(B05) Study of the Z' boson at e^+e^- collider

FY2022 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 Tension

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

KEKB and Belle

Z' searches in B-factories

the invisible Z' search

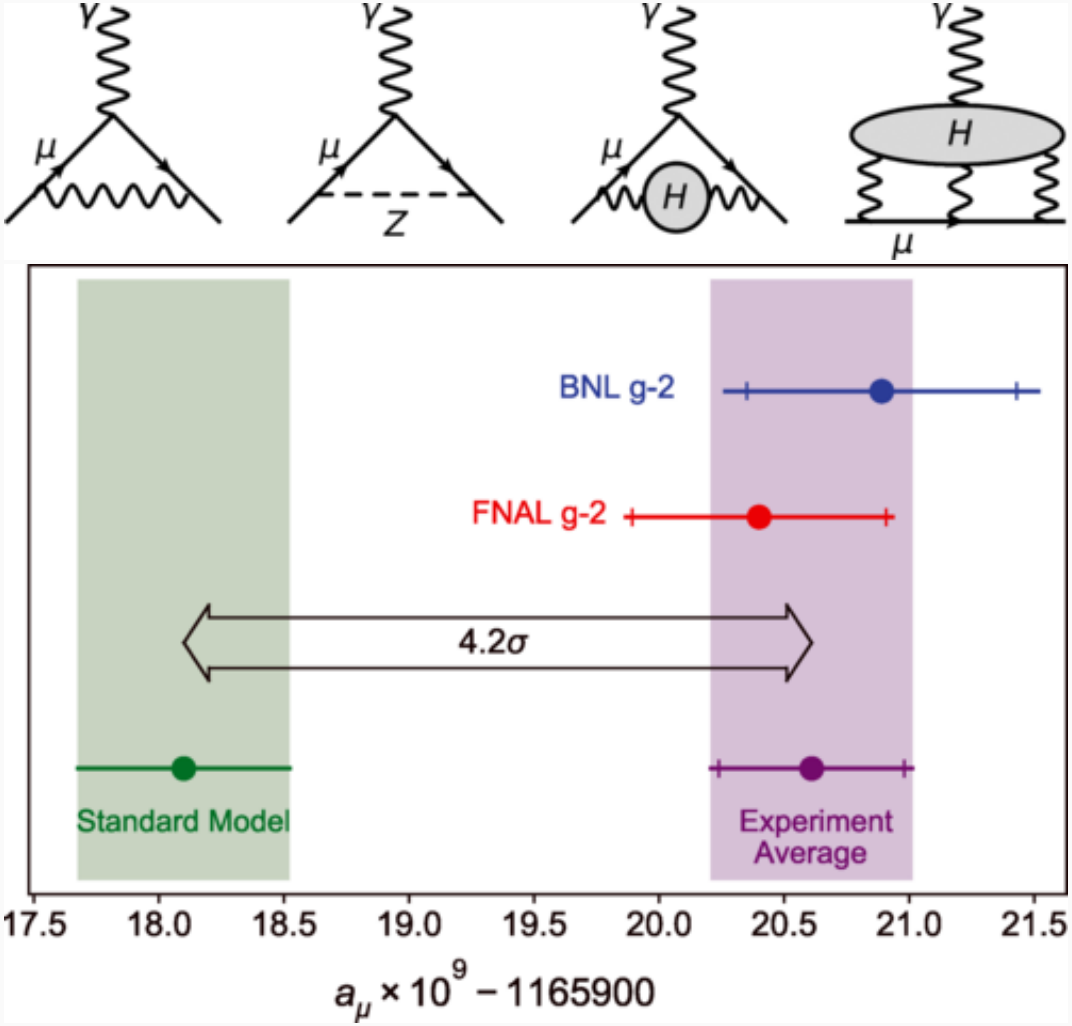
the Belle II invisible Z' search

the leptophylic scalar search @ Belle

Summary

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

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



Tension remains!

Extra Leptophylic $U(1)$ 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 $L_3 = L_\mu - L_\tau$

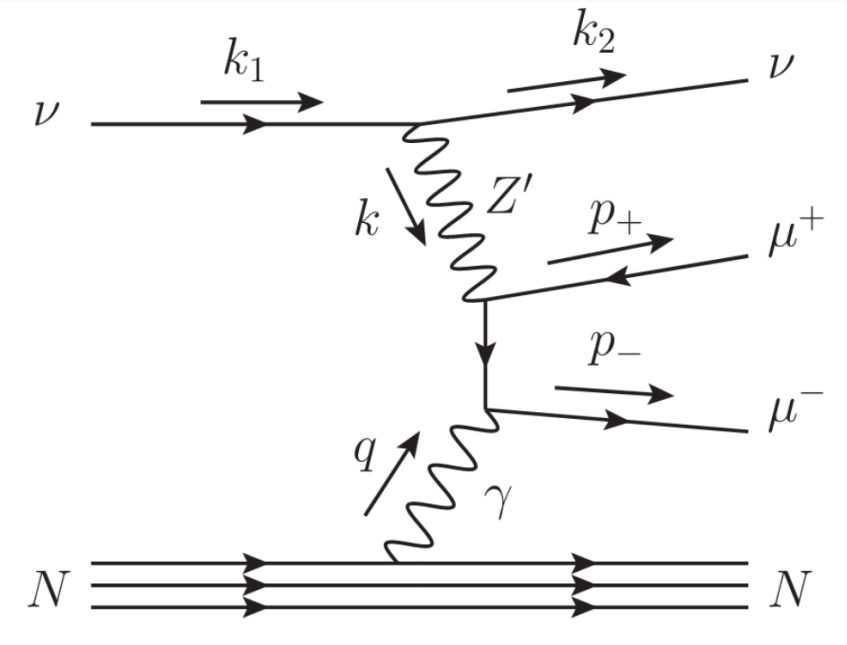
Three different new gauge groups

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



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

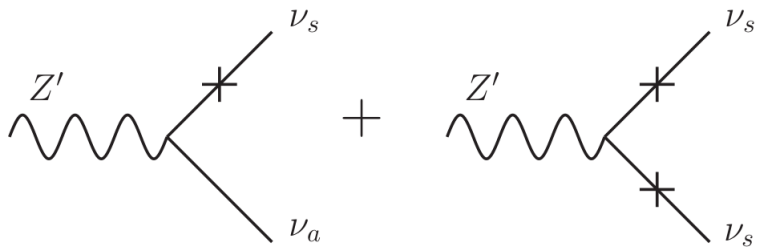
$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}}$$

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.

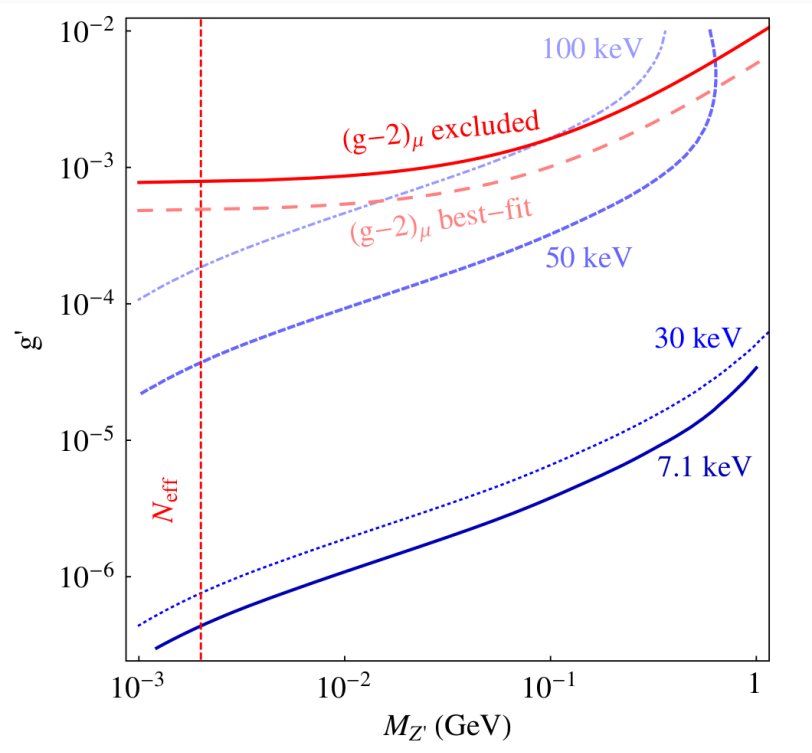


$$\begin{pmatrix}\nu_a\\ \nu_s\end{pmatrix} \equiv \begin{pmatrix}\cos\theta_0 & \sin\theta_0\\ -\sin\theta_0 & \cos\theta_0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

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

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

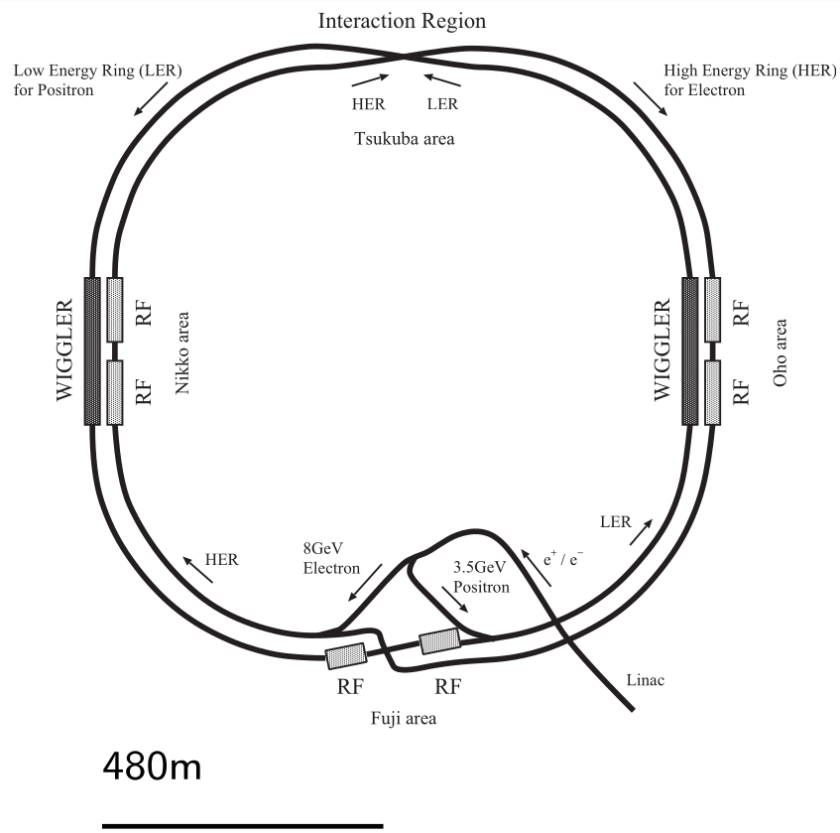
- $m_s = 7.1$ keV $\sin 2\theta_0 = 8 \times 10^{-6}$
- $m_s = 30$ keV $\sin 2\theta_0 = 2.2 \times 10^{-6}$
- $m_s = 50$ keV $\sin 2\theta_0 = 3.5 \times 10^{-8}$
- $m_s = 100$ keV $\sin 2\theta_0 = 5 \times 10^{-9}$
- $(Y_{\rm DM} = 4.7 \times 10^{-4}\ {\rm keV}/m_s)$

