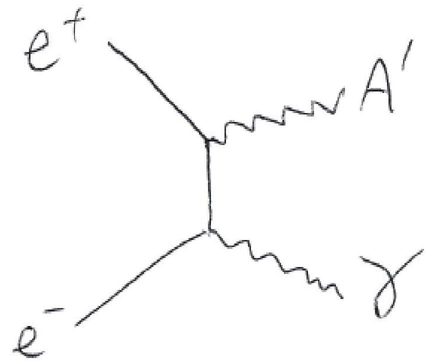
Opportunities with Phase 2: Dark Sector

E. Graziani

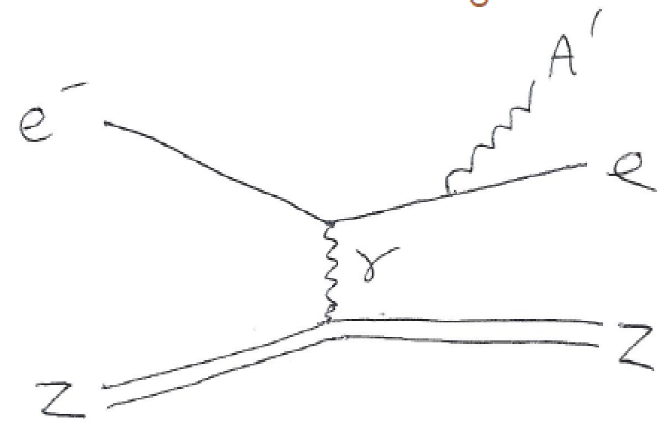
Dark photon production mechanisms

e^+e^- annihilation



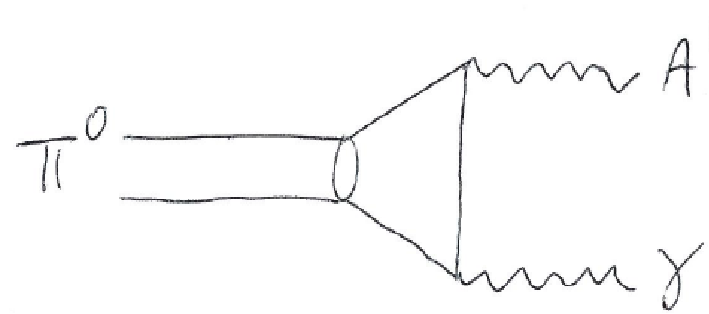
$$\sigma \propto \varepsilon^2 \alpha^2 \left(1 - m_{A'}^2 / E_{CM}^2\right) / E_{CM}^2$$

e^- bremsstrahlung



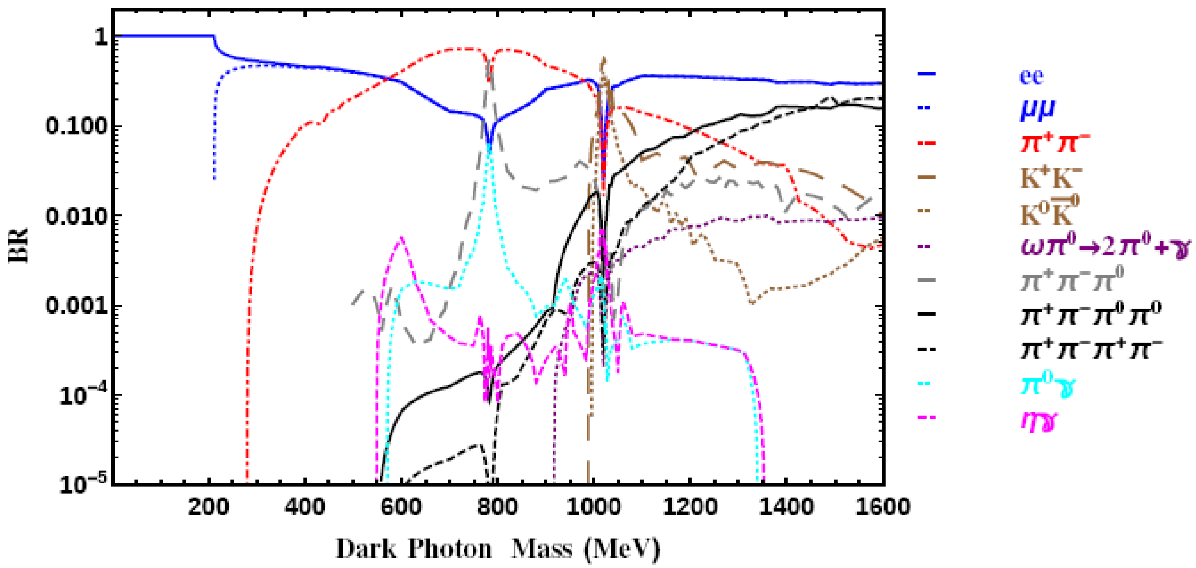
$$\sigma \propto \varepsilon^2 \alpha^3 Z^2 / m_{A'}^2$$

meson decay



$$\mathcal{B} = 2\varepsilon^2 \left(1 - m_{A'}^2 / m_{\pi^0}^2\right)^3$$

Dark photon visible decays



- The dark photon visible decay sector is quite crowded.

- Huge and impressive harvest of results during the last ~ 7 years, from colliders, fixed target, meson decay experiments.

- The possibility of explaining $(g\text{-}2)_\mu$ is now closed (mostly due to NA48/2 $\pi^0 \to \gamma e^+ e^-$ search)

- Still vast and interesting regions to explore, but they require luminosities well beyond Phase 2.

