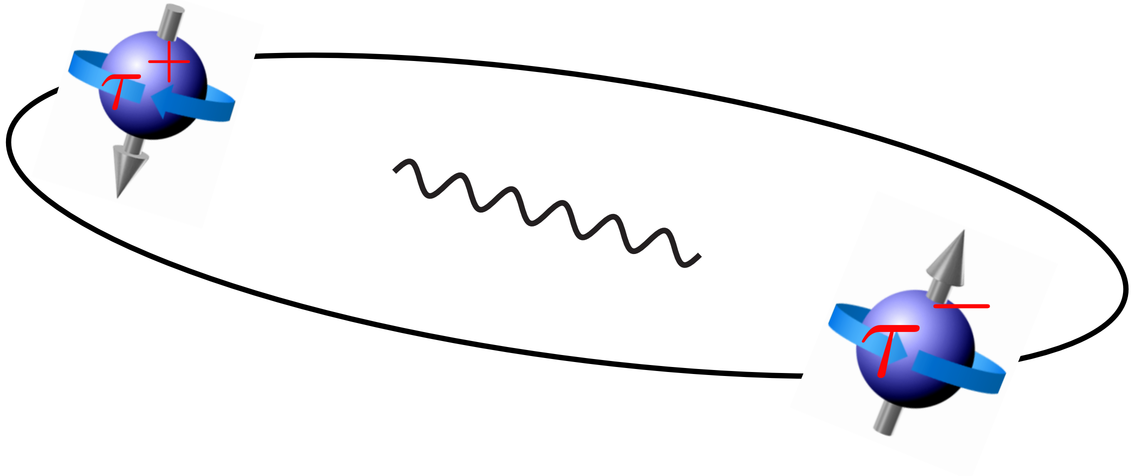
粒子物理与原子核物理
Particle and Nuclear Physics, Department of Modern Physics of USTC

Ditauonium



Hua-Sheng Shao

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

cnrs
LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES
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USTC Seminar
14 April 2023

Outline of the talk

- **Introduction**
- **Spectroscopy**
- **Discovery potential of para-ditauonium**
- **Discovery potential of ortho-ditauonium**
- **Conclusion**

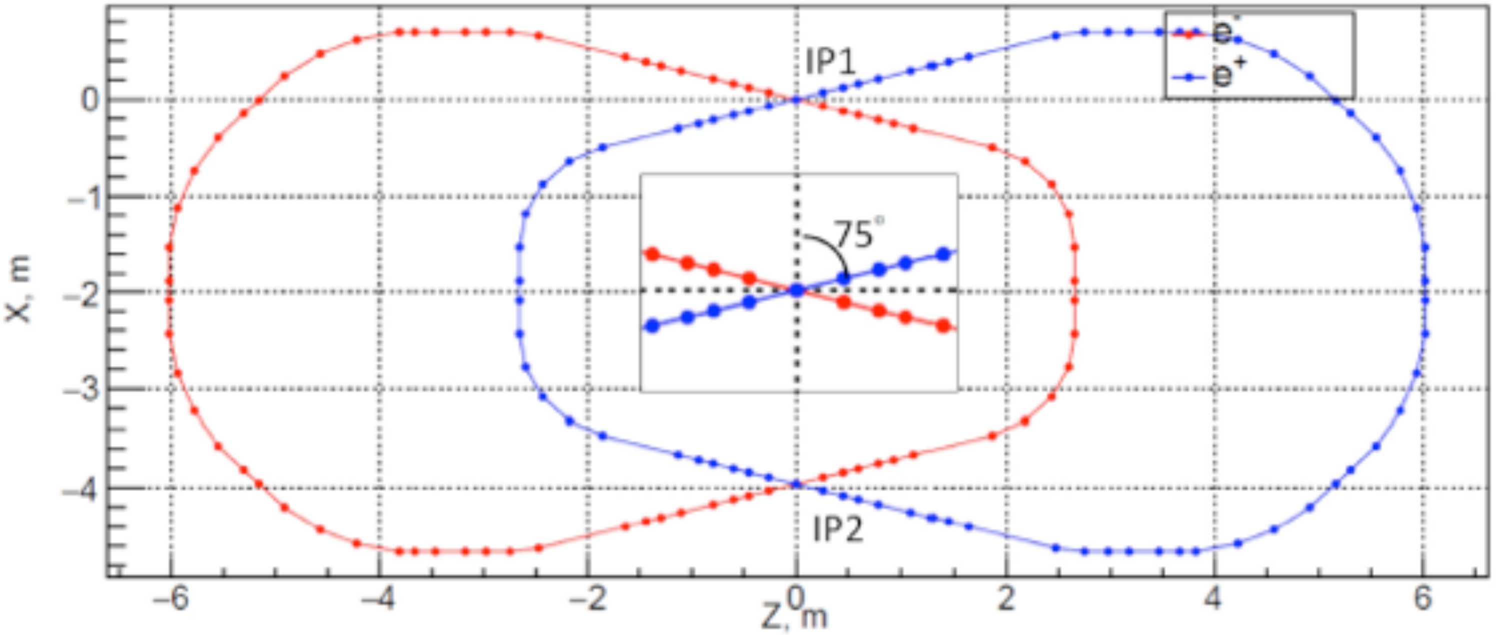
Introduction

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
  - Dimuonium ($\mu^+\mu^-$) has been proposed to look for in the dedicated e+e- machines with the intersecting storage rings (Crab Waist)



Novosibirsk (1708.05819), Fermilab DIMUS (2203.07144)

... + other proposals:

η meson decay at LHCb

Cid Vidal et al. (PRD19)

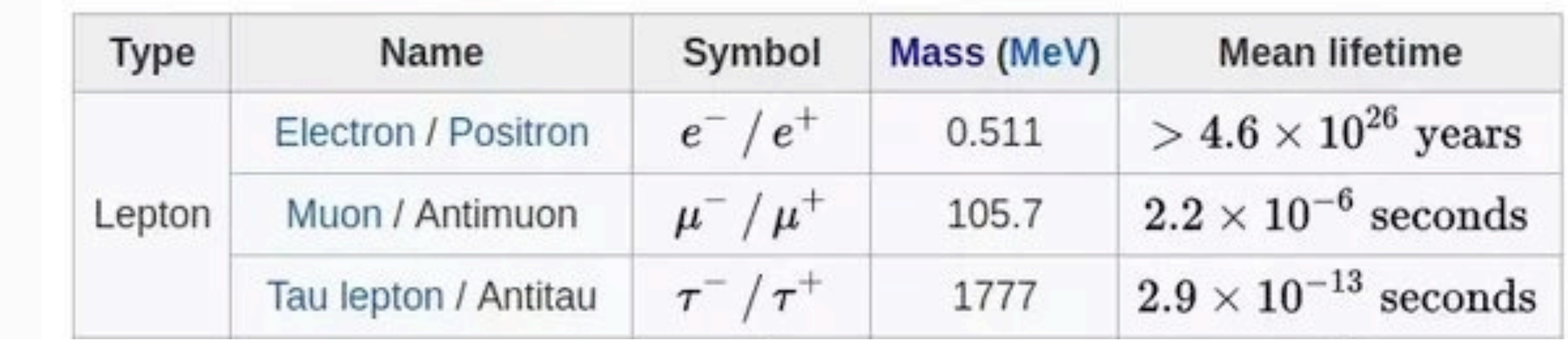
Fixed-target experiments

Lamm and Ji. (1712.03429)

Main background: pions

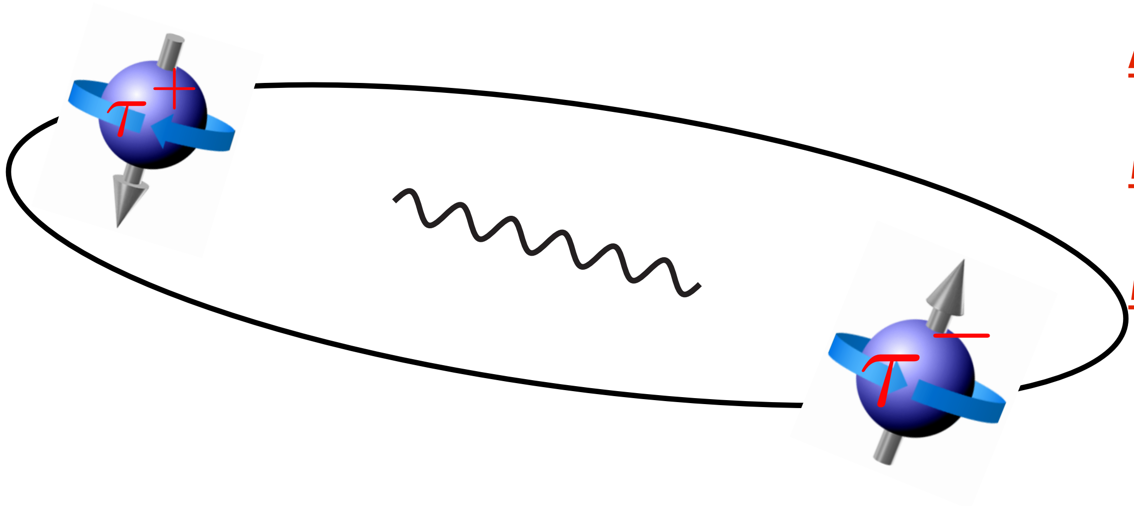
Leptonium: QED atoms

- **Opposite-charge leptons can form onium bound states**
  - Unlike electron and muon, tau lepton is heaviest and also has a shortest lifetime



Type	Name	Symbol	Mass (MeV)	Mean lifetime
Lepton	Electron / Positron	e^- / e^+	0.511	$> 4.6 \times 10^{26}$ years
	Muon / Antimuon	μ^- / μ^+	105.7	2.2×10^{-6} seconds
	Tau lepton / Antitau	τ^- / τ^+	1777	2.9×10^{-13} seconds

- Both $(\tau^\pm e^\mp)$ and $(\tau^\pm \mu^\mp)$ cannot form real bound states before tau decays, though some bound-state effects may exist
- Ditauonium $(\tau^+\tau^-)$ is the heaviest and most compact leptononium, which can undergo annihilation decays



Mass: 3553.696 MeV

Bohr radius : 30.4 fm (x3500 smaller than positronium)