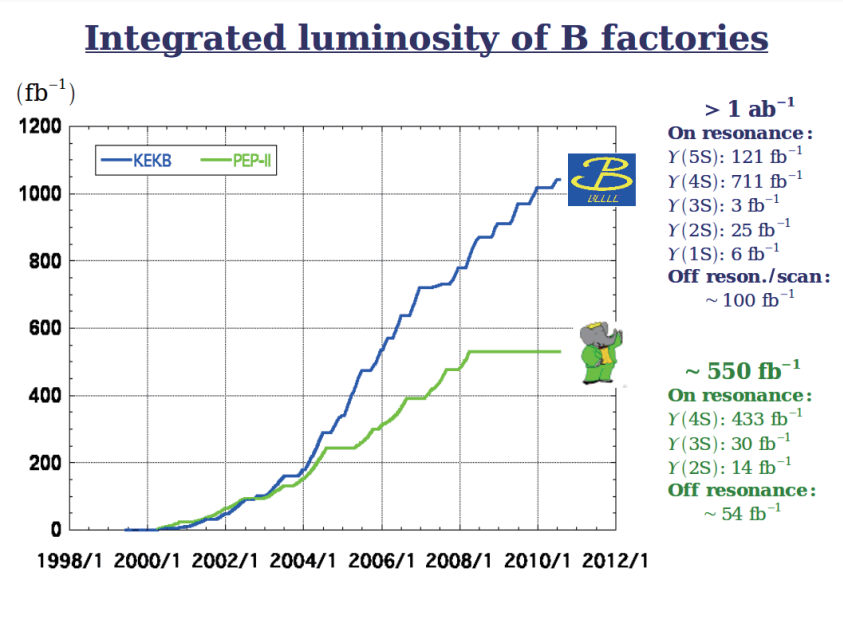
KEKB and Belle

The KEKB Accelerator

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

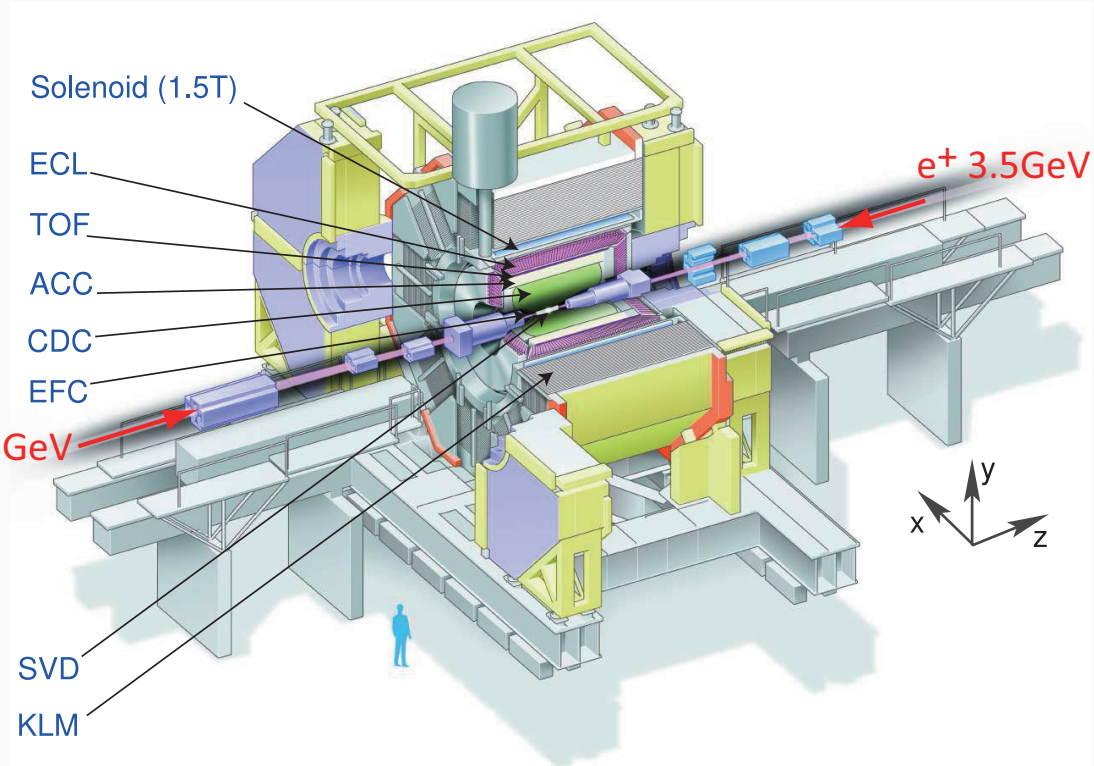
It's located in Tsukuba and has achieved a record Luminosity of 1 ab^{-1}





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

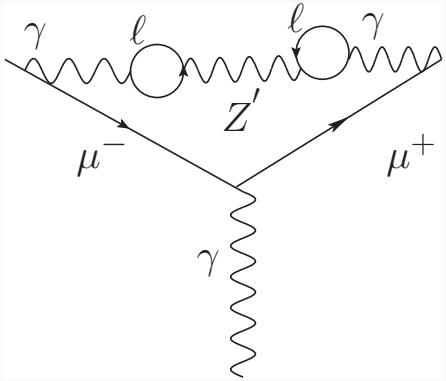
The Belle Detector

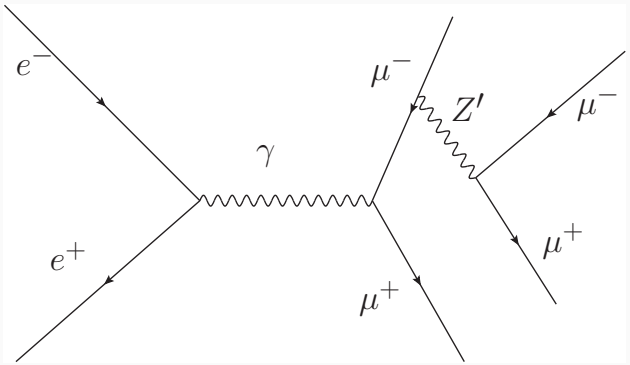


- SVD (Silicon Vertex Detector)
- EFC (Extreme Forward Calorimeter)
- ACC (Aerogel Cherenkov Counter)
- TOF (Time Of Flight)
- CDC (Central Drift Chamber)
- ECL (Electromagnetic Calorimeter)
- KLM ($K_L^0 - \mu$)

Z' searches in B-factories

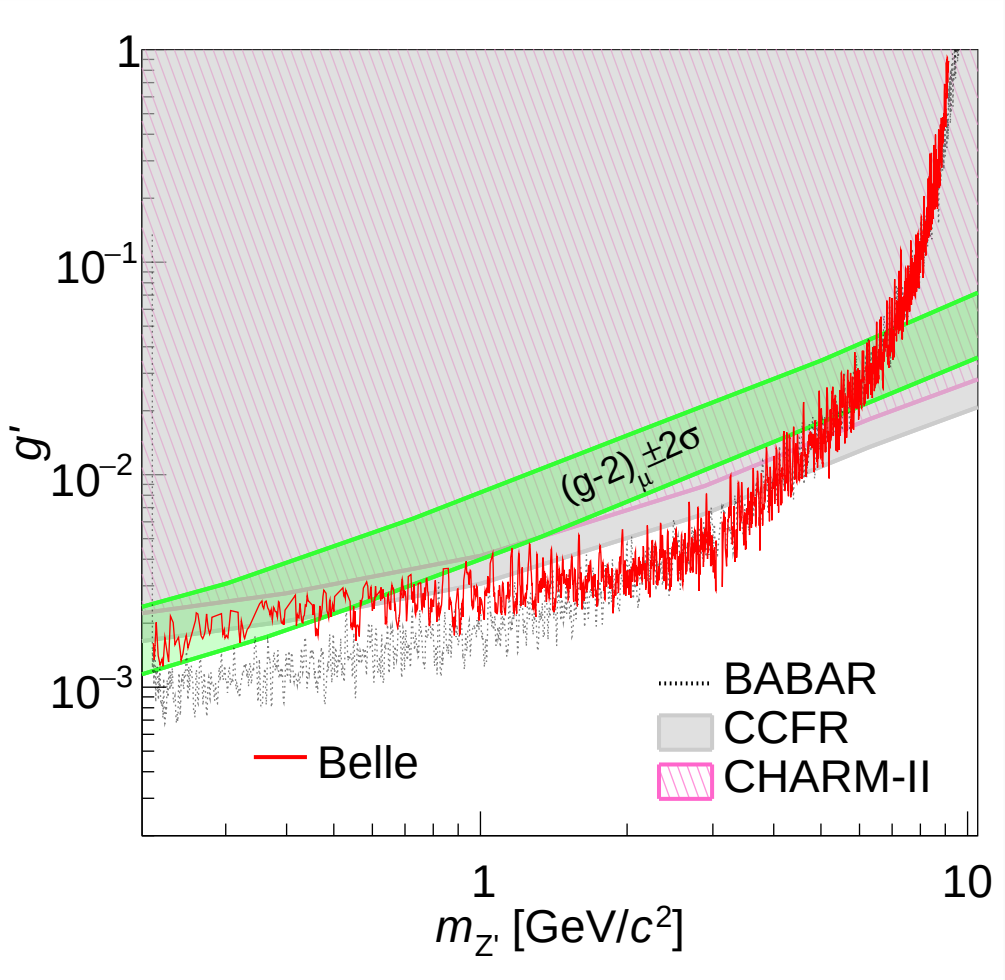
Visible Z' search in B-factories





- Motivated by:
  - the $(g-2)_\mu$
  - connection to **sterile neutrinos** as a dark matter candidate
- $Z' \to \mu^+\mu^-$
- $Z' \to$ 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 Search 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 we learned in the Z' visible search?

