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Vienna 12/08/2019

“First results and prospects for dark sector physics @ Belle II”

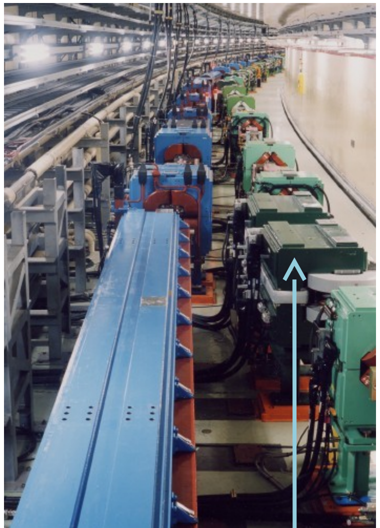
HEPHY INSTITUT FÜR HOCHENERGIEPHYSIK

FWF Der Wissenschaftsfonds.

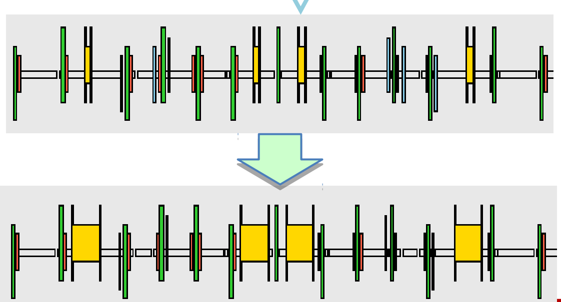
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Belle II

KEKB to SuperKEKB

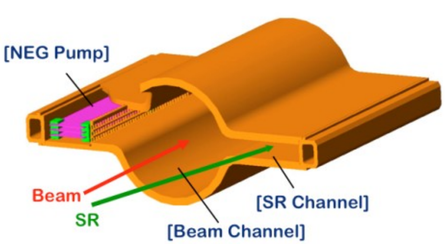


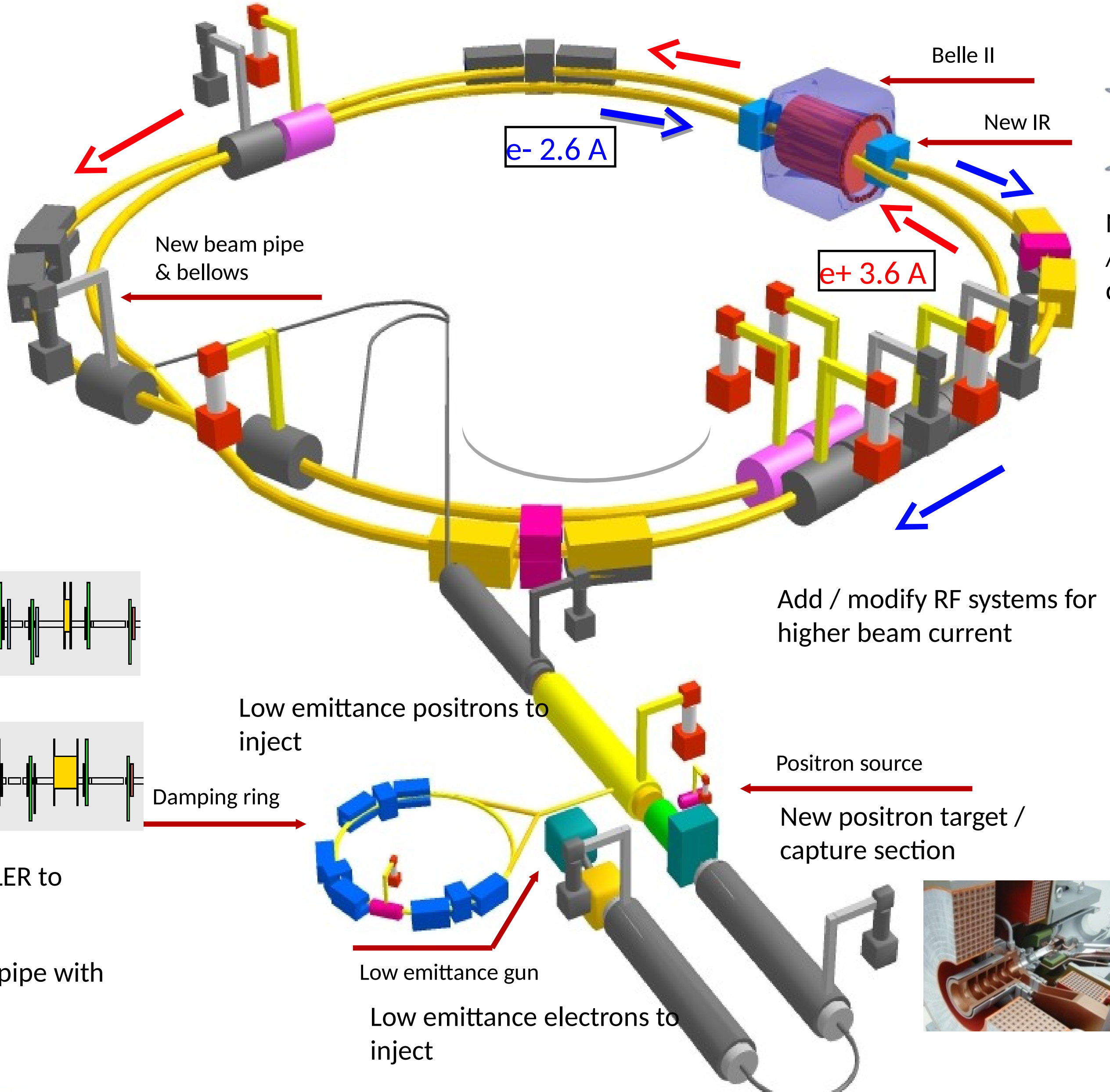
Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

TiN-coated beam pipe with antechambers

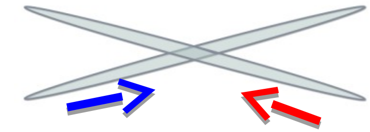




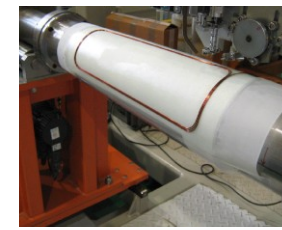
Low emittance positrons to inject

Low emittance electrons to inject

Colliding bunches



New superconducting /permanent final focusing quads near the IP

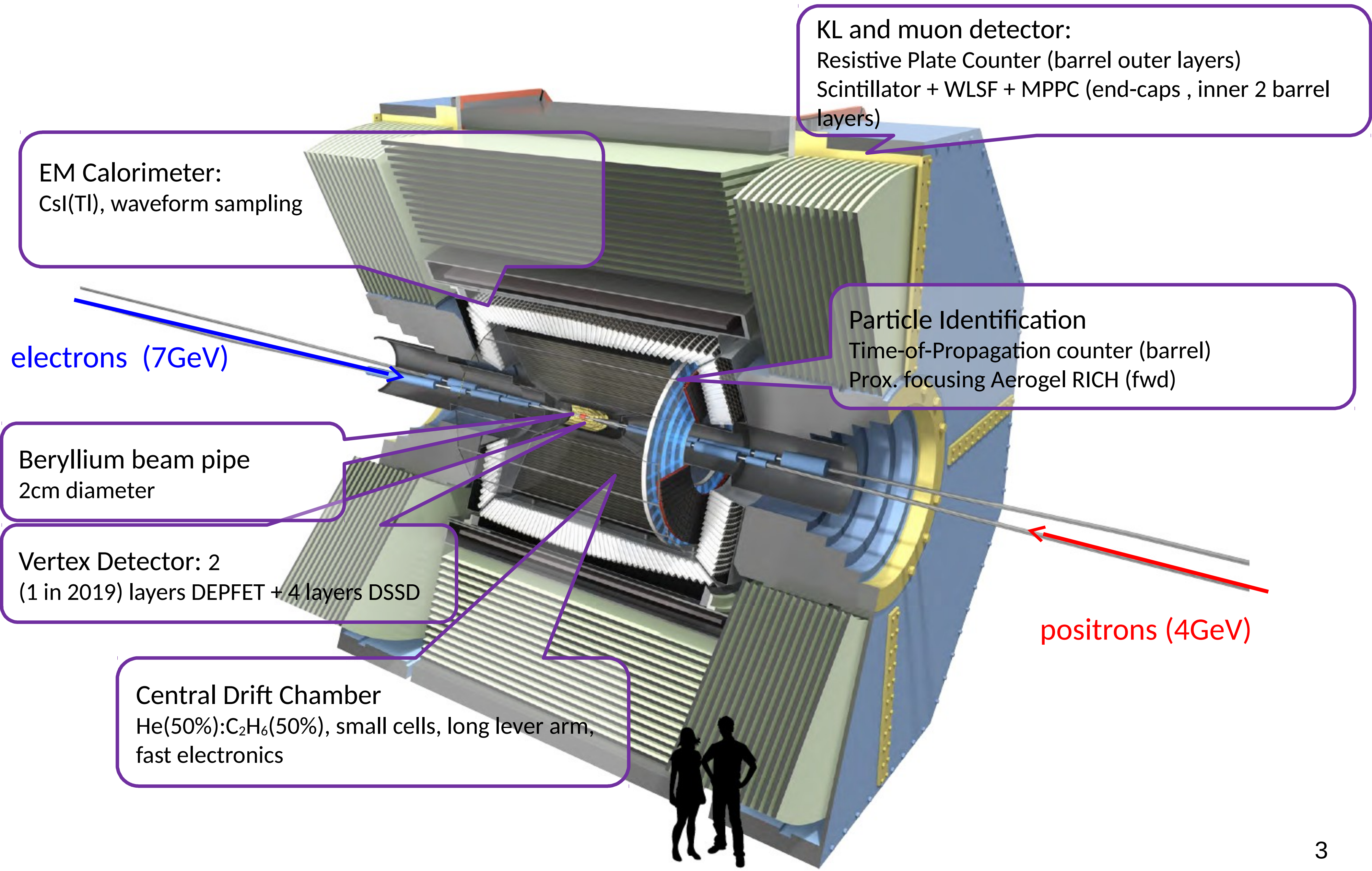


Add / modify RF systems for higher beam current

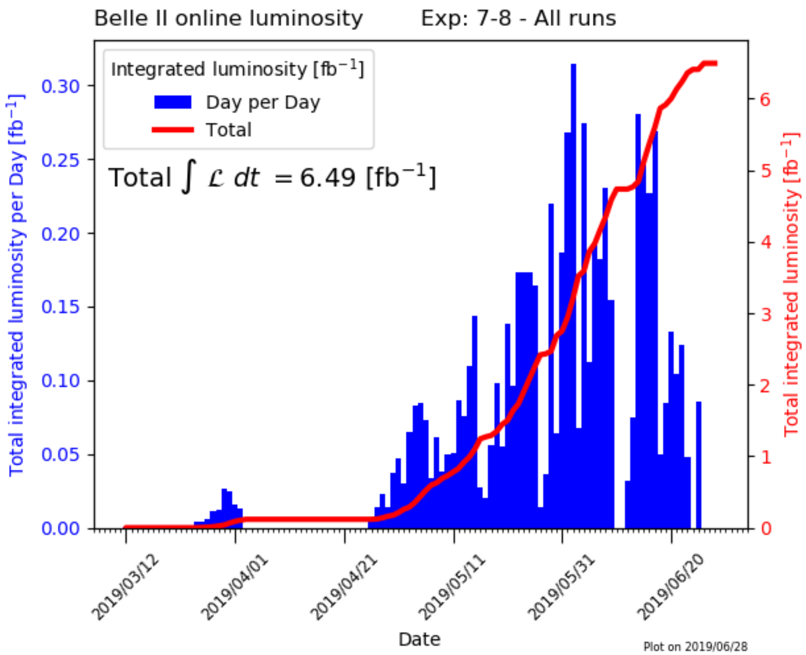
New positron target / capture section

To obtain x40 higher luminosity

Belle II Detector Elements

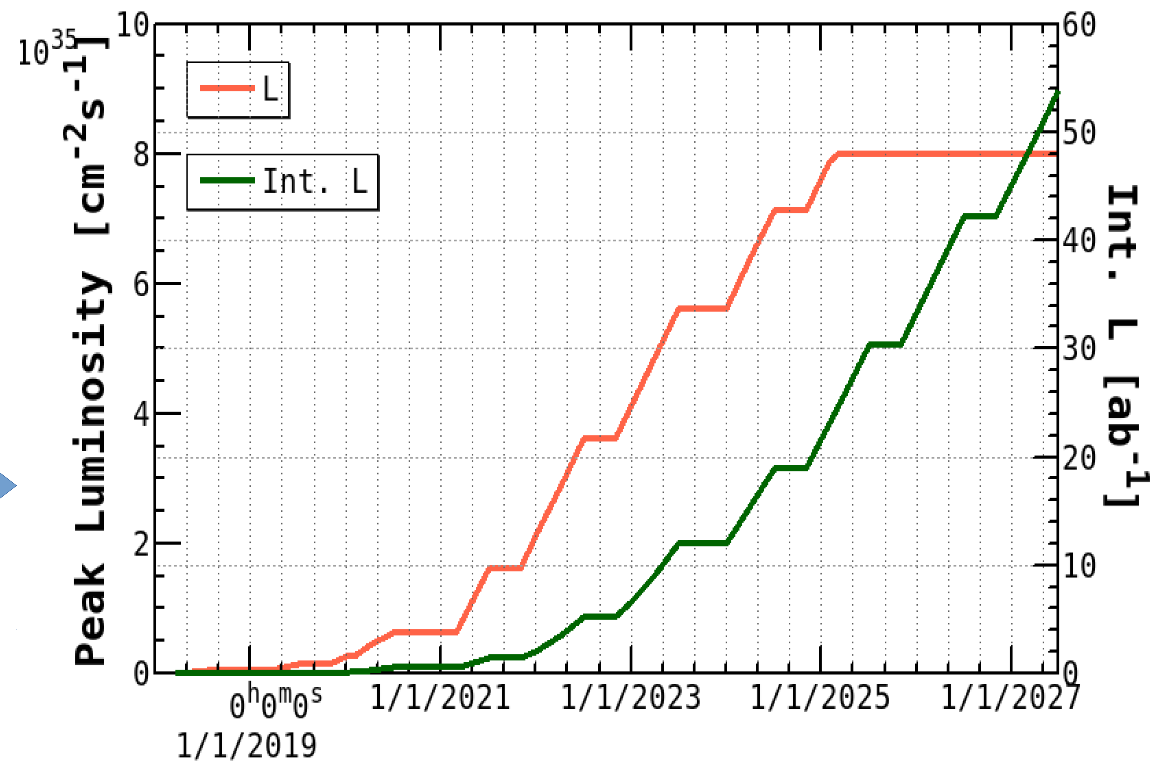


Belle II Luminosity Status and Plans



Integrated luminosity collected in spring-summer 2019 run

Plans for data taking



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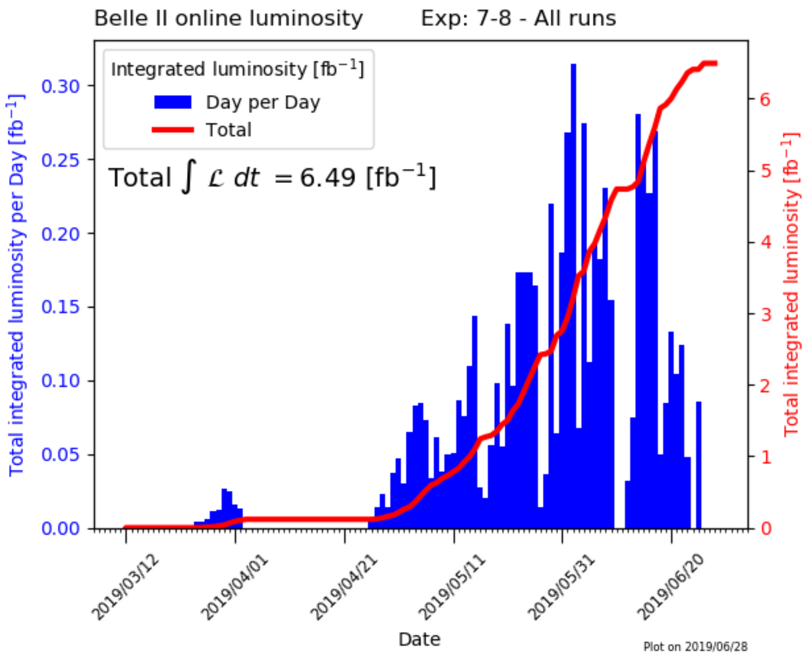

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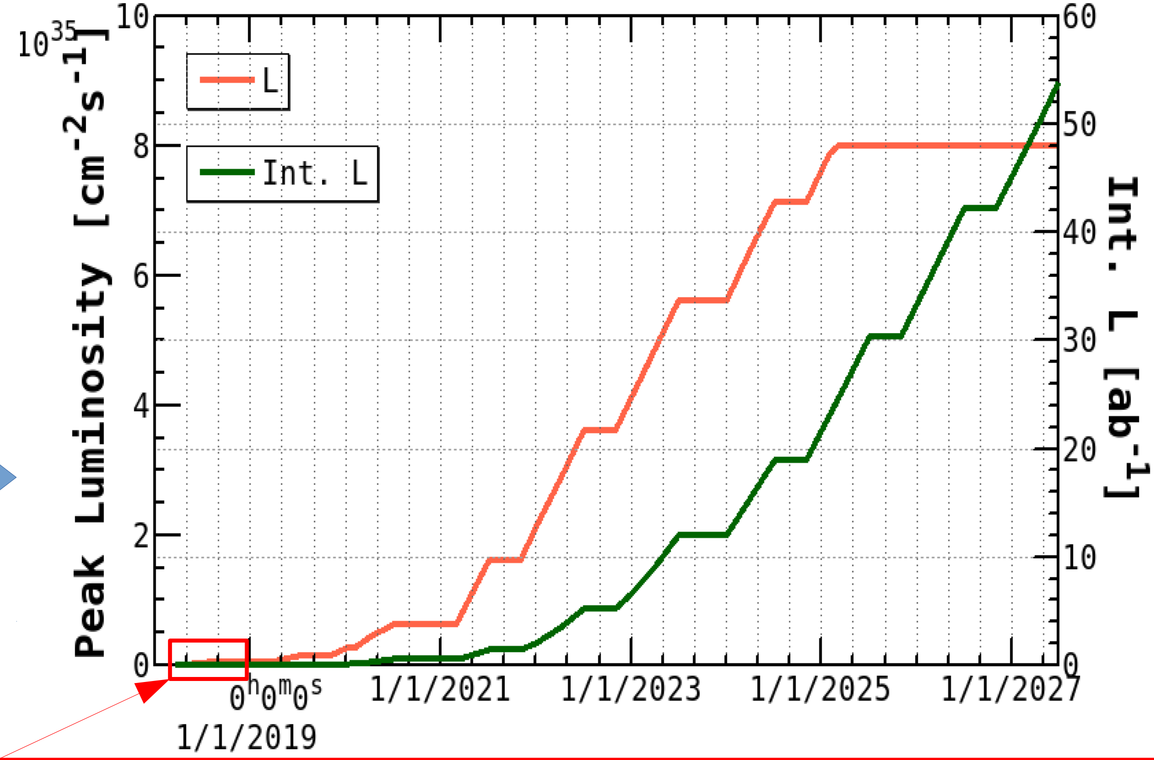

In addition 0.5 fb-1 have been collected in 2018 during commissioning of Super-KEKB
Full Belle II detectorw/o Vertex detector→ **Used for first Belle II physics results shown today**

A B-Factory is NOT just a B-Factory

A B-Factory is NOT just a B-Factory

The Belle II Phyiscs book
arXiv:1808.10567

Physics process	Cross section [nb]	Cuts
$\Upsilon(4S)$	1.05 ± 0.10	-
$u\bar{u}(\gamma)$	1.61	-
$d\bar{d}(\gamma)$	0.40	-
$s\bar{s}(\gamma)$	0.38	-
$c\bar{c}(\gamma)$	1.30	-
$e^+e^-(\gamma)$	300 ± 3 (MC stat.)	$10° < \theta^*_{e's} < 170°$, $E^*_{e's} > 0.15$ GeV
$e^+e^-(\gamma)$	74.4	e's ($p >$0.5GeV) in ECL
$\gamma\gamma(\gamma)$	4.99 ± 0.05 (MC stat.)	$10° < \theta^*_{\gamma's} < 170°$, $E^*_{\gamma's} > 0.15$ GeV
$\gamma\gamma(\gamma)$	3.30	γ's ($p >$0.5GeV) in ECL
$\mu^+\mu^-(\gamma)$	1.148	-
$\mu^+\mu^-(\gamma)$	0.831	μ's ($p >$0.5GeV) in CDC
$\mu^+\mu^-\gamma(\gamma)$	0.242	μ's ($p >$0.5GeV) in CDC, ≥ 1 γ ($E_\gamma >$0.5GeV) in ECL
$\tau^+\tau^-(\gamma)$	0.919	-
$\nu\bar{\nu}(\gamma)$	0.25×10^{-3}	-
$e^+e^-e^+e^-$	39.7 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV
$e^+e^-\mu^+\mu^-$	18.9 ± 0.1 (MC stat.)	$W_{\ell\ell} > 0.5$GeV

https://en.wikipedia.org/wiki/Barn_(unit)

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
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microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

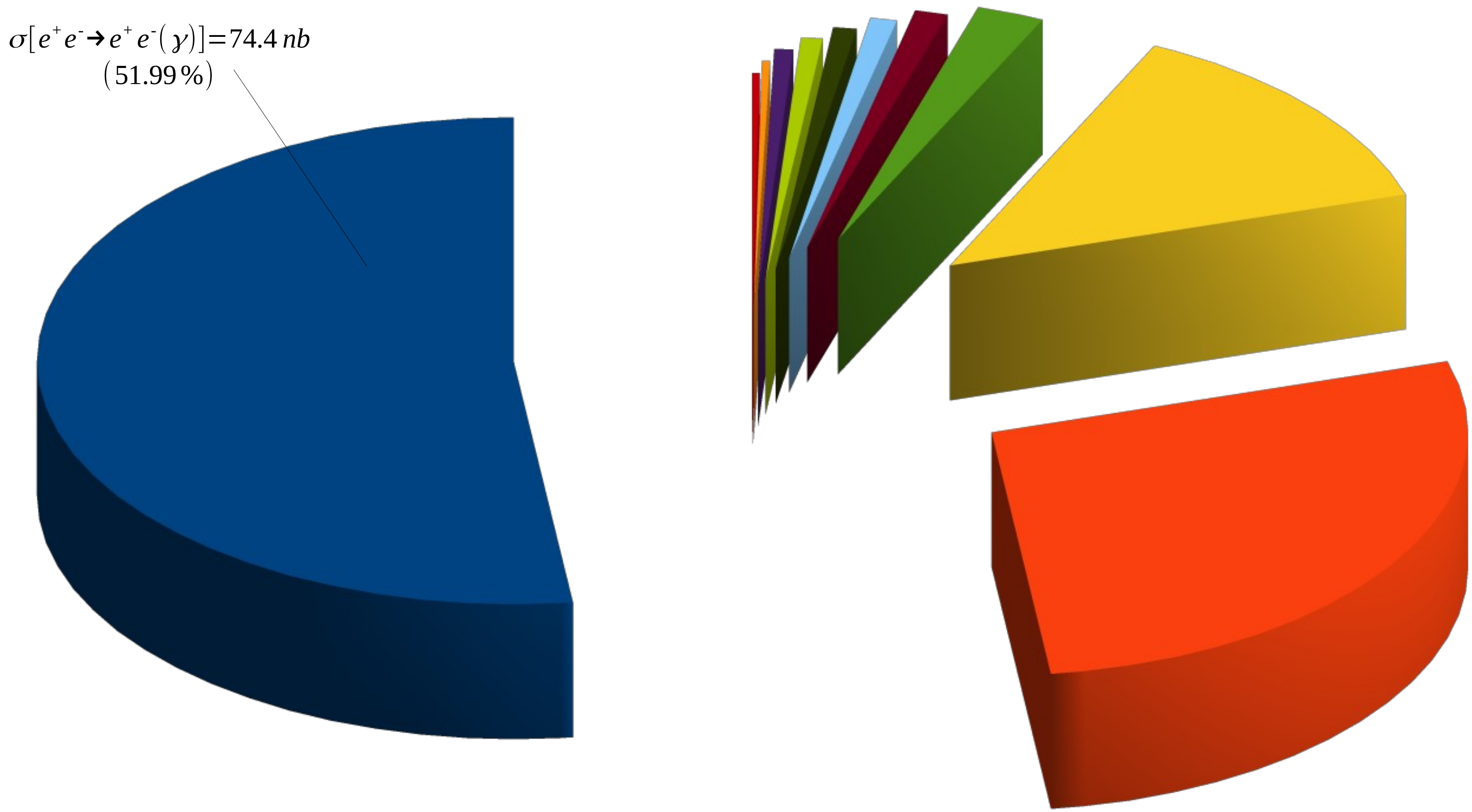
Remember!! $N = L \times \sigma$

Cross-section of the process to be studied in the specific experiment

Number of events of a process

Luminosity of an experiment

A B-Factory is NOT just a B-Factory



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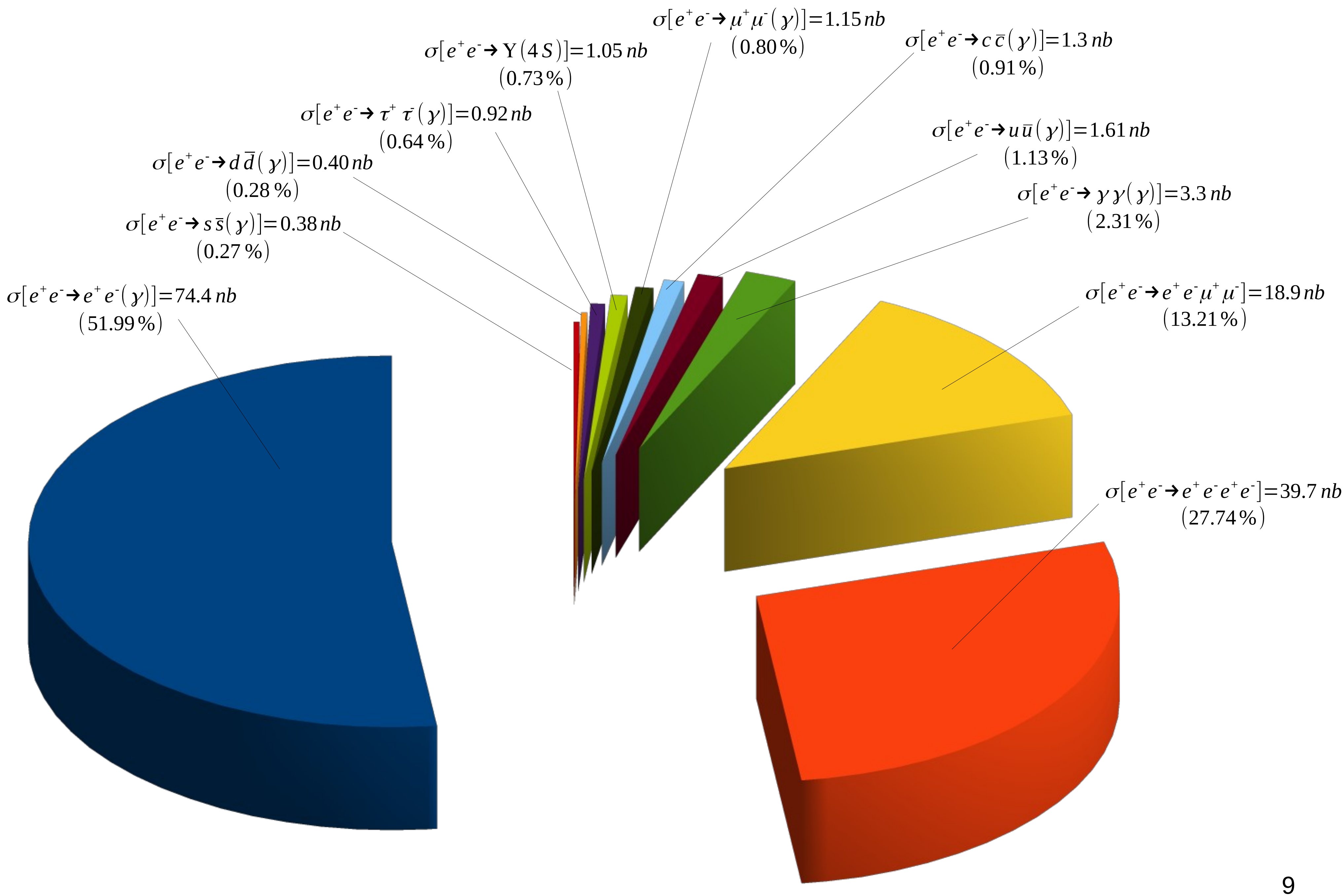

