Exotic atom production with UPCs

Joint EF07 and EF06 discussion: UPC physics with ion beams

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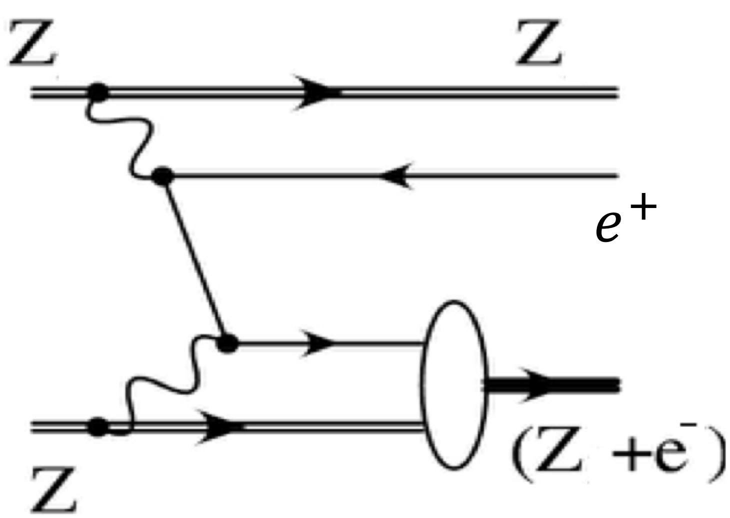
Pair Production with Atomic Capture



Bertulani, Baur,
Phys. Rep. 163, 299 (1988)
Brazilian J. Phys. 18, 559 (1988)

$$Z + Z \to (Z + e^-) + Z + e^+$$

Ingredients:

1. Perturbation theory
2. Sommerfeld-Maue wavefunction (e^+)

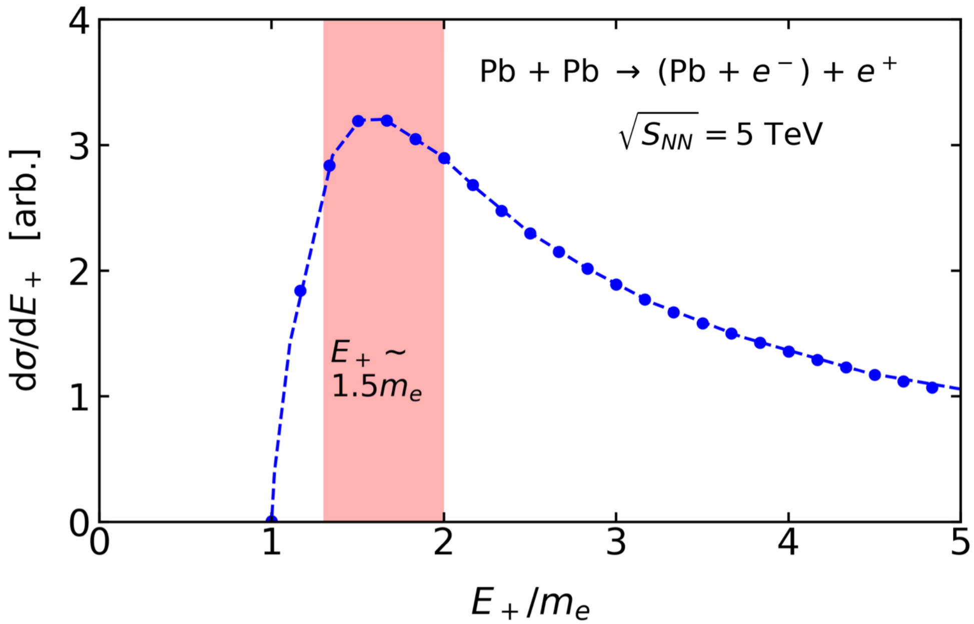
$$\Psi_+ = \left[\frac{2\pi a_+}{e^{2\pi a_+} - 1}\right]^{1/2} e^{-i\boldsymbol{k}_+\cdot\boldsymbol{r}} \left[1 + \frac{i}{2E_+}\boldsymbol{\alpha}\cdot\boldsymbol{\nabla}\right] F(\boldsymbol{k}_+, \boldsymbol{r})\, v$$

$$a_+ = \frac{Z\alpha}{\mathrm{v}_+}$$

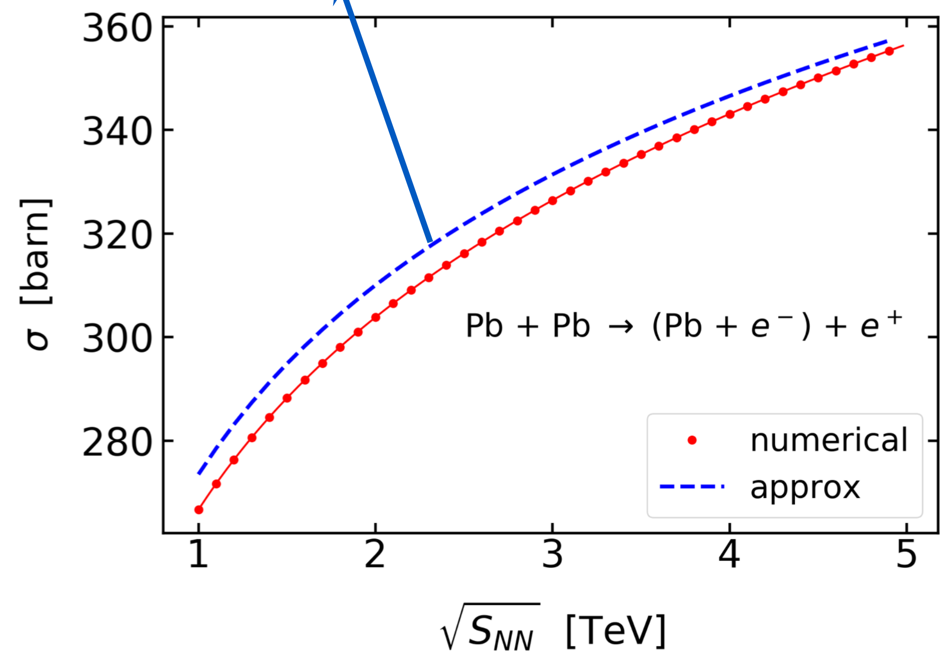
3. Bound state wavefunction (e^-)

$$\Psi_- = \left[\frac{(Zm\alpha)^3}{\pi}\right]^{1/2} \left[1 + \frac{i}{2}(Z\alpha)\boldsymbol{\alpha}\cdot\frac{\boldsymbol{r}}{r}\right] e^{-(Zm\alpha)r}\, u$$