From SLAC Dark Sectors Workshop executive summary

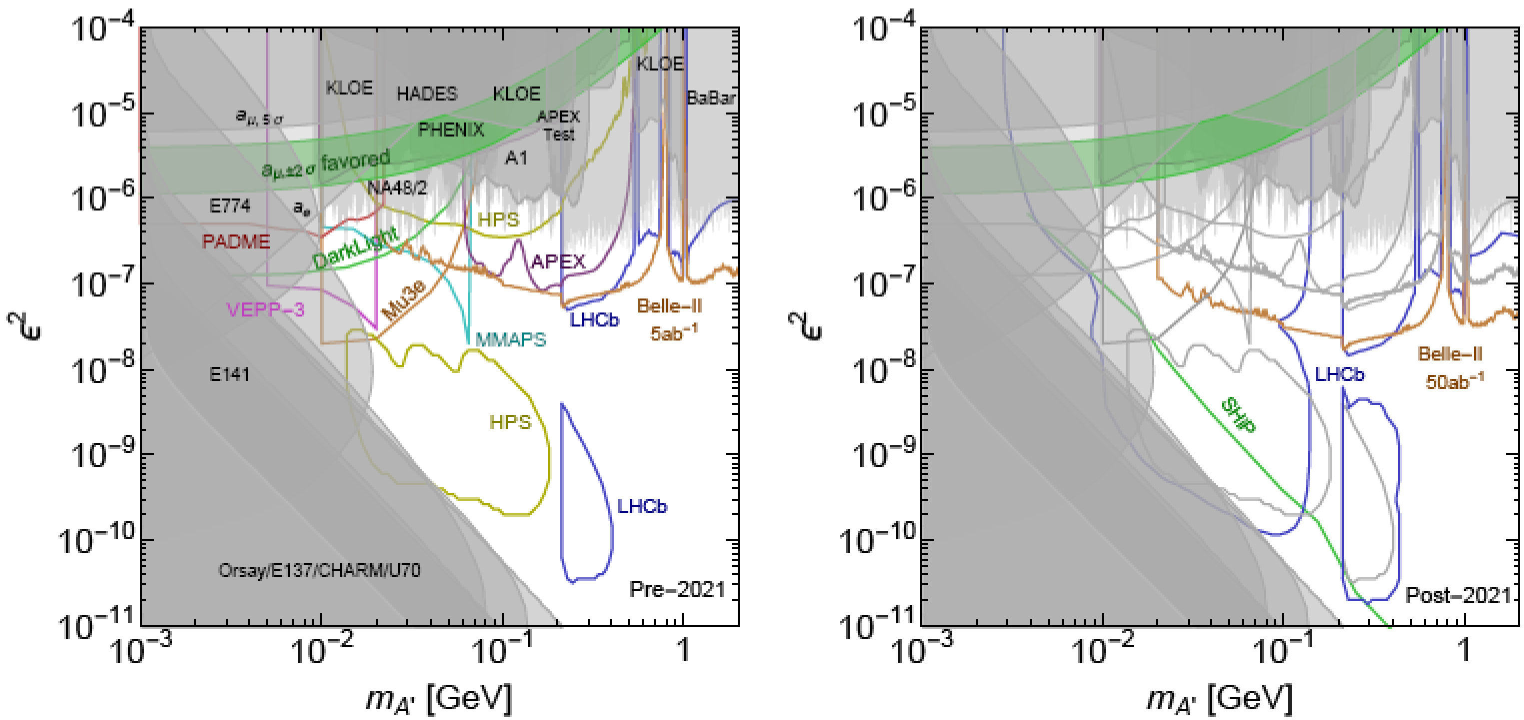


FIG. 4: Sensitivity to A' for exclusive experiments seeking visible decay modes $A' \to \ell^+\ell^-$. **Left:** Experiments capable of delivering results over the next 5 years to 2021. Shaded regions show existing bounds. Green band shows 2σ region in which an A' can explain the discrepancy between the calculated and measured value for the muon $g-2$. **Right:** Longer term prospects beyond 2021 for experimental sensitivity. All projections on left plot are repeated in gray here. Note that LHCb and Belle-II can probe to higher masses than 2 GeV and SHIP can probe to lower values of ϵ than indicated.

One real golden channel at Phase 2: search for the invisible decays of the dark photon

- Much more unconstrained wrt visible decay case
- May still probe $(g-2)_{\mu}$ anomaly
- May give access to light dark matter
- Requires specific triggers (not guaranteed at higher luminosities)
- Both signal and background come from the continuum $\rightarrow$
- $\rightarrow$ can be searched at any c.m. energy, provided machine conditions are good

From B2TIP report (draft)

14.6 Search for a Dark Photon decaying into Light Dark matter (C. Hearty, T. Ferber)

Dark sectors are an exciting topic in particle physics. These theories introduce new particles that interact gravitationally with standard model matter, but do not interact directly via the SM electroweak or strong forces. Such particles would be the dark matter that is observed astronomically.

14.6.1 Theory

There are a variety of theories that involve a dark sector. One of the simplest includes a dark photon A' that mixes with strength ε to the standard model photon [59]. Annihilation of heavy dark matter fermions would produce an A', which would decay to standard model particles, if the A' is the lightest dark sector particle. This process could explain the positron excess observed by PAMELA, Fermi LAT, and AMS [60, 61, 62]. These observations are consistent with an A' mass $M_{A'}$ in the MeV/c^2 to GeV/c^2 range. With this mass, the A' could be radiatively produced in e^+e^- collisions, $e^+e^- \to \gamma A'$.

The cross section for this process is proportional to $\varepsilon^2\alpha^2/E^2_{CM}$ [63]. The decay branching fractions of the A' are the same as a virtual photon of mass $M_{A'}$ (i.e. $e^+e^- \to \gamma^* \to X$).

A significant number of experiments have recently published results of A' searches where the A' decays into charged lepton pairs. Several other dedicated experiments will proceed over the next several years. A recent search by BaBar for the radiative production of the A' in the e^+e^- and $\mu^+\mu^-$ final states used 514 fb^{-1} of data [64]. The standard model rates for $e^+e^- \to \gamma e^+e^-$ and $e^+e^- \to \gamma\mu^+\mu^-$ are large, and the search for the A' consists of a search for a narrow peak in the dilepton mass spectrum on top of a large background.

If the A' is not the lightest dark sector particle, it will dominantly decay into light dark matter via $A' \to \chi\bar{\chi}$. Since the interaction probability of dark matter with the detector is negligible, the experimental signature of such a decay will be a mono-energetic ISR photon γ_{ISR} with energy $E_\gamma = (E^2_{CM} - M^2_{A'})/(2E_{CM})$. This search requires a L1 trigger that is sensitive to single photons which was not available at Belle and only partially available at BaBar. BaBar recorded about 57 fb^{-1} of data with various single photon triggers in its final year of operations, including a scan above $\Upsilon(4S)$. 28 fb^{-1} of this data recorded at the $\Upsilon(3S)$ resonance was used in a search for invisible decays of the light Higgs A^0, $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible. The result was presented in a conference note [65], but has not yet been published.

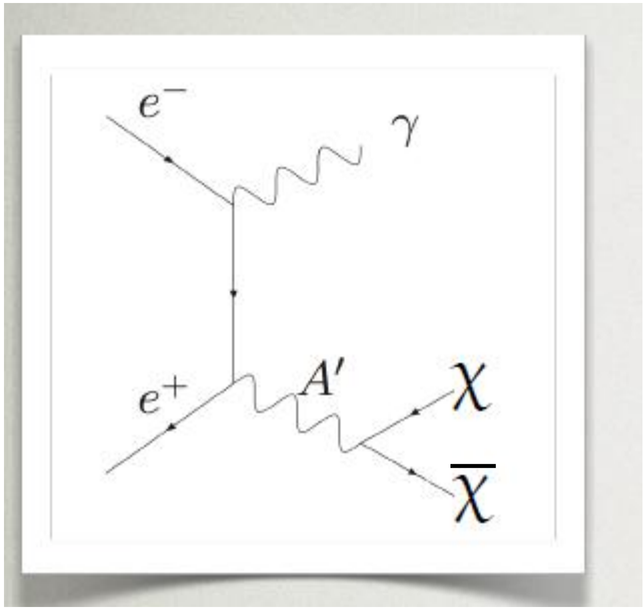
14.6.2 Experiment

Monte Carlo Simulation

Signal MC events ($e^+e^- \to \gamma A', A' \to \chi\bar{\chi}$) are generated using MadGraph [66] and a model based on [67] that includes a dark photon A' and fermionic dark matter χ. Each signal sample is generated using a fixed dark photon mass $m_{A'}$ = [0.1, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 8.5, 8.75, 9.0, 9.25, 9.5, 9.75] GeV and contains 50000 events. Events are generated for a maximal photon pseudo-rapidity of $\eta^*_\gamma < 1.681$, which corresponds to $|\cos(\theta^*_\gamma)| = 0.933$. The beam energy is set to $E^* = 10.58$ GeV. We assume a dark matter mass $m_\chi = 1$ MeV, and we set the coupling to $g_e = g_\chi$. The decay width of the dark photon is set to the tree–level width which increases slowly with $m_{A'}$ and is of $\mathcal{O}$(MeV). We assume that all decays of the A' are into $\chi\bar{\chi}$ and set the kinetic mixing parameter to $\epsilon = 1$. The resulting cross section, including vacuum polarization corrections (up to about 10 %), is shown in Fig. 14.3.

