Dark matter search at BELLE

FY2023 - “What is dark matter?”

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on behalf of the Belle(II) collaborations

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Dark sector searches in Belle

Extra Leptophilic $U(1)$ gauge boson, Z'

The invisible Z' search

Punzi Loss Neural Net

Final 2d fit

Summary

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Belle dark sector searches summary

1. Dark photon and dark higgs
    - $e^+e^- \to A'h'(\to A'A')$
2. Quark coupled gauge boson
    - $\eta \to U'(\to \pi\pi)\gamma$
3. CP-odd Higgs Boson and low mass DM
    - $\Upsilon(1S) \to \gamma A^0(\to \chi\chi)$
4. Dark photon from B^0
    - $B^0 \to A'A'(\to ee, \mu\mu, \pi\pi)$
5. Visible Z'
    - $e^+e^- \to Z'(\to \mu^+\mu^-)\mu^+\mu^-$
6. Leptophilic Scalar
    - $e^+e^- \to \tau^+\tau^-\phi_L(\to ee, \mu\mu)$
7. Invisible Z'
    - $Z' \to \nu_l\nu_l(\chi, \bar{\chi})$
8. Dark photon

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$(g-2)_\mu$ 2021 and 2023 measurements

$(g-2)_\mu$ 2021 measurement PRL 126, 141801 - 2021

$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$ corresponding to 4.2σ

$(g-2)_\mu$ 2023 measurement 2308.06230

$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (249 \pm 48) \times 10^{-11}$ corresponding to 5.1σ

Some options

1. The gap between SM and the Experimental result can be bridged with an improved calculation of a_μ^{SM}
2. Experimental corrections
3. ~~**New Physics is the reason for the gap**~~
    - Not sure anymore
    - "New physics behind the $g-2$ problem?"
    - $e^+e^- \rightarrow$ New particle$\pi^+\pi^-$
4. ?

Simplest Z' PRD 44, 2118 - 1991

$L_{e,\mu,\tau}$ are the lepton numbers

$L_1 = L_e - L_\mu$, $L_2 = L_e - L_\tau$ and $L_3 = L_\mu - L_\tau$

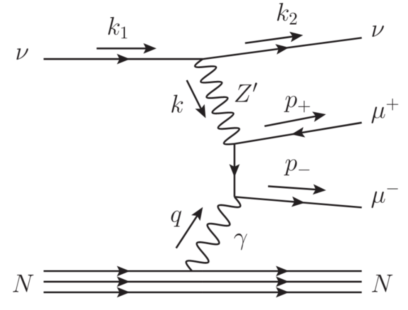
Three different new gauge groups

so that $G_{\text{SM}} \otimes U(1)_{L_{1,2,3}}$

allows for an additional neutral gauge boson $(Z'_1, Z'_2$, and $Z'_3)$

Z'_1 and Z'_2 mediate $L_1 = L_e - L_\mu$ and $L_2 = L_e - L_\tau$

Neutrino Trident Z' PRL 113, 091801 - 2013



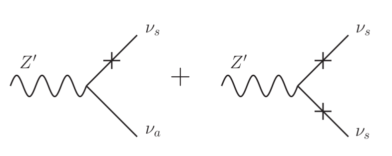
$$\mathcal{L}_{Z'} = -\frac{1}{4}(Z')_{\alpha\beta}(Z')^{\alpha\beta} + \frac{1}{2}m_{Z'}^2 Z'_\alpha Z'^\alpha + \underbrace{g' Z'_\alpha(\bar{\ell}_2\gamma^\alpha \ell_2 - \bar{\ell}_3\gamma^\alpha \ell_3 + \bar{\mu}_R\gamma^\alpha \mu_R - \bar{\tau}_R\gamma^\alpha \tau_R)}$$

$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu \mu + g'\bar{\tau}\gamma^\mu Z'_\mu \tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu \nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu \nu_{\tau,L}}$$

where the g' is the $U(1)$ gauge coupling, $(Z')_{\alpha\beta} = \partial_\alpha Z'_\beta - \partial_\beta Z'_\alpha$ is the field strength, $\ell_2 = (\nu_\mu, \mu_L)$ and $\ell_3 = (\nu_\tau, \tau_L)$ are the electroweak doublets. The g' coupling the new gauge boson Z' to the electroweak doublets and the that enhances the rate of neutrino trident production in the $\nu_\mu N \to N\nu\mu^+\mu^-$ process.

