A heavy ion flashlight for discovering axions

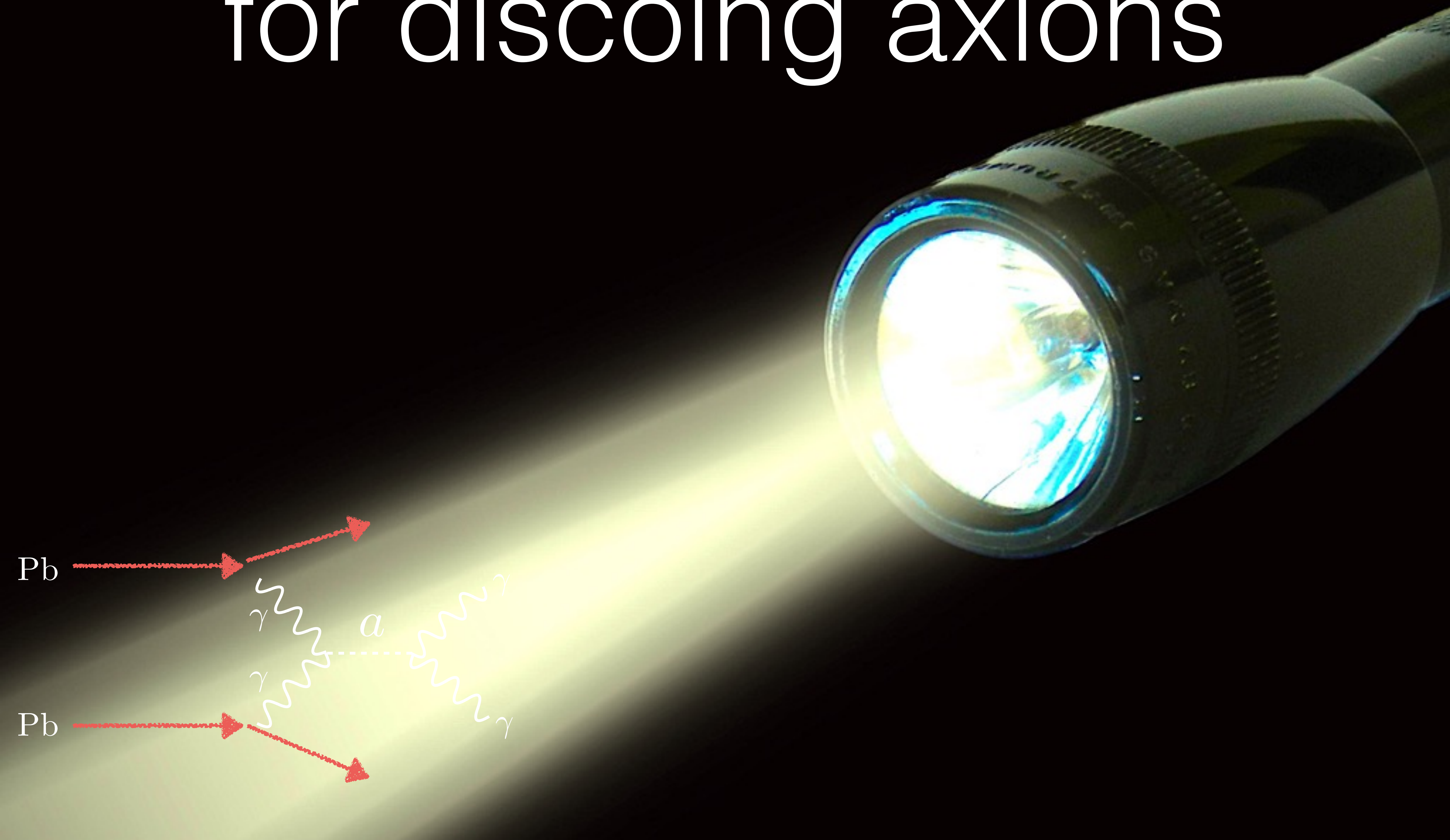
Tom Melia, Berkeley

with Simon Knapen, Tongyan Lin, Tim Lou 1607.06083

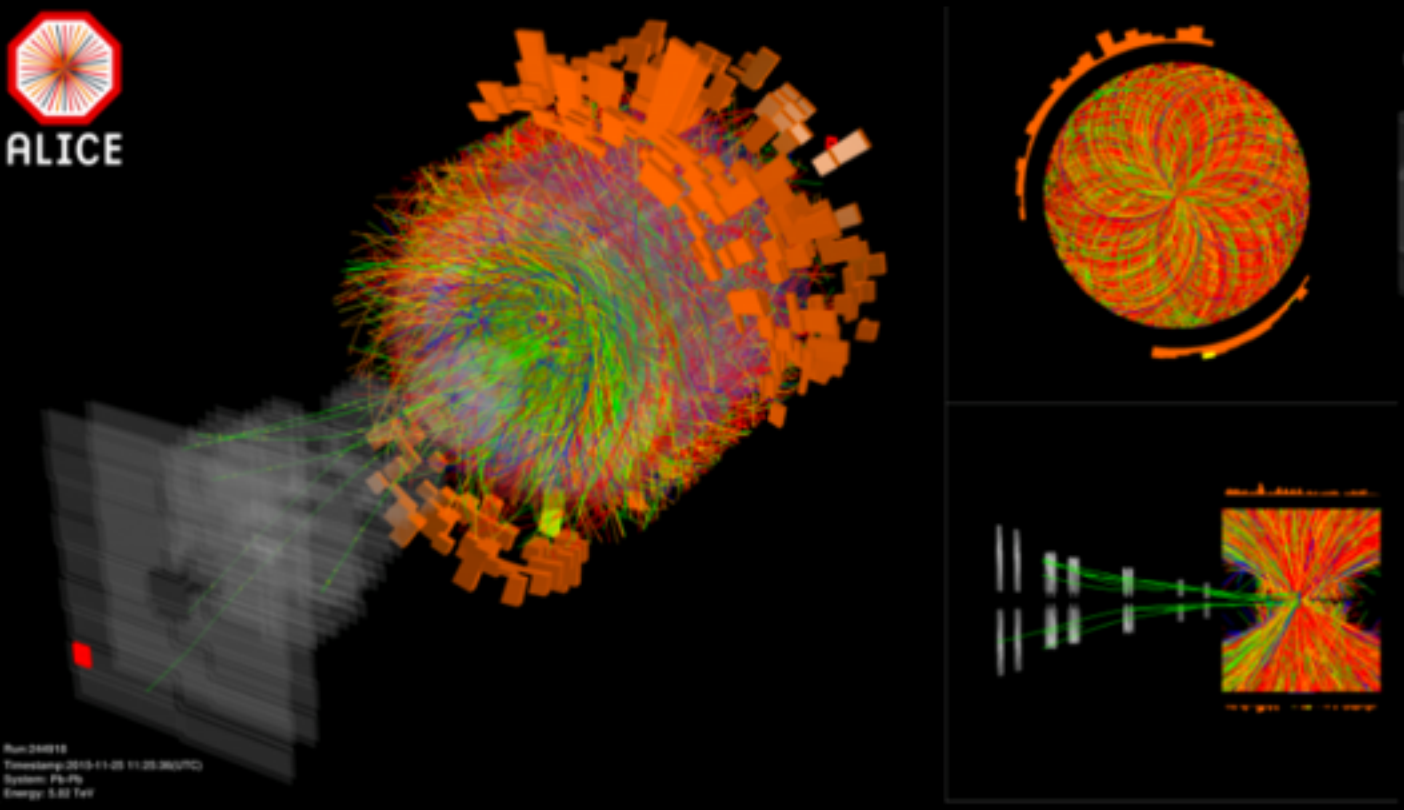
A heavy ion flashlight for discoing axions

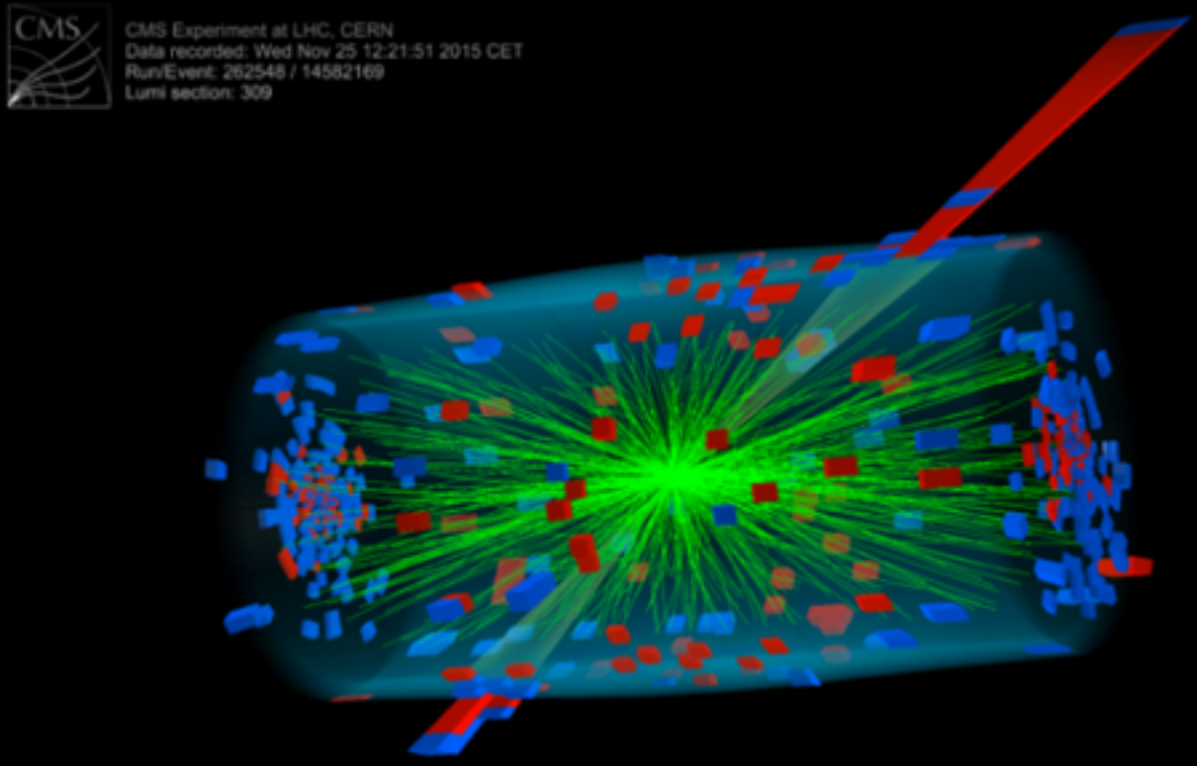
A heavy ion flashlight for discoing axions

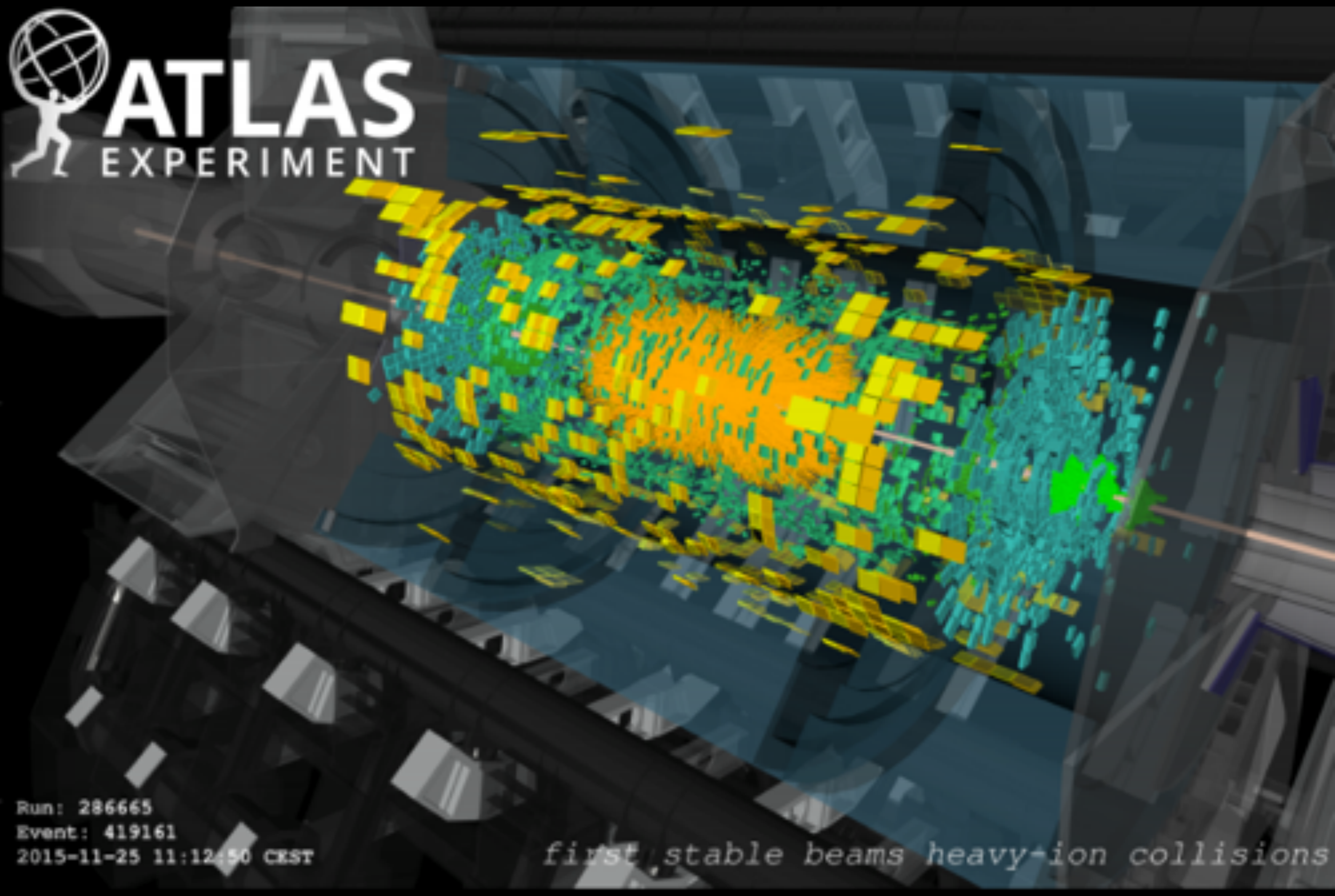
A heavy ion flashlight for discoing axions

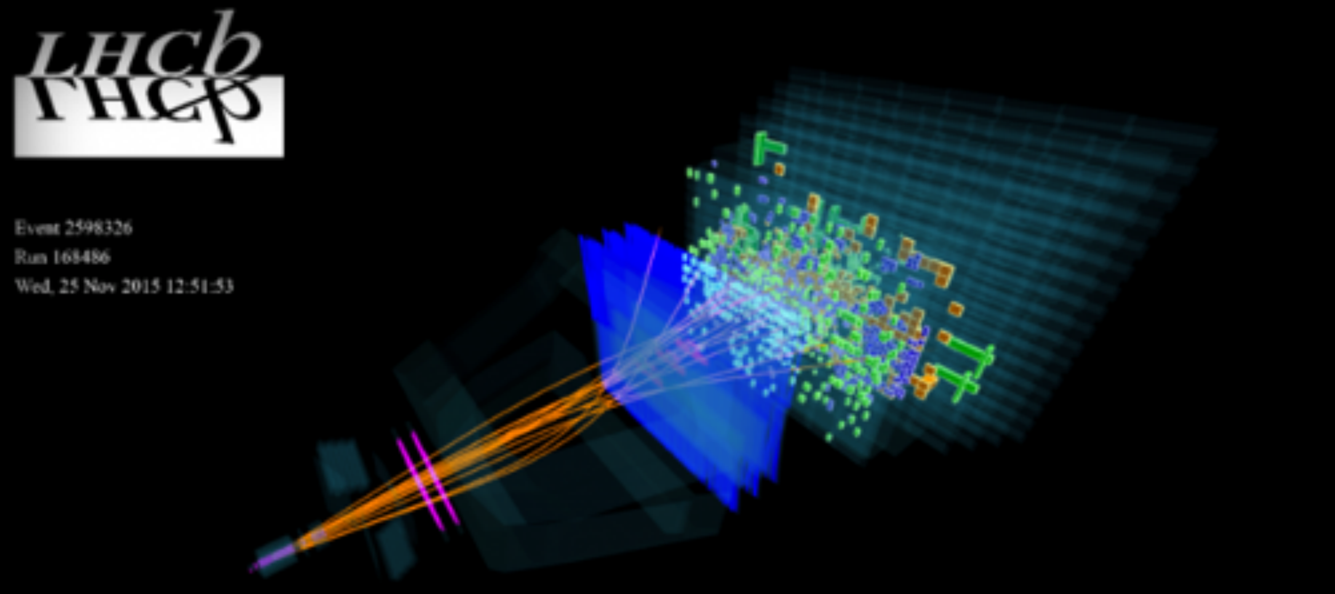


Pb-Pb in each experiment

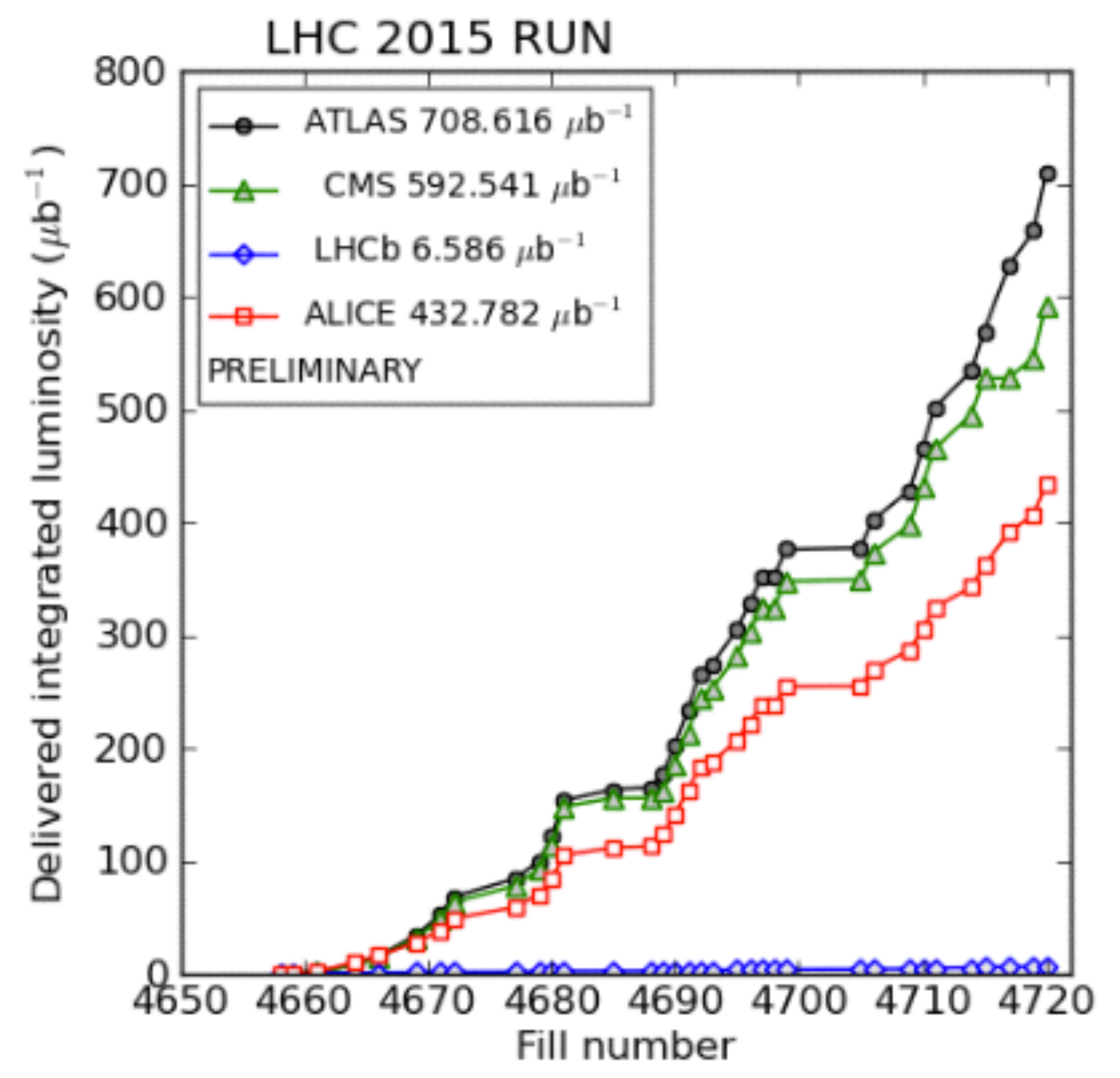




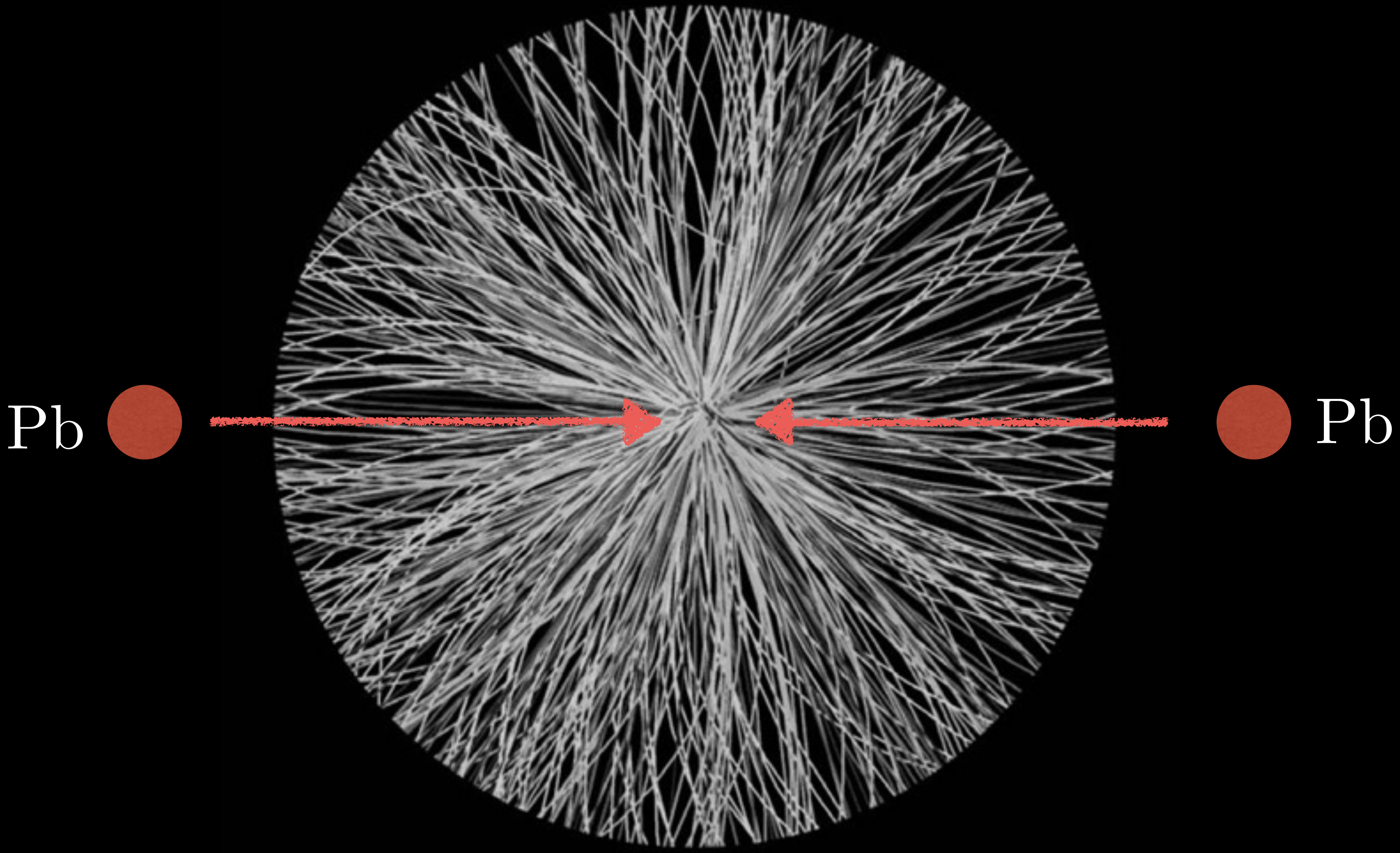




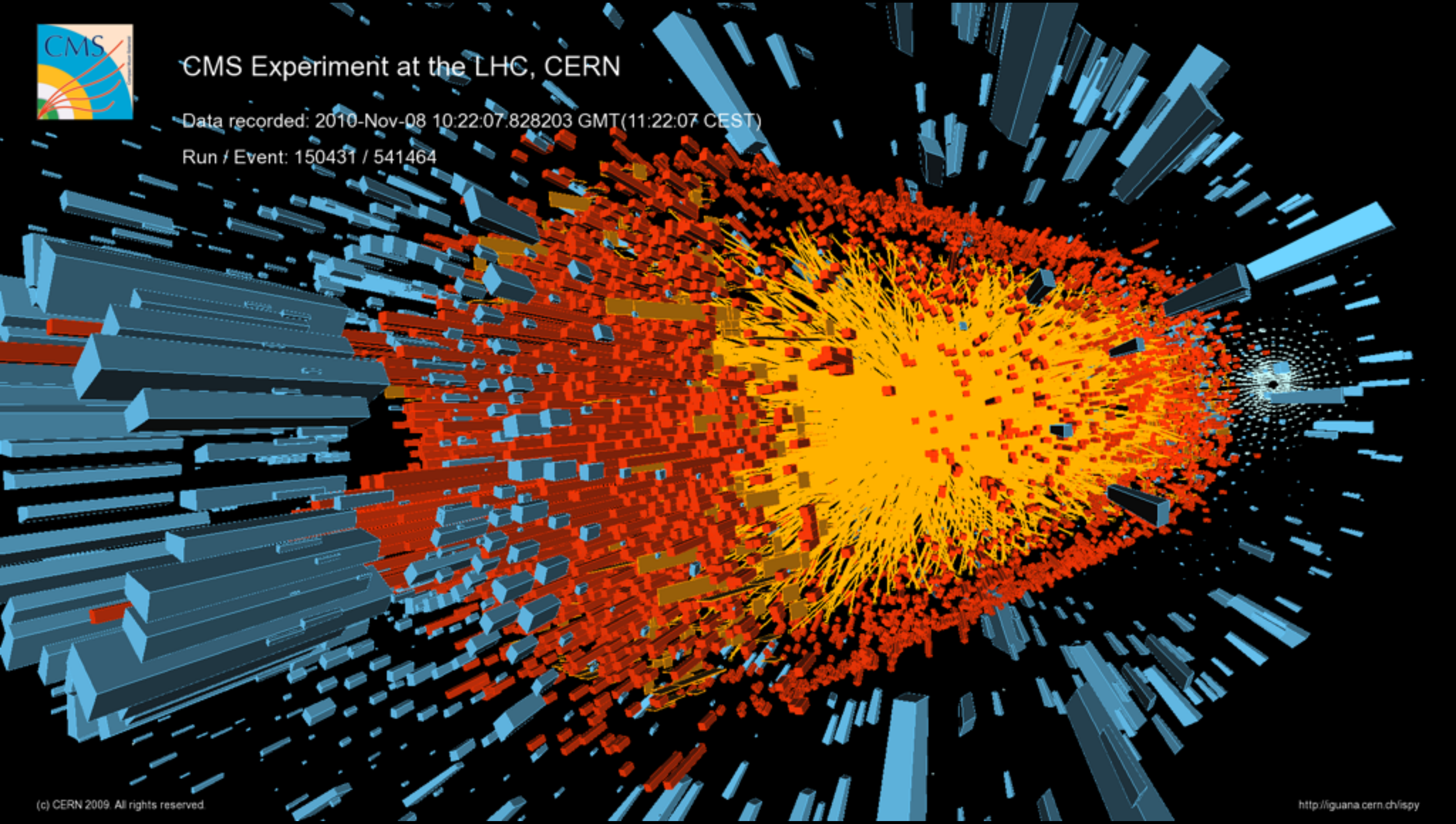
LHC Pb-Pb collisions



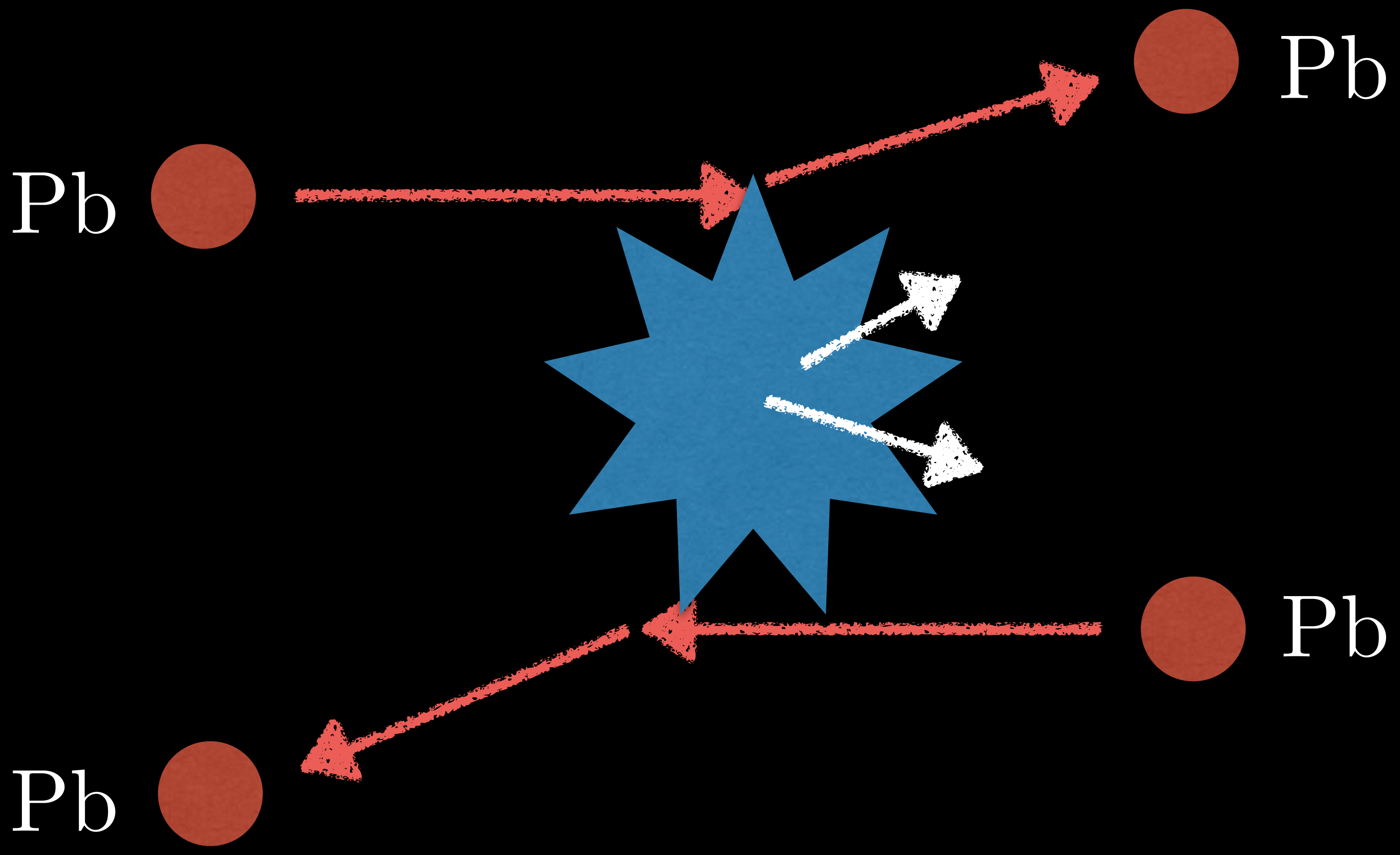
Head-on collisions (5.5 TeV nuc-nuc)



