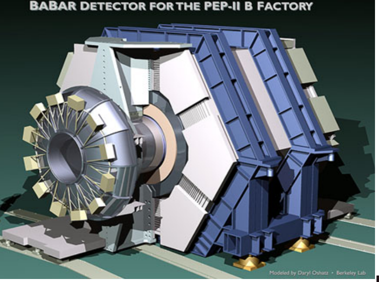
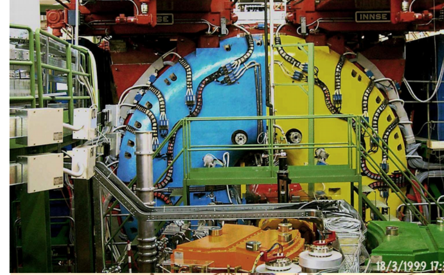
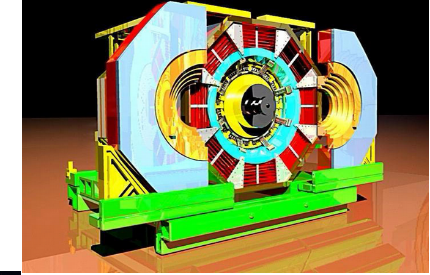
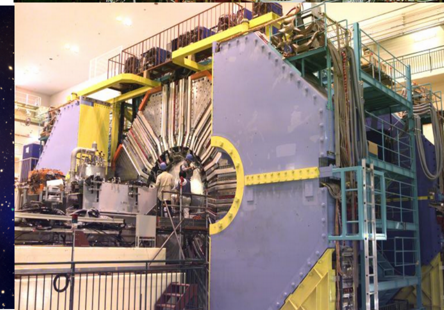
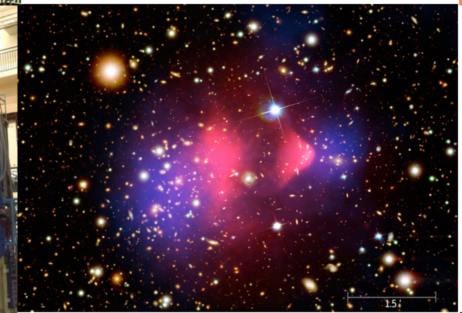
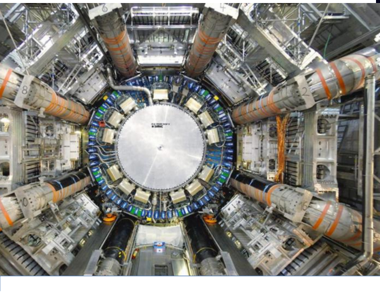
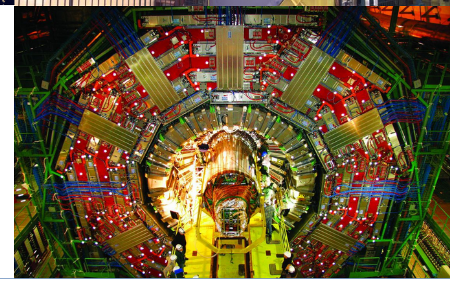
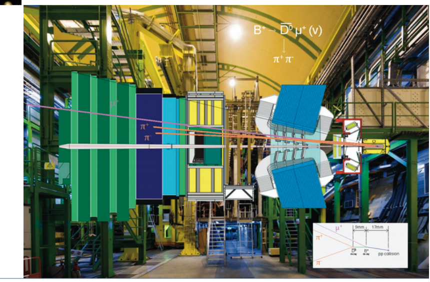


Light dark matter at colliders

Gianluca Inguglia, HEPHY (Vienna)

Roma, *03/12/2018*

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

Belle II

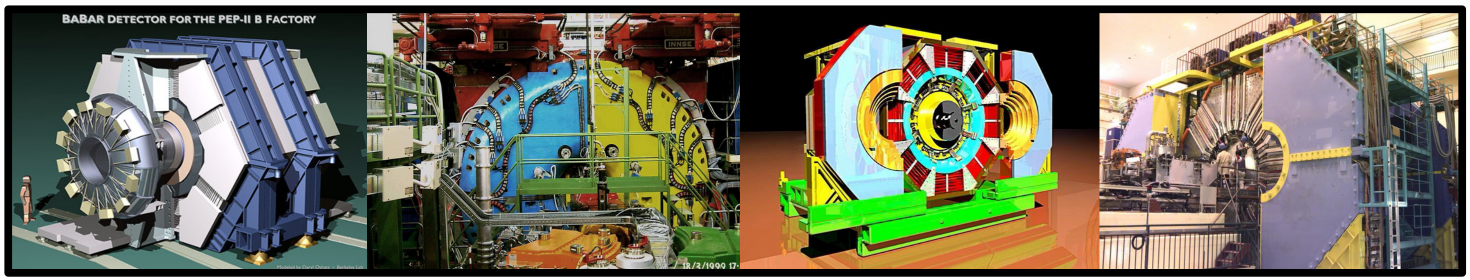
FWF Der Wissenschaftsfonds.

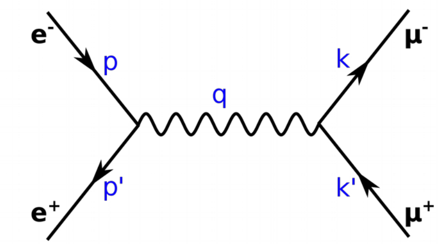
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Outline

1) Kinetic mixing and the dark photon
2) A light & dark Z' boson
3) Decays of Y(1S) to dark matter

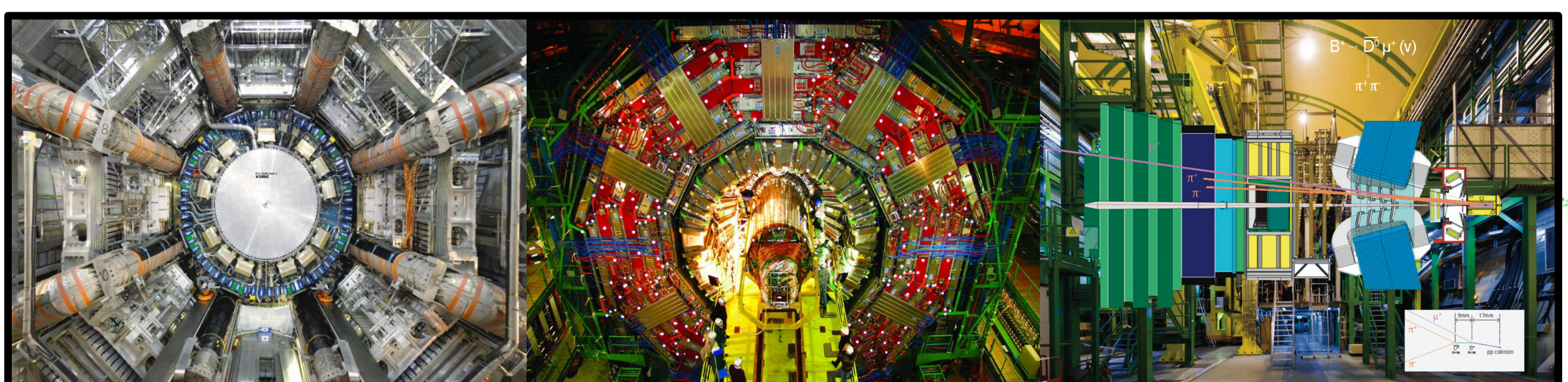
PART 1

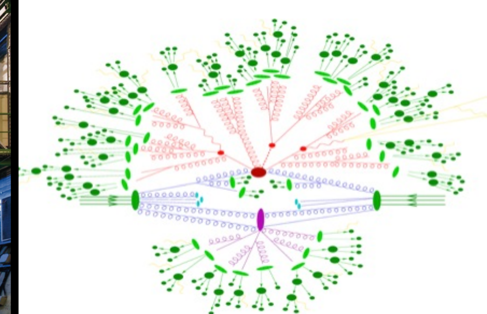




- Long lived dark photon search

PART 2

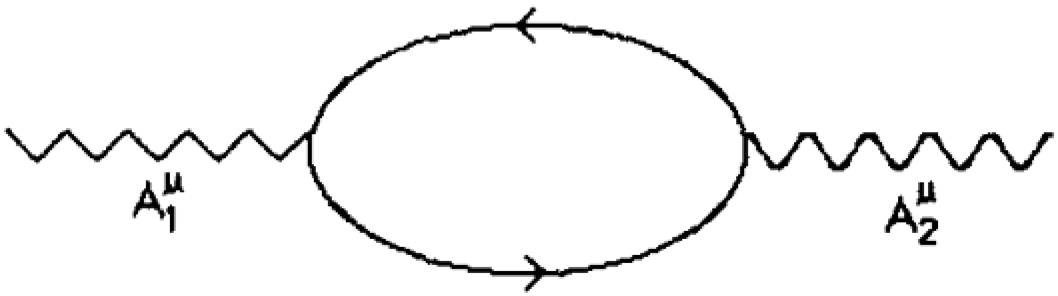




The general idea: kinetic mixing γ-A'

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:



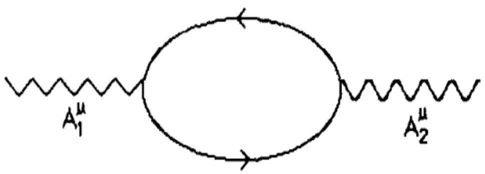
- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$.
- For the dark photon to acquire mass an extended Higgs sector can be required to break the new U(1)' symmetry.

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).

Consideration about dark sectors

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' .



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

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

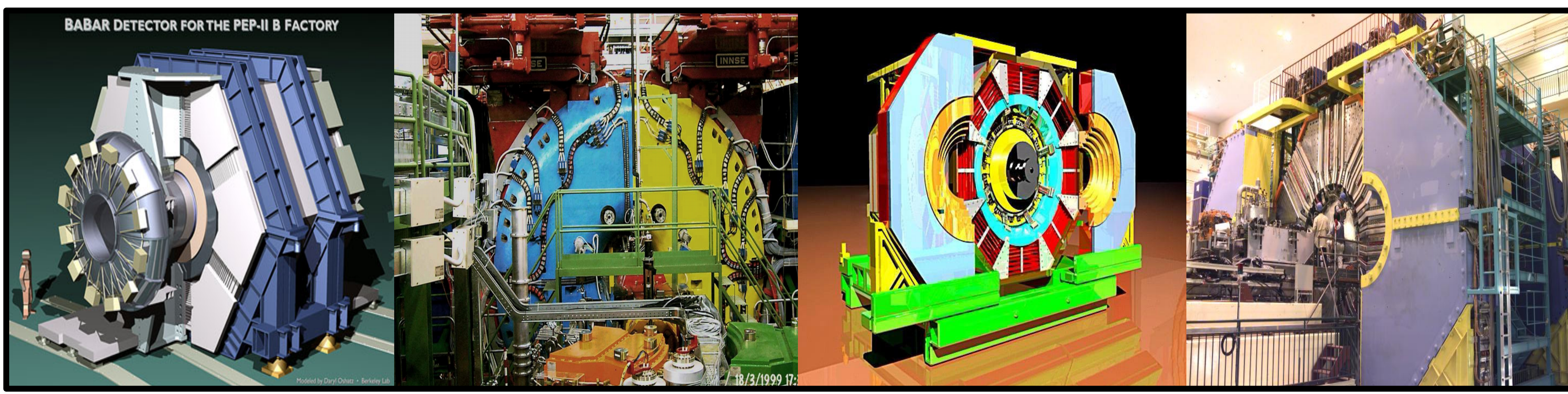
Kinetic mixing strength

- M(A') ~ GeV scale → mixing with the photon, decays to SM final states possible
- M(A') ~ EW scale → mixing with Z^0, effects in rare decays (Υ, B, ..) through loops[1], decays to SM final states possible
- 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

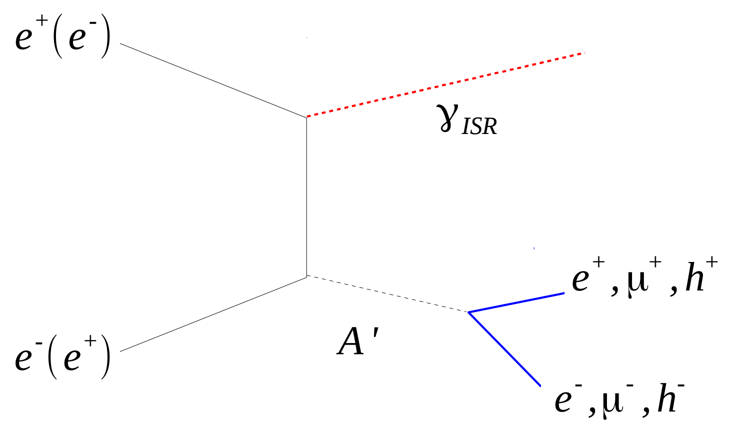
Invisible B/Υ decays not accessible at hadron colliders→Belle II

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

Dark photon searches in e+e- collisions:
BABAR, KLOE, BESIII, Belle/Belle II



Dark photon searches in e+e- collisions
KLOE, BES III, BABAR & Belle + Belle II

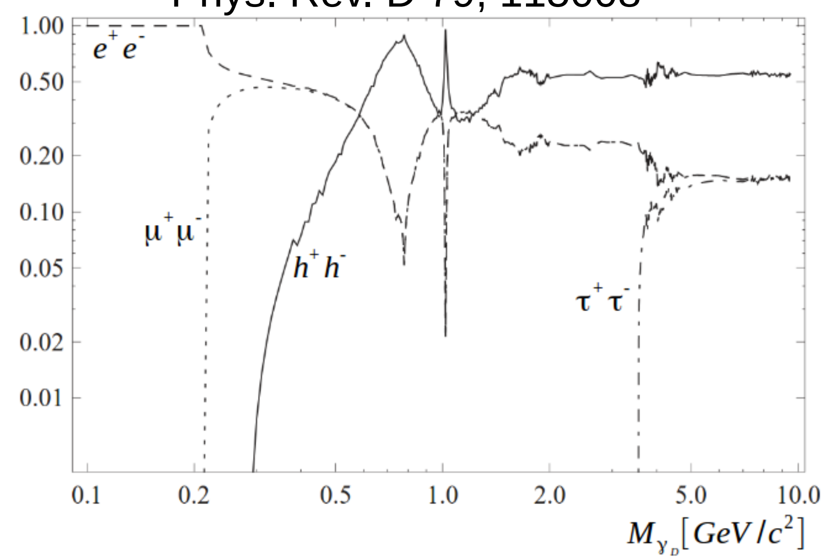


A'= dark photon.
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states. 2 charged tracks and 1 photon, prompt.

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

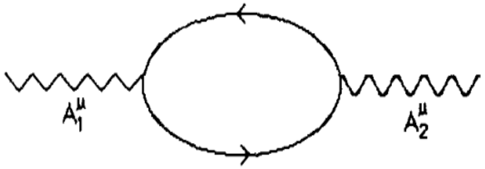
-Decays to leptons require $M_{A'}$>1.02 MeV/c^2
-Decays to hadrons require $M_{A'}$>0.36 GeV/c^2

B. Batell, et al.
Phys. Rev. D 79, 115008



Dark photon searches in e+e- collisions
KLOE, BES III, BABAR & Belle + Belle II

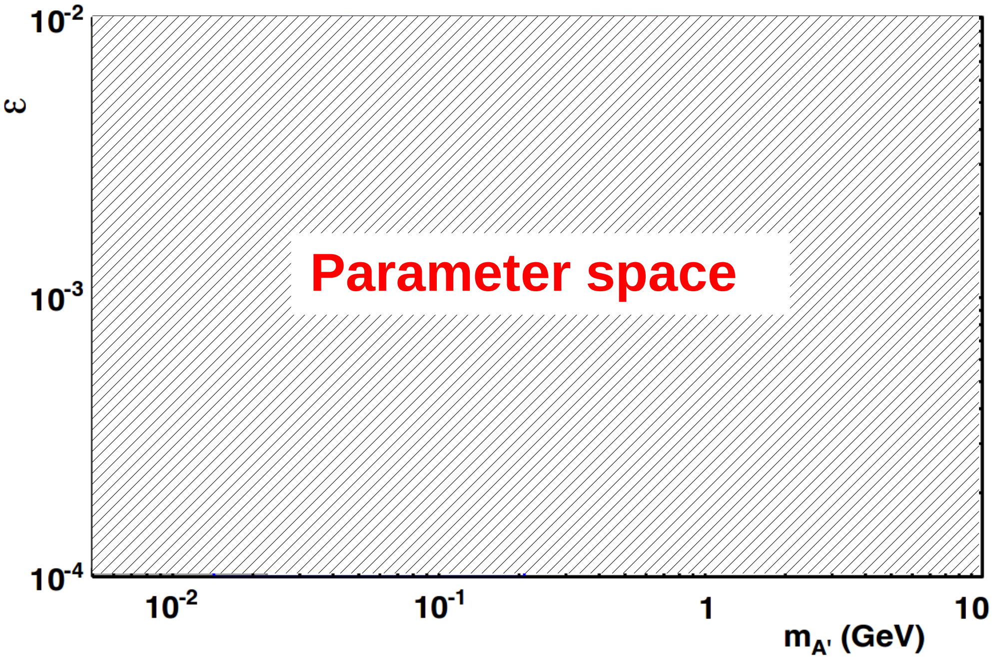
Most dark sector models require an additional U(1) symmetry responsible for the "interactions" between dark sector particles and SM particles through its gauge boson A' .



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

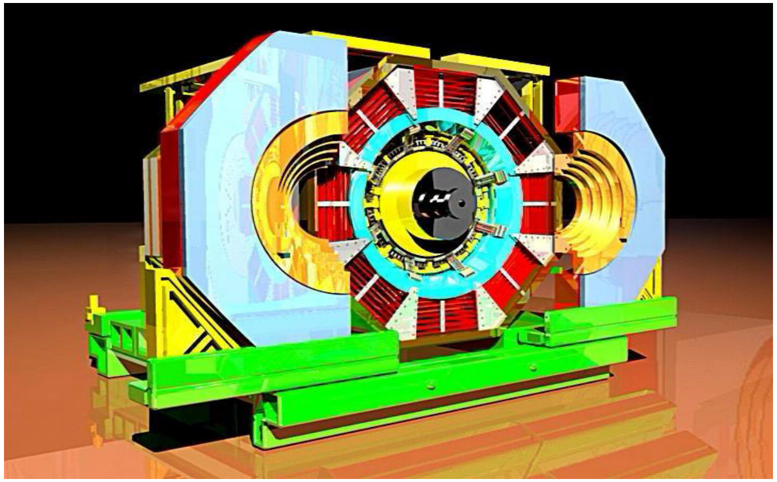
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).
B. Holdom, Phys. Lett. B **166**, 196 (1986)

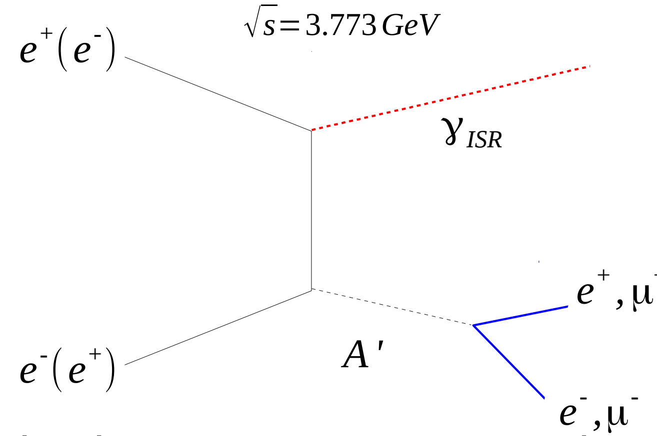
Kinetic mixing strength



Dark photon searches in e+e- collisions

BES III

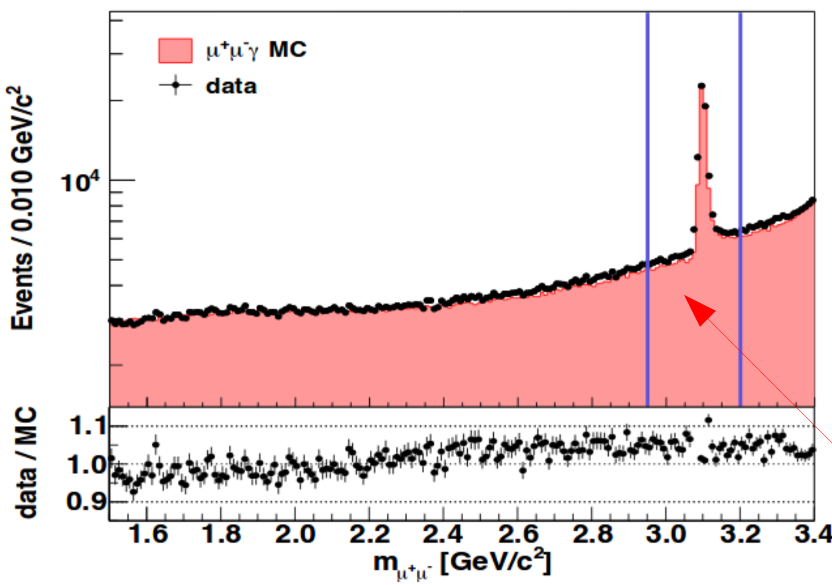


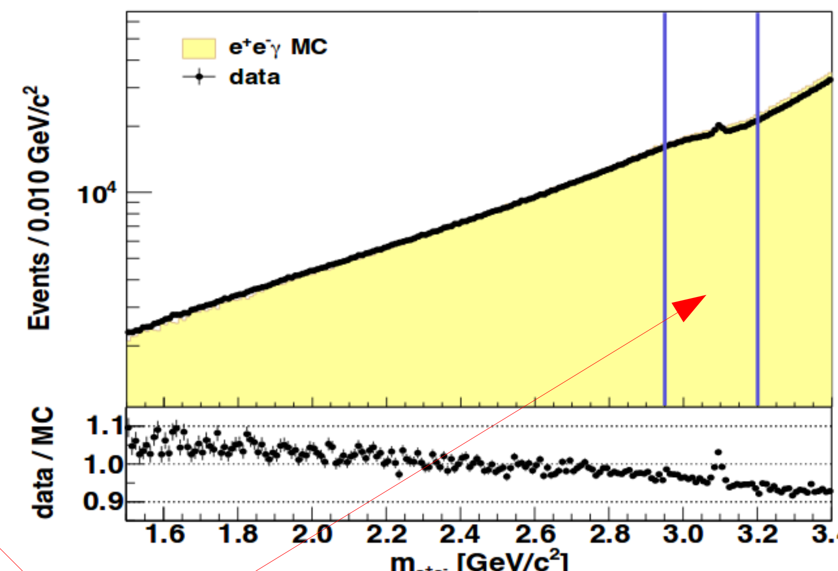


Physics Letters B 774, 252 (2017)

