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Virginia Tech
COFI Workshop – 21 May, 2018

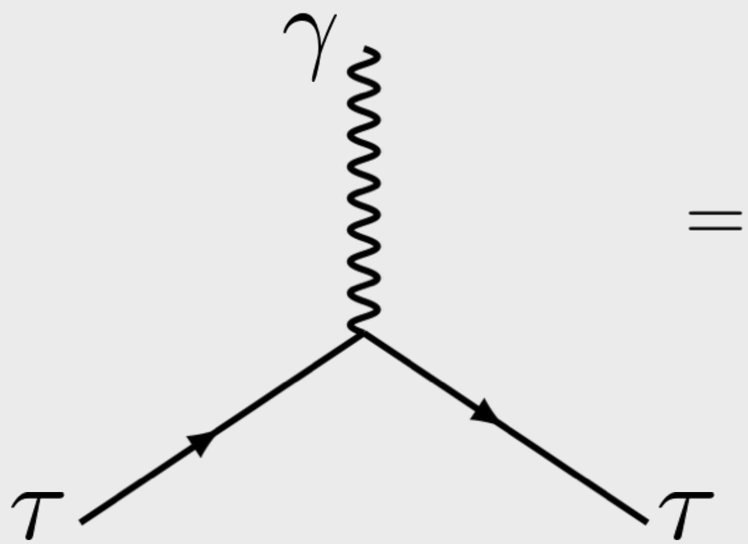
The Tau (g–2): Theory and Experiment

OUTLINE

- Theoretical Overview
  - Standard Model Contributions
  - The Effects of New Physics
- Experimental Status
  - Previous Measurements
  - Future Proposals
- Conclusions

THEORETICAL OVERVIEW

- The most general $\gamma\tau\tau$ vertex:



$$= \quad ie\left[\gamma^\mu F_1(q^2) + \frac{1}{2m_\tau}\left(iF_2(q^2) + F_3(q^2)\gamma_5\right)\sigma^{\mu\nu}q_\nu + \left(q^2\gamma^\mu - q^\mu \not{q}\right)\gamma_5 F_A(q^2)\right]$$

THEORETICAL OVERVIEW

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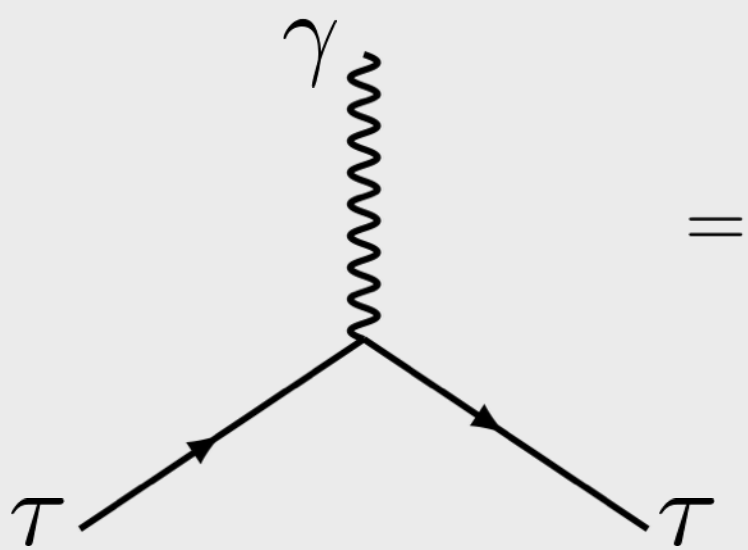

$$= \quad ie\left[\gamma^\mu \boxed{F_1(q^2)} + \frac{1}{2m_\tau}\left(i\boxed{F_2(q^2)} + \boxed{F_3(q^2)}\gamma_5\right)\sigma^{\mu\nu}q_\nu + \left(q^2\gamma^\mu - q^\mu \not{q}\right)\gamma_5 \boxed{F_A(q^2)}\right]$$

Charge

Magnetic dipole moment

Electric dipole moment

Anapole moment

THEORETICAL OVERVIEW

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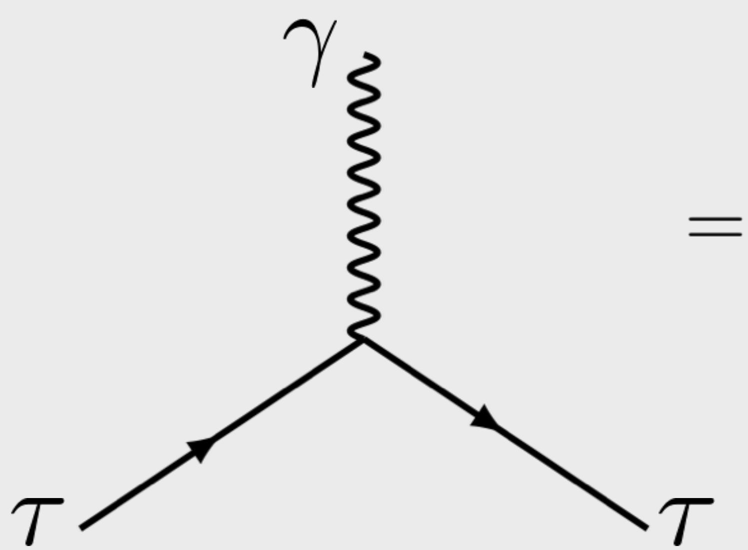

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$$d_\tau \equiv \frac{e}{2m_\tau}F_3(q^2=0)$$

THEORETICAL OVERVIEW

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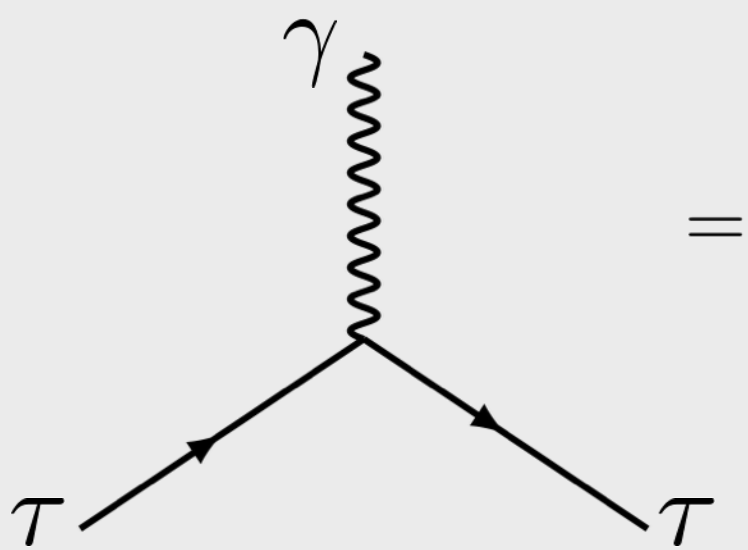

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$$F_2(q^2=0) \equiv a_\tau; \quad \mu_\tau = (2+2a_\tau)\frac{e}{4m_\tau}$$

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THEORETICAL OVERVIEW

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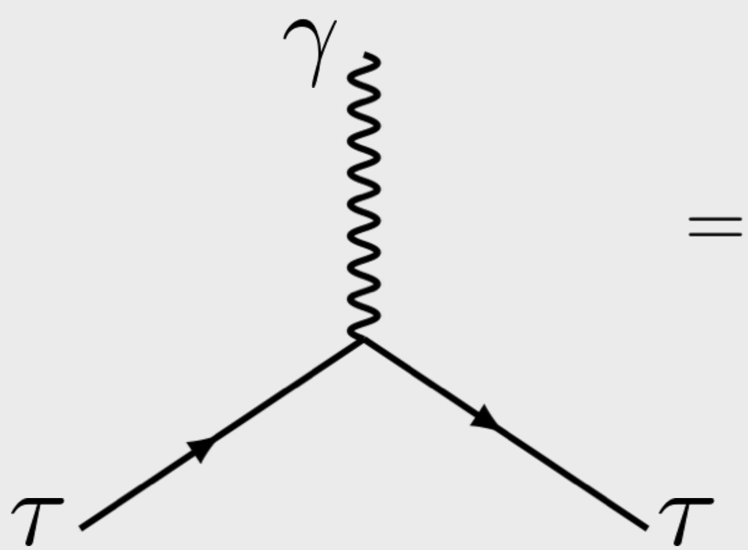

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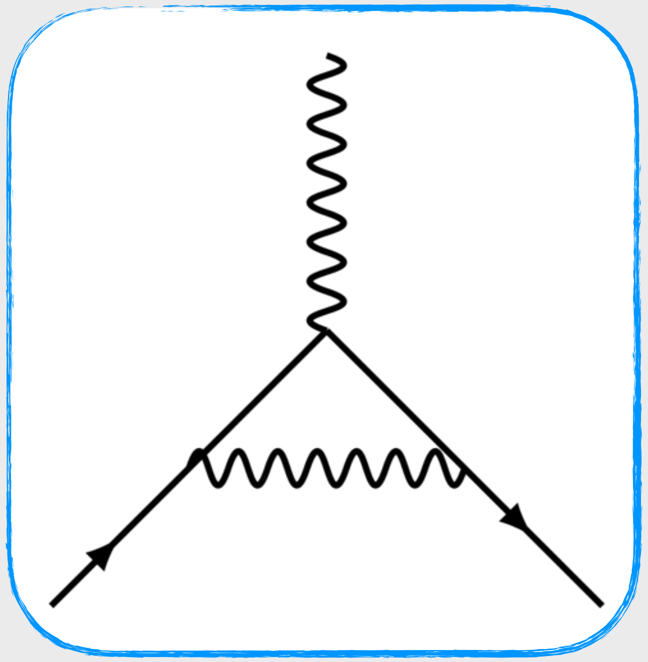
TAU (g-2) IN THE STANDARD MODEL

- Contributions from QED:

$$a_\tau^{\text{QED}} = A_1 + A_2\left(\frac{m_\tau}{m_e}\right) + A_2\left(\frac{m_\tau}{m_\mu}\right) + A_3\left(\frac{m_\tau}{m_e}, \frac{m_\tau}{m_\mu}\right);$$

$$A_i = A_i^{(2)}\left(\frac{\alpha}{\pi}\right) + A_i^{(4)}\left(\frac{\alpha}{\pi}\right)^2 + A_i^{(6)}\left(\frac{\alpha}{\pi}\right)^3 + \dots$$

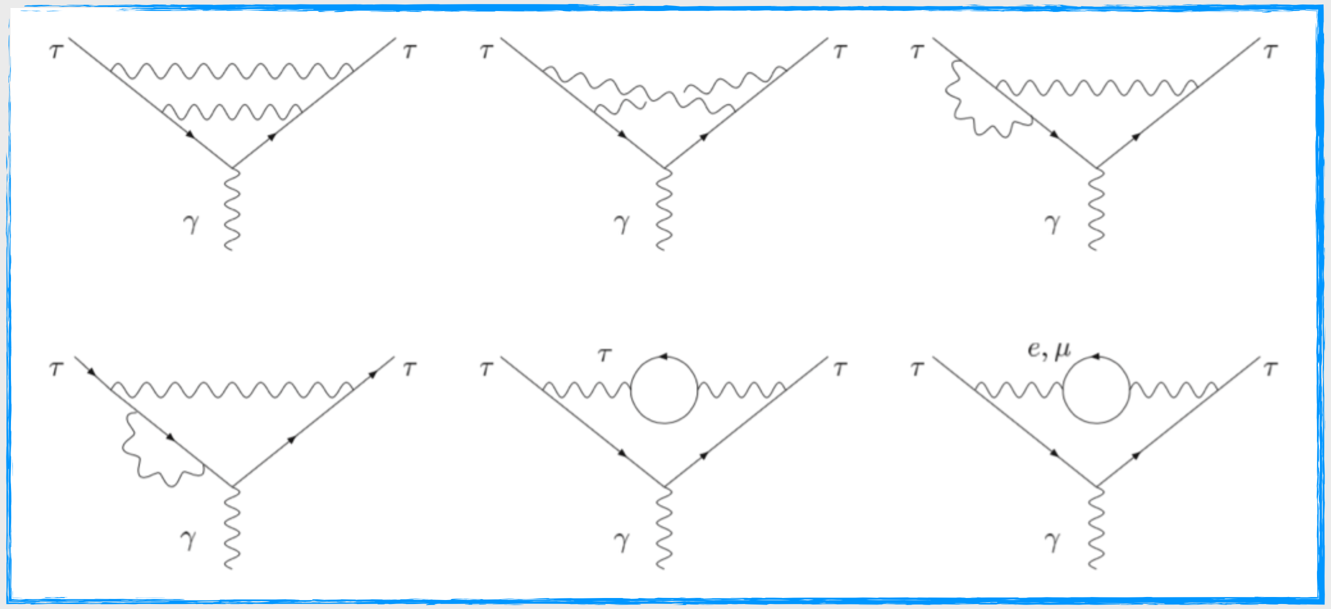
- One loop result



$$\Longrightarrow \boxed{A_1^{(2)} = \frac{1}{2}}$$

TAU (g-2) IN THE STANDARD MODEL

- Two loop results



$$A_1^{(4)} = \frac{197}{144} + \frac{\pi^2}{12} + \frac{3}{4}\zeta(3) - \frac{\pi^2}{2}\ln 2 = -0.328\,478\,965\,579\,193\,78\ldots$$

$$A_2^{(4)}(1/x) = -\frac{25}{36} - \frac{\ln x}{3} + x^2\left(4 + 3\ln x\right) + \frac{x}{2}\left(1 - 5x^2\right) \times \left[\frac{\pi^2}{2} - \ln x \ln\left(\frac{1-x}{1+x}\right) - \mathrm{Li}_2(x) + \mathrm{Li}_2(-x)\right] + x^4\left[\frac{\pi^2}{3} - 2\ln x \ln\left(\frac{1}{x} - x\right) - \mathrm{Li}_2(x^2)\right]$$

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g-2) IN THE STANDARD MODEL

- Two loop results

$$A_1^{(4)} = \frac{197}{144} + \frac{\pi^2}{12} + \frac{3}{4}\zeta(3) - \frac{\pi^2}{2}\ln 2$$
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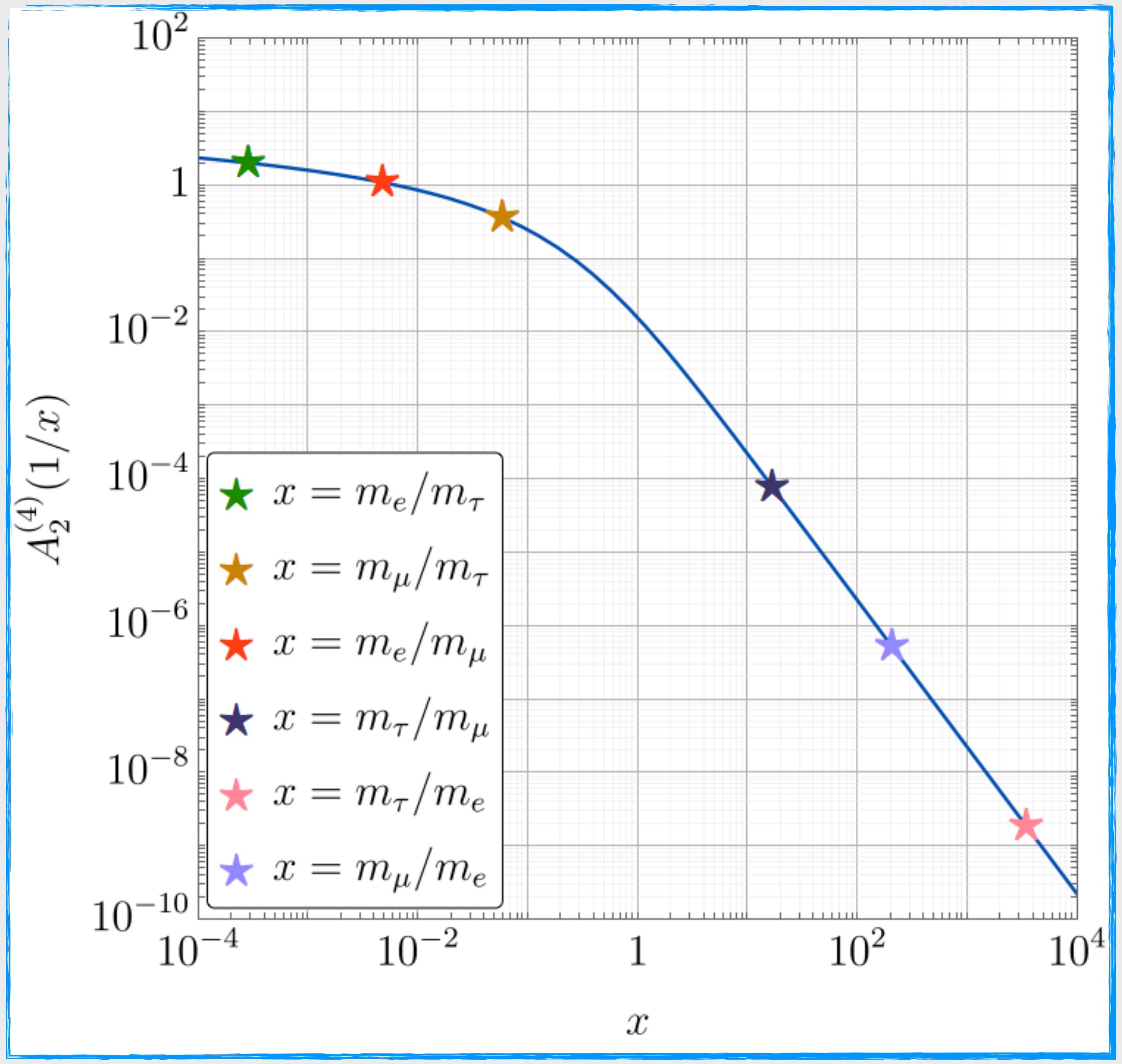

$$A_2^{(4)}(1/x) = -\frac{25}{36} - \frac{\ln x}{3} + x^2(4 + 3\ln x) + \frac{x}{2}(1 - 5x^2)$$
$$\times \left[\frac{\pi^2}{2} - \ln x \ln\left(\frac{1-x}{1+x}\right) - \mathrm{Li}_2(x) + \mathrm{Li}_2(-x)\right]$$
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Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

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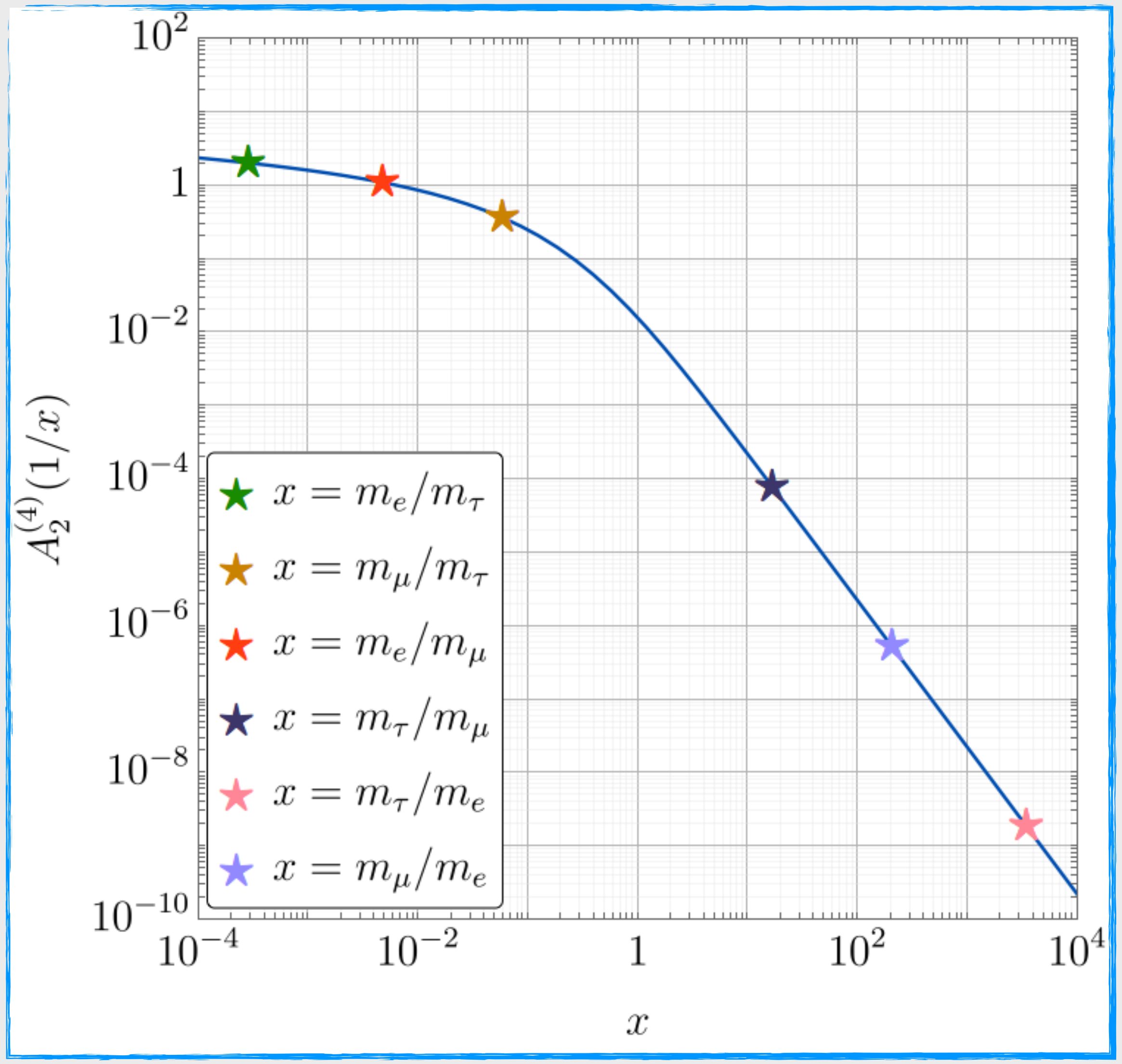

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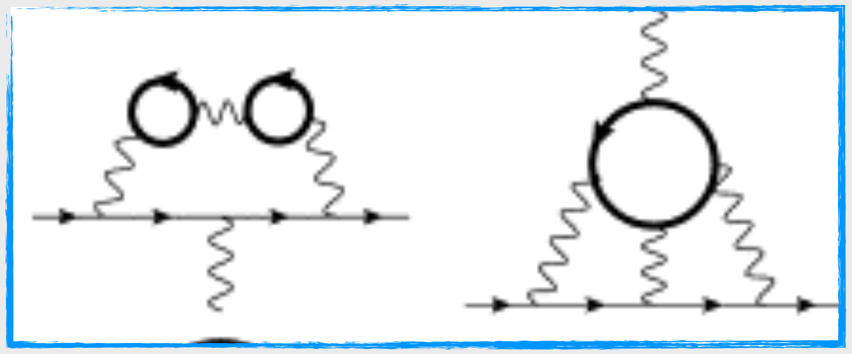
$$\boxed{A^{(4)} = 2.057\,457(93)}$$

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g–2) IN THE STANDARD MODEL

Kurz, et al., Nucl. Phys. B879 (2014) 1



- Three loops and beyond…

$$
\begin{aligned}
A_1^{(6)} &= \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5) - \frac{239}{2160}\pi^4 + \frac{28259}{5184} \\
&\quad + \frac{139}{18}\zeta(3) - \frac{298}{9}\pi^2 \ln 2 + \frac{17101}{810}\pi^2 \\
&\quad + \frac{100}{3}\left[\mathrm{Li}_4(1/2) + \frac{1}{24}\left(\ln^2 2 - \pi^2\right)\ln^2 2\right] \\
&= 1.181\,241\,456\,587\ldots
\end{aligned}
$$

$$
\begin{aligned}
A_2^{(6)}(m_\tau/m_e;\mathrm{vac}) &= 7.256\,99(41) \\
A_2^{(6)}(m_\tau/m_e;\mathrm{LBL}) &= 39.1351(11) \\
A_2^{(6)}(m_\tau/m_\mu;\mathrm{vac}) &= -0.023\,554(51) \\
A_2^{(6)}(m_\tau/m_\mu;\mathrm{LBL}) &= 7.033\,76(71)
\end{aligned}
$$

$$
A_3^{(6)}(m_\tau/m_e, m_\tau/m_\mu) = 3.347\,97(41)
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Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g−2) IN THE STANDARD MODEL

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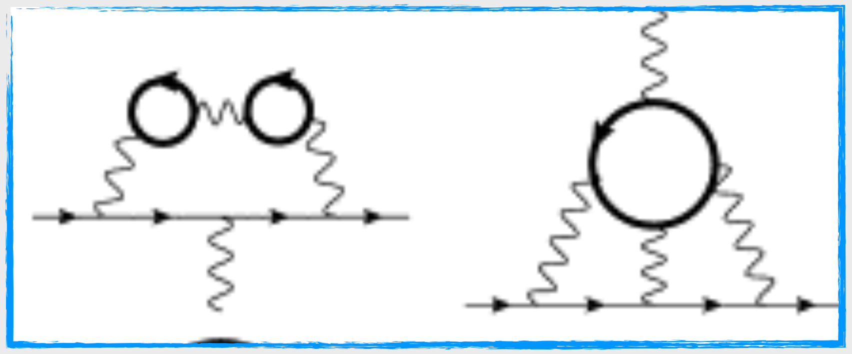

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\end{aligned}
$$

$$a_\tau^{\mathrm{QED}} = 117\,324(2)\times 10^{-8}$$

$$a_e^{\mathrm{QED}} = 115\,965\,218.1860(13)(720)\times 10^{-11}$$

$$a_\mu^{\mathrm{QED}} = 116\,584\,718.86(3)\times 10^{-11}$$

Error from estimate of four-loop contribution:

$$\pi^2\ln^2\left(m_\tau/m_e\right)\left(\alpha/\pi\right)^4$$

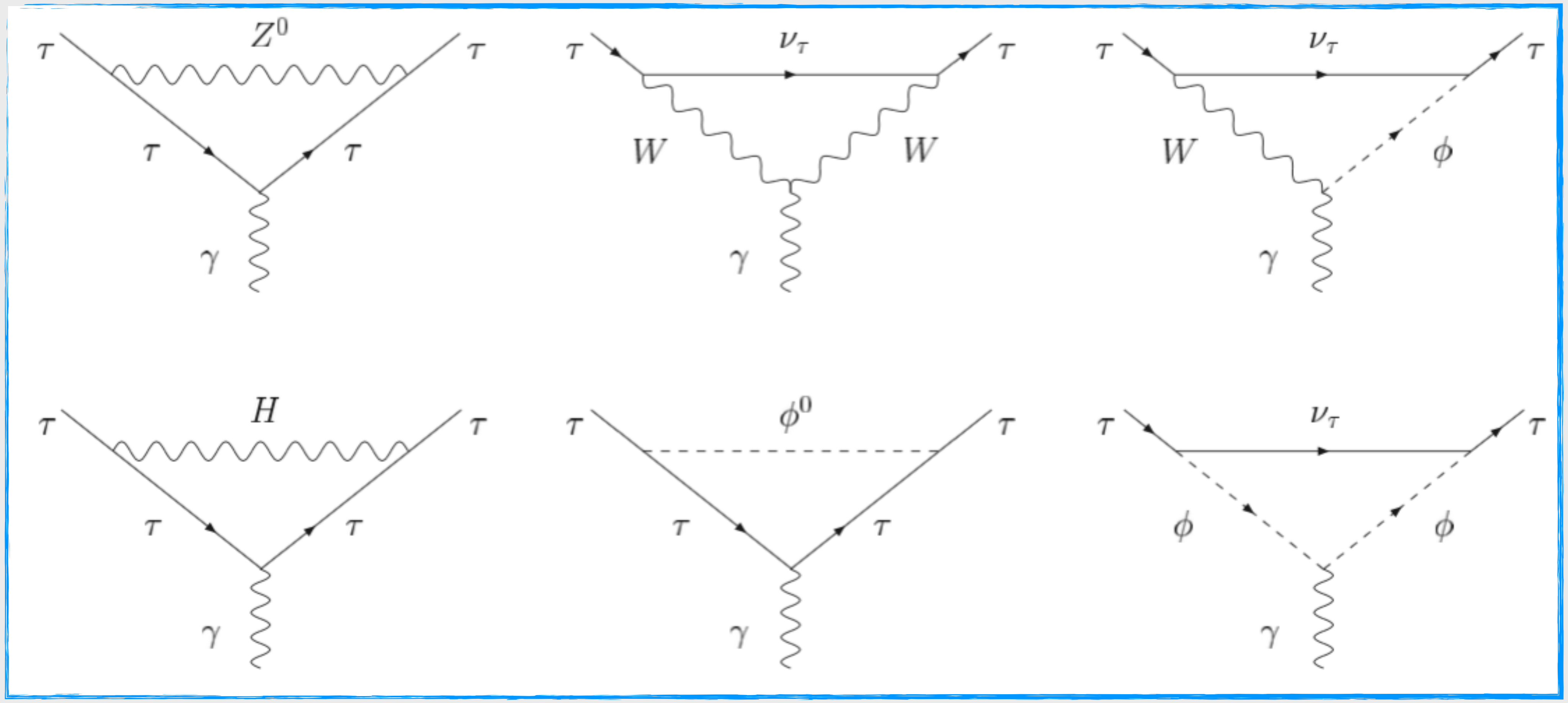
Aoyama, et al., Phys.Rev. D97 (2018) no.3, 036001; Jegerlehner, 1804.07409

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g-2) IN THE STANDARD MODEL

- Electroweak contributions

$$a_\tau^{\mathrm{EW}}(1\ \mathrm{loop}) = \frac{5G_\mu m_\tau^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+\mathcal{O}\left(\frac{m_\tau^2}{M_{Z,\,W,\,H}^2}\right)\right]$$
$$= 55.1(1)\times 10^{-8}$$



Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

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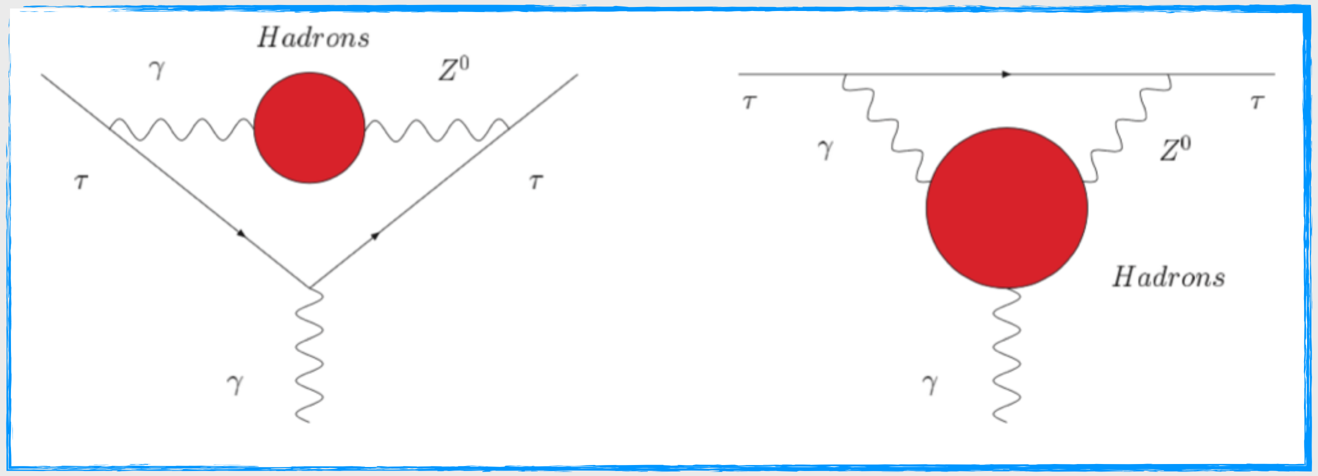

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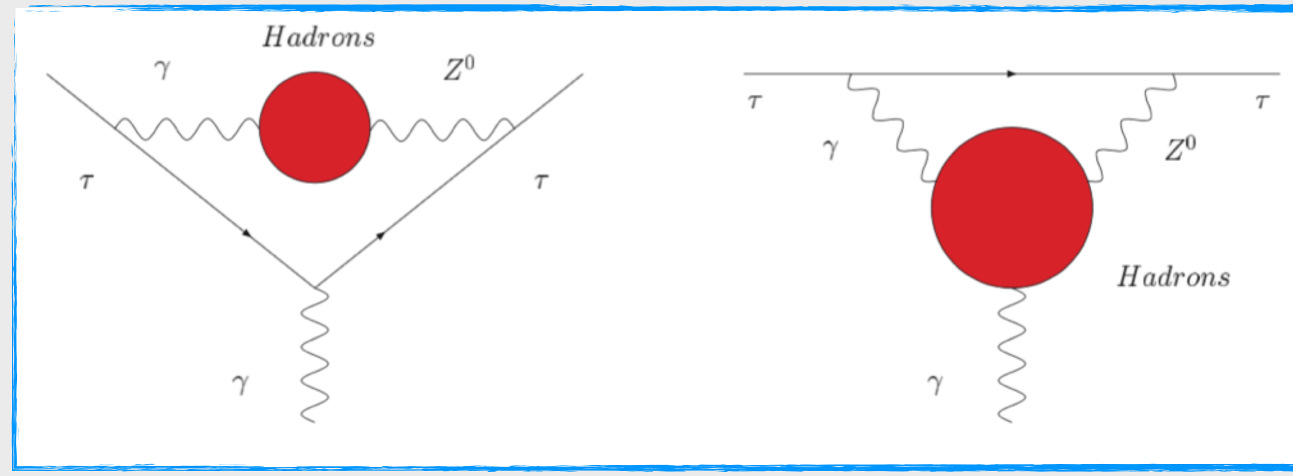
$$a_\tau^{\mathrm{EW}}(2\ \mathrm{loop;\ boson}) = -3.06\times 10^{-8}$$

$$a_\tau^{\mathrm{EW}}(2\ \mathrm{loop;\ fermion}) \approx \sum_f \frac{5G_\mu m_\tau^2}{24\sqrt{2}\pi^2}\left[\frac{\alpha}{\pi}\frac{18}{5}N_f I_3^f Q_f^2\,\Delta C(f)\right]$$

$$\Delta C(f)\begin{cases} \ln(M_Z^2/m_\tau^2)+5/6, & m_f<m_\tau \\ \ln(M_Z^2/m_\tau^2)-8\pi^2/27+11/18, & m_f=m_\tau \\ \ln(M_Z^2/m_f^2)-2, & m_\tau<m_f \\ \left[(M_Z^2/M_t^2)/6-2/3\right]\ln(M_t^2/M_Z^2)+ & \\ \quad(5/18)(M_Z^2/M_t^2)-4/3, & m_f=M_t \end{cases}$$

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g-2) IN THE STANDARD MODEL



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$$a_\tau^{\rm EW}(2\ \text{loop; total}) = -7.74\times 10^{-8}$$

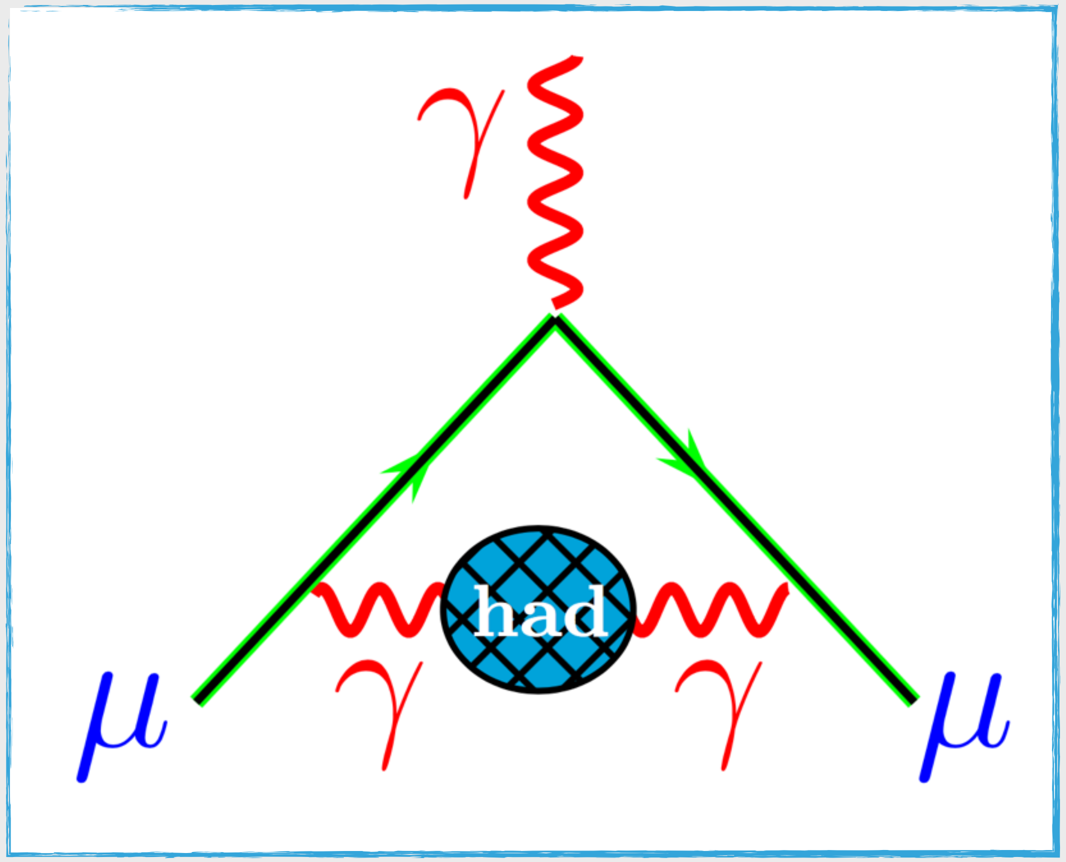
$$a_\tau^{\rm EW} = 47.4(5)\times 10^{-8}$$

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159

TAU (g–2) IN THE STANDARD MODEL

- Hadronic contributions

$$a_\ell^{\mathrm{HLO}} = \frac{m_\ell^2}{12\pi^3} \int_{4m_\pi^2}^{\infty} ds \, \frac{\sigma^{(0)}(e^+e^- \to \mathrm{hadrons}) K_\ell(s)}{s}$$



TAU (g−2) IN THE STANDARD MODEL

Gourdin & De Rafael, Nucl.Phys. B10 (1969) 667

$$K_\ell(s) = \frac{3s}{m_\ell^2}\int_0^1 dz\,\frac{z^2(1-z)}{z^2+\frac{s}{m_\ell^2}(1-z)}$$

