Probing Dark Forces with Polarized Beams at Chiral Belle
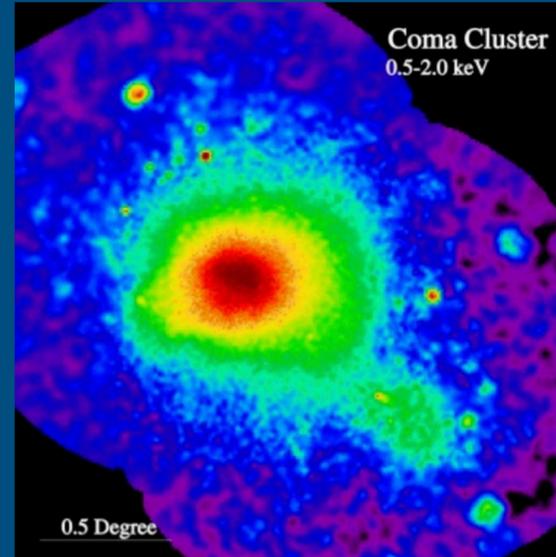
Afif Omar
Feb, 2026

PNW Collider Meetup

Outline

- Dark bosons

- What is "Chiral" Belle?

- How could (Chiral) Belle detect dark vectors?

- Mono-photon searches: backgrounds, reach, and discrimination power
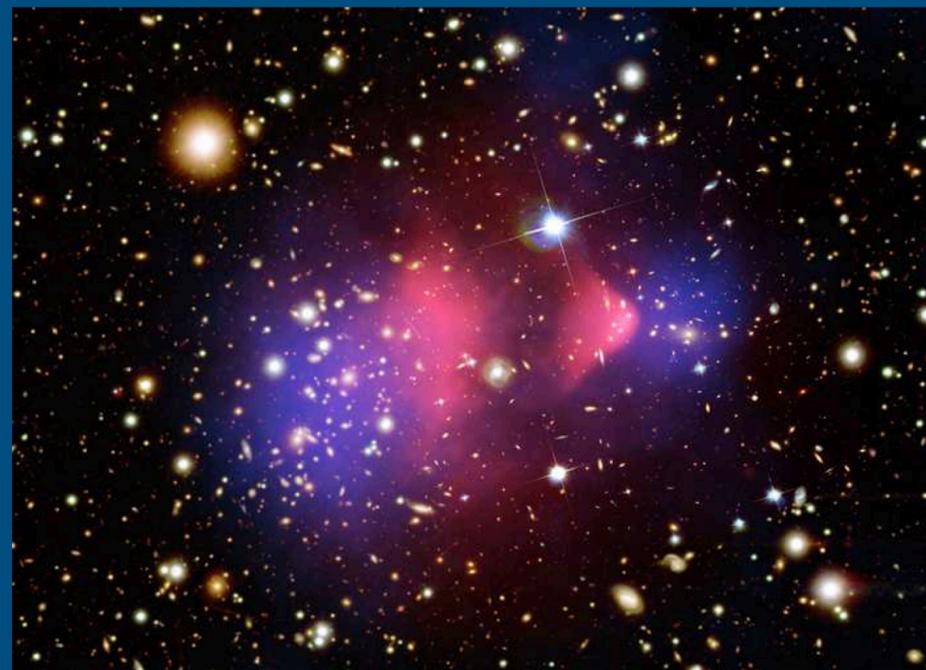
DM evidence

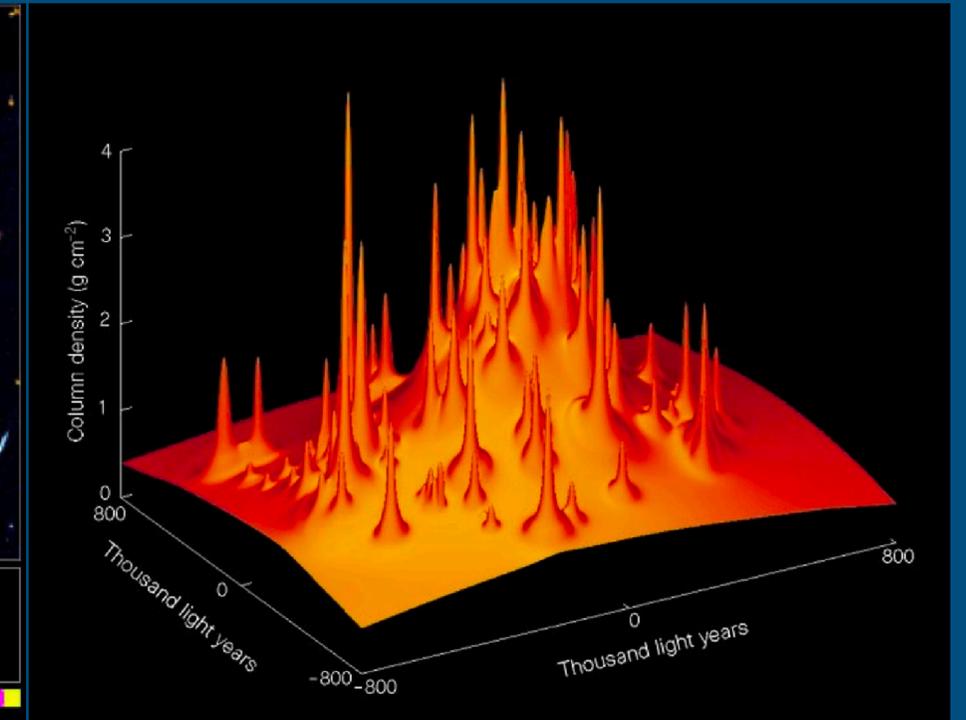velocity dispersion

ROSAT

Briel & Henry (97)

ESO/L. Calçada

W.N. Colley and E. Turner, J.A. Tyson, and NASA

A. Evrard (98), Tyson (98)

Chandra

bullet clusters

gravitational lensing

3

DM evidence

galaxy rotation

velocity dispersion

ROSAT

Coma Cluster
0.5-2.0 keV
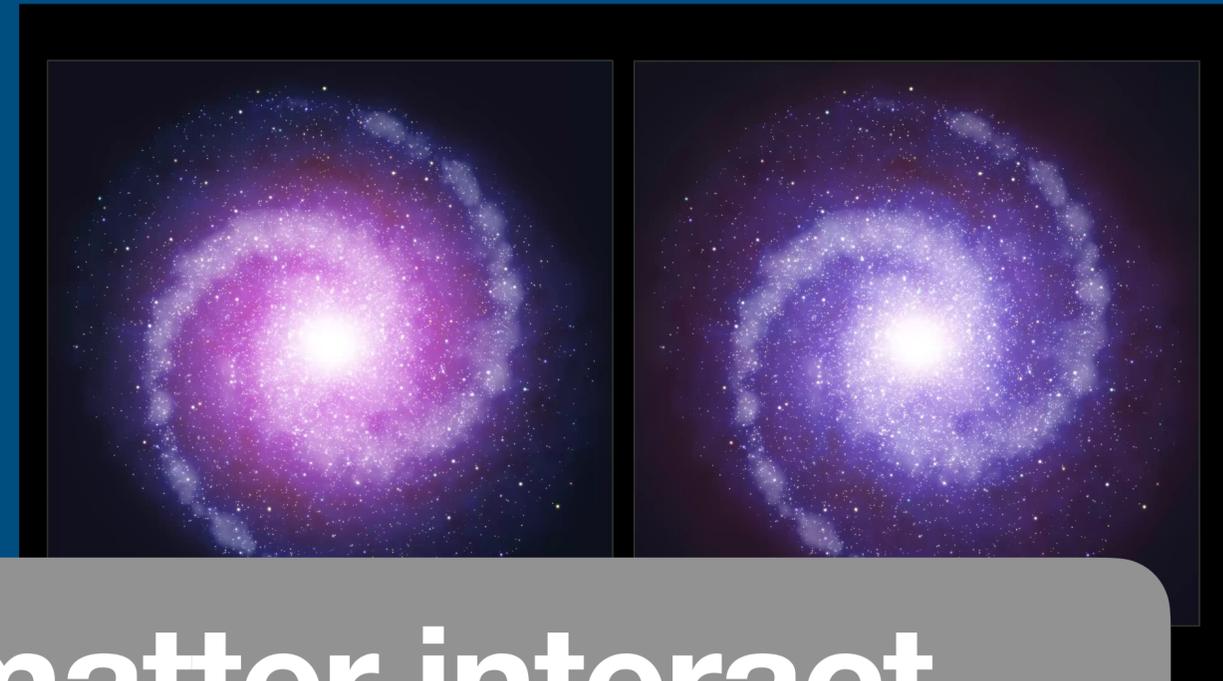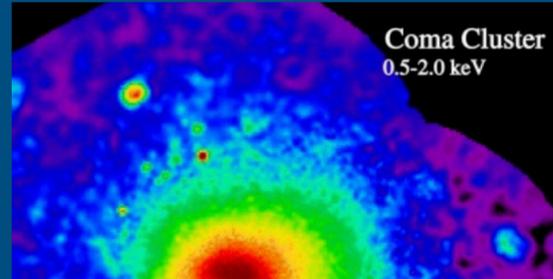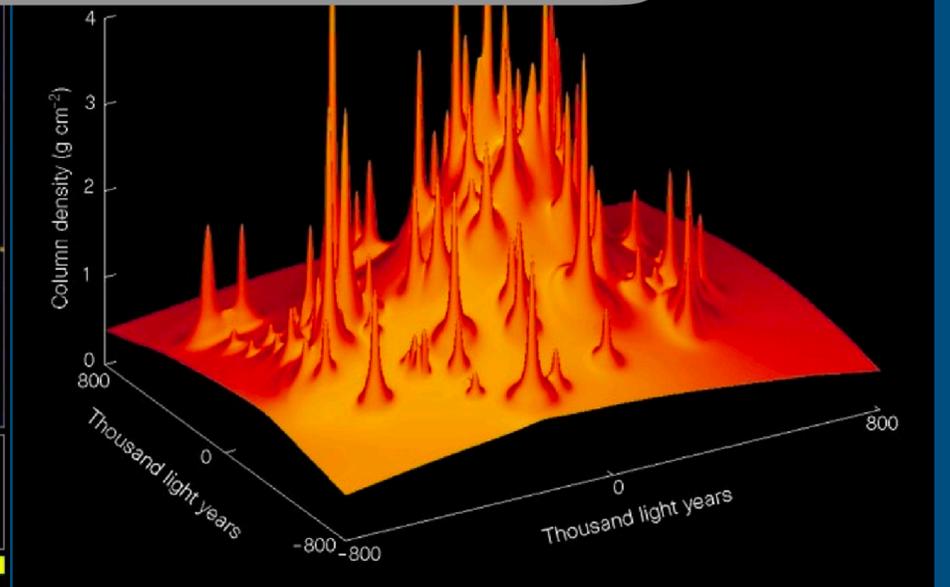
But does dark matter interact non-gravitationally?

Chandra

bullet clusters

W.N. Colley and E. Turner, J.A. Tyson, and NASA

Gravitational Lens
Galaxy Cluster 0024+1654
Hubble Space Telescope · WFPC2

A. Evrard (98), Tyson (98)

gravitational lensing

DM detection

DM detection

(on Earth)
Collider

SM

DM
(or SM..)

Direct
Detection
(on Earth)

SM

DM
(or SM..)

Indirect Detection
(in space)
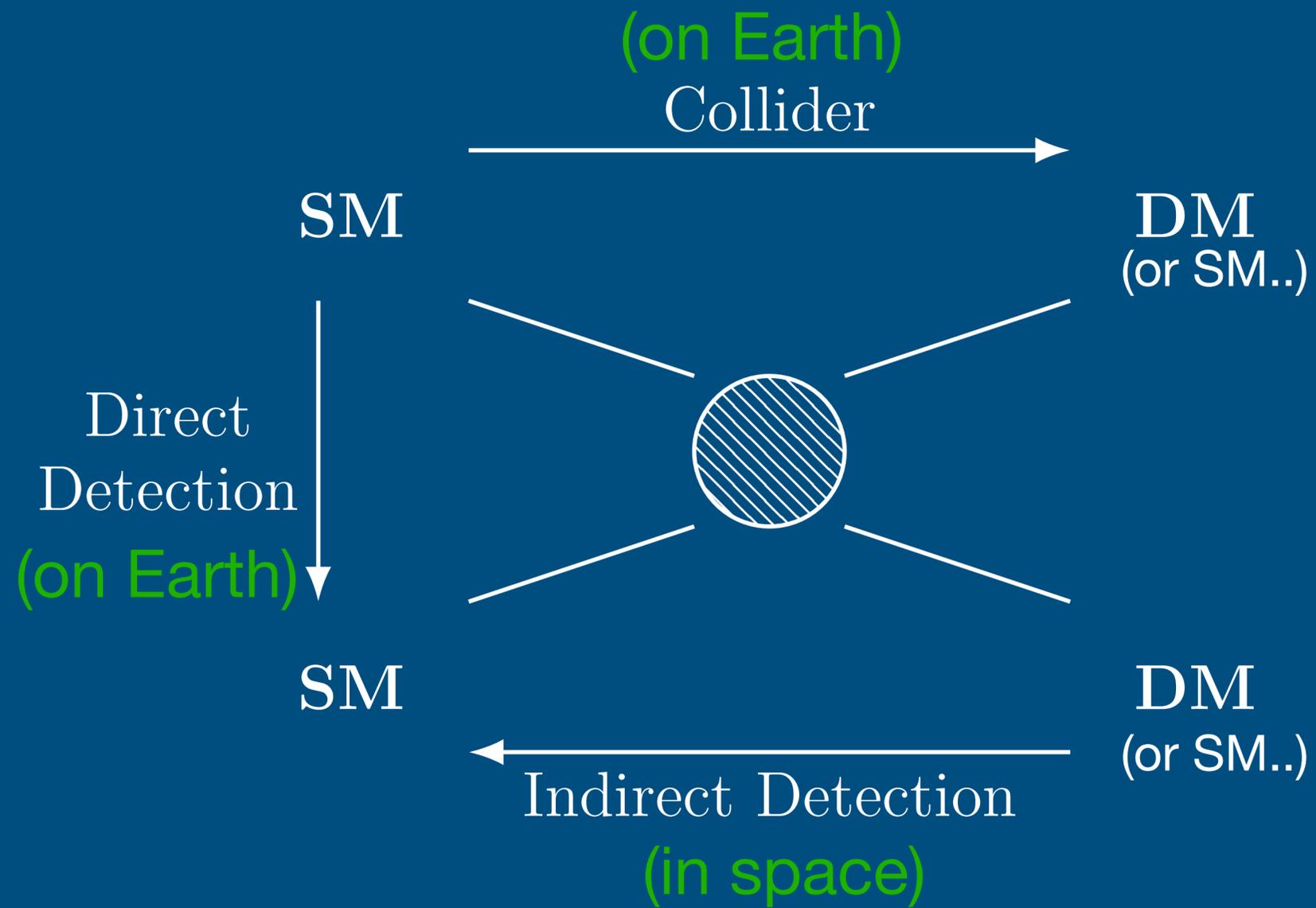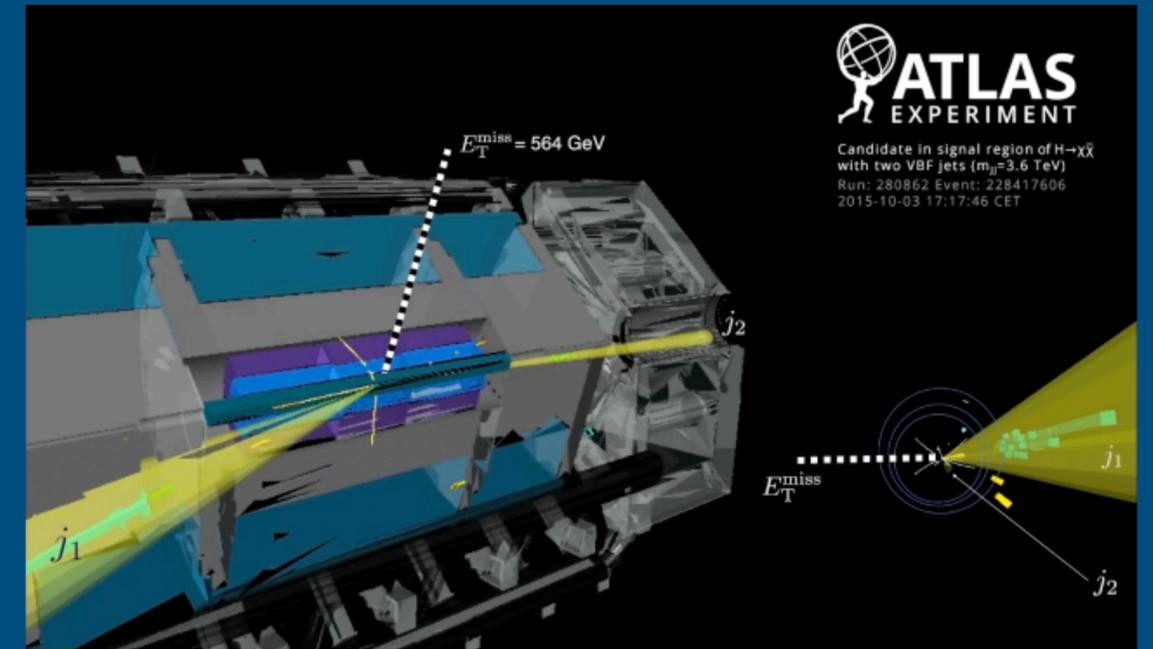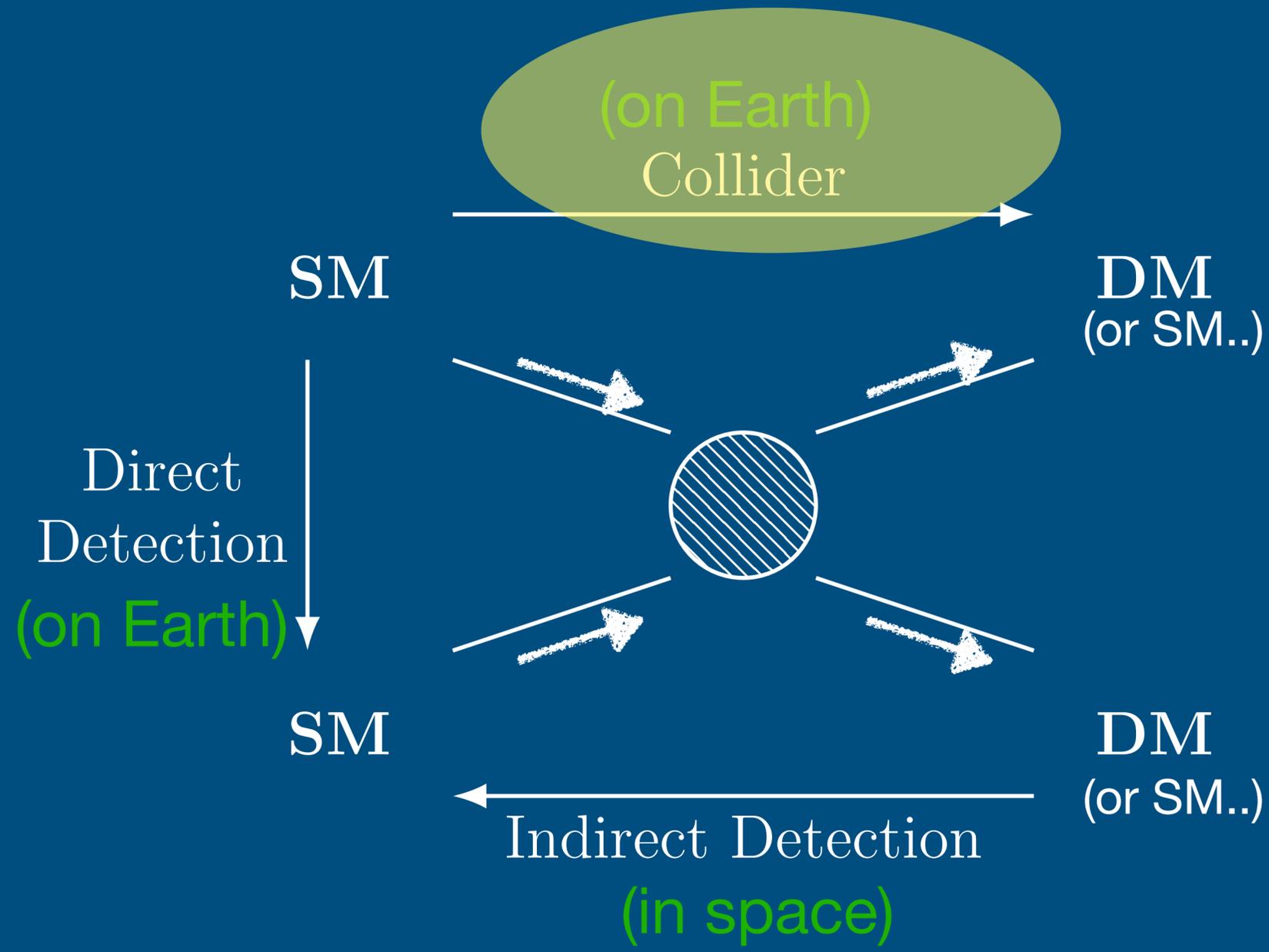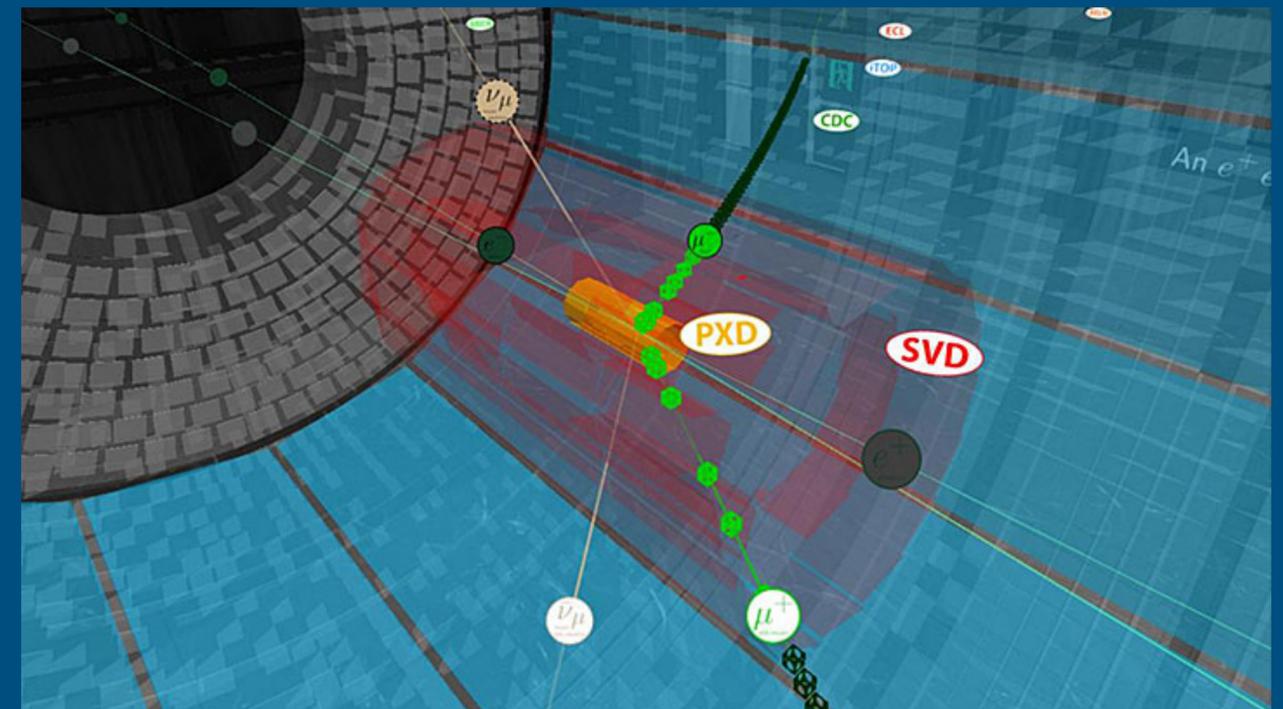
ATLAS

Duer et al, KEK, Belle

DM portals

Mediator

1. **Vector portal**

2. **Scalar portal**

3. **Neutrino portal**

$\gamma \rightsquigarrow \otimes \rightsquigarrow A'$

$h -- \otimes -- S$

$\nu — \otimes — N$

DM
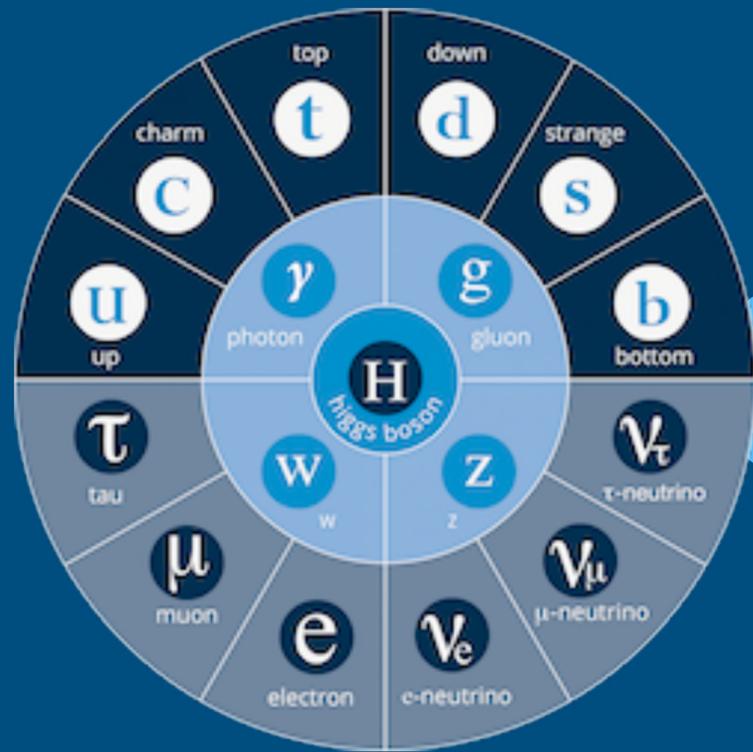
DM portals

Adapted from:
arXiv:2410.23454 - Canadian Subatomic
Physics community; Symmetry Magazine; ATLAS

Mediator
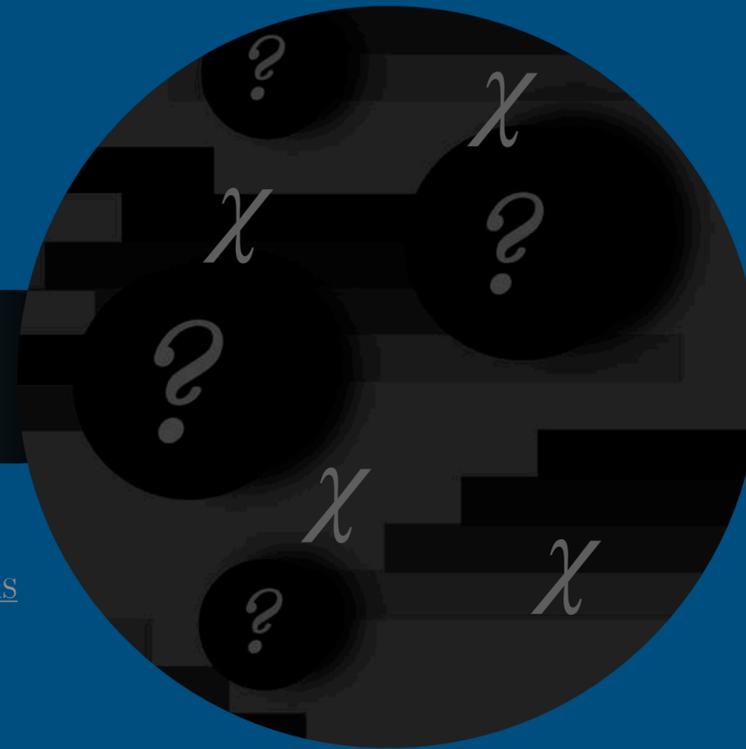
1. **Vector portal**

2. Scalar portal

3. Neutrino portal
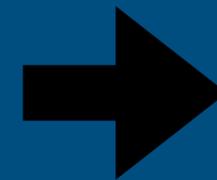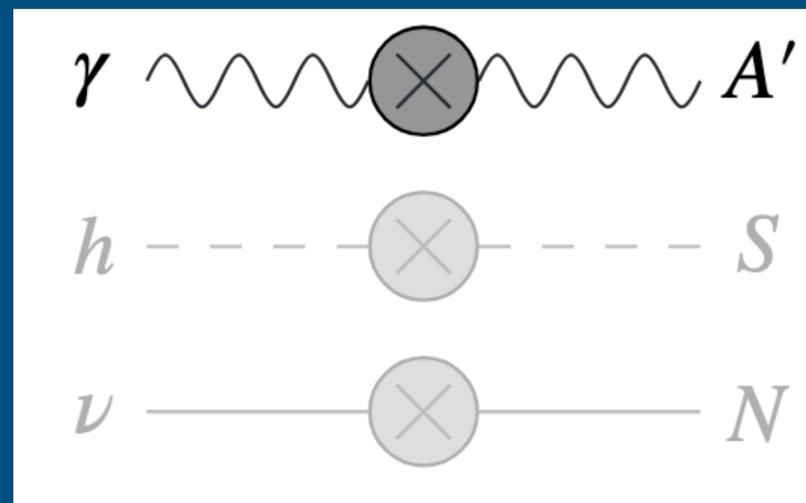
DM

X as a dark vector (spin-1) $\rightarrow V_\mu$

generic coupling to electrons

$$\mathscr{L} \supset -V_\mu \bar{e}\gamma^\mu(g_V + g_A\gamma^5)e$$

X **as a dark vector (spin-1)** $\rightarrow V_\mu$

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specific cases:

- Kinetically mixed dark photon $\mathscr{L} \supset \dfrac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$

-

-

-

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couplings are mostly vectorial*

specific cases:

- Kinetically mixed dark photon $\mathscr{L} \supset \dfrac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$ $g_V \simeq - \epsilon e, \quad g_A \simeq 10^{-3} \left(\dfrac{m_V}{5 \text{ GeV}} \right)^2 g_V$

-

-

-

*Curtin et al (14)

Okun (82), Galison and Manohar (84), Holdom (86)

X as a dark vector (spin-1) $\rightarrow V_\mu$

generic coupling to electrons

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specific cases:

- Kinetically mixed dark photon $g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3} \left(\dfrac{m_V}{5 \text{ GeV}} \right)^2 g_V$

- Mass mixed dark Z $\mathscr{L} \supset -2\epsilon_Z m_Z^2 Z_d^\mu Z_\mu$ $g_V \simeq -0.05\epsilon_Z e, \quad g_A \simeq -13 g_V$

-

-

X as a dark vector (spin-1) $\rightarrow V_\mu$

generic coupling to electrons

$$\mathscr{L} \supset -V_\mu \bar{e}\gamma^\mu(g_V + g_A\gamma^5)e$$

mass generated via Higgs or Stueckelberg mechanisms $\quad m_V \ll m_Z$

specific cases:

- Kinetically mixed dark photon $\quad g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3}\left(\dfrac{m_V}{5\text{ GeV}}\right)^2 g_V$

- Mass mixed dark $Z \quad g_V \simeq -0.05\epsilon_Z e, \quad g_A \simeq -13g_V$

- Right handed vector $\quad g_V \simeq g_A \qquad$ couples only to RH fermions $\qquad |g_A + g_V| \lesssim 10^{-4} \quad$ (APV limits)