Rydberg const (γ ionisation) : 3.76 keV

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

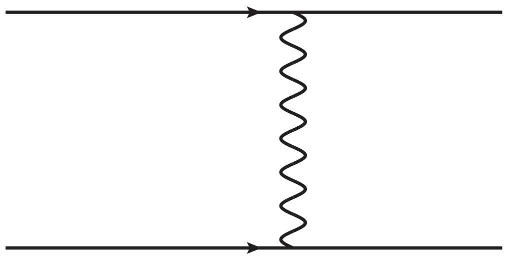
- **The masses of the states**

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

  - Determined within non-relativistic quantum mechanics

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

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



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

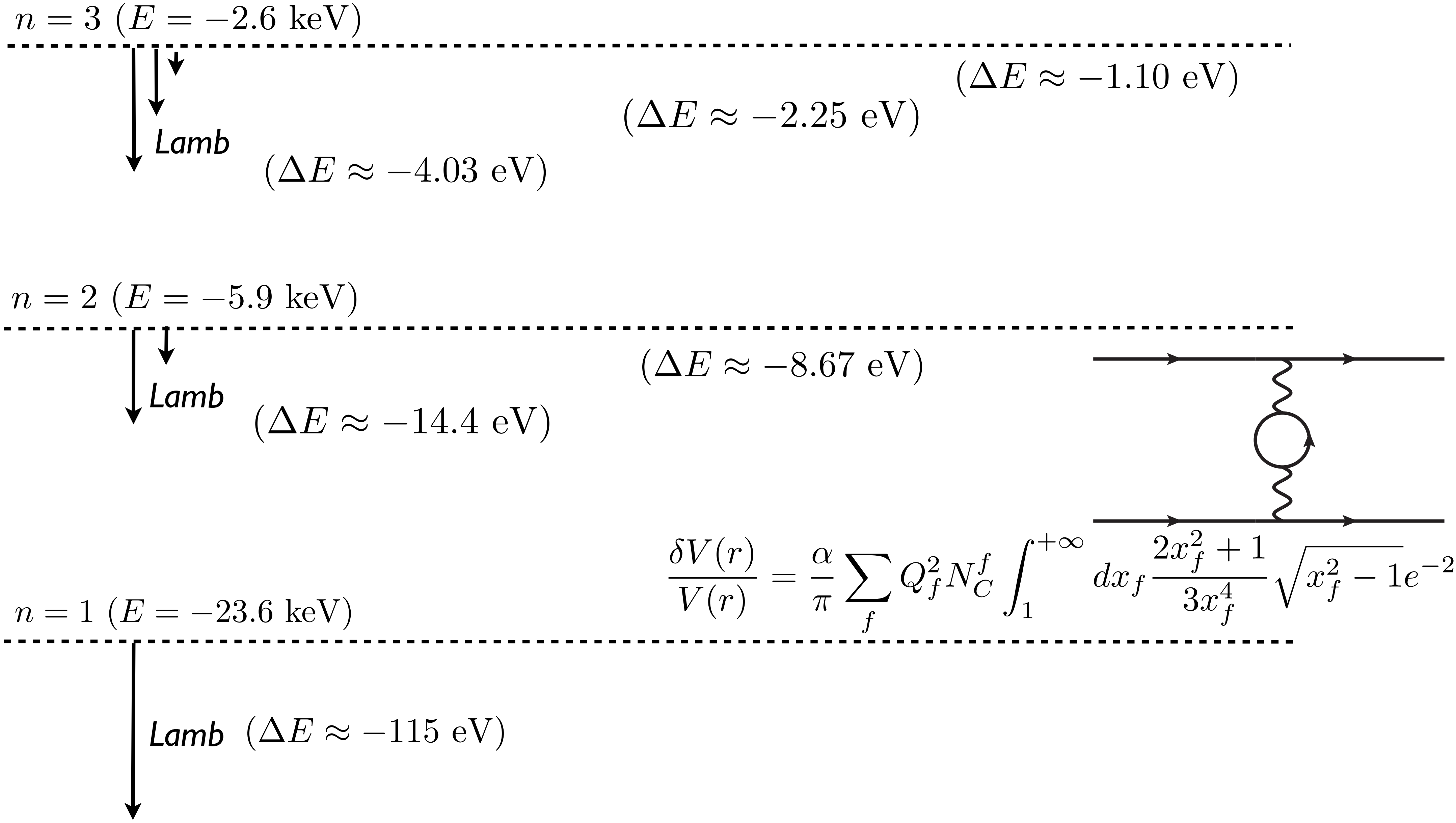
$n = 1\ (E = -23.6\ \mathrm{keV})$

Energy levels of ditauonium

- **The masses of the states**

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

  - Determined within non-relativistic quantum mechanics



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

Energy levels of ditauonium

- **The masses of the states**

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

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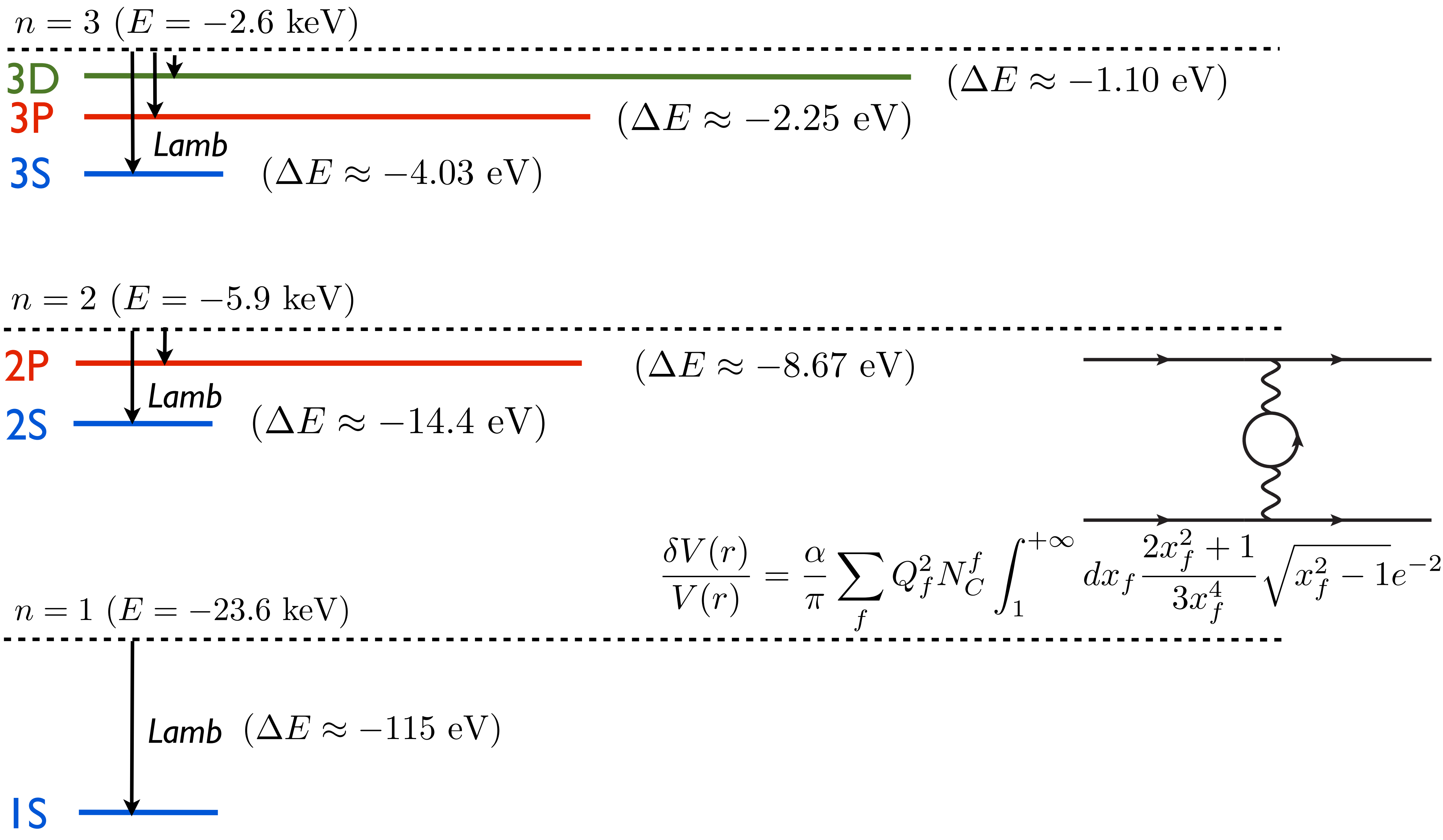
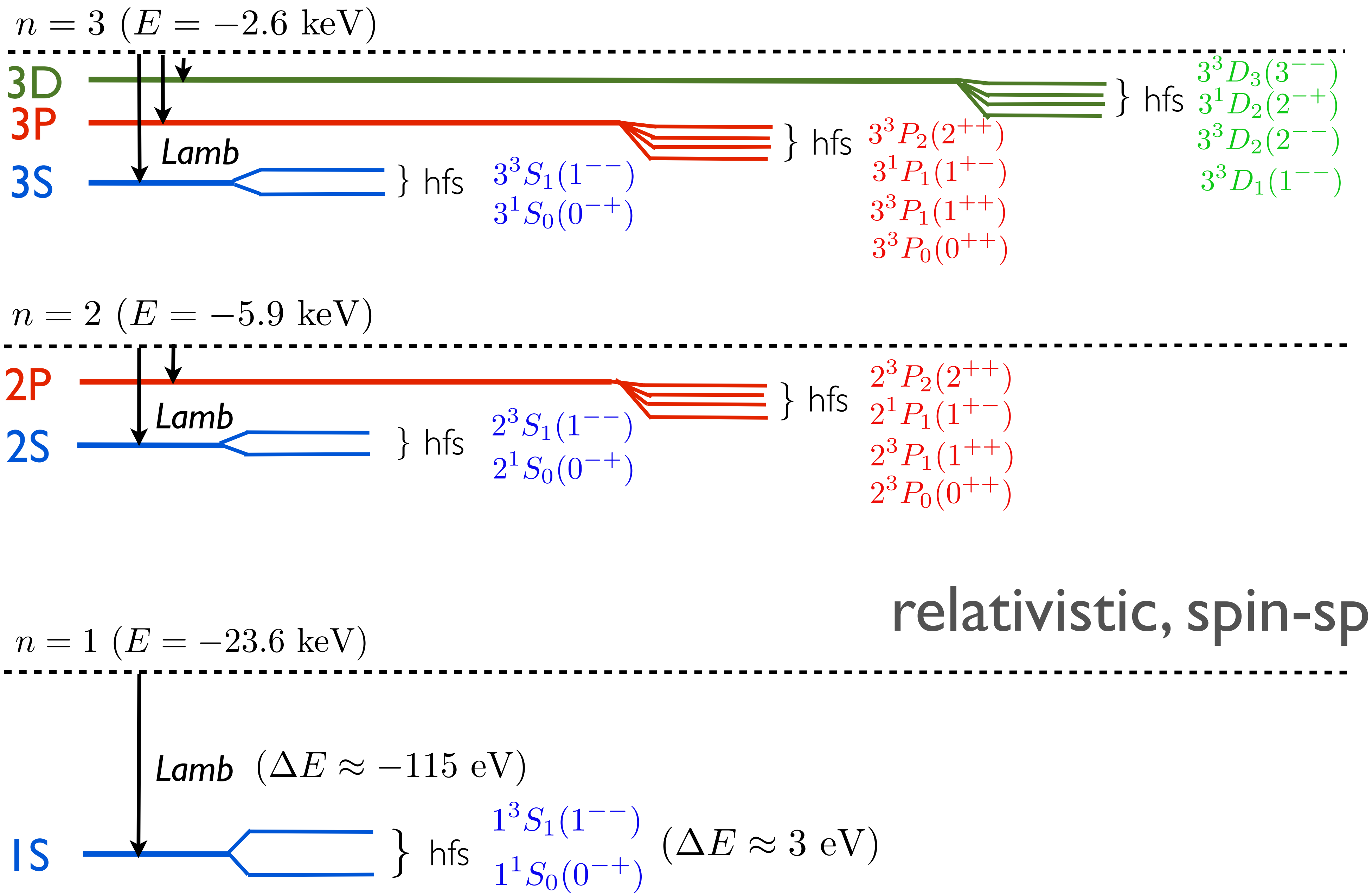


$$\frac{\delta V(r)}{V(r)}=\frac{\alpha}{\pi}\sum_f Q_f^2 N_C^f\int_1^{+\infty}dx_f\,\frac{2x_f^2+1}{3x_f^4}\sqrt{x_f^2-1}e^{-2m_f x_f r}$$

Energy levels of ditauonium

- **The masses of the states**
  - Determined within non-relativistic quantum mechanics

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



relativistic, spin-spin, LS, ...