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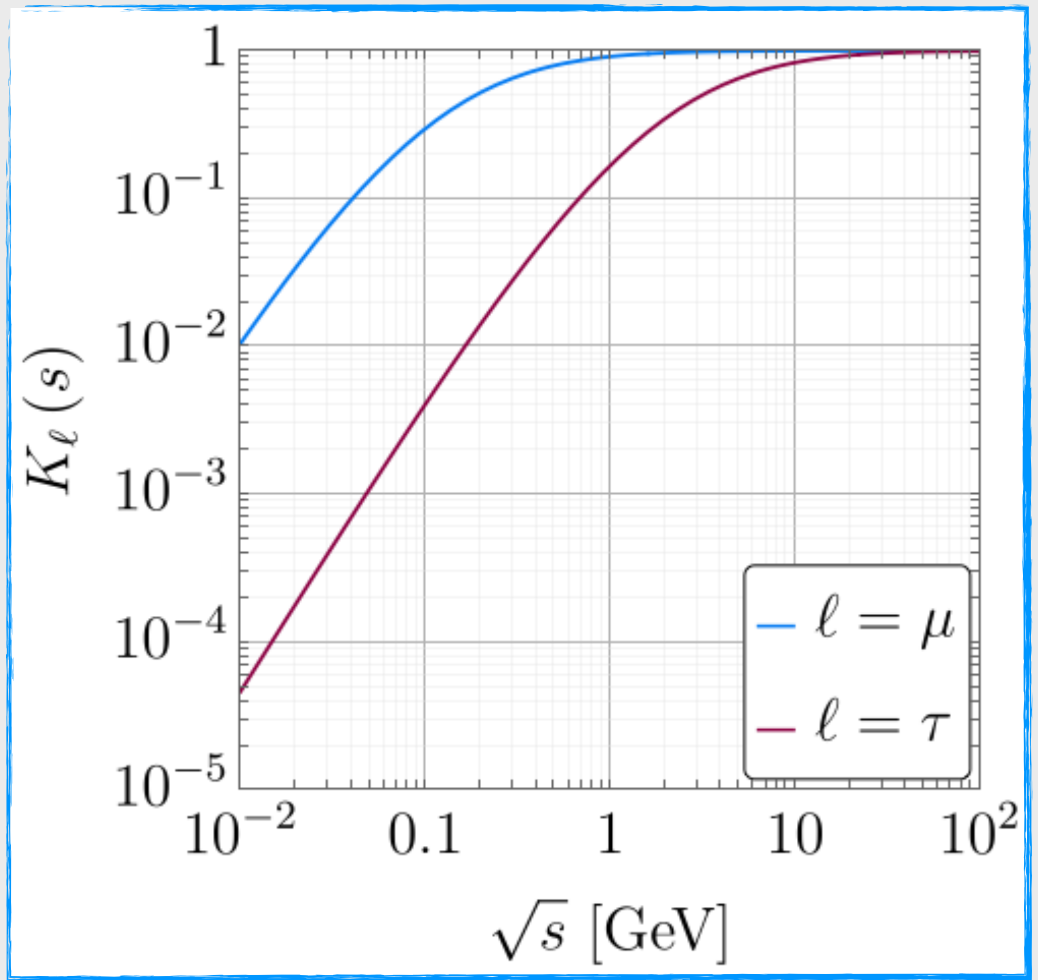

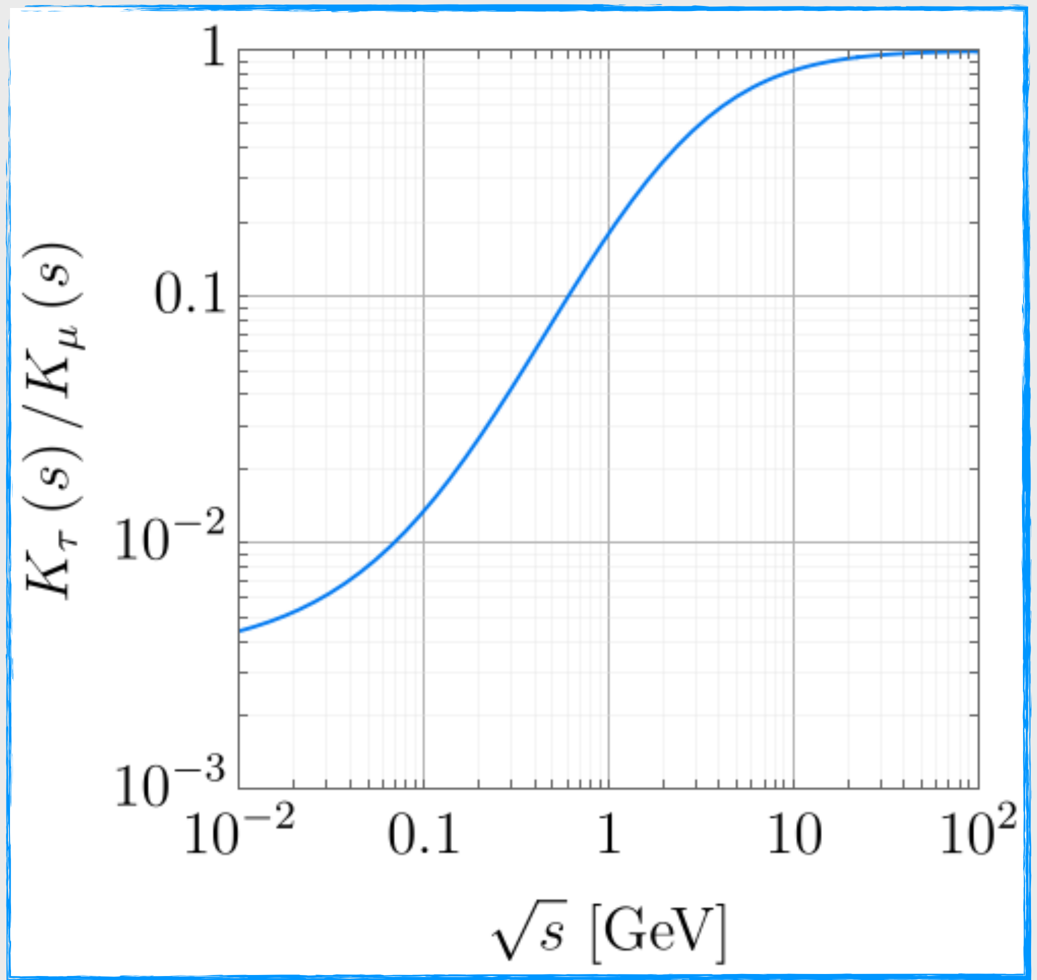

TAU (g-2) IN THE STANDARD MODEL

Experimentally-determined cross sections

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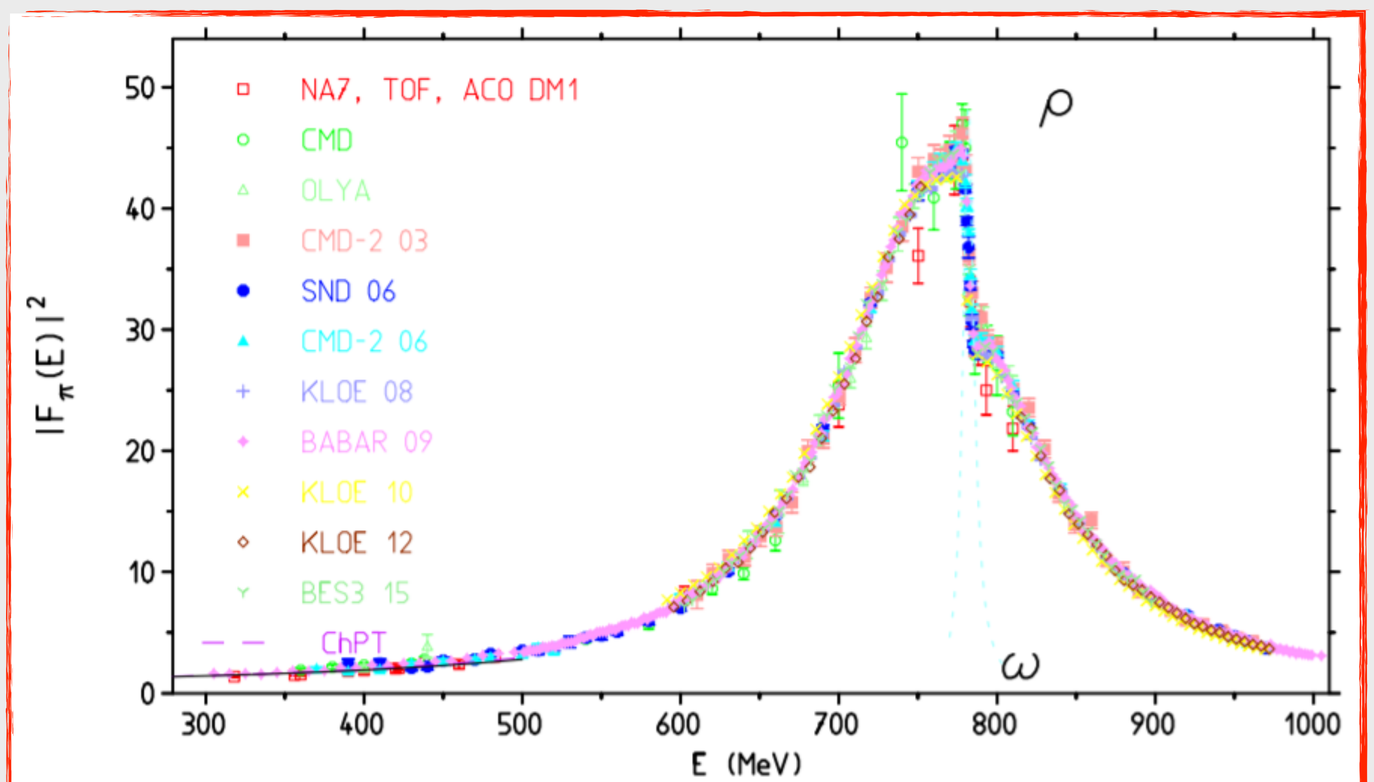

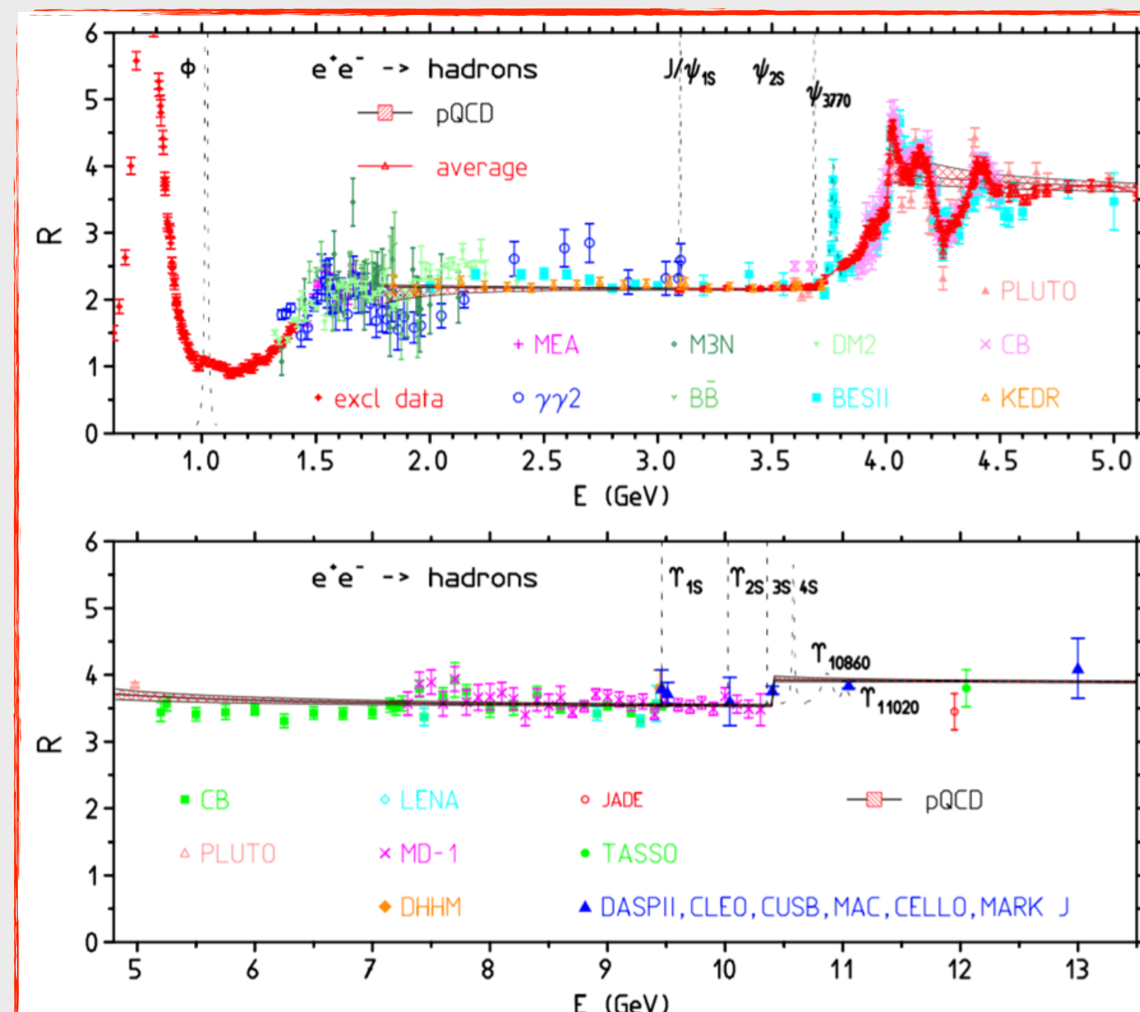

Jegerlehner, EPJ Web Conf. 166 (2018) 00022

TAU (g-2) IN THE STANDARD MODEL

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$$a_\tau^{\mathrm{HLO}} = 337.5(3.7) \times 10^{-8}$$

$$a_e^{\mathrm{HLO}} = 184.90(1.08) \times 10^{-14}$$

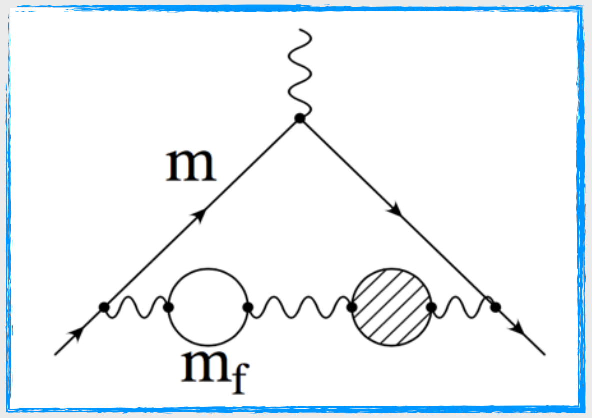
$$a_\mu^{\mathrm{HLO}} = 689.46(3.25) \times 10^{-11}$$

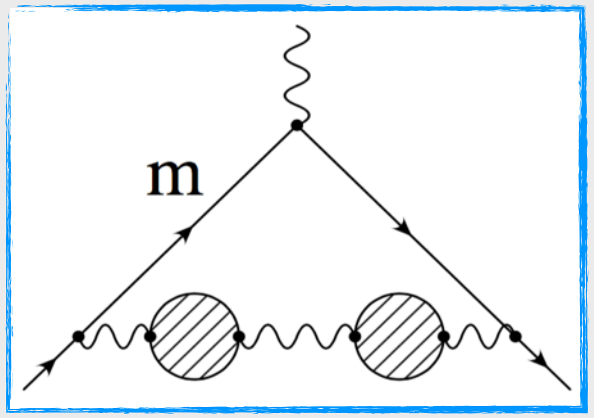
Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159; Jegerlehner, 1711.06089; 1804.07409

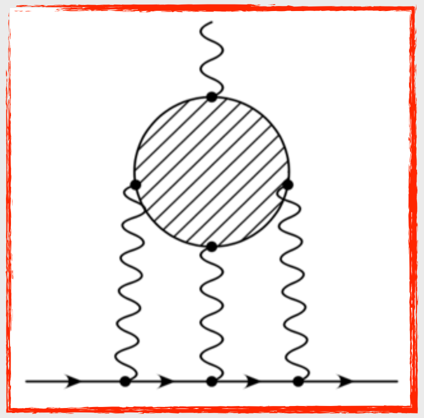
TAU (g-2) IN THE STANDARD MODEL

B. Krause, Phys.Lett. B390 (1997) 392

- Higher-order hadronic contributions:







$$a_\tau^{\rm HHO}(\text{vacuum}) = 7.6(2) \times 10^{-8}$$

$$a_e^{\rm HHO}(\text{vacuum; 2-loop}) = -22.13(0.12) \times 10^{-14}$$
$$a_e^{\rm HHO}(\text{vacuum; 3-loop}) = 2.80(0.02) \times 10^{-14}$$

$$a_\mu^{\rm HHO}(\text{vacuum; 2-loop}) = -992.7(6.7) \times 10^{-11}$$
$$a_\mu^{\rm HHO}(\text{vacuum; 3-loop}) = 12.24(0.10) \times 10^{-11}$$

$$a_\tau^{\rm HHO}(\text{LBL}) = 5(3) \times 10^{-8}$$

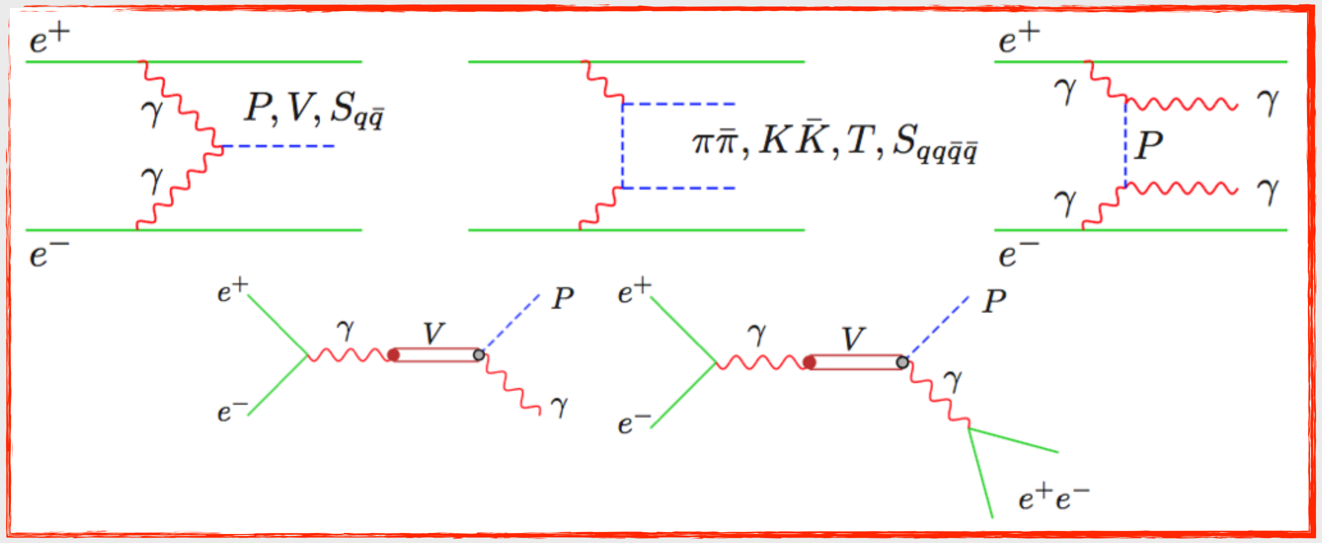
$$a_e^{\rm HHO}(\text{LBL}) = 3.7(0.5) \times 10^{-14}$$
$$a_\mu^{\rm HHO}(\text{LBL}) = 103.4(28.8) \times 10^{-11}$$

Possibility for dispersion-relation approach: Colangelo, et al., JHEP 1509 (2015) 074

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159; Jegerlehner, 1711.06089; 1804.07409

TAU (g-2) IN THE STANDARD MODEL

- Higher-order hadronic contributions:



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TAU (g-2) IN THE STANDARD MODEL

- The result:

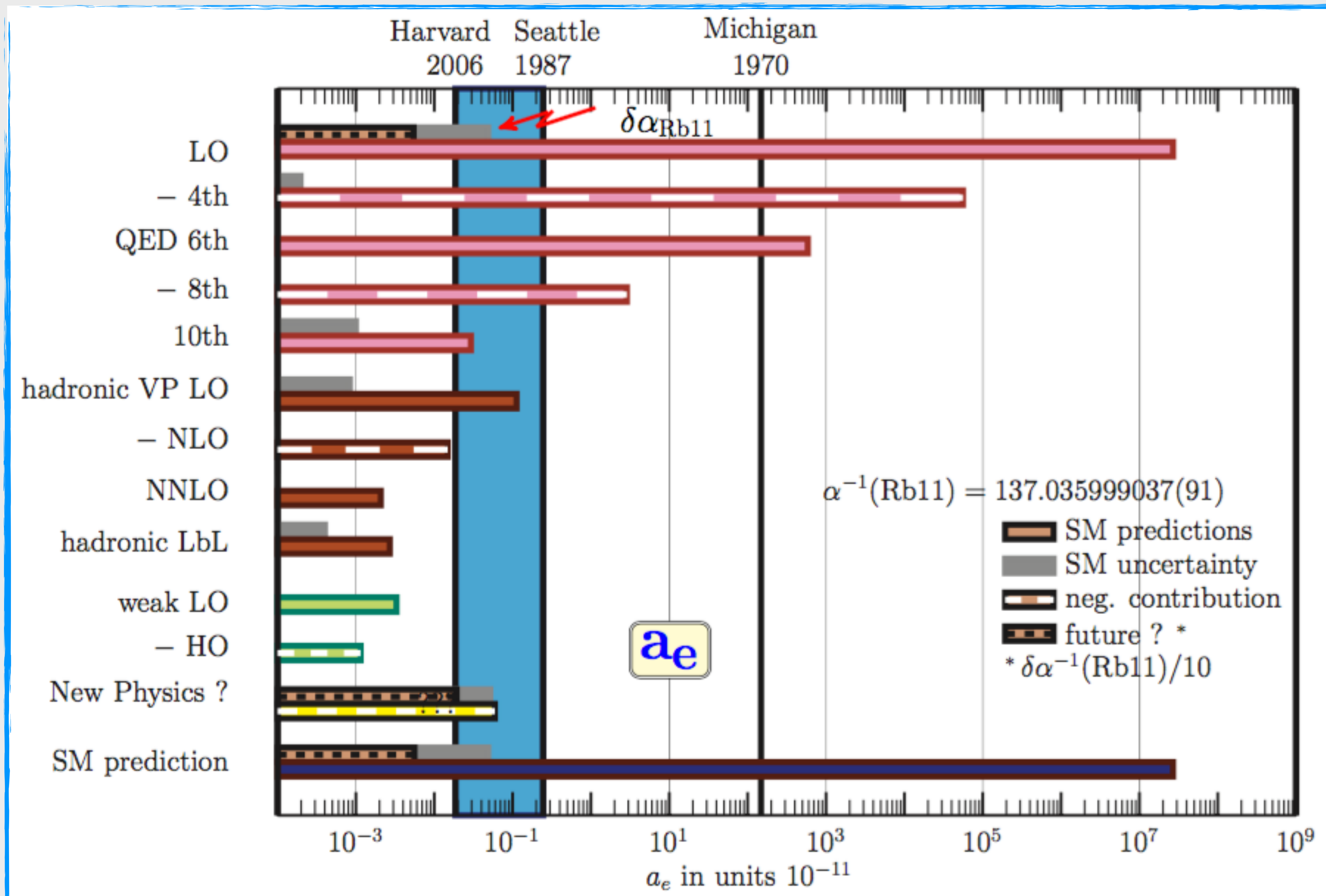
$$
\begin{aligned}
a_\tau^{\mathrm{SM}} &= a_\tau^{\mathrm{QED}} + a_\tau^{\mathrm{EW}} + a_\tau^{\mathrm{hadrons}} \\
&= 117\,721(5) \times 10^{-8}
\end{aligned}
$$

$$a_e^{\mathrm{SM}} = 115\,965\,218.173(77) \times 10^{-11}$$

$$a_\mu^{\mathrm{SM}} = 116\,591\,783(35) \times 10^{-11}$$

Eidelman & Passera, Mod.Phys.Lett. A22 (2007) 159; Jegerlehner, 1711.06089; 1804.07409

TAU (g-2) IN THE STANDARD MODEL



Jegerlehner, 1804.07409

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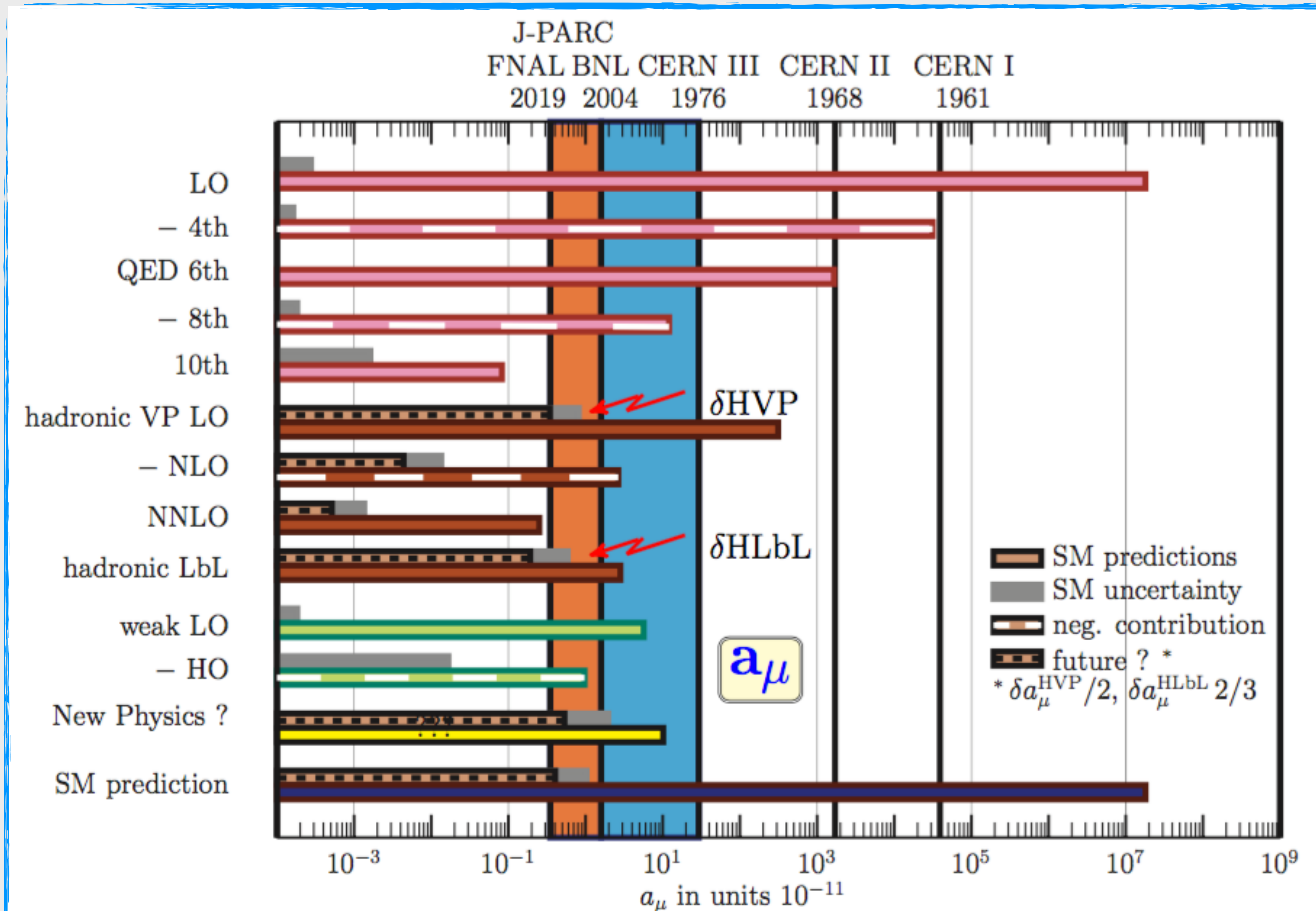
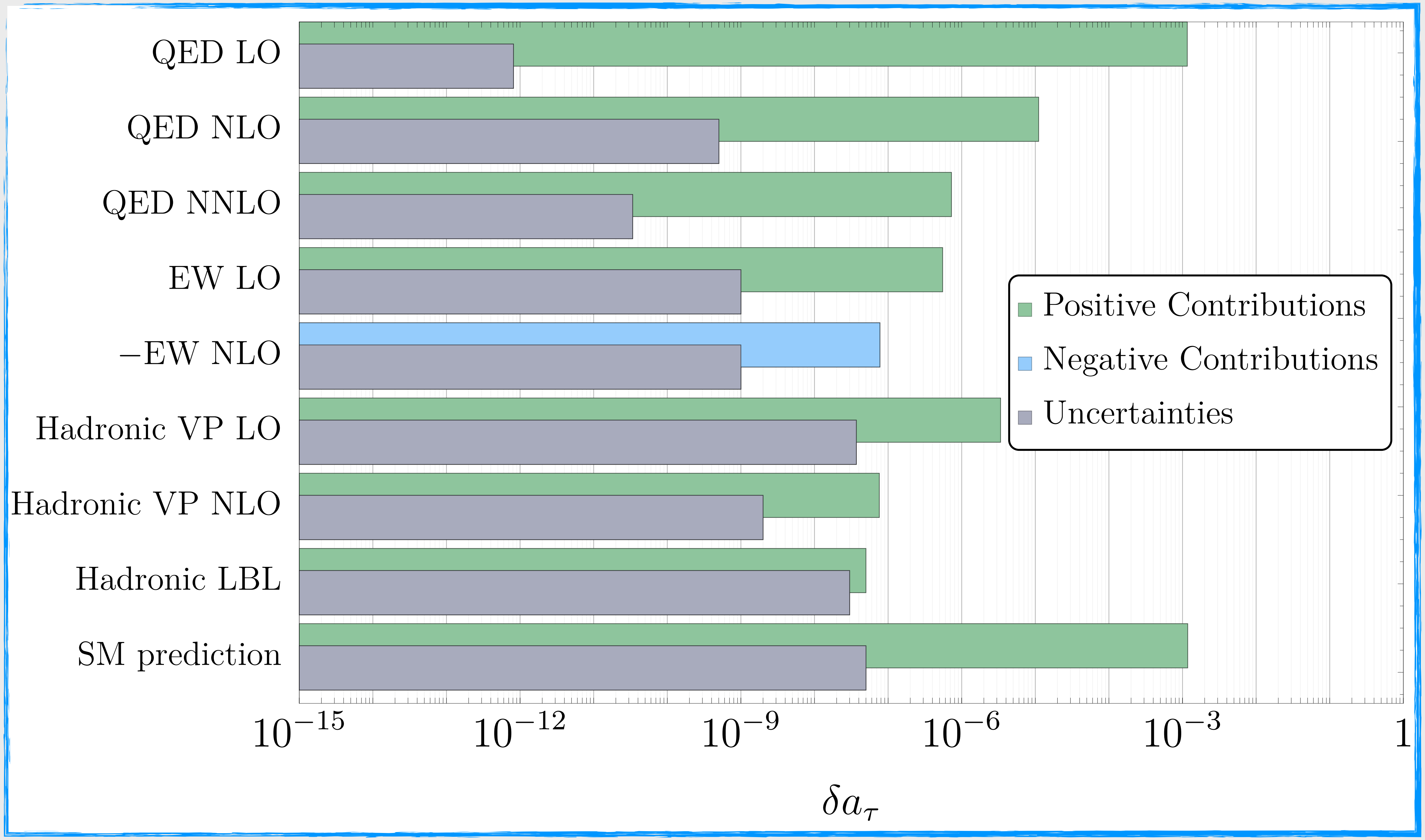


Jegerlehner, 1804.07409

TAU (g-2) IN THE STANDARD MODEL



INCORPORATING NEW PHYSICS – EFFECTIVE FIELD THEORY

- The Standard Model as an Effective Field Theory – SMEFT

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_5 + \mathcal{L}_6 + \ldots$$

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Renormalizable part

Nonrenormalizable part

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Nonrenormalizable part

$$\mathcal{L}_D = \frac{1}{\Lambda^{D-4}} \sum c_{\mathcal{O}} \mathcal{O}^D$$

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Scale of new physics

Operator in terms of pre-EWSB fields

INCORPORATING NEW PHYSICS – EFFECTIVE FIELD THEORY

- The operators we care about:

$$\mathcal{L}_6 \supset \frac{c_B g'}{2\Lambda^2}\left[\left(\overline{L}_L H\right)\sigma^{\mu\nu}\tau_R\right] B_{\mu\nu} + \frac{c_W g}{2\Lambda^2}\left[\left(\overline{L}_L \vec{\tau} H\right)\sigma^{\mu\nu}\tau_R\right]\cdot \vec{W}_{\mu\nu} + \text{h.c.}$$

- After EWSB, this becomes:

$$\begin{aligned}\mathcal{L} \supset\ & a_\tau \frac{e}{4m_\tau}\overline{\tau}\sigma_{\mu\nu}\tau F^{\mu\nu}\left(1+\frac{h}{v}\right) + \\ & a_Z \frac{e}{4m_\tau}\overline{\tau}\sigma_{\mu\nu}\tau Z^{\mu\nu}\left(1+\frac{h}{v}\right) + \\ & \left[\kappa_W \frac{e}{4\sqrt{2}m_\tau \sin\theta_W}\overline{\nu}_\tau\sigma_{\mu\nu}P_R\tau \left(W^\dagger\right)^{\mu\nu}\left(1+\frac{h}{v}\right) + \text{h.c.}\right]\end{aligned}$$

INCORPORATING NEW PHYSICS – EFFECTIVE FIELD THEORY

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$$\boxed{\begin{aligned}a_\tau &= \sqrt{2}(c_B - c_W)\frac{m_\tau v}{\Lambda^2} \\ a_Z &= -\sqrt{2}(c_W \cot\theta_W + c_B \tan\theta_W)\frac{m_\tau v}{\Lambda^2} \\ \kappa_W &= 2\sqrt{2}c_W \frac{m_\tau v}{\Lambda^2}\end{aligned}}$$

INCORPORATING NEW PHYSICS – EFFECTIVE FIELD THEORY

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The operator we want!

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Current best limit – combined analysis of:
  - LEP1 & SLD: $R_{\tau\mu} \equiv \left.\frac{\sigma(e^+e^- \to \tau^+\tau^-)}{\sigma(e^+e^- \to \mu^+\mu^-)}\right|_{s=M_Z^2} = 1.0011 \pm 0.0027$

$$\Longrightarrow \boxed{-5.2 < a_Z \cdot 10^3 < -1.2 \text{ or } 1.2 < a_Z \cdot 10^3 < 4.3}$$

  - LEP2:

$$R_{\tau\overline{\tau}} \equiv \frac{\sigma(e^+e^- \to \tau^+\tau^-)}{\sigma(e^+e^- \to \tau^+\tau^-)_{\text{SM}}} = 0.978 \pm 0.032 \Longrightarrow \boxed{-3.9 < a_\gamma \cdot 10^3 < 1.9}$$

  - Decay asymmetries:

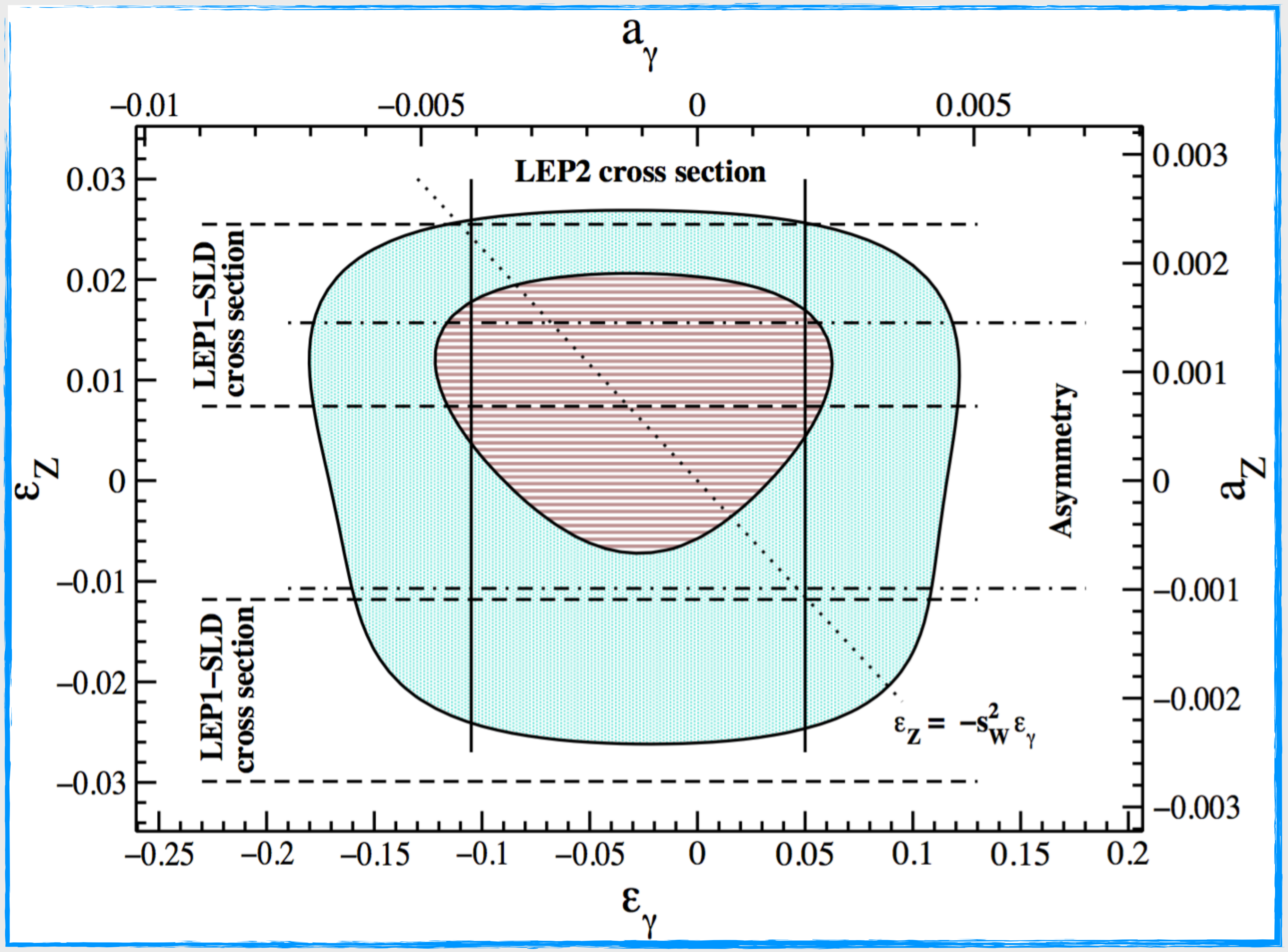
$$e^+e^- \to \tau^+\tau^- \to (h_1^\pm X)(h_2^\mp \overline{\nu}_\tau),\ h_{1,2} = \pi,\ \rho \Longrightarrow \boxed{a_Z \cdot 10^3 = 0.3 \pm 2.1}$$

  - *W* decay universality:

$$R_{\tau e}^W \equiv \frac{\Gamma(W \to \tau\nu)}{\Gamma(W \to e\nu)} = 1.002 \pm 0.030 \Longrightarrow \boxed{-12.7 < \kappa_W \cdot 10^3 < 8.3}$$

González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

EXPERIMENTAL STATUS OF THE TAU (g-2)