-

X as a dark vector (spin-1) $\rightarrow V_\mu$

generic coupling to electrons

$$\mathcal{L} \supset -V_\mu \bar{e}\gamma^\mu(g_V + g_A\gamma^5)e$$

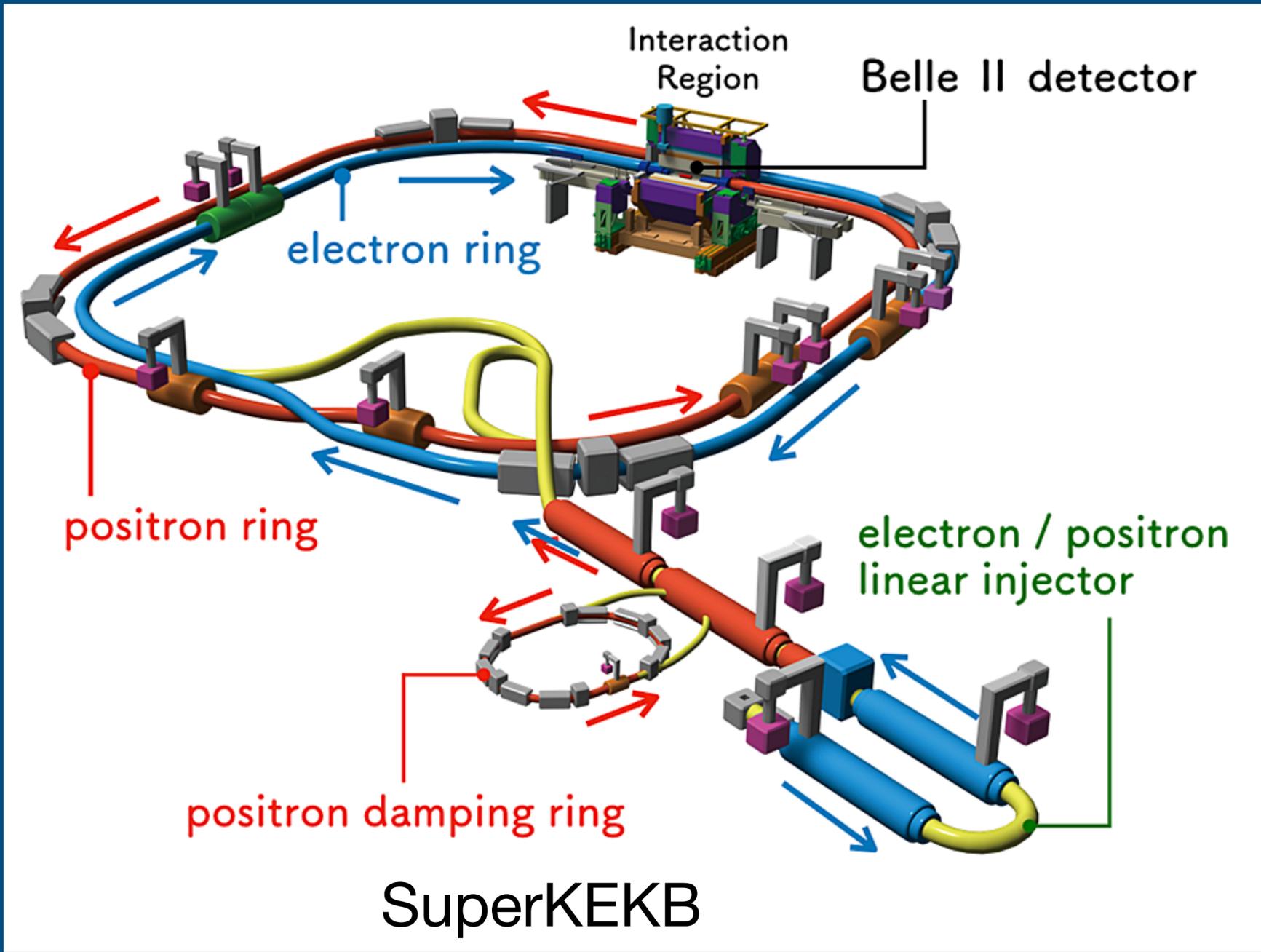mass generated via Higgs or Stueckelberg mechanisms $m_V \ll m_Z$

specific cases:

- Kinetically mixed dark photon $g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3}\left(\dfrac{m_V}{5\ \text{GeV}}\right)^2 g_V$

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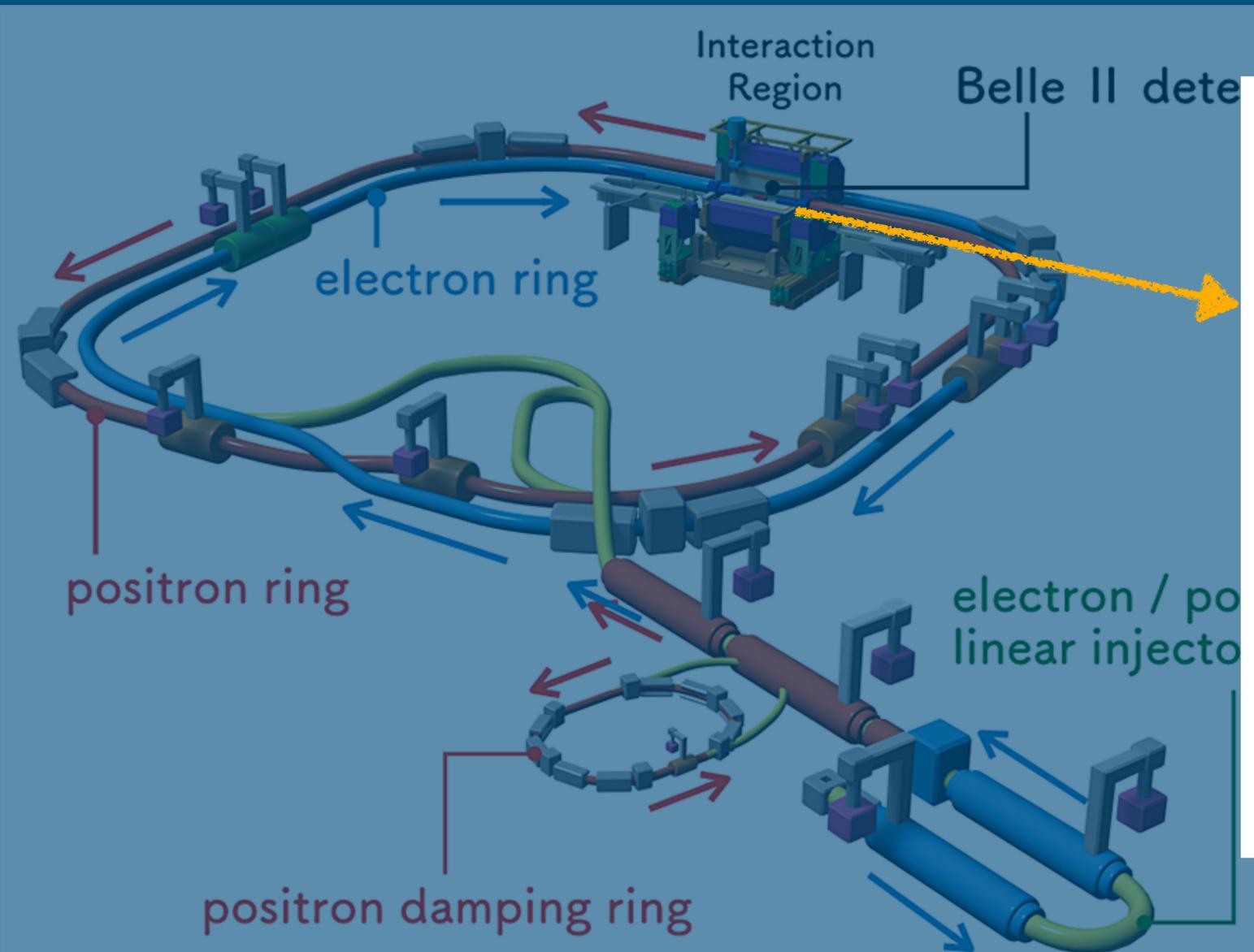- Generic dark vector   both kinetic and mass mixing

Outline

- Dark bosons

- What is "Chiral" Belle?

- How could (Chiral) Belle detect dark vectors?

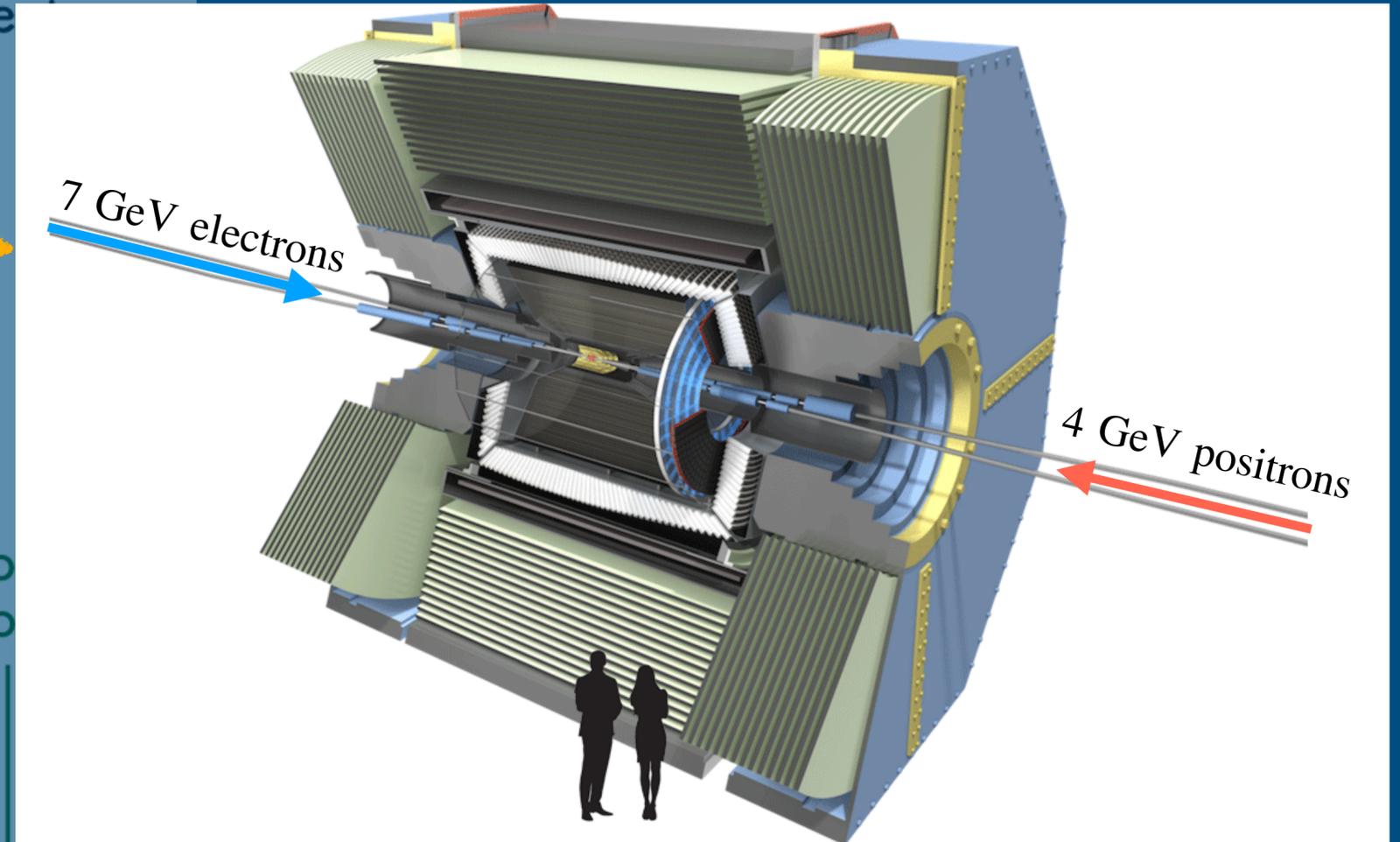- Mono-photon searches: backgrounds, reach, and discrimination power

The Belle II detector

Interaction Region

Belle II detector

electron ring

positron ring

electron / positron linear injector

positron damping ring

SuperKEKB

The Belle II detector

Interaction Region

Belle II detector

electron ring

positron ring

electron / positron linear injector

positron damping ring

$\sqrt{s} = 10.58$ GeV

7 GeV electrons

4 GeV positrons

Belle II

The Belle II detector
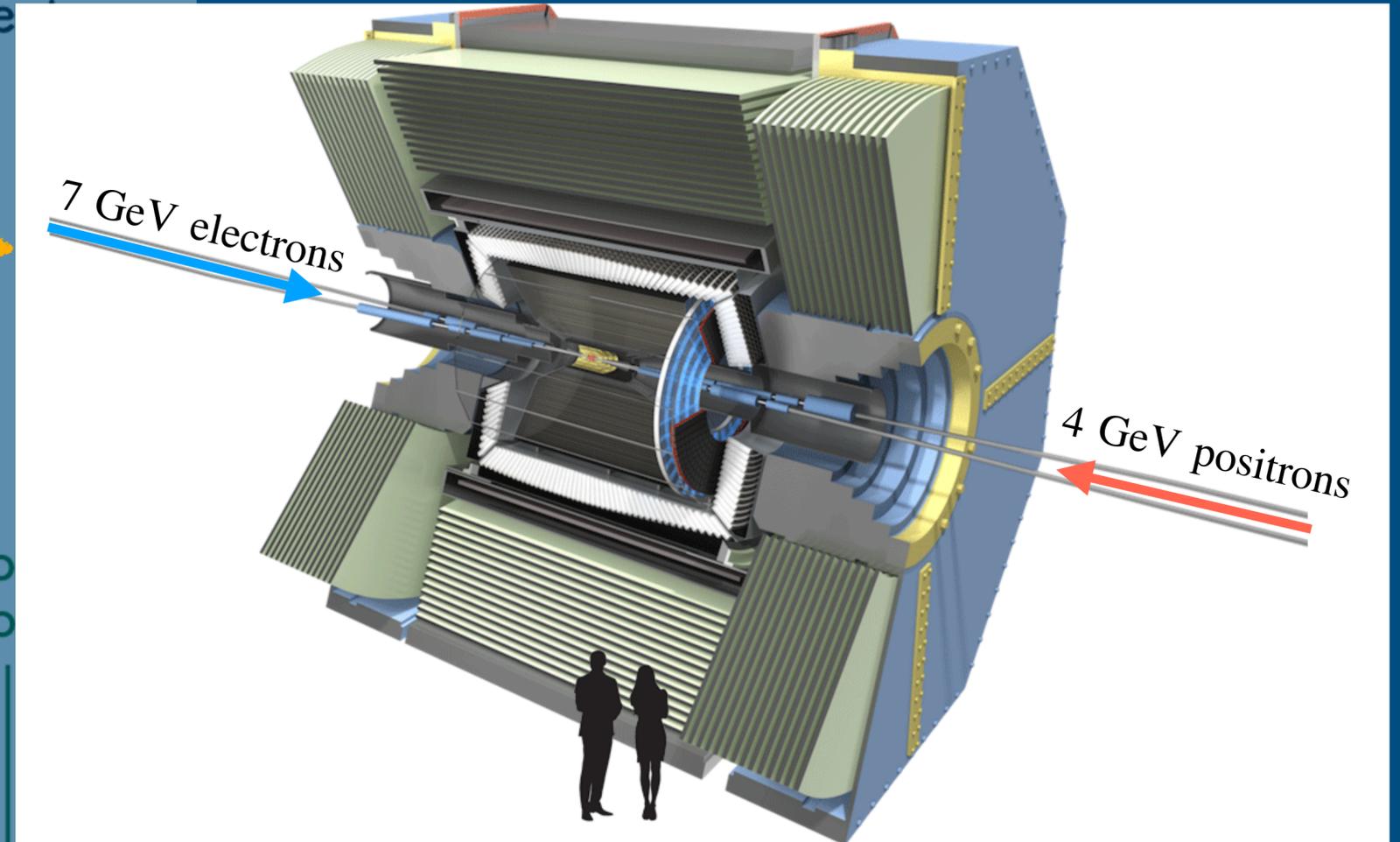
* Program includes:
  - LFV tests.
  - CKM unitarity.
  - CP violation.
  - Rare decays.
  - Dark sectors.

* A target luminosity $\sim 50 \ \text{ab}^{-1}$.

* Low systematics and backgrounds due to high integrated luminosity and colliding elementary particles.

$\sqrt{s} = 10.58 \ \text{GeV}$

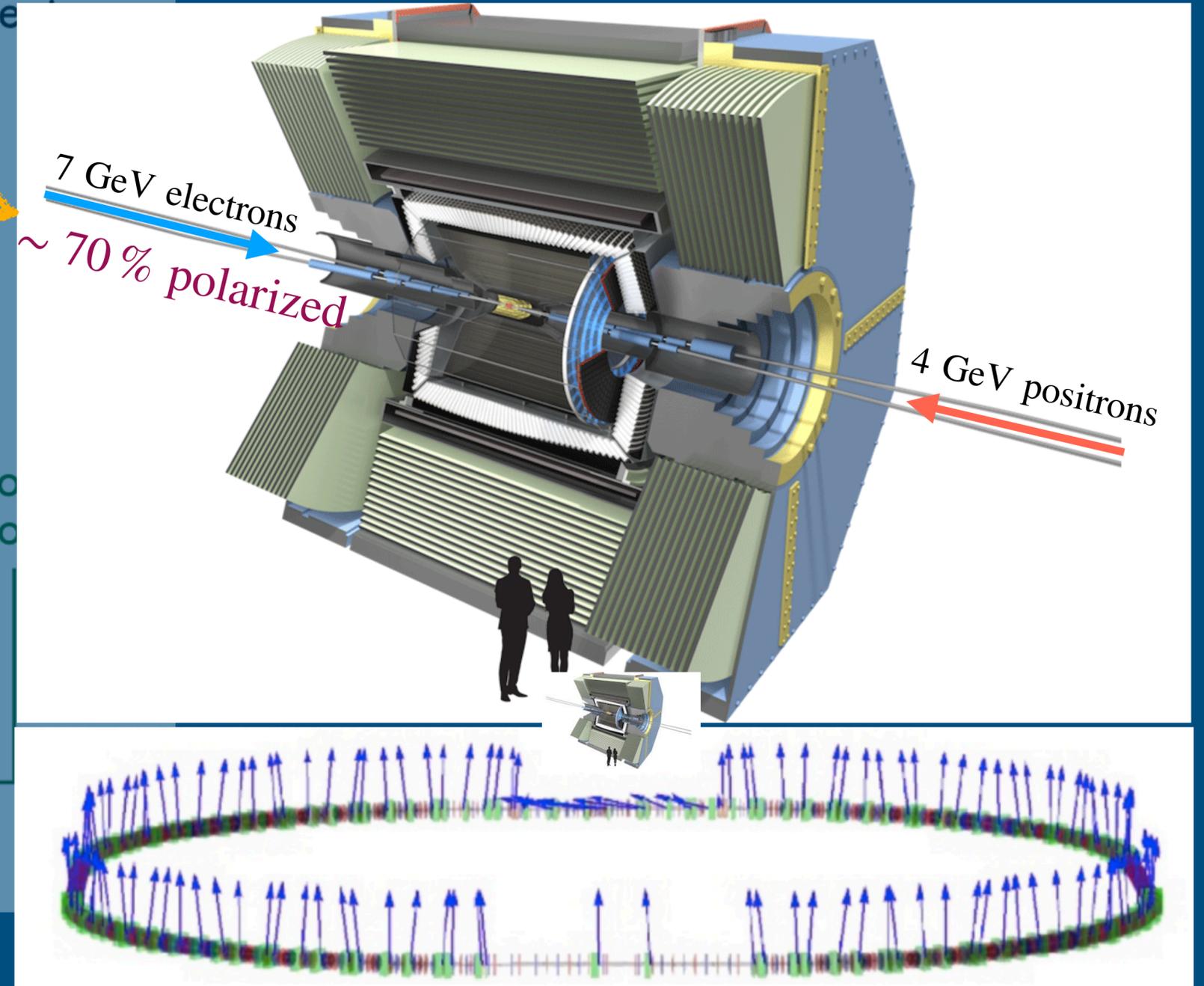7 GeV electrons

4 GeV positrons

Belle II

The Chiral Belle upgrade

- High precision weak NC measurements.
- NC universality measurements.
- $\tau\ g - 2$.
- Hadronic structure.
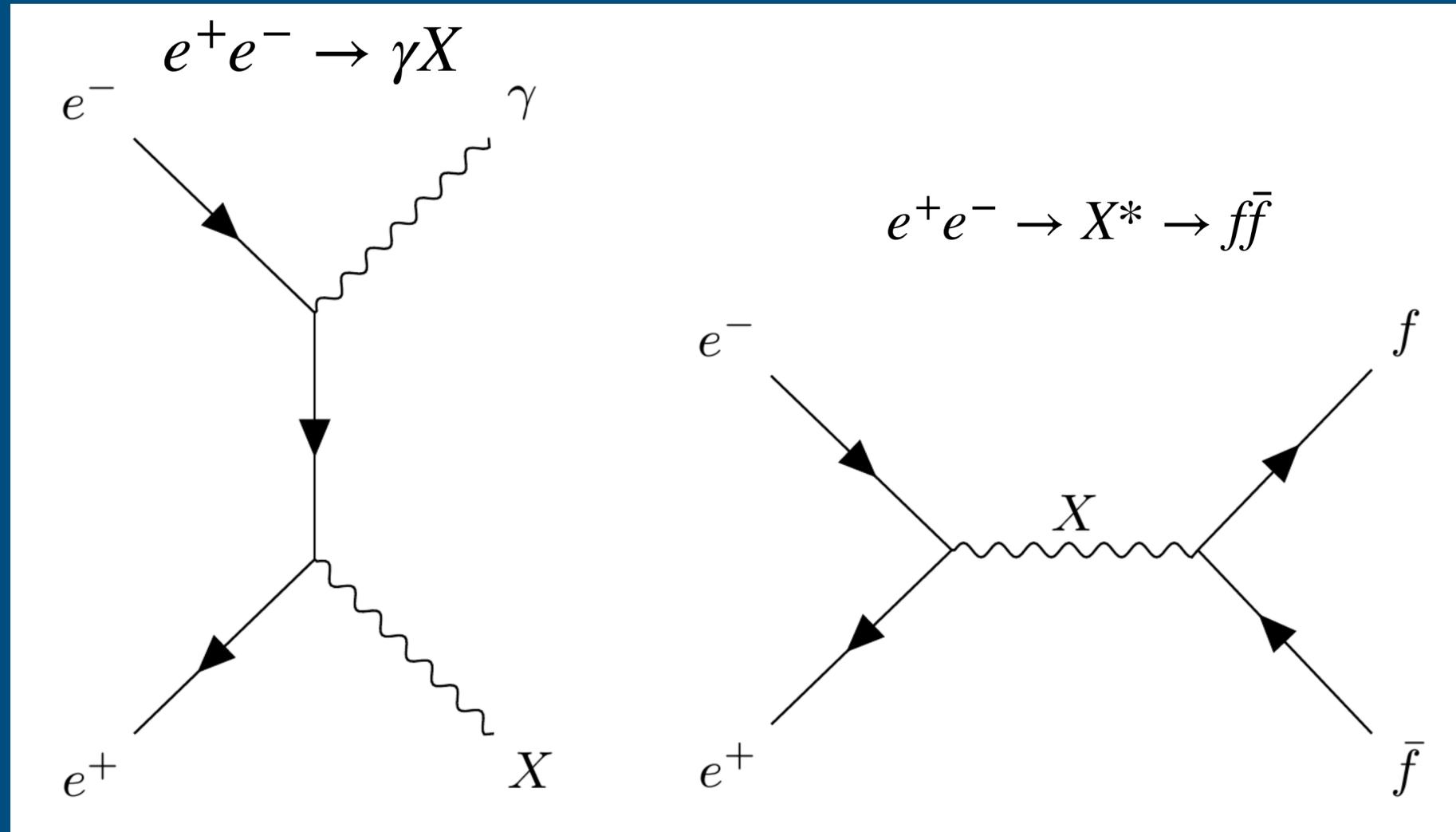- Richer dark sector phenomenology.

$\sqrt{s} = 10.58$ GeV

7 GeV electrons
~ 70 % polarized
4 GeV positrons

*M. Roney et al, Belle, Snowmass (21)

Outline

- Dark bosons

- What is "Chiral" Belle?

- How could (Chiral) Belle detect dark vectors?

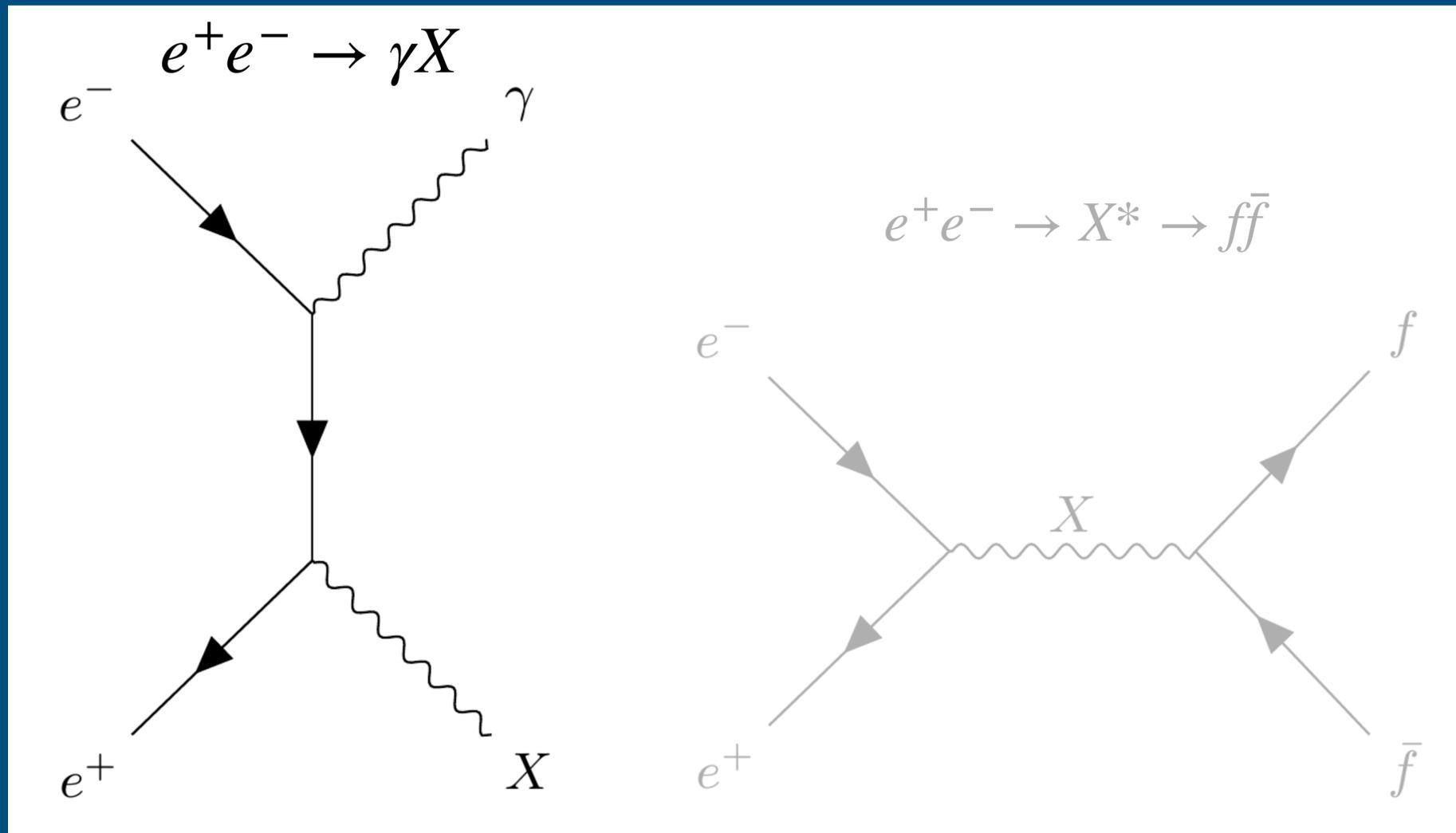- Mono-photon searches: backgrounds, reach, and discrimination power

Possible signals

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

$$e^+e^- \to X^* \to f\bar{f}$$

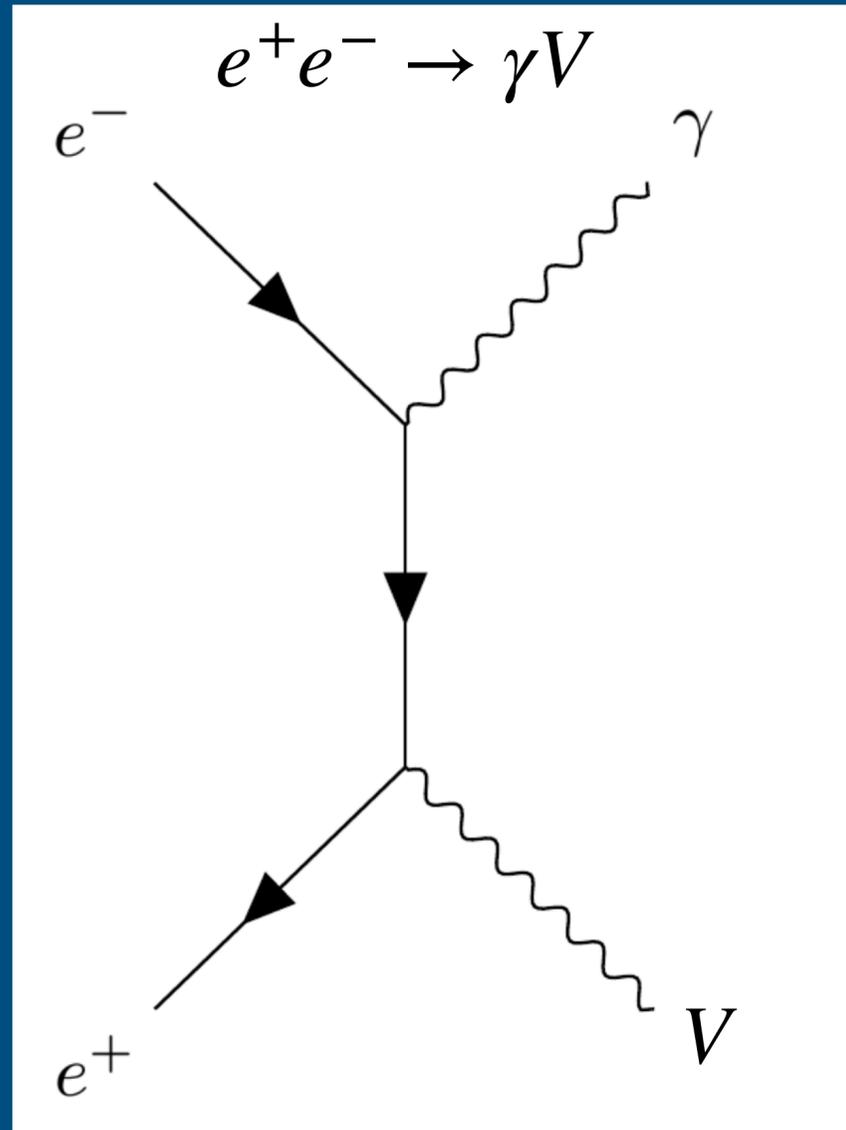Mono-photon production   "Bhabha"-type scattering