Pair Production with Capture



$$\sigma \sim \frac{33\pi}{10} \frac{(Z\alpha)^8}{m_e^2} \frac{1}{e^{2\pi Z\alpha} - 1} [\ln\gamma - 2.051]$$



Baur, Bertulani, NPA 505, 835 (1989)

Luminosity: $L = L_0 \exp(-\lambda t)$

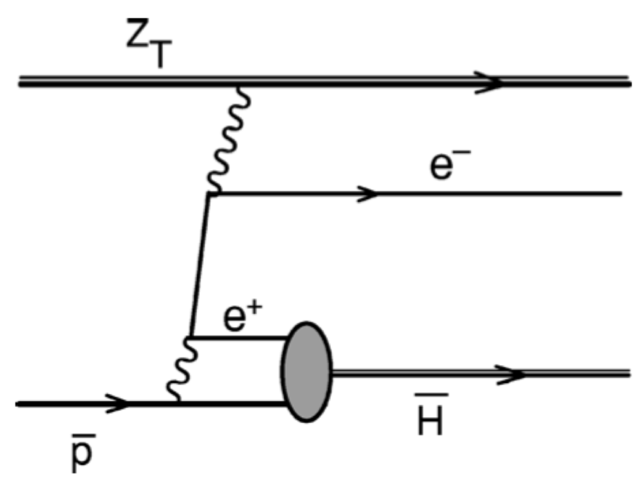
LHC, Pb+Pb → $\lambda \sim (2 \text{ hours})^{-1}$

Mainly K-shell capture, with ~ 20% capture in higher atomic orbitals.

Antihydrogen production:

Baur, PLB **311**, 343 (1993)

Munger, Brodsky, Schmidt, PRD 49, 3228 (1994)



The New York Times

WORLD | U.S. | N.Y. / REGION

Physicists Manage to Create The First Antimatter Atoms

By MALCOLM W. BROWNE
Published: January 5, 1996

1996

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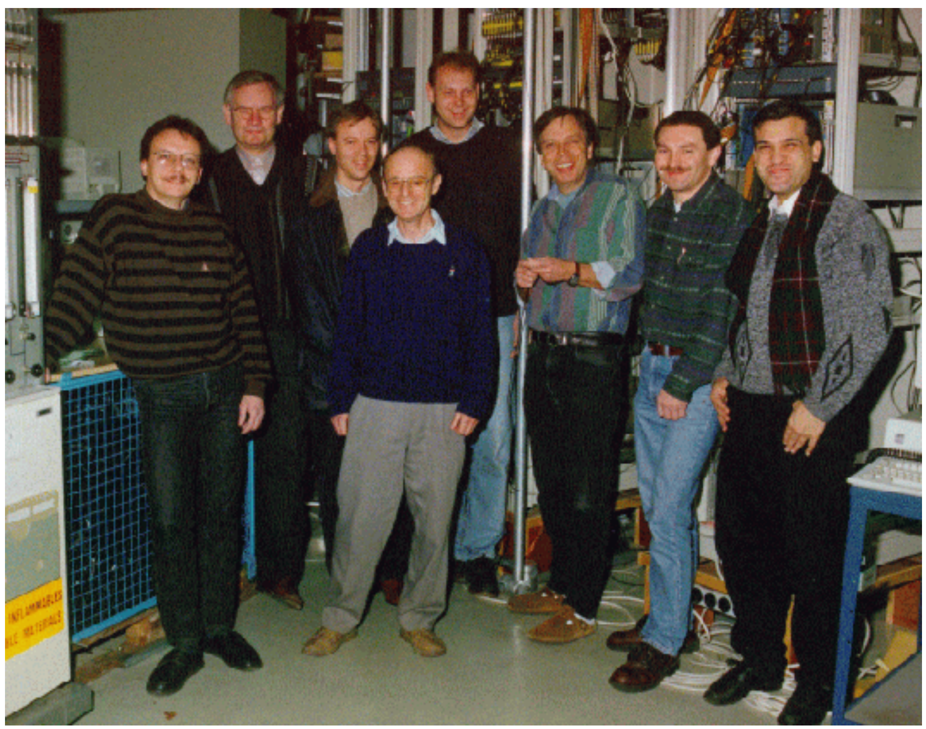
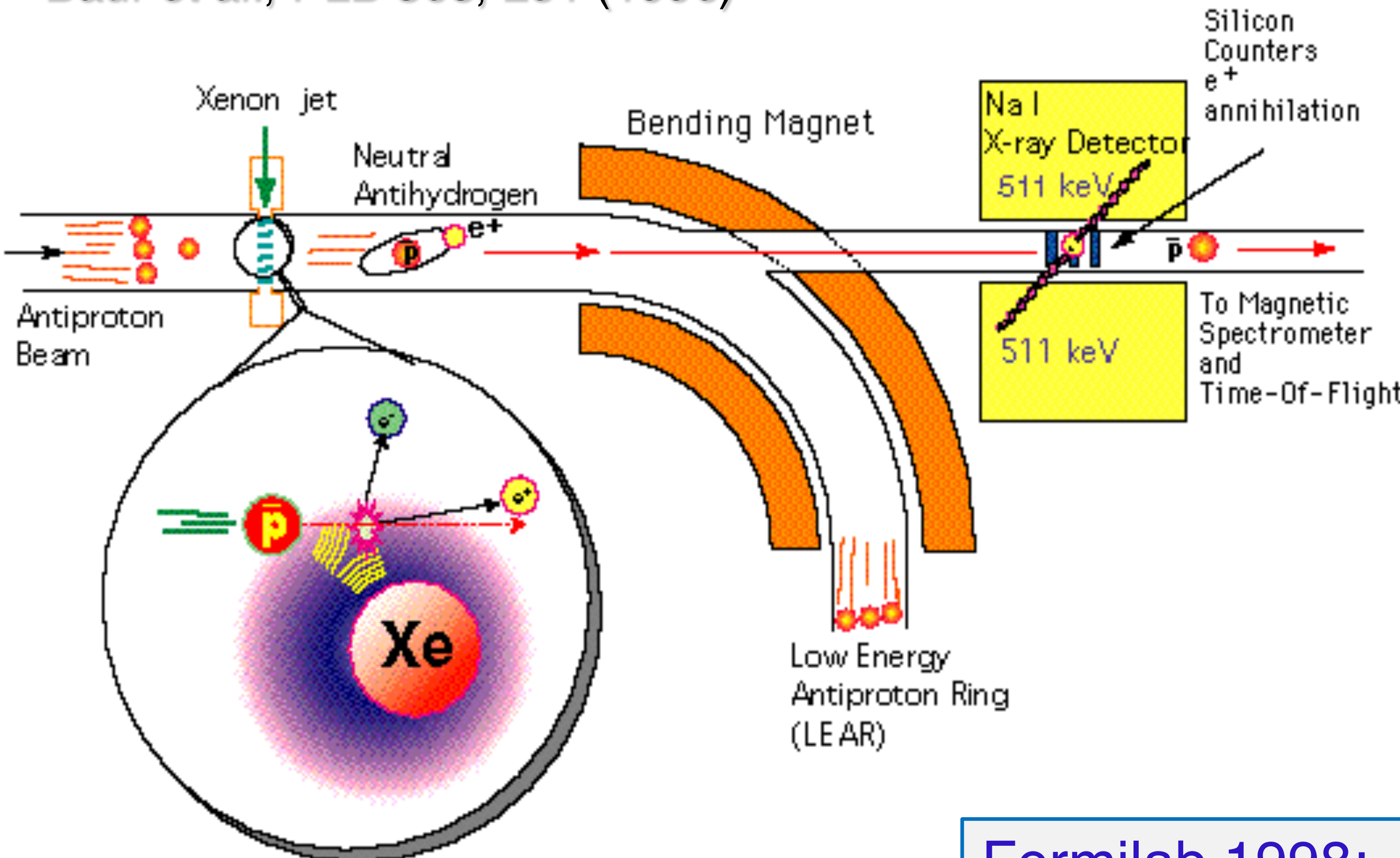
But the neutrality of antihydrogen, like that of ordinary hydrogen, renders it impossible to contain or manipulate using magnetic fields. Moreover, an antiatom cannot be contained in an ordinary vessel, since the slightest contact with the container's wall causes it to annihilate. Consequently, other groups are developing enormously sophisticated methods, including interacting lasers, to manipulate and secure antiparticles inside vacuum chambers.

