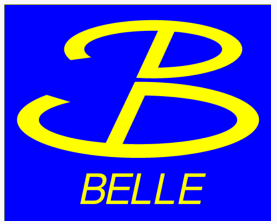
Dark matter search at Belle



3rd DMNet 2023 - Padova

Thomas Czank

2023, September 28th

TOKYO METROPOLITAN UNIVERSITY
東京都立大学

Experiment and Theory Tension

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

KEKB and Belle

Z' searches in Belle

The invisible Z' search

Punzi Loss Neural Net

The leptophilic scalar search @ Belle

Summary

Experiment and Theory Tension

$(g-2)_\mu$ 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

2 options

1. The gap between SM and the Experimental result can be bridged with an improved calculation of a_μ^{SM}
2. **New Physics is the reason for the gap**

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

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 $L_3 = L_\mu - L_\tau$

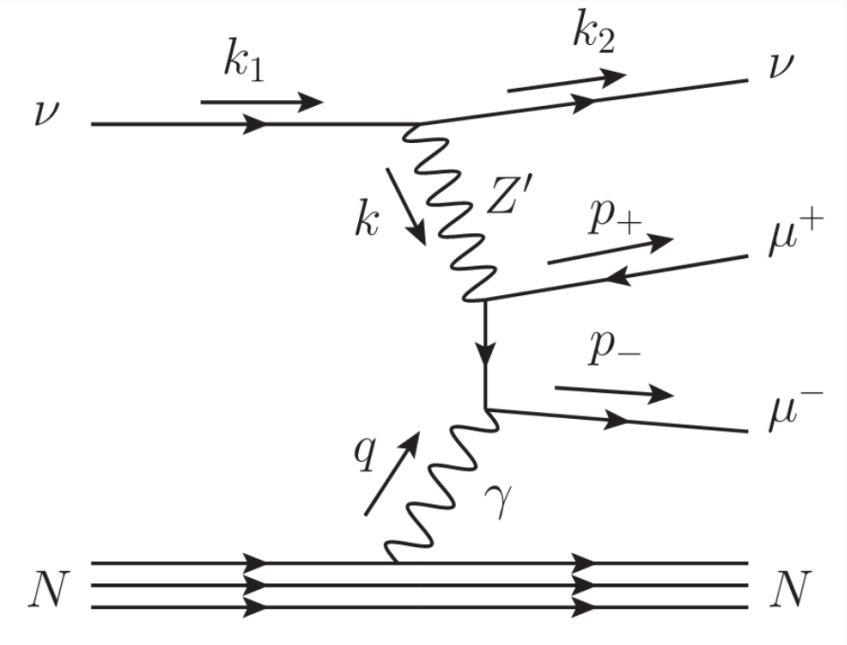
Three different new gauge groups

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



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

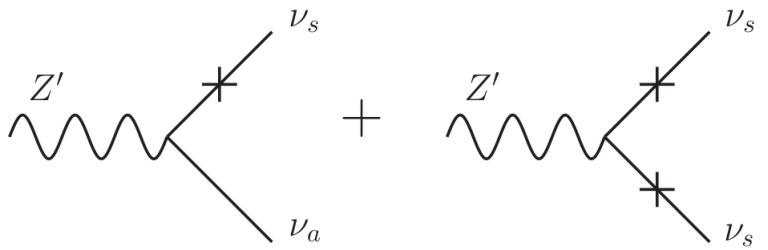
$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}}$$

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.

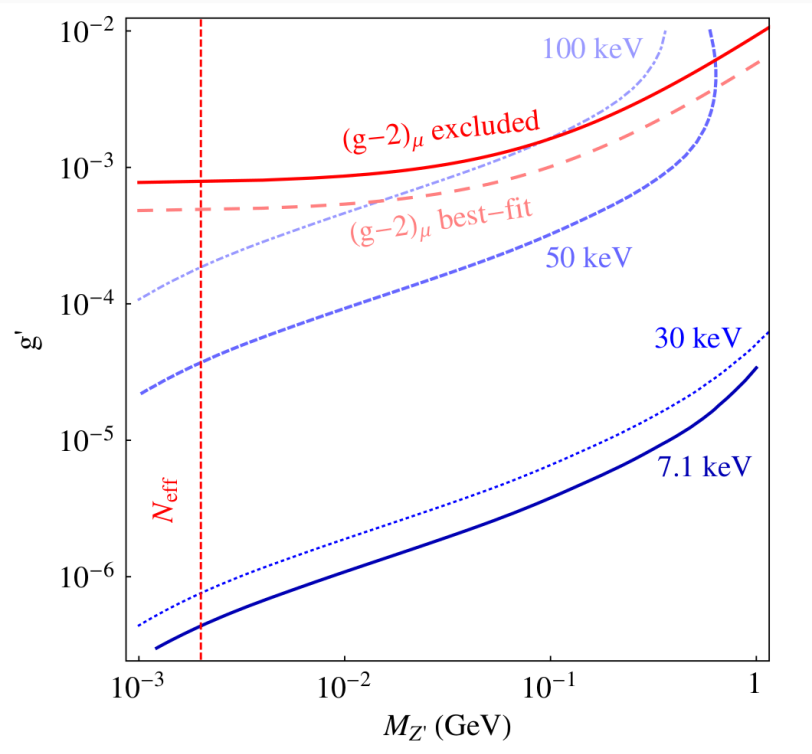


$$\begin{pmatrix}\nu_a\\ \nu_s\end{pmatrix} \equiv \begin{pmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

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

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
- $N_{\rm eff} \rightarrow M_{Z'} \gtrsim 2.0$ MeV from Planck measurement constraint 1303.5076
- Sterile neutrino candidates

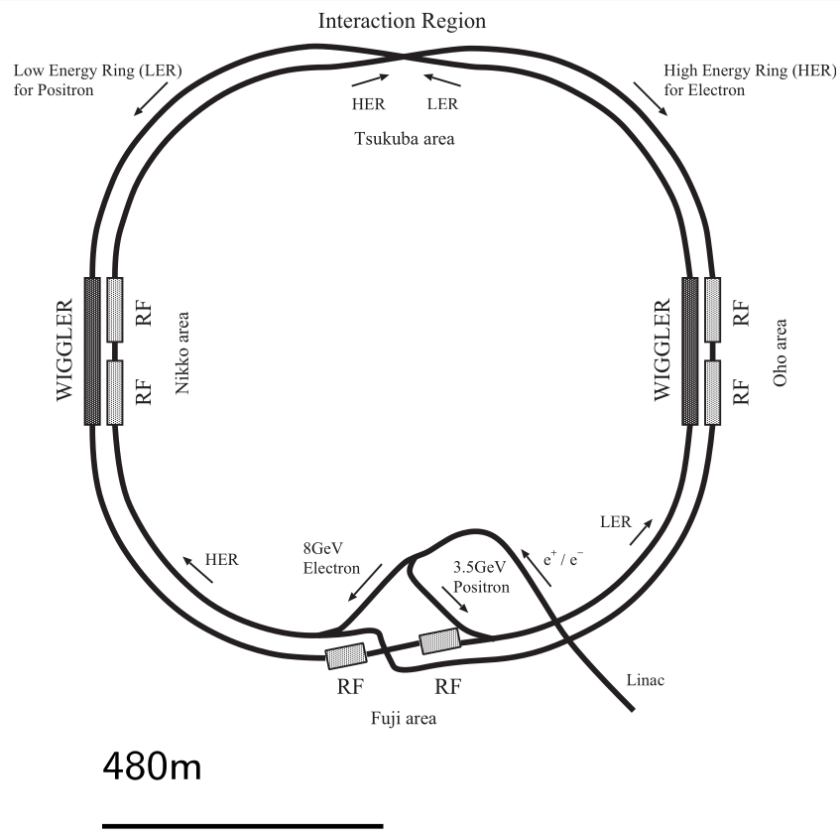
- $m_s = 7.1$ keV $\sin 2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV $\sin 2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV $\sin 2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV $\sin 2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\rm DM} = 4.7 \times 10^{-4}\ {\rm keV}/m_s)$

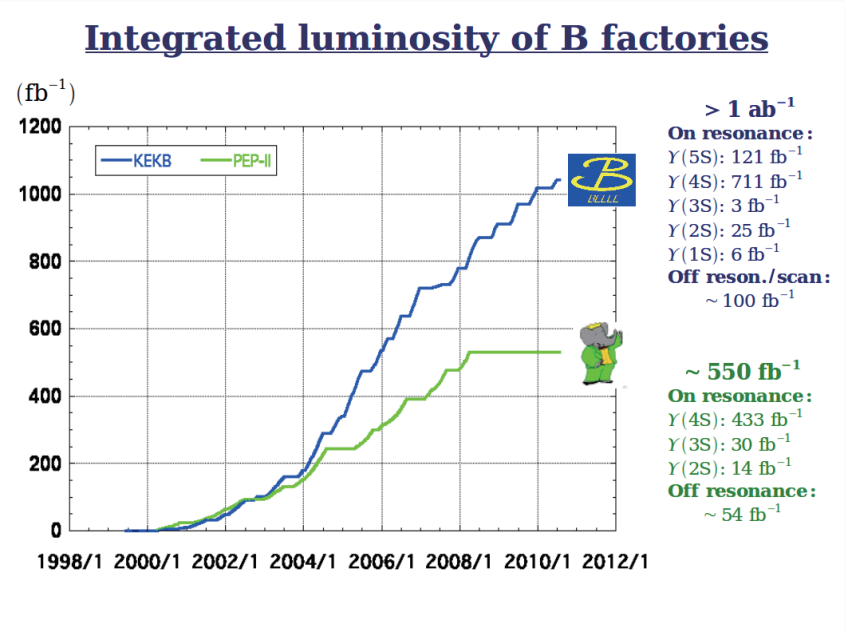
KEKB and Belle

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.

