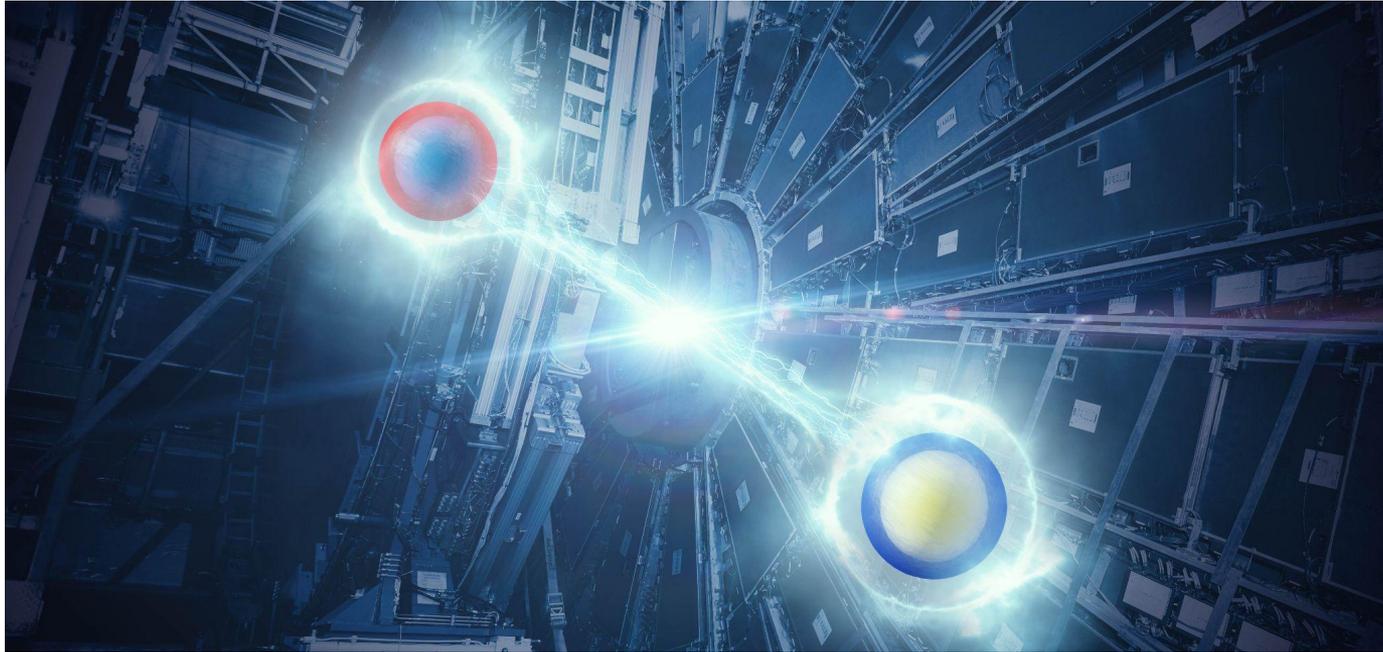# Quantum Decoherence at Colliders.
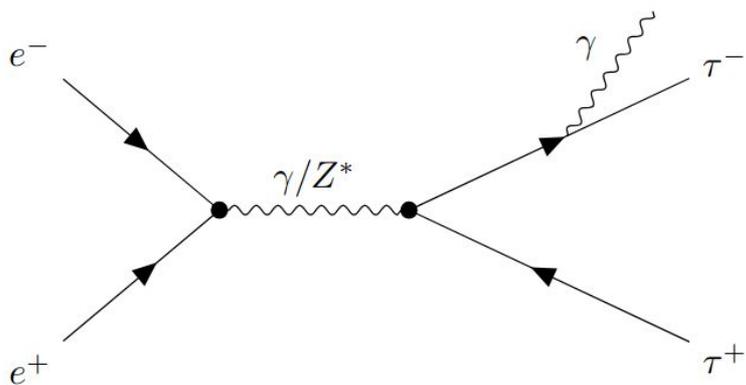
Rafael Aoude[1], José Manuel Camacho[2], Fabio Maltoni[3], María Moreno[4], Leonardo Satrioni[5], Marcel Vos[6] Guillermo García[7]

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Prospects for $e^+ e^- \rightarrow \tau^+ \tau^- \gamma$

Entanglement could be seen not only in tops but also in taus at BelleII and a future FCC operating in the Z-pole (Ehataht et al. 2024, M. Fabbrichesi et al. 2024) using hadronic polarimetry.