Baur et al,
PLB 368, 251 (1996)



First Production of AntiHydrogen

Baur et al., PLB 368, 251 (1996)



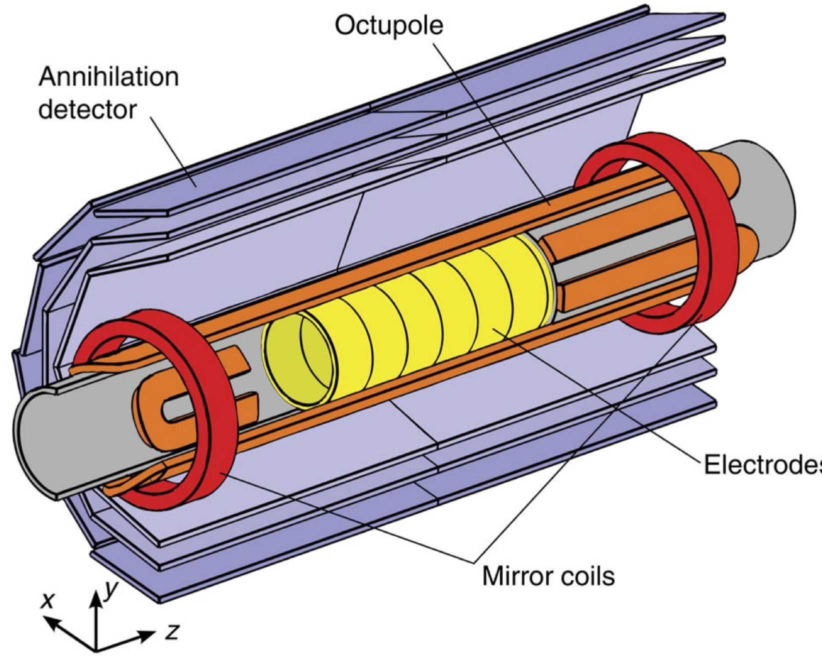
Fermilab 1998:

Blanford et al, PRL 80, 3037 (1998)

11 events as predicted

Bertulani, Baur, PRD 58, 034005 (1998)

Antihydrogen



- $96 trillion dollars per gram of antihydrogen (most expensive material to produce)

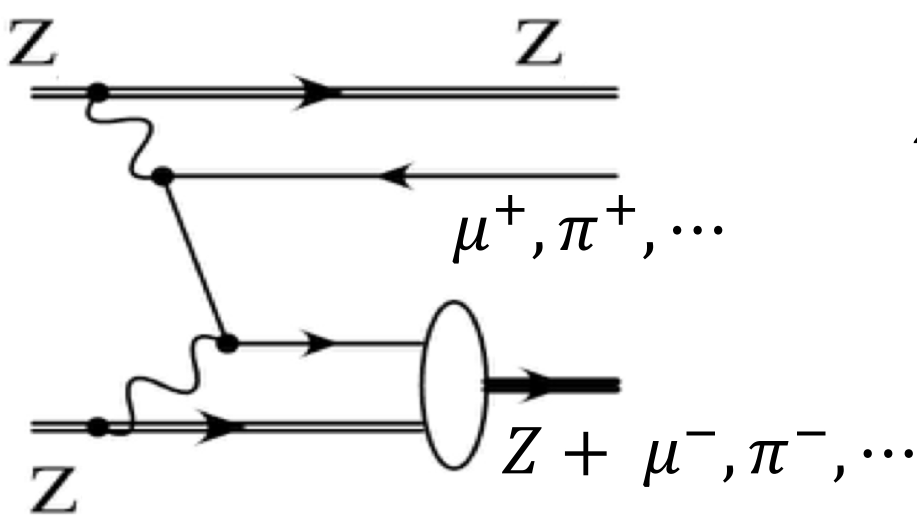
- CERN Antiproton Decelerator (AD) + atom trap

