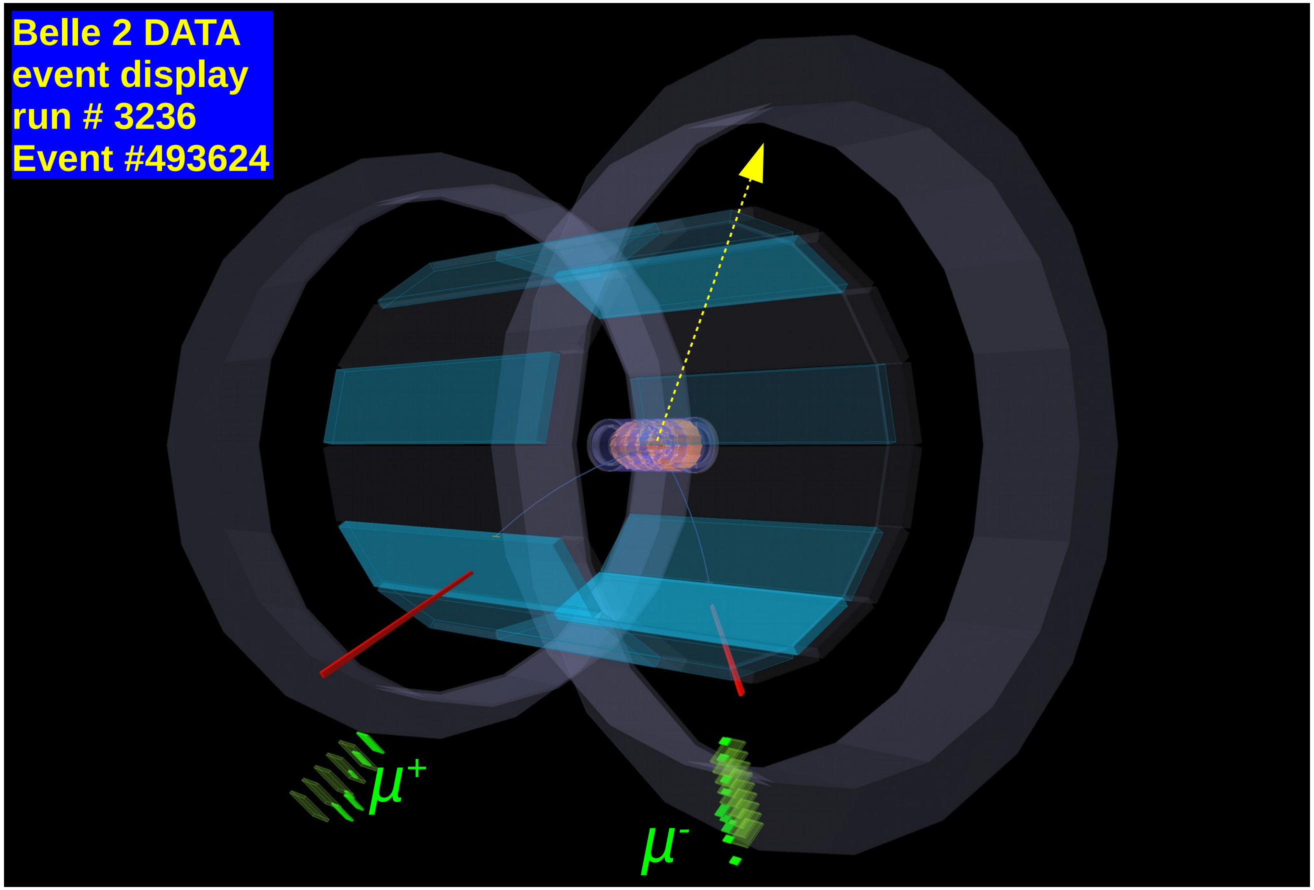
Les Rencontres de Physique de la Vallée d'Aoste
La Thuile 10-16/03/2019




**Gianluca Inguglia**
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*Vienna- Austria*
*(FWF P 31361-N36)*
***gianluca.inguglia@oeaw.ac.at***

***La Thuile 15/03/2019***

# *"Dark Sector Physics @ Belle II"*

HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

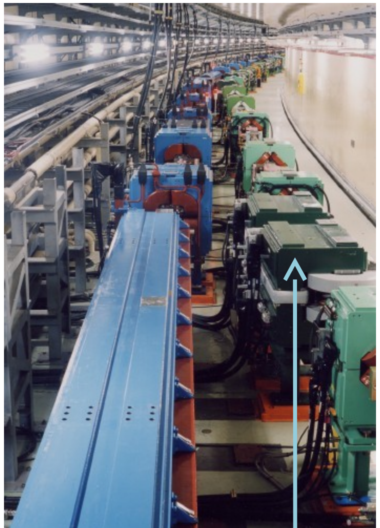
FWF Der Wissenschaftsfonds.

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

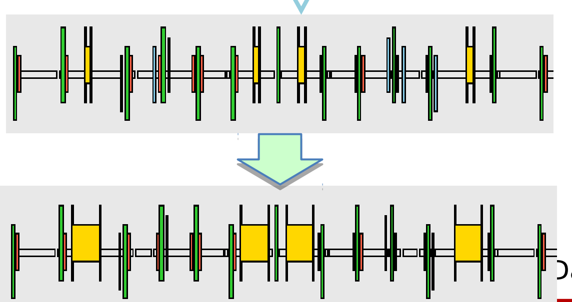
Belle II

See C. Cecchi's talk on Tuesday

# KEKB to SuperKEKB

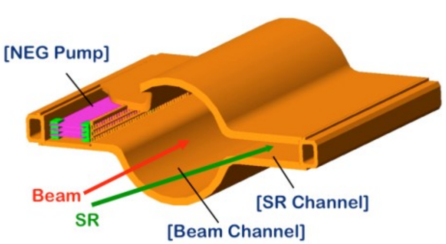


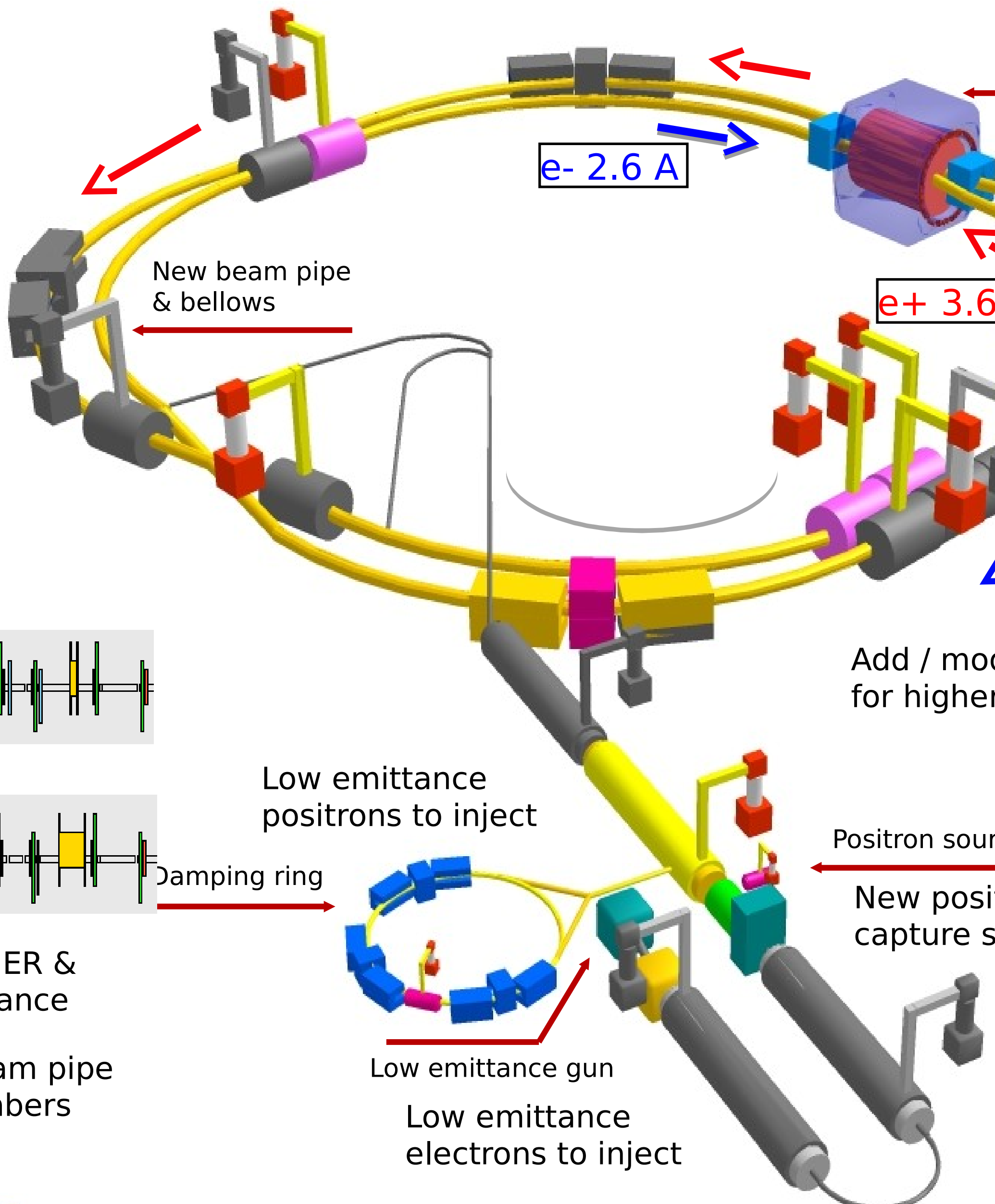
Replace short dipoles with longer ones (LER)



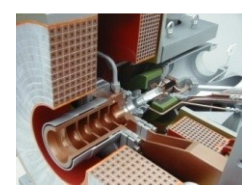
Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

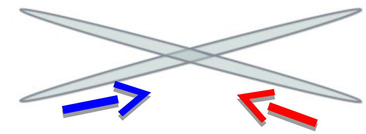


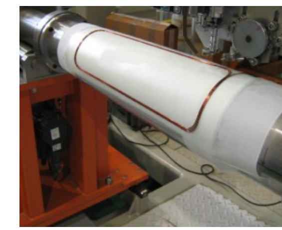

New positron target / capture section



Colliding bunches



New superconducting /permanent final focusing quads near the IP

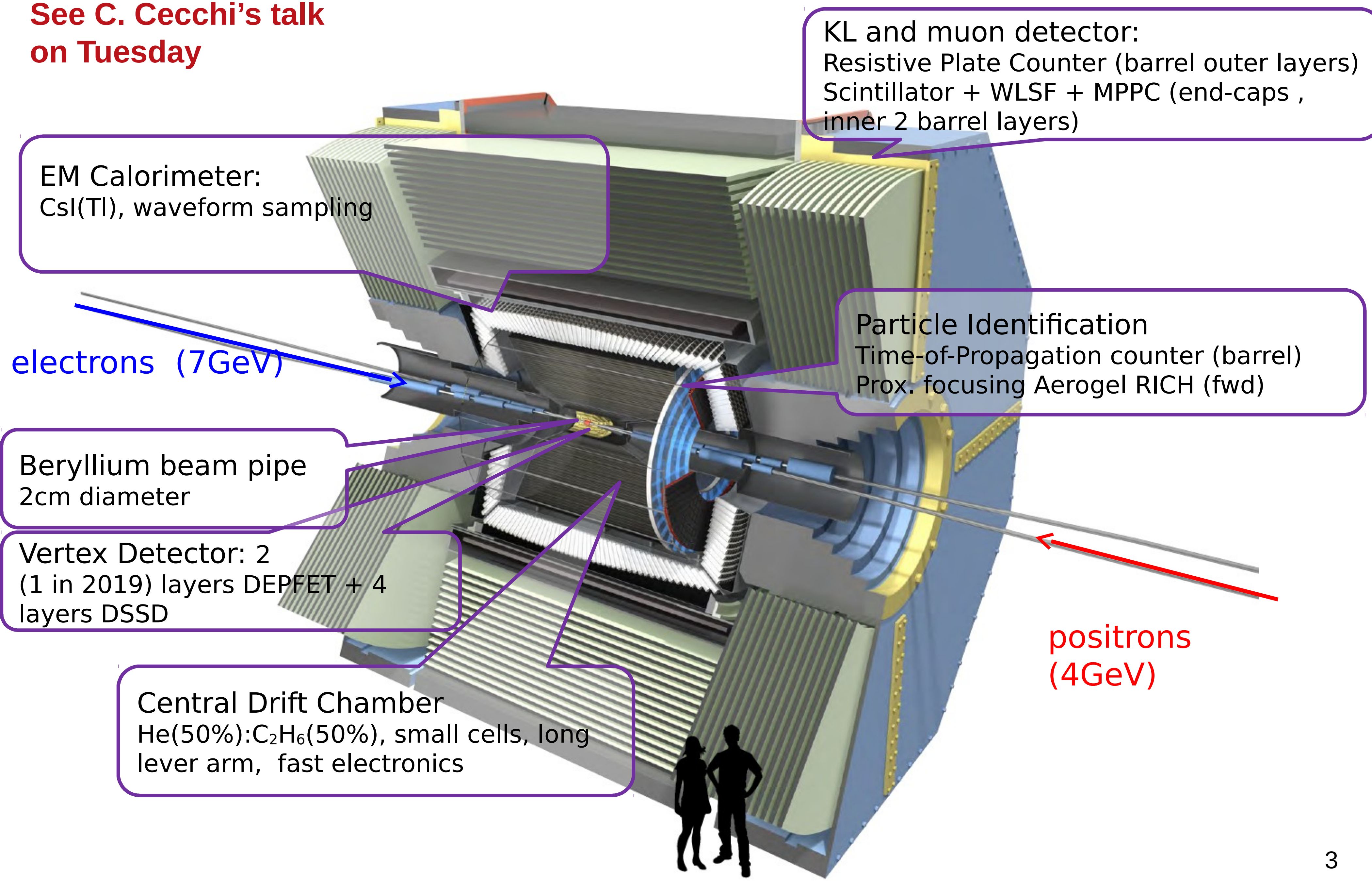


Add / modify RF systems for higher beam current

***To obtain x40 higher luminosity***

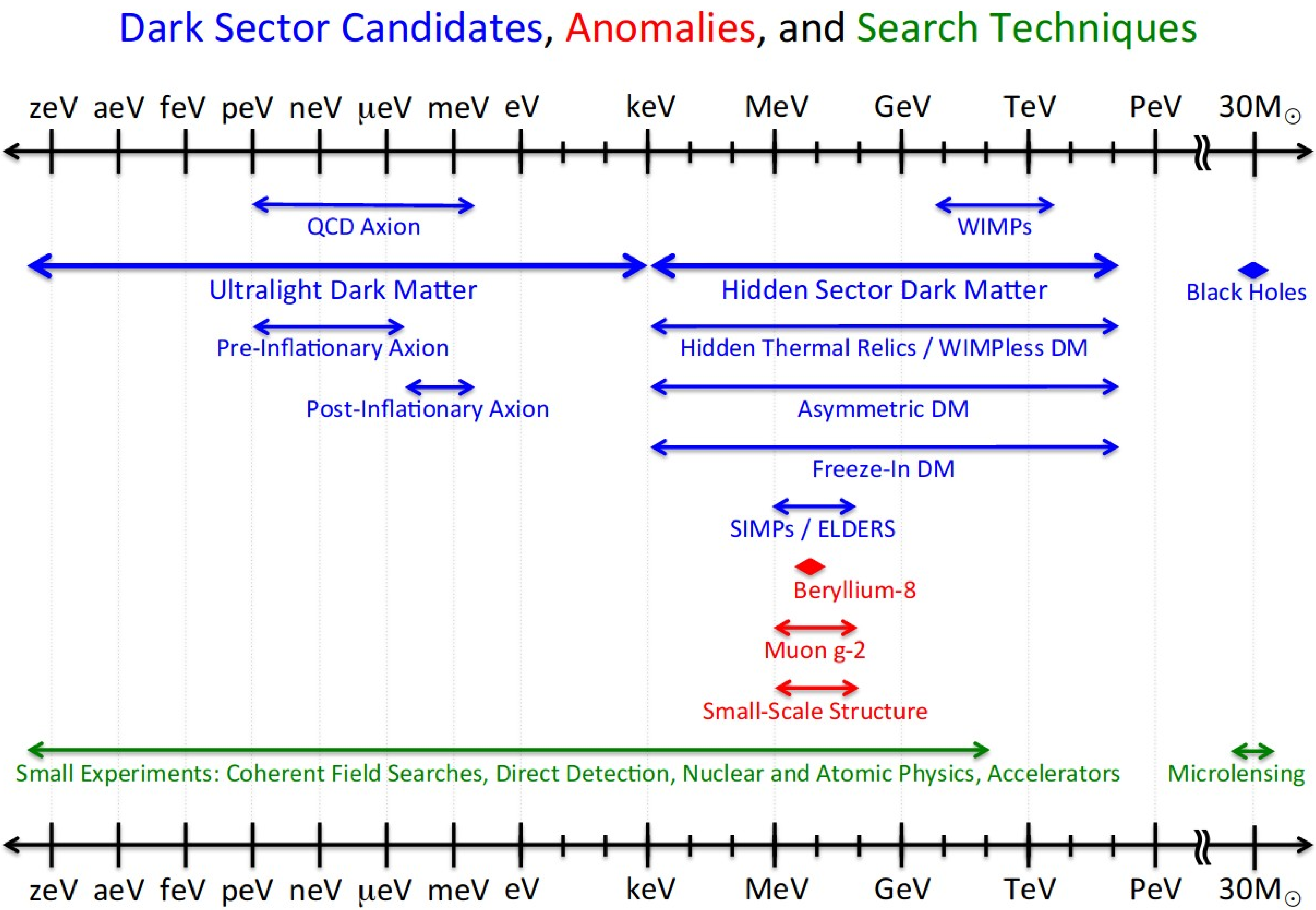
# Belle II Detector Elements

**See C. Cecchi's talk on Tuesday**



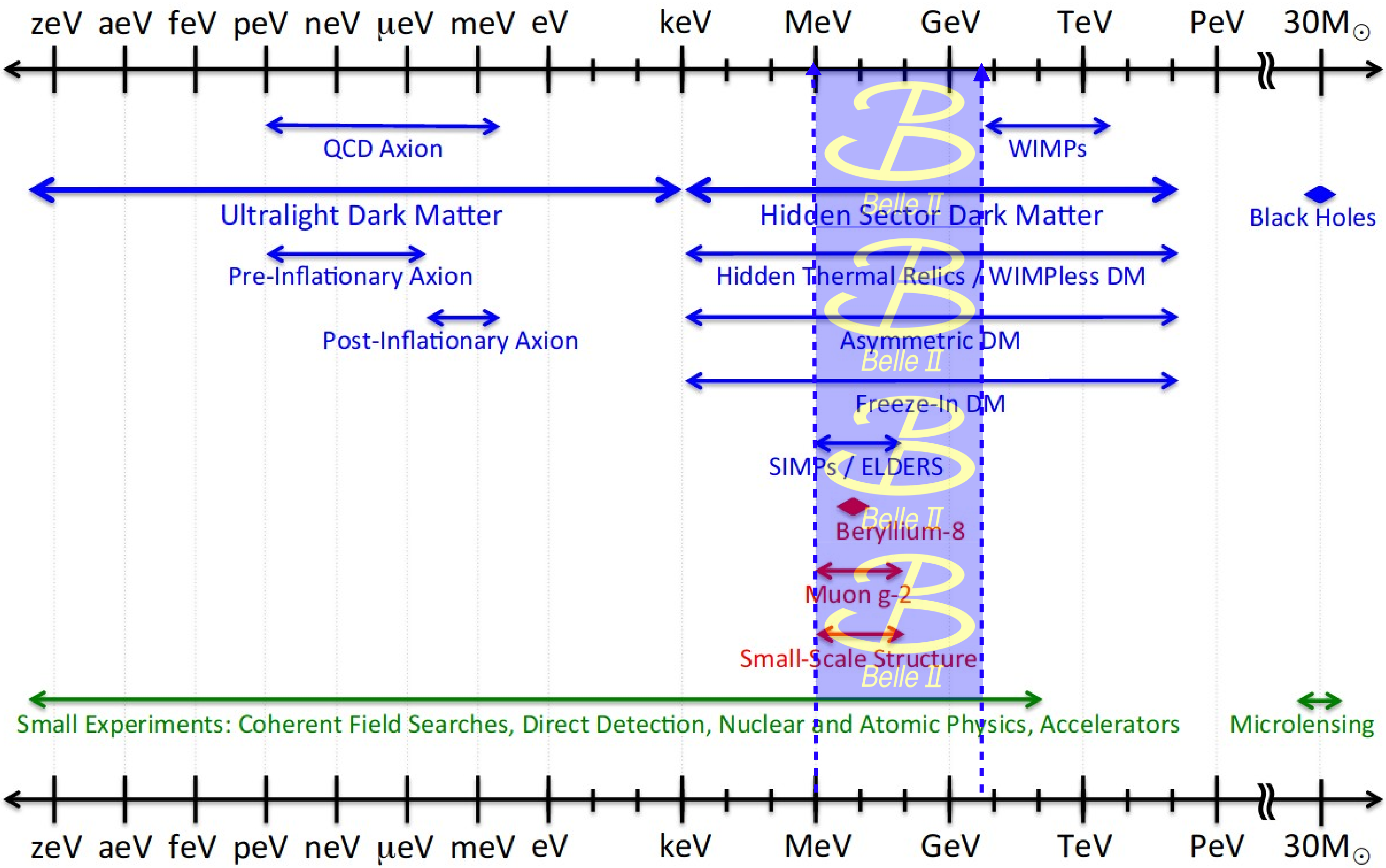
See next talk from P. Valente

ArXiv:1707.04591, see also next talk by P. Valente

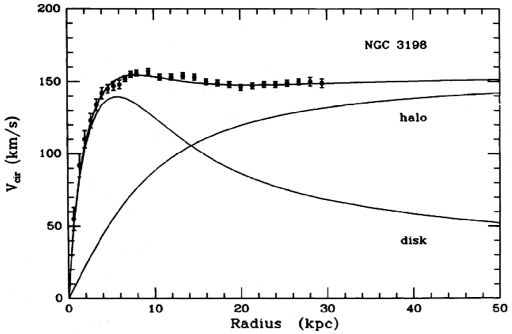


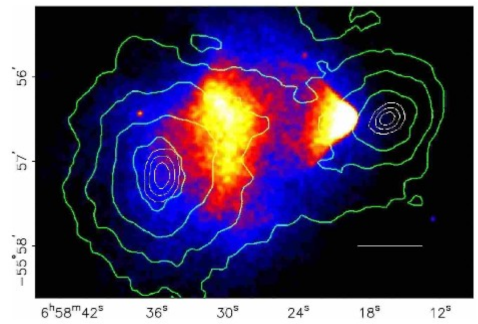
ArXiv:1707.04591, **see also next talk by P. Valente**

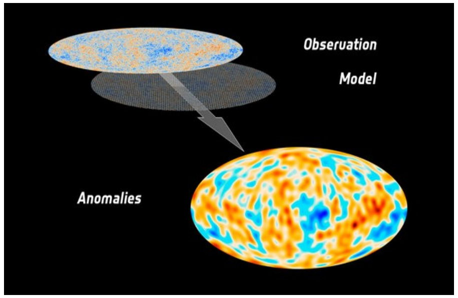
# Dark Sector Candidates, Anomalies, and Search Techniques

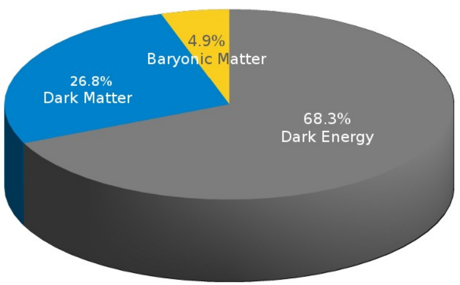


# Searching for Dark Matter and Forces @ Belle/Belle II





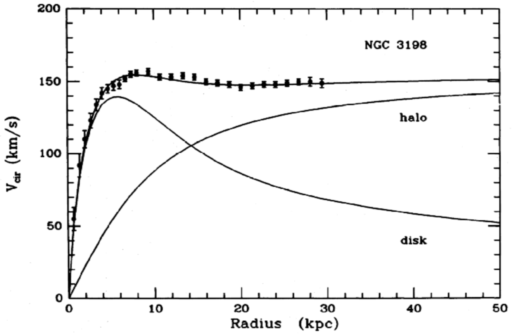

Belle II

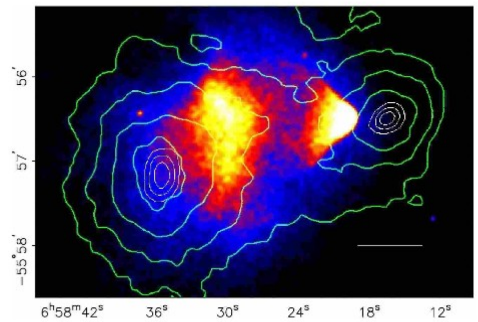
**Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.**

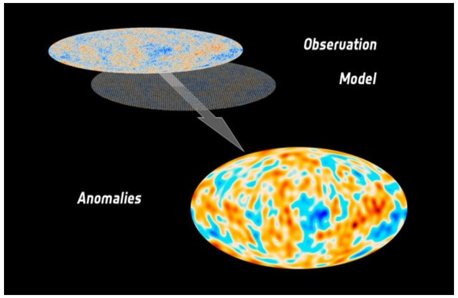
Belle II

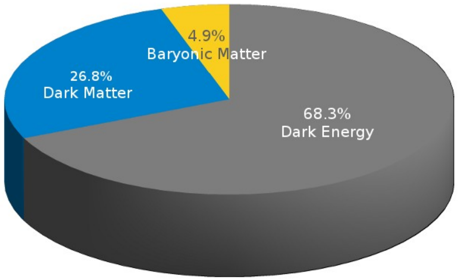
- **Vector portal** $\epsilon F_Y^{\mu\nu} F'_{\mu\nu} \ (dark\ photon\ A'), \sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l \ (dark\ Z')$
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \ (axion, alps)$
- **Scalar portal** $\lambda H^2 S^2 + \mu H^2 S \ (dark\ Higgs)$
- **Neutrino portal** $k(HL)N \ (sterile\ neutrinos)$
- **More ...**

# Searching for Dark Matter and Forces @ Belle/Belle II




Belle II

**Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.**

Belle II

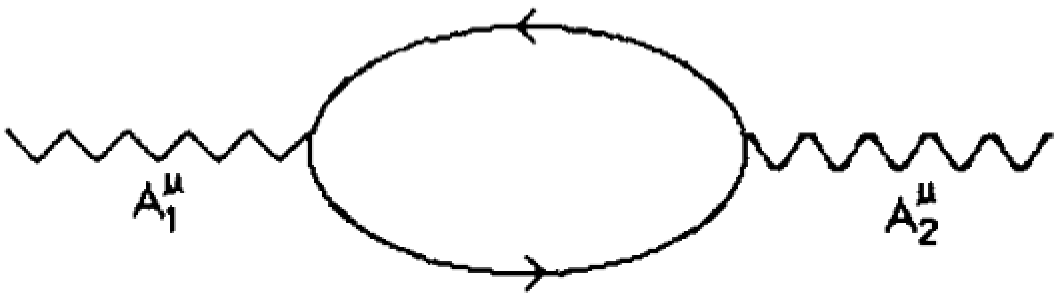
**Covered today!**

- **Vector portal** $\epsilon F_Y^{\mu\nu} F'_{\mu\nu}$ $(dark\ photon\ A'), \sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l$ $(dark\ Z')$
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ $(axion, alps)$
- **Scalar portal** $\lambda H^2 S^2 + \mu H^2 S$ $(dark\ Higgs)$
- **Neutrino portal** $k(HL)N$ $(sterile\ neutrinos)$
- **More ...**

# 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:

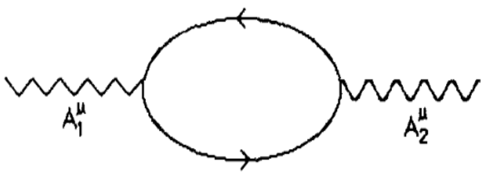



- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^{Y}_{\mu\nu} F'^{\mu\nu}$
- For the dark photon to acquire mass an extended Higgs sector might be required to break the new U(1)' symmetry (if dark sector is “Higgsed”)

Note: ϵ is the strength of the kinetic mixing could be as large as $10^{-2}$ for $m_{A'}$ in the GeV range, **the smaller the value of ϵ the longer A' lifetime** (i.e. **long lived**).

