$e^+e^- \to \mu^+\mu^- Z'(\mu^+\mu^-)$ @ BELLE

FY2021 学術変革領域研究「ダークマター」シンポジウム

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Experiment and Theory Tensions

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

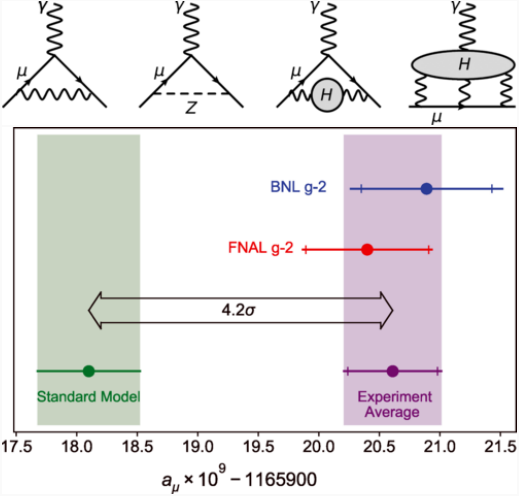
KEKB and Belle

Z' search in B-factories

Summary

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

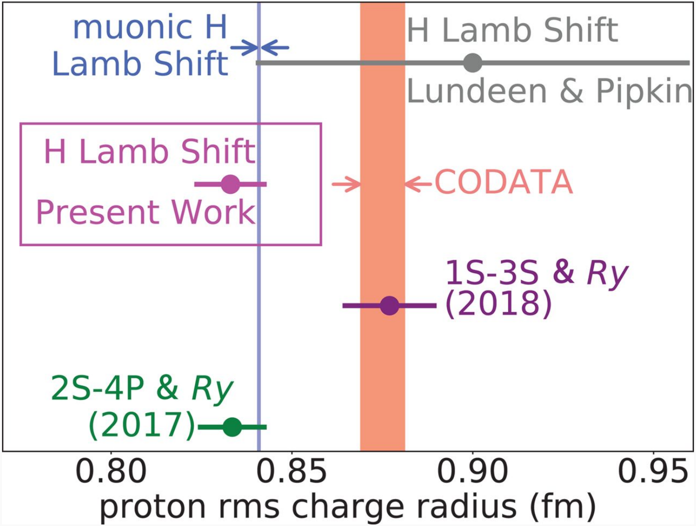
$$\Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11} \text{ corresponding to } 4.2\sigma$$



Tension remains!

Proton size anomaly Science 365, 6457 - 2019

Disagreement between proton size of **muonic** and **regular** Hydrogen



Tension is over!

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 $L_3 = L_\mu - L_\tau$

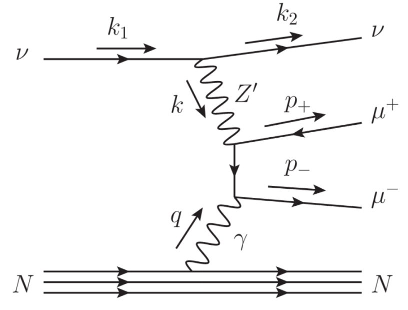
Three different new gauge groups

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



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

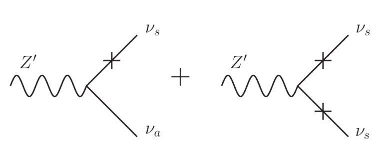
$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}}$$

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!

