Dark matter search at BELLE

3rd DMNet 2023 - Padova

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on behalf of the Belle(II) collaborations

2023, September 28th

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What is dark matter (DM)?

- Coma galaxy cluster gravitational mass luminosity discrepancy (Fritz Zwicky - 1937)
- CMB (Cosmic Microwave Background) radiation fluctuations
- Gravitational Lensing
- Galaxy rotation velocity problem

Galaxy Rotation Velocity Problem

PRL 177,201101 - 2016

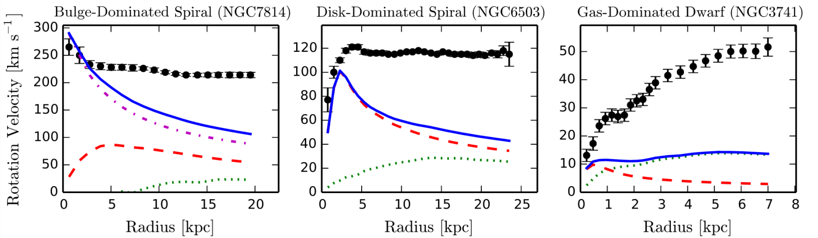
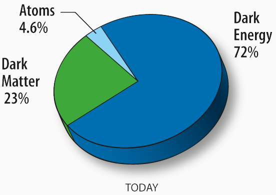


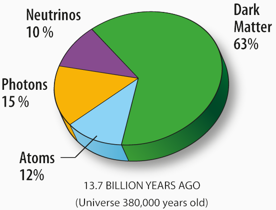
Figure 1: Black dots are the observed rotation velocities. The blue solid line represents all the visible components of the galaxy velocities added together.

There is extra invisible matter!

Weakly Interacting Massive Particle (WIMP) Searches

$$\chi\bar{\chi} \leftrightarrow e^+e^-, \mu^+\mu^-, q\bar{q}, W^+W^-, ZZ, HH, \ldots$$

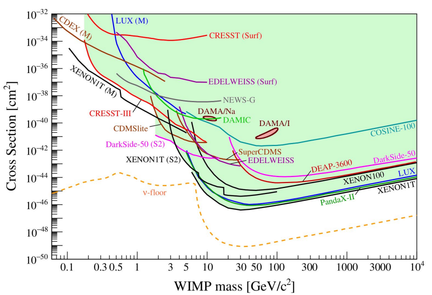


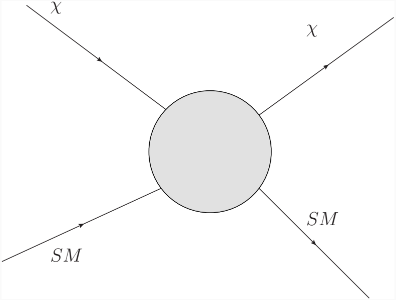


- Naturally produced with the correct thermal relic density (the **WIMP miracle**)
- WIMPS are Beyond the Standard Model candidates
- Prediction of signals that may be seen in the current and near-future experiments, collider experiments and direct detection

WIMP searches gap

APPEC 2021 status



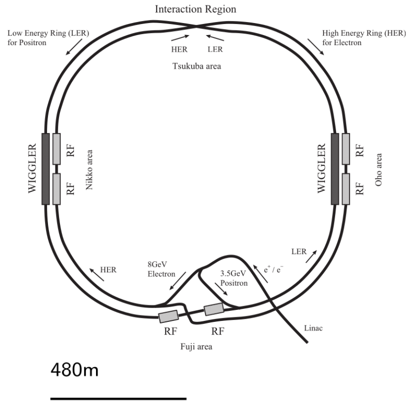


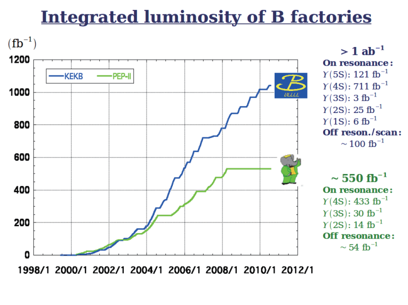
- Sensitive for 10 GeV $\sim$ 1 TeV
- **No Signal Found!** Yet
- under 10 GeV there is a **region without any constraints**, it could be studied by collider experiments