Neutrino trident production has not been observed so far!

Assuming that a sterile neutrino ν_s, that mixes weakly with the active $\nu_{a(\mu,\tau)}$ states, is added to the SM.

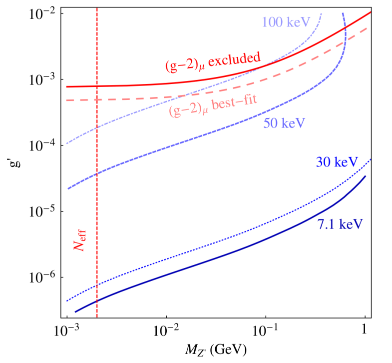


$$\begin{pmatrix}\nu_a \\ \nu_s\end{pmatrix} \equiv \begin{pmatrix}\cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$$

$$\Gamma_{Z'\to\nu_S} = \frac{g'^2 M_{Z'}}{12\pi}\frac{\sin^2 2\theta_m}{4}(1+\tan^2\theta_m)$$

A massive Z' with MeV $< m_{Z'} <$ GeV with coupling $10^{-2} < g' < 10^{-6}$ results in the correct relic abundance of sterile neutrinos DM

Sterile neutrino candidates PRD 89, 113004 - 2014

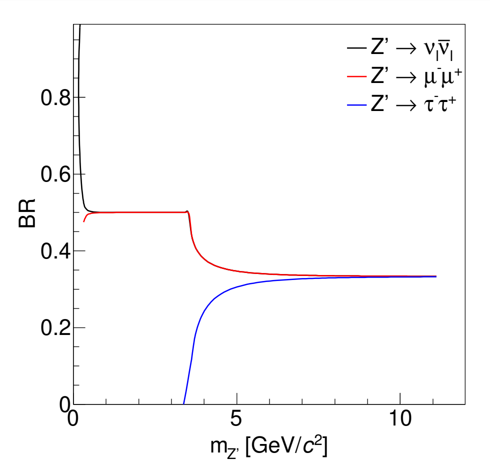


- $M_{Z'} - g'$ plane
- Magnetic moment of the muon anomaly favored region
- $N_{\text{eff}} \to M_{Z'} \gtrsim 2.0$ MeV from Planck measurement constraint 1303.5076
- Sterile neutrino candidates

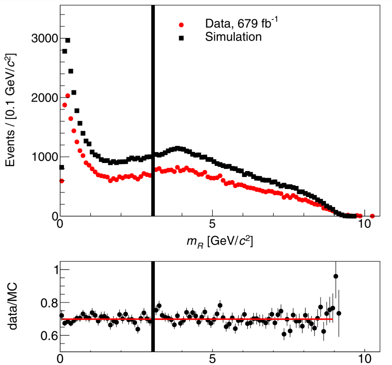
- $m_s = 7.1$ keV $\sin 2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV $\sin 2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV $\sin 2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV $\sin 2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\text{DM}} = 4.7 \times 10^{-4}\ \text{keV}/m_s)$

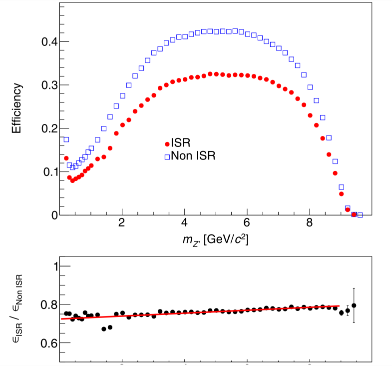
Z' decay width and Branching Ratio (BR)

