Discoverying (true) tauonium at colliders

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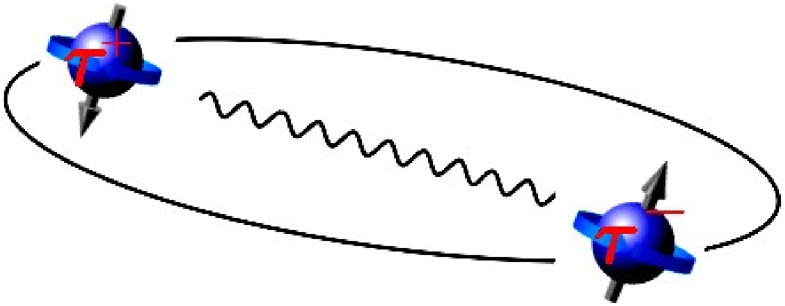
Details: arXiv:2202.02316 [hep-ph], 2204.07269 [hep-ph], arXiv:2302.07365 [hep-ph]

Exotic leptonium atoms

- Opposite-charge leptons ($\ell^\pm = e^\pm, \mu^\pm, \tau^\pm$) can form transient “onium” bound states under their QED interaction. Out of 6 possible exotic leptonic atoms (e^+e^-), ($\mu^\pm e^\mp$), ($\mu^+\mu^-$), ($\tau^\pm e^\mp$), ($\tau^\pm\mu^\mp$), ($\tau^+\tau^-$), only the two first (positronium in 1951) and (muonium in 1960) have been observed.

→ Para- ($J^{PC} = 0^{-+}$) and ortho- ($J^{PC} = 1^{--}$) leptonium ground states form depending on relative spin orientation of leptons.



- Ditauonium $\tau\equiv(\tau^+\tau^-)$, barely studied, is smallest & most-bound leptonium state:

  Mass: $m_\tau = 2m_\tau + E_{bind} =$ 3553.6962 ± 0.2400 MeV, $E_{bind} = -\alpha^2 m_\tau/(4n^2) = -23.7$ keV

  Bohr radius: $a_0 = 2/(\alpha\, m_\tau) =$ 30.4 fm (×3500 smaller than positronium)

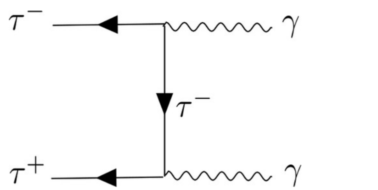
  Rydberg const (γ ionization): $R_\infty = m_\tau\alpha^2/4\pi =$ 3.76 keV (×3500 larger than positronium)

- Compared to other exotic atoms, ditauonium can provide:
  - → Precision SM: Most competitive measurement of the tau mass possible.
  - → New tests of QED & CPT symmetries at much higher masses (smaller distances).
  - → Sensitivity to any BSM enhanced by $(m_\ell/\Lambda_{BSM})^n$, unaffected by hadronic uncertainties.

Ditauonium partial widths & decays

- Para-τ decays mostly to γγ (BR≈80%):

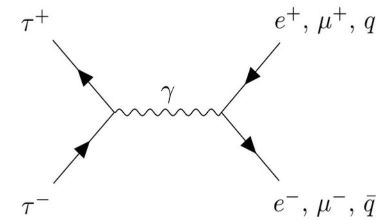
$$\Gamma^{(0)}(n^1S_0 \to \gamma\gamma) = \frac{\alpha^5 m_\tau}{2n^3} \underset{n=1}{=} 0.018384\ \text{eV}$$



- Ortho-τ has many open channels: e^+e^-, $\mu^+\mu^-$, $q\bar{q}$ BR≈20%, 20%, 45%

$$\Gamma^{(0)}(n^3S_1 \to e^+e^-,\mu^+\mu^-) = \frac{\alpha^5 m_\tau}{6n^3}$$

$$\Gamma^{(0)}(n^3S_1 \to q\bar{q}) = \frac{\alpha^5 m_\tau}{6n^3} R_{\text{had}}\left(m^2_{\mathcal{T}_0}\right) = 2.2\frac{\alpha^5 m_\tau}{6n^3}$$



- Weak decay of constituent τ±: $\Gamma_{(2)\tau\to X} = 2/\tau = 0.004535\ \text{eV}$ (τ ≈ 290 fs)

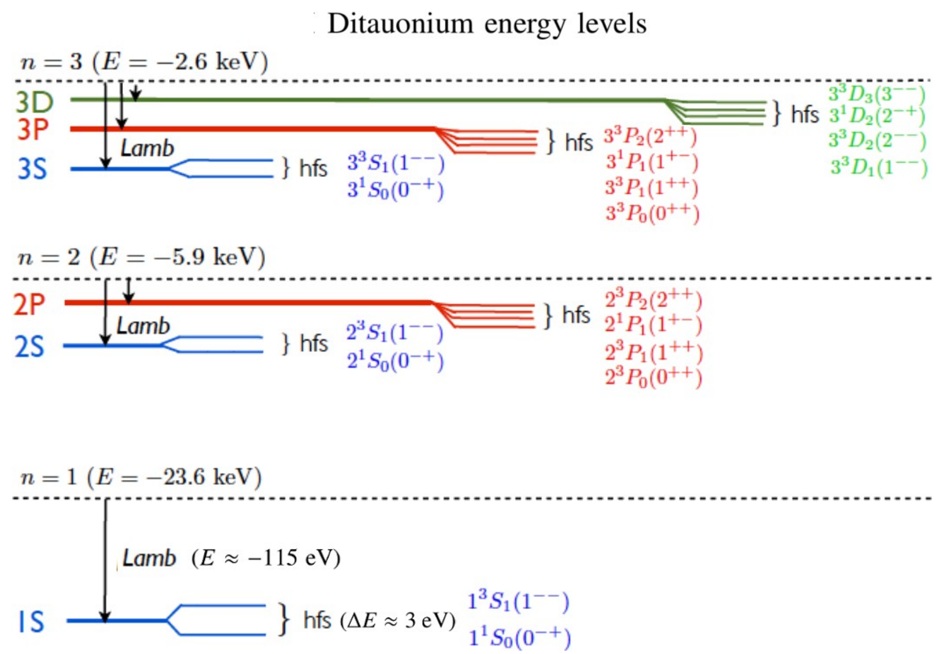
  BR_{eff} ≈ 19%,14% for para-,ortho-τ

- Ditauonium spectroscopy (NNLO* non-relativ. QED):

→ Lamb shifts:
$\Delta E^{1S,2S,\ldots} = -115.4, -14.4, \ldots$ eV

→ Hyperfine splittings:
$\Delta E_{\text{hfs}}(1^1S_0, 1^3S_1, \ldots) = -1.65, +1.29, \ldots$ eV

[DdE, R.Perez-Ramos, H-S. Shao: arXiv:2204.07269]



Ditauonium partial widths & decays

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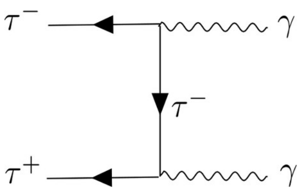
$$\Gamma^{(0)}(n^1\mathrm{S}_0 \to \gamma\gamma) = \frac{\alpha^5\, m_\tau}{2\, n^3} \underset{n=1}{=} 0.018384\ \mathrm{eV}$$



- Ortho-τ has many open channels: e^+e^-, $\mu^+\mu^-$, $q\bar{q}$
BR≈20%, 20%, 45%

$$\Gamma^{(0)}(n^3\mathrm{S}_1 \to e^+e^-, \mu^+\mu^-) = \frac{\alpha^5 m_\tau}{6n^3}.$$

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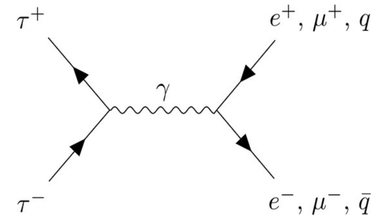
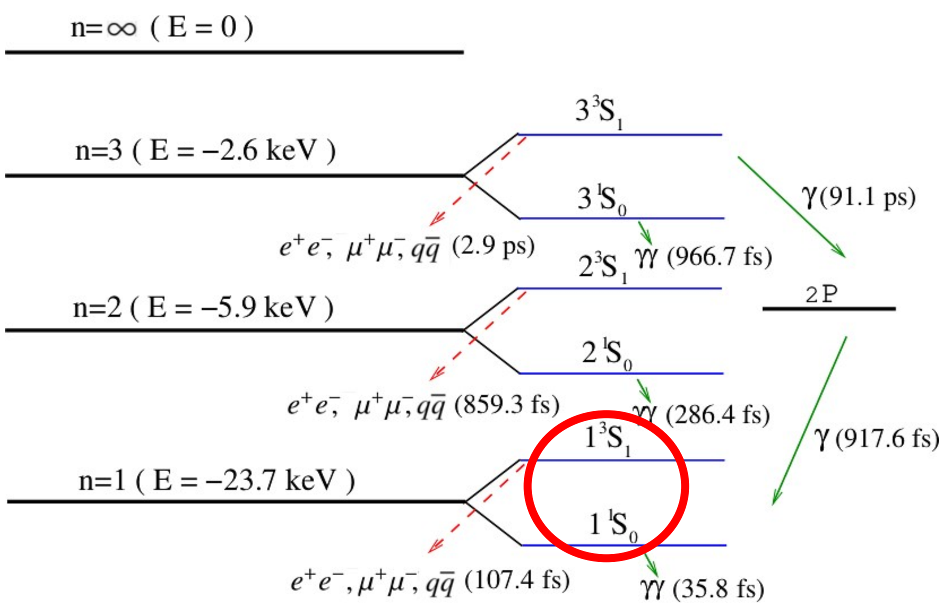