1 PeV 'fireballs'



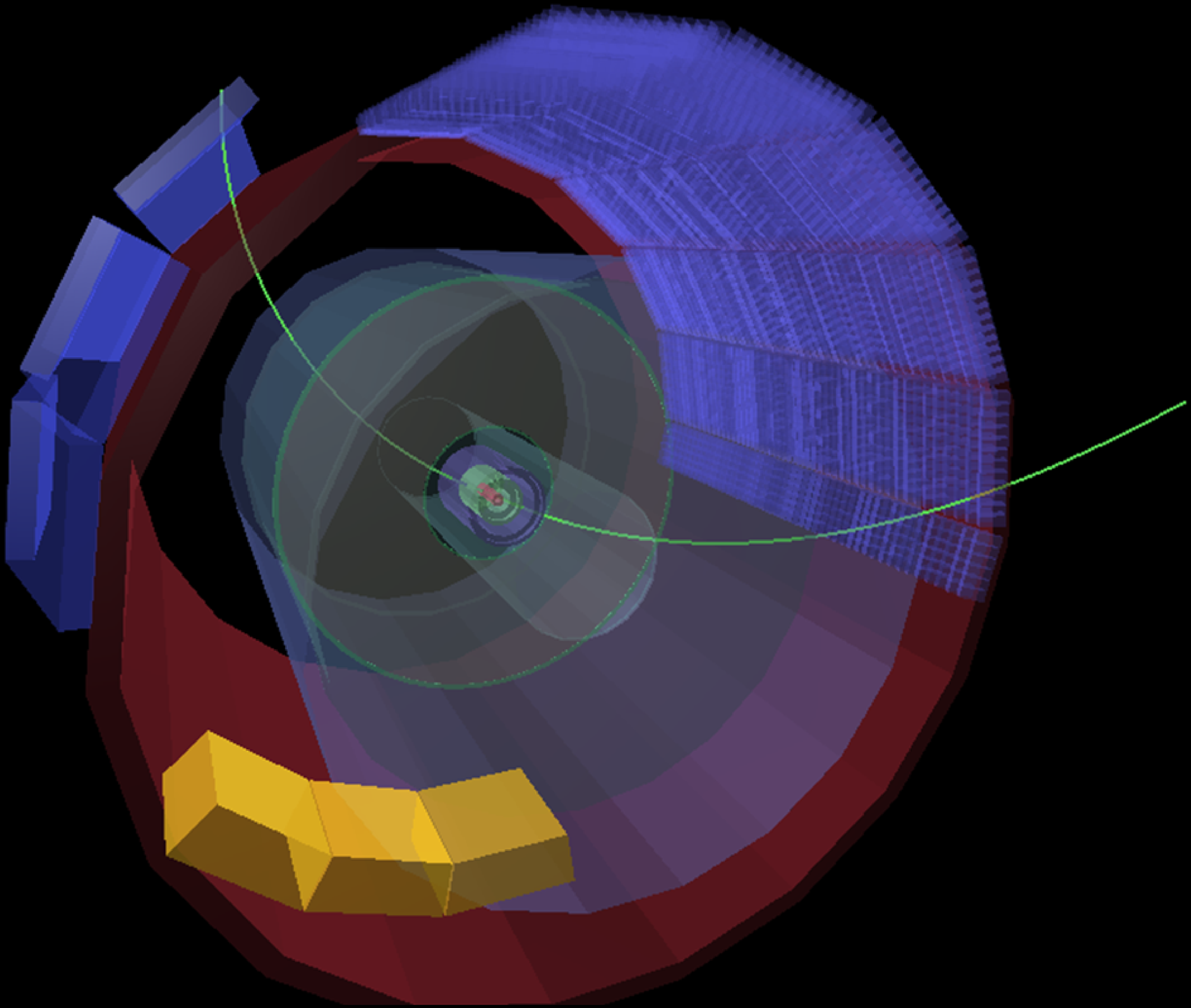
Ultra-peripheral collision



no ion break-up

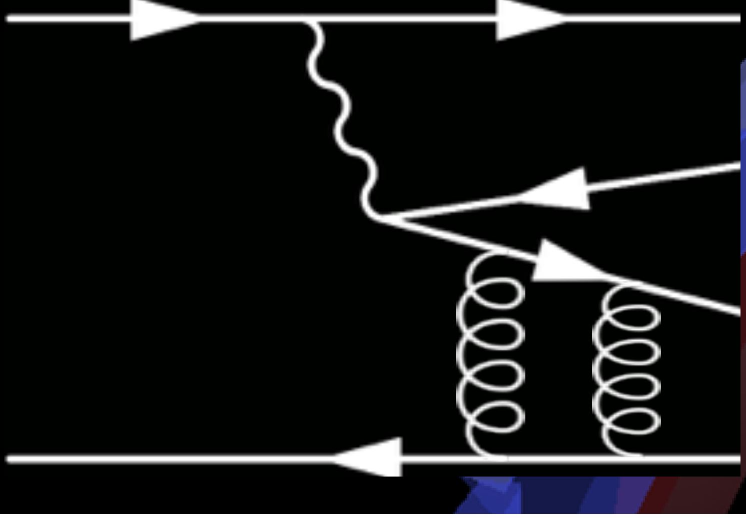
low multiplicity

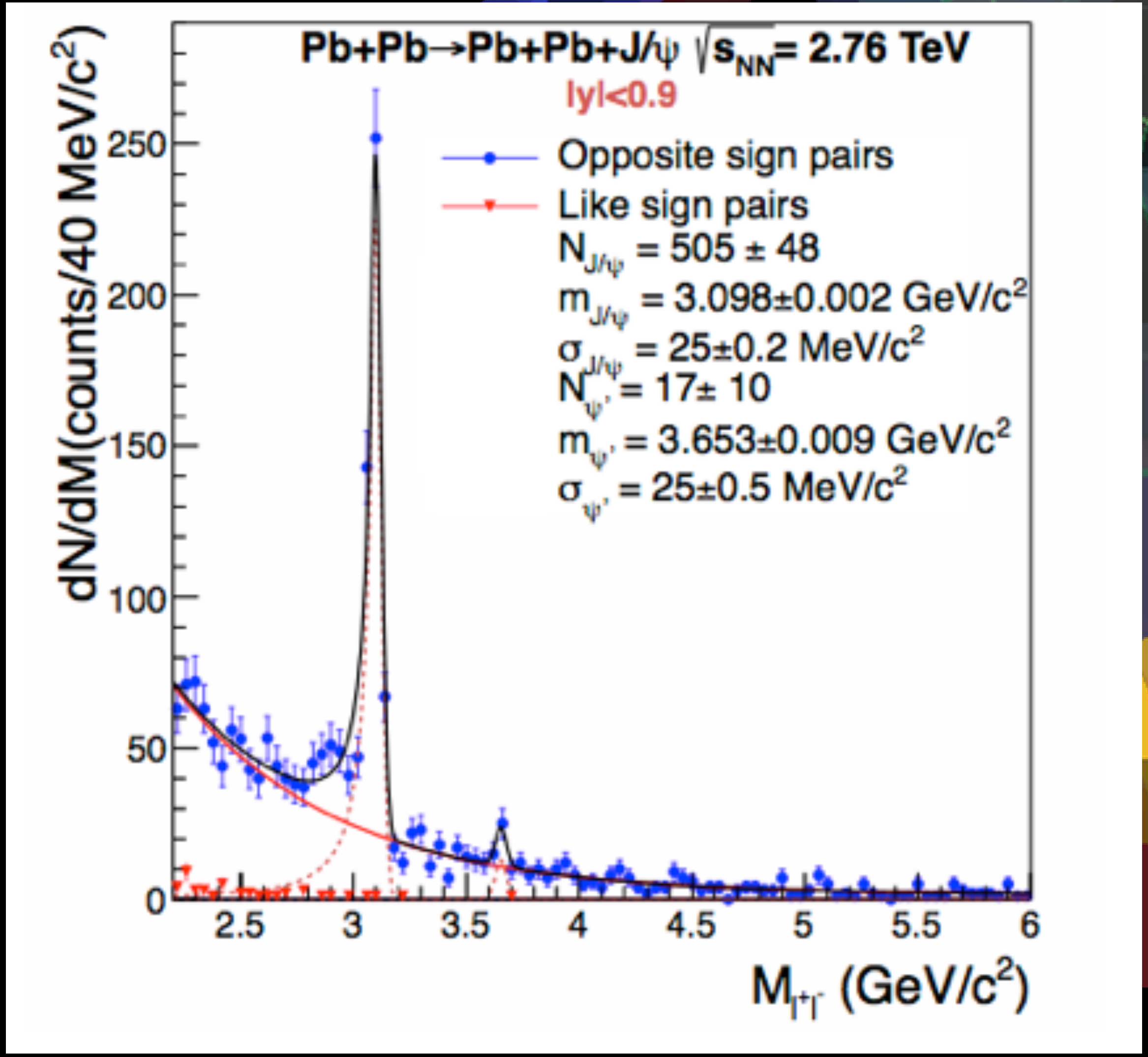
Ultra-peripheral collision

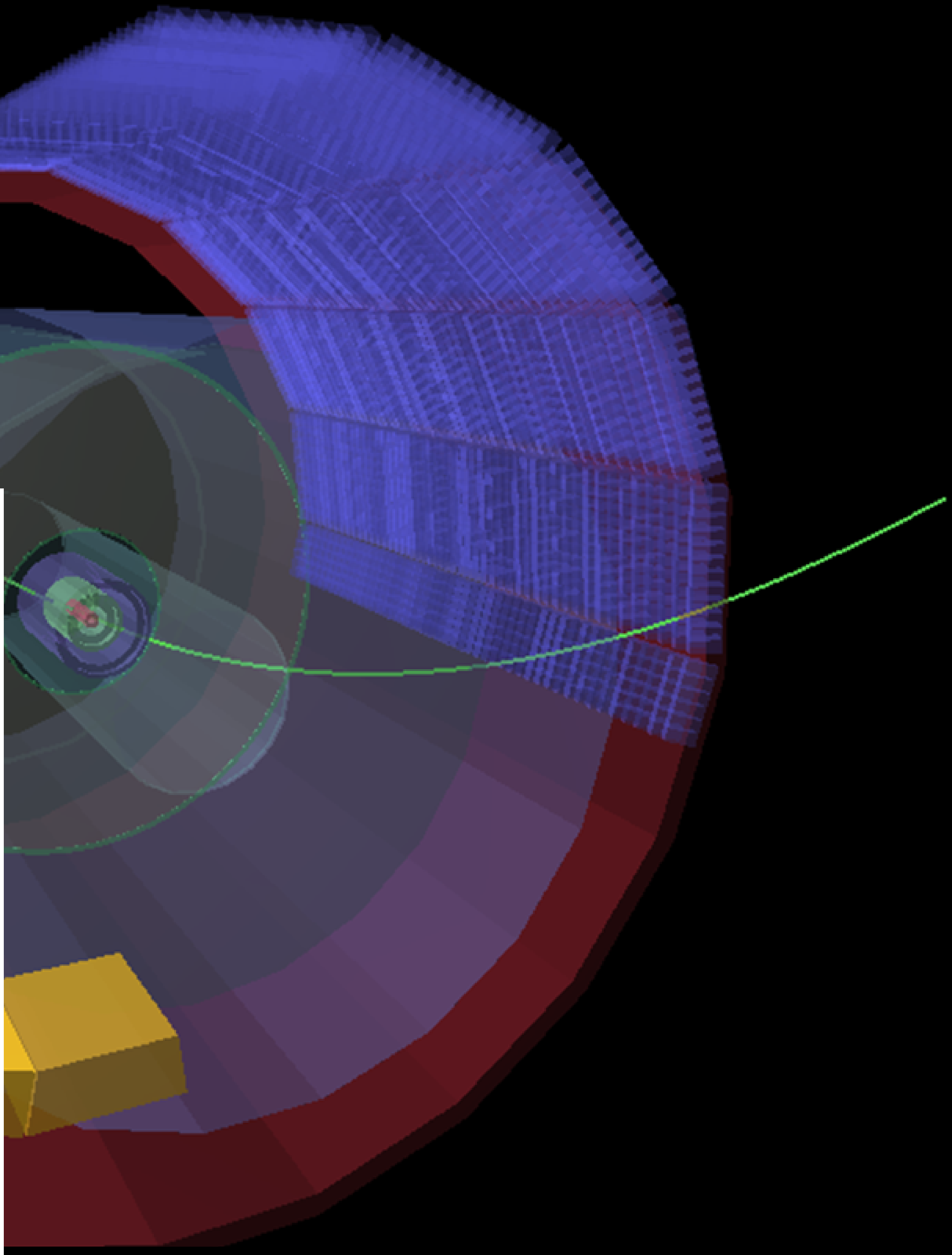


Ultra-peripheral collision

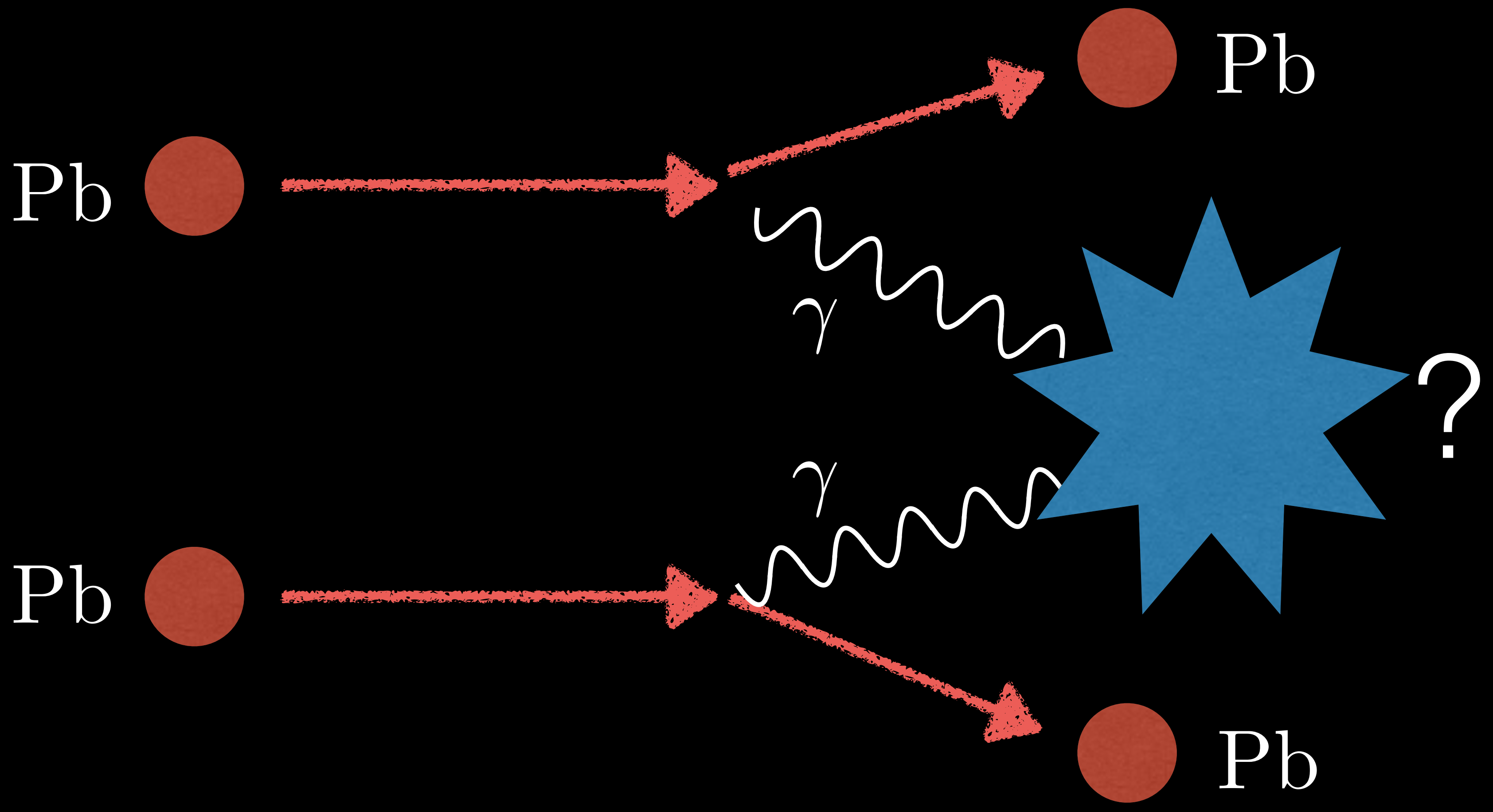
J/Ψ production



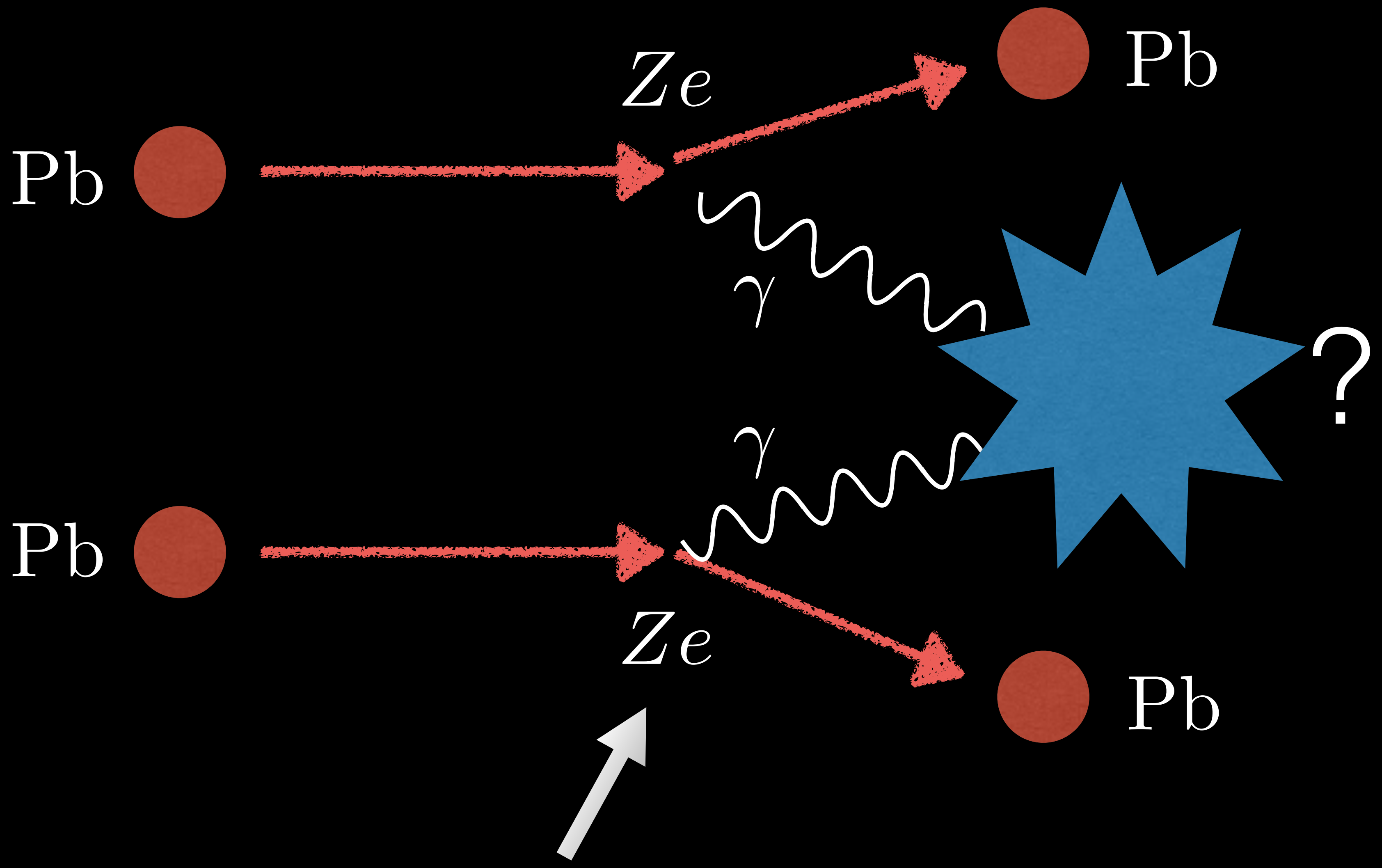




Heavy ion ‘photon collider’



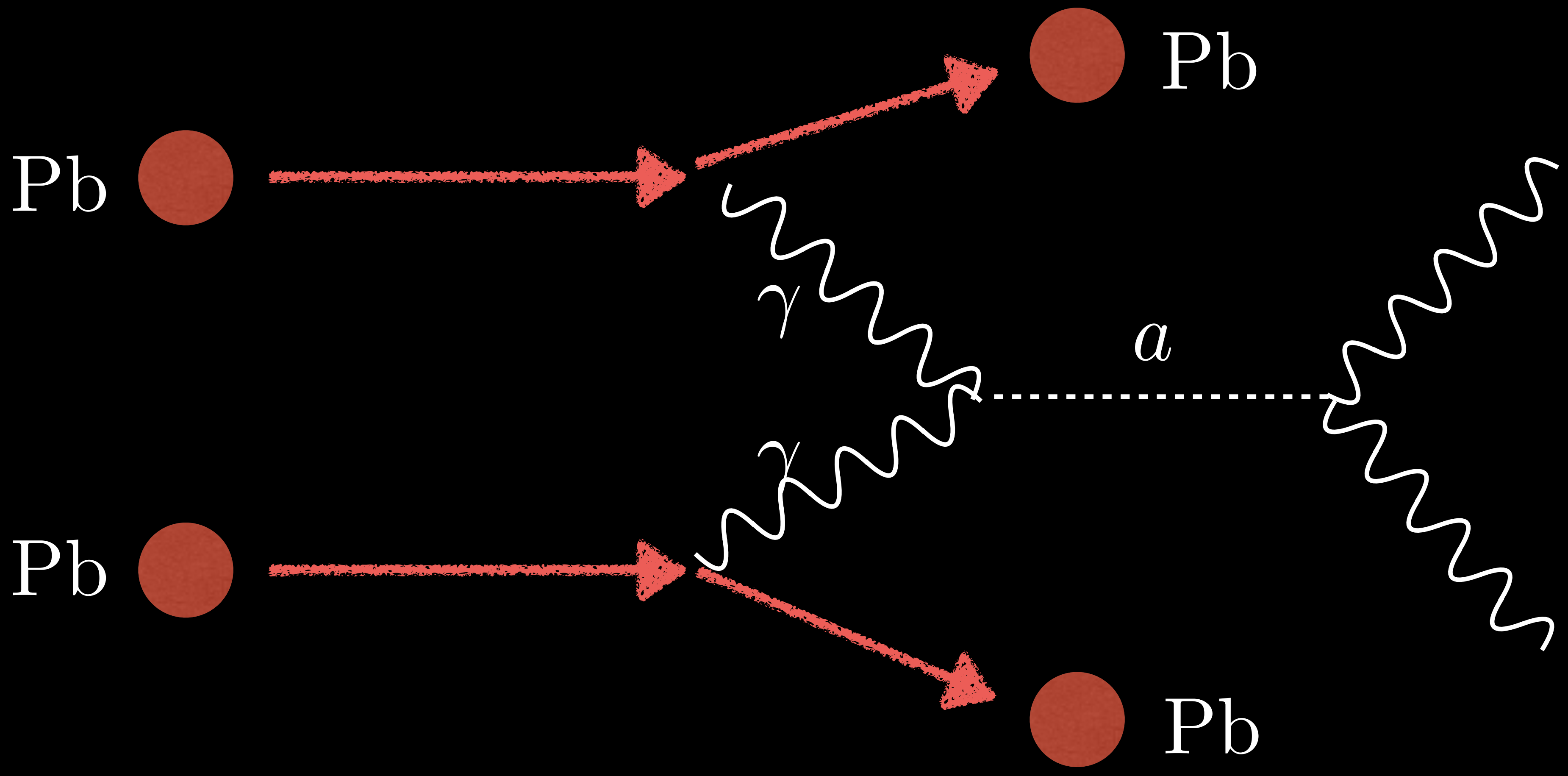
Heavy ion ‘photon collider’



Lead charge
Z=82

$Z^4 \sim 5\text{x}10^7$

Heavy ion ‘photon collider’



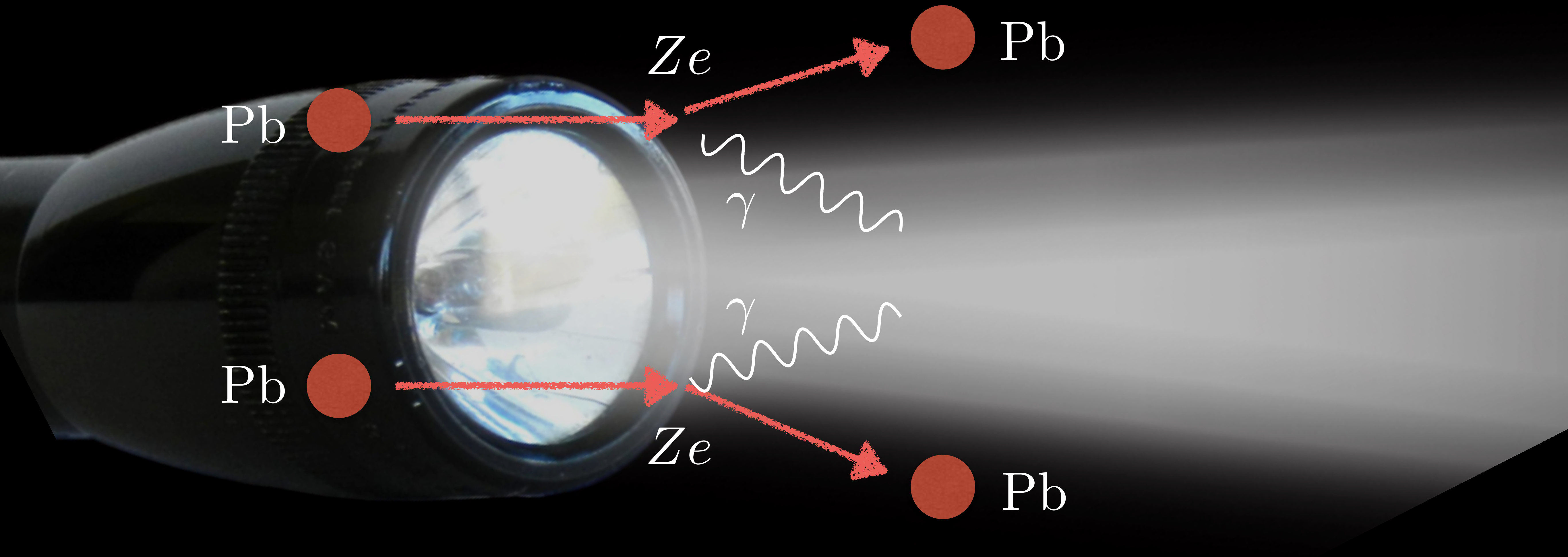
s/a

A. B. Balantekin, C. Bottcher, M. R. Strayer, and S. J. Lee
Phys. Rev. Lett. **55**, 461 (1985)

A.A. NATALE, *Mod. Phys. Lett. A*, **09**, 2075 (1994)

Heavy ion ‘photon collider’

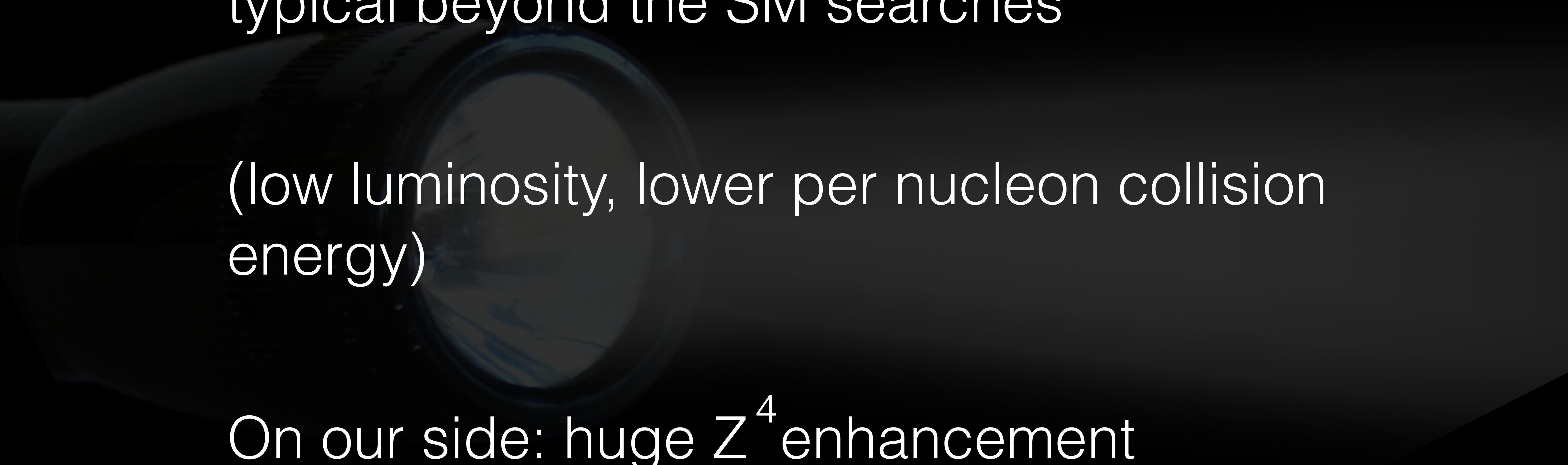
RHICs ‘Gold Flashlight’-> LHCs ‘Lead Flashlight’



