Dark Sector Physics with *BABAR* and Belle II

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On behalf of
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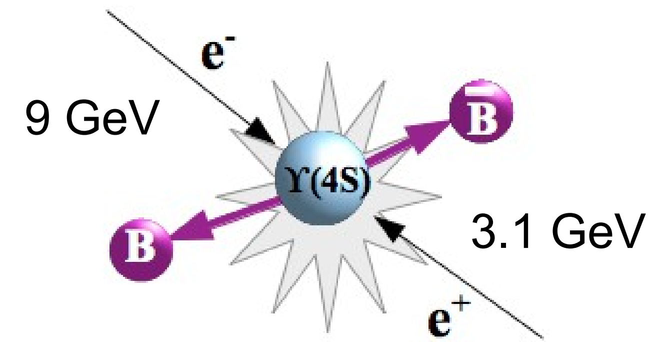
INSTITUTE OF PARTICLE PHYSICS

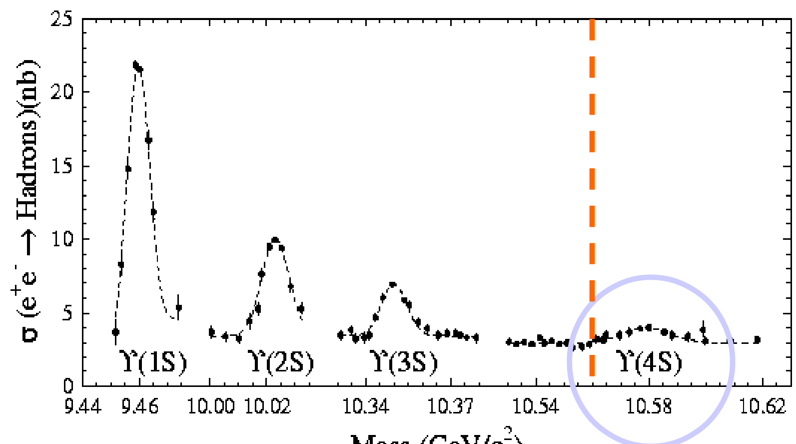
McGill

B Factories

B factories are e^+e^- colliders operating in the vicinity of the $\Upsilon(4S)$ resonance at ~10.5 GeV centre of mass energy



- Resonant production of $\Upsilon(4S) \rightarrow B\overline{B}$ along with continuum production of large samples of $e^+e^- \rightarrow l^+l^-$ ($l = e, \mu, \tau$) and $e^+e^- \rightarrow q\overline{q}$
- Asymmetric beam energies to create longitudinal boost of resulting $B\overline{B}$ mesons

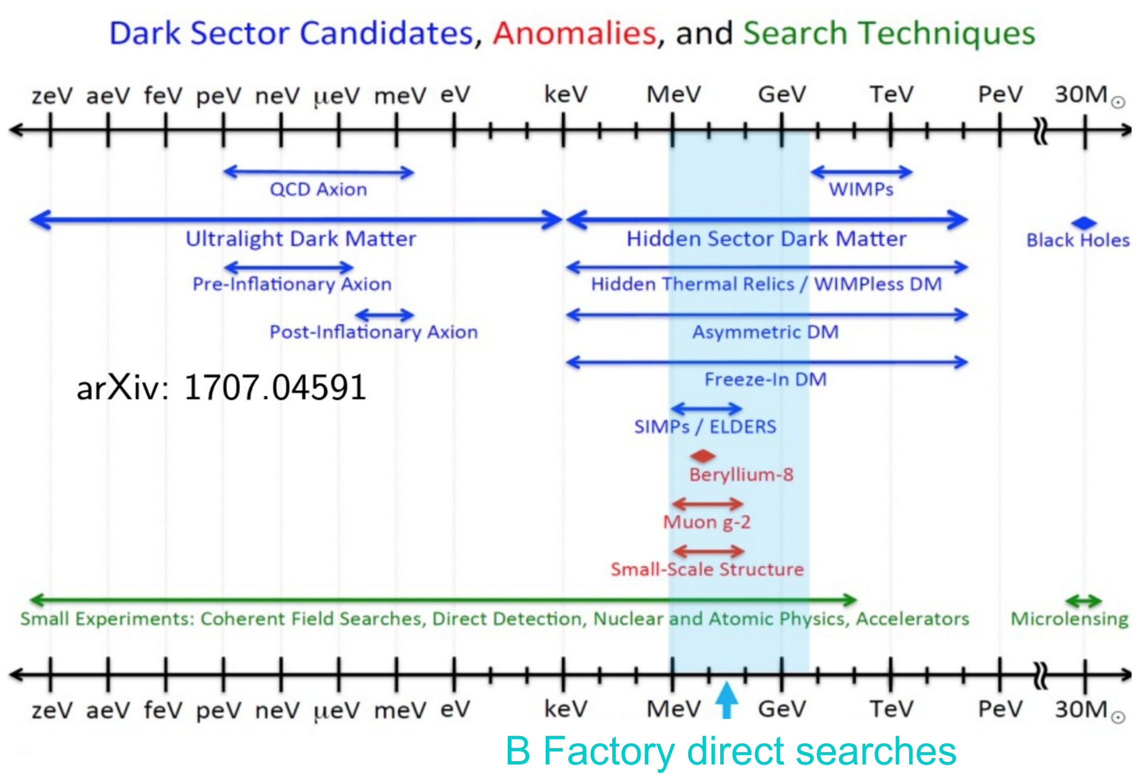


Process	σ (nb)
$b\overline{b}$	1.1
$c\overline{c}$	1.3
Light quark $q\overline{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Detectors optimized for B vertex separation and momentum measurement, K - π particle identification and precision calorimetry

Dark Sector @ B Factories

- Clean e^+e^- environment with hermetic (near 4π) detector coverage; good missing energy reconstruction
- Potential to reconstruct displaced vertices in $\sim 1\text{mm} < c\tau < \sim 10\text{cm}$ ($\sim 100\text{cm}$), with $c\tau > \sim 3\text{m}$ being "missing energy"
- Production of on-shell bosons via "radiative" $e^+e^- \to \gamma Z'$ and $e^+e^- \to f\bar{f}Z'$ "-strahlung" processes
- Inclusive trigger for (N_{tracks}>3) hadronic events, but low-multiplicity searches require dedicated triggers



Outline

BABAR searches:

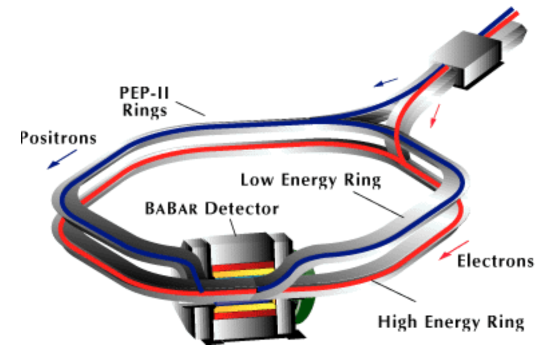
- Visible dark photon — Phys. Rev. Lett. 113, 201801 (2014)
- Invisible dark photon — Phys. Rev. Lett. 119, 131804 (2017)
- Muonic dark force $e^+e^- \to \mu^+\mu^- Z',\ Z' \to \mu^+\mu^-$ — Phys. Rev. D94 011102 (2016)

Belle II studies:

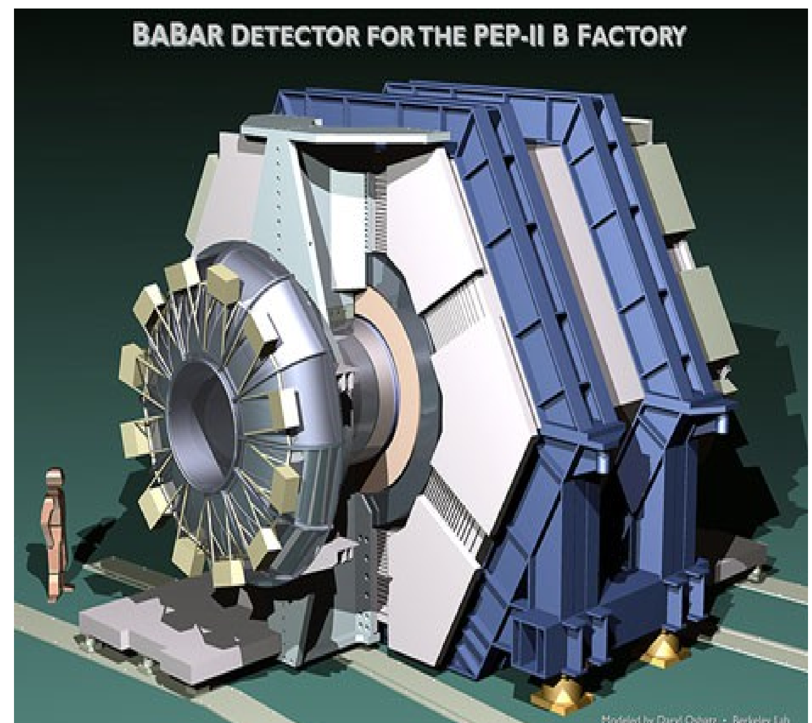
- Invisible Z' in $e^+e^- \to \mu^+\mu^- Z'$ — arXiv:1912.11276 [hep-ex] (submitted to PRL)
- Prospects for dark photon searches — arXiv:1808.10567 [hep-ex]
- ALP searches — JHEP 1712, 094 (2017)

BABAR

The BABAR experiment collected data from 1999 until 2008 at the SLAC PEP-II B factory



- 432 fb^{-1} $\Upsilon(4S)$ "on peak" (~470 x 10^{6} $B\bar{B}$ pairs)
- 53 fb^{-1} non-resonant "off peak"
- Smaller samples collected at the $\Upsilon(2S)$ and $\Upsilon(3S)$ energies
- A total of ~516 fb^{-1} potentially usable for dark sector searches



Unique BABAR data set remains of interest hence analysis activities are still ongoing

- Luminosity not yet superseded by Belle II

Dark photon

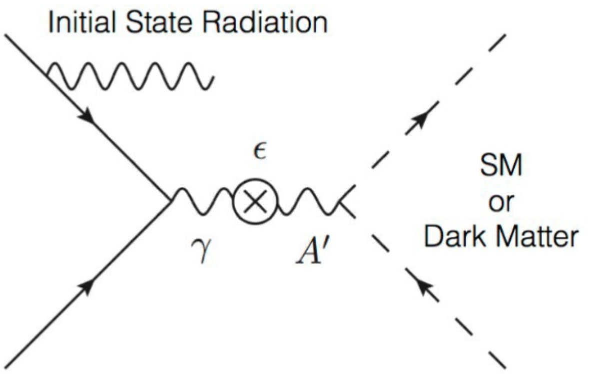
P. Fayet, Phys. Lett. B 95, 285 (1980)
P. Fayet Nucl. Phys. B 187, 184 (1981)
B. Holdom, Phys. Lett. B 166, 196 (1986)

Simplest dark sector scenario: add a new U(1) gauge symmetry, with associated charge carried by dark-sector fermions

- Spin-1 gauge boson "dark photon" A' (or γ_d, or Z_d in non-minimal models) can mix with SM photon, providing a "portal" to the dark sector.

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

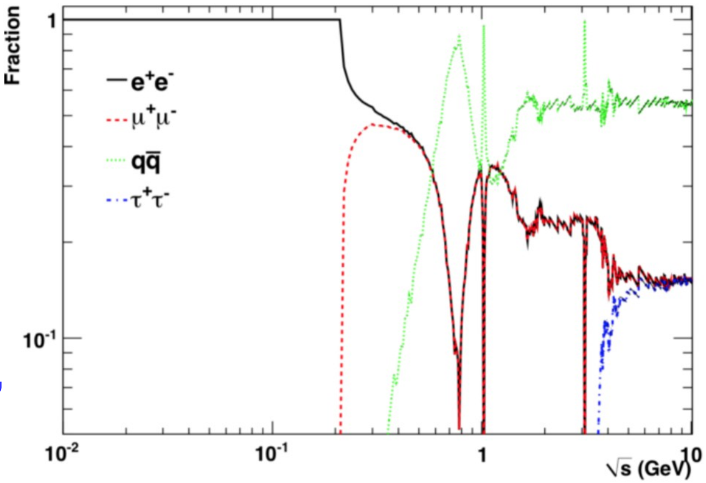
ϵ is the strength of the kinetic mixing



- ϵ could be as large as 10^{-2} for $m_{A'}$ in the GeV range

Lifetime: $\tau_{A'} \sim 1/(\epsilon^2 m_{A'})$

- Decays can either be "prompt" (relative to experimental resolution) or "displaced" (relative to production vertex)
- Decays to SM particles depend on kinematic accessibility, and details of model

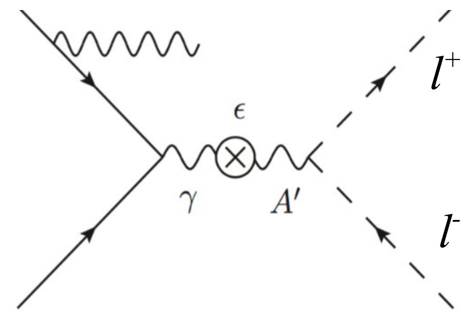


... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

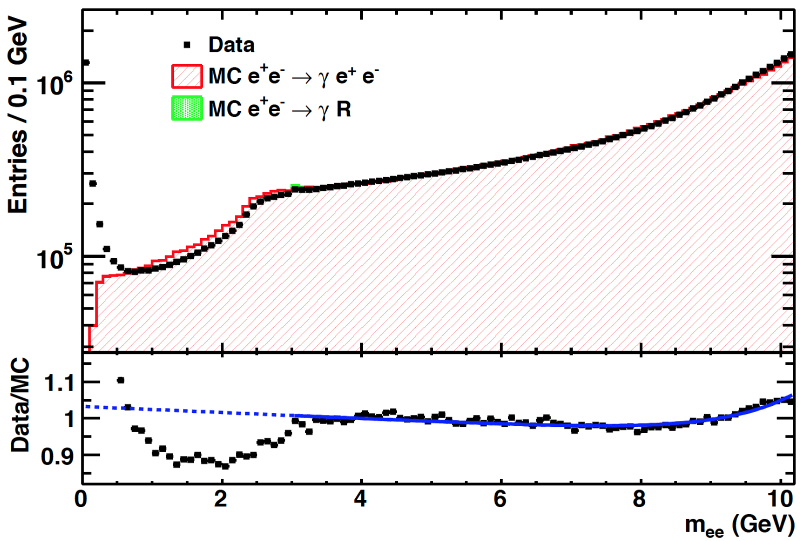
Visible dark photon decays

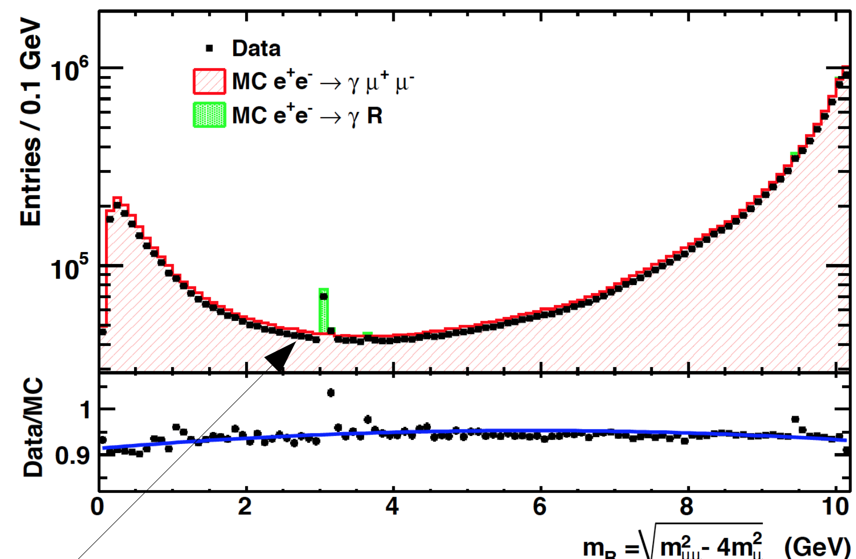
Phys. Rev. Lett. 113, 201801 (2014)
arXiv:1406.2980 [hep-ex]

BABAR search for $e^+e^- \rightarrow \gamma A'$ with $A' \rightarrow l^+l^-$ ($l = e, \mu$) using 516 fb^{-1} of data



- "Continuum" production, so can use all available CM energy data
- Dark photon width well below detector resolution hence use simulation templates to model signal





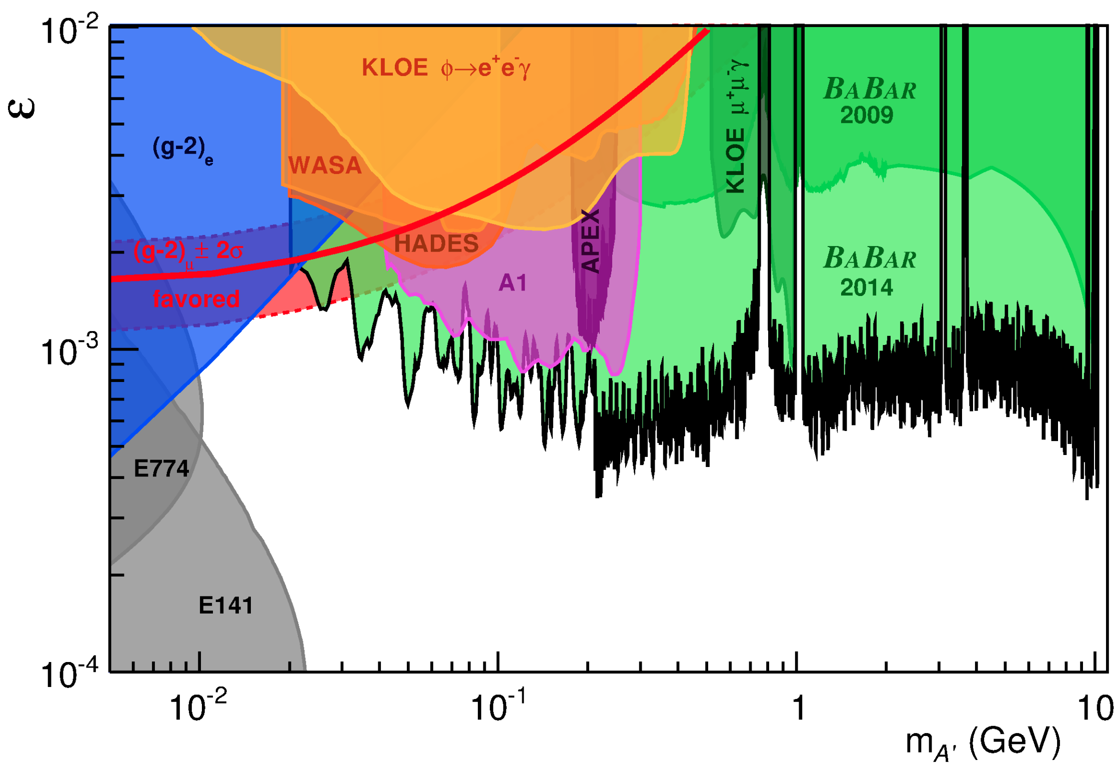
- Require photon energy >200 MeV
- Resonant backgrounds from J/ψ, $\psi(2S)$ etc but otherwise smoothly varying background, i.e. low reliance on simulation

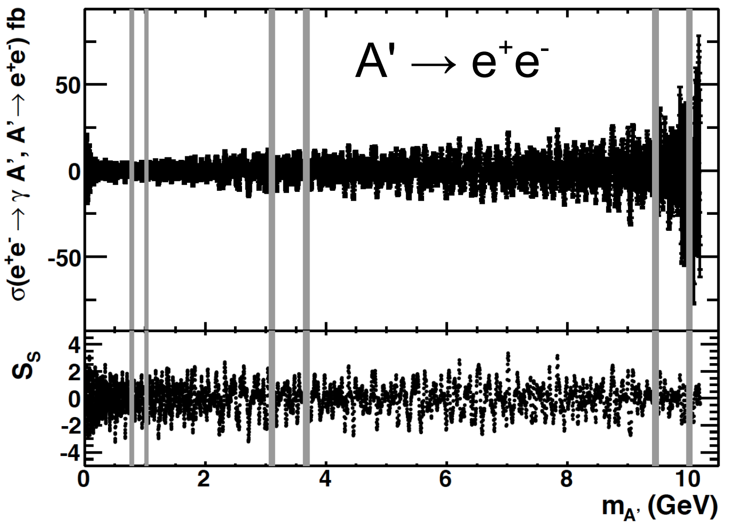
Visible dark photon decays

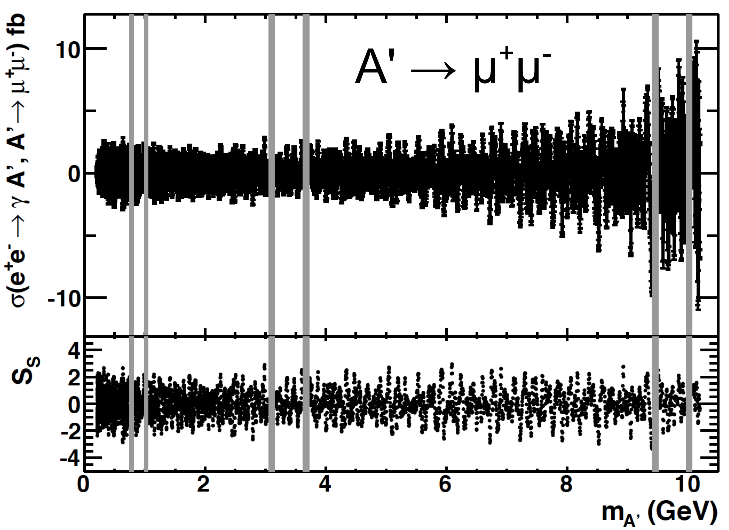
Phys. Rev. Lett. 113, 201801 (2014)
arXiv:1406.2980 [hep-ex]