# Dark Sector Searches: Constraining the Kinetic Mixing

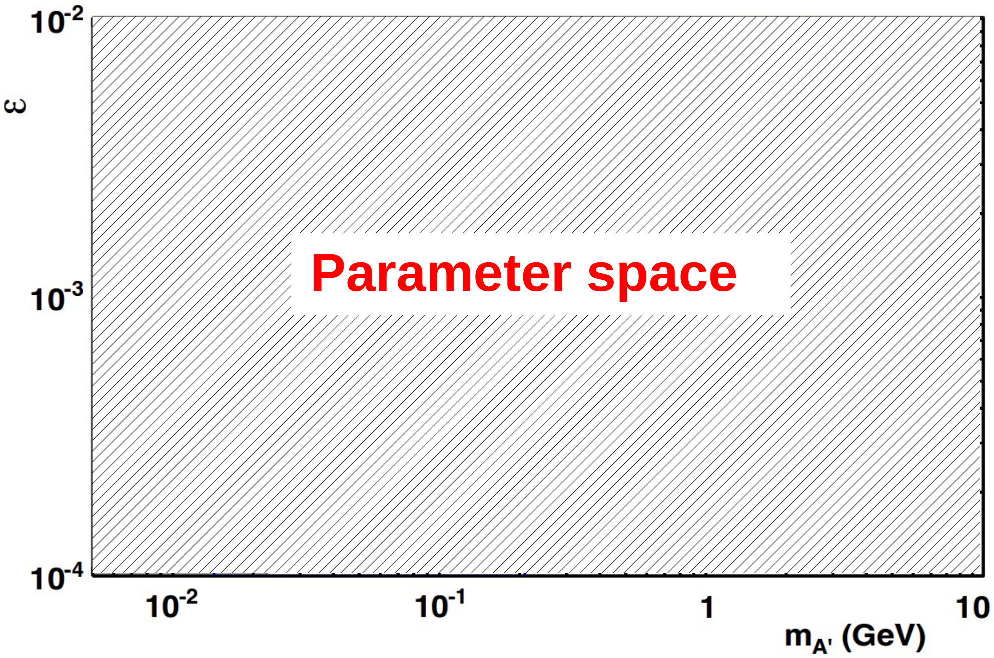
Most dark sector models require an additional U(1) symmetry responsible for the "interactions" between dark sector particles and SM particles through its gauge boson A' .




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

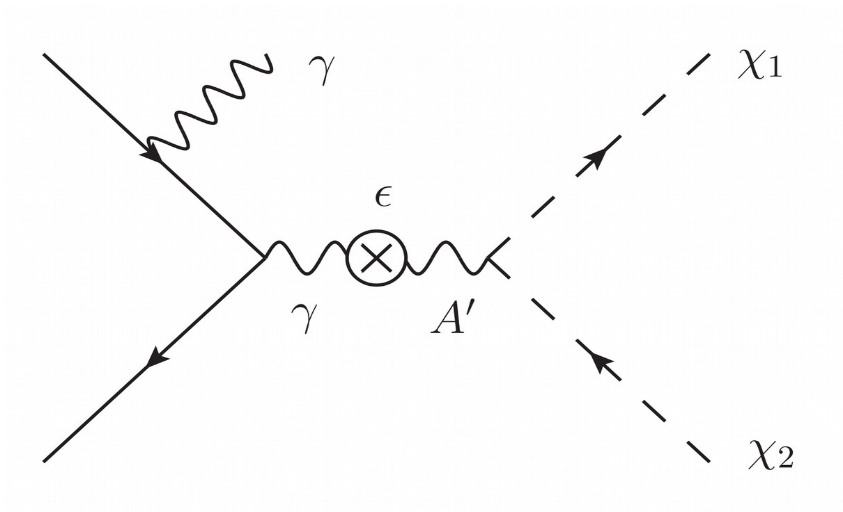
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).
B. Holdom, Phys. Lett. B **166**, 196 (1986)

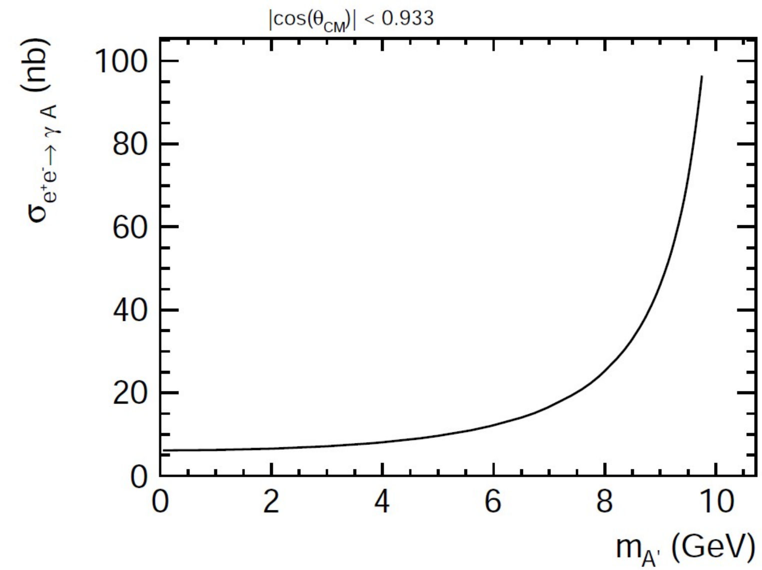
*Kinetic mixing strength*



# Dark Photon Search Strategy (invisible case)

**See the Belle II Phyiscs book arXiv:1808.10567**




*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 .

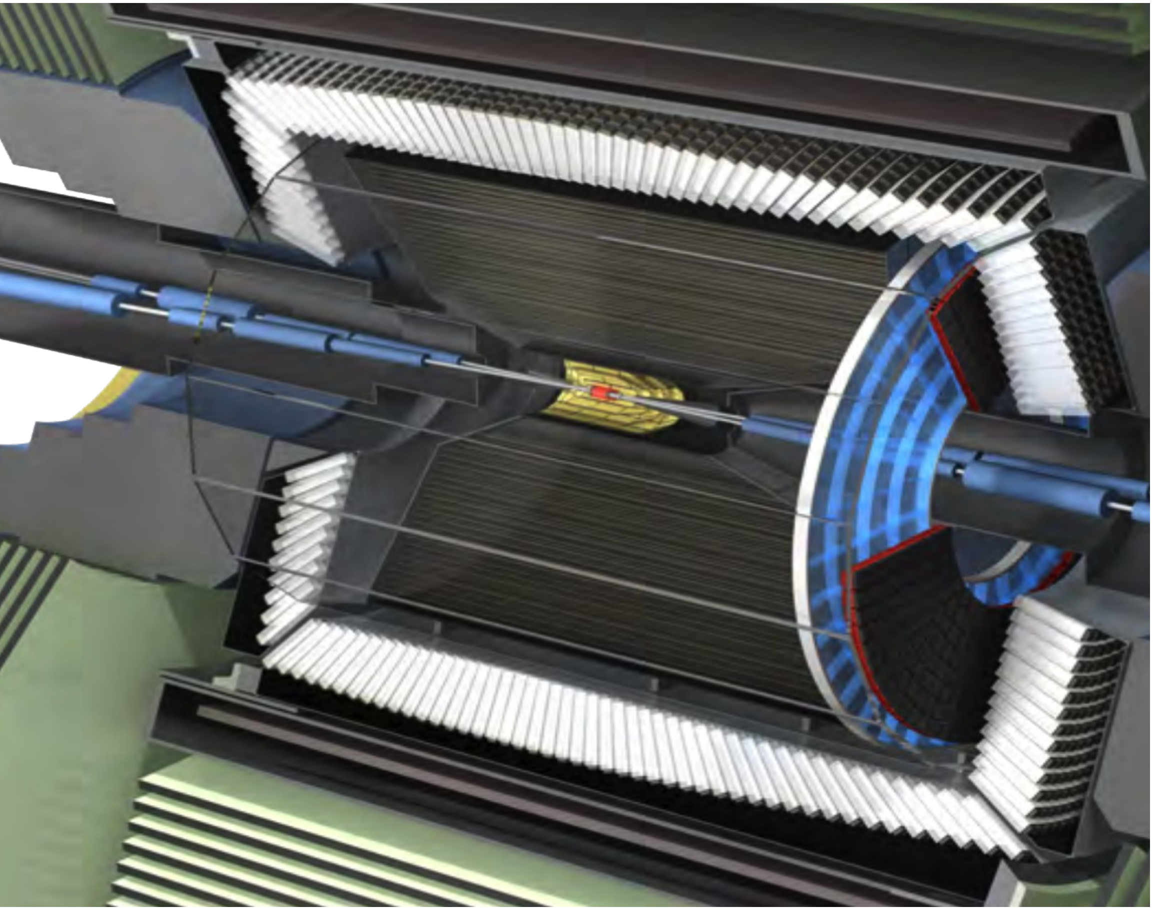
radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s} \;\; (on-shell)$

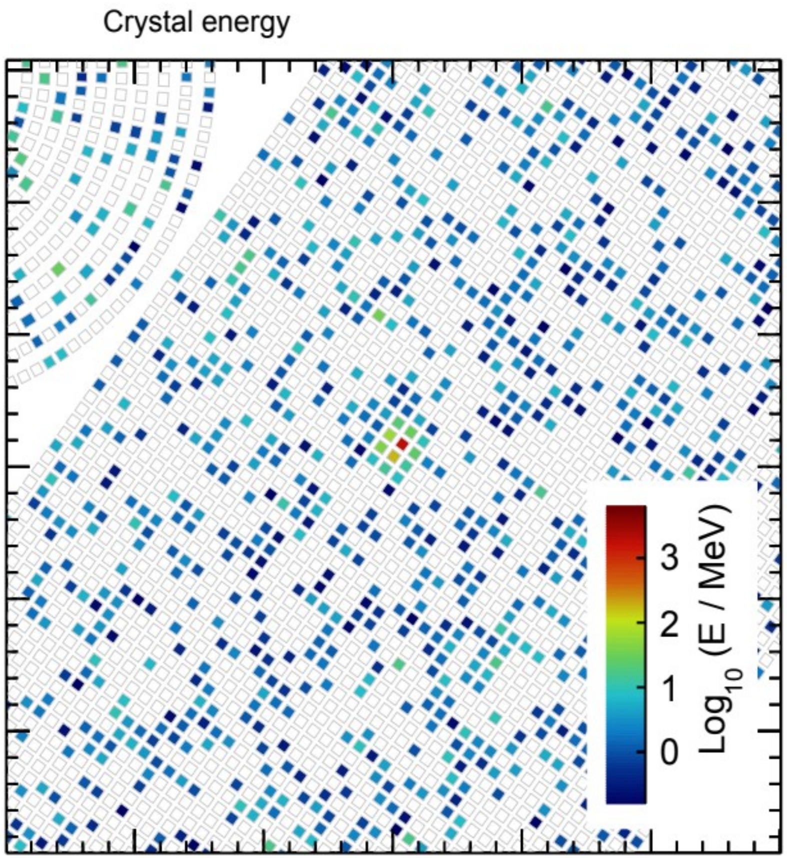
→ Only existing limits from BaBar based on 53 fb$^{-1}$ of data, *Phys. Rev. Lett.* ***119****, 131804 (2017)*

Since the decay products of the A' are invisible to the detector, only the ISR photon is visible. Therefore this analysis requires a single photon trigger.

# Photons in the electromagnetic calorimeter (ECL) 1/4

- Belle II calorimeter crystals are reused from Belle.
  - 8736 CsI(Tl) crystals
  - New readout electronics.
- New clustering → high luminosity environment.

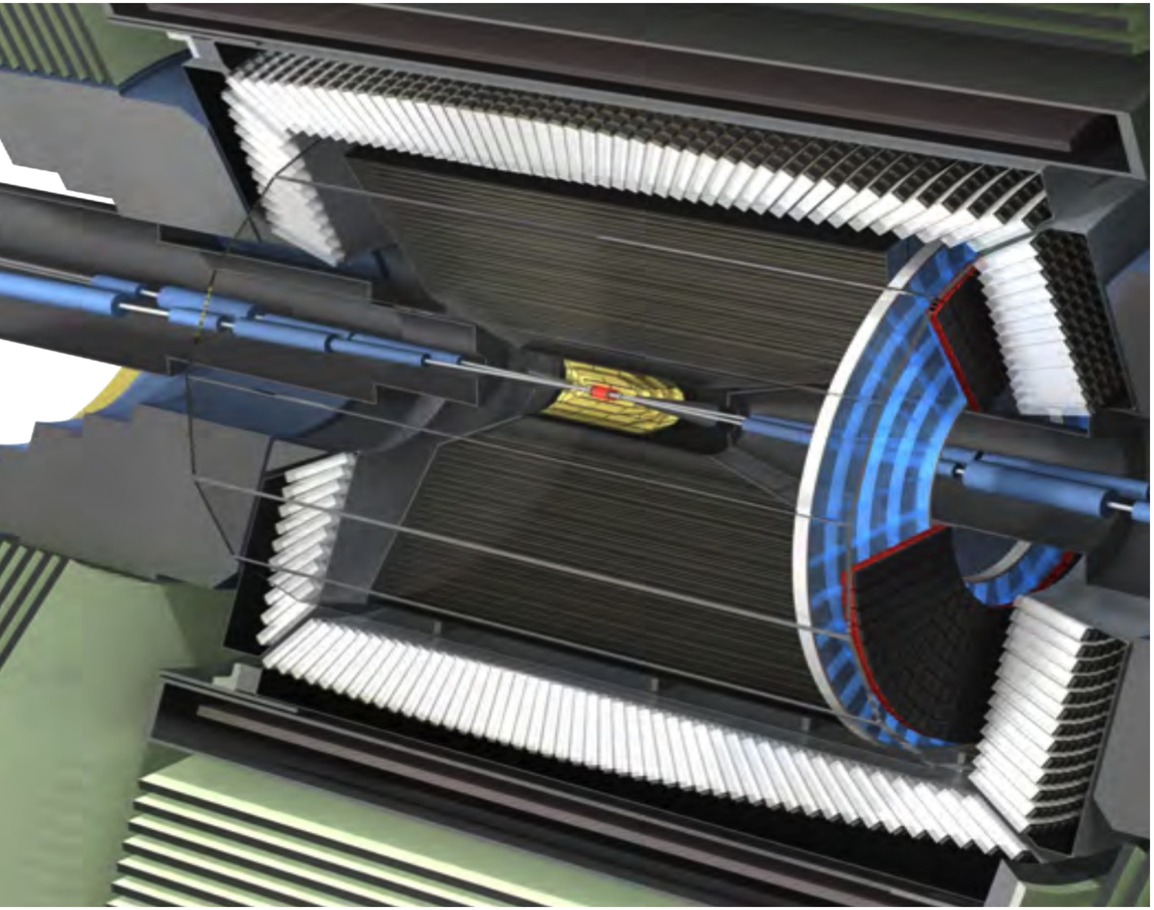


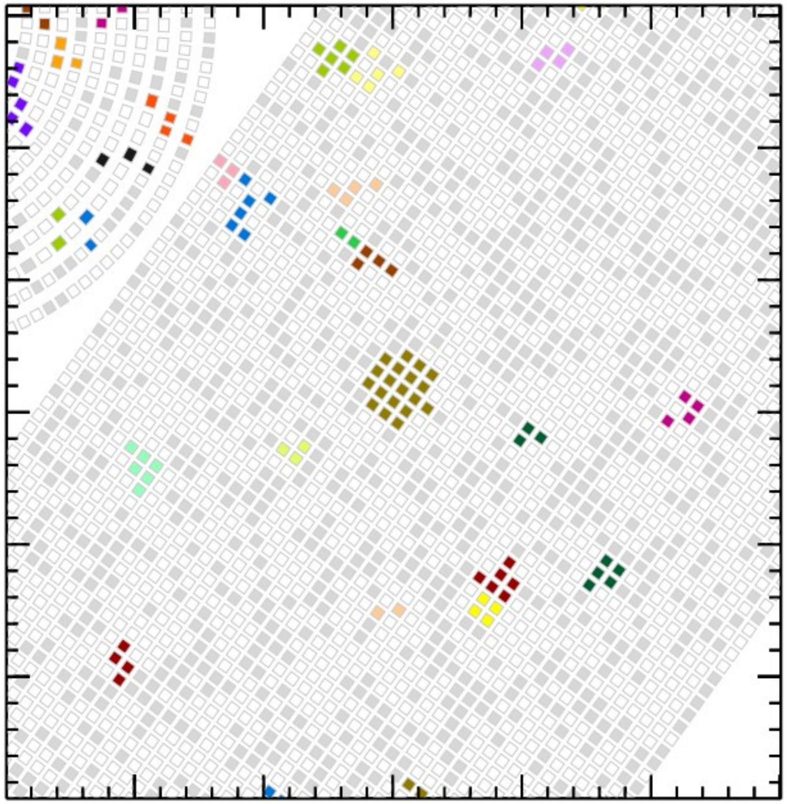



Nominal backgrounds
+ single 2.5 GeV photon

# Photons in the electromagnetic calorimeter (ECL) 2/4

- Belle II calorimeter crystals are reused from Belle.
  - 8736 CsI(Tl) crystals
  - New readout electronics.
- New clustering → high luminosity environment.

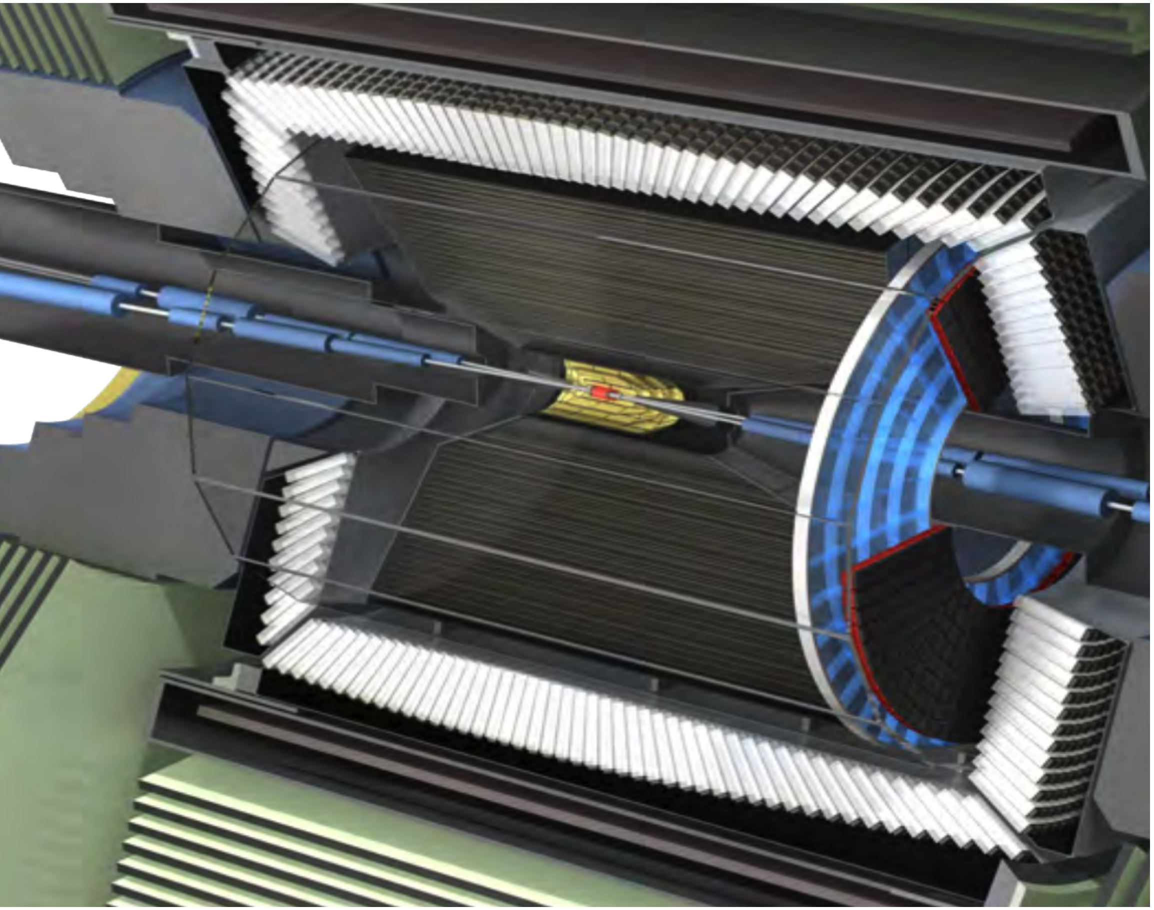


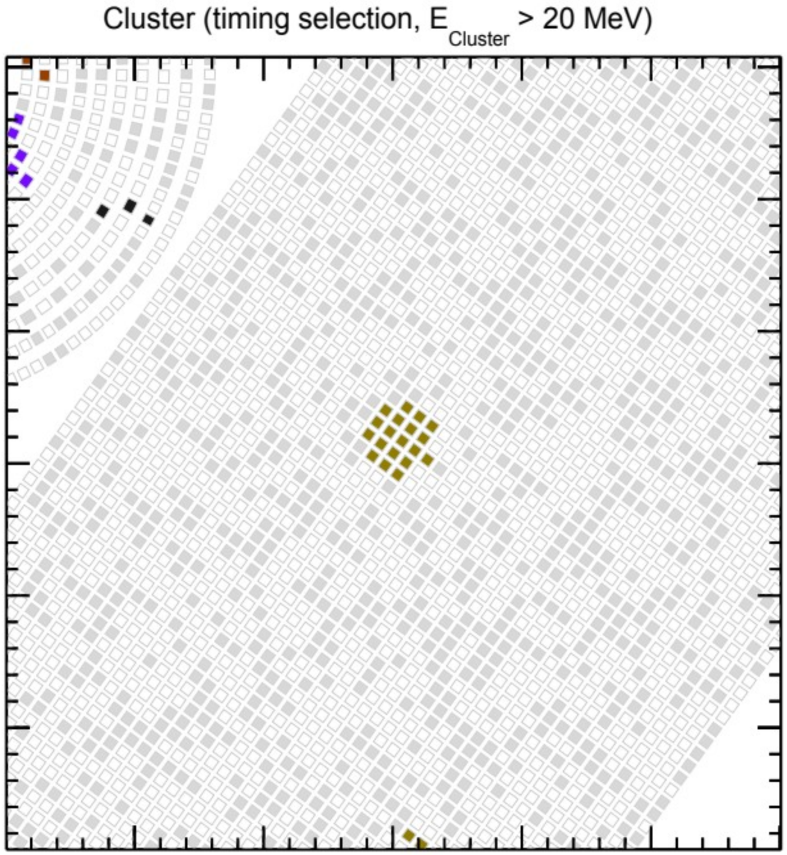



New clustering:
finds "showers"

# Photons in the electromagnetic calorimeter (ECL) 3/4

- Belle II calorimeter crystals are reused from Belle.
  - 8736 CsI(Tl) crystals
  - New readout electronics.
- New clustering → high luminosity environment.