Worlds most powerful* flashlight

*GeV

Heavy ion ‘photon collider’

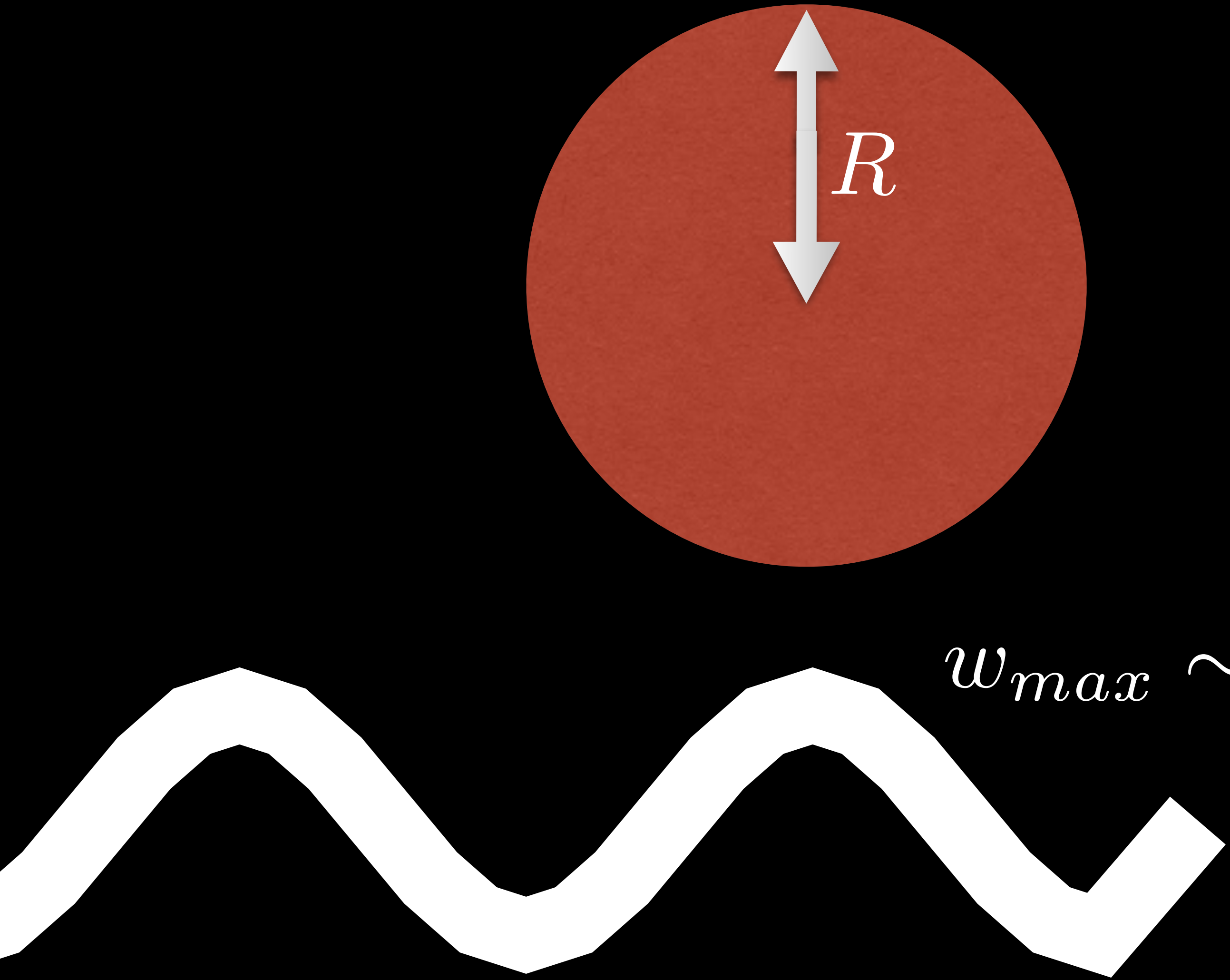


Pb-Pb collisions are not optimized for typical beyond the SM searches

(low luminosity, lower per nucleon collision energy)

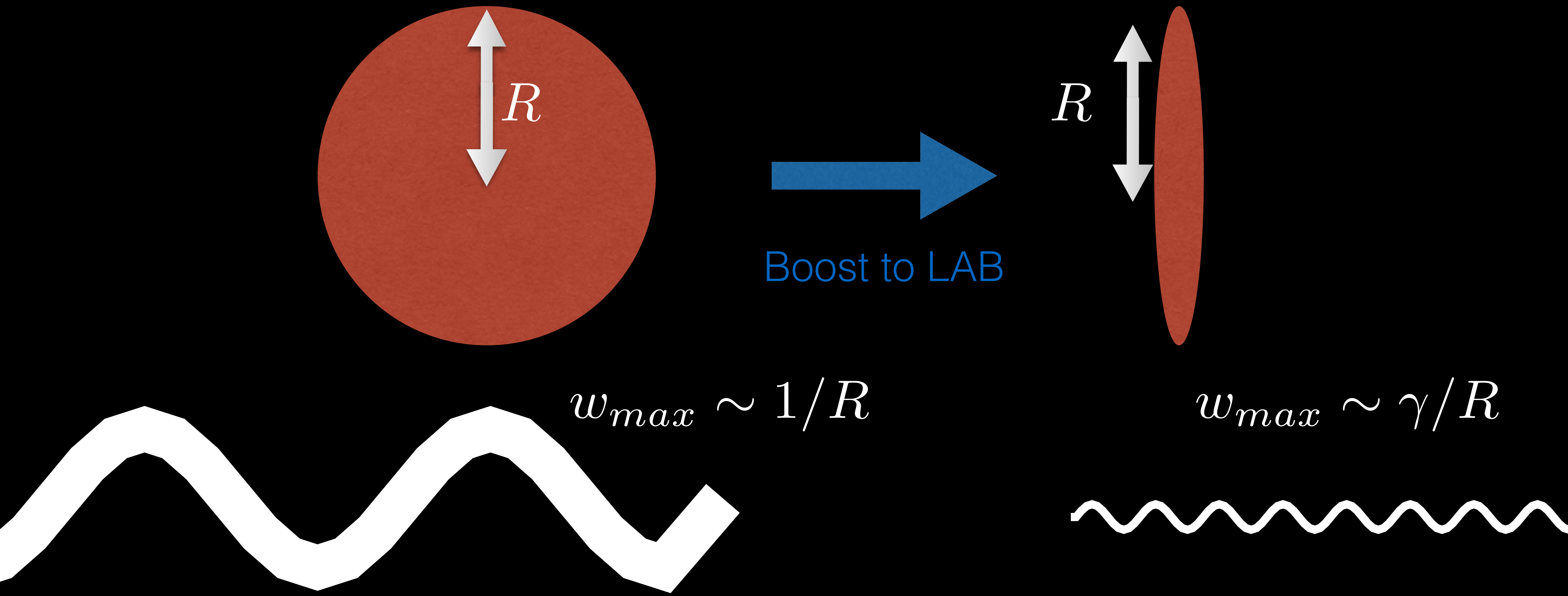
On our side: huge Z^4 enhancement
extremely efficient bkg rejection

Mass reach—quick estimate



$w_{max} \sim 1/R$

Mass reach—quick estimate

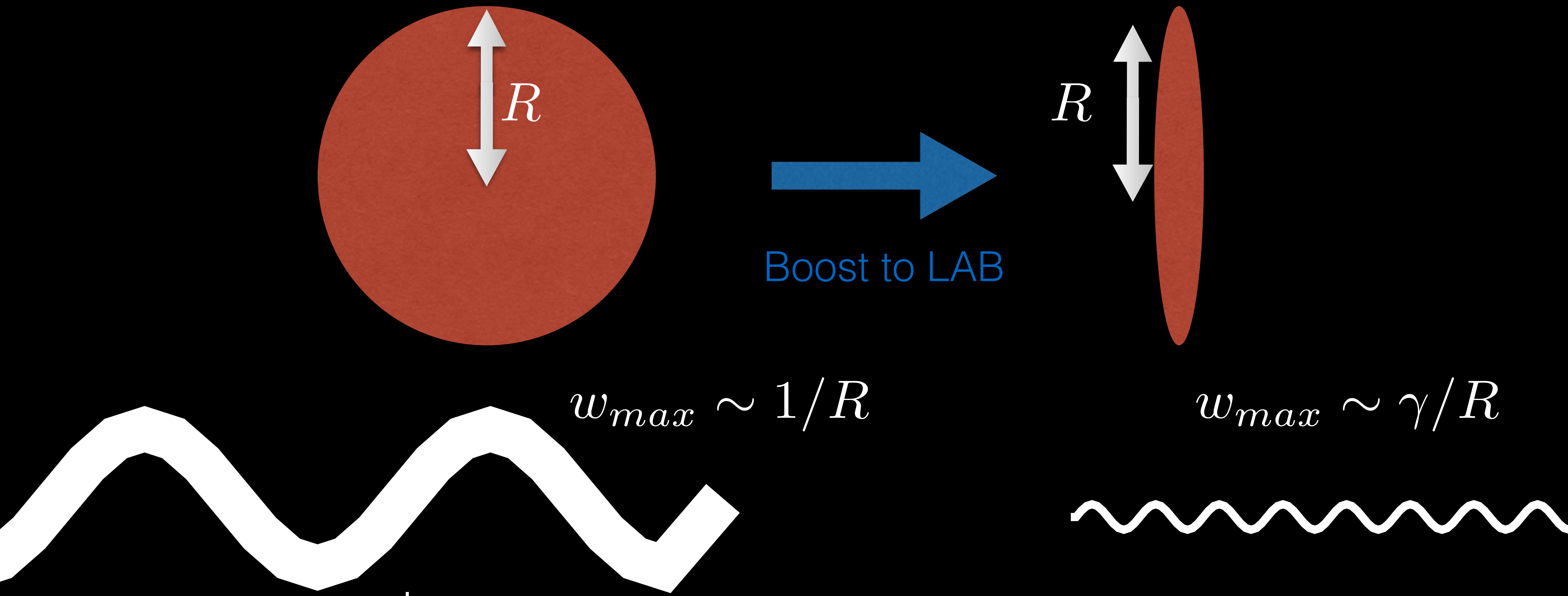


Boost to LAB

$$w_{max} \sim 1/R$$

$$w_{max} \sim \gamma/R$$

Mass reach—quick estimate

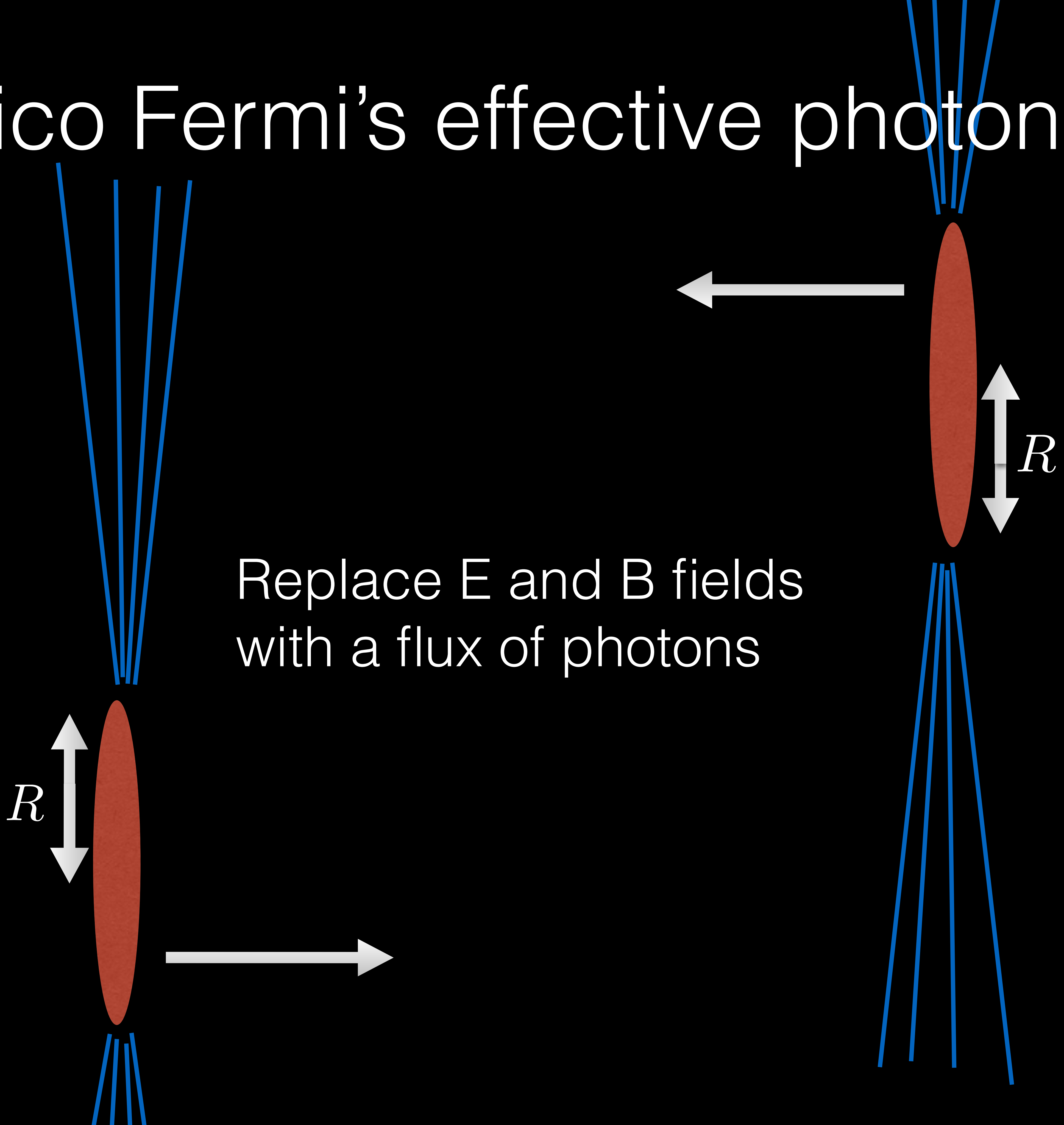


$w_{max} \sim 1/R$

$w_{max} \sim \gamma/R$

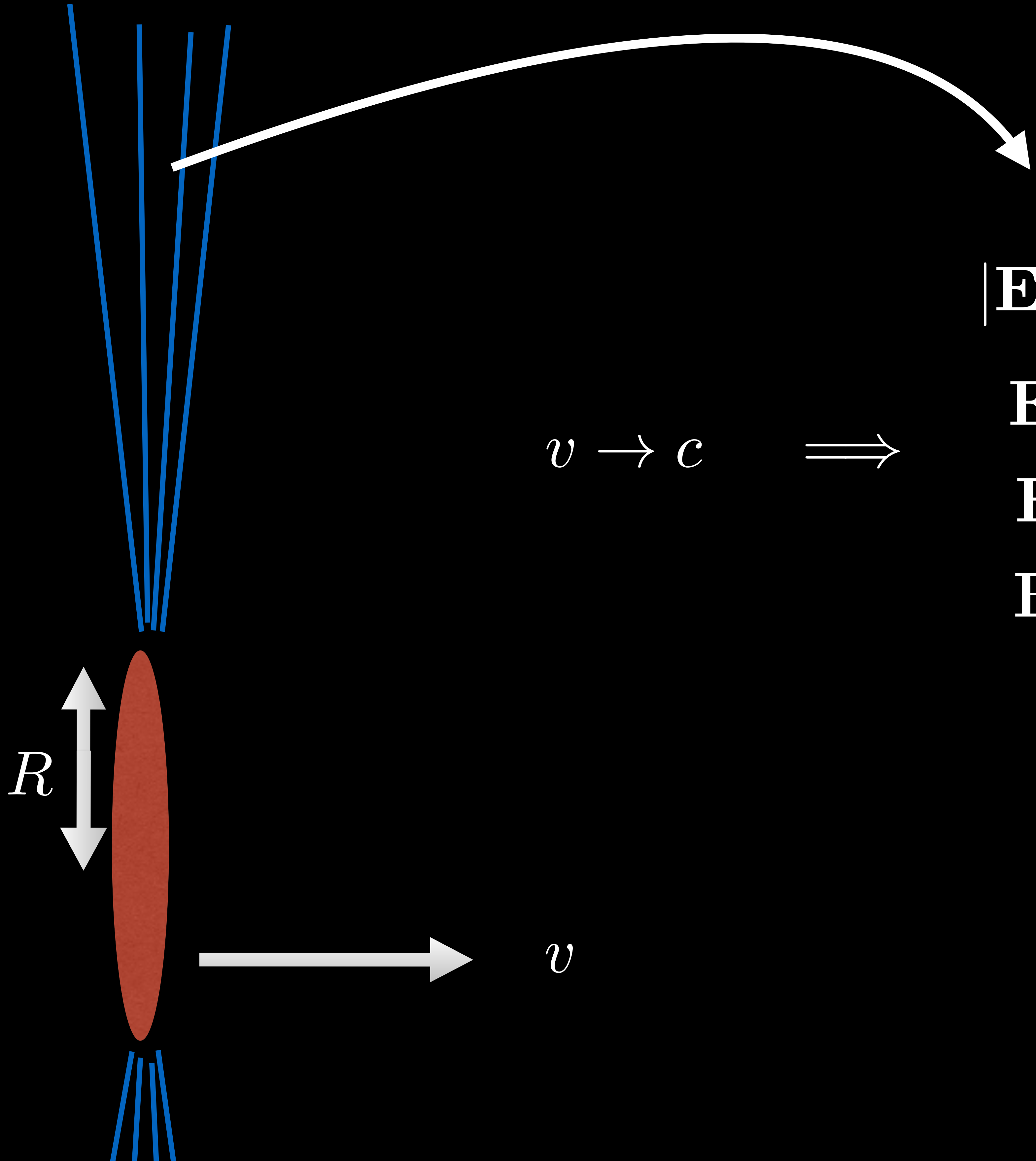
	$b_{\min} = 2R$	E_{nucleon}	$2\omega_{\max}$
p	1.6 fm	7.5 TeV	1500 GeV
Pb	14 fm	5.6 TeV	160 GeV

Enrico Fermi's effective photons



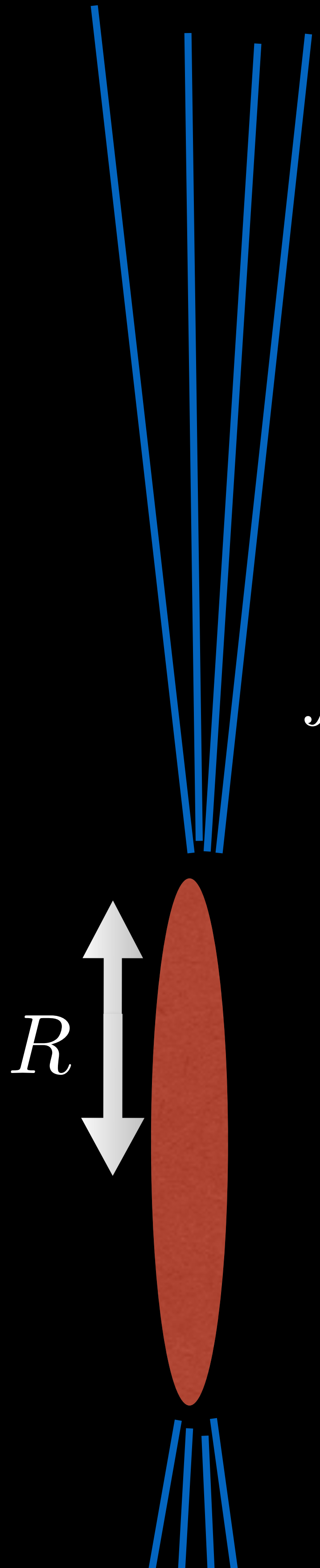
Replace E and B fields
with a flux of photons

Some Classical EM (see Jackson)



$$v \to c \quad \Longrightarrow \quad \begin{gathered} |\mathbf{E}| = |\mathbf{B}| \\ \mathbf{E} \perp \mathbf{B} \\ \mathbf{E} \perp \mathbf{v} \\ \mathbf{B} \perp \mathbf{v} \end{gathered}$$

Some Classical EM (see Jackson)



Equate energy fluxes

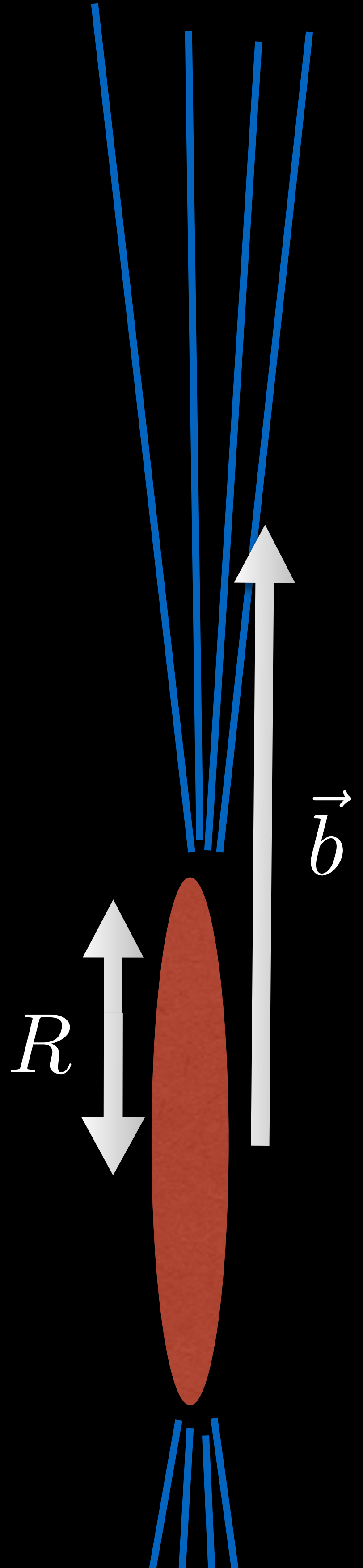
$$\int_{-\infty}^{\infty} dt \int d\mathbf{x}_\perp \cdot \mathbf{S}(\mathbf{x},t) = \int_0^{\infty} dE \int d\mathbf{x}_\perp \, E \, N(E,\mathbf{x}_\perp)$$

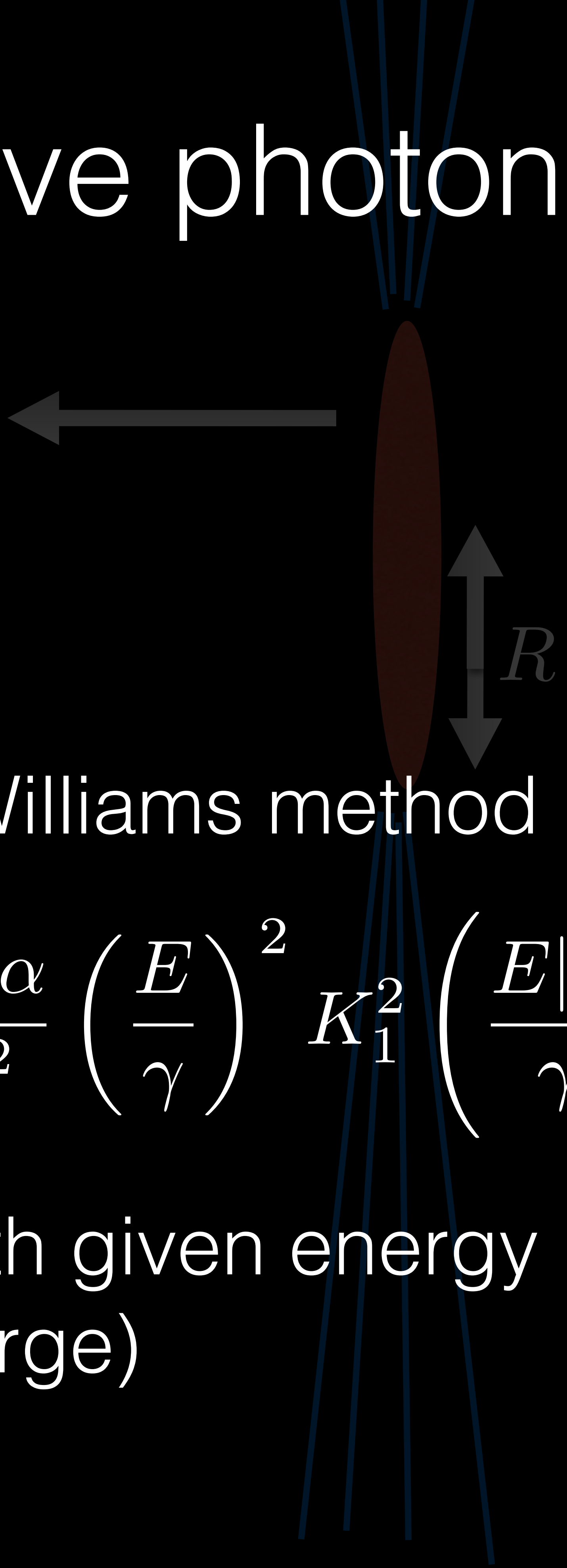
Poynting vector

Photon flux

$$\mathbf{S}(\mathbf{x},t) = \mathbf{E}(\mathbf{x},t) \times \mathbf{B}(\mathbf{x},t)$$

Enrico Fermi’s effective photons



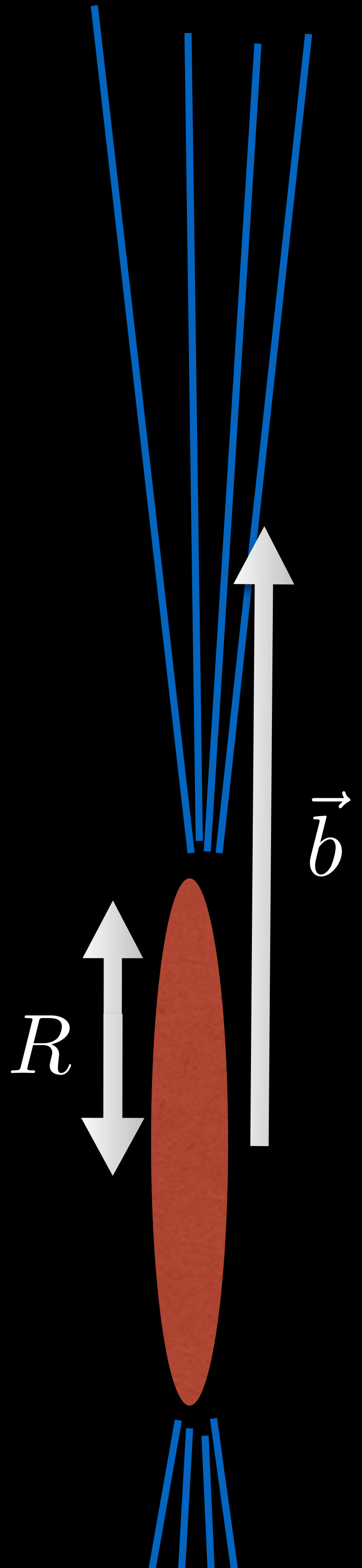


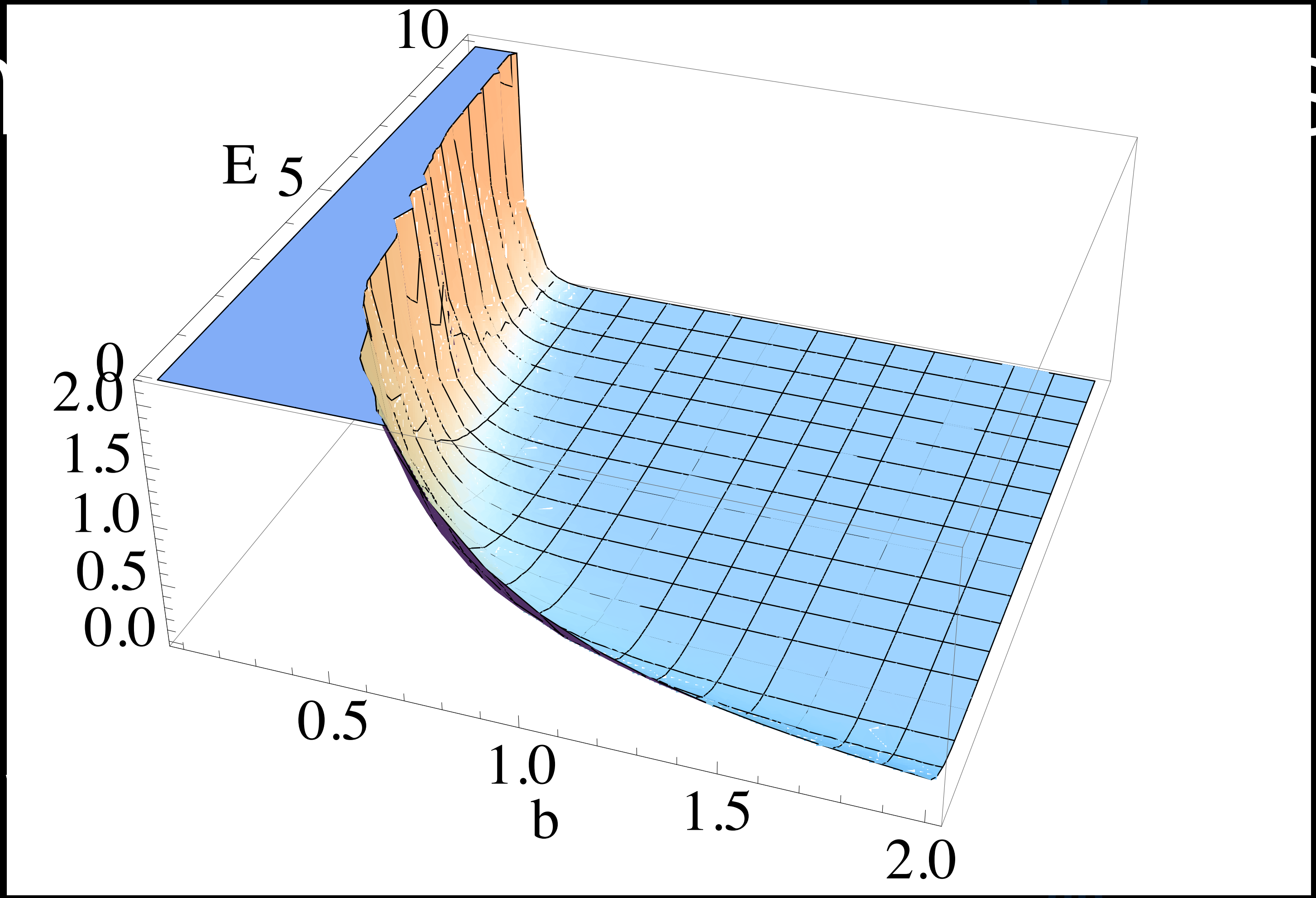
Weizsäcker—Williams method

$$N(E,\vec{b}) = \frac{Z^2\alpha}{\pi^2}\left(\frac{E}{\gamma}\right)^2 K_1^2\left(\frac{E|\vec{b}|}{\gamma}\right)$$

photon flux with given energy E
(point-like charge)

