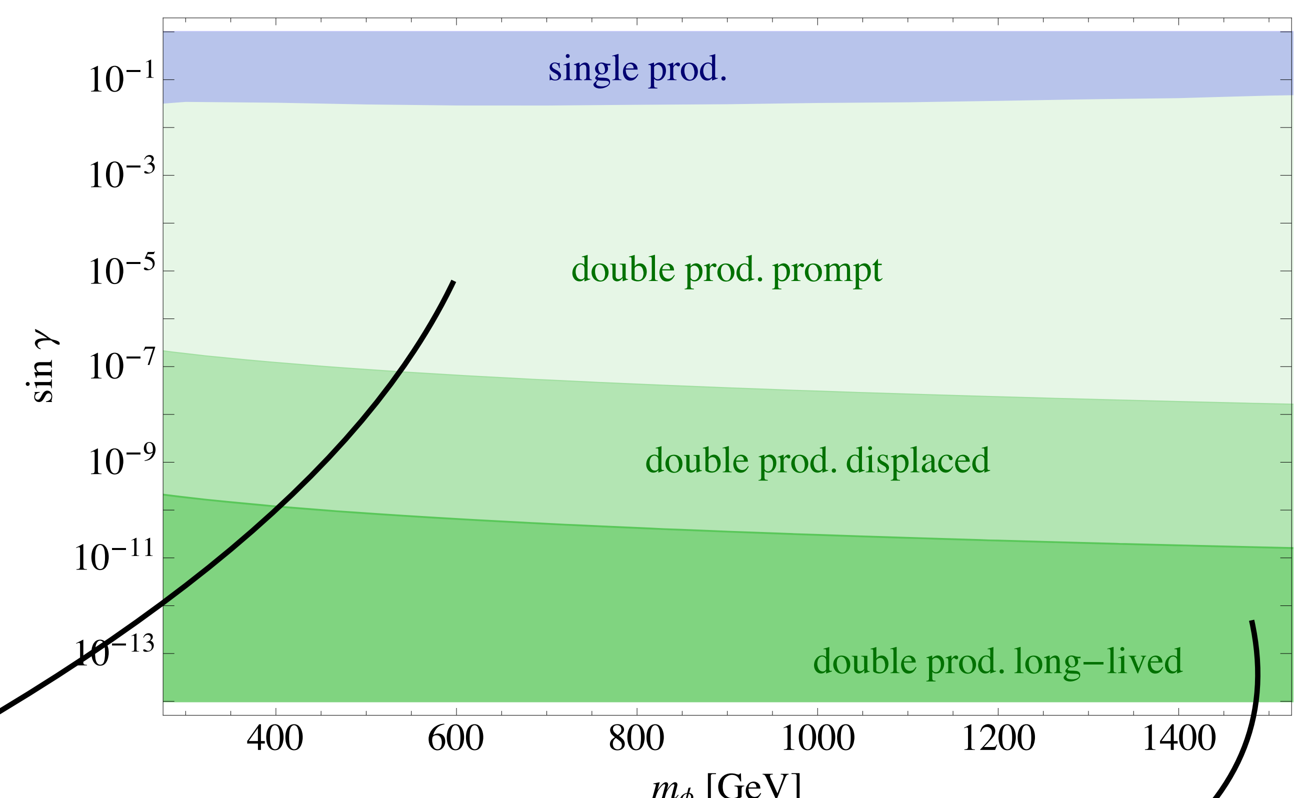




Pair production

- In the limit of small mixing angle, the single production rate of ϕ vanishes
  - the Lagrangian has an approximate Z_2 symmetry $\phi \to -\phi$ $\cancel{a_{HS}|H|^2 S}$
- Double production rate does not depend on the mixing: controlled by the portal coupling $\lambda_{HS}\, S^2|H|^2$





we focus on a region of small non-zero mixing: the singlet decays to SM bosons in the detector

ϕ is invisible: requires a different treatment

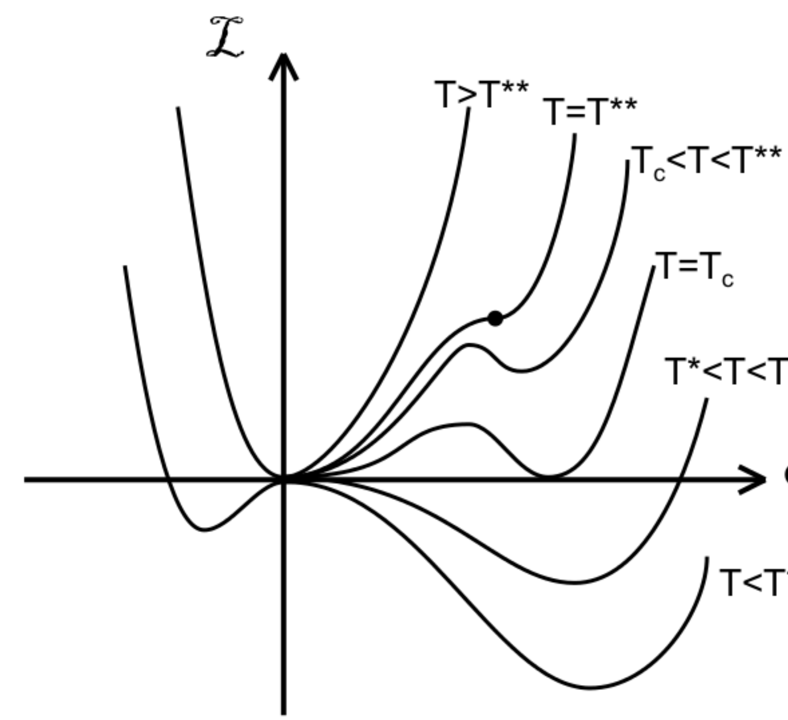
[see e.g. 1409.0005 and talk by R. Franceschini]

Electroweak phase transition

- In the SM, the EW phase transition is 2nd order (smooth $v(T)$ dependence)
  - ➡ 1ST order PT crucial for (EW) baryogenesis: need to be strongly out-of-equilibrium!
- Additional scalar singlets can give a 1st order PT:

1. Phase transition in the singlet potential:
   "light state with large coupling to Higgs"

$$m_S^2 = m_\phi^2 - \lambda_{HS}^2 v^2/2 < 0$$

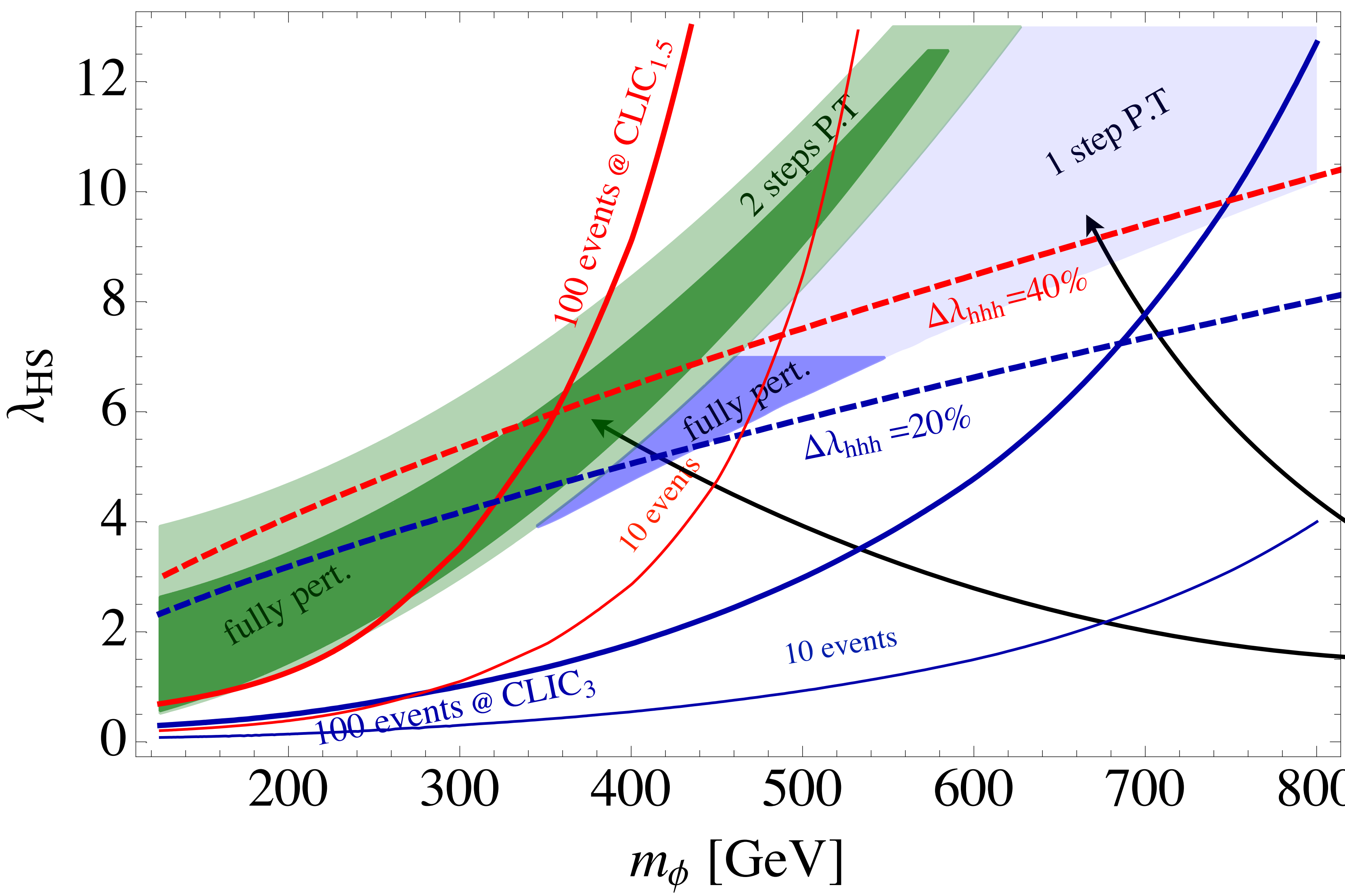


see talk by G. Panico

2. Singlet induces a negative effective quartic coupling for the Higgs $\quad \lambda_h^{\rm eff}(m_\phi, \lambda_{HS}) < 0$