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}

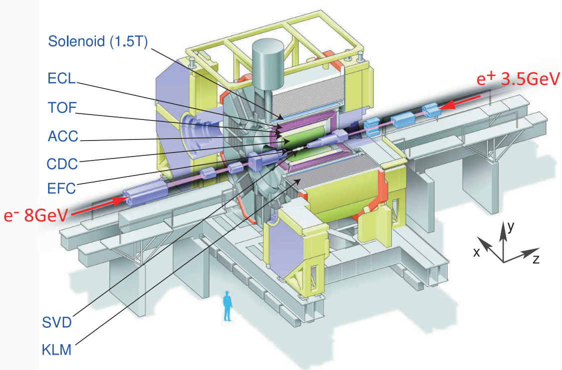




Operated from 1999 to 2010

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^0_L - μ)

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'
   - $e^+e^- \to Z'(\to \mu^+\mu^-)\mu^+\mu^-$
   - Check out Martina's talk on Belle II results
6. Leptophilic Scalar
   - $e^+e^- \to \tau^+\tau^-\phi_L(\to ee, \mu\mu)$
7. Invisible Z'
   - Check out Enrico's talk for Belle II results
   - Check out Laura's talk for Belle II results
   - $Z' \to \nu_l\nu_l(\chi, \bar{\chi})$
8. Dark photon

$(g-2)_\mu$ 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**~~
    - Apparently not, check Giovanni's talk from yesterday
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 $L_3 = L_\mu - L_\tau$

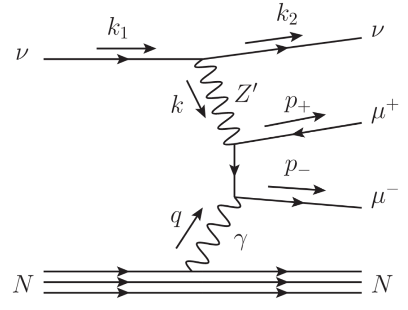
Three different new gauge groups

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



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

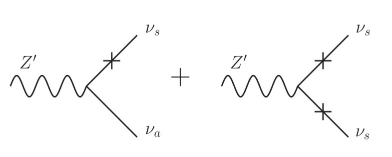
$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}}$$

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.

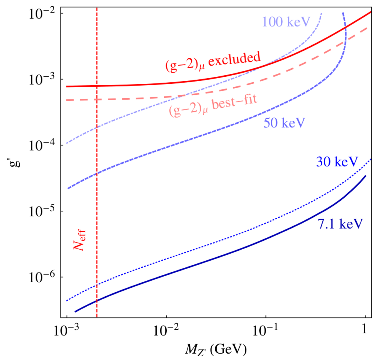


$$\begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

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

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

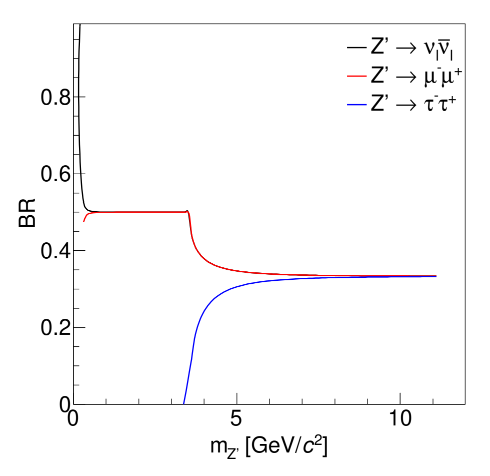


- $M_{Z'} - g'$ plane
- Magnetic moment of the muon anomaly favored region
- $N_{\text{eff}} \to M_{Z'} \gtrsim 2.0$ MeV from Planck measurement constraint 1303.5076
- Sterile neutrino candidates

