Dark Sector searches at BELLE

Anomalies and Precision in the Belle II Era

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KEKB and Belle

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

Light CP-odd Higgs Boson, A^0

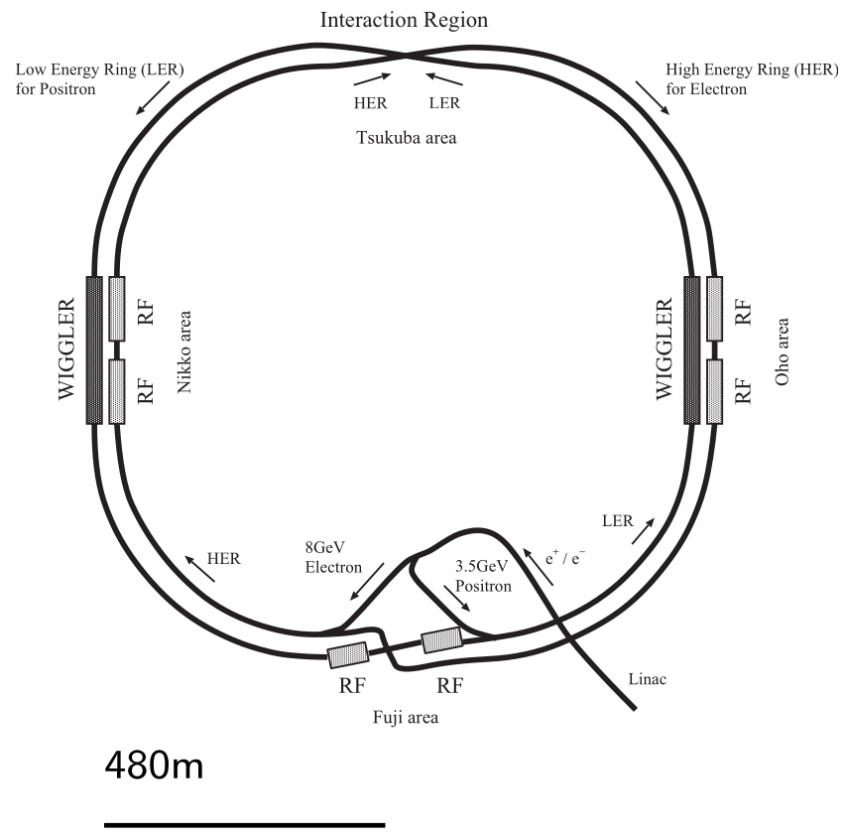
Dark Photon, A'

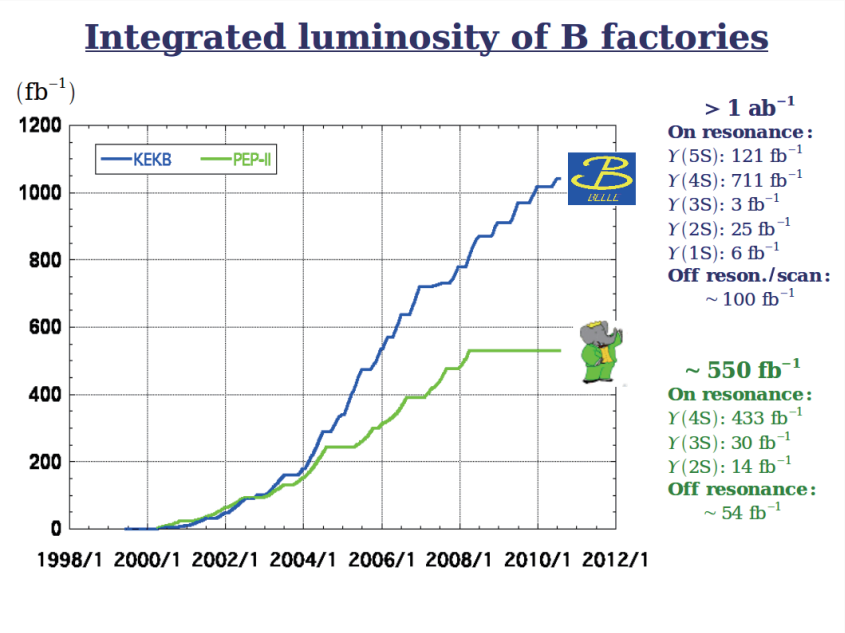
Summary

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.

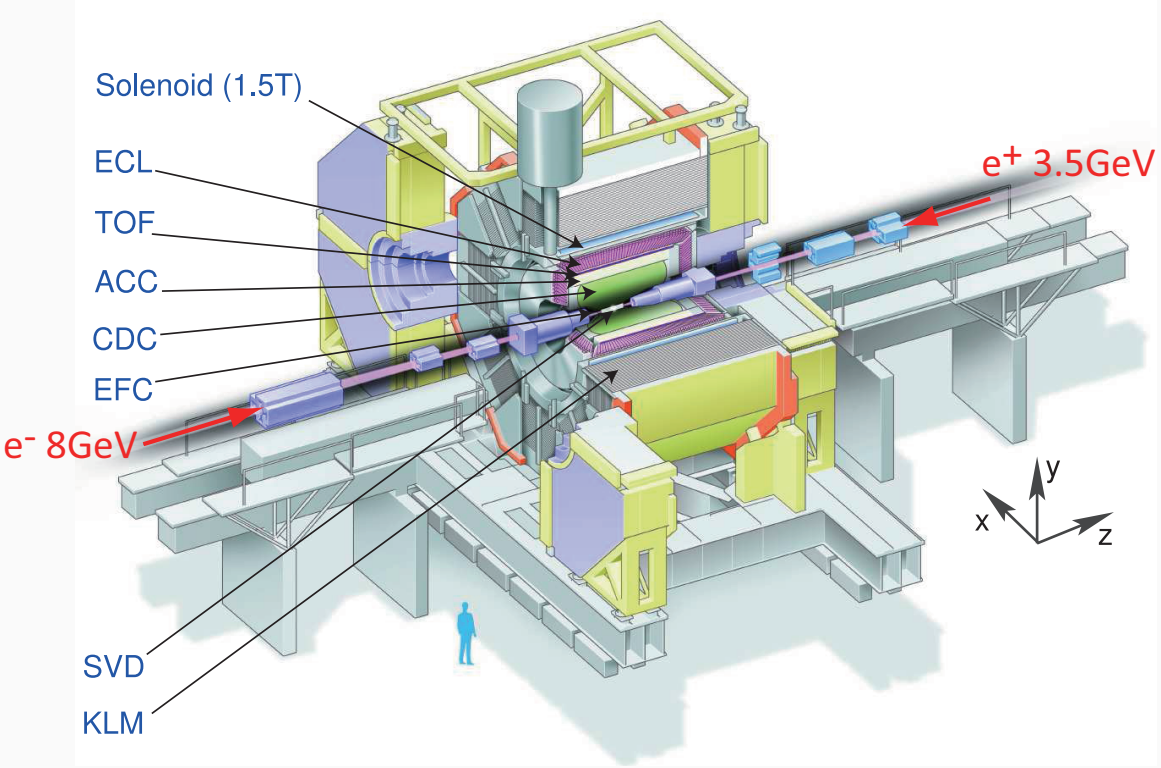
It's located in Tsukuba and has achieved a record Luminosity of 1 ab^{-1}





