Polarization effects in the search for dark vector boson in $e^+ e^-$ colliders

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Fei-Fan Lee, GLL and Vo Quang Nhat, arXiv:2008.07769 [hep-ph];
Phys.Rev.D 103 (2021) 1, 015016

Introduction and motivations

- **Growing interests in searching for DM related phenomenon with high statistics and high precision measurements.**

- **Such phenomenon has to do hidden sector*, assumed to interact with the visible sector through a messenger particle.**

- **A popular proposal for such a messenger is the so-called dark photon**, which mixes with $U(1)_Y$ in SM.**

***B. Holdom, Phys. Lett. 166B, 196 (1986); P. Galison and A. Manohar, Phys. Lett. 136B, 279 (1984)**
****J. Alexander *et al.*, arXiv:1608.08632 [hep-ph]**

Introduction and motivations

- **Such a mixing induces EM couplings between dark photon and SM fermions, which generate rich phenomenology.**
- **The search for light boson with the reaction e^+e^- —> A'+gamma has been proposed*.**
- **Many new proposals to search for dark photons with the above process—see the list next page**
- **These proposals are based upon either fixed target or electron-positron collider**

***C. Boehm and P. Fayet, Nucl. Phys. B 683, 219 (2004); N. Borodatchenkova, D. Choudhury and M. Drees, Phys. Rev. Lett. 96, 141802 (2006); P. Fayet, Phys. Rev. D 75, 115017 (2007).**

Introduction and motivations

- **V. Kozhuharov [PADME Collaboration], Nuovo Cim. C 40, no. 5, 192 (2017)**
- **T. Araki *et al.*, Phys. Rev. D 95, no. 5, 055006 (2017)**
- **B. Wojtsekhowski *et al.*, JINST 13, no. 02, P02021 (2018)**
- **I. Alikhanov and E. A. Paschos, Phys. Rev. D 97, no. 11, 115004 (2018)**
- **L. Marsicano *et al.*, Phys. Rev. D 98, no. 1, 015031 (2018)**
- **J. Jiang *et al.*, Eur. Phys. J. C 78, no. 6, 456 (2018)**

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Introduction and motivations

- **The dark photon interaction with EM current is given by**

$$\mathcal{L}_{\text{int}} = \varepsilon_\gamma e J^\mu_{\text{em}} A'_\mu \quad \varepsilon_\gamma \equiv \varepsilon \text{ in}$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B^{\mu\nu}A'_{\mu\nu} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}$$

- **The neutral current interaction is suppressed in the limit $M_{A'} << M_Z$**

- **The detection of A' determines the mixing parameter and the mass of the dark photon.**

- **On the other hand, there could be other mixing between dark boson and SM gauge bosons, such as***

$$\mathcal{L}_{\text{mass}} = \frac{1}{2}M_Z^2 Z^0_\mu Z^{0\mu} - \delta m^2 Z^0_\mu A'^\mu + \frac{1}{2}M^2_{A'}A'_\mu A'^\mu$$

***H. Davoudiasl, H. S. Lee and W. J. Marciano, Phys. Rev. D 85, 115019 (2012)**

Introduction and motivations

- **With the above mass mixing, an independent neutral current coupling between dark boson and SM fermions is induced:**

$$\mathcal{L}_{\rm int} = \varepsilon_Z \frac{g}{\cos\theta_W} J^{\mu}_{\rm NC} A'_{\mu} \text{ with } \varepsilon_Z \equiv \delta m^2 / M_Z^2$$

- **Considering both mixings, the interaction between dark boson (renamed as Z_d from now on) and SM fermions becomes**

$$e\varepsilon \bar{f}(g_{f,V}\gamma_{\mu} + g_{f,A}\gamma_{\mu}\gamma_5) f Z^{\mu}_d$$

- **In the search for Z_d with e^+e^- —> Z_d +gamma, can one determine the relative strength of vector and axial-vector couplings?**

- **The key is on the polarization of Z_d**

Outline

- **Heuristic derivation of Z_d-fermion interactions**
- **Ward-Takahashi identity and the polarization of Z_d in e^+e^- —> Z_d+gamma**
- **Differential cross section of e^+e^- —> Z_d+gamma for each polarization of Z_d and the decay distribution of Z_d —>$l^+ l^-$**
- **Searching for Z_d by e^+e^- —> Z_d+gamma and Z_d decaying to muon pairs in BaBar and Belle II**
- **Summary**

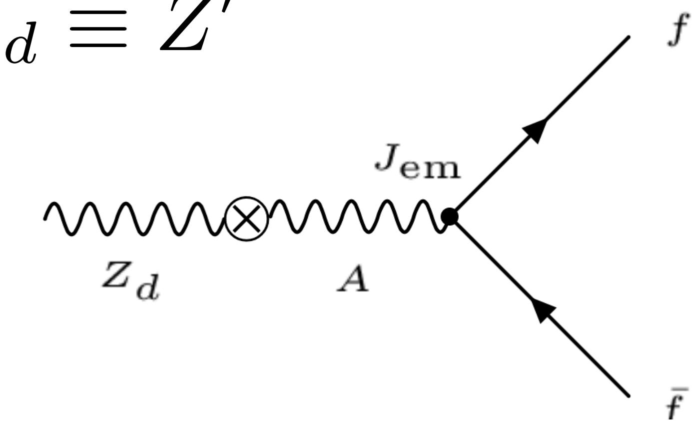
Heuristic derivation of Z_d-fermion interactions

$$Z_d \equiv Z'$$

The mixing terms give two point functions

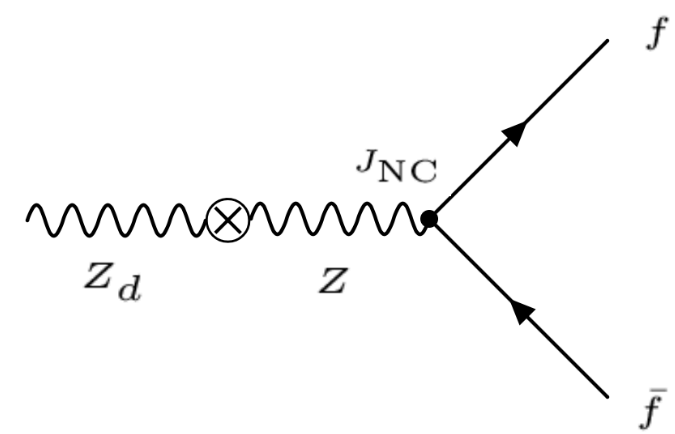
$$i\Pi^{\mu\nu}_{AZ_d} = i\varepsilon k^2 g^{\mu\nu},$$

$$i\Pi^{\mu\nu}_{ZZ_d} = -i(\varepsilon \tan\theta_W k^2 + \delta m^2) g^{\mu\nu},$$



The *EM* interactions of dark boson

$$ieJ^\alpha_{\text{em}} \frac{-ig_{\alpha\mu}}{k^2} i\varepsilon k^2 g^{\mu\nu} Z_{d\nu} = ie\varepsilon J^\nu_{\text{em}} Z_{d\nu}.$$