Scan di-lepton invariant mass in the range
$0.02\ \text{GeV} < m_{A'} < 10.2\ \text{GeV}$

- Obtain 90% C.L. upper limit on mixing strength ε as a function of A' mass at level of $O(10^{-3})$





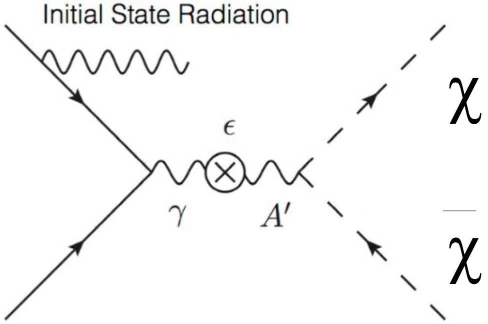


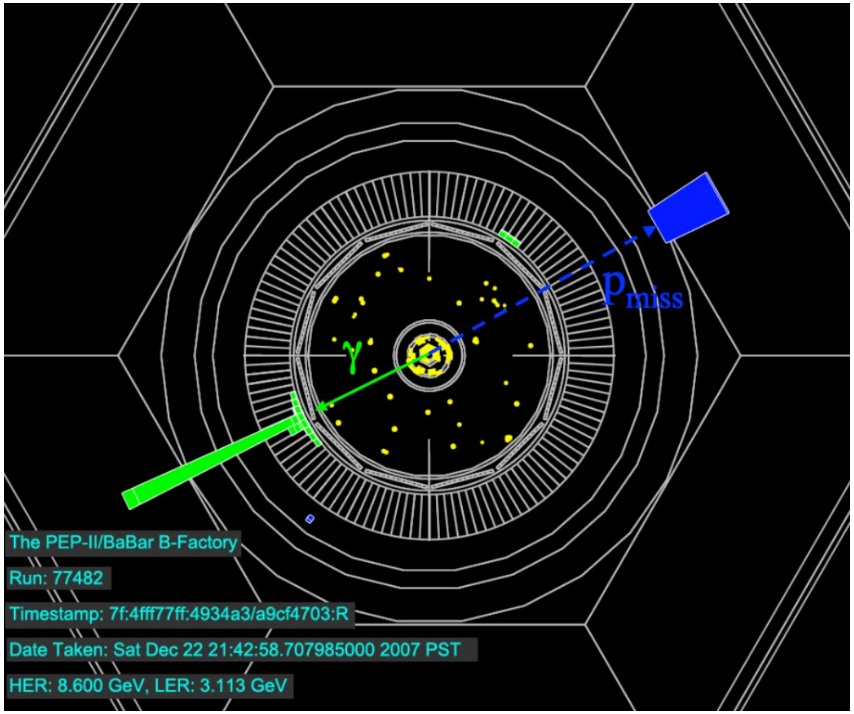
Invisible dark photon decays

Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

B Factories provide an excellent environment for missing energy searches

- Precisely known e^+e^- initial state
- Hermetic detector and good missing energy reconstruction





Search for invisible decay of $A' \to \chi\bar{\chi}$ via $e^+e^- \to \gamma A'$

- Final state contains only a single isolated photon in the detector
- A' mass determined from photon energy and CM energy:

$$E^*_\gamma = E^*_{beam} - \frac{m^2_{A'}}{4E^*_{beam}}$$

Invisible dark photon decays

B factories generally rely on "open trigger" targeting higher-multiplicity $B\bar{B}$ hadronic decay events

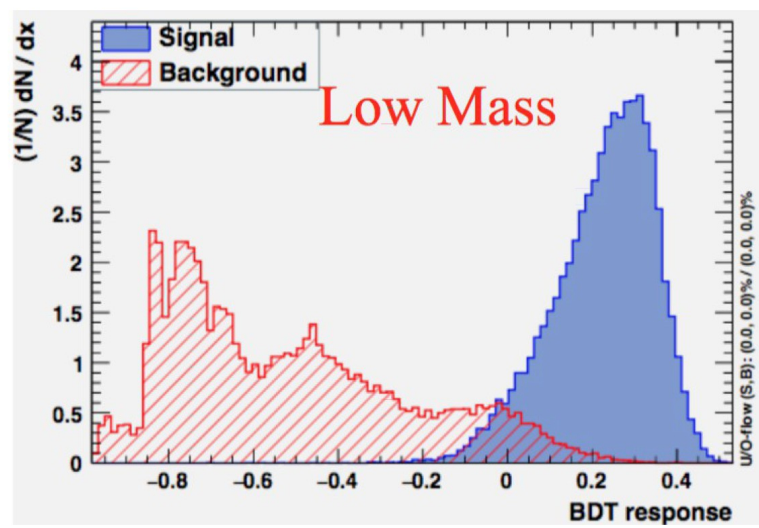
- Dedicated single photon trigger implemented during final running period (53 fb^{-1})
  - L1 (hardware) : 1 or more clusters with E_{lab} > 0.8 GeV
  - L3 (software): Two trigger lines: $E\gamma^*$ > 2 GeV or $E\gamma^*$ > 1 GeV and track veto

Backgrounds are from $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow e^+e^- \gamma$ events with undetected particles

- Offline selection aims to suppress events containing additional detector activity

BDT:
- Signal cluster shape parameters
- Additional calorimeter energy
- Properties of the second most energetic cluster: E^*, θ^*, $\Delta\Phi^*$
- Properties of muon system cluster (E^*, θ^*, $\Delta\Phi^*$) closest to the missing momentum direction

Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

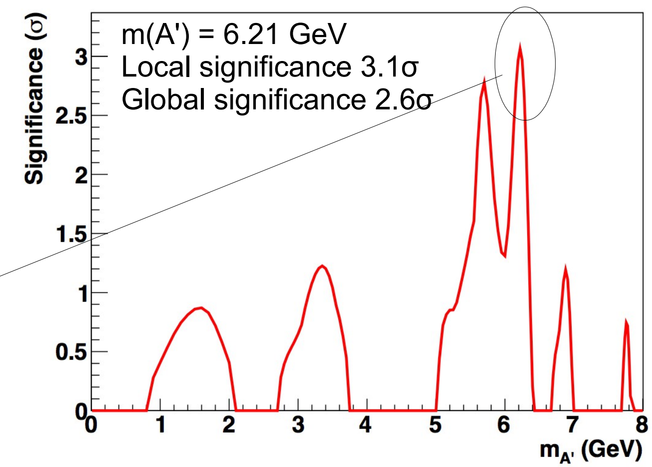


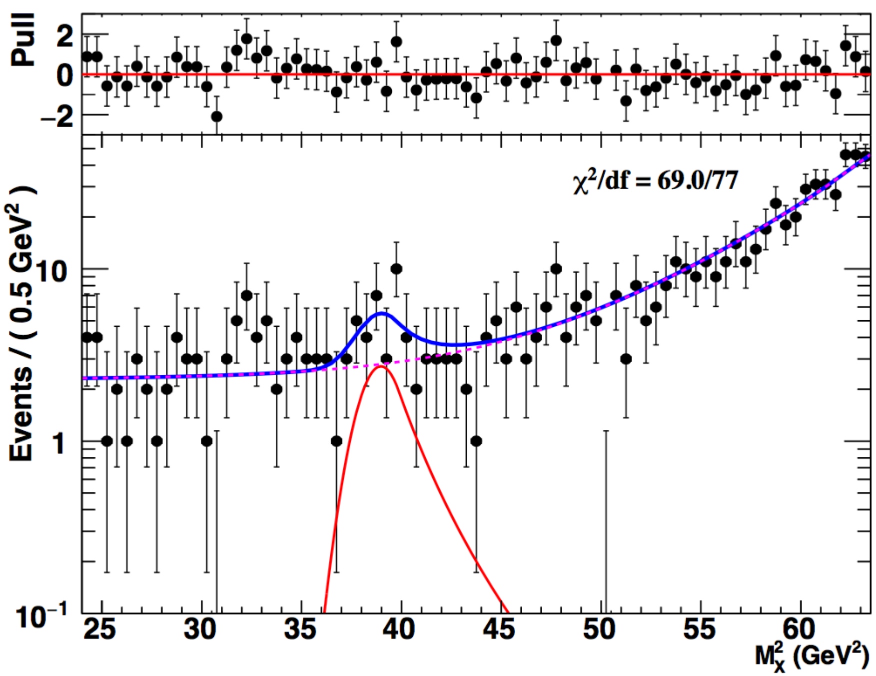
Invisible dark photon decays

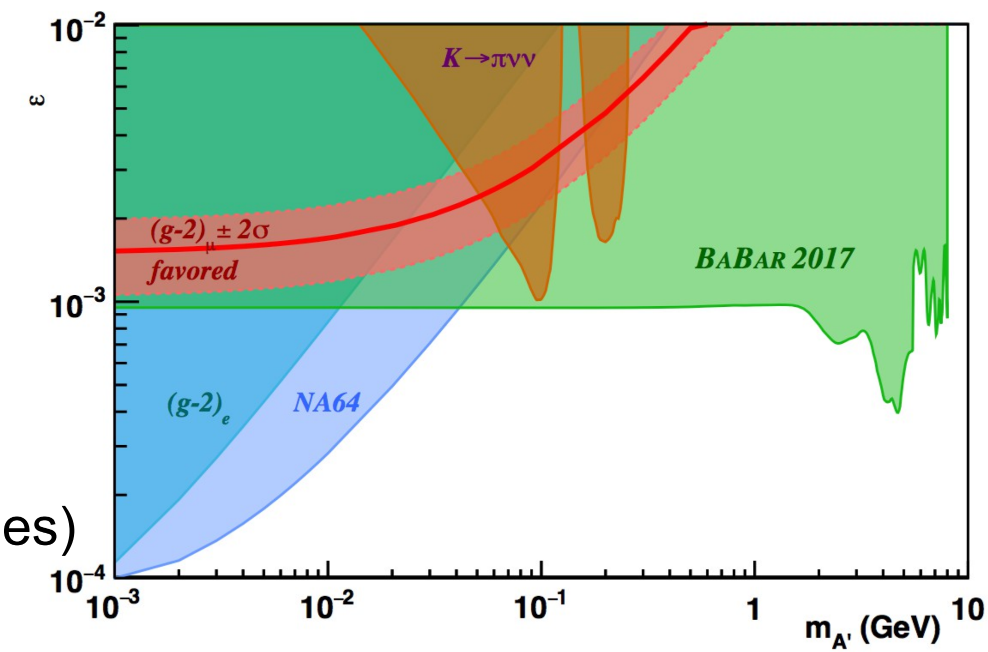
Phys.Rev.Lett. 119, 131804 (2017)
arXiv:1702.03327 [hep-ex]

Signal yield extracted from fits to the photon recoil mass

- Mass resolution driven by calorimeter resolution
- Background ultimately limited by detector hermeticity







No evidence of signal (116 mass hypotheses)

- Set limits on ε as a function of A' mass

Muonic dark force

Phys. Rev. D94 011102 (2016)
arXiv:1606.03501 [hep-ex]

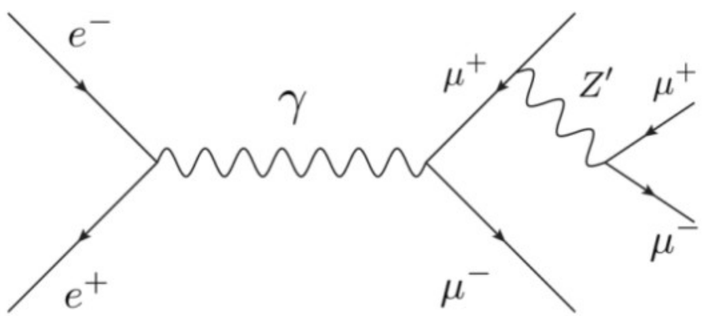
Non-minimal dark sector models can permit additional interactions between dark boson and SM particles

- Dark boson Z' which couples only to second and third generation leptons (SM fields are directly charged under dark force)

Motivated by various anomalies in the muon sector

He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991).
B. Batell, D. McKeen and M. Pospelov, Phys. Rev. Lett. B.107, 011803 (2011).

- g-2 discrepancy
- could also account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.



However, no model assumptions in analysis; results are more generally applicable

"Z'-strahlung" production of Z' in $e^+e^- \to \mu^+\mu^-$

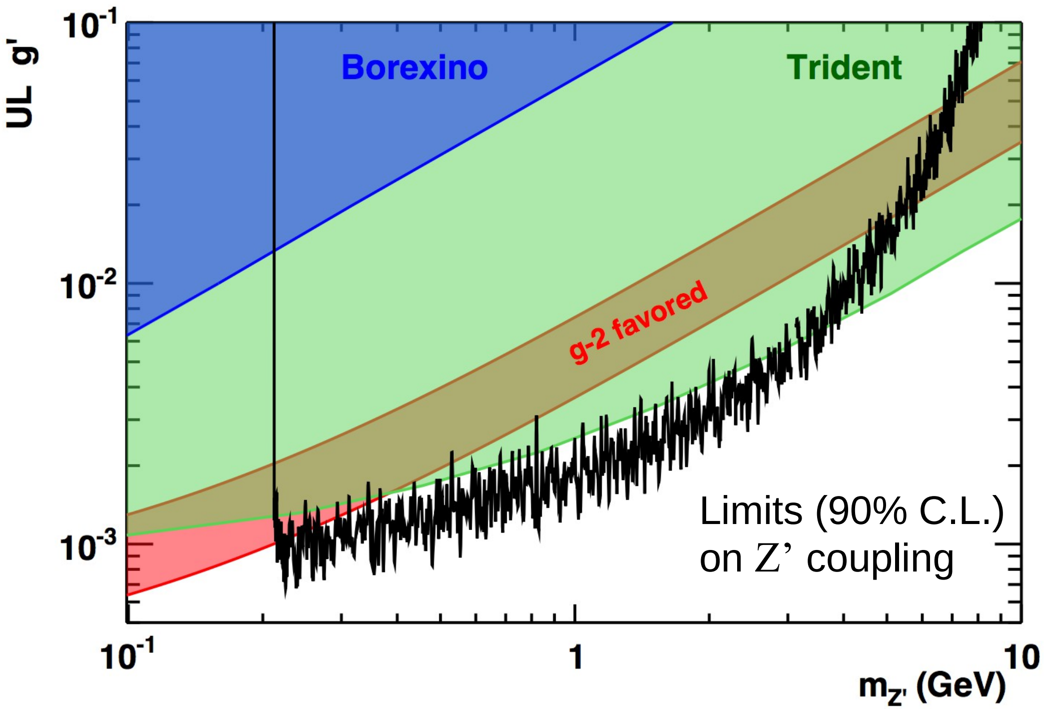
$$e^+e^- \to \mu^+\mu^- Z' , \; Z' \to \mu^+\mu^-$$

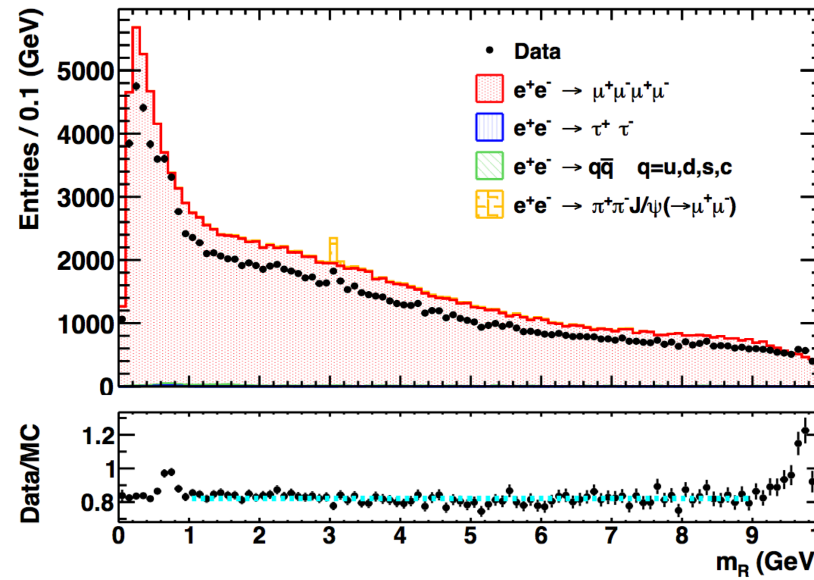
Muonic dark force

Phys. Rev. D94 011102 (2016)
arXiv:1606.03501 [hep-ex]

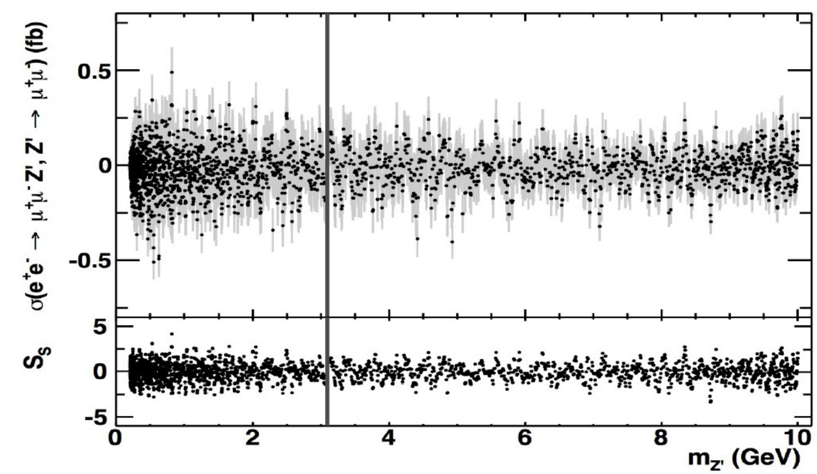
Search for a di-muon mass peak in
$e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

- QED combinatorial backgrounds, as well as peaking backgrounds from $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ and ρ, but very little reliance on MC
- No signal observed; cross section limits obtained at 90% C.L. at level of ~0.2 fb below $m_{Z'}$ of 10 GeV





Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_\mu^2)^{1/2}$



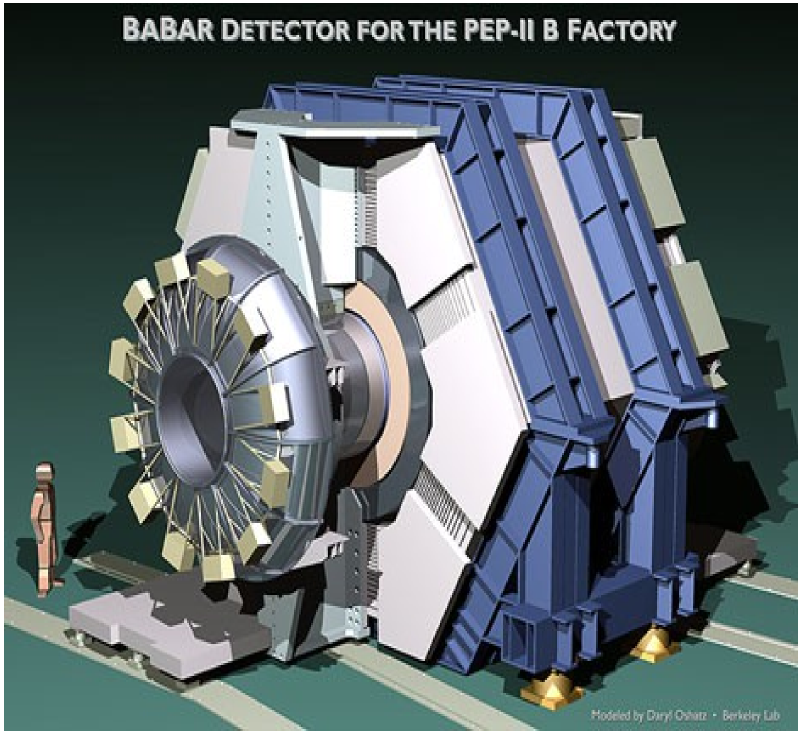
First direct experimental limits on Z' coupling; excludes most of region favoured by g-2 results

BABAR prospects

BABAR (still) has a unique and competitive data set available for for dark sector studies

- A number of analyses are still in progress, and new ideas are still being considered

Stay tuned...



