B-factory searches for forbidden/rare heavy flavour decays and dark photons

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on behalf of the *BABAR* and Belle Collaborations

Forbidden/rare heavy flavour decays

definitions for this talk

- "forbidden" = lepton and/or baryon number violating heavy flavour decays (LNV, BNV)
  - LN and BN conserved due to SM accidental symmetries
- "rare" = lepton flavour violating heavy flavour decays (LFV)
  - LF also SM accidental symmetry (conservation of each lepton flavour separately)
  - SM + neutrino mixing predicts minuscule charged LFV, not experimentally accessible
  - LNV always implies LFV
- "heavy flavour": b hadrons, c hadrons, τ leptons

forbidden

rare

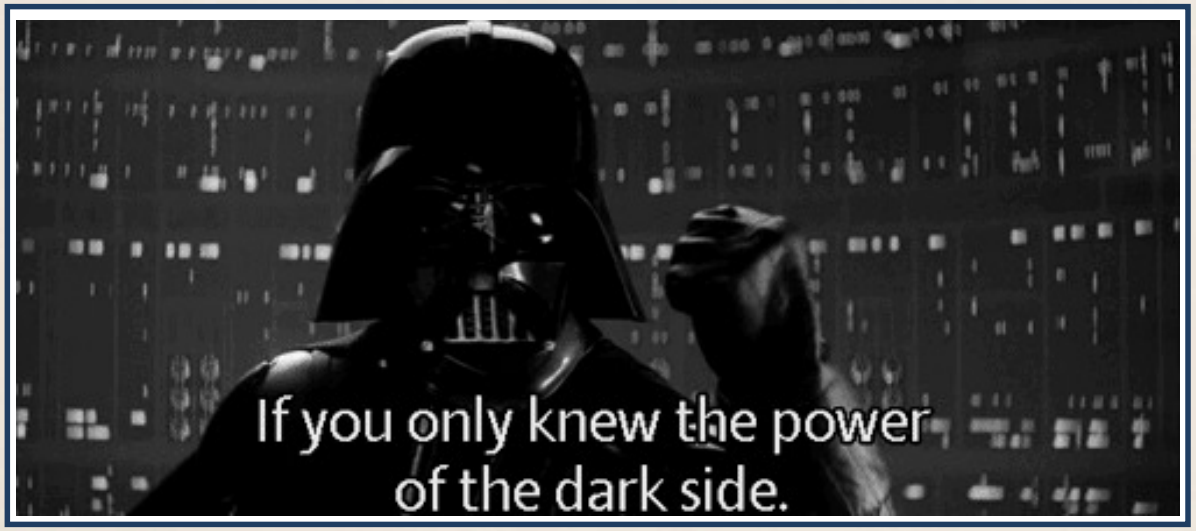
Forbidden/rare heavy flavour decays

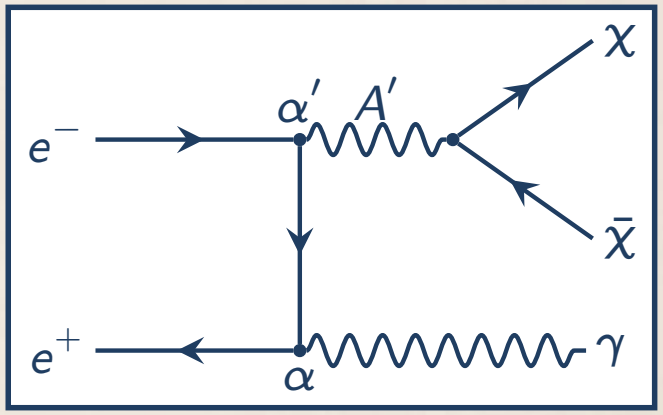
motivation

- why are these decays interesting? their detection would unveil New Physics, plus
  - no (or unmeasurably small) SM background, i.e., very precise SM predictions
  - many NP models naturally include possibly experimentally accessible signals
    - mainstream NP includes LFV (e.g. SUSY, LHT)
    - GUT, models with proton-decay NP include BNV
    - GUT, models with Majorana neutrinos NP include LNV

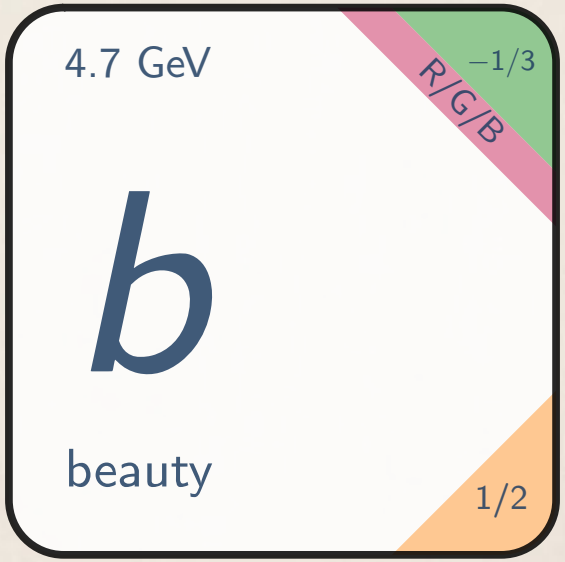
Dark Photon

- postulated member (A') of hidden/dark sector of New Physics models
  - may constitute Dark Matter and/or explain astrophysical anomalies
    - e.g. excess of positrons from galactic core [Astron.Astrophys. 407 (2003) L55]
  - may also explain the experiment vs. theory discrepancy on the muon $g-2$ anomaly
- may be produced in e^+e^- collisions at B-factories energies
  - kinetic mixing, i.e., photon-like coupling with smaller coupling constant α'





LNV/BNV/LFV on decays of *b* hadrons

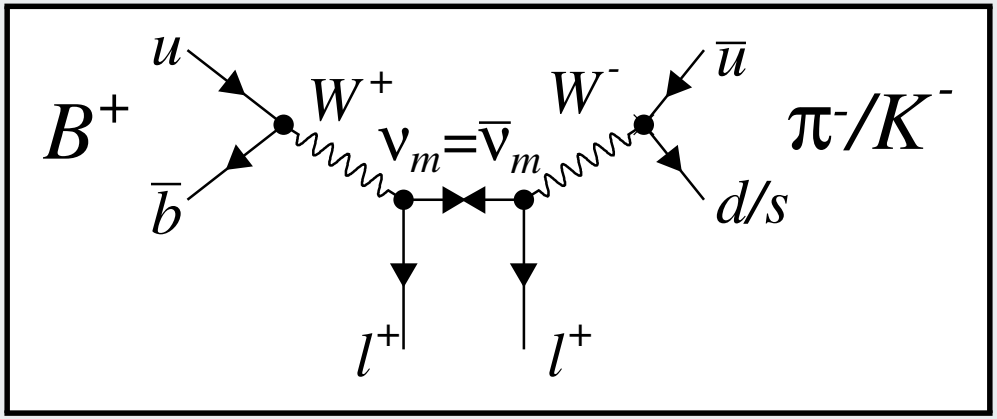


Searches for LNV / LFV B mesons decays

B-factory searches summary

- $B^0 \to \ell^+\ell'^-, \quad \ell^+\ell'^- = e^+\mu^-, e^+\tau^-, \mu^+\tau^-$
- $B^0 \to \pi^0 e^+\mu^-$
- $B^+ \to X^-\ell^+\ell'^+, \quad X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-, \quad \ell^+\ell'^+ = e^+e^+, \mu^+\mu^+, e^+\mu^+$
- $B^+ \to X^0\ell^+\nu_h(\to \ell'^+\pi^-), \quad X^0 = D^{*0}, \pi^0, \rho, \eta, \quad \ell^+\ell'^+ = e^+e^+, \mu^+\mu^+, e^+\mu^+$

Majorana neutrino mediation can produce two same-sign leptons



basic analysis strategy for B mesons decays at B-factories

- require for B candidate the expected $\begin{cases} m_{\mathrm{ES}} = \sqrt{(\sqrt{s}/2)^2 - \left|\vec{p}_B^{\,*}\right|^2} & \text{(beam-energy-substituted mass)} \\ \Delta E = E_B^* - \sqrt{s}/2 \end{cases}$
- no true SM background events expected
- combinatorial / peaking background from mis-id. particles, momentum resolution

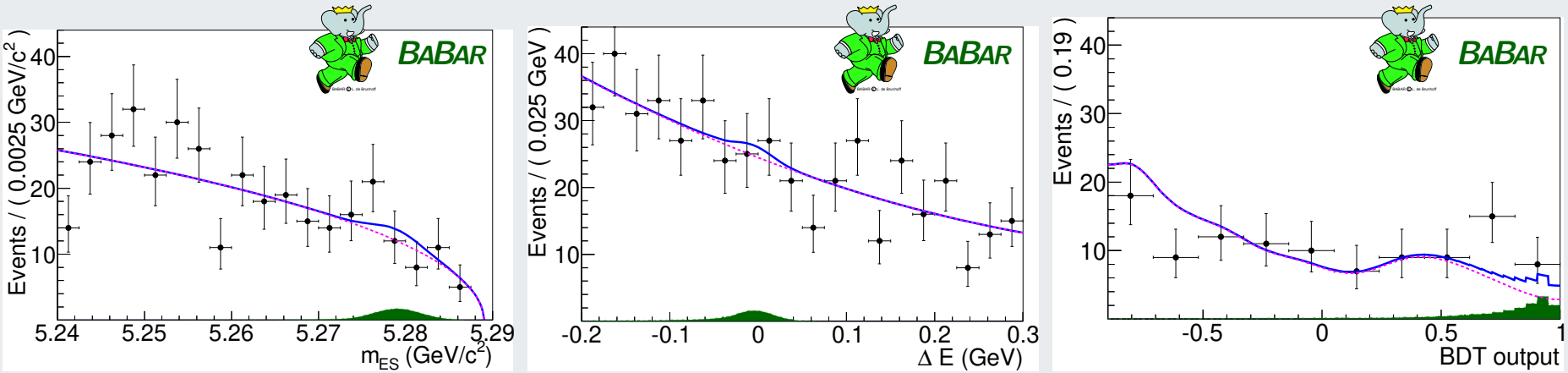
Searches for LNV / LFV B mesons decays

- *BaBar* PRD-RC 85, 071103 (2012)
  - $B^+ \to X^- \ell^+ \ell'^+, \quad X^- = \pi^-, K^-, \quad \ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+$
- *BaBar* PRD-RC 89, 011102 (2014)
  - extends previous search to other modes
  - $B^+ \to X^- \ell^+ \ell'^+, \quad X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-, \quad \ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$
- *BaBar* PRD 86, 012004 (2012)
  - $B^+ \to h^+ \tau^\pm \ell^\mp, \quad$ with $\ell = e, \mu$
- Belle PRD 84, 071106(R) (2011)
  - $B^+ \to X^- \ell^+ \ell'^+, \quad X^- = D^-, \quad \ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$
- Belle PRD 87, 071102 (2013) search for Majorana neutrino $\nu_h \to \ell^\pm \pi^\mp$
  - $B^+ \to X^0 \ell^+ \nu_h (\to \ell'^+ \pi^-) \quad X^0 \ell^\pm \nu_h (\to \ell^+ \pi^-), \quad X^0 = D^{*0}, \pi^0, \rho, \eta$
- *BaBar* PRD 77 032007 (2008) $B^0 \to e\mu$
- *BaBar* PRD 77 091104 (2008) $B^0 \to e\tau$, $B^0 \to \mu\tau$
- *BaBar* PRL 99 051801 (2007) $B^0 \to \pi^0 e\mu$
- *BaBar* PRD 73 092001 (2006) $B^0 \to K^0 e\mu$, $B^0 \to K^{*0} e\mu$

$B^+ \to X^- \ell^+ \ell'^+$, BABAR PRD-RC 85, 071103 (2012)

- $B^+ \to X^- \ell^+ \ell'^+$, $X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-$, $\ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$
- reconstruct B mass and energy, use BDT multivariate selector

$B^+ \to \pi^- e^+ \mu^+$: m, ΔE, BDT output



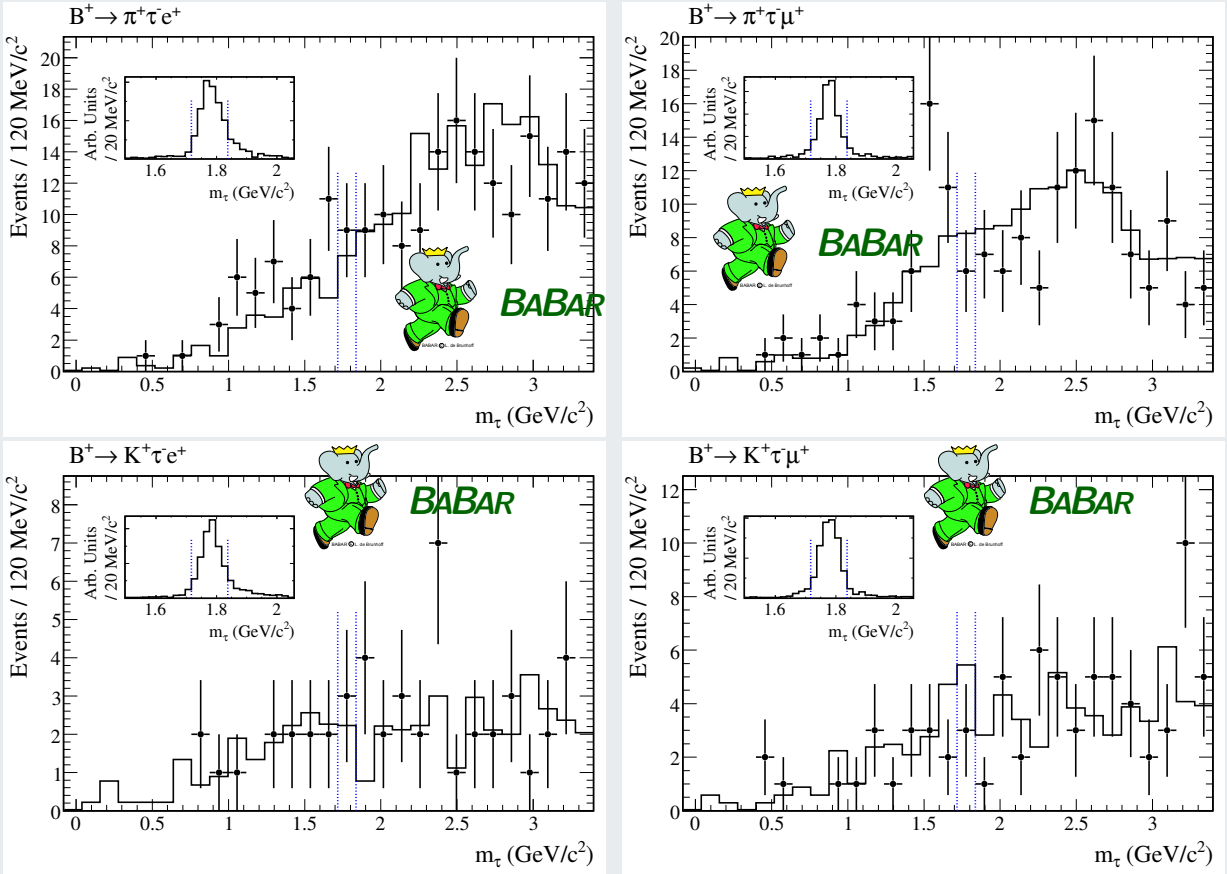
- no significant signal on signal (solid dark green) + bkg fits