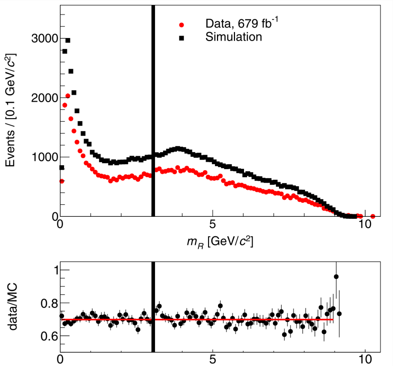
- $m_s = 7.1$ keV $\sin 2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV $\sin 2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV $\sin 2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV $\sin 2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\text{DM}} = 4.7 \times 10^{-4}$ keV$/m_s)$

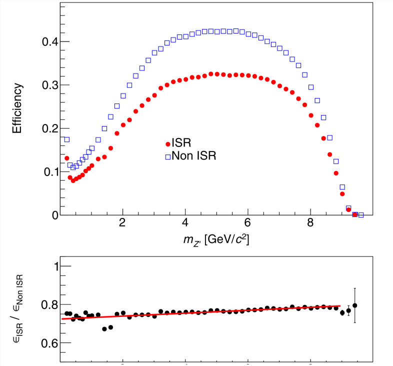
Z' decay width and Branching Ratio (BR)

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



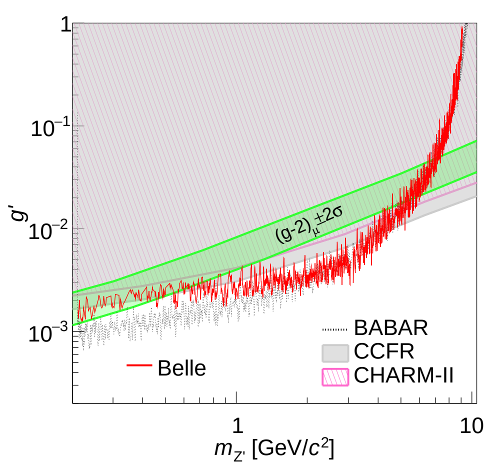
Past Z' Search @ Belle Analysis PRD 106 012003 - 2022





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

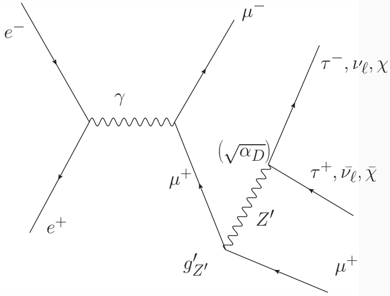
Past Z' Search @ Belle Results PRD 106 012003 - 2022



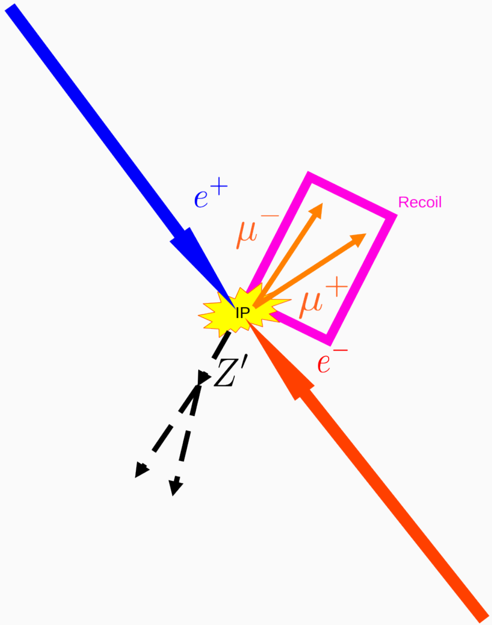
- No Z' signal was found
- Limit set for 0.212(dimuon mass)$\sim$ 10 GeV$/c^2$

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

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



What does it look like?