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Dark sector particles	**?? ± ??**	**?? > ??**

https://en.wikipedia.org/wiki/Barn_(unit)

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Remember!! $N = L \times \sigma$

Cross-section of the process to be studied in the specific experiment

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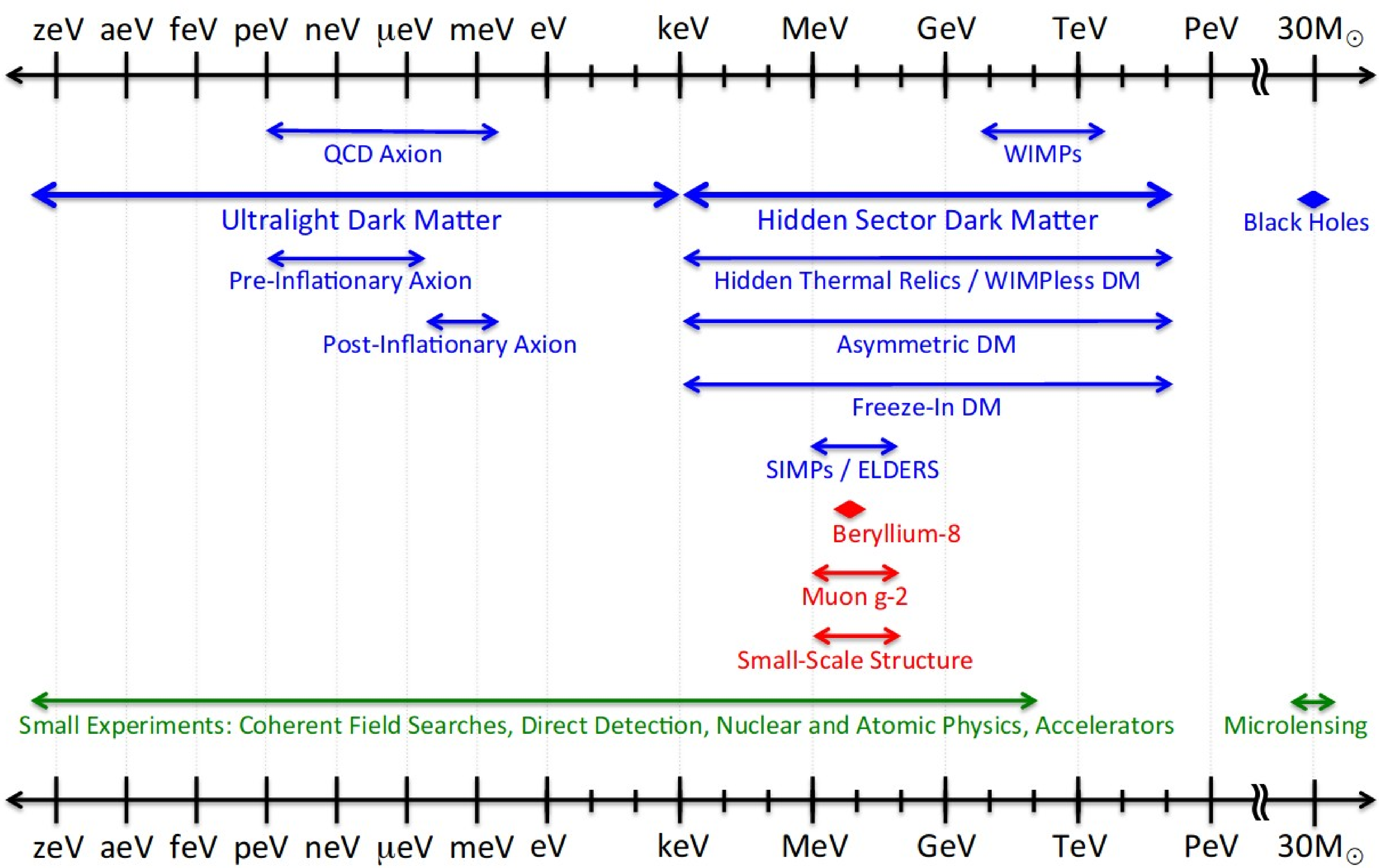
Luminosity of an experiment

ArXiv:1707.04591

Dark Sector Candidates, Anomalies, and Search Techniques



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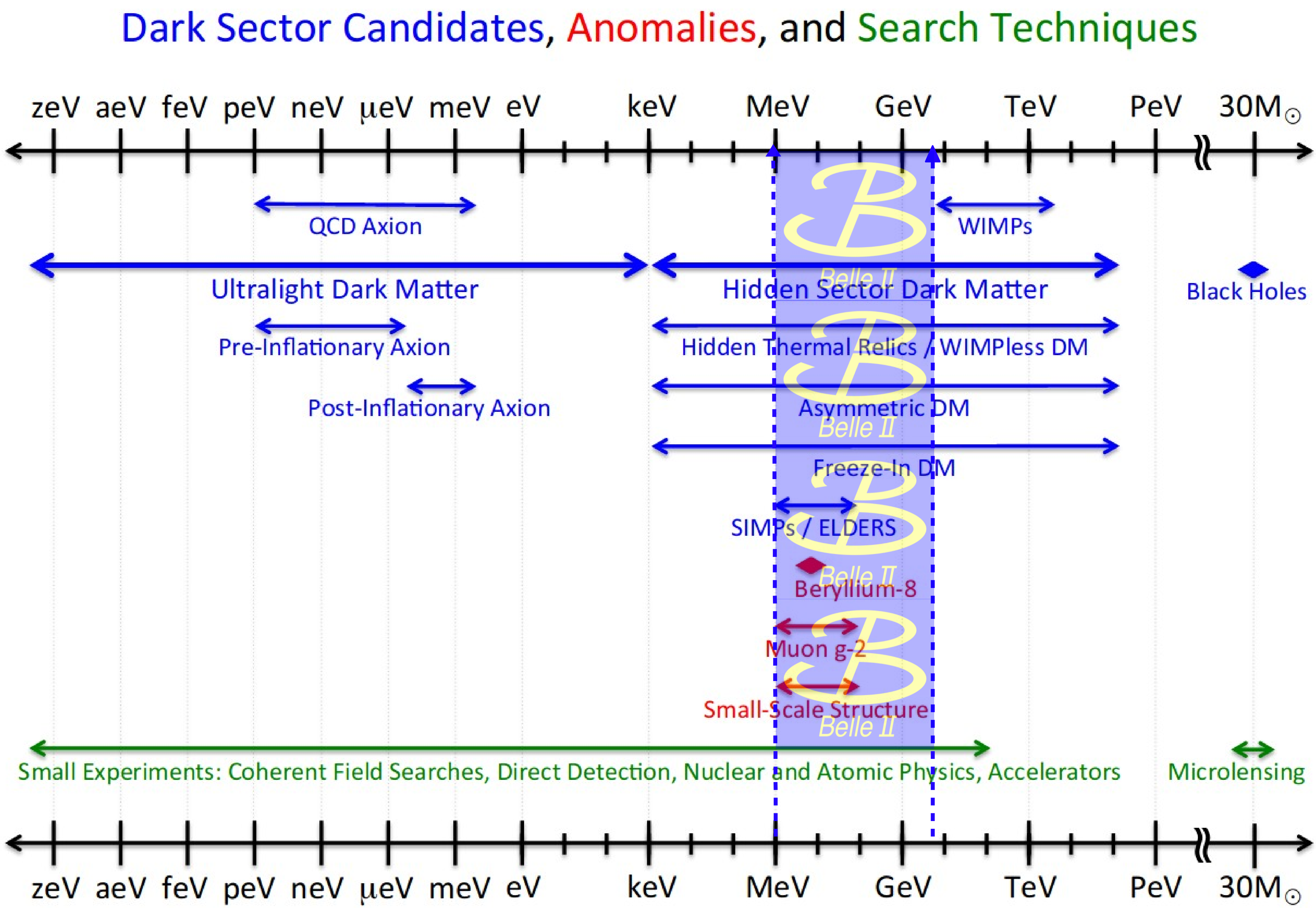
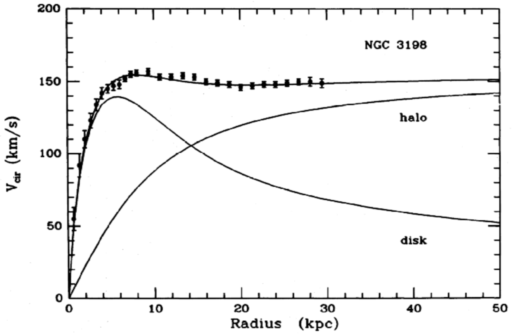
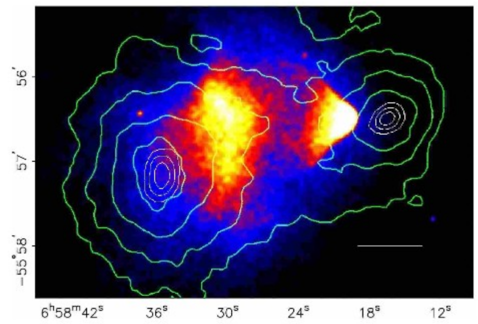
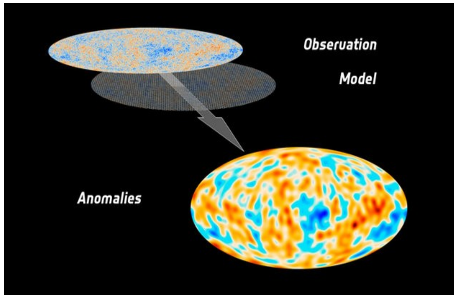
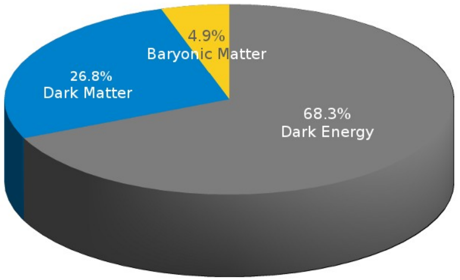


Searching for Dark Matter and Forces @ Belle/Belle II









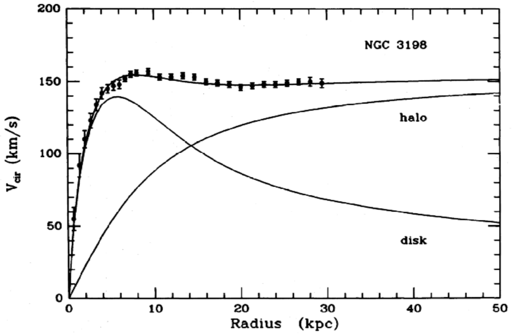
Belle II

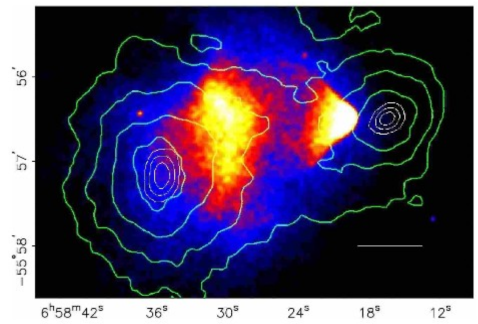
Search for events with missing energy, particle disappearance, dark forces, single/multi-photon final state events, etc.

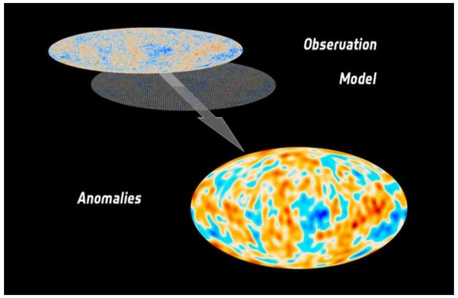
Belle II

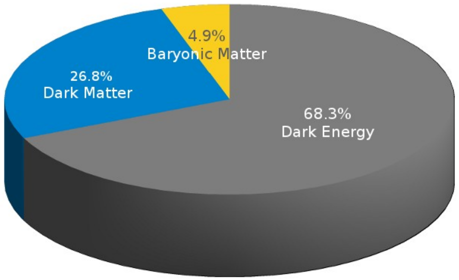
- **Vector portal** $\epsilon F_{Y}^{\mu\nu} F'_{\mu\nu}$ (dark photon A'), $\sum_{l} \theta g' \bar{l} \gamma^{\mu} Z'_{\mu} l$ (dark Z')
- **Axion portal** $\frac{G_{agg}}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$ (axion, alps)
- **Scalar portal**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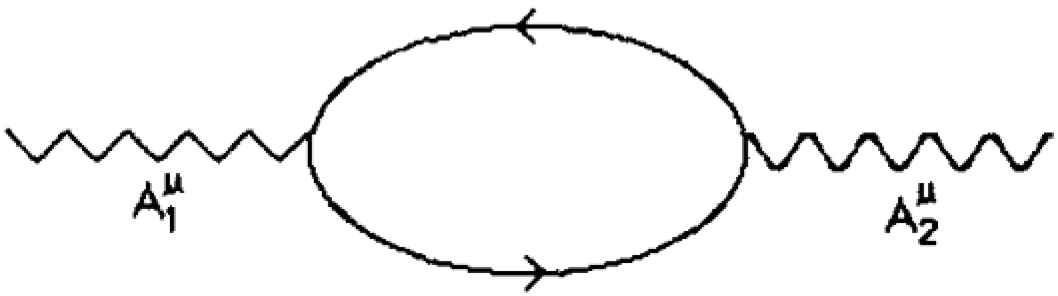
- **More ...**

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:

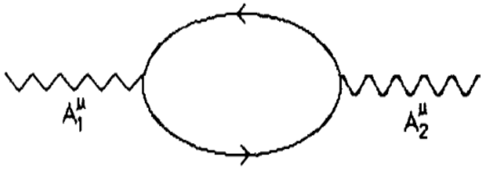


- The kinetic mixing is a term in the Lagrangian expressed by $\frac{1}{2}\epsilon F^Y_{\mu\nu} F'^{\mu\nu}$
- For the dark photon to acquire mass an extended Higgs sector might be required to break the new U(1)' symmetry (if dark sector is "Higgsed")

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

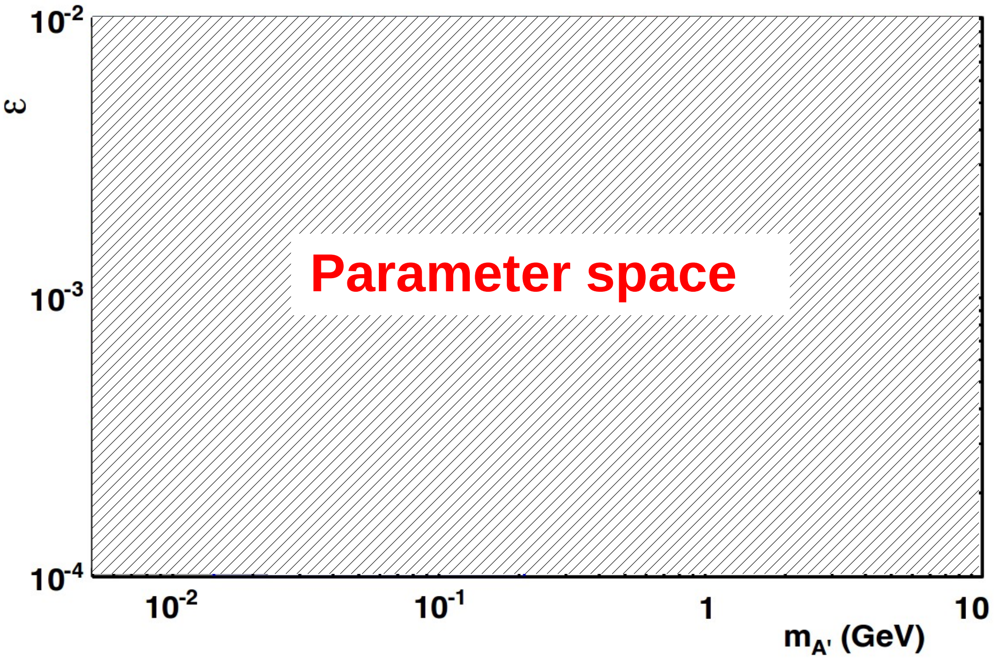
Most dark sector models require an additional U(1) symmetry responsible for the "interactions" between dark sector particles and SM particles through its gauge boson A' .



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

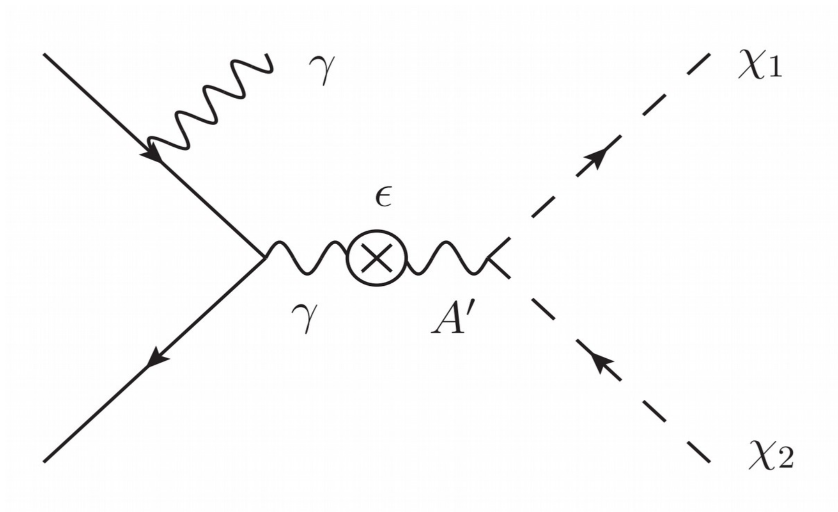
P. Fayet, Phys. Lett. B **95**, 285 (1980),
P. Fayet Nucl. Phys. B **187**, 184 (1981).
B. Holdom, Phys. Lett. B **166**, 196 (1986)

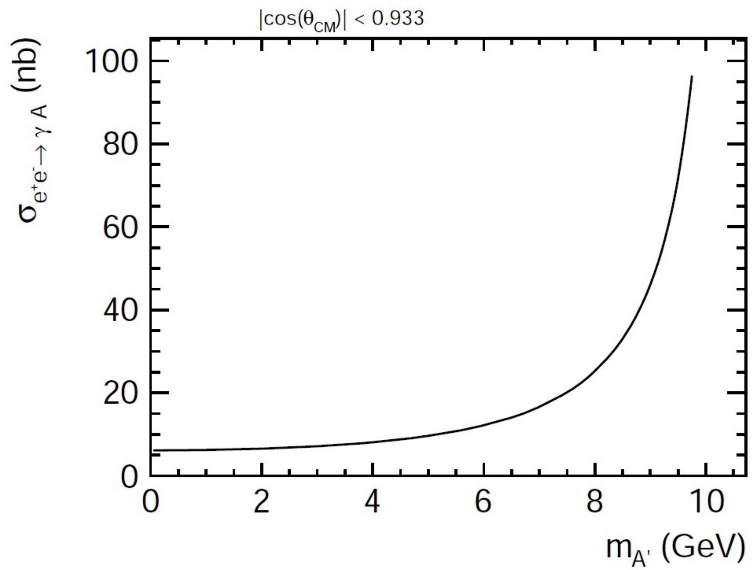
Kinetic mixing strength



Dark Photon Search Strategy (invisible case)

See the Belle II Physics 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 .

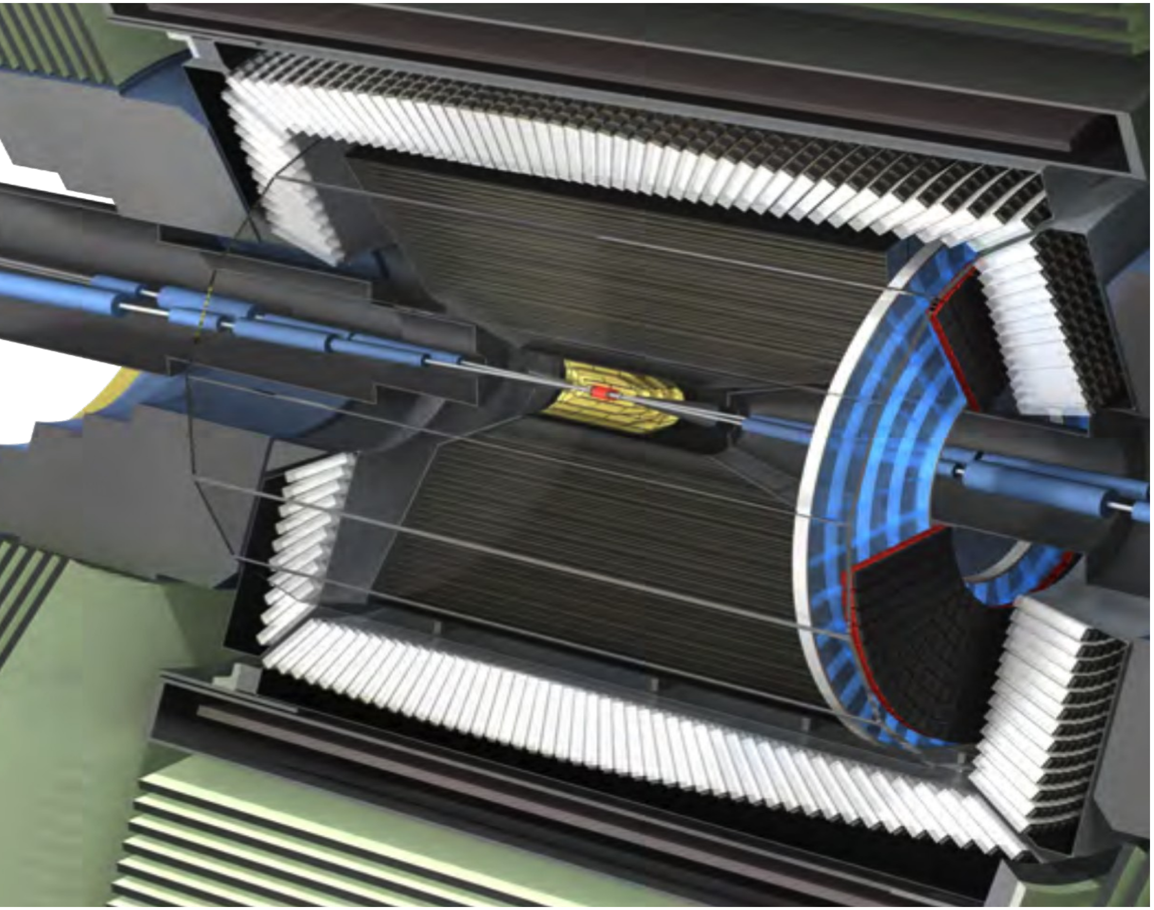
radiative production in e+e- collisions
only one photon in the final state with $E^*_\gamma = (s - M^2_{A'})/2\sqrt{s}\ \ (on-shell)$

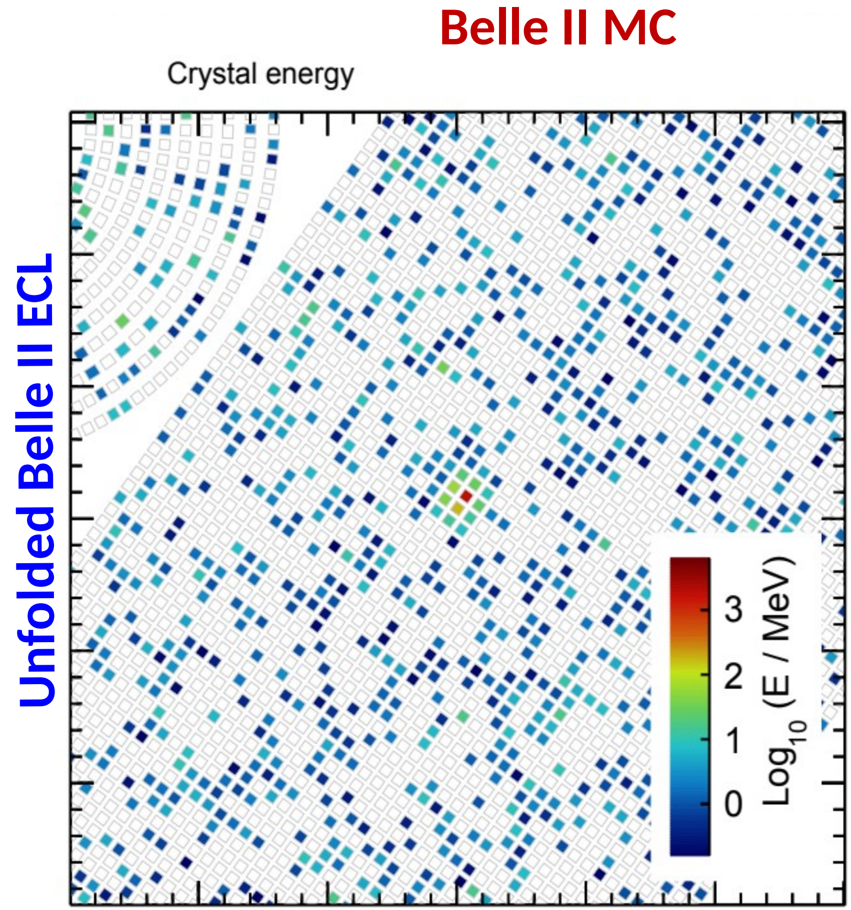
→ Only existing limits from BaBar based on 53 fb^{-1} of data, *Phys. Rev. Lett.* ***119****, 131804 (2017)*

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

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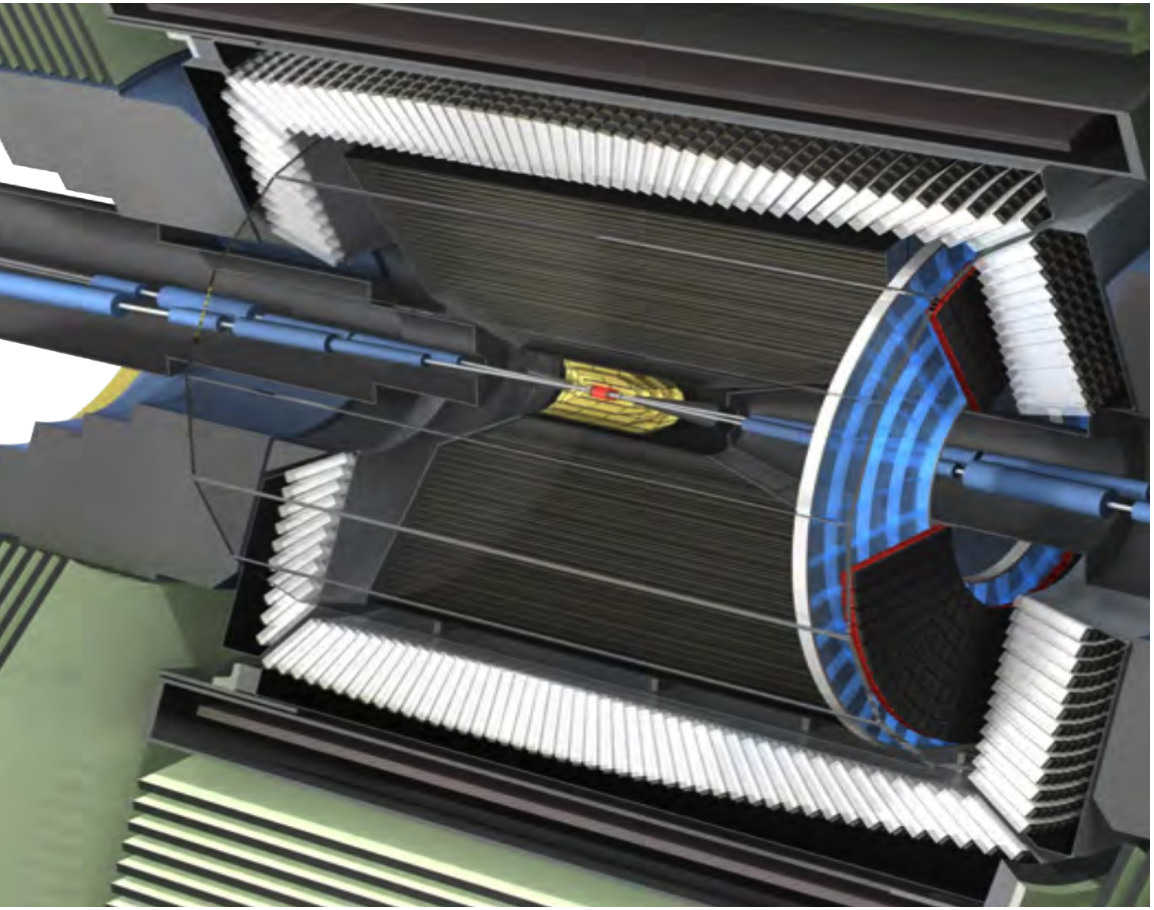