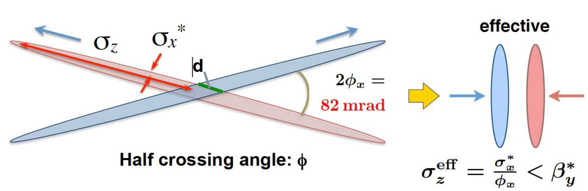
Belle II

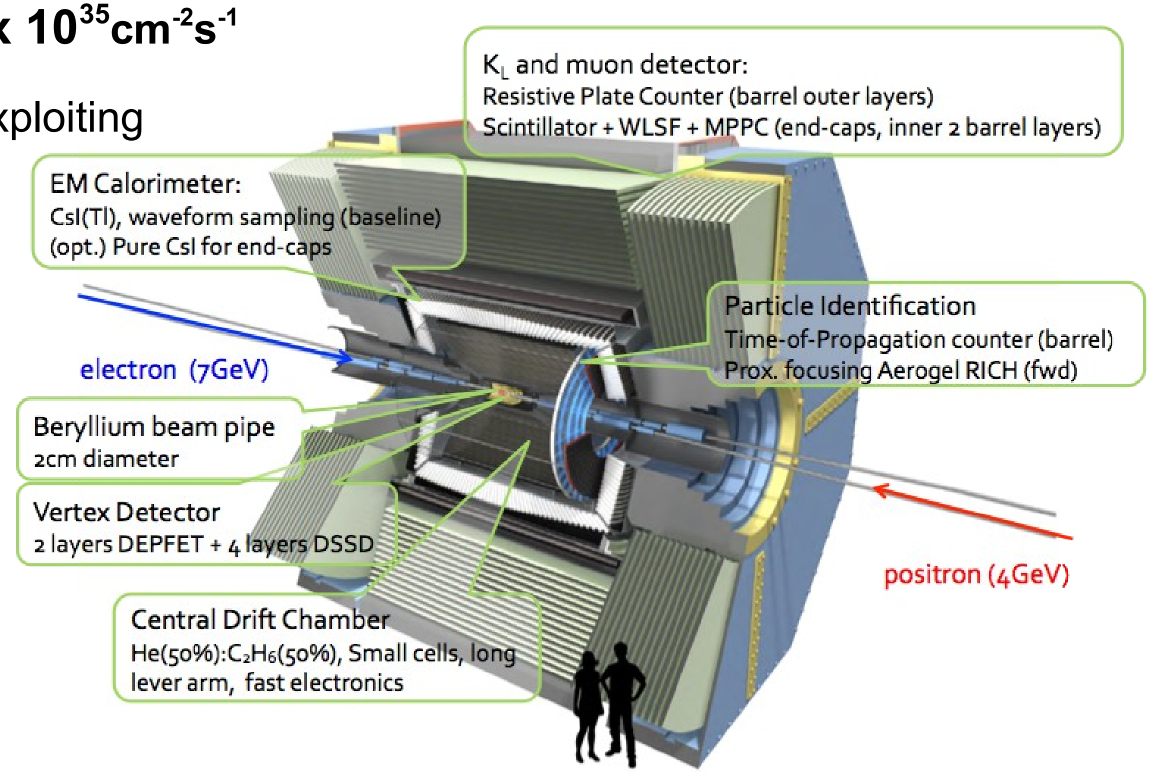
Belle II is the successor of the Belle experiment at the KEK laboratory in Tsukuba, Japan

- Intensity frontier “Super B Factory” flavour physics experiment
- Target data set of ~30x the combined integrated luminosity of BABAR + Belle
- ~800 collaborators from 26 countries, including over 260 graduate students

4 GeV on 7 GeV e^+e^- collisions at $8 \times 10^{35} cm^{-2}s^{-1}$

- Low-emittance “nanobeam” scheme exploiting ILC and light-source technologies
- Crossing angle at IP





Belle II

Experiment commissioning in three phases:

- First colliding beam data recorded (without vertex detectors) in spring 2018 "Phase 2"; 0.5 fb^{-1} recorded
- Vertex detectors installed for Phase 3 during 2019; more than 10 fb^{-1} of data recorded to date
- Run continuing until summer 2020; anticipating ~ 50 – 100 fb^{-1}

Focus is on commissioning of the SuperKEKB accelerator and Belle II detector rather than integration of luminosity

Benchmark Belle II performance based on detector simulation

- In some cases, competitive sensitivity even with very early data...
- Focus on low-hanging-fruit, accessible with modest luminosity
- Developments of dedicated low multiplicity triggers

Publications:

The Belle II Physics Book, Belle-II Collaboration (E. Kou et al.), arXiv:1808.10567 [hep-ex]

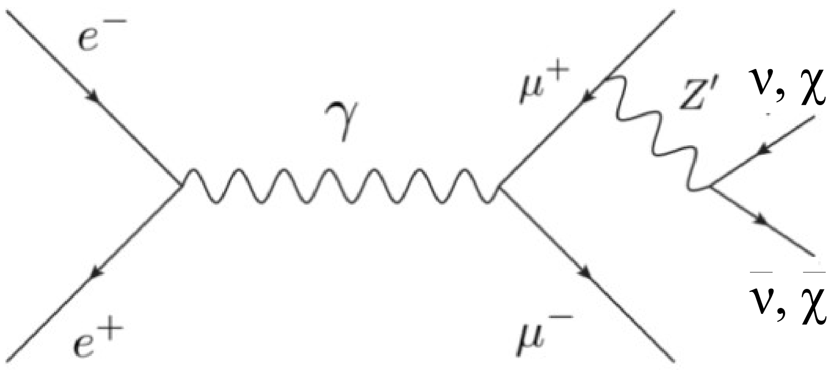
Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment, Belle-II Collaboration (F. Abudinén et al.). arXiv:1910.05365 [hep-ex]

Search for an invisibly decaying Z' boson at Belle II in $e^+e^- \to \mu^+\mu^- (\mu^+e^-)$ plus missing energy final states, Belle-II Collaboration (I. Adachi et al.), arXiv:1912.11276 [hep-ex]

Invisible Z'

Search for invisibly decaying Z' in $e^+e^- \rightarrow \mu^+\mu^- Z'$

- Z' arises from gauging of difference of leptonic μ and τ number $L_\mu - L_\tau$
- Z' couples to SM only through μ and τ and their associated neutrinos with coupling constant g'



B. Shuve and I. Yavin, Phys. Rev. D 89, 113004 (2014).
W. Altmannshofer, S. Gori, S. Profumo, and F. S. Queiroz, JHEP 12, 106 (2016).

Z' is produced via radiation off of a final state μ

- If $m_{Z'} < 2m_\mu$ then Z' decays to neutrinos
- Alternatively, expect $B(Z' \rightarrow \chi\bar{\chi})$ ~ 100% if direct decays are possible

Consider also the LFV scenario of $e^+e^- \rightarrow e^+\mu^- Z'$

- Identical search methodology, but with PID criteria changed for one of the two leptons

I. Galon and J. Zupan, JHEP 05, 083 (2017).
I. Galon, A. Kwa, and P. Tanedo, JHEP 03, 064 (2017).

Invisible Z'

Experimental signature is a $\mu^+\mu^-$ pair (or $e^+\mu^-$ pair in LFV scenario) with a peak in the missing mass

- Backgrounds originate from QED processes which mimic the $\mu^+\mu^-$ + missing energy final state, typically due to detector acceptance

Background sources:

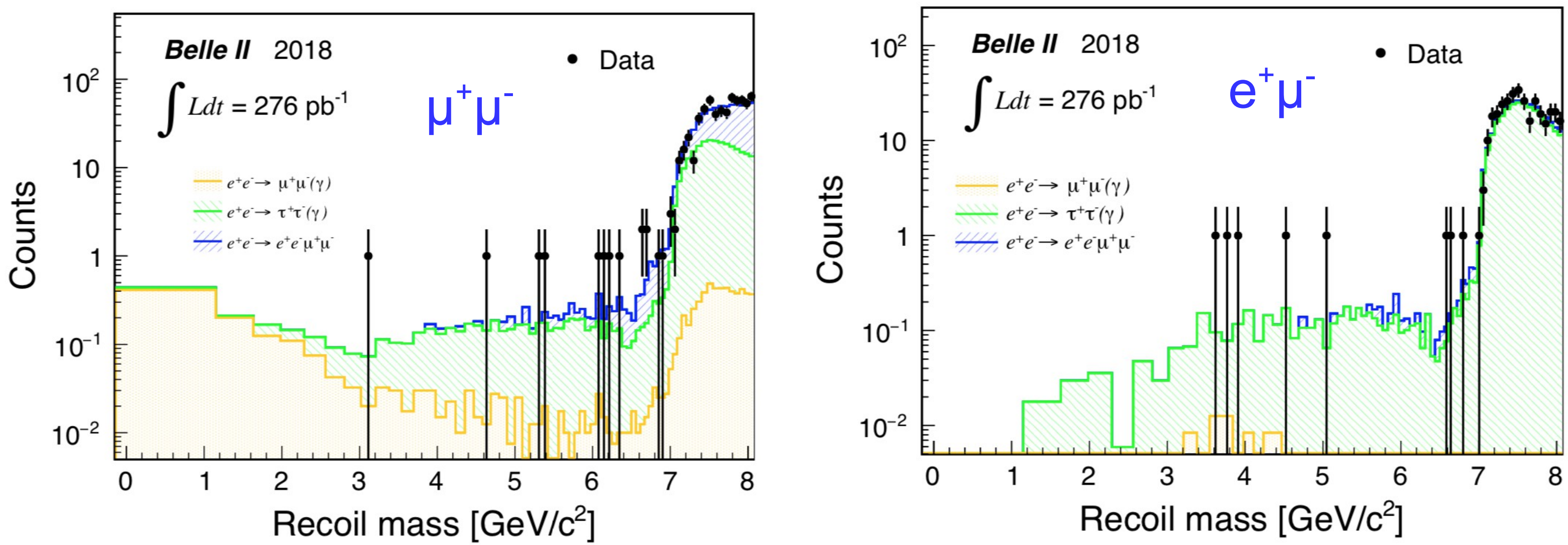
$e^+e^- \rightarrow \mu^+\mu^- \gamma(\gamma)$	undetected photon(s)
$e^+e^- \rightarrow \tau^+\tau^- \ (\gamma)$	muonic τ decays and mis-ID
$e^+e^- \rightarrow \mu^+\mu^- e^+e^-$	missing e^+e^-

276 pb^{-1} of good-quality data from 2018 “Phase 2” commissioning running

- Require p_{miss} to point into calorimeter barrel region
- Calorimeter-based particle identification (E/p)
- Reject events with additional energy E >0.4 GeV or any π^0 candidates
- Exploit kinematics to reduce $\tau^+\tau^-$ backgrounds

Signal extracted in 69 mass windows spanning the range
$m_{Z'} = 0.5 - 8\ \mathrm{GeV}/c^2$

- Each window defined to be ±2σ of the expected signal width at that mass



- No yield exceeds 3σ local significance in either nominal or LFV search

Invisible Z'

arXiv:1912.11276 [hep-ex]
(submitted to PRL)

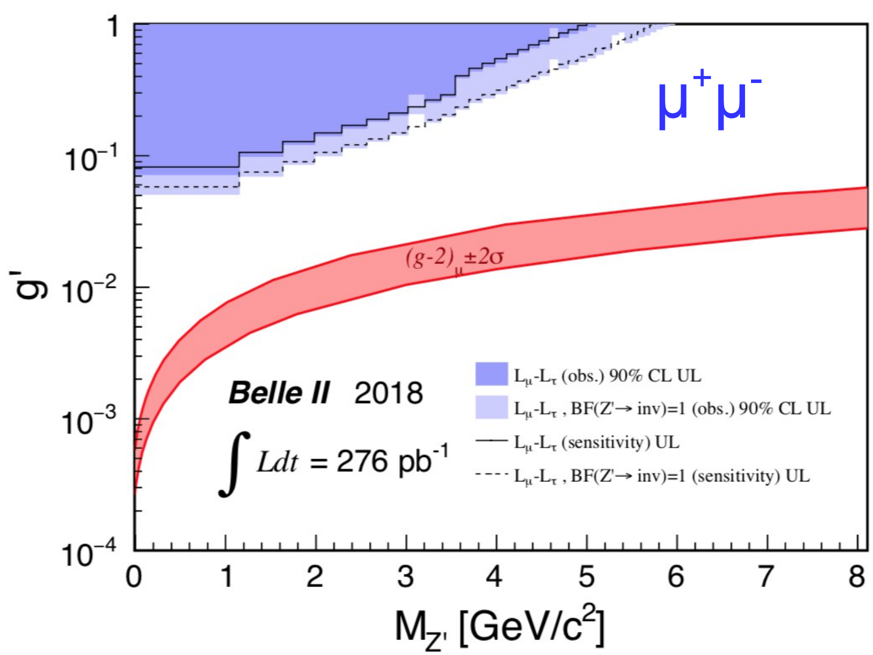
Systematics evaluated by comparison of data control samples to simulation

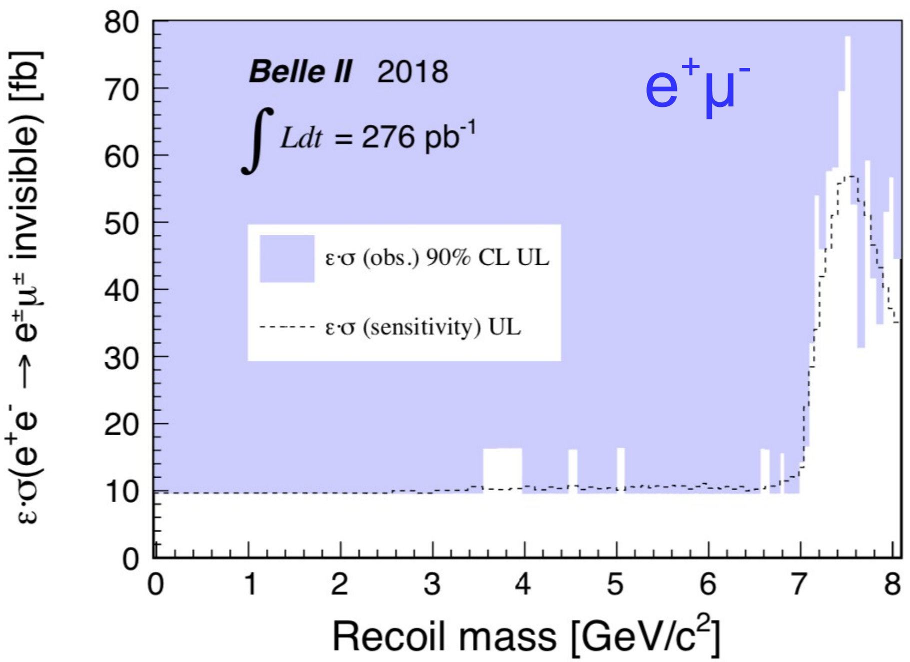
- Dominated by MC modelling of $\mu^+\mu^-$ yield in data

Source	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiency	6%	1%
Tracking efficiency	4%	4%
PID	4%	4%
Luminosity	0.7%	0.7%
τ suppression (background)	22%	22%
Background before τ suppression	2%	2%
Discrepancy in $\mu\mu$ yield (signal)	12.5%	-

Cross section limits on $e^+e^- \to \mu^+\mu^- Z'$ and $e^+\mu^- Z'$ for invisible Z' decays

- Interpreted as limit on coupling g' in context of $Z' \to \chi\bar{\chi}$





Invisible Dark Photon

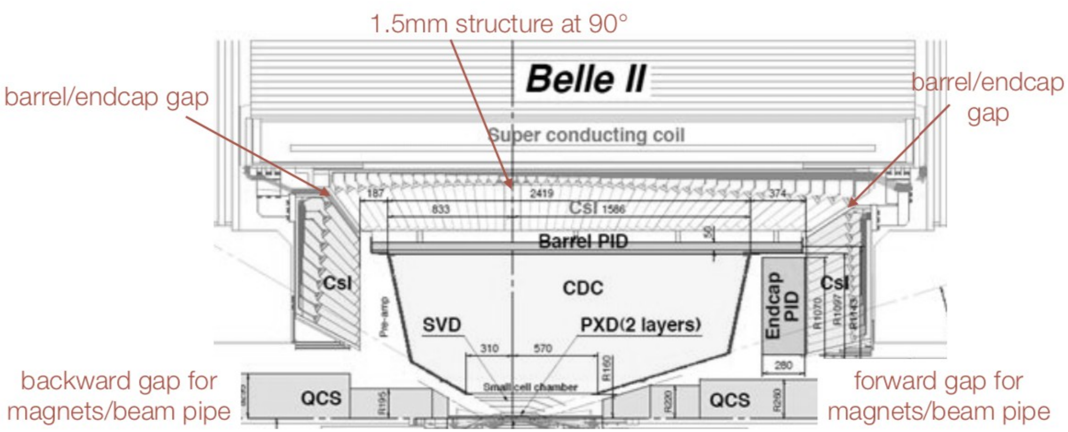
BABAR limits on VISIBLE dark photon based on 514 fb^{-1}

- Beyond reach of Belle II in 2020

However, INVISIBLE dark photon result only used 53 fb^{-1}

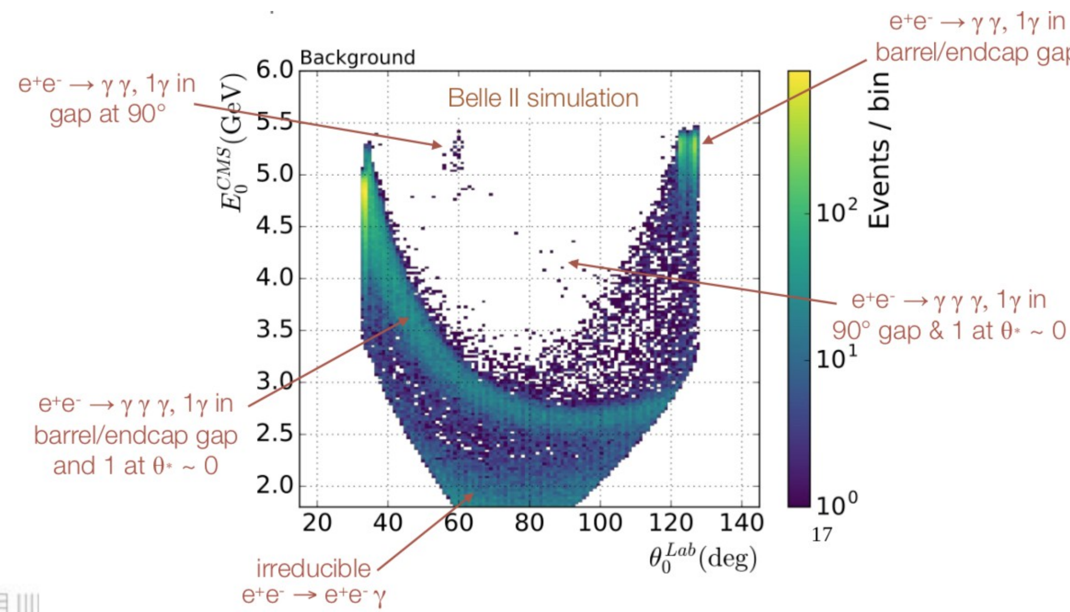
- Signal signature is a single photon; look for a peak in the recoil mass distribution:

$$E_\gamma = (s - m^2_{A'})/2\sqrt{s}$$



-0.94 < cosθ* < 0.96 Belle II
-0.92 < cosθ* < 0.89 BABAR

Backgrounds arise from QED sources with undetected particles; calorimeter hermeticity is the limiting factor:



Belle II has several advantages relative to BABAR analysis:

- Non-pointing cracks between crystals
- Greater solid-angle coverage (end caps and lower boost)
- Muon system can be used to detect particles missed by the calorimeter