The *Neutral-Current* interactions of dark boson

$$\frac{ig}{\cos\theta_W} J^\alpha_{\text{NC}} \frac{-i}{k^2 - M_Z^2}\left(g_{\alpha\mu} - \frac{k_\alpha k_\mu}{M_Z^2}\right) \cdot (-i)(\varepsilon \tan\theta_W k^2 + \delta m^2) g^{\mu\nu} Z_{d\nu}$$

$$= \frac{-ig}{\cos\theta_W} J^\nu_{\text{NC}} Z_{d\nu} \frac{(\varepsilon \tan\theta_W M_{Z_d}^2 + \delta m^2)}{(M_{Z_d}^2 - M_Z^2)}.$$

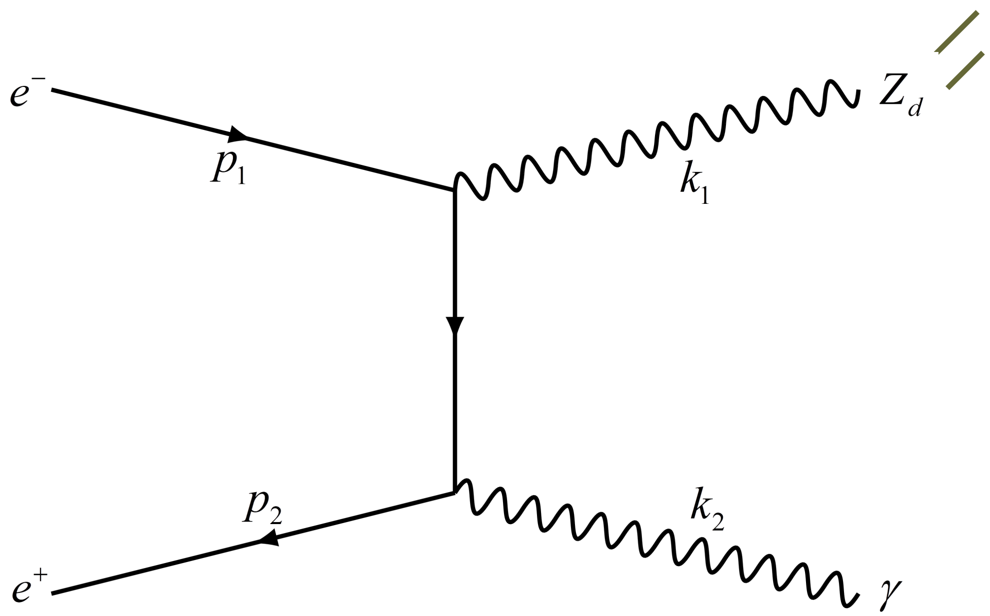
Heuristic derivation of Z_d-fermion interactions

In the limit $M_{Z_d} \ll M_Z$

$$\mathcal{L}_{\rm int} = \left(\varepsilon_\gamma e J^\mu_{\rm em} + \varepsilon_Z \frac{g}{\cos\theta_w} J^\mu_{\rm NC}\right) Z_{d\mu},$$

$$\varepsilon_Z \equiv \delta m^2 / m_Z^2.$$

Ward-Takahashi identity and Z_d polarization



$$\epsilon^\mu(k_1) = (|\vec{k}_1|, E_{Z_d}\hat{k}_1)/m_{Z_d}$$

$$= k_1^\mu/m_{Z_d} + \mathcal{O}(m_{Z_d}/E_{Z_d})$$

Z_d is expected to be transversely polarized for dark boson mass much less than CM energy

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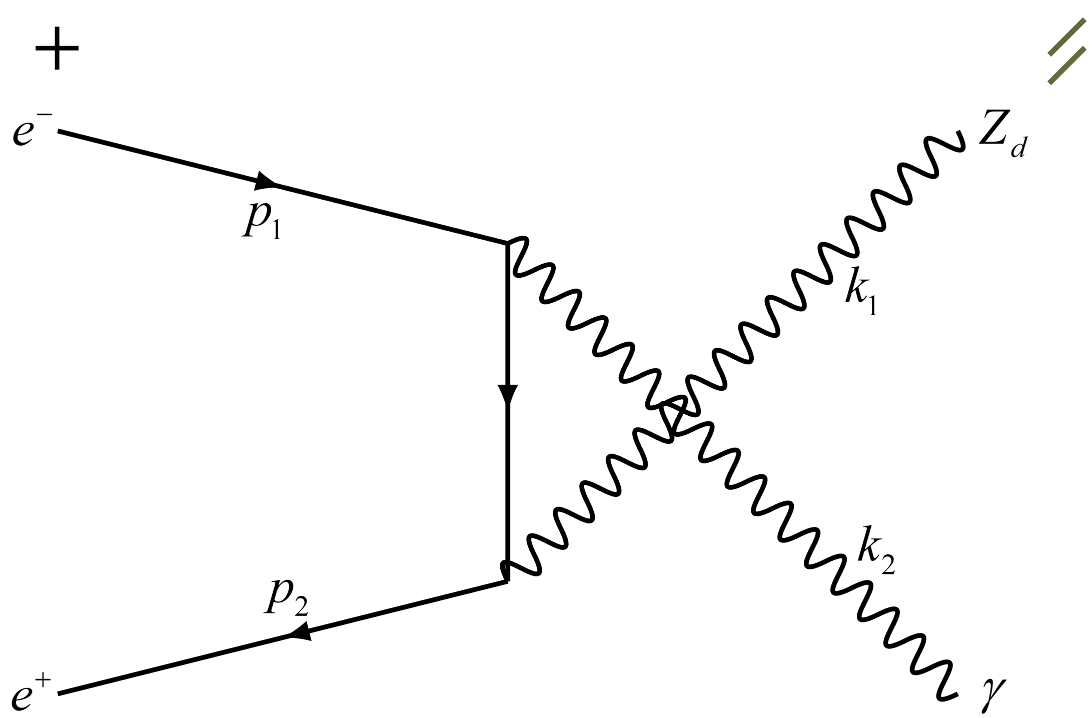
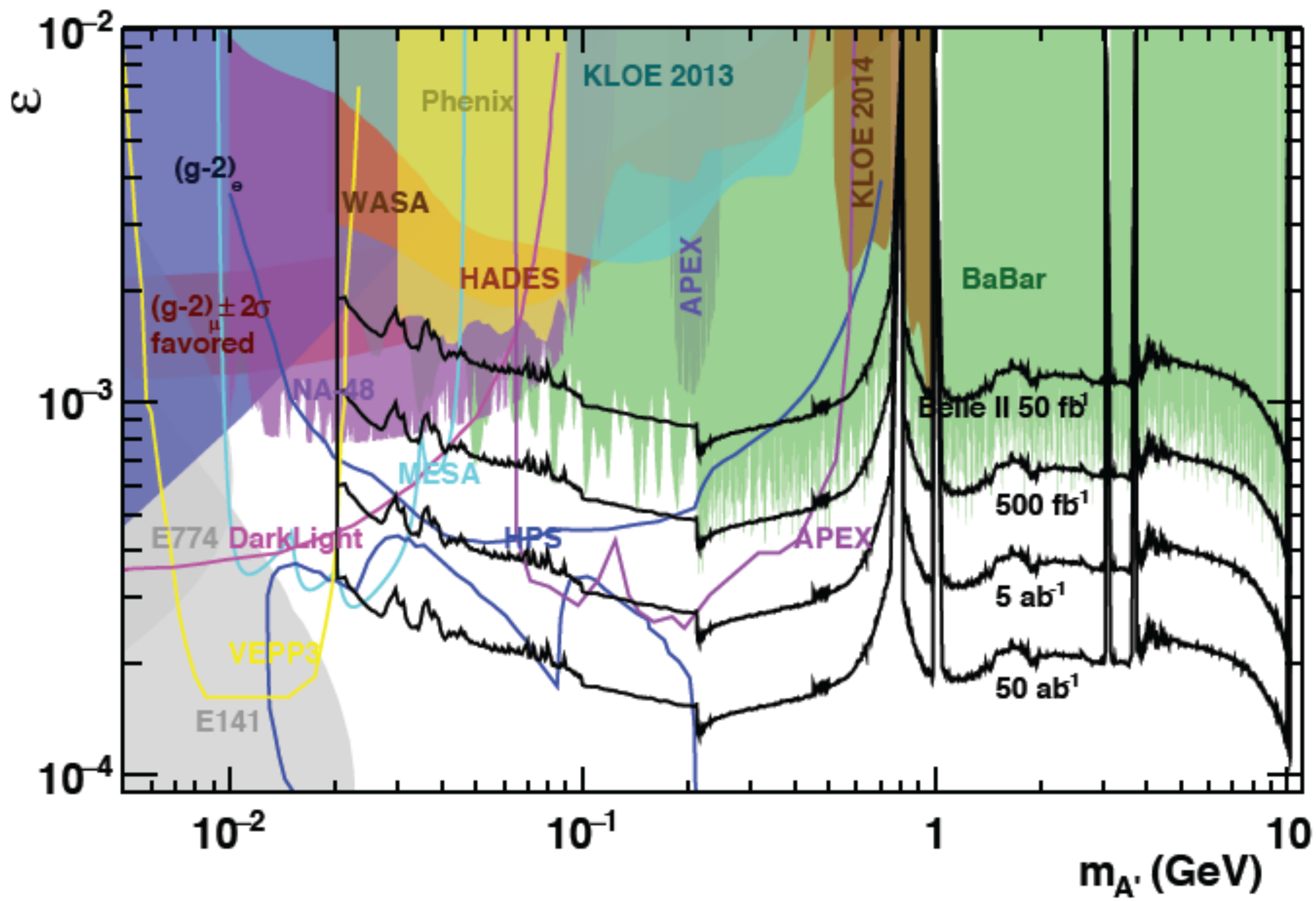