Enrico Fern s

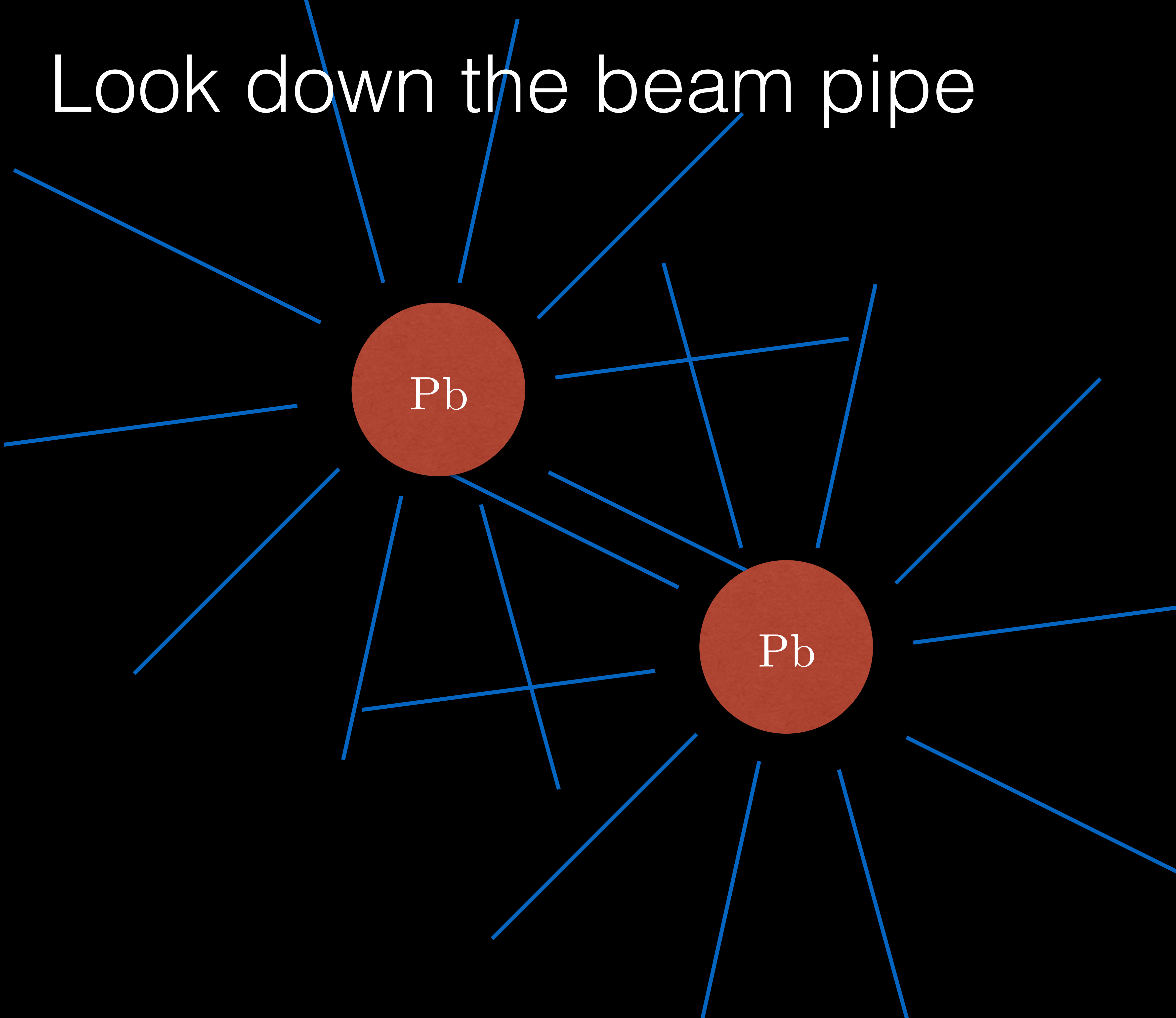




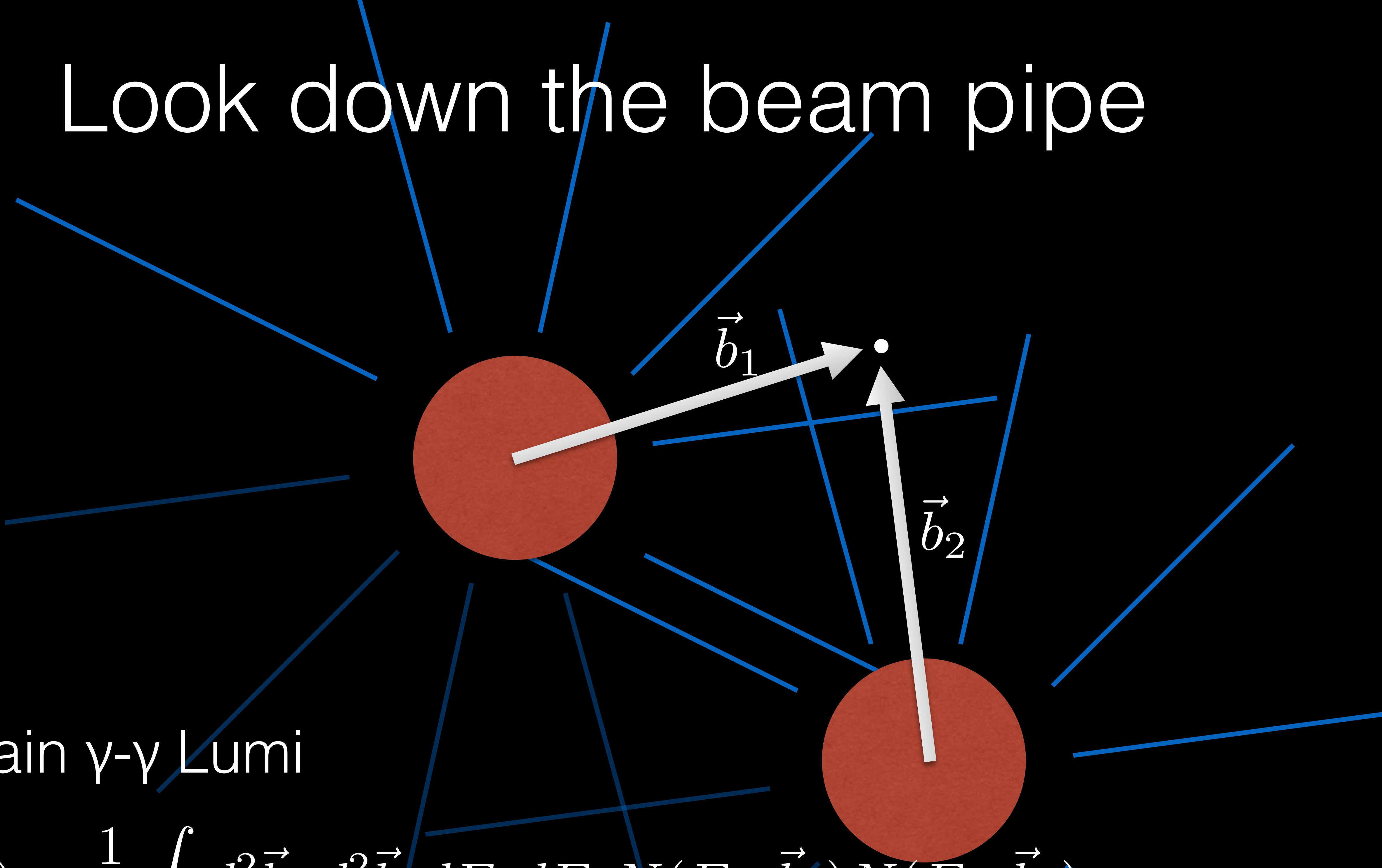
$$N(E,\vec{b}) = \frac{Z^2\alpha}{\pi^2}\left(\frac{E}{\gamma}\right)^2 K_1^2\left(\frac{E|\vec{b}|}{\gamma}\right)$$

photon flux with given energy E
(point-like charge)

Look down the beam pipe



Look down the beam pipe



Obtain γ-γ Lumi

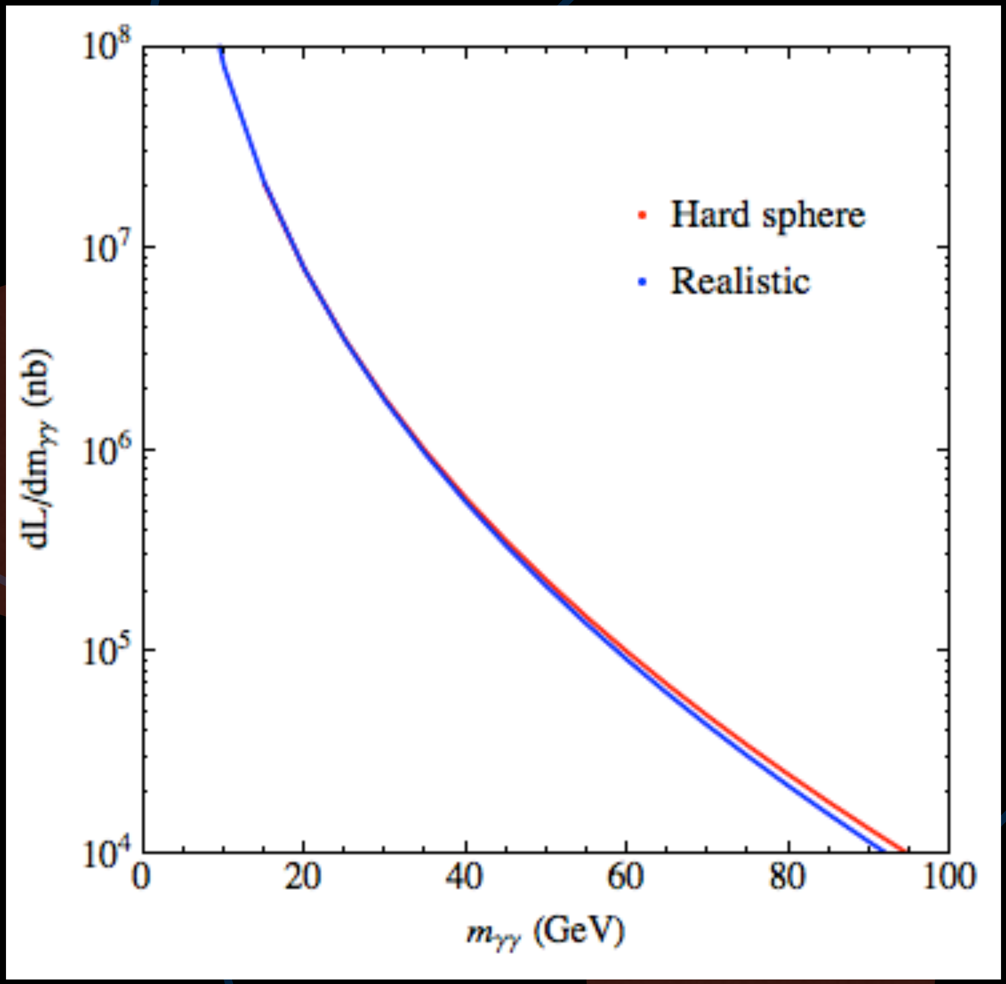
$$\mathcal{L}_{\gamma\gamma}(\hat{s}) = \frac{1}{\hat{s}} \int d^2\vec{b}_1\, d^2\vec{b}_2 dE_1 dE_2 N(E_1,\vec{b}_1)N(E_2,\vec{b}_2)$$
$$\times P(|\vec{b}_1-\vec{b}_2|)\delta(\hat{s}-4E_1E_2)$$

Restrict $|\vec{b}_{1,2}| > R$

‘No-breakup’ probability

STARlight public code…

S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth



Obtain γ-γ Lumi

$$\mathcal{L}_{\gamma\gamma}(\hat{s}) = \frac{1}{\hat{s}}\int d^2\vec{b}_1\, d^2\vec{b}_2 dE_1 dE_2 N(E_1,\vec{b}_1)N(E_2,\vec{b}_2)$$

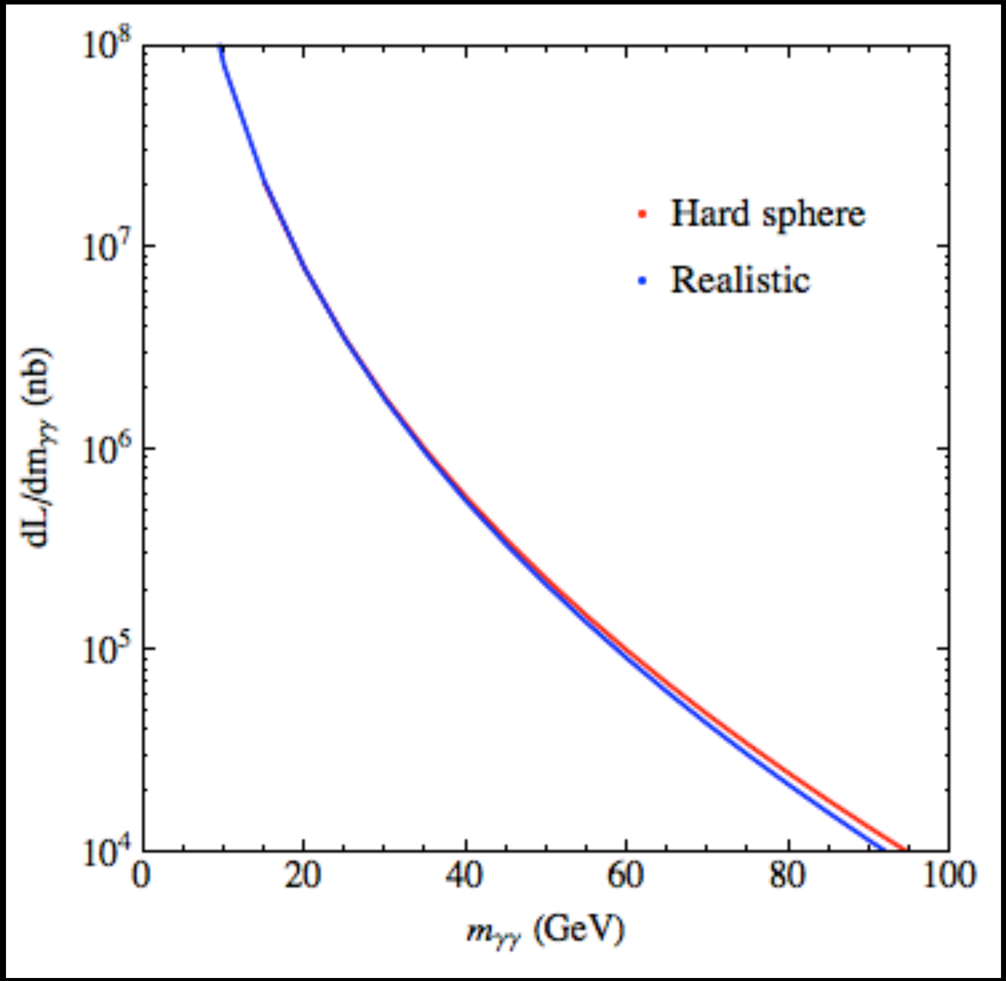
$$\times P(|\vec{b}_1 - \vec{b}_2|)\delta(\hat{s} - 4E_1E_2)$$

Restrict $|\vec{b}_{1,2}| > R$

'No-breakup' probability

Can you do it for the Higgs?

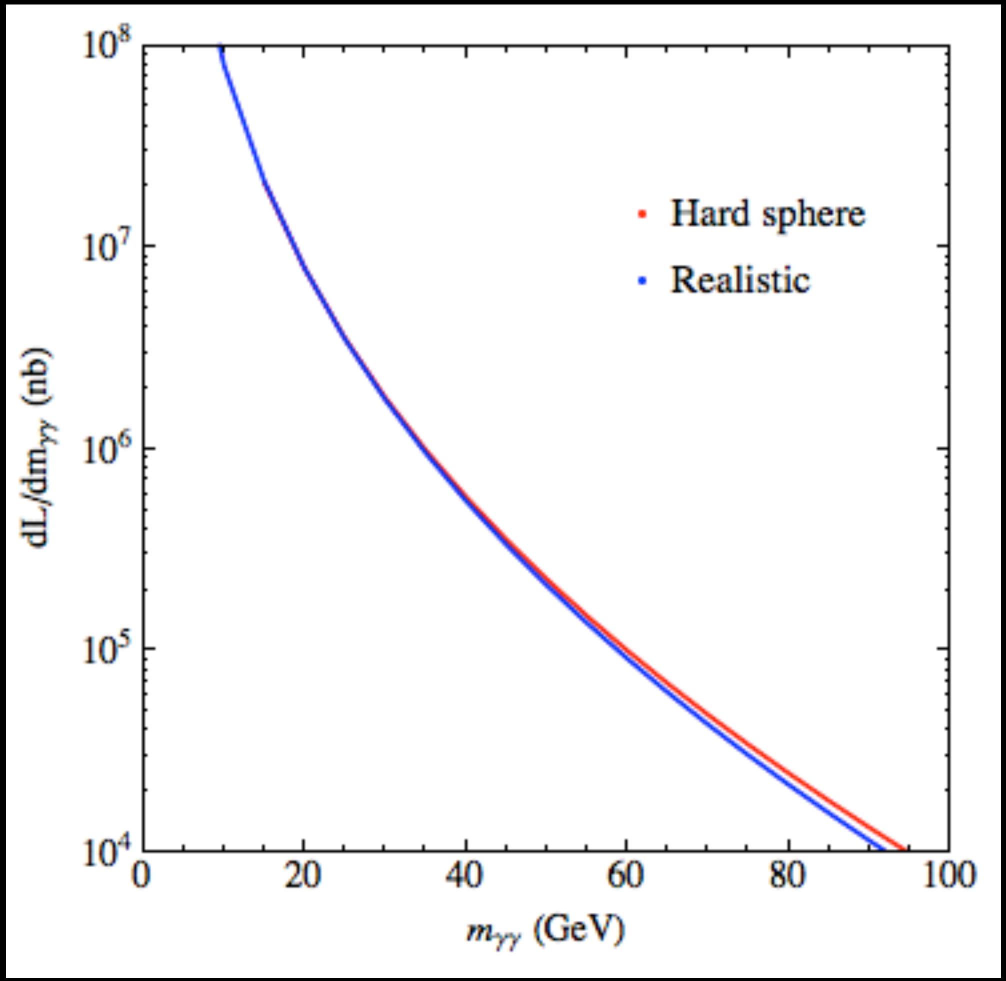
Asked 1989 by e.g. M. Drees, J. R. Ellis, and D. Zeppenfeld



$$\sigma_{\gamma\gamma\to H} = \frac{8\pi^2}{m_H}\Gamma(H \to \gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_H)$$

Can you do it for the Higgs?

Asked 1989 by e.g. M. Drees, J. R. Ellis, and D. Zeppenfeld



~ 100

$\sim 10^3$ nb

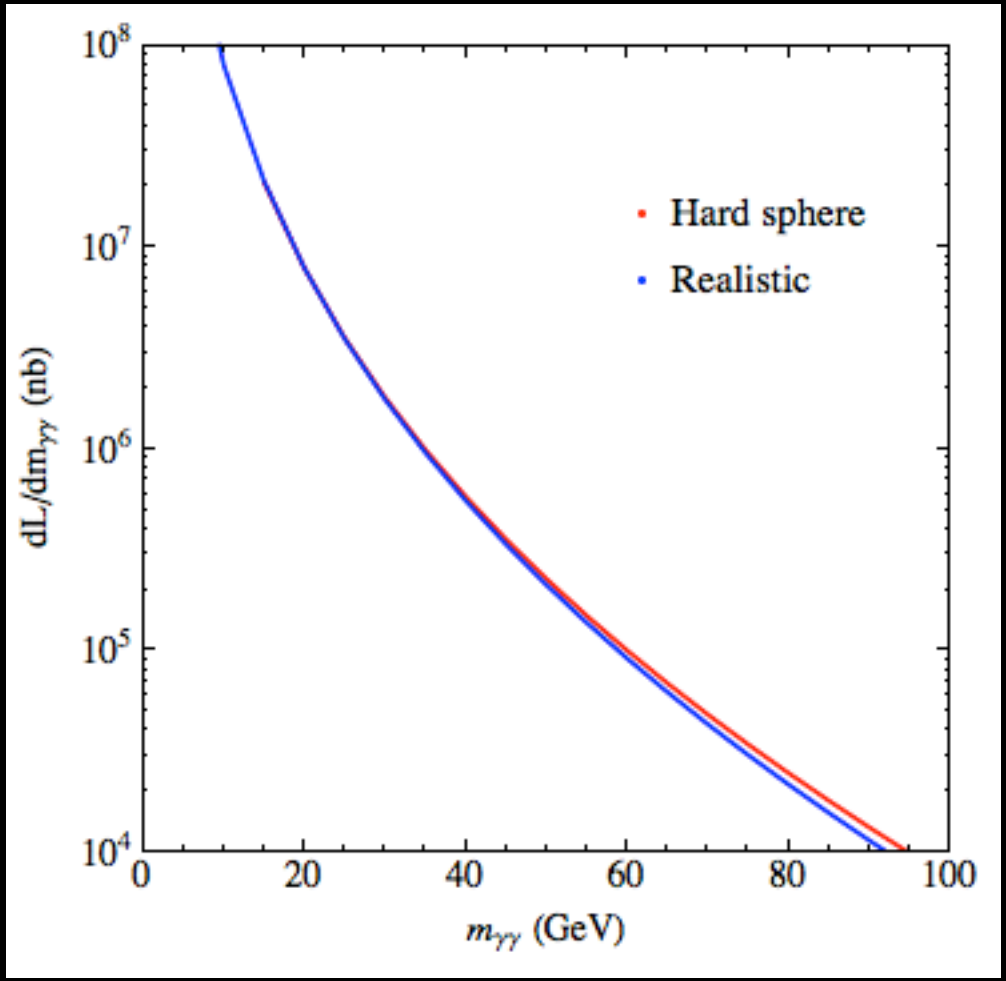
$$\sigma_{\gamma\gamma\to H} = \frac{8\pi^2}{m_H}\Gamma(H\to\gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_H)$$

~ 100 GeV

$\sim 10^{-3}$ MeV

Can you do it for the Higgs?

Asked 1989 by e.g. M. Drees, J. R. Ellis, and D. Zeppenfeld



$$\sigma_{\gamma\gamma\to H} = \frac{8\pi^2}{m_H}\Gamma(H\to\gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_H) \quad \sim \mathrm{pb}$$

$$\mathrm{pb} \times 10\,\mathrm{nb}^{-1} = 0.01$$

Can you do it for the Higgs?

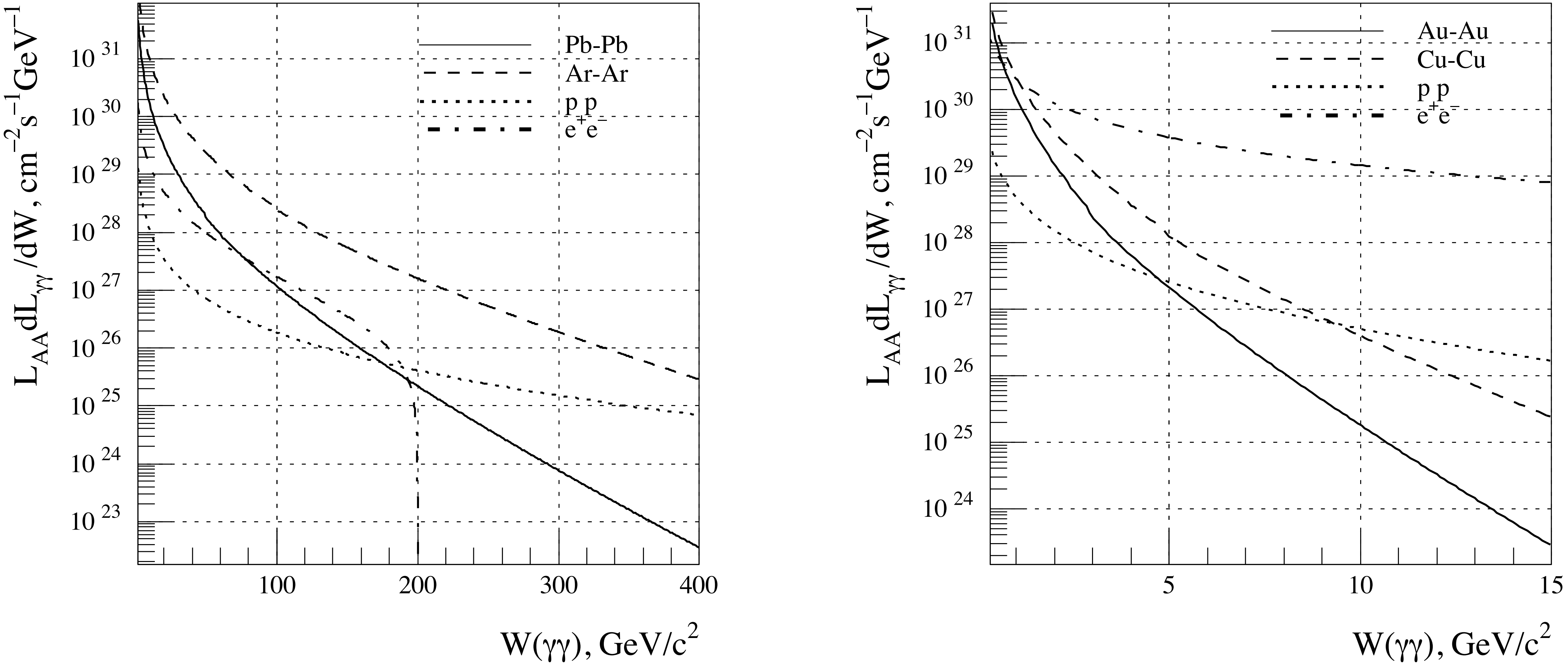
Asked 1989 by e.g. M. Drees, J. R. Ellis, and D. Zeppenfeld

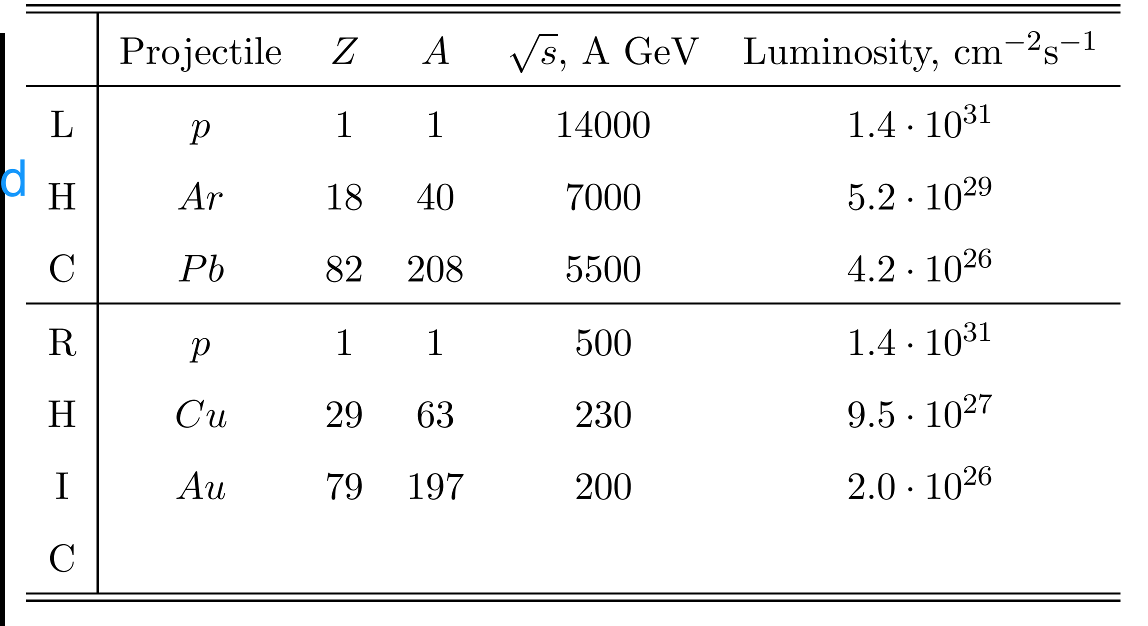
Close but not quite!

$$\sigma_{\gamma\gamma\to H} = \frac{8\pi^2}{m_H}\Gamma(H\to\gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_H) \quad \sim \mathrm{pb}$$

$$\mathrm{pb} \times 10\,\mathrm{nb}^{-1} = 0.01$$

Which ions are best?