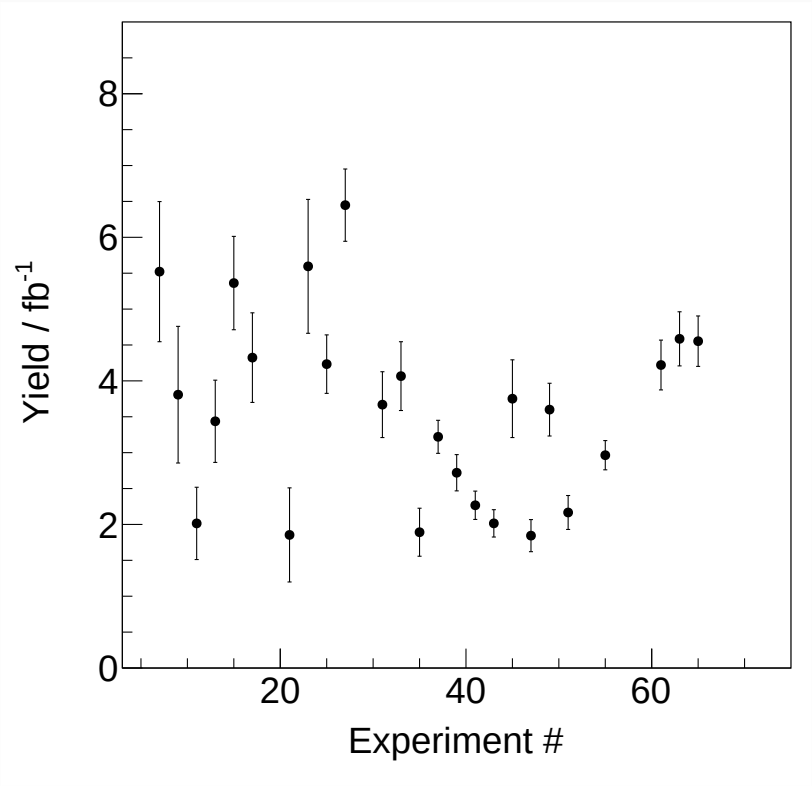


Figure 1: `HadronB` skim

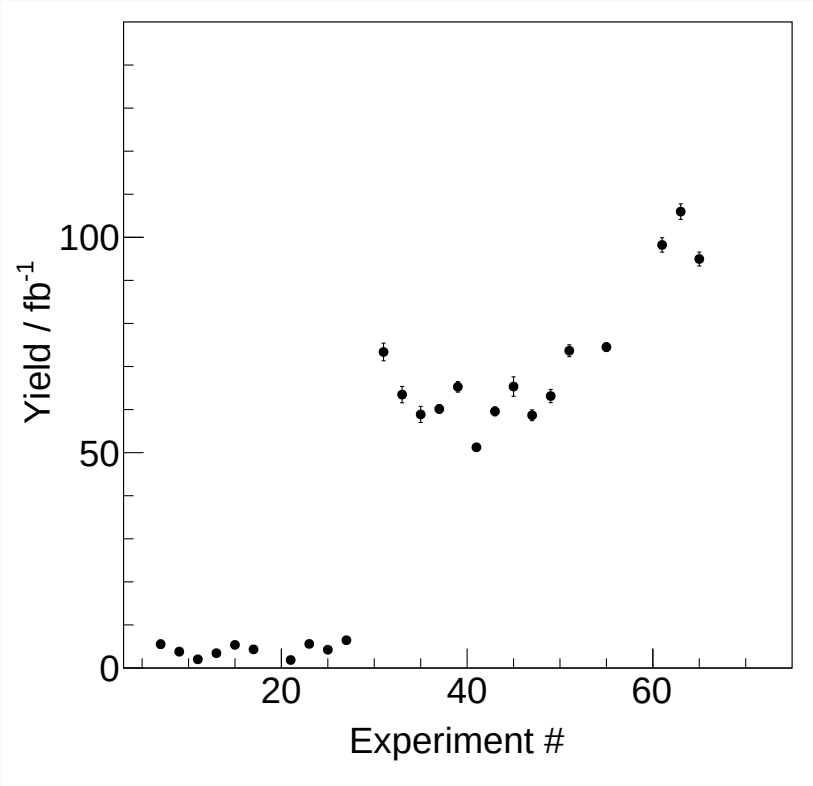


Figure 2: `tauskimA`

Definitions of tauskimA(B)

tauskimA

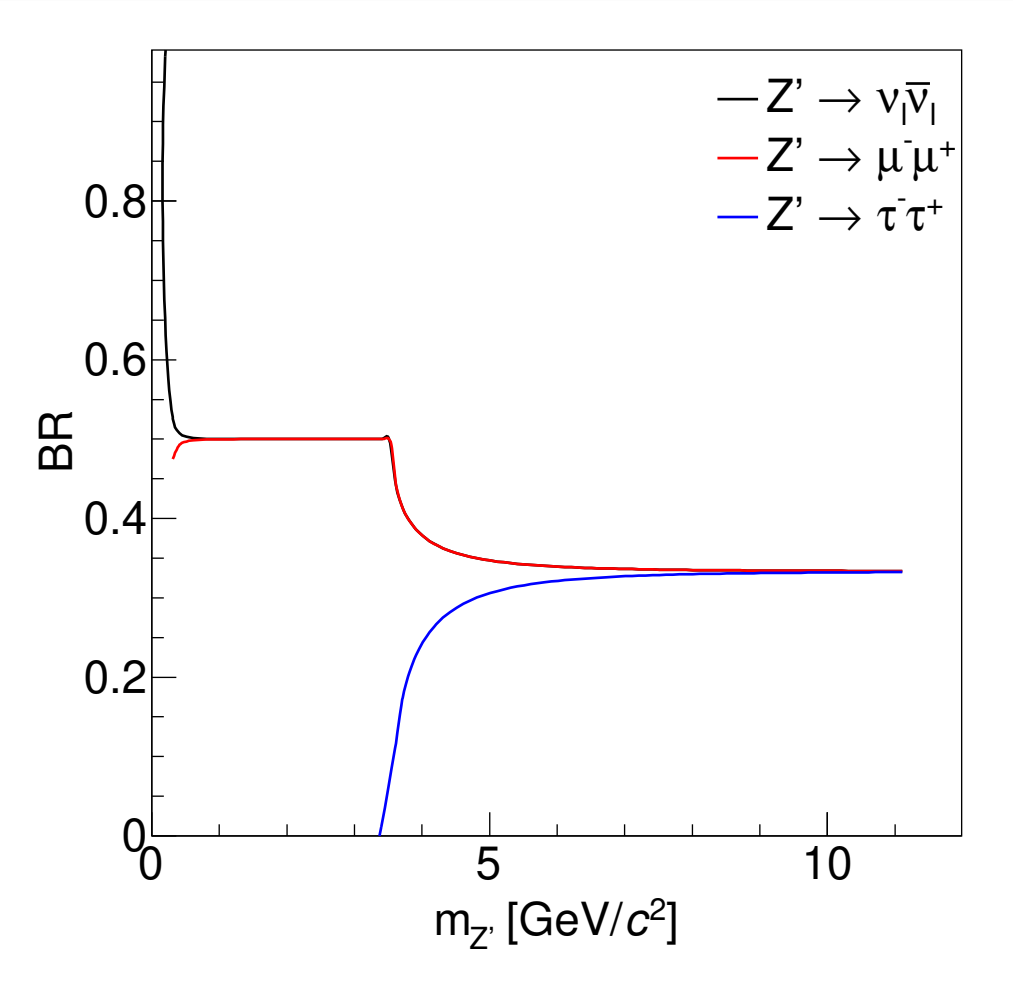
1. $2 \leq$ # q tracks ≤ 8
2. $|$charge sum$| \leq 2$
3. $\sum P^{\mathrm{CM}} < 10$ GeV$/c$
4. $\sum E(ECL) < 10$ GeV$/c$
5. $P_{t\mathrm{max}} > 0.5$ GeV$/c$
6. Evt vtx $|r| < 0.5$ cm, $|z| < 3$ cm
7. for 2 tracks events
   - 7.1 Sum of $P^{\mathrm{CM}} < 9$ GeV$/c$
   - 7.2 Sum of $E(ECL) < 9$ GeV
   - 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

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

Z' decay width and branching ratio

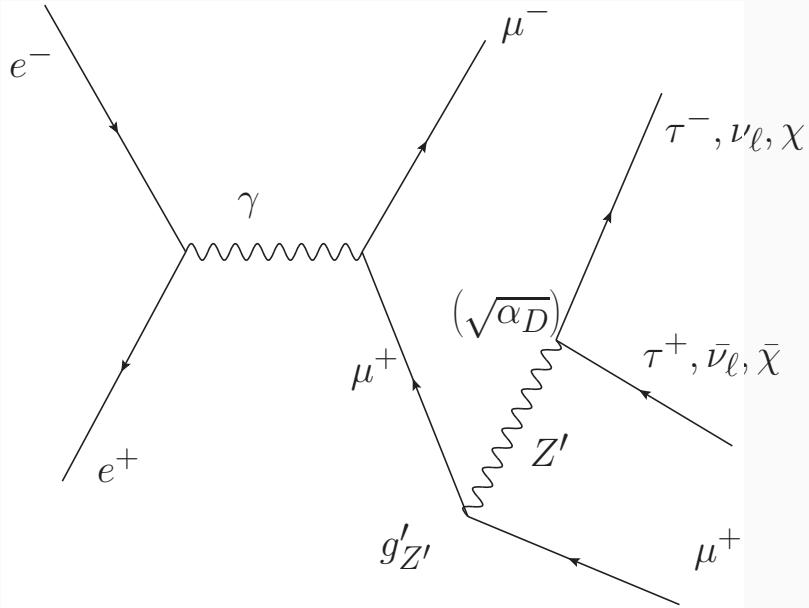
- $\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 m_{Z'}}{12\pi}\left(1+\frac{2m_\ell^2}{m_{Z'}^2}\right)\sqrt{1-\frac{4m_\ell^2}{m_{Z'}^2}}\,\theta(m_{Z'}-2m_\ell)$
- $\Gamma(Z' \to \nu_\ell \bar{\nu}_\ell) = \frac{(g')^2 m_{Z'}}{24\pi}$