- Weak decay of constituent τ±: $\Gamma_{(2)\tau\to X} = 2/\tau = 0.004535\ \mathrm{eV}$ (τ ≈ 290 fs)
$\mathrm{BR}_{\mathrm{eff}}$ ≈ 19%,14% for para-,ortho-τ

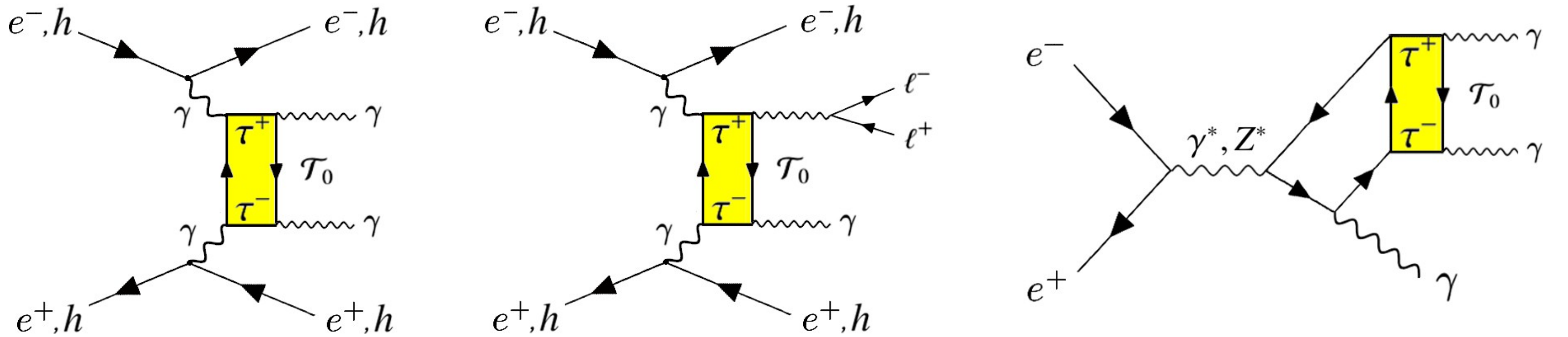
- Ditauonium spectroscopy (NNLO* non-relativ. QED):
  → Only the two lowest states (1^1S_0 & 1^3S_1) have lifetimes shorter (τ ≈ 27.6, 20.83 fs) than the weak decay of the constituents tau's.



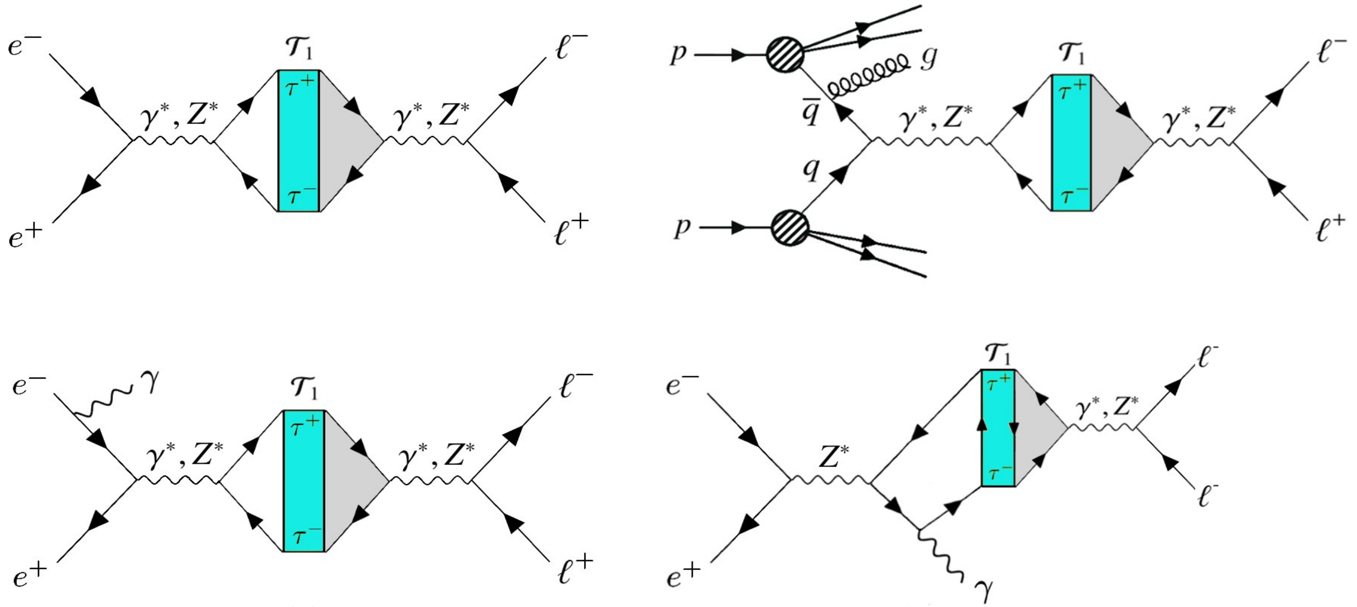
[DdE, R.Perez-Ramos, H-S. Shao: arXiv:2204.07269]

Ditauonium production at e⁺e⁻ & hadron colliders

- 3 para-ditauonium prod./decay channels: photon-photon, s-channel+γ

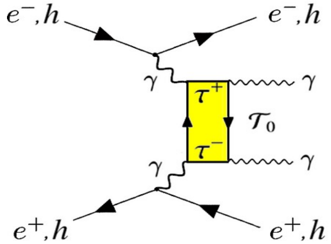


- 4 ortho-ditauonium prod./decay channels: s-channel fusion (w/ & w/o γ)



Para-ditauonium via $\gamma\gamma \rightarrow \tau_0 \rightarrow \gamma\gamma$

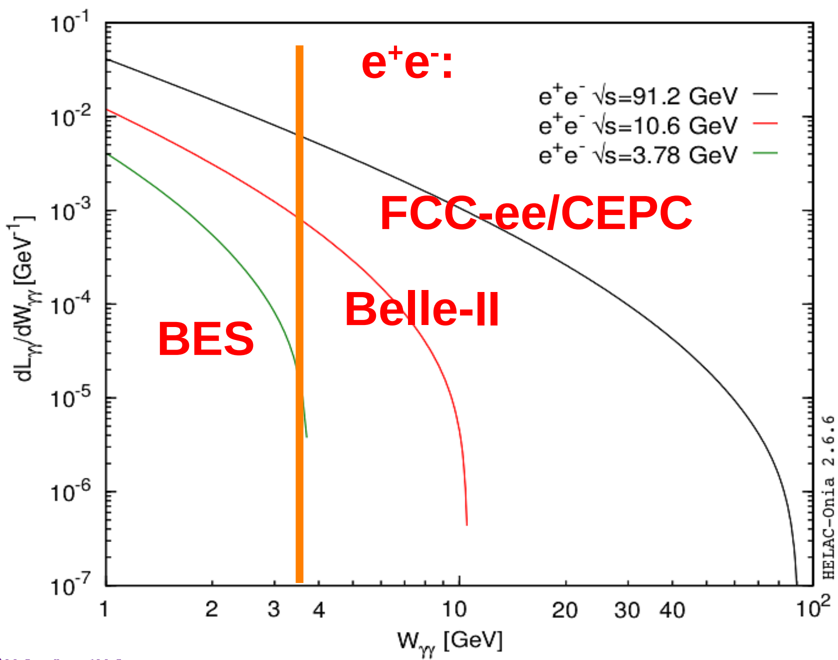
- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions via gamma-UPC 2207.03012 [hep-ph]

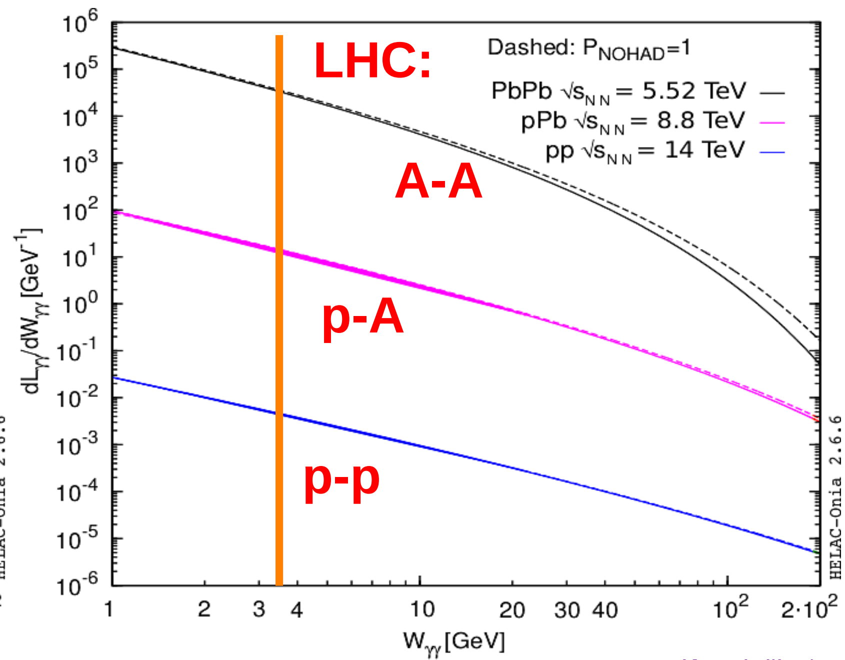


$$\sigma(a\,b \rightarrow a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$$