$$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma \mu^+\mu^-$$

untagged γ, *prompt*, $1.5 < M_{l^+l^-} < 3.4\,GeV/c^2 \quad (l = e, \mu)$

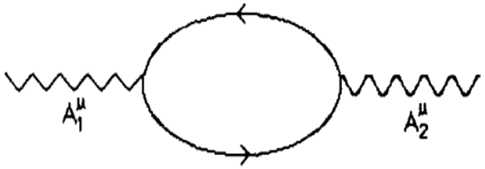




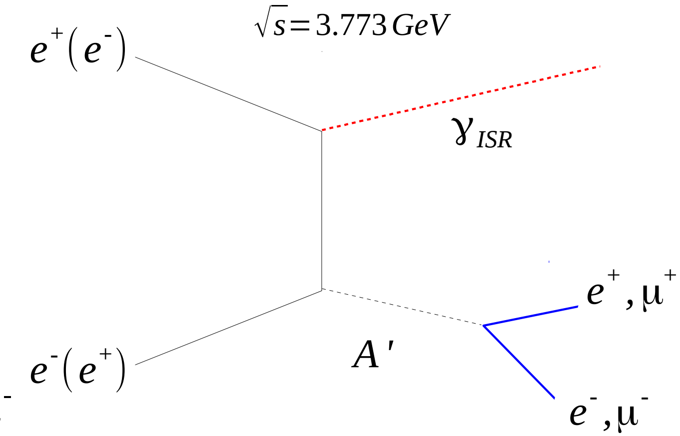
→ Regions excluded from the search

Dark photon searches in e+e- collisions

BES III

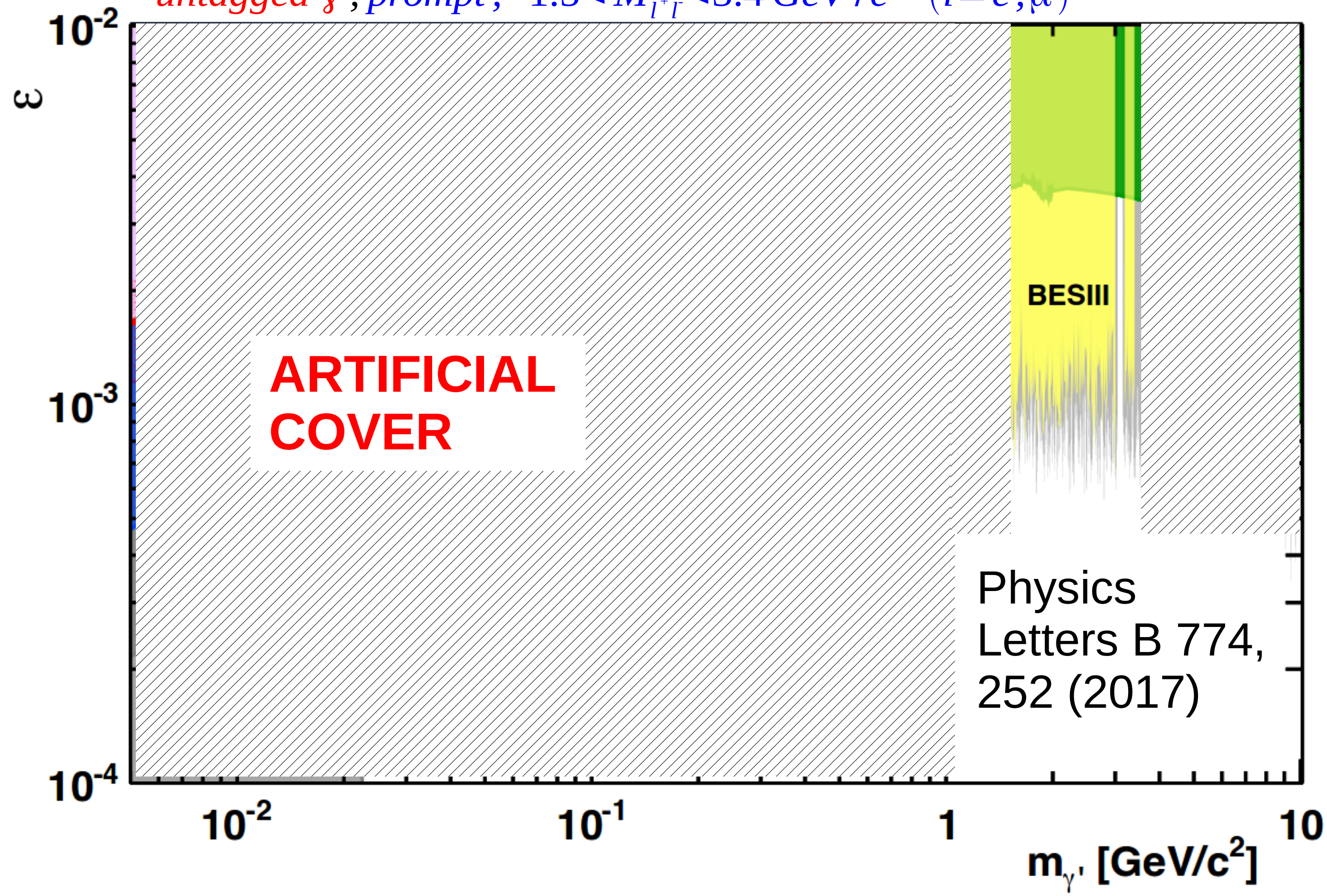


$$\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$$



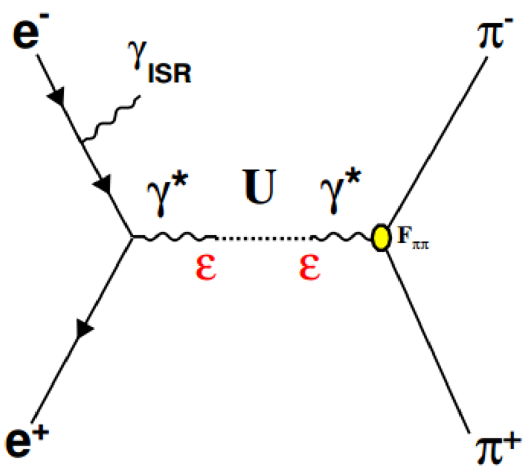
$$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$$

untagged γ, *prompt*, $1.5 < M_{l^+l^-} < 3.4\,GeV/c^2 \quad (l = e, \mu)$



Dark photon searches in e+e- collisions

KLOE-2



F. Cucciarello
ICHEP 16

Phys. Lett. B 757 (2016) 356

$$\varepsilon^2 = \frac{N_{CL_S}/\epsilon_{\rm eff}}{H \cdot I \cdot L}$$

N_{CL_S} = UL on number of U-boson candidates at 90% CL (CL_S technique)

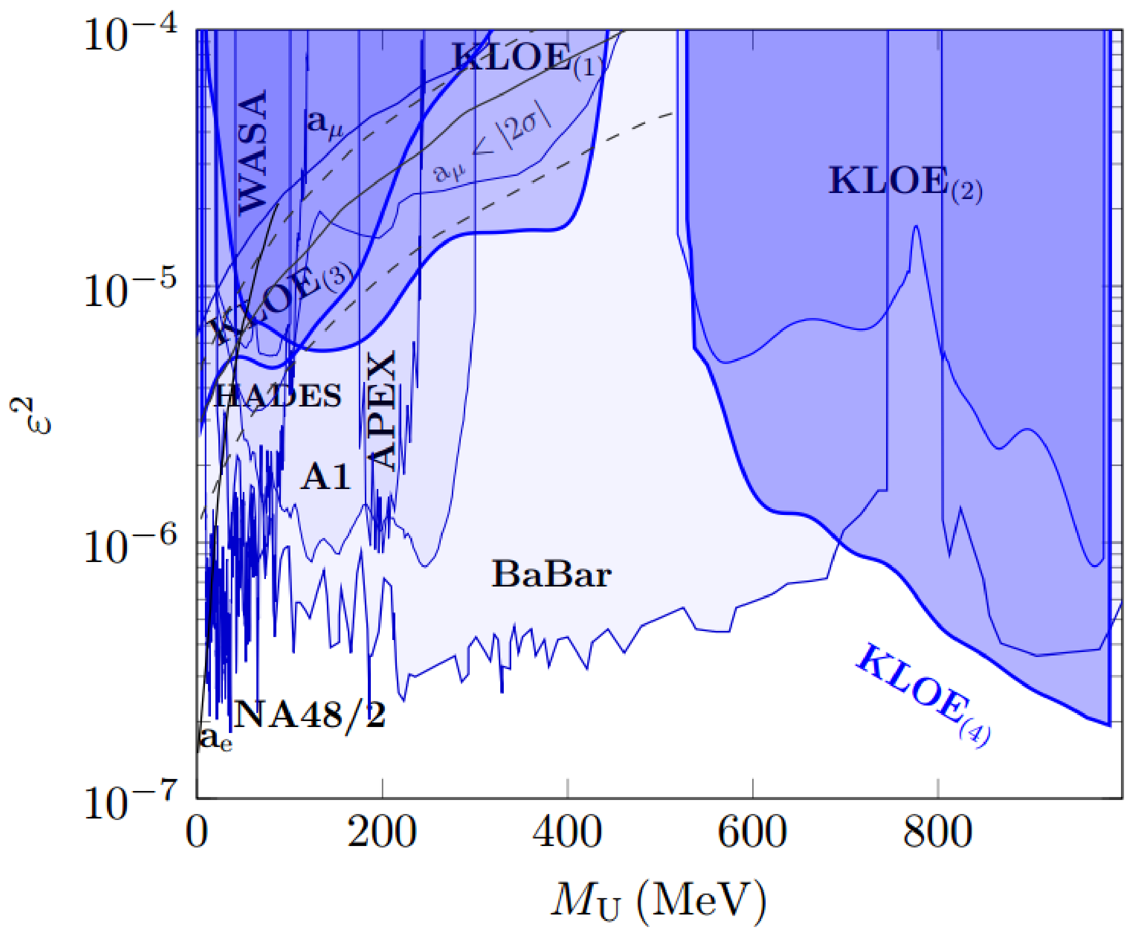
$$H = \frac{d\sigma_{\pi\pi\gamma}/dM_{\pi\pi}}{\sigma(\pi^+\pi^- \to \pi^+\pi^-, M)}$$

$I = \int \sigma^{U}_{\pi\pi} dM_{\pi\pi}$

$\epsilon_{\rm eff} = 2 - 40\%$

Systematic error $\leq 1\%$

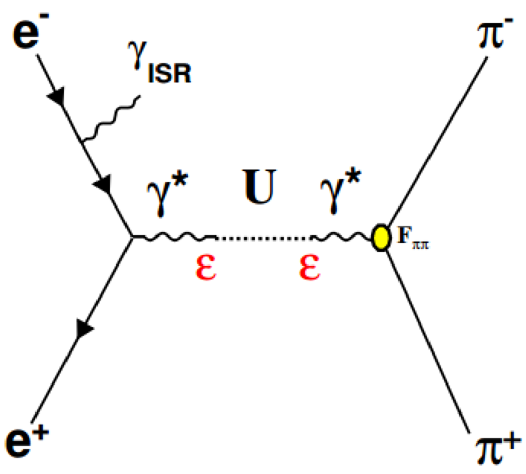
L=1.93 fb^{-1}



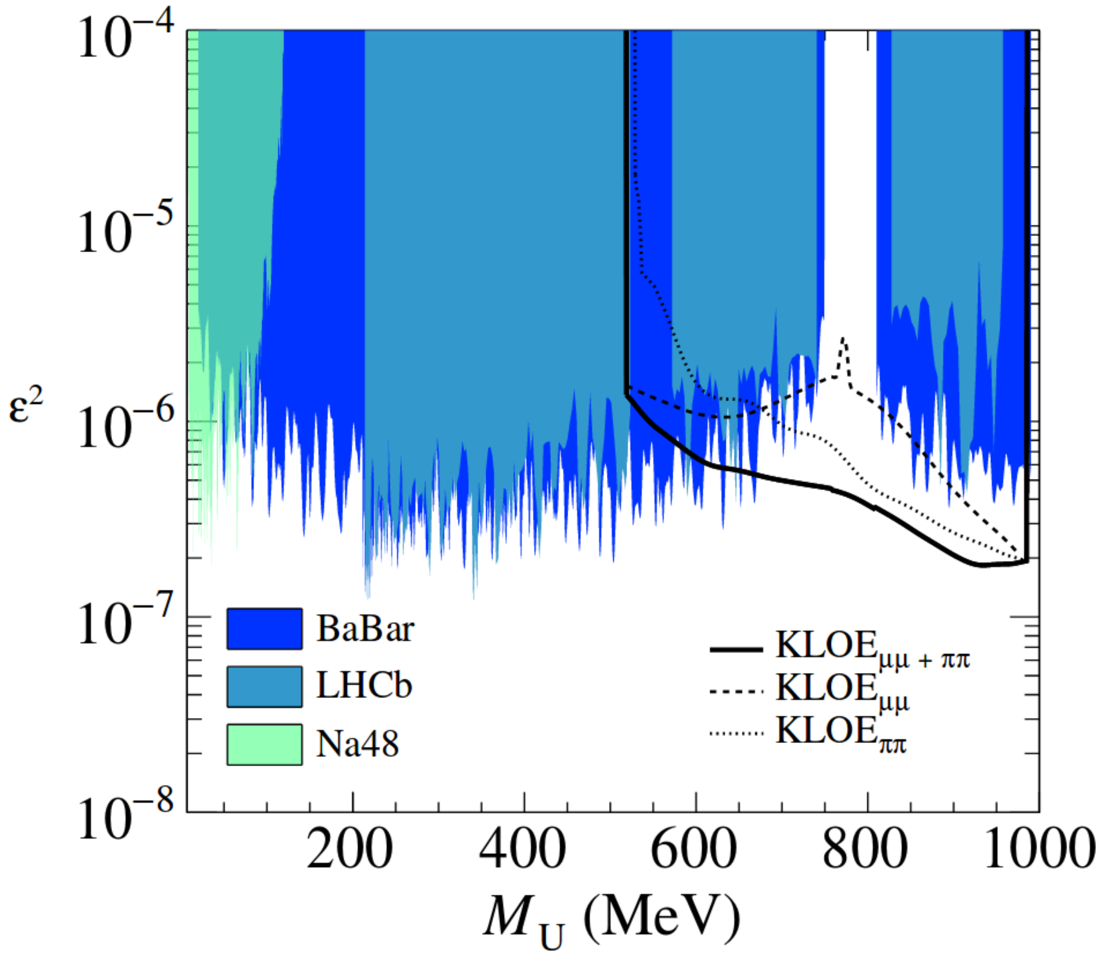
$\varepsilon^2 < 1.82 \times 10^{-5} - 1.93 \times 10^{-7}$ @ 90% C.L. for $527 < M_U < 987$ MeV

Dark photon searches in e+e- collisions

KLOE-2



Phys. Lett. B784 (2018) 336-341, arXiv:1807.02691 [hep-ex]



$$\epsilon^2 = \frac{\alpha'}{\alpha} = \frac{N_{CLS}}{\epsilon_{eff}\, L \cdot H \cdot I}$$

N_{CL_S} = UL on number of U-boson candidates at 90% CL (CL_S technique)

$$H = \frac{d\sigma_{\mu\mu\gamma}/dM_{\mu\mu}}{\sigma(e^+e^- \to \mu^+\mu^-, M_{\mu\mu})}$$

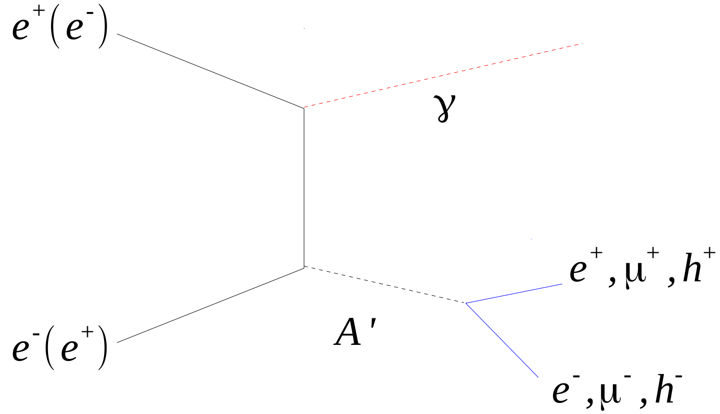
$$I = \int \sigma^U_{\mu\mu}\, dM_{\mu\mu}$$

Systematic error $\lesssim 1\%$

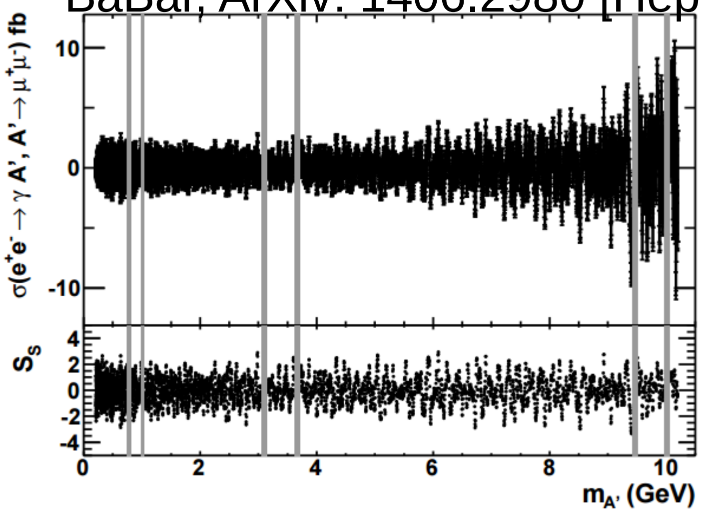
$L = 1.93\ \mathrm{fb}^{-1}$

“The combined upper limit, obtained after averaging the statistical fluctuations by a smoothing procedure, excludes values of ε^2 greater than $(13{-}2)\times10^{-7}$ in the U-mass range 519–987MeV”.

Dark photon searches in e+e- collisions
BABAR



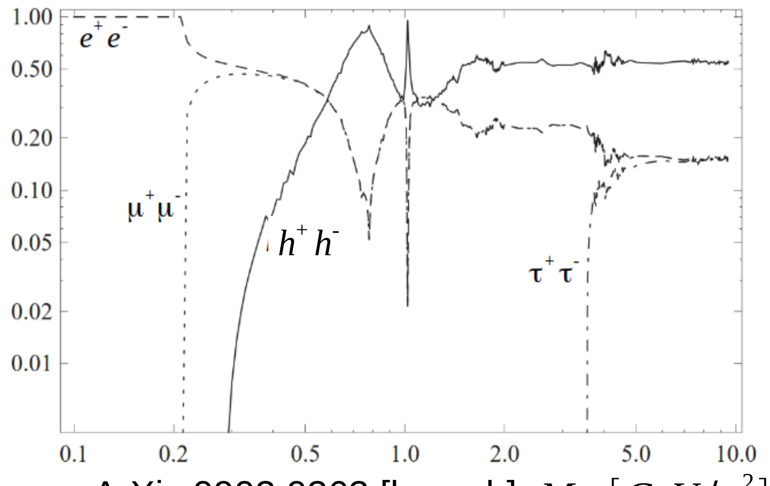
BaBar, ArXiv: 1406.2980 [Hep-Ex]



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

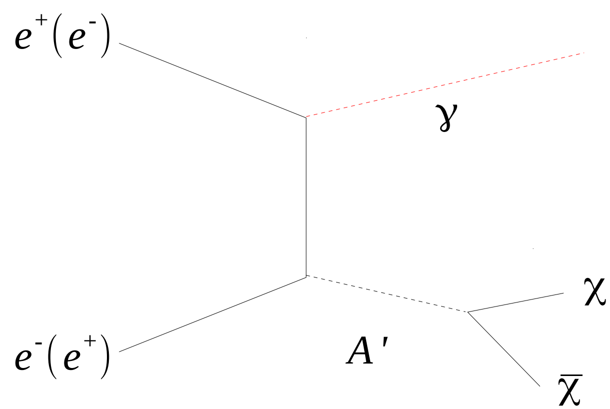


ArXiv:0903.0363 [hep-ph]

Dark photon searches in e+e- collisions

BABAR

See *R. Essig et al. JHEP11 (2013) 167.*



A'= dark photon, χ= dark matter particle (neutral under SU(3)xSU(2)xU(1))
A' decays to dark matter. One on-shell (mono-energetic) or one off-shell (broad spectrum) photon with different gamma spectrum .

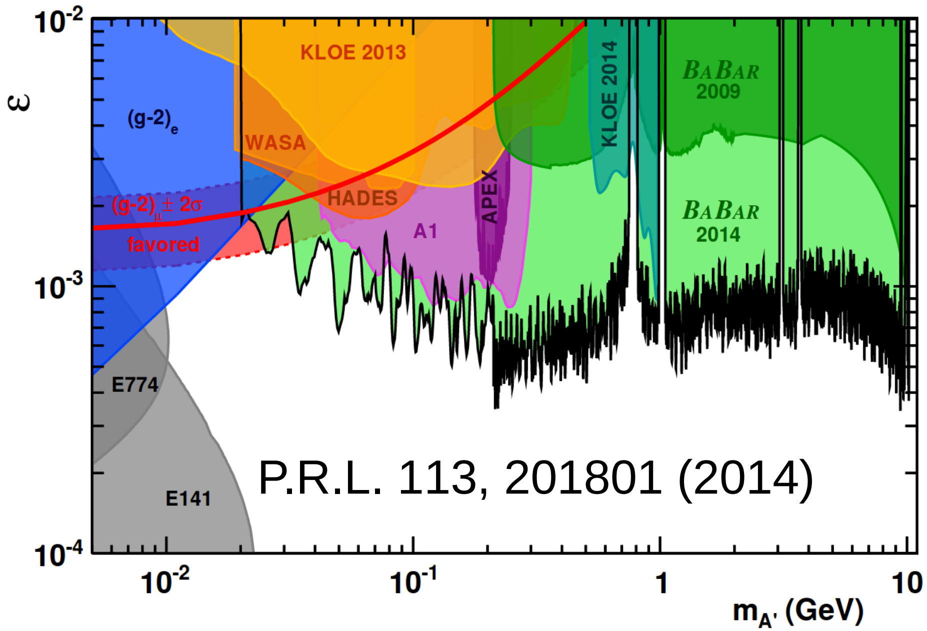
radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s} \ \ (on-shell)$
No existing limits

Requires high rate single photon trigger, not available in Belle, however the analysis is ongoing using photon conversion. The BaBar Collaboration implemented a single photon trigger (arXiv:0808.0017 [hep-ex]). Single photon trigger available at Belle II.