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



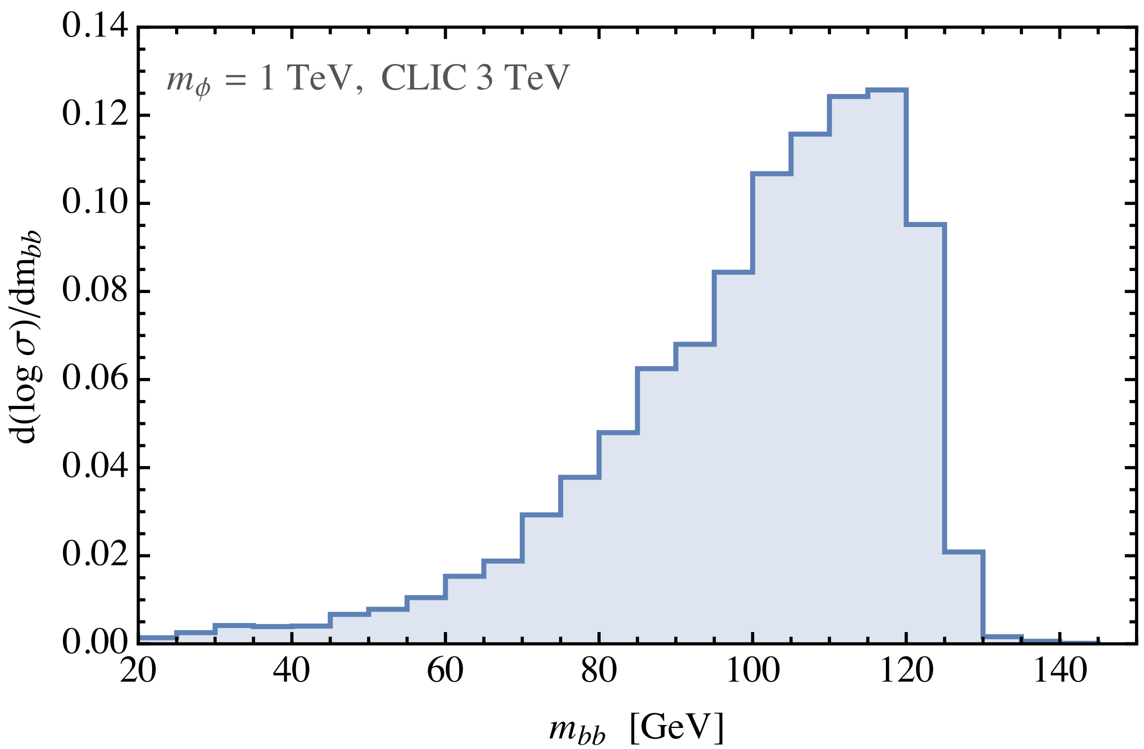
λ_{HS} also induces modifications of the triple-Higgs coupling

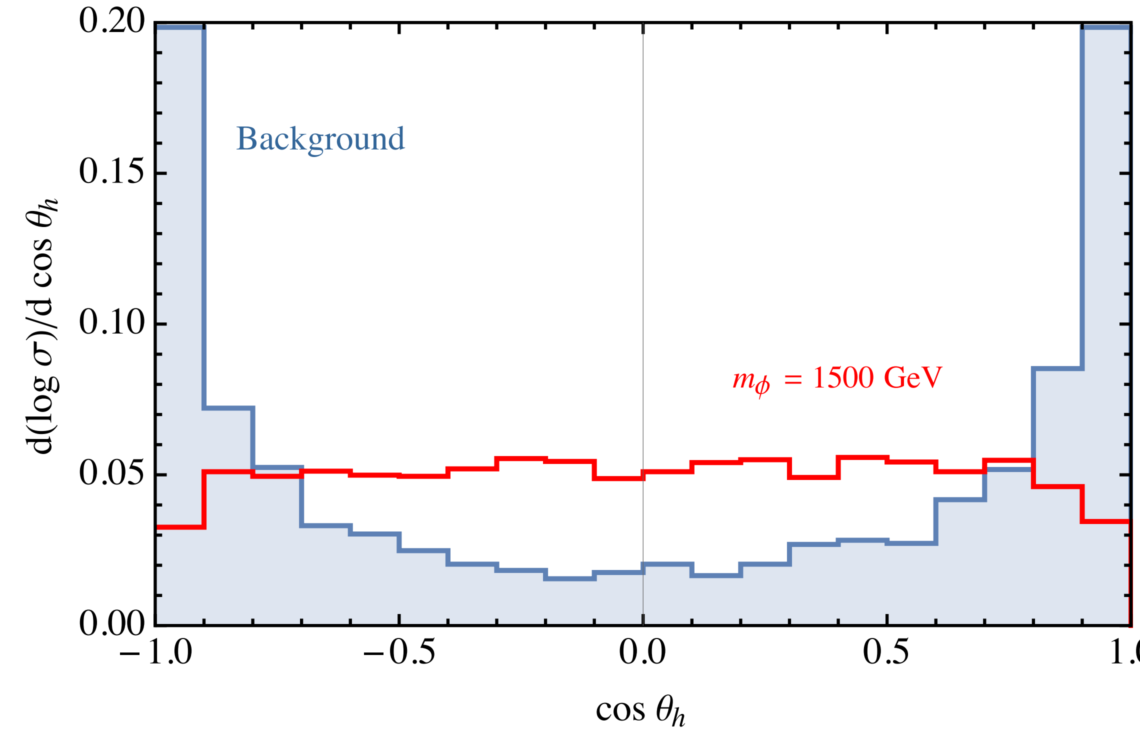
➡ see talk by G. Panico

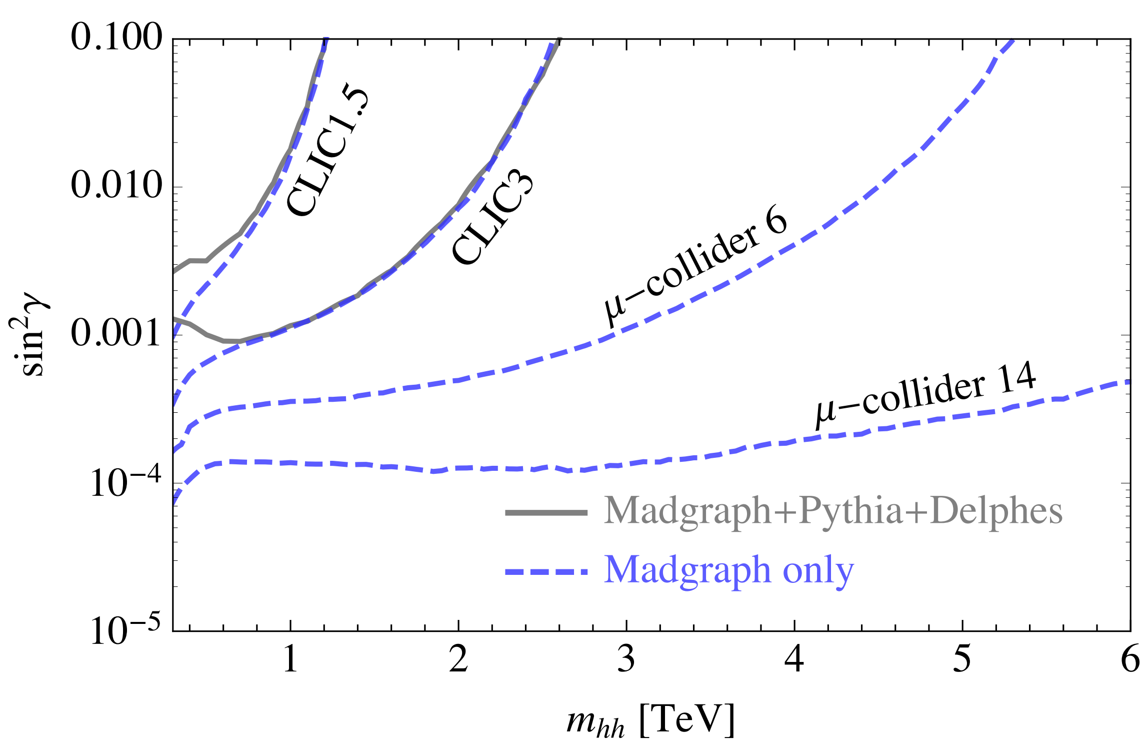
regions where 1st order EW phase transition can happen

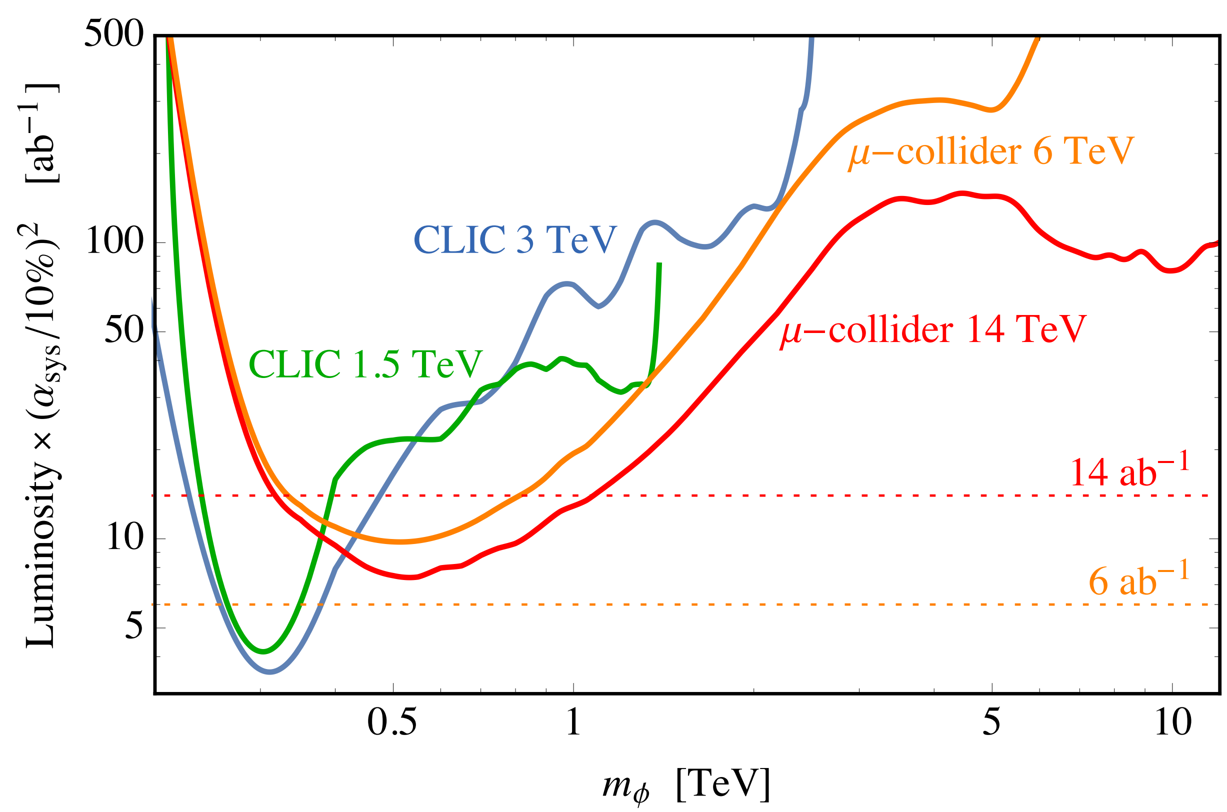
CLIC can fully test the region where singlet gives 1st order phase transition!