- $\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 m_{Z'}}{12\pi}\left(1 + \frac{2m_\ell^2}{m_{Z'}^2}\right)\sqrt{1 - \frac{4m_\ell^2}{m_{Z'}^2}}\,\theta(m_{Z'} - 2m_\ell)$
- $\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 m_{Z'}}{24\pi}$



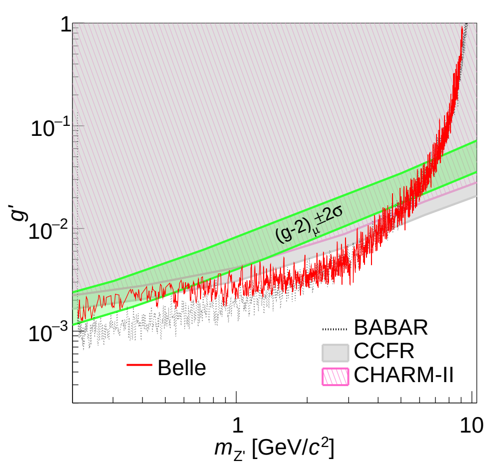
Past Z' Search @ Belle Analysis PRD 106 012003 - 2022





- reduced mass, m_R, scan
  - $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^{\text{PDG}^2}}$
- 1 background
  - $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  - non ISR MC
- Detection efficiency for ISR and non ISR

Past Z′ Search @ Belle Results PRD 106 012003 - 2022



- No Z' signal was found
- Limit set for 0.212(dimuon mass)~ 10 GeV$/c^2$

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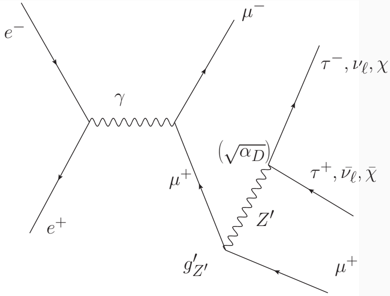
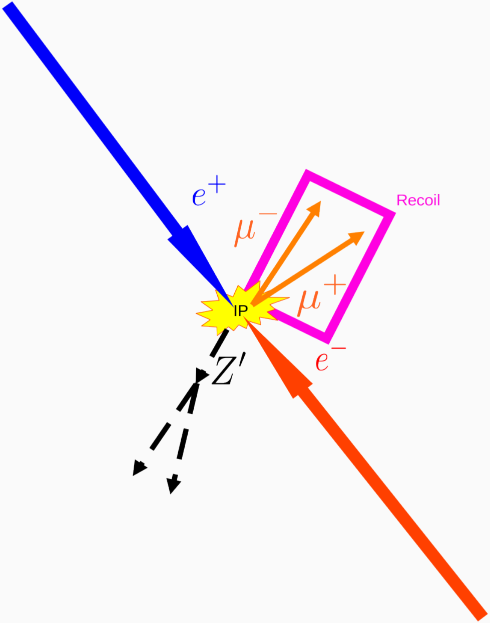
Summary

$Z' \rightarrow$ invisible ~~or not fully visible~~

- ~~$Z' \rightarrow \tau^+\tau^-$~~
  - Recent Belle II publication renders Belle analysis not competitive
- $Z' \rightarrow \chi\bar{\chi}$
- $Z' \rightarrow \nu_\ell \nu_\ell$



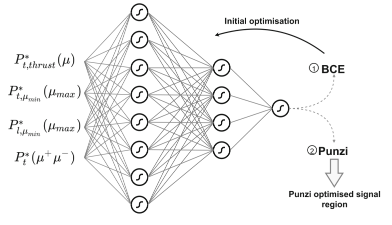
What does it look like?