- **ALPHA experiment CERN:**
  1S ←→ 2S transition → H same as $\overline{\mathrm{H}}$ within 200 ppt
  Moretti et al., Nature 419, 456 (2002) → no CPT violation
  → no "source" for baryon asymmetry

- **Hbar and anti-gravity:**
  Amole et al., Nature Com. 4, 1785 (2013)
  → $\pm$ ($\bar{H}$ gravitational)/($\bar{H}$ inertial) mass < 75 → not conclusive

- No antideuterium, antitritium, or antihelium atoms have ever been produced.

Production of exotic Atoms



Bertulani, Ellermann, PRC 81, 044910 (2010)

$$Z + Z \to (Z + \mu^-) + Z + \mu^+$$
$$\to (Z + \pi^-) + Z + \pi^+$$
$$\to \cdots$$

Ingredients:

1. Perturbation theory
2. LO + NLO

$$\Psi_+ = \left[\frac{2\pi a_+}{e^{2\pi a_+} - 1}\right]^{1/2} \left[e^{-i\boldsymbol{k}_+\cdot\boldsymbol{r}}\boldsymbol{v} + \Psi_{NLO}\right]$$

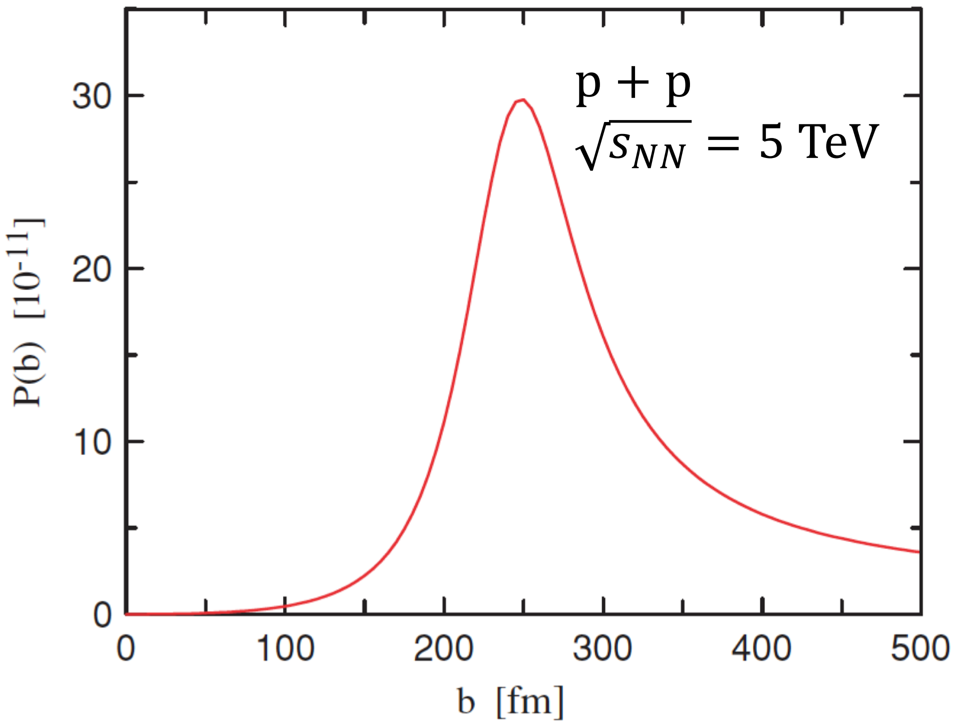
$$\Psi_{NLO} = \frac{Z\alpha}{2\pi^2}\int dq^3 e^{i\boldsymbol{q}\cdot\boldsymbol{r}} \frac{2\gamma^0 E_+ + i\boldsymbol{\gamma}\cdot(\boldsymbol{q}-\boldsymbol{k}_+)}{(\boldsymbol{q}-\boldsymbol{k}_+)^2 (q^2 - k_+^2)}$$

3. Virtual photons expanded in multipoles (E1, E2, $\cdots$)

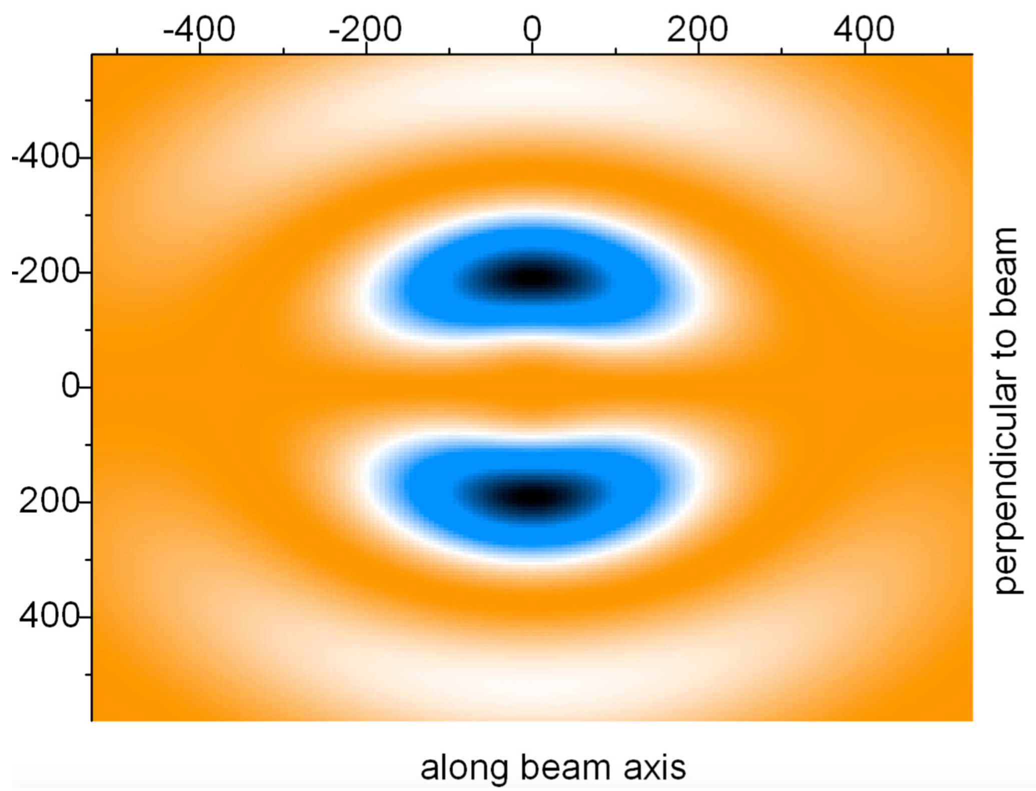
4. Bound state wavefunction for $\mu^-, \pi^-, \cdots$

