FTCF2024
USTC Hefei

The 2024 International Workshop on Future Tau Charm Facilities

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Prospects for ditauonium discovery at colliders

Hua-Sheng Shao

w/ David d'Enterria (arXiv:2202.02316, arXiv:2302.07365)
+ Redamy Perez-Ramos (arXiv:2204.07269)

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LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES

SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

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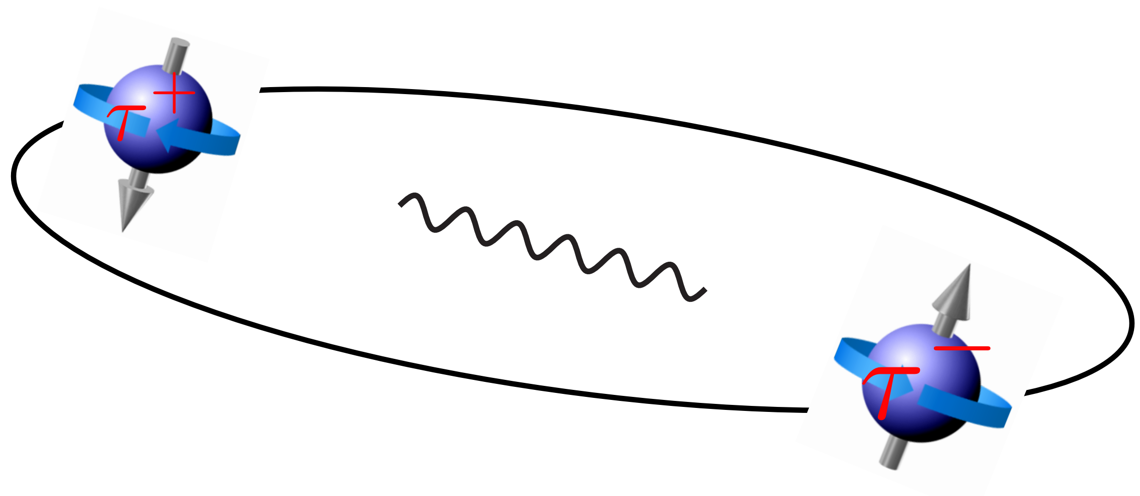
Leptonium: QED atoms

- **Opposite-charge leptons can form onium bound states**
  - Analogous to the hydrogen atom (a proton and an electron)
  - Pure QED interaction (unlike hydrogen atom)

  ⇒ *simplest atoms allow high-precision theory control*

  - Out of 6 possible combinations, only positronium (e^+e^-) and muonium ($\mu^{\pm}e^{\mp}$) have been observed experimentally
- Ditauonium ($\tau^+\tau^-$) is the heaviest and most compact leptononium, which can undergo annihilation decays



Why ditauonium ?

- **The properties of the tau lepton**
  - Precise tau mass determination *(will show you later, promising)*
  - Precise tau width determination *(14-20% via tau decays, not competitive)*
  - Anomalous magnetic dipole moment *(from hfs, challenging, or xs, not competitive)*
- **Precision tests of the Standard Model of particle physics**
  - Precise tests of QED — Karshenboim (Phys. Rept. 05)
  - Basic symmetry test (like CPT as done in positronium but at GeV scale)

    Bernreuther et al. (Z. Phys. C 88), Yamazaki et al. (PRL'10)
- **Direct or indirect sensitives to the BSM effects**
  - BSM effect is enhanced via $\mathcal{O}(m_\ell/\Lambda_{\rm BSM})$
  - Lepton flavour universality violation *(positronium vs dimuonium vs ditauonium)*
  - Tau-philic BSM interactions and particles without missing energy
  - ...

Spectroscopy

Energy levels of ditauonium

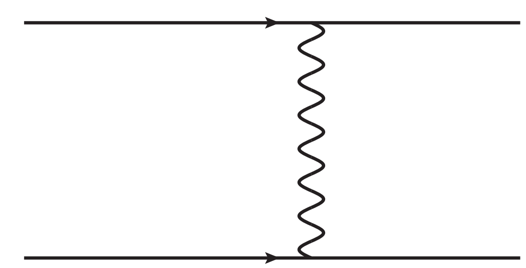
- **The masses of the states**

d'Enterria, Perez-Ramos, HSS (EPJC'22)

  - Determined within non-relativistic quantum mechanics

$n = 3\ (E = -2.6\ \text{keV})$

$n = 2\ (E = -5.9\ \text{keV})$



$$V(r) = -\frac{\alpha}{r}$$

$n = 1\ (E = -23.6\ \text{keV})$

Energy levels of ditauonium

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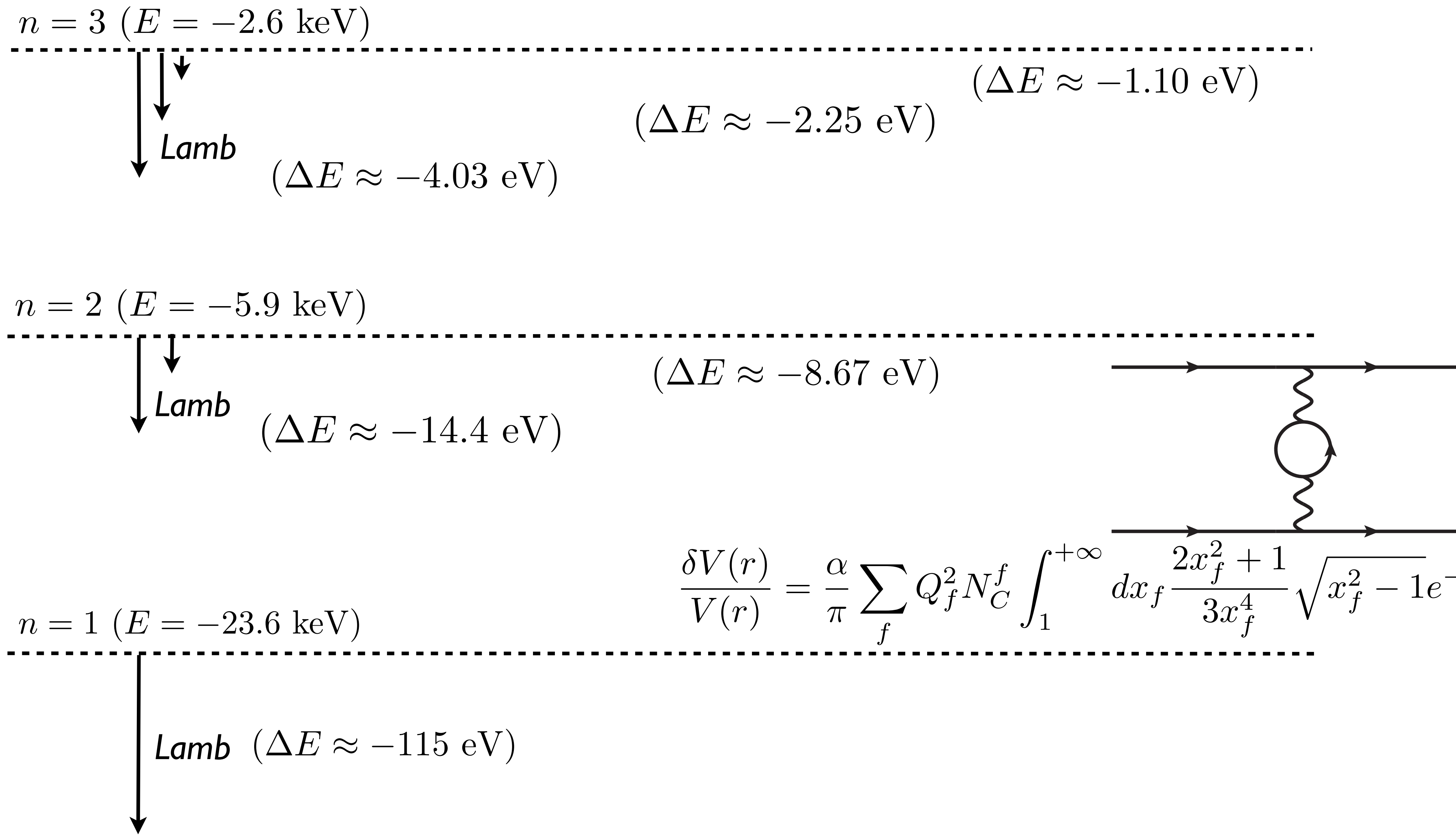

$$\frac{\delta V(r)}{V(r)} = \frac{\alpha}{\pi}\sum_f Q_f^2 N_C^f \int_1^{+\infty} dx_f \frac{2x_f^2+1}{3x_f^4}\sqrt{x_f^2-1}e^{-2m_f x_f r}$$