Background sources

gen	channel	survives
KKMC	~~$e^+e^- \to c\bar{c}$~~	no
	~~$e^+e^- \to d\bar{d}$~~	no
	~~$e^+e^- \to s\bar{s}$~~	no
	$e^+e^- \to \tau^+\tau^-$	YES
	$e^+e^- \to \mu^+\mu^-$	YES
BBBREM	~~$e^+e^- \to e^+e^-\gamma$~~	no
AAFH(Diag36)	~~$e^+e^- \to e^+e^-e^+e^-$~~	no
	~~$e^+e^- \to e^+e^-\tau^+\tau^-$~~	no
	$e^+e^- \to e^+e^-\mu^+\mu^-$	YES
	$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$	YES
	$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$	YES
PHOKHARA	~~$e^+e^- \to \mu^+\mu^-\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to n\bar{n}\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to p\bar{p}\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to \pi^+\pi^-\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to \Lambda\bar{\Lambda}\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to K^+K^-\gamma_{\text{ISR}}$~~	no
	~~$e^+e^- \to K^0K^0\gamma_{\text{ISR}}$~~	no
BABA	~~$e^+e^- \to \mu^+\mu^-$~~	no
	~~$e^+e^- \to \gamma\gamma$~~	no
	~~$e^+e^- \to e^+e^-$~~	no

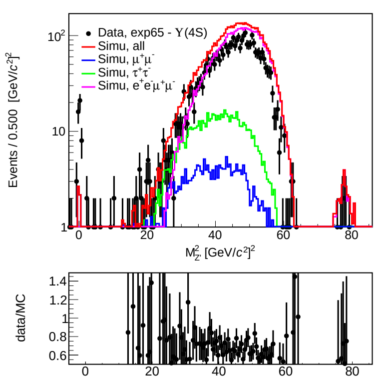
The Punzi Loss Neural Net selection

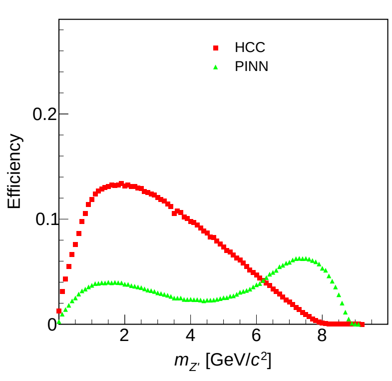


- Layers:
  1. input (32 nodes)
  2. hidden (64 nodes)
  3. hidden (64 nodes)
  4. hidden (32 nodes)
  5. hidden (16 nodes)
  6. hidden (8 nodes)
  7. output (1 node)

- $E^*_{\mu\mu}$
- $\cos\theta^*_{\text{rec}}$
- E_{sum}
- p — value
- ΔM
- ΔM_g
- p_{thrust}
- $p_l\text{min}^{\mu}$
- $p_l\text{max}^{\mu}$
- $p_t^{*Z'}\sin\alpha_M$
- $p_t^{*Z'}\sin\alpha_m$
- $p_t^{\mu\mu}$
- $\angle p_t^{\mu^-}p_{\text{thrust}}$
- $\angle p_t^{\mu^+}p_{\text{thrust}}$

Background sources and detection efficiency

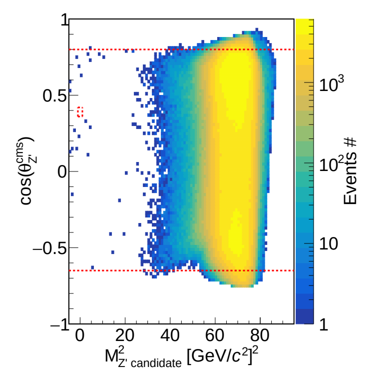




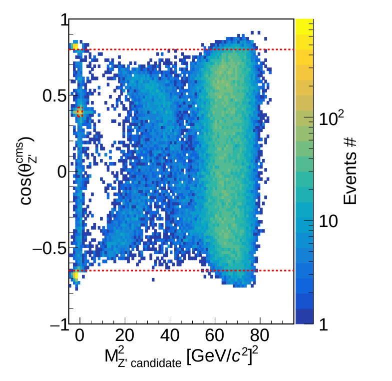
- Hand Crafted Cuts (HCC)
- PINN trained with 60 ab^{-1} MC samples