González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

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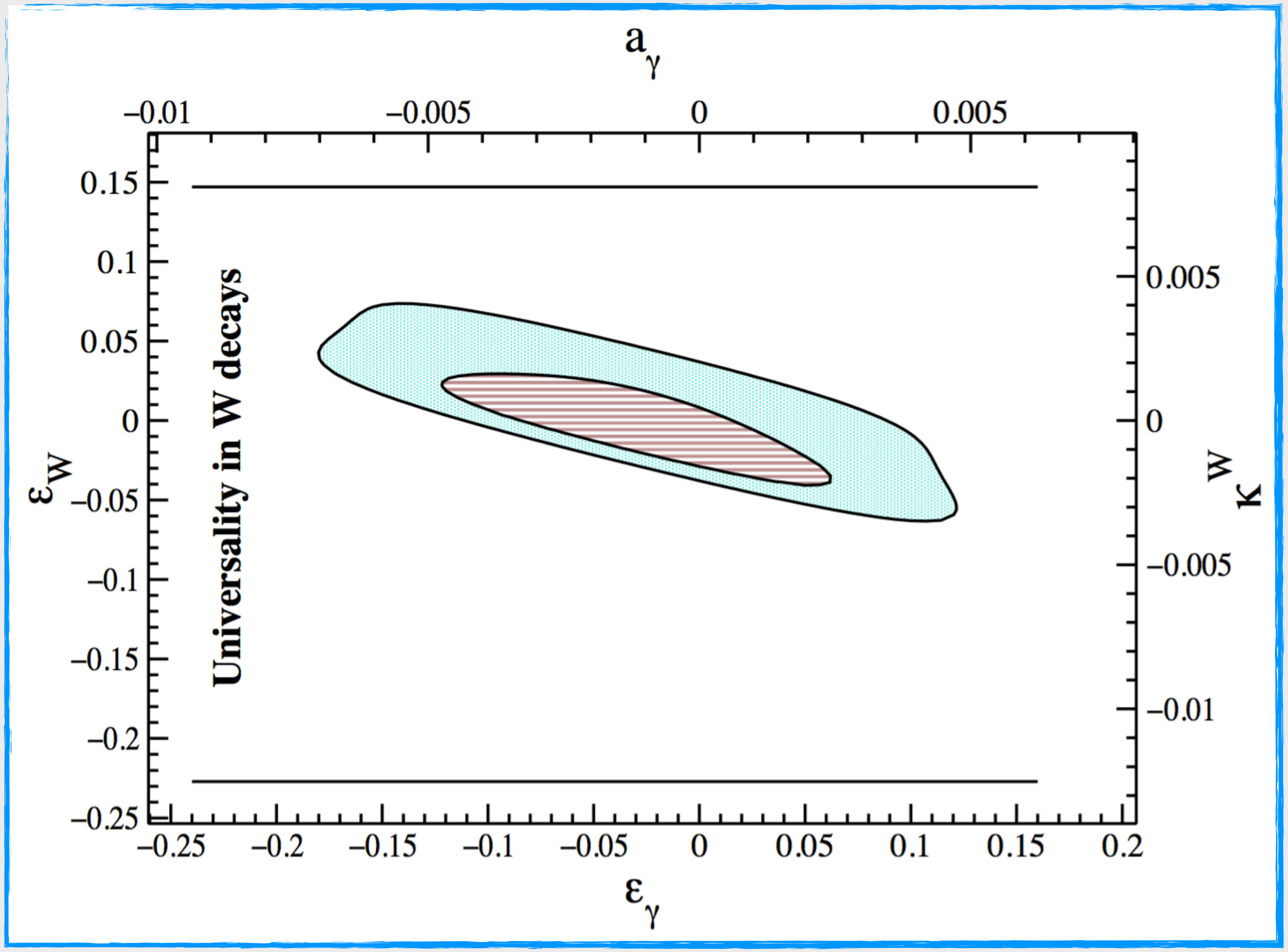
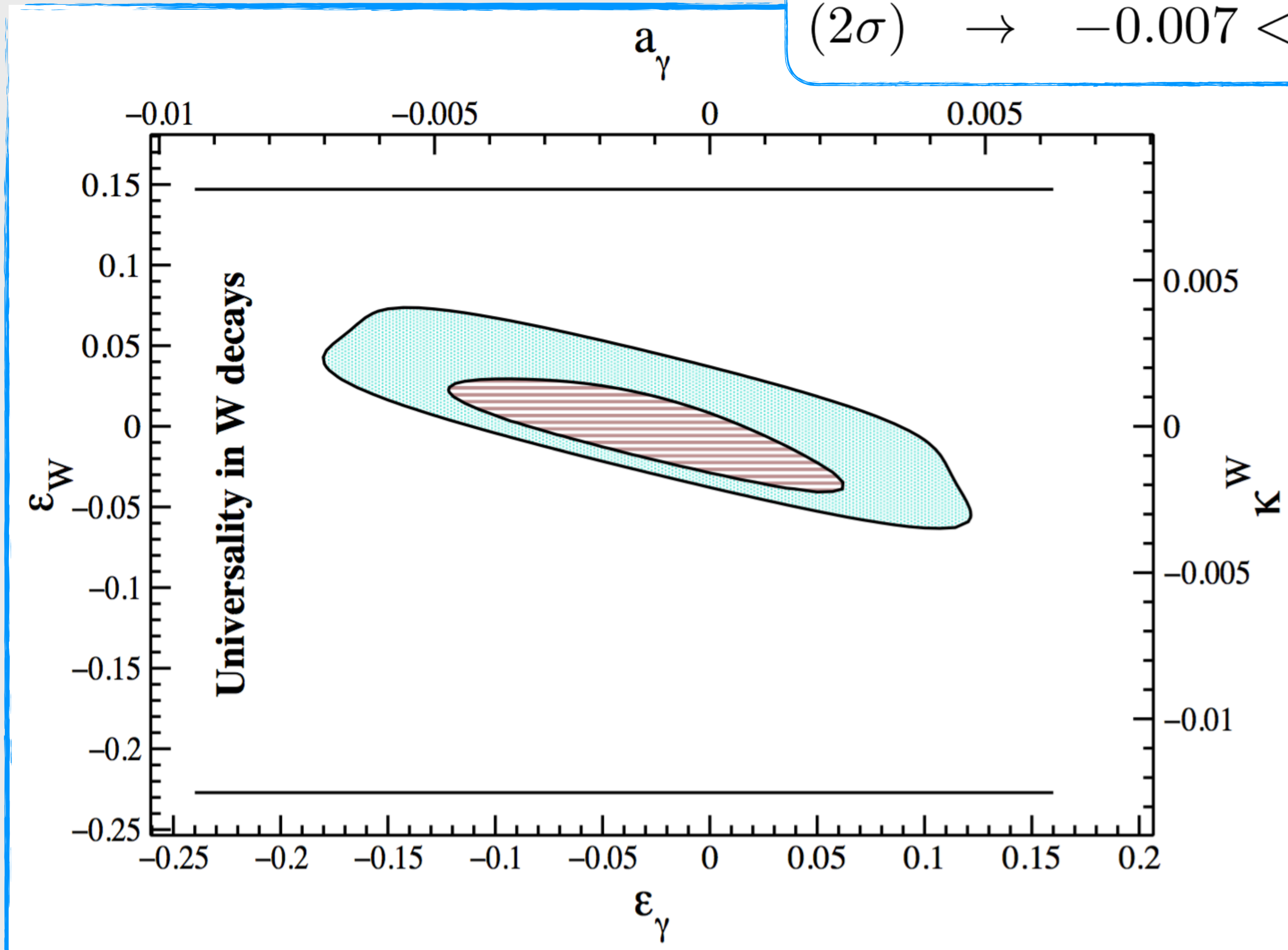


González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

EXPERIMENTAL STATUS OF THE TAU (g-2)

$$(1\sigma) \quad \rightarrow \quad -0.005 < a_\gamma < 0.002$$
$$(2\sigma) \quad \rightarrow \quad -0.007 < a_\gamma < 0.005$$



González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

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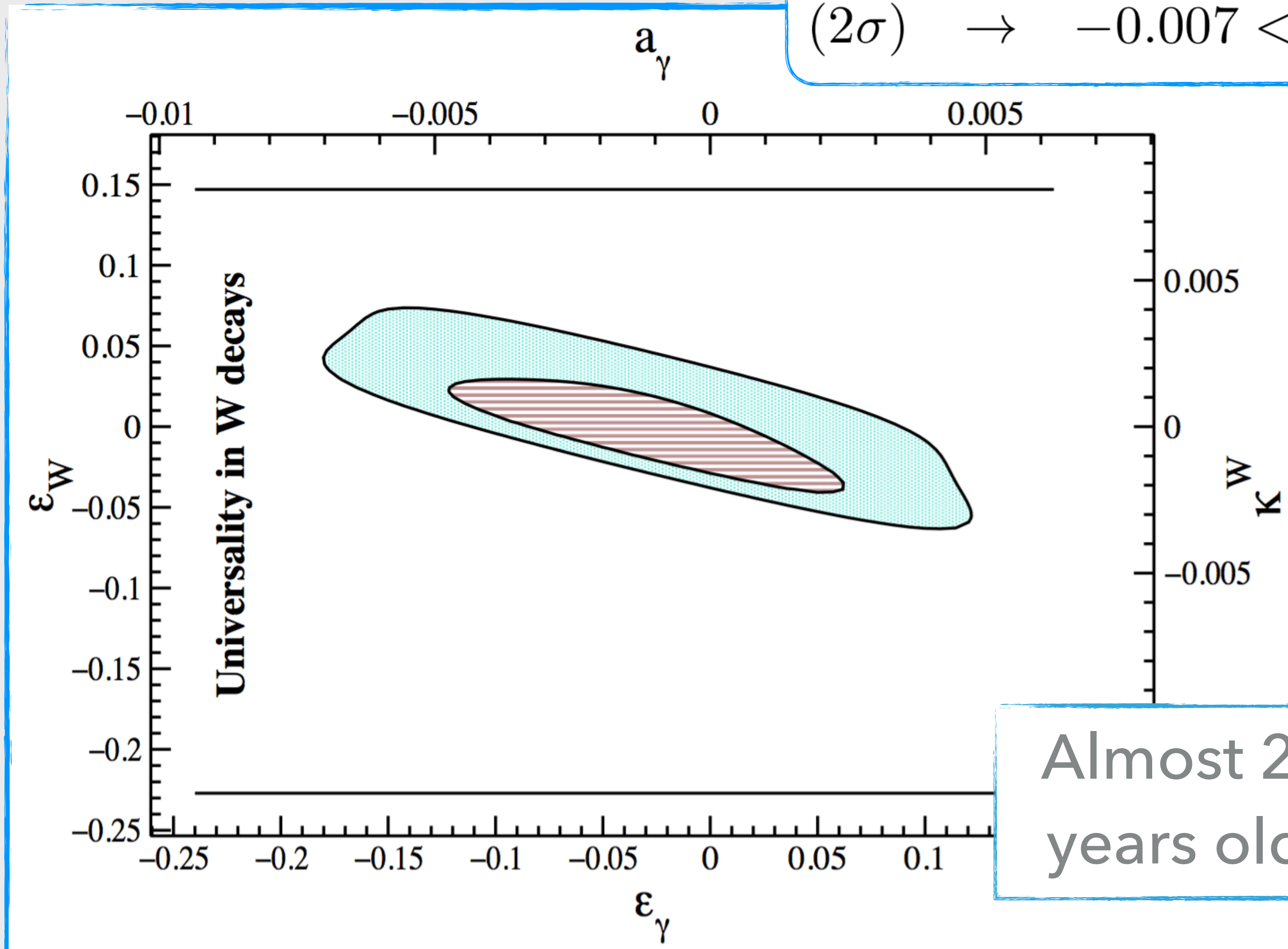


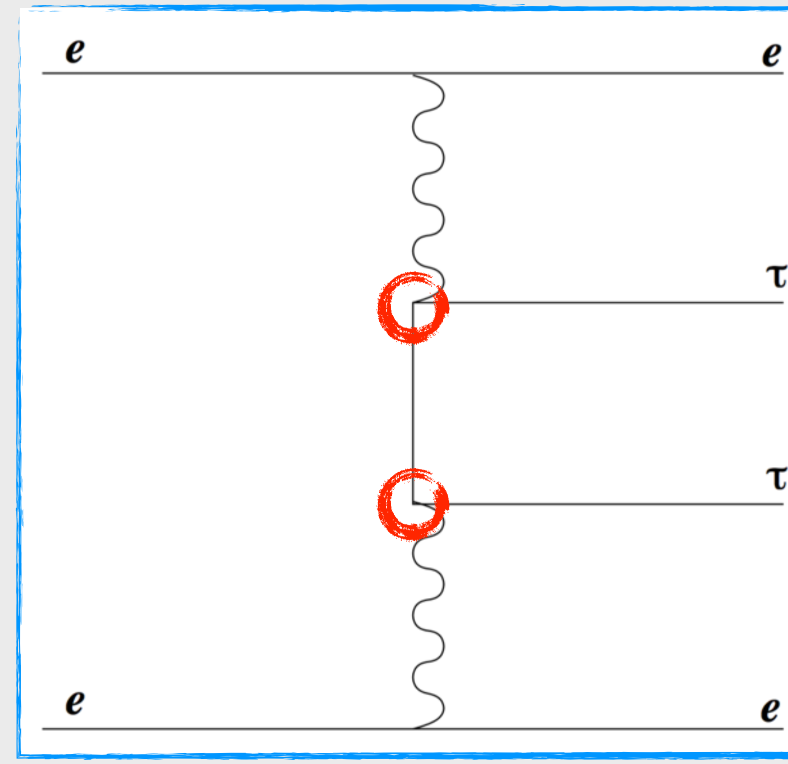
Almost 20 years old!

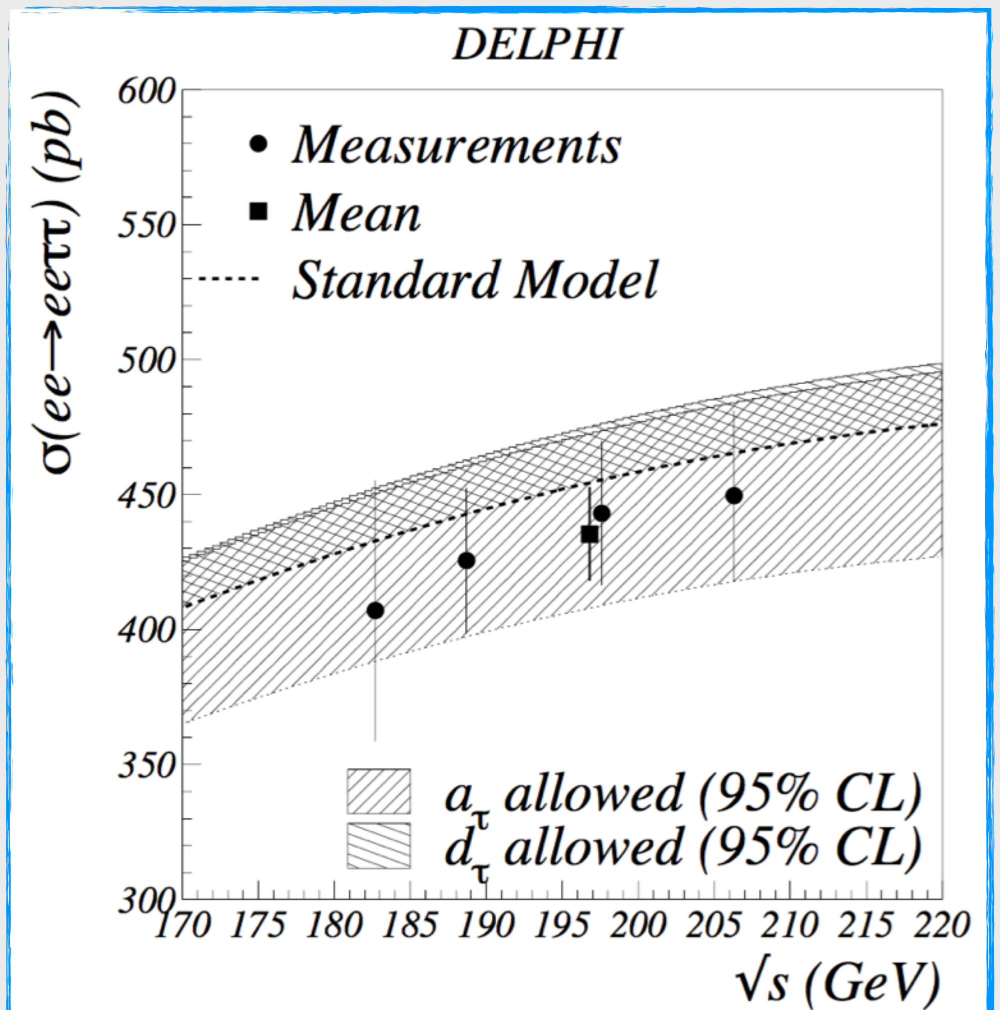
González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Limit from DELPHI

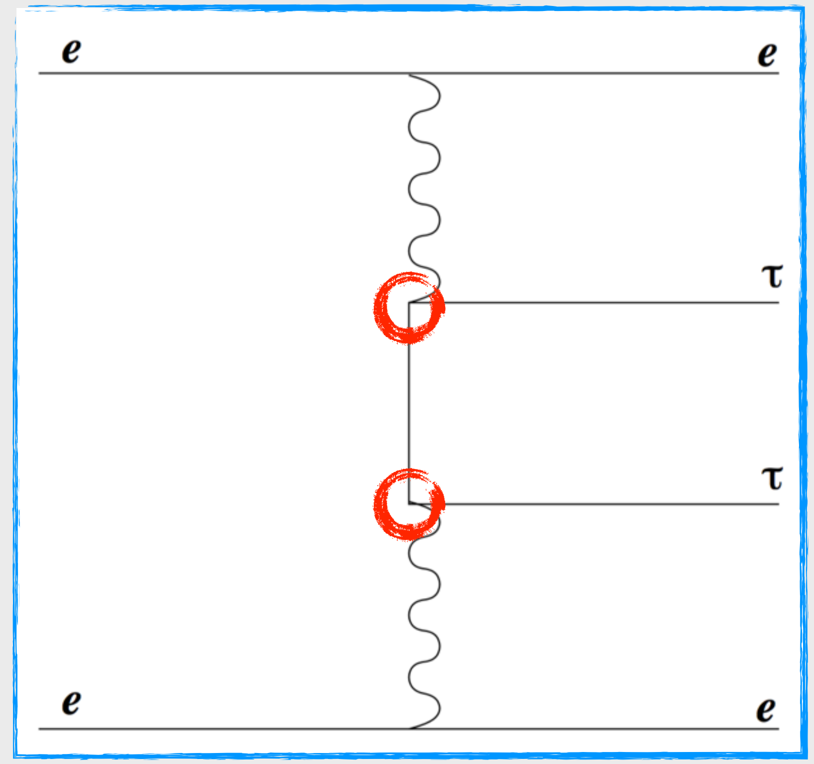
Year	Observed	Expected	σ_{meas}, pb	σ_{MC}, pb	$\sigma_{meas}/\sigma_{MC}$
1997	211	224 ± 18	$401 \pm 32 \pm 36$	428.2 ± 0.5	0.94 ± 0.11
1998	629	652 ± 24	$419 \pm 19 \pm 18$	436.7 ± 0.5	0.96 ± 0.06
1999	909	937 ± 39	$436 \pm 16 \pm 21$	448.5 ± 0.5	0.97 ± 0.06
2000	641	665 ± 32	$443 \pm 20 \pm 24$	459.4 ± 0.5	0.97 ± 0.07





$$-0.052 < a_\tau < 0.013 \ (95\% \ \mathrm{CL})$$

DELPHI Collaboration, Eur.Phys.J. C35 (2004) 159



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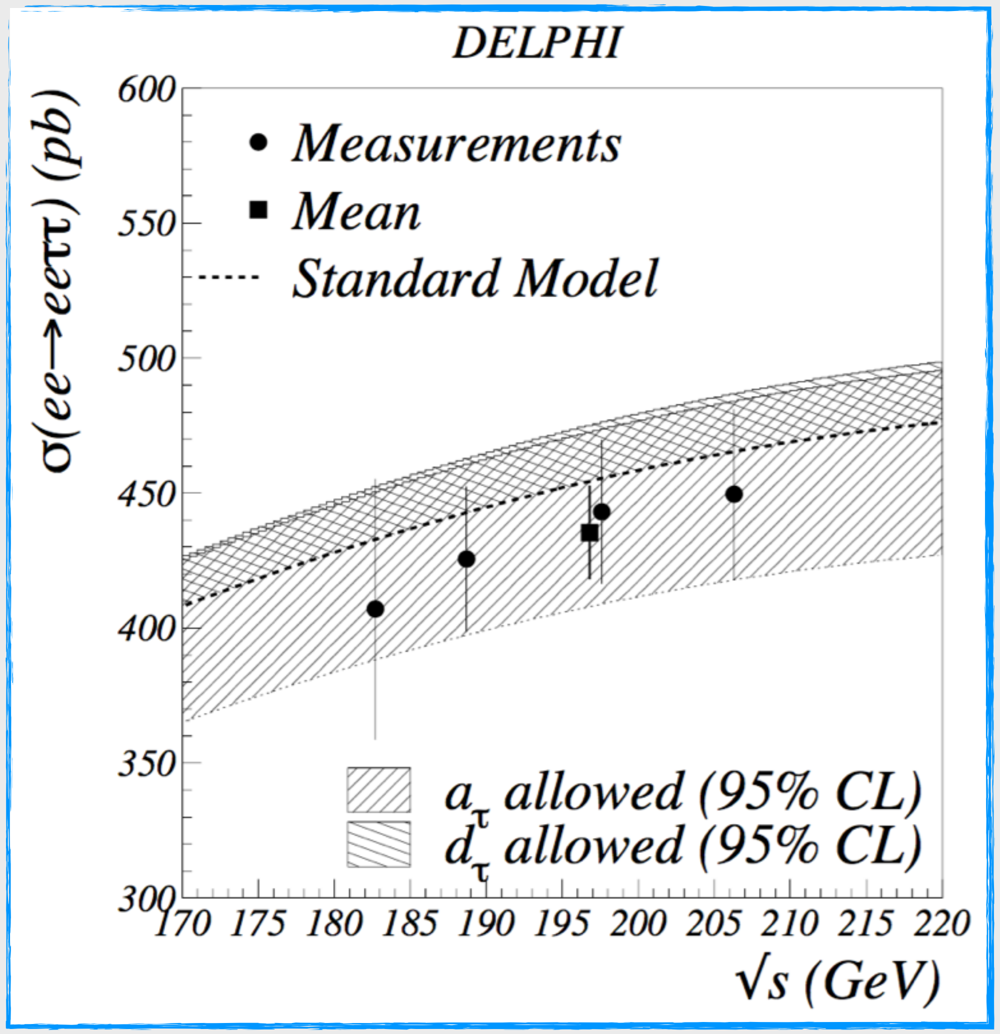

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Again, note the time elapsed!

DELPHI Collaboration, Eur.Phys.J. C35 (2004) 159

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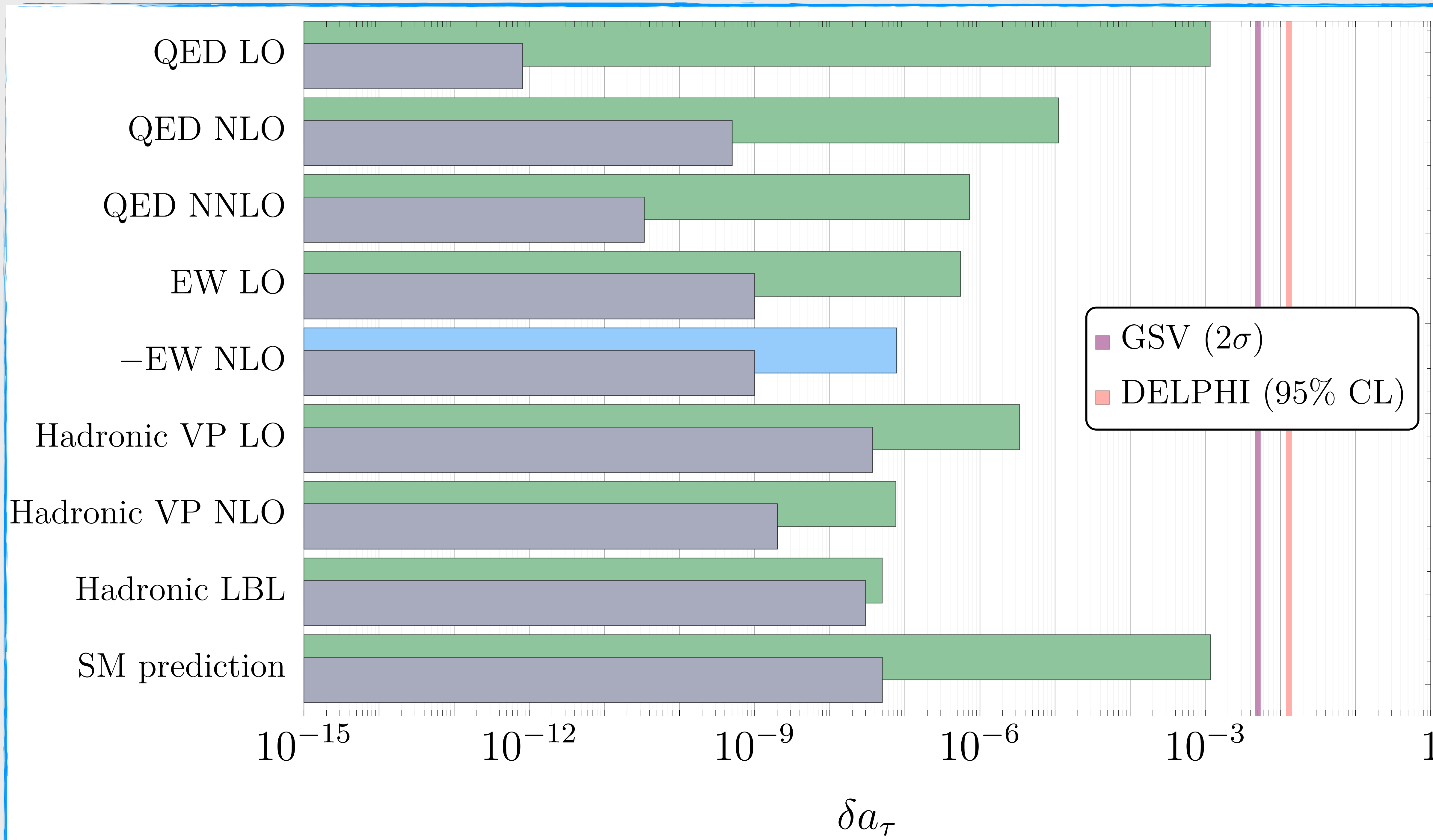
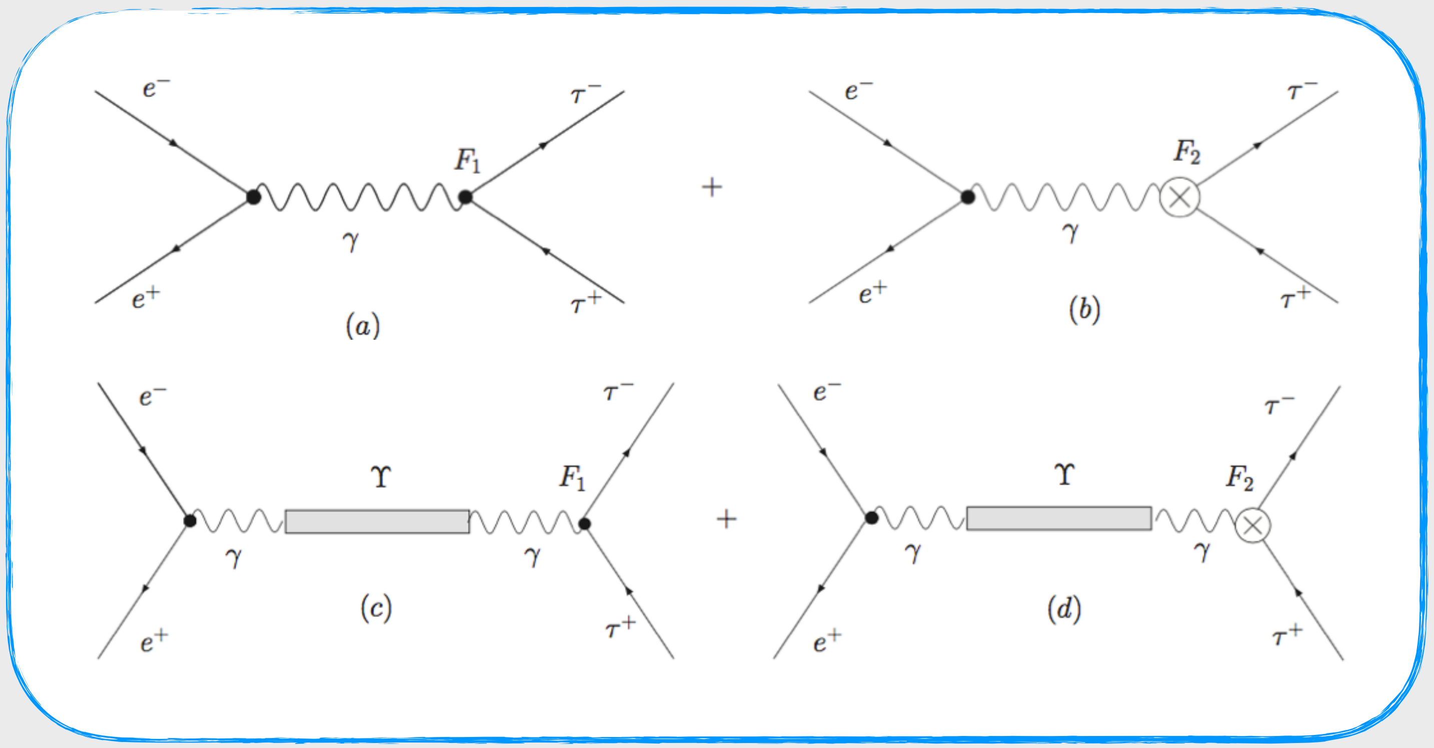


EXPERIMENTAL STATUS OF THE TAU (g-2)

- τ pairs at B factories - BELLE II

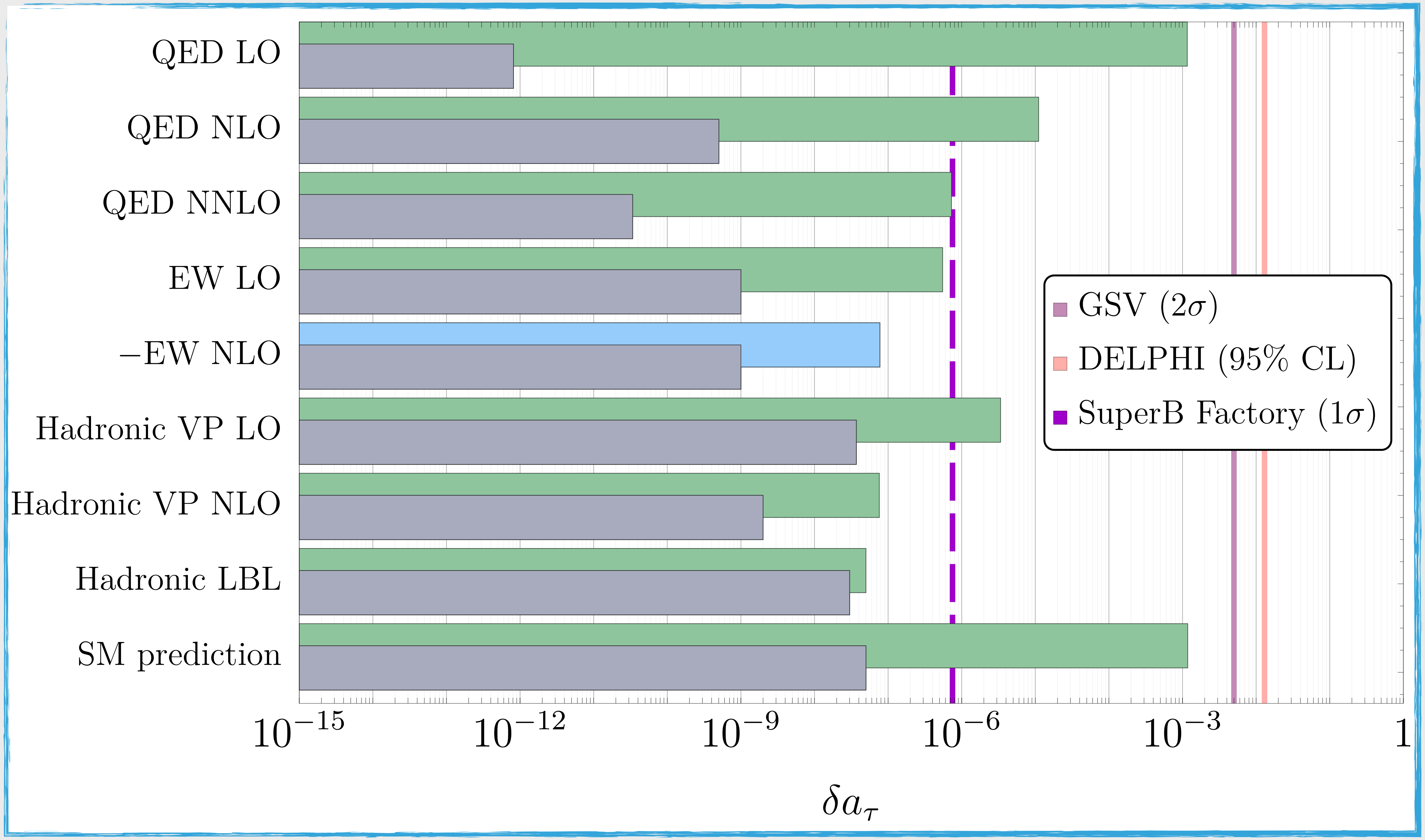


EXPERIMENT ⇓	OBSERVABLE: Cross Section $Re\{F_2\}$	Normal Asymmetry $Im\{F_2\}$	Transverse and Longitudinal Asymmetry combined* $Re\{F_2\}$
Babar+Belle $2ab^{-1}$	4.6×10^{-6}	2.1×10^{-5}	1.0×10^{-5}
Super B/Flavor Factory (1 yr. running) $15ab^{-1}$	1.7×10^{-6}	7.8×10^{-6}	3.7×10^{-6}
Super B/Flavor Factory (5 yrs. running) $15ab^{-1}$	7.5×10^{-7}	3.5×10^{-6}	1.7×10^{-6}

* Polarized electrons required

Bernabéu, et al., Nucl.Phys. B790 (2008) 160
Bernabéu, et al., JHEP 0901 (2009) 062
Eidelman, et al., JHEP 1603 (2016) 140

EXPERIMENTAL STATUS OF THE TAU (g-2)



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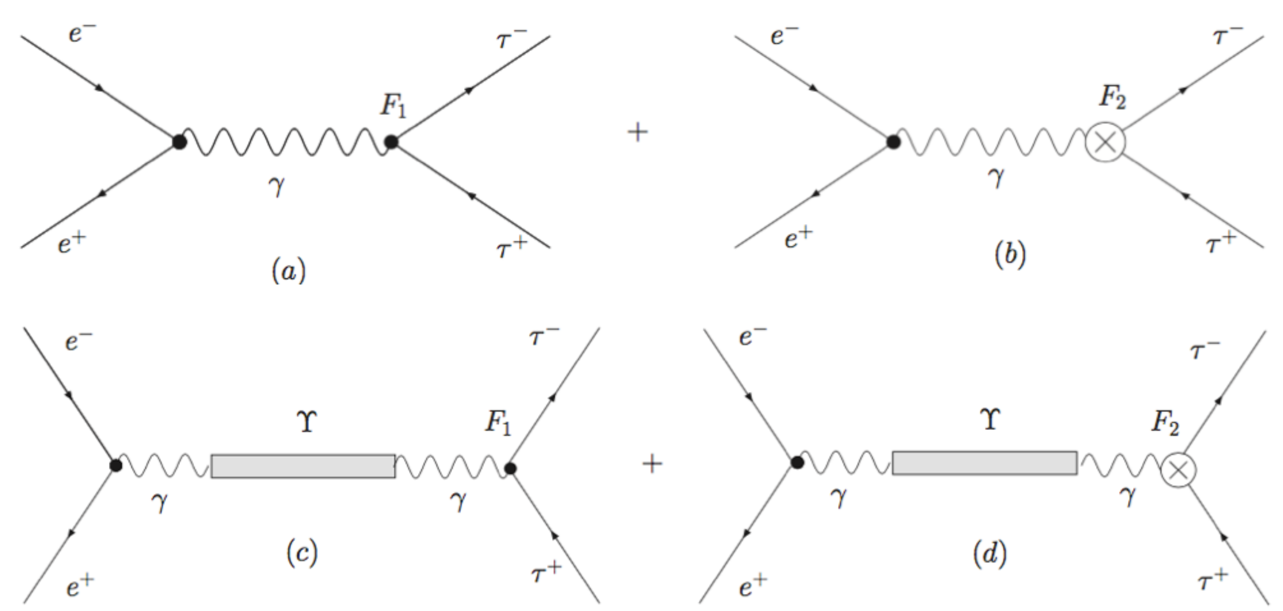

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Υ	M_Υ [GeV]	Γ_Υ [keV]	$\sigma_{\rm peak}$ [nb]	ρ	$\frac{\sigma_{\rm vis}^{\rm max}}{\sigma_{\rm non-res}}$
$\Upsilon(1S)$	9.46	54	101	6.2×10^{-3}	69%
$\Upsilon(2S)$	10.02	32	56	3.7×10^{-3}	22%
$\Upsilon(3S)$	10.36	20	68	2.3×10^{-3}	17%
$\Upsilon(4S)$	10.58	20×10^3	–	–	–

Not enough τ pairs are produced on resonance!