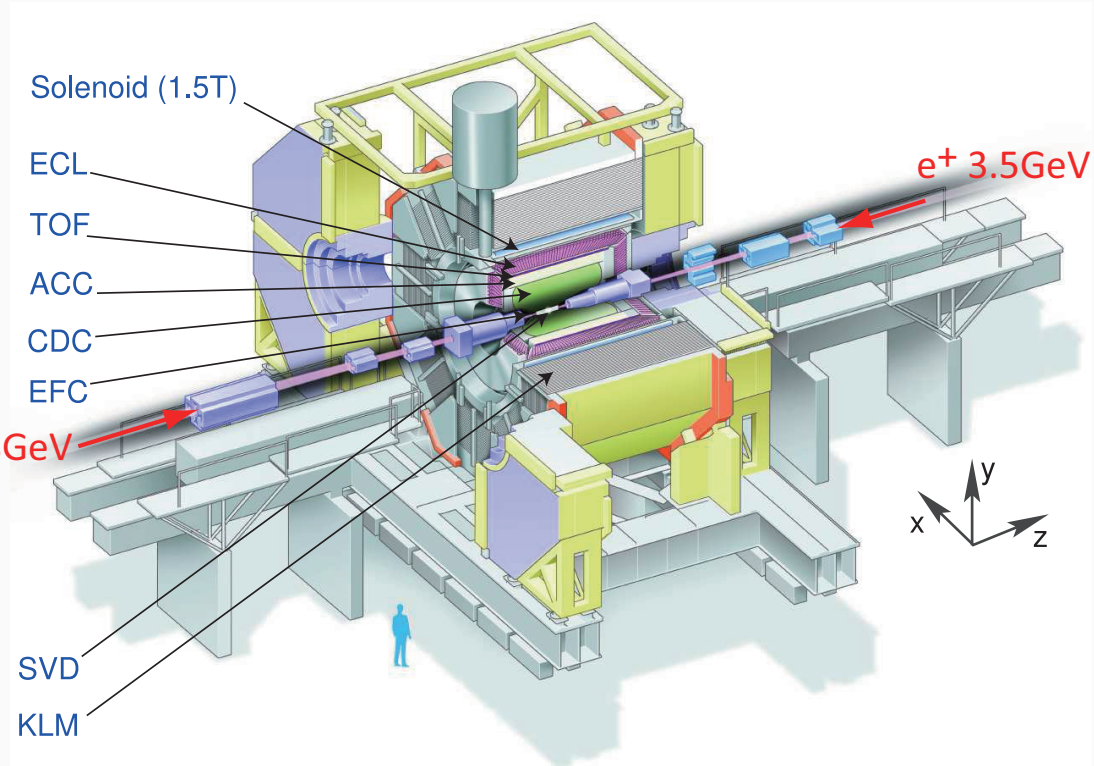
Located in Tsukuba and has achieved a record Luminosity of 1 ab^{-1}





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

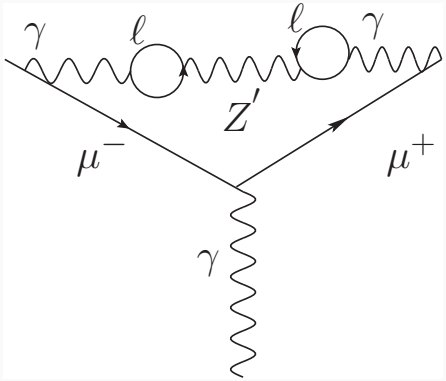
The Belle Detector

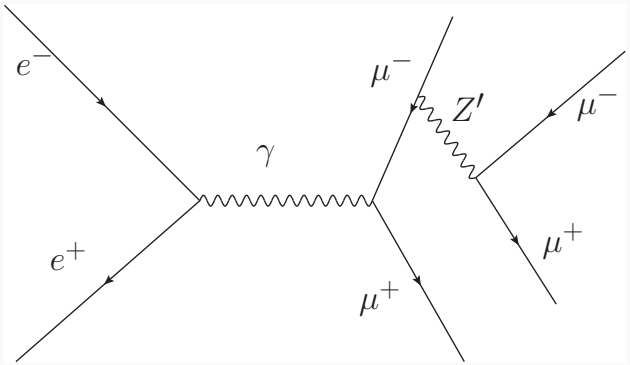


- SVD (Silicon Vertex Detector)
- EFC (Extreme Forward Calorimeter)
- ACC (Aerogel Cherenkov Counter)
- TOF (Time Of Flight)
- CDC (Central Drift Chamber)
- ECL (Electromagnetic Calorimeter)
- KLM (K_L^0 - μ)

Z' searches in Belle

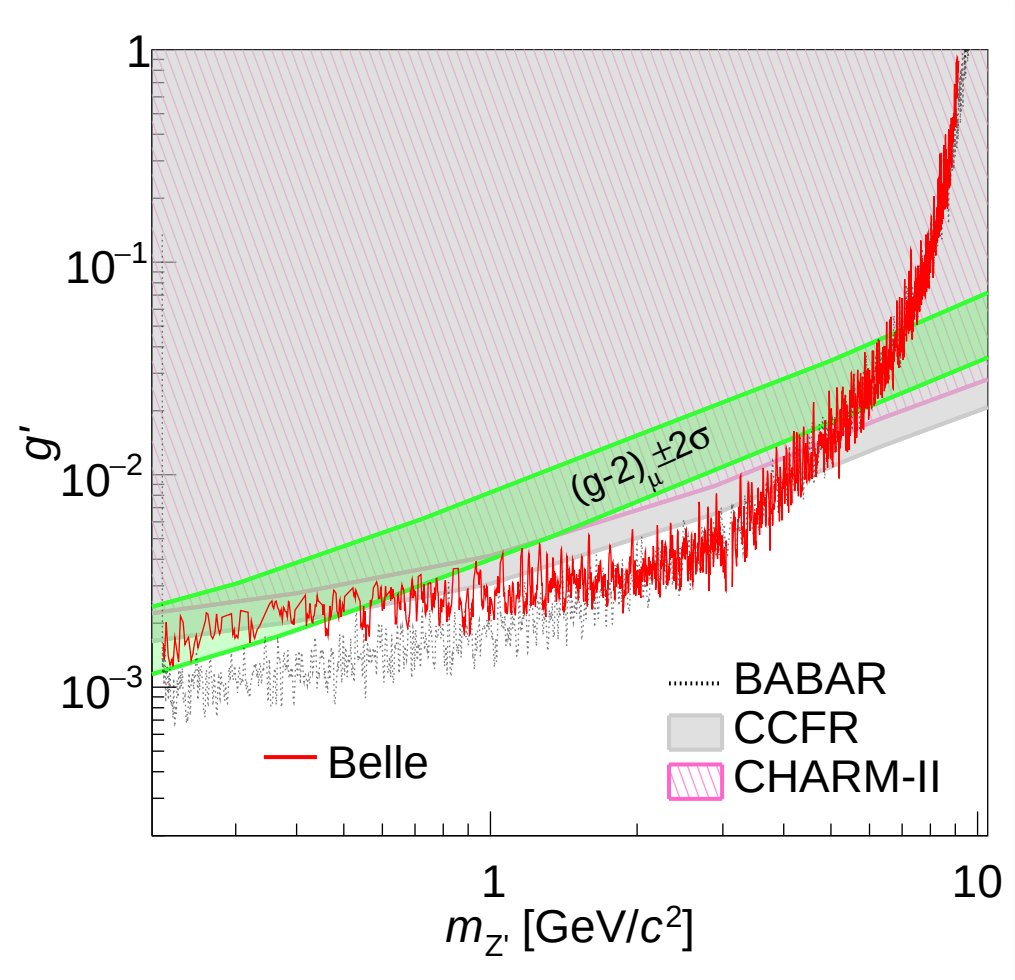
Z' search modes in B-factories





- Motivated by:
  - the $(g-2)_\mu$
  - connection to **sterile neutrinos** as a dark matter candidate
- $Z' \to \mu^+\mu^-$
  - Martina's talk on Belle II results
- $Z' \to$ invisible
  - $Z' \to \nu\nu$
  - $Z' \to \chi\bar{\chi}$
  - $Z' \to e^-\mu^+$ (LFV)
- $\phi_L \to \ell^+\ell^-$
- $A' \to \ell^+\ell^-$

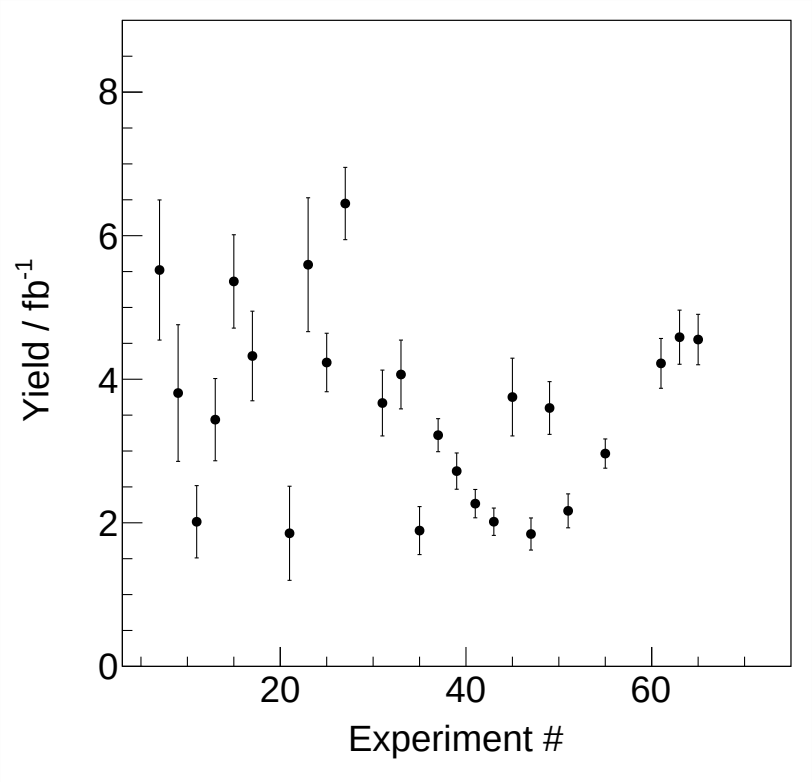
Past Z′ Search @ Belle PRD 106 012003 - 2022