Possible signals

Mono-photon production

The main signal: mono-photons

For $m_V < 10.58$ GeV

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

$\sqrt{s} = 10.58$ GeV

7 GeV electrons
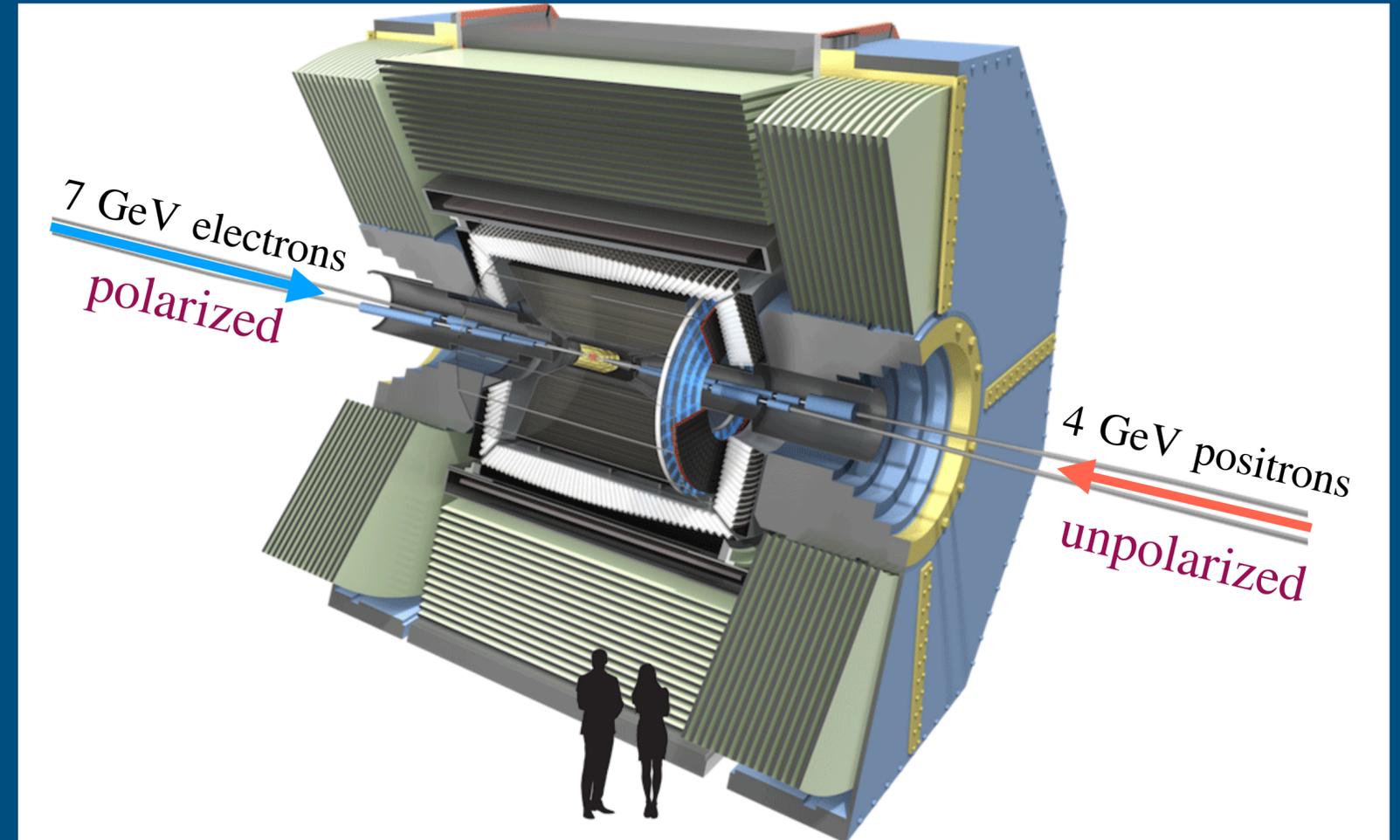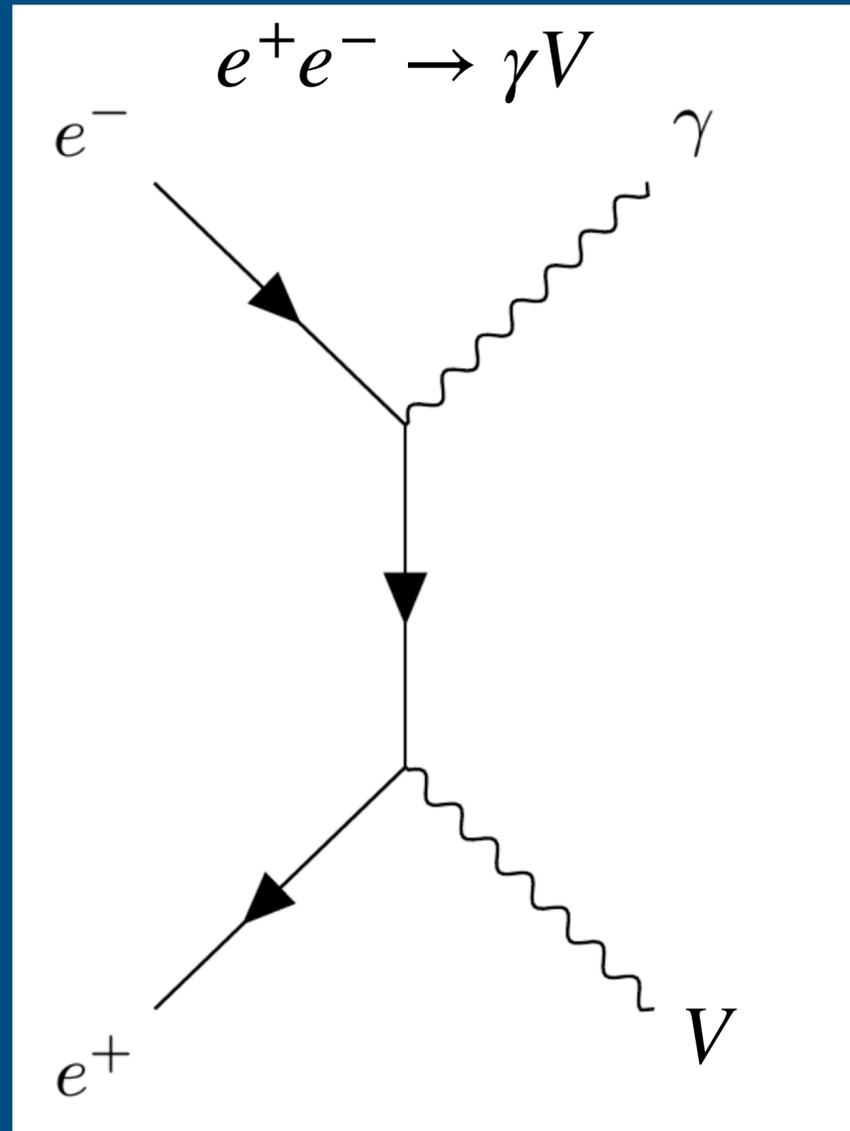polarized

4 GeV positrons
unpolarized
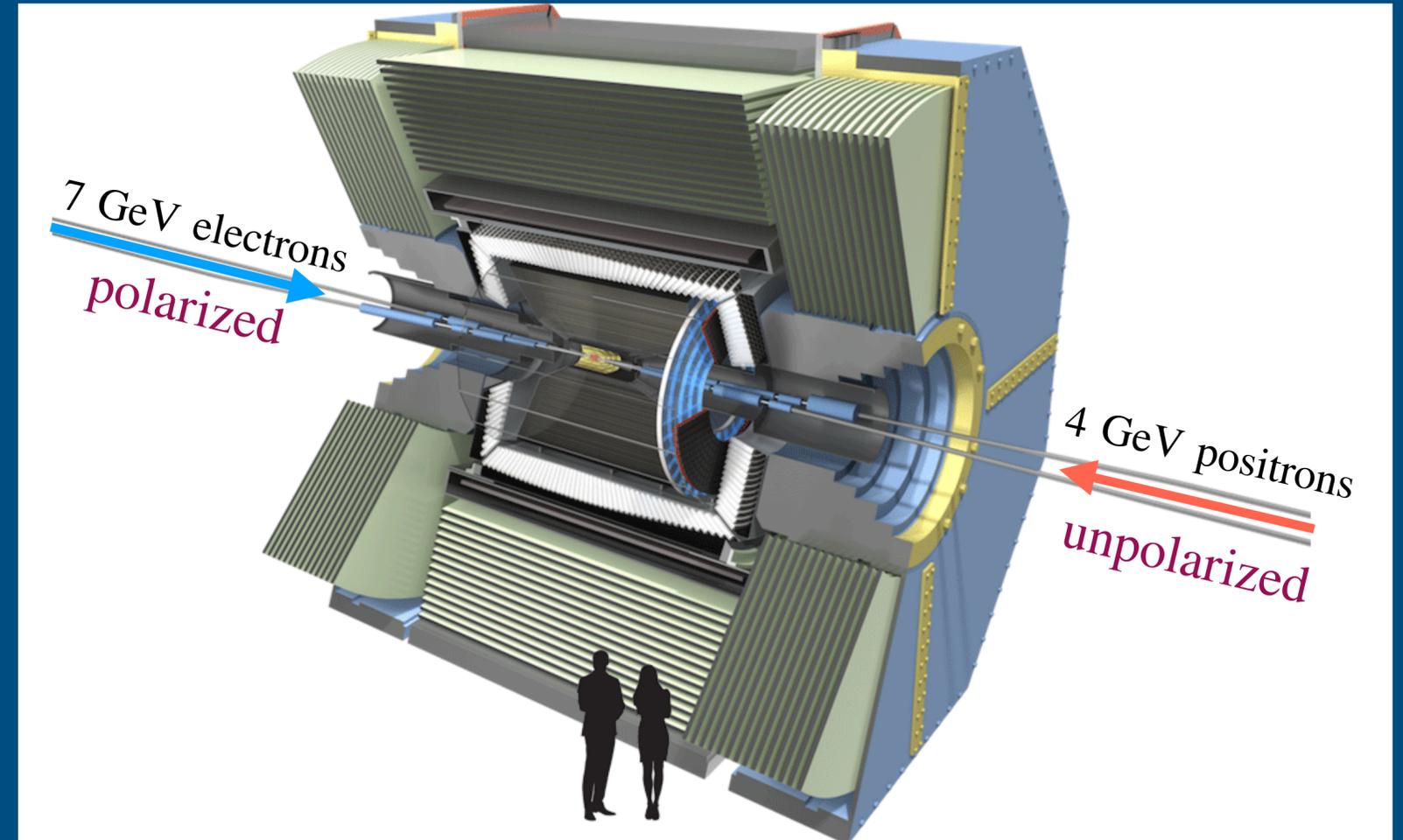
$$\frac{d\sigma_{R,L}}{d\cos\theta_\gamma^*} = \left(\frac{g_V \pm g_A}{e}\right)^2 \bar{\sigma}_{\gamma V}$$

The main signal: mono-photons

For $m_V < 10.58$ GeV

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

$\sqrt{s} = 10.58$ GeV

7 GeV electrons
polarized

4 GeV positrons
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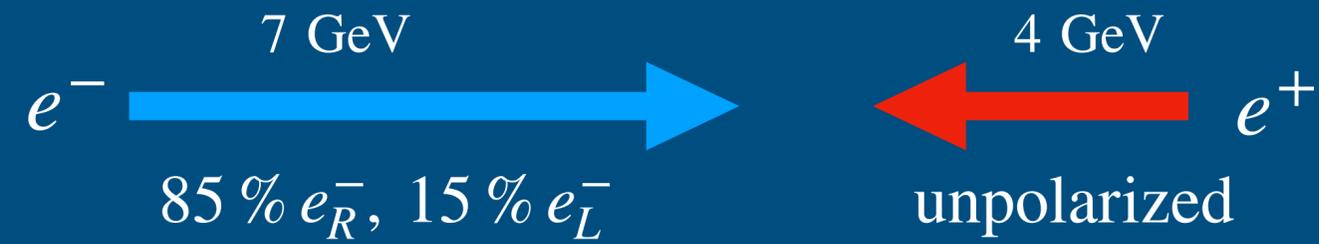$$\frac{d\sigma_{R,L}}{d\cos\theta_\gamma^*} = \left(\frac{g_V \pm g_A}{e} \right)^2 \bar{\sigma}_{\gamma V}$$

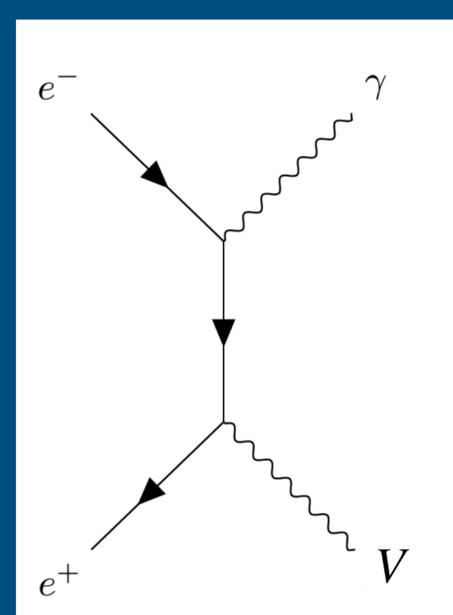depends on s, m_V, and θ_γ^*

A more realistic case: 70% polarization

$\sqrt{s} = 10.58$ GeV

7 GeV

4 GeV

e^-

e^+

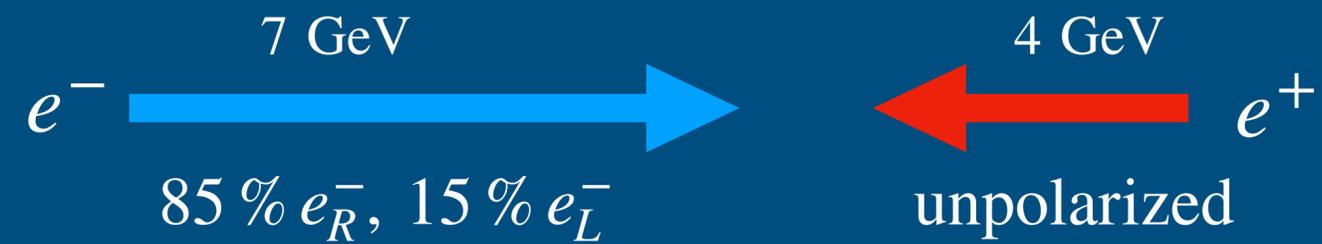$85\,\%\,e_R^-,\ 15\,\%\,e_L^-$

unpolarized

$$\sigma_R = \left(\frac{g_V^2}{e^2} + \frac{g_A^2}{e^2} + 1.4\frac{g_V g_A}{e^2} \right) \bar{\sigma}_{\gamma V}$$

A more realistic case: 70% polarization

$$\sqrt{s} = 10.58 \text{ GeV}$$

e^- 7 GeV   4 GeV e^+

$85\% \, e_R^-, \, 15\% \, e_L^-$ unpolarized

$$\sigma_R = \left(\frac{g_V^2}{e^2} + \frac{g_A^2}{e^2} + 1.4 \frac{g_V g_A}{e^2} \right) \bar{\sigma}_{\gamma V}$$

e^- 7 GeV   4 GeV e^+
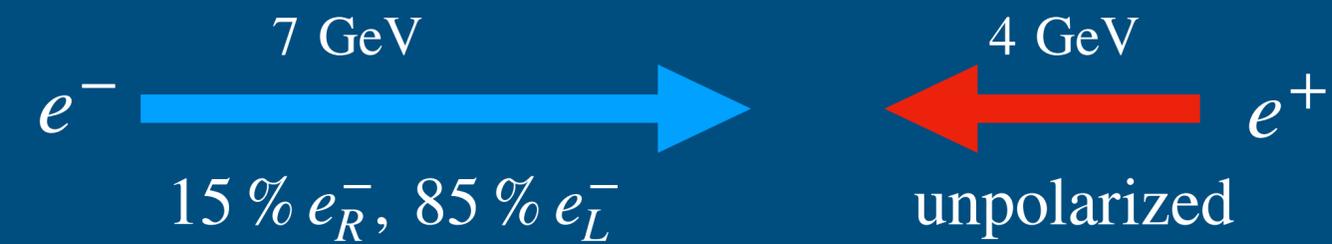
$15\% \, e_R^-, \, 85\% \, e_L^-$ unpolarized

$$\sigma_L = \left(\frac{g_V^2}{e^2} + \frac{g_A^2}{e^2} - 1.4 \frac{g_V g_A}{e^2} \right) \bar{\sigma}_{\gamma V}$$

Outline

- Dark bosons

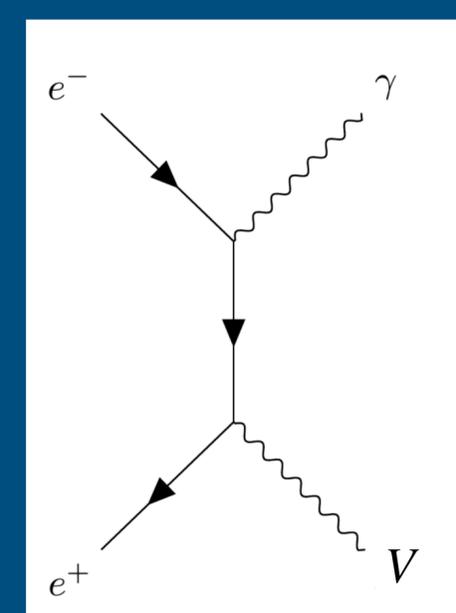- What is "Chiral" Belle?

- How could (Chiral) Belle detect dark vectors?

- Mono-photon searches: backgrounds, reach, and discrimination power

Backgrounds

dominant EM

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

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

Inefficiencies

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

smaller irreducible EW

$$e^+e^- \to \nu_l\bar{\nu}_l\gamma(\gamma)$$

other small backgrounds

$$e^+e^- \to \text{hadrons} + \gamma$$

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

can typically be vetoed from tracks

Backgrounds

dominant EM

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

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

Inefficiencies

$$e^+e^- \to \gamma\gamma$$ when one photon is missed due to reconstruction inefficiency ~ 10^{-6} *

smaller irreducible EW

$$e^+e^- \to \nu_l\bar{\nu}_l\gamma(\gamma)$$

other small backgrounds

$$e^+e^- \to \text{hadrons} + \gamma$$

$$e^+e^- \to \tau^+\tau^-\gamma$$ can typically be vetoed from tracks

Backgrounds

dominant EM

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

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

Inefficiencies

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

smaller irreducible EW

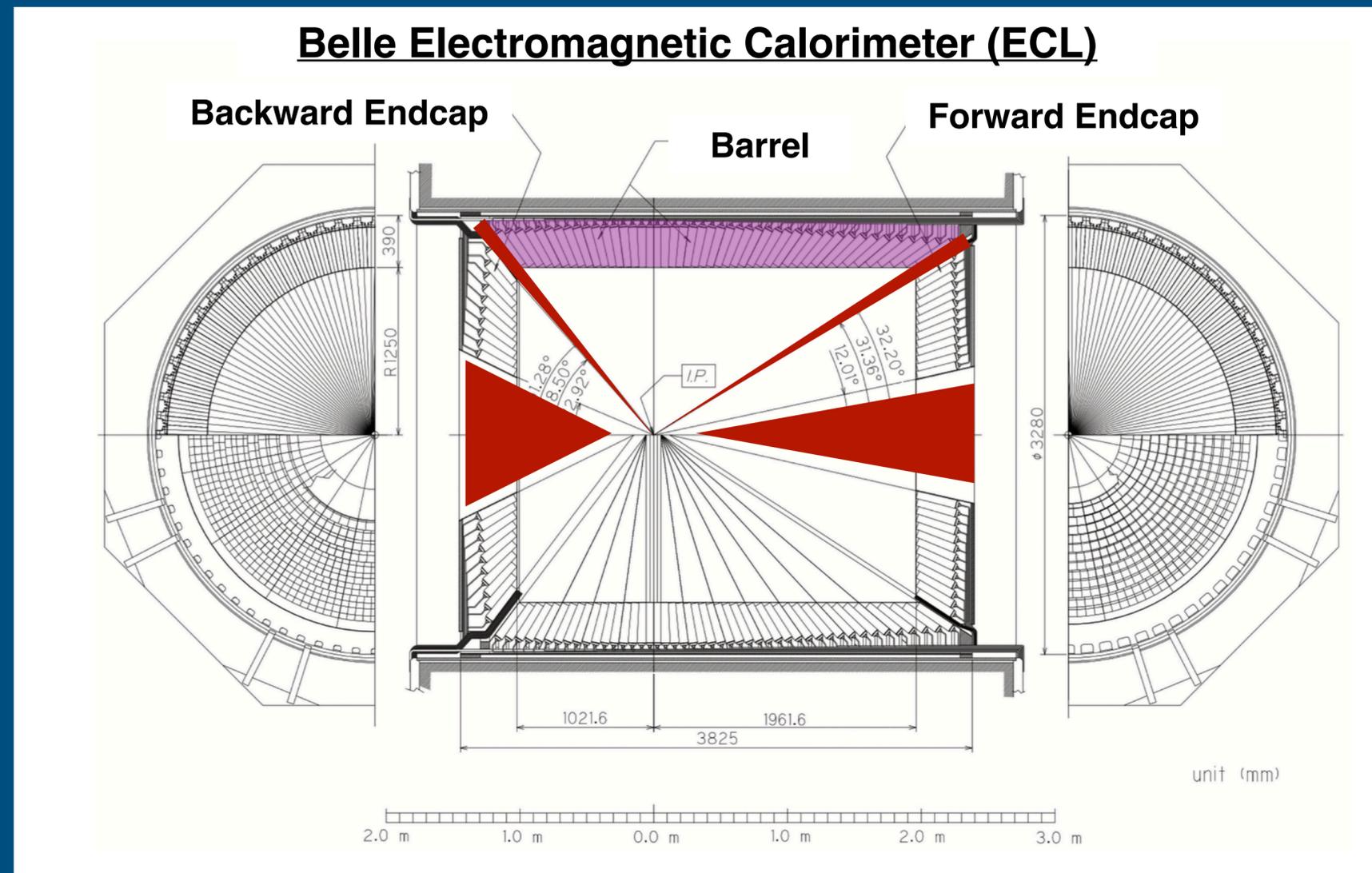$$e^+e^- \to \nu_l\bar{\nu}_l\gamma(\gamma)$$

Belle Electromagnetic Calorimeter (ECL)

Backward Endcap   Forward Endcap

Barrel

Adachi et al, Belle (18)

other small backgrounds

$$e^+e^- \to \text{hadrons} + \gamma$$

can typically be vetoed from tracks

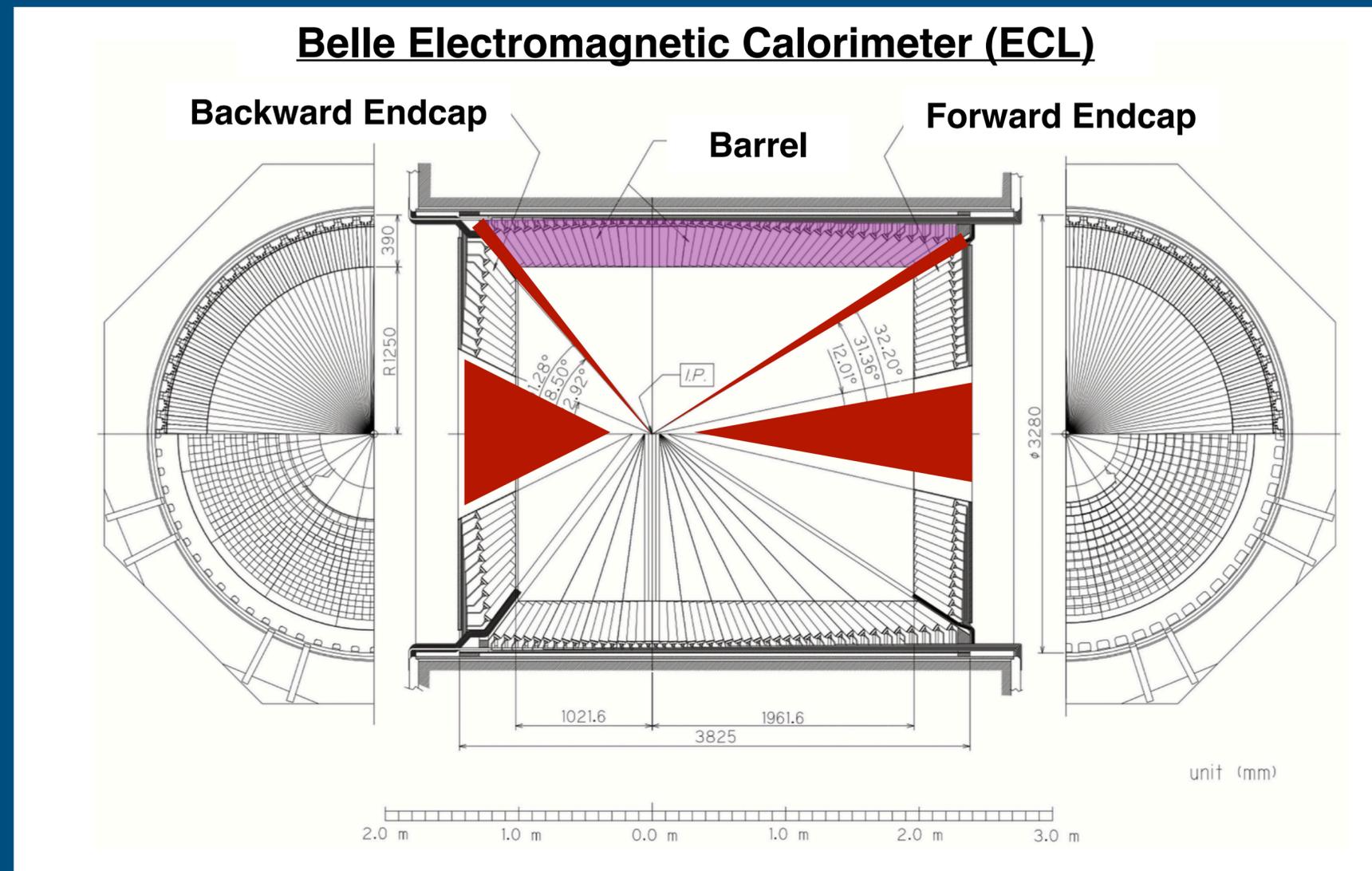$$e^+e^- \to \tau^+\tau^-\gamma$$

Backgrounds

20 fb^{-1}

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

$e^+ e^- \to \text{hadrons} + \gamma$

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

Belle Electromagnetic Calorimeter (ECL)
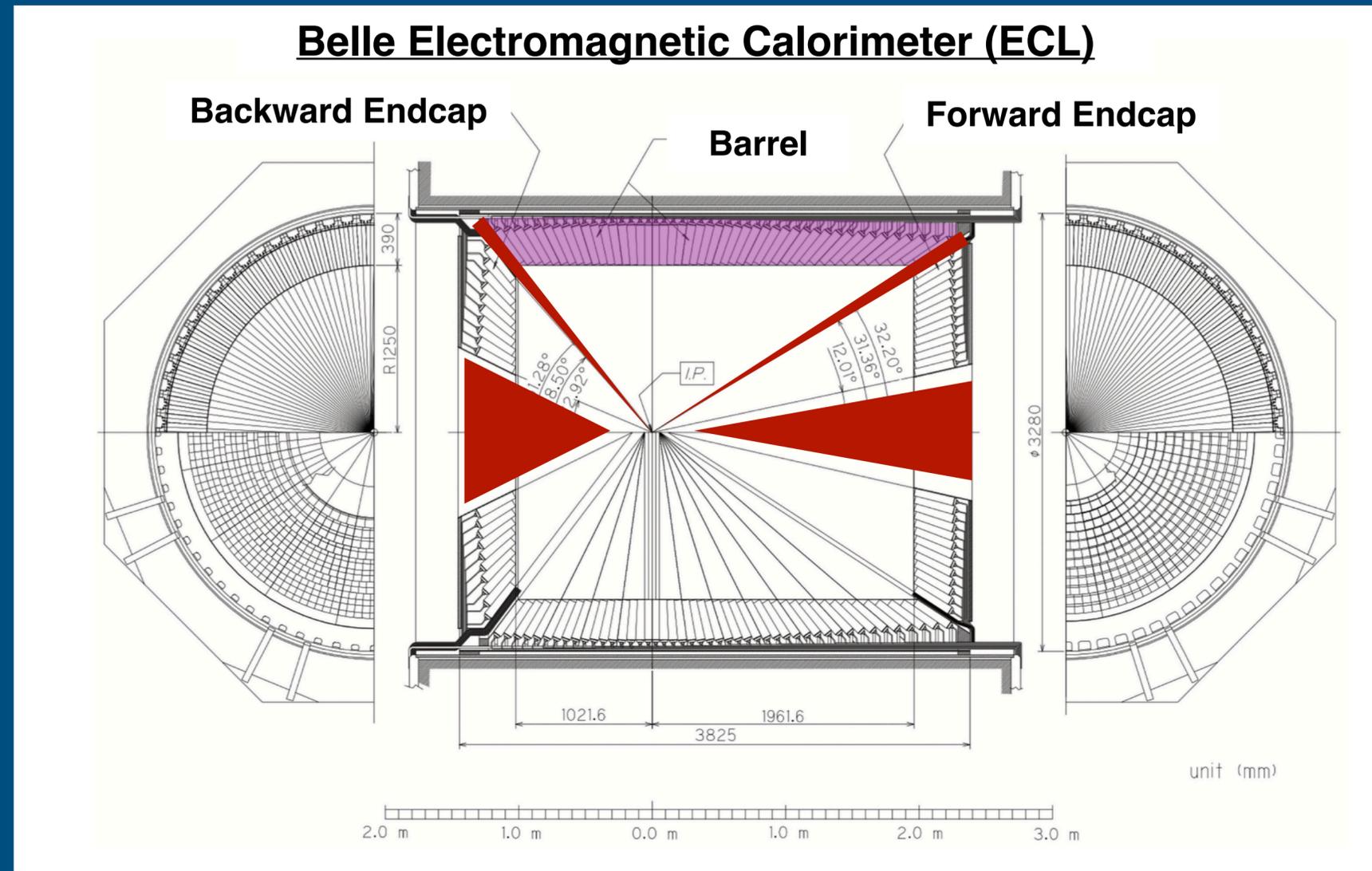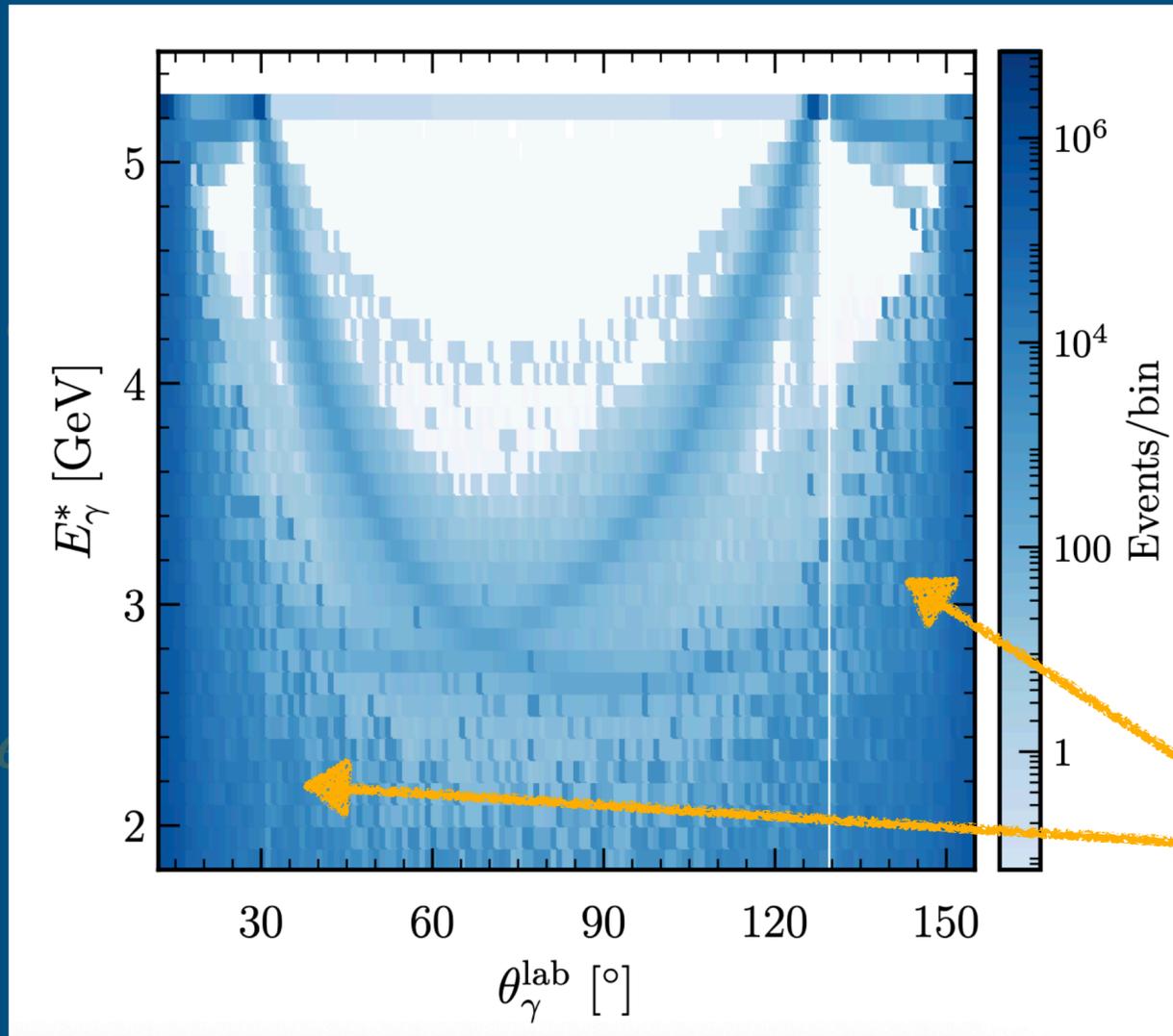

Backward Endcap   **Barrel**   **Forward Endcap**

Adachi et al, Belle (18)

- Polarization has a modest effect on backgrounds due to $e^+ e^- \to \nu \bar{\nu} \gamma (\gamma)$ processes.
- Signal angular distribution is the same, but its strength is modified, affecting the optimal cuts.

