Dark sector searches at Belle

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on behalf of the Belle collaboration

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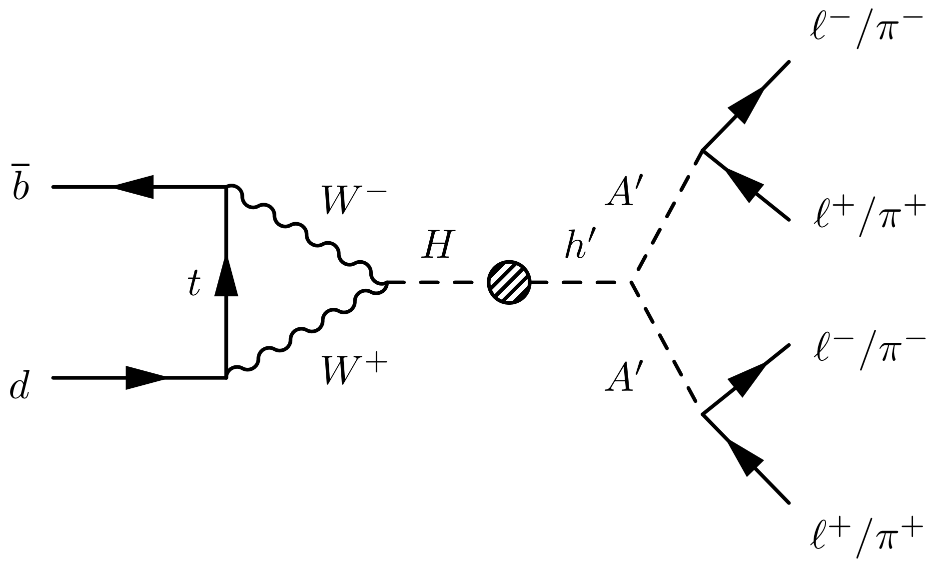
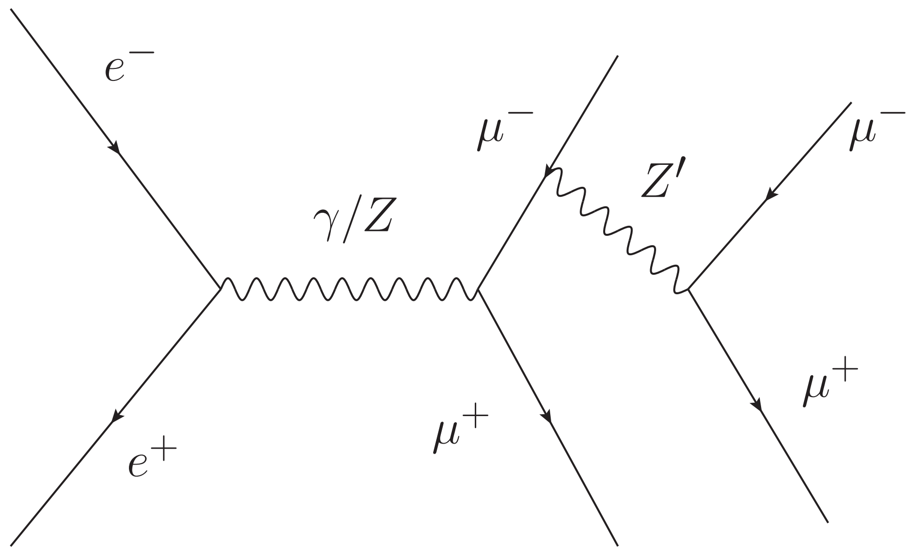
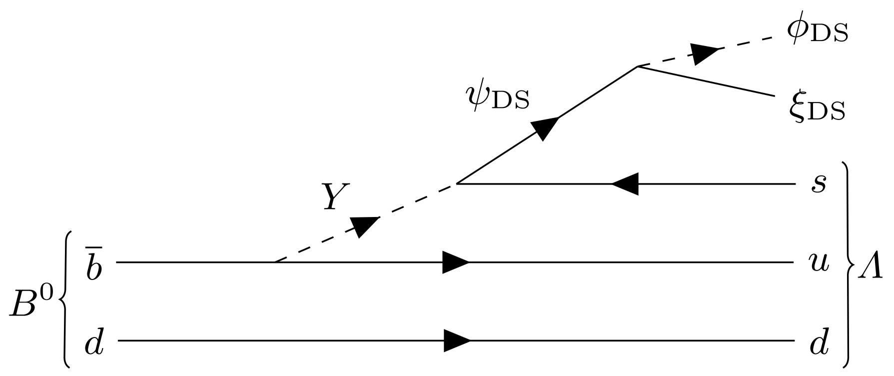
Introduction

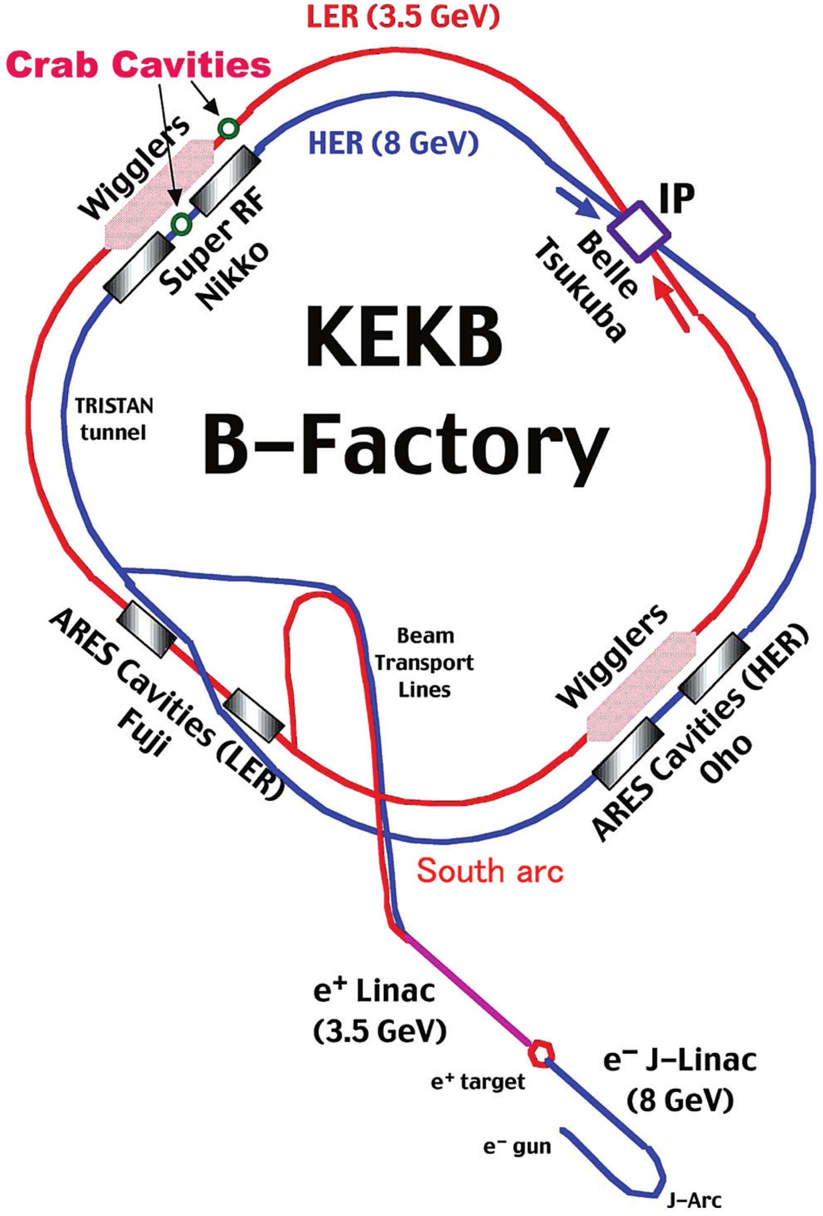
- $B^0 \to A'A'$
  - A' is a visible, prompt-decaying dark photon.
  - h' is a virtual dark Higgs, coming from the kinetic mixing with the H and decaying into an A' pair.
- $e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau} \to 4\mu$
  - $L_\mu - L_\tau$ is the lepton-number difference.
  - Assume prompt decay.
  - We only reconstruct the $Z' \to \mu^+\mu^-$ decay.
- $B^0 \to \Lambda\psi_{\mathrm{DS}}$
  - ψ_{DS} is a GeV-scale dark sector antibaryon.
  - Y is a TeV-scale bosonic colored mediator.
  - Use hadronic tagging.