Z' channel to sterile neutrinos PRD 89, 113004 - 2014

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

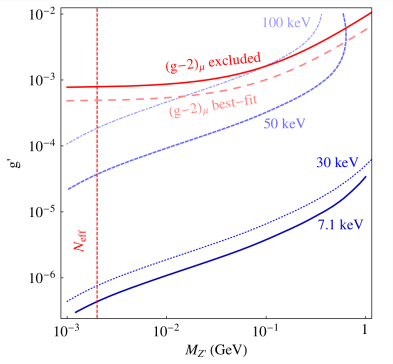


$$\begin{pmatrix}\nu_a\\ \nu_s\end{pmatrix} \equiv \begin{pmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

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

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



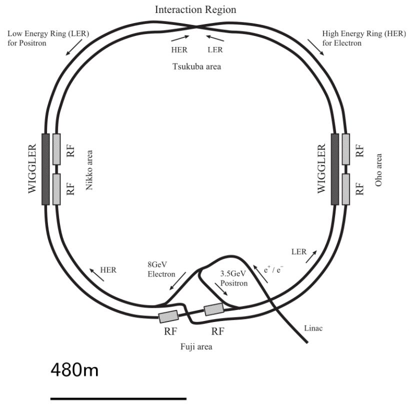
- $M_{Z'} - g'$ plane
- magnetic moment of the muon anomaly favored region
- $N_{\text{eff}} \to M_{Z'} \gtrsim 2.0$ MeV from Planck measurement constraint 1303.5076
- sterile neutrino candidates

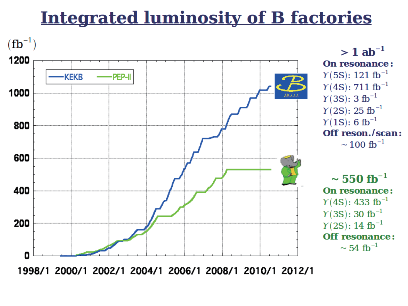
- $m_s = 7.1$ keV $\sin 2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV $\sin 2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV $\sin 2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV $\sin 2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\text{DM}} = 4.7 \times 10^{-4}$ keV$/m_s)$

The KEKB Accelerator

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

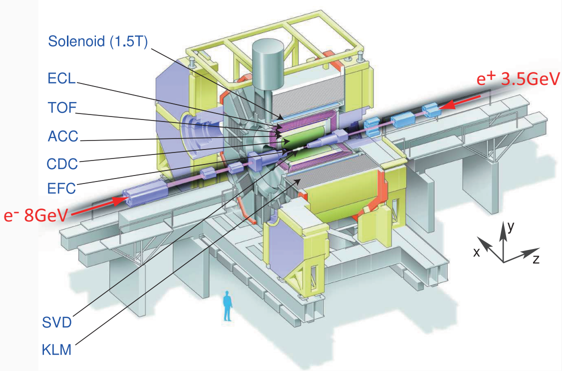
It's located in Tsukuba and has achieved a record Luminosity of 1 ab^{-1}





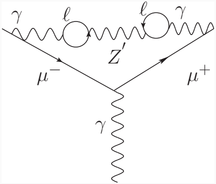
KEKB together with the Belle detector were responsible for confirming the Charge Parity Violation (CPV), the 2008 Nobel Prize of Physics.

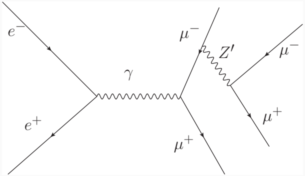
The Belle Detector



- SVD (Silicon Vertex Detector)
- EFC (Extreme Forward Calorimeter)
- ACC (Aerogel Cherenkov Counter)
- TOF (Time Of Flight)
- CDC (Central Drift Chamber)
- ECL (Electromagnetic Calorimeter)
- KLM ($K_L^0 - \mu$)