=0 for m_e —>0

BaBar search result and Belle II sensitivity to

$$A' \to e^+e^-, \mu^+\mu^-, hh$$

The Belle II physics book, arXiv:1808.10567



Take $\varepsilon = 7 \times 10^{-4}; m_{Z_d}/\sqrt{s} = 0.1,\ 0.3,\ \text{and } 0.8.$

J. P. Lees et al. [BaBar Collaboration], Phys. Rev. Lett. 113, no. 20, 201801 (2014)

Polarized amplitudes

θ the direction of Z_d with respect to e^- direction in CM frame

$$|\bar{\mathcal{M}}|^2_+ = \frac{8\pi^2\alpha^2\varepsilon^2}{(t-m_e^2)(u-m_e^2)}\left[(1+\cos^2\theta)(s^2+m_{Z_d}^4)+\rho\cos\theta(s-m_{Z_d}^2)^2\right],$$

$$|\bar{\mathcal{M}}|^2_- = \frac{8\pi^2\alpha^2\varepsilon^2}{(t-m_e^2)(u-m_e^2)}\left[(1+\cos^2\theta)(s^2+m_{Z_d}^4)-\rho\cos\theta(s-m_{Z_d}^2)^2\right],$$

$$|\bar{\mathcal{M}}|^2_\parallel = \frac{8\pi^2\alpha^2\varepsilon^2}{(t-m_e^2)(u-m_e^2)}(4m_{Z_d}^2 s\sin^2\theta),$$

