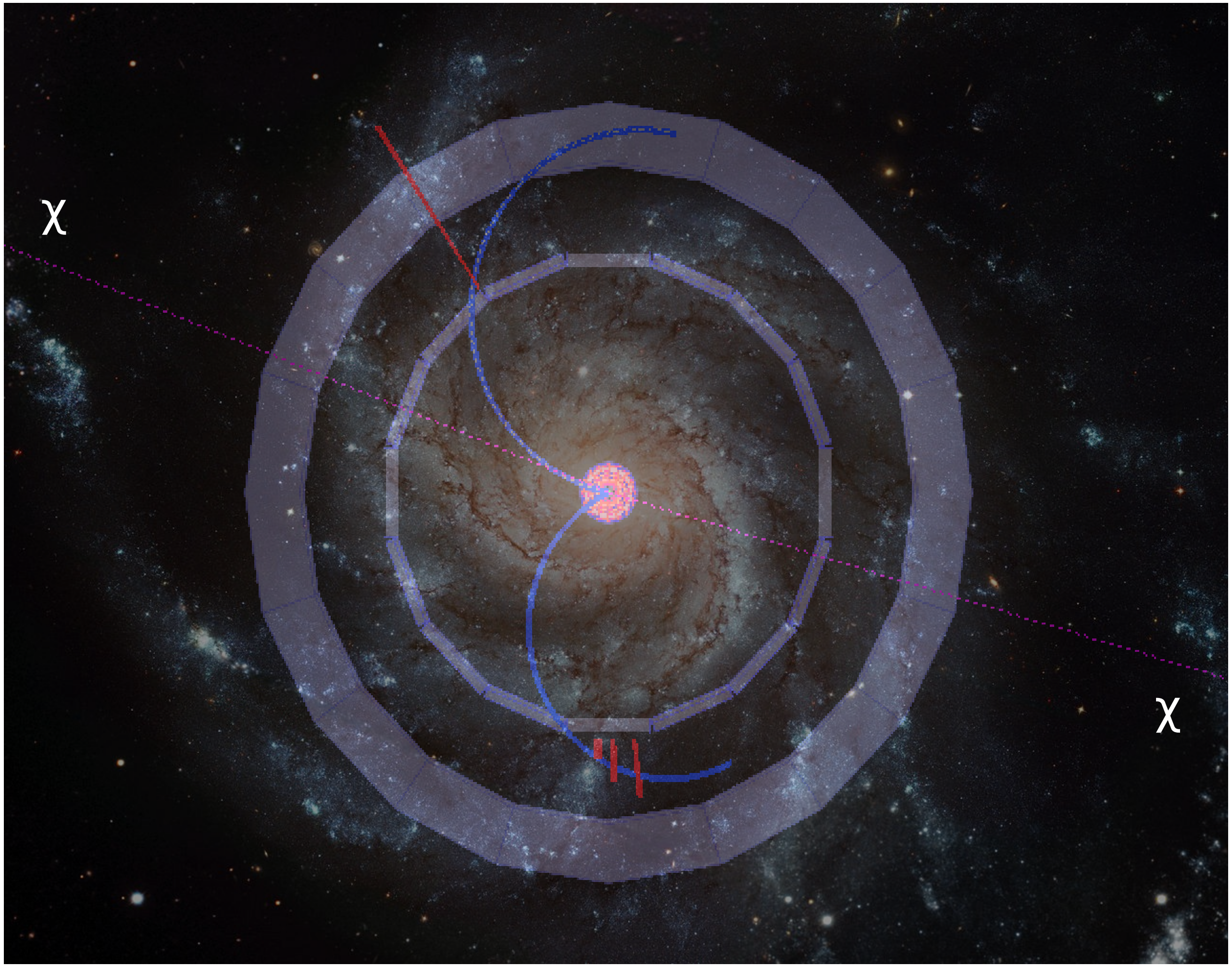


Gianluca Inguglia
Institute of High Energy Physics (HEPHY)
Vienna- Austria
(FWF P 31361-N36)
gianluca.inguglia@oeaw.ac.at

Karlsruhe 25/09/2018

"Dark sector physics with charged final states in Belle II"

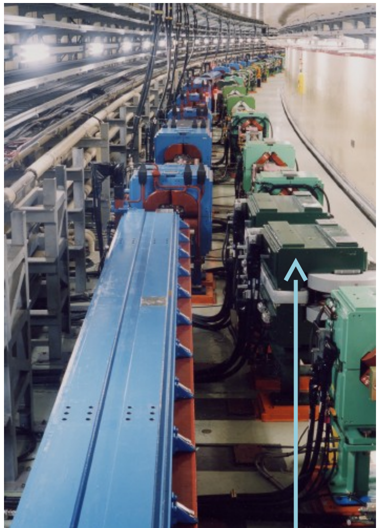
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

FWF Der Wissenschaftsfonds.

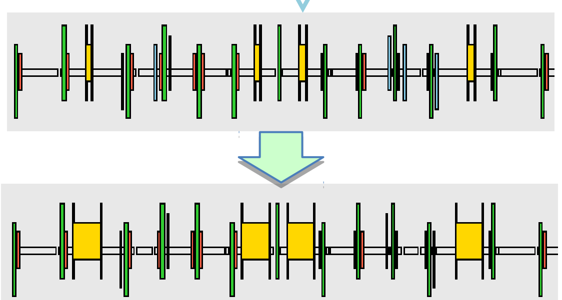
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Belle II

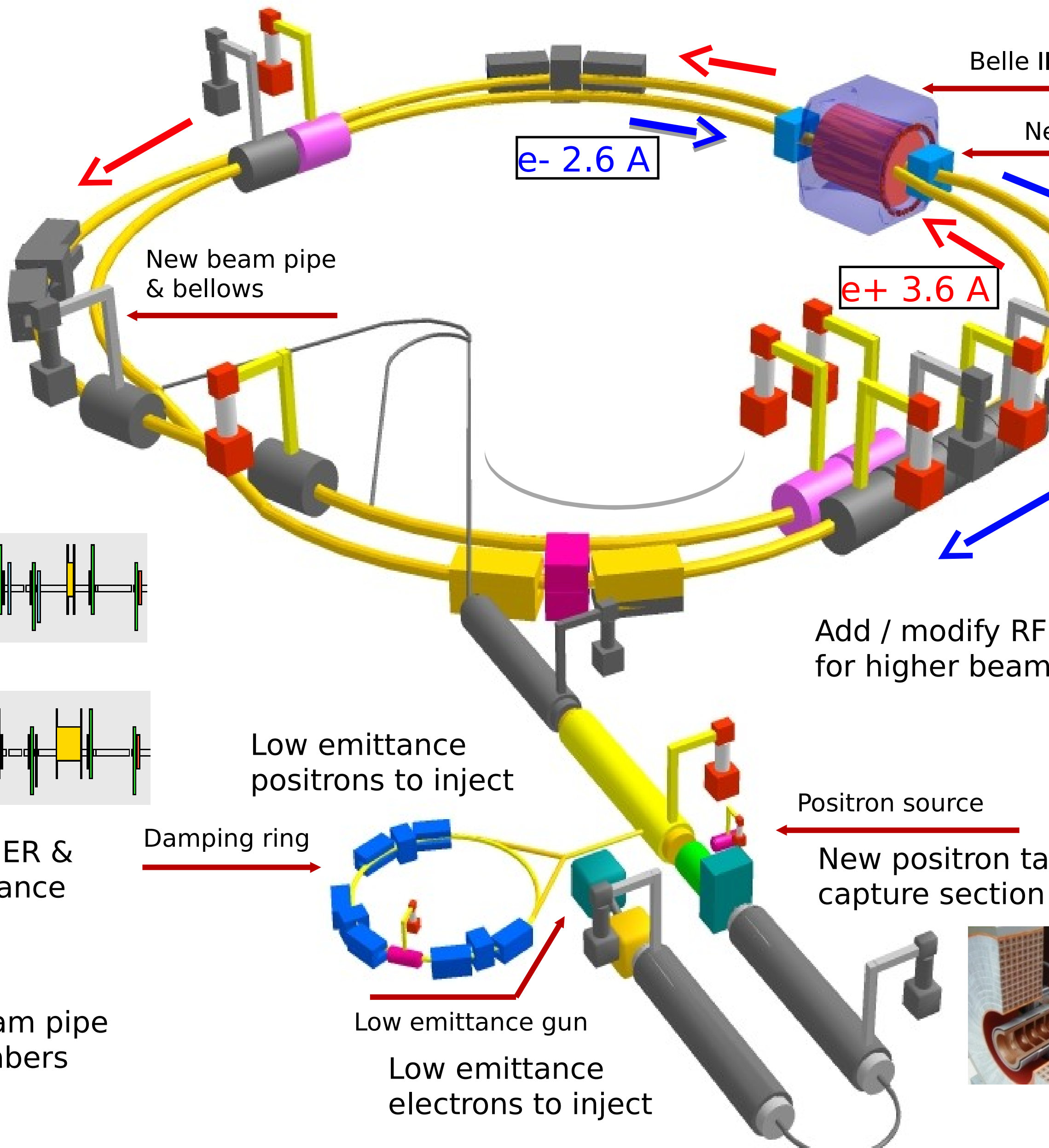
KEKB to SuperKEKB



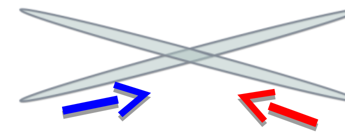
Replace short dipoles with longer ones (LER)



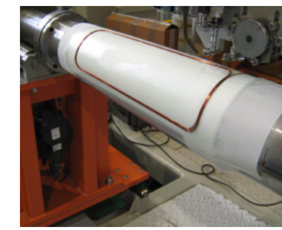
Redesign the lattices of HER & LER to squeeze the emittance



Colliding bunches

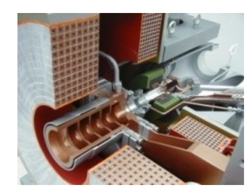


New superconducting /permanent final focusing quads near the IP

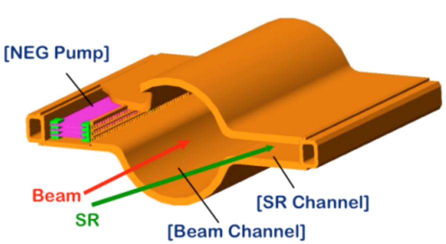


Add / modify RF systems for higher beam current

New positron target / capture section

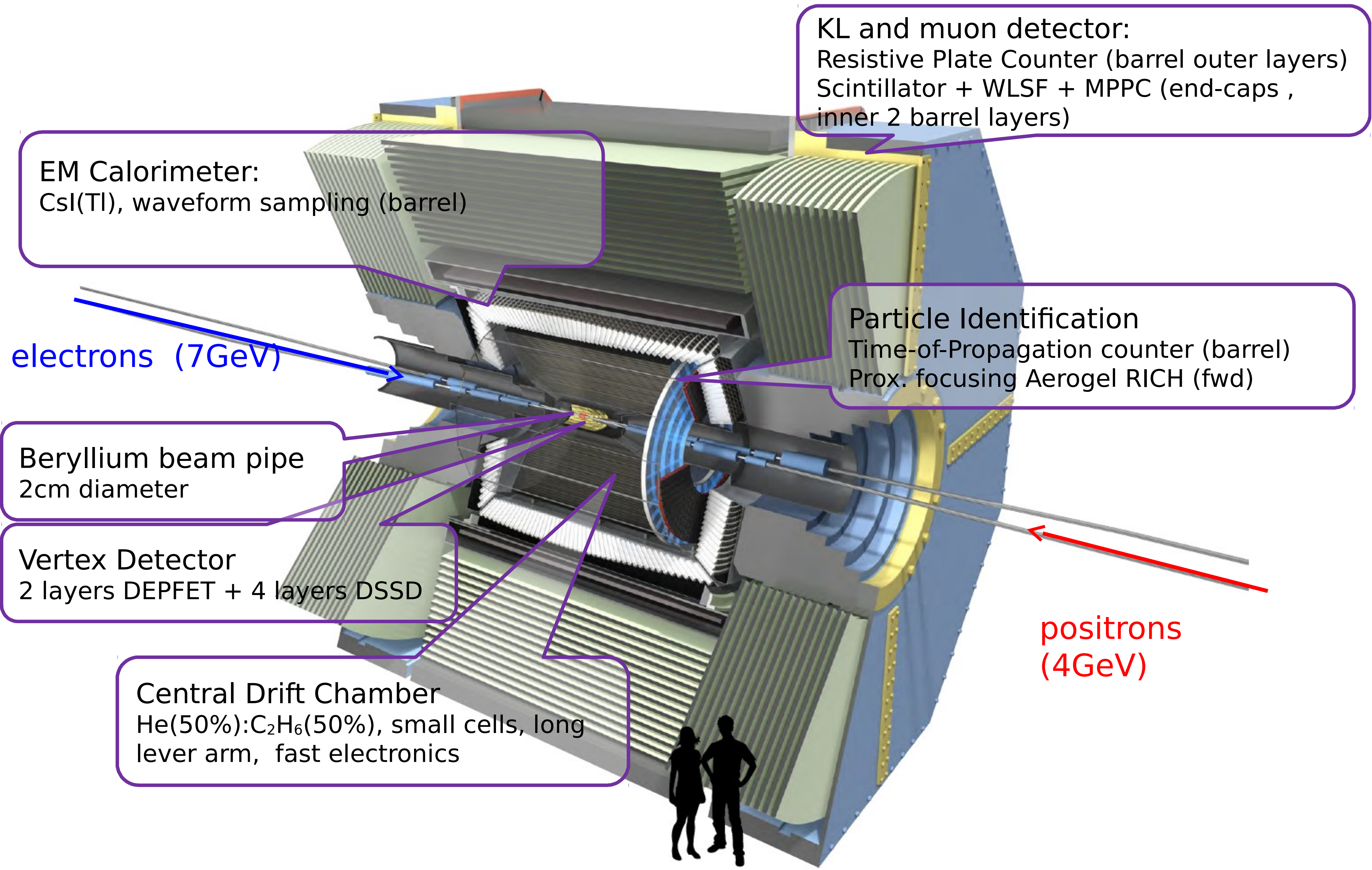


TiN-coated beam pipe with antechambers

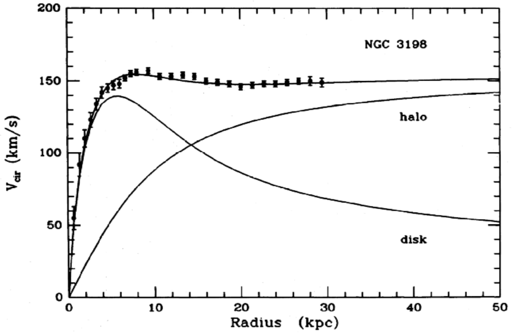


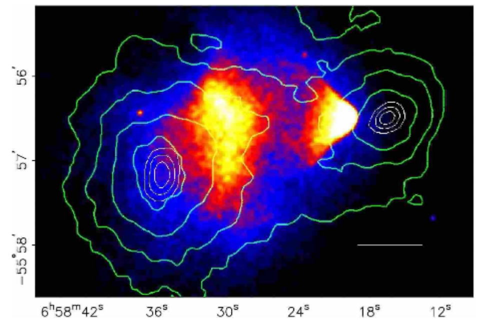
To obtain x40 higher luminosity

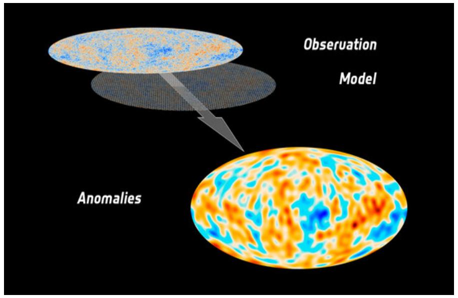
Belle II Detector Elements

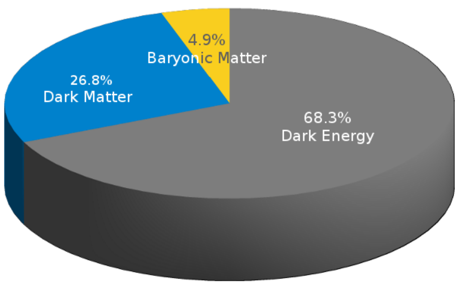


Dark sector searches @ BELLE and BELLE 2: Why?









- 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

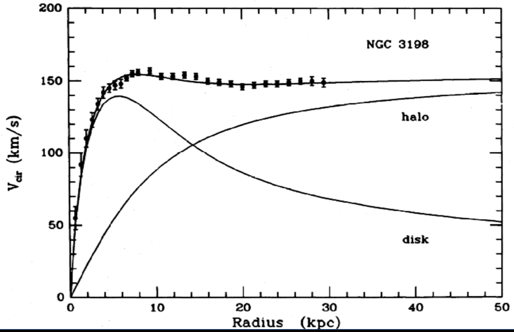
- One possibility is represented by the lightest **SUSY** particle (which is stable)
  - *But why should we have only one DM particle when density of DM is 5 times larger the density of visible matter (i.e. many SM particles)?*

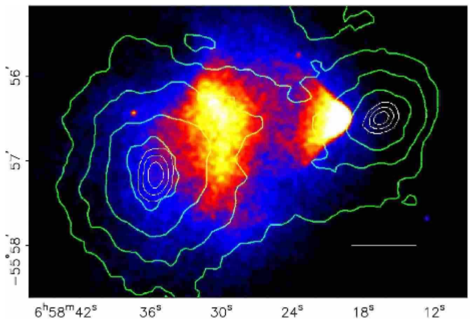
- Many new models have been and are currently being developed to propose a more complex sector for dark matter explaining also anomalies observed in astrophysical process → dark sector(s).

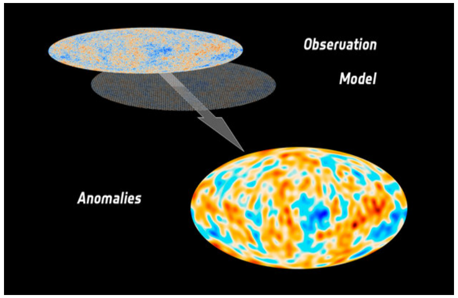
- Within dark sector models, **ADM** theories assign a certain importance to the fact that Ω_{DM}/Ω_{BM}~5. As for the **BAU** a tiny difference between particle-antiparticle in the early Universe has evolved to the observed Ω_{BM} today after the other particles-antiparticles have annihilated each other, something similar happened to DM particles-antiparticles.

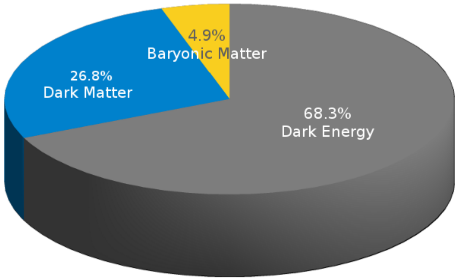
- I will not discuss details of the models but will rather discuss experimental signatures and searches at Belle2

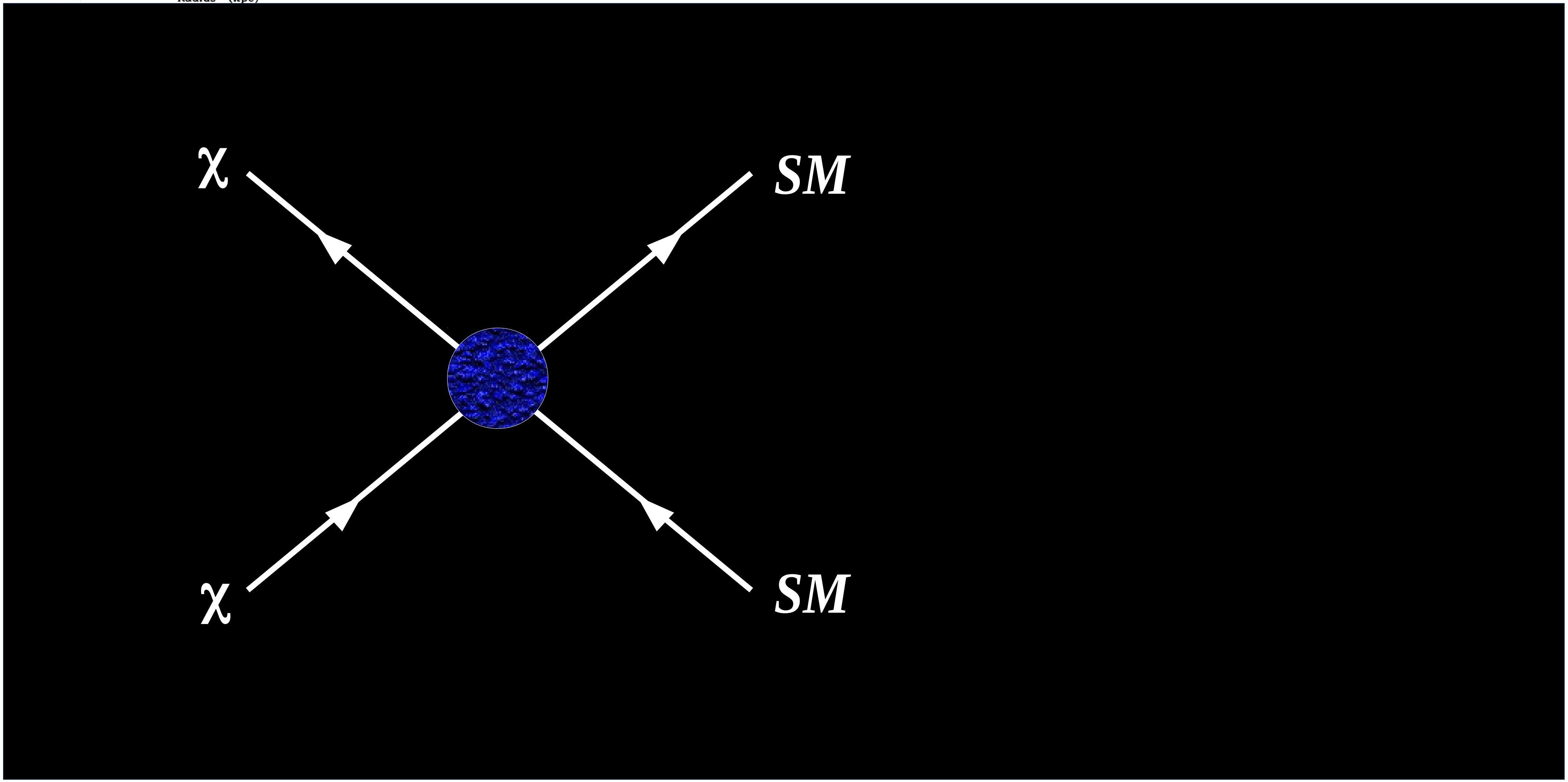
Searching for Dark Matter



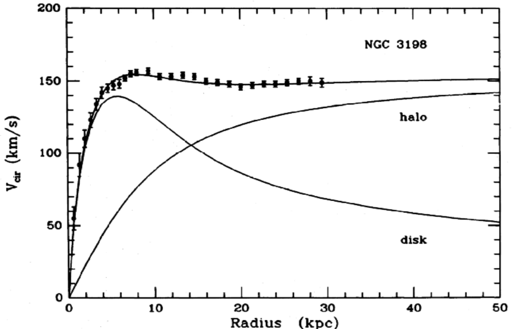


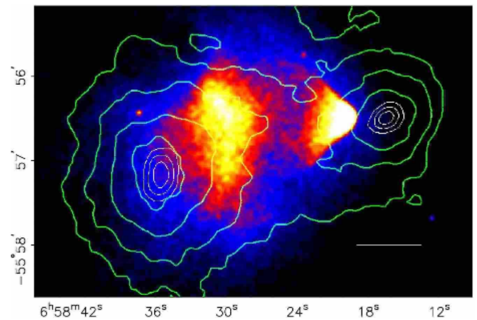


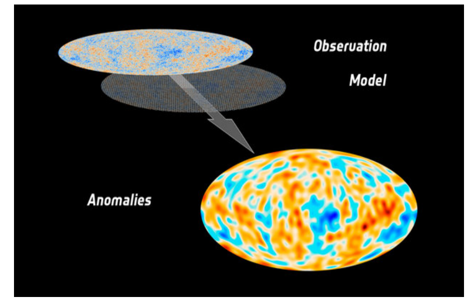


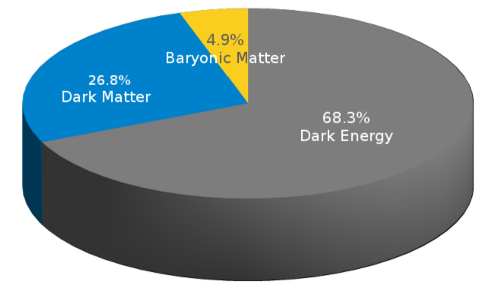


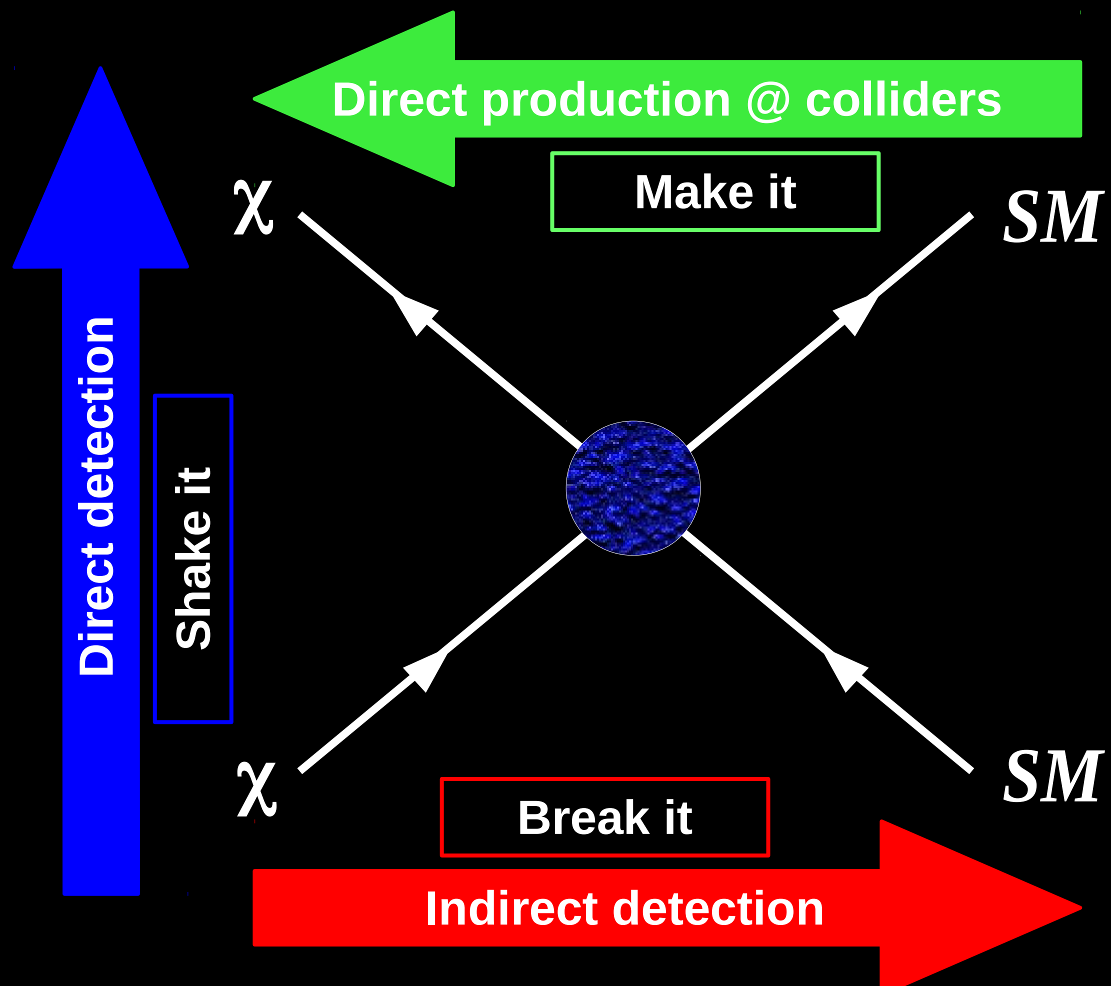
Searching for Dark Matter









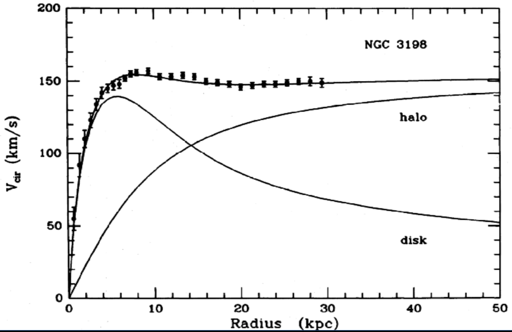


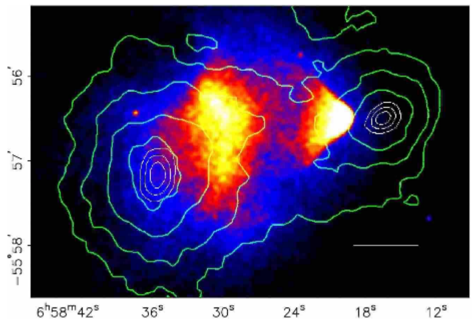
Search for events with missing energy, particle disappearance, dark forces, etc.

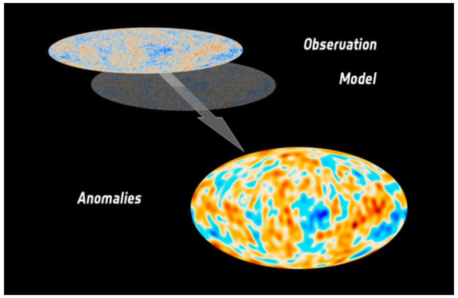
Search for interaction of DM particles with (usually) underground detectors: heat, scintillation light, etc..

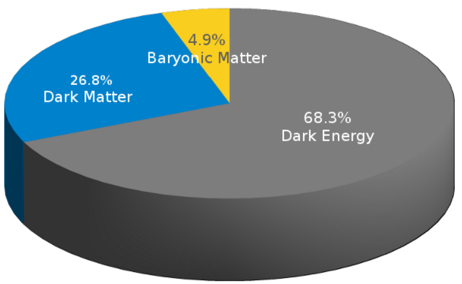
Space/earth based experiments: gamma ray energy excess, anti-particle excess, HE neutrinos etc.

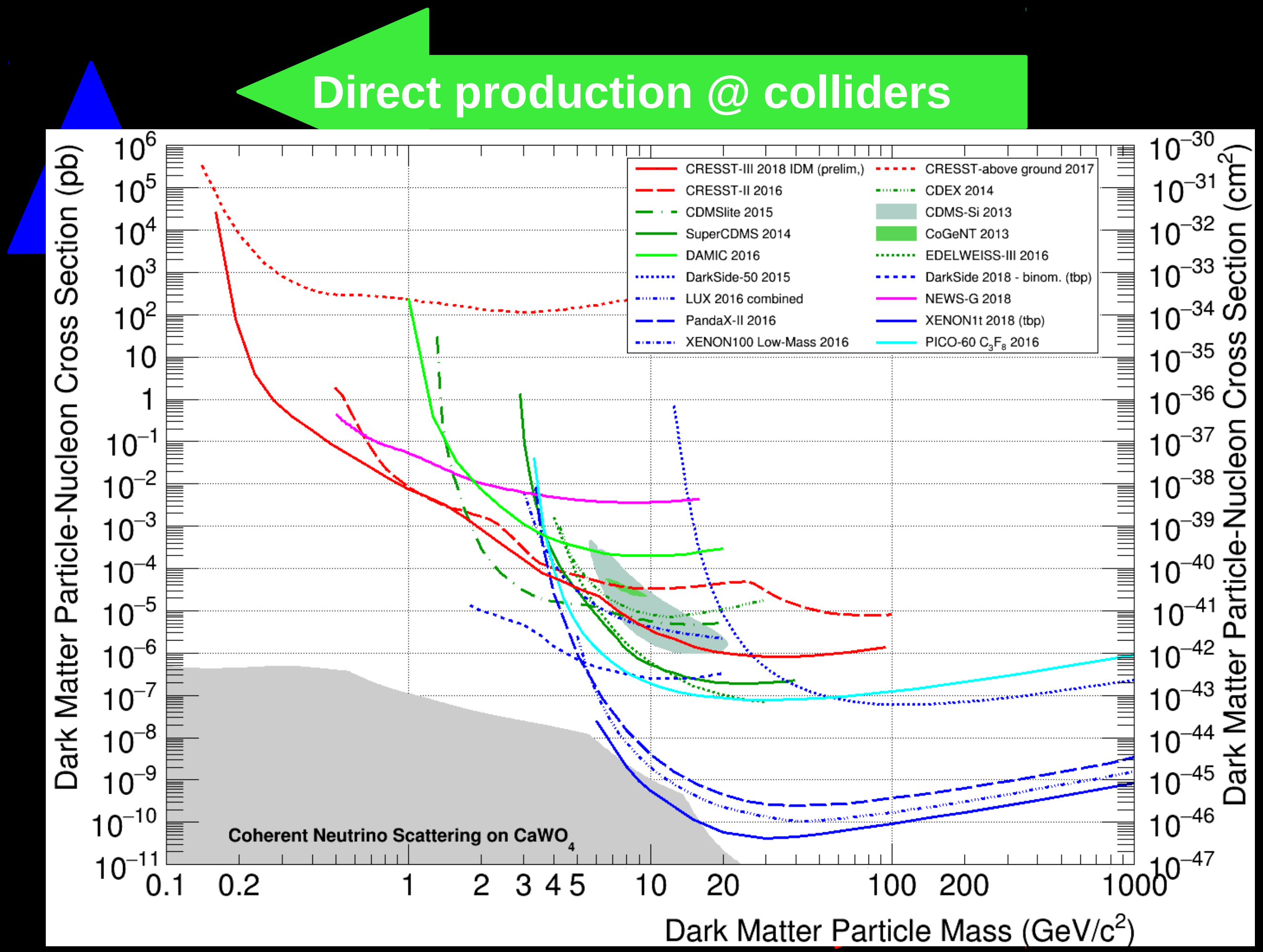
Searching for Dark Matter











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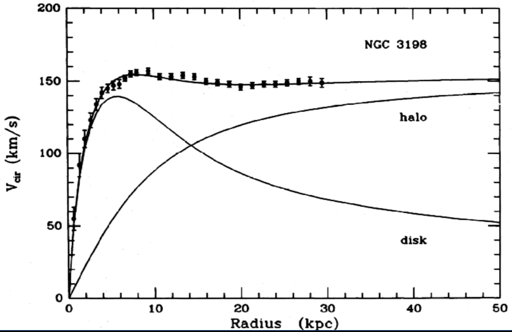
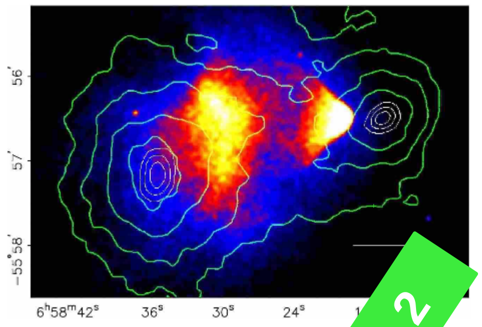
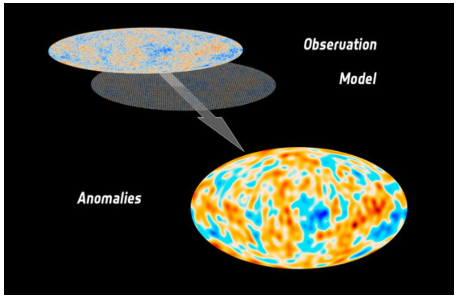
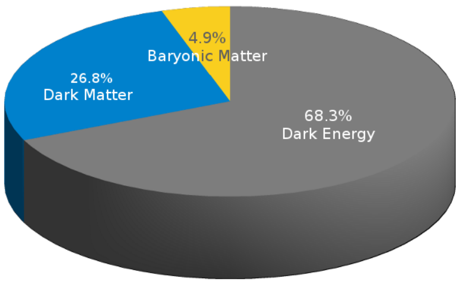
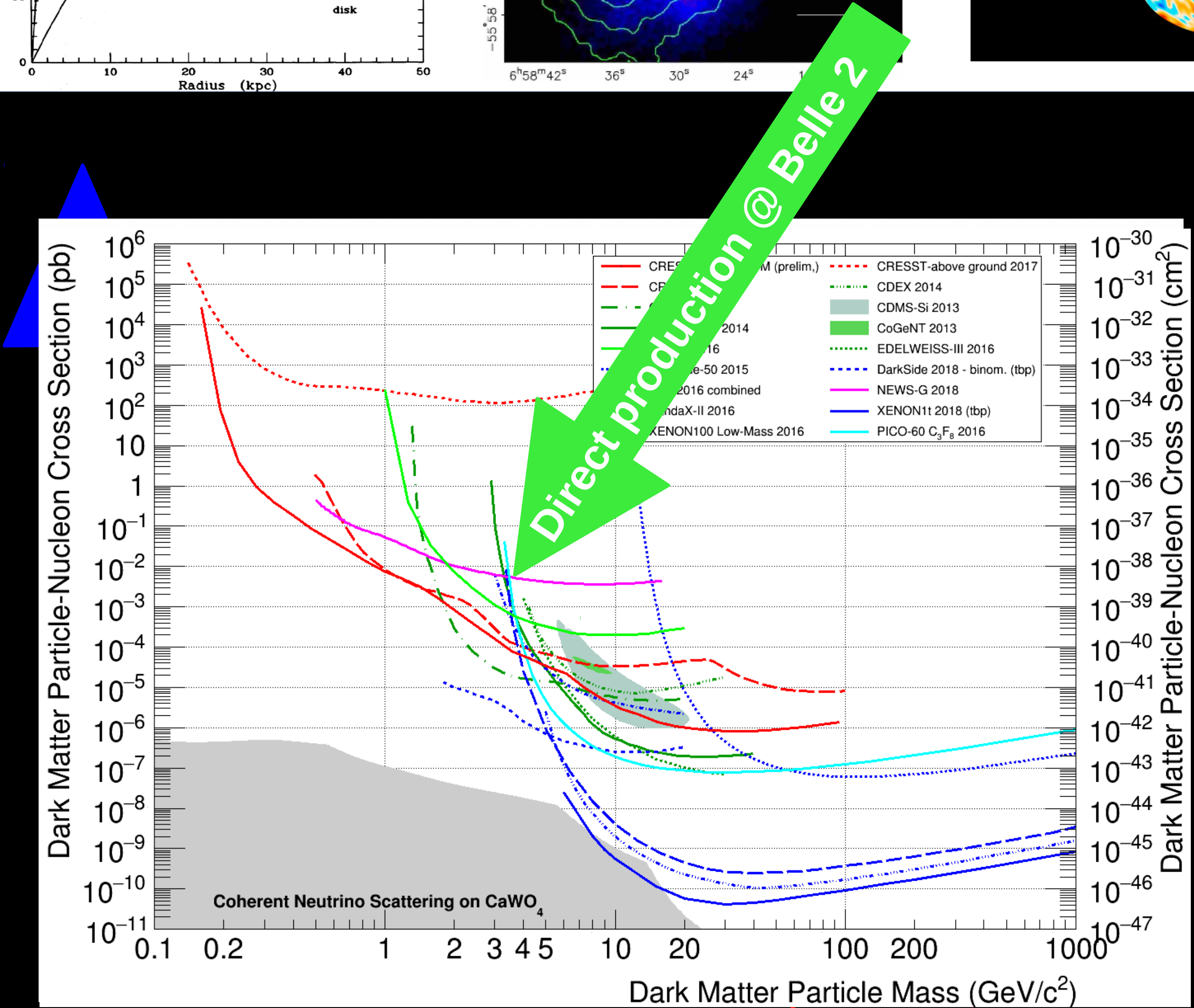
Searching for Dark Matter and Forces @ Belle/Belle II











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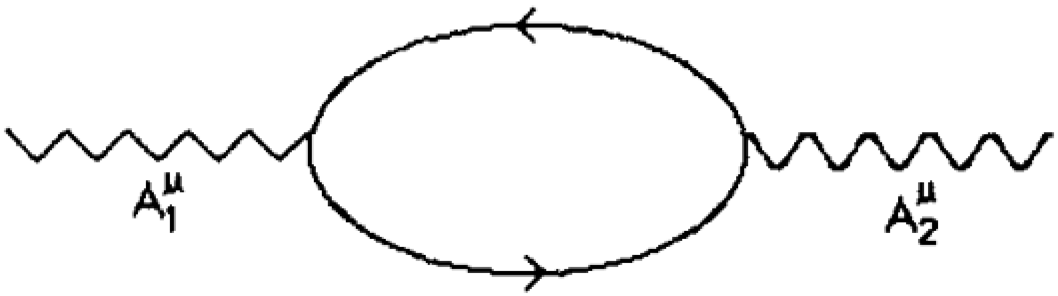
Dark Photon and Kinetic Mixing

Dark photon first proposed in P. Fayet, Phys. Lett. B **95**, 285 (1980), P. Fayet Nucl. Phys. B **187**, 184 (1981).

- (Holdom, 1986) A boson belonging to an additional U(1)' symmetry would mix kinetically with the photon:

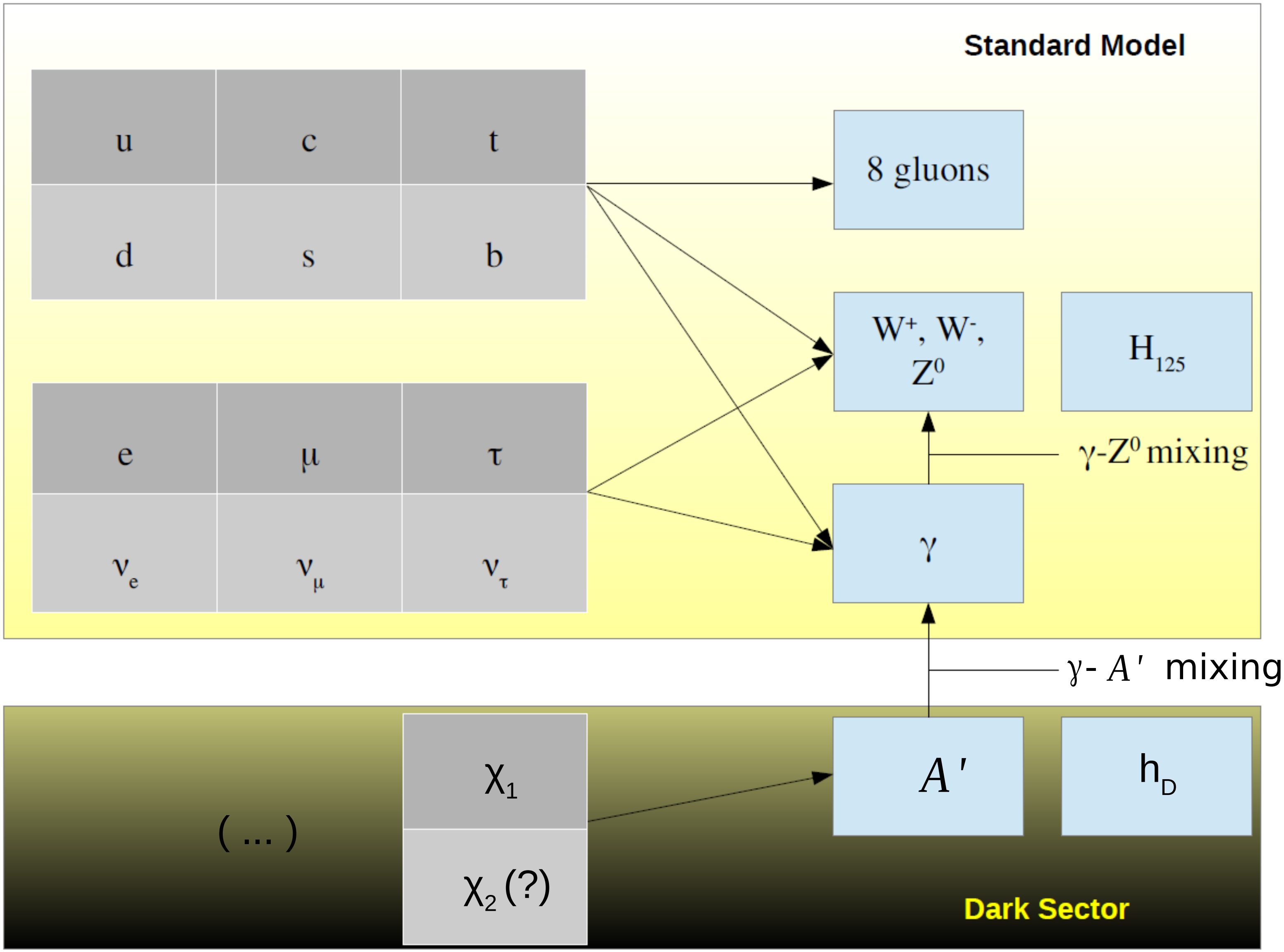


- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$
- For the dark photon to acquire mass an extended Higgs sector is required to break the new U(1)' symmetry

Note: ϵ is the strength of the kinetic mixing and it is supposed to be small, 10^{-5}-10^{-2}, **the smaller the value of ϵ the longer A' lifetime** (i.e. **long lived**).
The Mass of the new boson should be in the range few MeV to few Gev (Nima Arkani-Hamed et al. Phys. Rev. D **79,** 015014, 2009).

Dark Sector : How Does It Look Like?

A very simple example...



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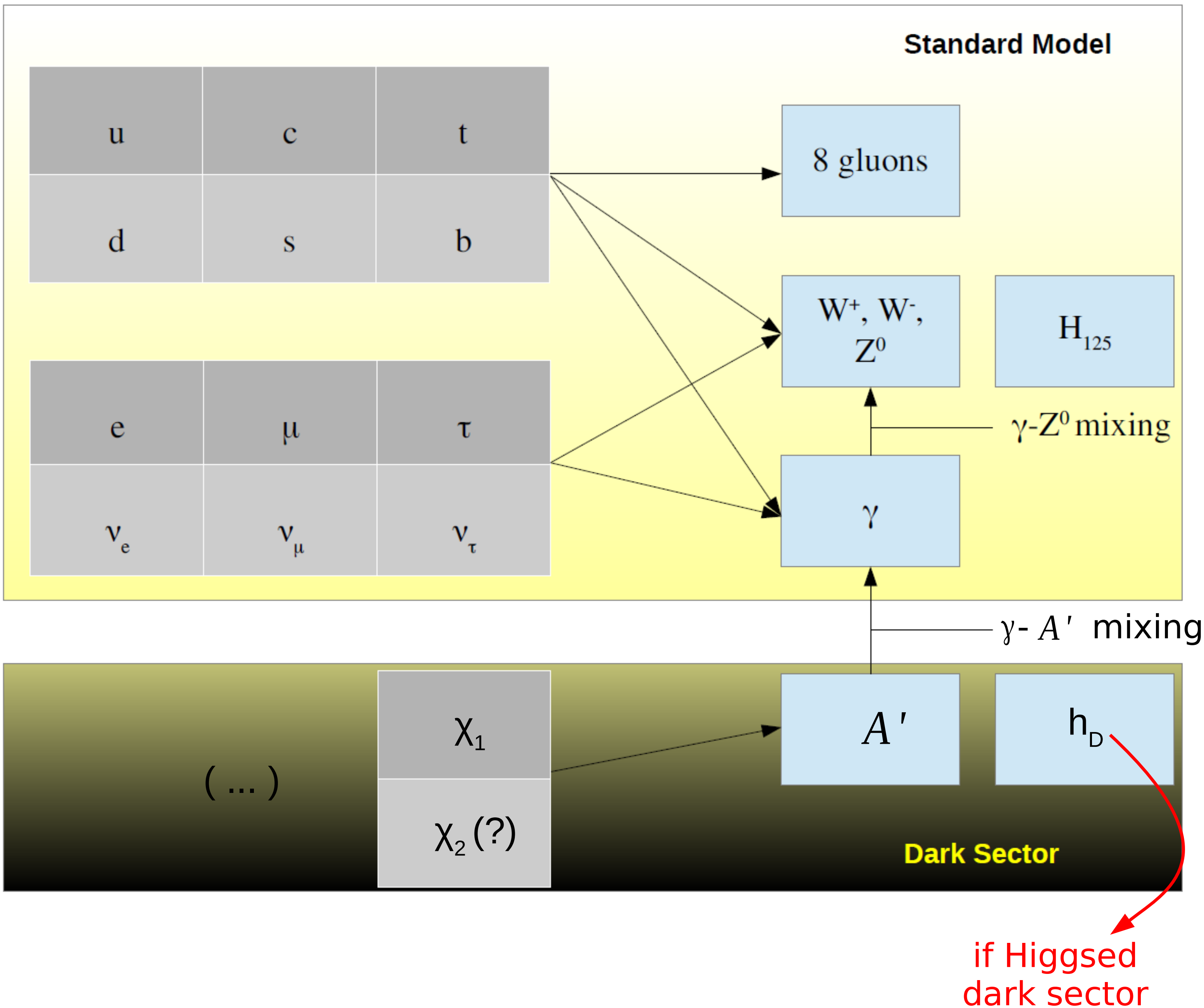
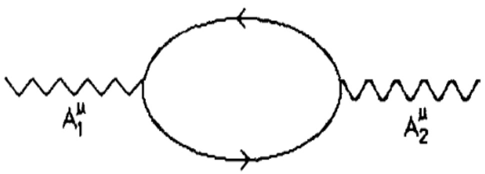


Dark sector searches @ BELLE and BELLE 2: Why?

A'= dark photon, H_D= dark Higgs boson, χ= dark matter

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' .



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

Kinetic mixing strength

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

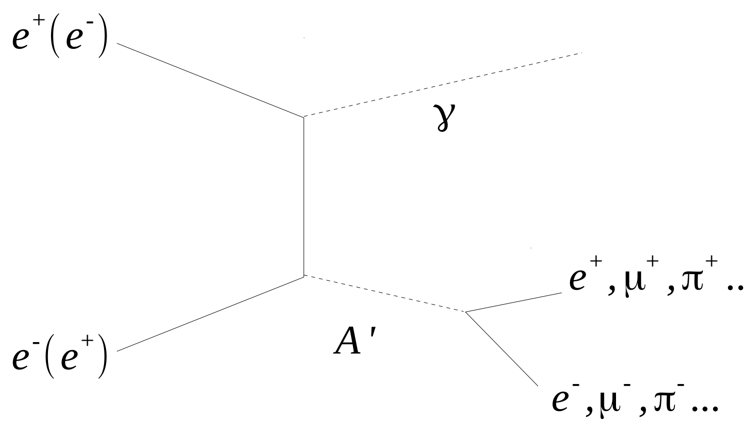
A massive force mediator of the extra U(1) symmetry requires the U(1) symmetry to be broken: extended Higgs sector

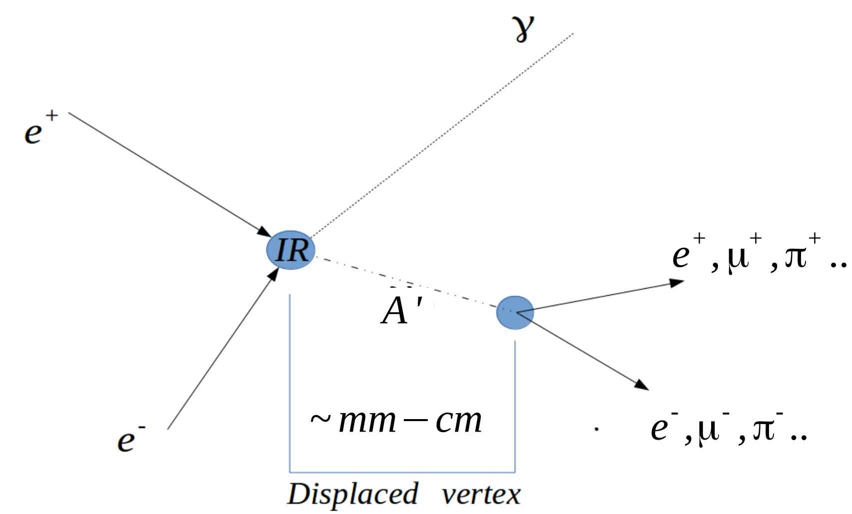
- M(A') ~ GeV scale → mixing with the photon, SM final states accessible
- M(A') ~ EW scale → mixing with Z^0, effects in rare decays (Υ, B, ..) through loops[1]
- M(A') ~ TeV scale → effects in rare decays (Υ, B, ..) through loops[1]
- $M(h_D)$~ GeV scale → dark higgs-strahlung, rare decays
- M(χ) ~ GeV scale: B→χχ,B→νχ; Υ(1S)→χχ;Υ(3S)→χχγ, A’ → χχ

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

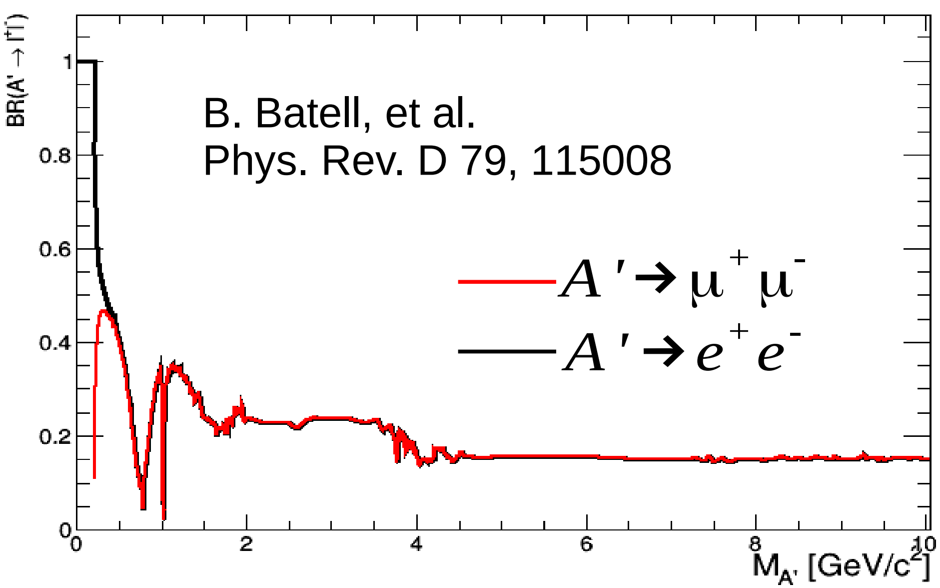
[1]Remember the lesson from the past, new particles are first seen indirectly or in loops: Z^0, charm, top

Dark Photon Search Strategy





A'= dark photon, L= long lived light gauge boson (model independent).
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, displaced vertex decay.



Dark Sector Searches: Constraining the Kinetic Mixing

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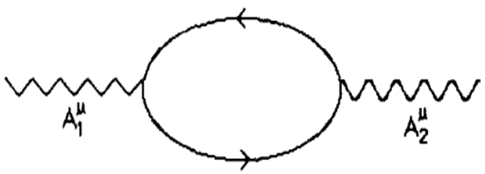

$$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$$

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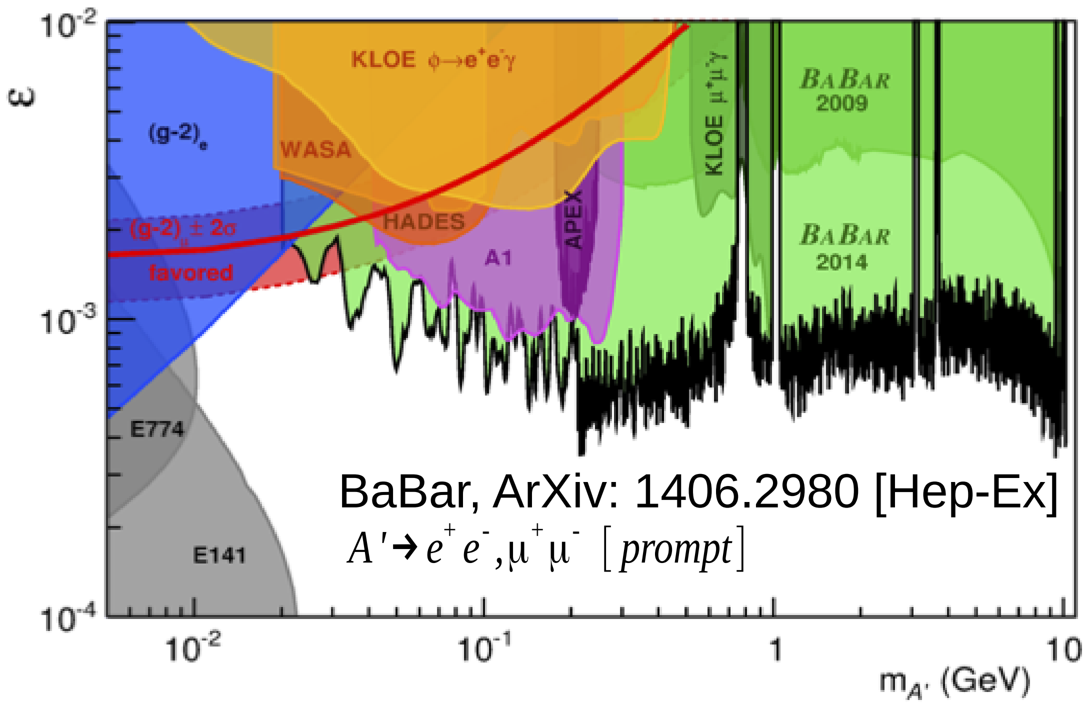
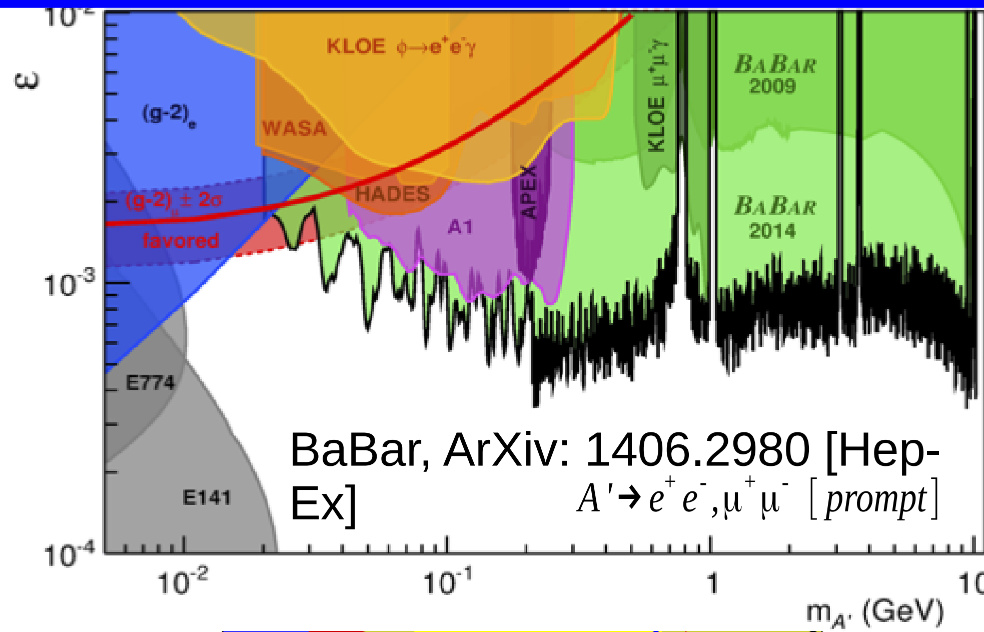
A massive force mediator of the extra U(1) symmetry requires the U(1) symmetry to be broken: extended Higgs sector



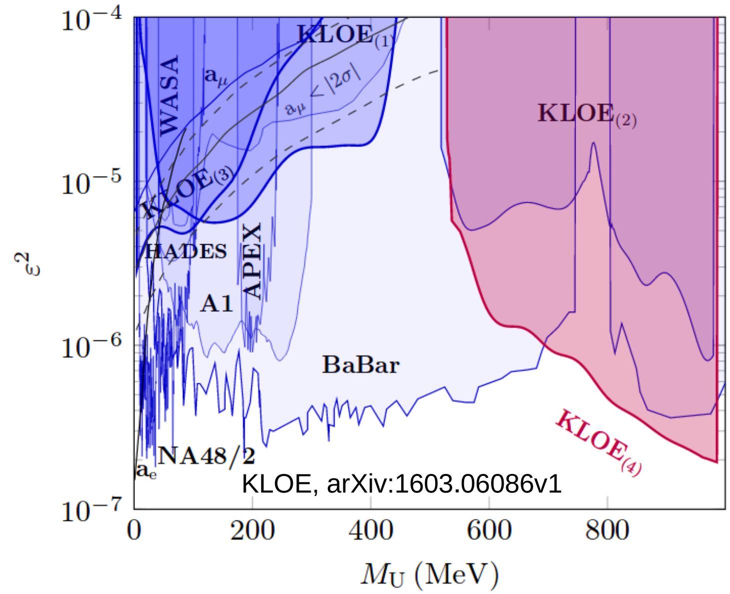
BaBar, ArXiv: 1406.2980 [Hep-Ex]

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

Dark Photon: Current UL to Kinetic Mixing

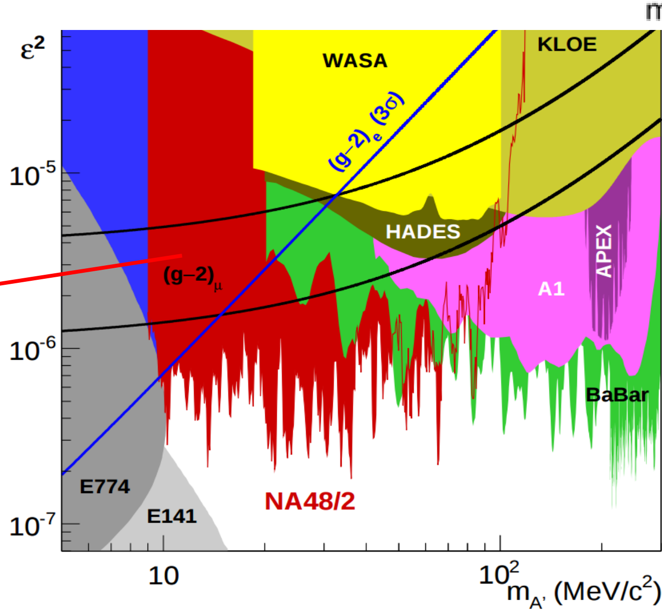


BaBar, ArXiv: 1406.2980 [Hep-Ex]



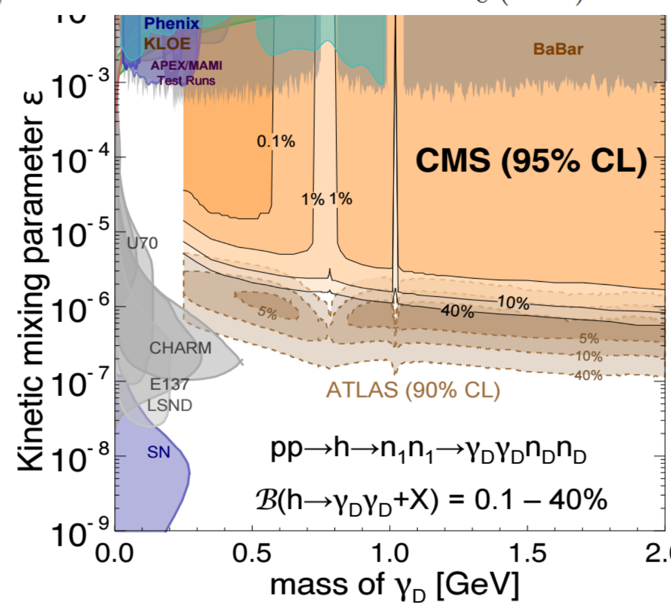
KLOE, arXiv:1603.06086v1

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



NA48 arXiv:1504.00607

π^0 decays



arXiv:1506.00424 [hep-ex]

Long lived, decays to leptons

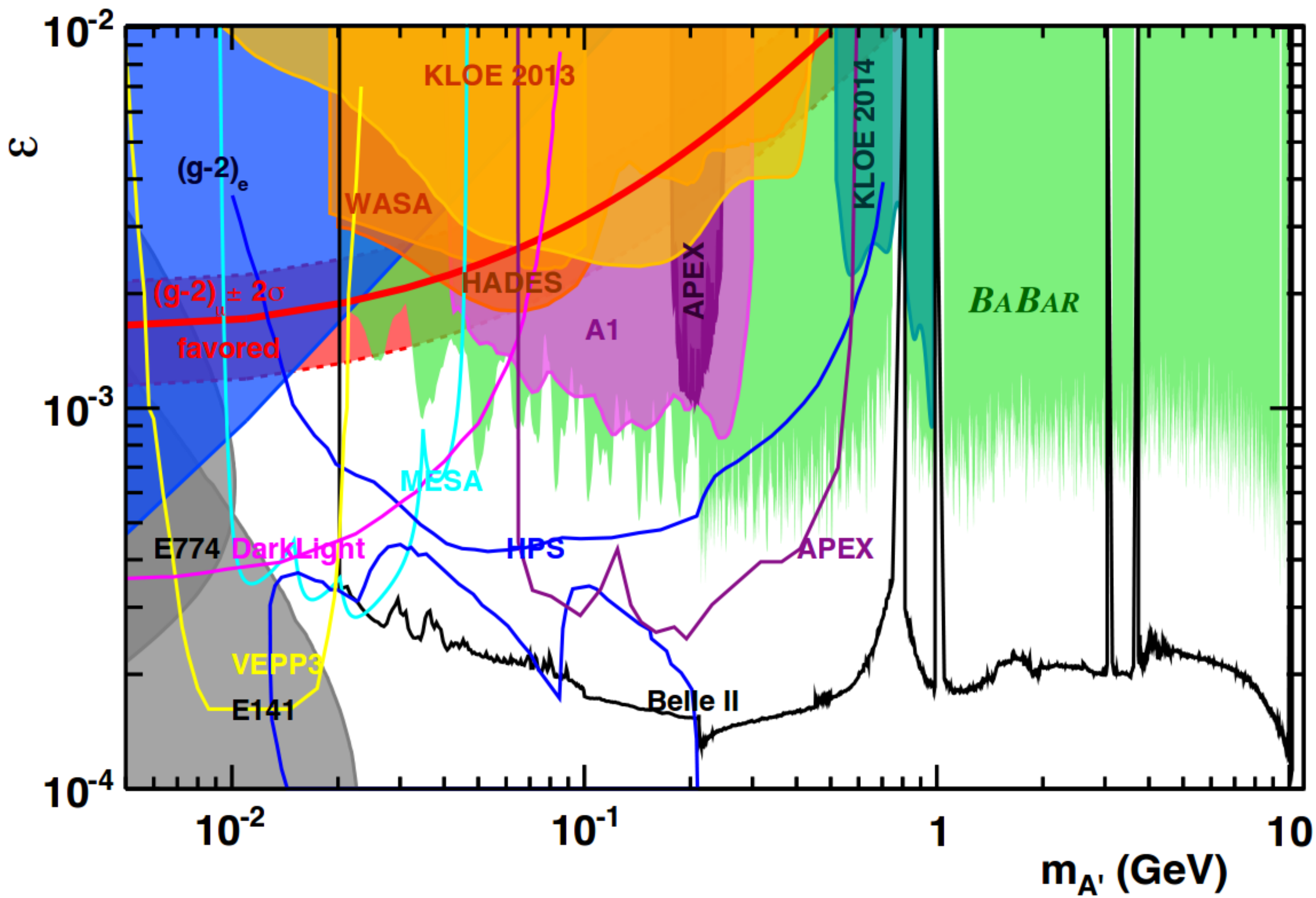
ATLAS + CMS:

highly model-dependent!

→ See M. Borsato’s talk for LHCb studies

Dark Photon: Expected Sensitivity @ Belle II

$$e^+e^- \rightarrow \gamma A' \rightarrow \gamma e^+e^-, \gamma \mu^+\mu^-, \quad prompt$$



Very conservative estimation of Belle II sensitivity to prompt decays of A' based on BABAR results projected to full Belle 2 luminosity

The L_μ-L_τ model in the context of dark sector searches: a dark Z'

Partial width results and BR derived from eqn. 2.12 of Essig et al. JHEP02(2015)157, arXiv:1412.0018 [hep-ph].

The model is a new gauge boson, Z', which couples to $L_\mu - L_\tau$. The interaction Lagrangian is

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

The equations for the partial widths are,

$$\Gamma(Z' \to \ell^+\ell^-) = \frac{(g')^2 M_{Z'}}{12\pi}\left(1 + \frac{2M_\ell^2}{M_{Z'}^2}\right)\sqrt{1 - \frac{4M_\ell^2}{M_{Z'}^2}}\,\theta(M_{Z'} - 2M_\ell),$$

$$\Gamma(Z' \to \nu_\ell\bar{\nu}_\ell) = \frac{(g')^2 M_{Z'}}{24\pi}.$$

$$BR(Z' \to invisible) = \frac{2\Gamma(Z' \to \nu_l \bar{\nu}_l)}{2\Gamma(Z' \to \nu_l \bar{\nu}_l) + \Gamma(Z' \to \mu\bar{\mu}) + \Gamma(Z' \to \tau\bar{\tau})}$$

- The branching fraction to one neutrino species is half of the branching fraction to one charged lepton flavour. The reason is, of course, that the Z' only couples to left-handed neutrino chiralities whereas it couples to both left- and right-handed charged leptons.
  - **For $M_{Z'} < 2M_\mu$ Br(Z'→invisible) =1.**
  - **For $2M_\mu < M_{Z'} < 2M_\tau$ Br(Z'→invisible)~1/2**
  - **For $M_{Z'} > 2M_\tau$ Br(Z'→ invisible)~1/3**

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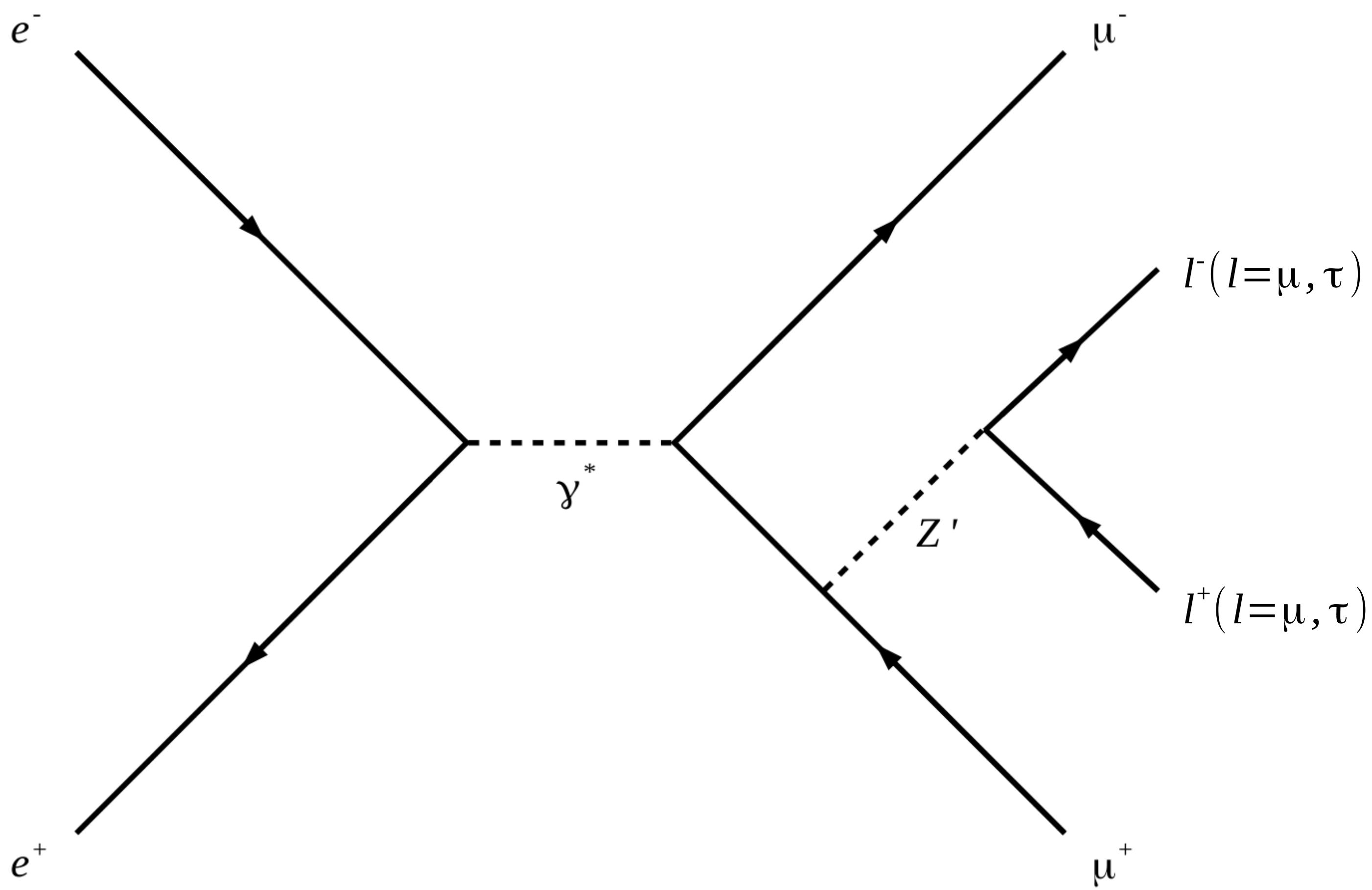

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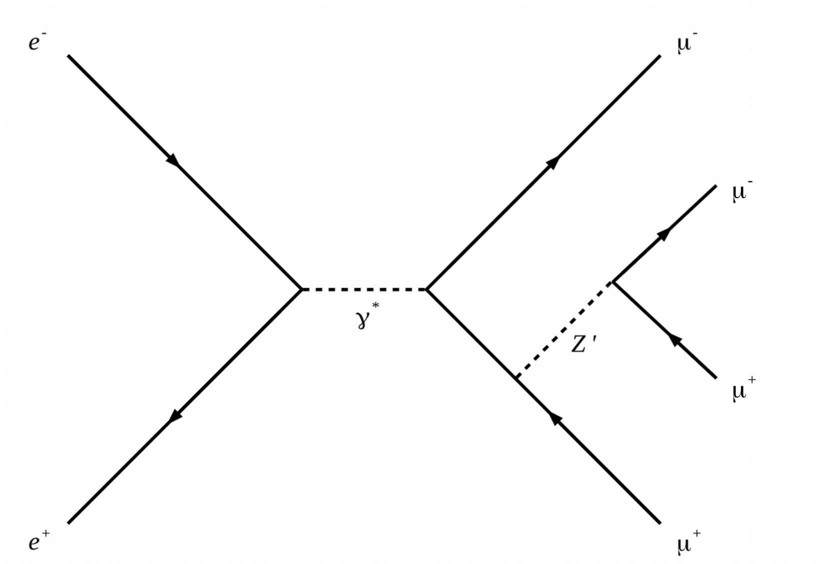
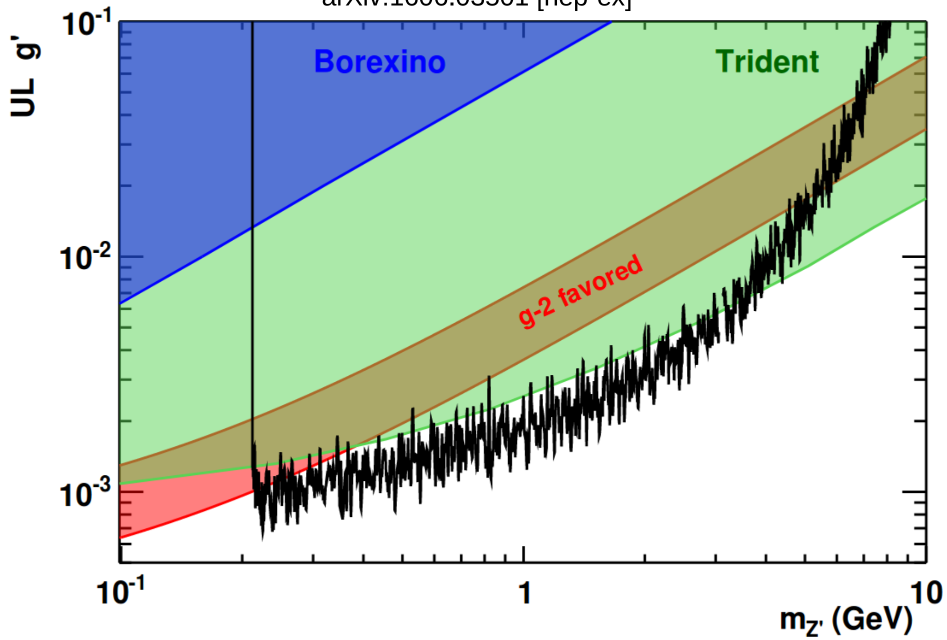


BABAR Coll.
Phys. Rev. D 94, 011102 (2016),
arXiv:1606.03501 [hep-ex]



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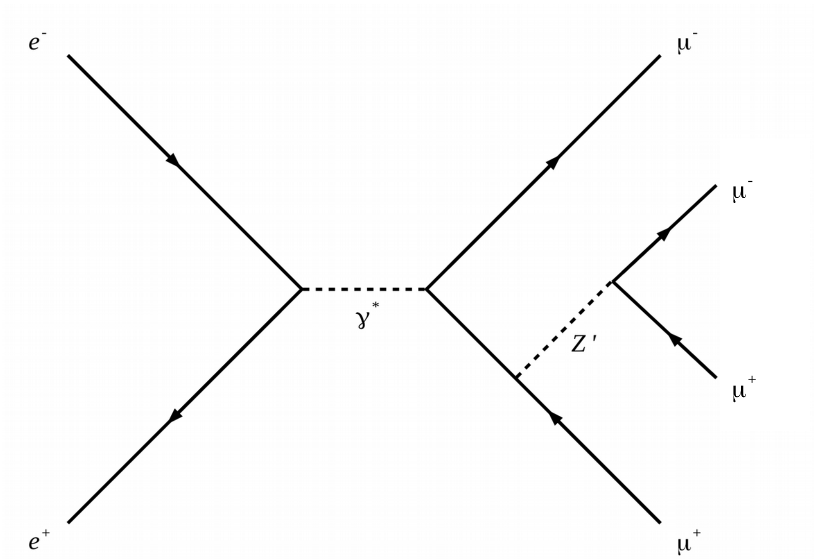

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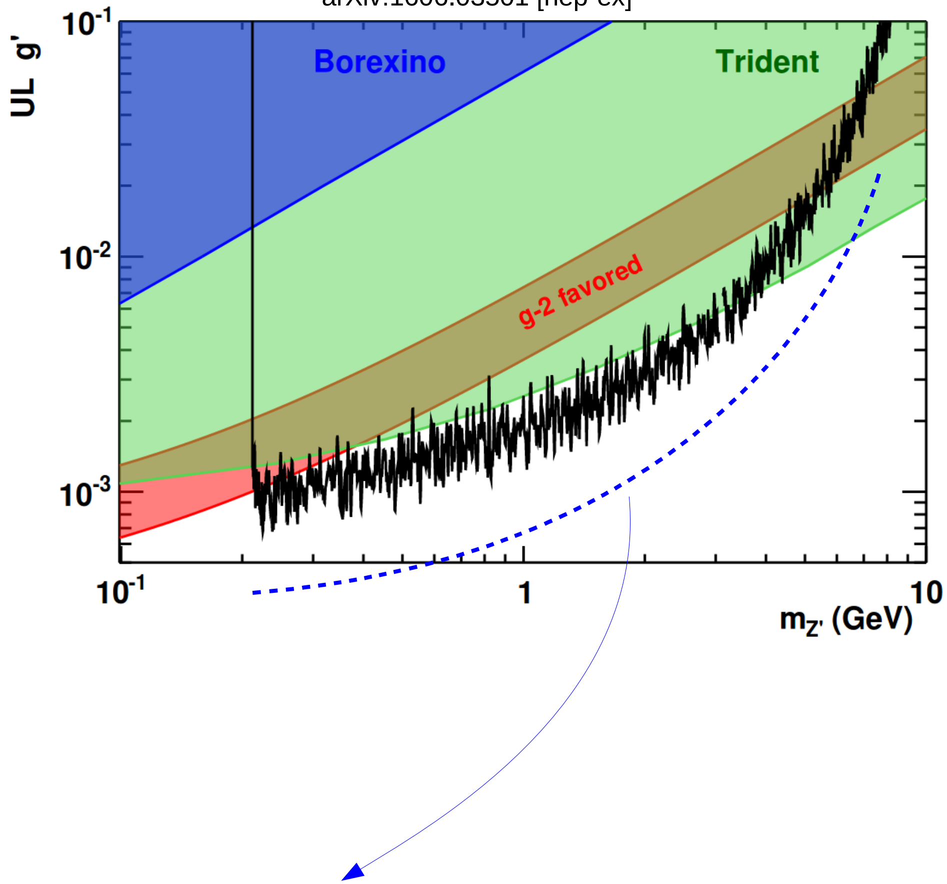
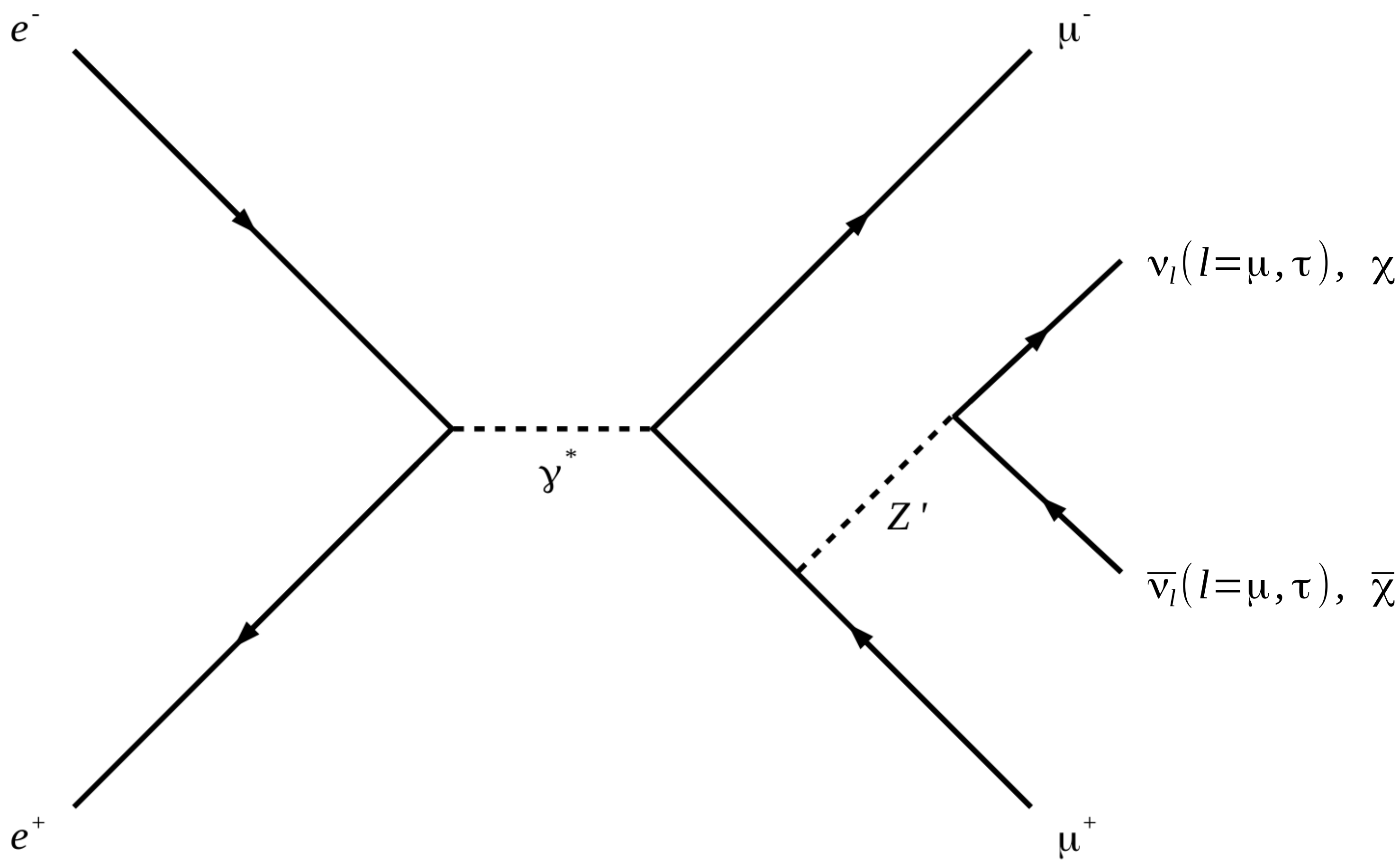
Phys. Rev. D 94, 011102 (2016),
arXiv:1606.03501 [hep-ex]



Rough projection to Belle II luminosity preliminary studies are ongoing

- The branching fraction to one neutrino species is half of the branching fraction to one charged lepton flavour. The reason is, of course, that the Z' only couples to left-handed neutrino chiralities whereas it couples to both left- and right-handed charged leptons.
  - **For $M_{Z'} < 2M_\mu$ Br(Z'→invisible) =1.**
  - **For $2M_\mu < M_{Z'} < 2M_\tau$ Br(Z'→invisible)~1/2**
  - **For $M_{Z'} > 2M_\tau$ Br(Z'→ invisible)~1/3**

The L_μ-L_τ model in the context of dark sector searches: a dark Z'



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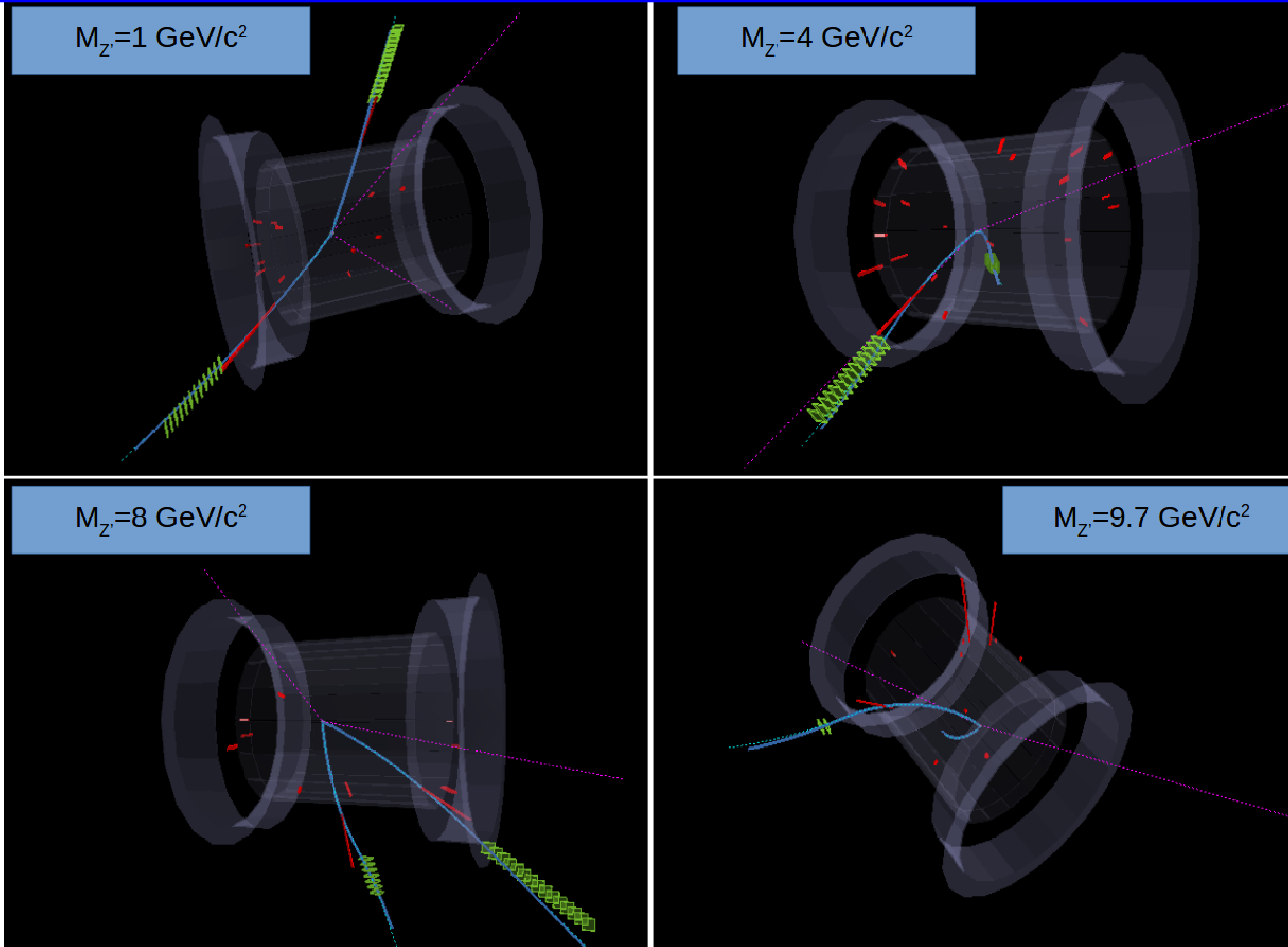
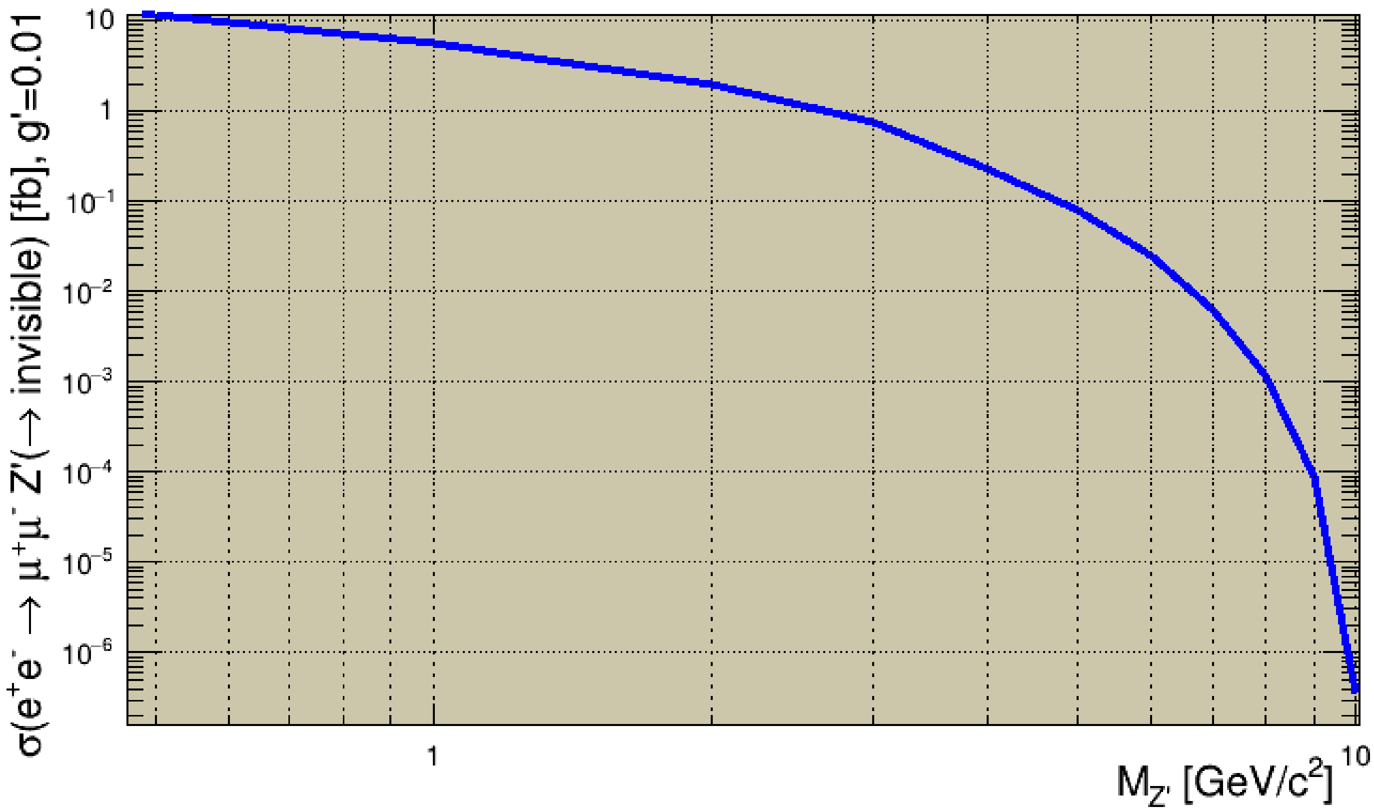
Z’ → invisible, Belle II Event Display



Cross section for Z’→ invisible (i)

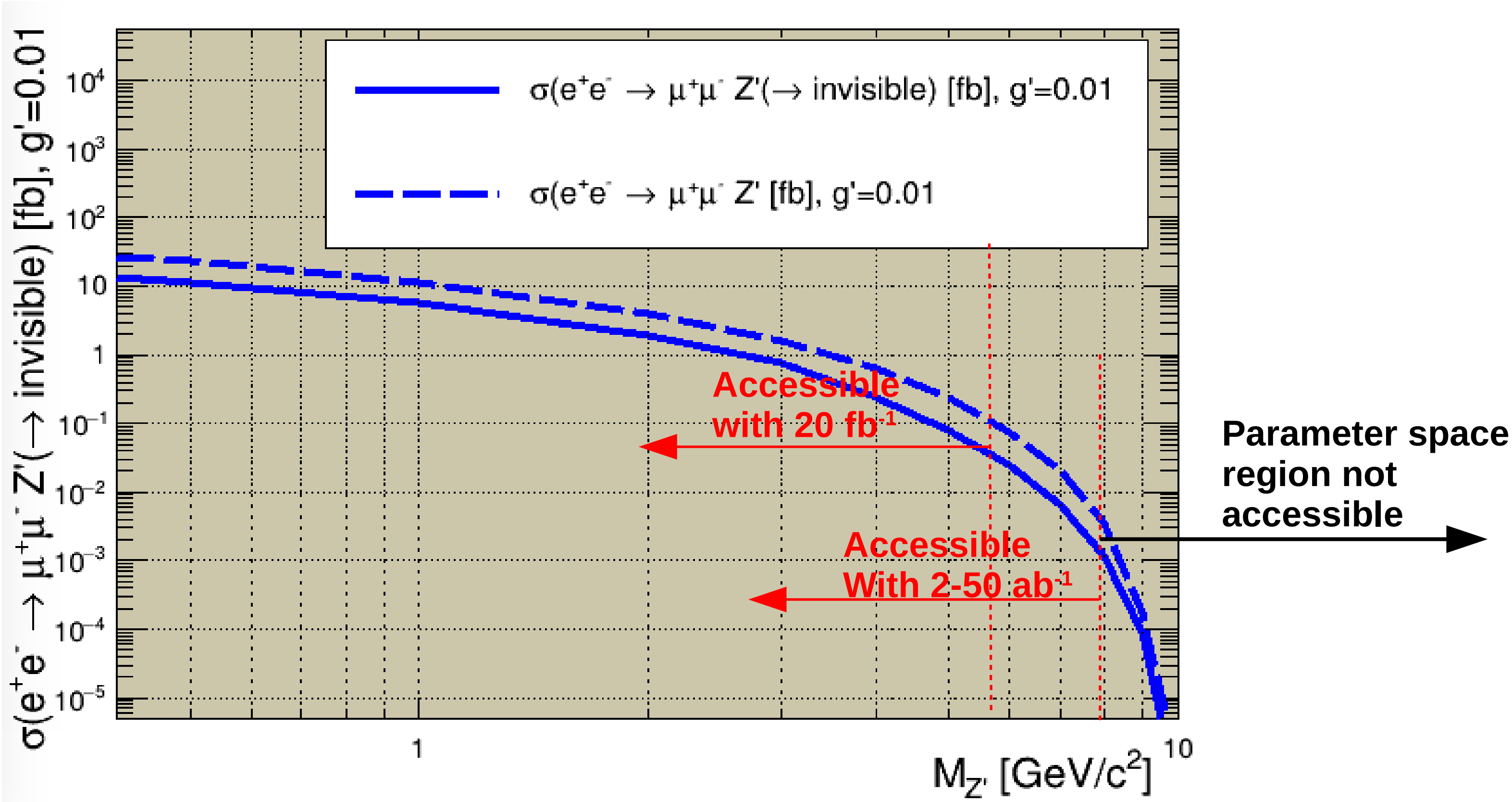


- Cross section provided by MadGraph for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \nu_\mu \bar{\nu}_\mu$ and multiplied by a factor 2 to account for $Z' \to \nu_\tau \bar{\nu}_\tau$ as this is the other channel that contribute to the invisible decays of Z’.
- It is assumed g’ = 0.01, cross section for different values of g’ can be obtained by considering that:

  ...the production process involves exactly one insertion of the g’ coupling in the matrix element, then we know that the cross section is proportional to g’^{2}. Let’s say you use g’ = 10^{-3} to generate events in MadGraph. Then, if I want the cross section for g’ = 10^{-4}, I simply take the cross section output by MG and multiply by $(10^{-1})^2$…

  ...private conversation with B. Shuve.

Cross section for Z'→ invisible (ii)



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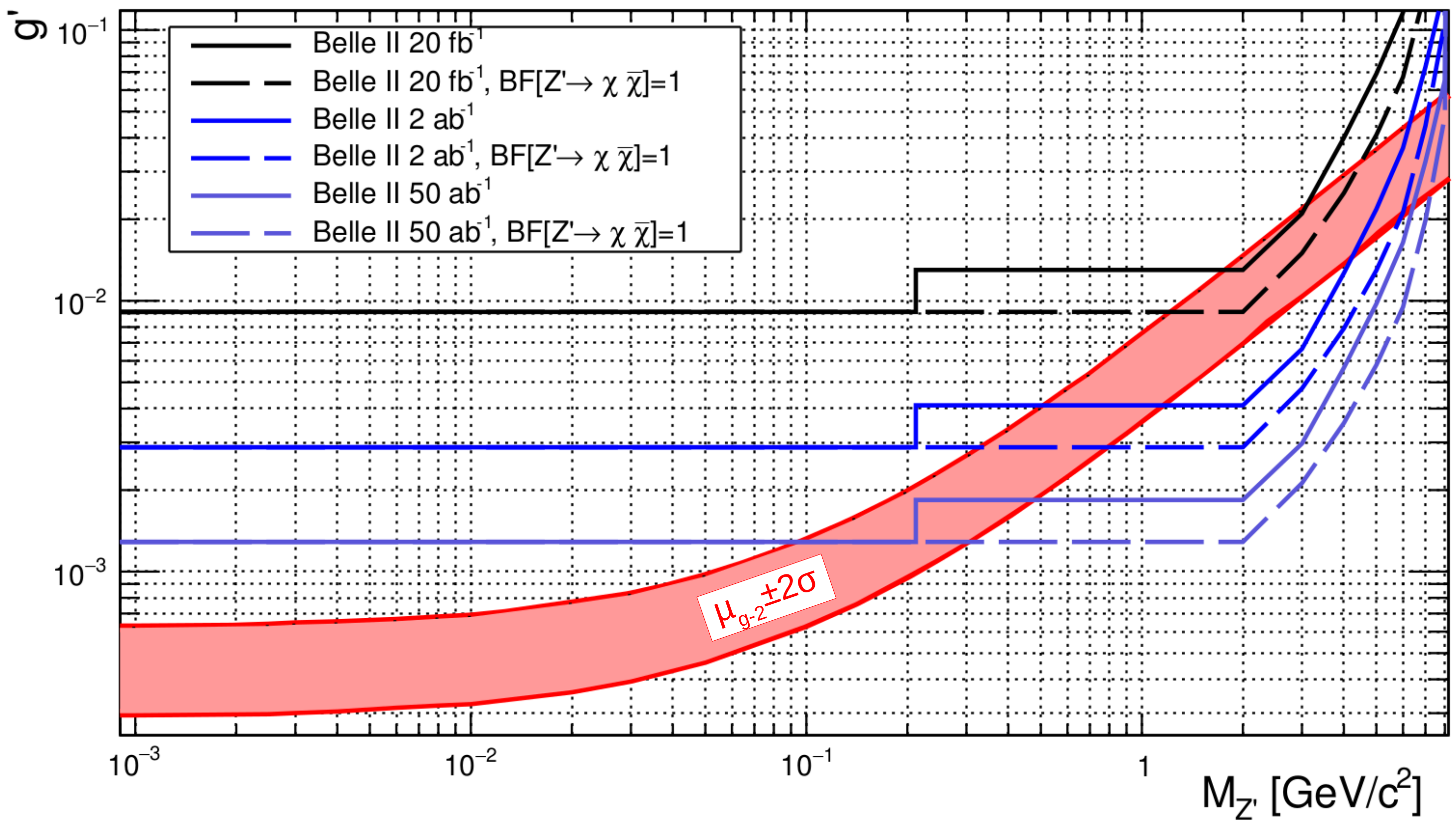
Belle II Expected Sensitivity

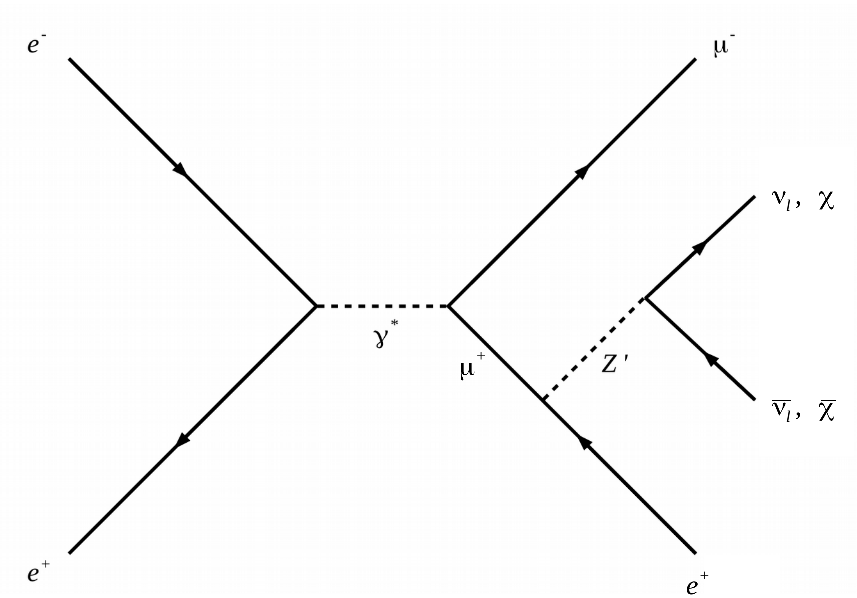
- Based only on expected background and luminosity
- Expected upper limits to g' value at 90% C.L.
- Bad mass resolution on the signal at low masses affects final sensitivity



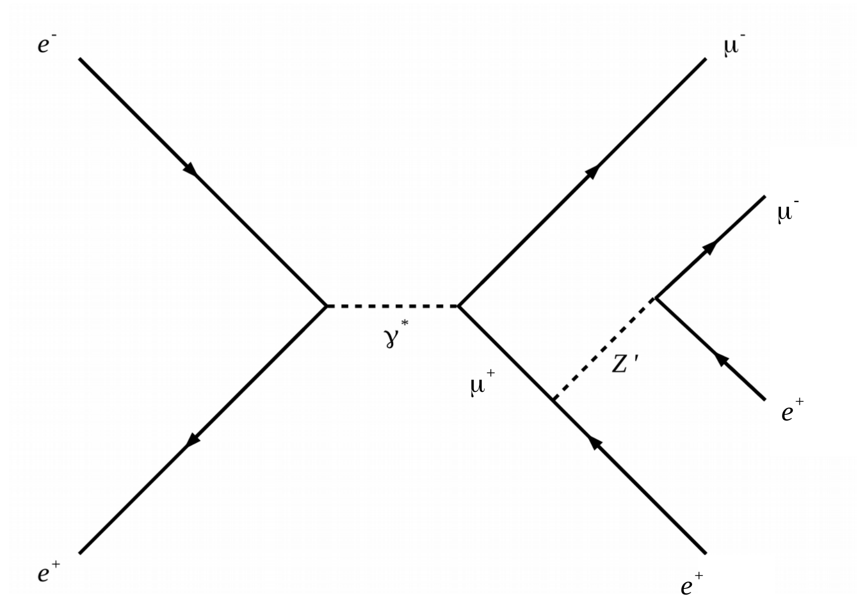
- Does not account for all the efficiencies (but sensitivity scale as $L^{1/4}$…)

What about a LFV Z'?

What about a LFV Z'?



$$final\ state: e^+\mu^- + invisible\,(+c.c.)$$



$$final\ state: 2e^+2\mu^-\,(+c.c.)$$

See for example arXiv:1610.08060 or ArXiv:1701.08767

- Complement the search for low mass Z' and low mass dark sector
- Alternative way to look into cLFV, complementing ongoing searches
- (Almost) background free
- Get a search for doubly charged bosons for free

- Work in progress at Belle II

Invisible Υ(1S) Decays @ Belle II

Υ(nS): bound state of a b quark and a b antiquark

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

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

$$e^+e^-\rightarrow\Upsilon(3S)$$
↓(4.4%)
$$\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$$
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$$e^+e^-\rightarrow\Upsilon(2S)$$
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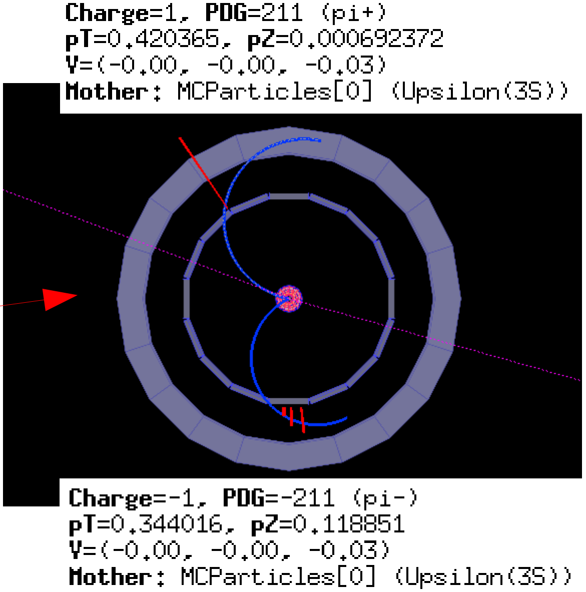
- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80**, 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Υ(1S)→νν

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



$\sim 900\ MeV\ available\ for\ P_{\pi\pi}$

$$M_{\Upsilon(3S)}=10.355\,GeV/c^2,\quad M_{\Upsilon(2S)}=10.023\,GeV/c^2,\quad M_{\Upsilon(1S)}=9.460\,GeV/c^2$$

$\sim 540\ MeV\ available\ for\ P_{\pi\pi}$

Invisible Y(1S) Decays @ Belle II

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

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

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

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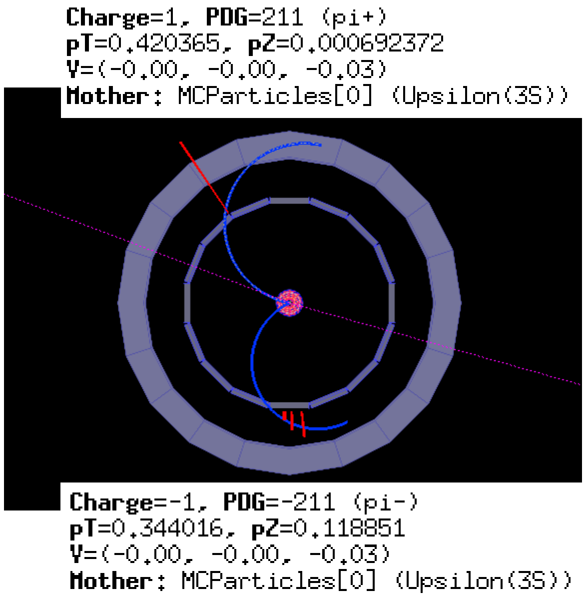
Belle2 Simulation
Y(3S)→$\pi^+\pi^-$Y(1S),
Y(1S)→ νν



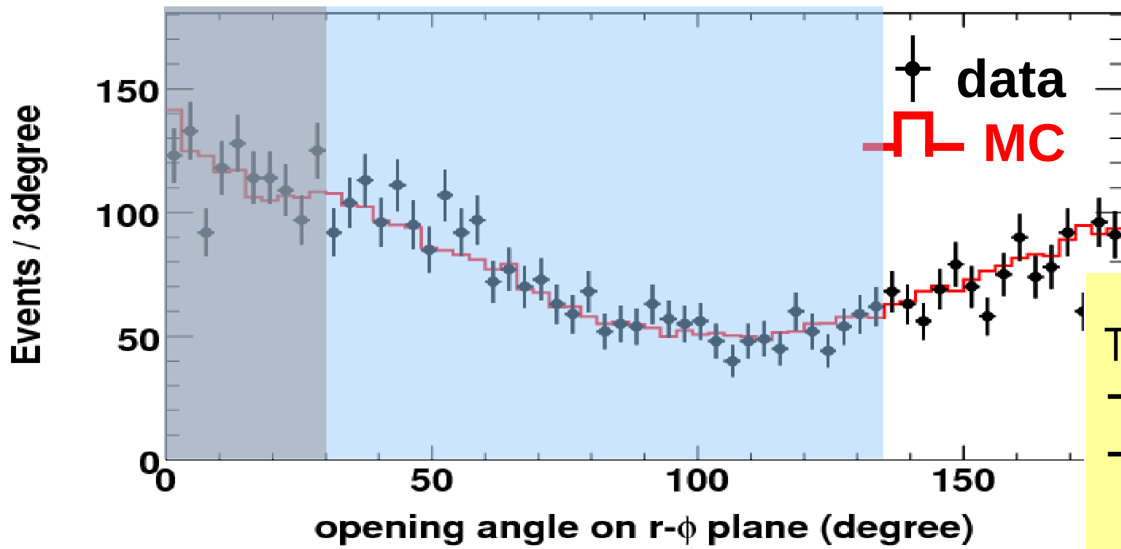
A signal of Y(1S)→*invisible* is an excess of events over the background in the M_r distribution at a mass equivalent to that of the Y(1S) (9.460 GeV/c²)

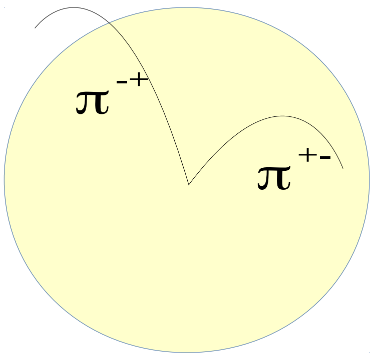
$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

Trigger Considerations

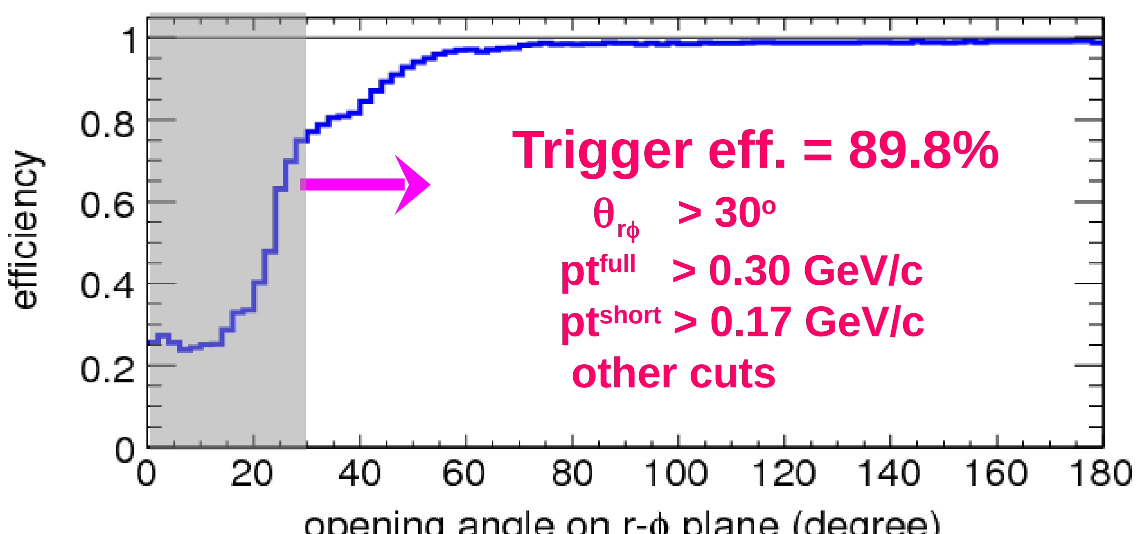
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

$\Upsilon(1S) \rightarrow \mu^+\mu^-$





Too low efficiency with usual condition (>135°)
→ Higher efficiency with looser condition
→ Special trigger condition was implemented
(~850 Hz, twice as usual condition)



Single track trigger was implemented, too with 1/500 pre-scale rate (pt>250 MeV/c)

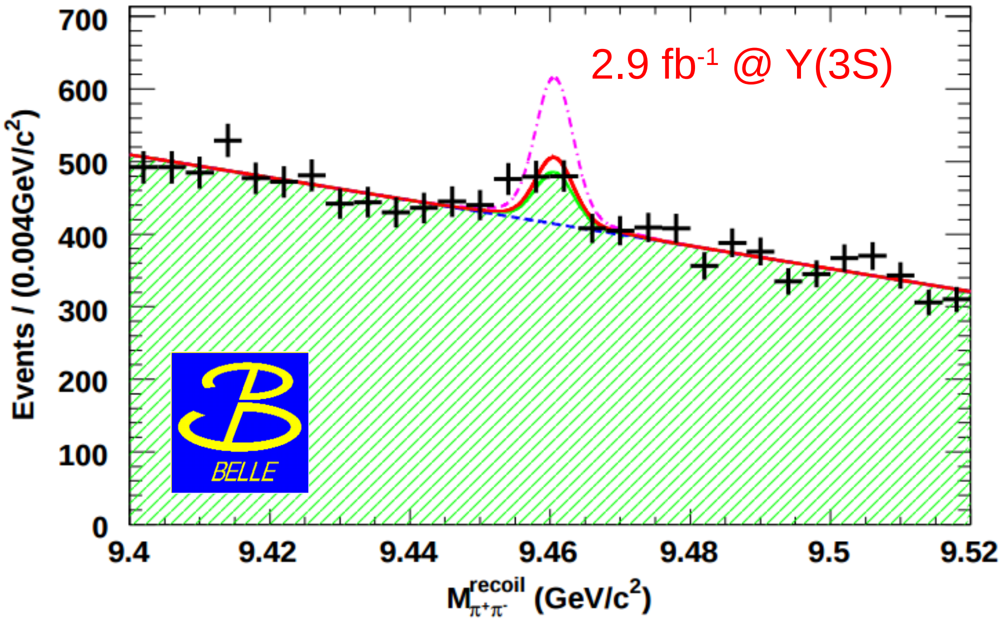
$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

for efficiency monitoring

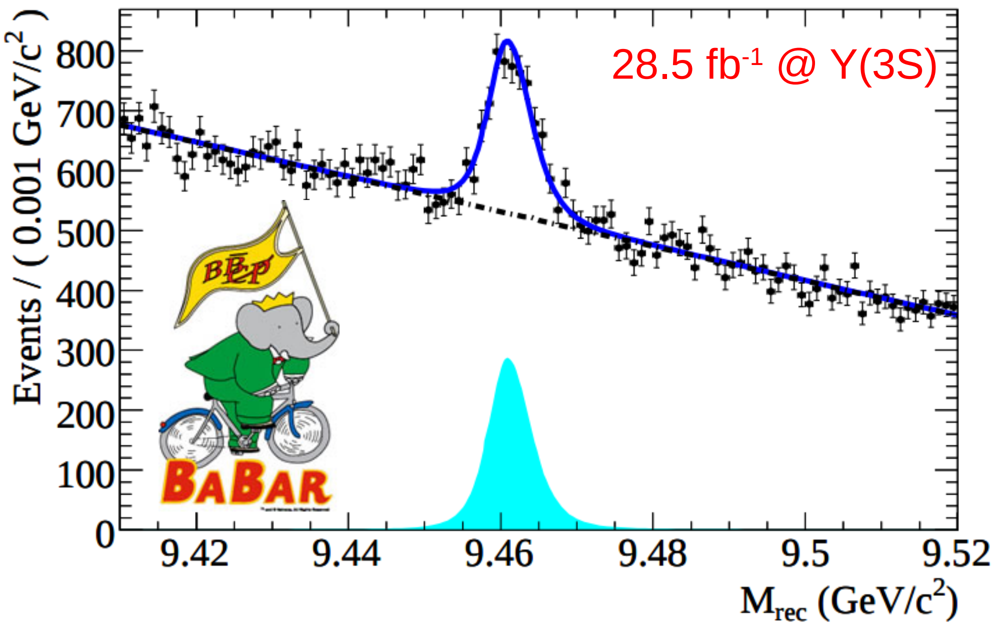
Invisible Y(1S) Decays: Signal or Background?

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

[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))



Invisible Y(1S) Decays: Belle II Discovery Potential

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

[belle]: http://arxiv.org/abs/hep-ex/0611041
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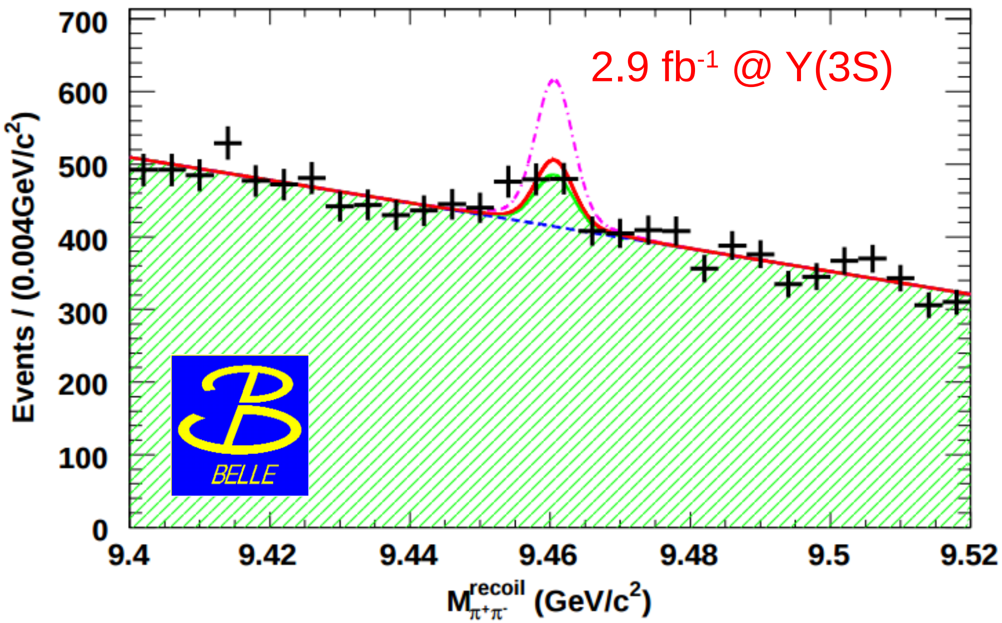

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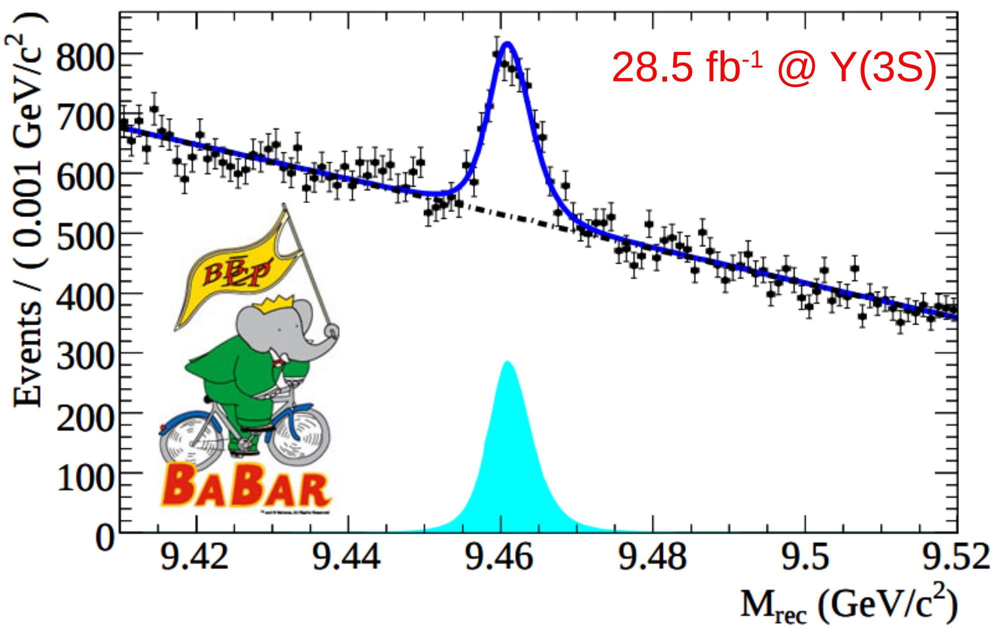

No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < 3x10^{-4} (BaBar) and BR(Y→νν) < 3.0x10^{-3}(Belle).

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→invisible)< 10^{-4} (NP) and Belle efficiencies.

Invisible Υ(1S) Decays: Signal or Background?

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

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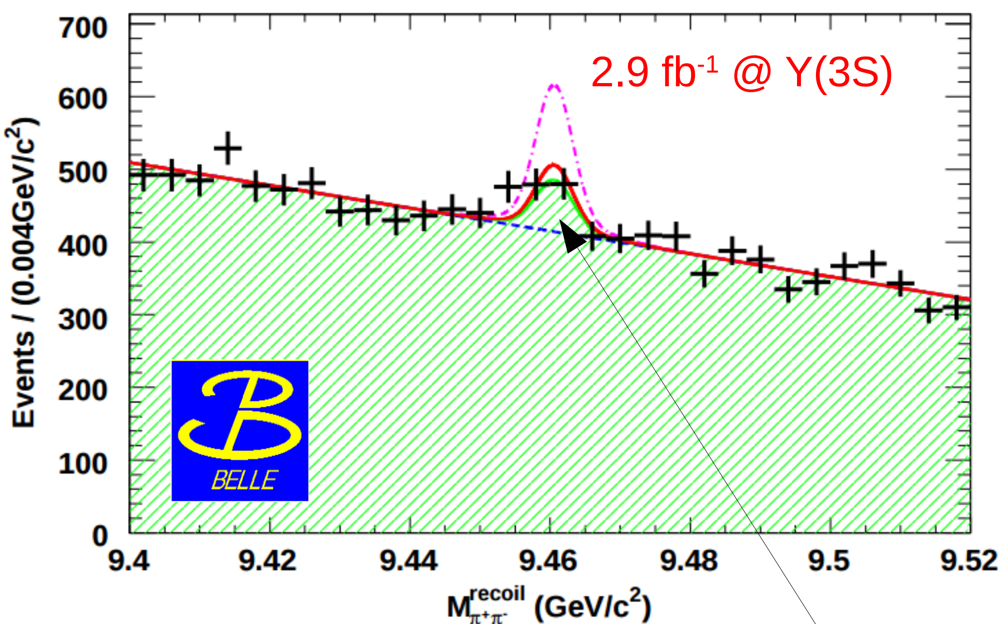

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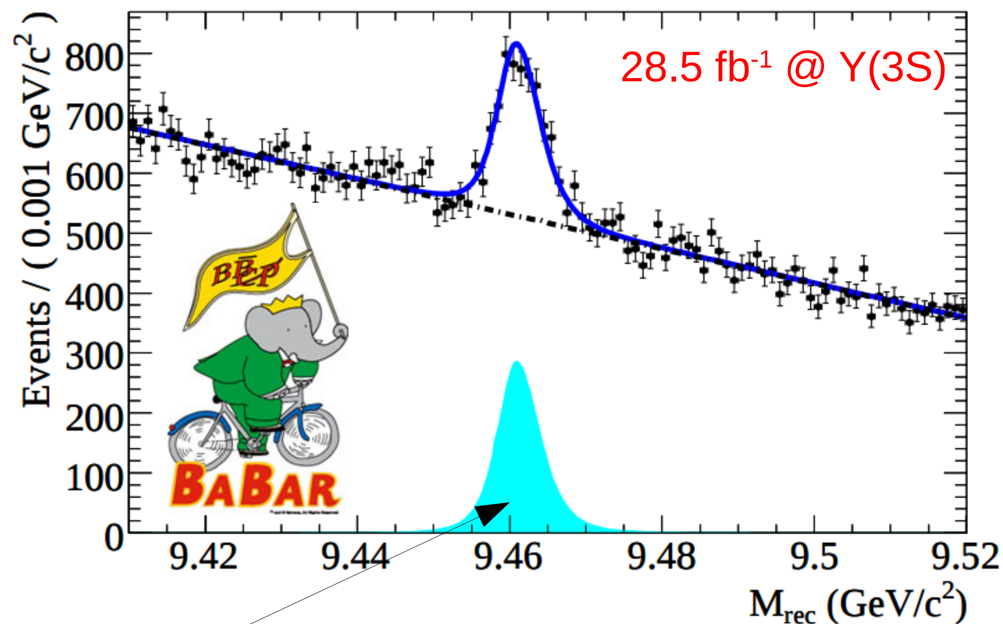
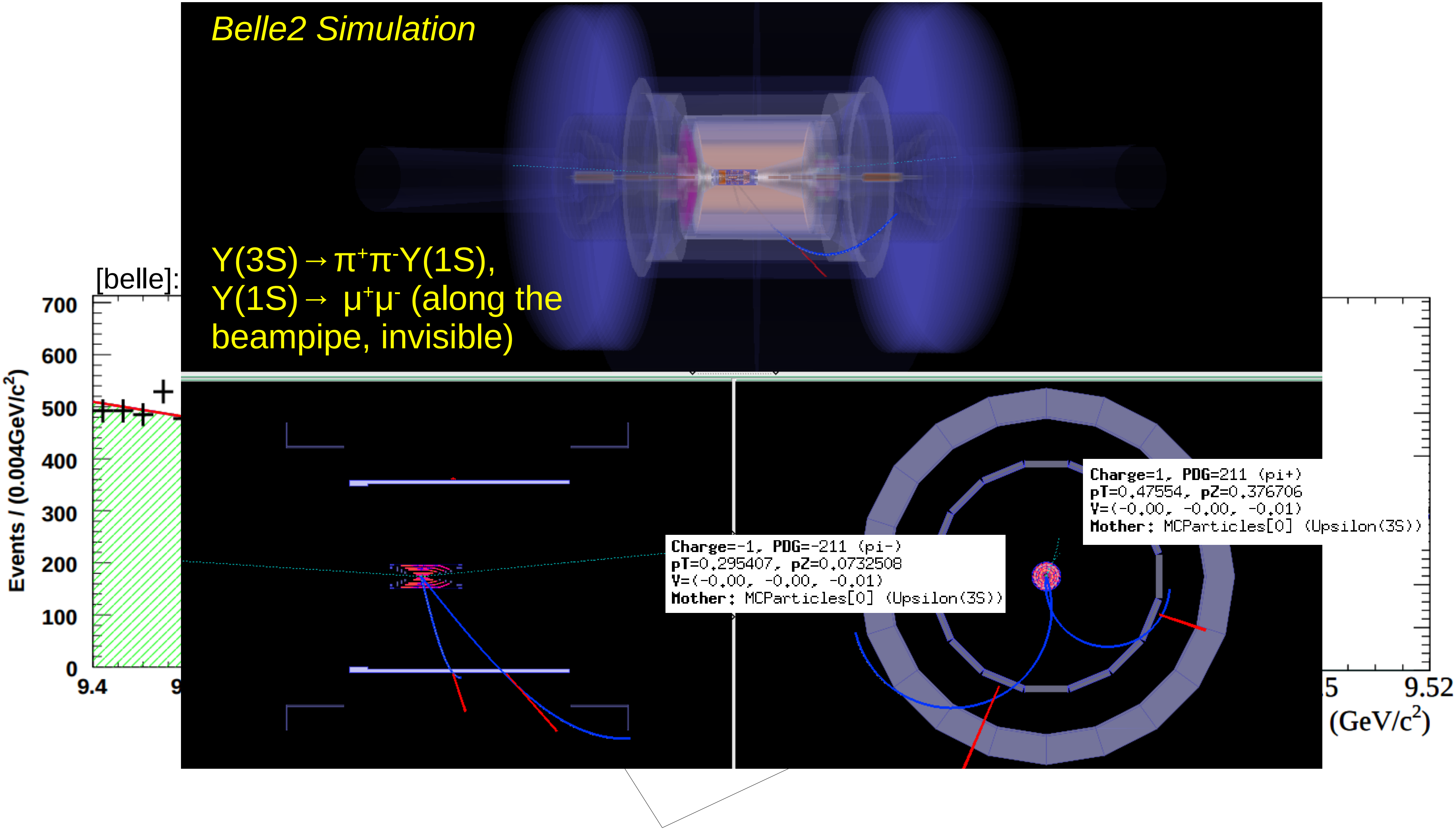


Irreducible peaking background when final states go undetected (i.e. detector supports, beampipe etc.) in the process $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S), \Upsilon(1S)\rightarrow undetected\ f.s.$

Invisible Y(1S) Decays: irreducible background



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Invisible Υ(1S) Decays @ Belle II: Expected Yields

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

$$BR(\Upsilon(1S)\rightarrow\nu\bar{\nu}) \sim 9.9\times10^{-6}$$

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Belle2 Simulation
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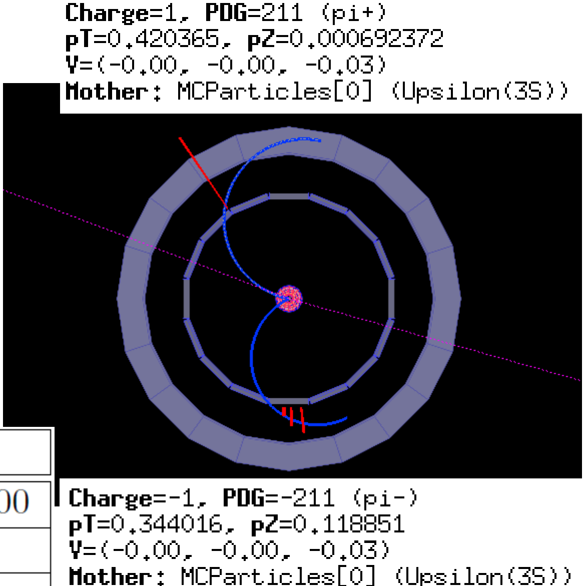
Υ(1S)→ νν



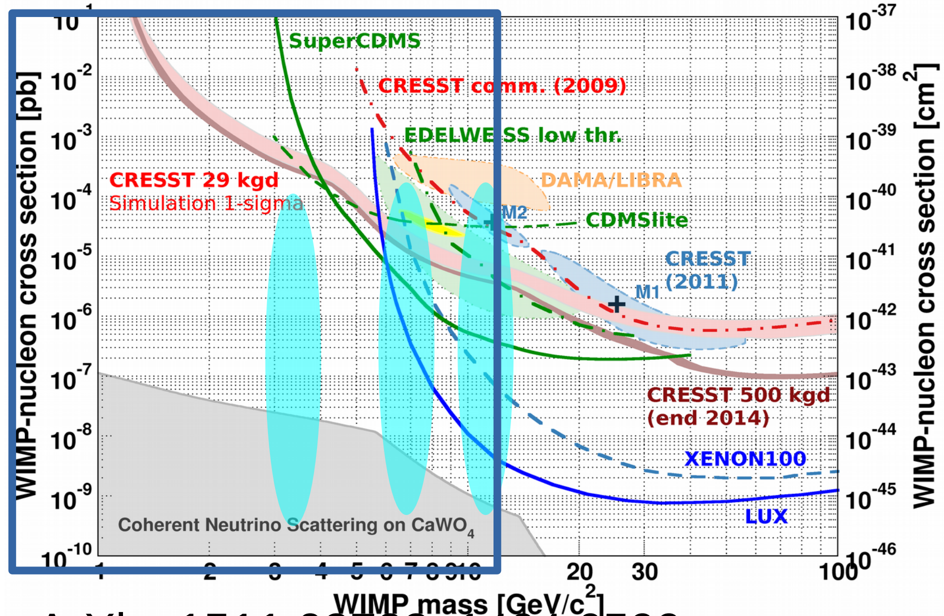
No signal was observed over the expected background and upper limits have been obtained: BR(Υ→νν) < $3\text{x}10^{-4}$ (BaBar) and BR(Υ→νν) < $3.0\text{x}10^{-3}$(Belle).

Process	$L_{int}(ab^{-1})$	ϵ	$N(\Upsilon(1S))$	$N_{\Upsilon(1S)\rightarrow\nu\bar{\nu}}$	N_{NP}
$\Upsilon(2S)\rightarrow\pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(2S)$	0.1-0.2	2.3×10^8	230-460	6900-13800
$\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$	0.2, $\Upsilon(3S)$	0.1-0.2	3.2×10^7	32-64	945-1890
$\Upsilon(4S)\rightarrow\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	5.5×10^6	5.5-11	165-310
$\Upsilon(5S)\rightarrow\pi^+\pi^-\Upsilon(1S)$	5.0, $\Upsilon(5S)$	0.1-0.2	7.6×10^6	7.6-15.2	228-456
$\gamma_{ISR}\Upsilon(2S)\rightarrow(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	1.5×10^8	150-300	4500-9000
$\gamma_{ISR}\Upsilon(3S)\rightarrow(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$	50.0, $\Upsilon(4S)$	0.1-0.2	3.5×10^7	35-70	1050-2100

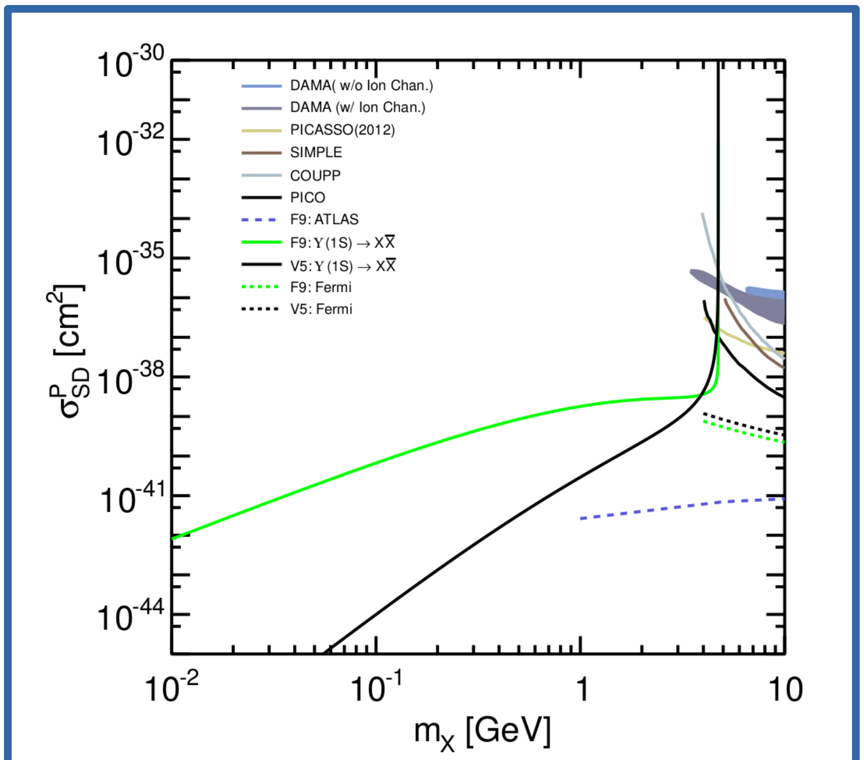
DM: The Synergy Between Theory, Direct and Collider Searches

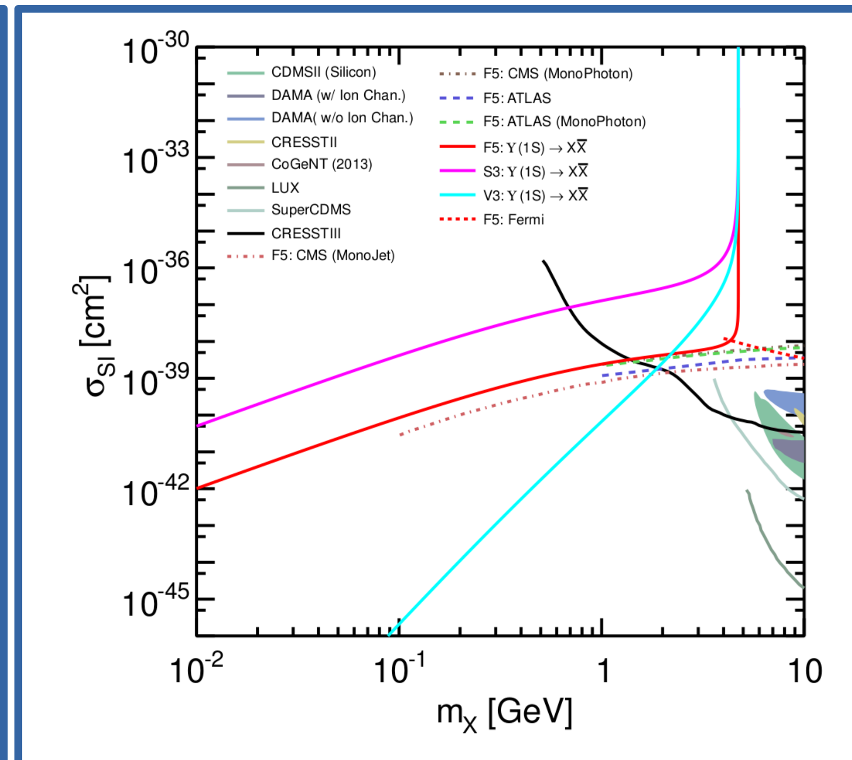
Theory work is needed in order to connect direct and indirect searches of dark matter.

- Shown here Υ(1S) → χχ vs. direct searches.
- Similar studies have performed also for dark photon dark matter (see for example J. Pradler et al. arXiv:1412.8378)



Extrapolation based on ArXiv: 1511.03728, 1404.6599





Eff. contact operators in for dark matter in Υ(1S) → invisible

ArXiv: 1404.6599

Name	Interaction Structure	Annihilation	Scattering
F5	$(1/\Lambda^2)\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$	Yes	SI
F6	$(1/\Lambda^2)\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q$	No	No
F9	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q$	Yes	SD
F10	$(1/\Lambda^2)\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q$	Yes	No
S3	$(1/\Lambda^2)\imath Im(\phi^\dagger\partial_\mu\phi)\bar{q}\gamma^\mu q$	No	SI
V3	$(1/\Lambda^2)\imath Im(B_\nu^\dagger\partial_\mu B^\nu)\bar{q}\gamma^\mu q$	No	SI
V5	$(1/\Lambda)(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu}q$	Yes	SD
V6	$(1/\Lambda)(B_\mu^\dagger B_\nu - B_\nu^\dagger B_\mu)\bar{q}\sigma^{\mu\nu}\gamma^5 q$	Yes	No
V7	$(1/\Lambda^2)B_\nu^{(\dagger)}\partial^\nu B_\mu\bar{q}\gamma^\mu q$	No	No
V9	$(1/\Lambda^2)\epsilon^{\mu\nu\rho\sigma}B_\nu^{(\dagger)}\partial_\rho B_\sigma\bar{q}\gamma_\mu q$	No	No

TABLE I. Effective contact operators which can mediate the decay of a $J^{PC} = 1^{--}$ quarkonium bound state. We also indicate if the operator can permit an s-wave dark matter initial state to annihilate to a quark/anti-quark pair; if so, then a bound can also be set by indirect observations of photons originating from dwarf spheroidal galaxies. Lastly, we indicate if the effective operator can mediate velocity-independent nucleon scattering which is either spin-independent (SI) or spin-dependent (SD).

Outlook

- Although the Belle II experiment is designed mainly for B-physics, the detector capabilities offer many possibilities to explore dark sector models,
  - in this talk we considered various example final states including charged particles in the final state and charged particles plus missing energy.

- 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 II experiment are ongoing and higher precision will be reached thanks to the great luminosity of Belle II at Super-KEK and thanks to improved hardware/software.

- We look forward to a bright future for dark sector physics.

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Thank you for your attention!