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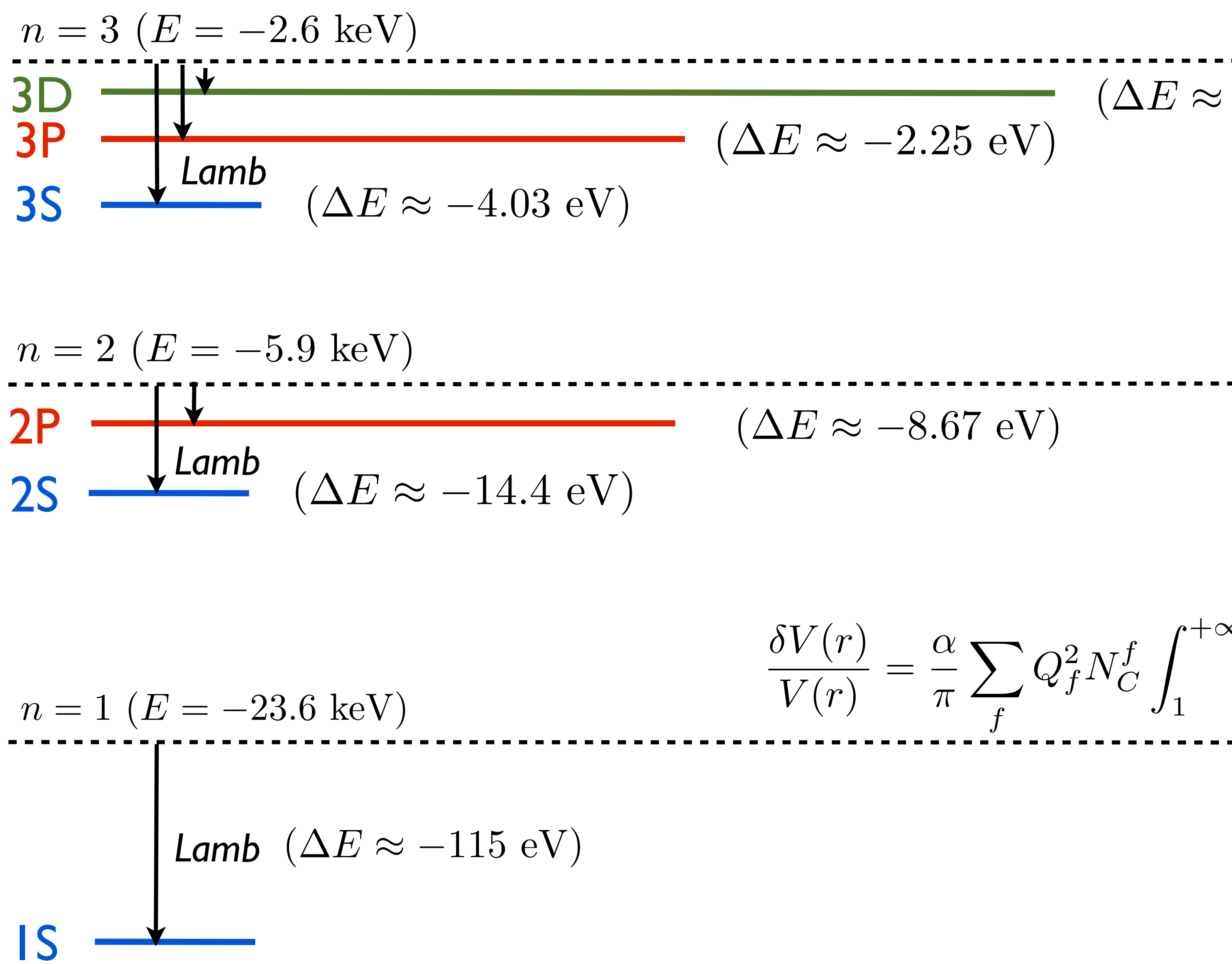

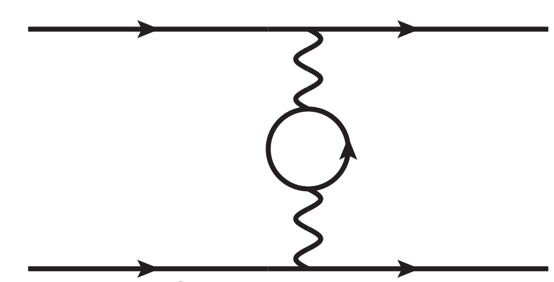

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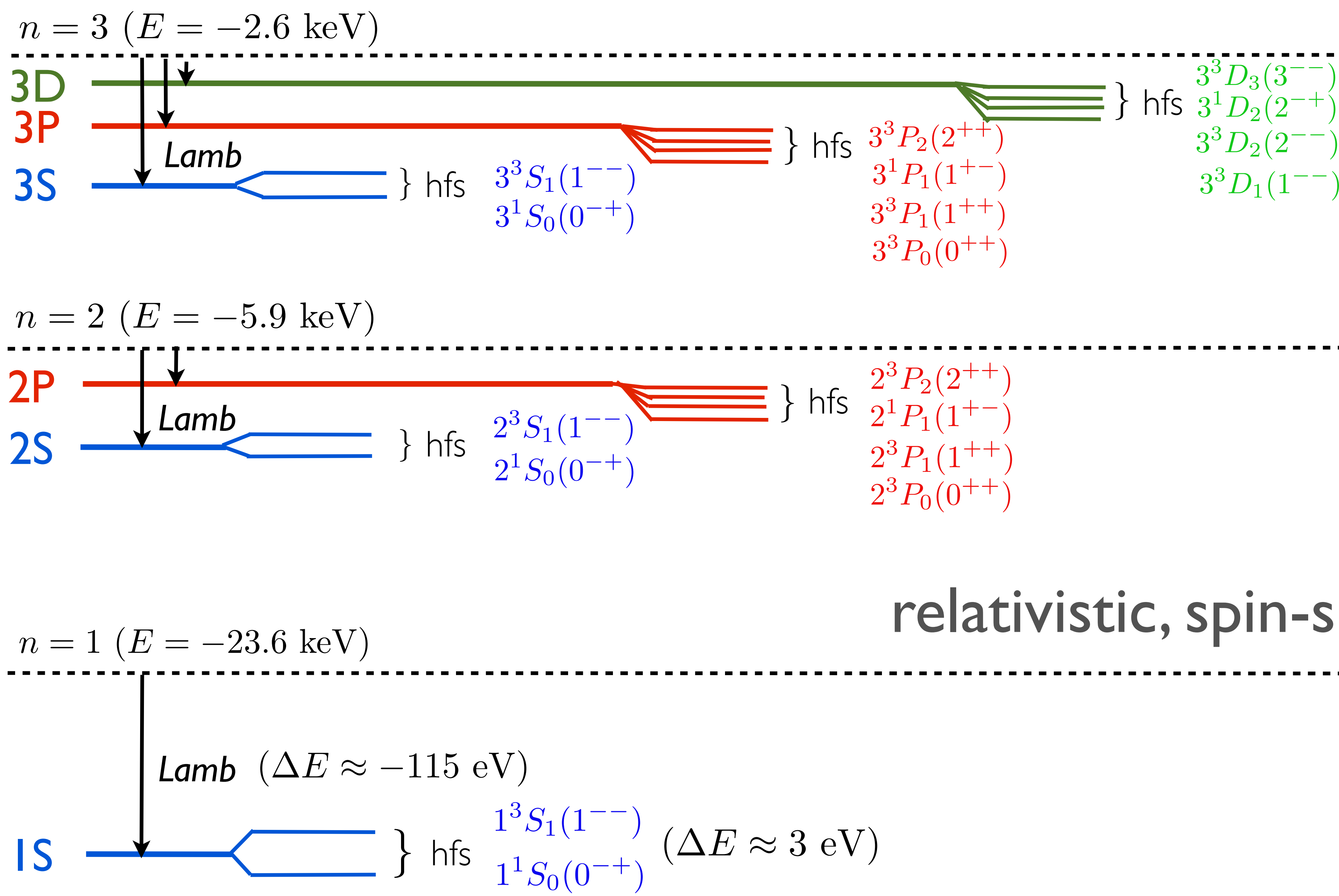