More details on the *hh*(4*b*) analysis









Applications: SUSY (the NMSSM)

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

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

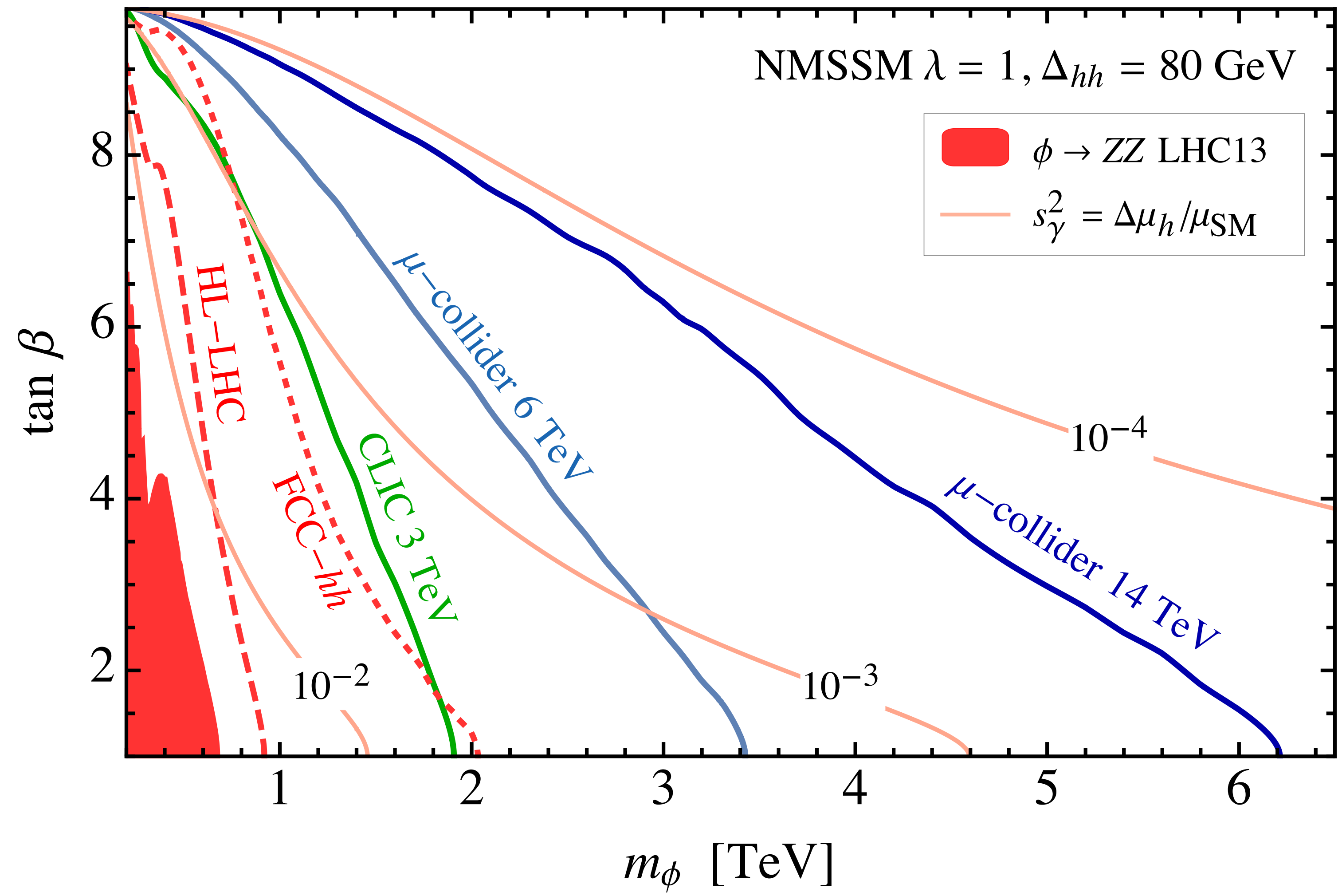
The singlet can be the lightest new state of the Higgs sector

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



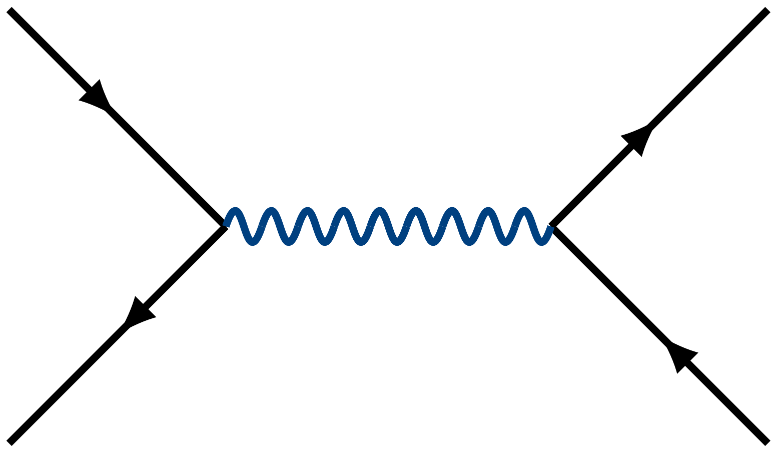
Weakly coupled & low mass: direct searches very powerful!

see Andrea's talk for sparticle production!

More resonances: Z’

Most typical example of direct search:

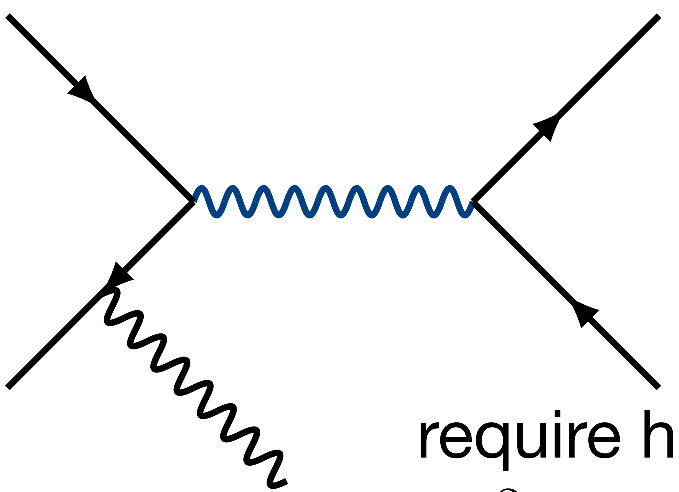
heavy s-channel resonance produced in Drell-Yan



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

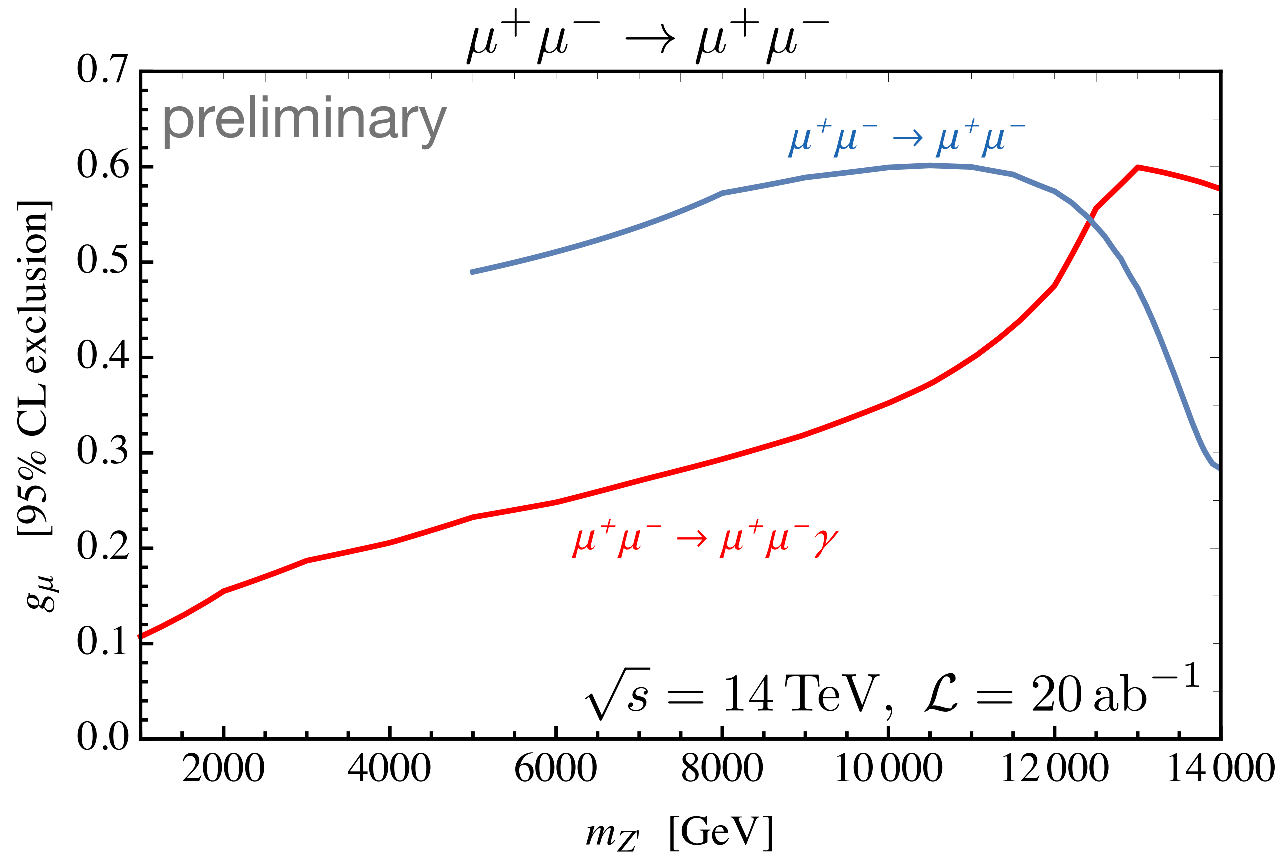
Problem: how do we look for resonances of unknown mass at fixed √s?