**Can photon decoherence occur in this scenario? Let's explore it!**

$$\longrightarrow \quad e^+ e^- \rightarrow \tau^+ \tau^- \gamma \rightarrow \pi^+ \pi^- \nu_\tau \bar{\nu}_\tau \gamma, \boxed{\left(\tau^- \rightarrow \pi^- \nu_\tau \right)}$$

Offers efficient polarimetry

Apparently, ISR is not a problem for this type of analysis (note: suppressed by central region cut at Belle 2, naturally suppressed at Z-pole)

Prospects for $e^+ e^- \rightarrow \tau^+ \tau^- \gamma$: Belle II

Experimental setting: Tomography produced for 10M events, Reweight produced for 1M events, non polarized electron beams

Angular cut applied in order to increase the entanglement per bin $\longrightarrow$ $cos(\theta_\tau^{\tau^+ \tau^- - RF}) = \hat{k_\tau} * Z \quad Z = (0,0,1)$ [in $\tau^+ \tau^-$ rest frame]
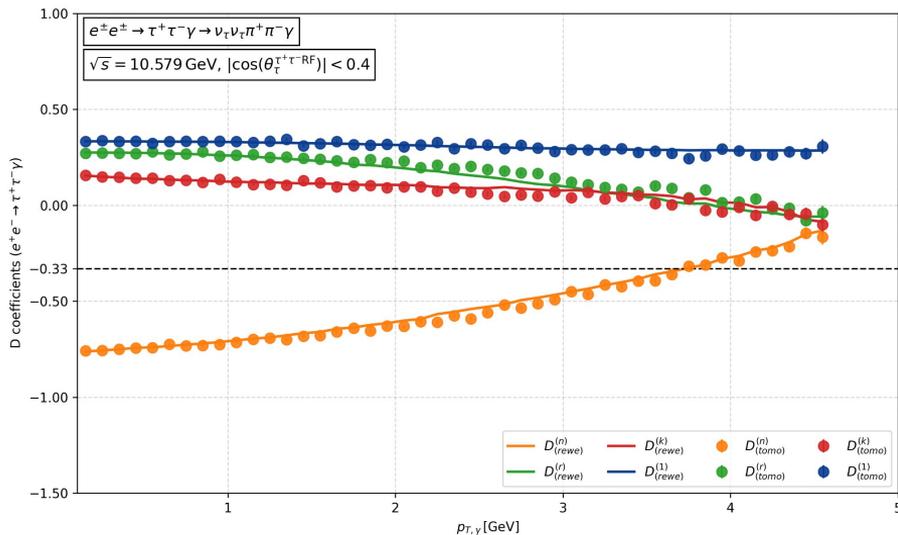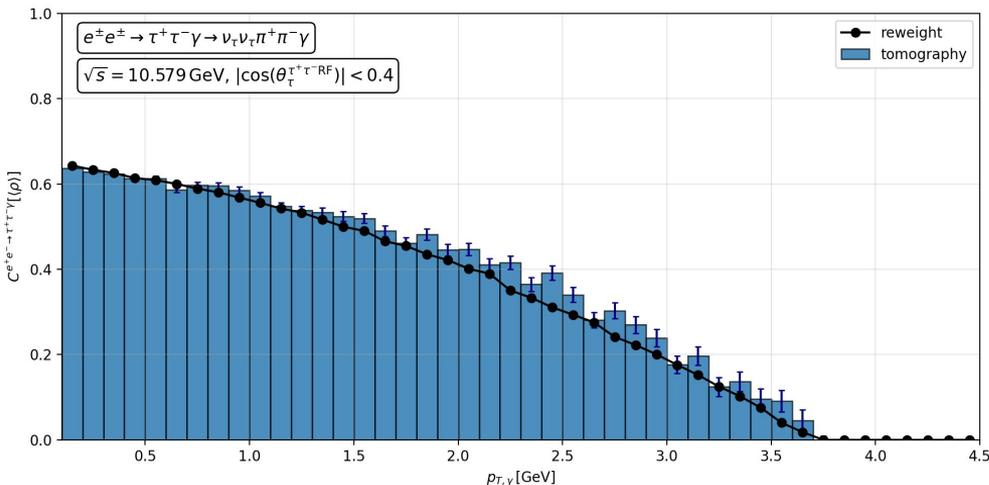
No signs of a tauonium singlet entanglement peak induced by hard photon radiation