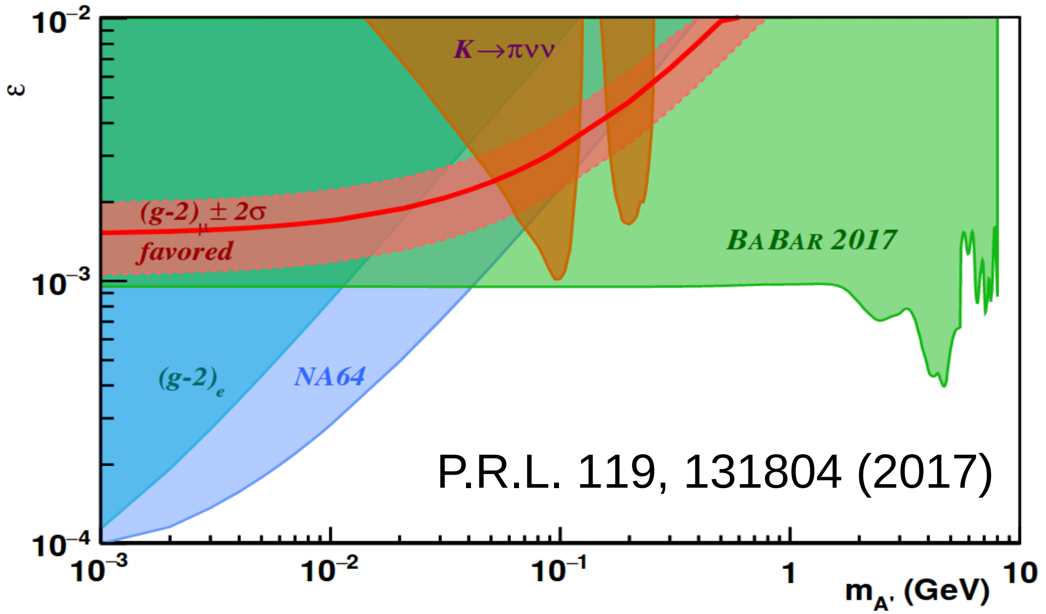
Dark photon searches in e+e- collisions

BABAR

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*



$e^+e^- \to \gamma A' \to \gamma \chi \bar{\chi}$ *

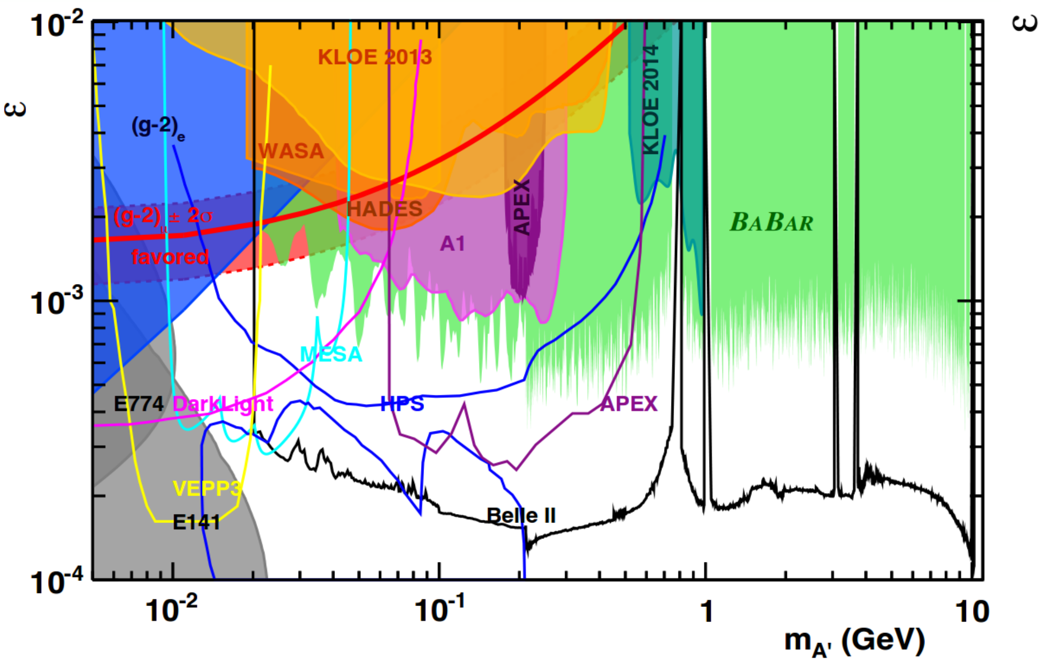


*The level 1 trigger required a single energy cluster > 800 MeV in the laboratory frame. Rate: 350 Hz (8% of the total) at a typical luminosity of 8×10^{33} running on the Υ(2S) or Υ(3S) resonances

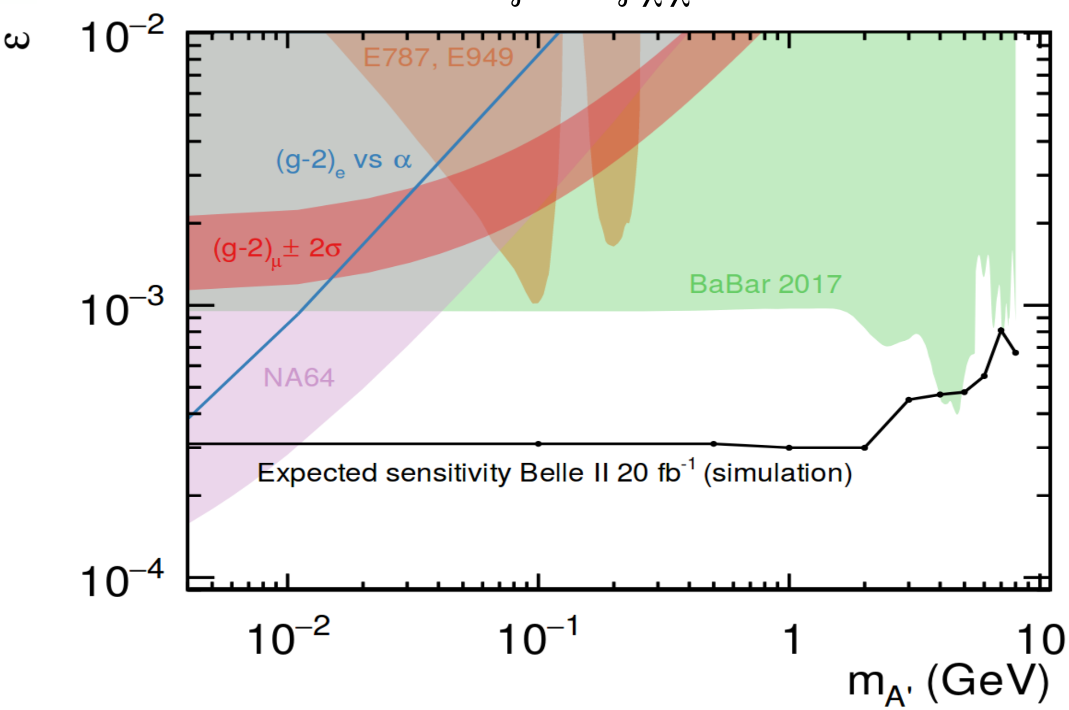
Dark photon searches in e+e- collisions

BABAR vs. Belle II

$e^+e^- \to \gamma A' \to \gamma e^+e^-, \gamma\mu^+\mu^-$, *prompt*



$e^+e^- \to \gamma A' \to \gamma\chi\bar{\chi}$ *



→ **See Belle II Physics book for the Belle II details: arXiv:1808.10567**

*The level 1 trigger required a single energy cluster > 800 MeV in the laboratory frame. Rate: 350 Hz (8% of the total) at a typical luminosity of 8×10^{33} running on the Υ(2S) or Υ(3S) resonances.

BABAR: invisible channels

BABAR:
Phys.Rev.Lett.107:021804,2011 $\Upsilon(1S) \rightarrow \gamma(A^0 \rightarrow)\chi\bar{\chi}$

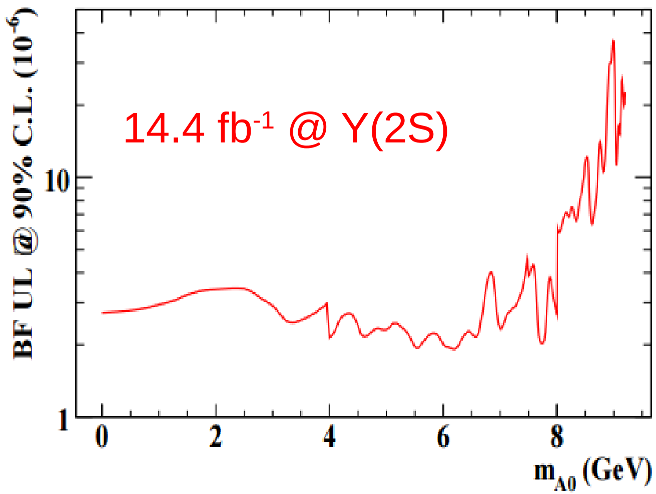


FIG. 2: 90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow$ invisible).

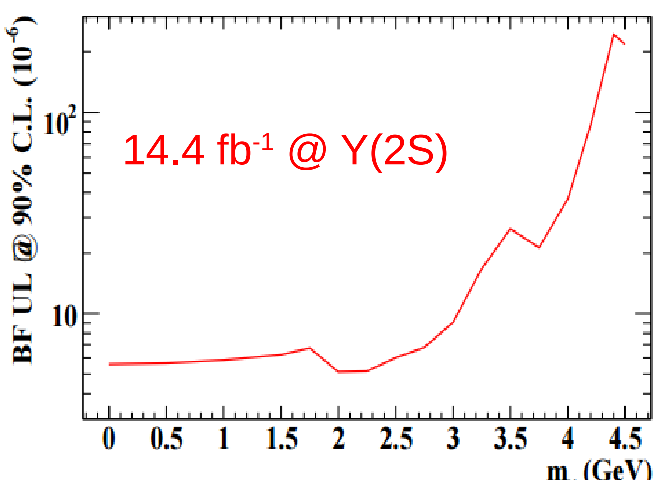
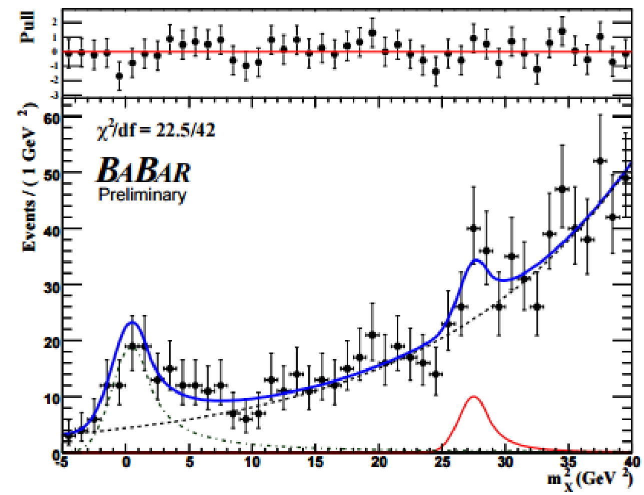
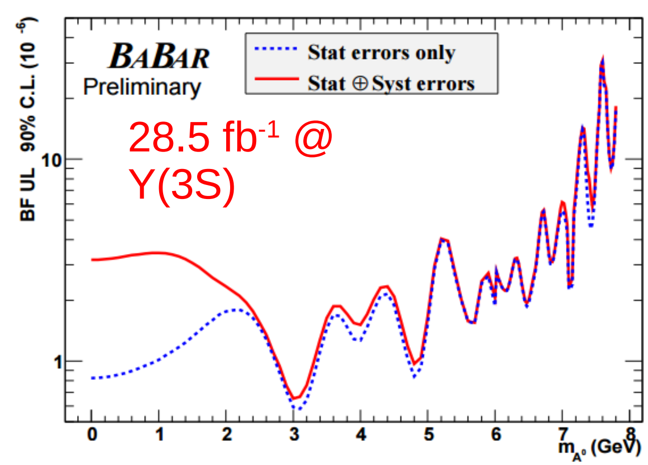


FIG. 3: 90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma\chi\bar{\chi})$.

BABAR:
arXiv:0808.0017
$e^+e^-[\Upsilon(3S)] \rightarrow \gamma_{ISR} A', A' \rightarrow \chi\bar{\chi}$





Invisible Υ(1S) decay searches in e+e- collisions
BABAR vs. Belle vs. Belle II

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

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

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

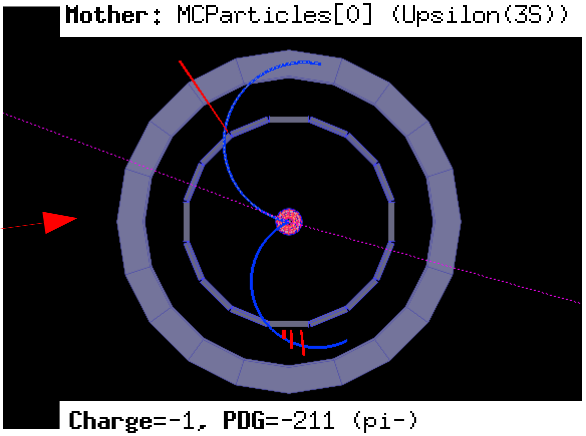
- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new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

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

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

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

Charge=1, PDG=211 (pi+)
pT=0.420365, pZ=0.000692372
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))



Charge=-1, PDG=-211 (pi-)
pT=0.344016, pZ=0.118851
V=(-0.00, -0.00, -0.03)
Mother: MCParticles[0] (Upsilon(3S))

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

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

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

Invisible Y(1S) decay searches in e+e- collisions

BABAR vs. Belle vs. Belle II

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

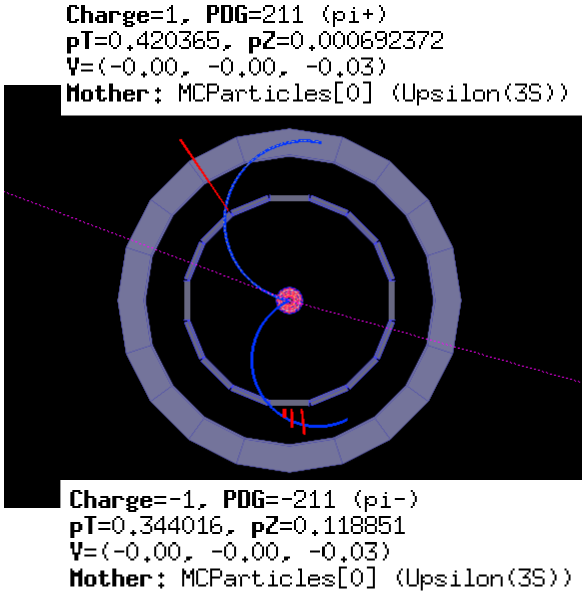
$$BR(Y(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$

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

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

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

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



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)

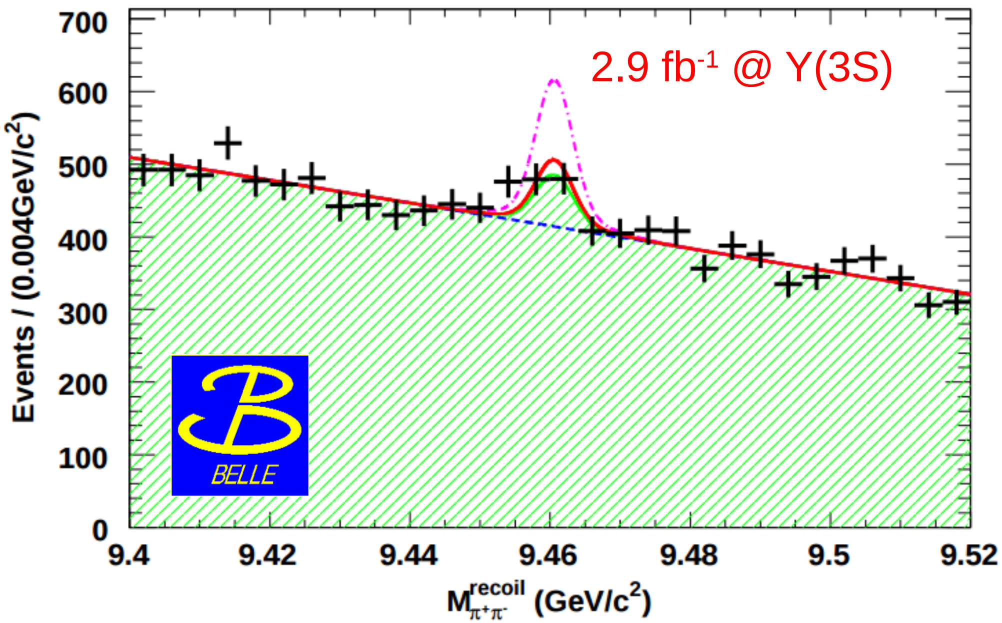
$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}\,E^{CMS}_{\pi^+\pi^-}$$

Invisible Y(1S) decay searches in e+e- collisions

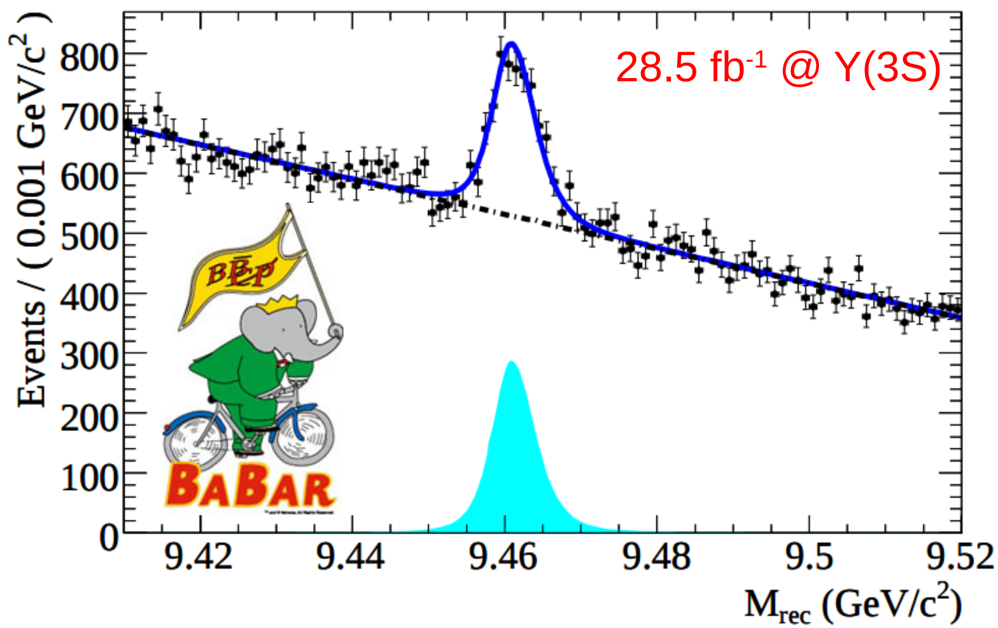
BABAR vs. Belle vs. Belle II

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

[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) decay searches in e+e- collisions

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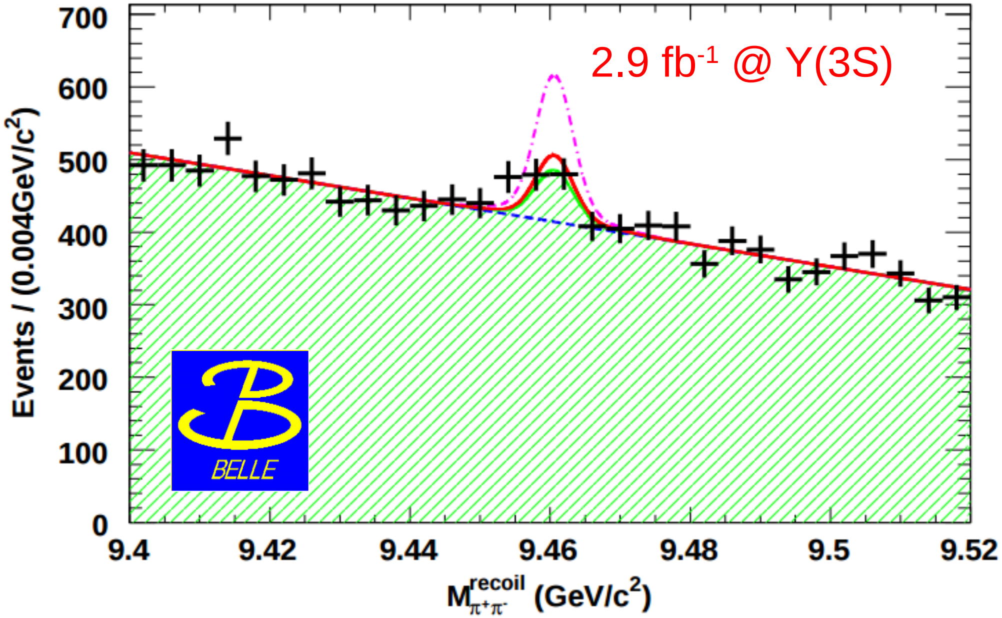

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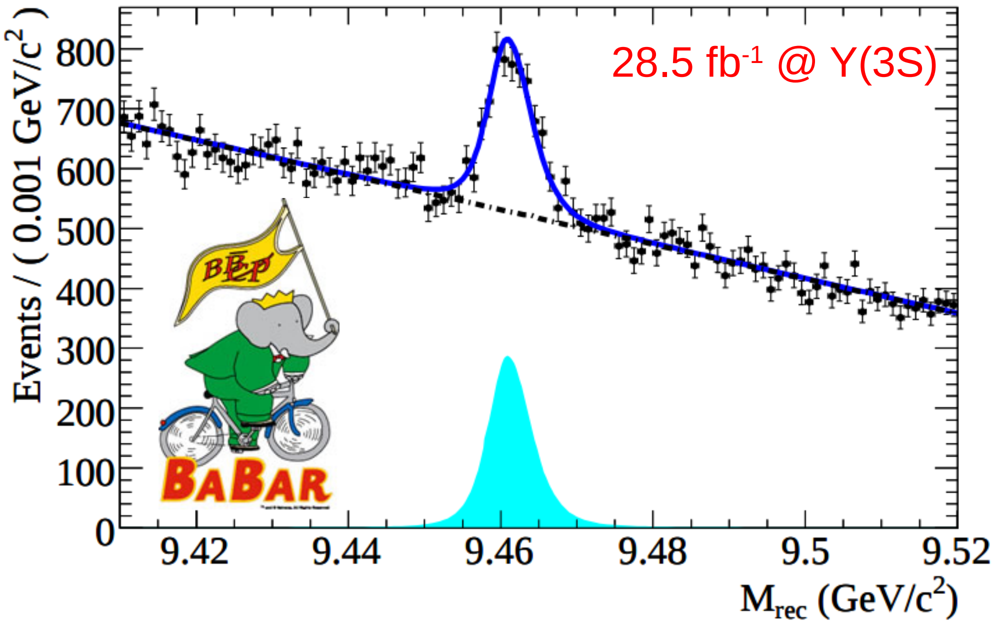
(2 months running @ Y(3S))



No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < 3×10^{-4} (BaBar) and BR(Y→νν) < 3.0×10^{-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.