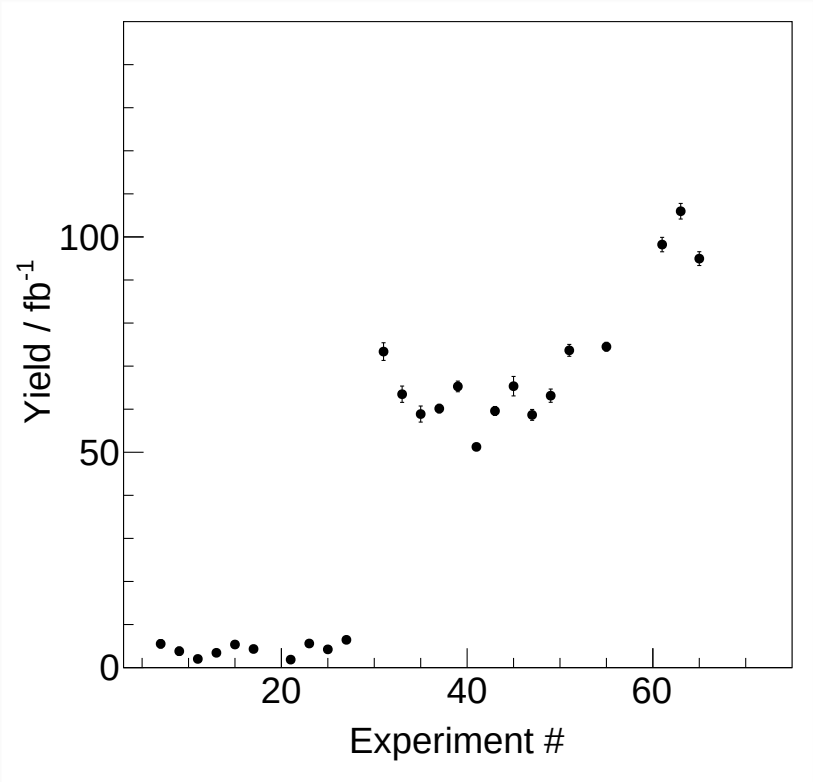
- No Z' signal was found
- Limit set for 0.212(dimuon mass)~ 10 GeV$/c^2$
- Z' contribution for the $(g-2)_\mu$ almost excluded

What did we learn in the Z' visible search?

HadronB skim



tauskimA



Definitions of tauskimA(B)

tauskimA

1. $2 \leq$ # q tracks ≤ 8
2. $|$charge sum$| \leq 2$
3. $\sum P^{\mathrm{CM}} < 10$ GeV$/c$
4. $\sum E(ECL) < 10$ GeV$/c$
5. $P_{t\mathrm{max}} > 0.5$ GeV$/c$
6. Evt vtx $|r| < 0.5$ cm, $|z| < 3$ cm
7. for 2 tracks events
   - 7.1 Sum of $P^{\mathrm{CM}} < 9$ GeV$/c$
   - 7.2 Sum of $E(ECL) < 9$ GeV
   - 7.3 $5 < \theta_{\mathrm{missingmomentum}} < 175^\circ$
8. $E_{\mathrm{rec}} > 3$ GeV or $P_t\mathrm{max} > 1.0$ GeV$/c$
9. for $2 \sim 4$ charged tracks
   - 9.1 $E_{\mathrm{tot}} < 9$ GeV or max opening angle $< 175^\circ$
   - 9.2 $N_{\mathrm{barrel}} \geq 2$ or $E(ECL)_{\mathrm{trk}} < 5.3$ GeV

Too tight for the visible Z'

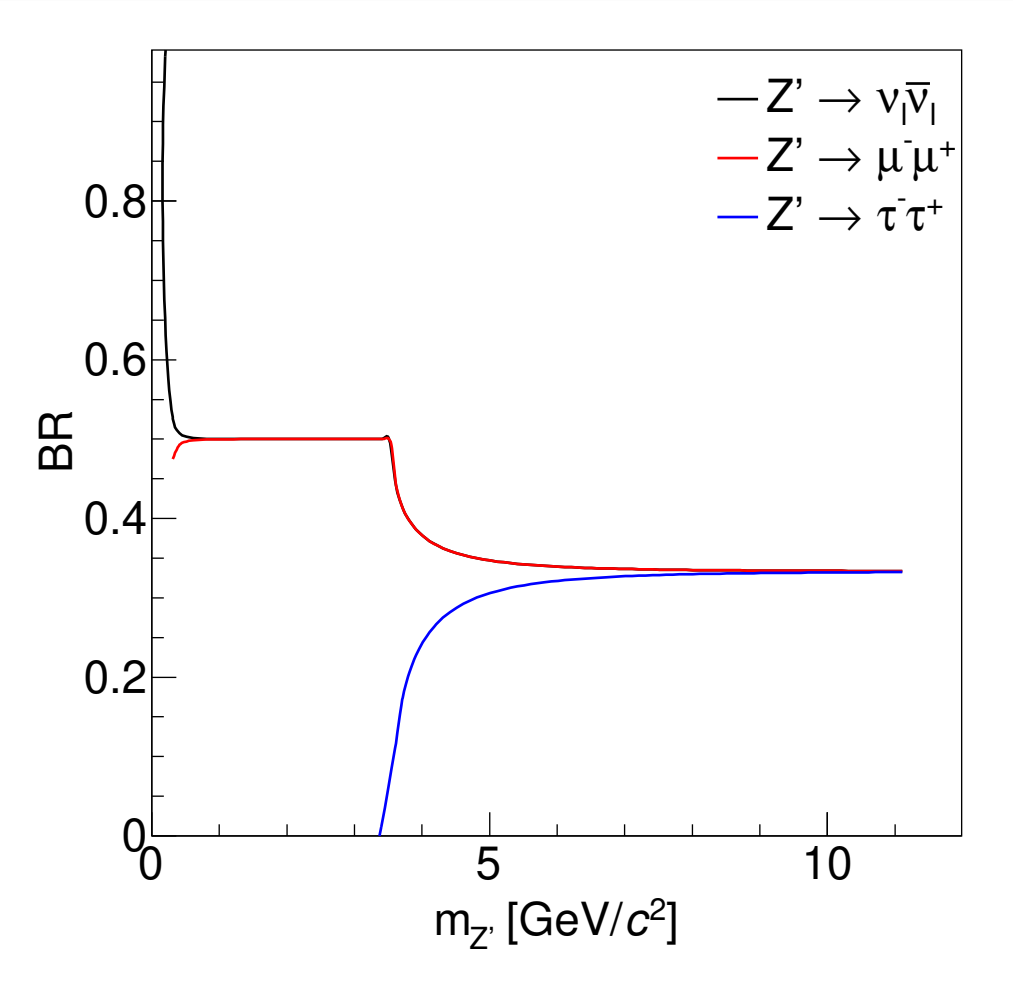
tauskimB

1. $2 \leq$ # q tracks ≤ 8
2. $|$charge sum$| \leq 2$
3. ~~$\sum P^{\mathrm{CM}} < 10$ GeV$/c$~~
4. ~~$\sum E(ECL) < 10$ GeV$/c$~~
5. $P_{t\mathrm{max}} > 0.5$ GeV$/c$
6. Evt vtx $|r| < 1.0$ cm, $|z| < 3$ cm
7. for 2 tracks events
   - 7.1 ~~Sum of $P^{\mathrm{CM}} < 9$ GeV$/c$~~
   - 7.2 Sum of $E(ECL) < 11$ GeV
   - 7.3 $5 < \theta_{\mathrm{missingmomentum}} < 175^\circ$
8. $E_{\mathrm{rec}} > 3$ GeV or $P_t\mathrm{max} > 1.0$ GeV$/c$
9. for $2 \sim 4$ charged tracks
   - 9.1 $E_{\mathrm{tot}} < 9$ GeV or max opening angle $< 175^\circ$ or $2 < \sum E(ECL) < 9$ GeV
   - 9.2 $N_{\mathrm{barrel}} \geq 2$ or $E(ECL)_{\mathrm{trk}} < 5.3$ GeV

Too loose for the invisible Z'

Z' decay width and Branching Ratio (BR)

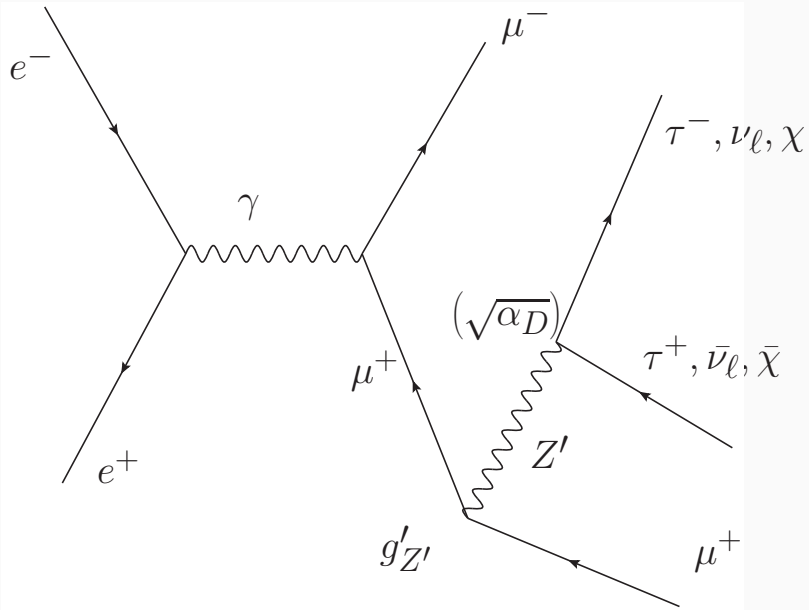
- $\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 m_{Z'}}{12\pi}\left(1+\frac{2m_\ell^2}{m_{Z'}^2}\right)\sqrt{1-\frac{4m_\ell^2}{m_{Z'}^2}}\,\theta(m_{Z'}-2m_\ell)$
- $\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{(g')^2 m_{Z'}}{24\pi}$