Invisible Dark Photon

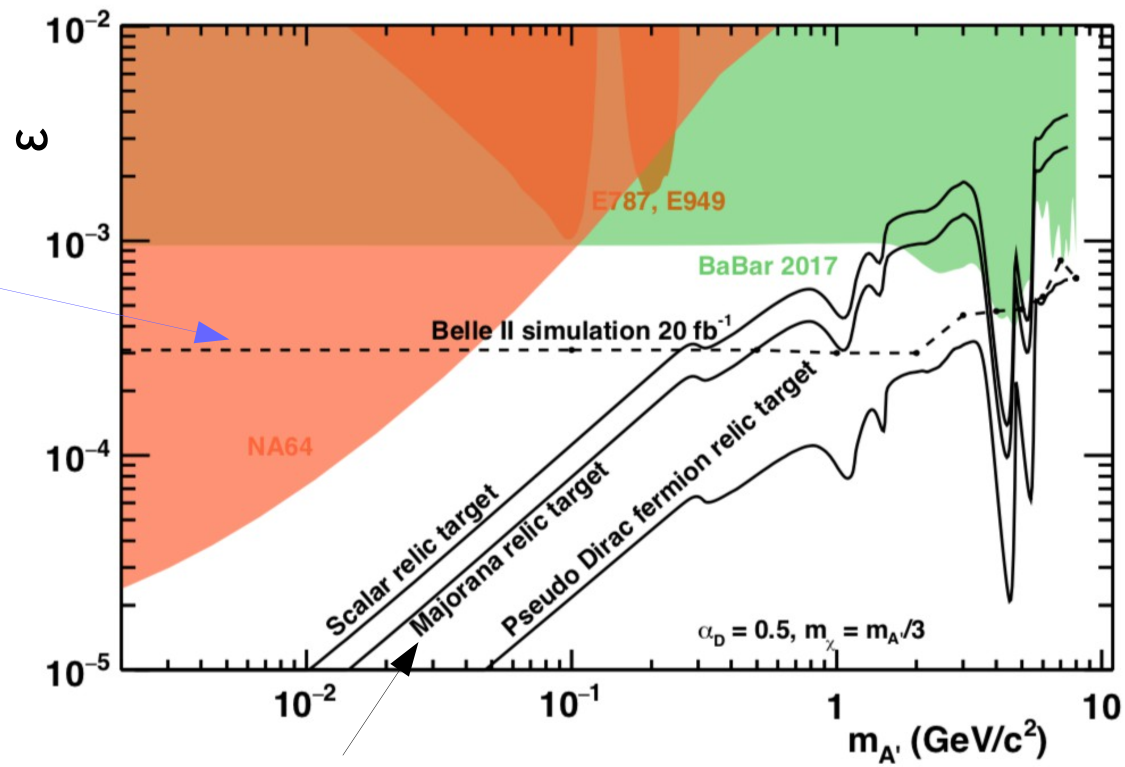
- Dedicated L1 trigger lines for more efficient candidate selection

Single photon trigger:
E_γ > 1GeV (veto events with additional clusters above 300 MeV)
E_γ > 2GeV (Bhabha and $\gamma\gamma$ vetos)

Invisible dark photon search anticipated to be competitive with relatively little data

- Studies still in progress; systematics still to be determined

Belle II projection (20 fb^{-1})
KEK-2018-27,
arXiv:1808.10567 [hep-ex]

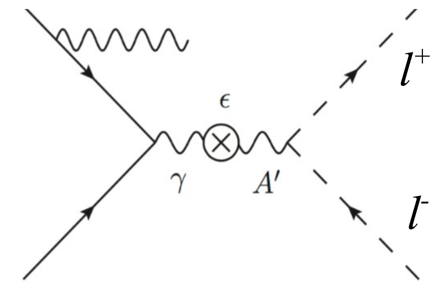


Astronomical dark matter predictions

Derived from E. Izaguirre, G. Krnjaic, P. Schuster, N. Toro, Phys. Rev. Lett. 115, 251301 (2015)

Visible Dark Photon

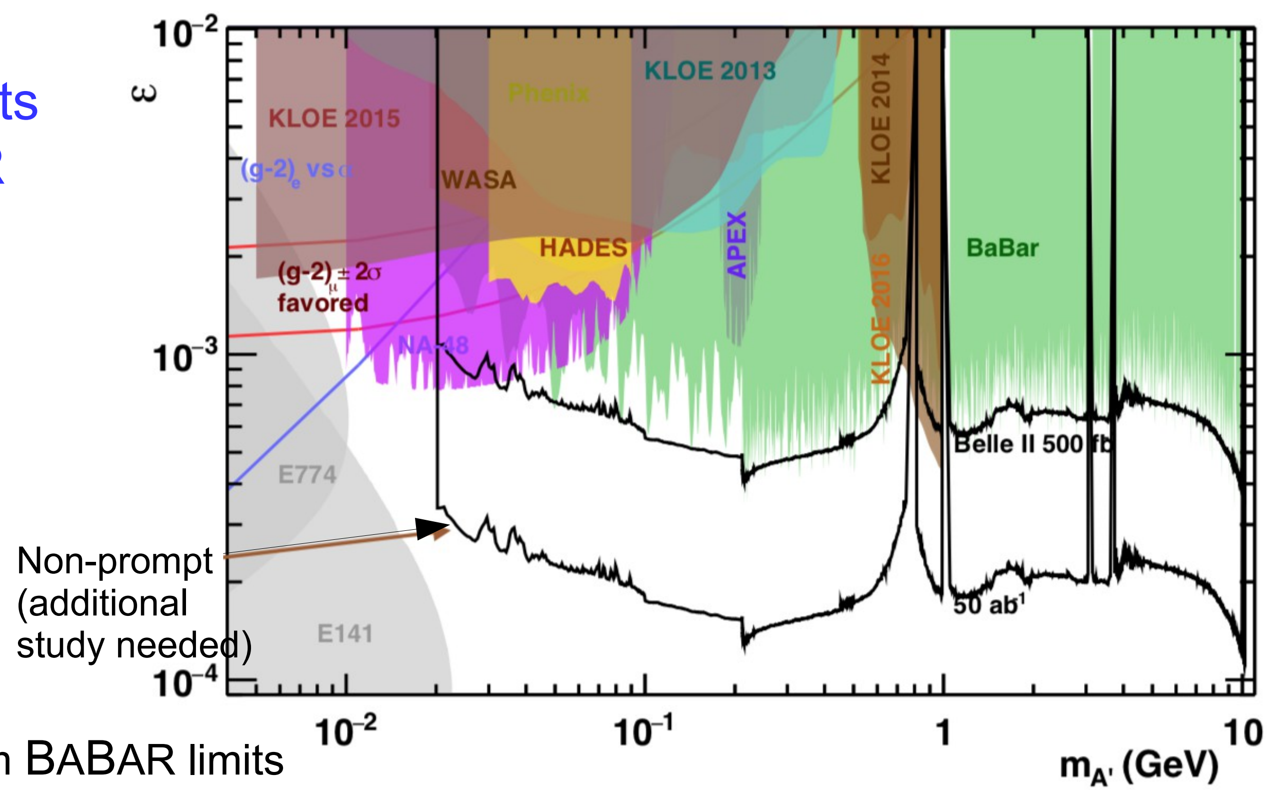
BABAR limits based on > 500 fb^{-1}; Belle II will require comparable data set to be competitive



- Final state is a photon, plus a lepton (or hadron) pair
- A' mass determined directly from decay daughters (not photon)
- Large SM backgrounds (particularly in electron mode); $\mu\mu\gamma$ is most sensitive mode above kinematic threshold

Some modest improvements possible relative to BABAR analysis:

- Trigger efficiency
- Improved mass resolution (better tracking/vertexing resolution of detector



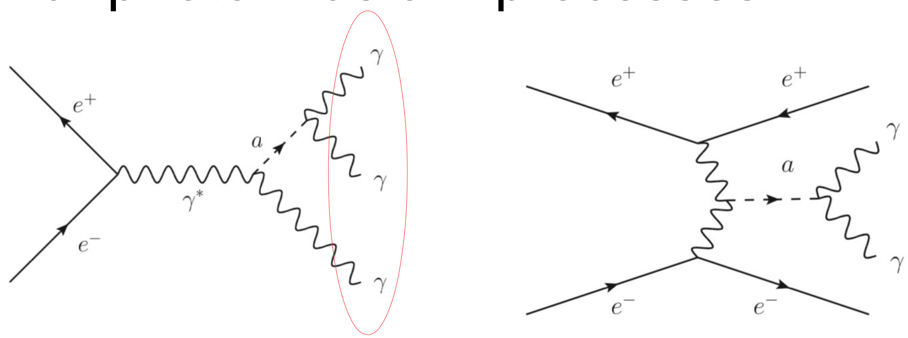
Projections based on scaling from BABAR limits

Axion-Like Particles

ALPs are pseudo-scalar particles that couple to bosons

- Unlike QCD axions, there is no specific relationship between coupling and mass

Consider case of coupling to photon. Production via “ALP-strahlung” and “photon fusion” processes



3γ final state

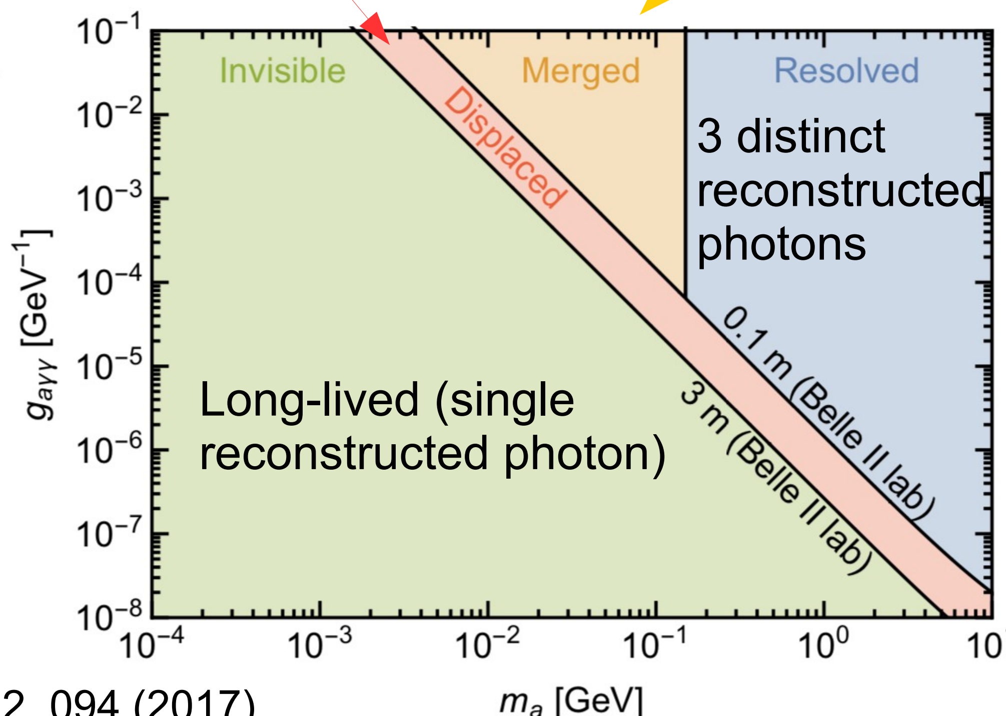
Lifetime depends on mass and coupling:

$$\tau \sim 1/m_a^3 g^2_{a\gamma\gamma}$$

- Several distinct experimental signatures depending on value

Non-prompt ALP decays within the detector volume

ALP daughter photons not resolved (reconstruct 2 clusters)



JHEP 1712, 094 (2017)

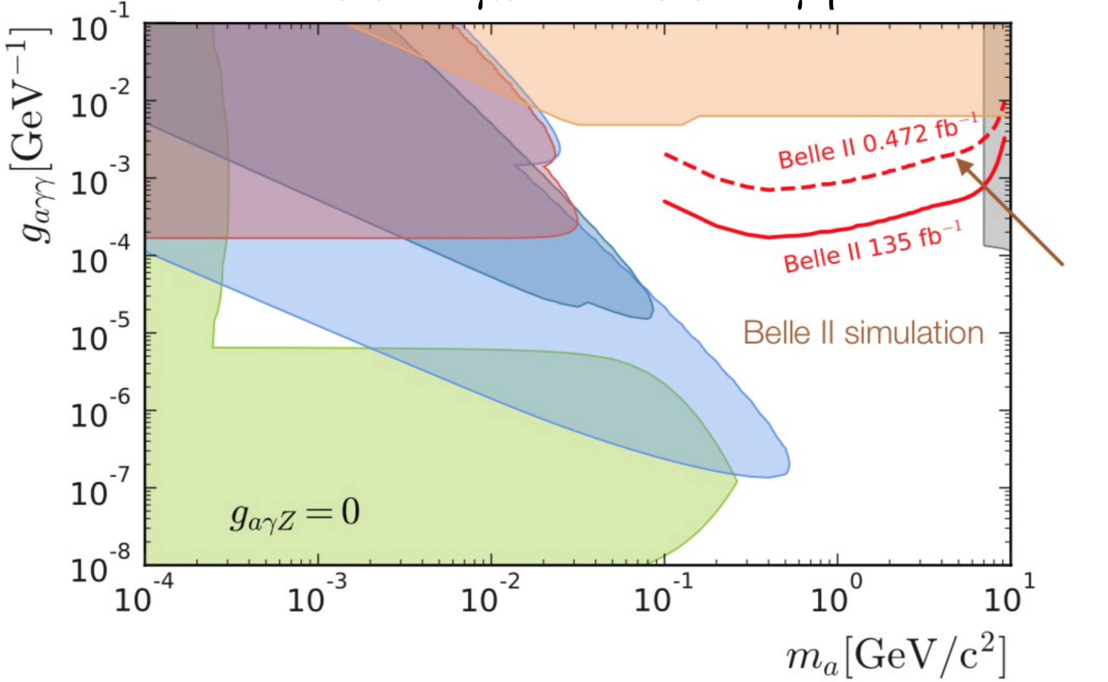
Axion-Like Particles

In 3γ analysis, signature is a bump in $m_{\gamma\gamma}$

- Non-peaking backgrounds from $e^+e^- \to \gamma\gamma(\gamma)$ and photon conversions $\gamma \to e^+e^-$ outside of tracking volume
- Peaking backgrounds from SM hadrons:

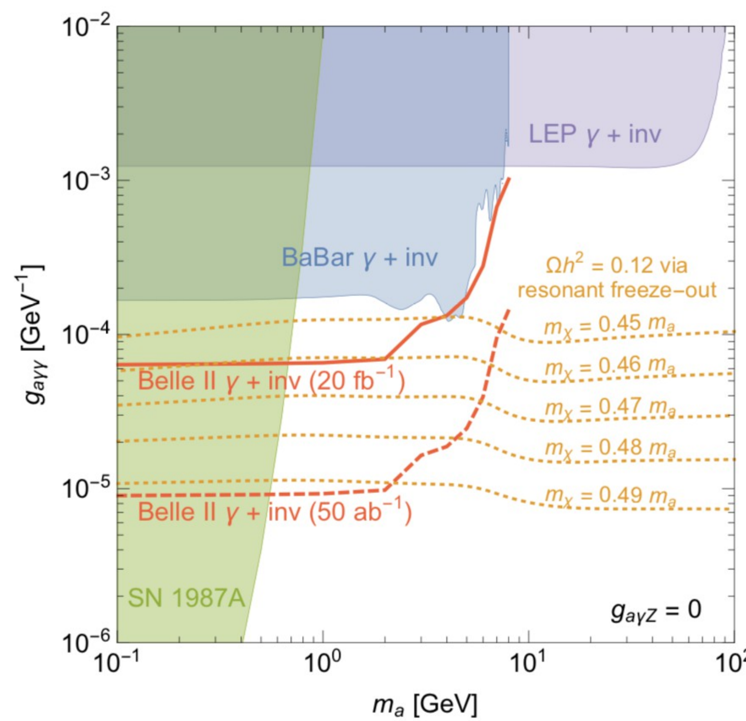
$$e^+e^- \to \gamma\omega,\ \omega \to \gamma\pi^0$$

$$e^+e^- \to \gamma\pi^0 \text{ and } e^+e^- \to \gamma\eta$$



Studies still ongoing, but competitive sensitivity expected already with existing data set

If ALP decays to dark matter, then single photon signature is relevant:



- ALP mediation of SM / dark matter interaction could explain observed abundance if $m_a \sim 2m_\chi$

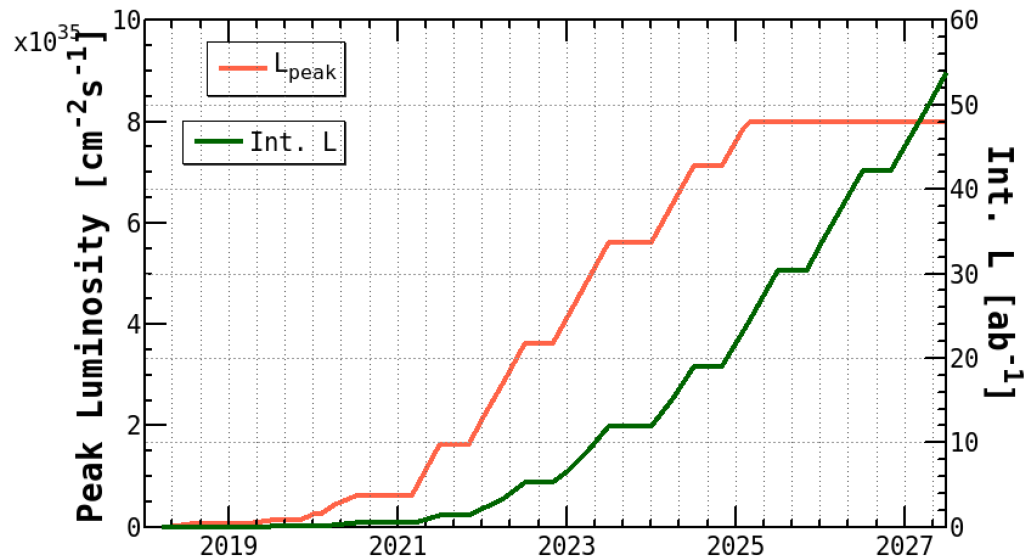
Conclusion

BABAR data set remains competitive and analyses are still in progress

- New results are anticipated in the near future.

First physics results are beginning to appear from Belle II

- Visible dark photon search submitted to PRL
- Low multiplicity triggers have been implemented for phase 3 data taking; physics studies ongoing
- ~10 fb^{-1} of data integrated during 2018; phase 3 data taking resumed last week
- ALPs and invisible dark photon analyses expected to be competitive with very modest data samples;



Backup slides

Dark sectors

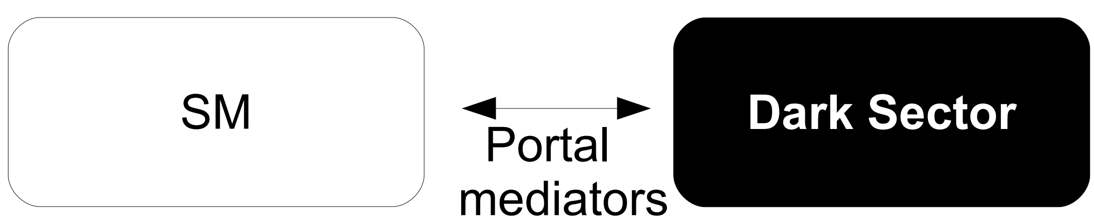
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct “sector”

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- EFT provides a number of “portals” to access this dark sector

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

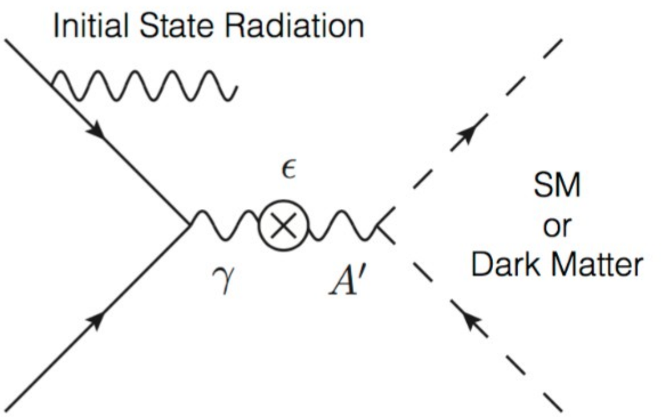
Vector portal | Higgs portal | Neutrino portal



Dark sector can be probed via mixing of the portal mediators with SM bosons

Dark Forces

- Search for decay of $e^+e^- \to \gamma A'$ via $A' \to \chi\bar{\chi}$ or into SM particles
  - "visible" $A' \to l^+l^-$, or
  - "Invisible" A' decays, with A' mass determined from photon energy:



.... however, dark sector could be much more extensive, with one or more Abelian or non-Abelian interactions, fermions and Higgs bosons

Can potentially be detected via one of a number of "portals" coupling the Dark Sector to the SM

Vector Portal → *Dark Photon*
Scalar Portal → *Higgs/Dark Scalars*
Pseudoscalar Portal → *Axion-like Particles*
Neutrino Portal → *Sterile Neutrinos*