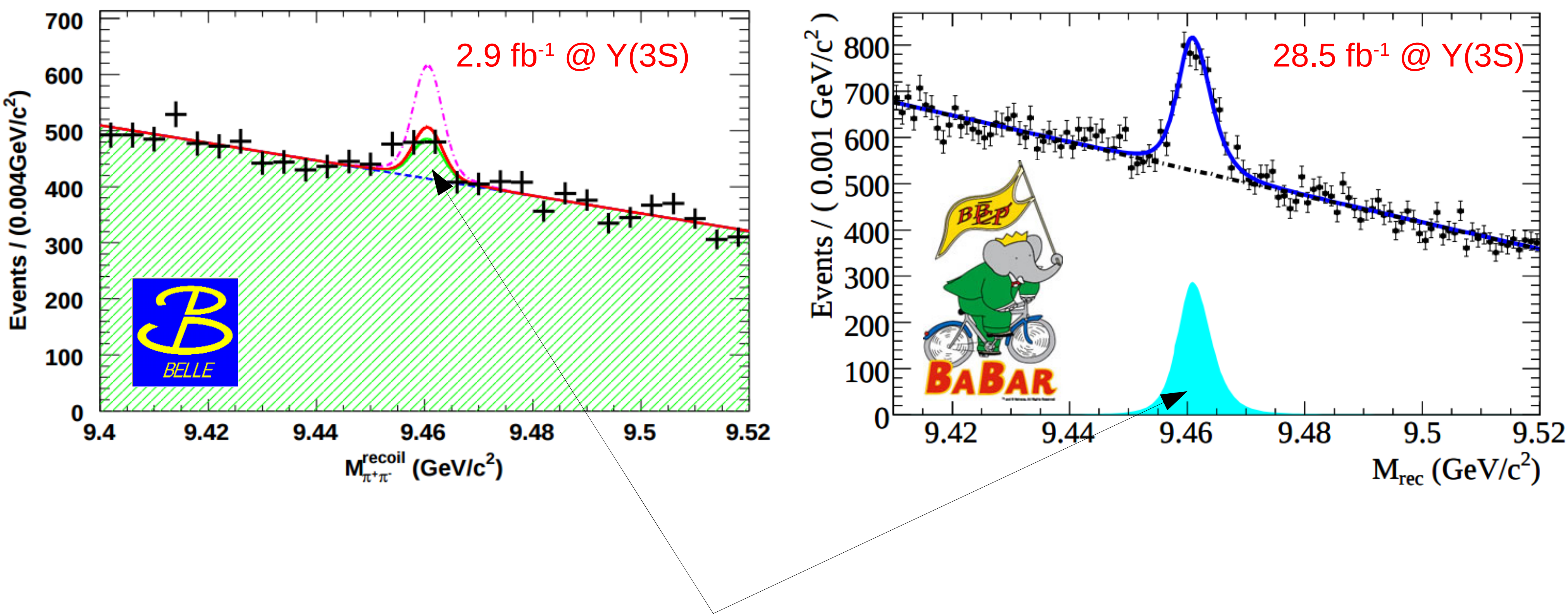
Invisible Υ(1S) decay searches in e+e- collisions

BABAR vs. Belle vs. Belle II

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

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

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

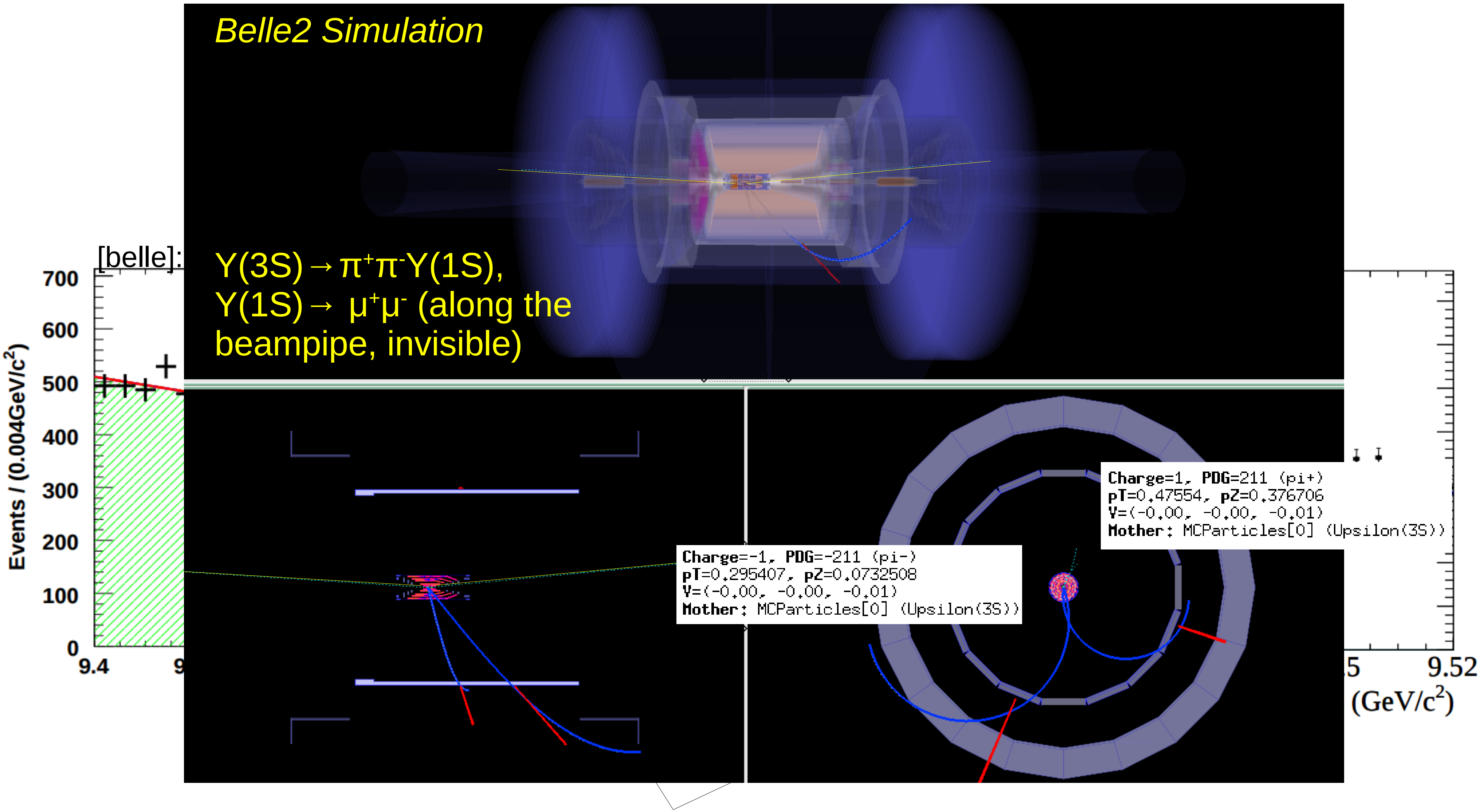


Irreducible peaking background when final states go undetected (i.e. detector supports, beampipe etc.) in the process $Y(3S) \rightarrow \pi^+\pi^- Y(1S), Y(1S) \rightarrow undetected\, f.s.$

Q: Can advanced machine learning techniques separate reduce this irreducible Background? Tests are planned..

Invisible Y(1S) decay searches in e+e- collisions

BABAR vs. Belle vs. Belle II



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

Invisible Υ(1S) decay searches in e+e- collisions

BABAR vs. Belle vs. Belle II

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

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

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

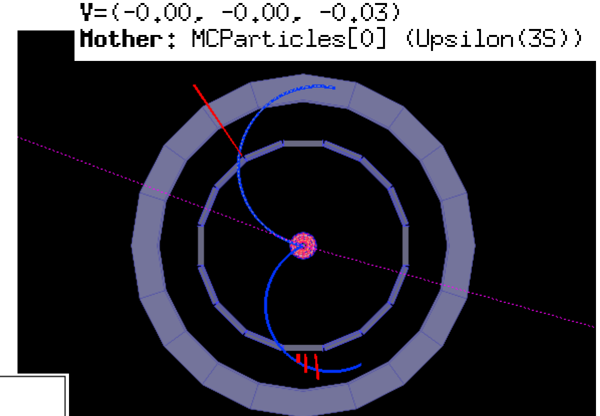
$e^+e^-\to\Upsilon(2S)$
$\downarrow$(18.1%)
$\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$
$\downarrow$
$\Upsilon(1S)\to invisible$

- 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 strongly constrain the SM Υ(1S)→νν

Belle2 Simulation
$\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$,
$\Upsilon(1S)\to\nu\nu$

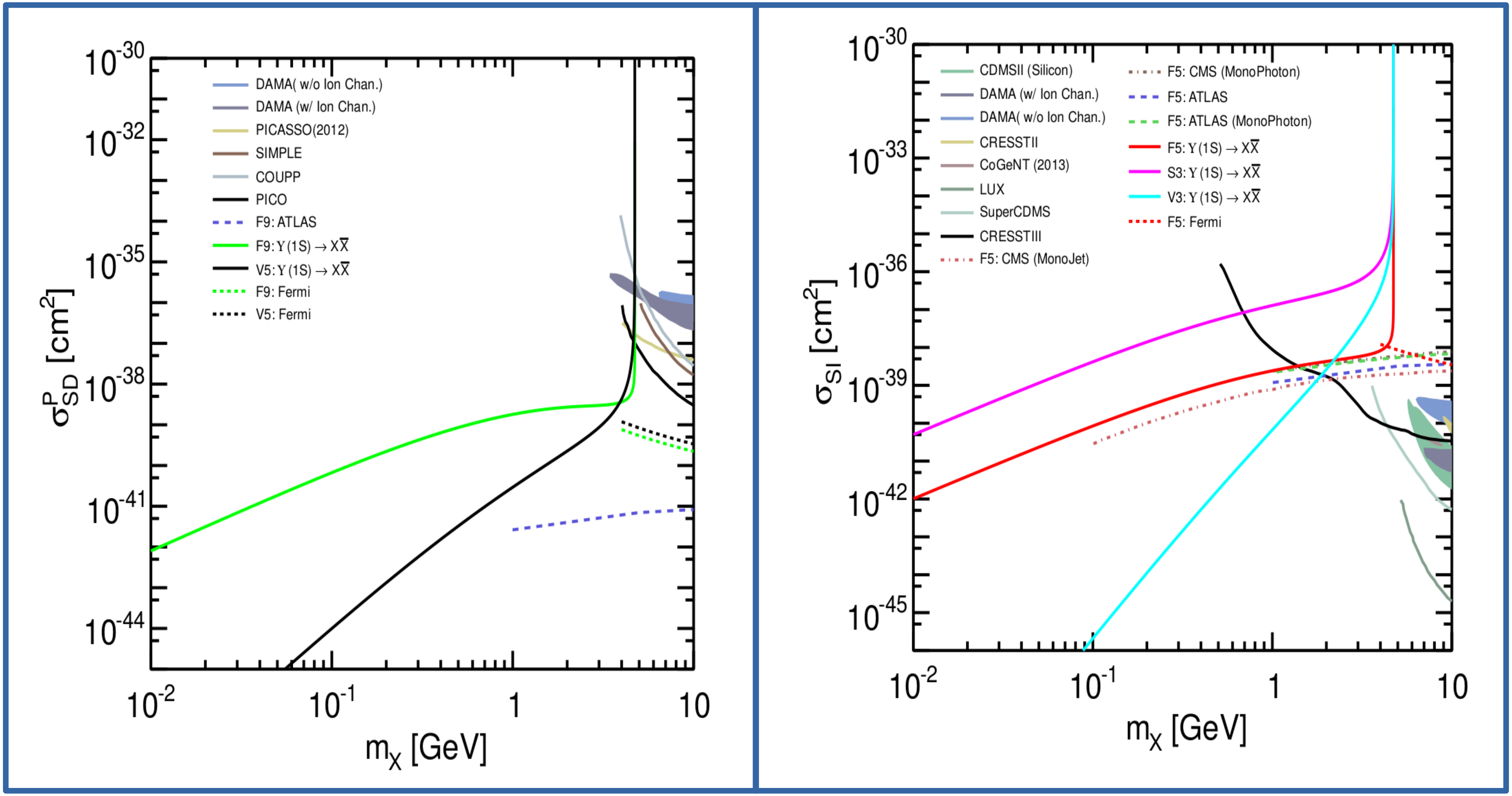


No signal was observed over the expected background and upper limits have been obtained: BR(Υ→νν) < 3×10^{-4} (BaBar) and BR(Υ→νν) < 3.0×10^{-3}(Belle).

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

Translating Υ(1S)→ invisible search to dark matter limits

Extrapolation based on ArXiv: 1511.03728, 1404.6599



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

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,

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

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

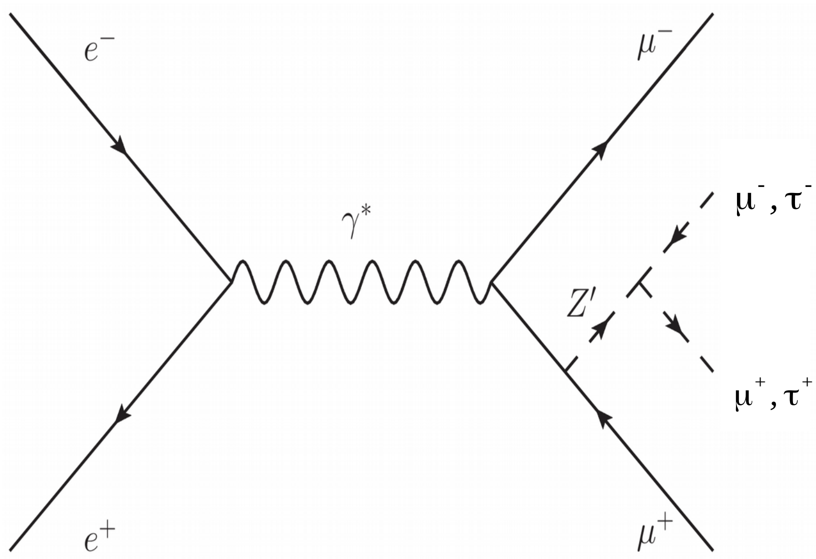
$$BR(Z'\rightarrow invisible) = \frac{2\Gamma(Z'\rightarrow \nu_l\bar{\nu}_l)}{2\Gamma(Z'\rightarrow \nu_l\bar{\nu}_l) + \Gamma(Z'\rightarrow \mu\bar{\mu}) + \Gamma(Z'\rightarrow \tau\bar{\tau})}$$

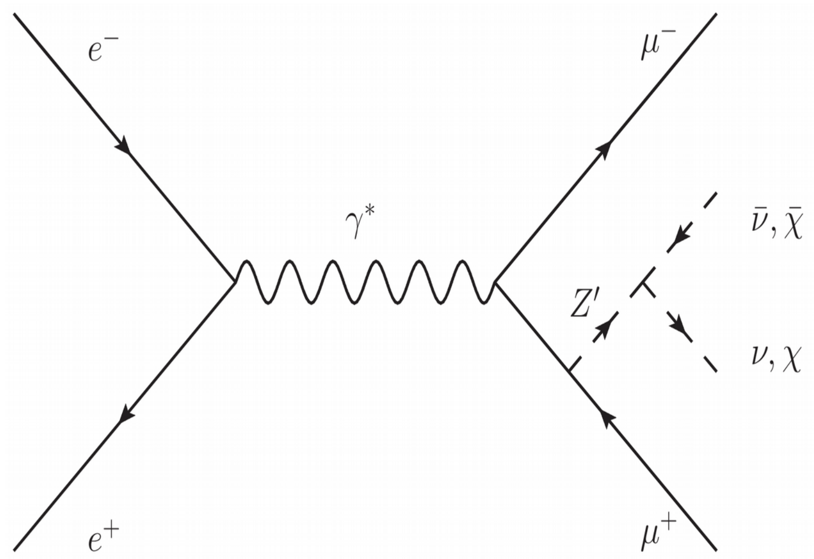
Partial width results and BR derived from eqn. 2.12 of Essig et al. JHEP02(2015)157, arXiv:1412.0018 [hep-ph]:

$$\Gamma(Z_D \to \bar{f}f) = \frac{N_c}{24\pi m_{Z_D}}\sqrt{1 - \frac{4m_f^2}{m_{Z_D}^2}}\left(m_{Z_D}^2\left(g_L^2 + g_R^2\right) - m_f^2\left(-6g_L g_R + g_L^2 + g_R^2\right)\right)$$

- 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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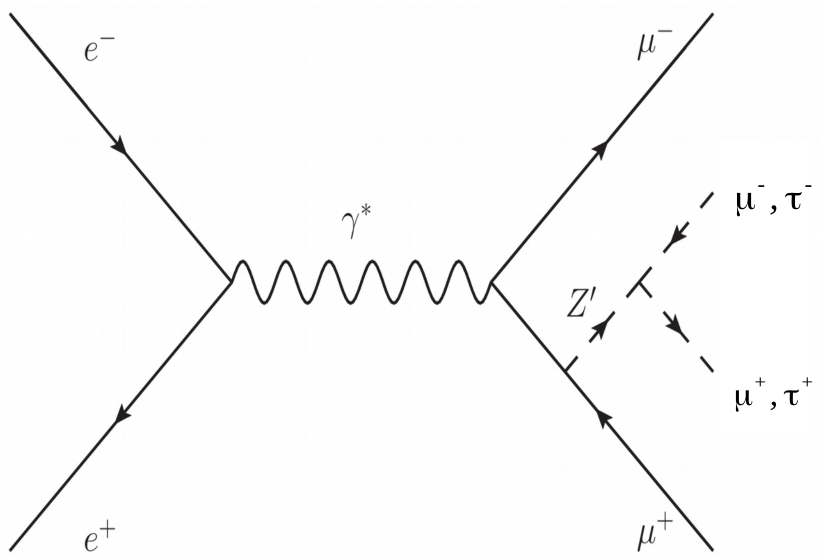