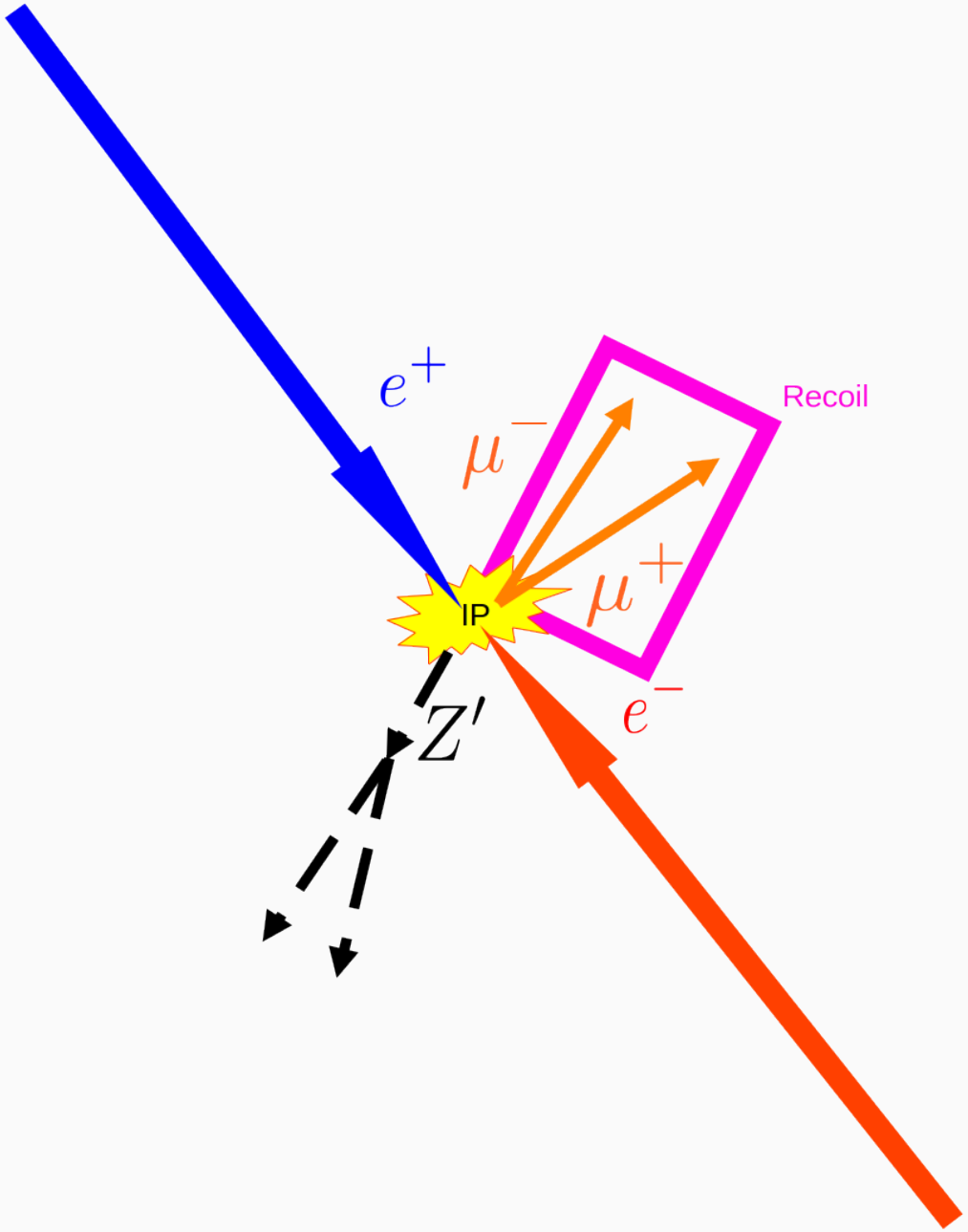
The invisible Z' search

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

- ~~$Z' \to \tau^+\tau^-$~~
  - 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?



$Z' \rightarrow$ 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

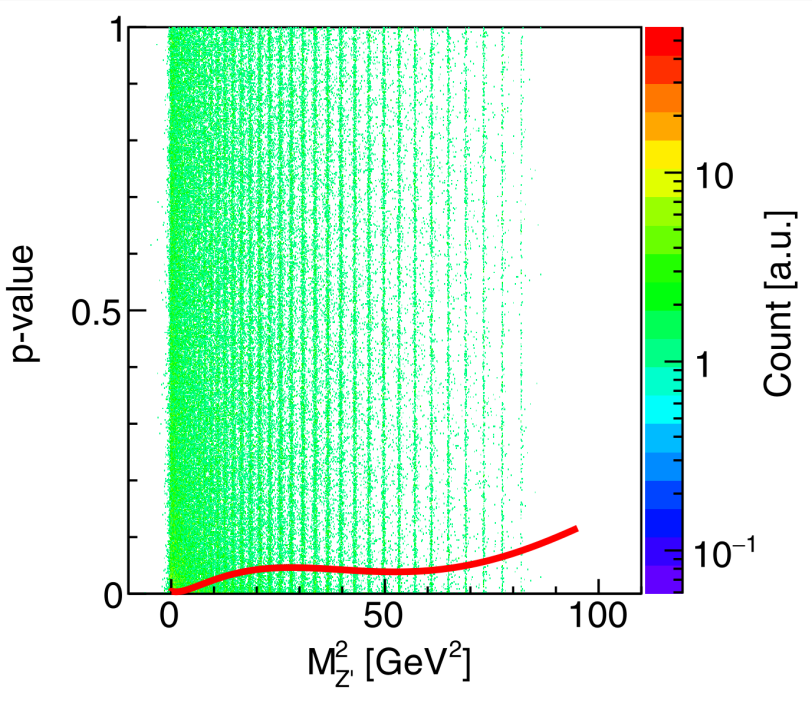
gen	channel	survives
KKMC	~~$e^+e^- \to c\bar{c}$~~	no
	~~$e^+e^- \to d\bar{d}$~~	no
	~~$e^+e^- \to s\bar{s}$~~	no
	$e^+e^- \to \tau^+\tau^-$	YES
	$e^+e^- \to \mu^+\mu^-$	YES
BBBREM	~~$e^+e^- \to e^+e^-\gamma$~~	no
AAFH(Diag36)	~~$e^+e^- \to e^+e^-e^+e^-$~~	no
	~~$e^+e^- \to e^+e^-\tau^+\tau^-$~~	no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

Z' invisible selection criteria list

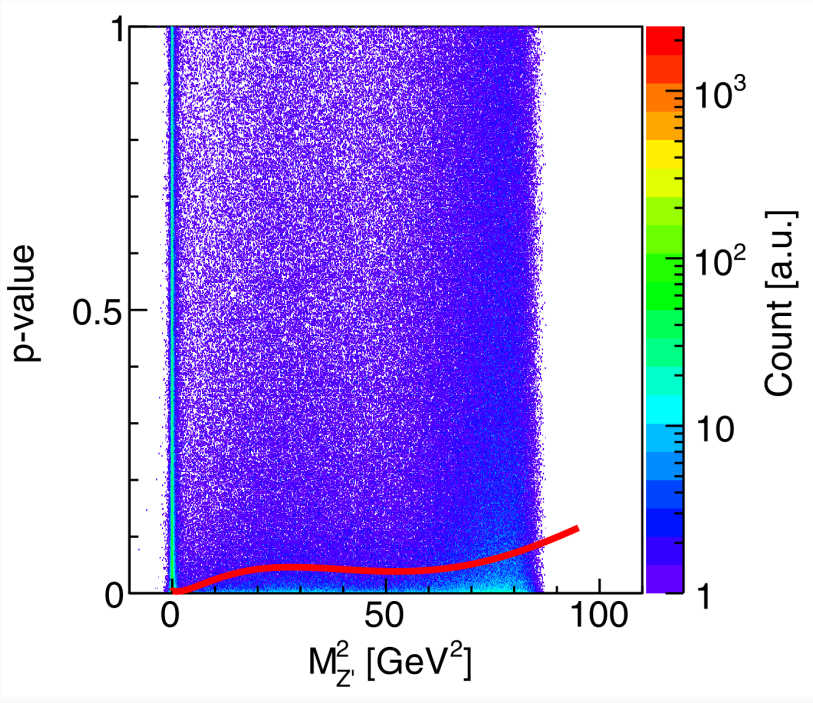
1. 2 tracks of opposite charge only, 2 μ ID
2. Vertex fit of the the 2 tracks, CL cut
3. Energy conservation dependent on $M^2_{Z'} = s + m^2_{\mu\mu} - 2E^*_{\mu\mu}\sqrt{s}$
4. Energy sum of neutral cluster, ECL
5. p_t of the two tracks sum dependent on $M_{Z'}$
6. 6.1 Mass conservation on $M_{Z'}$
   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. **tauskimB** replaced by **tauskimA**
11. $p_t^{*Z'}$ projection on $p^{*\mu}_{\text{max}}$ and $p^{*\mu}_{\text{min}}$

Cut example: p-value

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

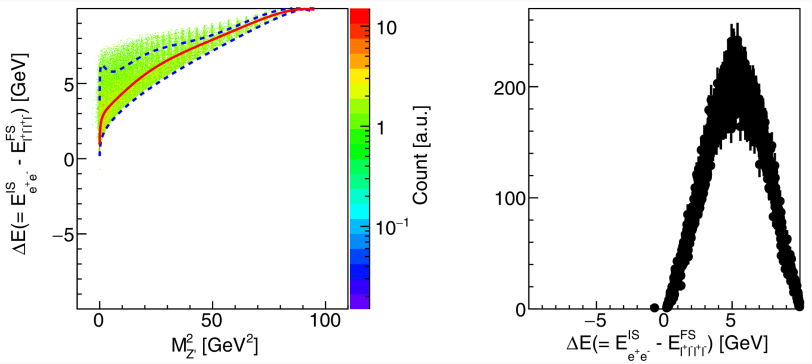


Selection curve for all Z' mass hypotheses signal MC.

