New collider searches for dark photons

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NNV annual meeting, subatomic physics section (Nov 04, 2022)

Based on work with Joerg Jaeckel

Radboud University

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- Dark photon model
- Displaced vertex at Belle II
- Searches at photon colliders (LUXE and Gamma Factory)

Dark photon model

New collider searches for dark photons

Motivation

- Dark matter should exist.
- Fail to find dark matter?

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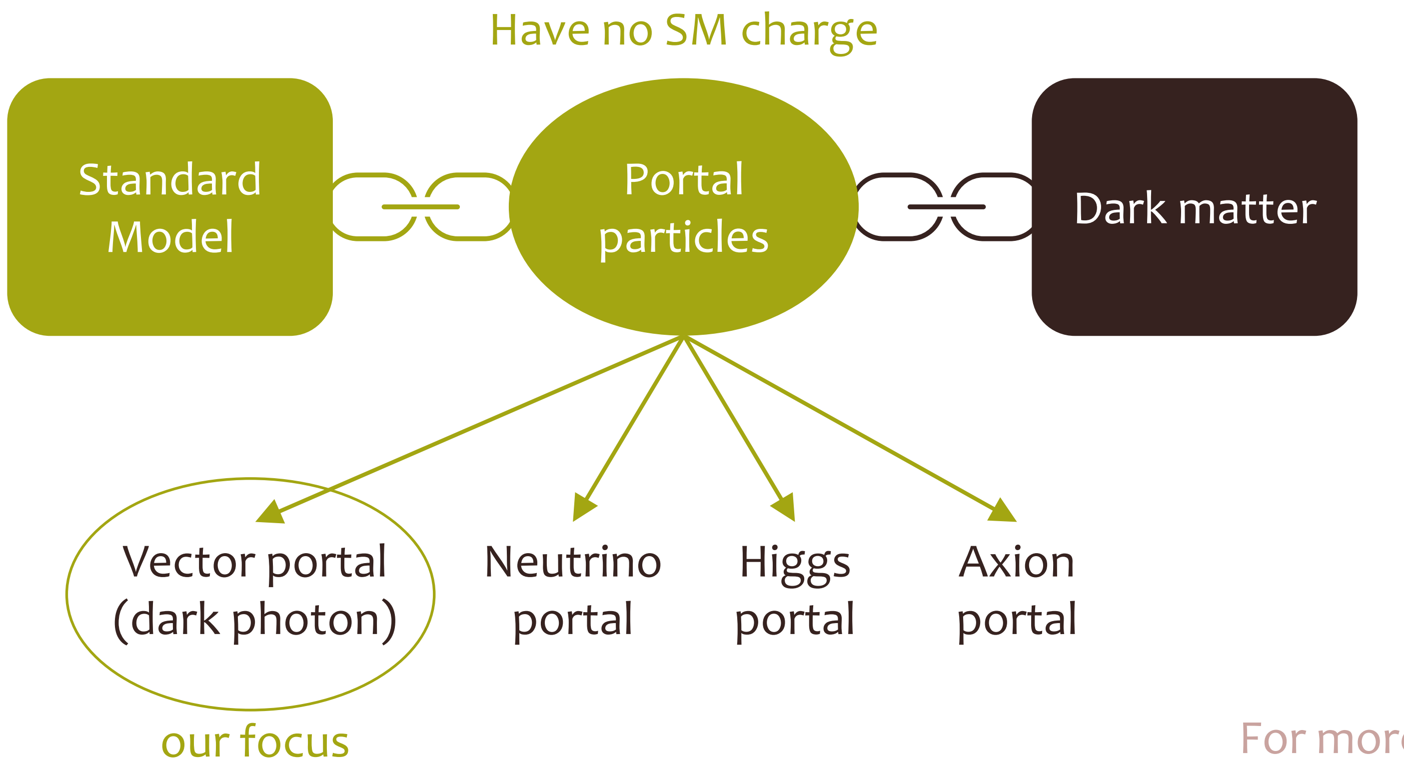


For more on portals to dark sector:
Batell, Pospelov, and Ritz (2009)
Batell, Blinov, Hearty, and McGehee (2022)

Motivation

- Dark matter should exist.
- Fail to find dark matter → look for portal particles.
- Some BSM models (e.g., string theory) predict additional U(1) symmetries.

Dark photon (X_μ)

$$\mathcal{L} = -\frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{1}{2}\boldsymbol{m_X^2}X^\mu X_\mu + \boldsymbol{\epsilon}eX^\mu J_\mu^{em} + SM + "dark"$$

$X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$

Dark photon mass

Kinetic mixing coupling

Originates from $-\frac{\epsilon}{2}X^{\mu\nu}F_{\mu\nu}$

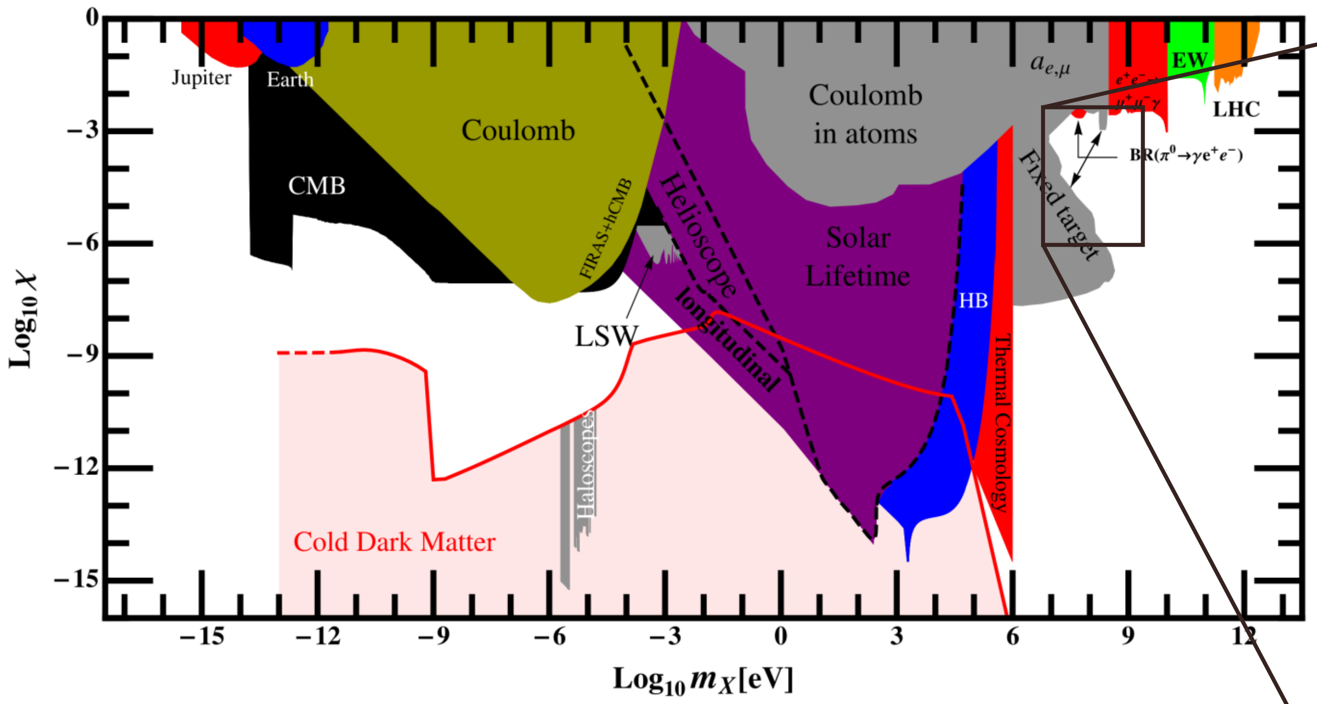
J_μ^{em} is SM electromagnetic current

→ Behaves like regular photon, but with coupling ϵe to SM fermions and is massive.

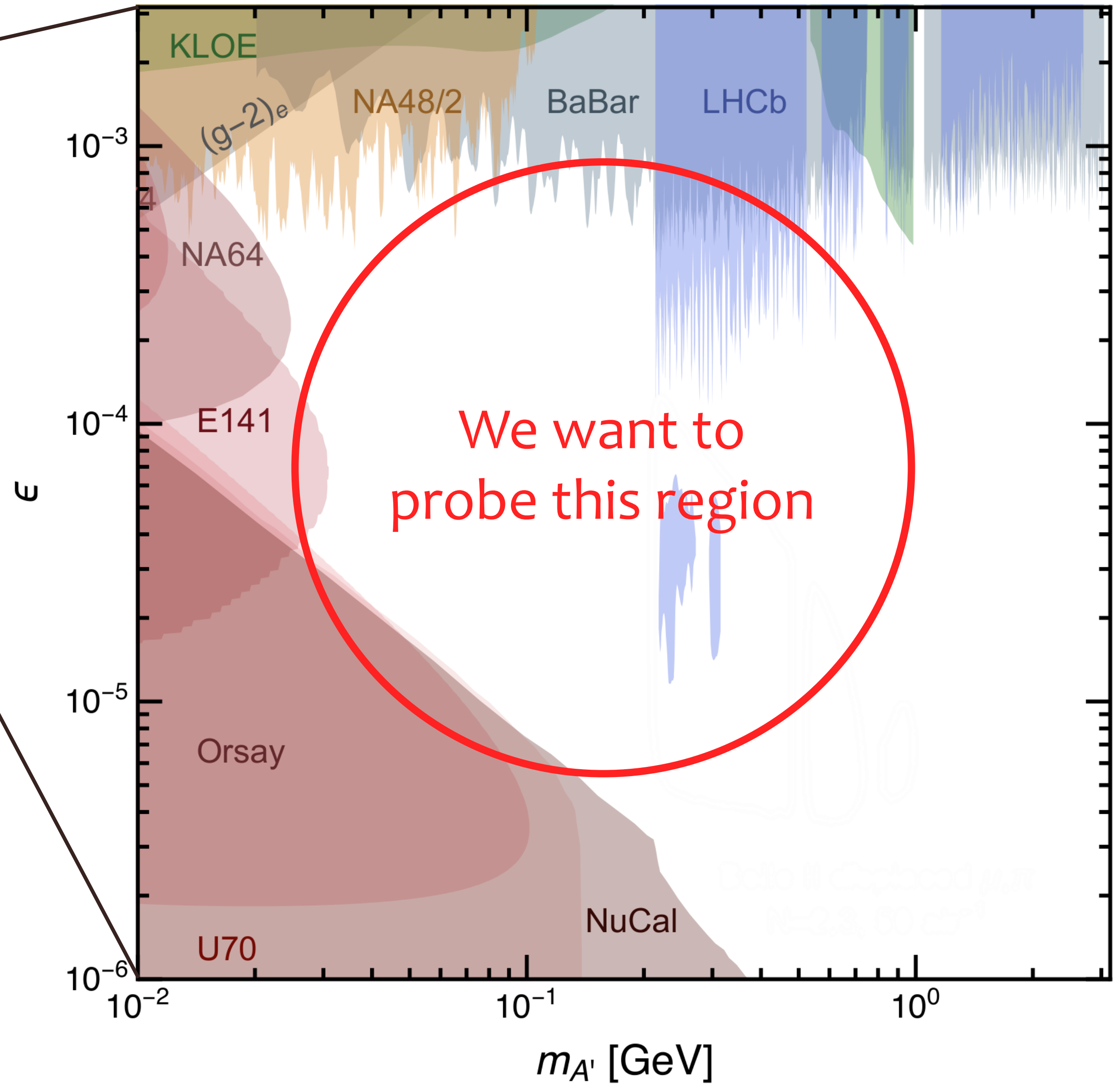
For more on dark photon model:
Holdom (1986)
Fabbrichesi, et al. (2020)

Existing limits on dark photons

Jaeckel (2013)



Adapted from Ferber, et al. (2022)



Kinetic mixing coupling

Dark photon mass

Places to search for feebly coupling dark photons

- e^+e^- colliders
  - Displaced vertex search at Belle II ← most promising
- Photon colliders
  - Beam dump experiment at LUXE
  - Bump hunt search at Gamma Factory

