Recent Results from BaBar: New Physics Searches

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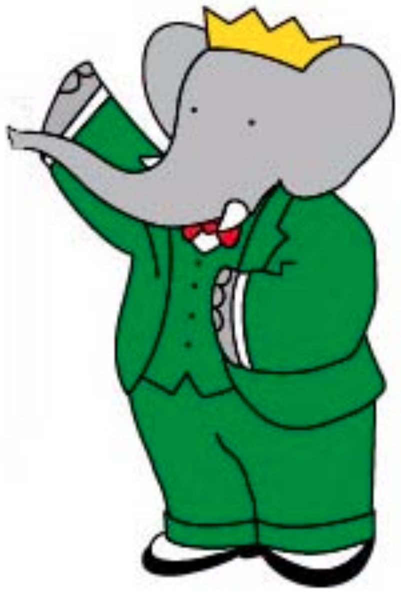
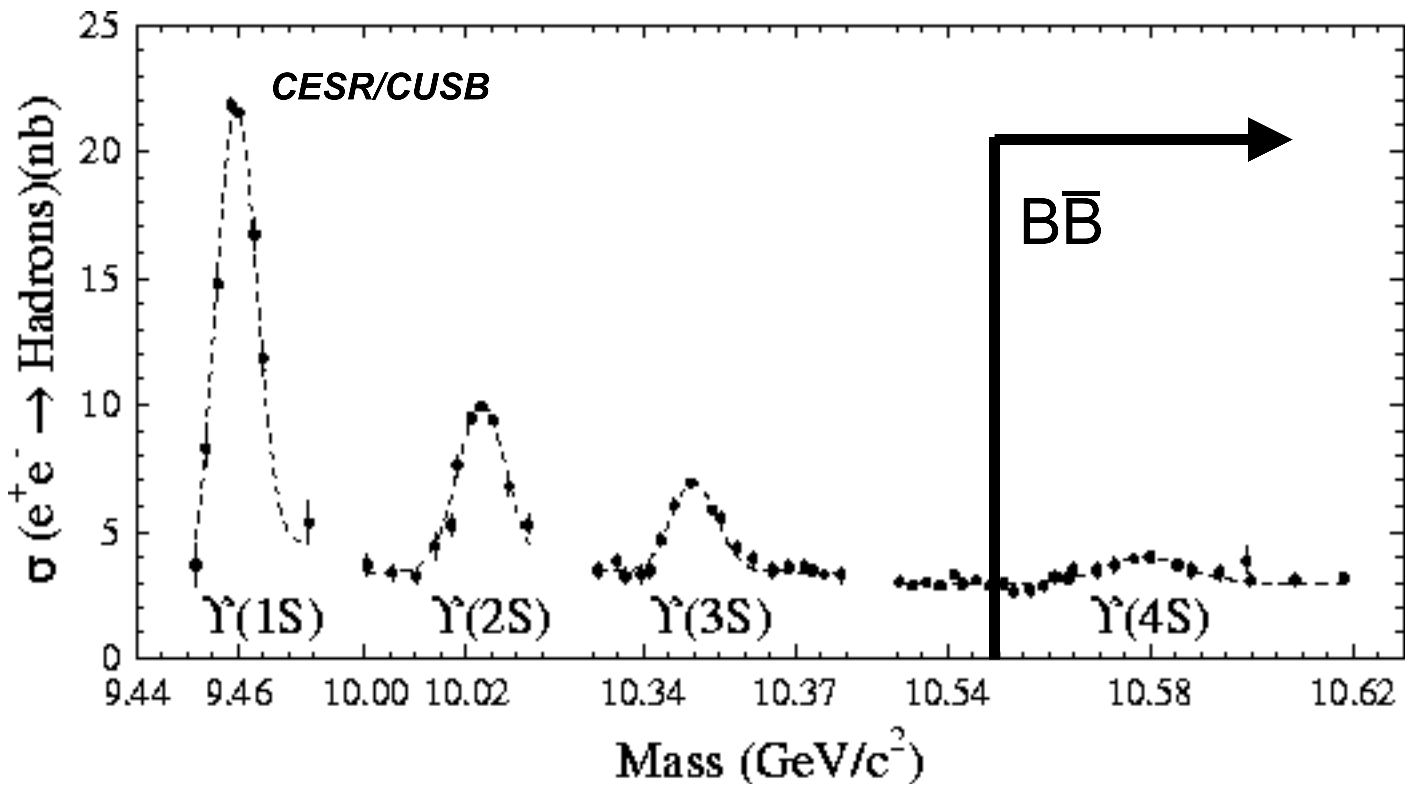
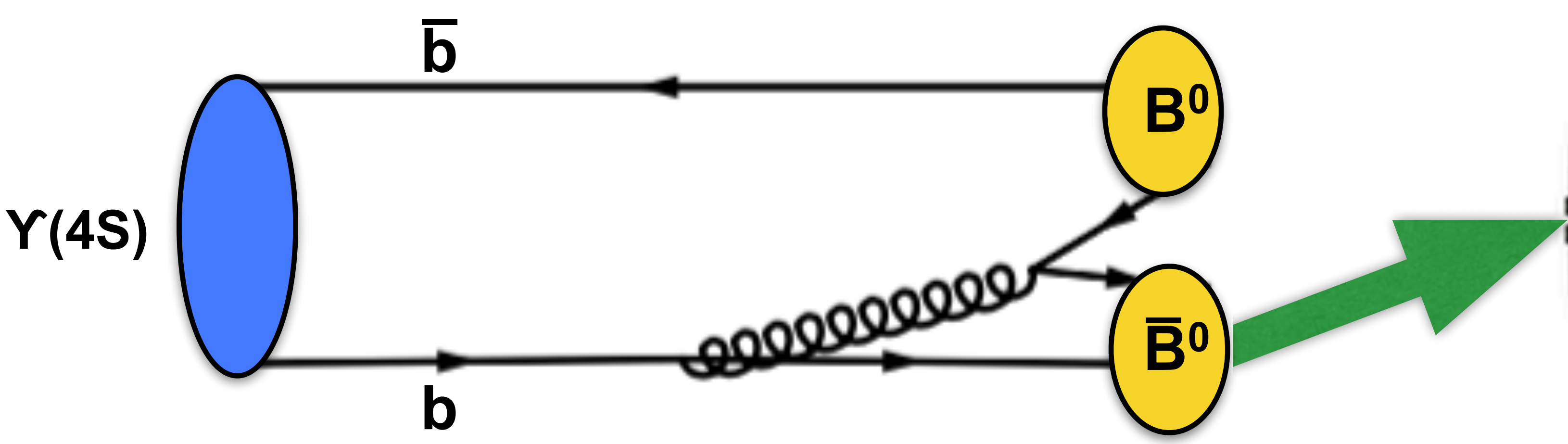
2105 SLAC Summer Institute
August 14 , 2015

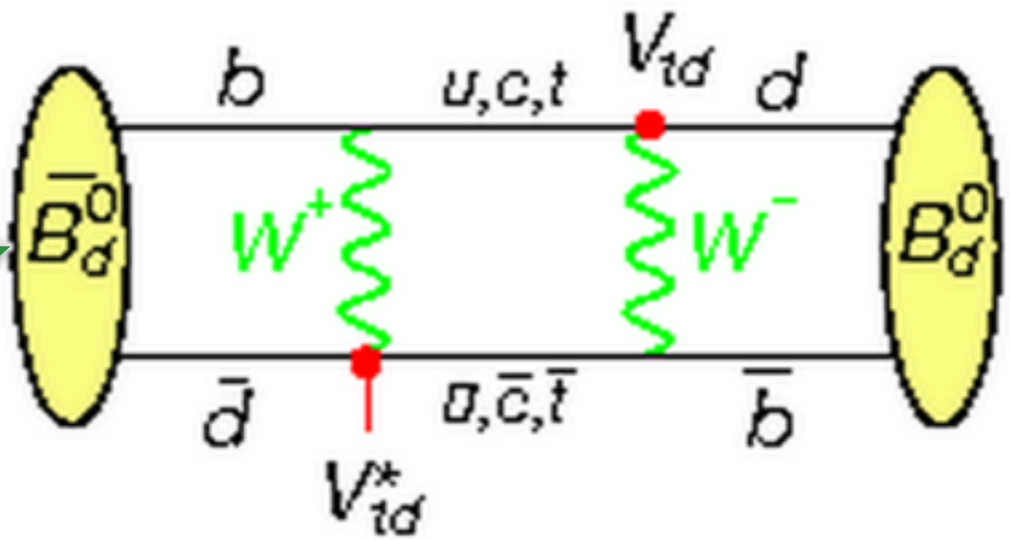


What is a B-Factory?

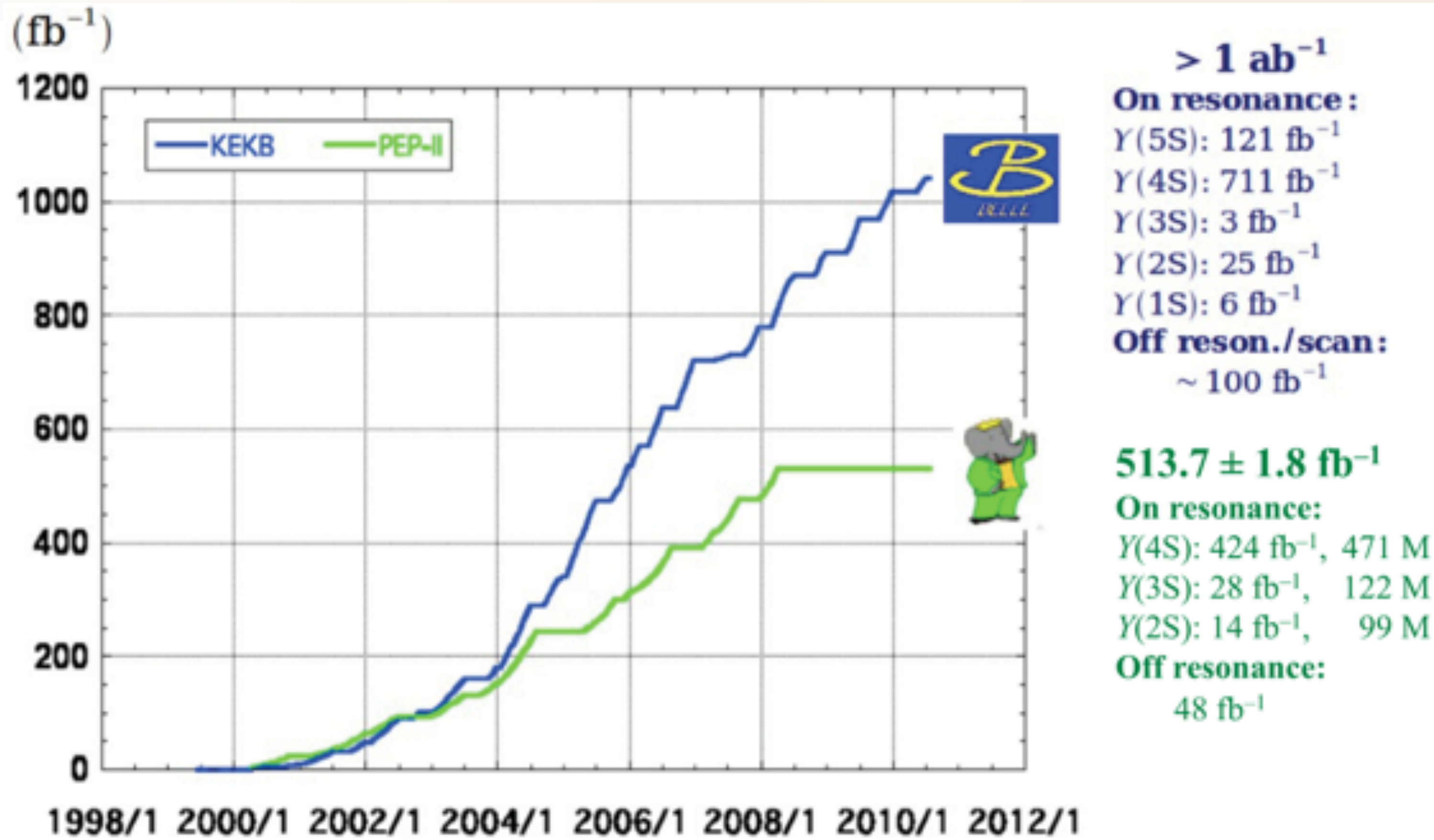


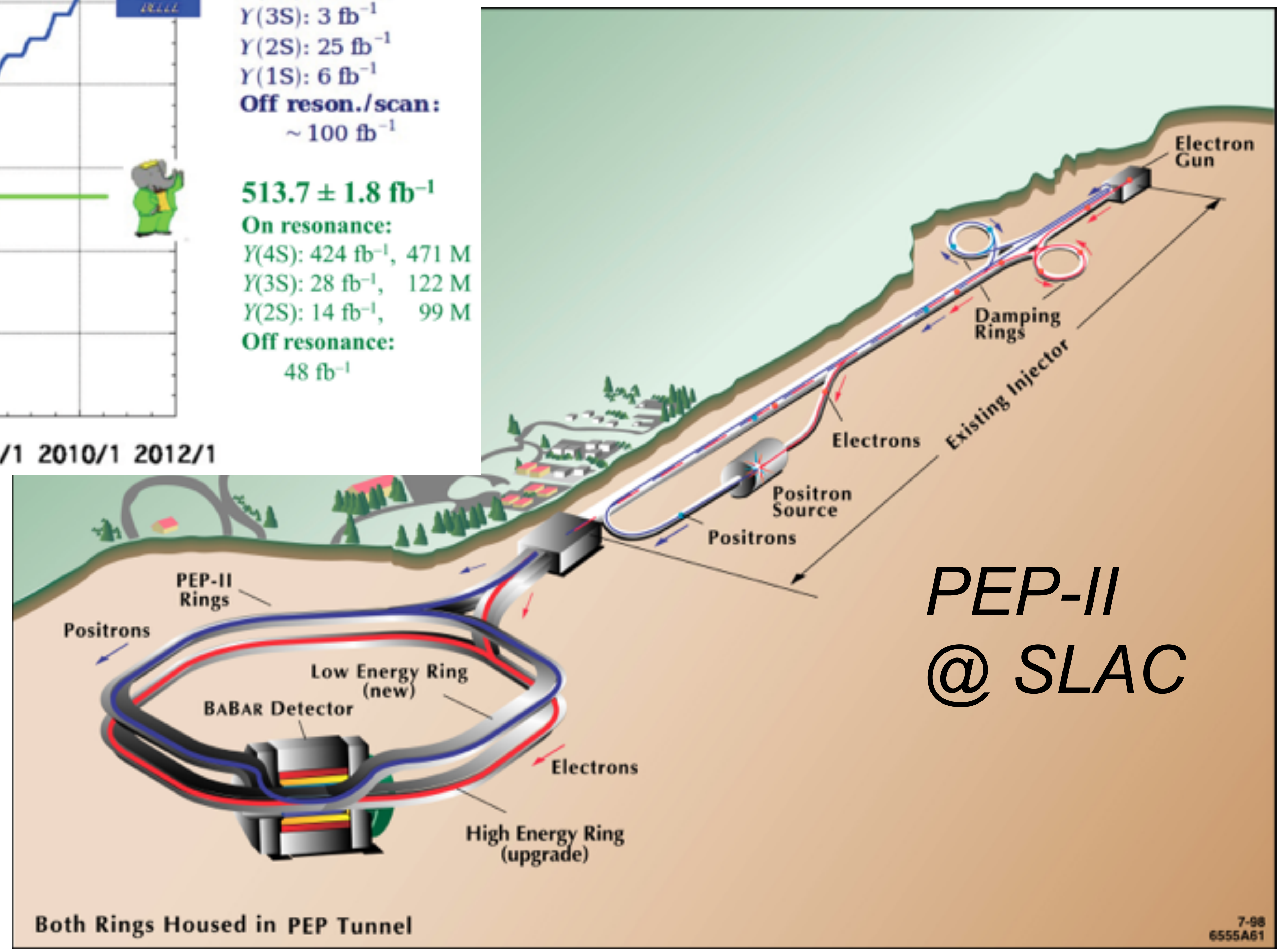
The **main** thrust of a B-Factory is to produce lots and lots of coherent B^0-$\bar{B}^0$ pairs in order to study CP-violation.