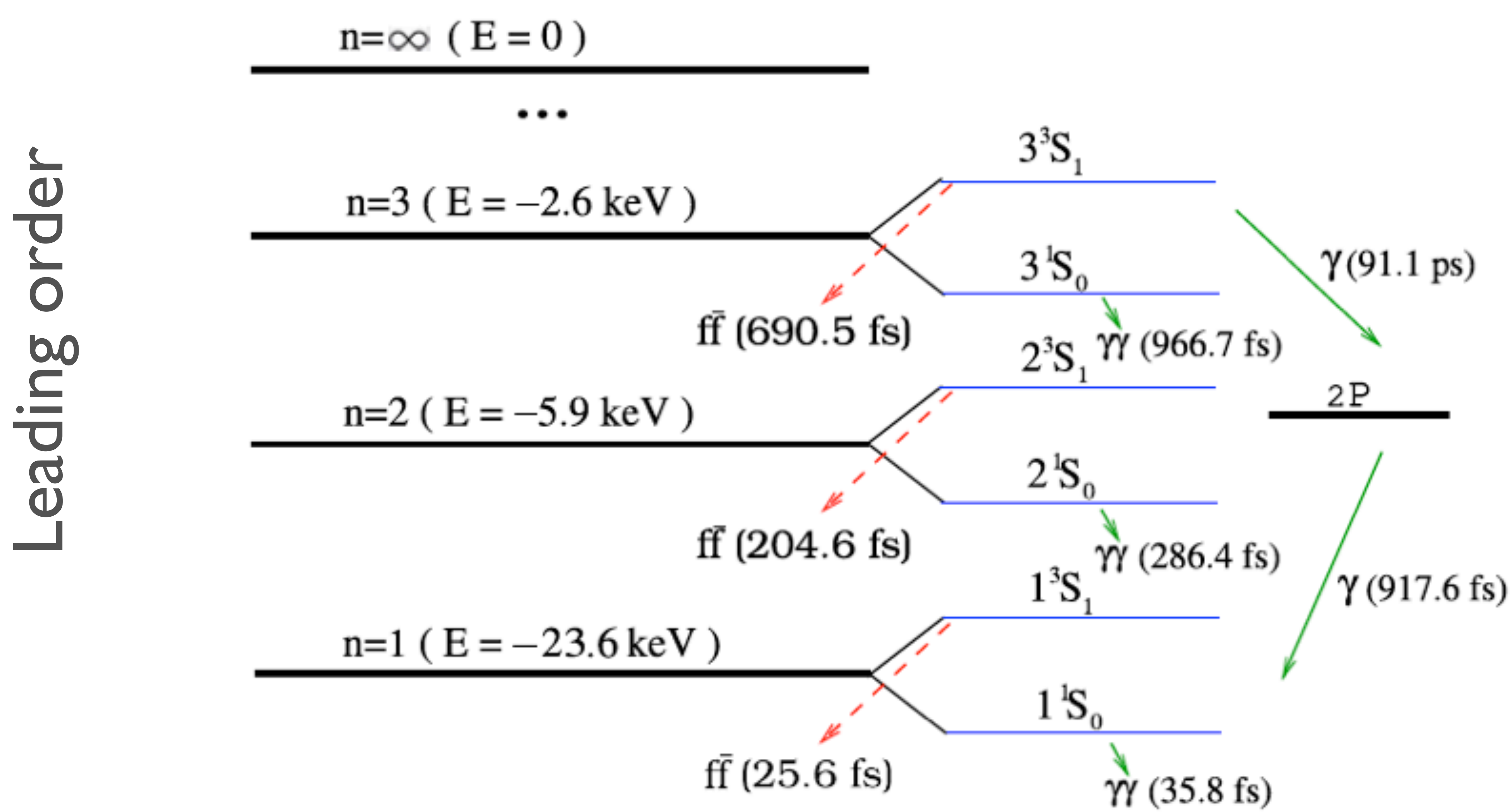
relativistic, spin-spin, LS, ...

Decay channels of ditauonium

- **Which are "real" bound states ?** d'Enterria, Perez-Ramos, HSS (EPJC'22)
  - Only the annihilation decays of the ground states (n=1) are faster than the weak decays of each constitute tau (290 fs)

    ⇨ *We will only focus on n=1 states*
  - Excited states will impact the di-tau cross section at threshold

Fu et al. (2305.00171)



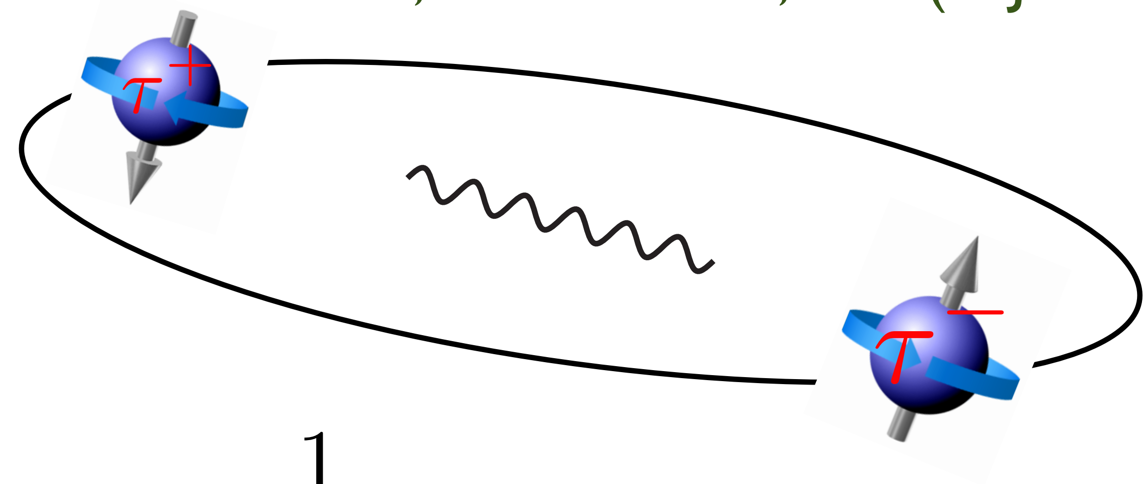
Decay channels of ditauonium

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)**

d'Enterria, Perez-Ramos, HSS (EPJC'22)

$$J^{PC} = 0^{-+}$$

  - Mainly to di-photon
  - Percent-level Dalitz decay
  - 19% tau weak decays



$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

$\mathcal{T}$ state	$m_\mathcal{X}$ (MeV)	J^{PC}	Γ_{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%

Decay channels of ditauonium

- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**

  $J^{PC} = 1^{--}$

  - Mainly to di-fermions
  - 14% tau weak decay

d'Enterria, Perez-Ramos, HSS (EPJC'22)

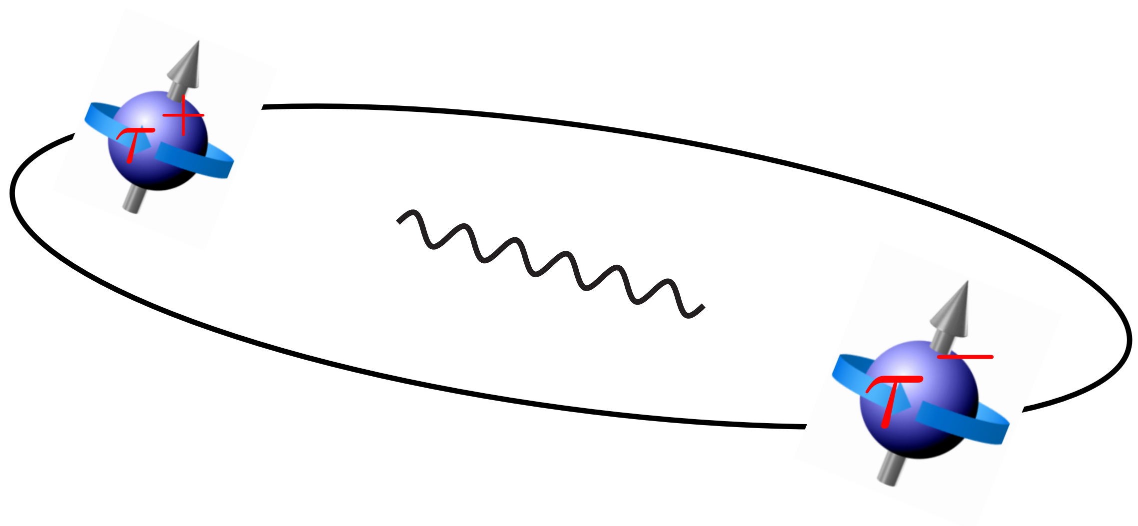
$$|\uparrow\uparrow\rangle$$

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|\downarrow\downarrow\rangle$$

$\mathcal{T}$ state	$m_{\mathcal{X}}$ (MeV)	J^{PC}	Γ_{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%

Prospects of ortho-ditauonium discovery

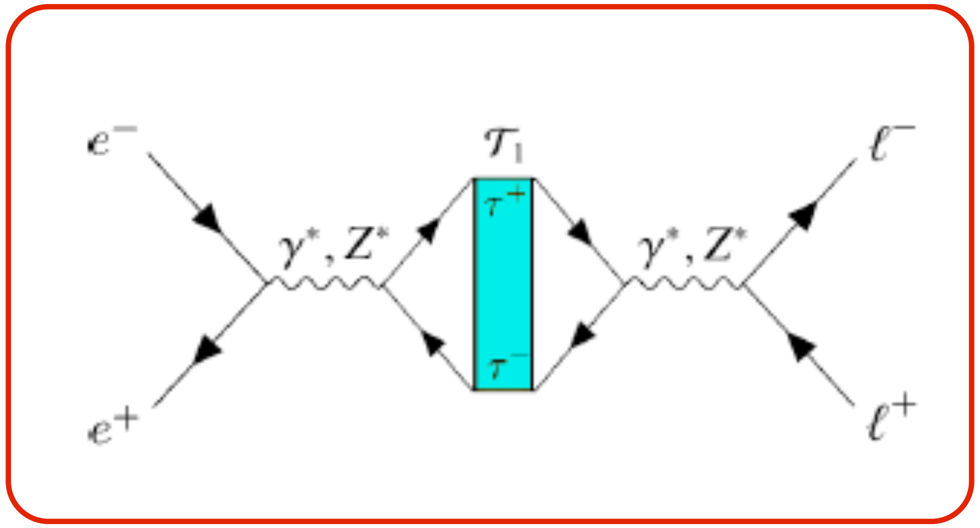


How to observe ditauonium ?