Displaced vertex at Belle II

New collider searches for dark photons

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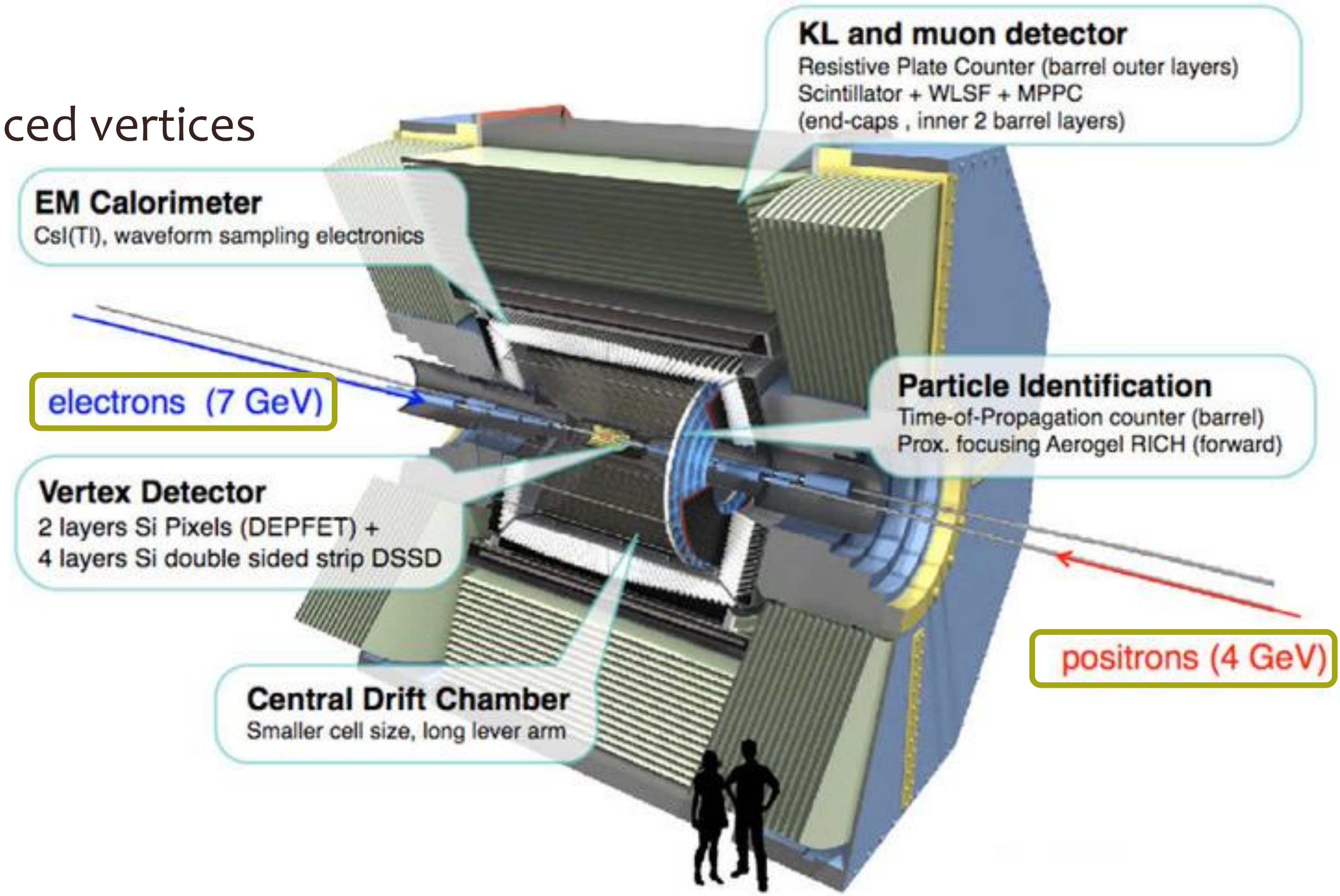
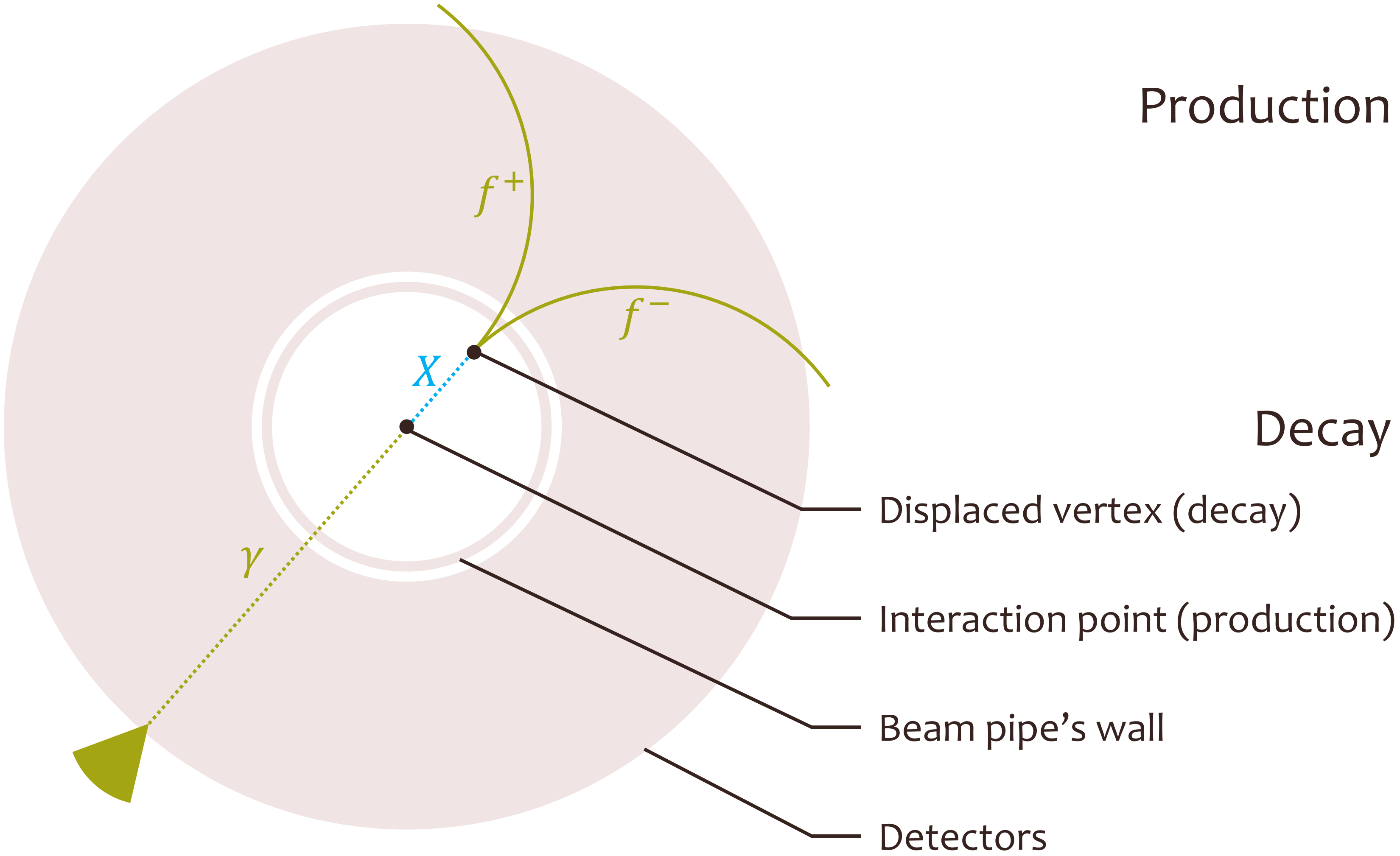
Belle II

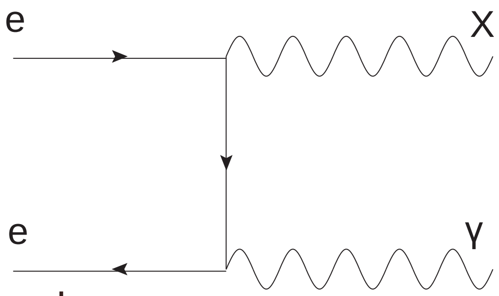
- e^+e^- collision at $\sqrt{s} = 10.58$ GeV.
- Why Belle II?
  - Good statistics
  - Low background
  - Algorithm suitable for finding displaced vertices

Belle II experiment
Matvienko (QUARKS-2018)



Signal





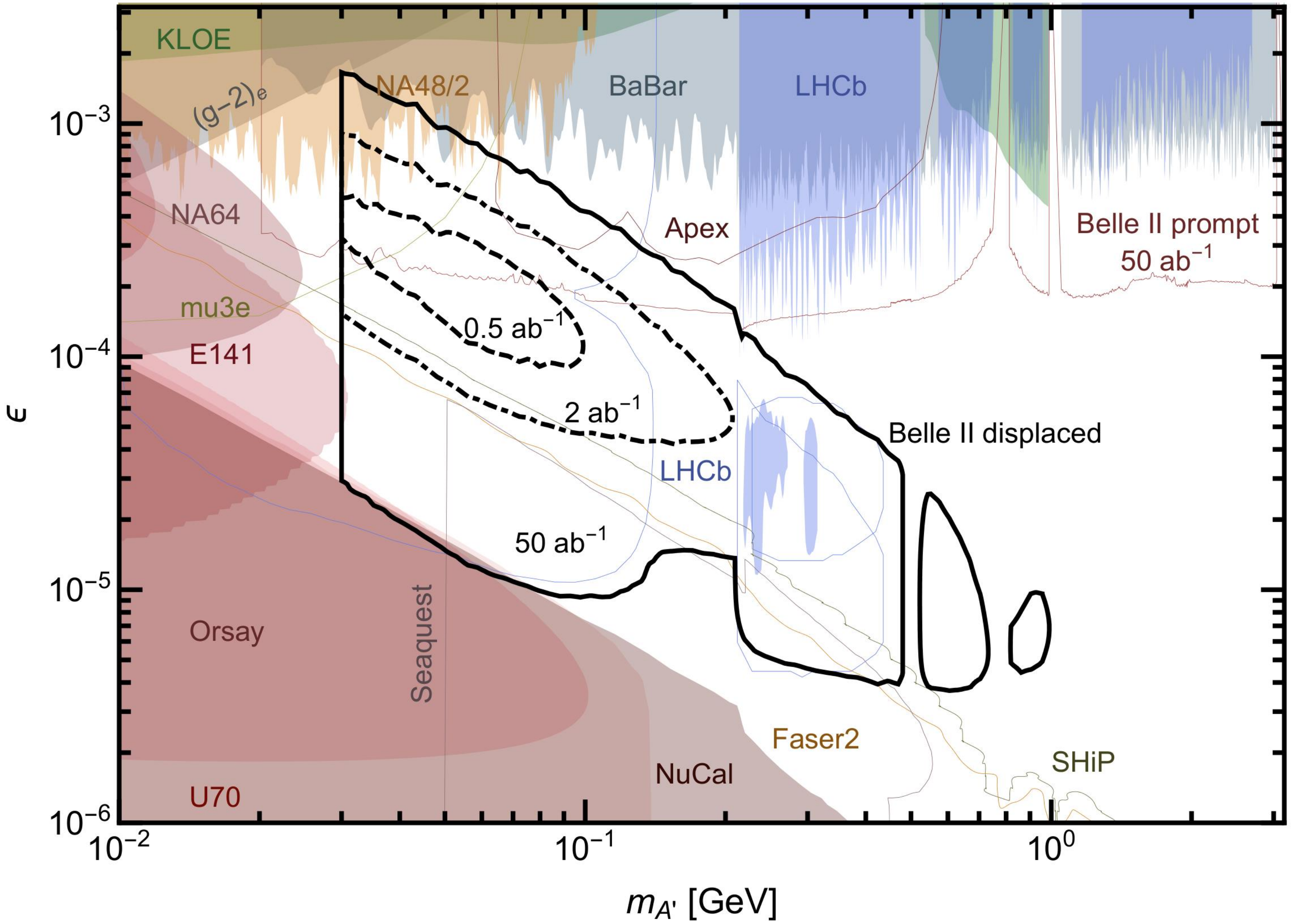
Production $e^+e^- \to \gamma X$

Travels a macroscopic distance (invisible)

Decay $X \to f^+f^-$

$(f = e, \mu, \pi, K)$

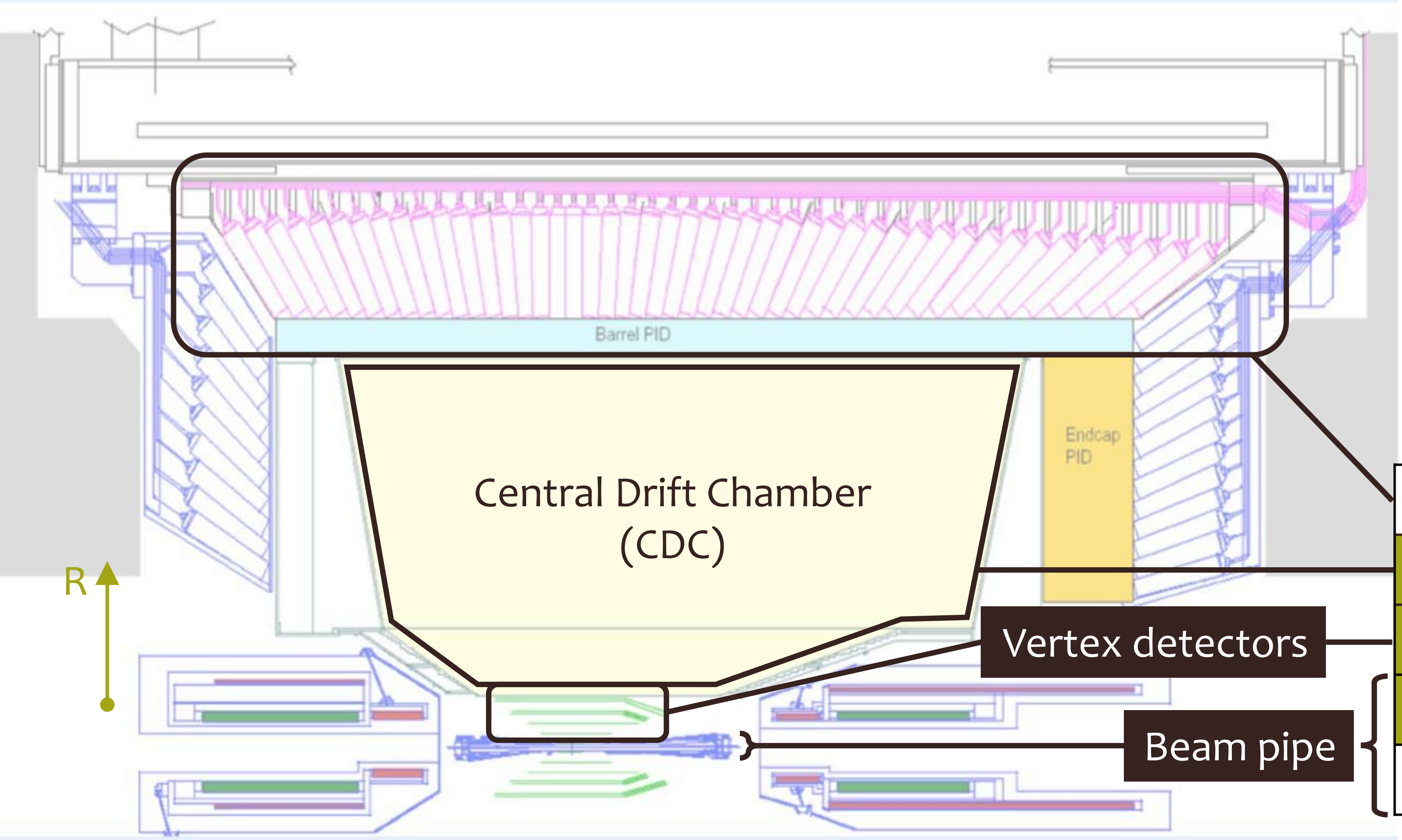
Sensitivity



Ferber, Garcia-Cely, and Schmidt-Hoberg (2022)

Where to find displaced vertices?

