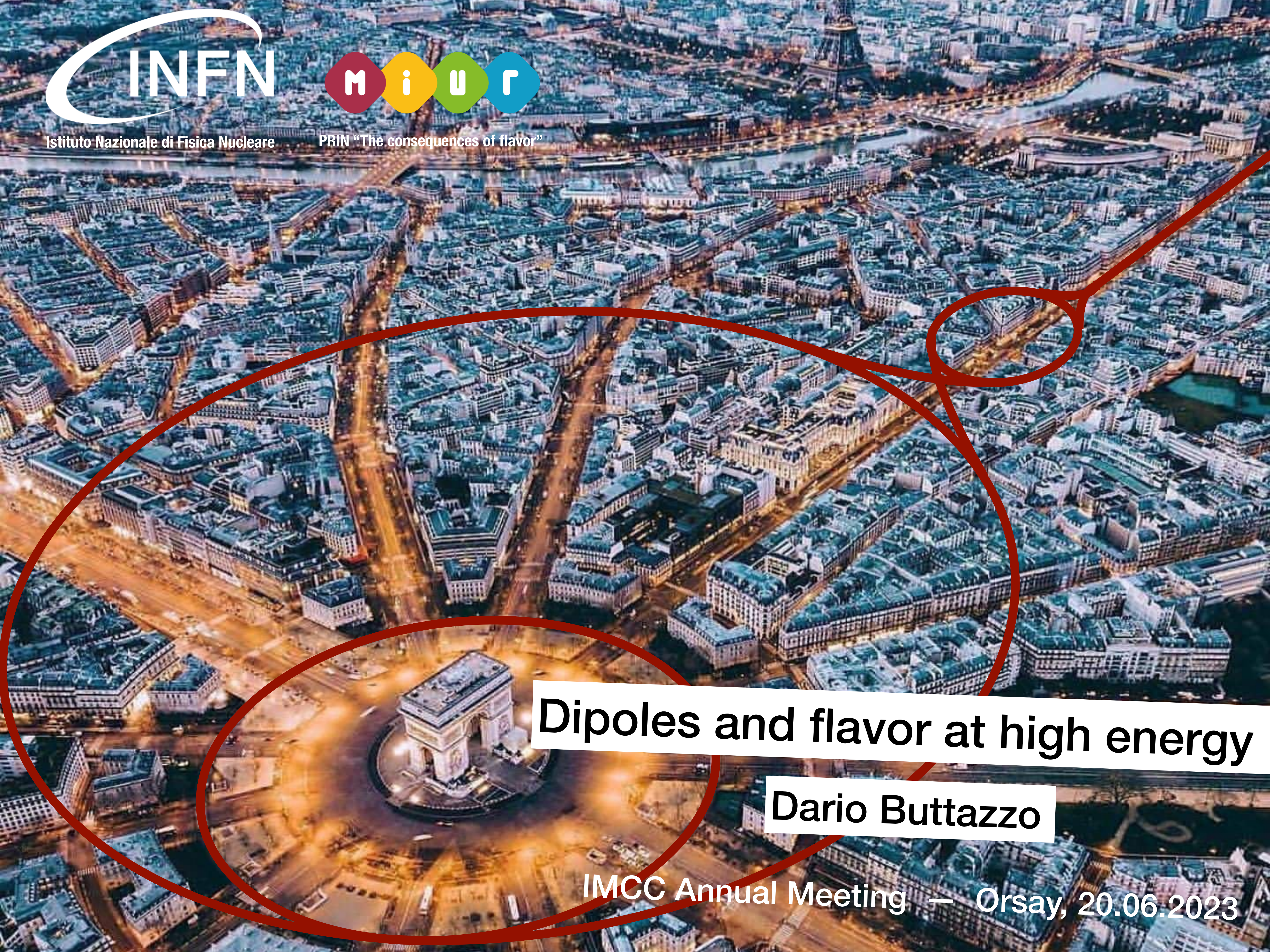


Istituto Nazionale di Fisica Nucleare
PRIN "The consequences of flavor"

Dipoles and flavor at high energy

Dario Buttazzo

IMCC Annual Meeting — Orsay, 20.06.2023

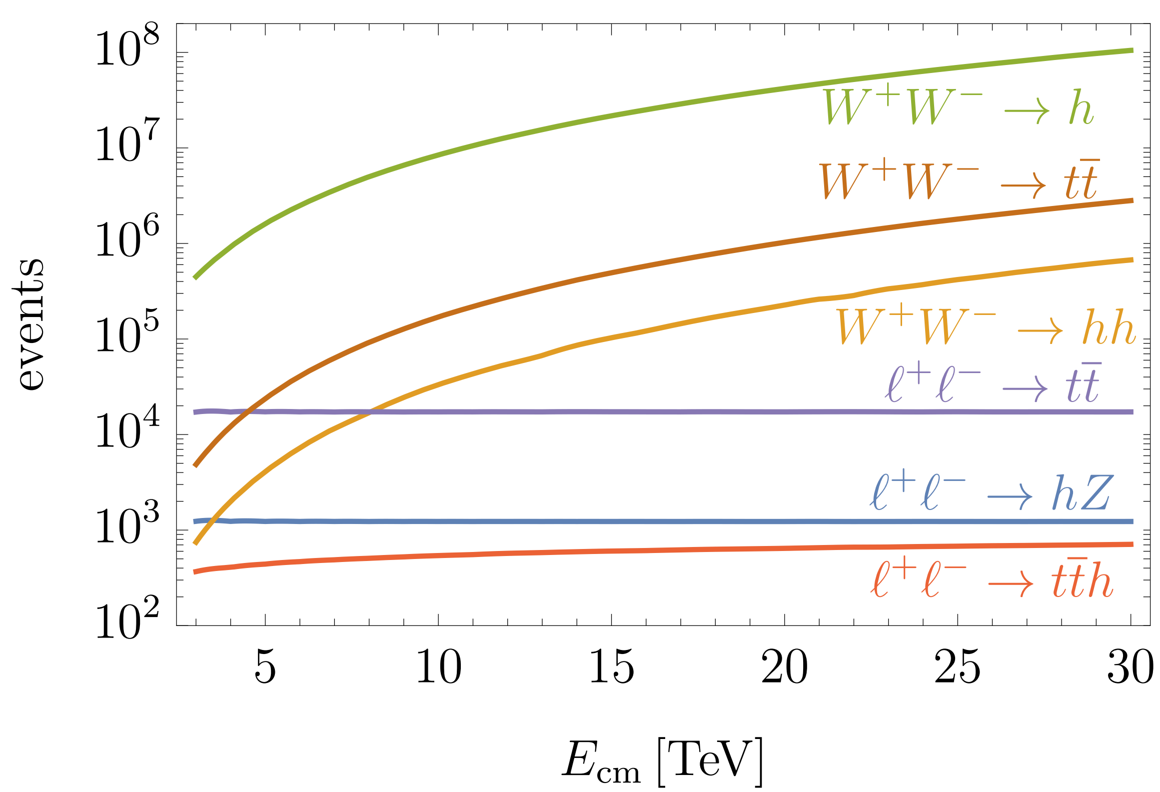
Flavor and precision

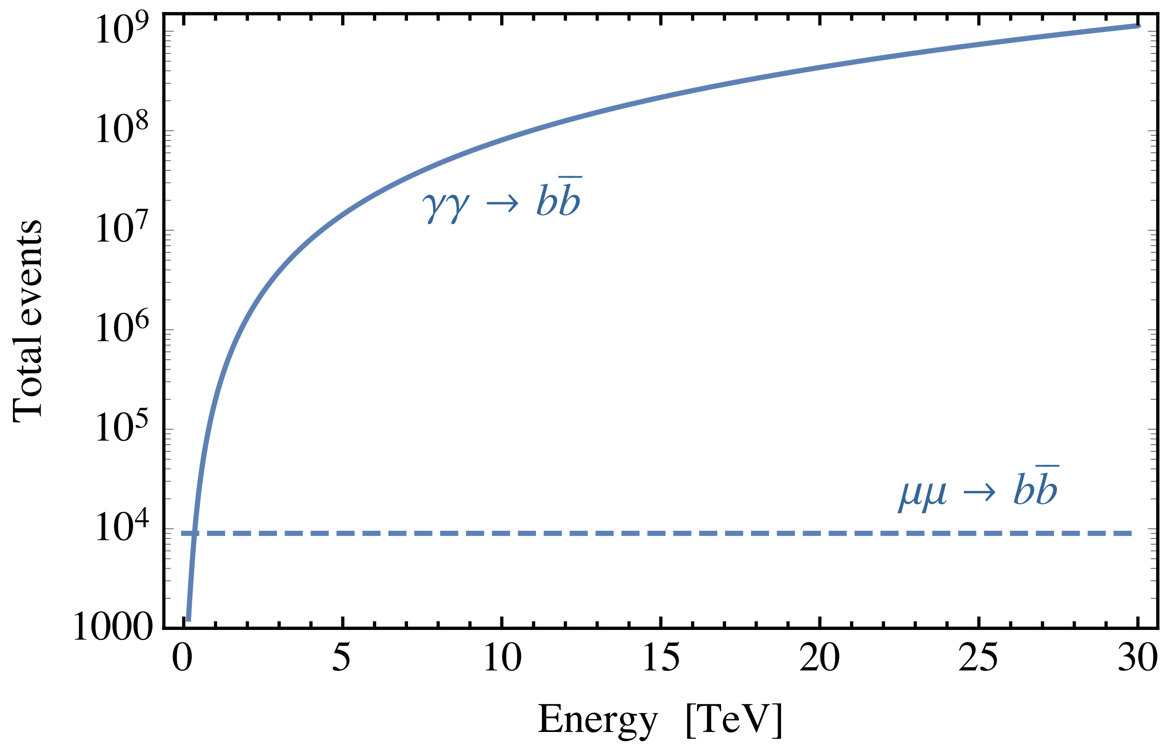
- Flavor processes: rare decays & tiny effects

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

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

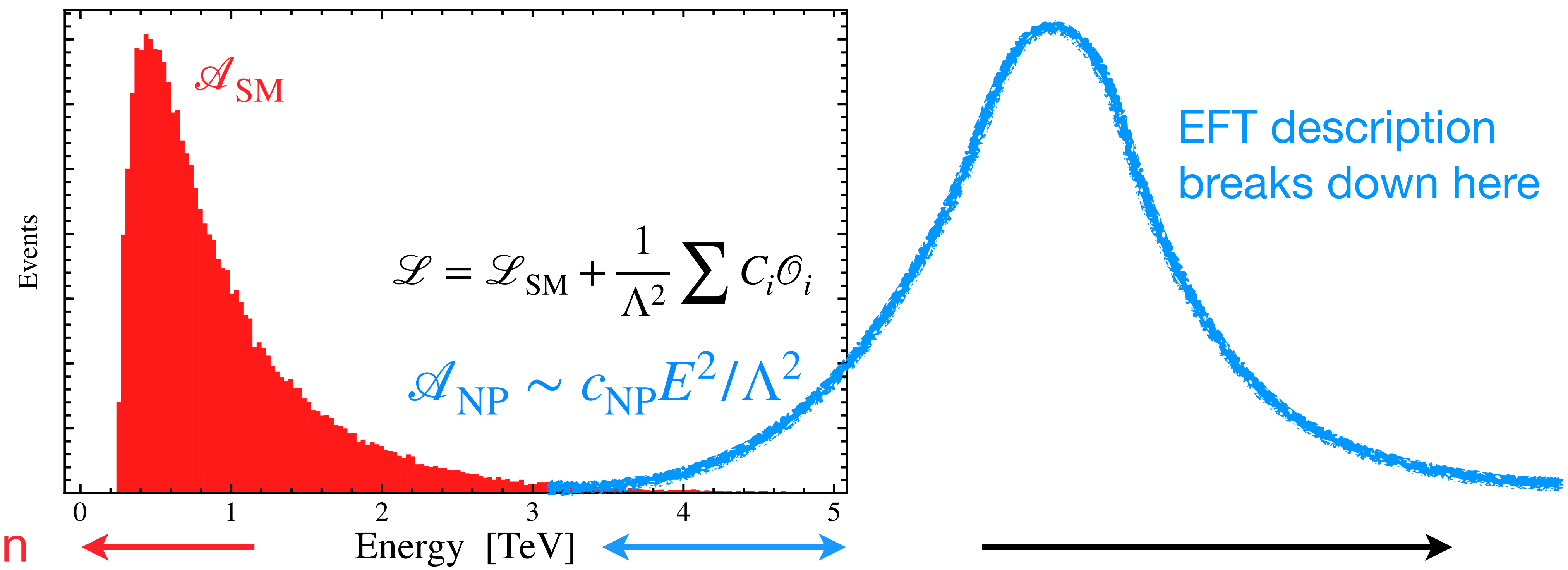
- Muon-collider: very large number of (clean) EW particles, but overall event rate not comparable to flavor factories





High-energy probes

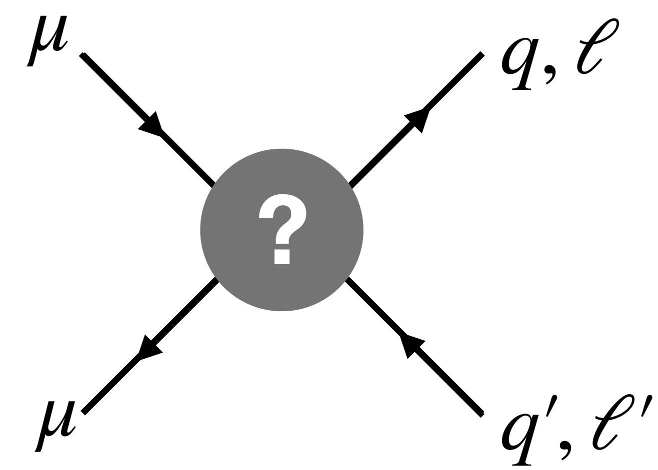
- New Physics effects are more important at high energies
  - ☛ NP is heavy compared to the flavor scale: EFT description



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

- As simple as this: $$\frac{\Delta\sigma(E)}{\sigma_{\rm SM}(E)} \propto \frac{E^2}{\Lambda^2_{\rm BSM}} \approx \begin{cases} 10^{-9}, & E \sim 1\,\text{GeV} \\ 10^{-5}, & E \sim 100\,\text{GeV} \\ 10\,\%\,, & E \sim 10\,\text{TeV} \end{cases}$$
  - taken to the extreme at a μ-collider with 10's of TeV
  - even more powerful for flavor processes: gain can be as large as $(E/m_\mu)^2$

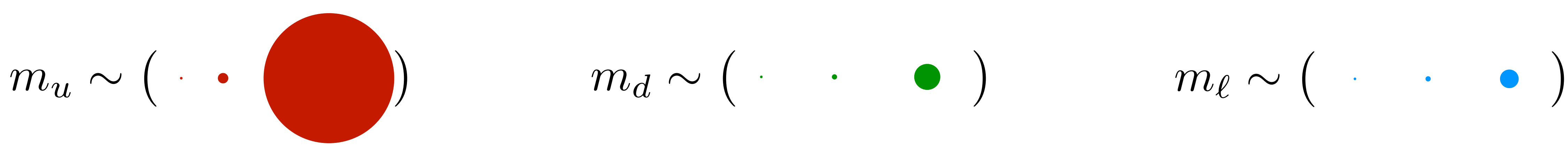
Flavor: muons vs. electrons



Collisions between 2nd generation particles

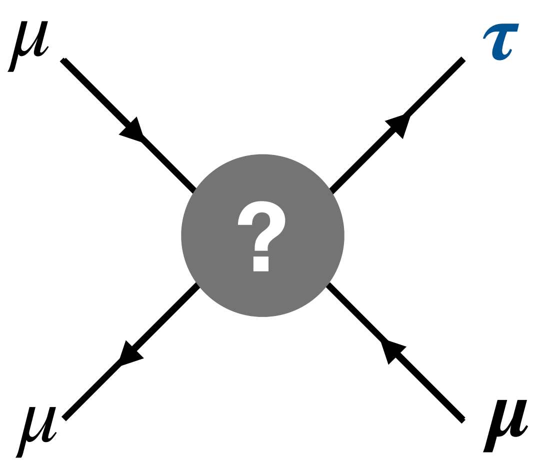
➡ muon collider can have access to flavor processes than cannot be efficiently probed elsewhere

- ✦ EW interactions are flavor-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 flavor universality maximally!