The background in this analysis is dominated by high cross section QED processes $e^+e^- \to e^+e^-\gamma(\gamma)$ and $e^+e^- \to \gamma\gamma(\gamma)$ that

The process



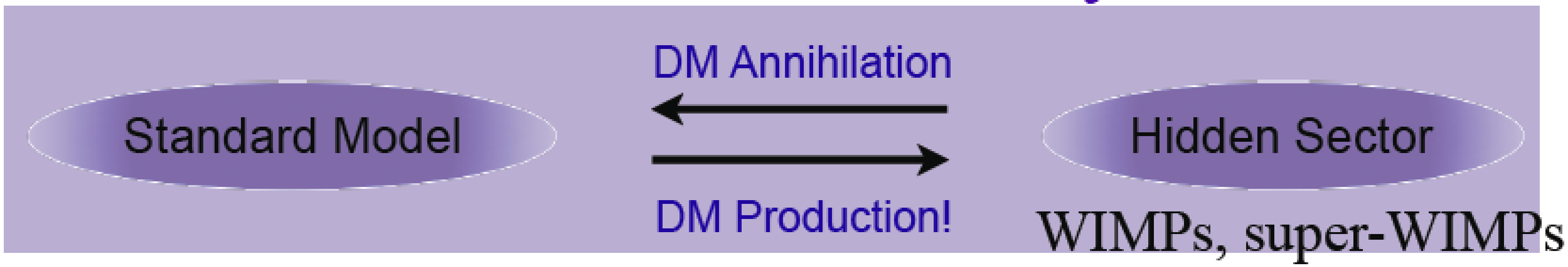
monochromatic photon

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

Kinematically equivalent description in terms of E_γ or $m_{A'}$ (missing mass)

If light dark matter $m_{A'} > 2m_\chi$ exists, then all BRs to SM particles ~ ε^2 $\Rightarrow$ $BR(A' \rightarrow \chi\overline{\chi}) \approx 100\%$, with χ escaping detection

Possible connection to WIMP-y dark matter



Mediators (SM Z, h etc or dark force)

Heavy WIMP/heavy mediators: - "mainstream" literature

Light WIMPs/light mediators: Boehm et al; Fayet; MP, Ritz, Voloshin; Hooper, Zurek; others

Heavy WIMPs/light mediators: Finkbeiner, Weiner; Pospelov, Ritz, Voloshin (secluded DM); Arkani-Hamed et al., many others

Light WIMPs/heavy mediators: does not work. (Except for super-WIMPs; or non-standard thermal history)

M. Pospelov

Light WIMPs due to light mediators direct production/detection

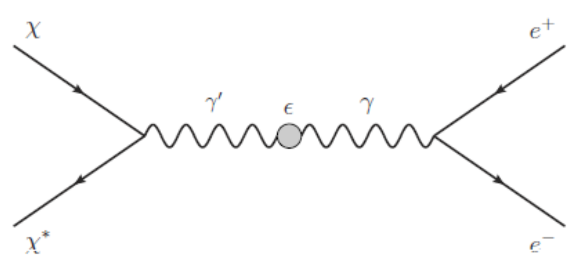
(Boehm, Fayet; MP, Riz, Voloshin ...) Light dark matter is not ruled out if one adds a light mediator.

WIMP paradigm: $\sigma_{\rm annih}(v/c) \sim 1 \text{ pbn} \implies \Omega_{\rm DM} \simeq 0.25,$

Electroweak mediators lead to the so-called Lee-Weinberg window,

$$\sigma(v/c) \propto \begin{cases} G_F^2 m_\chi^2 & \text{for } m_\chi \ll m_W, \\ 1/m_\chi^2 & \text{for } m_\chi \gg m_W. \end{cases} \implies \text{few GeV} < m_\chi < \text{few TeV}$$

If instead the annihilation occurs via a force carrier with light mass, DM can be as light as ~ MeV (and not ruled out by the CMB if it is a scalar).

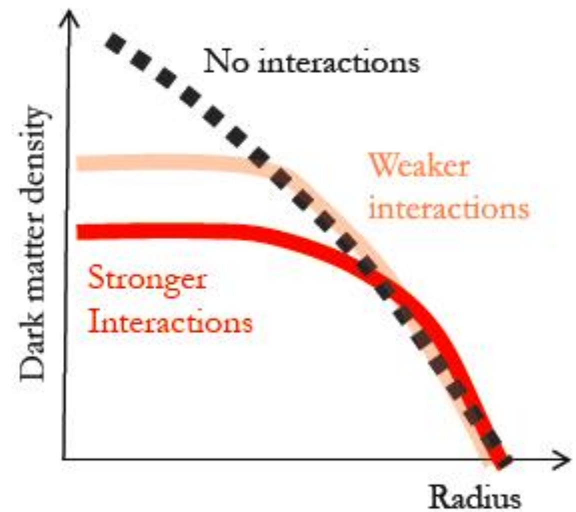


M. Pospelov

Dark matter and structure of galaxies

Core/cusp problem: Galaxies and clusters are less dense than cold dark matter (WIMPs) predictions

Moore (1994), Flores & Primack (1994)

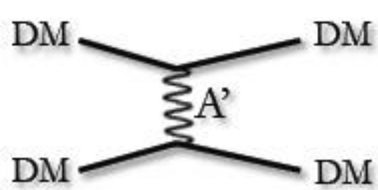


Self-interacting dark matter

Spergel & Steinhardt (2000)

MeV–GeV scale dark force

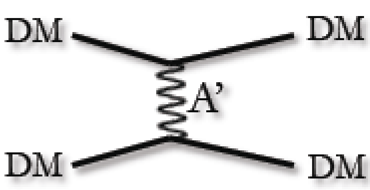
ST, Yu, Zurek (2013)