Cross-sectional view of Belle II
Adapted from Pestotnik (2015)

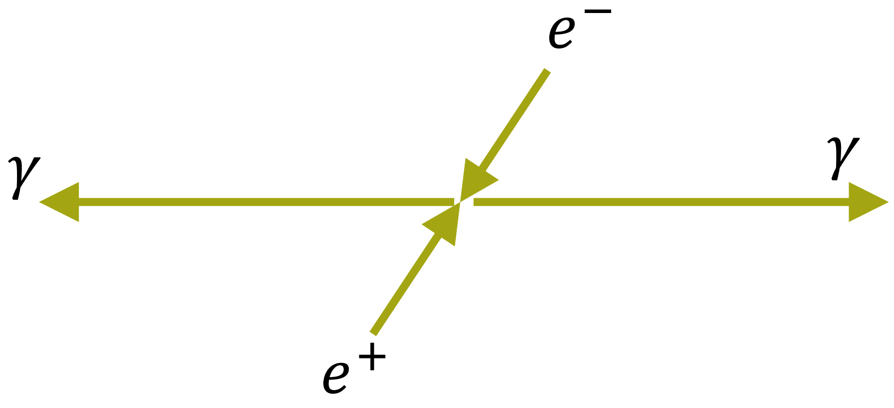


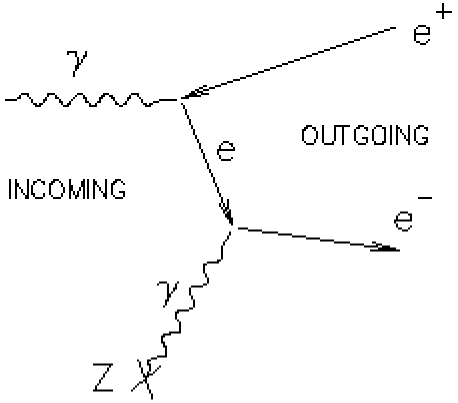
R > 60 cm	No tracking capability
17 cm < R < 60 cm	Maybe?
0.9 cm < R < 17 cm	Maybe?
0.2 cm < R < 0.9 cm	Promising
R < 0.2 cm	Large prompt background

Region categorization based on
Ferber, Garcia-Cely, and Schmidt-Hoberg (2022)

γ conversion (main background)

γ from $e^+e^- \to \gamma\gamma$ can convert in matter $\gamma \to f^+f^-$



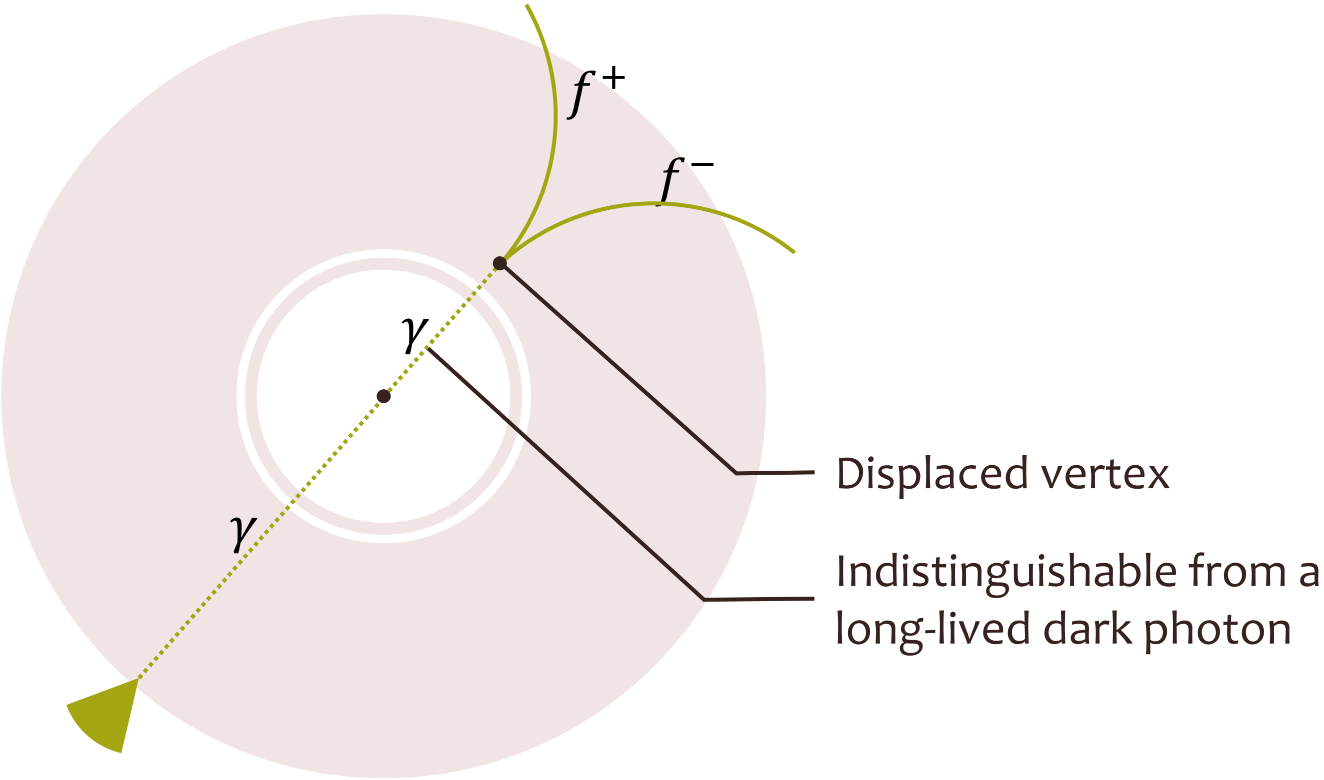


γ conversion in nucleus' EM field

Ferber, Garcia-Cely, and Schmidt-Hoberg (2022)

γ conversion (main background)

Main background for R > 0.9 cm.

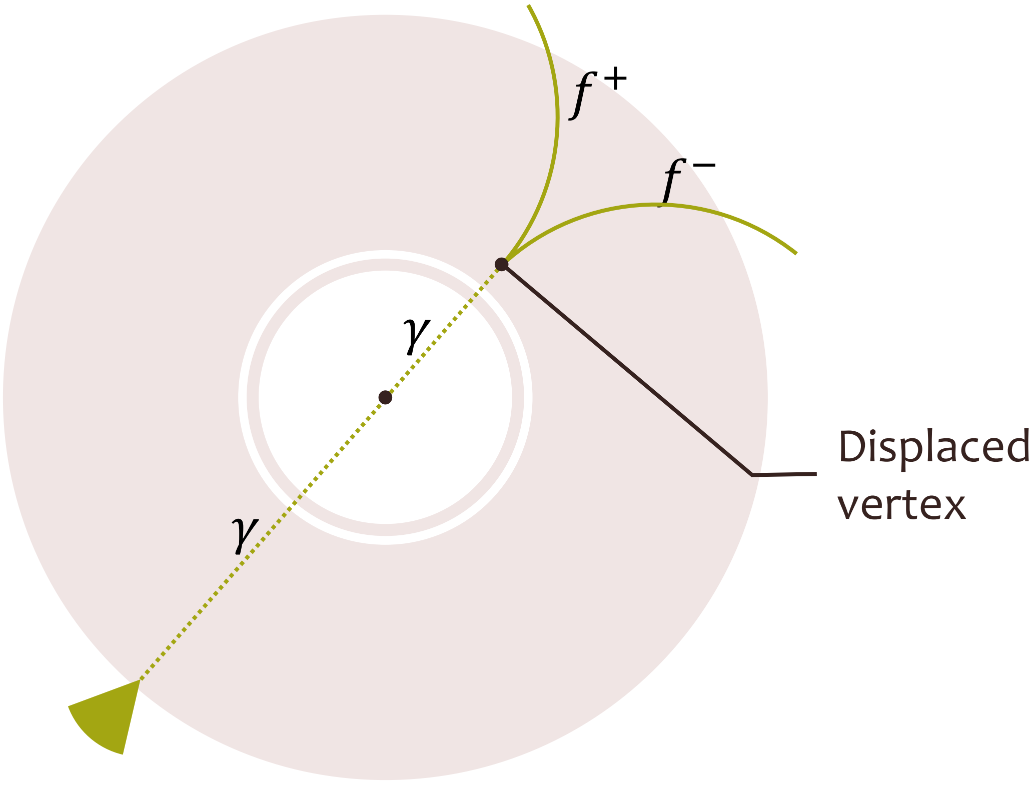


Ferber, Garcia-Cely, and Schmidt-Hoberg (2022)

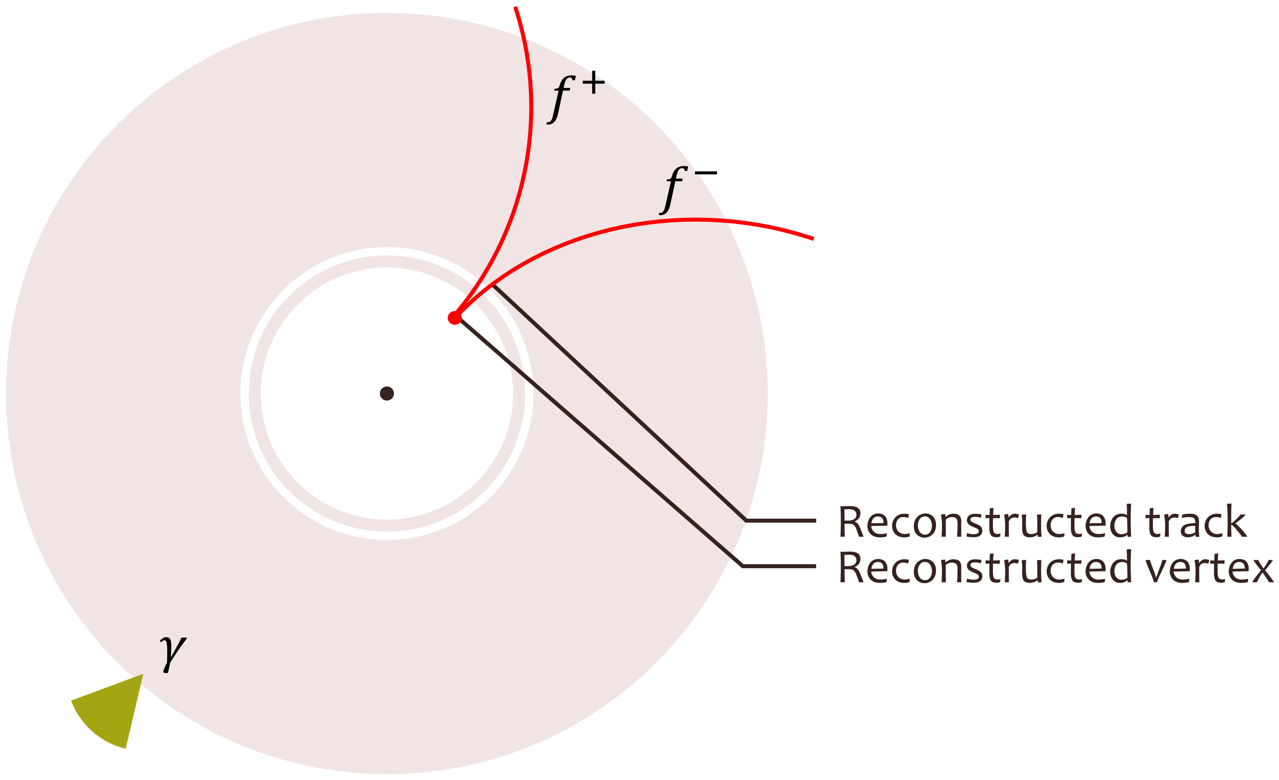
γ conversion (main background)

For 0.2 cm < R < 0.9 cm, background is due to misreconstruction.

What really happens



What we see



Ferber, Garcia-Cely, and Schmidt-Hoberg (2022)

γ conversion (main background)

For 0.2 cm < R < 0.9 cm, we choose

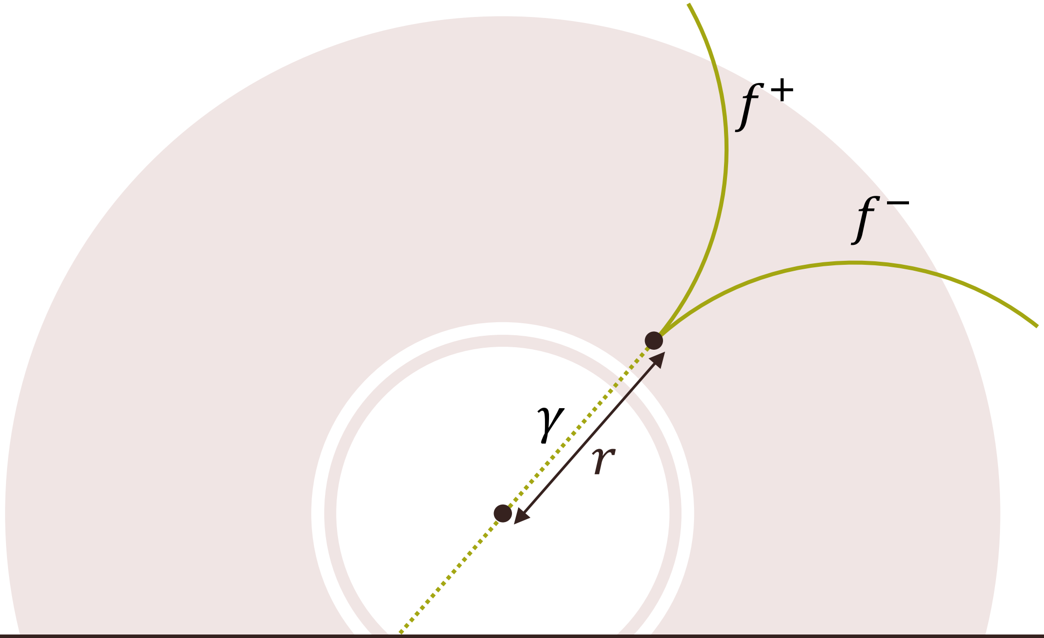
$$p^{\text{misreconstruct}} \approx p^{\text{MfC}} \times \frac{0.9\text{ cm} - 0.2\text{ cm}}{r}$$