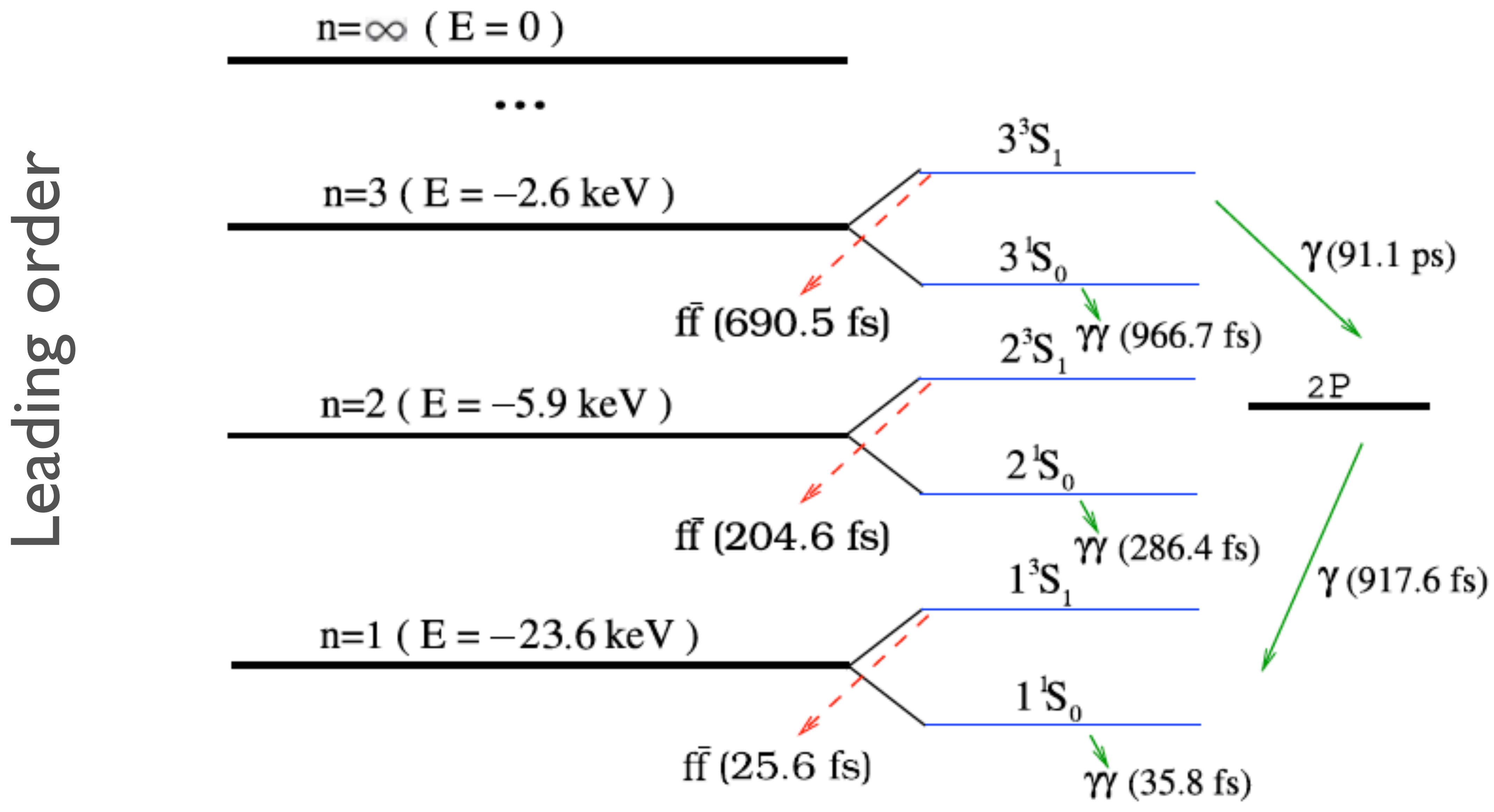
Decay channels of ditauonium

- **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*



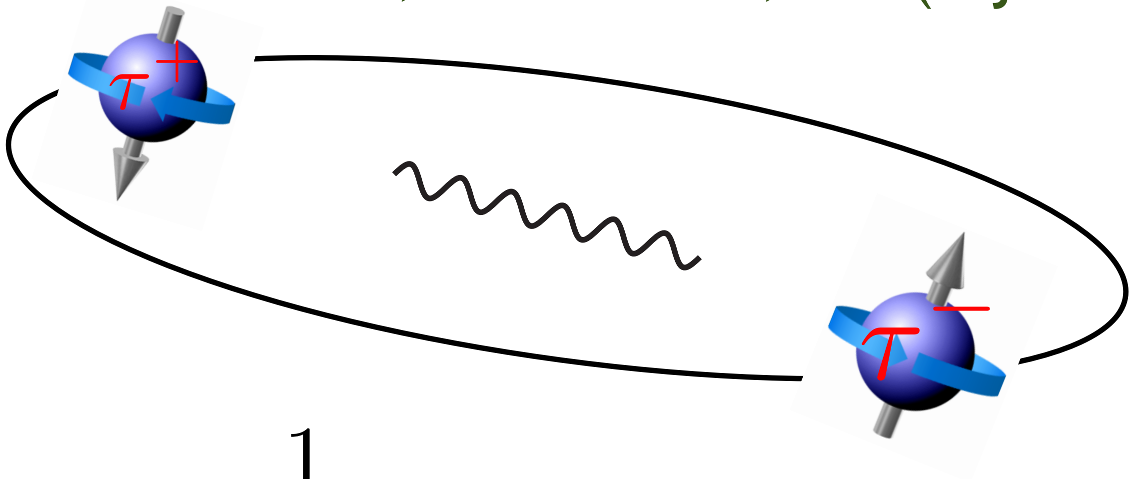
Decay channels of ditauonium

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

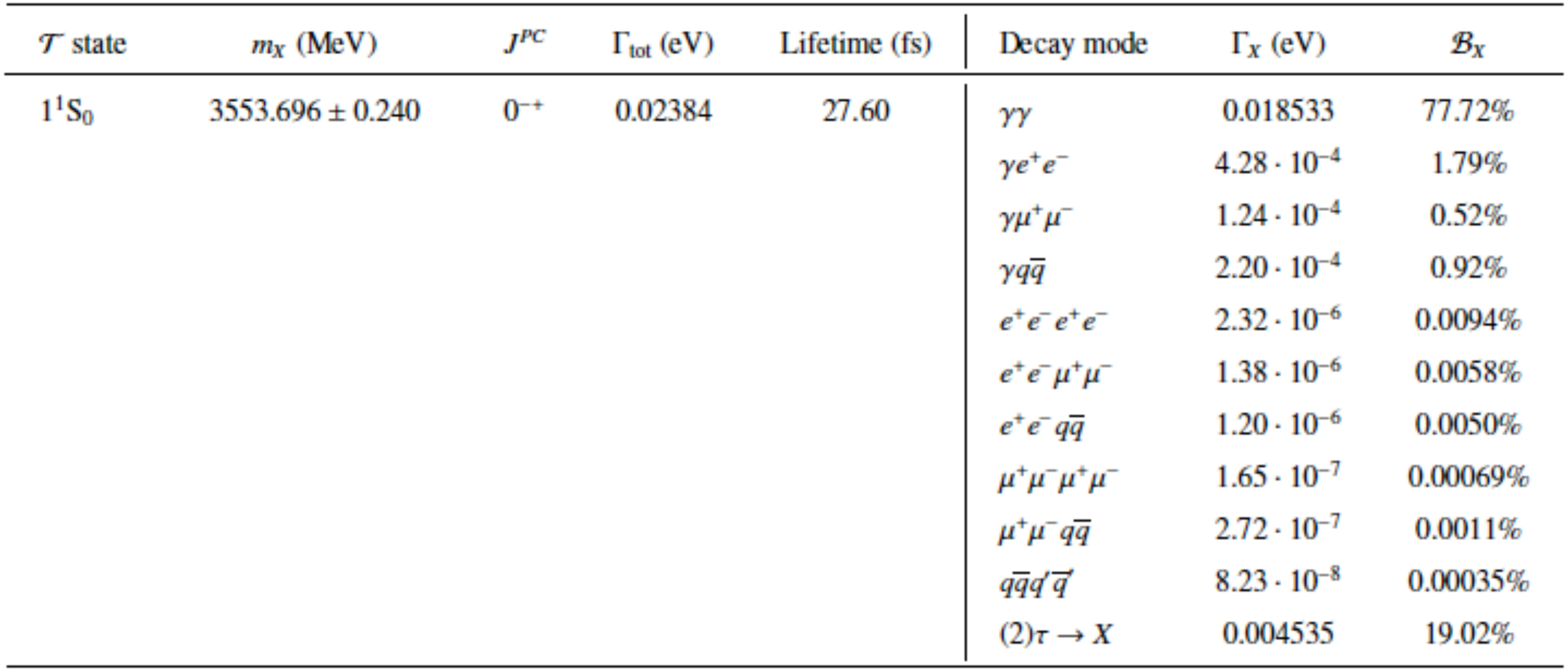
d'Enterria, Perez-Ramos, HSS (EPJC'22)

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

  - Mainly to di-photon
  - Percent-level Dalitz decay
  - O(10^{-4}) double-Dalitz decay
  - 19% tau weak decays



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



$\mathcal{T}$ state	m_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%

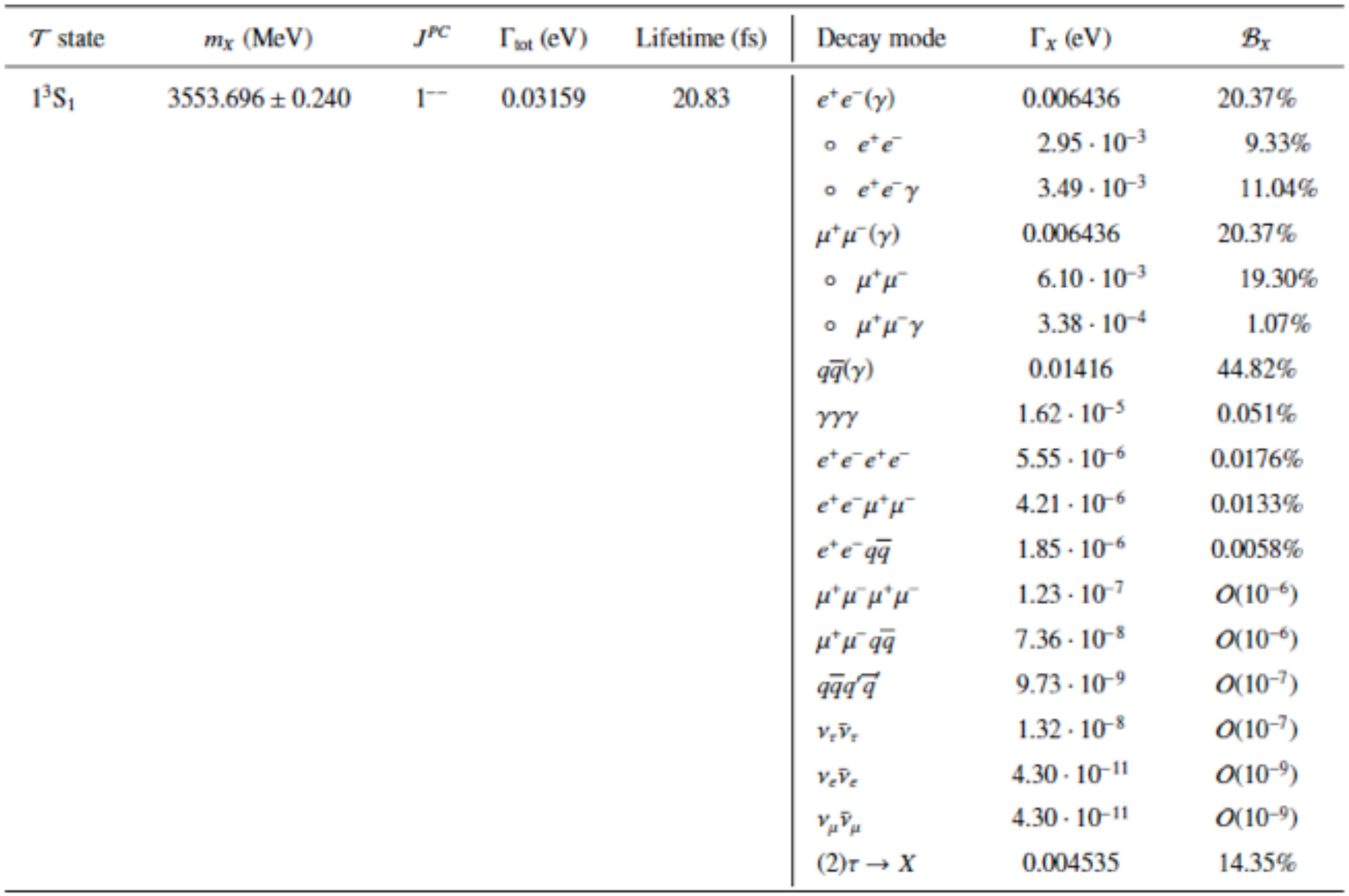
Decay channels of ditauonium

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

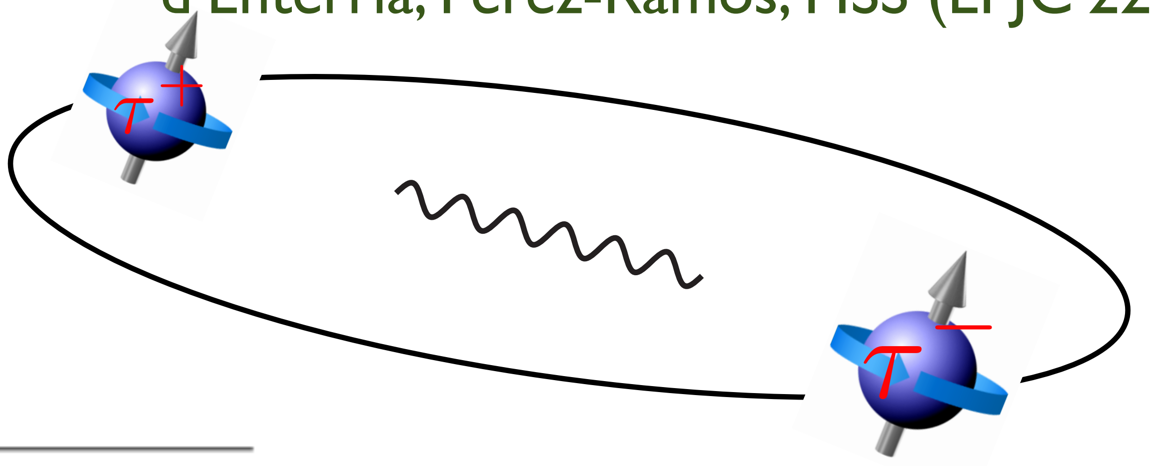
d’Enterria, Perez-Ramos, HSS (EPJC’22)

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

- Mainly to di-fermions
- O(10^{-4}) four-fermion decay
- 14% tau weak decay



$\mathcal{T}$ 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%



$$|\uparrow\uparrow\rangle$$

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

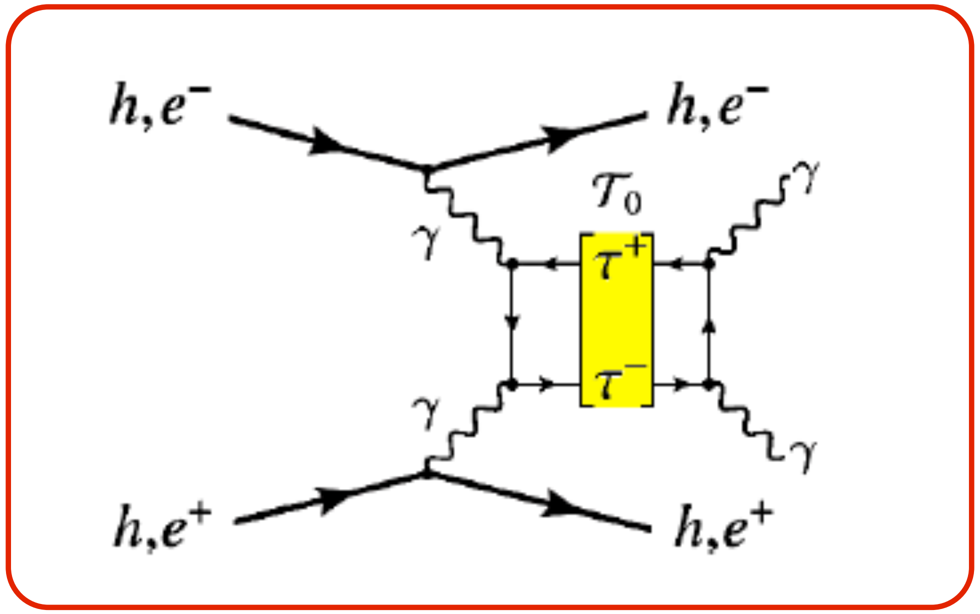
$$|\downarrow\downarrow\rangle$$

Discovery potential of para-ditauonium

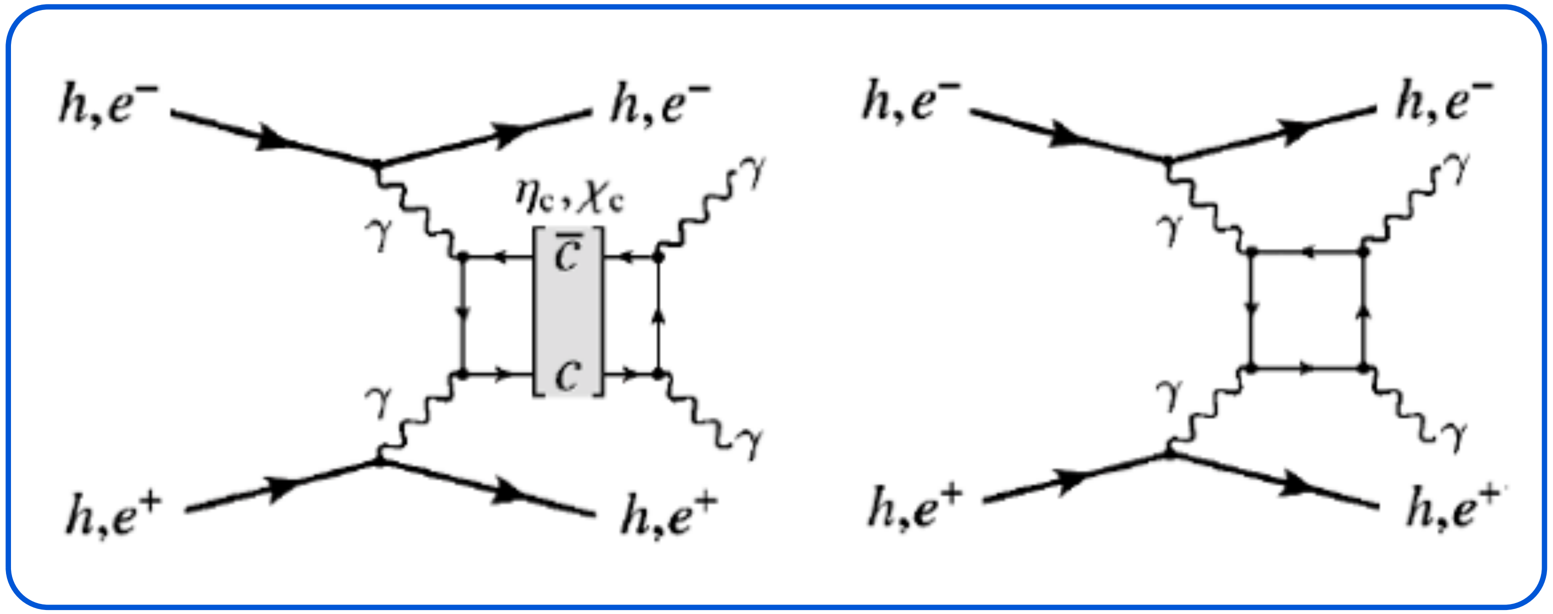
How to observe ditauonium ?