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

Lepton flavor violation

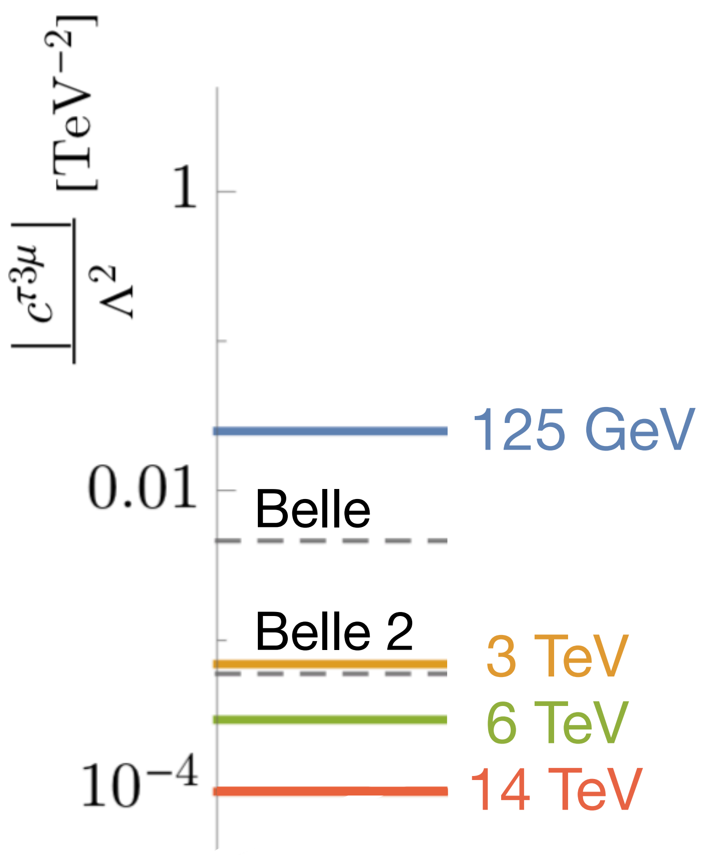


Four-fermion interactions: muon current coupled to flavor-violating bilinear

$$\frac{c_{\tau 3\mu}}{\Lambda^2}(\bar{\tau}_{L,R}\gamma^\rho \mu_{L,R})(\bar{\mu}_{L,R}\gamma_\rho \mu_{L,R})$$

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

  some of the strongest bounds on (generic) BSM interactions



- 3rd generation less severely constrained:

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

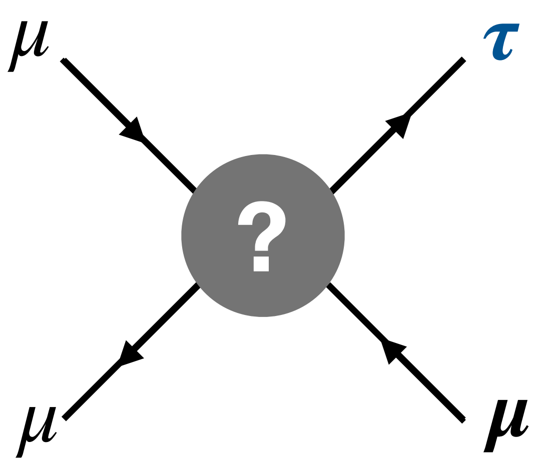
$$\text{BR}(\tau \to 3\mu) \sim \frac{m_W^4}{\Lambda^4} \qquad \sigma(\mu\bar{\mu} \to \tau\bar{\mu}) \sim \frac{E^2}{\Lambda^4}$$

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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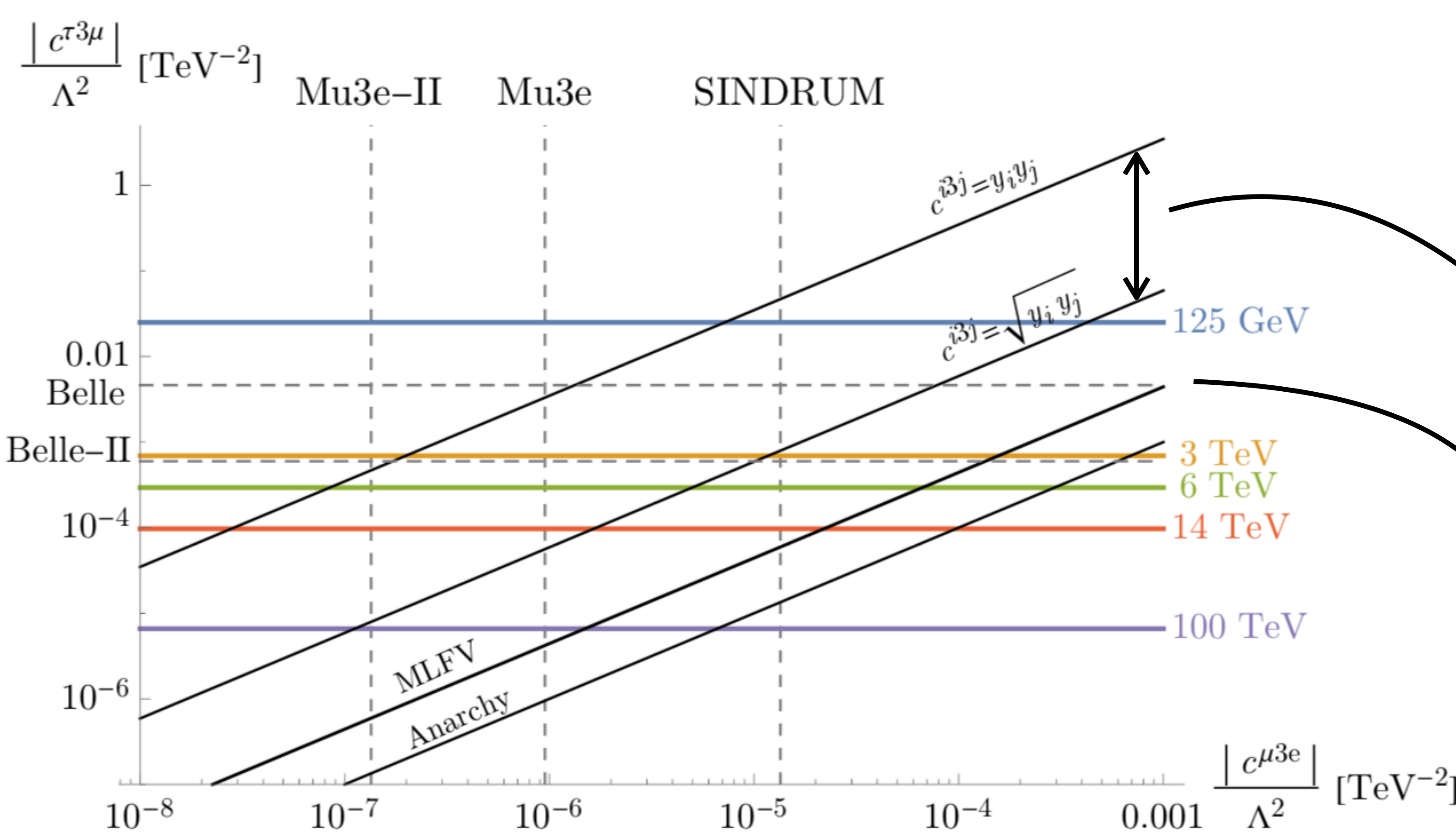


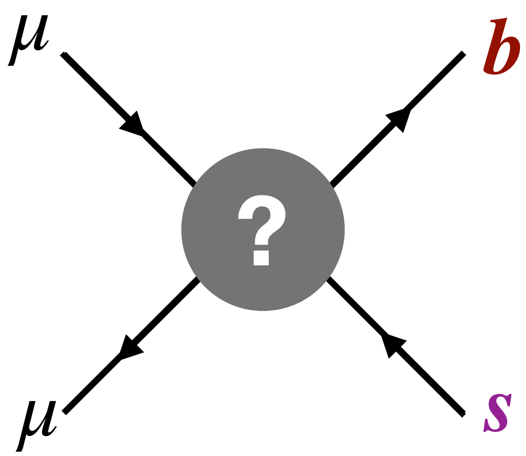
Correlation with $\mu \to 3e$: assumes flavor structure

~ 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

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

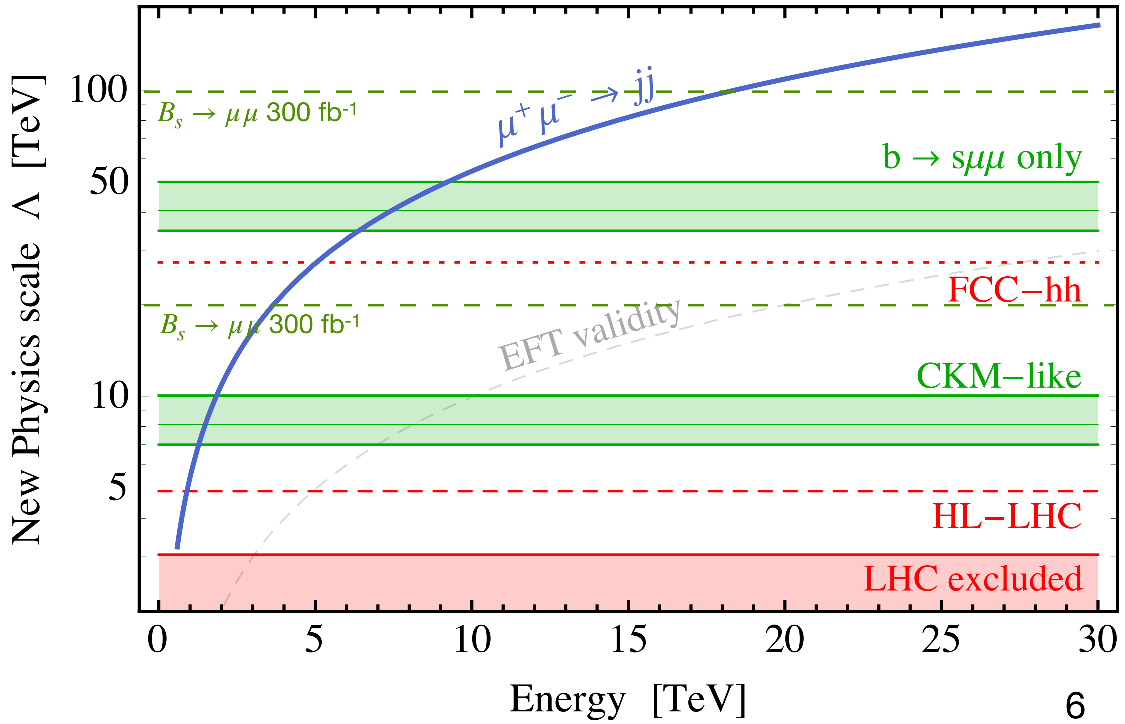
- Contributes to (semi-)leptonic rare B decays $b \to s\mu\mu$: branching ratios & angular observables of various hadronic processes

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

- Theory uncertainties: cannot improve indefinitely with rare decays

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

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



The muon g-2

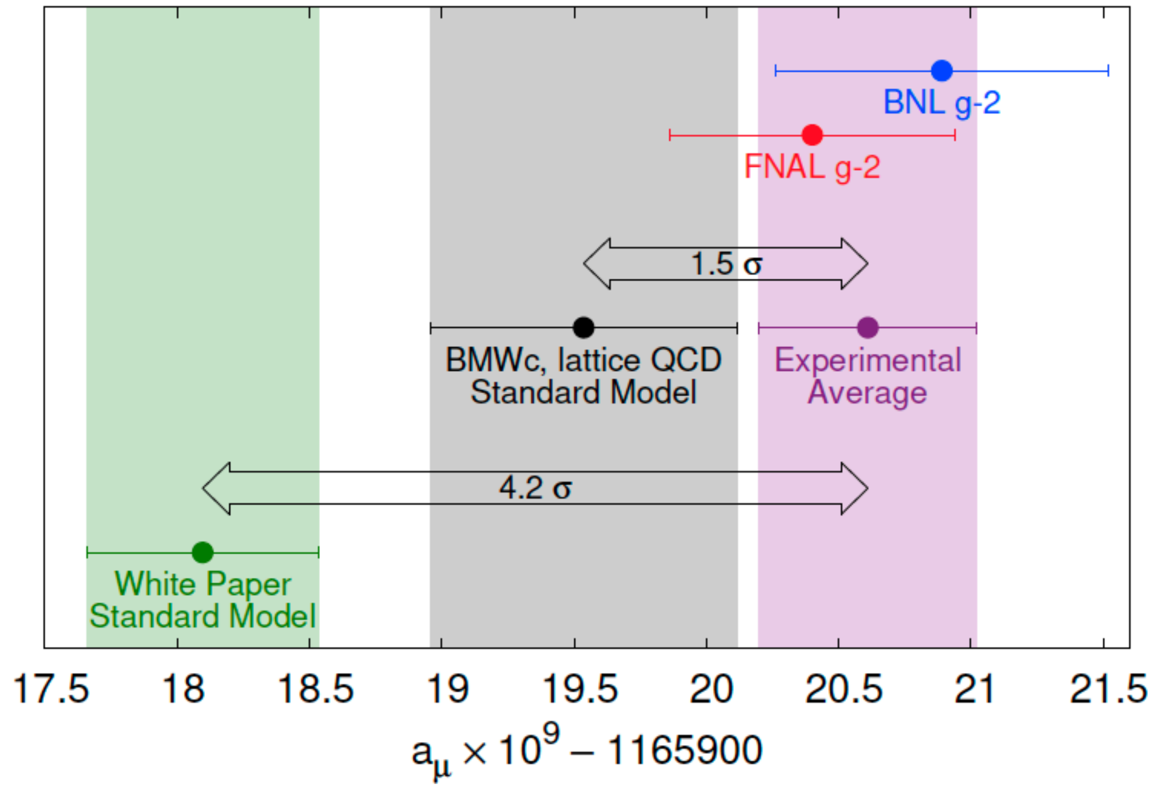
- Longstanding discrepancy between experimental results and SM prediction