$$\Psi_- = \left[\frac{(Zm\alpha)^3}{\pi}\right]^{1/2} \left[1 + \frac{i}{2}(Z\alpha)\boldsymbol{\alpha}\cdot\frac{\boldsymbol{r}}{r}\right] e^{-(Zm\alpha)r}\, u$$

Production of exotic Atoms

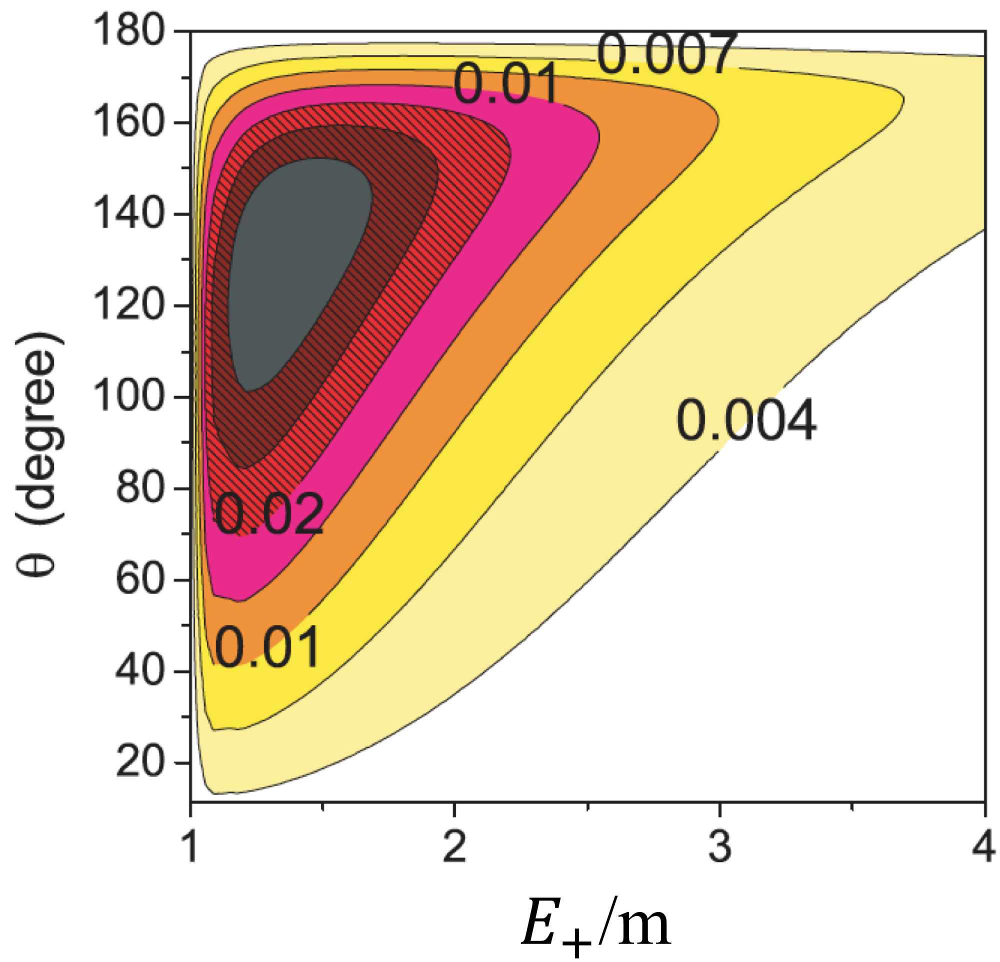


- Production dominated by electric dipole (~70%), but electric quadrupole has a substantial contribution (~30%)



- Production probability maximum at impact parameters $b \sim a^{H}_{\mu,\pi,\cdots}$ (Bohr radius)
e.g., $b \sim 255\ fm$ for muons

Production of Exotic Atoms



Angular distribution of the positive muon the beam direction of motion and energy of the free positive muon.

Production of Exotic Atoms

$$\sqrt{s_{NN}} = 5\ \text{TeV}$$

"Exotic" atom	pp	PbPb
muonic	44.8×10^{-4} pb	0.16 mb
pionic	21.3×10^{-4} pb	0.09 mb
kaonic	1.3×10^{-4} pb	4.3 μb
ρ atom	0.51×10^{-4} pb	1.3 μb
protonium	0.09×10^{-4} pb	0.5 μb

Cross sections for production of exotic atoms in pp and PbPb collisions at the LHC.