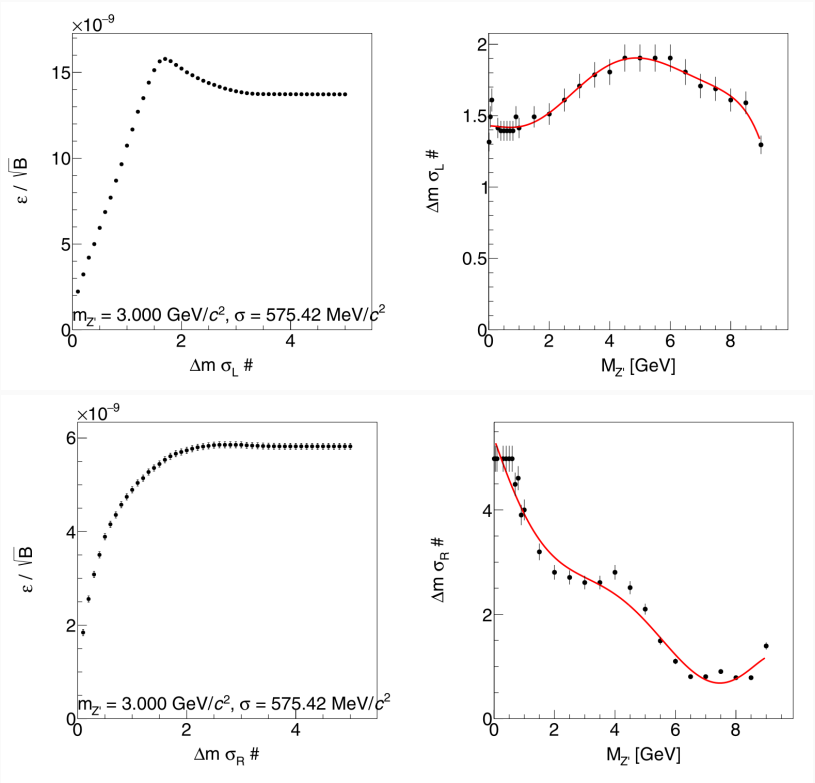


Selection curve for **exp65** data.

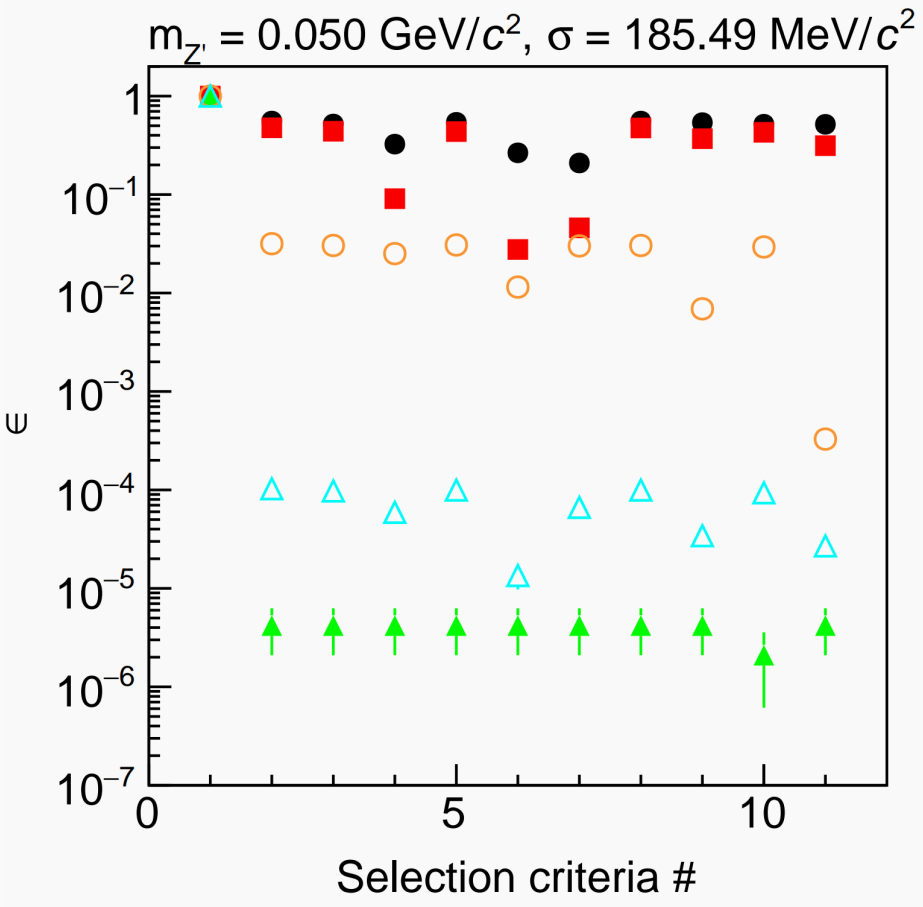
Cut example: ΔE

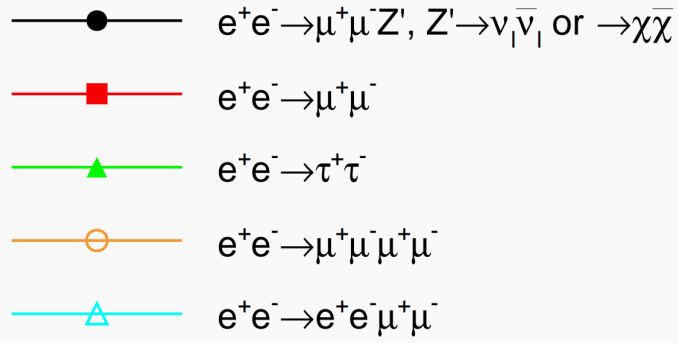


- How many σ should be taken to maximize FOM?
- On the left
- and on the right



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





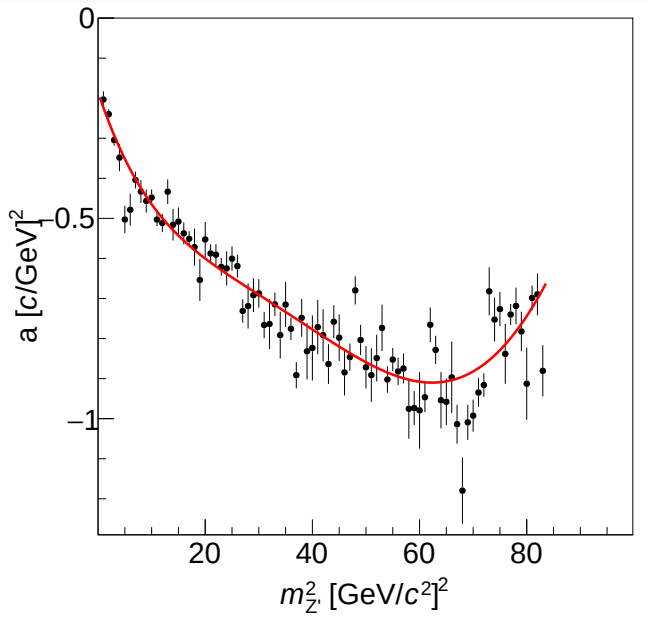
#0, no cuts
#1, 2 tracks & $\sum$Q=0
#2, CL_{vtx}
#3, Energy conservation
#4, E_{sum}
#5, p_t
#6a, Mass conservation
#6b, Open angle between tracks
#7, Recoiling muon pair polar angle
#8, $\cos(\phi_{FS} - \phi_\gamma)$
#9, $\theta_{missing\ Z'}$

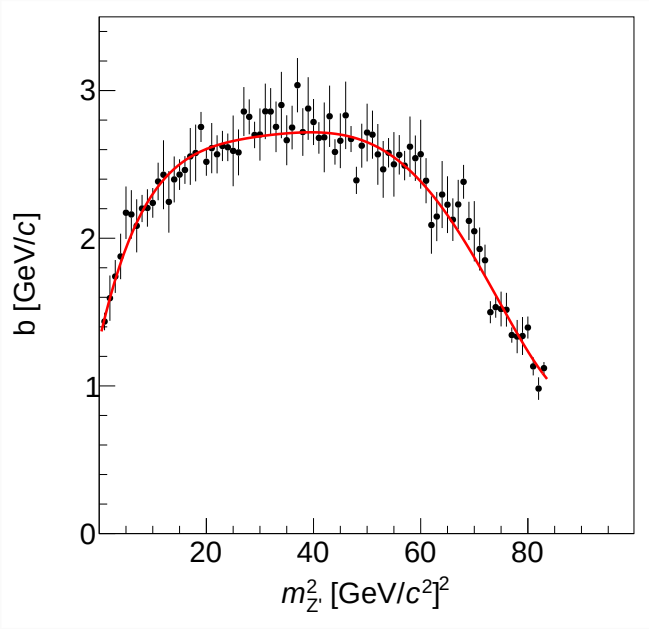
Extra cut from Belle II analysis

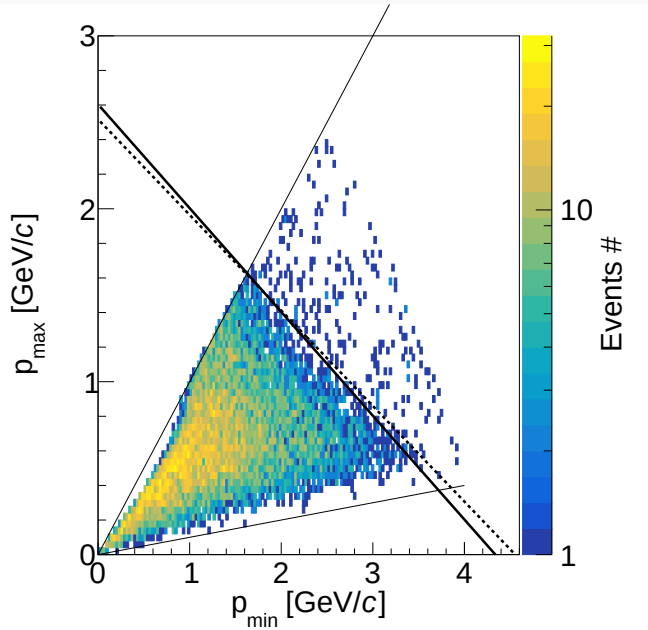
- Missing transverse momentum in cms: $p_t^{*Z'}$
- Maximum momentum muon in cms: $p_{\text{max}}^{*\mu}$
- Minimum momentum muon in cms: $p_{\text{min}}^{*\mu}$
- $\angle \mathbf{p}_t^{*Z'} \mathbf{p}_{\text{max}}^{*\mu} \equiv \alpha_M$
- $\angle \mathbf{p}_t^{*Z'} \mathbf{p}_{\text{min}}^{*\mu} \equiv \alpha_m$
- Projection: $p_t^{*Z'} \sin \alpha_M \equiv p_{\text{max}}$
- Projection: $p_t^{*Z'} \sin \alpha_m \equiv p_{\text{min}}$