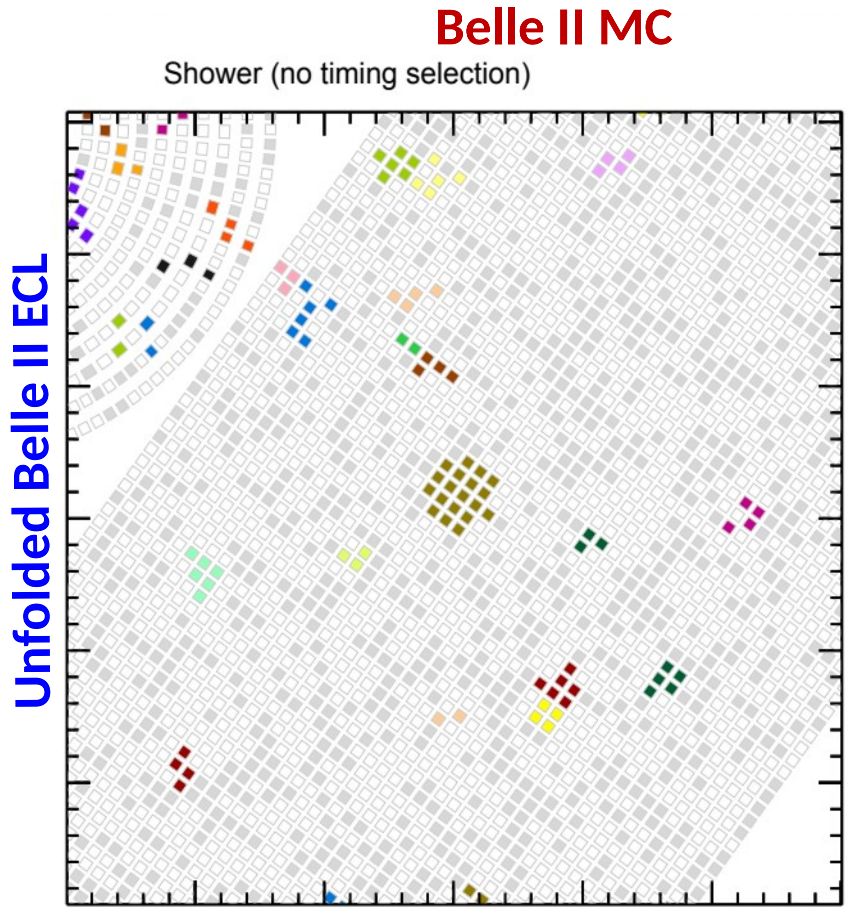

New clustering:
finds “showers”

Photons in the electromagnetic calorimeter (ECL) 3/4

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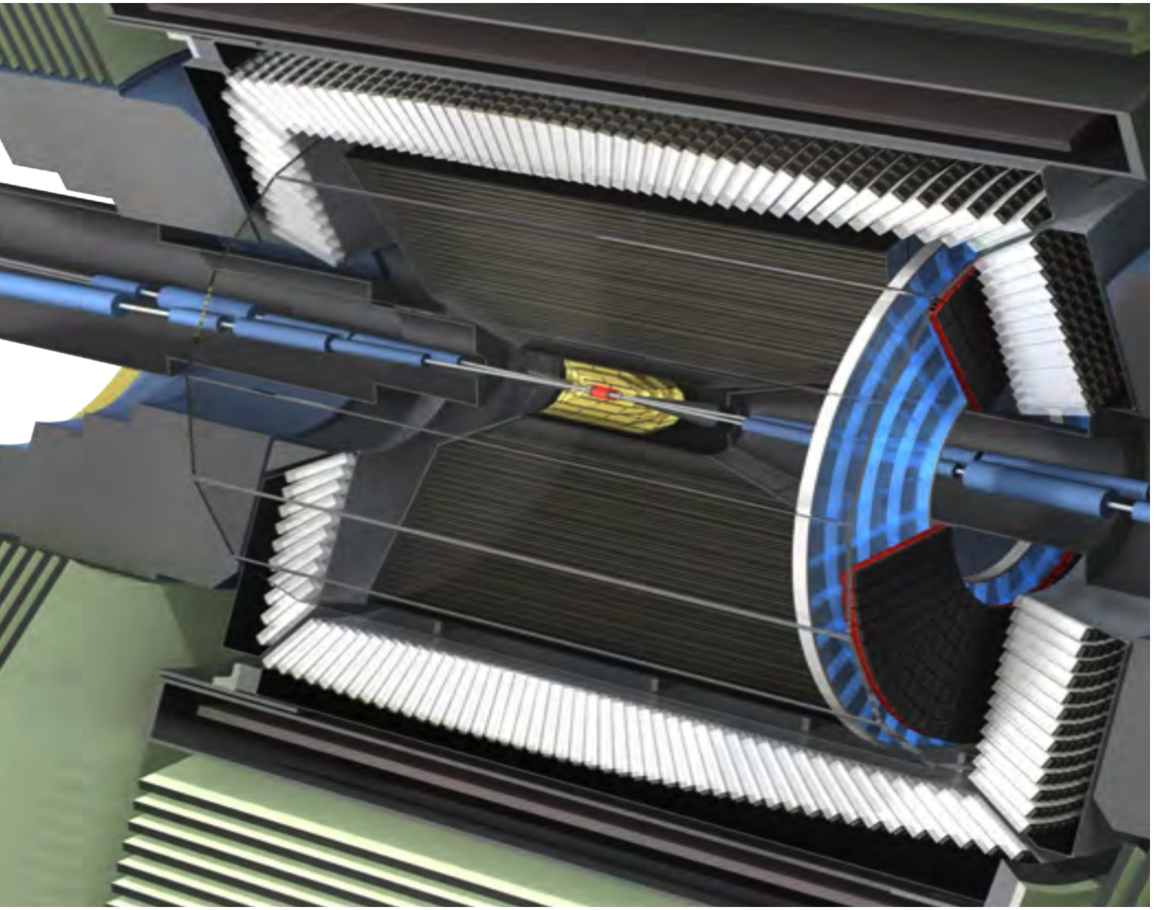

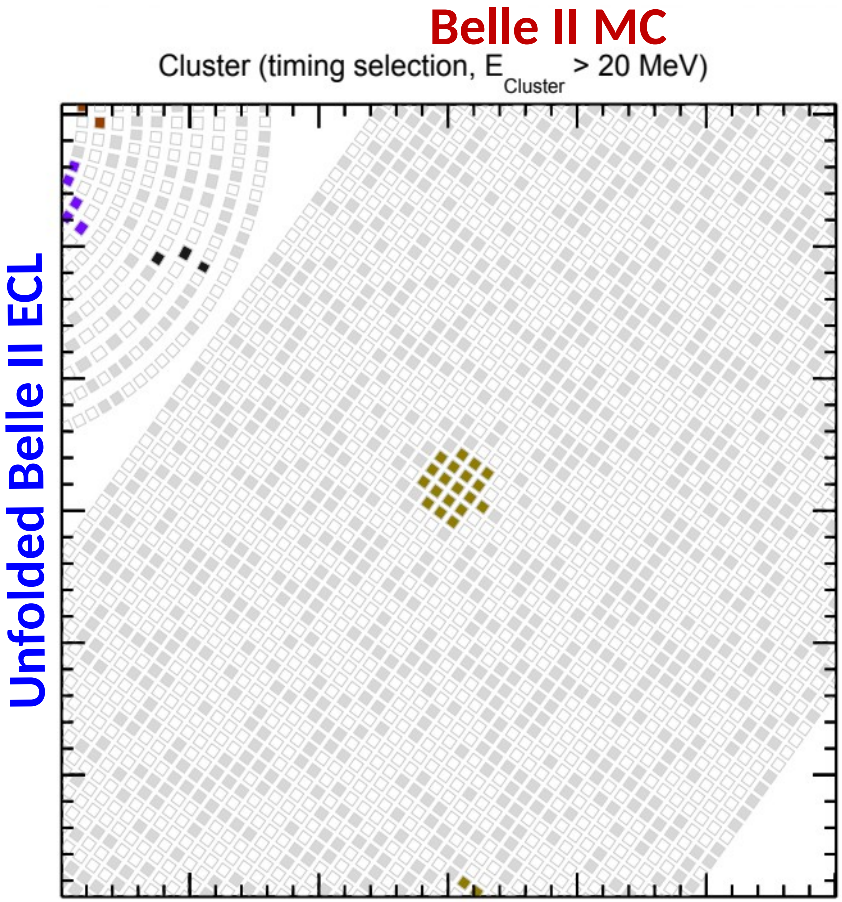

Timing and minimal cluster energy requirement

Photons in the electromagnetic calorimeter (ECL) 4/4

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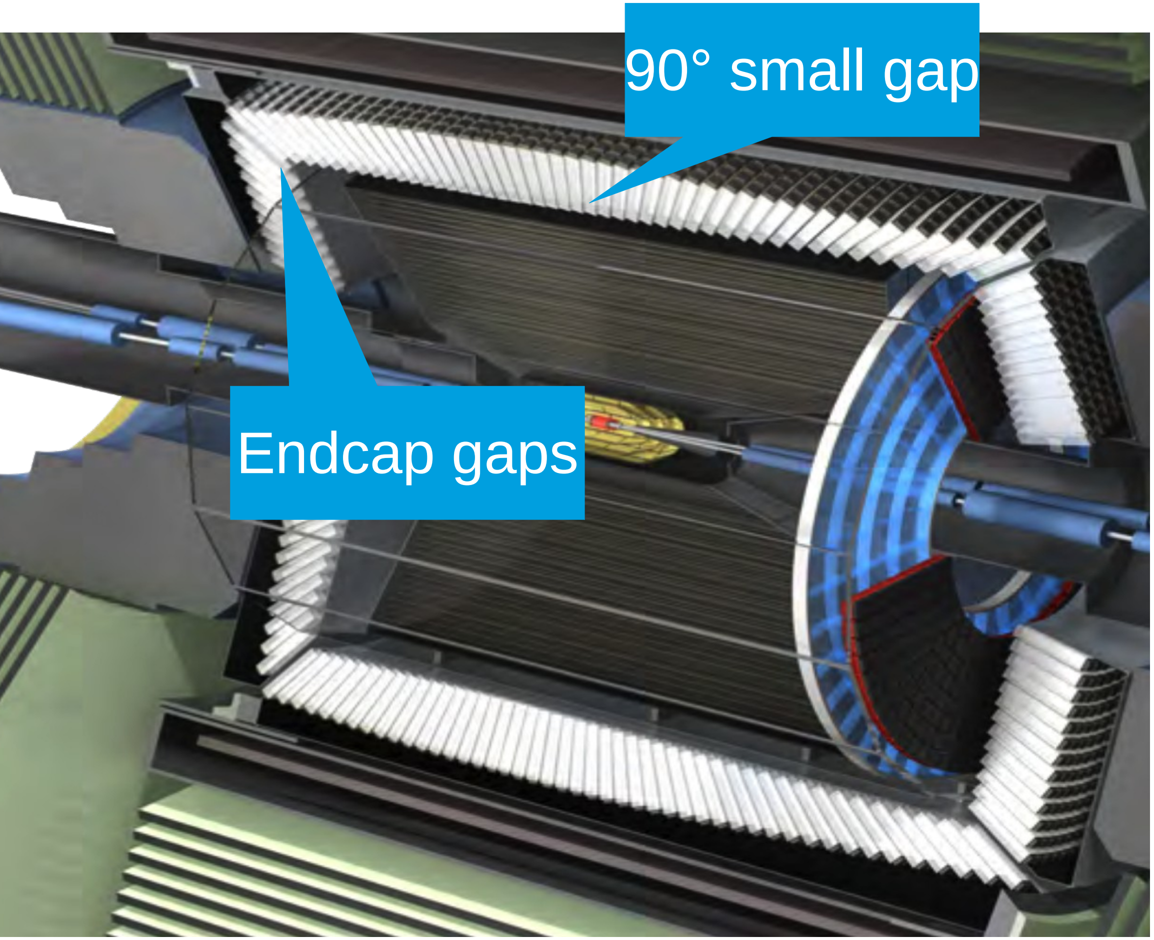
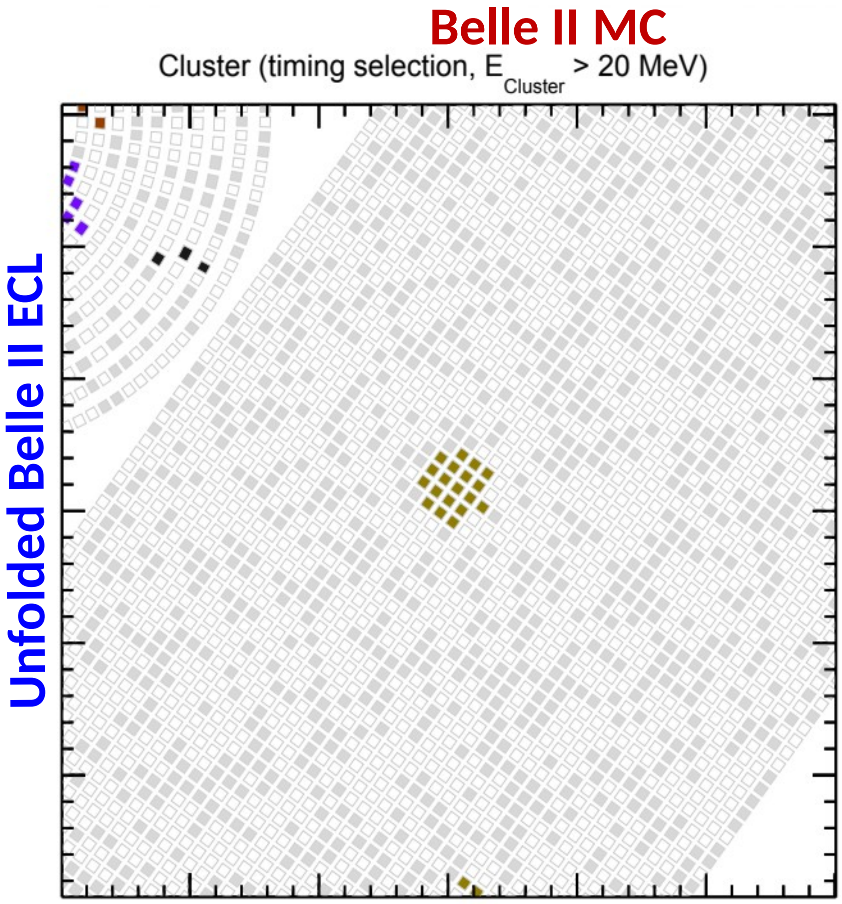




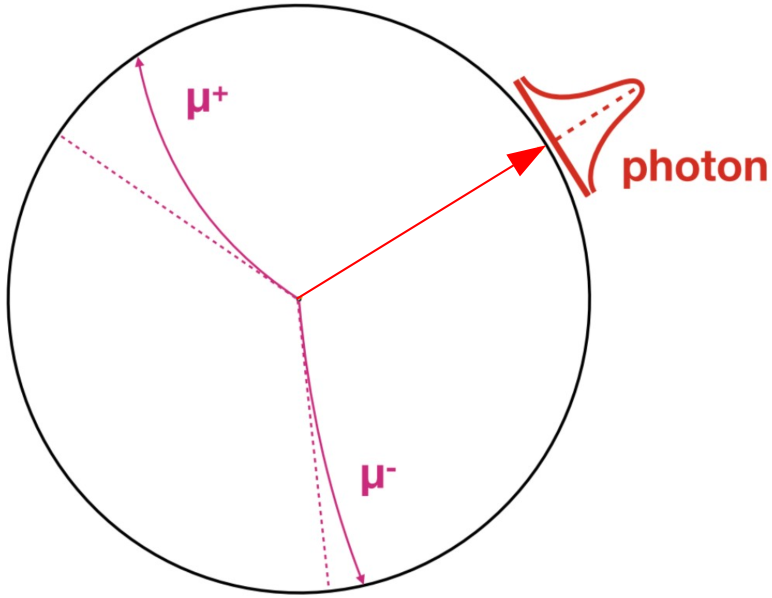
Timing and minimal cluster energy requirement

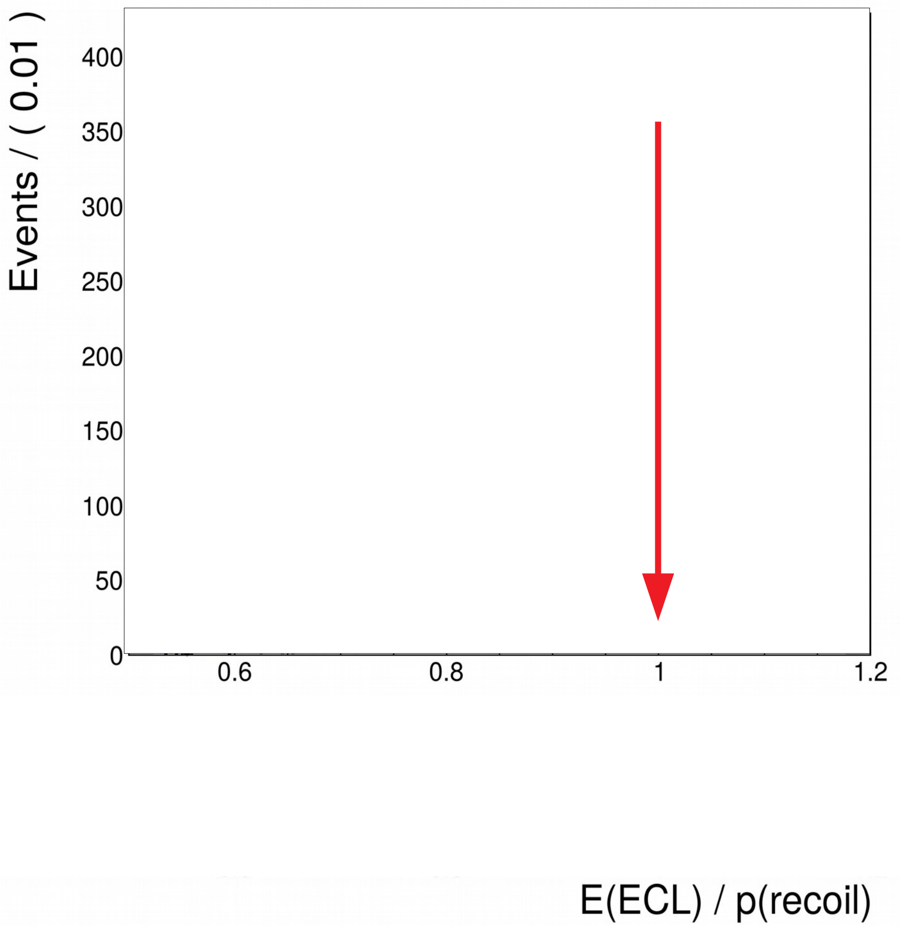
Dark photon → invisible, additional checks

Analysis

- $e^+e^- \to \gamma A' \to \gamma(\chi_1\chi_2)$
- General 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**

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





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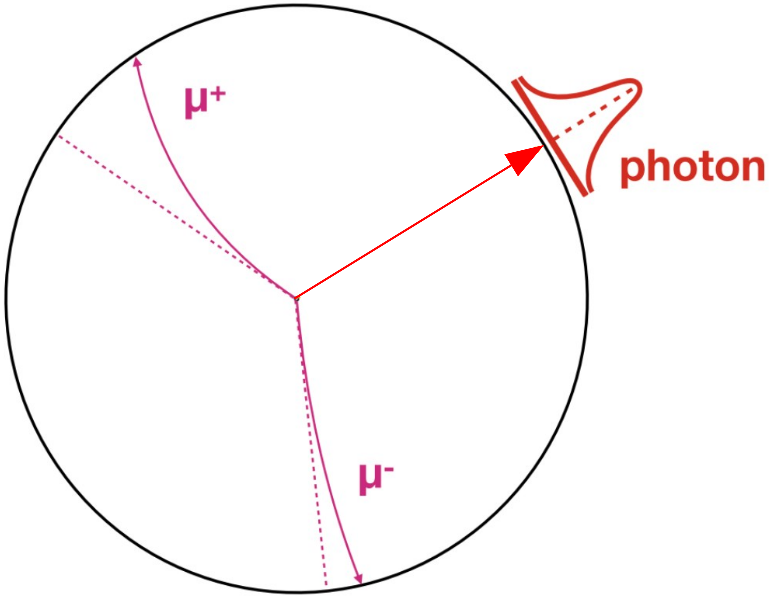

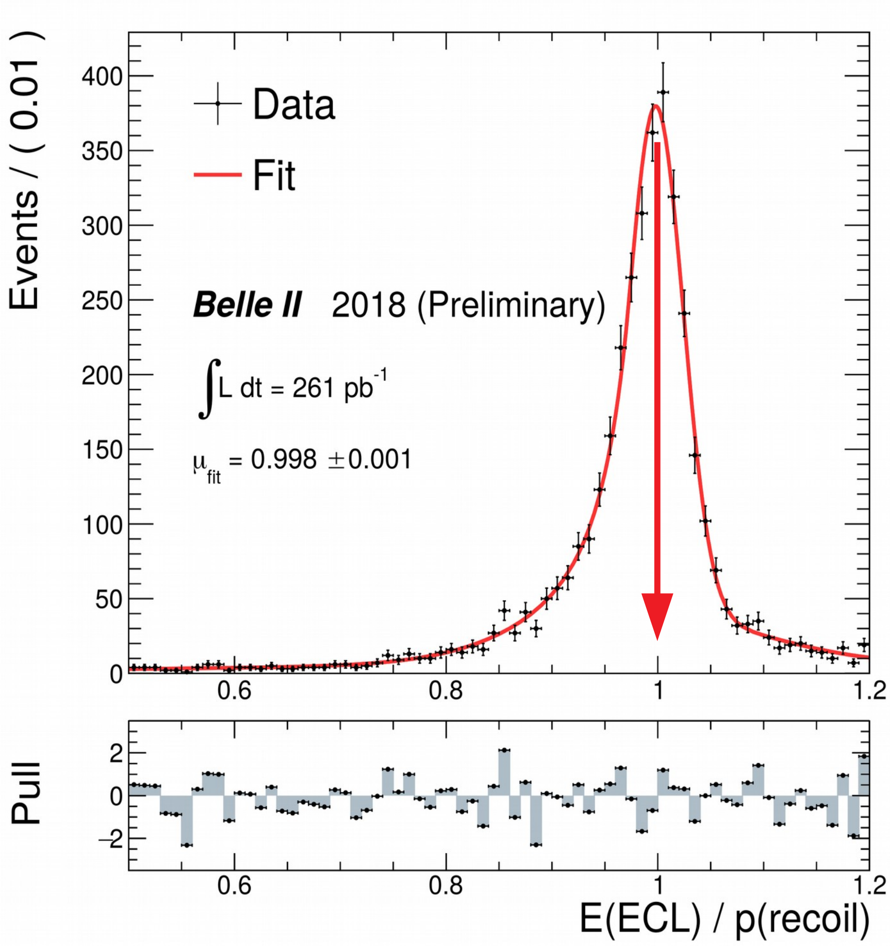

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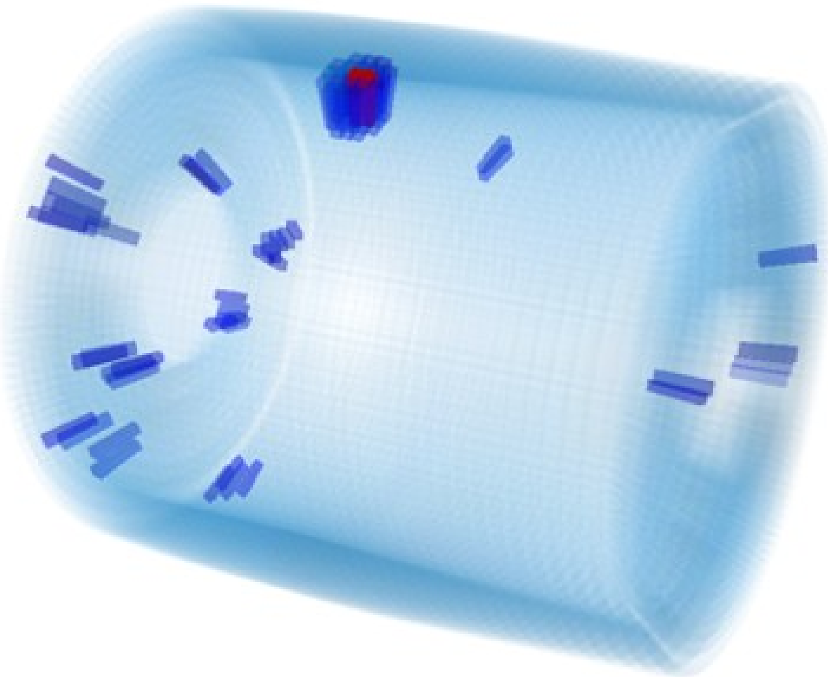

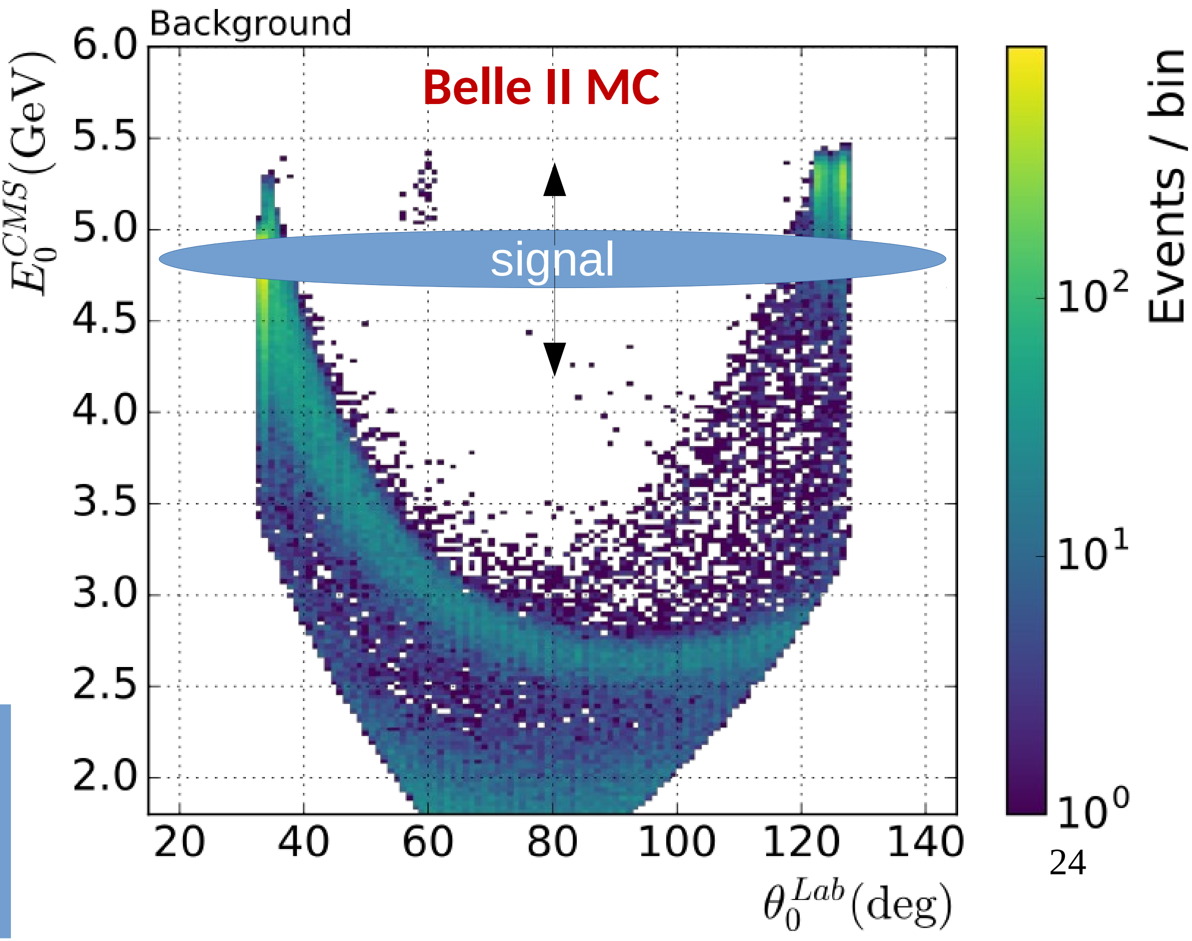

The signal would appear as an horizontal cluster of events:
fixed energy equivalent to the A' mass, spread over all angles