Backgrounds

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

20 fb^{-1}

$e^+e^- \to \text{hadrons} + \gamma$

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

Belle Electromagnetic Calorimeter (ECL)

Adachi et al, Belle (18)

two photons missed in beam pipe

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

Backgrounds

dominant background $\quad e^+ e^- \to \gamma\gamma\gamma$

20 fb^{-1}

$e^+ e^- \to \text{hadrons} + \gamma$

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

Belle Electromagnetic Calorimeter (ECL)

Adachi et al, Belle (18)

second photon missed in the endcap gaps

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

Backgrounds

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

Belle Electromagnetic Calorimeter (ECL)

Backward Endcap   Barrel   Forward Endcap

Adachi et al, Belle (18)

both photons missed in the forward endcap

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

20 fb^{-1}

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

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

Backgrounds

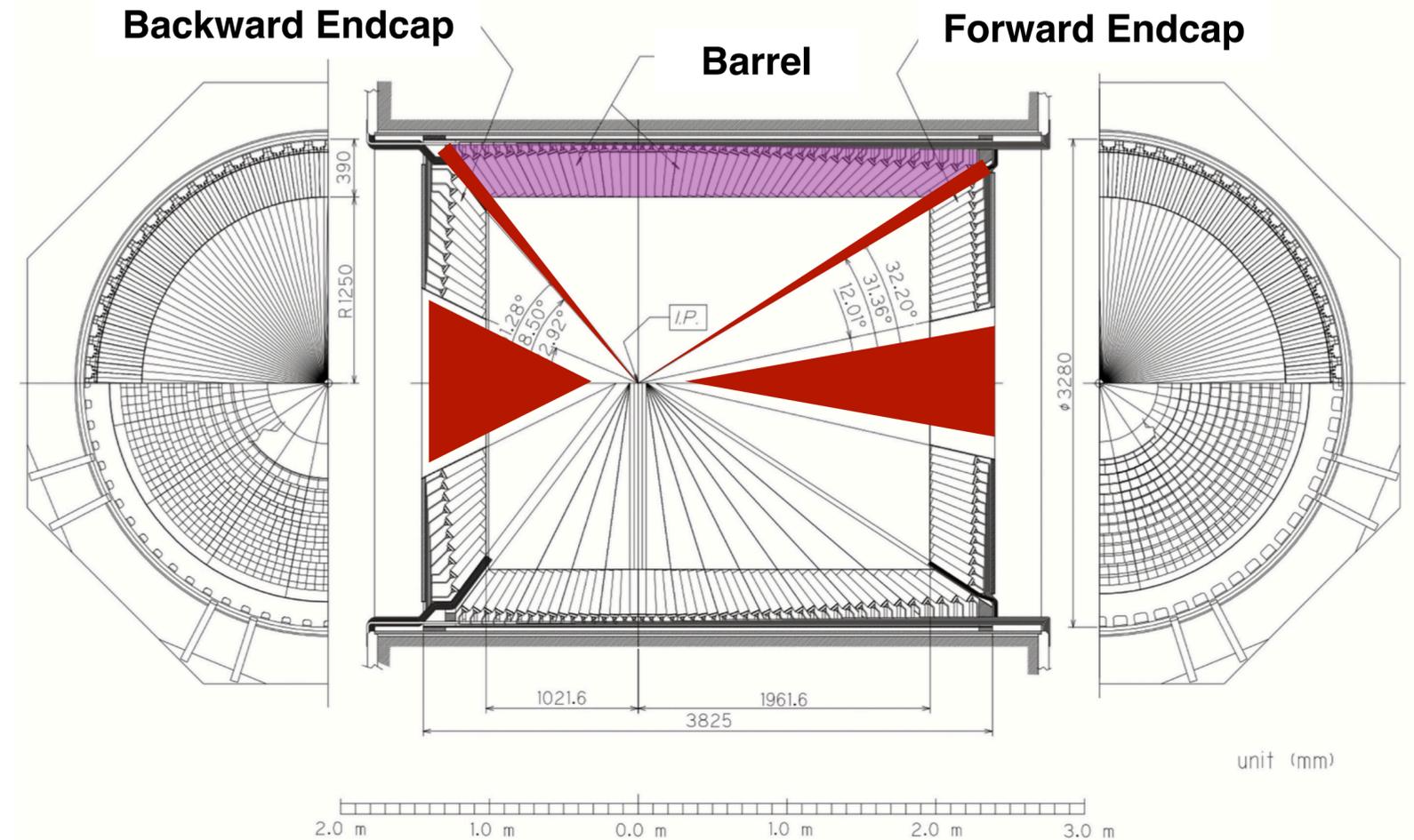20 fb^{-1}

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

Backward Endcap

Barrel

Forward Endcap
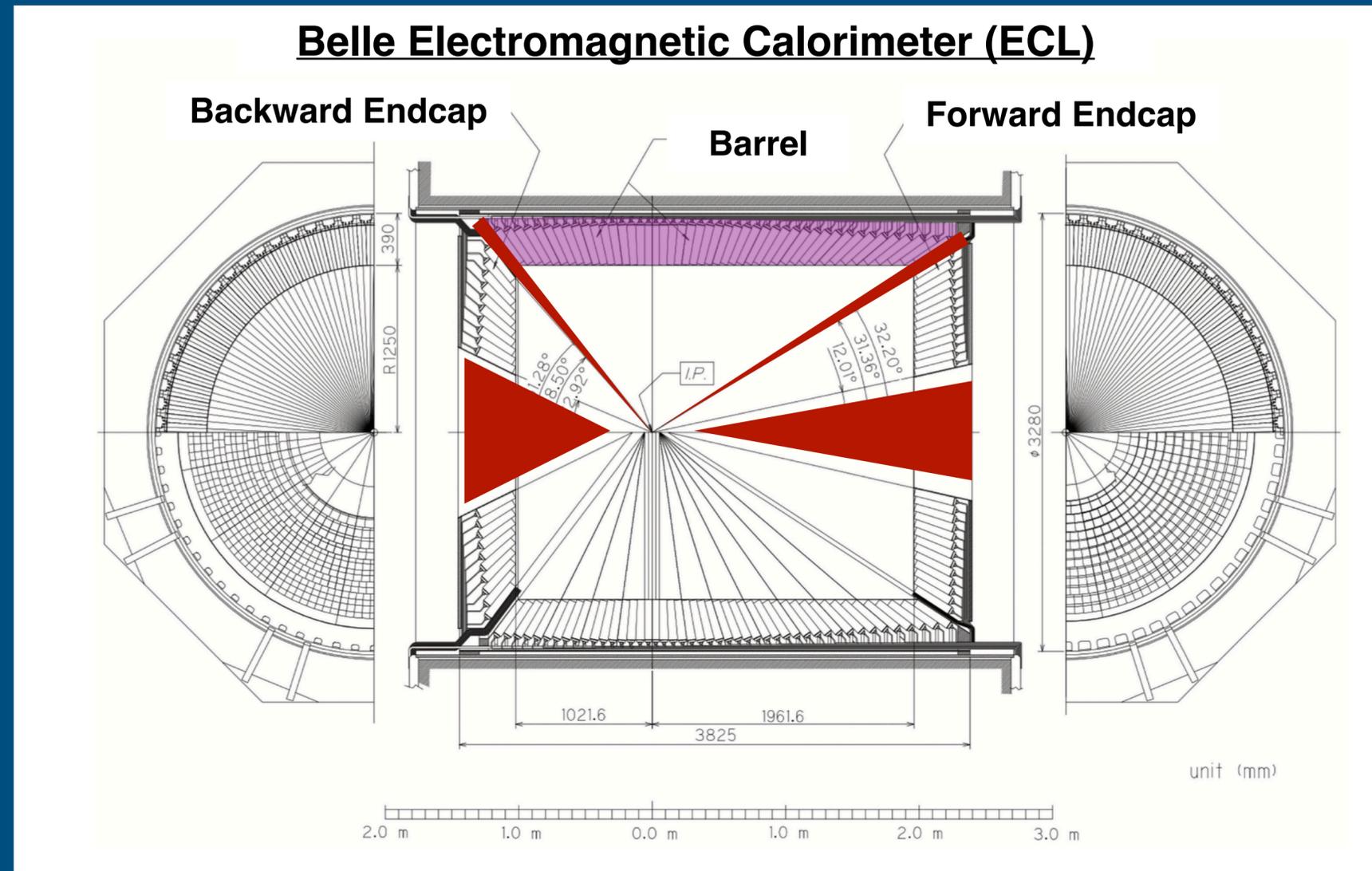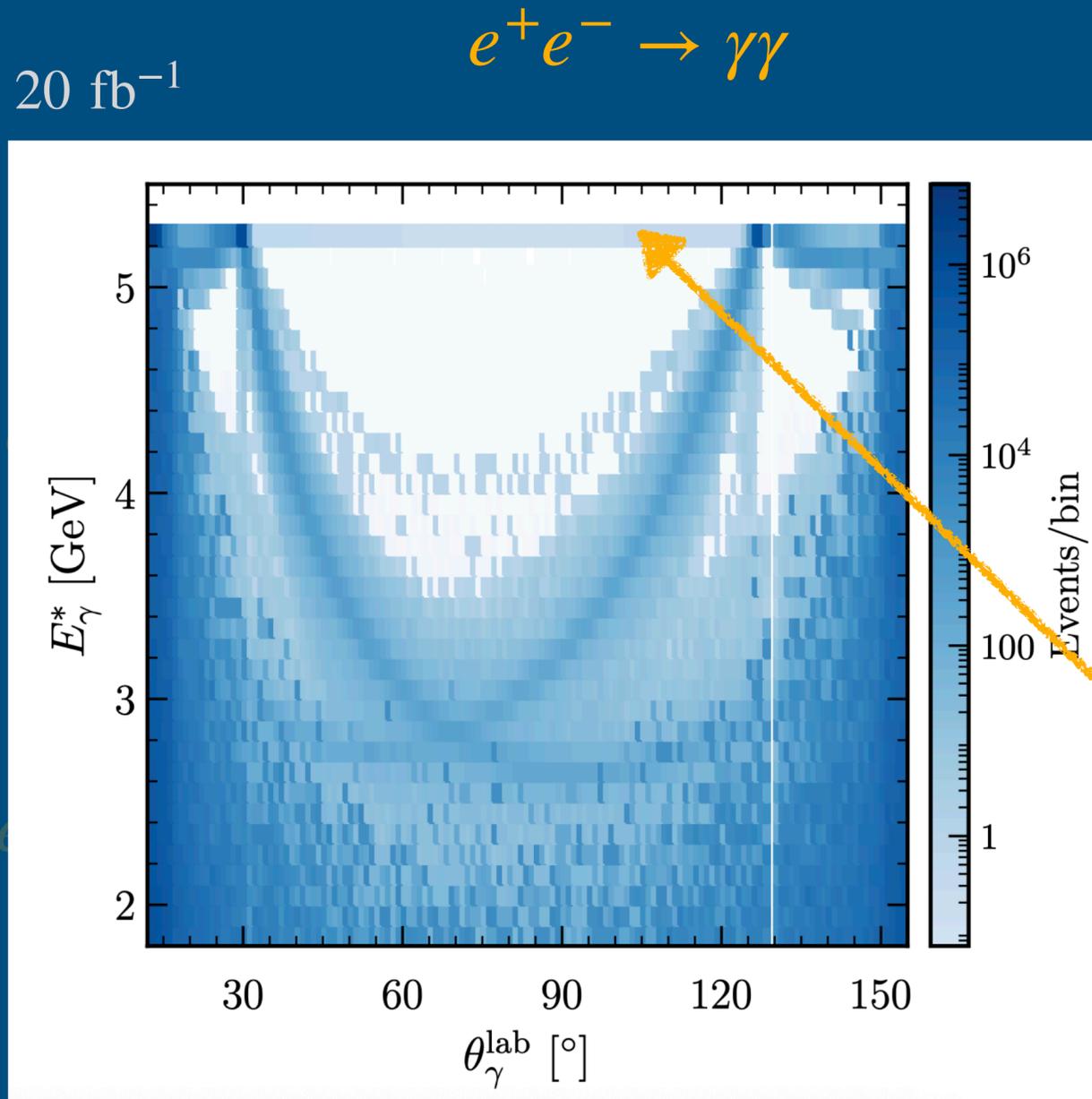
Adachi et al, Belle (18)

missed photon due to inefficiency
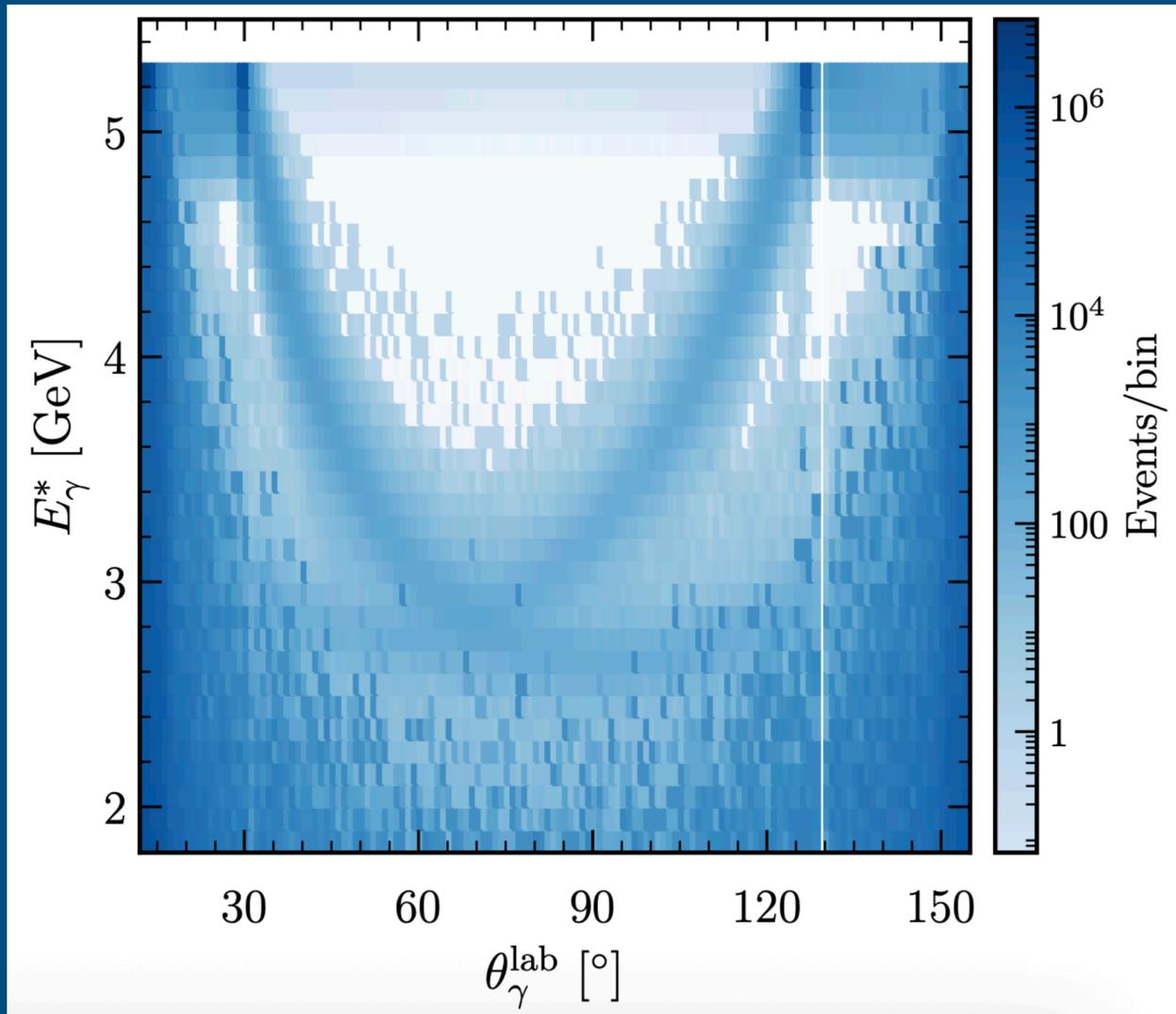
C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]
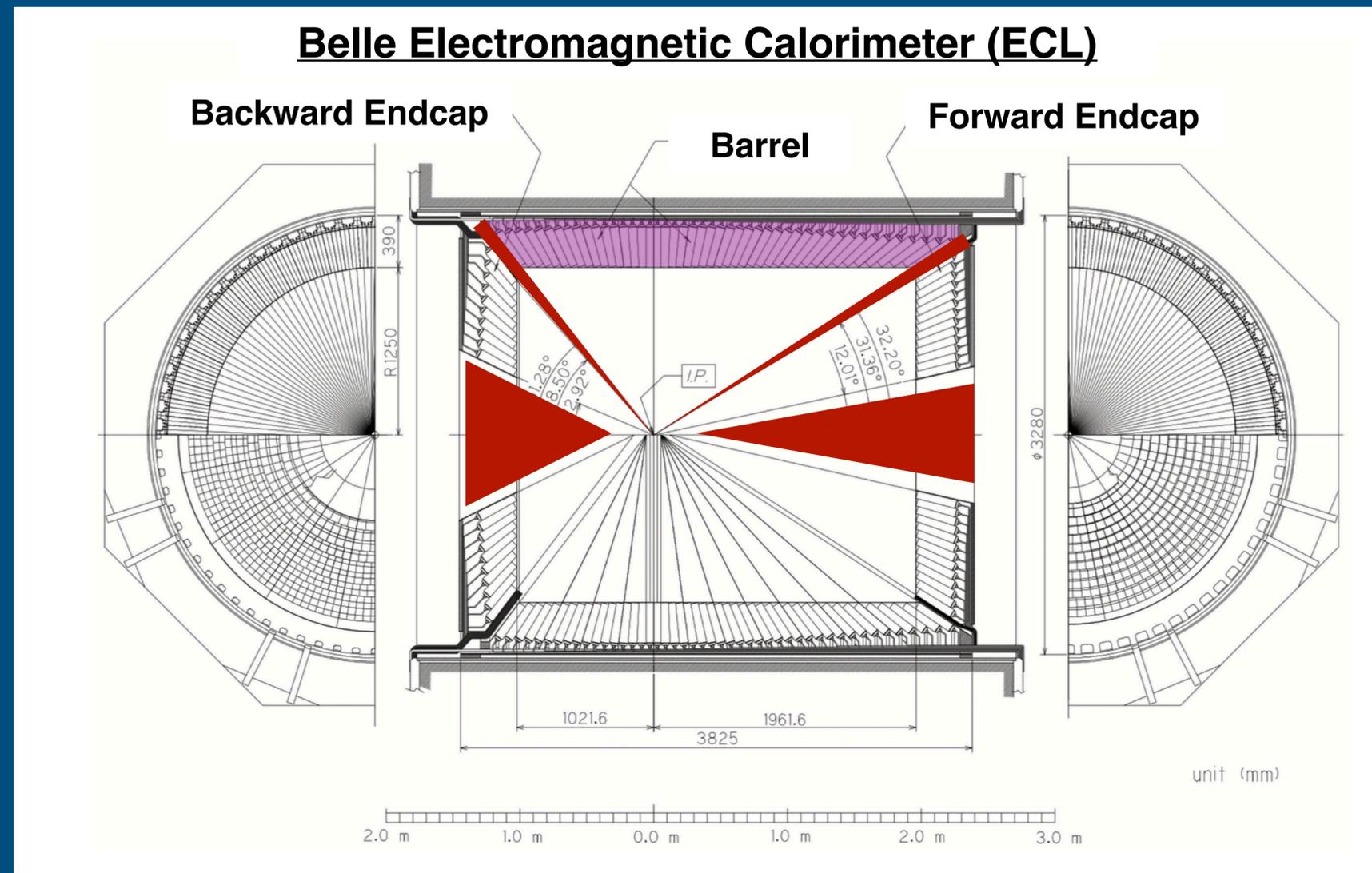
$e^+ e^- \to \text{hadrons} + \gamma$

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

36

Backgrounds

smeared events

20 fb^{-1}

Backward Endcap   Barrel   Forward Endcap

Adachi et al, Belle (18)

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

$e^+e^- \to \text{hadrons} + \gamma$

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

To simulate detector energy resolution* ~
$\sigma_E/E = 0.0225$
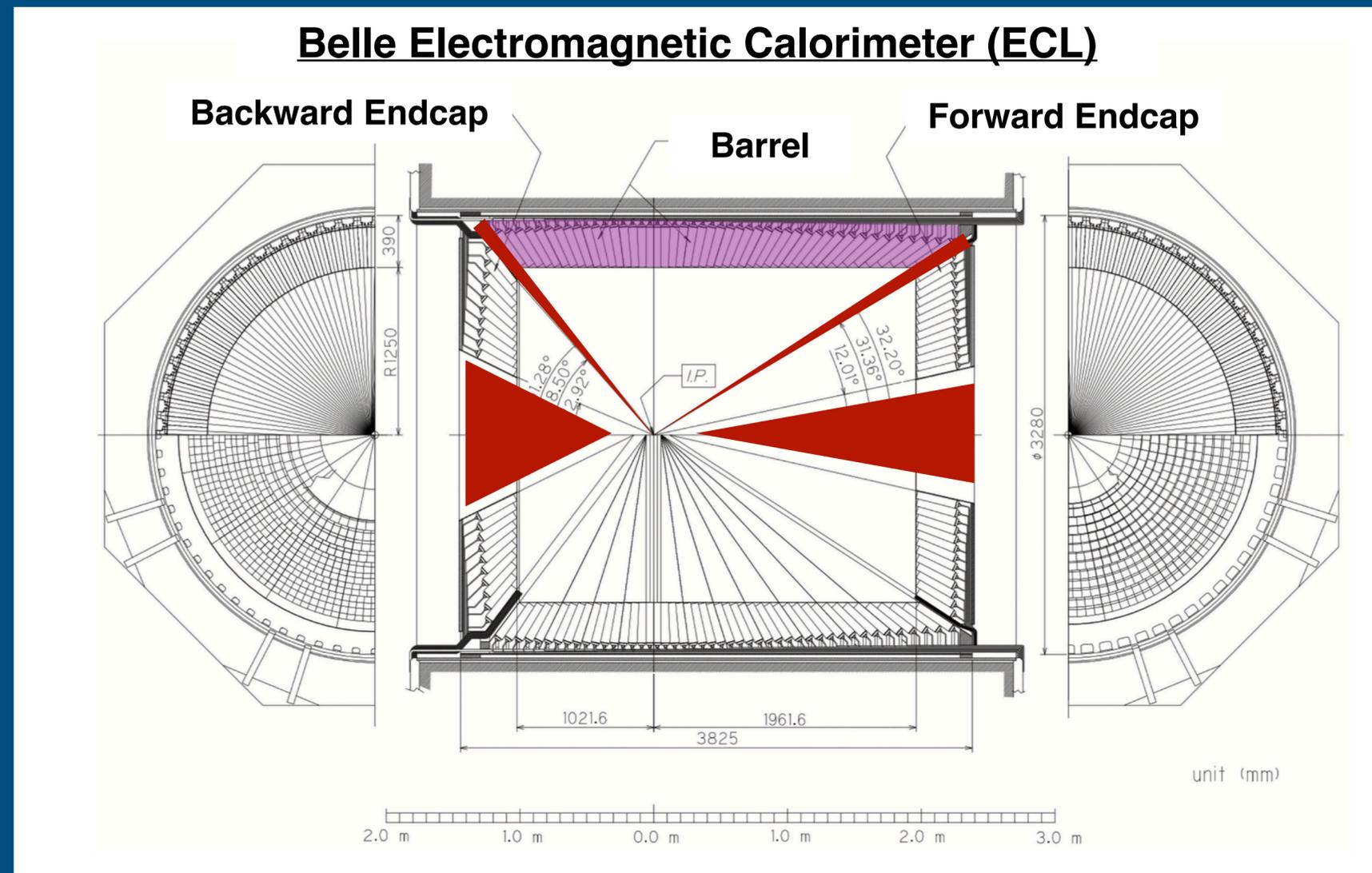
*Adachi et al, Belle, (18)

Backgrounds

20 fb^{-1} cuts example

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

$e^+ e^- \to \text{hadrons} + \gamma$

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

Belle Electromagnetic Calorimeter (ECL)

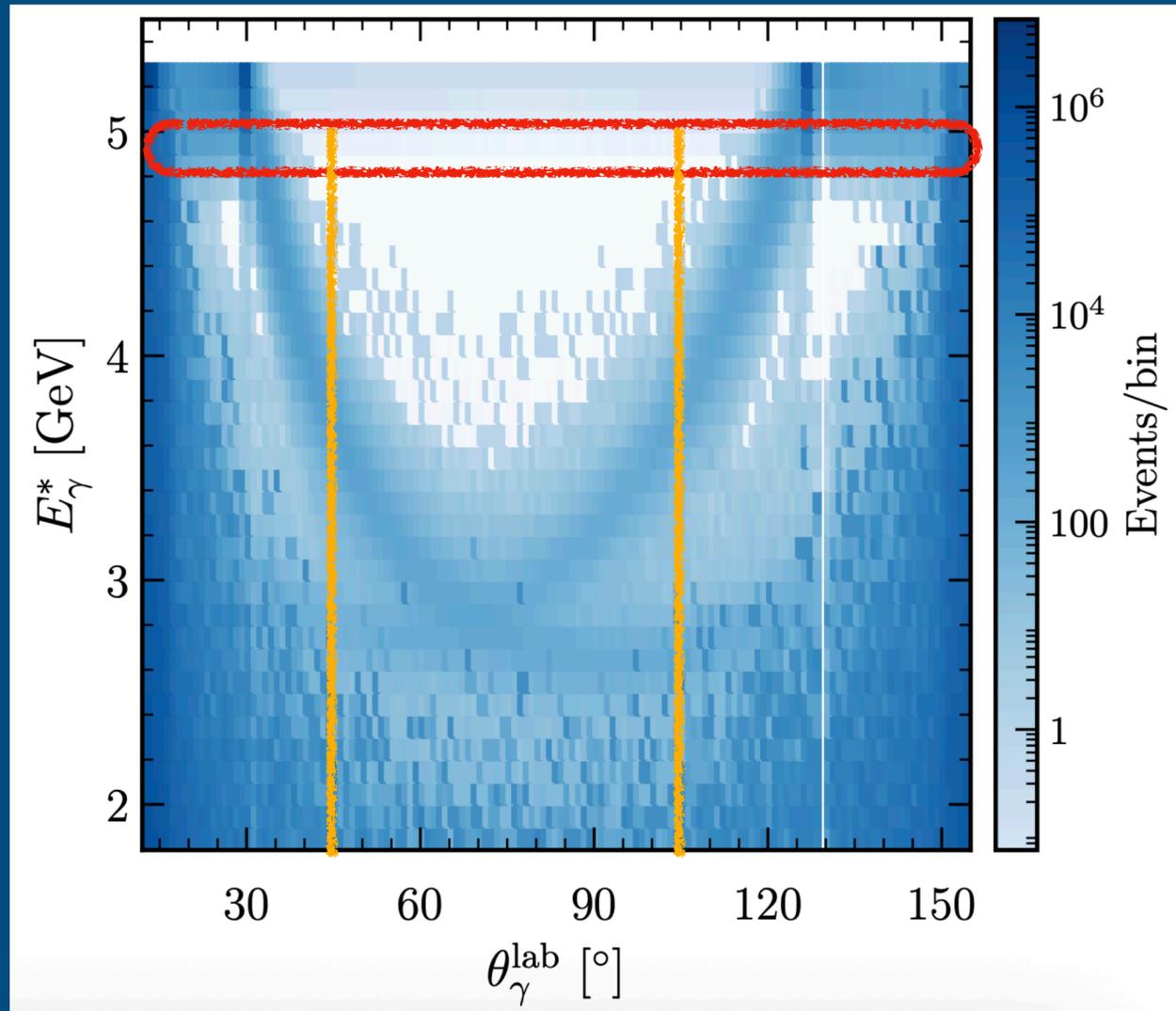**Backward Endcap**   **Barrel**   **Forward Endcap**
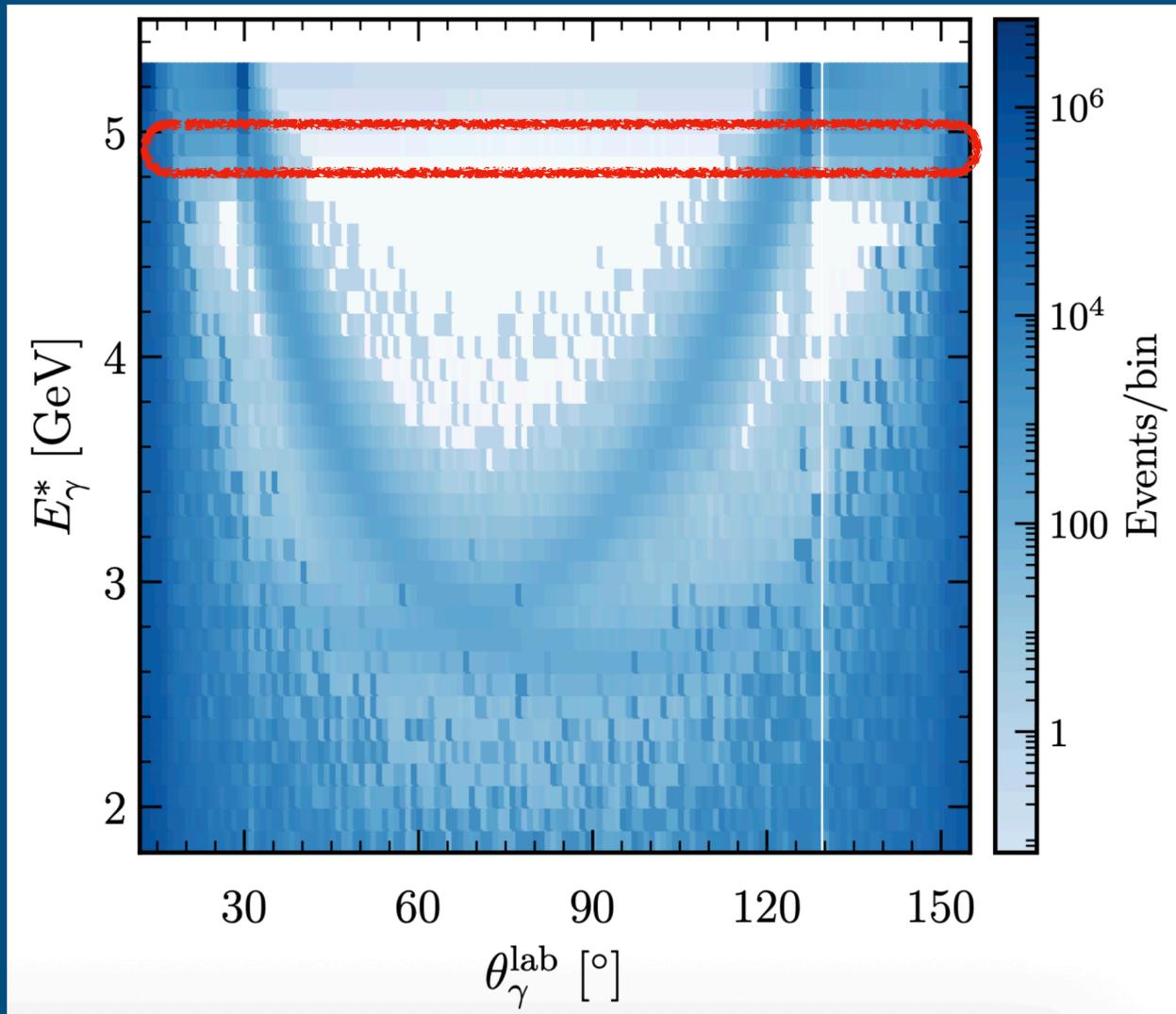
Adachi et al, Belle (18)