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

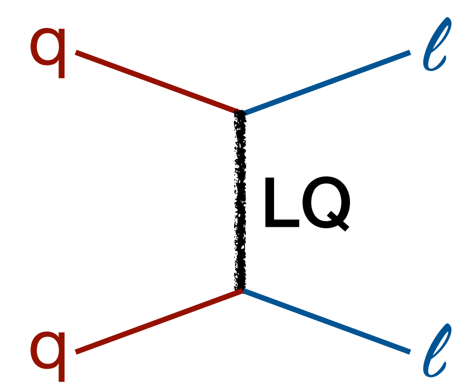
($\mu\mu \to ff$ cross-section)

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

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

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

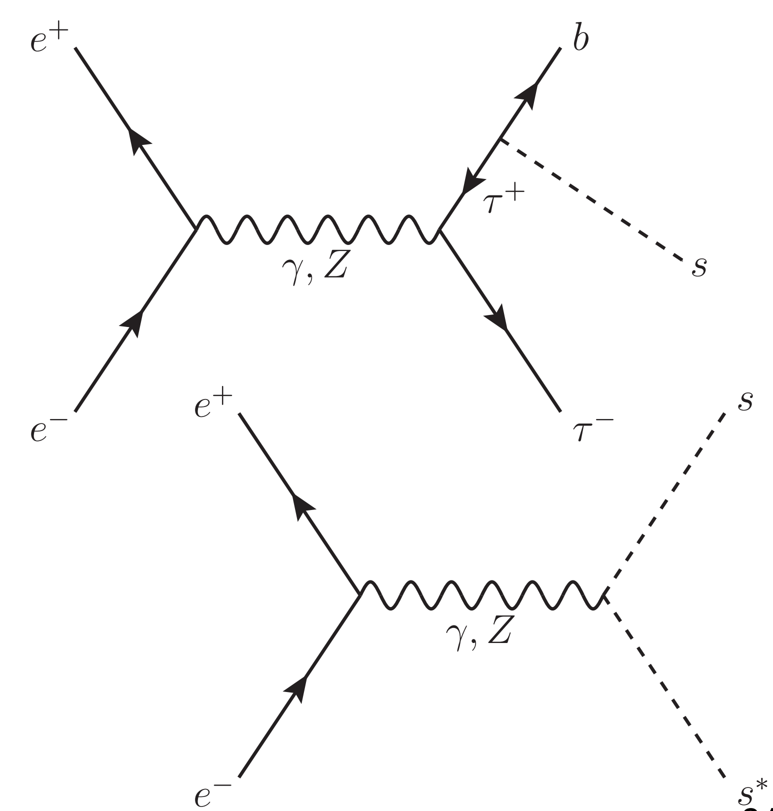


➡ $\sqrt{s}$ > 3 TeV interesting range for lepton colliders

3rd generation LQ production at a lepton collider:

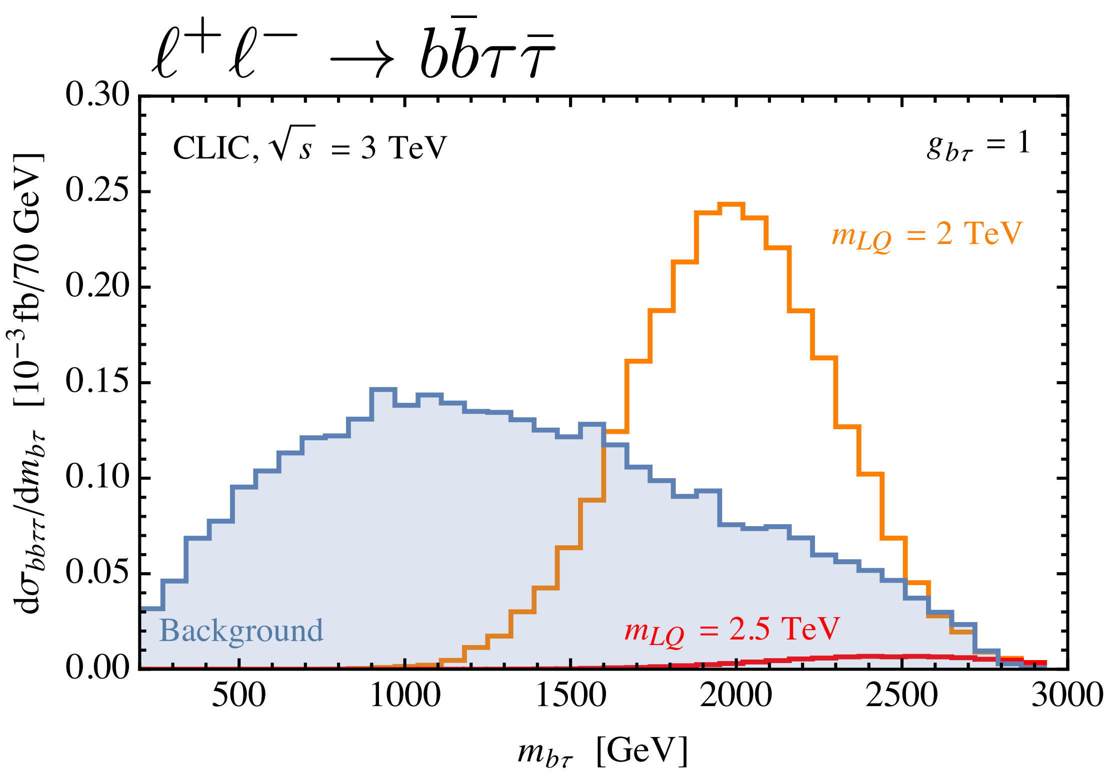
- Pair production: large cross-section when allowed, does not depend on coupling to fermions
- Single production: radiation from bb or ττ pair

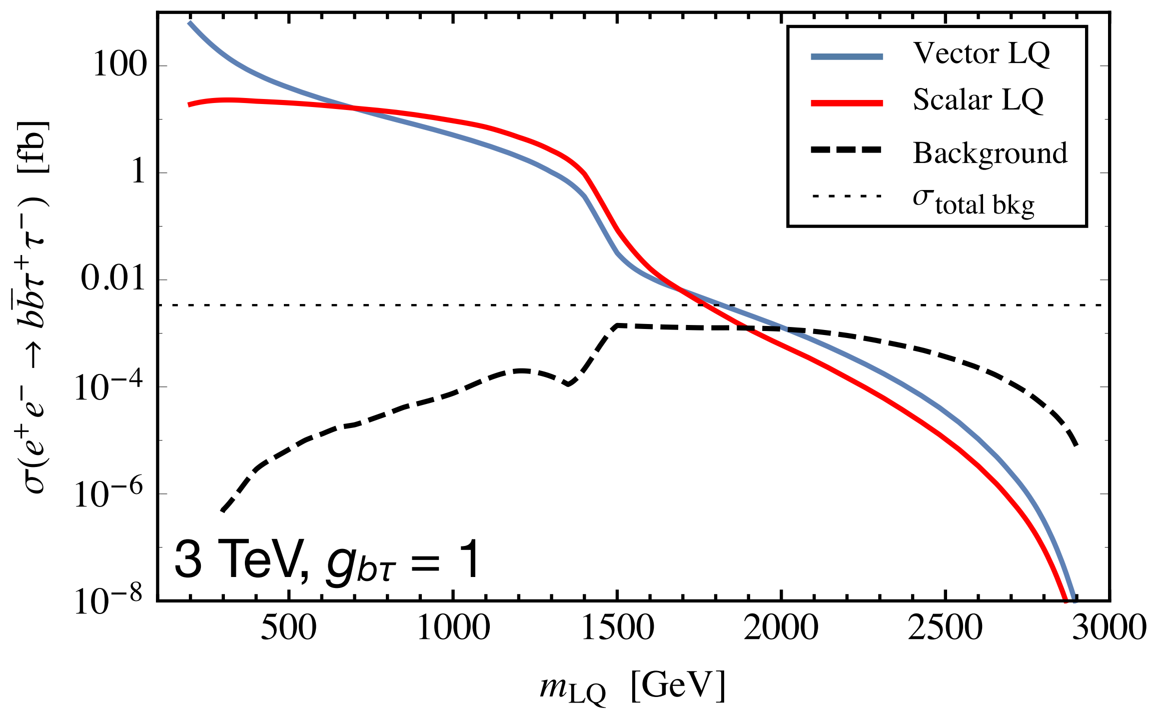
➡ bbττ final state, with $m_{b\tau} \sim M_{LQ}$