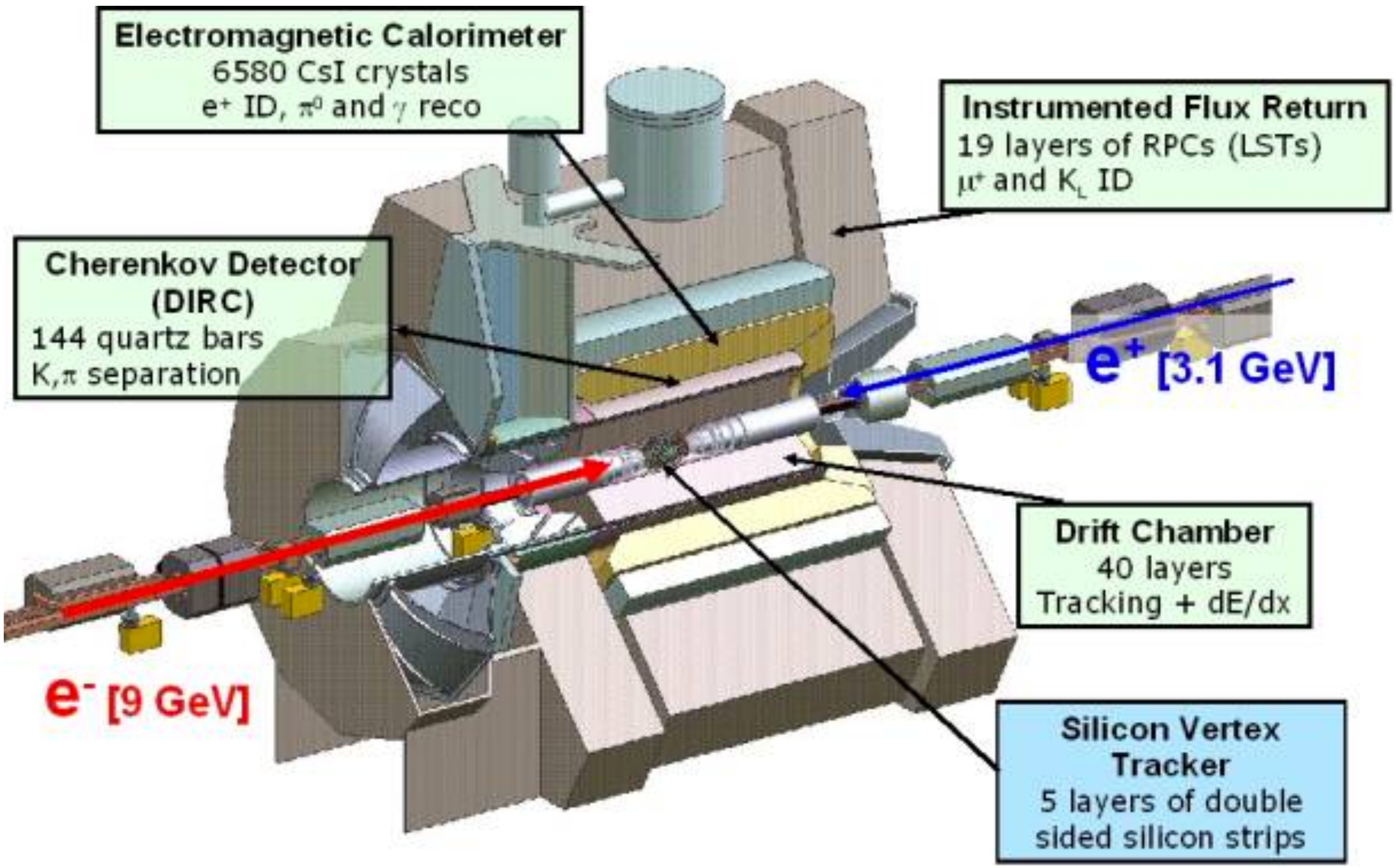


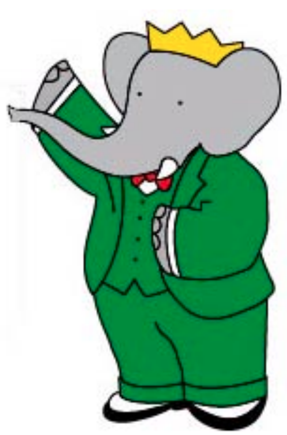
Asymmetric B-Factories: PEP-II and KEKB



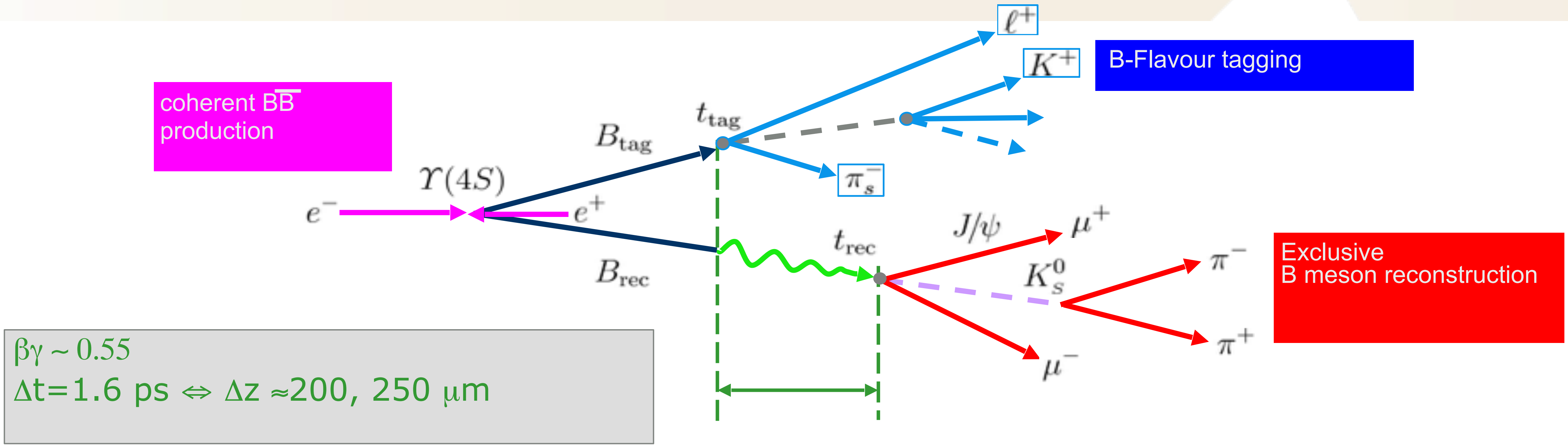


B-Factory Detectors (e.g. BaBar)





Guiding the design…



e^+e^- B-Factories:

Typical error on Δt ~ 0.8 ps

The Δt resolution function obtained from high stat. B→DX

Events tagged using the charge of the leptons, kaons, pions

Effective tagging efficiency (including mistag-rate) ~30%

LHCb:

Typical error on Δt ~ 0.05 ps

Effective tagging efficiency (including mistag-rate) ~5%

Searches for New Physics in B-Factories

- Indirect searches:
  - This is what B-Factories are all about…

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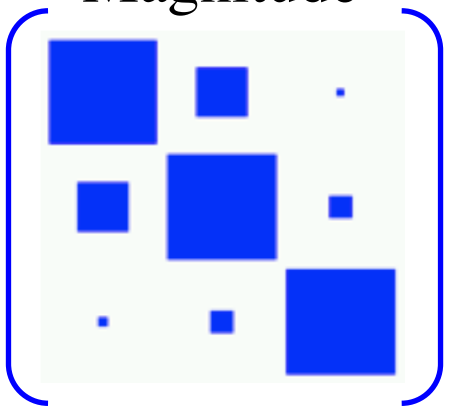
The CKM Matrix

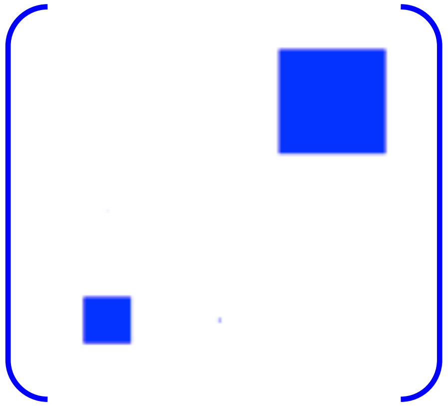
$$V_{pq} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \propto$$

Magnitude



x

Phase



CKM⇔quarks

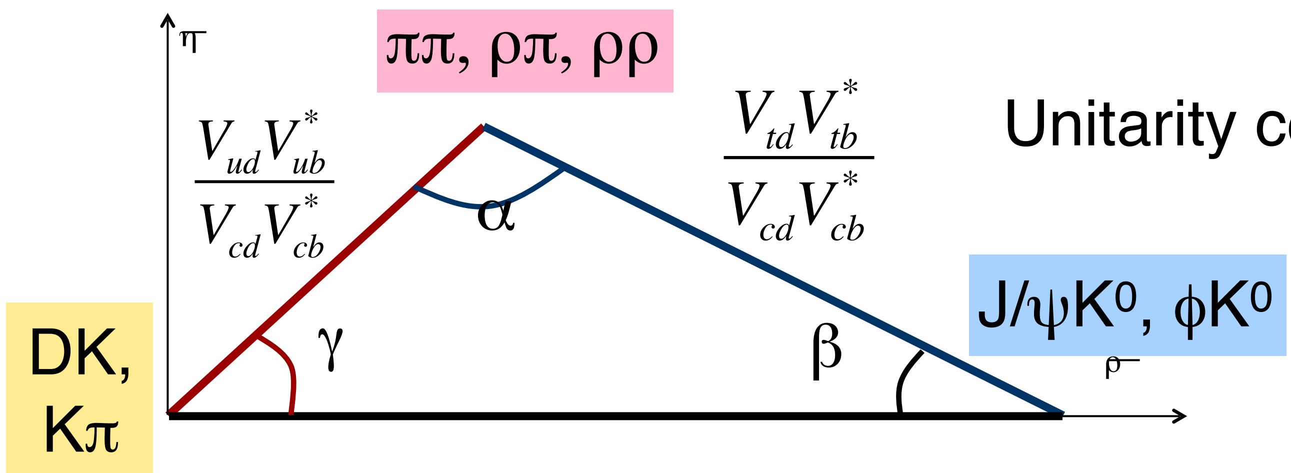
PMNS⇔leptons

$$\approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = \sin\theta_C = 0.22$$

Searches for New Physics in B-Factories

- Indirect searches:
  - This is what B-Factories are all about…

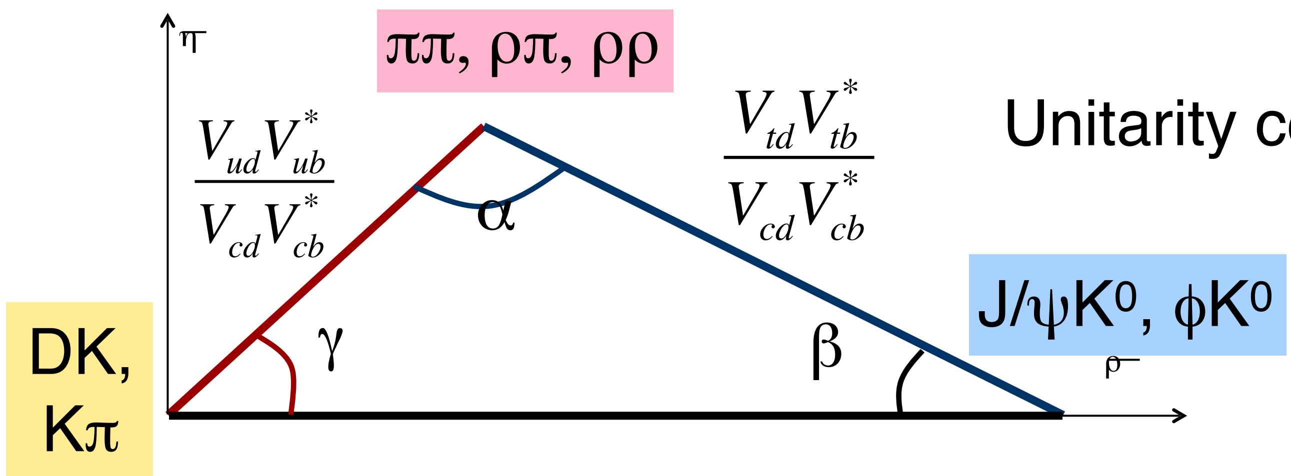


Unitarity condition: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

"Unitarity Triangle"