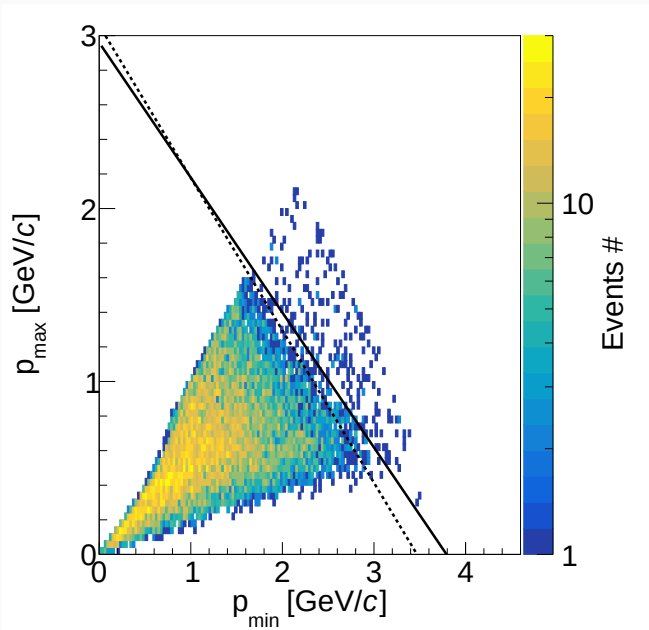
Diagonal cut

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

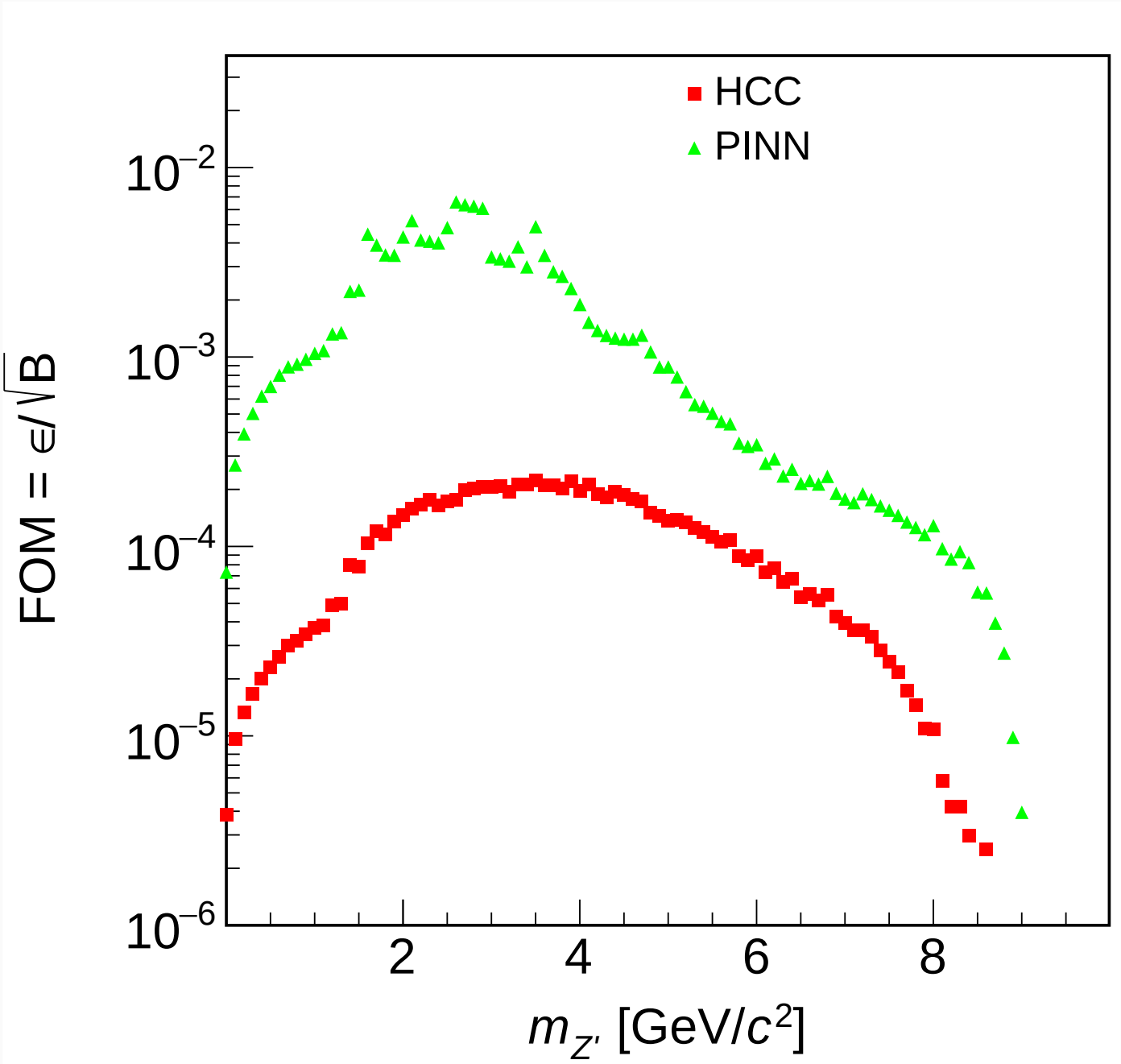




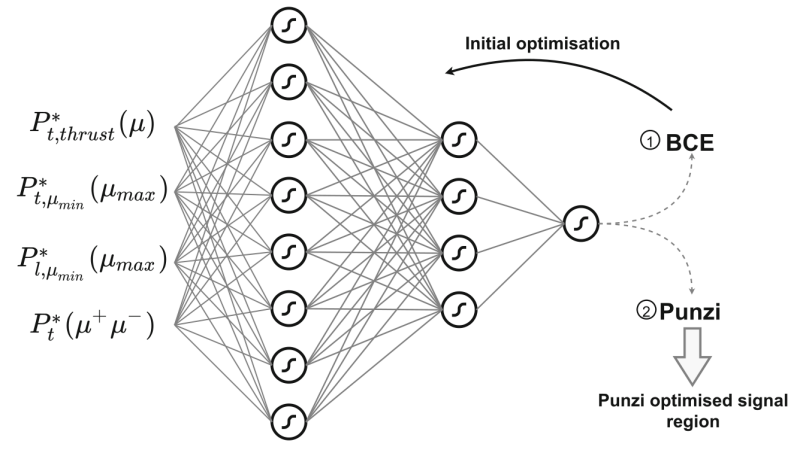




FOM comparison



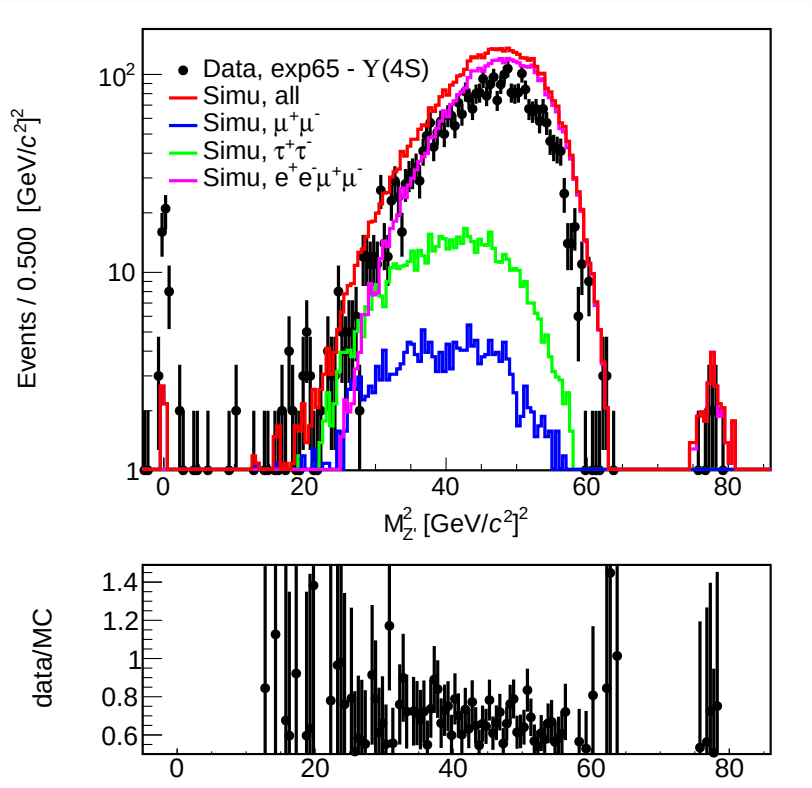
The Punzi Loss Neural Net selection

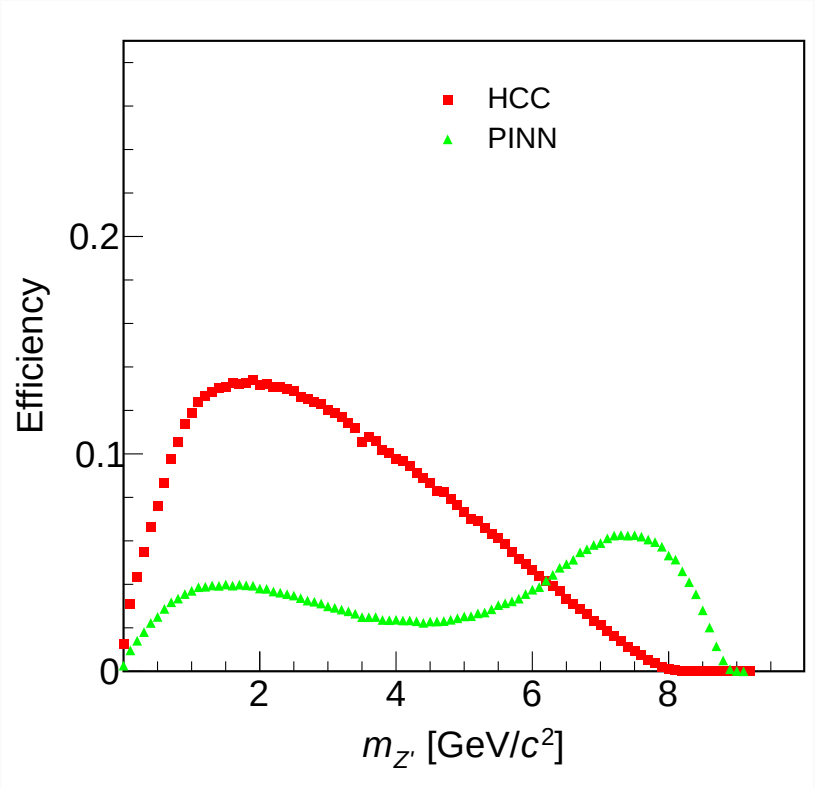


- Layers:
  1. input (32 nodes)
  2. hidden (64 nodes)
  3. hidden (64 nodes)
  4. hidden (32 nodes)
  5. hidden (16 nodes)
  6. hidden (8 nodes)
  7. output (1 node)