- **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

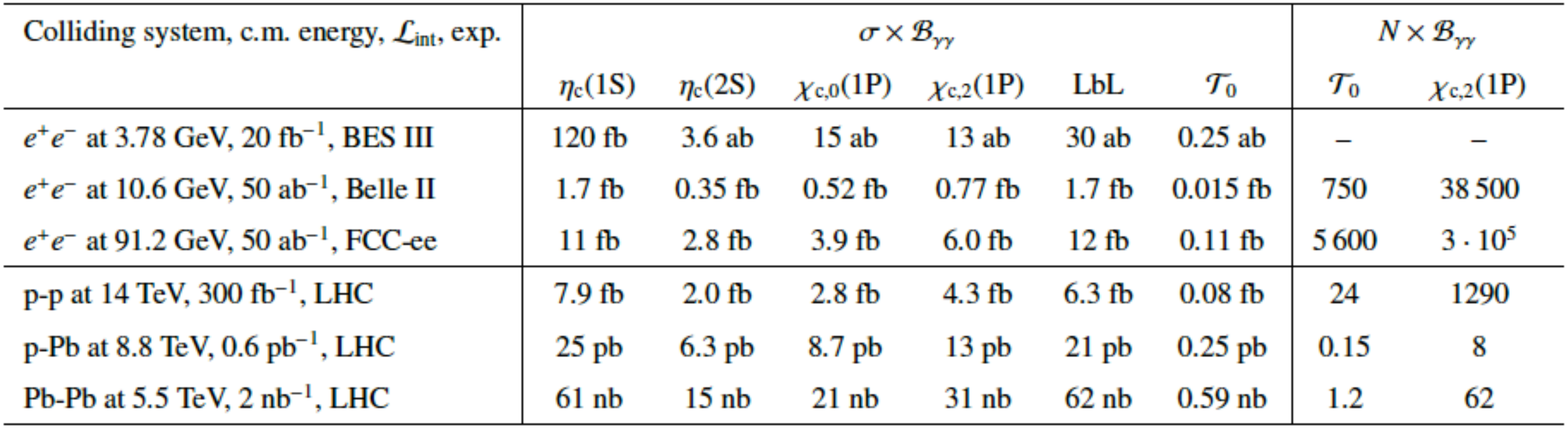
⇨ **gamma-UPC** d'Enterria, HSS (JHEP'22)

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)
  - LbL cross sections are computed with MadGraph5_aMC@NLO

    Alwall et al. (JHEP'14)



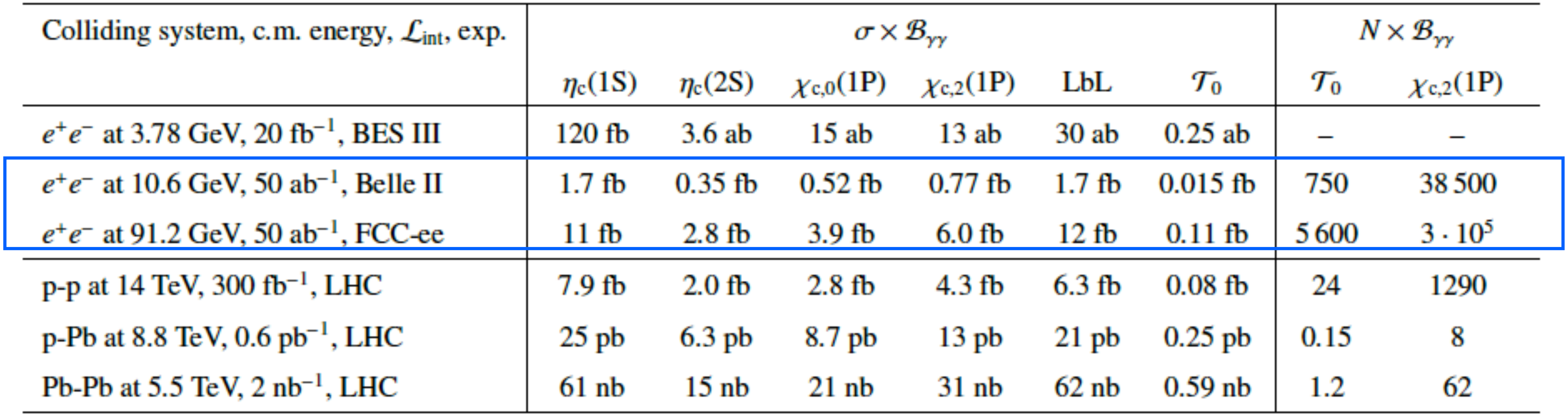
Colliding system, c.m. energy, $\mathcal{L}_{\rm int}$, exp.	$\sigma \times \mathcal{B}_{\gamma\gamma}$						$N \times \mathcal{B}_{\gamma\gamma}$	
	$\eta_c(1S)$	$\eta_c(2S)$	$\chi_{c,0}(1P)$	$\chi_{c,2}(1P)$	LbL	$\mathcal{T}_0$	$\mathcal{T}_0$	$\chi_{c,2}(1P)$
e^+e^- at 3.78 GeV, 20 fb^{-1}, BES III	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

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

$$\begin{array}{ccccccccc} \sigma(\eta_c(1S)) & : & \sigma(\chi_{c2}(1P)) & : & \sigma(\chi_{c0}(1P)) & : & \sigma(\eta_c(2S)) & : & \sigma(\mathcal{T}_0) \\ 100 & & 50 & & 30 & & 25 & & 1 \end{array}$$

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)
  - LbL cross sections are computed with MadGraph5_aMC@NLO Alwall et al. (JHEP'14)



Colliding system, c.m. energy, $\mathcal{L}_{\text{int}}$, 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

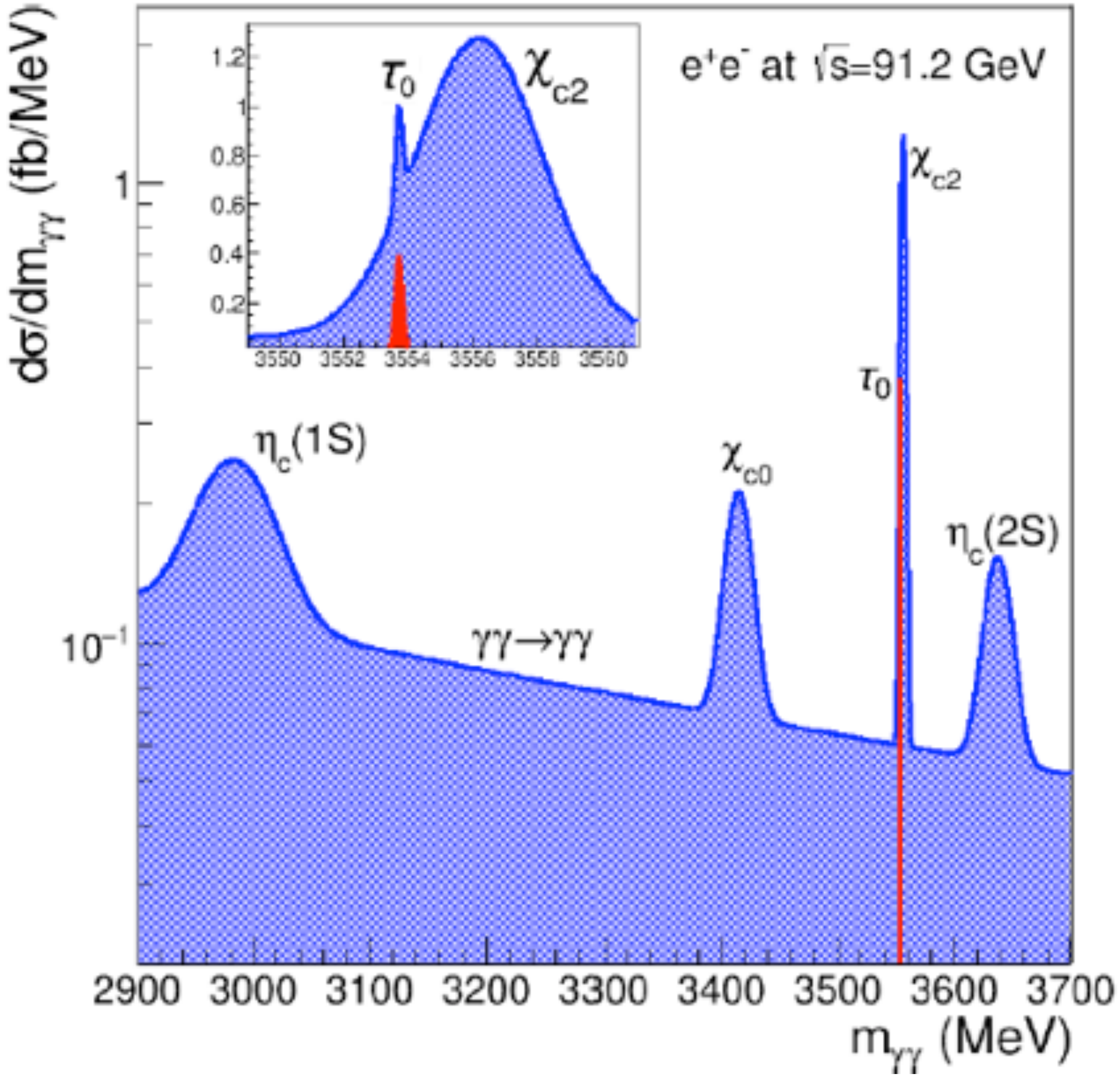
$$\sigma(\eta_c(1S)) : \sigma(\chi_{c2}(1P)) : \sigma(\chi_{c0}(1P)) : \sigma(\eta_c(2S)) : \sigma(\mathcal{T}_0)$$

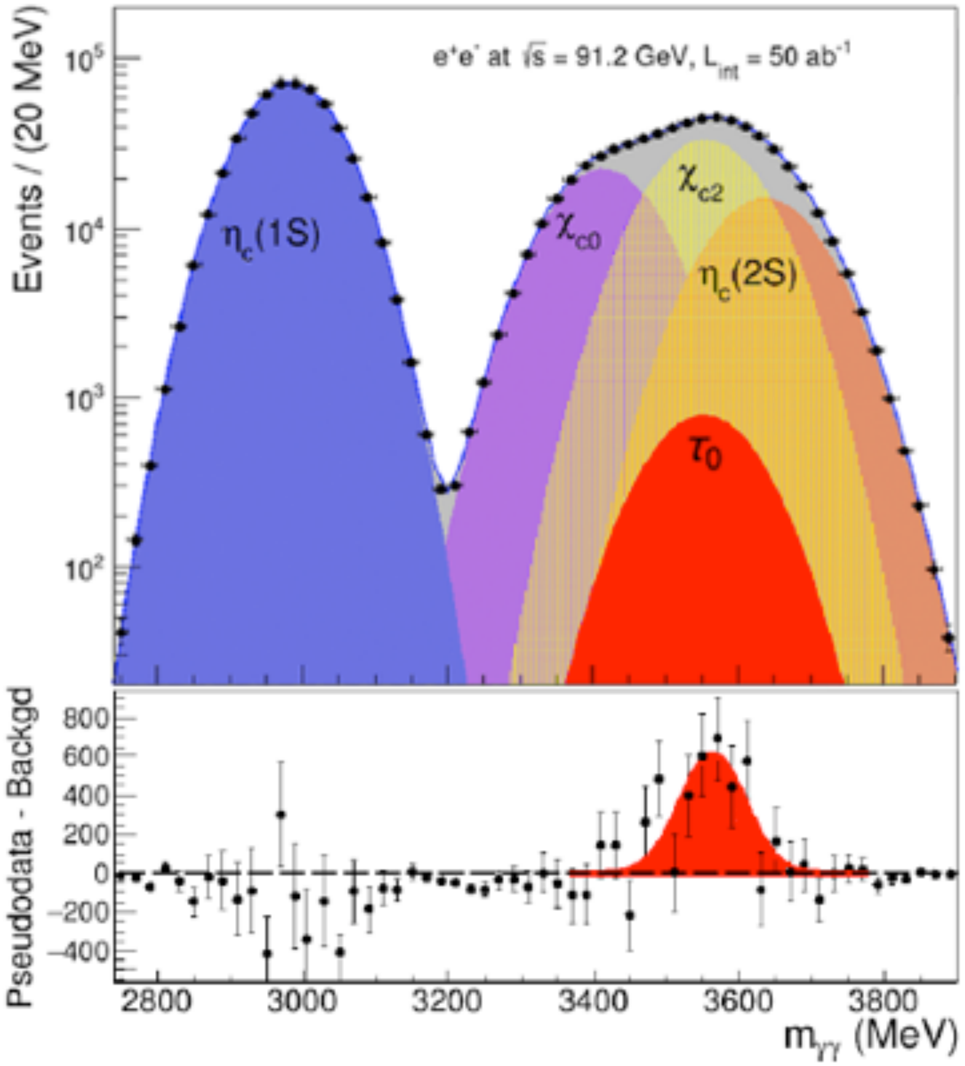
100 50 30 25 1

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.:* $\sim 100\%$





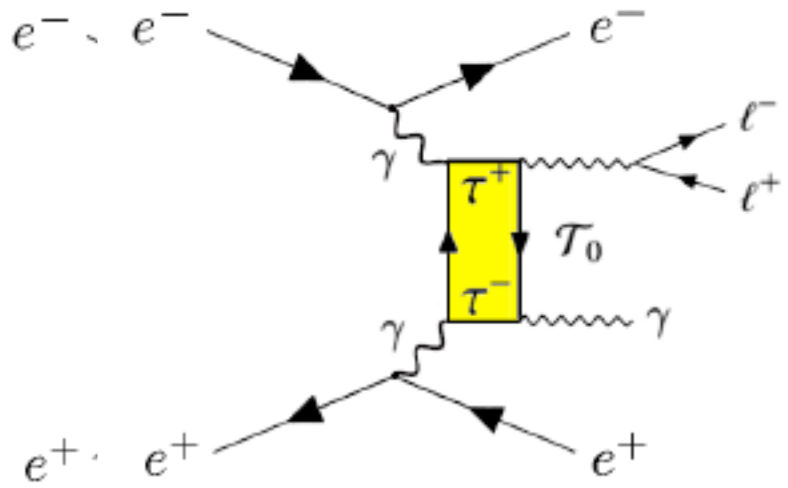
How to observe ditauonium ?