Prospects for $e^+e^- \to \tau^+\tau^-\gamma$: Z-pole

Experimental setting: Tomography produced for 10M events, Reweight produced for 1M events, non polarized electron beams
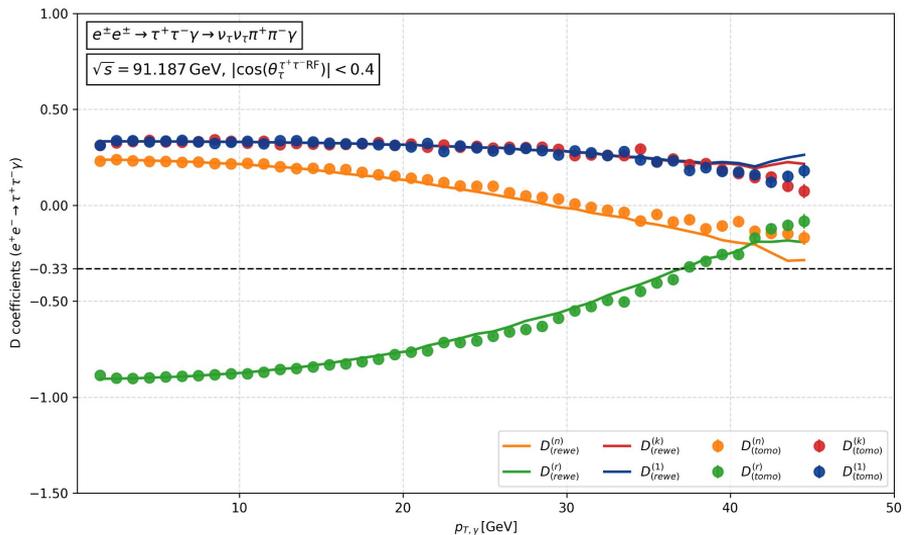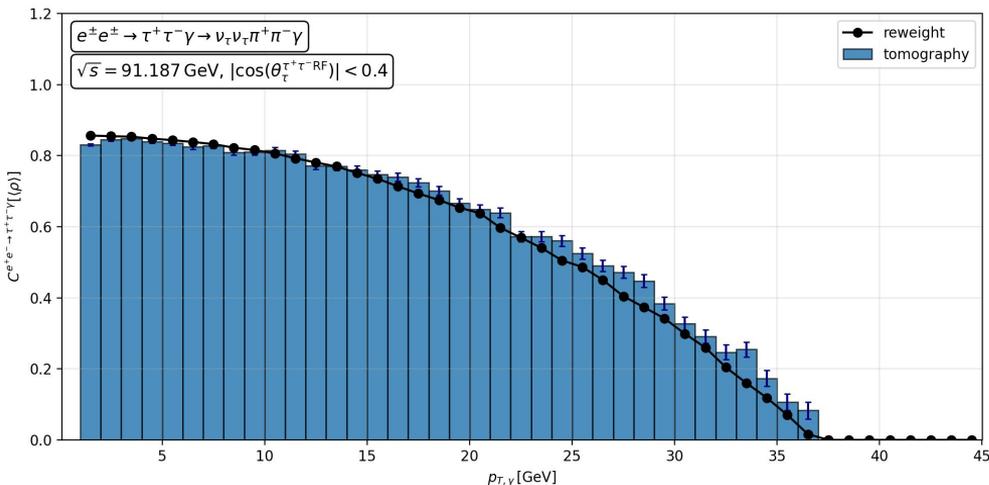