- $E^*_{\mu\mu}$
- $\cos\theta^*_{\text{rec}}$
- E_{sum}
- $p-\text{value}$
- ΔM
- ΔM_g
- $p_l\text{min}^\mu$
- $p_l\text{max}^\mu$
- 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

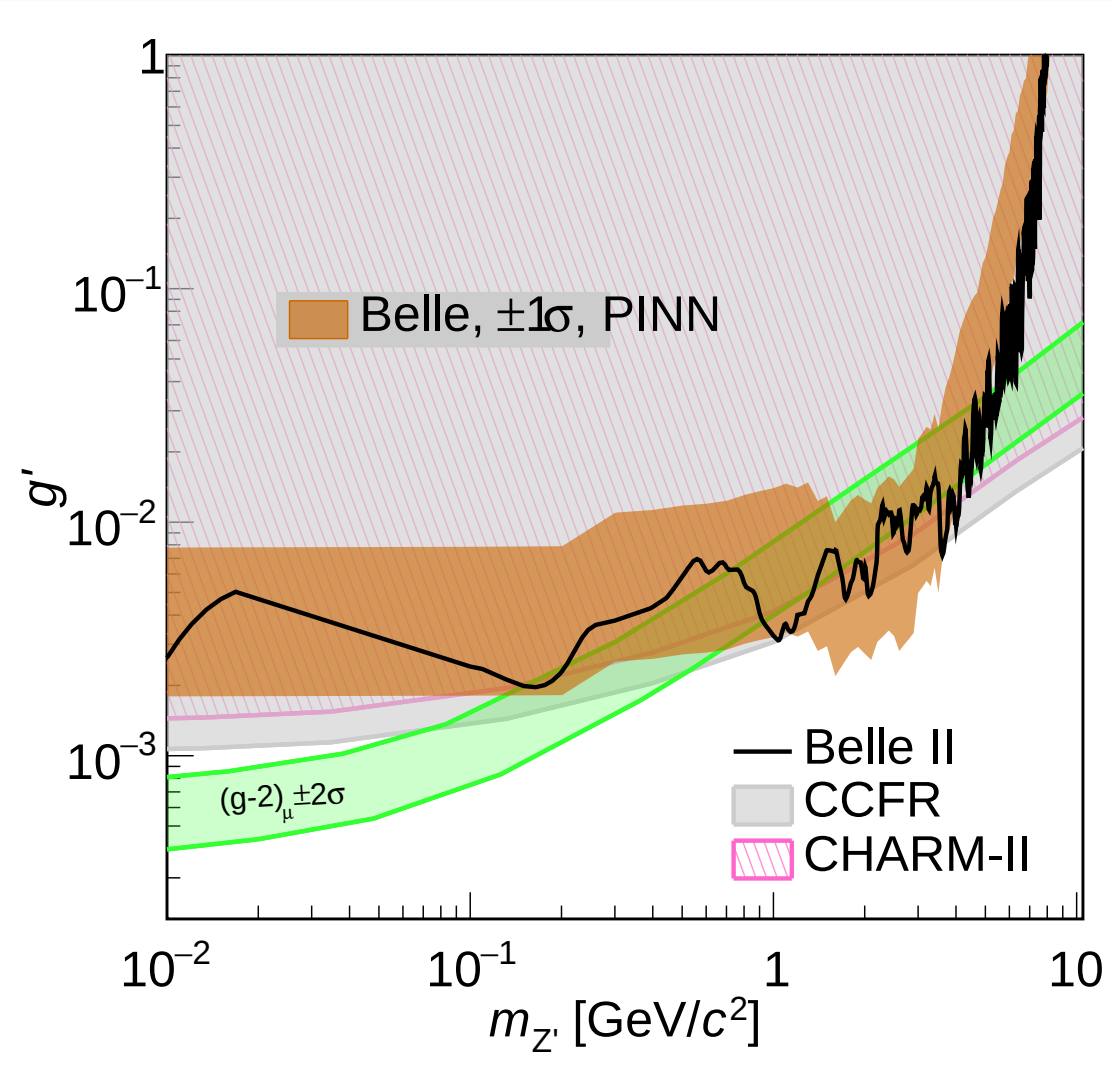




Hand Crafted Cuts (HCC)

Physical Informed Neural Network (PINN)

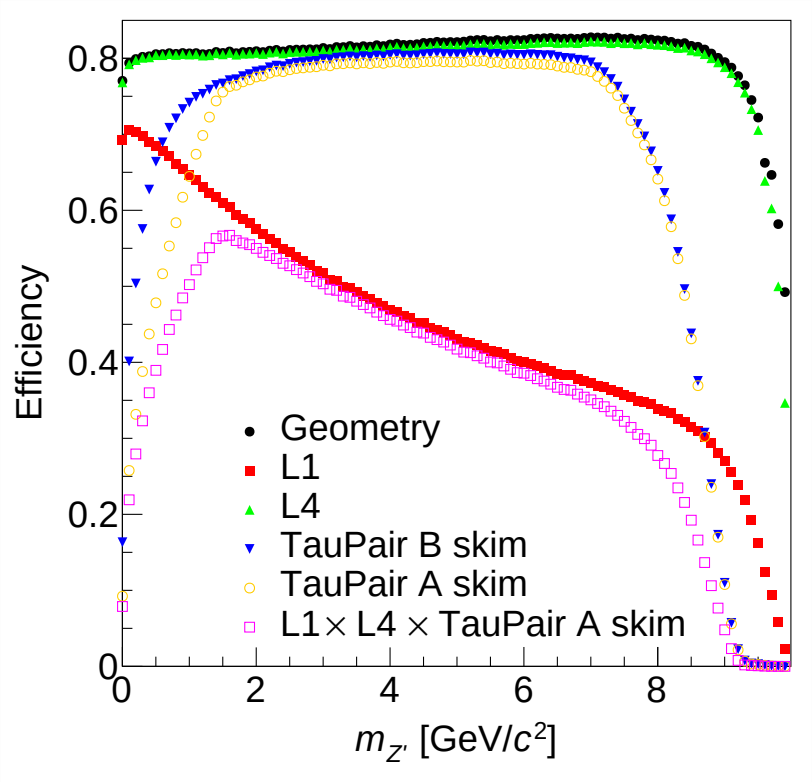
Preliminary Limit in Comparison with Belle II 79.1 fb^{-1}



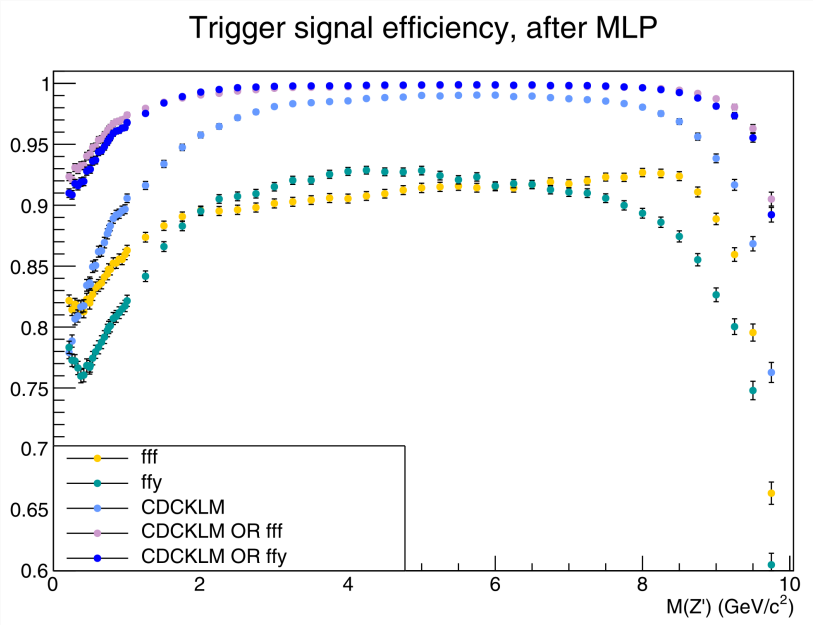
- PINN trained with 60 ab^{-1} MC samples
- Extrapolation on 3% of the total Belle data (**exp 65**)

Trigger Efficiency (Signal)

