Light Higgs & Dark Gauge Bosons

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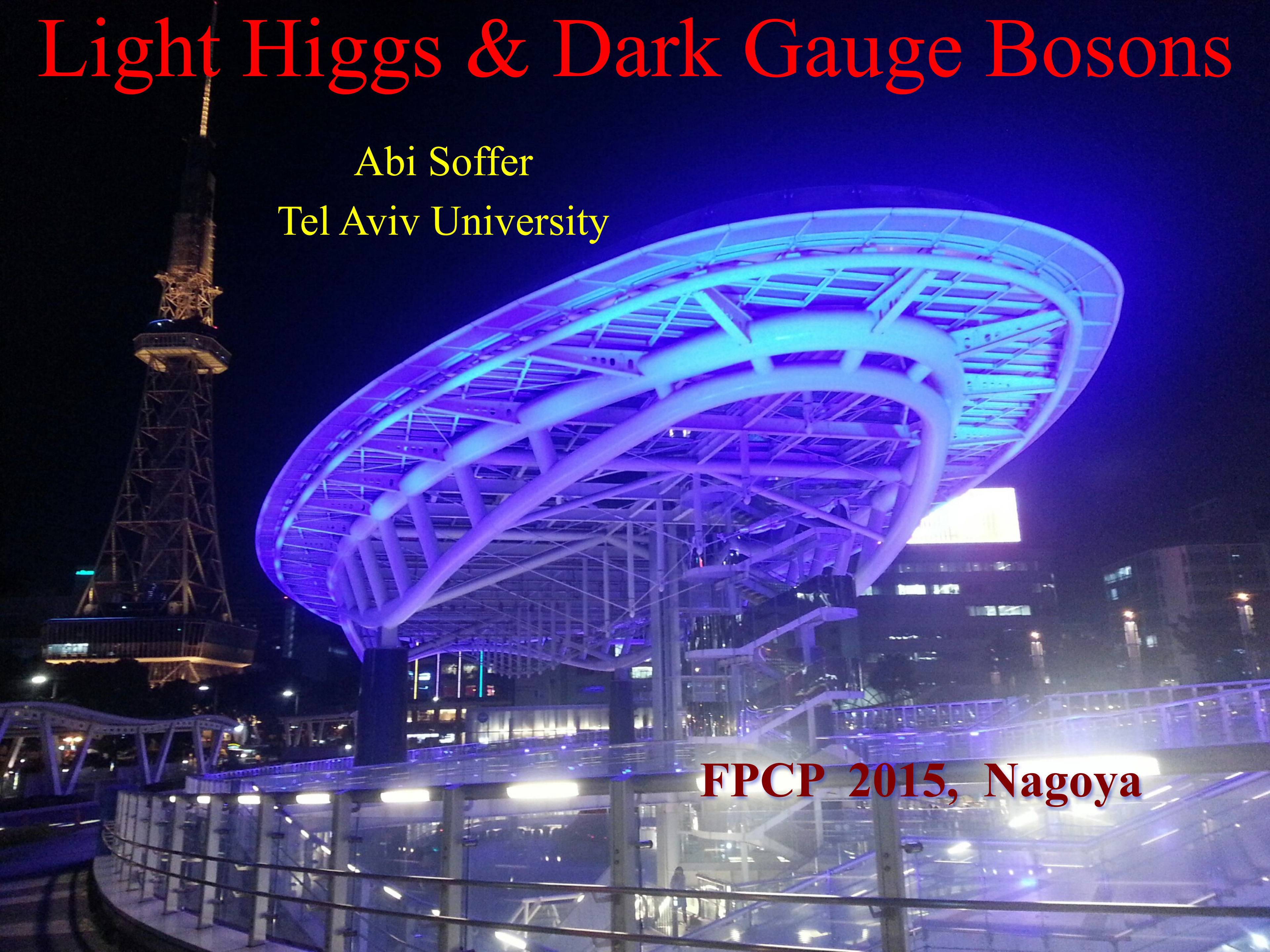
FPCP 2015, Nagoya



Introduction

- We often think of DM as one particle – the WIMP
  - E.g., the SUSY LSP
- But DM may involve rich phenomenology, an entire "dark sector"
  - Why should the SM particles, which account for only ~1/5 of the matter in the universe, have all the fun?
- Interactions serve as "portals" between the SM sector and the dark sector

- This applies to any sector that is "hidden" due to lack of strong interactions, not necessarily related to dark matter.