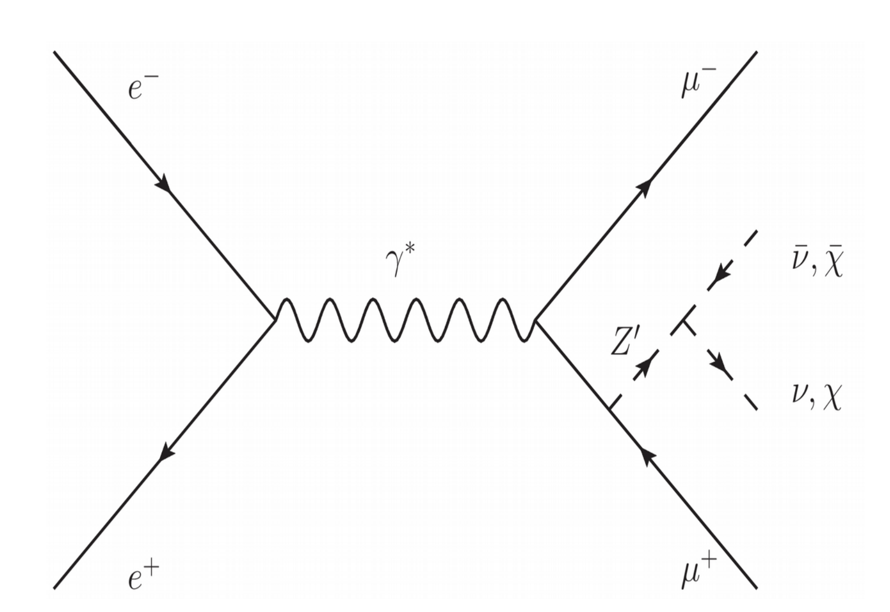

- **Final state: $\mu^+\mu^-$ +nothing**

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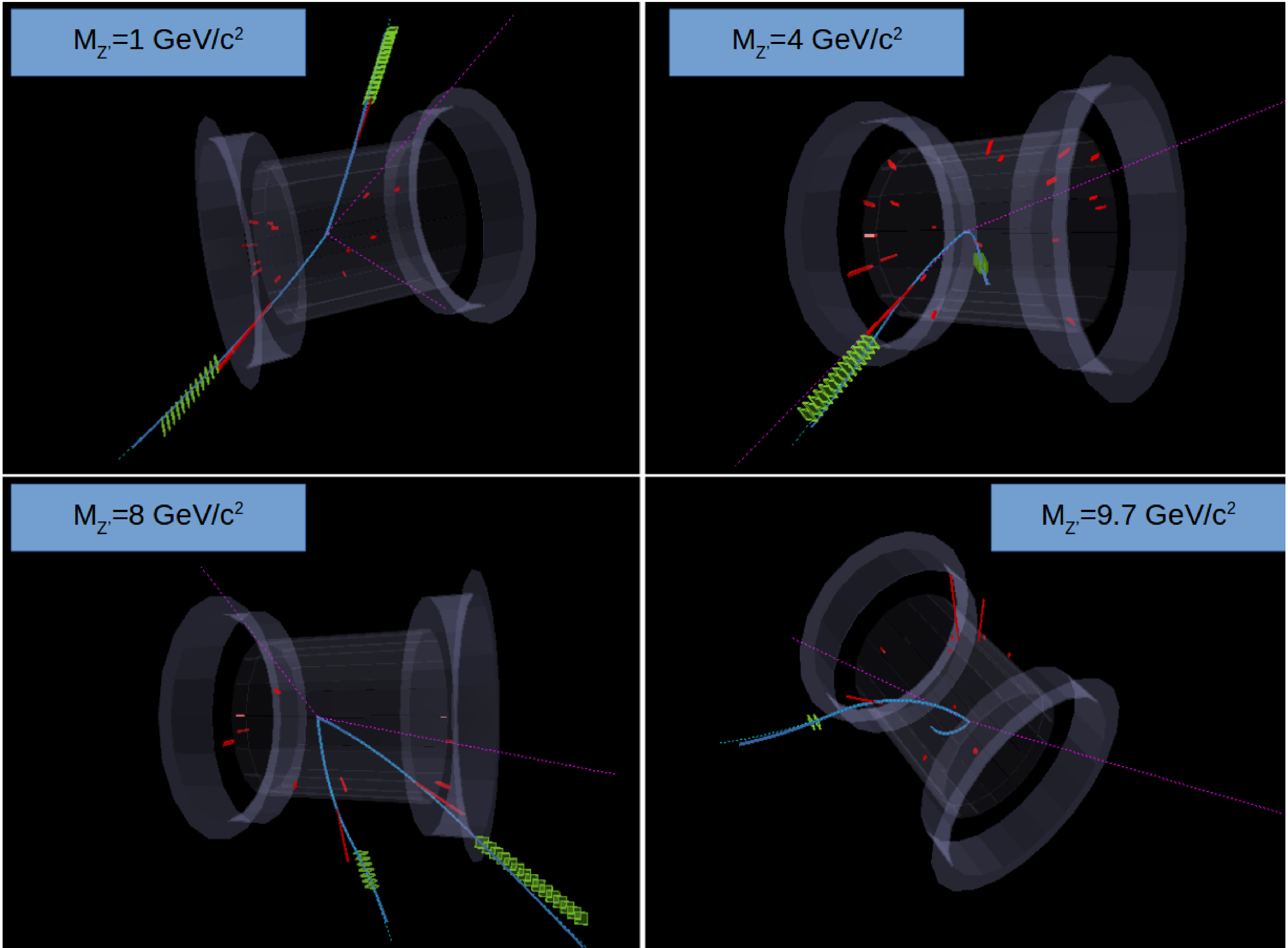
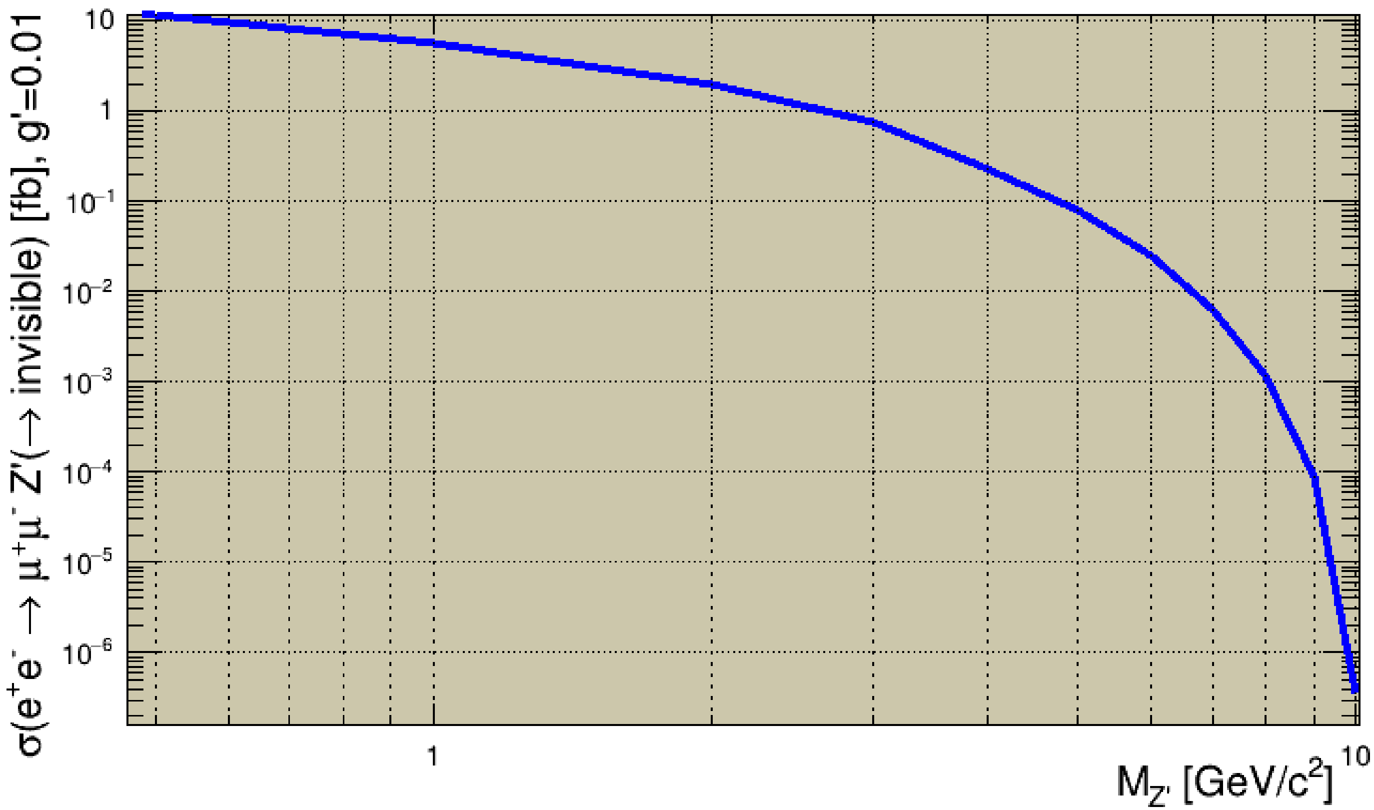
Z’ → invisible, Belle 2 event display (MC simulation)



Cross section for Z’→invisible



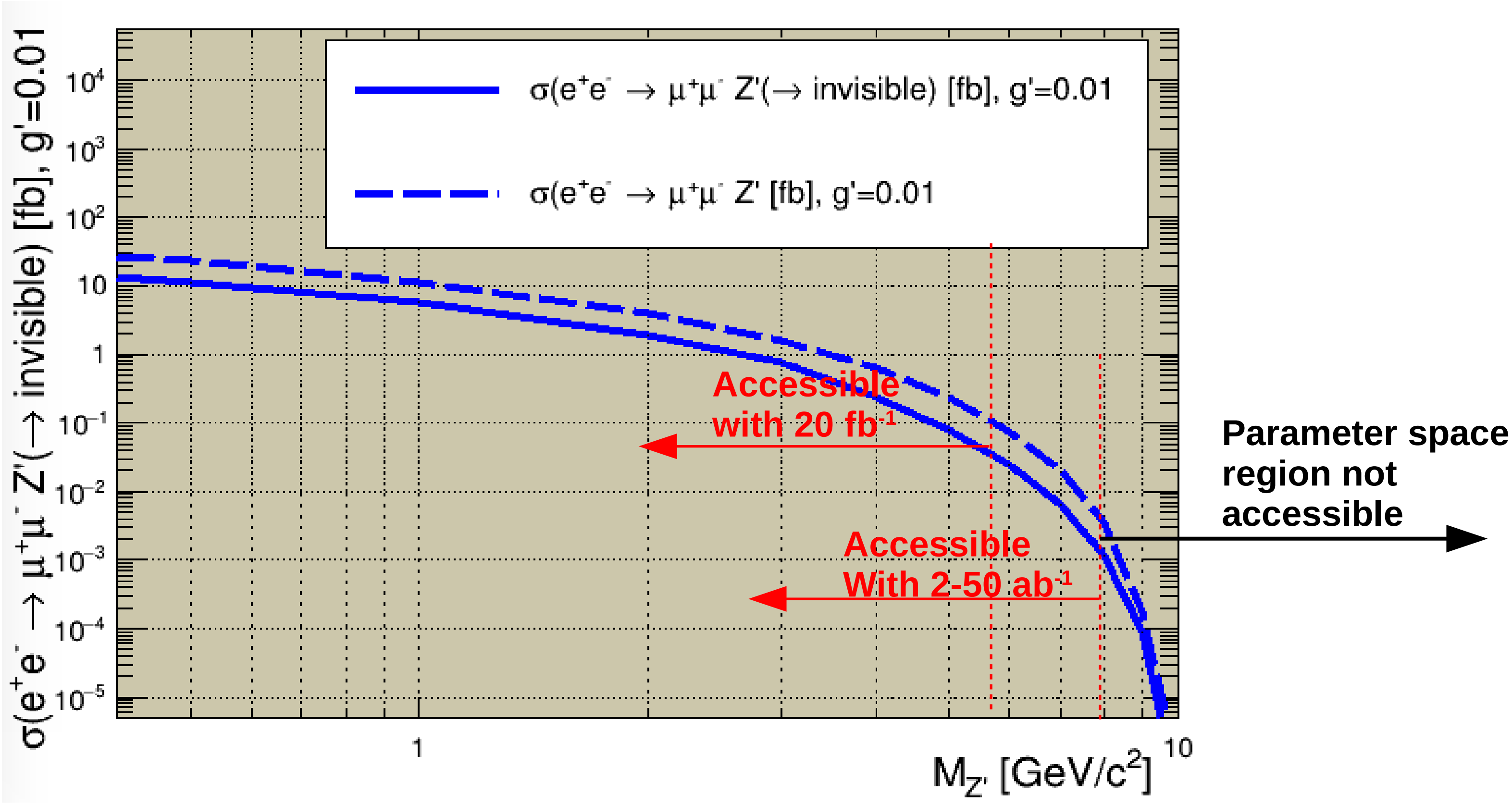
- Cross section provided by MadGraph for $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \nu_\mu \bar{\nu}_\mu$ and multiplied by a factor 2 to account for $Z' \to \nu_\tau \bar{\nu}_\tau$ as this is the other channel that contribute to the invisible decays of Z’.

- 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



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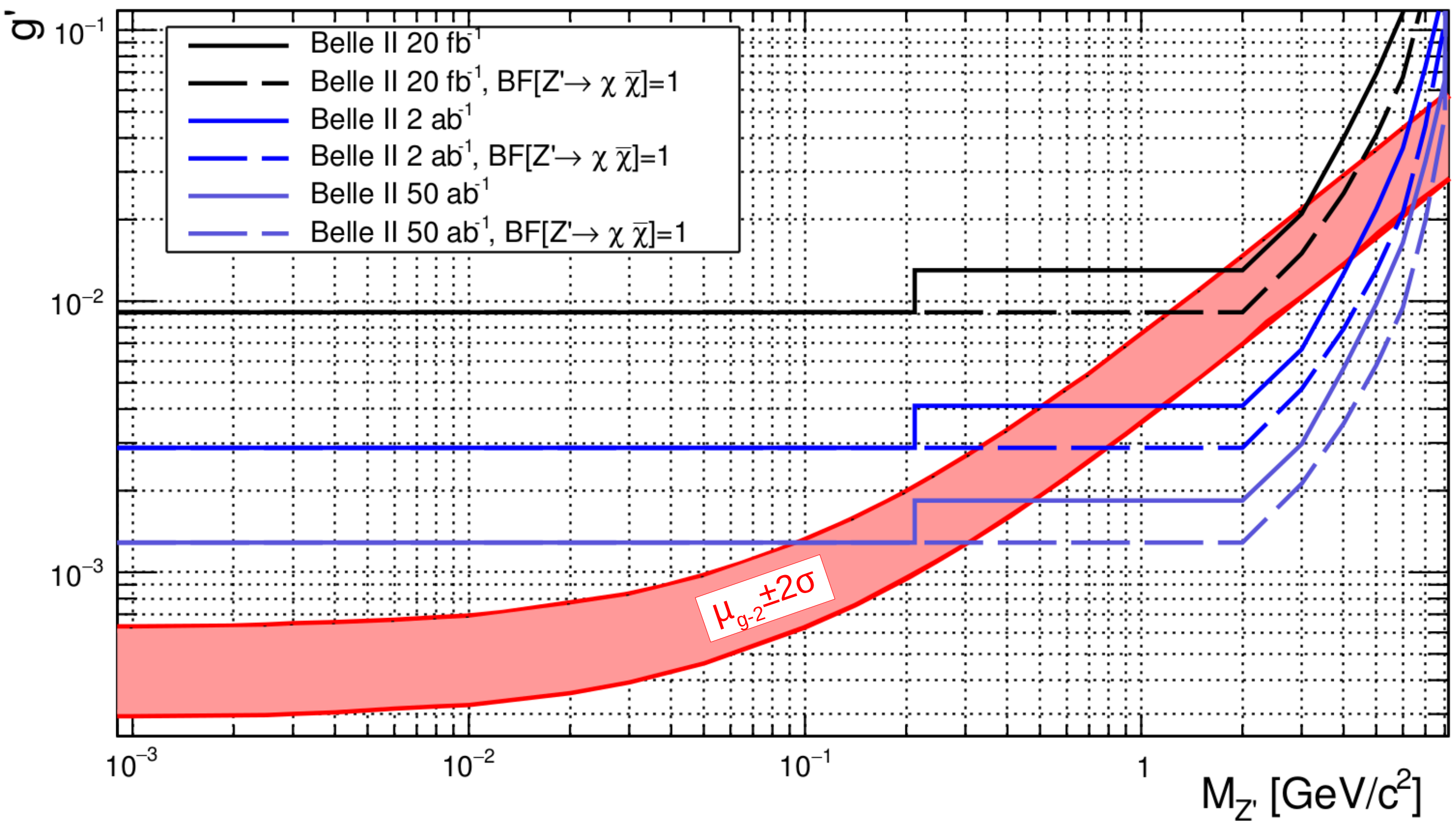
Belle II, expected sensitivity for Z’→invisible

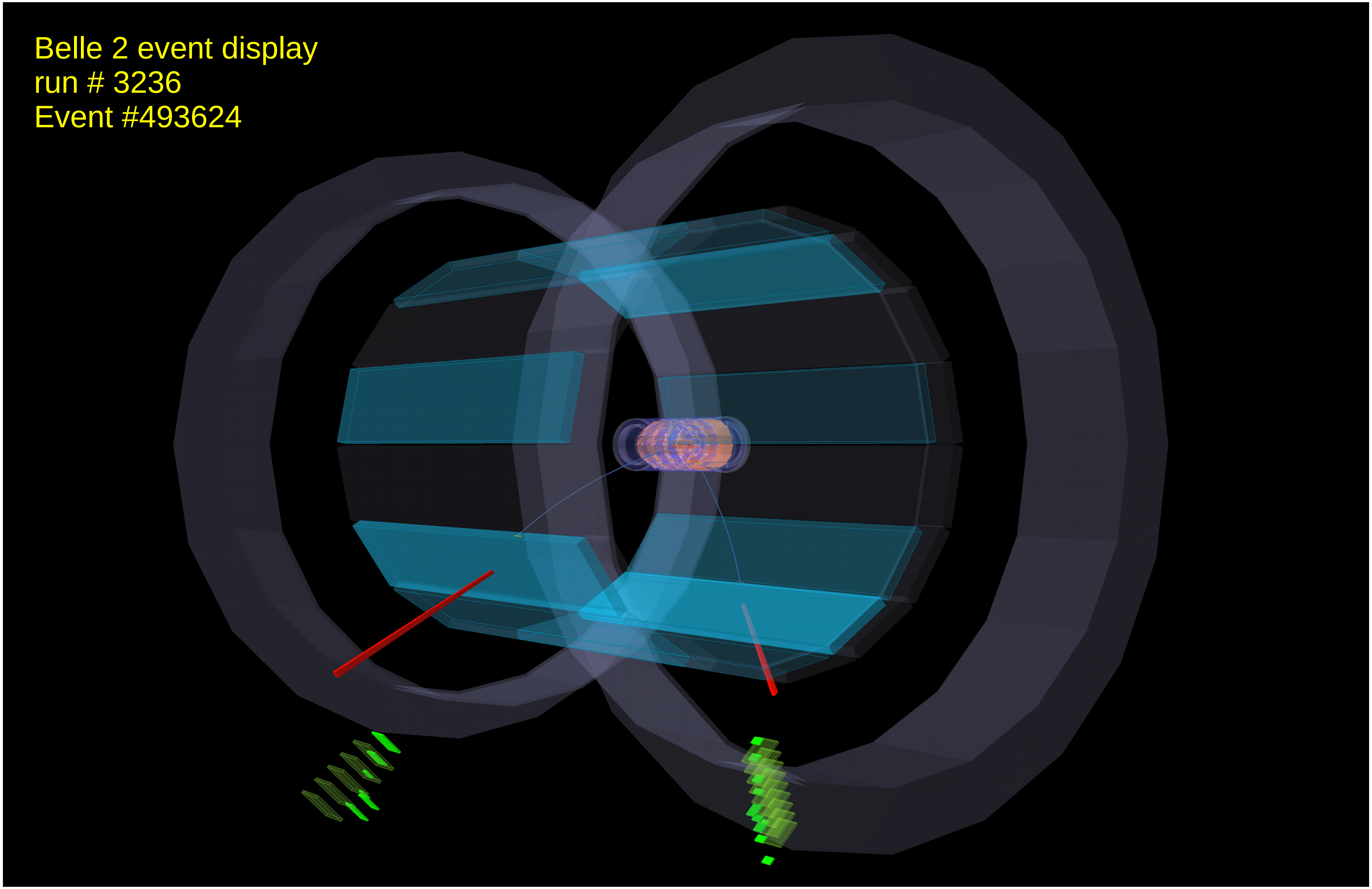
- Based only on expected background and luminosity
- Expected upper limits to g’ value at 90% C.L.
- Bad mass resolution on the signal at low masses affects final sensitivity



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

- Red band shows the preferred (±2σ) region of the parameter space assuming the muon g-2 anomaly being generated by a Z’ boson.

Belle II 2018 data, event display



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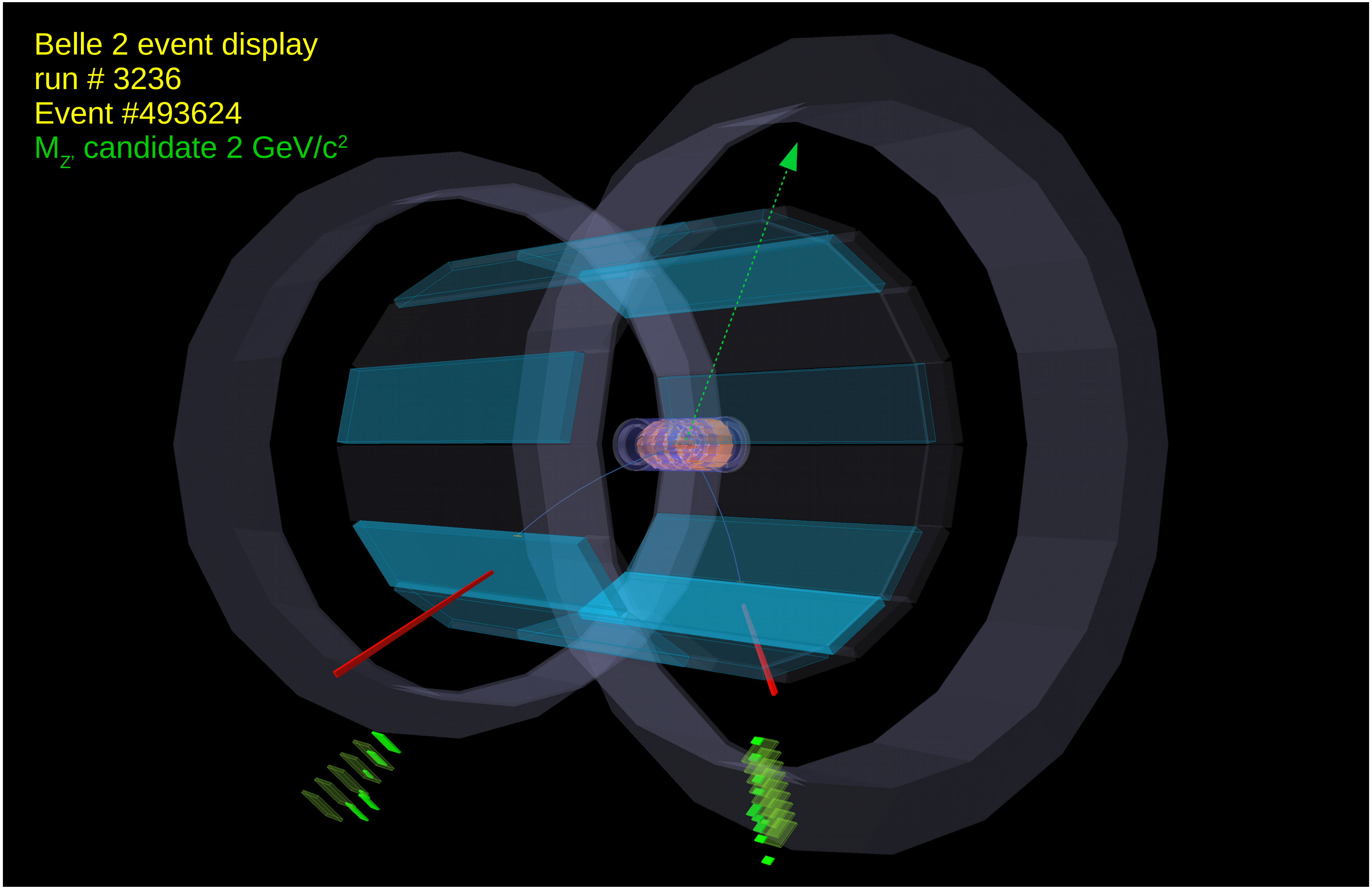
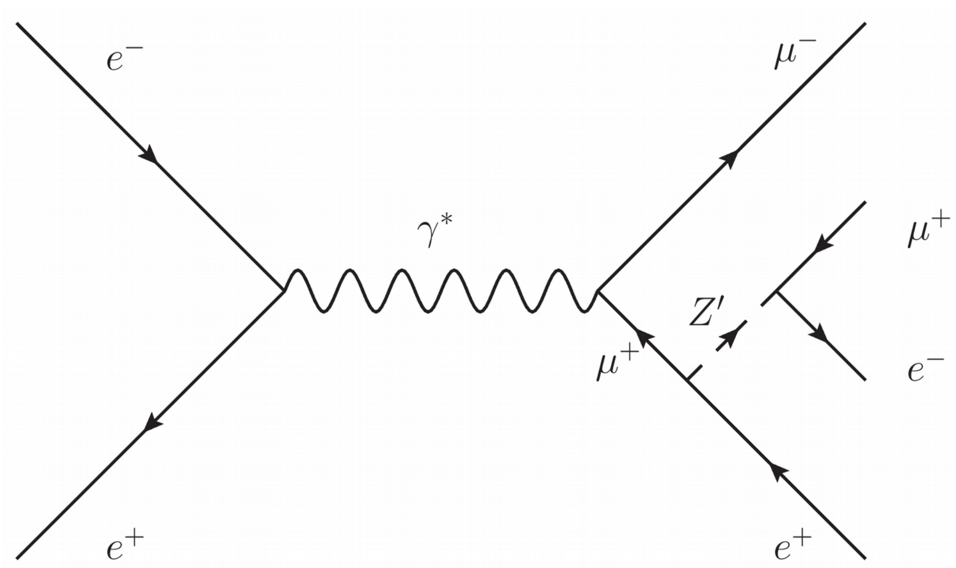


What about (charged) Lepton Flavour Violation

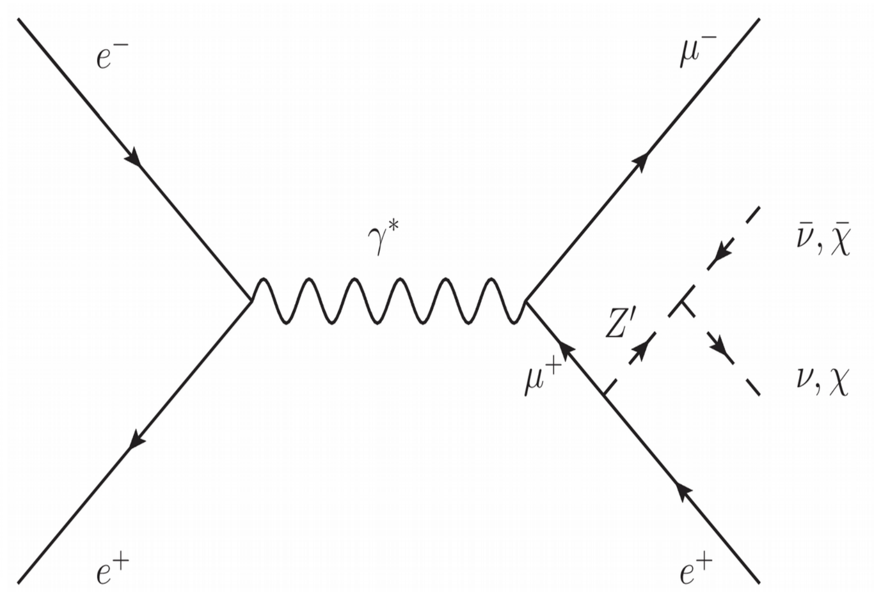
We consider now a different model, in which the Z' does not couple only to *e* and *μ*, but it couples to all leptons and we allow for lepton flavour violation.