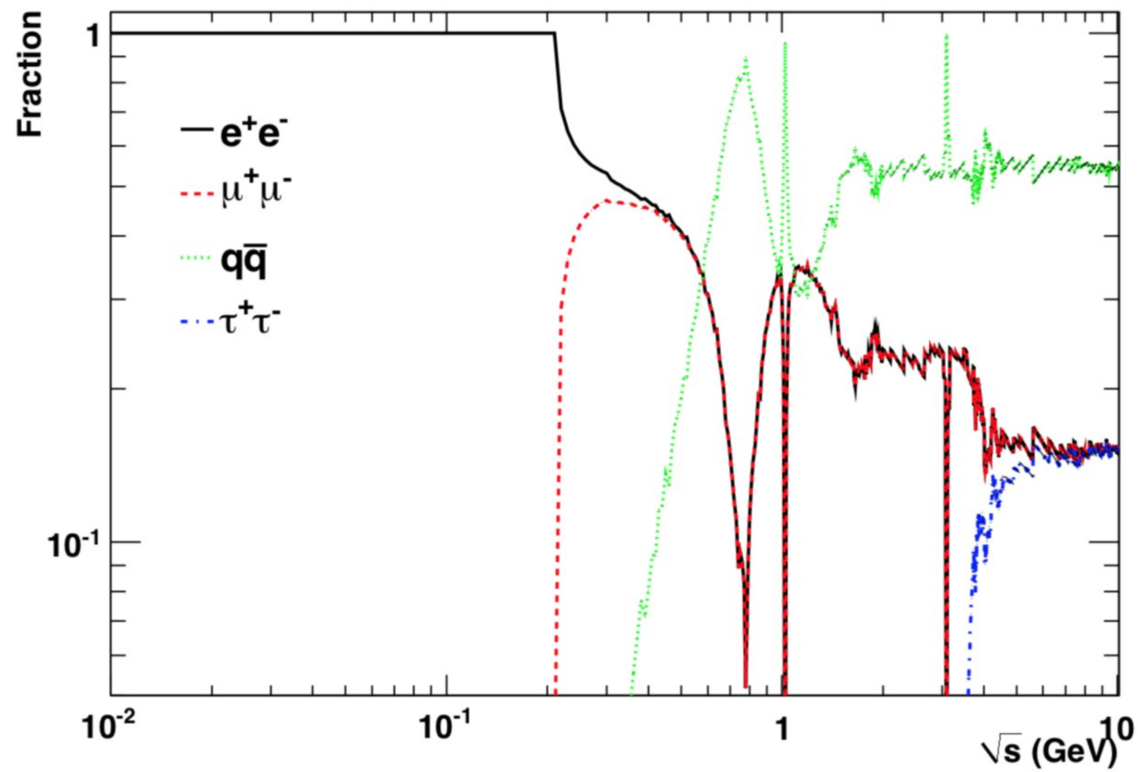
- Sensitivity studies performed in the context of "Belle II physics book" (B2TiP), to be published in near future
- ALP sensitivity studies: arxiv: 1709.00009

Typically, these are narrow resonance ("bump hunt") searches in low multiplicity data samples

Dark photon

Permitted decays depend on the relative masses of dark fermions and mediator, and of SM fermions

- Models are highly predictive:



Experimentally, the important feature is a reconstructable narrow A' resonance in a clearly defined topology, i.e a “bump hunt”

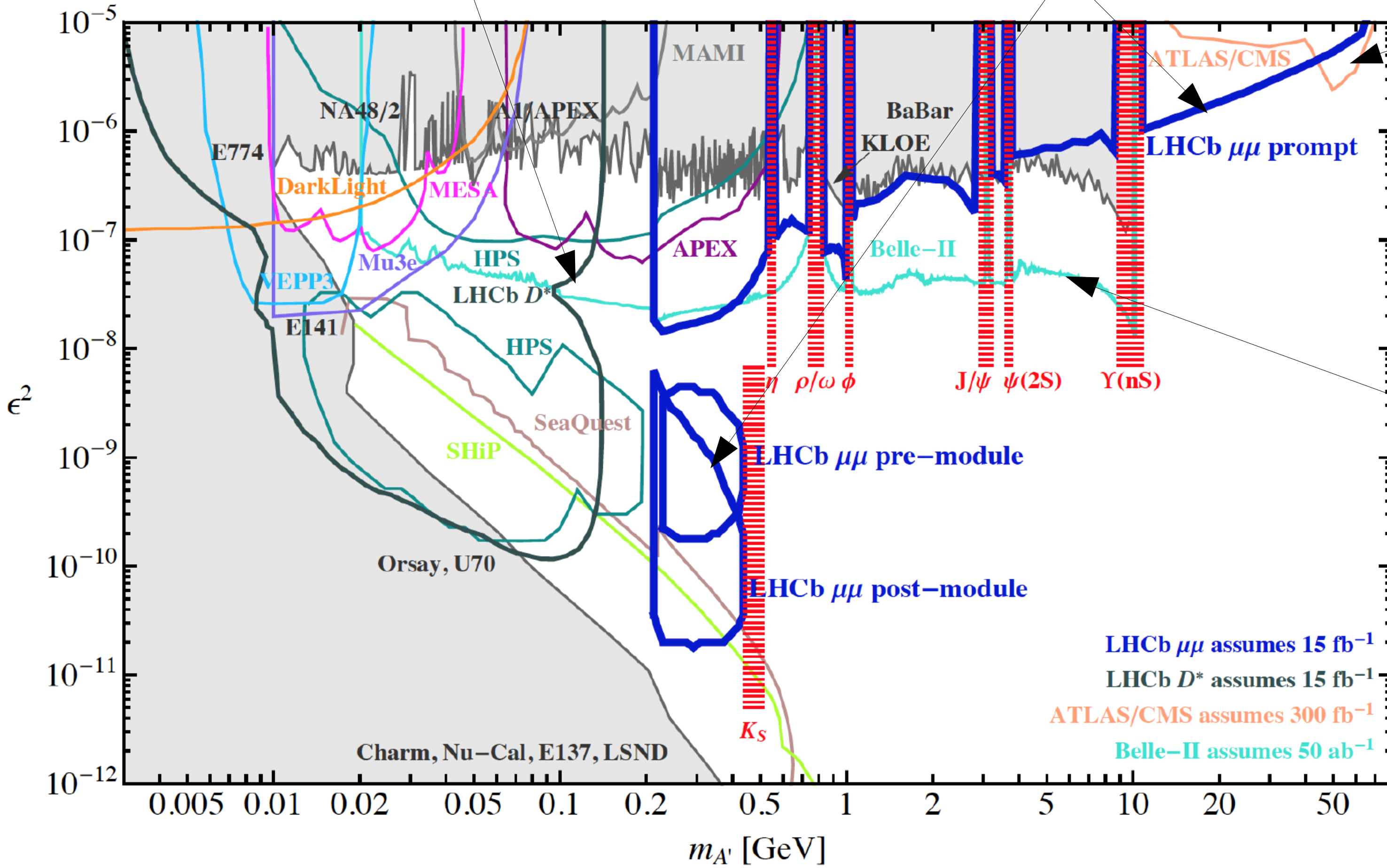
- E.g. search for decay of $e^+e^- \rightarrow \gamma A'$ via $A' \rightarrow \chi\bar{\chi}$ or into SM particles
  - “visible” $A' \rightarrow l^+l^-$, decaying promptly or with a displaced vertex
  - “Invisible” A' decays, with A' mass determined from missing energy constraints

Visible dark photon prospects

Phys. Rev. Lett. 116, 251803
arXiv:1603.08926 [hep-ex]

$D^{*0} \rightarrow D^0 e^+ e^-$
(prompt and displaced)

$A' \rightarrow \mu^+ \mu^-$



Similar methodology can be used by CMS and ATLAS (bump hunt in di-muon spectrum)

Belle II projection

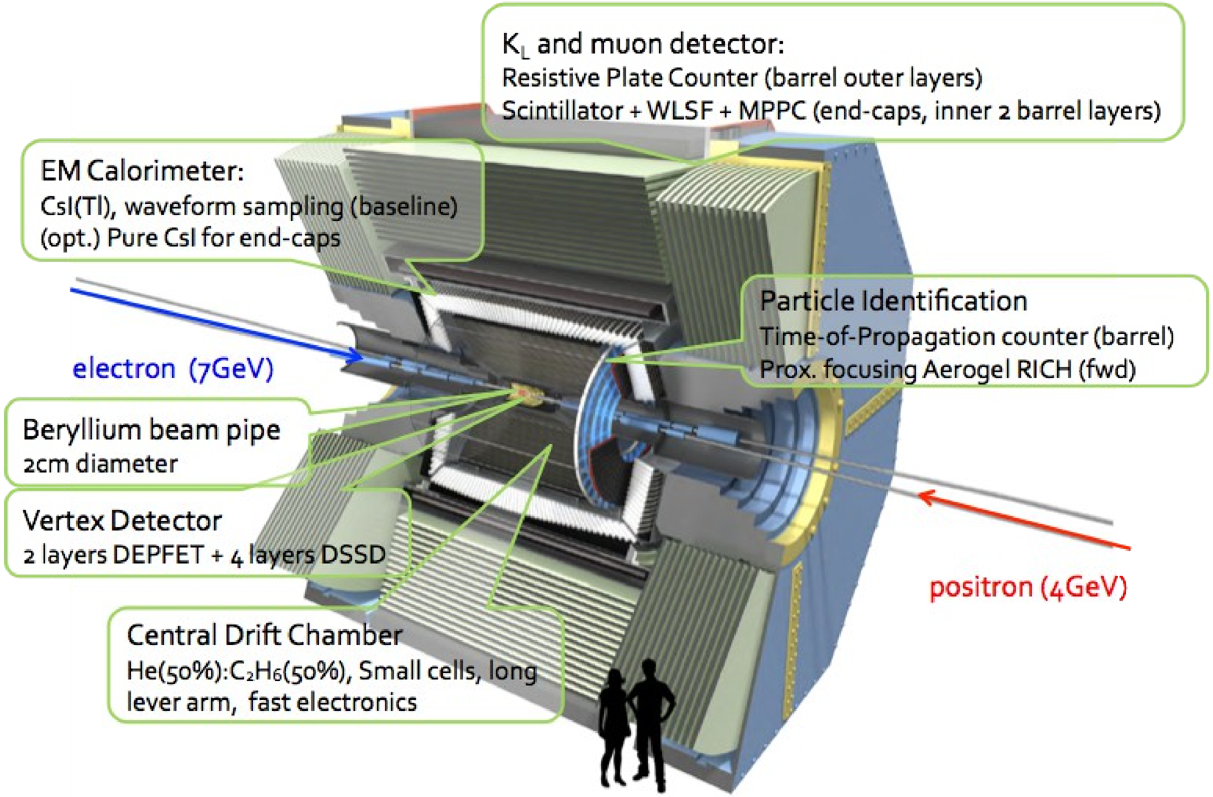
Light meson Dalitz decays
$\pi^0,\ \eta \rightarrow e^+ e^- \gamma$

Belle II Detector

Anticipate ~40x increased instantaneous luminosity, and greatly increased beam background rates

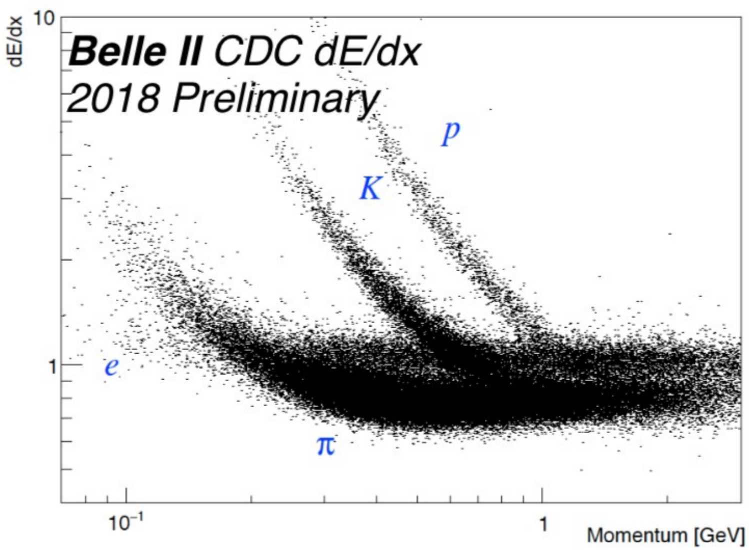
Very substantial "upgrades" to the original Belle detector:

- Replacement of beam pipe and redesign of entire inner detector (including vertex detectors and drift chamber)
- New quartz-bar Time-of-Propagation PID in barrel region
- Retain existing CsI(TI) calorimeter crystals, but front-end electronics, feature extraction and reconstruction software entirely new
- Entirely new software framework and distributed computing environment

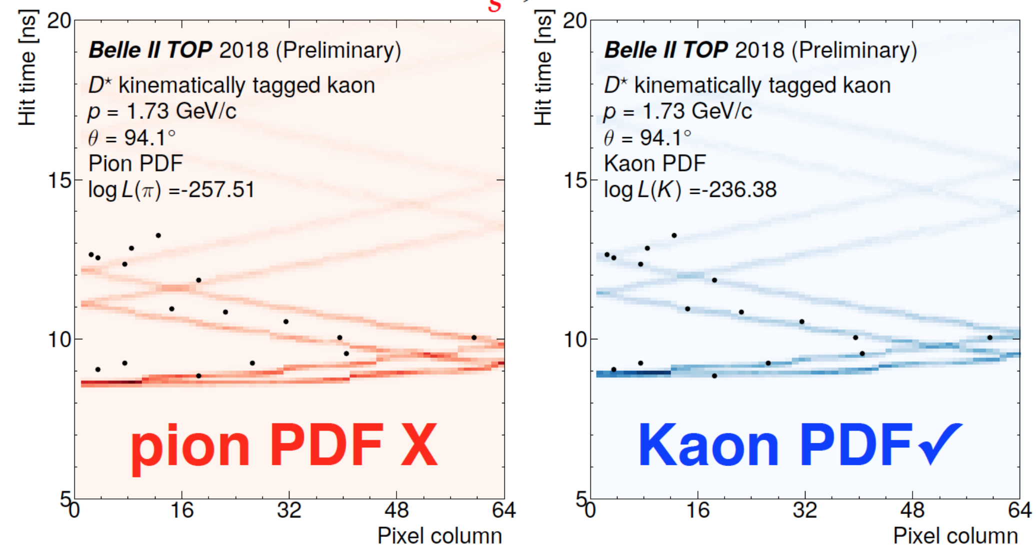


Particle Identification

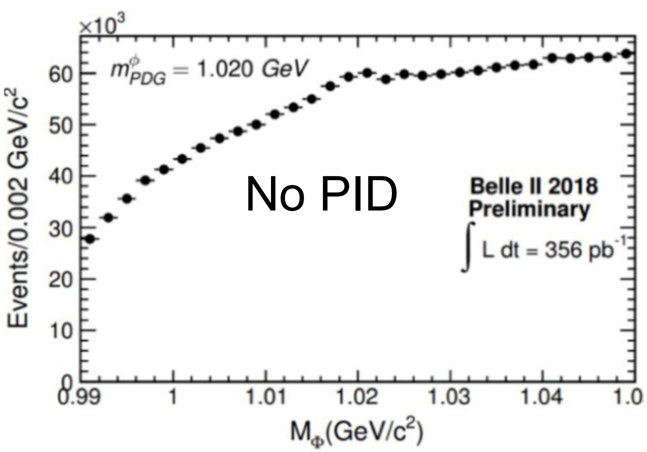
Central Drift Chamber (CDC)

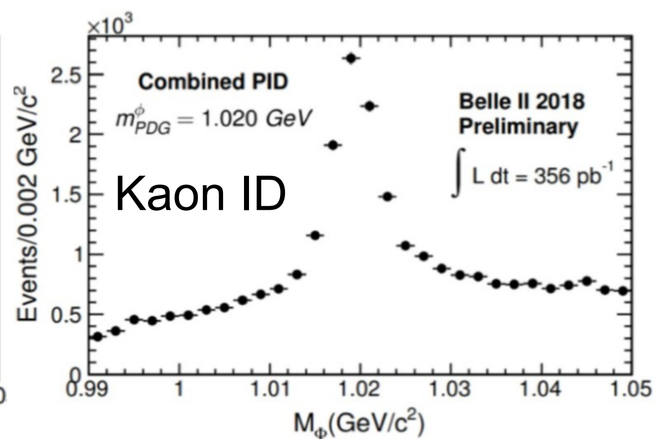


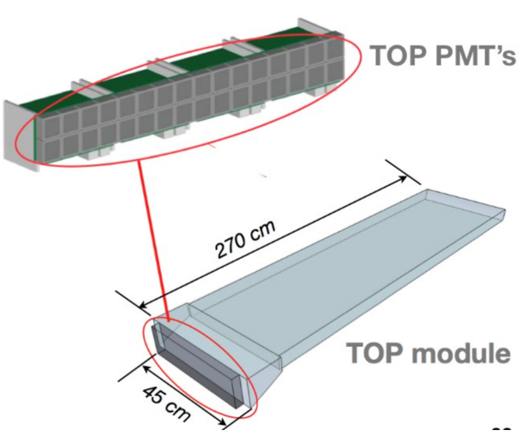
$D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$



Time of Propagation (TOP) detector





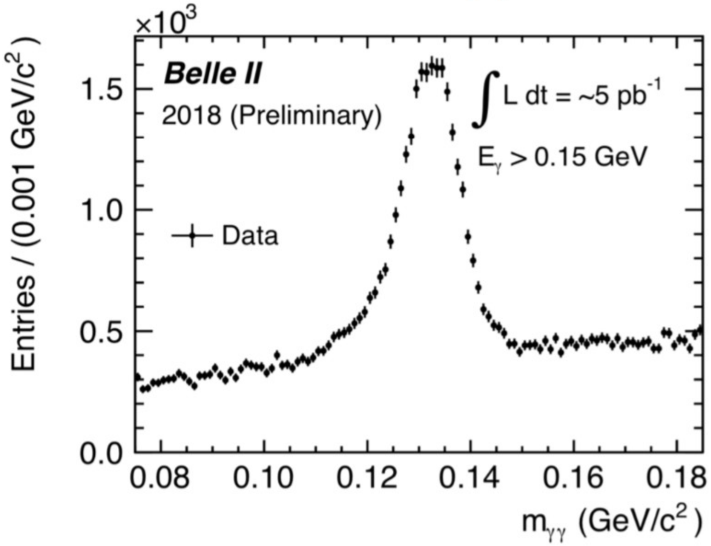


$\Phi \to K^+K^-$ reconstruction

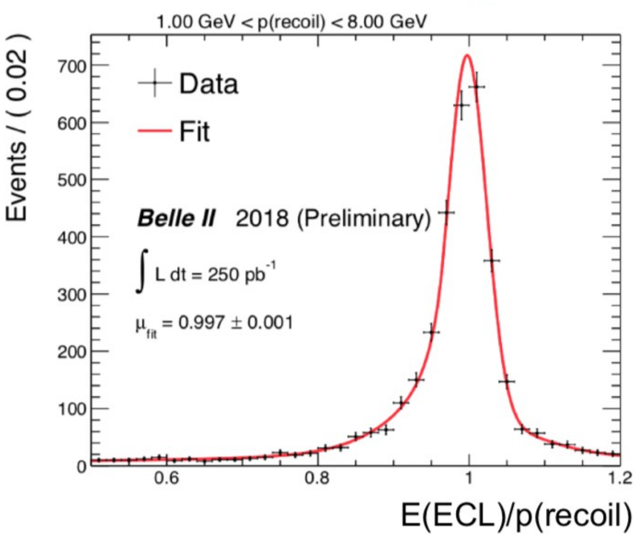
Calorimetry

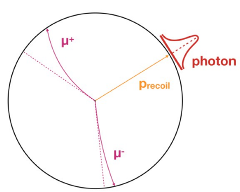
- Neutrals reconstruction using calorimeter clusters

