Observing ditauonium via $\gamma\gamma$ fusion in e^+e^- collisions

David d'Enterria (CERN)
Hua-Sheng Shao (LPTHE, Paris)

FCC

Details in: arXiv:2202.02316 [hep-ph], 2204.07269 [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 depending on relative spin orientation of leptons.
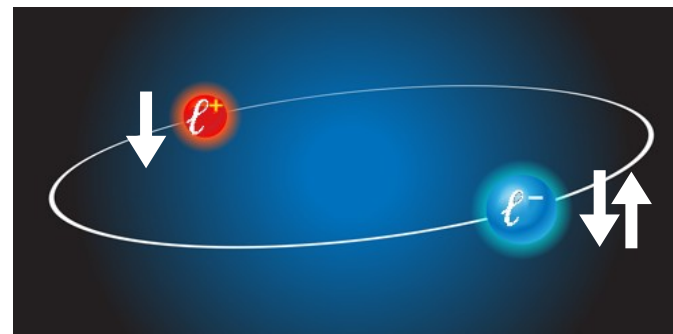
■ Ditauonium $\tau_0\equiv(\tau^+\tau^-)$, barely studied, is the smallest & most-bound leptonium state:

Mass: $m_{\tau 0} = 2m_\tau + E_{bind}$ = 3553.696 MeV, $E_{bind} = -\alpha^2 m_\tau/(4n^2)$ = −23.7 keV

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

Rydberg const (γ ionization): $R_\infty = m_\tau \alpha^2/4\pi$ = 3.76 keV ($\times$3500 larger than positronium)
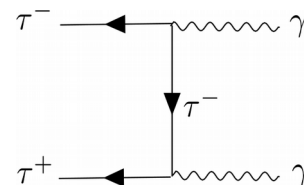
■ Compared to other exotic atoms, ditauonium can provide:

→ New tests of QED and CPT symmetries at much higher masses (smaller distances).
→ Sensitivity to any BSM enhanced by $(m_\ell/\Lambda_{BSM})^n$, unaffected by hadronic uncertainties.

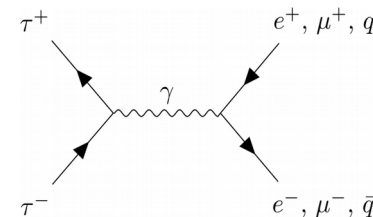■ Para-τ_0 decays mostly to $\gamma\gamma$ (BR $\approx$ 80%):

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

■ Ortho-τ_0 has many open channels: e^+e^-, $\mu^+\mu^-$, $q\bar{q}$ BR $\approx$ 20%, 20%, 45%

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

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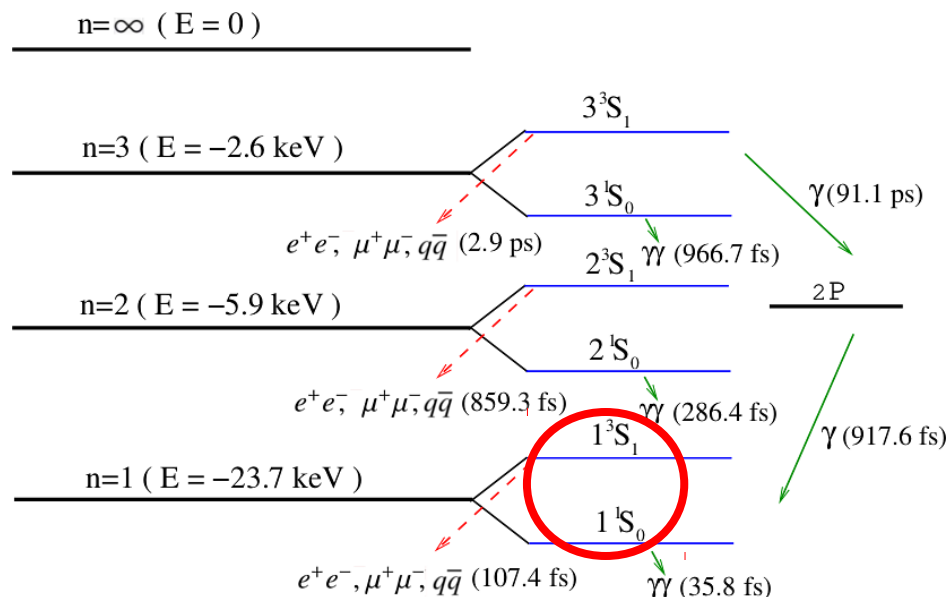