	Projectile	Z	A	$\sqrt{s}$, A GeV	Luminosity, cm^{-2}s^{-1}
L	p	1	1	14000	$1.4 \cdot 10^{31}$
H	Ar	18	40	7000	$5.2 \cdot 10^{29}$
C	Pb	82	208	5500	$4.2 \cdot 10^{26}$
R	p	1	1	500	$1.4 \cdot 10^{31}$
H	Cu	29	63	230	$9.5 \cdot 10^{27}$
I	Au	79	197	200	$2.0 \cdot 10^{26}$
C					

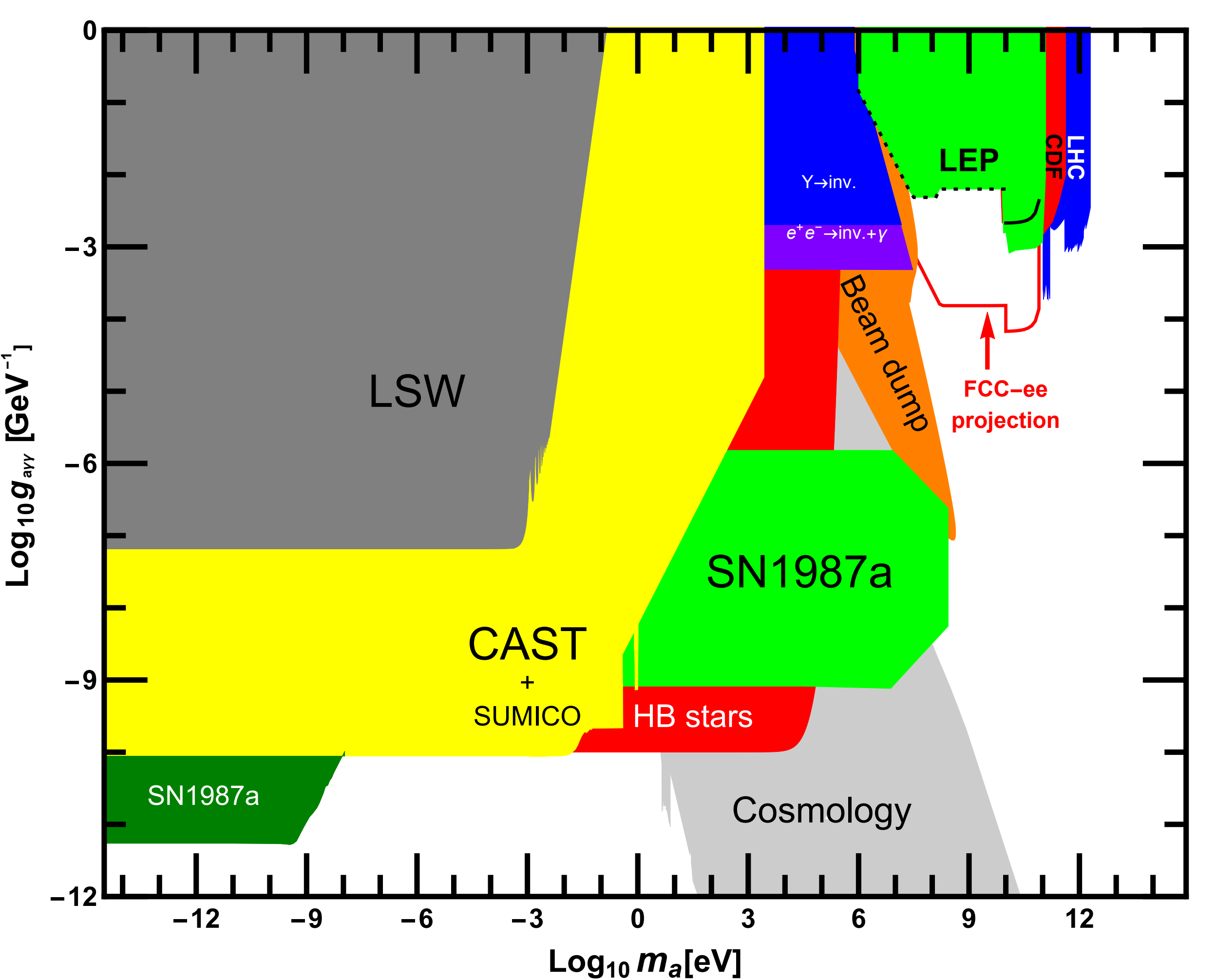
G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, and Y. Kharlov (1991)

Search for axion like particles

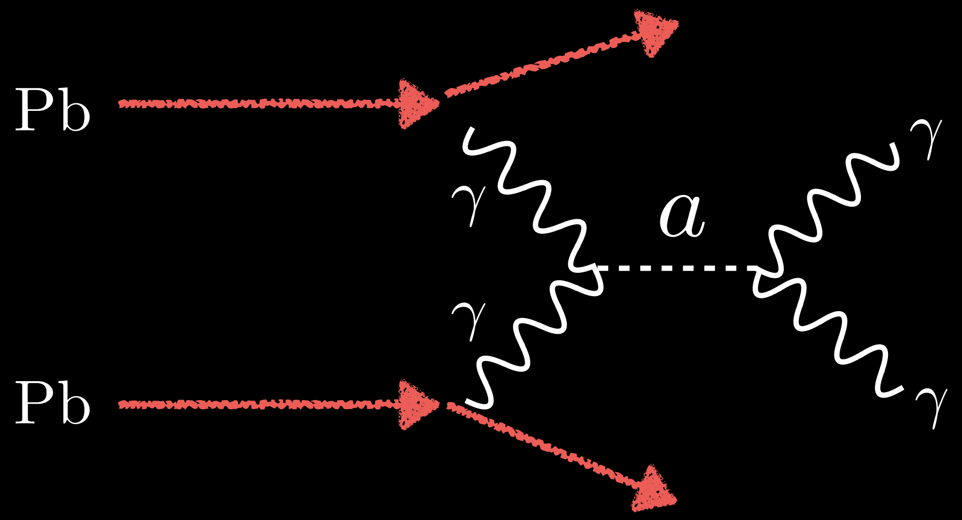
Knapen, Lin, Lou, TM 16

$$\frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$

e.g. pseudo Nambu-Goldstone boson from some spontaneously broken symmetry



Jaeckel, Spannowsky 15



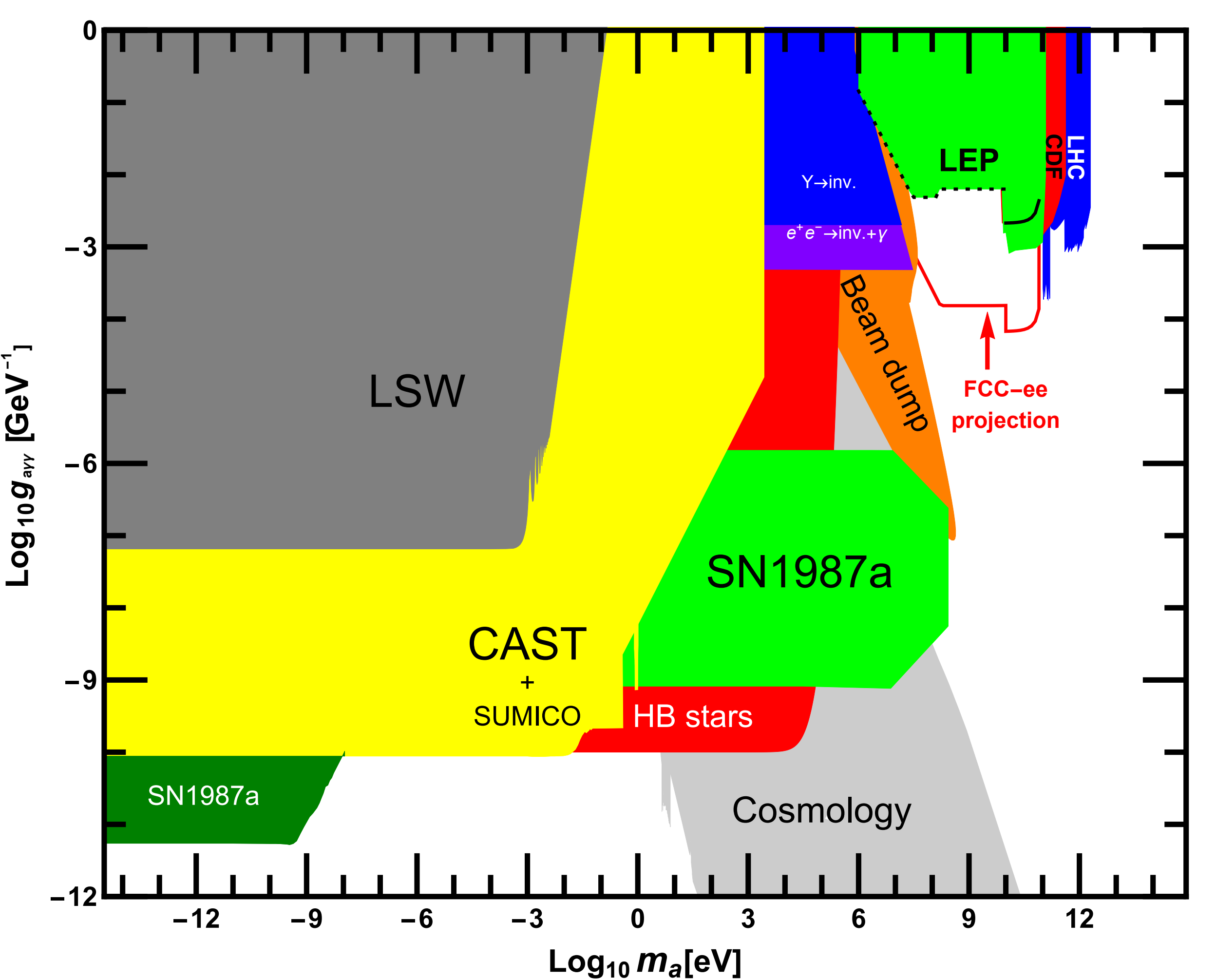
Sensitive to mass range M~GeV

Search for axion like particles

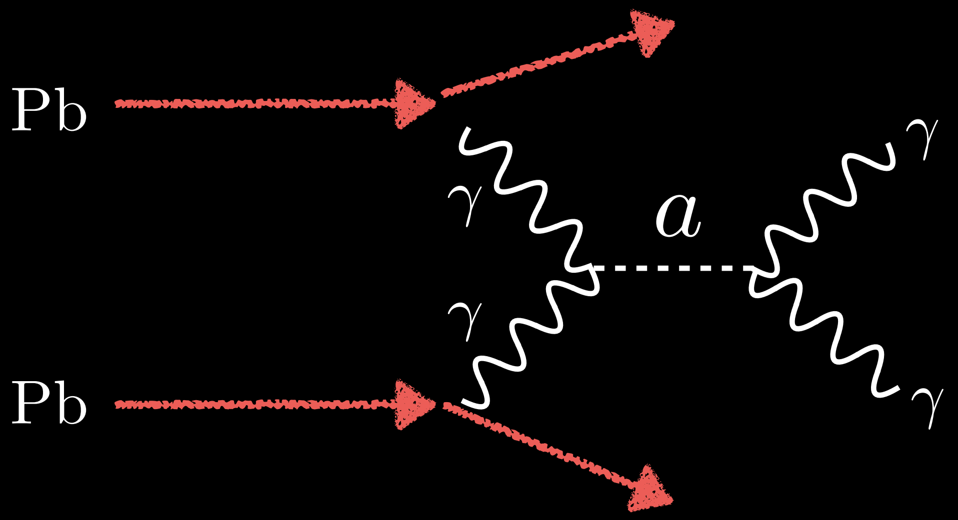
Knapen, Lin, Lou, TM 16

$$\frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}\frac{a}{\Lambda}F\widetilde{F}$$

e.g. pseudo Nambu-Goldstone boson from some spontaneously broken symmetry



Jaeckel, Spannowsky 15



$$\sigma_a = \frac{8\pi^2}{m_a}\Gamma(a \to \gamma\gamma)\mathcal{L}_{\gamma\gamma}(m_a^2)$$

$$\Gamma = \frac{1}{64\pi}\frac{m_a^3}{\Lambda^2}$$

How to trigger?

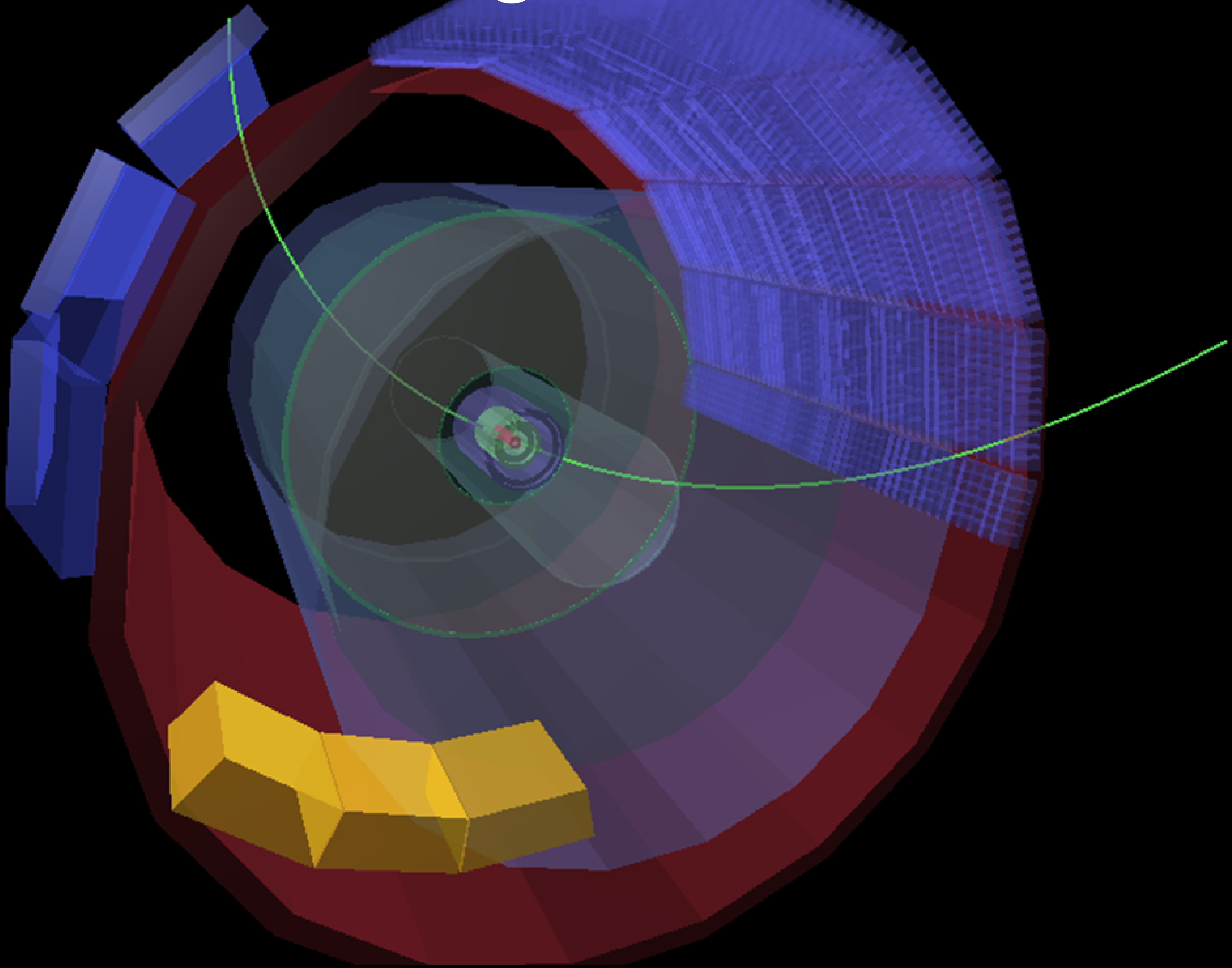
Two new triggers prepared (CMS Ultra-Peripheral Collisions working group analysis, to appear)

Two photons with E > 2 GeV and no hadronic activity in one of the forward calorimeters

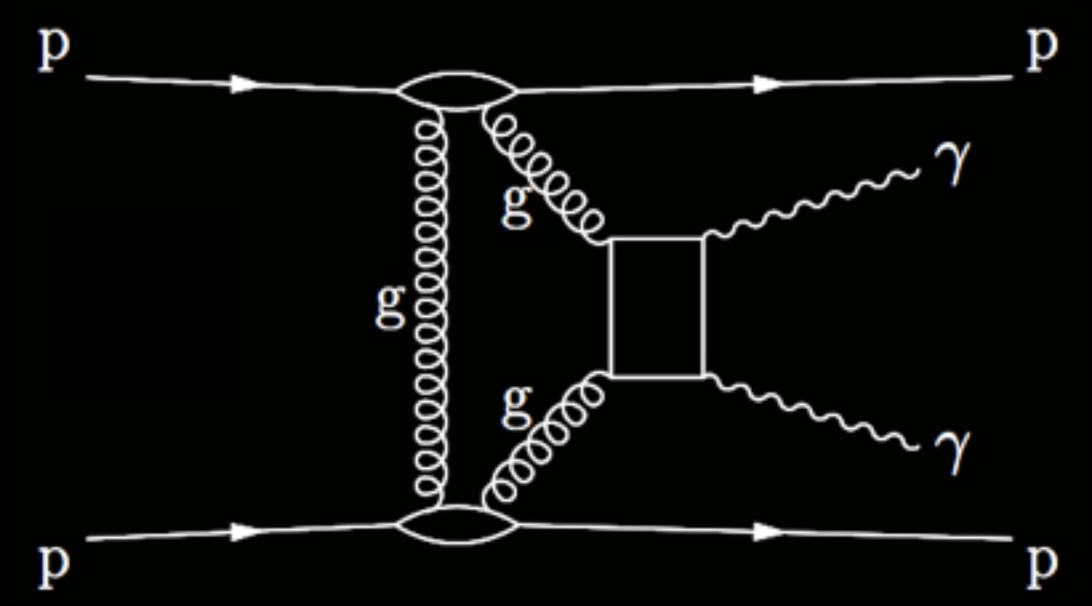
One photon E > 5 GeV and no hadronic activity in one of the forward calorimeters

It’s like LEP!

..but with LHC-grade detectors

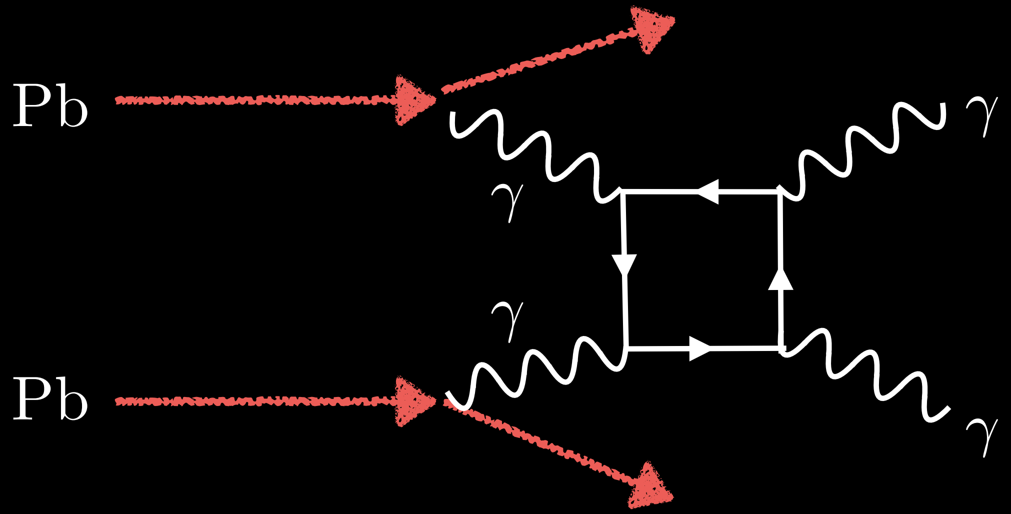


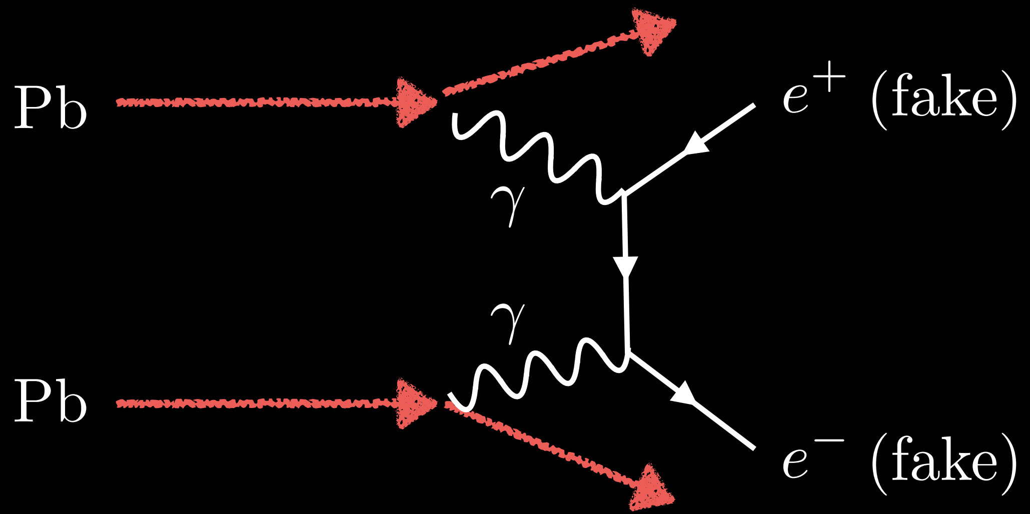
Backgrounds



CEP (Central exclusive production)

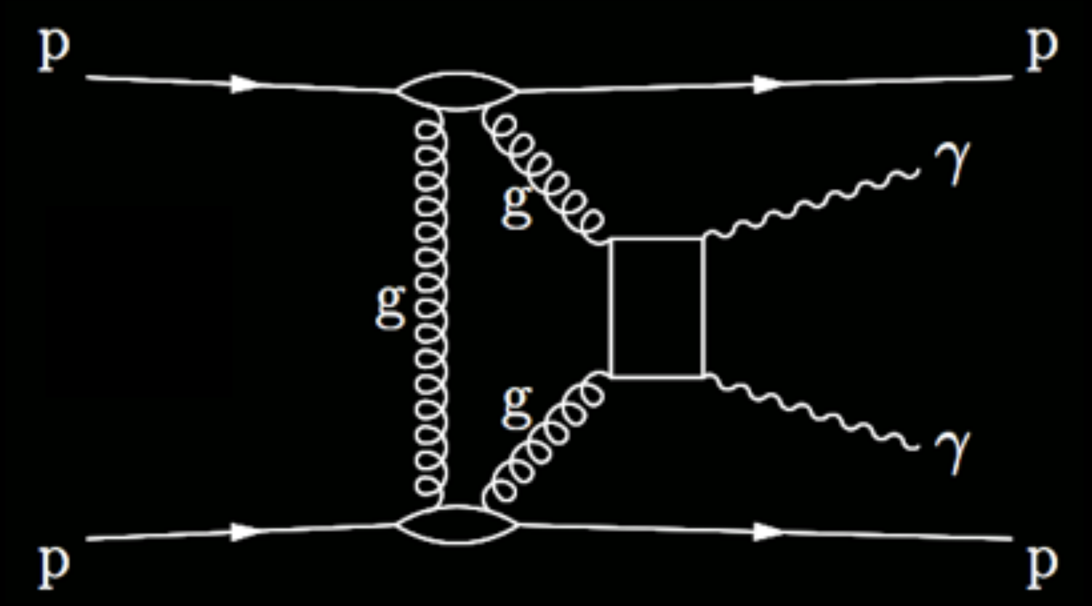
LBL (Light by light)





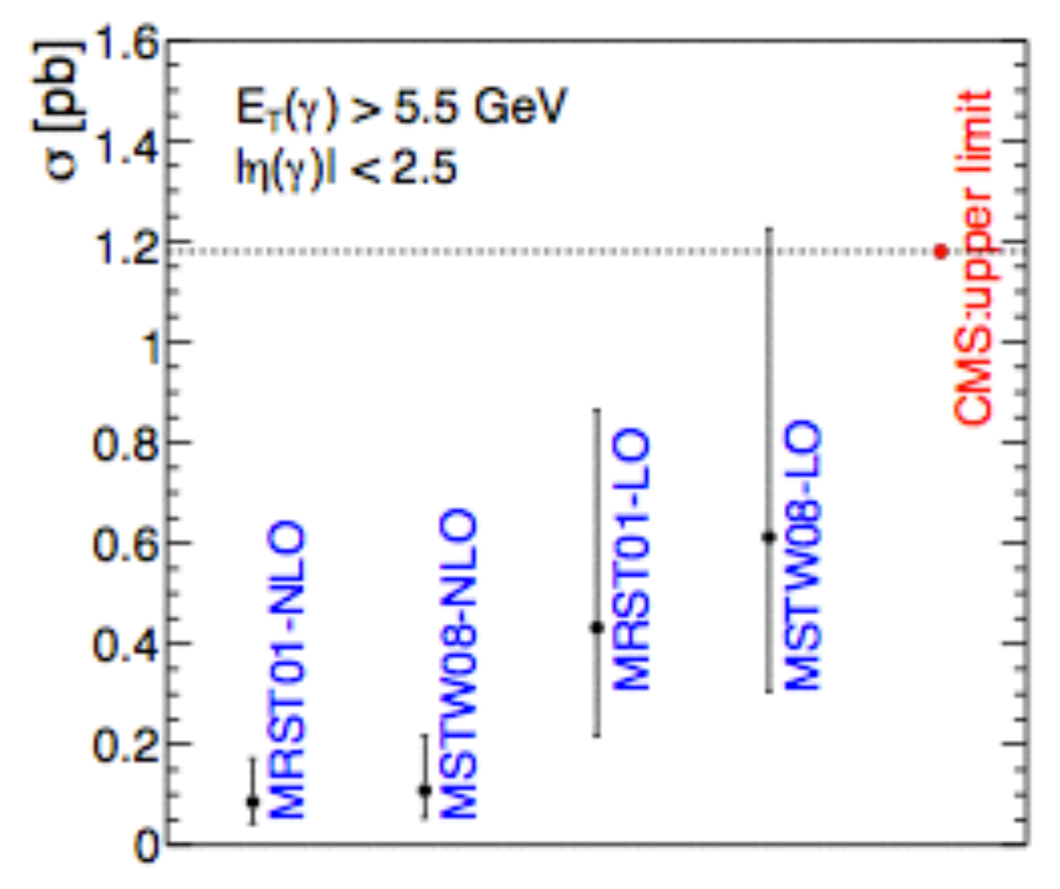
Fakes

Backgrounds



CEP (Central exclusive production)

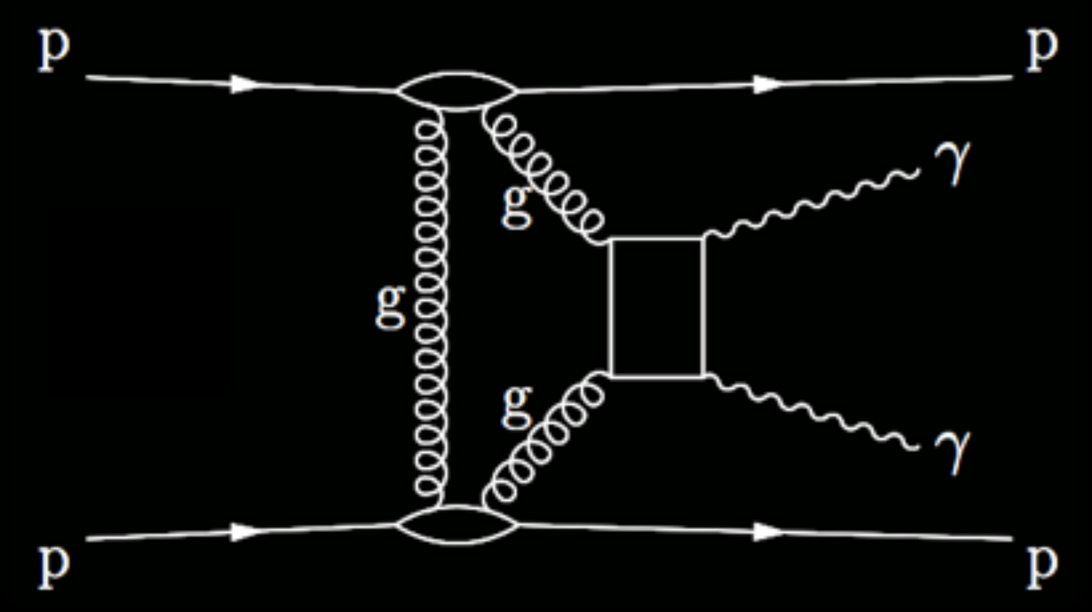
L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling (2010-)
—SuperCHIC



CMS 7 TeV, 36 pb^{-1}

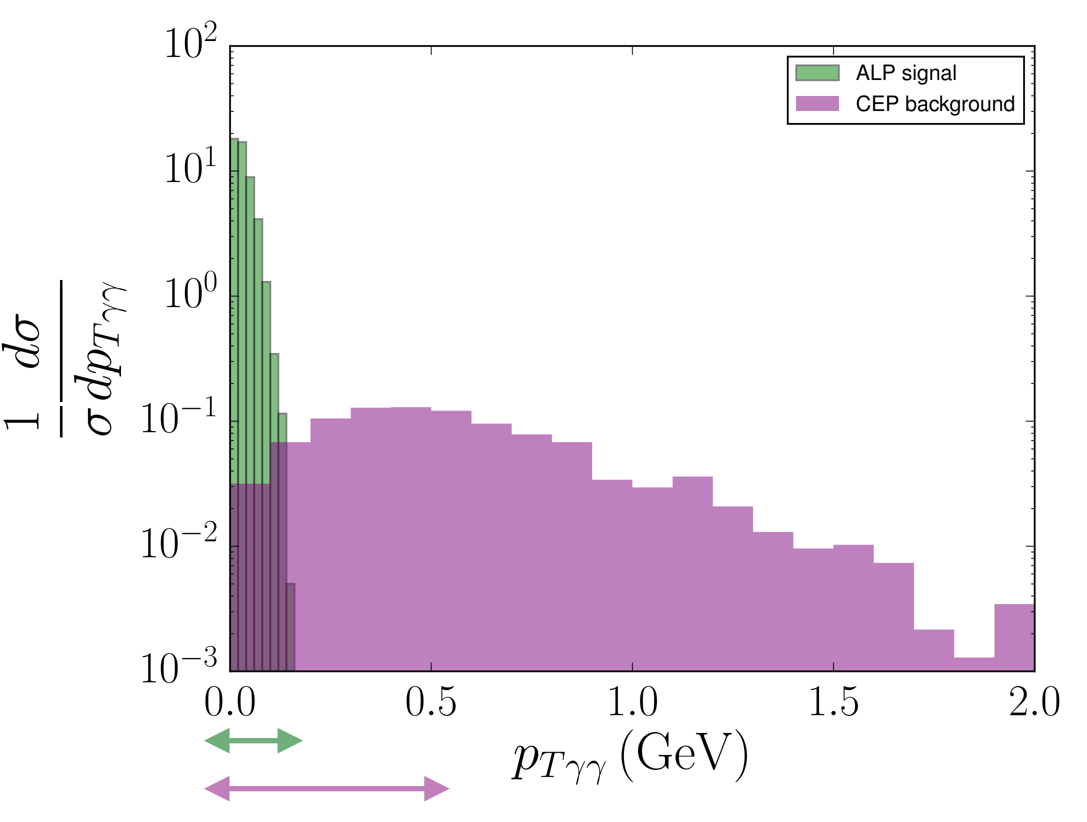
In p-p collisions: theory and expt. upper bound

Backgrounds



CEP (Central exclusive production)

L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling (2010-)
—SuperCHIC

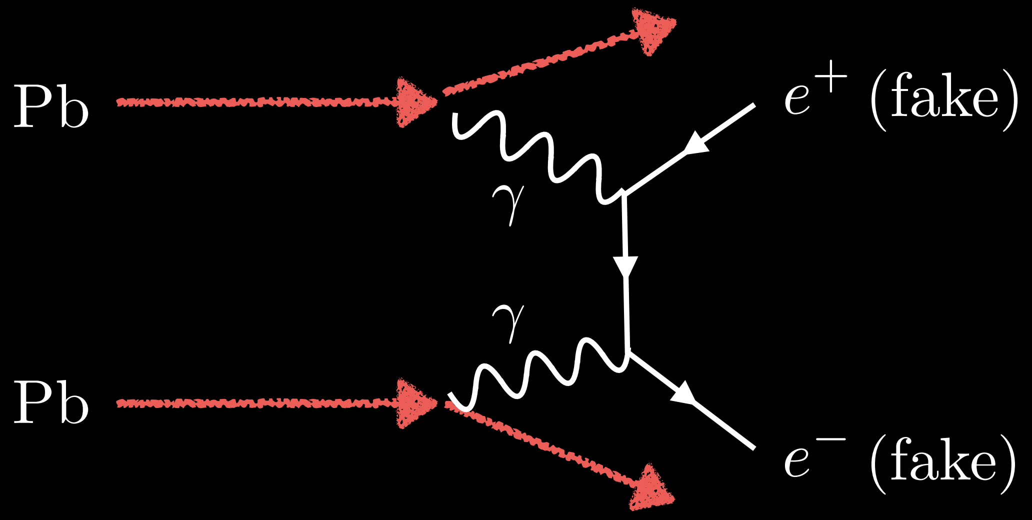


Scale to Pb-Pb? Uncertain, but even A^2 scaling it is small and largely reducible

50 MeV ~ 1 / R_{Pb}
1 GeV ~ 1/ R_p

$A^{1/3}$ more reasonable?