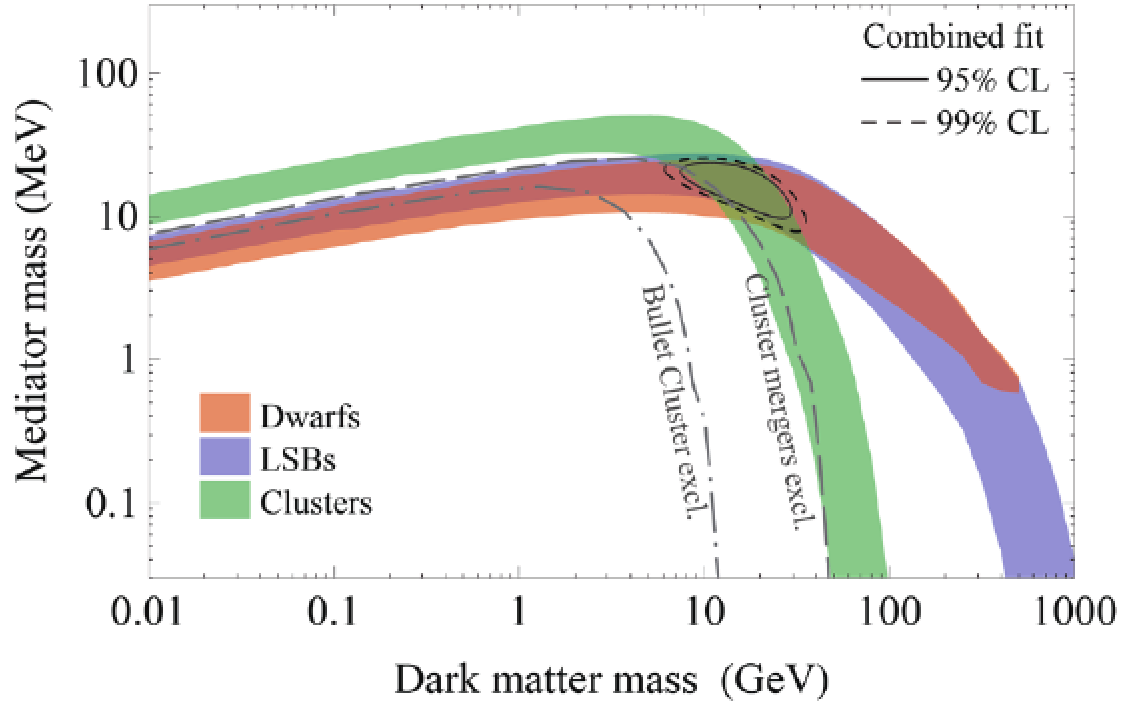


S. Tulin

Dark matter with dark photon

Self-interactions via
gauge boson mediator





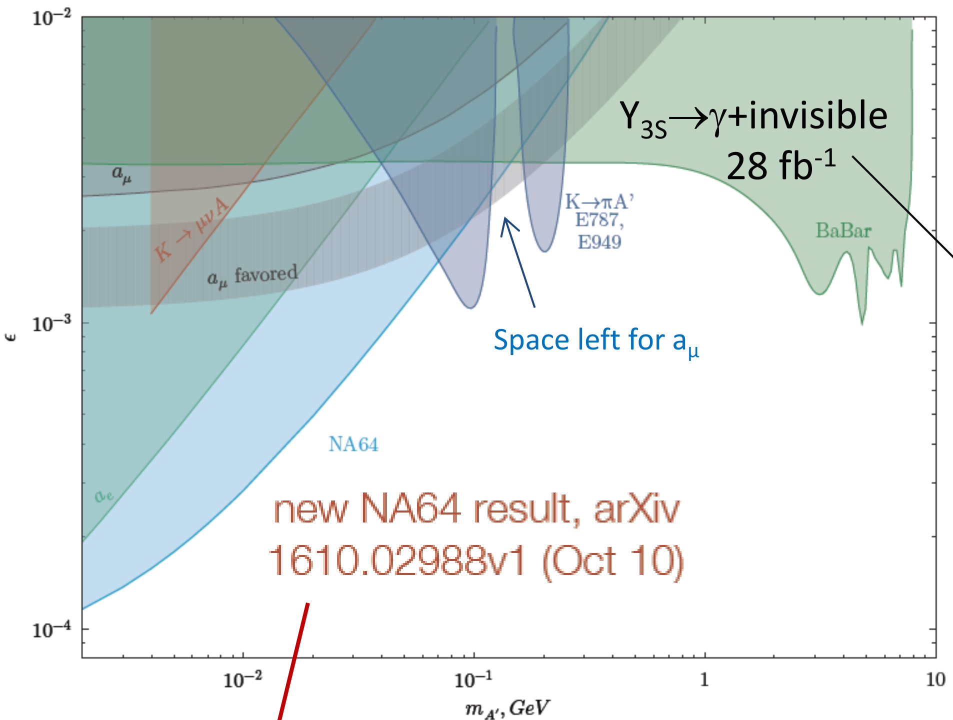
Kaplinghat, ST, Yu (2013)

Model-dependent: Dark sector parameters can be fit from astrophysical data.
Not fixed how dark photon couples to Standard Model (kinetic mixing unknown)

Model-independent: Dark sector particles below GeV scale to get large enough cross section

S. Tulin

Dark photon to invisible: present situation



Two week data taking run in July
(criticized result)

BaBar took a small portion (~54 fb^{-1}) of the full data set with a single photon trigger.

Belle never had one

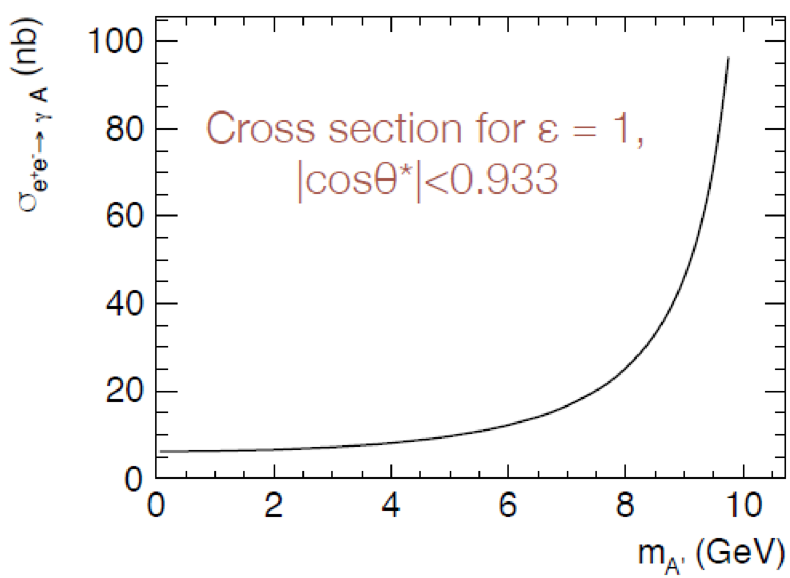
Unpublished (conference paper) reinterpretation of a $Y_{3S}\rightarrow\gamma+h_0$ search. Angular distributions are quite different (vector vs scalar). Some refinement of the measurement expected. Former Belle II projections were based on this result.

From C. Hearty presentation at October Belle II GM

MC samples

- All produced by Torben, at CLUMEQ (McGill), Phase 2 geometry and background levels.
  - Bhabhas and radiative Bhabhas scaled by 0.025; others by 0.1, using 12th BG campaign (no two-photon)

- Signal: MadGraph, various A′ masses



From C. Hearty presentation at October Belle II GM

Backgrounds

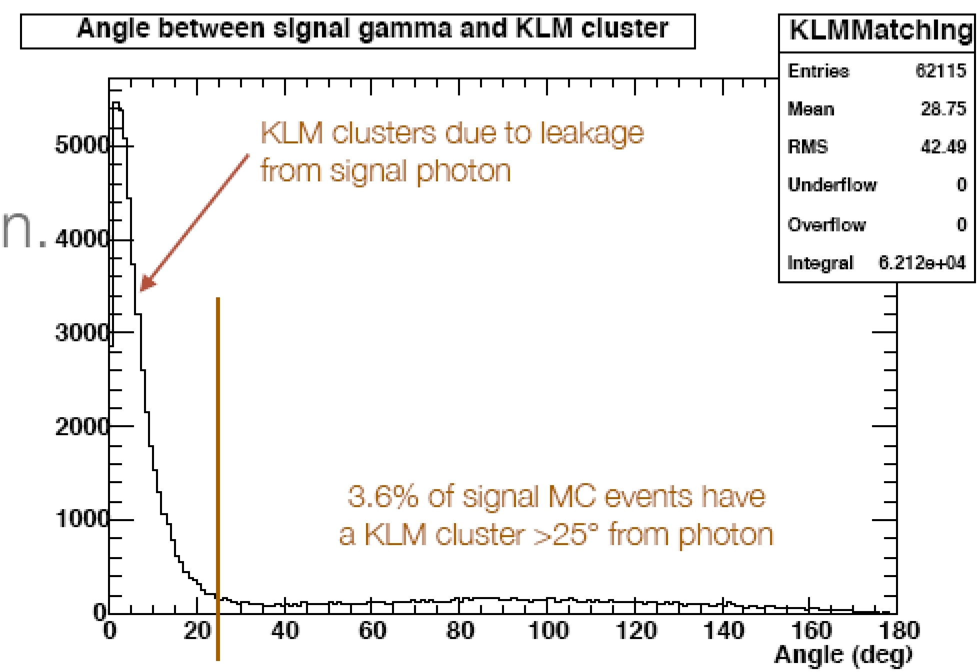
- Irreducible: final state has only one photon in [12°,157°]
  - 2M events with $E^* > 1.8$ GeV and $22° < \theta < 139°$ in $20\ fb^{-1}$ (0.1 nb); E and θ are strongly correlated.
  - 85% due to radiative Bhabhas
  - 15% due to $e^+e^- \to \gamma\ \gamma\ (\gamma)$ (minimum 3 photons in final state)

- Reducible: two photons in detector, one of which is missed in both ECL and KLM

From C. Hearty presentation at October Belle II GM

Event selection (other than final cut on θ_{lab})

- E^* >1.8 GeV with no other ECL cluster with E^* > 0.1 GeV
- No tracks with p_t>0.2 GeV/c
- No KLM cluster >25° (3D angle in center of mass) from signal photon.
- Not optimized.