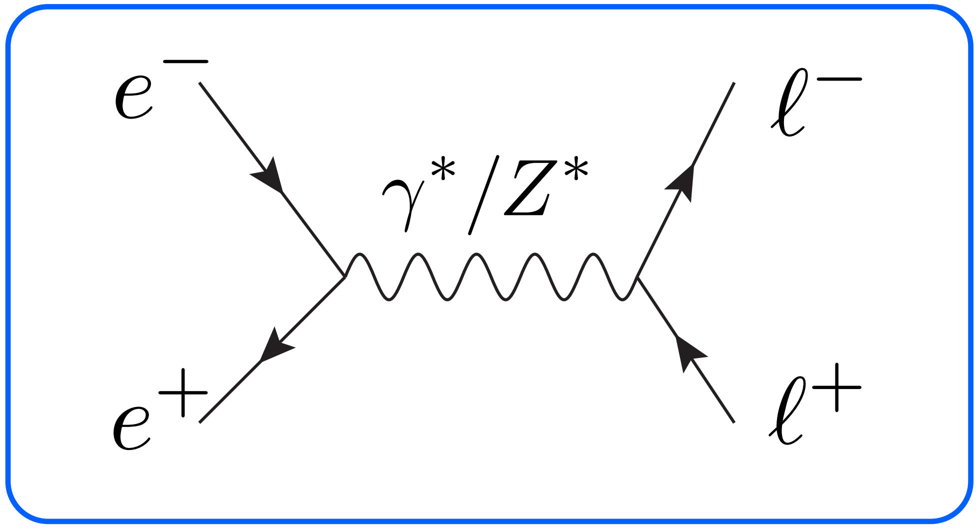
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Threshold scan at e+e-

d'Enterria, HSS (PLB'23)

Signal



Background



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

Huge cross section ! Why not observed yet ?

- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Two important effects are missing ...

    Monochromatization of beam energies

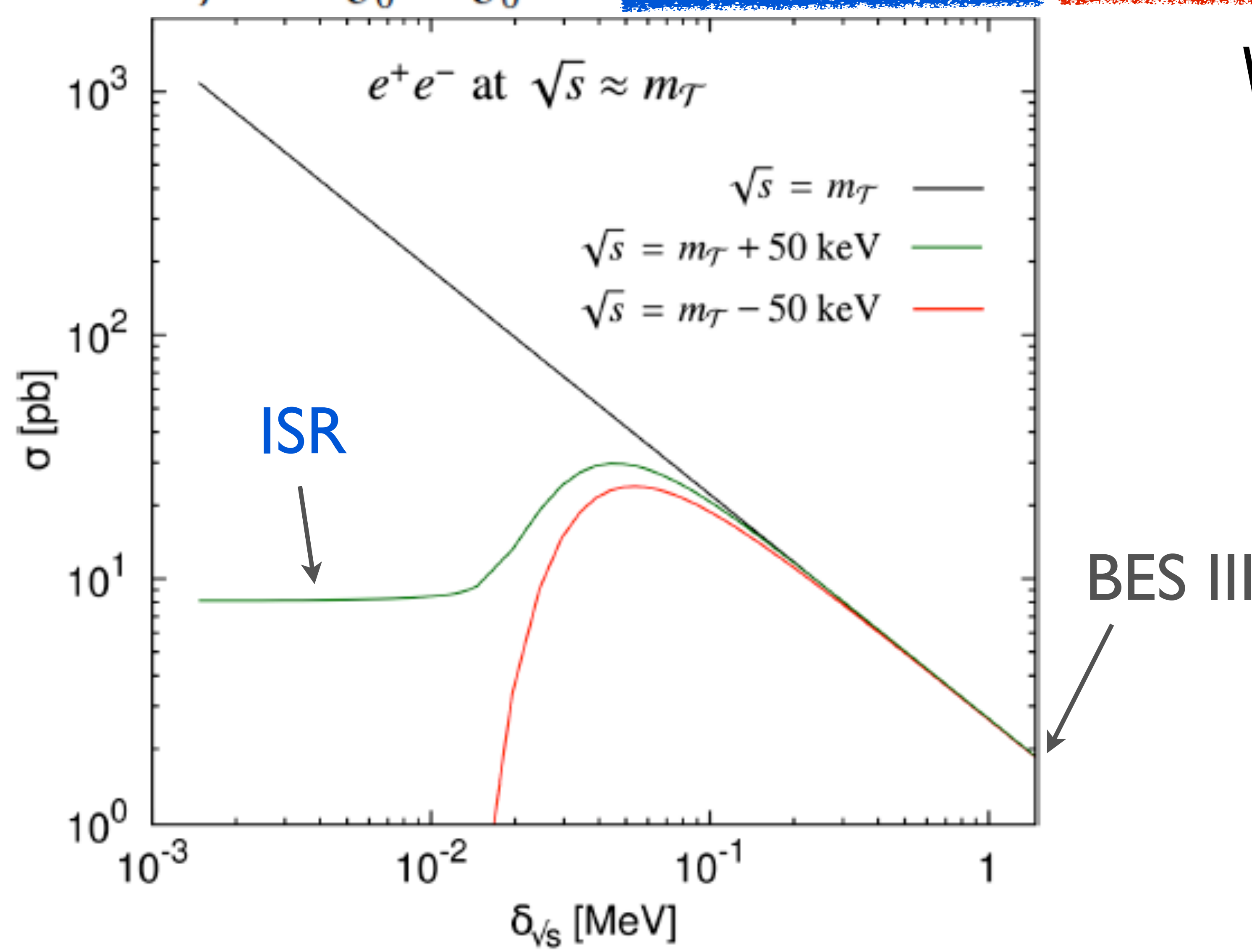
    Initial-state photon radiation (ISR)

d'Enterria, HSS (PLB'23)

ISR energy spread

$$\sigma^{\text{actual}}(e^+e^- \to \mathcal{T}_1) = \frac{12\pi^2\Gamma_{e^+e^-}(\mathcal{T}_1)}{m_{\mathcal{T}}} \int_0^1 dx_1 \int_0^1 dx_2 f_{e^-/e^-}(x_1, s) f_{e^+/e^+}(x_2, s) V_2\left(\sqrt{x_1x_2s}; m_{\mathcal{T}}, \Gamma_{\text{tot}}(\mathcal{T}_1), \sqrt{x_1x_2}\delta_{\sqrt{s}}\right)$$

Voigtian function



Wednesday, January 10, 24

How to observe ditauonium ?

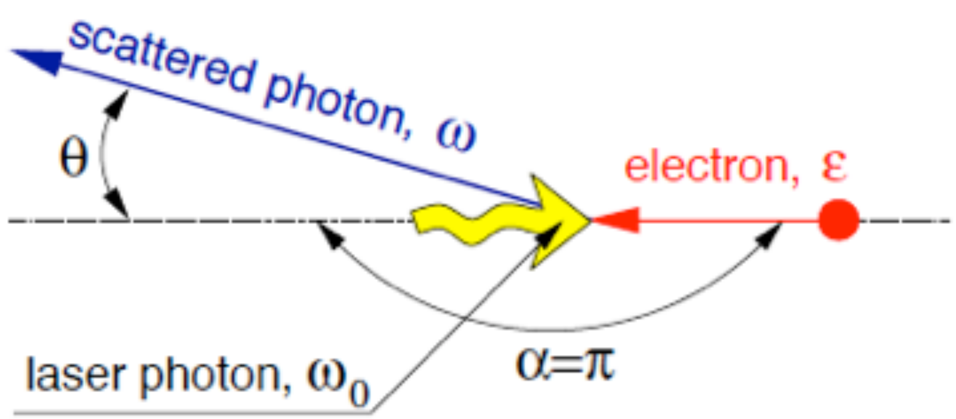
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Larger signal yields requires:

d'Enterria, HSS (PLB'23)

The good accuracy of $\sqrt{s}$ (as close as possible to $m_{\mathcal{T}}$)

Beam energy measurement system at BEPC II allows 2×10^{-5} accuracy

Abakumova et al. (1109.5771)



The applications of the same technique at three different lepton colliders can reach accuracies of the actual c.m. energy not worse than 50 keV. Achasov et al. (JINST'20)

E.g. BEPC II+VEPP-2000

The good precision of $\sqrt{s}$ (as small as possible of $\delta_{\sqrt{s}}$)

Monochromatization has been studied in the literature since Renieri in 1975 for ADONE.

Active studies in the FCC-ee community (see a recent talk by A. Faus-Golfe)

Possible to reach $\delta_{\sqrt{s}} = 50\ \mathrm{keV}$, but the price to pay is the reduction of the integrated luminosity

How to observe ditauonium ?

- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Threshold scan at e+e-

d'Enterria, HSS (PLB'23)

Colliding system, $\sqrt{s}$ ($\delta_{\sqrt{s}}$ spread), $\mathcal{L}_{\rm int}$, experiment	σ			N			$S/\sqrt{B}$
	$\mathcal{T}_1$	$\tau^+\tau^-$	$\mu^+\mu^-$	$\mathcal{T}_1$	$\mathcal{T}_1 \to \mu^+\mu^-$	$\mu^+\mu^-$	
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

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d'Enterria, HSS (PLB'23)

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- Ortho-ditauonium can be observed at STCF without monochromatization
- With monochromatization to $\delta_{\sqrt{s}} = 100$ keV and 10 times smaller luminosity, we can use ditauonium to precisely determine the mass of the tau lepton

How to observe ditauonium ?