where $\rho = 4g_{f,V}g_{f,A}$. $\qquad g_{f,V}^2 + g_{f,A}^2 = 1$

***m_e* is neglected except in the denominator**

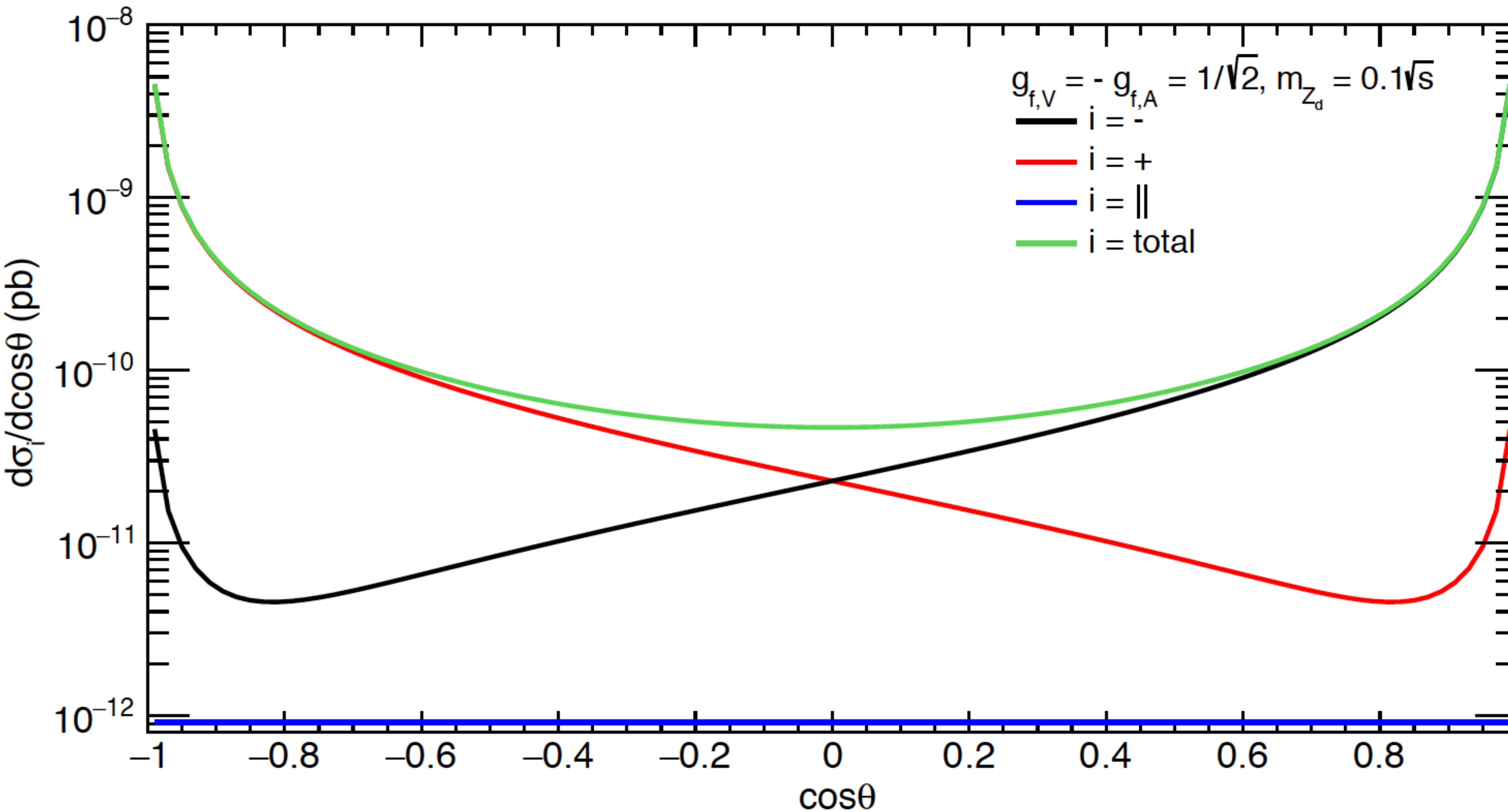
Polarized differential cross sections

$$\frac{d\sigma_i}{d\cos\theta} = \frac{1}{32\pi s}(1 - \frac{m_{Z_d}^2}{s})|\mathcal{M}|_i^2$$

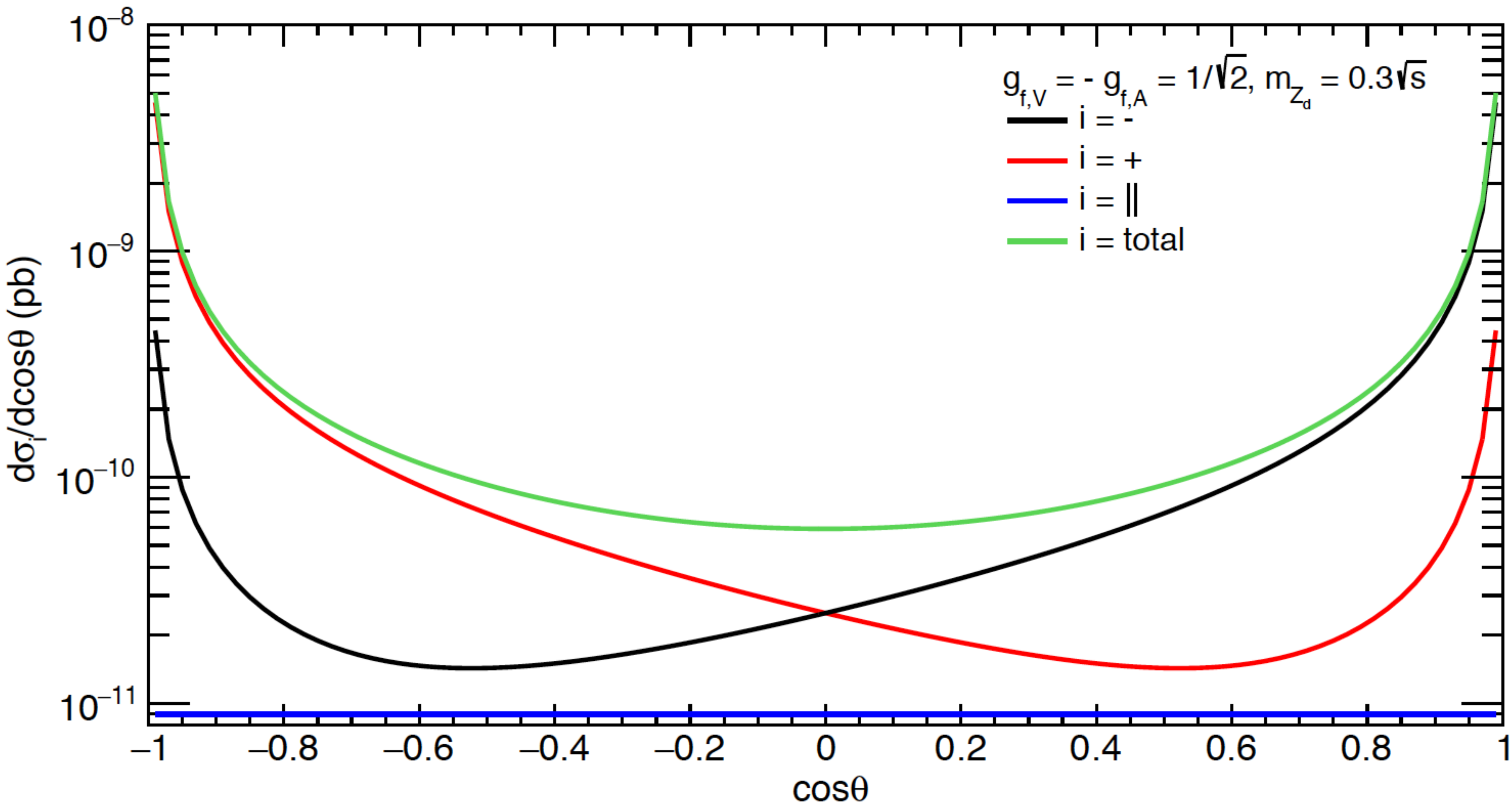
Differential cross section for longitudinal state is clearly suppressed by $m_{Z_d}^2/s$