Timing and minimal cluster energy requirement

# Photons in the electromagnetic calorimeter (ECL) 4/4

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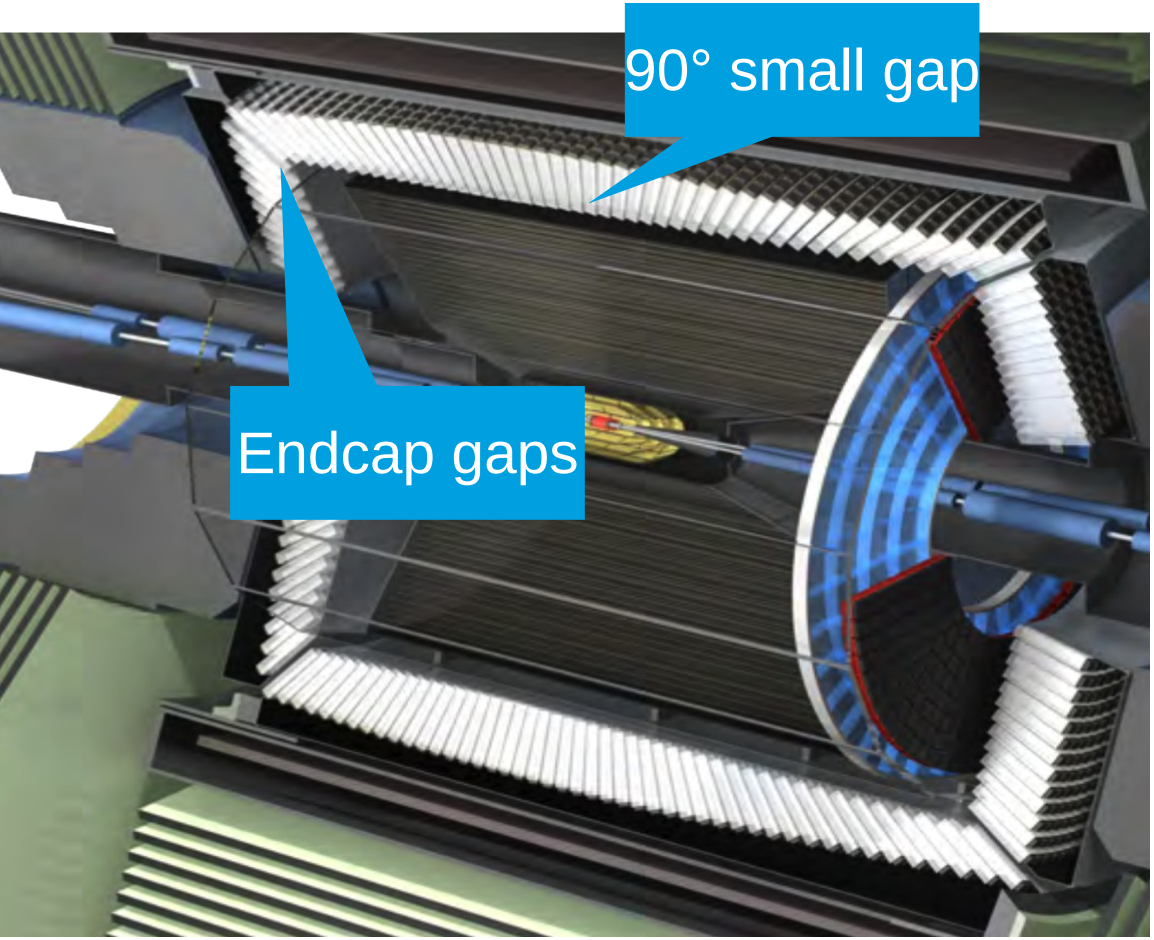
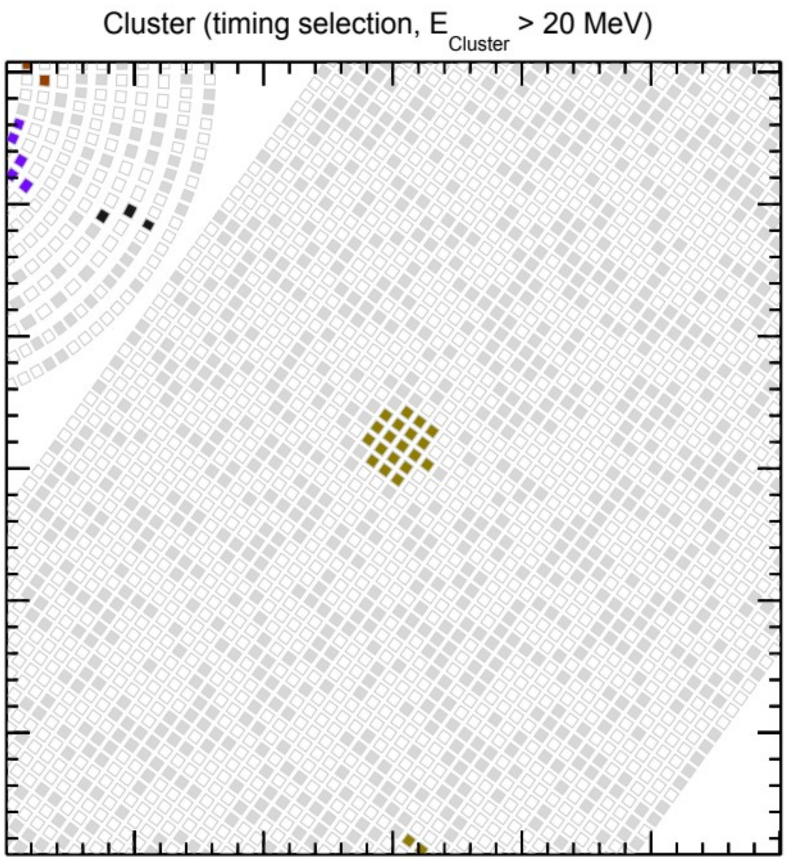
- New clustering → high luminosity environment.



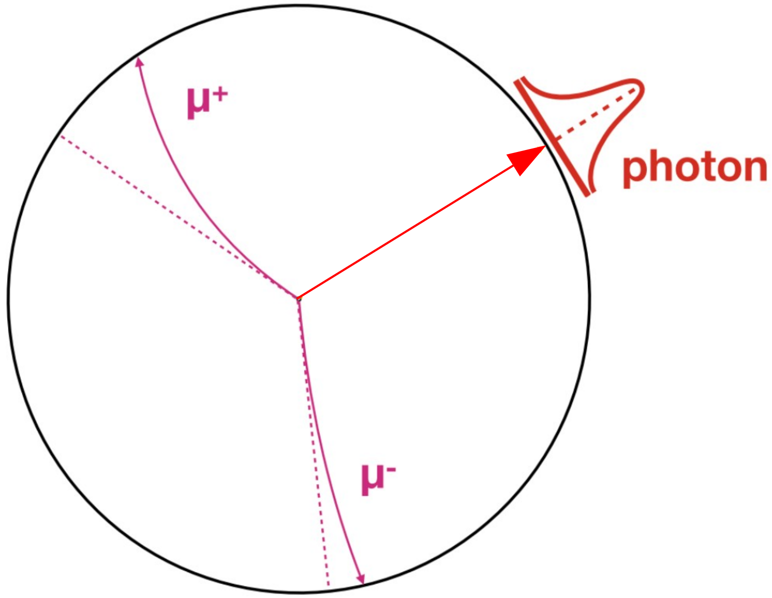

Timing and minimal cluster energy requirement

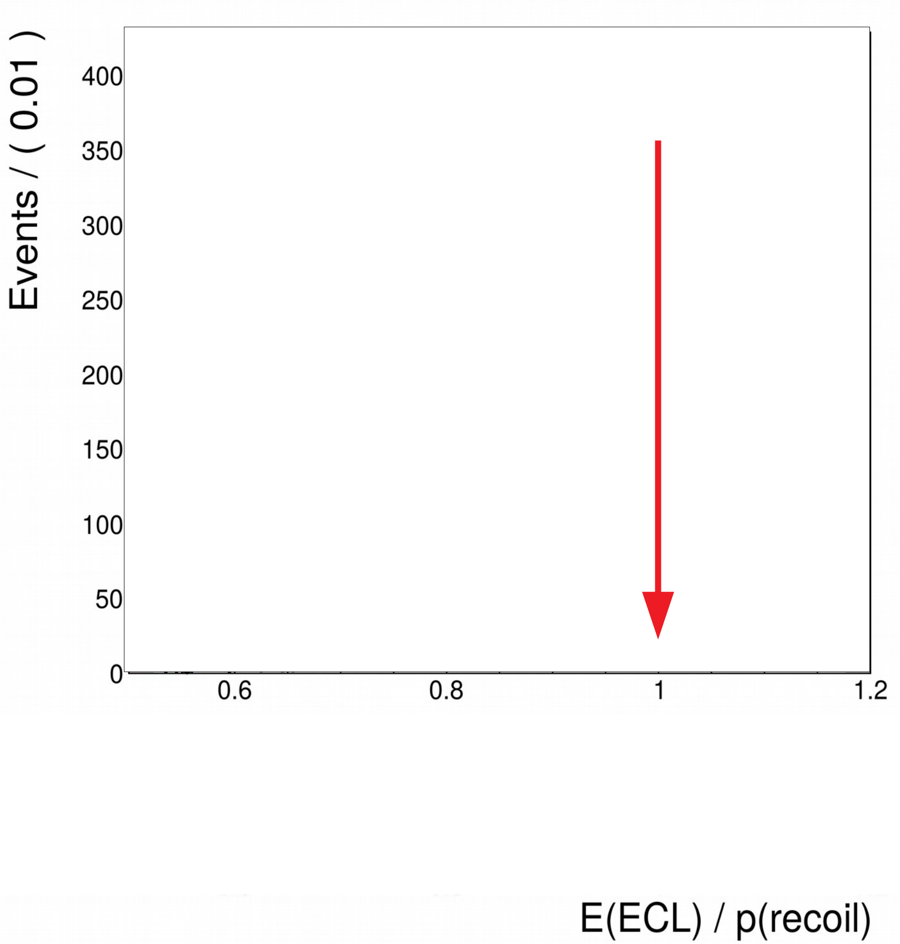
# Dark photon → invisible, additional checks

## Analysis

- $e^+e^- \rightarrow \gamma A' \rightarrow \gamma(\chi\chi)$
- Generic strategy: nothing in the event except one photon. (no tracks, other good photon clusters). Search for a bump in the recoil mass spectrum.
- **Check that the ECL works properly**

$e^+e^- \rightarrow \mu^+\mu^-\gamma$



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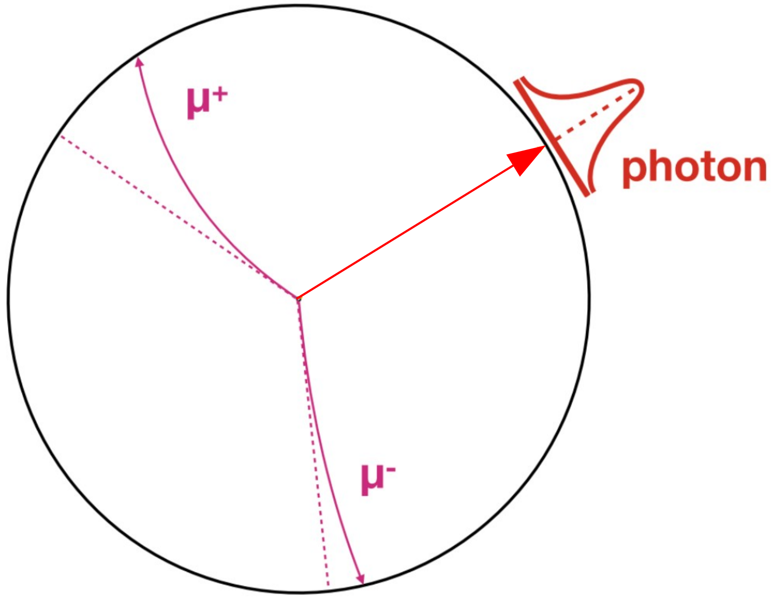


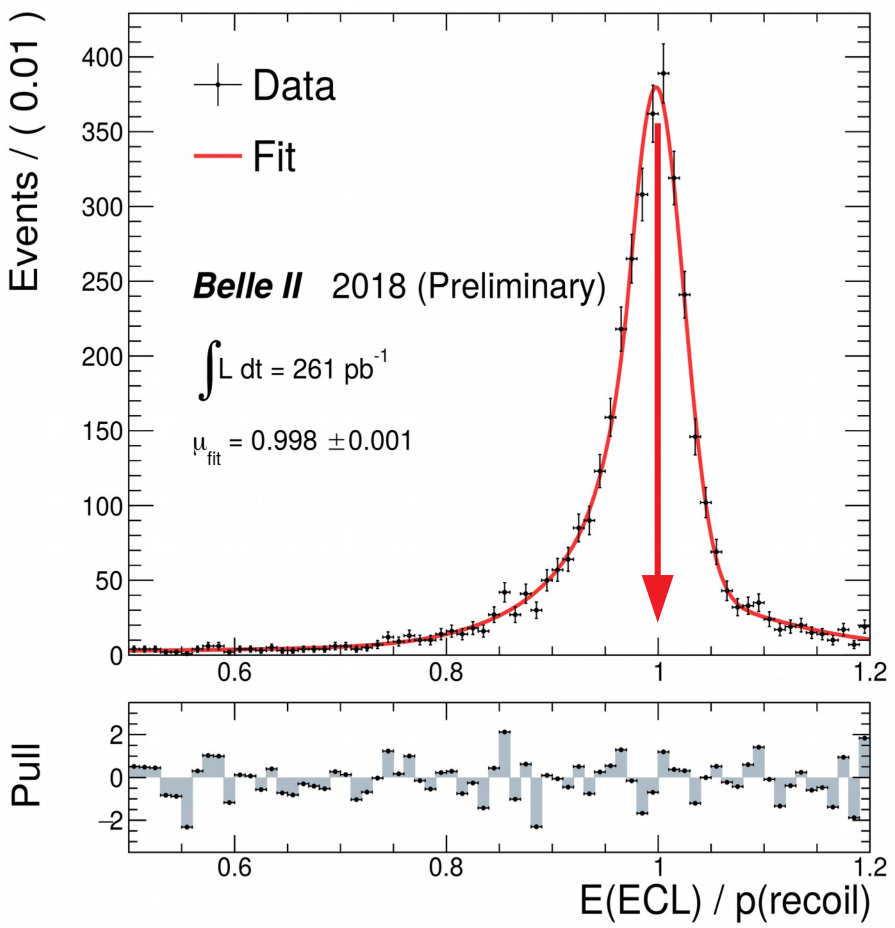

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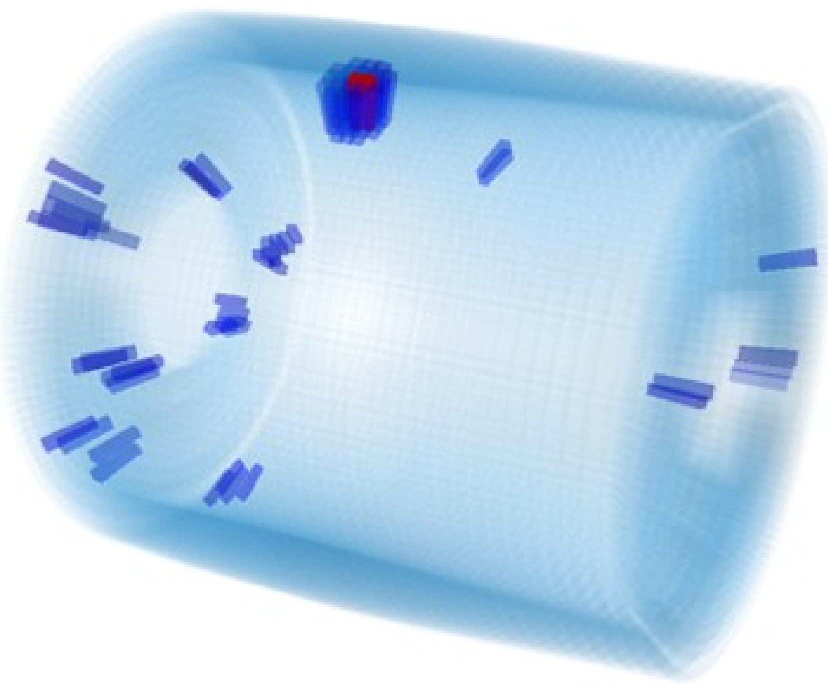
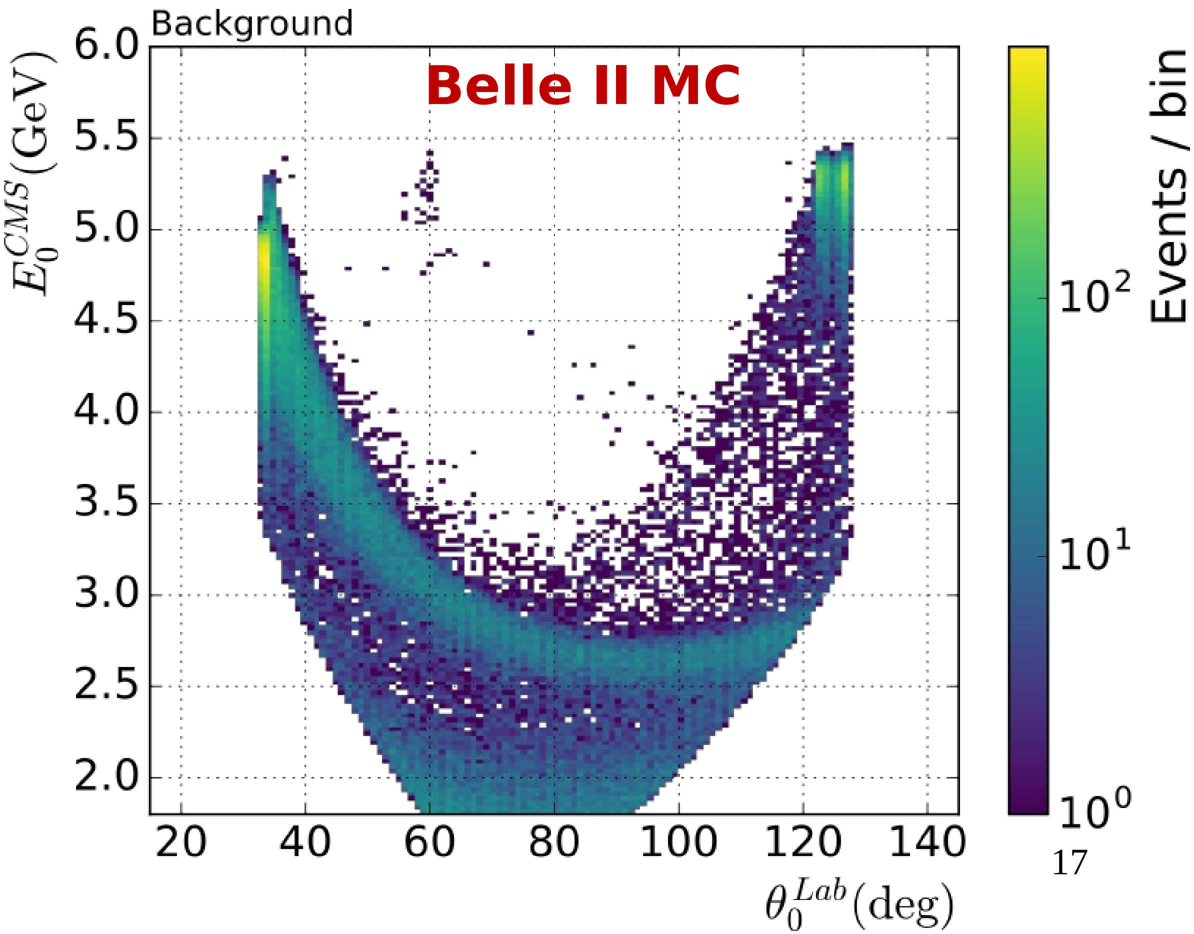
- **Backgrounds** $e^+e^- \rightarrow e^+e^-\gamma(\gamma)$ and $e^+e^- \rightarrow \gamma\gamma(\gamma)$





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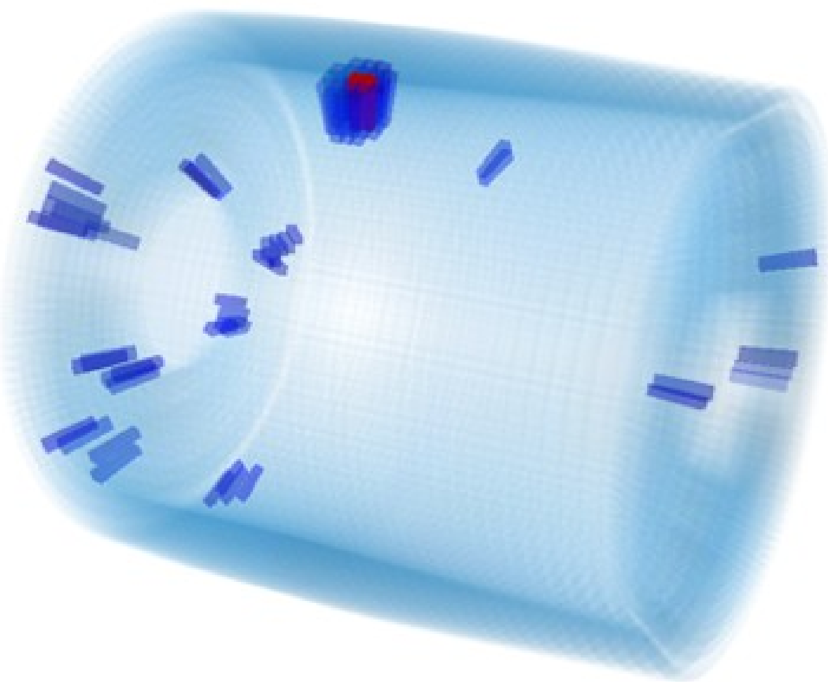
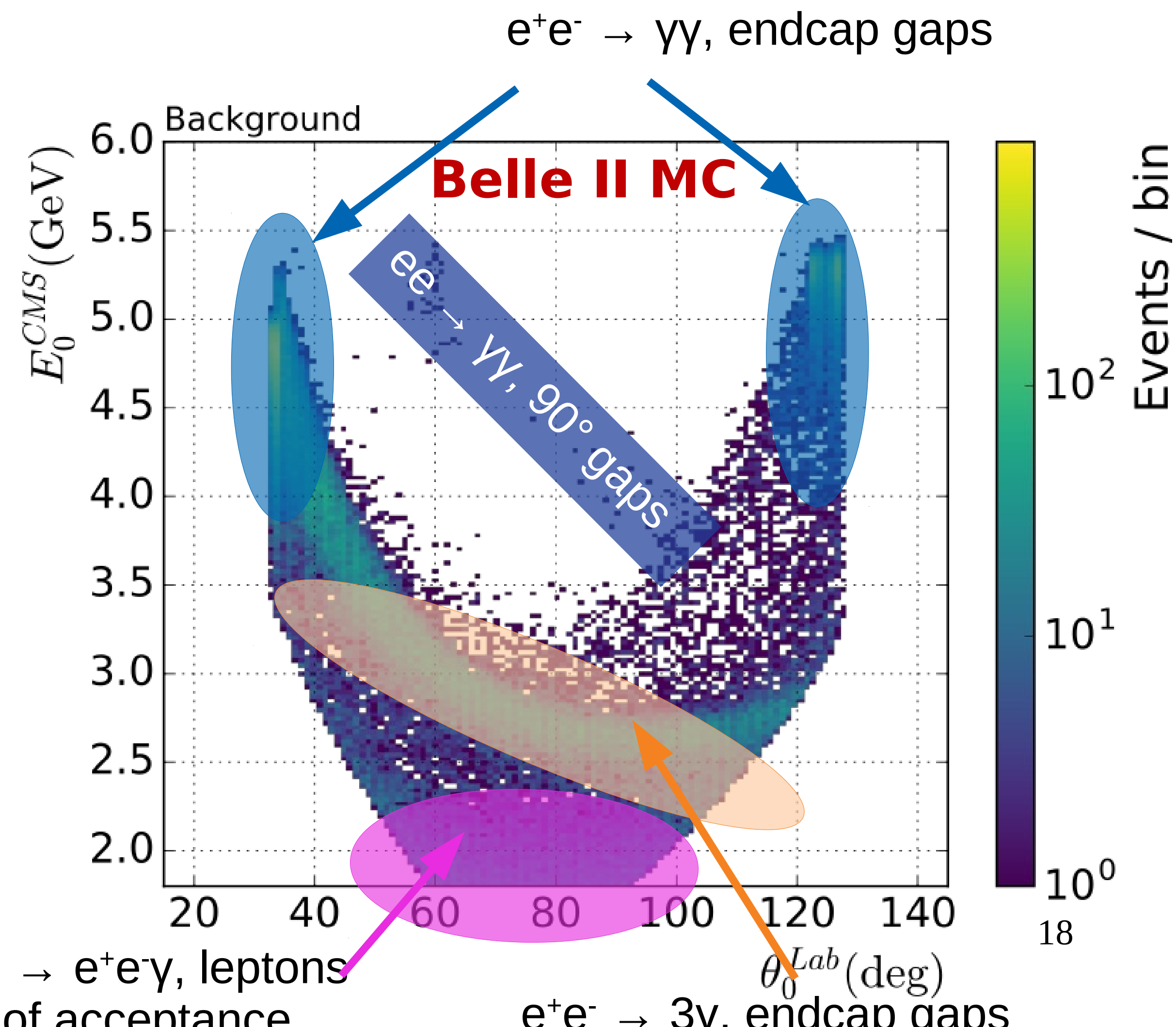
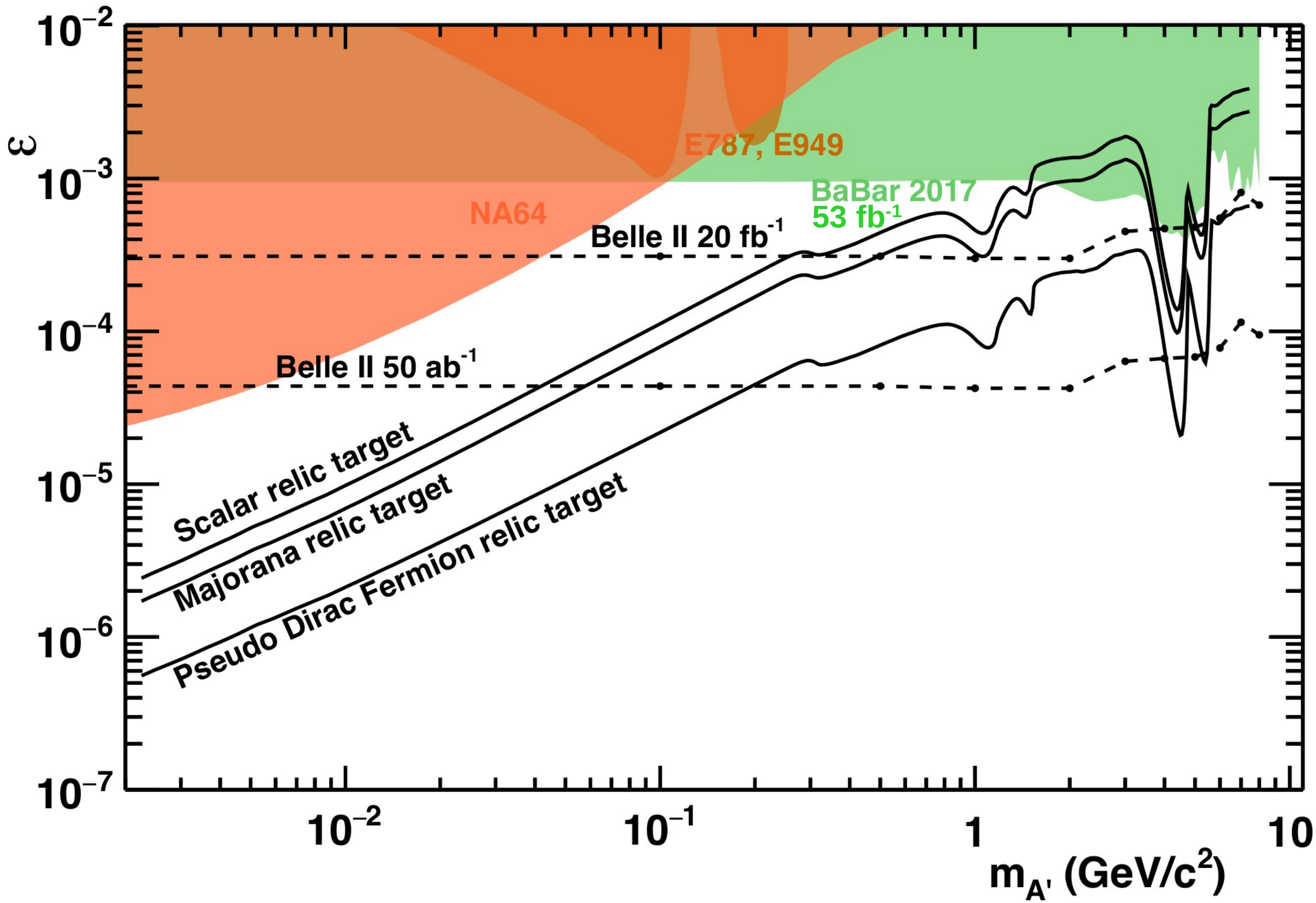