For a mass hypothesis, take a cut in E_γ^* that contains 95% of signal events

$$E_\gamma^* = \frac{\sqrt{s}}{2} \left(1 - \frac{m_V^2}{s} \right)$$
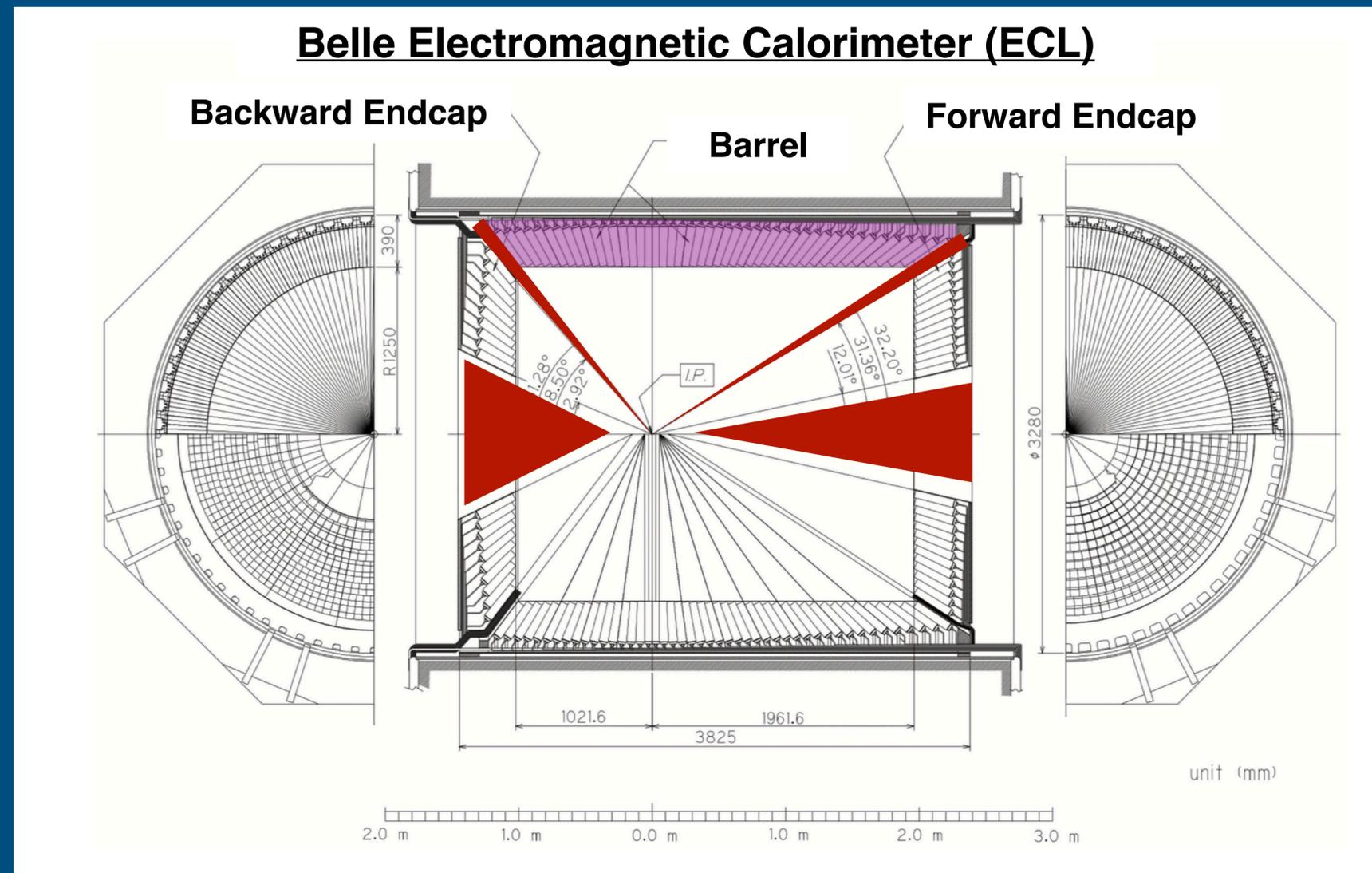
Backgrounds

20 fb^{-1}

cuts example

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

$e^+e^- \to \text{hadrons} + \gamma$

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

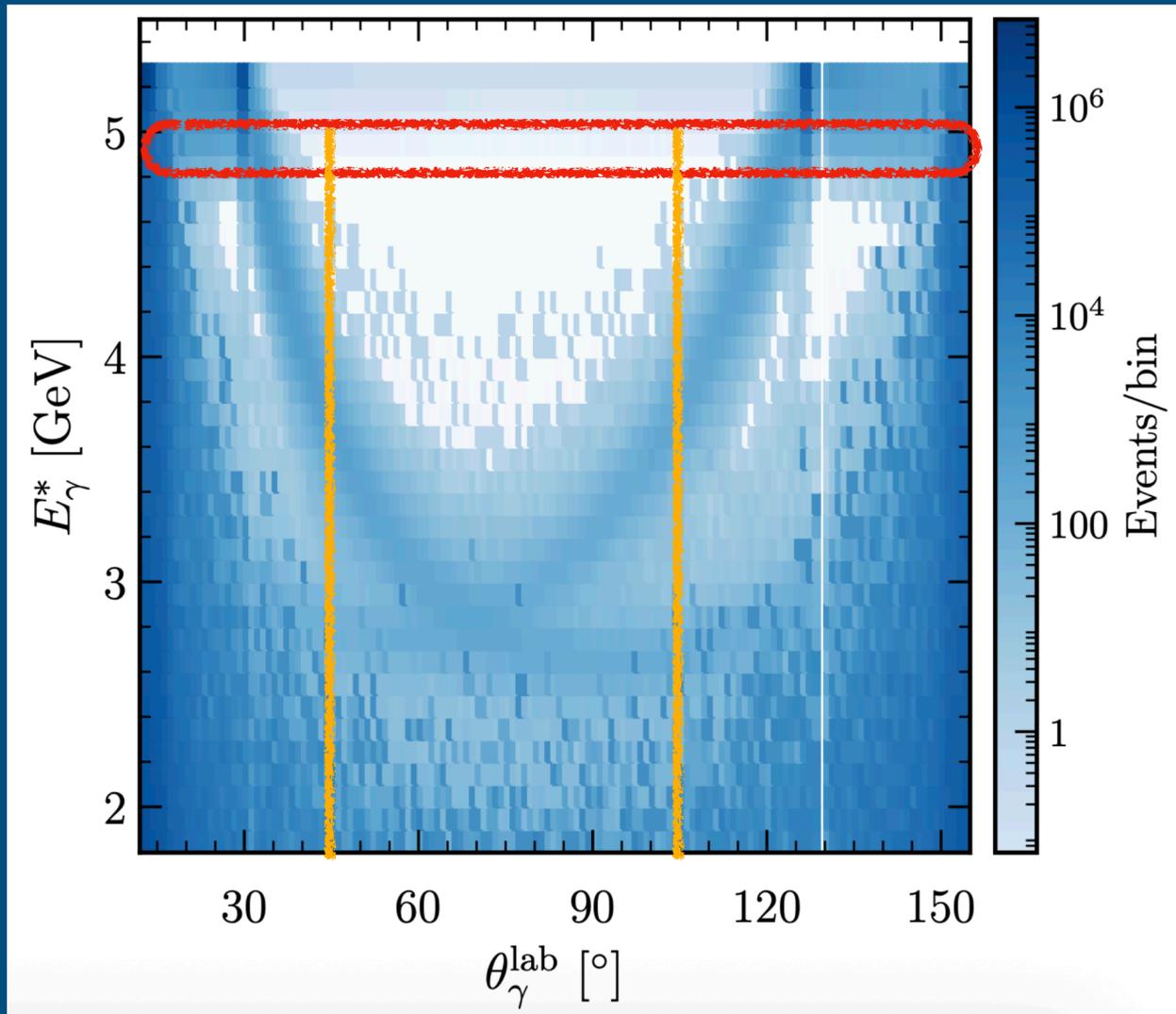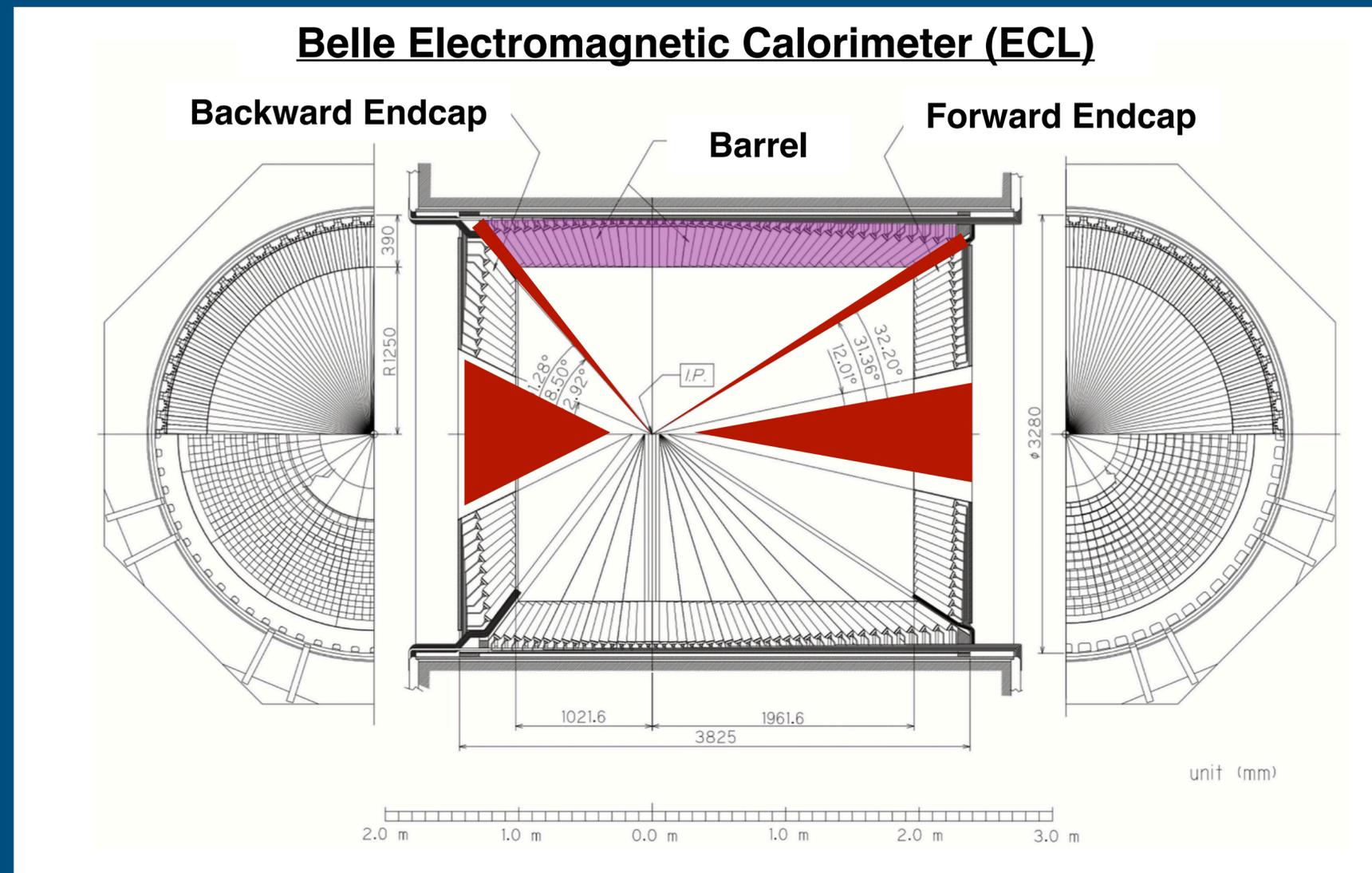## Belle Electromagnetic Calorimeter (ECL)

Backward Endcap

Barrel

Forward Endcap

Adachi et al, Belle (18)

taking a cut in $\theta_\gamma^{\text{lab}}$ that maximizes*

$$z = \sqrt{2(s - b\log(1 + s/b))}$$

*Cowan et al, (11)

Backgrounds

cuts example

20 fb^{-1}

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

$e^+e^- \to \text{hadrons} + \gamma$

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

Backward Endcap Forward Endcap

Barrel

Adachi et al, Belle (18)

taking a cut in $\theta_\gamma^{\text{lab}}$ that maximizes*
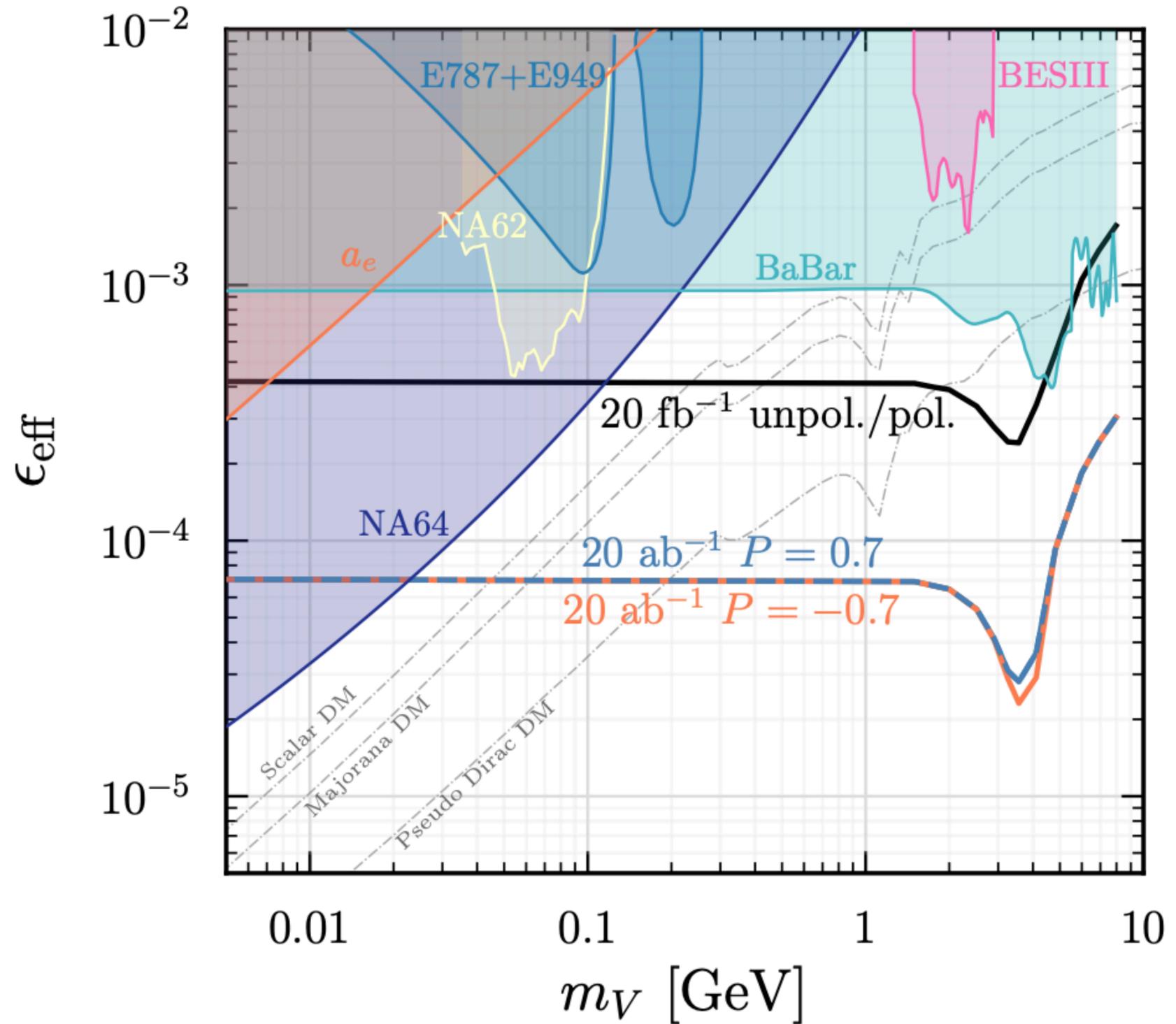
$$z = \sqrt{2(s - b\log(1 + s/b))}$$

$$s \propto \epsilon_{\text{eff}}^2 \ \bar{\sigma}_{\gamma V}(E_\gamma^*, \theta_\gamma^{\text{lab}})$$

40

*Cowan et al, (11)

Reach

$$\text{signal} \propto \epsilon_{\text{eff}}^2 \, \bar{\sigma}_{\gamma V}$$

$$\epsilon_{\text{eff}}^2 = (g_V^2 + g_A^2 - 2Pg_Vg_A)/e^2$$

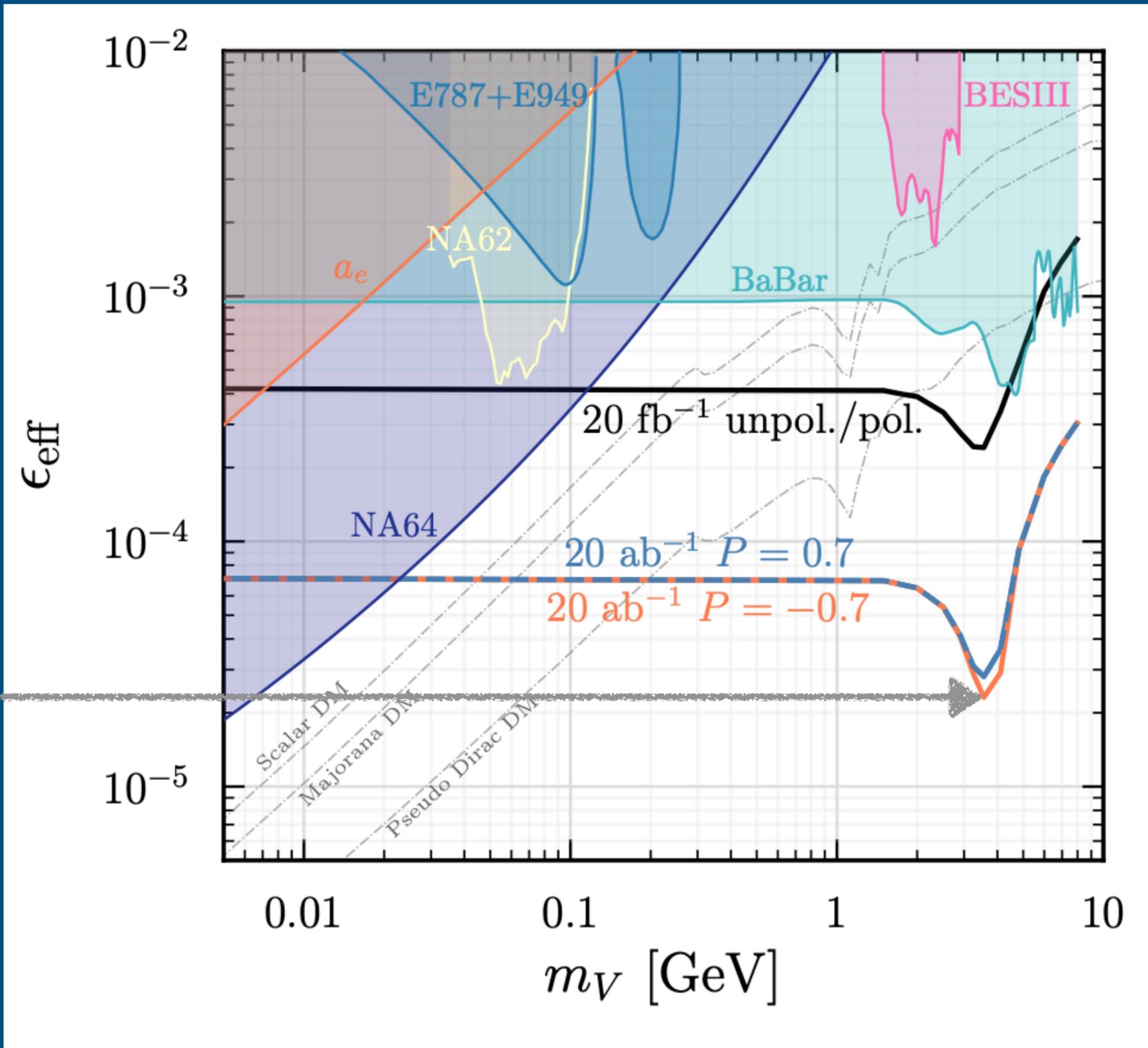$$P \equiv \frac{L - R}{L + R} = 2L - 1 = 1 - 2R$$

Reach

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neutrino background becomes significant at this luminosity

$$P \equiv \frac{L-R}{L+R} = 2L - 1 = 1 - 2R$$

Reach

$$\epsilon_{\text{eff}}^2 = (g_V^2 + g_A^2 - 2Pg_Vg_A)/e^2$$

neutrino background
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luminosity

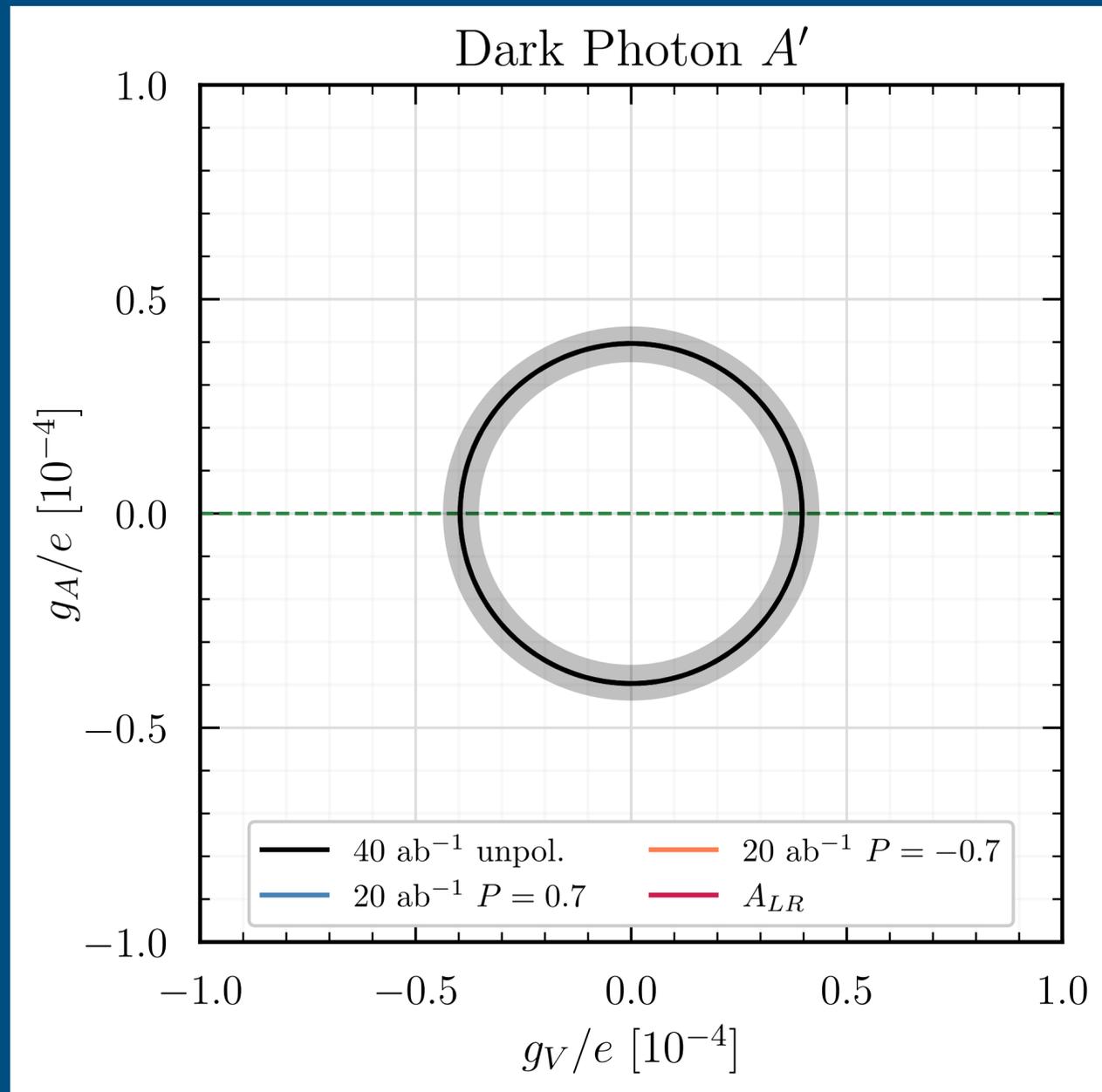$$P \equiv \frac{L - R}{L + R} = 2L - 1 = 1 - 2R$$

Great!
Can we do more?

C. H de Lima, D. McKeen, **AO**, D. Tuckler [2507.15931]

Discriminating power of polarized beams

For a 5σ discovery, with $m_V \simeq 3.7$ GeV

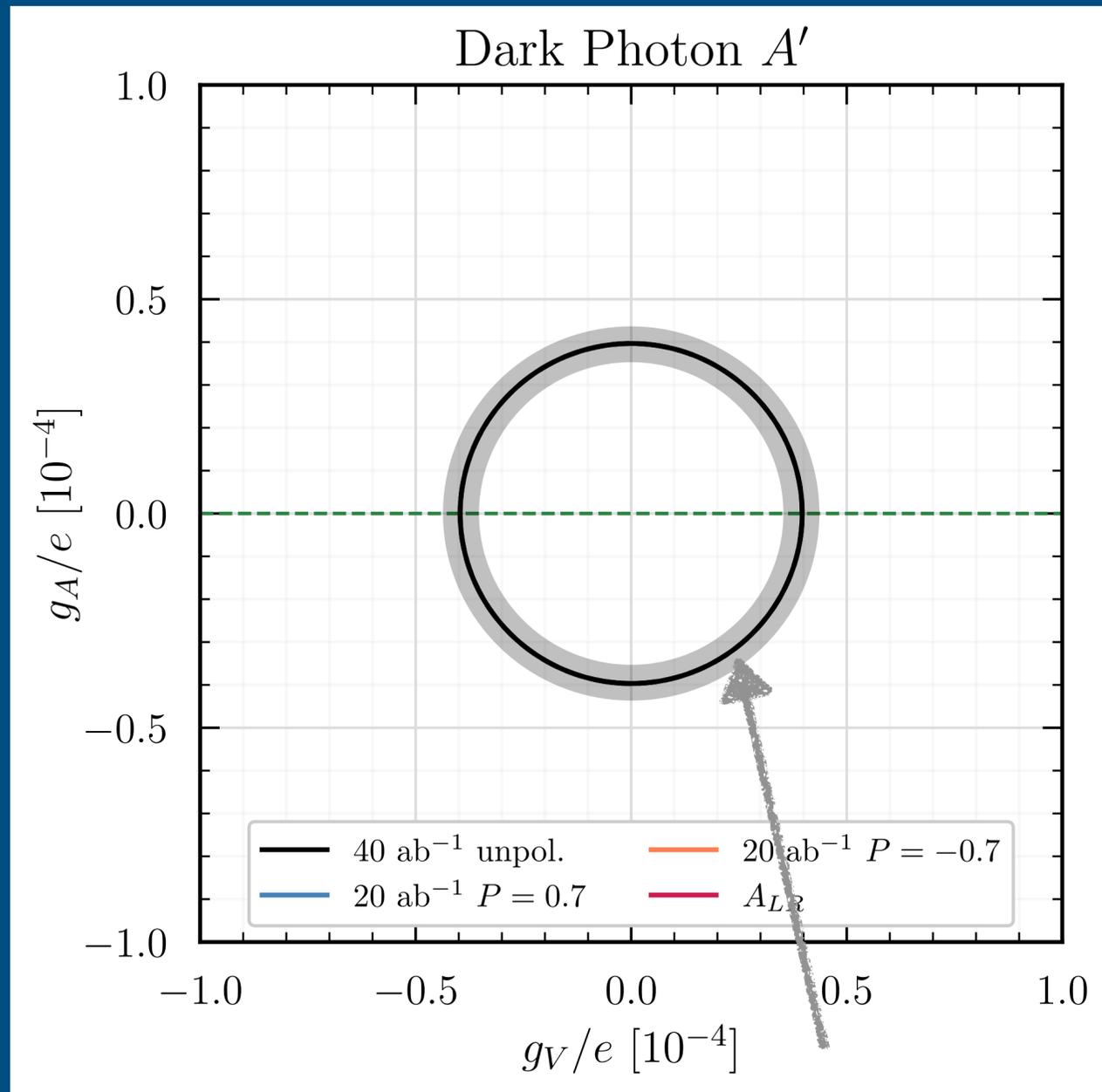$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3} \left(\frac{m_V}{5 \text{ GeV}} \right)^2 g_V$$

Dark Photon A'

Legend:
- 40 ab^{-1} unpol.
- 20 ab^{-1} $P = 0.7$
- 20 ab^{-1} $P = -0.7$
- A_{LR}

x-axis: g_V/e $[10^{-4}]$
y-axis: g_A/e $[10^{-4}]$

$$P \equiv \frac{L - R}{L + R} = 2L - 1 = 1 - 2R$$

Discriminating power of polarized beams

For a 5σ discovery, with $m_V \simeq 3.7$ GeV

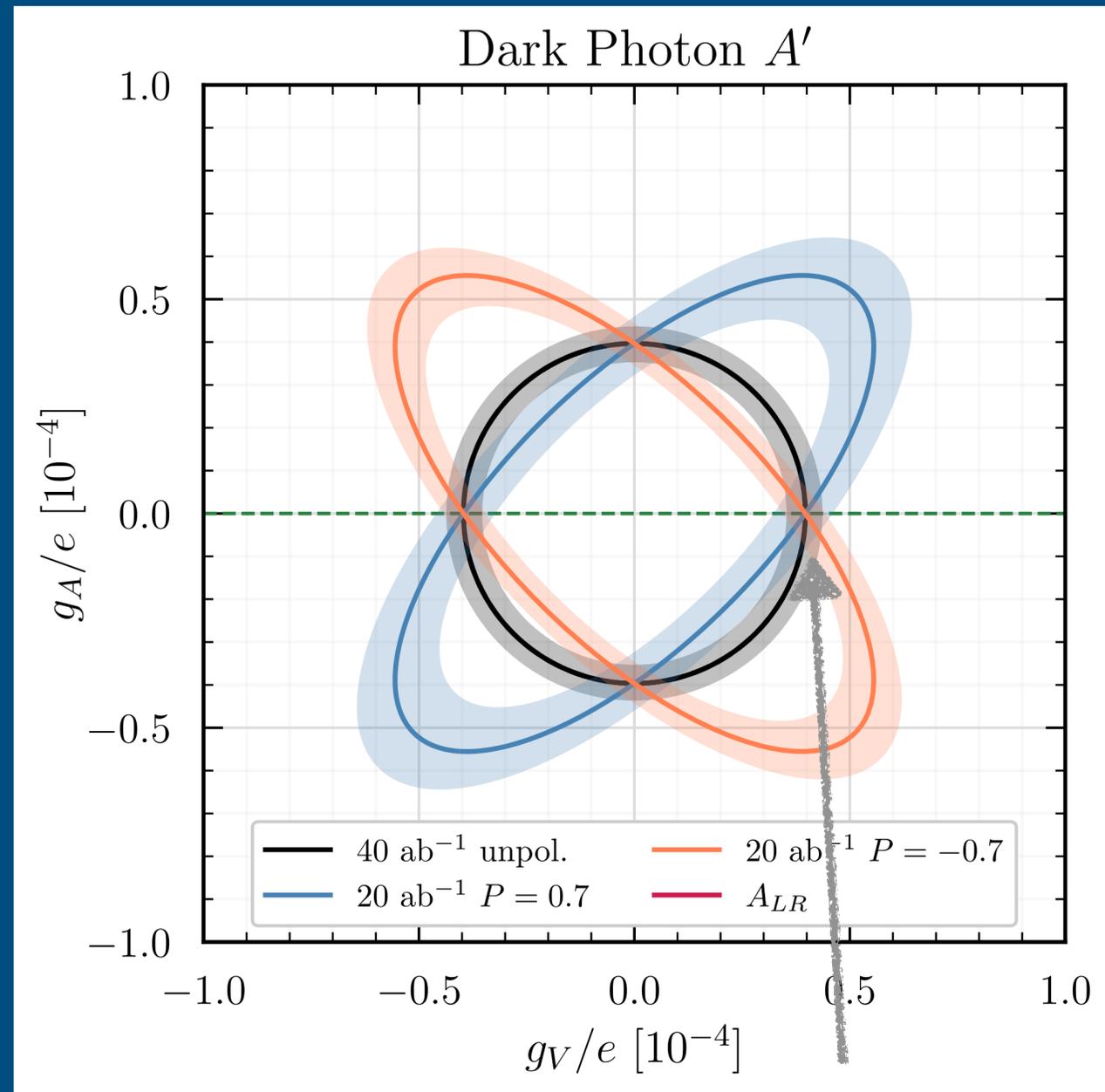$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3} \left(\frac{m_V}{5 \text{ GeV}} \right)^2 g_V$$