Polarized differential cross sections-numerical results

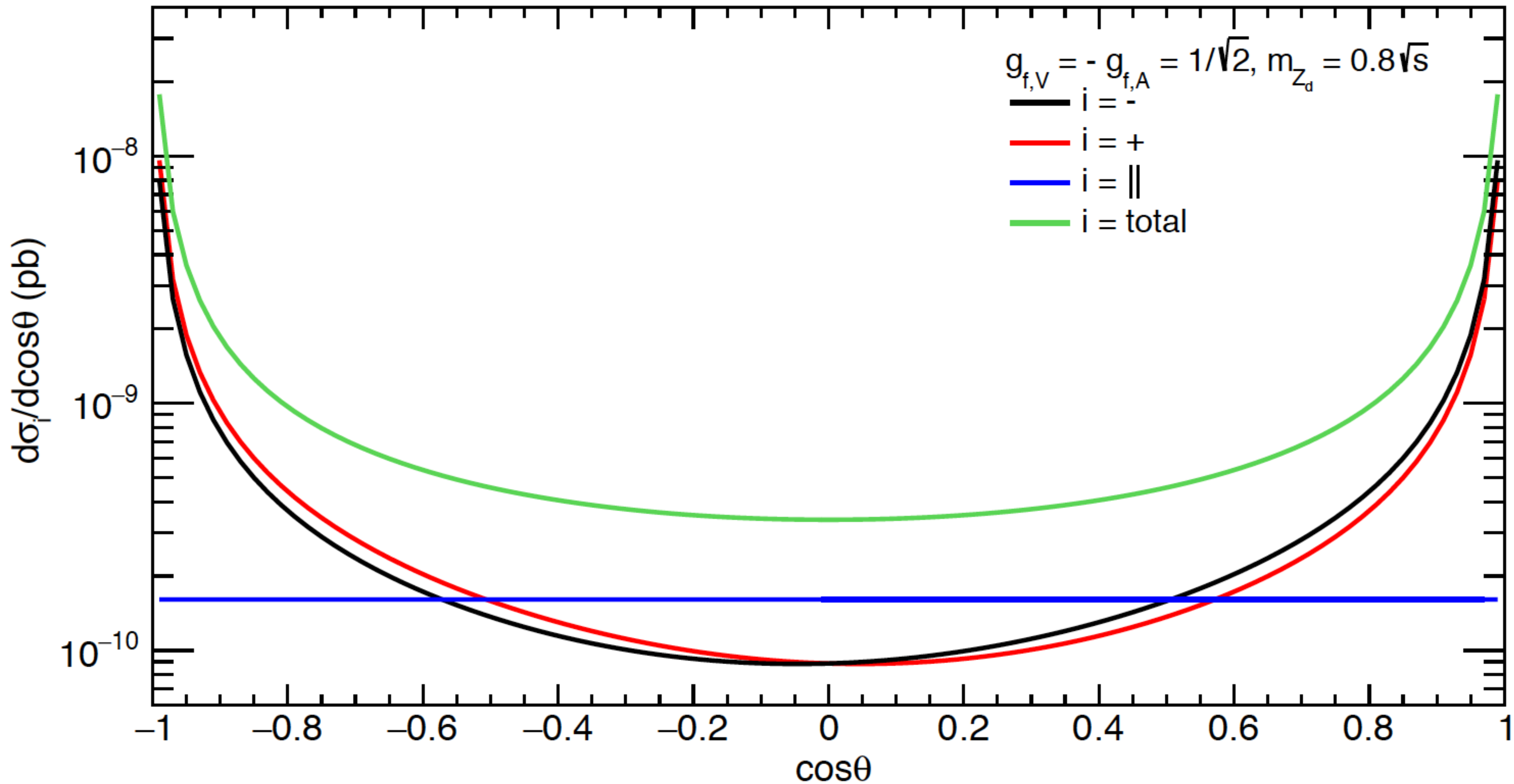
$\varepsilon = 7 \times 10^{-4}; \sqrt{s} = 10.58$ GeV CM frame **V-A coupling**



Polarized differential cross sections-numerical results



Polarized differential cross sections-numerical results



Longitudinal polarization is now equally important
Helicity +1 and -1 states getting closer to each other

Z_d decay distributions and the parity violation parameter $\rho \equiv 4 g_{l,V} g_{l,A}$

Angular distributions of Z_d decays

θ_d the angle between l^- direction in the Z_d rest frame and the Z_d boost direction

Helicity +1 state

$$\frac{d\Gamma^{+}_{l^+l^-}}{d\cos\theta_d} = \frac{\alpha\varepsilon^2 y}{2m_{Z_d}}\left[2g_{l,V}^2 m_l^2 + (1+\cos^2\theta_d)p_l^2 + \rho\cos\theta_d E_l p_l\right]$$

Helicity -1 state

$$\frac{d\Gamma^{-}_{l^+l^-}}{d\cos\theta_d} = \frac{\alpha\varepsilon^2 y}{2m_{Z_d}}\left[2g_{l,V}^2 m_l^2 + (1+\cos^2\theta_d)p_l^2 - \rho\cos\theta_d E_l p_l\right]$$

Longitudinal state

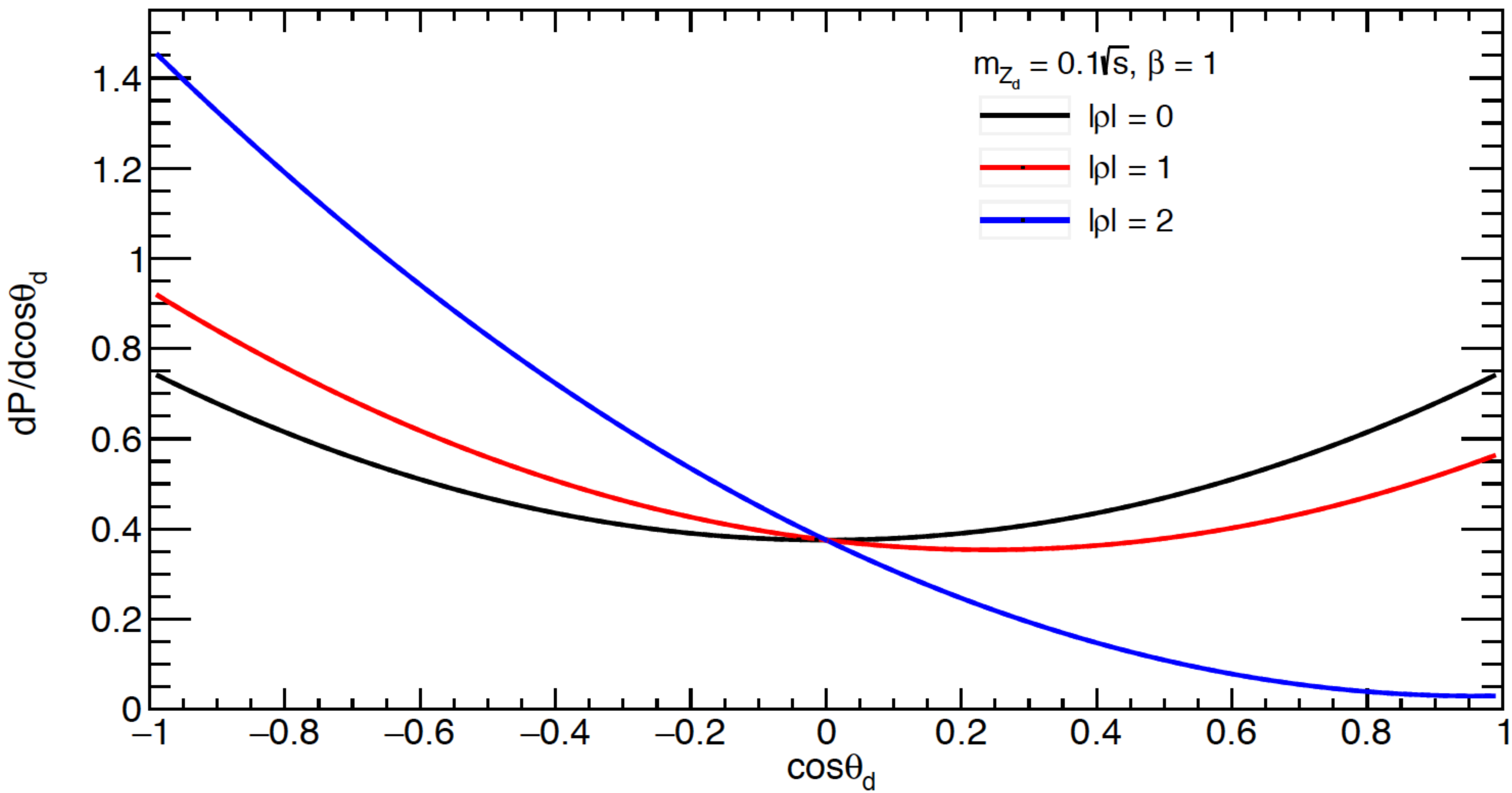
$$\frac{d\Gamma^{||}_{l^+l^-}}{d\cos\theta_d} = \frac{\alpha\varepsilon^2 y}{m_{Z_d}}\left[g_{l,V}^2 m_l^2 + \sin^2\theta_d p_l^2\right]$$