Bernabéu, et al., Nucl.Phys. B790 (2008) 160
Bernabéu, et al., JHEP 0901 (2009) 062
Eidelman, et al., JHEP 1603 (2016) 140

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Radiative τ decays: $\tau^- \rightarrow \ell^- \nu_\tau \overline{\nu}_\ell \gamma$

$$\frac{d^6\Gamma(y_0)}{dx\,dy\,d\Omega_\ell\,d\Omega_\gamma} = \frac{\alpha G_F^2 m_\tau^5}{(4\pi)^6}\frac{x\beta_\ell}{1+\delta_W}\left[G + x\beta_\ell\,\hat{n}\cdot\hat{p}_\ell J + y\,\hat{n}\cdot\hat{p}_\gamma K + xy\beta_\ell\ \left(\hat{p}_\ell\times\hat{p}_\gamma\right)L\right]$$

$$x = 2E_\ell/m_\tau,\ y = 2E_\gamma/m_\tau,\ \beta_\ell = \sqrt{1-4r^2/x^2},\ r = m_\ell/m_\tau$$

Eidelman, et al., JHEP 1603 (2016) 140

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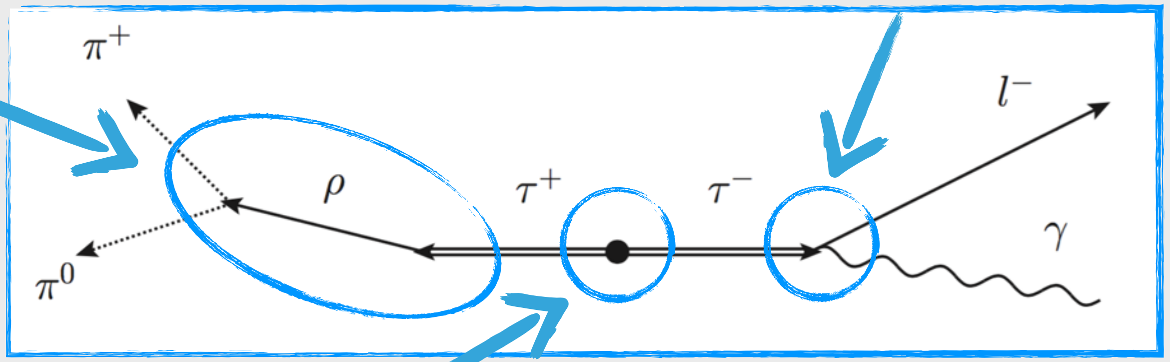
$$\frac{d^5\Gamma(\tau^\pm(\hat{n}^\pm)\to\pi^\pm\pi^0\nu)}{dm_{\pi\pi}^2\,d\Omega_\rho\,d\Omega_{\pi\rho}} = \kappa_\rho\left[A' \mp \hat{n}^\pm\cdot\vec{B}'\right]W(m_{\pi\pi}^2)$$

$$\frac{d^6\Gamma(\tau^\mp(\hat{n}^\mp)\to\ell^\mp\nu\nu\gamma)}{dx\,dy\,d\Omega_\ell\,d\Omega_\gamma} = \kappa_{\ell\gamma}\left[A \pm \hat{n}^\mp\cdot\vec{B}^\mp\right]$$



$$\frac{d\sigma(\hat{n}^-,\hat{n}^+)}{d\Omega_\tau^*} = \frac{\alpha^2\beta_\tau^*}{64(E_\tau^*)^2}\left[D_0 + D_{ij}n_i^- n_j^+\right]$$

Eidelman, et al., JHEP 1603 (2016) 140

EXPERIMENTAL STATUS OF THE TAU (g-2)

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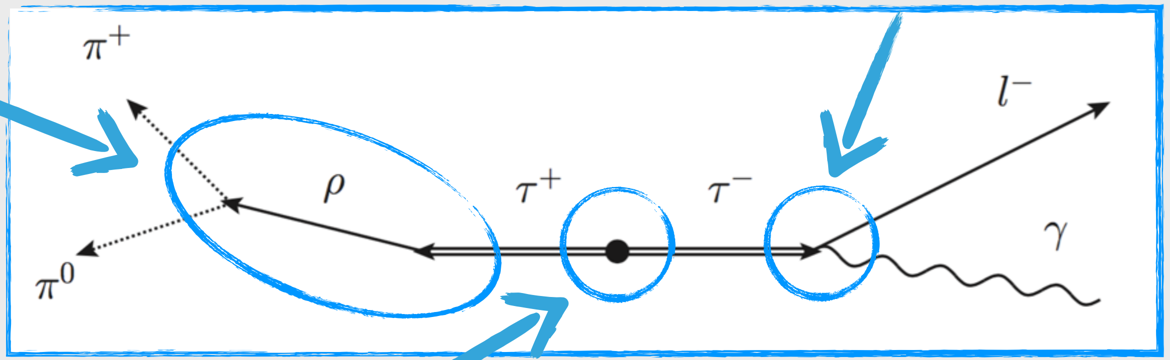

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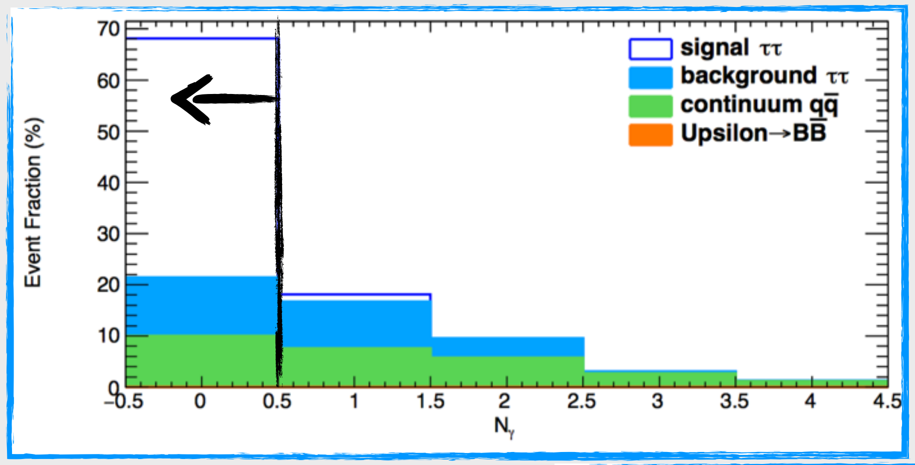
	Belle (ρ)	Belle II (ρ)	Belle (full)	Belle II (full)	DELPHI
$\tilde{a}_\tau$	0.16	0.023	0.085	0.012	0.017

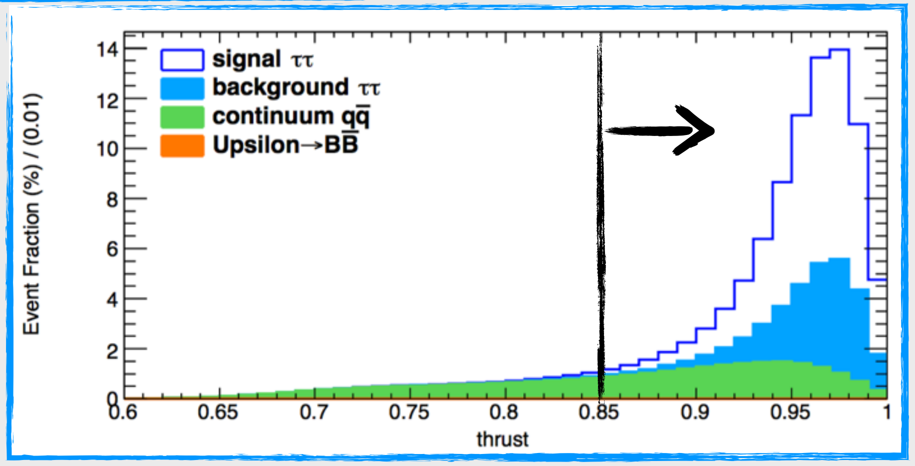
Eidelman, et al., JHEP 1603 (2016) 140

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Analysis of Belle II: $e^+e^- \to \tau^+\tau^-$

Mode	Sig. $\tau\tau$ (pb)	Bkg. $\tau\tau$ (pb)	Cont. (pb)	Upsilon (fb)
$a_1 + a_1$	3.09	0.00	0.52	0.40
$a_1 + \rho$	16.14	0.39	1.22	1.32
$a_1 + \pi$	9.30	0.70	0.64	0.68
$\pi + \pi$	7.42	2.50	0.51	0.53
$\pi + \rho$	24.13	3.16	1.07	1.01
$\rho + \rho$	20.96	1.60	0.93	1.21
total	81.04	8.35	4.89	5.16





Chen & Wu, 1803.00501

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Analysis of Belle II: $e^+e^- \to \tau^+\tau^-$

$$\sigma \propto M_0 + M_1\left(\frac{a_\tau}{2m_\tau}\right) + M_2\left(\frac{a_\tau}{2m_\tau}\right)^2$$

$$\mathcal{OO} \equiv \left(\frac{M_1}{\mathrm{GeV}}\right)\frac{1}{M_0}$$

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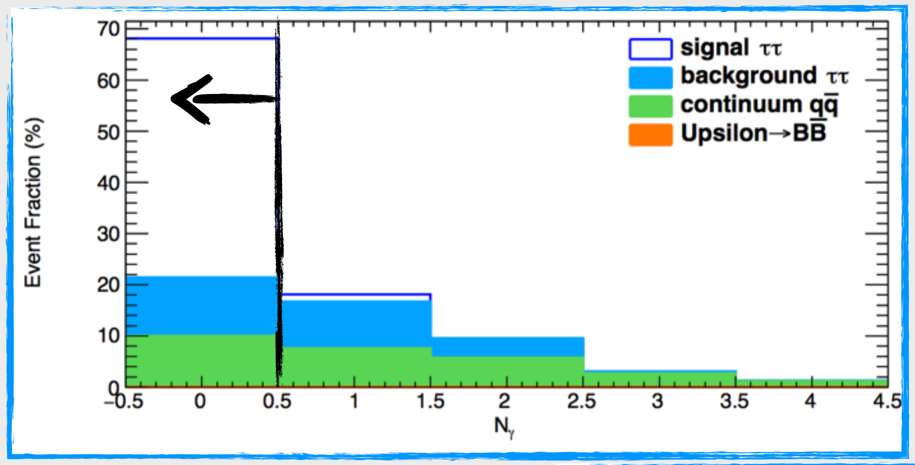
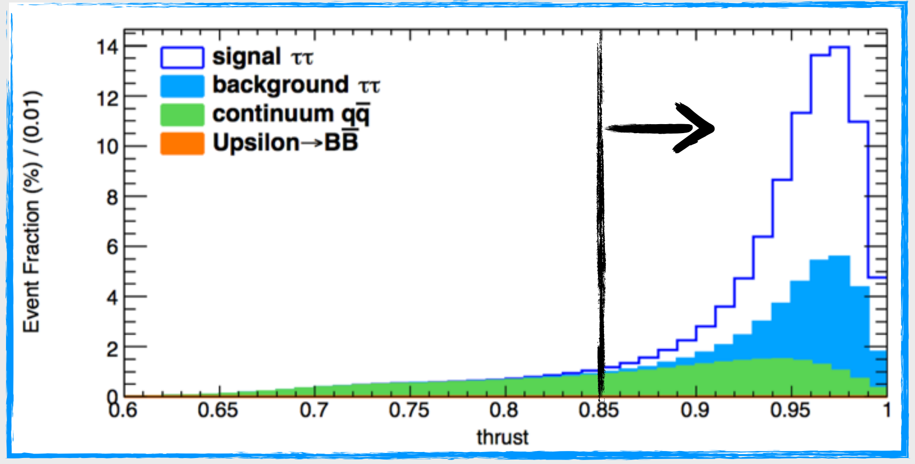
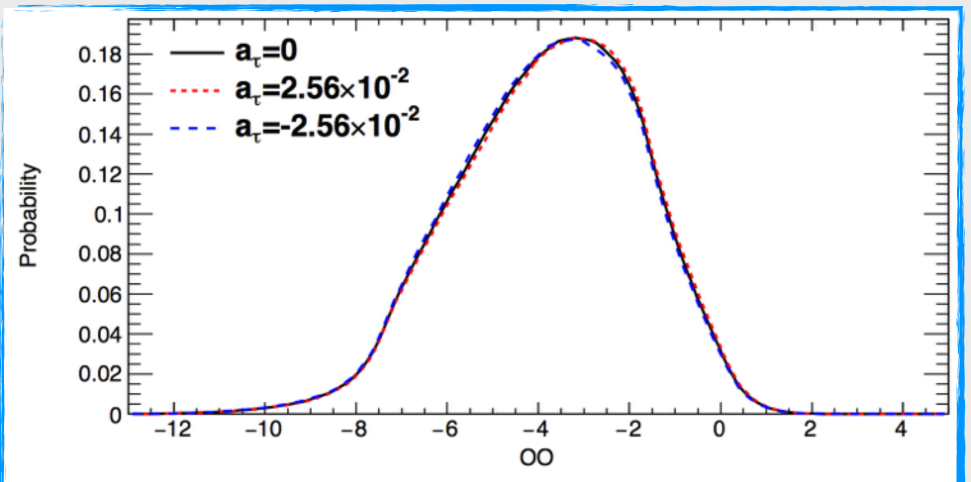
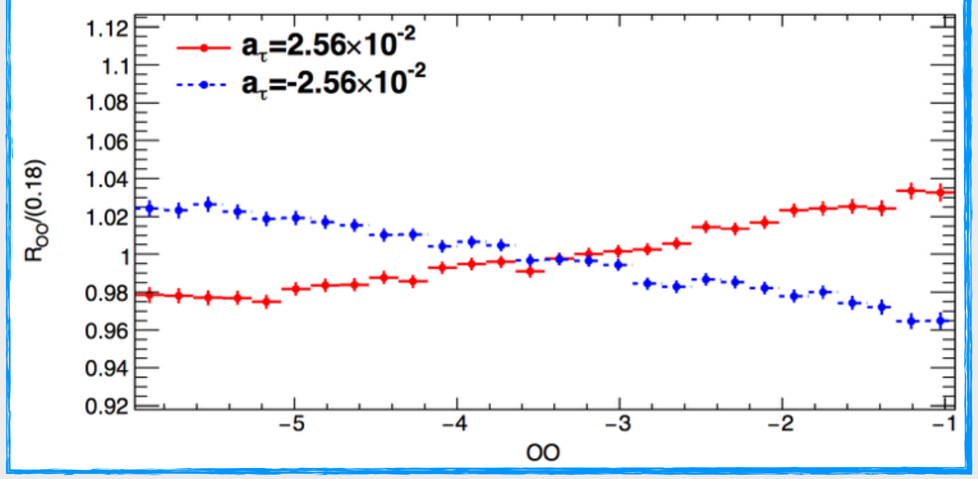








Chen & Wu, 1803.00501

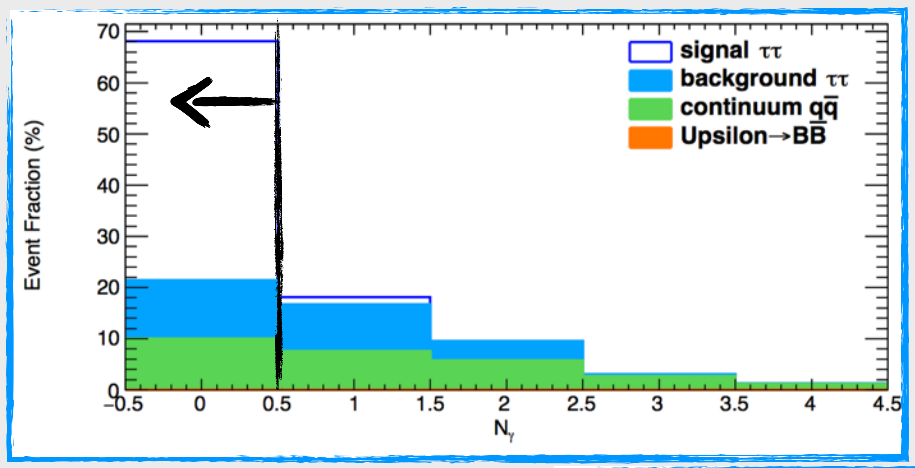
EXPERIMENTAL STATUS OF THE TAU (g-2)

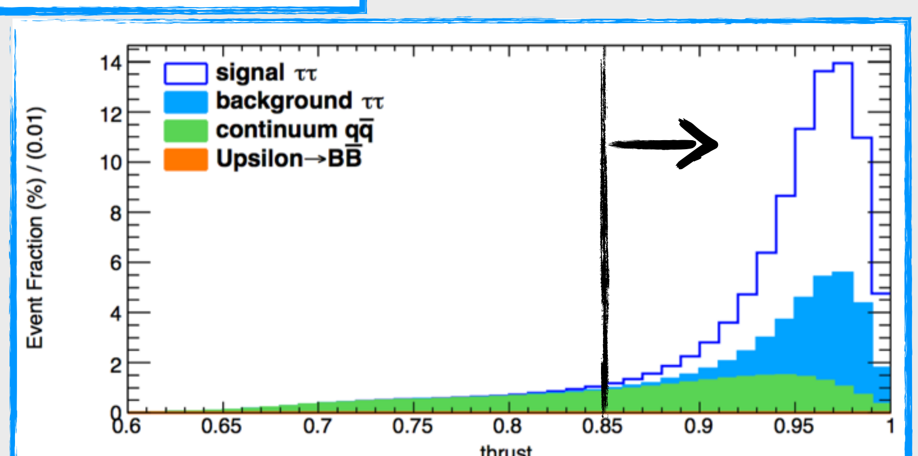
- Analysis of Belle II: $e^+e^- \to \tau^+\tau^-$

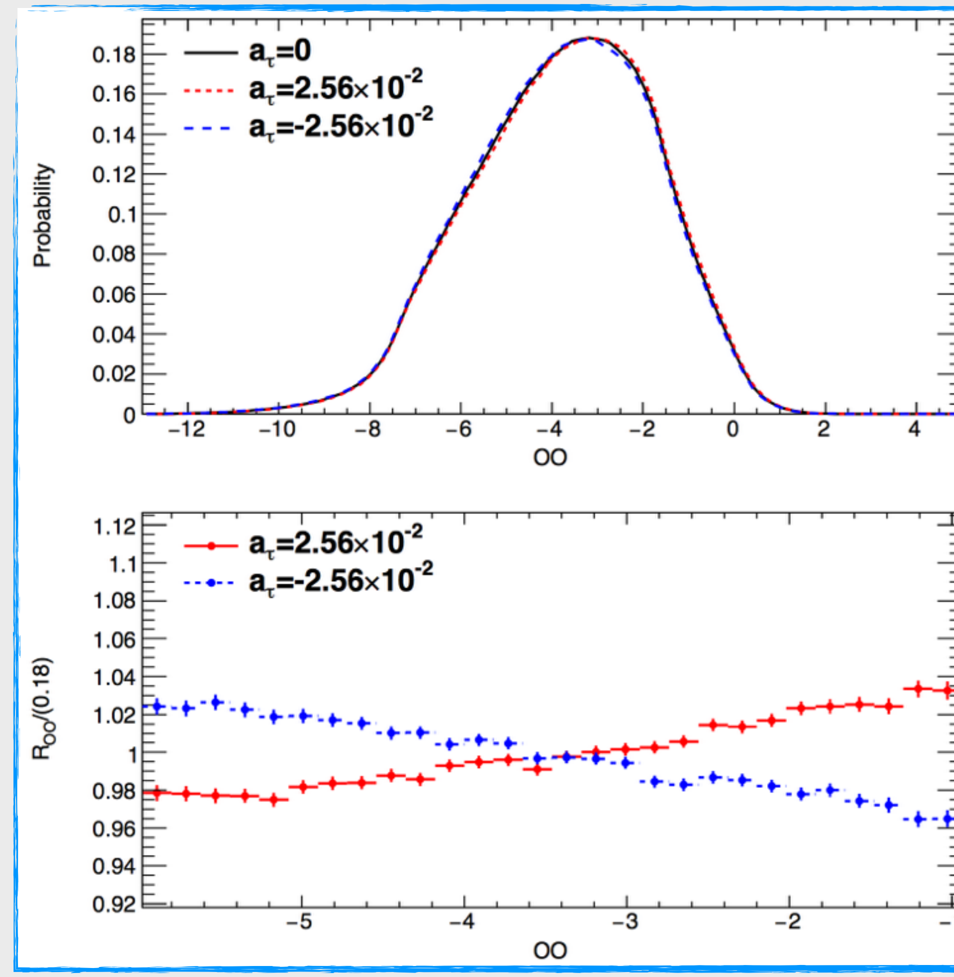
$$\sigma \propto M_0 + M_1 \left(\frac{a_\tau}{2m_\tau}\right) + M_2 \left(\frac{a_\tau}{2m_\tau}\right)^2$$

$$\mathcal{OO} \equiv \left(\frac{M_1}{\mathrm{GeV}}\right)\frac{1}{M_0}$$

Mode	Sig. $\tau\tau$ (pb)	Bkg. $\tau\tau$ (pb)	Cont. (pb)	Upsilon (fb)
$a_1 + a_1$	3.09	0.00	0.52	0.40
$a_1 + \rho$	16.14	0.39	1.22	1.32
$a_1 + \pi$	9.30	0.70	0.64	0.68
$\pi + \pi$	7.42	2.50	0.51	0.53
$\pi + \rho$	24.13	3.16	1.07	1.01
$\rho + \rho$	20.96	1.60	0.93	1.21
total	81.04	8.35	4.89	5.16



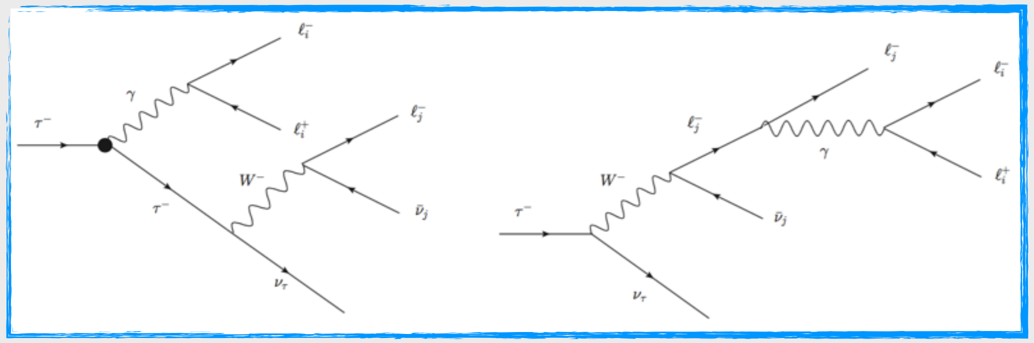




$\mathcal{L}$	1 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$\lvert d_\tau \rvert$ (e·cm)	1.48×10^{-18}	4.67×10^{-19}	2.09×10^{-19}
$\lvert \Delta a_\tau \rvert$	1.27×10^{-4}	4.02×10^{-5}	1.80×10^{-5}

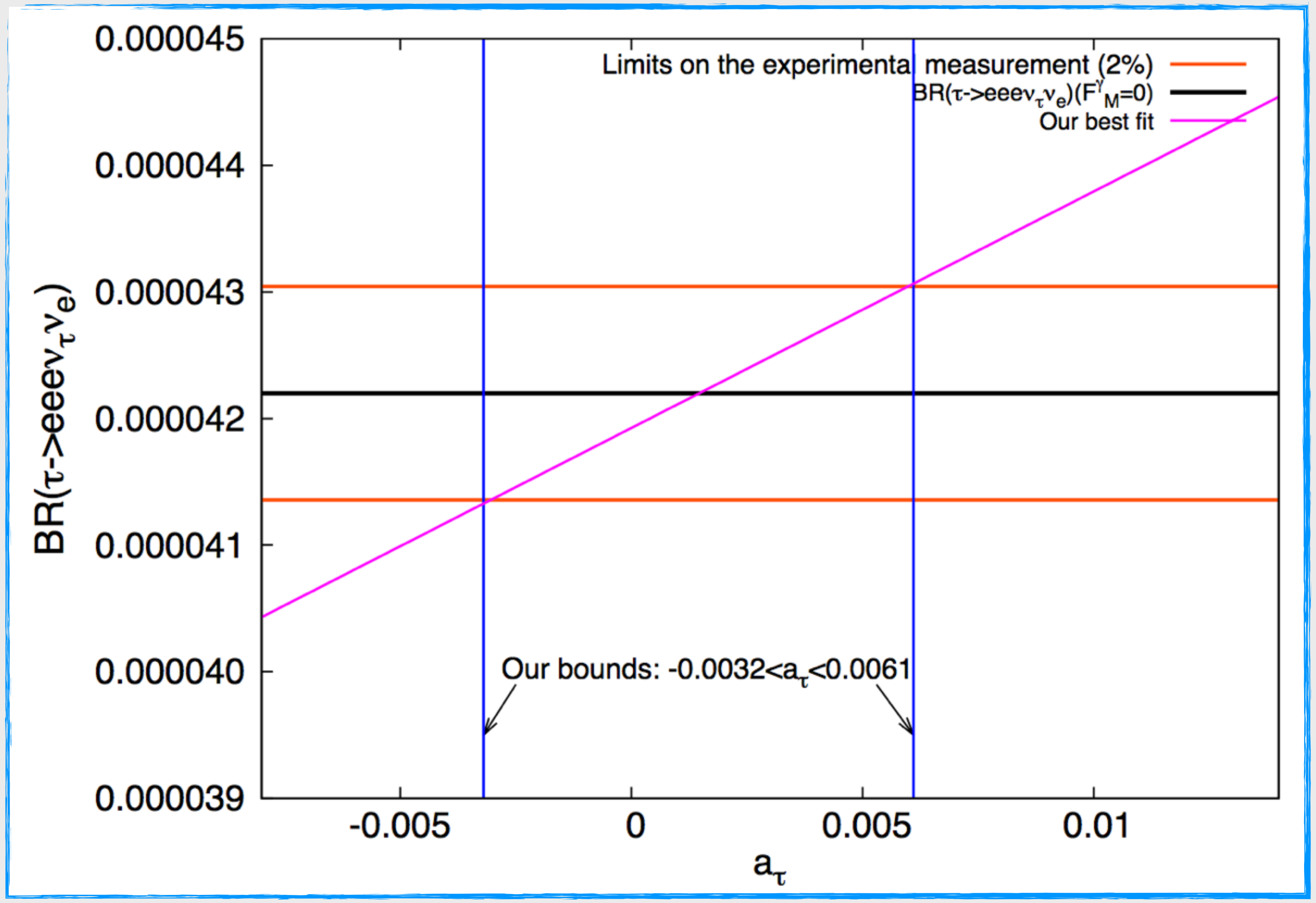
Chen & Wu, 1803.00501

EXPERIMENTAL STATUS OF THE TAU (g-2)



- Five-body lepton decays

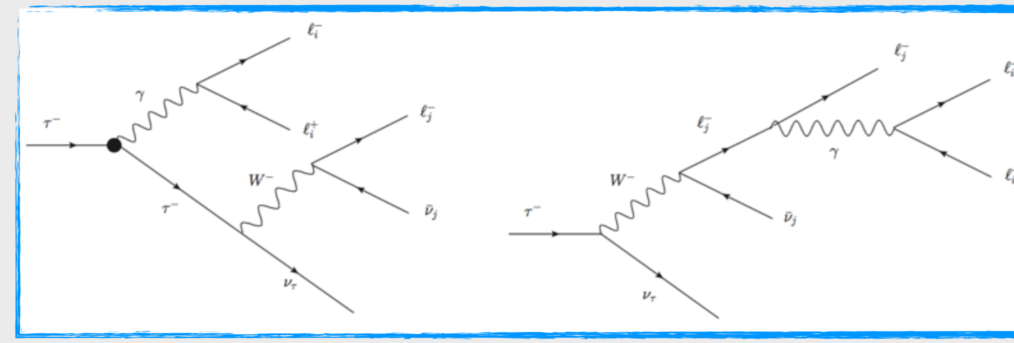
$$\begin{aligned} \mathrm{BR}(\tau^- \to e^- e^+ e^- \overline{\nu}_e \nu_\tau) &= 2.7^{+1.5+0.4+0.1}_{-1.1-0.4-0.3} \times 10^{-5} \quad \text{(CLEO II)} \\ &= 4.22 \pm 0.02 \times 10^{-5} \quad \text{(theory)} \end{aligned}$$



Arroyo-Ureña, et al., Int.J.Mod.Phys. A32 (2017) no.33, 1750195

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Five-body lepton decays



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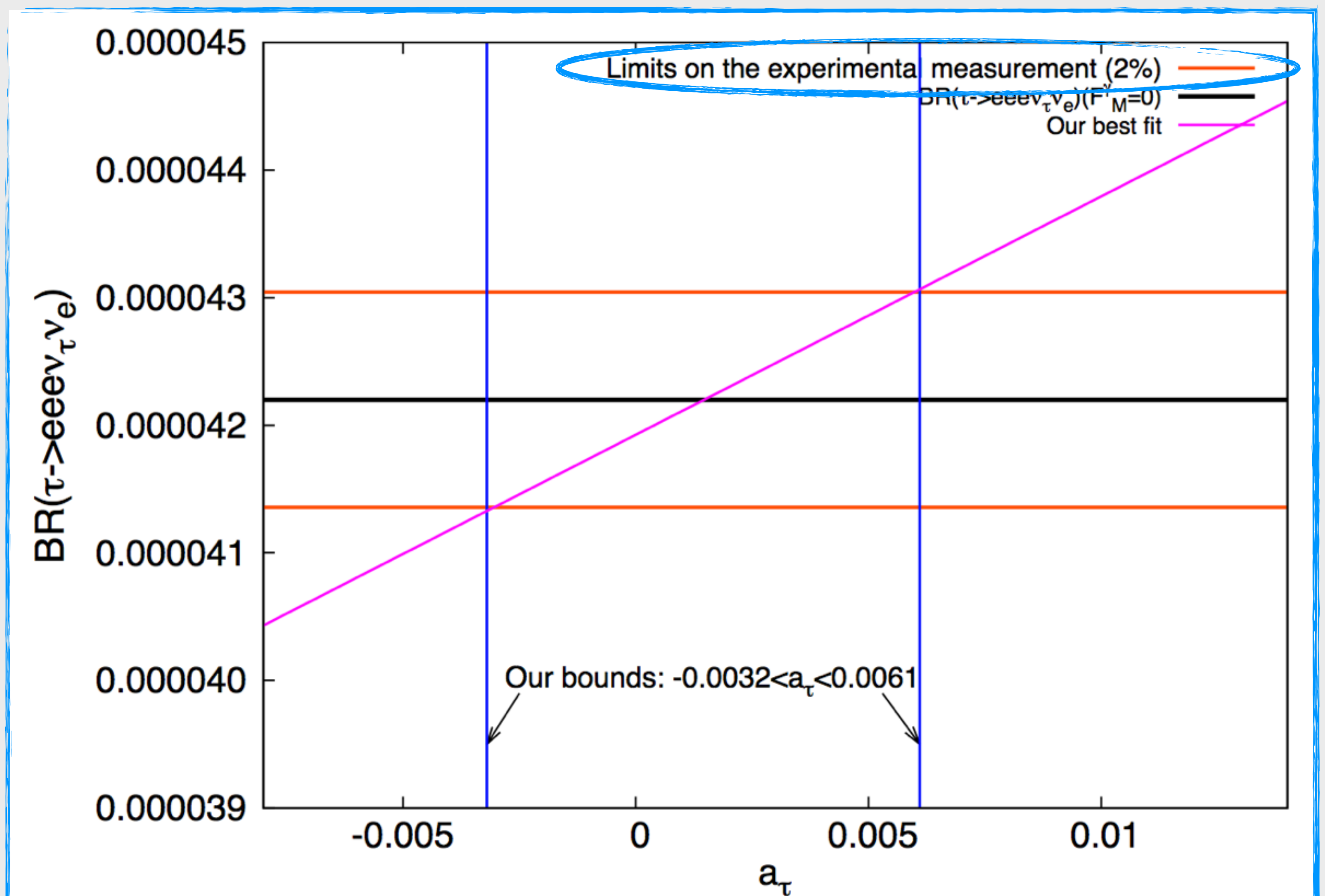

Expected sensitivity after BELLE II

Arroyo-Ureña, et al., *Int.J.Mod.Phys. A32 (2017) no.33, 1750195*

EXPERIMENTAL STATUS OF THE TAU (g-2)

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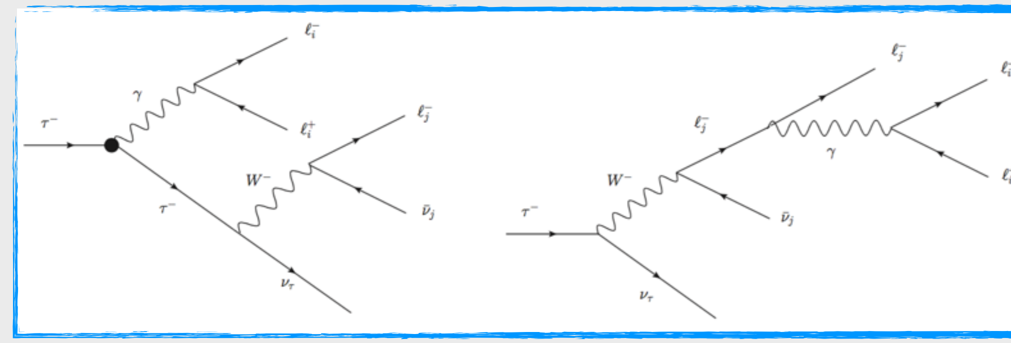

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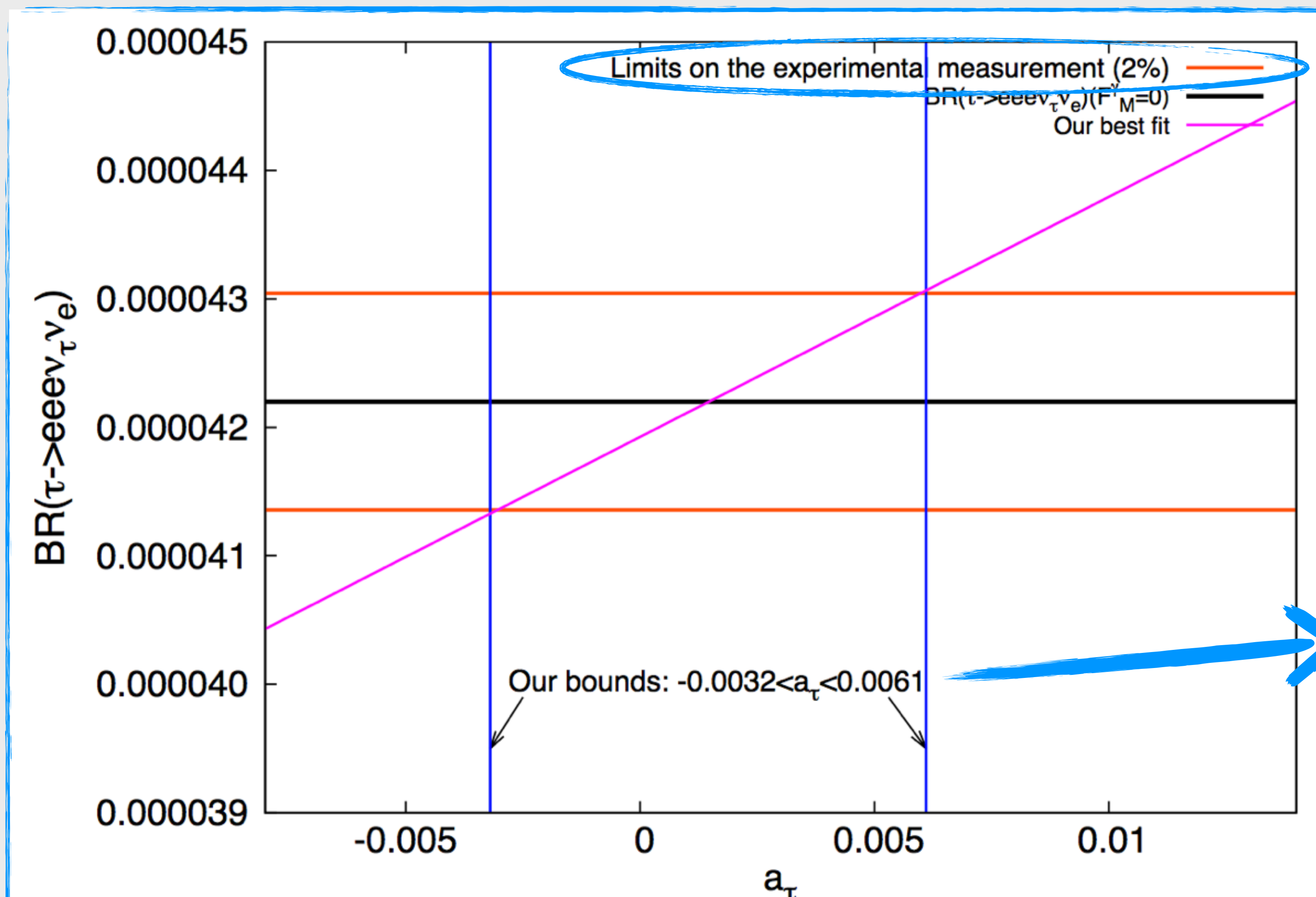


Expected sensitivity after BELLE II

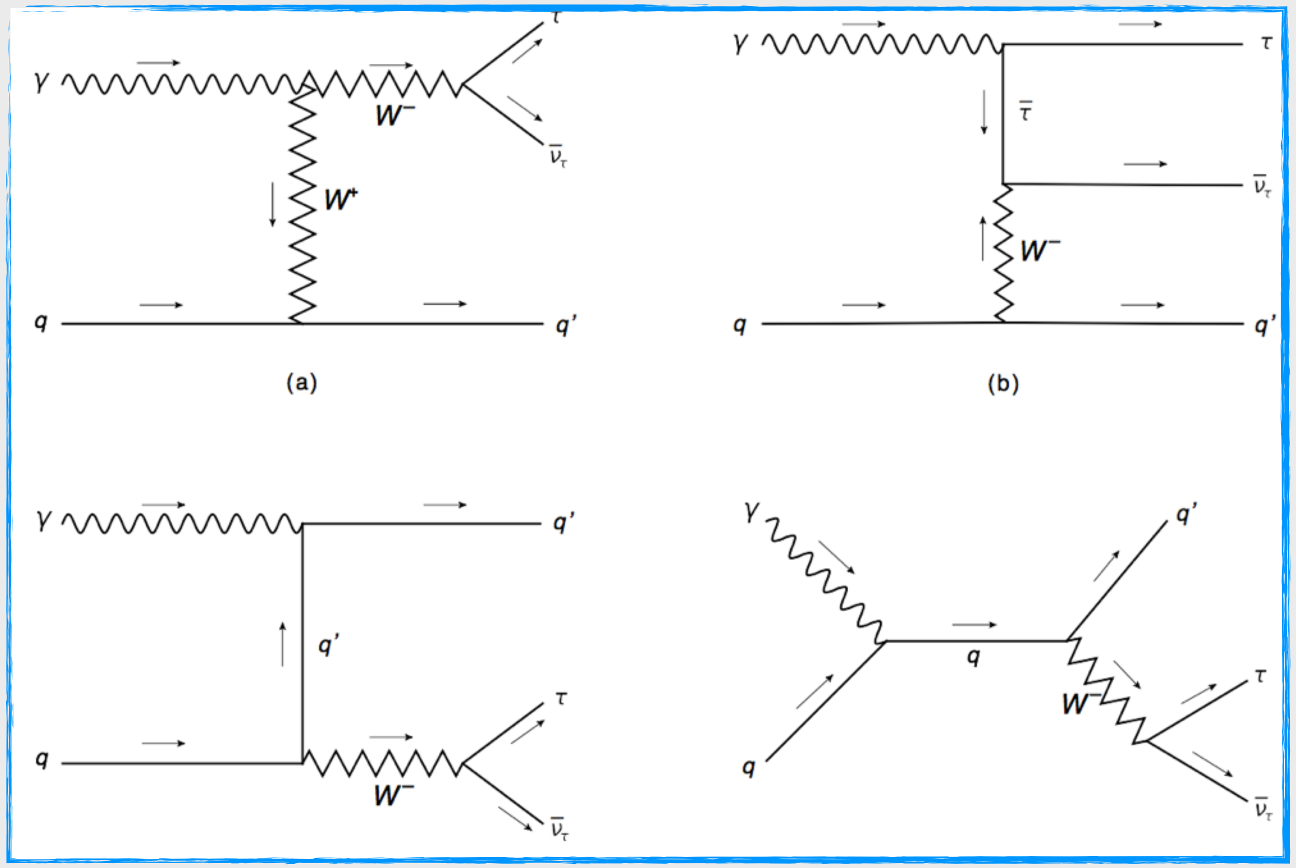
$$-0.0032 < a_\tau < 0.0061$$

Arroyo-Ureña, et al., Int.J.Mod.Phys. A32 (2017) no.33, 1750195

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Determination at the LHC

$$pp \to p\gamma^* p \to p\tau\overline{\nu}_\tau q' X$$



Köksal, et al., 1711.02405

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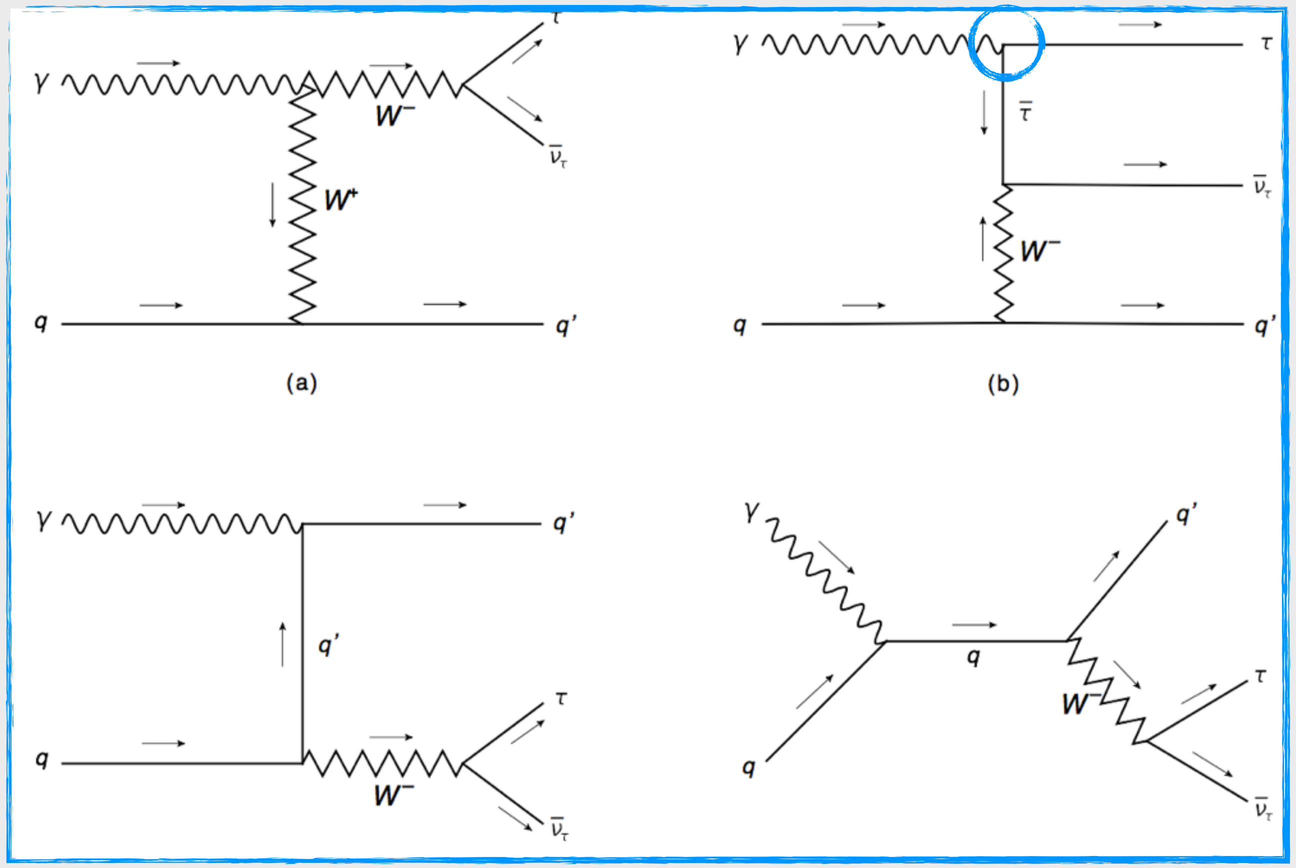

