Precision physics at a muon collider

Flavor, Higgs, g-2, etc…

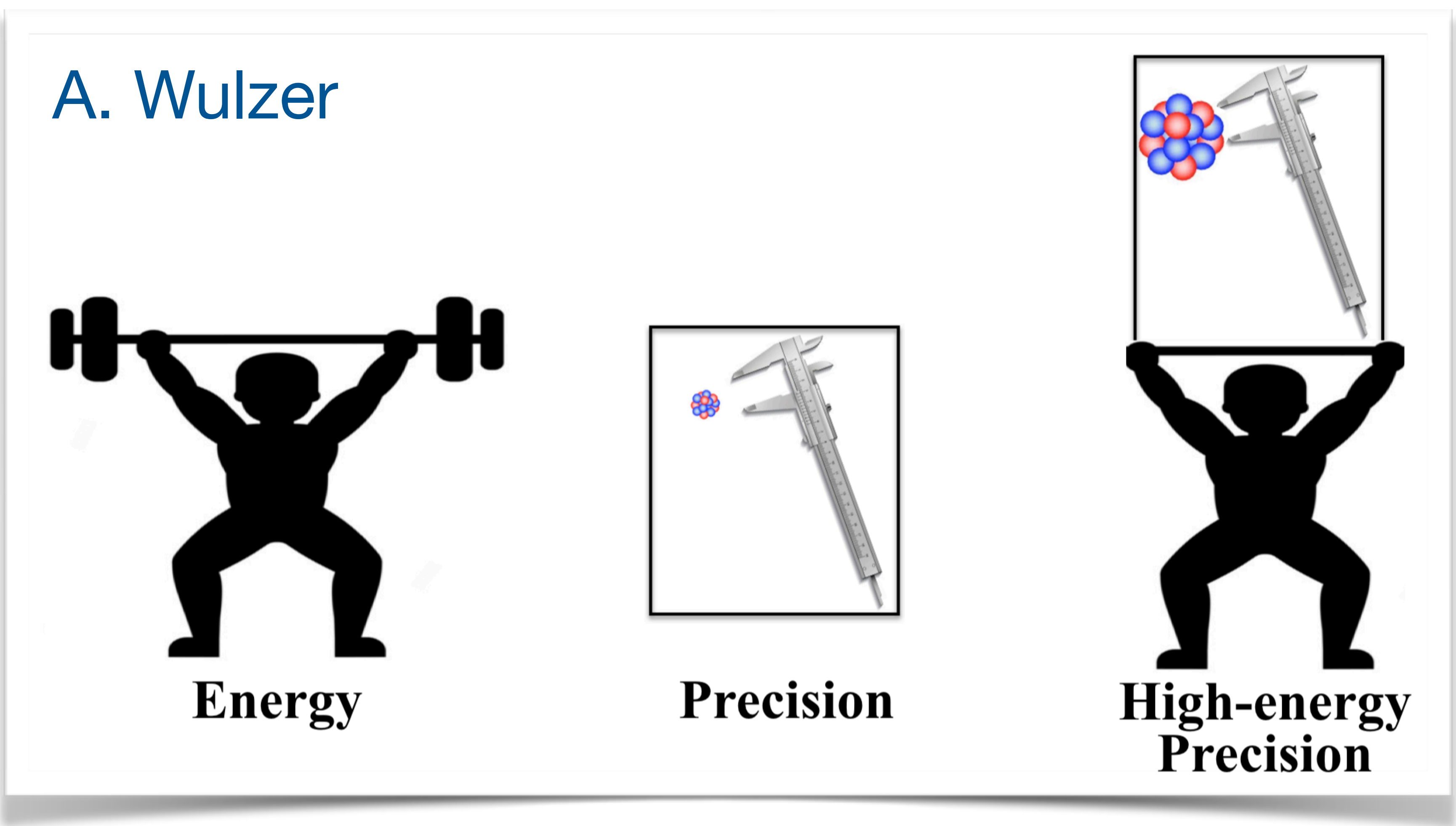
Dario Buttazzo

Muon Collider Benchmarks Workshop — Pittsburgh, 18.11.2023

Energy AND Precision

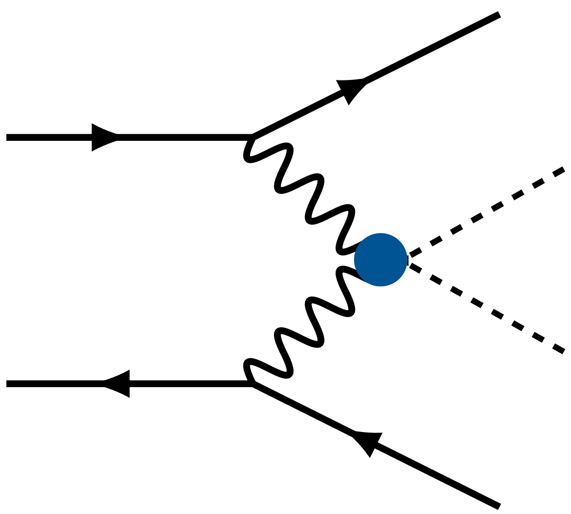
A muon collider is an amazing discovery machine: production of EW particles up to several TeV of mass…

… but also a tool for precision measurements

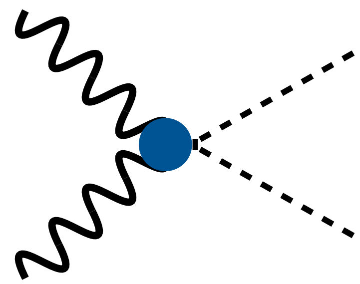


Two paths to precision

- High rate: more events = better precision



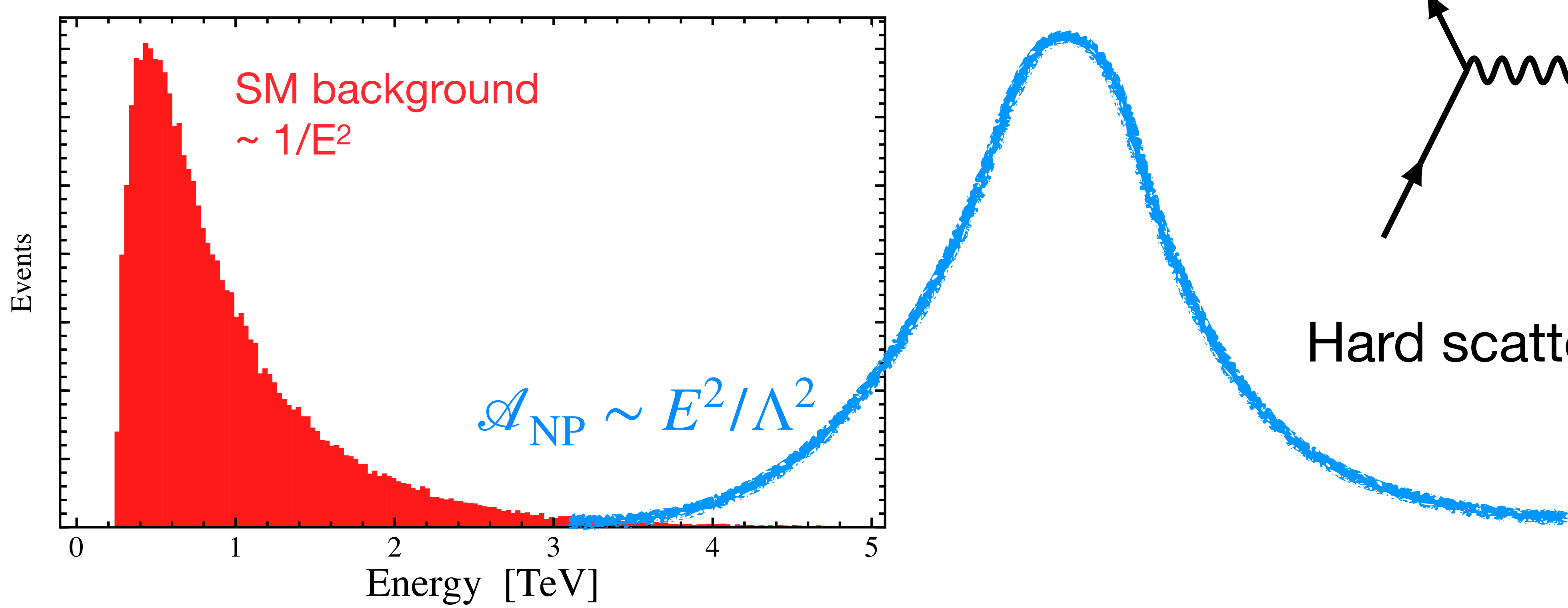
$$\approx \frac{s}{\hat{s}} \log \frac{s}{\hat{s}}$$

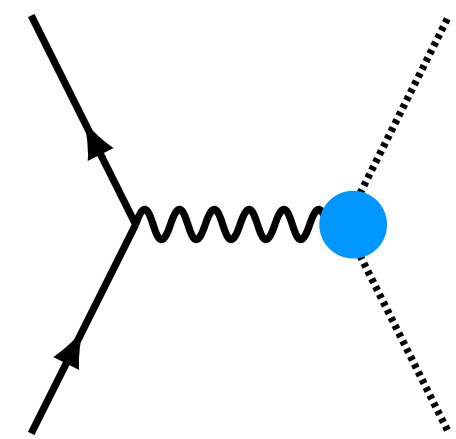


For "soft" SM final state $\hat{s} \sim m_{\mathrm{EW}}^2$
cross-section is enhanced

$\sigma_{\mathrm{SM}} \sim \log(s/m_{\mathrm{EW}}^2)\,/\,m_{\mathrm{EW}}^2$

- High energy: new physics effects grow

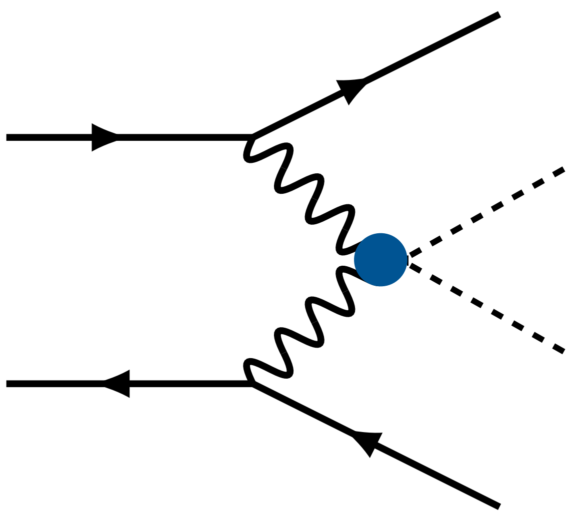




Hard scattering $\sigma_{\mathrm{SM}} \sim 1/s$

High rate probes

- High rate: more events = better precision



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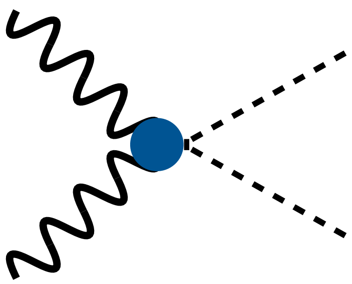
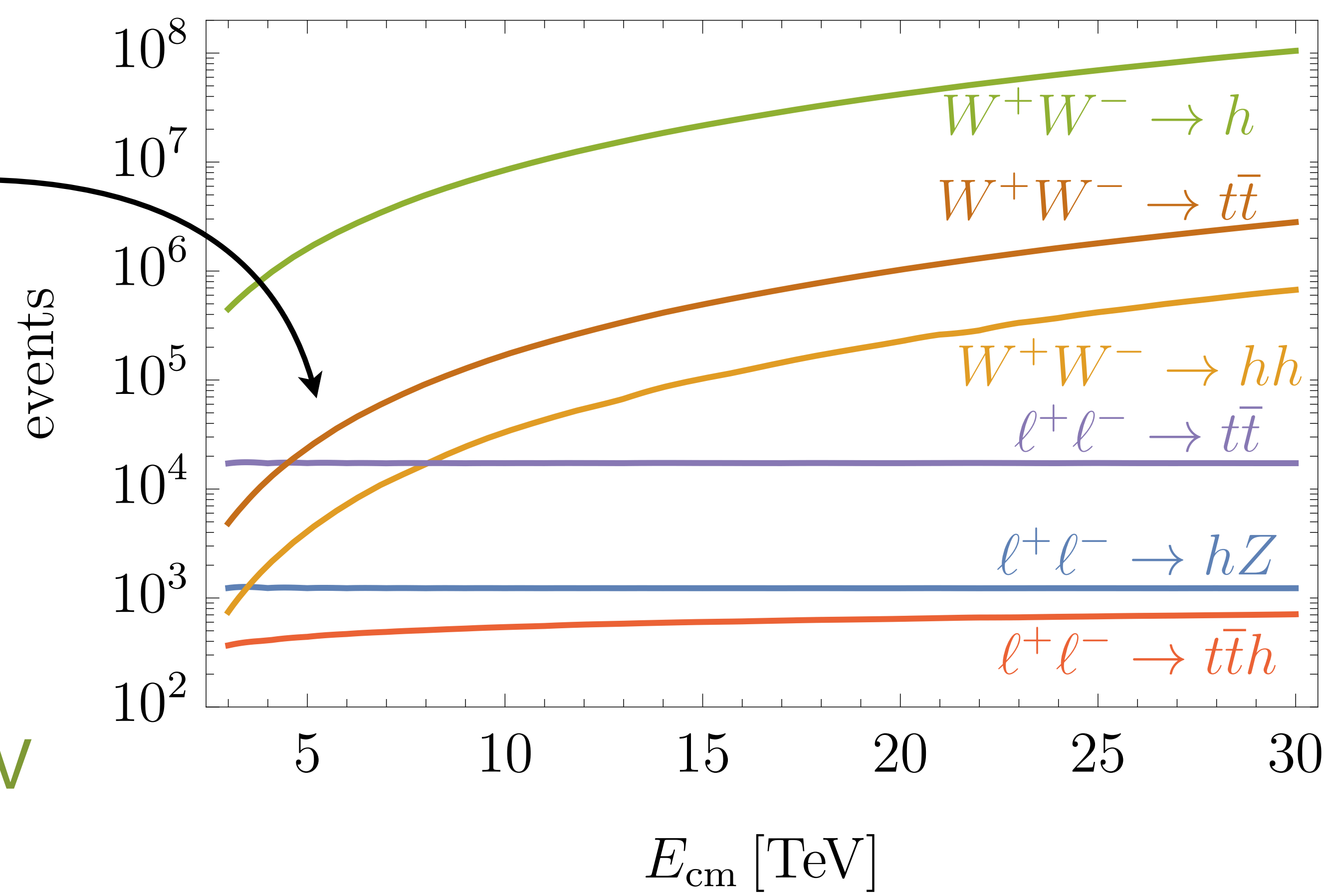


A High Energy Lepton Collider is a "vector boson collider"

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

Dawson 1985

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



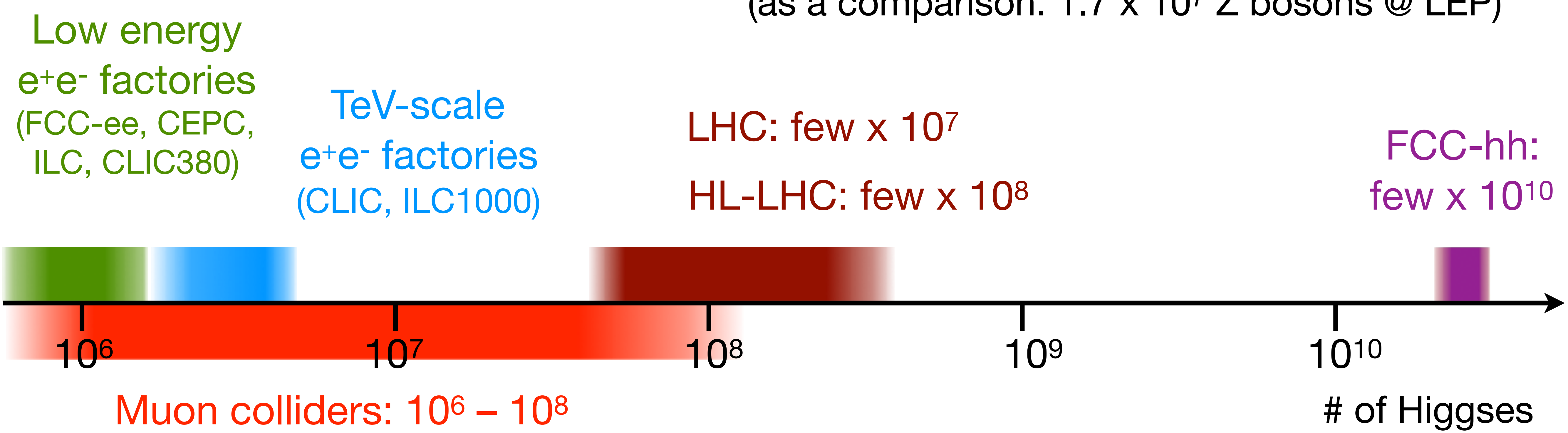
- Huge single Higgs rate in vector-boson-fusion: 10^7-10^8 Higgs bosons at 10-30 TeV

High rate probes: Higgs physics

A 10+ TeV muon collider is a perfect Higgs factory!

- Signal-only estimate: ~ 10^7 Higgses at 10 TeV + efficiencies, BR
  - ☛ rough estimate: 10^{-3} for dominant decay channels @ 10 TeV

(as a comparison: 1.7 x 10^7 Z bosons @ LEP)



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"Muon smasher guide" 2103.14043 Forslund, Meade 2203.09425

κ-0 fit	HL-LHC	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 1500	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh	$\mu^+\mu^-$ **10000**
κ_W [%]	1.7	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14	0.06
κ_Z [%]	1.5	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12	0.23
κ_g [%]	2.3	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49	0.15
κ_γ [%]	1.9	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29	0.64
$\kappa_{Z\gamma}$ [%]	10.	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69	1.0
κ_c [%]	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95	0.89
κ_t [%]	3.3	–	6.9	1.6	–	–	2.7	–	–	–	1.0	6.0
κ_b [%]	3.6	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43	0.16
κ_μ [%]	4.6	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41	2.0
κ_τ [%]	1.9	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44	0.31

→ dominant channels ~ other Higgs factories

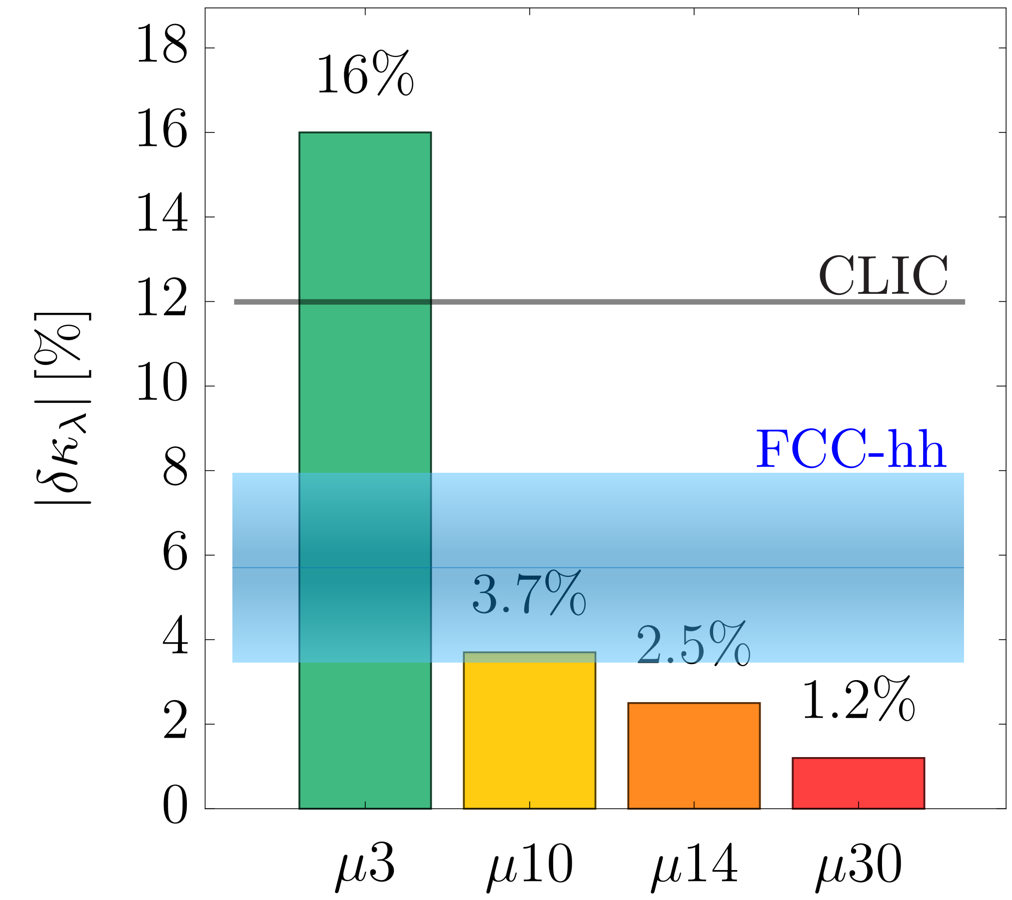
→ rare modes much better (~ hadron collider)