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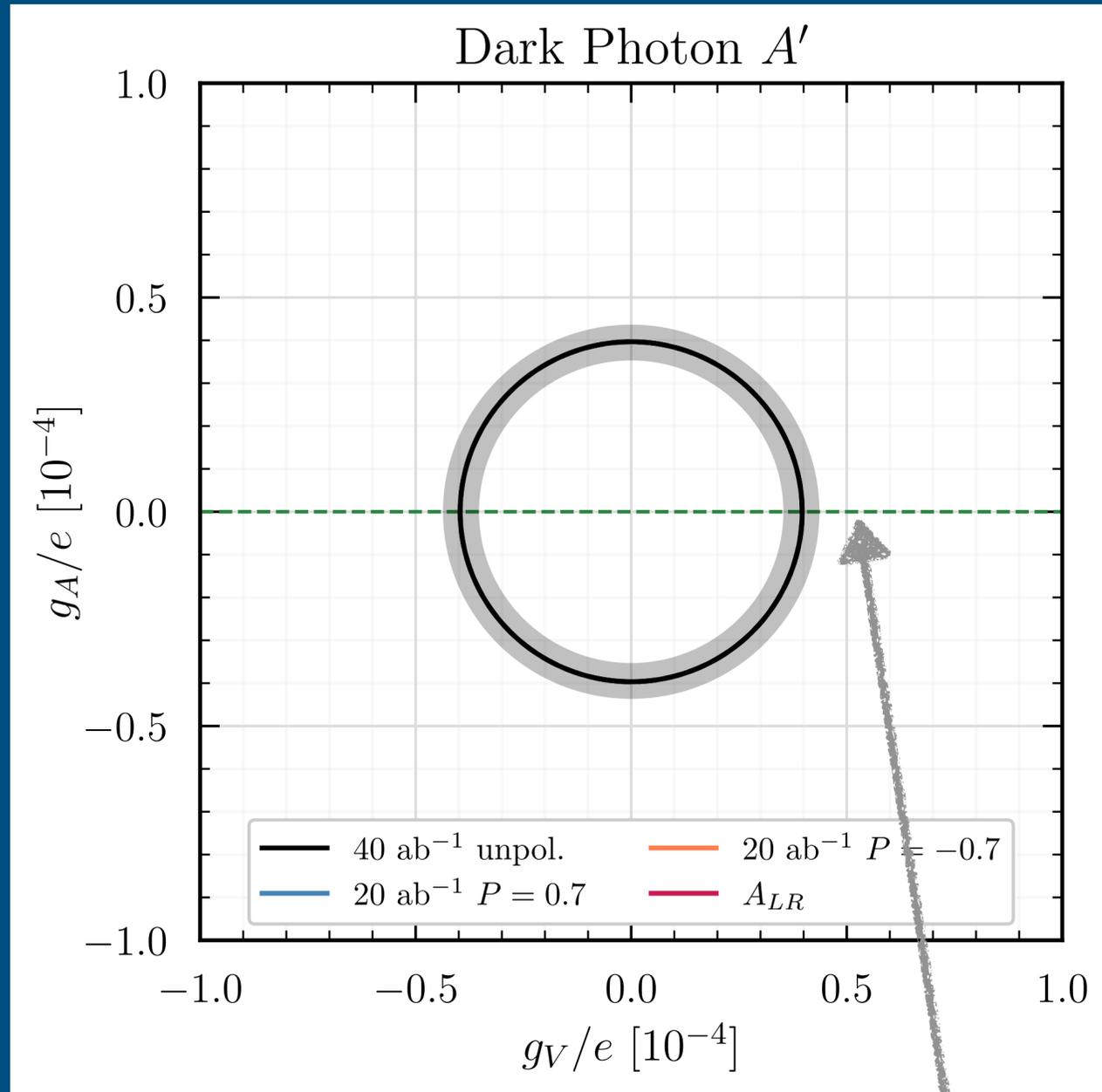
the assumed underlying model

$$P \equiv \frac{L - R}{L + R} = 2L - 1 = 1 - 2R$$

Discriminating power of polarized beams
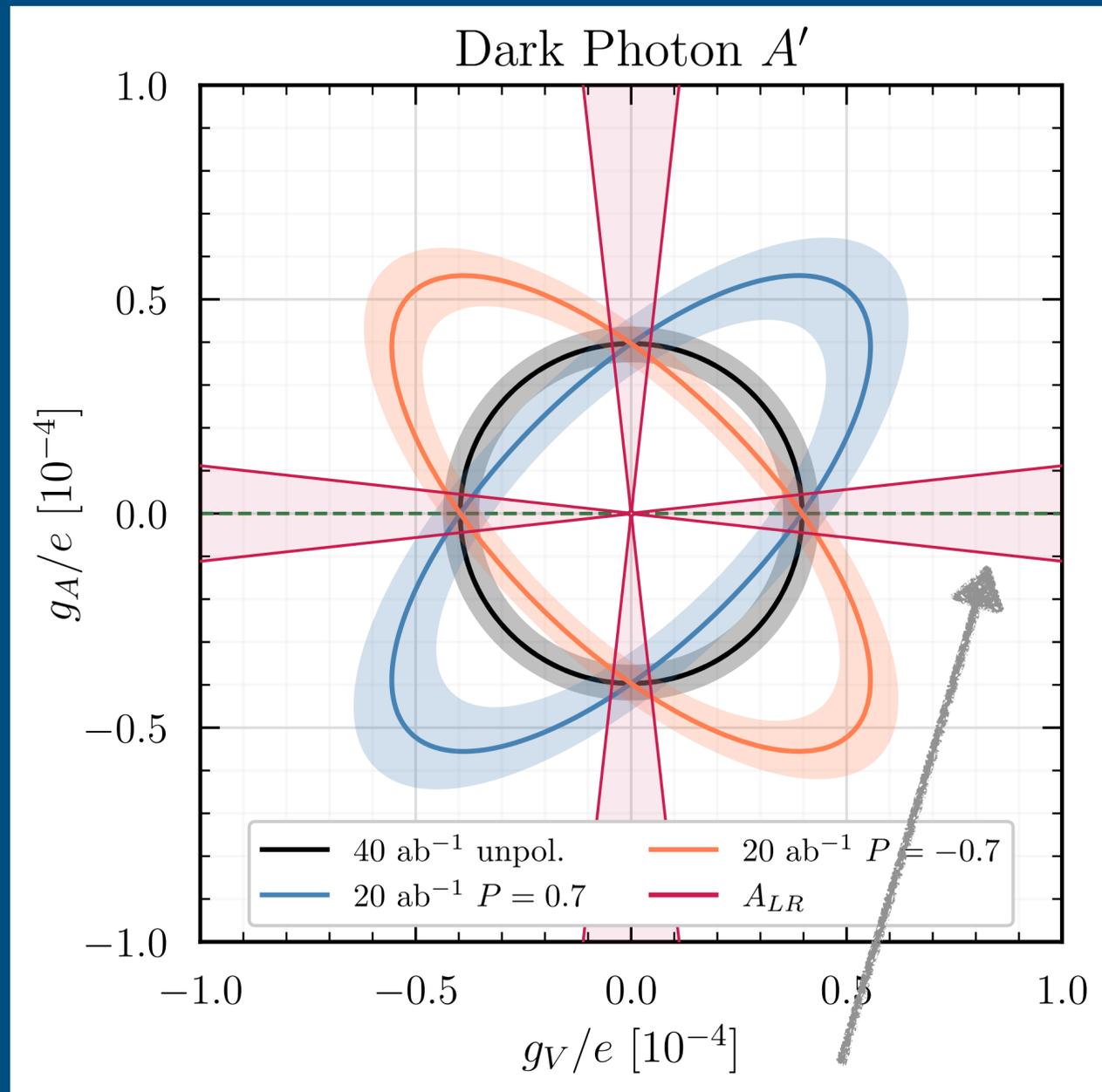
For a 5σ discovery, with $m_V \simeq 3.7$ GeV

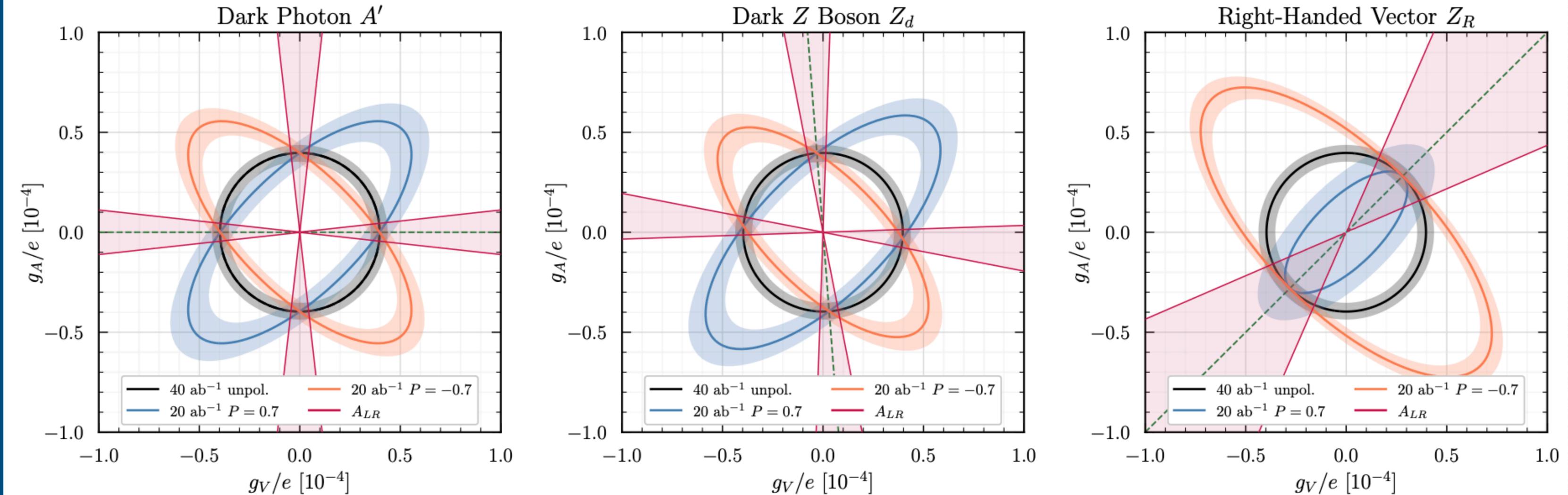$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3}\left(\frac{m_V}{5\ \text{GeV}}\right)^2 g_V$$

Dark Photon A'

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- 20 ab^{-1} $P = 0.7$
- 20 ab^{-1} $P = -0.7$
- A_{LR}

x-axis: $g_V/e\ [10^{-4}]$
y-axis: $g_A/e\ [10^{-4}]$

shaded areas are the preferred $\pm 1\sigma$ regions

$$P \equiv \frac{L-R}{L+R} = 2L - 1 = 1 - 2R$$

Discriminating power of polarized beams

For a 5σ discovery, with $m_V \simeq 3.7$ GeV

$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3} \left(\frac{m_V}{5 \text{ GeV}} \right)^2 g_V$$

Dark Photon A'

Legend:
- 40 ab^{-1} unpol.
- 20 ab^{-1} $P = 0.7$
- 20 ab^{-1} $P = -0.7$
- A_{LR}

Axes: g_A/e [10^{-4}] vs g_V/e [10^{-4}]

regions of intersection overlap
with the assumed model

$$P \equiv \frac{L-R}{L+R} = 2L - 1 = 1 - 2R$$

Discriminating power of polarized beams

For a 5σ discovery, with $m_V \simeq 3.7$ GeV

Dark Photon A'

$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3} \left(\frac{m_V}{5 \text{ GeV}} \right)^2 g_V$$

Reduces systematics.

Does not fix absolute scale

$$P \equiv \frac{L-R}{L+R} = 2L - 1 = 1 - 2R$$

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\frac{2g_V g_A}{g_V^2 + g_A^2} P$$

Discriminating power of polarized beams

For a 5σ discovery, with $m_V \simeq 3.7$ GeV

$$g_V \simeq -\epsilon e, \quad g_A \simeq 10^{-3}\left(\frac{m_V}{5 \text{ GeV}}\right)^2 g_V$$

$$g_V \simeq -0.05\epsilon_Z e, \quad g_A \simeq -13g_V$$

$$g_A = g_V$$

Discriminating power of polarized beams
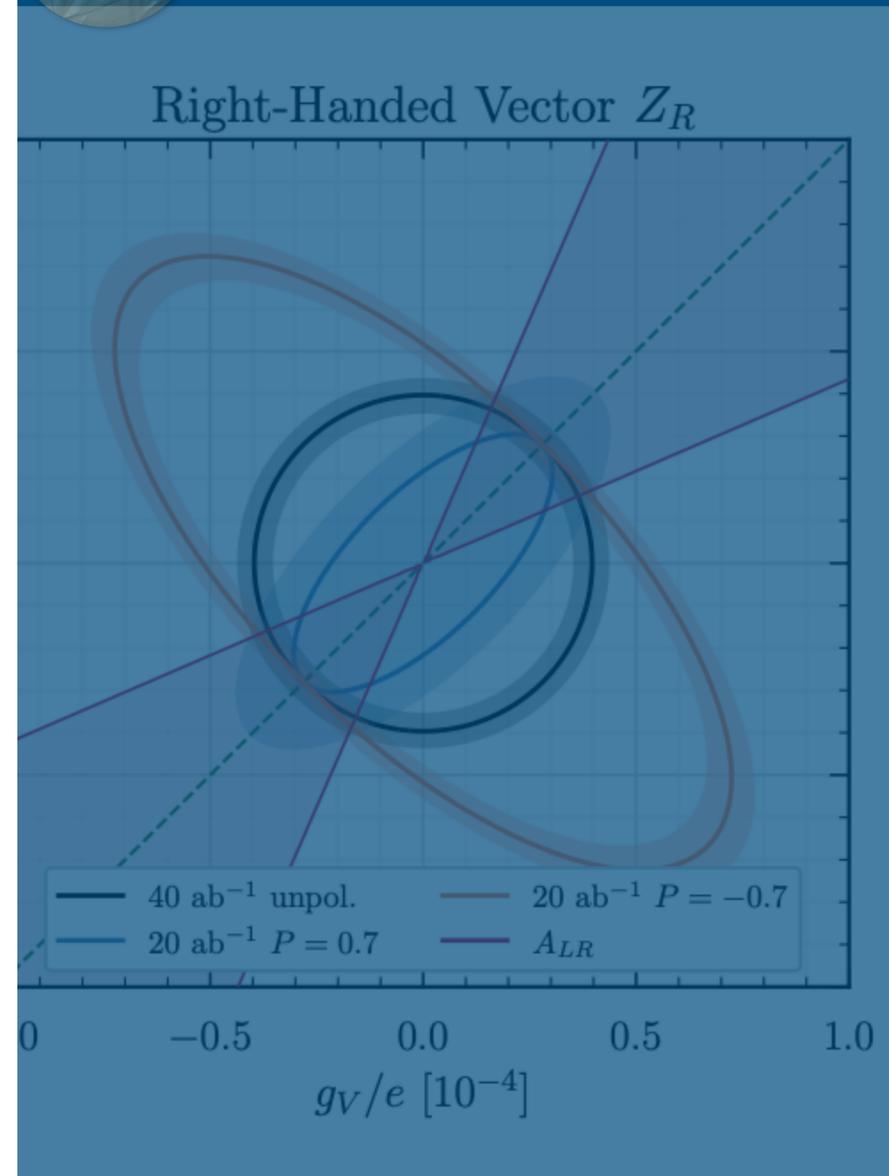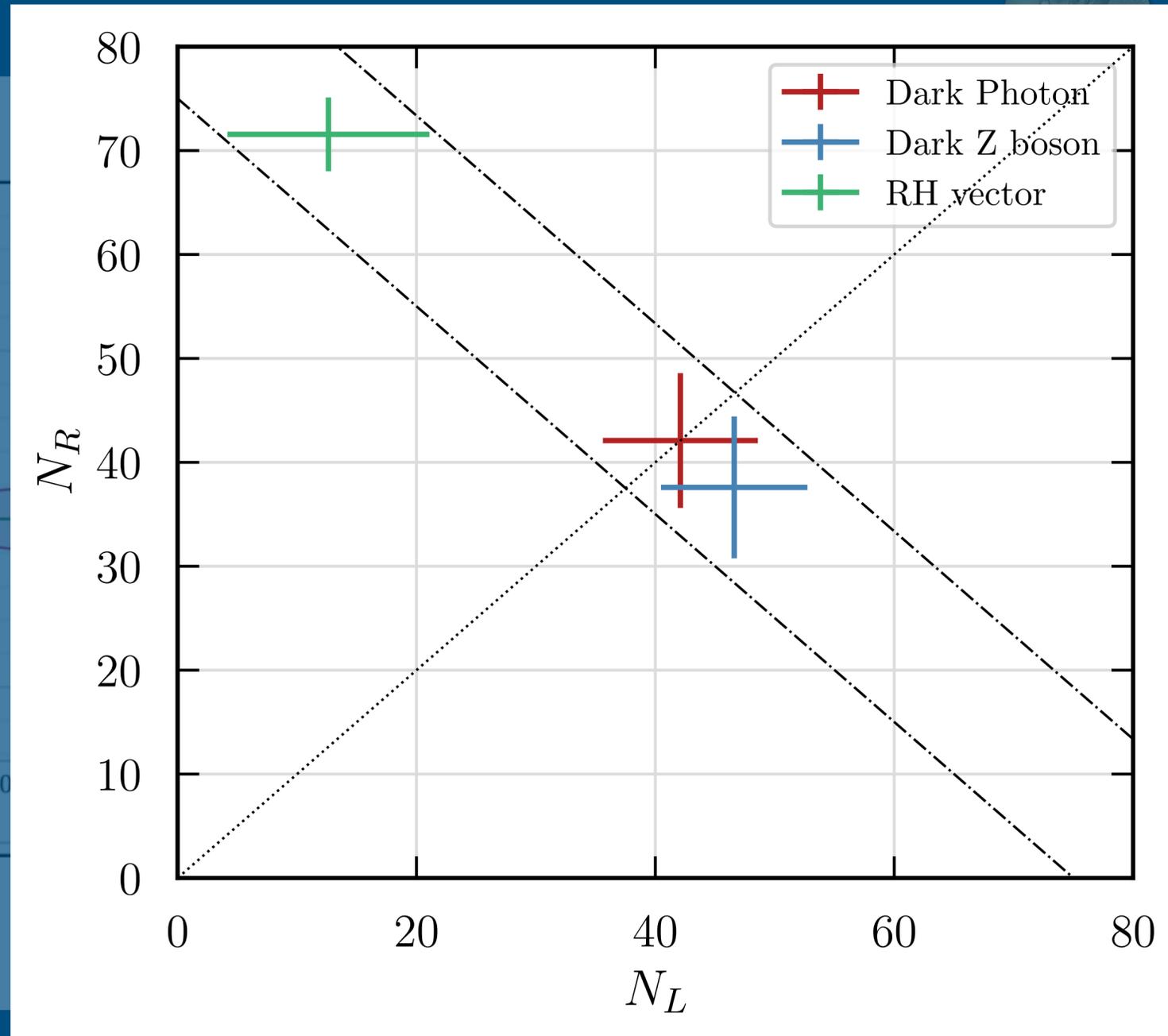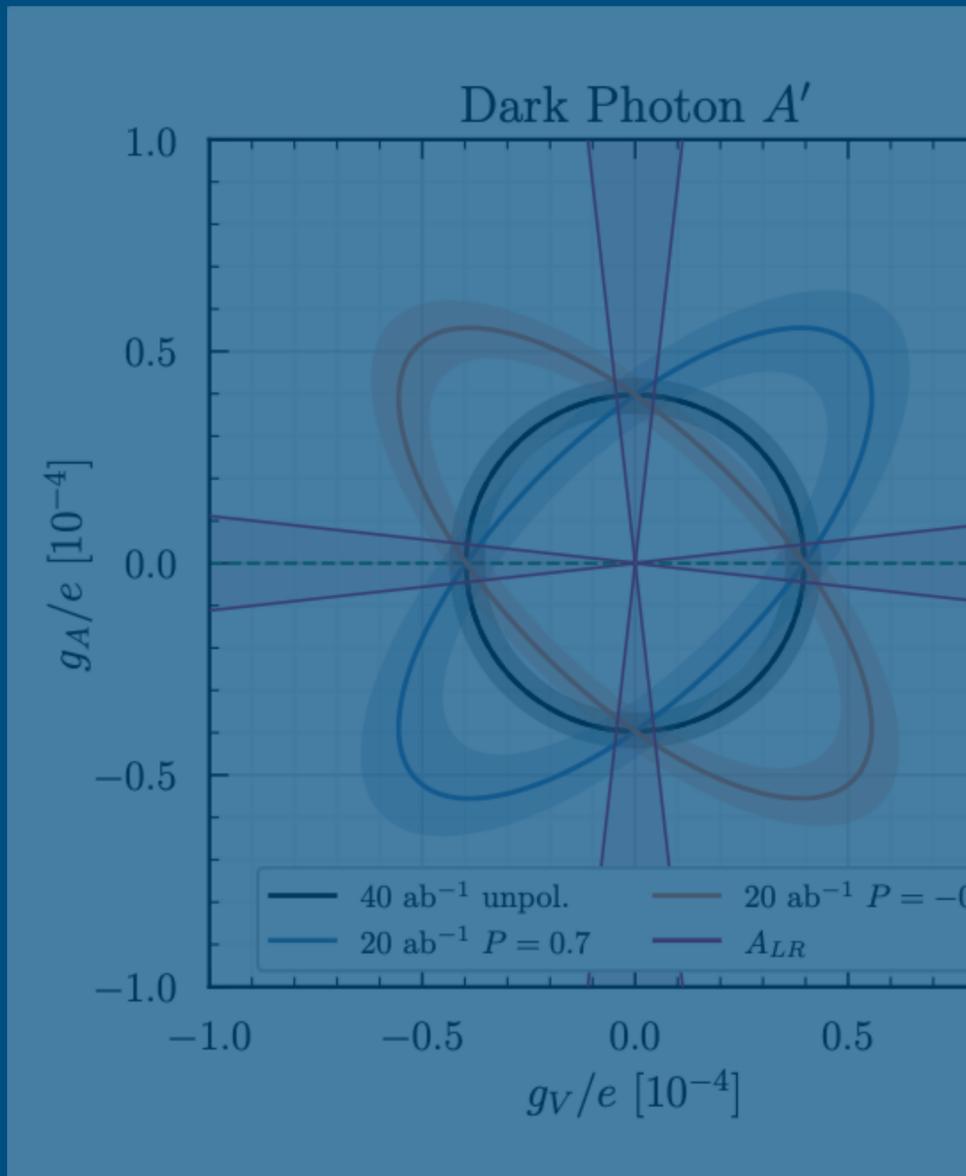
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$$g_A = g_V$$

Summary

Summary and outlook

- The mono-photon process $e^+e^- \rightarrow \gamma X$ offers good prospects for detecting dark vectors at (Chiral) Belle.

- Unpolarized Belle II will provide world leading sensitivity in its search of dark sectors.

- Polarizing the beams will open a new window into the nature of dark sector interactions.

- The biggest backgrounds are currently from detector geometry and reconstruction inefficiencies.

- Neutrino background is polarization dependent. **(Chiral) Belle could enable the measurement of the Weinberg angle in the neutrino sector!** Neutrino Floor of Belle, similar to DM direct detection experiments. Ongoing work.

Backup slides

DM detection
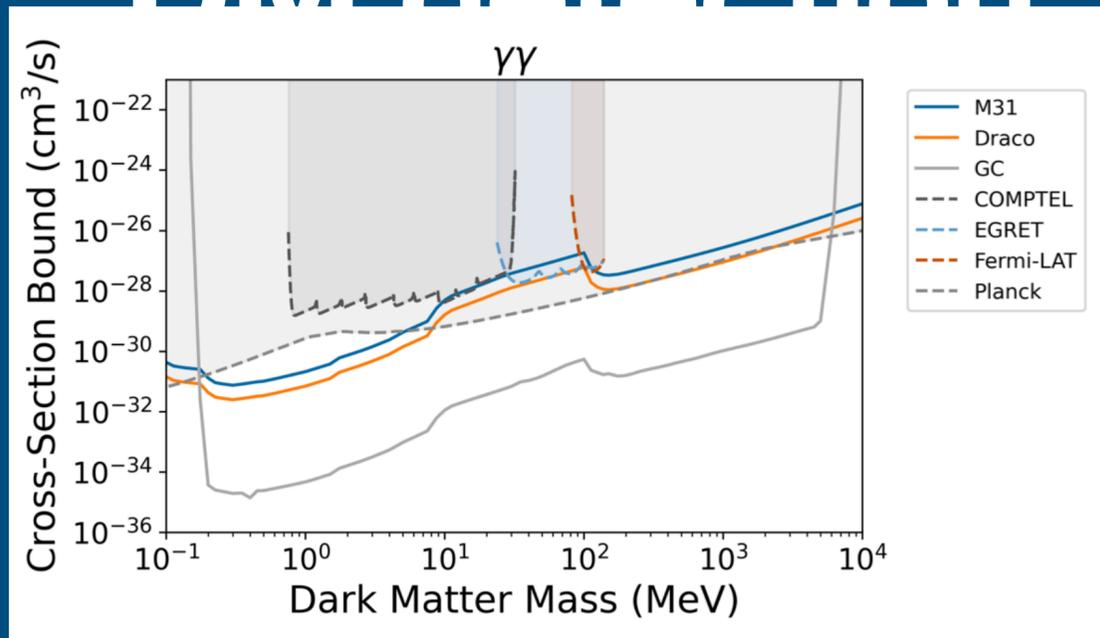
(on Earth)

SM

N, e

Direct
Detection
(on Earth)

N, e

SM
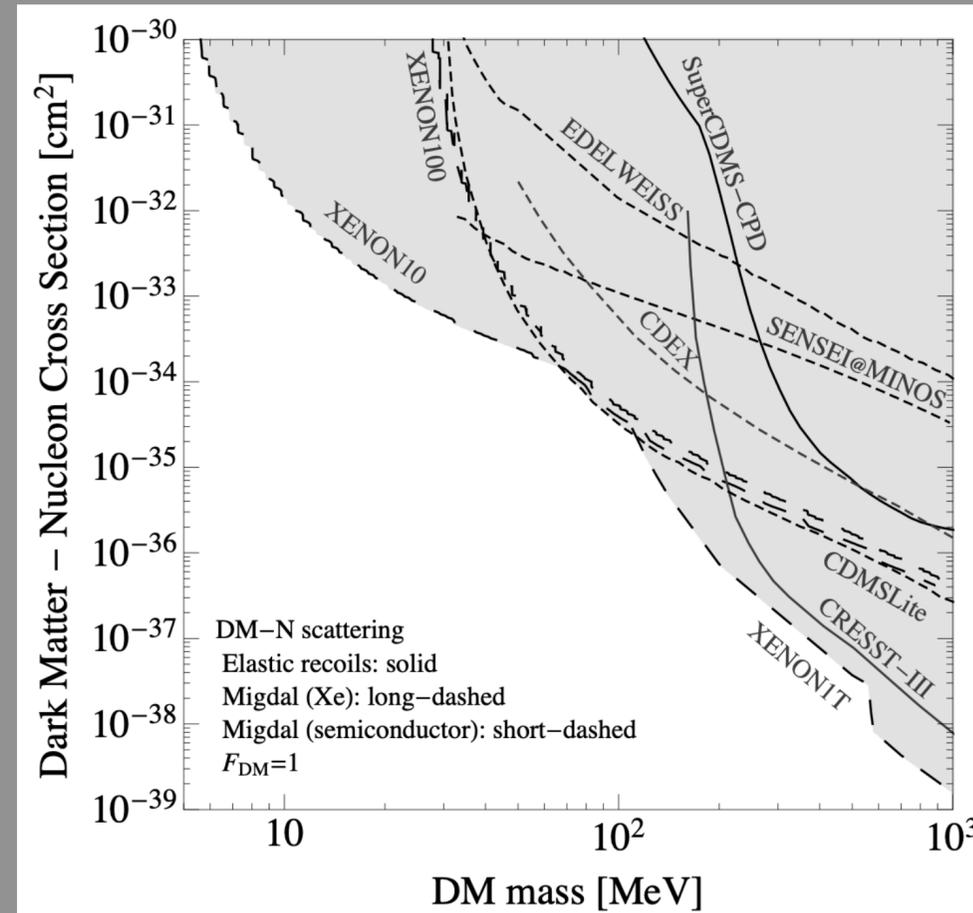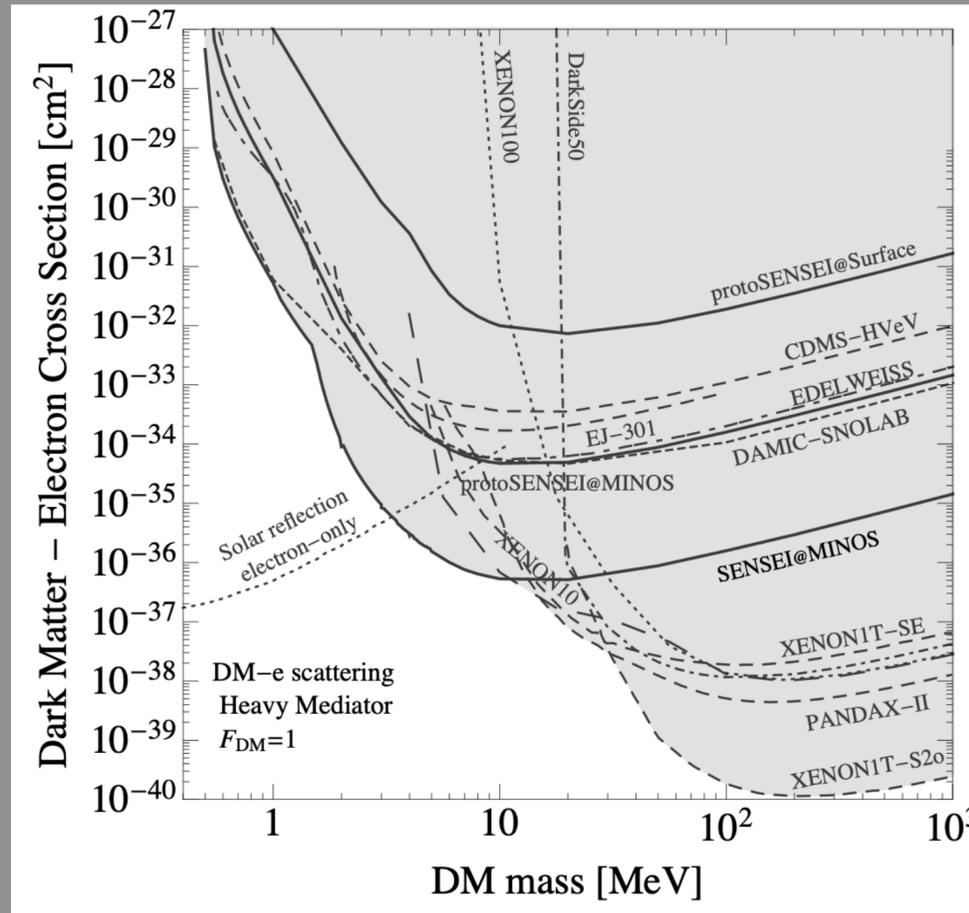
Essig, et al, Snowmass (2021)