Dark photon → invisible

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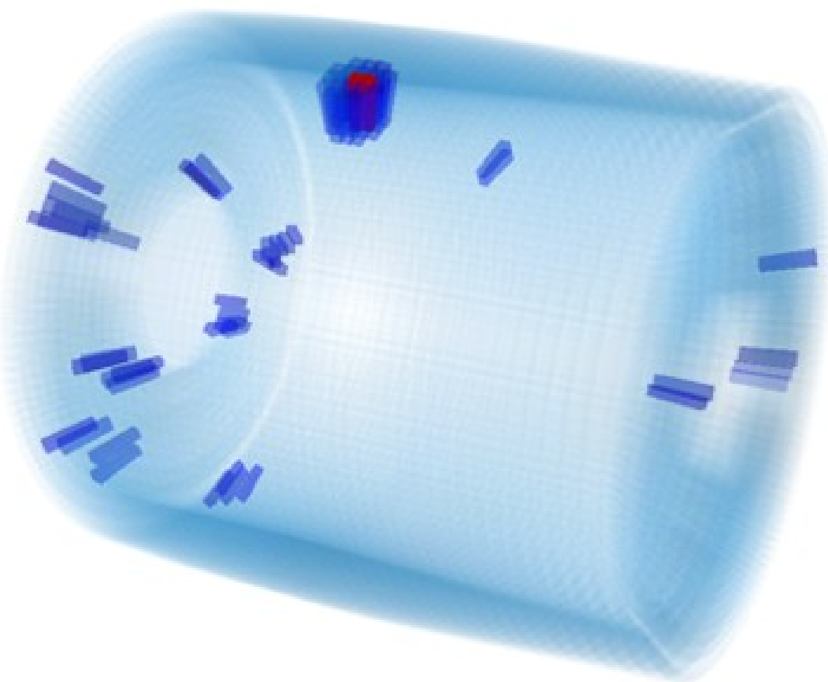
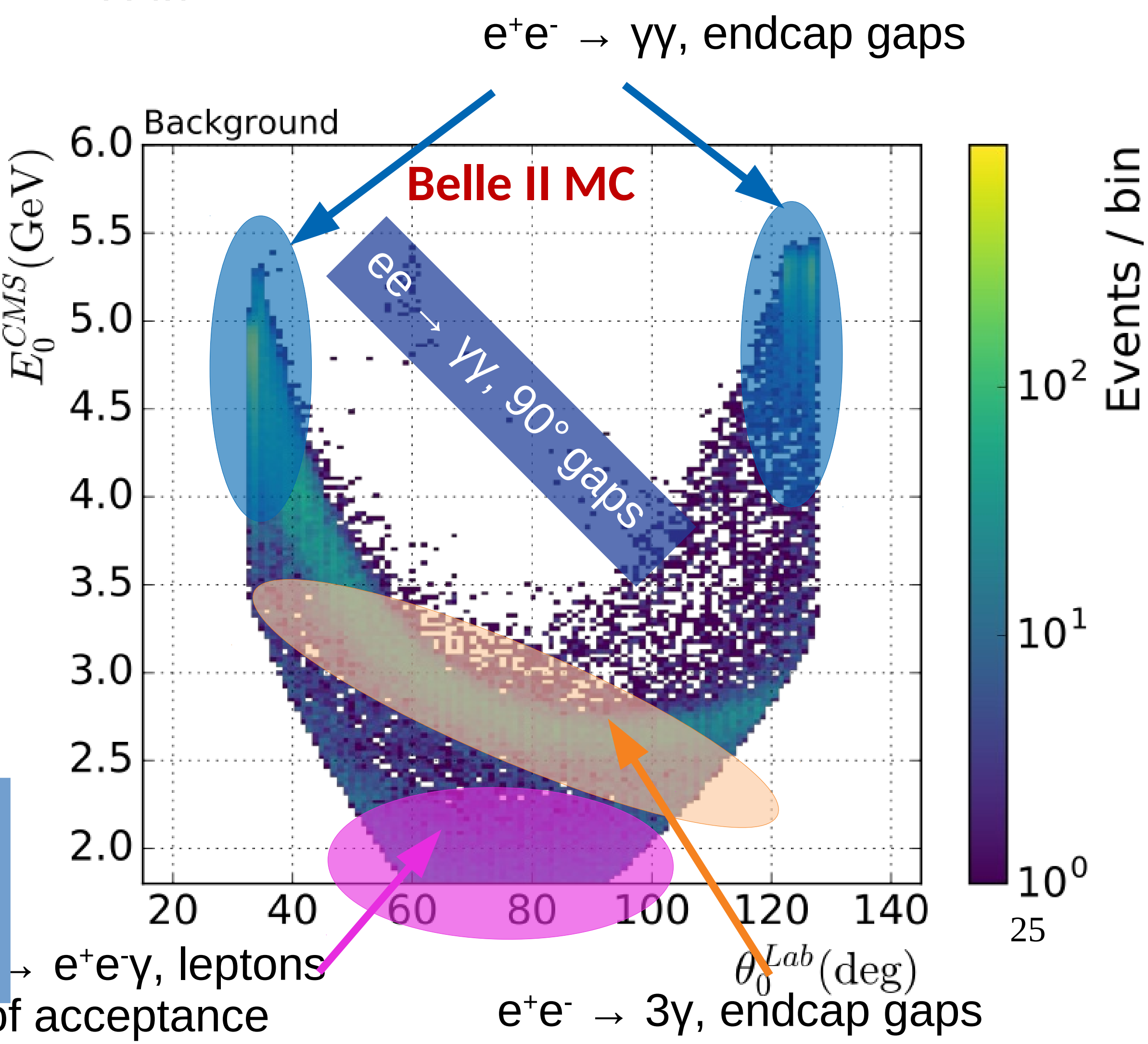
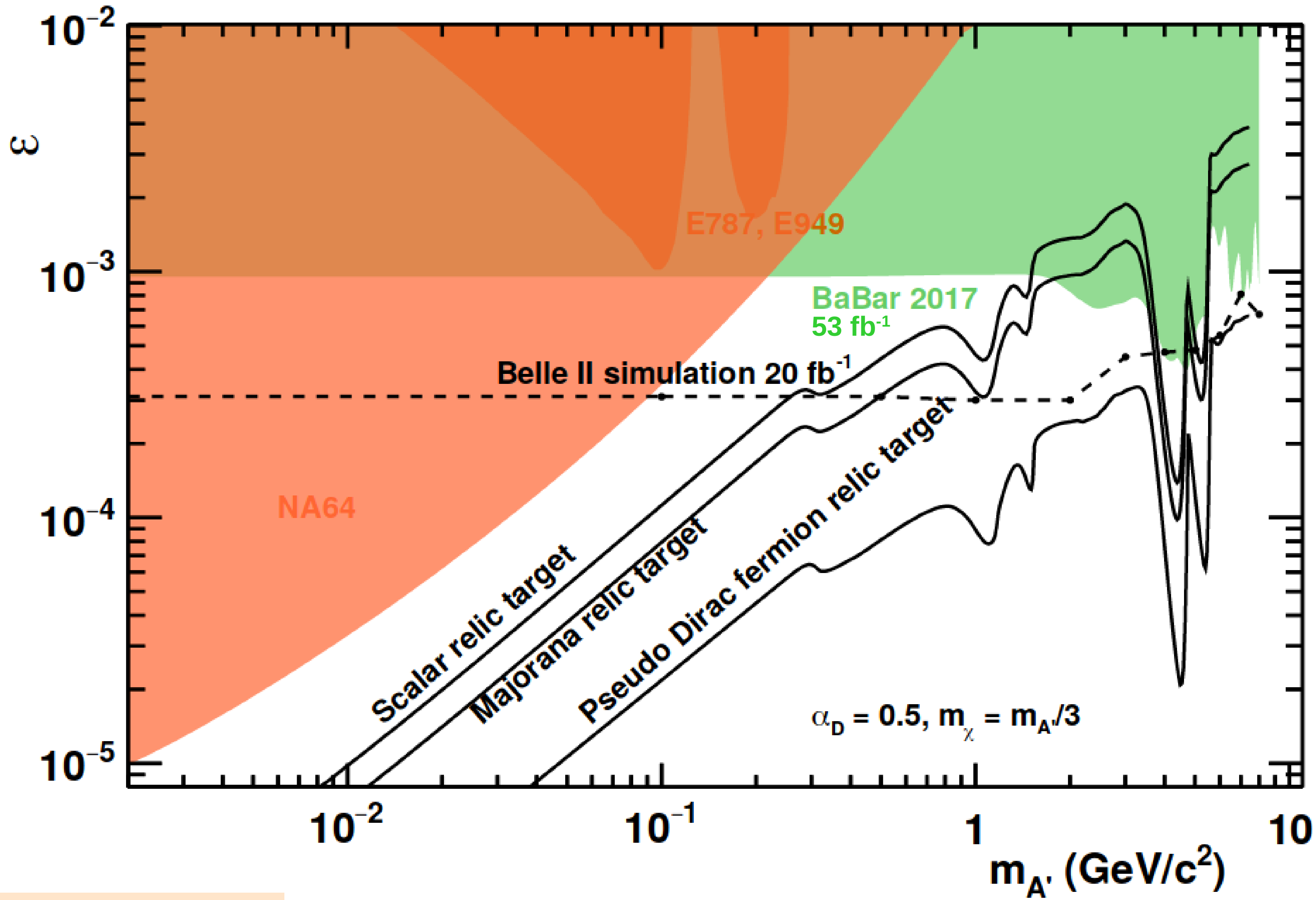
- General strategy: nothing in the event except one photon. (no tracks, other good photon clusters). Search for a bump in the recoil mass spectrum.
- **Backgrounds** $e^+e^- \to e^+e^-\gamma(\gamma)$ and $e^+e^- \to \gamma\gamma(\gamma)$





The signal would appear as an horizontal cluster of events: fixed energy equivalent to the A' mass, spread over all angles

Dark photon → invisible, Belle 2 expected sensitivity

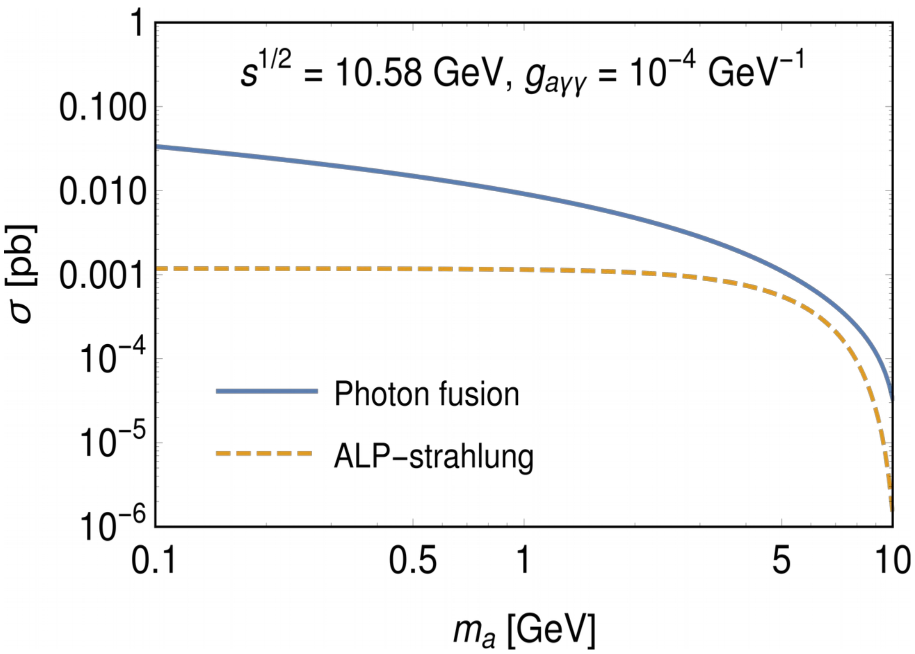


The Belle II Phyiscs book
arXiv:1808.10567
BaBar's analysis
[PRL.119.131804](PRL.119.131804)