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

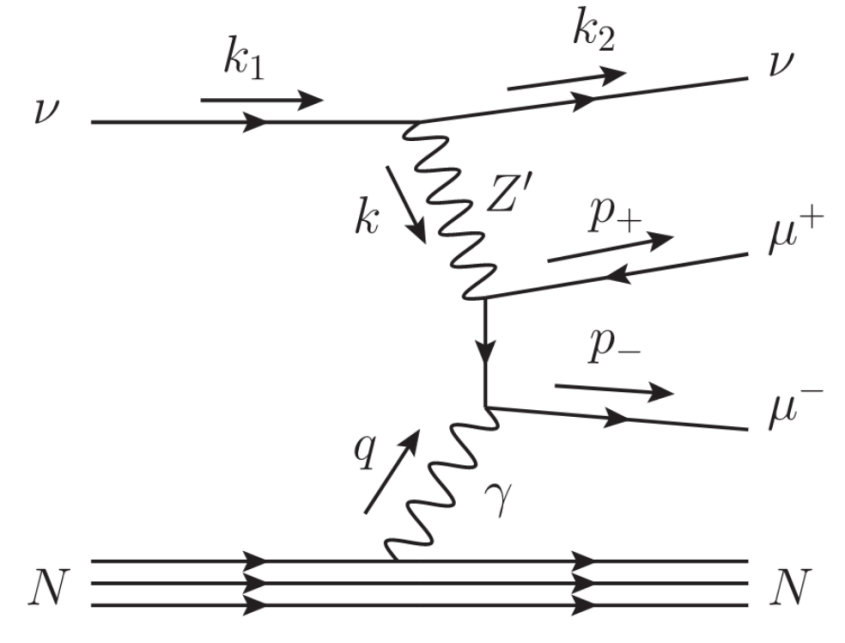
The Belle Detector



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

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

Origins of Z' PRL 113, 091801 - 2013

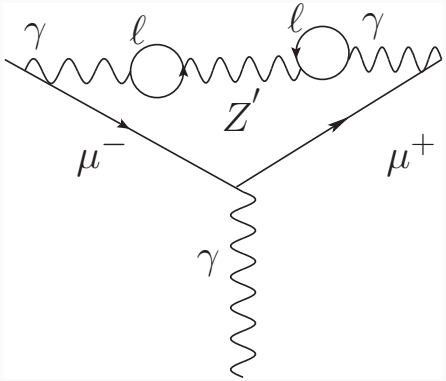


$$\mathcal{L}_{Z'} = -\frac{1}{4}(Z')_{\alpha\beta}(Z')^{\alpha\beta} + \frac{1}{2}m_{Z'}^2 Z'_\alpha Z'^\alpha + \underbrace{g' Z'_\alpha(\bar{\ell}_2\gamma^\alpha\ell_2 - \bar{\ell}_3\gamma^\alpha\ell_3 + \bar{\mu}_R\gamma^\alpha\mu_R - \bar{\tau}_R\gamma^\alpha\tau_R)}$$

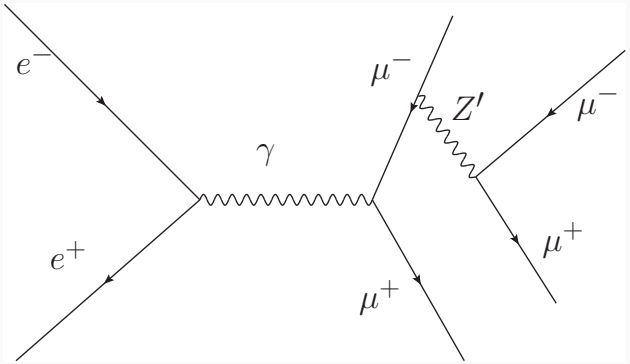
$$\boxed{\mathcal{L}_{\text{int}} = -g'\bar{\mu}\gamma^\mu Z'_\mu\mu + g'\bar{\tau}\gamma^\mu Z'_\mu\tau - g'\bar{\nu}_{\mu,L}\gamma^\mu Z'_\mu\nu_{\mu,L} + g'\bar{\nu}_{\tau,L}\gamma^\mu Z'_\mu\nu_{\tau,L}}$$

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.

Z' search in B-factories

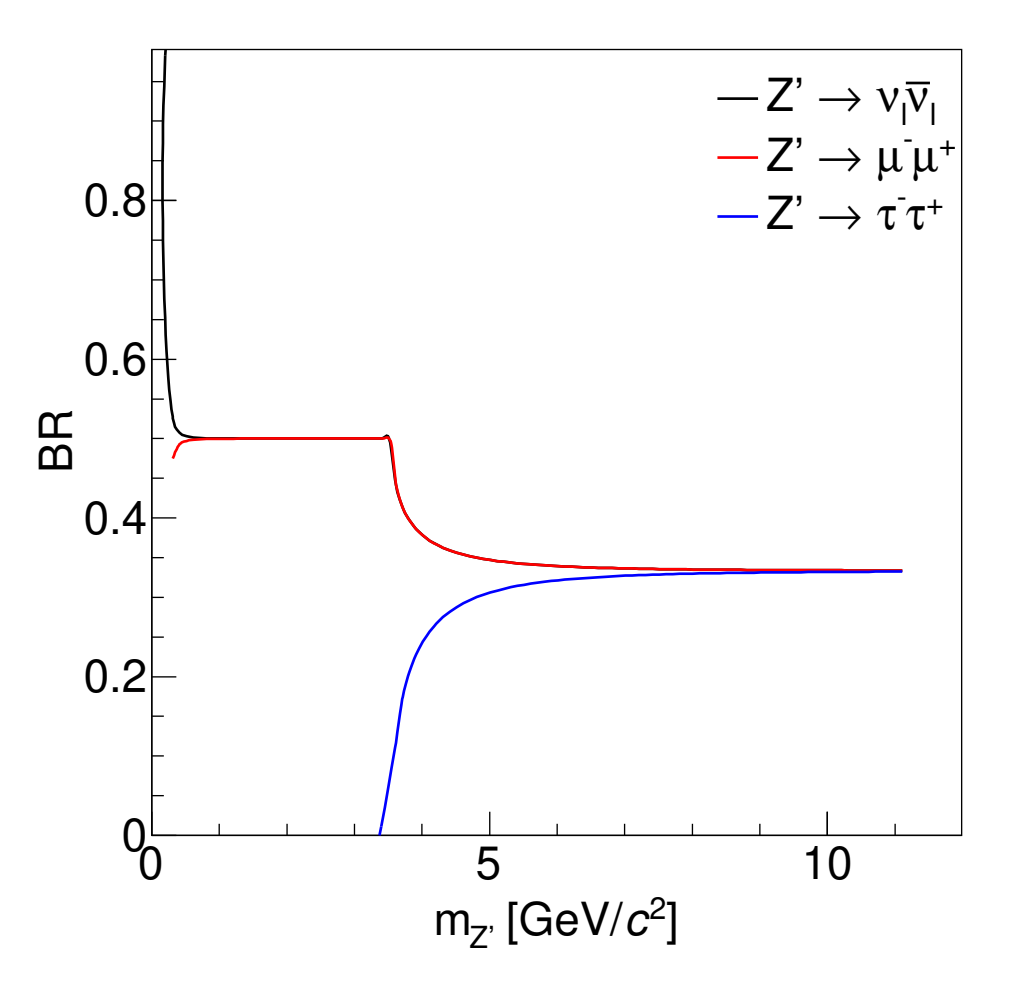


- A model initially motivated by the $(g-2)_\mu$ **problem** but recently Z' as a channel for **sterile neutrinos** as a dark matter candidate.
- We aim to look for a Z' signal using full available Belle data, or setting a more stringent limit on g'