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

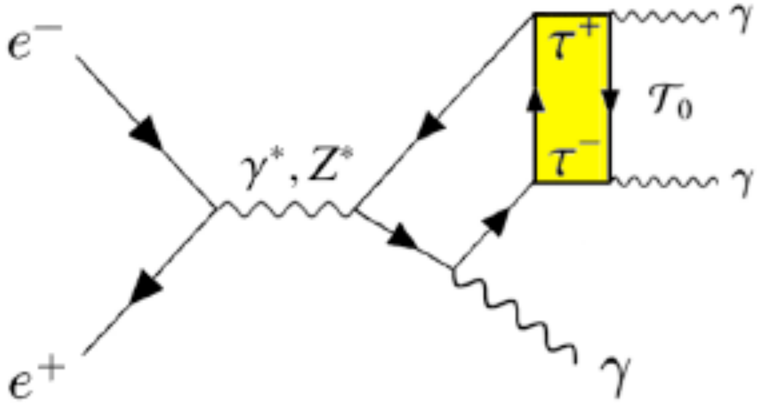
    FCC-ee 5σ
    Belle II 3σ
  - Main challenge

    Control the lineshapes of charmonia, in particular χ_{c2}
  - We consider other possibilities, but turn out to be challenging

Dalitz decay



FSR photon



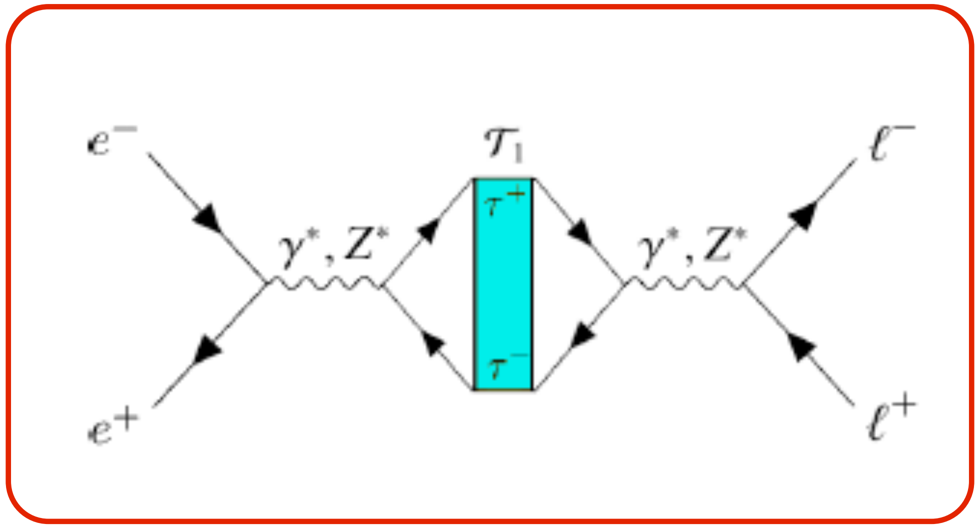
Discovery potential of ortho-ditauonium

How to observe ditauonium ?

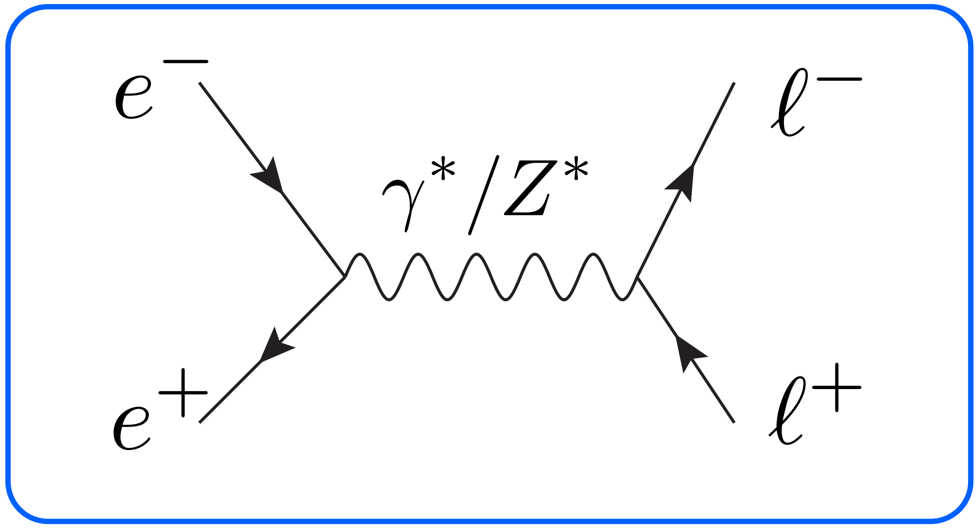
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Threshold scan at e+e-

d’Enterria, HSS (2302.07365)

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 ?

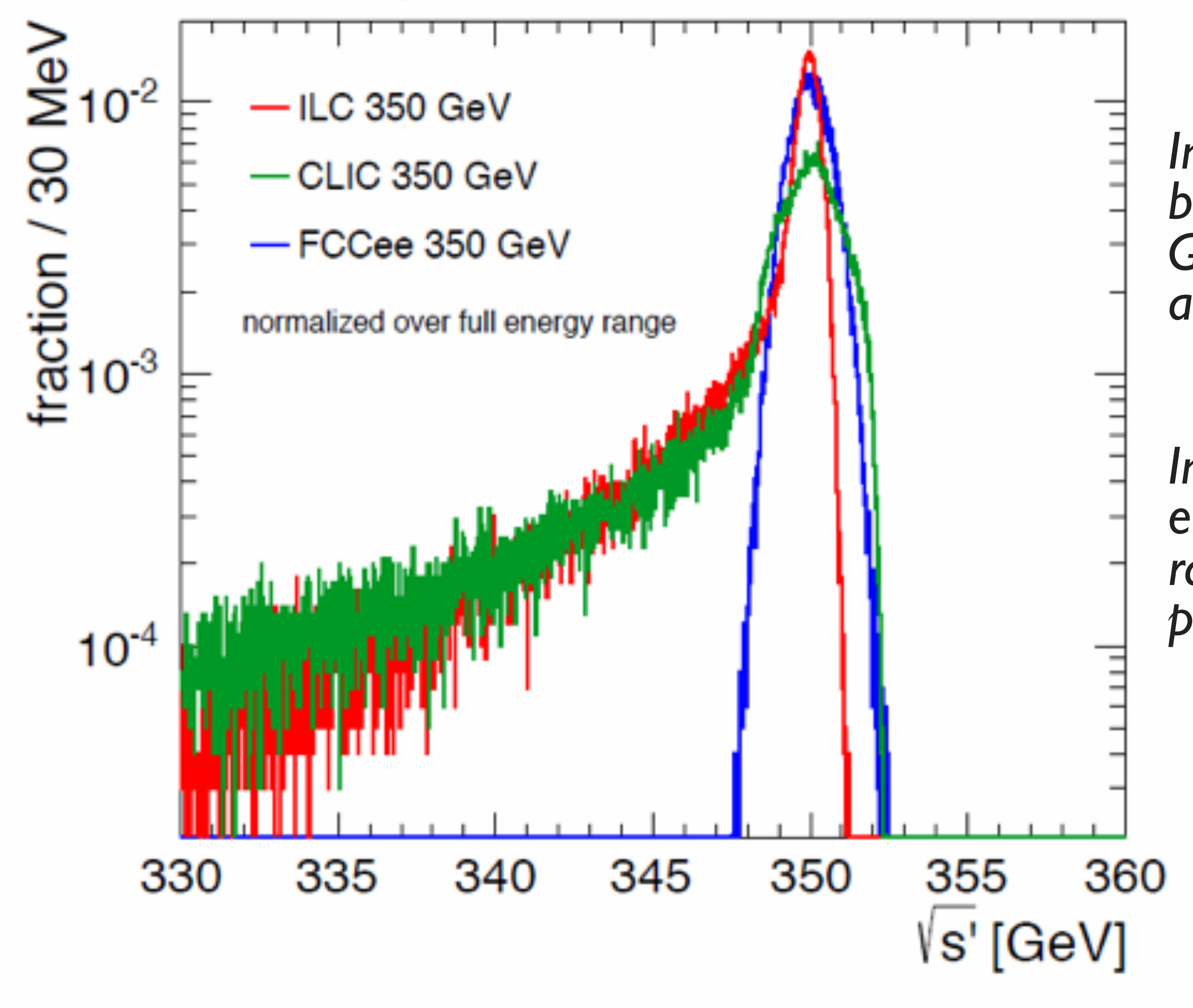
How to observe ditauonium ?

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

d'Enterria, HSS (2302.07365)

Monochromatization of beam energies

Initial-state photon radiation (ISR) *-> always lower center-of-mass energy*



In the high-energy circular collider, beamstrahlung causes an additonal Gaussian energy spread because particles are trapped on synchortron oscillation

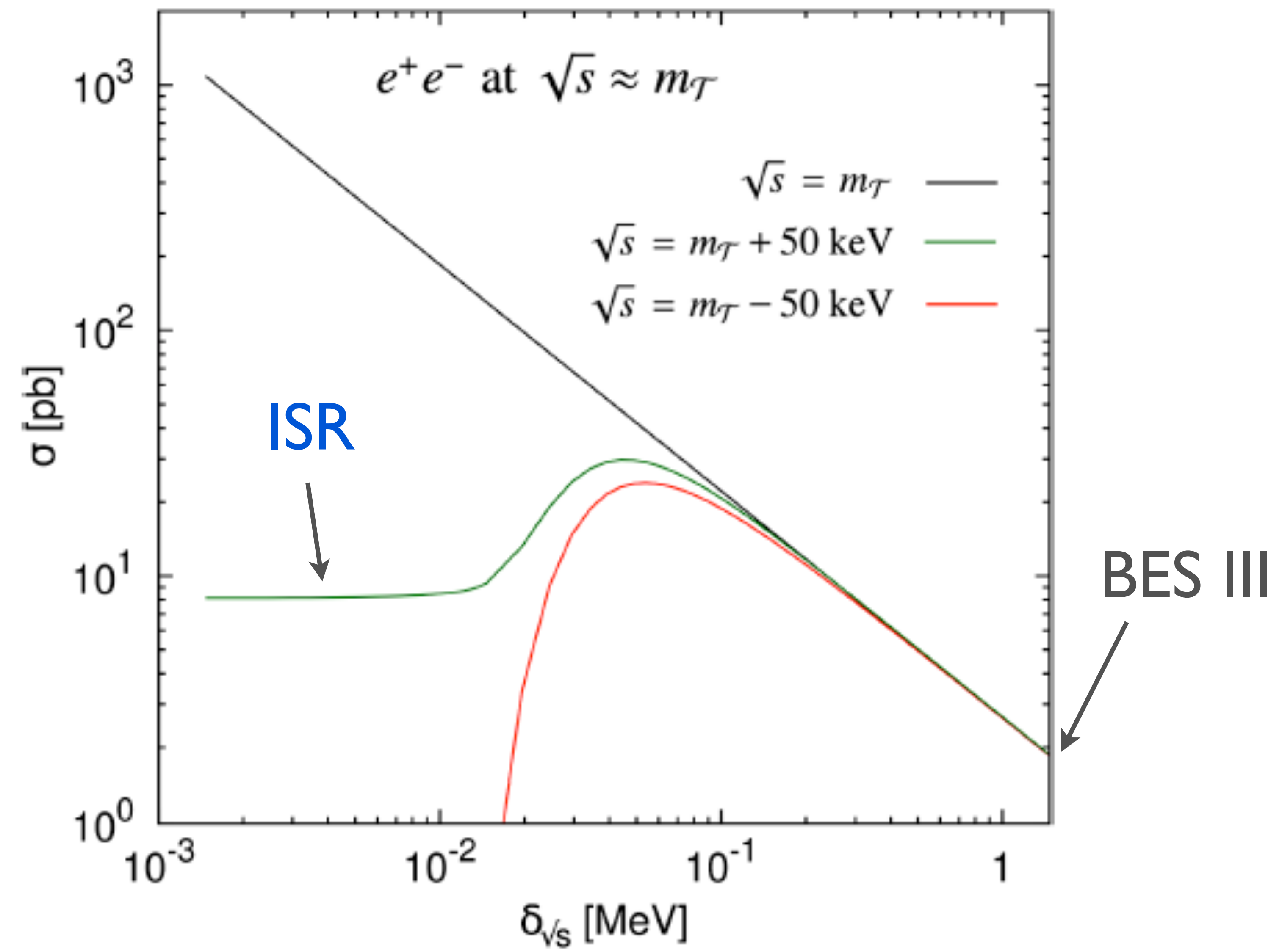
In the low-energy circular collider, relative energy spread is mainly due to synchrotron radiation emitted when a ultra-relativistic particle passes through a bending magnet

How to observe ditauonium ?