- Photon-photon luminosity for e^+e^- & ultraperipheral p-p, p-A & A-A collisions

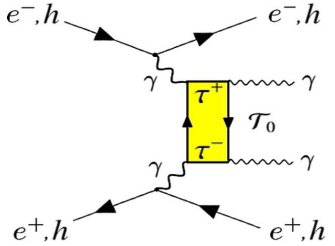
$$\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(AB)}}{\mathrm{d}W_{\gamma\gamma}} = \frac{2W_{\gamma\gamma}}{s_{\mathrm{NN}}}\int\frac{\mathrm{d}E_{\gamma_1}}{E_{\gamma_1}}\frac{\mathrm{d}E_{\gamma_2}}{E_{\gamma_2}}\delta\left(\frac{W_{\gamma\gamma}^2}{s_{\mathrm{NN}}}-\frac{4E_{\gamma_1}E_{\gamma_2}}{s_{\mathrm{NN}}}\right)\frac{\mathrm{d}^2N^{(AB)}_{\gamma_1/Z_1,\gamma_2/Z_2}}{\mathrm{d}E_{\gamma_1}\mathrm{d}E_{\gamma_2}}$$





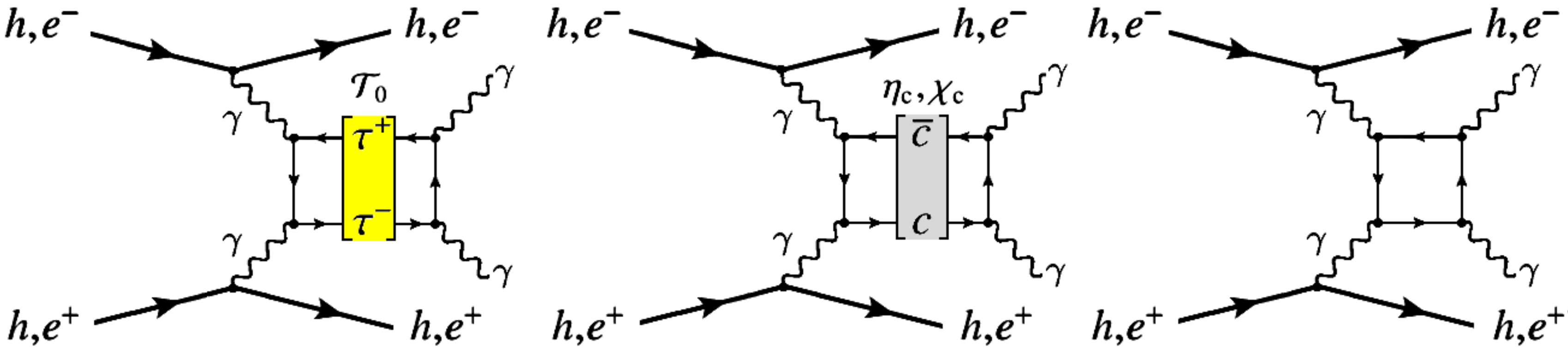
Para-ditauonium via $\gamma\gamma \rightarrow \tau_0 \rightarrow \gamma\gamma$: Backgrounds

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions via gamma-UPC 2207.03012 [hep-ph]



$$\sigma(a\,b \to a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$$

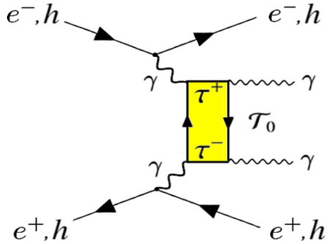
- Backgrounds within $m_{\gamma\gamma} \approx$ 2.9–3.7 GeV:
  - → C-even charmonium: 3 $c\bar{c}$: $\eta_c(2S)$, $\chi_{c1,2}$ resonances within ~100 MeV of τ_0
  - → Light-by-light scattering (LbL) continuum.



→ Charmonia resonances have $\mathcal{O}$(keV) diphoton widths: $\mathcal{O}(10^5)$ larger than para-τ_0. But, diphoton BR is $\mathcal{O}(10^4)$ larger for para-τ_0 than for c-cbar states.

Para-ditauonium via $\gamma\gamma \rightarrow \tau_0 \rightarrow \gamma\gamma$: Yields

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions via gamma-UPC 2207.03012 [hep-ph]



$$\sigma(a\,b \rightarrow a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$$

- Results for e^+e^- and ultraperipheral p-p, p-A & A-A collisions:

Colliding system, c.m. energy, $\mathcal{L}_{\rm int}$, exp.	$\sigma \times \mathcal{B}_{\gamma\gamma}$						$N \times \mathcal{B}_{\gamma\gamma}$	
	$\eta_c(1S)$	$\eta_c(2S)$	$\chi_{c,0}(1P)$	$\chi_{c,2}(1P)$	LbL	$\mathcal{T}_0$	$\mathcal{T}_0$	$\chi_{c,2}(1P)$
e^+e^- at 3.78 GeV, 20 fb^{-1}, BES III	120 fb	3.6 ab	15 ab	13 ab	30 ab	0.25 ab	–	–
e^+e^- at 10.6 GeV, 50 ab^{-1}, Belle II	1.7 fb	0.35 fb	0.52 fb	0.77 fb	1.7 fb	0.015 fb	750	38 500
e^+e^- at 91.2 GeV, 50 ab^{-1}, FCC-ee	11 fb	2.8 fb	3.9 fb	6.0 fb	12 fb	0.11 fb	5 600	$3 \cdot 10^5$
p-p at 14 TeV, 300 fb^{-1}, LHC	7.9 fb	2.0 fb	2.8 fb	4.3 fb	6.3 fb	0.08 fb	24	1290
p-Pb at 8.8 TeV, 0.6 pb^{-1}, LHC	25 pb	6.3 pb	8.7 pb	13 pb	21 pb	0.25 pb	0.15	8
Pb-Pb at 5.5 TeV, 2 nb^{-1}, LHC	61 nb	15 nb	21 nb	31 nb	62 nb	0.59 nb	1.2	62

→ Relative prod. x-sections: $\eta_c(1S):\chi_{c2}(1P):\chi_{c0}(1P):\eta_c(2S):\tau_0 \approx 100:50:30:25:1$

→ Para-τ_0 x-sections increase with $\sqrt{s}$ and Z^4:

Largest x-sections (0.6 nb) in PbPb UPC (but handful of evts expected at LHC)

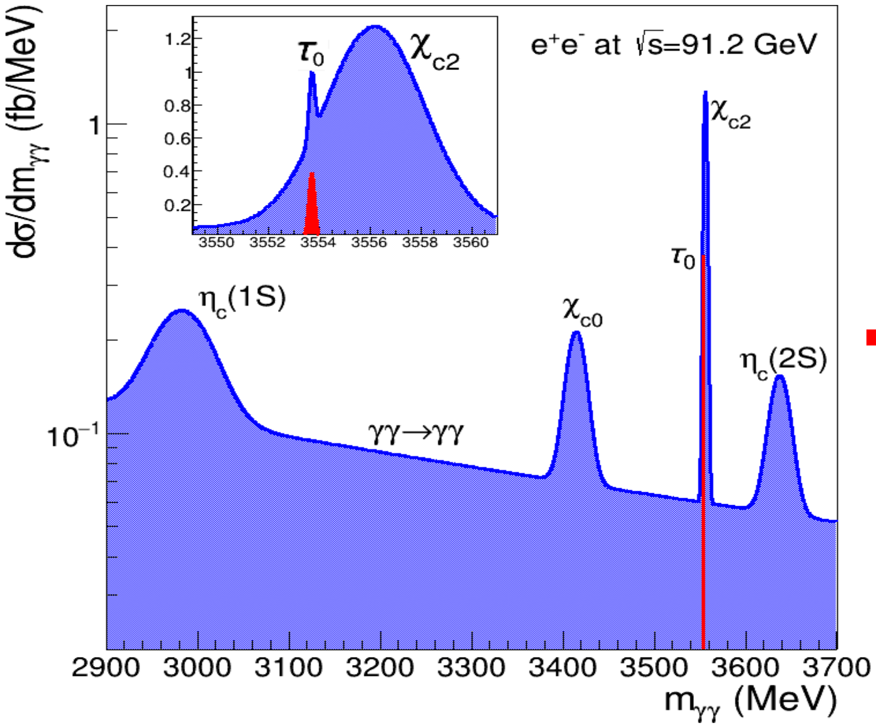
Largest yields: 750, 5600 counts at Belle-II, FCC-ee thanks to $\mathcal{L}_{\rm int}$ = 50 ab^{-1}.