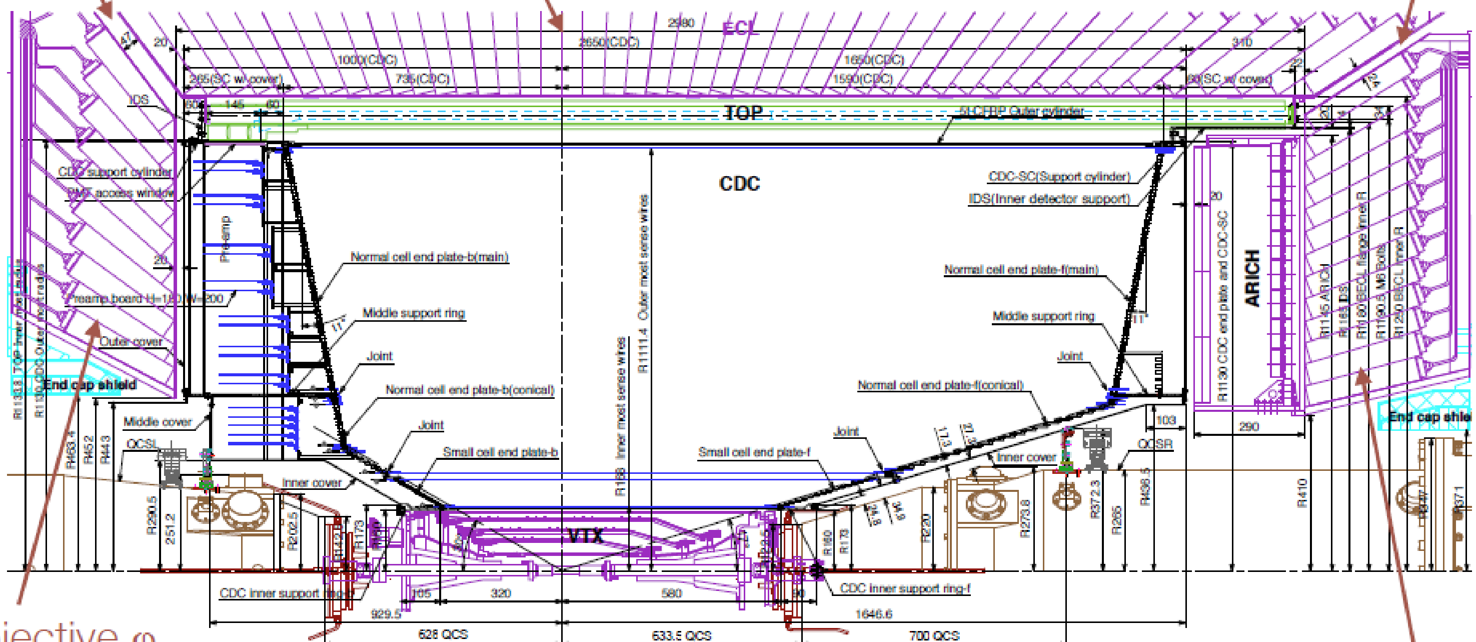
From C. Hearty presentation at October Belle II GM

Sources of ECL inefficiency (in order of importance)

1. barrel/endcap gap

4. 1.5mm structure at 90°

2. barrel/endcap gap



3. projective φ cracks in endcaps

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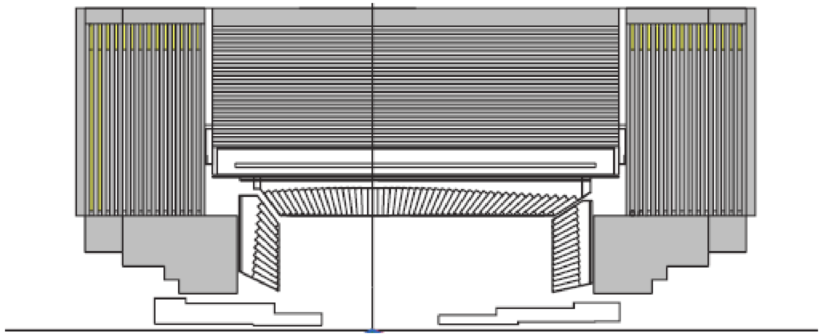
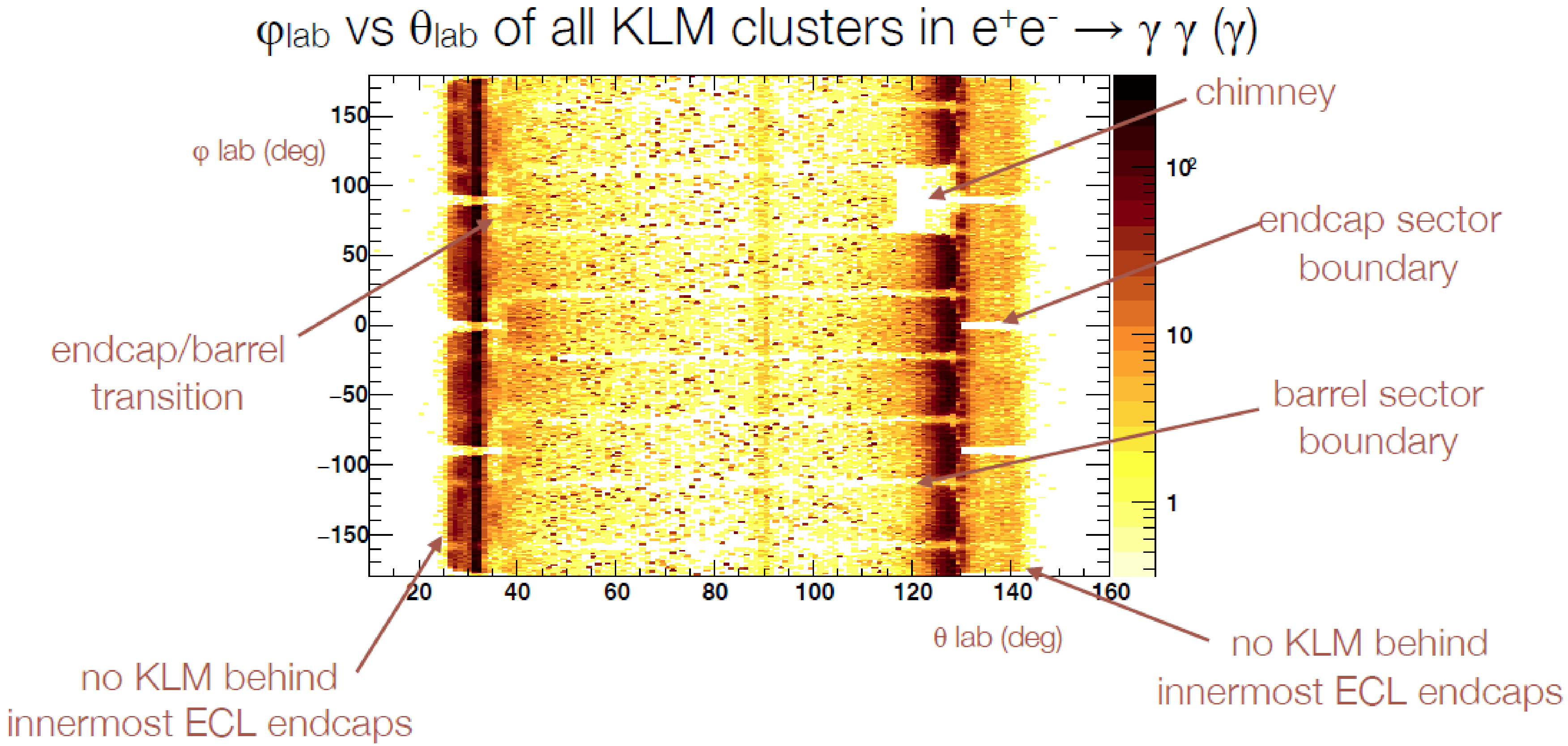
5. γ non-conversion 3×10^{-6}