Belle Trigger



Belle II Trigger



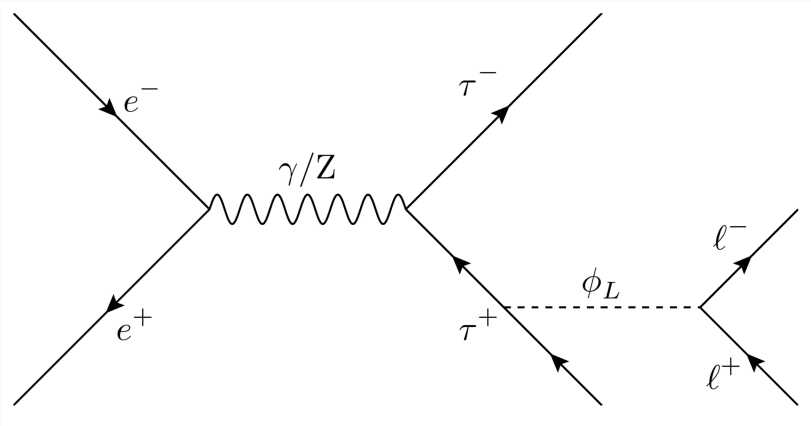
The leptophilic scalar search @ Belle

Origins PRD 93, 035006 - 2016

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 tracks
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

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. $\theta^{\text{CM}}_{\text{miss}} \in [30^\circ, 150^\circ]$

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

SR (Signal Region) Signal Score > 0.5

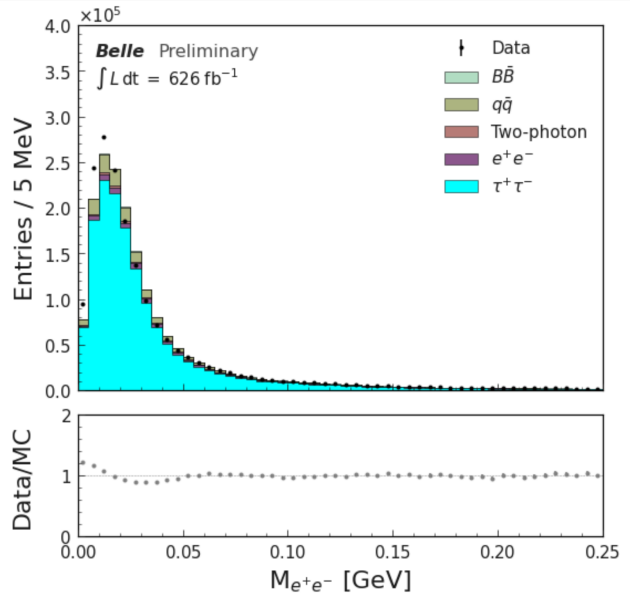
1. $\phi_L \to e^+e^-(\mu^+\mu^-)$

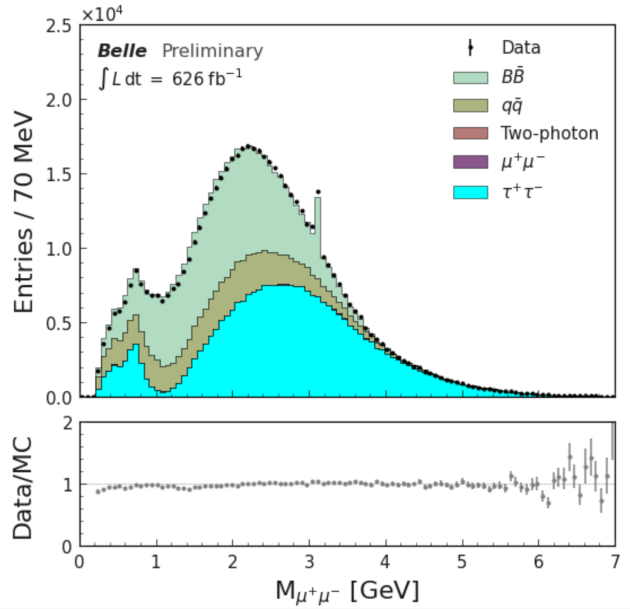
GCR (General Control Region)

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

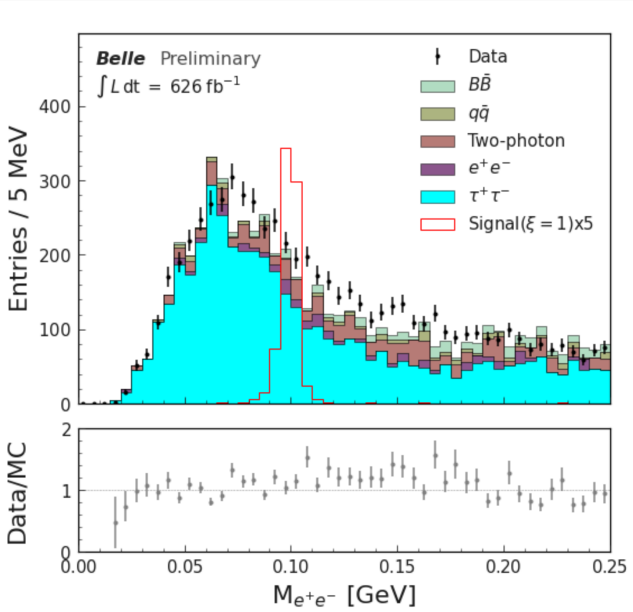
Results: GCR and SR 2207.07476

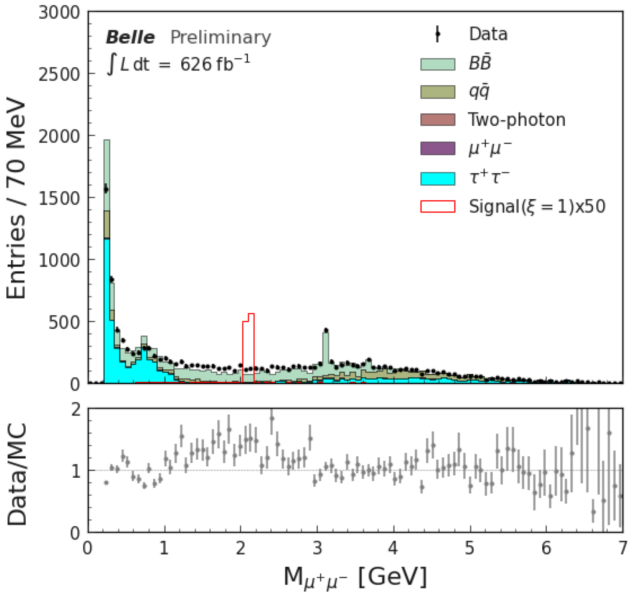
GCR



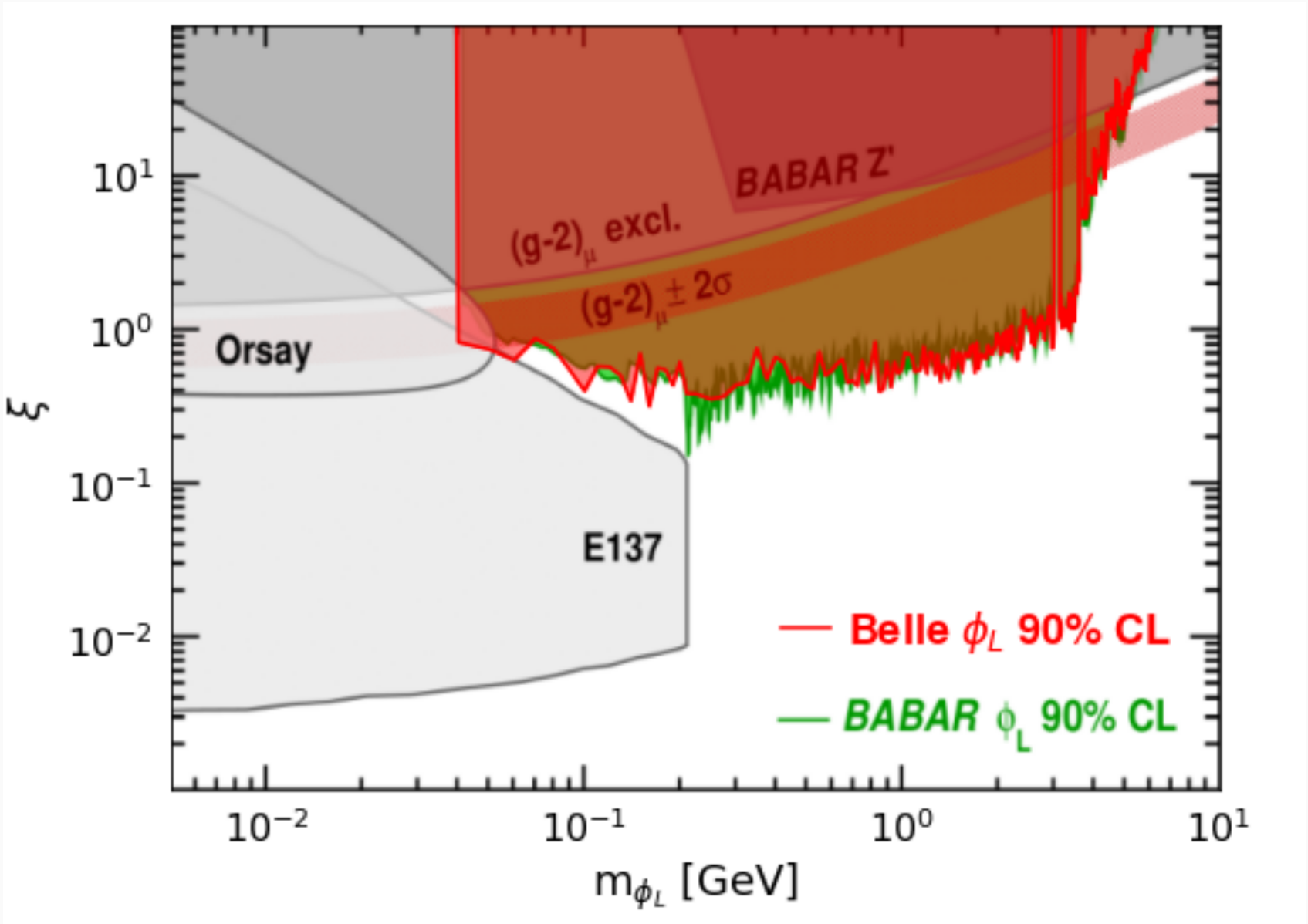


SR





Results: ξ coupling limit 2207.07476



Summary

Summary

Leptophilic Z' and ϕ_L outlook

- Finally touching very low mass parameter spaces in Belle
- 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