- Also tension between lattice and dispersive computation of SM

  - If you trust lattice: 4σ tension in $e^+e^- \to$ hadrons cross-section

  - If you trust e^+e^-: 4σ tension in muon g-2

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



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

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

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

Muon g-2 @ muon collider

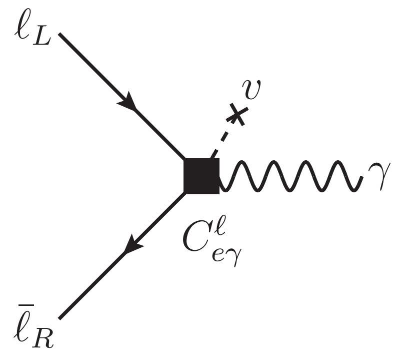
- If new physics is light enough (i.e. weakly coupled), a Muon Collider can directly produce the new particles ☛ direct searches: model-dependent

Capdevilla et al. 2006.16277

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

At low energy

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

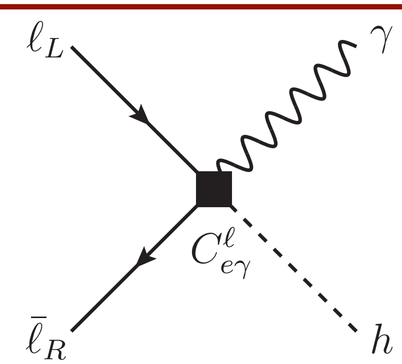


Dipole operator generates both Δa_μ and $\mu\mu \to h\gamma$

B, Paradisi 2012.02769

At high energy

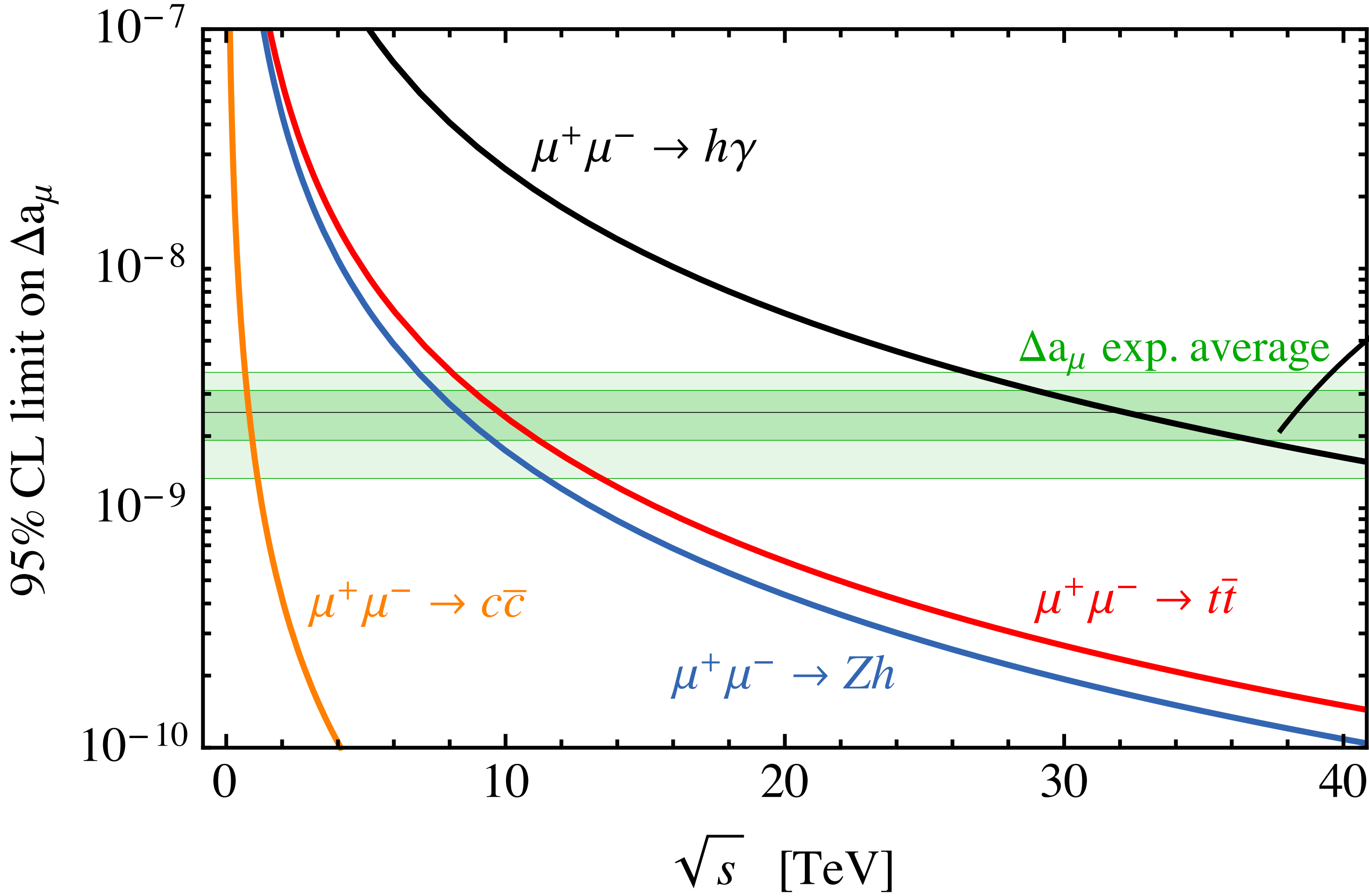
$$\sigma_{\mu^+\mu^- \to h\gamma} = \frac{s}{48\pi} \frac{|C_{e\gamma}|^2}{\Lambda^4} \approx 0.7\,\text{ab} \left(\frac{\sqrt{s}}{30\,\text{TeV}}\right)^2 \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2$$



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

need E > 10 TeV

Muon g-2 @ muon collider



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

(with reasonable assumptions on detector performance)

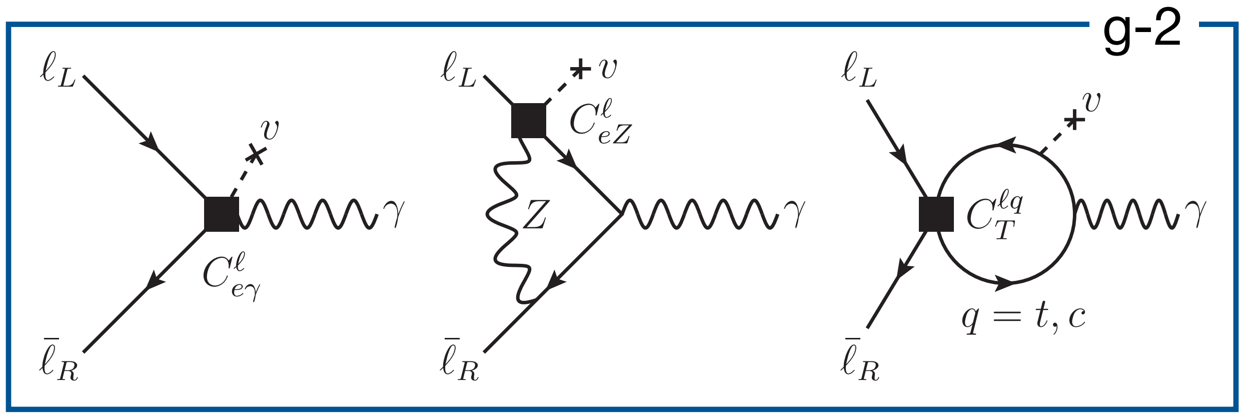
This result is completely model-independent!

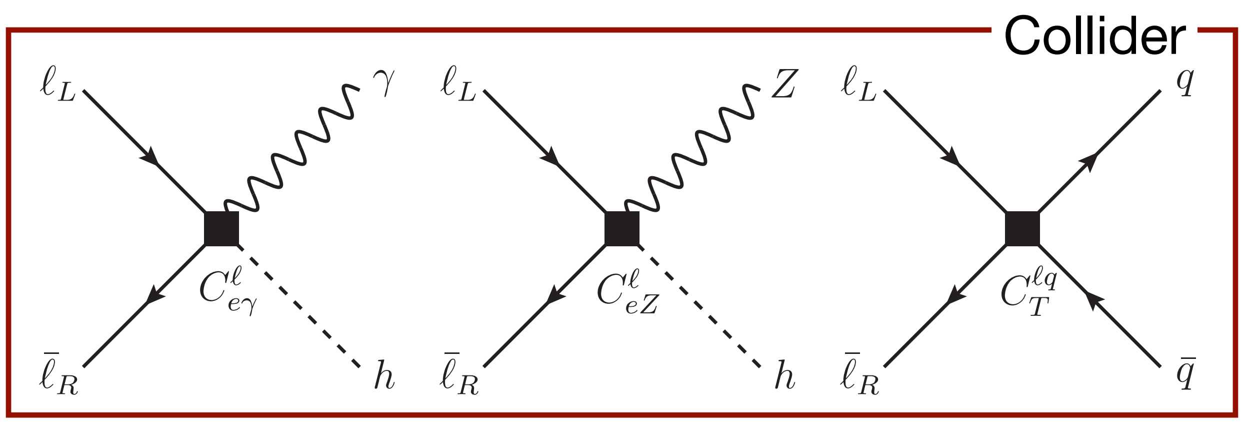
B, Paradisi 2012.02769

- Other operators enter g-2 at 1 loop:

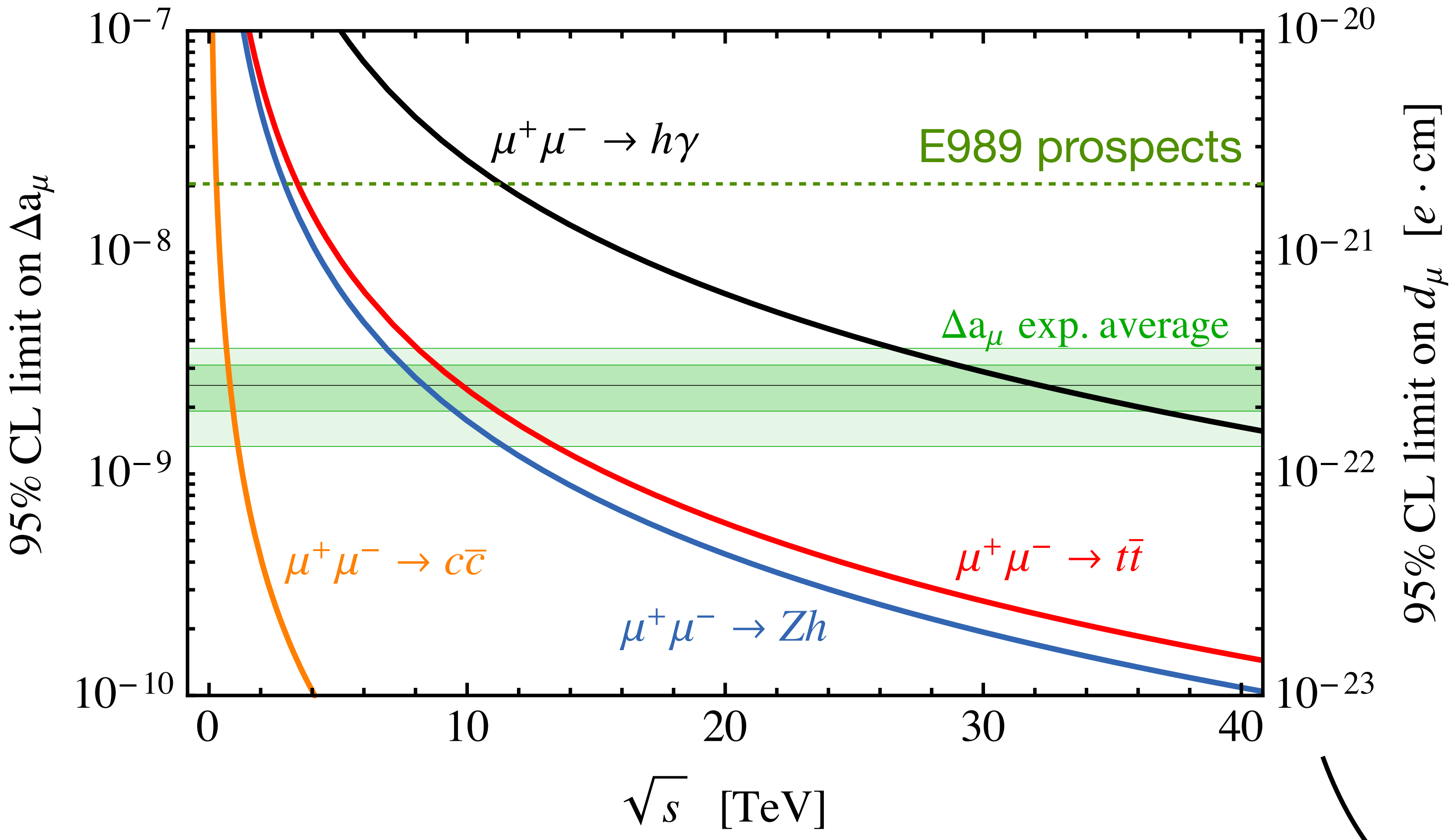
$$\Delta a_\mu \approx \left(\frac{250\,\mathrm{TeV}}{\Lambda^2}\right)^2 \left(C_{e\gamma} - \frac{C_{Tt}}{5} - \frac{C_{Tc}}{1000} - \frac{C_{eZ}}{20}\right)$$

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





Muon EDM @ muon collider



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B, Paradisi 2012.02769

Muon EDM for free!