Para-ditauonium via $\gamma\gamma \to \tau_0 \to \gamma\gamma$ (Belle II/FCC-ee)

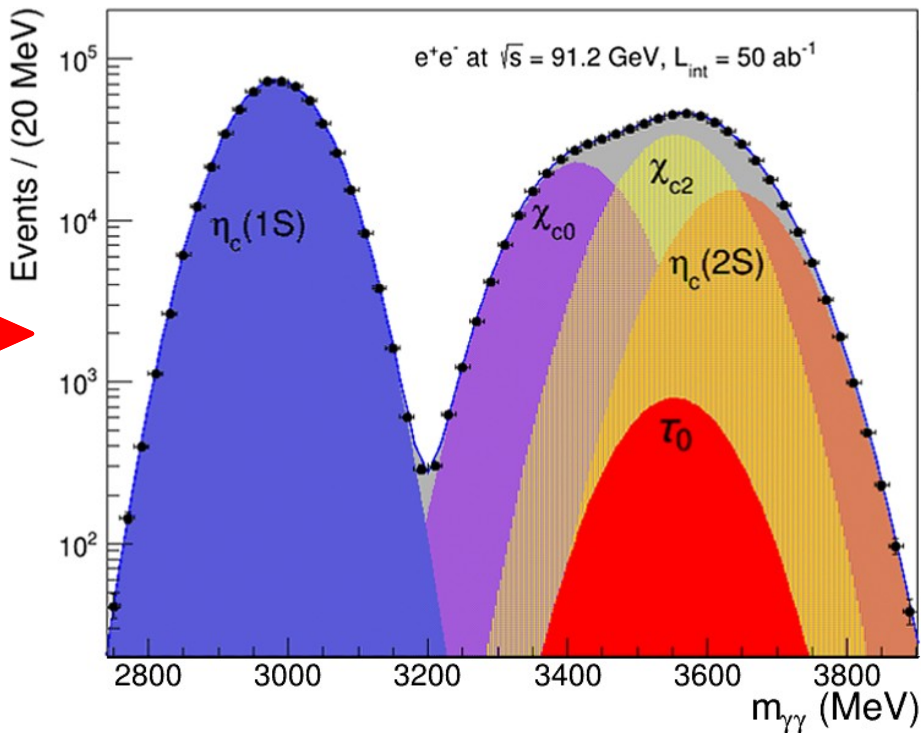
- Trigger: Require two exclusive 1.5–2 GeV photons back-to-back with $m_{\gamma\gamma} \approx m_{\tau 0}$
- Reco. performances (Belle-II type: high-reso low-energy crystal ECAL):
  Acceptance: $10^\circ < \theta_\gamma < 170^\circ$. Mass resolution: ~2%. Photon reco effic. ~100%.

  → All diphoton resonances Gaussian-smeared with ~70 MeV widths:

Generator-level x-sections (0.1-MeV τ_0 width)



Reconstructed yields (LbL subtracted)



- Ditauonium signal swamped by overlapping χ_{c2}(1P) & neighboring χ_{c0}(1P), η_c(2S)

Para-ditauonium via $\gamma\gamma \to \tau_0 \to \gamma\gamma$ (Belle II/FCC-ee)

- 1-million events generated for signal & backgrounds. Run MVA (BDT) with 12 different single-γ and γ-pair kinematic variables for signal/backgds separation:
  - (i) Strong discrimination power (factor of ~20) of LbL continuum from signal.
  - (ii) No discrimination achieved for overlapping charmonia (decay-γ angular modulation of tensor χ_{c2} different than scalar τ_0 signal, but ×50 suppressed yields).

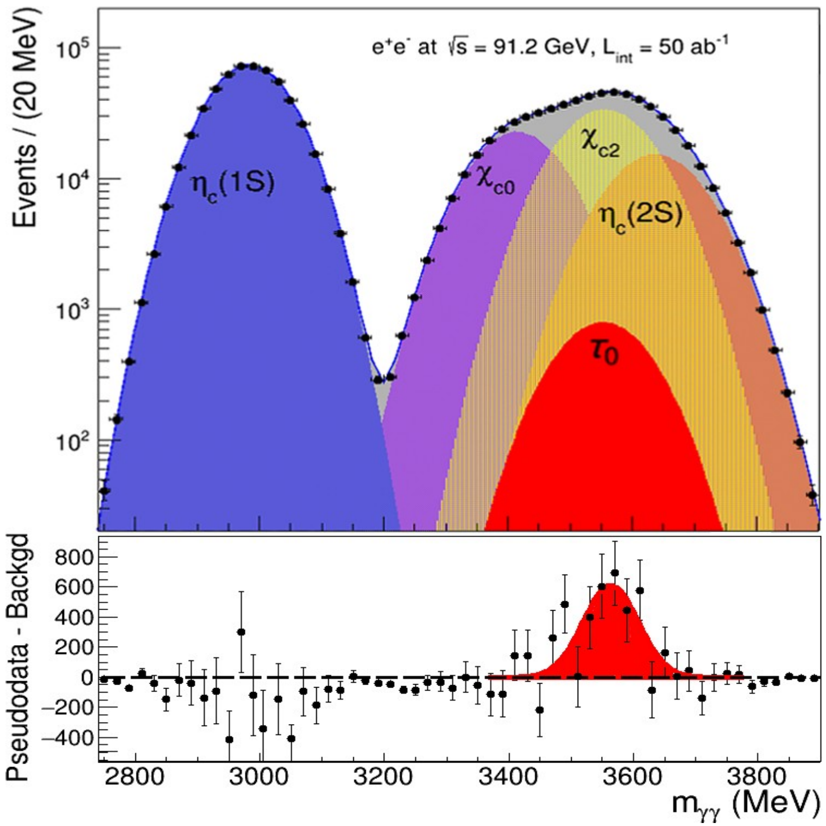
- Signal extracted through multi-Gaussian $m_{\gamma\gamma}$ fit.
- Statistical significance derived from profile-likelihood of fits assuming signal presence or backgd-only, with 0.3% background syst. uncertainty:

Significance (Belle-II) ≈ 3σ

Significance (FCC-ee) ≈ 5σ

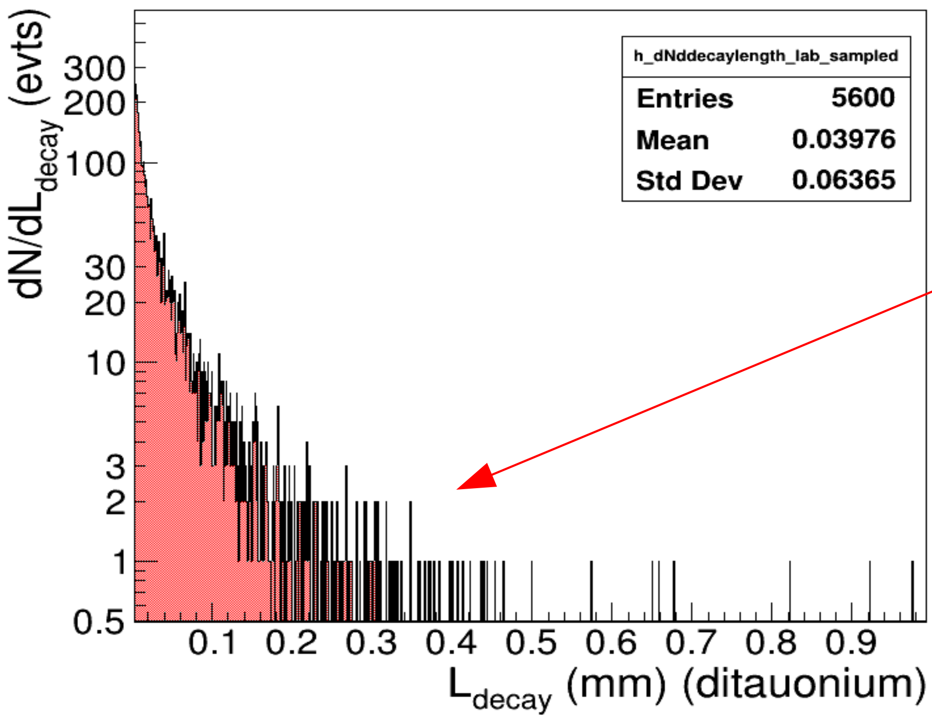
→ Pseudodata–null-hypothesis fit residuals:

Reconstructed yields (LbL subtracted)



Para-ditauonium via $\gamma\gamma \to \tau_0$ Dalitz decays?

- Whereas background ccbar resonances decay directly from the IP, the para-τ_0 has a lifetime of $\tau \approx 28$ fs, i.e. a decay-length $c\tau \approx 8$ μm.



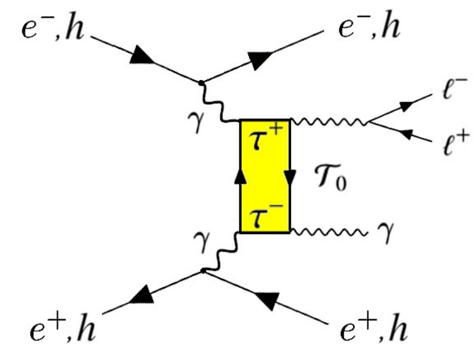
→ For $\beta\gamma \approx 3$: $\langle L_{vtx} \rangle \approx 25$ μm tail of events up to ~1-mm. Any single event would be an unambiguous τ_0 observation!

→ However, diphoton vertex pointing capabilities are much coarser: 1-cm range for LHC-type EM calos.

Pico-second(!) γ ToF needed to separate <1mm distances ☹

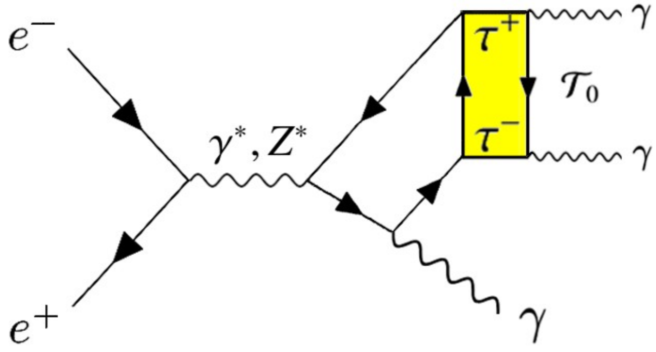
- Displaced charged lepton vertices from Dalitz decays $\tau_0 \to e^+e^-\gamma$, $\mu^+\mu^-\gamma$ with BR~2.3%?
- $\mathcal{O}(150)$, $\mathcal{O}(25)$ signal counts at FCC-ee/Belle-II...