See for example arXiv:1610.08060 or ArXiv:1701.08767

What about (charged) Lepton Flavour Violation



$final\ state: e^+ e^- \mu^+ \mu^-$



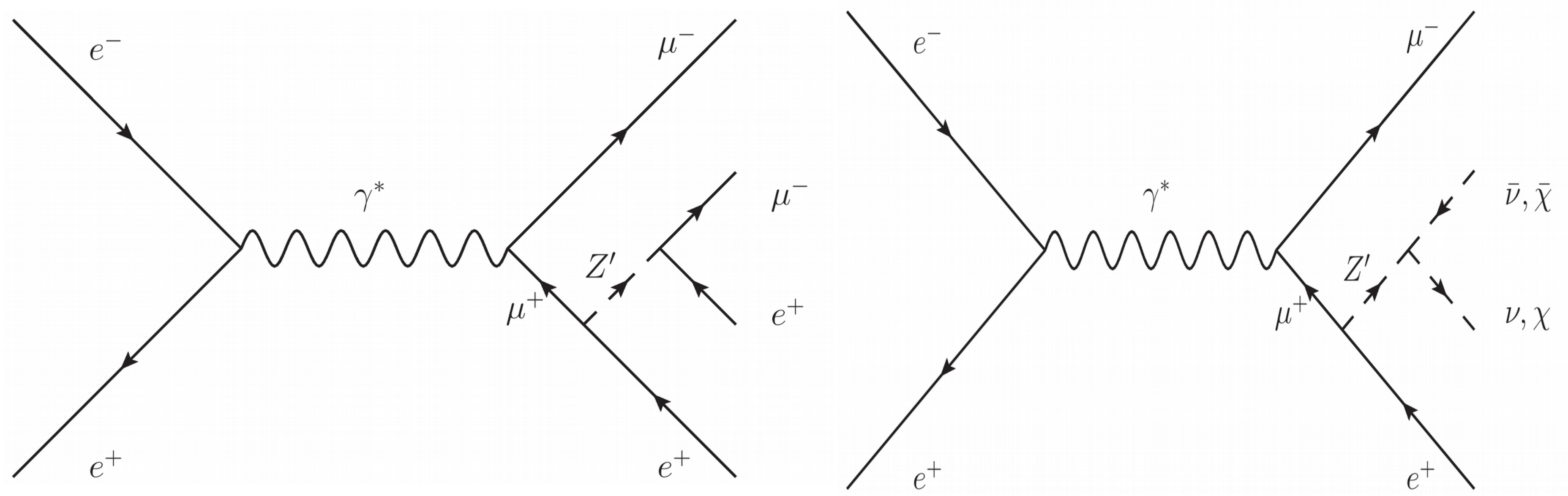
$final\ state: e^+ \mu^- + invisible\,(+c.c.)$

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

- Work in progress at Belle II

What about (charged) Lepton Flavour Violation



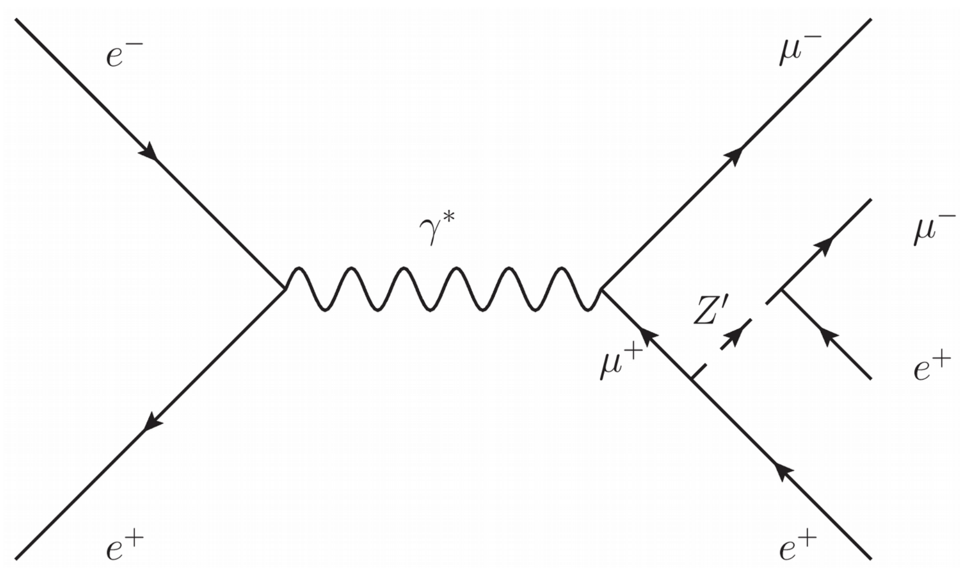
final state: $2e^+ 2\mu^-$ *final state*: $e^+\mu^- + invisible\,(+c.c.)$

See for example ArXiv:1610.08060 or ArXiv:1701.08767

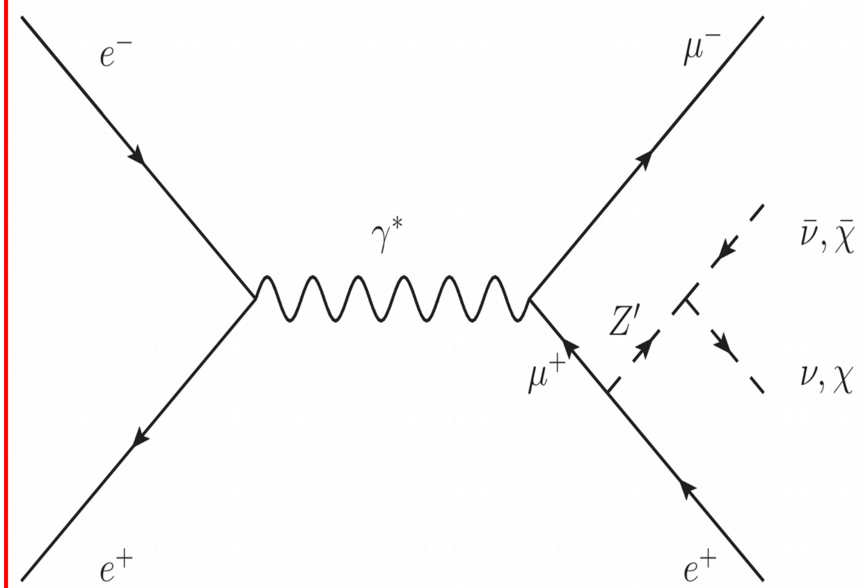
- Complement the search for low mass Z’ and low mass dark sector
- Alternative way to look into cLFV, complementing ongoing searches
- (Almost) background free
- Get a search for doubly charged bosons for free

- Work in progress at Belle II

What about (charged) Lepton Flavour Violation



$final\ state: 2e^+ 2\mu^-$



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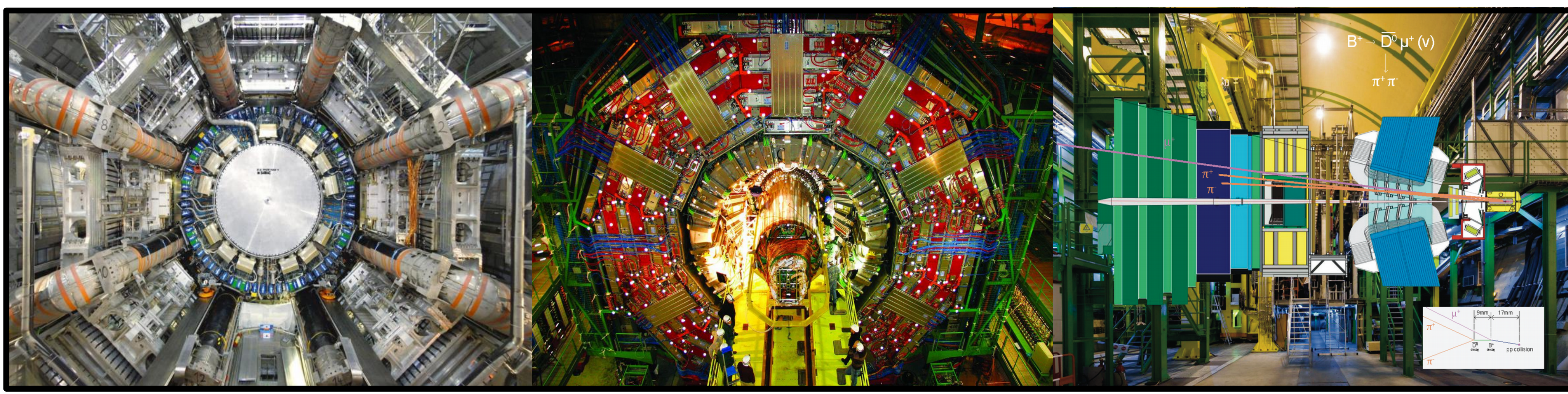
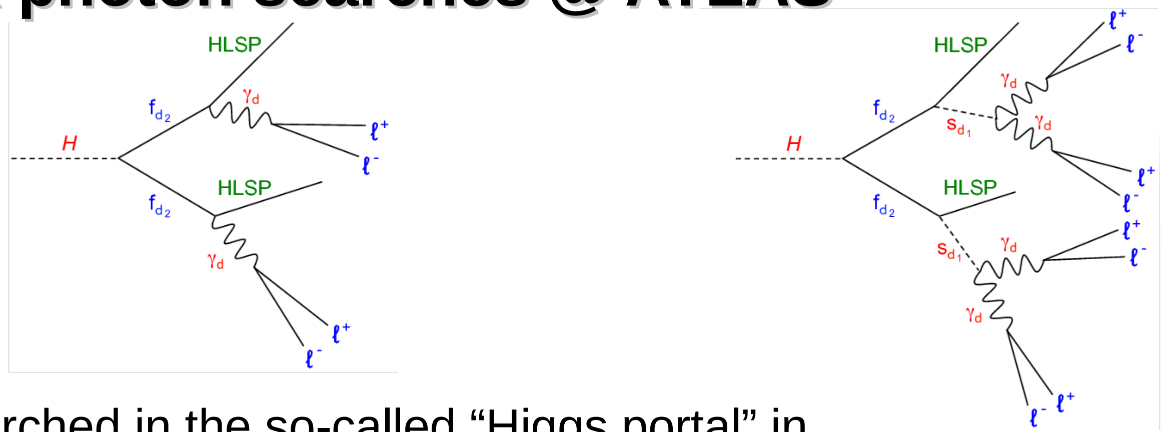
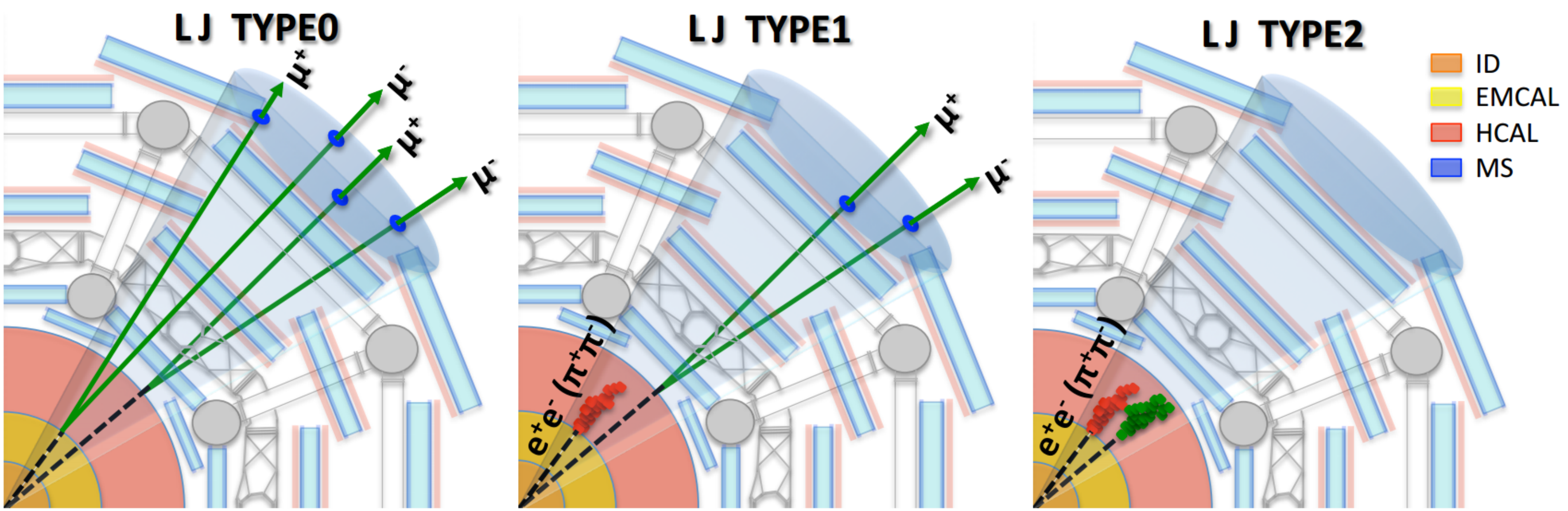
Dark photon searches in pp collisions:
ATLAS, CMS, LHCb



Dark photon searches @ ATLAS

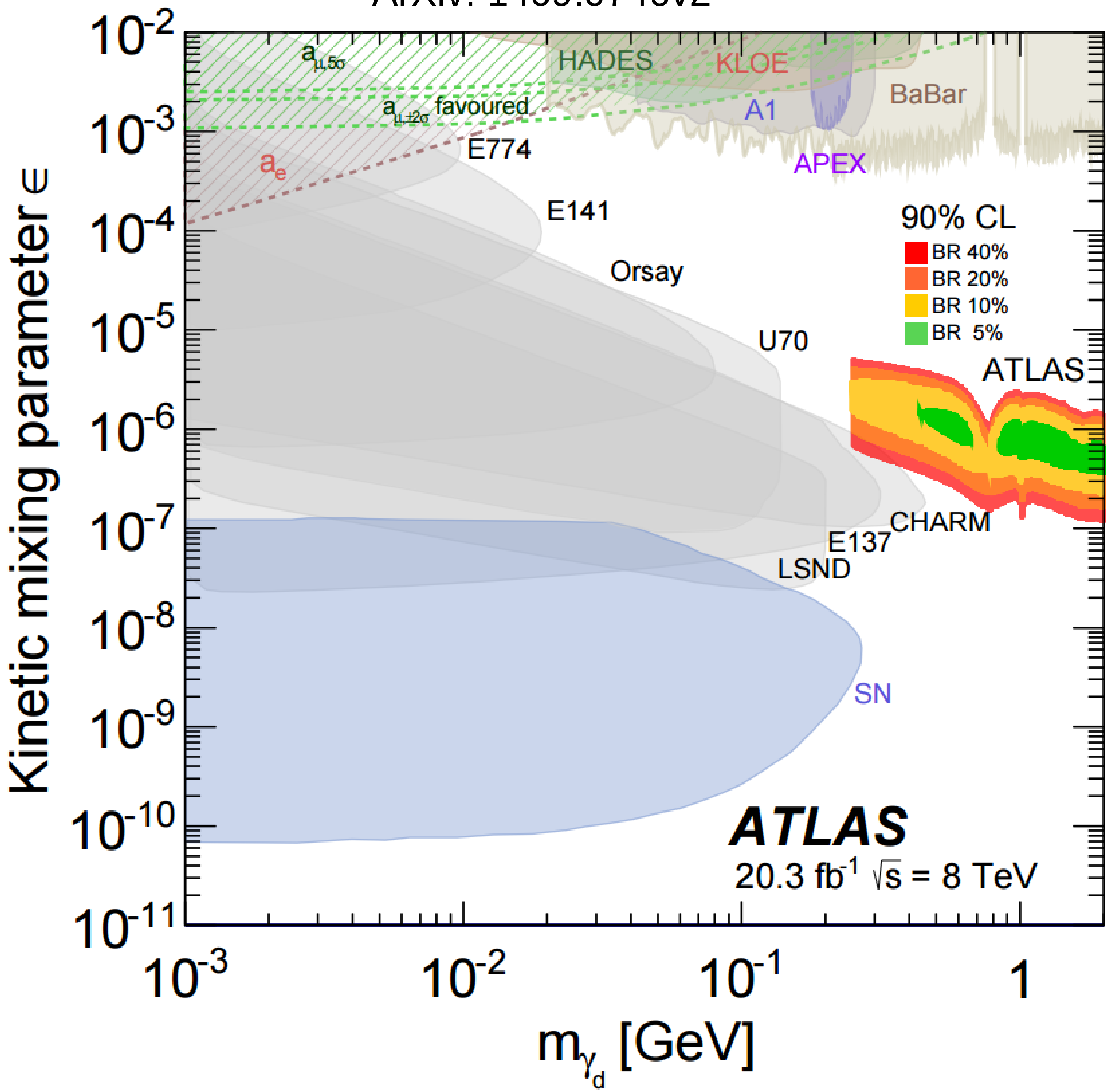


- Dark photon searched in the so-called "Higgs portal" in
  - The Higgs boson decays to dark fermions; dark fermions decay to
    - 1) A Hidden Lightest Stable Particle and a dark photon
    - 2) A Hidden Lightest Stable Particle and a dark scalar
      - The dark scalar decays to a dark photon pair



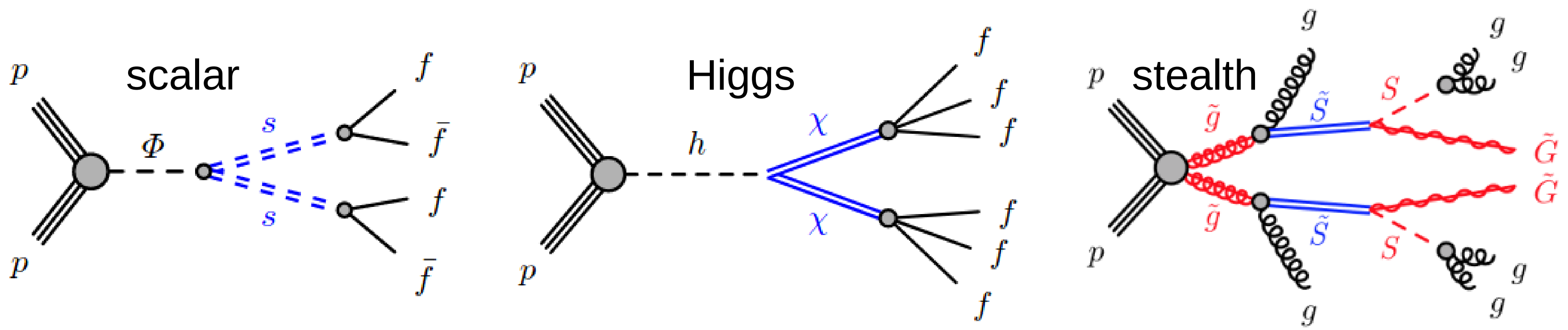
Dark photon searches @ ATLAS

ArXiv: 1409.0746v2



Long lived particle searches @ ATLAS

- arXiv:1811.07370 [hep-ex]
  - Similar techniques as shown before
- Search for macroscopic decay lengths of scalar particles under different assumptions



- The analysis strategy includes:

  1) the case of two observed isolated vertices coming from two long lived particles,

  2) The case in which only one decay vertex is seen in combination with other activity in the detector. This is to increase the sensitivity (probability to observe two long lived particles inside the detector is small for decay lengths grater than 5m).