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

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

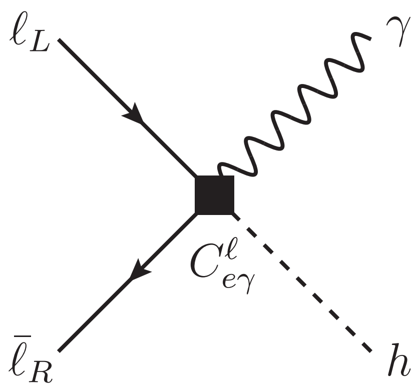
Collider constrains $|C_{e\gamma}|^2$

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

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

Lepton g-2 from rare Higgs decays

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

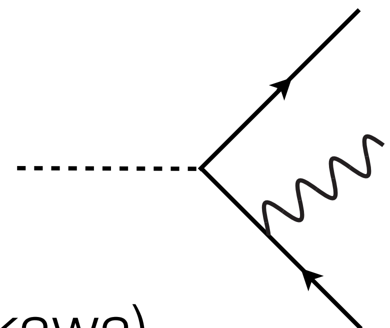


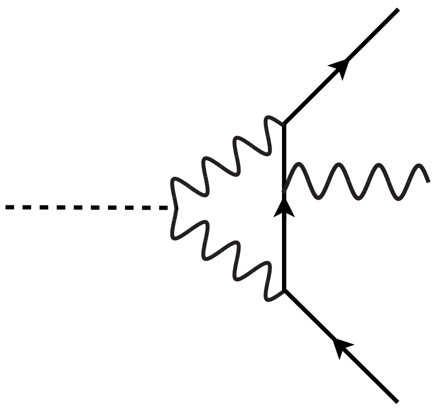
$$\Gamma^{(\mathrm{NP})}_{h\to\ell^+\ell^-\gamma} = \frac{\alpha\,|\,C_{e\gamma}|^2 m_h^5}{192\pi^2\Lambda^4}$$

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

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

(tree-level is suppressed by lepton Yukawa)





Han, Wang 1704.00790

- Muon g-2: rate is too small ☹️

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

(mainly one-loop)

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

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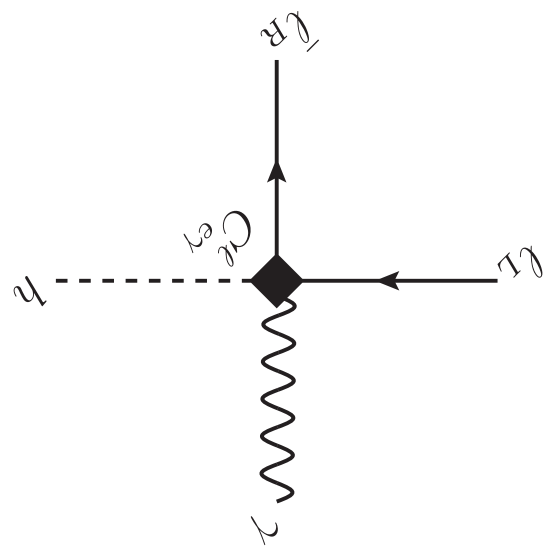

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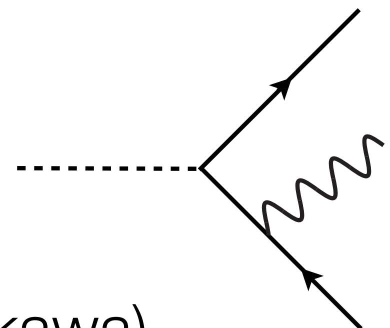

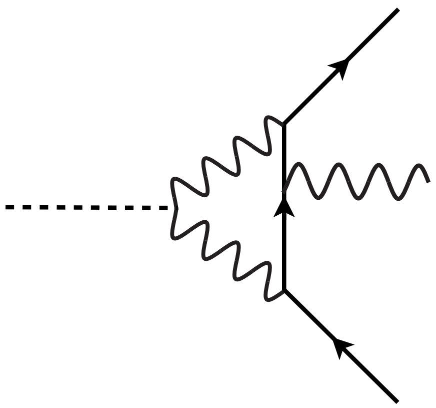

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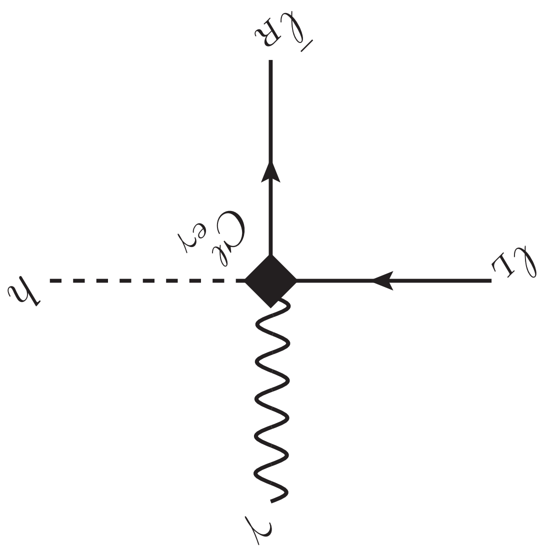

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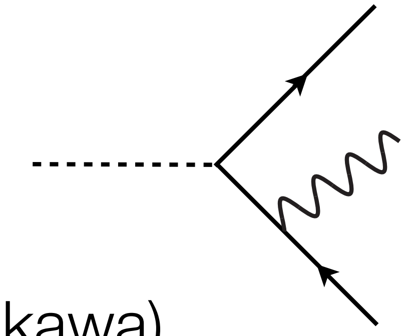

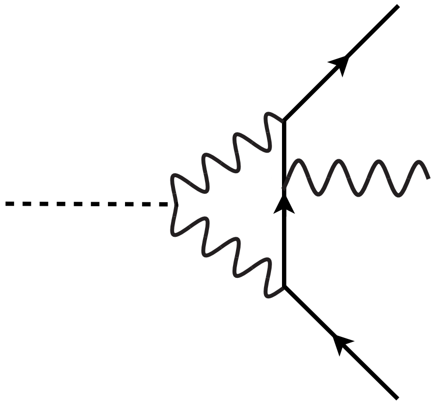

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☛ What about the tau?

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

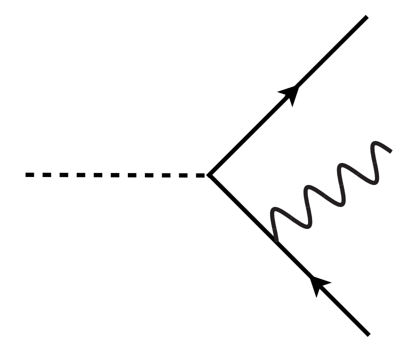
hep-ex/0406010

Can be improved to few 10-3 at HL-LHC 1908.05180

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

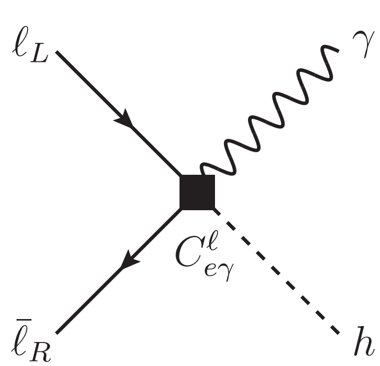
$$\mathrm{BR}^{(\mathrm{SM})}_{h\to\tau^+\tau^-\gamma} \approx 5\times 10^{-4}$$

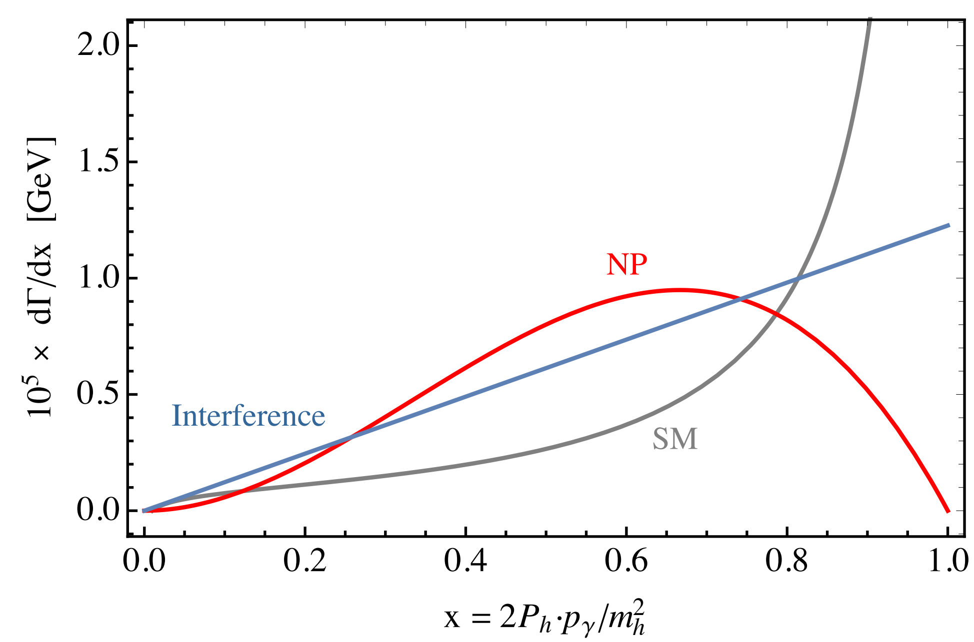
(with cut on soft collinear photon)



could be measured at few % level by Higgs factory

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





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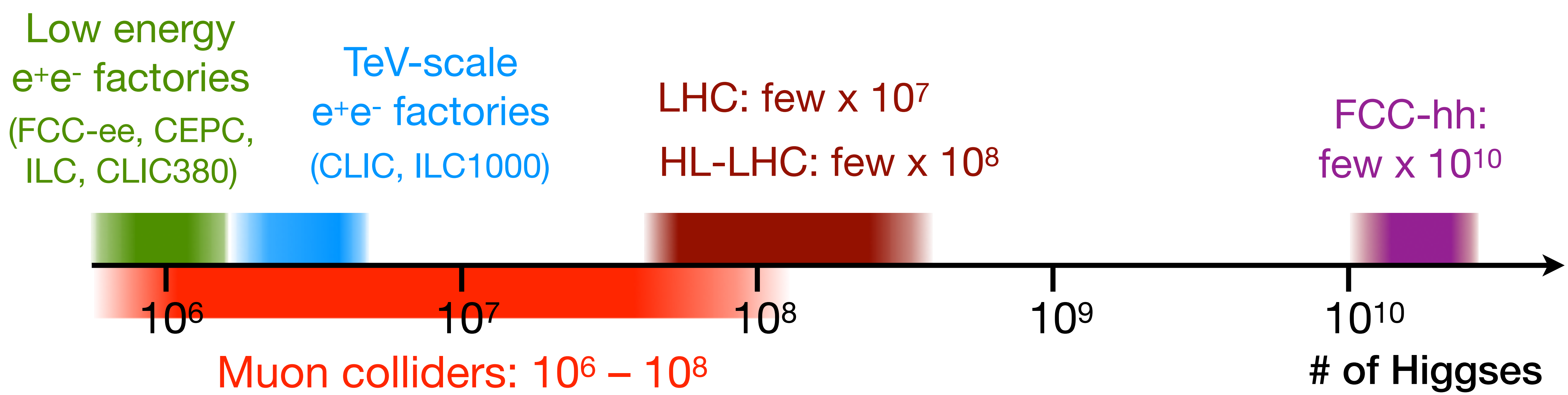
✦ **MuC:** 10^7 Higgs bosons @ 10 TeV $\Rightarrow$ 5k $H\to\tau\tau\gamma$ events, 2% precision on SM,

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



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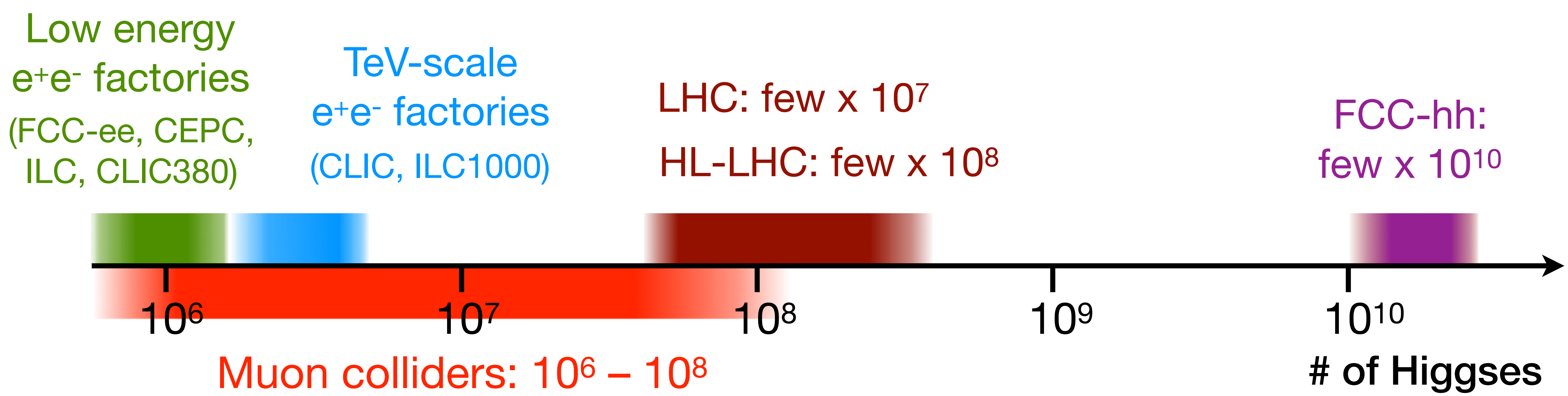


- **e+e- factory:** ~ 400 $H\to\tau\tau\gamma$ events $\Rightarrow$ 5% precision on SM, $\Delta a_\tau \lesssim \text{few}\times 10^{-4}$

- **LHC:** large number of Higgs bosons, but large backgrounds

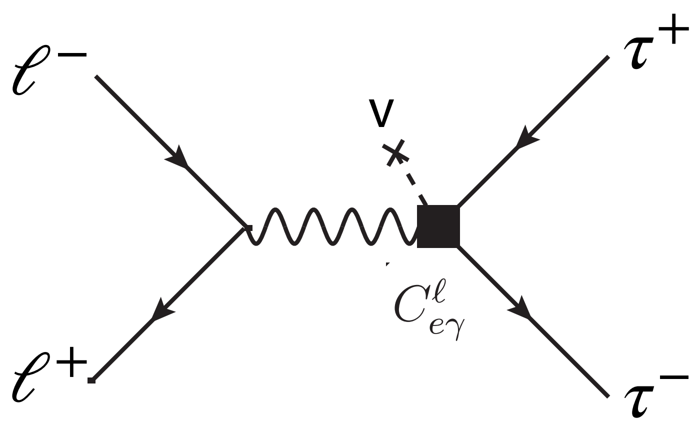
  Rescaling $H\to\tau\tau$ searches ~ 350 reconstructed $H\to\tau\tau\gamma$ events at HL-LHC,

  but 10x more background $\Rightarrow$ 20% precision on SM, $\Delta a_\tau \lesssim 5\times 10^{-4}$

Tau g-2 from high-energy probes

Further possibilities to measure Δa_τ precisely from high-energy probes

✦ Pair production



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

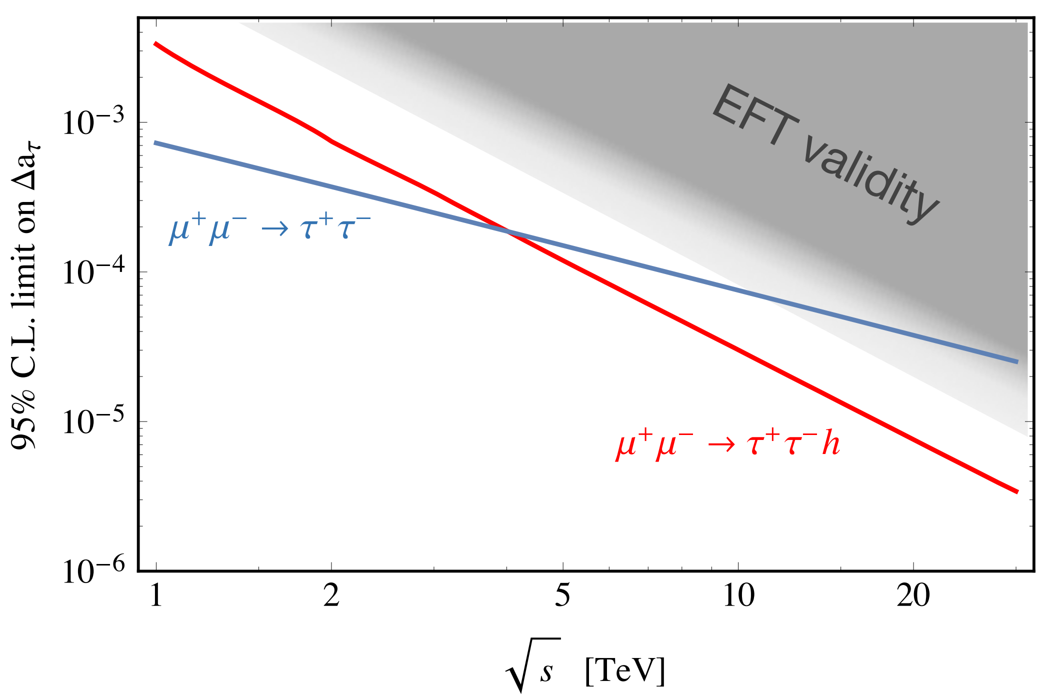
$$\sigma_{\rm NP} = \frac{4\pi\alpha^2}{3}\frac{|C^\ell_{e\gamma}|^2 v^2}{\Lambda^4} \sim \frac{\pi\alpha^2\Delta a_\ell^2}{6m_\ell^2}$$

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

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

EFT description breaks down above few TeV!