# Dark photon → invisible, Belle 2 expected sensitivity

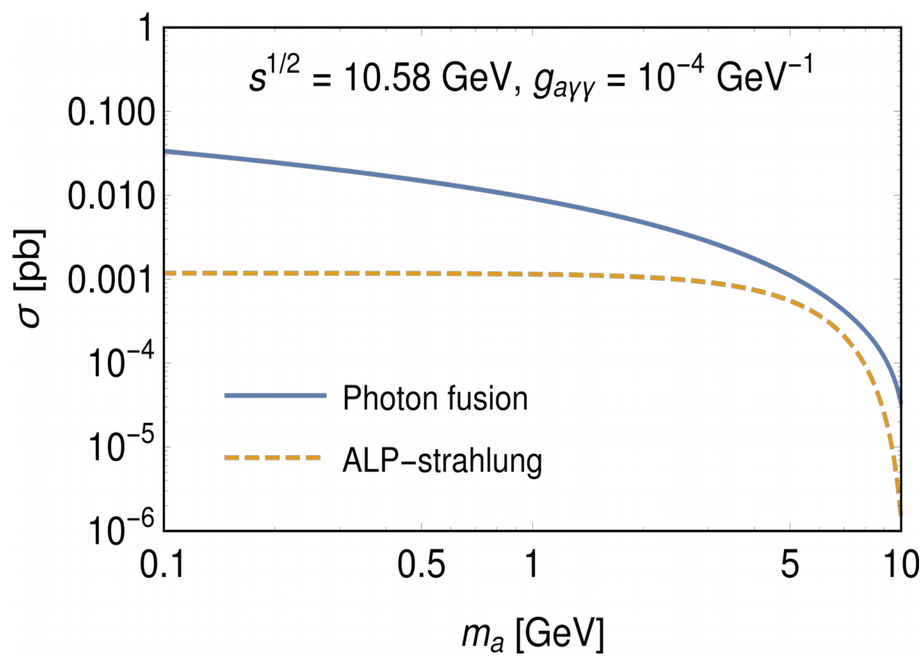



The Belle II Phyiscs book
arXiv:1808.10567
BaBar's analysis
PRL.119.131804

Why does Belle II perform better than BaBar?
→ no ECL cracks pointing to the interaction regions

# Axion Like Particles (ALPs) at Belle II

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

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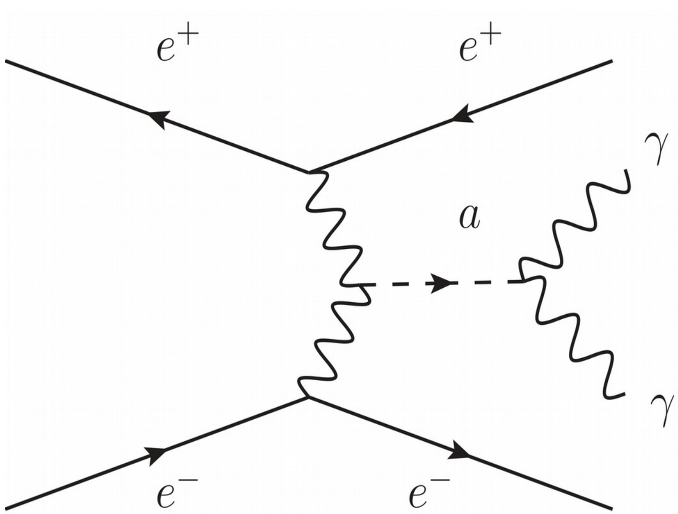
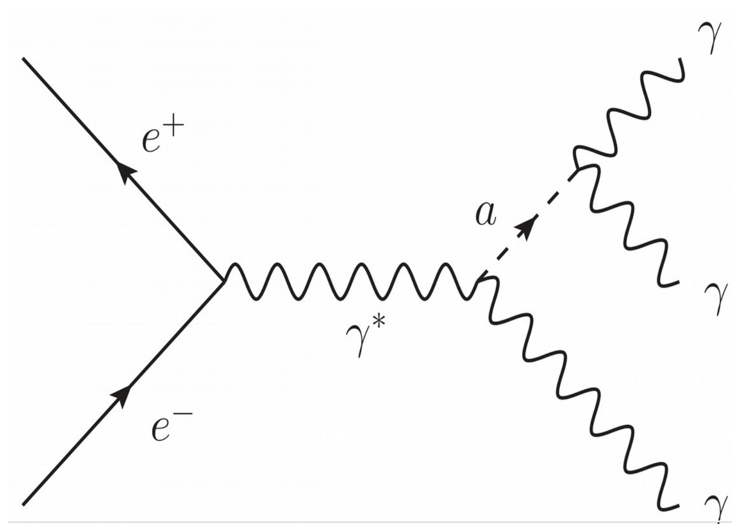
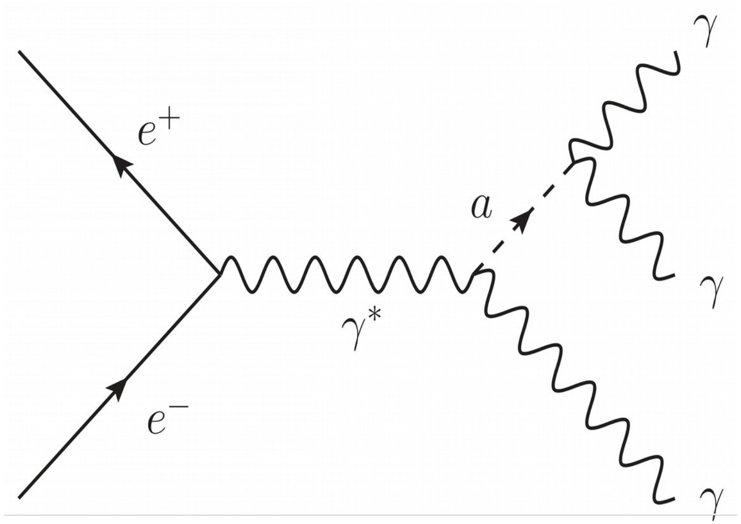
Photon fusion

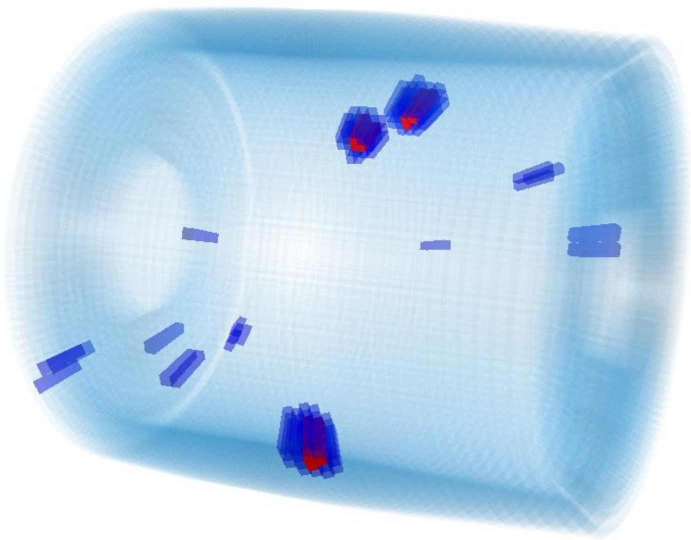


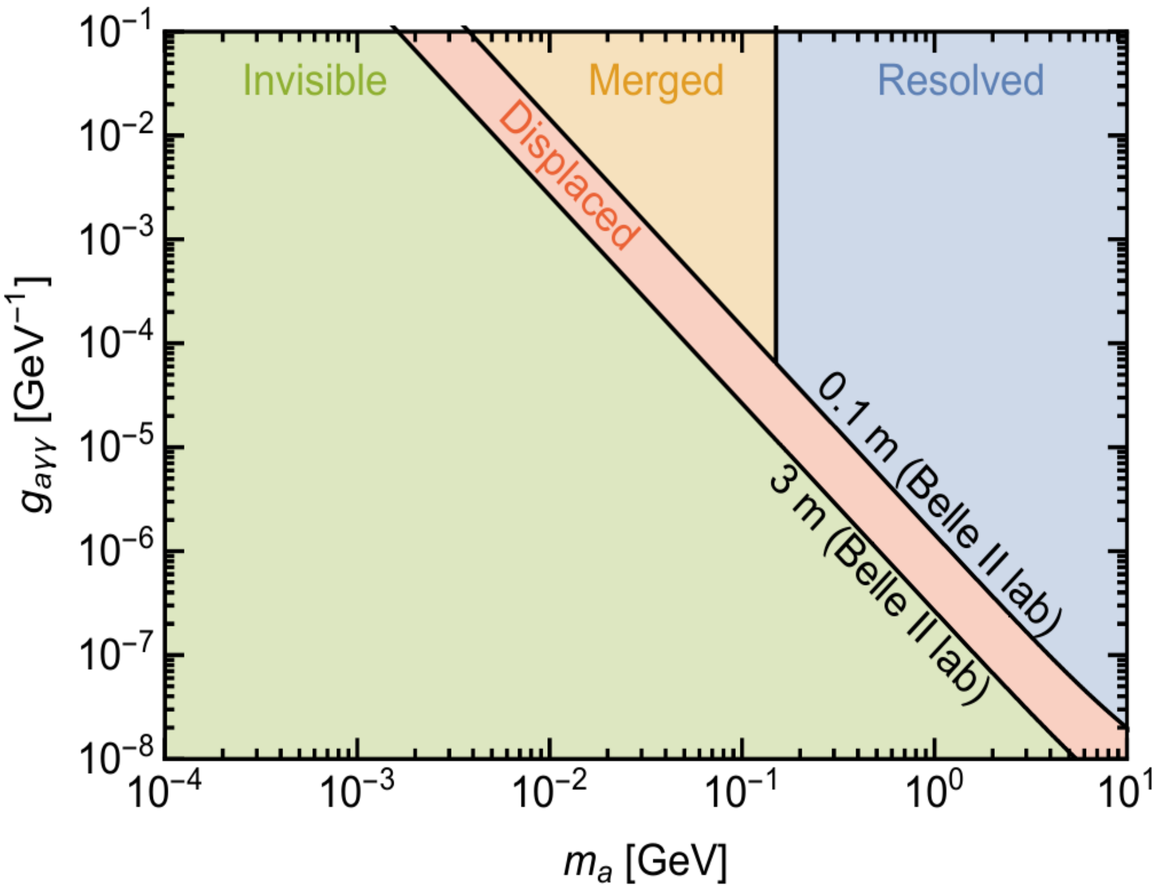

ALP-strahlung



# Axion Like Particles (ALPs) at Belle II



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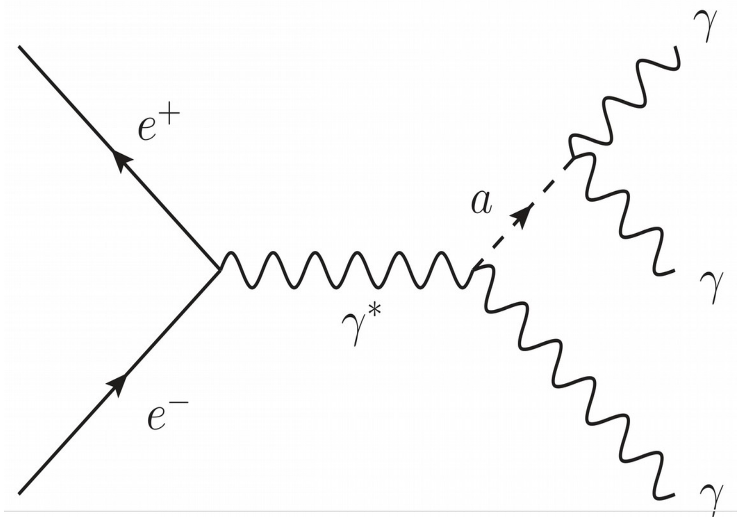
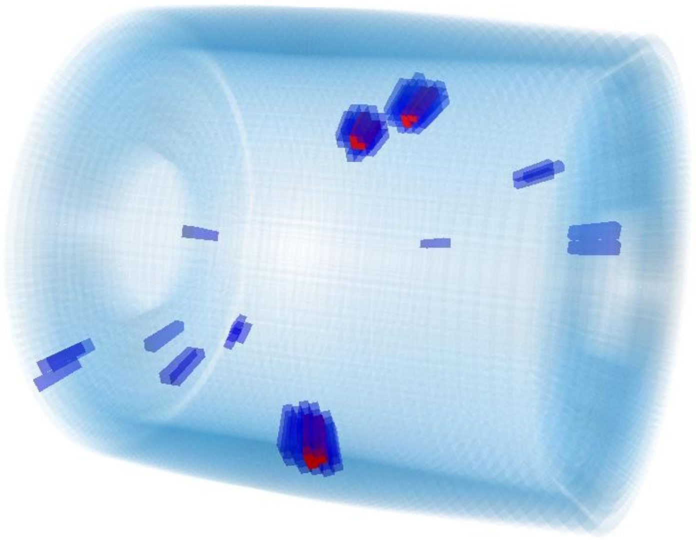
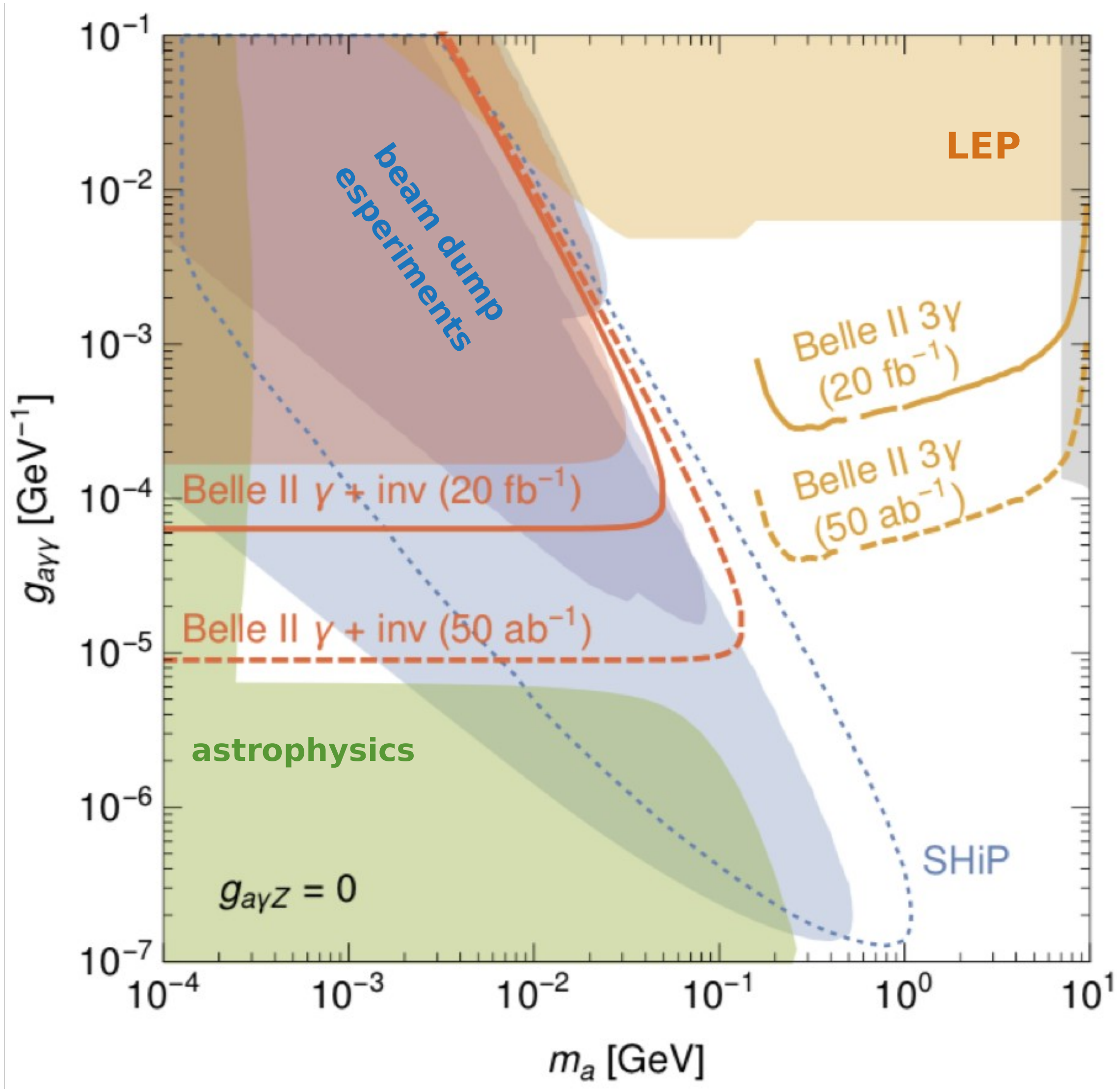
- Three photons that add up to the beam energy + bump on di-photon mass.
- SM background: $e^+e^- \rightarrow \gamma\gamma(\gamma)$, $e^+e^- \rightarrow e^+e^-(\gamma)$, and $e^+e^- \rightarrow$ scalar$+\gamma(\gamma)$

# Axion Like Particles (ALPs) at Belle II



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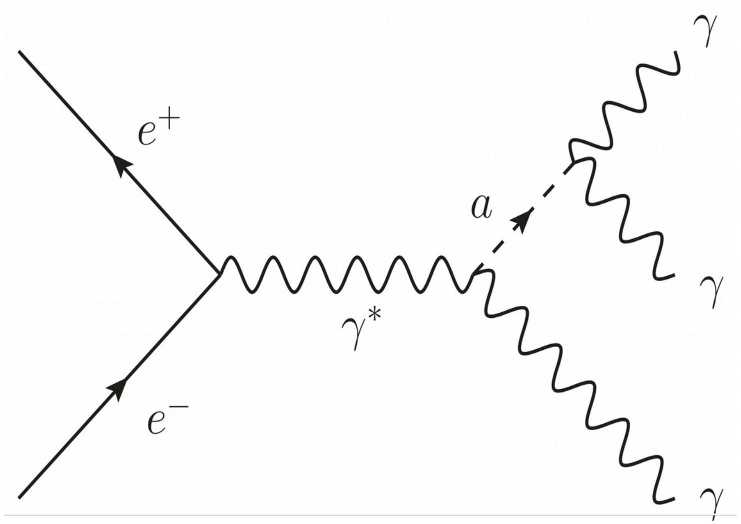
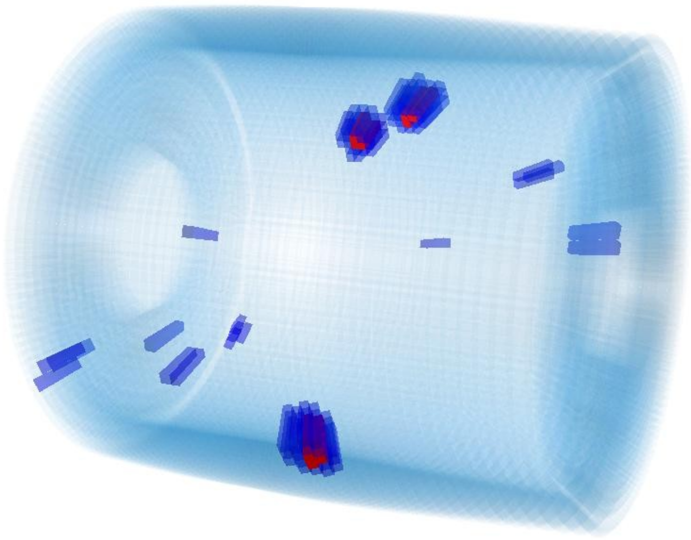
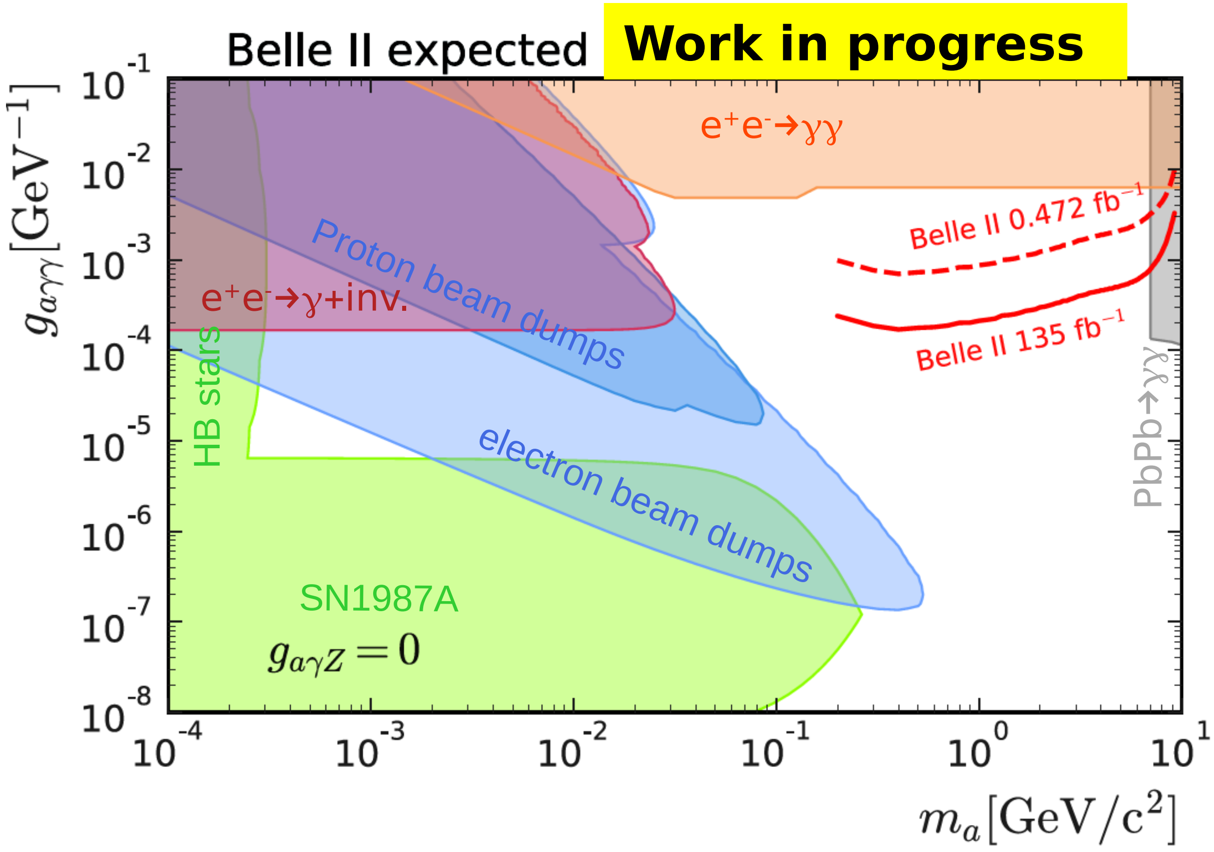
# Axion Like Particles (ALPs) at Belle II