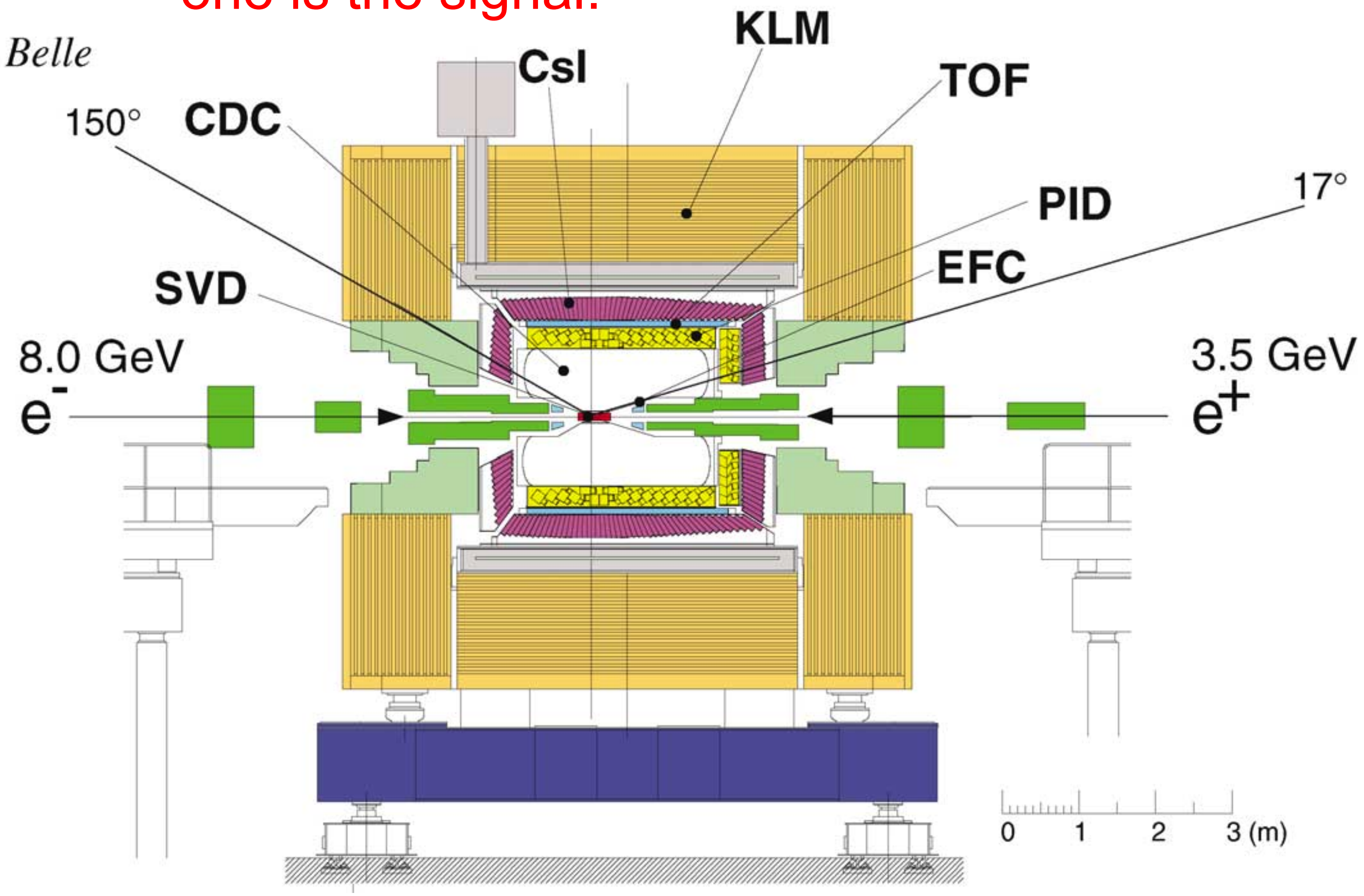


KEKB and Belle



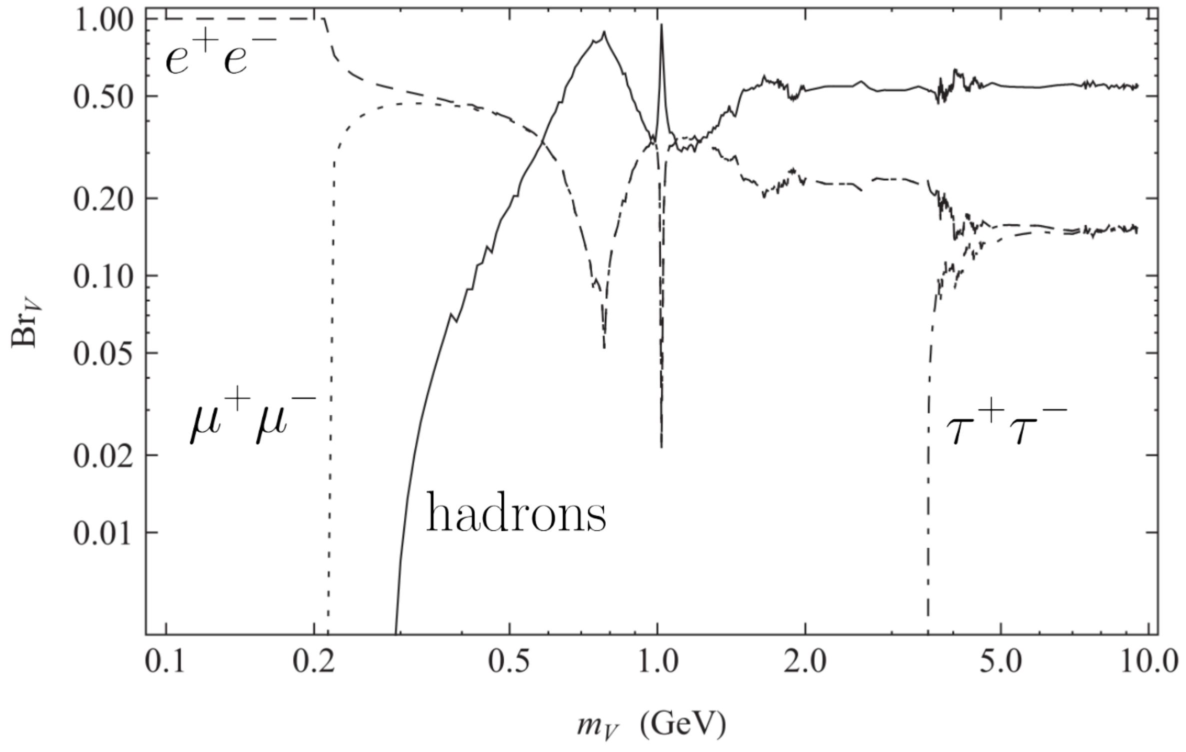
$1040\ \mathrm{fb}^{-1}$ of data was collected by Belle.

- $711\ \mathrm{fb}^{-1}$ of $\Upsilon(4S) = 772\times10^6\ B\bar{B}$. In each $B\bar{B}$ event, one B meson is the tag and the other one is the signal.