Searches for New Physics in B-Factories

- Indirect searches:
  - This is what B-Factories are all about…



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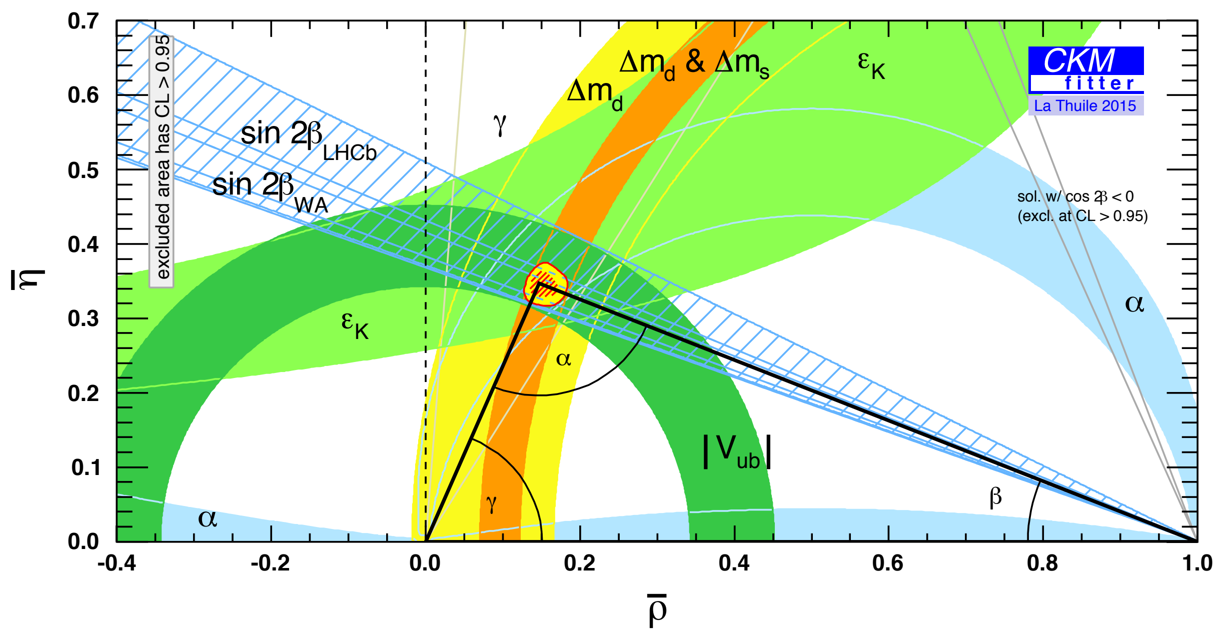
"Unitarity Triangle"



$\bar{\rho} = 0.15 \pm 0.01$

$\bar{\eta} = 0.34 \pm 0.01$

This is a triumph of the HEP community!

Searches for New Physics in B-Factories

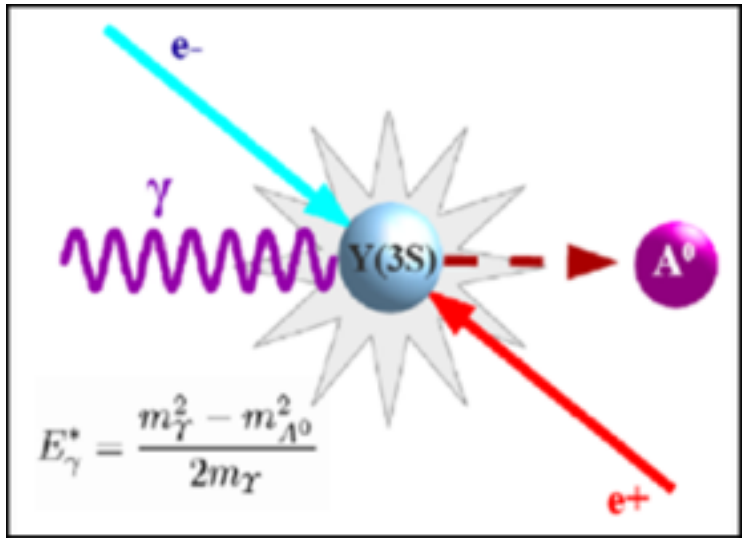
- Indirect searches:
  - This is what B-Factories are all about…
  - …but not the only thing…
- Direct searches:
  - searches for light higgs (A^0)
  - searches for dark sectors
  - …this is what the rest of the talk is about…

Searches for the light CP-Odd Higgs: A^0

- The A^0 is a CP-Odd Higgs particle that comes up in 2-Higgs Doublet Models (2HDM)…along with h^0, H^0, and $H^\pm$
- Its mass *could* be light (~MeV-GeV) → search for it at B-Factories
- 2HDM can be seen as a generic extension of SM but also arise naturally in SUSY models (in particular the NMSSM)

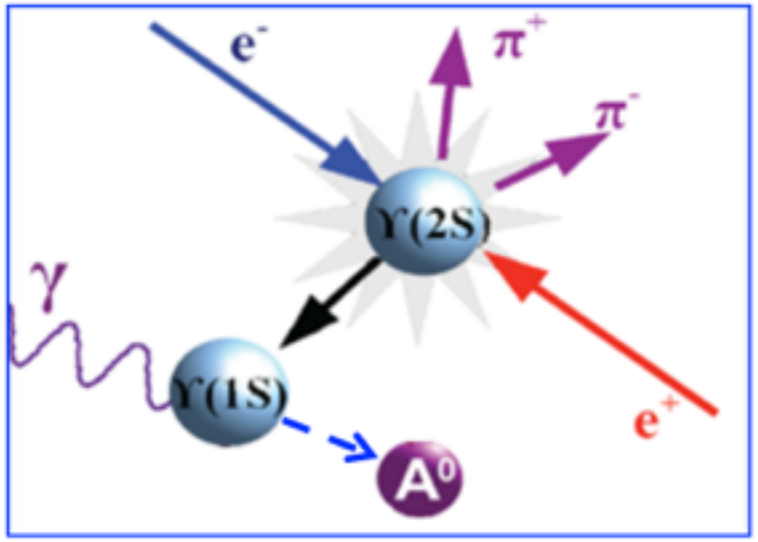
- B-Factories look for A^0 in two ways:
  - directly from radiative decay of Υ(nS):

$$\Upsilon(nS) \to \gamma A^0 \to f\,\bar{f}$$



  - from the cascade of Υ(nS)→Υ(1s):

$$\Upsilon(nS) \to \Upsilon(1S)\pi\pi \text{ (or } \gamma) \\ \downarrow \\ \gamma A^0 \to f\,\bar{f}$$



  - …looking for the cascade from Υ(nS) greatly reduces the background (ensures you have a $\bar{b}b$ state)

Search for $A^0 \to c\bar{c}$

- 13.6 fb^{-1} on $\Upsilon(2S)$ resonance:
  - $(98.3 \pm 0.9) \times 10^6$ $\Upsilon(2S)$ mesons
  - $(17.5 \pm 0.3) \times 10^6$ $\pi^+\pi^-$ $\Upsilon(1S)$ decays
- Reconstruct at least ***one*** D-meson in one of:

  $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K_S\pi^+\pi^-$

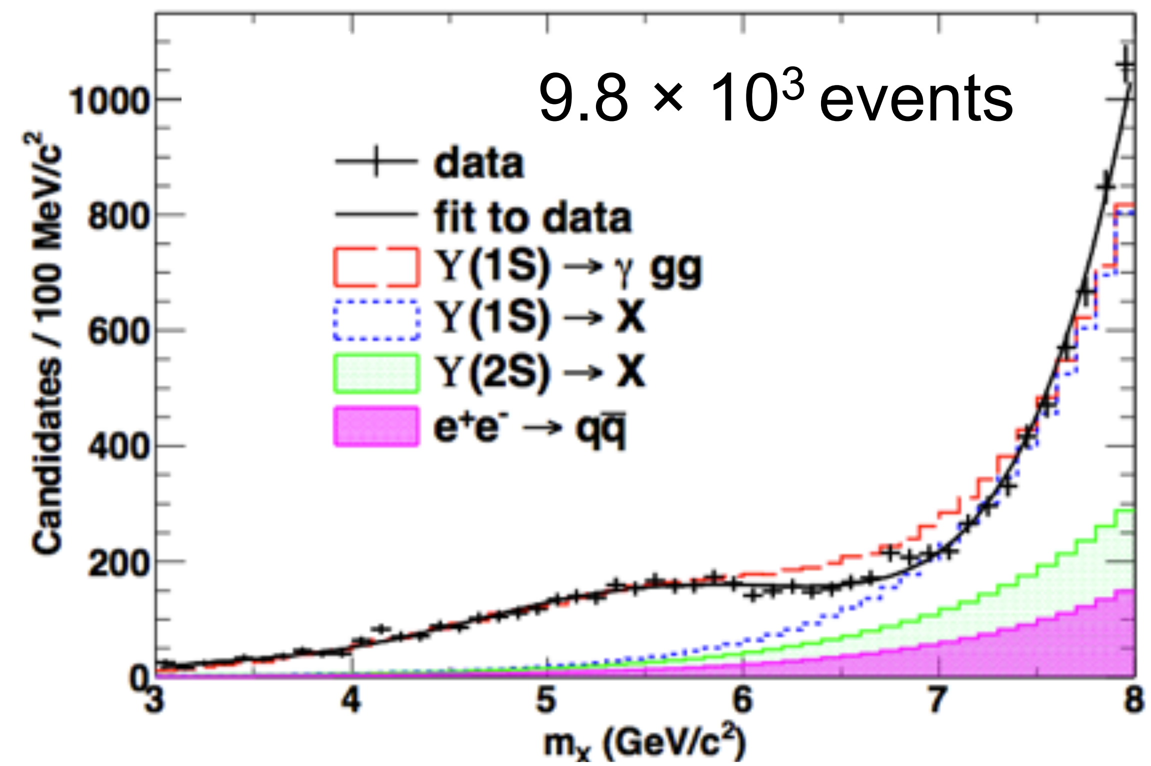
  $D^+ \to K^-\pi^+\pi^+$

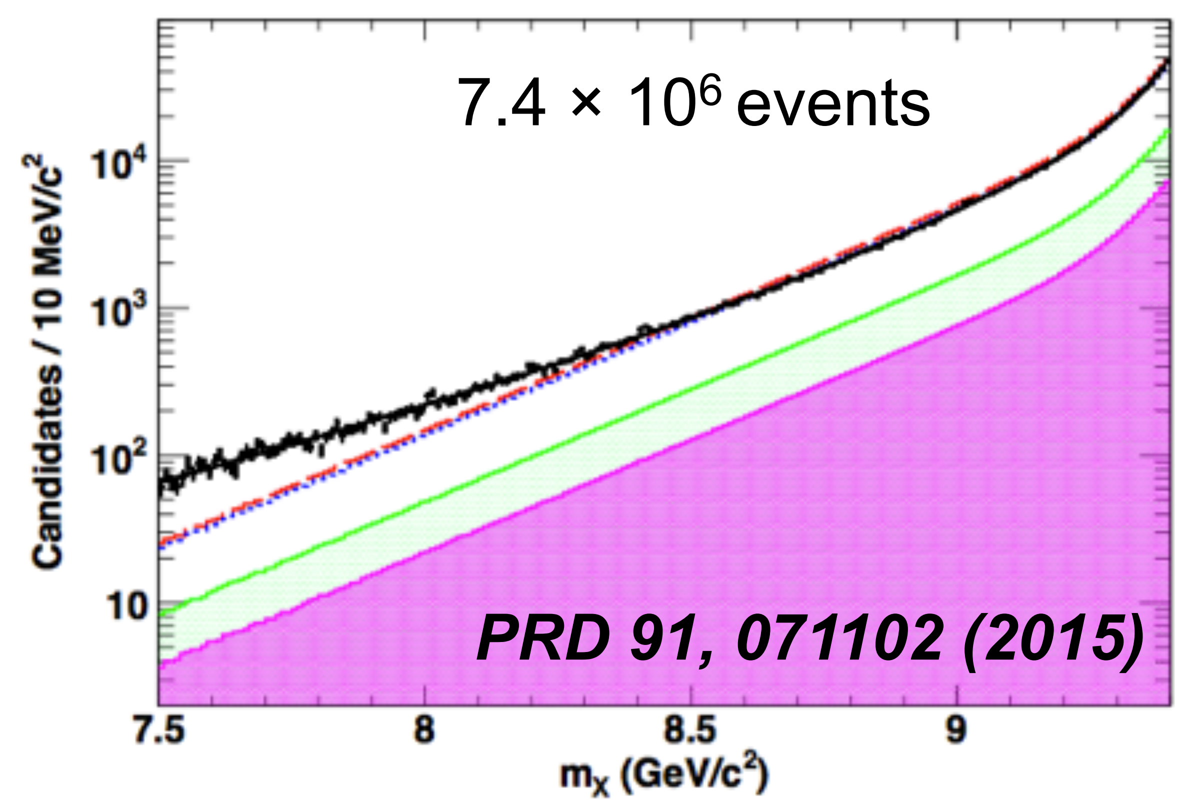
  $D^{*+} \to \pi^+ D^0(\to K^-\pi^+\pi^0)$