No signs of a tauonium singlet entanglement peak induced by hard photon radiation

Prospects for e^+e^- collisions: pT cut analysis

Now, we will focus on an experimentally-driven analysis, examining how entanglement scales with different pT cuts applied to the FSR (gluon in tops - photon in taus)

Experimental setting: Tomography produced for 1M events, non polarized electron beams
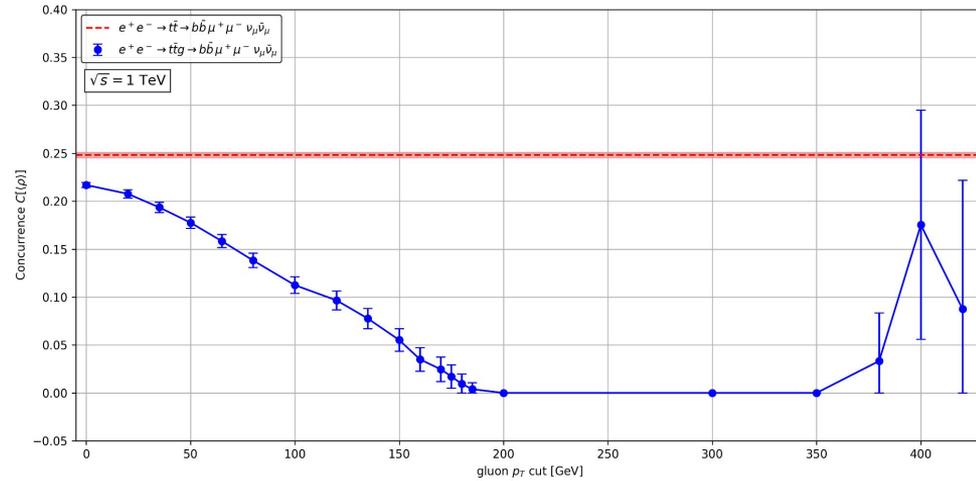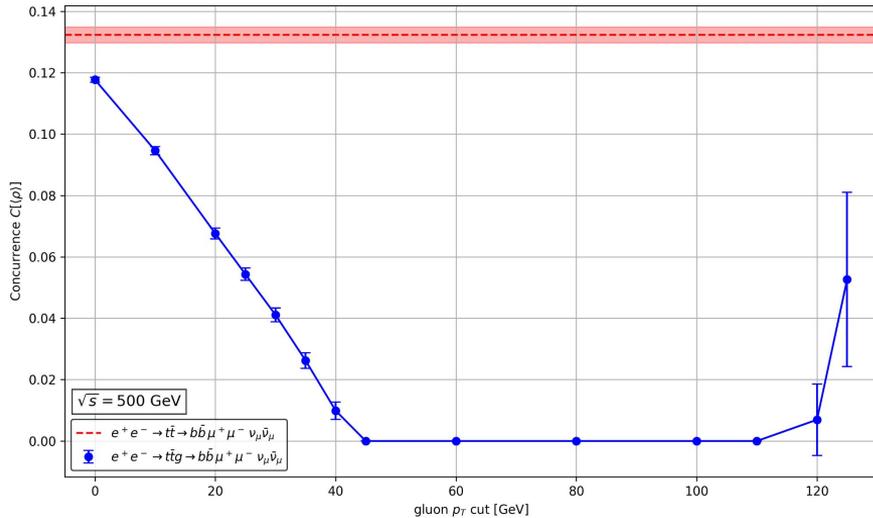
Decoherence exhibits a quasi-linear dependence on the pT cut applied