- Many recent searches – I will focus on the most recent ones

Dark photon *A'*

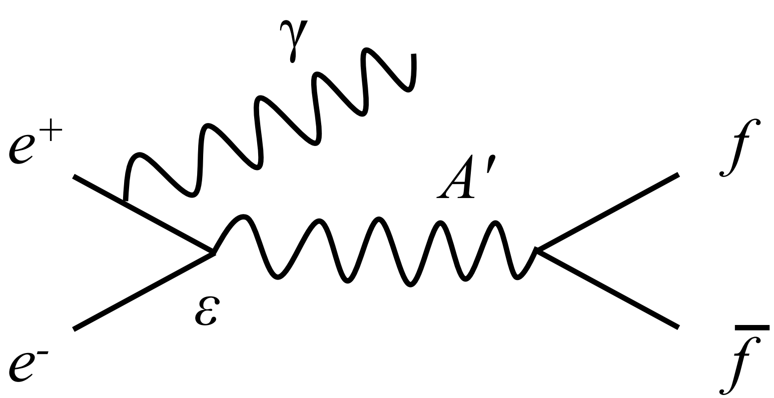
- Arises from a U(1) gauge interaction in the dark sector
- Can obtains mass via U(1) symmetry breaking
- Kinetic mixing of *A'* with SM photon ("vector portal"):

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m^2_{A'}}{2} A'_\mu A'^\mu - \frac{\varepsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Mixing parameter (ε)

SM U(1) field ($F^{\mu\nu}$)

Dark U(1) field ($F'_{\mu\nu}$)

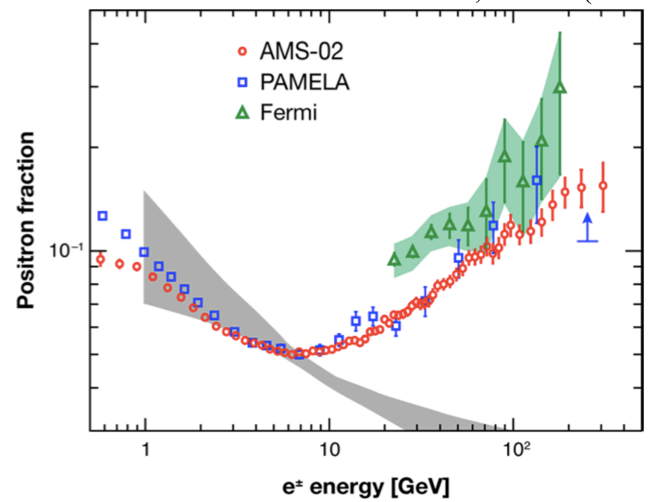


Astrophysical interest

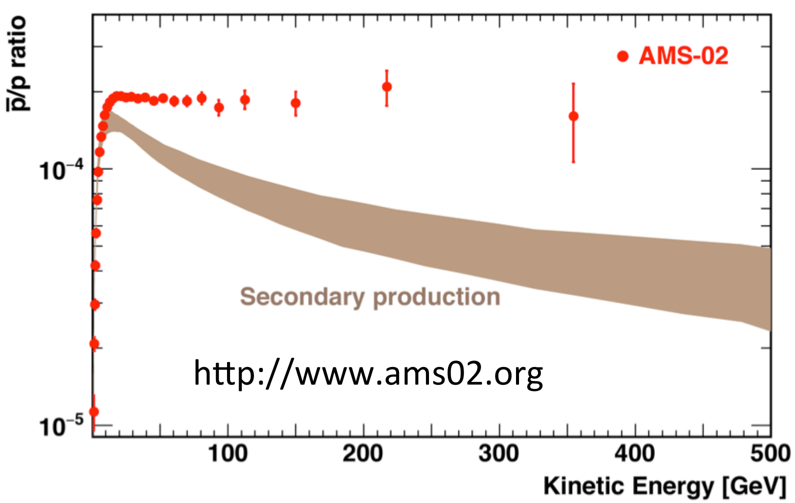
PRL 110, 141102 (2013)
Nature 458, 607 (2009)
PRL 108, 011103 (2012).