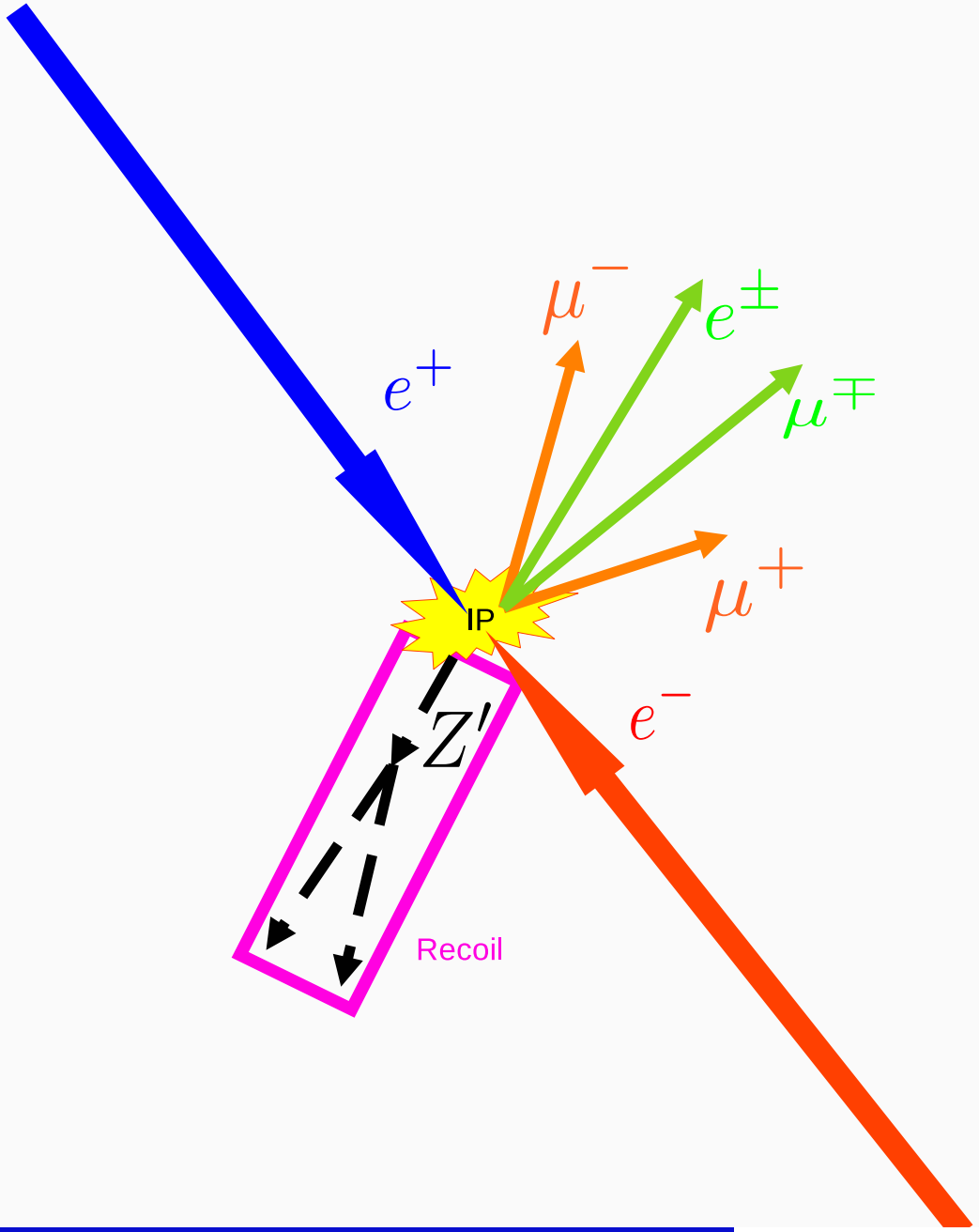
the invisible Z' search

$Z' \to$ invisible or not fully visible

- $Z' \to \tau^+\tau^-$
- $Z' \to \chi\bar{\chi}$
- $Z' \to \nu_\ell\nu_\ell$



What does it look like?



$Z' \rightarrow$ invisible original cuts

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 integration of backgrounds around ($\pm 3\sigma$) Z' mass
- $\frac{\varepsilon}{\sqrt{B}}$ maximized

Background sources

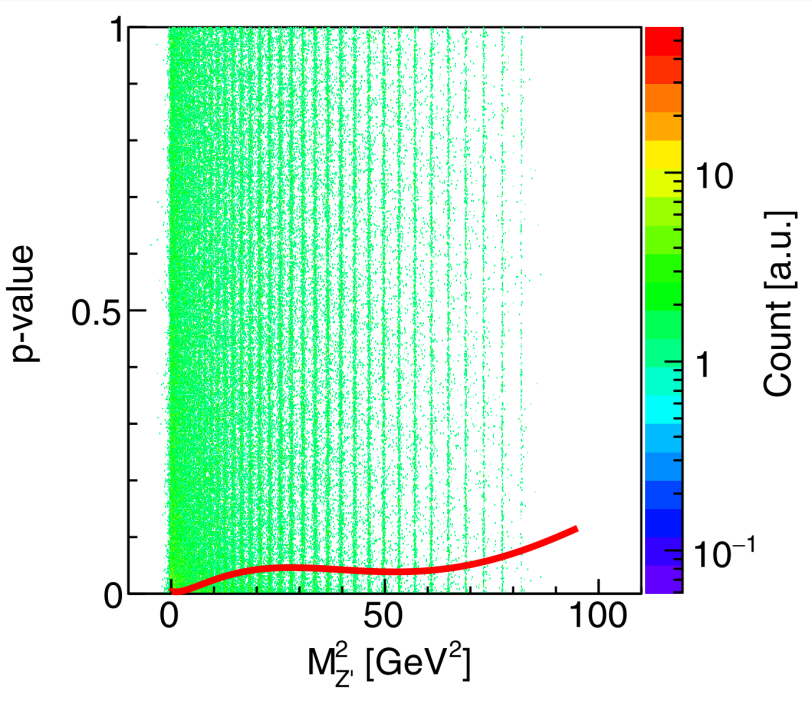
gen	channel	xs (fb)	number of events
KKMC	$e^+e^- \to c\bar{c}$	1330.12	10^6
	$e^+e^- \to d\bar{d}$	404.60	10^6
	$e^+e^- \to s\bar{s}$	378.85	10^6
	$e^+e^- \to \tau^+\tau^-$	916.65	10^6
	$e^+e^- \to \mu^+\mu^-$	1143.54	10^6
BBBREM	$e^+e^- \to e^+e^-\gamma$	irrelevant	10^6
AAFH(Diag36)	$e^+e^- \to e^+e^-e^+e^-$	39.3×10^6	10^6
	$e^+e^- \to e^+e^-\tau^+\tau^-$	0.0214×10^6	10^6
	$e^+e^- \to e^+e^-\mu^+\mu^-$	19.1×10^6	10^6
	$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$	0.000336×10^6	10^6
	$e^+e^- \to \mu^+\mu^-\tau^+\tau^-$	76.4	10^6
PHOKHARA	$e^+e^- \to \mu^+\mu^-\gamma_{\text{ISR}}$	irrelevant	3×10^6
	$e^+e^- \to n\bar{n}\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to p\bar{p}\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to \pi^+\pi^-\pi^0\pi^0\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to \pi^+\pi^-\gamma_{\text{ISR}}$	irrelevant	3×10^6
	$e^+e^- \to \Lambda\bar{\Lambda}\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to K^+K^-\gamma_{\text{ISR}}$	irrelevant	10^6
	$e^+e^- \to K^0K^0\gamma_{\text{ISR}}$	irrelevant	10^6
BABA	$e^+e^- \to \mu^+\mu^-$	irrelevant	2×10^6
	$e^+e^- \to \gamma\gamma$	irrelevant	2.9×10^6
	$e^+e^- \to e^+e^-$	irrelevant	2×10^6

Z' invisible cut list BN1679

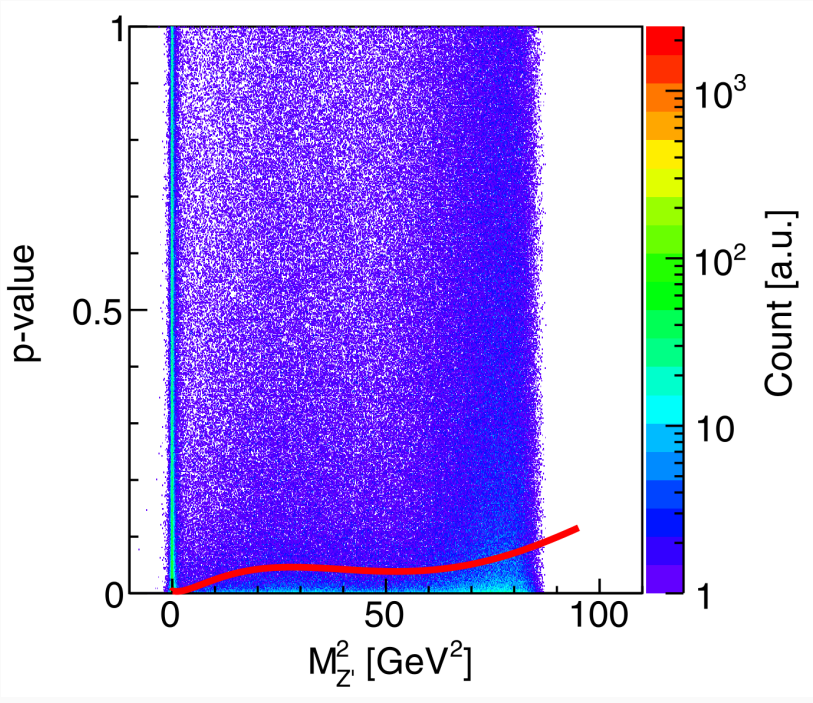
1. 2 tracks of opposite charge only, 1 μ ID
2. vertex fit of the the 2 tracks, CL cut
3. energy conservation dependent on $M^2_{Z'} = s + m^2_{\mu\mu} - 2E^*_{\mu\mu}\sqrt{s}$
4. energy sum of neutral cluster, ECL
5. p_t of the two tracks sum dependent on $M_{Z'}$
6. 6.1 $\Upsilon(nS)$ veto on $M_{Z'}$
   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` from `KVertexFitter` BN193

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

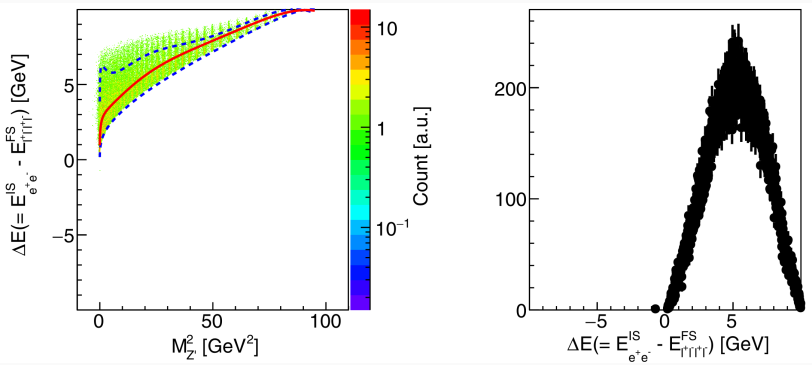


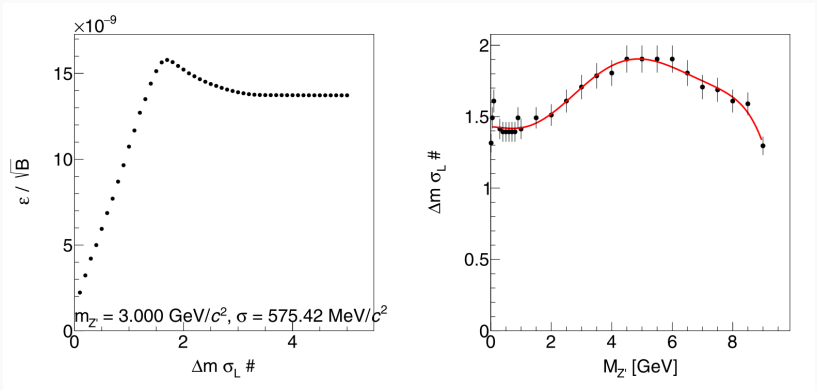
Selection curve for all Z' mass hypotheses signal MC.