  - …fraction of possible final states included in efficiency (JETSET)…

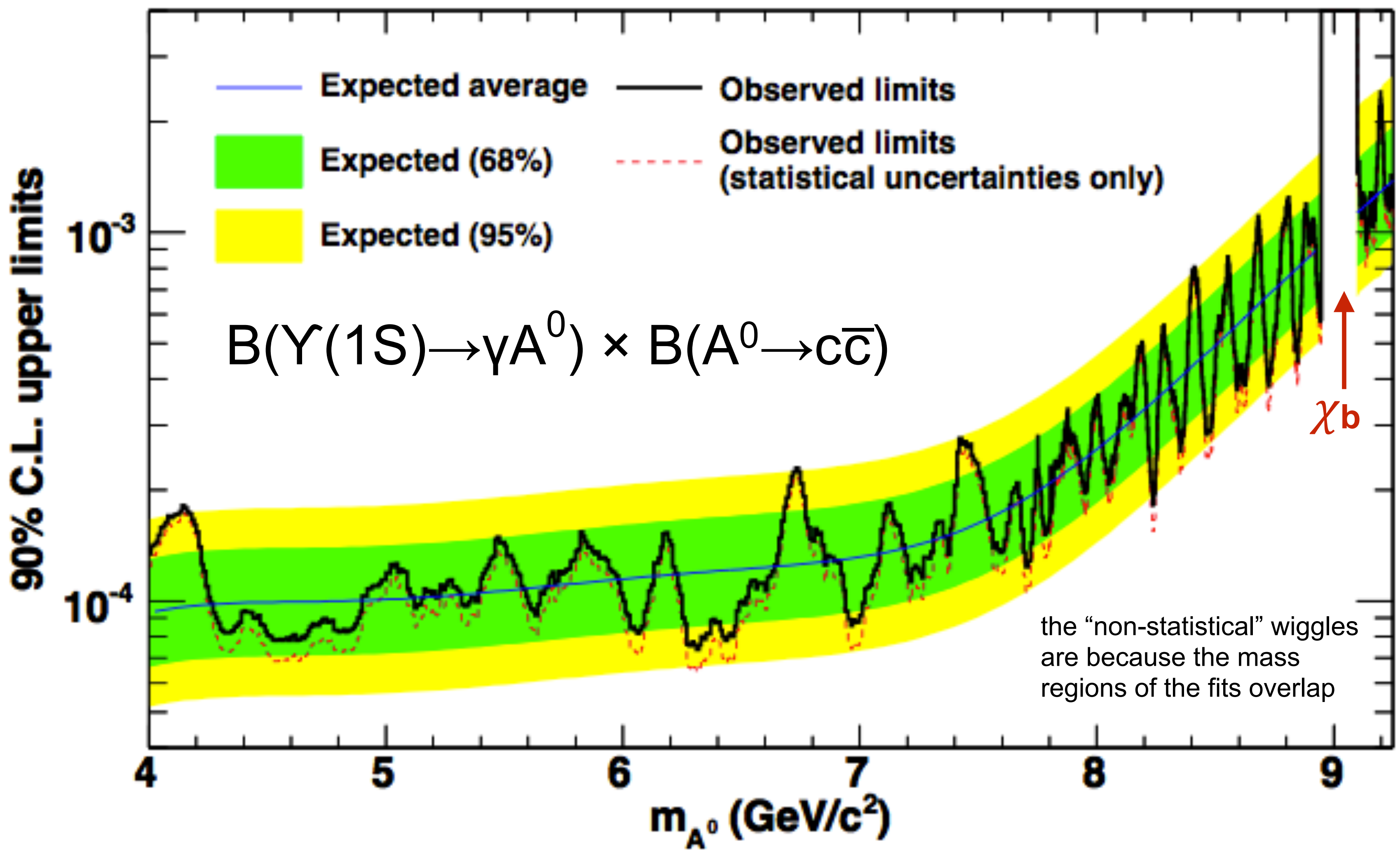
$$m_R^2 = M_{\Upsilon(2S)}^2 + m_{\pi\pi}^2 - 2M_{\Upsilon(2S)}E_{\pi\pi}$$

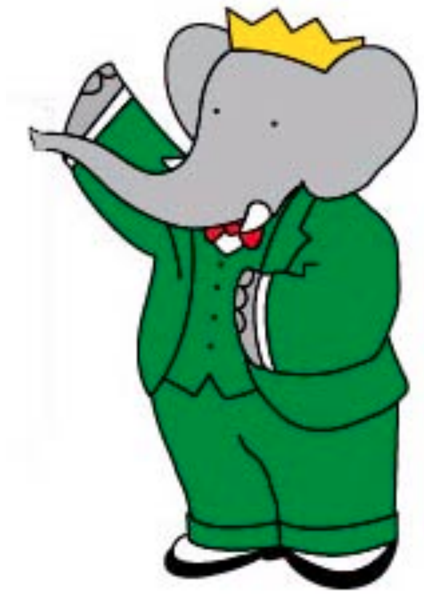
- Dataset split into high- and low-mass regions because of very different background shapes





Search for $A^0 \to c\bar{c}$ upper limits





- Perform a scan in M_X on the plots on previous page..
  - step along in mass fitting the signal contribution to a Crystal Ball™ function and the background to a second-order polynomial (floating)
- No significant signal observed (either with or without accounting for the trials factor), so an upper limit is calculated

PRD 91, 071102 (2015)

A comprehensive suite of searches…

$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	arXiv:0808.0017 [hep-ex]
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	PRL 103, 081801 (2009)
$\Upsilon(2S, 3S) \to \gamma A^0, A^0 \to$ hadrons	PRL 107, 221801 (2011)
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	PRL 107, 021804 (2011)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	PRD 87, 031102 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	PRD 88, 031102 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ gg,ss	PRD 88, 031701 (2013)
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ cc	PRD 91, 071102 (2015)

New interactions beyond the SM?

vector → $\frac{1}{2}\epsilon F^{Y}_{\mu\nu}F'^{\mu\nu}$ **dark photon**

Higgs → $\epsilon_h |h|^2 |\phi|^2$ **dark scalar**

neutrino → $\epsilon_\nu (hL)\psi$ **sterile neutrino**

axion → $\frac{1}{f_a} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ **ALPSs**

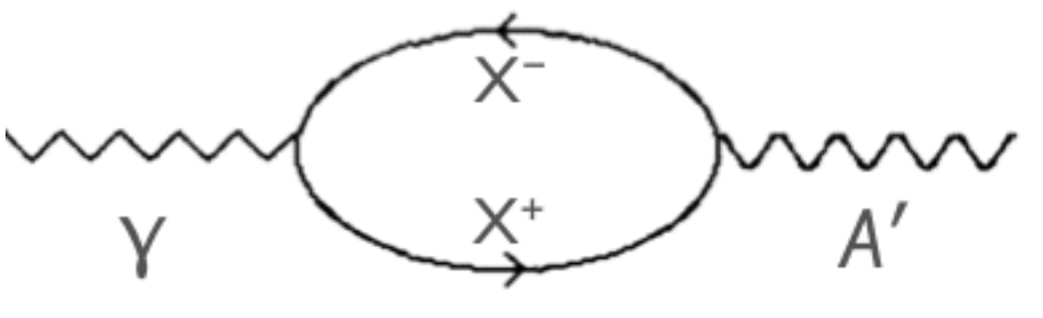
Kinetic mixing from the vector portal

an old idea: if there is an additional U(1) symmetry in nature, there will be mixing between the photon and the new gauge boson

Holdom, Phys. Lett B166, 1986

$$\mathcal{L}_{U(1)'} = -\frac{1}{4}V_{\mu\nu}^2 - \boxed{\frac{\epsilon}{2}V_{\mu\nu}F^{\mu\nu}} + |D_\mu\phi|^2 - V(\phi)$$

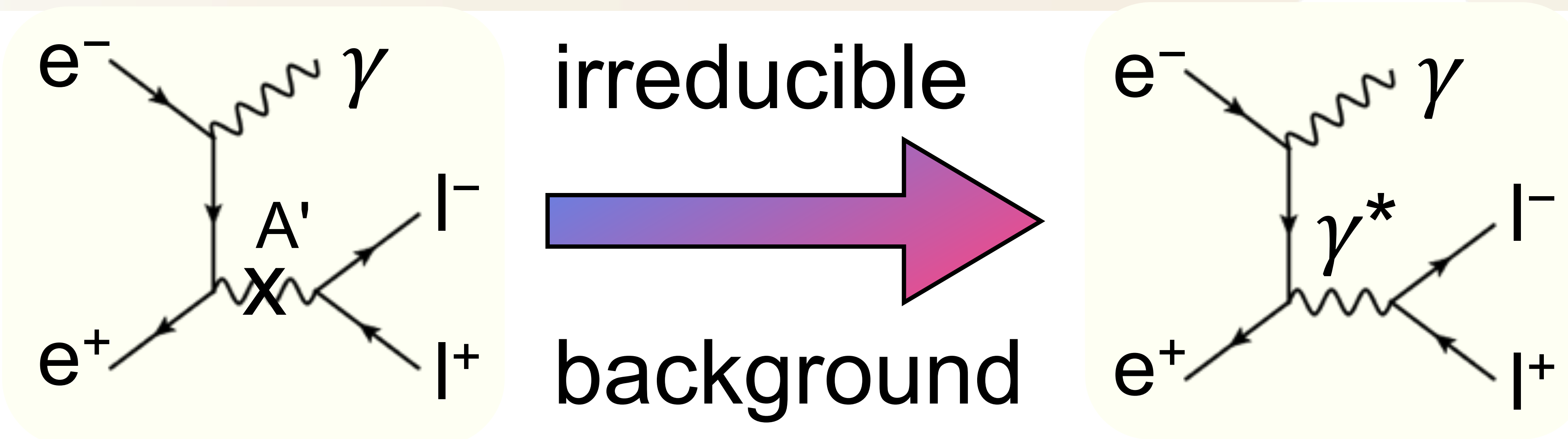
Kinetic Mixing term



NOTE: A^0 (light higgs) != A' (dark photon) !!!

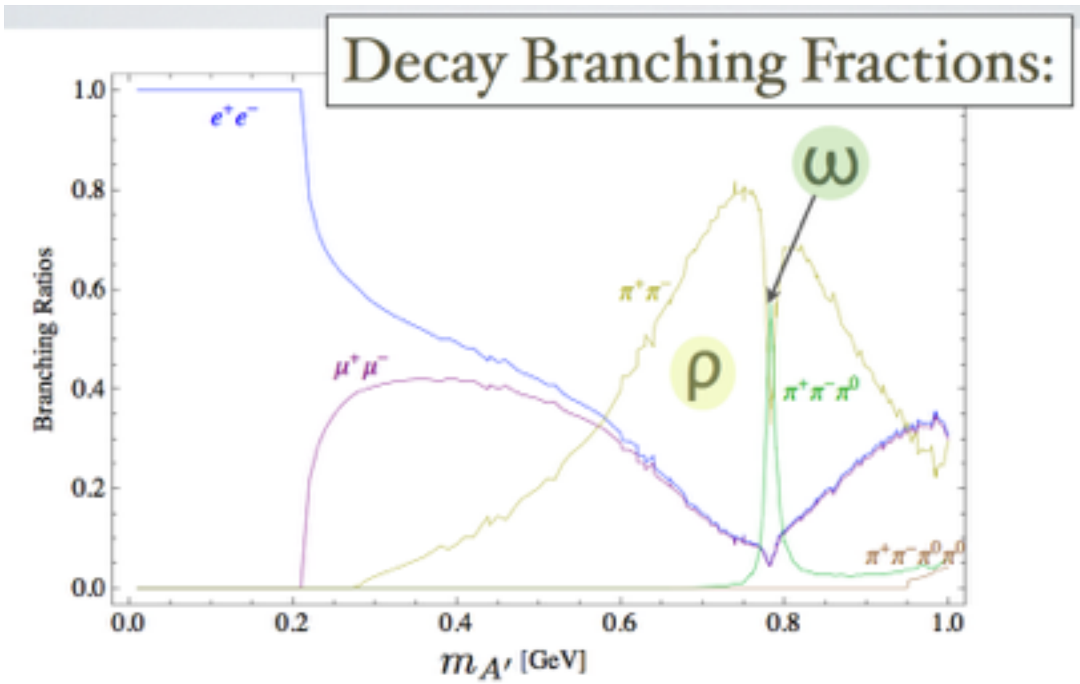
- extremely general conclusion…even arises from broken symmetries
- gives coupling of normal charged matter to the new ***"dark photon"*** q=εe
- dark photon could get mass via a "dark higgs" mechanism (or elsewhere)

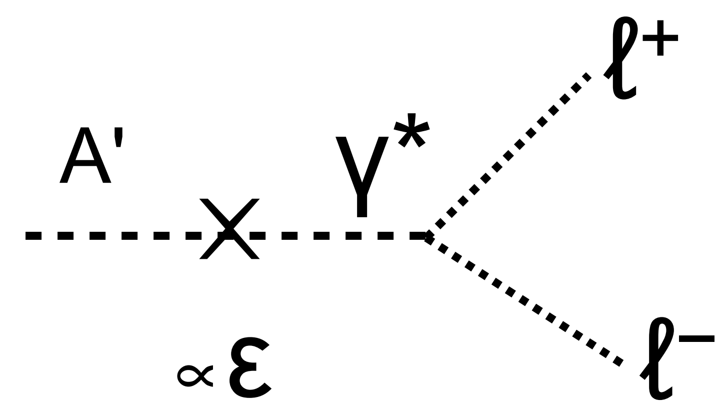
Dark photon production at e^+e^- colliders



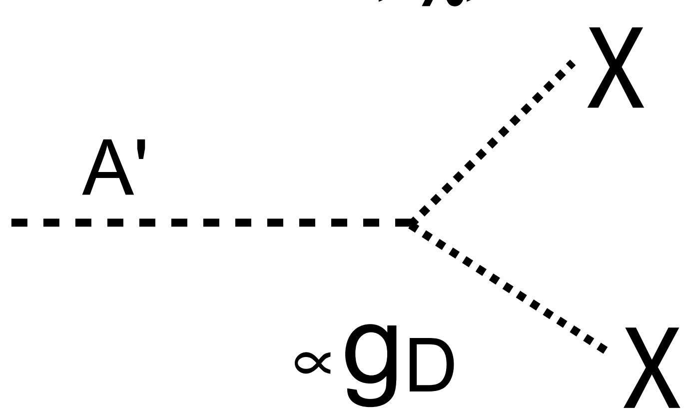
- The flavor factories (BaBar, Belle(-II), KLOE) are great places to look for dark photons:
  - high luminosity
    - not quite high enough to get to displaced-vertex regions
  - excellent acceptance & PID
    - also makes them good places to look for non-minimal dark sector (A'h, non-Abelian, etc)
  - good mass resolution ~ few MeV
- The primary *signature* is very similar to the A^0 searches…look for a bump over a continuum spectrum…

