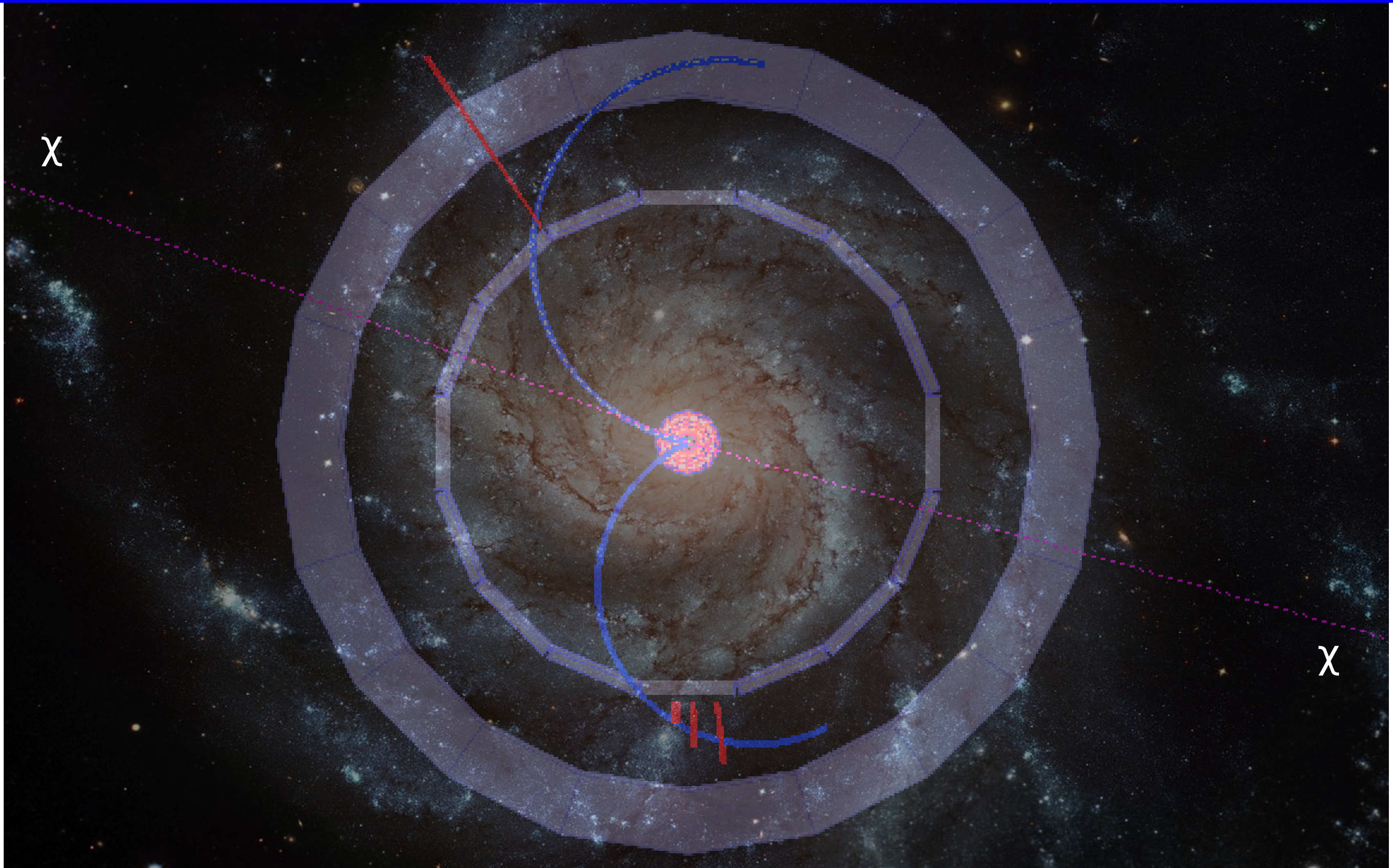
Searches for dark forces and particles at Belle and Belle II



MUJ 2015 / Annual Meeting Matter and Universe

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DESY

HELMHOLTZ | ASSOCIATION

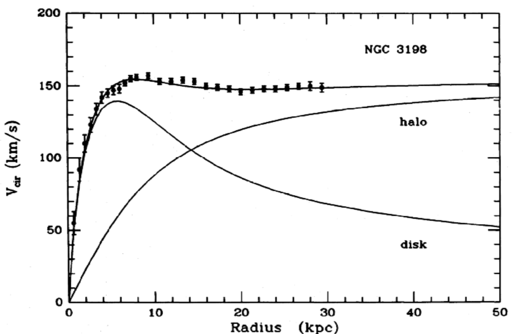
Gianluca Inguglia- DESY

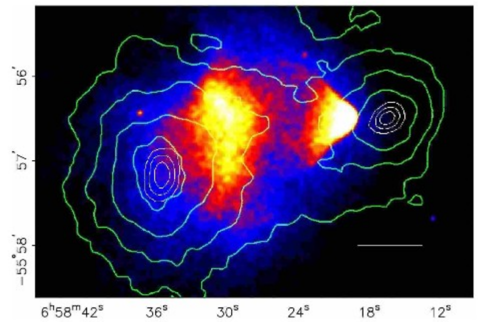
29/09/2015

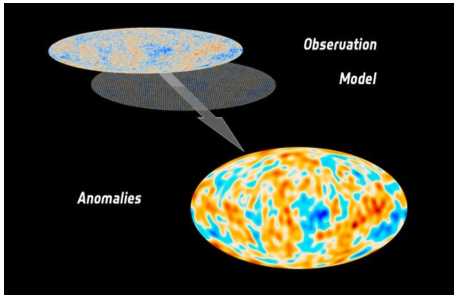
BELLE

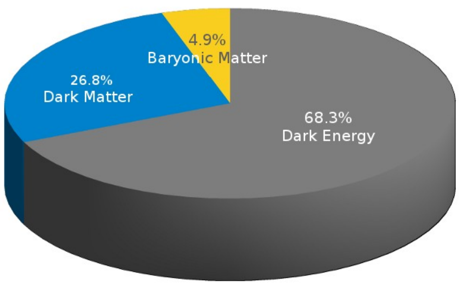
Belle II

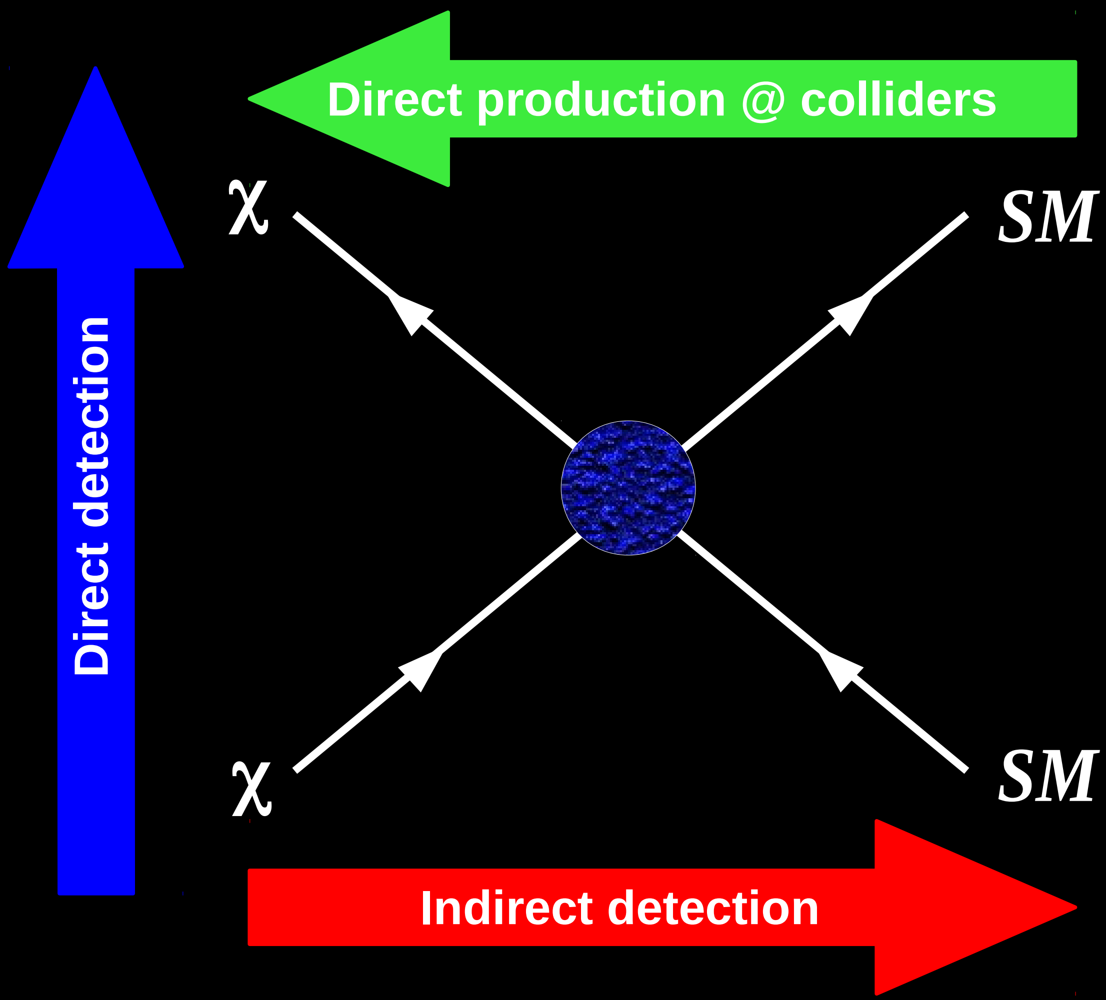
Dark sector searches @ BELLE and BELLE 2: Why?









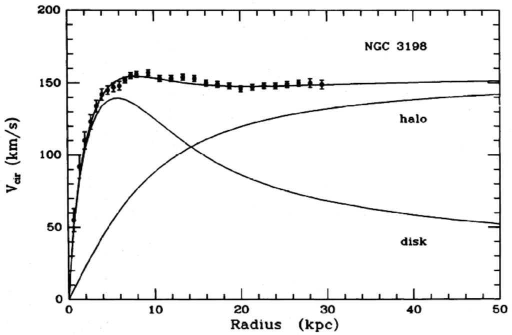


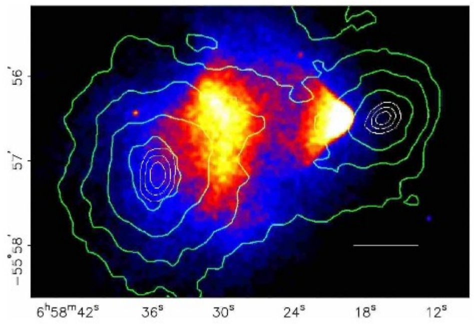
Search for events with missing energy, particle disappearance, dark forces, etc.

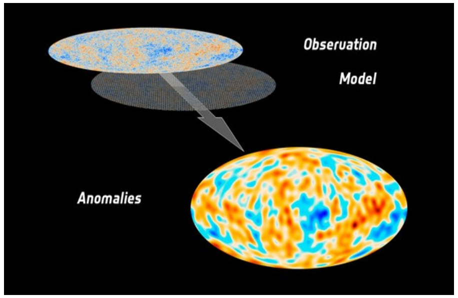
Search for interaction of DM particles with (usually) underground detectors: heat, scintillation light, etc..

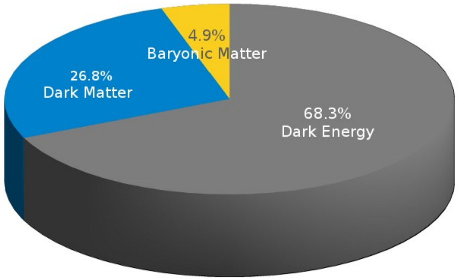
Space/earth based experiments: gamma ray energy excess, anti-particle excess, HE neutrinos etc.

Dark sector searches @ BELLE and BELLE 2: Why?





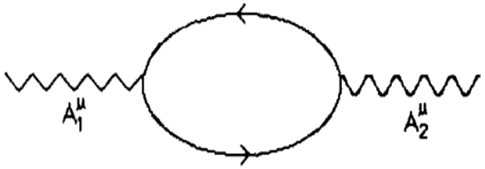




- Various reasons to agree that dark matter (DM) exists
  - But the nature of DM is unknown and understanding what dark matter is represents one of the biggest challenge our community is facing this days
- One possibility is represented by the lightest **SUSY** particle (which is stable)
  - *But why should we have only one DM particle when density of DM is 5 times larger the density of visible matter (i.e. many SM particles)?*
- Many new models have been and are currently being developed to propose a more complex sector for dark matter explaining also anomalies observed in astrophysical process → dark sector(s).
- Within dark sector models, **ADM** theories assign a certain importance to the fact that Ω_{DM}/Ω_{BM}~5. As for the **BAU** a tiny difference between particle-antiparticle in the early Universe has evolved to the observed Ω_{BM} today after the other particles-antiparticles have annihilated each other, something similar happened to DM particles-antiparticles.
- I will not discuss details of the models but will rather discuss experimental signatures and smocking guns at Belle/Belle2

Dark sector searches @ BELLE and BELLE 2: Why?