$Z' \to$ invisible handmade selection

How were the cuts elaborated?

- 2D histogram $x : M^2_{Z'}$
- Signal resolution σ is obtained under the studied cut
- ε detection efficiency at fixed Z' mass under cuts
- B is the integration of backgrounds around ($\pm 3\sigma$) Z' mass
- $\frac{\varepsilon}{\sqrt{B}}$ maximized

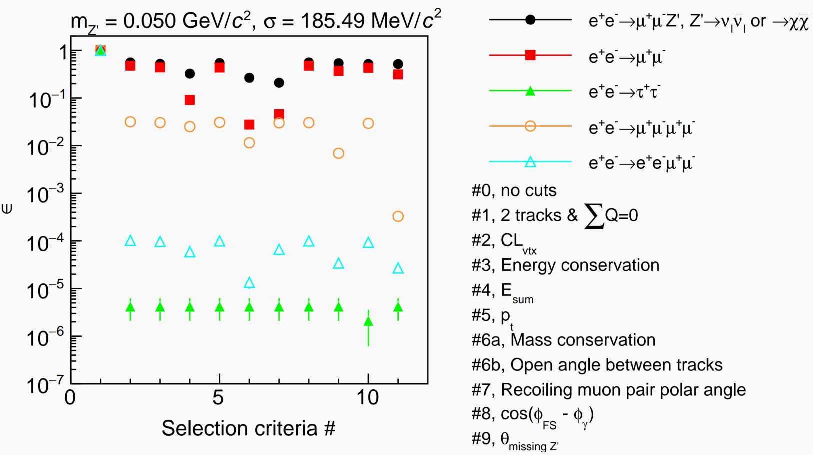
Background sources

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

Z' invisible selection criteria list

1. 2 tracks of opposite charge only, 2 μ ID
2. Vertex fit of the the 2 tracks, CL cut
3. Energy conservation dependent on $M_{Z'}^2 = s + m_{\mu\mu}^2 - 2E_{\mu\mu}^* \sqrt{s}$
4. Energy sum of neutral cluster, ECL
5. p_t of the two tracks sum dependent on $M_{Z'}$
6. 6.1 Mass conservation on $M_{Z'}$
   6.2 Opening angle between tracks
7. Recoil muon pair polar angle
8. Azimuthal angle difference between final state 4-vector and neutral clusters
9. Z' missing angle cut
10. $p_t^{*Z'}$ projection on $p_{\mathrm{max}}^{*\mu}$ and $p_{\mathrm{min}}^{*\mu}$

Cut effects on $m_{Z'} = 50$ MeV$/c^2$ $\sigma = 185.5$ MeV$/c^2$

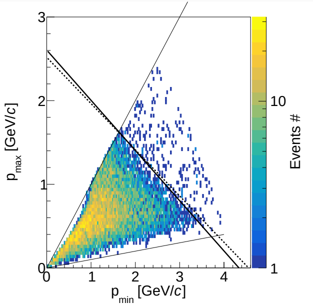


Diagonal cut

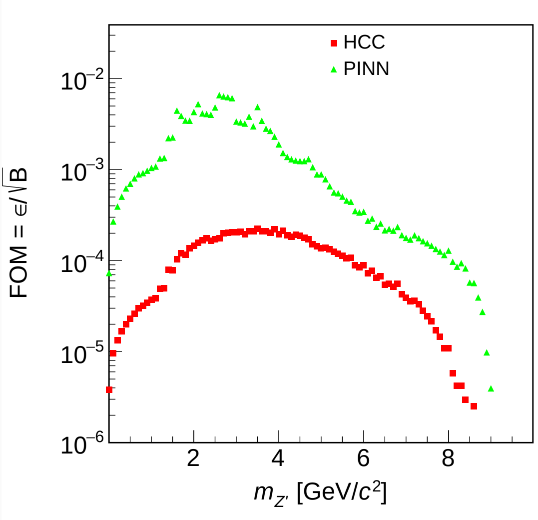
$e^+e^- \to \tau^+\tau^-$

- Missing transverse momentum in cms: $p_t^{*Z'}$
- Maximum momentum muon in cms: $p_{\text{max}}^{*\mu}$
- Minimum momentum muon in cms: $p_{\text{min}}^{*\mu}$

