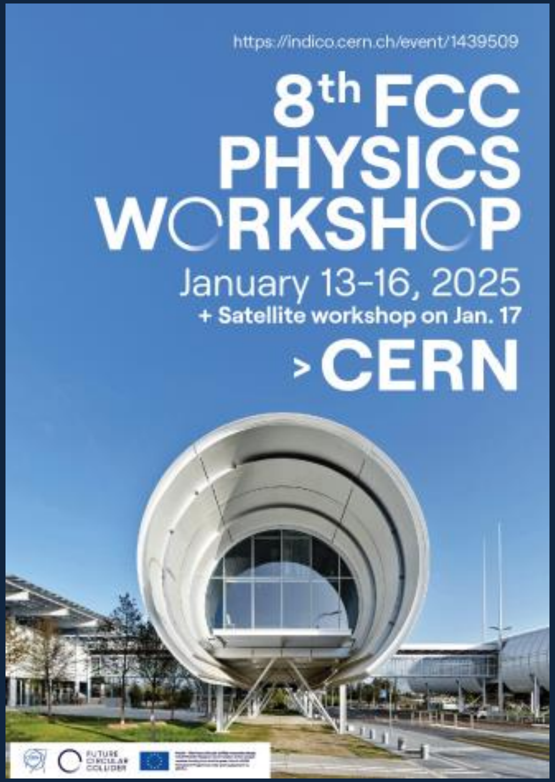
Measuring τ g-2 via $\gamma\gamma \to \tau\tau$ process at the FCC-ee



15 January 2025

D. d'Enterria, M. Pitt, M. Selvaggi

(CERN)

Outline

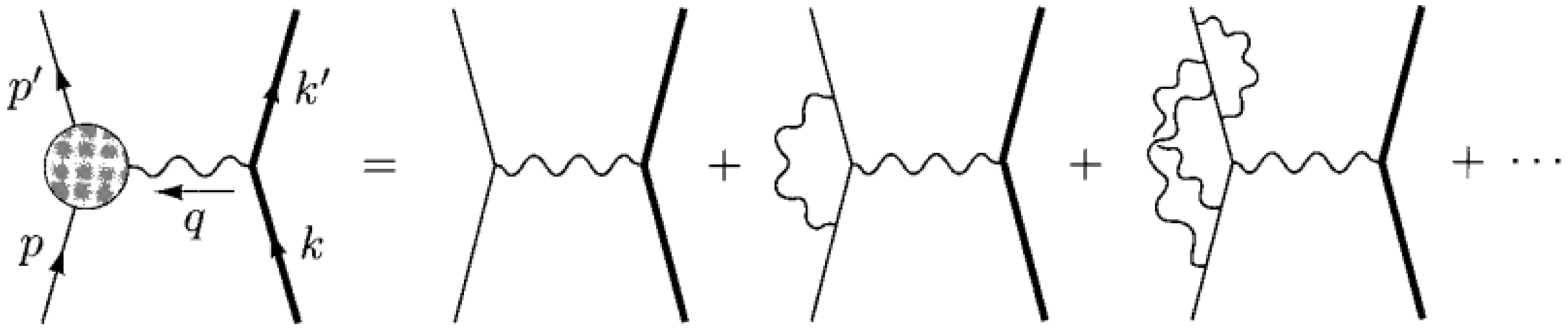
- Lepton anomalous magnetic moments (g-2)
- Past studies
- Feasibility at the FCC-ee

Lepton anomalous magnetic moments (g-2)

Photon lepton coupling

- The photon – lepton vertex (scattering of lepton from an external electromagnetic field):

$$\Gamma^\mu(p',p) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_\ell} F_2(q^2)$$



M. Peskin & D. Schroeder (Sec 6.2)

Photon lepton coupling

- The photon – lepton vertex (scattering of lepton from an external electromagnetic field):

$F_2(0) = 1$

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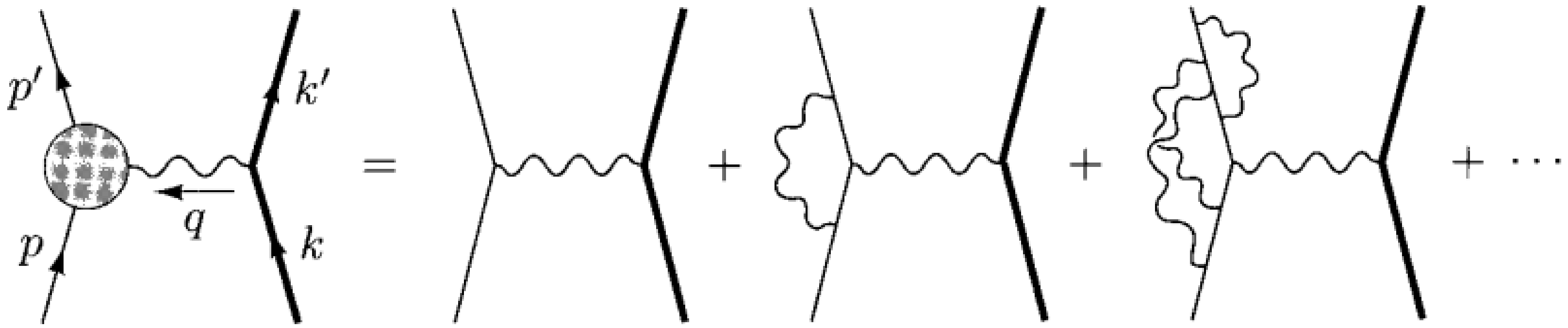


M. Peskin & D. Schroeder (Sec 6.2)

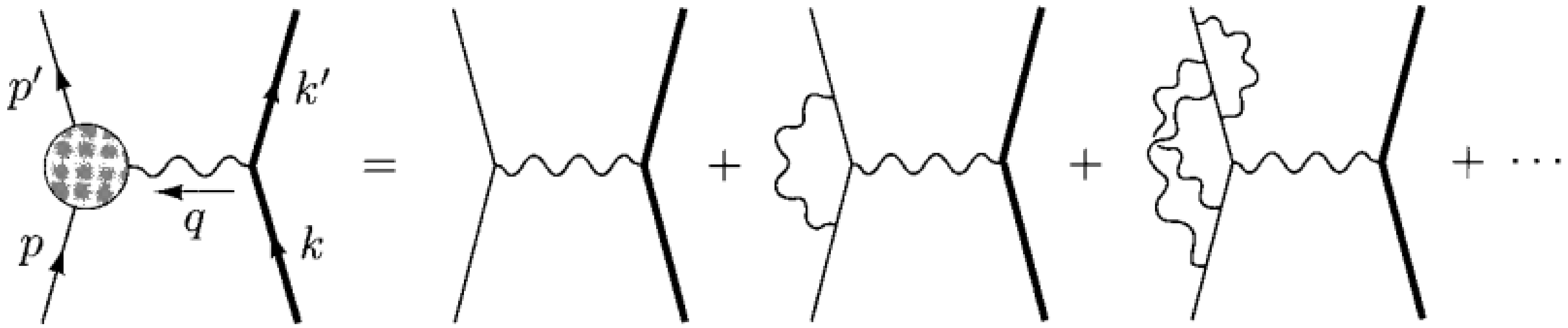
Photon lepton coupling

- The photon – lepton vertex (scattering of lepton from an external electromagnetic field):

$F_2(0) = 1$

$F_2(0) = \frac{g-2}{2} \equiv a_\ell$

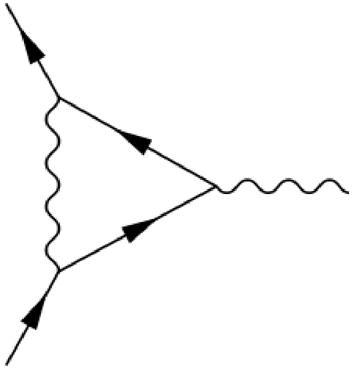
$$\Gamma^\mu(p', p) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2m_\ell} F_2(q^2)$$



M. Peskin & D. Schroeder (Sec 6.2)

Photon lepton coupling

- Corrections to photon-lepton coupling

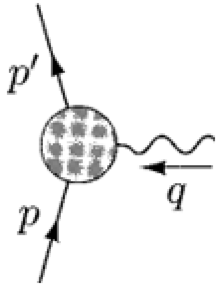


$$a_\ell^{LO} = \frac{\alpha}{2\pi} \approx 0.0011613758$$

J. Schwinger Phys. Rev. 73 (1948) 416

Photon lepton coupling

- Corrections to photon-lepton coupling

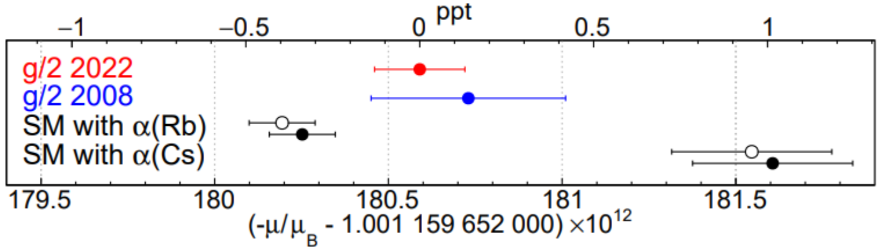


$$a_e = a_e^{NnLO}(\text{QED}) + \underbrace{a_e(\text{Weak})}_{1.7\times 10^{-12}} + \underbrace{a_e(\text{Hadron})}_{0.03\times 10^{-12}} = \mathbf{1159652181.6(7)\times 10^{-12}}$$

$$a_e^{NnLO}(\text{QED}) = \frac{1}{2}\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

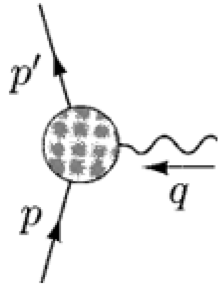
- For electrons, precision tests agrees up to 10 significant figures with the theory, which goes well beyond the LO term