Z' search in B-factories

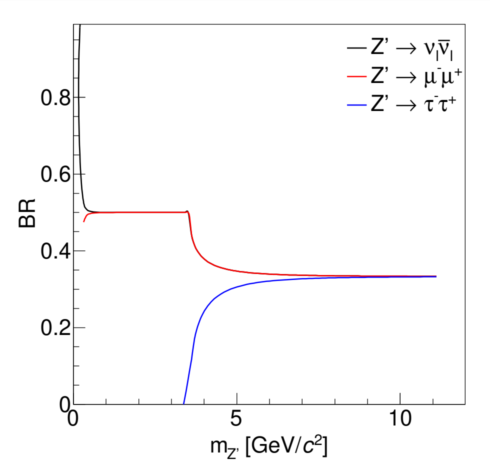




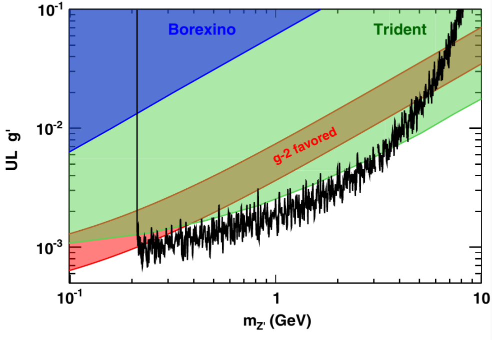
- Motivated by:
  - the $(g-2)_\mu$
  - connection to **sterile neutrinos** as a dark matter candidate
  - a way to relax the Hubble tension (very light Z' (invisible))
    JHEP 2019, 71 - (2019)
- We looked for a Z' signal using 643 fb^{-1} of the total Belle luminosity

Z' decay width and branching ratio

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



Past Search PRD 94 011102 - 2016

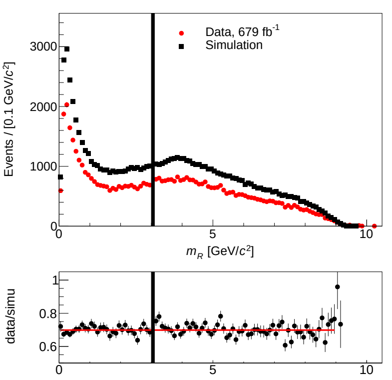


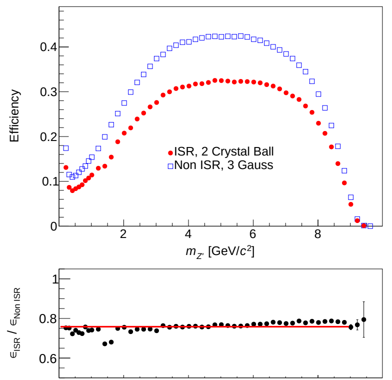
- No Z' signal was found
- limit set for 0.212(dimuon mass)~ 10 GeV$/c^2$
- Z' contribution for the $(g-2)_\mu$ almost excluded

Belle Search 2109.08596

- Z' defined as oppositely charged promptly decayed $\mu^{\pm}$ pair, while two other charged tracks are another $\mu^{\pm}$ pair generated from initial interaction
- **4 charged tracks requirement**
- **2 positive muon** or **2 negative muon** ids requirement
- We also use a kinematic fitter that requires energy and momentum conservation
- using ECL we reject the sum of energies of electromagnetic clusters above 30 MeV not associated with charged tracks that are less than 200 MeV
- $m_{\mu^+\mu^-}$ not in $m_{J/\psi} \pm 0.030$ GeV (J/ψ veto)
- for the $\Upsilon(2S, 3S)$ samples rejection of the $m_{\mu^+\mu^-}$ not in $m_{\Upsilon(1S)} \pm 100$ MeV
- $m_{4\mu}$ in $M_{\text{CMS}} \pm 500$ MeV

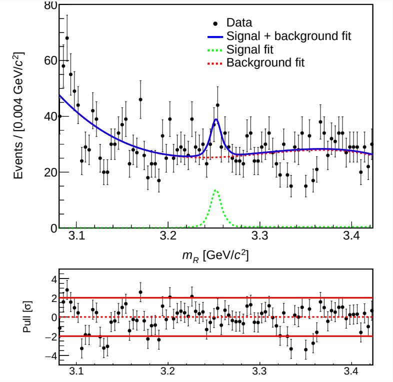
Results 2109.08596

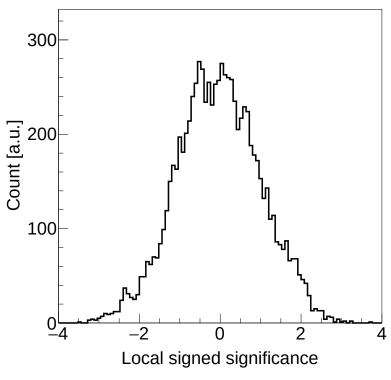




- reduced mass, m_R, scan
  - $m_R = \sqrt{m_{\mu\mu}^2 - 4 m_\mu^{\text{PDG}\,2}}$
- 1 surviving background
  - $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  - non ISR MC