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

d'Enterria, HSS (2302.07365)

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



ISR

BES III

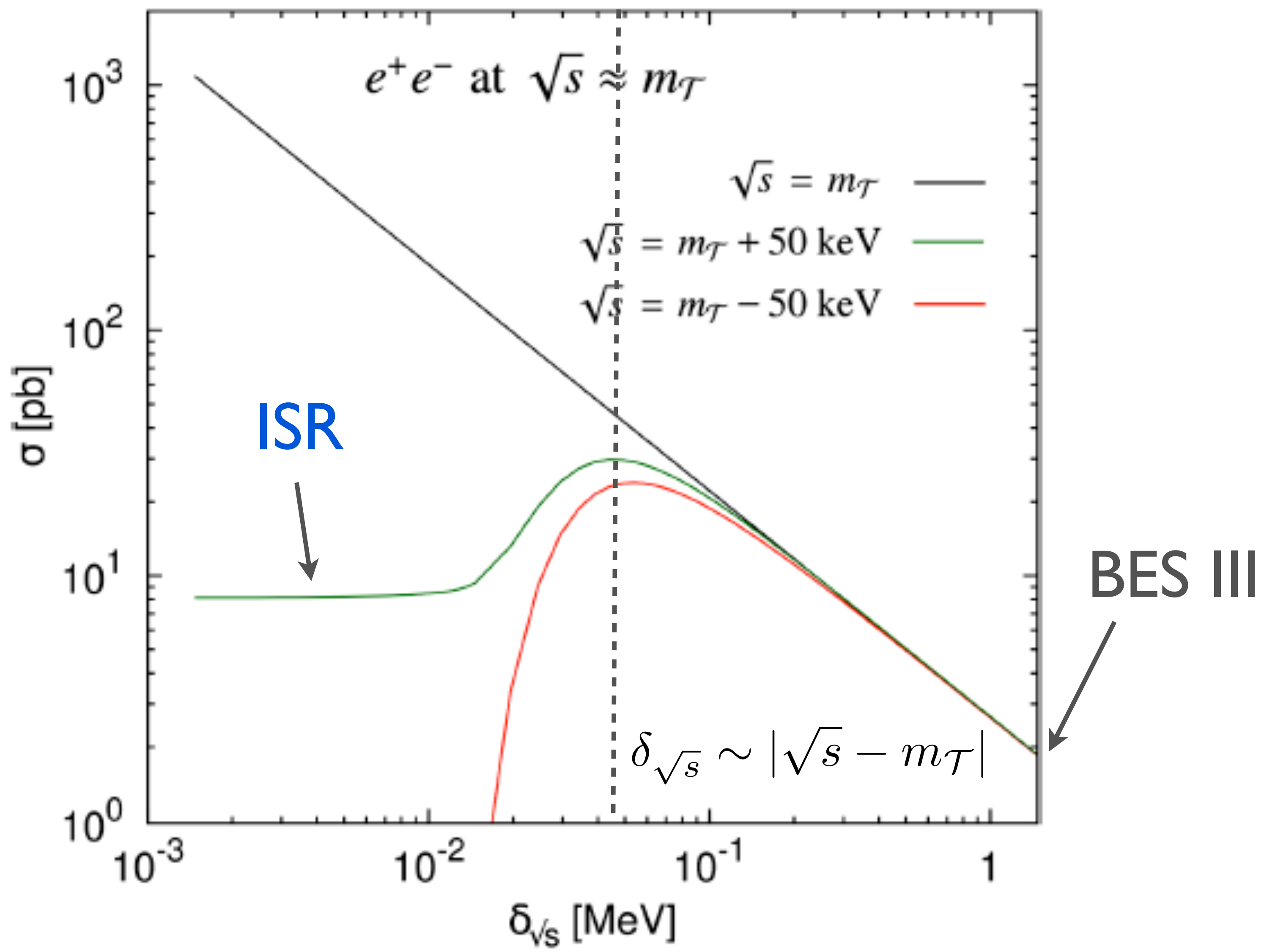
How to observe ditauonium ?

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

d'Enterria, HSS (2302.07365)

Voigtian function

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



ISR

BES III

How to observe ditauonium ?

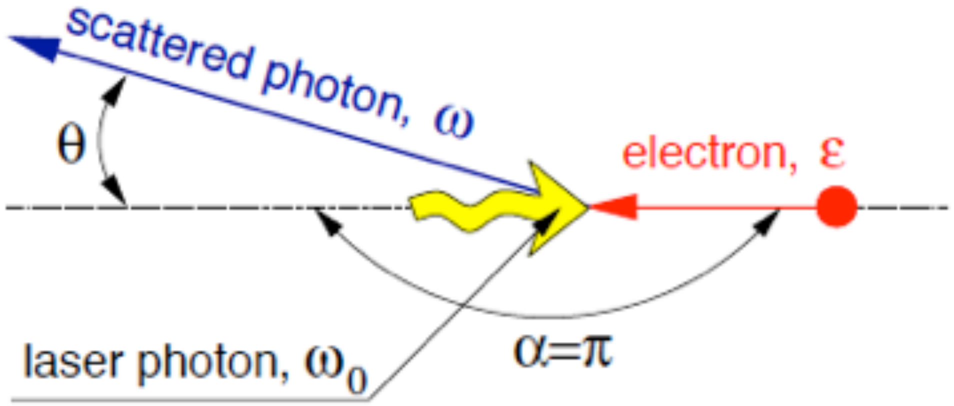
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Larger signal yields requires:

d’Enterria, HSS (2302.07365)

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

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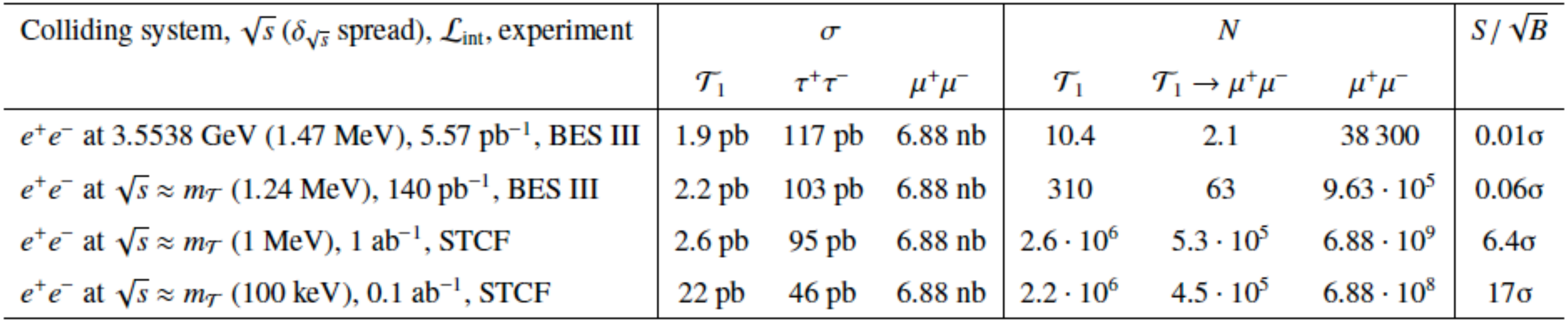
d'Enterria, HSS (2302.07365)



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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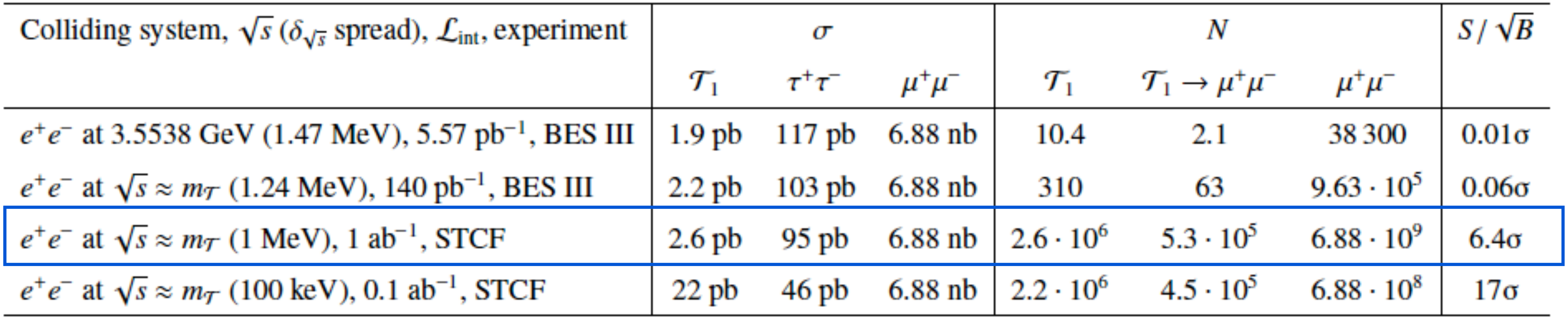

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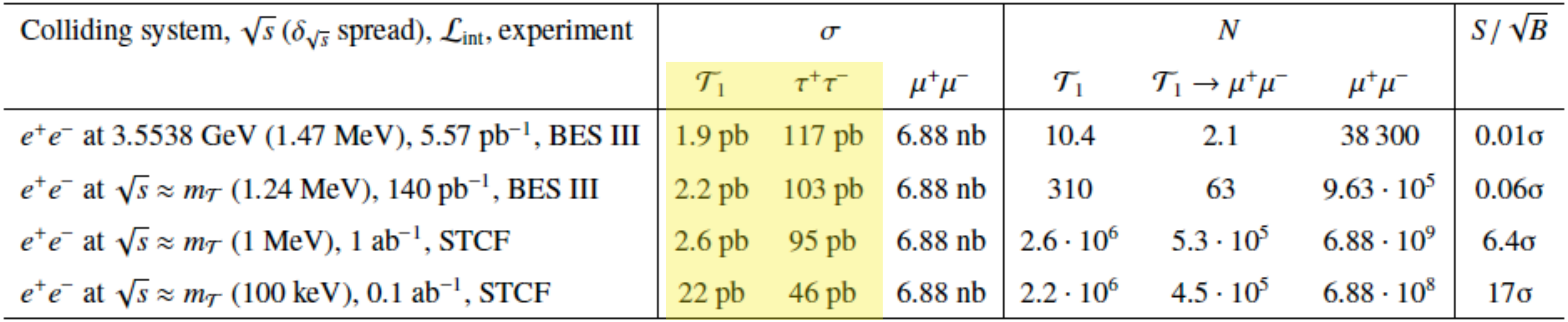

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- Ditauonium contributes 2% (50%) of the di-tau cross section w/o (w/) beam energy monochromatization.

How to observe ditauonium ?

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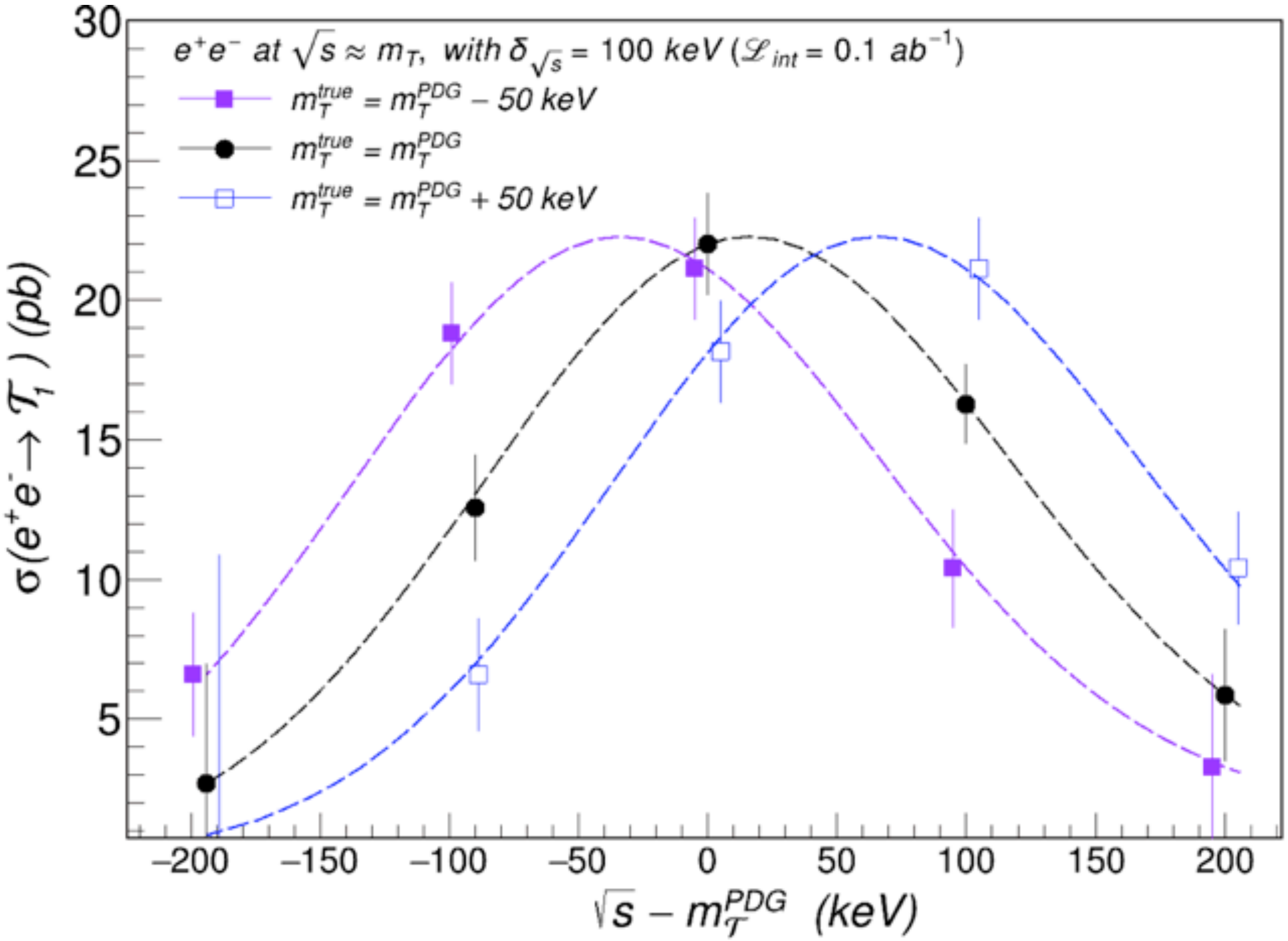
  - Threshold scan at e+e-

    d’Enterria, HSS (2302.07365)
    - As a bonus of the ditauonium observation, we can also precisely determine the mass of the tau lepton with monochromatization