Selection curve for **`exp65`** data.

Cut example: ΔE





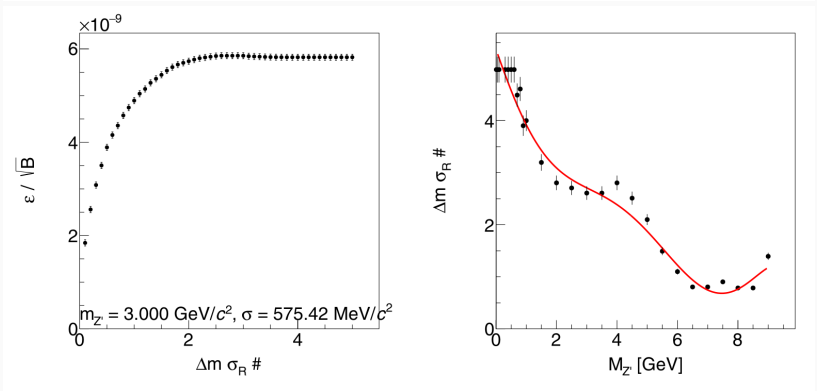
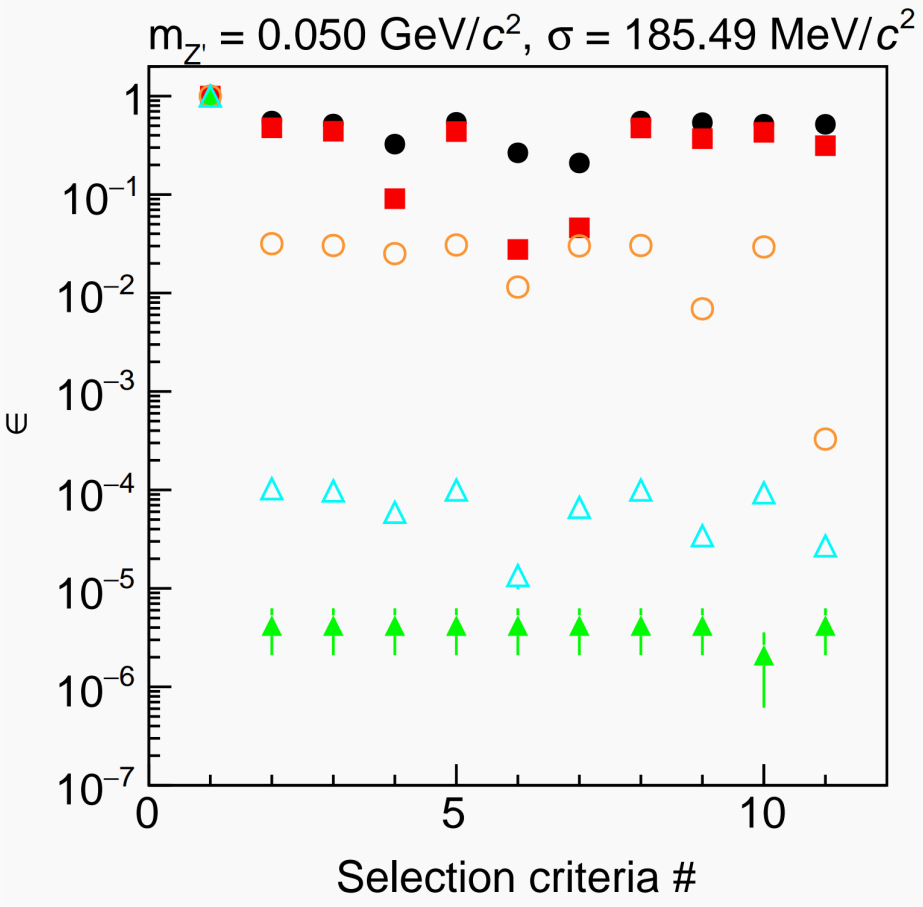
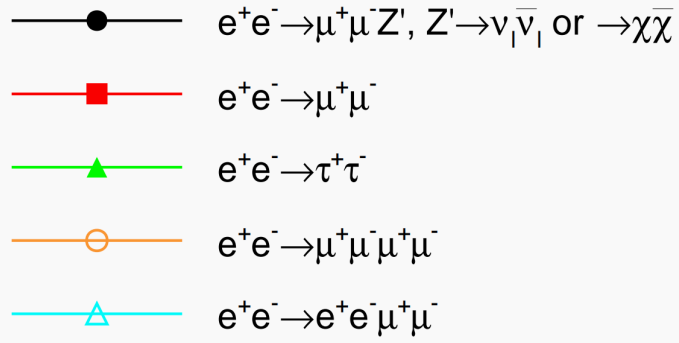


Figure 3: All Z' mass candidates signal

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

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





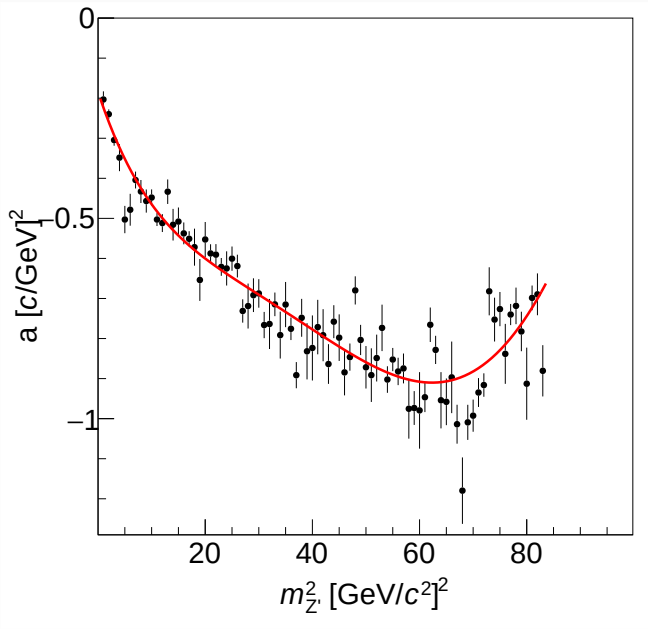
#0, no cuts
#1, 2 tracks & $\sum$Q=0
#2, CL_{vtx}
#3, Energy conservation
#4, E_{sum}
#5, p_t
#6a, Mass conservation
#6b, Open angle between tracks
#7, Recoiling muon pair polar angle
#8, $\cos(\phi_{FS} - \phi_\gamma)$
#9, $\theta_{missing\ Z'}$

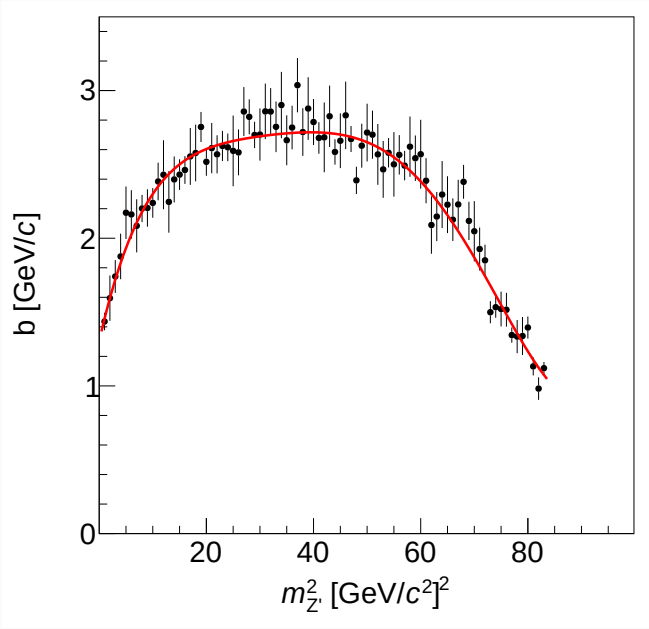
Extra cut from Belle II analysis

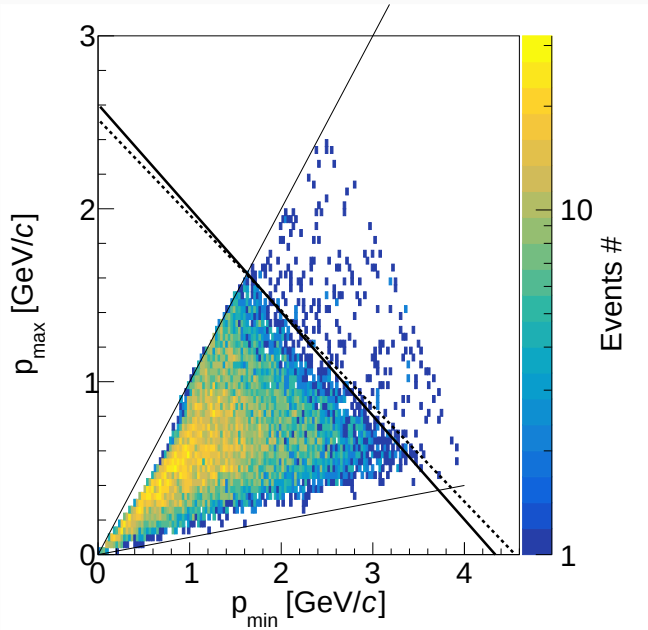
- missing transverse momentum in cms: $p_t^{*Z'}$
- maximum momentum muon in cms: $p_{\text{max}}^{*\mu}$
- minimum momentum muon in cms: $p_{\text{min}}^{*\mu}$
- projection: $p_t^{*Z'} \sin \angle \mathbf{p}_t^{*Z'} \mathbf{p}_{\text{max}}^{*\mu}$