Köksal, et al., 1711.02405

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Determination at the LHC

$$d_\tau \equiv \frac{e}{2m_\tau} F_3(q^2 = 0)$$

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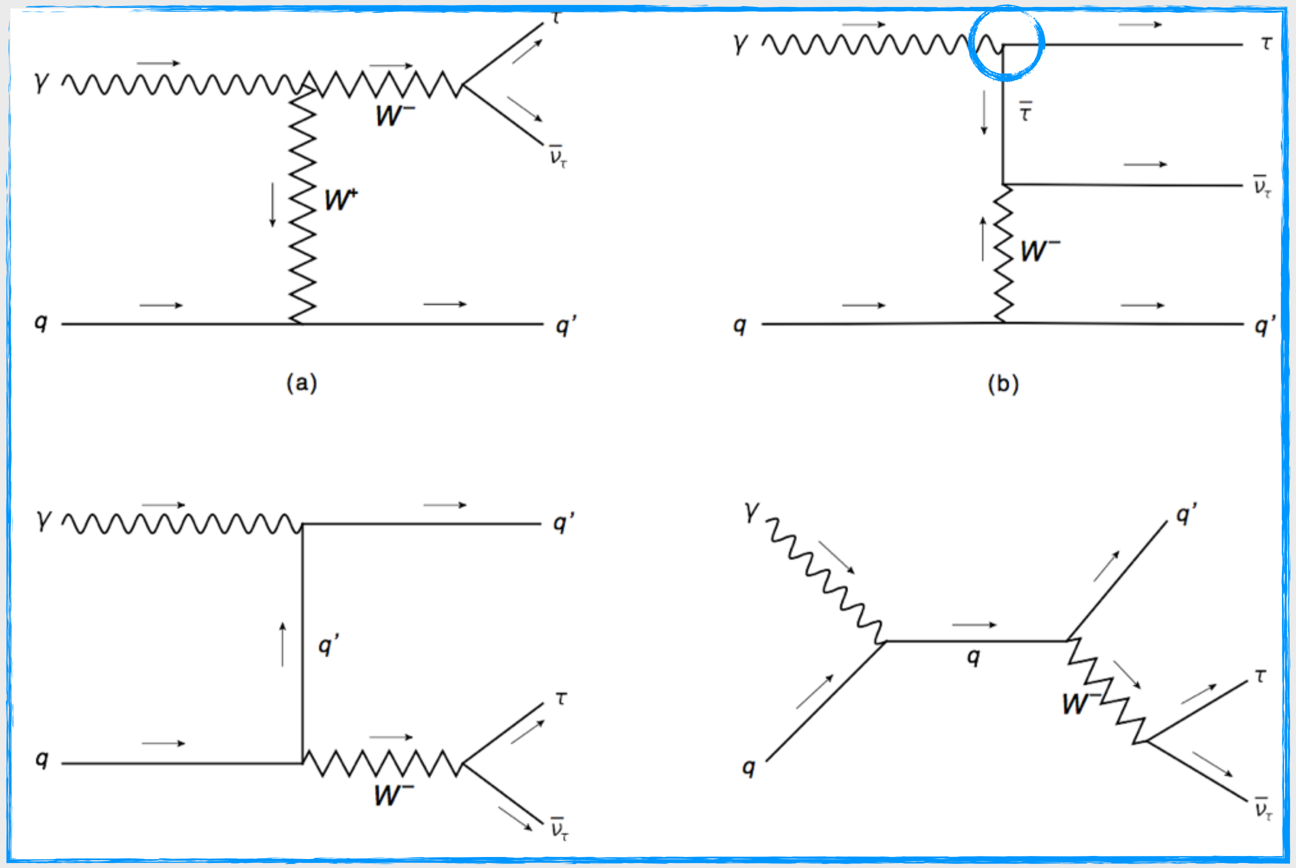

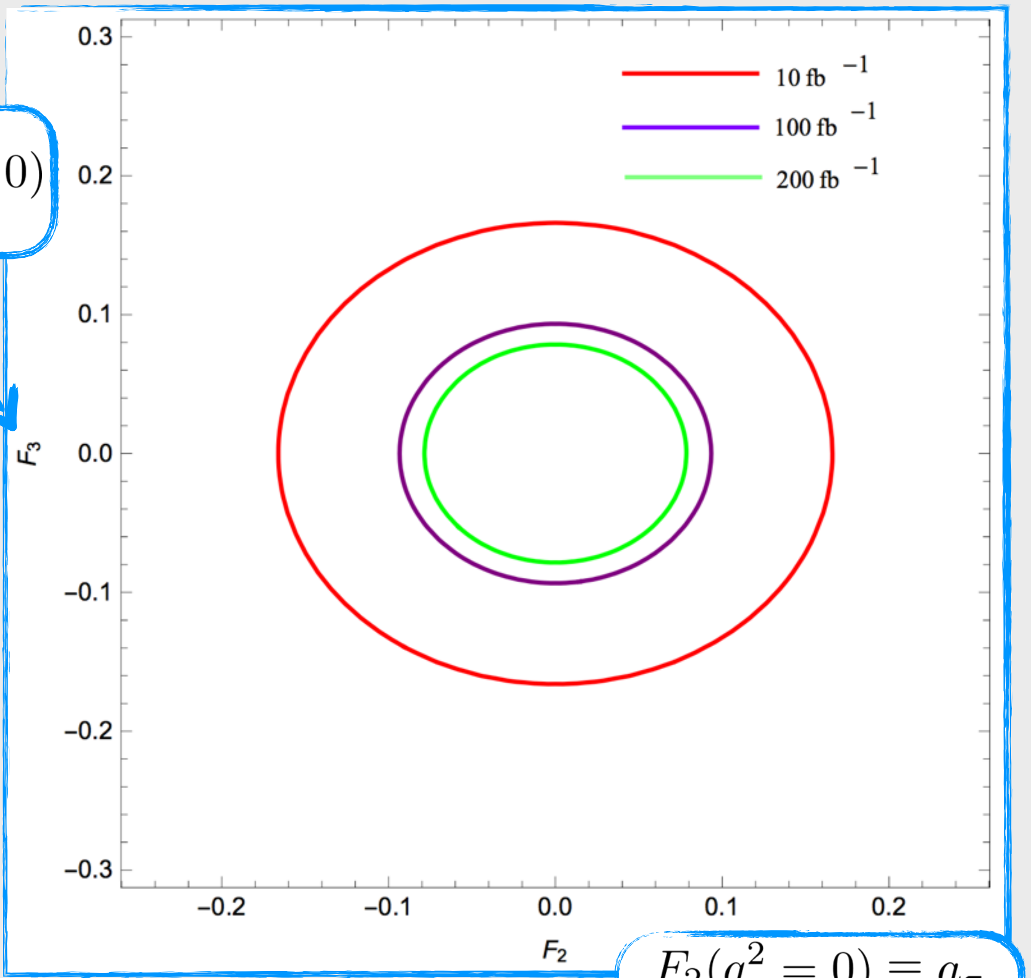

$$F_2(q^2 = 0) \equiv a_\tau$$

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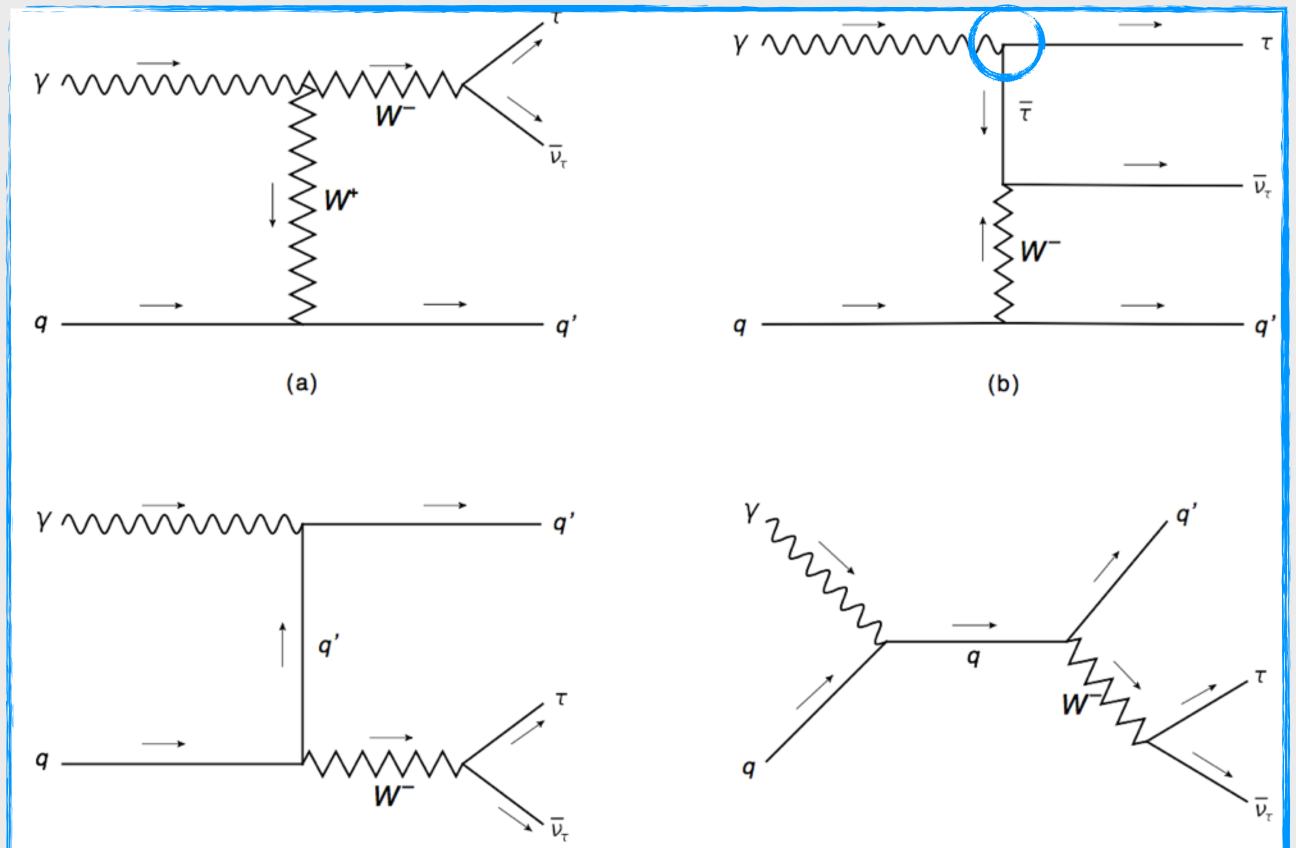

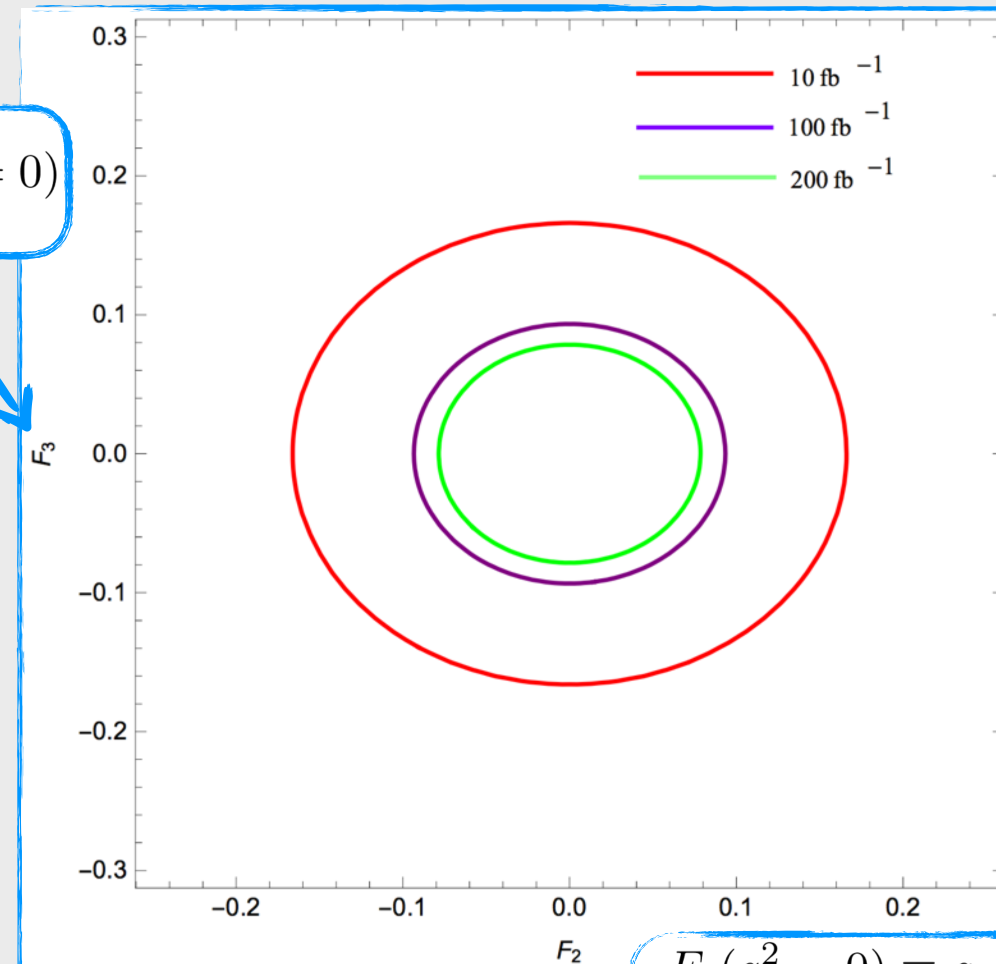

$$F_2(q^2 = 0) \equiv a_\tau$$

$\sqrt{s}$ (TeV)	Luminosity(fb^{-1})	0%	3%	5%	7%
14	10	(-0.0372, 0.0420)	(-0.0529, 0.0577)	(-0.0658, 0.0706)	(-0.0771, 0.0819)
	50	(-0.0242, 0.0290)	(-0.0498, 0.0546)	(-0.0642, 0.0690)	(-0.0762, 0.0809)
	100	(-0.0200, 0.0248)	(-0.0493, 0.0541)	(-0.0640, 0.0688)	(-0.0760, 0.0808)
	200	(-0.0165, 0.0212)	(-0.0491, 0.0539)	(-0.0639, 0.0687)	(-0.0760, 0.0807)
33	100	(-0.0108, 0.0152)	(-0.0325, 0.0368)	(-0.0424, 0.0467)	(-0.0505, 0.0548)
	500	(-0.0067, 0.0110)	(-0.0323, 0.0366)	(-0.0423, 0.0466)	(-0.0504, 0.0547)
	1000	(-0.0054, 0.0097)	(-0.0323, 0.0366)	(-0.0423, 0.0466)	(-0.0504, 0.0547)
	3000	(-0.0037, 0.0081)	(-0.0323, 0.0366)	(-0.0423, 0.0466)	(-0.0504, 0.0547)

$$|a_\tau| \approx \text{few} \times 10^{-2}$$

Köksal, et al., 1711.02405

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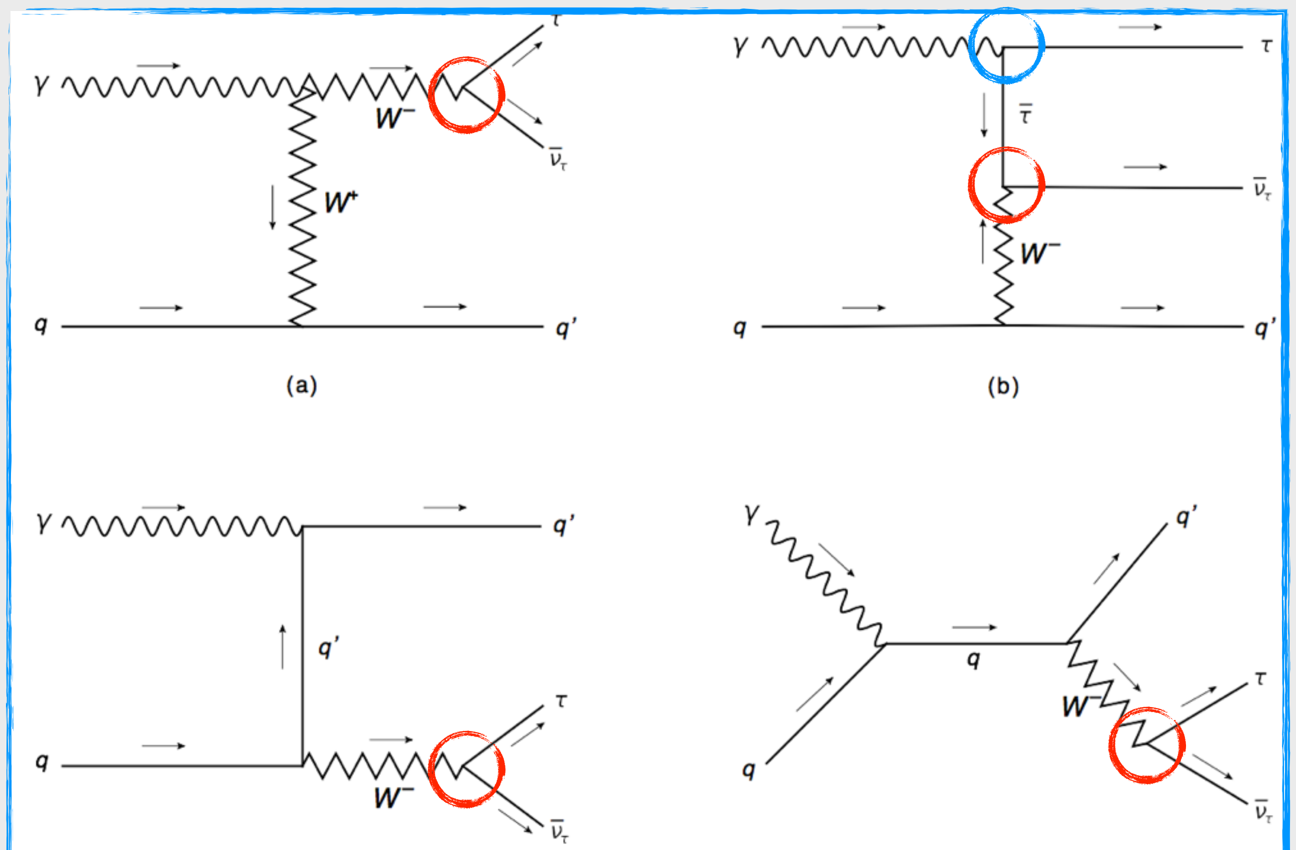

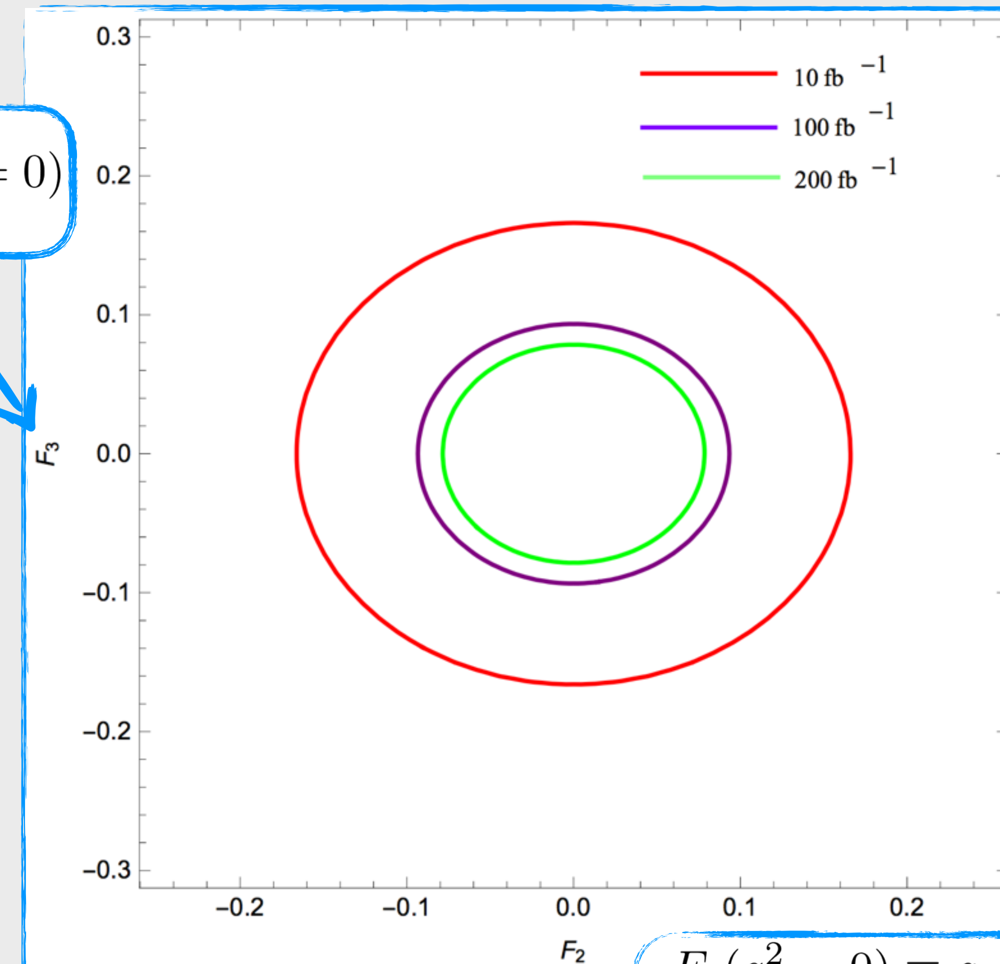

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33	1000	(-0.0054, 0.0097)	(-0.0323, 0.0366)	(-0.0423, 0.0466)	(-0.0504, 0.0547)
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Köksal, et al., 1711.02405

EXPERIMENTAL STATUS OF THE TAU (g-2)

- Nonstandard Higgs decay: $H \to \tau^+\tau^-\gamma$

$$\mathcal{L} \supset a_\tau \frac{e}{4m_\tau}\bar{\tau}\sigma_{\mu\nu}\tau F^{\mu\nu}\left(1+\frac{h}{v}\right)$$

Galon, et al., JHEP 1612 (2016) 111

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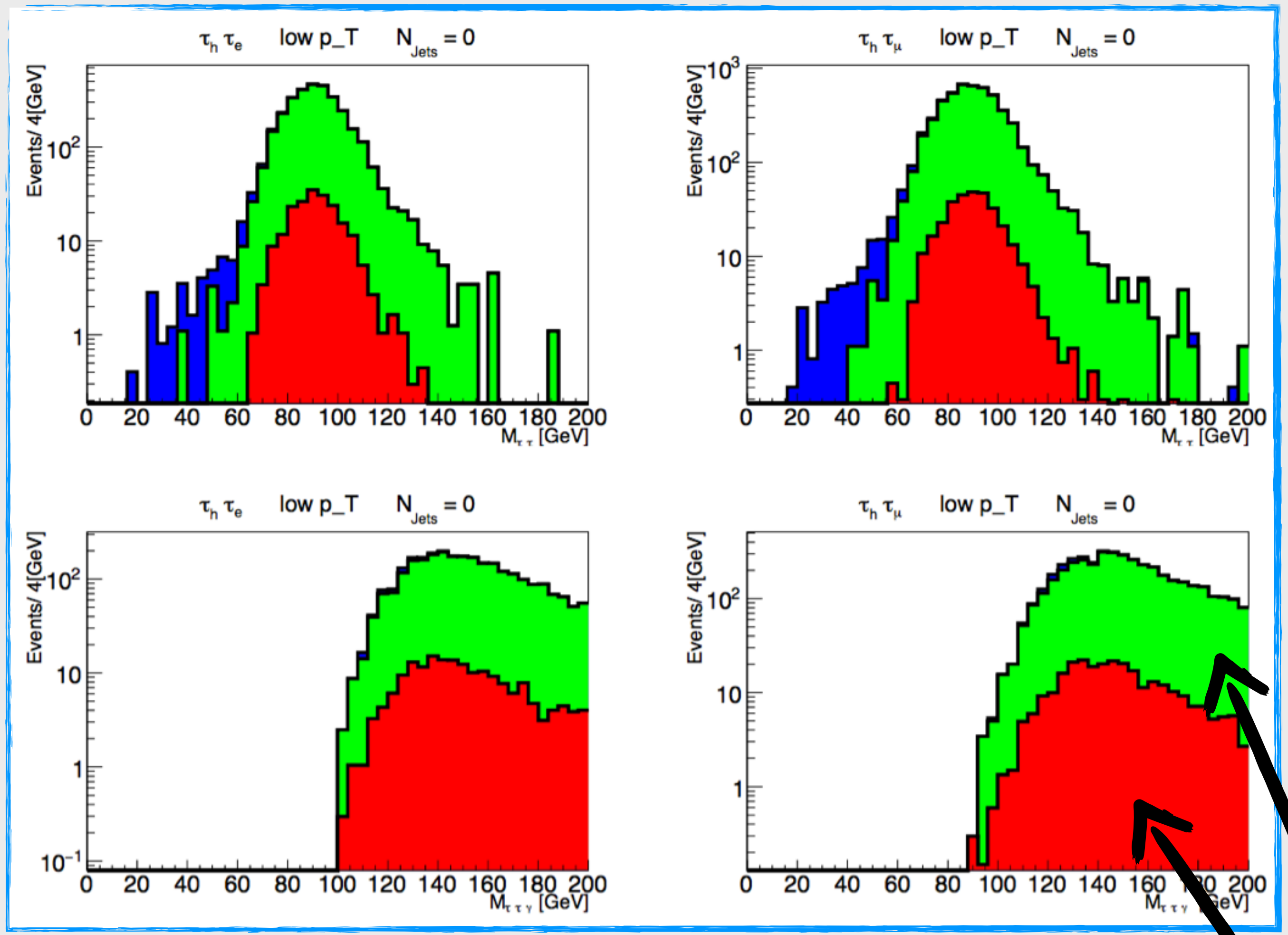

$pp \to Z + j(\gamma)$

$pp \to Z + \gamma$

Galon, et al., JHEP 1612 (2016) 111

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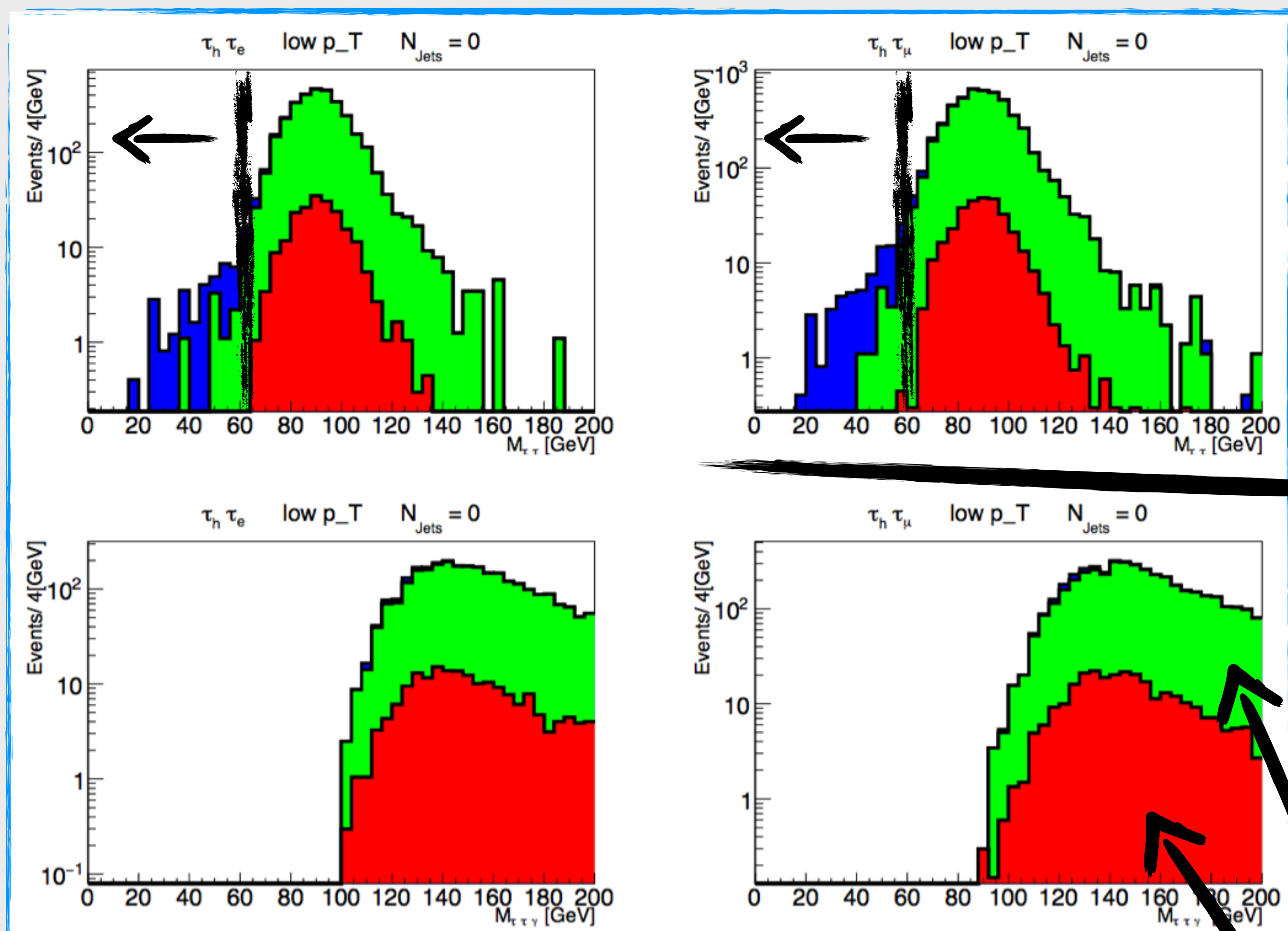

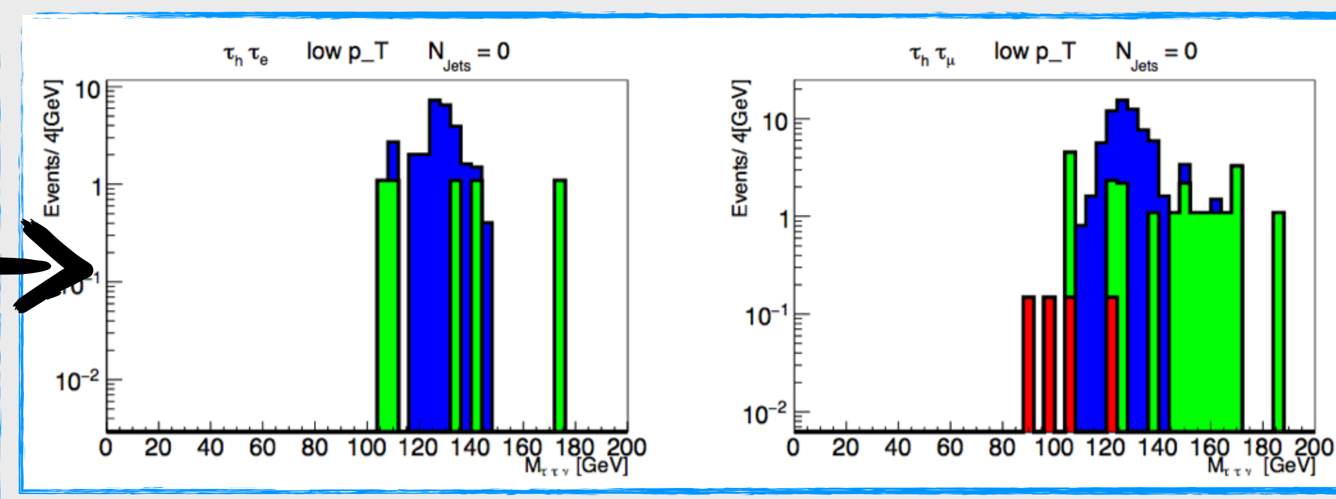

$$\boxed{pp \to Z + j(\gamma)}$$

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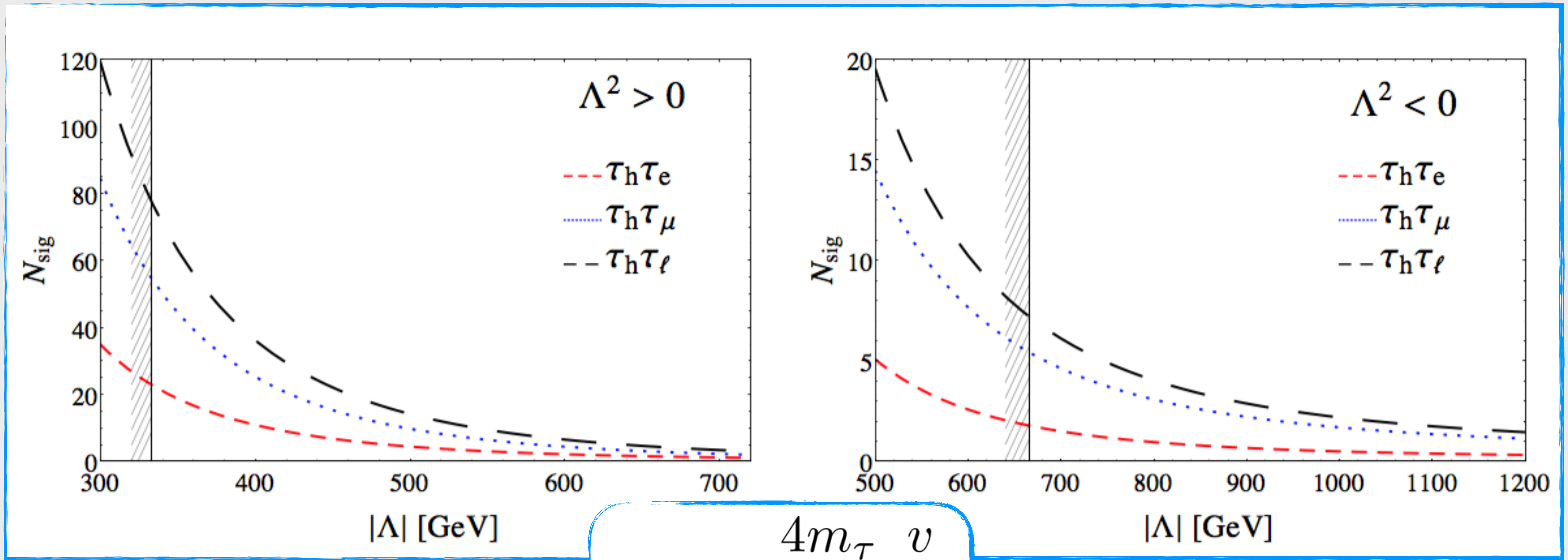