$$y = \sqrt{1 - 4m_l^2/m_{Z_d}^2}$$

Forward-backward asymmetry of leptons from Z_d decays

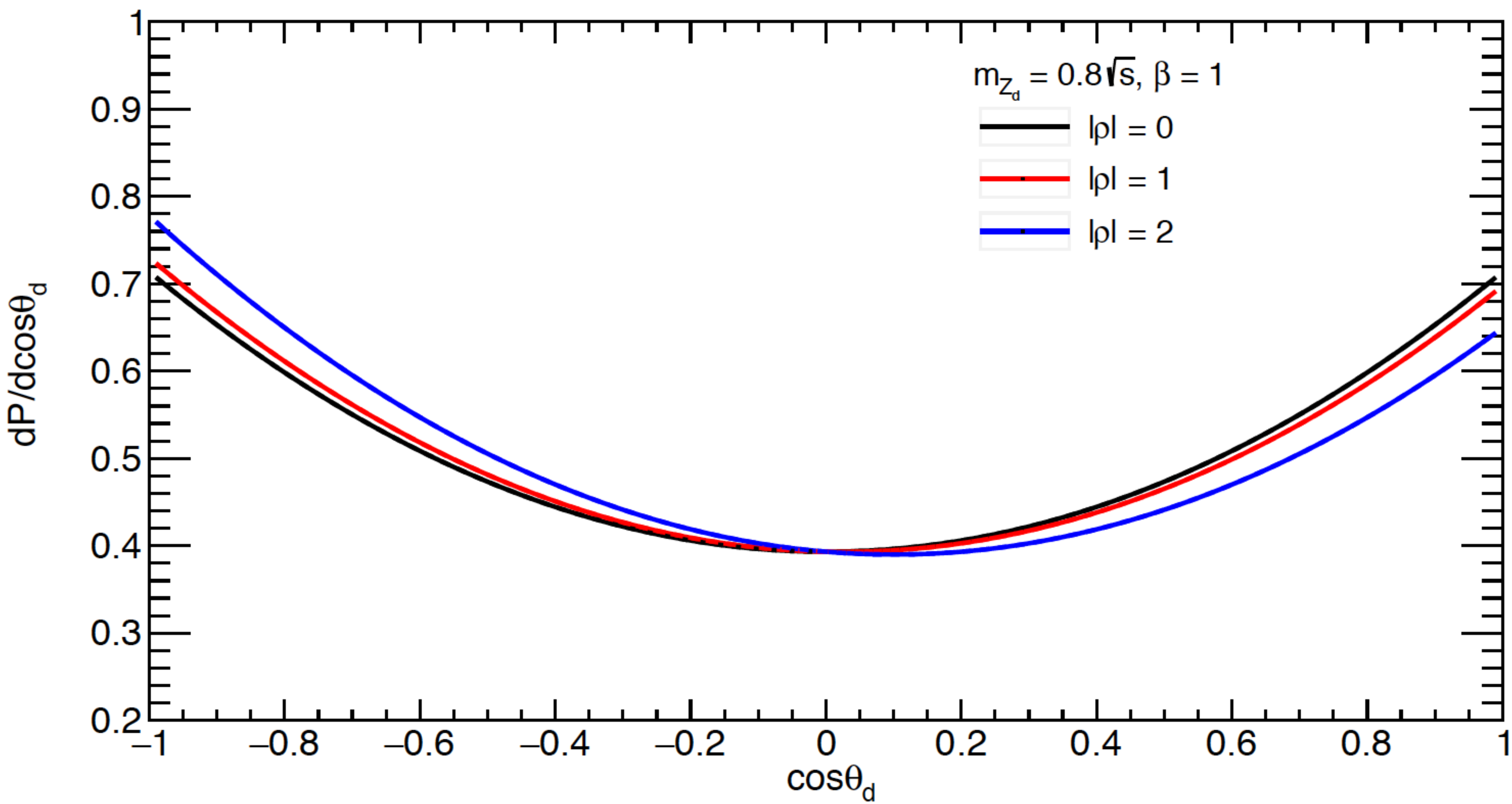
Z_d produced in the backward direction $-1 \leq \cos\theta \leq 0$

$$m_{Z_d} = 0.1\sqrt{s}, \beta \equiv p_l/E_l = 1$$



Forward-backward asymmetry of leptons from Z_d decays

$$m_{Z_d} = 0.8\sqrt{s}, \beta \equiv p_l/E_l = 1$$



Double angular distributions; correlation between Z_d and lepton directions

$$\frac{d^2P}{d\kappa d\xi} = \frac{1}{\sigma_T \cdot \Gamma_{l^+l^-}} \sum_i \left(\frac{d\sigma^i}{d\cos\theta}\right) \cdot \left(\frac{d\Gamma^i_{l^+l^-}}{d\cos\theta_d}\right)$$

i: polarization index

$$= Q_0(\kappa,\xi) + Q_2(\kappa,\xi)\rho^2$$

$$\kappa = \cos\theta, \ \ \xi = \cos\theta_d$$

Q_0: even in both κ and ξ
Q_2: odd in both κ and ξ

$$Q_2\rho^2 \sim (p_l/E_l)\rho^2(1-m^2_{Z_d}/s)^2\kappa\xi/(1-\kappa^2)$$

Changes sign when $\kappa \cdot \xi$ changes sign;
Reaching to maximum for ultra-relativistic lepton and the limit $s \gg m^2_{Z_d}$

Signal event asymmetry

$$\kappa = \cos\theta, \;\; \xi = \cos\theta_d$$

$$\mathcal{A}_{\rm PN} \equiv \frac{S(\kappa\cdot\xi > 0) - S(\kappa\cdot\xi < 0)}{S(\kappa\cdot\xi < 0) + S(\kappa\cdot\xi > 0)} = \frac{3}{4}\left(\frac{\rho^2}{4}\right)\frac{-\ln\left(1-\kappa_m^2\right)}{\ln\left(\frac{1+\kappa_m}{1-\kappa_m}\right) - \kappa_m}$$

κ_m : maximum of κ $\quad -\kappa_m$: minimum of κ

ξ : fully integrated

$\kappa_m = 0.95 \Rightarrow \mathcal{A}_{\rm PN} = 0.64 \times (\rho^2/4)$ $\quad \varepsilon_\gamma = \varepsilon_Z \;\; \rho = 1.74$