$B^+ \to h^+\tau^\pm\ell^\mp$, BABAR PRD 86, 012004 (2012)

analysis

- require B_{tag} fully reconstructed in hadronic mode
- indirectly reconstruct tau mass using B_{tag}, h, ℓ, E_{beam}
- $\vec{p}_\tau = -\vec{p}_{\text{tag}} - \vec{p}_h - \vec{p}_\ell$, $E_\tau = E_{\text{beam}} - E_h - E_\ell$, $m_\tau = \sqrt{E_\tau^2 - |\vec{p}_\tau|^2}$

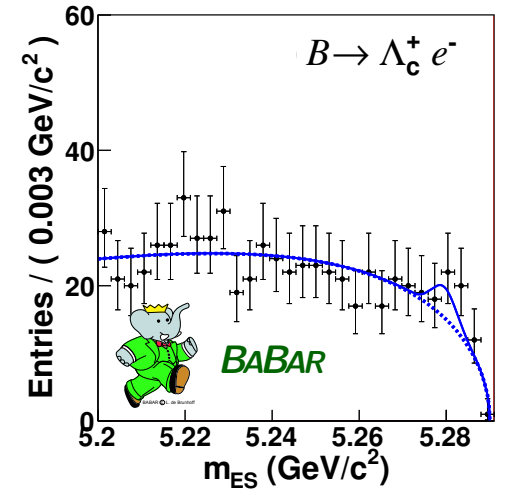
indirectly reconstructed m_τ distributions

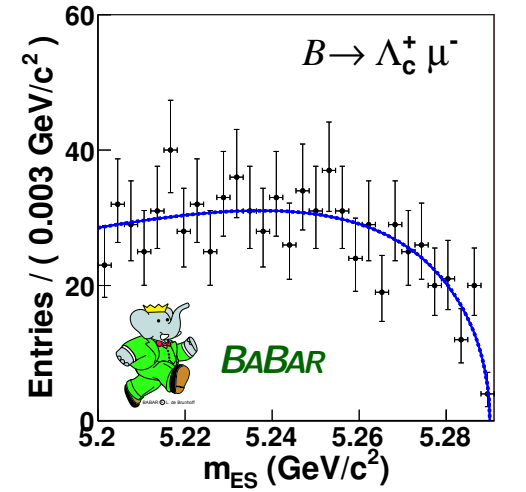


$B \to (\overleftrightarrow{\Lambda}, \Lambda_c^+)\ell$, BNV/LNV, *BABAR* PRD-RC D83, 091101 (2011)

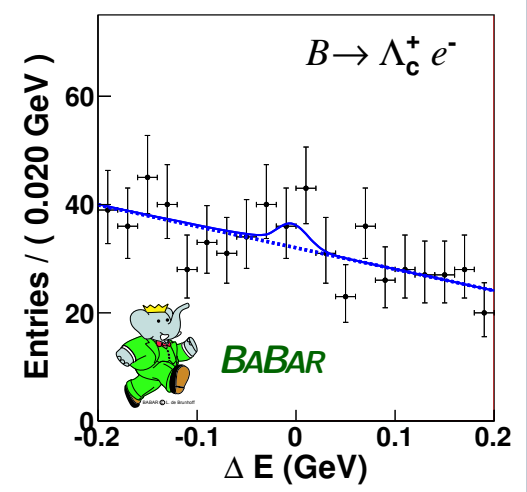
- searches for: $B^0 \to \Lambda_c^+ \ell^-$, $B^- \to \Lambda \ell^-$, $B^- \to \bar{\Lambda} \ell^-$

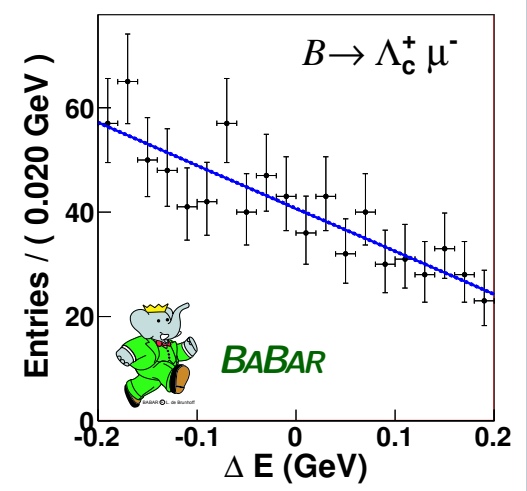
m_{ES}





ΔE





Searches for LFV Υ decays

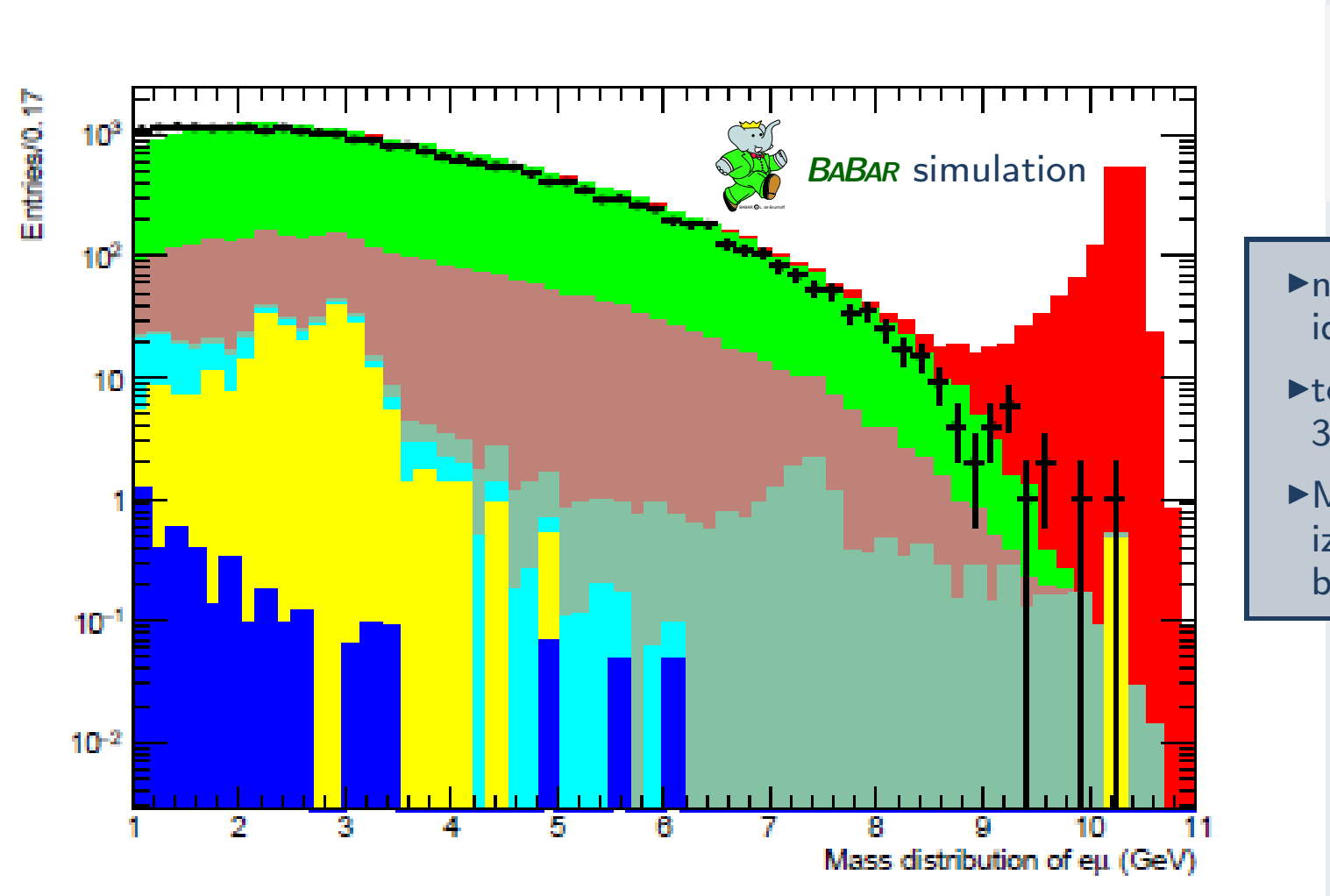
- *BABAR* PRL 104, 151802 (2010)
  - $\Upsilon(2S, 3S) \to \ell^\pm \ell'^\mp, \quad \ell^\pm \ell'^\mp = e^\pm \tau^\mp, \mu^\pm \tau^\mp$
- *BABAR* preliminary, N. Tasneem, Lake Louise, Feb 2018
  $\Upsilon(3S) \to e^\pm \mu^\mp$,

Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

- search in $27\,\mathrm{fb}^{-1}$ $\Upsilon(3S)$ sample
  - $\Gamma_{\Upsilon(4S)} \approx 1000 \times \Gamma_{\Upsilon(3S)} \quad \Rightarrow \quad \mathcal{B}[\Upsilon(3S) \to e\mu] \approx 1000 \times \mathcal{B}[\Upsilon(4S) \to e\mu]$
- require 1 identified e candidate + 1 identified μ candidate
- measured p_e^*, p_μ^* compatible with $\frac{\sqrt{s}}{2}$: $\quad \sqrt{p_e^{*2} + m_e^2} \simeq \frac{\sqrt{s}}{2} \quad \sqrt{p_\mu^{*2} + m_\mu^2} \simeq \frac{\sqrt{s}}{2}$
- both tracks in EMC acceptance: $24^\circ < \theta_{\mathrm{lab}} < 130^\circ$
- e and μ tracks back-to-back, $\theta_{e\mu}^{\mathrm{CM}} > 179^\circ$
- μ energy deposit in EMC $> 50\,\mathrm{MeV}$
- non-peaking background estimated with data ($78\,\mathrm{fb}^{-1}$ $\Upsilon(4S)$ sample)
- peaking background studied in simulated events vs. data inverting well simulated cuts

Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

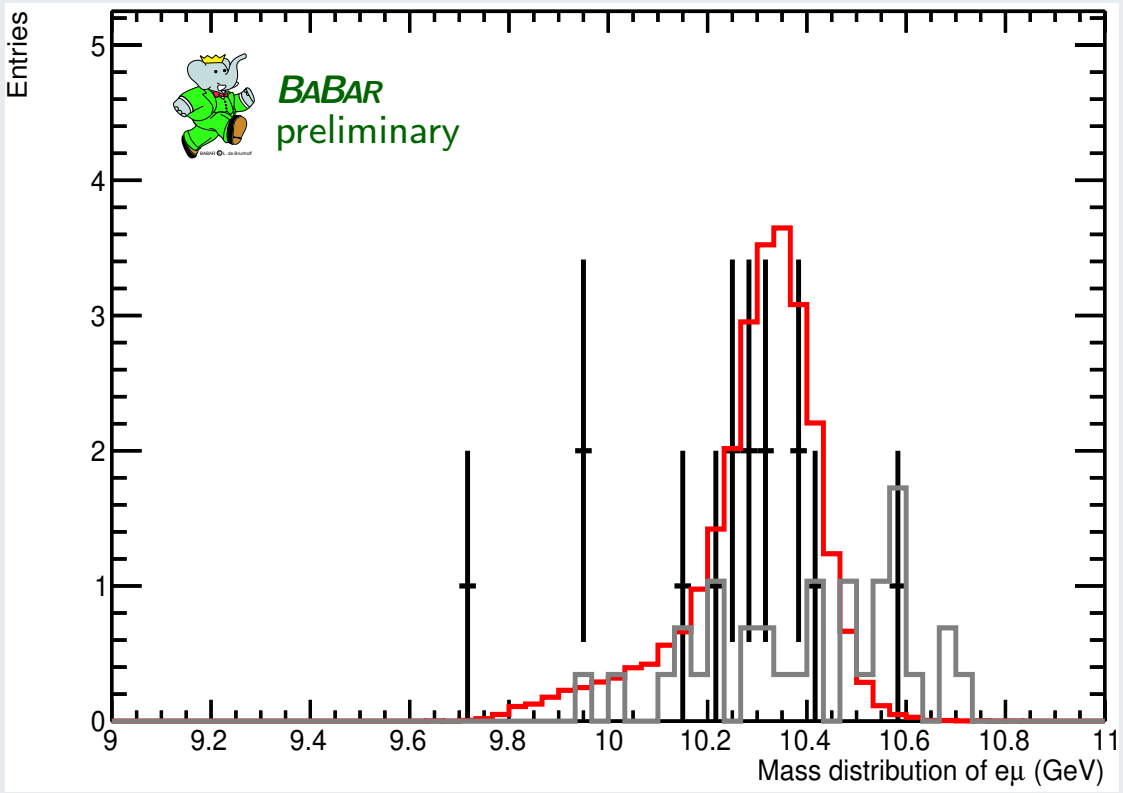
Data vs. simulated signal (red) and expected backgrounds



- no selection but identified e and μ
- test on unblinded $3\,\mathrm{fb}^{-1}$ of data
- MC signal normalization arbitrary, to be visible in the plot

Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

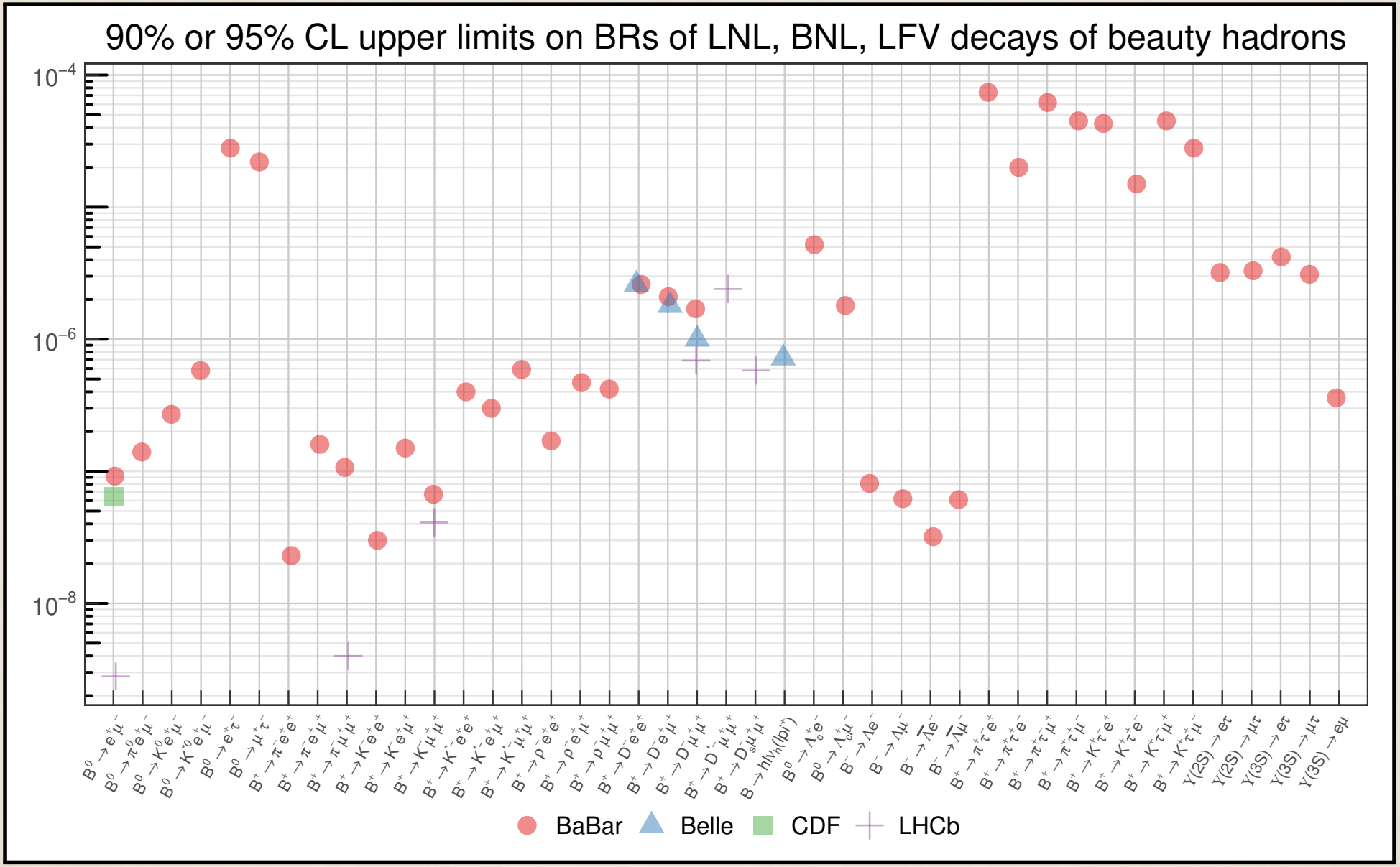
Mass distribution after all selection requirements