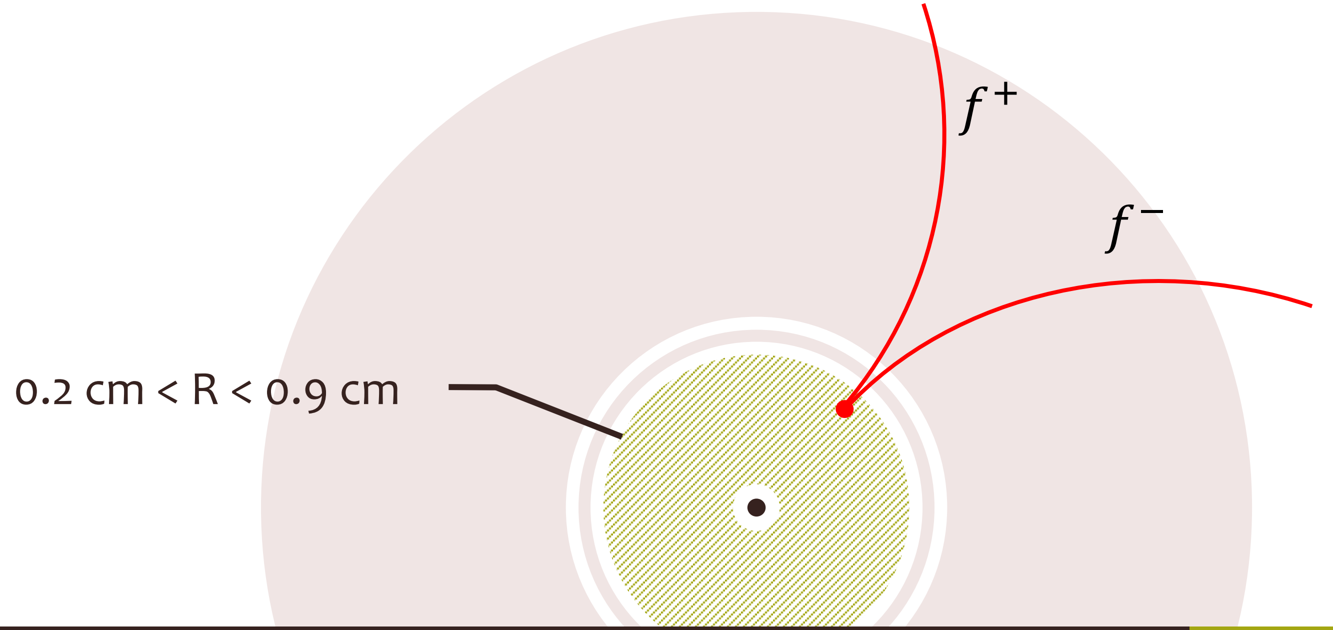
Probability that a vertex is misreconstructed

Parameter (currently, $p^{MfC} = 1$)

Radial distance to correct vertex ($r > 1$ cm)

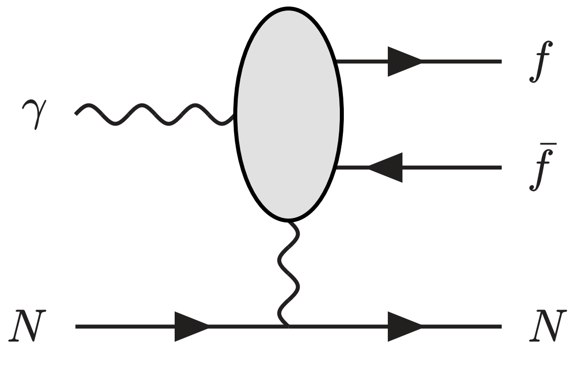
Following our discussion with Torben Ferber from Belle II



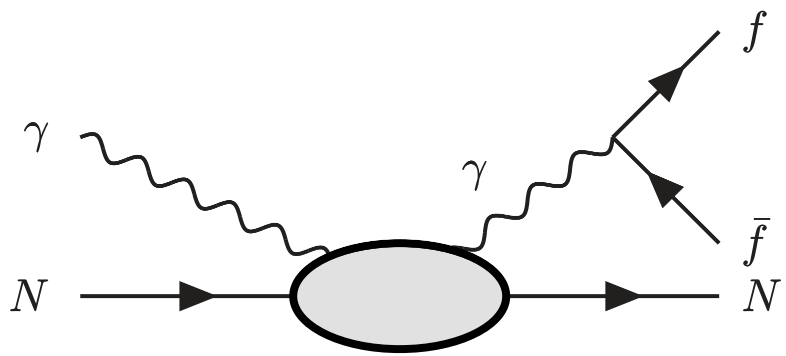


Compute γ conversion cross section

$$\gamma(q) + N(p) \to f^-(l_-) + f^+(l_+) + N(p')$$



Bethe-Heitler (BH) diagram

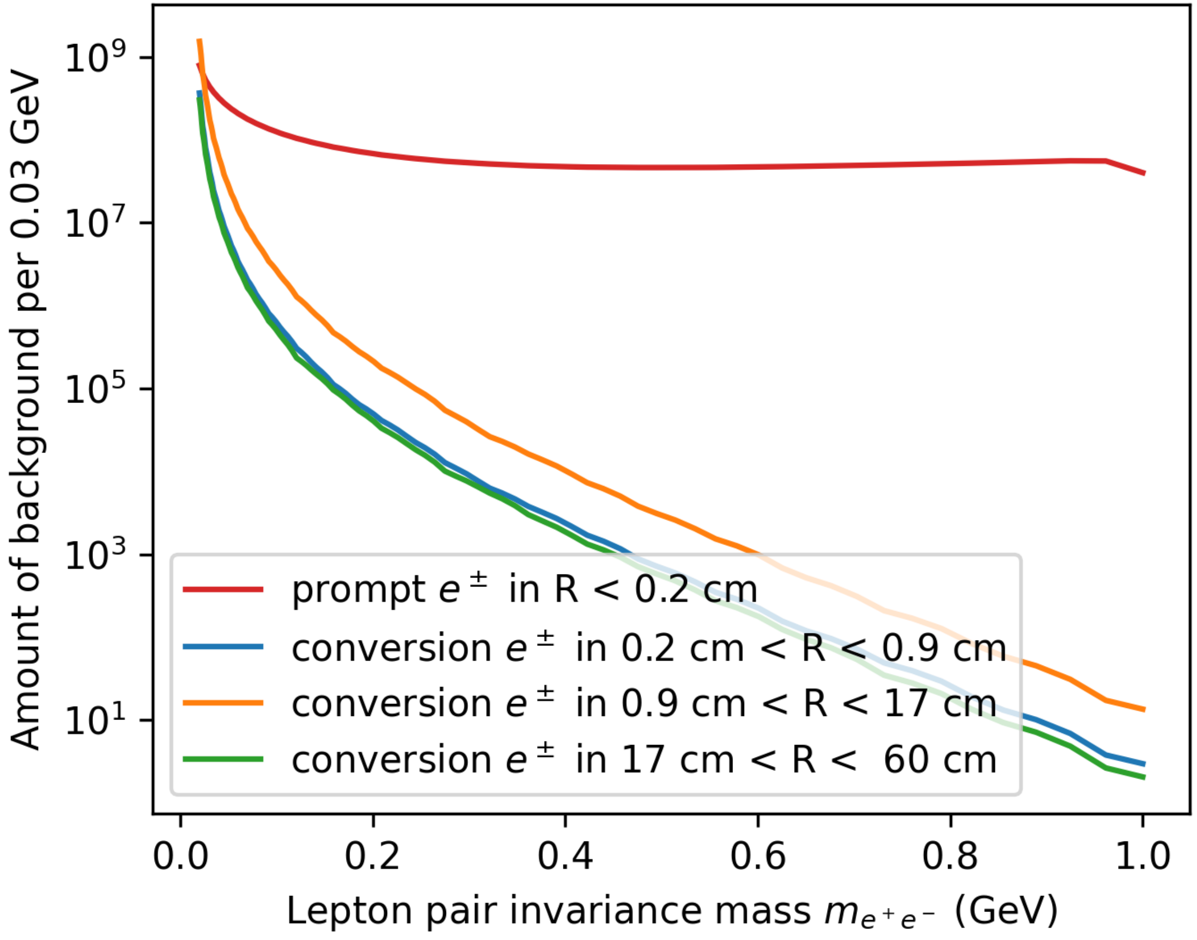


Timelike Compton scattering (TCS) diagram

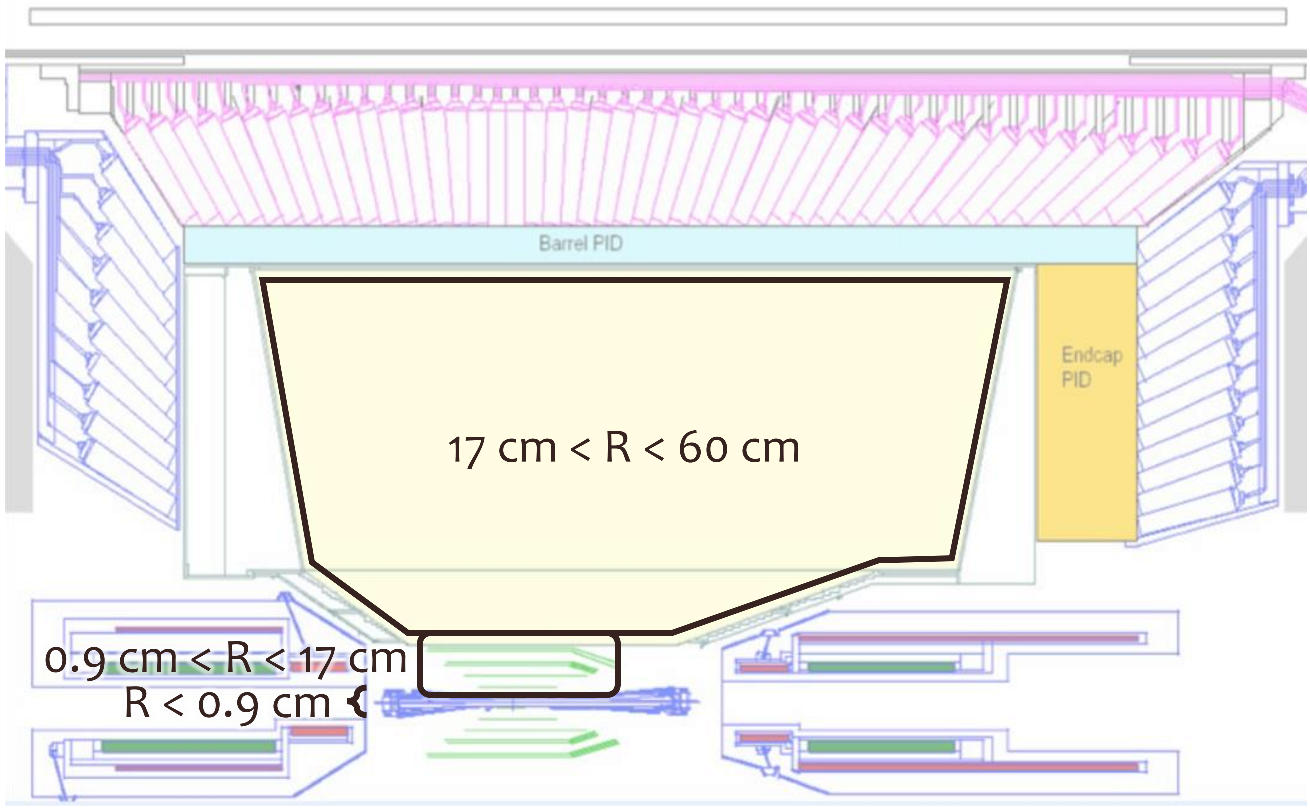
Suppressed

Background estimation

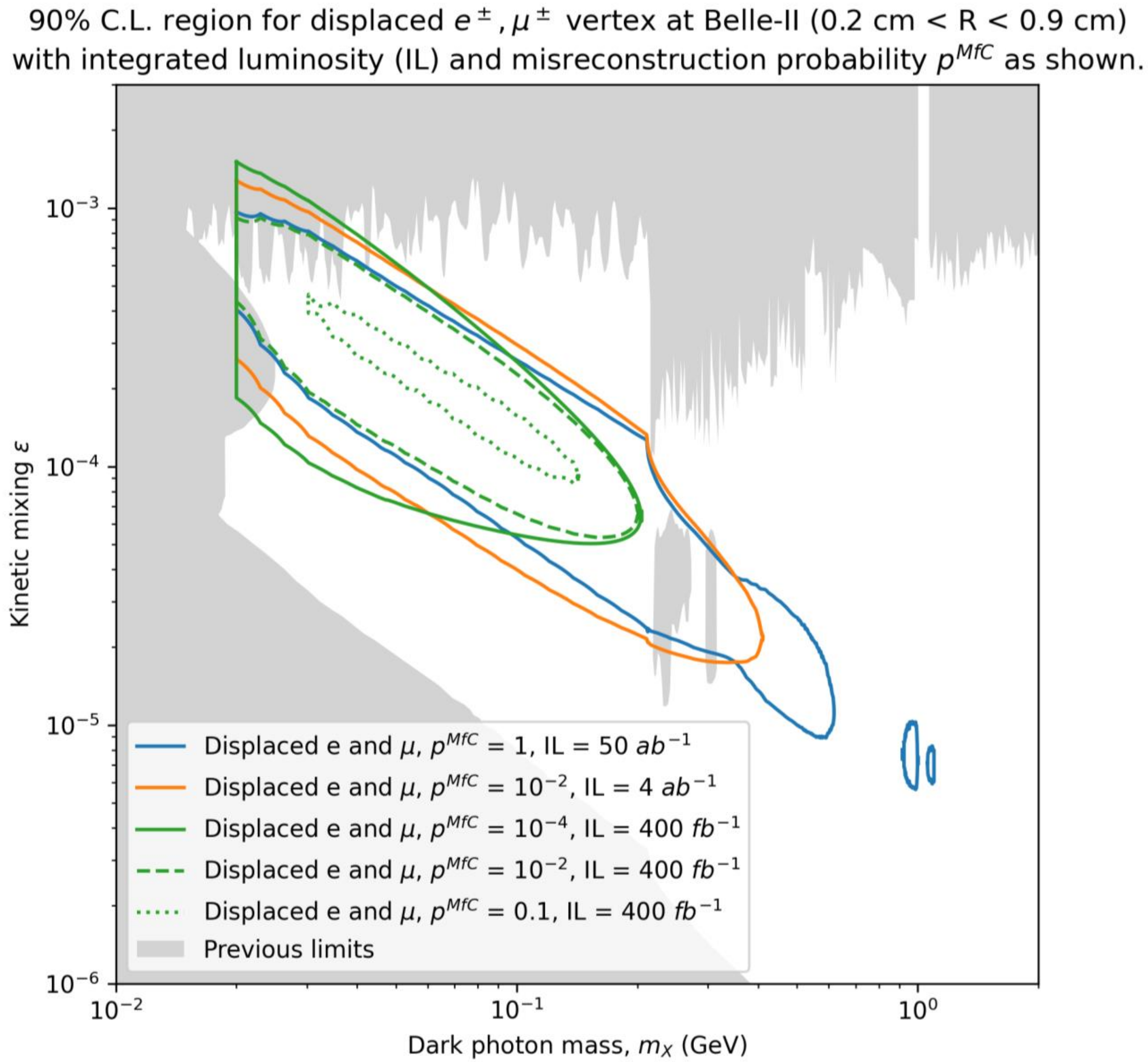
Number of background events
for integrated luminosity of 50 ab^{-1}.