$\kappa_m = 0.80 \Rightarrow \mathcal{A}_{\rm PN} = 0.55 \times (\rho^2/4)$ $\quad \varepsilon_\gamma = \varepsilon_Z \tan\theta_W \;\; \rho = -2$

$V - A$

This parameter has to be calculated with actual detector acceptance

Prospect of probing parity violation parameter ρ at Belle II

Belle II calorimeter angular coverage* $12.4^\circ \leq \theta_\gamma^{\rm lab} \leq 155.1^\circ$

Corresponding photon rapidity range $-1.51 \leq \eta_\gamma^{\rm lab} \leq 2.22$

Boost velocity from LAB to CM

$$\beta_{\rm CM} = (E_{e^-} - E_{e^+})/(E_{e^-} + E_{e^+}) = 3/11$$

7GeV 4GeV

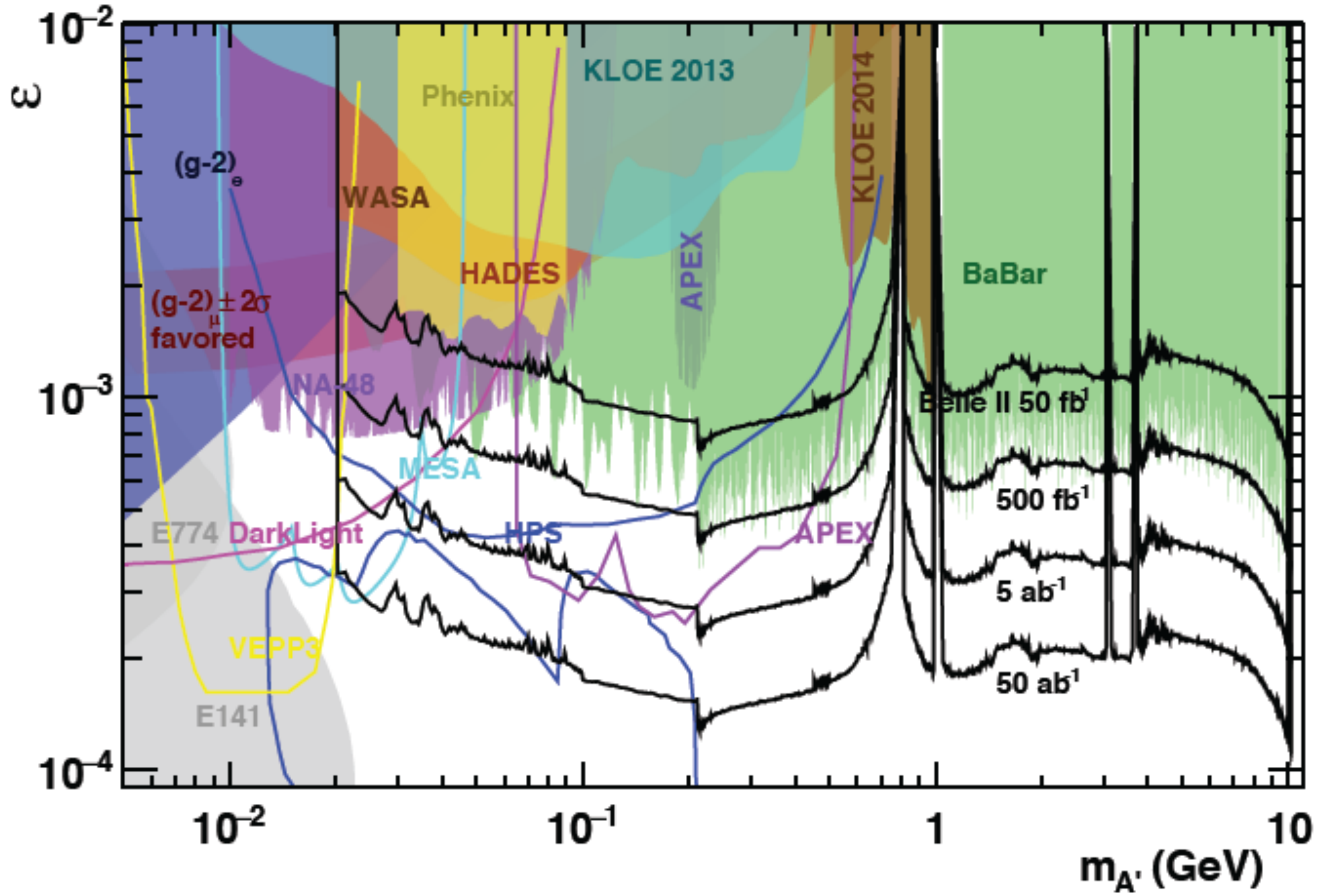
$$\eta_\gamma^{\rm CM} = \eta_\gamma^{\rm lab} + \ln((1-\beta_{\rm CM})/(1+\beta_{\rm CM}))/2 \Rightarrow -1.79 \leq \eta_\gamma^{\rm CM} \leq 1.94$$

K_L-muon detector angular coverage $25^\circ \leq \theta_{\mu^\pm}^{\rm lab} \leq 150^\circ \Rightarrow -1.60 \leq \eta_{\mu^\pm}^{\rm CM} \leq 1.23$

*I. Adachi *et al.* [Belle II], Nucl. Instrum. Meth. A 907, 46-59 (2018)

BaBar search result and Belle II sensitivity to $A' \to e^+e^-, \mu^+\mu^-, hh$

The Belle II physics book, arXiv:1808.10567



J. P. Lees et al. [BaBar Collaboration], Phys. Rev. Lett. 113, no. 20, 201801 (2014)

Belle II sensitivity is comparable to BaBar results for the same integrated luminosity

Calculating $\mathcal{A}_{\rm PN}$ in Belle II

$$\mathcal{A}_{\rm PN} \equiv \frac{S(\kappa \cdot \xi > 0) - S(\kappa \cdot \xi < 0)}{S(\kappa \cdot \xi < 0) + S(\kappa \cdot \xi > 0)}$$