$\pi^0 \to \gamma\gamma$

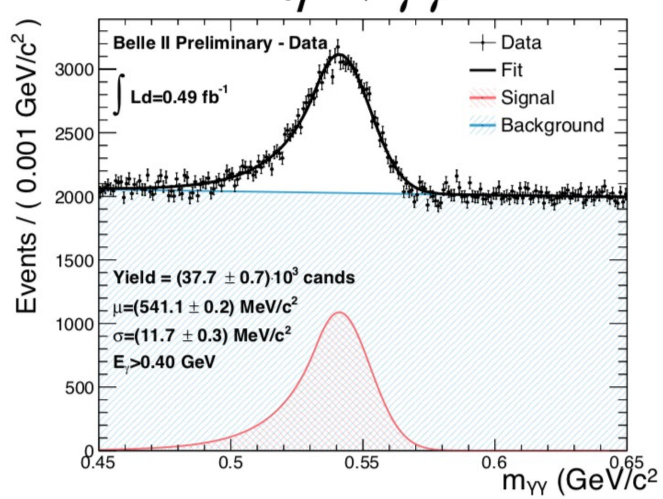


$e^+e^- \to \mu^+\mu^-\gamma$





$\eta \to \gamma\gamma$

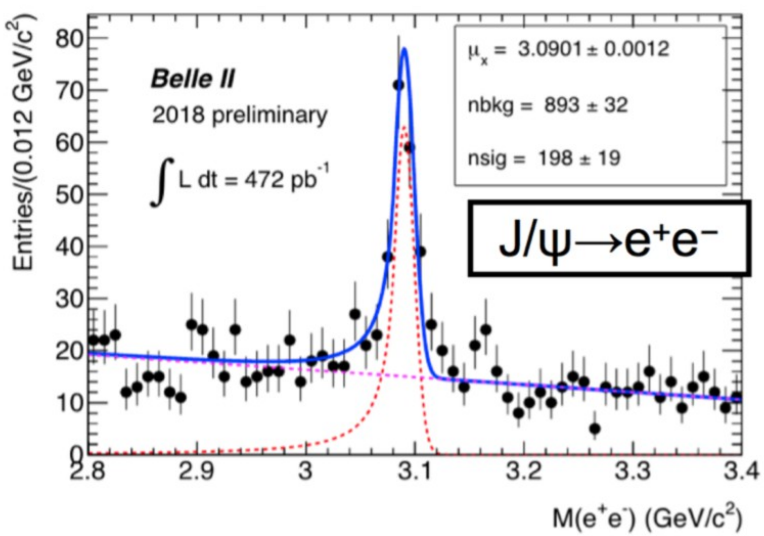


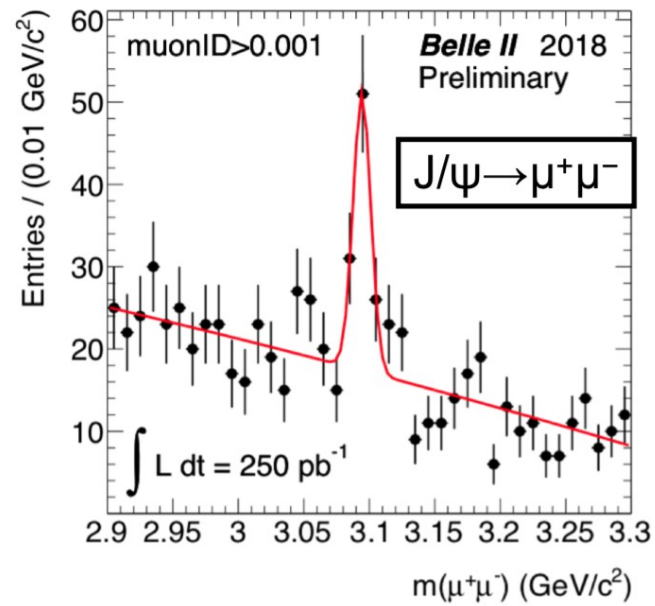
Single photon energy resolution based on $\mu^+\mu^-\gamma$ events

Belle II commissioning

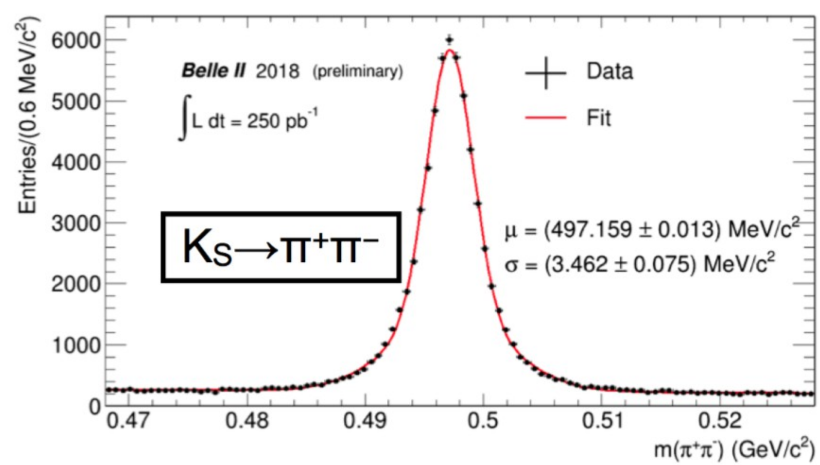
2018 SuperKEKB commissioning run provided opportunity to validate detector performance with colliding beams

- Achieved instantaneous luminosity of 5.5 x 10^{33} cm^{-2} s^{-1}
- Recorded 472 pb^{-1} integrated luminosity (~1 million B mesons)
- Only one sector of vertex detector installed



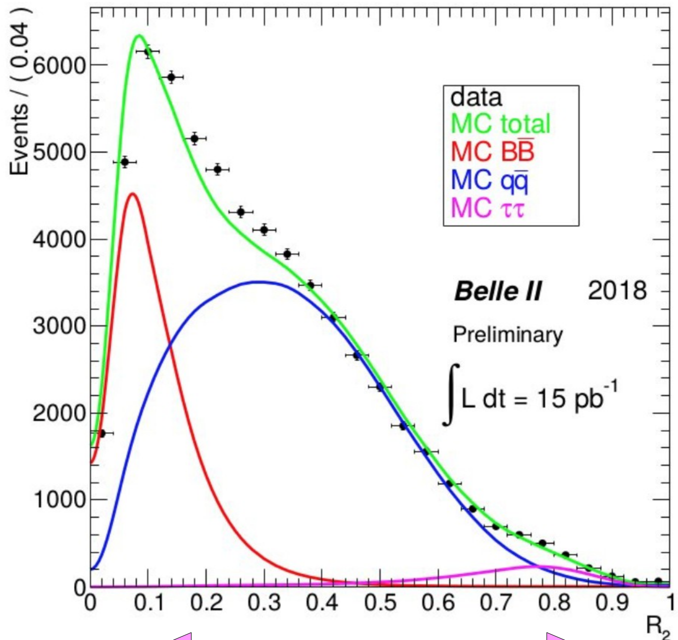


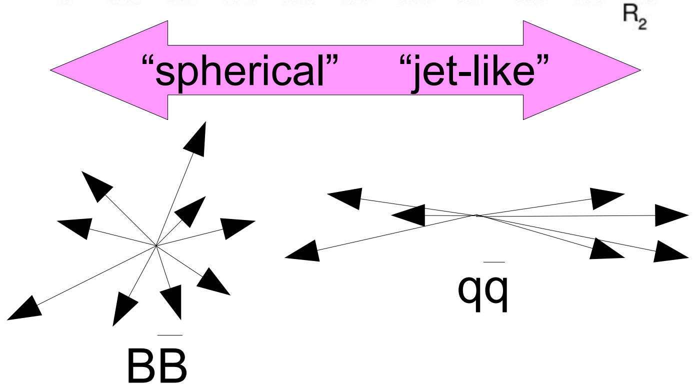
- Track reconstruction (using CDC and partial vertex detector)
- Alignment and solenoid B field are well understood

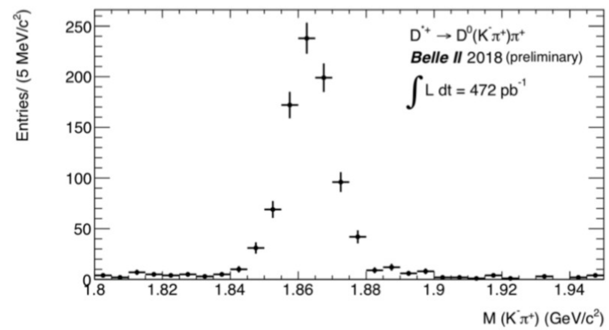


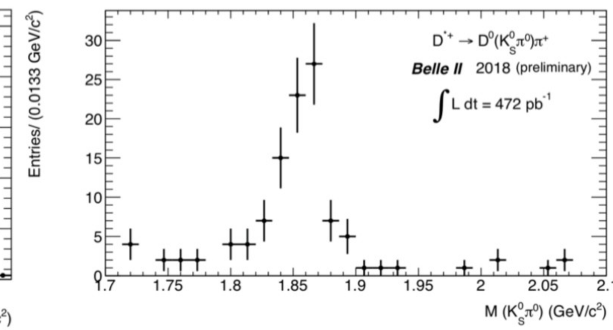
B reconstruction

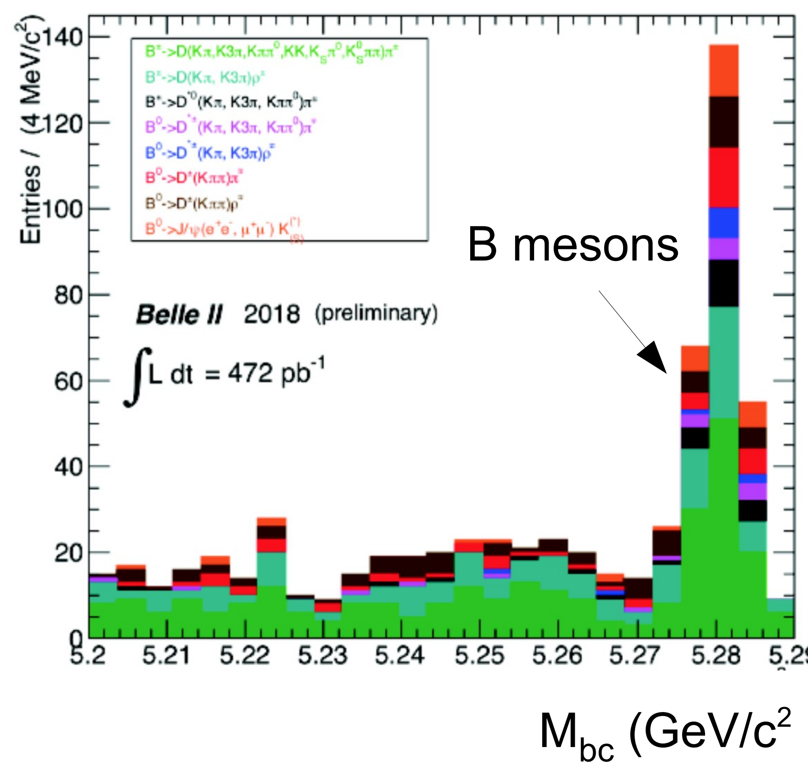
Topological event shapes:











Evidence that SuperKEKB was operating on the ϒ(4S) resonance

What's so "Super"?

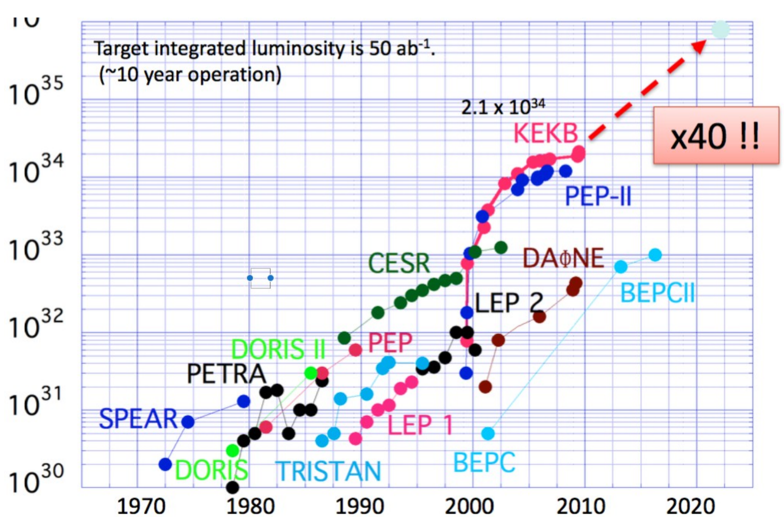
How to get to 8×10^{35} $cm^{-2}s^{-1}$:

- Very high charge density bunches
- Bunch crossings every 6ns (~1.2m spacing)
- Low emittance beams
- Tiny beam spot at IP

$$L = \frac{\gamma_{\pm}}{2er_e}(1+a)\frac{R_L}{R_{\xi}}\left(\frac{I_{\pm}\xi_{y\pm}}{\beta^*_{y\pm}}\right)$$

beam current **x2** beam-beam param. **x1**

vertical beta function **x20**



	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		**2500**	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP $\beta x^*/\beta y^*$ [mm]	1200/5.9		32/**0.27**	25/**0.30**
beam-beam param. ξy	0.129	0.090	0.088	0.081
Bunch Length Sz [mm]	6.0	6.0	6.0	5.0
Horizontal Beam Size sx^* [µm]	150	150	10	11
Vertical Beam Size sy^* [nm]	0.94		48	62
Half crossing angle φ [mrad]	11		41.5	
Beam energy Eb [GeV]	3.5	8	4	7.007
Beam currents Ib [A]	1.64	1.19	**3.6**	**2.6**
Lifetime t [min]	133	200	**6**	**6**
Luminosity L [$cm^{-2}s^{-1}$]	**2.1×10^{34}**		**8×10^{35}**	

Short beam lifetime requires continuous ("trickle") injection during live data taking

What's so "Super"?

e^+e^- collisions provide a very rich data set and a clean analysis environment

"Inclusive" hadronic and low multiplicity datasets are key features:

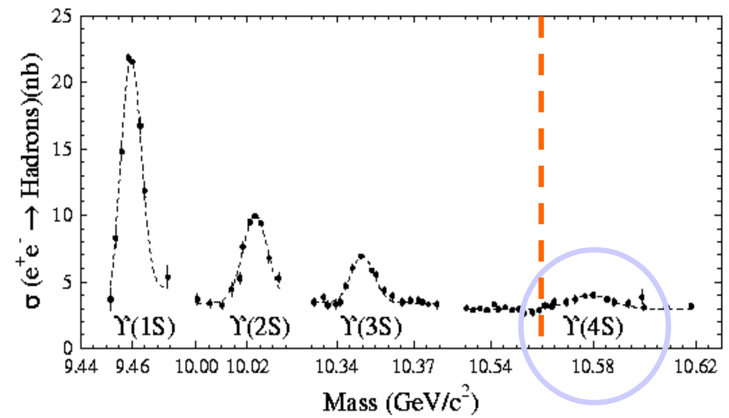
- Target data sample has a cross section of ~ 5 – 10 nb

8 x10^{35} $cm^{-2}s^{-1}$ luminosity yields ~5 kHz of "interesting" physics events

- O(1 kHz) of $B\bar{B}$ events
- ~30 kHz Bhabhas within detector acceptance
  - Level 1 trigger rejection essential!
  - Probability of multiple collisions per bunch crossing (aka "pileup"): <0.02%

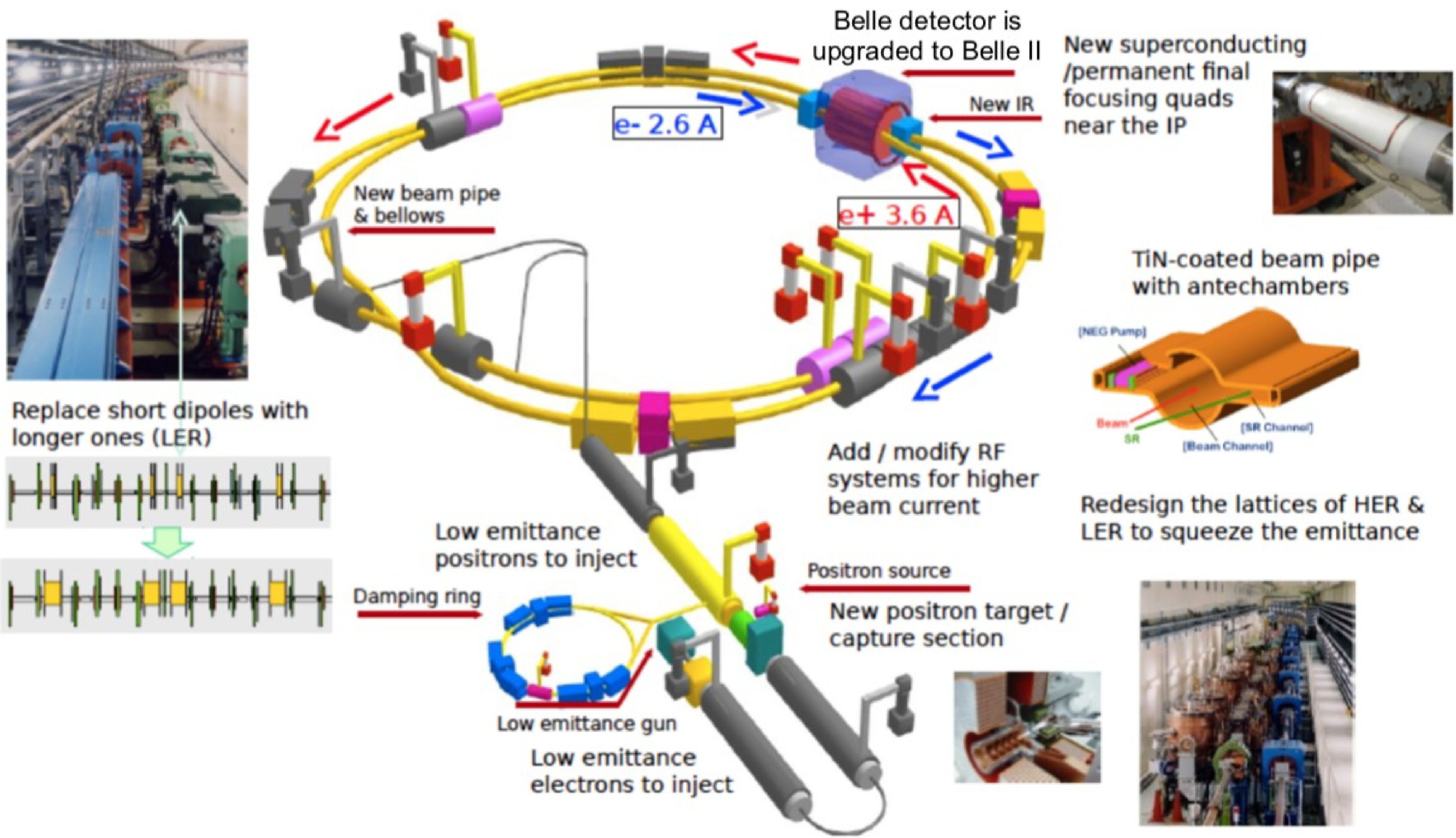
50 ab^{-1} integrated luminosity implies ~55 billion $B\bar{B}$ pairs in target data sample

- Analysis sensitivity in B, τ and charm to O(10^{-9}) branching fractions



Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

SuperKEKB



Belle detector is upgraded to Belle II
New superconducting /permanent final focusing quads near the IP
New IR
e- 2.6 A
e+ 3.6 A
New beam pipe & bellows
TiN-coated beam pipe with antechambers
[NEG Pump]
Beam
SR
[SR Channel]
[Beam Channel]
Replace short dipoles with longer ones (LER)
Add / modify RF systems for higher beam current
Redesign the lattices of HER & LER to squeeze the emittance
Low emittance positrons to inject
Damping ring
Positron source
New positron target / capture section
Low emittance gun
Low emittance electrons to inject

SuperKEKB

	KEKB Achieved LER	KEKB Achieved HER	SuperKEKB LER	SuperKEKB HER
RF frequency f [MHz]	508.9			
# of Bunches N	1584		2500	
Horizontal emittance εx [nm]	18	24	3.2	4.6
Beta at IP $\beta x^*/\beta y^*$ [mm]	1200/5.9		32/0.27	25/0.30
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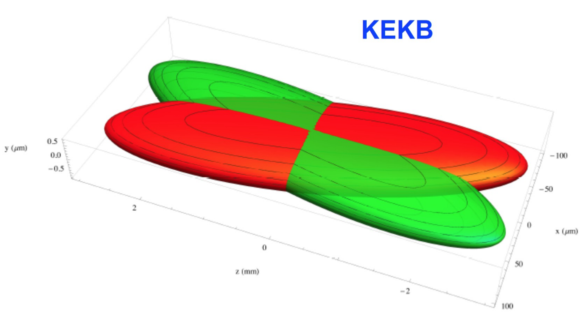
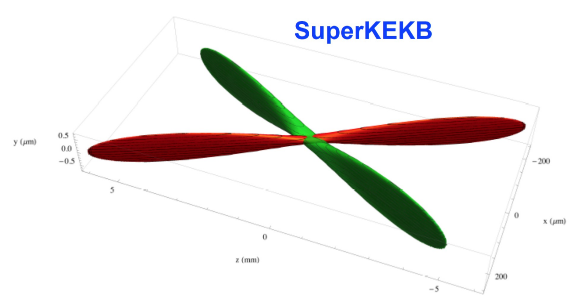
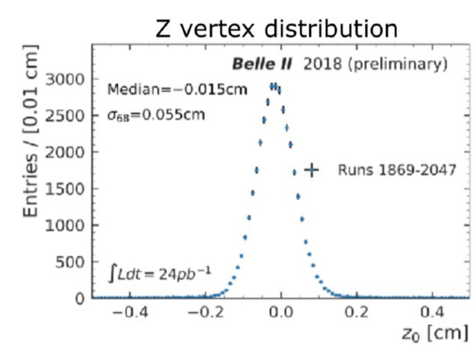
Beam currents Ib [A]	1.64	1.19	3.6	2.6
Lifetime t [min]	133	200	6	6
Luminosity L [$cm^{-2}s^{-1}$]	**2.1×10^{34}**		**8×10^{35}**	