  But para-τ_0 produced almost at rest ($\beta\gamma \approx 0.06$) ☹



Para-ditauonium via $e^+e^- \to \tau_0 + \gamma$?

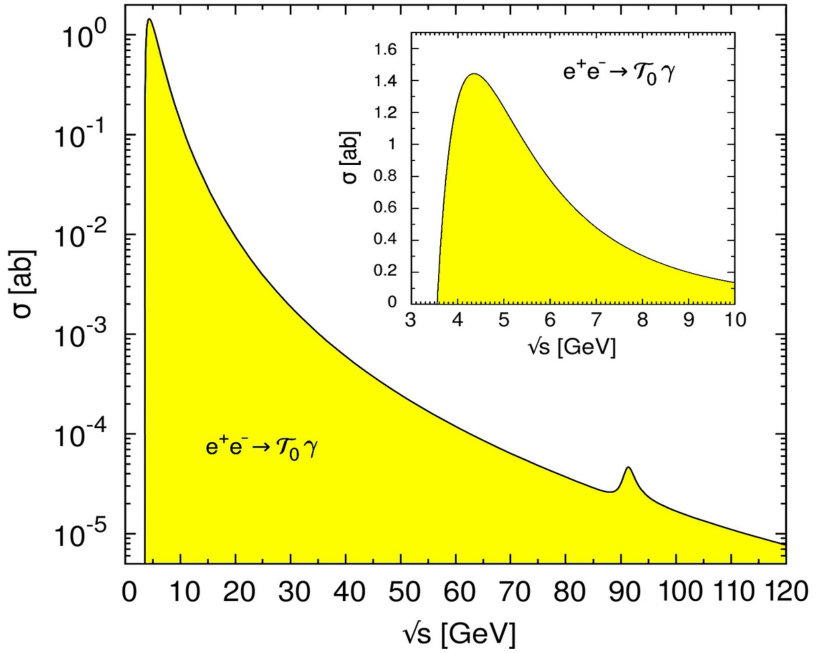
- s-channel production of para-ditauonium plus FSR in e^+e^- collisions:



$$\sigma(e^+e^- \to \mathcal{T}_0 + \gamma) \approx \frac{2}{3}\frac{\pi\alpha^6}{n^3}\frac{m_{\mathcal{T}}^2}{s^2}\left(1 - \frac{m_{\mathcal{T}}^2}{s}\right)$$

- Tiny cross sections, in the (sub)attobarn range:

Colliding system, $\sqrt{s}$, $\mathcal{L}_{\rm int}$, detector	$\sigma(\mathcal{T}_0 + \gamma) \times \mathcal{B}_{\gamma\gamma}$	$N(\mathcal{T}_0(\gamma\gamma) + \gamma)$
e^+e^- at 4.3 GeV, 1 ab^{-1}, STCF	1.1 ab	1
e^+e^- at 7 GeV, 1 ab^{-1}, STCF	0.37 ab	0.37
e^+e^- at 3.78 GeV, 20 fb^{-1}, BES III	0.69 ab	0.014
e^+e^- at 10.6 GeV, 50 ab^{-1}, Belle II	0.085 ab	4
e^+e^- at 91.2 GeV, 50 ab^{-1}, FCC-ee	$3.6 \cdot 10^{-5}$ ab	–

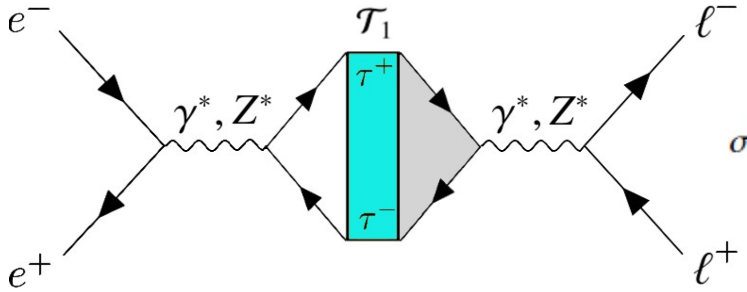


Negligible events expected, swamped by huge backgrounds:

$$\sigma(e^+e^- \to \gamma\gamma\gamma) \times \mathcal{L}_{\rm int} = 15\ \mathrm{pb} \times 50\ \mathrm{ab}^{-1} = 7.5 \cdot 10^8\ \text{events at Belle II}$$ ☹

Ortho-ditauonium via $e^+e^- \to \mathcal{T}_1$ fusion

- Resonant s-channel production of ortho-ditauonium in e^+e^- collisions:



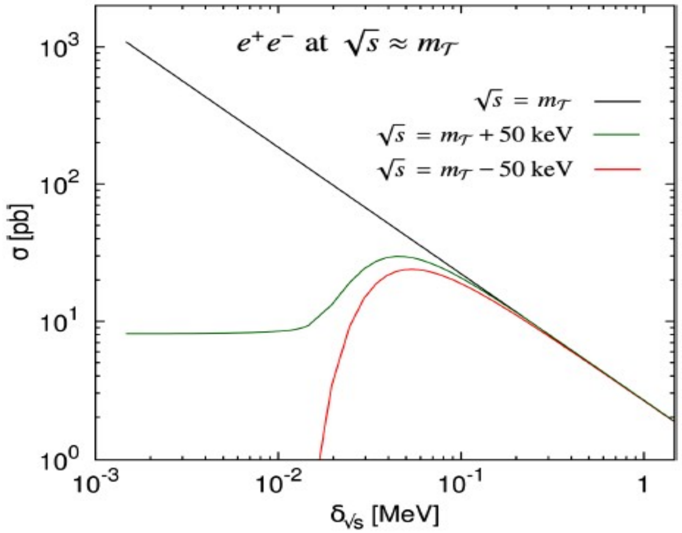
$$\sigma^{\rm ideal}(e^+e^- \to \mathcal{T}_1) = \frac{12\pi\Gamma_{\rm tot}(\mathcal{T}_1)\,\Gamma_{e^+e^-}(\mathcal{T}_1)}{(s-m_{\mathcal{T}}^2)^2 + \Gamma_{\rm tot}^2(\mathcal{T}_1)\,m_{\mathcal{T}}^2} \overset{\sqrt{s}=m_{\mathcal{T}}}{=} 236.6\ \mu{\rm b}$$

- Actual Breit-Wigner x-section reduced by $>10^7$, down to 2–20 pb, due to:
  - ISR & beam-energy spread $\delta_{\sqrt{s}}$ (reduceable via monochromatization)
  - Accurate knowledge of m_τ peak position required for $\sqrt{s}$.

$$\sigma^{\rm actual}(e^+e^- \to \mathcal{T}_1) = \frac{12\pi^2\Gamma_{e^+e^-}(\mathcal{T}_1)}{m_{\mathcal{T}}}\int_0^1 dx_1\int_0^1 dx_2 f_{e^-/e^-}(x_1,s) f_{e^+/e^+}(x_2,s) V_2\left(\sqrt{x_1x_2 s}; m_{\mathcal{T}}, \Gamma_{\rm tot}(\mathcal{T}_1), \sqrt{x_1x_2}\delta_{\sqrt{s}}\right)$$

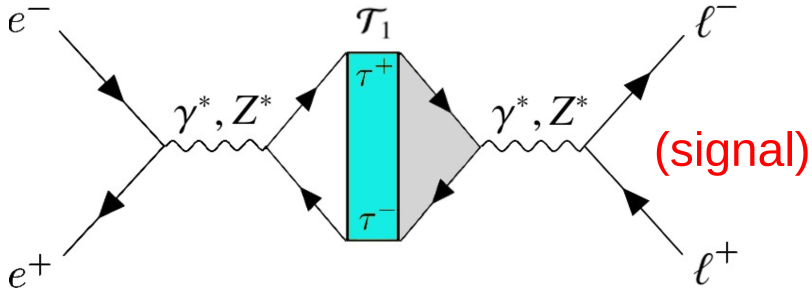
- Threshold-scan around $\sqrt{s} = 2m_\tau$:

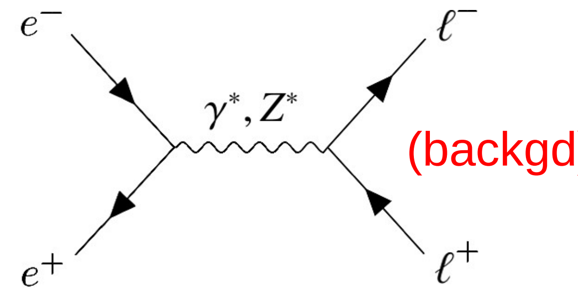
Colliding system, $\sqrt{s}$ ($\delta_{\sqrt{s}}$ spread), $\mathcal{L}_{\rm int}$, experiment	σ	N
e^+e^- at 3.5538 GeV (1.47 MeV), 5.57 pb^{-1}, BES III	1.9 pb	10.4
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (1.24 MeV), 140 pb^{-1}, BES III	2.2 pb	310
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (1 MeV), 1 ab^{-1}, STCF	2.6 pb	$2.6 \cdot 10^6$
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (100 keV), 0.1 ab^{-1}, STCF	22 pb	$2.2 \cdot 10^6$



Ortho-ditauonium observation via $e^+e^- \rightarrow \mathcal{T}_1$ fusion

- Resonant s-channel production of ortho-ditauonium in e^+e^- collisions:





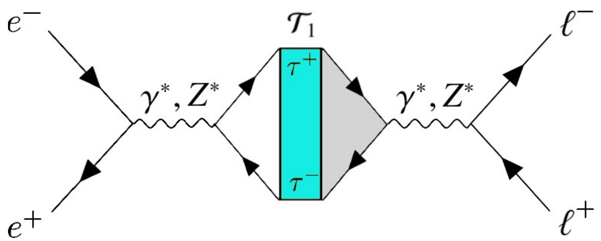
- Actual Breit-Wigner x-section reduced by $>10^7$, down to 2–20 pb, due to:
  – ISR & beam-energy spread $\delta_{\sqrt{s}}$ (reduceable via monochromatization)
  – Accurate knowledge of m_τ peak position required for $\sqrt{s}$.
- Threshold-scan around $\sqrt{s} = 2m_\tau$: $\sigma^{\text{actual}}(e^+e^- \rightarrow \mathcal{T}_1) = \frac{12\pi^2\Gamma_{e^+e^-}(\mathcal{T}_1)}{m_{\mathcal{T}}} \int_0^1 dx_1 \int_0^1 dx_2 f_{e^-/e^-}(x_1, s) f_{e^+/e^+}(x_2, s) V_2\left(\sqrt{x_1x_2s}; m_{\mathcal{T}}, \Gamma_{\text{tot}}(\mathcal{T}_1), \sqrt{x_1x_2}\delta_{\sqrt{s}}\right)$

Colliding system, $\sqrt{s}$ ($\delta_{\sqrt{s}}$ spread), $\mathcal{L}_{\text{int}}$, experiment	σ			N			$S/\sqrt{B}$
	$\mathcal{T}_1$	$\tau^+\tau^-$	$\mu^+\mu^-$	$\mathcal{T}_1$	$\mathcal{T}_1 \rightarrow \mu^+\mu^-$	$\mu^+\mu^-$	
e^+e^- at 3.5538 GeV (1.47 MeV), 5.57 pb^{-1}, BES III	1.9 pb	117 pb	6.88 nb	10.4	2.1	38 300	0.01σ
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (1.24 MeV), 140 pb^{-1}, BES III	2.2 pb	103 pb	6.88 nb	310	63	$9.63 \cdot 10^5$	0.06σ
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (1 MeV), 1 ab^{-1}, STCF	2.6 pb	95 pb	6.88 nb	$2.6 \cdot 10^6$	$5.3 \cdot 10^5$	$6.88 \cdot 10^9$	6.4σ
e^+e^- at $\sqrt{s} \approx m_{\mathcal{T}}$ (100 keV), 0.1 ab^{-1}, STCF	22 pb	46 pb	6.88 nb	$2.2 \cdot 10^6$	$4.5 \cdot 10^5$	$6.88 \cdot 10^8$	17σ

- Ortho-τ_1 observable at STCF (6.4σ) on top of $\mu^+\mu^-$ continuum in default run (1 ab^{-1})
- Note: Ditauonium contributes 2% of the di-tau x-section at $\sqrt{s} = 2m_\tau$ at STCF

Ultraprecise tau mass via $e^+e^- \to \mathcal{T}_1 \to \mu^+\mu^-$

- STCF with 0.1-MeV monochromatization & 4 mass points runs (0.1 ab^{-1} each) can determine very accurately peak excess of $\mu^+\mu^-$ events corresponding to the ortho-τ_1 resonant mass point (provided true m_τ is known to within ±50 keV):

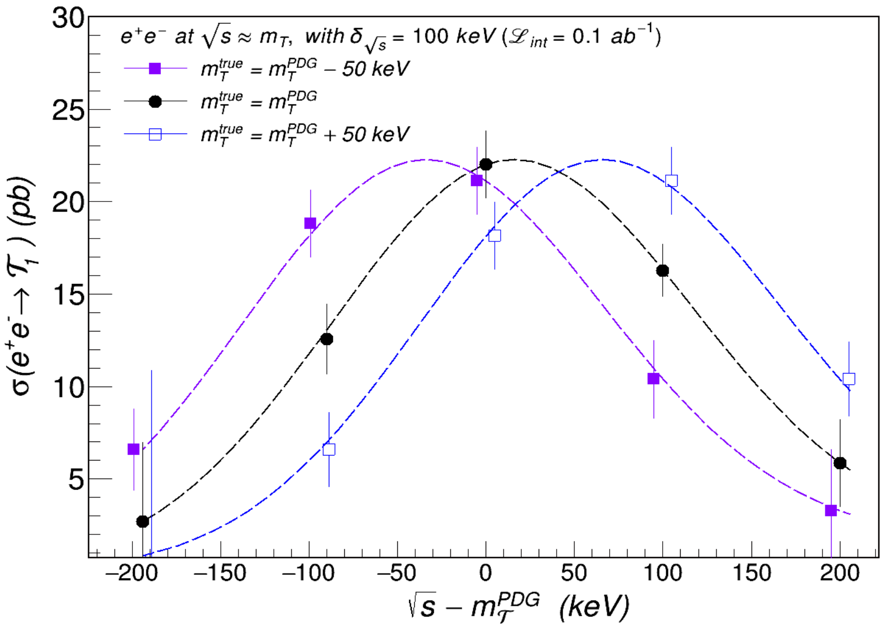


Colliding system, $\sqrt{s}$ ($\delta_{\sqrt{s}}$ spread), $\mathcal{L}_{int}$, experiment	σ			N		$S/\sqrt{B}$
	$\mathcal{T}_1$	$\tau^+\tau^-$	$\mu^+\mu^-$	$\mathcal{T}_1 \to \mu^+\mu^-$	$\mu^+\mu^-$	
e^+e^- at $\sqrt{s} \approx m_\mathcal{T}$ (1 MeV), 1 ab^{-1}, STCF	2.6 pb	95 pb	6.88 nb	$5.3 \cdot 10^5$	$6.88 \cdot 10^9$	6.4σ
e^+e^- at $\sqrt{s} \approx m_\mathcal{T}$ (100 keV), 0.1 ab^{-1}, STCF	22 pb	46 pb	6.88 nb	$4.5 \cdot 10^5$	$6.88 \cdot 10^8$	17σ

- The accuracy of the m(τ_1) position depends only on the accuracy of the beam energy calibration:

With BES-III (BEMS method): $\Delta_{\sqrt{s}}=10^{-5}$

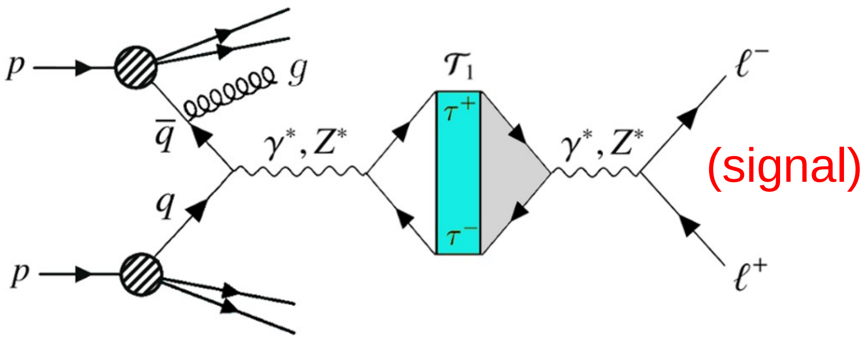
$\Rightarrow \mathcal{O}$(25 keV) tau mass precision

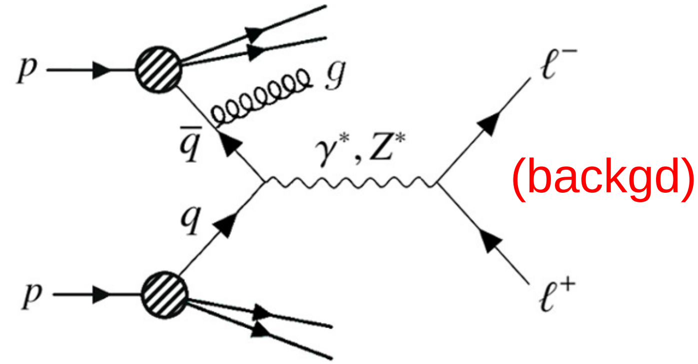


- Impact of ultraprecise m_τ:
  - Improved LFU tests ($\propto m_{e,\mu}^5/m_\tau^5$)
  - CKM $|V_{ij}|$ elements from τ decays
  - Any other SM checks that parametrically depend on ratios of e,μ,τ masses

Ortho-ditauonium via DY+j production at the LHC

- Drell-Yan production of ortho-ditauonium + jet in pp colls. at 14 TeV:

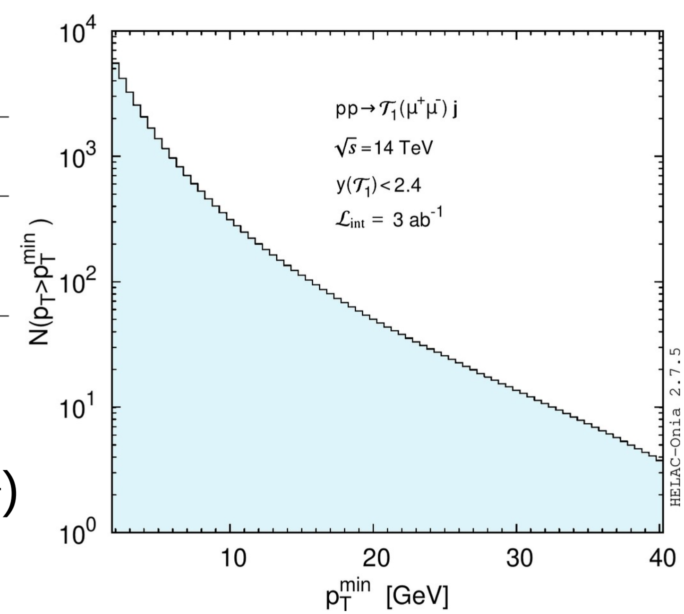




Back-to-back jet required to boost ortho-τ_1 decay (displaced secondary dimuon vertex) & eliminate DY backgds. Only combinatorial heavy-Q dimuon sources left.