From C. Hearty presentation at October Belle II GM

Sources of KLM inefficiency

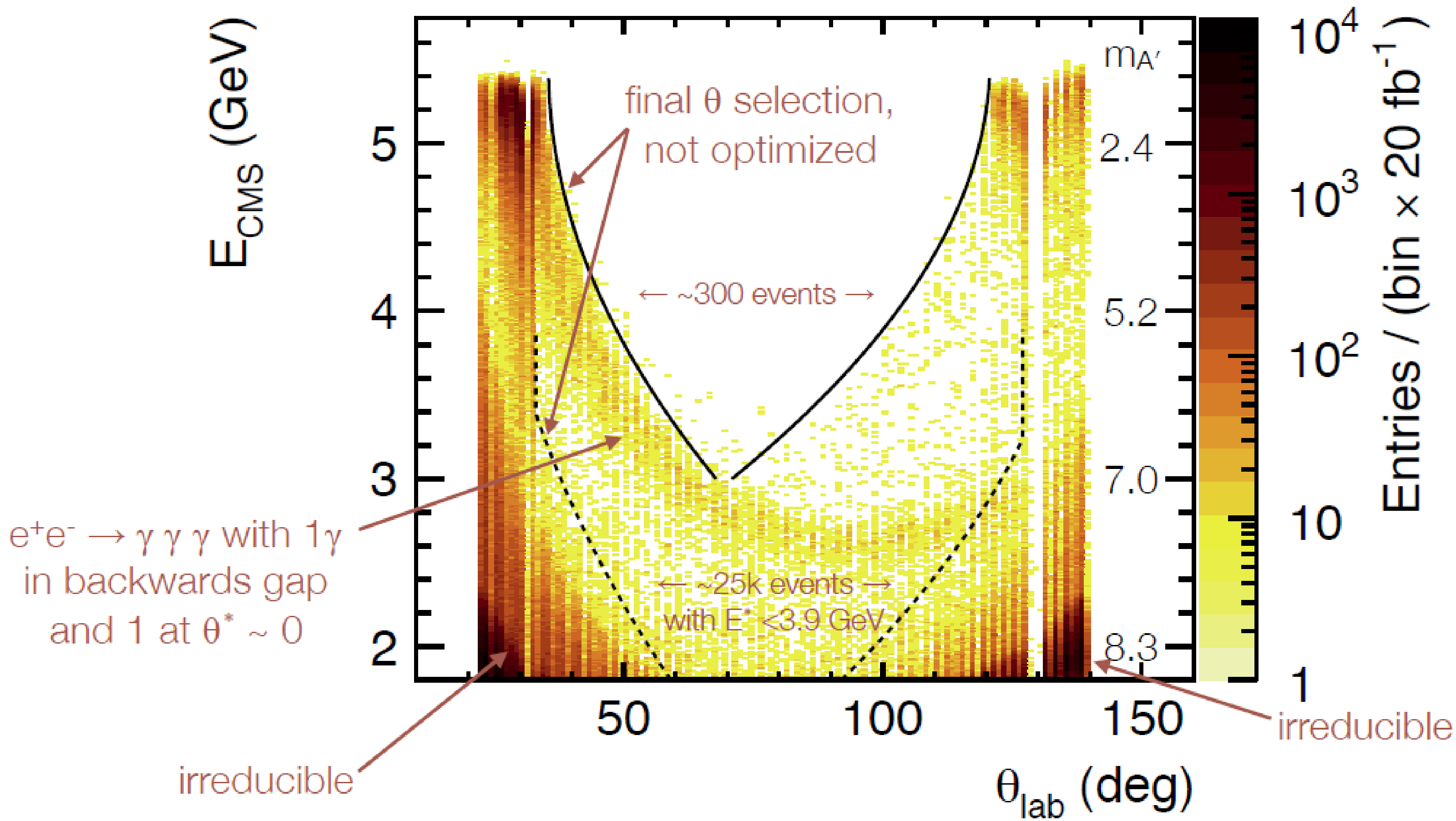




From C. Hearty presentation at October Belle II GM

Predicted backgrounds in 20 fb^{-1}

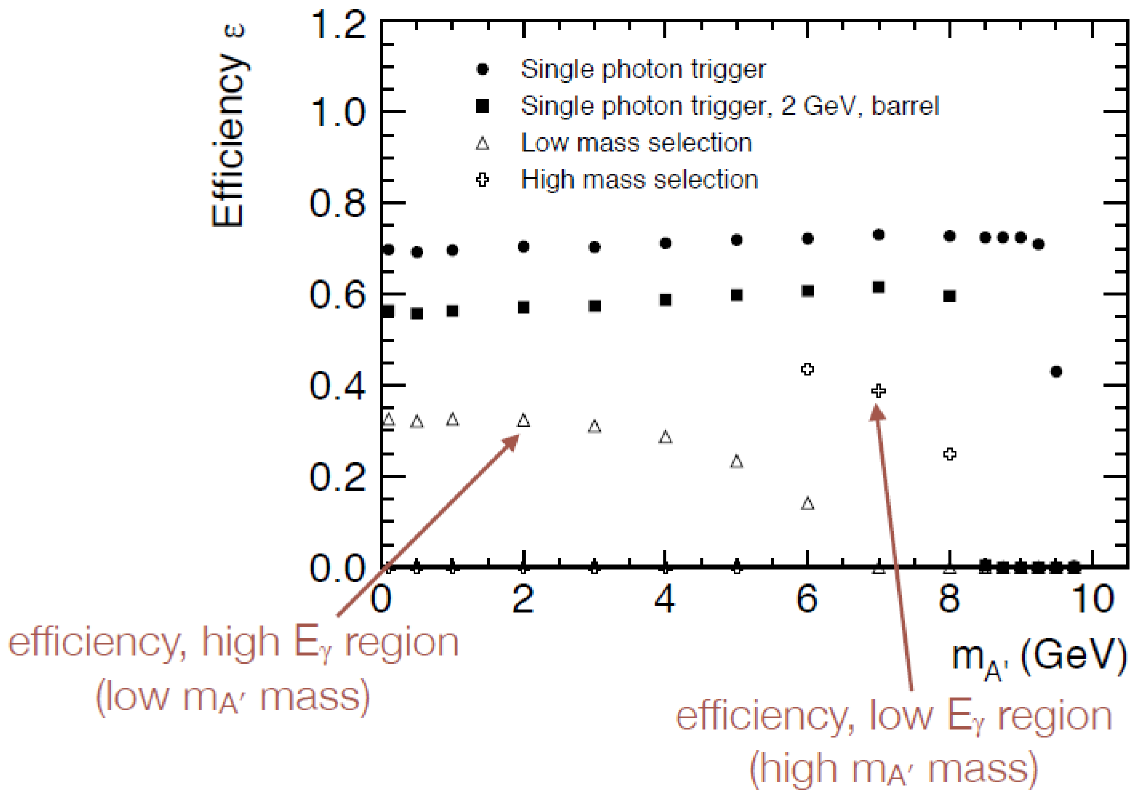
- Final sample is almost entirely $e^+e^- \to \gamma\,\gamma\,(\gamma)$ with $\geq 3\gamma$



From C. Hearty presentation at October Belle II GM

Efficiency for signal events

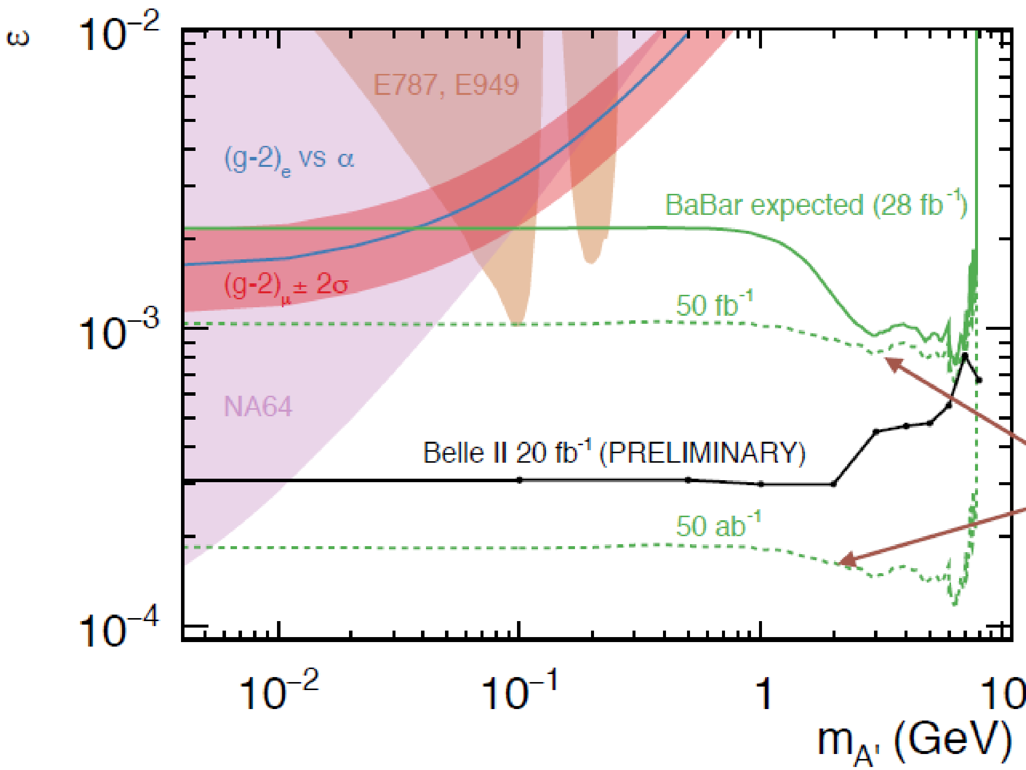
- Signal inefficiency is dominated by acceptance.