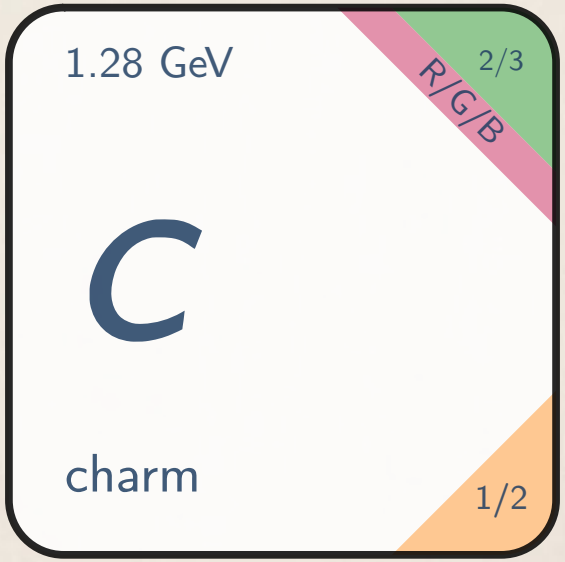
- red: simulated signal
- gray: estimated background
- points with errors: data

- $\mathcal{B}[\Upsilon(3S) \to e\mu] = (1.0 \pm 1.4\,\text{stat.} \pm 0.8\,\text{syst.}) \cdot 10^{-7}$
- $\mathcal{B}[\Upsilon(3S) \to e\mu] < 3.6 \cdot 10^{-7}$ 90% CL

Limits on BRs of LNV/BNV/LFV decays of B, Υ hadrons



LNV/BNV/LFV on decays of charm hadrons



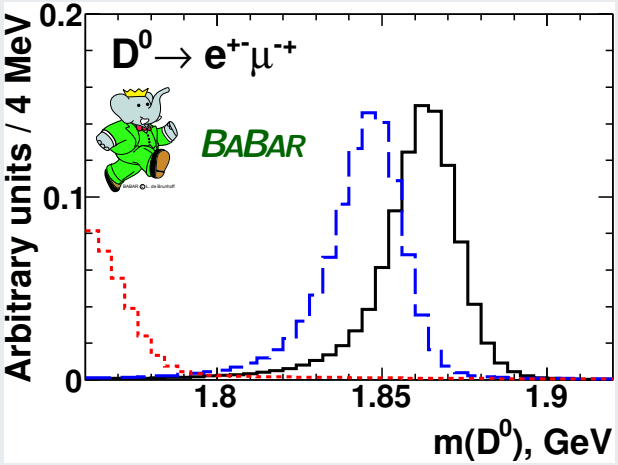
Searches for LNV / LFV charmed hadron decays

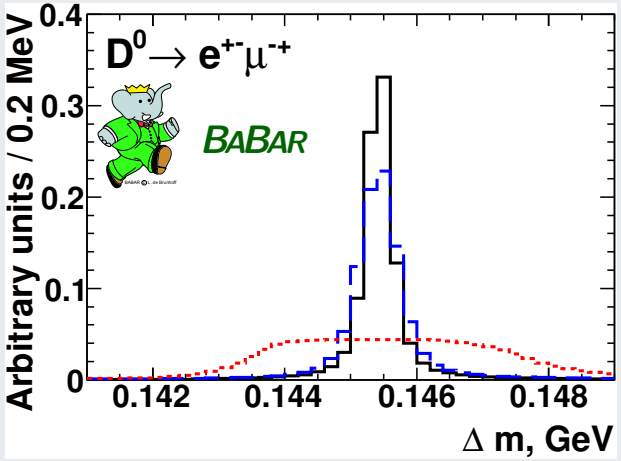
BABAR PRD 84, 072006 (2011)

- $X_c^+ \to h^\pm \ell^\mp \ell^{(\prime)+}$, $X_c^+ = D^+, D_s^+, \Lambda_c^+$, $h = \pi^-, K^-, \bar{p}$, $\ell^{(\prime)+} = e^+, \mu^+$
- LNV (and/or LFV): $\ell\ell^{(\prime)} = e^\pm e^\pm,\ \mu^\pm\mu^\pm,\ e^\pm, \mu^\pm,\ e^\pm\mu^\mp$
- FCNC: $\ell\ell^{(\prime)} = e^\pm e^\mp,\ \mu^\pm\mu^\mp$

BABAR PRD 86, 032001 (2012)

- search for $D^{*+} \to D^0\pi^+$, $D^0 \to e^\pm\mu^\mp$
- (analysis also searches for FCNC decays $D^0 \to e^+e^-$, $D^0 \to \mu^+\mu^-$)
- require $p^*_{D^0} > 2.5$ GeV to select $e^+e^- \to c\bar{c}$, removing B decays





m_{D^0} and Δm plots

- $\Delta m = m(D^0\pi^+) - m(D^0)$
- black: $D^0 \to e^+\mu^-$
- blue: misid $D^0 \to \pi^+\pi^-$
- red: misid $D^0 \to K^-\pi^+$

Searches for LNV / LFV charmed hadron decays (older)

BABAR PRL 93 191801 (2004)

- $D^0 \to e\mu$

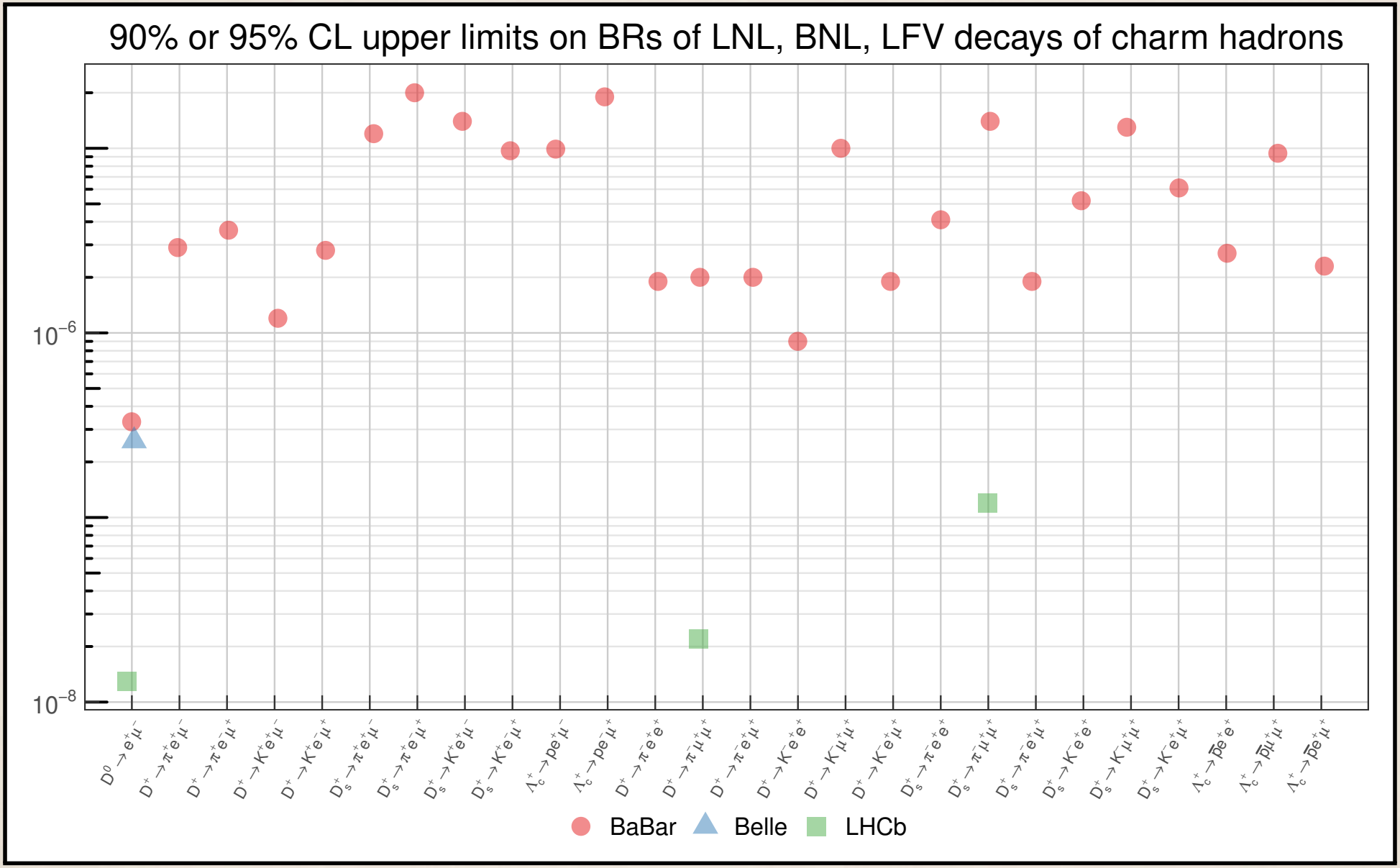
BABAR PRL 99 051801 (2007)

- $D^0 \to \pi^0 e\mu$

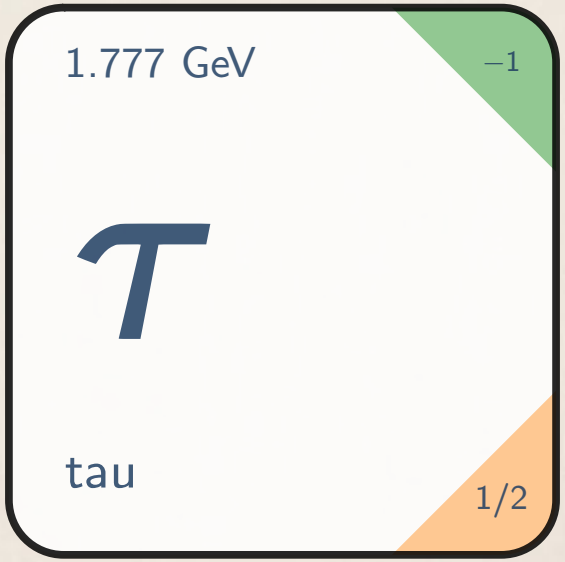
BABAR PRD 73 092001 (2006)

- $D^0 \to K^0 e\mu, \quad D^0 \to K^{*0} e\mu,$

Limits on BRs of LNV/BNV/LFV decays of charm hadrons



LNV/BNV/LFV tau decays



LFV tau decays

- clean and powerful tool to search for New Physics
- B factories are the best experimental facilities for these searches

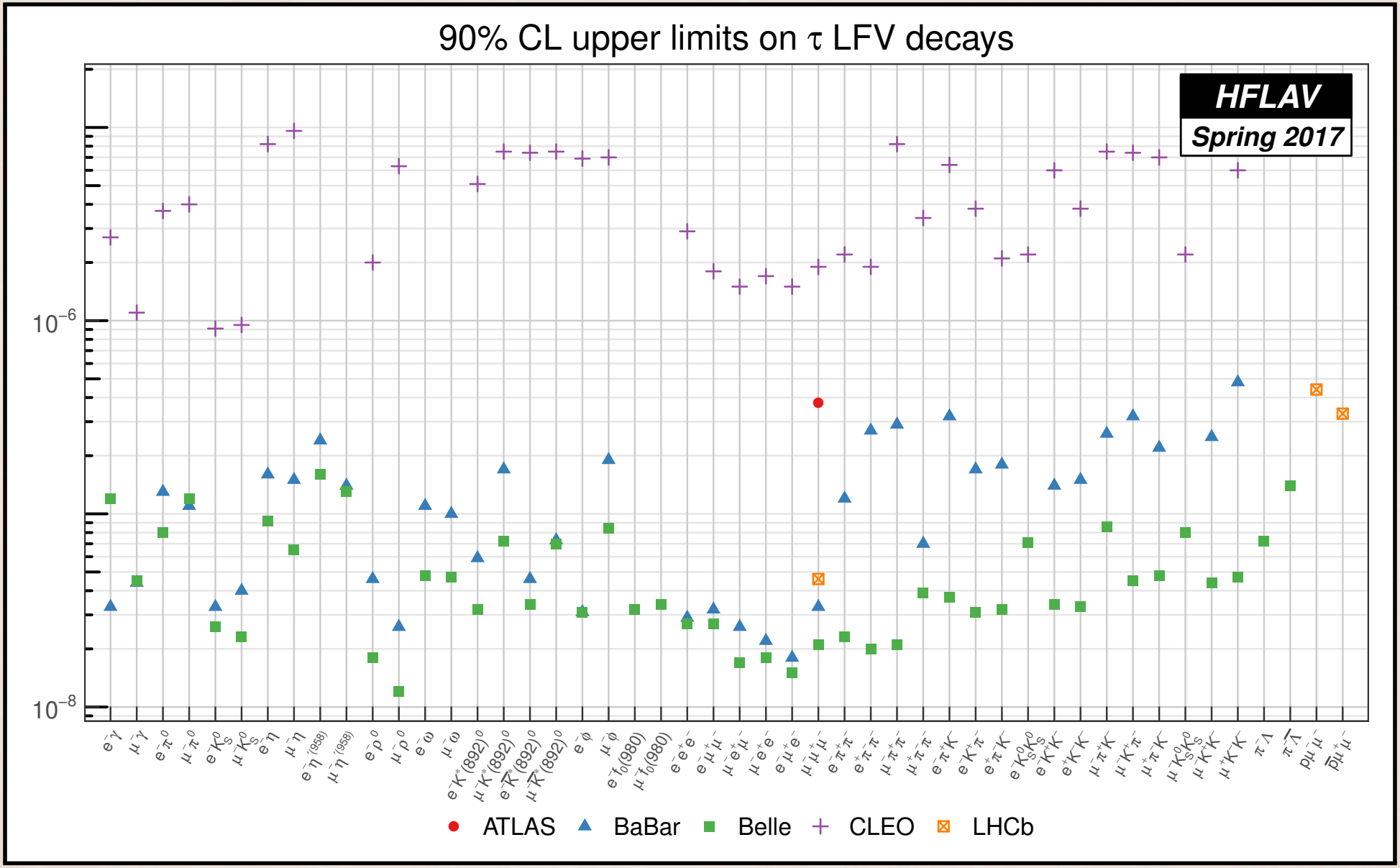
typical LFV tau decay search at B-factory