B, Greljo, Marzocca, Nardecchia 2018

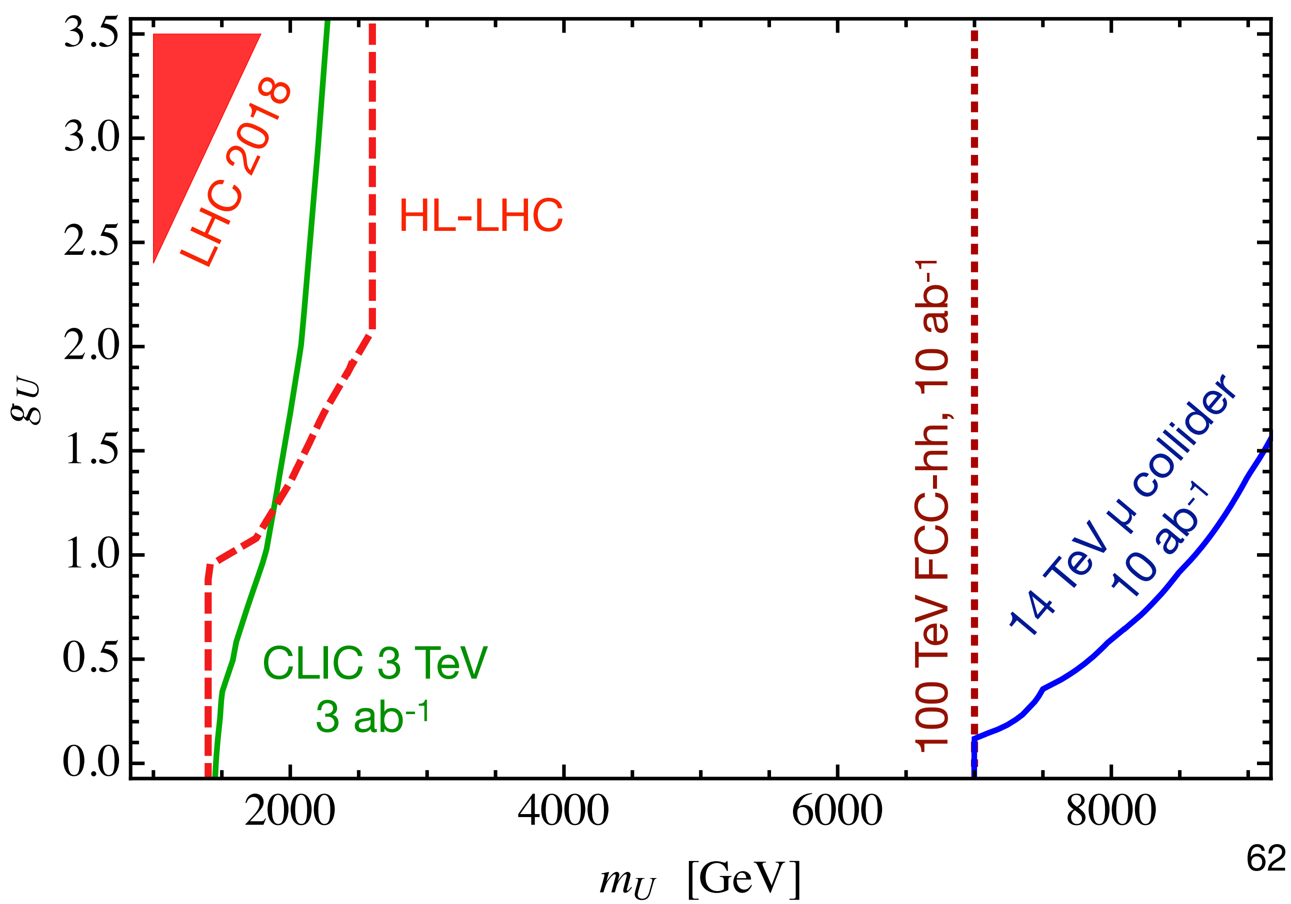
Coloured resonances: Leptoquarks





- 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

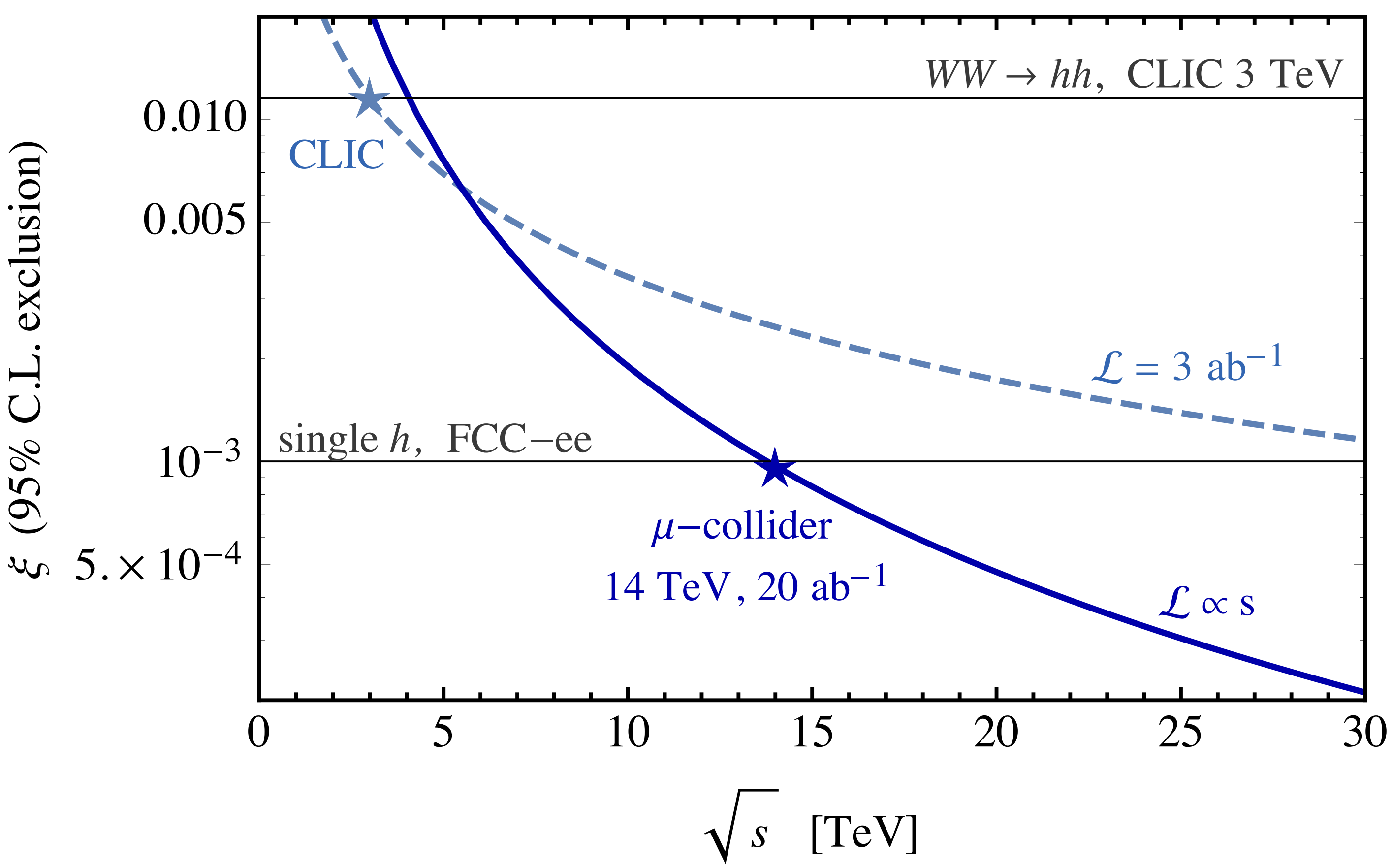


hh at high mass

- E = 3 TeV, $\mathcal{L}$ = 3 ab^{-1}: $\xi = c_H v^2 \lesssim 0.01$ Contino et al. 1309.7038

- Rescale to higher energies: $\xi \propto \frac{1}{E^2} \frac{1}{\sqrt{N_{\rm bkg}}} \propto \frac{1}{E^2} \frac{1}{\sqrt{\mathcal{L}/E^2}} = \frac{1}{E\sqrt{\mathcal{L}}}$

(assumption: cuts rescaled with E, and bkg composition unchanged)



High-energy WW → *hh* becomes more sensitive than Higgs pole physics at energies > 14 TeV

$\sqrt{s} = 14\,\text{TeV},\ \mathcal{L} = 20\,\text{fb}^{-1}$

$\xi < 10^{-3} \qquad c_H^{-1/2} > 8\,\text{TeV}$

$\sqrt{s} = 30\,\text{TeV},\ \mathcal{L} = 90\,\text{fb}^{-1}$

$\xi < 2\times 10^{-4} \qquad c_H^{-1/2} > 17\,\text{TeV}$

More details on the *hh*(4*b*) analysis

Efficiencies for signal and background:

Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	90%	95%
4 b-tags	50%	35%
$m_{bb} \in [88, 129]$ GeV	64%	23%
$\lvert\cos\theta\rvert < 0.94$	96%	63%
$m_{4b} \in [770, 1070]$ GeV	98%	2.8%
Total efficiency	27%	1.3×10^{-3}

(a) CLIC 1.5 TeV, $m_\phi = 1$ TeV

Cut	ϵ_{sig}	$\epsilon_{\text{bkg}}^{4b2\nu}$
$E_{\text{miss}} > 30$ GeV	94%	96%
4 b-tags	51%	33%
$m_{bb} \in [88, 137]$ GeV	60%	15%
$\lvert\cos\theta\rvert < 0.95$	97%	58%
$m_{4b} \in [1.5, 2.04]$ TeV	91%	0.7%
Total efficiency	26%	2×10^{-4}

(b) CLIC 3 TeV, $m_\phi = 2$ TeV

WW fusion

- Single and double production cross-sections:

$$\sigma_{e\bar{e}\to\nu\bar{\nu}S} = \sin^2\gamma\,\frac{g^4}{256\pi^3}\frac{1}{v^2}\left[2\Big(\frac{m_\phi^2}{s}-1\Big)+\Big(\frac{m_\phi^2}{s}+1\Big)\log\frac{s}{m_\phi^2}\right] \simeq \sin^2\gamma\frac{g^4}{256\pi^3}\frac{\log\frac{s}{m_\phi^2}-2}{v^2},$$

$$\sigma_{e\bar{e}\to\nu\bar{\nu}SS} = \frac{g^4|\lambda_{HS}|^2}{49152\pi^5}\,\frac{1}{m_\phi^2}\Big[\log\frac{s}{m_\phi^2}-\frac{14}{3}+\frac{m_\phi^2}{s}\big(3\log^2\frac{s}{m_\phi^2}+18-\pi^2\big)+\mathcal{O}\Big(\frac{m_\phi^4}{s^2}\Big)\Big],$$