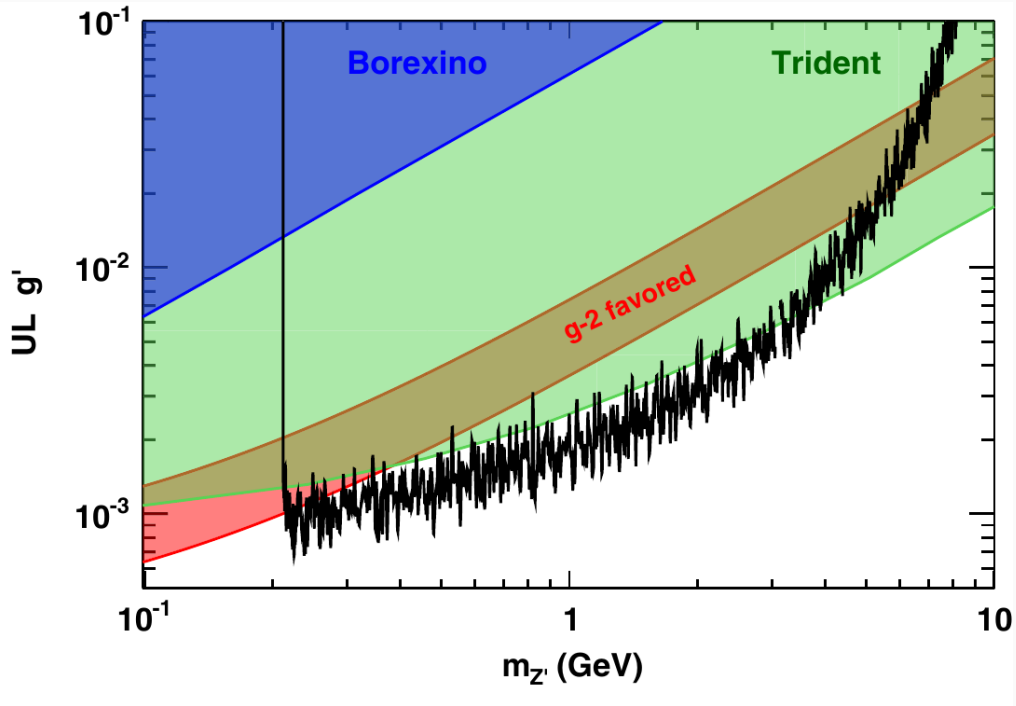


Z' decay width and branching ratio

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



Past Search PRD 94 011102 - 2016

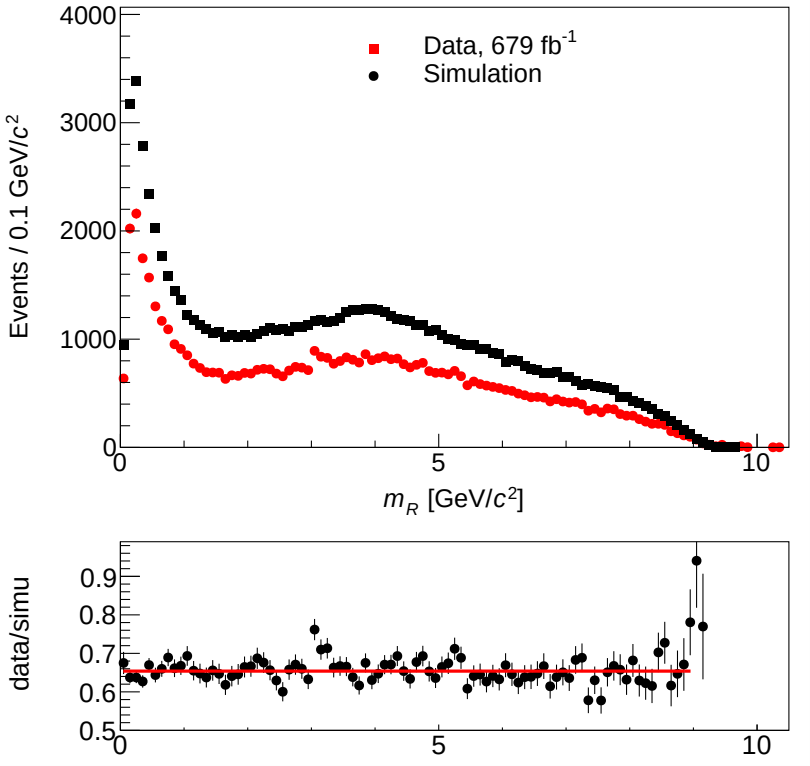


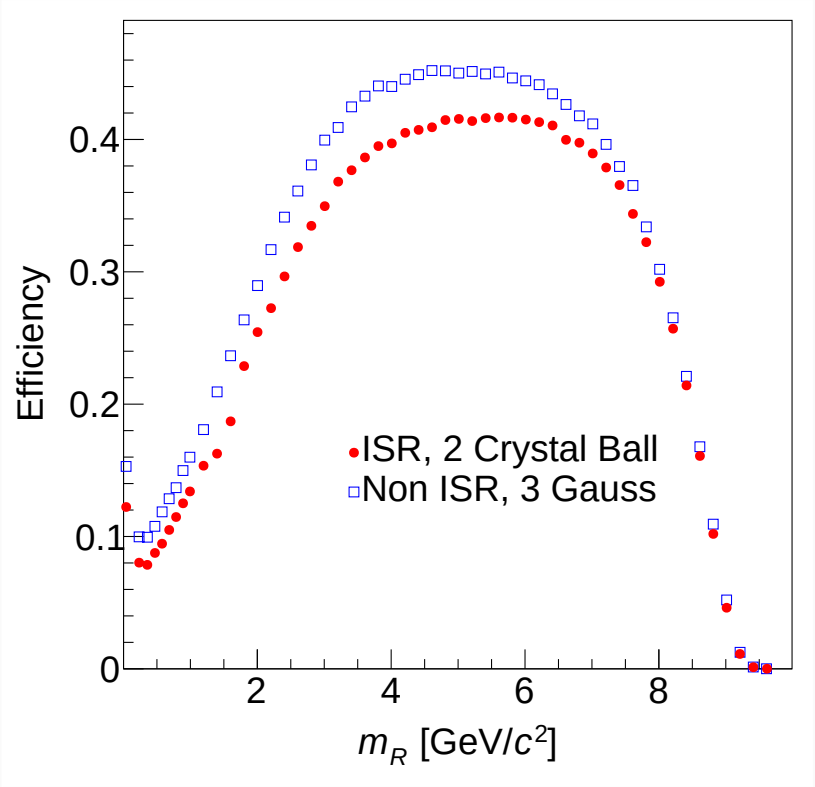
- No Z' signal was found
- limit on the coupling was set for the BaBar mass range ($0 \sim 10$ GeV)
- g' limit almost excludes Z' contribution in $g-2$ for the BaBar mass range

Belle Search

- 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** <u>or</u> **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

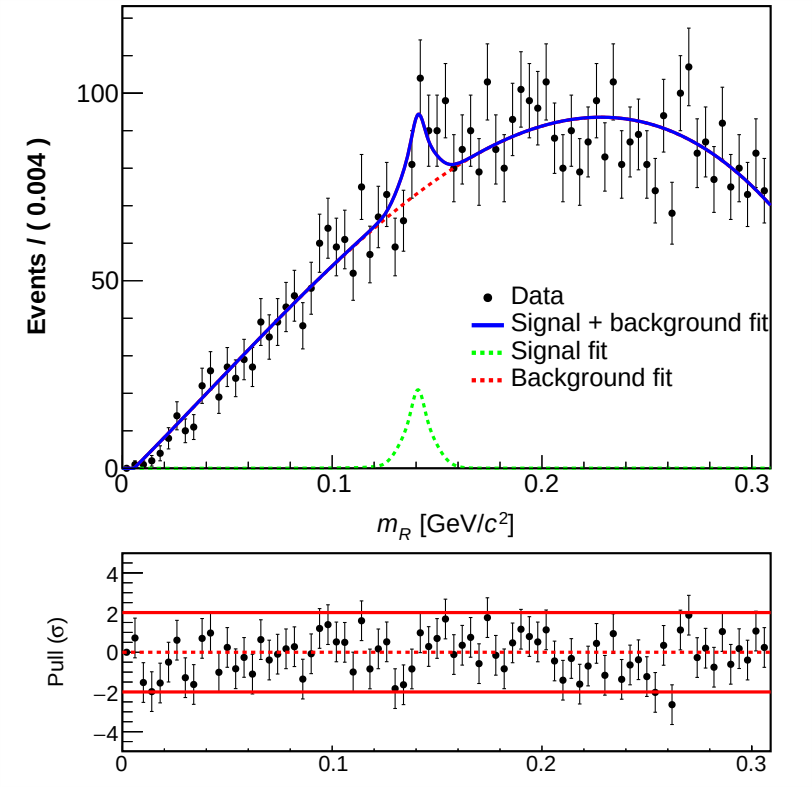
Results

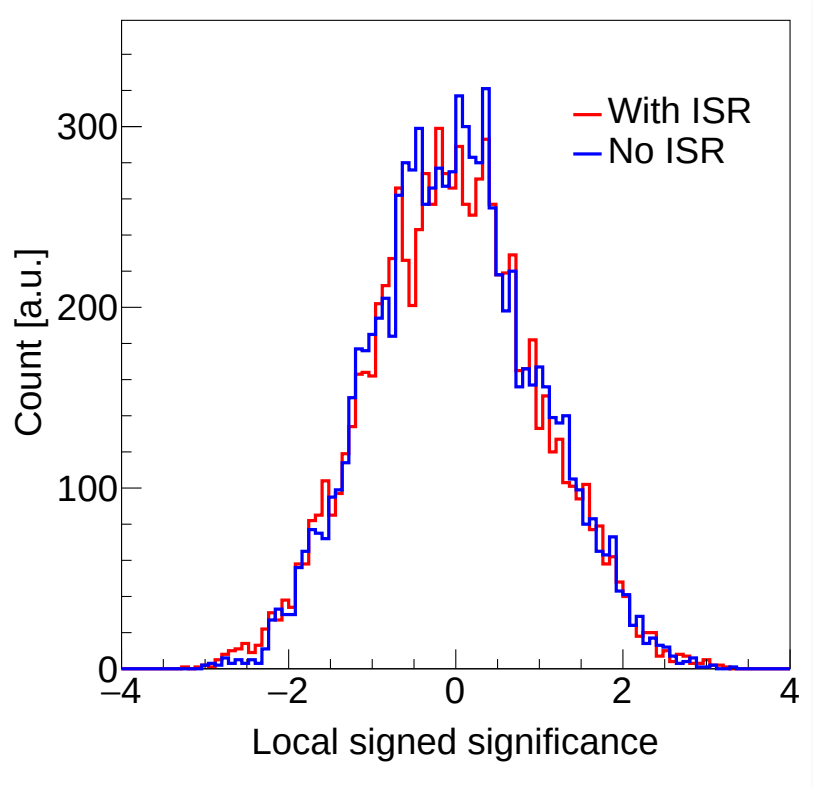




- reduced mass, m_R, scan
  - $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^{\mathrm{PDG}^2}}$
- 1 background
  - $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  - non ISR MC
- Detection efficiency for ISR and non ISR