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  - Threshold scan at e+e-

d'Enterria, HSS (PLB'23)

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- Ortho-ditauonium can be observed at STCF without monochromatization
- With monochromatization to $\delta_{\sqrt{s}} = 100$ keV and 10 times smaller luminosity, we can use ditauonium to precisely determine the mass of the tau lepton
- Ditauonium contributes 2% (50%) of the di-tau cross section w/o (w/) beam energy monochromatization.

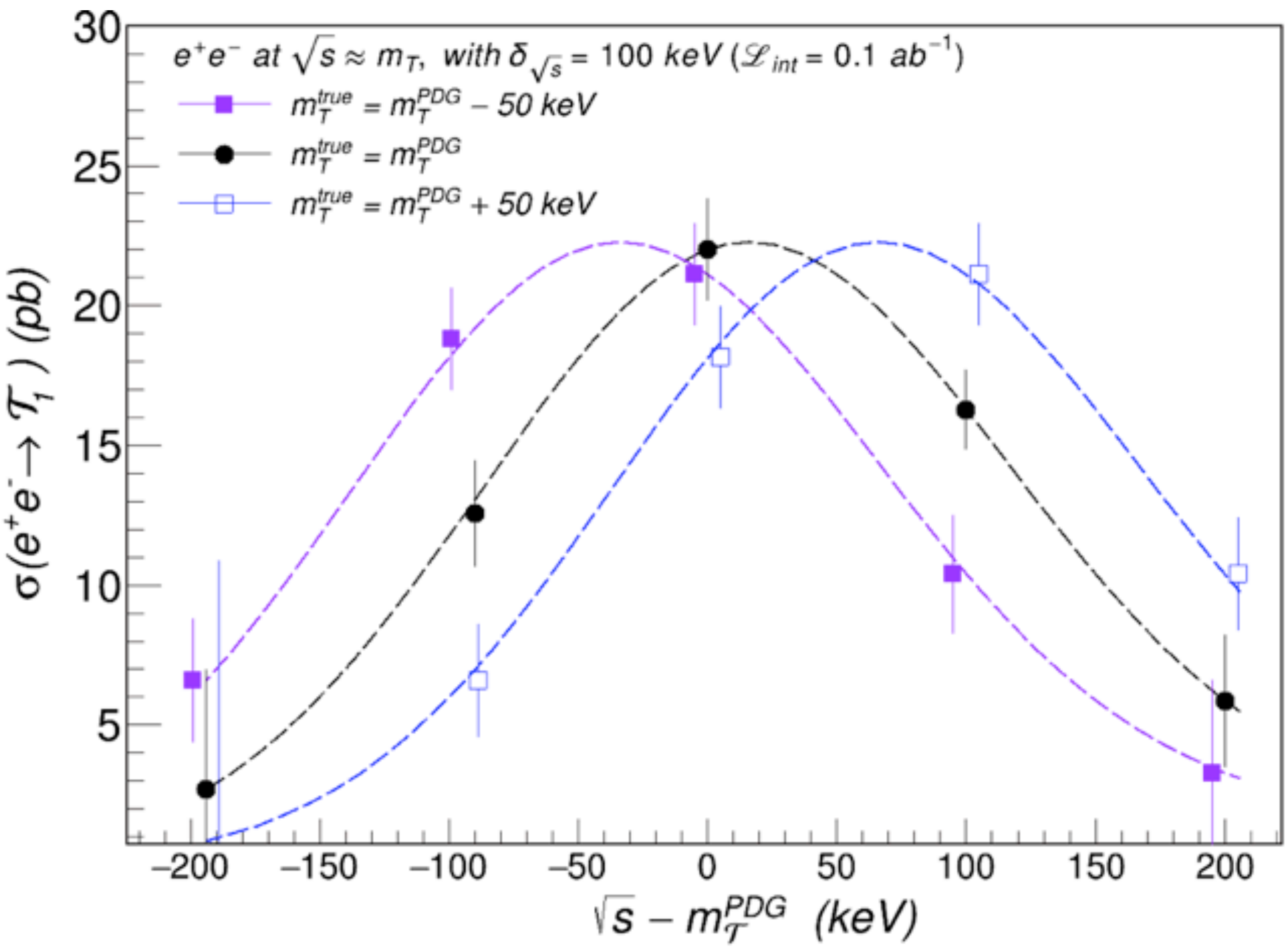
How to observe ditauonium ?

- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Threshold scan at e+e-

d'Enterria, HSS (PLB'23)

    - As a bonus of the ditauonium observation, we can also precisely determine the mass of the tau lepton with monochromatization

$$m_\tau = (m_\mathcal{T} - E_{\text{bind}})/2 \longrightarrow \delta m_\tau = 25 \text{ keV}$$



How to observe ditauonium ?

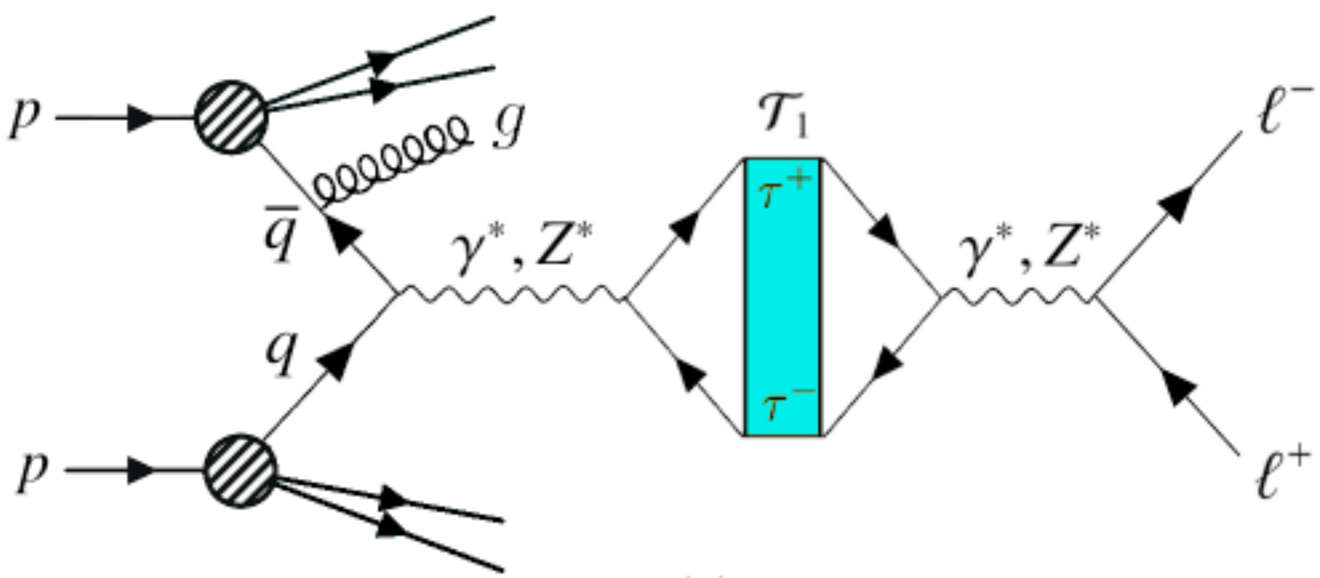
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Exploring other possibilities

d'Enterria, HSS (PLB'23)

$$pp \to \mathcal{T}_1 + j \text{ @ LHC}$$

Using displaced vertex to kill huge backgrounds

Remaining challenge: combinatorial backgrounds (mainly from heavy quark decays)



Colliding system, $\sqrt{s}$, $\mathcal{L}_{\text{int}}$, detector	σ_{NLO}		$N(\mathcal{T}_1 + j)$		with $L_{xy} > 30\,(100)\,\mu\text{m}$	
	$\mathcal{T}_1 + X$	$\mathcal{T}_1 + j$	$\mathcal{T}_1 \to e^+e^-$	$\mathcal{T}_1 \to \mu^+\mu^-$	$\mathcal{T}_1 \to \ell^+\ell^-$	$\mathcal{T}_1 \to \mu^+\mu^-$
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	–	–

How to observe ditauonium ?

- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Exploring other possibilities

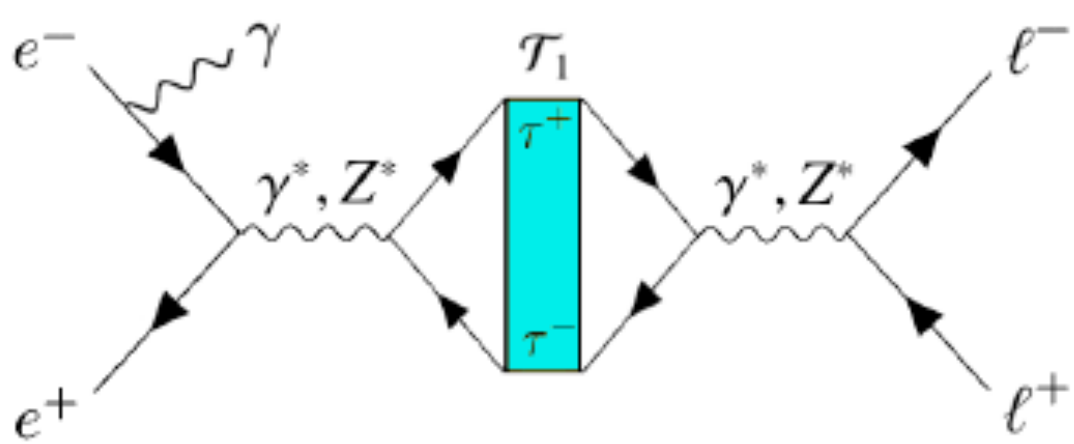
d'Enterria, HSS (PLB'23)

$$e^+e^- \to \mathcal{T}_1 + \gamma \text{ @ Belle II}$$

Using displaced vertex to kill huge backgrounds

If L_{xy} > 15 (20) μm, the total expected number of events would be 8 (4).