Backgrounds



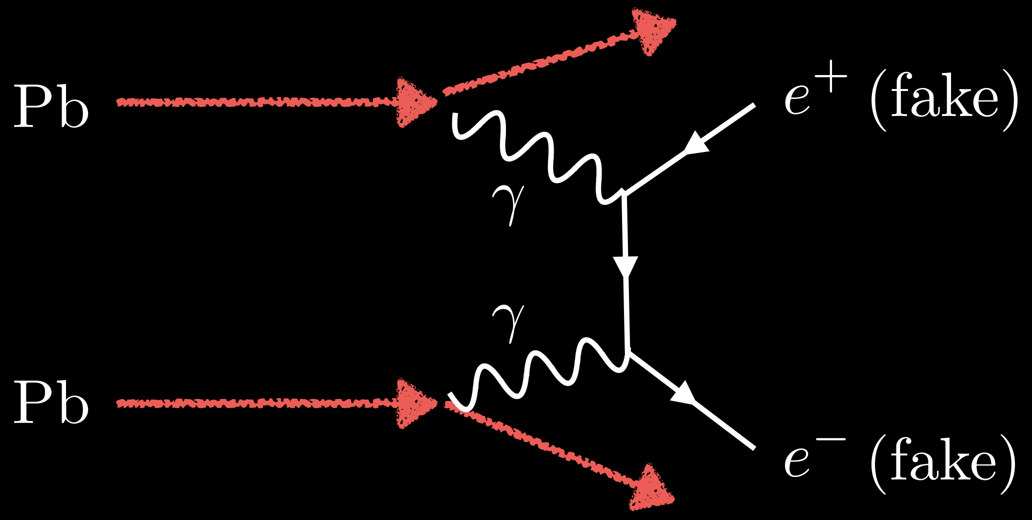
Fakes

S. R. Klein, J. Nystrand, J. Seger, Y. Gorbunov, and J. Butterworth
—STARlight

This process has a cross section around 0.1-1 millibarn

Assuming ~1% fake rate, this is in the 10-100 nb region

(

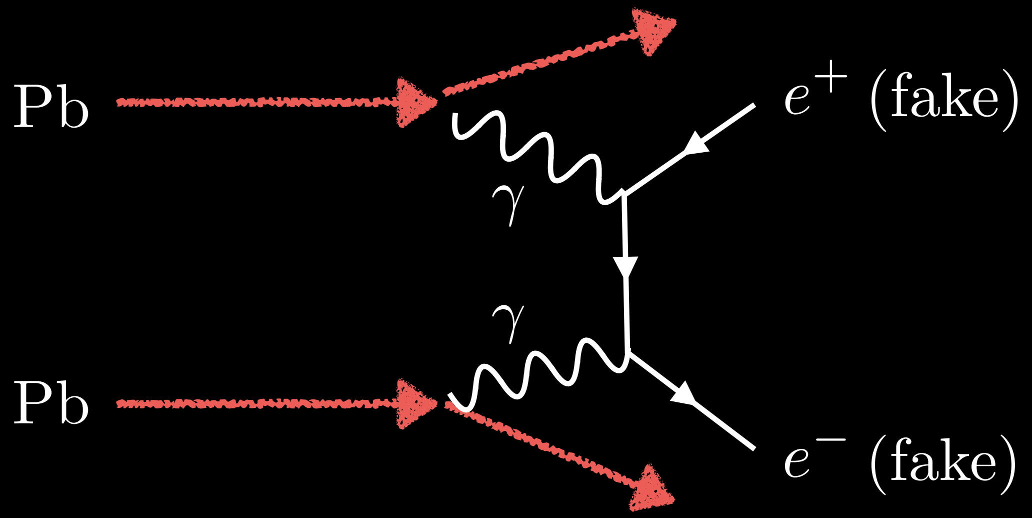


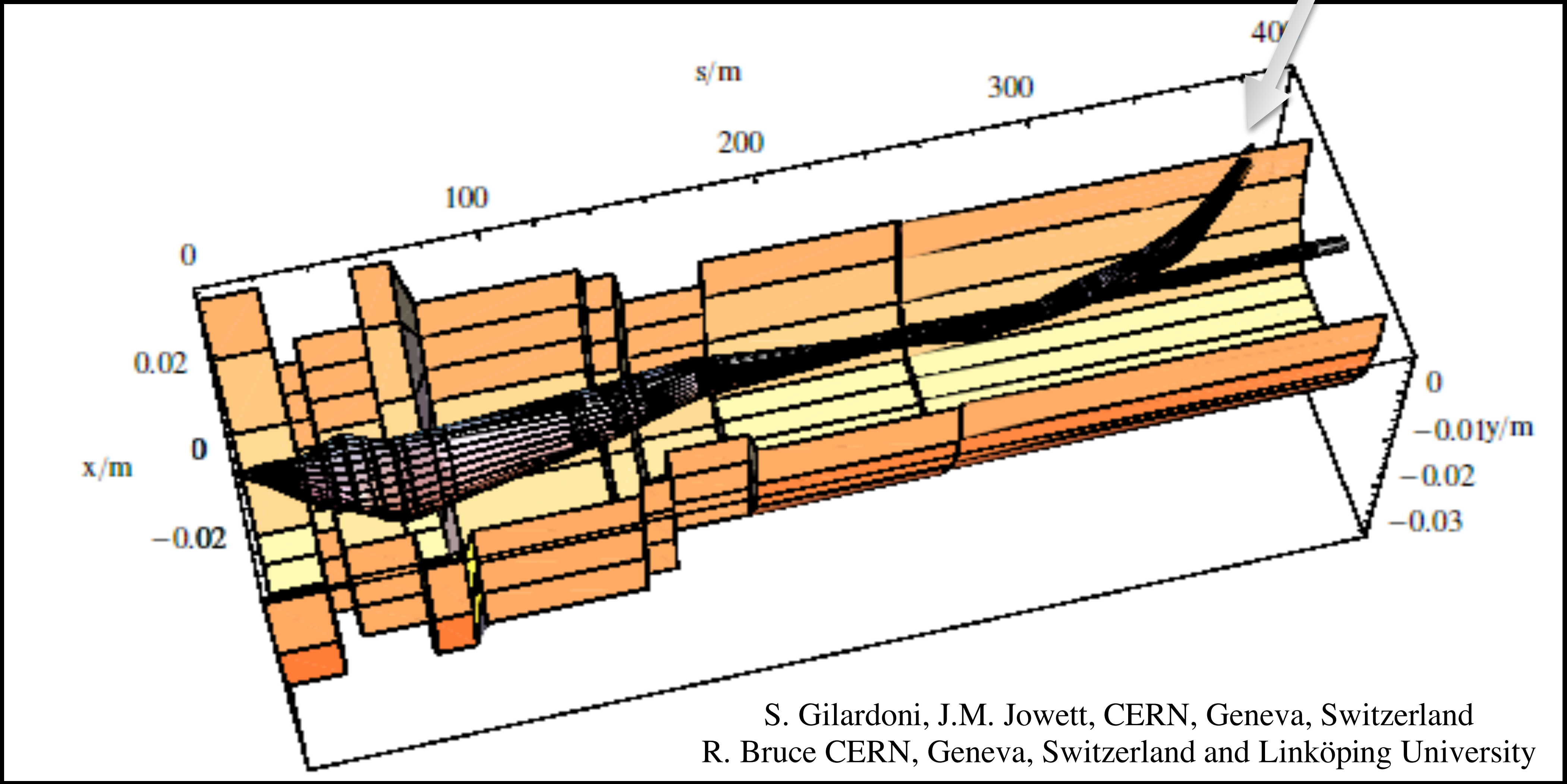
Electron capture ~100 b (!) S. R. Klein, arXiv:0005032

$$\mathrm{Pb}^{82+} + \mathrm{Pb}^{82+} \to \mathrm{Pb}^{81+} + \mathrm{Pb}^{82+} + e^+$$

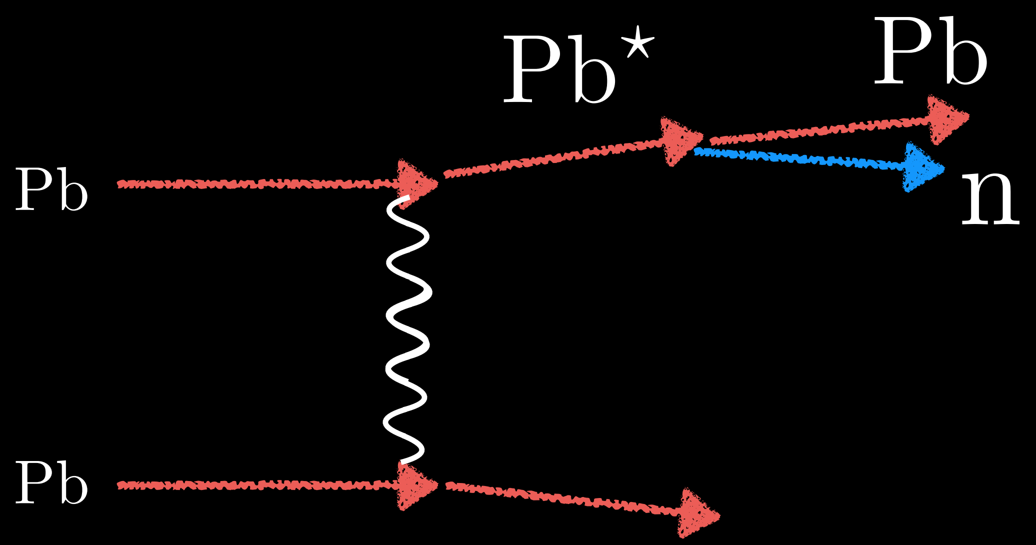
Magnets bend this differently

Magnet quenching with too much luminosity

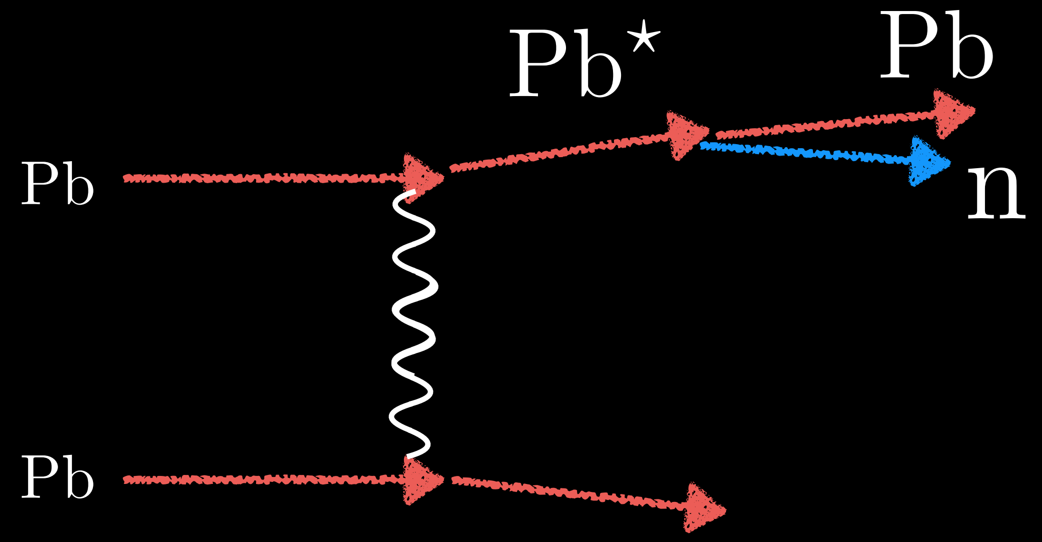




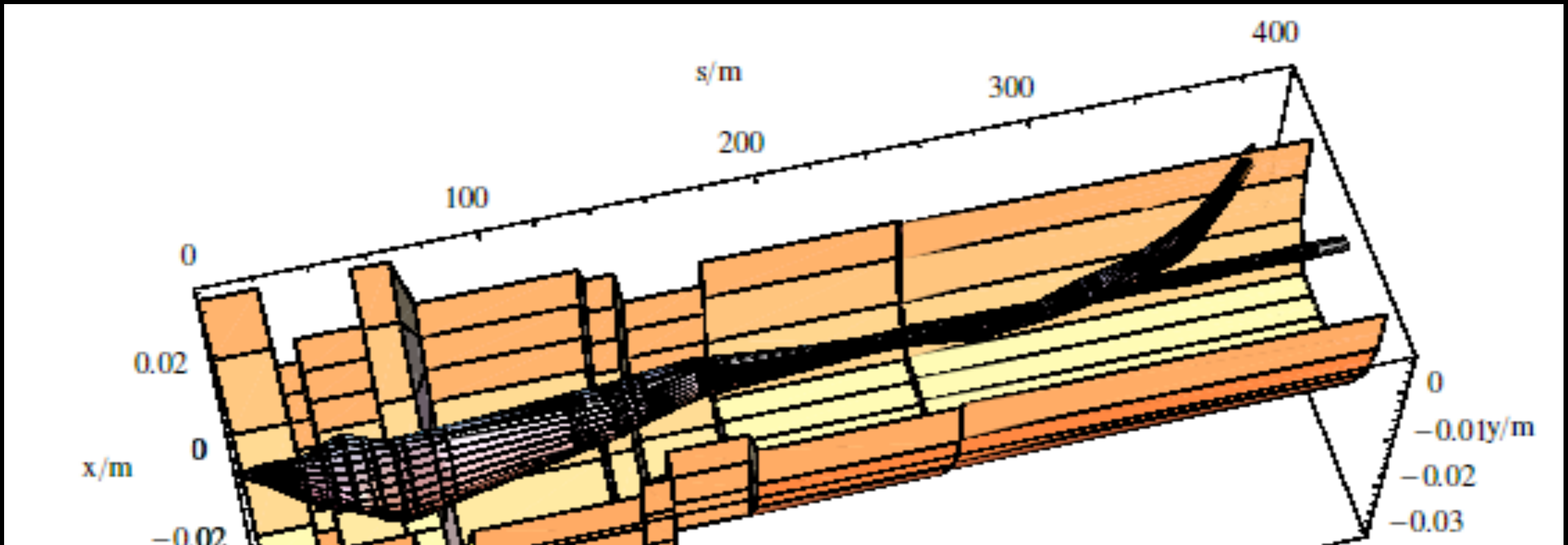
S. Gilardoni, J.M. Jowett, CERN, Geneva, Switzerland
R. Bruce CERN, Geneva, Switzerland and Linköping University



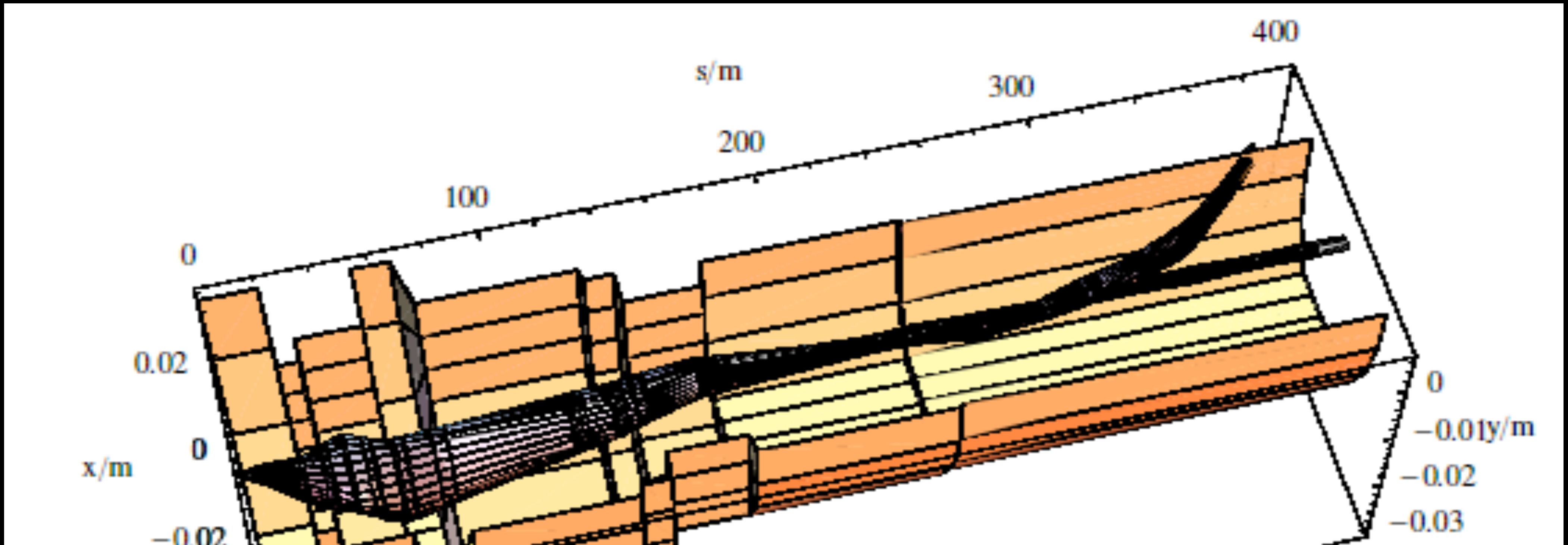
Similar rate for EM excitation of the nucleus and ejection of a neutron



Similar rate for EM excitation of the nucleus and ejection of a neutron



	Projectile	Z	A	$\sqrt{s}$, A GeV	Luminosity, $\mathrm{cm}^{-2}\mathrm{s}^{-1}$
L	p	1	1	14000	$1.4 \cdot 10^{31}$
H	Ar	18	40	7000	$5.2 \cdot 10^{29}$
C	Pb	82	208	5500	$4.2 \cdot 10^{26}$
R	p	1	1	500	$1.4 \cdot 10^{31}$
H	Cu	29	63	230	$9.5 \cdot 10^{27}$
I	Au	79	197	200	$2.0 \cdot 10^{26}$
C					



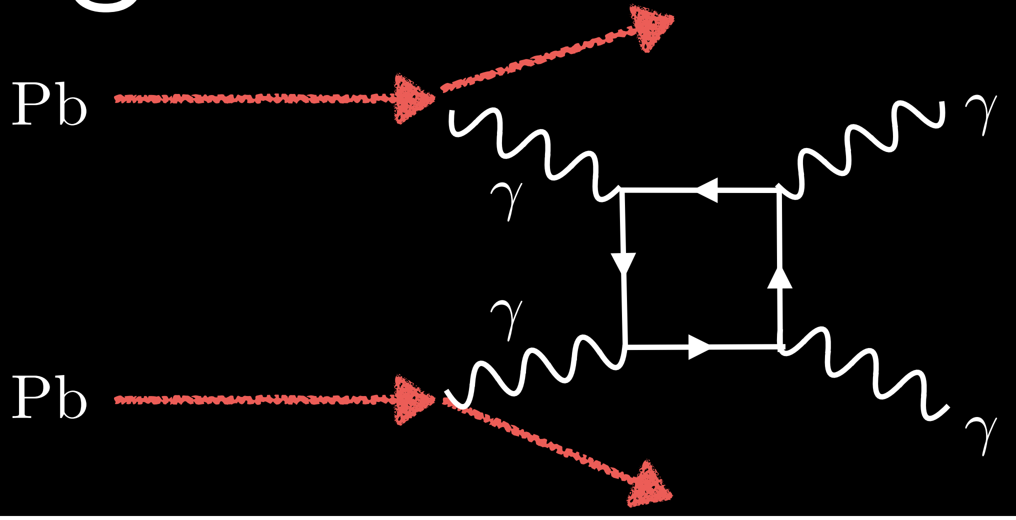
)

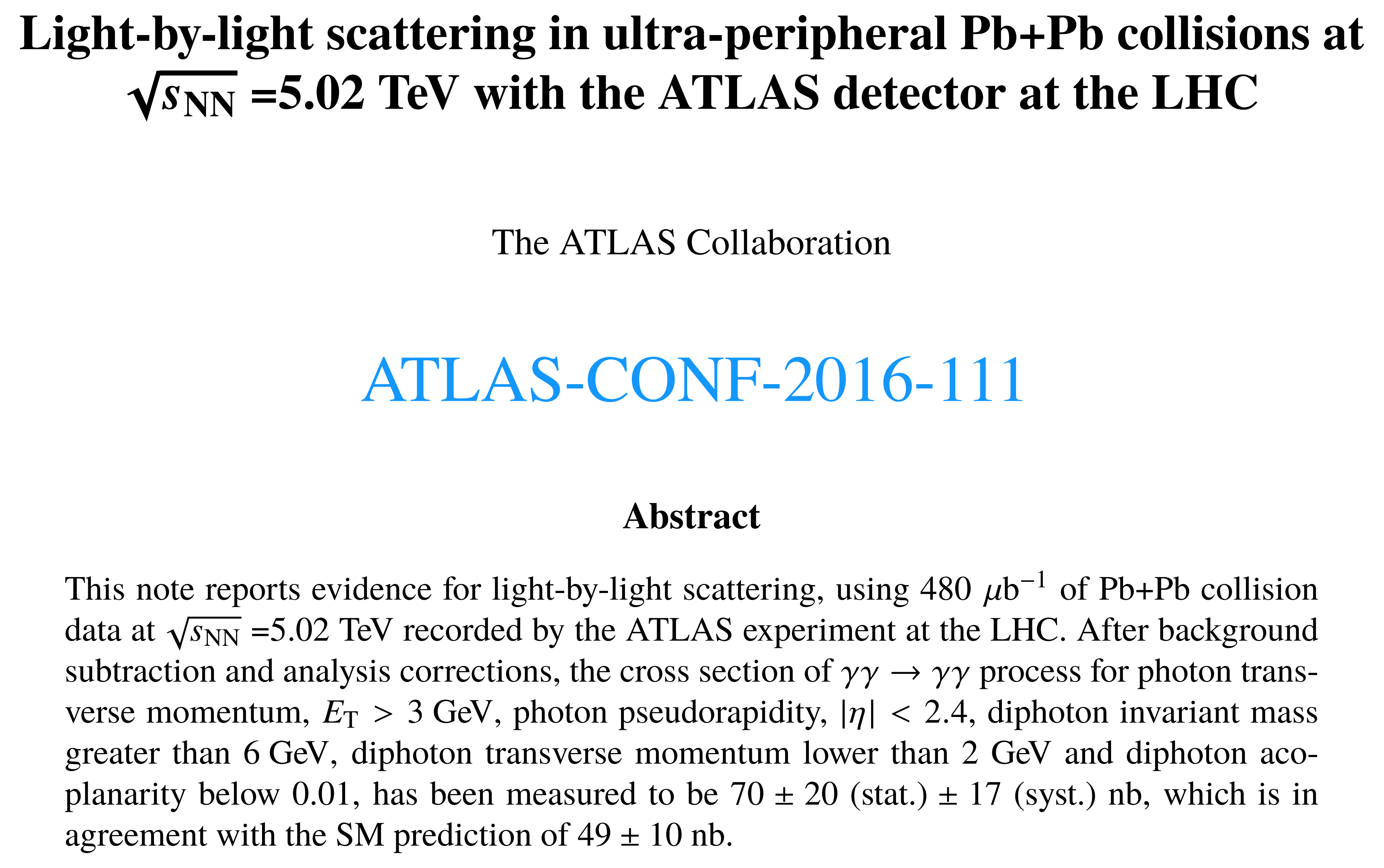
Backgrounds

LBL (Light by light)

D. d'Enterria and G. G. da Silveira (2013)

Z. Bern, A. De Freitas, L. J. Dixon, A. Ghinculov, and H. L. Wong (2001)





Light-by-light scattering in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV with the ATLAS detector at the LHC

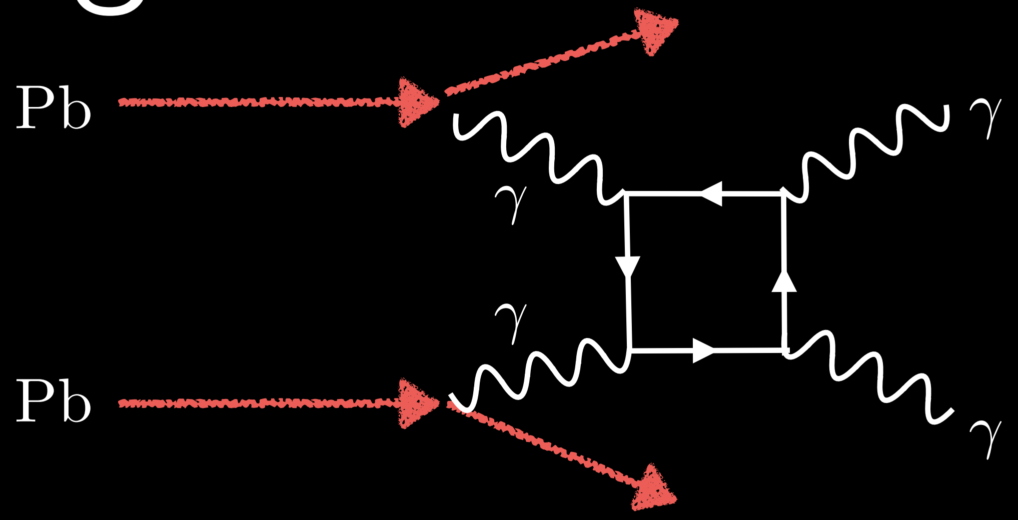
The ATLAS Collaboration

ATLAS-CONF-2016-111

Abstract

This note reports evidence for light-by-light scattering, using 480 $\mu\mathrm{b}^{-1}$ of Pb+Pb collision data at $\sqrt{s_{\mathrm{NN}}}$ =5.02 TeV recorded by the ATLAS experiment at the LHC. After background subtraction and analysis corrections, the cross section of $\gamma\gamma \to \gamma\gamma$ process for photon transverse momentum, $E_{\mathrm{T}} > 3$ GeV, photon pseudorapidity, $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, has been measured to be 70 ± 20 (stat.) ± 17 (syst.) nb, which is in agreement with the SM prediction of 49 ± 10 nb.