Decays of the dark photon





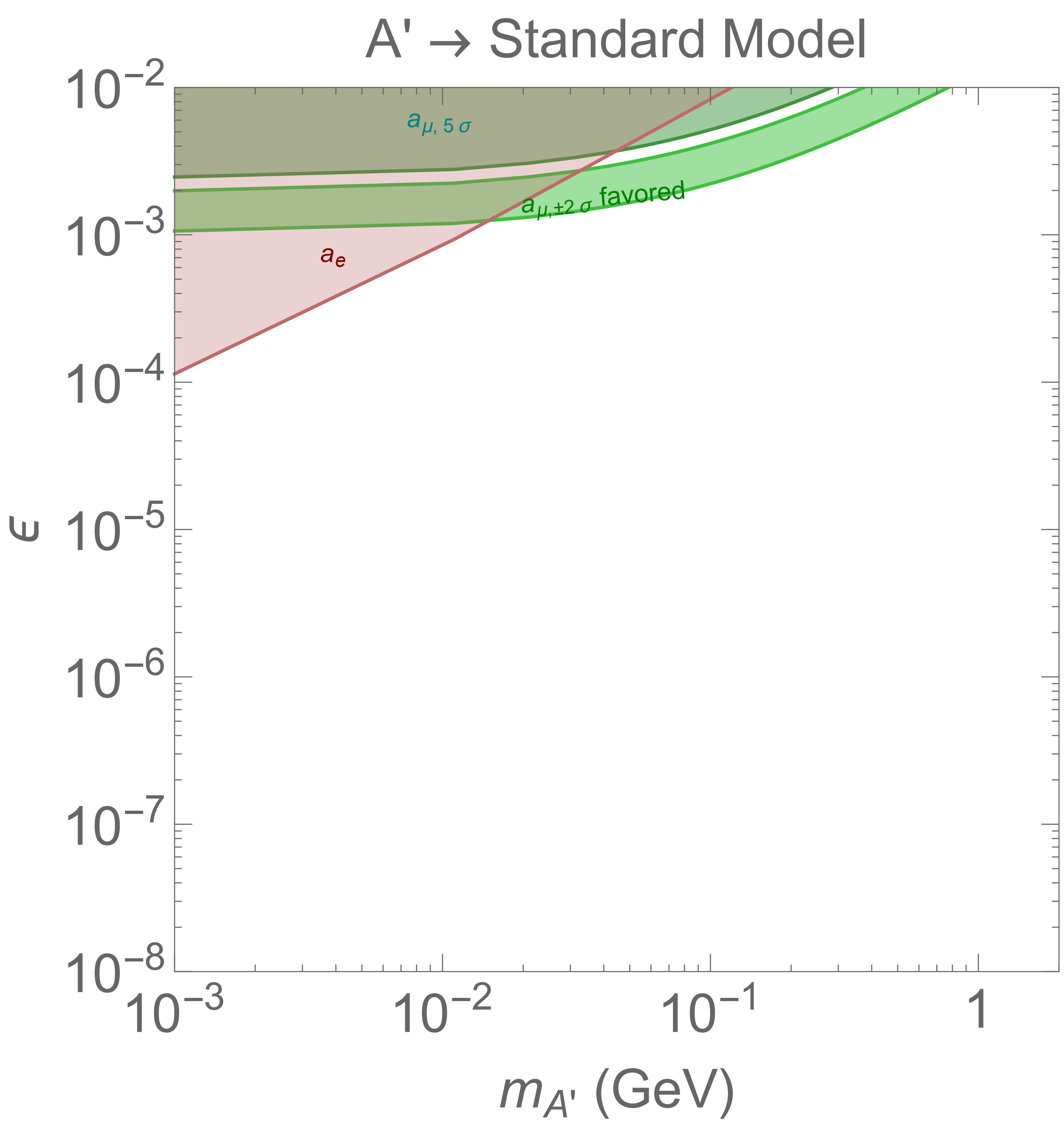
⇒***BUT,*** if there is a state, χ, with dark charge and is lighter than m(A′)/2



χ = light, hidden sector dark matter

…unless $g_D \ll \varepsilon$, ***A′ decays to dark sector will dominate***

Search phase-space

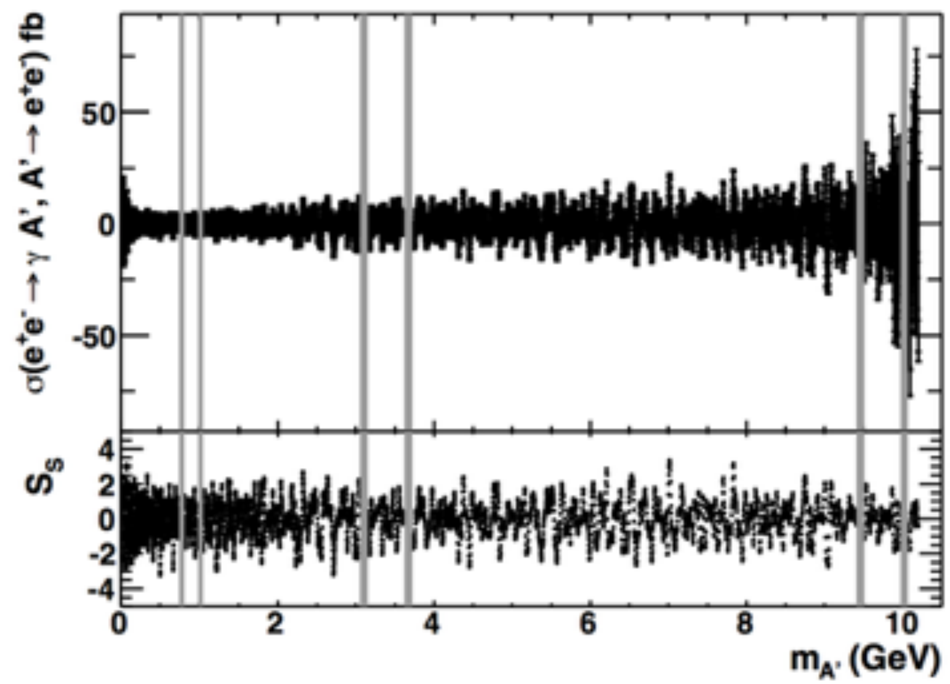


Start off with 2 indirect constraints:
g-2 of electron & muon

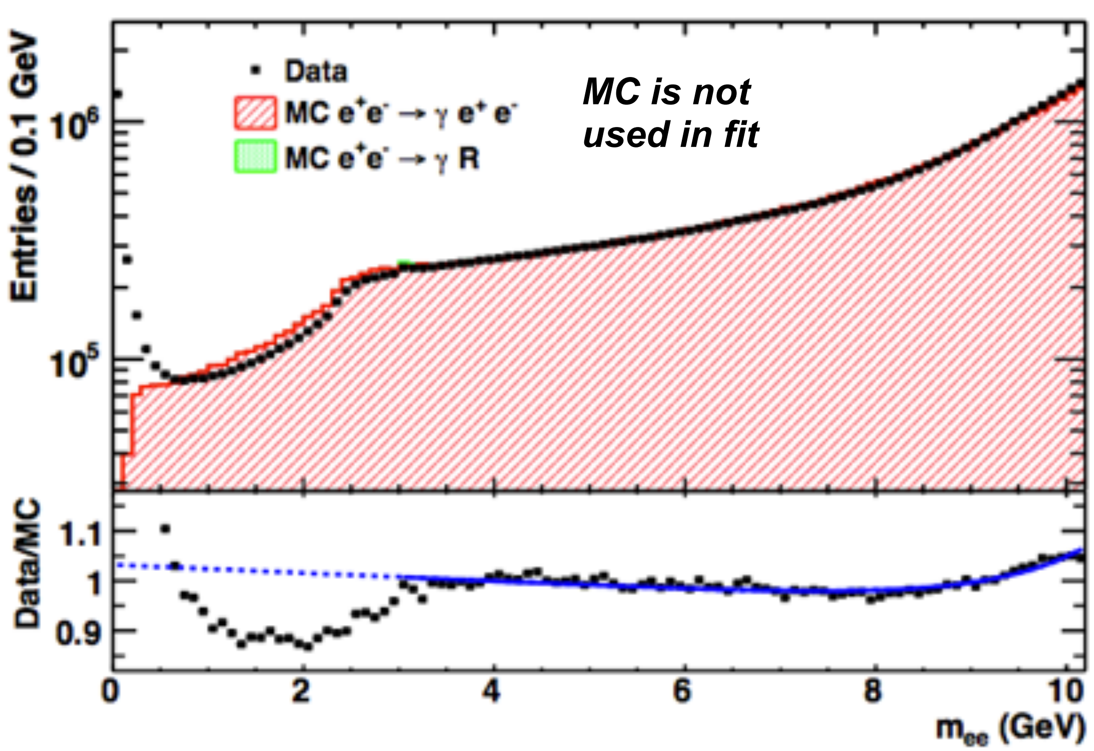
But! A ~3**σ** anomaly in g_μ-2
…interesting territory!

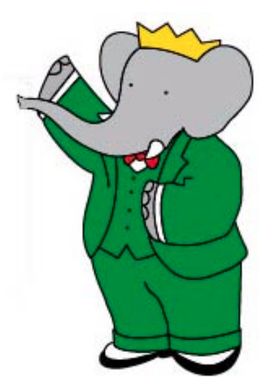
Search for dark photon in $e^+e^- \to \gamma \ell^+ \ell^-$

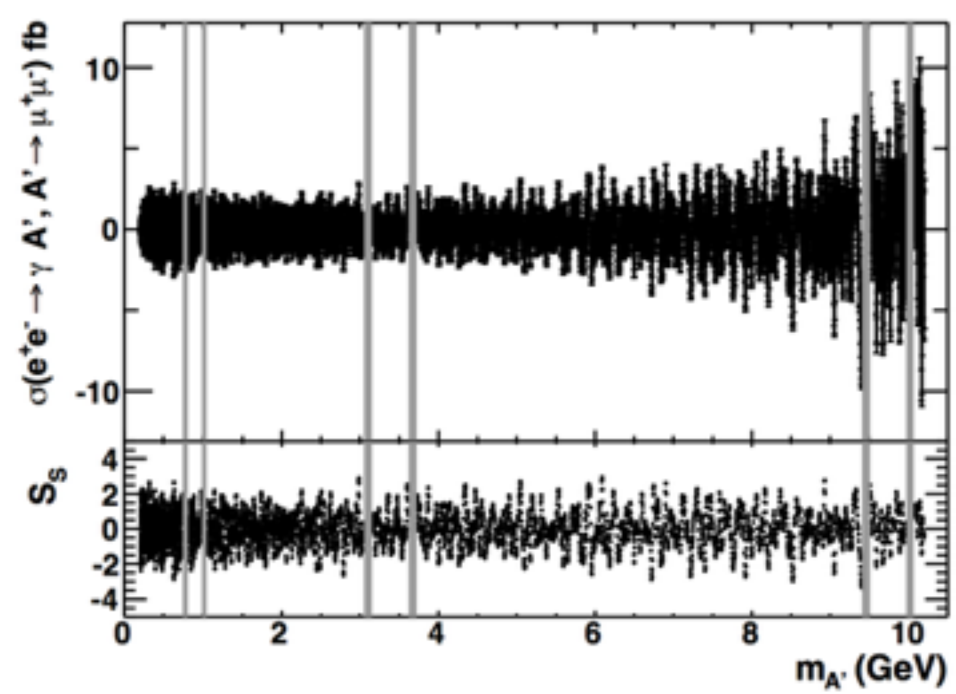
- this analysis uses the ***FULL*** BaBar dataset
  - 514 fb^{-1} of data…ϒ(4S), ϒ(3S), ϒ(2S) & off resonance
- fully reconstruct the γ and both ℓ's, either e^+e^- or $\mu^+\mu^-$
  - some care is taken to remove $\gamma \to e^+e^-$ conversions at low e^+e^- mass
- scan in $\ell^+\ell^-$ mass, fitting signal (non-parametric) + background (polynomial) in small mass steps