MC Background and test data sample (5%)

$ee\mu\mu$

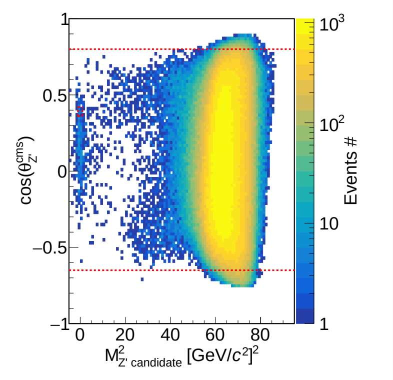


$\mu\mu$

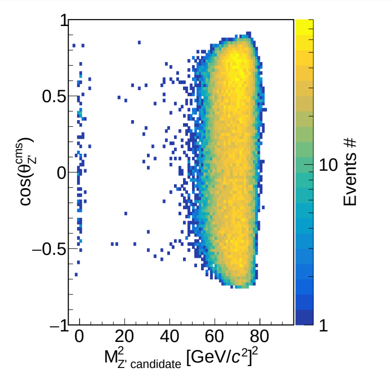


MC Background and test data sample (5%)

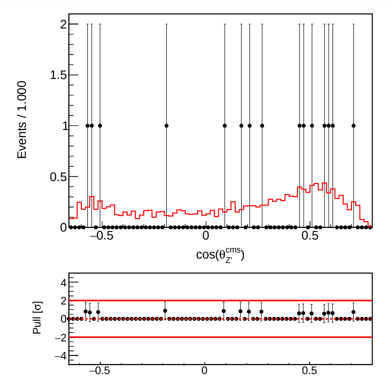
$\tau\tau$

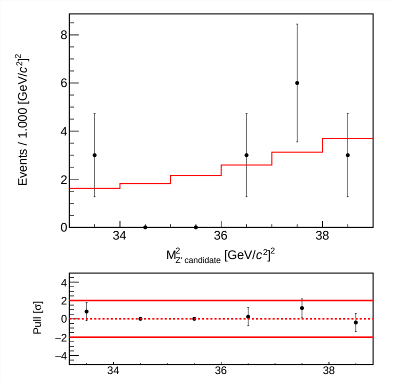


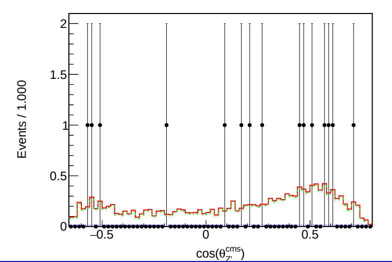
test data sample

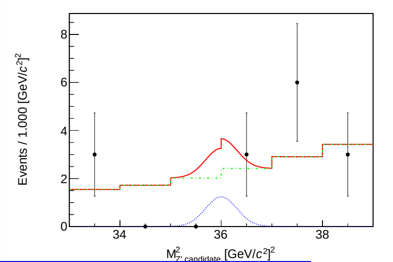


Fit examples: $m'_Z = 6$ GeV$/c^2$

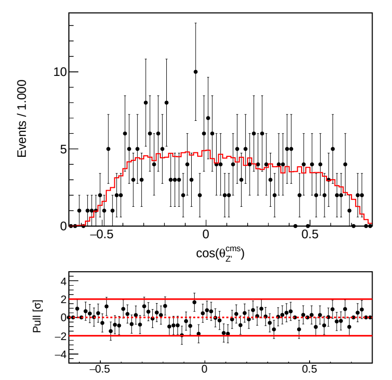


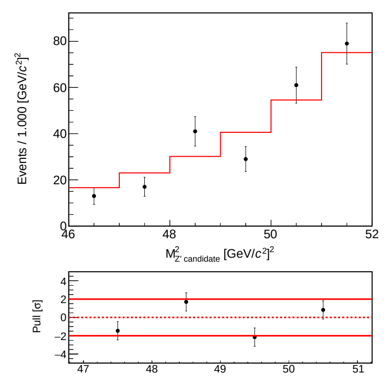


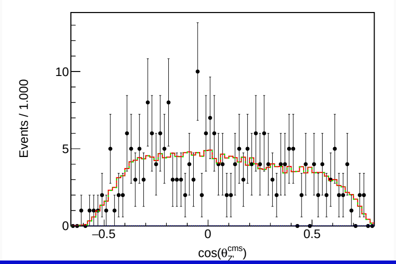


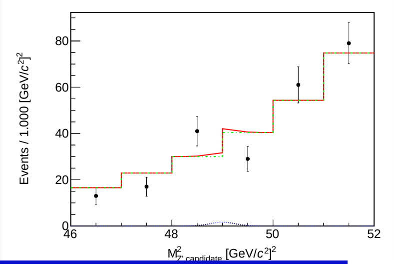


Fit examples: $m'_Z = 7\ \text{GeV}/c^2$

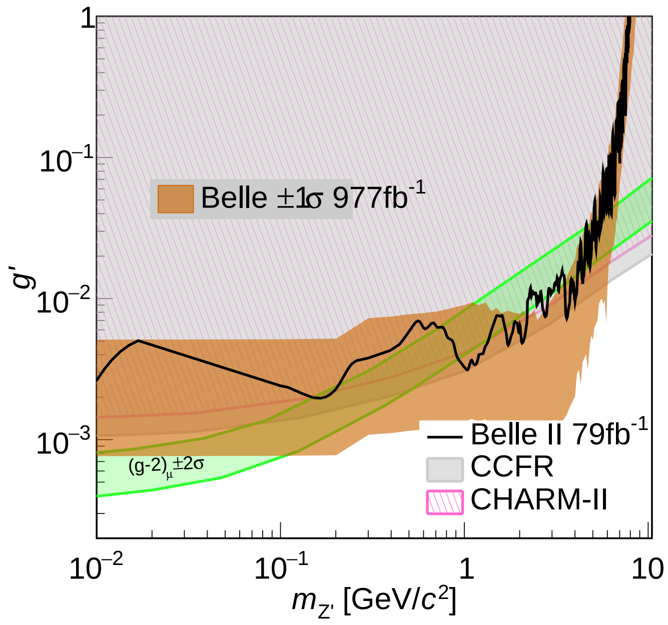