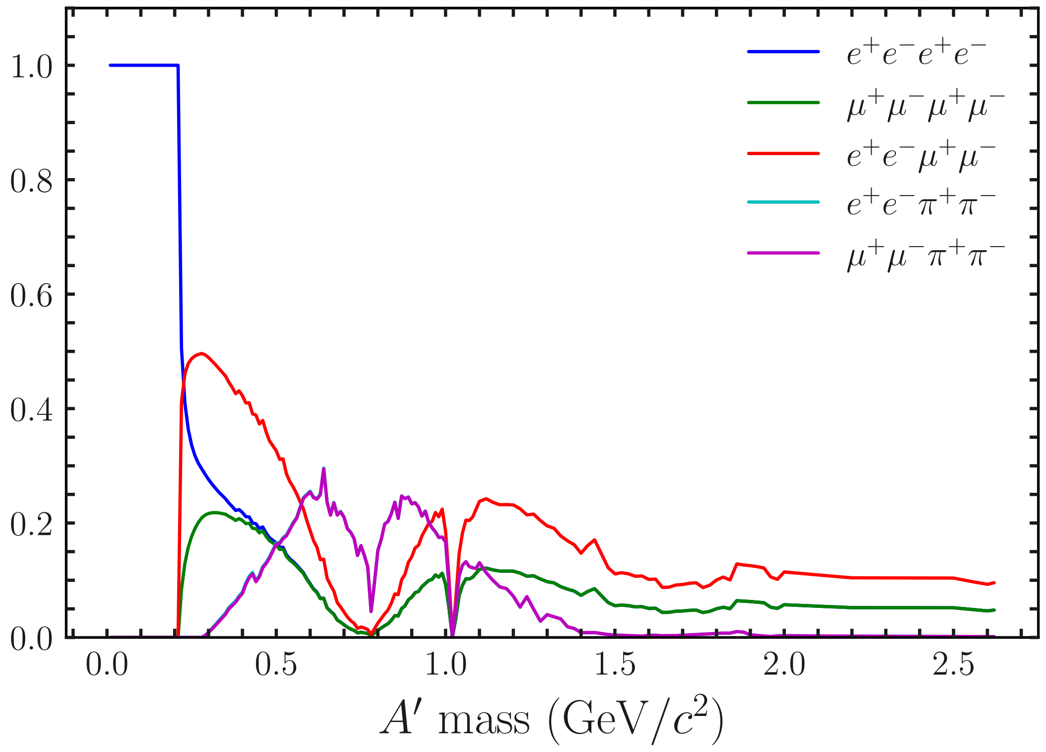


$B^0 \to A'A'$: Introduction. JHEP **04** 191.

- A short-lived and 100% visible dark photon is assumed.
  - Target final states: 5 decay modes $(4e, 2e2\mu, 4\mu, 2e2\pi, 2\mu2\pi)$ combined to $B^0 \to A'A'$.
  - Kinematically allowed A' mass is $10 - 2620$ MeV: 10 and 20 MeV intervals.



Relative A' branching fraction. PRD **79** 115008



Relative B^0 branching fraction for each final state

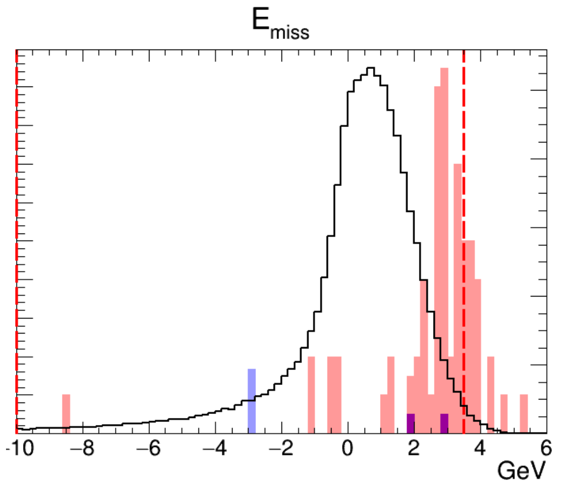
$B^0 \to A'A'$: Background suppression

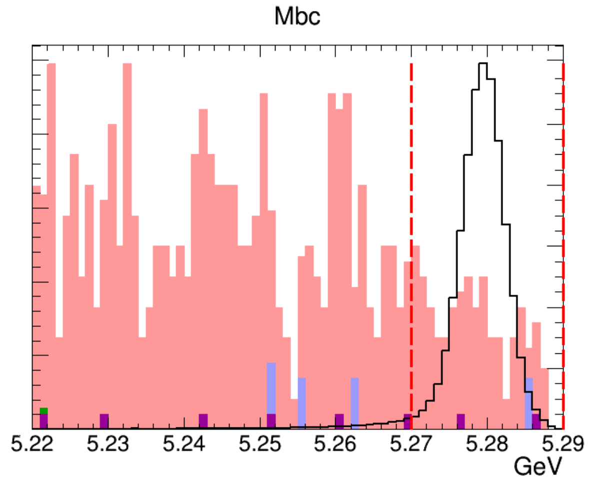
- Possible Standard Model resonances to be identified as A' are rejected:
  - $J/\psi \to l^+l^-$ and $\psi(2S) \to l^+l^-$.
  - $D^0 \to \pi^+\pi^-$, including $K^-\pi^+$ with misidentified $K^\pm$.
  - Light mesons (K_S^0, ρ^0, ϕ, etc.).
- $e^+e^- \to q\bar{q}$ continuum events suppression using 16 event-shape variables:
  - Including B^0 candidate momentum direction, angle between thrust axis of B^0 candidate and other particles, and (modified) Fox-Wolfram moments.
  - Only applied for $l^+l^-\pi^+\pi^-$ final states. No background in the four-lepton modes.
  - Fischer discriminant training is performed using the TMVA package.
- Small amount of combinatorial background:
  - Leptons mostly from semileptonic decays of quarks. (Missing energy from neutrinos).

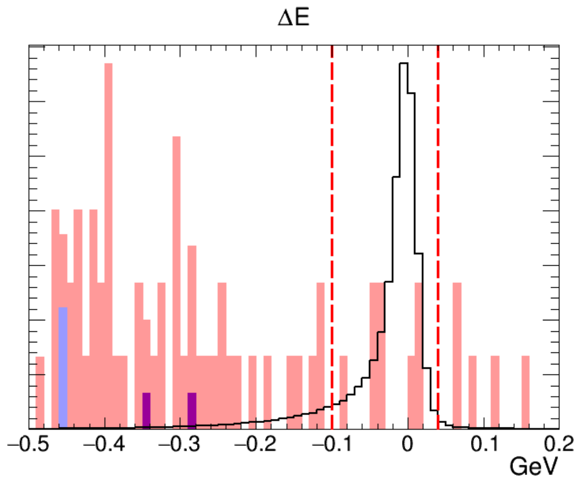
$B^0 \to A'A'$: Event reconstruction

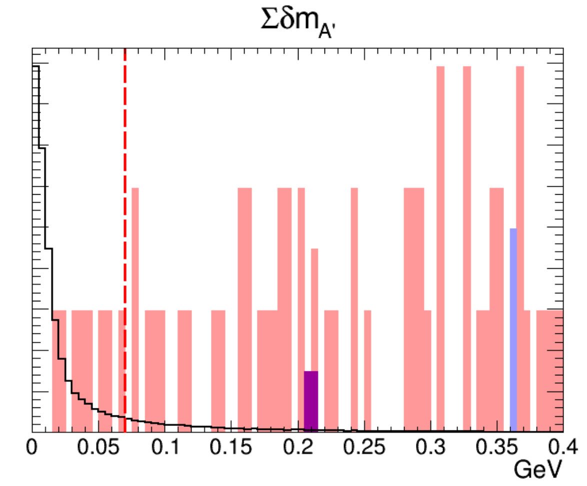
- Require at least four charged tracks, including at least one e^+e^- or $\mu^+\mu^-$ pair.
  - Each track should appear near the interaction point with a good track fitting.
- After combining two A' to form a B^0, five variables, defined in the center-of-mass frame, are used to judge the quality of B^0.
  - M_{bc}: beam-energy constrained mass.
  - ΔE: energy difference between beam and B^0 candidate.
  - Missing energy of the event.
  - $\Delta M_{A'}$: $\left|M_{A'_1} - M_{A'_2}\right|$.
  - $\sum \delta M_{A'}$: $\left|M_{A'_1} - m_{A'}\right| + \left|M_{A'_2} - m_{A'}\right|$.
    - ✓ $M_{A'_{1,2}}$: reconstructed $A'_{1,2}$ mass.
    - ✓ $m_{A'}$: target A' mass.