■ Weak decay of constituent $\tau^\pm$: $\quad \Gamma_{(2)\tau \to X} = 2/\tau = 0.004535 \text{ eV} \quad (\tau \approx 290 \text{ fs})$

BR$_{\text{eff}} \approx$ 19%,14% for para-,ortho-τ_0

■ Ditauonium spectroscopy:

→ Only the two lowest states (1^1S_0 and 1^3S_1) have lifetimes shorter than the weak-decay of their constituents tau's.

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

Ditaunioum production

■ 3 possible production mechanisms of heavy leptonium considered so far:

(i) s-channel fusion in e^+e^- colls. for ortho-τ_0:

Tricky, it requires $\ll$100-keV beam monochromatization.

(ii) s-channel two-photon fusion for para-τ_0:
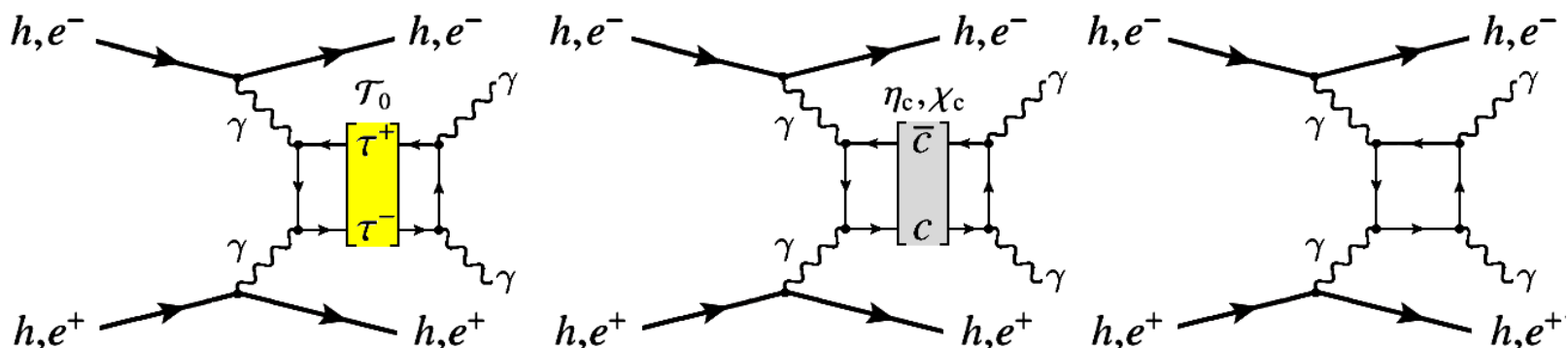
Mentioned in literature, never actually studied.

(iii) B-meson decays for ortho-τ_0:

Tiny... $BR(B \to K^{(*)} \tau_0) \sim 10^{-13}$ [Fael&Mannel, arXiv:1803.08880]

■ We investigate for the first time the photon-fusion production mechanism at e^+e^- and hadron colliders, including all backgrounds:

→ C-even charmonium: 3 $c\bar{c}$: $\eta_c(2S)$, $\chi_{c1,2}$ resonances within $\lesssim$100 MeV of τ_0

→ Light-by-light scattering (LbL) continuum.

Resonance 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):

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

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

Resonance	J^{PC}	m_X (MeV)	Γ_{tot} (MeV)	$\Gamma_{\gamma\gamma}$ (MeV)	$\mathcal{B}_{\gamma\gamma}$
$\mathcal{T}_0$	0^{-+}	3553.696 ± 0.240	$2.28 \cdot 10^{-8}$	$1.83 \cdot 10^{-8}$	$\sim 80\%$
$\eta_c(1S)$	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 $\mathcal{O}(\text{keV})$ 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.
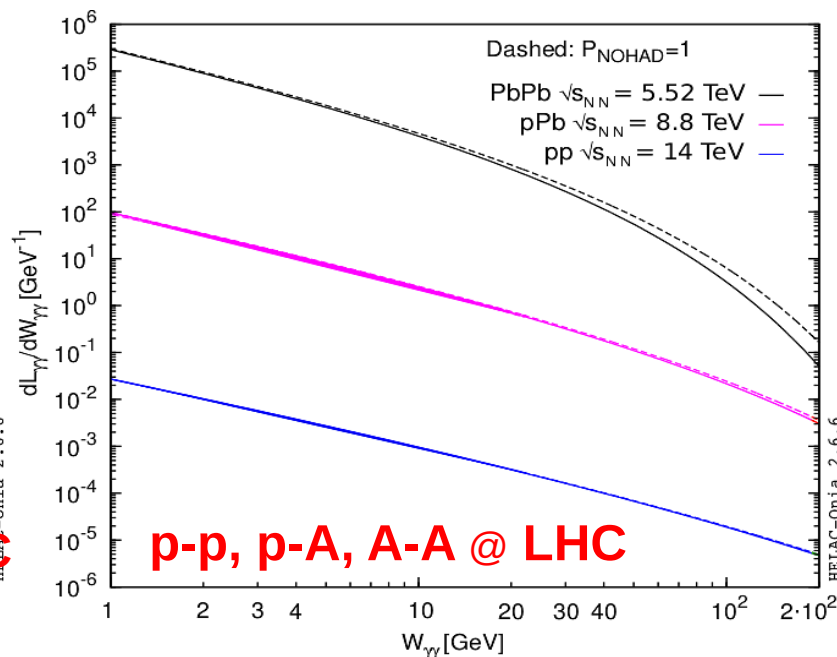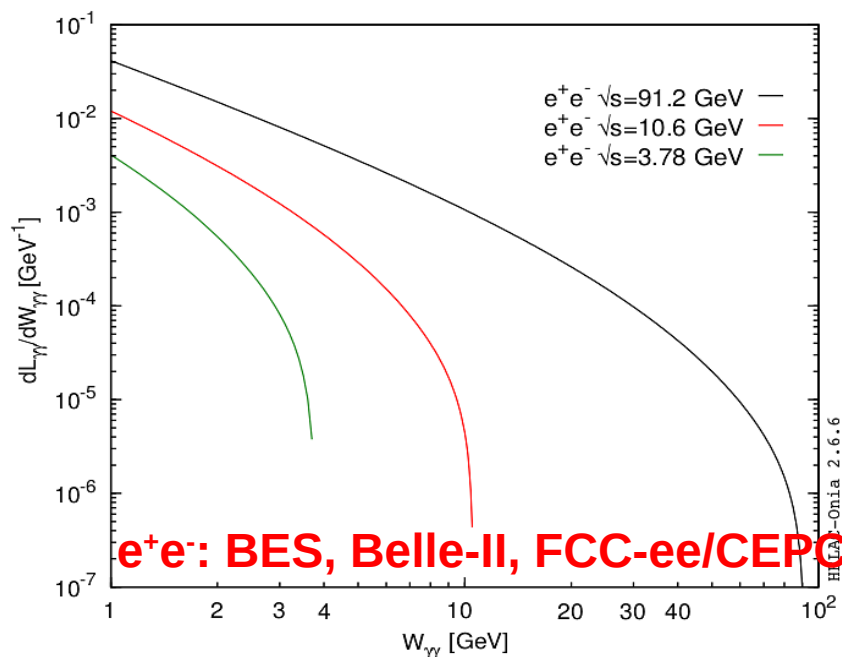
■ Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for γγ collisions via gamma-UPC 2207.03012 [hep-ph]

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

■ Photon-photon luminosity for e⁺e⁻ and ultraperipheral p-p, p-A & A-A collisions

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

γγ collision x-sections (signal & backgds)

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for γγ 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, $\mathcal{L}_{int}$, 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 $\Gamma^2(\gamma\gamma)/(\Gamma(tot)\cdot m^2_x)$ 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 $\mathcal{L}_{int}$ = 50 ab^{-1}.

Ditauonium analysis strategy

■ 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: Requires high-reso FCC-ee crystal calo): Acceptance: $10° < \theta_\gamma < 170°$. Mass resolution: ~2%. Photon reco effic. ~100%.

→ Effectively, all diphoton resonances are Gaussian-smeared with ~70 MeV widths:

Generator-level x-sections (0.1-MeV τ_0 width)
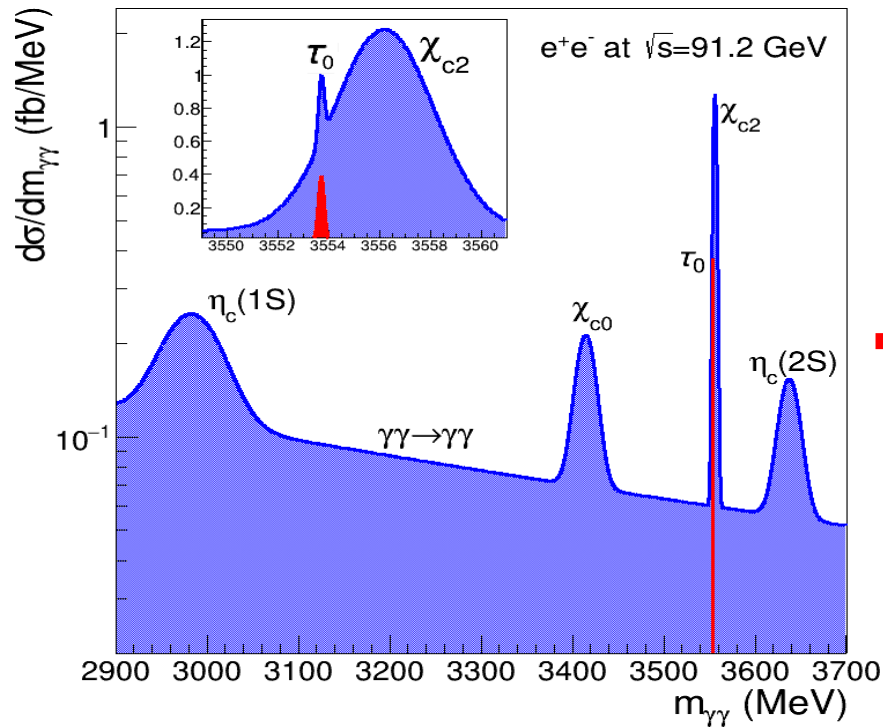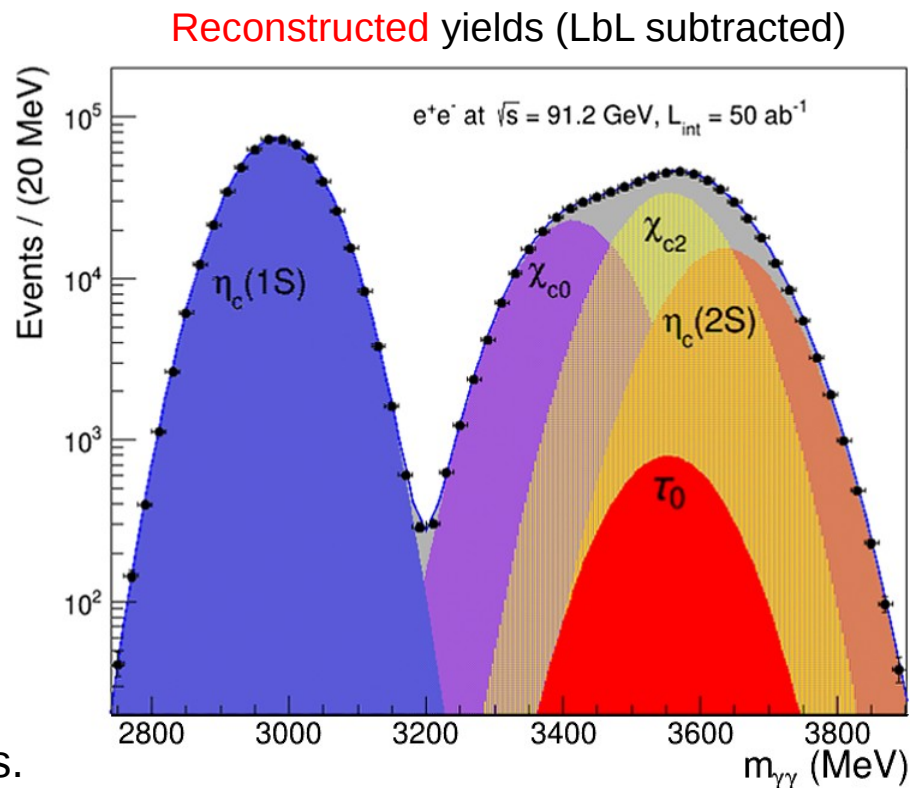
Reconstructed yields (LbL subtracted)
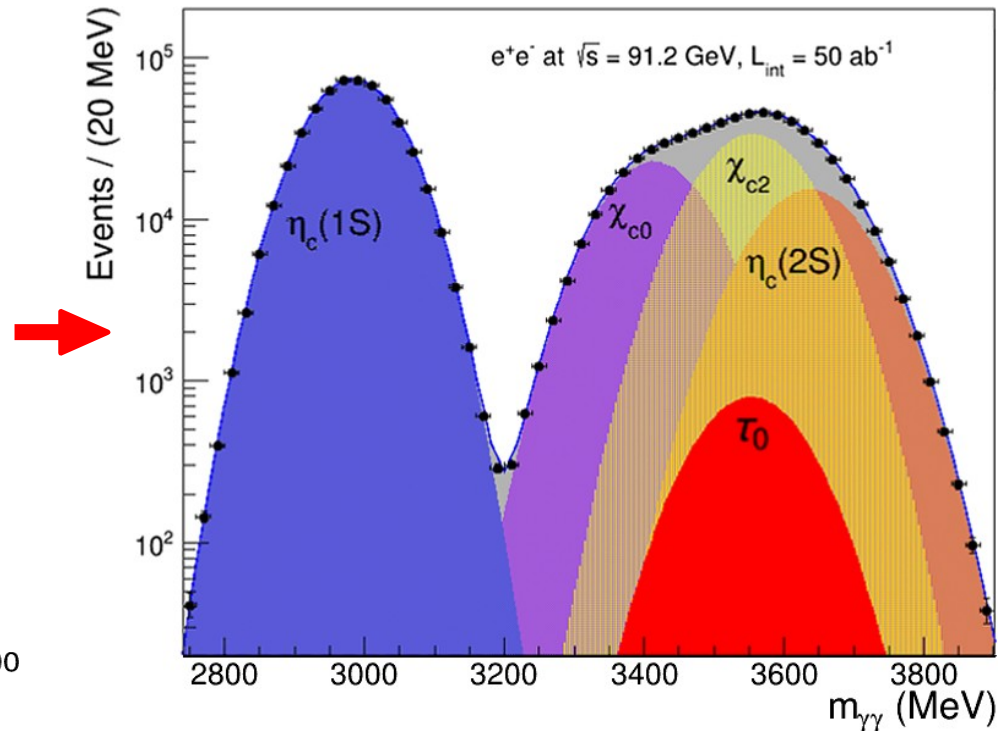
■ Ditauonium signal swamped by overlapping χ_{c2}(1P) & neighboring χ_{c0}(1P), η_c(2S)

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:

  → η_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}, η_c(2S): Partial overlap with signal. Exploit ~100M $\gamma\gamma \rightarrow \chi_{c0}, \eta_c \rightarrow X$ 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 $\gamma\gamma \rightarrow \chi_{c2} \rightarrow X$ decays (e.g. 11M evts. for X=4π) to determine its lineshape to within $\mathcal{O}$(0.2%).

Reconstructed yields (LbL subtracted)

e^+e^- at $\sqrt{s}$ = 91.2 GeV, L_{int} = 50 ab^{-1}

Ditauonium stat. significance

- 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.

- Statistical significance derived from profile-likelihood of fits assuming signal presence or backgd-only, with 0.3% background syst. uncertainty:
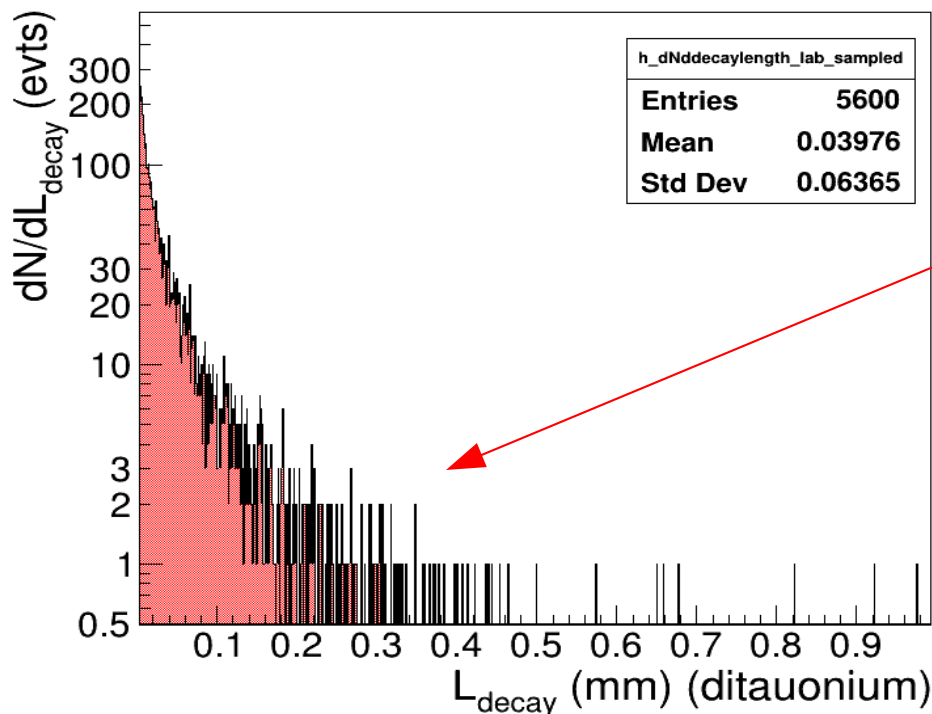
  Significance (Belle-II) $\approx 3\sigma$

  Significance (FCC-ee) $\approx 5\sigma$

→ Pseudodata–null-hypothesis fit residuals:

Reconstructed yields (LbL subtracted)
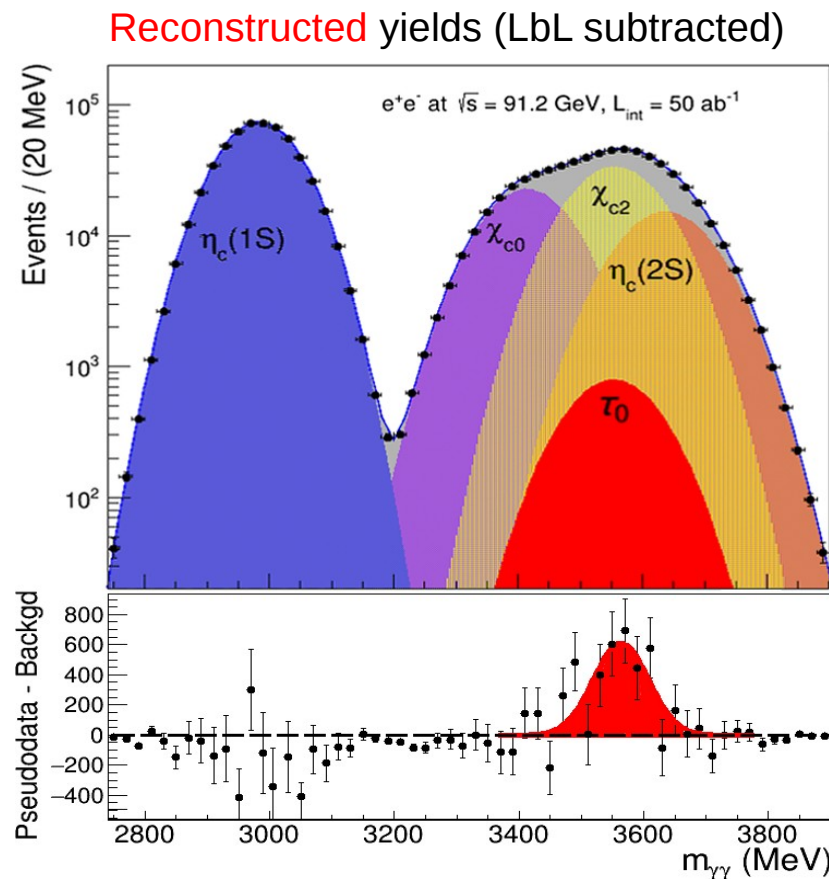
Ditauonioum via displaced vertex?

■ Whereas all charmonium resonances decay within $\mathcal{O}$(nm) from the IP, the para-τ_0 has a lifetime of $\tau \approx 40$ fs, i.e. $c\tau \approx 10$ μm.