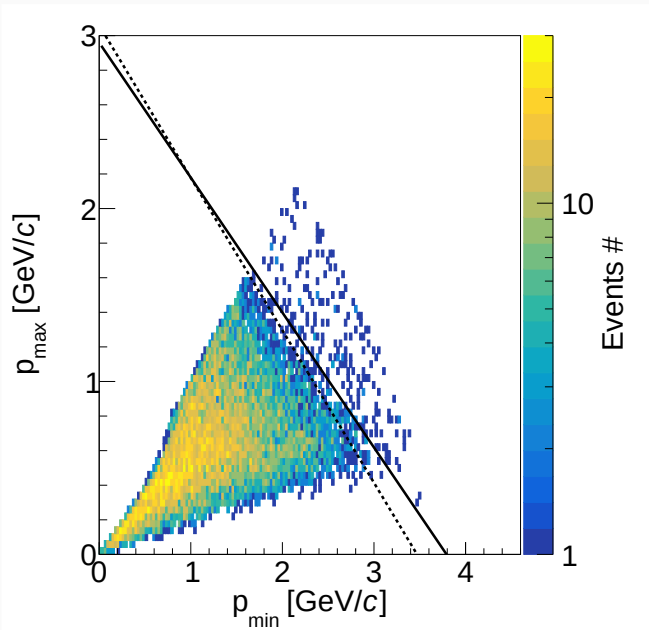
Diagonal cut

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

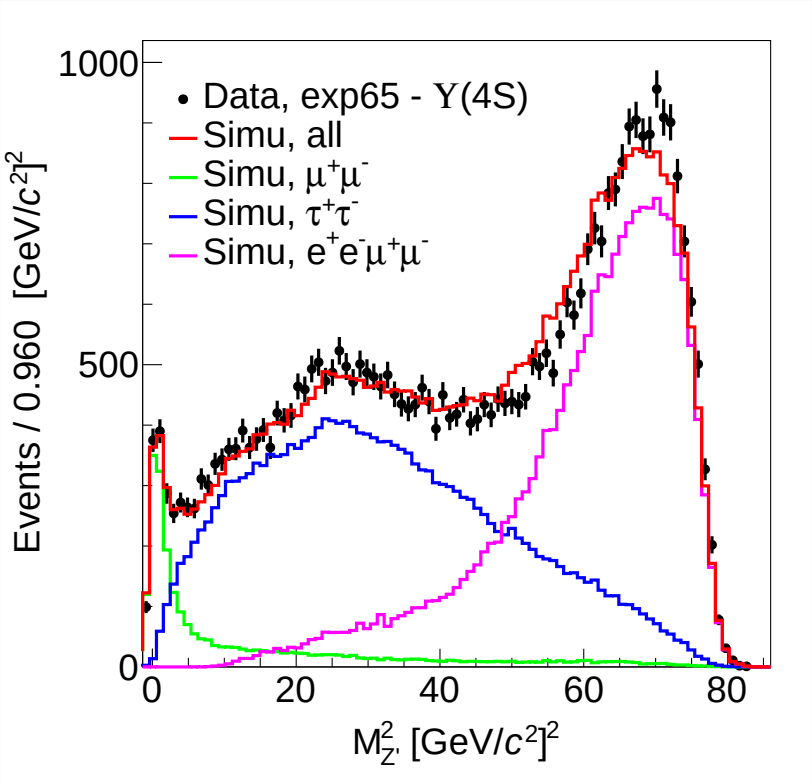


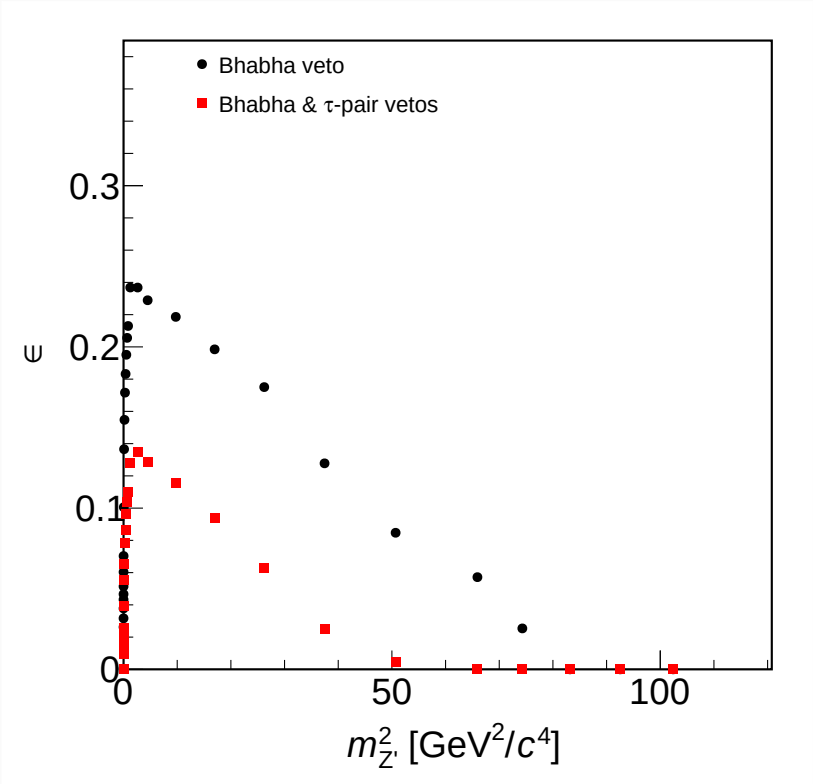




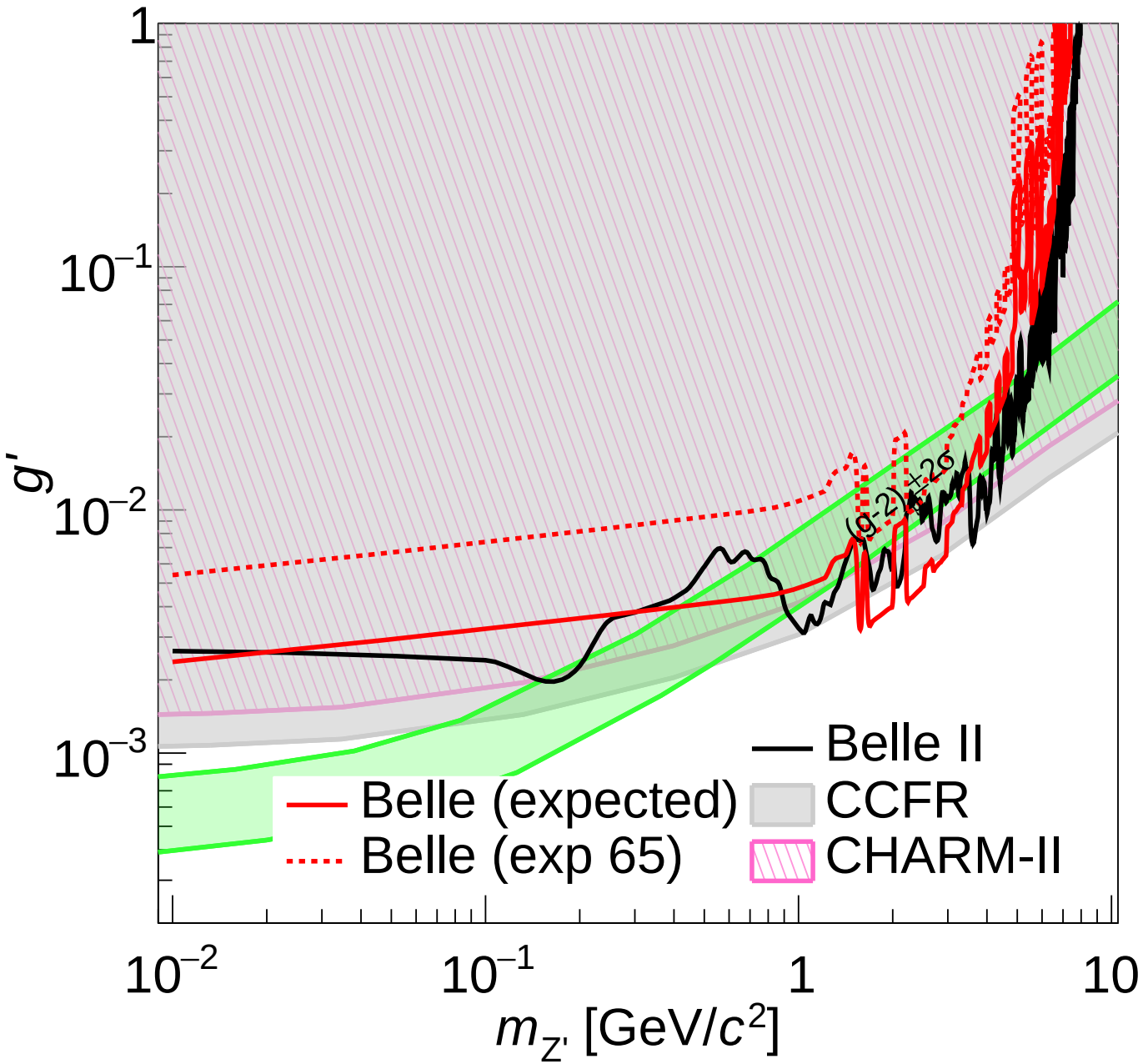


Background sources and detection efficiency

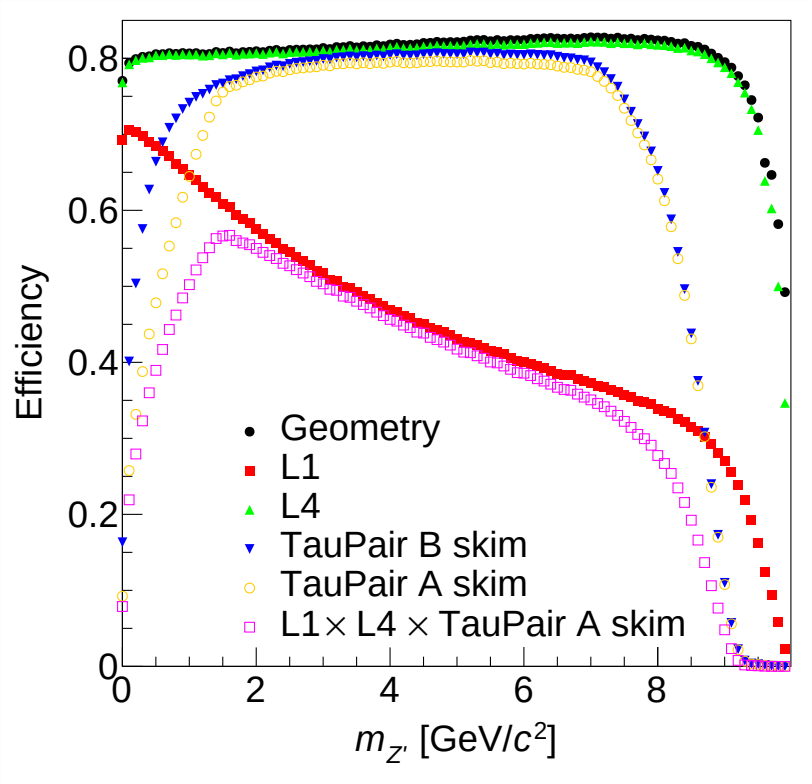




New Limit in Comparison with Belle II 79.1 fb^{-1}



Why is the Belle II small sample so much better?