Exotic Atoms

- The proton radius puzzle
  - Atomic spectroscopy: 0.8768 ± 0.0069 fm
  - Rutherford scattering: 0.8775 ± 0.005 fm
  - Muonic hydrogen: 0.842 ± 0.001 fm

    (Bezginov et al., Science 365, 1007 (2019))

- Nuclear skins → EoS of neutron stars

- Laser spectroscopy of pionic atoms
  - $\pi^{-}\ {}^{4}He \rightarrow$ constraining mass of muon antineutrino

    Hori et al., Nature 581, 37 (2020)

- Kaonic atom X-ray data → most precise value of antikaon-nucleon scattering lengths, tests of QED

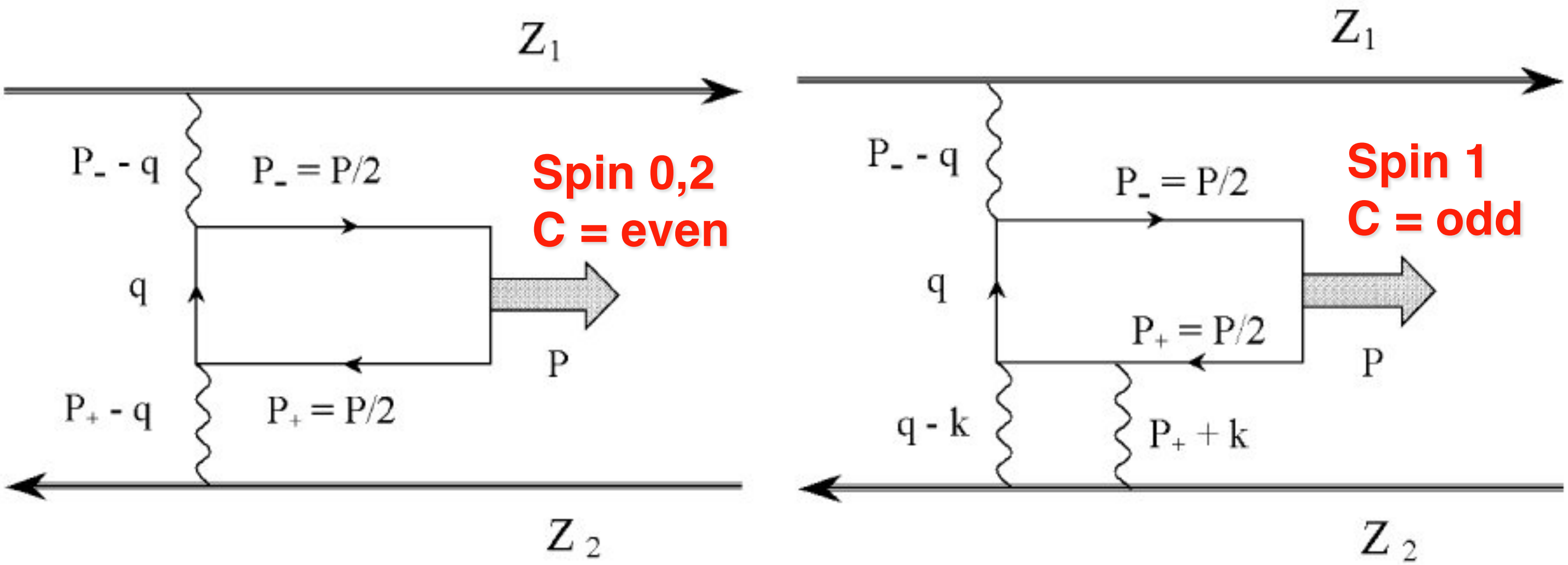
    Bazzi et al., PLB 704, 113 (2011)

- Protonium $\mathrm{p\bar{p}}$ → antiprotonic Rydberg constant, antiproton/electron mass ratio

    Zurlo et al., PRL 97, 153401 (2006)

Meson production and decay widths

Bertulani, Navarra, NPA703 (2002) 861



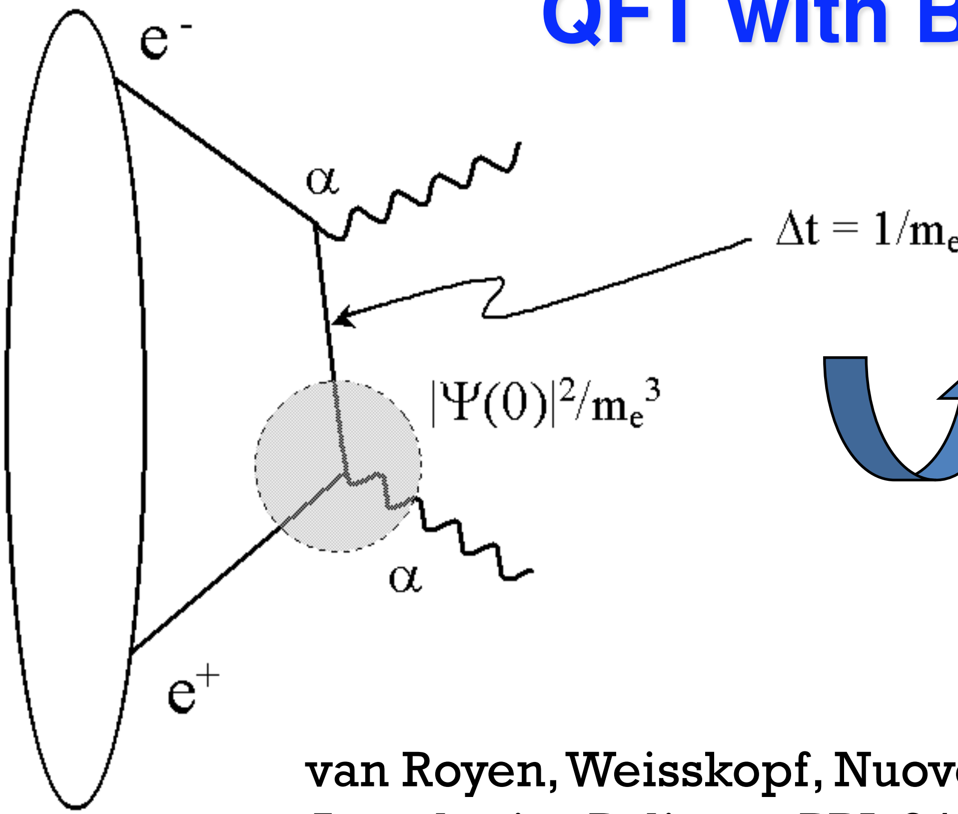
$$\mathcal{M} = -ie^2 \bar{u}\left(\frac{P}{2}\right)\left[\int \frac{d^4q}{(2\pi)^4} \not{A}^{(1)}\left(\frac{P}{2}-q\right)\frac{\not{q}+m}{q^2-m^2} \times \not{A}^{(2)}\left(\frac{P}{2}+q\right) + \not{A}^{(1)}\left(\frac{P}{2}+q\right)\frac{\not{q}+m}{q^2-m^2}\not{A}^{(2)}\left(\frac{P}{2}-q\right)\right] v\left(\frac{P}{2}\right)$$