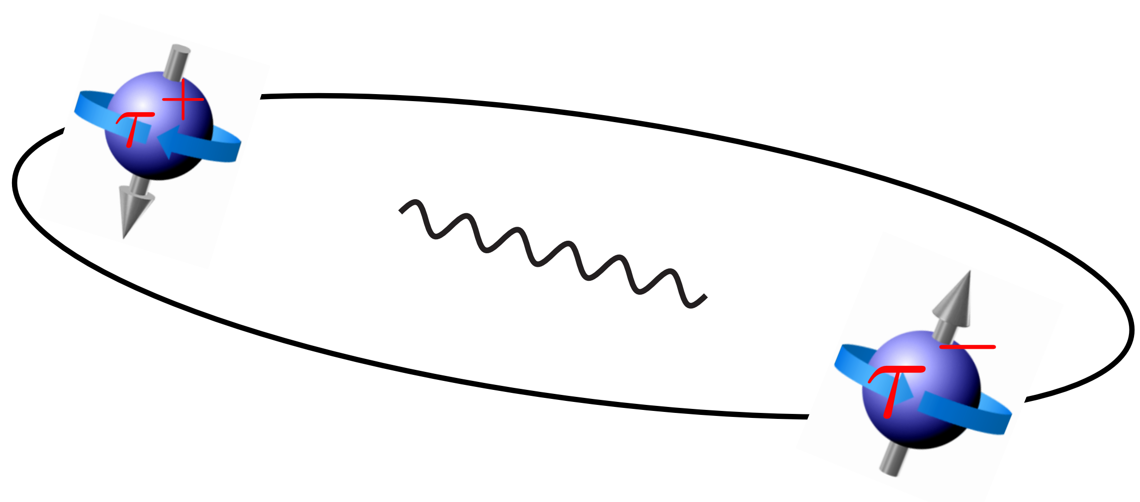
Remaining challenge: instrumental effects.



$$10^\circ < \theta^{\text{lab}}_{\ell^\pm,\gamma} < 170^\circ \qquad m_{\ell^+\ell^-} \in (m_{\mathcal{T}} \pm 5 \text{ MeV})$$

Colliding system, $\sqrt{s}$, $\mathcal{L}_{\text{int}}$, detector	σ			$N(\mathcal{T}_1+\gamma)$		with $L_{xy} > 30\ \mu$m	
	$\mathcal{T}_1+\gamma$	$\mu^+\mu^-+\gamma$	$e^+e^-+\gamma$	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	e^+e^-
e^+e^- at 10.6 GeV, 50 ab^{-1}, Belle II	7.1 ab	51 fb	1.9 pb	73	73	0.5	0.5

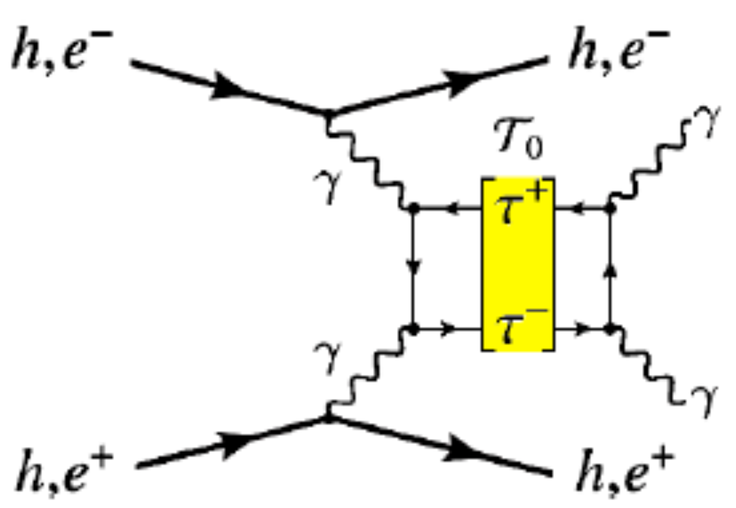
Prospects of para-ditauonium discovery



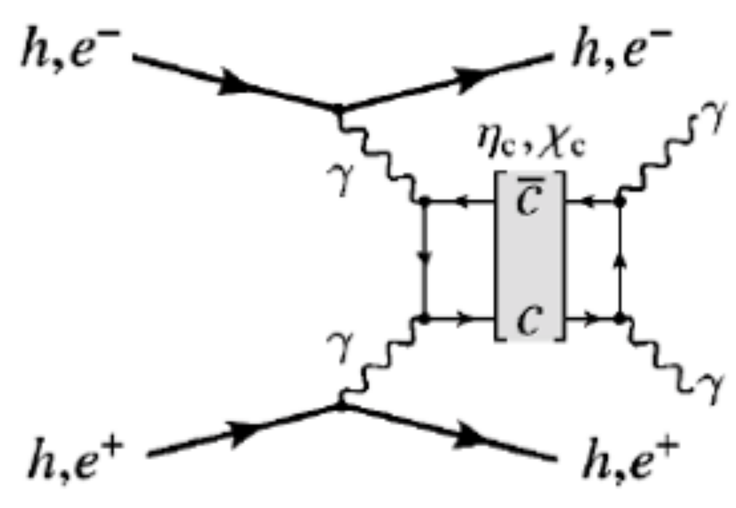
How to observe ditauonium ?

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)** d'Enterria, HSS (PRD'22)

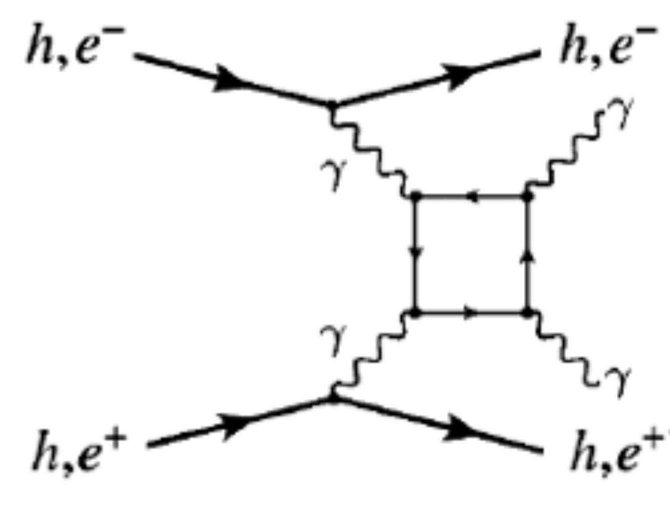
Signal



C-even charmonium



Light-by-Light



- Cross sections for signal and backgrounds are simulated with the equivalent-photon approximation (EPA)
- For e+e-, we used the well-known improved Weizsacker-Williams function
- For hadron-hadron, we considered the ultra-peripheral collisions, where the initial hadrons are intact

⇨ **gamma-UPC** d'Enterria, HSS (JHEP'22)

How to observe ditauonium ?

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)** d'Enterria, HSS (PRD'22)
  - Cross sections for resonances are computed with HELAC-Onia HSS (CPC'13,CPC'16)
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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

- Cross sections increase with center-of-mass energy and Z^4
- Large charmonium background

$$\sigma(\eta_c(1S)) : \sigma(\chi_{c2}(1P)) : \sigma(\chi_{c0}(1P)) : \sigma(\eta_c(2S)) : \sigma(\mathcal{T}_0)$$