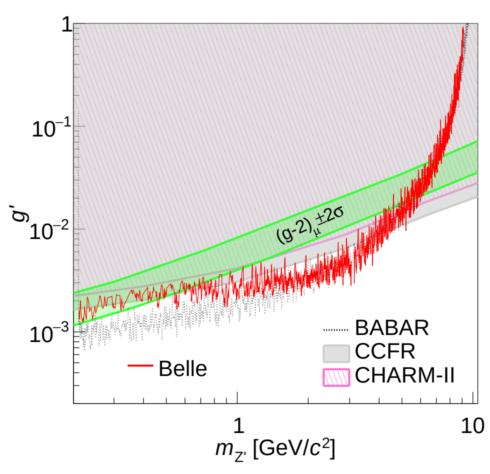
1. MC bkg and data ratio: 0.69
2. $\epsilon_{\text{ISR}}/\epsilon_{\text{NonISR}}$: 0.76
3. 1 and 2 reconciled by the vacuum polarization factor: 0.92





- Two CB single mean for Signal
- Third-order poly for bkg
- Highest local significance 3.72σ
  - $m_{Z'} = 3.26$ GeV$/c^2$
  - $m_R = 3.23$ GeV$/c^2$

Z' coupling 2109.08596



- ISR Signal MC analysis
- Some improvements on middle and high Z' mass g' limit
- Submitted to PRD

Summary

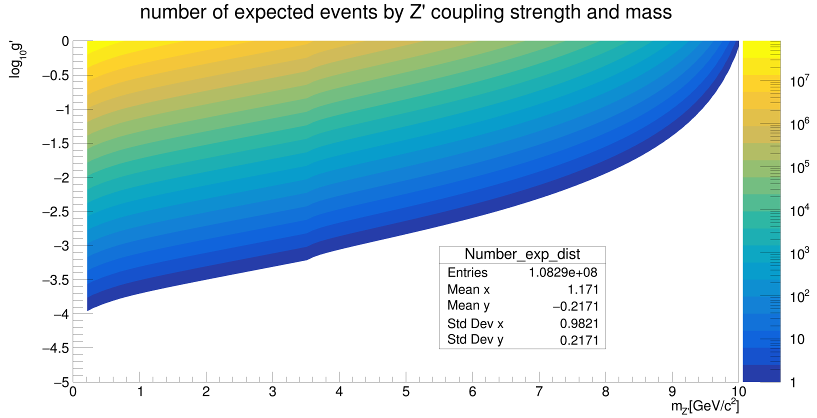
Summary

Leptophylic Z' outlook

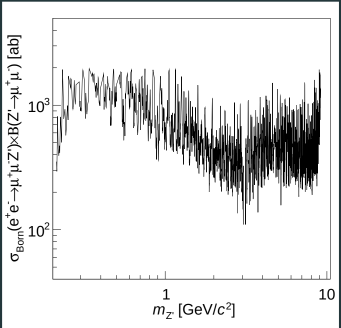
- improvement on invisible channel (Belle II)
- visible channel new measurement (Belle II)
- invisible channel new measurement (Belle)
- kinetic mixing factor reinterpretation
- combination with other dark sector models

Back up

Z' Number of Expected Events



Z' cross section



The visible cross section corresponds to:

$$\sigma_{\mathrm{V}} = \frac{N}{\mathcal{L}\mathcal{B}\epsilon}$$

and the Born cross section is given by:

$$\sigma_{\mathrm{B}} = \frac{N_{\mathrm{ISR}}}{\mathcal{L}\mathcal{B}\epsilon_{\mathrm{ISR}}(1+\delta)|1-\Pi|^2}$$