$$m_\tau = (m_{\mathcal{T}} - E_{\rm bind})/2$$



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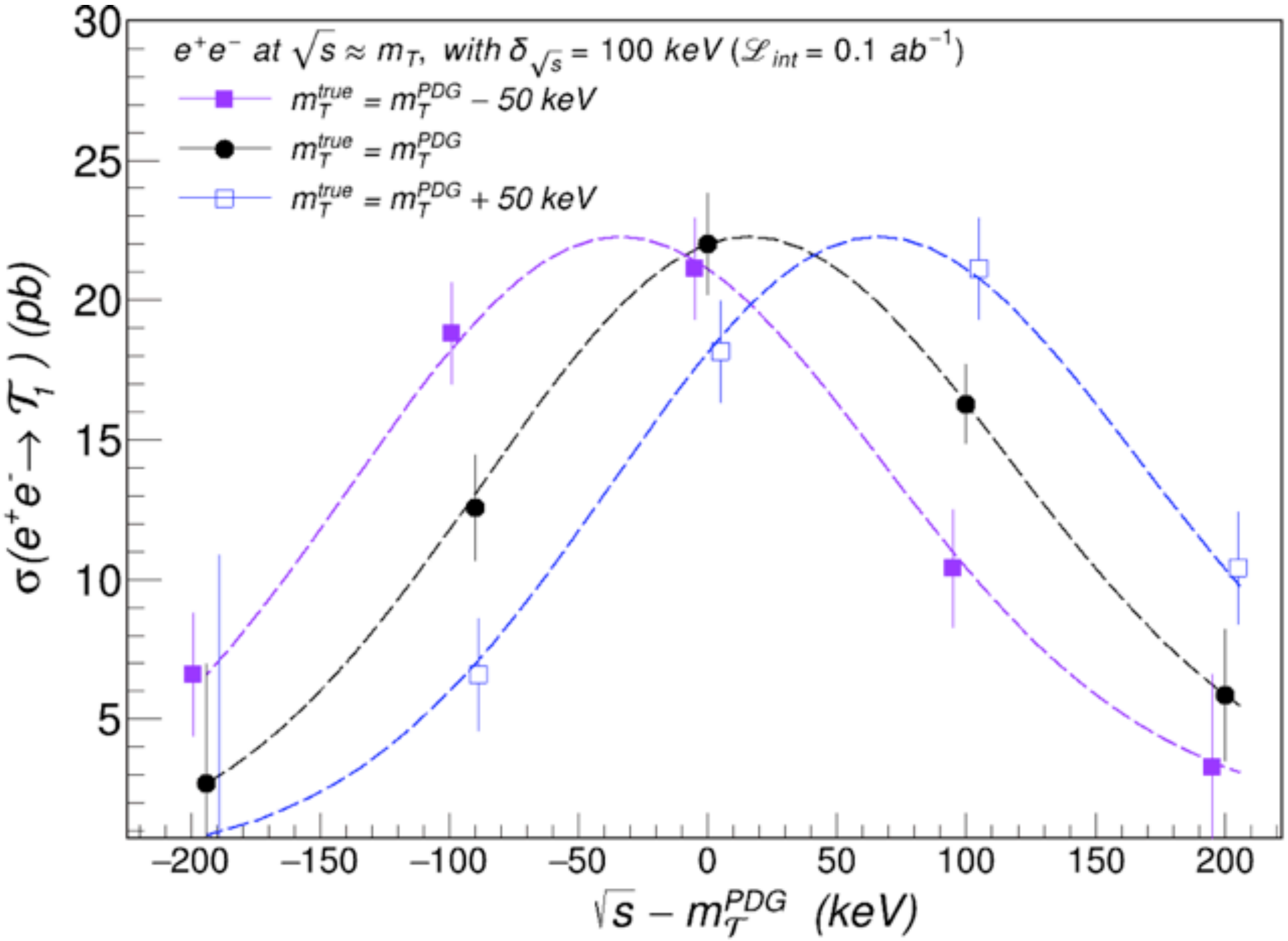
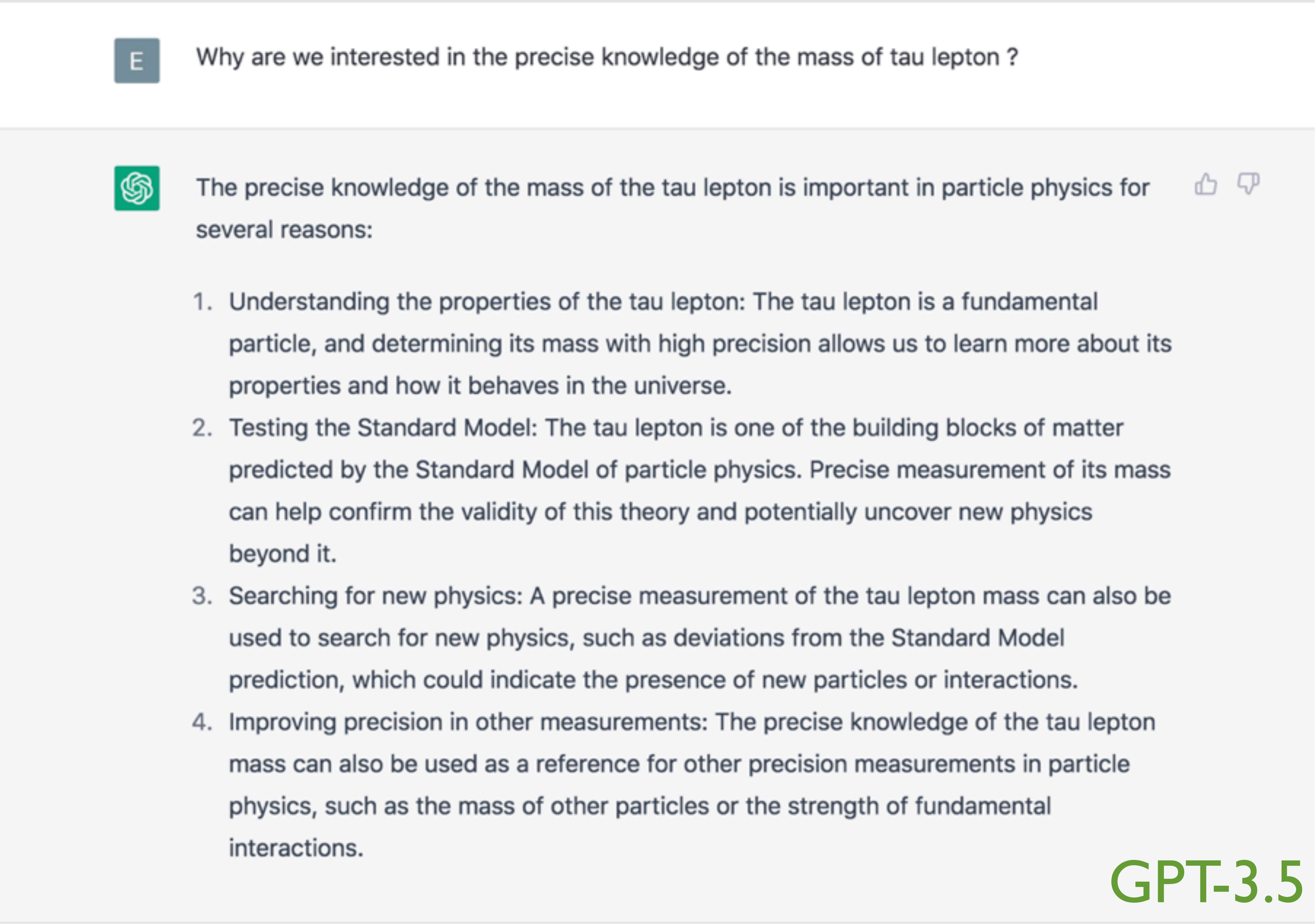
$$m_\tau = (m_{\mathcal{T}} - E_{\text{bind}})/2 \xrightarrow{\qquad\qquad} \delta m_\tau = 25 \text{ keV}$$



What we can learn from a precise m_τ?



E

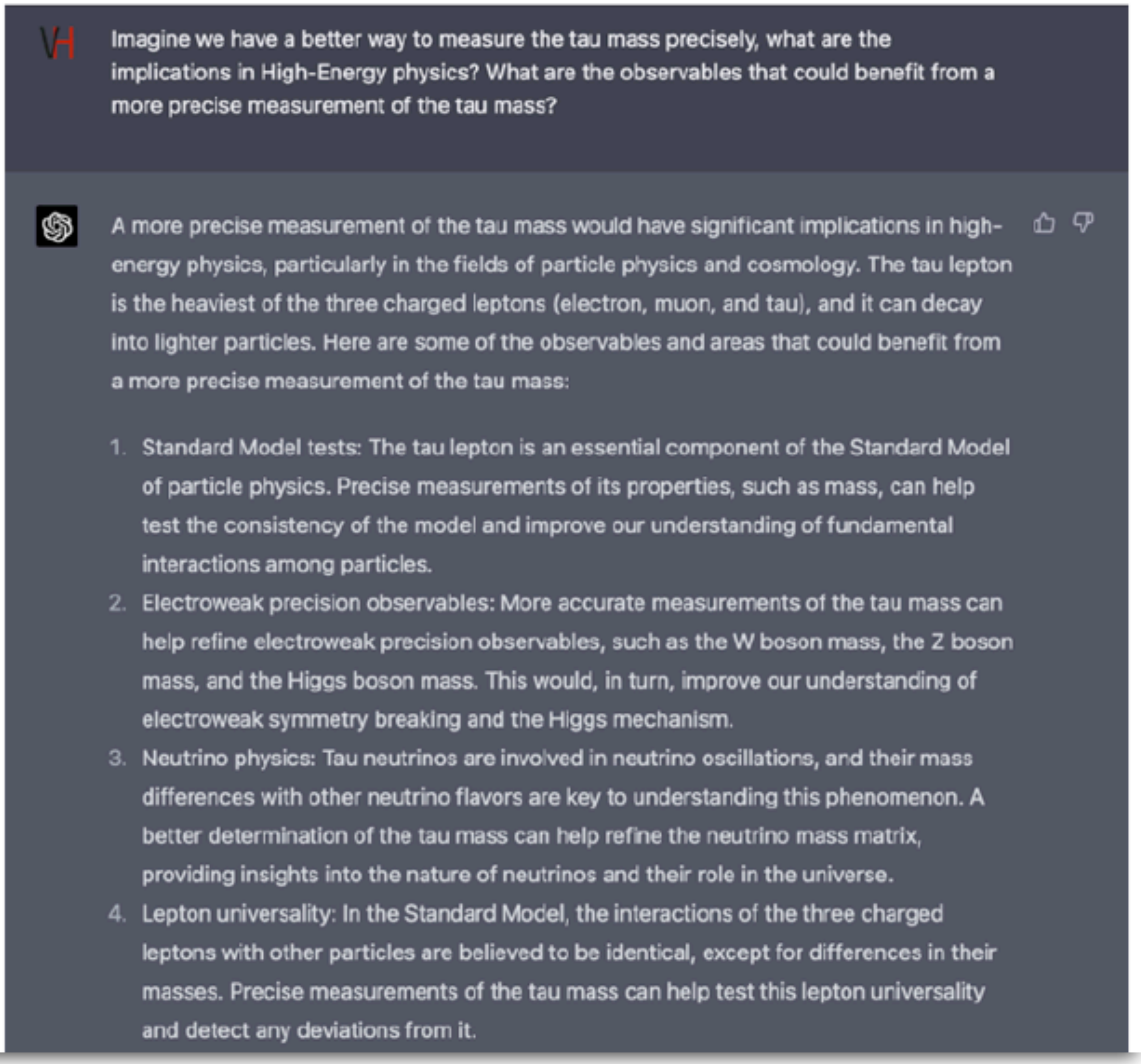
Why are we interested in the precise knowledge of the mass of tau lepton ?

The precise knowledge of the mass of the tau lepton is important in particle physics for several reasons:

1. Understanding the properties of the tau lepton: The tau lepton is a fundamental particle, and determining its mass with high precision allows us to learn more about its properties and how it behaves in the universe.
2. Testing the Standard Model: The tau lepton is one of the building blocks of matter predicted by the Standard Model of particle physics. Precise measurement of its mass can help confirm the validity of this theory and potentially uncover new physics beyond it.
3. Searching for new physics: A precise measurement of the tau lepton mass can also be used to search for new physics, such as deviations from the Standard Model prediction, which could indicate the presence of new particles or interactions.
4. Improving precision in other measurements: The precise knowledge of the tau lepton mass can also be used as a reference for other precision measurements in particle physics, such as the mass of other particles or the strength of fundamental interactions.

GPT-3.5

What we can learn from a precise m_τ?



Imagine we have a better way to measure the tau mass precisely, what are the implications in High-Energy physics? What are the observables that could benefit from a more precise measurement of the tau mass?

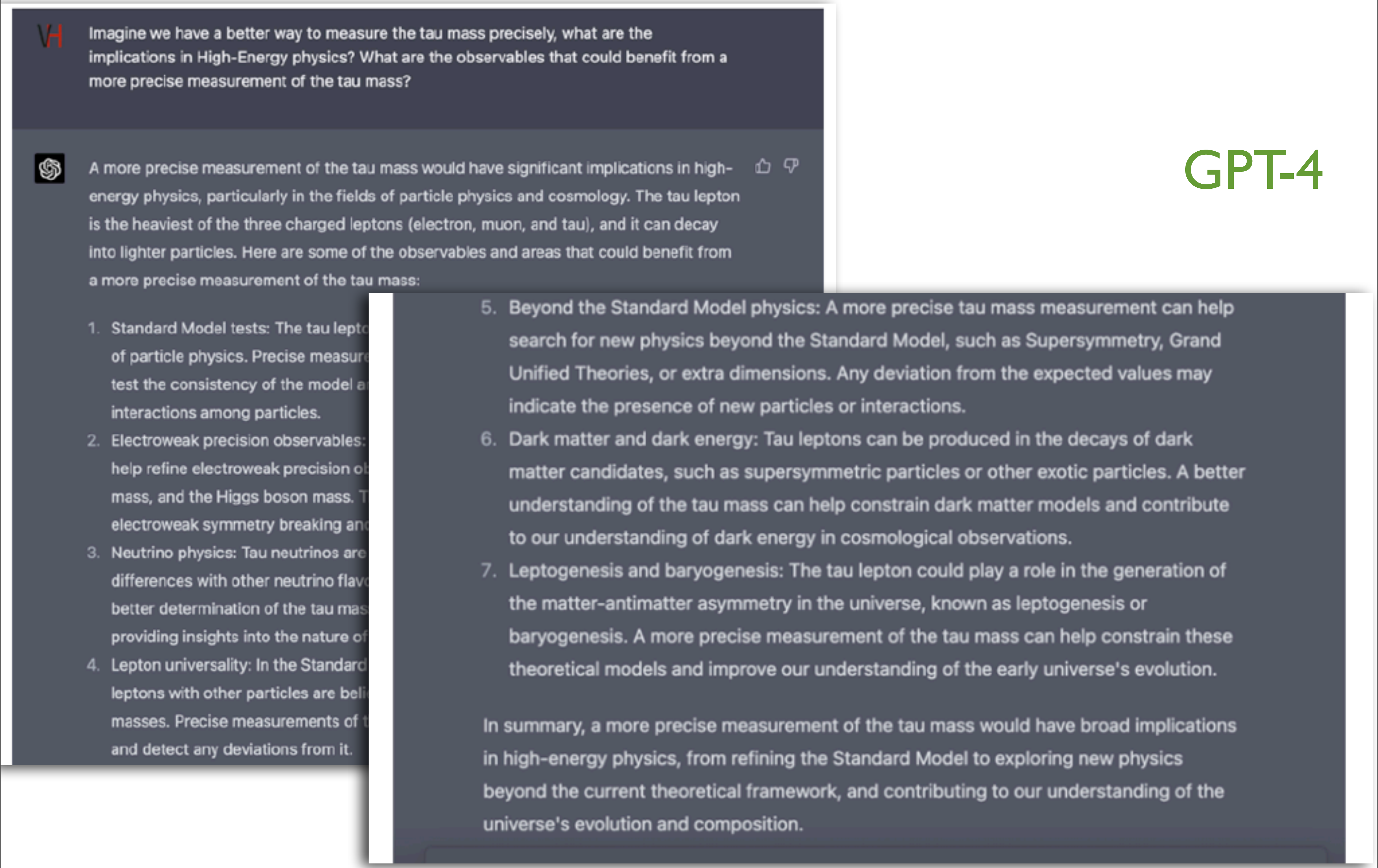
A more precise measurement of the tau mass would have significant implications in high-energy physics, particularly in the fields of particle physics and cosmology. The tau lepton is the heaviest of the three charged leptons (electron, muon, and tau), and it can decay into lighter particles. Here are some of the observables and areas that could benefit from a more precise measurement of the tau mass:

1. Standard Model tests: The tau lepton is an essential component of the Standard Model of particle physics. Precise measurements of its properties, such as mass, can help test the consistency of the model and improve our understanding of fundamental interactions among particles.
2. Electroweak precision observables: More accurate measurements of the tau mass can help refine electroweak precision observables, such as the W boson mass, the Z boson mass, and the Higgs boson mass. This would, in turn, improve our understanding of electroweak symmetry breaking and the Higgs mechanism.
3. Neutrino physics: Tau neutrinos are involved in neutrino oscillations, and their mass differences with other neutrino flavors are key to understanding this phenomenon. A better determination of the tau mass can help refine the neutrino mass matrix, providing insights into the nature of neutrinos and their role in the universe.
4. Lepton universality: In the Standard Model, the interactions of the three charged leptons with other particles are believed to be identical, except for differences in their masses. Precise measurements of the tau mass can help test this lepton universality and detect any deviations from it.

GPT-4

What we can learn from a precise m_τ?

GPT-4



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A more precise measurement of the tau mass would have significant implications in high-energy physics, particularly in the fields of particle physics and cosmology. The tau lepton is the heaviest of the three charged leptons (electron, muon, and tau), and it can decay into lighter particles. Here are some of the observables and areas that could benefit from a more precise measurement of the tau mass:

1. Standard Model tests: The tau lept
   of particle physics. Precise measur
   test the consistency of the model a
   interactions among particles.
2. Electroweak precision observables:
   help refine electroweak precision o
   mass, and the Higgs boson mass. T
   electroweak symmetry breaking an
3. Neutrino physics: Tau neutrinos are
   differences with other neutrino flav
   better determination of the tau mas
   providing insights into the nature o
4. Lepton universality: In the Standard
   leptons with other particles are bel
   masses. Precise measurements of t
   and detect any deviations from it.
5. Beyond the Standard Model physics: A more precise tau mass measurement can help search for new physics beyond the Standard Model, such as Supersymmetry, Grand Unified Theories, or extra dimensions. Any deviation from the expected values may indicate the presence of new particles or interactions.
6. Dark matter and dark energy: Tau leptons can be produced in the decays of dark matter candidates, such as supersymmetric particles or other exotic particles. A better understanding of the tau mass can help constrain dark matter models and contribute to our understanding of dark energy in cosmological observations.
7. Leptogenesis and baryogenesis: The tau lepton could play a role in the generation of the matter-antimatter asymmetry in the universe, known as leptogenesis or baryogenesis. A more precise measurement of the tau mass can help constrain these theoretical models and improve our understanding of the early universe's evolution.

In summary, a more precise measurement of the tau mass would have broad implications in high-energy physics, from refining the Standard Model to exploring new physics beyond the current theoretical framework, and contributing to our understanding of the universe's evolution and composition.

What we can learn from a precise m_τ?

Koide formula

From Wikipedia, the free encyclopedia

The **Koide formula** is an unexplained empirical equation discovered by Yoshio Koide in 1981. In its original form, it relates the masses of the three charged leptons; later authors have extended the relation to neutrinos, quarks, and other families of particles.[1]:64–66

Formula [edit]

The Koide formula is

$$Q=\frac{m_e+m_\mu+m_\tau}{\left(\sqrt{m_e}+\sqrt{m_\mu}+\sqrt{m_\tau}\right)^2}=0.666661(7)\approx\frac{2}{3},$$

where the masses of the electron, muon, and tau are measured respectively as m_e = 0.510 998 946(3) MeV/c^2, m_μ = 105.658 3745(24) MeV/c^2, and m_τ = 1 776.86(12) MeV/c^2; the digits in parentheses are the uncertainties in the last digits.[2] This gives Q = 0.666 661(7).[3]

- $m_\tau^{\rm Koide}=1776.969\ {\rm MeV}$ vs. $m_\tau^{\rm PDG}=1776.86\pm0.12\ {\rm MeV}$
- Fine tuning or naturalness ?
- Hidden new symmetry ?
- Numerology ?

How to observe ditauonium ?

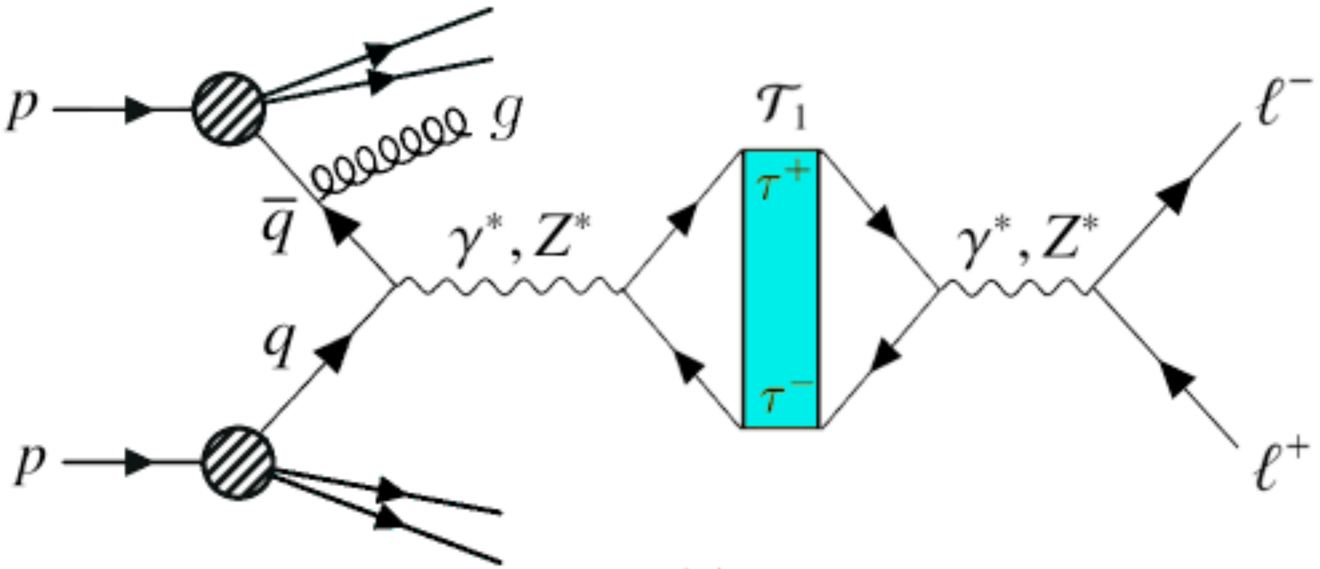
- **The spin-triplet state (ortho-ditauonium $\mathcal{T}_1$)**
  - Exploring other possibilities

d'Enterria, HSS (2302.07365)

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

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	–	–

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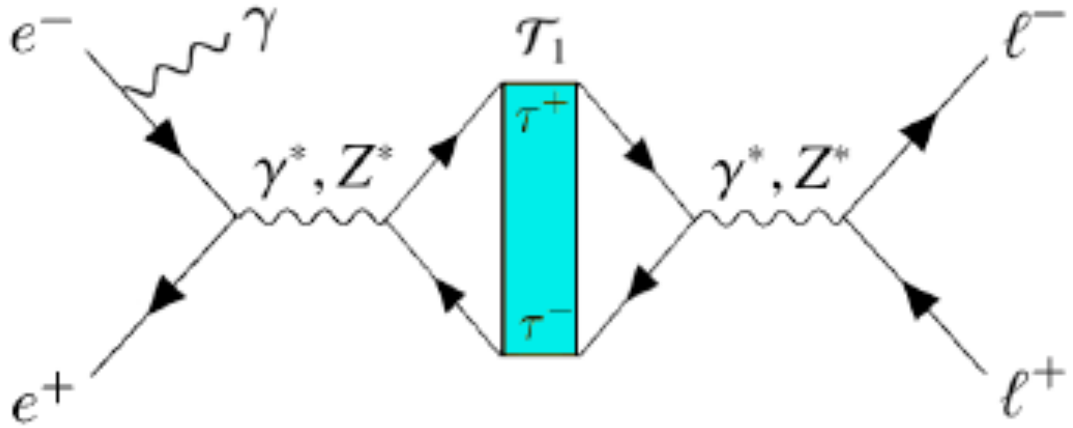
d'Enterria, HSS (2302.07365)

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

Using displaced vertex to kill huge backgrounds

If L_{xy} > 15 (20) $\mu\mathrm{m}$, the total expected number of events would be 8 (4).

Remaining challenge: instrumental effects.



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

Colliding system, $\sqrt{s}$, $\mathcal{L}_{\mathrm{int}}$, 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

How to observe ditauonium ?

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

    The rest are hopeless either plagued with huge backgrounds or too-few signal events ! d'Enterria, HSS (2302.07365)
  - B decay ?

Fael & Mannel (1803.08880)

	$B \to K$ ortho		$B \to K^*$ ortho	
ℓ	$\delta_{\bar{c}c}$	Br	$\delta_{\bar{c}c}$	Br
τ	0.18	1.4×10^{-13}	0.21	3.0×10^{-13}

Conclusion

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- 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.

$$\gamma\gamma \to \mathcal{T}_0 \to \gamma\gamma \text{ @ FCC} - \text{ee \& Belle II}$$
$$e^+e^- \to \mathcal{T}_1 \to \mu^+\mu^- \text{ @ STCF}$$
$$pp \to \mathcal{T}_1 j \to \mu^+\mu^- j \text{ @ LHC}$$

- 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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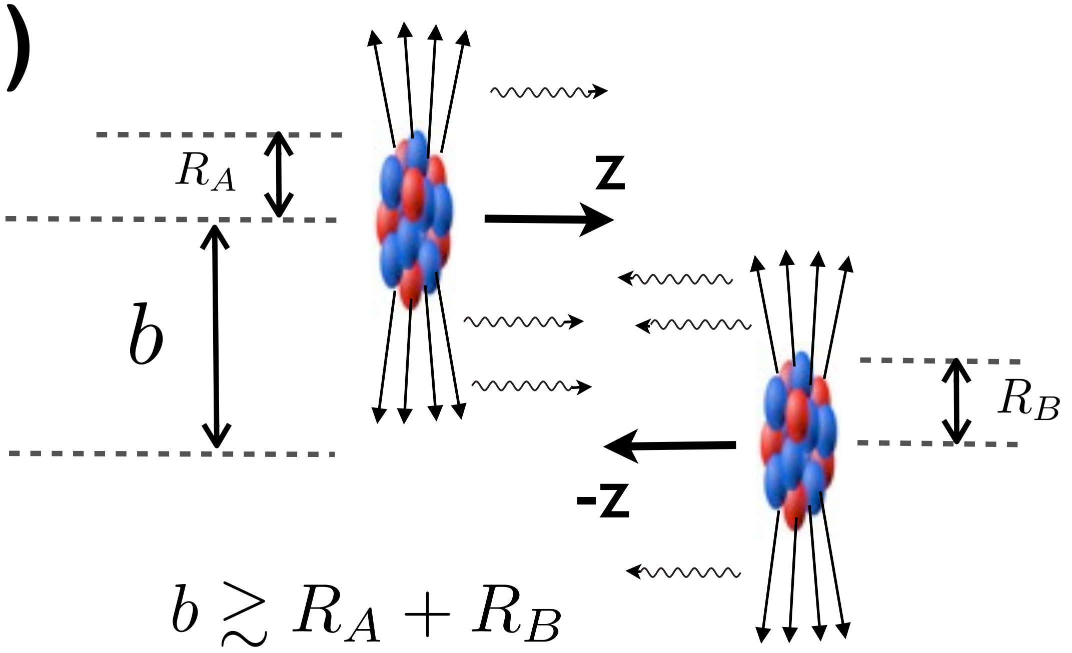
Thank you for your attention !

Backup Slides

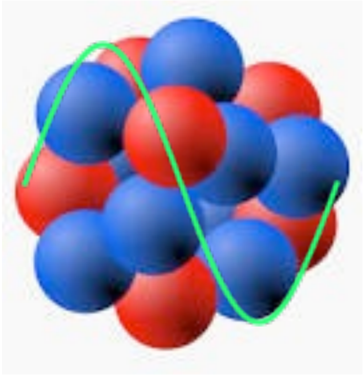
Brief on ultra-peripheral collsions

- **Ultra-Peripheral Collisions (UPCs)**



- **Large photon flux** $\propto Z^2$

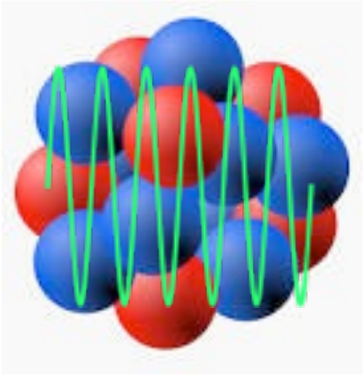
- **Photon may interact either coherently or incoherently**



$\lambda \gtrsim R_A$

Coherent

vs



$\lambda < R_A$

Incoherent

- **Coherent photon virtuality** $Q^2 < R_A^{-2}$

⇨ Equivalent Photon Approximation

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)