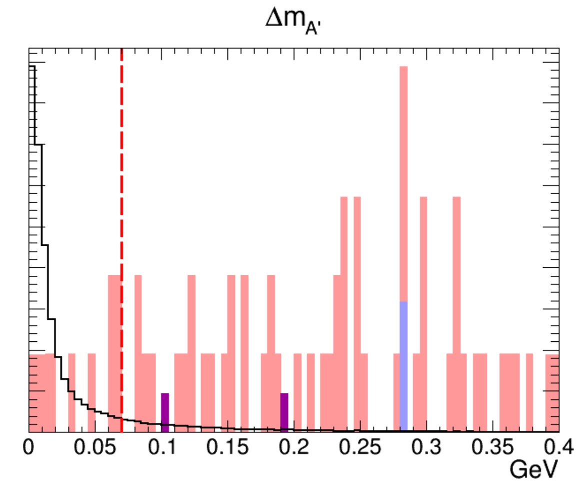
Signal / Background MC
(arbitrary scale)
$m_{A'} = 2.0\ \mathrm{GeV}$
$ee\mu\mu$ final state





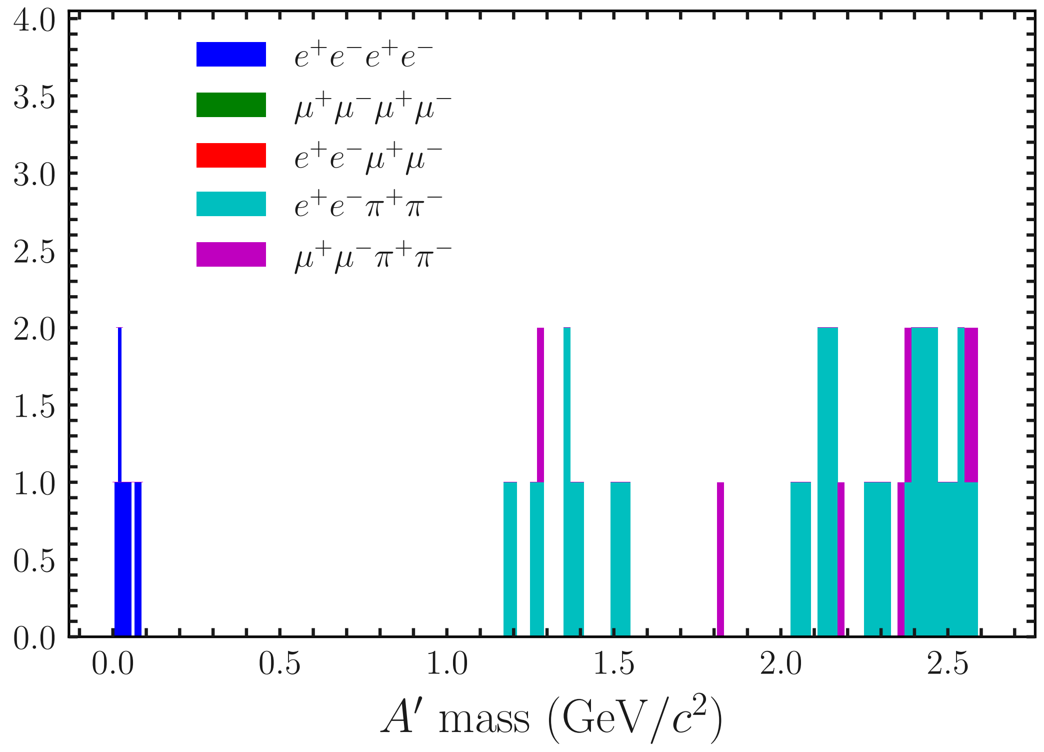




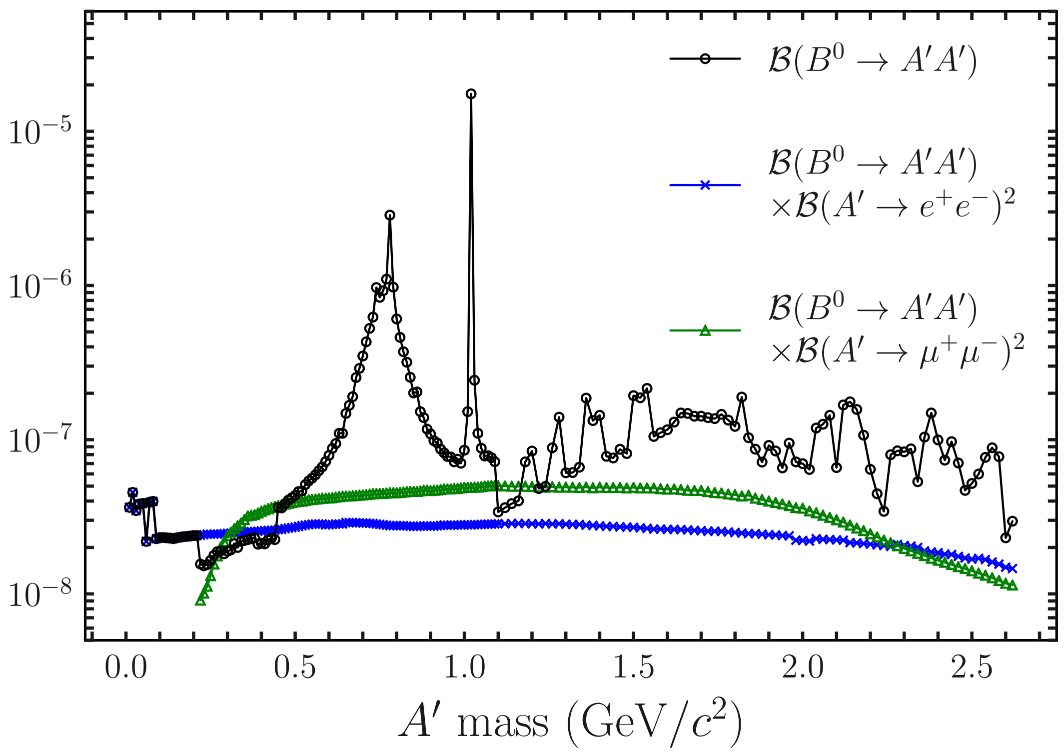


$B^0 \to AA'$: Results

- No significant excess of signal is observed → upper limits are obtained.
- Calculate upper limits using Feldman-Cousins unified approach.
  - Mostly $\mathcal{O}(10^{-8} - 10^{-7})$. Near the light meson rejection region up to $\mathcal{O}(10^{-5})$.