100 : 50 : 30 : 25 : 1

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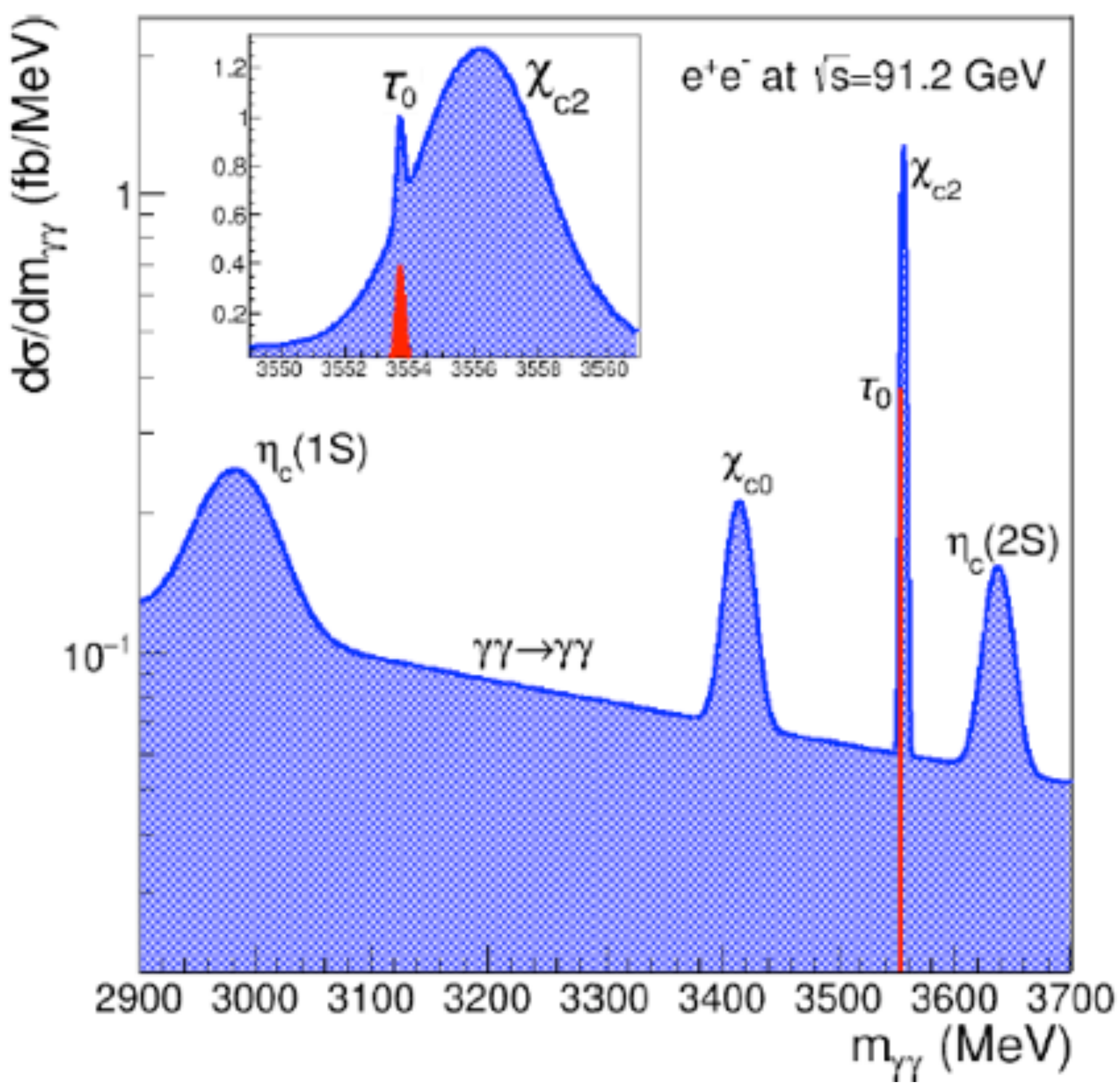
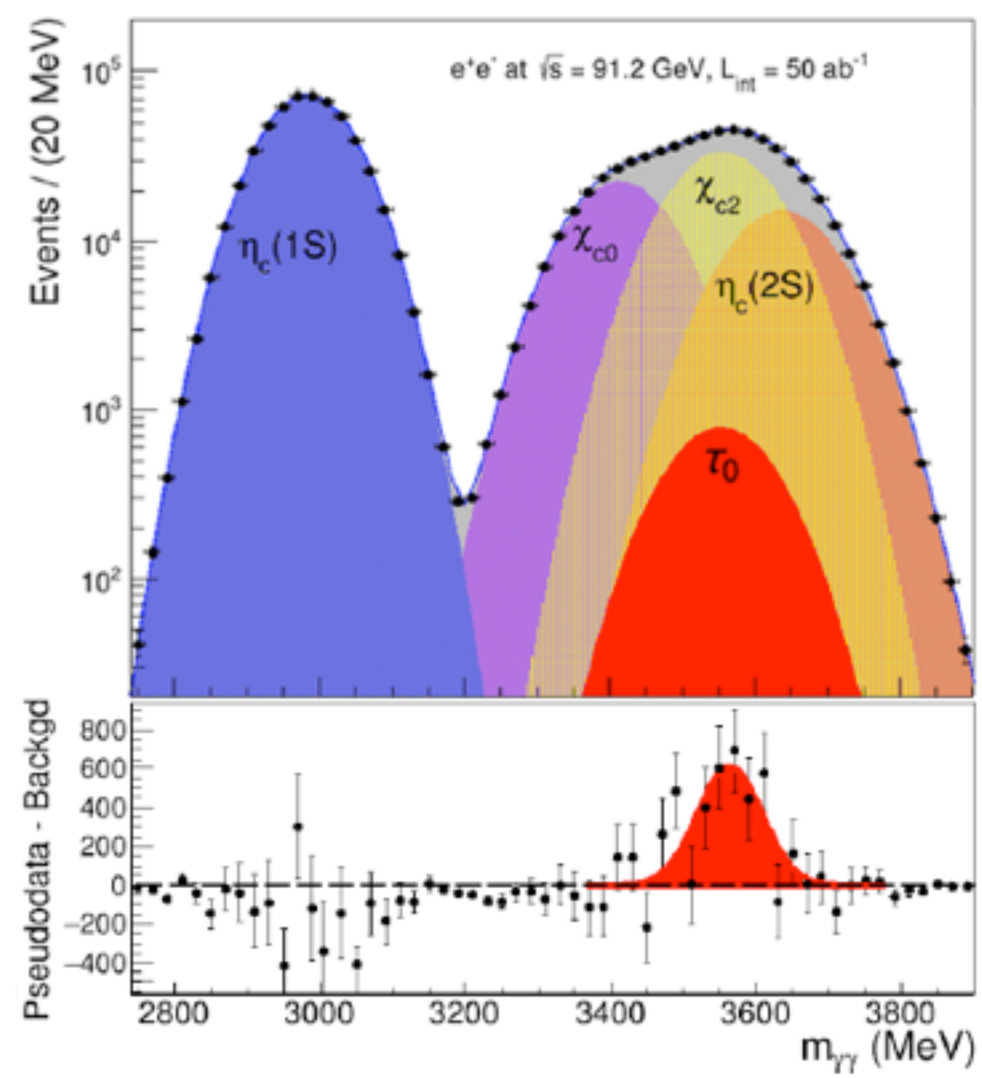
How to observe ditauonium ?

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)** d'Enterria, HSS (PRD'22)
  - Trigger: two back-to-back exclusive 1.5-2 GeV photons w/ $m_{\gamma\gamma} \approx m_{\mathcal{T}_0}$
  - Reconstruction performance (Belle-II type & high-resolution FCC-ee crystal calo)

Acceptance: $10^\circ < \theta_\gamma < 170^\circ$ *Mass resolution:* $\sim 2\%$ *Photon reco effic.:* $\sim 100\%$

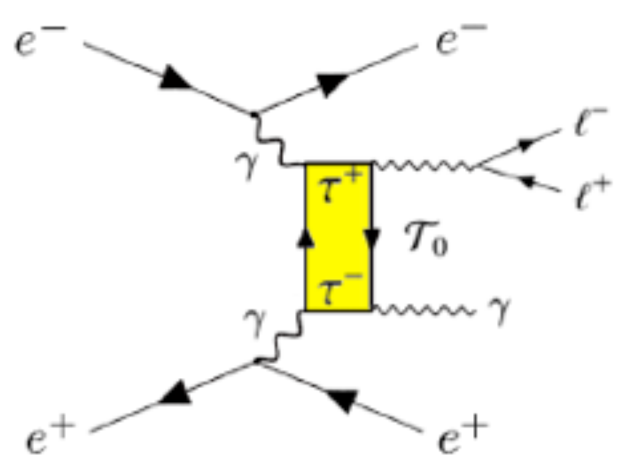




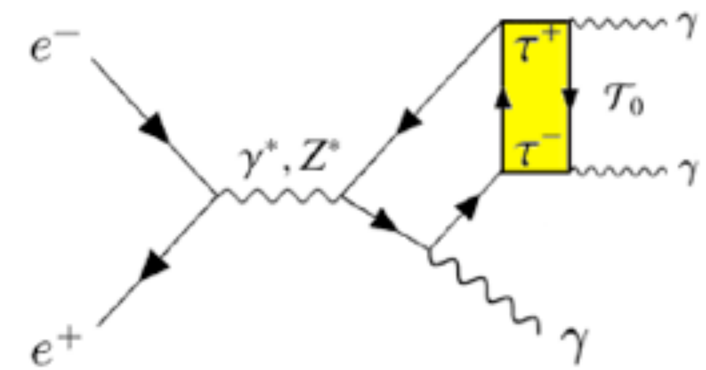
How to observe ditauonium ?

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)** d'Enterria, HSS (PRD'22)
  - Significance
    FCC-ee 5σ
    Belle II 3σ
  - Main challenge
    Control the lineshapes of charmonia, in particular χ_{c2}
  - We consider other possibilities, but turn out to be challenging

Dalitz decay



FSR photon



	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
$\mathrm{Br}(\Upsilon(nS) \to \gamma \mathcal{T}_0) =$	5.4×10^{-12}	3.7×10^{-12}	4.0×10^{-12}

Wednesday, January 10, 24

Conclusion

- Ditauonium can provide an interesting probe to study several aspects of particle physics.
- In QED, we can predict its energy levels and decay channels precisely.
- Its observation feasibilities at colliders have been explored.

$$e^+e^- \to \mathcal{T}_1 \to \mu^+\mu^- \ @ \ \mathrm{STCF}$$

$$pp \to \mathcal{T}_1 j \to \mu^+\mu^- j \ @ \ \mathrm{LHC}$$

$$\gamma\gamma \to \mathcal{T}_0 \to \gamma\gamma \ @ \ \mathrm{FCC-ee} \ \& \ \mathrm{Belle\ II}$$

- With beam monochromatization, ditauonium at STCF can in fact allow a precise determination of the mass of tau lepton at O(25 keV)

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- In QED, we can predict its energy levels and decay channels precisely.