Backgrounds



LBL (Light by light)

D. d'Enterria and G. G. da Silveira (2013)

Z. Bern, A. De Freitas, L. J. Dixon, A. Ghinculov, and H. L. Wong (2001)

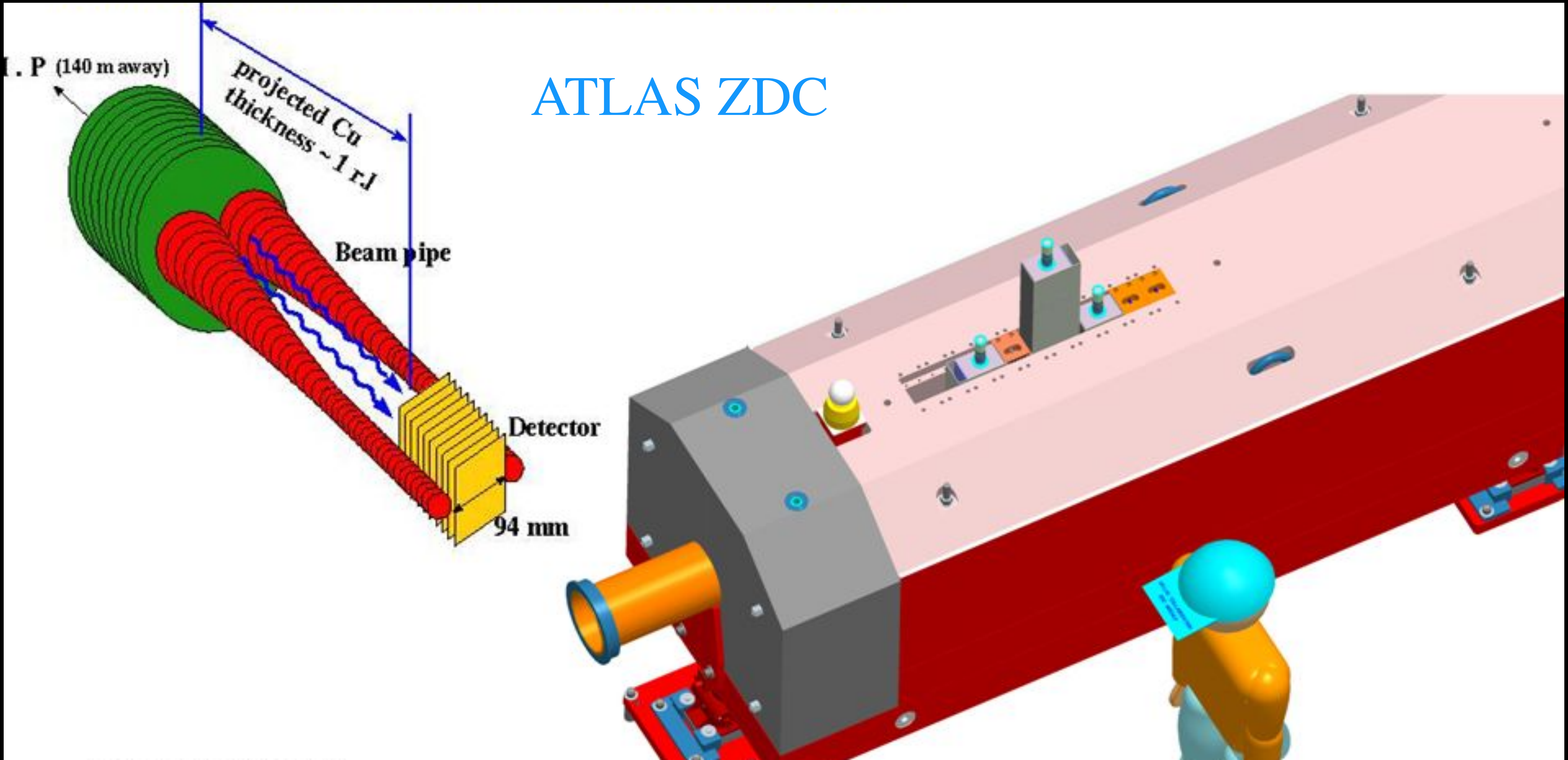
Trigger

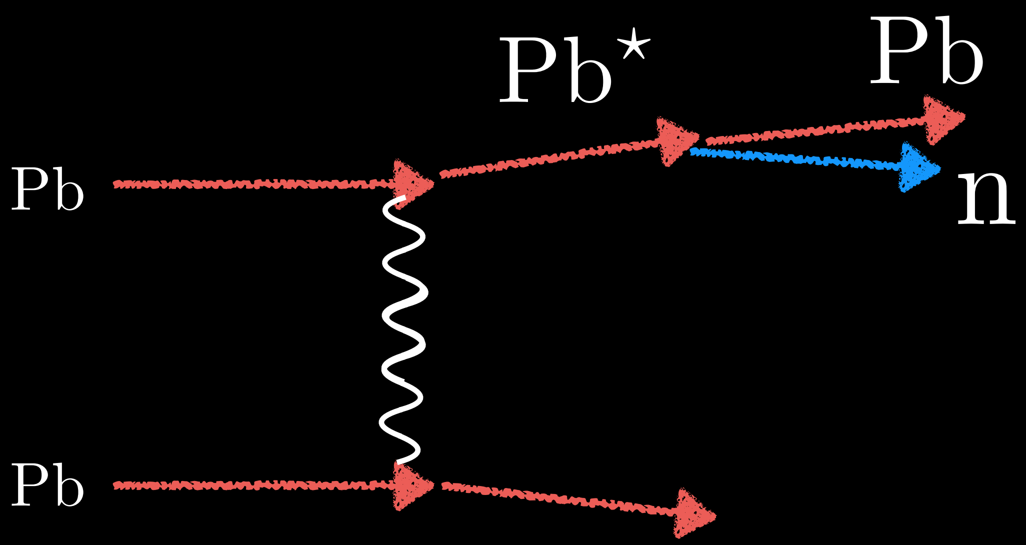
5 GeV < ET < 200 GeV in Ecal

<= 1 hit in inner ring of MBTS
<= 10 hits in pixel detector

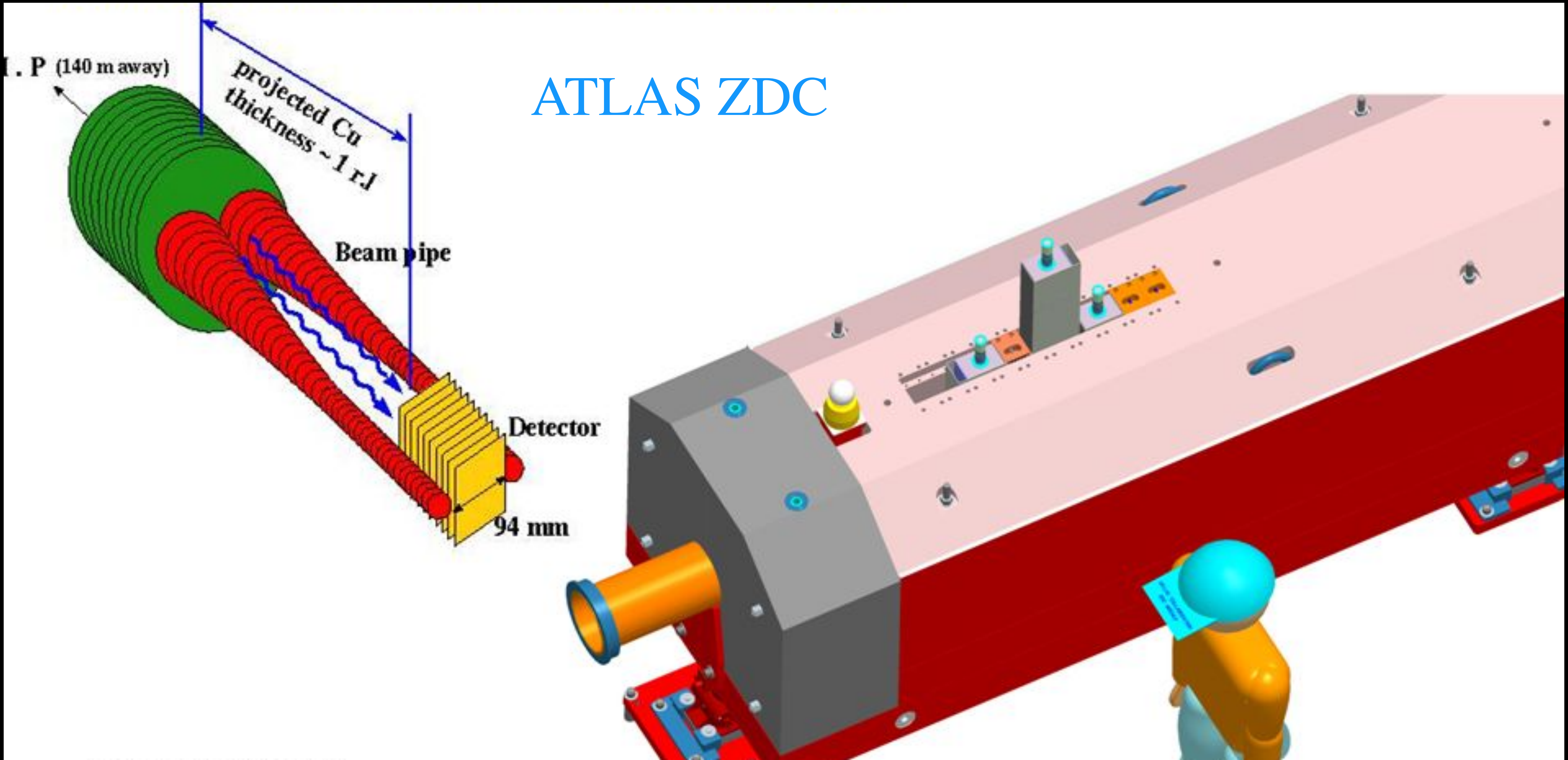
(

Zero degree calorimeters



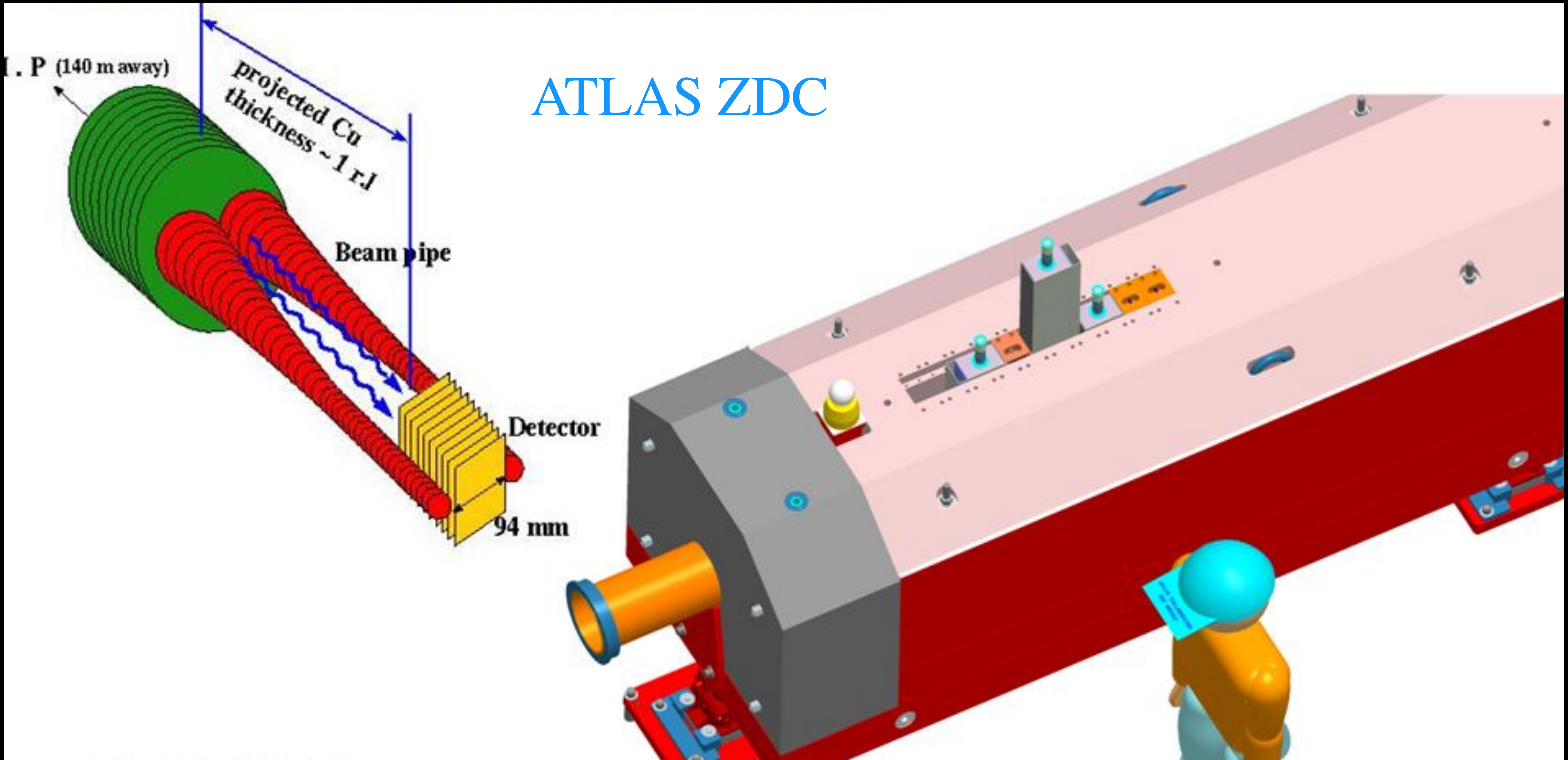

Pb
Pb*
Pb
n
Pb

ATLAS ZDC


I . P (140 m away)
projected Cu thickness ~ 1 r.l
Beam pipe
Detector
94 mm

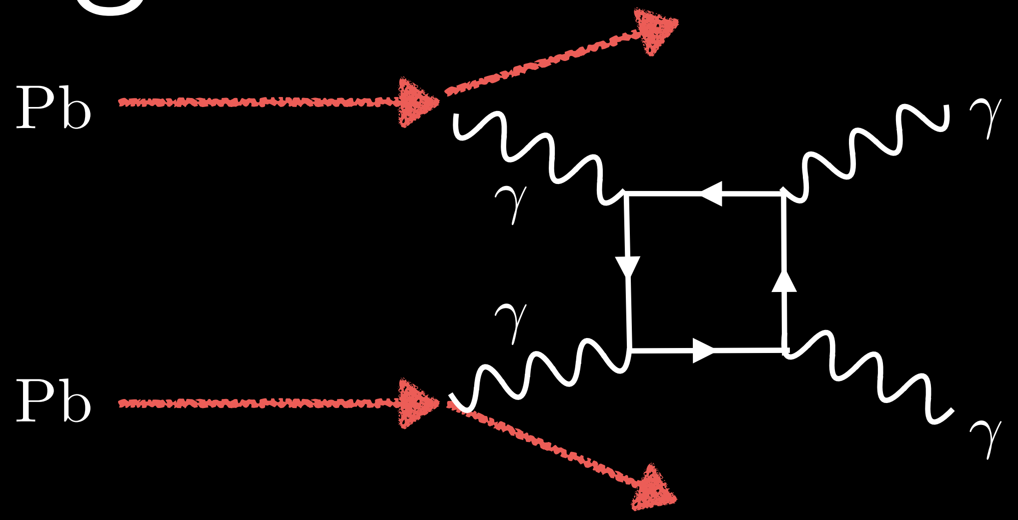
Trigger efficiency for LBL scattering estimated using this effect…

…but potential use for new searches?



)

Backgrounds



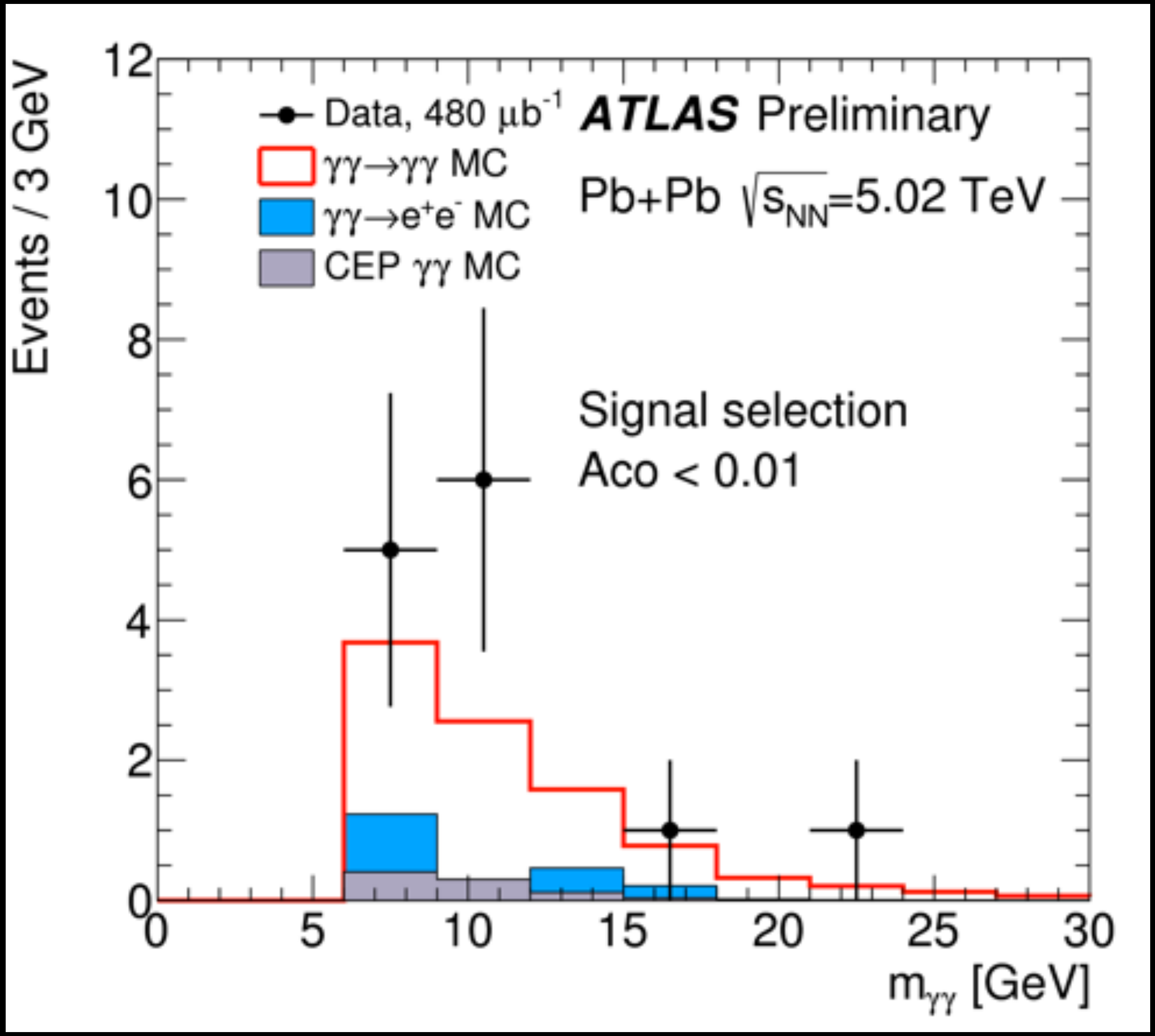
LBL (Light by light)

D. d'Enterria and G. G. da Silveira (2013)

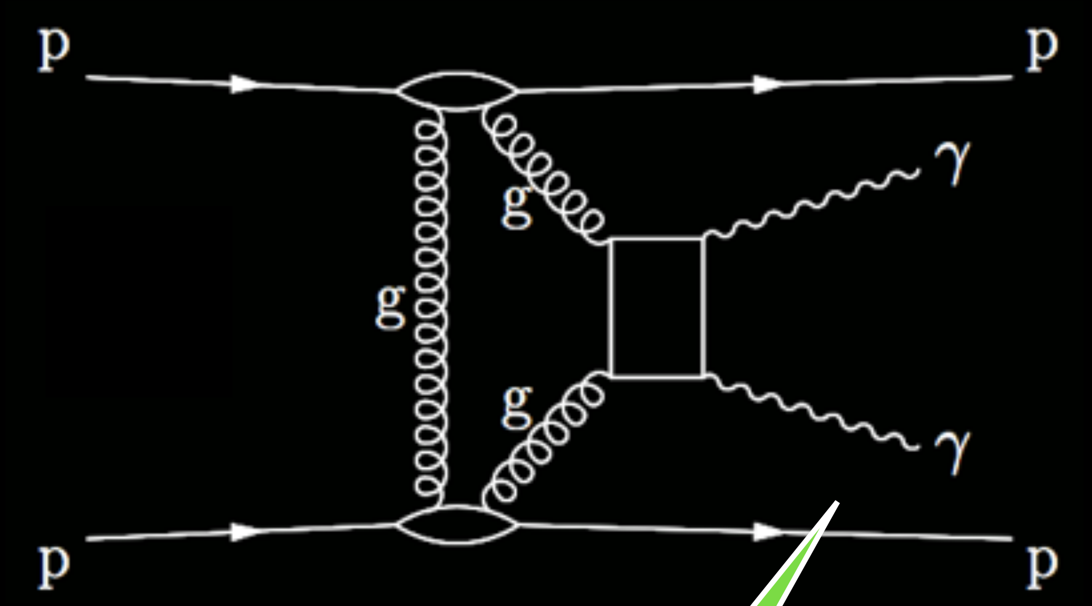
Z. Bern, A. De Freitas, L. J. Dixon, A. Ghinculov, and H. L. Wong (2001)

4.4 sigma observation

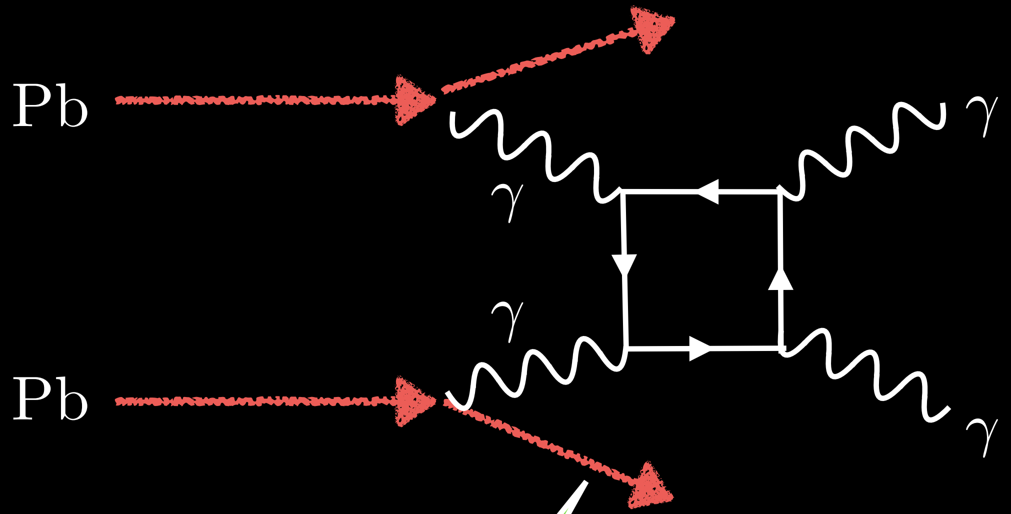
~50 nb cross section



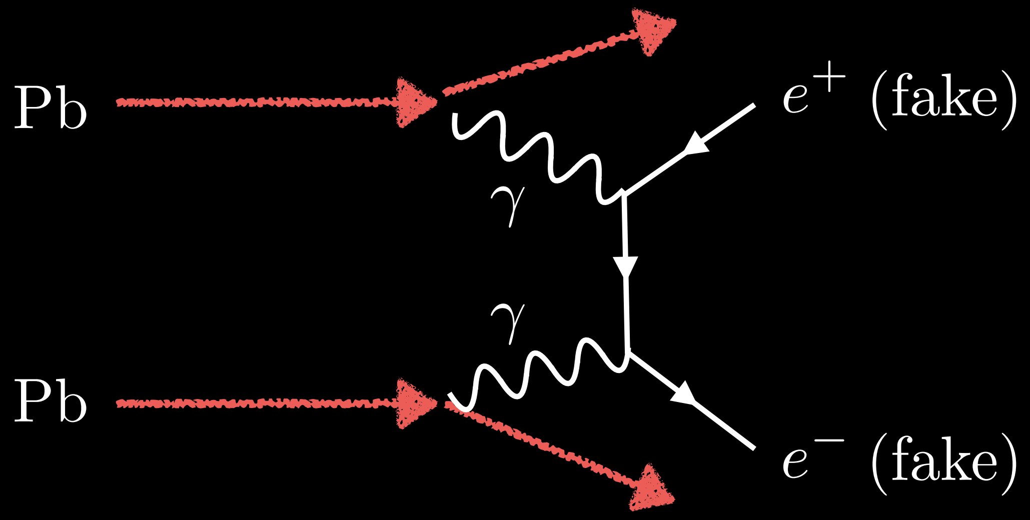
Backgrounds



CEP (Central exclusive production) ✓

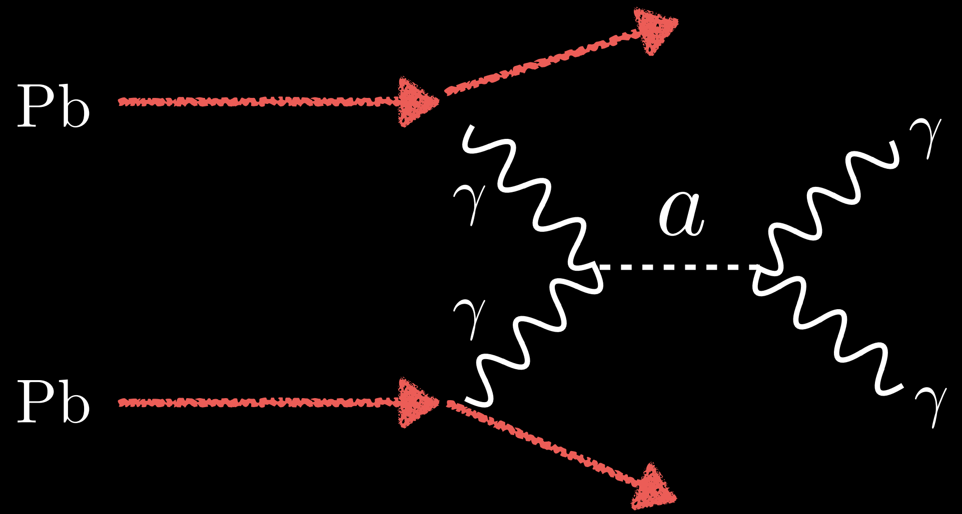


LBL (Light by light) ✓

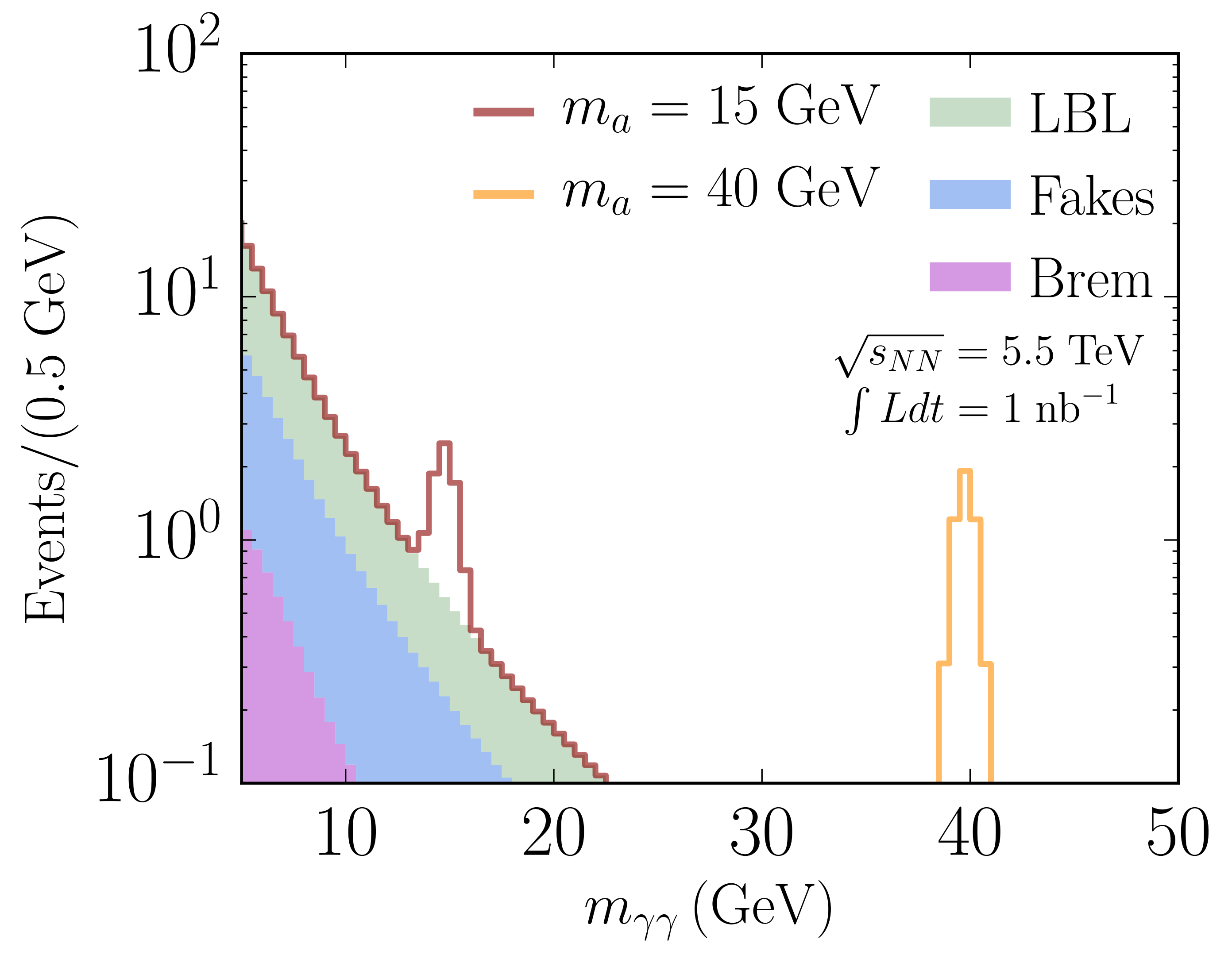


Fakes ✓

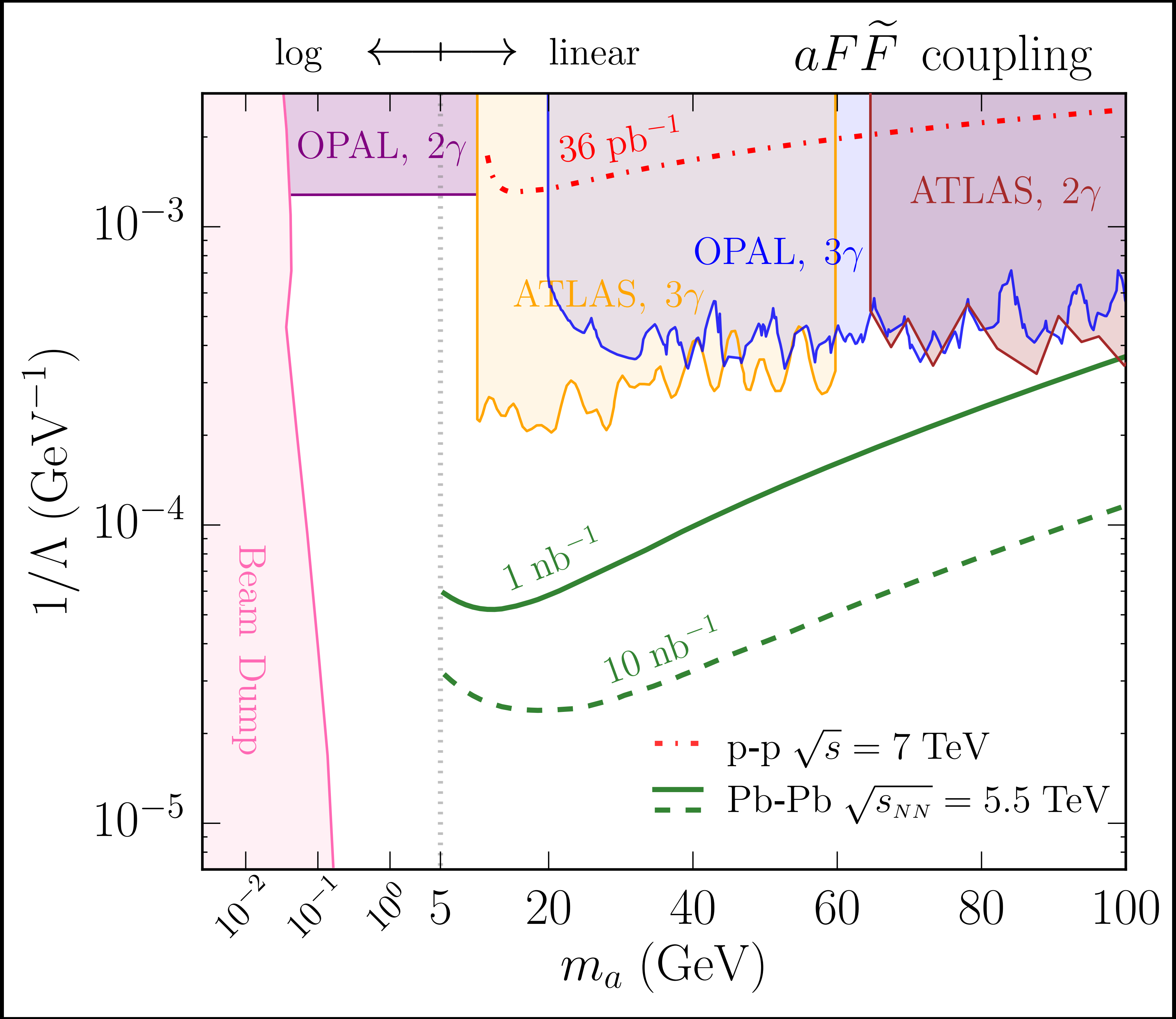
Injected signal



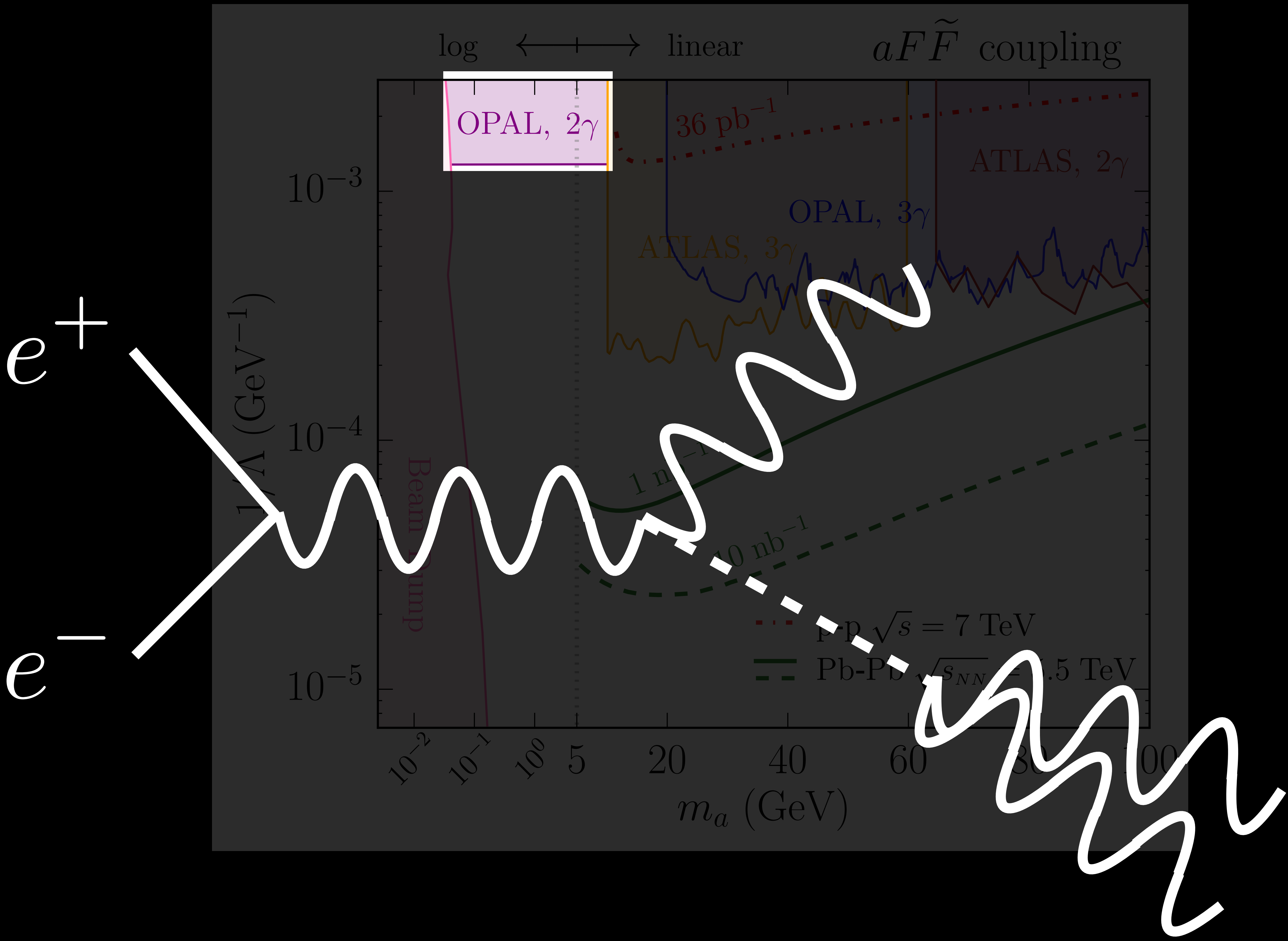
Further cuts: $|\eta_\gamma| < 2.5$ $|\Delta\phi - \pi| < 0.04$