Observed events in Belle data

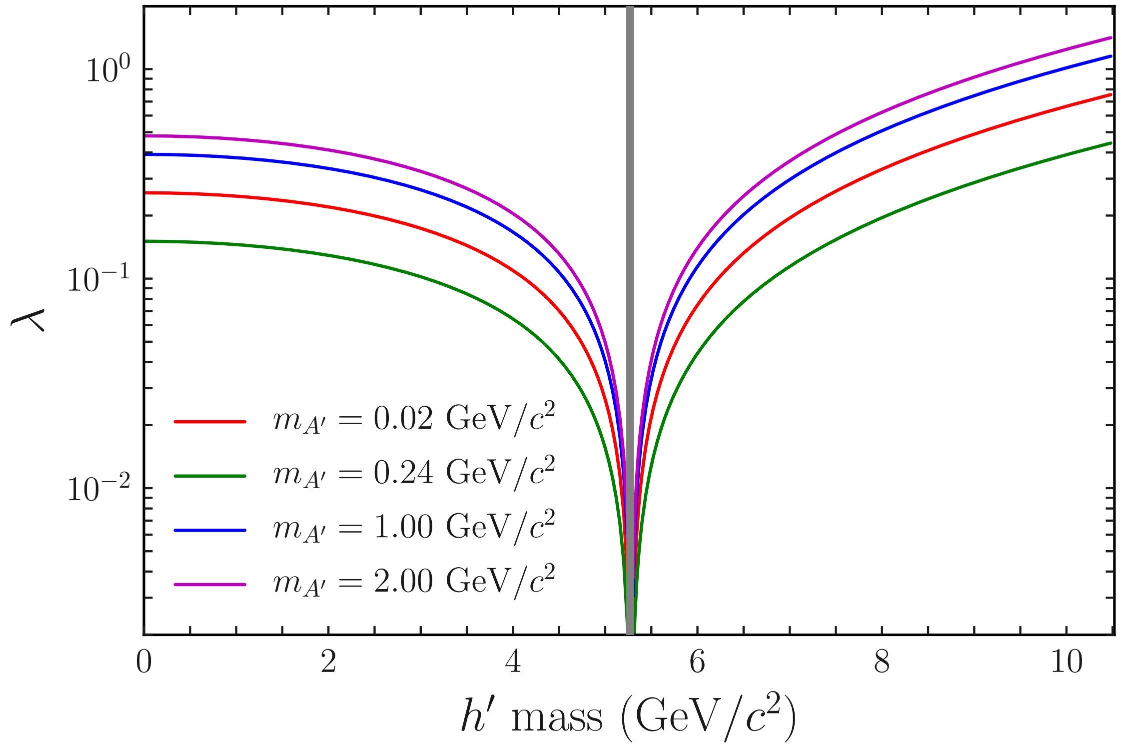


90% CL upper limits on the branching fractions

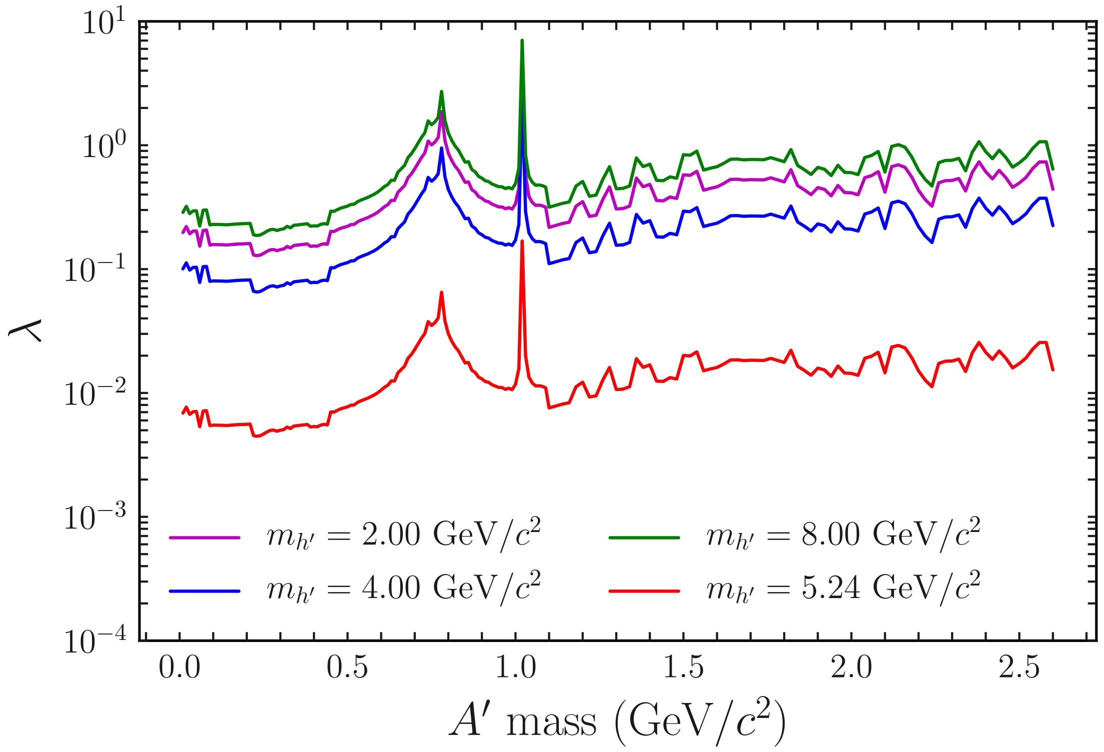
$B^0 \to A'A'$: Results

- Higgs portal coupling λ is derived using the following equation: PRD **83** 054005

$$\mathcal{B}(B^0 \to A'A') \simeq 7 \times 10^{-7} \times \lambda^2 \times V_{A'A'}^{1/2} \times \frac{V_{A'A'} + 12 m_{A'}^4 / m_{B^0}^4}{(1 - m_{h'}^2/m_{B^0}^2)^2} \qquad V_{A'A'} = 1 - 4m_{A'}^2/m_{B^0}^2$$



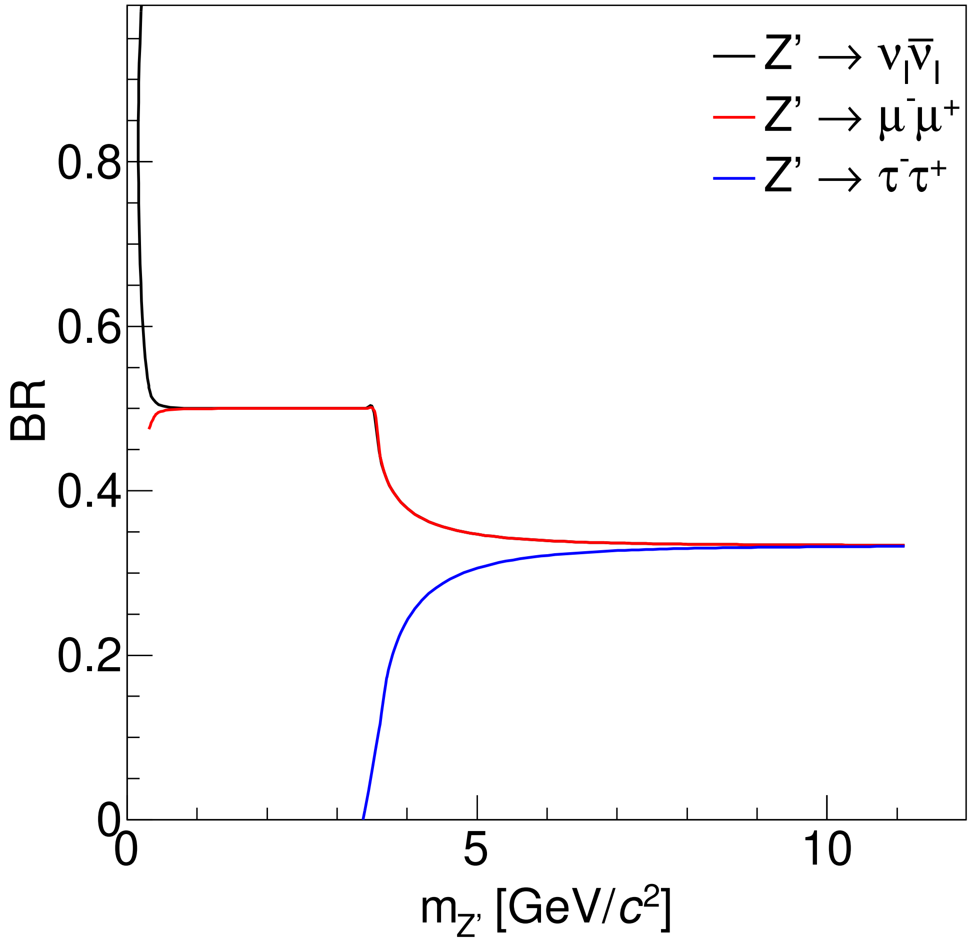
90% CL limits on λ versus h' mass for various A' masses



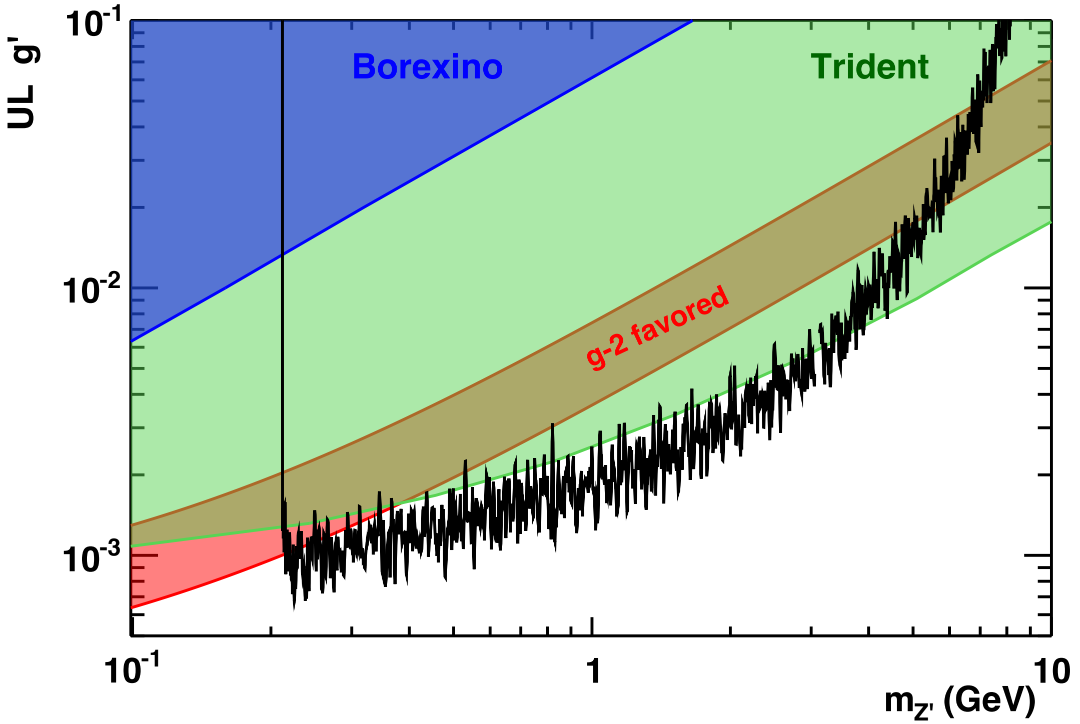
90% CL limits on λ versus A' mass for various h' masses