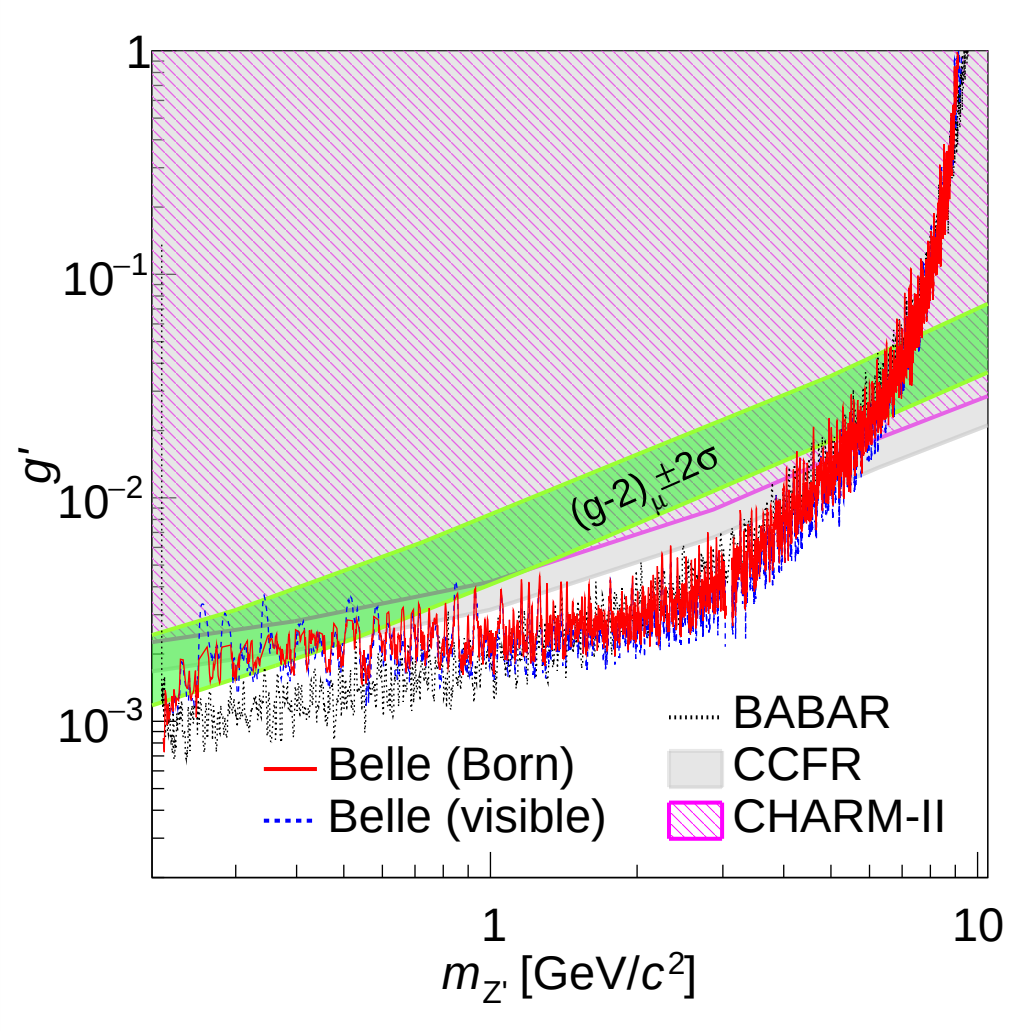
Results





- Two CB single mean for Signal
- Third-order poly for bg
- Highest local significance 3.19σ
  - $m_{Z'} = 0.254$ GeV/c^2
  - $m_R = 0.141$ GeV/c^2

Z' coupling



- Proper treatment of ISR
- Some gains on low and high Z' mass range

Light CP-odd Higgs Boson, A^0

$\Upsilon(1S) \to \gamma A^0(\chi\chi)$ PRL 122, 011801

- Motivated by μ-problem
- New Physics, NMSSM
- Dark matter at 100 GeV/c^2

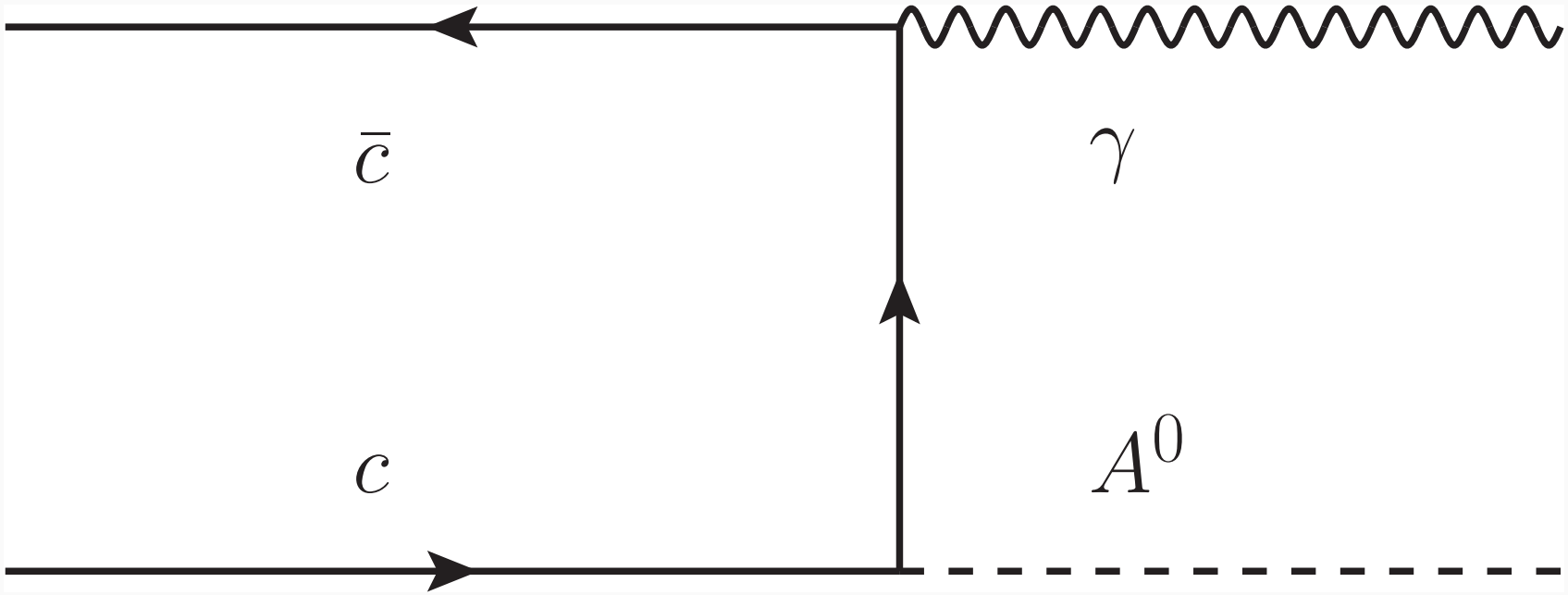


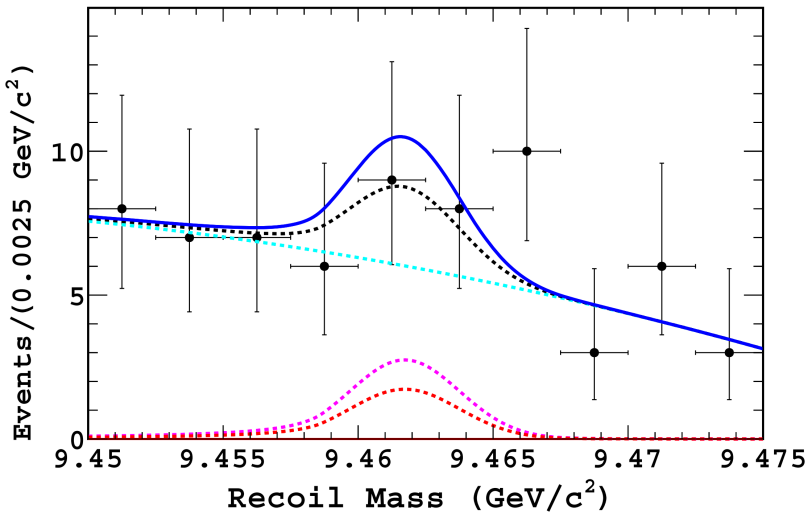
Figure 1: PRL 39, 1304

- $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$
- 157 $\times 10^6 \Upsilon(2S)$ sample
- 3 detectable particles only