- $\angle \mathbf{p}_t^{*Z'} \mathbf{p}_{\text{max}}^{*\mu} \equiv \alpha_M$
- $\angle \mathbf{p}_t^{*Z'} \mathbf{p}_{\text{min}}^{*\mu} \equiv \alpha_m$
- Projection: $p_t^{*Z'} \sin \alpha_M \equiv p_{\text{max}}$
- Projection: $p_t^{*Z'} \sin \alpha_m \equiv p_{\text{min}}$

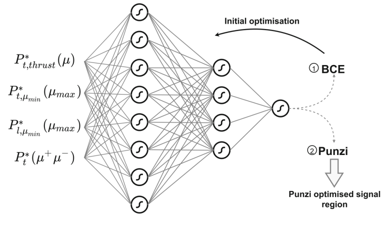


FOM comparison



The Neural Net outperforms the handmade cuts!

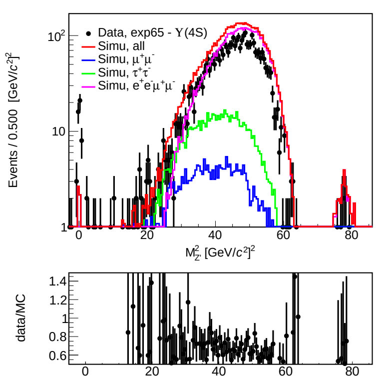
The Punzi Loss Neural Net selection

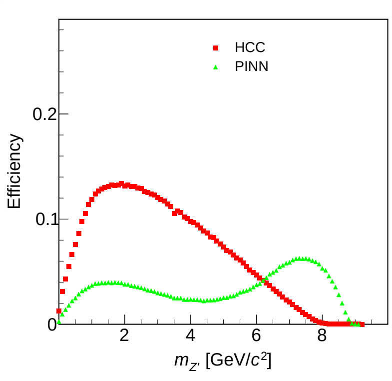


- Layers:
  1. input (32 nodes)
  2. hidden (64 nodes)
  3. hidden (64 nodes)
  4. hidden (32 nodes)
  5. hidden (16 nodes)
  6. hidden (8 nodes)
  7. output (1 node)

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

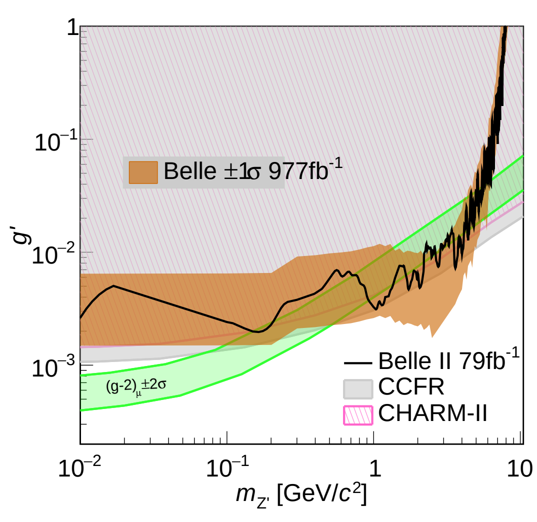
Background sources and detection efficiency





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

Preliminary Limit in Comparison with Belle II 79.1 fb^{-1}

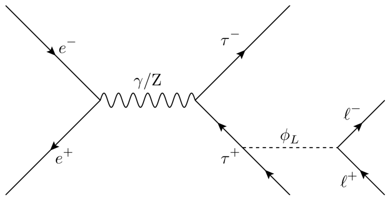


- Belle II has a much better data for the $Z' \to$ invisible

What if instead of the vector boson mediator (Z', A') a leptophilic dark Higgs (ϕ_L) is responsible for $(g-2)_\mu$?