PRL 130 (2023) 071801



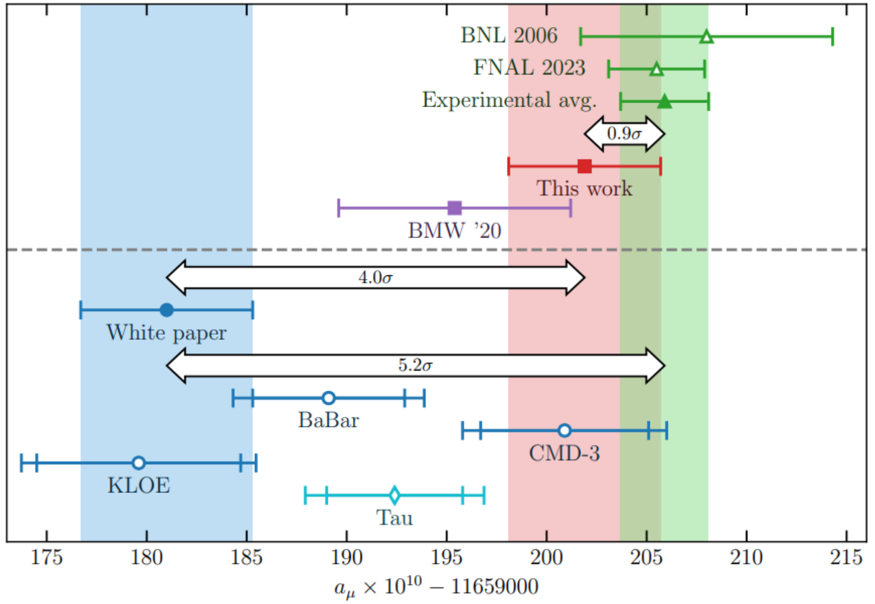
Photon lepton coupling

- Corrections to photon-lepton coupling

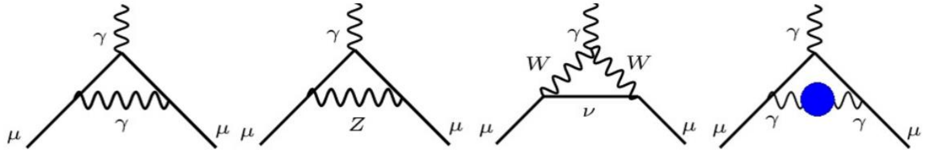


$$a_\mu = a_\mu(\text{QED}) + \underbrace{a_\mu(\text{EW})}_{15.4\times10^{-10}} + \underbrace{a_\mu(\text{HVP})}_{714\times10^{-10}} = \mathbf{11659201\times10^{-10}}$$

[2407.10913](https://arxiv.org/abs/2407.10913)

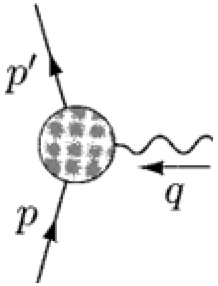


- For electrons, precision tests agrees up to 10 significant figures with the theory, which goes well beyond the LO term
- For muons, the measured precision ~ theoretical



Photon lepton coupling

- Corrections to photon-lepton coupling



$$a_\tau = a_\tau(\mathrm{QED}) + \underbrace{a_\tau(\mathrm{EW})}_{\mathbf{47 \times 10^{-8}}} + \underbrace{a_\tau(\mathrm{Hadron})}_{\mathbf{347 \times 10^{-8}}} = \mathbf{117721(5) \times 10^{-8}}$$

- For electrons, precision tests agrees up to 10 significant figures with the theory, which goes well beyond the LO term
- For muons, the measured precision ~ theoretical
- For taus, the measurement of the a_τ is still a dream ([M. Perl, 5th WEIN Symposium 1998])

Past studies

Tau lepton g-2 at LEP

- The measurement of the tau – photon coupling, $\Gamma^{\mu}(p', p) = \gamma^{\mu} F_1(q^2) + \frac{i\sigma^{\mu\nu} q_{\nu}}{2m_{\ell}} F_2(q^2)$, and a constraint on a_{τ} was first performed at LEP

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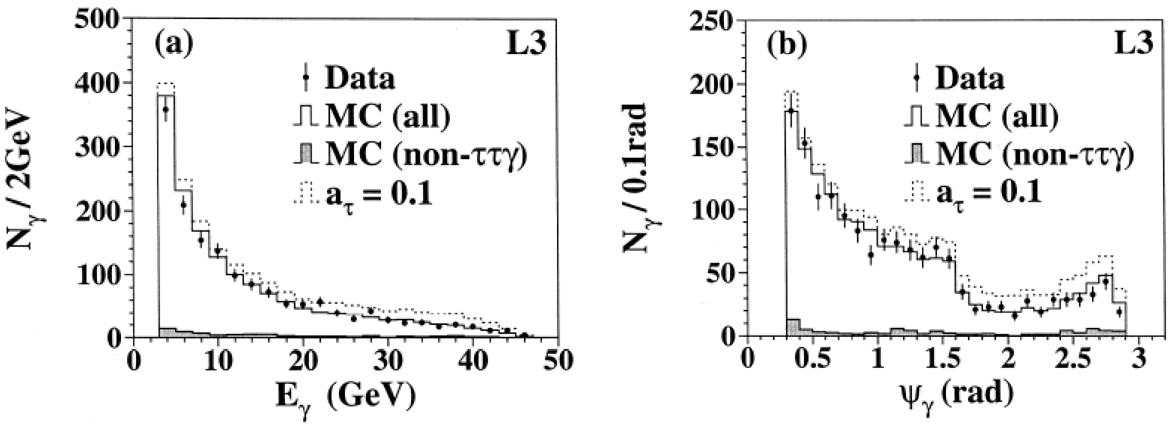
PLB 434 (1998) 169

L3: $\sqrt{s} = \mathrm{m_Z}$ and $\mathcal{L} = 100\, pb^{-1}$

Selection: $e^+e^- \rightarrow \tau^+\tau^-\gamma$



-0.052 < a_{τ} < 0.058 $(\sim 50 \times a_{\tau}^{LO})$

Tau lepton g-2 at LEP

- The measurement of the tau – photon coupling, $\Gamma^{\mu}(p',p) = \gamma^{\mu}F_1(q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m_{\ell}}F_2(q^2)$, and a constraint on a_{τ} was first performed at LEP

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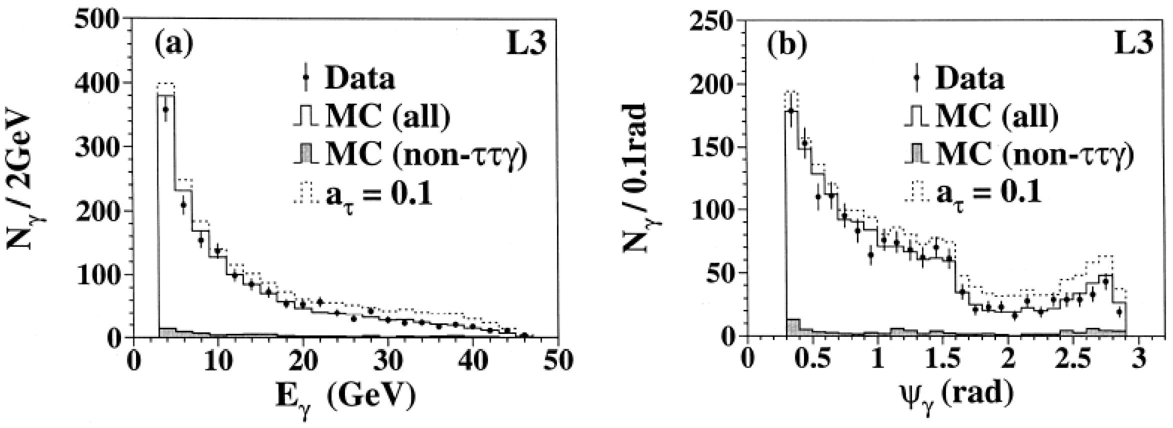
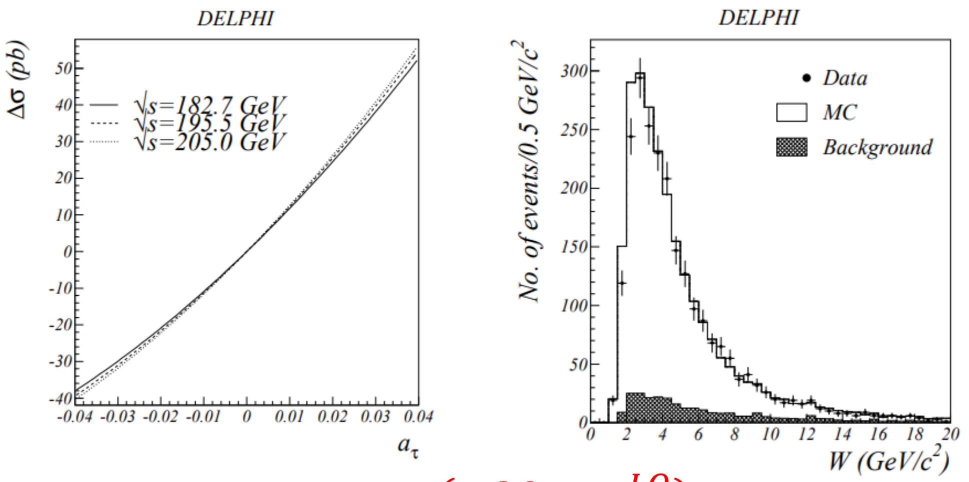