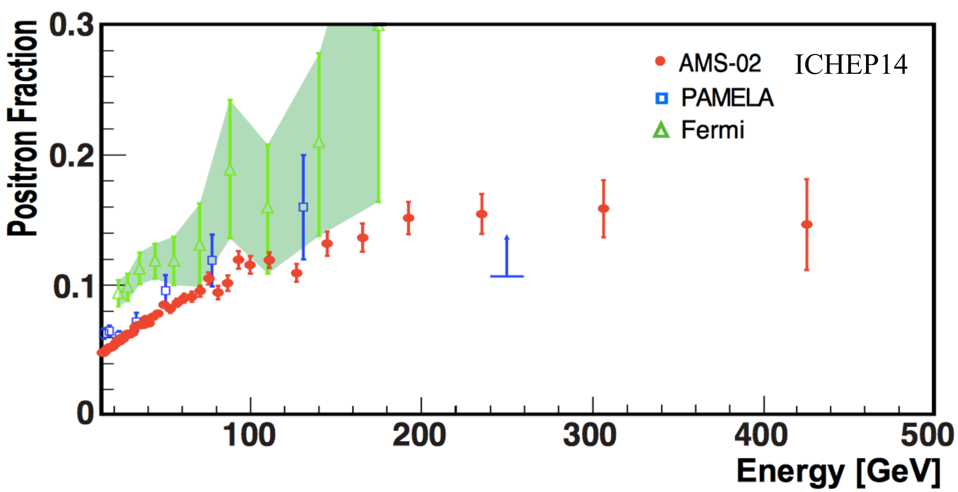
PRD 79, 015014 (2009) Arkani-Hamed et al.

- ~TeV DM: $\chi\chi \rightarrow A'A' \rightarrow (e^+e^-)(e^+e^-)$
- Initial lack of antiproton excess
  $\rightarrow$ $m_{A'} <$ few GeV



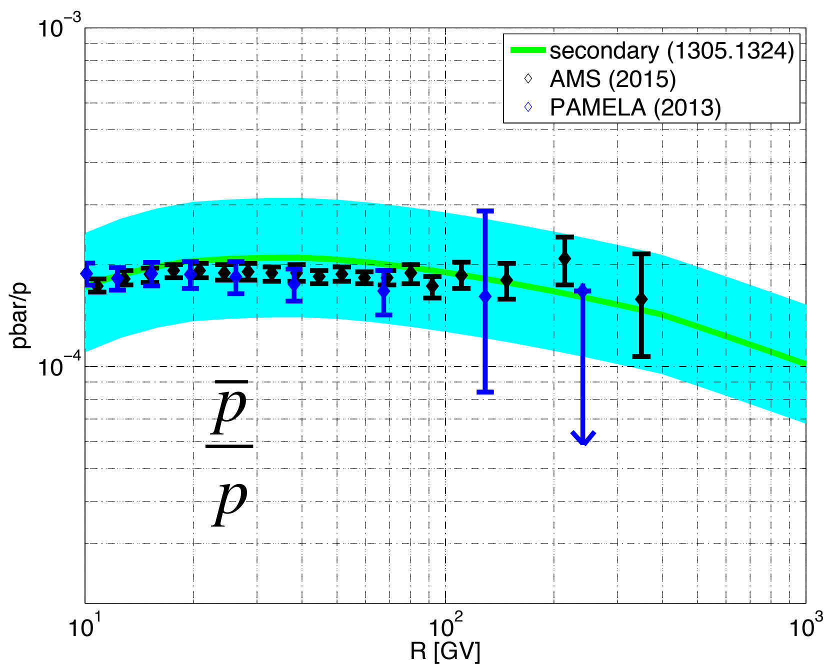
- Possible antiproton excess now observed:

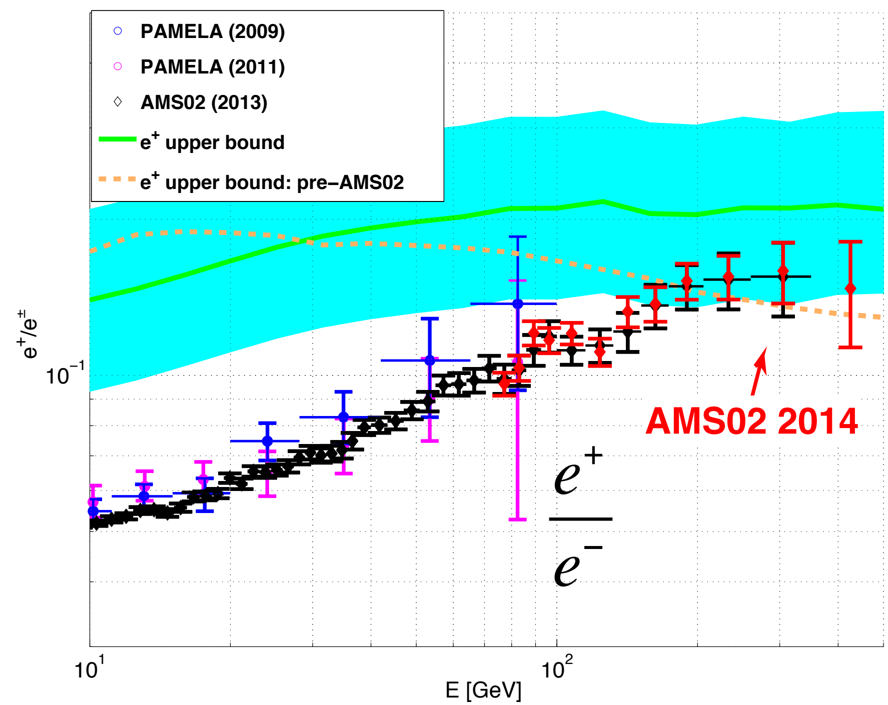




There may not be an excess…

- Astrophysical explanations, e.g.:
  - 1505.01236: nearby supernova
  - 1305.1324: secondary production

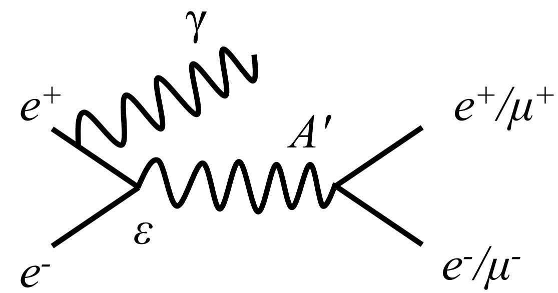




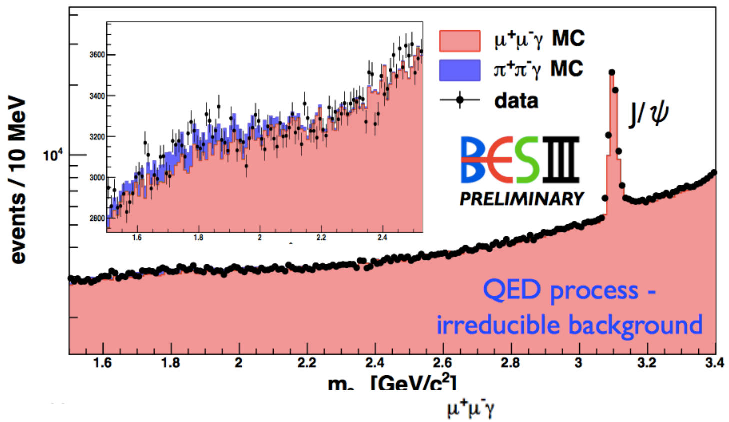
- Nonetheless, these unexpected results raised interest in low-mass dark states, leading to interesting new searches