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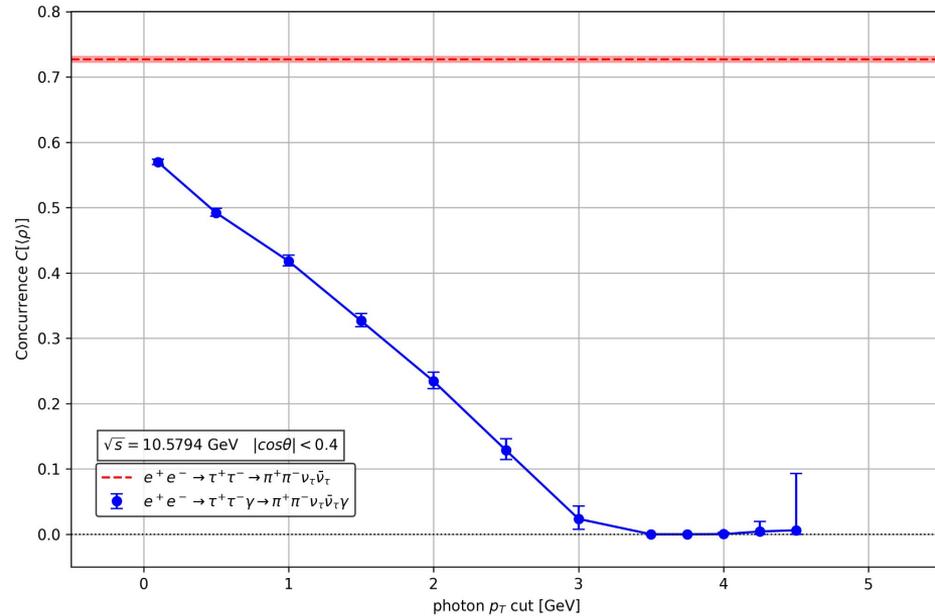
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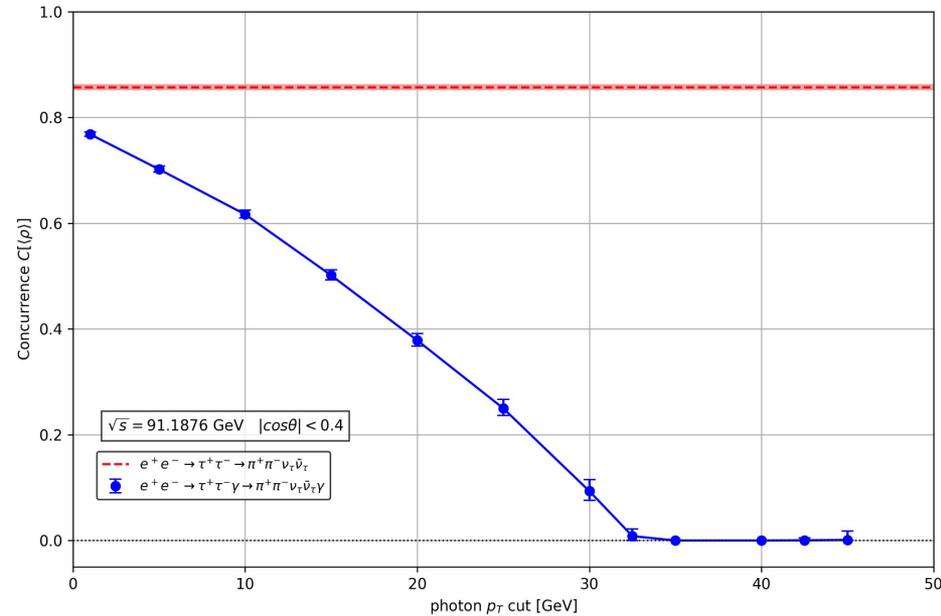
<u>Quantum observables for decoherence</u>