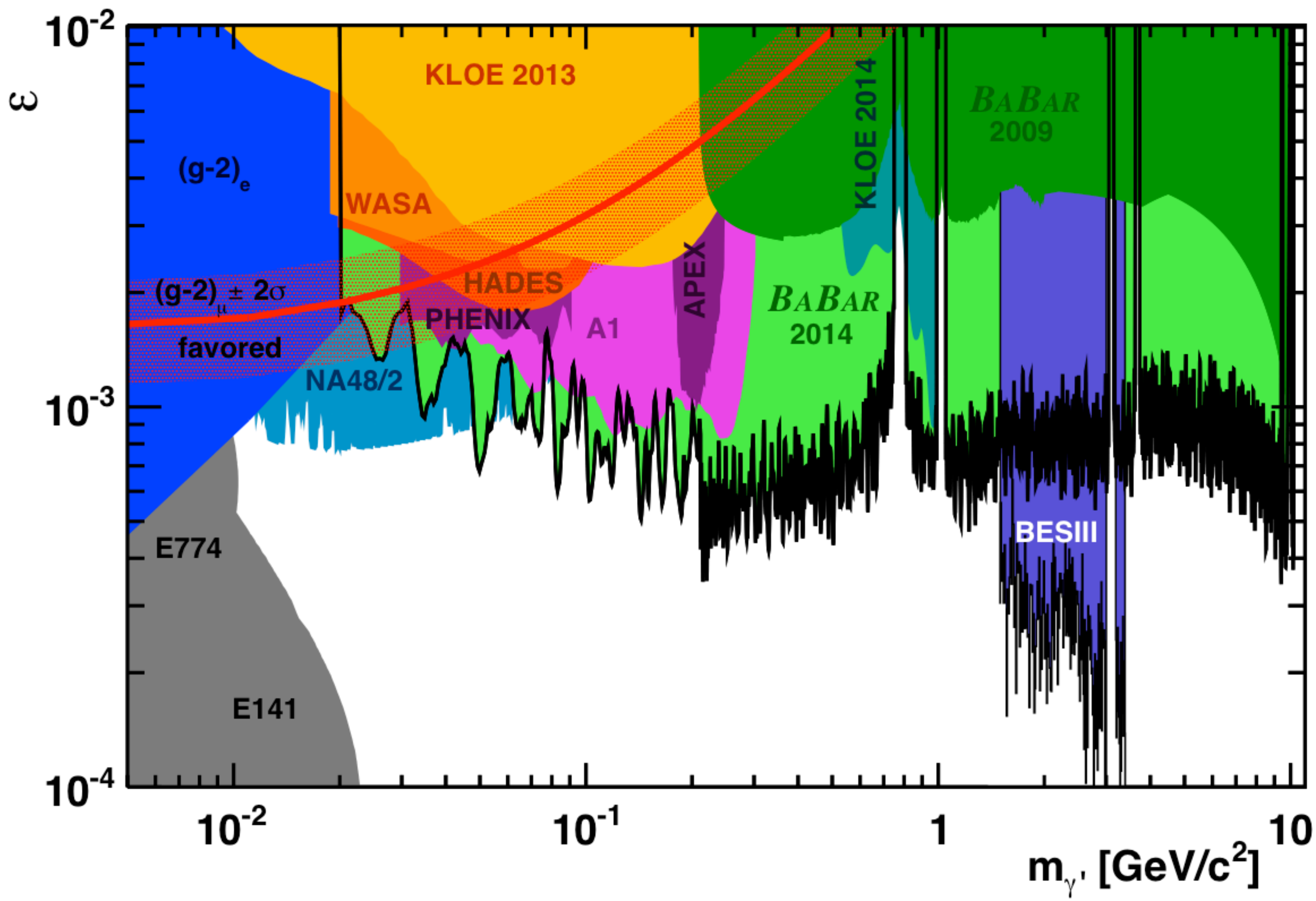
arXiv:1406.2980





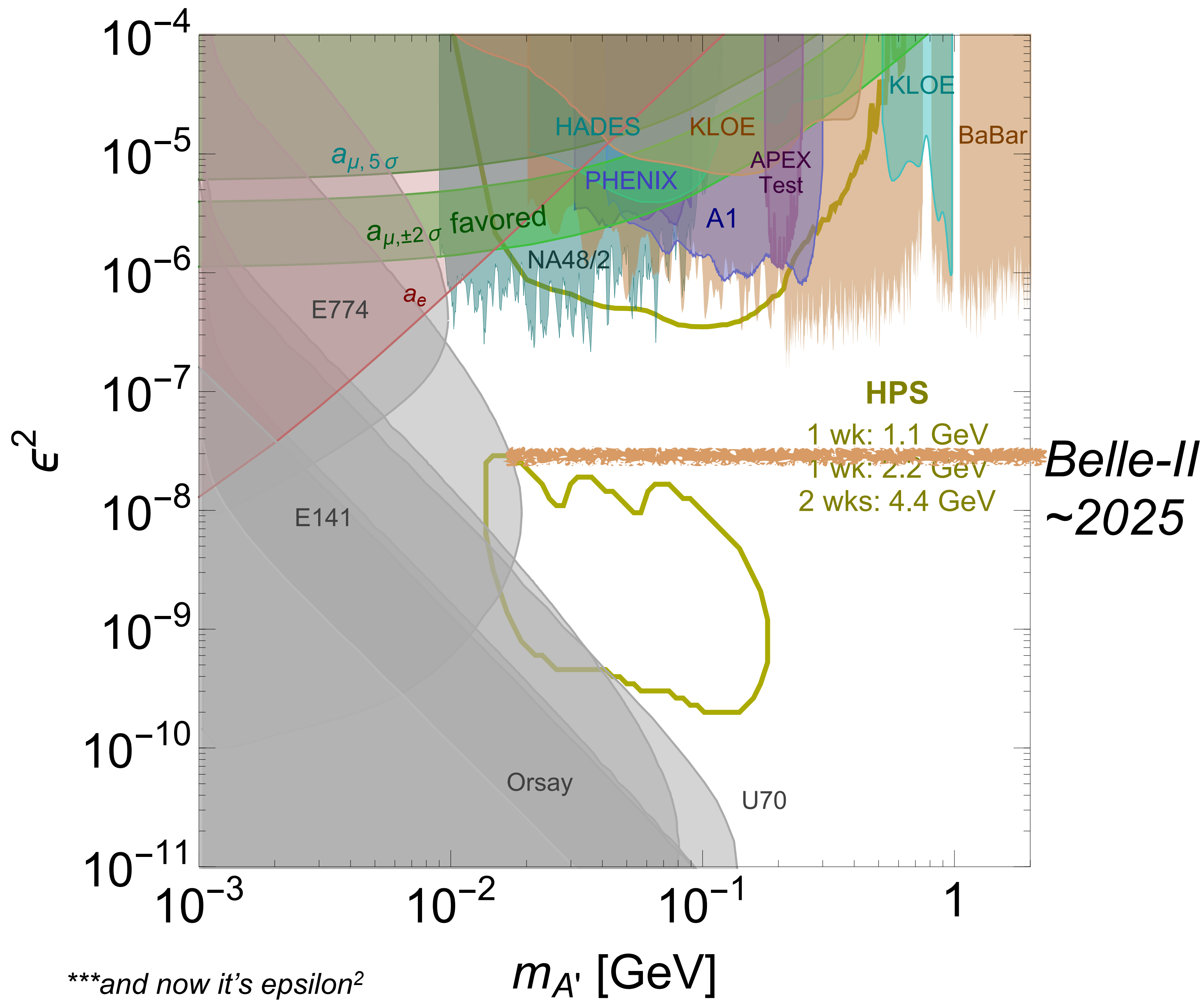


Limits on dark photon coupling from BaBar



Plot courtesy of B. Echenard

Current dark photon limits (+ HPS)

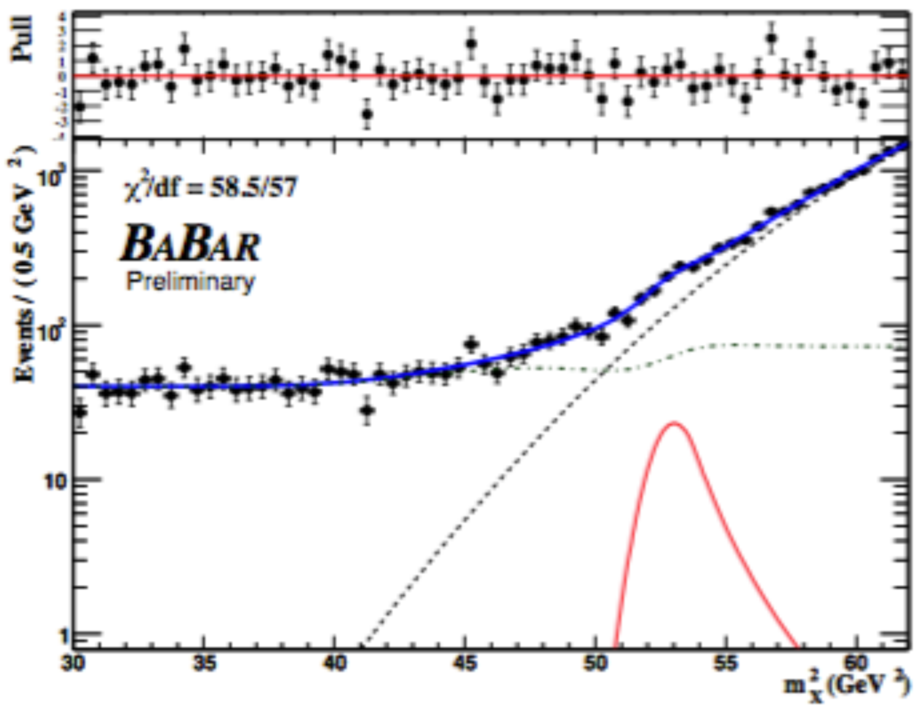


***and now it's epsilon[2]

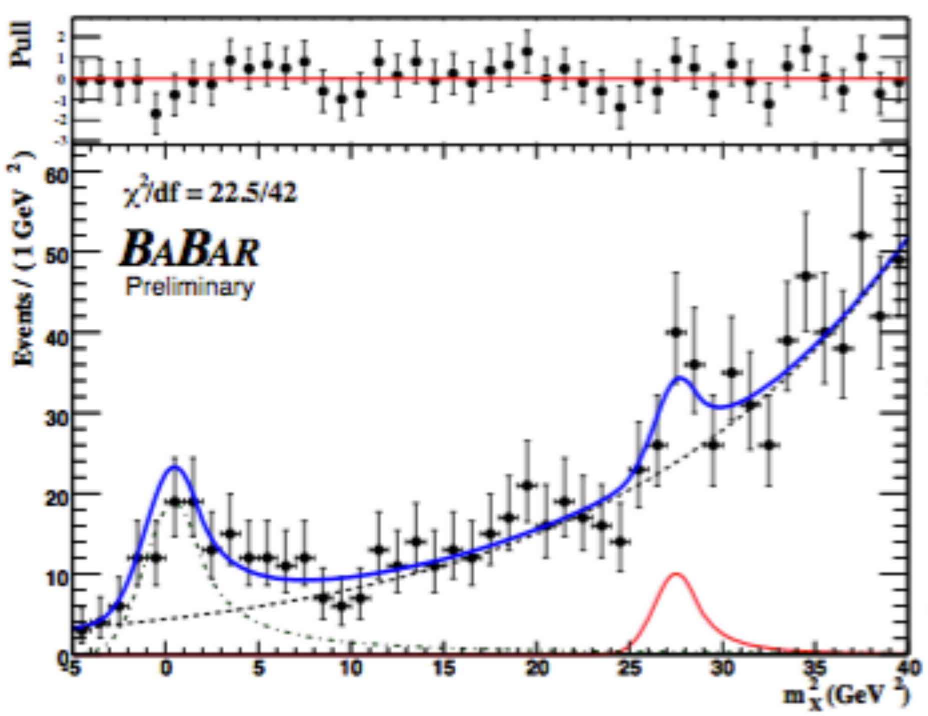
A number of other experiments have probed the g-2 region as well (with null results)…

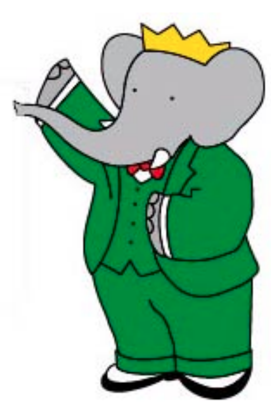
…but still a large amount of phase space to probe and (near) future experiments will search a large fraction of it. Takashi Maruyama will talk about this in detail in a later talk.

A^0 (and dark photon) →Invisible decays



arxiv.org:0808.0017v1





- Search for CP-Odd Higgs by looking for:

  $\Upsilon(3S) \rightarrow \gamma A^0$

  ↓

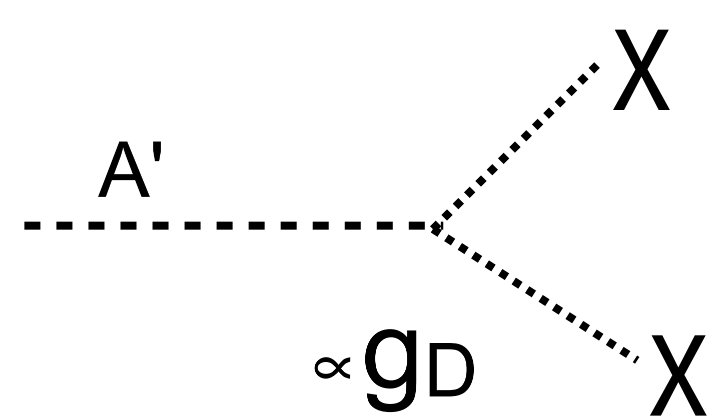
  nothing

- reconstruct the missing mass with:

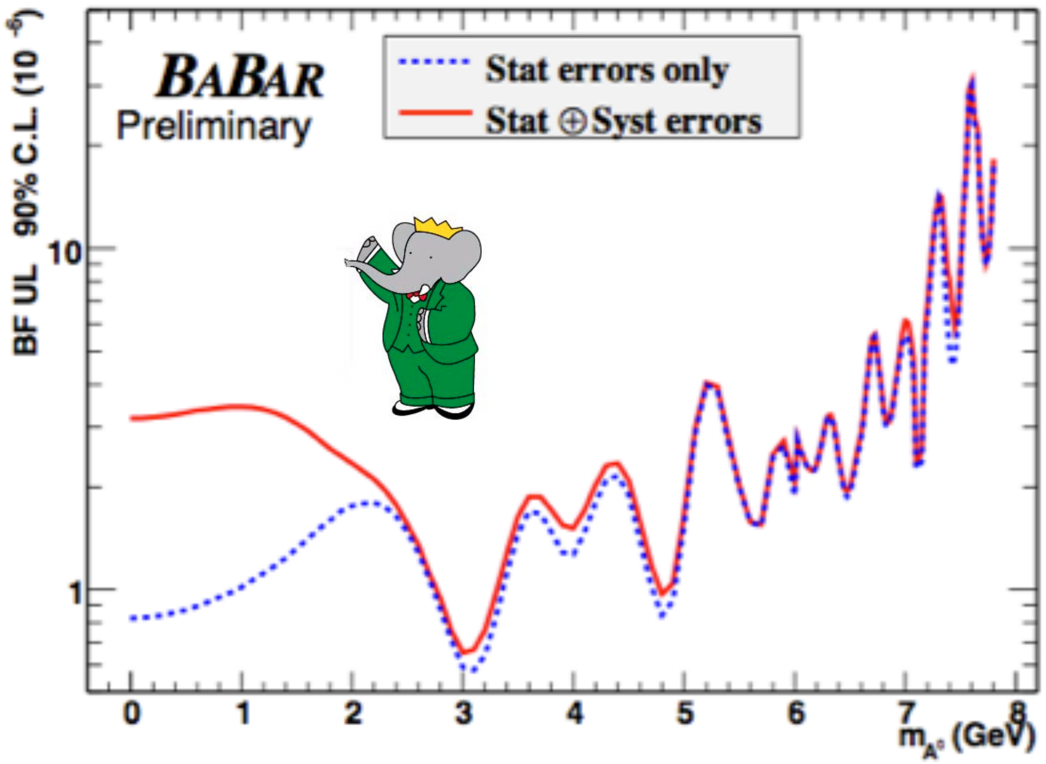
$$E_\gamma^* = \frac{m_\Upsilon^2 - m_{A^0}^2}{2m_\Upsilon}$$

$$m_X^2 \equiv m_{\Upsilon(3S)}^2 - 2E_\gamma^* m_{\Upsilon(3S)}$$

- Scan in the missing mass, just like the others..
- This can also be used to look for invisible A' decays!