$e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$: Introduction

Branching ratio as a function of the Z' mass



- PRD **89** 113004: $Z'_{L_\mu - L_\tau}$ can be:
  - A potential source of muon $g-2$ anomaly.
  - An accessing channel for sterile neutrinos (dark matter candidates).
- The target final state is $Z' \to \mu^+\mu^-$ within kinematically allowed mass range.
  - Full Belle dataset ($\sim 1\ \mathrm{ab}^{-1}$) is used.
- Z' coupling by BaBar: PRD **94** 011102.



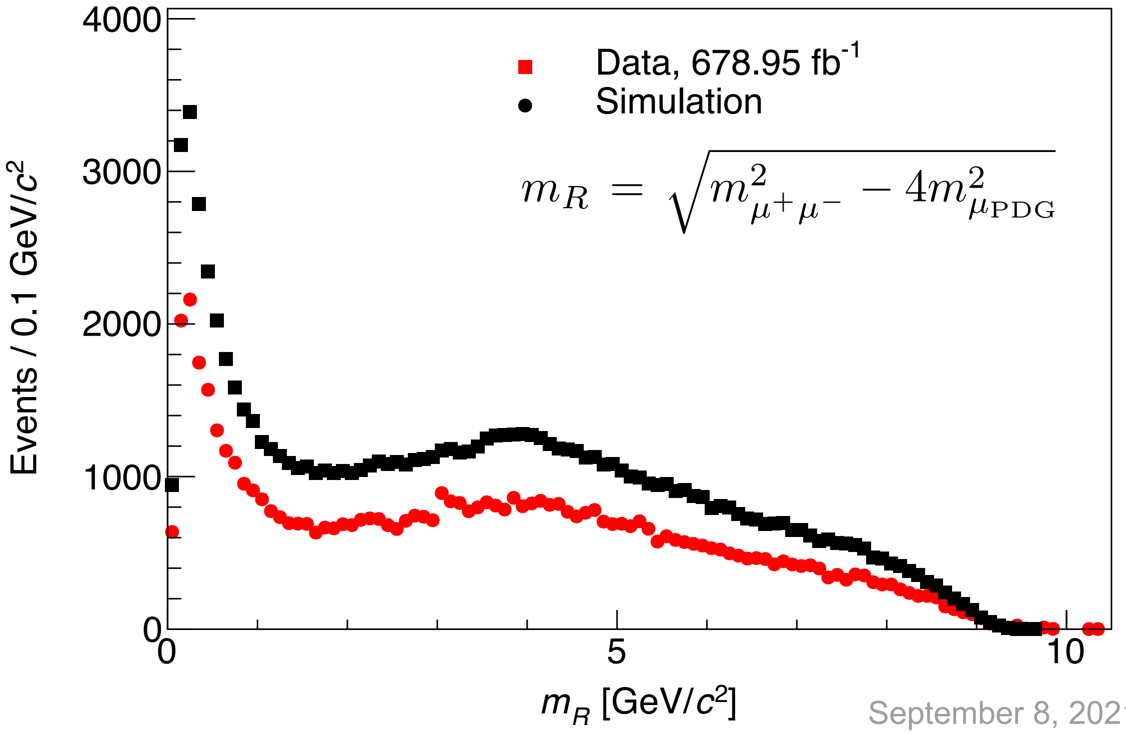
90% CL limit of coupling g' from BaBar

$e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$: Event reconstruction

- Require four charged tracks, and the sum of charges should be zero.
  - At least two same-signed tracks are identified as muons.
- Selection criteria:
  - The energy remaining in the ECL (Electromagnetic Calorimeter) without track association $< 200\ \mathrm{MeV}$.
  - Apply $m_{J/\psi} \pm 30\ \mathrm{MeV}$ and $m_{\Upsilon(1S)} \pm 100\ \mathrm{MeV}$ rejection cuts to the di-muon invariant mass.
  - Four-muon invariant mass is within initial beam energy $\pm 500\ \mathrm{MeV}$.

- Background in Belle data:
  - $e^+e^- \to 2\mu J/\psi$ or $2\pi J/\psi$
  - $e^+e^- \to p\bar{p}$ or $n\bar{n}$
  - $e^+e^- \to 4\mu$
  - $e^+e^- \to 4\pi$
  - $e^+e^- \to 2e2\mu$
  - $e^+e^- \to 2\mu 2\tau$
  - $e^+e^- \to 2\mu$
  - $e^+e^- \to 2\tau$
  - $e^+e^- \to q\bar{q}$
  - …

Validation check: Simulation does not include ISR.

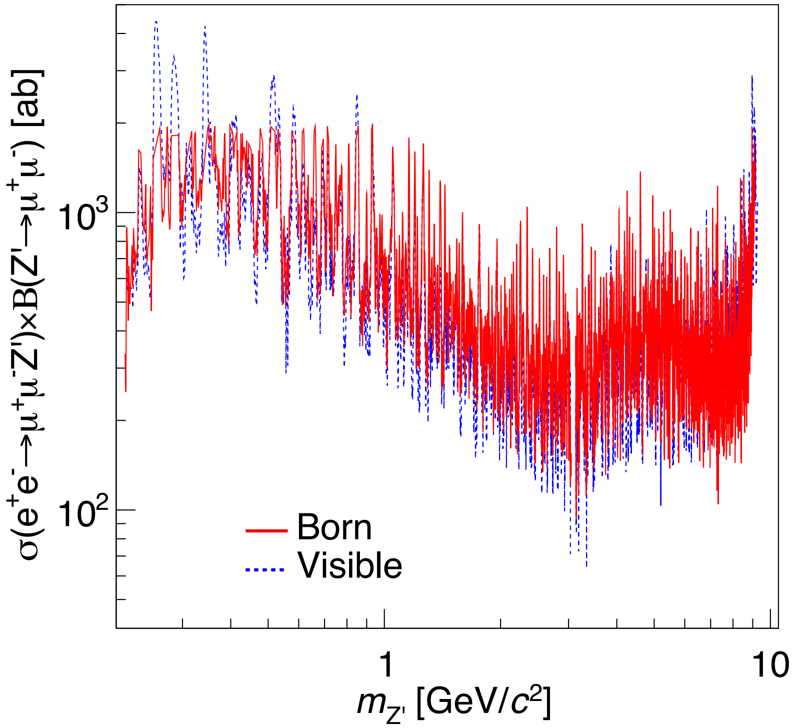


$e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$: Preliminary results

- The coupling constant g' is obtained using the Born cross section.
  - The Born cross section is calculated using the signal yield, $N_{\rm obs}$:

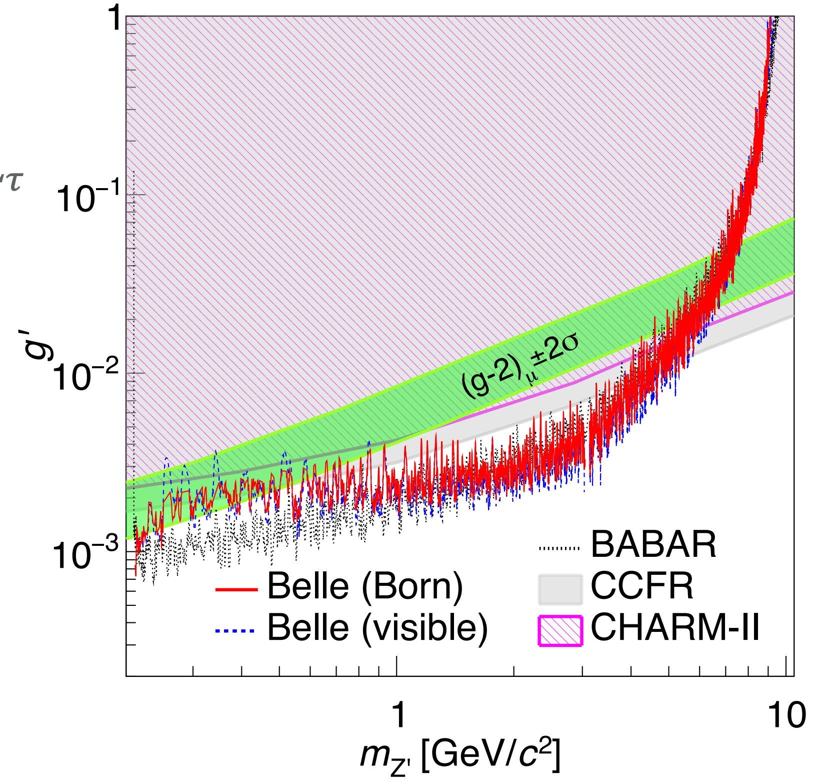
$$\frac{g'^2}{g_0'^2} = \frac{\sigma_{\rm Born}}{\sigma_{\rm theory}}, \qquad \sigma_{\rm Born} = \frac{N_{\rm obs}}{\mathcal{L} \times \mathcal{B} \times \varepsilon_{\rm rec}}$$

where $\sigma_{\rm theory}$ is the theoretical cross section with coupling g_0', $\mathcal{L}$ is the integrated luminosity, $\mathcal{B}$ is the branching ratio of $Z' \to \mu^+\mu^-$, and $\varepsilon_{\rm rec}$ is the reconstruction efficiency. $N_{\rm obs}$ is extracted by $M_{Z'}$ fitting.



90% CL upper limits on the cross section for $e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$

90% CL upper limits on g'



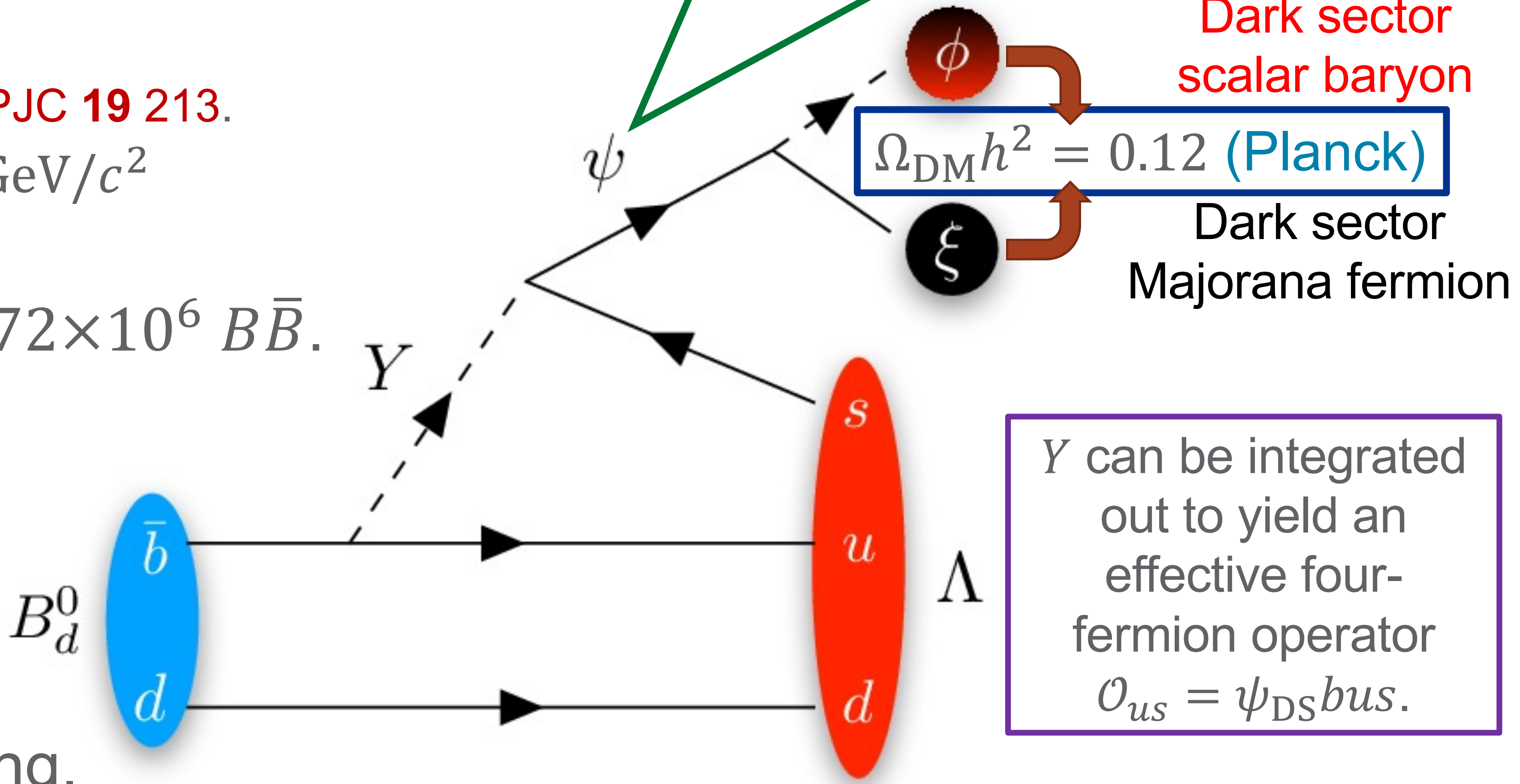
$B^0 \to \Lambda\psi_{\text{DS}}$: Introduction

NEW

- B-Mesogenesis: Baryogenesis and Dark Matter from B Mesons. PRD **99** 035031.
  - $\mathcal{B}(B^0 \to \Lambda\psi_{\text{DS}} + \text{mesons}) > 10^{-4}$
    - ✓ From A^q_{SL} world averages.
  - $\mathcal{B}(B^0 \to \Lambda\psi_{\text{DS}}) \lesssim 2{\times}10^{-4}$
    - ✓ ALEPH search at the Z peak. EPJC **19** 213.
  - ATLAS & CMS: $m(\psi_{\text{DS}}) \lesssim 3.5\ \text{GeV}/c^2$
    - ✓ JHEP **10** 244, JHEP **02** 144.
- We use 711 fb^{-1} of $\Upsilon(4S) = 772{\times}10^6\ B\bar{B}$.
- Signal side: $B^0 \to \Lambda\psi_{\text{DS}}$
  - Reconstruct: $\Lambda \to p\pi^-$
  - $1.0\ \text{GeV} \lesssim m(\psi_{\text{DS}}) \lesssim 4.2\ \text{GeV}$
- Tag side: $B^0 \to$ hadronic tagging.

$1.5\ \text{GeV} < m(\psi_{\text{DS}})$

"Neutron stars exclude light dark baryons"
PRL **121** 061802.



Y can be integrated out to yield an effective four-fermion operator $\mathcal{O}_{us} = \psi_{\text{DS}}bus$.