$$a_\tau \equiv -\frac{4m_\tau}{e}\frac{v}{\Lambda^2}$$

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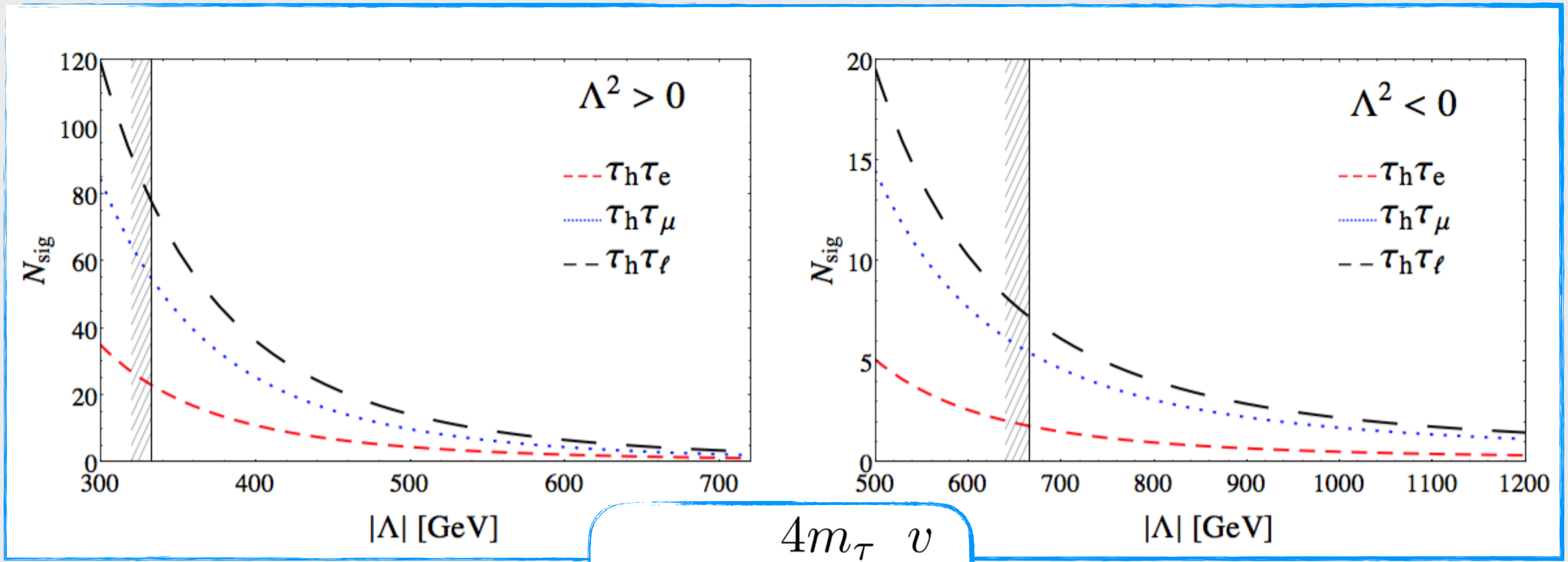
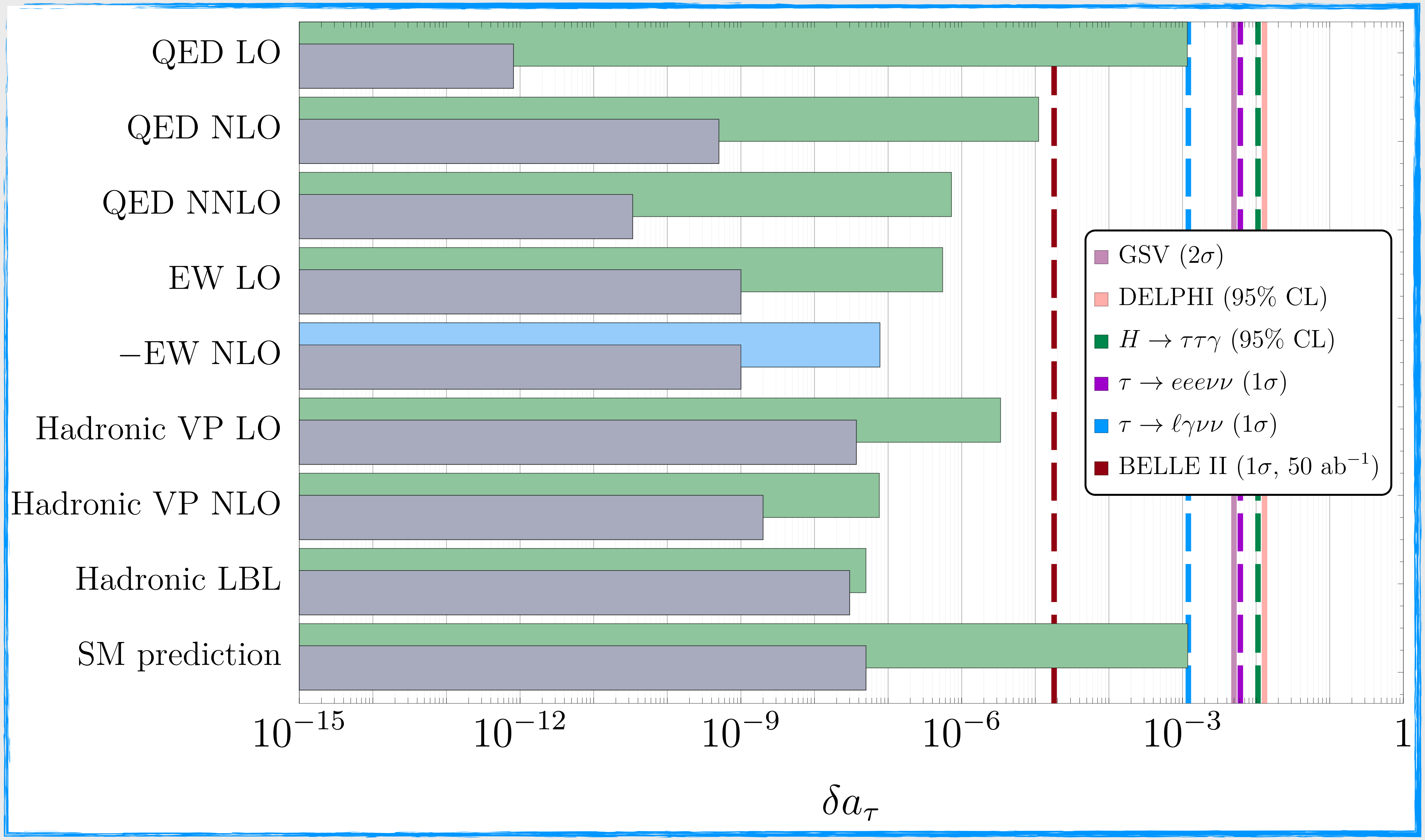


$$a_\tau \equiv -\frac{4m_\tau}{e}\frac{v}{\Lambda^2}$$

$$-0.0144 < a_\tau < 0.0106 \quad (95\%\ \mathrm{CL})$$

Galon, et al., JHEP 1612 (2016) 111

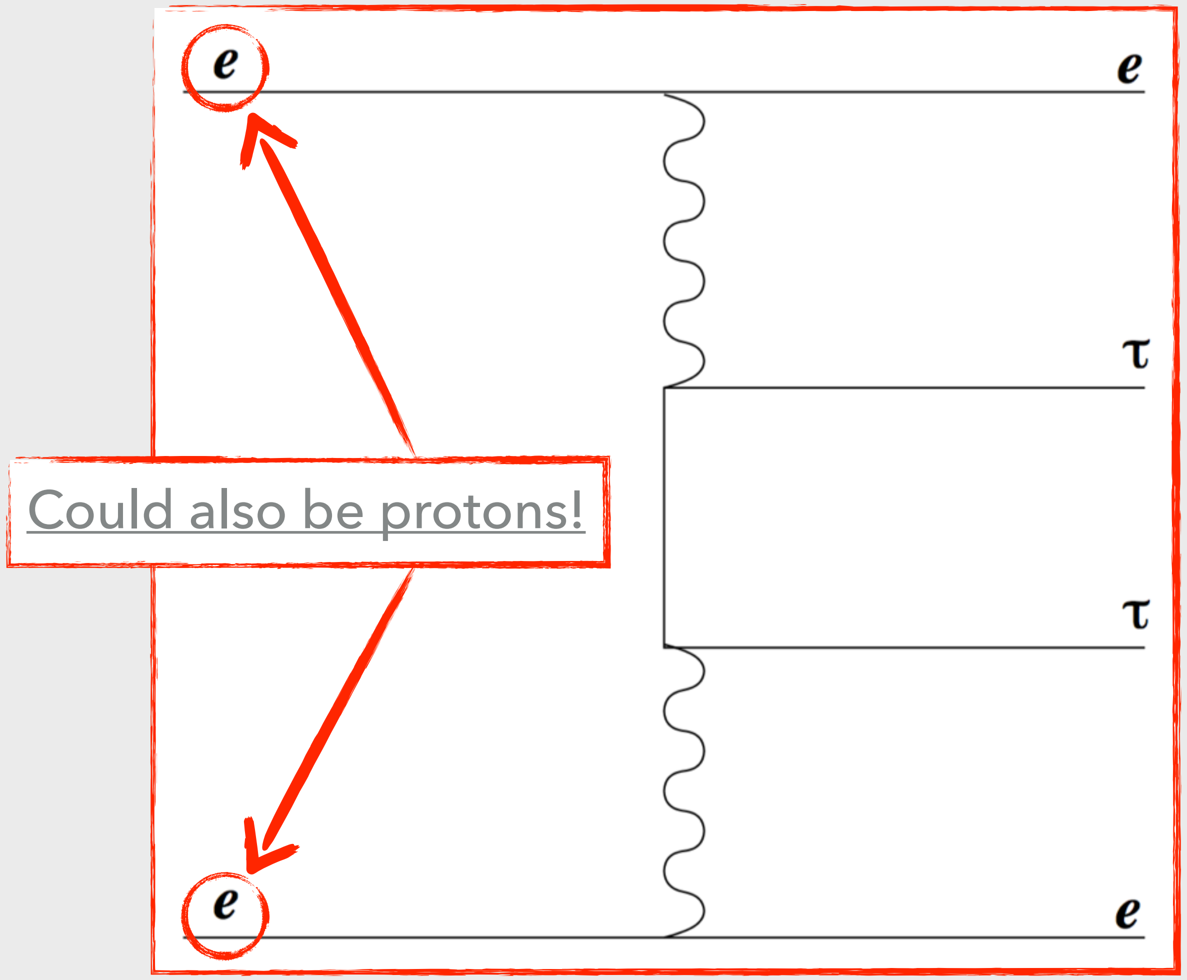
EXPERIMENTAL STATUS OF THE TAU (g-2)



PHOTON COLLIDERS AND THE TAU (g-2)

- *Internal* photons vs. *real* photons

$$d\sigma = \int \frac{dL_{\gamma\gamma}}{dW}\, d\sigma_{\gamma\gamma\to\tau\tau}(W)\, dW$$



Cornet & Illana, Phys.Rev. D53 (1996) 1181
Atağ & Billur, JHEP 1011 (2010) 060

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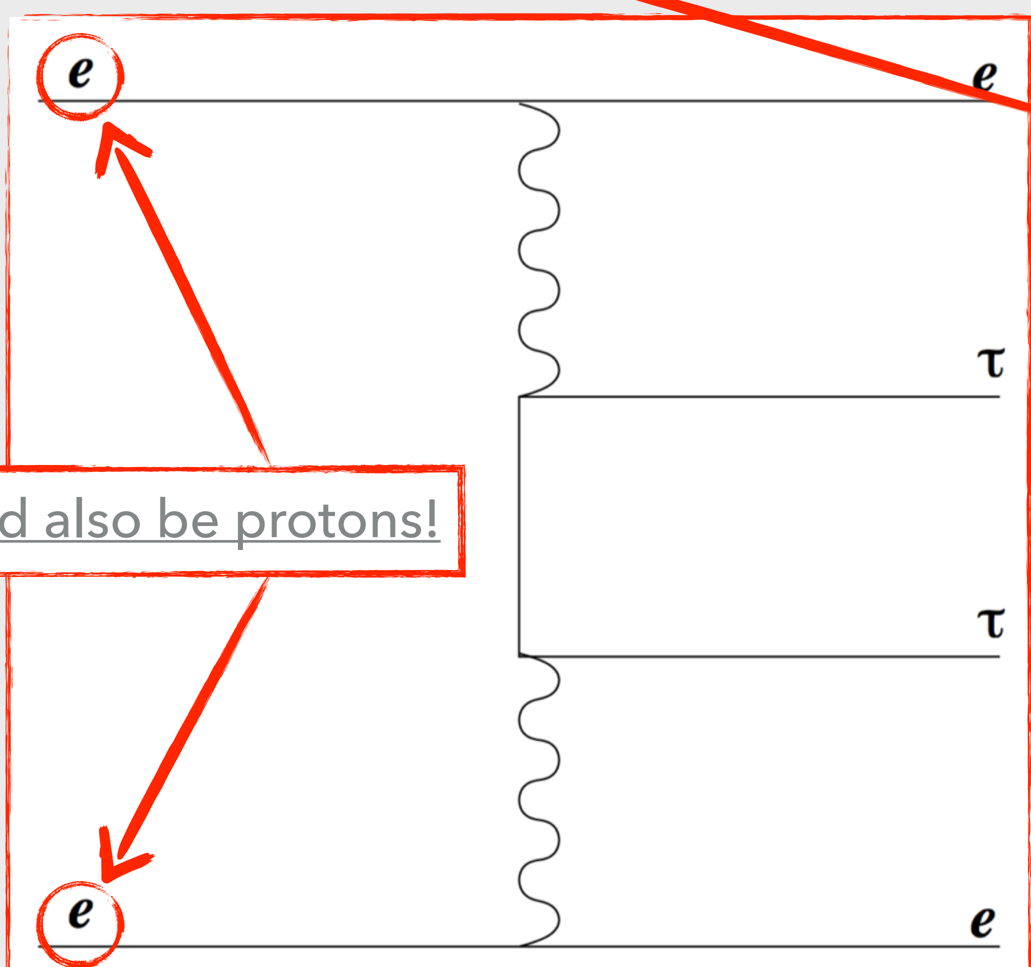
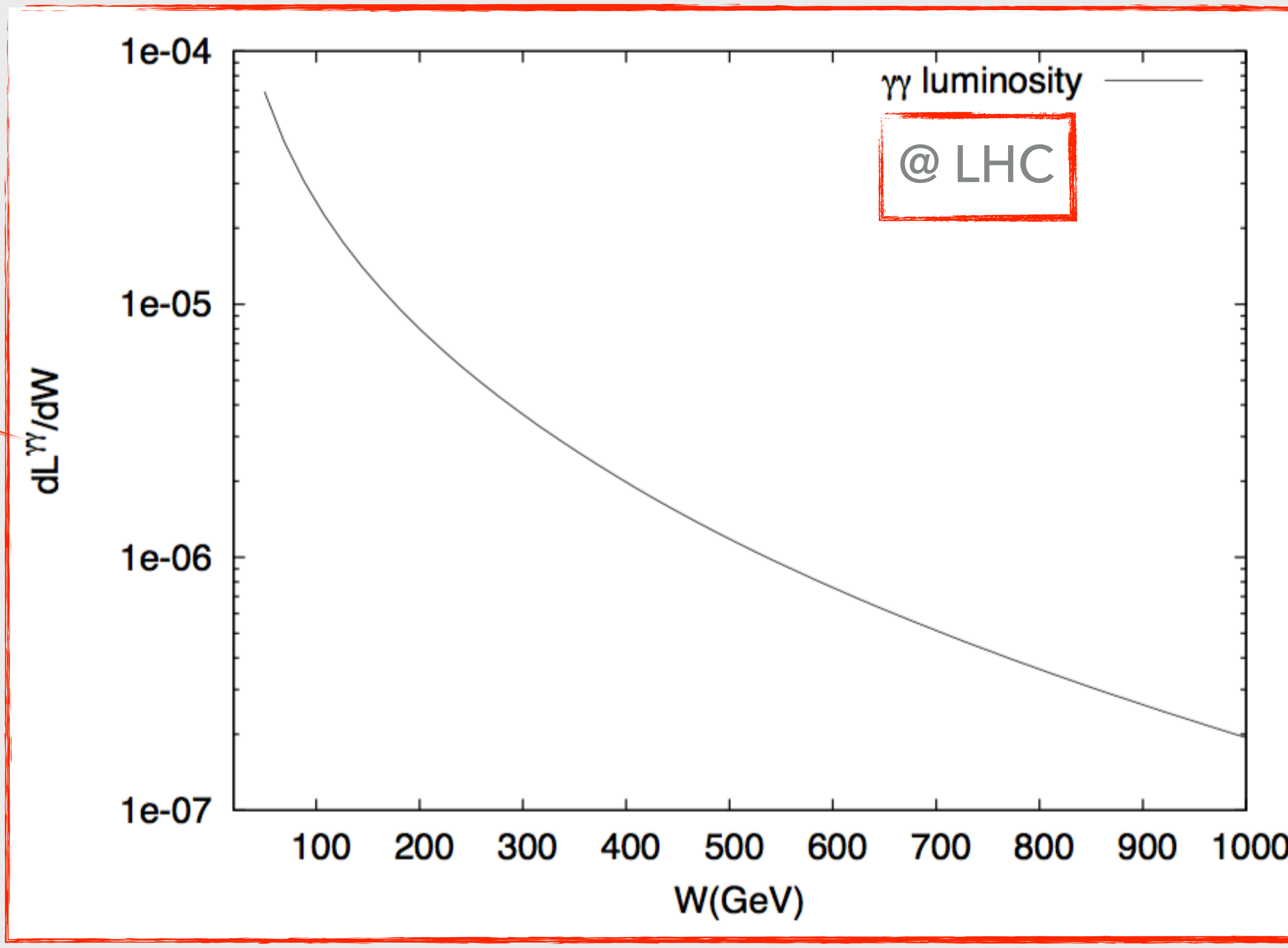


Could also be protons!



Best-case scenario:

$$|a_\tau| < \text{few} \times 10^{-3}$$

Cornet & Illana, Phys.Rev. D53 (1996) 1181
Atağ & Billur, JHEP 1011 (2010) 060

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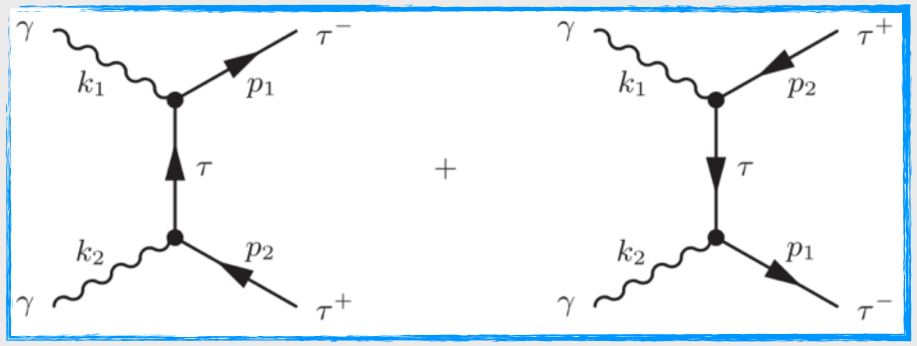

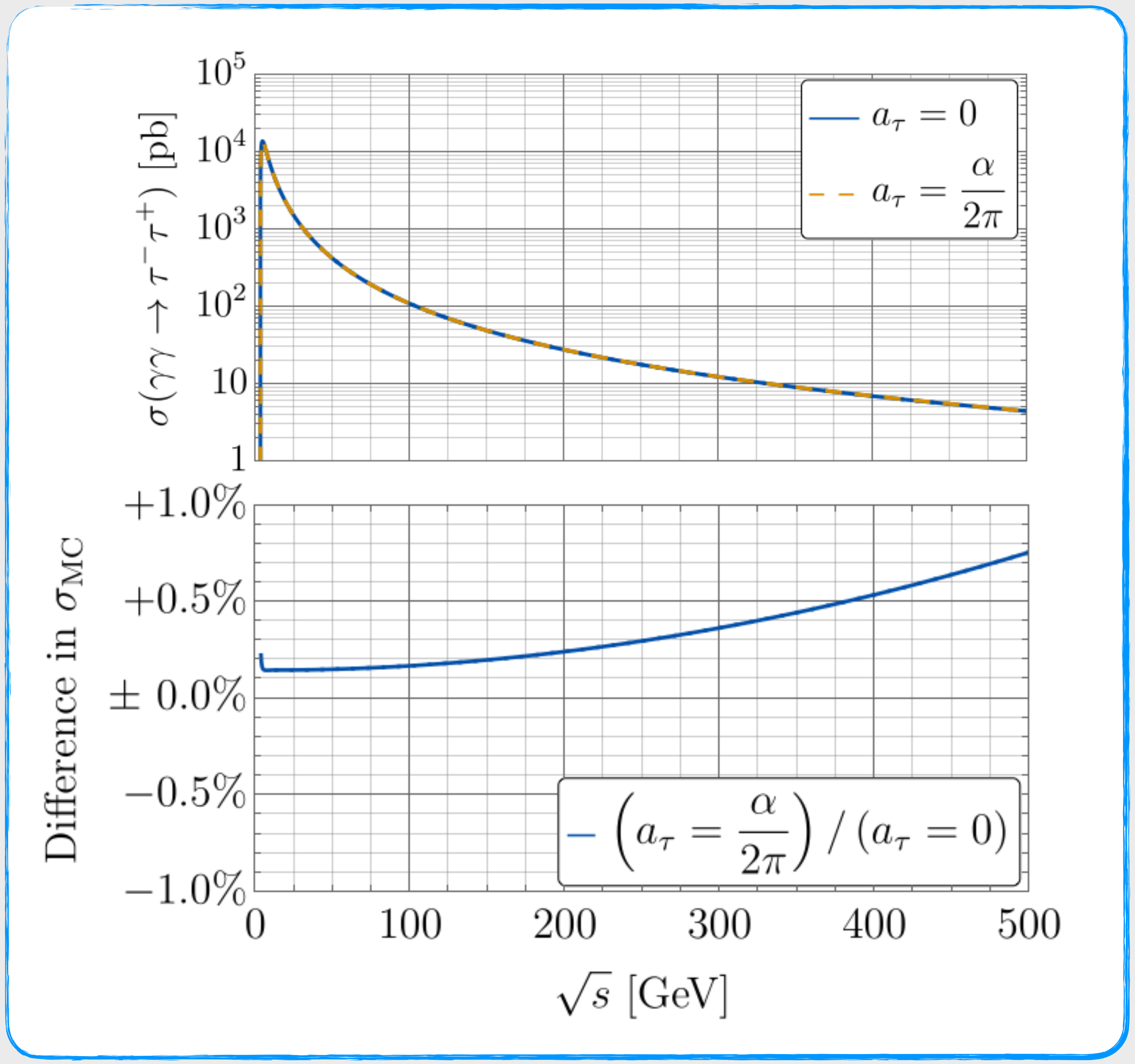

Aeppli & Soni, Phys.Rev. D46 (1992) 315

Tabares & Sampayo, Phys.Rev. D65 (2002) 053012

PHOTON COLLIDERS AND THE TAU (g-2)

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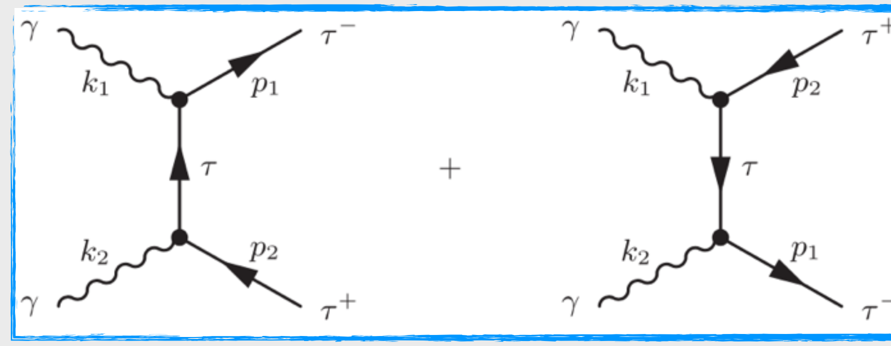
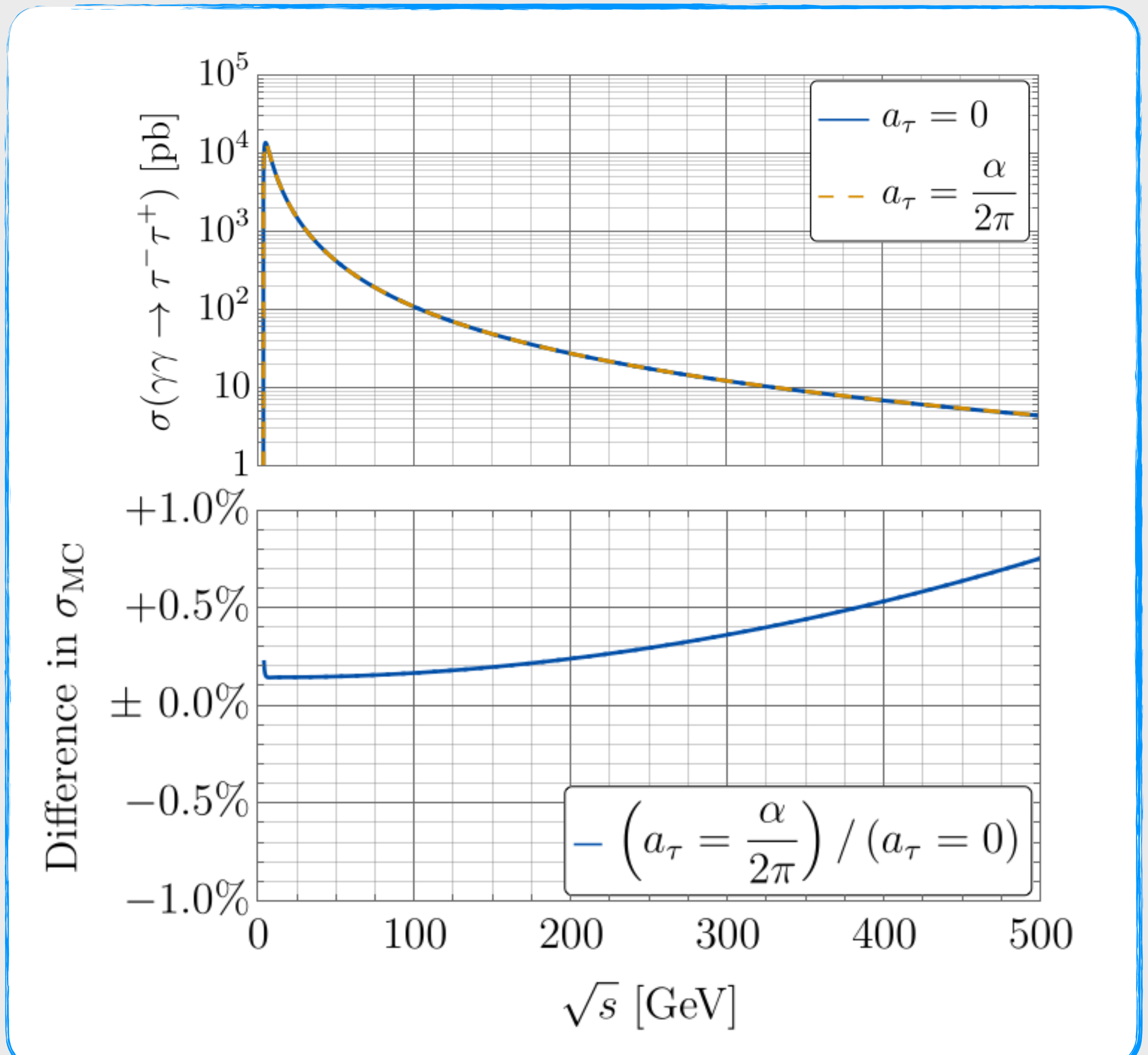
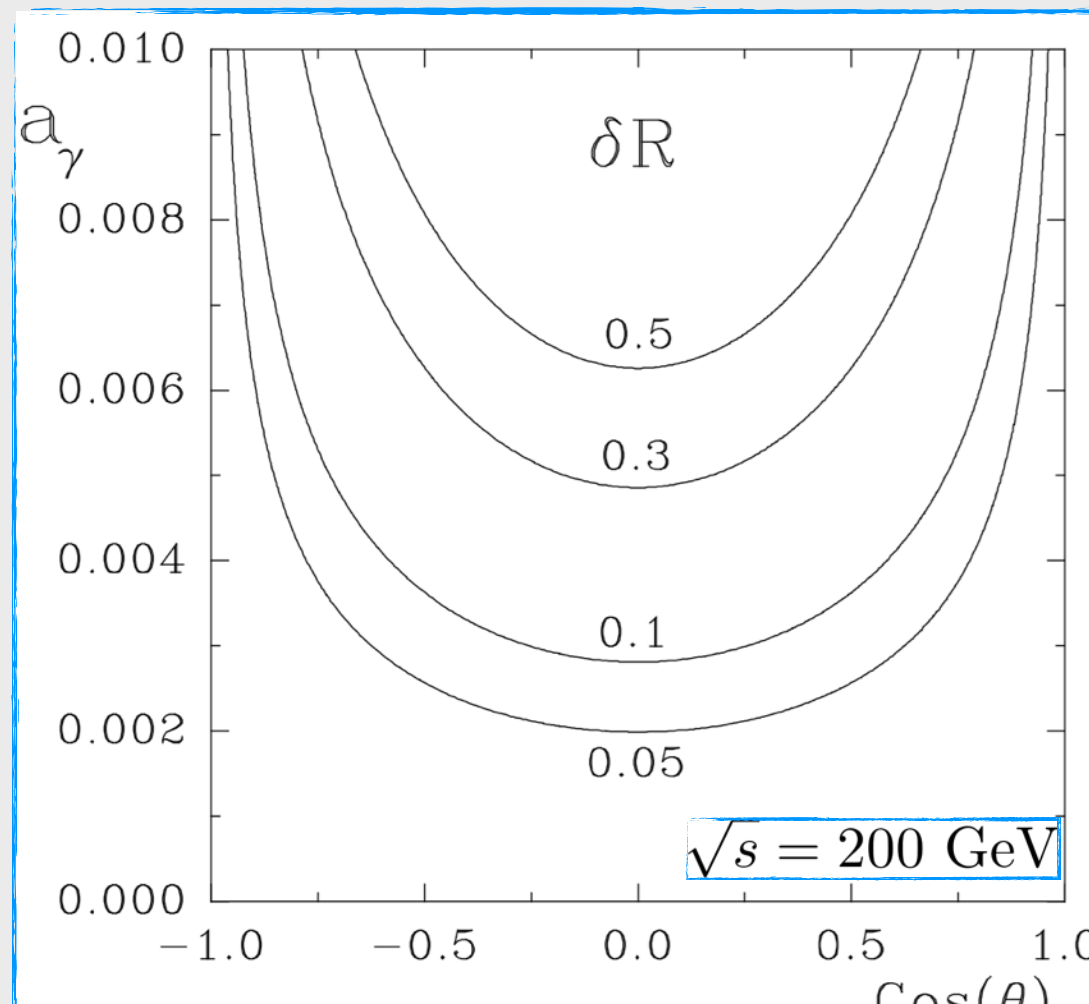


$$R(\theta) \equiv \frac{d\sigma/d\Omega|_{\gamma\gamma\to\tau\tau}}{d\sigma/d\Omega|_{\gamma\gamma\to\mu\mu}}$$

$$\approx 1 + \frac{a_\tau^2 s}{m_\tau^2}\frac{\sin^2\theta}{1+\cos^2\theta}\left[1+\frac{a_\tau^2 s}{64 m_\tau^2}\sin^2\theta\right]$$





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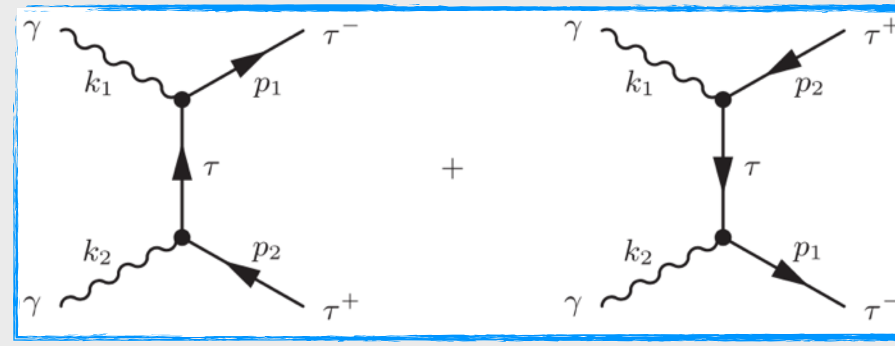

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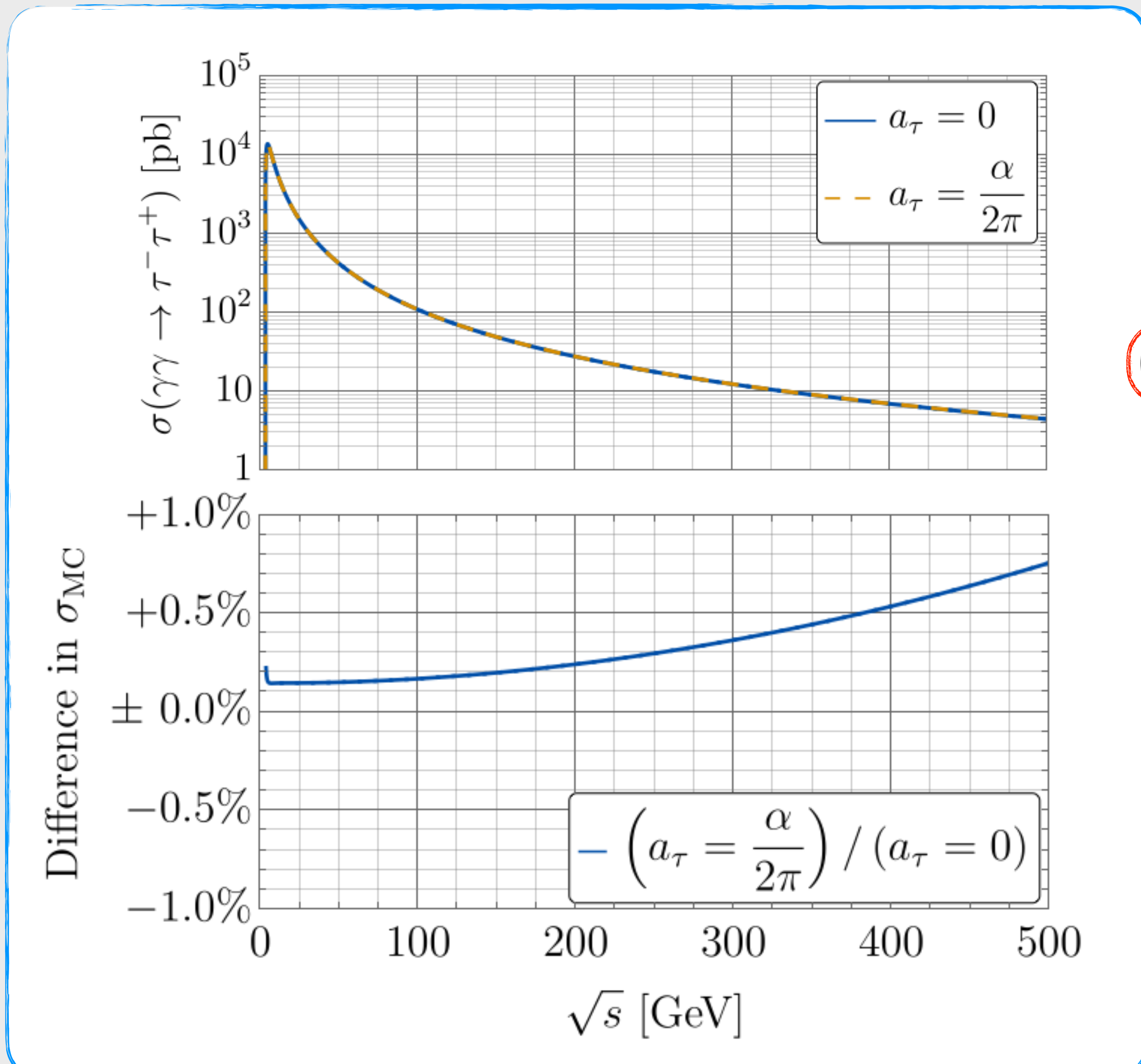
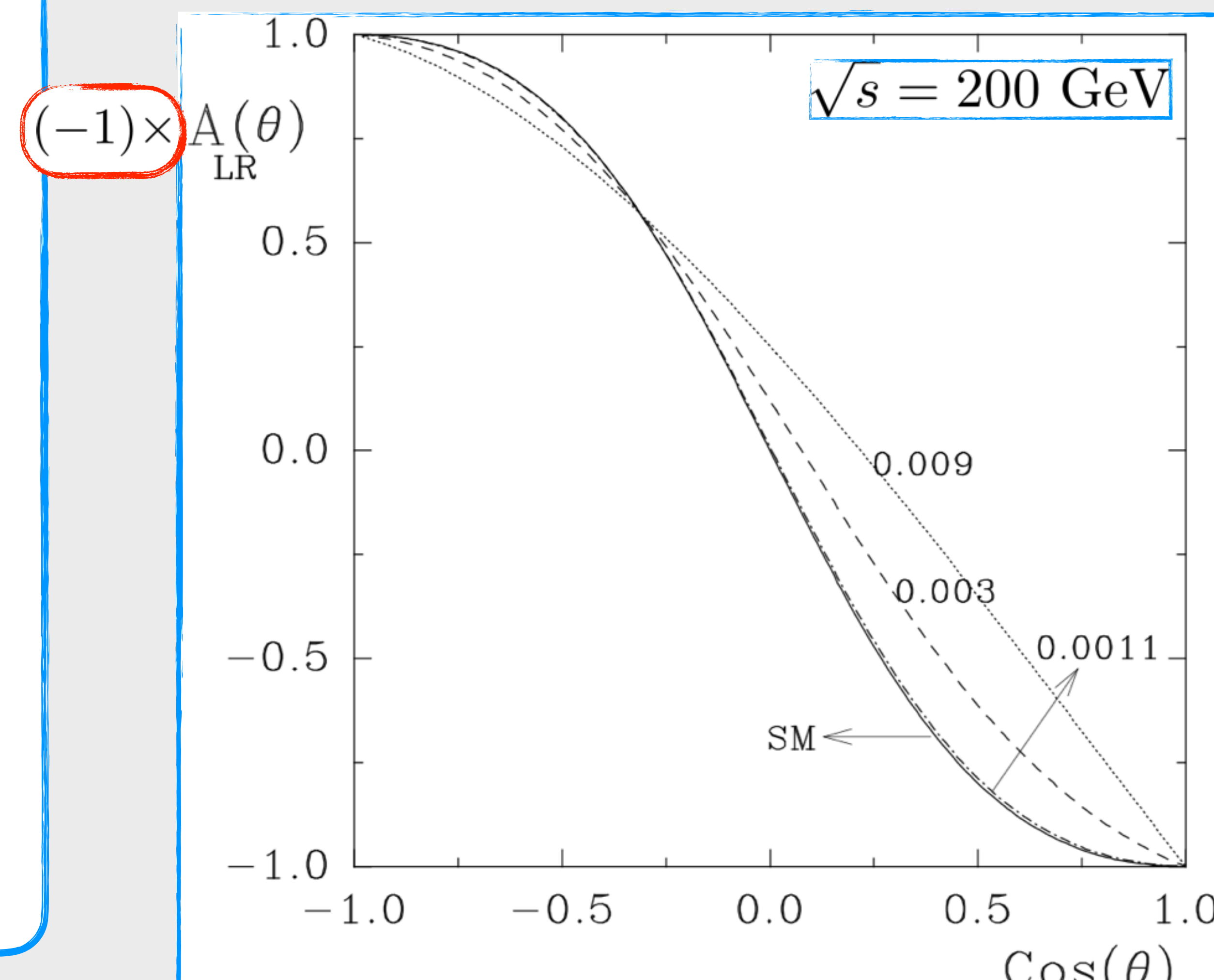


$$\mathcal{A}_{\mathrm{LR}}(\theta) \equiv \frac{d\sigma/d\Omega_{\mathrm{L}} - d\sigma/d\Omega_{\mathrm{R}}}{d\sigma/d\Omega_{\mathrm{L}} + d\sigma/d\Omega_{\mathrm{R}}}$$



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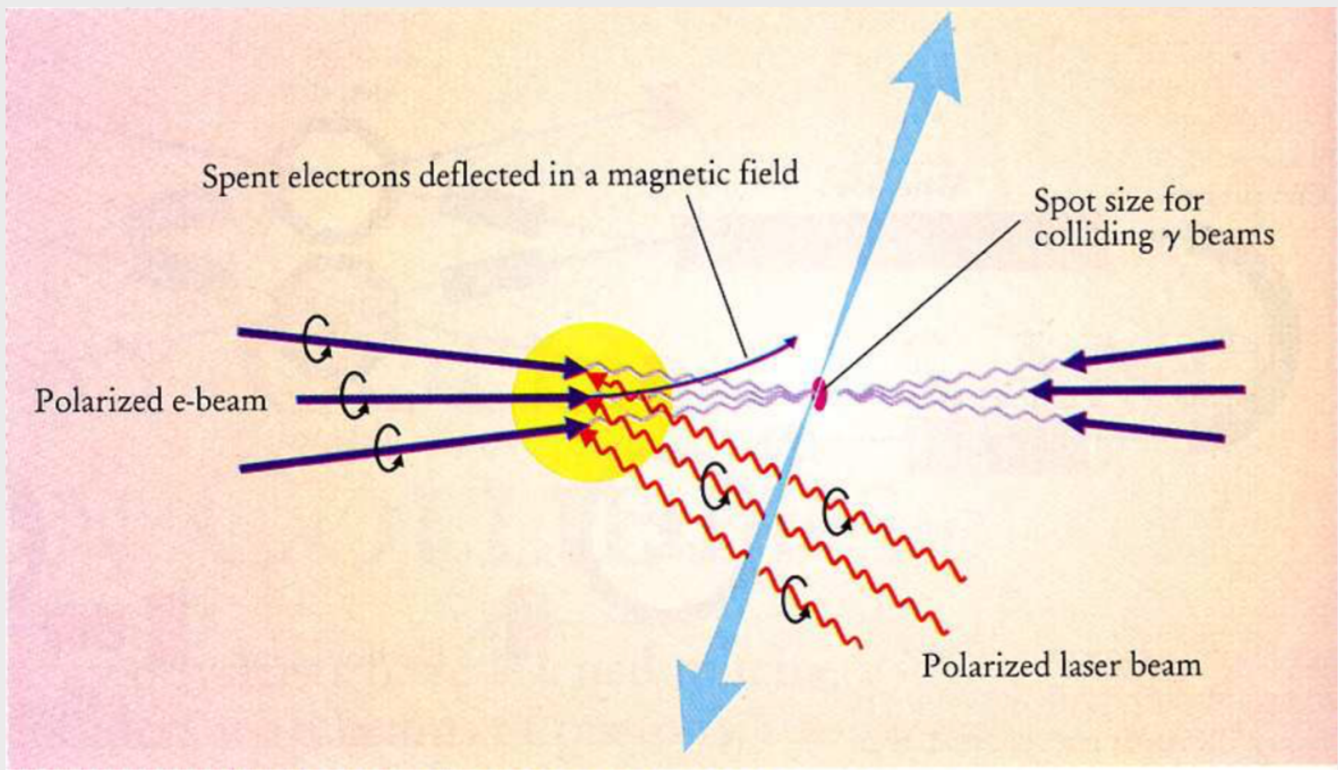
PHOTON COLLIDERS — AN OVERVIEW