-0.052 < a_{τ} < 0.058 $(\sim 50 \times a_{\tau}^{LO})$

EPJC 35 (2004) 159

DELPHI: $\sqrt{s} \cong 200$GeV and $\mathcal{L} = 650\,pb^{-1}$

Selection: $\gamma\gamma \rightarrow \tau^+\tau^-$



-0.052 < a_{τ} < 0.013 $(\sim 30 \times a_{\tau}^{LO})$

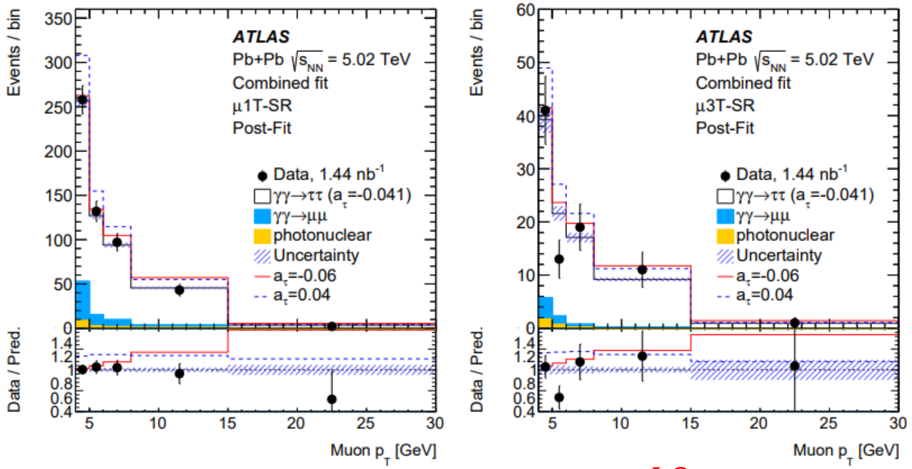
Tau lepton g-2 at LHC

- The measurement of the tau – photon coupling, $\Gamma^{\mu}(p',p) = \gamma^{\mu} F_1(q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2m_{\ell}} F_2(q^2)$, and a constraint on a_{τ} was also performed at the LHC, first in PbPb UPC ($\gamma\gamma \rightarrow \tau\tau$)

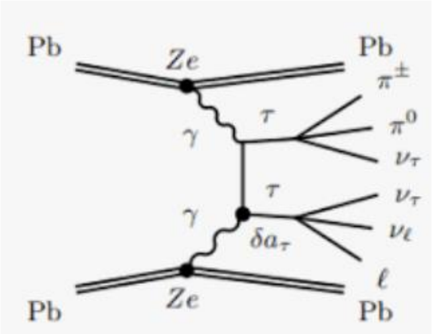
PRL 131 (2023) 151802

ATLAS: $\sqrt{s_{NN}} = 5.02$TeV and $\mathcal{L} = 1.44\ nb^{-1}$

Selection: $\gamma\gamma \rightarrow \tau^{+}\tau^{-}$



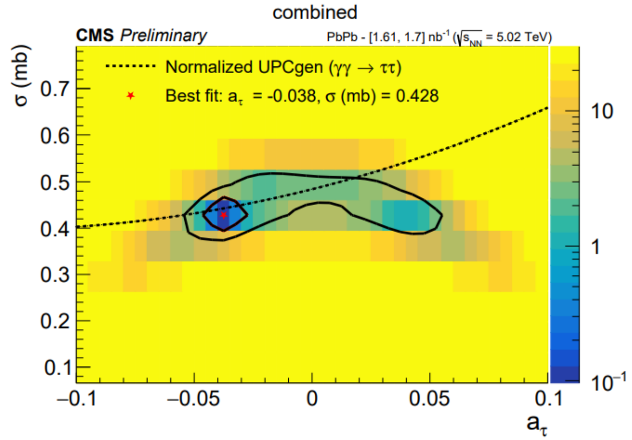
-0.057 < a_{τ} < 0.024 $(\sim 70 \times a_{\tau}^{LO})$



CMS-PAS-HIN-24-0011

CMS: $\sqrt{s_{NN}} = 5.02$TeV and $\mathcal{L} = 1.7\ nb^{-1}$

Selection: $\gamma\gamma \rightarrow \tau^{+}\tau^{-}$



-0.054 < a_{τ} < 0.018 $(\sim 60 \times a_{\tau}^{LO})$

Tau lepton g-2 at LHC

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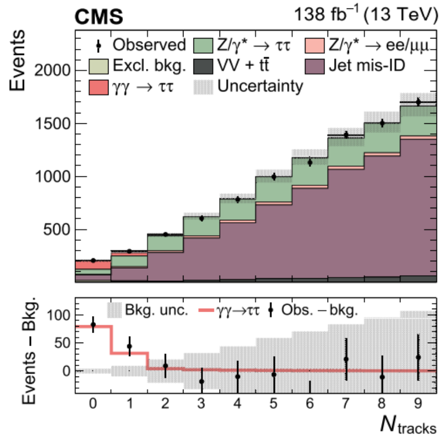
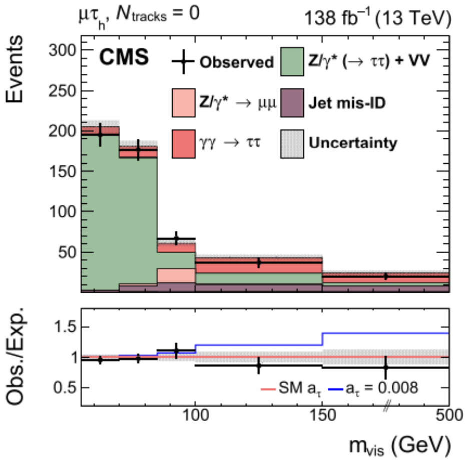
ROPP 87 (2027) 107801

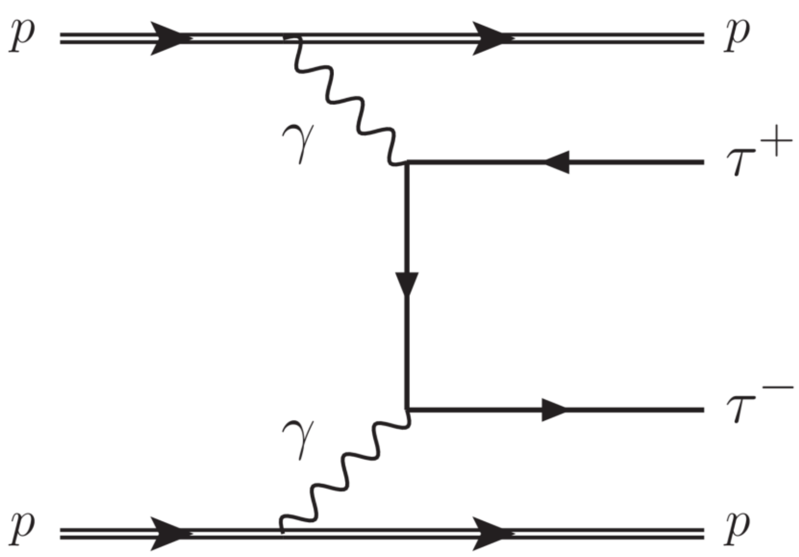
CMS: $\sqrt{s} = 13$TeV and $\mathcal{L} = 138\ fb^{-1}$

Selection: $\gamma\gamma \rightarrow \tau^{+}\tau^{-}$





-0.004 < a_{τ} < 0.004 $(\sim 3.5 \times a_{\tau}^{LO})$



Tau lepton g-2 at LHC

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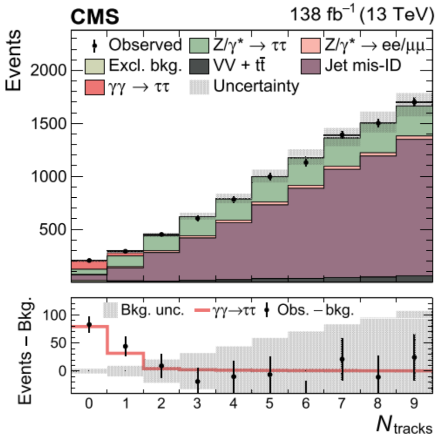
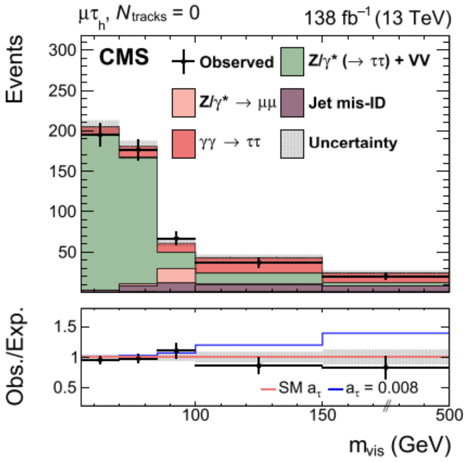
ROPP 87 (2027) 107801

CMS: $\sqrt{s} = 13$TeV and $\mathcal{L} = 138\ fb^{-1}$

Selection: $\gamma\gamma \to \tau^+\tau^-$



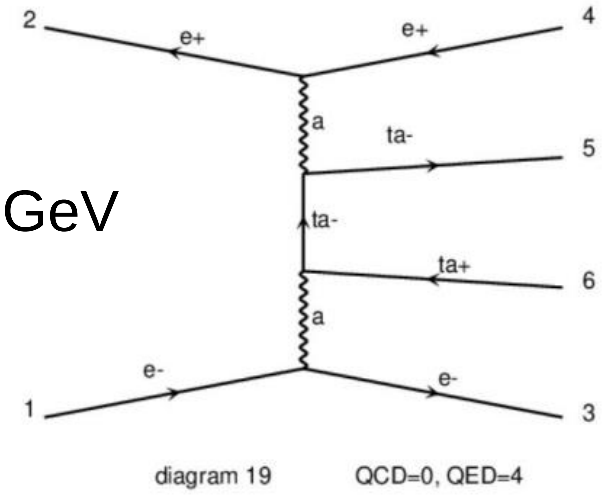


-0.004 < a_τ < 0.004 $(\sim 3.5 \times a_\tau^{LO})$

Feasibility at the FCC-ee

Tau lepton g-2 at FCC-ee

- Processes were generated with Madgraph5 and processed with Pythia + Delphes using the FCCee framework.



- Event generator: MG5_aMC v3.5.3
  - For the 4 nominal runs: $\sqrt{s} = 91.2$ GeV, 160 GeV, 240 GeV, 365 GeV
  - Using full matrix element at LO (not the EPA photon flux)
  - Taus generated with $|\eta|<3$
- Parton shower:
  - Pythia 8.311 with ISR + FSR
- Detector simulation:
  - Delphes with card_IDEA.tcl and edm4hep_IDEA.tcl

electromatnetic

Tau lepton g-2 at FCC-ee

- Processes were generated with Madgraph5 and processed with Pythia + Delphes using the FCCee framework.