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

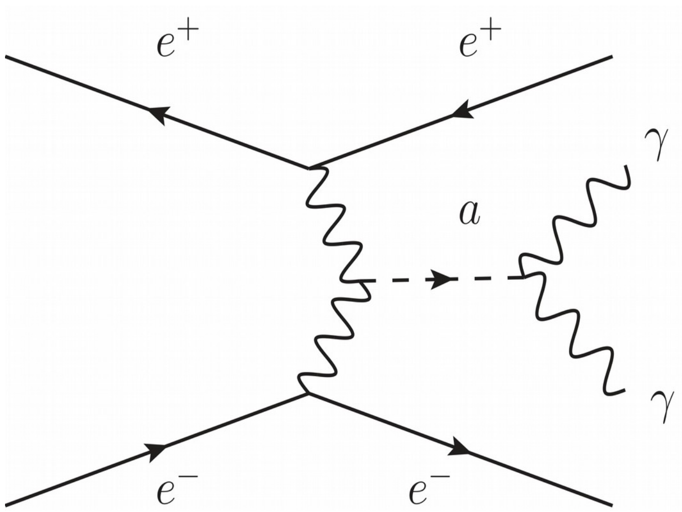
Axion Like Particles (ALPs) at Belle II

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

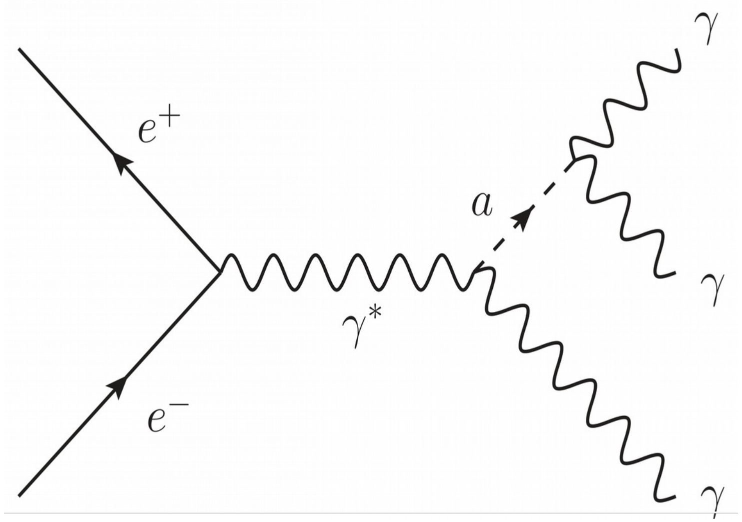


JHEP 1712 (2017) 094

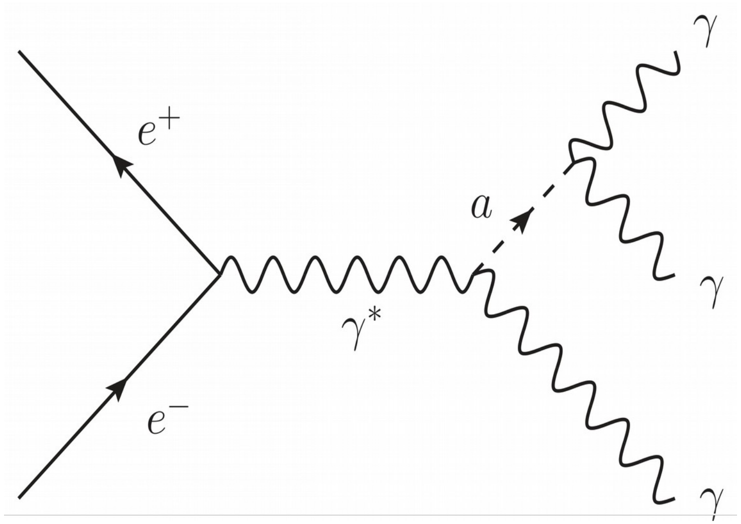
Photon fusion

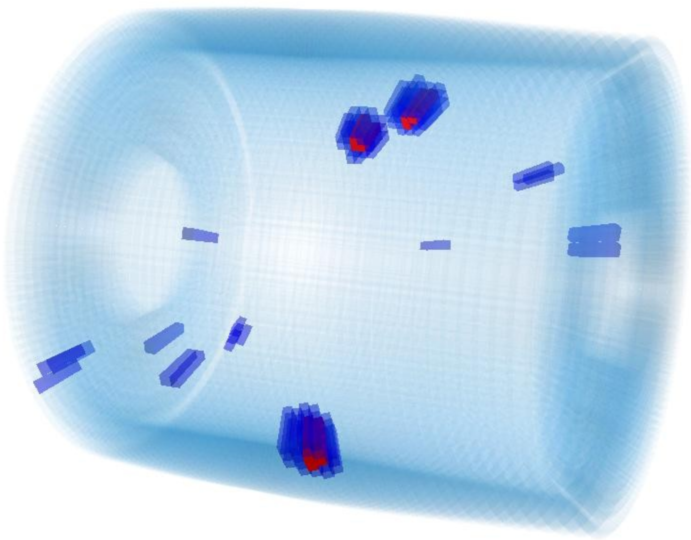


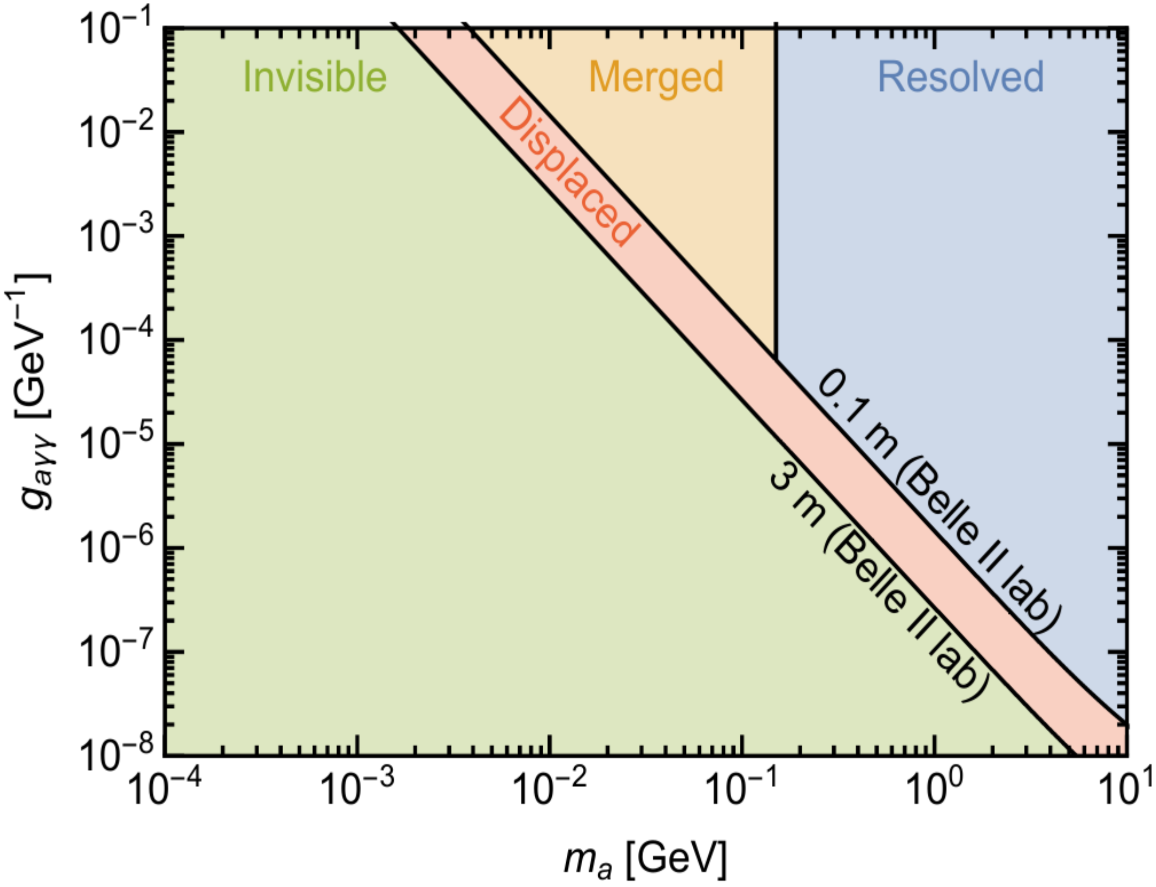
ALP-strahlung



Axion Like Particles (ALPs) at Belle II



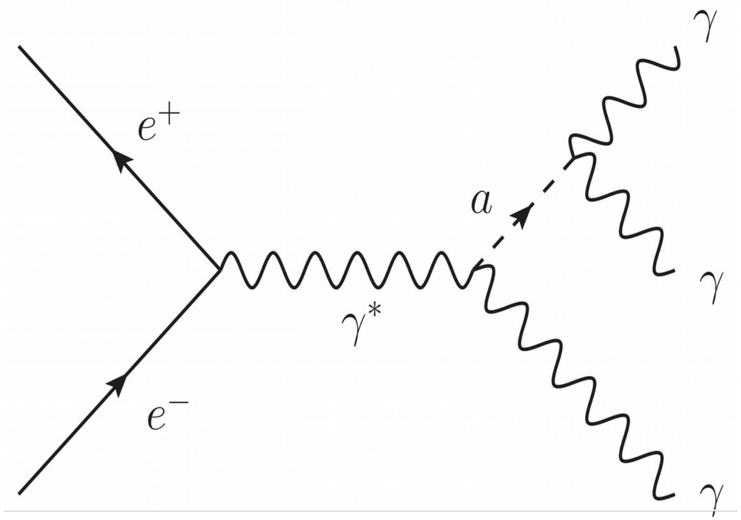


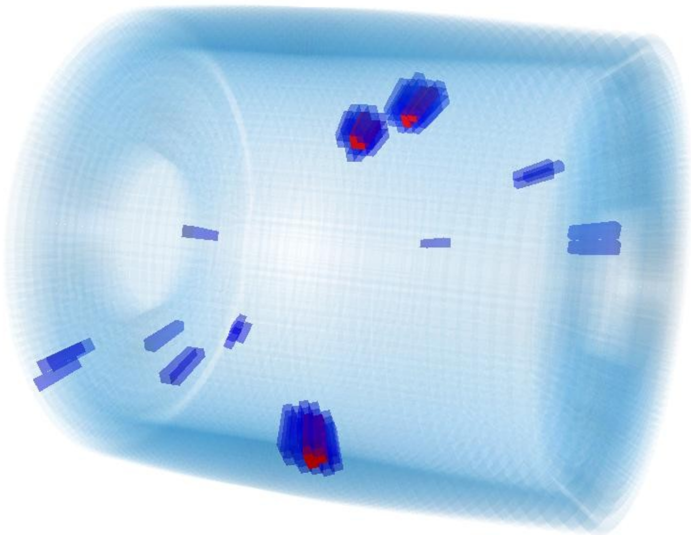


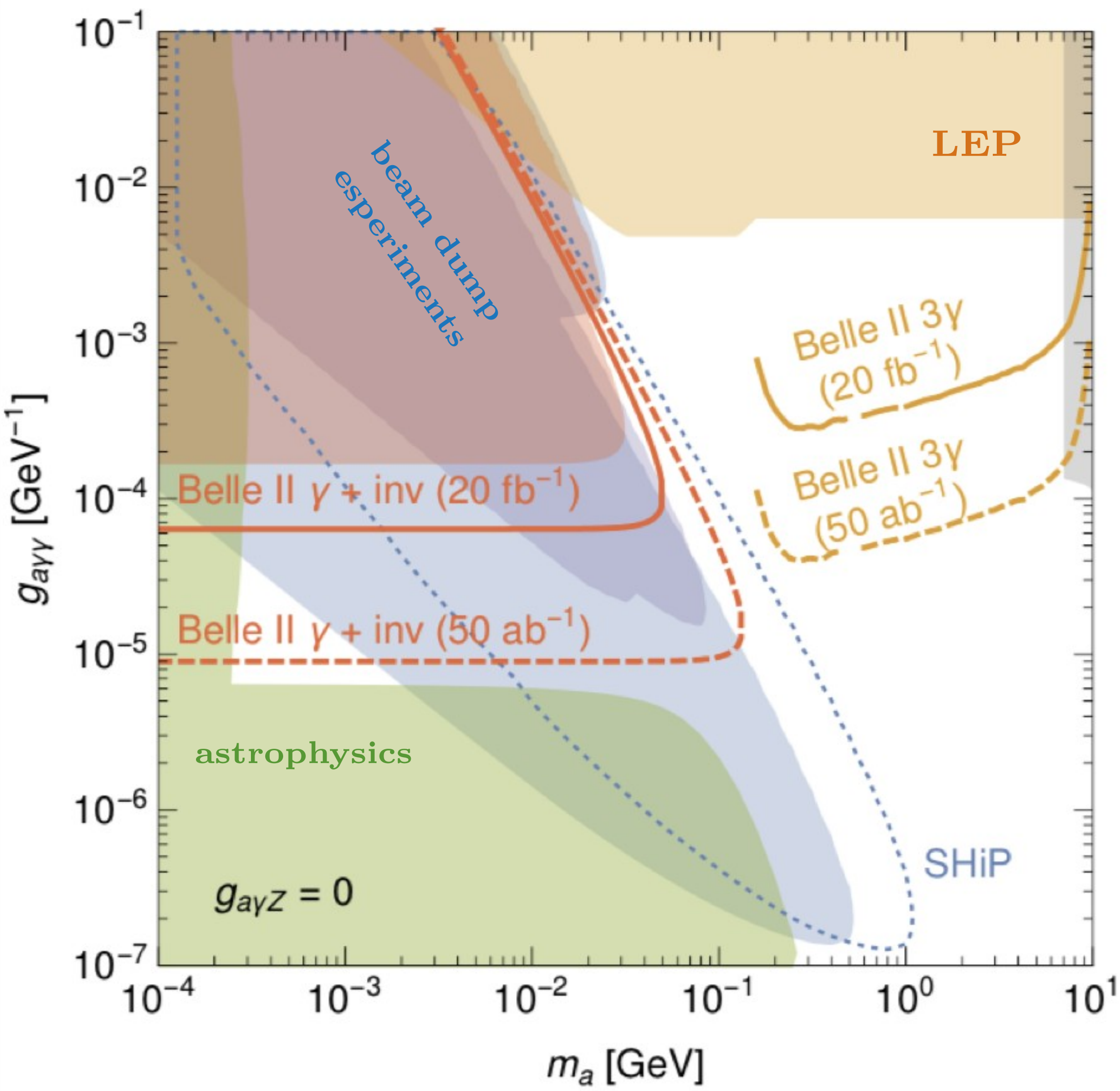
JHEP 1712 (2017) 094

- 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







JHEP 1712 (2017) 094

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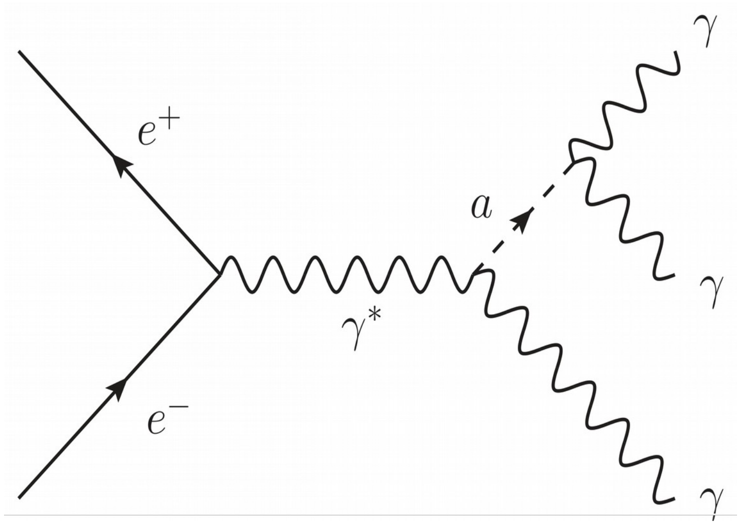
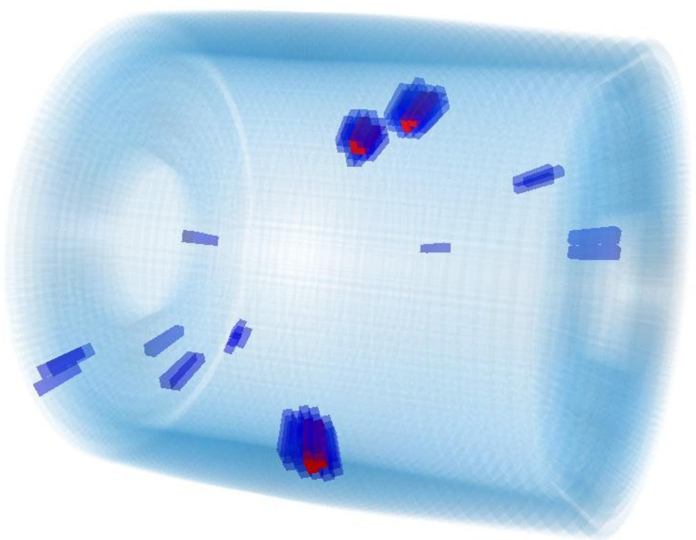
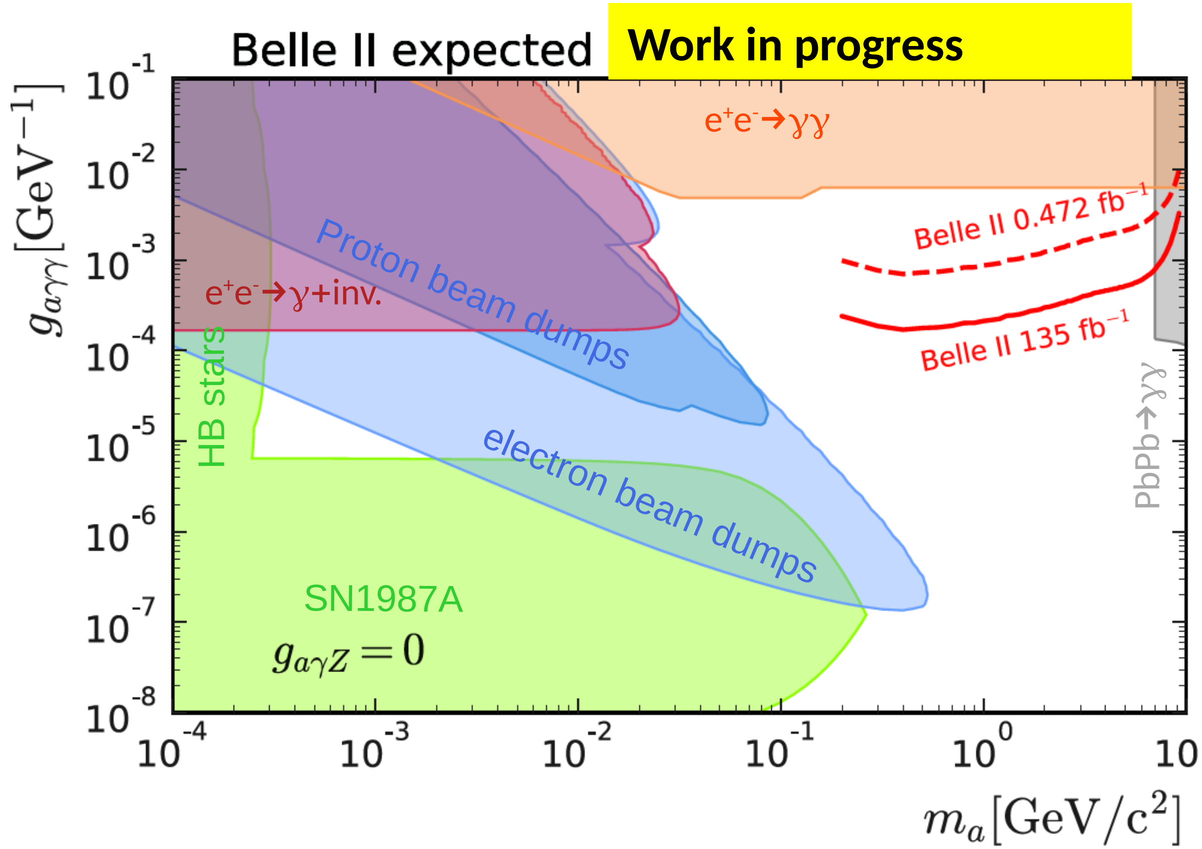
Axion Like Particles (ALPs) at Belle II







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

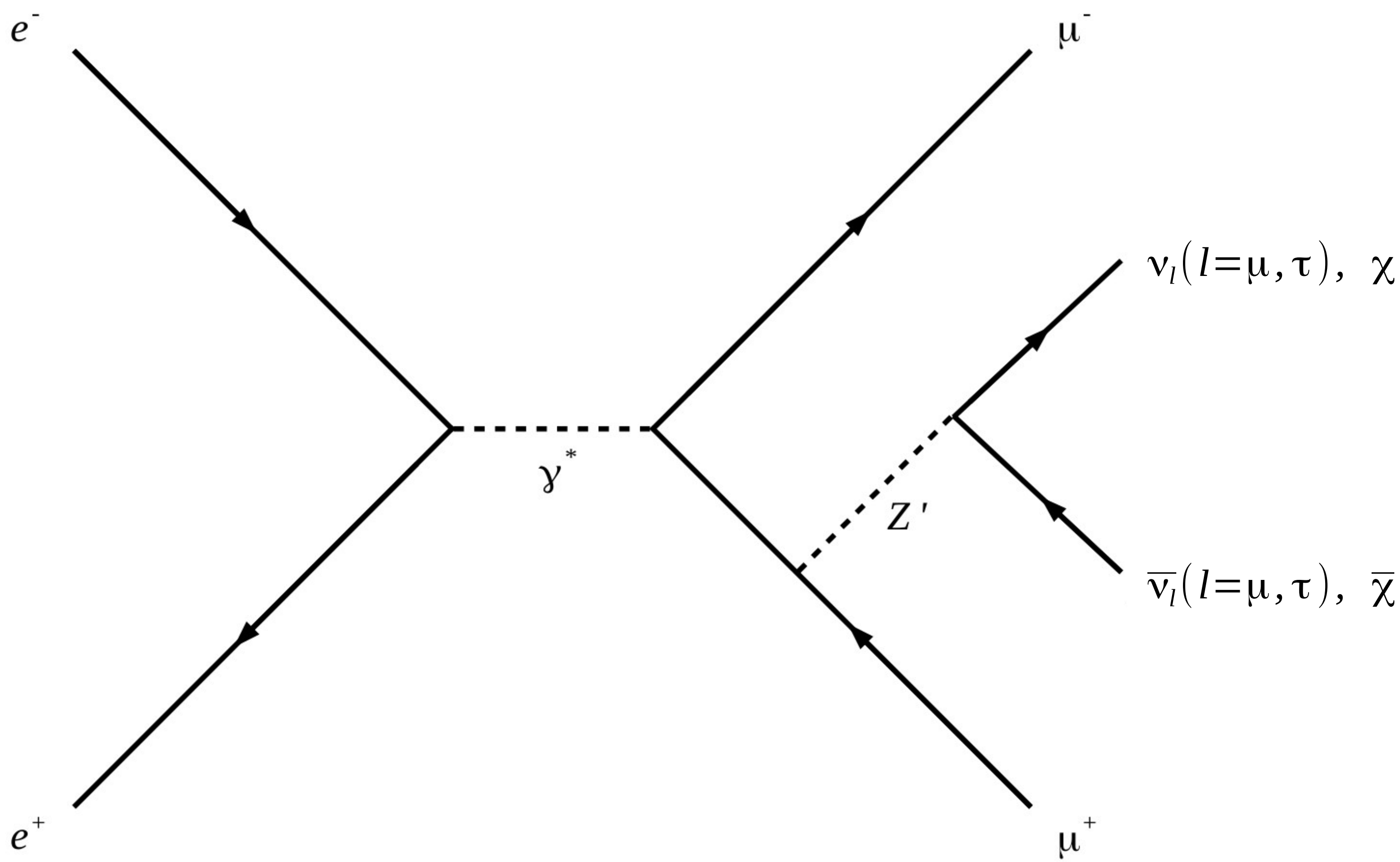
- The branching fraction to one neutrino species is half of the branching fraction to one charged lepton flavour. The reason is, of course, that the Z' only couples to left-handed neutrino chiralities whereas it couples to both left- and right-handed charged leptons.

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

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 $M_{Z'} > 2\chi$ → BF[Z'→χχ]~1**
  (see for example: https://arxiv.org/abs/1403.2727)

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



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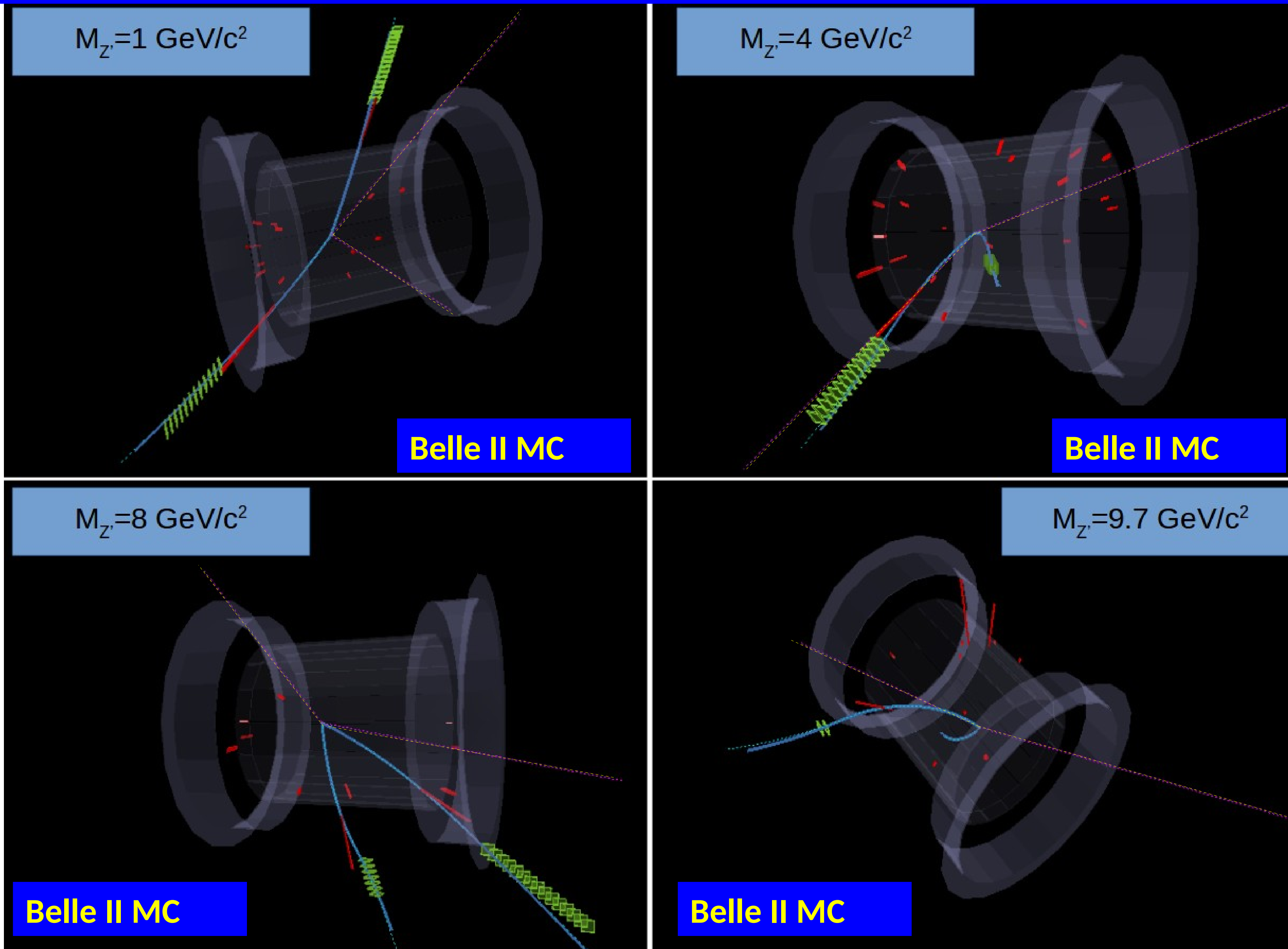
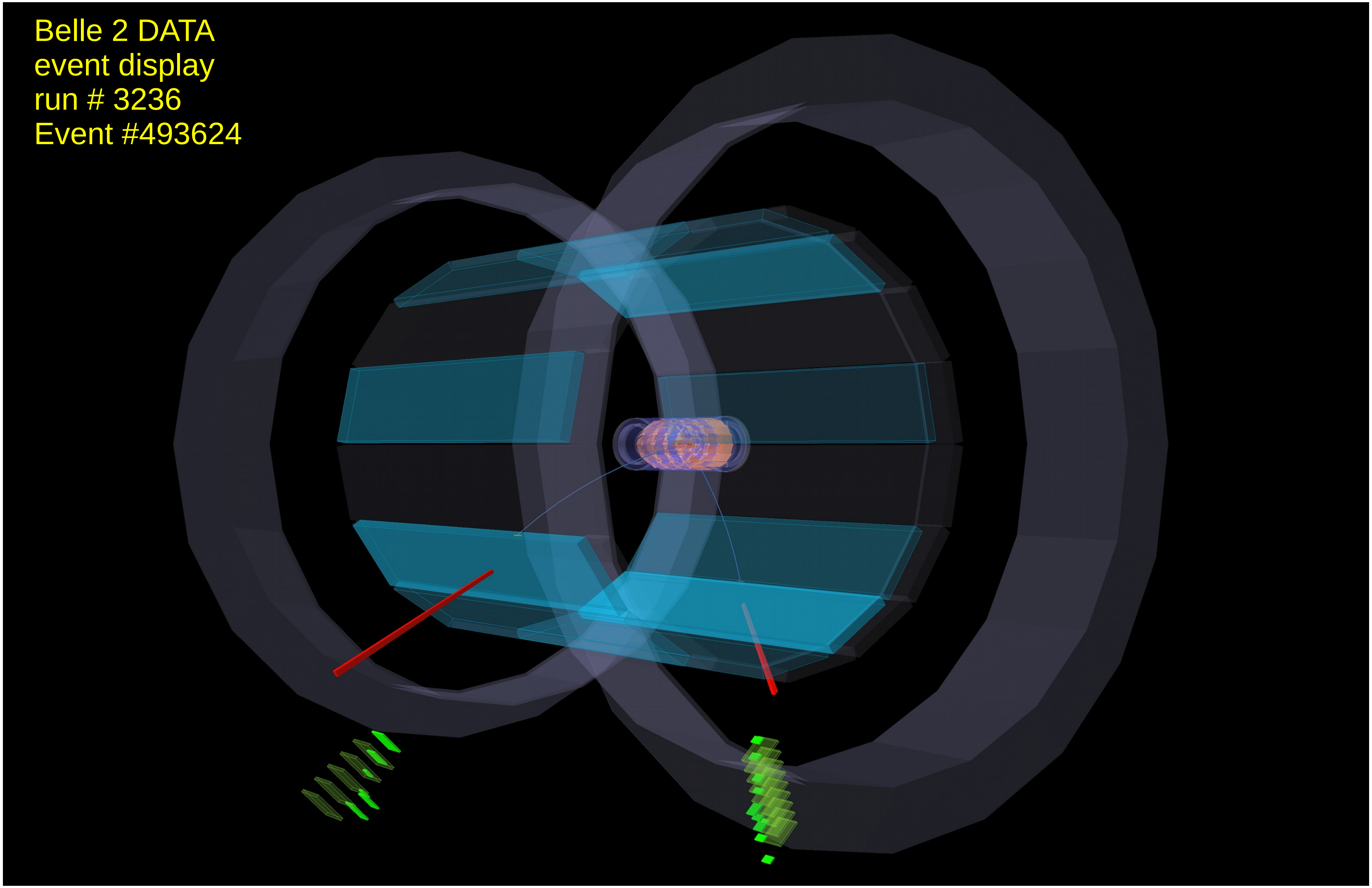
If $M_{Z'}$>2χ→ BF[Z'→χχ]~1

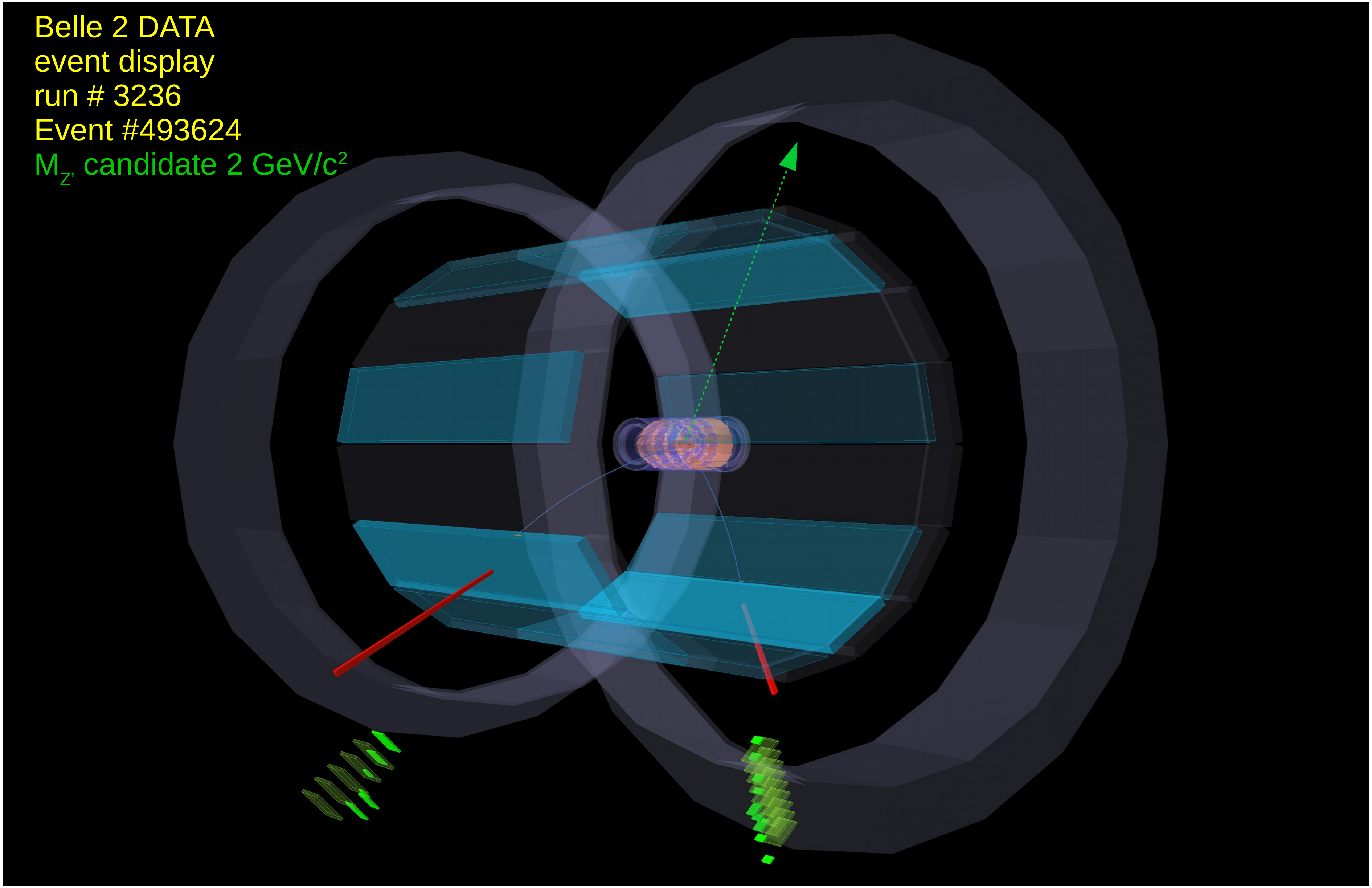
$Z' \rightarrow$ invisible, Belle II Event Display



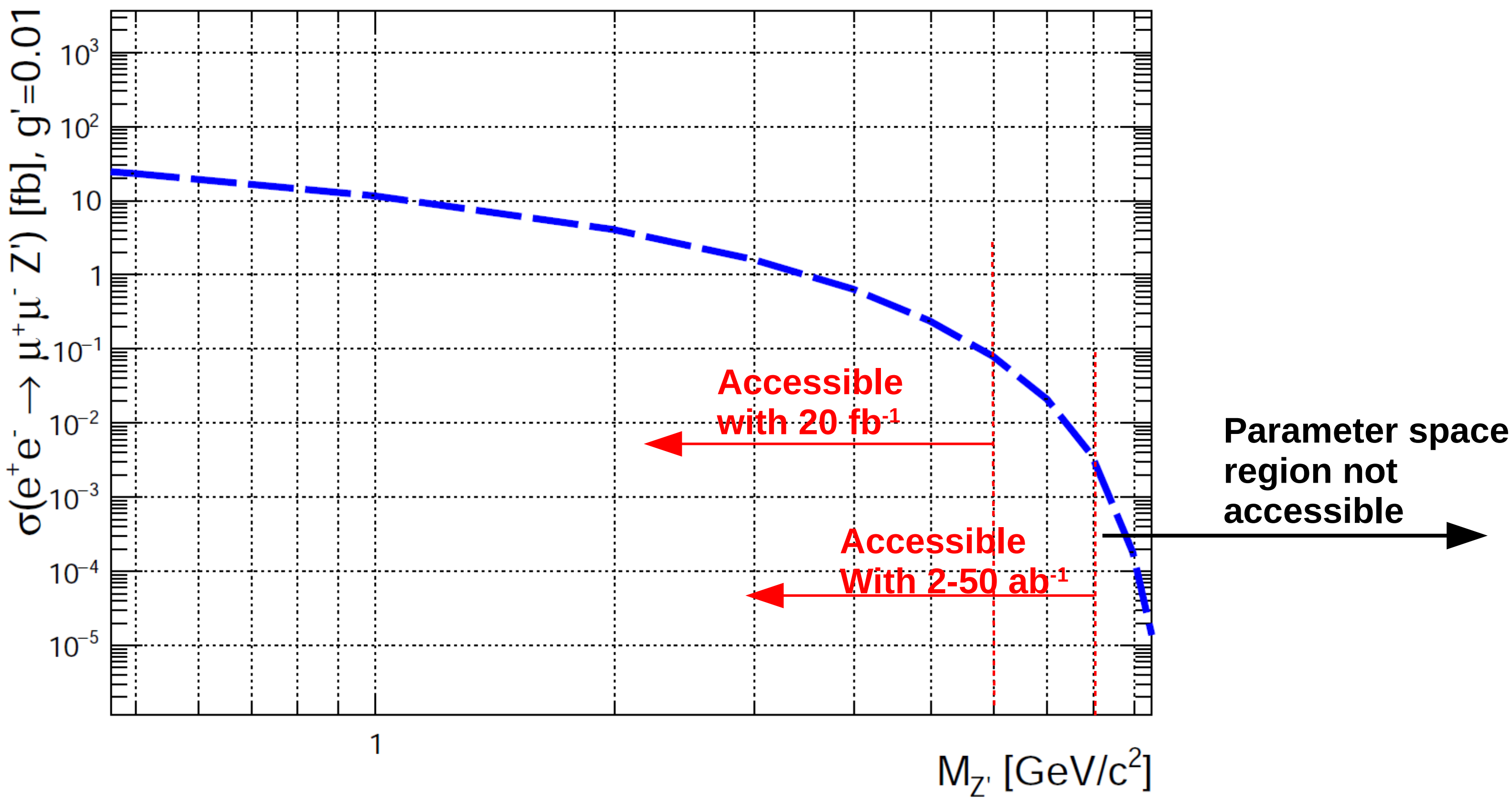
Belle II Event Display



Belle II Event Display



Cross section for Z’→ invisible (ii)

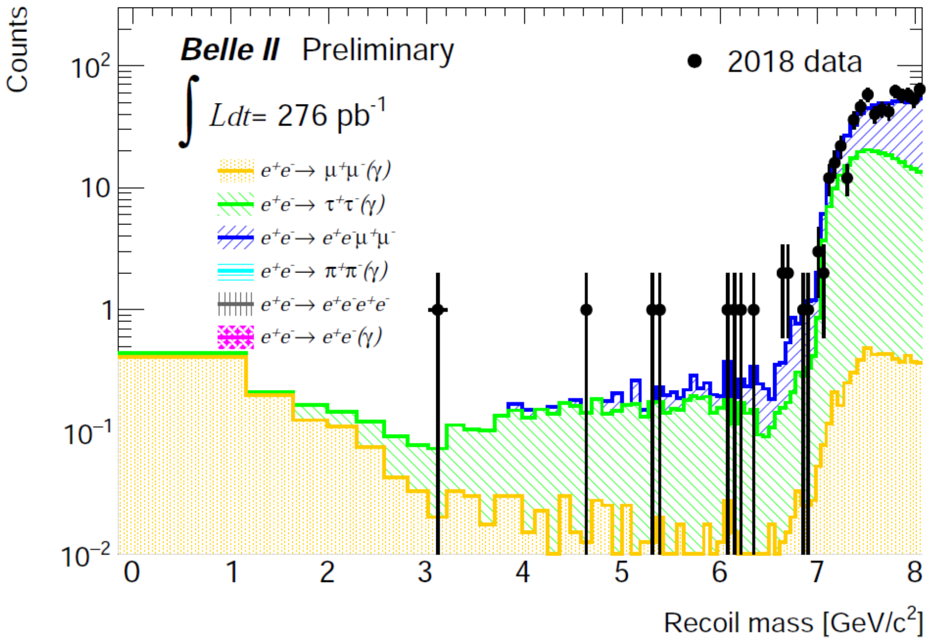


- Cross section provided by MadGraph for $e^+e^- \rightarrow \mu^+\mu^- Z'$, $Z' \rightarrow \nu_\mu \bar{\nu}_\mu$ and multiplied by a factor 2 to account for $Z' \rightarrow \nu_\tau \bar{\nu}_\tau$ as this is the other channel that contribute to the invisible decays of Z’.