Could probe Δa_τ ~ few 10^{-5}



w/ Levati, Maltoni, Paradisi, Wang

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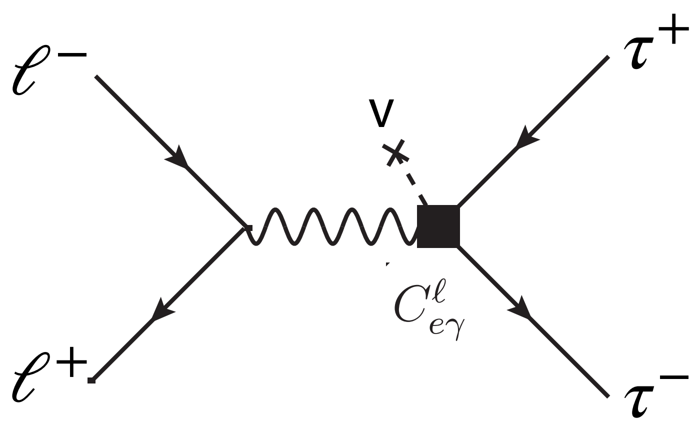

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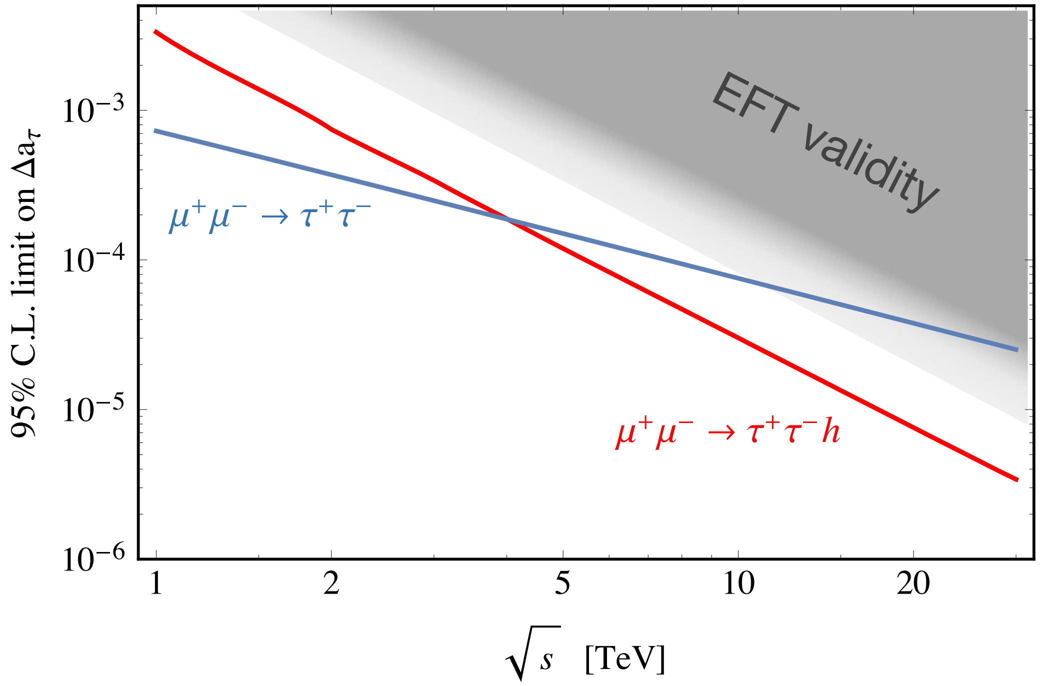

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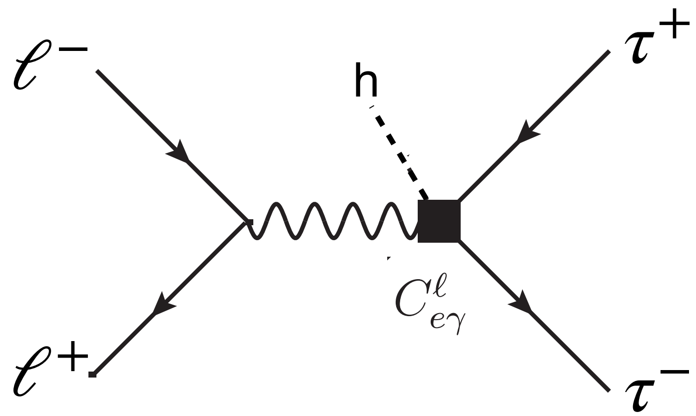
- ✦ $H\tau\tau$ associated production

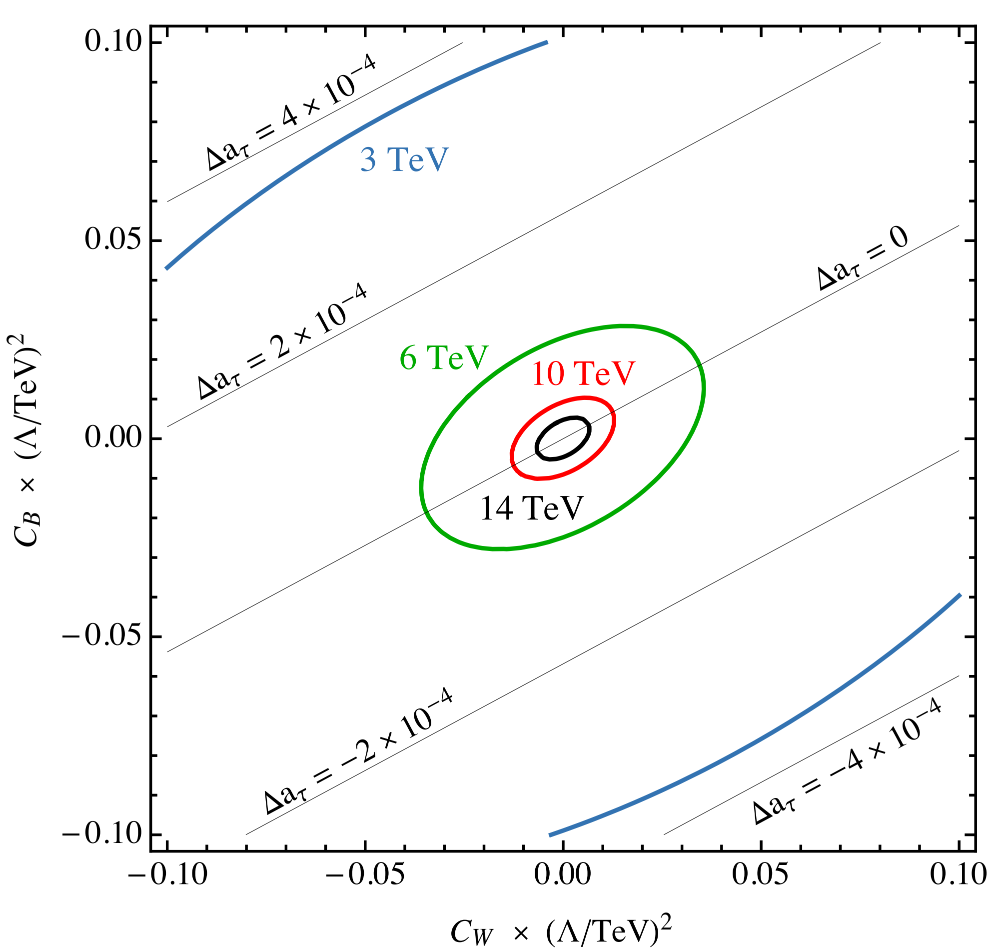
work in progress with Levati, Paradisi, Maltoni, Wang

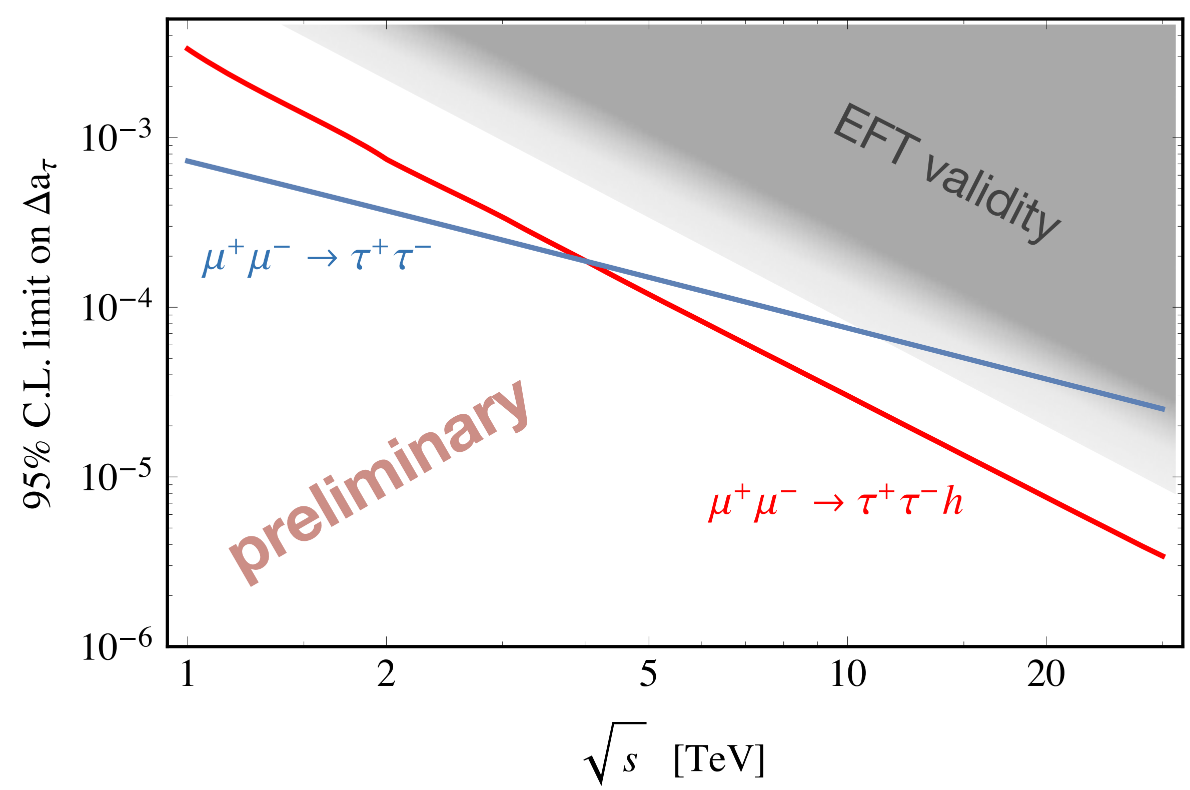


- ▸ Main background from μμ → $Z\gamma$

(where Z is mistaken for H)

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





also a bound on tau EDM!

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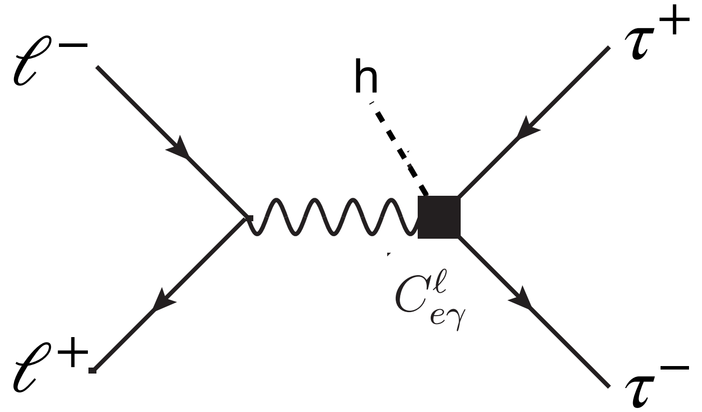

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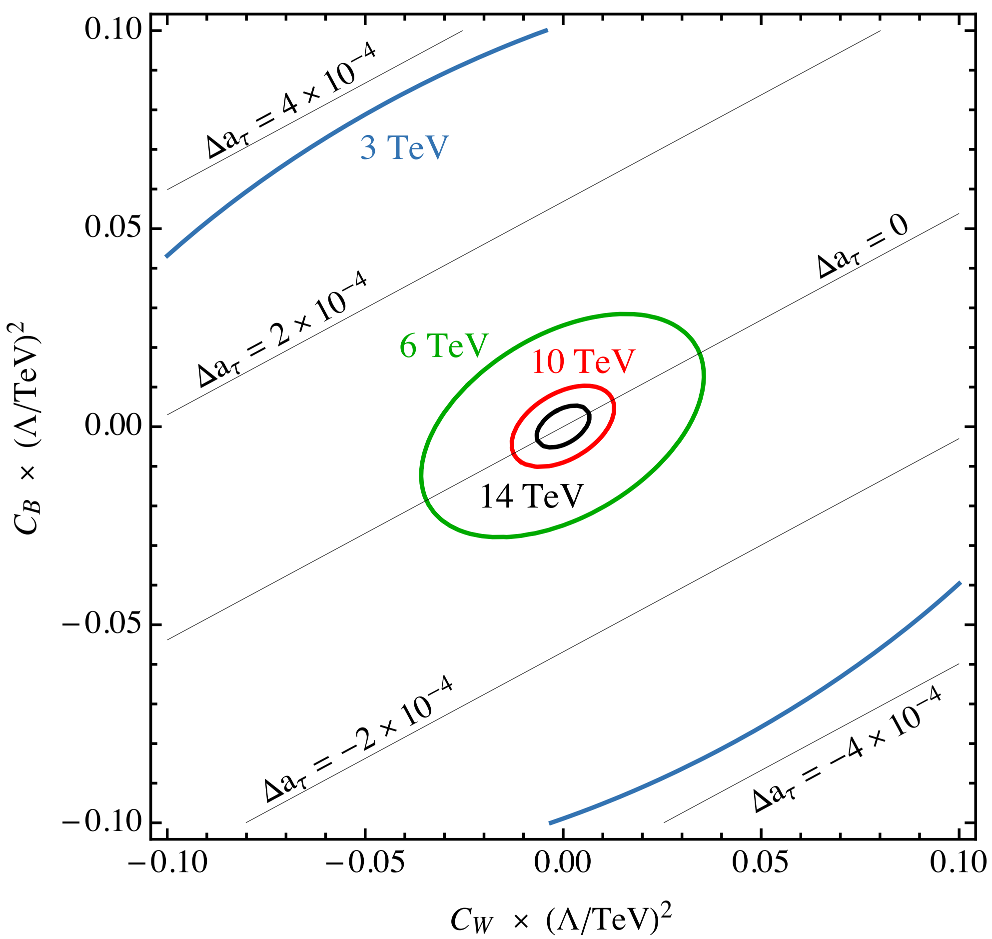
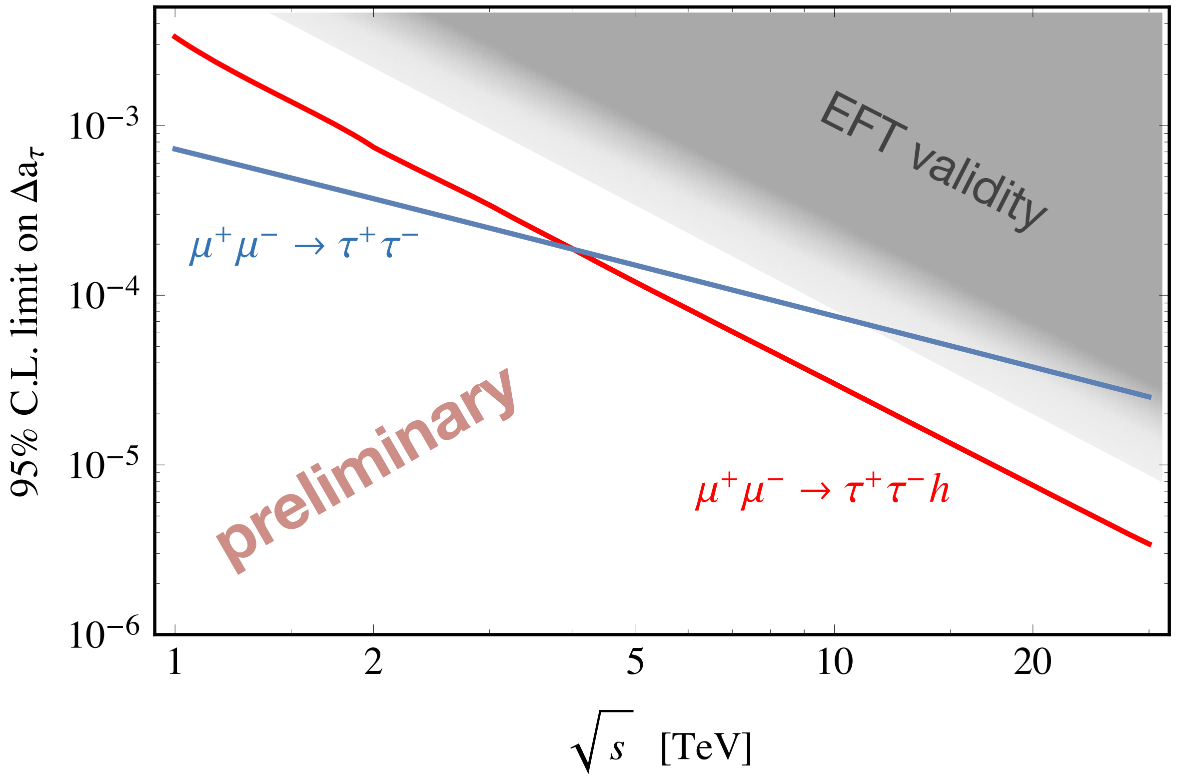