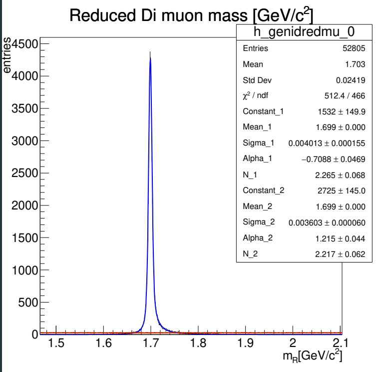
Signal shape based only on true events

Fitting function 2 Crystal Balls with single mean

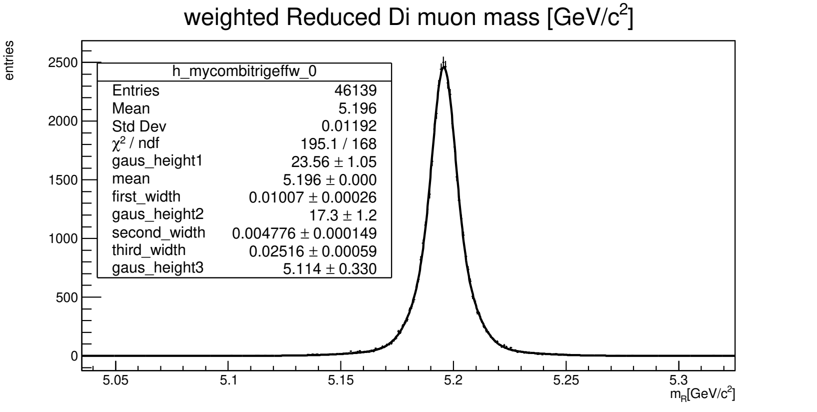
$$f_1(x) = \begin{cases} e^{-\frac{(x-\mu)^2}{2\sigma_1^2}} & \text{if } \frac{x-\mu}{\sigma_1} > -\alpha_1 \\ (C_1 - \frac{x-\mu}{\sigma_1})^{-N_1} & \text{if } \frac{x-\mu}{\sigma_1} < -\alpha_1 \end{cases}$$

$$f_2(x) = \begin{cases} e^{-\frac{(x-\mu)^2}{2\sigma_2^2}} & \text{if } \frac{x-\mu}{\sigma_2} > -\alpha_2 \\ (C_2 - \frac{x-\mu}{\sigma_2})^{-N_2} & \text{if } \frac{x-\mu}{\sigma_2} < -\alpha_2 \end{cases}$$

$$g(x) = x_0 + ax + bx^2 + cx^3$$

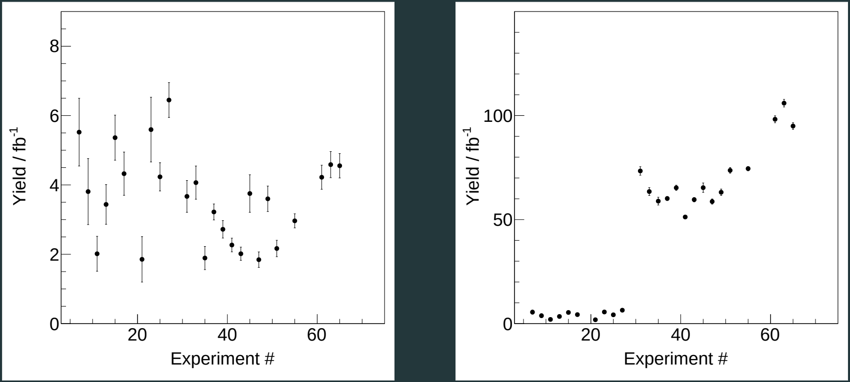


Non ISR sample pdf



Z' resolutions

Belle sample `tauskimA` not usable



`tauskimA(B)`