- Cross sections at ATLAS/CMS, ALICE/LHCb:

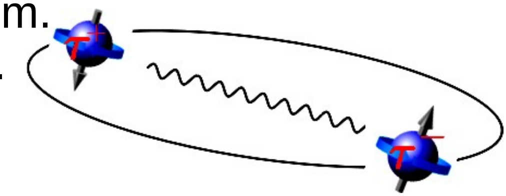
Colliding system, $\sqrt{s}$, $\mathcal{L}_{\rm int}$, detector	$\sigma_{\rm NLO}$ $\mathcal{T}_1 + X$	$\sigma_{\rm NLO}$ $\mathcal{T}_1 + j$	$N(\mathcal{T}_1 + j)$ $\mathcal{T}_1 \to e^+e^-$	$N(\mathcal{T}_1 + j)$ $\mathcal{T}_1 \to \mu^+\mu^-$	with $L_{xy} > 30$ (100) μm $\mathcal{T}_1 \to \ell^+\ell^-$	with $L_{xy} > 30$ (100) μm $\mathcal{T}_1 \to \mu^+\mu^-$
p-p at 14 TeV, 3 ab^{-1}, ATLAS/CMS	42^{+11}_{-19} fb	18 ± 9 fb	1100	1100	130 (10)	130 (10)
p-p at 14 TeV, 300 fb^{-1}, LHCb	42^{+11}_{-19} fb	18 ± 9 fb	110	110	5 (–)	5 (–)
p-p at 114.6 GeV, 10 fb^{-1}, ALICE/LHCb	$2.2^{+0.3}_{-0.4}$ fb	1 ± 0.5 fb	<10	<10	–	–



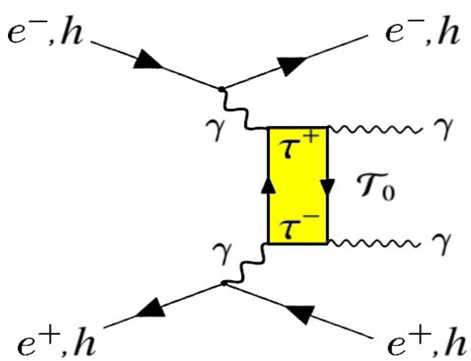
- About 130 (10) displaced dimuon events with $L_{xy} > 30$ (100) μm expected in ATLAS/CMS (3 ab^{-1}) Observation feasible (even with less int. lumi)!

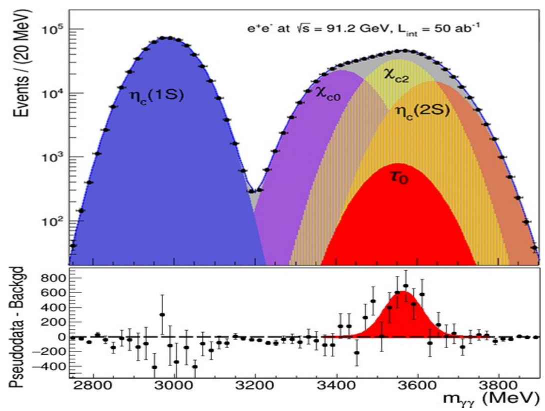
Summary (I)

- **First-ever comprehensive study** of **ditauonium** production/detection in the lab:
  - → Unobserved. Heaviest & most compact leptonic "atomic" system.
  - → Tests of bound QED & CPT symmetries at high-mass (BSM?).
  - → Ultraprecise τ mass extraction possible via $e^+e^- \rightarrow \tau_1 \rightarrow \mu^+\mu^-$



- **Para-ditauonium**: Observable via γγ fusion at high-lumi e^+e^- colliders:

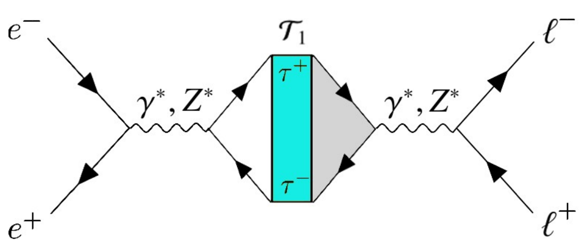


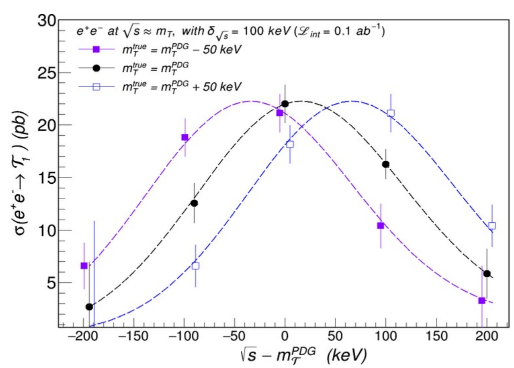


– Requires accurate in-situ measure of overlapping ccbar resonances.

– Stat. significance (multi-Gaussian $m_{\gamma\gamma}$ fit): *S*(Belle-II/FCC-ee)≈3σ,5σ

- **Ortho-ditauonium**: Observable as s-channel resonance at STCF e^+e^- at $\sqrt{s} = 2m_\tau$:



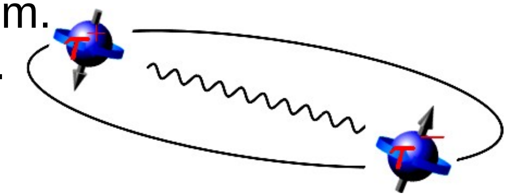


– Dimuon excess (>6σ) in a nominal STFC year (1 ab^{-1})

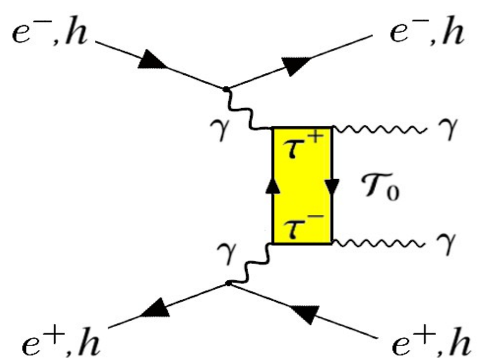
– With 0.1-MeV beam monochrom. tau mass with 25-keV (or better) precision (beam calibration).

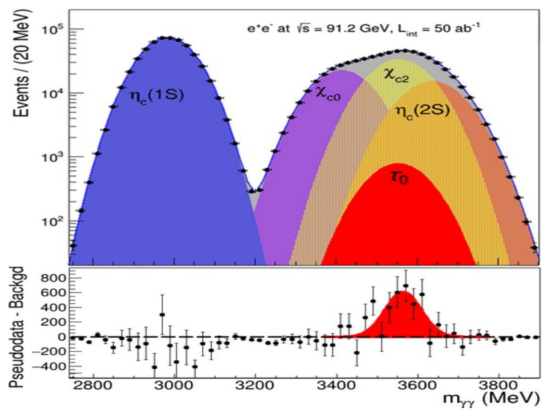
Summary (II)

- First-ever comprehensive study of ditauonium production/detection in the lab:
  - → Unobserved. Heaviest & most compact leptonic "atomic" system.
  - → Tests of bound QED & CPT symmetries at high-mass (BSM?).
  - → Ultraprecise τ mass extraction possible via $e^+e^- \to \mathcal{T}_1 \to \mu^+\mu^-$



- Para-ditauonium: Observable via $\gamma\gamma$ fusion at high-lumi e^+e^- colliders:

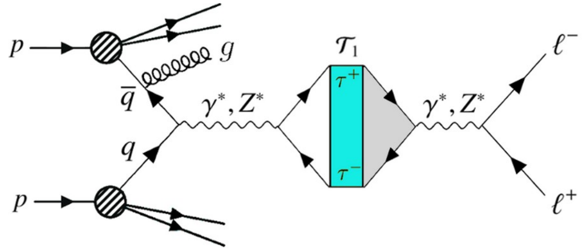


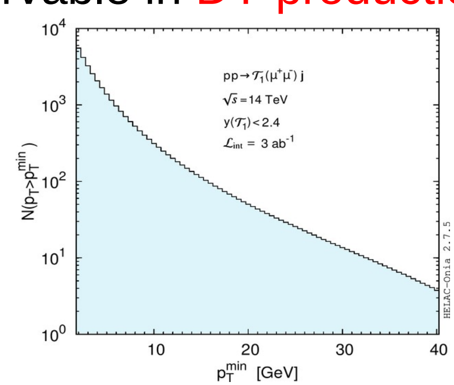


– Requires accurate in-situ measure of overlapping ccbar resonances.

– Stat. significance (multi-Gaussian $m_{\gamma\gamma}$ fit): S(Belle-II/FCC-ee)≈3σ,5σ

- Ortho-ditauonium+jet: Observable in DY production in p-p collisions at the LHC:





– N_{evts}=130 (10) displaced dimuon with L_{xy} > 30 (100) μm at ATLAS/CMS (3 ab^{-1}).

– Observation feasible (even with less int. lumi)!