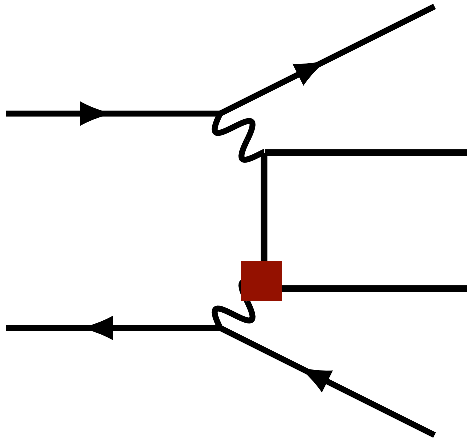
also a bound on tau EDM!

Tau g-2 from high-intensity probes

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

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

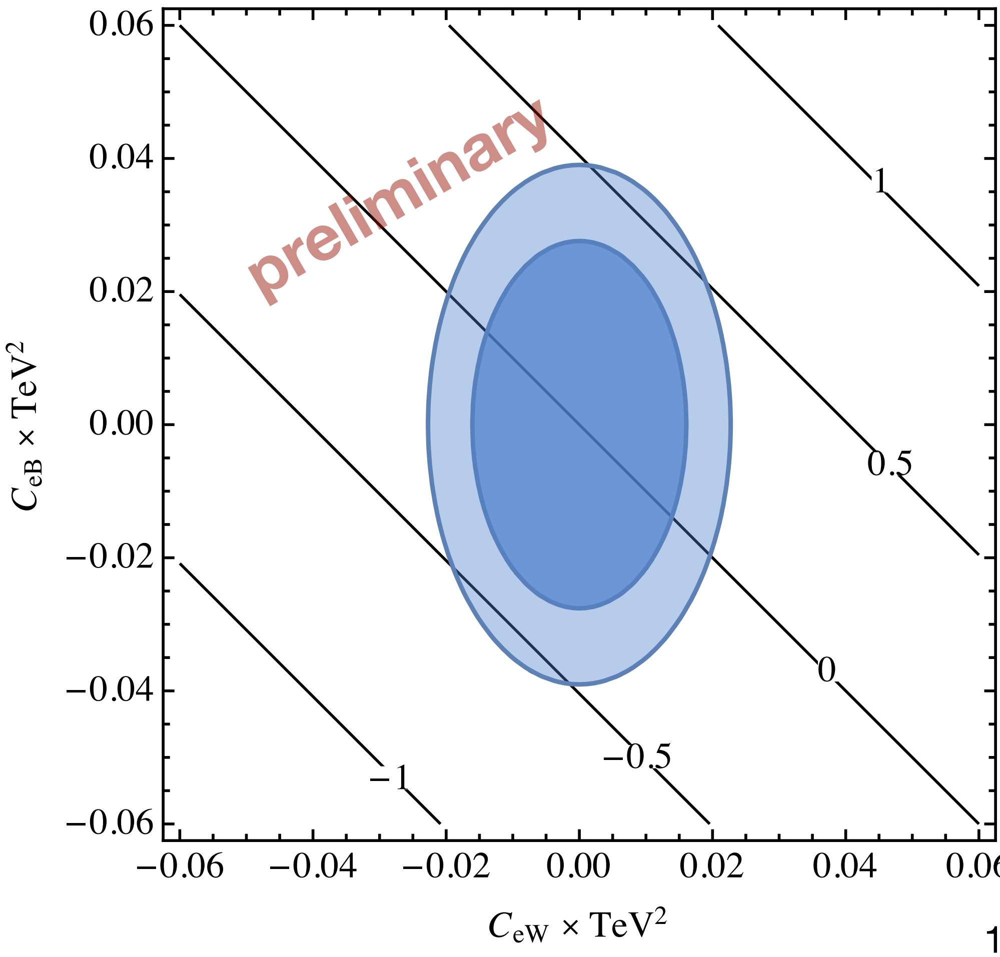
(same as LEP bound)



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

work in progress with Levati, Paradisi, Maltoni, Wang

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



- 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}

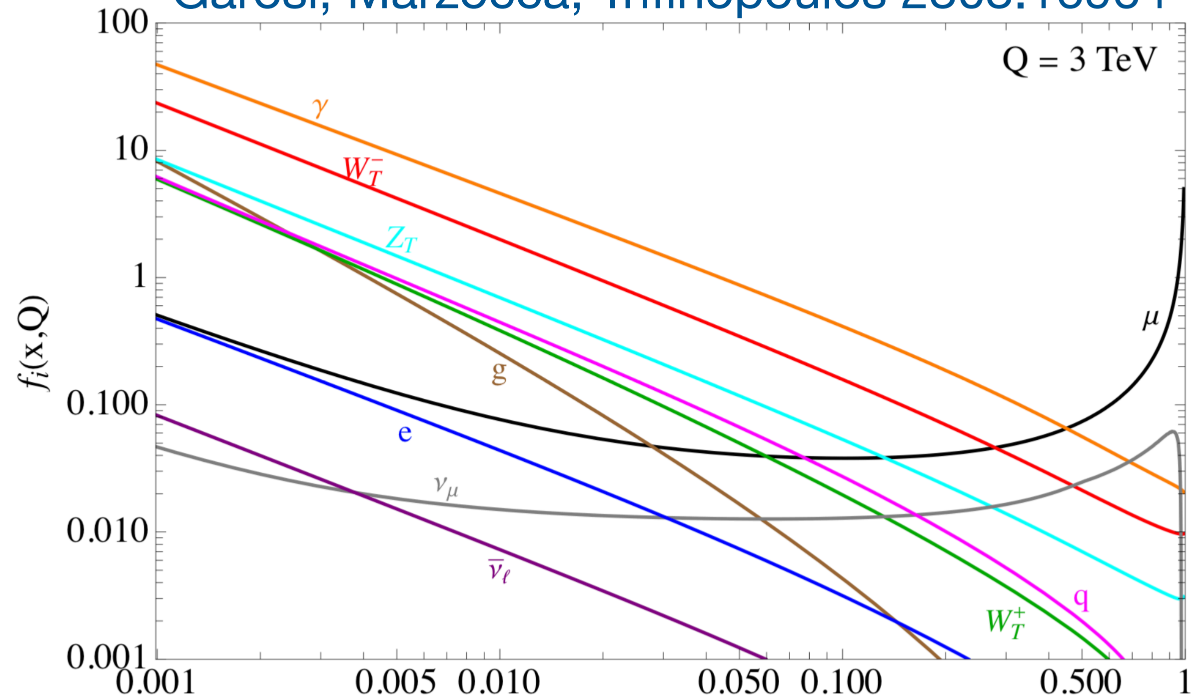
Radiation & high-energy neutrinos

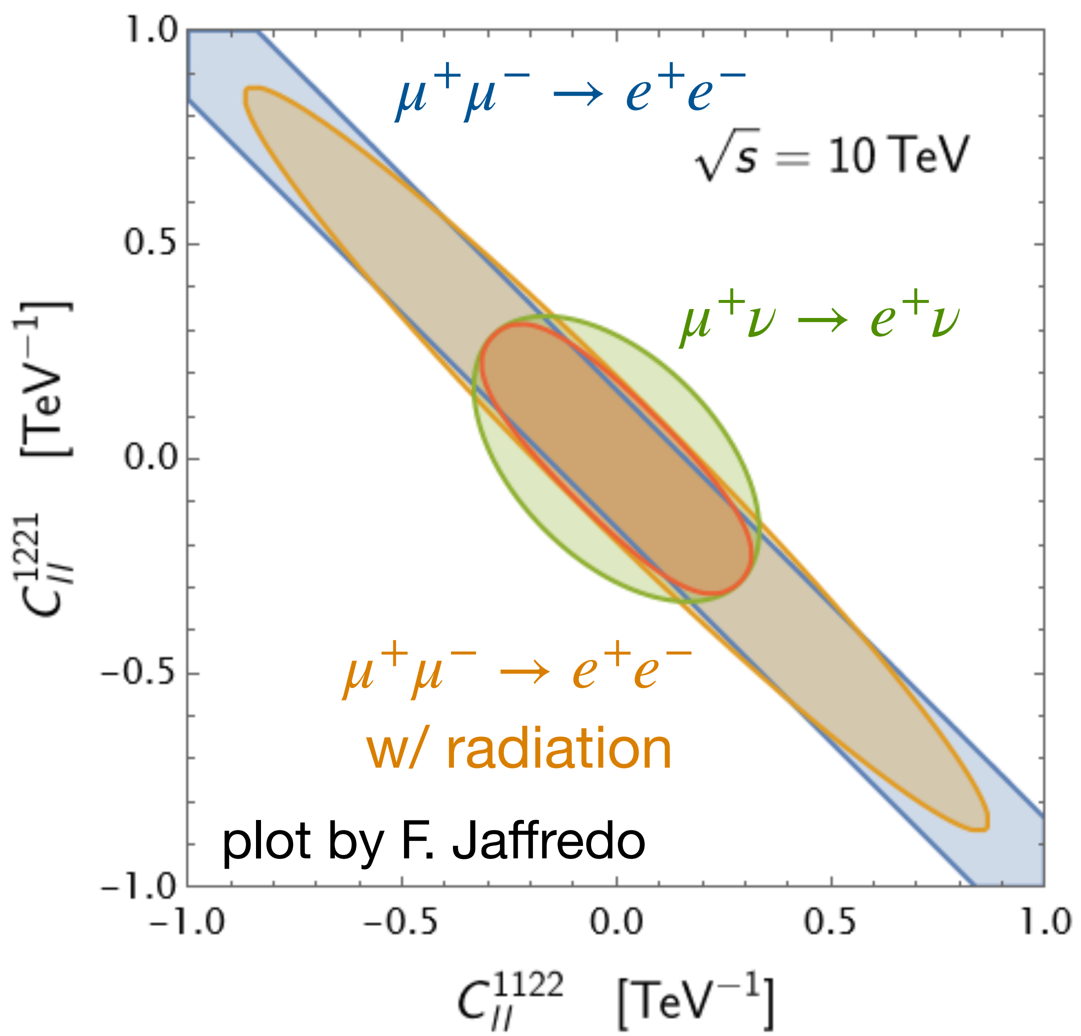
- Radiation effects are important.
- Hard neutrinos from $\mu^{\pm} \to W^{\pm}\nu$ have a large PDF $\Longrightarrow$ can access neutrino initial state at high energy!

  ☛ talks by David, Alfredo, David

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

Garosi, Marzocca, Trifinopoulos 2303.16964



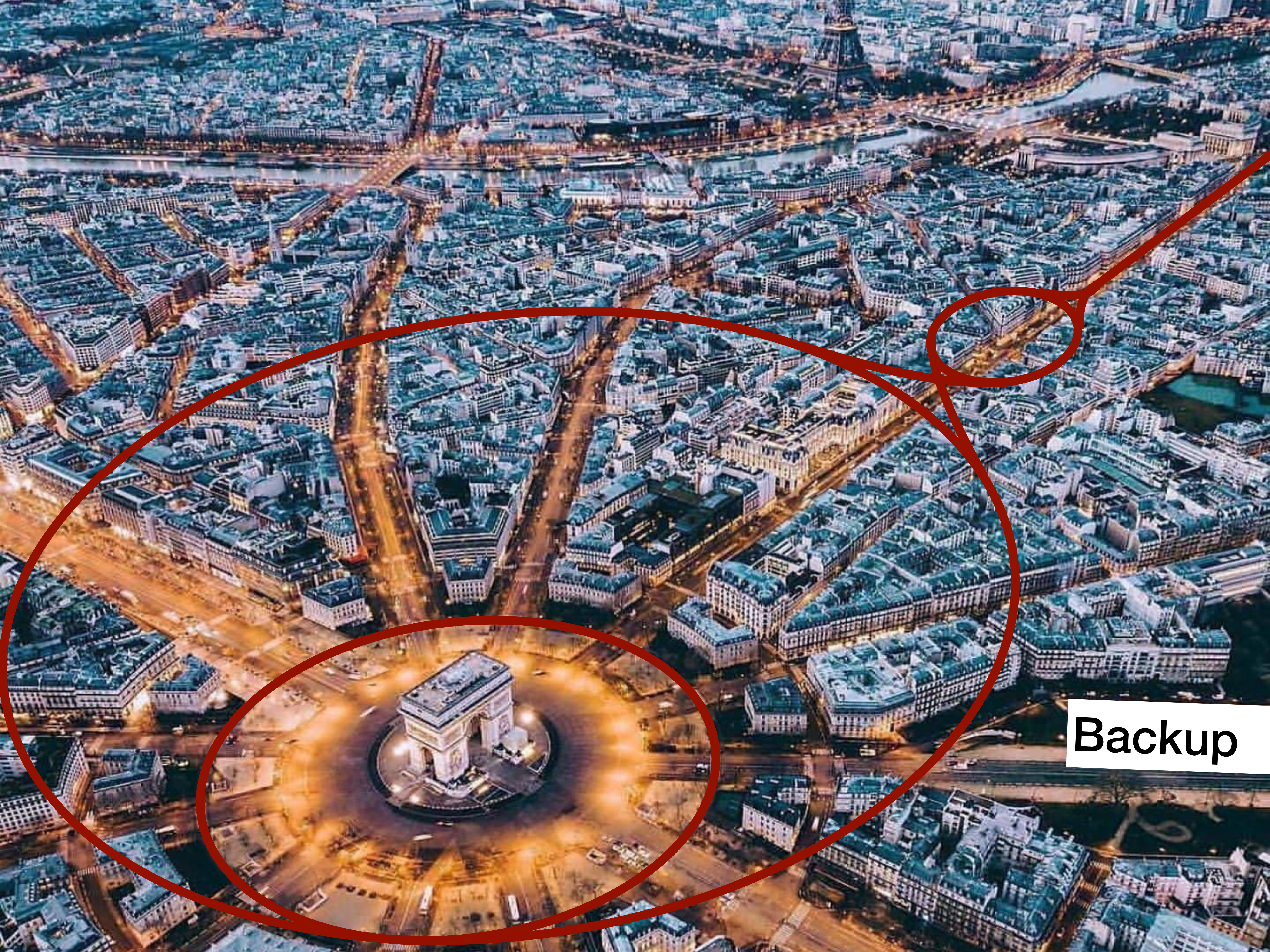


- Directly probe neutrino interactions at high energy: usual E² gain
  - can put strong constraints on BSM neutrino physics