E.g., parapositronium (S = 0)
orthopositronium (S = 1)

Spin 0	$\bar{u}Bv \longrightarrow \sqrt{2M}\ \mathrm{tr}\left(\frac{B}{\sqrt{2}}\right)\Psi(0)$
Spin 1	$\bar{u}Bv \longrightarrow \sqrt{2M}\ \mathrm{tr}\left(\frac{\hat{\epsilon}.\boldsymbol{\sigma}}{\sqrt{2}}B\right)\Psi(0)$

at LHC for PbPb at $\sqrt{s_{NN}} = 5$ TeV
$\sigma \sim 425$ mb

QFT with Bound states



$$\Gamma \sim \alpha^2 |\Psi(0)|^2 / m_e^2$$

RECIPE

- replace electrons by quarks
- get rid of $|\psi(0)|^2$

van Royen, Weisskopf, Nuovo Cimento A 50, 617 (1967)
Appelquist, Politzer, PRL 34, 365 (1975)

$$\Gamma_{\gamma\gamma}^{J=0} = \frac{48\pi\alpha^2}{M^2} |\Psi(0)|^2 \sum_i Q_i^4 \qquad \Gamma_{\gamma\gamma}^{(J=2)} = (2J+1)\Gamma_{\gamma\gamma}^{(J=0)} = 5\,\Gamma_{\gamma\gamma}^{(J=0)}$$

Example: parapositronium (S = 0)

$$|\Psi(0)|^2 = (m_e \alpha)^3 / 8\pi n^3$$

Study of positronium propagation in thin metals
Abnomalous mean free path

Exploring Widths of various Mesons at CERN

Bertulani, PRC 79, 047901 (2009)

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
$a_0^{K\bar{K}}$ (980)	(0^{++})	0.6	0.30 ± 0.10	$\longrightarrow K\bar{K} \longrightarrow \gamma\bar{\gamma}$	3.1mb
$a_0^{q\bar{q}}$ (980)		1.5		Hypothetical, NR q-model	8.6 mb
$a_0^{q\bar{q}}$ (980)		1.0		Hypothetical, R q-model	5.5 mb
$f_0^{K\bar{K}}$ (980)	(0^{++})	0.6	$0.29^{+0.07}_{-0.09}$	$\longrightarrow K\bar{K} \longrightarrow \gamma\bar{\gamma}$	3.1 mb
$f_0^{q\bar{q}}$ (980)		4.5		Hypothetical, NR q-model	25.8 mb
$f_0^{q\bar{q}}$ (980)		2.5		Hypothetical, R q-model	14.3 mb
f_0 (1200)		3.25–6.46	Unknown	For $m_q = 0.33$ to 0.22 GeV	9.6–21 mb
f_2(1274)	(2^{++})	1.75–4.04	2.6 ± 0.24	$\Gamma_{\gamma\gamma}(f_0) / \Gamma_{\gamma\gamma}(f_2) = 1.86$–1.60	21–49 mb
$f_2^{\lambda=2}$ (1274)		1.71–3.93		$(\lambda = 0) / (\lambda = 2) = 0.022$–0.029	20–44 mb
$f_2^{\lambda=0}$ (1274)		0.04–0.11			0.09–0.23 mb
f_0 (1800)		2.16–2.52	Unknown	2^3P_0 radial excitation	2.5–3.1 mb
f_2 (1800) $(\lambda = 2)$		1.53–2.44		2^3P_2 radial excitation	1.7–2.9 mb
f_2 (1800) $(\lambda = 0)$		0.08–0.16		”	0.08–14 mb
f_2 (1525)	(2^{++})	0.17	0.081 ± 0.009	$s\bar{s}$, $m_s = 0.55$ GeV fixed	0.86 mb
f_2' (1525) $(\lambda = 0)$		0.065		”	0.21 mb
f_2' (1525) $(\lambda = 2)$		0.9×10^{-3}		”	0.42 μb
f_4 (2050)		0.36–1.76	Unknown	$^3F_4$	0.03–0.14 mb
f_4 (2050) $(\lambda = 2)$		0.33–1.56		”	0.02–0.13 mb
f_4 (2050) $(\lambda = 0)$		0.03–0.20		”	2–12 μb
f_3 (2050)		0.50–2.49	Unknown	$^3F_3$	0.03–0.13 mb
f_2 (2050)		2.48–11.11	Unknown	$^3F_2$	0.12–0.53 mb
f_2 (2050) $(\lambda = 2)$		1.85–8.49		”	0.09–0.46 mb
f_2 (2050) $(\lambda = 0)$		0.63–2.62		”	0.01–0.07 mb
$f_0^{K^*K^*}$ $(\simeq 1750)$		$\simeq$0.05–0.1	Unknown	Vector-vector molecule	0.19 mb

Exploring Widths of various Mesons at CERN

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
η_c	(0^{-+})	3.4–4.8	$6.7^{+0.9}_{-0.8}$	$m_c = 1.4$–1.6 GeV	0.26–0.34 mb
$\eta_c(3790)$		1.85–8.49	1.3 ± 0.6	$m_c = 1.4$ GeV	0.06–0.1 mb
$\eta'_c(3790)$		3.7	Unknown	$m_c = 1.4$ GeV	0.11 mb
$\eta_c(4060)$		3.3	Unknown		0.09 mb
$\eta^{1D}_{c2}(3840)$		$20. \times 10^{-3}$	Unknown		0.15 μb
$\eta^{2D}_{c2}(4210)$		$35. \times 10^{-3}$	Unknown		0.14 μb
$\eta^{1G}_{c4}(4350)$		0.92×10^{-3}	Unknown		0.08 μb
χ_2	(2^{++})	0.56	0.258 ± 0.019	$(\lambda = 2)/(\lambda = 0) = 0.005$	82 μb
χ_0	(0^{++})	1.56	0.276 ± 0.033	$\Gamma_{\gamma\gamma}(\chi_0)/\Gamma_{\gamma\gamma}(\chi_2) = 2.79$	0.05 mb
χ'_2	(2^{++})	0.64	Unknown		0.09 mb
$h_{c2}(3840)$		20×10^{-3}	Unknown	$^1D_2$	82 μb
$\chi_2(4100)$		30×10^{-3}	Unknown	$^3F_2$	0.11 μb