Backup slides

Ditauonium partial widths & decays

$\mathcal{T}$ state	$m_{\mathcal{X}}$ (MeV)	J^{PC}	$\Gamma_{\rm tot}$ (eV)	Lifetime (fs)	Decay mode	Γ_X (eV)	$\mathcal{B}_X$
1^1S_0	3553.696 ± 0.240	0^{-+}	0.02384	27.60	$\gamma\gamma$	0.018533	77.72%
					γe^+e^-	$4.28 \cdot 10^{-4}$	1.79%
					$\gamma\mu^+\mu^-$	$1.24 \cdot 10^{-4}$	0.52%
					$\gamma q\bar{q}$	$2.20 \cdot 10^{-4}$	0.92%
					$e^+e^-e^+e^-$	$2.32 \cdot 10^{-6}$	0.0094%
					$e^+e^-\mu^+\mu^-$	$1.38 \cdot 10^{-6}$	0.0058%
					$e^+e^-q\bar{q}$	$1.20 \cdot 10^{-6}$	0.0050%
					$\mu^+\mu^-\mu^+\mu^-$	$1.65 \cdot 10^{-7}$	0.00069%
					$\mu^+\mu^-q\bar{q}$	$2.72 \cdot 10^{-7}$	0.0011%
					$q\bar{q}q'\bar{q}'$	$8.23 \cdot 10^{-8}$	0.00035%
					$(2)\tau \to X$	0.004535	19.02%

$\mathcal{T}$ state	$m_{\mathcal{X}}$ (MeV)	J^{PC}	$\Gamma_{\rm tot}$ (eV)	Lifetime (fs)	Decay mode	Γ_X (eV)	$\mathcal{B}_X$
1^3S_1	3553.696 ± 0.240	1^{--}	0.03159	20.83	$e^+e^-(\gamma)$	0.006436	20.37%
					∘ e^+e^-	$2.95 \cdot 10^{-3}$	9.33%
					∘ $e^+e^-\gamma$	$3.49 \cdot 10^{-3}$	11.04%
					$\mu^+\mu^-(\gamma)$	0.006436	20.37%
					∘ $\mu^+\mu^-$	$6.10 \cdot 10^{-3}$	19.30%
					∘ $\mu^+\mu^-\gamma$	$3.38 \cdot 10^{-4}$	1.07%
					$q\bar{q}(\gamma)$	0.01416	44.82%
					$\gamma\gamma\gamma$	$1.62 \cdot 10^{-5}$	0.051%
					$e^+e^-e^+e^-$	$5.55 \cdot 10^{-6}$	0.0176%
					$e^+e^-\mu^+\mu^-$	$4.21 \cdot 10^{-6}$	0.0133%
					$e^+e^-q\bar{q}$	$1.85 \cdot 10^{-6}$	0.0058%
					$\mu^+\mu^-\mu^+\mu^-$	$1.23 \cdot 10^{-7}$	$\mathcal{O}(10^{-6})$
					$\mu^+\mu^-q\bar{q}$	$7.36 \cdot 10^{-8}$	$\mathcal{O}(10^{-6})$
					$q\bar{q}q'\bar{q}'$	$9.73 \cdot 10^{-9}$	$\mathcal{O}(10^{-7})$
					$\nu_\tau\bar{\nu}_\tau$	$1.32 \cdot 10^{-8}$	$\mathcal{O}(10^{-7})$
					$\nu_e\bar{\nu}_e$	$4.30 \cdot 10^{-11}$	$\mathcal{O}(10^{-9})$
					$\nu_\mu\bar{\nu}_\mu$	$4.30 \cdot 10^{-11}$	$\mathcal{O}(10^{-9})$
					$(2)\tau \to X$	0.004535	14.35%

Para-ditauonium production via γγ collisions

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approx. (EPA) for γγ collisions (implemented in HelacOnia2.6/gamma-UPC):

$$\sigma(a\,b \to a\,b + X) = 4\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}(X)}{m_X^2}\left.\frac{\mathrm{d}\mathcal{L}_{\gamma\gamma}^{(a\,b)}}{\mathrm{d}W_{\gamma\gamma}}\right|_{W_{\gamma\gamma}=m_X}$$

- Diphoton charmonium resonances within $m_{\gamma\gamma} \approx 2.9$–$3.7$ GeV:

Resonance	J^{PC}	m_X (MeV)	$\Gamma_{\rm tot}$ (MeV)	$\Gamma_{\gamma\gamma}$ (MeV)	$\mathcal{B}_{\gamma\gamma}$
$\mathcal{T}_0$	0^{-+}	3553.696 ± 0.240	$2.28 \cdot 10^{-8}$	$1.83 \cdot 10^{-8}$	~80%
$\eta_c(1S)$	0^{-+}	2983.9 ± 0.5	32.0 ± 0.7	$(5.06 \pm 0.34) \cdot 10^{-3}$	$(0.0158 \pm 0.0011)\%$
$\eta_c(2S)$	0^{-+}	3637.5 ± 1.1	11.3 ± 3.1	$(2.15 \pm 1.47) \cdot 10^{-3}$	$(0.019 \pm 0.013)\%$
χ_{c0}	0^{++}	3414.71 ± 0.30	10.8 ± 0.6	$(2.203 \pm 0.097) \cdot 10^{-3}$	$(0.0204 \pm 0.0009)\%$
χ_{c2}	2^{++}	3556.17 ± 0.07	1.97 ± 0.09	$(5.614 \pm 0.197) \cdot 10^{-4}$	$(0.0285 \pm 0.0010)\%$

→ Charmonia resonances have $\mathcal{O}$(keV) diphoton widths: $\mathcal{O}(10^5)$ larger than para-τ_0. But, the diphoton BR is $\mathcal{O}(10^4)$ larger for para-τ_0 than for c-cbar states.

$\gamma\gamma$ collision x-sections (signal & backgds)

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions via gamma-UPC: 2207.03012 [hep-ph].
- σ(LbL) computed with MG5@NLO (virtual box) with same photon fluxes.
- Results for e^+e^- and ultraperipheral p-p, p-A & A-A collisions:

Colliding system, c.m. energy, $\mathcal{L}_{\rm int}$, exp.	$\sigma \times \mathcal{B}_{\gamma\gamma}$						$N \times \mathcal{B}_{\gamma\gamma}$	
	$\eta_c(1S)$	$\eta_c(2S)$	$\chi_{c,0}(1P)$	$\chi_{c,2}(1P)$	LbL	$\mathcal{T}_0$	$\mathcal{T}_0$	$\chi_{c,2}(1P)$
e^+e^- at 3.78 GeV, 20 fb^{-1}, BES III	120 fb	3.6 ab	15 ab	13 ab	30 ab	0.25 ab	–	–
e^+e^- at 10.6 GeV, 50 ab^{-1}, Belle II	1.7 fb	0.35 fb	0.52 fb	0.77 fb	1.7 fb	0.015 fb	750	38 500
e^+e^- at 91.2 GeV, 50 ab^{-1}, FCC-ee	11 fb	2.8 fb	3.9 fb	6.0 fb	12 fb	0.11 fb	5 600	$3 \cdot 10^5$
p-p at 14 TeV, 300 fb^{-1}, LHC	7.9 fb	2.0 fb	2.8 fb	4.3 fb	6.3 fb	0.08 fb	24	1290
p-Pb at 8.8 TeV, 0.6 pb^{-1}, LHC	25 pb	6.3 pb	8.7 pb	13 pb	21 pb	0.25 pb	0.15	8
Pb-Pb at 5.5 TeV, 2 nb^{-1}, LHC	61 nb	15 nb	21 nb	31 nb	62 nb	0.59 nb	1.2	62

(~10% uncertainties, today)

→ Relative production x-sections: $\eta_c(1S):\chi_{c2}(1P):\chi_{c0}(1P):\eta_c(2S):\tau_0 \approx 100:50:30:25:1$ driven by their different $\Gamma^2(\gamma\gamma)/(\Gamma(\mathrm{tot})\cdot m^2_X)$ ratios.

→ Cross sections increase with $\sqrt{s}$ and Z^4:

Largest x-sections (0.6 nb) in PbPb UPC (but handful of evts expected at LHCb)
Largest yields: 750, 5600 counts at Belle-II, FCC-ee thanks to $\mathcal{L}_{\rm int}$ = 50 ab^{-1}.

Para-ditauonium signal extraction

- 1-million events generated for signal & backgrounds. Run MVA (BDT) with 12 different single-γ and γ-pair kinematic variables for signal/backgds separation:
  (i) Strong discrimination power (factor of ~20) of LbL continuum from signal.
  (ii) No discrimination achieved for overlapping charmonia (decay γ angular modulation of tensor χ_{c2} different than scalar τ_0 signal, but $\times$50 suppressed yields)

- Signal extracted through multi-Gaussian $m_{\gamma\gamma}$ fit, by considering:
  → $\eta_c(1S)$: No overlap w/ signal ("std.candle"): 0.5M clean evts to fully control E_γ scale&res. plus exp. & theory uncertainties.
  → χ_{c0}, $\eta_c(2S)$: Partial overlap with signal. Exploit ~100M $\gamma\gamma \to \chi_{c0},\eta_c \to X$ decays with $\times$50 larger BRs (e.g. X=3- and 4-mesons) to fully remove their contamination.
  → χ_{c2}: Full overlap with signal! Exploit alternative $\gamma\gamma \to \chi_{c2} \to X$ decays (e.g. 11M evts. for X=4π) to determine its lineshape to within $\mathcal{O}$(0.2%).

Reconstructed yields (LbL subtracted)