    ☛ talk by Zahra this afternoon
  - complementary to $\mu^+\mu^-$ scattering, can remove flat directions and probe operators with different flavor structure

Summary

- High energy muon collider offers new ways to test flavor:
  - 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 improve lepton g-2 and EDM bound by orders of magnitude
- Rare Higgs decays + Higgs production
- Radiative corrections: access to neutrino interactions



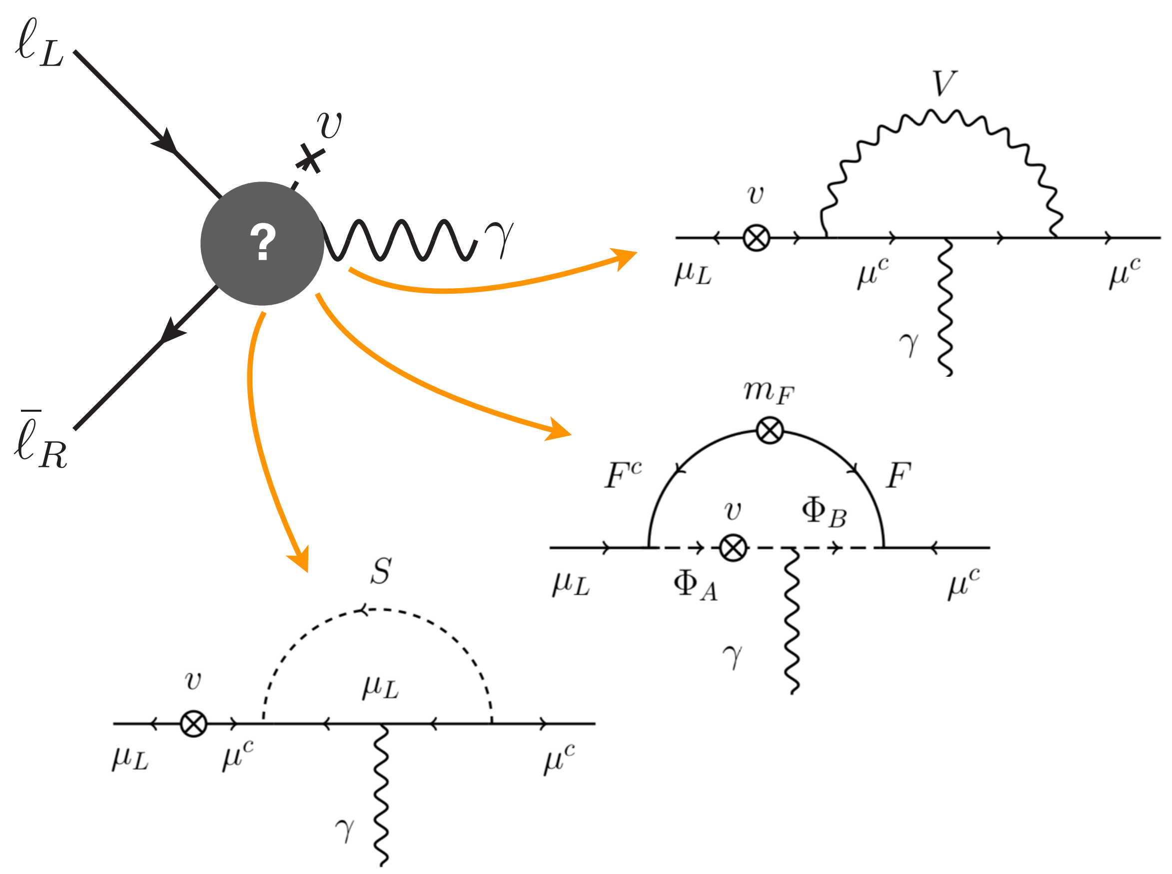
Backup

Muon g-2 @ muon collider: direct searches

- 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

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

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



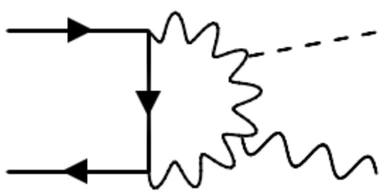
- A 20–30 TeV muon collider can test the most motivated, weakly coupled models

Capdevilla et al. 2006.16277, 2101.10334

Muon g-2 @ muon collider

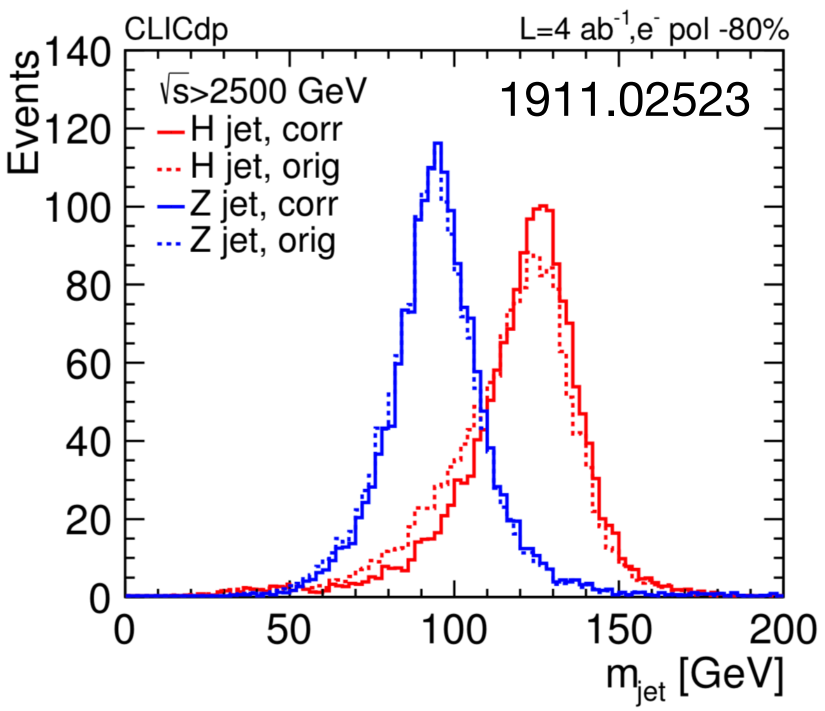
- SM irreducible background is small: $\sigma^{(SM)}_{\mu^+\mu^-\to h\gamma} \approx 10^{-2}\,\mathrm{ab}\left(\frac{30\,\mathrm{TeV}}{\sqrt{s}}\right)^2$

  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)



Search in h → bb channel:

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

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

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

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

Beyond tree-level

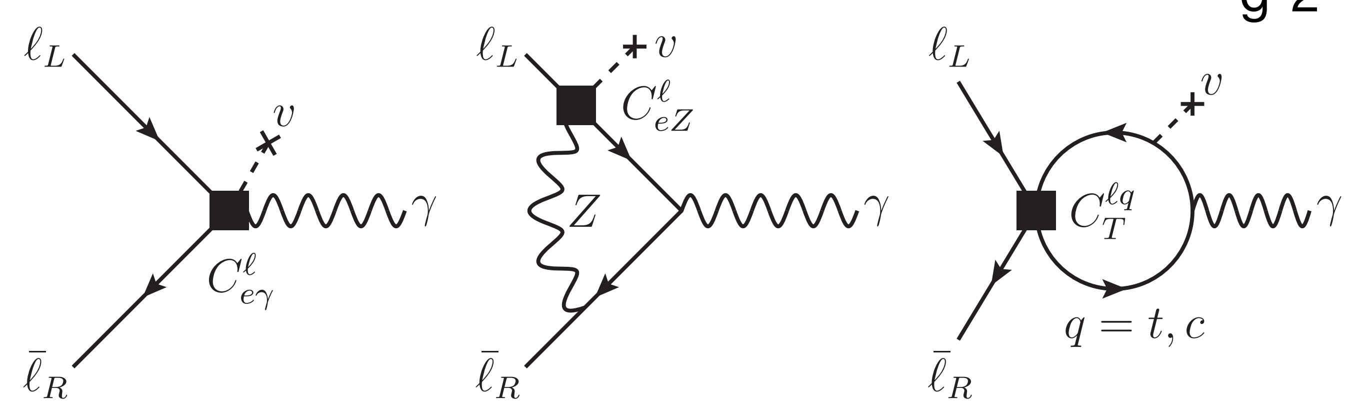
- Other operators contribute to g-2 at one loop:

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

(+ other effects suppressed by y_μ)

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

g-2



Including 1-loop running:

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

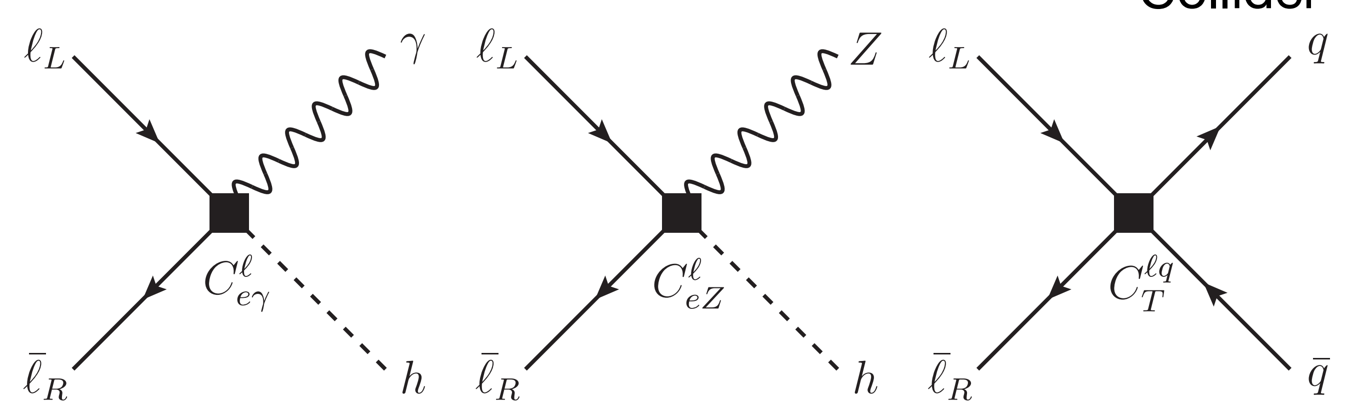
$$\approx \left(\frac{250\,\text{TeV}}{\Lambda^2}\right)^2(C_{e\gamma} - 0.2C_{Tt} - 0.001C_{Tc} - 0.05C_{eZ})$$

B, Paradisi 2012.02769

Full set of operators can be probed at high energy

$$\mu^+\mu^- \to h\gamma$$
$$\mu^+\mu^- \to hZ$$
$$\mu^+\mu^- \to q\bar{q}$$

Collider



Muon g-2 @ muon collider

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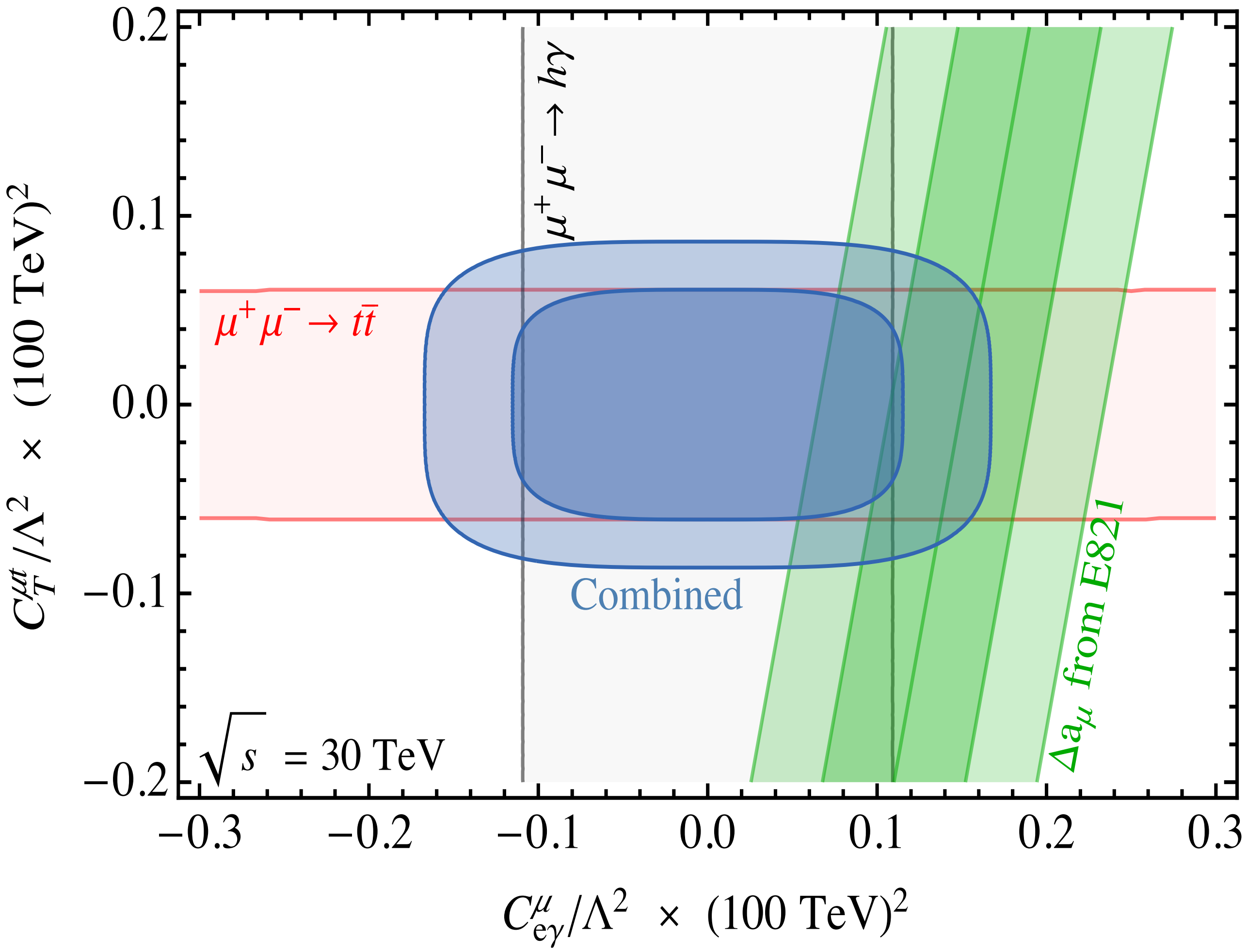
- Full set of operators with $\Lambda \gtrsim 100$ TeV can be probed at a high energy muon collider