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$$e^+e^- \to \mathcal{T}_1 \to \mu^+\mu^- \text{ @ STCF}$$

$$pp \to \mathcal{T}_1 j \to \mu^+\mu^- j \text{ @ LHC}$$

$$\gamma\gamma \to \mathcal{T}_0 \to \gamma\gamma \text{ @ FCC} - \text{ee \& Belle II}$$

- With beam monochromatization, ditauonium at STCF can in fact allow a precise determination of the mass of tau lepton at O(25 keV)

Thank you for your attention !

Backup Slides

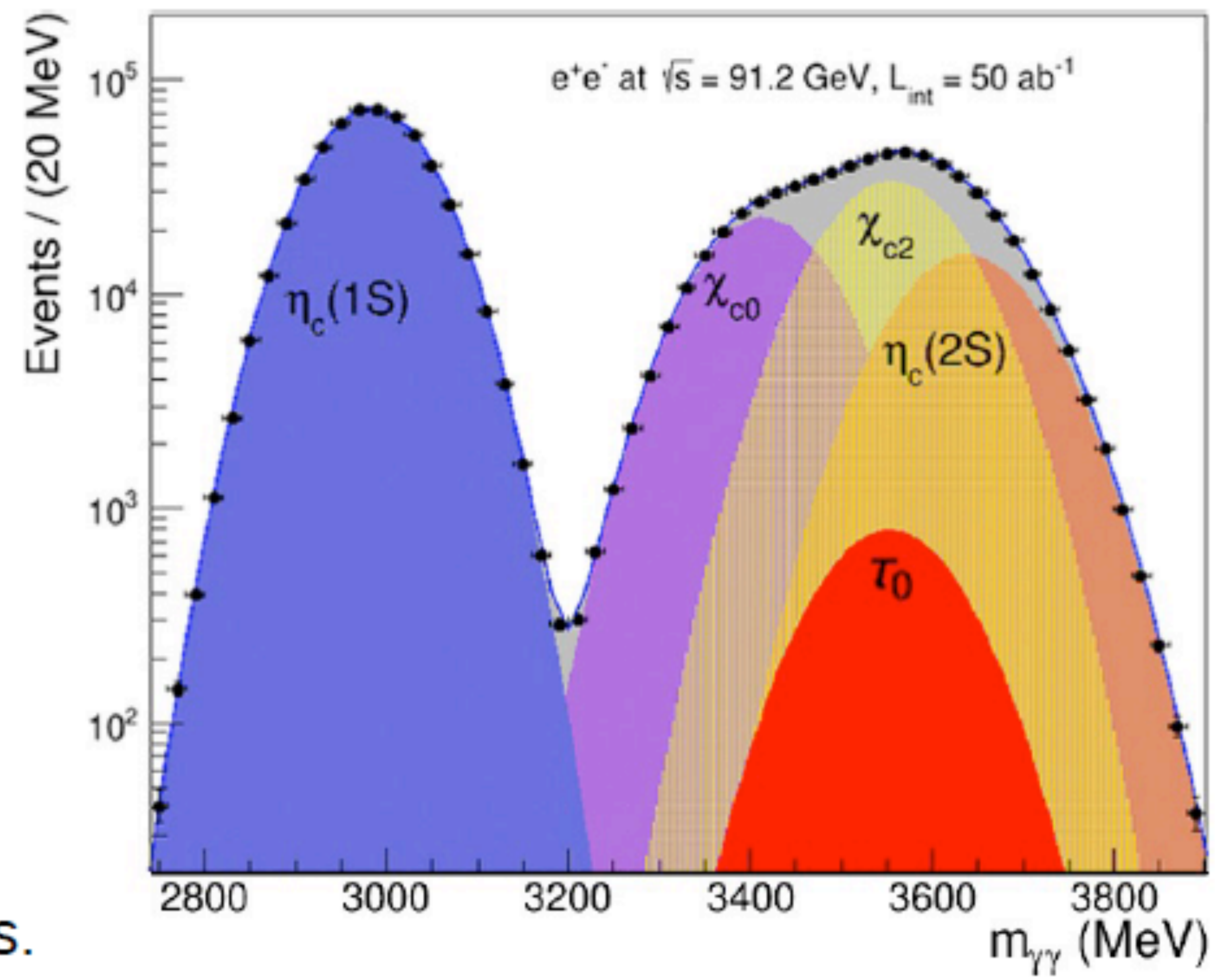
How to observe ditauonium ?

d'Enterria, HSS (PRD'22)

- 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)

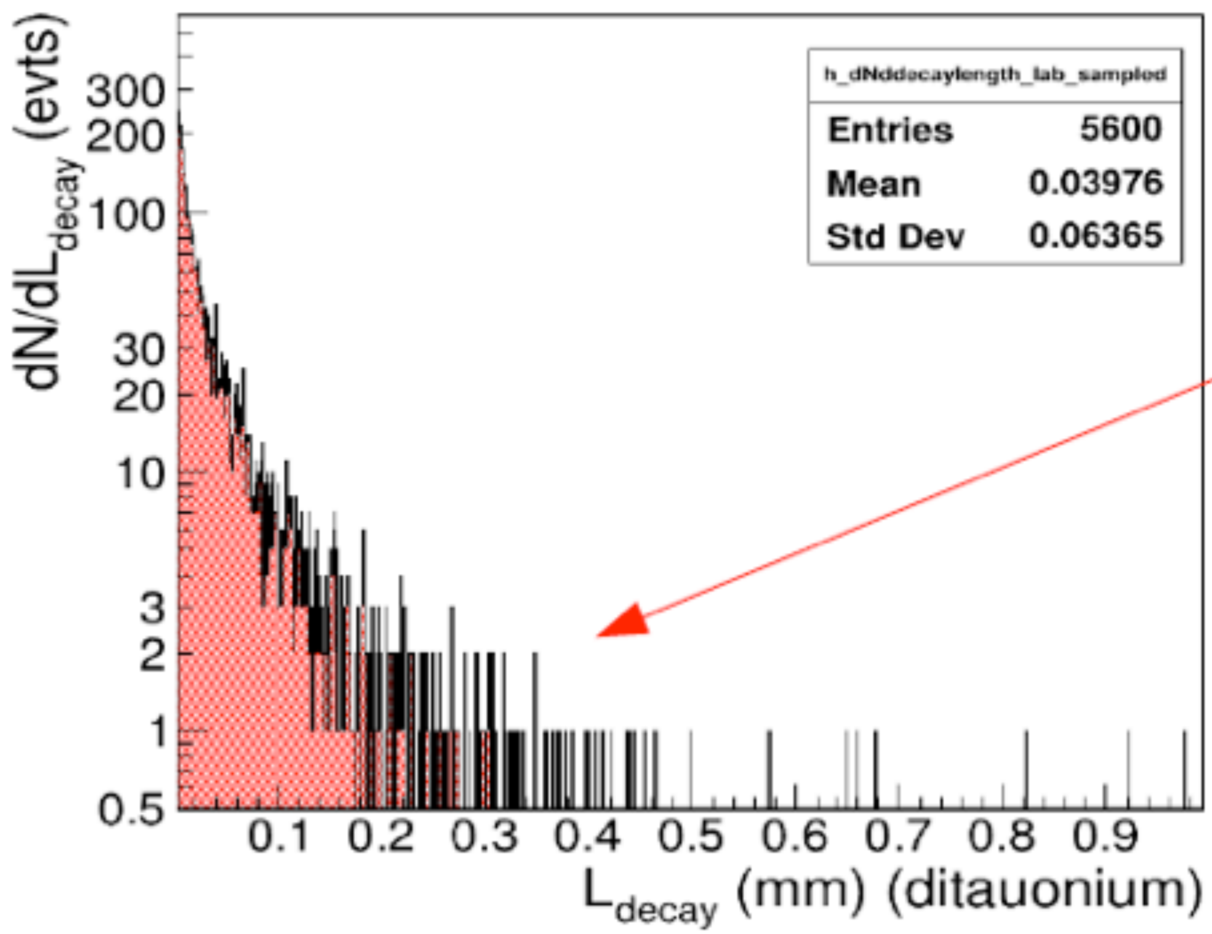
- Signal extracted through multi-Gaussian $m_{\gamma\gamma}$ fit, by considering:
  - → $\eta_c(1S)$: No overlap w/ signal ("std.candle"): 0.5M clean evts to fully control E_γ scale&res. plus exp. & theory uncertainties.
  - → χ_{c0}, $\eta_c(2S)$: Partial overlap with signal. Exploit ~100M $\gamma\gamma \to \chi_{c0}, \eta_c \to X$ decays with ×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)



How to observe ditauonium ?

- **The spin-singlet state (para-ditauonium $\mathcal{T}_0$)** d'Enterria, HSS (PRD'22)
  - Whereas the charmonium resonances decay directly from the IP, the $\mathcal{T}_0$ has a proper lifetime of 28 fs, i.e. a decay length 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 ($\beta\gamma \approx 0.06$) ☹