- neutrinoless tau decay facilitates reconstruction
- reconstruct tau from final state particles, e.g., $\mu\gamma$, $\ell^-\ell^+\ell^-$, $\ell^- h$, $\ell^- h^+ h'^-$
- compute energy-constrained invariant mass of tau candidate m_{EC}
  - constraint: in center-of-mass frame, $E^* = \frac{\sqrt{s}}{2}$
- compute energy of tau candidate in CM, E^*, and $\Delta E = E^* - \frac{\sqrt{s}}{2}$
- fit for signal on $m_{\mathrm{EC}} - \Delta E$ plane
- LFV tau decay candidates peak on both m_{EC} and ΔE

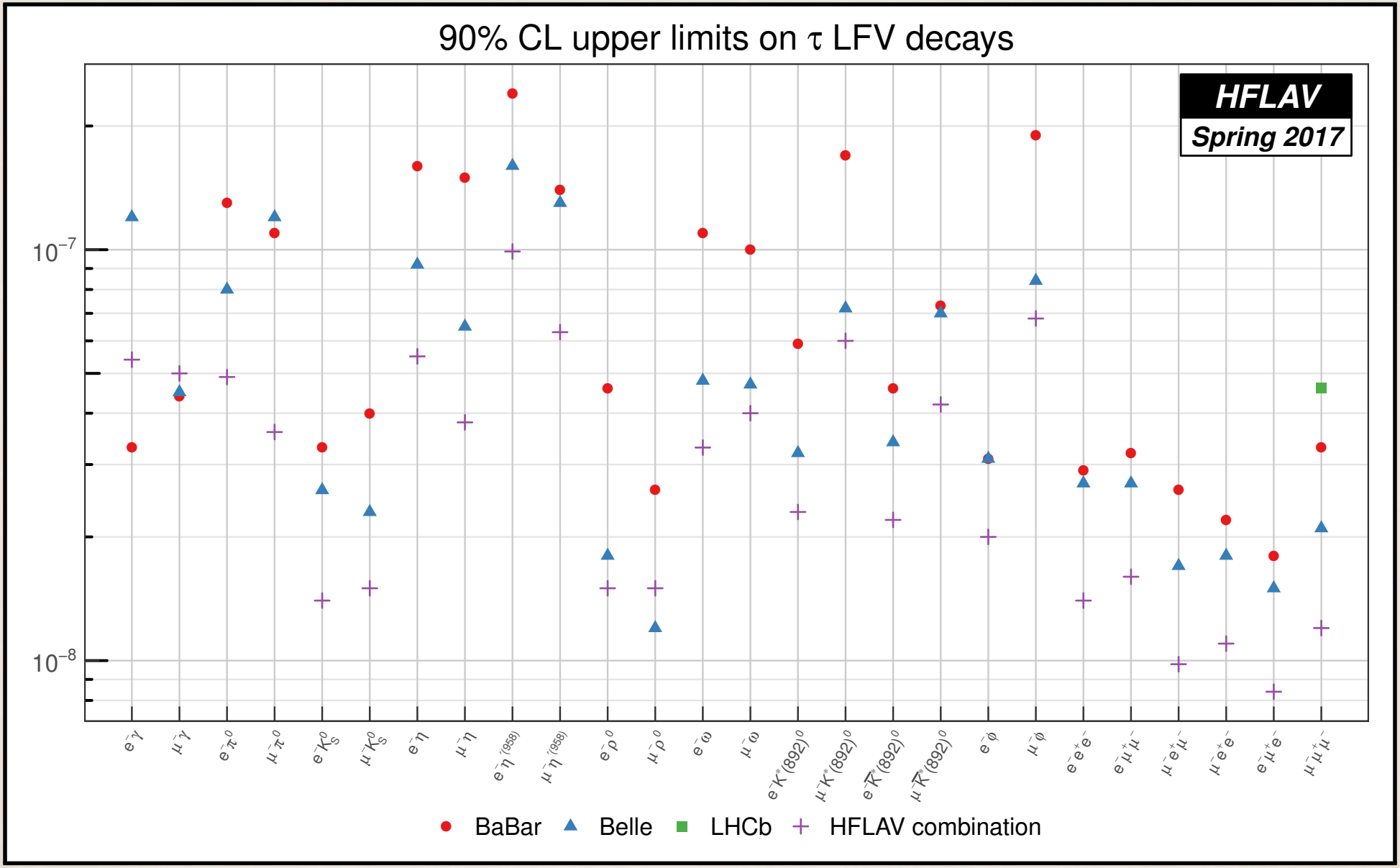
Most recent LFV searches results from the B-Factories

- BaBar $\tau \to 3$ leptons, PRD 81 111101 (2010)
- Belle $\tau \to 3$ leptons, PLB 687 139 (2010)
- Belle $\tau \to \ell K_S^0$, $\tau \to \ell K_S^0 K_S^0$, PLB 692 4 (2010)
- Belle $\tau \to \ell V$, PLB 699 251 (2011)
- Belle $\tau \to \ell h h'$, PLB 719 346 (2013)

HFLAV collects limits on BRs of Tau LFV/LNV/BNV decays

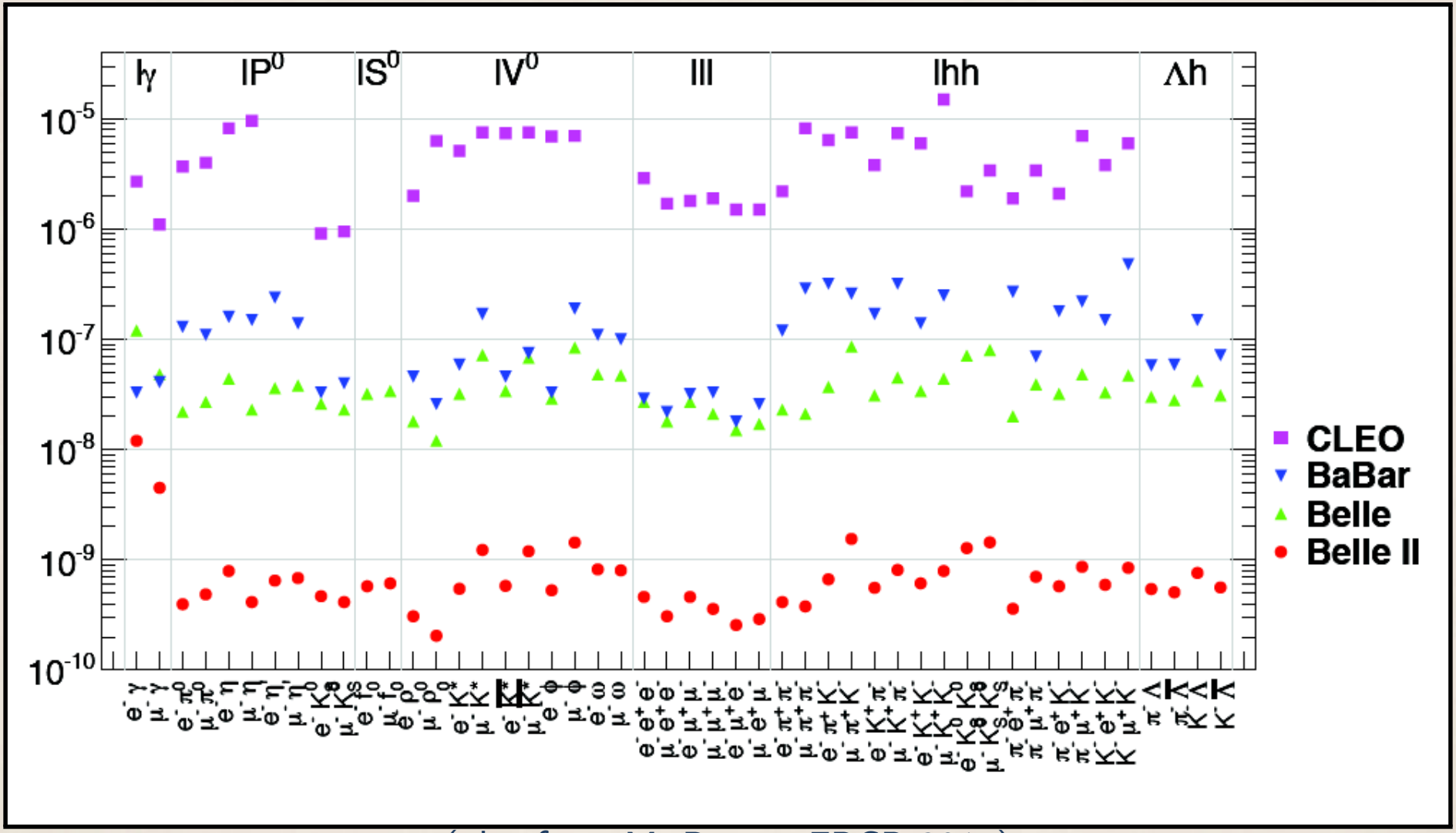


HFLAV combined limits on BRs of Tau LFV/LNV/BNV decays



Belle II expected limits on BRs of Tau LFV/LNV/BNV decays

branching fraction 90% CL upper limits



(plot from M. Barret, FPCP 2015)

Dark photon searches

Dark Photon models

- vector boson (A') belonging to hidden-sector accounting for dark matter
- coupling (loose) to SM matter via kinetic mixing with photon, $\Delta\mathcal{L} = -\frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}$
- mass of order GeV
- A' may be invisible, decaying into lighter dark-matter particles that escape detection
  - long-lived & feebly interacting, or decaying into lighter dark-matter particles that escape detection
  - spoiling limits obtained assuming it must decay into ordinary matter particles
- A' may also decay to ordinary matter
  - kinetic mixing predicts relative branching fractions to available decay modes
- in some models, dark photon can couple preferentially to some flavours
  - muonic dark force

Most recent or important Dark Photon searches

Search for dark photon decaying to electrons or muons

- *BABAR* PRL 113 201801 (2014) $e^+e^- \to A'\gamma$, $A' \to e^+e^-,\ \mu^+\mu^-$ $(514\,\mathrm{fb}^{-1})$

Search for dark photon decaying to invisible

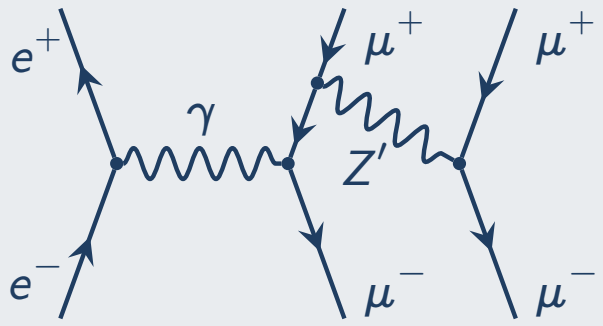
- *BABAR* PRL 119 131804 (2017) $e^+e^- \to A'\gamma$, $A' \to$ invisible $(53\,\mathrm{fb}^{-1})$
  - relies on special single-photon trigger

Search for dark photon in η decays and decaying to $\pi^+\pi^-$

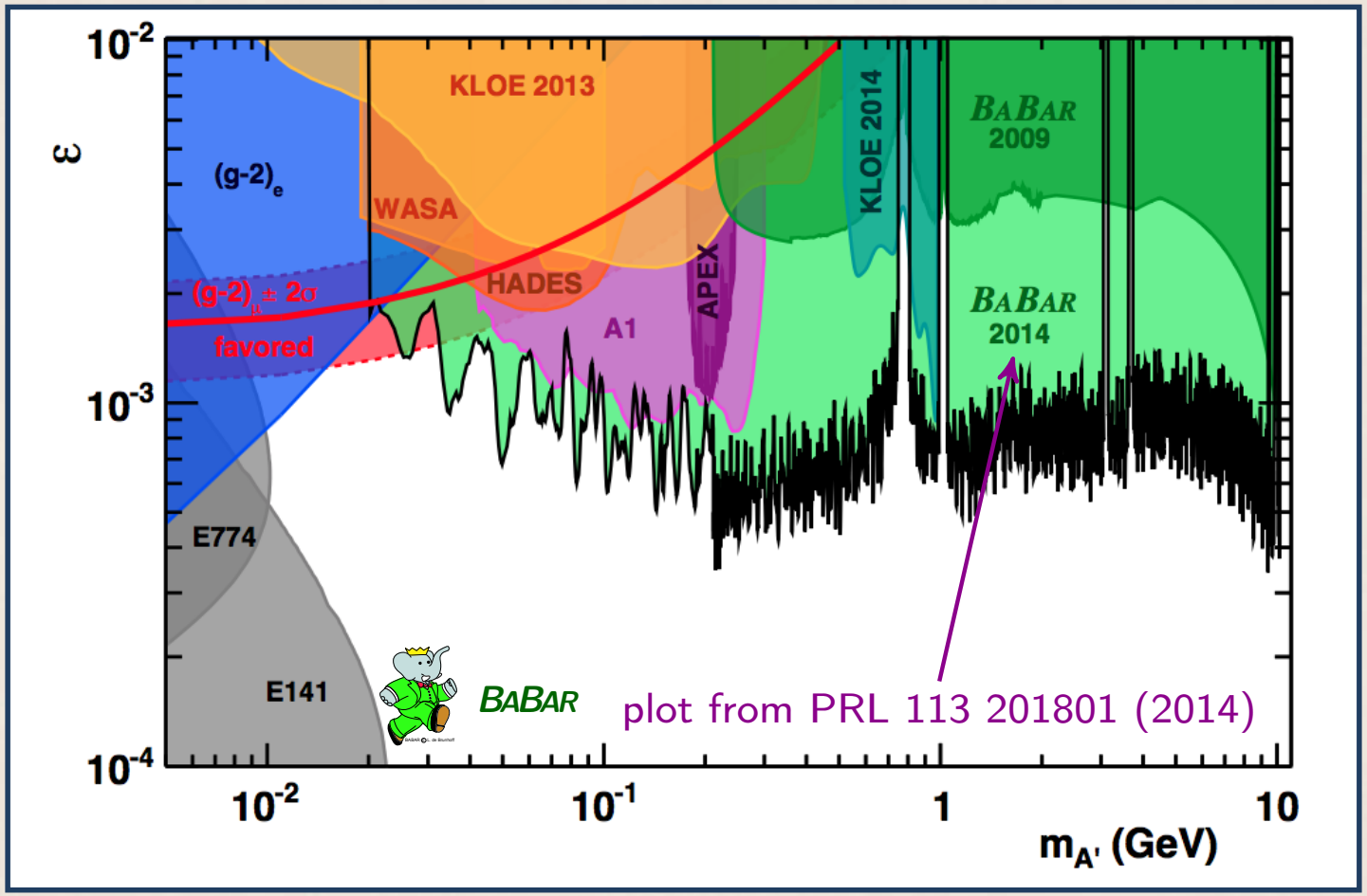
- Belle PRD 94 092006 (2016) $D^0 \to K_S\eta$, $\eta \to A'\gamma$, $A' \to \pi^+\pi^-$ $(977\,\mathrm{fb}^{-1})$