We don't know yet. (We suspect it's the single photon trigger)

the Belle II invisible Z' search

Selection Criteria 2212.03066

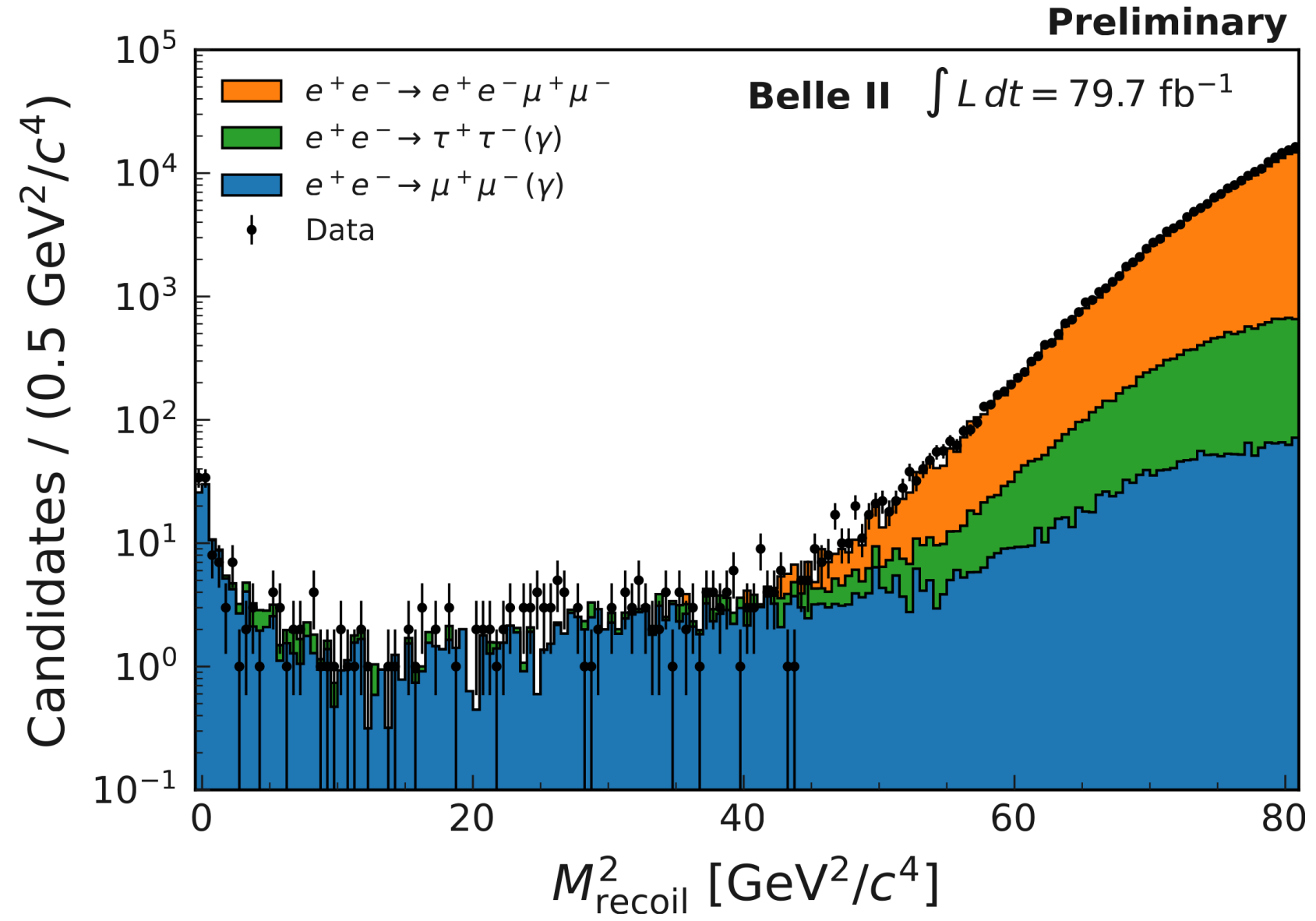
1. 1 pair of tracks with $\theta \in [37^\circ, 120^\circ]$
2. 2 track trigger
3. Bhabha like events veto
4. 2 tracks from IP
5. transverse distance from IP < 0.5 cm
6. longitudinal distance from IP < 2 cm
7. net charge of the event is zero
8. 2 track IDs are μ
9. $p_t > 0.4$ GeV$/c$
10. veto on $\angle_{\mu\mu} > 179^\circ$
11. $\theta_{\text{recoil}} \in [34^\circ, 123^\circ]$
12. all photons amount to less then 0.5 GeV energy
13. no photon within 15°

Remaining background

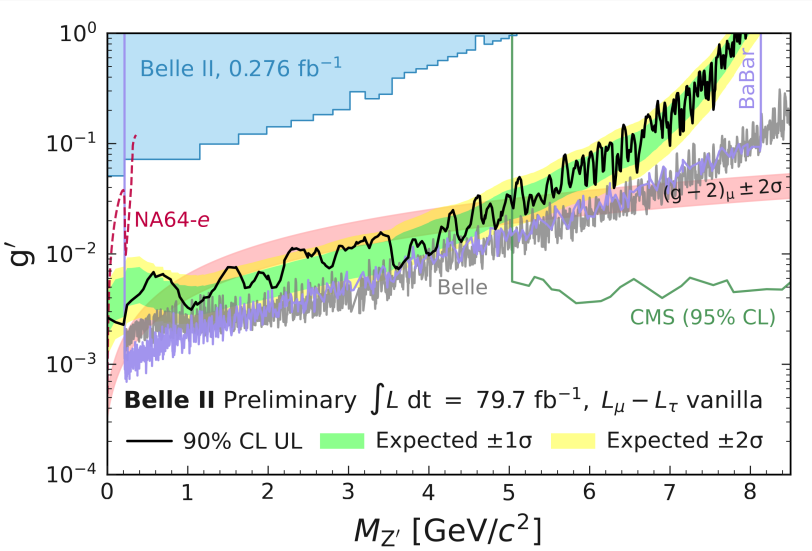
1. $e^+e^- \to \tau^+\tau^-(\gamma)$
2. $e^+e^- \to e^+e^-\mu^+\mu^-$
3. $e^+e^- \to \mu^+\mu^-(\gamma)$

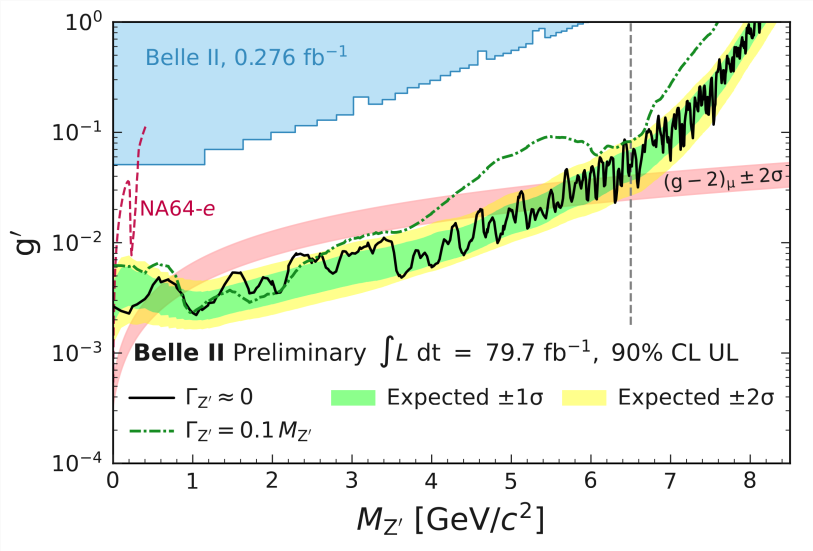
Neural Network FOM optmization Punzi-loss

Results: Background and data 2212.03066



Results: Vanilla Z' dark Z' parameter spaces 2212.03066





the leptophylic scalar search @ Belle

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

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

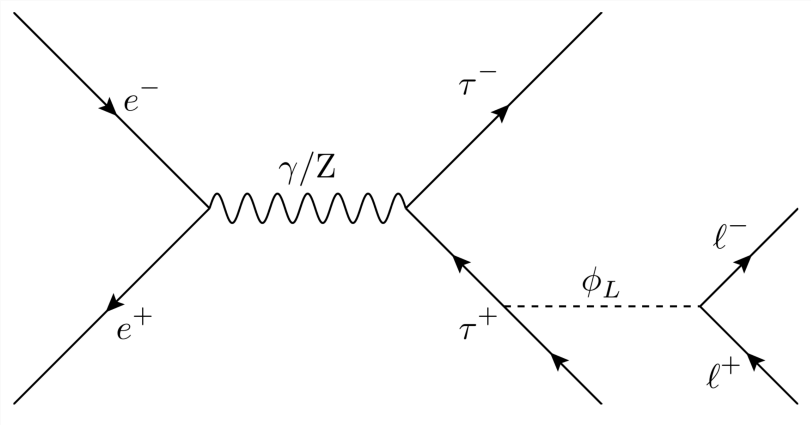


Figure 4: Main process for the ϕ_L production

- 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 $m_{\phi_L} > 2mu_\mu(\tau)$