Selection and background

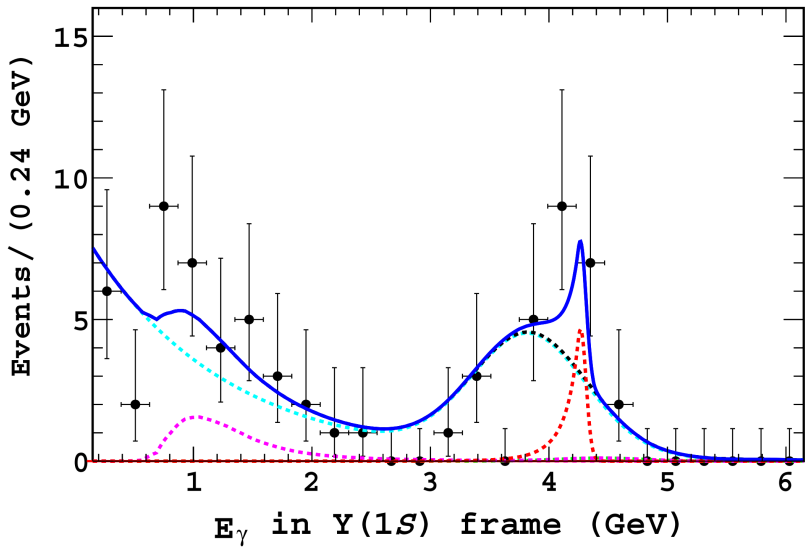
- L1 trigger
- ECL energy $> 1.0(3.0)$ with(out) cosmic ray veto
- $M_{A^0} < 8.97$ GeV$/c^2$ and $M_\chi < 4.44$ GeV$/c^2$
- 2 oppositely charged tracks from IP
- ± 4 cm (beam-axis) and 2 cm (transverse to beam)
- $\mathcal{L}_\pi > 0.6$ and $\mathcal{L}_e < 0.1$
- 1st γ $E^*_\gamma > 0.15$ GeV and $-0.63 < \cos\theta < 0.84$
- $M^2_{\text{recoil}} = s + M^2_{\pi\pi} - 2\sqrt{s}E^{**}_{\pi\pi}, \sqrt{s} = m_{\Upsilon(2S)}$
- M^2_{recoil} close to $m_{\Upsilon(1S)}$
- $\pi\pi$ $\chi^2/$ ndf < 11 and $\theta^*_{\pi\pi} > 45^\circ$ vertex constrained fit
- $\cos\theta_{\pi^\pm\gamma} < 0.97$ bremsstrahlung γ and FSR
- $(\phi_{\pi\pi} - \phi_\gamma) > -0.97$ $e^+e^- \to \gamma\pi^+\pi^-$
- 2nd γ $E^*_\gamma < 0.18$ GeV long lived SM particle opposing γ
- $|180^\circ - |\phi_\gamma - \phi_{\text{long}}|| > 20^\circ$ $\Upsilon(1S) \to \gamma K_L K_L [f_2'(1525, 1270)]$
- Irreducible background
  - $\Upsilon(2S) \to \tau^+\tau^-$
  - $\Upsilon(1S) \to \ell^+\ell^-$
  - $\Upsilon(1S) \to \gamma hh$ $h =$ hadrons

Results

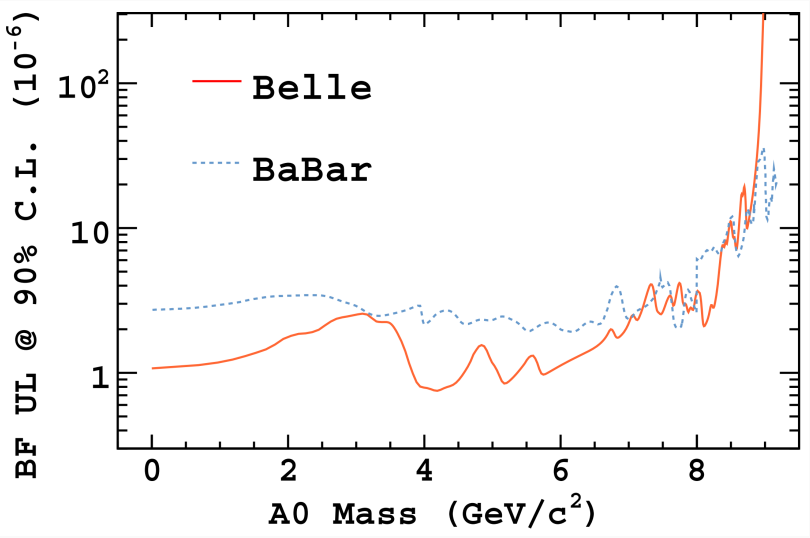


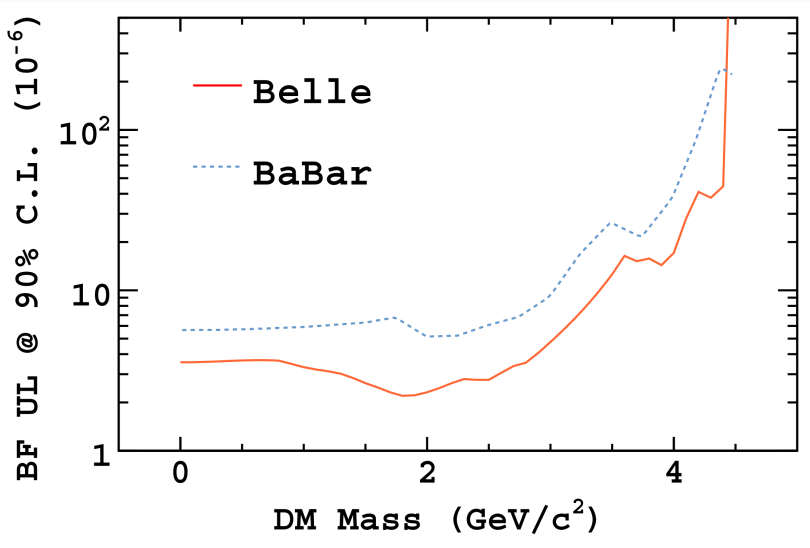
- Signal CB M_{recoil} fit
- Bg second-order Chebyshev poly
- $M_{A^0} = 2.946$ GeV$/c^2$ 2.1σ

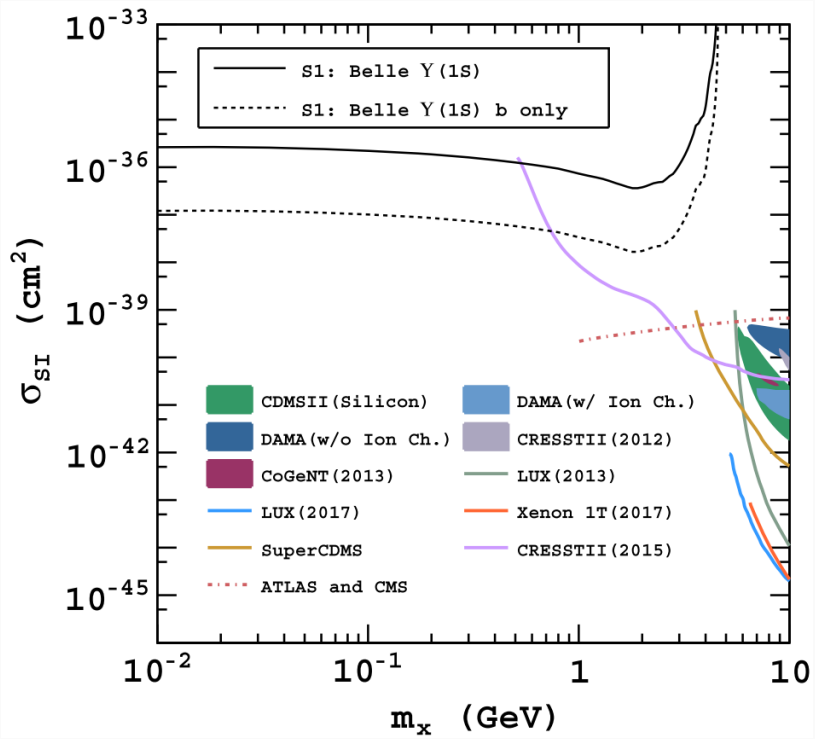
- Signal custom broad function
- Leptonic bg Exponential function
- Hadronic bg Gaussian function



Results



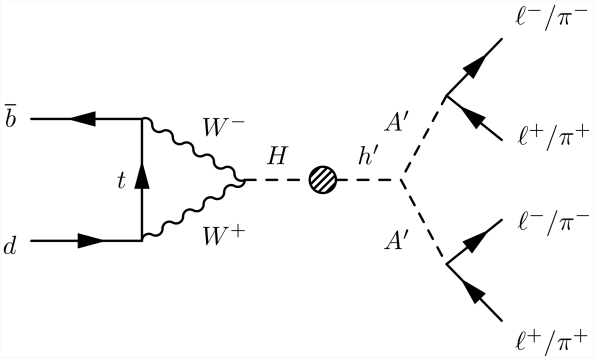




- (Left Top) $\mathcal{B}(\Upsilon(1S) \to \gamma A^0(\to \chi\chi))$
- (Left Bottom) $\mathcal{B}(\Upsilon(1S) \to \gamma\chi\chi)$
- (Right) WIMP-nucleon scattering cross section

$B^0 \to A'A'$ JHEP 04 (2021) 191

- Short-lived and completely visible A' assumed
- 5 decay modes ($4e, 2e2\mu, 4\mu, 2e2\pi$ and $2\mu2\pi$)
- Kinematically allowed A' mass (10–2620 MeV/c^2) with 10–20 MeV/c^2 interval