Search for muonic dark force

- *BABAR* PRD 94 011102 (2016) $(514\,\mathrm{fb}^{-1})$
- final state 4 muons

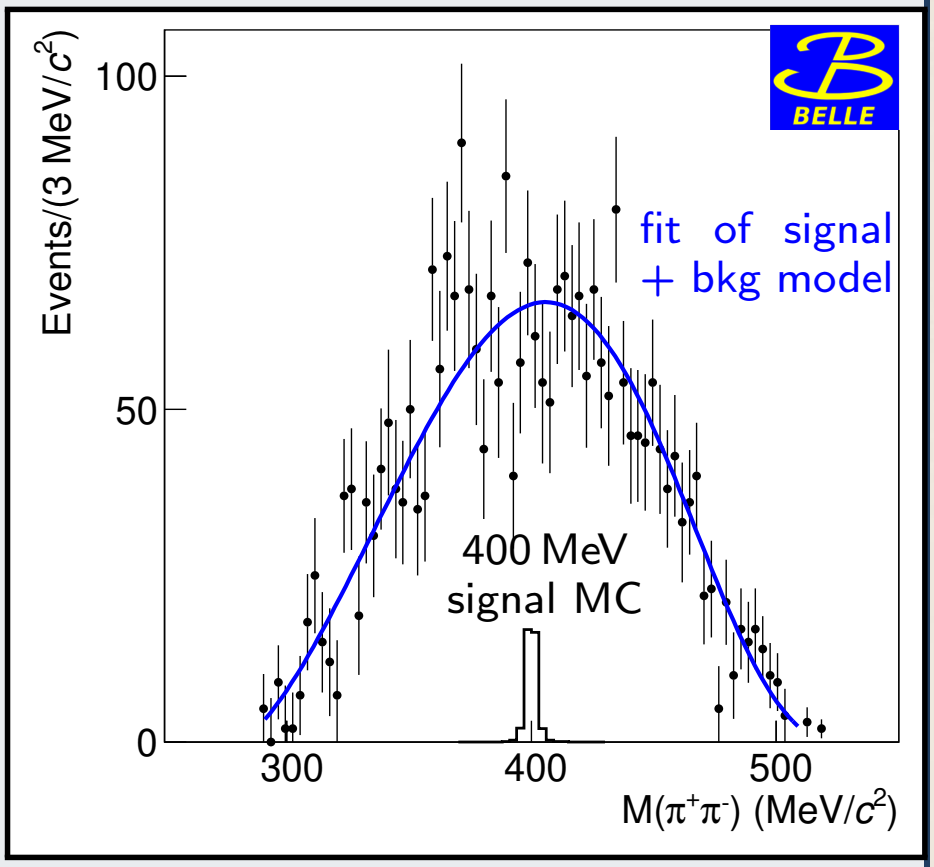


Experimental constraints on Dark Photon decaying to visible states

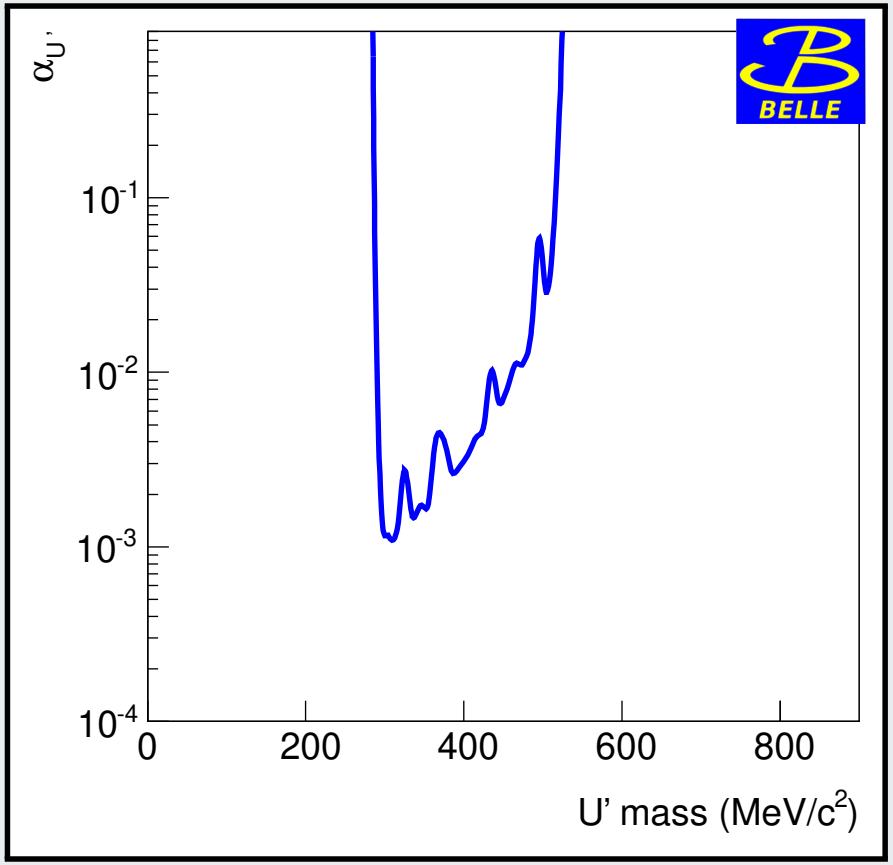


Experimental constraints on Dark Photon in $\eta \to U'\gamma$, $U' \to \pi^+\pi^-$

$m(\pi^+\pi^-)$ of U' data candidates

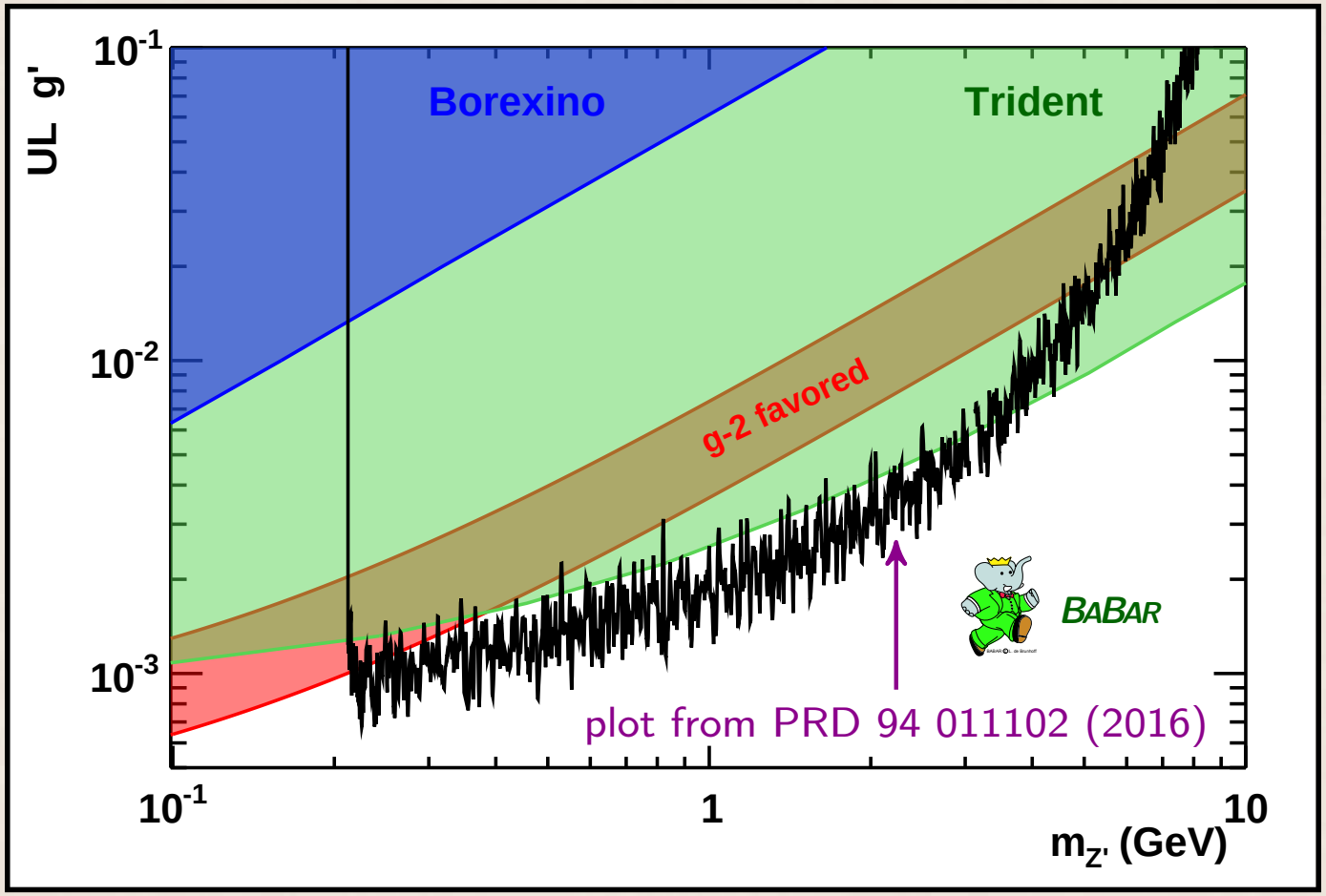


limits on U' mass and coupling

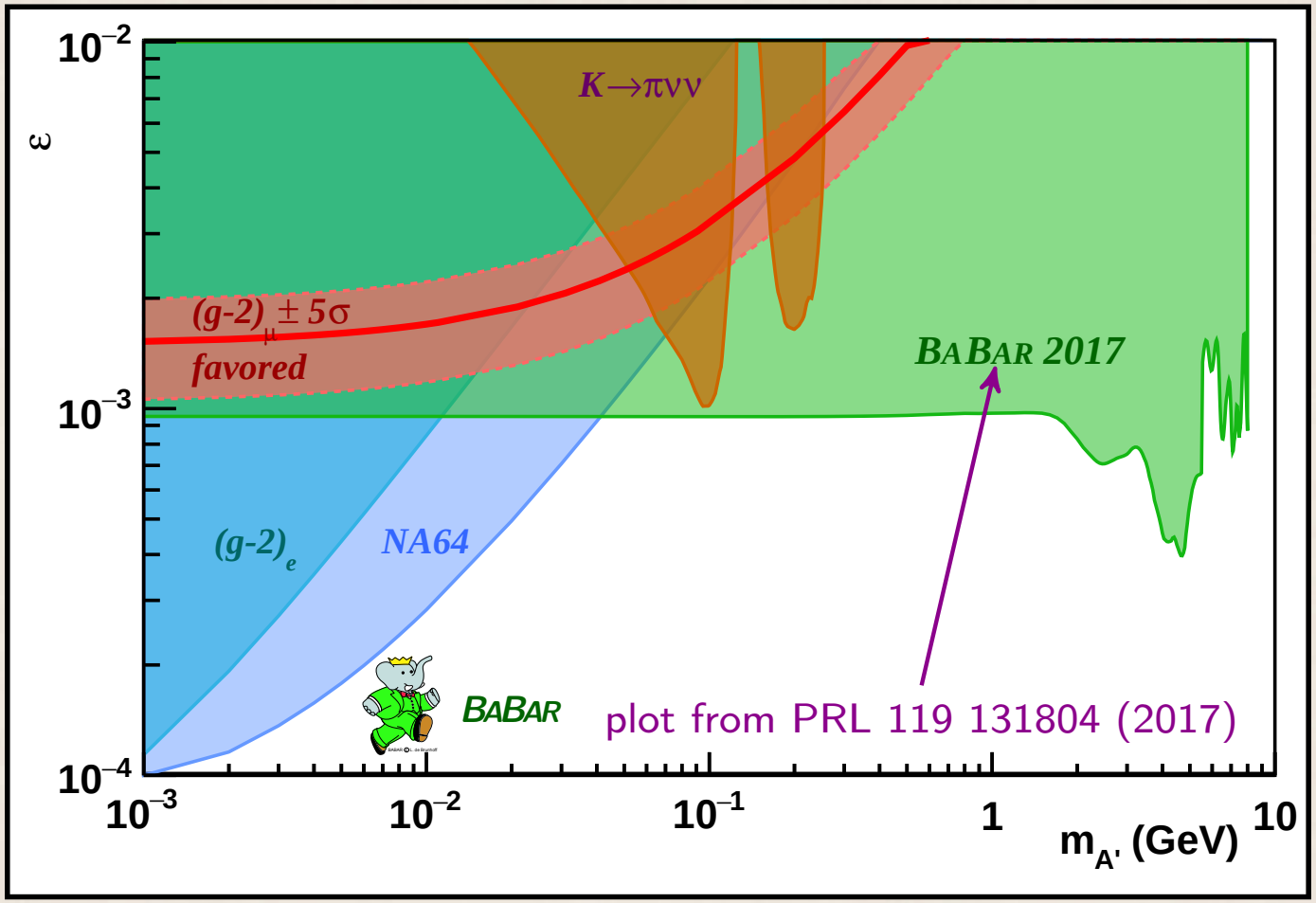


- plots from PRD 94 092006 (2016)
- $\alpha_{U'} = \epsilon^2/(4\pi)$ in terms of ϵ of previous dark photon plots