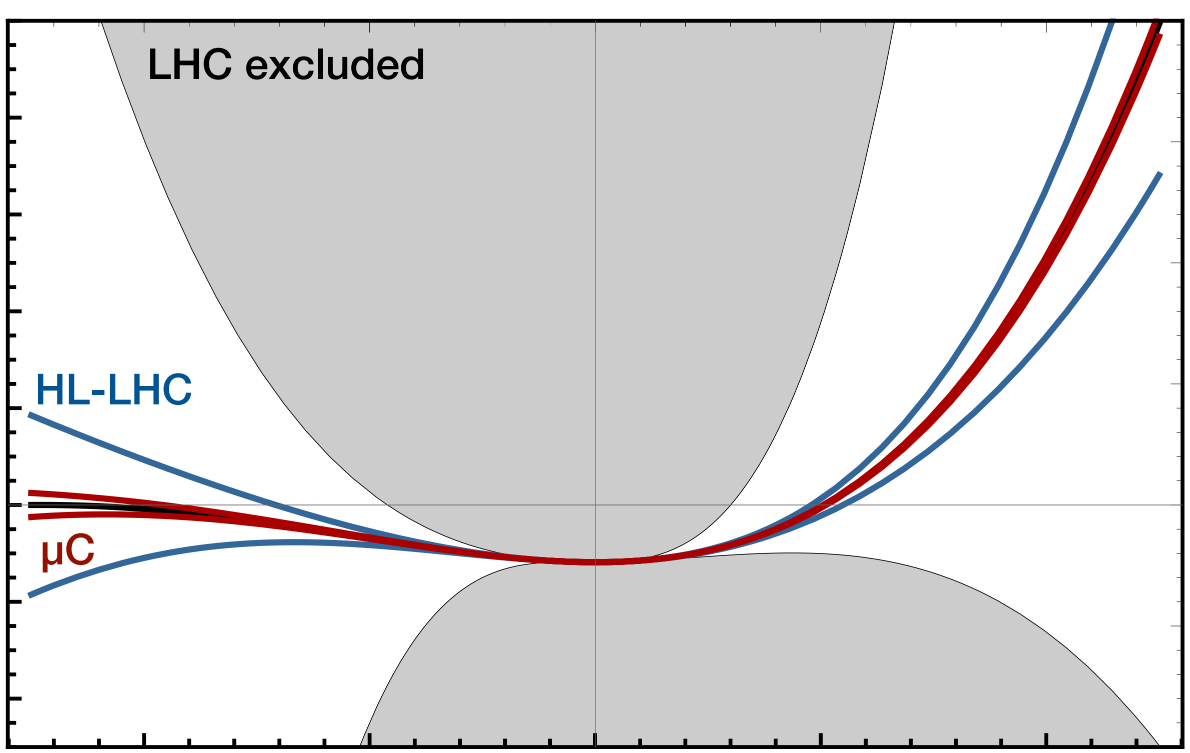
Double Higgs production

- Large double Higgs VBF rate: Higgs trilinear coupling from hh → 4b

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

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





credits: Craig, Petrossian-Byrne

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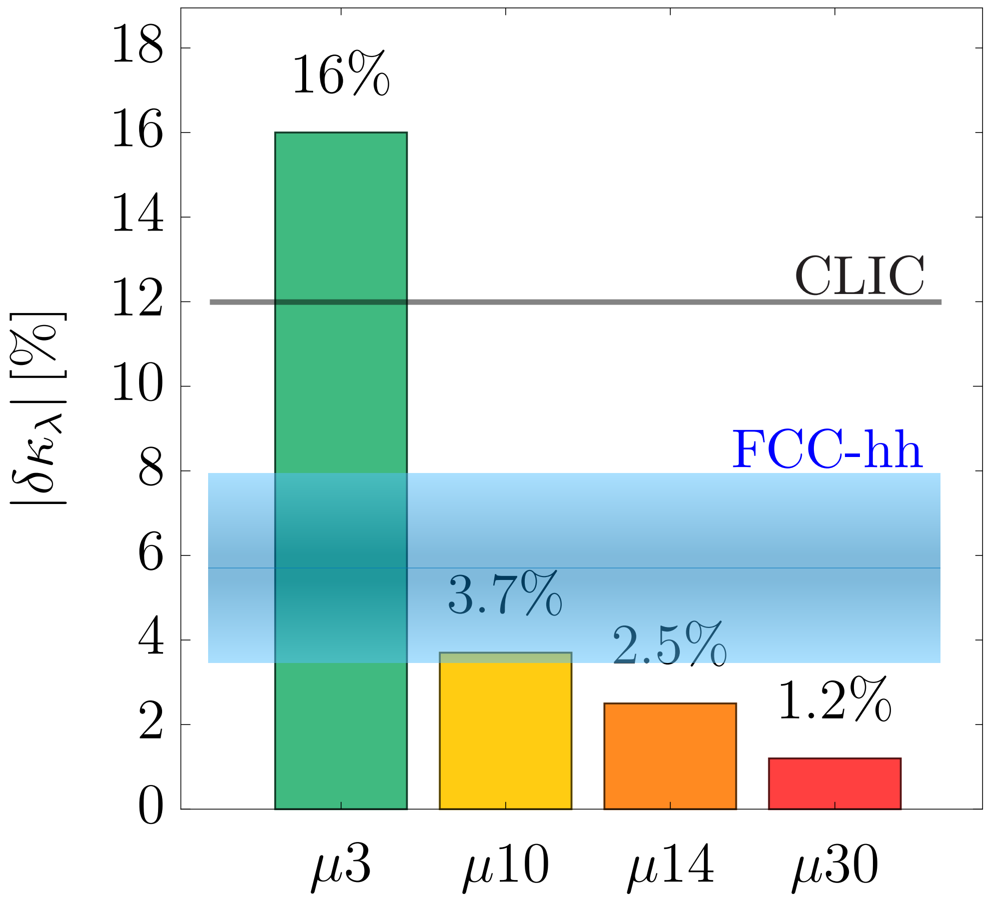

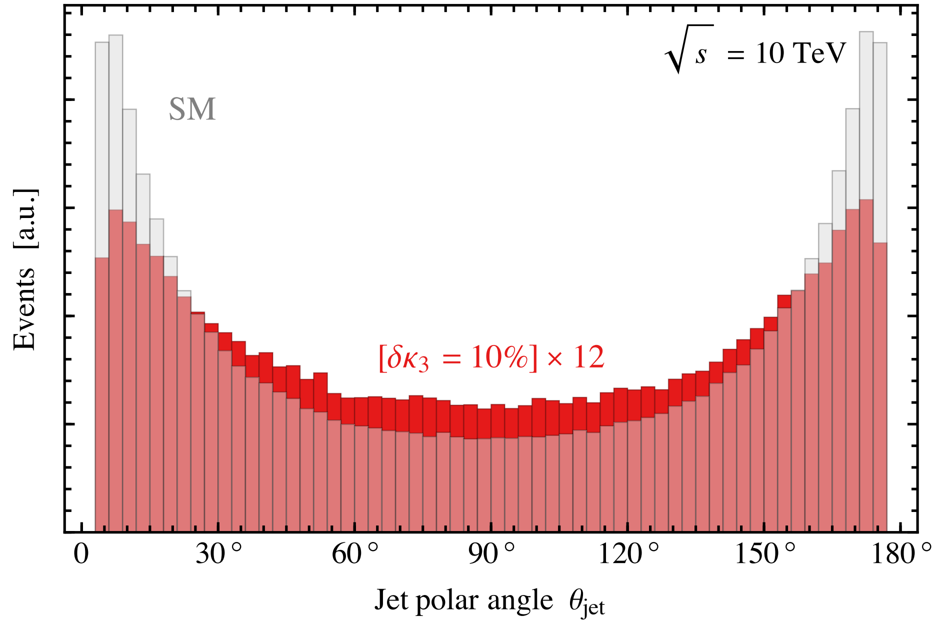

- Weak dependence on angular acceptance (signal is in the central region)
- Some dependence on detector resolution (to remove backgrounds)

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see also CLIC study 1901.05897

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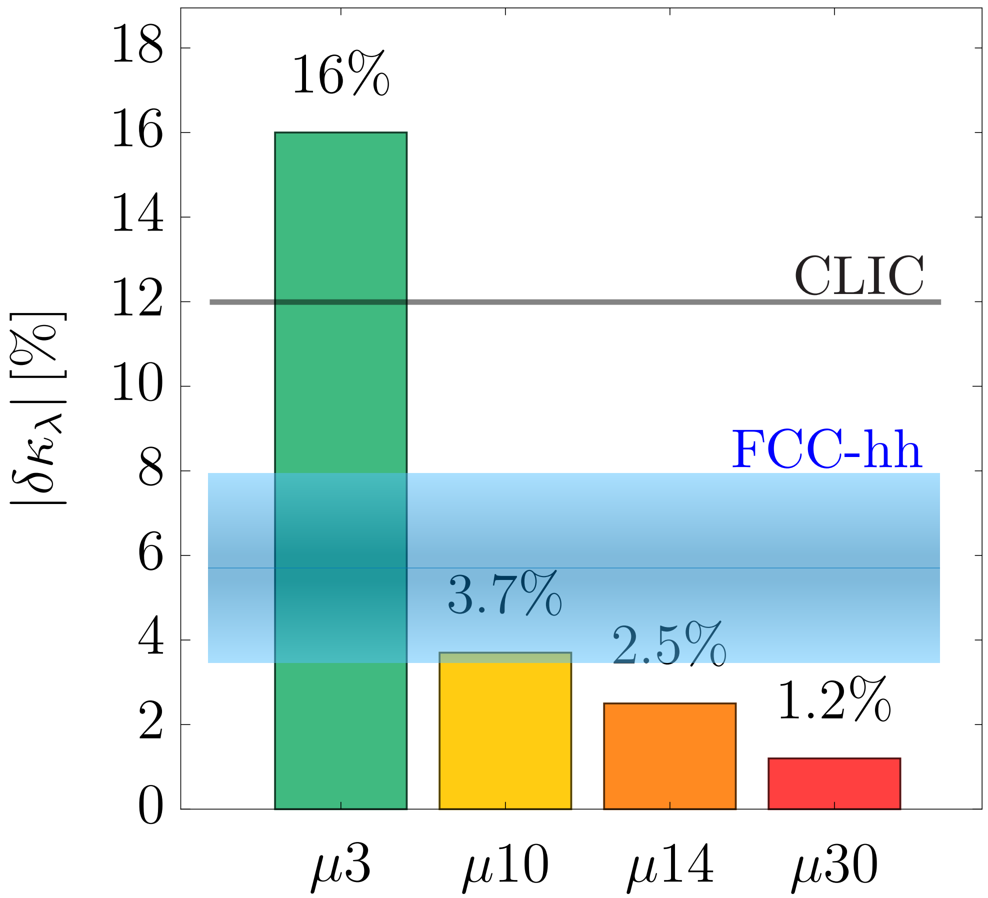

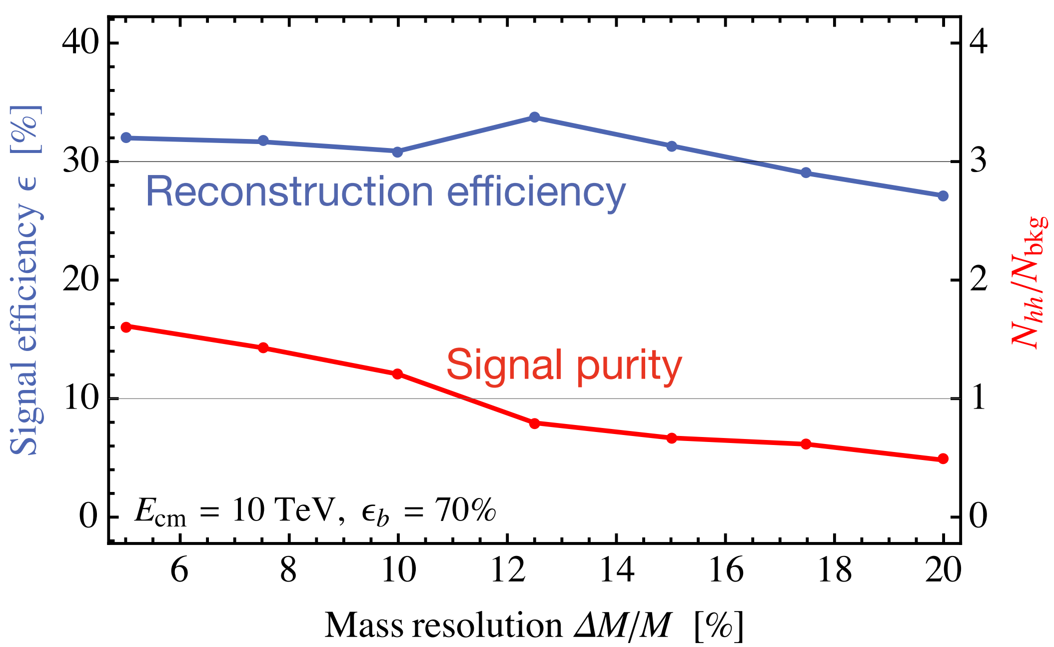

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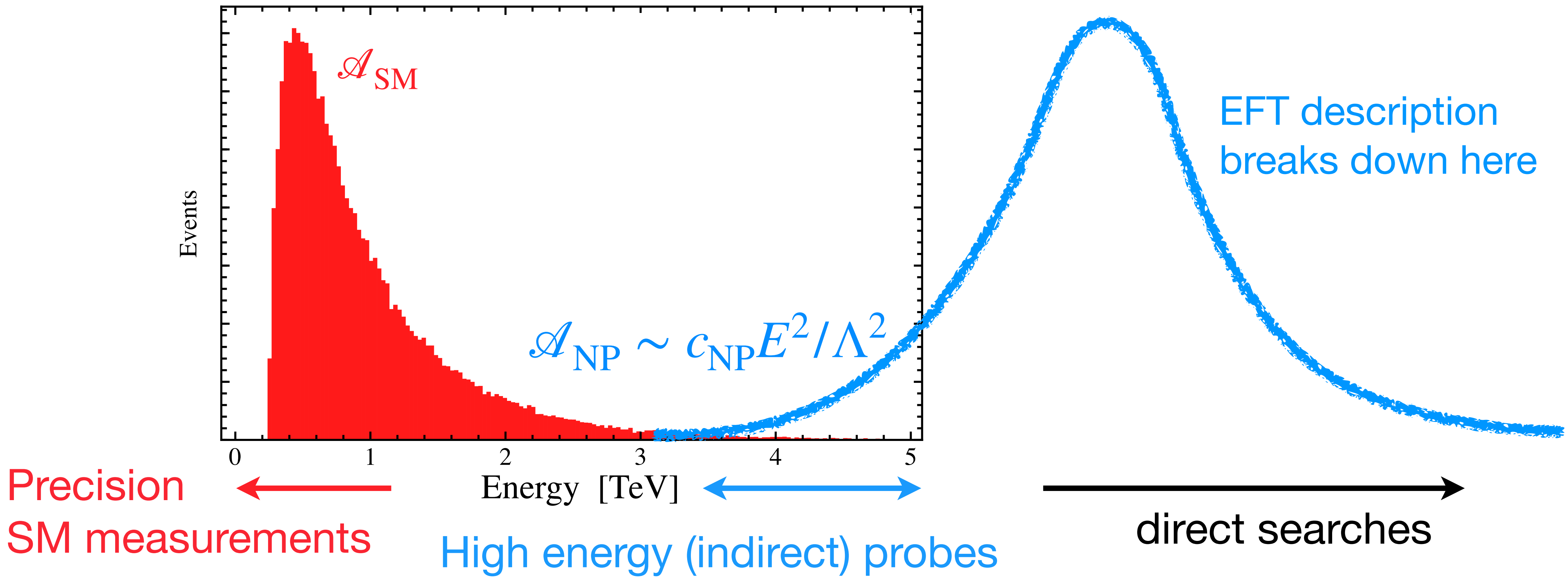
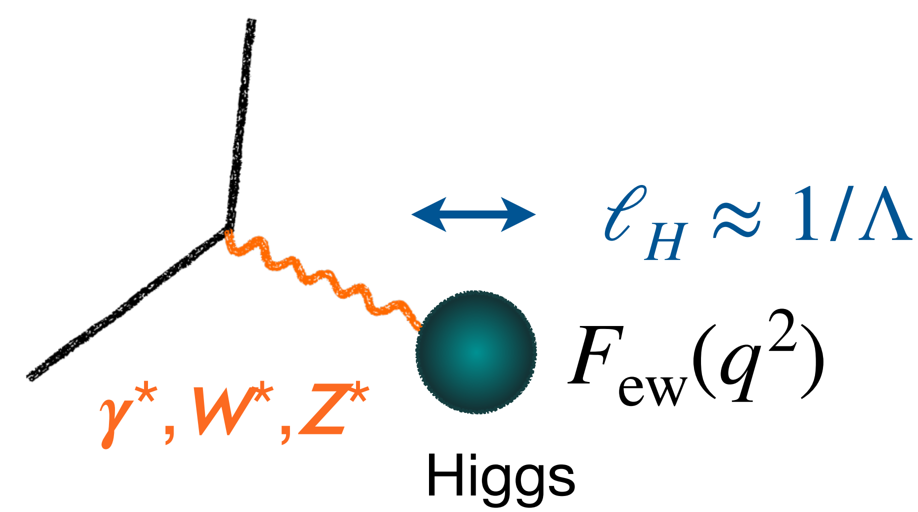
High-energy probes

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



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



- EW high-energy probes: μC can test scales of 100 TeV or more!