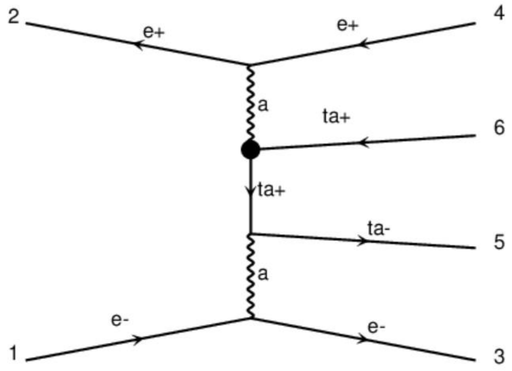
○ BSM model – using EFT model for $(g-2)_\tau$ extraction (approach valid only up to a_τ^{LO} term)

In the SM Lagrangian electromagnetic moments arise from:

$$\mathcal{L} \supset \frac{1}{2}\bar{\tau}\sigma^{\mu\nu}\left(a_\tau \frac{e}{2m_\tau} - i d_\tau \gamma_5\right)\tau_R F_{\mu\nu}$$

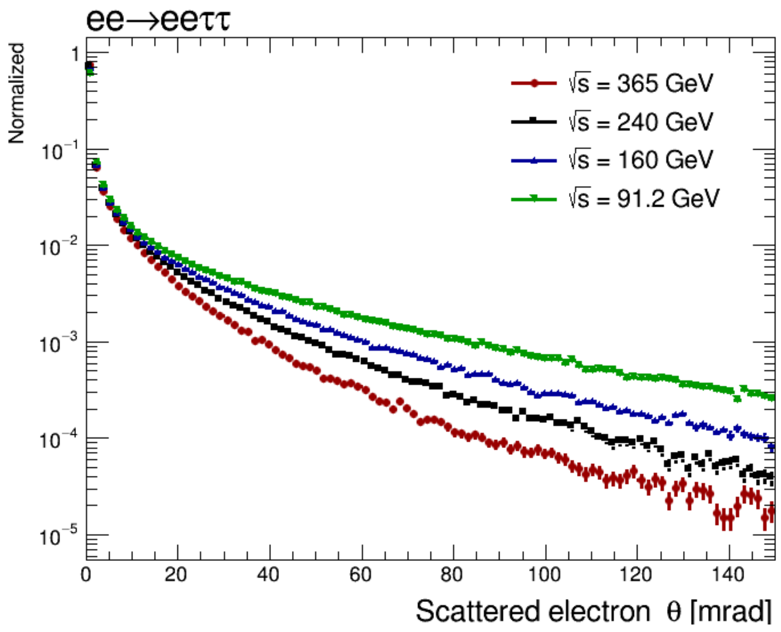
Deviation from the SM of a_τ can be parametrized in terms of dim-6 BSM Lagrangian:

$$\mathcal{L}_{\text{BSM}} = \frac{C_{\tau B}}{\Lambda^2}\overline{L}_L \sigma^{\mu\nu}\tau_R H B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2}\overline{L}_L \sigma^{\mu\nu}\tau_R \sigma^i H W^i_{\mu\nu} + \text{h.c.,} \quad (3)$$



Tau lepton g-2 at FCC-ee

- Electron / positron kinematics (GEN level)
  - Ideally, we need to tag very-forward e+/- (θ→0) to select processes from the fusion of (quasi)real photons (sensitive to (g-2)_tau)
    - For increasing $\sqrt{s}$, less e+/- are centrally scattered



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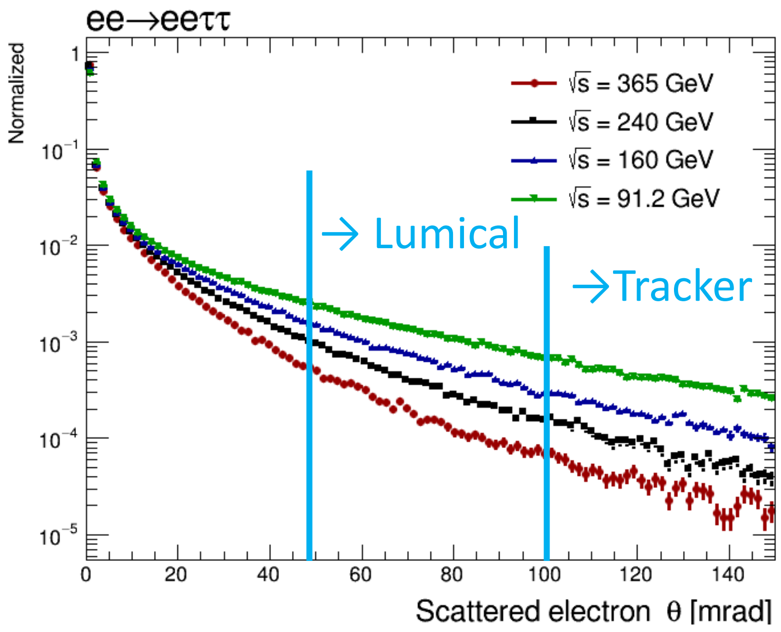
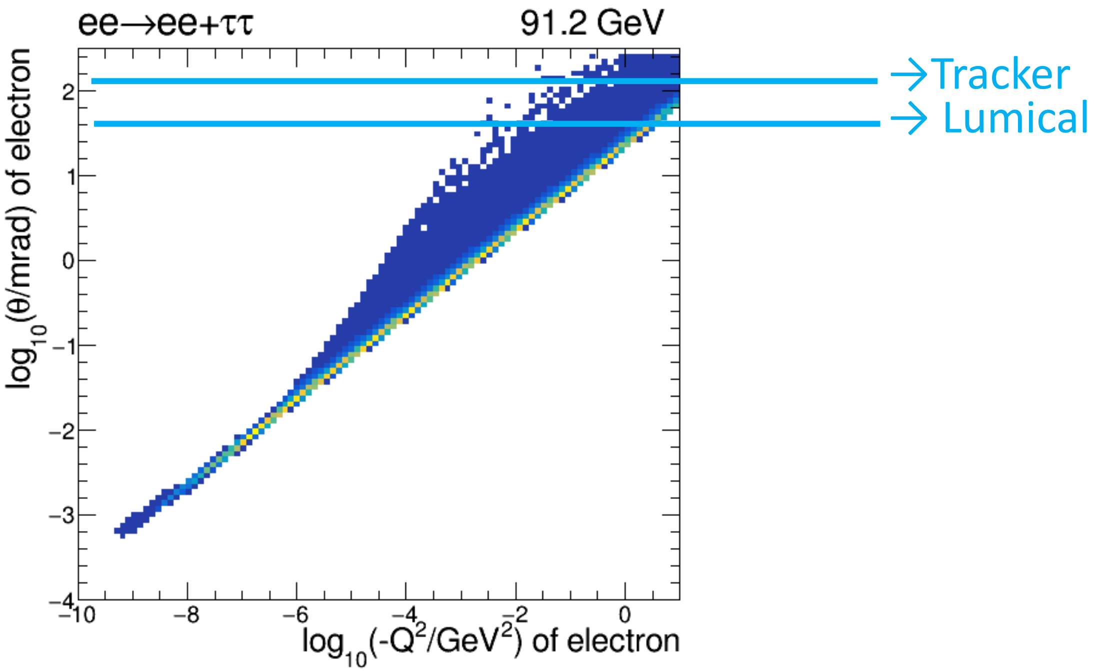
Elastic scattering $\theta_{MAX} = \sqrt{\frac{-q^2_{min}}{E_{BEAM}}}$





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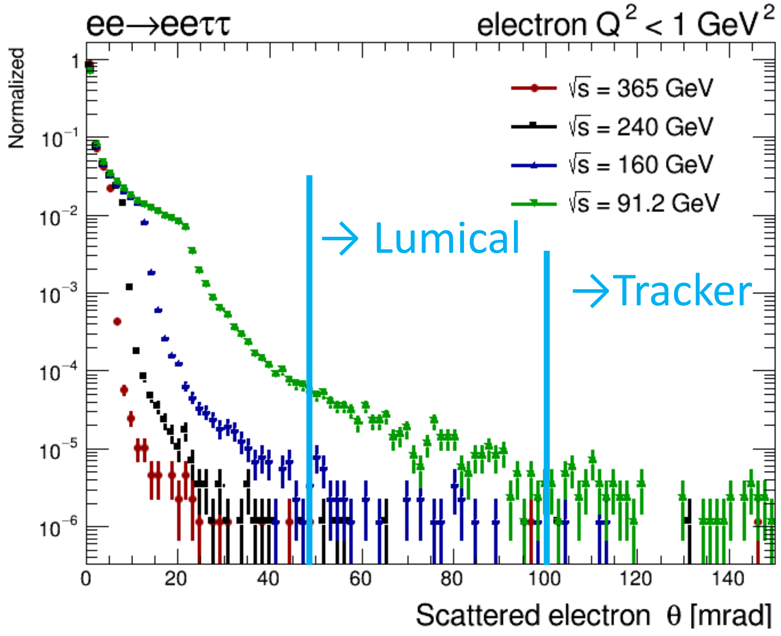