Experimental constraints on Dark Muonic Force

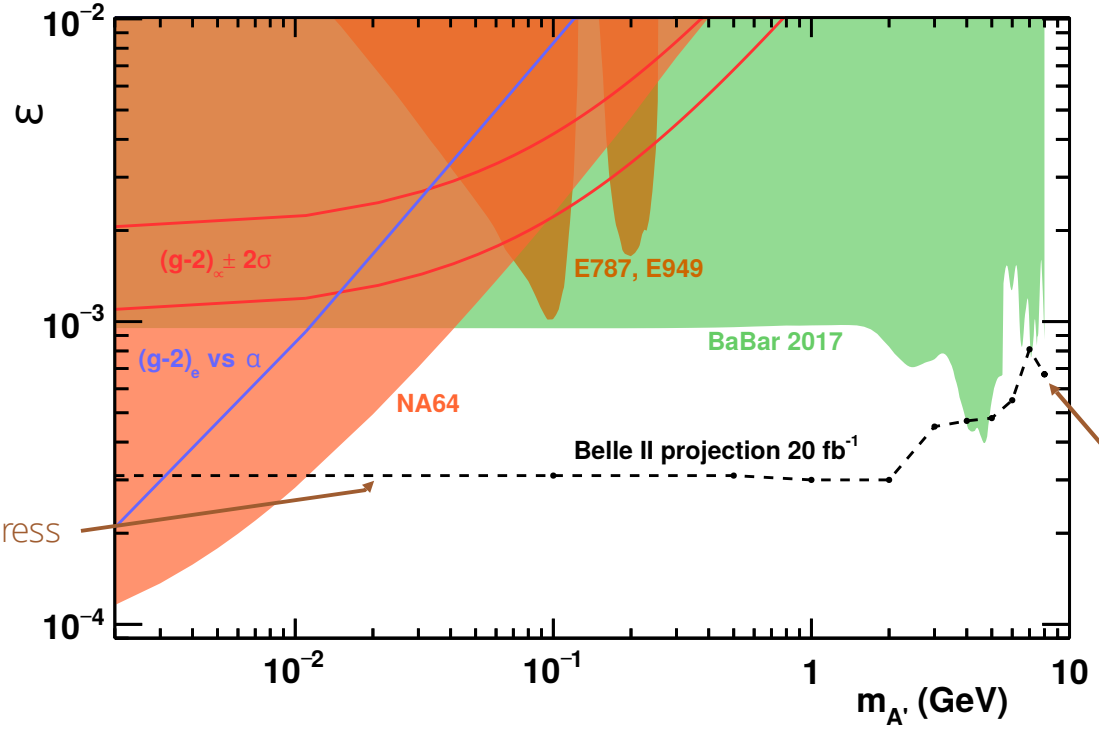


Experimental constraints on Dark Photon decaying to invisible



Belle II sensitivity for Dark Photon to invisible

- Belle II has
  - dedicated single-photon trigger for searches
  - more hermetic electromagnetic calorimeter w.r.t. *BaBar* (non projective)
- Chris Hearty estimated the Belle II sensitivity for Dark Photon to invisible (U.S. Cosmic Visions: New Ideas in Dark Matter, March 2017)

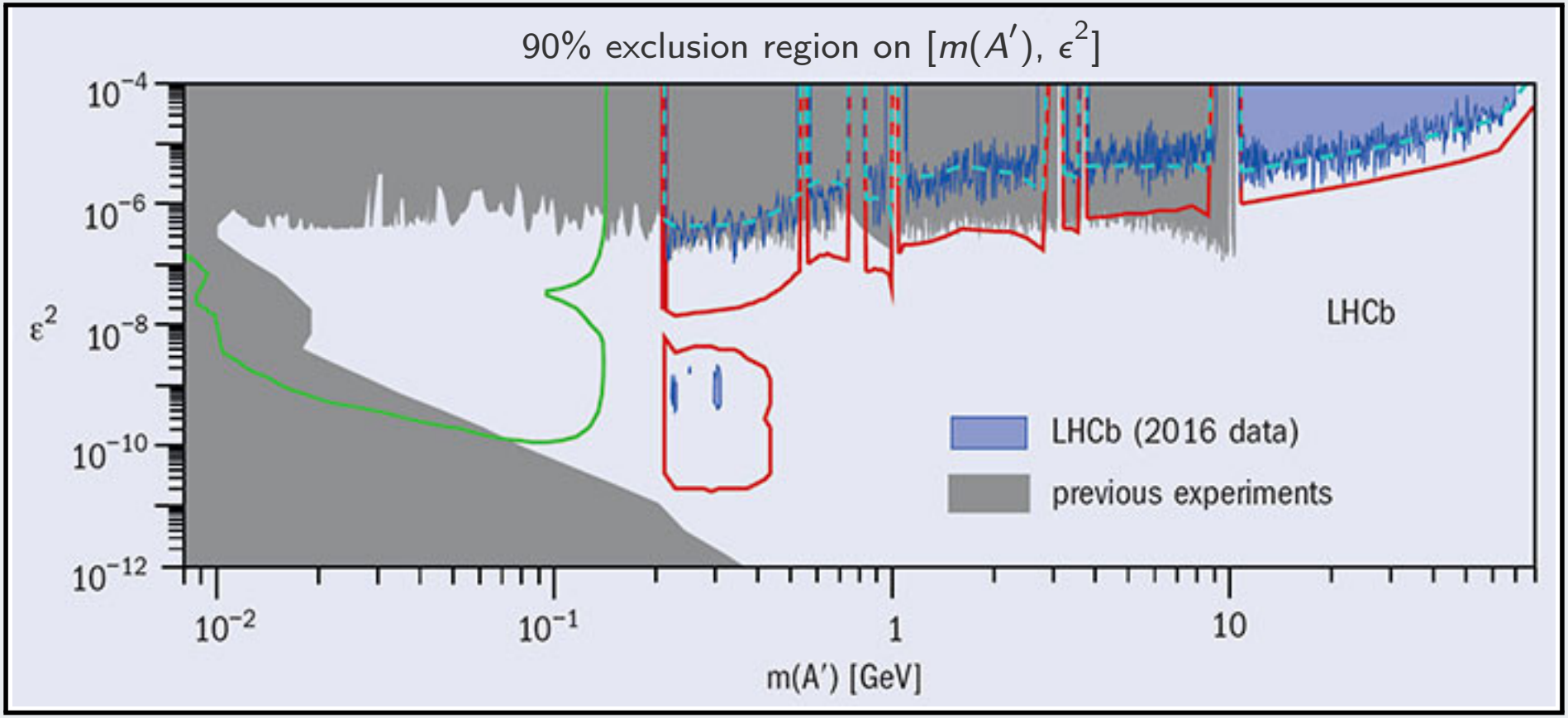


better calorimeter hermeticity to suppress $e^+e^- \to \gamma\gamma$

Reach masses of 9.1–9.5 GeV/c^2 with lower trigger threshold (vs 8 GeV/c^2 for BaBar)

Many present and future facilities other than *B*-factories effective on Dark Photon searches, e.g., LHCb, SHiP, . . .

LHCb on CERN Courier Jan 15, 2018, see also PRL 116 251803 (2016)



Red and green are expectations for LHC Run 3.

Dashed cyan curve is expectation rescaled to 2016 LHCb data sample.


Conclusions

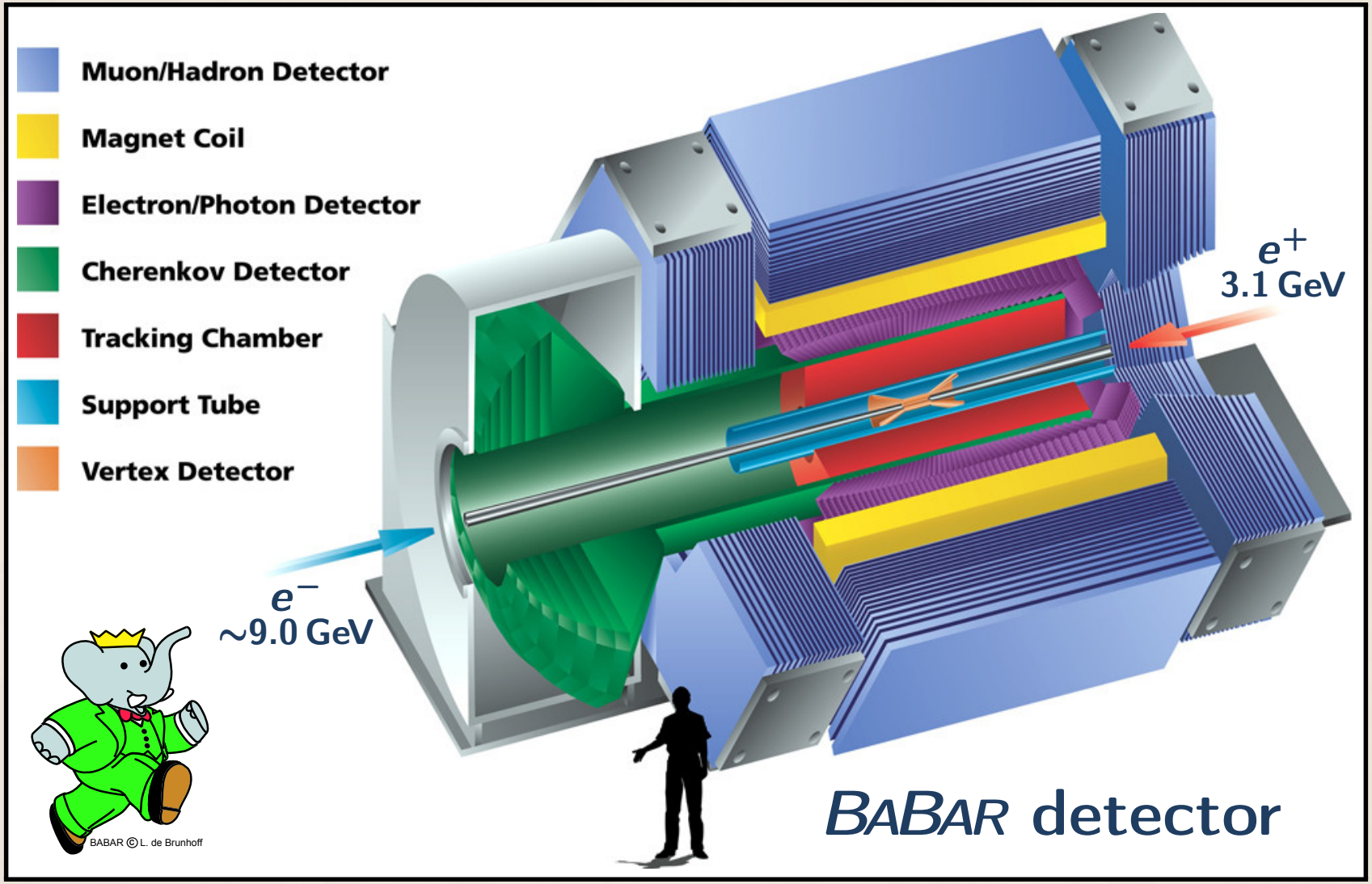
Summary and conclusions

- no evidence of New Physics on B-factories searches for
  - LNV, BNV and LFV decays of B mesons, charmed hadrons, tau
  - dark photons
- B-factories are
  - best location for tau LFV, LNV and BNV searches
  - competitive for dark photon searches
  - competitive for B meson, charm hadron LFV, LNV and BNV searches
- Belle II will significantly improve experimental reach on
  - tau LFV, LNV and BNV searches
  - dark photon searches
- LHCb competitive on
  - bottom and charm hadron LFV, LNV and BNV searches
  - dark photon searches

SM rules still what is rare or forbidden

Backup Slides

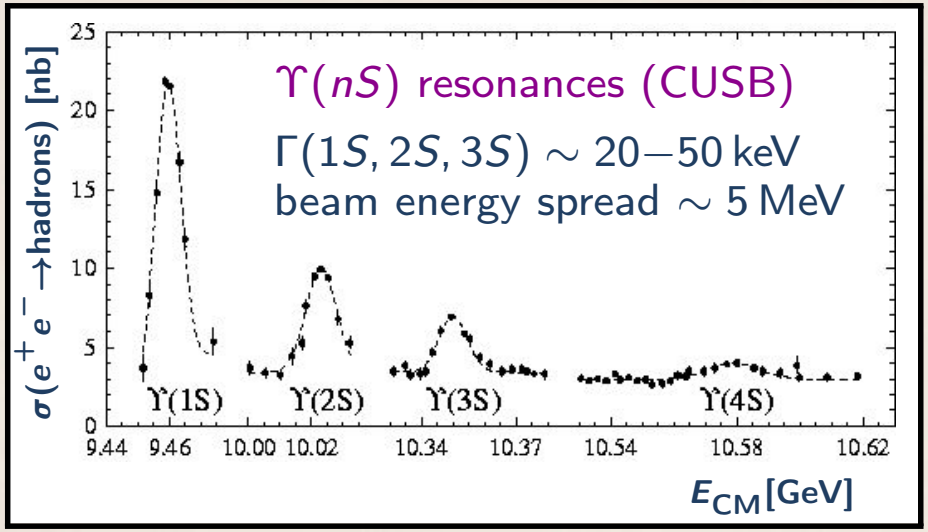
BABAR detector at PEP-II, SLAC National Accelerator Laboratory



BABAR main focus: study of CP violation in B mesons

BABAR: CM energy, collected luminosity

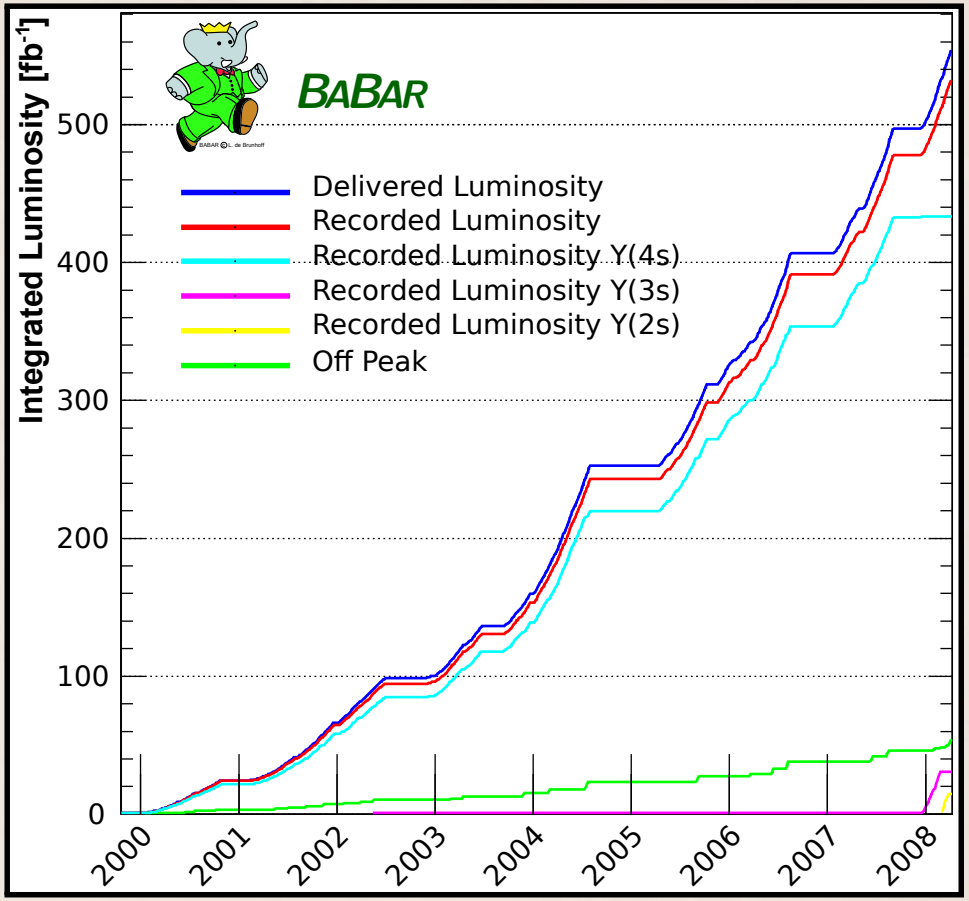
center-of-mass energies



data samples (large and clean)

	events	$\mathcal{L}(\text{fb}^{-1})$
$\Upsilon(4S) \to B\bar{B}$	$471 \cdot 10^6$	424
$\Upsilon(3S) \to$ visible	$121 \cdot 10^6$	28
$\Upsilon(2S) \to$ visible	$99 \cdot 10^6$	14
off-peak		48
single-γ trigger $\Upsilon(4S, 3S, 2S)$		53