From C. Hearty presentation at October Belle II GM

Projected upper limits on ε as a function of $m_{A'}$ for 20 fb^{-1} Phase 2 data set

- Limits are much better than earlier projections derived from BaBar because of better detector performance.
  - no projective cracks in φ; fully functioning muon system



** note MC truth-based background estimation **

earlier projections

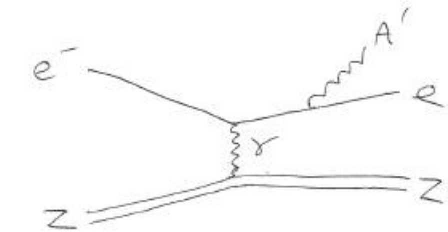
Big improvement wrt former projections based on BaBar: mostly due to the non-projective cracks of ECL

Probably optimistic, but anyway a solid indication of a very interesting potential reach. Main concerns are about:

- Truth Monte Carlo vs real life
- Machine conditions
- Trigger performances (or, more generally, sustainability)

Anyway, let's take literally this estimate and locate it in time, somewhere in late 2018

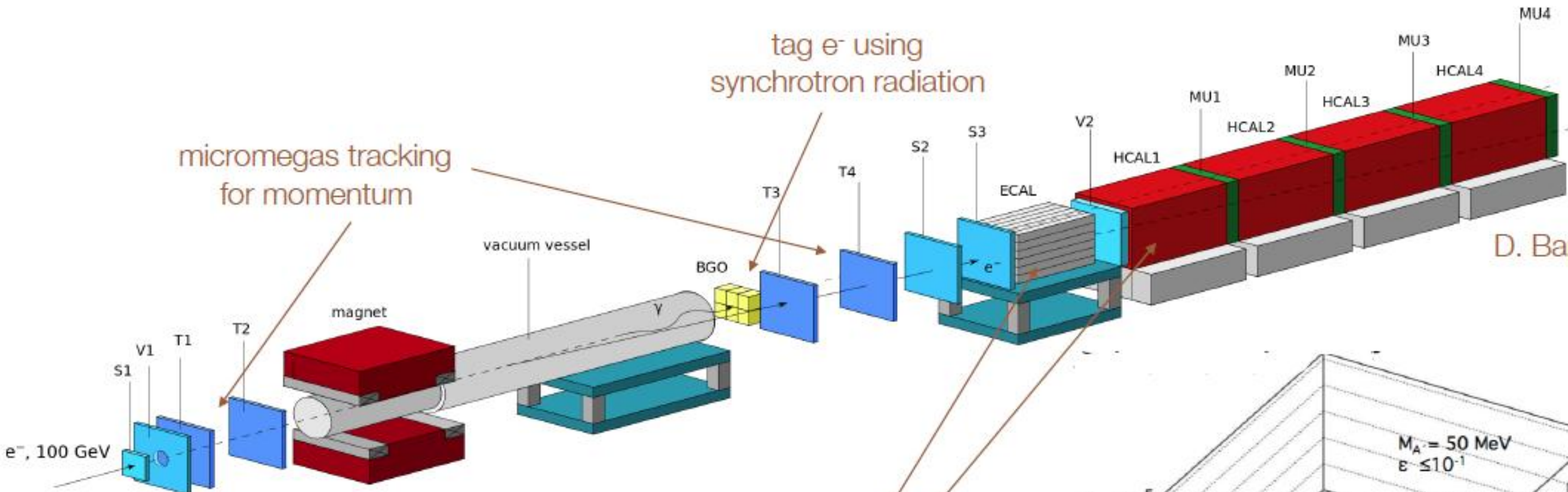
NA64 (CERN): search for invisible A′ decays using an active beam dump



- 100 GeV e⁻ from H4 beam line. 2 week run in July

tag e⁻ using synchrotron radiation

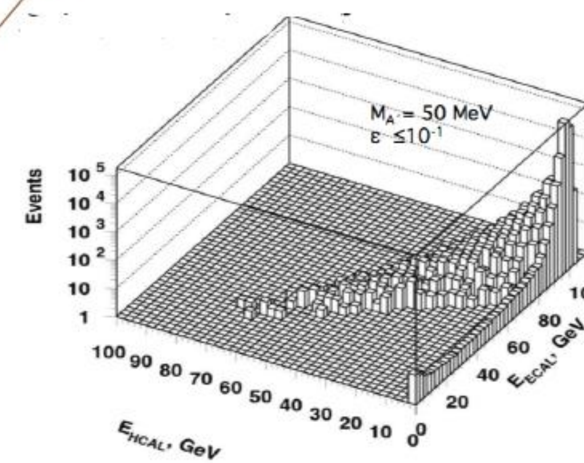
micromegas tracking for momentum



D. Banerjee

5x10[10] e⁻/month

SM processes will deposit full energy in ECAL+HCAL; A′ will give no energy in HCAL and low energy in ECAL