Belle II expected limits
- No systematics incuded
- Dominant $e^+e^- \to \gamma\gamma$ background taken into account
- beam background negligible
- 135 fb$^{-1}$ projection assumes no veto of $\gamma\gamma$ events in barrel at trigger level

- Three photons that add up to the beam energy + bump on di-photon mass.
- SM background: $e^+e^- \to \gamma\gamma(\gamma)$, $e^+e^- \to e^+e^-(\gamma)$, and $e^+e^- \to$ scalar+$\gamma(\gamma)$

# The $L_\mu$-$L_\tau$ model in the context of dark sector searches: a dark Z'

- The model is a new gauge boson, called a Z', which couples to $L_\mu$-$L_\tau$.
  - **For $M_{Z'} < 2M_\mu$ $Br(Z' \rightarrow invisible) = 1$.**
  - **For $2M_\mu < M_{Z'} < 2M_\tau$ $Br(Z' \rightarrow invisible) \sim 1/2$**
  - **For $M_{Z'} > 2M_\tau$ $Br(Z' \rightarrow invisible) \sim 1/3$**

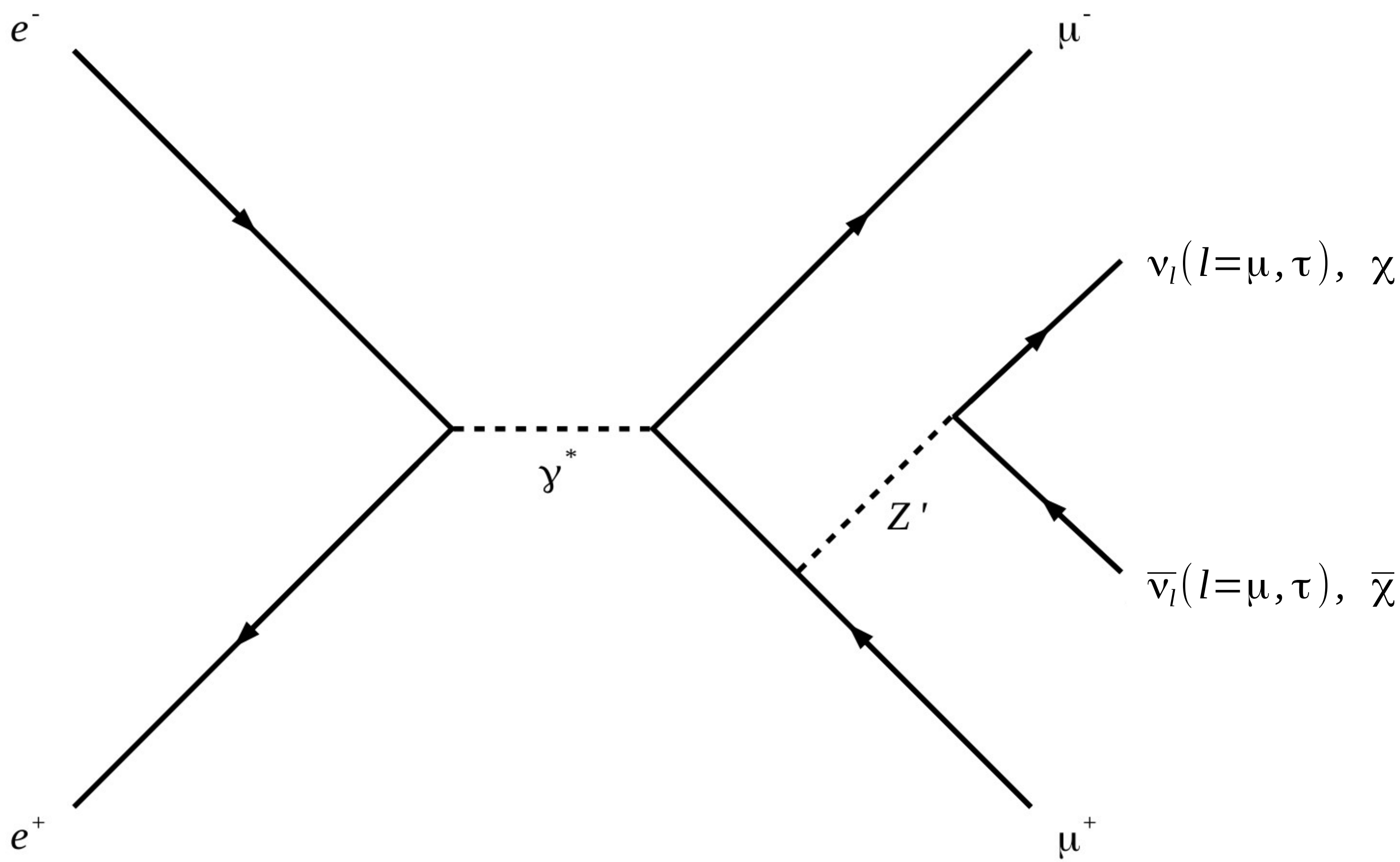
- The branching fraction to one neutrino species is half of the branching fraction to one charged lepton flavour. The reason is, of course, that the Z' only couples to left-handed neutrino chiralities whereas it couples to both left- and right-handed charged leptons.

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

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

- **Very important: If $M_{Z'} > 2\chi \rightarrow$ $BF[Z' \rightarrow \chi\chi] \sim 1$**
  **(see for example: https://arxiv.org/abs/1403.2727)**

# The $L_\mu$-$L_\tau$ model in the context of dark sector searches: a dark Z’

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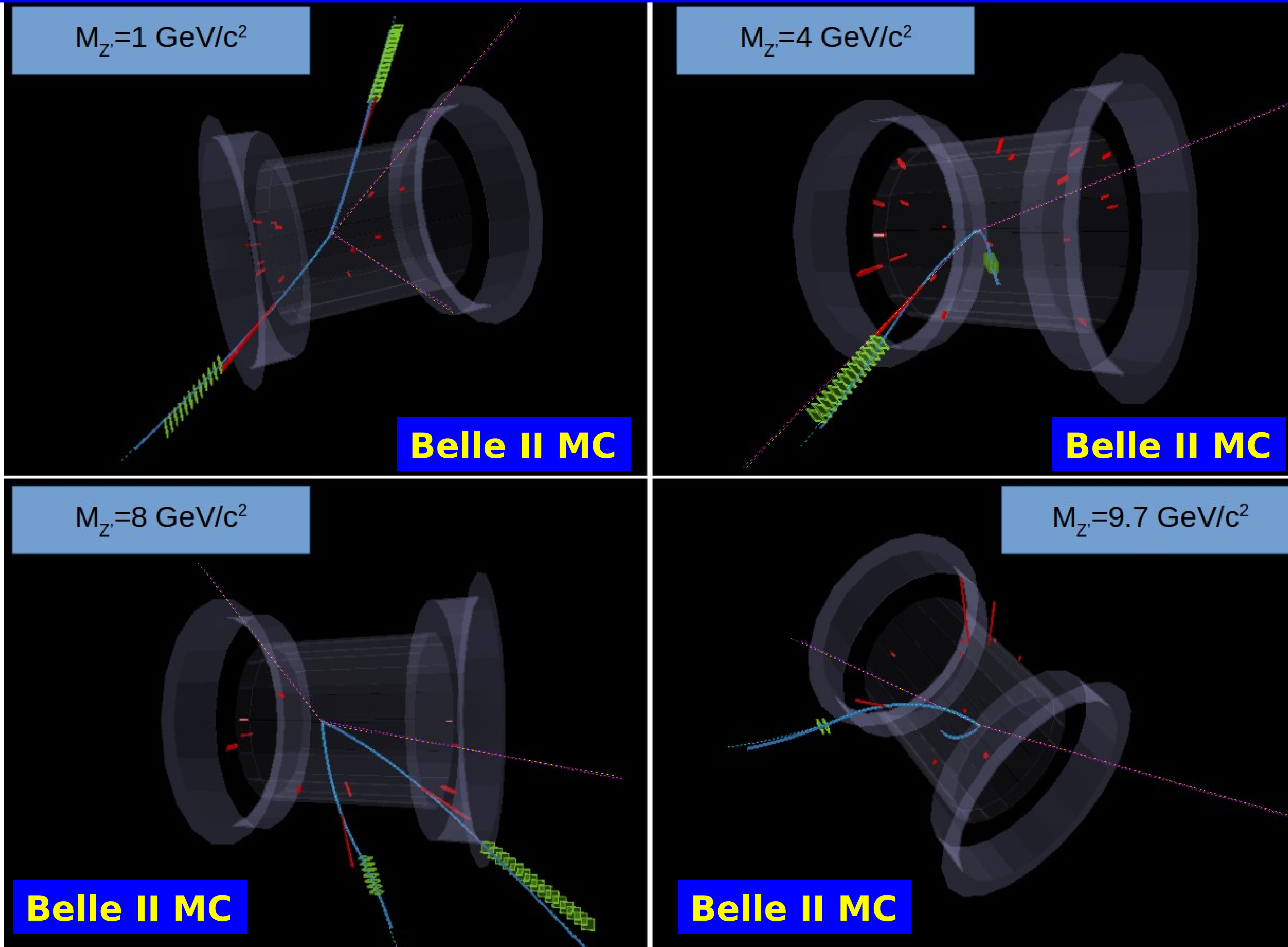
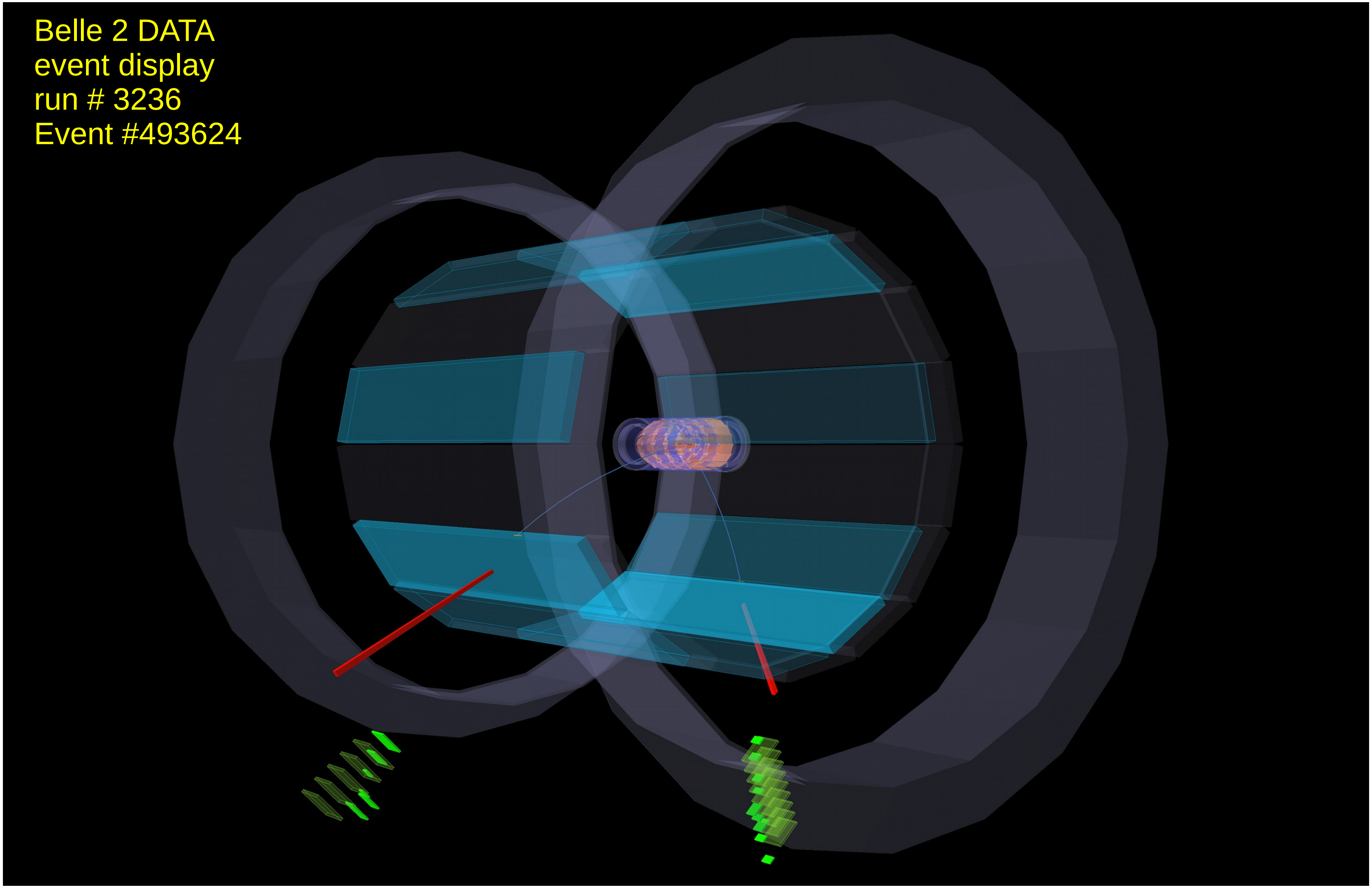
  - **For $M_{Z'} < 2M_\mu$ Br(Z’ → invisible) =1.**
  - **For $2M_\mu < M_{Z'} < 2M_\tau$ Br(Z’ → invisible)~1/2**
  - **For $M_{Z'} > 2M_\tau$ Br(Z’ → invisible)~1/3**

**If $M_{Z'} > 2\chi$ → BF[Z’ → $\chi\chi$]~1**

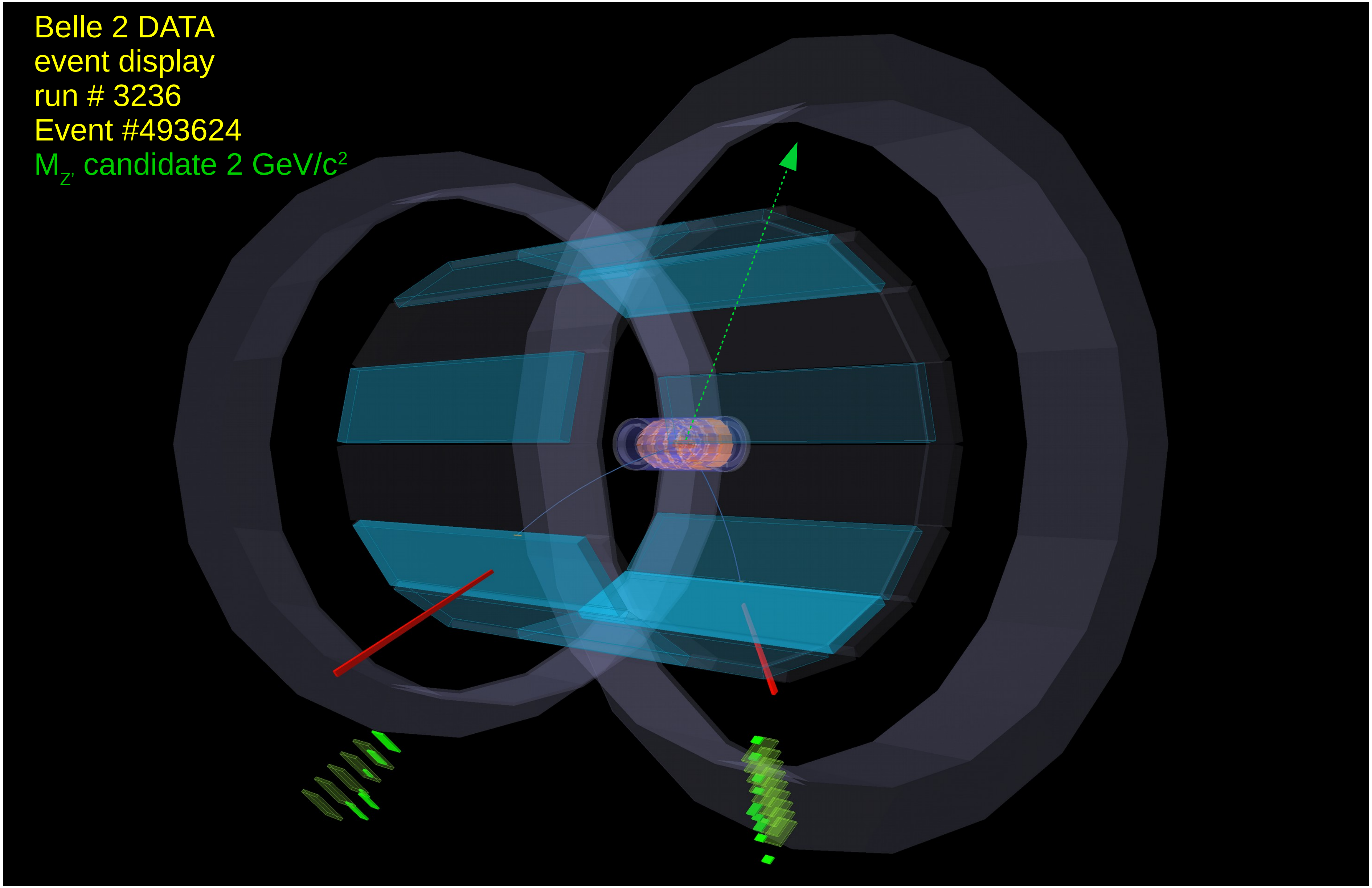
# Z’ → invisible, Belle II Event Display



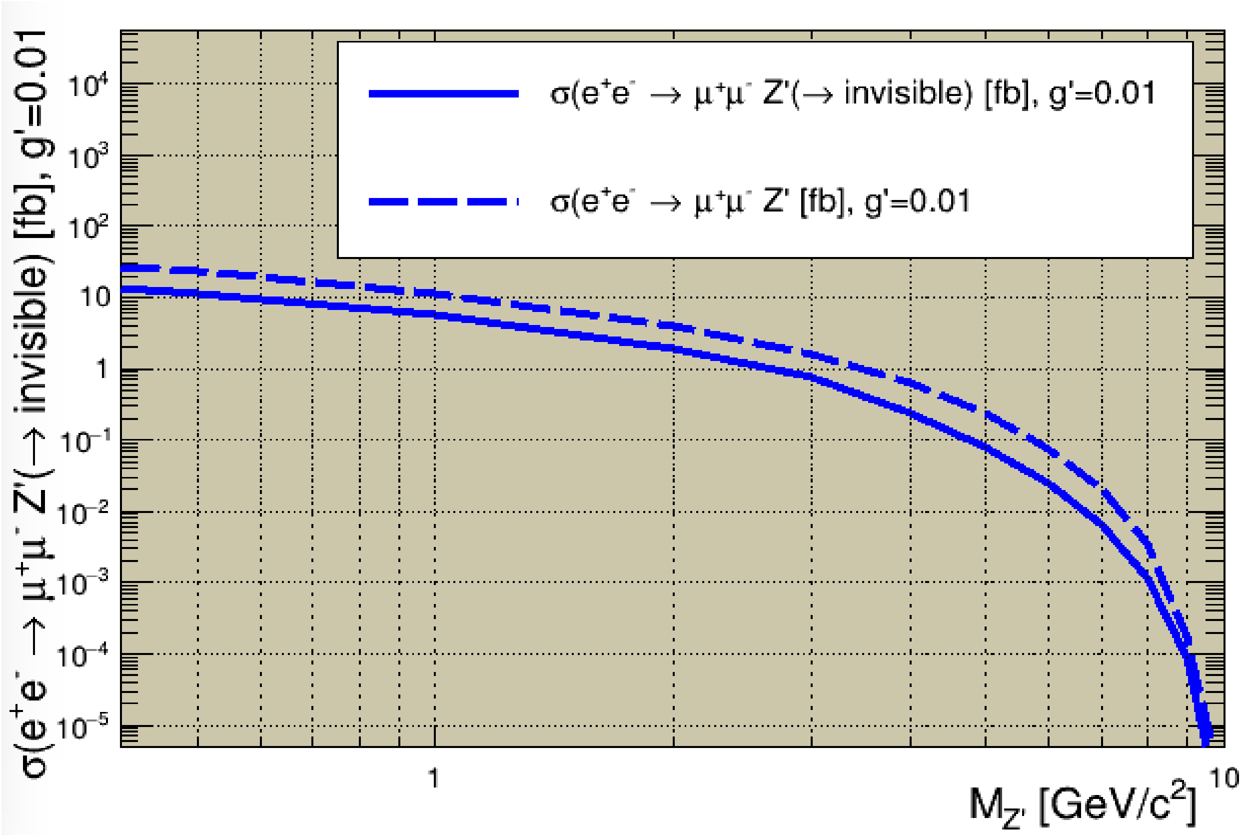
# Belle II Event Display



# Belle II Event Display

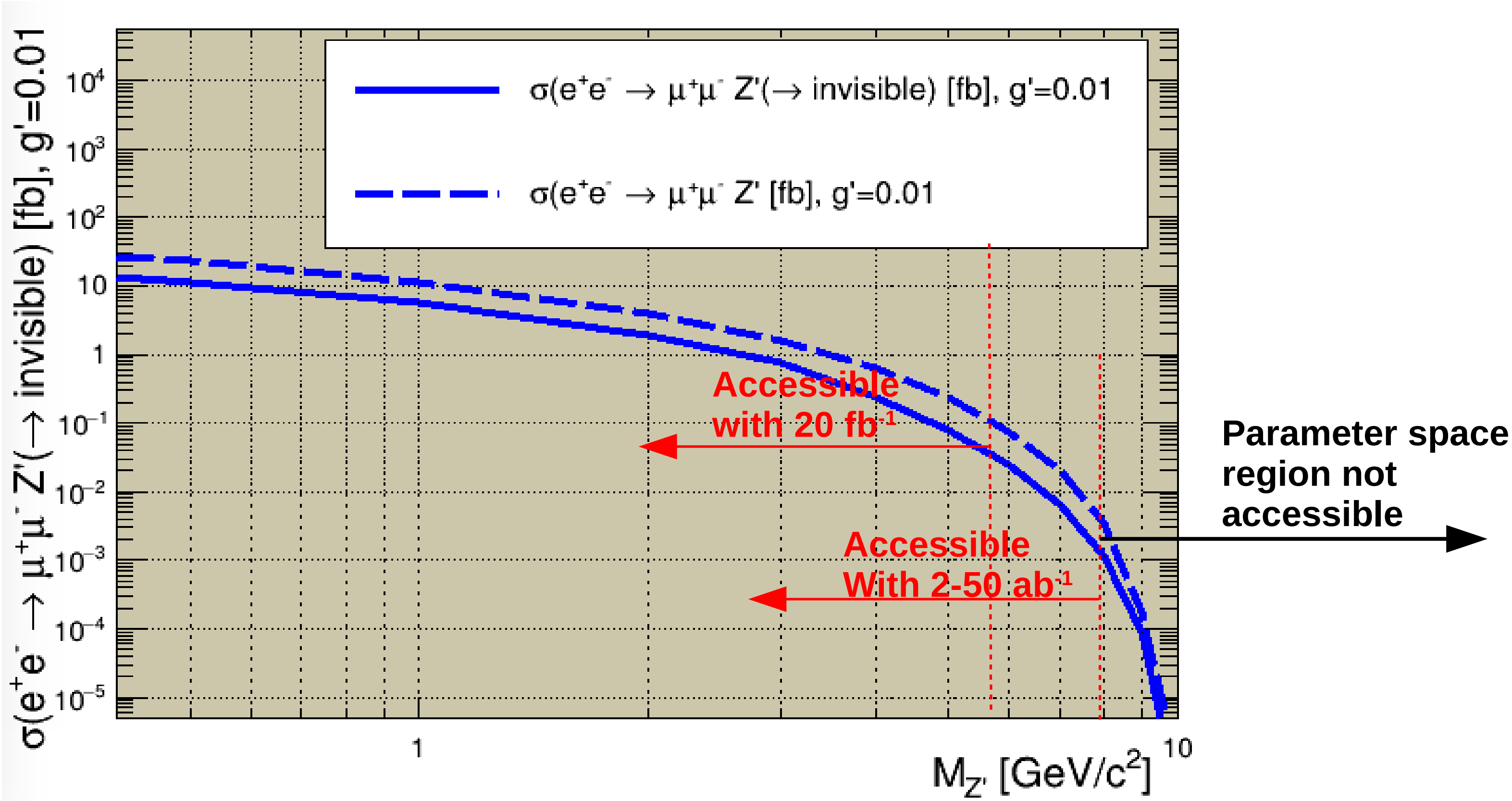


# Cross section for Z’→ invisible (ii)




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

# Cross section for Z’→ invisible (ii)




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

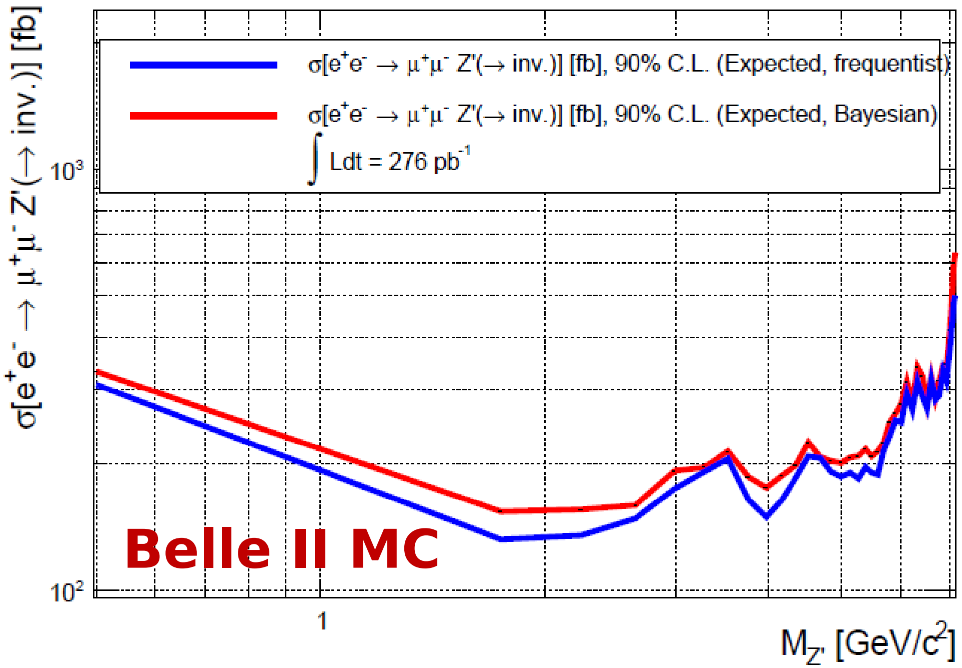
- Different masses are accessible with different luminosity: the larger the luminosity, the higher the mass of the Z’ that can be probed at Belle II.