integrated luminosity over time



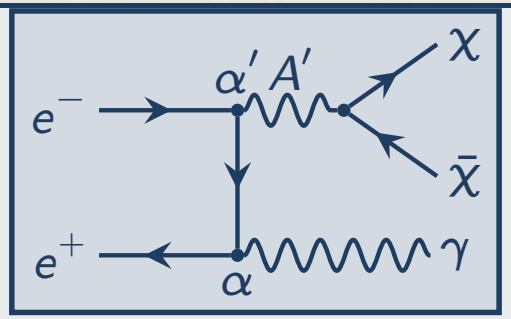
data-taking ended in April 2008

The BABAR search

Analysis strategy

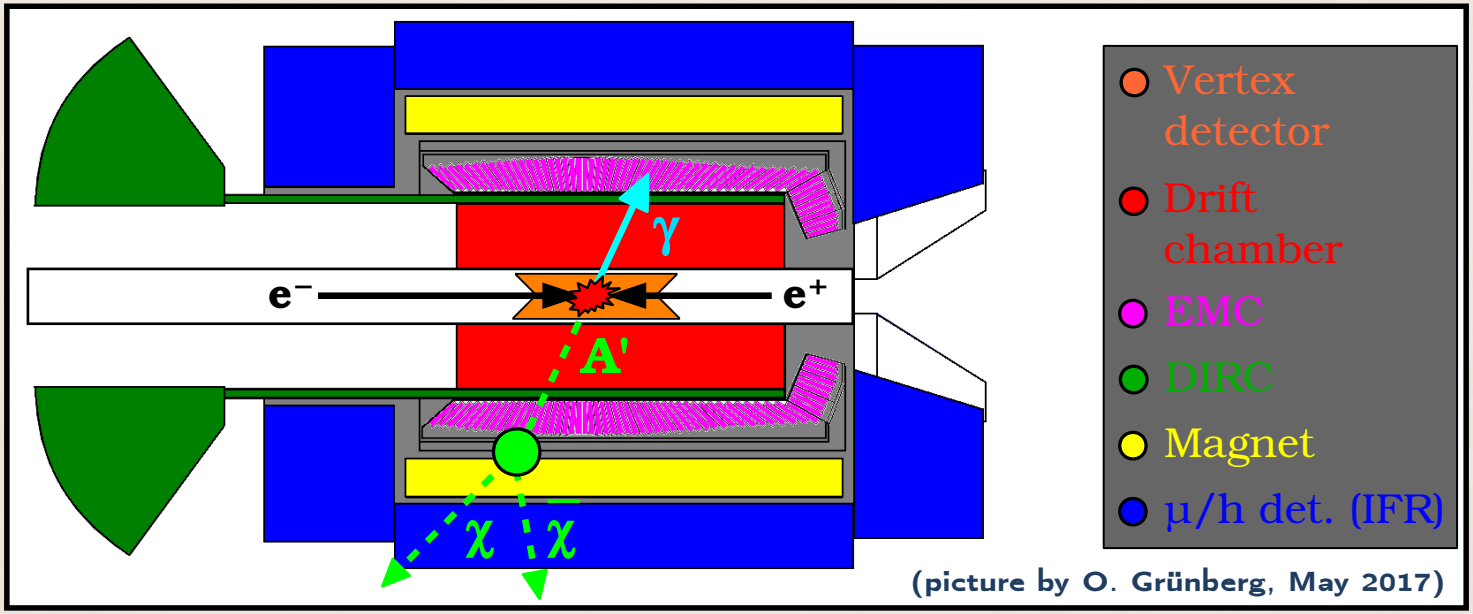
search for

- $e^-e^+ \to \gamma A'$, $A' \to$ invisible (e.g. $\chi\bar{\chi}$)
  i.e. one single photon and nothing else



$$\sigma \propto \alpha'\alpha = \epsilon^2\alpha^2$$

- reconstruct A' mass, $M^2_{A'} = s - 2\sqrt{s}E^*_\gamma$
- scan $M^2_{A'}$ distribution, fitting bumps over smooth background, compute significance
  [A' decay width $\Gamma_{A'}$ expected $\ll$ experimental resolution on $M_{A'}$]



(picture by O. Grünberg, May 2017)

Trigger

BABAR collected $\sim$53 fb^{-1} of data with dedicated single photon triggers during its last year of data taking, mostly collected at the $\Upsilon(3S)$ and $\Upsilon(2S)$ peaks

Hardware trigger

- ≥ 1 EMC cluster with $E_{\mathrm{LAB}} > 800$ MeV
- 52.9 fb^{-1} data sample

Software triggers

- high energy photon trigger line
  - $E^*_\gamma > 2$ GeV
  - no track from interaction region (SVT [+DCH])
  - active on full 52.9 fb^{-1} data sample
- low energy photon trigger line
  - $E^*_\gamma > 1$ GeV
  - no track from interaction region (SVT [+DCH])
  - active on 35.9 fb^{-1} out of the total 52.9 fb^{-1} data sample

Low-mass and high-mass pre-selections

Low-mass $-4 < M^2_{A'} < 36\,\text{GeV}^2$

- approximately $0 < M_{A'} < 5.5\,\text{GeV}$
- background:
  - $e^+e^- \to \gamma\gamma$ with lost γ
  - peaking at $M_{A'} = 0$
  - low tail away from $M_{A'} = 0$
- $E^*_\gamma > 3\,\text{GeV}$
- $|\cos\theta^*_\gamma| < 0.6$ against radiative Bhabha
- no track from interaction region
- no DCH-only track with $p^* > 1\,\text{GeV}$

High-mass $24 < M^2_{A'} < 69\,\text{GeV}^2$

- approximately $5.5 < M_{A'} < 8.0\,\text{GeV}$
- background:
  - $e^+e^- \to e^+e^-\gamma$ with lost e^+e^-
  - tail of $e^+e^- \to \gamma\gamma$
  - large but smooth background
- $E^*_\gamma > 1.5\,\text{GeV}$
- $|\cos\theta^*_\gamma| < 0.6$ against radiative Bhabha
- no track from interaction region
- no DCH-only track with $p^* > 0.1\,\text{GeV}$

Boosted Decision Tree (BTD) discriminant

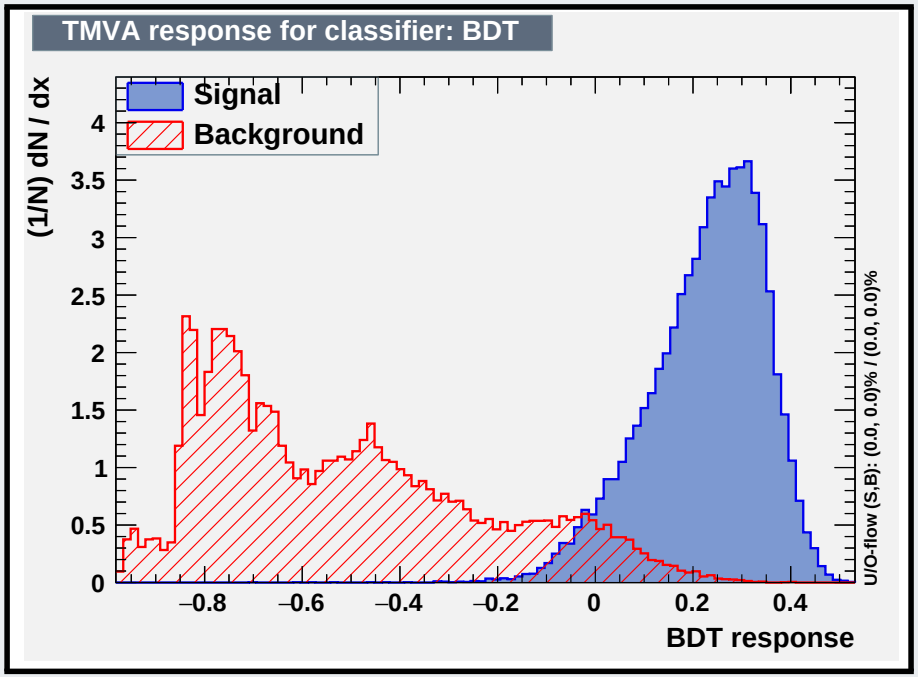
12 input variables

- fired vs. expected EMC crystals
- two transverse moments of EMC shower
- total EMC energy other than most energetic photon
- CM energy and polar angle of 2nd most energetic EMC cluster
- azimuthal angle difference $\Delta\phi_{12}$ between the highest and second-highest energy EMC clusters (the $e^+e^- \to \gamma\gamma$ events with partial energy deposit in the EMC tend to peak at $\Delta\phi_{12} \sim \pi$)
- distance of missing momentum from EMC crystal edges in θ and ϕ
- angle $\Delta\phi_{NH}$ between the primary photon and the IFR cluster closest to the missing momentum direction ($e^+e^- \to \gamma\gamma$ events peak at $\cos\Delta\phi_{NH} \sim -1$)
- variable measuring how close is missing momentum to uninstrumented IFR regions
- $\cos\theta^*_\gamma$ (discriminates between signal and background distributions)

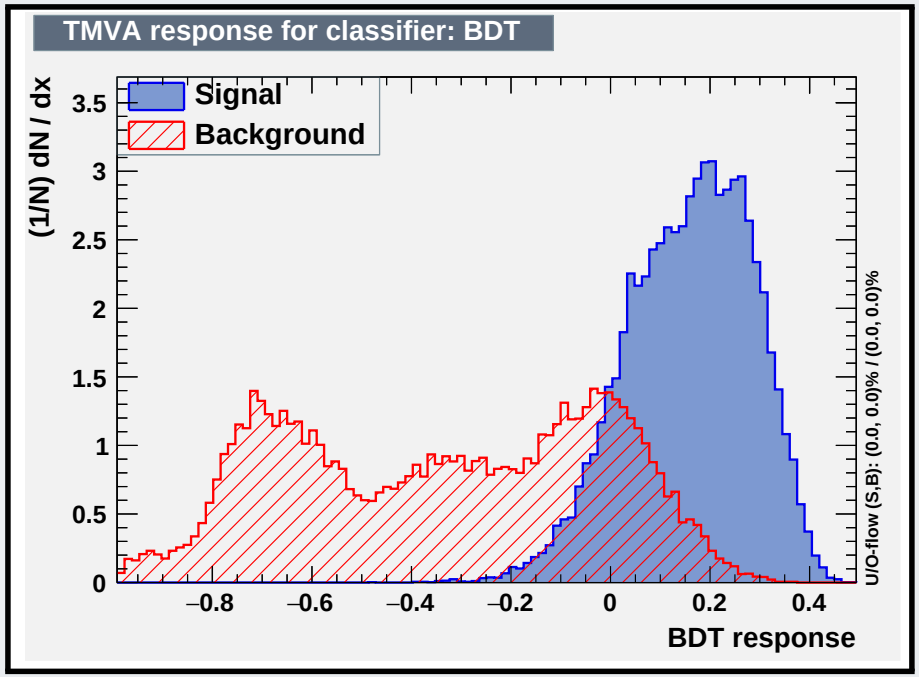
- background sample: 25k ($3\,\mathrm{fb}^{-1}$) of $\Upsilon(3S)$ data
- signal sample: 25k simulated $e^+e^- \to A'\gamma$, $A' \to$ invisible, uniform mass distribution
- BDT trained separately in low-mass and high-mass regions

BDT response

Low-mass selection



High-mass selection



(TMVA = Toolkit for MultiVariate Analysis, `http://tmva.sourceforge.net/`)

Tight, loose and background selection regions

tight selection region, R_T

- BDT cut, $\mathrm{FoM}_1 = \dfrac{\epsilon_S}{\max(N_{\mathrm{BKG}}, 2.3)}$
  - maximal suppression of peaking bkg
  - appropriate for low-mass A'
- $-0.4 < \cos\theta^*_\gamma < 0.6$
  ($e^+e^- \to \gamma\gamma$ photons in EMC barrel)

loose selection region, R_L

- BDT cut, $\mathrm{FoM}_2 = \dfrac{\epsilon_S}{\sqrt{N_{\mathrm{BKG}}}}$
  - appropriate for high-mass A'
  - smooth background

background selection region, R_B

- select background using BDT output
  (use to fit background shape on data)

define 9 + 4 non-overlapping data samples

9 low-mass ($0.0 < M_{A'} < 5.5$ GeV) samples

- $\{R_{L'}, R_T, R_B\} \times \{2S, 3S, 4S\} = 9$ samples
  - $R_{L'} = R_L$, but excluding R_T

4 high-mass ($5.5 < M_{A'} < 8.0$ GeV) samples

- $\{R_L, R_B\} \times \{2S, 3S\} = 4$ samples

Selection of signal and background samples

tight optimization (FoM_1 / R_T)

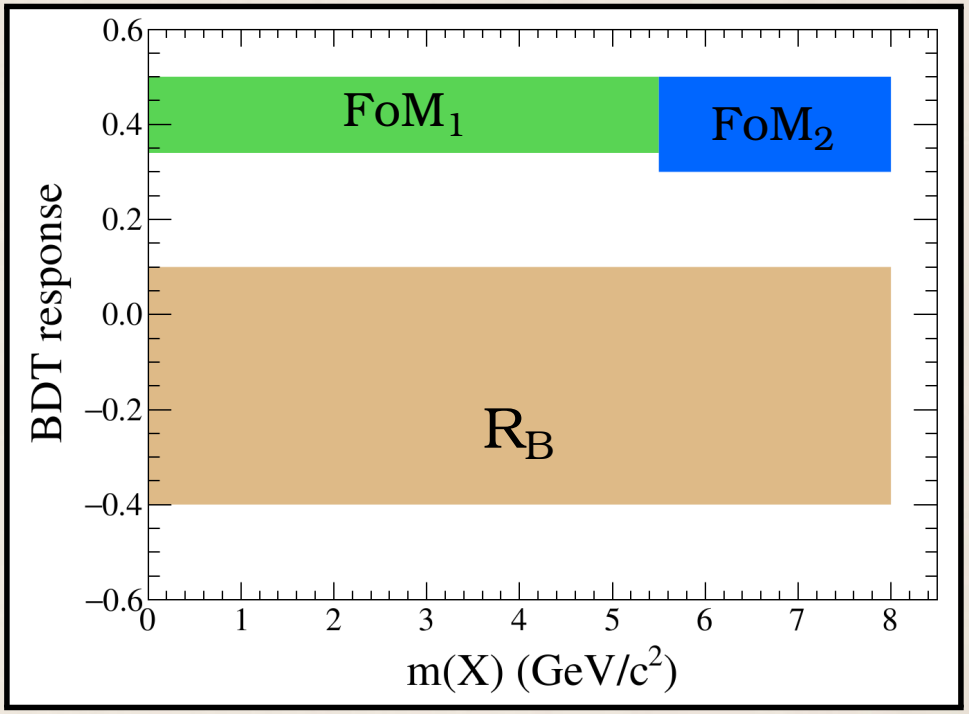
- bkg at low $M'_{A'}$:
  - $e^+e^- \to \gamma\gamma$ with lost γ
  - peaking bkg at $M_{A'} = 0$
  - low tail away from $M_{A'} = 0$
- $\mathrm{FoM}_1 = \dfrac{\epsilon_S}{\max(N_{\mathrm{BKG}}, 2.3)}$
  - maximal suppression of peaking bkg
  - poor S/B separation fitting $M_{A'}$ peak

loose optimization (FoM_2 / R_L)