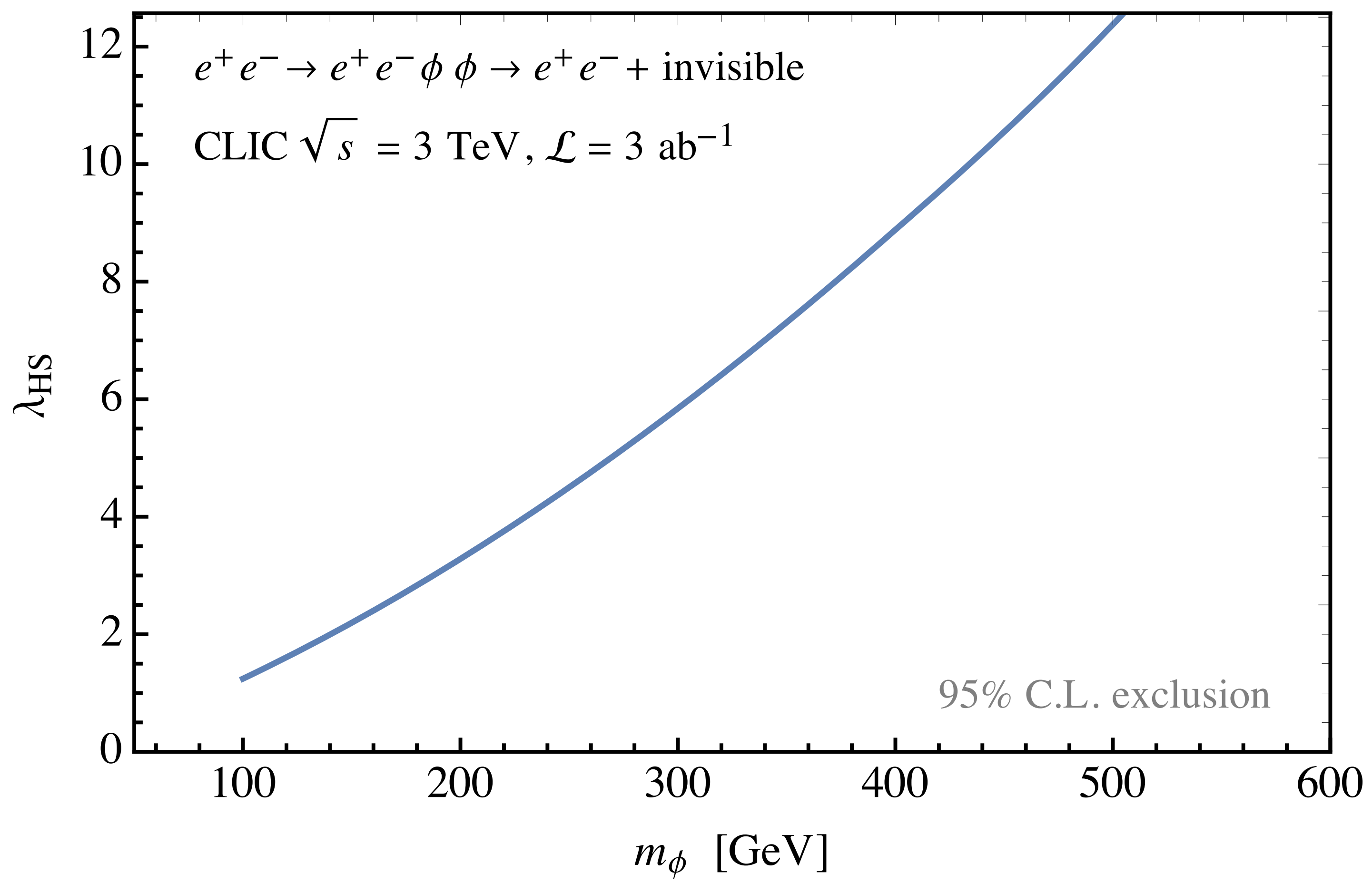
from W-pdf's $$\frac{d\sigma}{d\hat{s}} = \frac{\hat{\sigma}_{V_iV_j\to X}(\hat{s})}{s}\,\mathscr{C}_{V_iV_j}(\hat{s}), \quad \text{with} \quad \mathscr{C}_{V_iV_j}(\hat{s}) = \int_{\hat{s}/s}^{1}\frac{dx}{x}f_{V_i}(x)f_{V_j}(\frac{\hat{s}x}{s})$$

- Approximate limit on mixing angle:

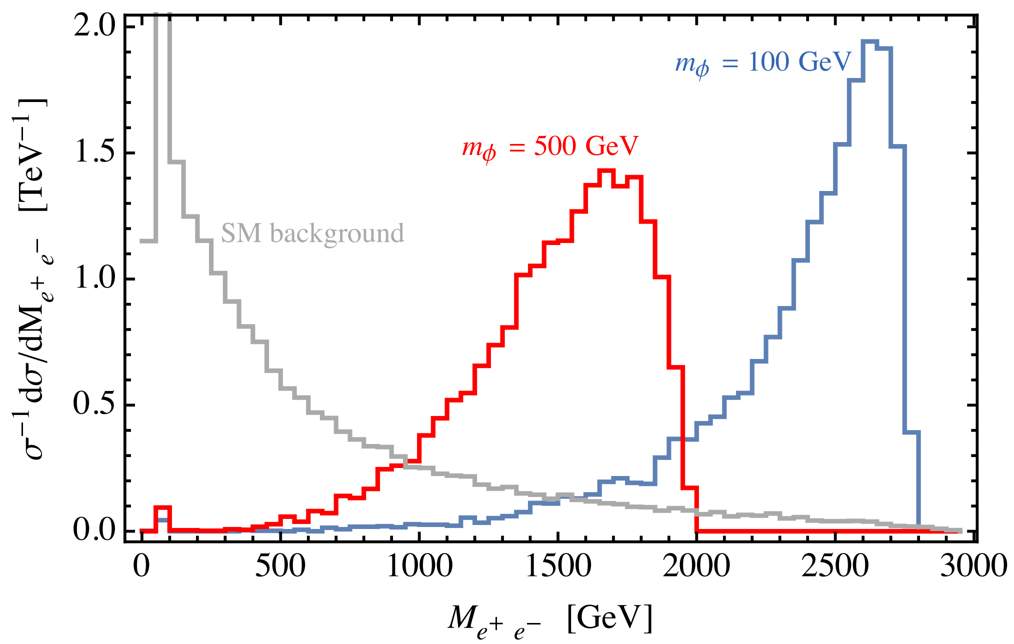
$$\sin^2\gamma\times\mathrm{BR}(\phi\to f)\approx 0.02\left(\frac{1/\mathrm{fb}}{L}\right)\times\left[\log\frac{s}{m_\phi^2}-2+\frac{m_\phi^2}{s}\Big(\log\frac{s}{m_\phi^2}+2\Big)\right]^{-1}$$