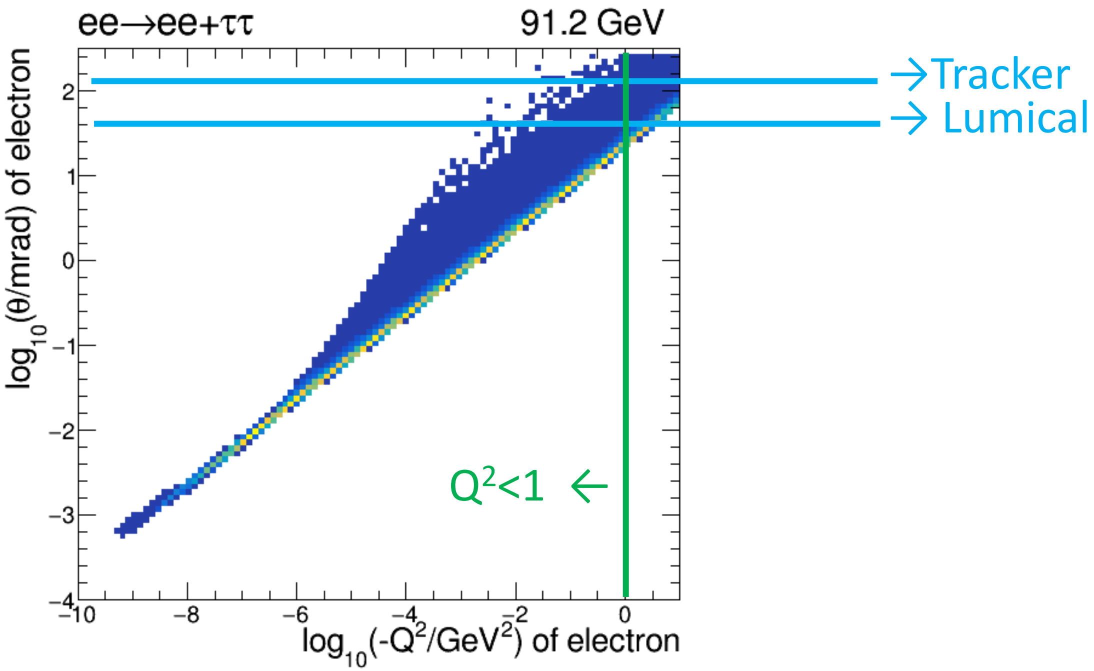

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  - Ideally, we need to tag very-forward e+/- (θ→0) to select processes from the fusion of (quasi)real photons (sensitive to (g-2)_tau)
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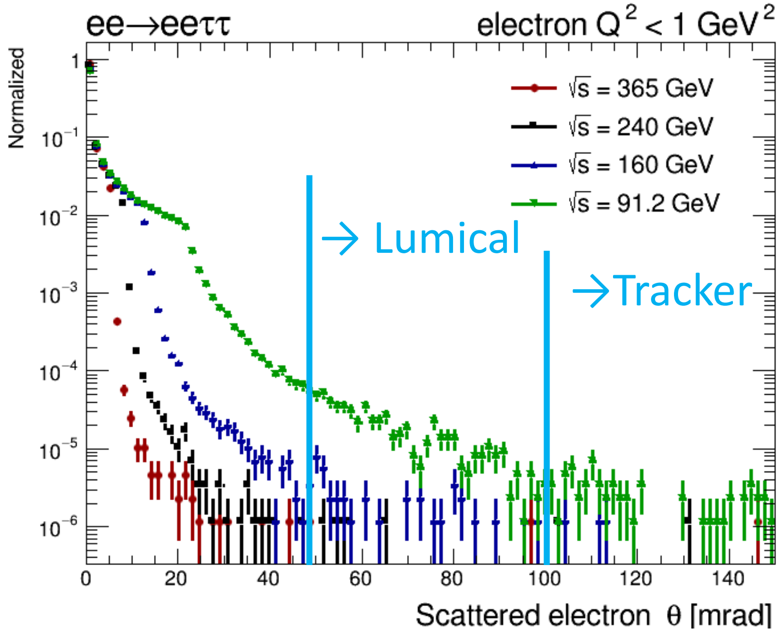
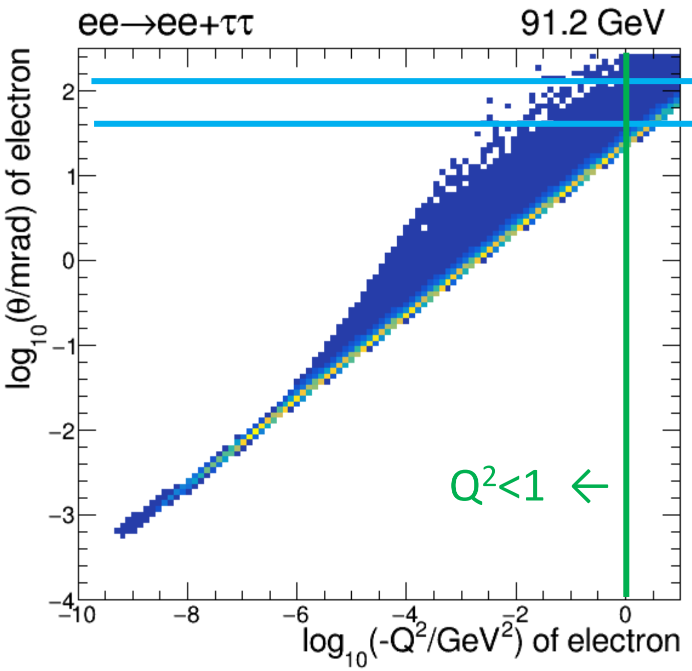
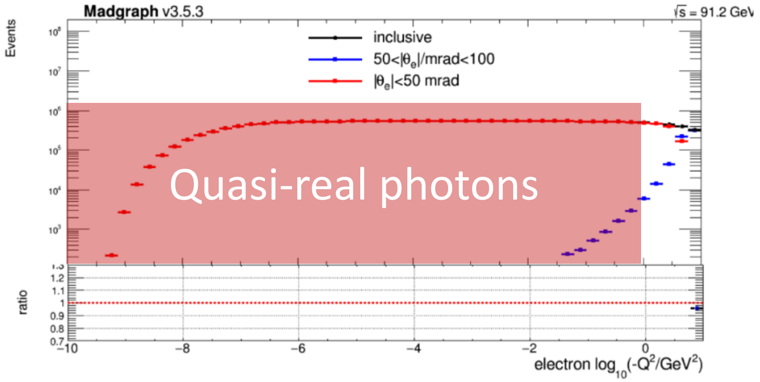


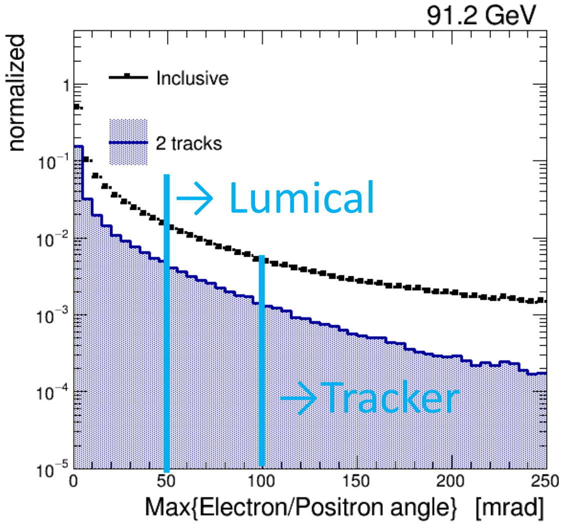


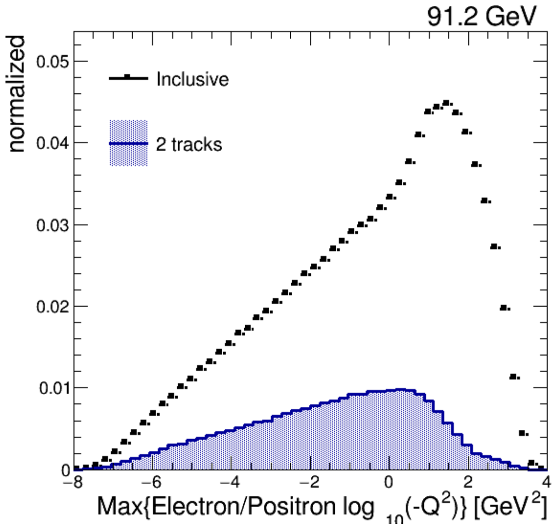


Analysis strategy (LEP style)

- Event selection:
  - Exactly two tracks ($\tau \rightarrow \pi\nu + n\pi^0$ decays only <u>for now</u>) with p > 300 MeV

Cut efficiency
23.17%





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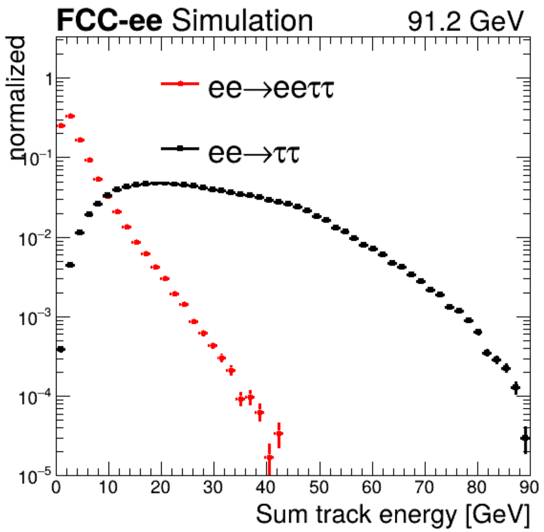
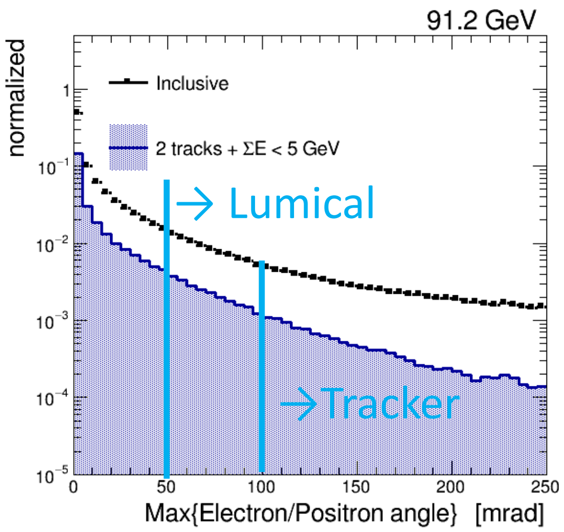
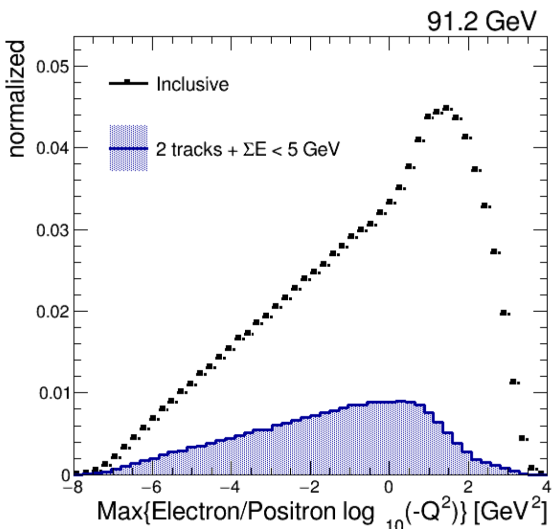
  - To suppress $ee \to \ell\ell$ choose ΣE_{TRK}<5 GeV