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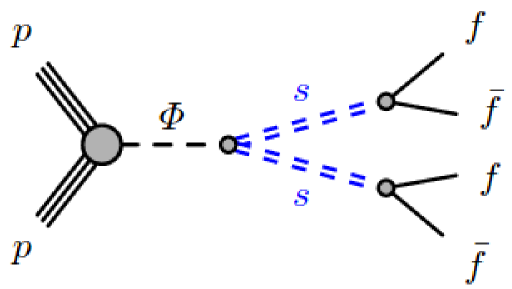

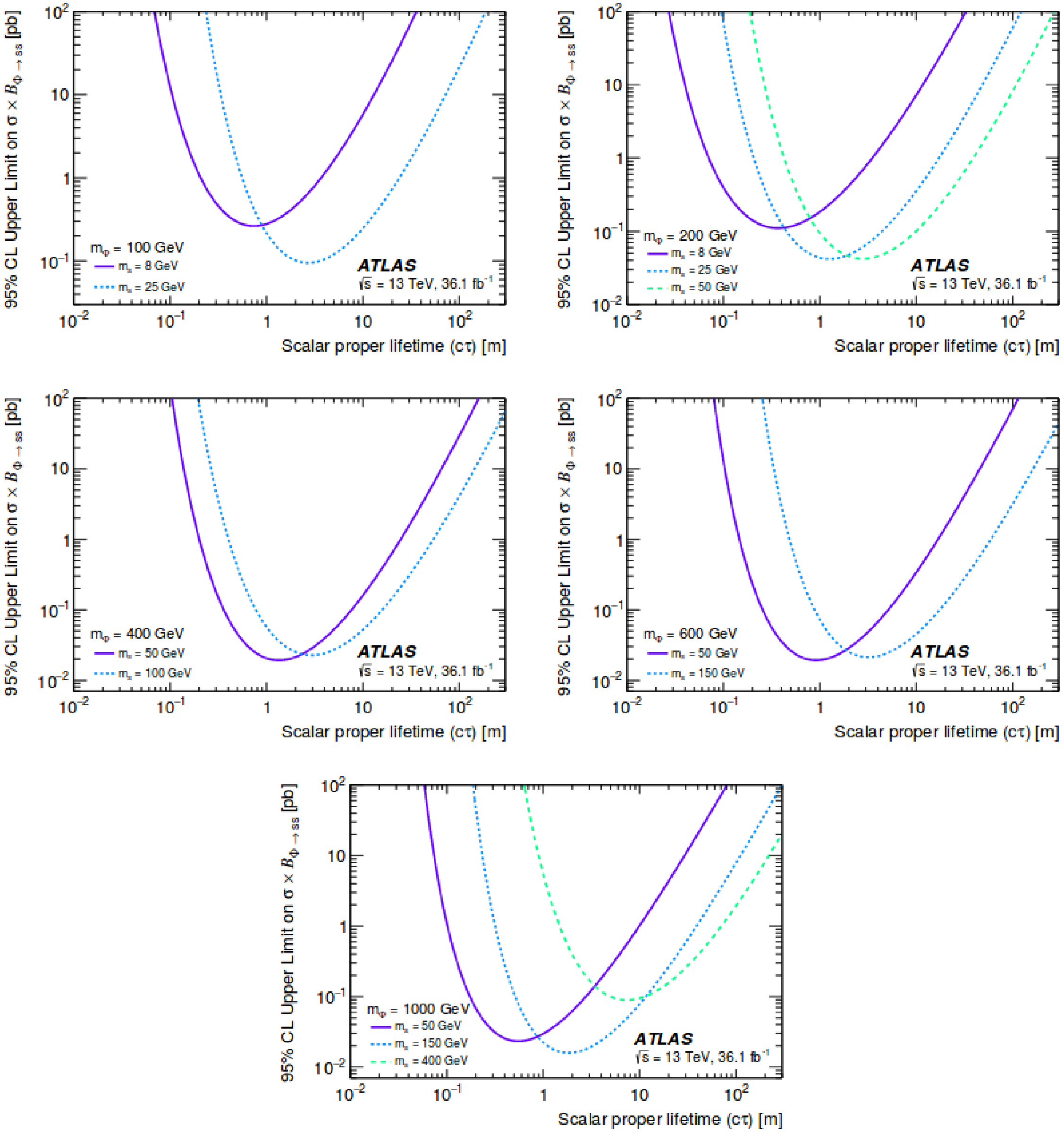

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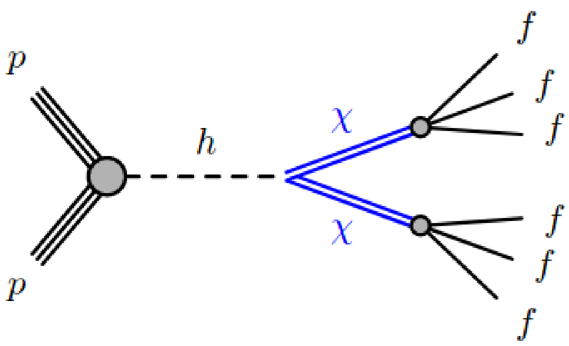
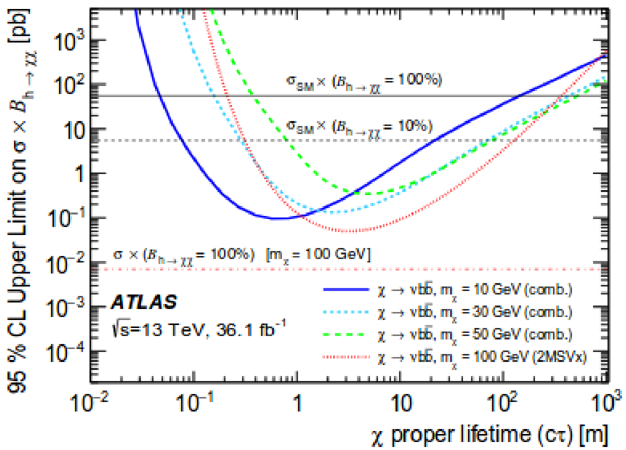
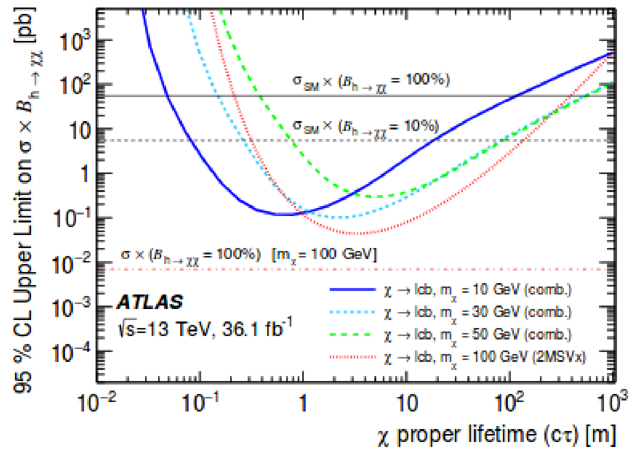
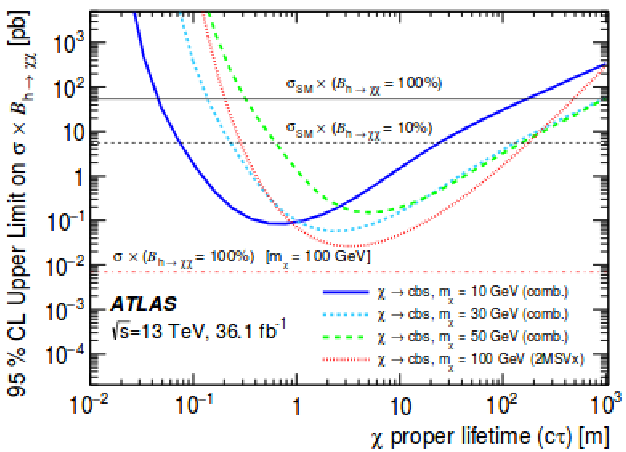




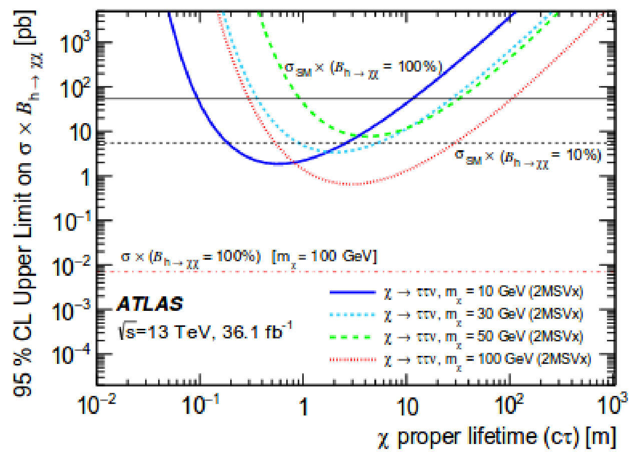
(a)



(b)



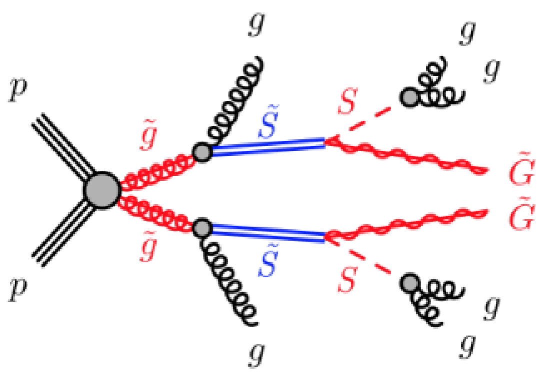
(c)

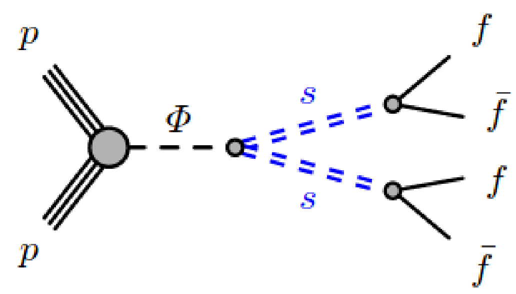


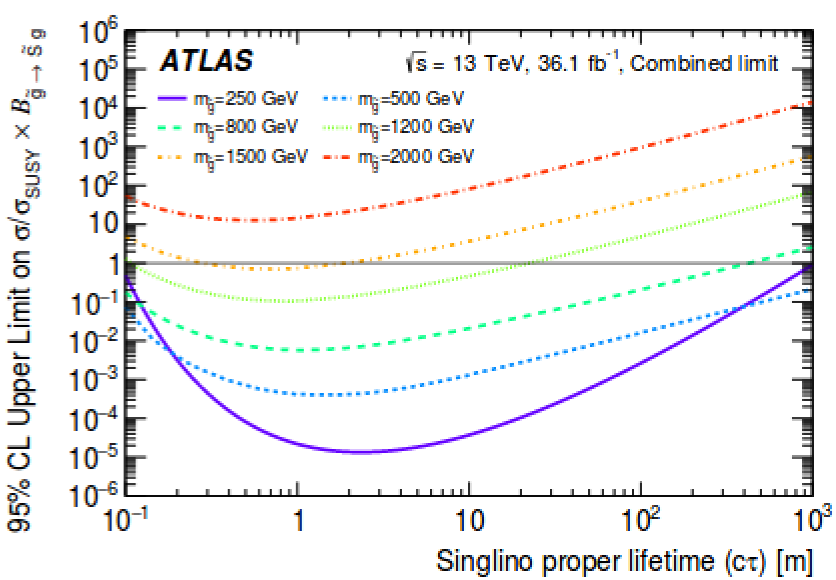
(d)

Long lived particle searches @ ATLAS

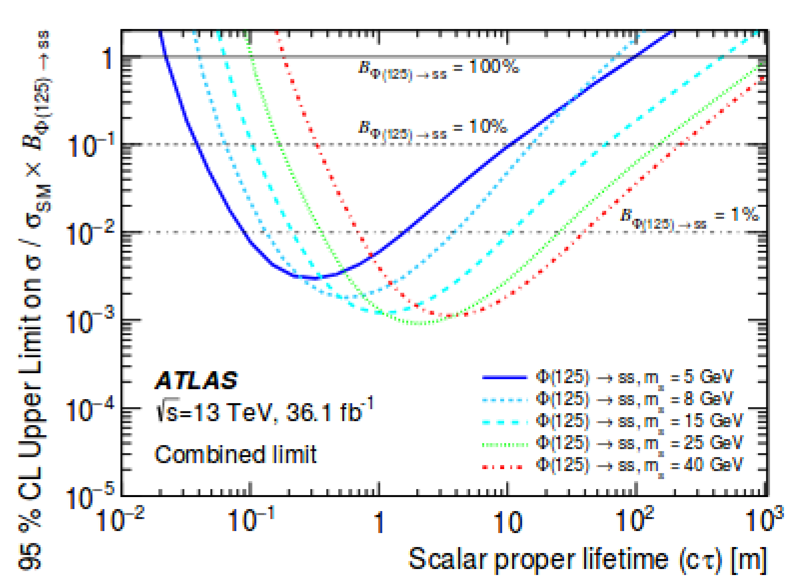
- arXiv:1811.07370 [hep-ex]
  - Similar techniques as shown before
- Search for macroscopic decay lengths of scalar particles under different assumptions







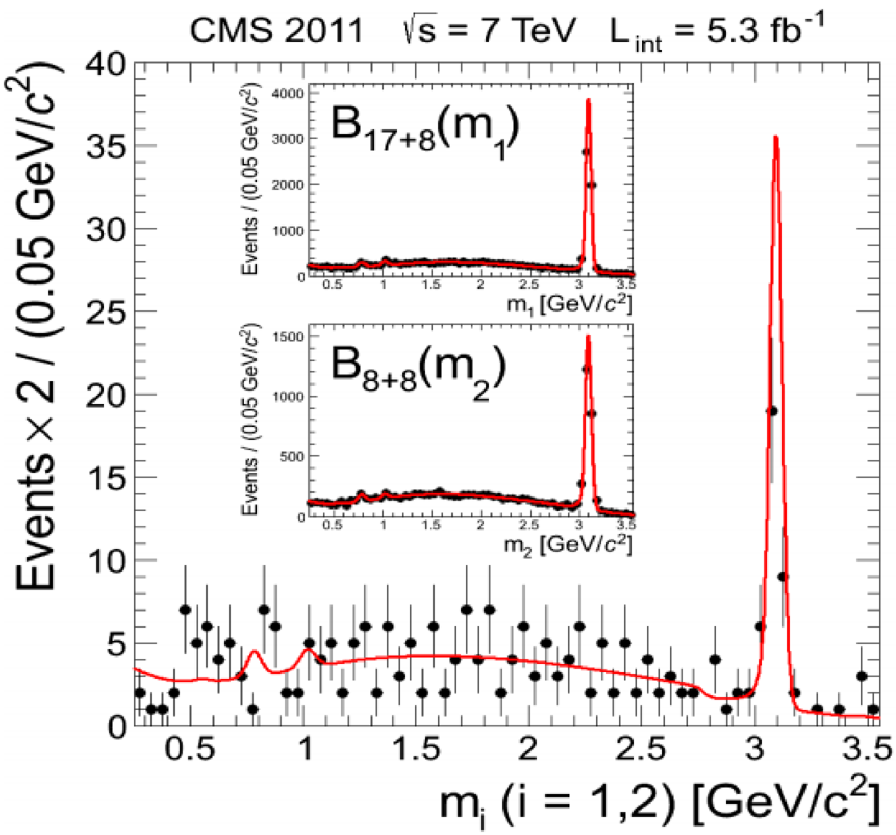
(a)

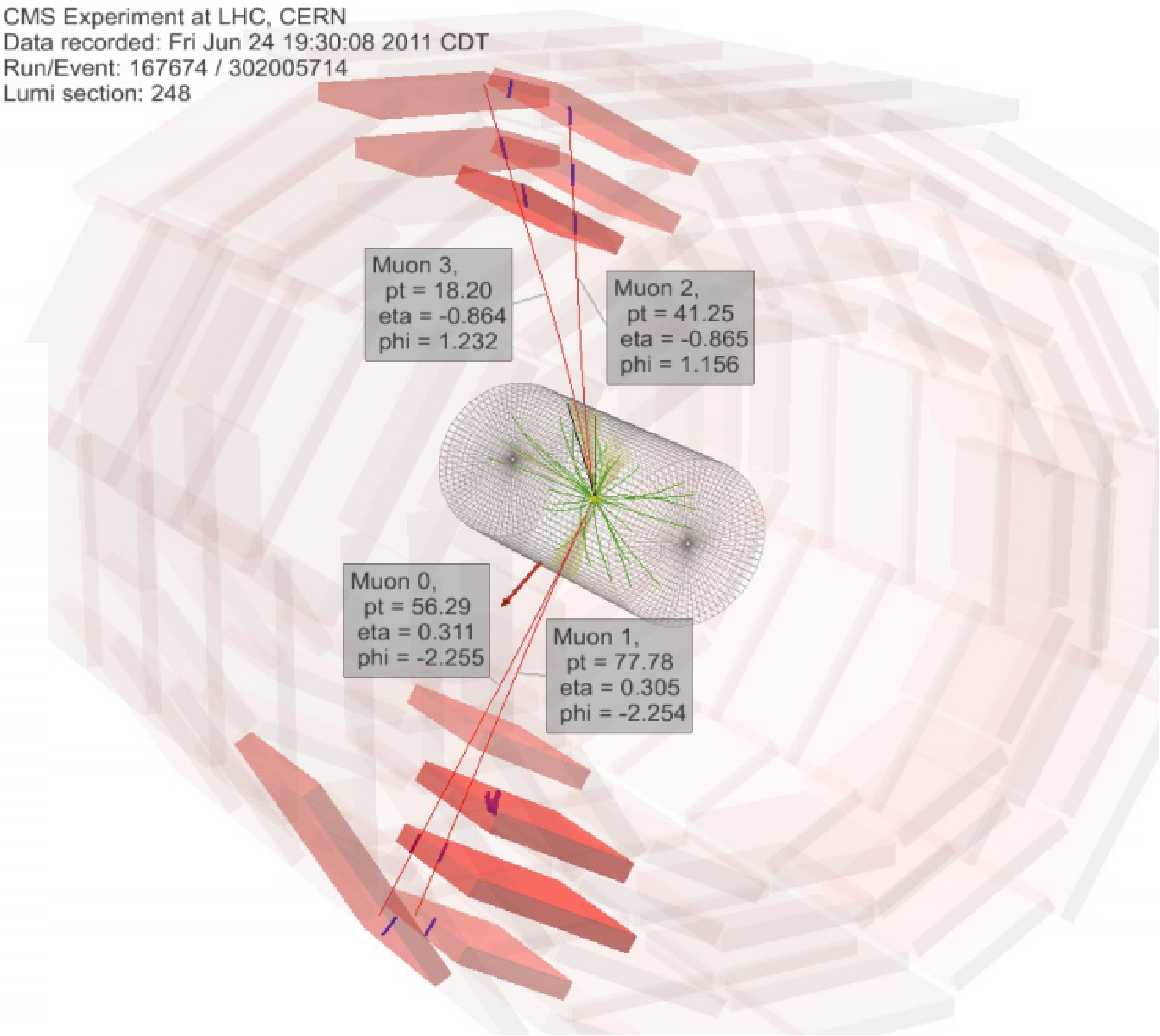


(b)

Dark photon searches @ CMS

- Select 4-muon events
- Look for di-muon invariant mass bump at low mass in *isolated* muon pairs



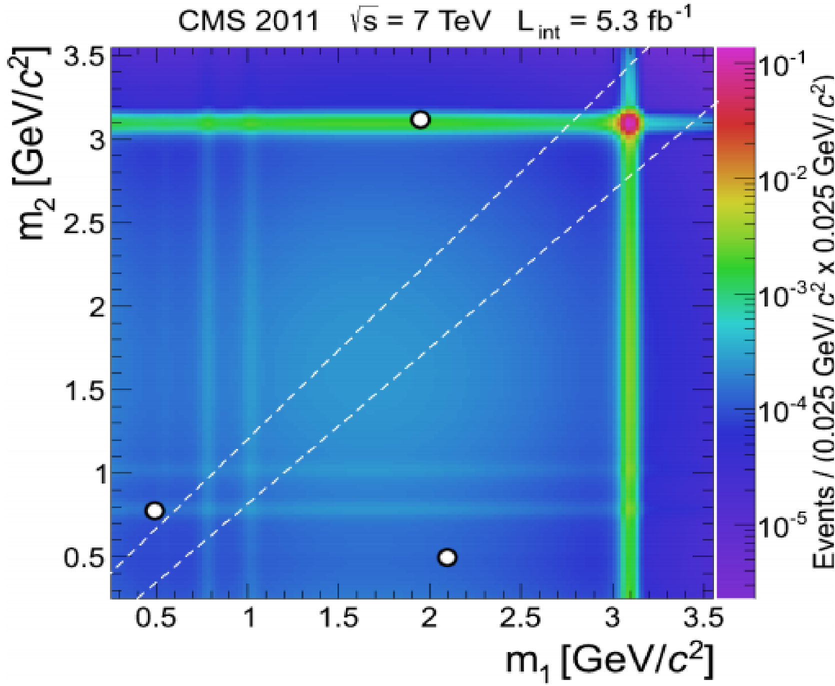


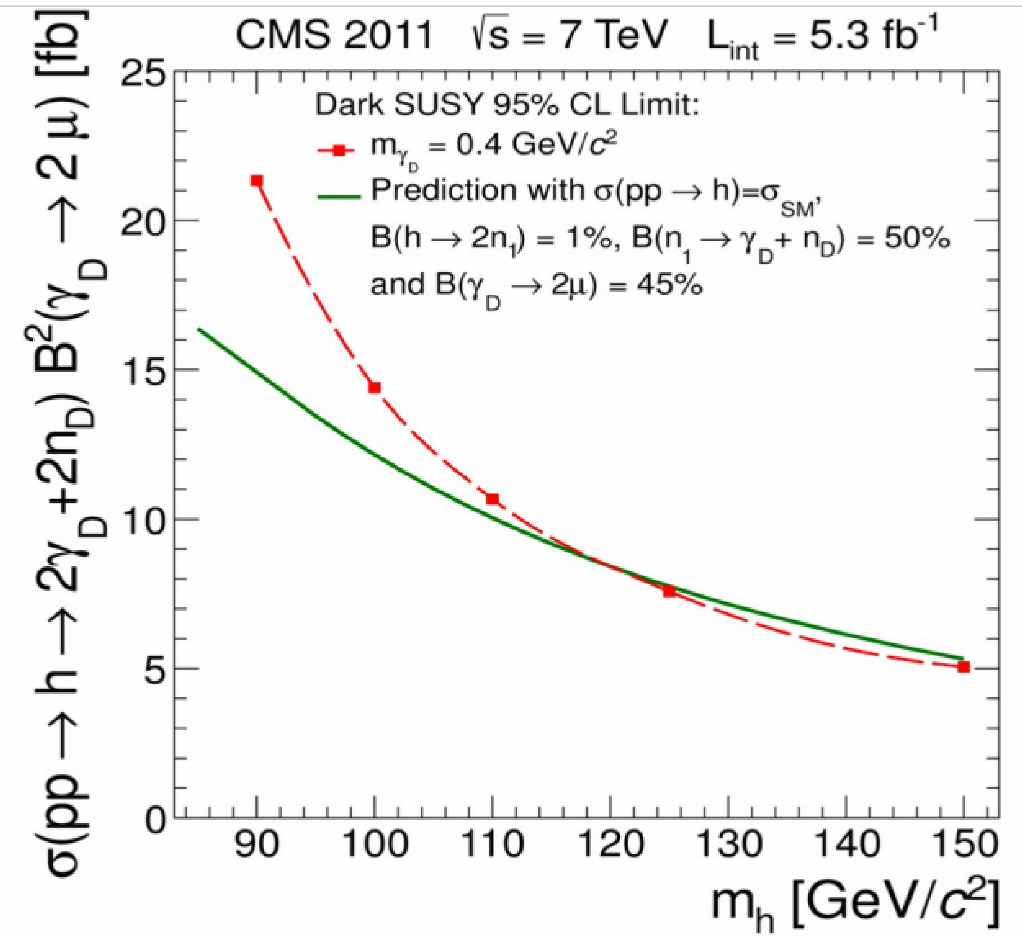
Andy Haas

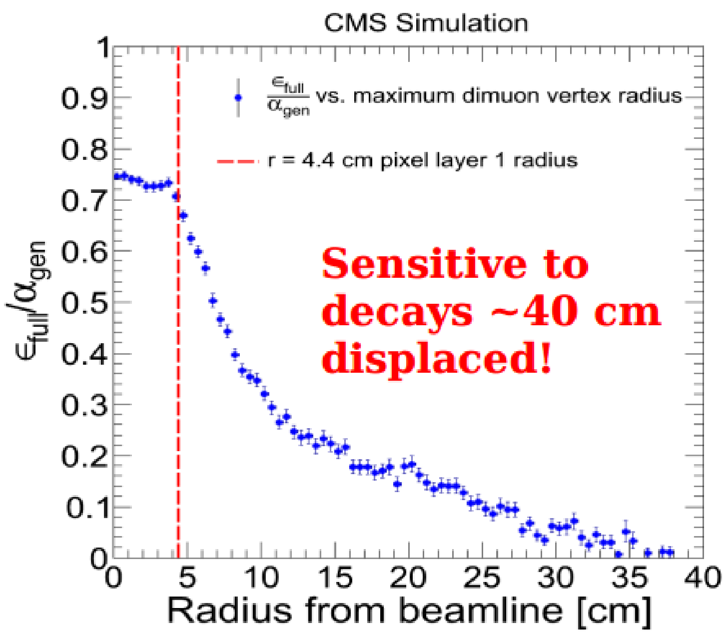
Search for Higgs boson decays to a dark photon pair plus X