Most dark sector models require an additional U(1) symmetry responsible for the "interactions" between dark sector particles and SM particles through its gauge boson A' .



$$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$$

P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).
B. Holdom, Phys. Lett. B **166**, 196 (1986)

Kinetic mixing strength

A massive force mediator of the extra U(1) symmetry requires the U(1) symmetry to be broken: extended Higgs sector

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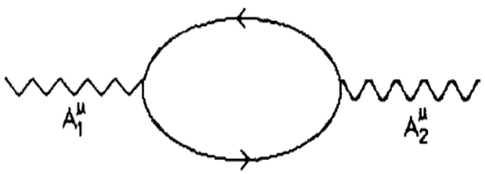

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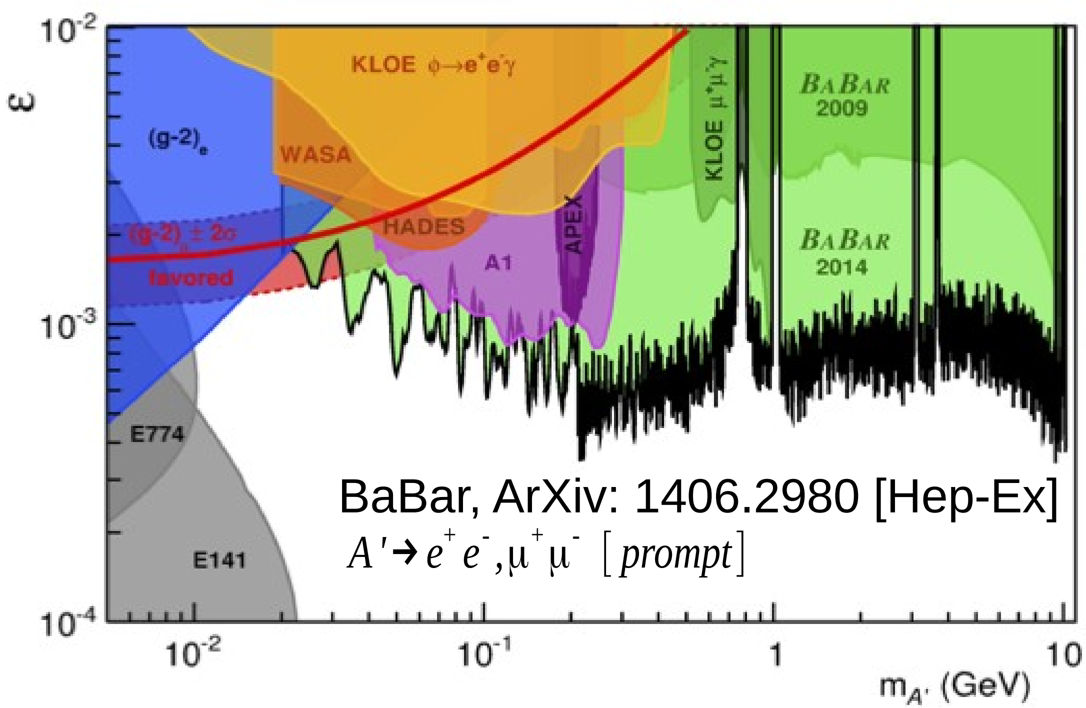

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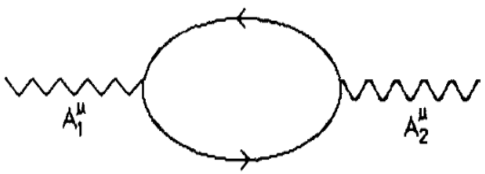

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Kinetic mixing strength

A massive force mediator of the extra U(1) symmetry requires the U(1) symmetry to be broken: extended Higgs sector

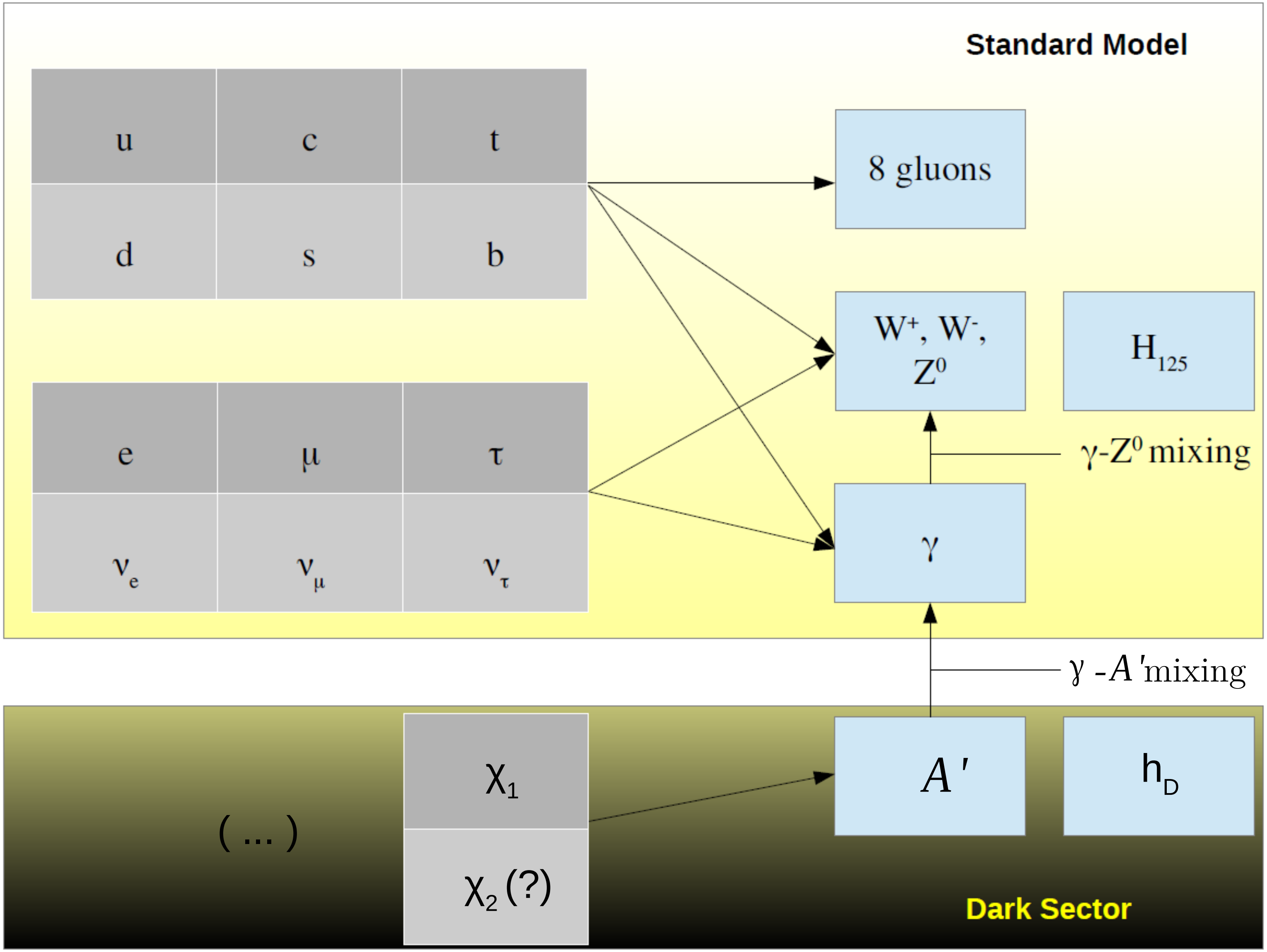
- M(A') ~ GeV scale → mixing with the photon, SM final states accessible
- M(A') ~ EW scale → mixing with Z^0, effects in rare decays (Y, B, ..) through loops[1]
- M(A') ~ TeV scale → effects in rare decays (Y, B, ..) through loops[1]
- $M(H_D)$~ GeV scale → dark higgs-strahlung, rare decays (not covered today)
- M(χ) ~ GeV scale: $B \to \chi\chi$, $B \to \nu\chi$; $Y(1S) \to \chi\chi$; $Y(3S) \to \chi\chi\gamma$, $\gamma_D \to \chi\chi$

Invisible B/Y decays not accessible at hadron colliders → BELLE2!

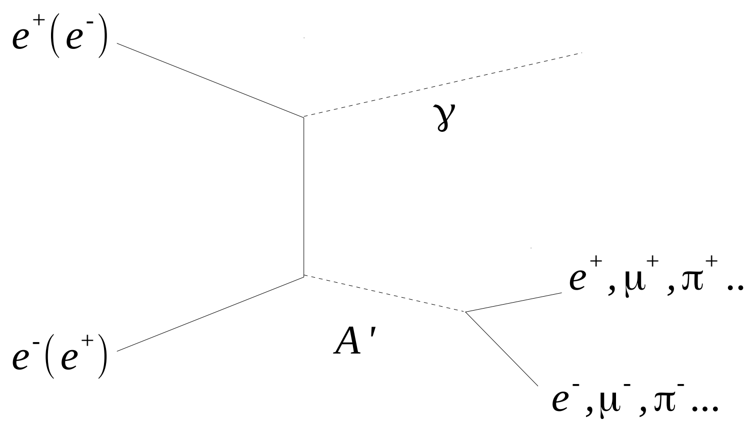
[1]Remember the lesson from the past, new particles are first seen indirectly or in loops: Z^0, charm, top

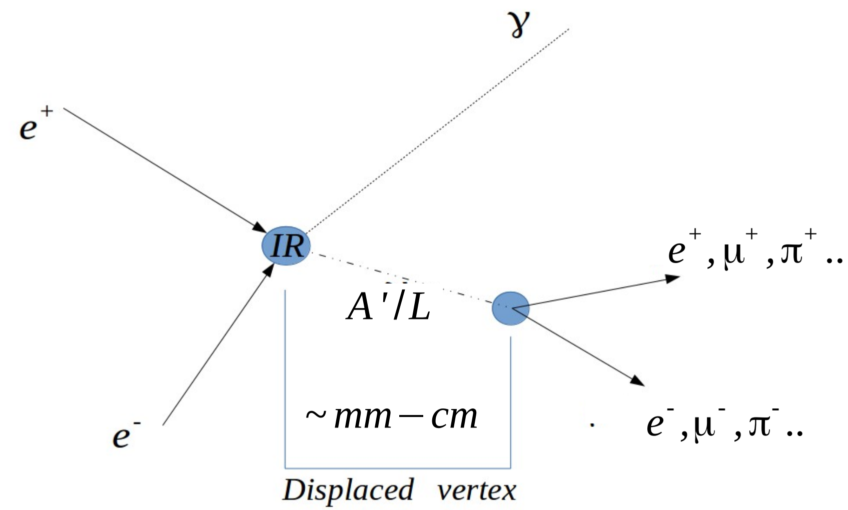
Dark sector : how does it look like?

A very simple example...



Dark photon and long lived gauge bosons @ BELLE





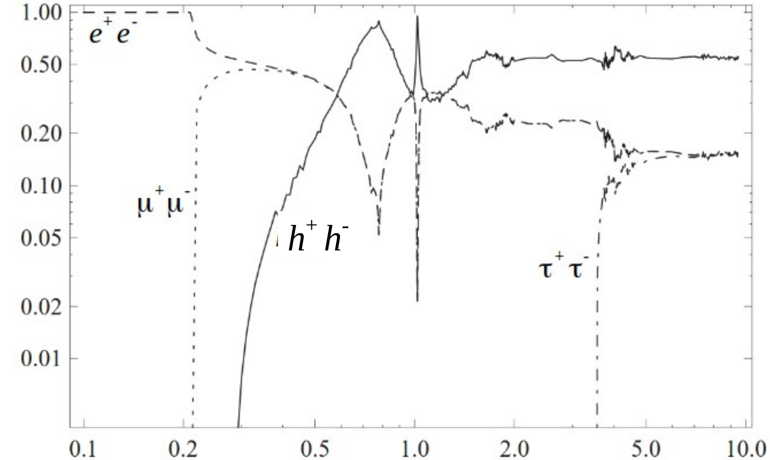
A'= dark photon, L= long lived light gauge boson.
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, prompt or displaced vertex decay. Could require dedicated trigger to increase efficiencies, especially for the displaced vertex case.