We have defined four observable that match decoherence:

$$\Delta C[\rho] = C[\rho](t\bar{t}) - C[\rho](t\bar{t}g) \qquad \longrightarrow \qquad \Delta C[\rho] > 0$$

$$R_{C[\rho]} = \frac{C[\rho](t\bar{t}g)}{C[\rho](t\bar{t})} \qquad \longrightarrow \qquad R_{C[\rho]} < 1$$

Conditions for decoherence

$$\Delta D_n = D_n(t\bar{t}) - D_n(t\bar{t}g) \qquad \longrightarrow \qquad \Delta D_n > 0$$

$$R_{D_n} = \frac{D_n(t\bar{t}g)}{D_n(t\bar{t})} \qquad \longrightarrow \qquad R_{D_n} < 1$$

We are going to calculate the significance for this conditions being fulfilled in experimental achievable scenarios

Detection of FSR induced decoherence in e^+e^- collisions

Significance for the detection of these decoherence conditions

$$e^+e^- \to t\bar{t}$$

Machine	$\int \mathcal{L}\,dt$ [ab^{-1}]	Final state	# $t\bar{t}$ events	$D_n[t\bar{t}]$: $e^+e^- \to$ $t\bar{t}$	$D_n[t\bar{t}]$: $e^+e^- \to$ $t\bar{t}g$	$\Delta D_n[t\bar{t}]$ $t\bar{t}g - t\bar{t}$	significance $(\Delta D_n > 0)$	$R_{D_n} = D_n^{t\bar{t}g}/D_n^{t\bar{t}}$	significance $(R_{D_n} < 1)$
linear e^+e^-	8	ee, $\mu\mu$, eμ	$5 \cdot 10^6 \times 4\%$	-0.421	-0.351 ($p_T > 35$GeV)	0.071±0.019	3.67 σ	0.831±0.045	3.69 σ
(LCF)	8	ll' & e,μ + jets	$5 \cdot 10^6 \times 19\%$	idem	idem	idem±0.009	7.35 σ	idem±0,023	7.39 σ
$\sqrt{s} = 500$ GeV	8	all channels	$5 \cdot 10^6 \times 30\%$	idem	idem	idem±0.008	7.52 σ	idem±0.022	7.55 σ
linear e^+e^-	8	ee, $\mu\mu$, eμ	$10^6 \times 4\%$	-0.500	-0.343 ($p_T > 175$GeV)	0.157±0.036	4.32 σ	0.687±0.071	4.35 σ
(LCF)	8	ll' & e,μ + jets	$10^6 \times 19\%$	idem	idem	idem±0.017	9.39 σ	idem±0.028	9.47 σ
$\sqrt{s} = 1$ TeV	8	all channels	$10^6 \times 30\%$	idem	idem	idem±0.015	9.98 σ	idem±0.033	10.1 σ

Machine	$\int \mathcal{L}\,dt$ [ab^{-1}]	Final state	# $t\bar{t}$ events	$C[t\bar{t}]$: $e^+e^- \to$ $t\bar{t}$	$C[t\bar{t}]$: $e^+e^- \to$ $t\bar{t}g$	ΔC $t\bar{t} - t\bar{t}g$	significance $(\Delta C[t\bar{t}] > 0)$	R= $C^{t\bar{t}g}[t\bar{t}]/C^{t\bar{t}}[t\bar{t}]$	significance $(R < 1)$
linear e^+e^-	8	ee, $\mu\mu$, eμ	$5 \cdot 10^6 \times 4\%$	0.133	0.026 ($p_T > 35$GeV)	0.105±0.026	3.81 σ	0.207±0.194	3.88 σ
(LCF)	8	ll' &e,μ + jets	$5 \cdot 10^6 \times 19\%$	idem	idem	idem±0.014	7.27 σ	idem±0.107	7.38 σ
$\sqrt{s} = 500$ GeV	8	all channels	$5 \cdot 10^6 \times 30\%$	idem	idem	idem±0.013	7.57 σ	idem±0.104	7.59 σ
linear e^+e^-	8	ee, $\mu\mu$, eμ	$10^6 \times 4\%$	0.248	0.017 ($p_T > 175$GeV)	0.225±0.038	5.48 σ	0.068±0.151	5.64 σ
(LCF)	8	ll' &e,μ + jets	$10^6 \times 19\%$	idem	idem	idem±0.0225	10.3 σ	idem±0.083	11.02 σ
$\sqrt{s} = 1$ TeV	8	all channels	$10^6 \times 30\%$	idem	idem	idem±0.021	10.48 σ	idem±0.078	11.6 σ