Outgoing
Particle

LUX-LZ

54

DM detection

Direct
Detection

γ, e^-, π^-

SM

Ind

DM detection

SM

DM

Direct
Detection

SM

DM

e^-

e^+

χ

χ

γ

DM detection

e^-

SM

invisible

DM

χ

χ
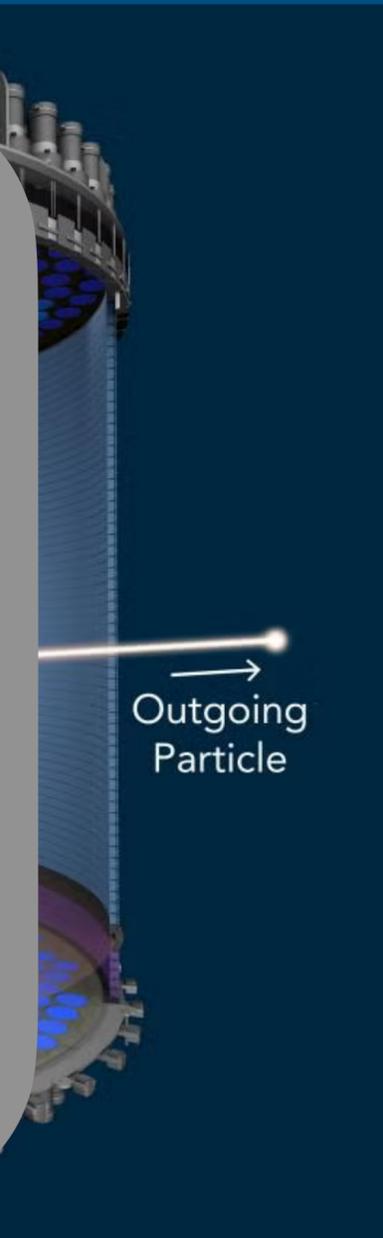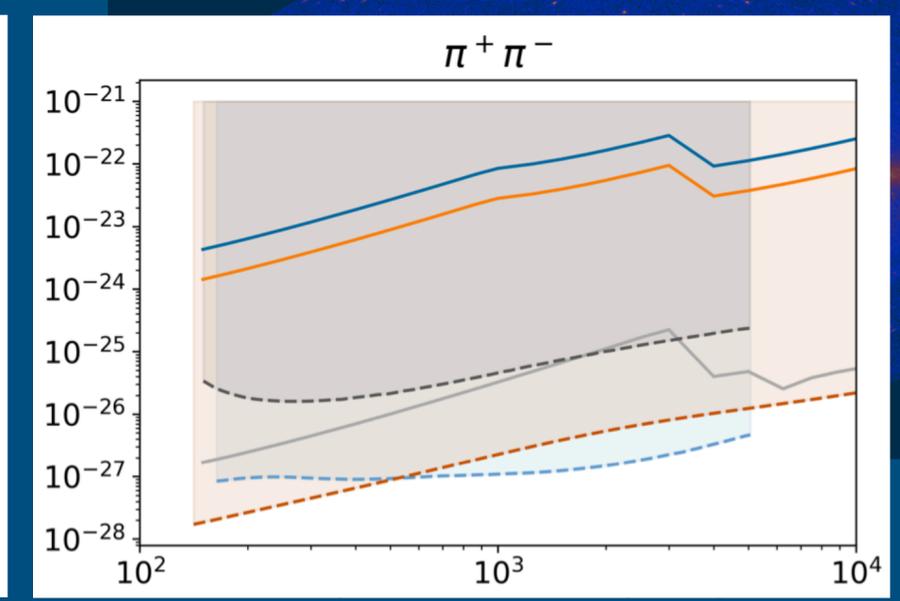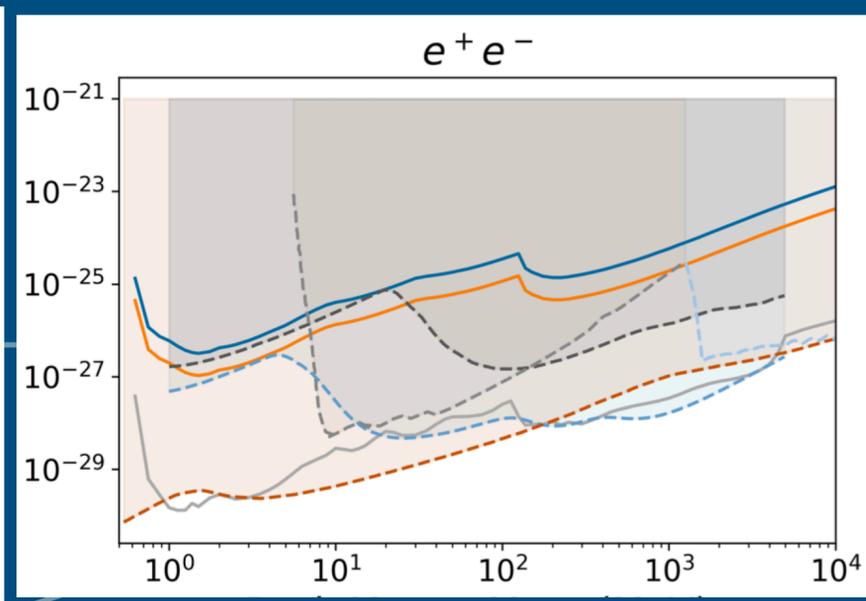
Direct Detection

SM

e^+

γ

DM

E_T^{miss} = 564 GeV

Candidate in signal region of H→χχ with two VBF jets (m_{jj}=3.6 TeV)

j_1

j_2

E_T^{miss}

PXD

SVD

DM detection

Direct Detection

invisible

e^-

χ

χ

e^+
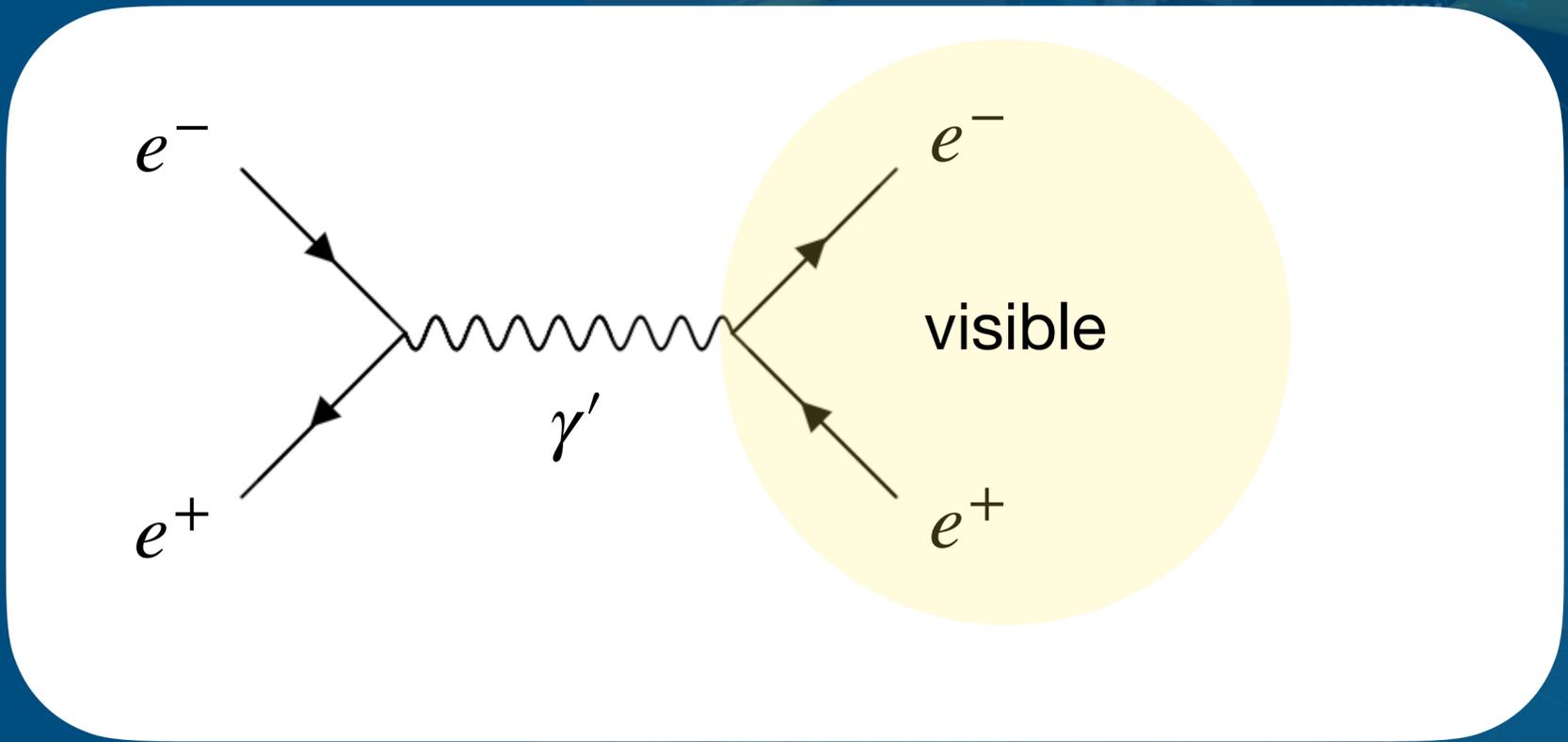
γ

visible

e^-

e^-

e^+

e^+

γ'
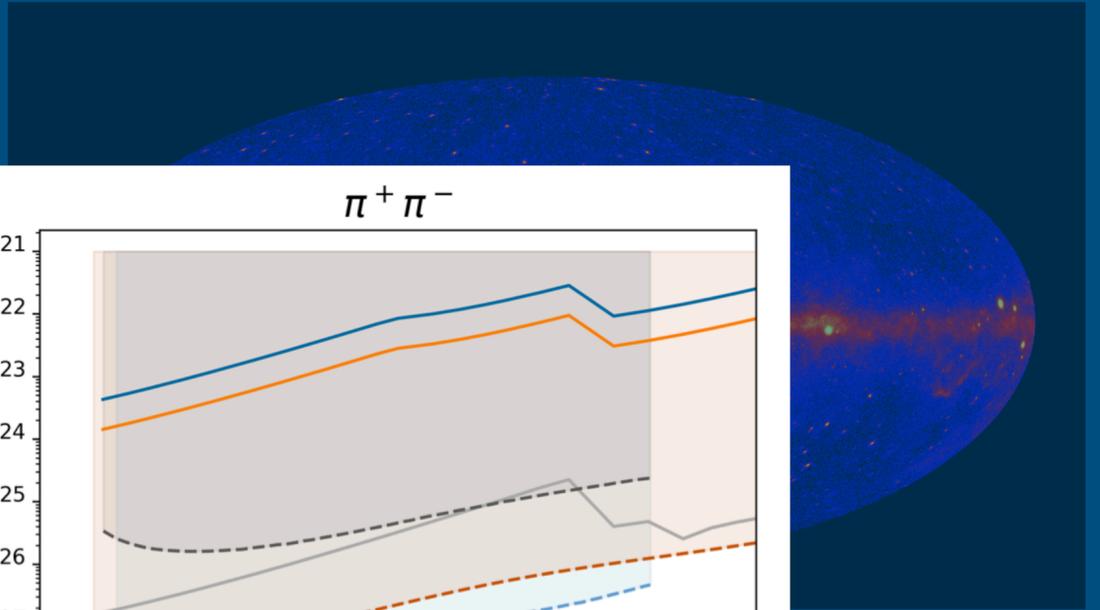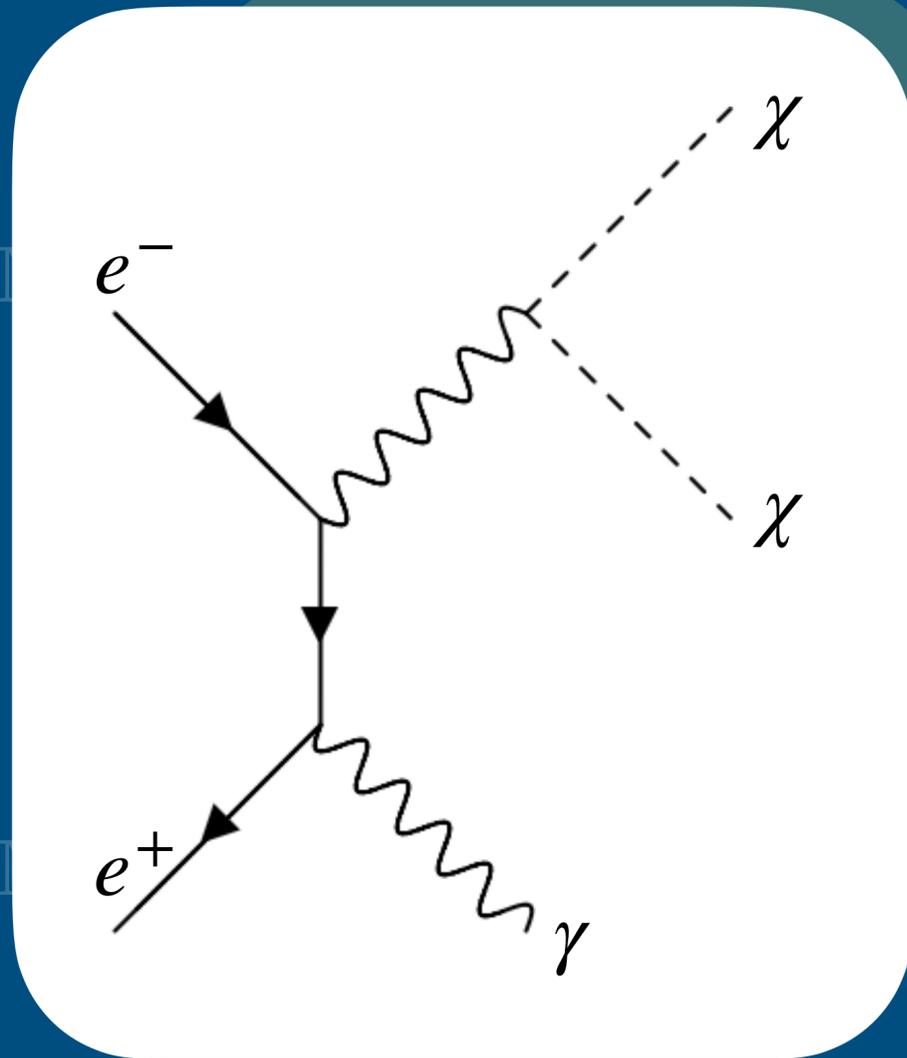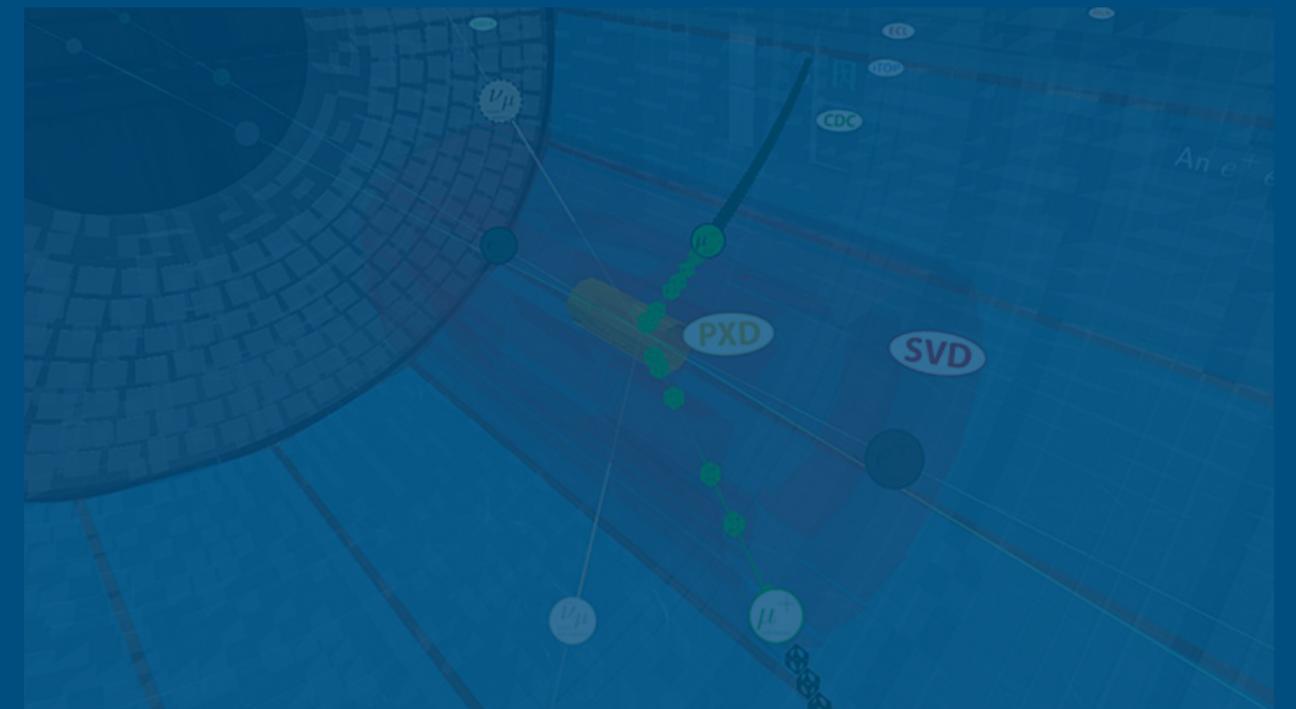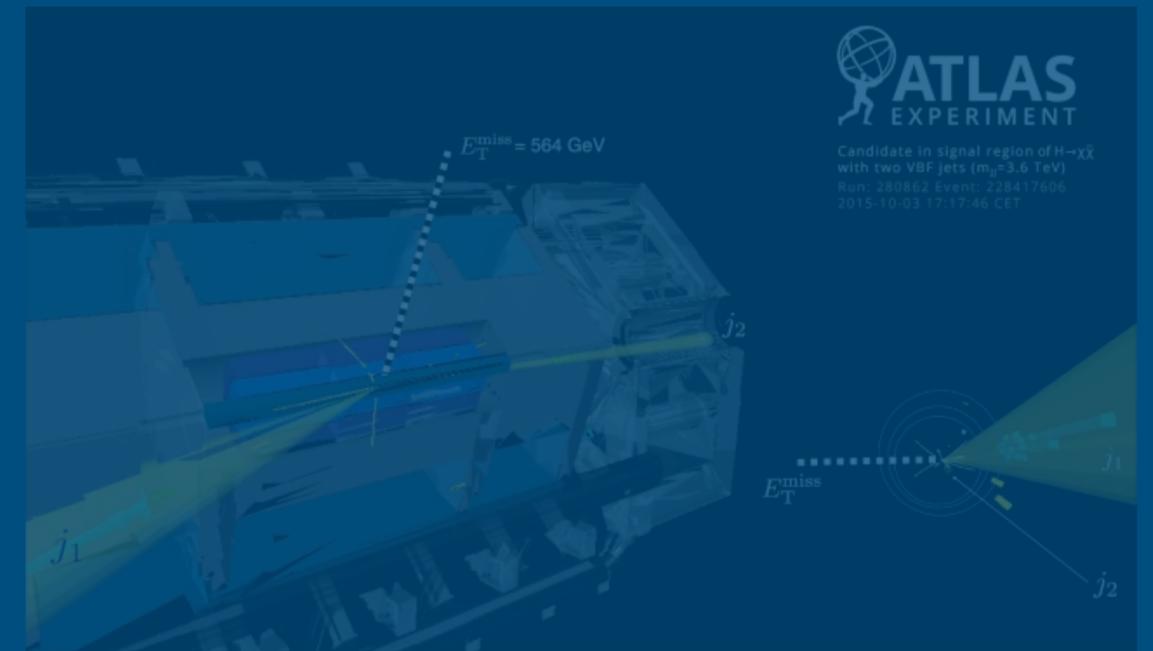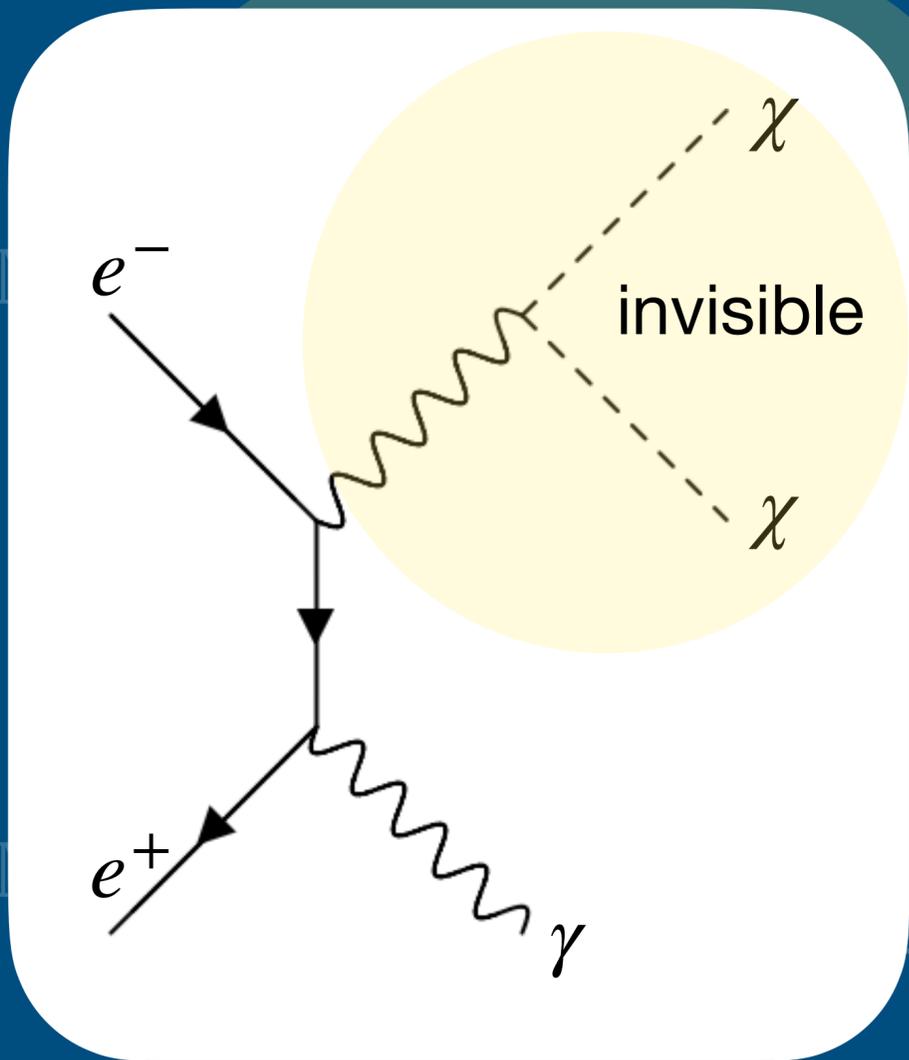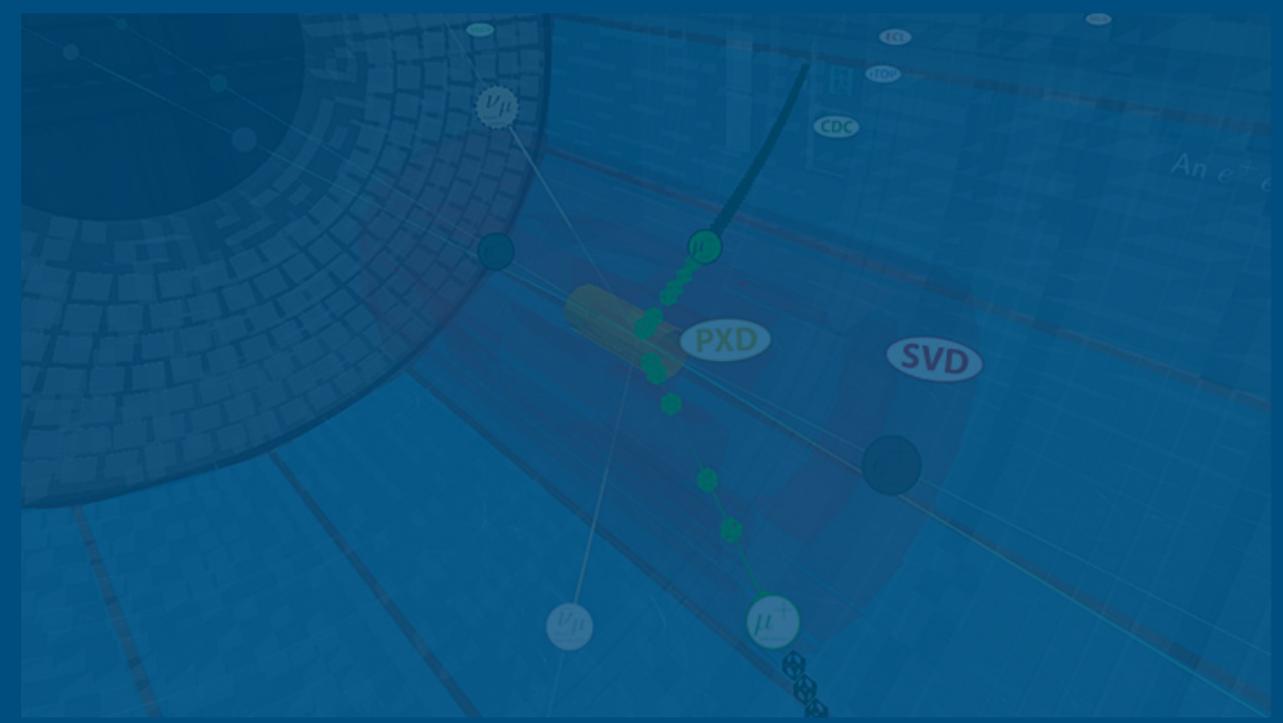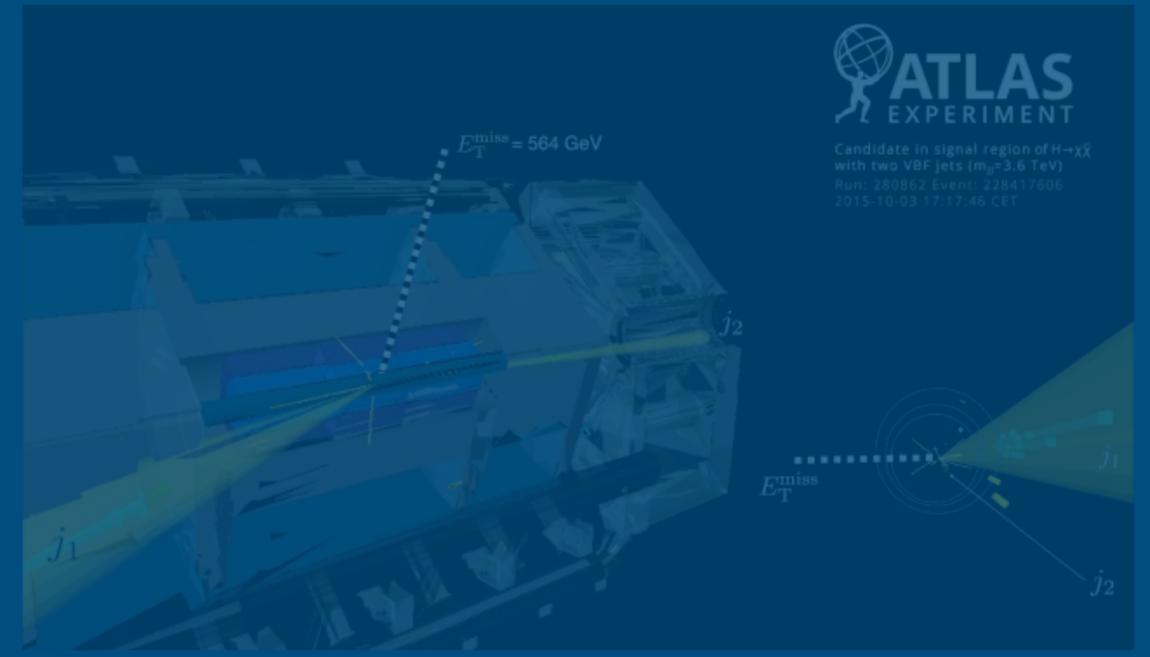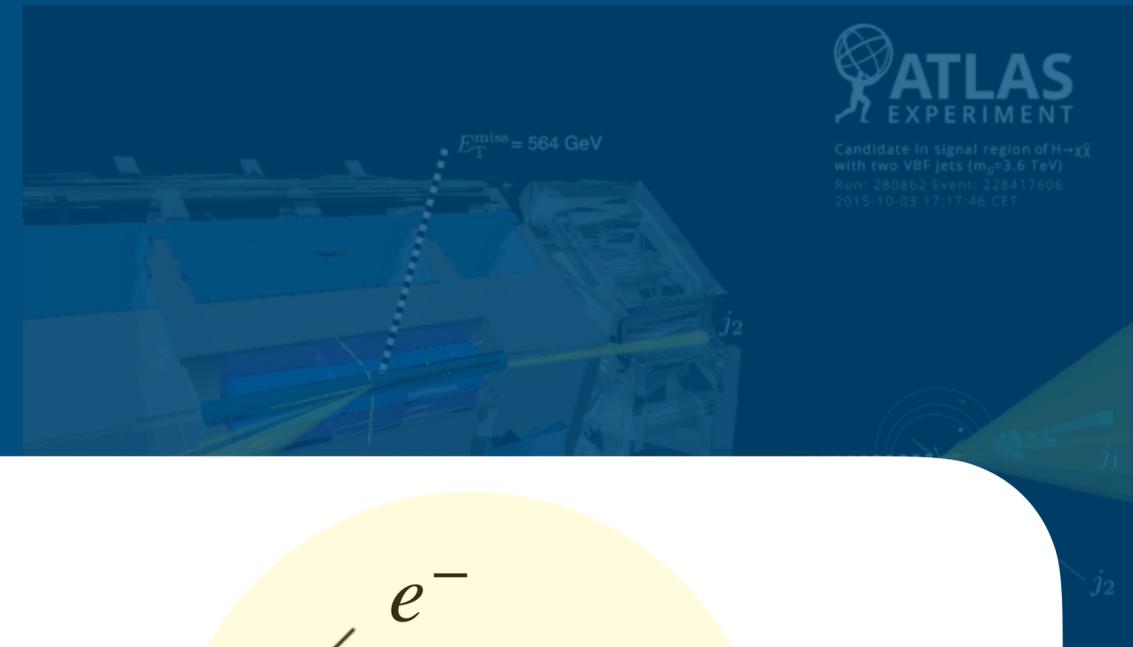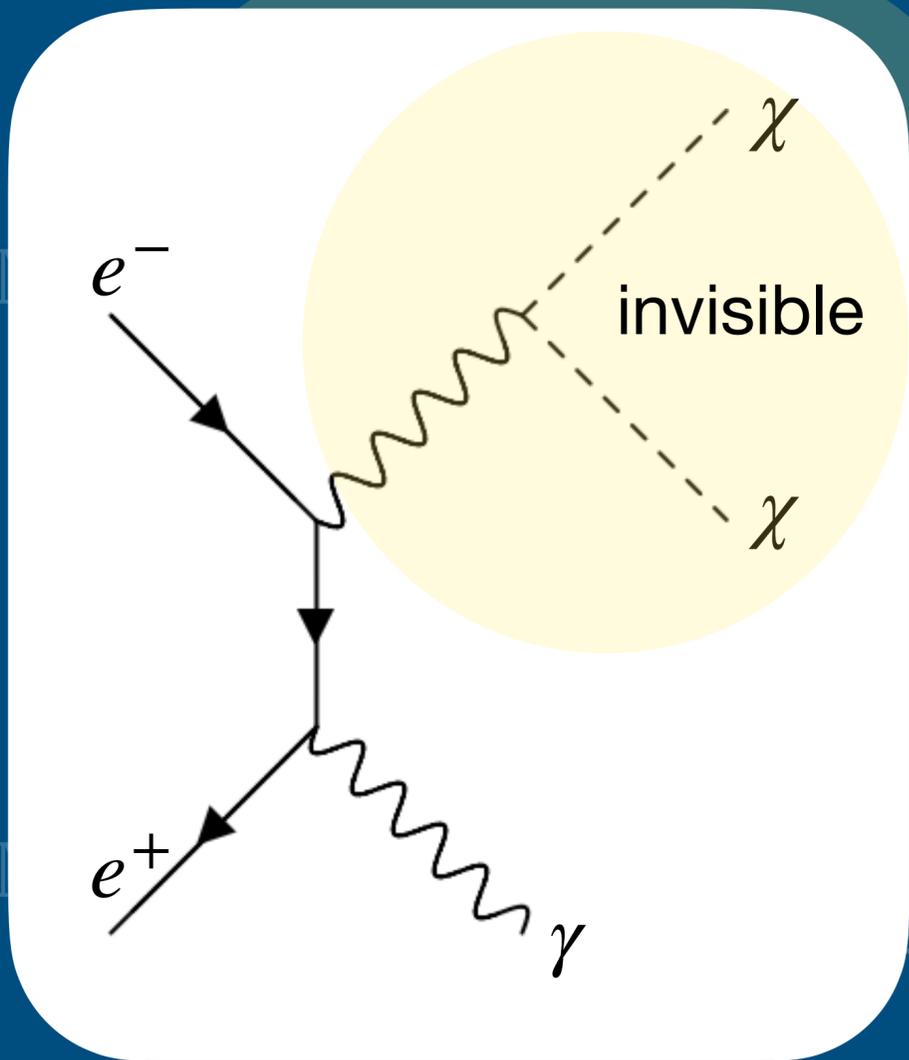
DM detection
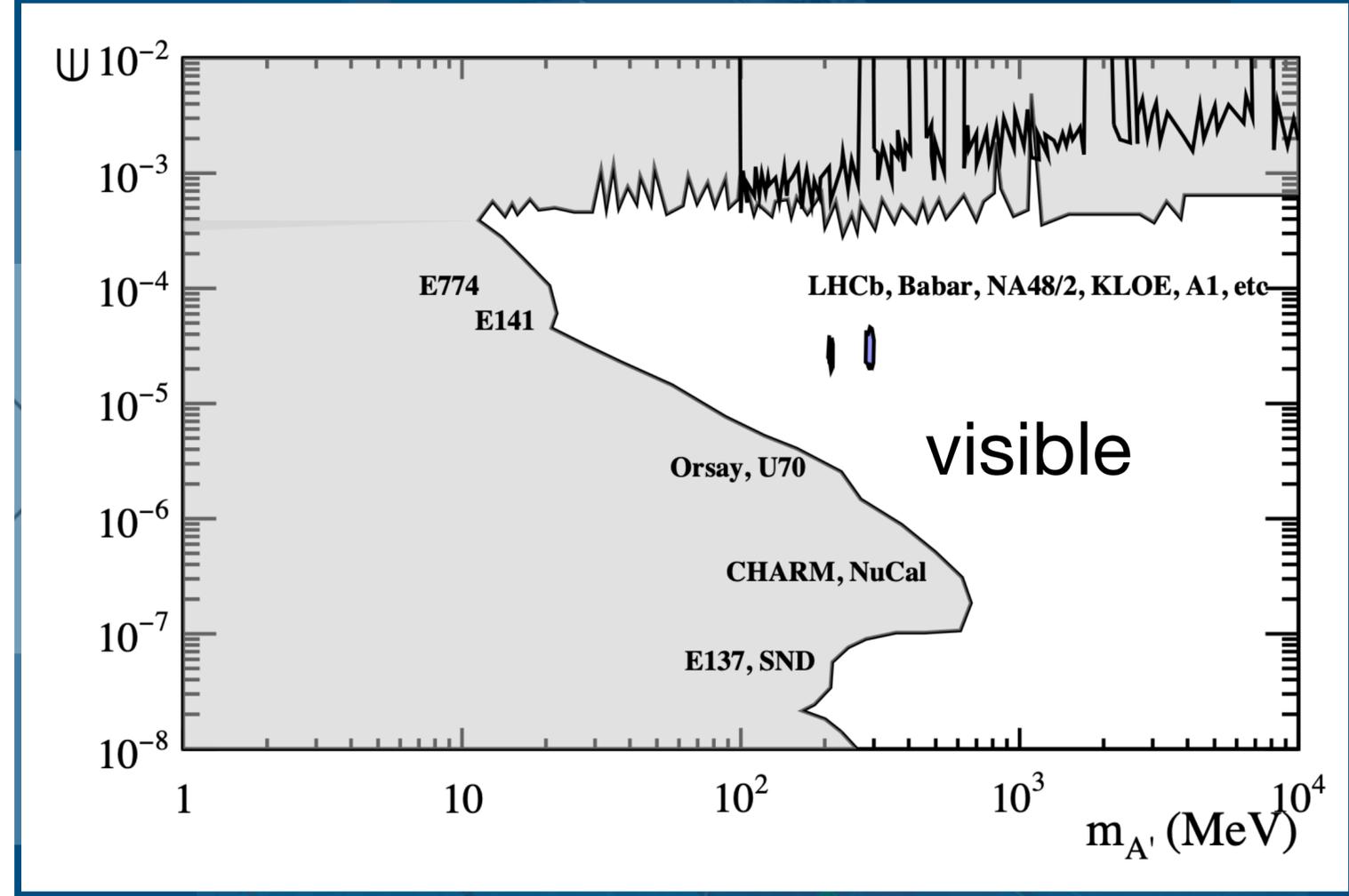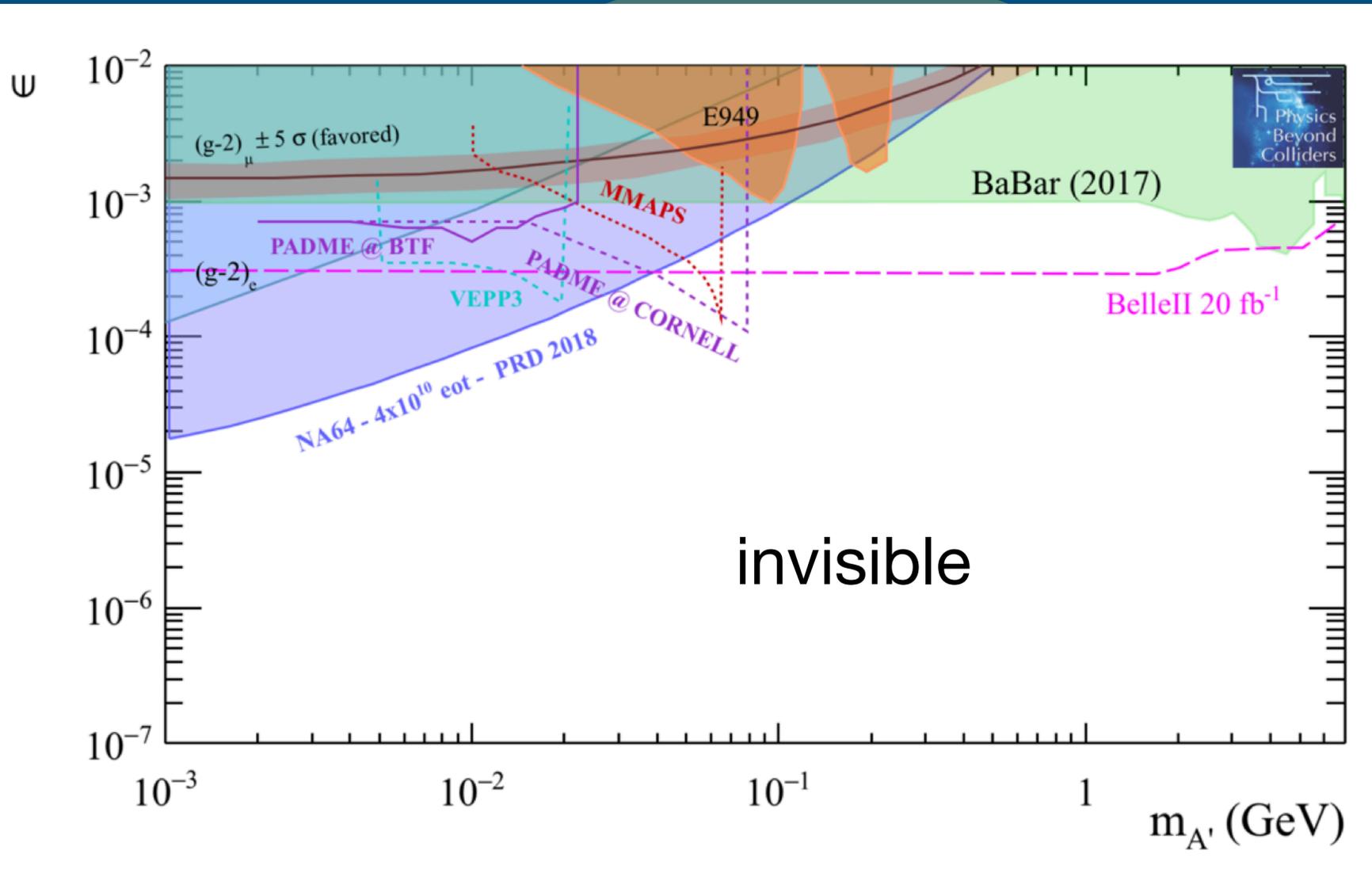
J. Beacham et al, CERN (19)