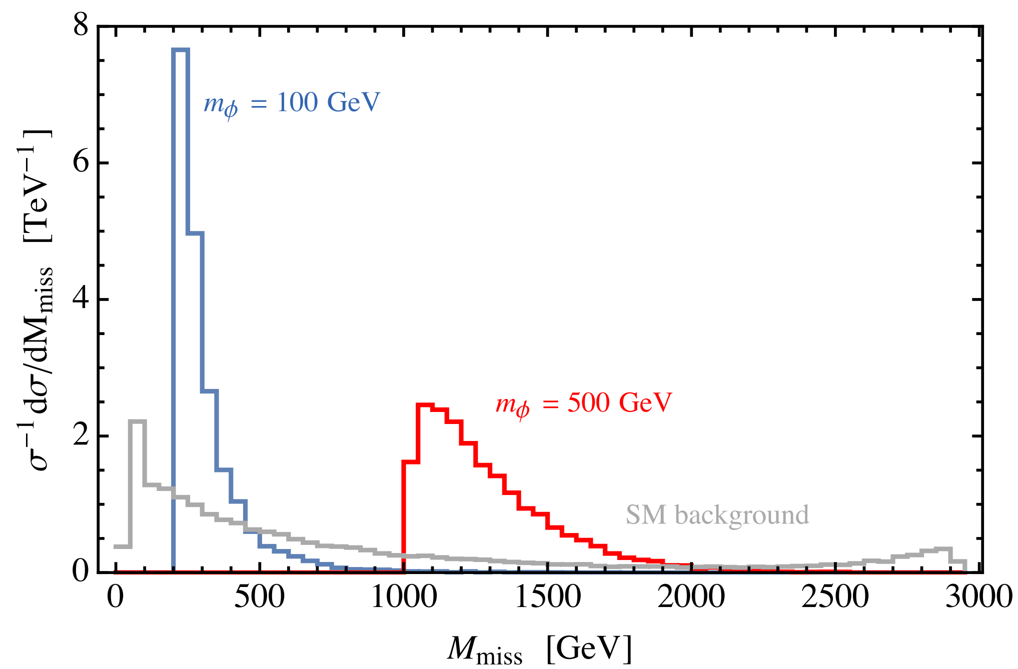
Invisible singlet

- Double production of singlet in Z-fusion, singlet decays invisibly



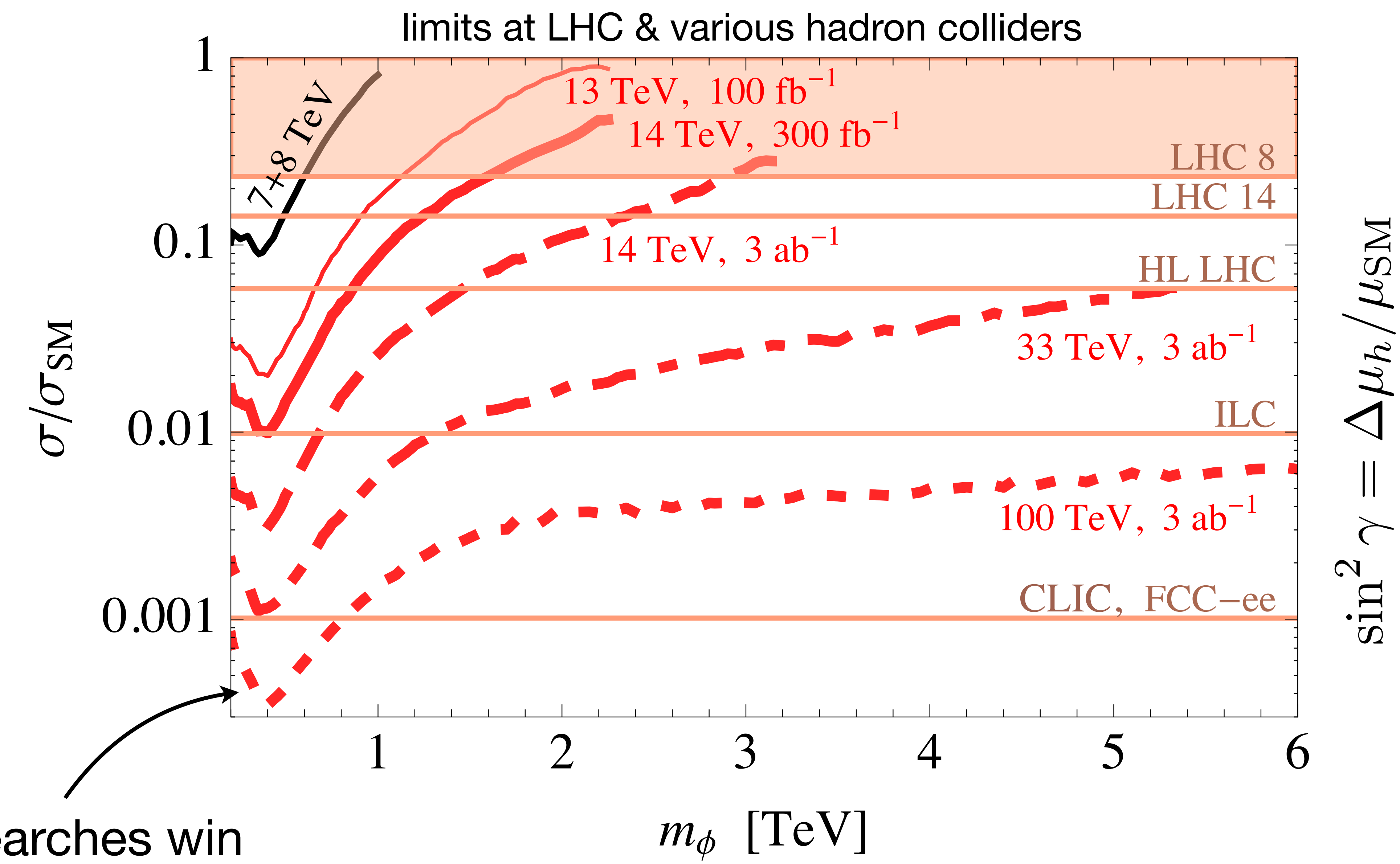
cuts on missing mass
and e+e- invariant mass





Direct vs indirect searches

Very easy to relate direct searches and Higgs couplings: [see also 1505.05488]



direct searches win
at lower masses

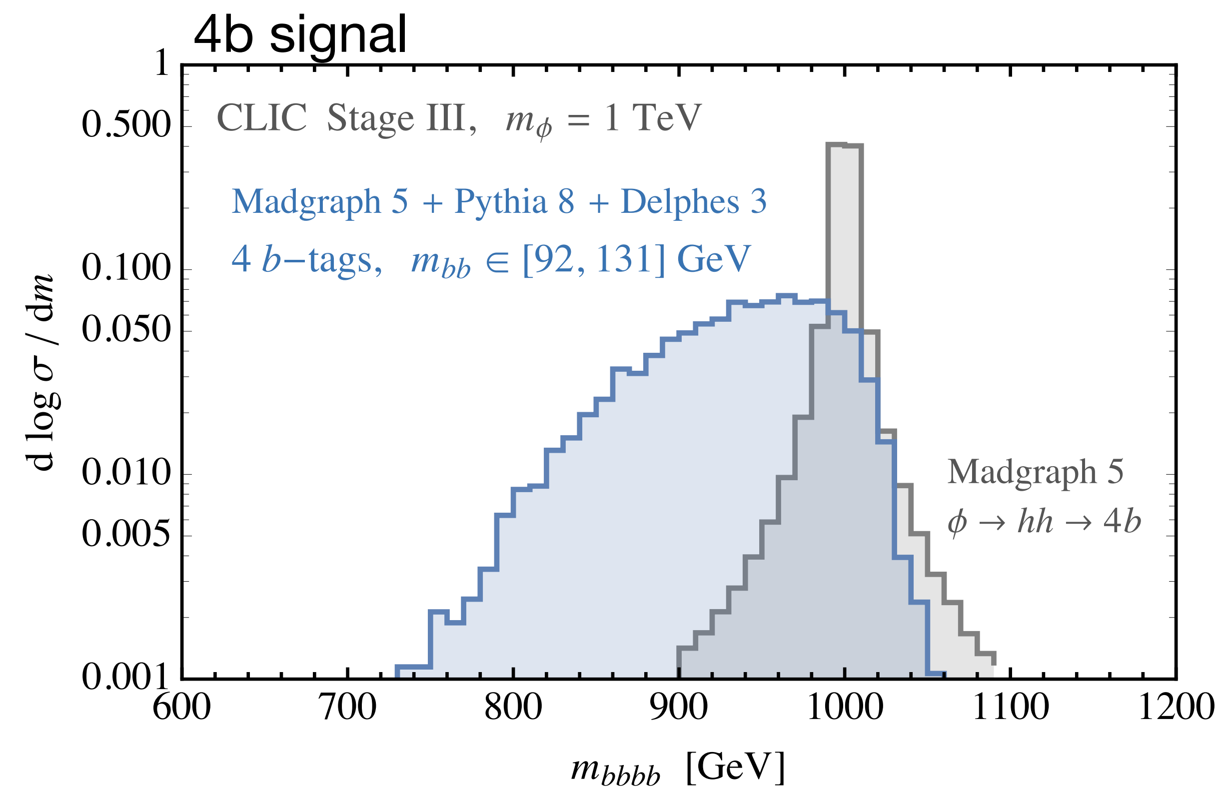
What about a Muon Collider?

$hh(4b)$ decay channel

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

1807.04743 — 3 TeV CLIC

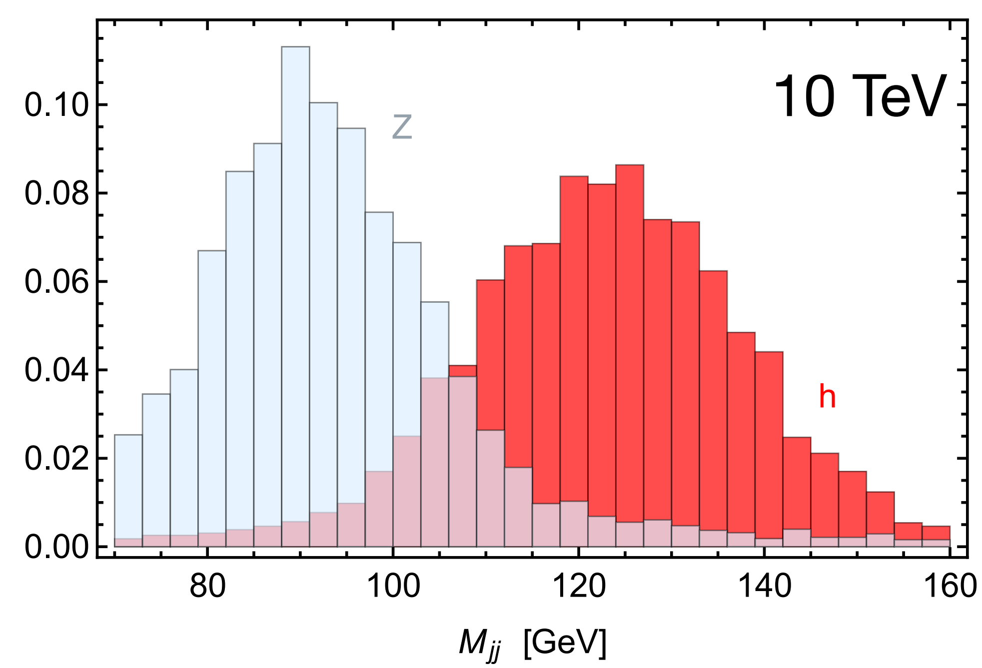
- Detector simulation with CLICdp Delphes card
- VLC exclusive jet reconstruction, N = 4, R = 0.7 + 4 b-tags (loose tagging algorithm)
- h reconstruction: select the b pairs that give the best fit to two 125 GeV Higgs bosons, 90 GeV < m_{bb} < 130 GeV
- ϕ reconstruction: $0.75\, m_\phi < m_{4b} < 1.05\,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