Substantial upgrade of KEKB collider to provide e^+e^- collisions at $8\times10^{35} cm^{-2}s^{-1}$ luminosity for Belle II

- Low-emittance "nanobeam" scheme exploiting ILC and light-source technologies
- 4 GeV (e^+) on 7 GeV (e^-)
- New positron damping ring and positron beam vacuum chamber
- New final focus region







σ = 55μm

Invisible Dark Photon

Selection optimized for best upper limit on A' production cross section

- Use BDT to define "Background" ($\mathcal{R}_B$), "Loose" ($\mathcal{R}_L$) and "Tight" ($\mathcal{R}_T$) * selection criteria

  * lowM only

- Background shape taken from "background" data
  - Parametrized as 2nd order polynomial (sum of exponentiated polynomials) in low (high) M region, plus Crystal Ball peaking function for peaking backgrounds

- Signal parametrized using Crystal Ball function with mass-dependent width (determined from simulation); validated with $e^+e^- \to \gamma\gamma$ control samples

Dataset	"lowM"				"highM"		
Dataset	$\mathcal{L}$	Selection			$\mathcal{L}$	Selection	
		$\mathcal{R}_B$	$\mathcal{R}_L'$	$\mathcal{R}_T$		$\mathcal{R}_B$	$\mathcal{R}_L$
$\Upsilon(2S)$	$15.9\,\text{fb}^{-1}$	22,590	42	6	$15.9\,\text{fb}^{-1}$	405,441	324
$\Upsilon(3S)$	$31.2\,\text{fb}^{-1}$	68,476	129	26	$22.3\,\text{fb}^{-1}$	719,623	696
$\Upsilon(4S)$	$5.9\,\text{fb}^{-1}$	7,893	16	9			

9 independent samples

4 independent samples

Invisible Dark Photon

Different backgrounds contribute to the low and high mass regions

$4\ \text{GeV}^2 < M_X^2 < 36\ \text{GeV}^2$

$24\ \text{GeV}^2 < M_X^2 < \begin{cases} 69.0\ \text{GeV}^2 & (\Upsilon(3S)) \\ 63.5\ \text{GeV}^2 & (\Upsilon(2S)) \end{cases}$

Low M_X

- $e^+e^- \to \gamma\gamma$ in which a photon escapes detection

Require:

- $E_\gamma^* > 3$ GeV in range $|\cos\theta_\gamma^T| < 0.6$
- No drift chamber tracks with $p^* > 1$ GeV
- Multivariate discriminator

High M_X

- $e^+e^- \to e^+e^-\gamma$ in which the electron and positron escape detection

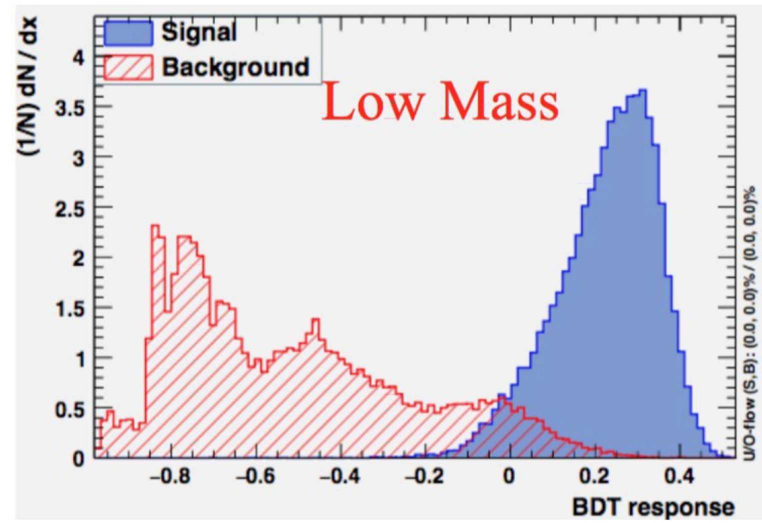
Require:

- $E_\gamma^* > 1.5$ GeV in range $|\cos\theta_\gamma^T| < 0.6$
- Transverse shower shape consistent with EM shower
- No drift chamber tracks with $p^* > 0.1$ GeV
- Multivariate discriminator

Invisible Dark Photon

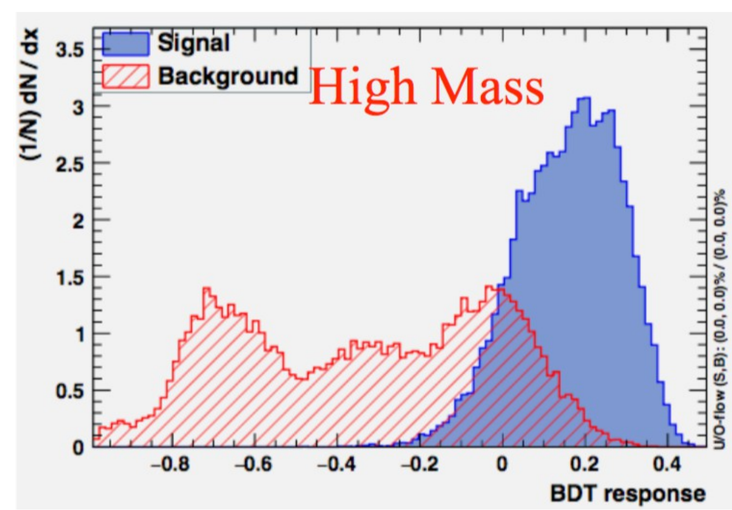
Boosted Decision Tree (BDT) selector to discriminate signal candidates

- Trained separately for low and high mass samples
- Training samples:
  - Simulated signal events with uniform A' mass distribution
  - Background data events from $\Upsilon(3S)$ sample (~3 fb^{-1})



12 discriminating variables:

  - Cluster shape parameters for signal candidate cluster
  - Total calorimeter energy, excluding signal candidate cluster
  - Properties of the second most energetic cluster: E^*, θ^*, $\Delta\Phi^*$
  - Properties of the IFR cluster (E^*, θ^*, $\Delta\Phi^*$) closest to the missing momentum direction

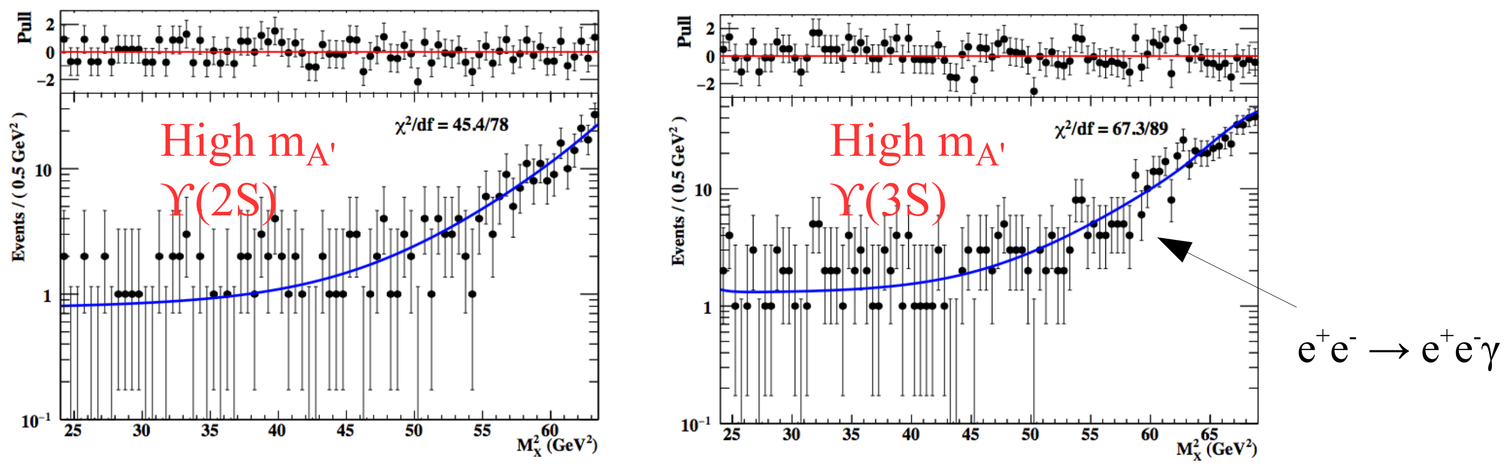


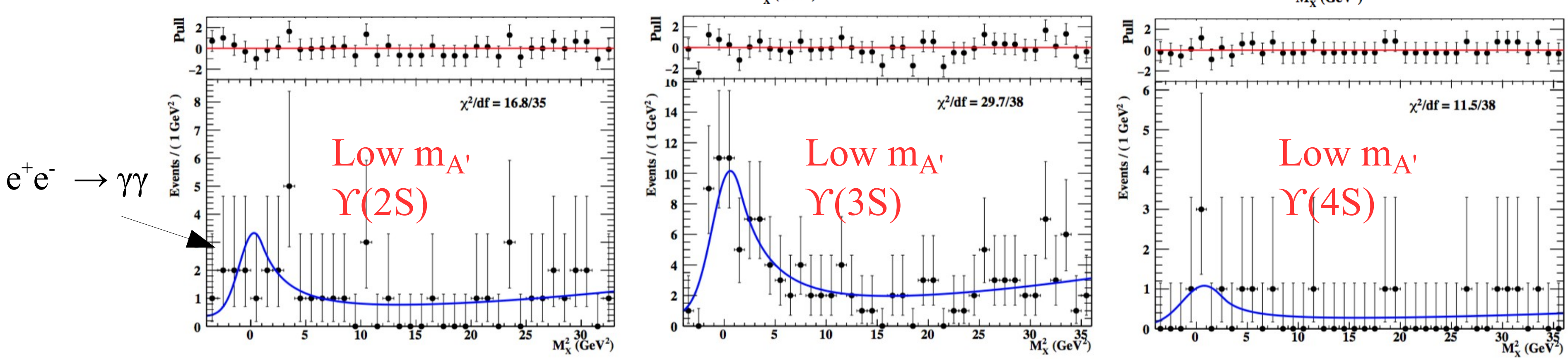
Invisible Dark Photon

Cross section of A' determined from unbinned extended maximum likelihood fits to M_X distribution in range 0 – 8.0 GeV

- Simultaneous fits to $\Upsilon(2S)$, $\Upsilon(3S)$ and (for low-M_X) $\Upsilon(4S)$ samples
- Step size equal to half the mass resolution

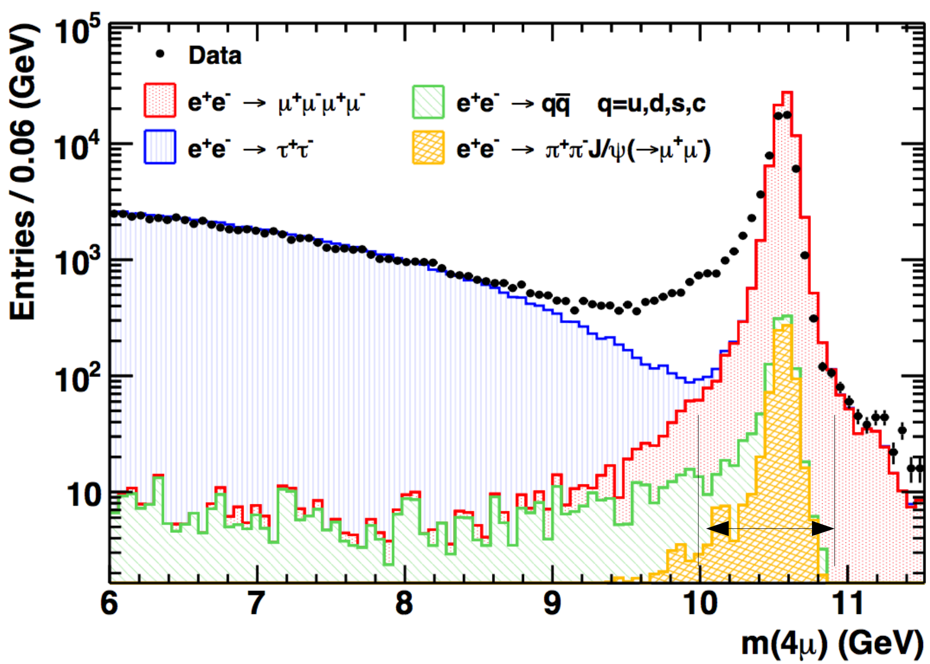
Example fits:





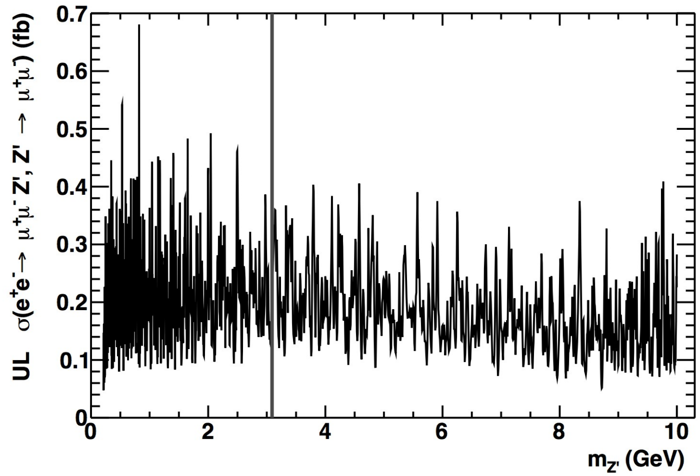
Muonic dark force

- Background is primarily from QED processes, in particular
  $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Select events with 4 tracks, including two same-sign identified muons; veto events with additional calorimeter energy exceeding 200 MeV
- $\Upsilon(3S), \Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ backgrounds rejected by vetoing events with a di-track mass combination within 100 MeV of the $\Upsilon(1S)$

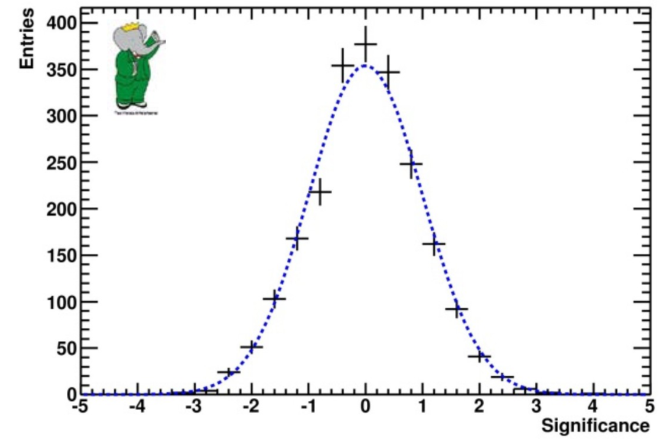


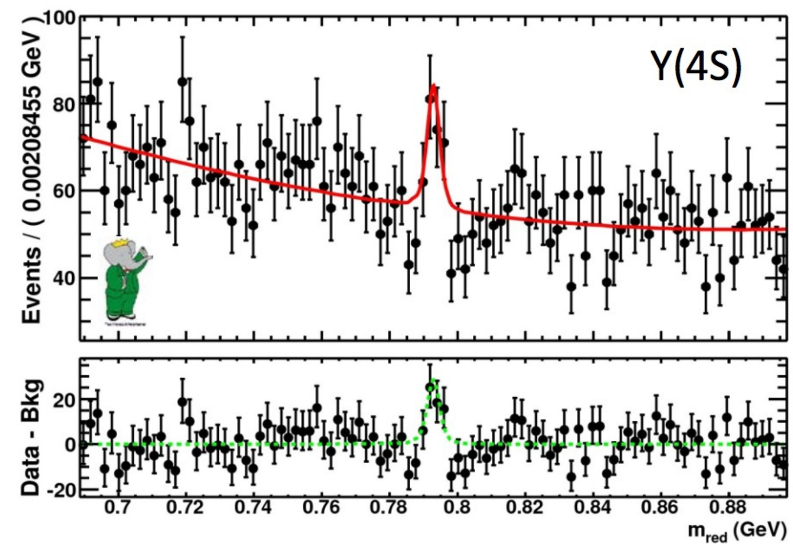
- ISR not modelled in simulation; corrected at analysis level
- Retain events with $m(4\mu)$ within 500 MeV of nominal CM energy
- Kinematic fit of 4μ mass to CM energy and interaction point imposed
  - no rejection applied; improves di-muon resolution

Muonic dark force results



Limit on $\sigma(e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^-)$





Most significant fit

Local significance: 4.3σ
Global significance: 1.6σ

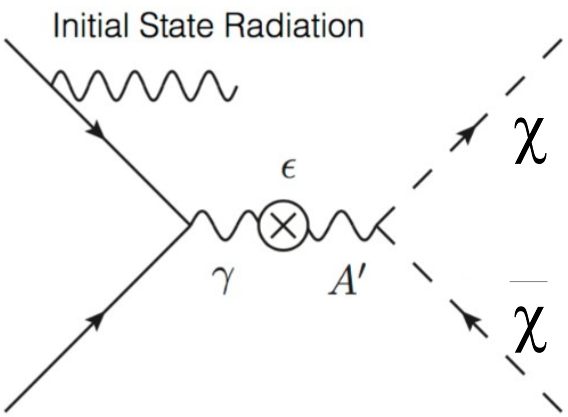
Invisible dark photon decays

BABAR provides an excellent environment for missing energy searches

- Precisely known e^+e^- initial state; hermetic detector

Search for invisible decay of $A' \rightarrow \chi\chi$ via $e^+e^- \rightarrow \gamma A'$

- Final state has only a single isolated photon in the detector
- A' mass determined from photon energy and CM energy:

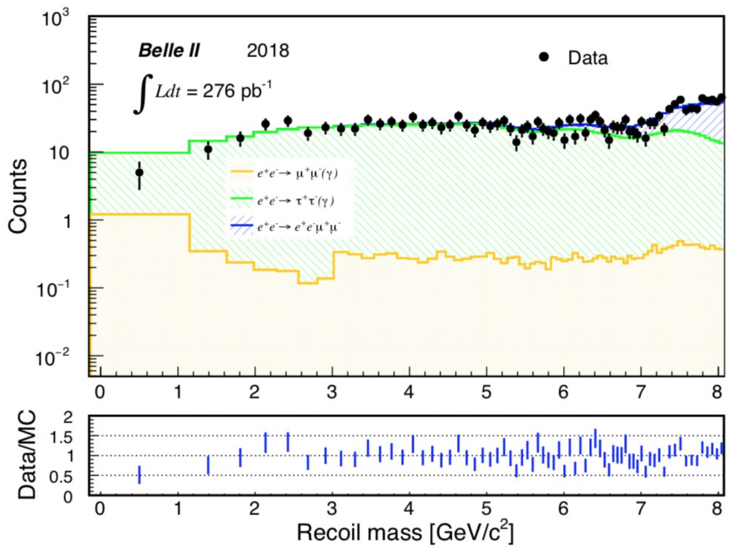


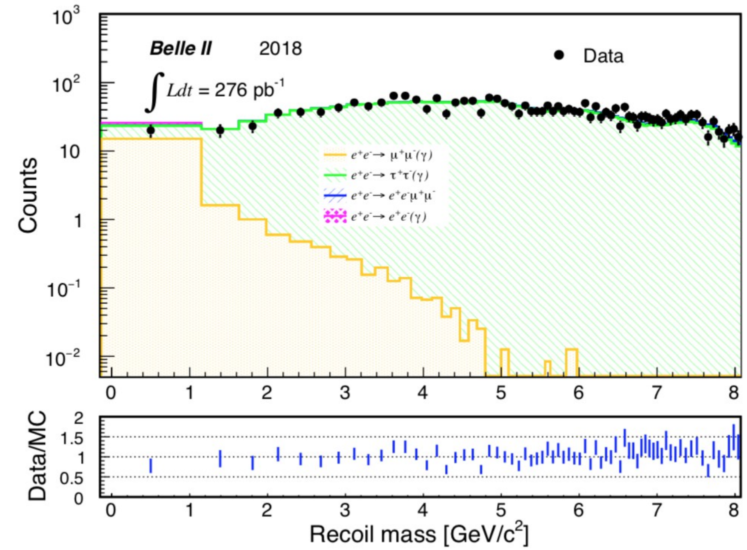
A' production expected to be independent of Υ resonances, hence can combine Υ(2S), Υ(3S), Υ(4S) and non-resonant datasets for additional statistical power