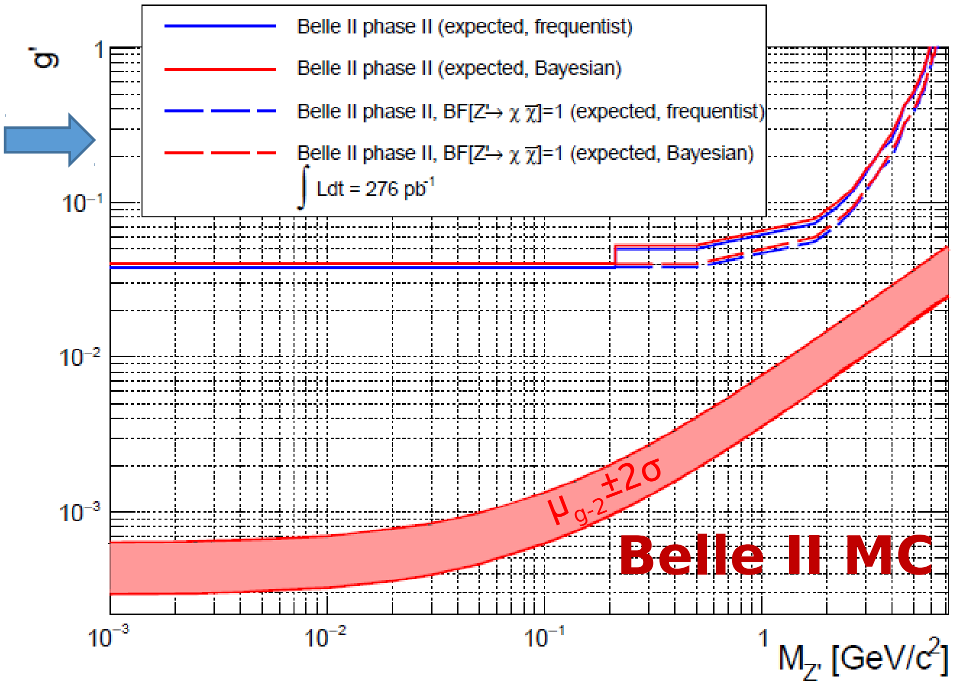
# Z' sensitivity on phase II data (expected)

Path to publication: data validation, data unblinding.

**L=276 $pb^{-1}$**

**Work in progress**

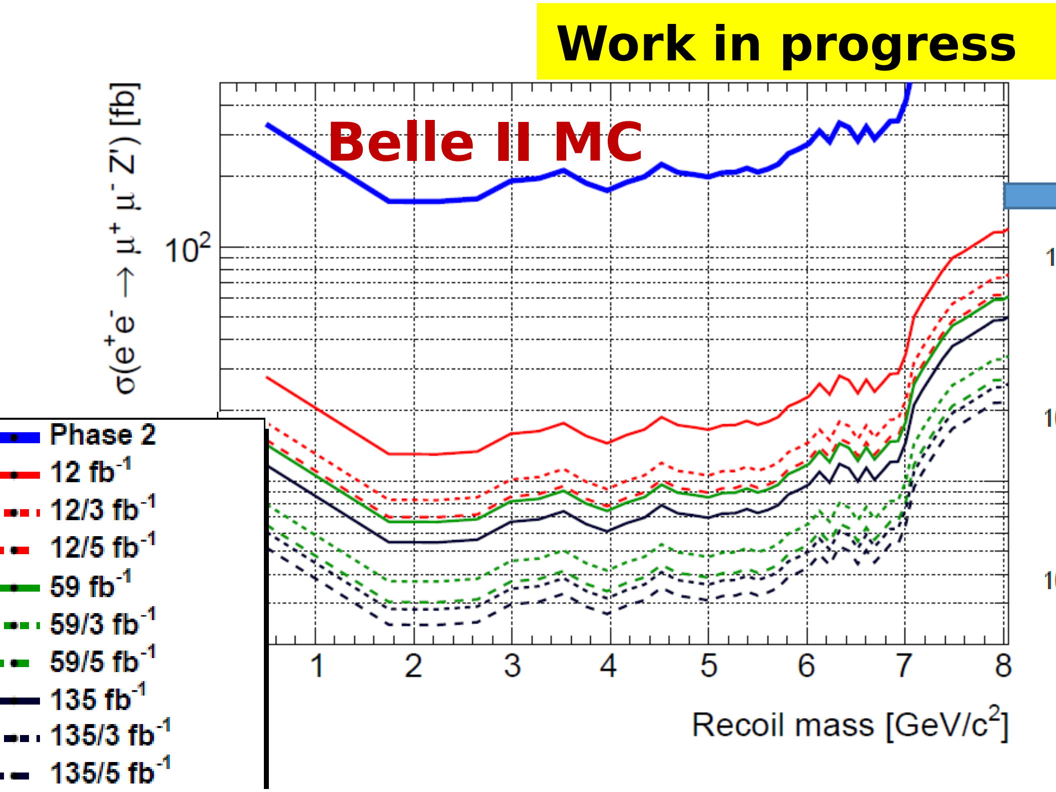


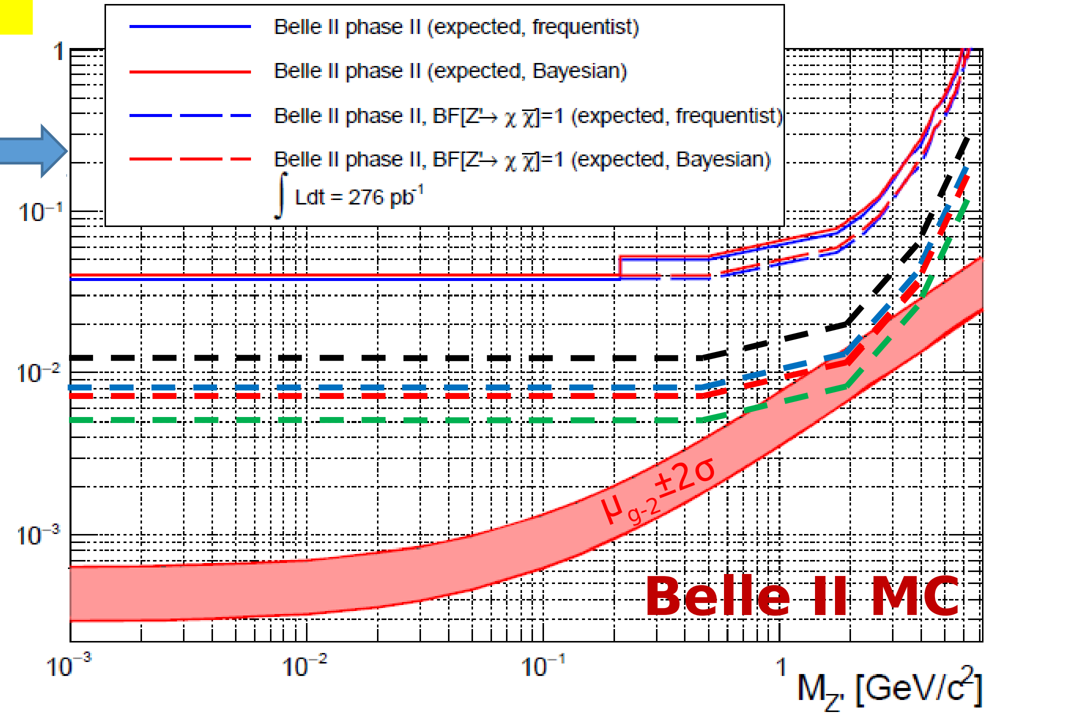




Systematic effects:

- trigger + tracking + PID + mass resolution systematics included (~10%)
- possible additional systematics on background estimate not included (0-30 %)
- analysis optimisation still undergoing -> details might change
- other systematic effects expected to be negligible

# Z' sensitivity on early phase III data (expected) and projection




Possible (big) factors of improvement beyond luminosity:

- PID (up to 7 on τ bkg)
- Resolution (VXD)
- Vertex fit →τ rejection
- MVA vs linear cut analysis
- See also previous slide for assumptions on systematics

→ same background or background reduced by factors 3 and 5

| | |
|---|---|
| black dashed | $12\ fb^{-1}$ |
| blue dashed | $59\ fb^{-1}$ |
| red dashed | $135\ fb^{-1}$ |
| green dashed | $135\ fb^{-1}$, B/5 |

# Conclusions

- 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 photons, charged particles, and (large) missing energy in the final state.

- 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 is required.

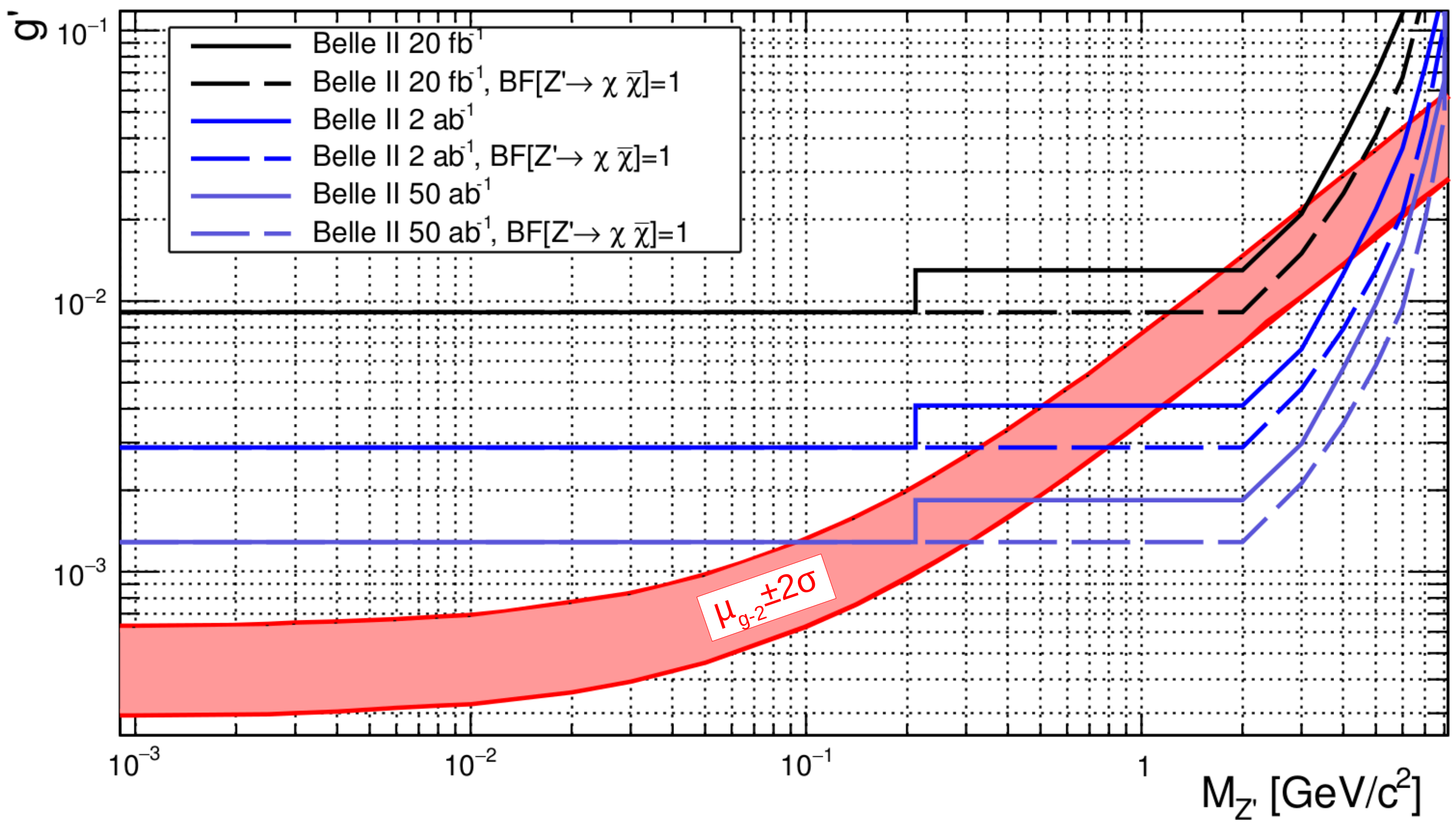
- Many searches at the Belle II experiment are ongoing and higher precision will be reached thanks to the great luminosity of Belle II at Super-KEK and thanks to improved hardware/software. First results are to be released soon.

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

**Thank you for your attention!**

# Z' sensitivity on phase III data (expected)

- 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

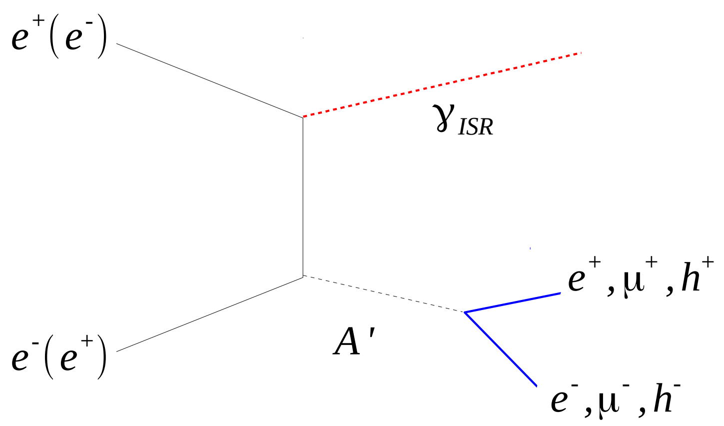


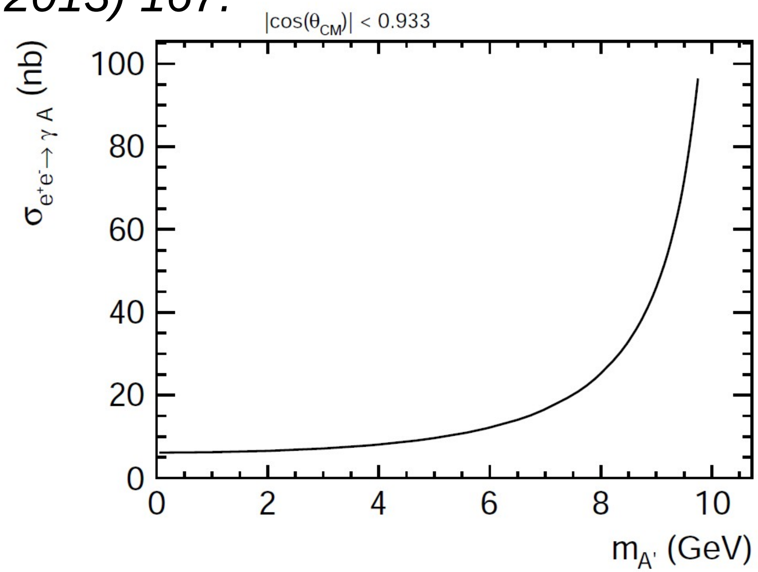

- Does not account for all the efficiencies (but sensitivity scale as $L^{1/4}$…)

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

# Dark Photon Search Strategy (visible case)

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

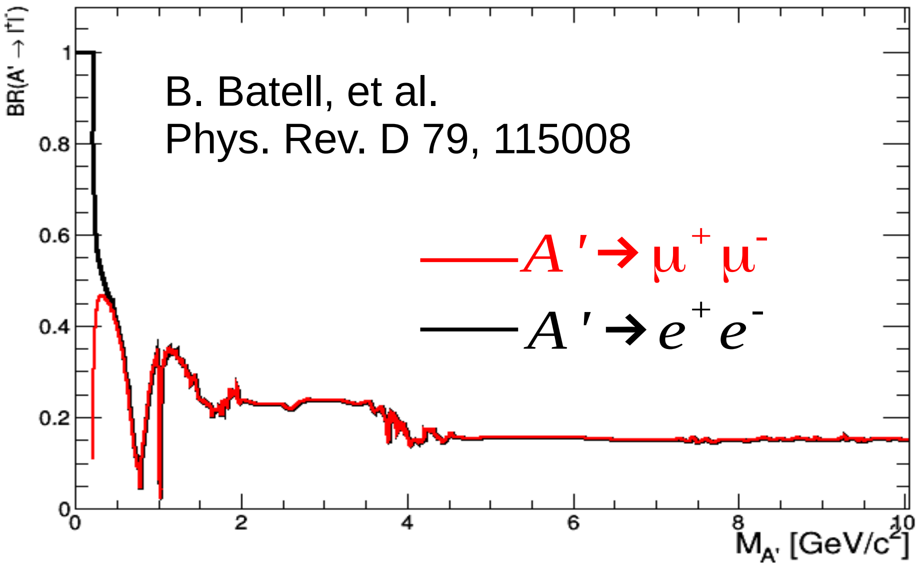


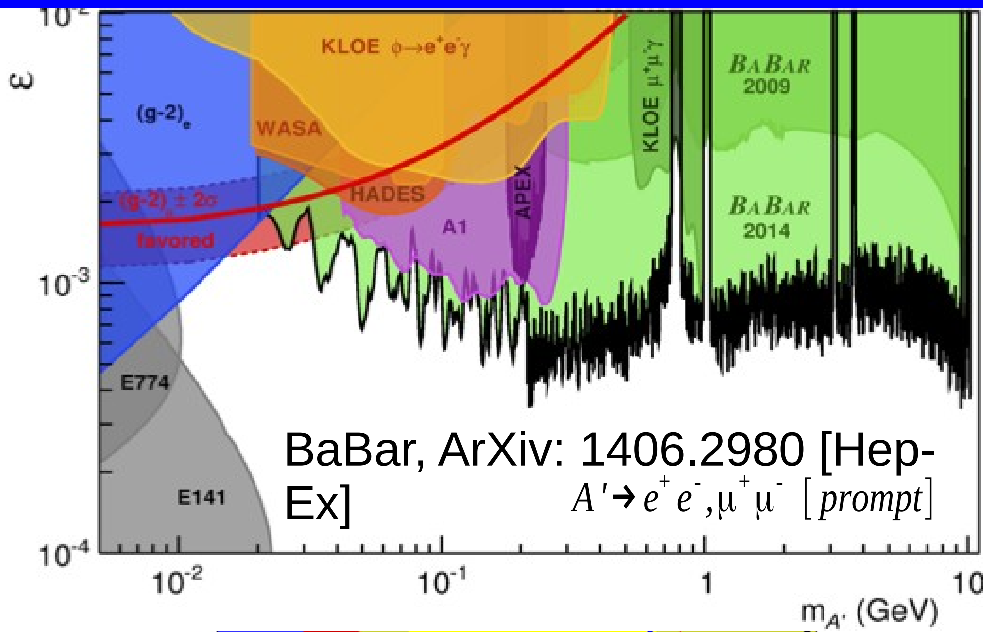

*A'*= dark photon, L= long lived light gauge boson (model independent).
*A'* decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states with 2 oppositely charged tracks and 1 photon.

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

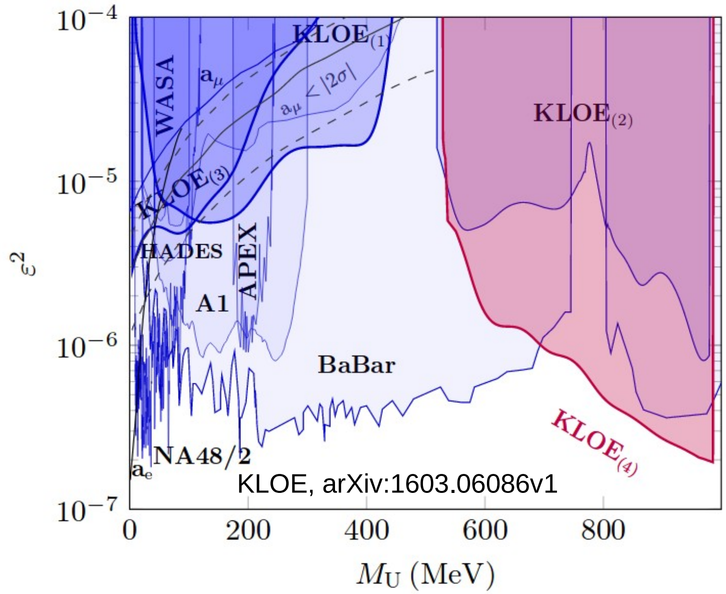
**Note**
- If $M_\chi < M_{A'}/2$ → invisible A' decays to dark matter!