"*A'* " decays depend on $M_{A'}$:

-Decays to leptons require $M_{A'}$>1.02 MeV/c^2
-Decays to hadrons require $M_{A'}$>0.36 GeV/c^2

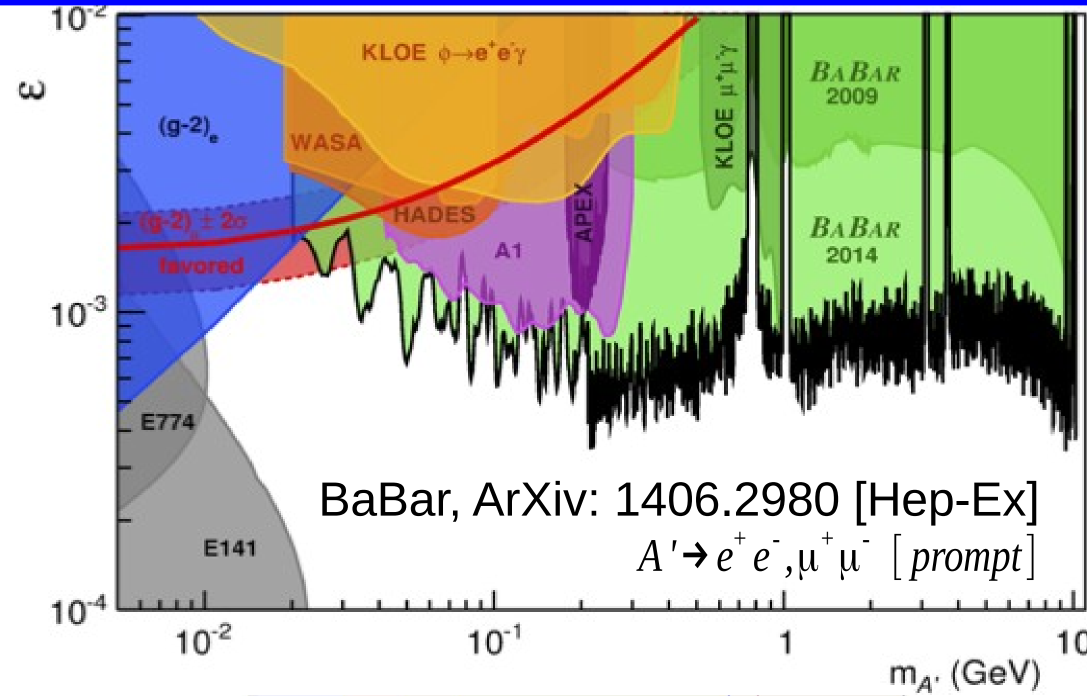
New search just started for the reaction:

$$e^+e^- \rightarrow Y(2S);\ \ Y(2S) \rightarrow \pi^+\pi^- Y(1S);$$
$$Y(1S) \rightarrow A^0\gamma;\ \ A^0 \rightarrow \chi^0\chi^0$$



ArXiv:0903.0363 [hep-ph] $M_{A'}[GeV/c^2]$

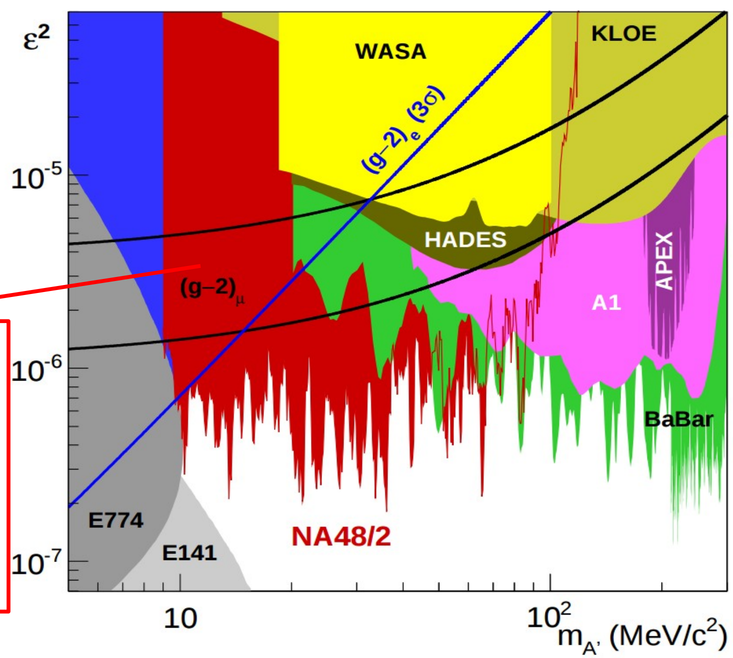
Dark photon: current limits



BaBar, ArXiv: 1406.2980 [Hep-Ex]

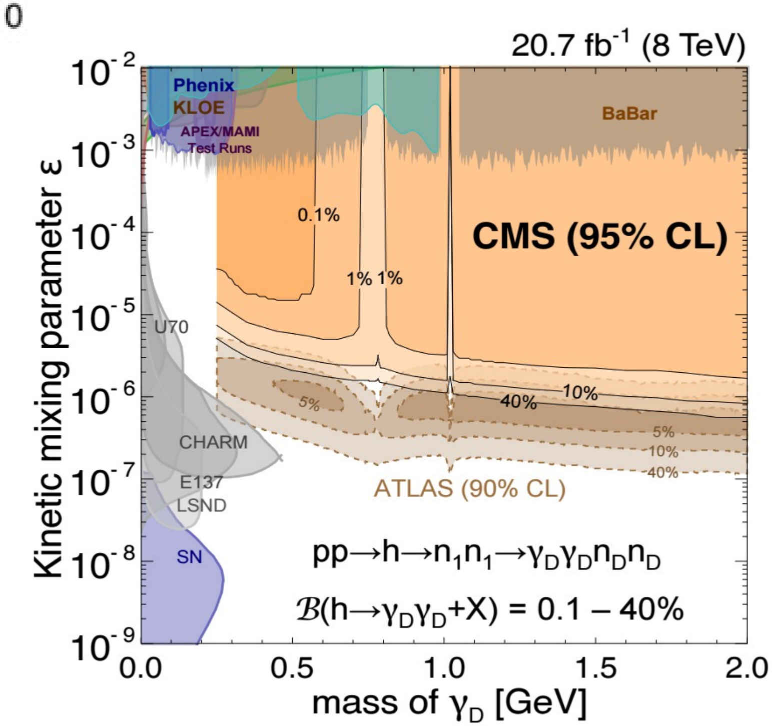
$A' \to e^+e^-, \mu^+\mu^-$ [prompt]

Many constraints for different region of the parameter space from different experiments.
Shown here:
-top left: BaBar ,
-bottom left NA48,
-bottom right CMS (containing ATLAS)



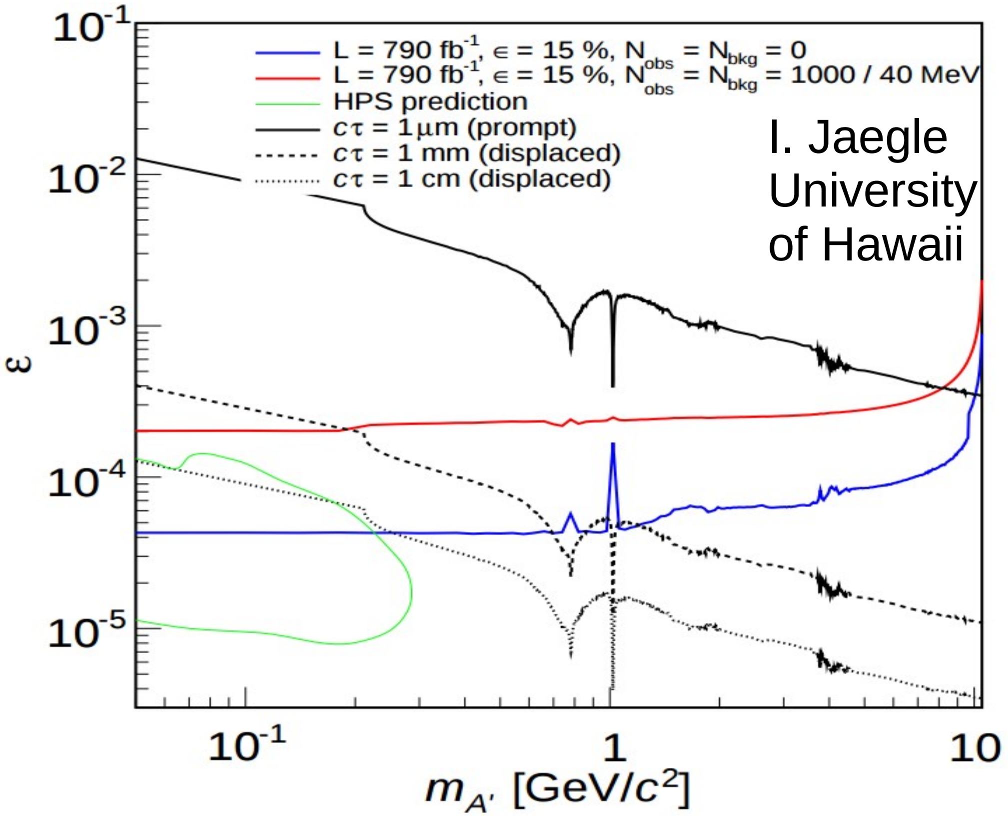
dark photon explanation of $(g-2)_\mu$ ruled out for $A' \to e^+e^-$

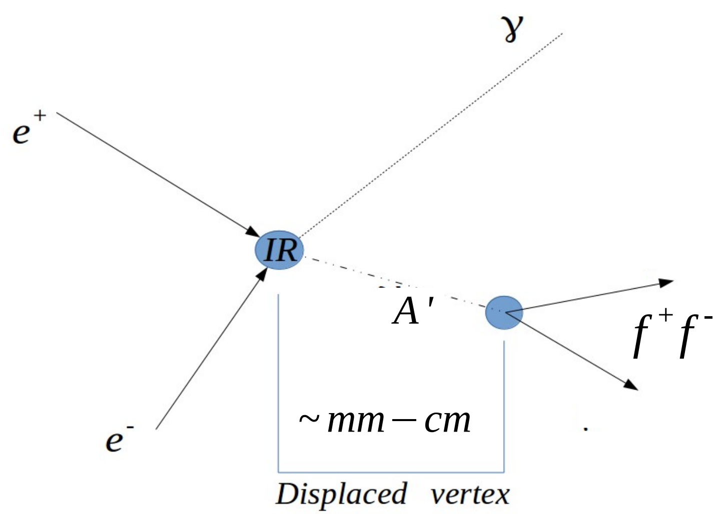
NA48 arXiv:1504.00607
π^0 decays



arXiv:1506.00424 [hep-ex]
Long lived, decays to leptons

Long lived A' or gauge boson search @ BELLE: expected limits





This search is a part of more general search for long lived gauge bosons currently performed with Belle data. For this more general analysis we are studying the decays:

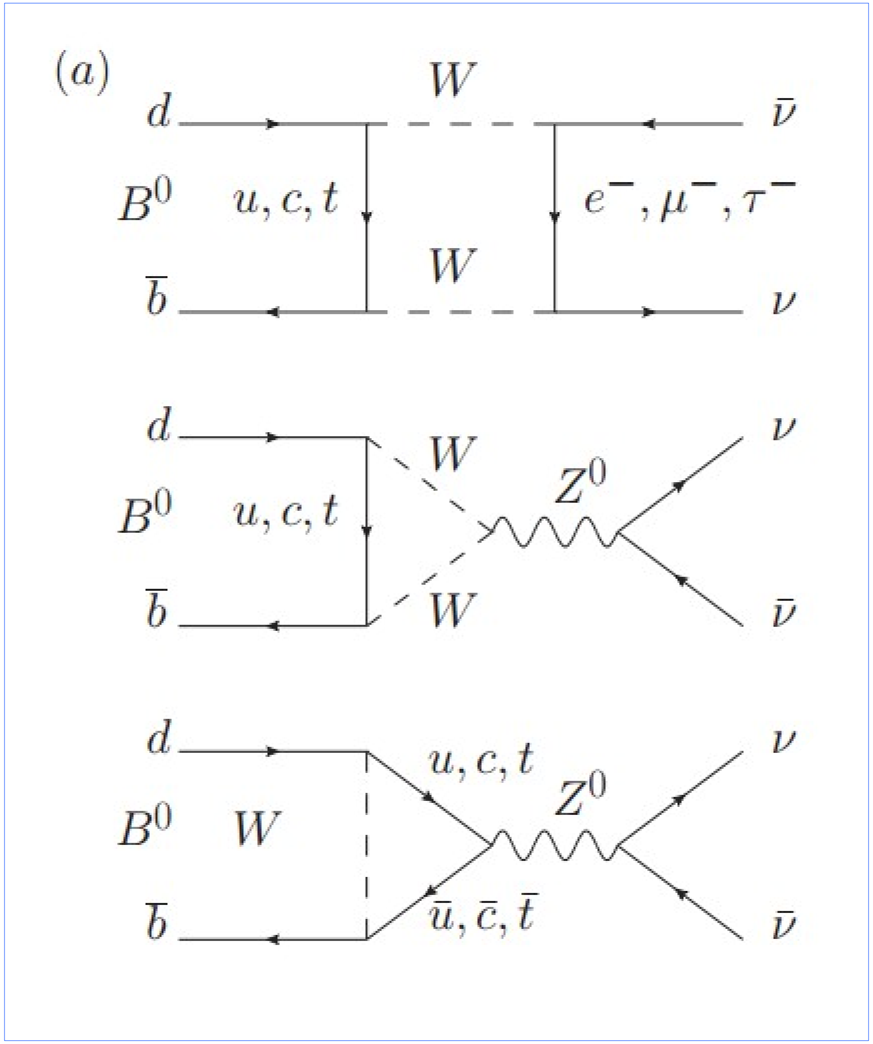
$$A'/L \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$

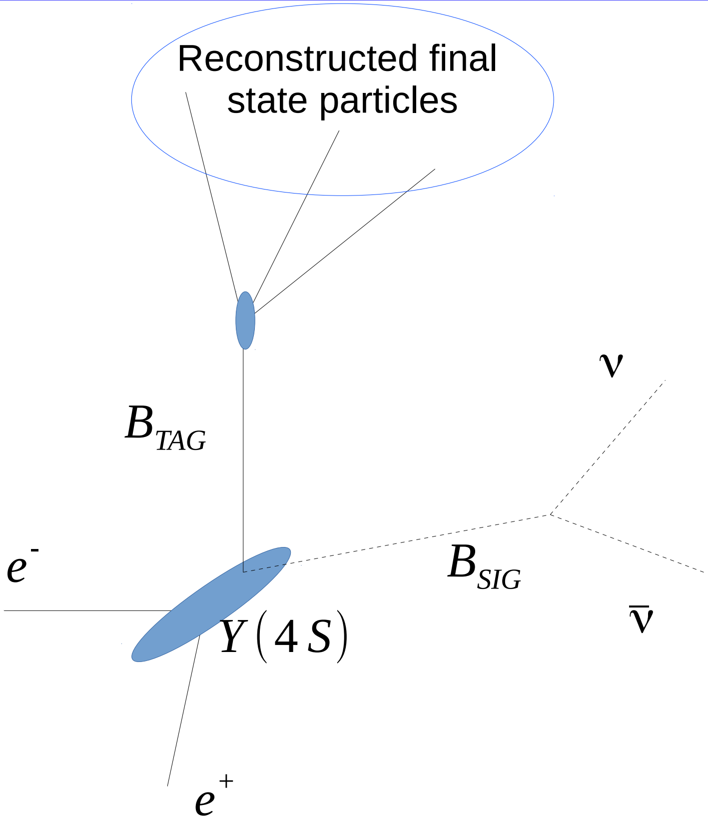
$$L \rightarrow e^+\mu^-, e^-\mu^+, K^+K^-$$

$$M_{A'/L} = 0.1 - 10\, GeV/c^2$$

With Belle 2 data (Bellex40) and improved detector/trigger/software performance one would expect a much higher discovery potential (i.e. $\varepsilon \sim 10^{-6}$).

B meson disappearance



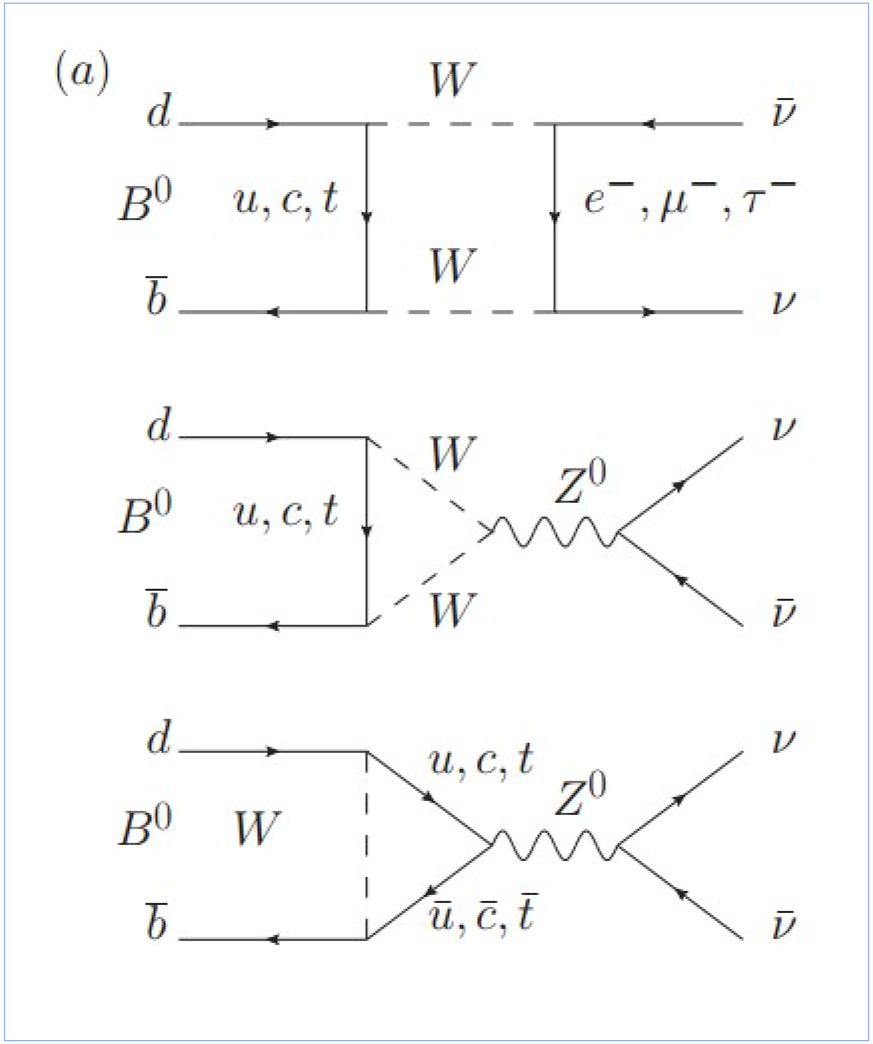


What does a signal look like?

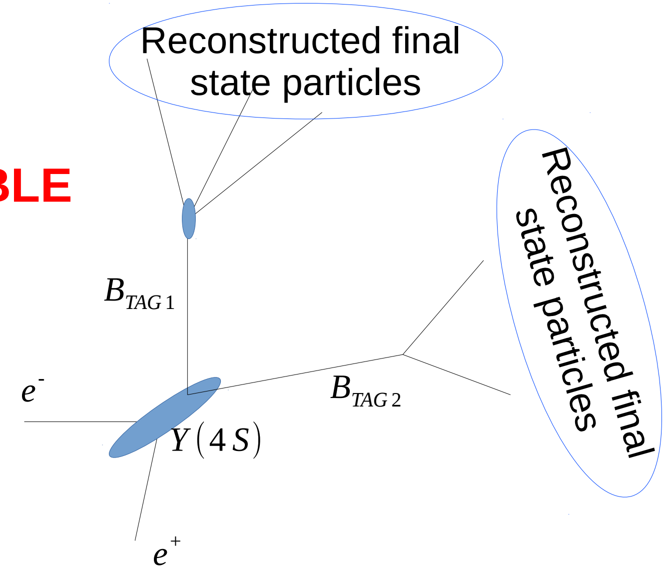
$$\mathcal{BR}(B^0 \to \nu\bar{\nu}) = \frac{G_F^2 \alpha^2 f_B^2}{16\pi^3 \sin^4\theta_W \Gamma_B} |V_{tb}V_{td}^*|^2 m_\nu^2 M_B \sqrt{1 - 4\frac{m_\nu^2}{M_B^2}} X^2(x_t) \simeq 1.24 \times 10^{-25}$$

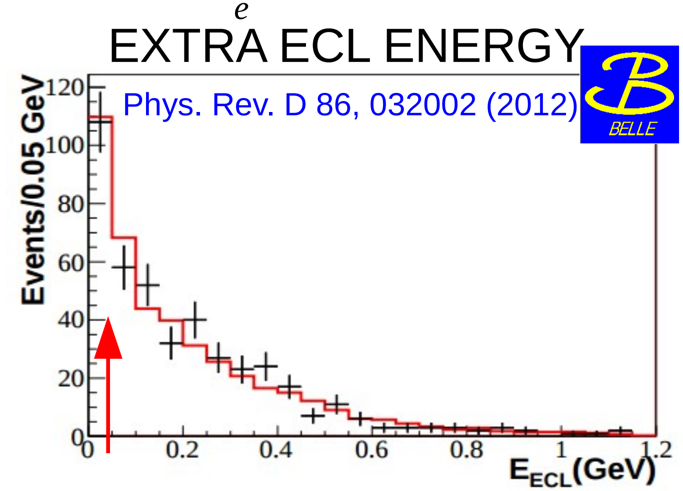
$$\mathcal{BR}(B^0 \to \nu\bar{\nu}\gamma) = \frac{G_F^2 \alpha^2 f_B^2}{72\pi^4 \sin^4\theta_W \Gamma_B} |V_{tb}V_{td}^*|^2 F_B^2 M_B^5 X^2(x_t) \simeq 1.96 \times 10^{-9}$$

B meson disappearance



DOUBLE TAG





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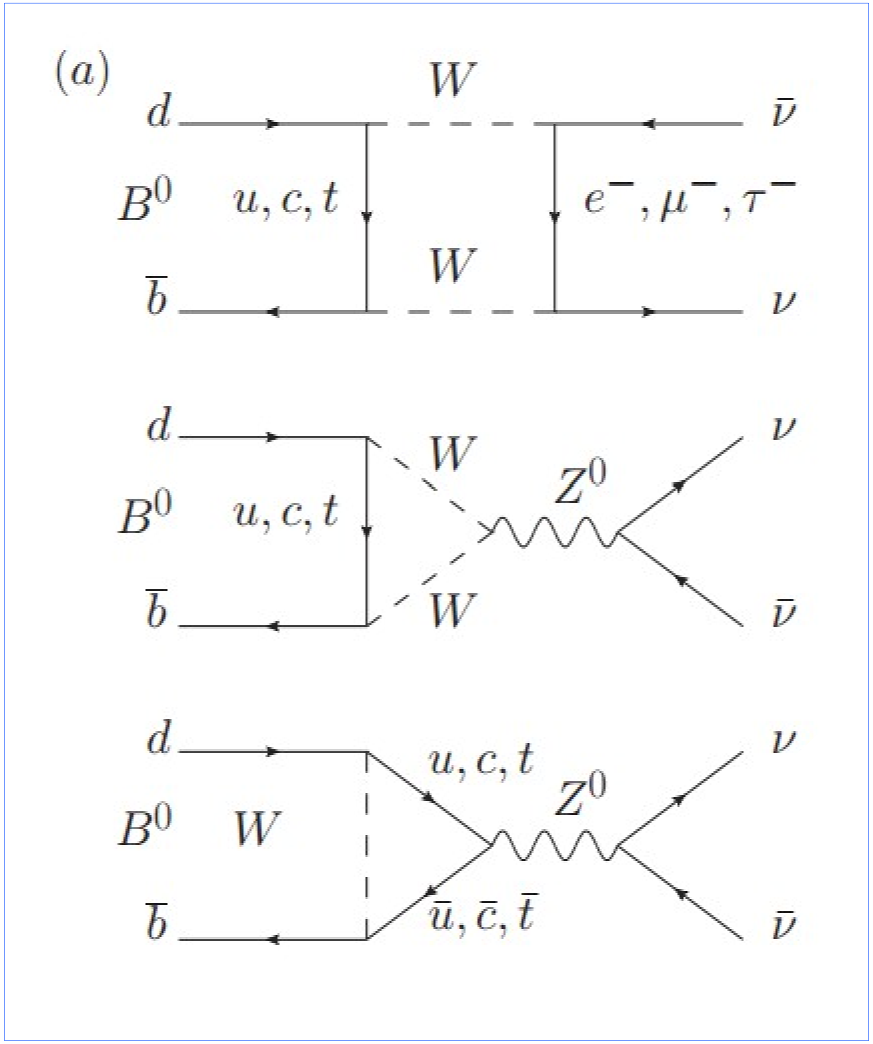
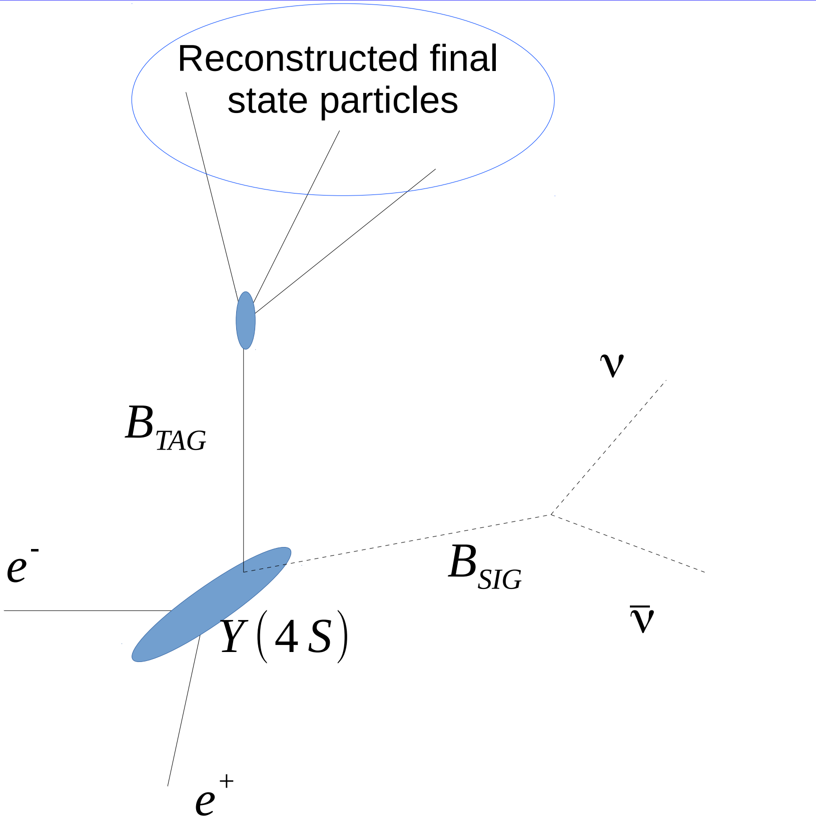
B meson disappearance





What does a signal look like?

A signal is represented by an excess of events over the expected background in the extra ECL energy distribution around zero

$$\mathcal{BR}(B^0 \to \nu\bar{\nu}) = \frac{G_F^2 \alpha^2 f_B^2}{16\pi^3 \sin^4\theta_W \Gamma_B} |V_{tb}V_{td}^*|^2 m_\nu^2 M_B \sqrt{1 - 4\frac{m_\nu^2}{M_B^2}} X^2(x_t) \simeq 1.24 \times 10^{-25}$$

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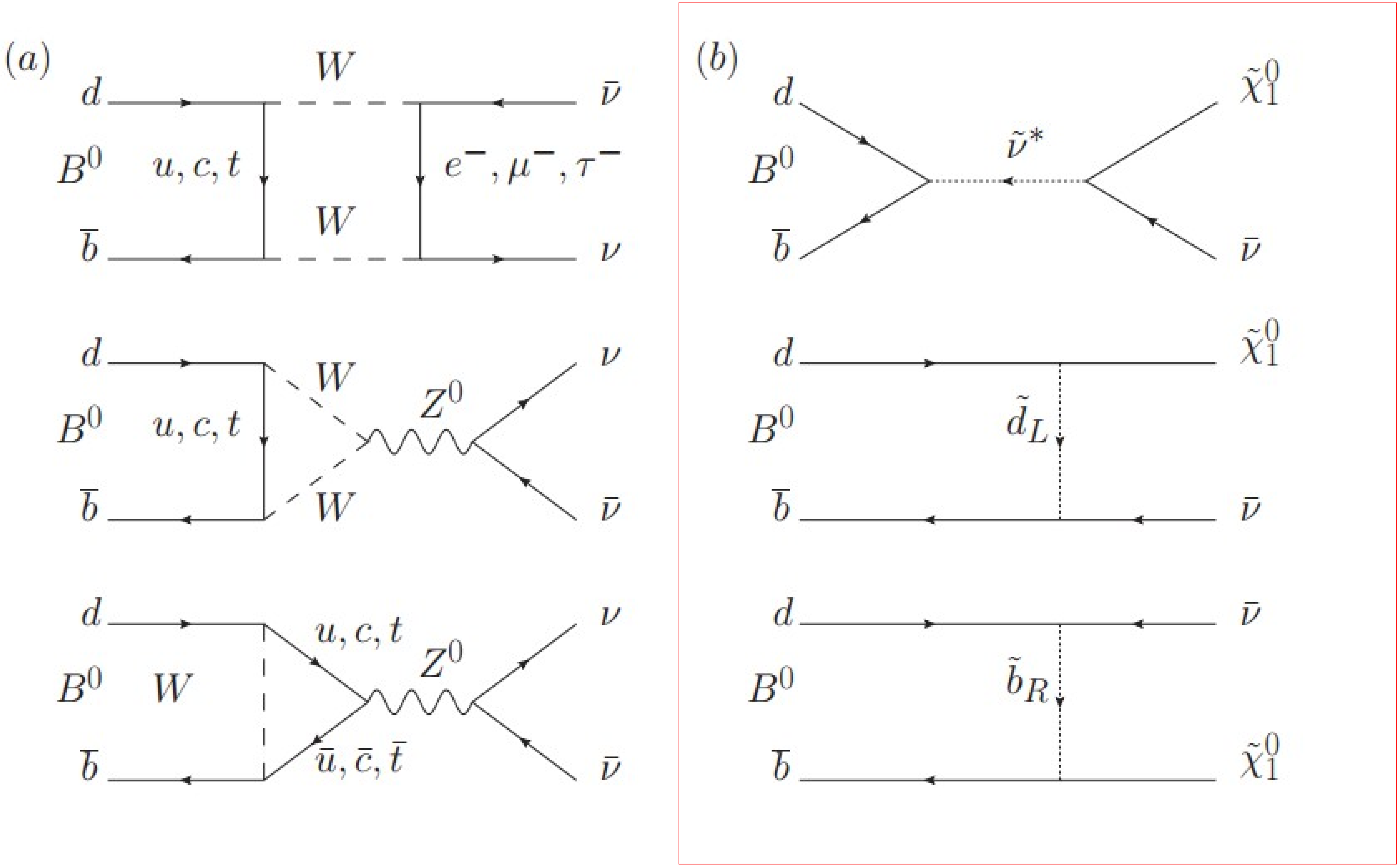
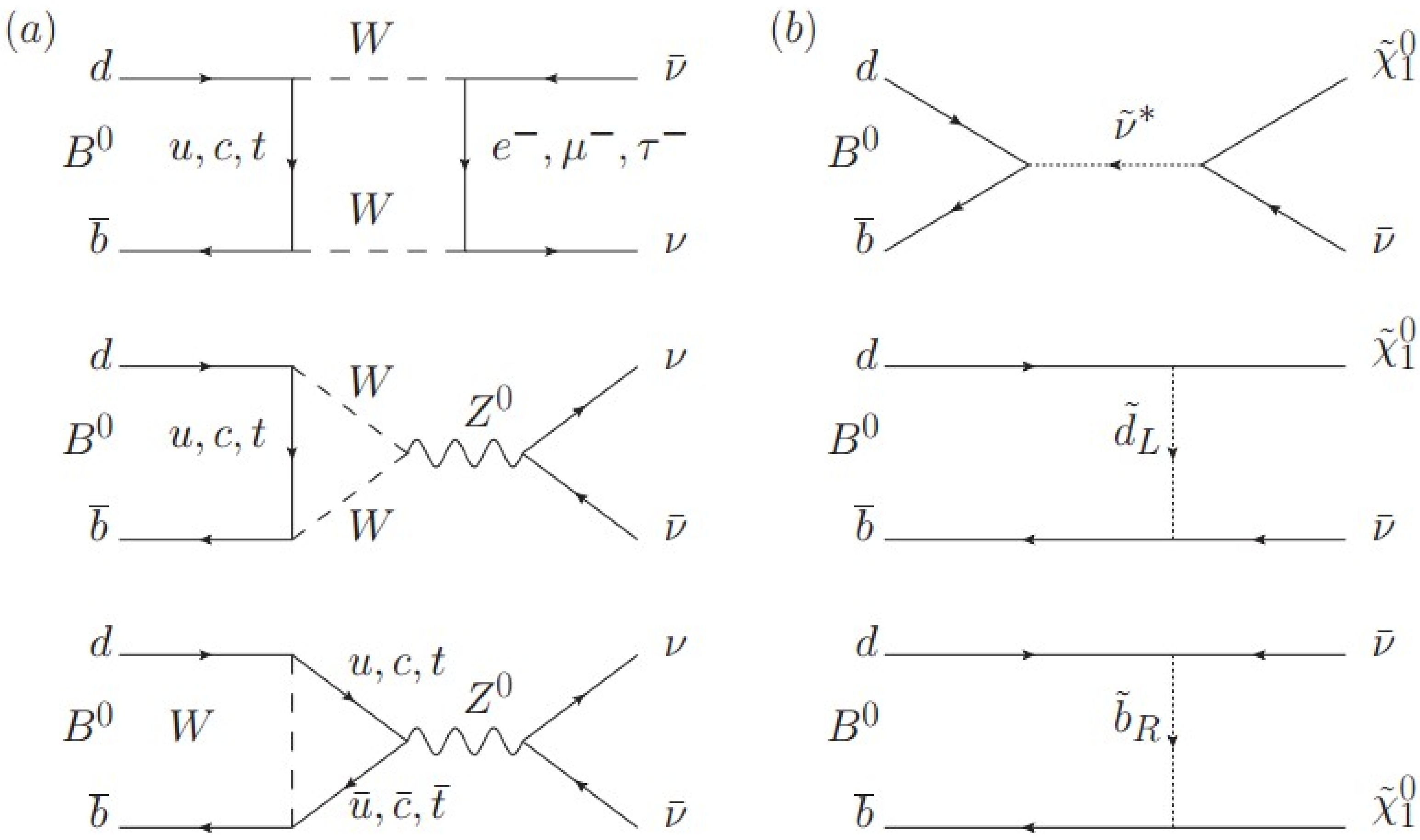


Additional decay topologies arise from new physics models
These new topologies will affect the BR of B to invisible final states, if they exist, making B to invisible “observable” (**BR as high as 10^{-6}**) [Phys. Rev. D **65**, 015001 (2002)].
Of course this is a high risk measurement..

B meson disappearance



$BABAR\,(471\times10^6\,B\bar{B}\ \ pairs):\quad BR(B\rightarrow\nu\bar{\nu})<2.4\ \ 10^{-5}(\epsilon_{sig}\sim18\times10^{-4}),$

Phys. Rev. D 86, 051105 (2012) $BR(B\rightarrow\nu\bar{\nu}\gamma)<1.7\ \ 10^{-5}(\epsilon_{sig}\sim16\times10^{-4})$

$BELLE\,(657\times10^6\,B\bar{B}\ \ pairs):\quad BR(B\rightarrow\nu\bar{\nu})<1.3\ \ 10^{-4}(\epsilon_{sig}\sim2.2\times10^{-4})$

Phys. Rev. D 86, 032002 (2012)

Ongoing sensitivity studies at Belle 2, probably **up to BR~10^{-6}**

Υ(1S) invisible decays at Belle 2

Υ(nS): bound state of a b quark and a $\bar{b}$ antiquark

$$\frac{BR(\Upsilon(1S)\rightarrow\nu\bar{\nu})}{BR(\Upsilon(1S)\rightarrow e^+e^-)}=\frac{27G^2M^4_{\Upsilon(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

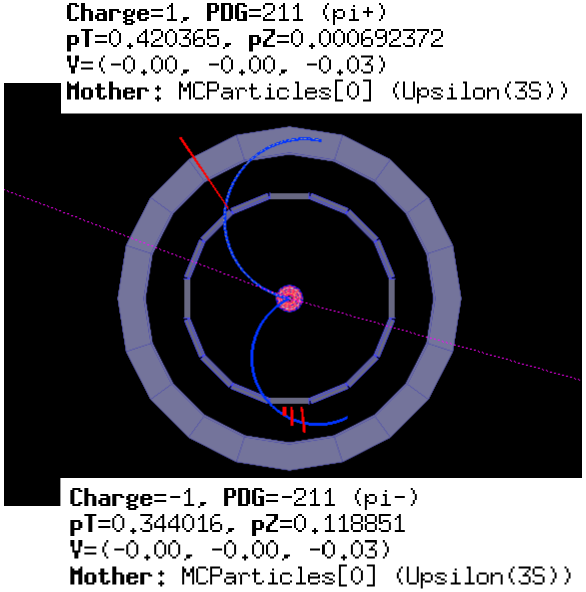
$$BR(\Upsilon(1S)\rightarrow\nu\bar{\nu})\sim9.9\times10^{-6}$$

- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Υ(1S)→νν

$$e^+e^-\rightarrow\Upsilon(3S)$$
$$\downarrow(4.4\%)$$
$$\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$$
$$\downarrow$$
$$\Upsilon(1S)\rightarrow invisible$$

$$e^+e^-\rightarrow\Upsilon(2S)$$
$$\downarrow(18.1\%)$$
$$\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$$
$$\downarrow$$
$$\Upsilon(1S)\rightarrow invisible$$

Belle2 Simulation
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν



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$$BR(\Upsilon(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$

$$e^+e^-\to\Upsilon(3S)$$
$\downarrow$(4.4%)
$$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$$
$\downarrow$
$$\Upsilon(1S)\to invisible$$

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$\downarrow$(18.1%)
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- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80**, 115019, 2009]
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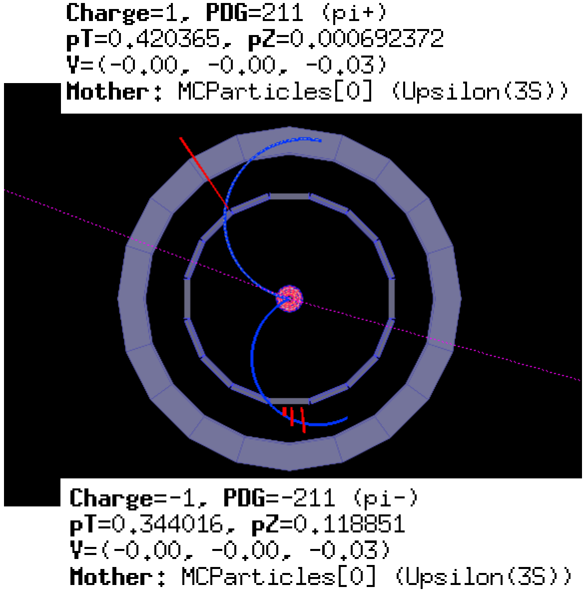
- In absence of new physics enhancement, Belle2 should be able to observe the SM Υ(1S)→νν

Belle2 Simulation
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν



A signal of Υ(1S)→*invisible* is an excess of events over the background in the M_r distribution at a mass equivalent to that of the Υ(1S) (9.460 GeV/c²)

$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

Y(1S) invisible decays at Belle 2

Y(nS): bound state of a b quark and a $\bar{b}$ antiquark

$$\frac{BR(Y(1S)\rightarrow\nu\bar{\nu})}{BR(Y(1S)\rightarrow e^+e^-)}=\frac{27G^2M^4_{Y(1S)}}{64\pi^2\alpha^2}\left(-1+\frac{4}{3}\sin^2\theta_W\right)^2=4.14\times10^{-4}$$

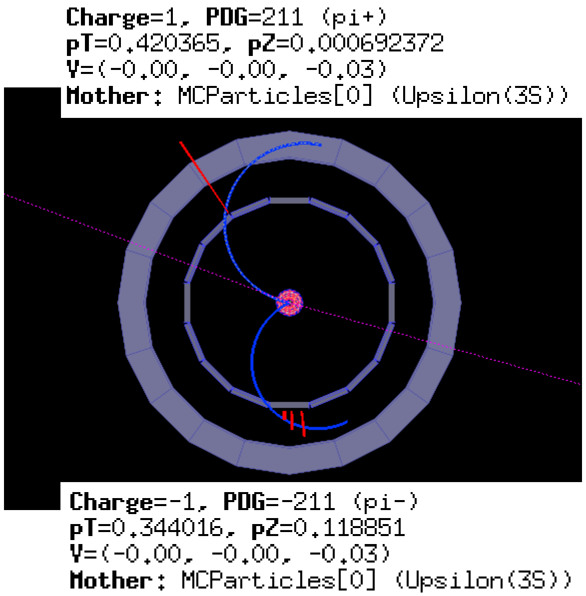
$$BR(Y(1S)\rightarrow\nu\bar{\nu})\sim9.9\times10^{-6}$$

$$e^+e^-\rightarrow Y(3S)$$
$\downarrow$ (4.4%)
$$Y(3S)\rightarrow\pi^+\pi^-Y(1S)$$
$$\downarrow$$
$$Y(1S)\rightarrow invisible$$

$$e^+e^-\rightarrow Y(2S)$$
$\downarrow$ (18.1%)
$$Y(2S)\rightarrow\pi^+\pi^-Y(1S)$$
$$\downarrow$$
$$Y(1S)\rightarrow invisible$$

- Low mass dark matter particles however might might play a role in the decays of Y(1S), having $Y(1S)\rightarrow\chi\chi$ if kinematic allowed. [Phys. Rev. D **80**, 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance $Y(1S)\rightarrow\nu\nu(\gamma)$. [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM $Y(1S)\rightarrow\nu\nu$

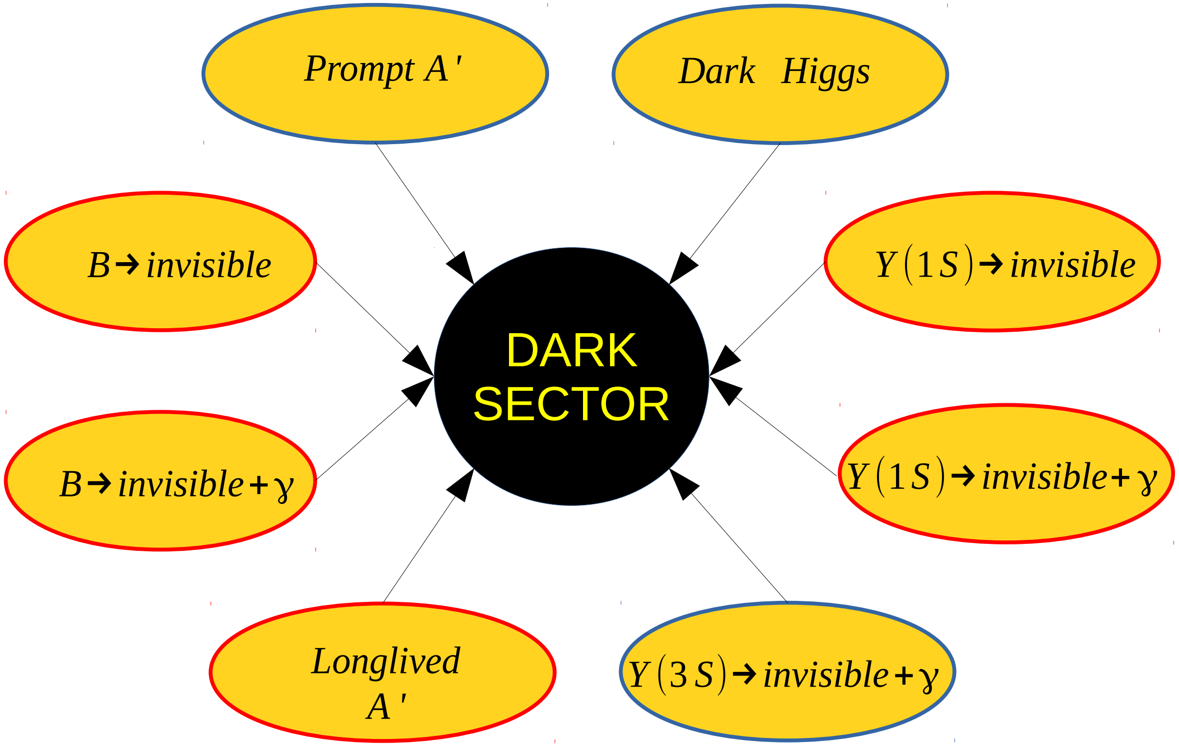
Belle2 Simulation
$Y(3S)\rightarrow\pi^+\pi^-Y(1S)$,
$Y(1S)\rightarrow\nu\nu$



No signal was observed over the expected background and upper limits have been obtained: $BR(Y\rightarrow\nu\nu) < 2.5\times10^{-4}$ (BaBar) and $BR(Y\rightarrow\nu\nu) < 3.0\times10^{-3}$ (Belle).

At Belle 2 one would expect to collect >200fb^{-1} of data @ Y(3S) (ongoing discussion for Y(2S) data taking and trigger) allowing one to reconstruct between 30 and 300 events, assuming 10^{-5} (SM)<$BR_{Y\rightarrow invisible}$< 10^{-4} (NP).

DARK SECTOR SEARCHES AT THE BELLE 2 EXPERIMENT



- Many decay topologies are available at (Super) flavour factories to constrain and eventually discover dark sector particles.

- A task force aimed at the study of dark sector, giving particular relevance to final states with missing energy need to be created.

- It is a high risk project, but it would allow one to fully exploit the Belle 2 experiment potentials in terms of the complementarity wrt other projects (i.e. LHCb). Potential discoveries will have a strong impact on future research.
  - In the hypothesis of null outcome in terms of new physics one could however be able to observe and measure the rare decay $\Upsilon(1S) \to \nu\nu$ which would provide additional insights about the flavour structure of the standard model: win-win project.

Conclusions

- Discovering dark matter is today one of the biggest challenges we are facing, but more important is the understanding of its nature
  - Synergy between different experiments and Collaborations is required.
- Many searches at the Belle experiment are ongoing and an higher precision will be reached thanks to the great luminosity of Belle 2 at Super-KEK and to improved hardware/software.
- Searches for dark sector(s) at Belle 2 will be performed, and thanks to the possibility to study invisible final states one can fully exploit the complementarity with respect to hadron collider experiments.
- Searching for dark sector particles and forces (or new physics in general) in invisible final states might be seen as an high risk project.
  - Perhaps it is..
  - Perhaps it is an high opportunity project..
  - Perhaps both!

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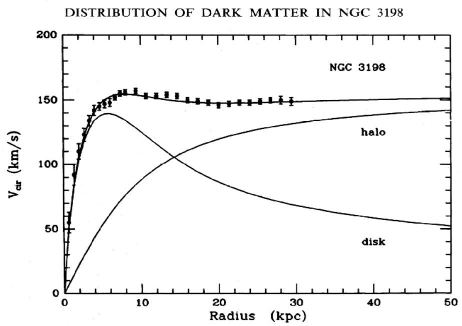
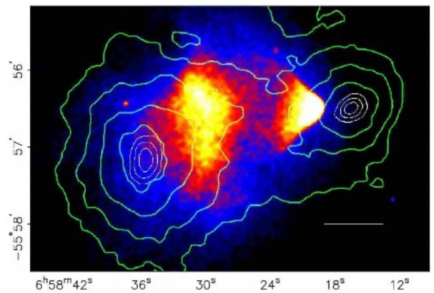
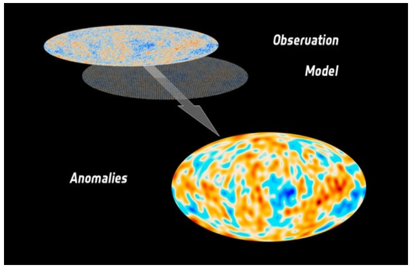
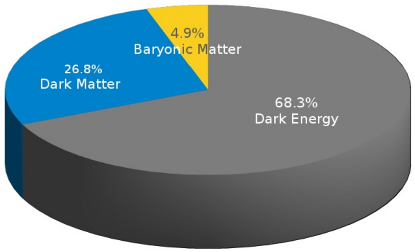
Thank you for your attention!

Dark sector searches @ BELLE and BELLE 2: Why?

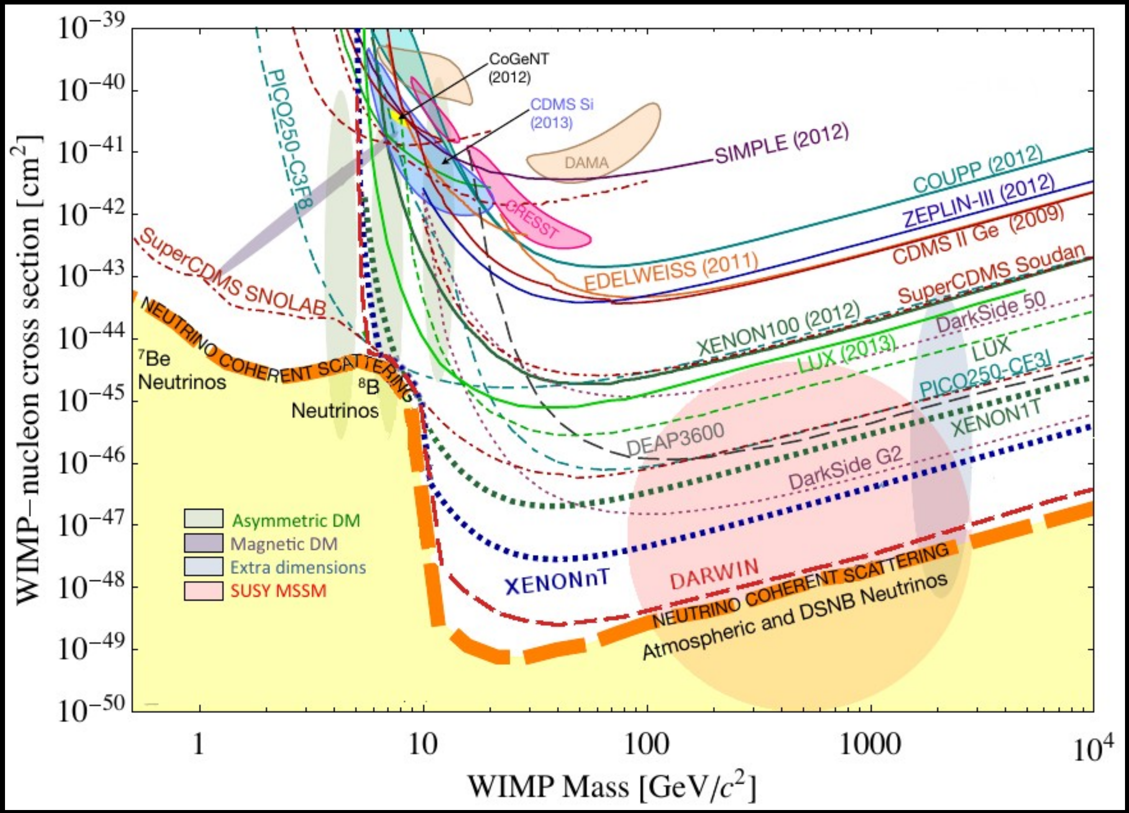








Direct detection

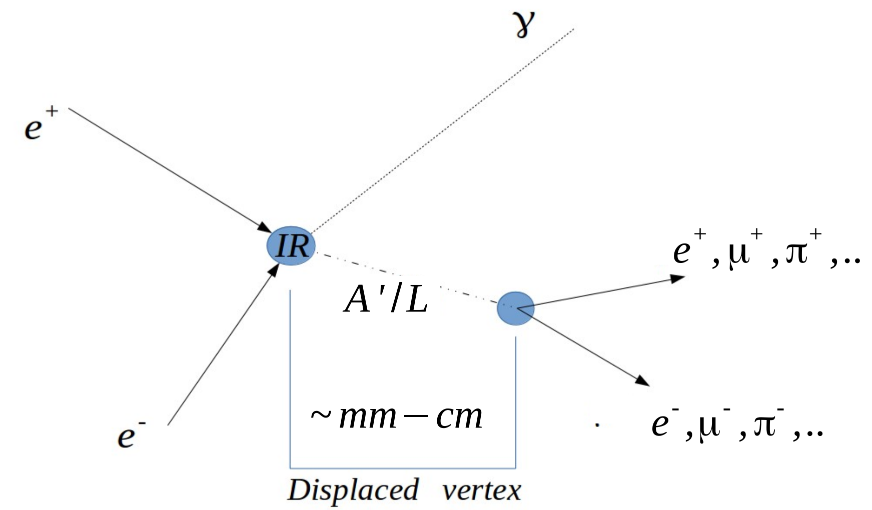


Search for interaction of DM particles with (usually) underground detectors: heat, scintillation light, etc..

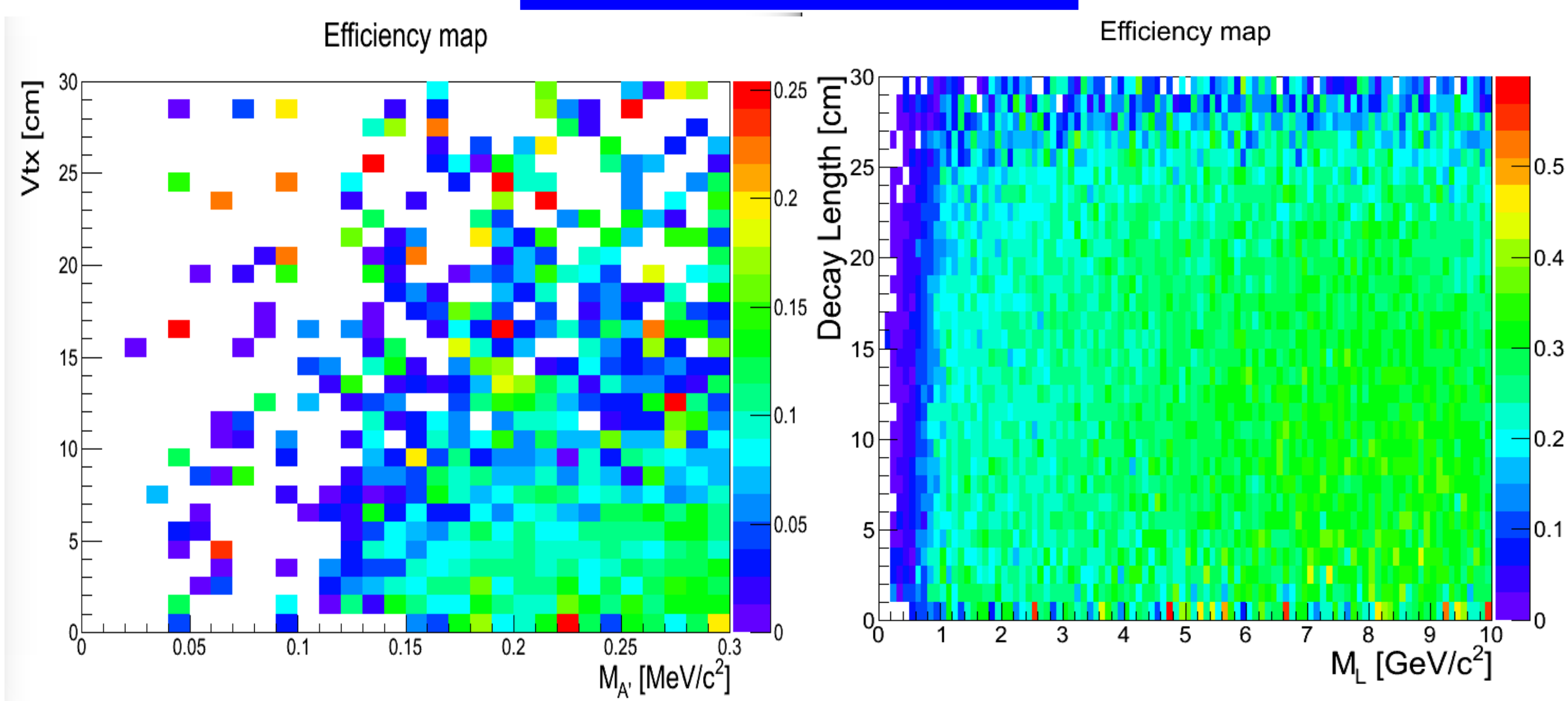
Dark photon and long lived gauge bosons @ BELLE

Ongoing analysis, approaching final stage

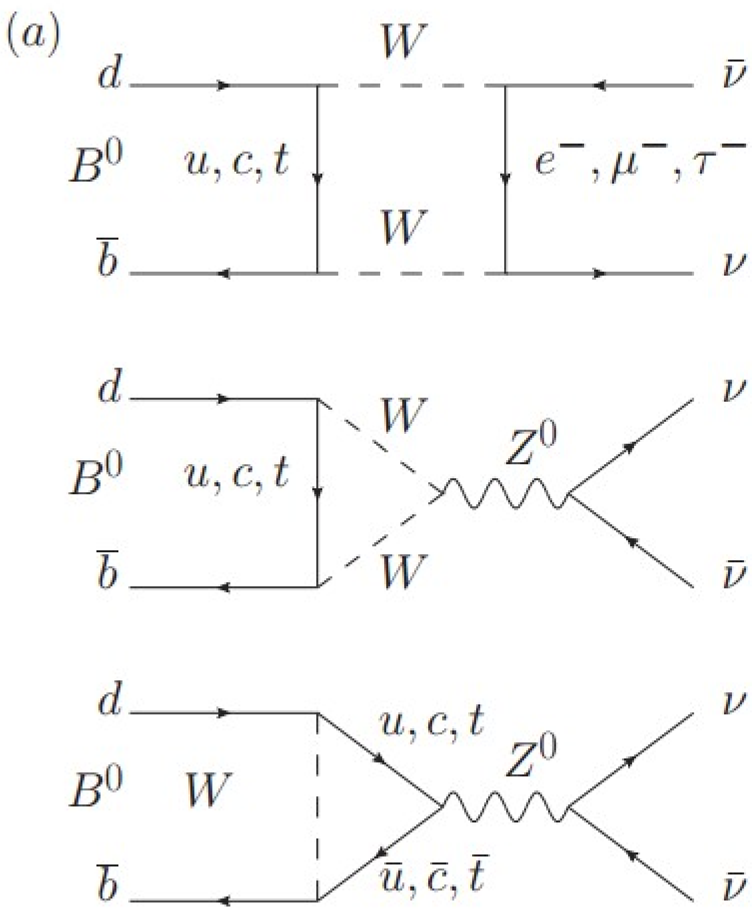
$$A'/L \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$$
$$L \rightarrow e^+\mu^-, e^-\mu^+, K^+K^-$$
$$M_{A'/L} = 0.1 - 10\, GeV/c^2$$
$$W_{A'/L} = 1\, KeV/c^2$$
$$c\tau = 1,\ \ 5,\ \ 10\ \ cm$$

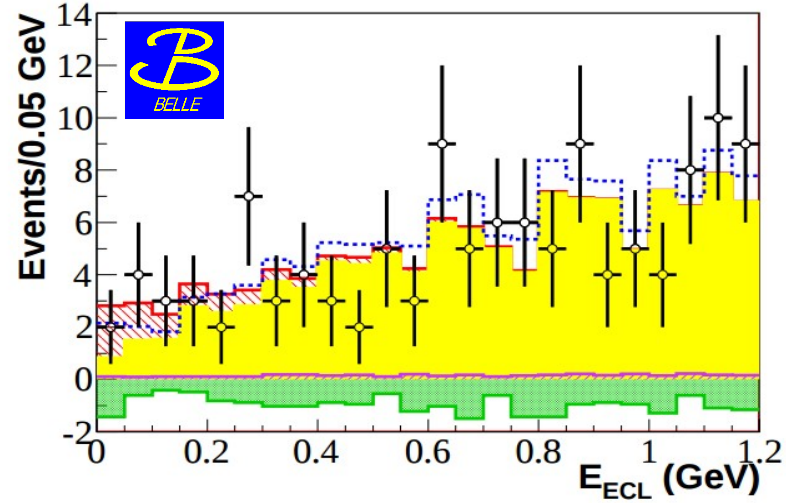


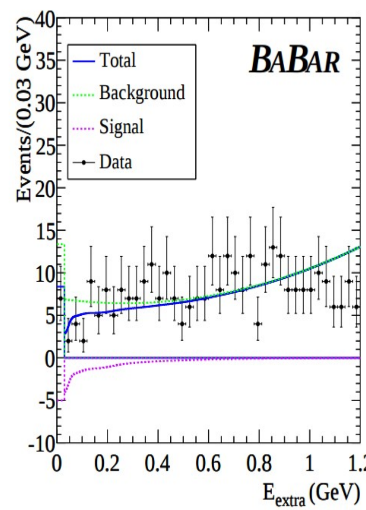
BELLE SIMULATION

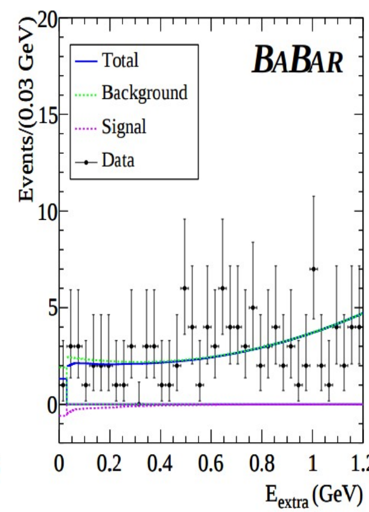


B meson disappearance









$BABAR\,(471\times10^{6}\,B\overline{B}\ \ pairs):\quad BR(B\to\nu\bar{\nu})<2.4\ \ 10^{-5}(\epsilon_{sig}\sim18\times10^{-4}),$

Phys. Rev. D 86, 051105 (2012) $\quad BR(B\to\nu\bar{\nu}\gamma)<1.7\ \ 10^{-5}(\epsilon_{sig}\sim16\times10^{-4})$

$BELLE\,(657\times10^{6}\,B\overline{B}\ \ pairs):\quad BR(B\to\nu\bar{\nu})<1.3\ \ 10^{-4}(\epsilon_{sig}\sim2.2\times10^{-4})$

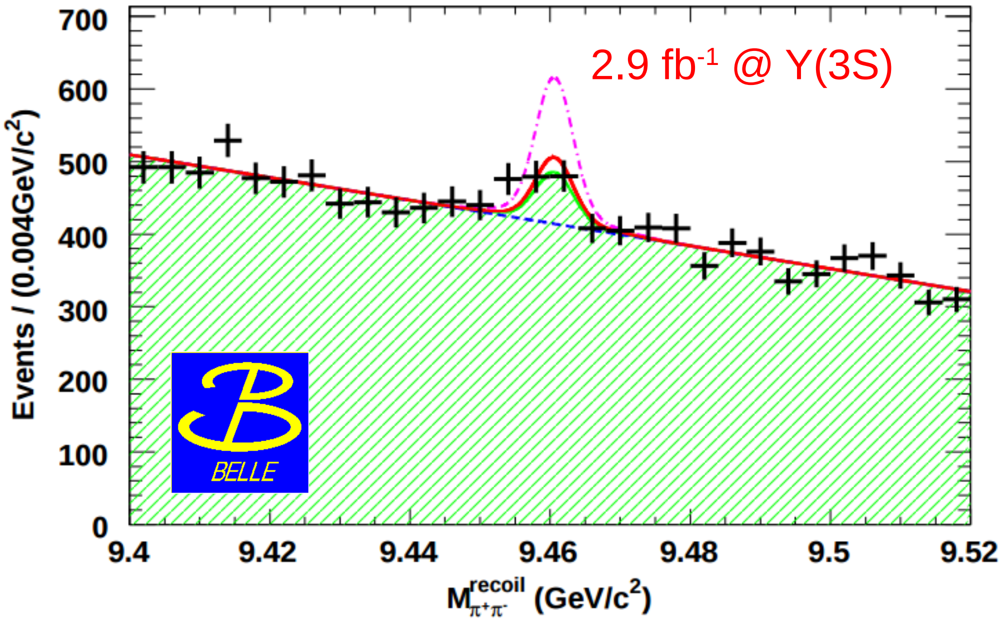
Phys. Rev. D 86, 032002 (2012)

Ongoing sensitivity studies at Belle 2, probably up to BR~10^{-6}

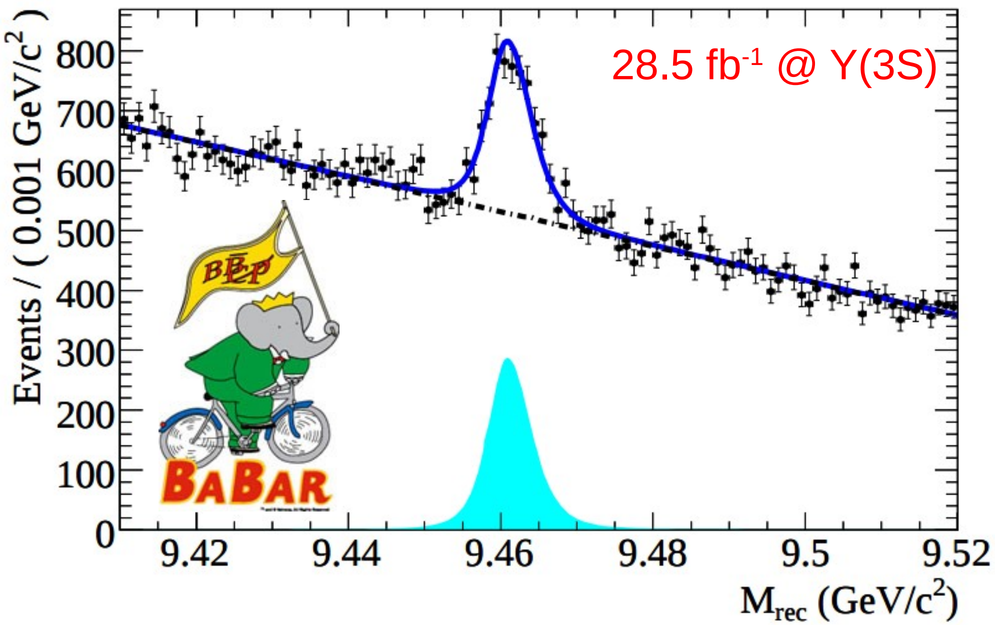
Y(1S) invisible decays: signal and background

$$M_r^2 = s + M_{\pi^+\pi^-} - 2\sqrt{s}E_{\pi^+\pi^-}^{CMS}$$

[belle]: http://arxiv.org/abs/hep-ex/0611041
(1 week running @ Y(3S))