- 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' search on phase II data: results

PRL paper in preparation to be submitted soon



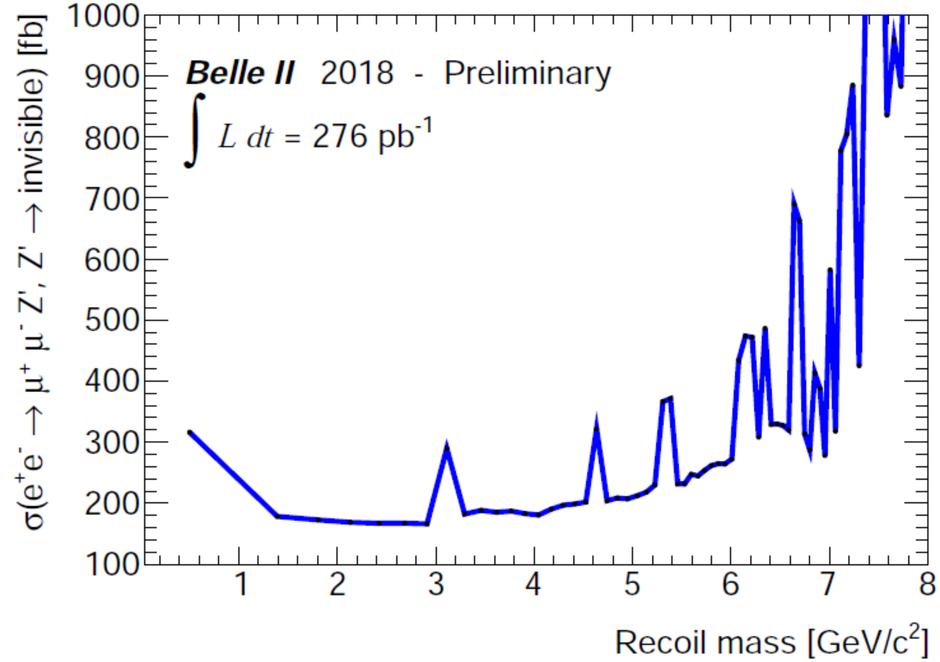
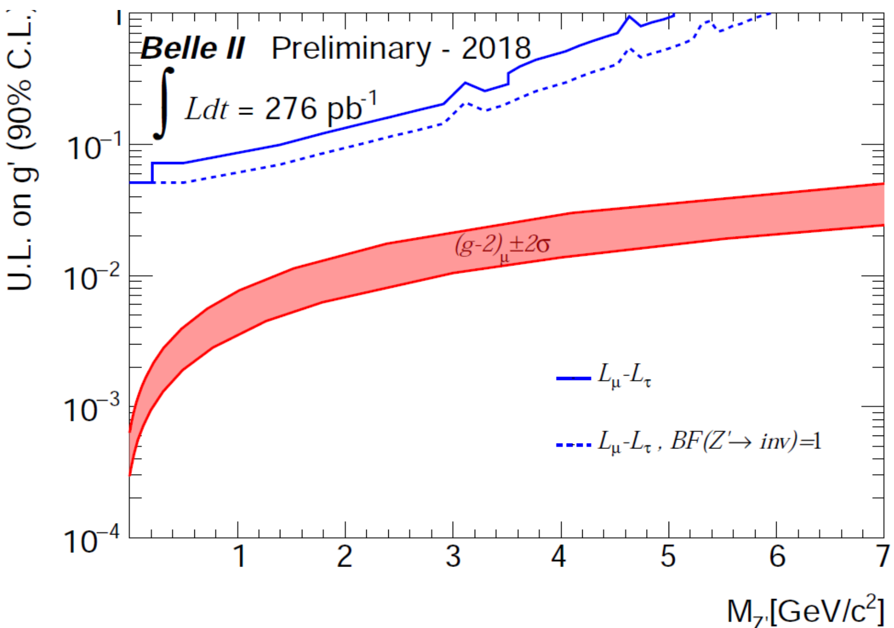
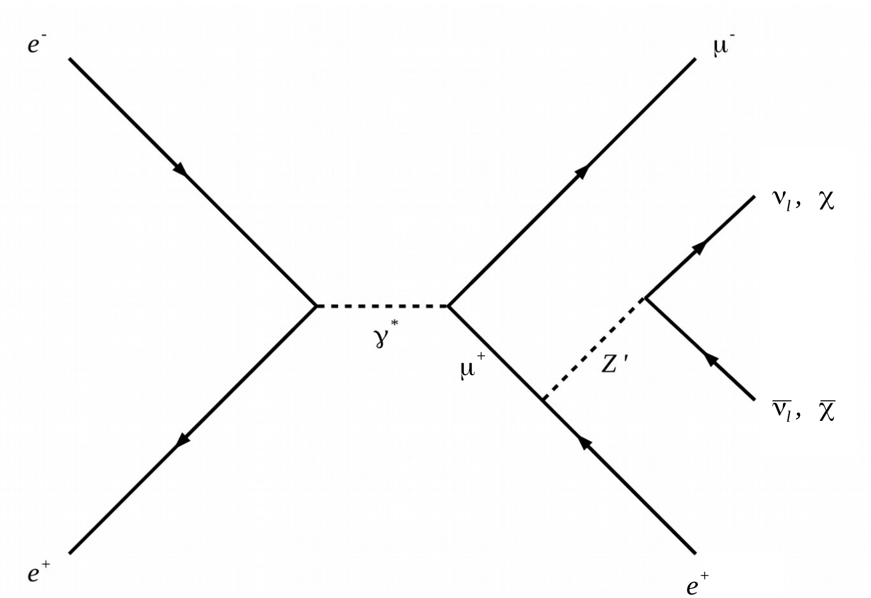


TABLE I: List of systematic uncertainties

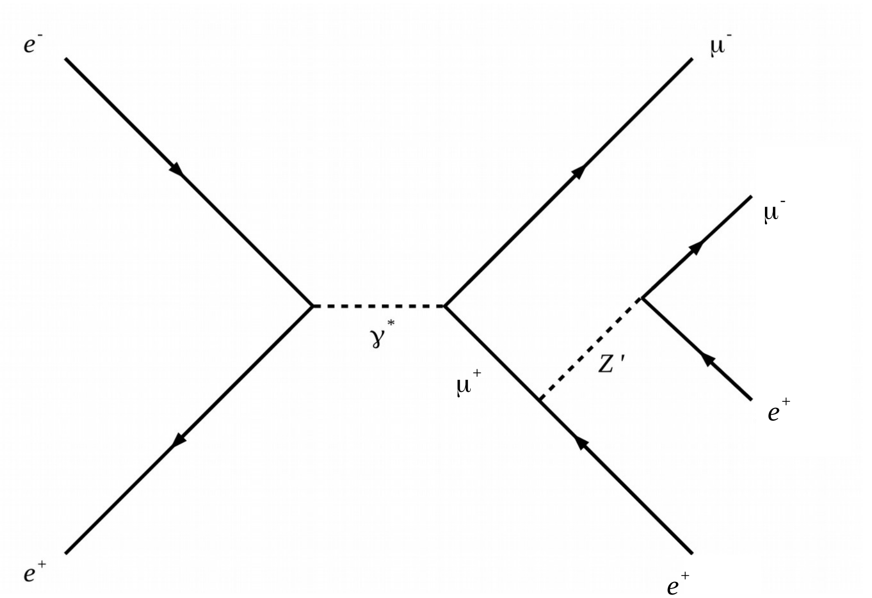
Source	Error
Trigger efficiency	4%
Tracking efficiency	4%
PID	4%
luminosity	1.5%
τ suppression (background)	22%
discrepancy in muon yields (background)	2%
discrepancy in muon yields (signal efficiency)	12.5%



What about a LFV Z'?



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



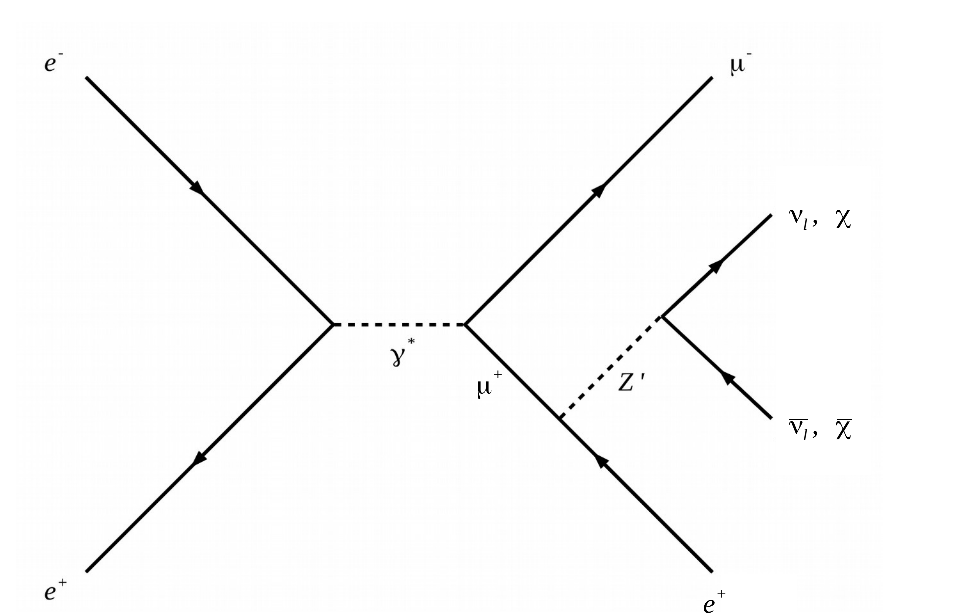
$final\ state: 2e^+2\mu^-\,(+c.c.)$

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

- A model for this final state is however not available...see next slide

What about a LFV Z'?



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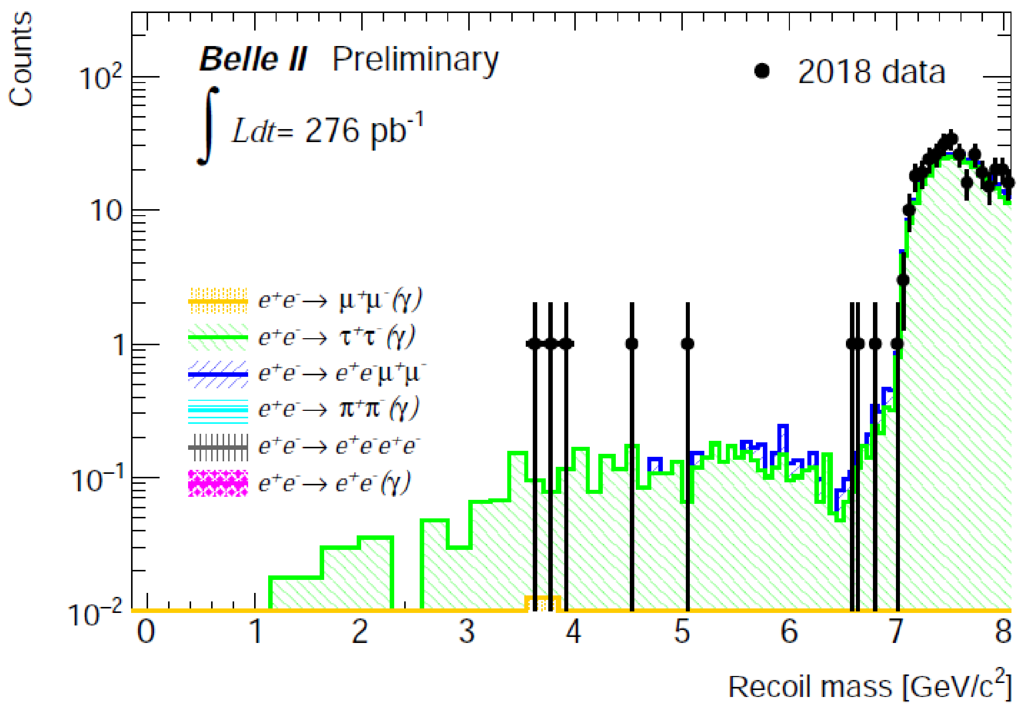

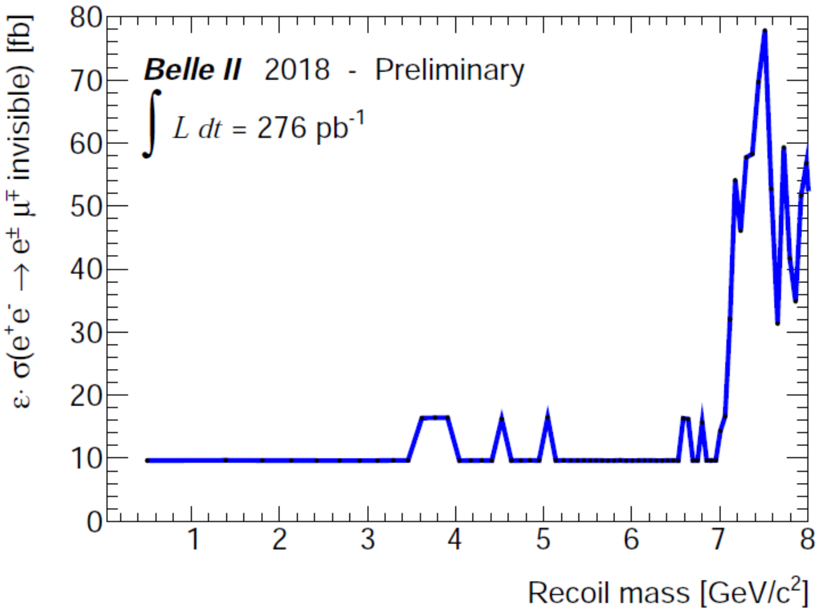

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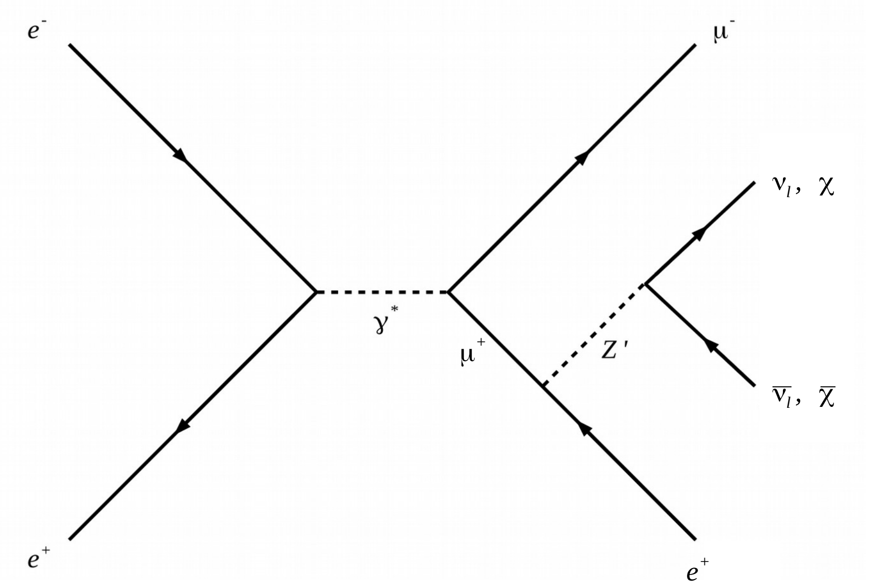

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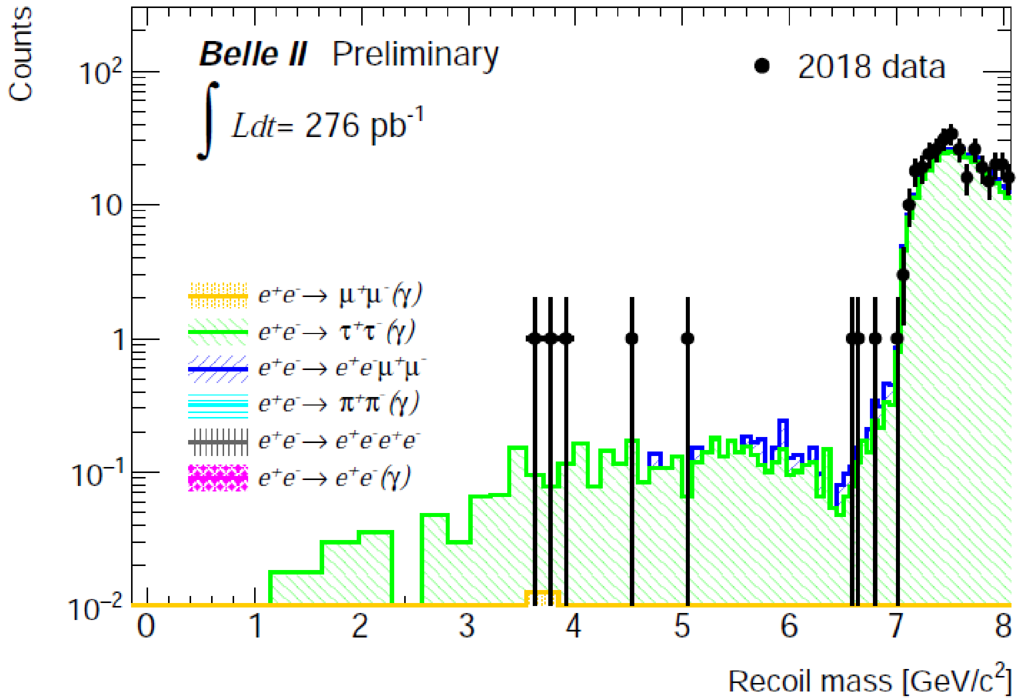
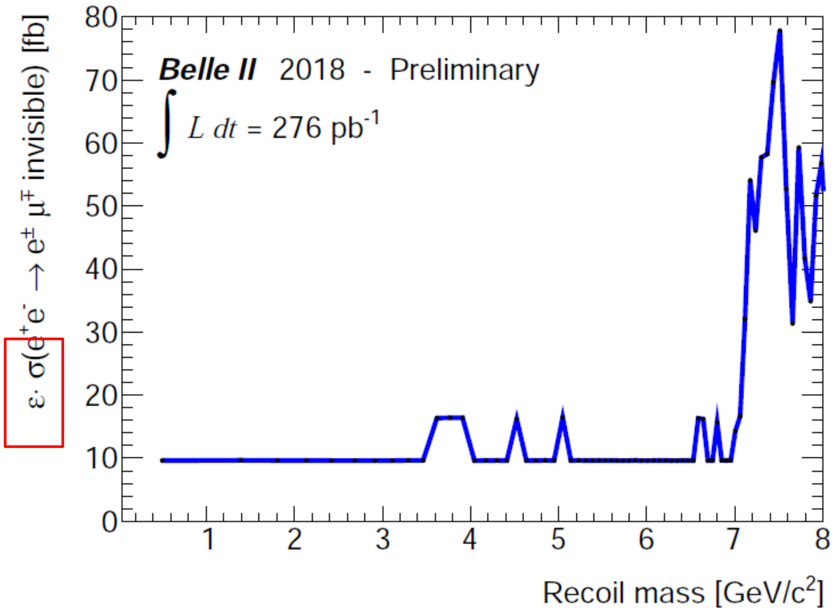
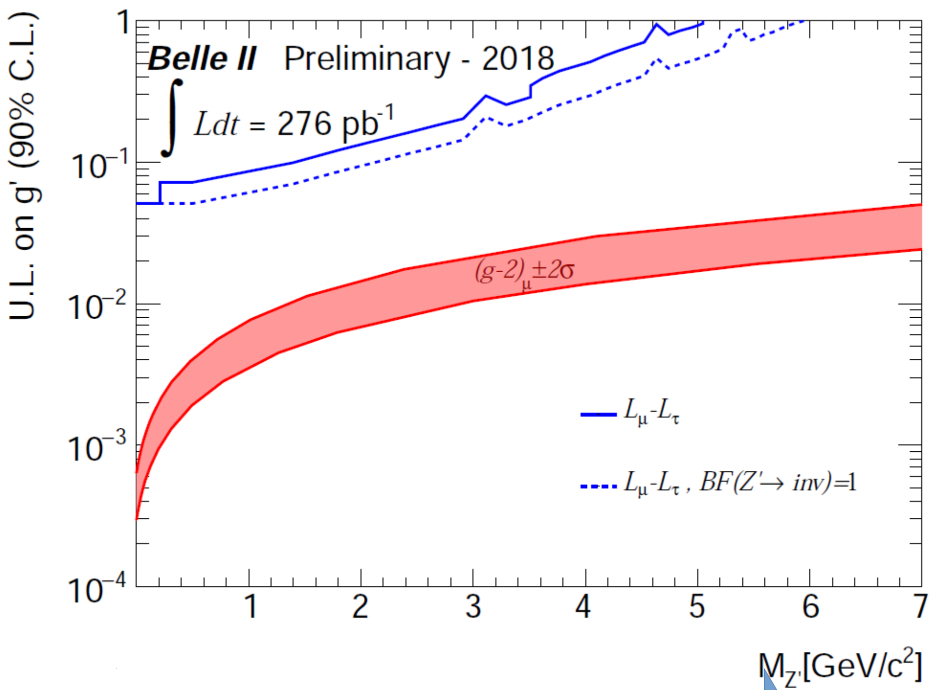


Limits are set in a model-independent way to εxσ= efficiency (flat) x cross section

Theory input needed for future work!



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



Assuming ~20000-200000 larger samples of data (5-50 ab^{-1})

Assuming systematics from 26% to 3%

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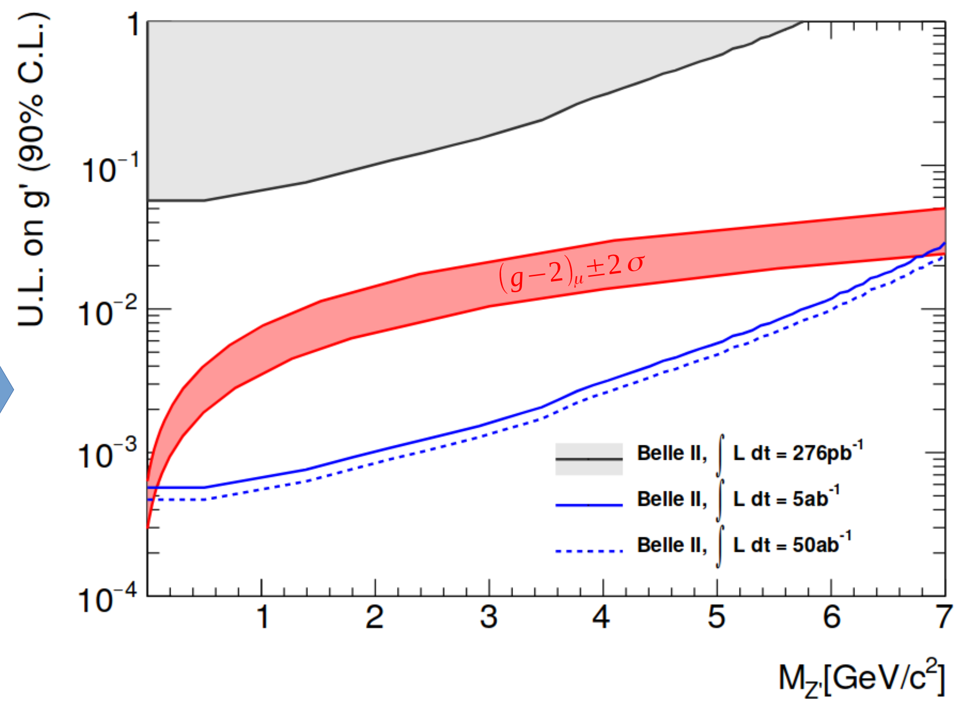


Conclusions

- 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.
  - **First Belle II results shown today**

- 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.

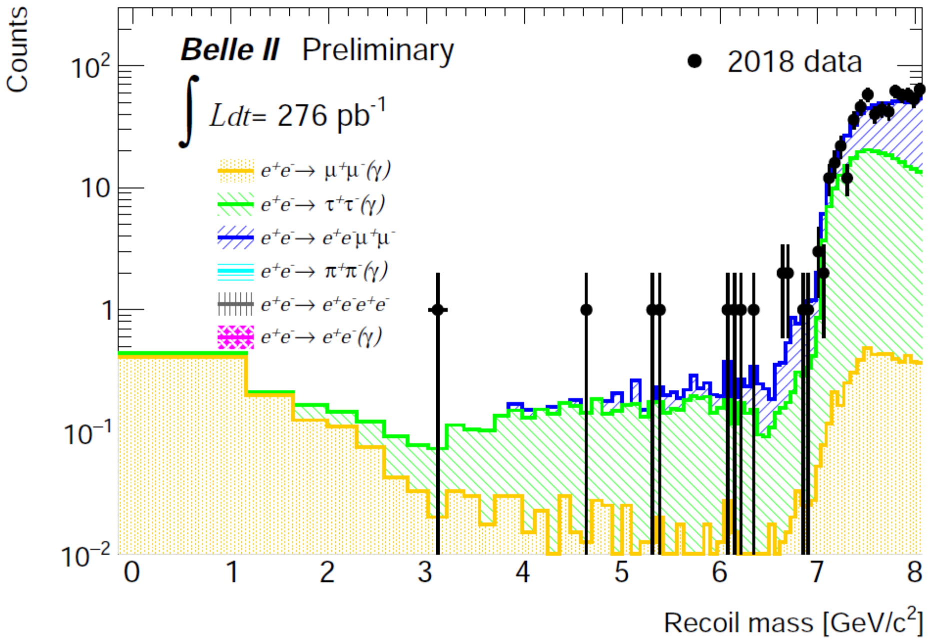
- Many searches at the Belle II experiment are ongoing and higher precision will be reached thanks to the great luminosity of Belle II at Super-KEK and thanks to improved hardware/software.

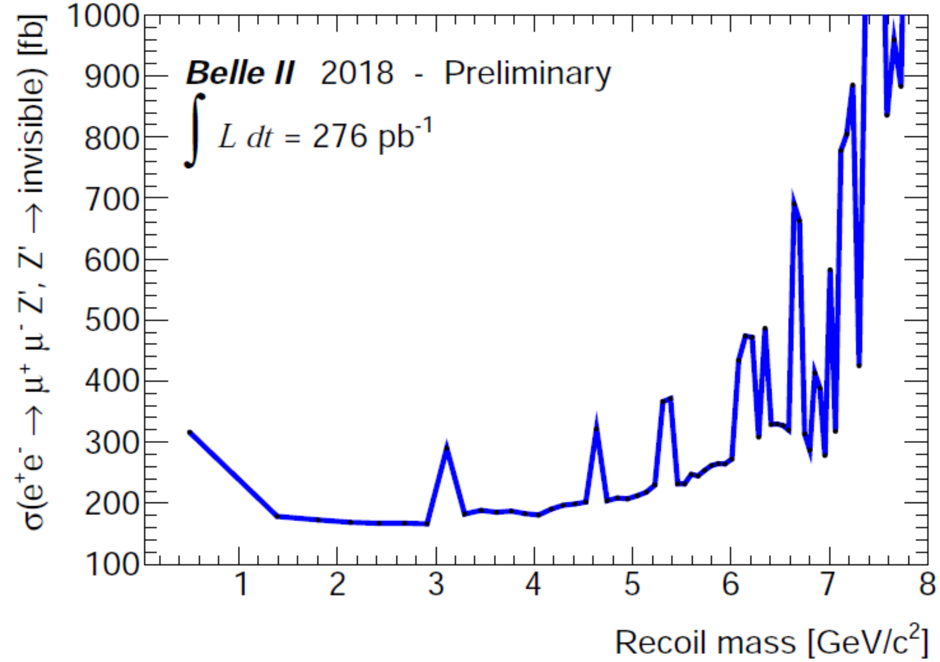
- We look forward to a bright future for dark sector physics.

Thank you for your attention!