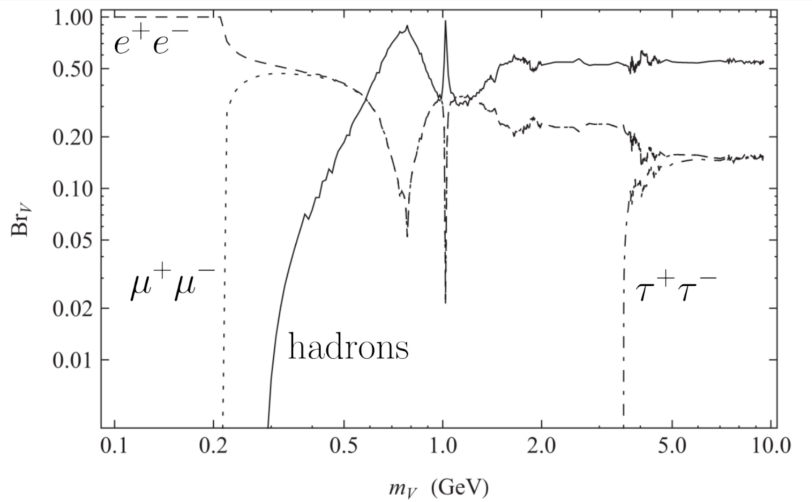


Figure 2: PRD 79, 115008

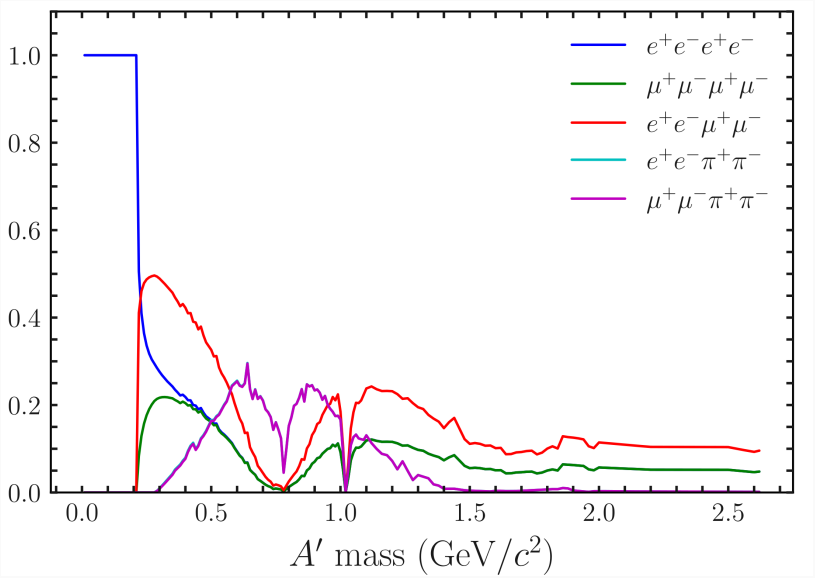


Figure 3: This study $\mathcal{B}$

Selection

Similar SM candidates

- $J/\psi, \psi(2S) \to \ell^+\ell^-$
- $D^0 \to \pi^+\pi^-(K^-\pi^+)$
- light mesons (K_S, ρ^0, ϕ)

$e^+e^- \to q\bar{q}$ suppression using 16 event shape variables

- B^0 momentum direction, angle between thrust axis of B^0 and others, modified Fox-Wolfram moments
- **only** for $\ell^+\ell^-\pi^+\pi^-$
- Fisher discriminant training with TMVA

Small amount of combinatorial background

- Leptons are mostly from semi-leptonic decay of quarks
- missing energy from neutrinos

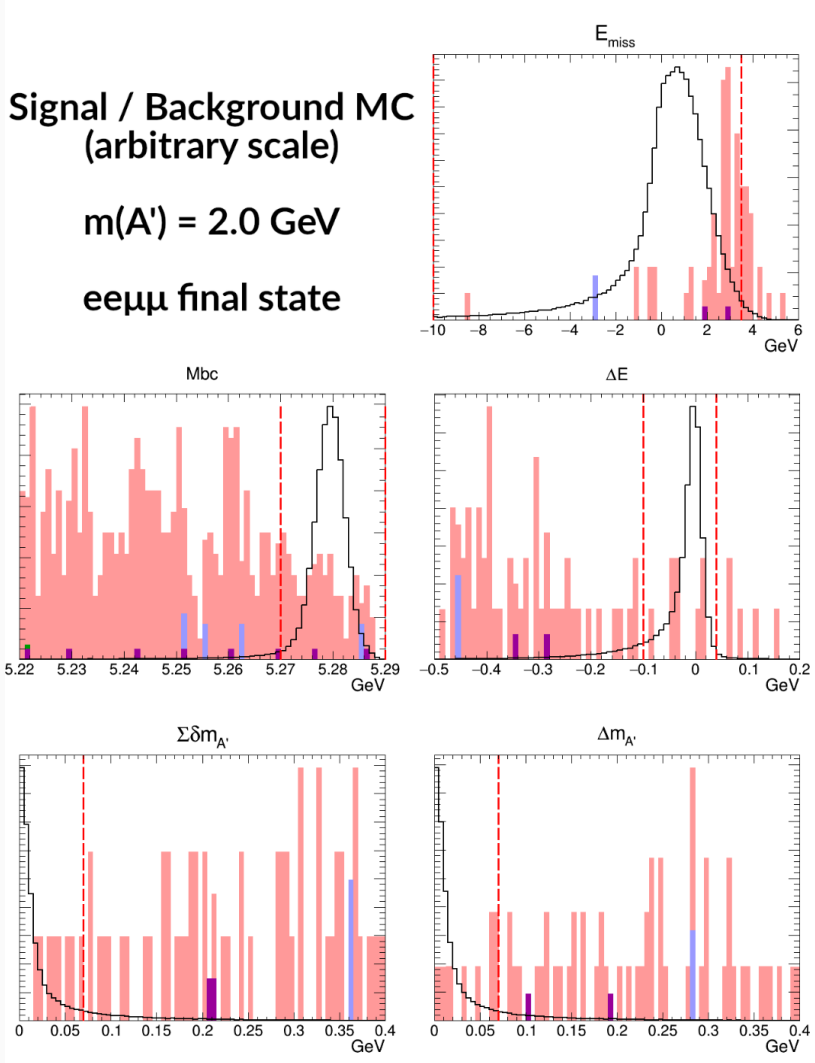
Event Reconstruction

at least 4 charged tracks, at least one e^+e^- or $\mu^+\mu^-$ pair

- Tracks near the IP

combining A' and B^0, 5 variables for B^0 quality

- M_{bc} beam-constrained mass
- ΔE energy difference between beam and B^0
- Missing energy of an event
- $\Delta M_{A'}$ $|M_{A'_1} - M_{A'_2}|$
- $\sum \delta M_{A'}$ $|M_{A'_1} - m_{A'}| + |M_{A'_2} - m_{A'}|$
  - $M_{A'_{1,2}}$ reconstructed $A'_{1,2}$ mass
  - $m_{A'}$ target A' mass