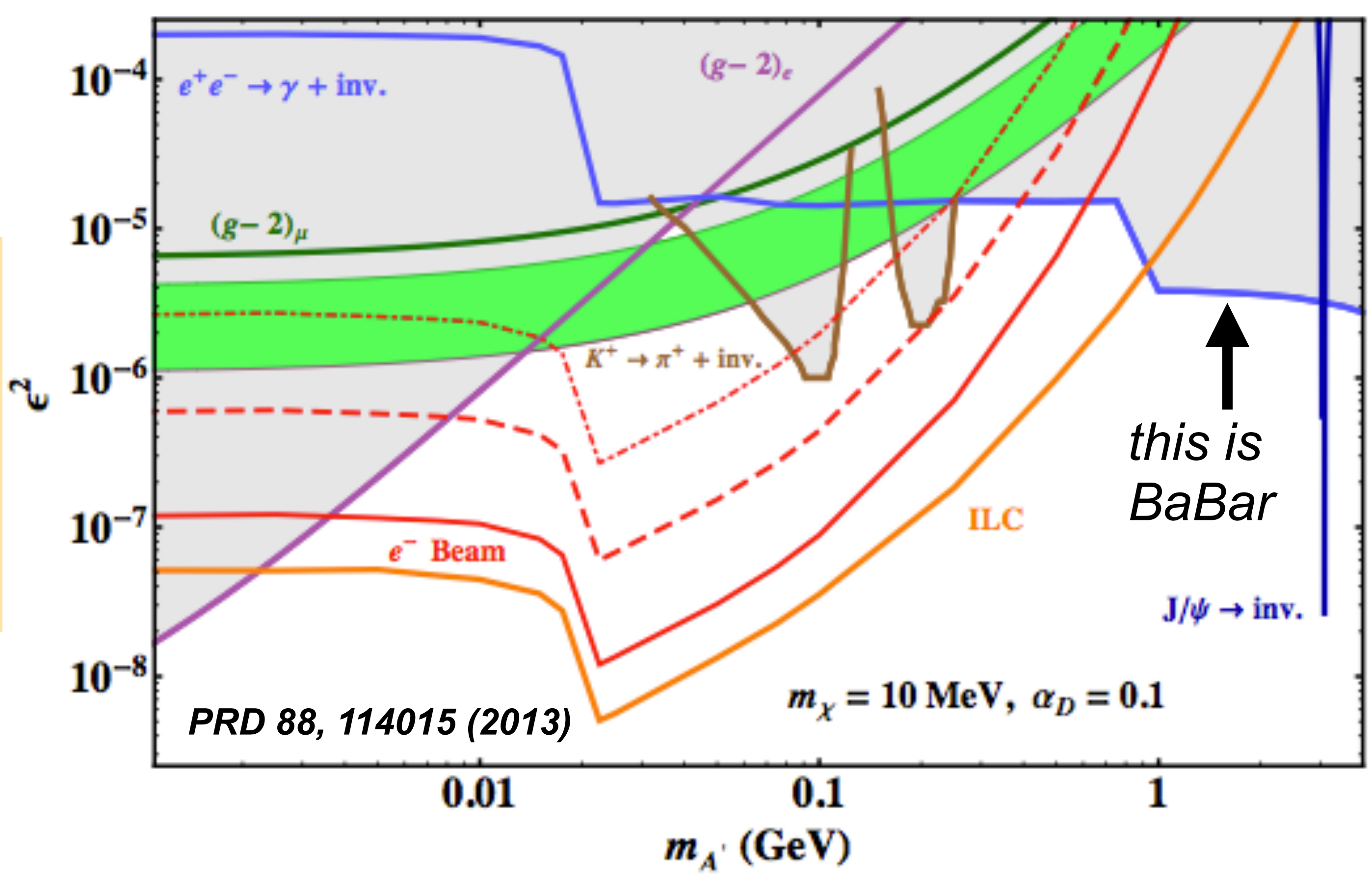


Dark photon → invisible constraints



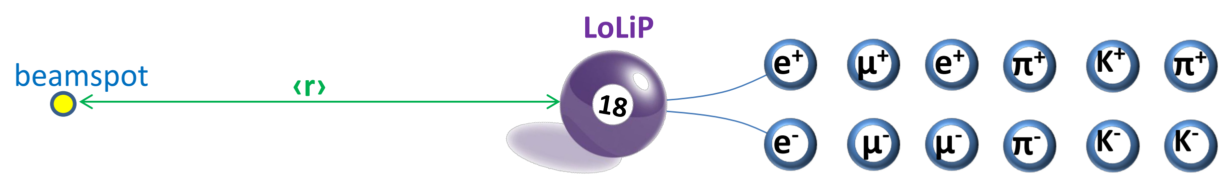
The constraint on A'→$\chi\chi$ is more complicated than the visible searches…depends on: ε, m(A'), α_D, m(χ) → look at projections

There are a few proposals being developed (in various stages of reality) for experiments designed to look for these sorts of decays and light dark matter in general…it's an exciting time!

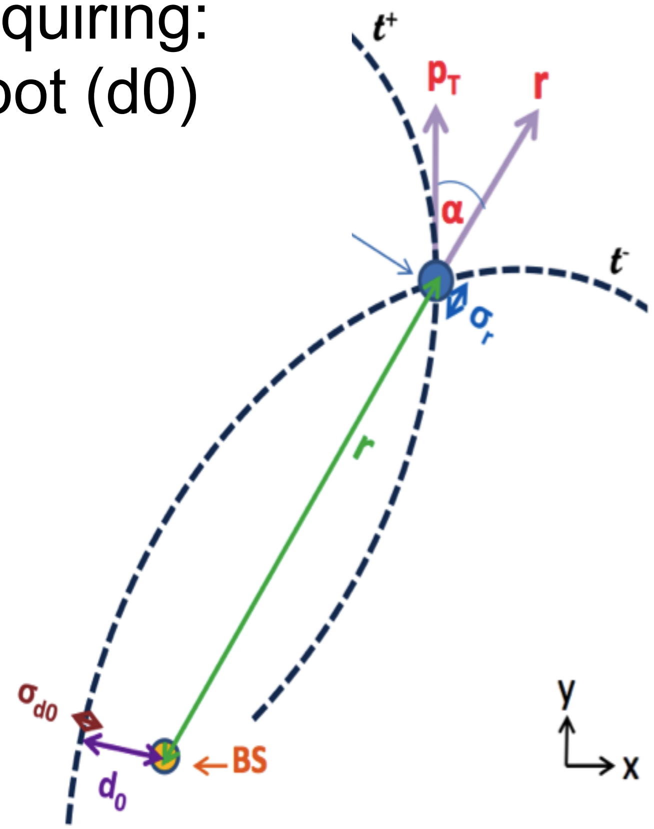


Search for displaced decays @ BaBar

- Many BSM models include possible meta-stable states…i.e. particles that decay on the lab scale: ~100μ - few m distances



- BaBar search vertexed f^+f^- tracks (where f = K,π,e, or μ) requiring:
  - each track was inconsistent with originating from beam spot (d0)
  - no tracker hits before the vertex
  - the vertex position wasn't near likely converter material (beampipe, support tube, drift chamber wall)



Upper limits vs m of

- ➢ Model independent: σ(e+e → L) × BF(L → f) × ε(f)

  at or near Y(4S), at Y(2S,3S)

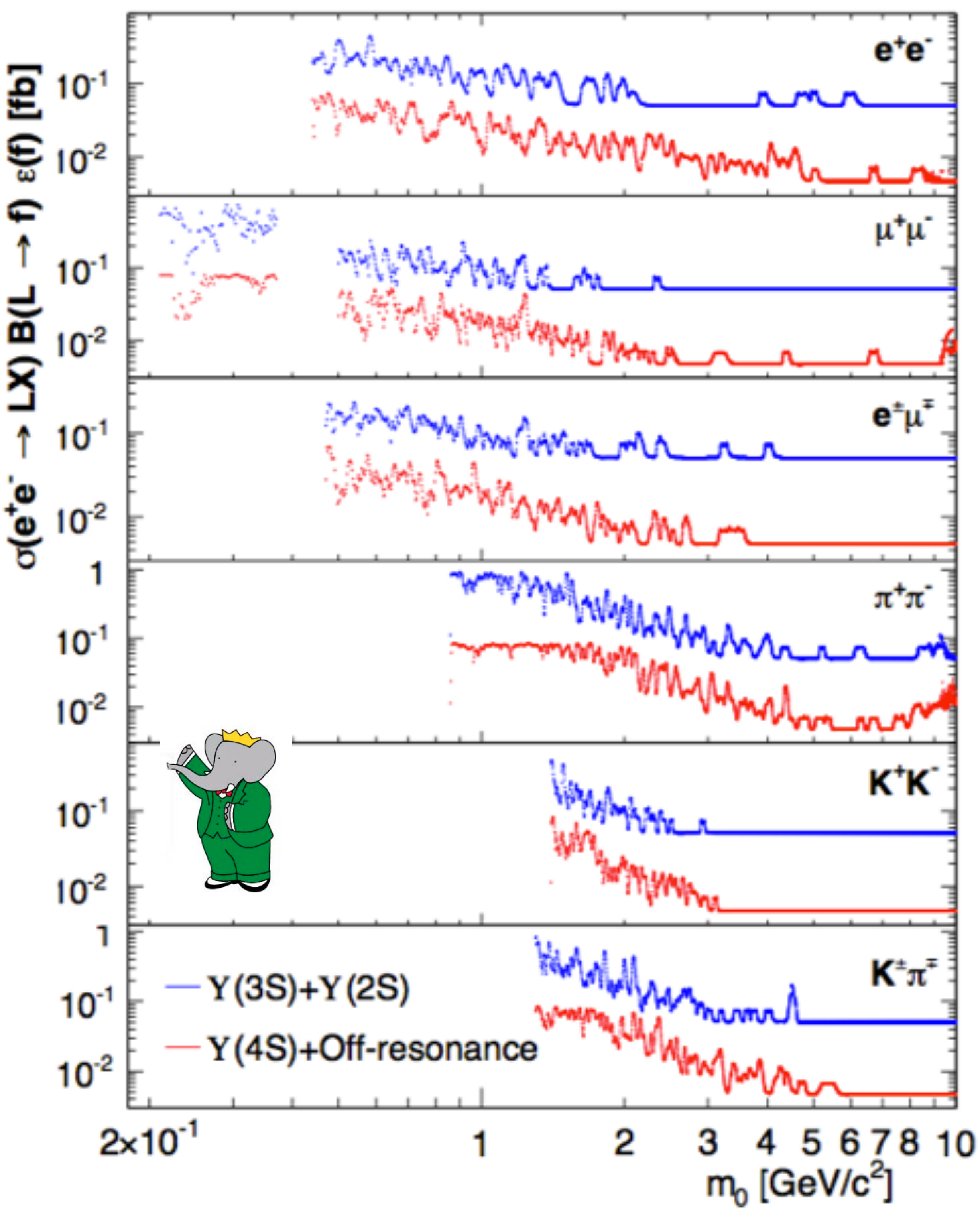
  giving tables of ε(m, p_t, cτ)

- ➢ Model dependent: BF(B → X_s L) × BF(L → f)

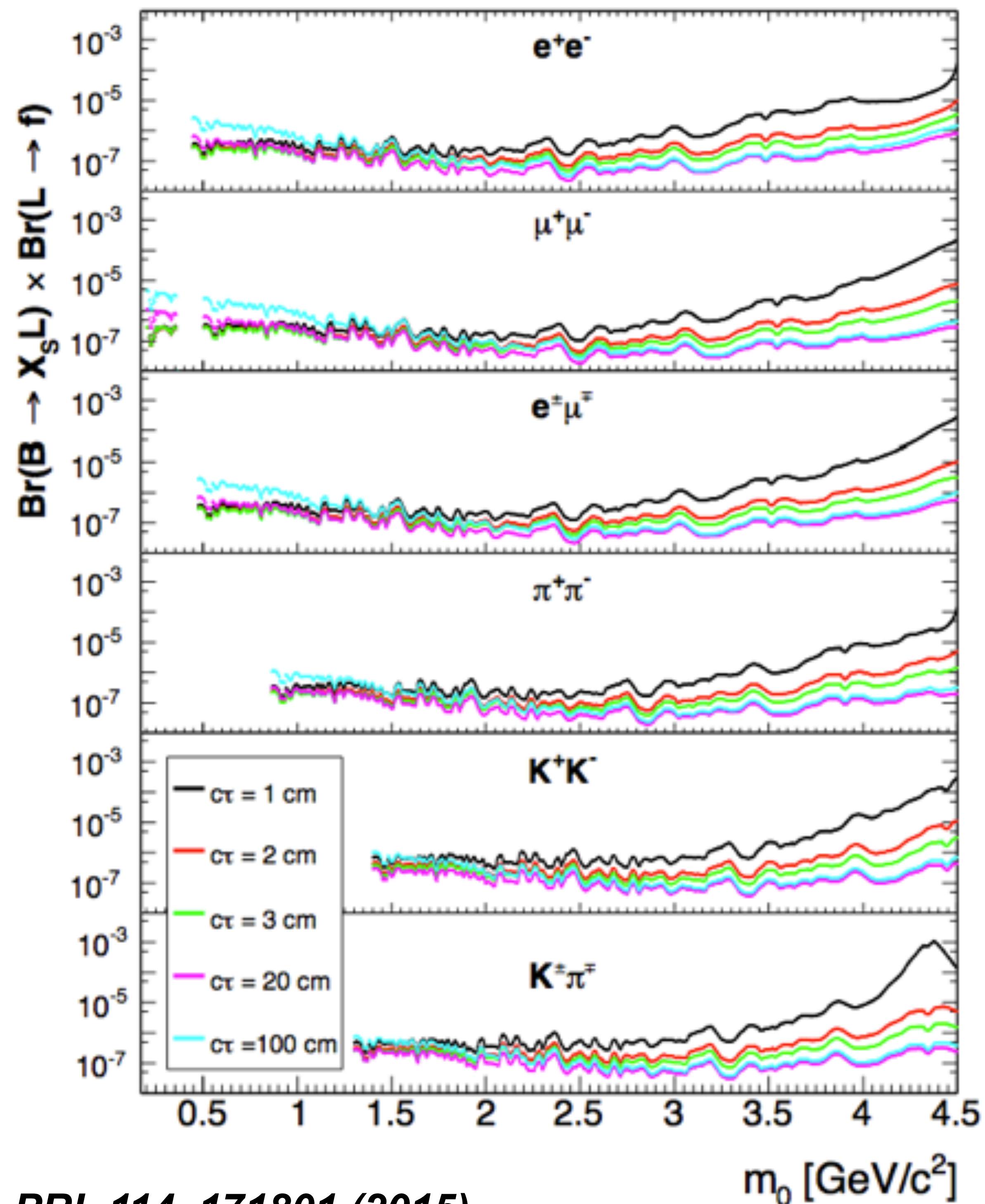
Supplement to PRL114, 171801 (2015)