- bkg at high $M'_{A'}$:
  - $e^+e^- \to e^+e^-\gamma$ with lost e^+e^-
  - tail of $e^+e^- \to \gamma\gamma$
  - $N_{\mathrm{BKG}} \gg 1$ but smooth
- $\mathrm{FoM}_2 = \dfrac{\epsilon_S}{\sqrt{N_{\mathrm{BKG}}}}$

Pure background selection (R_B)

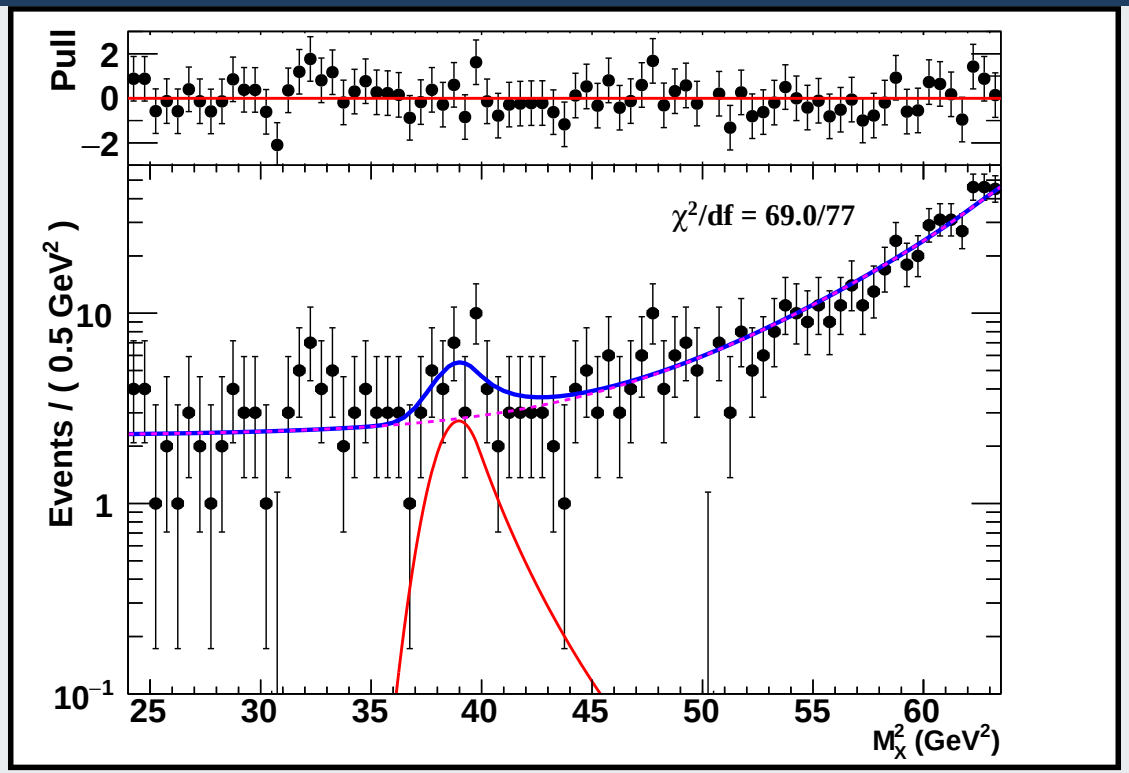
- select pure bkg (for simultaneous fits)



Signal PDF

- Crystal Ball for $e^+e^- \to A'\gamma$, from simulation (parameters depend on $M_{A'}$)
- correct simulated resolution using real data sample $e^+e^- \to \gamma\gamma$, where one photon converts to e^+e^- in detector material

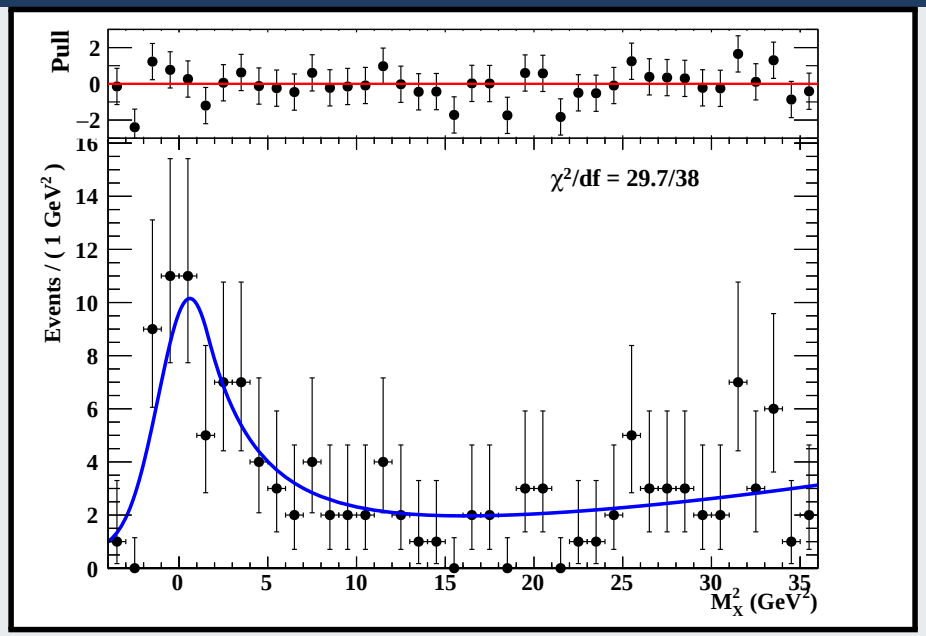
Example signal+background fit



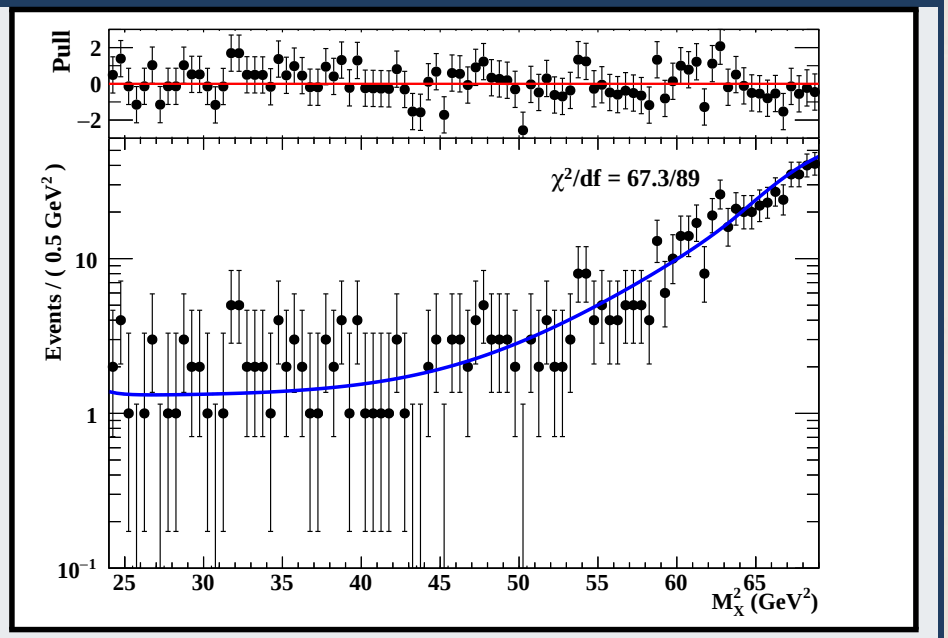
Background PDF

- low-mass region: second-order polynomial + Crystal Ball for $e^+e^- \to \gamma\gamma$
- high-mass region: sum of exponentiated polynomials

Example low-mass background fit



Example high-mass background fit



Fits and signal yield significance

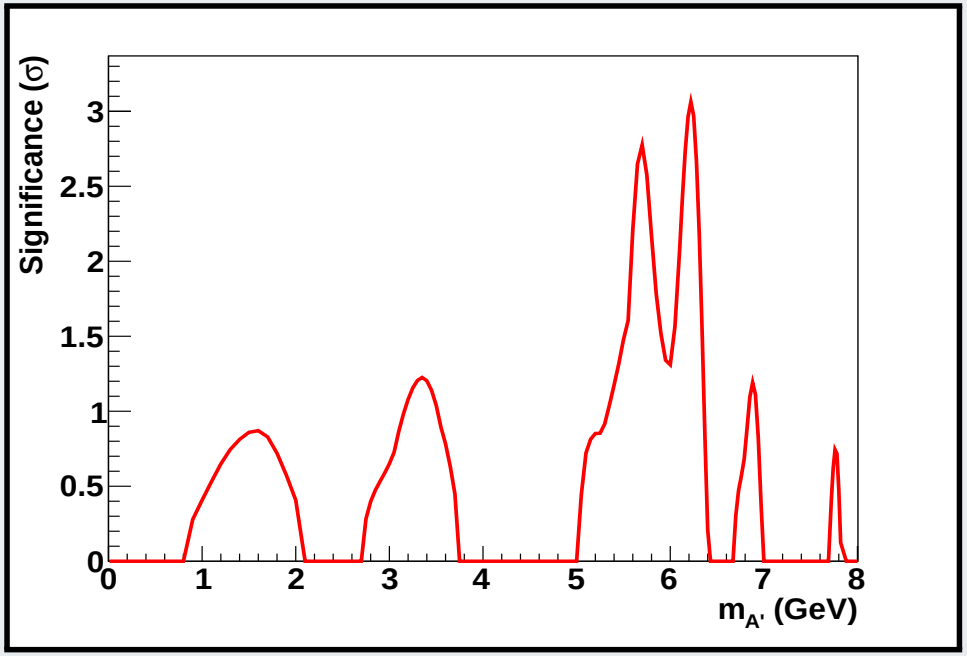
fit

- simultaneous unbinned extended maximum likelihood fit on all 9+4 samples
- signal normalization fixed to zero on 2 background data samples
- fit bkg shape on bkg region, float just bkg normalization on tight/loose signal regions
- scan total of 166 $M^2_{A'}$ values (spaced by about half the resolution)

signal significance

- local significance from likelihood-ratio test
$$\sigma = \sqrt{2\ln(L_{\max}/L_0)}$$
- local maximum of $3.1\,\sigma$ at $M_{A'} = 6.21\,\text{GeV}$
- overall global significance $2.6\,\sigma$ (estimated look-elsewhere effect with parametrized simulations)
- compute upper limits (both bayesian and frequentist)

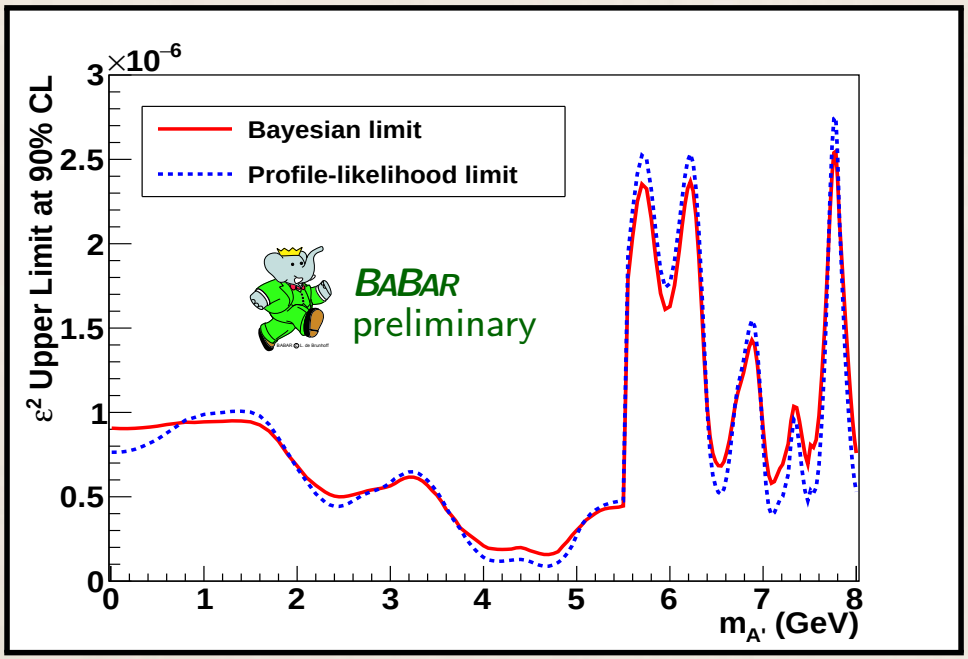
signal significance plot



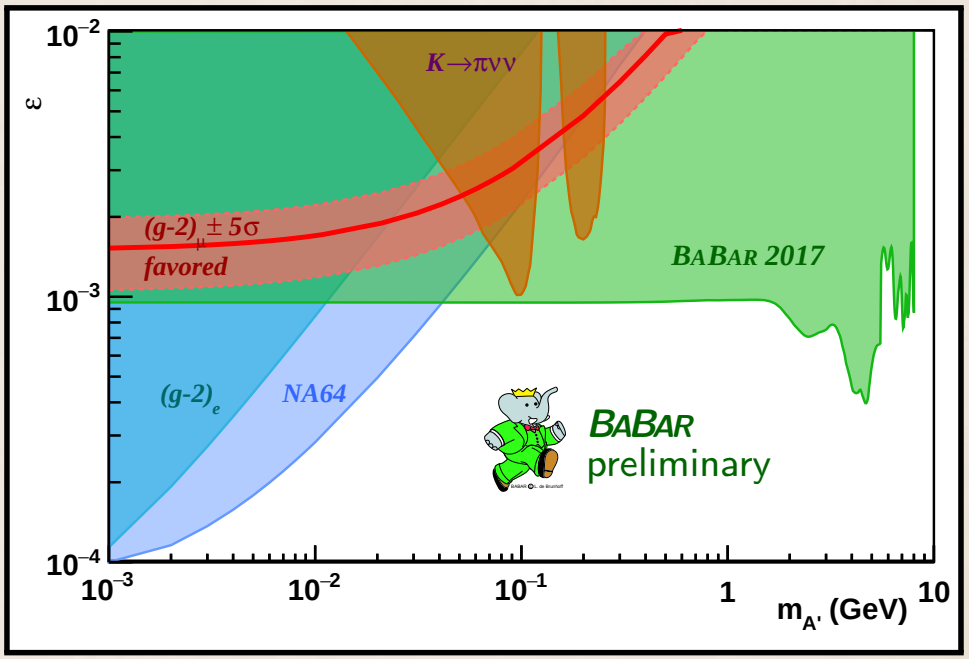
Constraints on Dark Photon theory model

- significant improvement over previous searches
- rule out entire region preferred by possible muon $(g-2)$ anomaly
- search can be re-interpreted to constrain models with invisible narrow resonance

A'-mass-dependent limit on ϵ^2



constraints on mass and coupling



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