Dark photon searches @ CMS

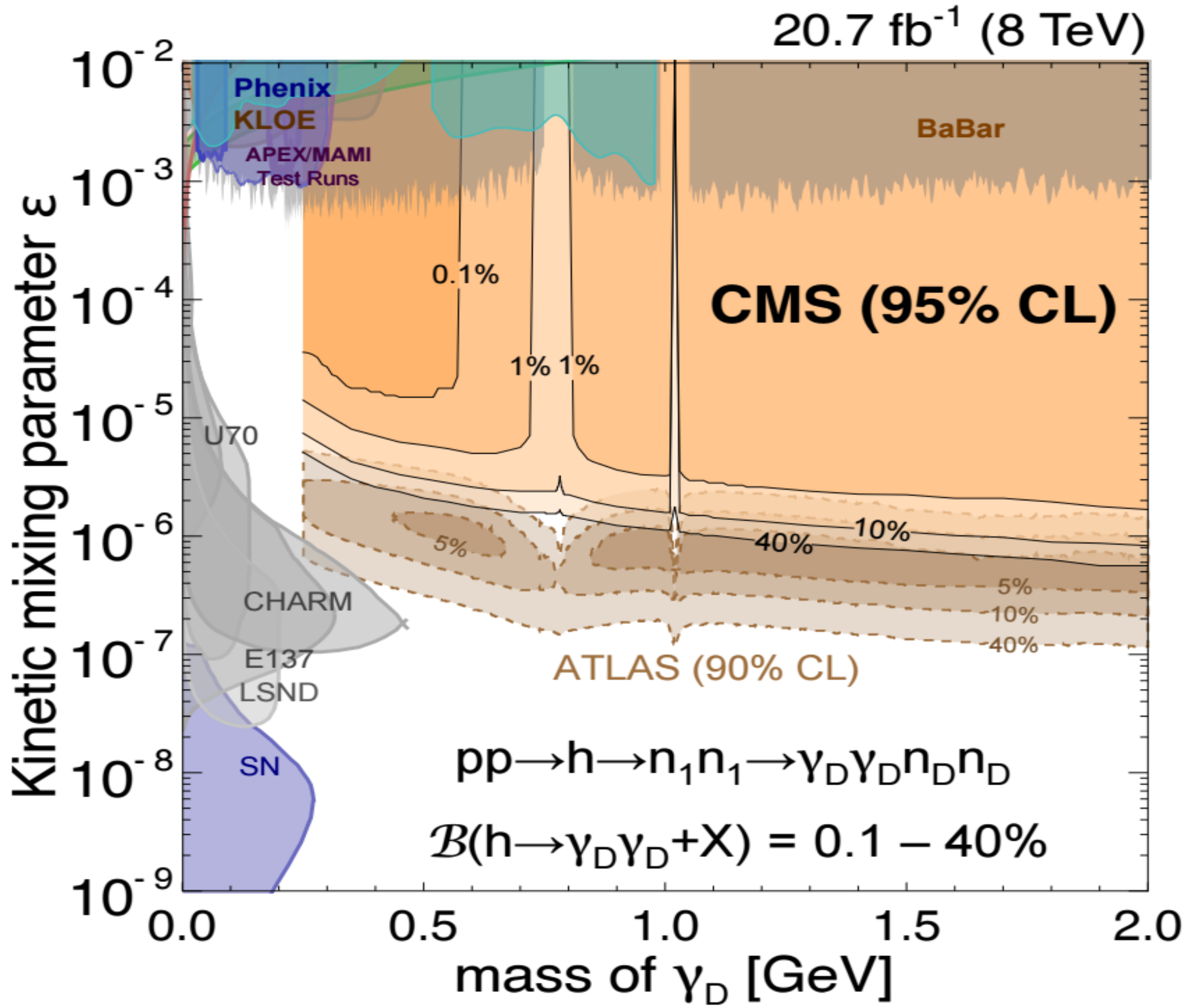
- Look for two mu+ mu- pairs to have the same mass
- Exclude SM H decays with ~1% BR to muon-jets







Dark photon searches @ CMS



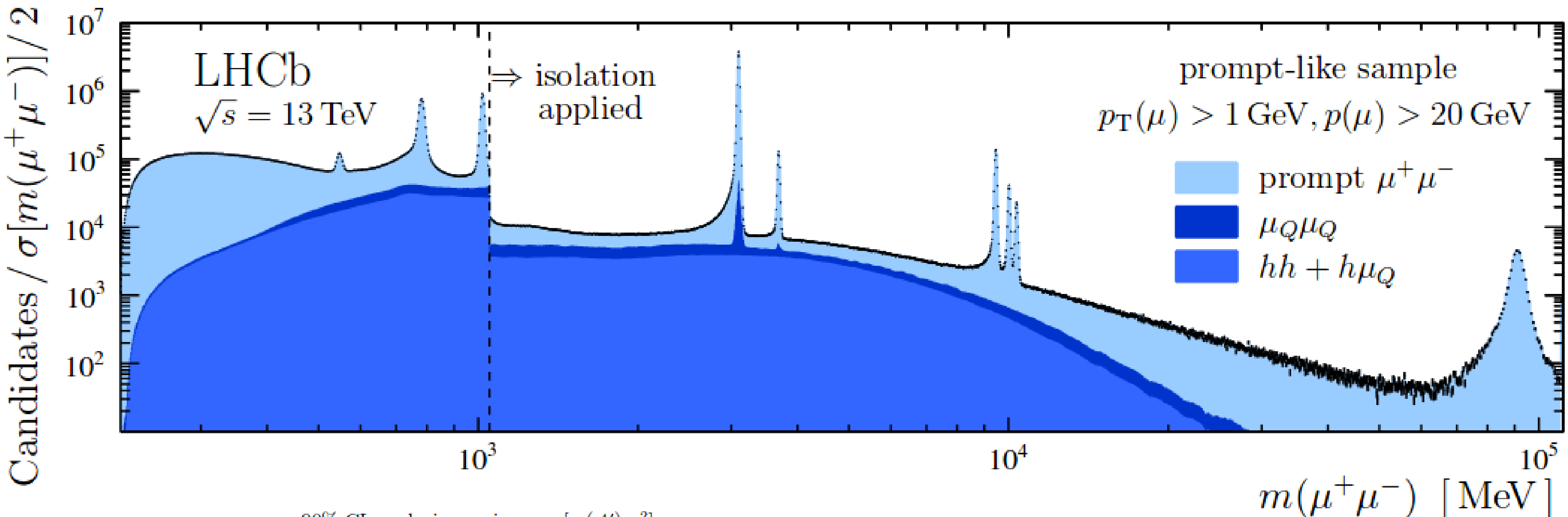
arXiv:1506.00424 [hep-ex]

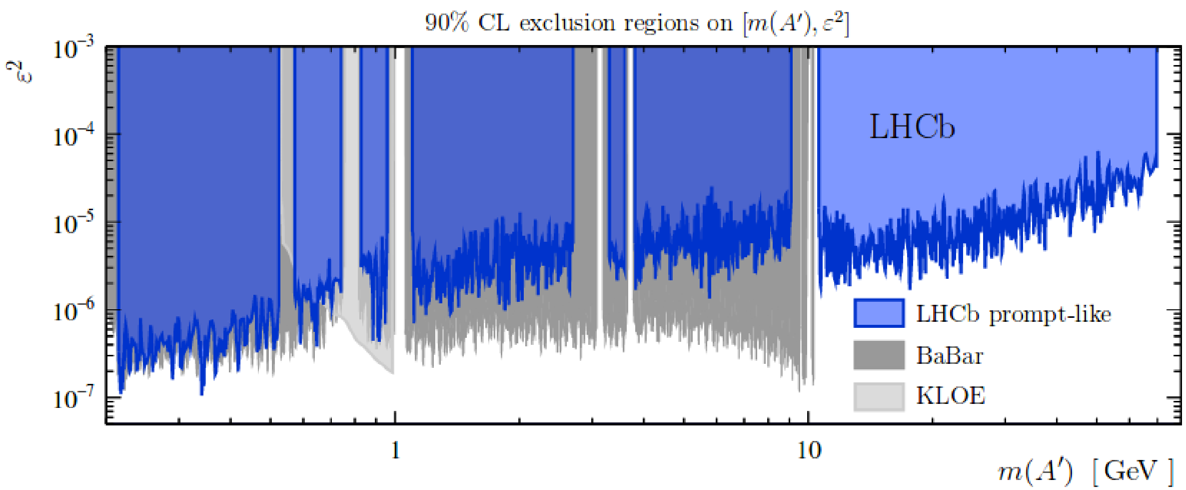
"This search constrains a large, previously unconstrained area of the parameter space. Unlike the other results in the figure, the CMS and ATLAS limits are model-dependent and only valid under the assumption that B(h → 2n1 → 4μ + X) ≠ 0"

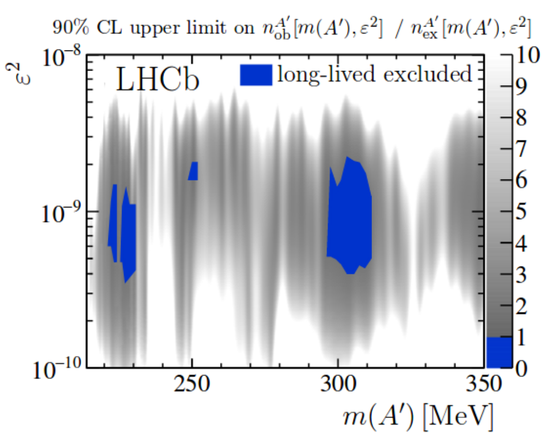
Dark photon searches @ LHCb
A' → $\mu^+\mu^-$, prompt and displaced searches

$$n_{\rm ex}^{A'}[m(A'),\varepsilon^2] = \varepsilon^2 \left[\frac{n_{\rm ob}^{\gamma^*}[m(A')]}{2\Delta m}\right] \mathcal{F}[m(A')]\,\epsilon_{\gamma^*}^{A'}[m(A'),\tau(A')]$$

Phys. Rev. Lett. **120** 061801
ArXiv: 1710.02867 [hep-ex]







Dark photon searches @ LHCb

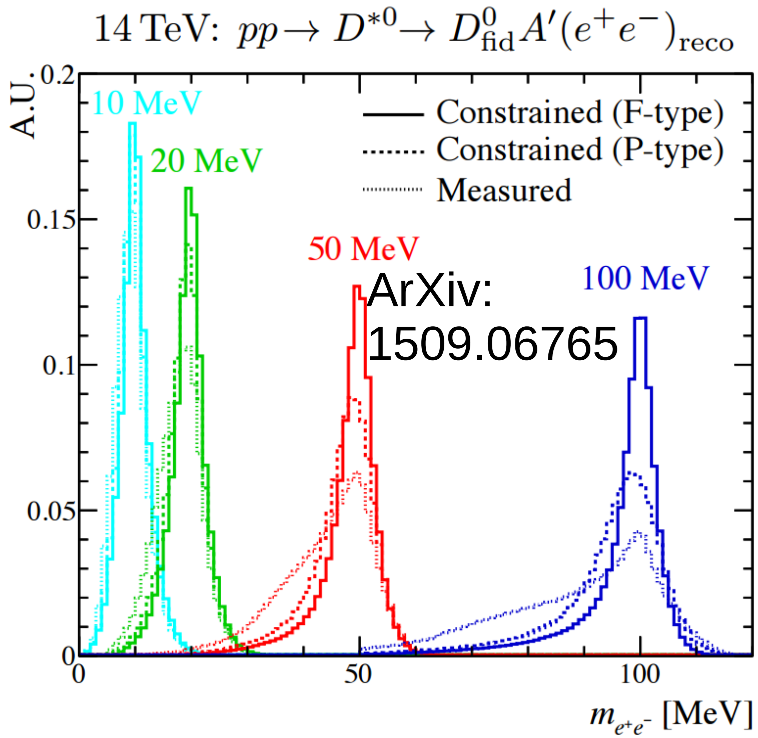
Preliminary studies for run 3: from ~2021

During run 3 LHCb will run in a "triggerless" Mode. Plan to search for

- low mass dark photon in the reaction:

$$D^{*0} \to D^0 \gamma$$

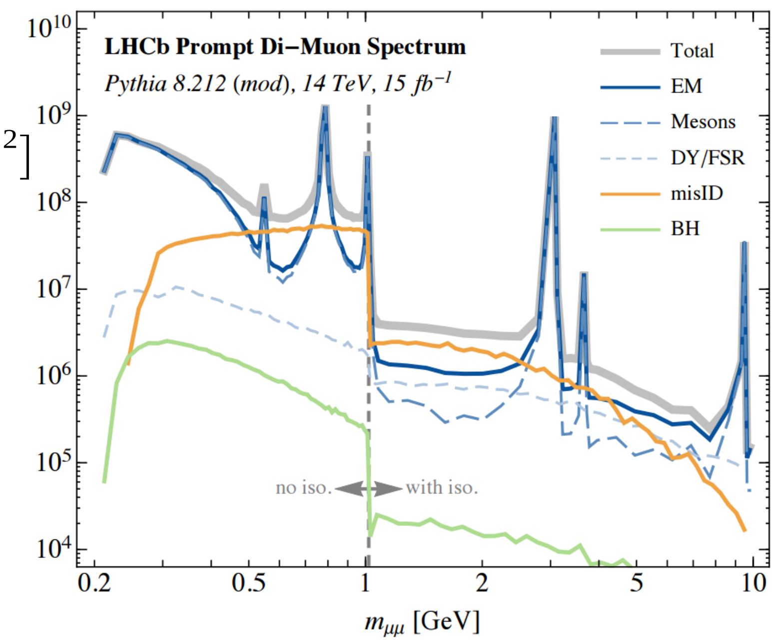
$$\frac{\Gamma(D^{*0}) \to D^0 A'}{\Gamma(D^{*0}) \to D^0 \gamma} = \epsilon^2 \left(1 - \frac{M_{A'}^2}{\Delta m_D^2}\right)^{3/2}$$



- Prompt and displaced vertex decays of the dark photon in the mass region $[2m_\mu, 50\, GeV/c^2]$ in the reaction:

$$pp \to X A', \quad A' \to \mu^+\mu^-$$

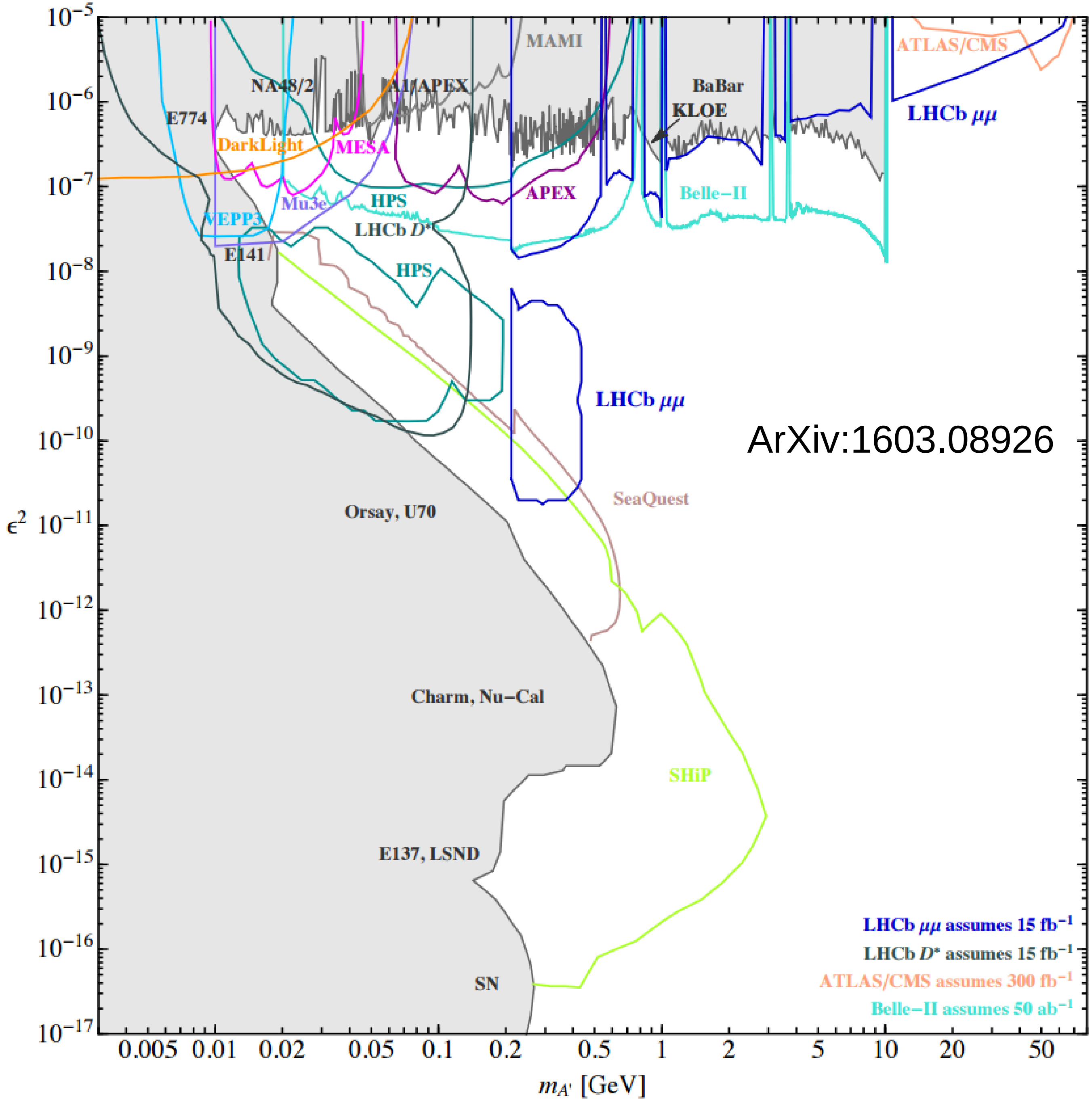
$$\Gamma_{A'} \approx \Gamma(A' \to l^+ l^-) = \frac{1}{3}\alpha\epsilon^2 m_{A'} \sqrt{1 - \frac{4m_l^2}{m_{A'}^2}} \left(1 + \frac{2m_l^2}{m_{A'}^2}\right)$$



ArXiv:1603.08926

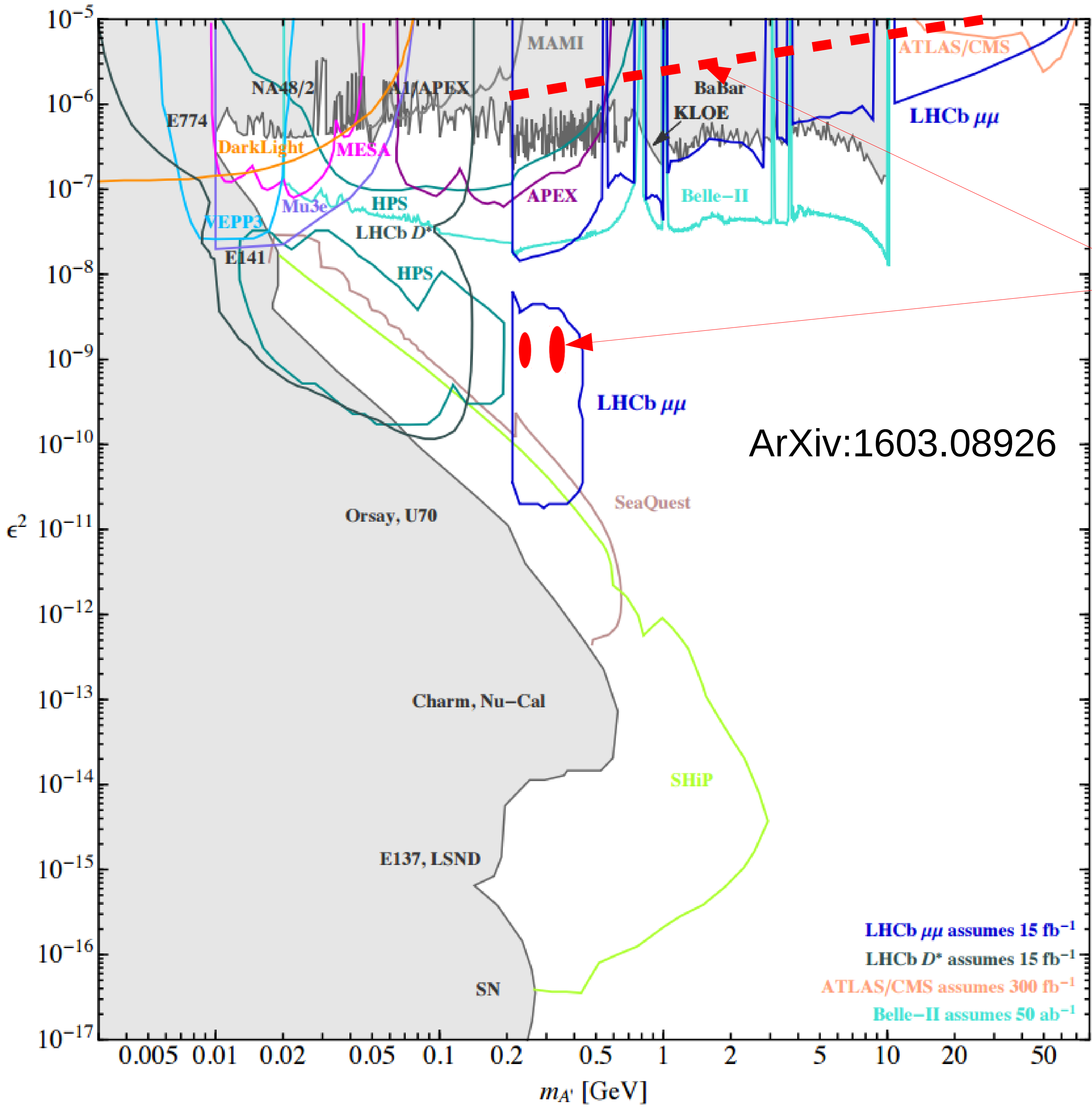
Dark photon searches @ LHCb

Expected sensitivity during run 3: from ~2021



ArXiv:1603.08926

Dark photon searches @ LHCb
Expected sensitivity during run 3: from ~2021



Hand overlay of LHCb 2018 results

Conclusions

- The lack of solid experimental evidences for WIMPs might imply that DM belong to a more complicated dark sector with dark interactions/dark forces.
- Many diverse experiments currently searching an planning searches for dark forces/dark sector.
- Searches are of general interests and many people are joining the effort.
- The “Dark Sectors 2016 Workshop: Community Report”, arXiv:1608.08632, summurise the strategies and the experimental opportunities for the next 5-10 years.

THANK YOU FOR YOUR ATTENTION!

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).