Cut efficiency
23.17%
16.90%



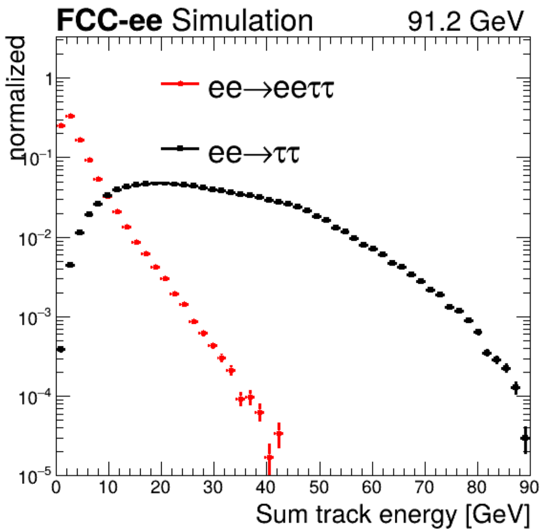


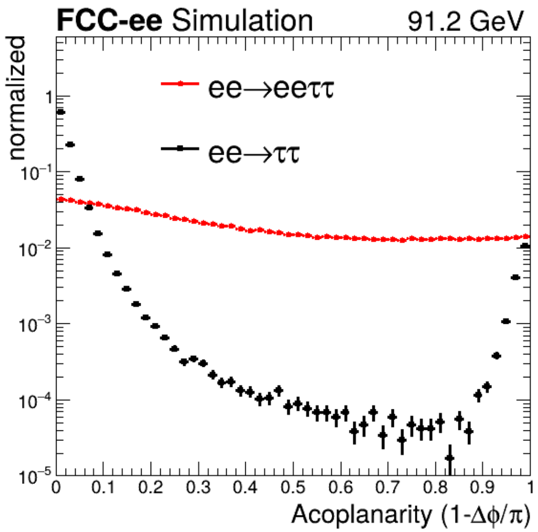


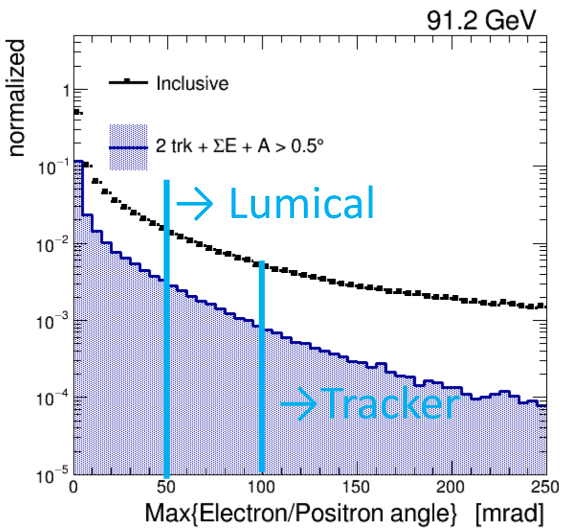
Analysis strategy (LEP style)

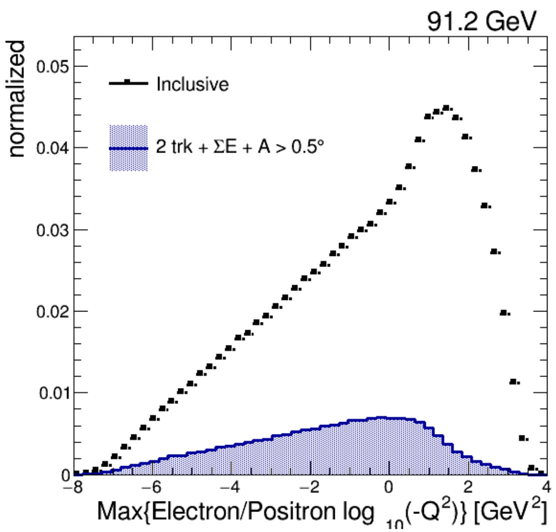
- Event selection:
  - Exactly two tracks ($\tau \rightarrow \pi\nu + n\pi^0$ decays only for now) with p > 300 MeV
  - To suppress $\mathrm{ee} \rightarrow \ell\ell$ choose ΣE_{TRK}<5 GeV
  - To enhance $\mathrm{ee} \rightarrow \mathrm{ee} + \tau\tau$ select acoplanarity A = (1-Δφ/π) > 0.5 deg

Cut efficiency
23.17%
16.90%
16.66%









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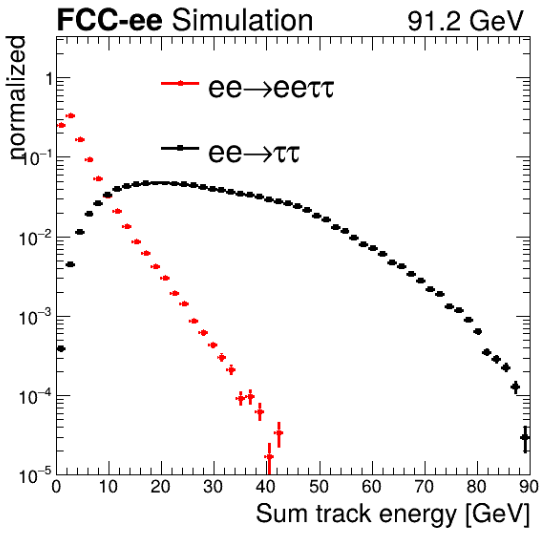
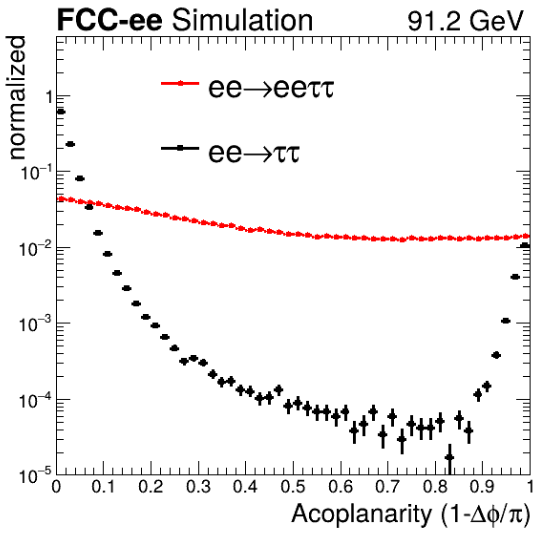
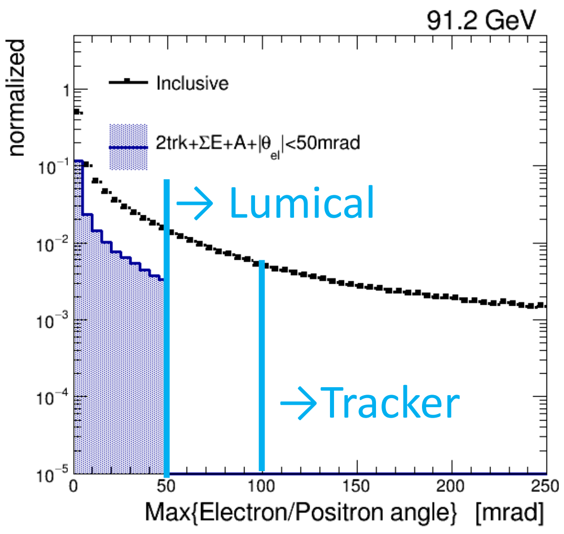
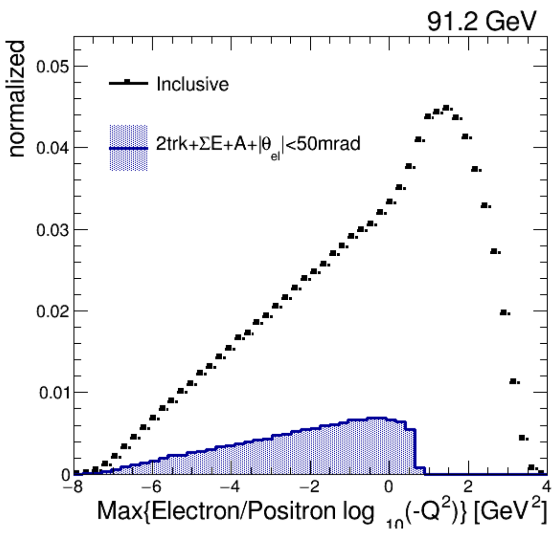
  - Exactly two tracks ($\tau \rightarrow \pi\nu + n\pi^0$ decays only for now) with p > 300 MeV
  - To suppress $ee \rightarrow \ell\ell$ choose ΣE_{TRK}<5 GeV
  - To enhance $ee \rightarrow ee + \tau\tau$ select acoplanarity A = (1-Δφ/π) > 0.5 deg
  - Veto beam e+/- in "lumical+tracker" ($|\theta_e|$ > 50 mrad at truth level)