Mesons	J^{PC}	$\Gamma^{th}_{\gamma\gamma}$ (keV)	$\Gamma^{exp}_{\gamma\gamma}$ (keV)	Obs.	$\sigma^{X}_{\gamma\gamma}$
$\eta^{1S}_b(9400)$		0.17×10^{-3}	Unknown		19 nb
$\eta^{2S}_b(9400)$		0.13×10^{-3}	Unknown		16 nb
$\eta^{3S}_b(9480)$		0.11×10^{-3}	Unknown		14 nb
$\eta^{1D}_{b2}(10150)$		$33. \times 10^{-6}$	Unknown		0.4 nb
$\eta^{2D}_{b2}(10450)$		$69. \times 10^{-6}$	Unknown		0.8 nb
$\eta^{1G}_{b4}(10150)$		$59. \times 10^{-6}$	Unknown		0.7 nb
$\eta_b(9366)$	(0^{-+})	0.17	Unknown		0.12 μb
η'_b		0.13	Unknown		0.17 μb
η''_b		0.11	Unknown	$s\bar{s}$, $m_s = 0.55$ GeV fixed	0.15 μb
$\chi_{b2}(9913)$	(2^{++})	3.7×10^{-3}	Unknown		0.09 μb
$\chi_{b0}(9860)$	(0^{++})	$13. \times 10^{-3}$	Unknown		0.08 μb

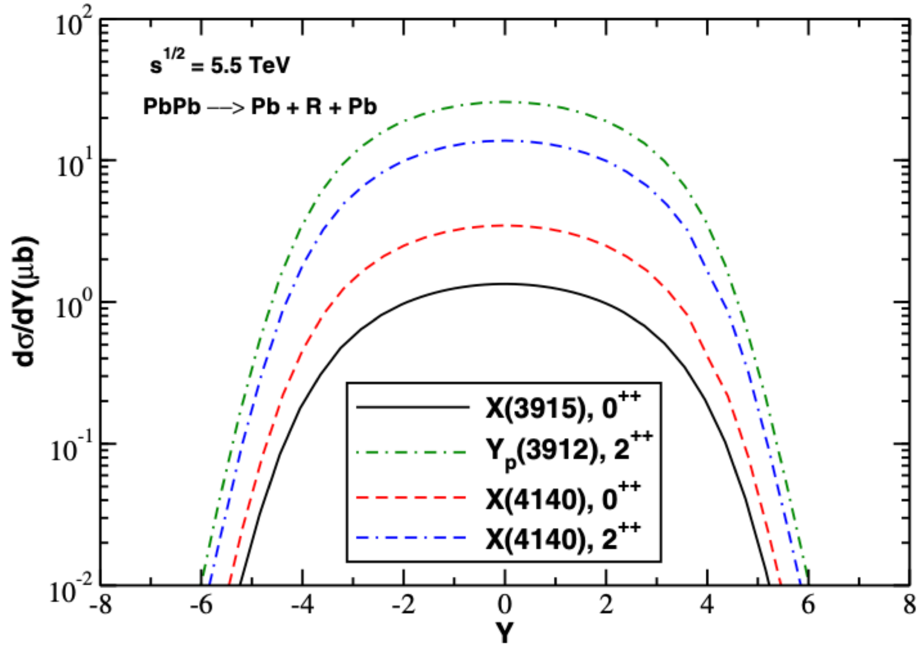
Exploring Widths of various Mesons at CERN

	J^{PC}	$\Gamma_{\gamma\gamma}^{th}$ (keV)	$\Gamma_{\gamma\gamma}^{th}$ (keV)	Cross section (mb)
π_0	(0^{-+})	$3.4 – 6.4 \times 10^{-3}$	$8.4 \pm 0.6 \times 10^{-3}$	27 – 52
π (1300)	(0^{-+})	0.43 – 0.49	unknown	0.69 – 0.71
π (1880)		0.74 – 1.0	unknown	0.8 - 1.1
π_2 (1670)	(2^{-+})	0.11 – 0.27	< 0.072	0.41 – 1.1
π_2 (2130)	$2^{-+})$	0.10 – 0.16	unknown	0.36 – 0.54
π_2 (2330)		0.21 – 1.6	unknown	0.04 – 0.31

→ Needs a dedicated experimental collaboration

Widths of Exotic Charmonium at CERN

Bertulani, Goncalves, Moreira, Navarra
Phys. Rev. D 94, 094024 (2016)



PbPb collisions using different form factors

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (μb)		σ_F (μb)	
			2.76 TeV	5.5 TeV	2.76 TeV	5.5 TeV
X(3940), 0^{++}	3943	0.33	4.2	8.2	6.5	11.8
X(3940), 2^{++}	3943	0.27	17.2	33.6	26.5	48.4
X(4140), 0^{++}	4143	0.63	6.5	12.9	10.2	18.7
X(4140), 2^{++}	4143	0.50	26.0	51.2	40.3	74.3
Z(3930), 2^{++}	3922	0.083	5.4	10.5	8.3	15.2
X(4160), 2^{++}	4169	0.363	18.4	36.4	28.6	52.7
Y_p(3912), 2^{++}	3919	0.774	50.5	98.6	77.9	142.2
X(3915), 0^{++}	3919	0.20	2.6	5.1	4.0	7.34

Summary

- UPC can be very useful to new findings and precision exp.
- e.g.,
  - witness: Σ^0 lifetime
  - Antihydrogen (CERN 1996)
  - Exotic atoms as test of strong interaction
  - Meson widths
  - PDFs