Example: Double Higgs at high mass

- Di-Higgs production is affected by two operators:

$$\mathcal{O}_6 = -\lambda |H|^6$$

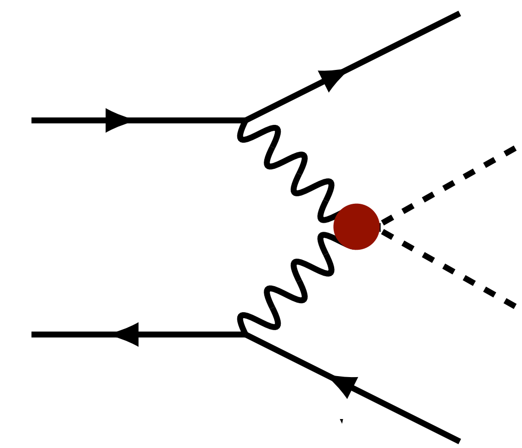
$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

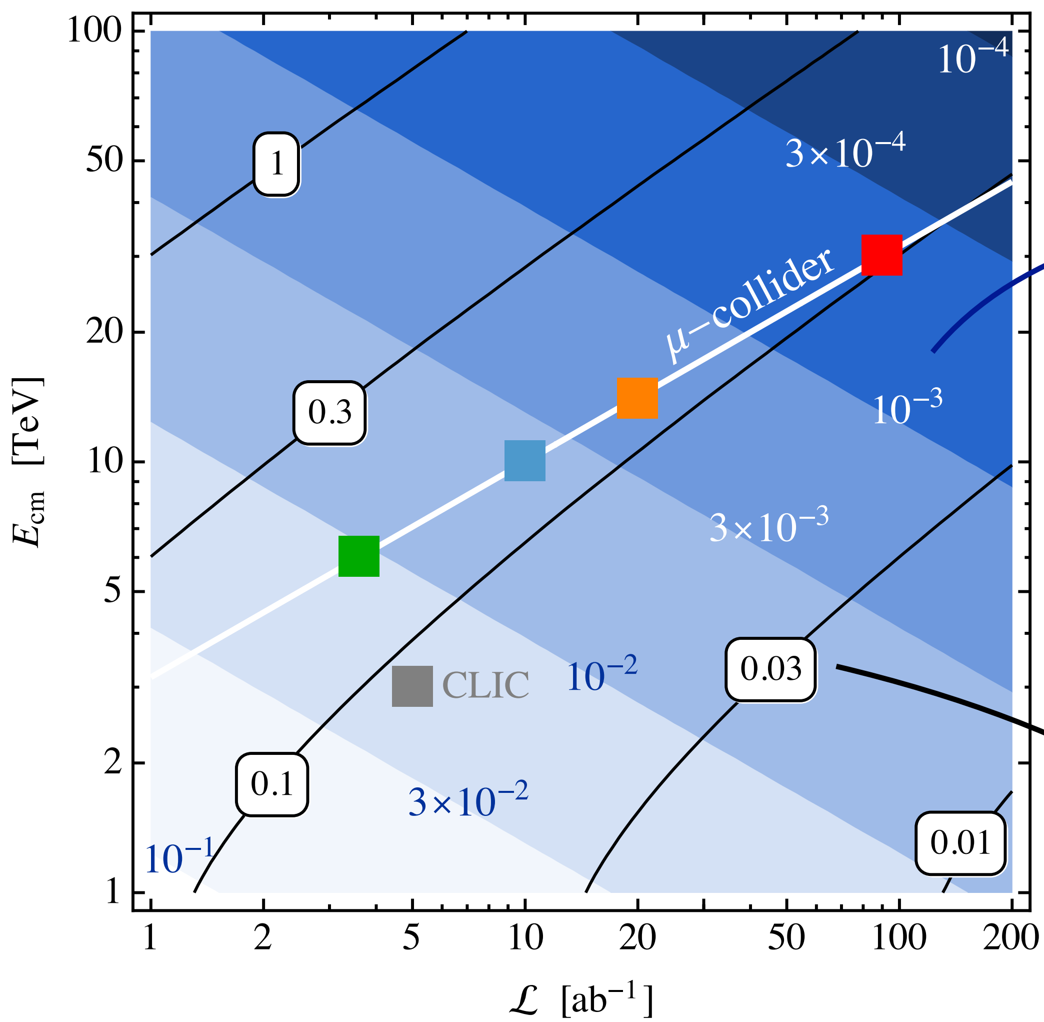
- NP contribution from $\mathcal{O}_H$ grows as E^2:

  high mass tail gives a *direct* measurement of C_H

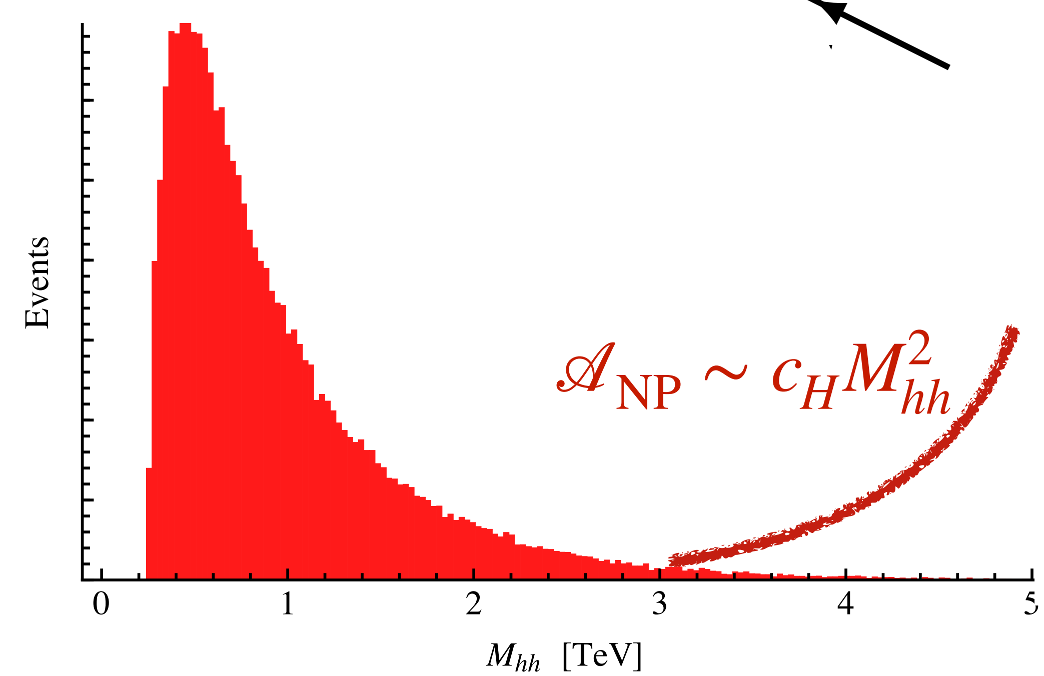
High-energy WW → *hh* more sensitive than Higgs pole physics at energies ≳ 10 TeV

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





$\xi \equiv C_H v^2$



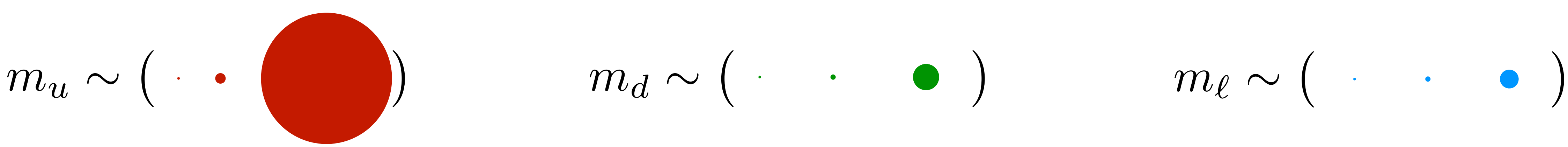
(see also Contino et al. 1309.7038)

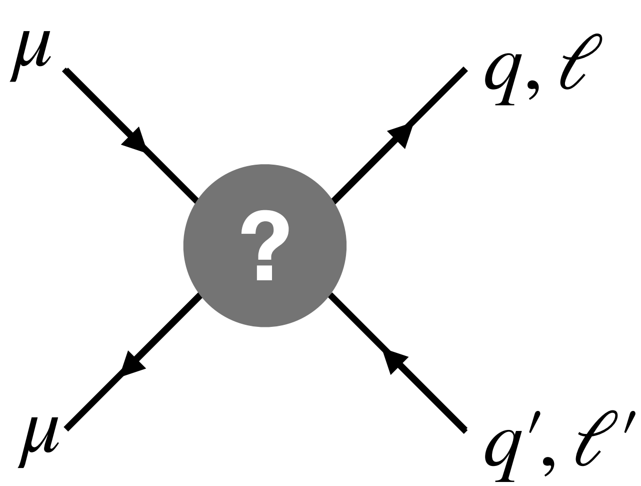
S/B low-precision measurement

Flavour: muons vs. electrons

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

- EW interactions are flavour-universal: an accidental property of the gauge lagrangian, *not* a fundamental symmetry of nature!
  - Example: Yukawa couplings, the only non-gauge interactions in the SM, violate flavour universality maximally!





A muon collider collides 2nd generation particles:

- can have access to flavor processes than cannot be efficiently probed elsewhere
- could test flavour structure

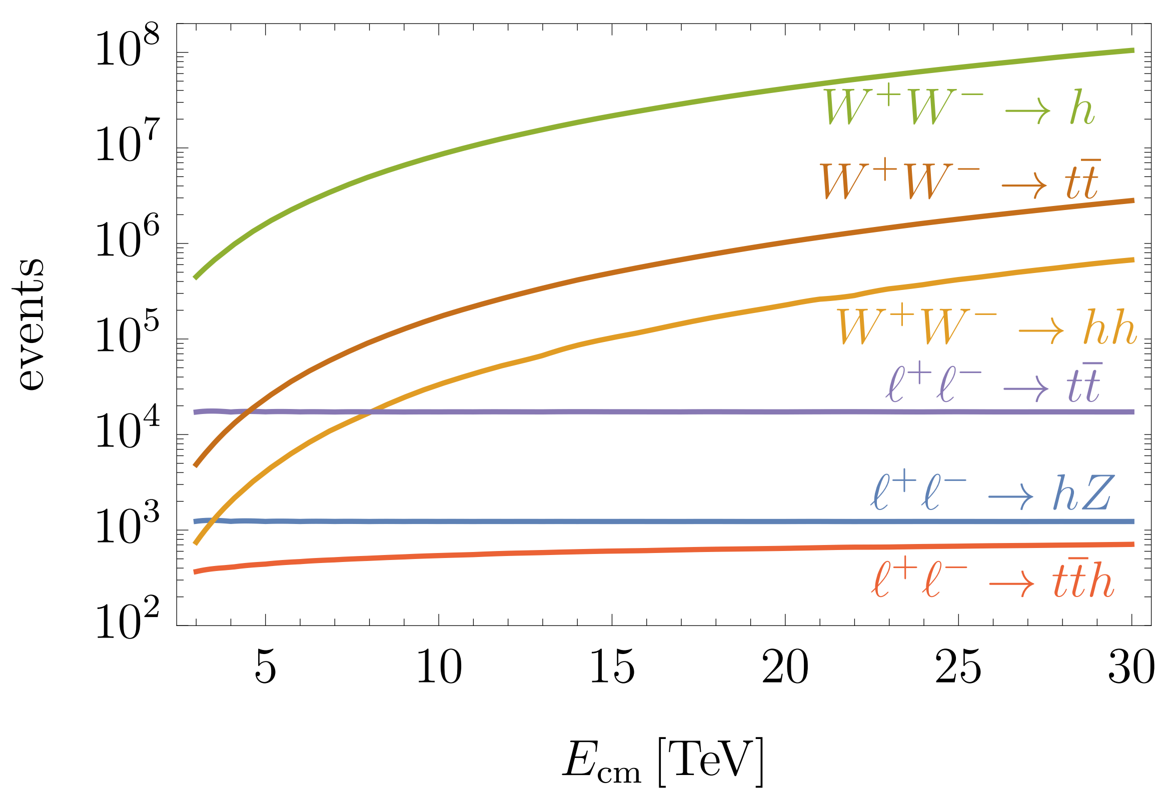
Flavor and precision

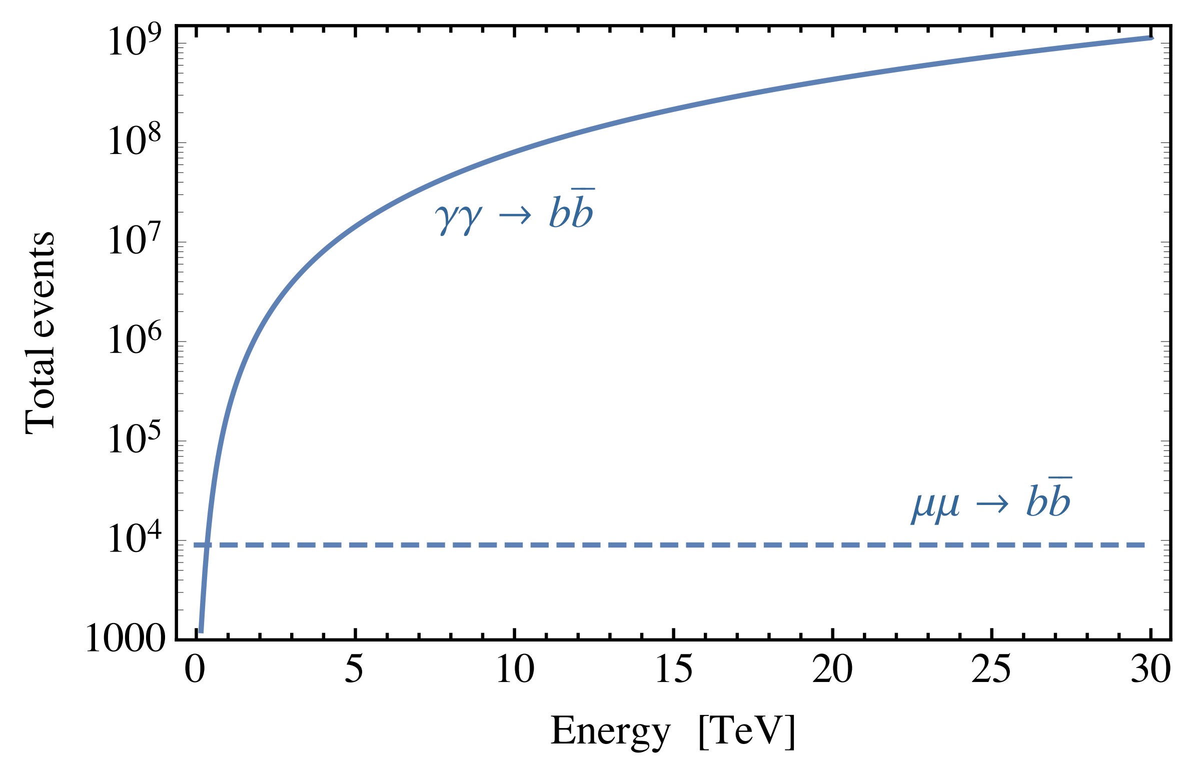
- Flavor processes: rare decays & tiny effects

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

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

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





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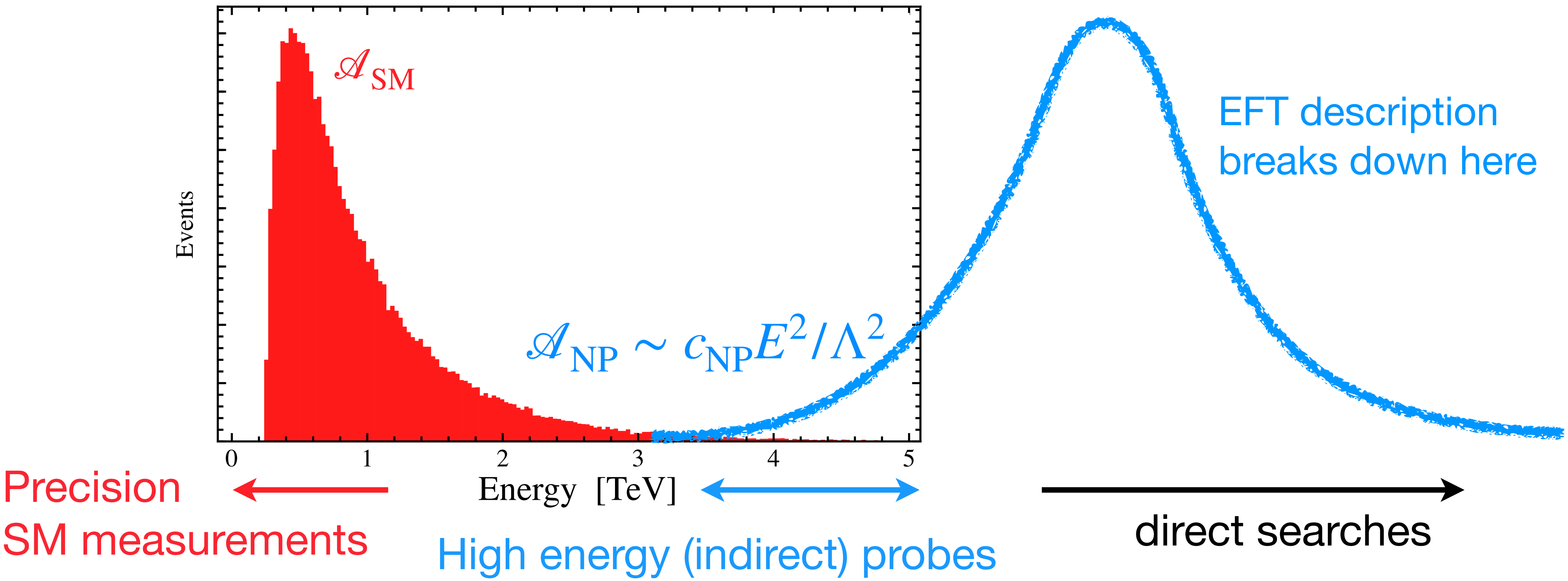

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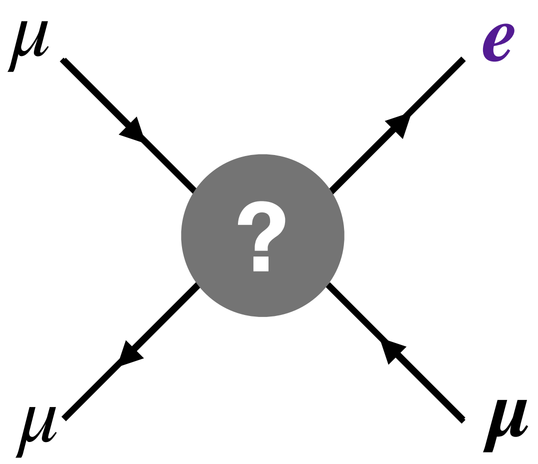
- very powerful at a μ-collider with 10’s of TeV
- taken to the extreme for flavor processes: gain can be as large as $(E/m_\mu)^2$

Lepton flavor violation



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

$$\frac{c_{e3\mu}}{\Lambda^2}(\bar{e}_{L,R}\Gamma\,\mu_{L,R})(\bar{\mu}_{L,R}\Gamma\,\mu_{L,R})$$

- Charged lepton flavor violating processes: $\tau \to \ell\gamma$, $\mu \to$ eγ, $\mu \to$ 3e

  some of the strongest bounds on (generic) BSM interactions

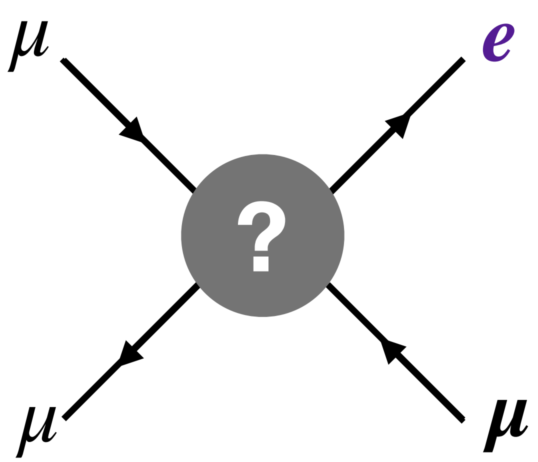
$$\mathrm{BR}(\mu \to e\gamma) \lesssim 4 \times 10^{-13}$$

$$\mathrm{BR}(\mu \to 3e) \lesssim 10^{-12}$$

$$\Lambda \gtrsim 10^6\,\mathrm{TeV} \times \frac{\alpha}{4\pi}$$

not in reach of any collider experiment ☹️

Lepton flavor violation



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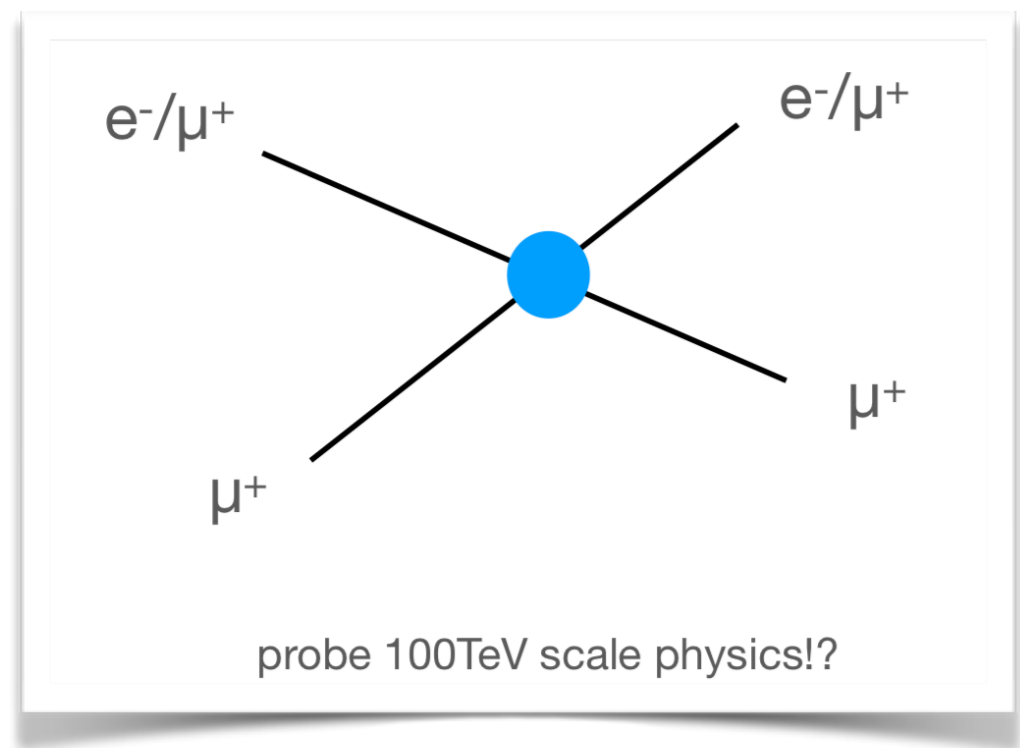
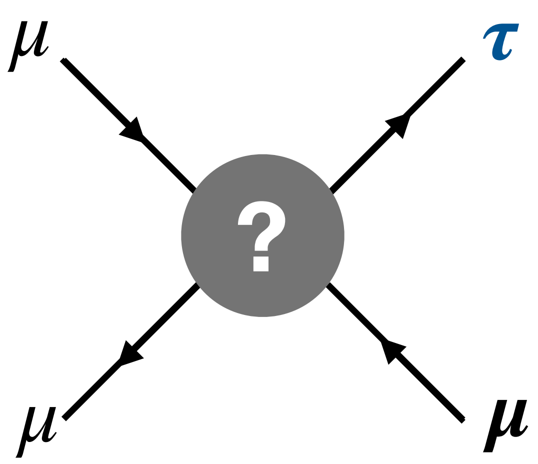
$$\Lambda \gtrsim 10^6\,\mathrm{TeV} \times \frac{\alpha}{4\pi} \times \text{small}$$

can probe larger set of operators than $\mu \to e\gamma$, $\mu \to 3e$? 🤔



☛ talk by Ryuichiro

Lepton flavor violation



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☛ talk by Sam yesterday!