Cut efficiency
23.17%
16.90%
16.66%
13.49%



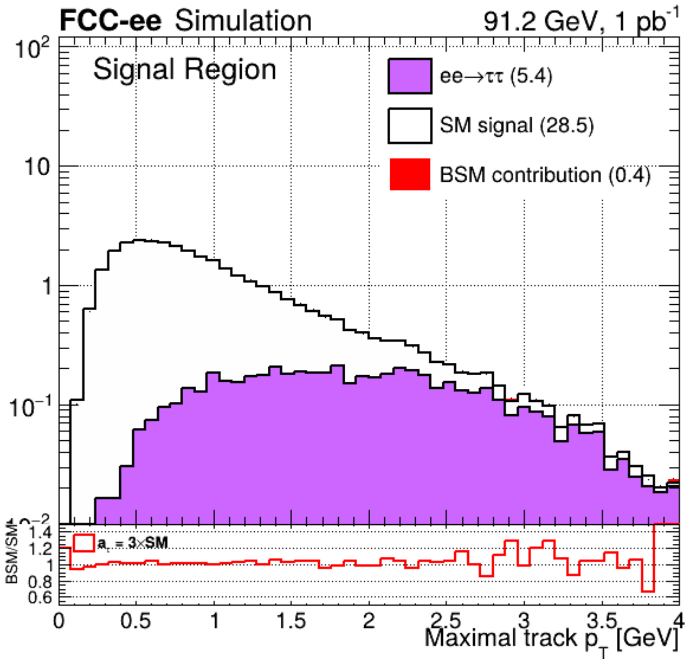






Tau lepton g-2 at FCC-ee

- Energy dependence and g-2
  - BSM contributions are enhanced at high photon energies
  - Backgrounds are suppressed at high √s

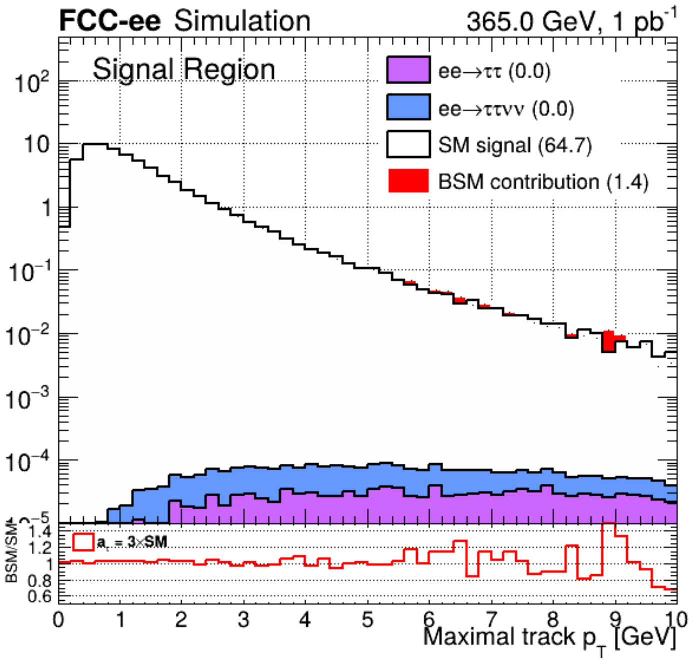


BSM/SM ~1.5% @ mZ

2e4 events → CMS limit

With N ~30 / pb a single experiment supersede CMS limit with < 1 fb^{-1}

(few hours at FCC-ee assume no systematics)



BSM/SM ~2.1% @ m_{tt}

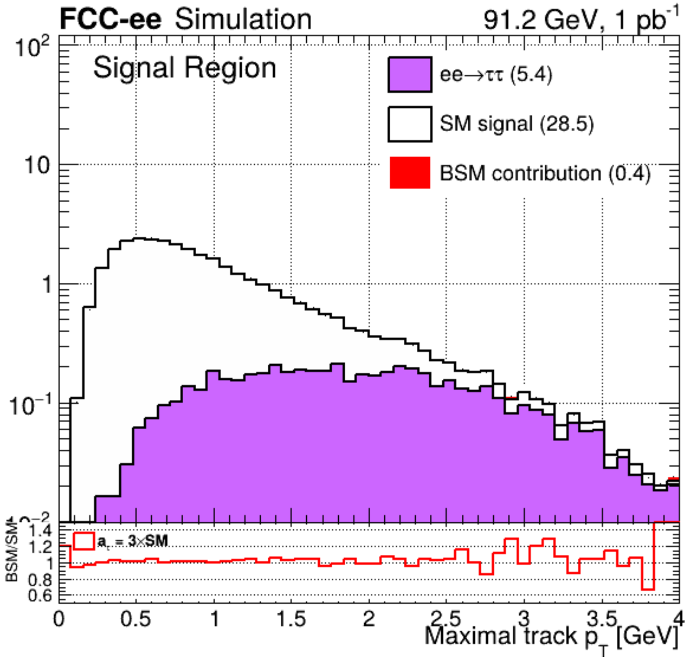
1e4 events → CMS limit

With N ~60 / pb a single experiment supersede CMS limit with < 1 fb^{-1}

(few days at FCC-ee assume no systematics)

Tau lepton g-2 at FCC-ee

- Energy dependence and g-2
  - BSM contributions are enhanced at high photon energies
  - Backgrounds are suppressed at high √s



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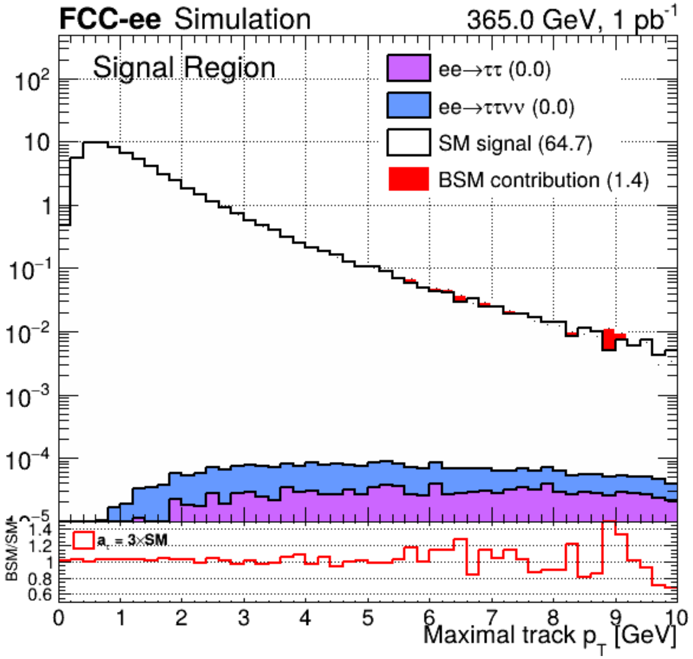


BSM/SM ~2.1% @ m_{tt}

1e4 events → CMS limit

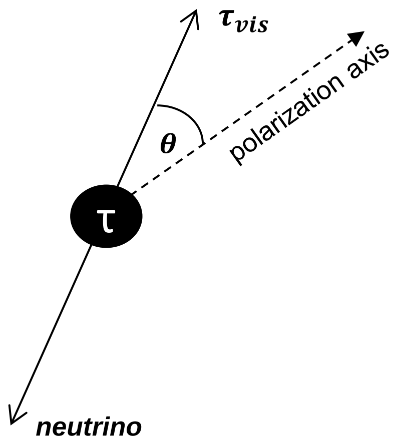
With N ~60 / pb a single experiment supersede CMS limit with < 1 fb^{-1}

(few days at FCC-ee assume no systematics)

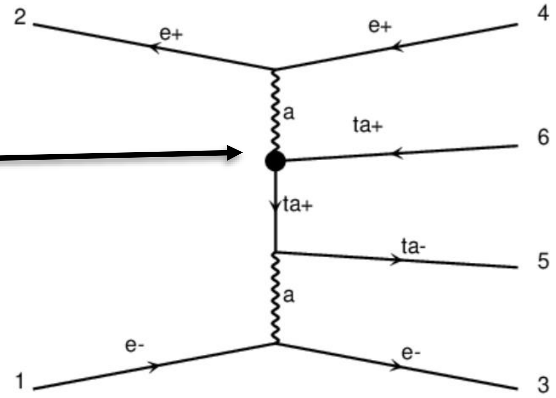
NOTE: EFT is just a preliminary approach (as it does not allow to extract a_τ exactly), a complete extraction will be provided in the upcoming studies.

Tau lepton g-2 at FCC-ee

- Tau polarization and g-2
  - In hadronic tau decays polarization variables can be used to discriminate dipole moment:



$$\mathcal{L} \sim \bar{\tau}\sigma^{\mu\nu}\left(a_\tau \frac{e}{2m_\tau}\right)\tau_R F_{\mu\nu}$$



Tau polarization	SM [pb]	BSM [pb]
(+,+) or (-,-)	155.0	158.8
(+,-) or (+,-)	175.4	179.3
Apply high PT selection: Average τ pT > 10 GeV		
(+,+) or (-,-)	0.98	1.12
(+,-) or (+,-)	11.0	11.0

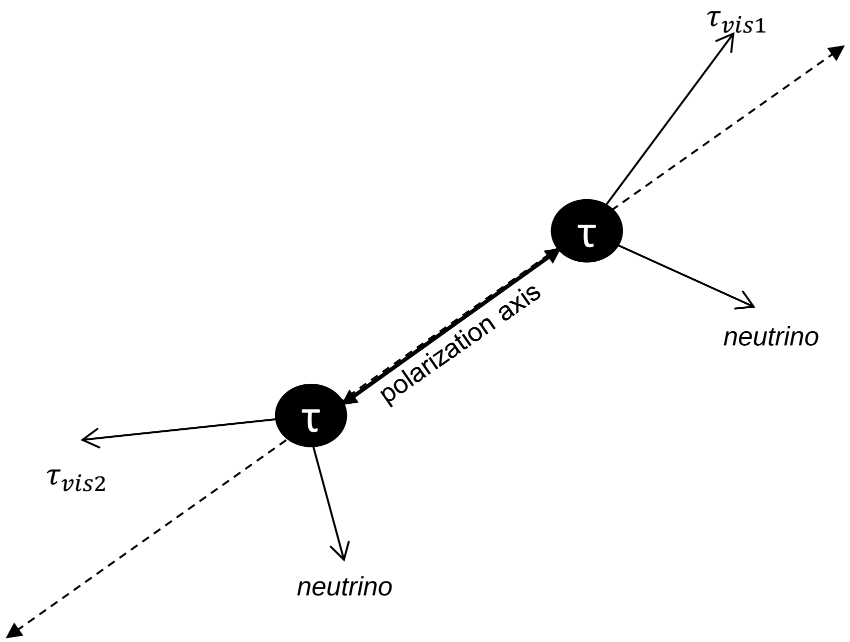
Modification of the strength of the magnetic moment will impact the spin correlations:

- More at high pT region (2.5% → 10%)

Tau lepton g-2 at FCC-ee

- Tau polarization and g-2

For spin correlations, the polarization axis can be defined along the τ boost, from $\tau\tau$ boost frame ($\tau\tau$ CoM):



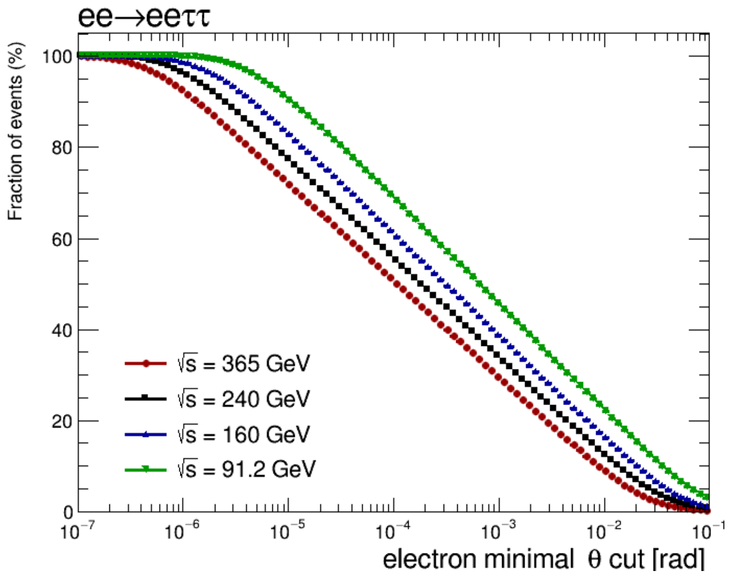
The decay angle with respect to the τ boost from $\tau\tau$ rest frame ($cos\theta$), can be expressed in terms of variables measured in $\tau\tau$ rest frame:

$$cos\theta = \frac{E_{vis} - E_{\nu}}{P_W} = \frac{2E_{vis} - \gamma m_{\tau}}{\gamma\beta m_{\tau}}$$

The $\tau\tau$ rest frame can be reconstructed from outgoing electron/positron kinematics

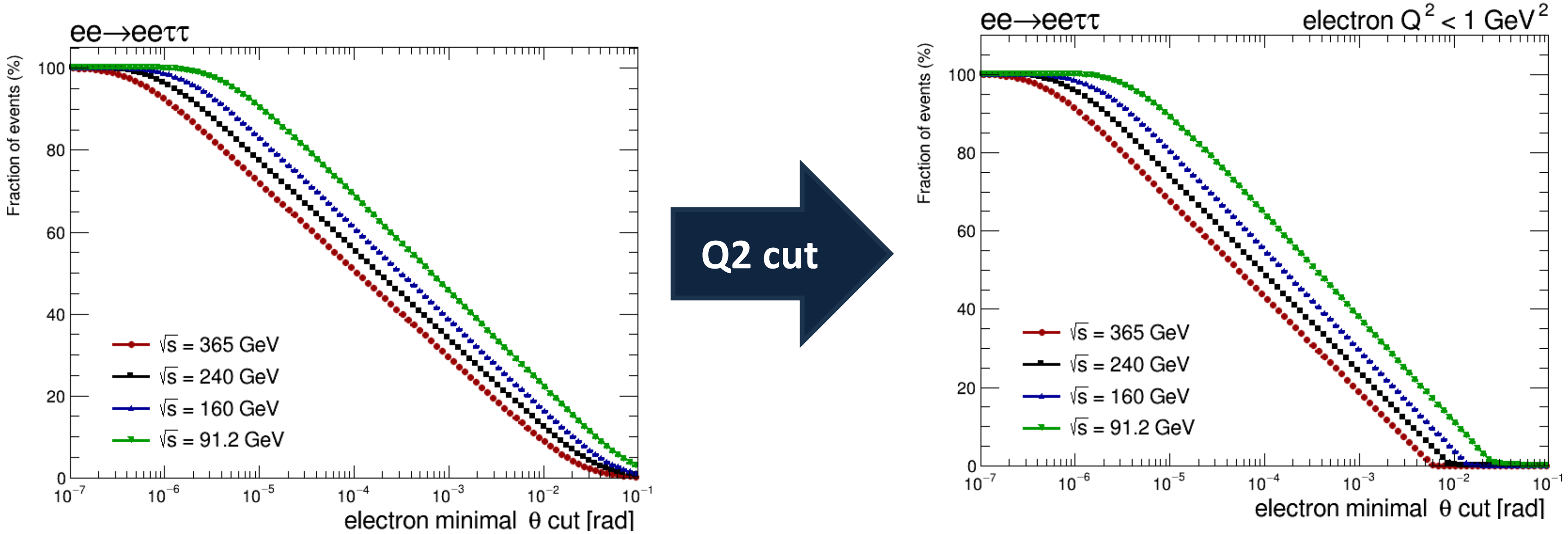
Tau lepton g-2 at FCC-ee

- Electron / Positron tagging
  - ➢ Electron/Positron acceptance depends on the lepton transport and the location of the detectors (distance from the IP and distance from the beam center)



Tau lepton g-2 at FCC-ee

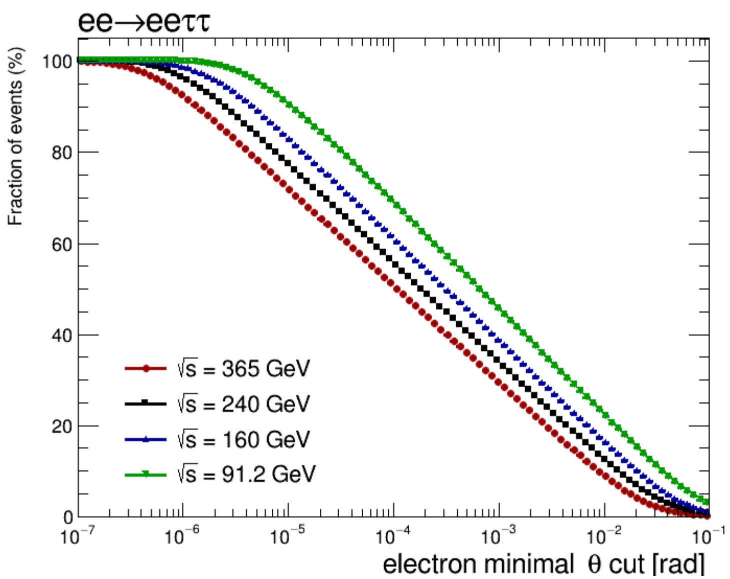
- Electron / Positron tagging
  - Electron/Positron acceptance depends on the lepton transport and the location of the detectors (distance from the IP and distance from the beam center)
  - To reach few mrad we would need to install e+/- taggers inside the beampipe.



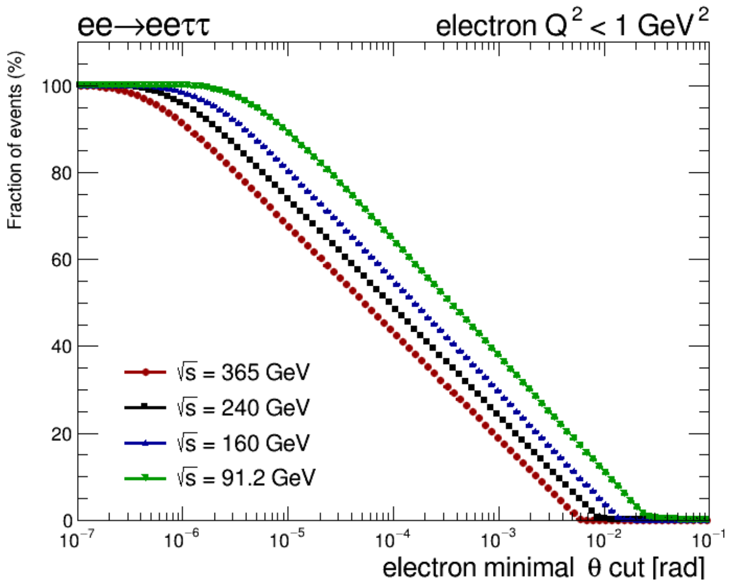
Tau lepton g-2 at FCC-ee

Electron / Positron tagging

- Electron/Positron acceptance depends on the lepton transport and the location of the detectors (distance from the IP and distance from the beam center)
- To reach few mrad we would need to install e+/- taggers inside the beampipe.
- The discussions with MDI is starting.



Q2 cut



Summary

Conclusions

- Magnetic moment (g-2) of the tau lepton can be measured at the FCC-ee:
  - First exploratory studies indicate that one can measure the LO quantum correction (Schwinger term) with FCC-ee data at $\sqrt{s}$ = 90 (and 365) GeV as it starts.
  - Already with a few days of running, we can achieve the CMS upper limits of 3xSM.
- More precise determination of a_τ require e+/- tagging inside the beampipe
  - This would benefit all photon-photon BSM/SM studies (ALPs, Missing mass, dipole moment of quarks, light resonances and hadronic states)

Upcoming studies

- Change EFT-approach by a study that allows to derive the measurable a_τ value.
- Study the possible locations for e-/e+ taggers. Need also to understand electron transport through the FCC-ee magnetic lattice.

Backup

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs