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

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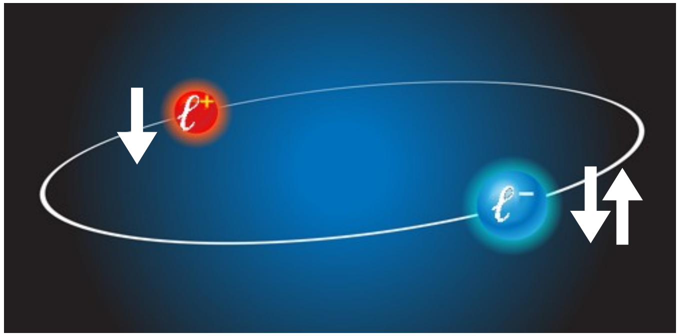
Details in: arXiv:2202.02316 [hep-ph]

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 (×3500 smaller than positronium)

  Rydberg const (γ ionization): $R_\infty = m_\tau \alpha^2/4\pi$ = 9.46 keV (×3500 larger than positronium)

- Compared to other exotic atoms, ditauonium can provide:

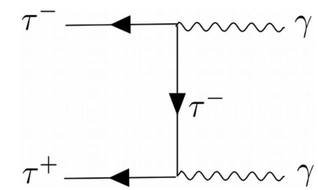
  → New tests of QED and CPT symmetries at much higher masses (smaller distances).

  → Sensitivity to any BSM enhanced by $(m_\ell/\Lambda_{BSM})^n$, unaffected by hadronic uncertainties.

Ditauonium partial widths & decays

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

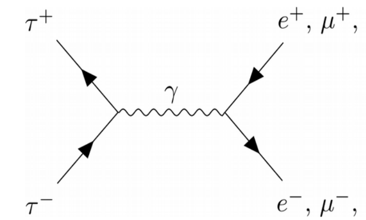
$$\Gamma^{(0)}(n^1S_0 \to \gamma\gamma) = \frac{\alpha^5 m_\tau}{2n^3} \underset{n=1}{=} 0.018384\text{ eV}$$



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

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

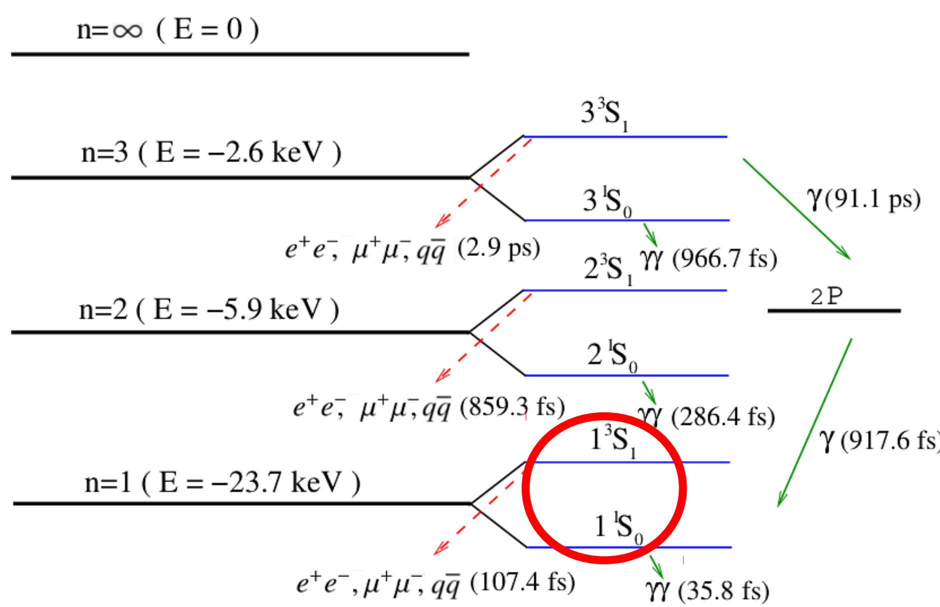
$$\Gamma^{(0)}(n^3S_1 \to q\bar{q}) = \frac{\alpha^5 m_\tau}{6n^3} R_{\text{had}}\left(m^2_{\mathcal{T}_0}\right) = 2.2\frac{\alpha^5 m_\tau}{6n^3}$$



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

- 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.

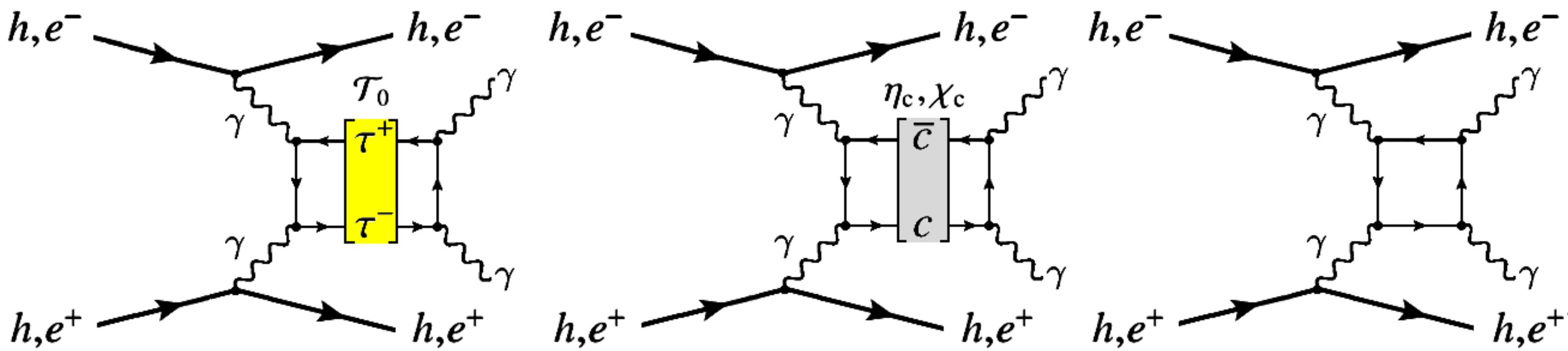


[DdE, R.Perez-Ramos, to be submitted]

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 <100-keV beam monochromatization.
  - (ii) s-channel two-photon fusion for para-τ_0:
    Estimated 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 η_c, χ_c resonances within ≲100 MeV of τ_0
  - → Light-by-light scattering (LbL) continuum.



Resonance production via $\gamma\gamma$ collisions

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions (implemented in HelacOnia2.6):

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

- Diphoton charmonium resonances within $m_{\gamma\gamma} \approx 2.9$–$3.7$ 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 $\mathcal{O}$(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.

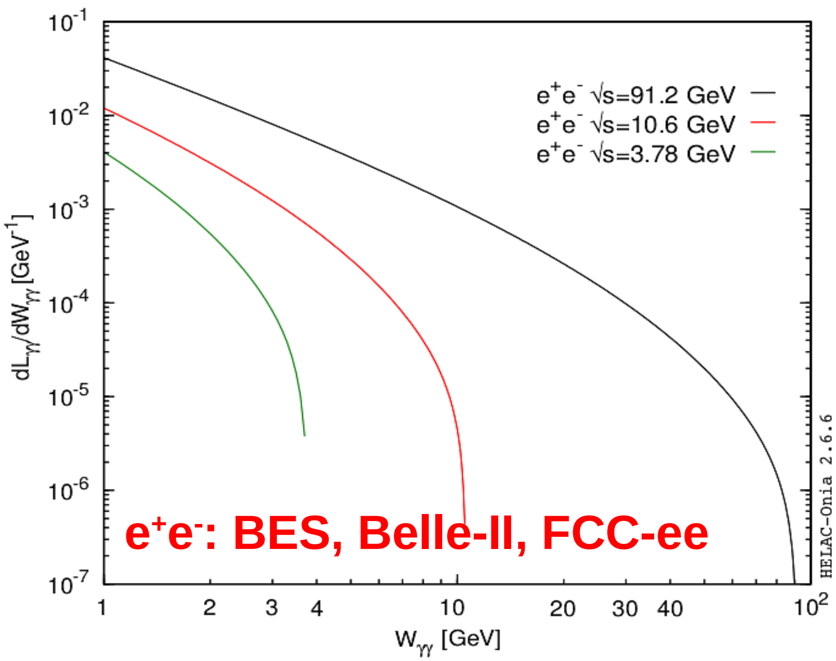
Photon-photon luminosities in e^+e^- & UPC

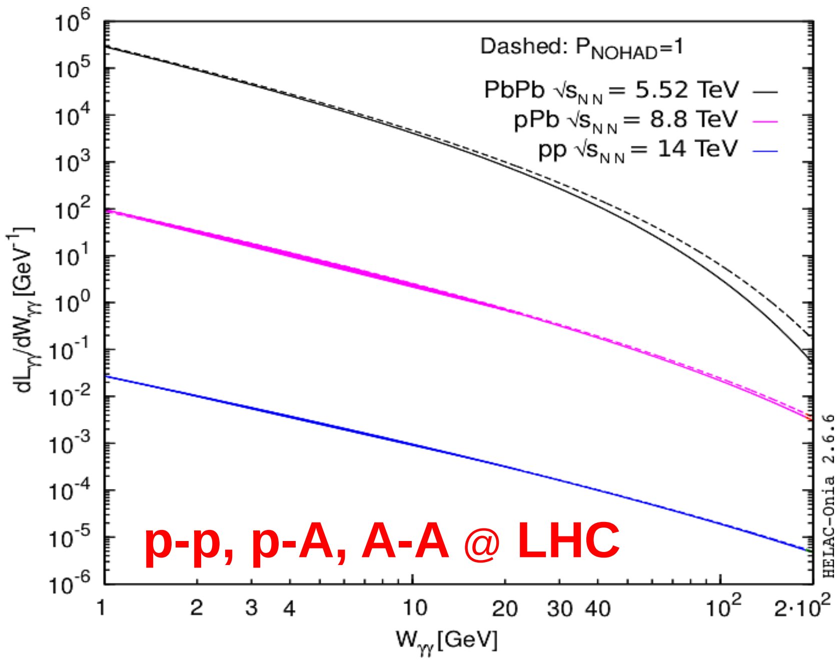
- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for γγ collisions (implemented in HelacOnia2.6):

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

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

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





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

- Cross sections for signal & backgrounds computed in the Weizsäcker-Williams approximation (EPA) for $\gamma\gamma$ collisions (implemented in HelacOnia2.6).
- 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 $\rm fb^{-1}$, BES III	120 fb	3.6 ab	15 ab	13 ab	30 ab	0.25 ab	–	–
e^+e^- at 10.6 GeV, 50 $\rm ab^{-1}$, 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 $\rm ab^{-1}$, 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 $\rm fb^{-1}$, 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 $\rm pb^{-1}$, 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 $\rm nb^{-1}$, 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 $\Gamma^2(\gamma\gamma)/(\Gamma(\text{tot})\cdot m^2_X)$ ratios.

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

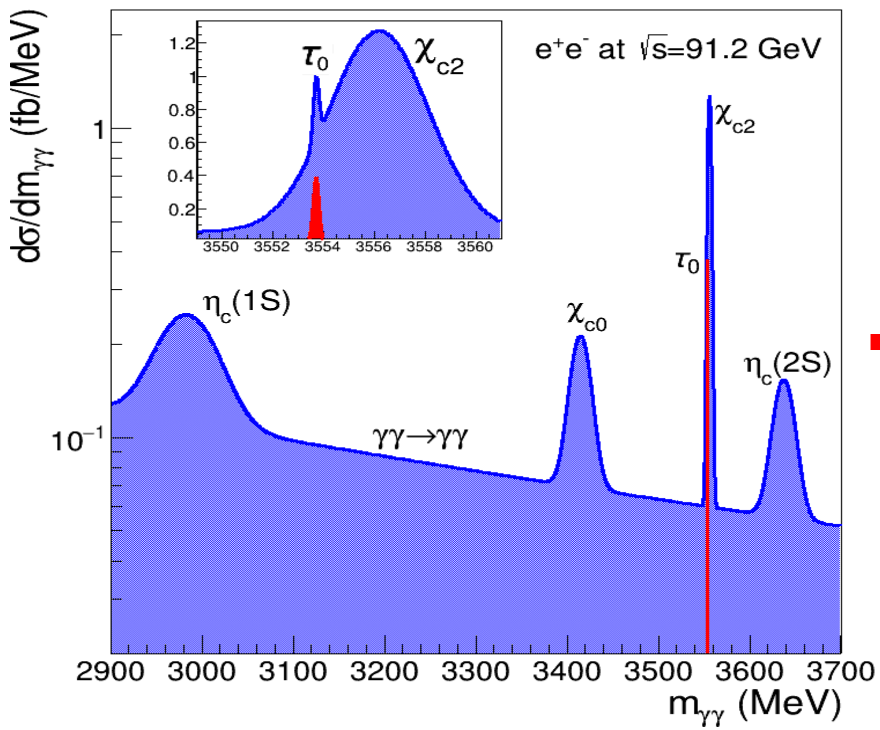
Largest x-sections (0.6 nb) in PbPb UPC (but handful of evts expected at LHCb)

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

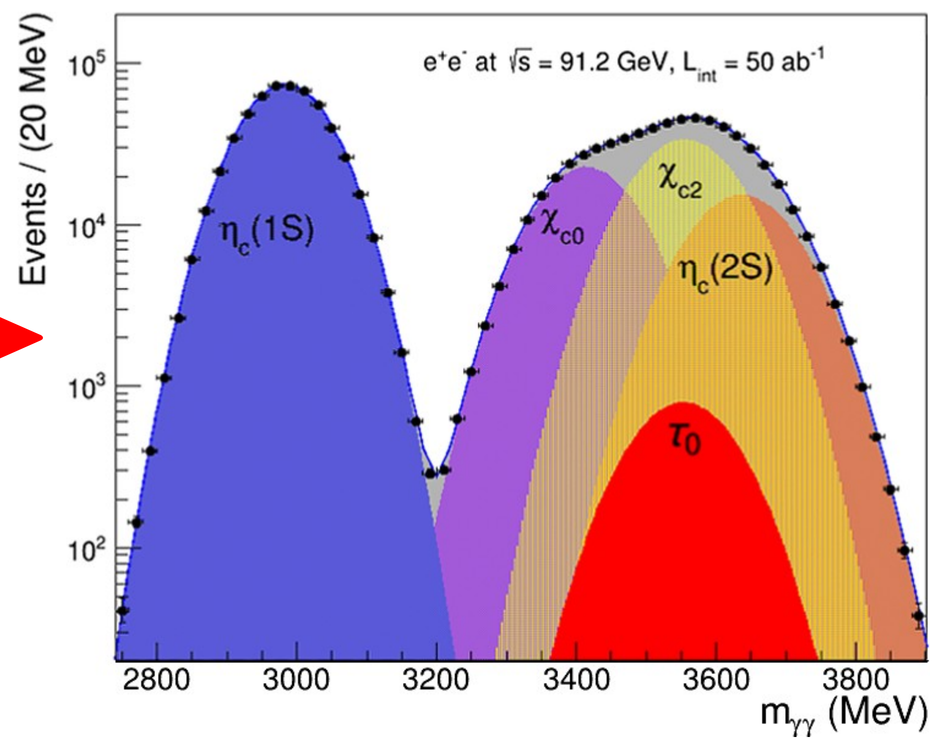
Ditauonium analysis strategy

- 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: $10^\circ < \theta_\gamma < 170^\circ$. 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)



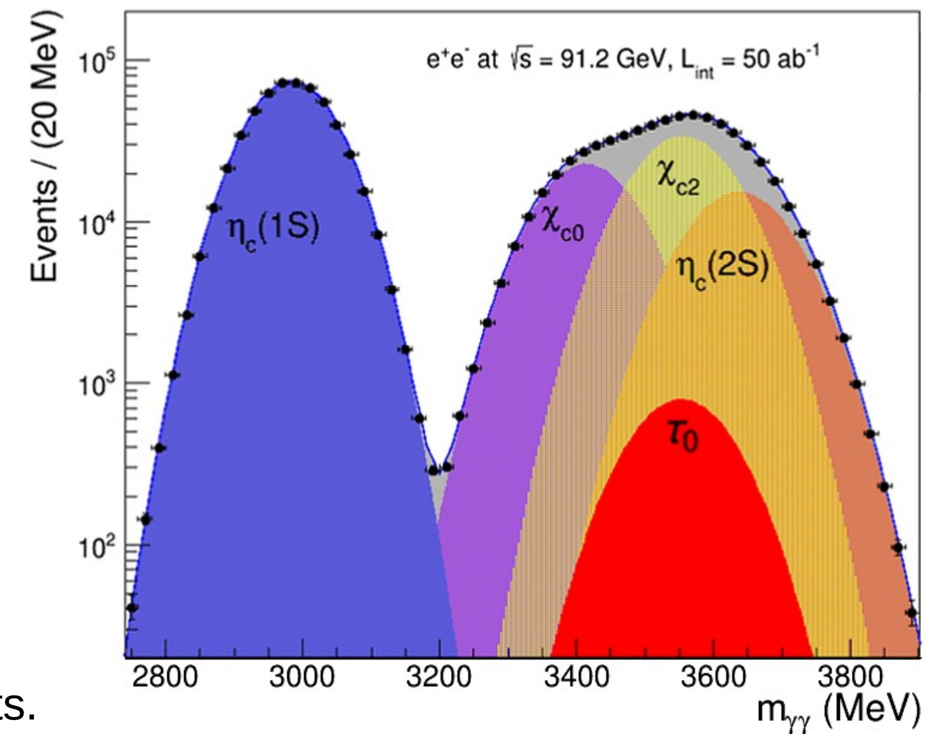
- Ditauonium signal swamped by overlapping χ_{c2}(1P) & neighboring χ_{c0}(1P), η_c(2S)

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 $\gamma\gamma\to\chi_{c0},\eta_c\to X$ 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)



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.

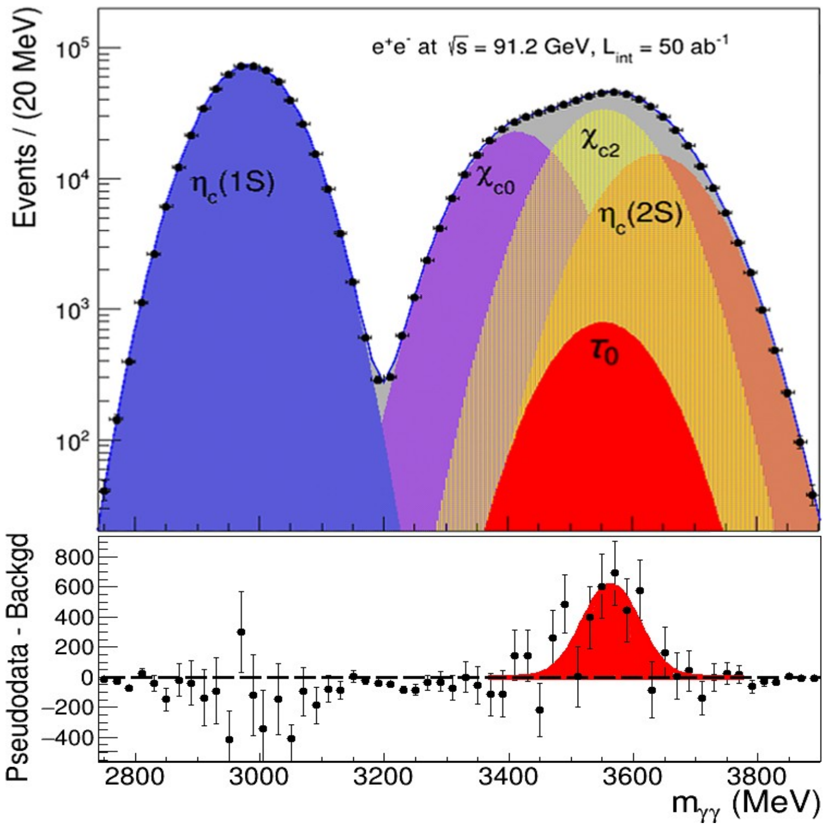
- Statistical significance derived from profile-likelihood of fits assuming signal presence or backgd-only, with 0.3% background syst. uncertainty:

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

  Significance (Belle-II) $\approx 3\sigma$

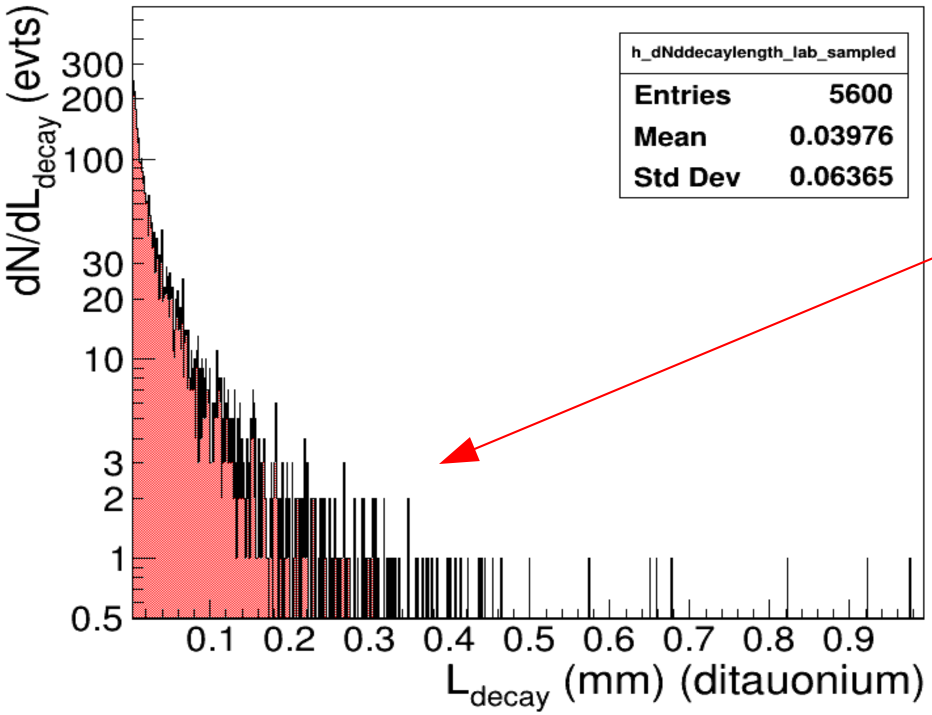
→ Pseudodata–null-hypothesis fit residuals:

Reconstructed yields (LbL subtracted)



Ditaunioum 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 $\beta\gamma \approx 3$: $\langle L_{vtx} \rangle \approx 30$ 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.

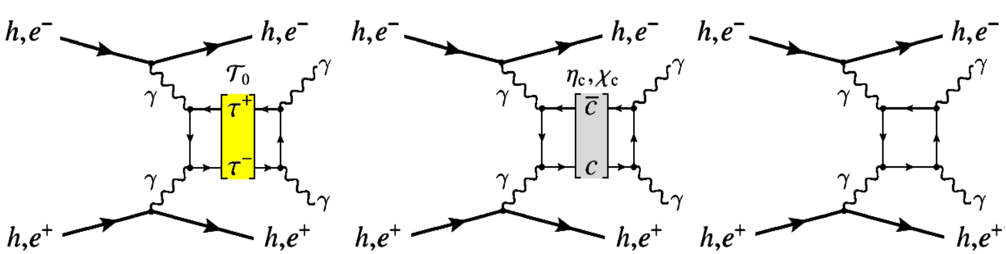
Pico-second(!) γ ToF needed

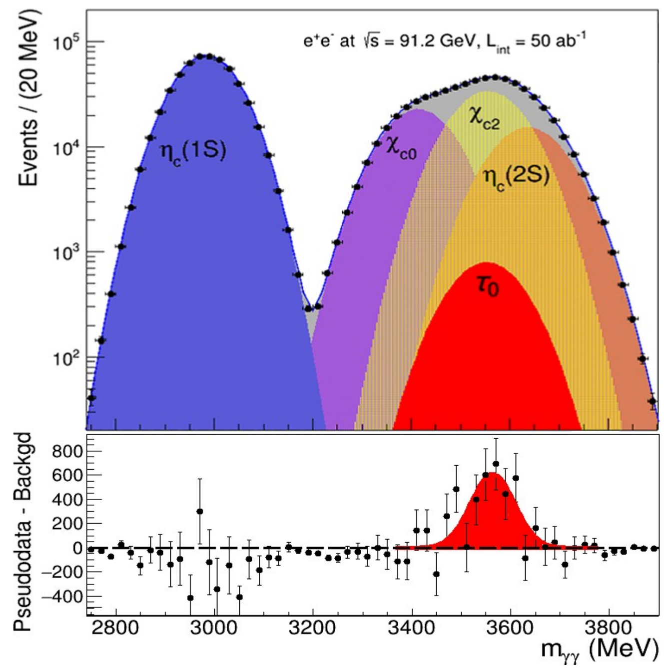
to separate <1mm distances ☹

- 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 ($\mathcal{O}$(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 $\gamma\gamma$-collisions at LHC & e^+e^-:
  - → Ratios of S & B: $\eta_c(1S) : \chi_{c2}(1P) : \chi_{c0}(1P) : \eta_c(2S) : \tau_0 \approx 100 : 50 : 30 : 25 : 1$
  - → FCC-ee(90 GeV, 50 ab^{-1}): 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 $\approx 5\sigma$
- FCC-ee detector requirements:
  - → Need detector with high energy resolution crystal calorimeter: $\delta E_\gamma \approx 2\%$ at $E_\gamma \approx 1.7$GeV
  - → Alternative: mm-vertex γ pointing capabilities (impossible?), or exploit τ_0 Dalitz decays.

Backup slides