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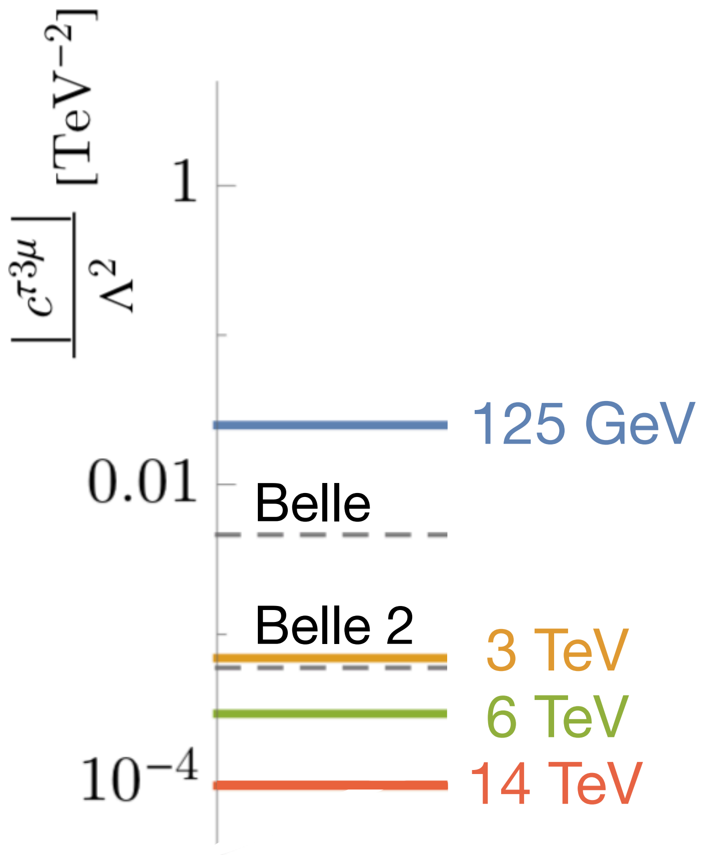


- 3rd generation less severely constrained:

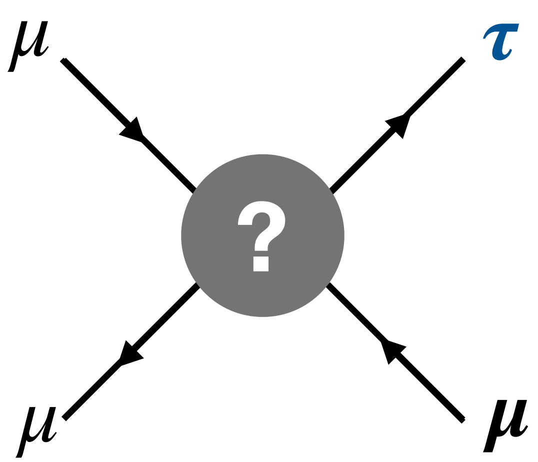
  $\tau \to 3\mu$ constrains NP scale Λ > 15 TeV [Belle]

$$\mathrm{BR}(\tau \to 3\mu) \sim \frac{m_W^4}{\Lambda^4} \qquad \sigma(\mu\bar{\mu} \to \tau\bar{\mu}) \sim \frac{E^2}{\Lambda^4}$$

already at 3 TeV the same sensitivity as Belle II, Λ > 40 TeV

"Muon smasher guide" 2103.14043
Homiller, Lu, Reece 2203.08825

Lepton flavor violation



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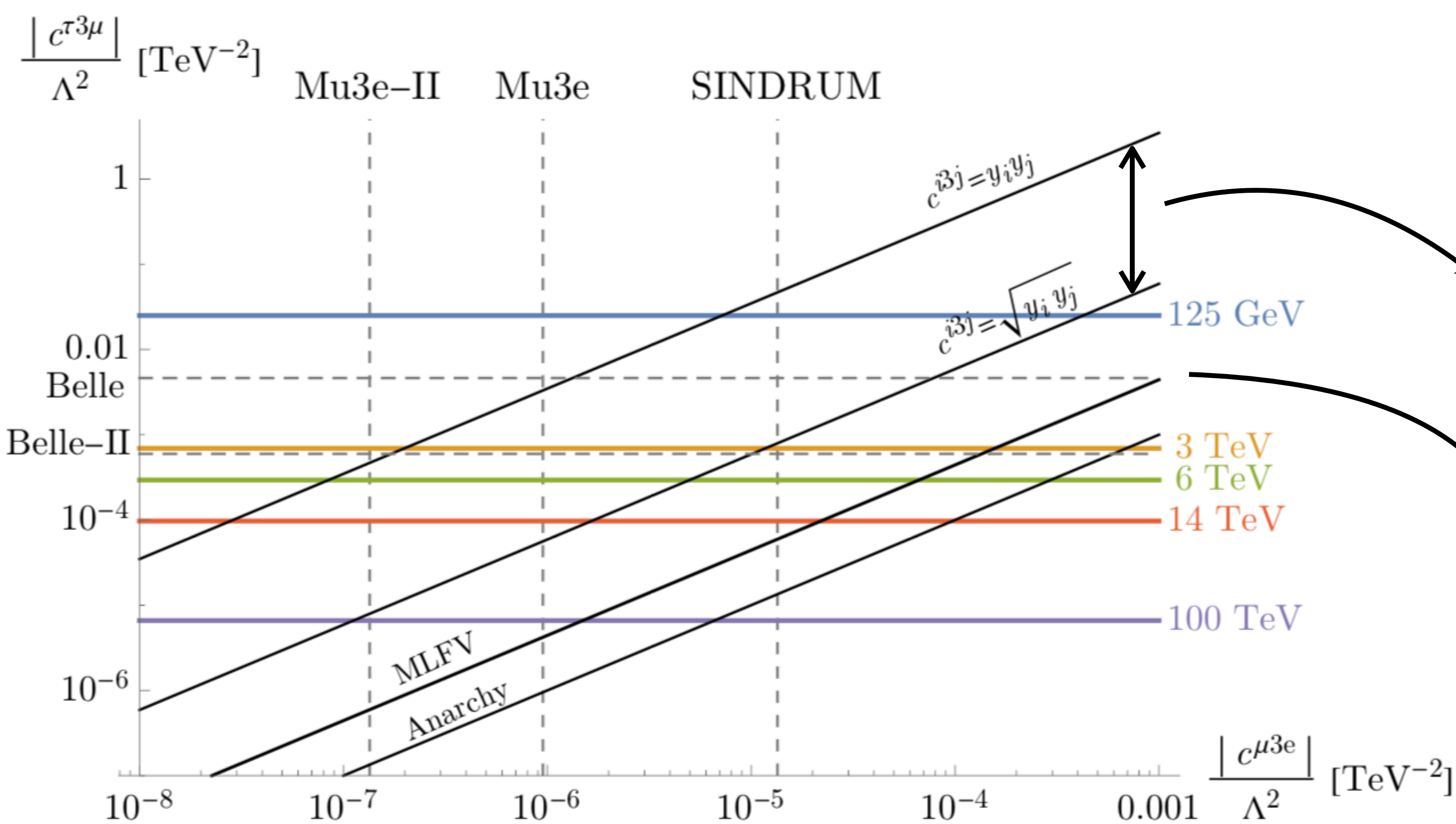


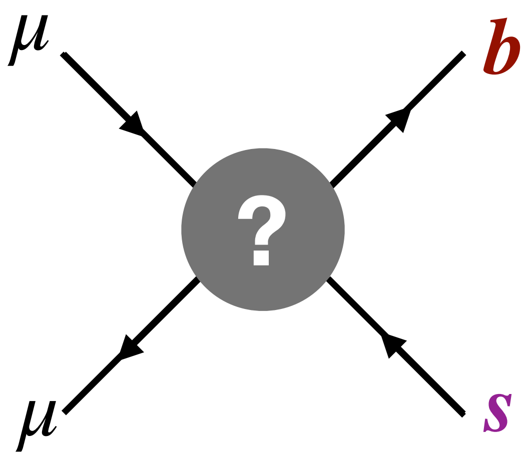
Correlation with $\mu \to 3e$: assumes flavor structure

~ quark sector: competes with Mu3e

~ neutrino sector

"Muon smasher guide" 2103.14043
Homiller, Lu, Reece 2203.08825

Quark flavor violation



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

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

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

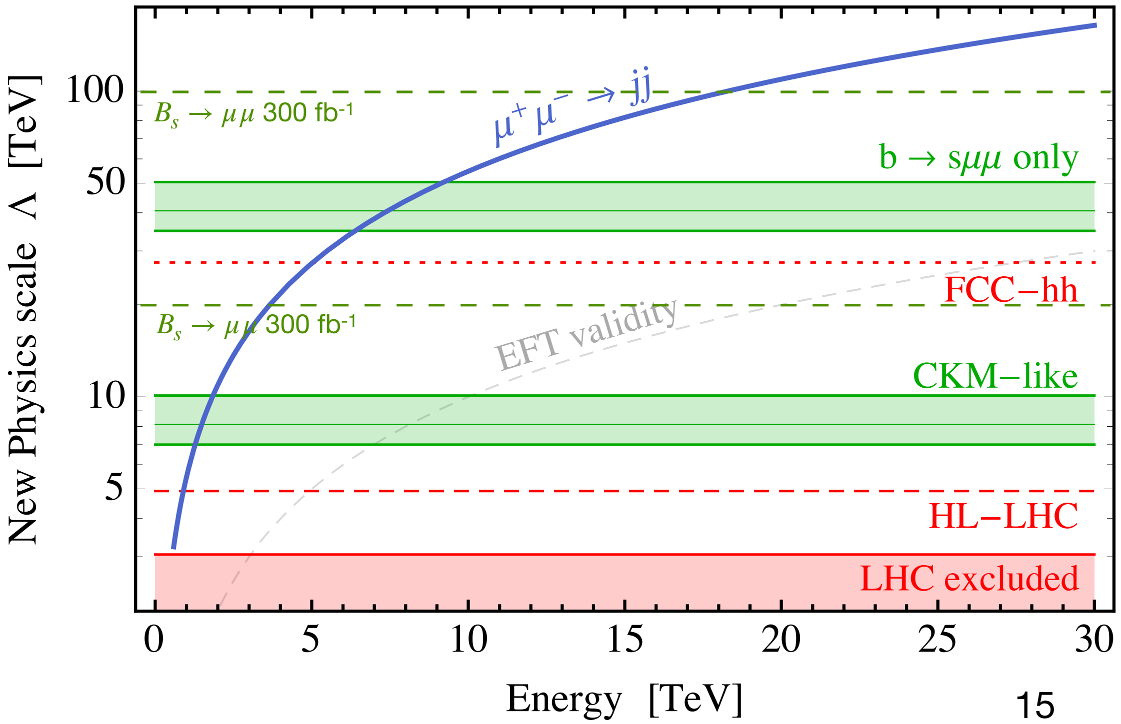
$$B_s \to \mu\mu, \qquad B \to K^{(*)}\mu\mu, \qquad B_s \to \phi\mu\mu, \qquad \Lambda_b \to \Lambda\mu\mu$$

- Theory & systematic uncertainties: rare decays cannot improve indefinitely

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

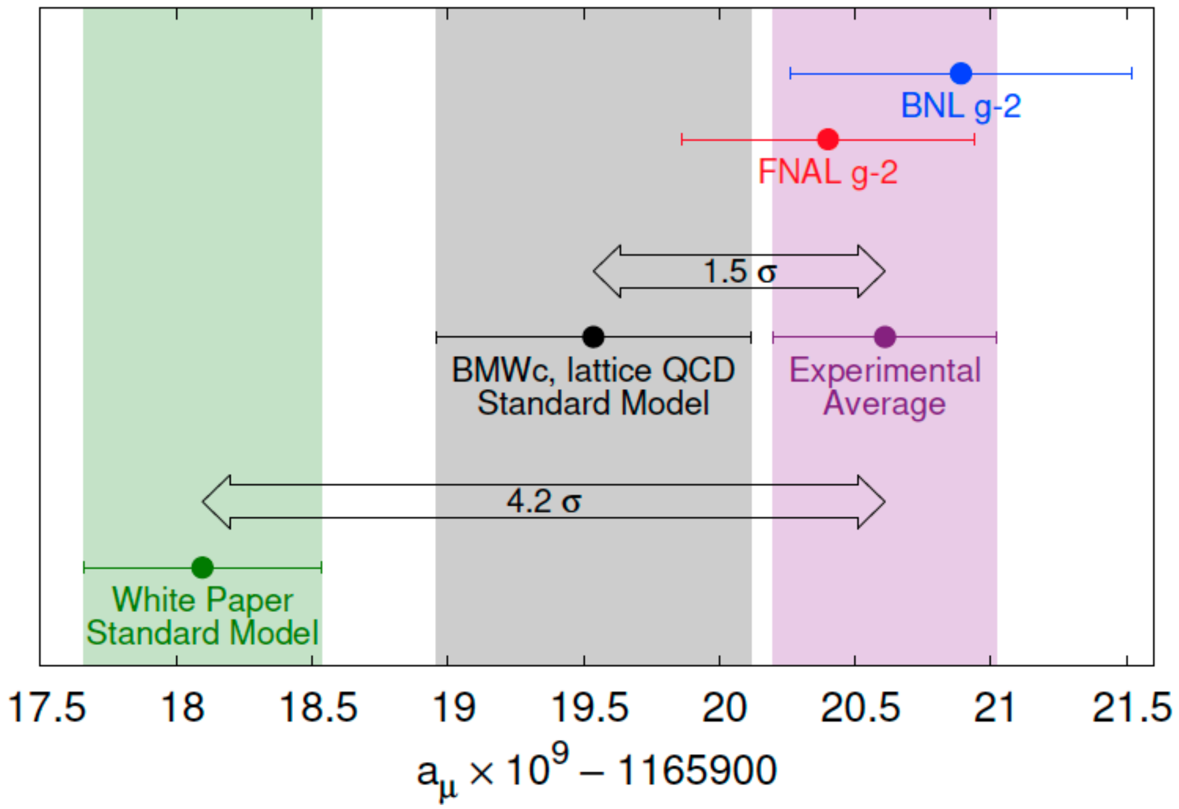
Azatov, Garosi, Greljo, Marzocca, Salko, Trifinopoulos 2205.13552

see also Altmannshofer et al. 2306.15017



The muon g-2

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



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

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

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

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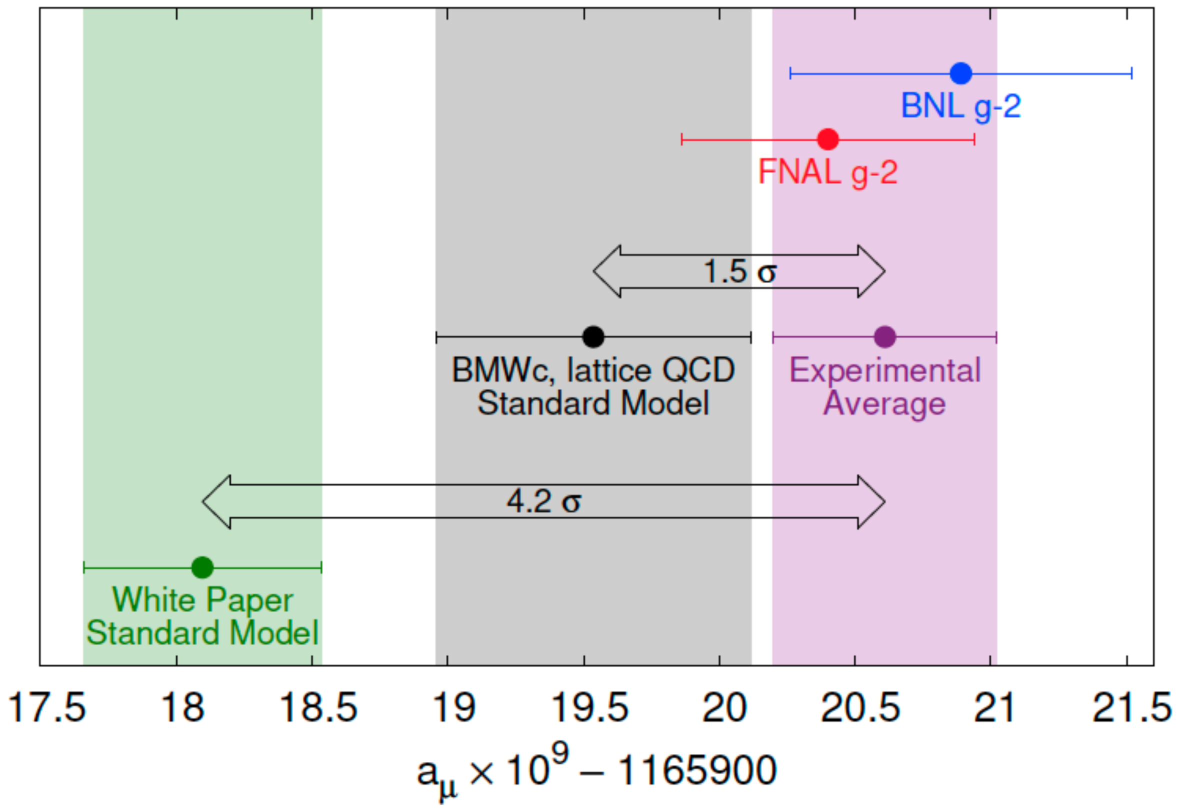

$$\Delta a_\mu = ???$$

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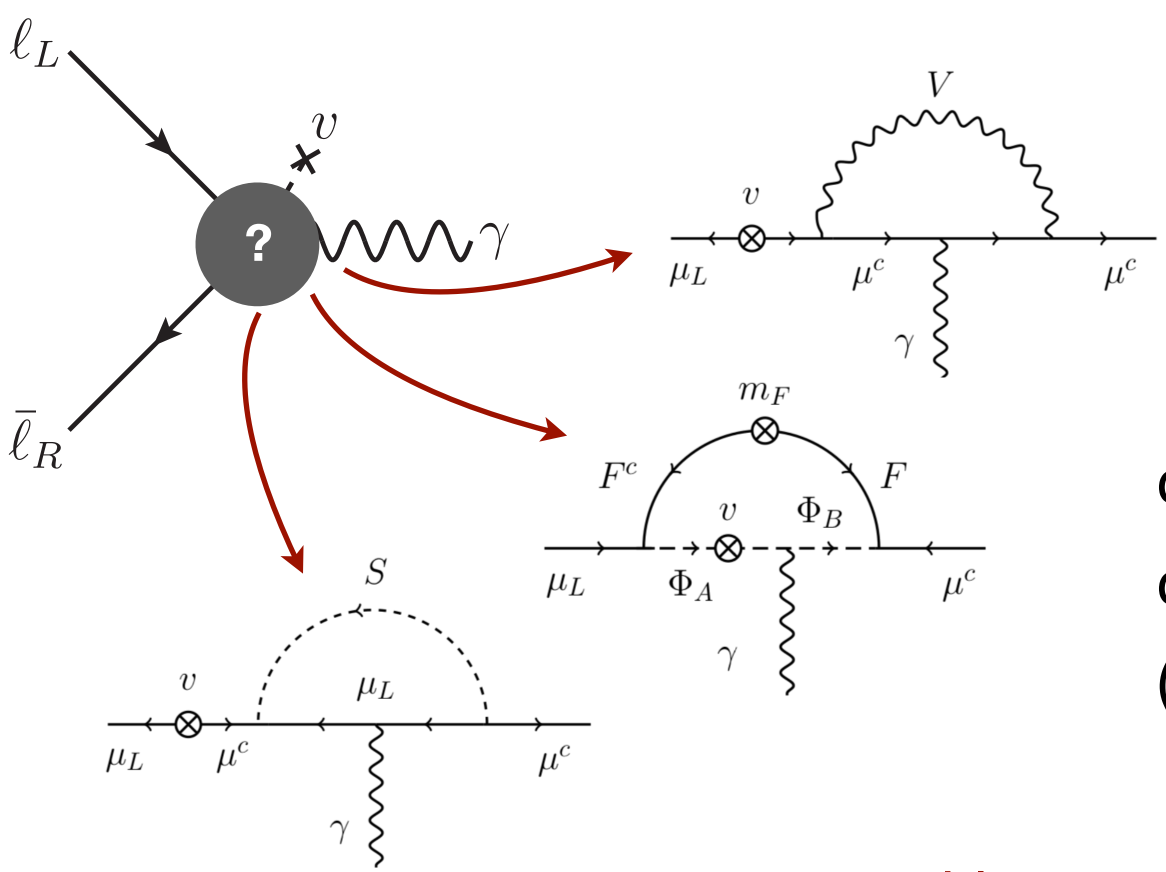
Muon g-2 @ muon collider

- Example: muon g-2. Can it be tested at high energies at a 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
2101.10334

classify New Physics that
can enter the loop
(under reasonable assumptions)

weakly coupled models w/ MFV
⇒ new states below ~ 20 TeV

Muon g-2 @ muon collider

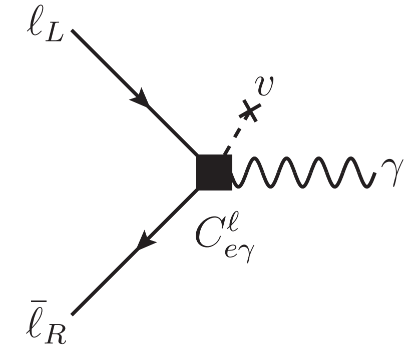
- Example: muon g-2. Can it be tested at high energies at a muon collider?