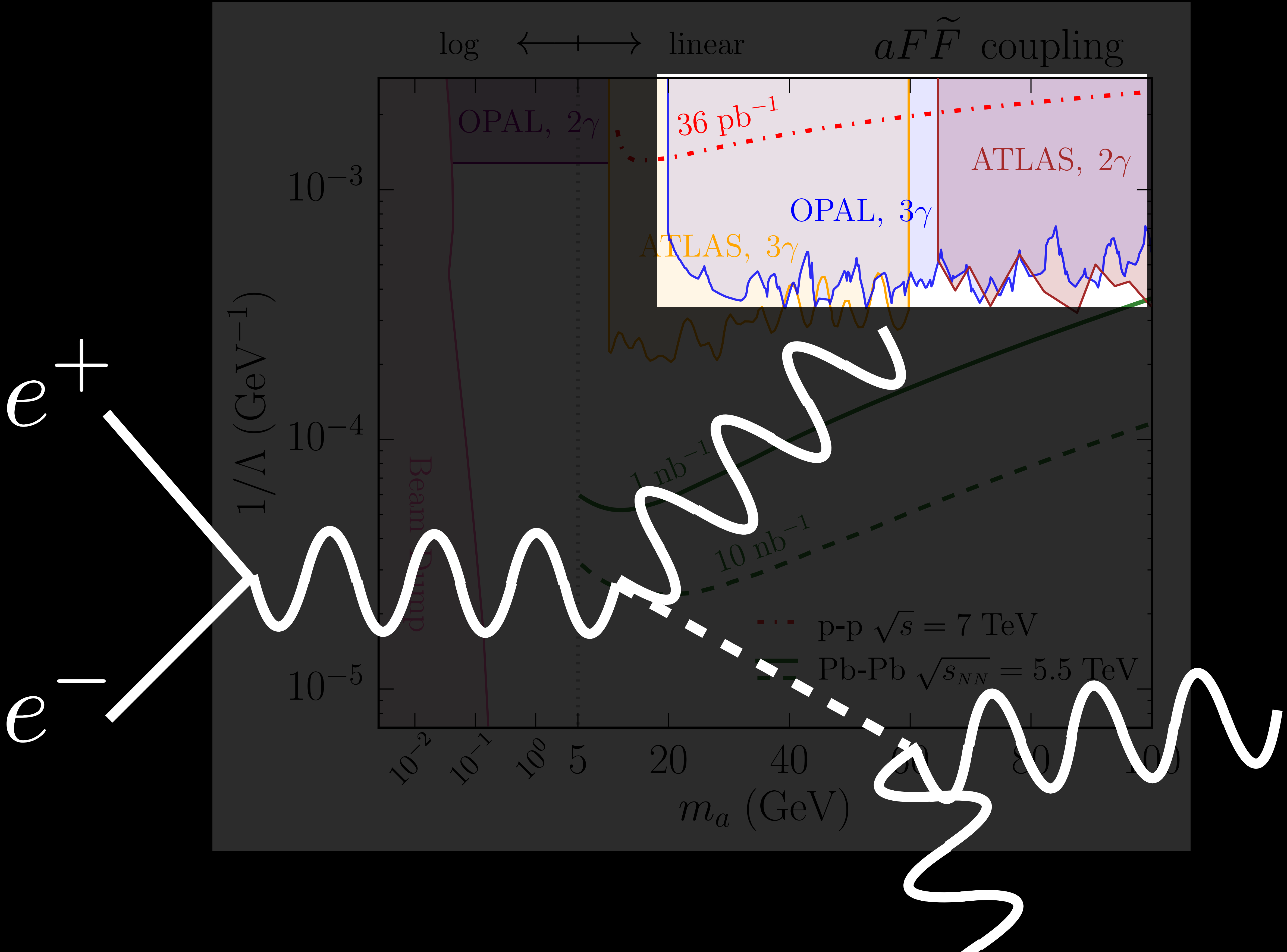
Projected sensitivity



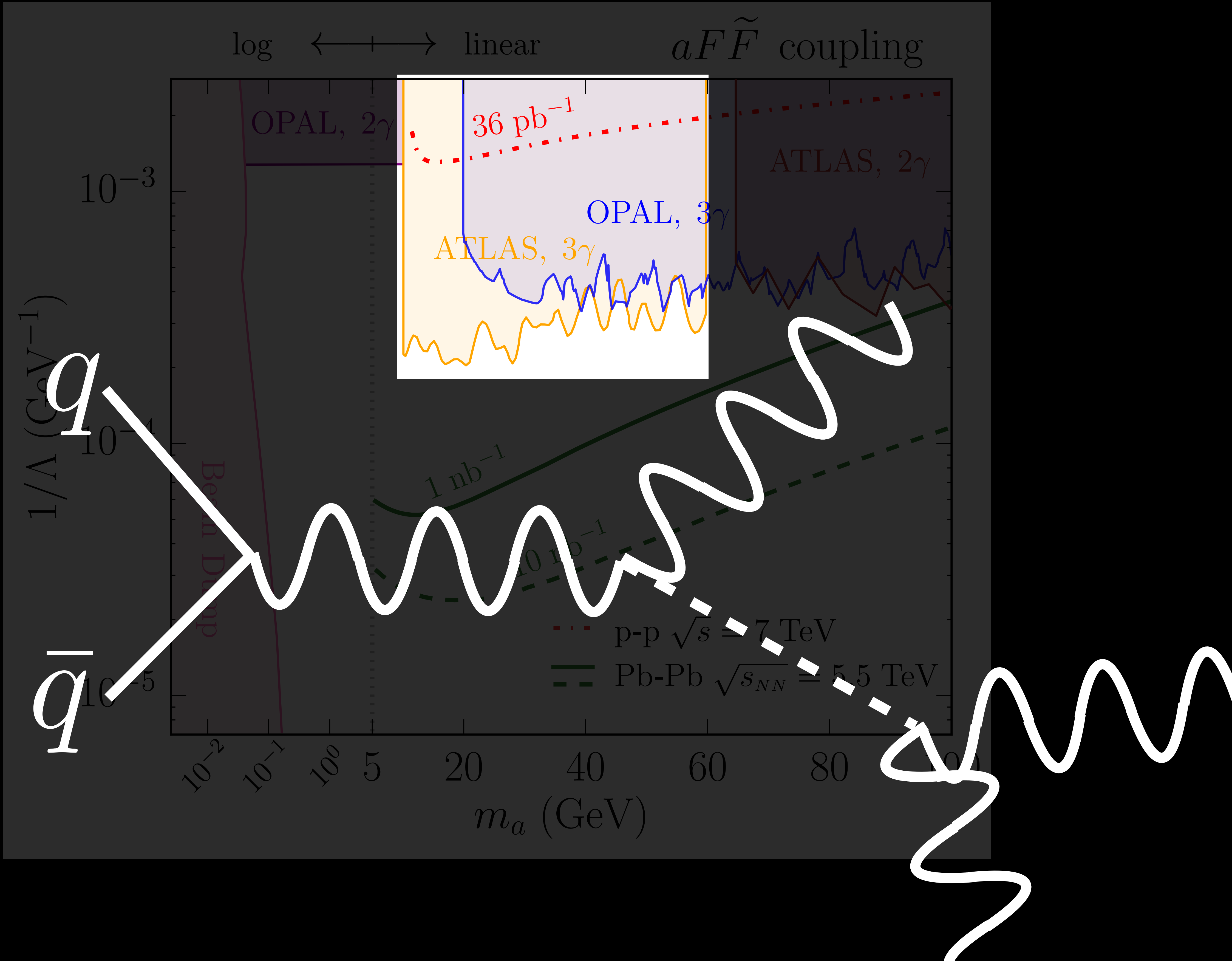
Projected sensitivity



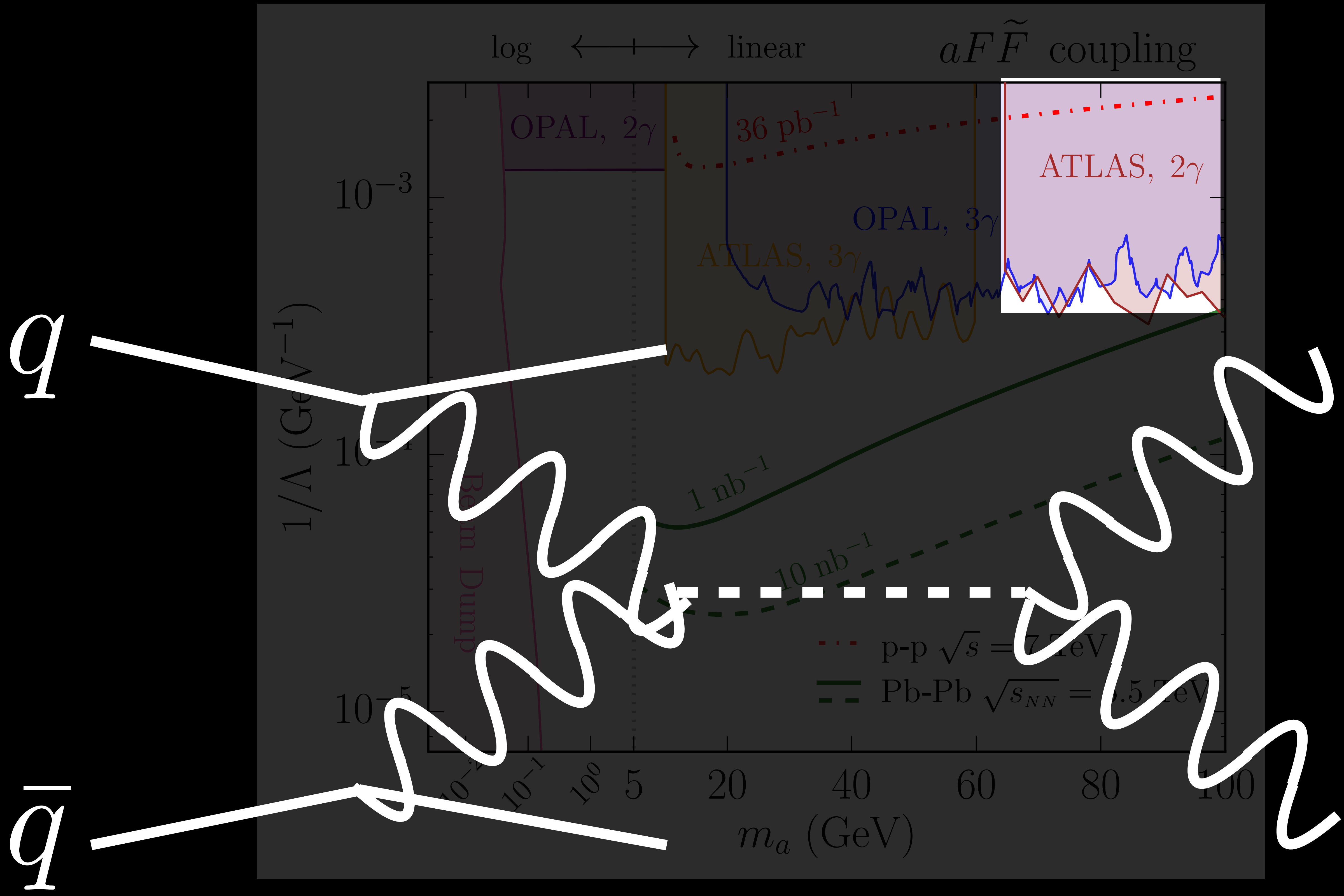
Projected sensitivity



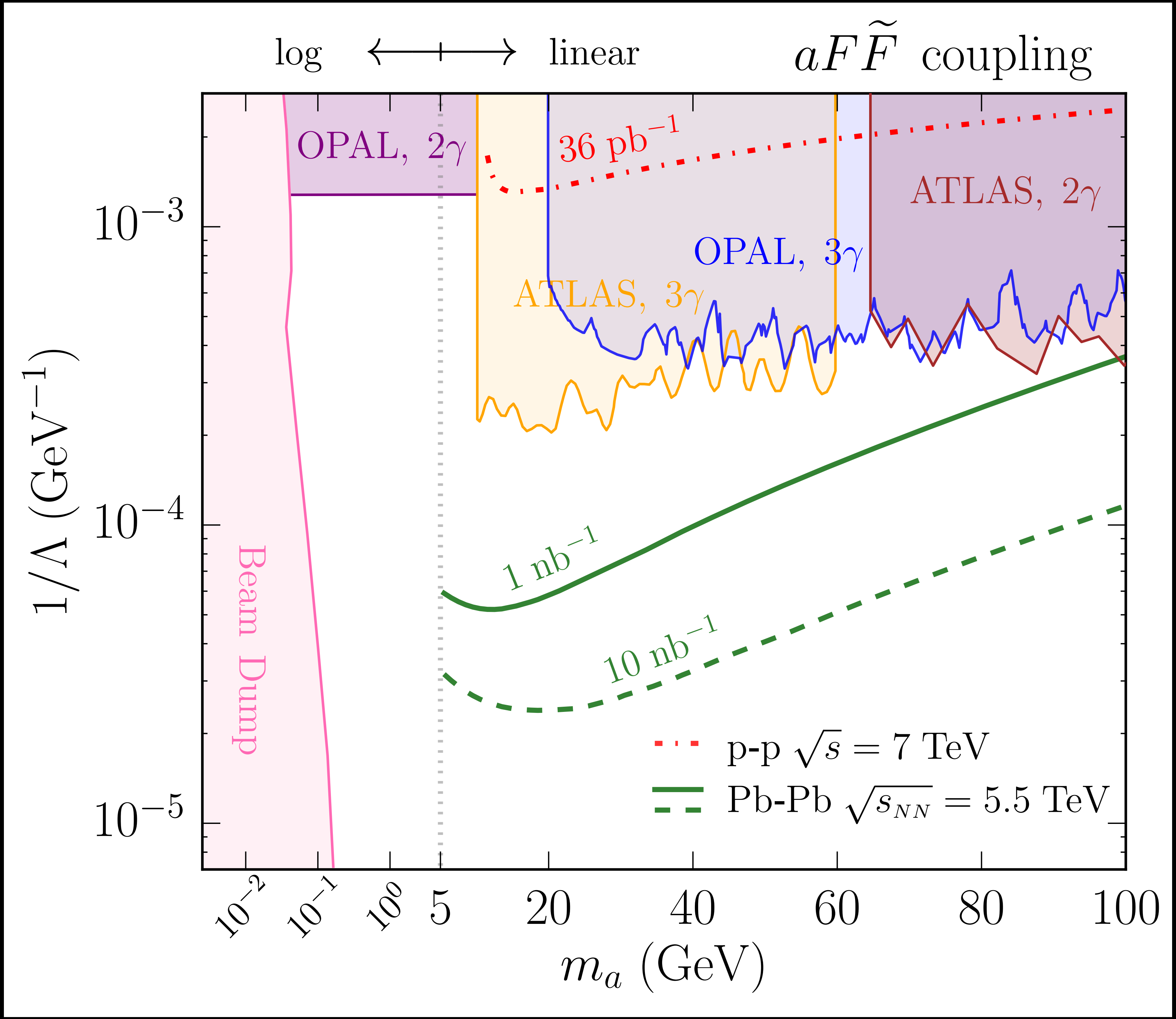
Projected sensitivity



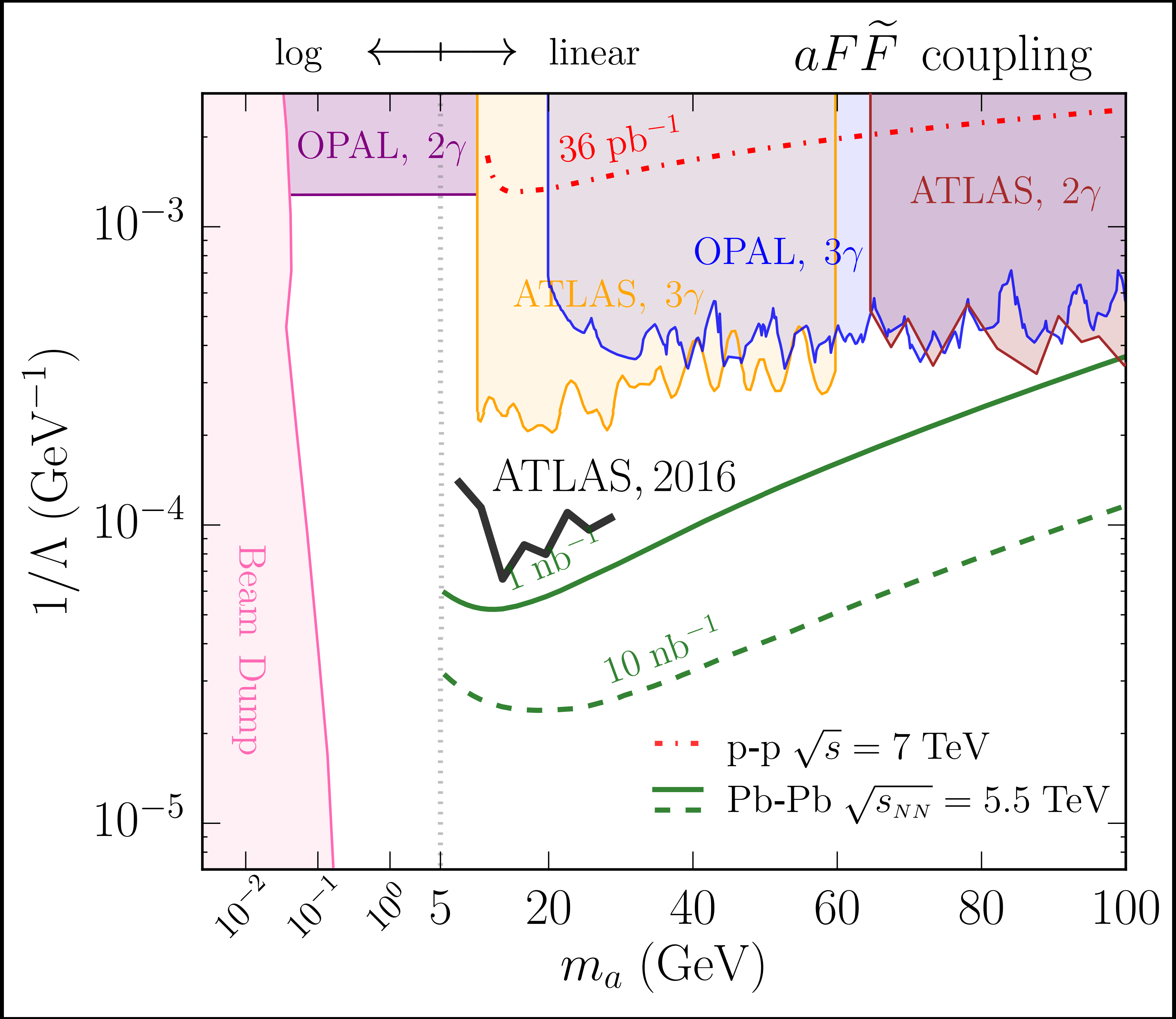
Projected sensitivity



Projected sensitivity

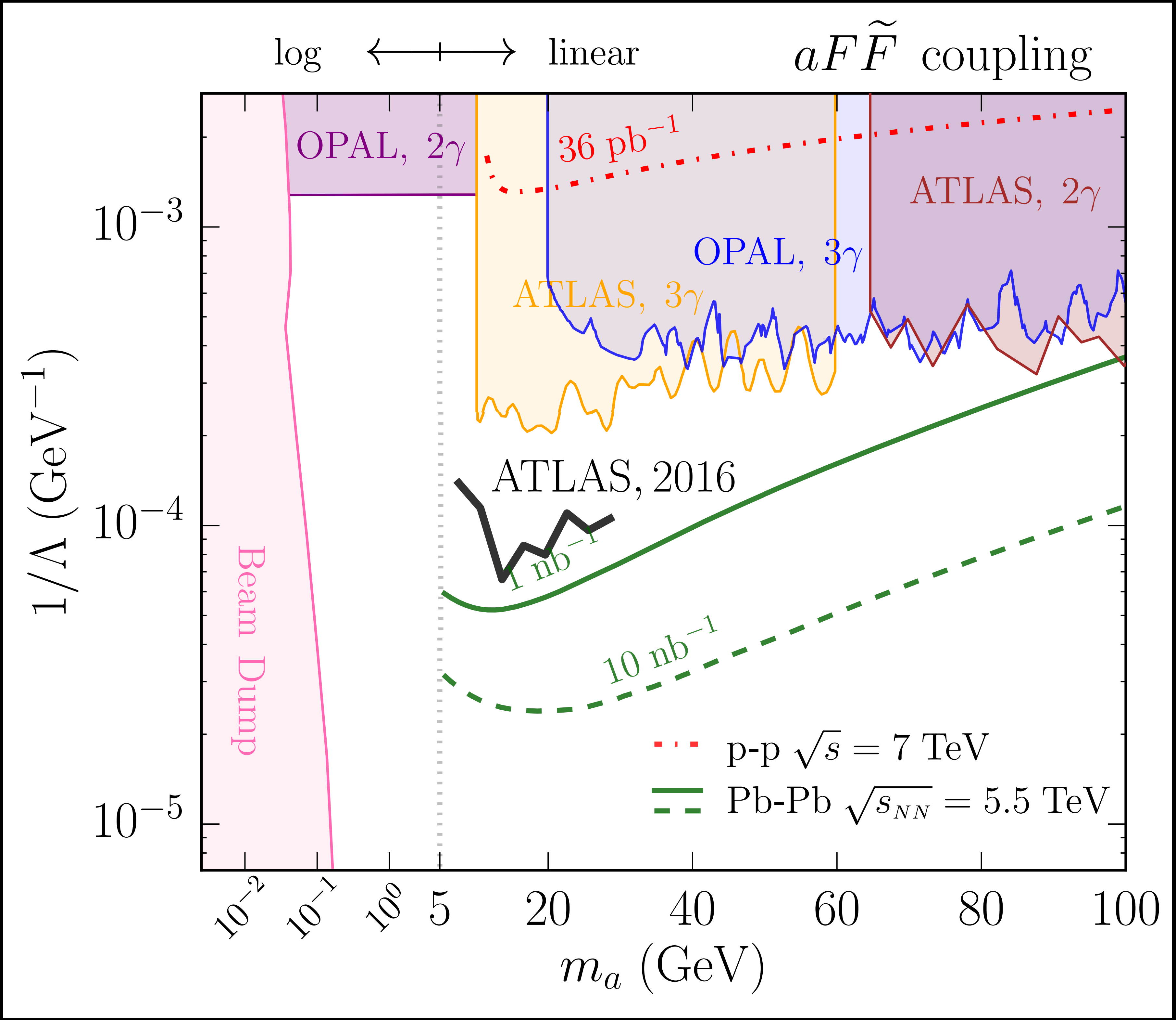


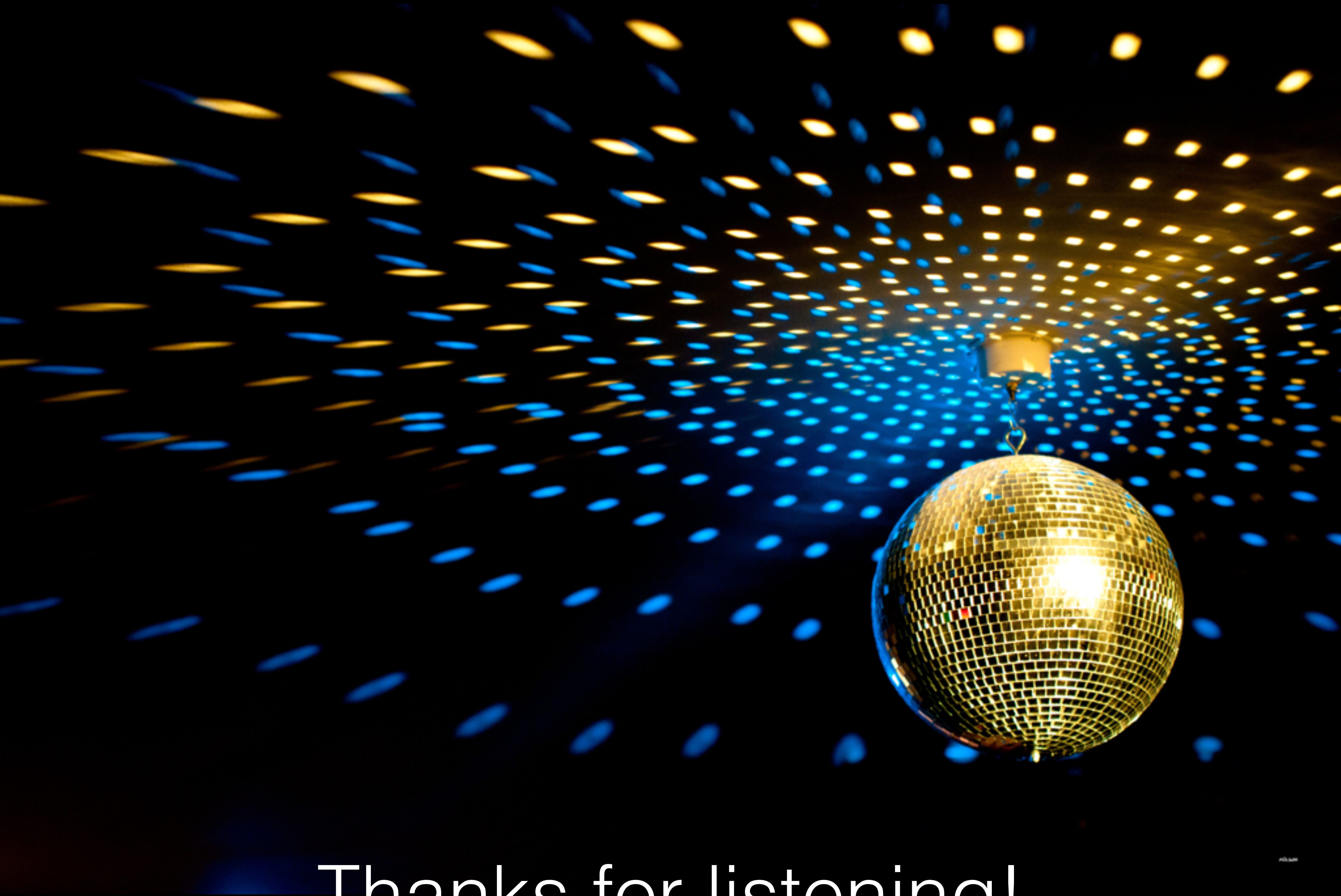
New limit set



ATLAS-CONF-2016-111

As far as we are aware, only place heavy ions can better the p-p program for BSM





Thanks for listening!