Results

- No significant excess for a signal

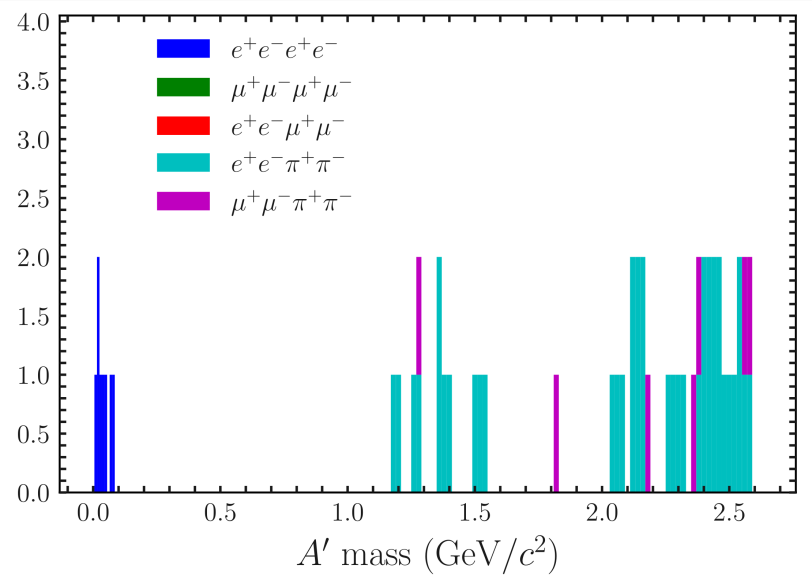


Figure 4: Observed events

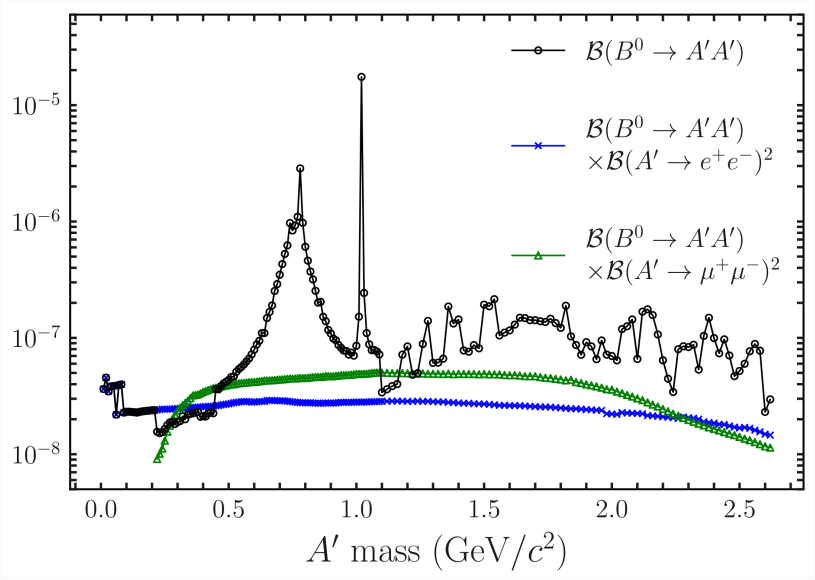


Figure 5: 90% C.L. upper limit on the $\mathcal{B}$

Upper limits for parameter space set with Feldman-Cousings

- Mostly $\mathcal{O}(10^{-8} - 10^{-7})$
- $\mathcal{O}(10^{-5})$ near light meson region

Higgs portal coupling λ

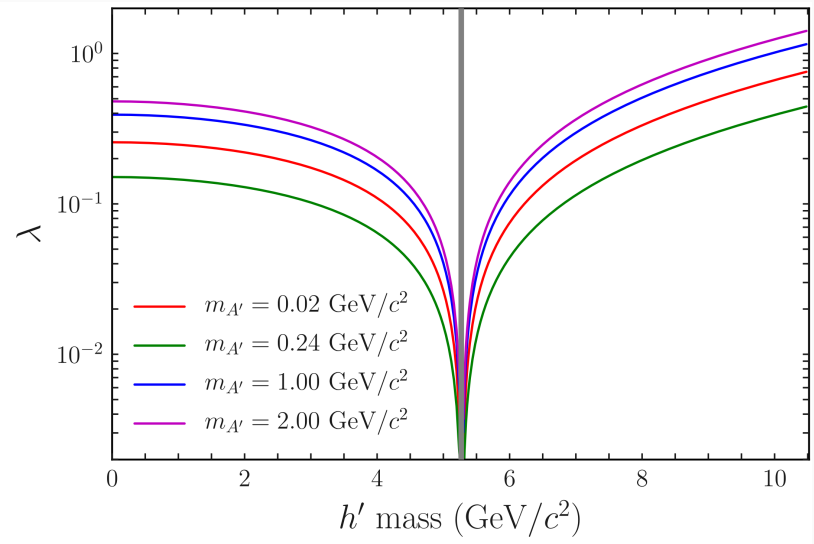


Figure 6: 90% C.L. limits of λ versus h' mass for various A' masses

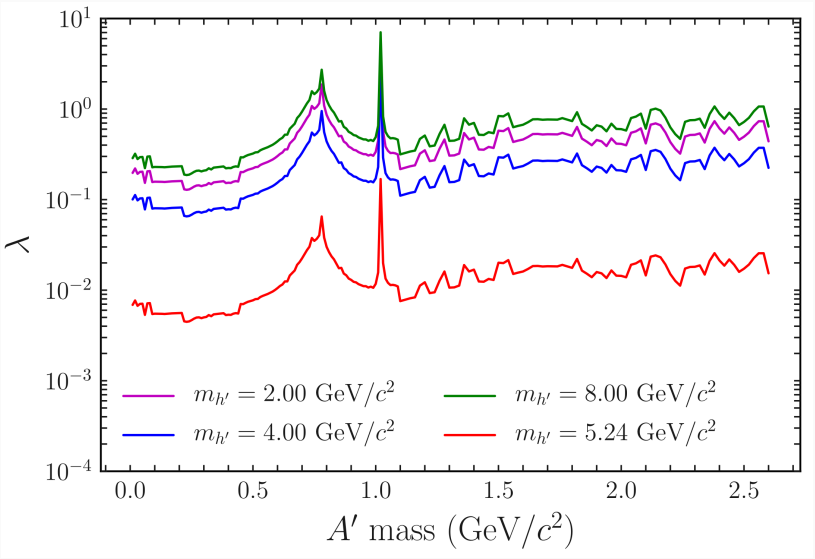


Figure 7: 90% C.L. limits of λ versus A' mass for various h' masses

Higgs coupling PRD 83 054005

$$\mathcal{B}(B^0 \to A'A') \simeq$$
$$7\times10^{-7}\times\lambda^2\times V_{A'A'}^{1/2}\times\frac{V_{A'A'}+12m_{A'}^4/m_{B^0}^4}{(1-m_{h'}^2/m_{B^0}^2)^2}, V_{A'A'} = 1-4m_{A'}^2/m_{B^0}^2$$

Summary

KEKB and Belle

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

Light CP-odd Higgs Boson, A^0

Dark Photon, A'