[babar]: http://arxiv.org/abs/0908.2840
(2 months running @ Y(3S))



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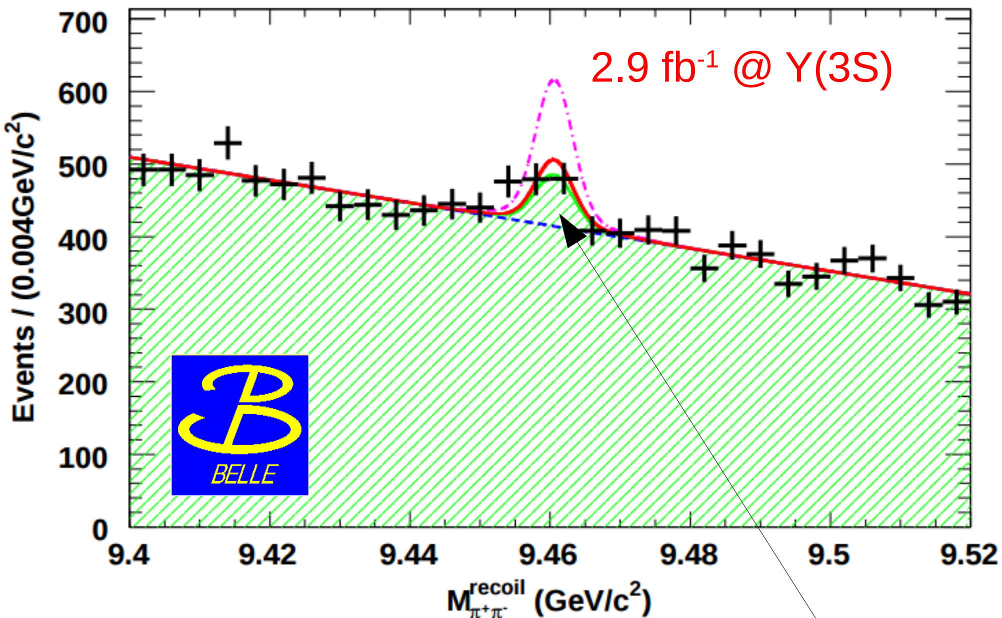

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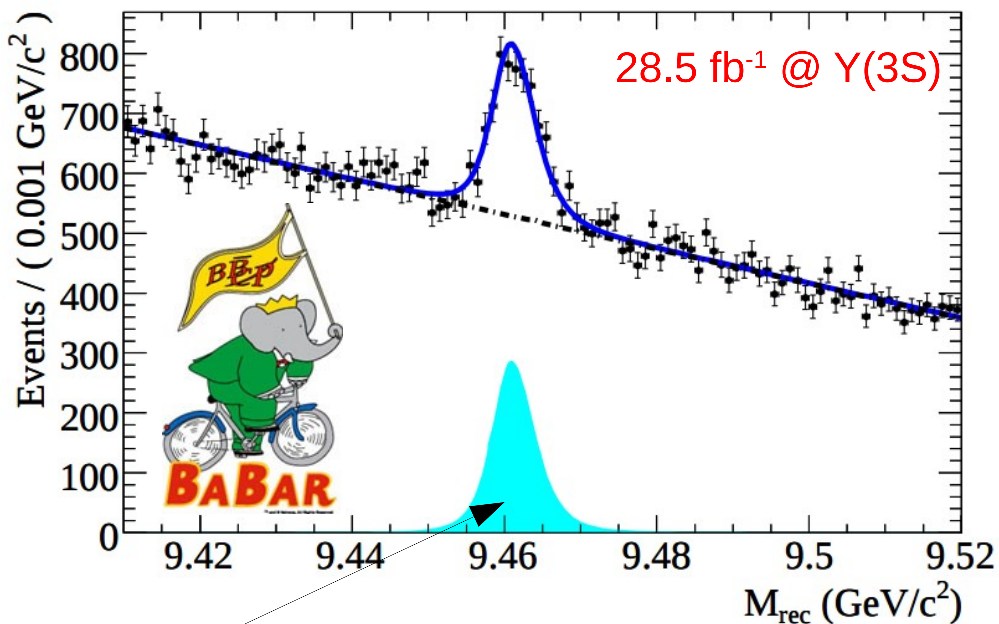
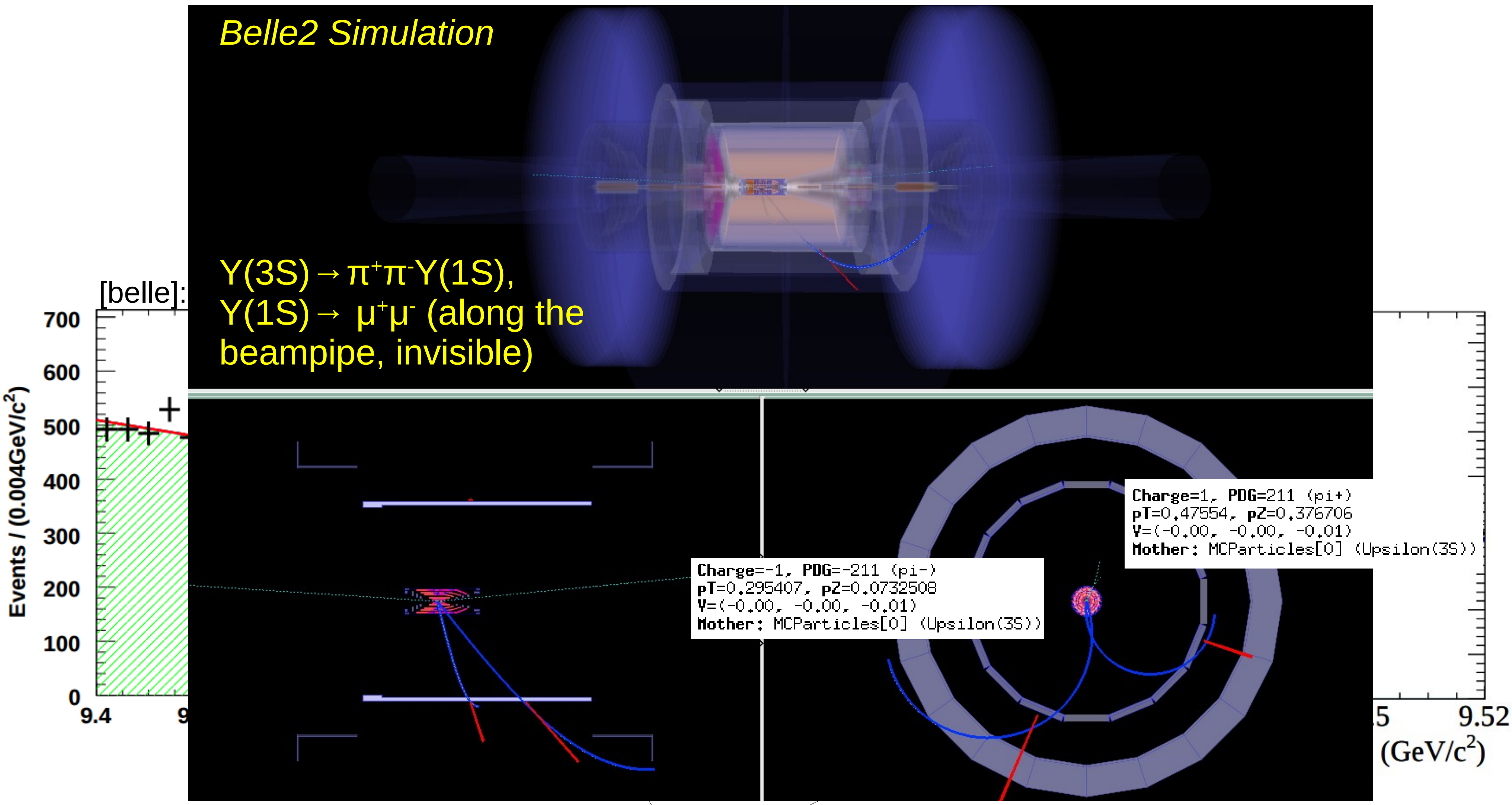


Irreducible peaking background when final states go undetected (i.e. detector supports, beampipe etc.) in the process $Y(3S) \rightarrow \pi^+\pi^- Y(1S), Y(1S) \rightarrow undetected\ f.s.$

Υ(1S) invisible decays: signal and background

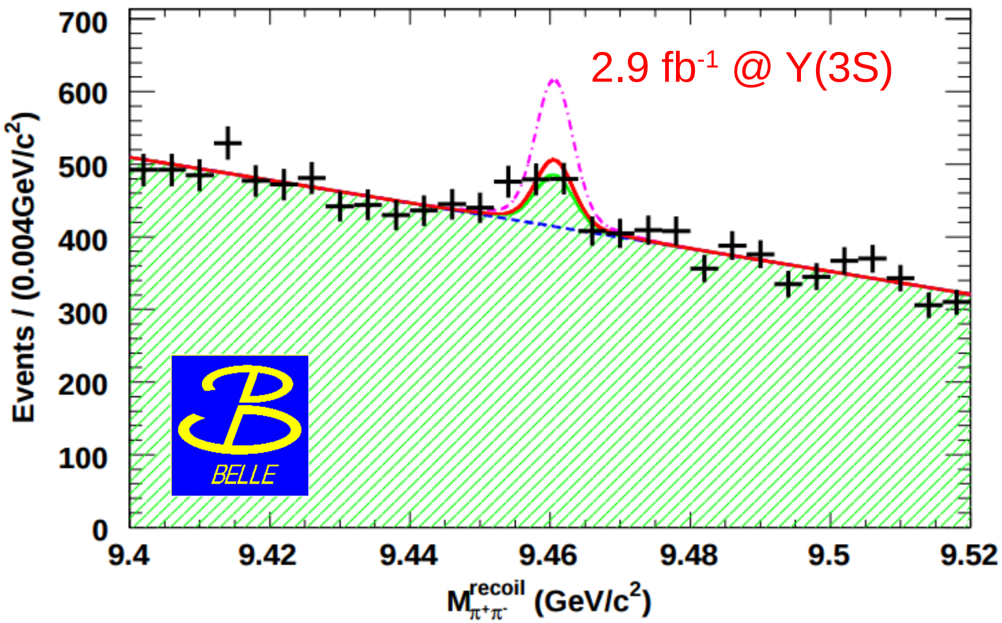


Irreducible peaking background when final states go undetected (i.e. detector supports, beampipe etc.) in the process $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S), \Upsilon(1S) \rightarrow undetected\, f.s.$

Y(1S) invisible decays: what to expect

$$M_r^2 = s + M_{\pi^+\pi^-} - 2\sqrt{s}E_{\pi^+\pi^-}^{CMS}$$

[belle]: http://arxiv.org/abs/hep-ex/0611041
(1 week running @ Y(3S))



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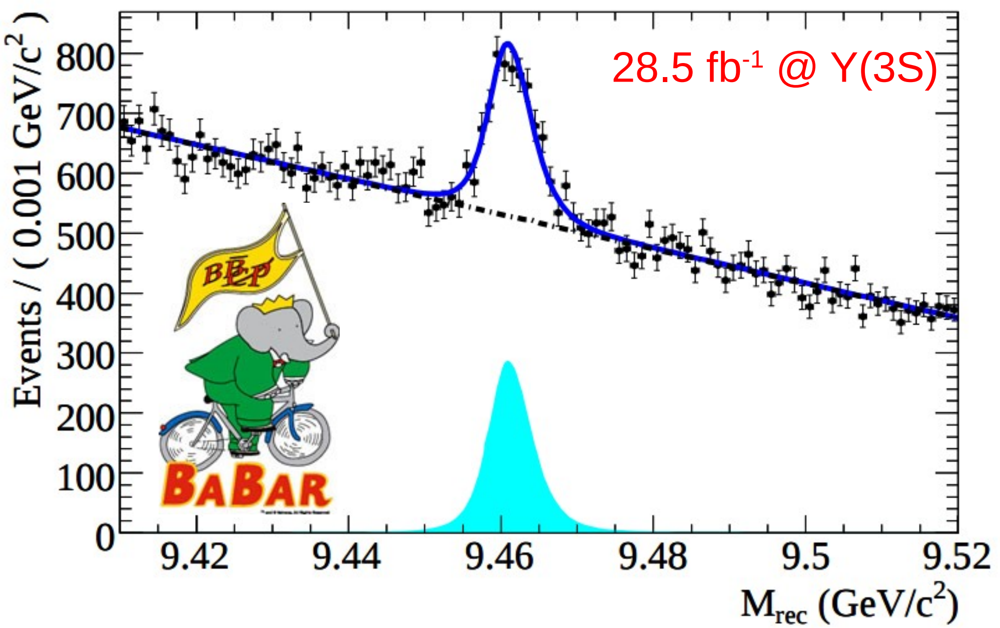

No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < 2.5x10^{-4} (Belle) and BR(Y→νν) < 3.0x10^{-3}(Babar).

At Belle 2 one would expect to collect >200fb^{-1} of data @ Y(3S) (ongoing discussion for Y(2S) data taking and trigger) allowing one to reconstruct between 30 and 300 events, assuming 10^{-5} (SM)<BR(Y→invisible)< 10^{-4} (NP) and Belle efficiencies.