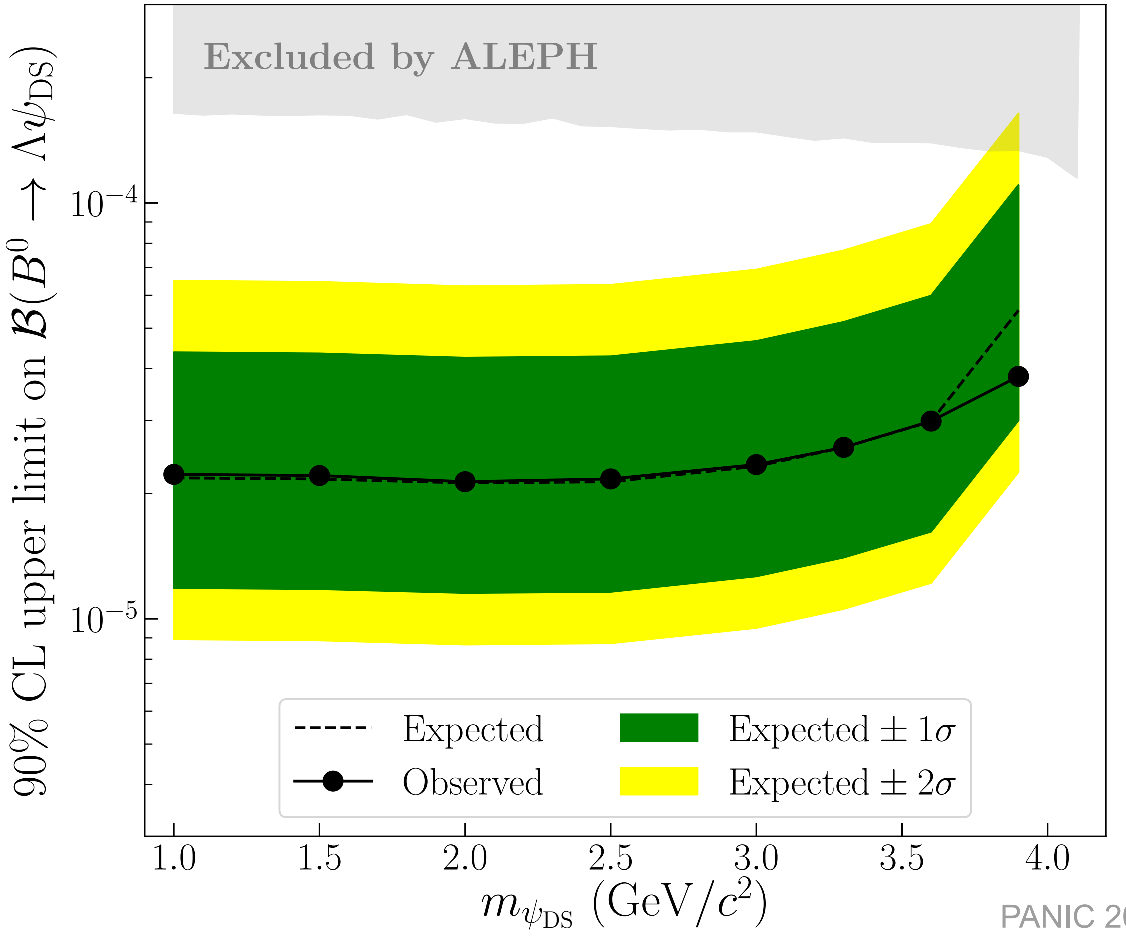
$B^0 \to \Lambda\psi_{\mathrm{DS}}$: Event reconstruction

- No extra tracks in the event.
- B-tag cuts applied:
  - $5.27\ \mathrm{GeV}/c^2 < M_{\mathrm{bc}} < 5.29\ \mathrm{GeV}/c^2$
  - $-0.06\ \mathrm{GeV} < \Delta E < 0.06\ \mathrm{GeV}$
- $-0.88 < \cos\theta_{\mathrm{miss}} < 0.95$
- Λ selection: momentum dependent criteria based on four parameters.
- Proton PID: $\mathcal{L}_{p/K} > 0.6$, $\mathcal{L}_{p/\pi} > 0.6$
- Suppress continuum events:
  - Optimize a Punzi FOM: R_2, $\cos\theta_{\mathrm{TBTO}}$
  - R_2: Event-based ratio of the second to zeroth Fox-Wolfram moments.
  - $\cos\theta_{\mathrm{TBTO}}$: The cosine of the angle between the thrust axis of the Λ and the thrust axis of the tagged B.
- Signal region: Based on the energy remaining in the ECL without track association. (We require that the expected number of background events $\cong 3$).
- Background mostly comes from:
  - Continuum: $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$
  - $B \to \mathrm{baryon}\ \overline{\mathrm{baryon}} + (\mathrm{meson})$.
  - In addition, small contributions from charmonium decays.

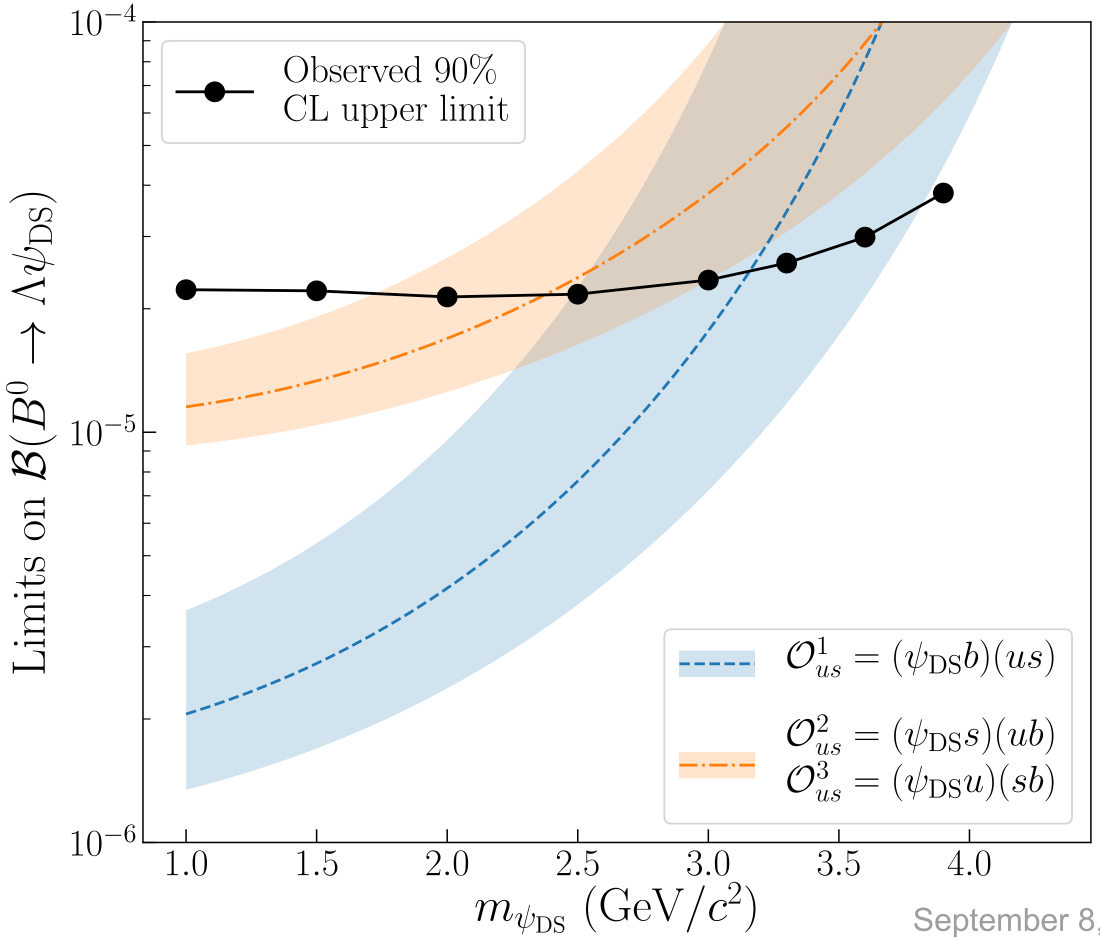
$B^0 \to \Lambda\psi_{\mathrm{DS}}$: Preliminary results

- No significant excess of signal is observed → upper limits are obtained.
- We calculate upper limits using a counting method (based on a Poisson "on/off" model): $\mathcal{O}(10^{-5})$.

90% CL upper limits on $\mathcal{B}(B^0 \to \Lambda\psi_{\mathrm{DS}})$



Lower bounds on $\mathcal{B}(B^0 \to \Lambda\psi_{\mathrm{DS}})$
for B-Mesogenesis. PRD **104** 035028.



Dark sector searches: Summary

- **No significant observation for dark sector.**
- $B^0 \to A'A'$ result was published in JHEP **04** 191.
  - 90% CL upper limits on the branching fraction are mostly $\mathcal{O}(10^{-8})$.
  - Higgs portal coupling constraint versus $m(h')$ and $m(A')$ is obtained.
- $e^+e^- \to \mu^+\mu^- Z'_{L_\mu - L_\tau}$ provides a limit for the $Z'll$ coupling constant.
  - The Belle result is competitive with the BaBar result.
- $B^0 \to \Lambda\psi_{\mathrm{DS}}$ result is the first search for B-Mesogenesis.
  - The upper limits, $\mathcal{O}(10^{-5})$, are by an order of magnitude better than ALEPH bounds.

Thank you