X as a dark vector (spin-1) $\rightarrow V_\mu$

generic coupling to electrons

$$\mathscr{L} \supset - V_\mu \bar{e} \gamma^\mu (g_V + g_A \gamma^5) e$$

mass generated via Higgs or Stueckelberg mechanisms $m_V \ll m_Z$

specific cases:

- Kinetically mixed dark photon $g_V \simeq - \epsilon e, \quad g_A \simeq 10^{-3} \left(\dfrac{m_V}{5 \text{ GeV}} \right)^2 g_V$

    assumes $\sin^2 \theta_W \simeq 0.23$

- Mass mixed dark Z $\mathscr{L} \supset - 2 \epsilon_Z m_Z^2 Z_d^\mu Z_\mu$ $g_V \simeq - 0.05 \epsilon_Z e, \quad g_A \simeq - 13 g_V$

-
    In 2HDM $\sim \delta \times m_V / m_Z$, and APV limits $\delta \lesssim 10^{-2}$

-

Backgrounds

a charged particle is considered 'lost' if it carries $p_T \lesssim 0.2 \text{ GeV}$

dominant EM

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

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

when one photon is mi

smaller irreducible EW
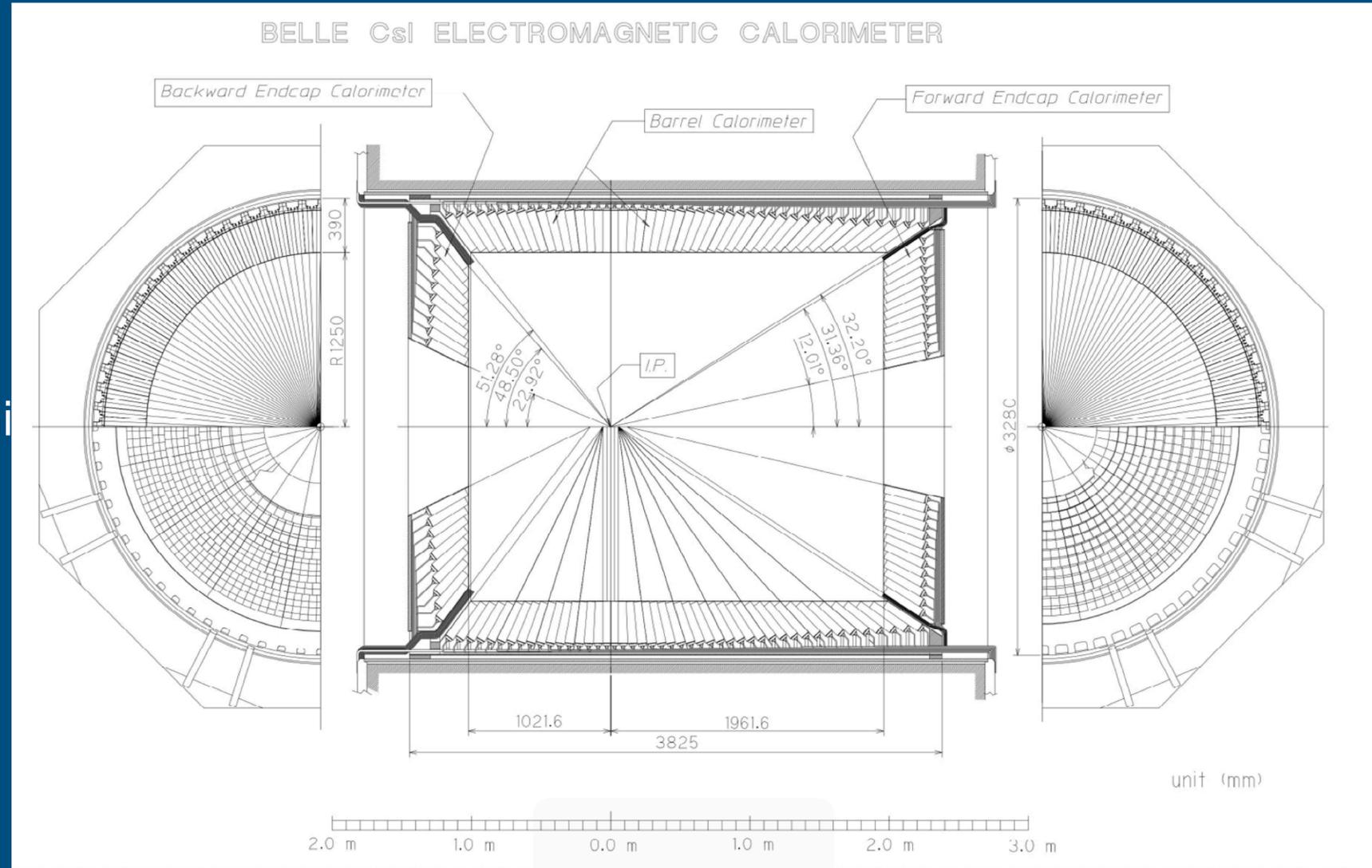
$$e^+e^- \to \nu_l\bar{\nu}_l\gamma(\gamma)$$

other small backgrounds

$$e^+e^- \to \text{hadrons} + \gamma$$

can typically be vetoed from tracks

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

BELLE CsI ELECTROMAGNETIC CALORIMETER

* Altmannshofer et al, Belle, (19)

What if X is a scalar?

Generic spin-0 boson:

$$\mathcal{L} \supset -\phi\bar{e}(g_S + ig_P\gamma^5)e \qquad \text{coupling to electrons}$$

$$\mathcal{L} \supset \frac{\phi}{\Lambda}\left(g_{\gamma\gamma}F^{\mu\nu}F_{\mu\nu} + \bar{g}_{\gamma\gamma}F^{\mu\nu}\tilde{F}_{\mu\nu}\right) \qquad \text{coupling to photons}$$

What if X is a scalar?

Generic spin-0 boson:

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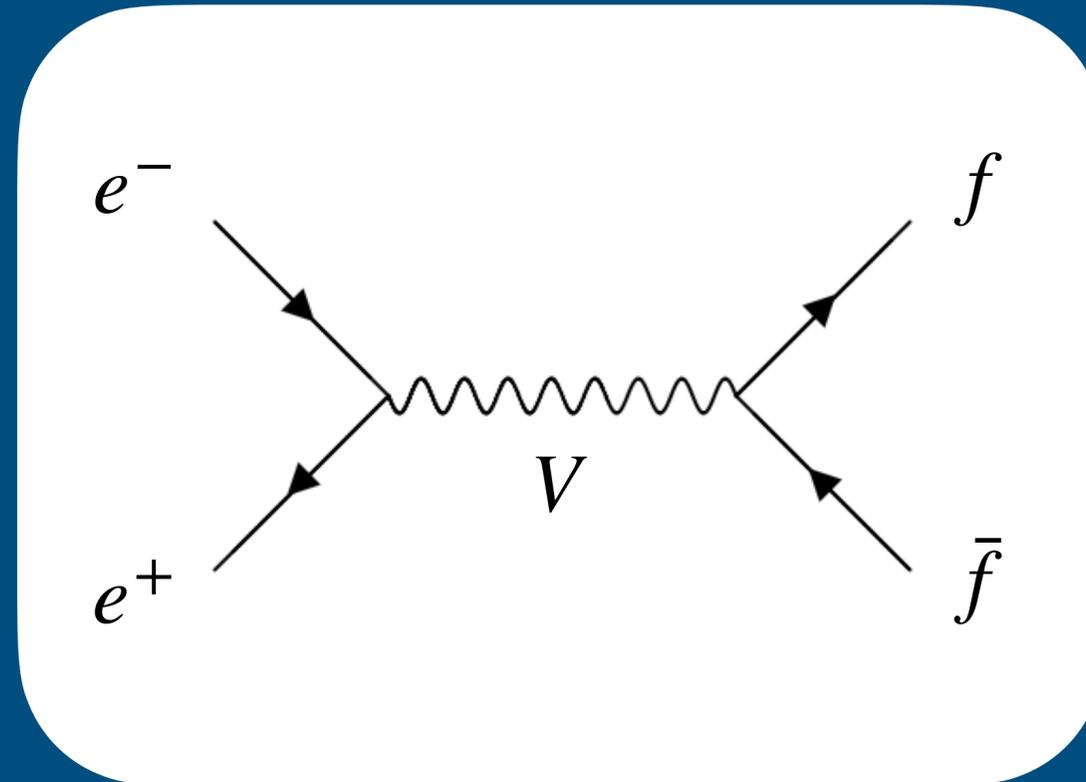
coupling to photons

This yields $\quad\quad \sigma_R = \sigma_L$

Could be probed via the angular distribution in the case of a positive signal!

Other possible signals?

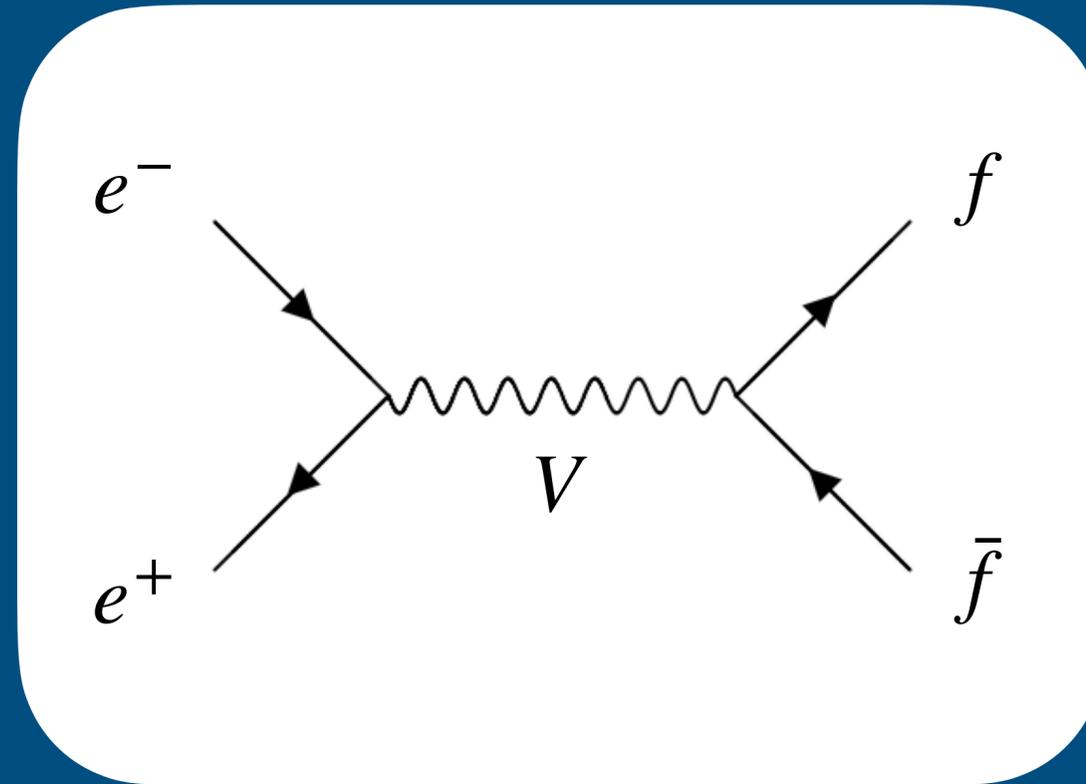$$\sqrt{s} = 10.58 \text{ GeV}$$

* for $f\bar{f}$ not e^-e^+

$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \simeq \frac{s}{m_V^2 - s} \frac{2}{Q_f} \frac{g_A^e g_V^f}{e^2} \langle P \rangle$$

Other possible signals?

for universal coupling ($m_V = 5$ GeV) *

$$\frac{\sqrt{g_A g_V}}{e} \lesssim 2 \times 10^{-3}$$

$\sqrt{s} = 10.58$ GeV

e^- f

V

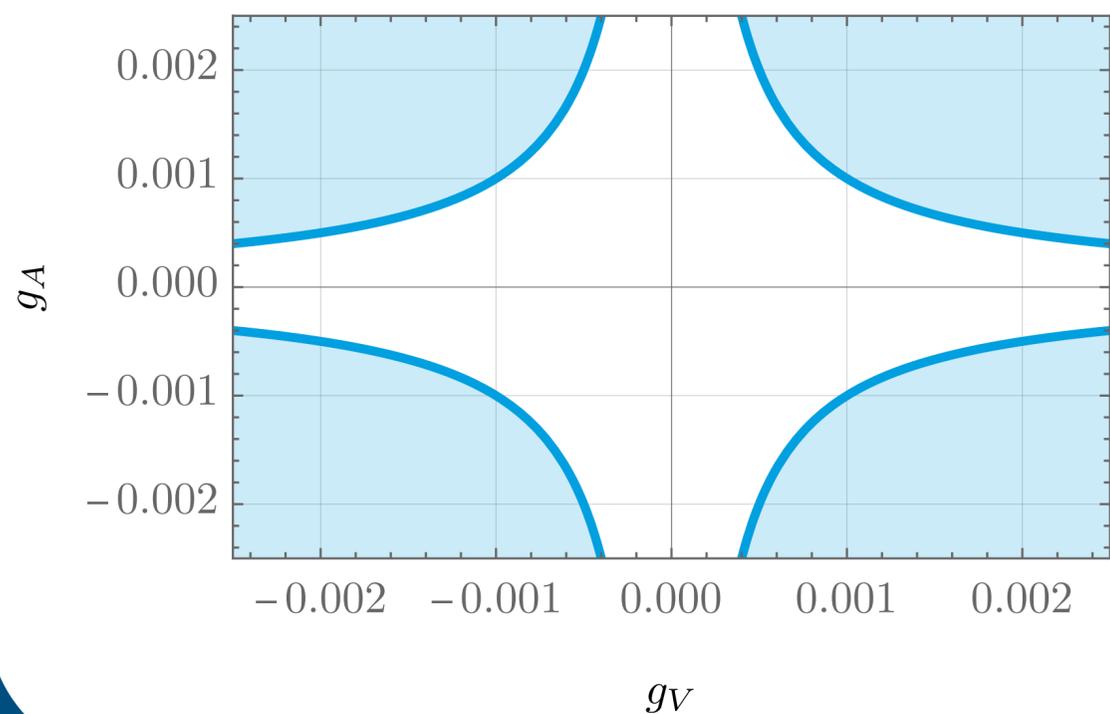e^+ $\bar{f}$

* for $f\bar{f}$ not $e^- e^+$

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* Using precision SM measurements estimates of $A_{LR}^{\mu^+ \mu^-}$, and 20 ab^{-1} of data. Aleksejevs et al (20)
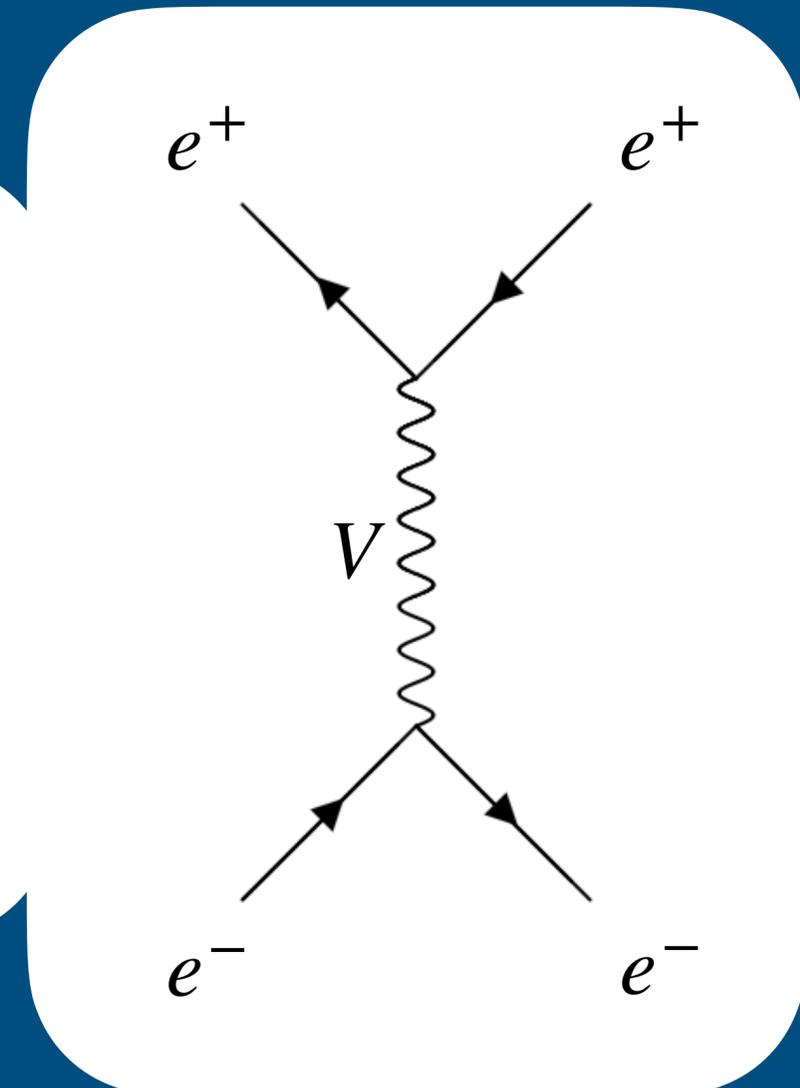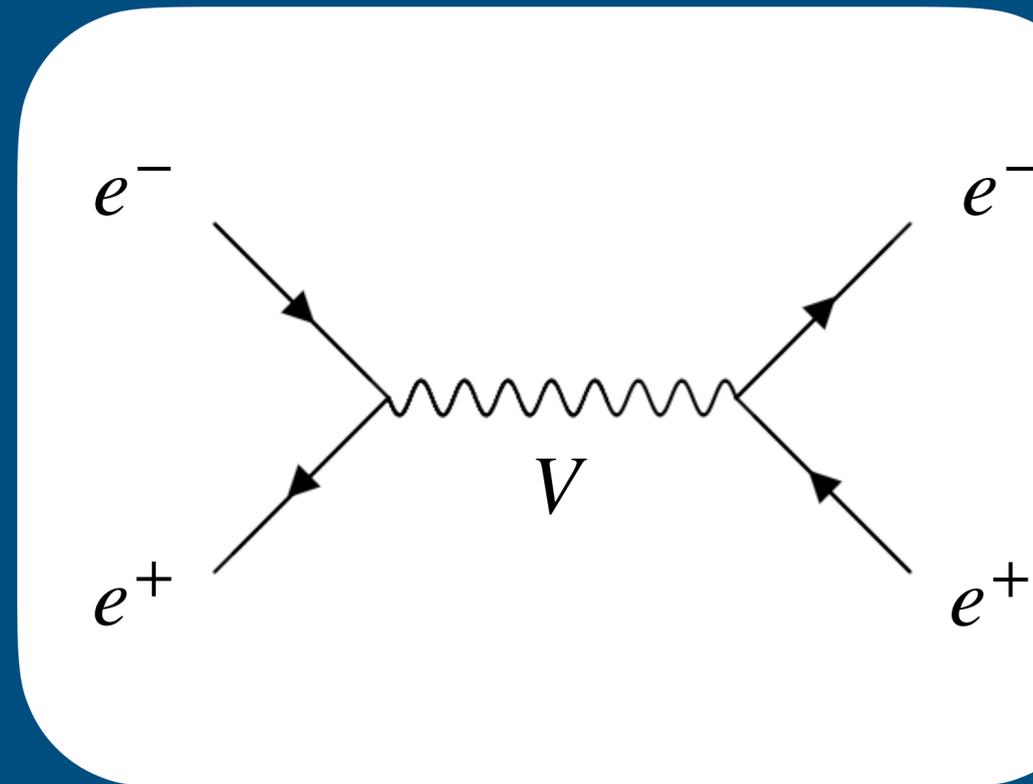
Other possible signals?

for universal coupling ($m_V = 5$ GeV) *

$$\frac{\sqrt{g_A g_V}}{e} \lesssim 3 \times 10^{-3}$$

$\sqrt{s} = 10.58$ GeV

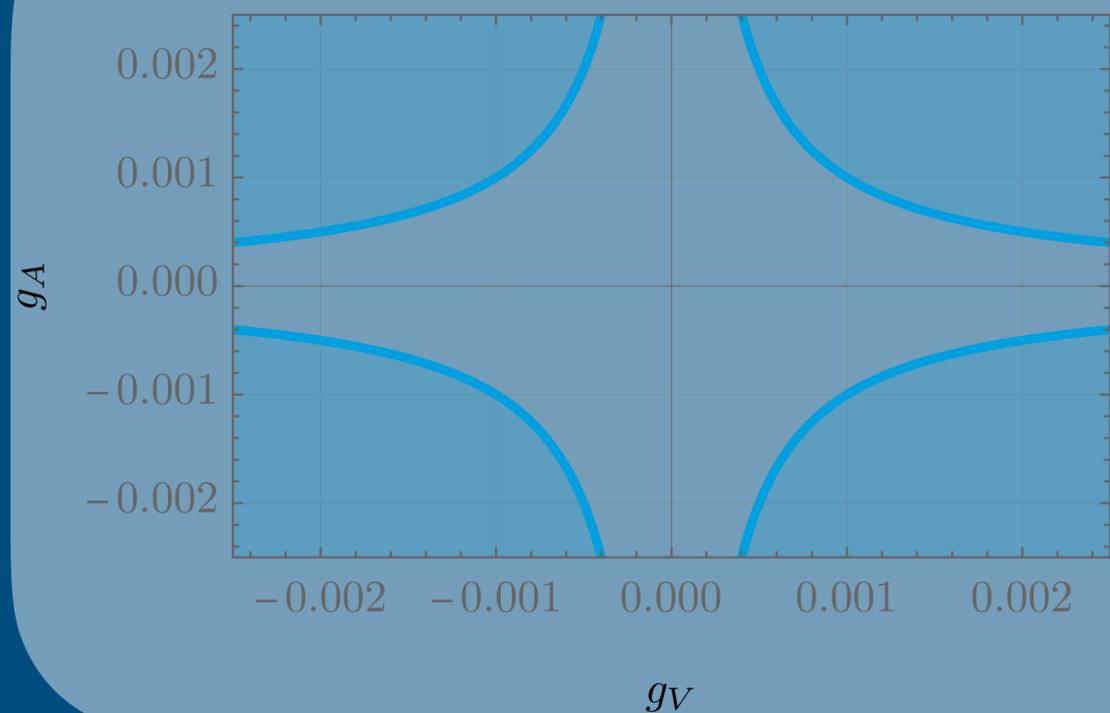$$A_{LR} \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Other possible signals?

$$\sqrt{s} = 10.58 \text{ GeV}$$

➡ Those signals are not as strong as the mono-photon channel.

➡ This channel becomes important if the dark vector is heavier and is produced off-shell

$$A_{LR} \equiv \frac{}{\sigma_L + \sigma_R}$$