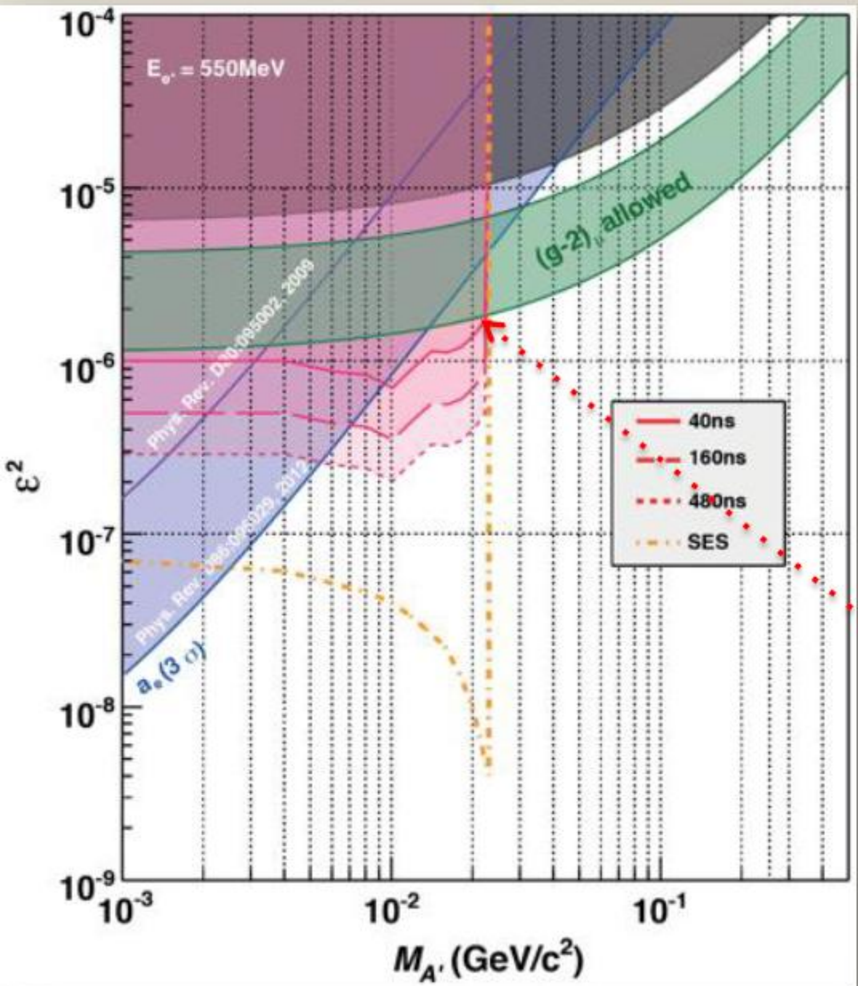


NA64: Preliminary schedule of the experiment

Item	Activities	2014 Q1 Q2 Q3 Q4	2015 Q1 Q2 Q3 Q4	2016 Q1 Q2 Q3 Q4	2017 Q1 Q2 Q3 Q4	2018 Q1 Q2 Q3 Q4	2019 Q Q2 Q3 Q4	2020 Q1 Q2 Q3 Q4
	LHC operation SPS operation							
Experiment Phase I	Prototypes design	**						
	Prototypes fabrication:	****	***					
	ECAL&HCAL	**	***					
	Tracker	**	***					
	Sc counters							
	VETO counter		**					
	Decay volume							
	DAQ	***	***					
	Delivery at CERN		*					
	Assembly, commissioning		*					
	Test run		**					
Experiment Phase II	Technical design report		*	*				
	R&D			*				
	TDR approval			**				
	Detector production			****				
	Detector installation			*				
	Commissioning			*				
	Experiment operation			**	*****	***		*****
Beam	magnet		**					
	SR vacuum line		***					

They will run all along 2017 (and part of 2018)

PADME (LNF) will start by ~ mid 2018
(after KLOE-2 roll out)



- Based on 2.5×10^{10} fully GEANT4 simulated 550MeV e+ on target events
  - Number of BG events is extrapolated to 1×10^{13} electrons on target
- Using $N(A'\gamma)=\sigma(N_{BG})$
- δ enhancement factor $\delta(M_{A'}) = \sigma(A\square\gamma)/\sigma(\gamma\gamma)$ with ε=1 due to A' mass

$$\frac{\Gamma(e^+e^- \to A'\gamma)}{\Gamma(e^+e^- \to \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \cdot \delta$$

PADME 2 years of data taking at 60% efficiency with bunch length of 40 ns
10^{13} EOT = **6000 e⁺/bunch × 3.1·10⁷s · 49 Hz**

PADME can explore in a ***model-independent way the*** favorite by $(g\text{-}2)_\mu$ band up to $M^2_{A'} = 2m_e E_{e+}$

E_{e+}=550 MeV: $M_{A'} < 23.7$ MeV/c^2

E_{e+}=750 MeV: $M_{A'} < 27.7$ MeV/c^2

E_{e+}=1 GeV: $M_{A'} < 32$ MeV/c^2

KLOE-2 implemented a single photon trigger (~ 350 MeV threshold, barrel only) right now and will (hopefully) run with it up to the end of the data taking (approximately additional 2 fb^{-1} by mid 2018). Rough potential reach ~ 10^{-3}, but more studies are needed (it might be sustantially better or worse, depending on how well machine background is rejected).

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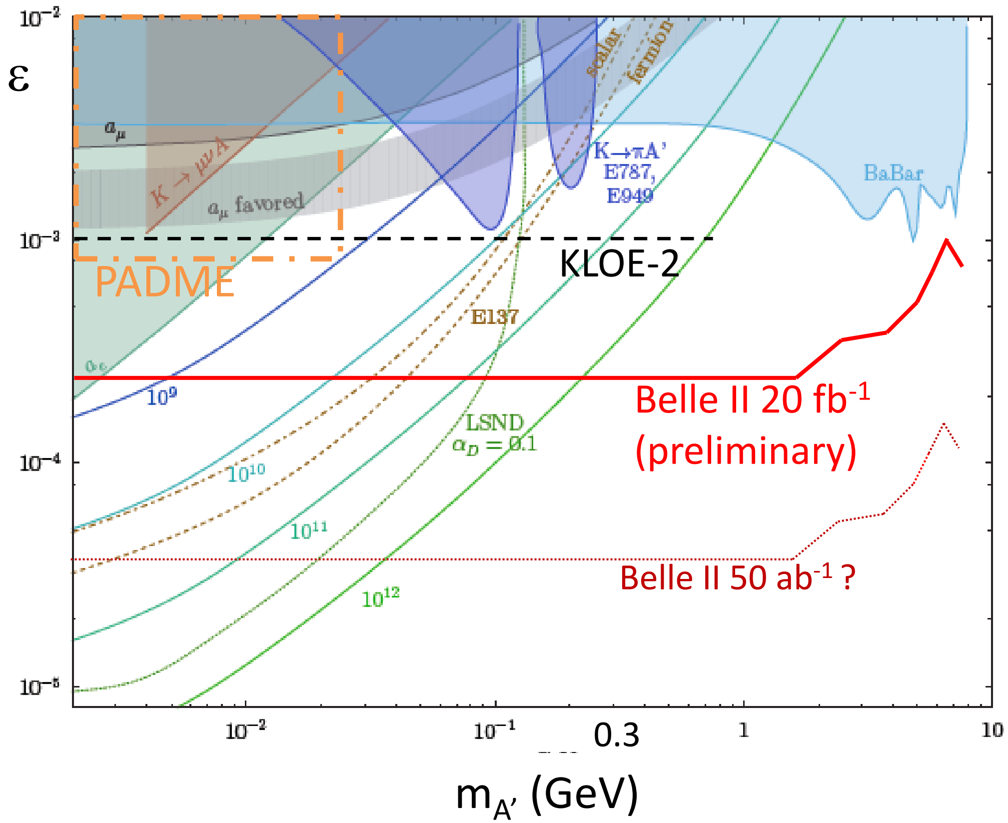

A very interesting picture for us , both along horizontal and vertical scales

Don't take these numbers to the last digit. Lines drawn 'by eye'

Venendo a noi …

La misura è per ora saldamente nelle mani del gruppo di Vancouver/British Columbia (Chris & Torben)

Un possibile spazio di inserimento potrebbe riguardare l’utilizzo del KLM, nelle cui attività di commissioning saremo in ogni caso coinvolti.

KLM può essere usato sia per rivelare fotoni, sia per sopprimere i fondi derivanti da inefficienze di ECL in regioni specifiche.
Inoltre, campioni di $e^+e^- \to \mu^+ \mu^-$ e $e^+e^- \to \mu^+ \mu^- \gamma$ possono consentire una «radiografia» di alta precisione del calorimetro, essendo questa ricerca molto sensibile ad inefficienze, cracks, ecc …

Su questa base abbiamo avuto un breve approccio con Chris allo scorso GM, per il momento senza seguito.

Il gruppo di Roma3 conterà su un nuovo dottorando ad inizio di gennaio (G. De Pietro).
Se decidesse di scegliere questo come argomento di tesi, naturalmente, l’attività potrebbe subire un boost.

BACKUP SLIDES

From C. Hearty presentation at October Belle II GM

Single photon triggers

- Two level 1 triggers for single photon physics. Both exclude lowest angle ECL trigger towers (angles updated since June).

- 1 GeV: $E^* > 1$ GeV, 2nd cluster must have $E^* < 0.2$ GeV
  - cut on 2nd cluster is new since June B2GM

- 2 GeV: $E^* > 2$ GeV, not a Bhabha, not $\gamma\gamma$
  - "aggressive" Bhabha veto:
    $p_1^* > 3$ GeV/c, $p_2^* > 1$ GeV/c, angle >143°,
    ≥1 track associated with an ECL cluster E^*>3 GeV
  - $\gamma\gamma$ veto:
    E_1^*>2.5 GeV, E_2^*>2.5 GeV, >150°, no long tracks

Single photon trigger background cross sections nb

	$\gamma\gamma$	wide angle Bhabhas (both $e^{\pm}$ have $\theta^{*}>1°$)	TEEGG (1 $e^{\pm}$ with $\theta^{*}<1°$)	Total nb
1 GeV	0.2	0.4	1.6	2.2
2 GeV	0.5	2.9	0.1	3.5

- 1 GeV trigger is dominated by true 1γ events; 2 GeV by radiative Bhabhas.
- 2 GeV trigger is also used for ISR physics