Sessler, Physics Today (March 1998) p. 48

$$\omega_m = \frac{x}{x+1} E_0$$

$$x = \frac{4E_0\omega_0 \cos^2 \alpha_0/2}{m_e^2 c^4} \approx 15.3 \left[\frac{E_0}{\mathrm{TeV}}\right] \left[\frac{\omega_0}{\mathrm{eV}}\right]$$

Telnov, Nucl.Instrum.Meth. A472 (2001) 43
Serbo, Acta Phys.Polon. B37 (2006) 1333
Sekaric, hep-ph/0512307

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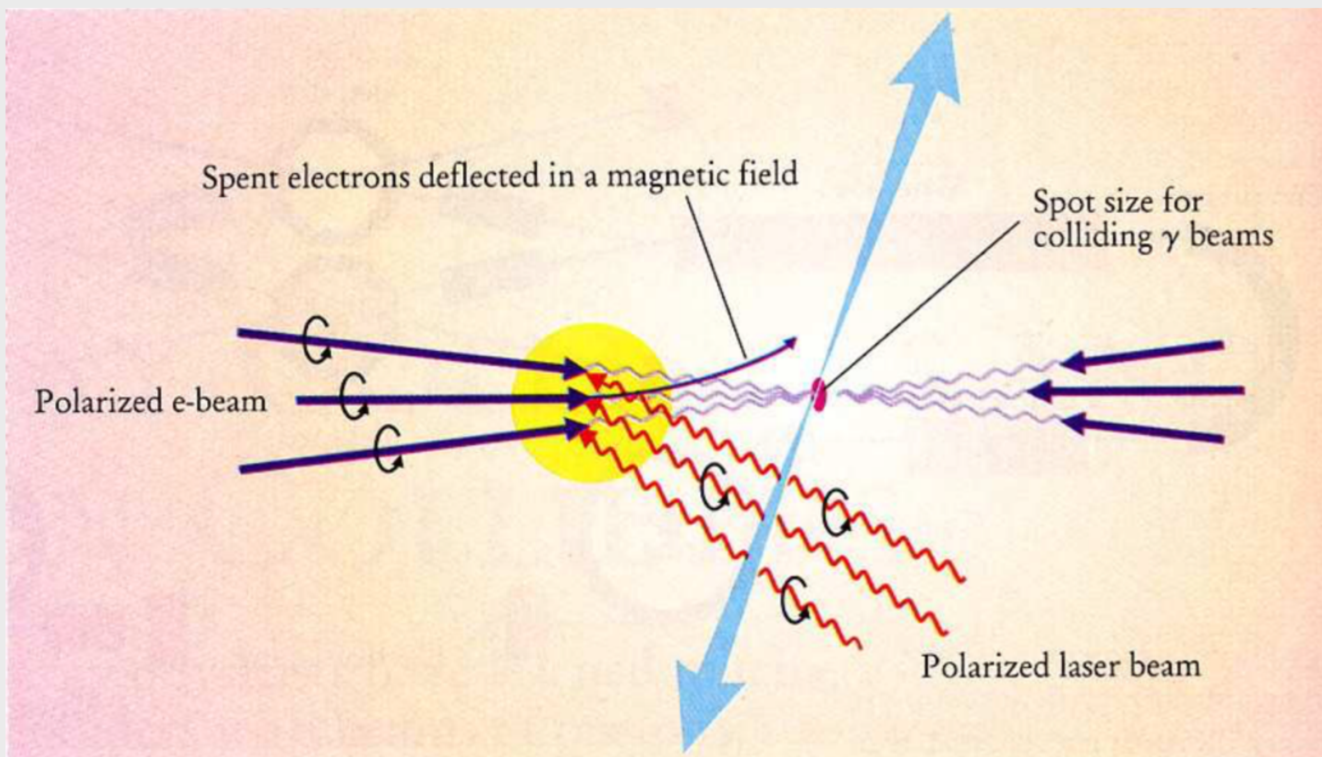

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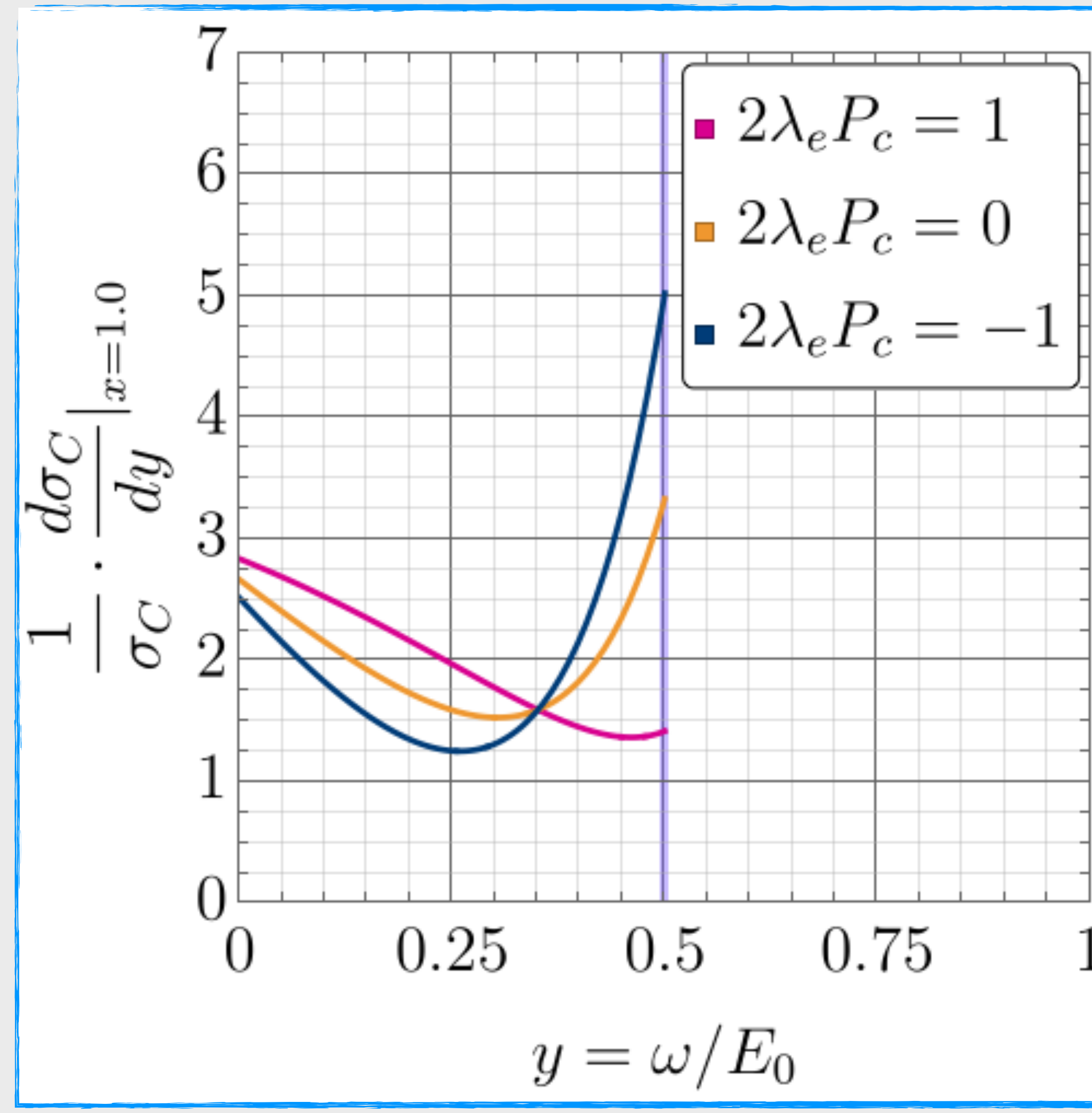

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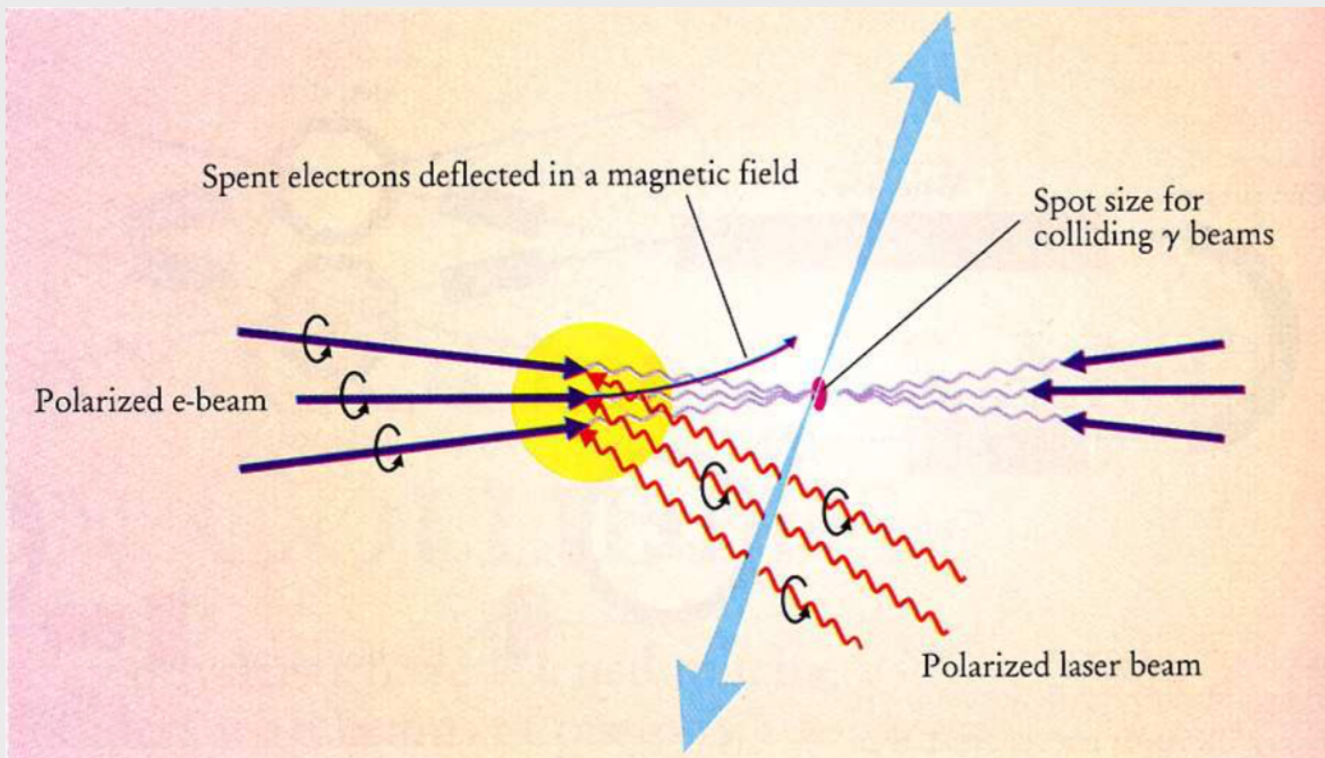

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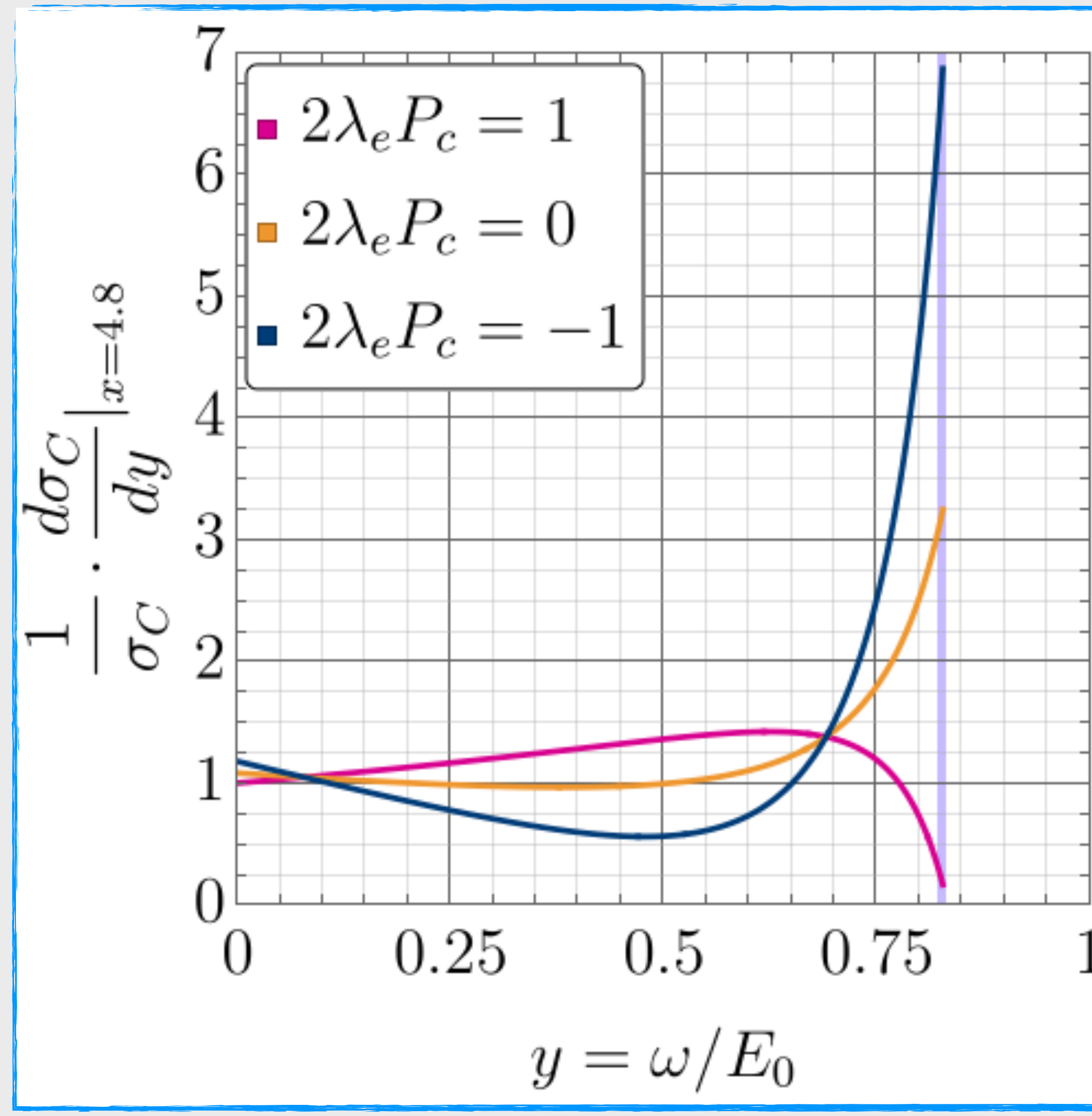

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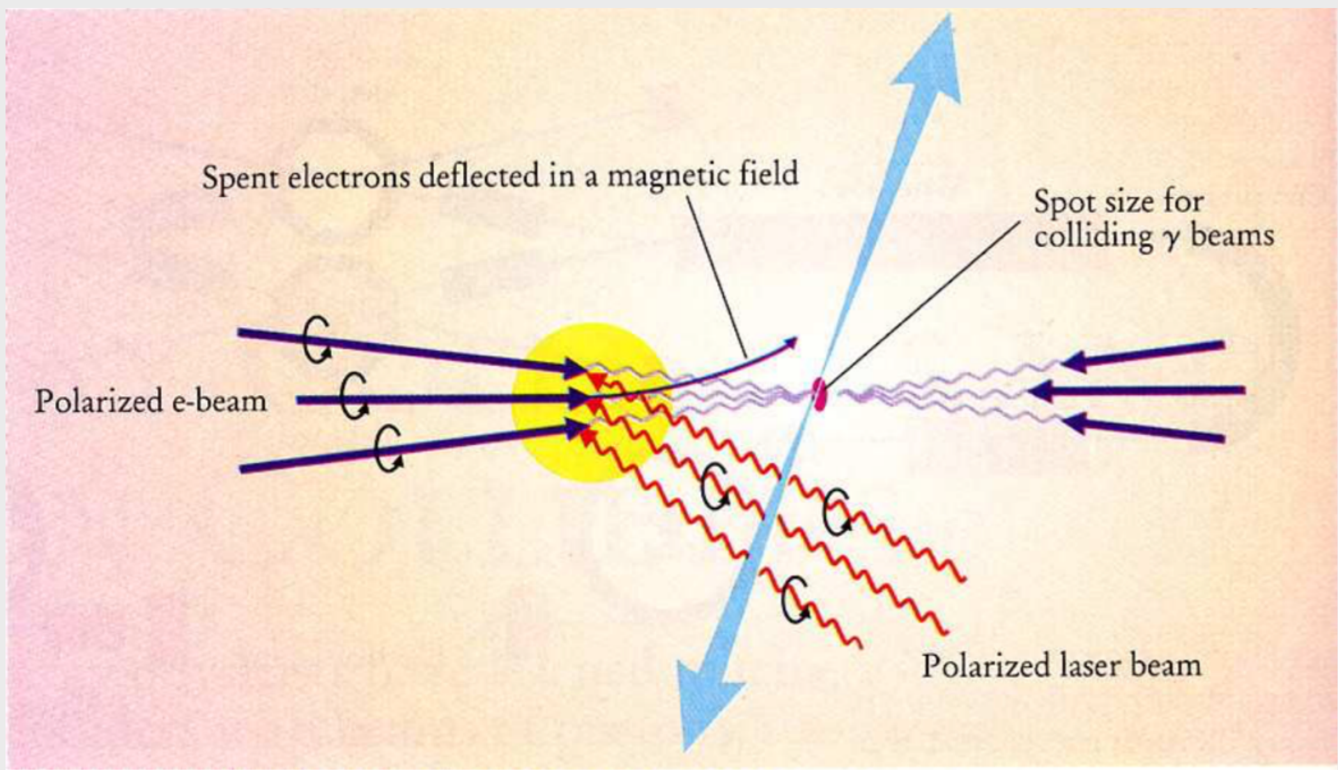
Sekaric, hep-ph/0512307

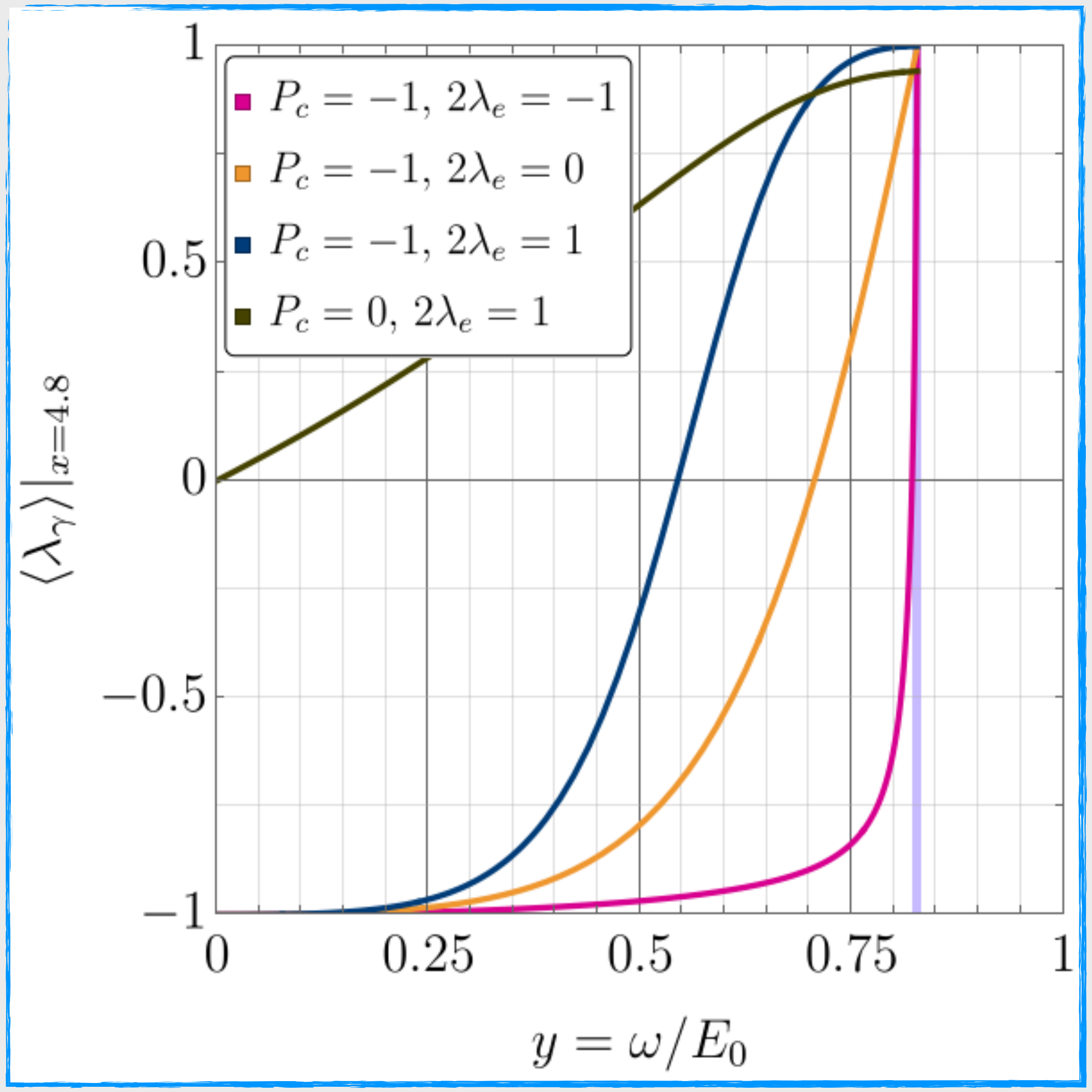
PHOTON COLLIDERS – AN OVERVIEW



Sessler, Physics Today (March 1998) p. 48

$$\omega_m = \frac{x}{x+1} E_0$$

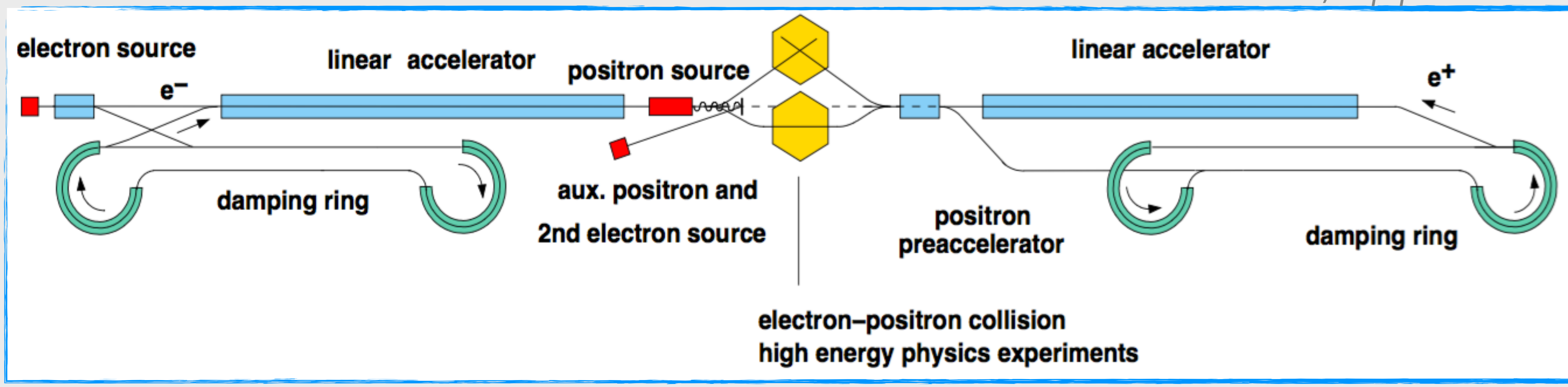
$$x = \frac{4E_0\omega_0 \cos^2 \alpha_0/2}{m_e^2 c^4} \approx 15.3 \left[\frac{E_0}{\text{TeV}}\right] \left[\frac{\omega_0}{\text{eV}}\right]$$



Telnov, Nucl.Instrum.Meth. A472 (2001) 43
Serbo, Acta Phys.Polon. B37 (2006) 1333
Sekaric, hep-ph/0512307

TESLA – A TEV-SCALE PHOTON COLLIDER

Sekaric, hep-ph/0512307



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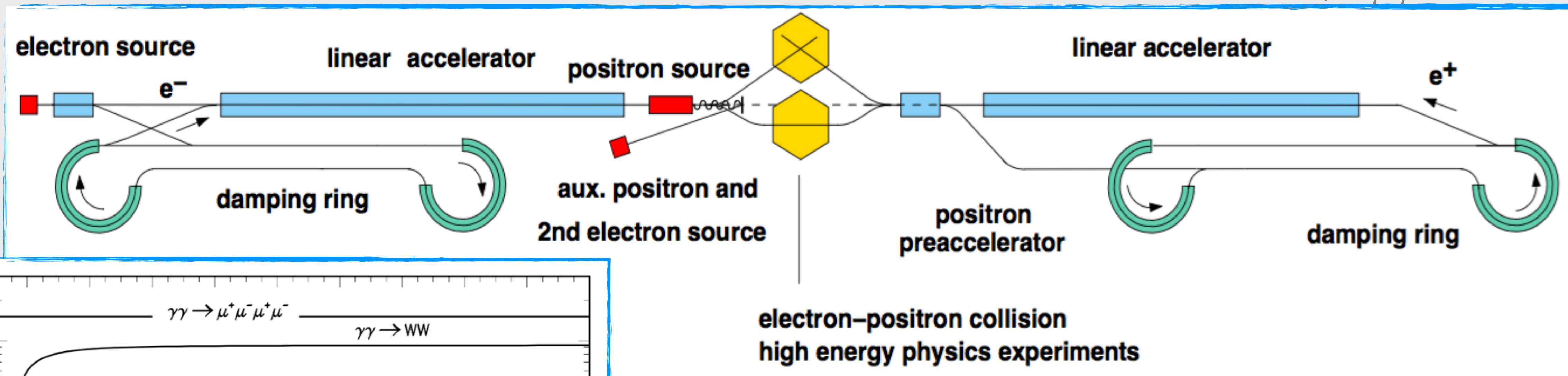
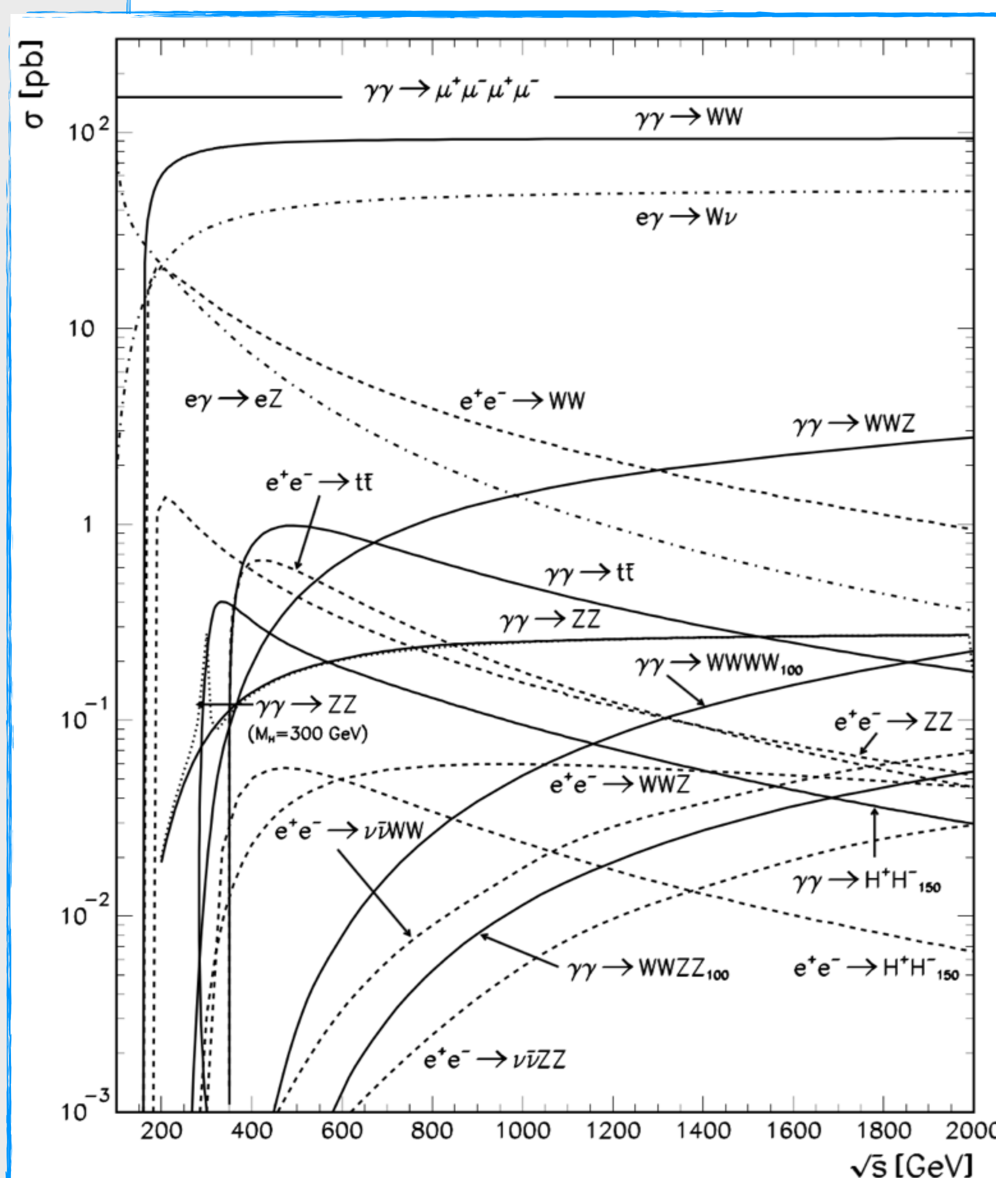
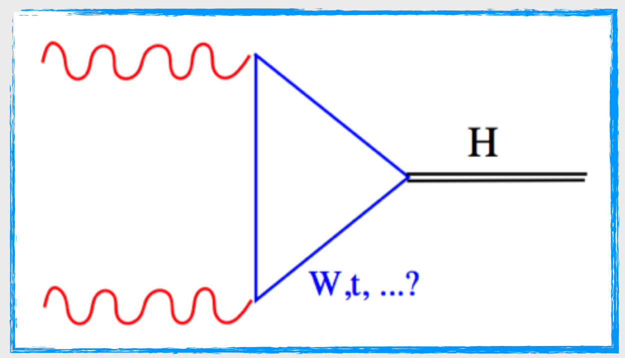
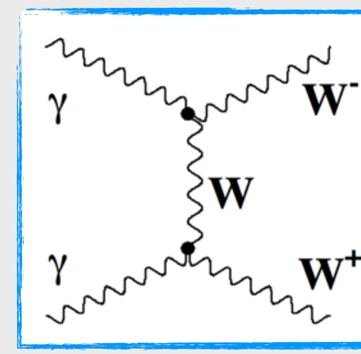
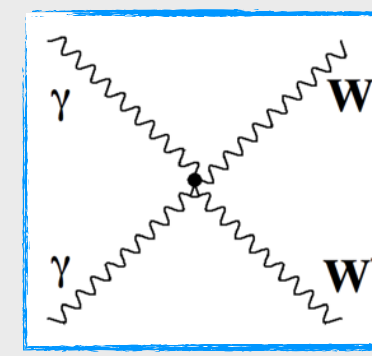
Sekaric, hep-ph/0512307











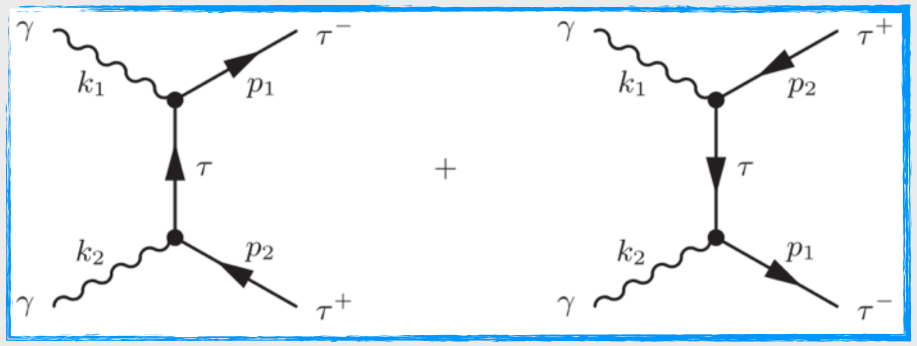
$\approx 100\ \mathrm{fb}^{-1}\mathrm{yr}^{-1}$

γe luminosity $(z > 0.8 z_{max})$	$L_{\gamma e}[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	0.94
$\gamma\gamma$ luminosity $(z > 0.8 z_{max})$	$L_{\gamma\gamma}[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.1

$$E_0 \sim 250\ \mathrm{GeV} \implies \lambda_0 \sim 1\,\mu\mathrm{m}$$

Serbo, Acta Phys.Polon. B37 (2006) 1333
Sekaric, hep-ph/0512307

TESLA – A TEV-SCALE PHOTON COLLIDER

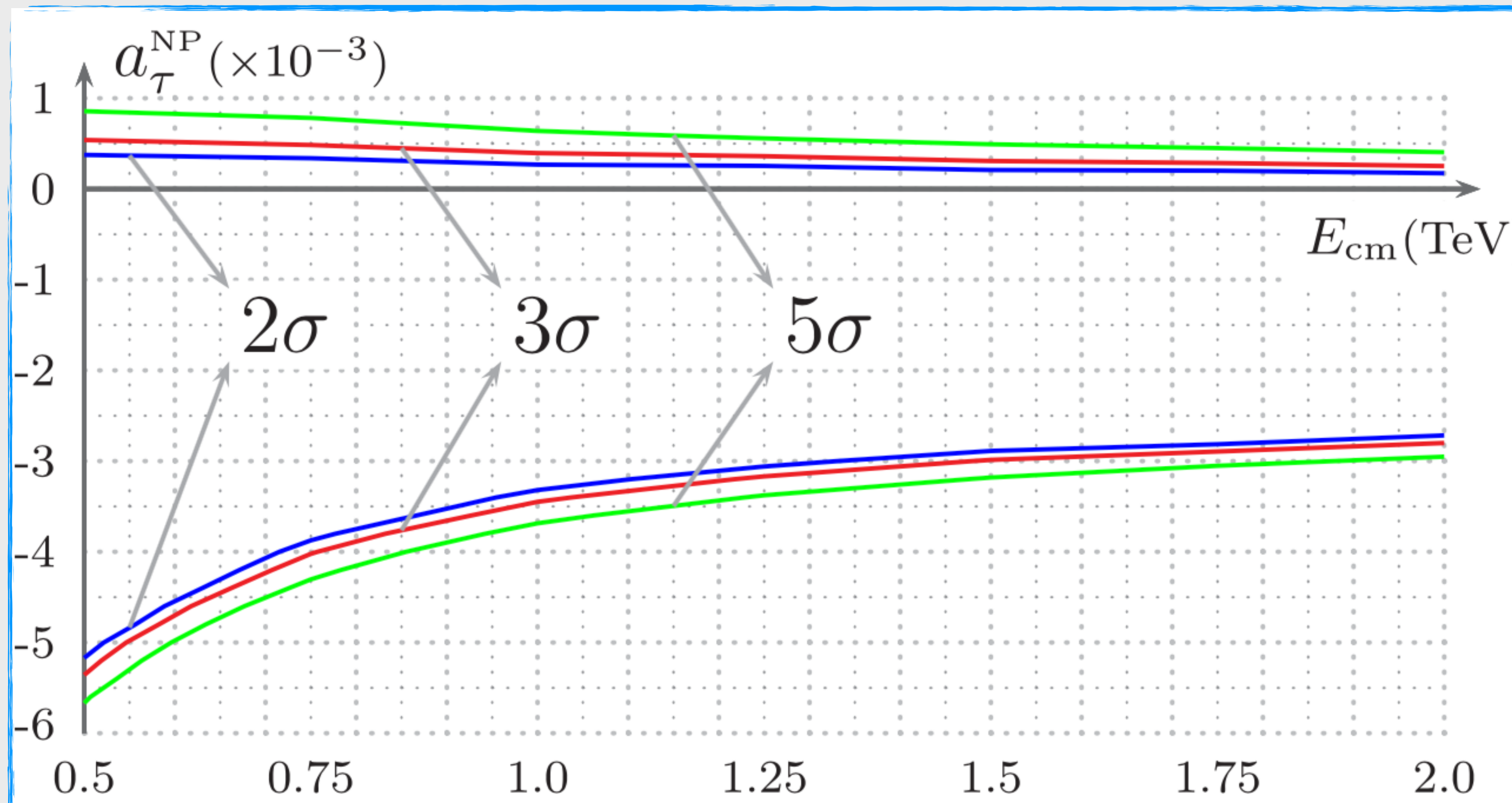


τ decay modes	$e^-\bar{\nu}_e\nu_\tau$	$\mu^-\bar{\nu}_\mu\nu_\tau$	$\pi^-\nu_\tau$	$\pi^-\pi^0\nu_\tau$	$\pi^-\pi^+\pi^-\nu_\tau$	$\pi^-2\pi^0\nu_\tau$
Branching (%)	17.84	17.37	11.06	25.41	9.82	9.17
Efficiency	0.22	0.22	0.58	0.58	0.58	0.58

$$P_\tau^{ij} \equiv \frac{N_+^{ij} - N_-^{ij}}{N_+^{ij} + N_-^{ij}}$$

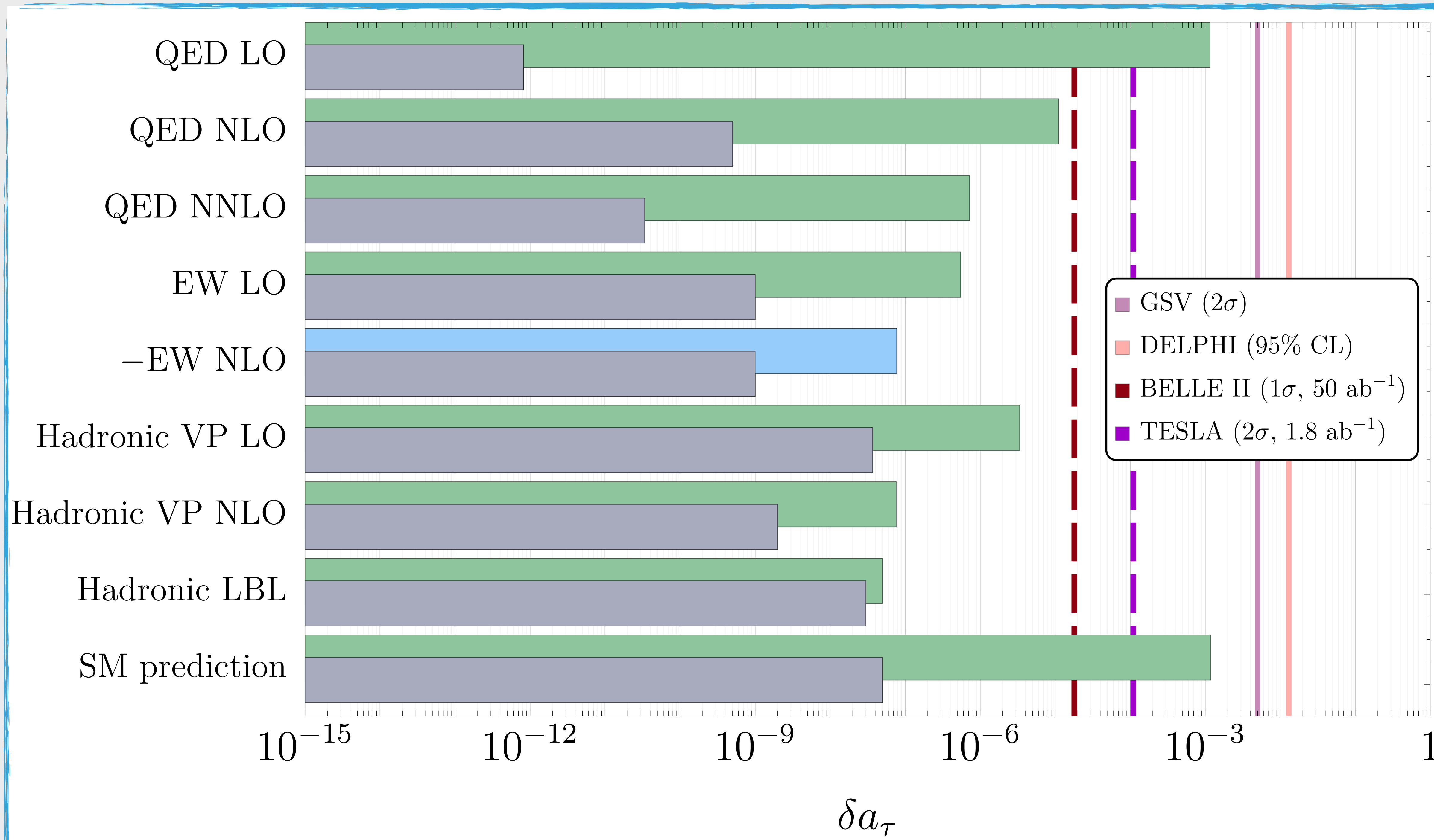
$$F = \sum_{k=1}^{n} \epsilon_k \mathrm{Br}_k$$

$$\left|\frac{\delta P_\tau^{++}(a_\tau)}{\Delta P_\tau^{++}(a_\tau)}\right| = \sqrt{\frac{\mathrm{CL}}{F}}$$