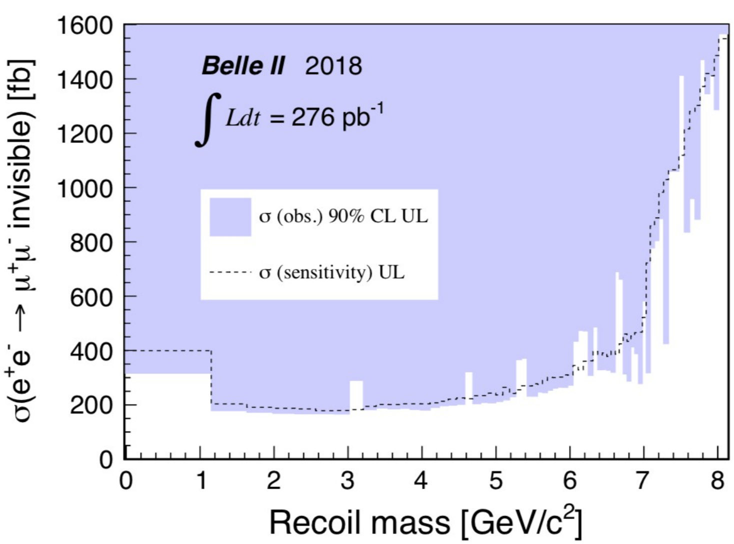
- Assume A' width negligible compared to experimental resolution
- Either there is a single A' in the region 0< mA' < 8 GeV, or if more than one, then they do not interfere

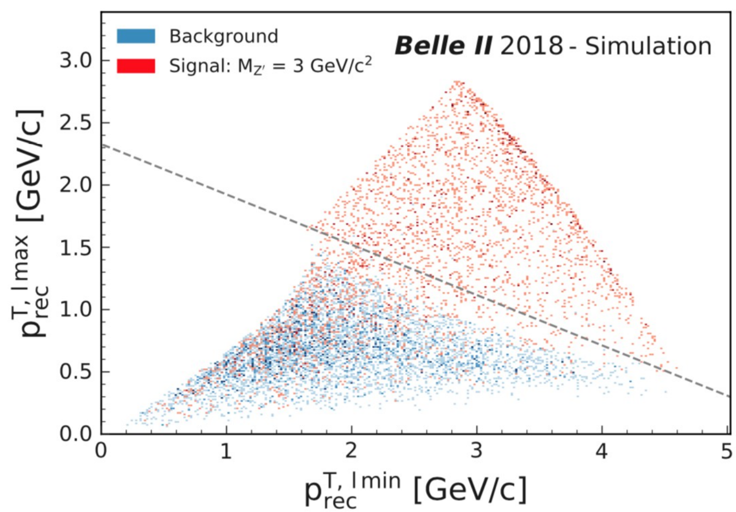
Phys.Rev.Lett. 119 (2017) no.13, 131804
arXiv:1702.03327 [hep-ex]

Invisible Z'



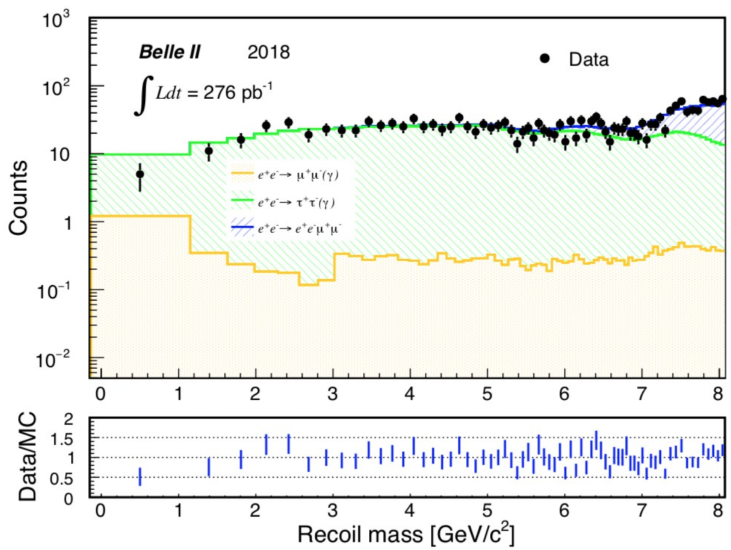




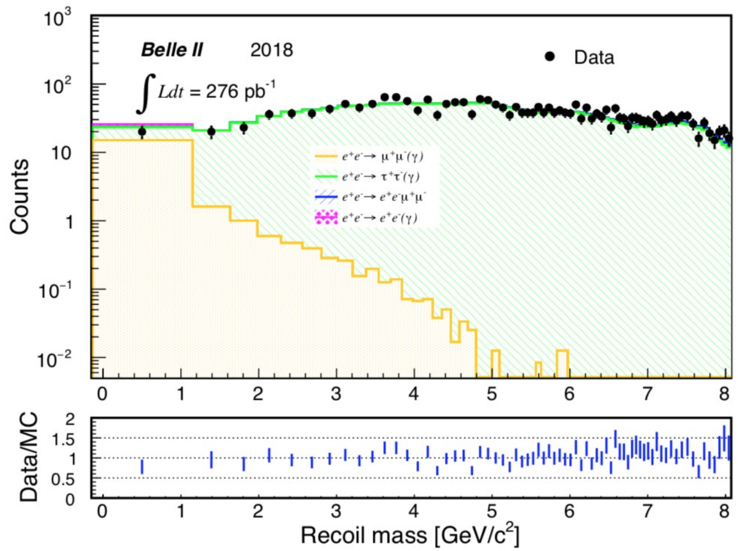


Transverse recoil momentum with respect to the lepton with higher (lmax) And lower (lmin) momentum

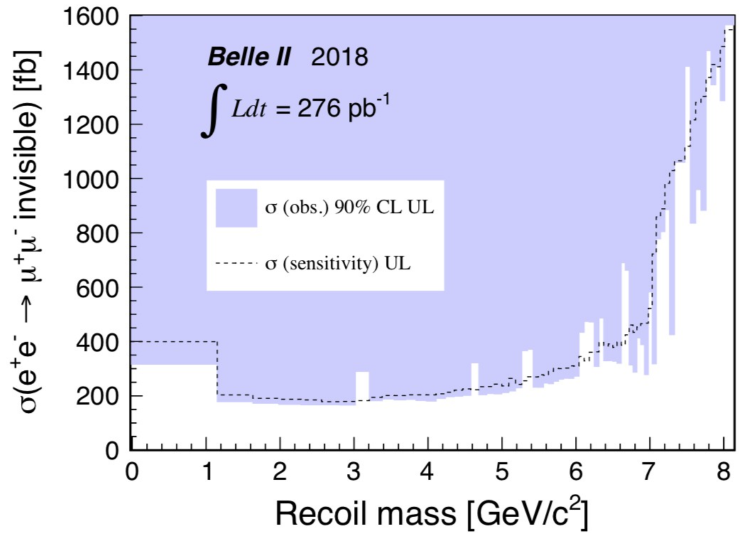
Invisible Z'



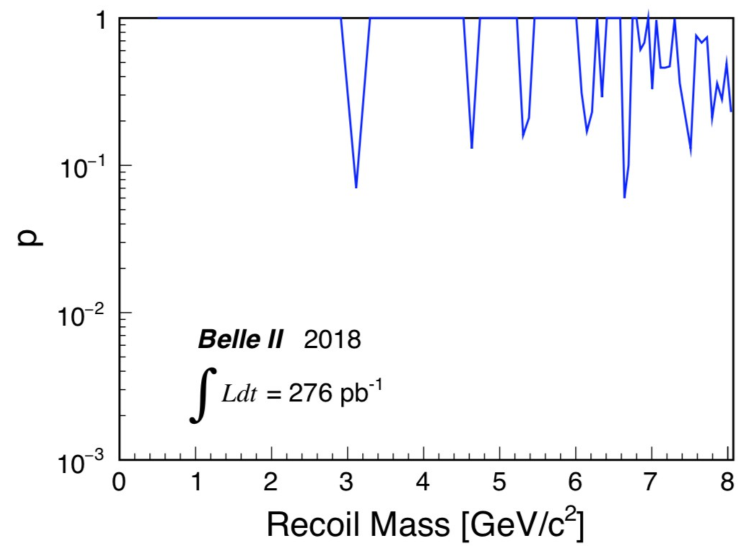
Belle II 2018
$\int Ldt$ = 276 pb^{-1}
Data
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$e^+e^- \to e^+e^-\mu^+\mu^-$
Counts
Data/MC
Recoil mass [GeV/c^2]



Belle II 2018
$\int Ldt$ = 276 pb^{-1}
Data
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to \tau^+\tau^-(\gamma)$
$e^+e^- \to e^+e^-\mu^+\mu^-$
$e^+e^- \to e^+e^-(\gamma)$
Counts
Data/MC
Recoil mass [GeV/c^2]

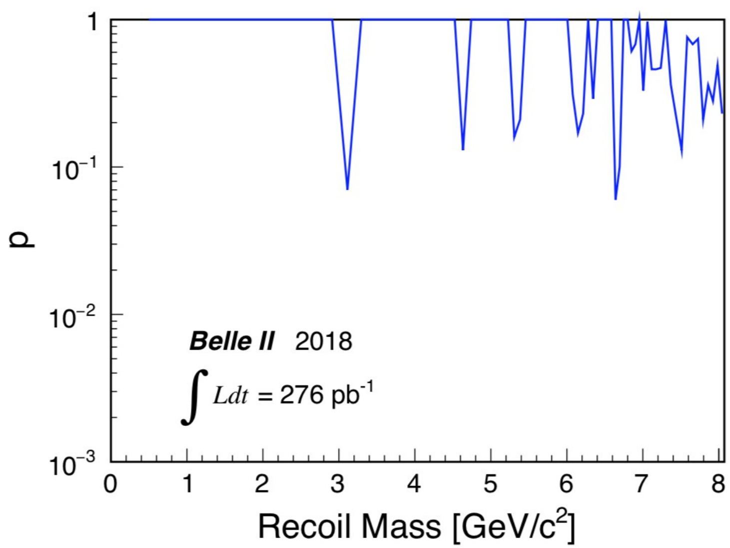


Belle II 2018
$\int Ldt$ = 276 pb^{-1}
σ (obs.) 90% CL UL
σ (sensitivity) UL
$\sigma(e^+e^- \to \mu^+\mu^-$ invisible) [fb]
Recoil mass [GeV/c^2]

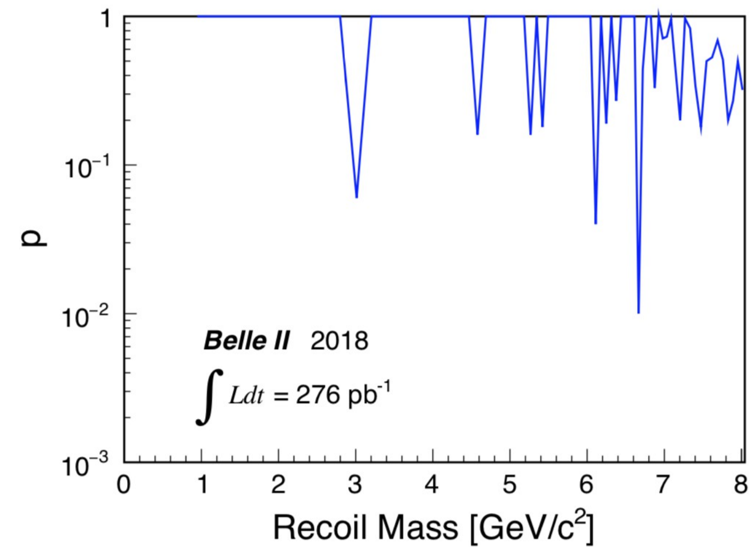


Belle II 2018
$\int Ldt$ = 276 pb^{-1}
p
Recoil Mass [GeV/c^2]

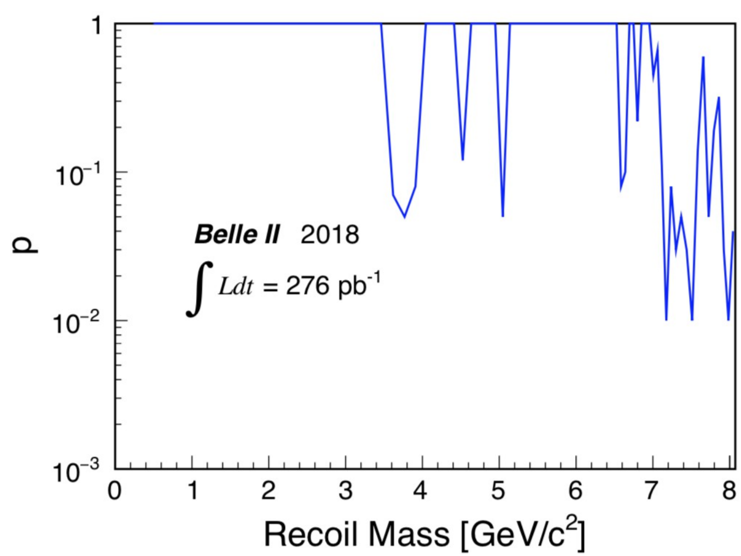
Invisible Z'



p
1
10⁻¹
10⁻²
10⁻³
0 1 2 3 4 5 6 7 8
Recoil Mass [GeV/c²]
Belle II 2018
∫Ldt = 276 pb⁻¹



p
1
10⁻¹
10⁻²
10⁻³
0 1 2 3 4 5 6 7 8
Recoil Mass [GeV/c²]
Belle II 2018
∫Ldt = 276 pb⁻¹



p
1
10⁻¹
10⁻²
10⁻³
0 1 2 3 4 5 6 7 8
Recoil Mass [GeV/c²]
Belle II 2018
∫Ldt = 276 pb⁻¹

Dark Higgs

arXiv:1502.00084

Dark U(1) spontaneously broken by Higgs mechanism, resulting in one or more dark Higgs bosons h'

- Three possible scenarios:
  - mh' < mA' leads to long-lived h' (decays to SM fermions)
  - MA'<mh' < 2mA' ; h' $\rightarrow$ A'A'*, with A'* $\rightarrow$ ll
  - Mh' > 2mA' ; h' $\rightarrow$ A'A'

Belle considers the third case

- Production via “Higgs-strahlung” in $e^+e^- \rightarrow$ A'h' with h'$\rightarrow$ A'A'
- A' decaying to SM or invisible particles

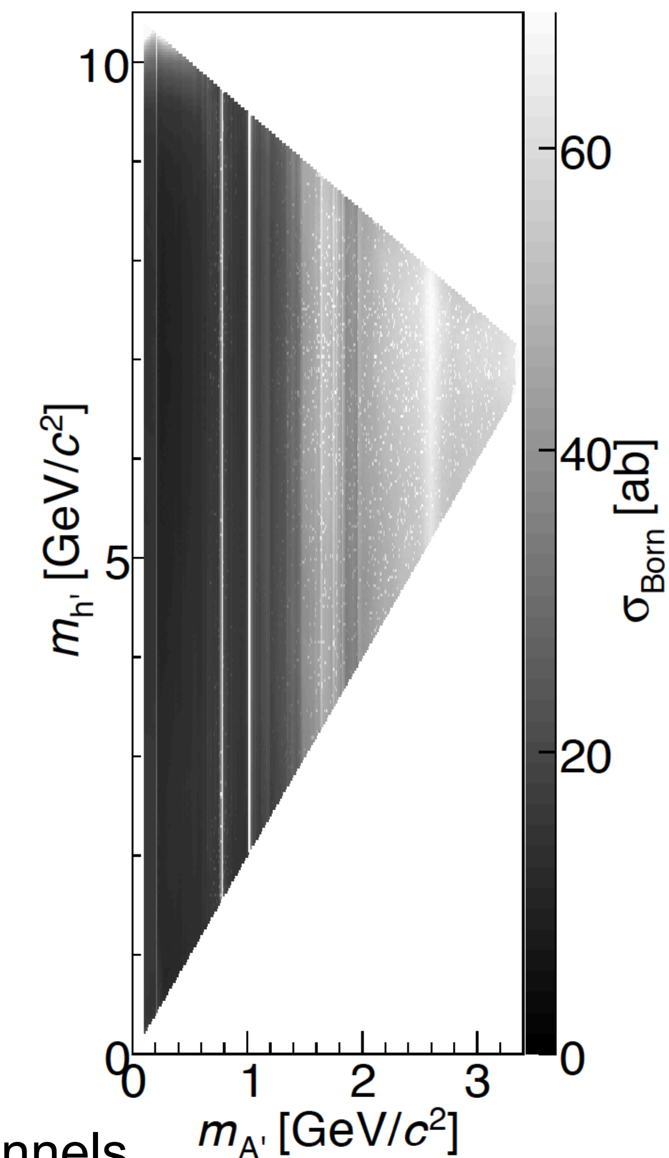
Previous BABAR study
ArXiv:1202.1313[hep-ex]

Dark Higgs

Experimentally, higher multiplicity final states and additional mass constraints results in very low QED backgrounds

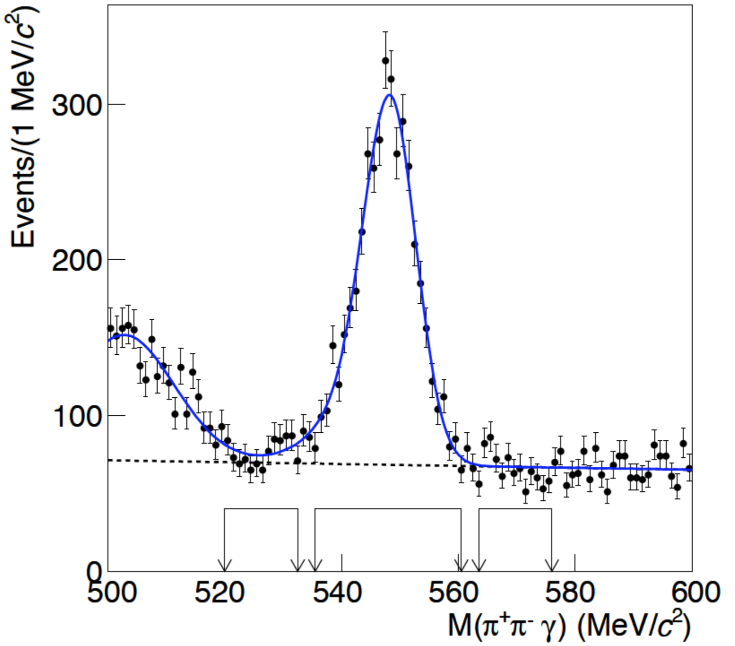
- Vertex constraints enforce “prompt” production
- Require multiple pairs of oppositely charged particles
- Use event kinematics to determine missing mass in “invisible X” channels

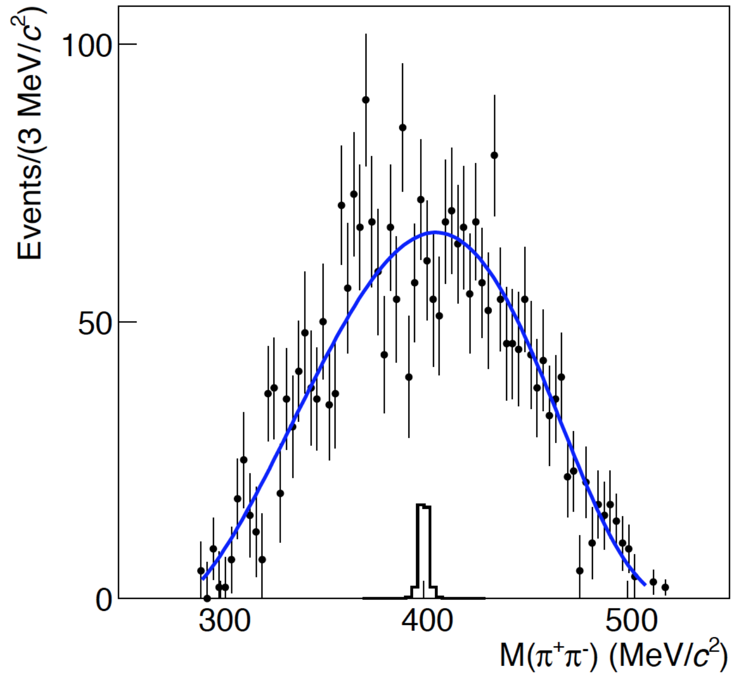
Final-state	Events	Final-state	Events
$3(e^-e^+)$	1	$2(\mu^+\mu^-)(e^+e^-)$	1
$3(\mu^+\mu^-)$	2	$2(\mu^+\mu^-)(\pi^+\pi^-)$	1
$3(\pi^+\pi^-)$	147	$2(\pi^+\pi^-)(e^+e^-)$	5
$2(e^+e^-)(\mu^+\mu^-)$	7	$2(\pi^+\pi^-)(\mu^+\mu^-)$	6
$2(e^+e^-)(\pi^+\pi^-)$	2	$(e^+e^-)(\mu^+\mu^-)(\pi^+\pi^-)$	7
$2(e^+e^-)X$	572	$(e^+e^-)(\mu^+\mu^-)X$	30
$2(\mu^+\mu^-)X$	20		



Search for 13 final states including missing energy channels

Dalitz decays





arXiv:1609.05599