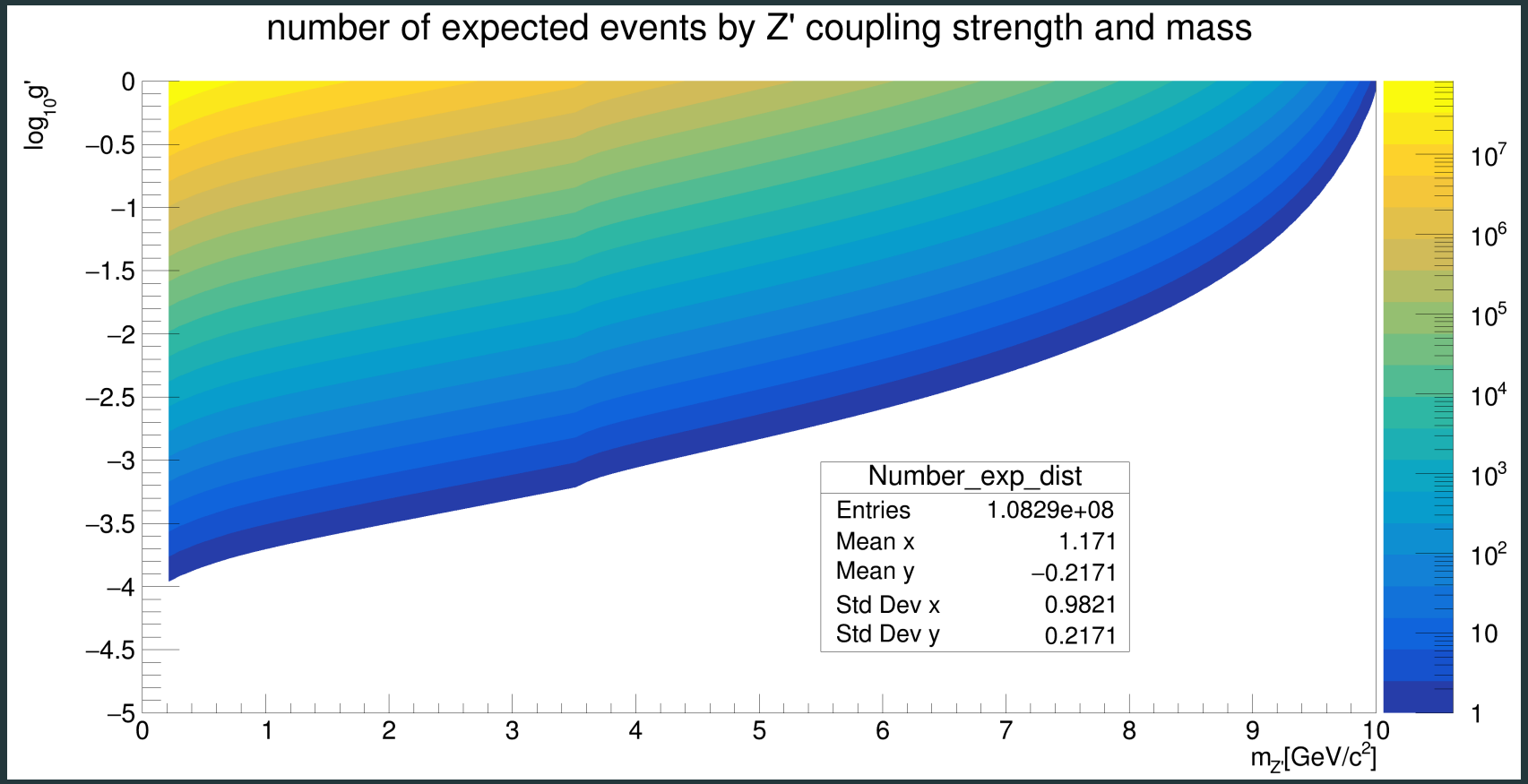
Summary

Summary

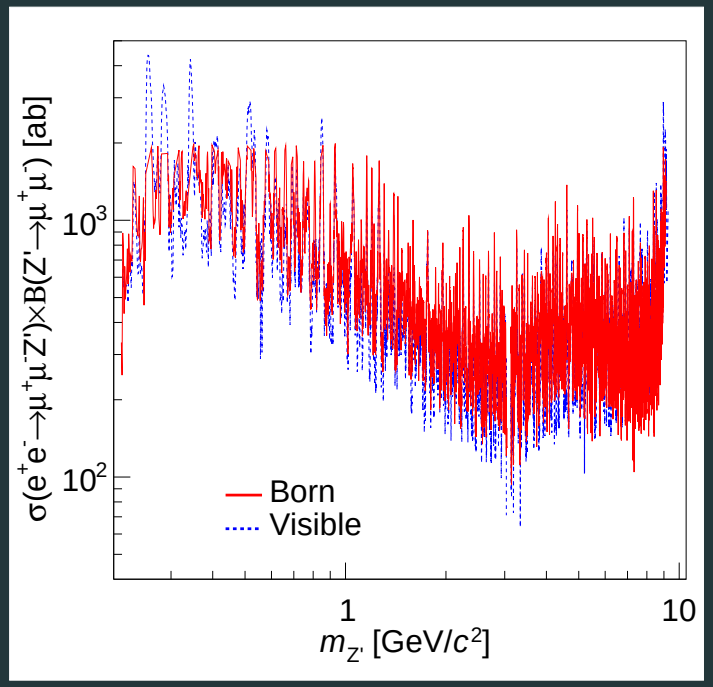
1. Leptophylic Z' outlook
   - improvement on invisible channel (Belle II)
   - visible channel new measurement (Belle II)
   - invisible channel new measurement (BELLE)
2. CP-odd Higgs Boson outlook
   - Belle II measurement
3. Dark Photon from B^0 meson
   - Belle II measurement
4. Other
   - $B^+ \to aK^+$ (ALP) on going at BELLE
   - monopole

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:

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

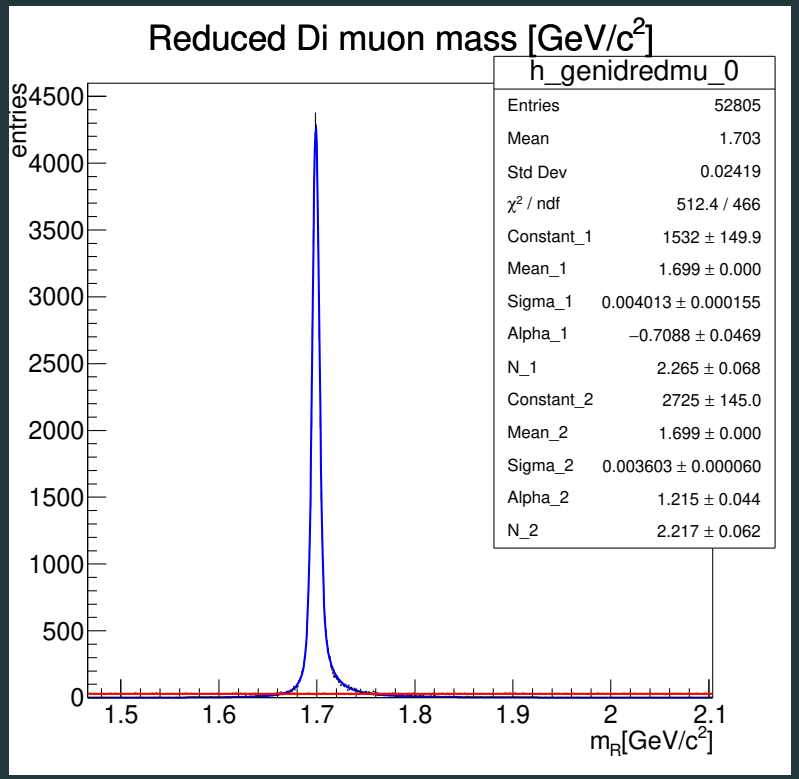
Signal shape based only on true events

Fitting function 2 Crystal Balls with single mean

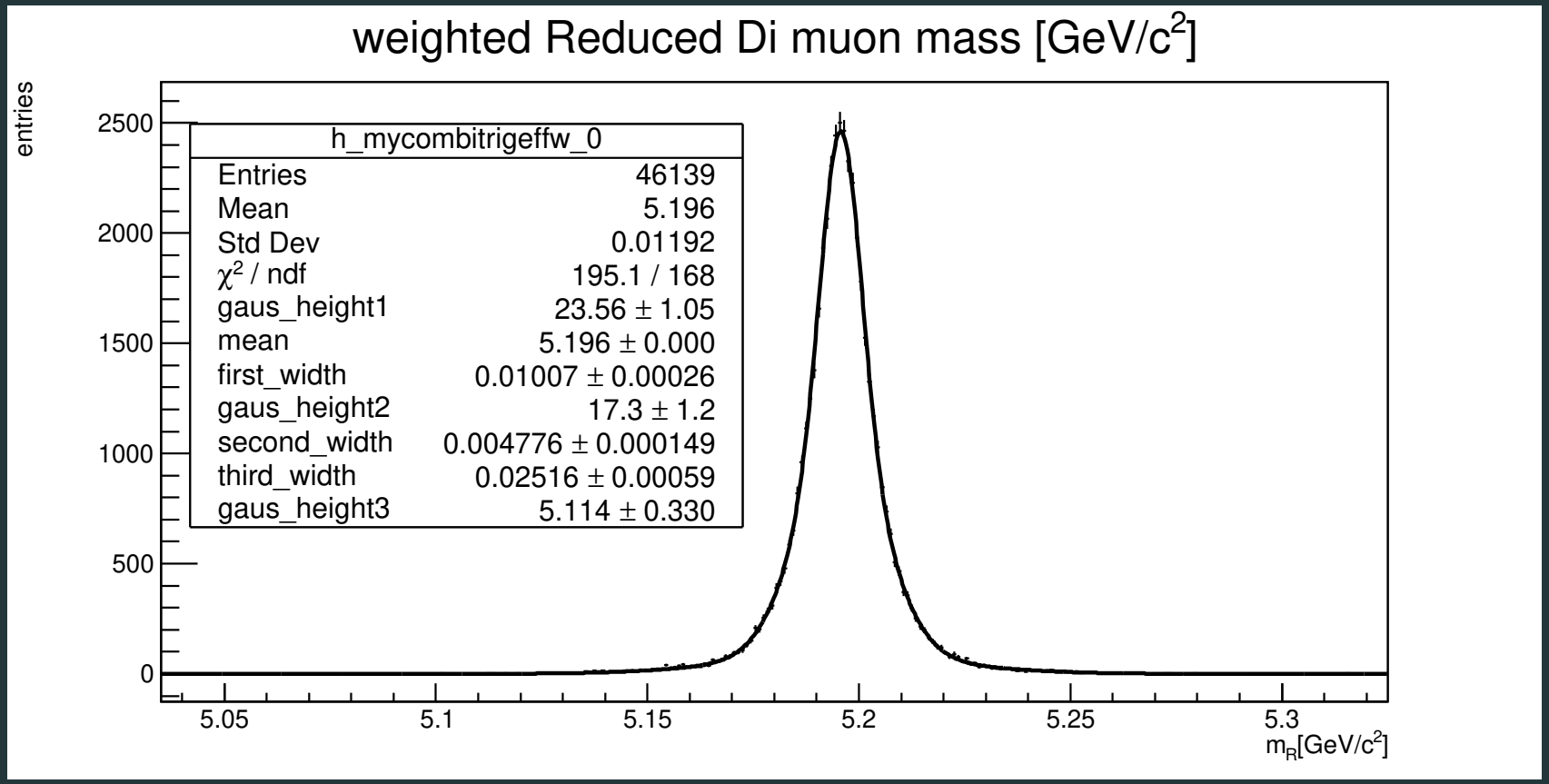
$$f_1(x) = \begin{cases} e^{-\frac{(x-\mu)^2}{2\sigma_1^2}} & \text{if } \frac{x-\mu}{\sigma_1} > -\alpha_1 \\ (C_1 - \frac{x-\mu}{\sigma_1})^{-N_1} & \text{if } \frac{x-\mu}{\sigma_1} < -\alpha_1 \end{cases}$$

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

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



Non ISR sample pdf



Z' resolutions