Detection of FSR induced decoherence in e^+e^- collisions

Significance for the detection of these decoherence conditions

$$e^+e^- \to \tau^+\tau^- \ (\tau^- \to \pi^-\nu_\tau)$$

Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L} dt$ [ab^{-1}]	# $t\bar{t}$ events	$D_n[\tau^+\tau^-]$: $e^+e^- \to$ $\tau^+\tau^-$	$D_n[\tau^+\tau^-]$: $e^+e^- \to$ $\tau^+\tau^-\gamma$	$\Delta D_n[\tau^+\tau^-]$ $\tau^+\tau^-\gamma - \tau^+\tau^-$	significance $(\Delta D_n > 0)$	$R_{D_n} = D_n^{\tau^+\tau^-\gamma}/D_n^{\tau^+\tau^-}$	significance $(R_{D_n} < 1)$
Belle II 2025	10.579	0.5	5×10^8	-0.818	$-0.488(p_T > 2\text{GeV})$	0.331 ± 0.011	$28.8\,\sigma$	0.596 ± 0.014	$28.9\,\sigma$
Belle II Tarjet	10.579	50	5×10^{10}	idem	idem	idem ± 0.002	$288\,\sigma$	idem ± 0.001	$289\,\sigma$
Z-pole (GigaZ) GeV	91.2	0.1	10^8	-0.911	$-0.5846(p_T > 20\text{GeV})$	0.327 ± 0.018	$17.5\,\sigma$	0.641	$17.54\,\sigma$
Z-pole (TeraZ)	91.2	300	2×10^{11}	idem	idem	idem ± 0.0006	$958\,\sigma$	idem ± 0.0003	$960\,\sigma$

Machine	$\sqrt{s}$ [GeV]	$\int \mathcal{L} dt$ [ab^{-1}]	# $\tau^+\tau^-$ events	$C[\tau^+\tau^-]$: $e^+e^- \to$ $\tau^+\tau^-$	$C[\tau^+\tau^-]$: $e^+e^- \to$ $\tau^+\tau^-\gamma$	$\Delta C[\tau^+\tau^-]$ $\tau^+\tau^- - \tau^+\tau^-\gamma$	significance $(\Delta C[\tau^+\tau^-] > 0)$	$R = C^{\tau^+\tau^-\gamma}/C^{\tau^+\tau^-}$	significance $(R < 1)$
Belle II 2025	10.579	0.5	5×10^8	0.726	$0.234 \ (p_T > 2\text{GeV})$	0.492 ± 0.017	$27.2\,\sigma$	$0.323 \pm$	$27.9\,\sigma$
Belle II Tarjet	10.579	50	5×10^{10}	idem	idem	idem ± 0.002	$277\,\sigma$	idem ± 0.002	$279\,\sigma$
Z-pole (GigaZ) GeV	91.2	0.1	10^8	0.858	$0.381 \ (p_T > 20\text{GeV})$	0.477 ± 0.029	$16.32\,\sigma$	0.444 ± 0.034	$16.40\,\sigma$
Z-pole (TeraZ)	91.2	300	2×10^{11}	idem	idem	idem ± 0.0005	$895\,\sigma$	idem ± 0.001	$864\,\sigma$

Thanks for your attention!!