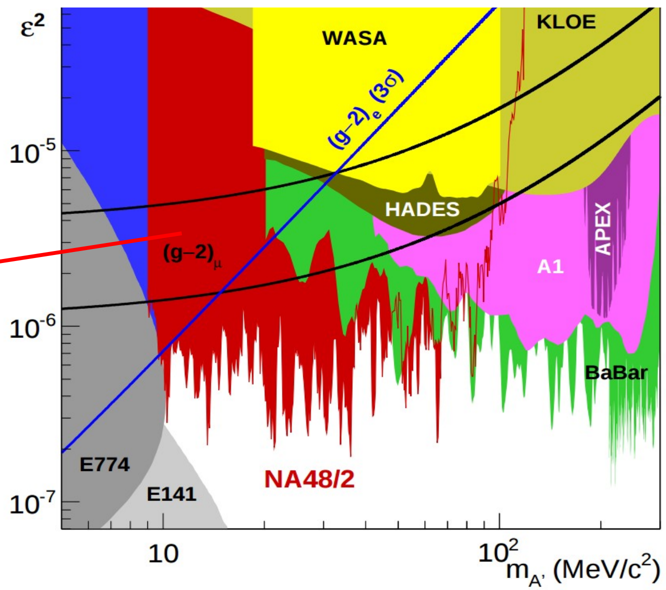
# Dark Photon: Current UL to Kinetic Mixing




BaBar, ArXiv: 1406.2980 [Hep-Ex] $A' \to e^+e^-, \mu^+\mu^-$ [*prompt*]

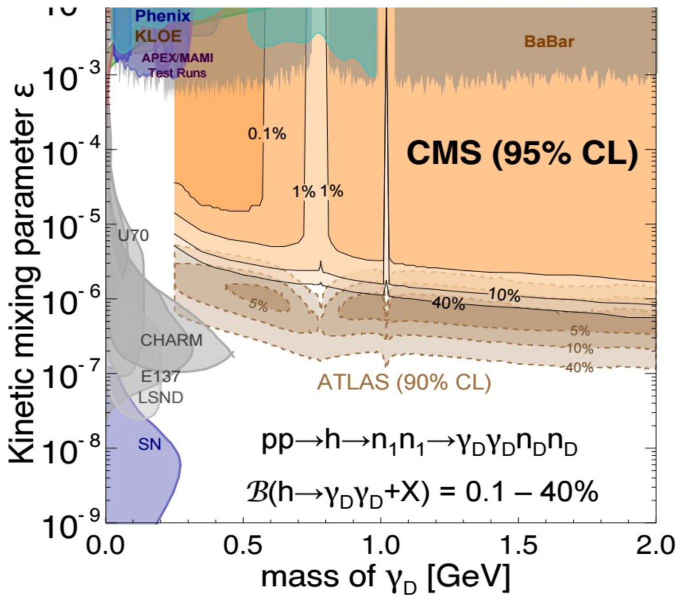



KLOE, arXiv:1603.06086v1




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

NA48 arXiv:1504.00607
$\pi^0$ decays




ATLAS + CMS:

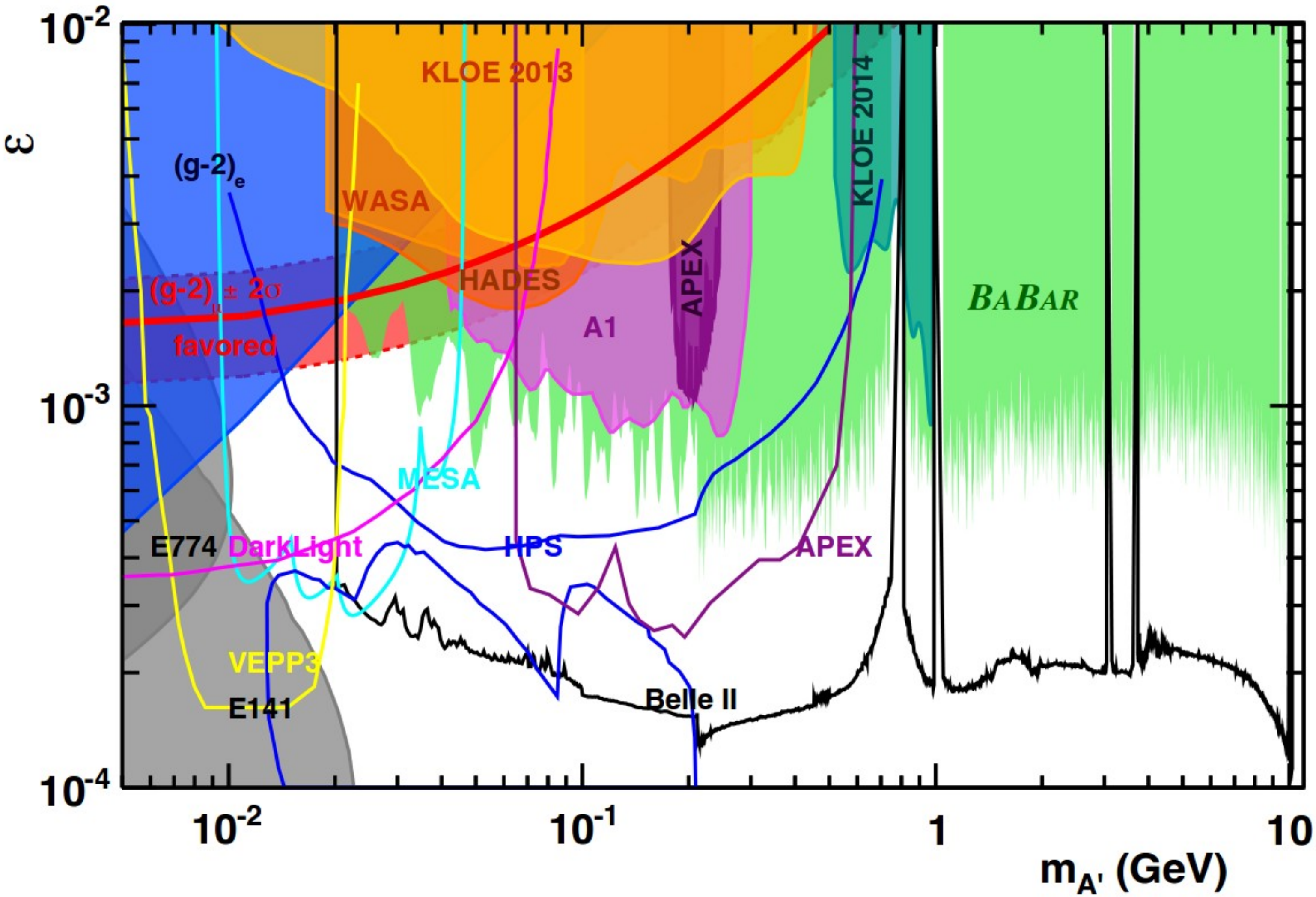
highly model-dependent!

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

→ See M. Borsato’s talk for LHCb studies

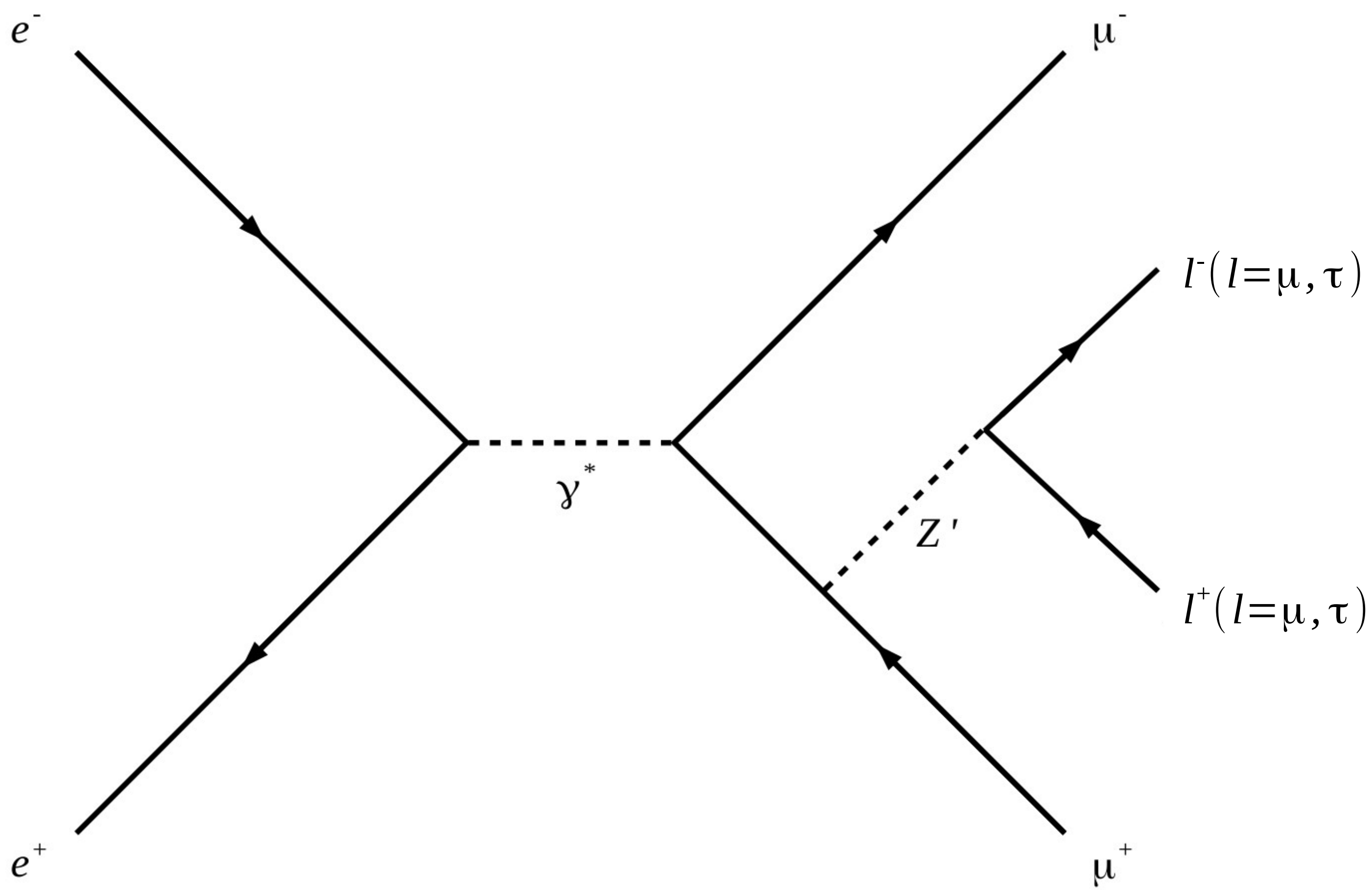
# Dark Photon: Expected Sensitivity @ Belle II

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




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

# The $L_\mu$-$L_\tau$ model in the context of dark sector searches: a dark Z'




- 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**
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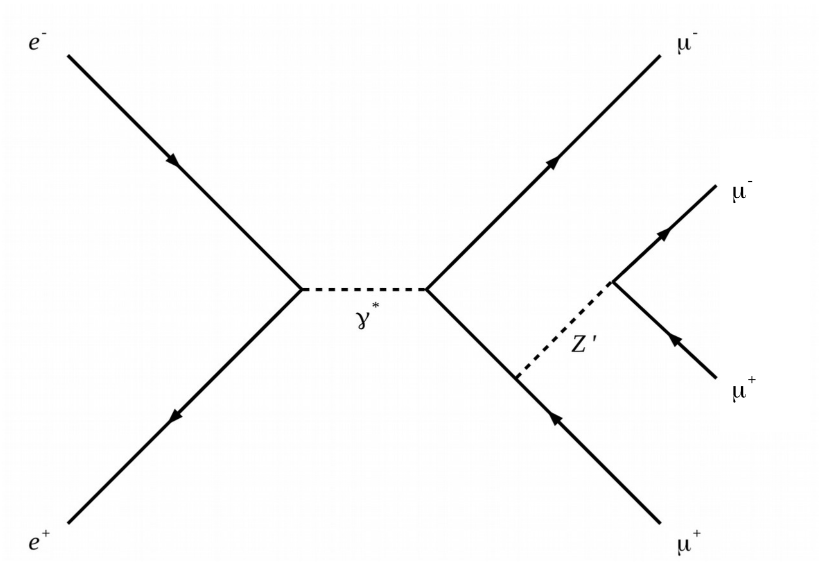
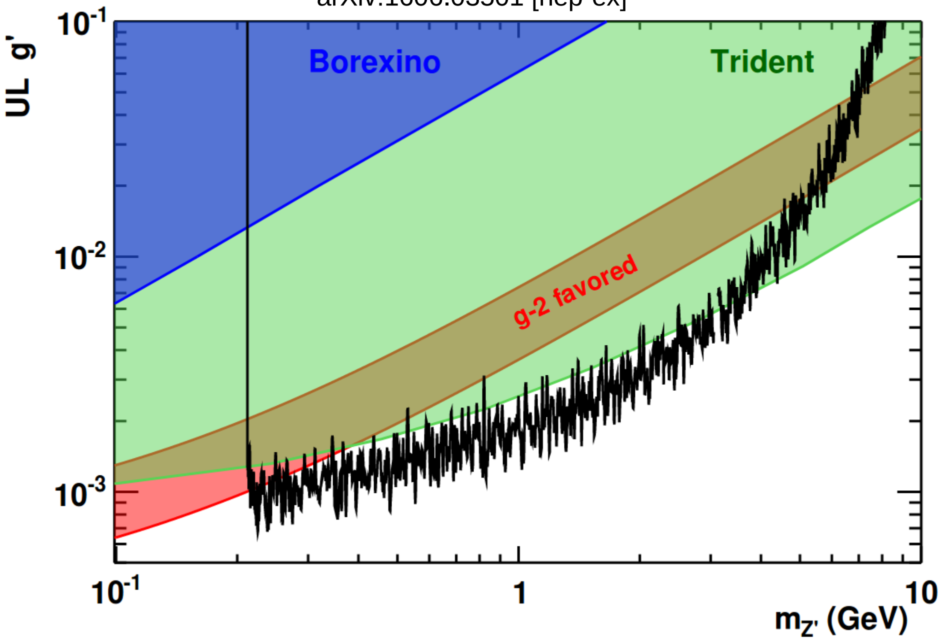



BABAR Coll.
Phys. Rev. D 94, 011102 (2016),
arXiv:1606.03501 [hep-ex]

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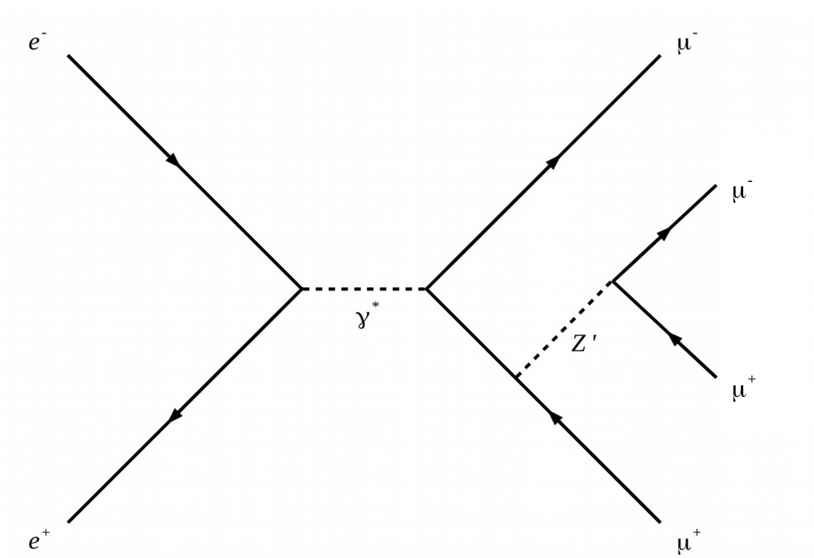
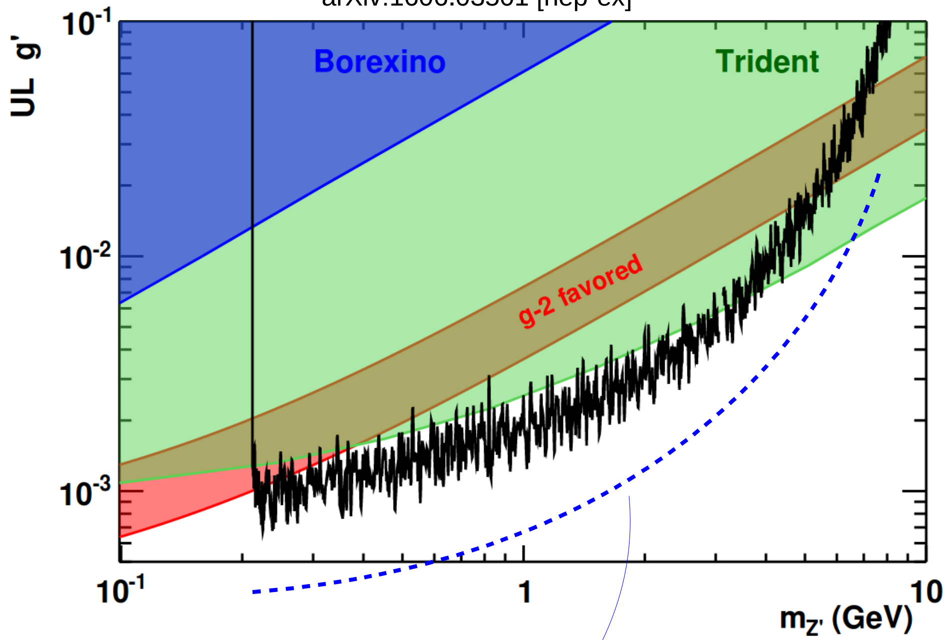



BABAR Coll.
Phys. Rev. D 94, 011102 (2016),
arXiv:1606.03501 [hep-ex]




**Rough projection to Belle II luminosity preliminary studies are ongoing**

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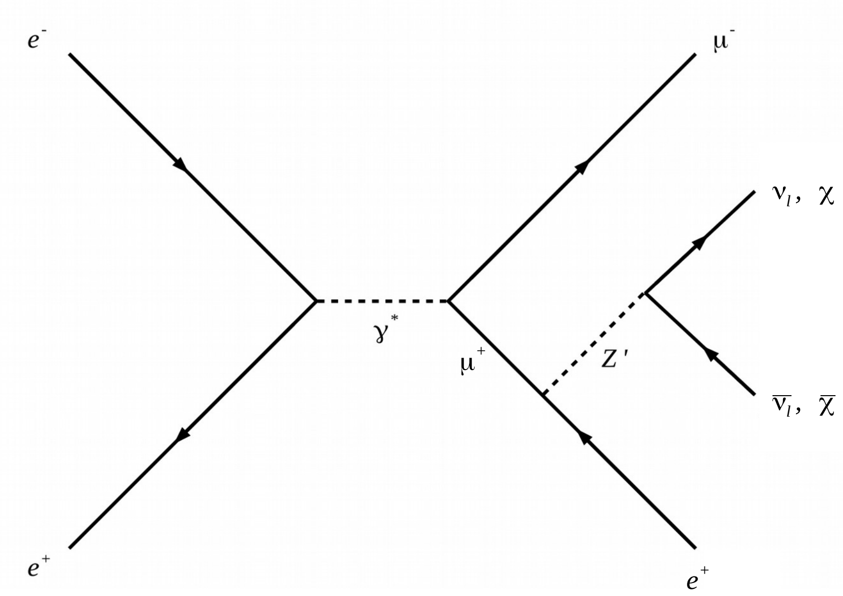
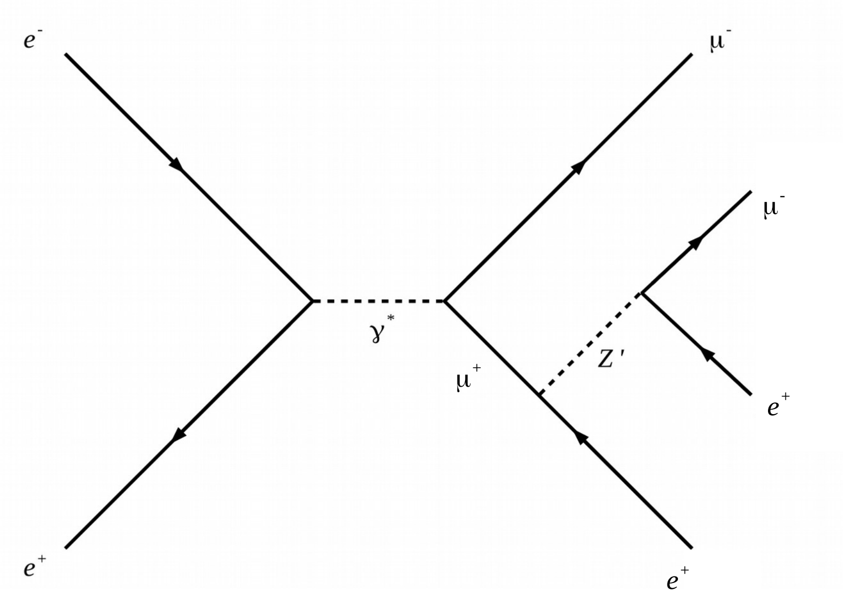
# What about a LFV Z'?




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




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

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*

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

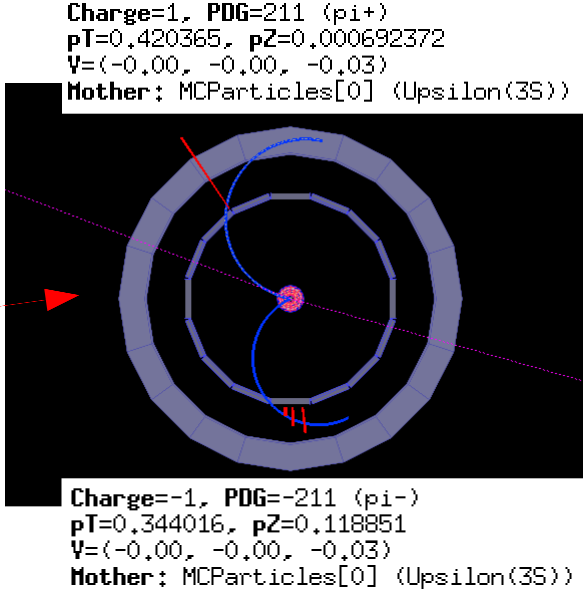
$$BR(\Upsilon(1S)\to\nu\bar{\nu})\sim9.9\times10^{-6}$$

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

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

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

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




$\sim 900\ MeV$ *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 Υ(1S) Decays @ Belle II

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

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

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

$e^+e^-\to Y(2S)$
↓(18.1%)
$Y(2S)\to\pi^+\pi^-Y(1S)$
↓
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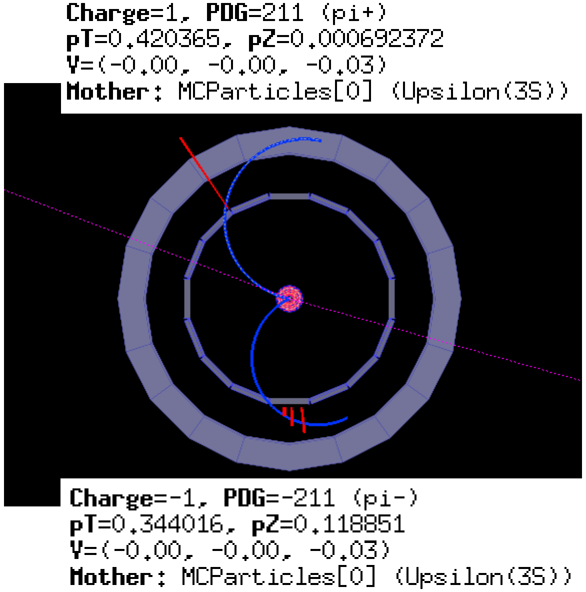
- Also, new mediators (Z', $A^0$, $h^0$) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new physics enhancement, Belle2 should be able to observe the SM Υ(1S)→νν

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



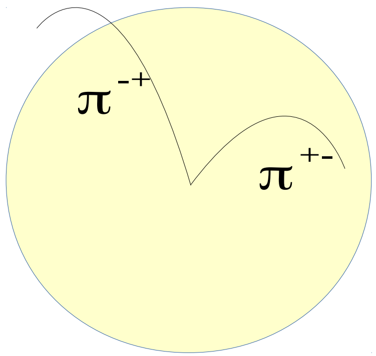

A signal of Υ(1S)→*invisible* is an excess of events over the background in the $M_r$ distribution at a mass equivalent to that of the Υ(1S) (9.460 GeV/c²)

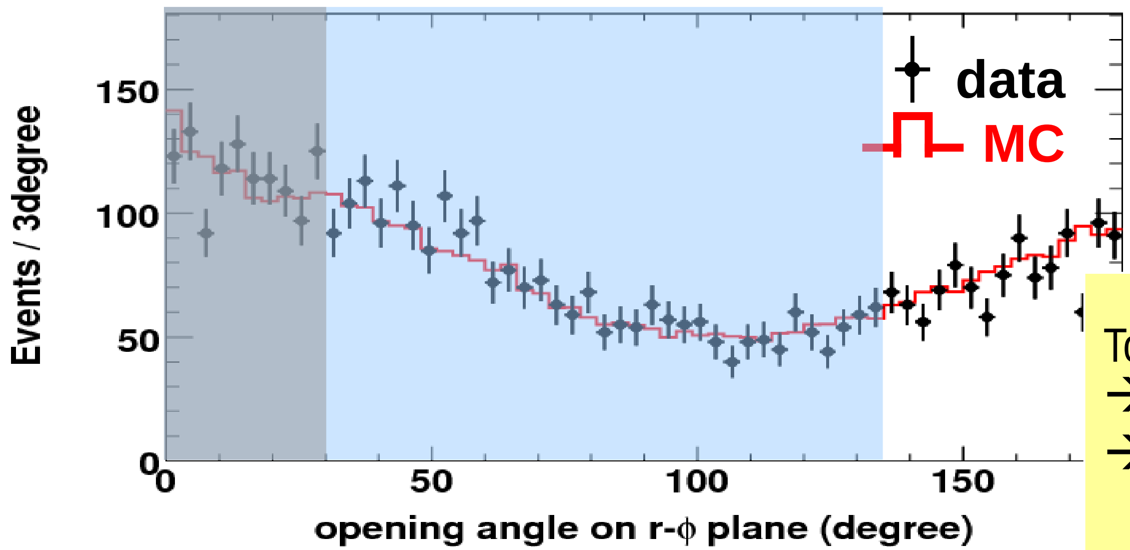
$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

# Trigger Considerations

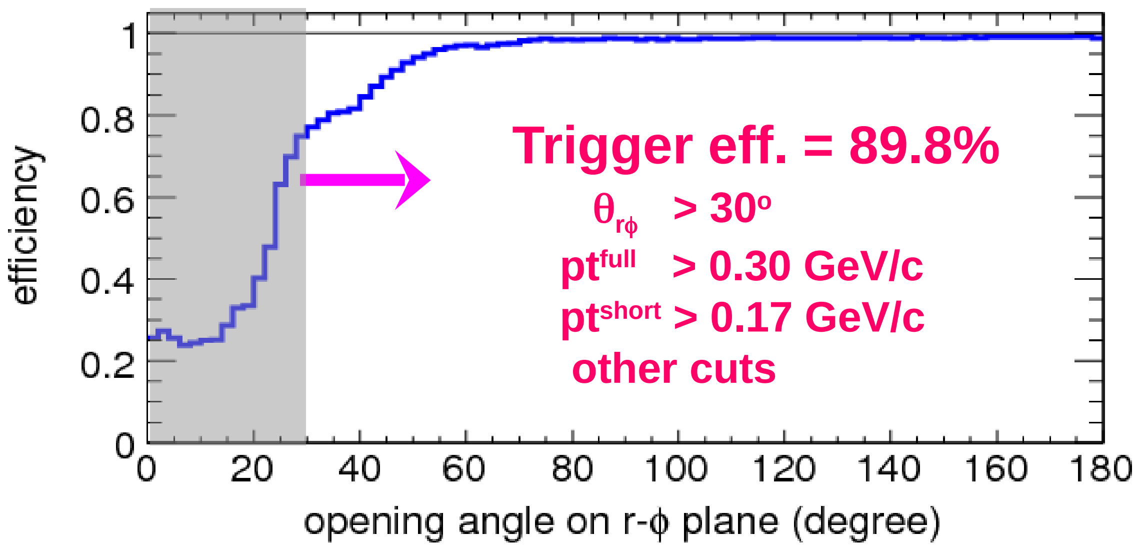
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