Current g' limit in comparison with Belle II 79.1 fb^{-1}



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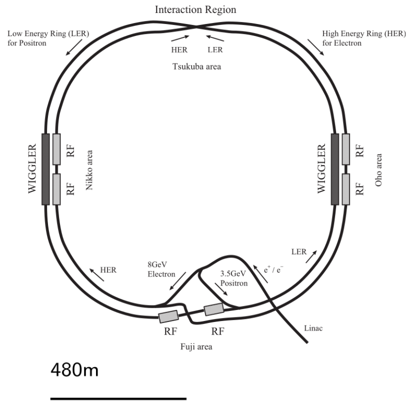
- Belle full data (~1 ab^{-1}) analysis of the Z' invisible hopefully before winter
  - Currently using Belle II machinery tuned to the Belle background and efficiency
- Belle searches are still viable (For a while)
- Belle II machinery can work greatly provided some tuning considering Belle data conditions

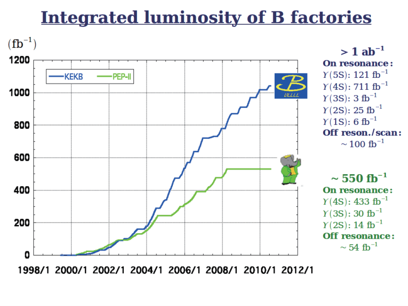
Back up

The KEKB Accelerator

KEKB is an e^+e^- collider made up of two rings, a High Energy Ring, HER and a Low Energy Ring, LER.