Z’ search on phase II data: results

PRL paper in preparation to be submitted soon





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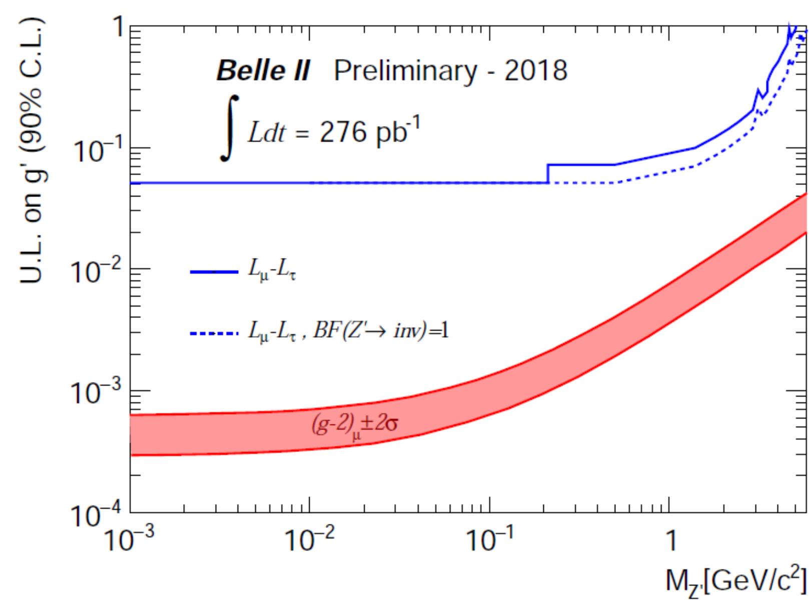
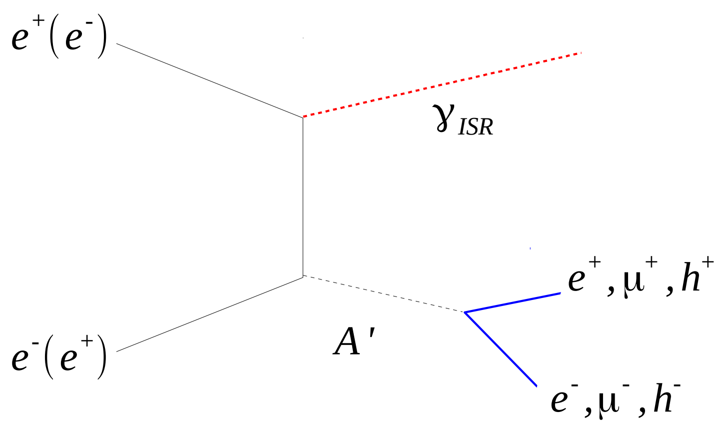
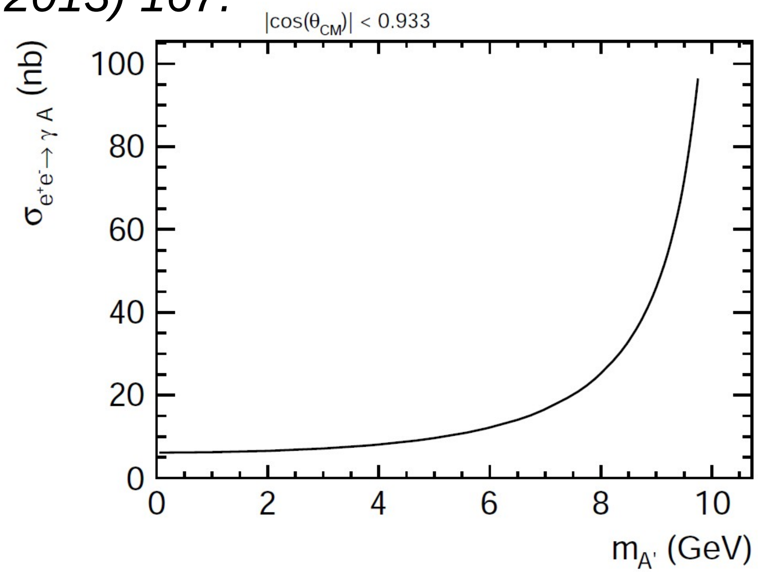


Dark Photon Search Strategy (visible case)

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



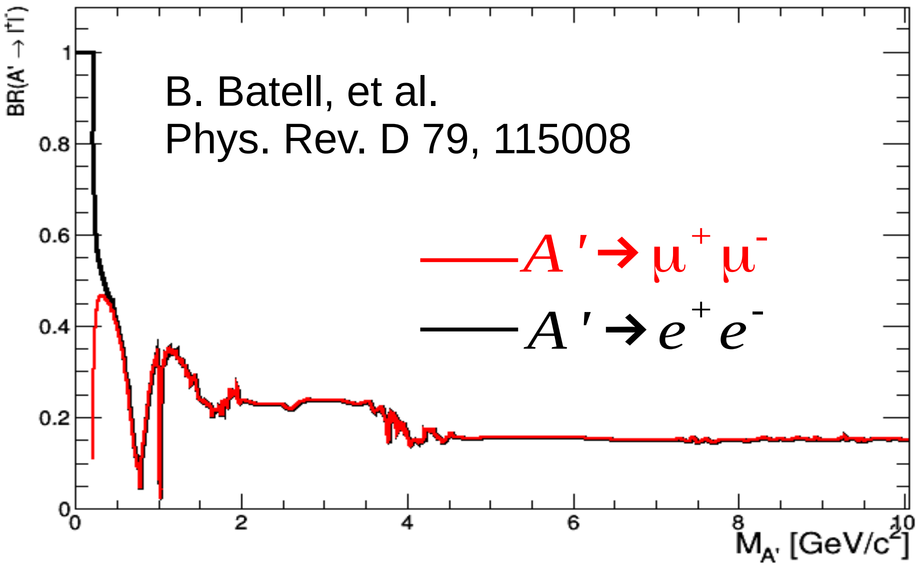


A'= dark photon, L= long lived light gauge boson (model independent).
A' decays to SM final states through kinetic mixing (if allowed by kinematics). Low multiplicity final states with 2 oppositely charged tracks and 1 photon.

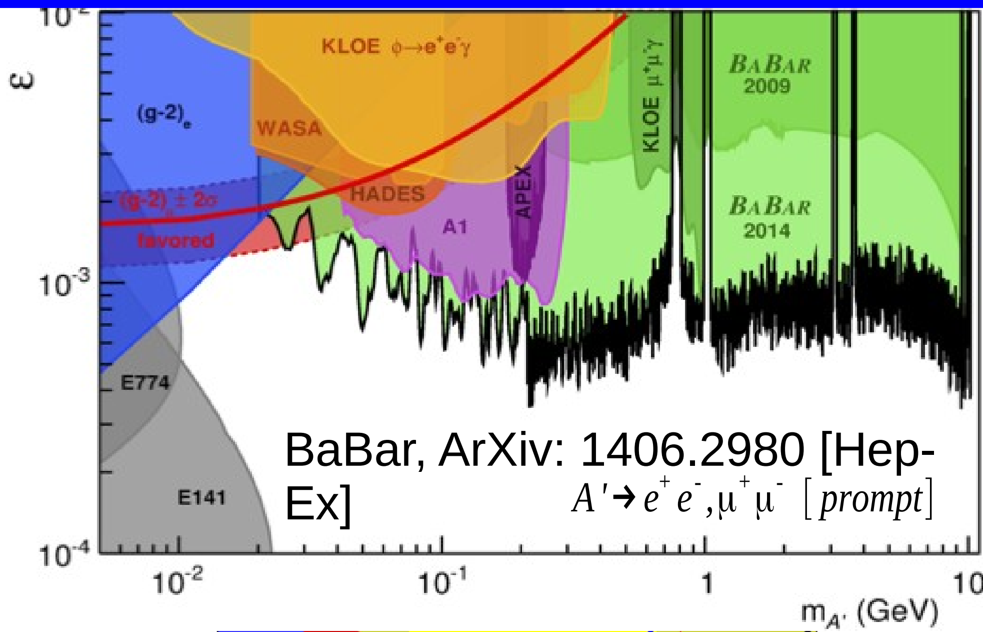
- Decays to leptons require $M_{A'}$>1.02 MeV/c^2
- Decays to hadrons require $M_{A'}$>0.36 GeV/c^2

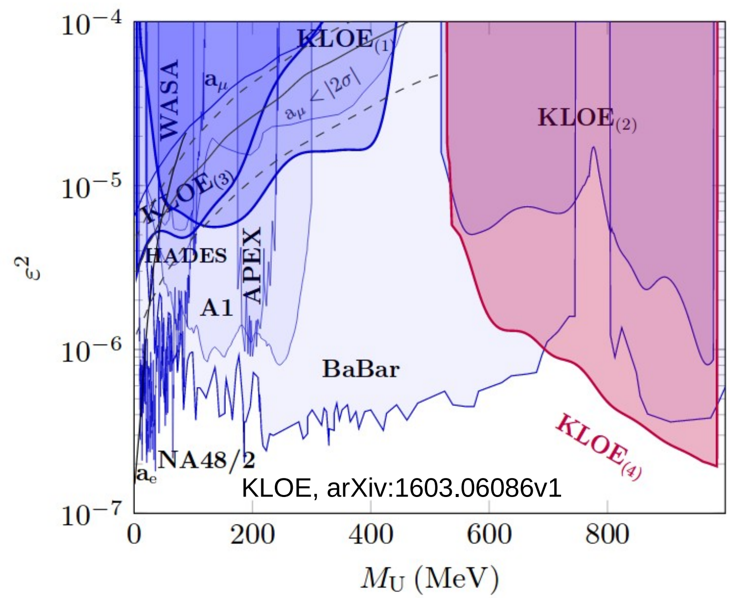
Note

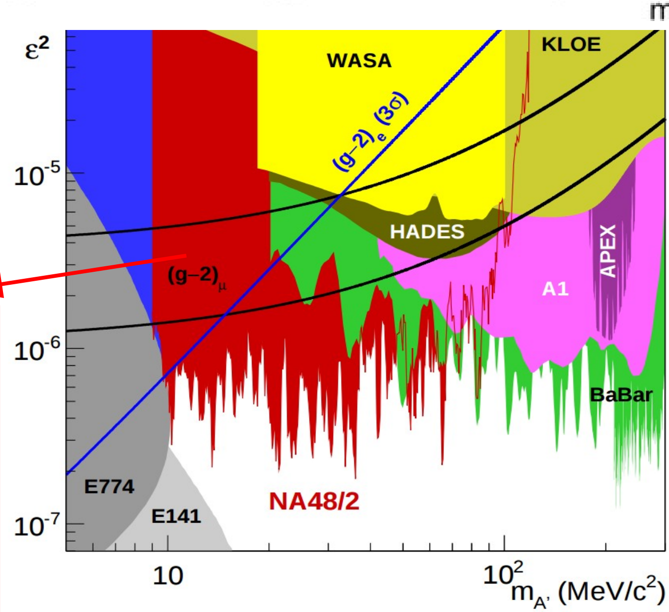
- If $M_\chi < M_{A'}/2$ → invisible A' decays to dark matter!



Dark Photon: Current UL to Kinetic Mixing

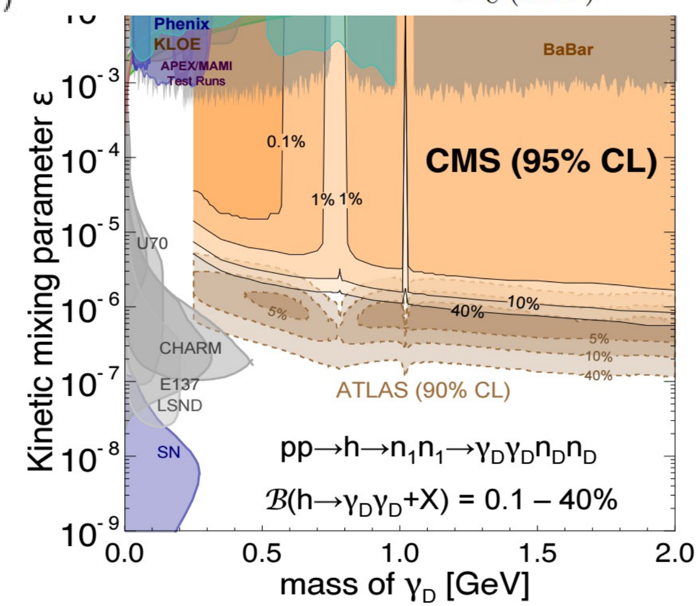






dark photon explanation of $(g-2)_\mu$ ruled out for A' $\to e^+e^-$

NA48 arXiv:1504.00607
π^0 decays



ATLAS + CMS:

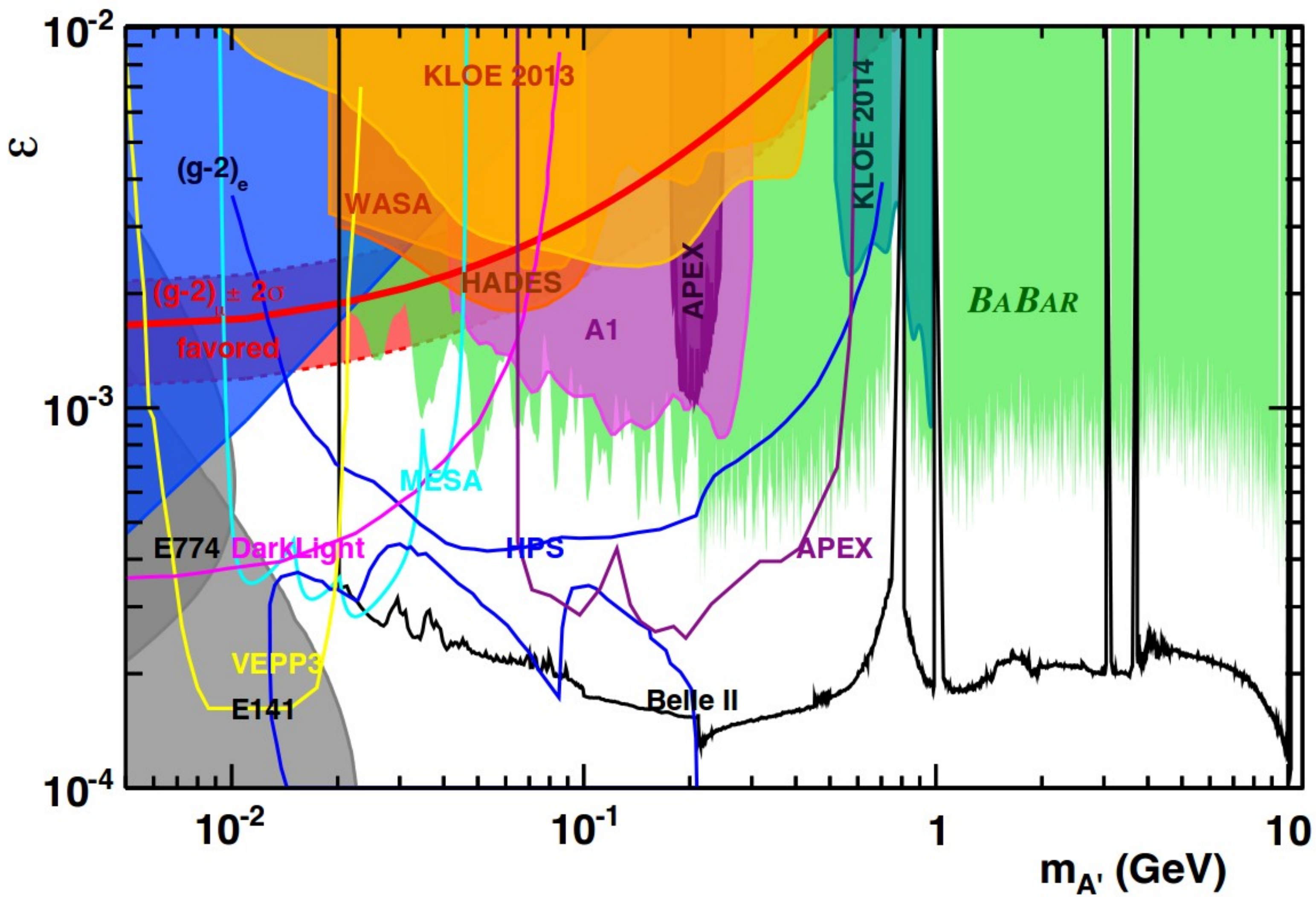
highly model-dependent!

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

→ See M. Borsato's talk for LHCb studies

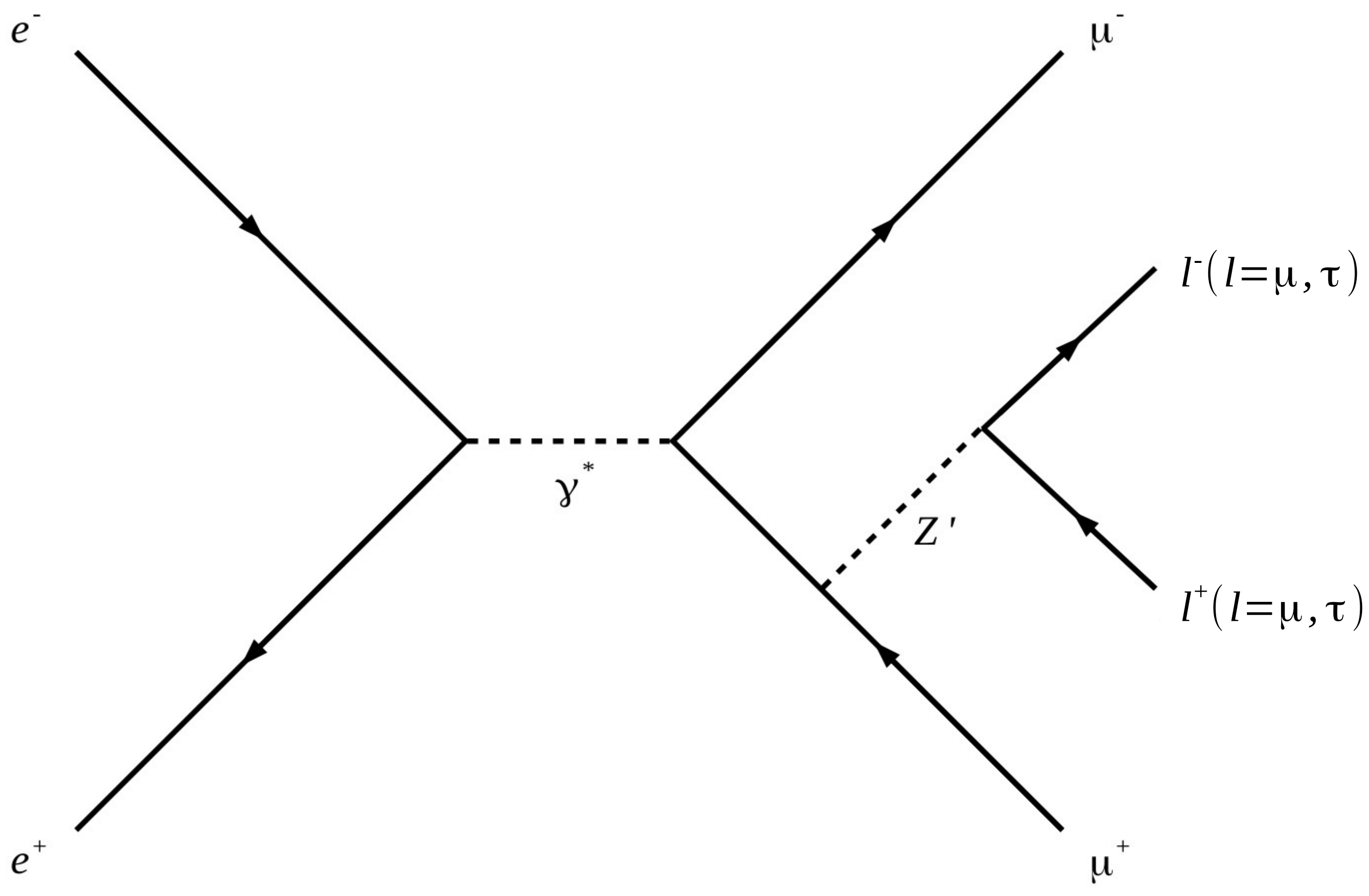
Dark Photon: Expected Sensitivity @ Belle II

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



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

The L_μ-L_τ 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.**
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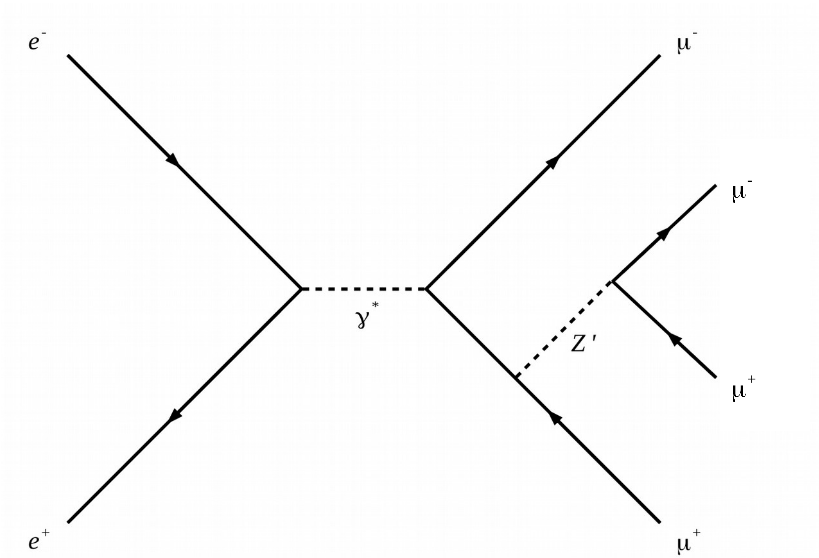
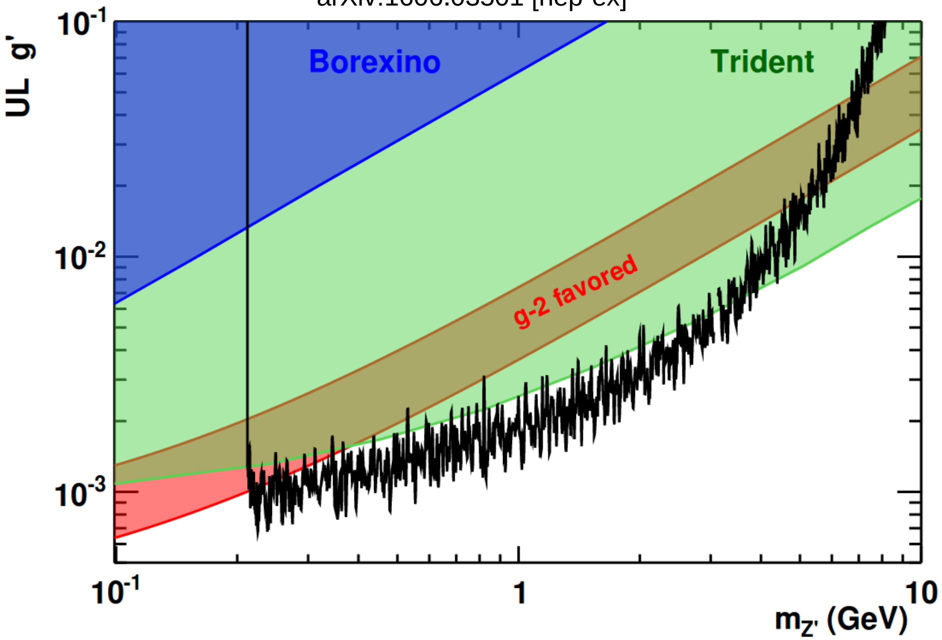


BABAR Coll.
Phys. Rev. D 94, 011102 (2016),
arXiv:1606.03501 [hep-ex]



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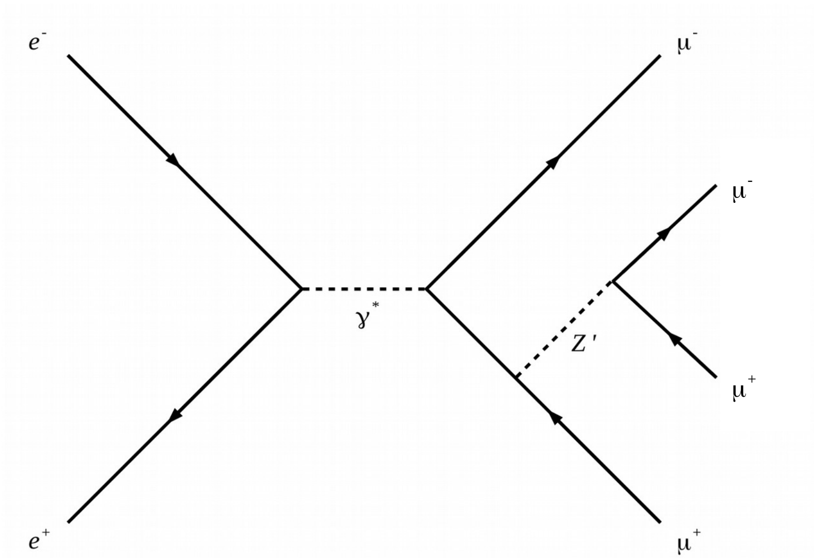

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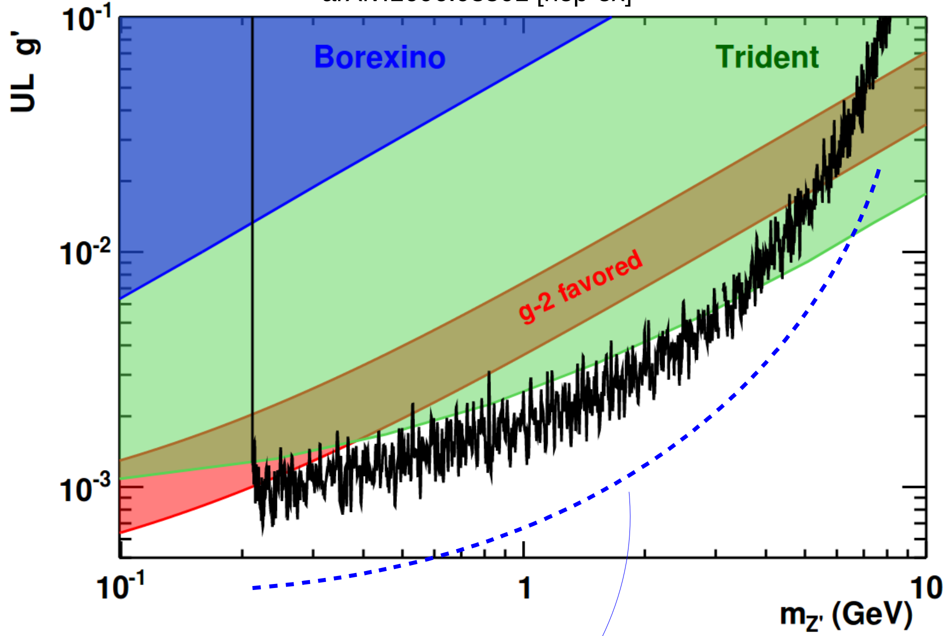

Rough projection to Belle II luminosity preliminary studies are ongoing

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

Invisible Υ(1S) Decays @ Belle II

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

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

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

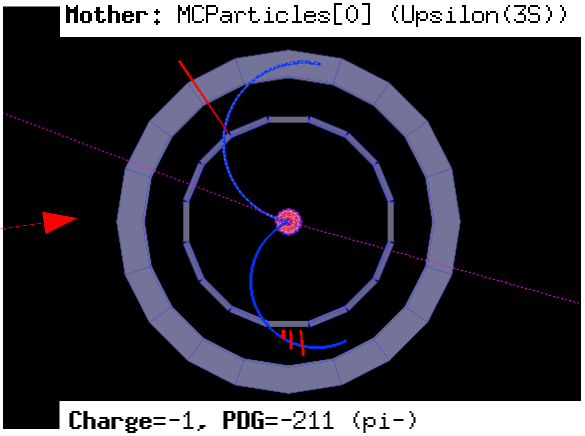
- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having Υ(1S)→χχ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance Υ(1S)→νν(γ). [Phys. Rev. D **81**, 054025, 2010]
- In absence of new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

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

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

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

$\sim900\ MeV\ available\ for\ P_{\pi\pi}$

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

$\sim540\ MeV\ available\ for\ P_{\pi\pi}$

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

$e^+e^-\to Y(2S)$
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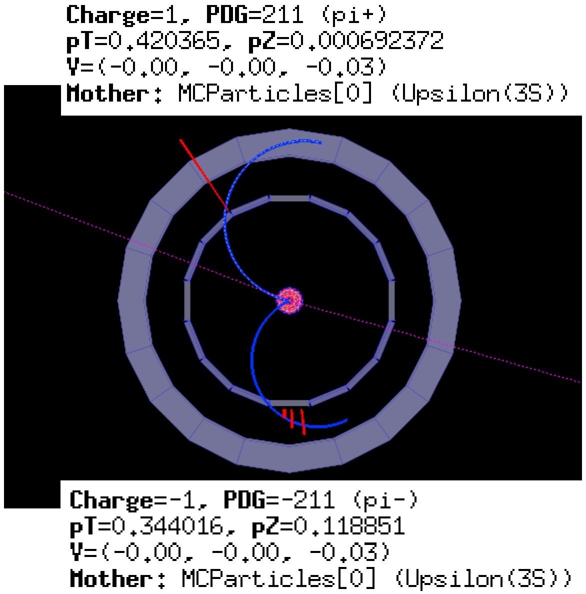
Belle2 Simulation
Υ(3S)→$\pi^+\pi^-$Υ(1S),
Υ(1S)→ νν



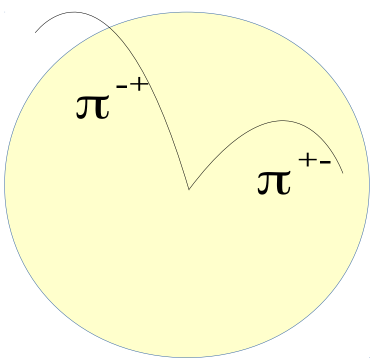
A signal of Υ(1S)→*invisible* is an excess of events over the background in the M_r distribution at a mass equivalent to that of the Υ(1S) (9.460 GeV/c²)