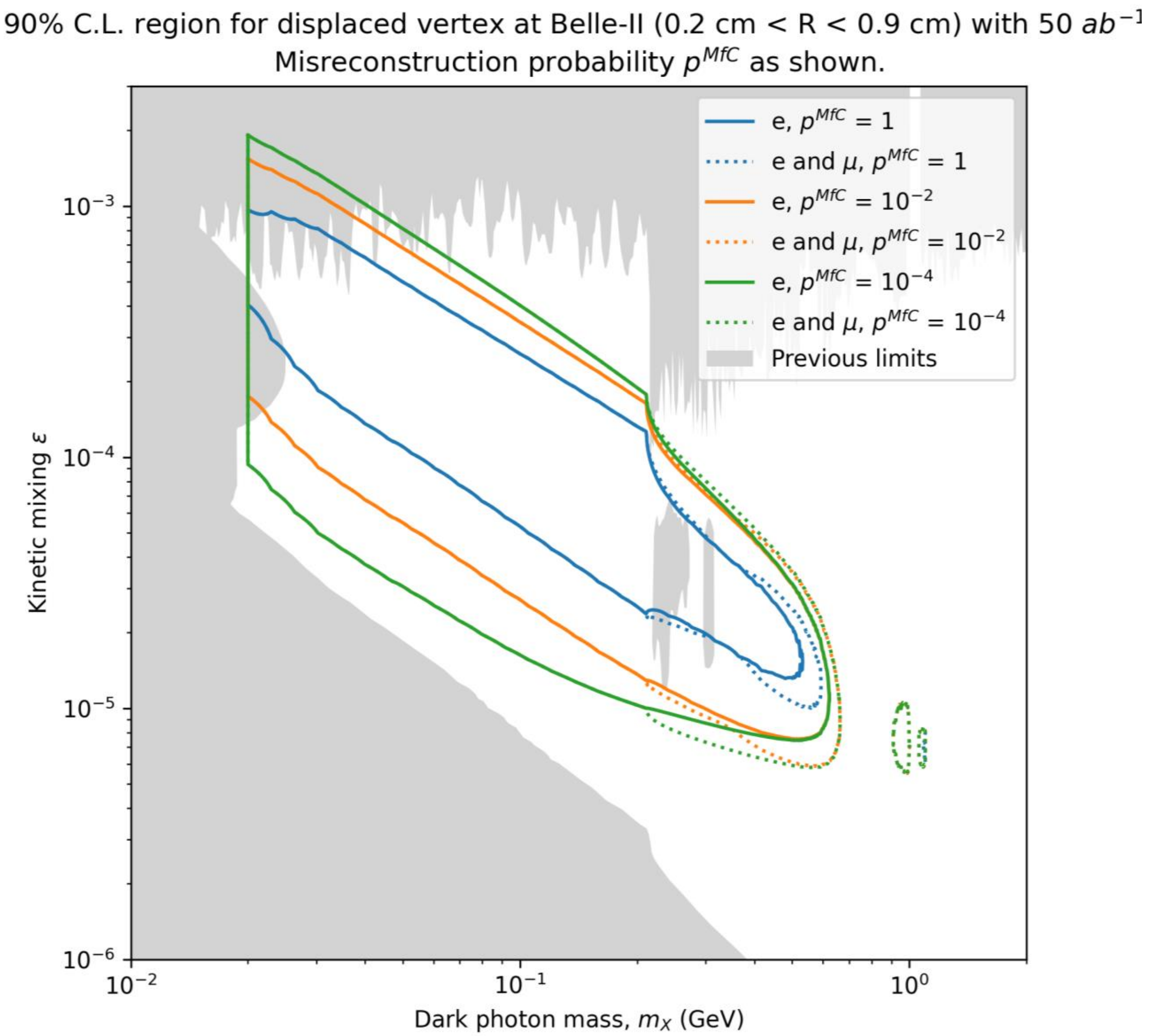


Cross-sectional view of Belle II
Adapted from Pestotnik (2015)



Phase space coverage





Searches at photon colliders

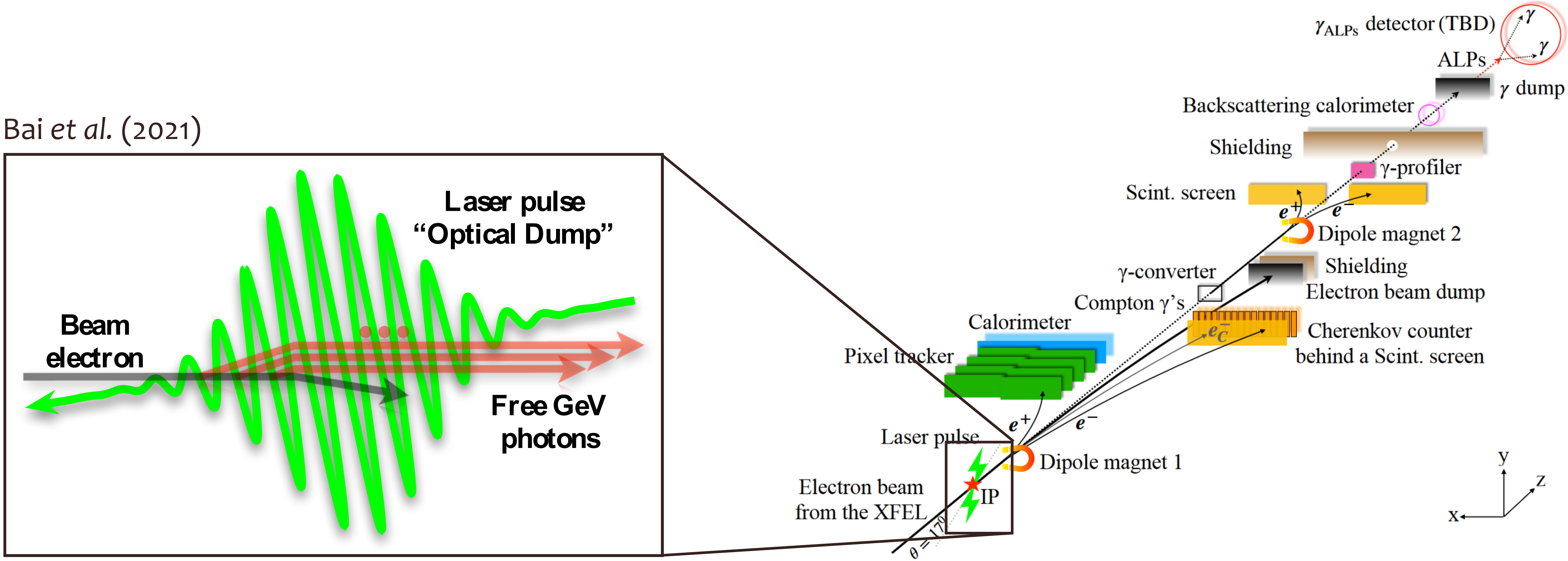
New collider searches for dark photons

LUXE

- Proposed $e^-\gamma$ collider at DESY, Hamburg

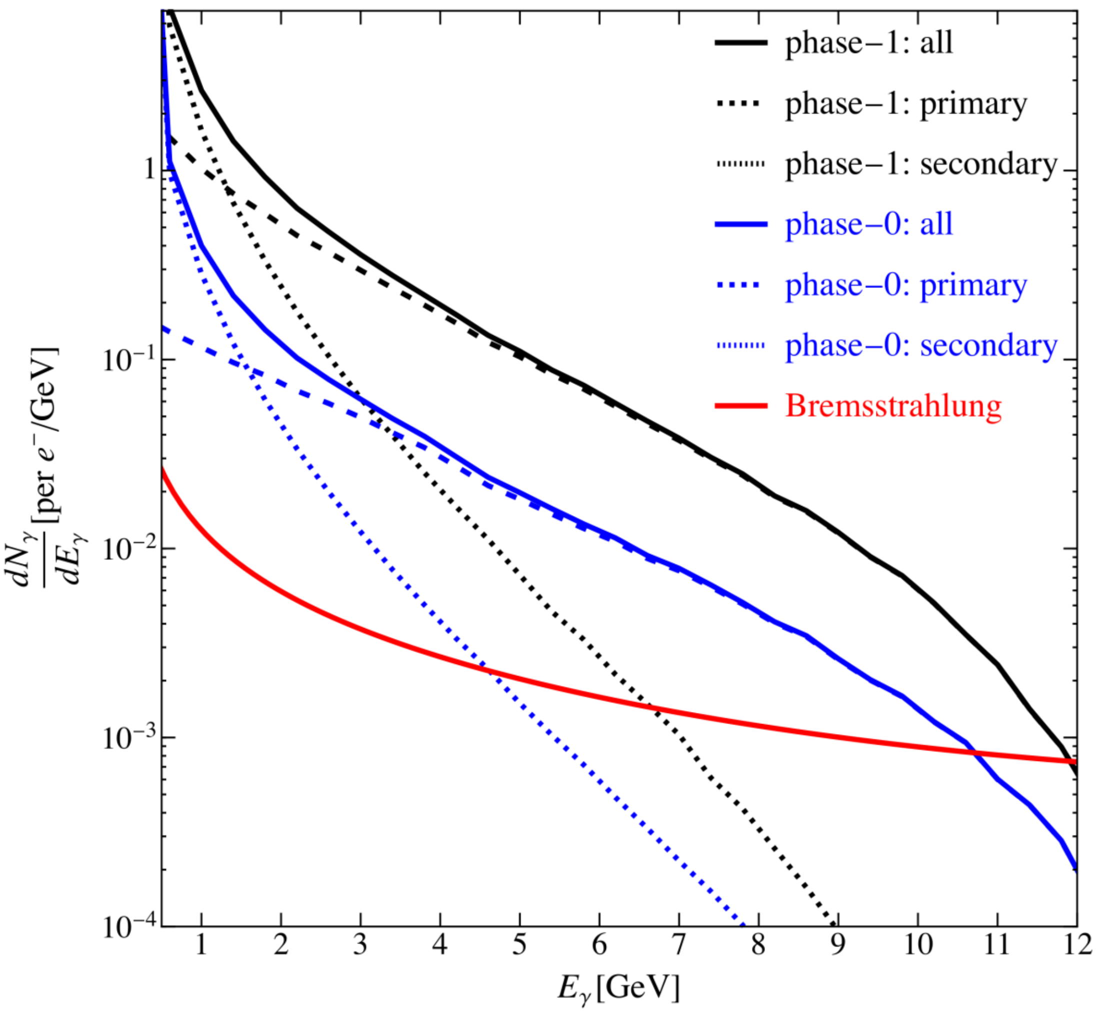
Adapted from
Abramowicz *et al.* (2019)

Bai *et al.* (2021)