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

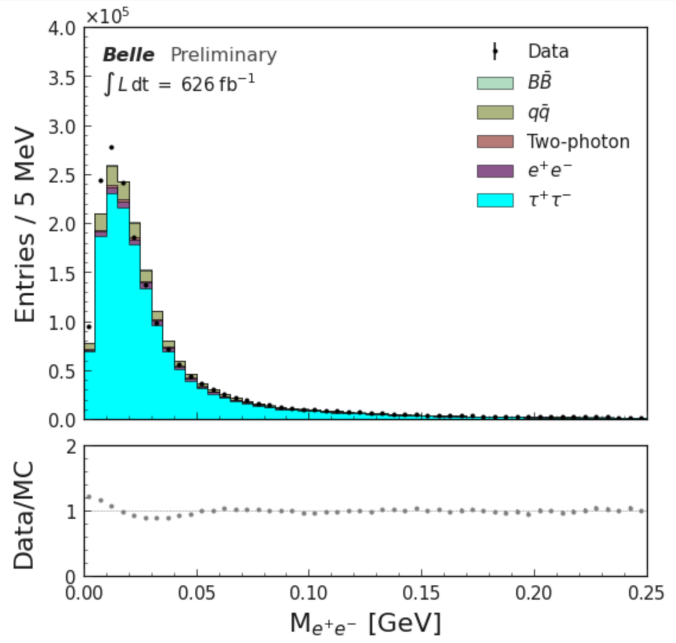
SR (Signal Region) Signal Score > 0.5

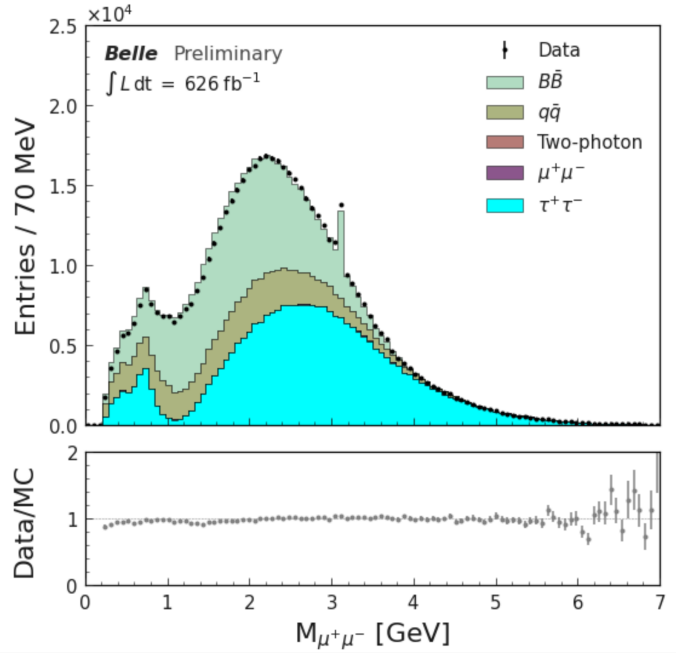
1. $\phi_L \to e^+e^-(\mu^+\mu^-)$

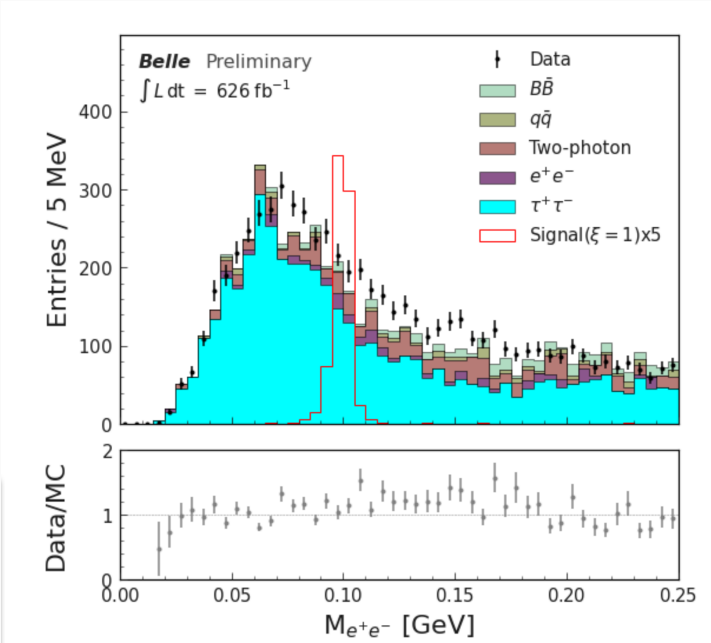
GCR (General Control Region)

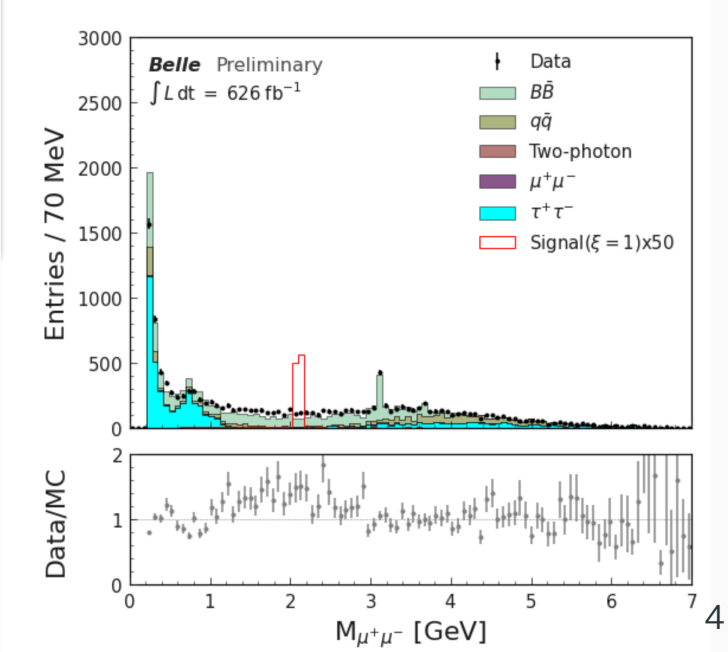
2. $\tau^+\tau^-$
3. $e^+e^-(\mu^+\mu^-)$
4. $q\bar{q}$
5. $B\bar{B}$

Results: GCR and SR 2207.07476

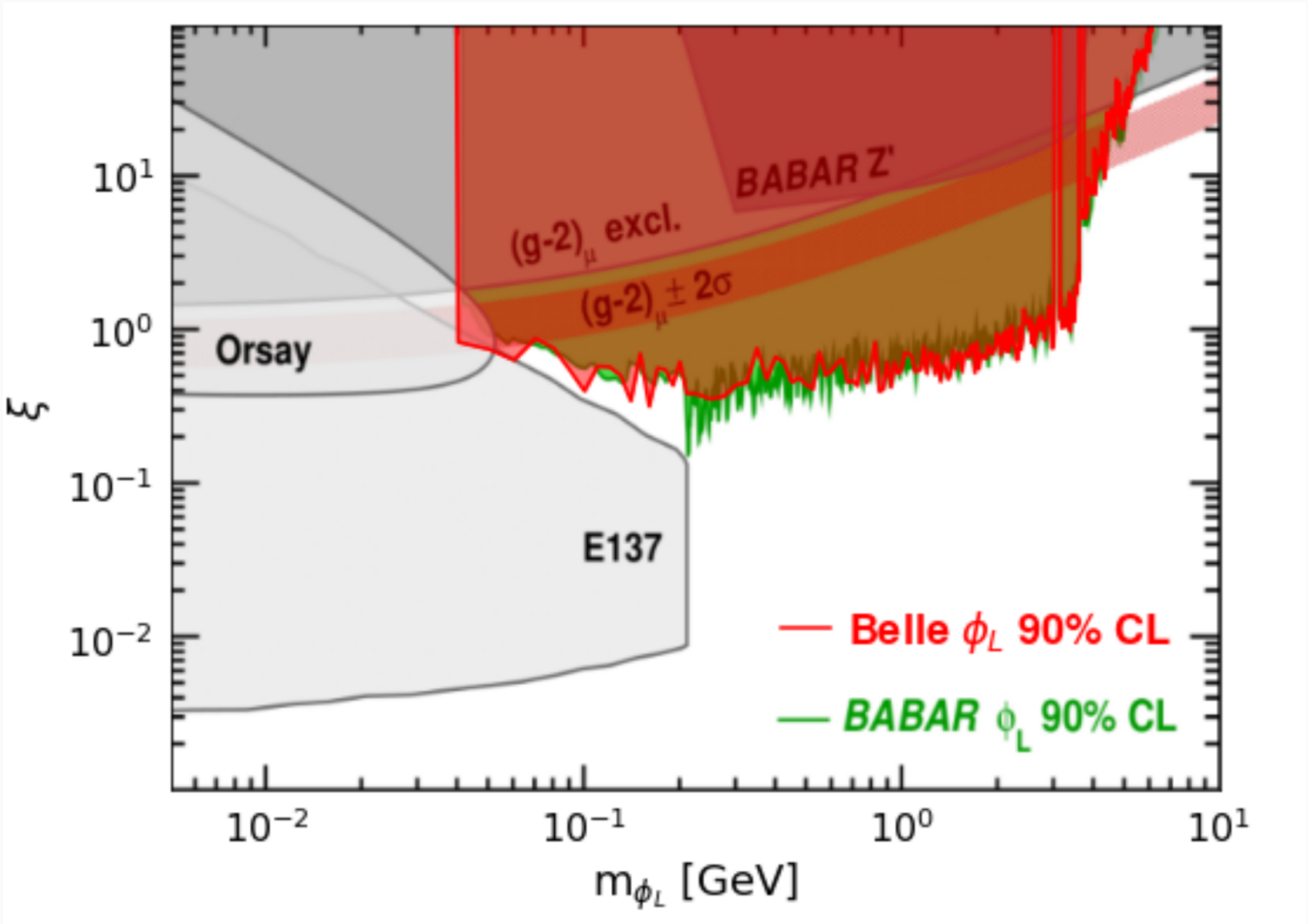








Results: ξ coupling limit 2207.07476



Summary

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Leptophylic Z' and ϕ_L outlook

- Finally touching very low mass Z' parameter space in collider experiments
- Belle II already has collected more than 400 fb^{-1}
  - Update on Z' invisible analyses is ongoing
- Belle full data (~1 ab^{-1}) analysis of the Z' invisible has just started collaboration internal review
  - Belle II developed machinery being tested with Belle test sample
- ϕ_L analysis still to be done at Belle II