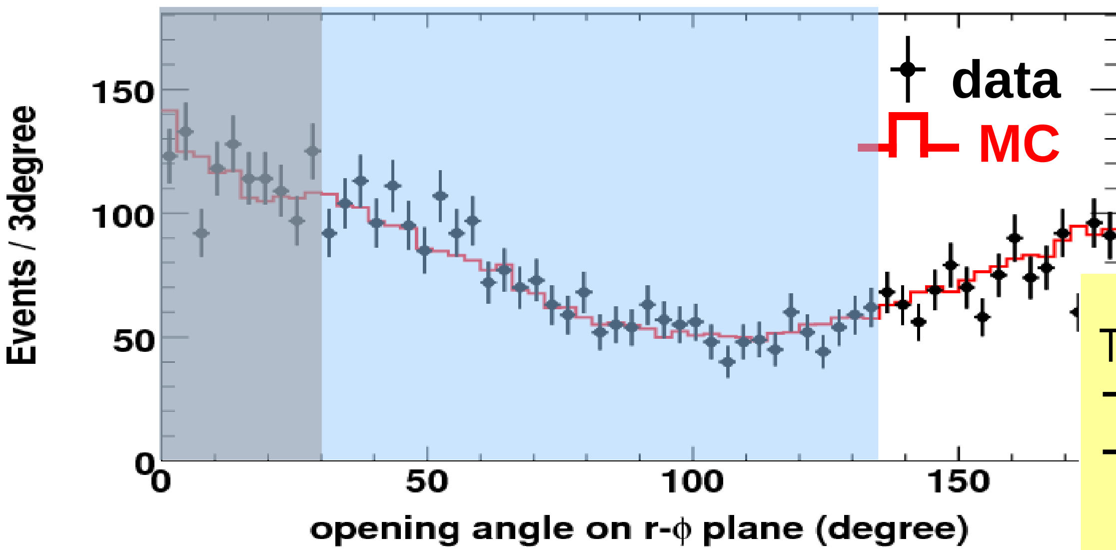
$$M_r^2=s+M_{\pi^+\pi^-}-2\sqrt{s}E^{CMS}_{\pi^+\pi^-}$$

Trigger Considerations

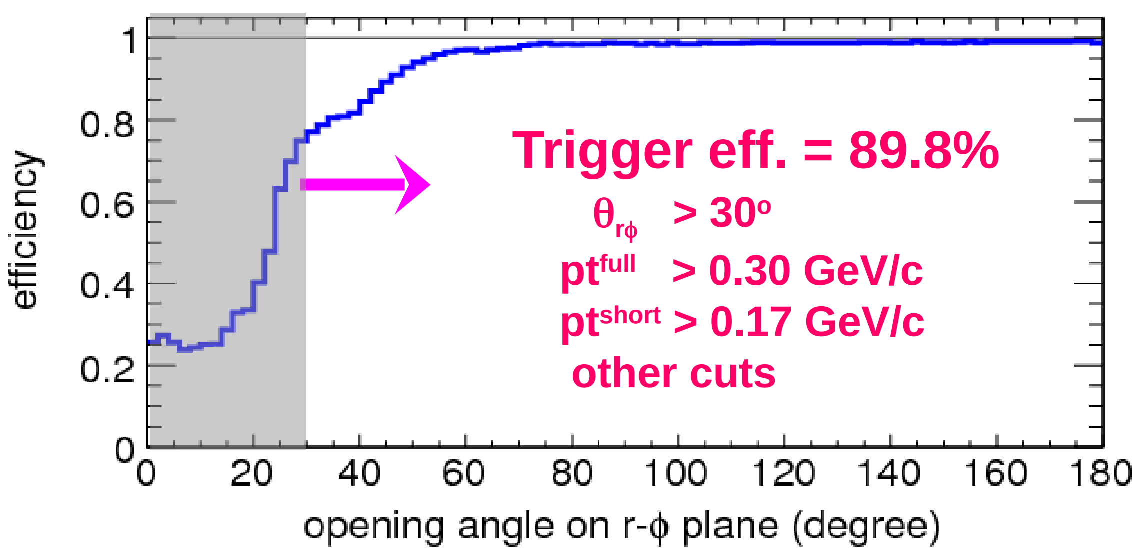
$\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$

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





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)

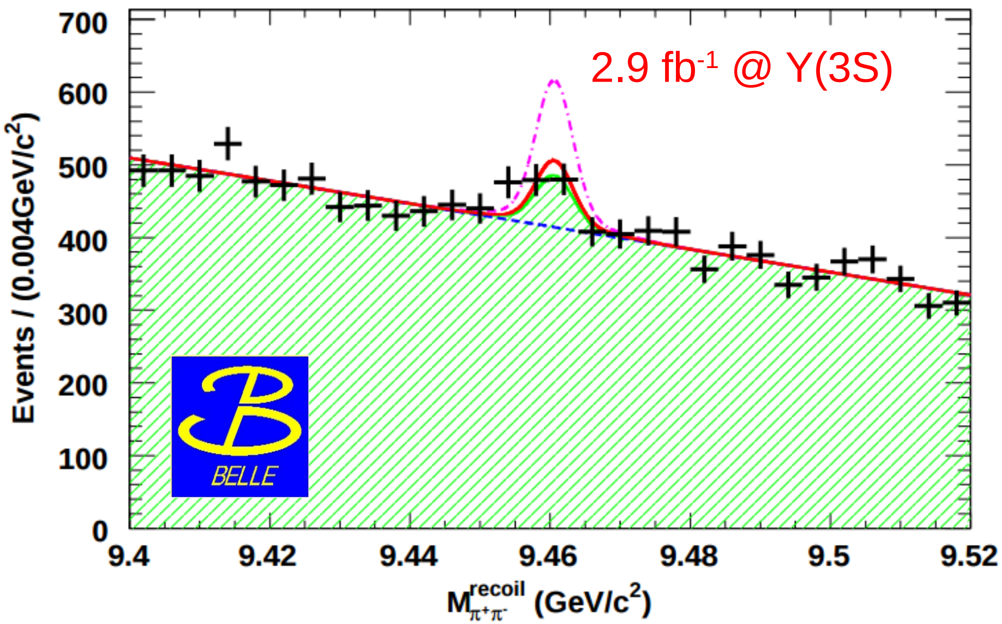
$$\frac{\text{2-track trigger \& 1-track trigger}}{\text{1-track trigger}}$$

for efficiency monitoring

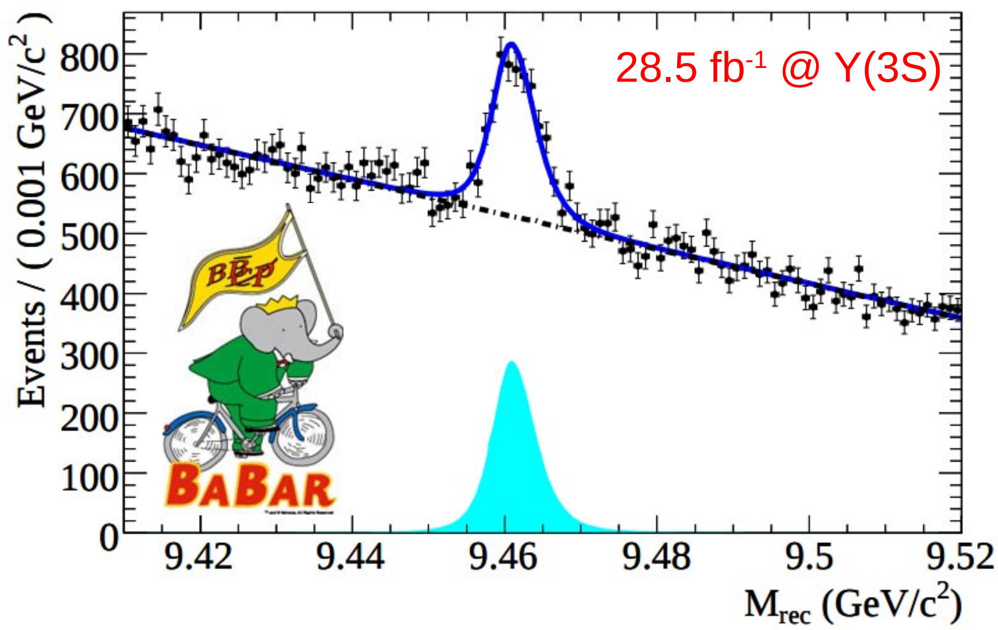
Invisible Υ(1S) Decays: Signal or Background?

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

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



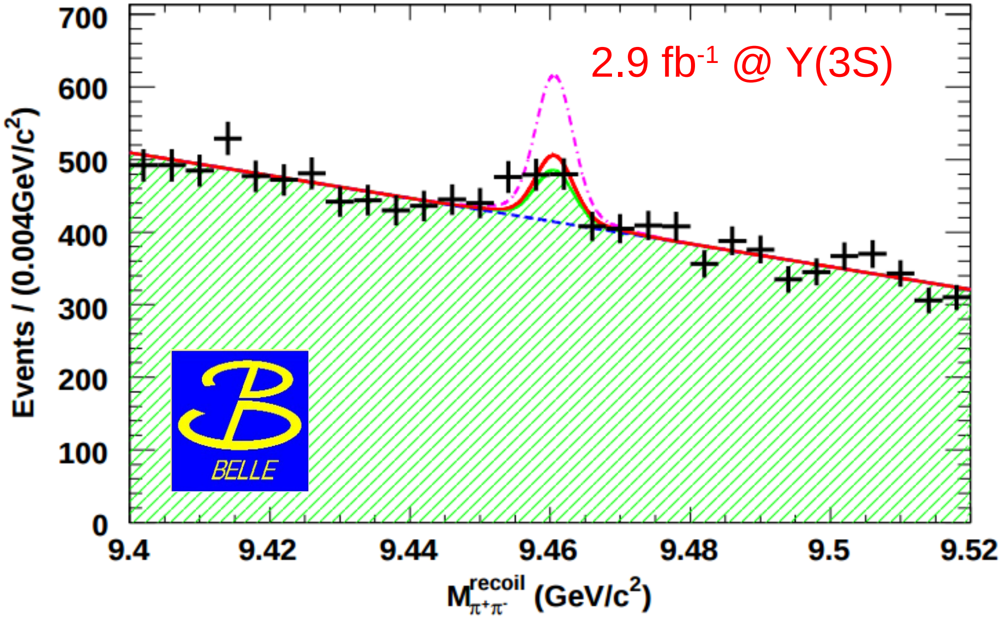
[babar]: http://arxiv.org/abs/0908.2840
(2 months running @ Υ(3S))



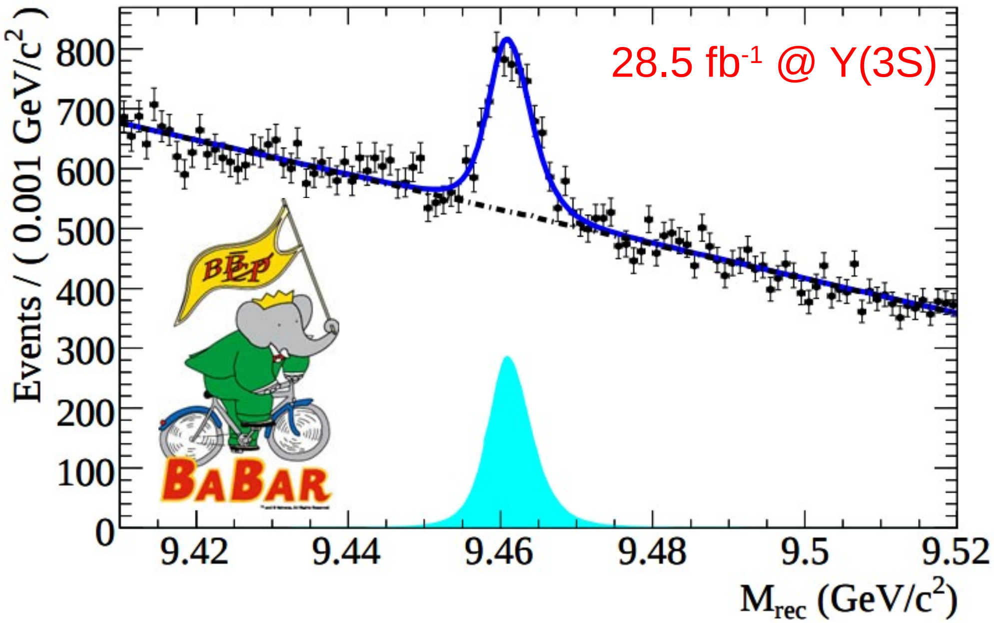
Invisible Υ(1S) Decays: Belle II Discovery Potential

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

[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))



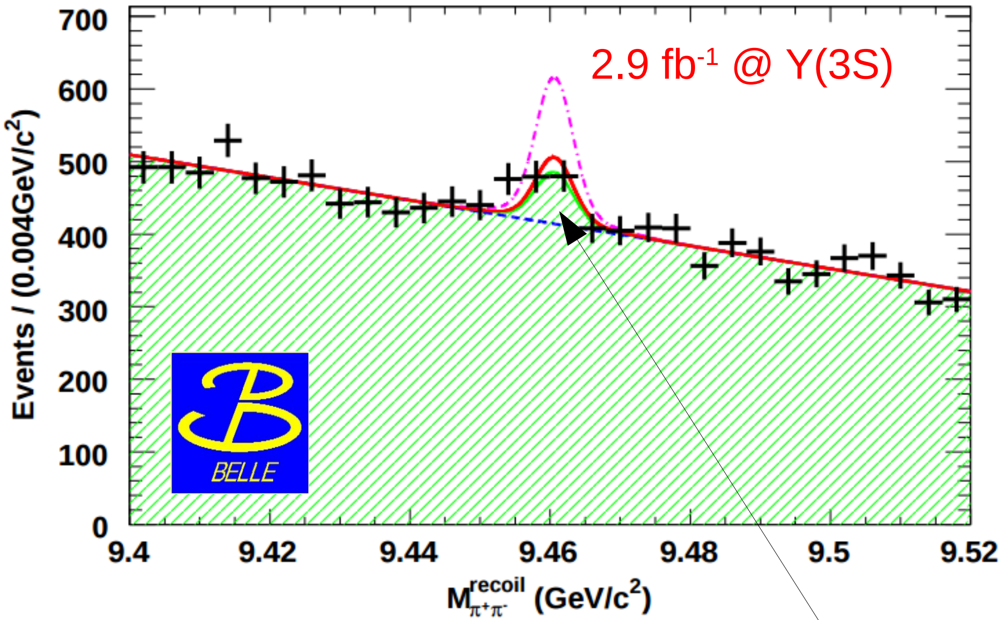
No signal was observed over the expected background and upper limits have been obtained: BR(Υ→νν) < $3x10^{-4}$ (BaBar) and BR(Υ→νν) < $3.0x10^{-3}$(Belle).

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.

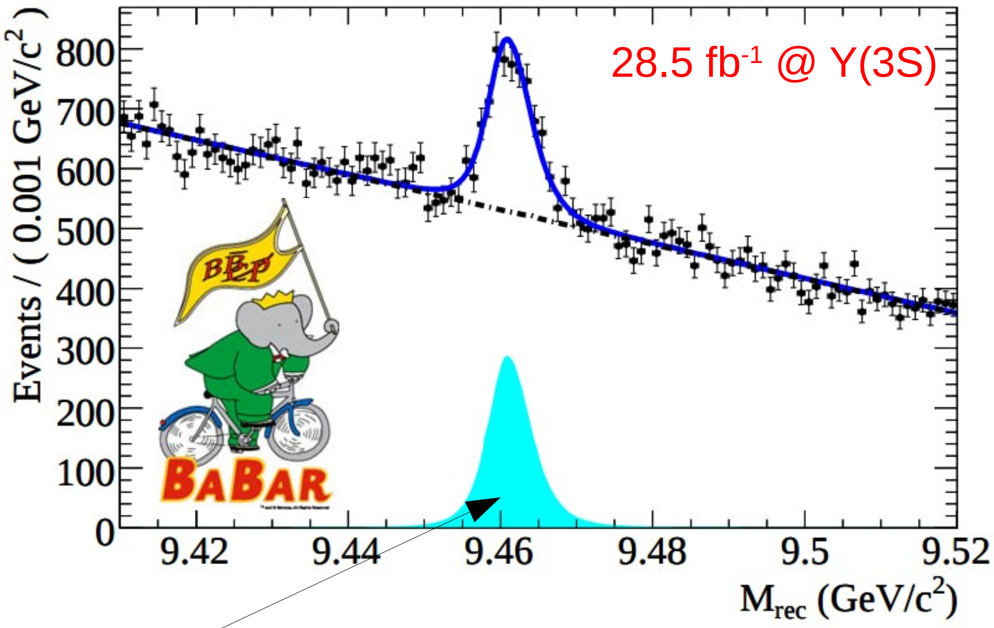
Invisible Y(1S) Decays: Signal or Background?

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

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

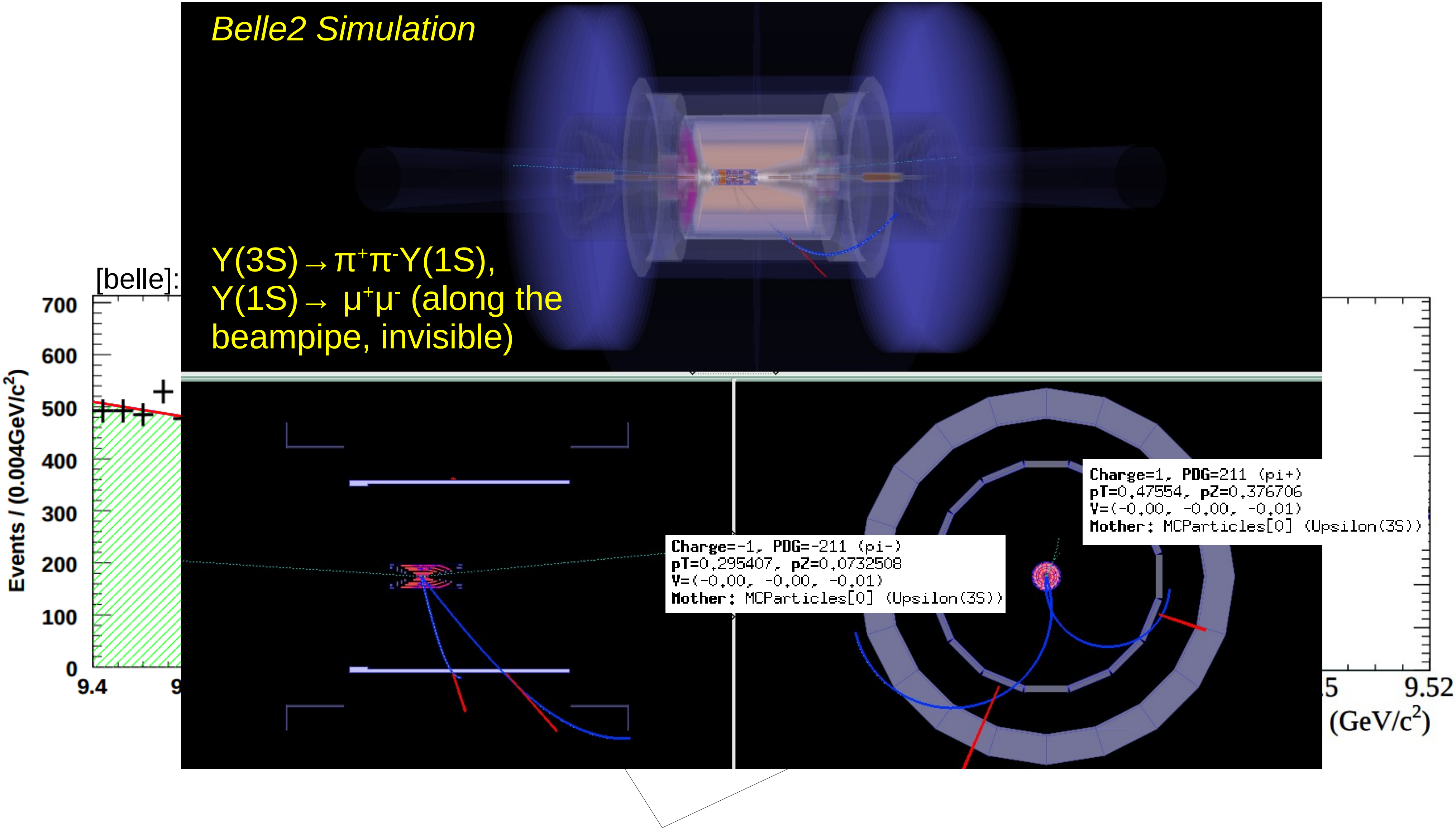


[babar]: http://arxiv.org/abs/0908.2840
(2 months running @ Y(3S))



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

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

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

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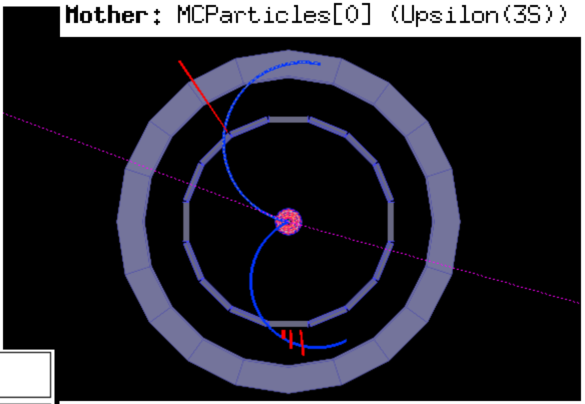
- Low mass dark matter particles however might might play a role in the decays of Υ(1S), having $\Upsilon(1S)\to\chi\chi$ if kinematic allowed. [Phys. Rev. D **80,** 115019, 2009]
- Also, new mediators (Z', A^0, h^0) or SUSY particles might enhance $\Upsilon(1S)\to\nu\nu(\gamma)$. [Phys. Rev. D **81**,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

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

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))

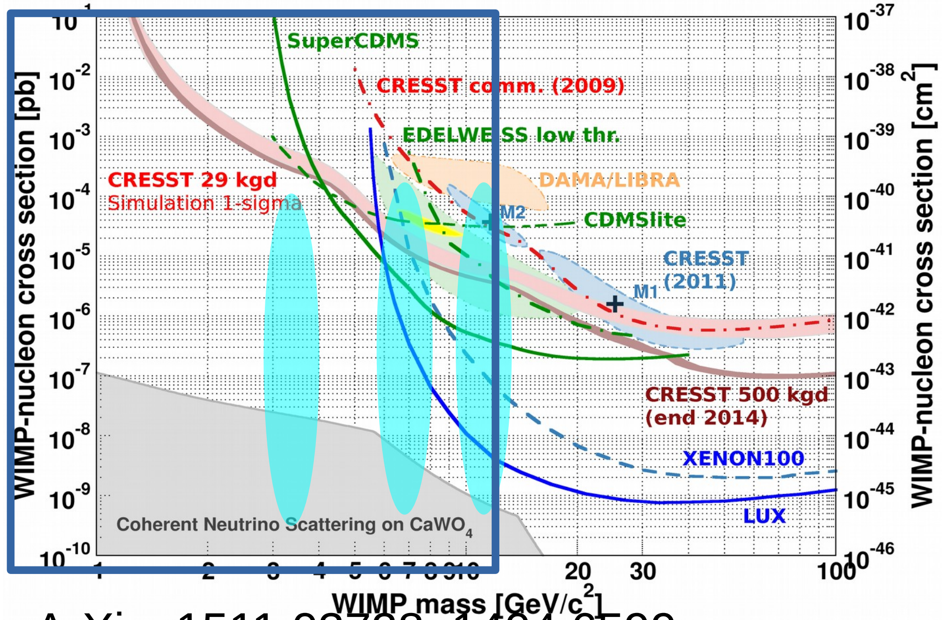
No signal was observed over the expected background and upper limits have been obtained: $BR(\Upsilon\to\nu\nu) < 3\times10^{-4}$ (BaBar) and $BR(\Upsilon\to\nu\nu) < 3.0\times10^{-3}$(Belle).

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

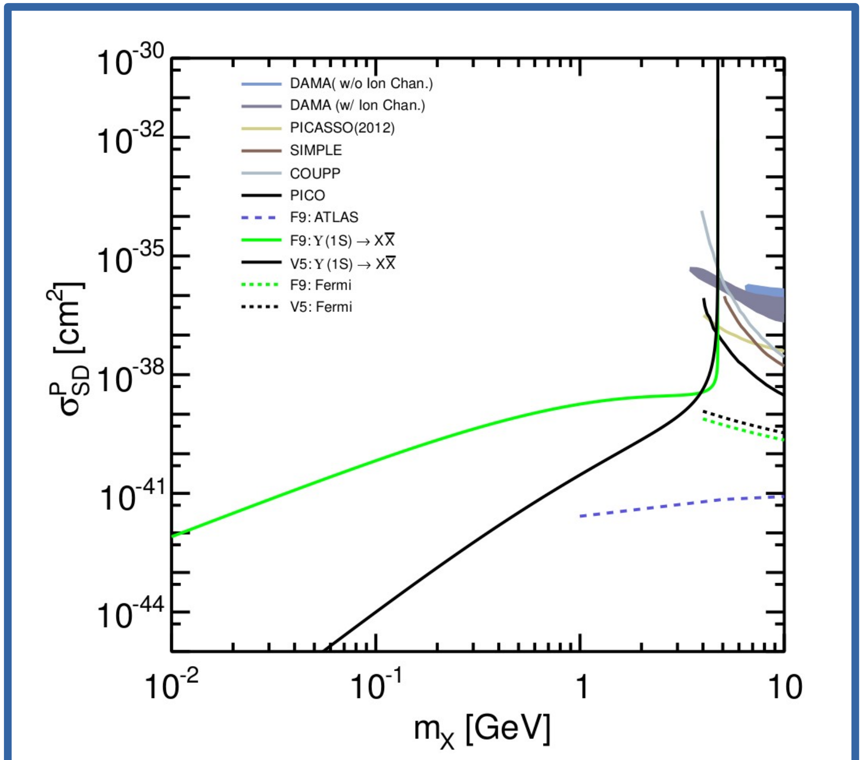
DM: The Synergy Between Theory, Direct and Collider Searches

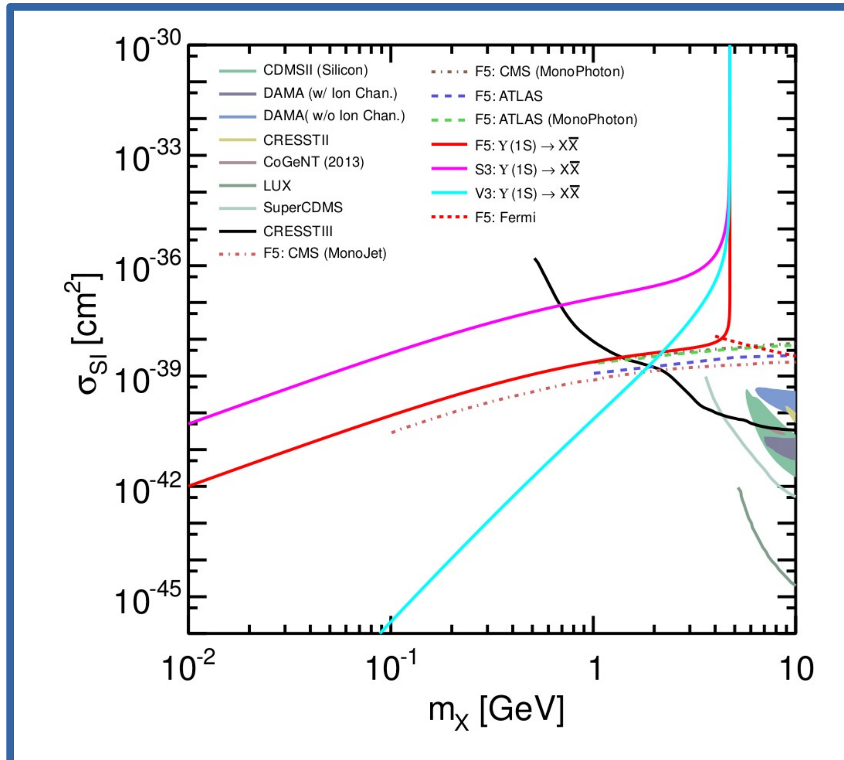
Theory work is needed in order to connect direct and indirect searches of dark matter.

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