$\mathcal{L} = -\xi \sum_\ell \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$

ϕ_L production



- ℓ are all leptons, and m_ℓ their masses
- ξ is the coupling strength
- $v = 246$ GeV is the vacuum expectation value of the Higgs Field

Search for the ϕ_L at Belle 2207.07476

Signal decay modes (MadGraph 5)

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

1. $\phi_L \to e^+e^-$ for $m_{\phi_L} \leq 2m_\mu$
2. $\phi_L \to \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu(\tau)$

Data sample and backgrounds

- 626 fb^{-1} $= 562(\Upsilon(4S)) + 64(\Upsilon(4S) - 60$ MeV)

1. $e^+e^- \to q\bar{q}$, $q = u, d, s, c$
2. $e^+e^- \to \ell^+\ell^-$, $\ell = e, \mu, \tau$
3. unsimulated $e^+e^- \to \tau^+\tau^- e(\mu)^+ e(\mu)^-$

Selection Criteria 2207.07476

1. events with 4 track
2. Transverse distance from IP < 1 cm
3. Longitudinal distance from IP < 5 cm
4. Net charge of the event is zero
5. At least one track ID is μ or e

Reconstruction

1. ϕ_L from ee or $\mu\mu$ common vertex
2. remaining 2 tracks are daughters from τ
3. Efficiencies corresponding to 98% and 83%

Major background

- $e^+e^- \to \tau\tau$
- to remove radiative Bhabha ($\mu\mu$) a rectangular cut
    1. $M_{\text{miss}} \in [2, 6]$ GeV$/c^2$
    2. $\theta_{\text{miss}}^{\text{CM}} \in [30^\circ, 150^\circ]$

Analysis 2207.07476

To suppress the surviving background a boosted decision tree (BDT), `GradientBoostingClassifier` from `scikit-learn` assigns 5 BDT scores