→ For $\beta\gamma \approx 3$: $<L_{vtx}> \approx 30$ 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 ☹

■ Potential alternative: Search for displaced e^+e^-, $\mu^+\mu^-$ vertices from ditauonium Dalitz decays $\tau_0 \rightarrow e^+e^-\gamma$, $\mu^+\mu^-\gamma$ with BR~3%: $\mathcal{O}$(100) signal counts at FCC-ee and $\mathcal{O}$(20) at Belle-II with ZERO background. Dedicated analysis required.

Summary

■ **First-ever feasibility study** to produce & measure **ditauonium** in the lab:

→ **Heaviest & most compact** purely leptonic "atomic" system.

→ Tests of **bound state QED & CPT symmetries** at **high-mass** (potential BSM effects).

■ Computed EPA x-sections for signal & backgds in **γγ-collisions at LHC & e⁺e⁻**:

→ Ratios of S & B: **$\eta_c(1S) : \chi_{c2}(1P) : \chi_{c0}(1P) : \eta_c(2S) : \tau_0 \approx 100 : 50 : 30 : 25 : 1$**

→ **Belle-II (10.6 GeV): 15 ab, 750 counts | FCC-ee(90 GeV): 0.11 fb, 5600 counts.**
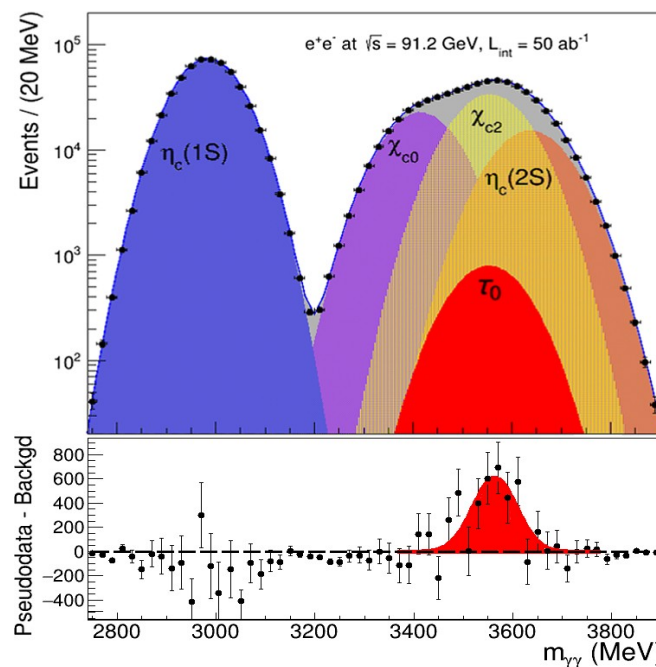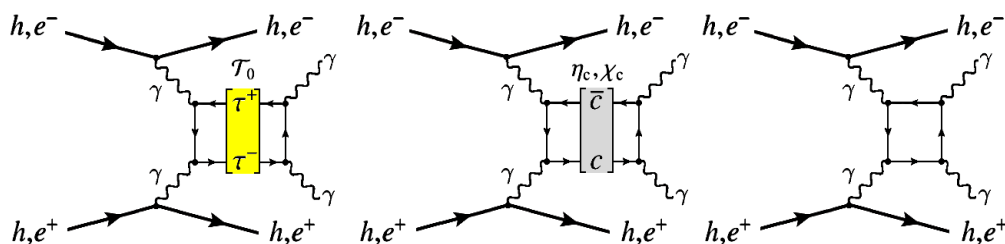
→ Exp./Theory uncertainties controlled thanks to very large $\gamma\gamma \to \eta_c(1S) \to \gamma\gamma$ "std. candle" sample.

→ Irreducible backgd. syst. uncertainties controlled within 0.2% via huge $\gamma\gamma \to \chi_{c0,2}, \eta_c(2S) \to X$ samples.

→ **Stat. significance ≈ 3σ (Belle-II), 5σ (FCC-ee)**

■ FCC-ee/CEPC detector requirements:

→ Need detector with **high energy resolution crystal calorimeter**: $\delta E_\gamma \approx 2\%$ at $E_\gamma \approx 1.7\,\text{GeV}$

→ Alternative: **mm-vertex γ pointing** capabilities (impossible?), or exploit τ_0 Dalitz decays.

Backup slides