Located in Tsukuba and has achieved a record Luminosity of 1 ab^{-1}

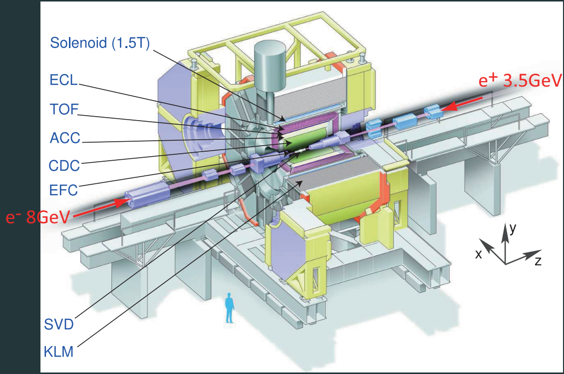




Operated from 1999 to 2010

KEKB together with the Belle detector were responsible for confirming the CPV formalism in the quark sector, the 2008 Nobel Prize of Physics.

The Belle Detector



SVD (Silicon Vertex Detector)

EFC (Extreme Forward Calorimeter)

ACC (Aerogel Cherenkov Counter)

TOF (Time Of Flight)

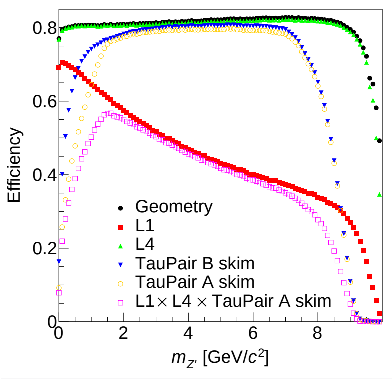
CDC (Central Drift Chamber)

ECL (Electromagnetic Calorimeter)

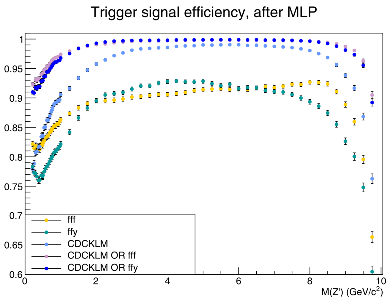
KLM (K_L^0 - μ)

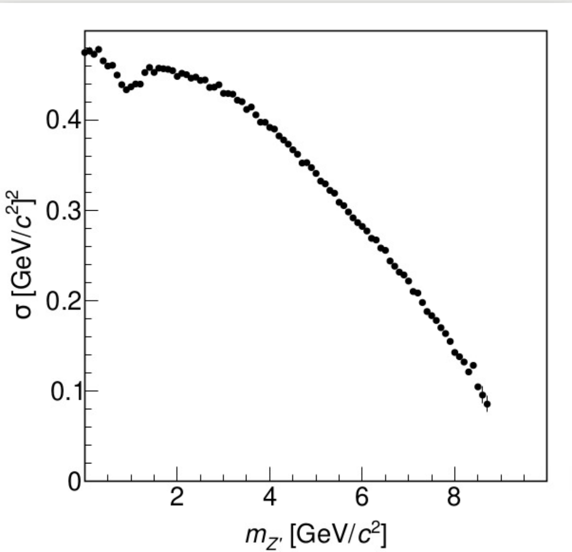
Trigger Efficiency (Signal)

Belle Trigger



Belle II Trigger





Resolution