Signal

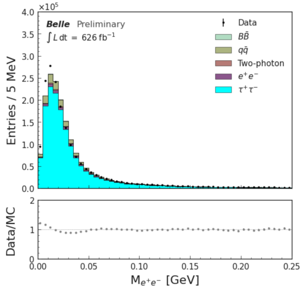
1. $\phi_L \to e^+e^-(\mu^+\mu^-)$

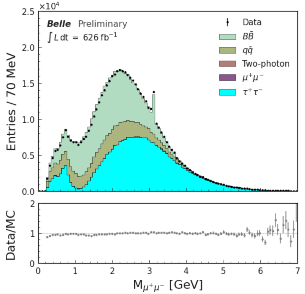
Background

2. $\tau^+\tau^-$
3. $e^+e^-(\mu^+\mu^-)$
4. $q\bar{q}$
5. $B\bar{B}$

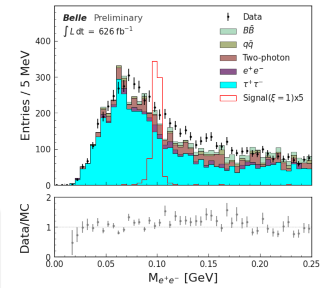
Results: GCR and SR 2207.07476

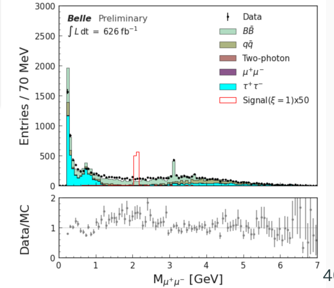
Background



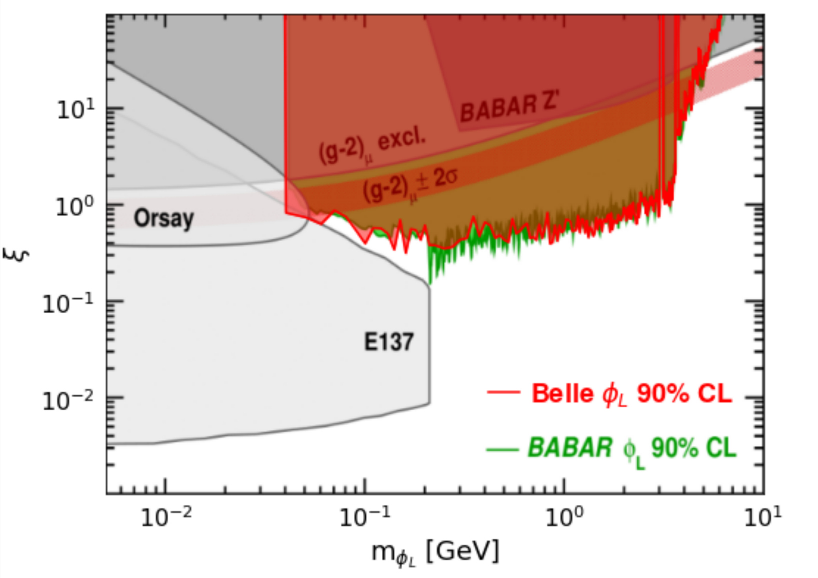


Signal





Results: ξ coupling limit 2207.07476



- Finally touching very low mass parameter spaces in Belle

Summary

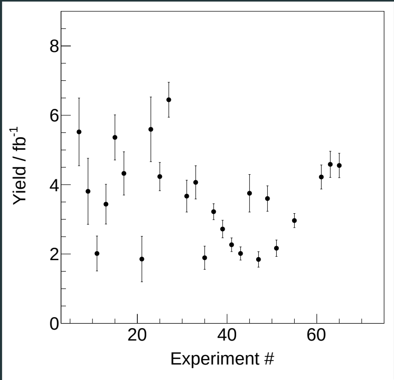
- Belle full data (~1 ab^{-1}) analysis of the Z' invisible hopefully before winter
  - Currently using Belle II machinery tuned to the Belle background and efficiency
- Belle searches are still viable (For a while)
- Belle II machinery can work greatly provided some tuning considering Belle data conditions

Back up

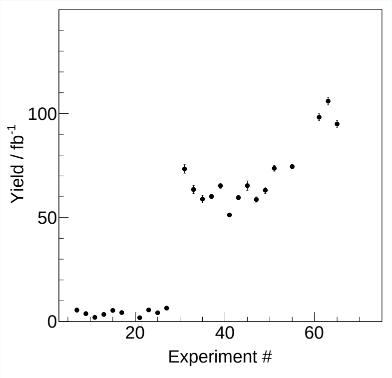
Z’ visible search @ Belle

What did we learn in the Z' visible search?

HadronB skim



tauskimA



tauskimA

$2 \leq q \leq$ **8**
$|$**charge sum**$| \leq 2$
$\sum P^{\text{CM}} < 10$ **GeV**$/c$
$\sum E(ECL) < 10$ **GeV**$/c$
$P_{t\text{max}} > 0.5$ **GeV**$/c$
Evt vtx $|r| < 0.5$ **cm,** $|z| < 3$ **cm**
for 2 tracks events

- **Sum of** $P^{\text{CM}} < 9$ **GeV**$/c$
- **Sum of** $E(ECL) < 9$ **GeV**
- $5 < \theta_{\text{missingmomentum}} < 175^\circ$

$E_{\text{rec}} > 3$ **GeV or** $P_t\text{max} > 1.0$ **GeV**$/c$
for $2 \sim 4$ **charged tracks**

- $E_{\text{tot}} < 9$ **GeV or max opening angle** $< 175^\circ$
- $N_{\text{barrel}} \geq 2$ **or** $E(ECL)_{\text{trk}} < 5.3$ **GeV**