Signal efficiency ε_{sig} ~ 25 – 30%

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

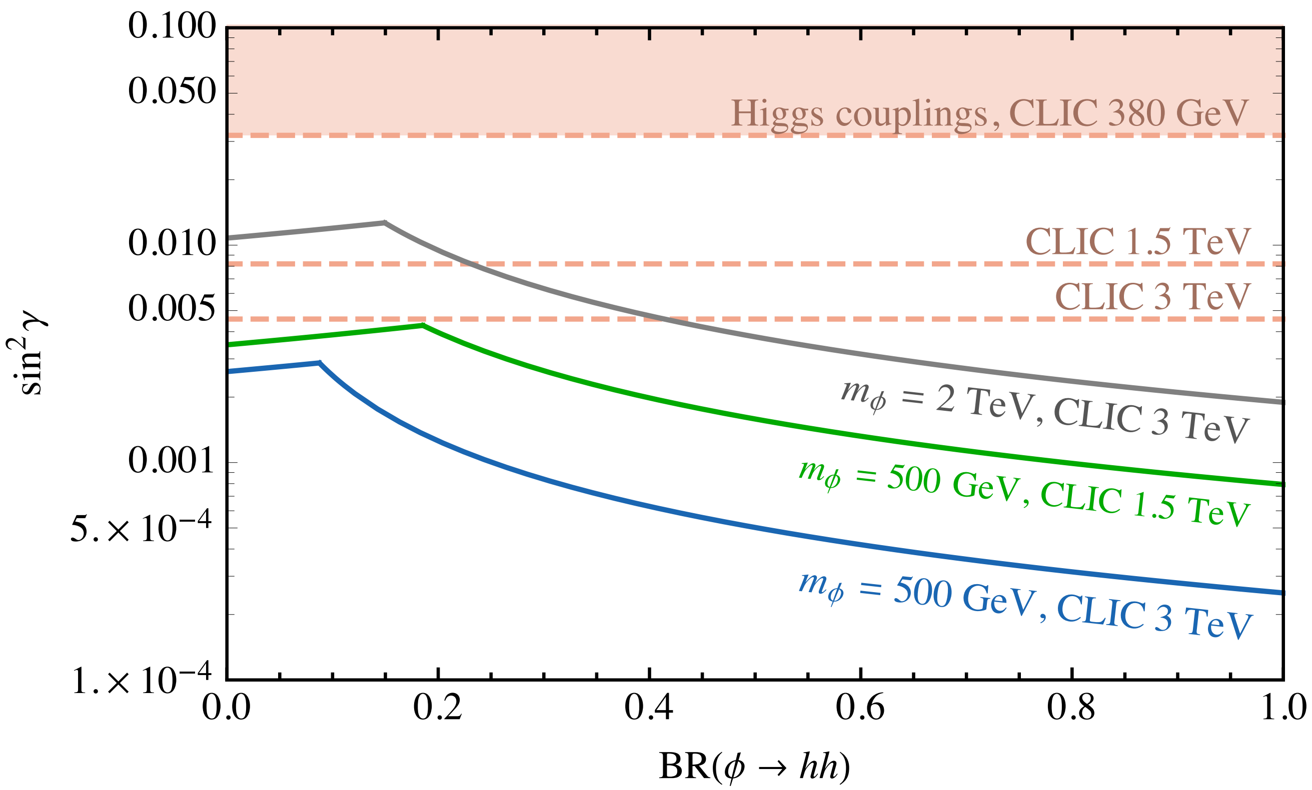
Checked (at parton level) that results still hold at 10 TeV: ε_{sig} ~ 30% assuming similar detector performance



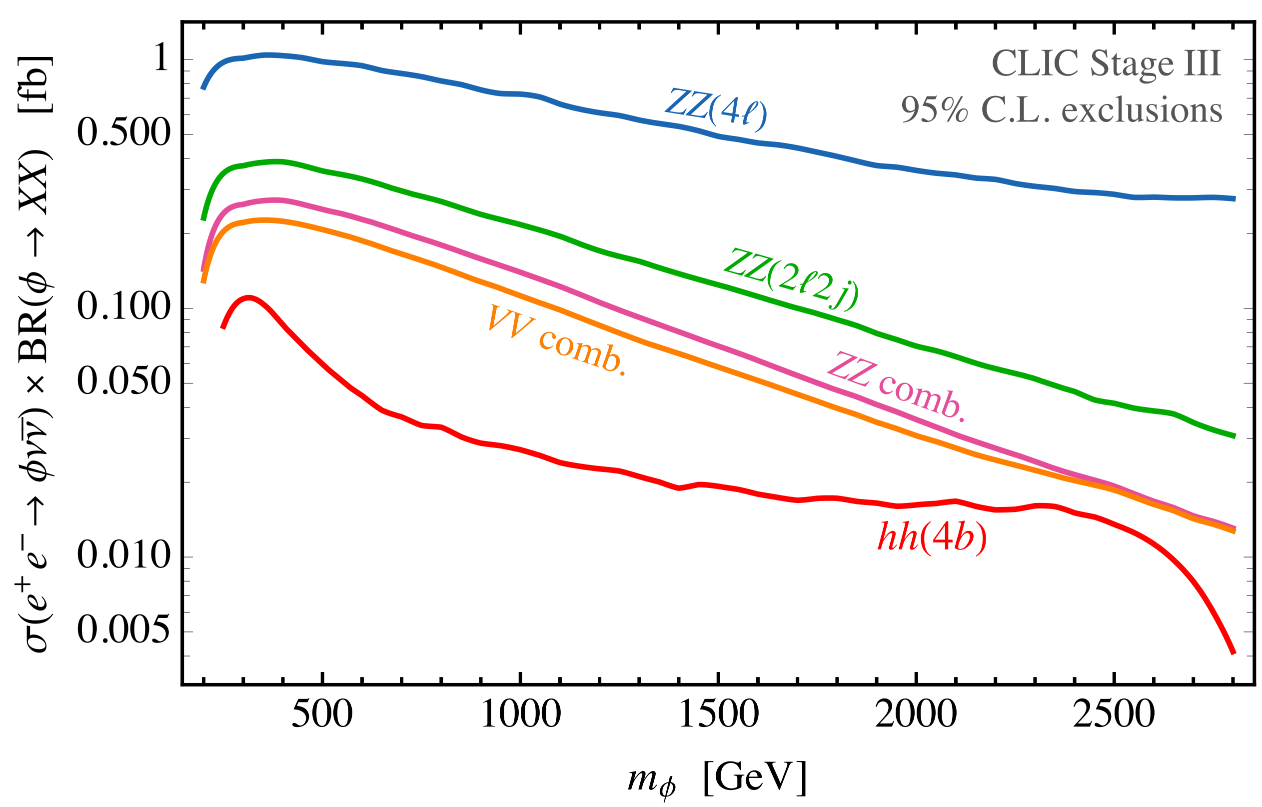
(see also my talk of last month)

The reach in di-bosons at CLIC

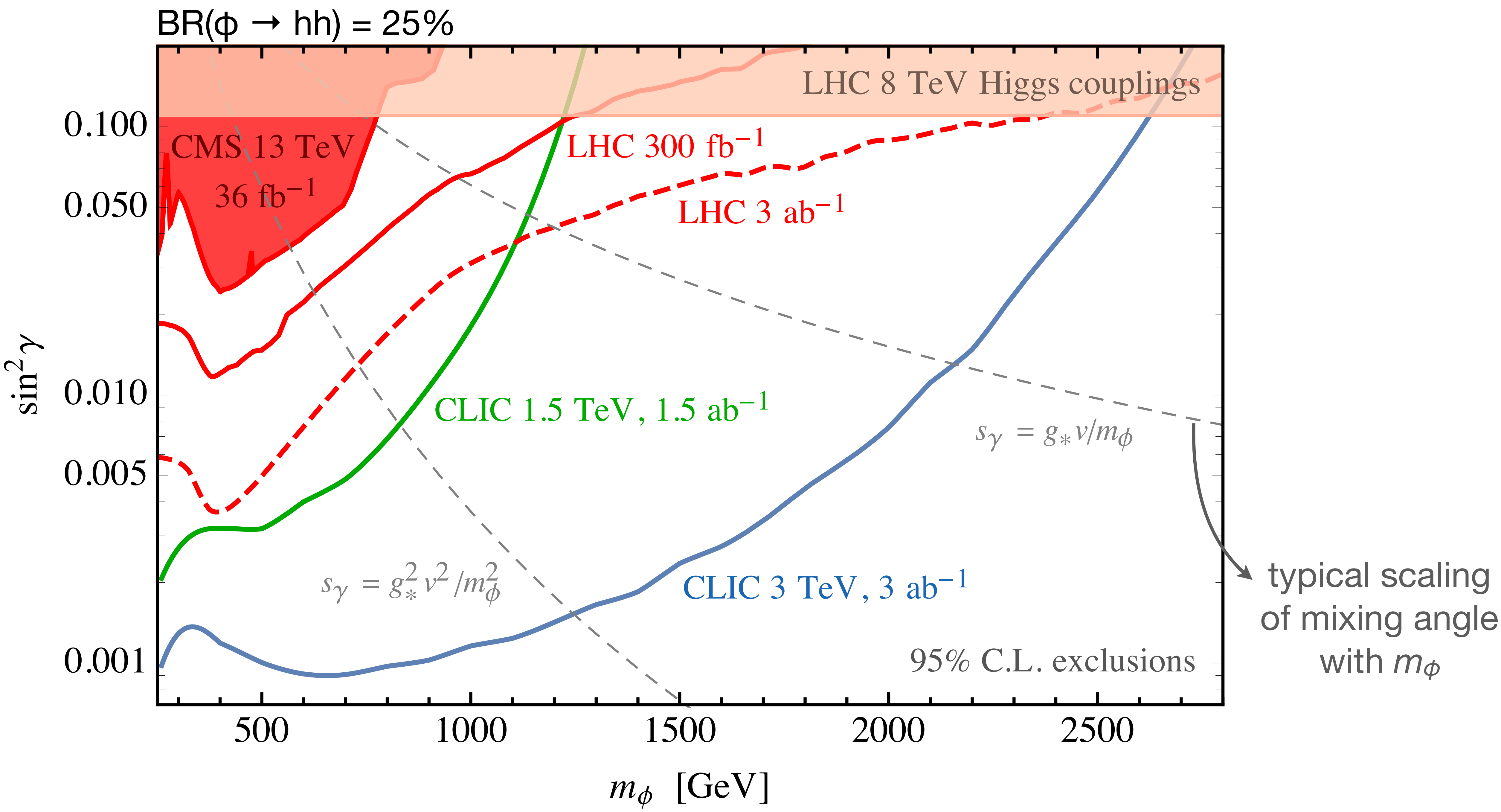
- For BR($\phi \to hh$) ~ 0.25, the most sensitive channel is $\phi \to hh \to 4b$
- Low backgrounds: limits depend weakly on ϕ mass and collider energy
- $\phi \to VV$ less sensitive, but complementary (BR($\phi \to hh$) can be small)
- $\phi \to VV$ analysis done at parton-level: ZZ inv. mass in a window around the resonance peak… we checked that it reproduces the full result very well



good agreement with 1807.04284



Direct vs indirect reach



CLIC @ 3 TeV is capable to significantly
improve over the reach of HL-LHC