- If new physics is heavy: EFT!

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

At low energy

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



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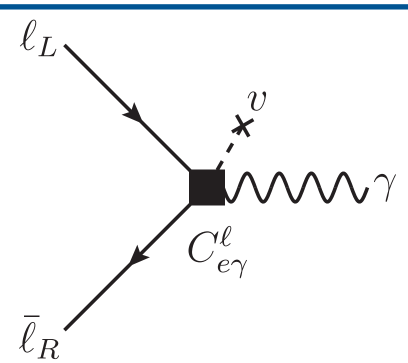
- Example: muon g-2. Can it be tested at high energies at a muon collider?

- If new physics is heavy: EFT!

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

At low energy

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



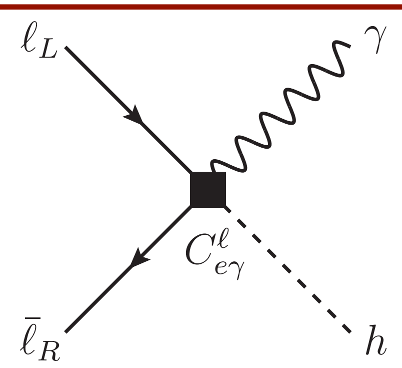
Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

At high energy

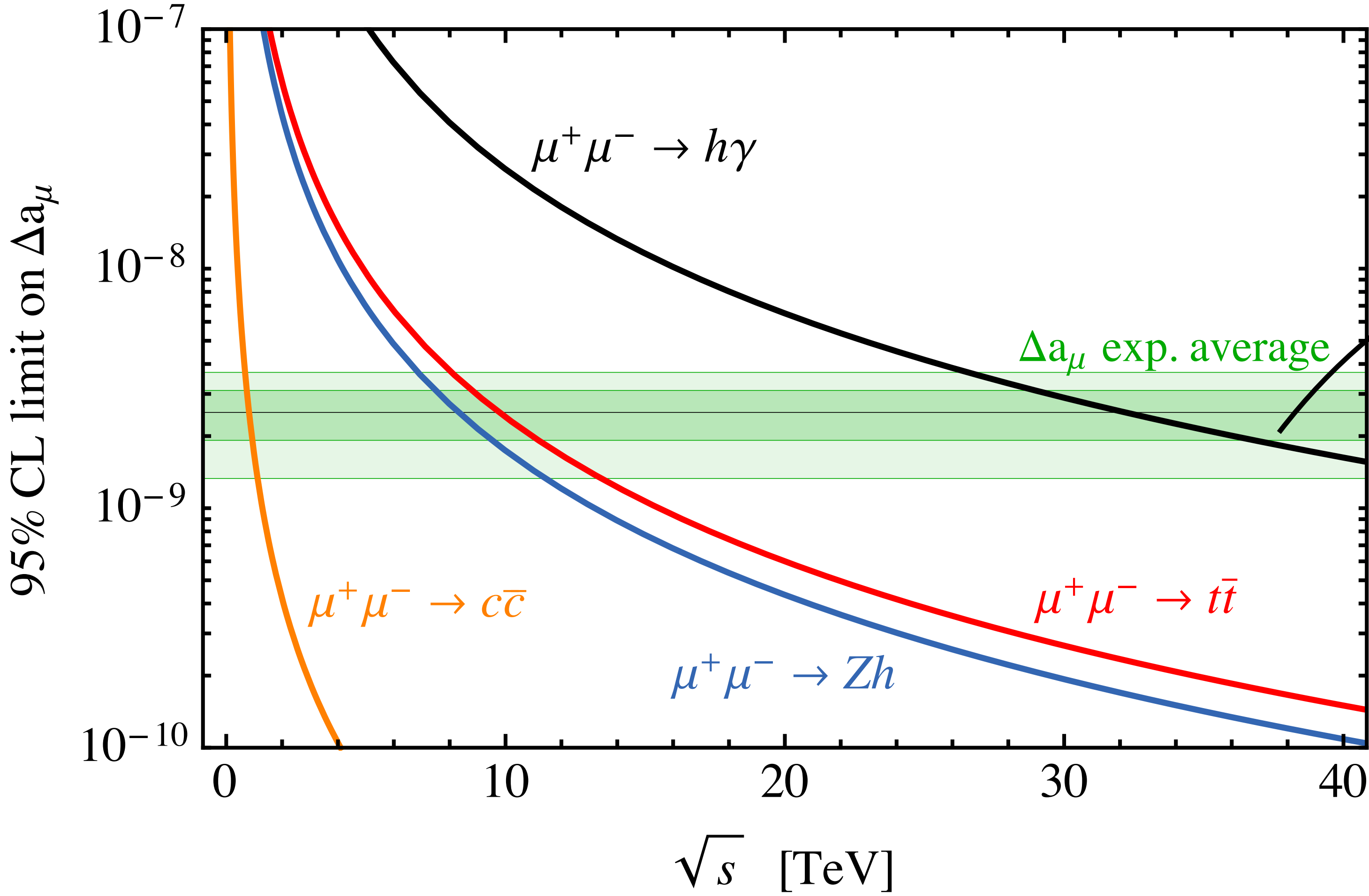
$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\mathrm{ab} \left(\frac{\sqrt{s}}{30\,\mathrm{TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$

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

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)

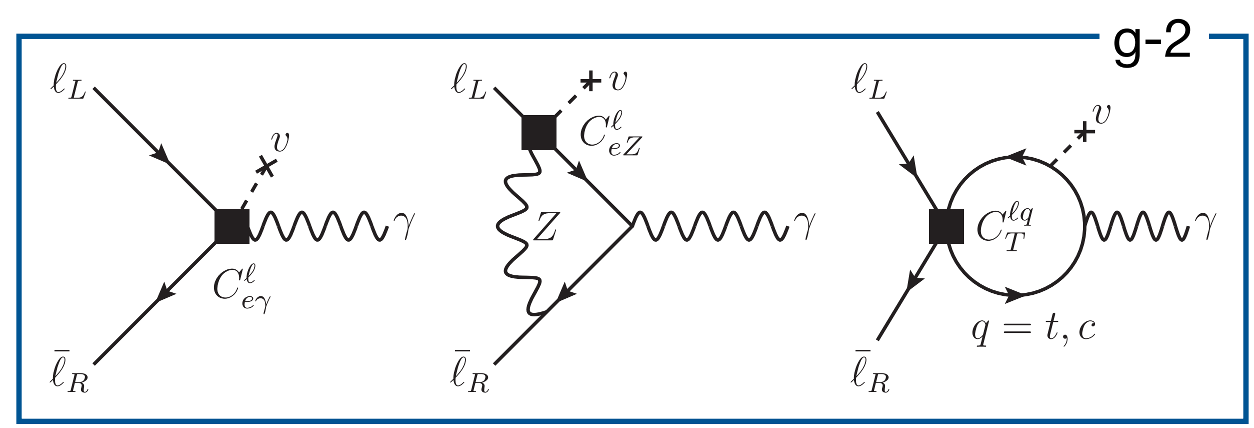
This result is completely model-independent!

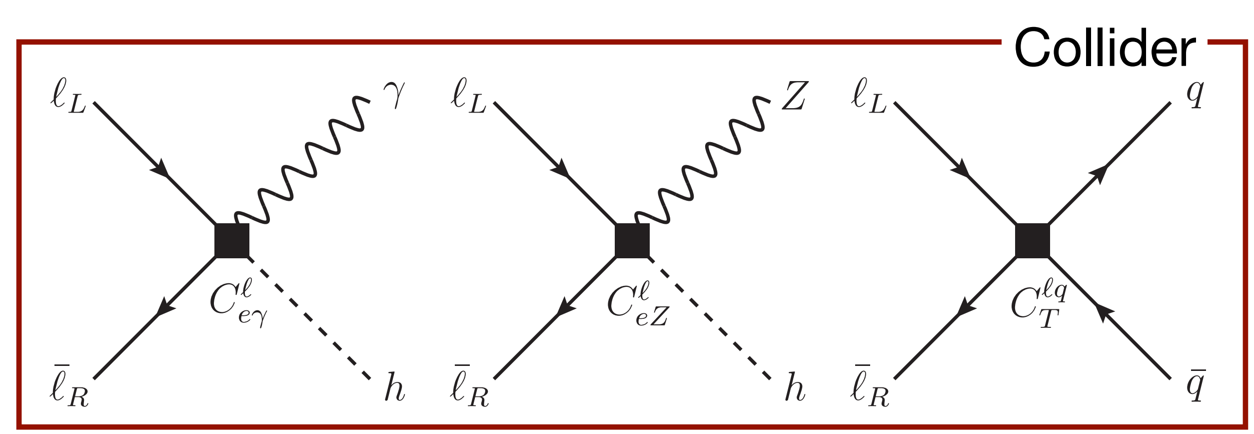
B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

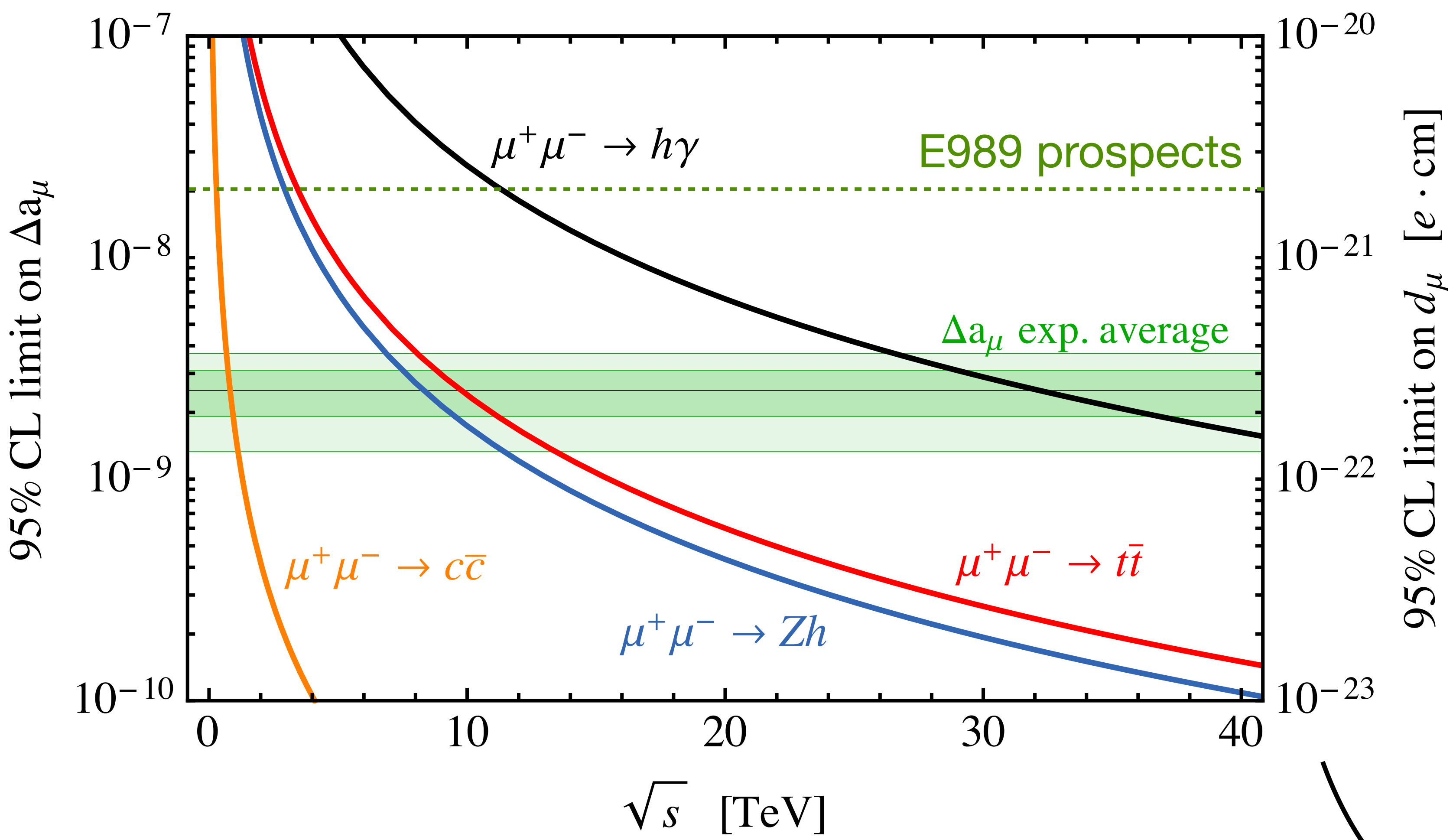
$$\Delta a_\mu \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

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





Muon EDM @ muon collider



Exp. value of Δa_μ 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!

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

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

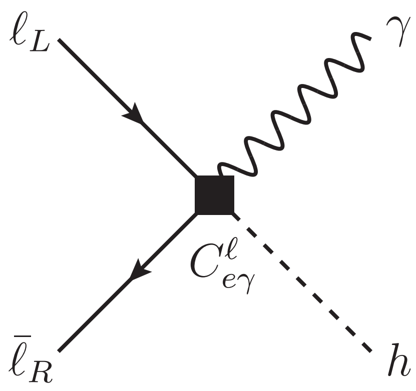
Collider constrains $|C_{e\gamma}|^2$

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

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

Lepton g-2 from rare Higgs decays

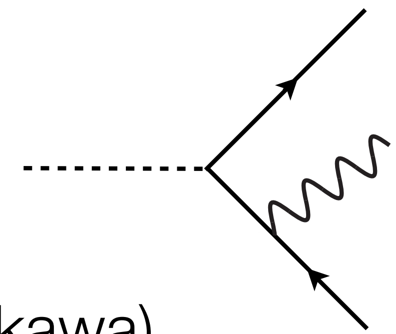
- Dipole operator contributes also to h $\to \ell\ell\gamma$ decays

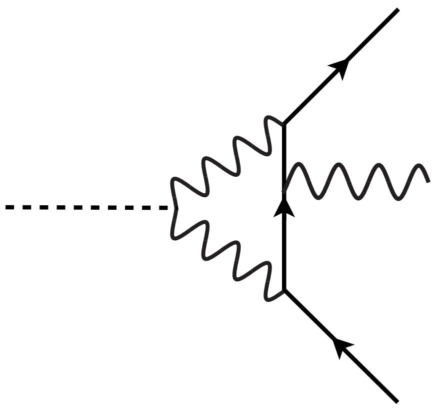


$$\Gamma^{(\mathrm{NP})}_{h\to\ell^+\ell^-\gamma} = \frac{\alpha\,|C_{e\gamma}|^2 m_h^5}{192\pi^2\Lambda^4}$$

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

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





Han, Wang
1704.00790

(tree-level is suppressed by lepton Yukawa)

- Muon g-2: rate is too small ☹

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

(mainly one-loop)

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

Lepton g-2 from rare Higgs decays

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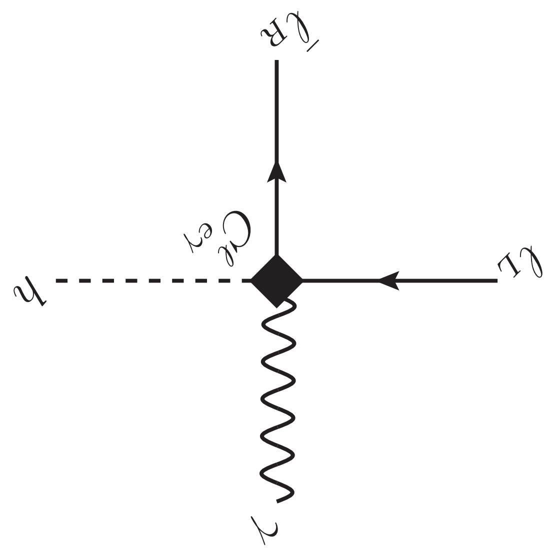

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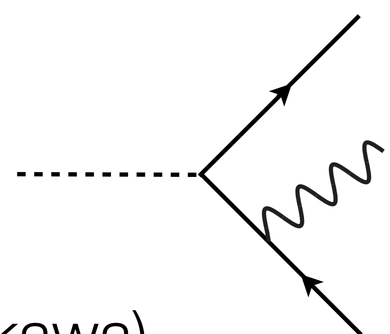

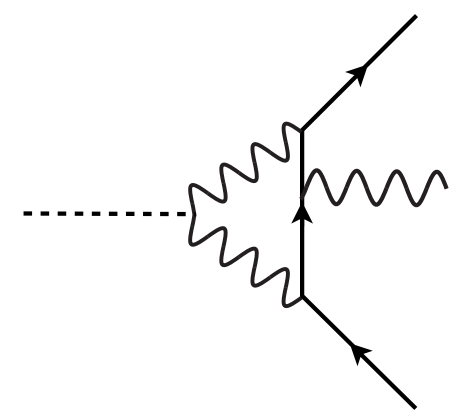

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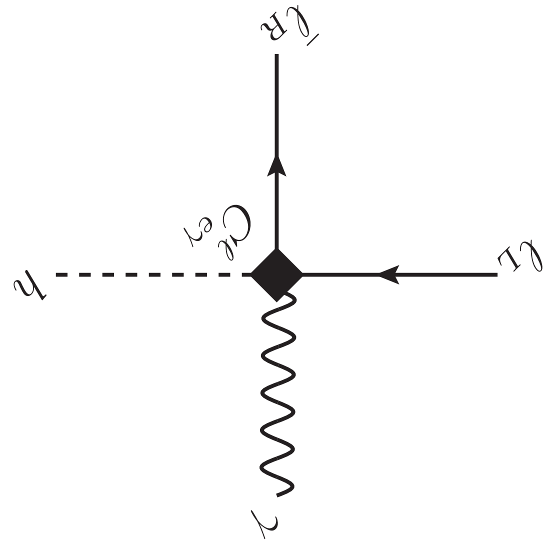

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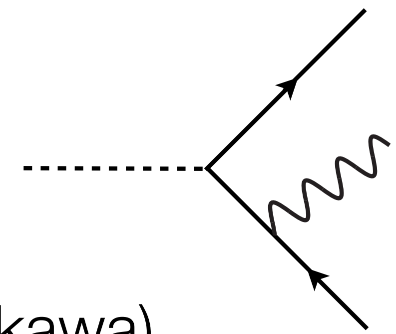

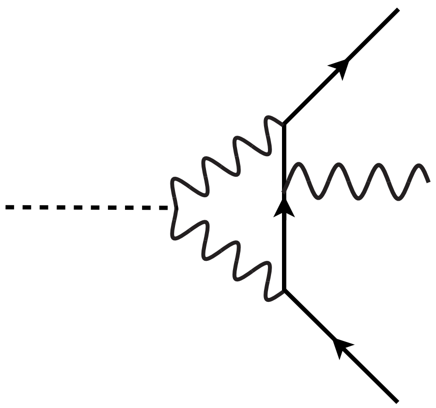

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☛ What about the tau?