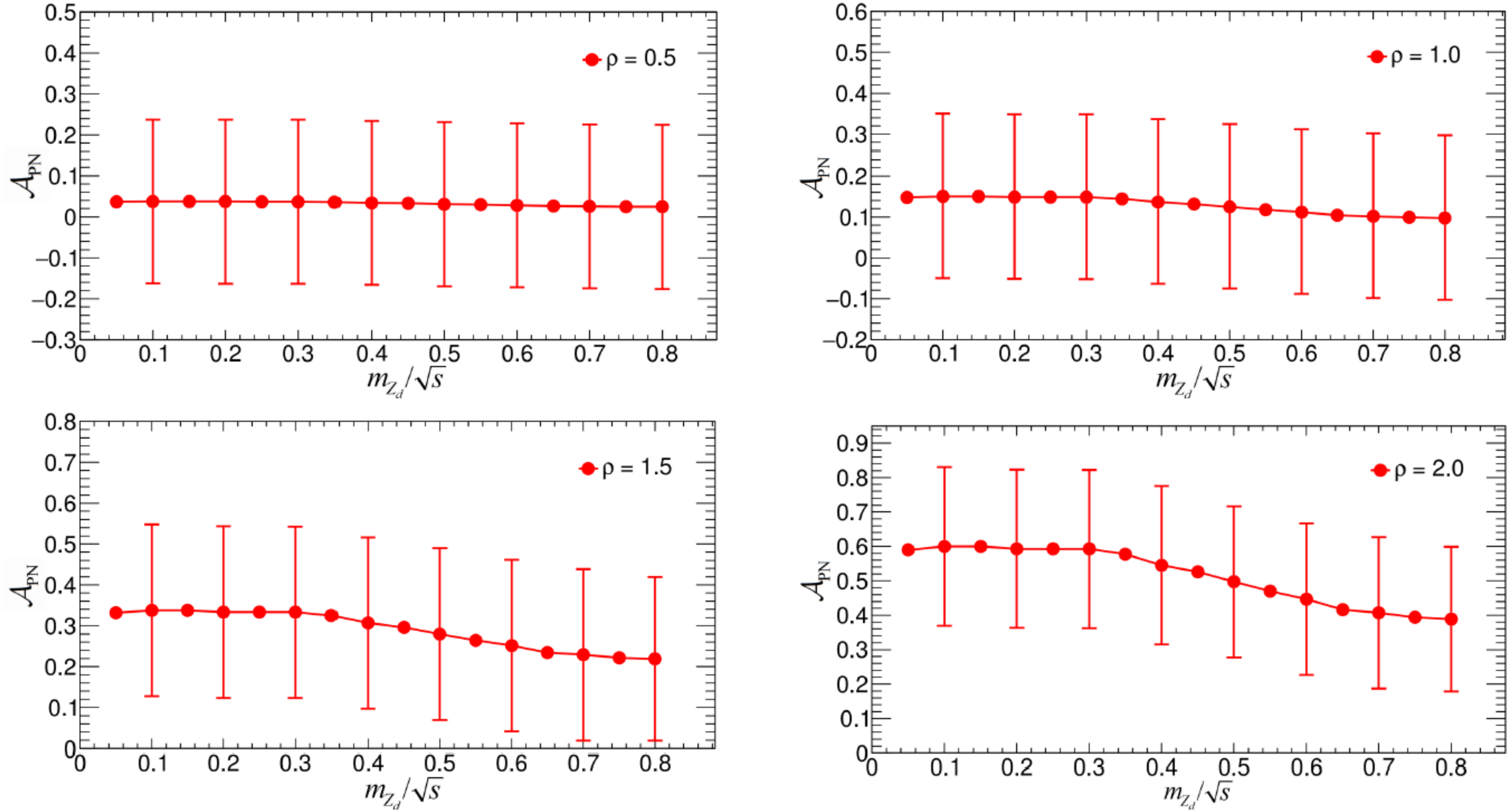
$$\sigma_{\mathcal{A}_{\rm PN}} = \sqrt{1 + \mathcal{A}_{\rm PN}^2}(\sqrt{B}/S)$$

Assume a 5 σ detection of dark boson signature at 50 ab^{-1}

$$S = 5\sqrt{B}$$

CalcHEP version 3.7.5, A. Pukhov, A. Belyaev, and N. Christensen, 2019

Results



Detection significance and asymmetry parameter

$$\chi^2 = 2\left(n\ln(\frac{n}{w}) + w - n\right)$$

n: observed event number
w: expected event number

n=*S*+*B*, *w*=*B*

Detection significance $\frac{S}{\sqrt{B}} \cdot \sigma$

Simultaneous fittings to $\kappa \cdot \xi > 0$ and $\kappa \cdot \xi < 0$ event bins

$$\chi^2 = 2\left(n_a\ln(\frac{n_a}{w_a}) + w_a - n_a\right) + 2\left(n_b\ln(\frac{n_b}{w_b}) + w_b - n_b\right)$$

$$n_{a,b} = S_{a,b} + B_{a,b} \quad (S_a + S_b = S,\ B_a + B_b = B)$$

$$\mathcal{A}_{\mathrm{PN}} = (S_a - S_b)/(S_a + S_b)$$

Detection significance $\frac{S}{\sqrt{B}}\sqrt{1 + \mathcal{A}_{\mathrm{PN}}^2} \cdot \sigma$

Numerical results with Belle II detector angular coverage

Cross section* for QED background $e^+e^- \to \gamma\mu^+\mu^-$ with photon and muon rapidity ranges and ~5 MeV energy resolution for the invariant mass $M_{\mu^+\mu^-}$

$$\sim 7.76 \times 10^{-2}\ \mathrm{pb}\ \ \mathrm{for}\ M_{\mu^+\mu^-} \simeq 0.5\ \mathrm{GeV}$$

$$\sim 2.48 \times 10^{-2}\ \mathrm{pb}\ \ \mathrm{for}\ M_{\mu^+\mu^-} \simeq 2.0\ \mathrm{GeV}$$

1.5 MeV to 8 MeV energy resolution taken in BaBar analysis

Assume a 5σ detection of dark boson signature at 50 ab^{-1}

$$S = 9850,\ \ B = 3.88 \cdot 10^6 \qquad m_{Z_d} = 0.5\ \mathrm{GeV}$$

$$S = 5700,\ \ B = 1.30 \cdot 10^6 \qquad m_{Z_d} = 2.0\ \mathrm{GeV}$$

*CalcHEP version 3.7.5, A. Pukhov, A. Belyaev, and N. Christensen, 2019

Summary on asymmetry parameters, event numbers and detection significance

$\|\rho\|$	0.00		1.74		2.00	
m_{Z_d}/GeV	0.5	2.0	0.5	2.0	0.5	2.0
$\mathcal{A}_{\mathrm{PN}}$	0.0	0.0	0.43	0.44	0.58	0.60
Det. Sig. (Eq. (15))	5.0σ	5.0σ	5.4σ	5.5σ	5.8σ	5.8σ
$S(\kappa \cdot \xi > 0)$	4925	2817	7040	4053	7780	4507
$S(\kappa \cdot \xi < 0)$	4925	2817	2810	1581	2070	1127
$\mathrm{Br}(Z_d \to \mu^+\mu^-)$	40%	24%	21%	7.5%	17%	6.7%
$\varepsilon \cdot 10^4$	3.3	3.2	4.6	5.7	5.1	6.1

Conclusions

- **We have discussed the search for dark boson with the process $e^+e^- \to Z_d+$gamma in the e^+e^- collider**

- **The dark boson is shown to be transversely polarized when the dark boson mass is much less than the CM energy**

- **We analyze the muon angular distributions from polarized Z_d decays and define the asymmetry parameter $\mathcal{A}_{\rm PN}$ which is proportional to the square of parity violation parameter $\rho \equiv 4 g_{l,V}\, g_{l,A}$.**
- **We calculate the asymmetry parameter with Belle II detector angular coverage and discuss its consequences on the dark boson search.**