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




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)

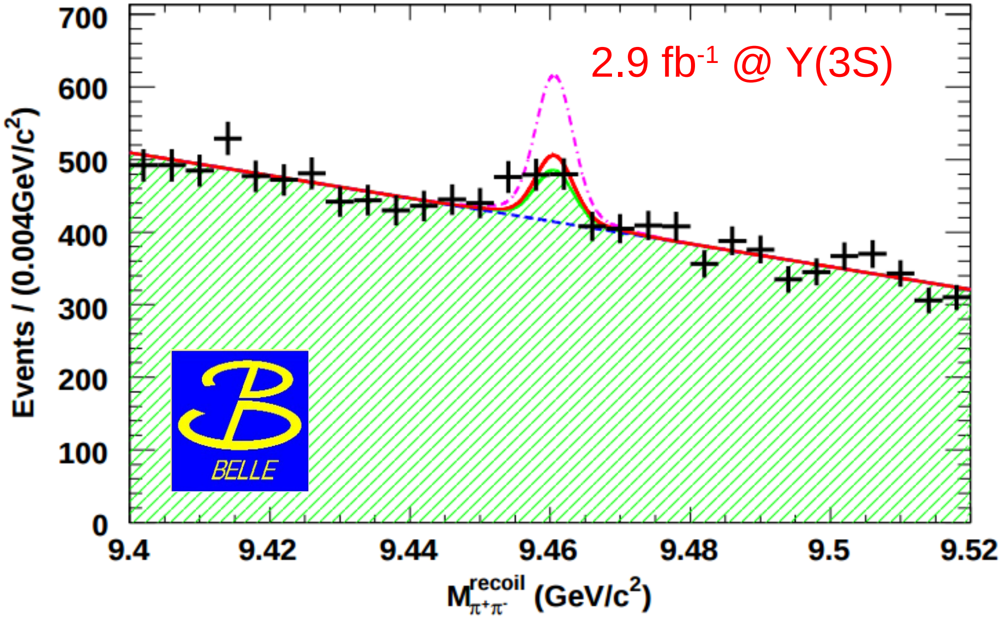
$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

for efficiency monitoring

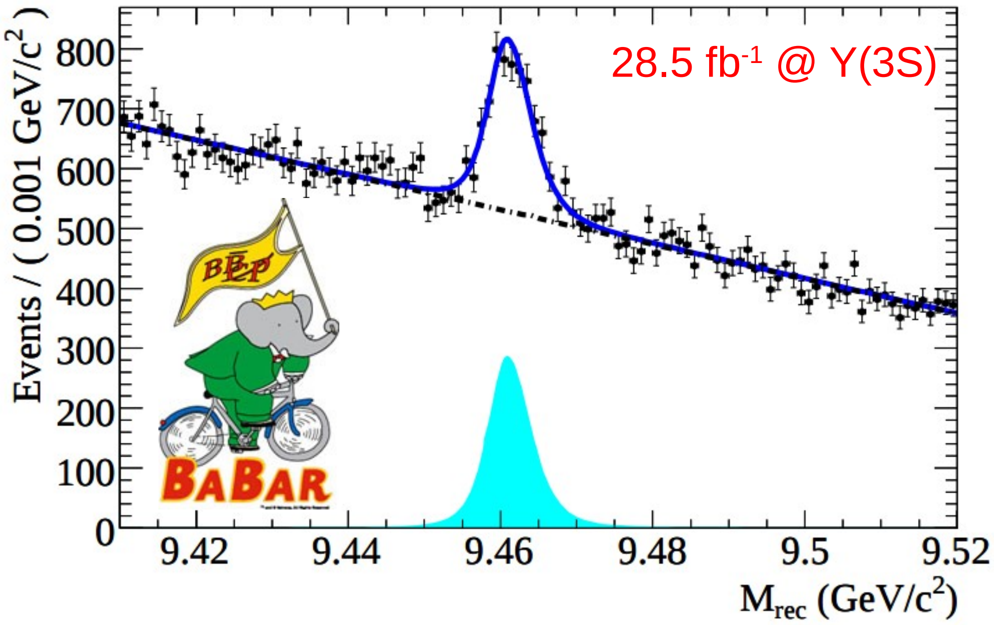
# Invisible Υ(1S) Decays: Signal or Background?

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

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



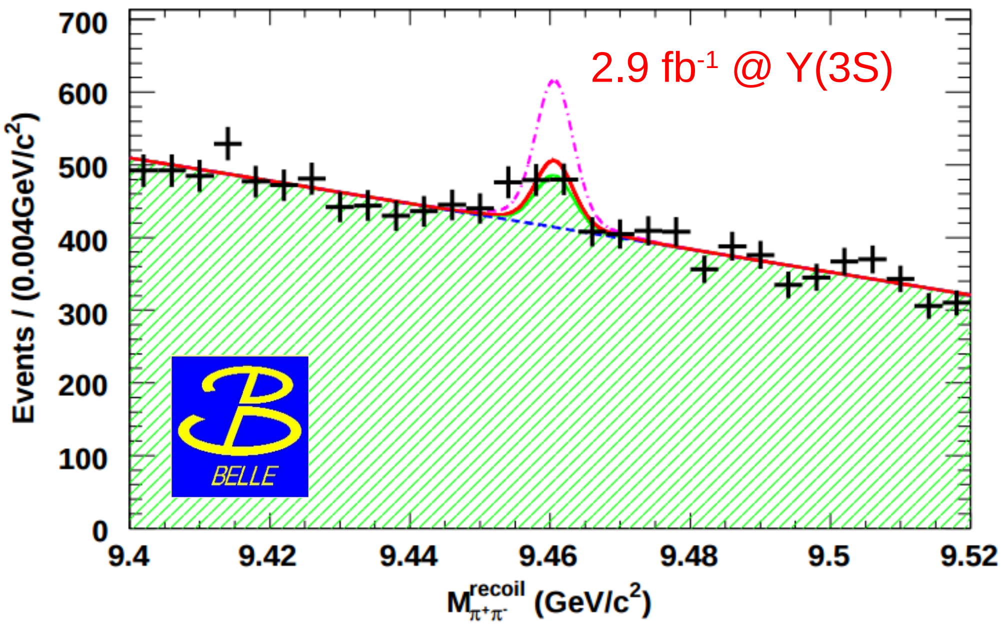

[babar]: http://arxiv.org/abs/0908.2840
(2 months running @ Υ(3S))



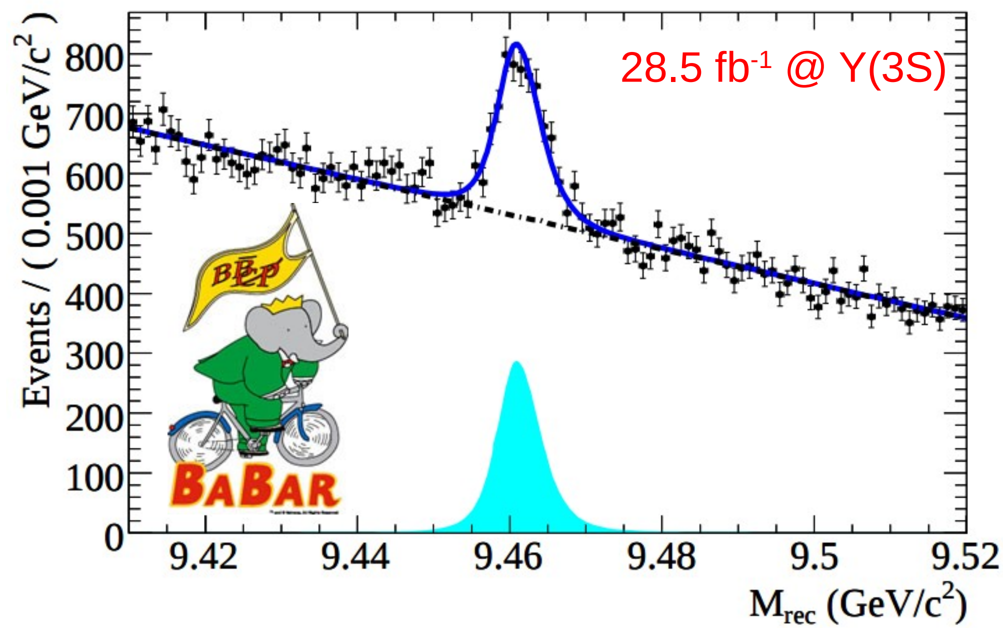
# Invisible Υ(1S) Decays: Belle II Discovery Potential

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

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




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



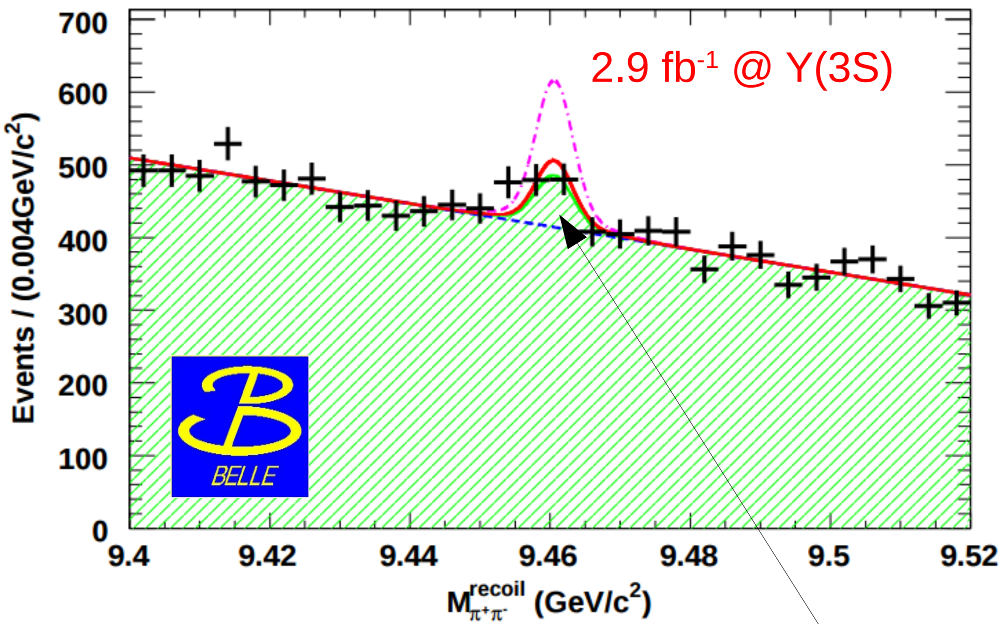

No signal was observed over the expected background and upper limits have been obtained: BR(Υ→νν) < $3\times10^{-4}$ (BaBar) and BR(Υ→νν) < $3.0\times10^{-3}$(Belle).

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

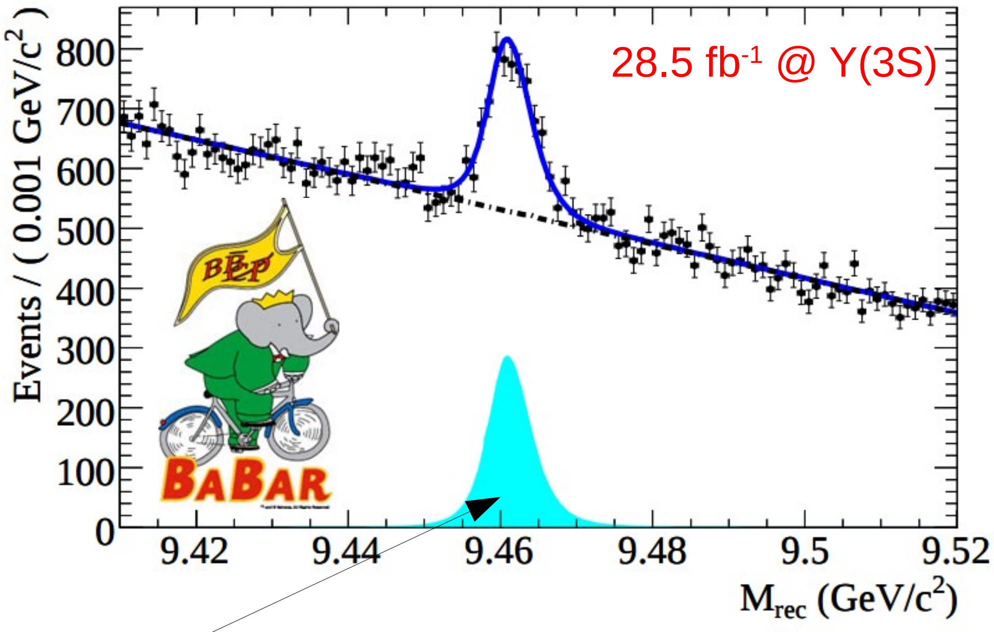
# Invisible Υ(1S) Decays: Signal or Background?

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

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

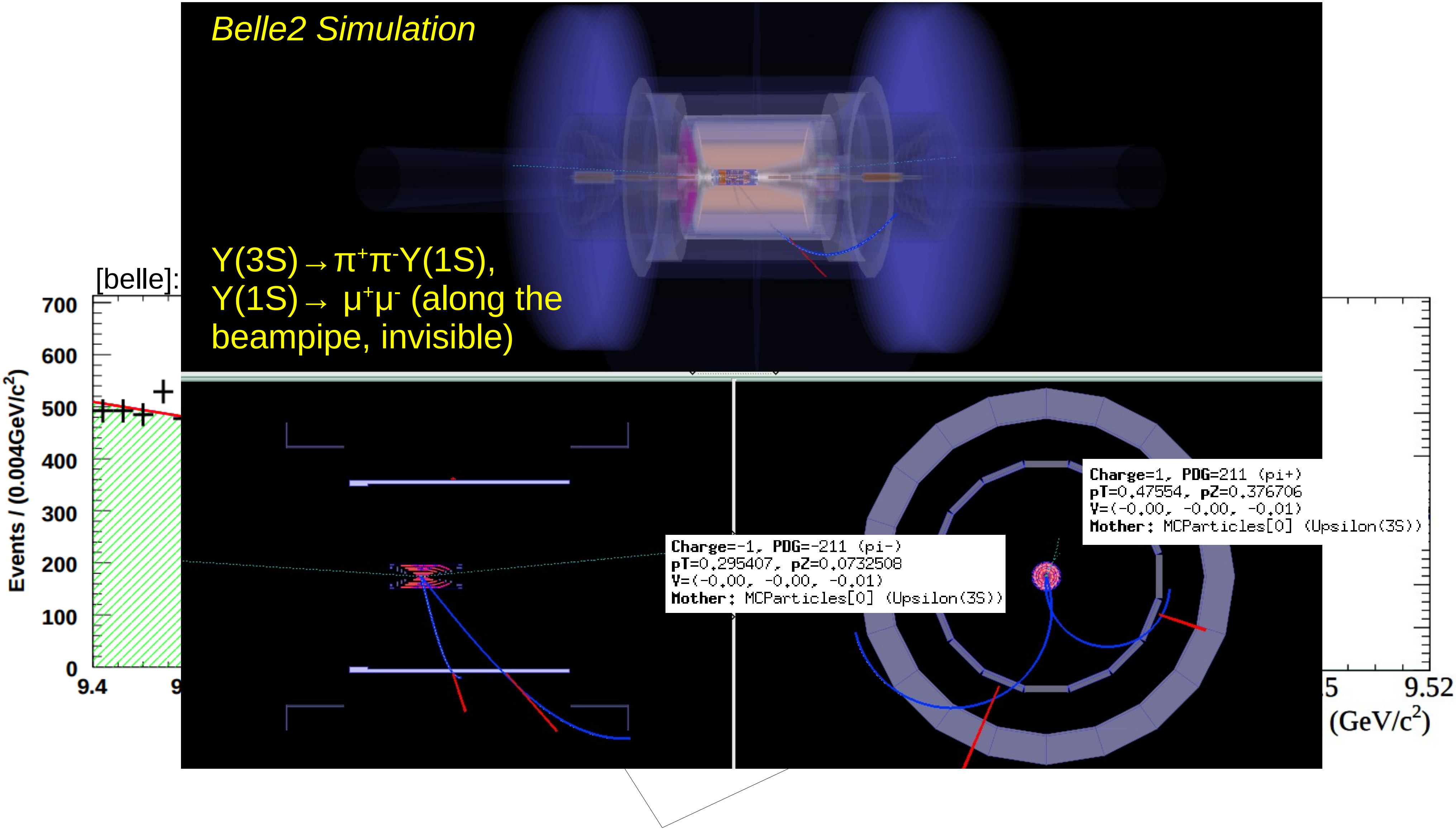



[babar]: http://arxiv.org/abs/0908.2840
(2 months running @ Υ(3S))




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

# Invisible Υ(1S) Decays: irreducible background




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 Y(1S) Decays @ Belle II: Expected Yields

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

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

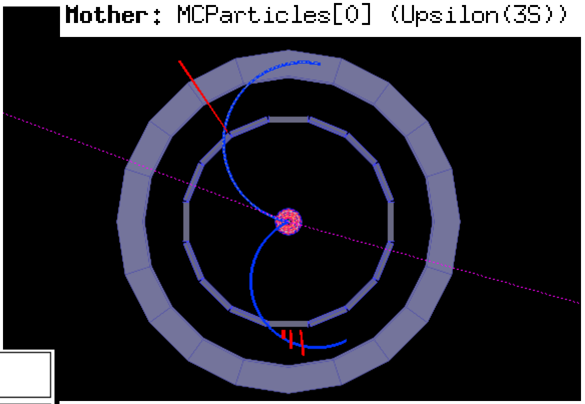
$$e^+e^-\rightarrow Y(3S)$$
↓(4.4%)
$$Y(3S)\rightarrow\pi^+\pi^-Y(1S)$$
↓
$$Y(1S)\rightarrow invisible$$

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

- 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 strongly constrain the SM Y(1S)→νν

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

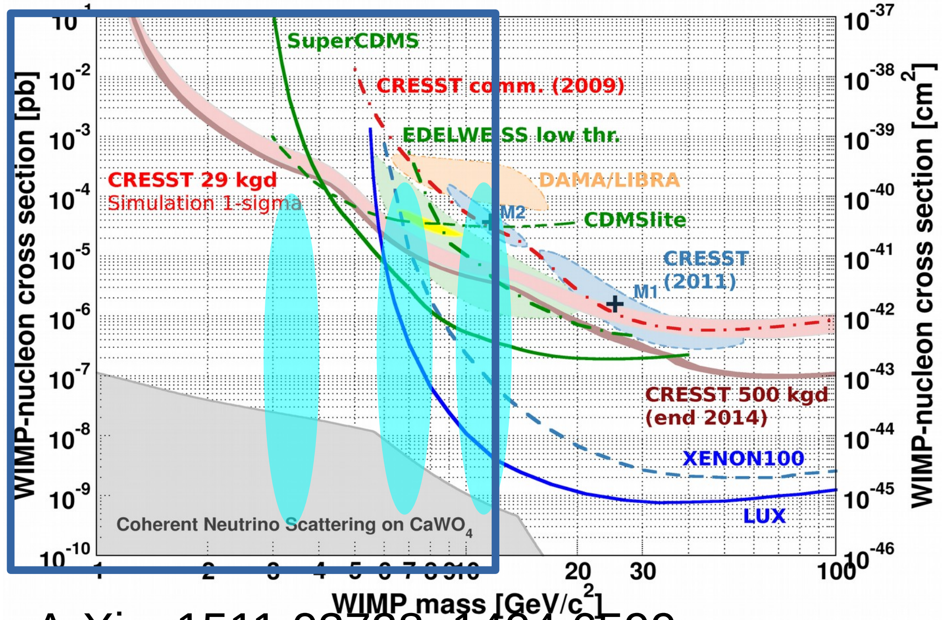
No signal was observed over the expected background and upper limits have been obtained: BR(Y→νν) < $3\times10^{-4}$ (BaBar) and BR(Y→νν) < $3.0\times10^{-3}$(Belle).

| Process | $L_{int}(ab^{-1})$ | $\epsilon$ | $N(\Upsilon(1S))$ | $N_{\Upsilon(1S)\to\nu\bar{\nu}}$ | $N_{NP}$ |
|---|---|---|---|---|---|
| $\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S)$ | 0.2, $\Upsilon(2S)$ | 0.1-0.2 | $2.3\times10^8$ | 230-460 | 6900-13800 |
| $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ | 0.2, $\Upsilon(3S)$ | 0.1-0.2 | $3.2\times10^7$ | 32-64 | 945-1890 |
| $\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S)$ | 50.0, $\Upsilon(4S)$ | 0.1-0.2 | $5.5\times10^6$ | 5.5-11 | 165-310 |
| $\Upsilon(5S)\to\pi^+\pi^-\Upsilon(1S)$ | 5.0, $\Upsilon(5S)$ | 0.1-0.2 | $7.6\times10^6$ | 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 | $1.5\times10^8$ | 150-300 | 4500-9000 |
| $\gamma_{ISR}\Upsilon(3S)\to(\gamma_{ISR})\pi^+\pi^-\Upsilon(1S)$ | 50.0, $\Upsilon(4S)$ | 0.1-0.2 | $3.5\times10^7$ | 35-70 | 1050-2100 |

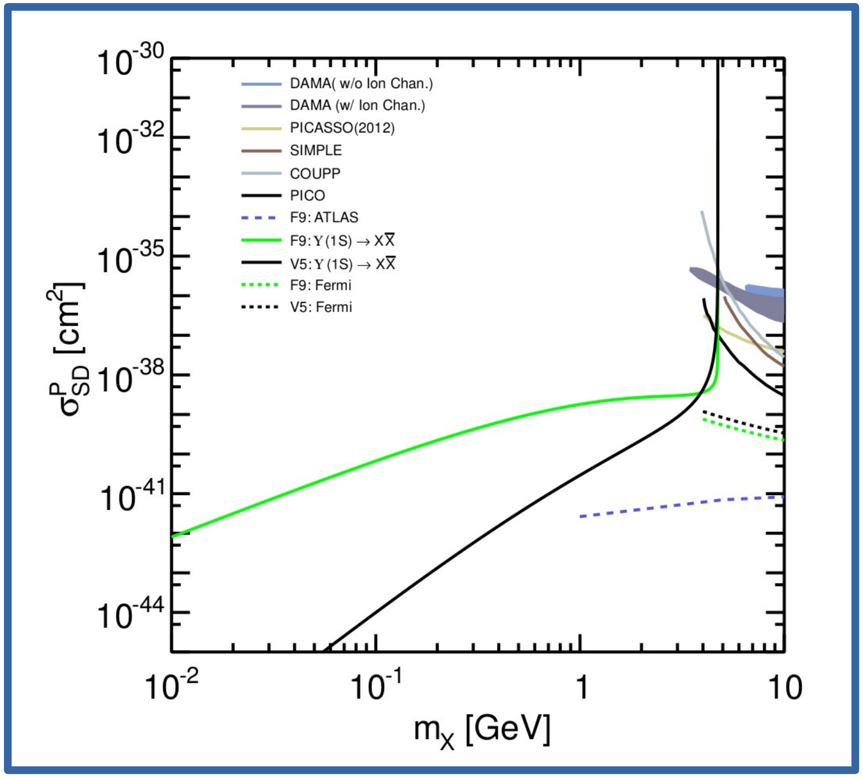
# DM: The Synergy Between Theory, Direct and Collider Searches

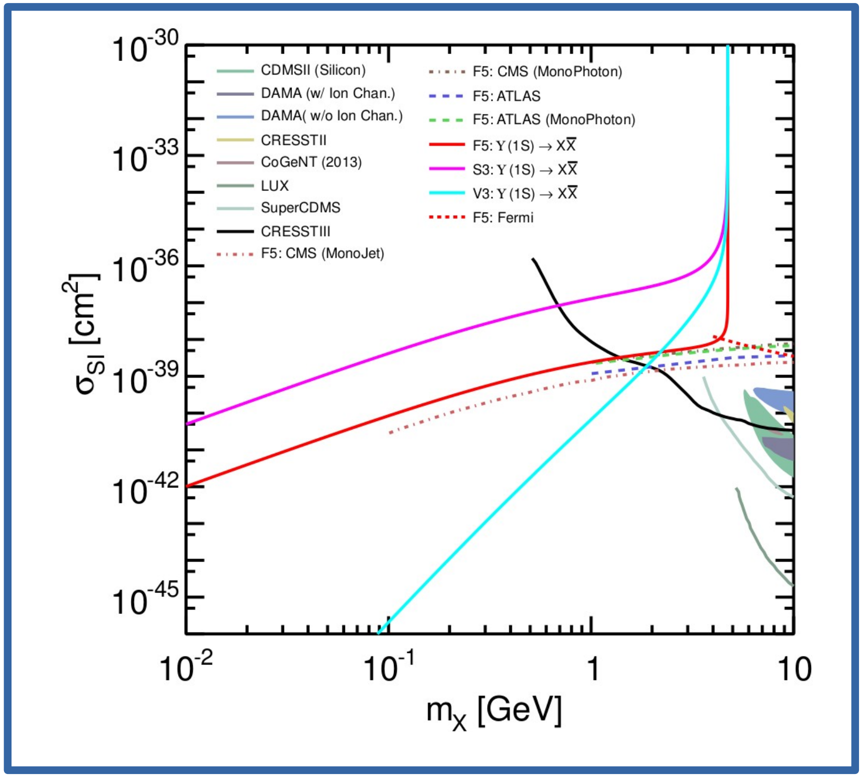
Theory work is needed in order to connect direct and indirect searches of dark matter.

- Shown here $\Upsilon(1S) \to \chi\chi$ 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 Y(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).