Lepton g-2 from rare Higgs decays

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

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

if $C^\ell_{e\gamma}$ scales as y_ℓ

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

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

hep-ex/0406010

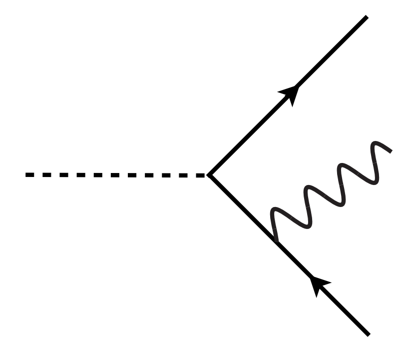
Can be improved to few 10-3

at HL-LHC 1908.05180

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

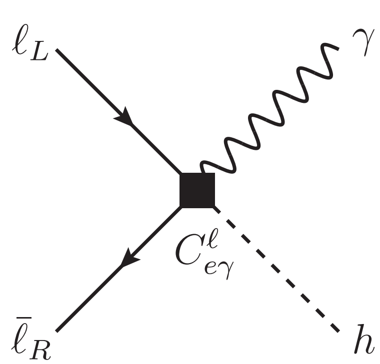
$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5 \times 10^{-4}$$

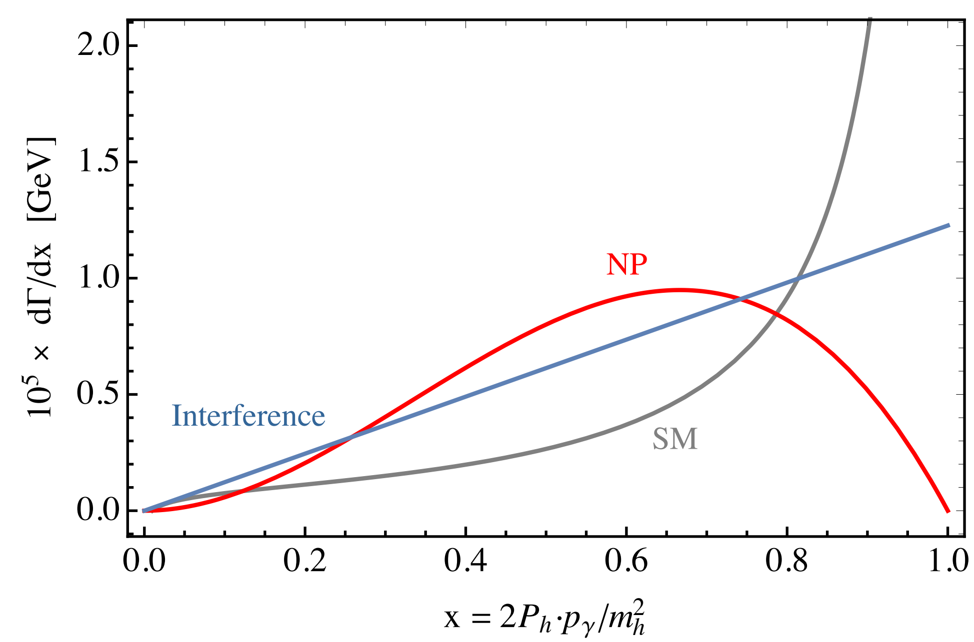
(with cut on soft collinear photon)



could be measured at few % level by Higgs factory

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



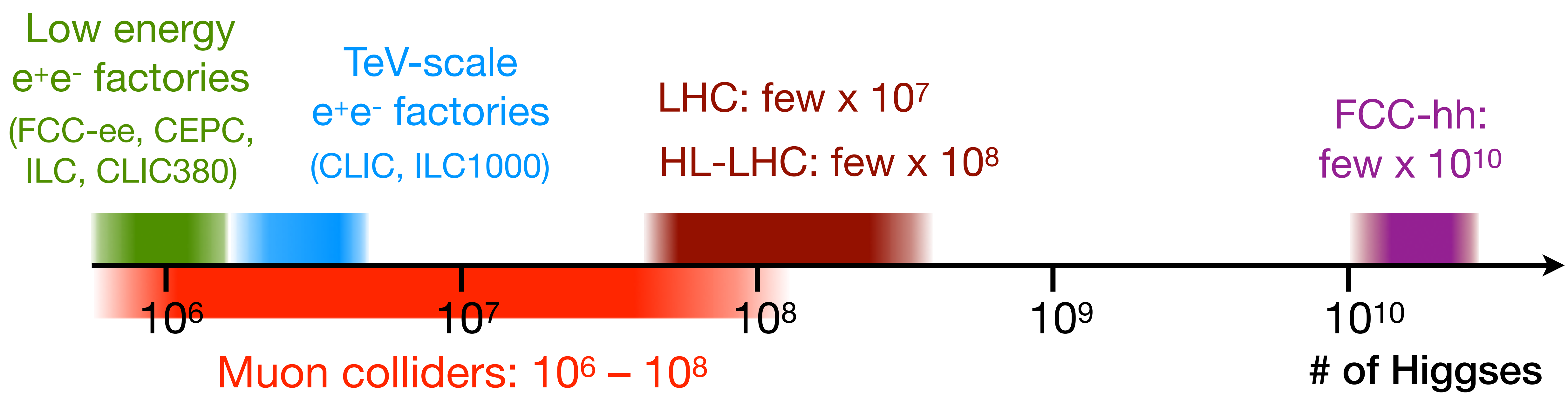


Lepton g-2 from rare Higgs decays

$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4} \qquad \mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2\times \Delta a_\tau$$

- **MuC:** 10^7 Higgs bosons @ 10 TeV $\Rightarrow$ 5k $H\to\tau\tau\gamma$ events, 2% precision on SM,

$\Delta a_\tau \lesssim 3\times 10^{-5}$ (signal only) 3 o.o.m. improvement of current limit!



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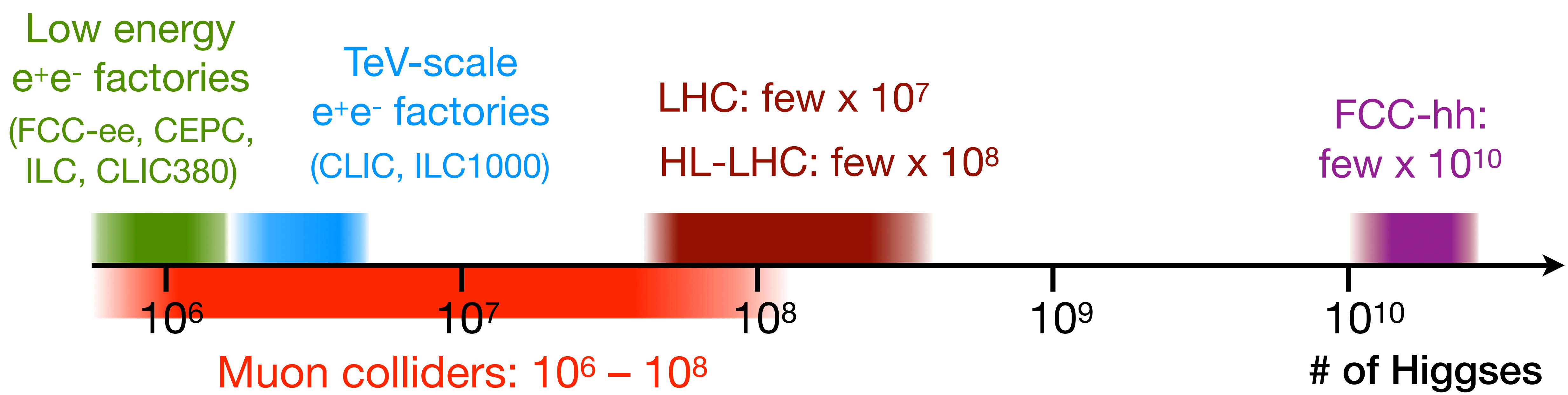

- ✦ **e+e- factory:** ~ 400 $H\to\tau\tau\gamma$ events $\Rightarrow$ 5% precision on SM, $\Delta a_\tau \lesssim \mathrm{few}\times 10^{-4}$
- ✦ **LHC:** large number of Higgs bosons, but large backgrounds
  Rescaling $H\to\tau\tau$ searches ~ 350 reconstructed $H\to\tau\tau\gamma$ events at HL-LHC,
  but 10x more background $\Rightarrow$ 20% precision on SM, $\Delta a_\tau \lesssim 5\times 10^{-4}$

Lepton g-2 from rare Higgs decays

$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4} \qquad \mathrm{BR}^{(\mathrm{NP})}_{h\to\tau^+\tau^-\gamma} \approx 0.2\times \Delta a_\tau$$

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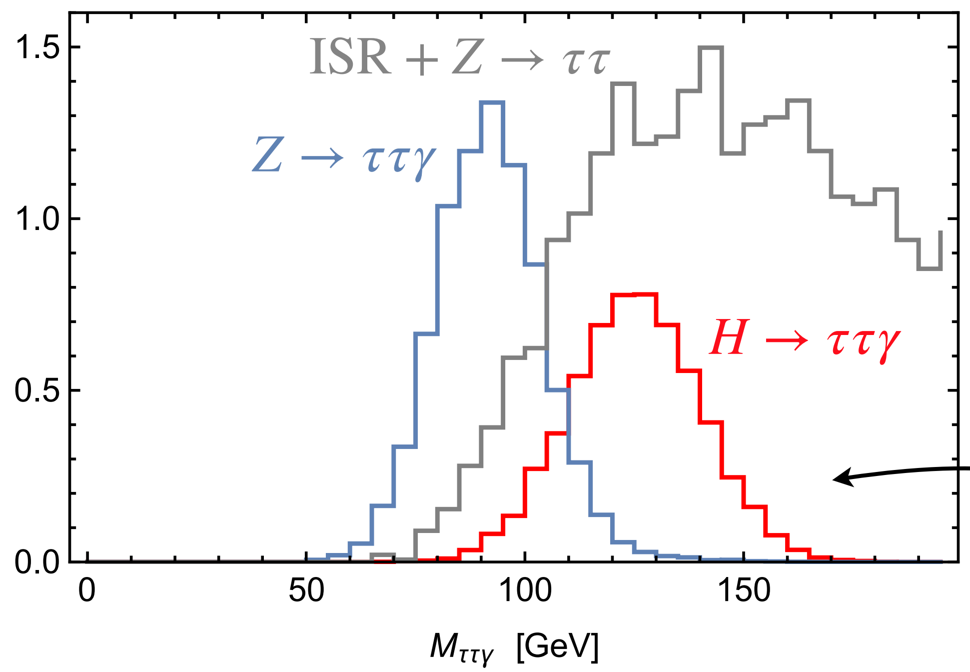
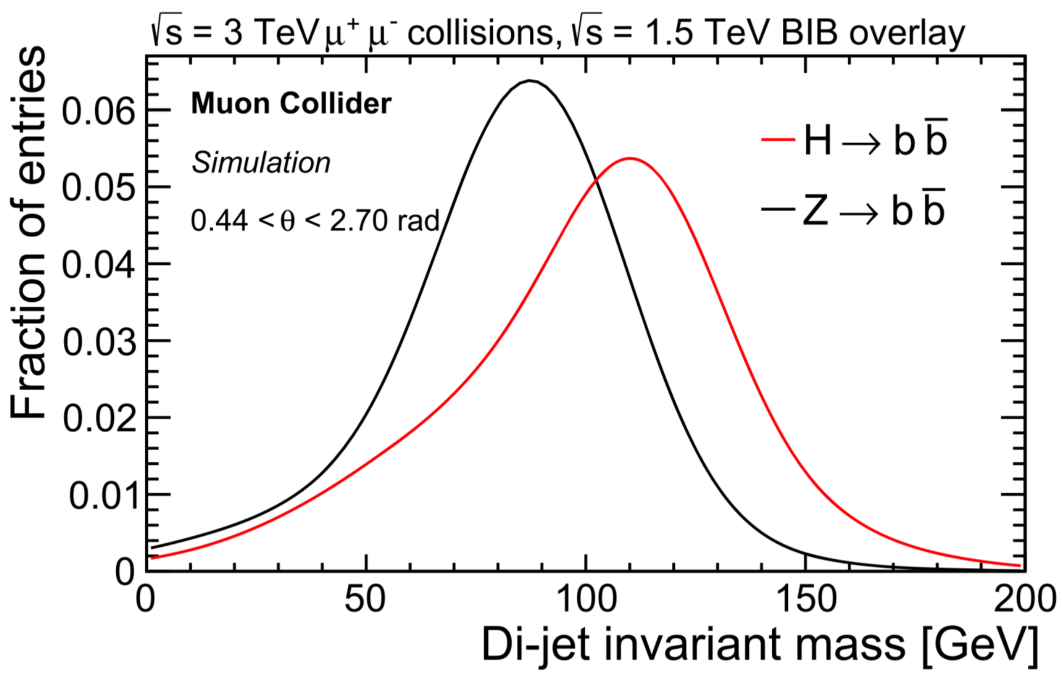
  $\Delta a_\tau \lesssim 3\times 10^{-5}$ (signal only) 3 o.o.m. improvement of current limit!

- Caveat: need to be able to reconstruct Higgs mass in di-tau channel w/ reasonable precision

- Reducible background: γ + Z



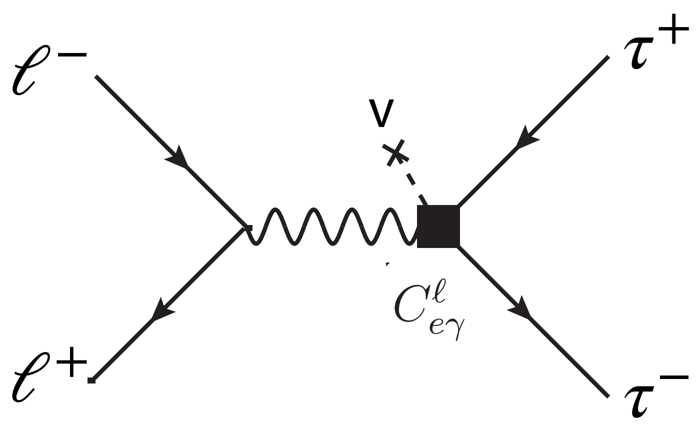


10% resolution on invariant mass

Tau g-2 from high-energy probes

Further possibilities to measure Δa_τ precisely from high-energy probes

- ✦ Pair production



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

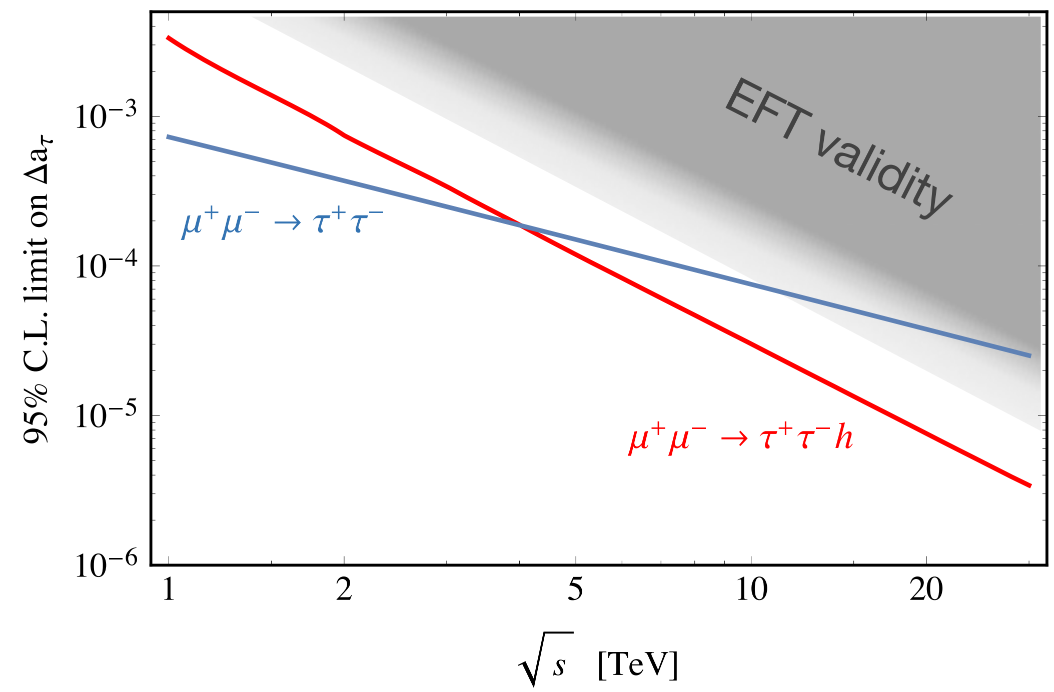
$$\sigma_{NP} = \frac{4\pi\alpha^2}{3}\frac{|C^\ell_{e\gamma}|^2 v^2}{\Lambda^4} \sim \frac{\pi\alpha^2 \Delta a_\ell^2}{6m_\ell^2}$$

Limit on g-2: $\Delta a_\ell \lesssim \frac{\text{const.}}{\sqrt{\mathscr{L}}} \sim E^{-1}$

- equivalently, $\Lambda \sim \sqrt{E}$

EFT description breaks down above few TeV!

Could probe Δa_τ ~ few 10^{-5}



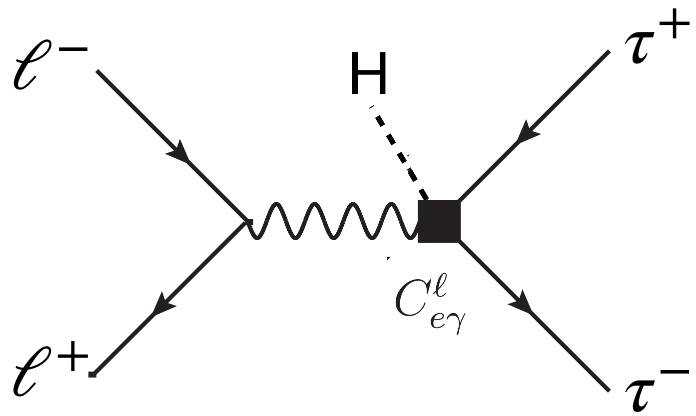
w/ Levati, Maltoni, Paradisi, Wang

Tau g-2 from high-energy probes

Further possibilities to measure Δa_τ precisely from high-energy probes

- $H\tau\tau$ associated production

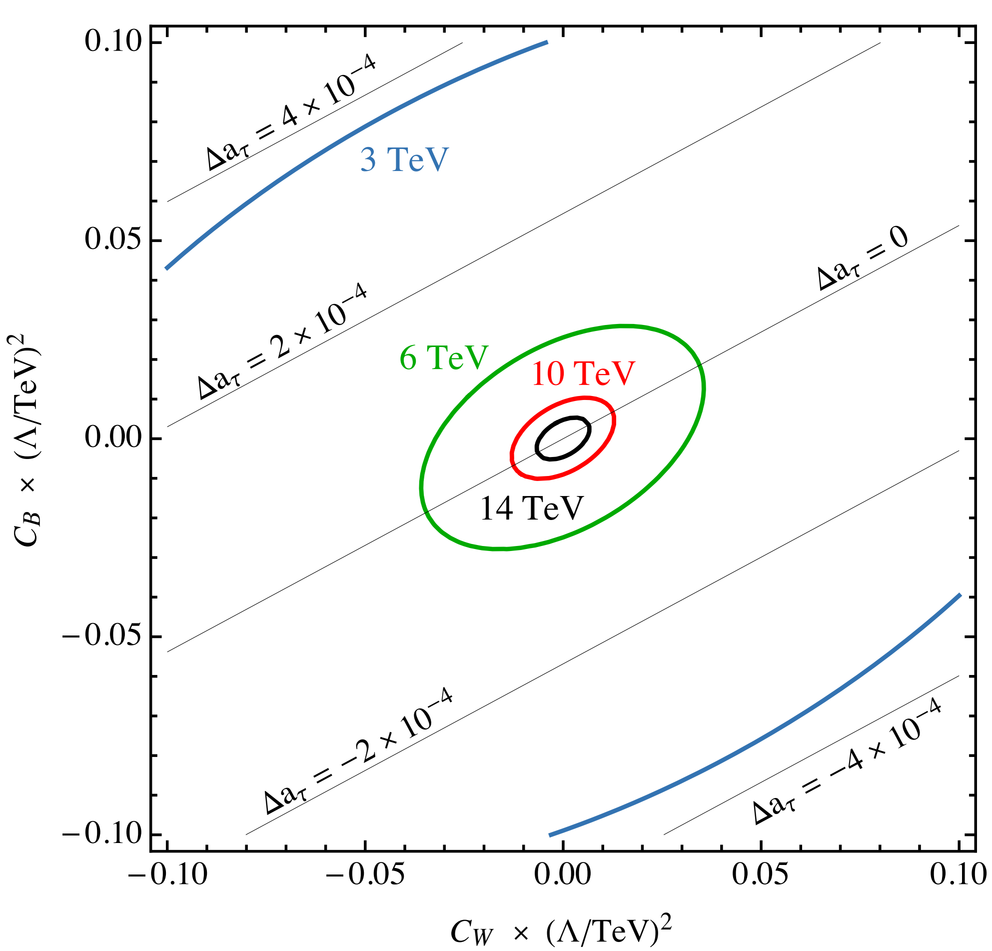
DB, Levati, Paradisi, Maltoni, Wang
to appear…