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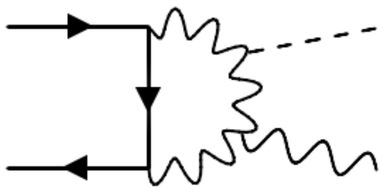

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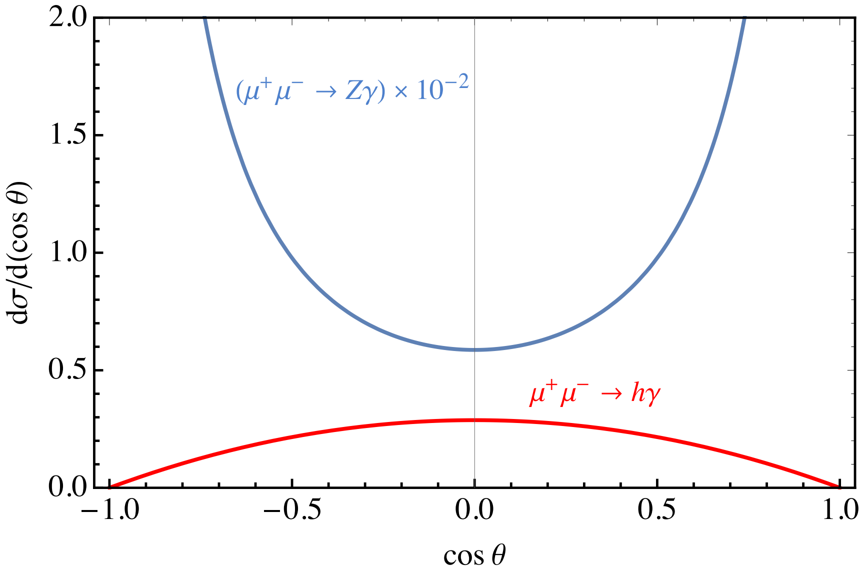
$$\frac{d\sigma_{\mu\mu\to h\gamma}}{d\cos\theta} = \frac{|C^{\mu}_{e\gamma}(\Lambda)|^2}{\Lambda^4}\frac{s}{64\pi}(1-\cos^2\theta)$$

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



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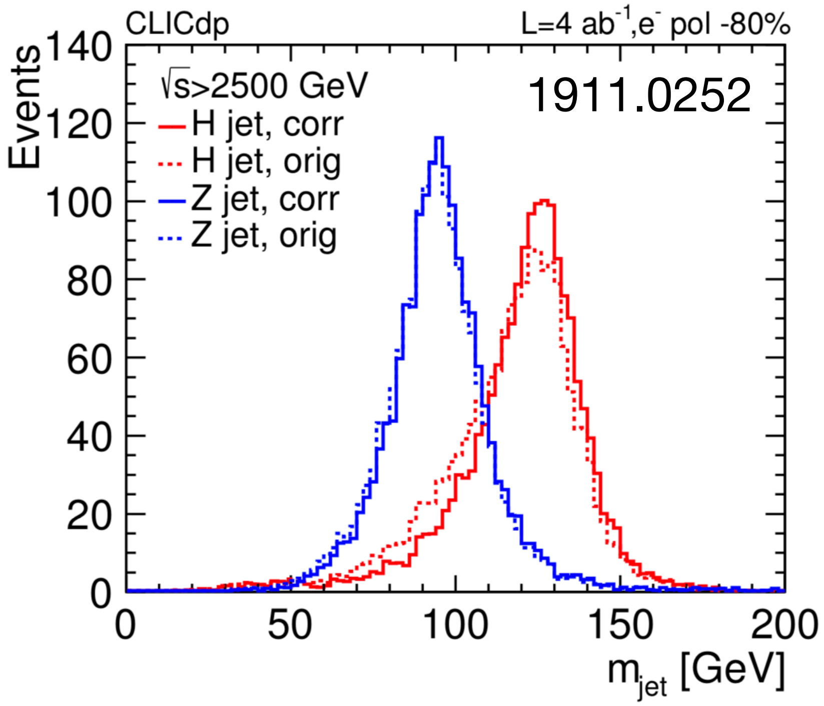


New physics: $$\frac{d\sigma_{NP}}{dx_1 dx_2} = \frac{1}{192\pi^3}\frac{Q^2}{\Lambda^4}\left[(Q_\mu e\,\mathcal{C}_\gamma)^2 + \left(\frac{g\,\mathcal{C}_Z}{4c_w}\right)^2\right](2x_1x_2 - x_1 - x_2 + 1)$$

Interference:

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

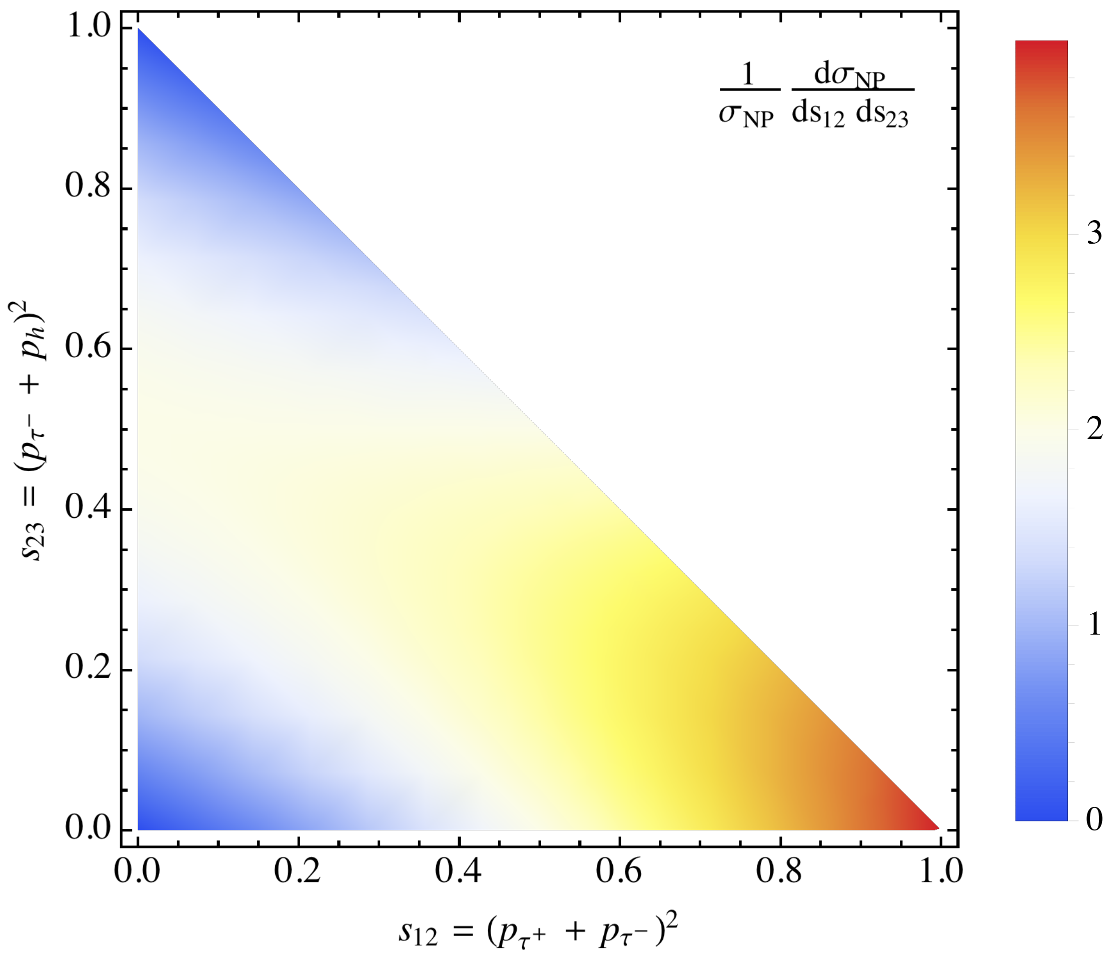
Standard Model:

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

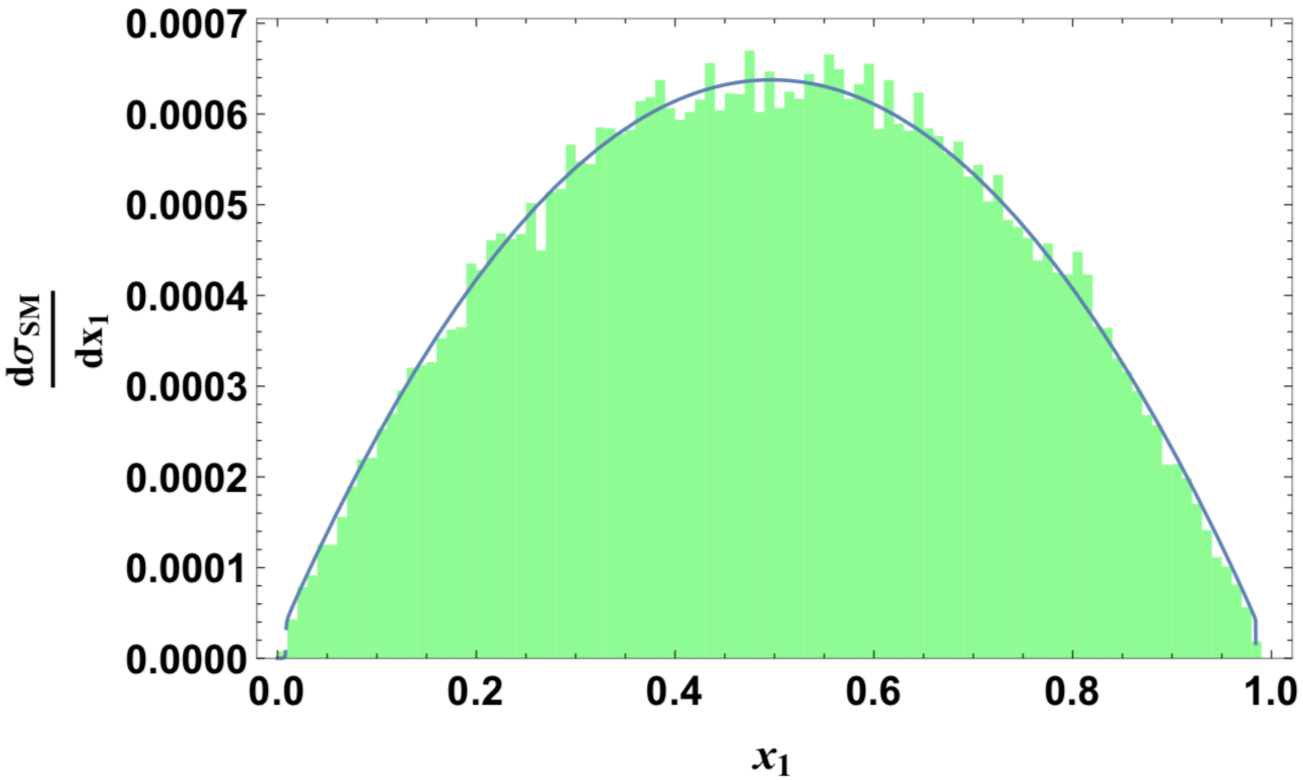
$$\frac{d\sigma_2}{dx_1 dx_2} = \frac{1}{3\cdot 2^{14}\pi^3}\frac{m_\tau^2 g^4}{v^2 c_w^4}\frac{1}{Q^2}\left[\frac{1-x_1}{1-x_2} - 2 + \frac{1-x_2}{1-x_1}\right];$$

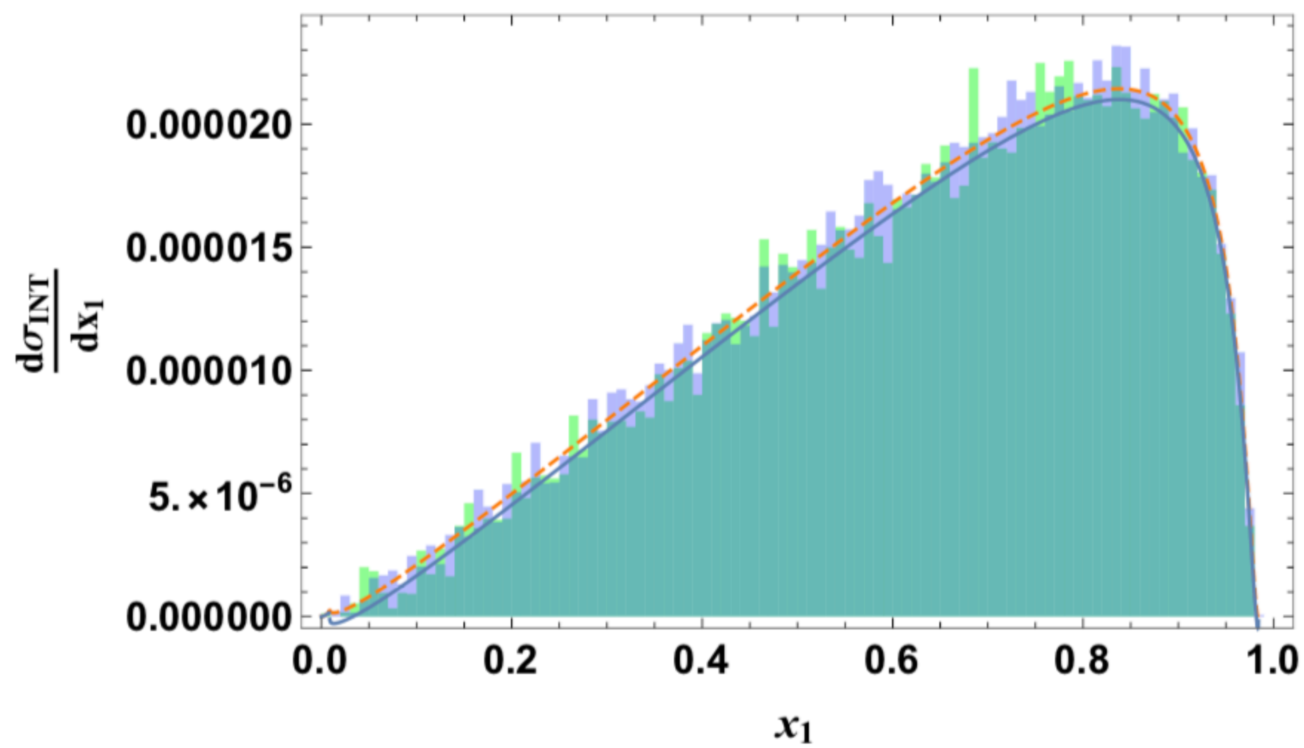
$$\frac{d\sigma_3}{dx_1 dx_2} = \frac{1}{6\cdot 2^{16}\pi^3}\frac{g^8}{c_w^8}\frac{v^2}{Q^4}\left[\frac{x_1x_2 + x_1 + x_2 - 1}{(x_1 + x_2 - 1)^2}\right];$$

Out[∘]=



H$\tau\tau$ signal





(c)