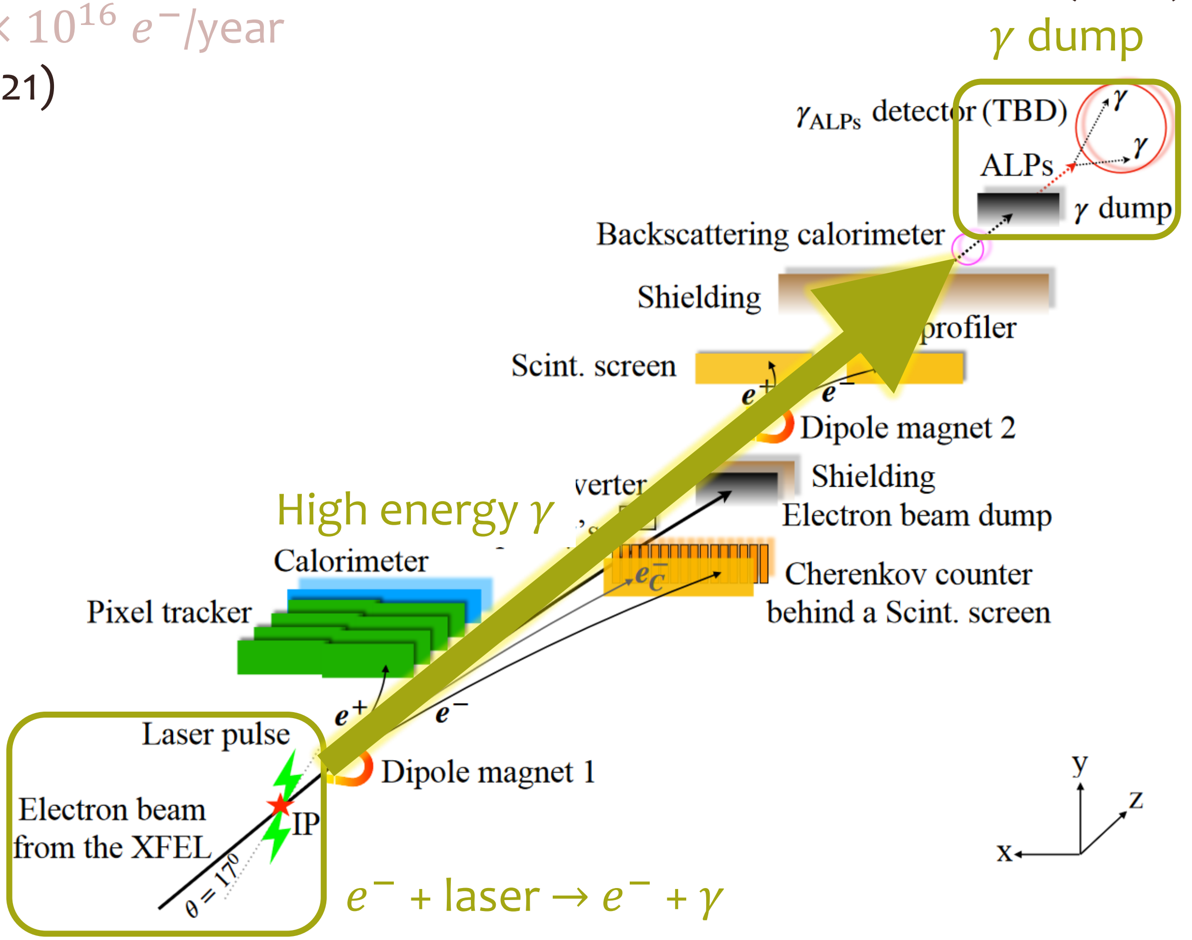
LUXE

- $e^- \gamma$ collider

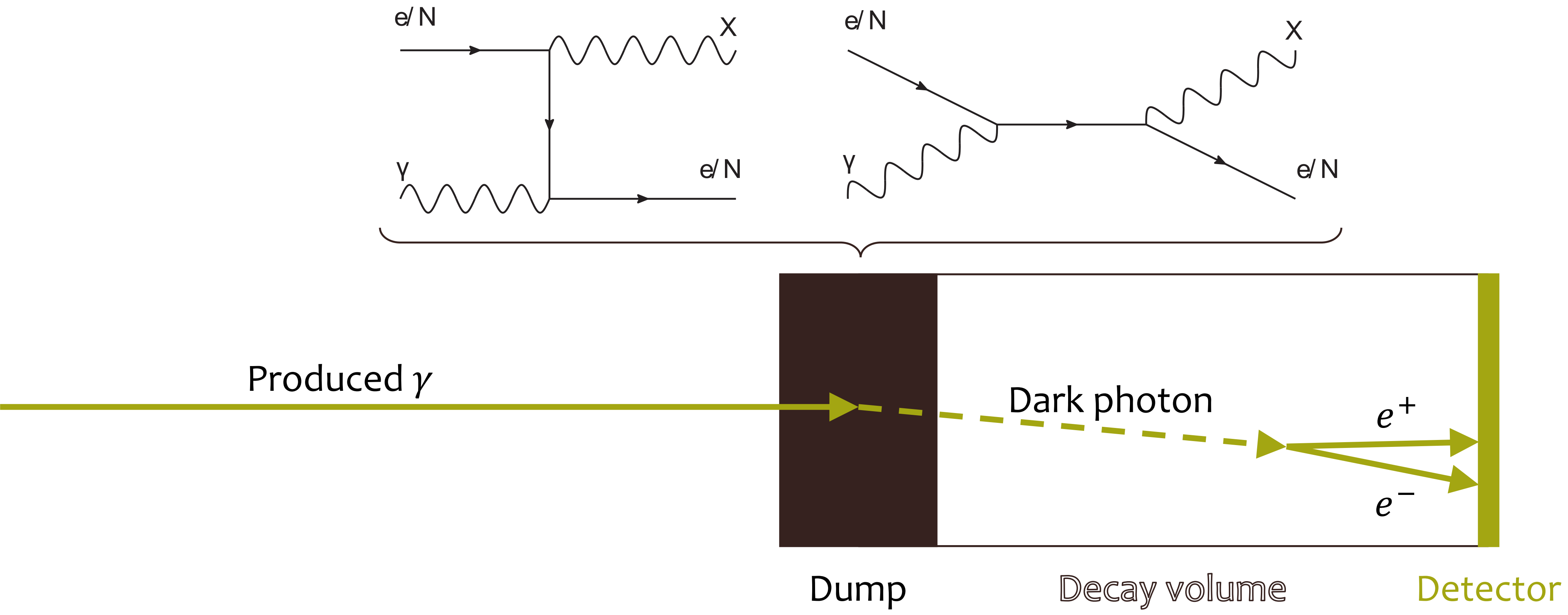


Photon spectrum per e^-
Expect 1.5×10^{16} e^-/year
Bai *et al.* (2021)

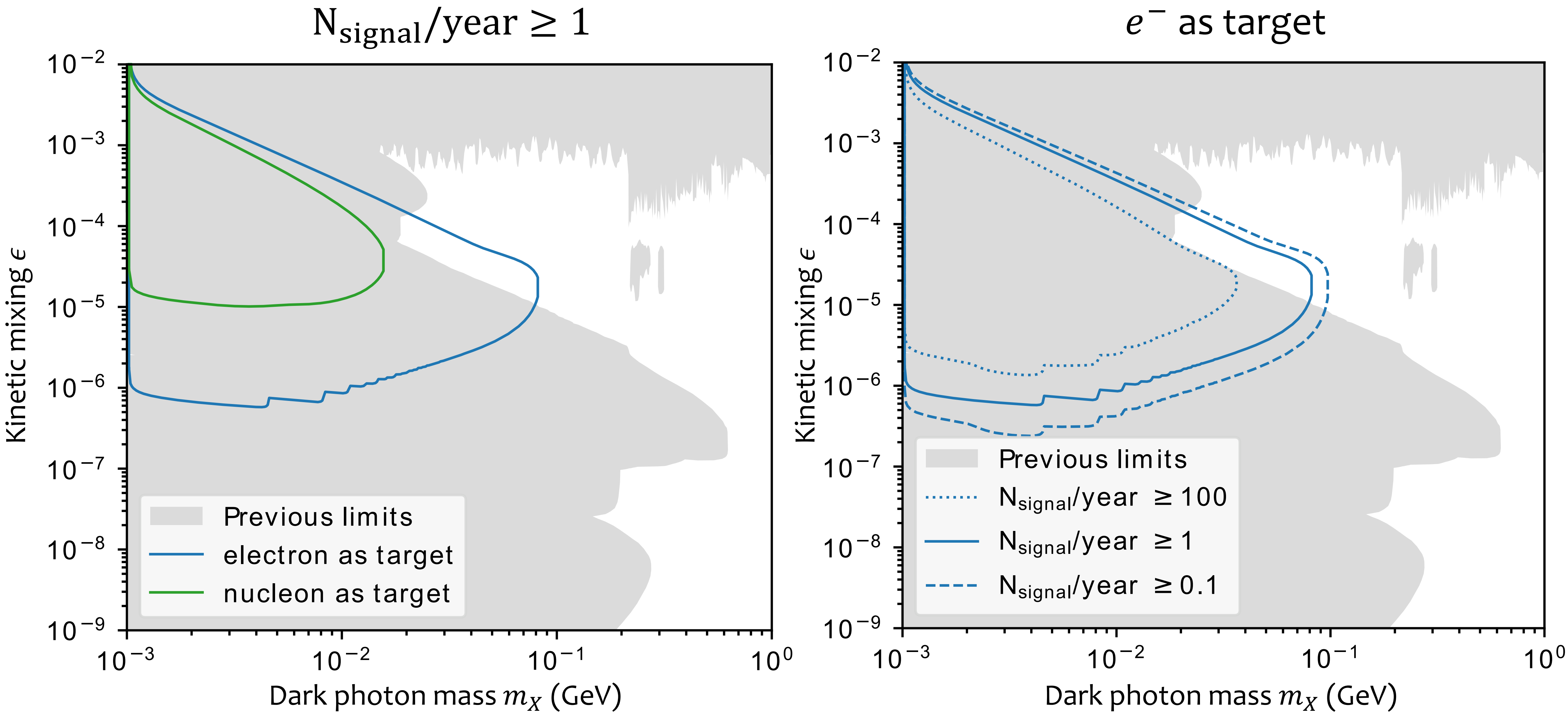
Adapted from
Abramowicz *et al.* (2019)