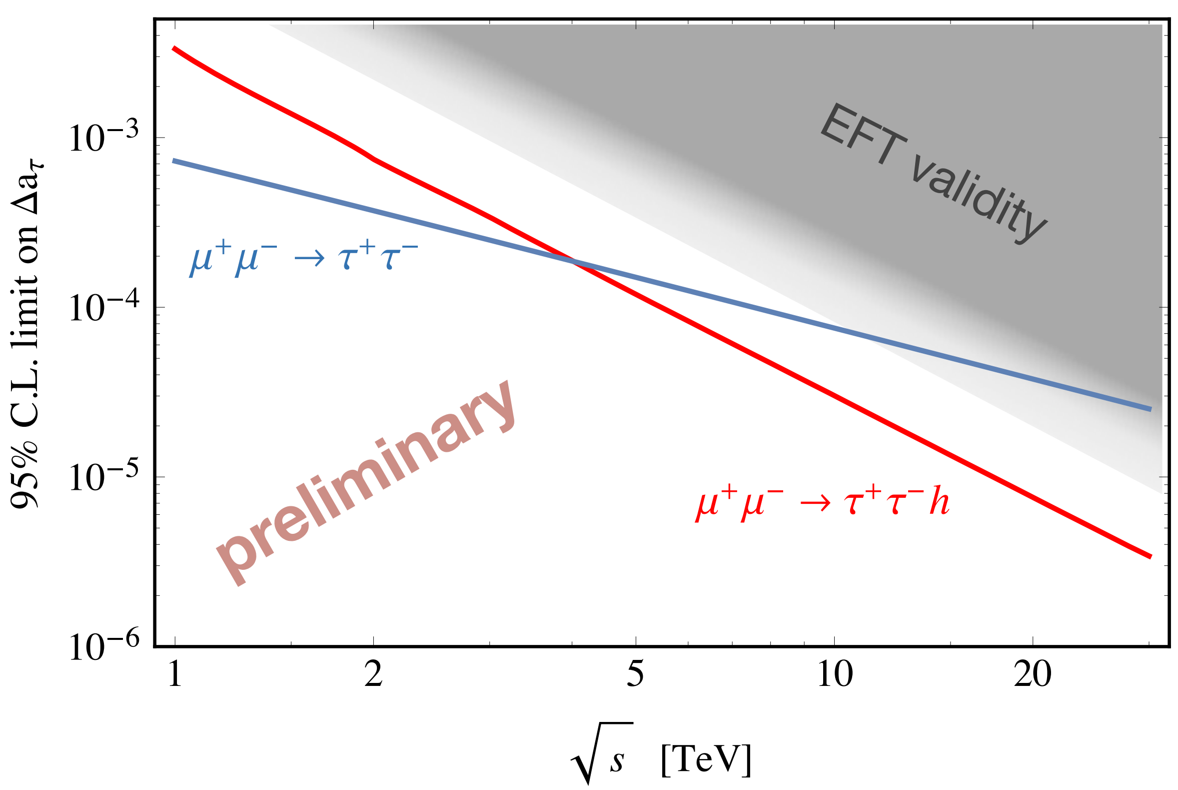


- Main background from μμ → Zγ

(where Z is mistaken for H)

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





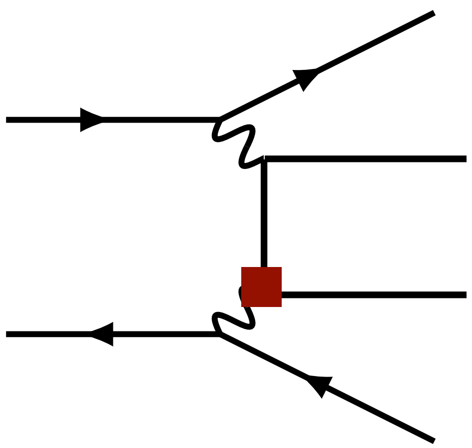
also a bound on tau EDM!

Tau g-2 from high-intensity probes

A high-energy lepton collider has a huge VBF rate!

- ✦ Δa_τ from vector boson scatterings $\ell^+\ell^- \to \ell^+\ell^-\tau^+\tau^-, \nu\bar{\nu}\tau^+\tau^-$

(same as LEP bound)



$$\sim \left(\frac{C_{e\gamma}}{\Lambda^2}\right)^2 + \mathcal{O}\left(m_\tau^2/\Lambda^2\right)$$

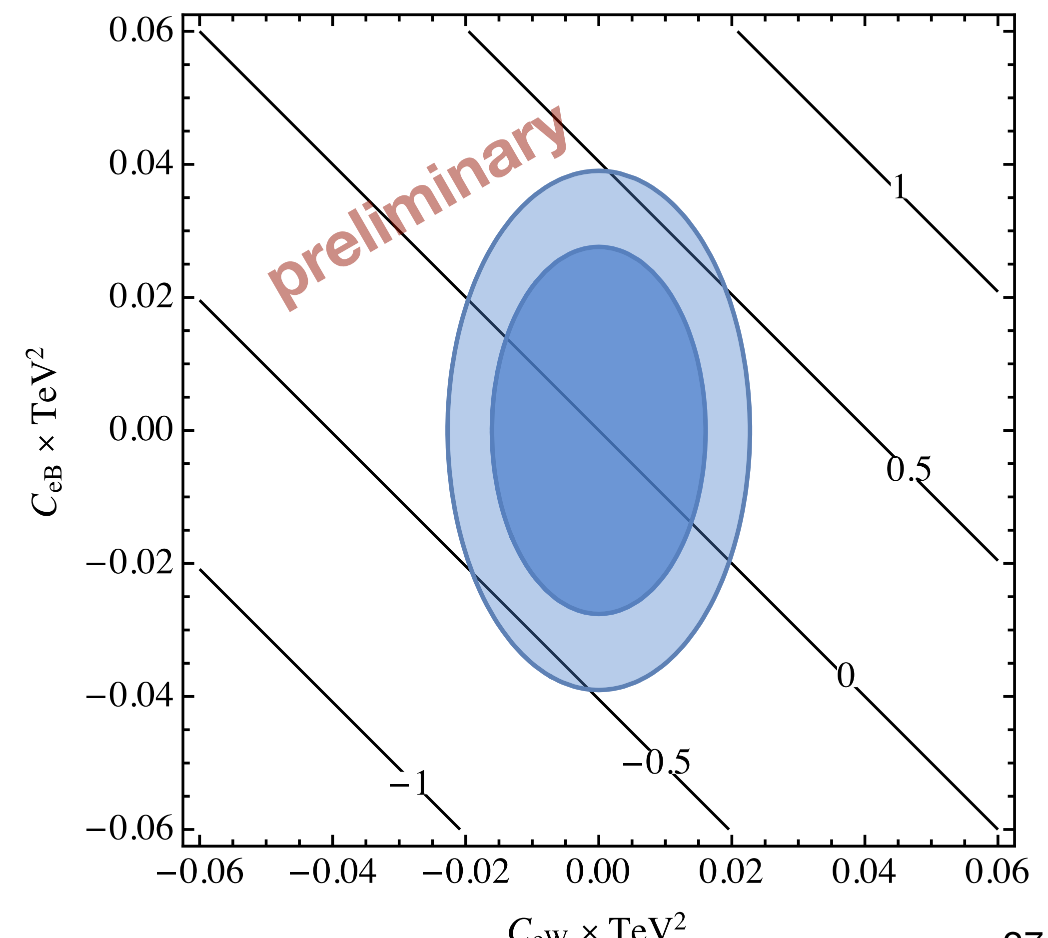
- Caveat: VBF is a “soft” process,
  EFT mainly affects high-mass region

Still, could probe Δa_τ ~ few 10^{-5}

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

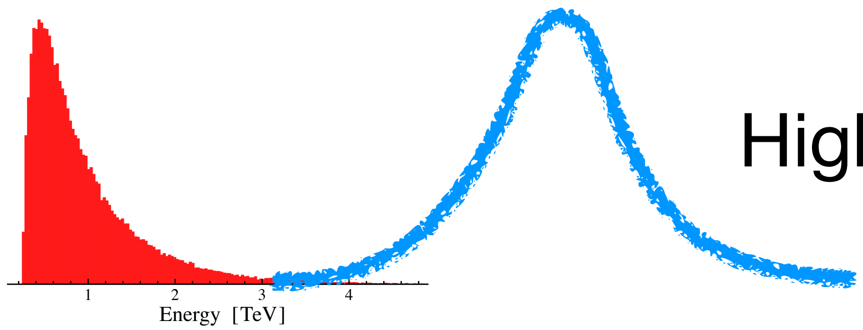
work in progress with Levati, Paradisi, Maltoni, Wang

$\Delta a_\tau \times 10^4$ from $\ell^+\ell^- \to \tau^+\tau^-\nu\bar{\nu}$

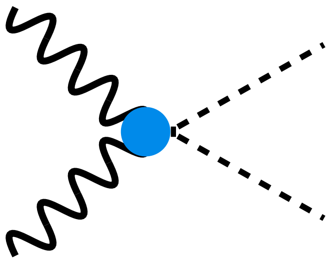


Summary

- High energy muon collider offers two paths to precision measurements



High energy



High rate (VBF)

- New ways to test flavor @ μCollider:

gain from high energy probes

access to second generation processes

- Bounds on lepton- and quark-flavor violating interactions can surpass low-energy precision measurements!

- Can exploit rare Higgs decays + Higgs production @ high energy to access 3rd generation physics (tau)
- Can improve lepton g-2 and EDM bound by orders of magnitude

Backup

Radiation & high-energy neutrinos

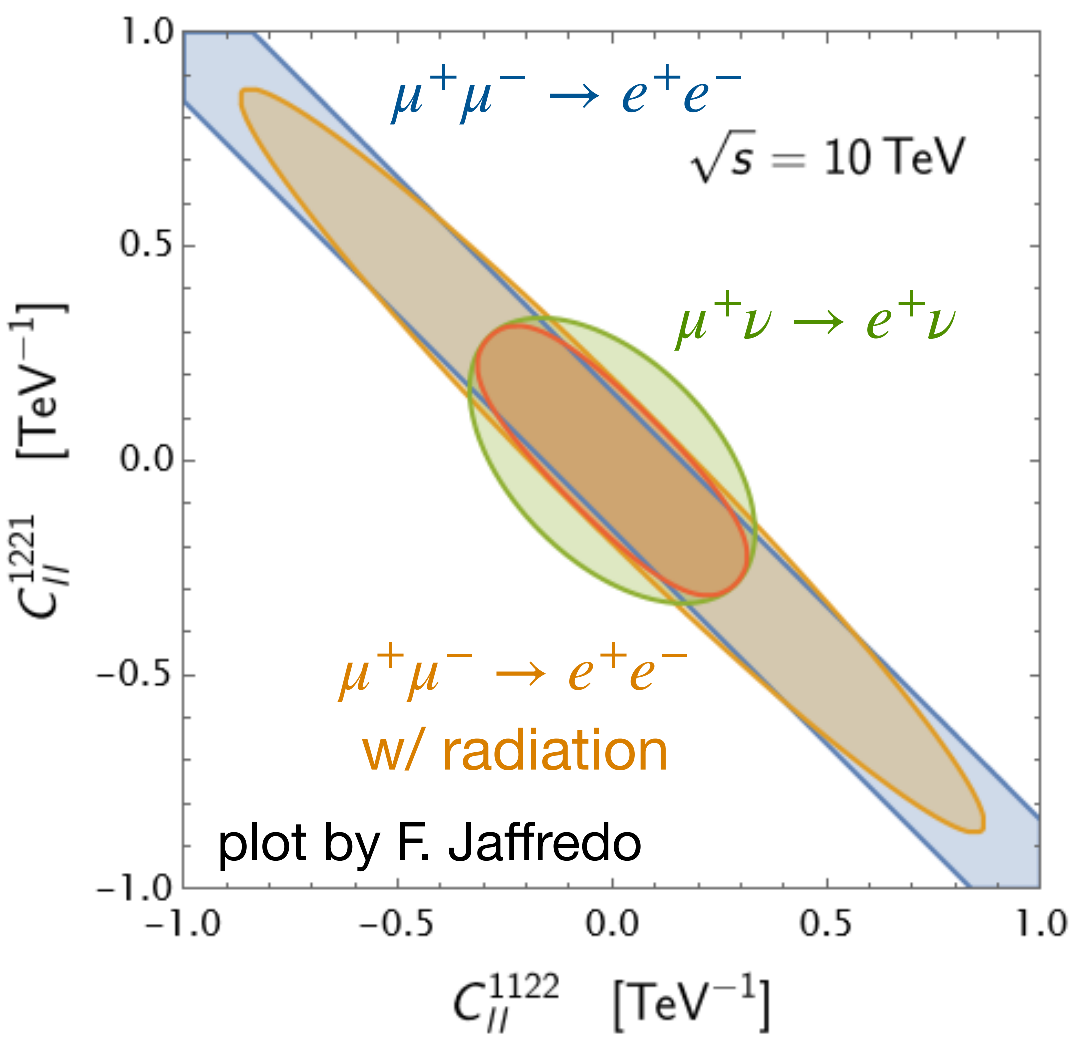
✦ Radiation effects are important.

☛ talks by David, Andrea, Davide

✦ Hard neutrinos from $\mu^\pm \to W^\pm \nu$ have a large PDF

$\Longrightarrow$ can access neutrino initial state at high energy!

see also Chen, Glioti, Rattazzi, Ricci, Wulzer 2202.10509



✦ Directly probe neutrino interactions at high energy: usual E^2 gain

- ✦ can put strong constraints on BSM neutrino physics

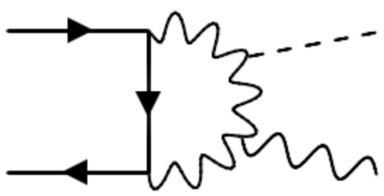
  ☛ previous talk by Zahra

- ✦ complementary to $\mu^+\mu^-$ scattering, can remove flat directions and probe operators with different flavor structure

Muon g-2 @ muon collider

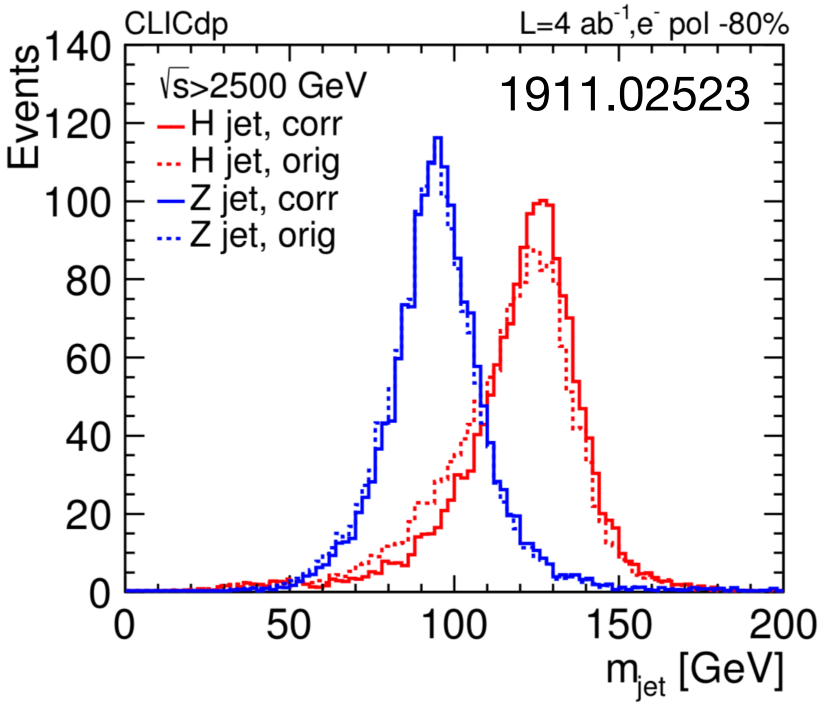
- SM irreducible background is small: $\sigma^{(SM)}_{\mu^+\mu^-\to h\gamma} \approx 10^{-2}\,\text{ab}\left(\frac{30\,\text{TeV}}{\sqrt{s}}\right)^2$

  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)



Search in h → bb channel:

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

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

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

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

Beyond tree-level

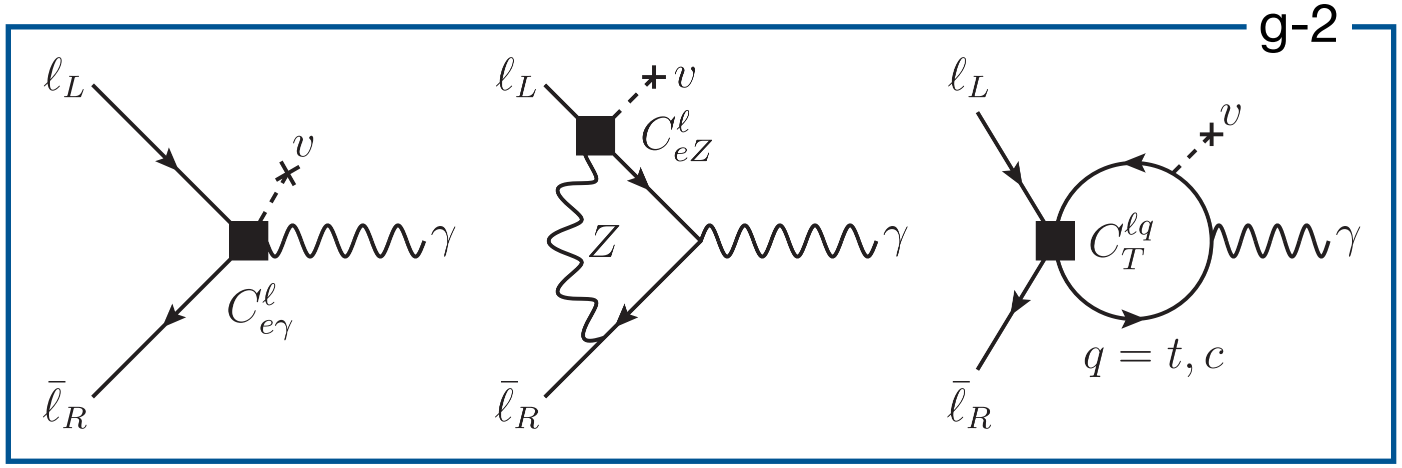
- Other operators contribute to g-2 at one loop:

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

(+ other effects suppressed by y_μ)

$$|H|^2 W^a_{\mu\nu} W^{\mu\nu,a} \qquad |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}$$



Including 1-loop running:

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

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

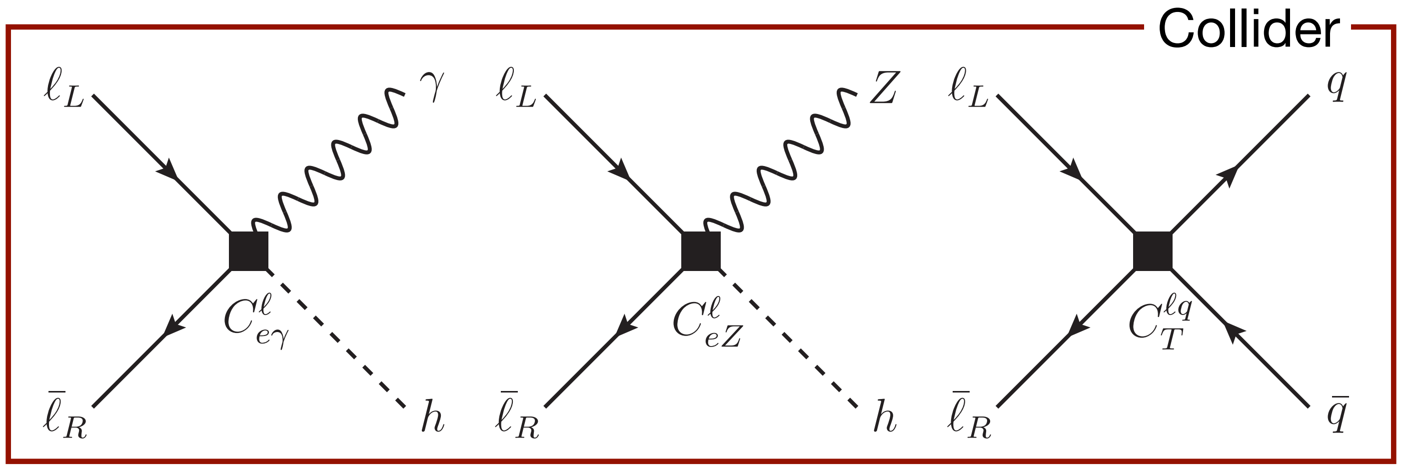
B, Paradisi 2012.02769

Full set of operators can be probed at high energy

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

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

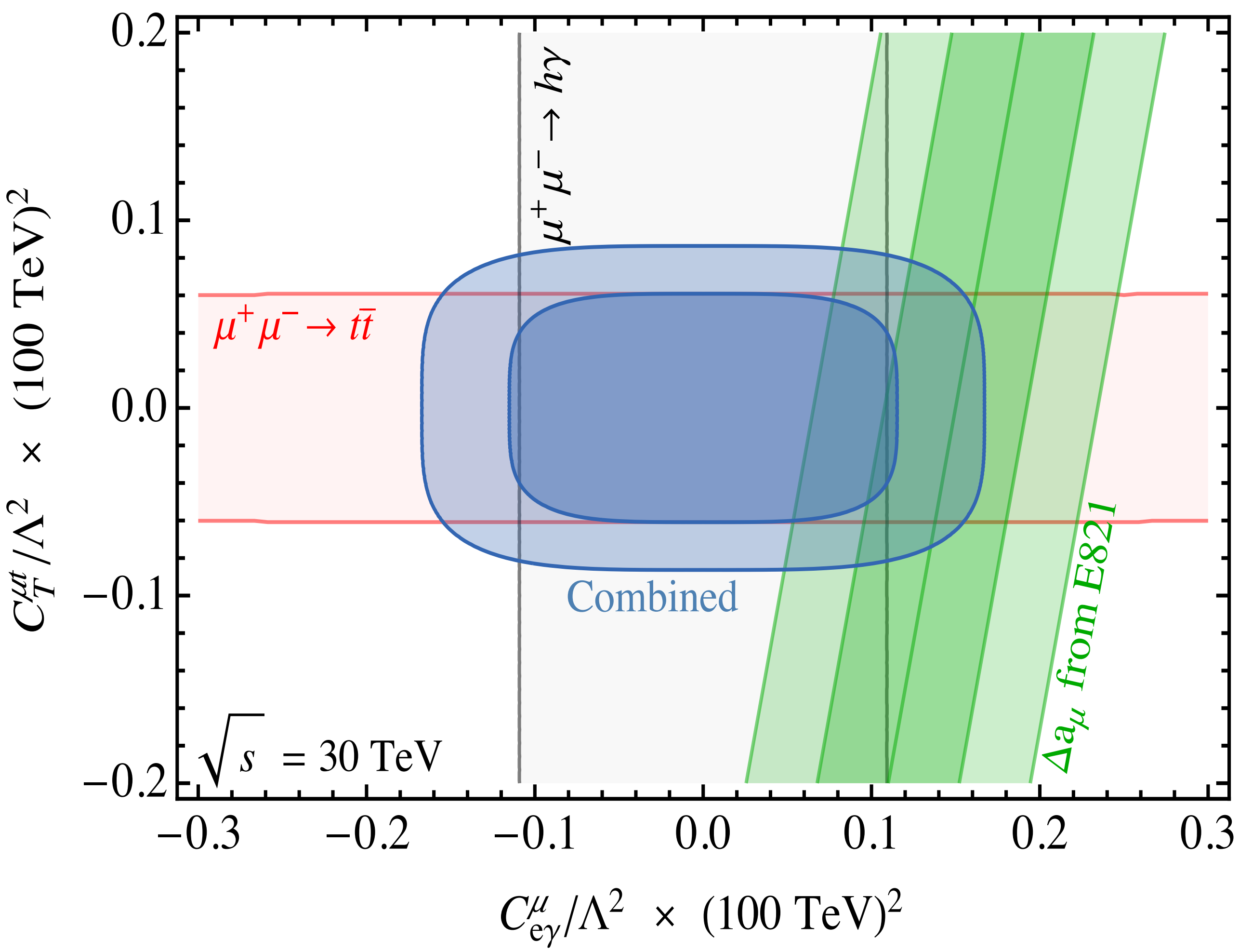
$\mu^+\mu^- \to q\bar{q}$



Muon g-2 @ muon collider

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

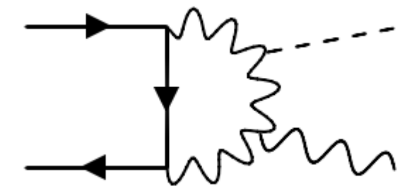
- Full set of operators with $\Lambda \gtrsim 100$ TeV can be probed at a high energy muon collider



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

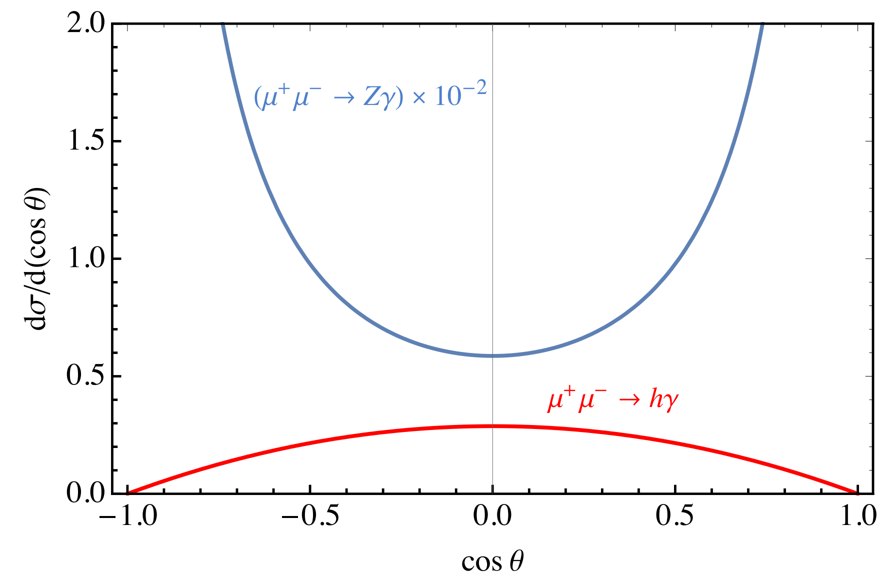


- Main background from $\mu\mu \to Z\gamma$ (where Z is mistaken for H)

  (large due to transverse Z polarizations)

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

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



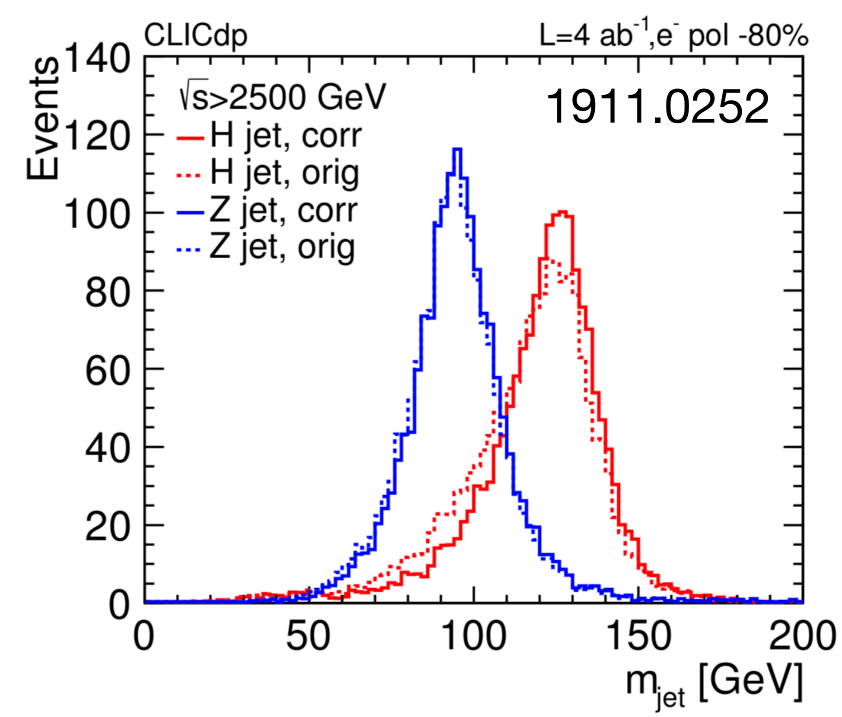
Search in h → bb channel:

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

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%

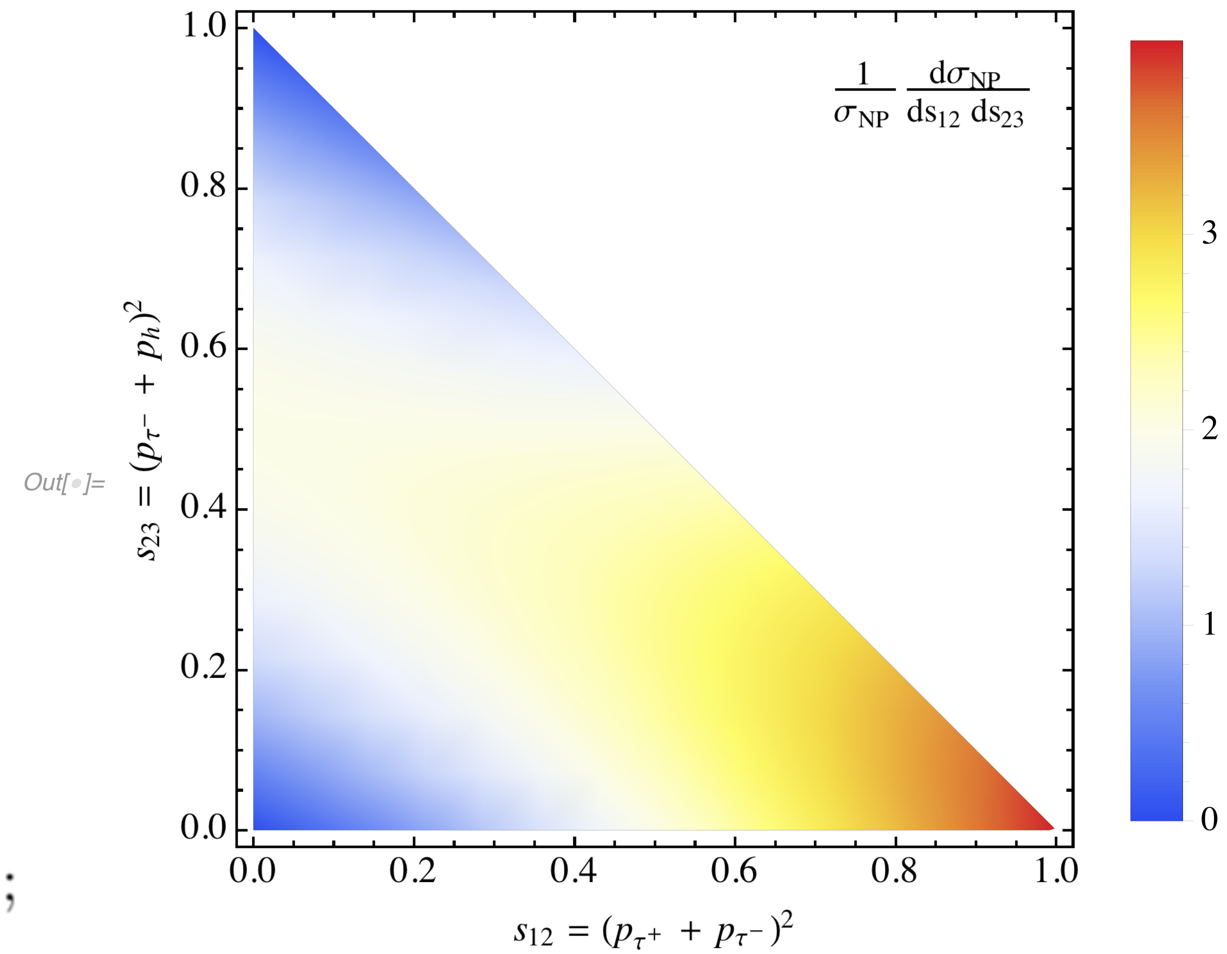


H$\tau\tau$ signal

New physics: $$\frac{d\sigma_{NP}}{dx_1 dx_2} = \frac{1}{192\pi^3}\frac{Q^2}{\Lambda^4}\left[(Q_\mu e\,\mathcal{C}_\gamma)^2 + \left(\frac{g\,\mathcal{C}_Z}{4c_w}\right)^2\right](2x_1x_2 - x_1 - x_2 + 1)$$

Interference:

$$\frac{d\sigma_{N\gamma}}{dx_1 dx_2} = -\frac{\sqrt{2}}{96\pi^3}\frac{m_\tau}{v}\frac{e^3}{\Lambda^2}Q_\mu\,\mathcal{C}_\gamma;$$



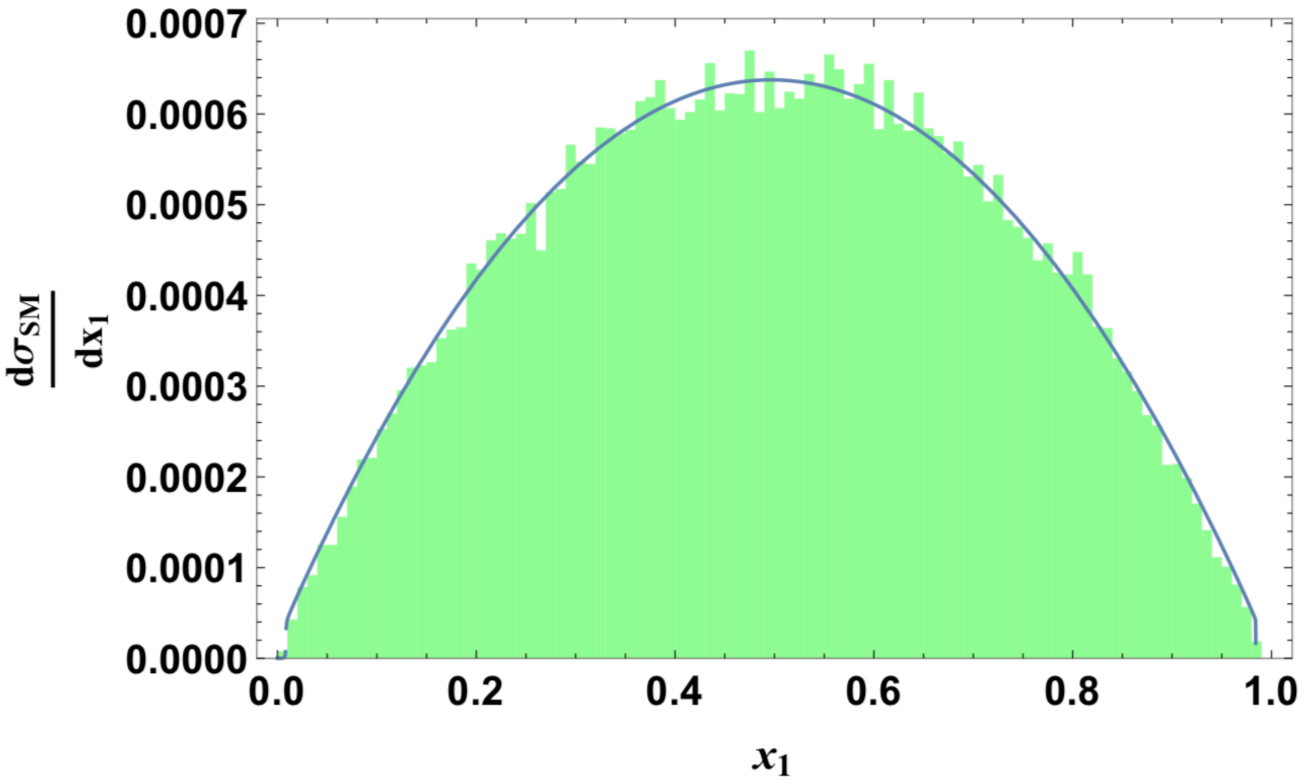
Standard Model:

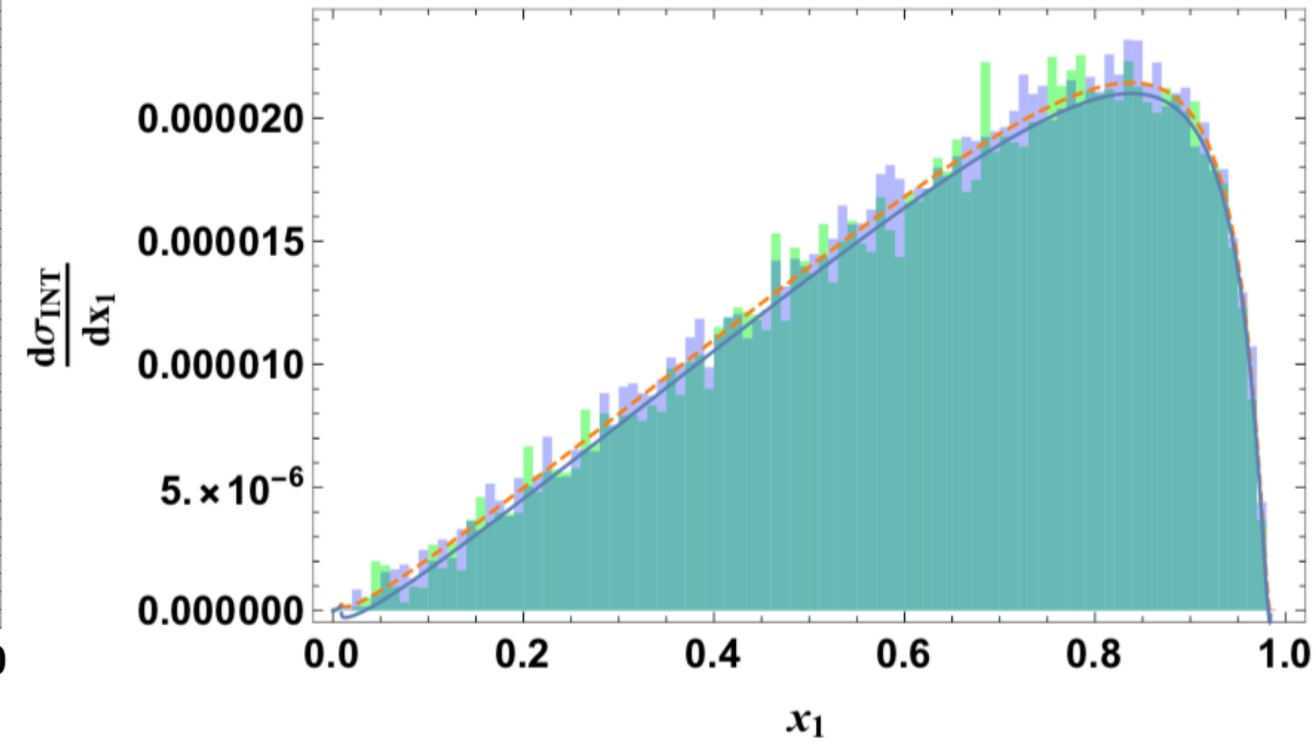
$$\frac{d\sigma_\gamma}{dx_1 dx_2} = \frac{1}{192\pi^3}\frac{m_\tau^2 e^4}{v^2}\frac{1}{Q^2}\left[\frac{1-x_1}{1-x_2} + 2 + \frac{1-x_2}{1-x_1}\right];$$

$$\frac{d\sigma_2}{dx_1 dx_2} = \frac{1}{3\cdot 2^{14}\pi^3}\frac{m_\tau^2 g^4}{v^2 c_w^4}\frac{1}{Q^2}\left[\frac{1-x_1}{1-x_2} - 2 + \frac{1-x_2}{1-x_1}\right];$$

$$\frac{d\sigma_3}{dx_1 dx_2} = \frac{1}{6\cdot 2^{16}\pi^3}\frac{g^8}{c_w^8}\frac{v^2}{Q^4}\left[\frac{x_1x_2 + x_1 + x_2 - 1}{(x_1 + x_2 - 1)^2}\right];$$

H$\tau\tau$ signal





(c)