BaBar displaced vertex search results

Model Independent



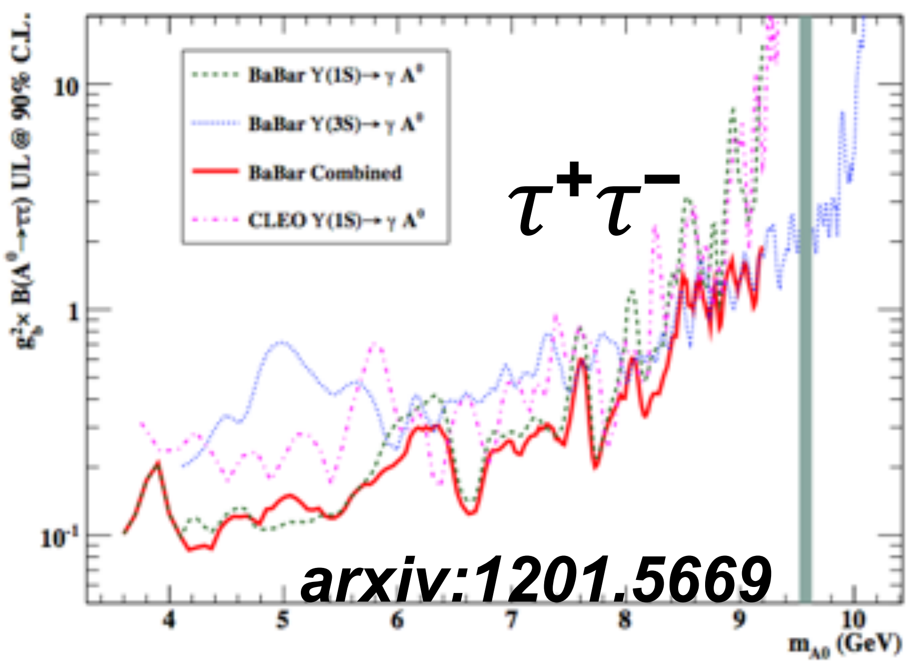
***Inflaton Model** (with strangeness=-1)*

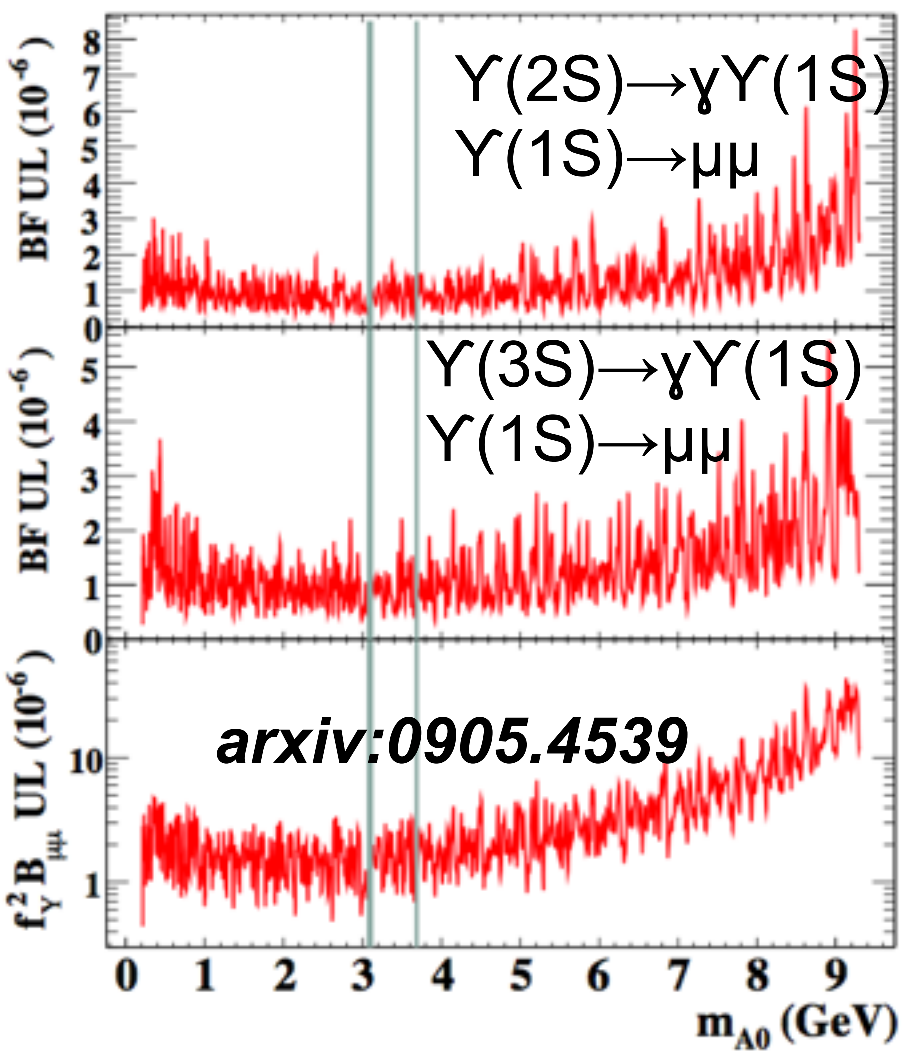


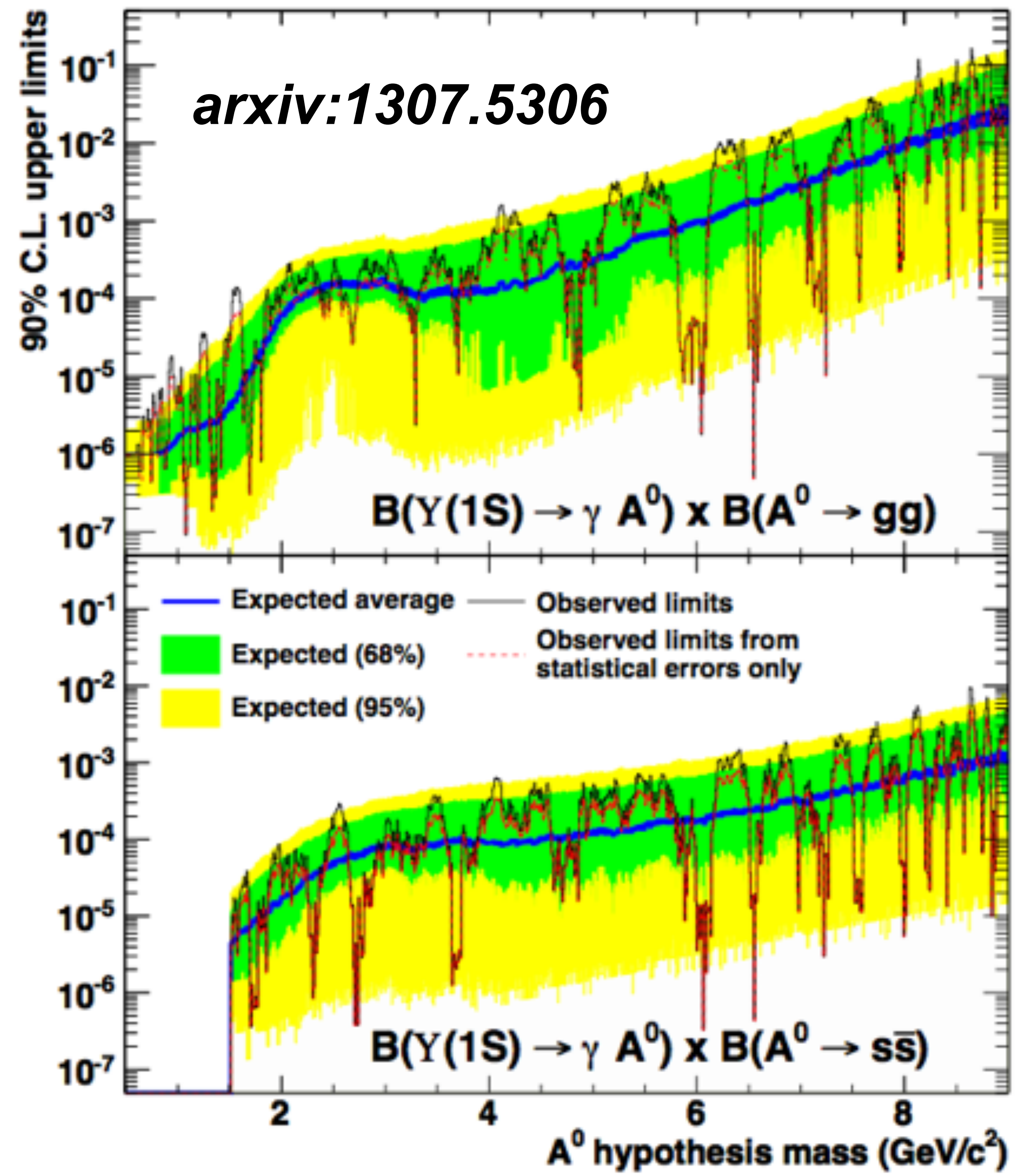
PRL 114, 171801 (2015)

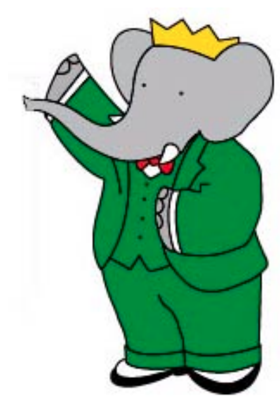
Summary

- The B-Factories (not just BaBar/Belle but also LHCb) have been incredibly successful in probing the quark flavor sector…and testing its consistency with the SM
  - Belle-II will be carrying that to the next level starting in few years
- The combination of beam-intensity/precision detectors are also a great place to look for new physics
  - here I've talked about new "low-energy" physics — lights Higgs and dark sector particles — but there are other potential states as well
  - in addition, high-scale NP can have direct effects at these low energies… charged LFV in tau decays is an example where the B-Factories have an outsized impact
- The B-Factory searches (including Belle-II) for dark photons (both visible & invisible decays) from ~1-10 GeV will be very hard to beat in the foreseeable future

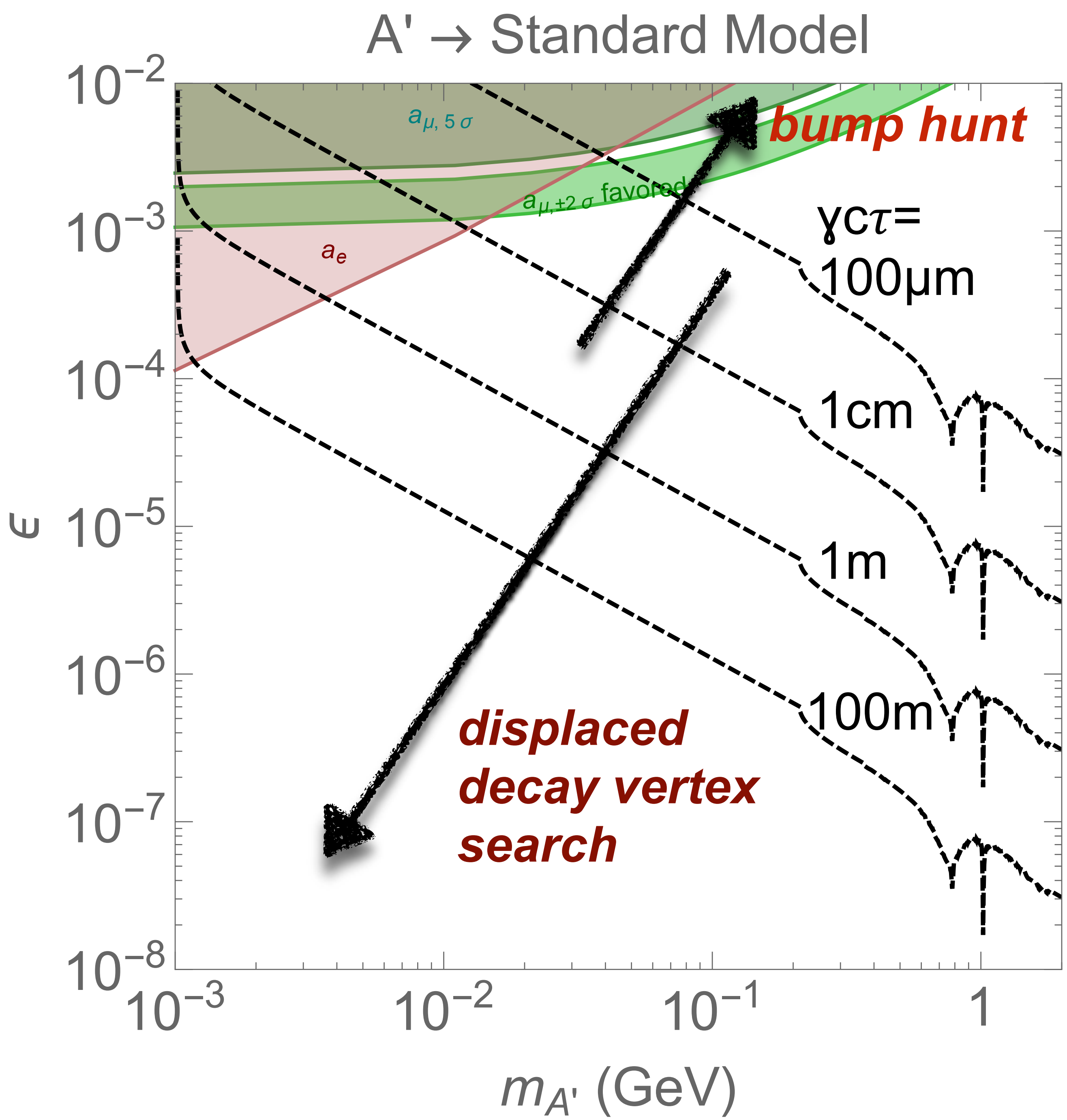

BaBar Υ(1S)→γ A0
BaBar Υ(3S)→γ A0
BaBar Combined
CLEO Υ(1S)→γ A0
τ+τ−
arxiv:1201.5669
m_A0 (GeV)


Υ(2S)→γΥ(1S)
Υ(1S)→μμ
Υ(3S)→γΥ(1S)
Υ(1S)→μμ
arxiv:0905.4539
BF UL (10^-6)
m_A0 (GeV)


arxiv:1307.5306
90% C.L. upper limits
B(Υ(1S) → γ A0) x B(A0 → gg)
Expected average
Observed limits
Expected (68%)
Observed limits from statistical errors only
Expected (95%)
B(Υ(1S) → γ A0) x B(A0 → ss̄)
A0 hypothesis mass (GeV/c2)



thinking about direct searches…



assume $E_{A'}$=20GeV

if (γcτ<~100 μm)
bump-hunt;

if (γcτ > 1 m)
displaced decay;

…some mushy middle where both handles are useful;