Beam dump at LUXE

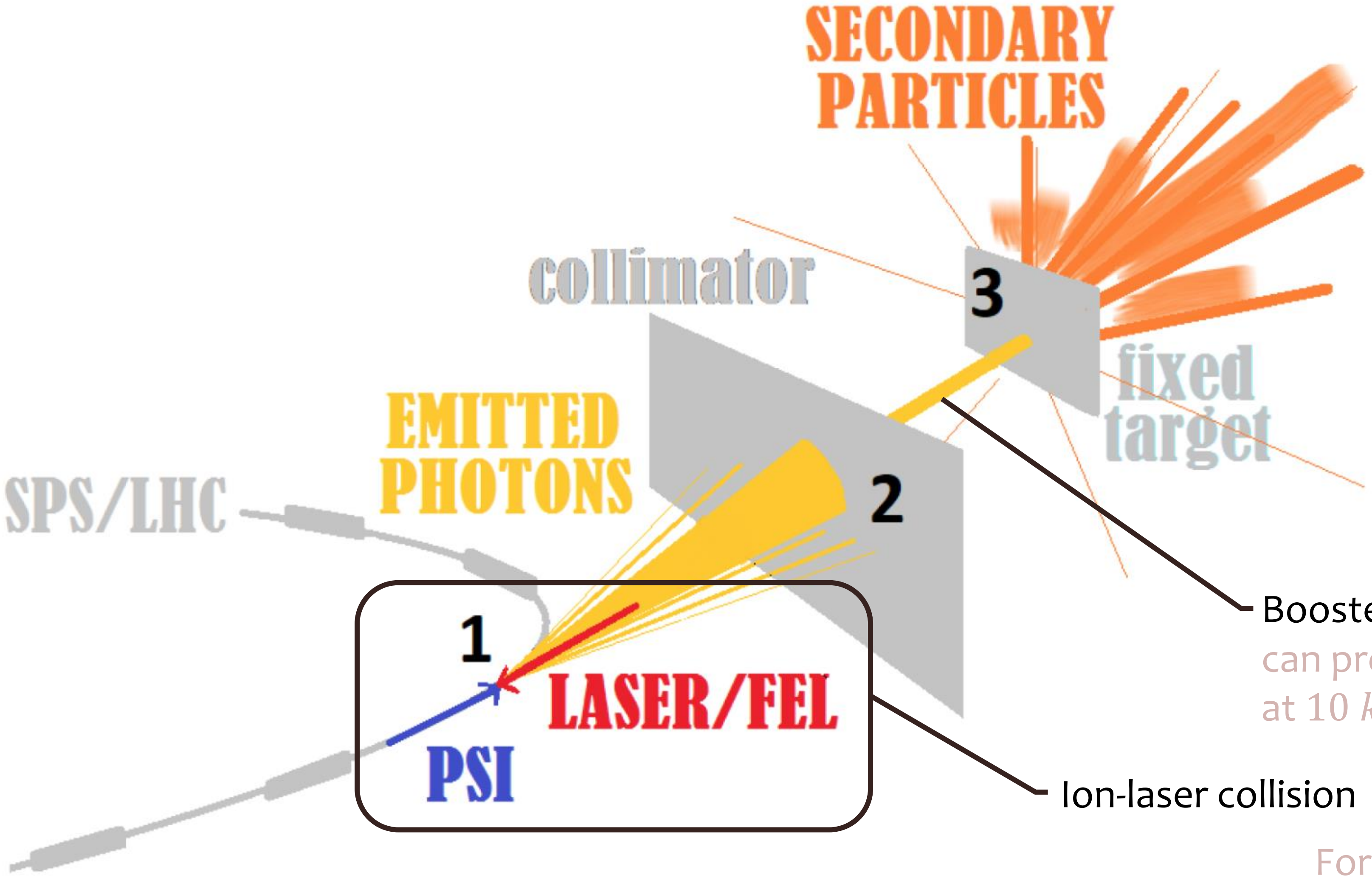


Beam dump at LUXE



Gamma Factory proposed at CERN

Krasny, Muon Collider workshop, 2018



Boosted photons
can produce $10^{17}\ \gamma/s$
at $10\ keV - 400\ MeV$

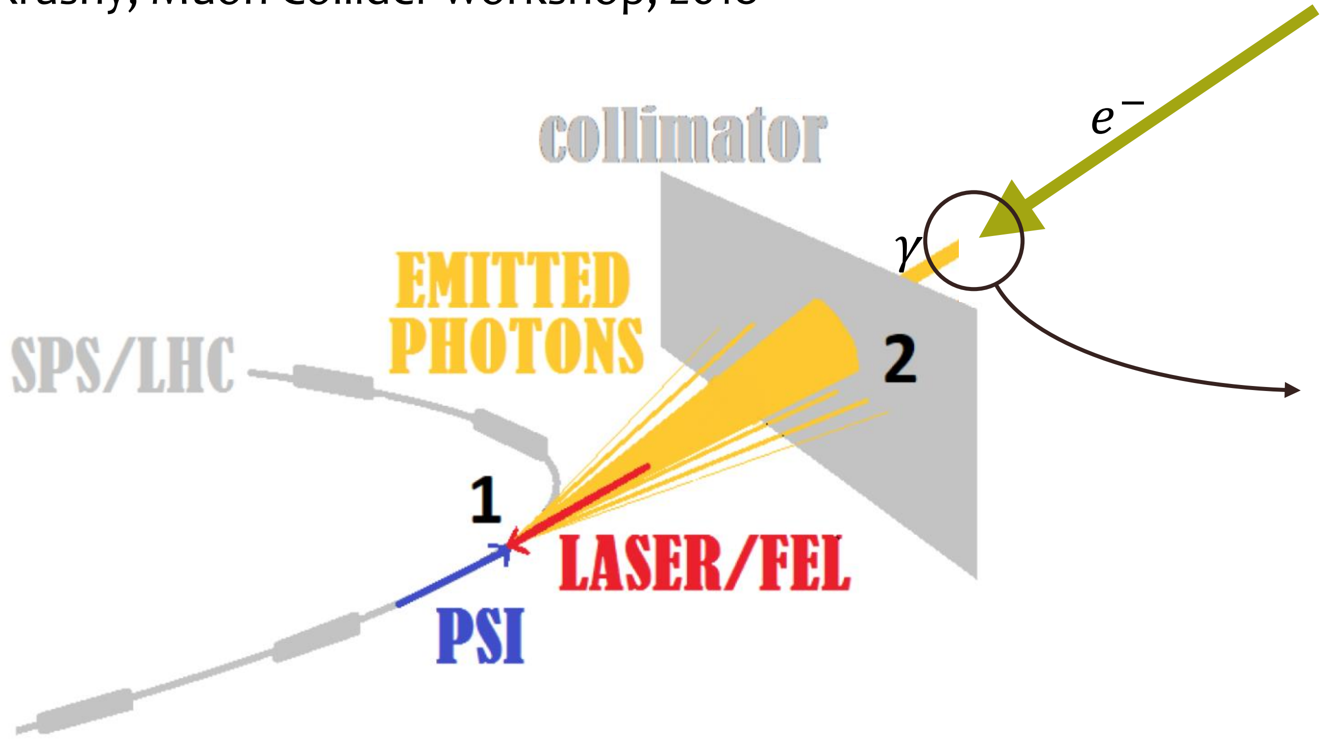
Ion-laser collision

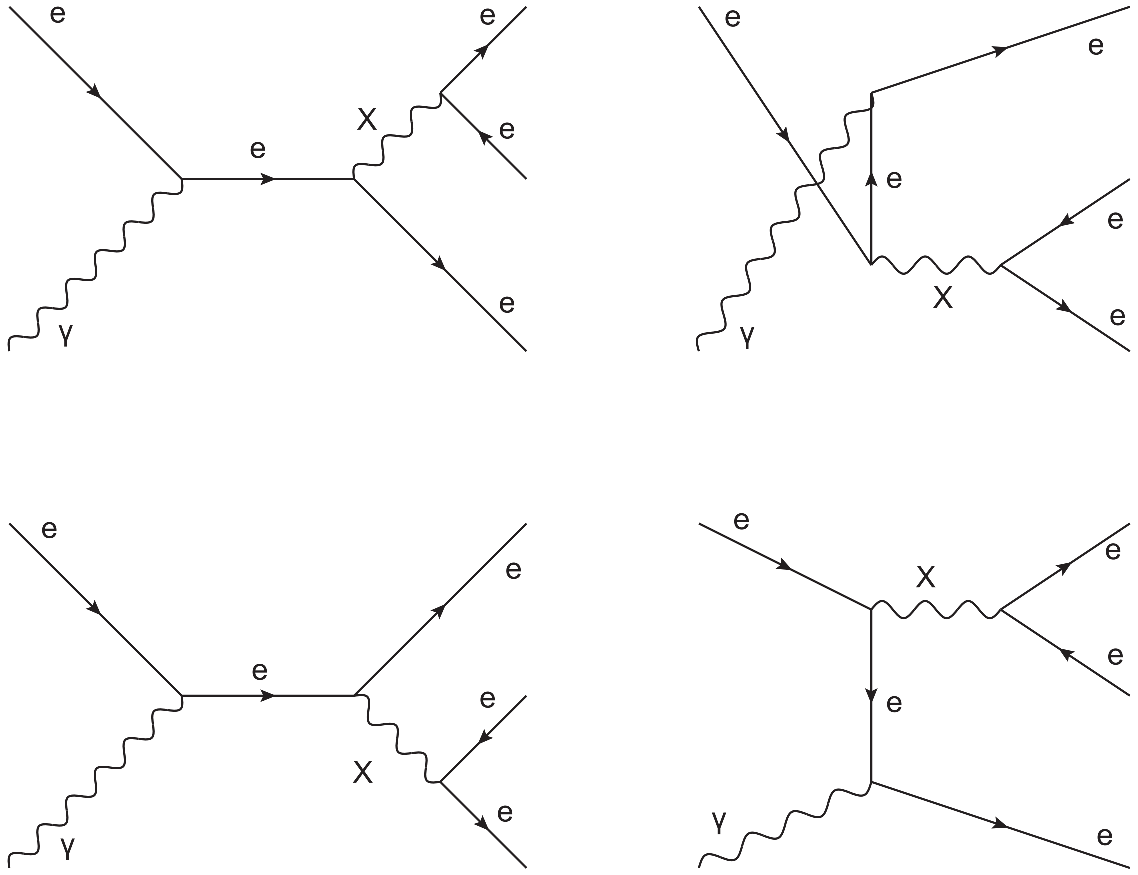
For more on Gamma Factory:
Krasny et al (2019)

Bump hunt at Gamma Factory

$e^- + \gamma \to e^- + e^+ + e^-$

Krasny, Muon Collider workshop, 2018

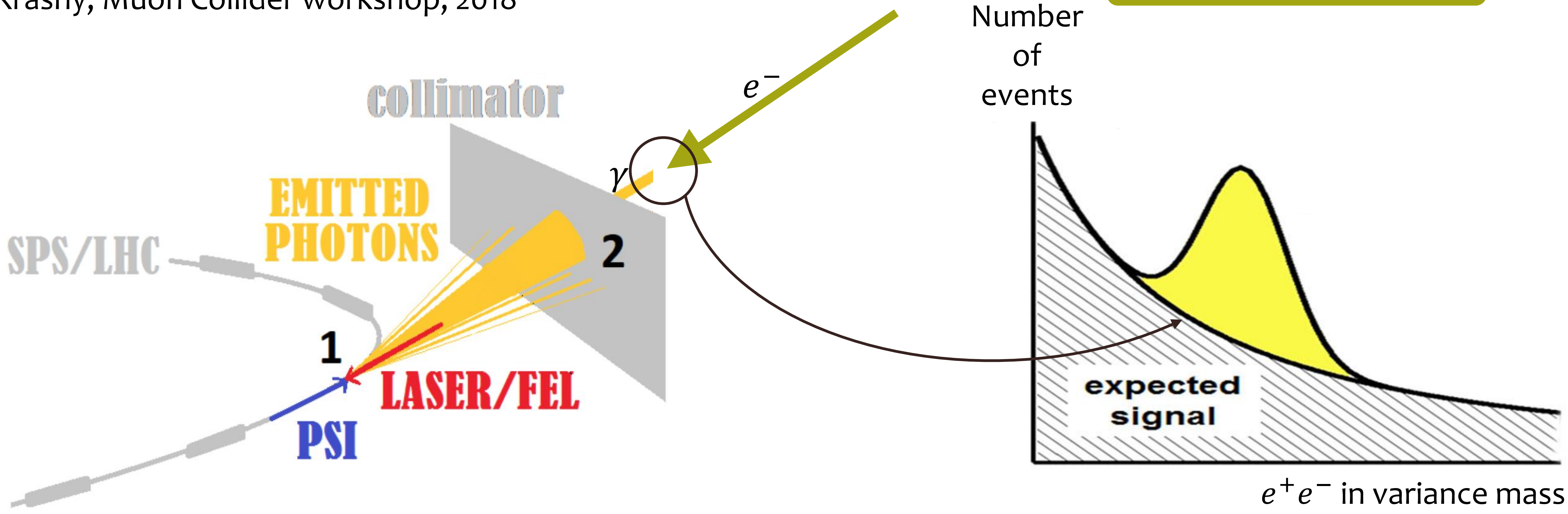




Bump hunt at Gamma Factory

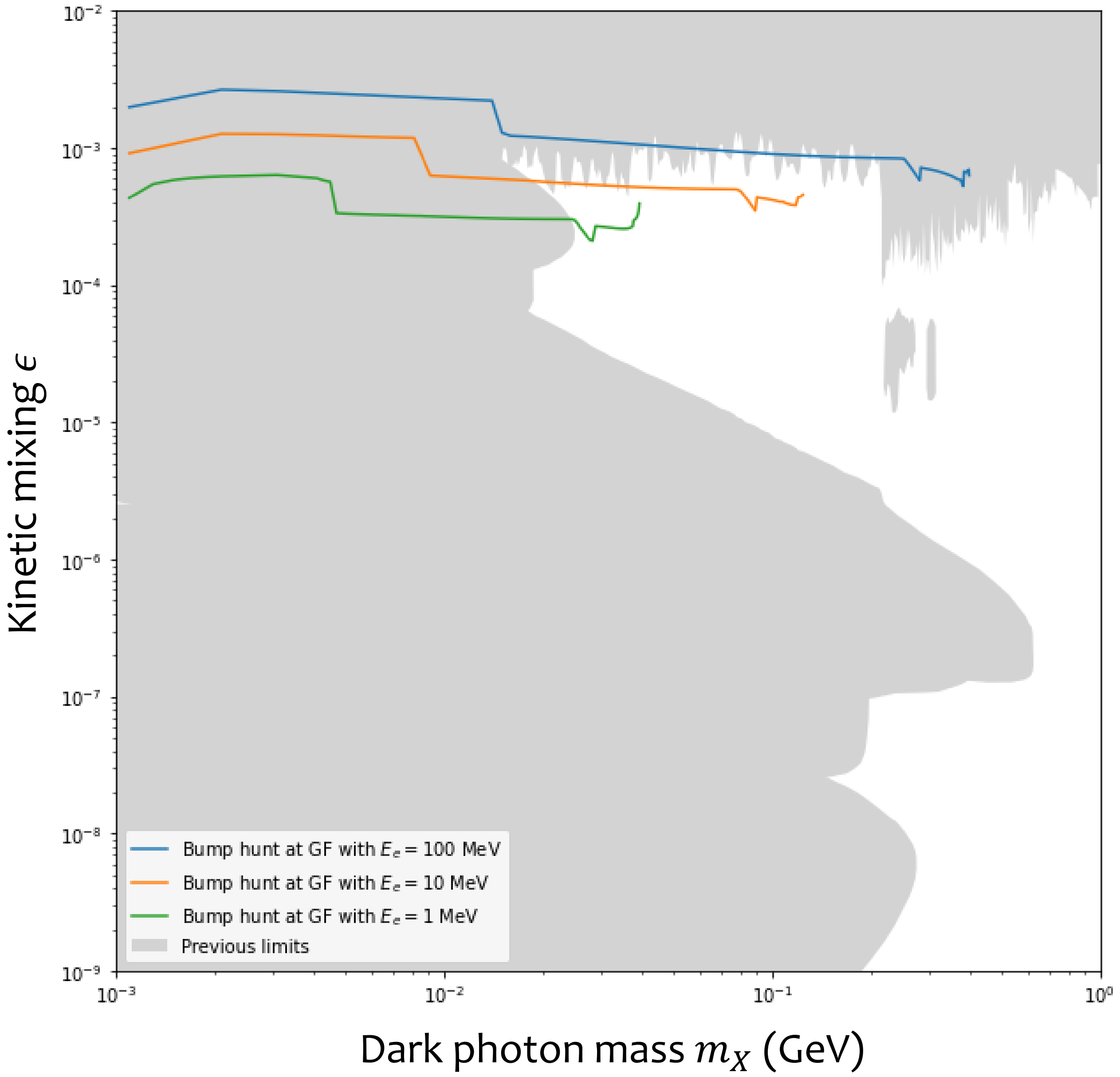
$$e^- + \gamma \rightarrow e^- + e^+ + e^-$$

Krasny, Muon Collider workshop, 2018



Adapted from image by Fermilab

Bump hunt at Gamma Factory



Regions above the lines are covered by Gamma Factory at 95% C.L.

Assume integrated luminosity of $10^{40}\ \mathrm{cm}^{-2}$

THANK YOU FOR LISTENING

Anh Vu Phan

28 October 2022

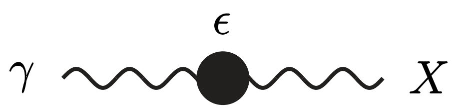
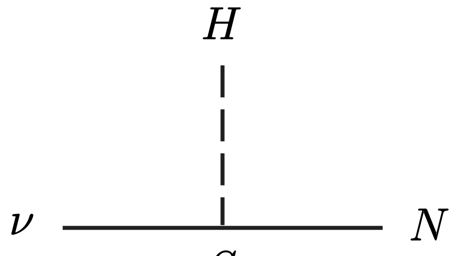
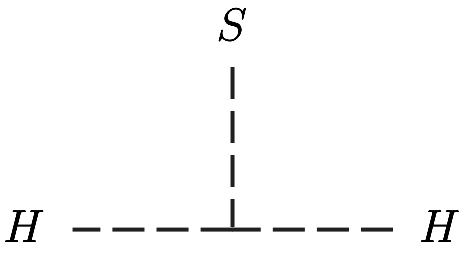
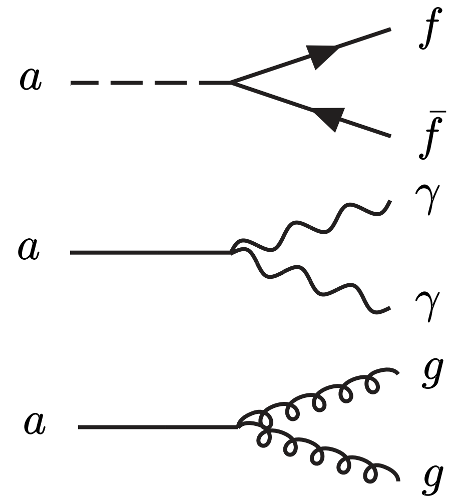
Based on work with Joerg Jaeckel

BACK-UP SLIDES

Anh Vu Phan

28 October 2022

Based on work with Joerg Jaeckel

Vector portal (dark photon)	$\frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu}$		Holdom (1986) Fabbrichesi, et al. (2020)
Neutrino portal	$yLHN$		Falkowski, et al. (2009)
Higgs portal	$(\mu S + \lambda S^2)H^{\dagger}H$		Patt and Wilczek (2006)
Axion portal	$c_{ff}\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_\mu\gamma_5\psi$ $c_{\gamma\gamma}\frac{\alpha}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$ $c_{GG}\frac{\alpha_s}{4\pi}\frac{a}{f}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$		Peccei and Quinn (1977) Bauer, et al. (2021)

Signal

- Signal: photon + displaced e^+e^- pair.
- At high energy,

$$\frac{d\sigma_{e^+e^-\to\gamma X}}{d\cos\theta} = \frac{2\pi\alpha^2\chi^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right).$$