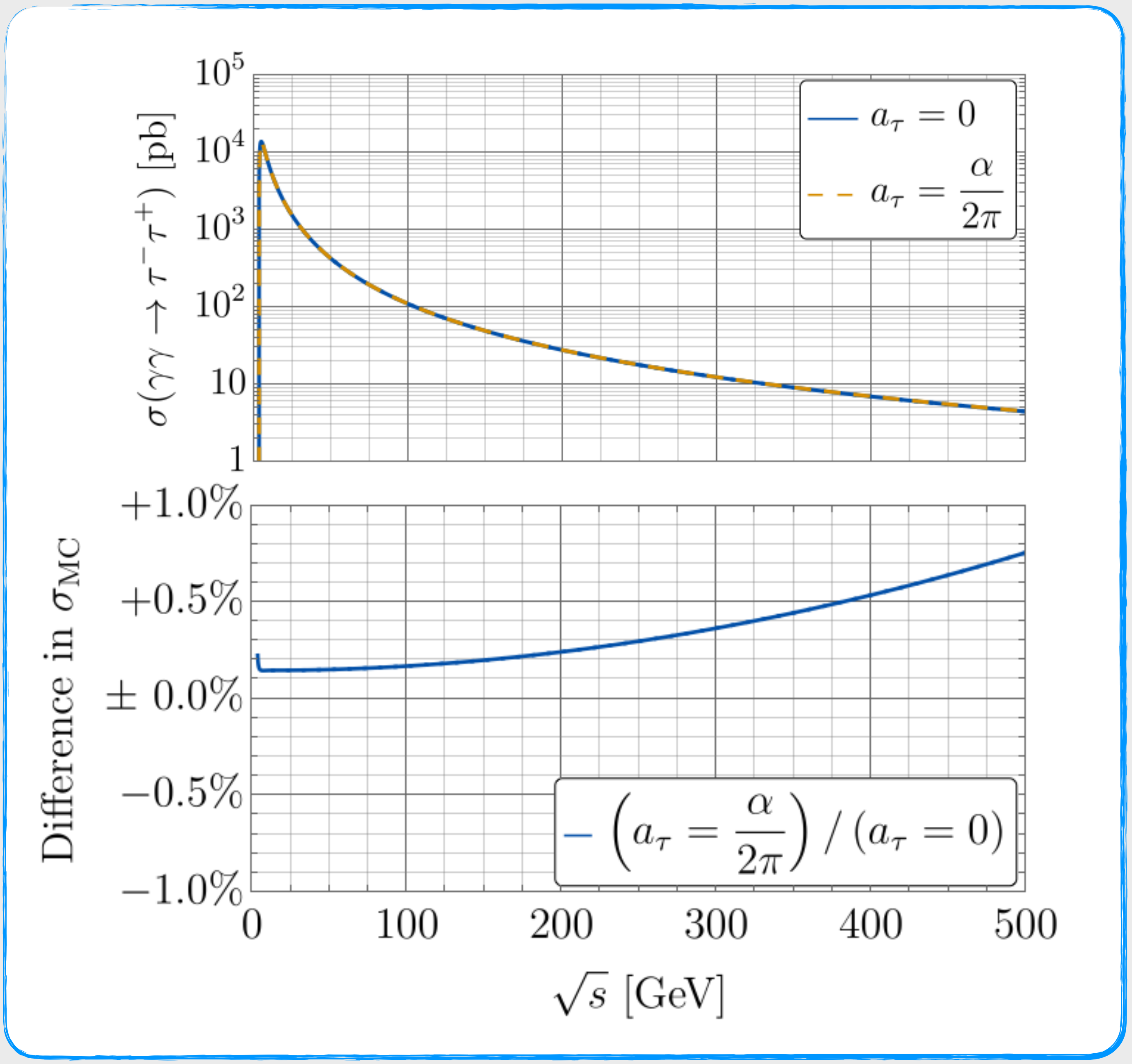


Peressutti & Sampayo, Phys.Rev. D86 (2012) 035016

TESLA – A TeV-SCALE PHOTON COLLIDER

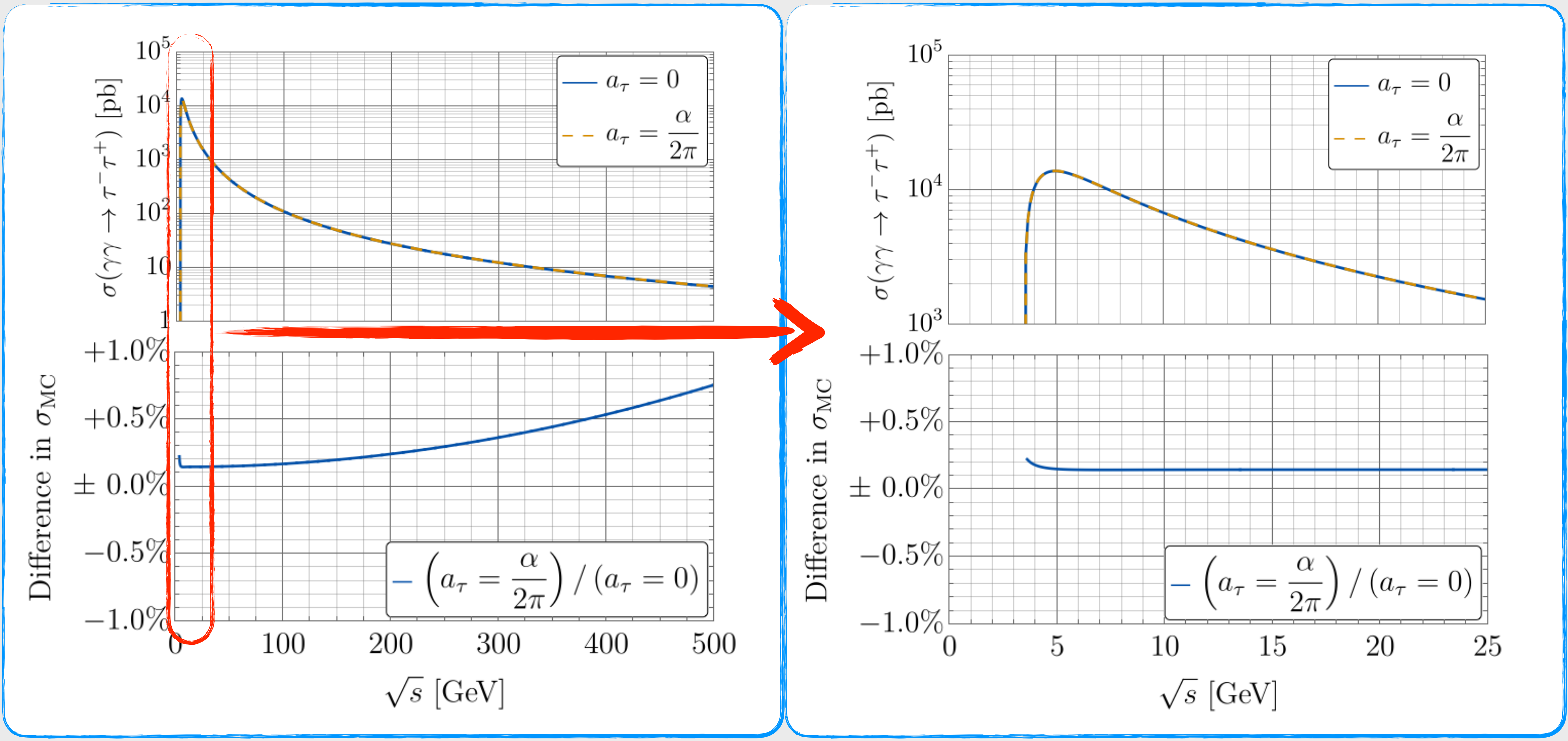


A MODEST PROPOSAL – A PHOTON-PHOTON TAU FACTORY



JMB, M. Mackenzie & M. Velasco, in preparation

A Modest Proposal — A Photon-Photon Tau Factory



JMB, M. Mackenzie & M. Velasco, in preparation

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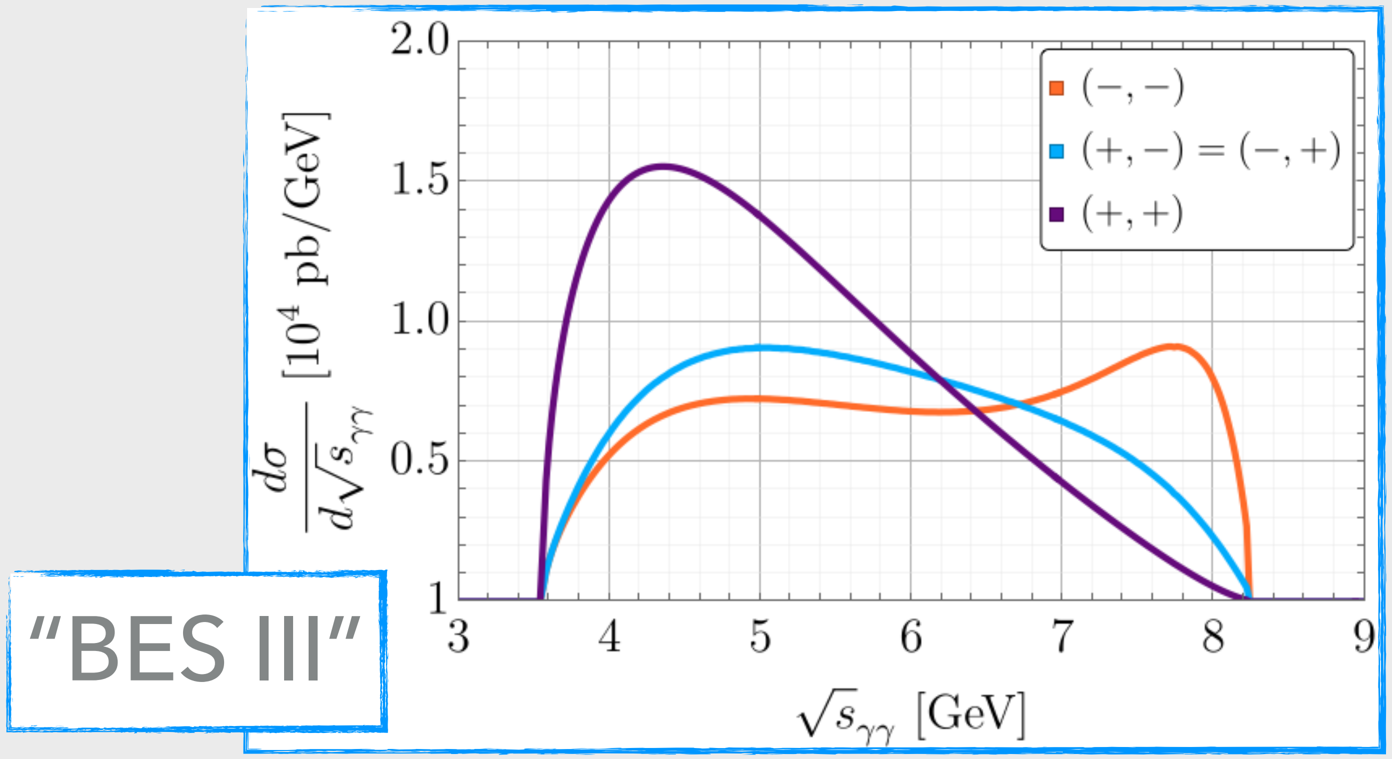

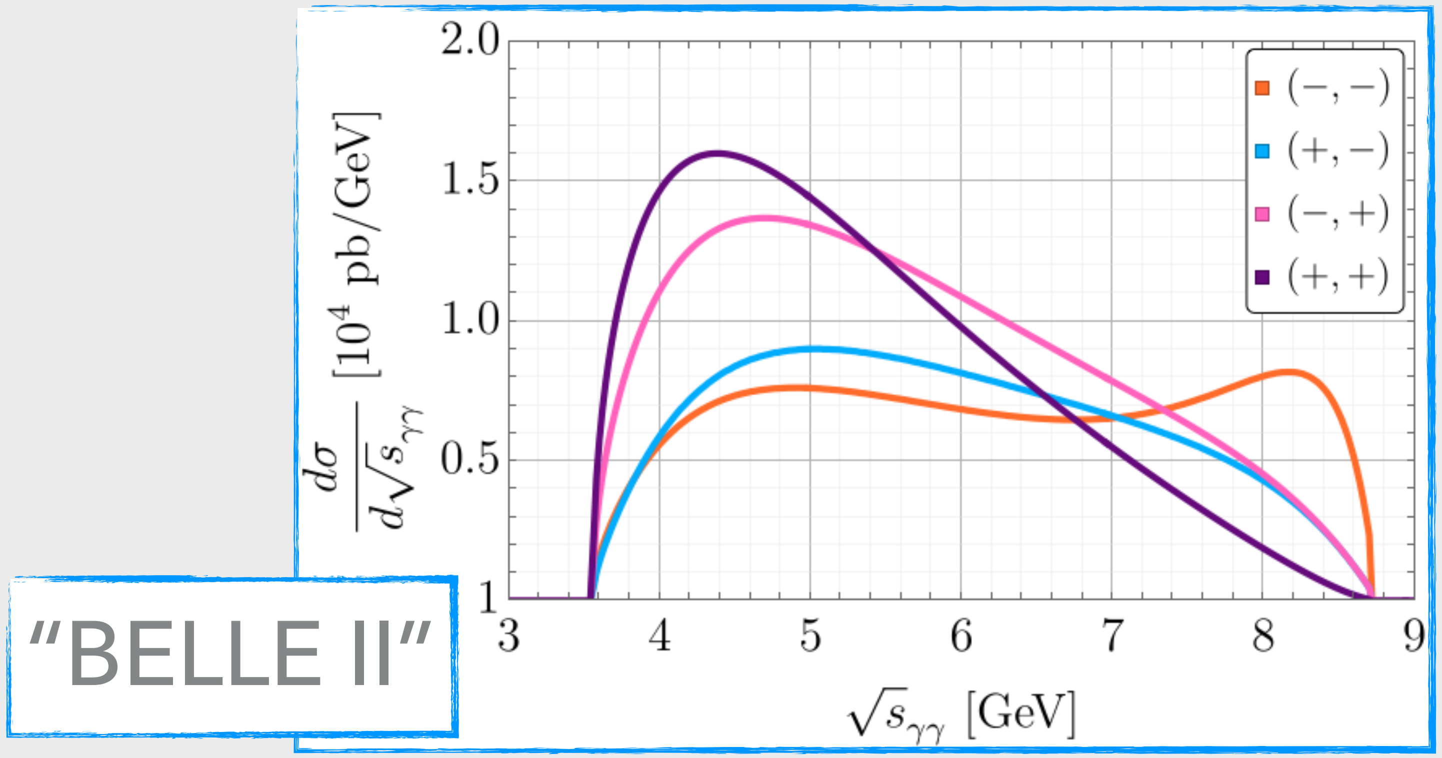

JMB, M. Mackenzie & M. Velasco, in preparation

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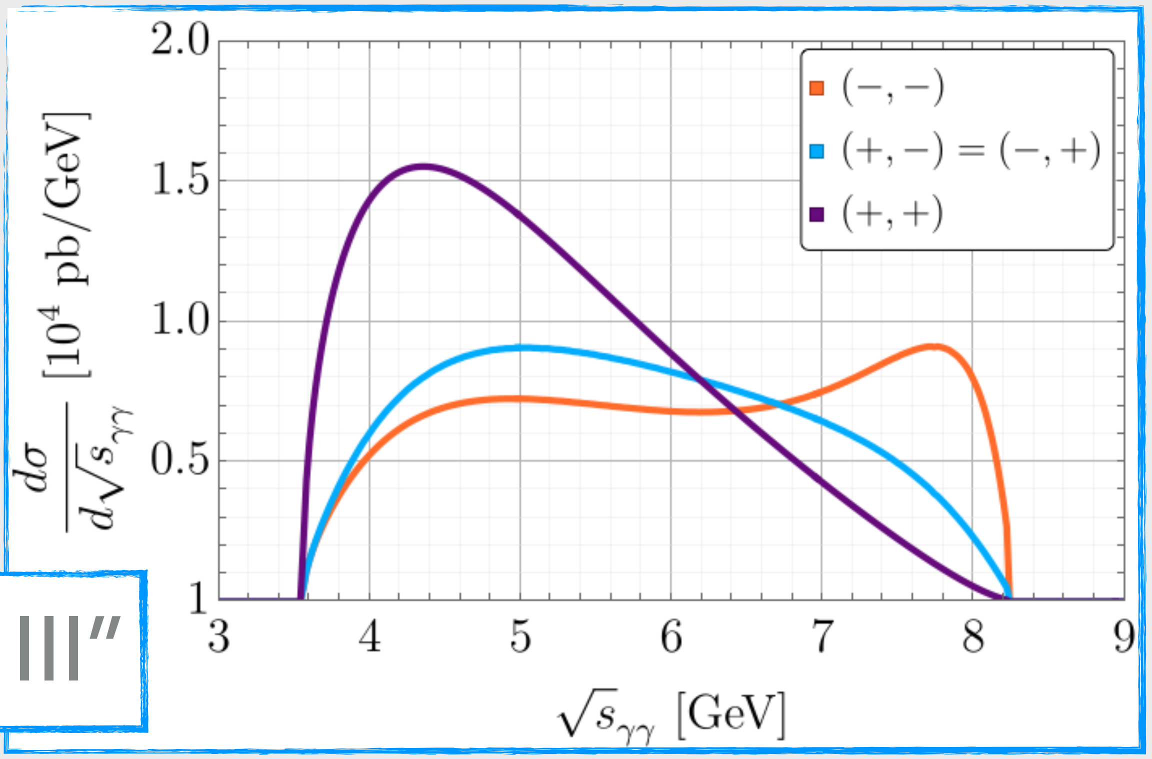
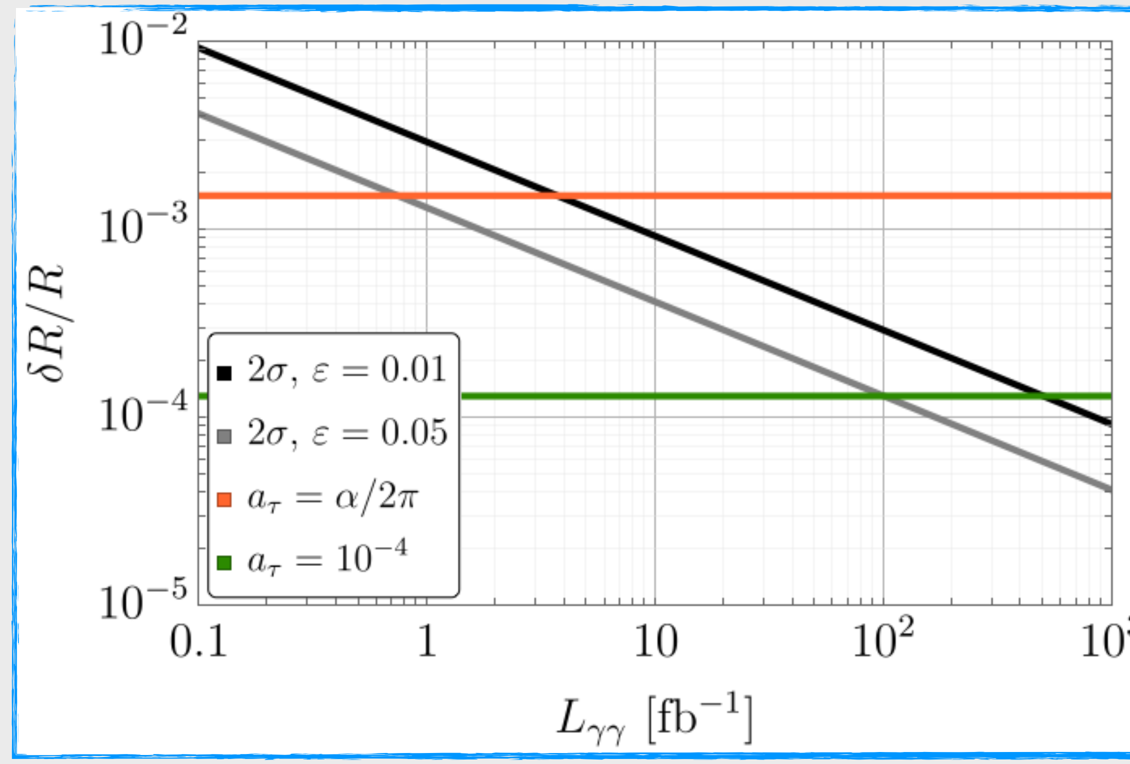
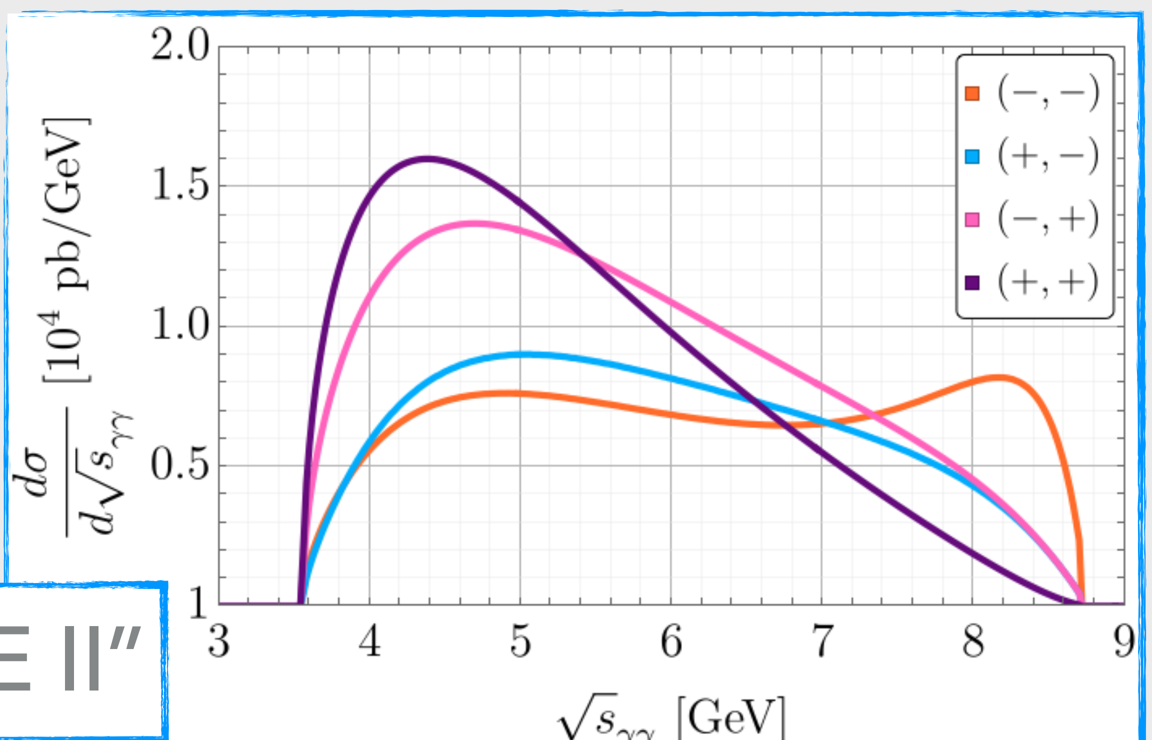
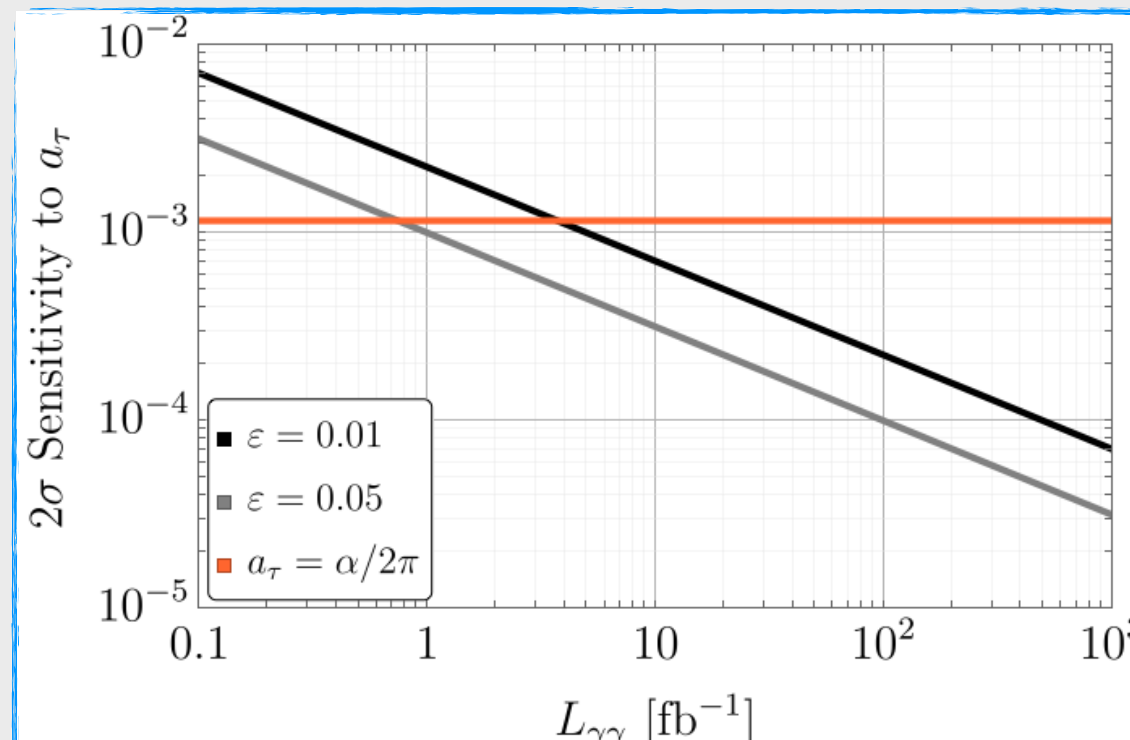


"BES III"





"BELLE II"



JMB, M. Mackenzie & M. Velasco, in preparation

A MODEST PROPOSAL — A PHOTON-PHOTON TAU FACTORY

- Additional considerations:
  - Laser energy: $x = 4.8,\ E_0 = 5.0\ \mathrm{GeV} \implies \lambda_0 \sim 20\ \mathrm{nm}$
  - Beam effects & systematics
    - "CompAZ" for TESLA; no use at low energies
  - Final state kinematics/ polarizations
  - Hadronic backgrounds
  - Loop effects

JMB, M. Mackenzie & M. Velasco, in preparation

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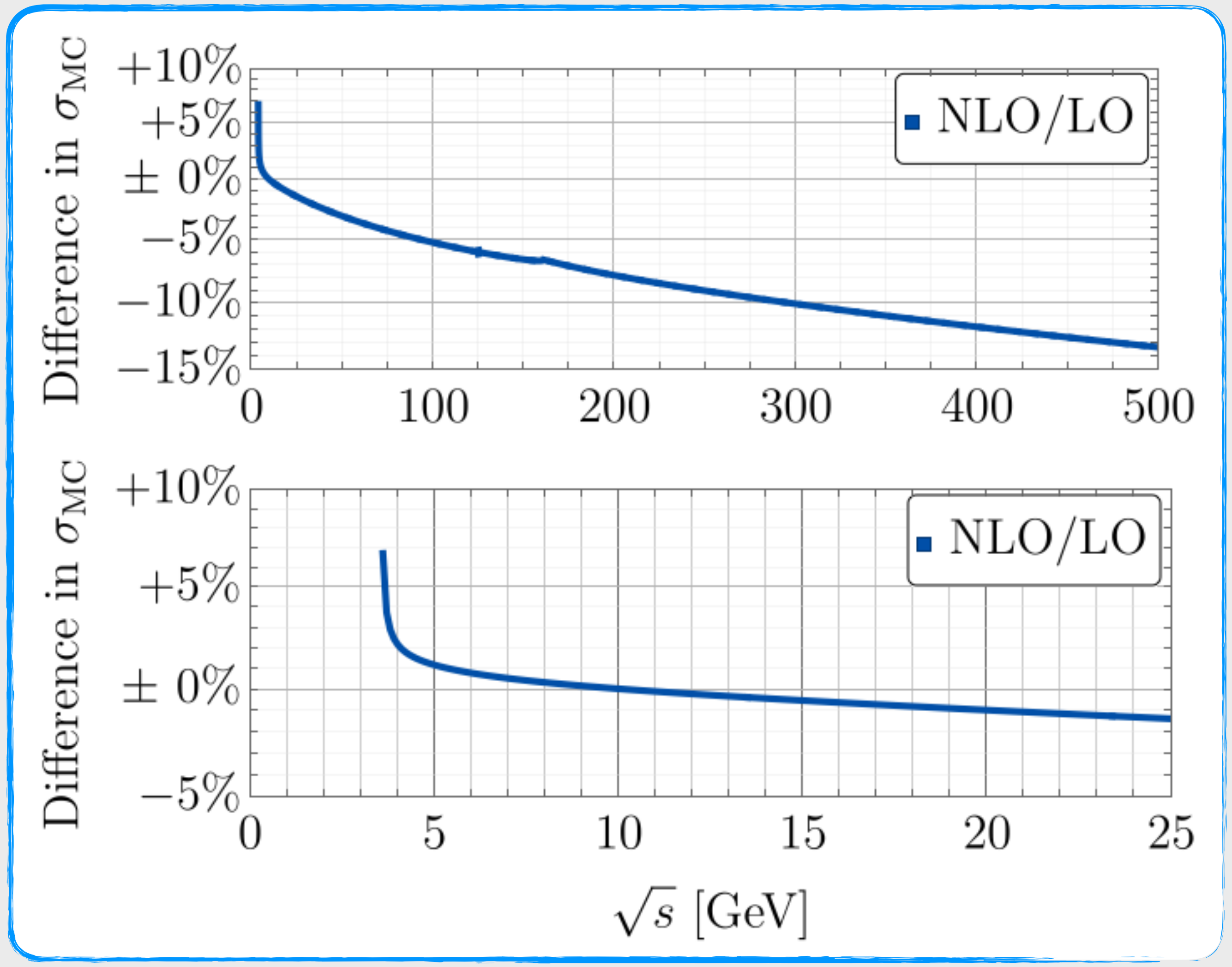

JMB, M. Mackenzie & M. Velasco, in preparation

CONCLUSIONS

- Consider the following statements:
  - The τ is fertile ground for discovering new physics
  - The magnetic moments of light leptons (e, μ) have been measured with unprecedented precision
- These indicate opportunities for $(g\text{-}2)_\tau$, but experiments have not been able to push against the SM expectation (yet!)
- Improvements on $(g\text{-}2)_\tau$ are expected, but not close to the level of e or μ. New ideas are needed!

Back-up Slides

DETAILS OF GSV ANALYSIS

$$R_{\tau\mu} = \sqrt{1-4r_Z^2}\left[1+2r_Z^2\frac{v^2-2a^2}{v^2+a^2}\right] - a_Z\left(\frac{6v\sqrt{1-4r_Z^2}}{v^2+a^2}\right)\sin\theta_W\cos\theta_W + \frac{a_Z^2}{2}\sqrt{1-4r_Z^2}\left(\frac{1+8r_Z^2}{v^2+a^2}\right)\sin^2\theta_W\cos^2\theta_W$$

$$r_Z = \frac{m_\tau}{M_Z},\; v = 2\sin^2\theta_W - \frac{1}{2},\; a = -\frac{1}{2}$$

$$\begin{aligned} R_{\tau\tau} &= 1 + F_1^\gamma(s)\left(\frac{M_Z}{2m_\tau}\right)a_\tau + F_2^\gamma(s)\left(\frac{M_Z}{2m_\tau}\right)^2 a_\tau^2 \\ &+ F_1^Z(s)\left(\frac{M_Z\sin\theta_W\cos\theta_W}{2m_\tau}\right)a_Z + F_2^Z(s)\left(\frac{M_Z\sin\theta_W\cos\theta_W}{2m_\tau}\right)^2 a_Z^2 \\ &+ F^{\gamma Z}(s)\left(\frac{M_Z}{2m_\tau}\right)\left(\frac{M_Z\sin\theta_W\cos\theta_W}{2m_\tau}\right)a_\tau a_Z \end{aligned}$$

$\sqrt{s}$(GeV)	F_1^γ	F_2^γ	F_1^Z	F_2^Z	$F^{\gamma Z}$
130	0.079	0.682	0.028	5.258	0.286
136	0.083	0.784	0.026	5.152	0.304
161	0.092	1.221	0.022	5.272	0.384
172	0.094	1.427	0.021	5.497	0.424
183	0.096	1.642	0.020	5.789	0.467
189	0.096	1.765	0.019	5.971	0.491

$$A_{cc}^{\mp} = \frac{\sigma_{cc}^{\mp}(+)-\sigma_{cc}^{\mp}(-)}{\sigma_{cc}^{\mp}(+)+\sigma_{cc}^{\mp}(-)} = \mp\left(\frac{m_\tau^2-2m_h^2}{m_\tau^2+2m_h^2}\right)\frac{1}{2}\frac{a}{v^2+a^2}\left[\frac{\sin\theta_W\cos\theta_W}{2r_Z}a_Z - vr_Z\right]$$

$$\sigma_{cc}^{\mp}(+) = \sigma(\cos\theta_{\tau^-} > 0,\ \cos\phi_{h^\mp} > 0) + \sigma(\cos\theta_{\tau^-} < 0,\ \cos\phi_{h^\mp} < 0)$$

$$\sigma_{cc}^{\mp}(-) = \sigma(\cos\theta_{\tau^-} > 0,\ \cos\phi_{h^\mp} < 0) + \sigma(\cos\theta_{\tau^-} > 0,\ \cos\phi_{h^\mp} < 0)$$

$$R_{\tau e}^W = (1-r_W^2)^3\left[1+\frac{r_W^2}{2}+\frac{3}{2}\frac{r_W}{r_Z}\cos\theta_W\kappa_W + \left(\frac{1+2r_W^2}{8r_Z^2}\right)\kappa_W^2\right],\; r_W = m_\tau/M_W$$

González-Sprinberg, et al., Nucl.Phys. B582 (2000) 3

DETAILS OF THE PHOTON COLLIDER CROSS SECTION

$$\sigma_C = \sigma_C^0 + 2\lambda_e P_c \tau_C$$
$$\sigma_C^0 = \frac{2\sigma_0}{x}\left[\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(x+1)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(x+1)^2}\right]$$
$$\tau_C = \frac{2\sigma_0}{x}\left[\left(1+\frac{2}{x}\right)\ln(x+1)-\frac{5}{2}+\frac{1}{x+1}-\frac{1}{2(x+1)^2}\right]$$
$$\sigma_0 = \pi r_e^2 = 0.25\ \mathrm{b}$$

$$\frac{d\sigma_C}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y}+1-y-4r(1-r)-2\lambda_e P_c \frac{y(2-y)}{1-y}(2r-1)\right]$$
$$\langle\lambda_\gamma\rangle = \frac{-P_c(2r-1)\left(\frac{1}{1-y}+1-y\right)+2\lambda_e x r\left(1+(1-y)(2r-1)^2\right)}{\frac{1}{1-y}+1-y-4r(1-r)-2\lambda_e P_c x r(2-y)(2r-1)}$$
$$r = \frac{y}{x(1-y)}$$

$$\frac{d\sigma\left(\gamma\gamma\to\tau^-_{\lambda_1}\tau^+_{\lambda_2}\right)}{d\sqrt{s}_{\gamma\gamma}}\left(\sqrt{s}_{\gamma\gamma}, x_1, x_2, E_1, E_2, \lambda_{e1}, \lambda_{e2}, P_{c1}, P_{c2}\right) =$$
$$\int_0^{\frac{x_1}{1+x_1}} dy_1 \left(\frac{1}{\sigma_C}\frac{d\sigma_C}{dy_1}\right)(x_1, y_1, \lambda_{e1}, P_{c1}) \times \left(\frac{1}{\sigma_C}\frac{d\sigma_C}{dy_2}\right)\left(x_2, y_2 = \frac{s}{4y_1E_1E_2}, \lambda_{e2}, P_{c2}\right) \times$$
$$\sum_{h_1,\,h_2=\pm1}\left(\frac{1+h_1\langle\lambda_\gamma\rangle(x_1,y_1,\lambda_{e1},P_{c1})}{2}\right)\left(\frac{1+h_2\langle\lambda_\gamma\rangle\left(x_2,y_2=\frac{s}{4y_1E_1E_2},\lambda_{e2},P_{c2}\right)}{2}\right)\times\frac{d\sigma\left(\gamma_{h_1}\gamma_{h_2}\to\tau^-_{\lambda_1}\tau^+_{\lambda_2}\right)}{d\sqrt{s}}\left(\sqrt{s}_{\gamma\gamma}\right)$$

Telnov, Nucl.Instrum.Meth. A472 (2001) 43
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