Too tight for the visible $Z^{'}$

tauskimB

$P_{t\text{max}} > 0.5$ **GeV**$/c$

$2 \leq q \leq$ **8**

$|$**charge sum**$| \leq 2$

$\cancel{\sum P^{\text{CM}} < 10 \text{ GeV}/c}$

$\cancel{\sum E(ECL) < 10 \text{ GeV}/c}$

Evt vtx $|r| < 1.0$ **cm,** $|z| < 3$ **cm**

for 2 tracks events

- **Sum of** $E(ECL) < 11$ **GeV**
- ~~**Sum of**~~ $\cancel{P^{\text{CM}} < 9 \text{ GeV}/c}$
- $5 < \theta_{\text{missingmomentum}} < 175^{\circ}$

$E_{\text{rec}} > 3$ **GeV or** $P_t\text{max} > 1.0$ **GeV**$/c$

for $2 \sim 4$ **charged tracks**

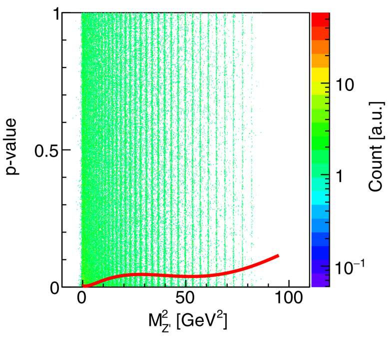
- $E_{\text{tot}} < 9$ **GeV or max opening angle** $< 175^{\circ}$ **or** $2 < \sum E(ECL) < 9$ **GeV**
- $N_{\text{barrel}} \geq 2$ **or** $E(ECL)_{\text{trk}} < 5.3$ **GeV**

Too loose for the invisible $Z^{'}$

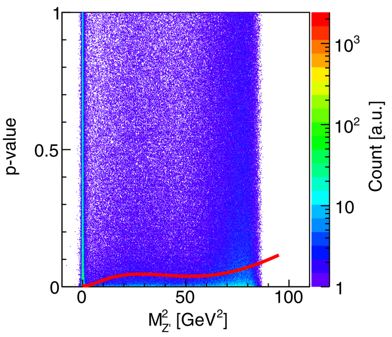
Z' invisible search @ Belle

Cut example: `p-value`

Track quality, `p-value`, based on Vertex Fitter

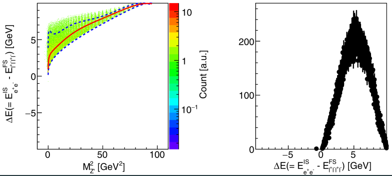


Selection curve for all $Z^{'}$ mass hypotheses signal MC.

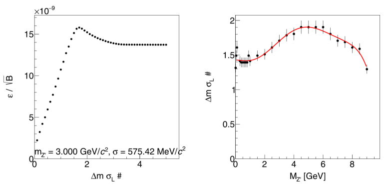


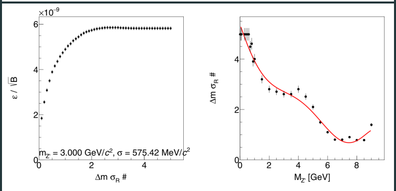
Selection curve for exp65 data.

Cut example: ΔE



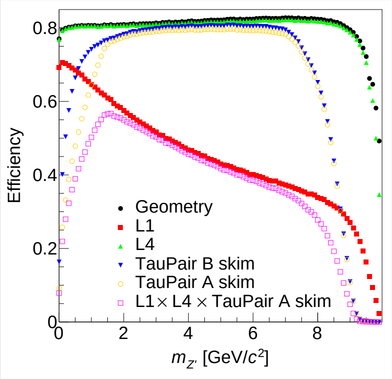
How many σ should be taken to maximize FOM?





Trigger Efficiency (Signal)

Belle Trigger



Belle II Trigger