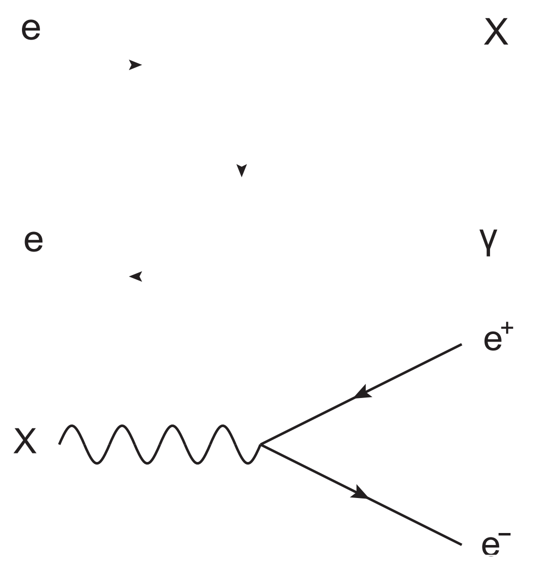
- Decay length (N_f: number of possible decay products)

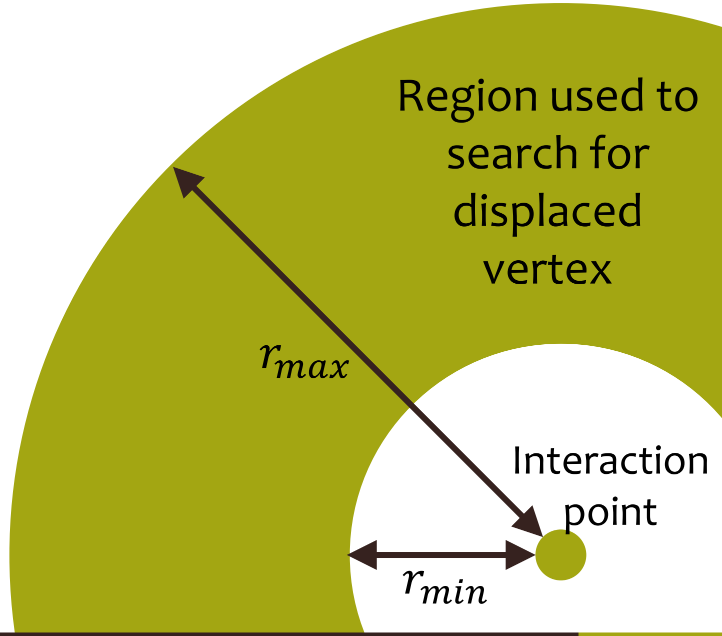
$$\lambda_X = \frac{\hbar c E_X}{m_X\Gamma_X}, \text{with } \Gamma_X = \frac{1}{3}\alpha\chi^2 m_X N_f.$$

- Number of signal events

$$S = LT\sigma_{e^+e^-\to\gamma X}\left(e^{-r_{min}/\lambda_X} - e^{-r_{max}/\lambda_X}\right).$$

- For Belle II, we search inside beam pipe (i.e. $r_{min} = 0.1\ cm$, $r_{max} = 0.9\ cm$).





BACK-UP SLIDES

Background: $e^+ e^- \to \gamma\gamma, \gamma + matter \to e^+ e^-$

- The number of photon conversion to e^+e^- satisfying our cuts is

Cross section for conversions satisfying cuts

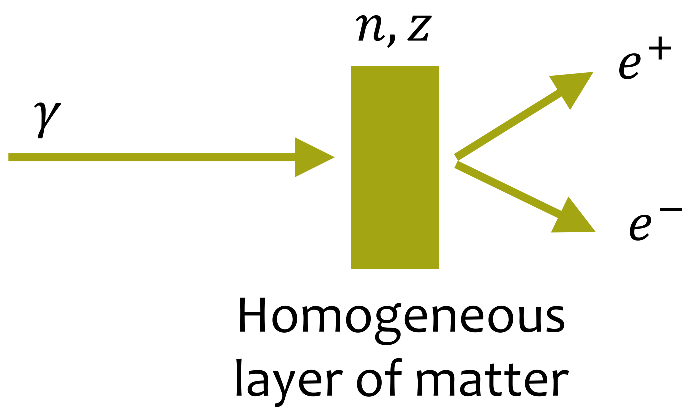
Atomic density

$$dN_{\gamma\to e^+e^-} = N_0 \frac{d\sigma}{\sigma}\left(1 - e^{-n\sigma z}\right)$$

Number of incident photons

Total conversion cross section

Thickness of matter layer

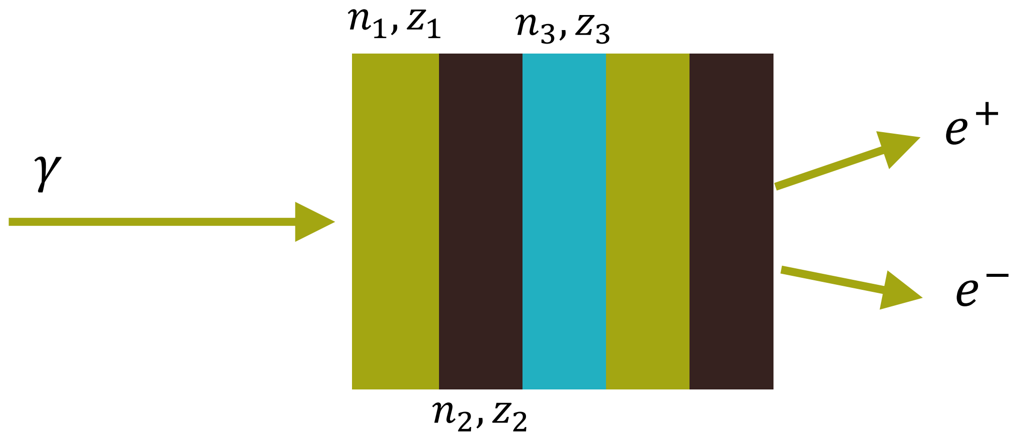


BACK-UP SLIDES

Background: $e^+ e^- \to \gamma\gamma, \gamma + matter \to e^+ e^-$

- For many layers of matter, conversion probability is

$$p_{\gamma\to e^+e^-} = \frac{dN_{\gamma\to e^+e^-}}{N_0} = \underbrace{\frac{d\sigma_1}{\sigma_1}(1 - e^{-n_1\sigma_1 z_1})}_{\text{Probability } \gamma \text{ converts in layer 1}} + \underbrace{e^{-n_1\sigma_1 z_1}}_{\text{Probability } \gamma \text{ survives layer 1}} \underbrace{\frac{d\sigma_2}{\sigma_2}(1 - e^{-n_2\sigma_2 z_2})}_{\text{Probability } \gamma \text{ converts in layer 2}} + \cdots$$



Compute γ conversion cross section

$$\gamma(q) + N(p) \to f^-(l_-) + f^+(l_+) + N(p')$$

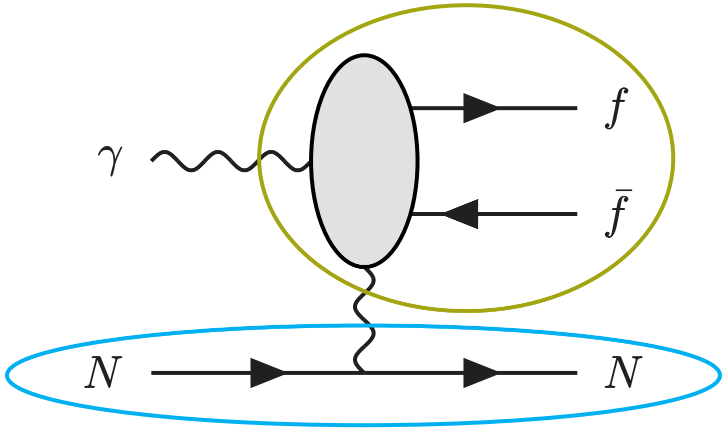
- Amplitudes

$$\mathcal{M}_{BH} = \frac{ie}{t}\varepsilon_\mu(q)\,\bar{N}(p')F_1(t)\gamma_\nu N(p)\,T^{\mu\nu}_{\gamma^*\gamma\to f\bar{f}}$$

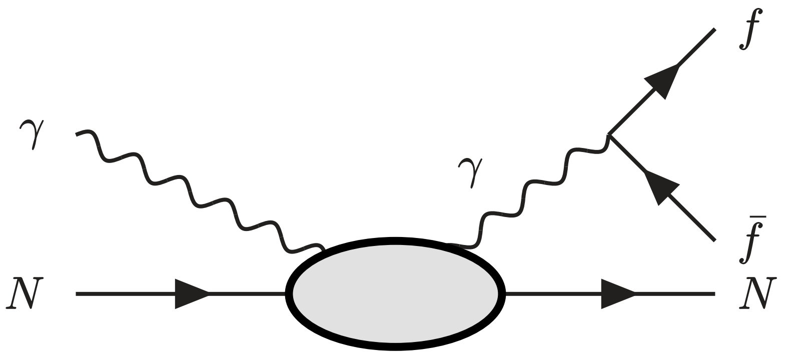
$t = (p - p')^2$

Nucleus form factor

For f = leptons, $T^{\mu\nu}_{\gamma^*\gamma\to f\bar{f}}$ is amplitude for $\gamma\gamma \to l^+l^-$



Bethe-Heitler (BH) diagram



Timelike Compton scattering (TCS) diagram

Compute γ conversion cross section

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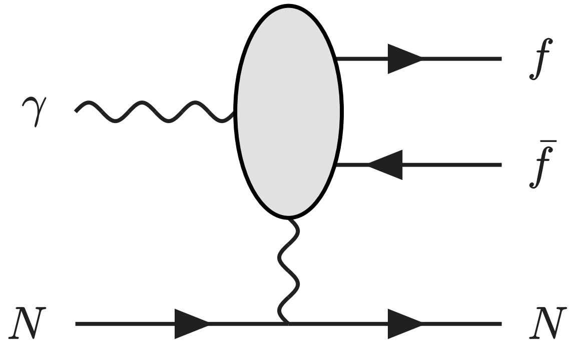
- Amplitudes

$$\mathcal{M}_{BH} = \frac{ie}{t}\varepsilon_\mu(q)\,\bar{N}(p')F_1(t)\gamma_\nu N(p)\,T^{\mu\nu}_{\gamma^*\gamma\to f\bar{f}}$$

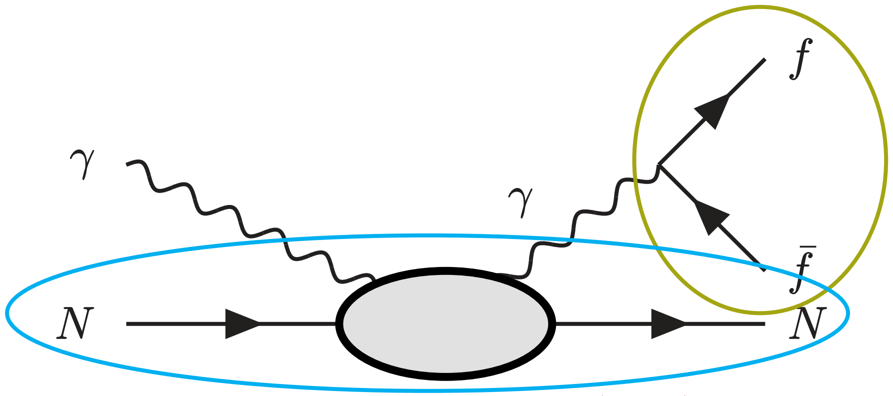
$$\mathcal{M}_{TCS} = \frac{ie^3}{m_{ff}^2}J_\nu(q')\varepsilon_\mu(q)\,\bar{N}(p')\left(\frac{1}{\alpha}T^{\mu\nu}_{fTCS}\right)N(p)$$

Gryniuk (2020)

$m_{ff}^2 = (l_+ + l_-)^2$ $\quad q' = l_+ + l_-$



Bethe-Heitler (BH) diagram



Timelike Compton scattering (TCS) diagram

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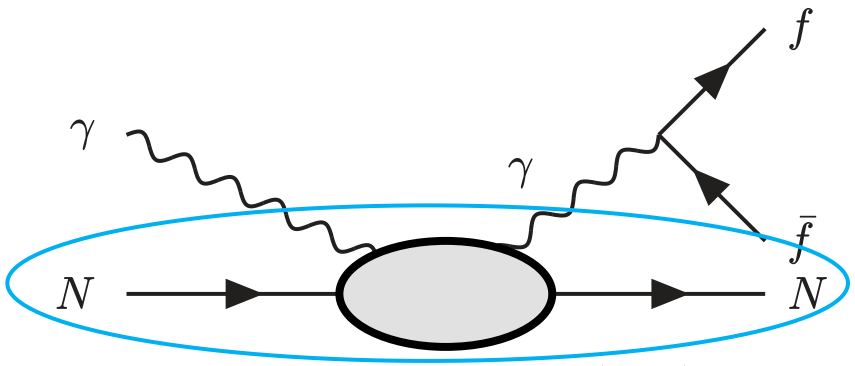
$$T^{\mu\nu}_{fTCS} \approx \left(-g^{\mu\nu} + \frac{q'^\mu q^\nu}{q\cdot q'}\right)f(\nu)$$

Gryniuk (2020)

Near-real, near forward limit ($m_{ff}^2, |t| \ll s$)

Spin-averaged forward real Compton amplitude

incoming photon energy (when $M_N \to \infty$)



Timelike Compton scattering (TCS) diagram

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$$T^{\mu\nu}_{fTCS} \approx \left(-g^{\mu\nu} + \frac{q'^\mu q^\nu}{q\cdot q'}\right)f(\nu)$$

Total unpolarized photoabsorption cross section of nucleus N.

Gryniuk, Hagelstein, and Pascalutsa (2015)

Optical theorem ⇒ $\mathrm{Im} f(\nu) = \frac{\nu}{4\pi}\sigma_{\gamma N}(\nu)$

Analyticity ⇒ $\mathrm{Re} f(\nu) = -\frac{Z^2\alpha}{M_N} + \frac{\nu^2}{2\pi^2}\mathcal{P}\int_0^\infty d\nu'\,\frac{\sigma_{\gamma N}(\nu')}{\nu'^2-\nu^2}$

Nucleus N with mass M_N and atomic number Z