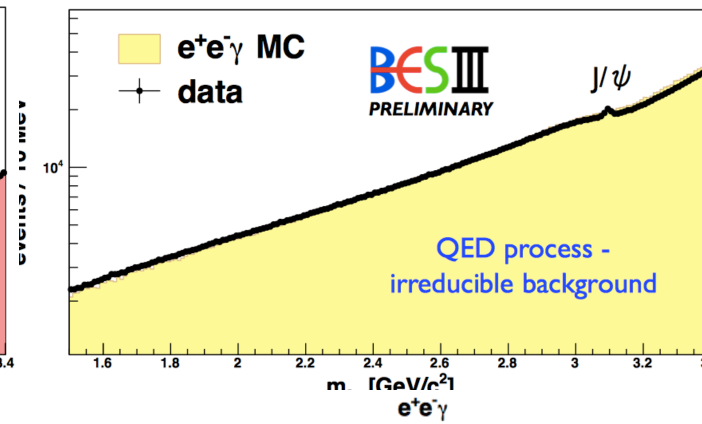
Latest dark-photon search: BESIII

Last week @ CHARM15:
https://indico.fnal.gov/getFile.py/access?contribId=112&sessionId=10&resId=0&materialId=slides&confId=8909

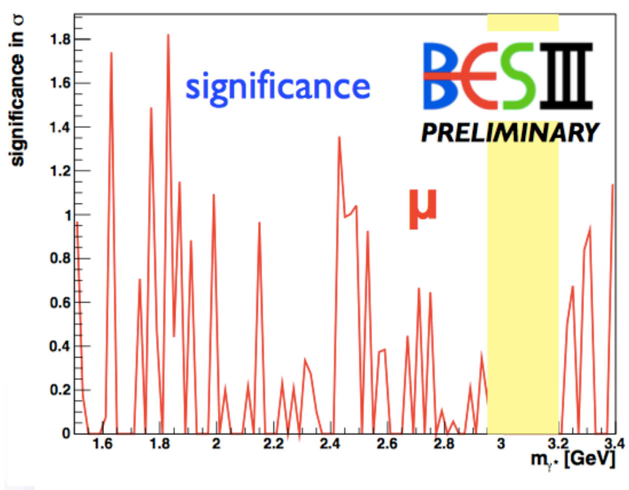


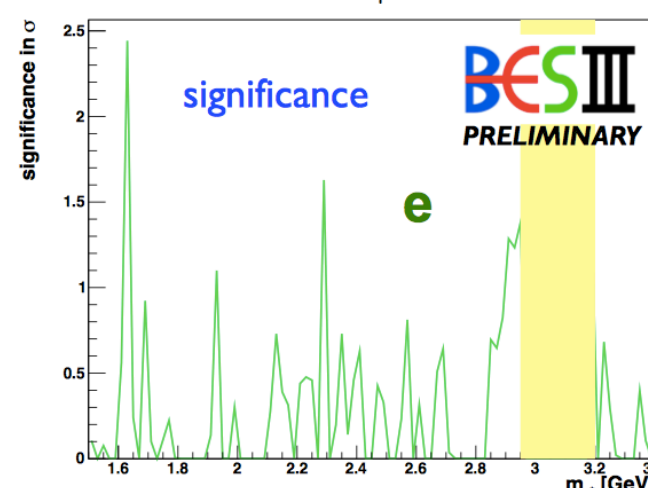
- Don't require ISR photon
- l^+l^- spectrum:





- Fit background with 4^{th}-order polynomial
- Search for signal peak
- Signal significance:





Limit summary

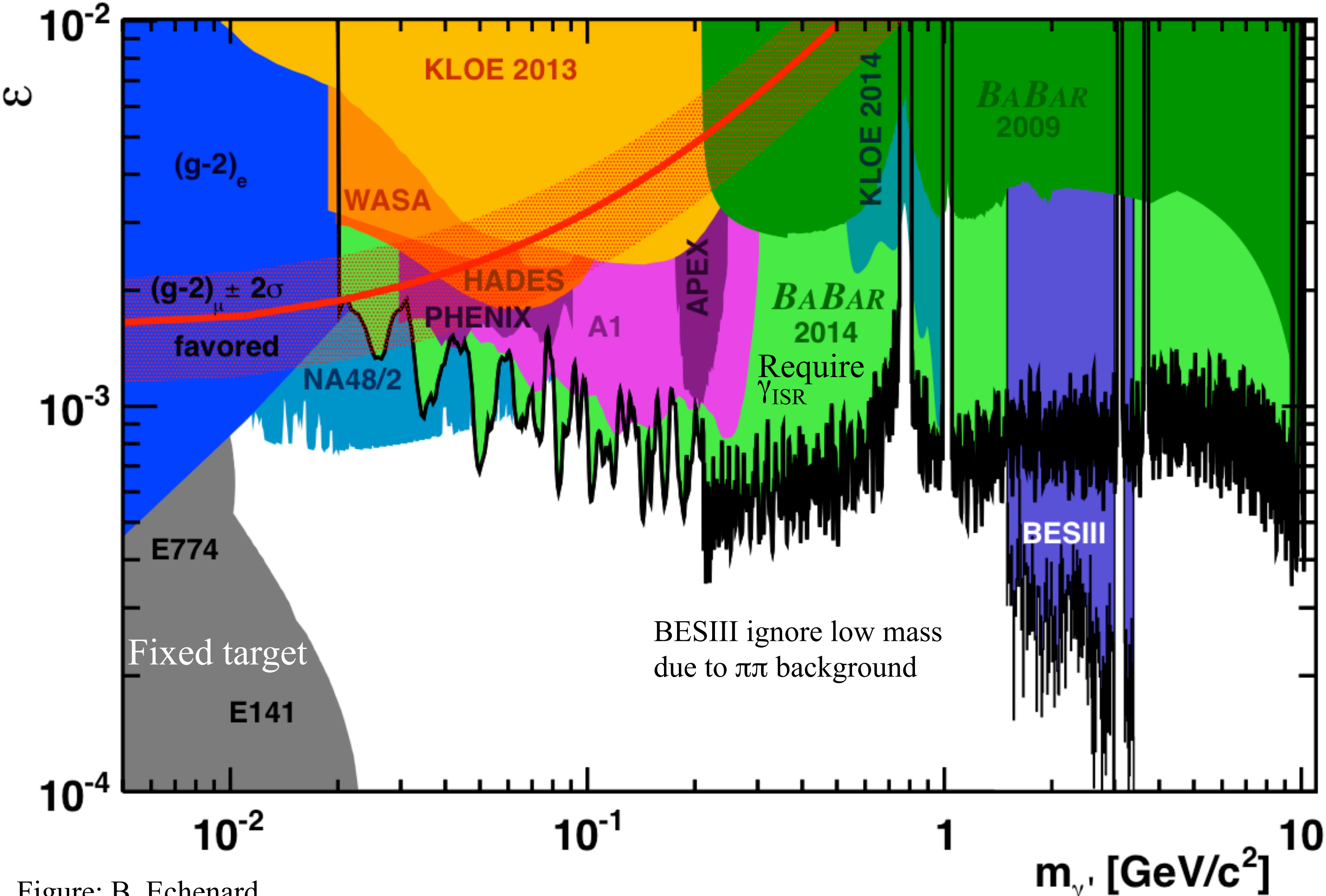
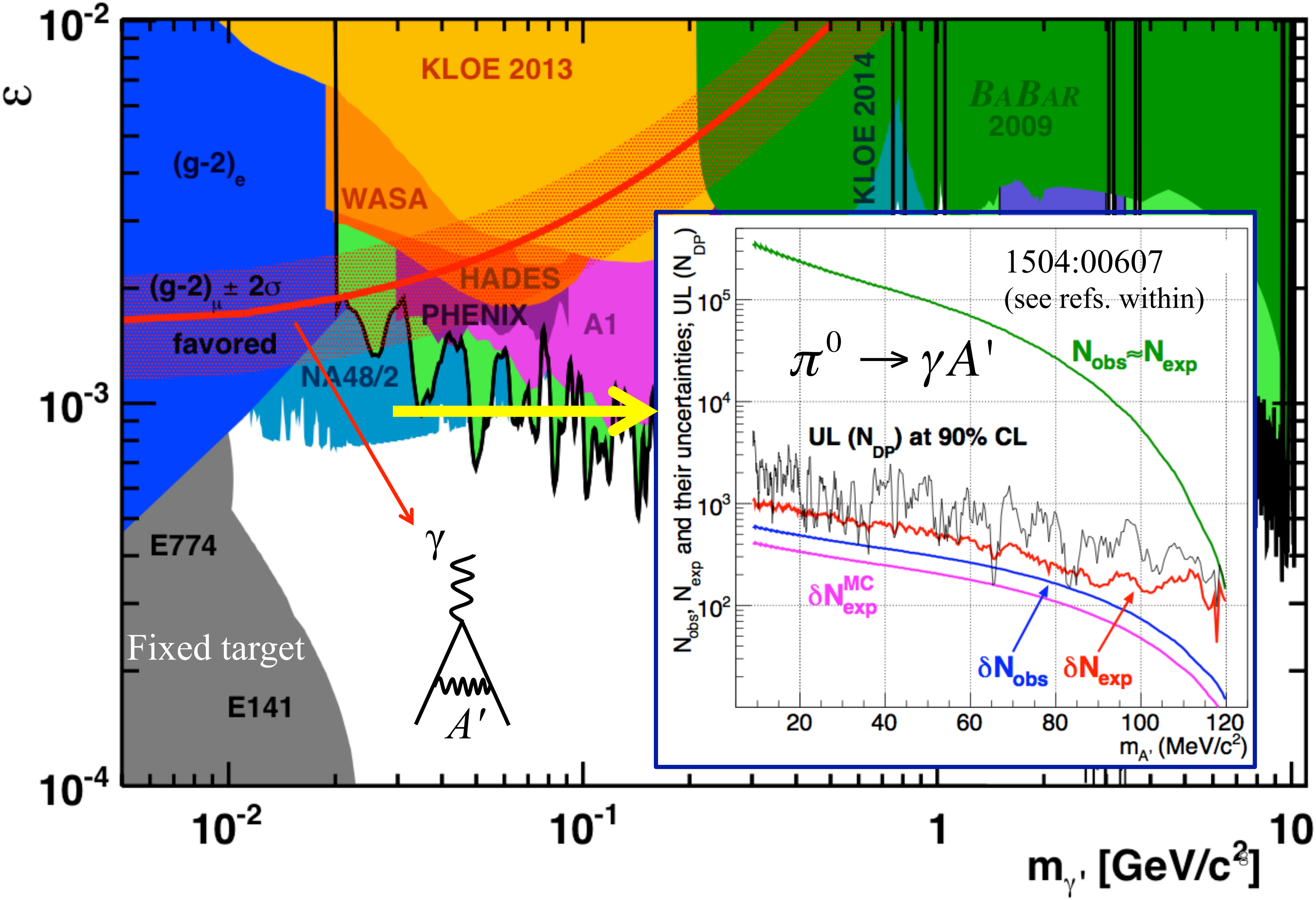


Figure: B. Echenard

The second-latest result: NA48



Reach in near future

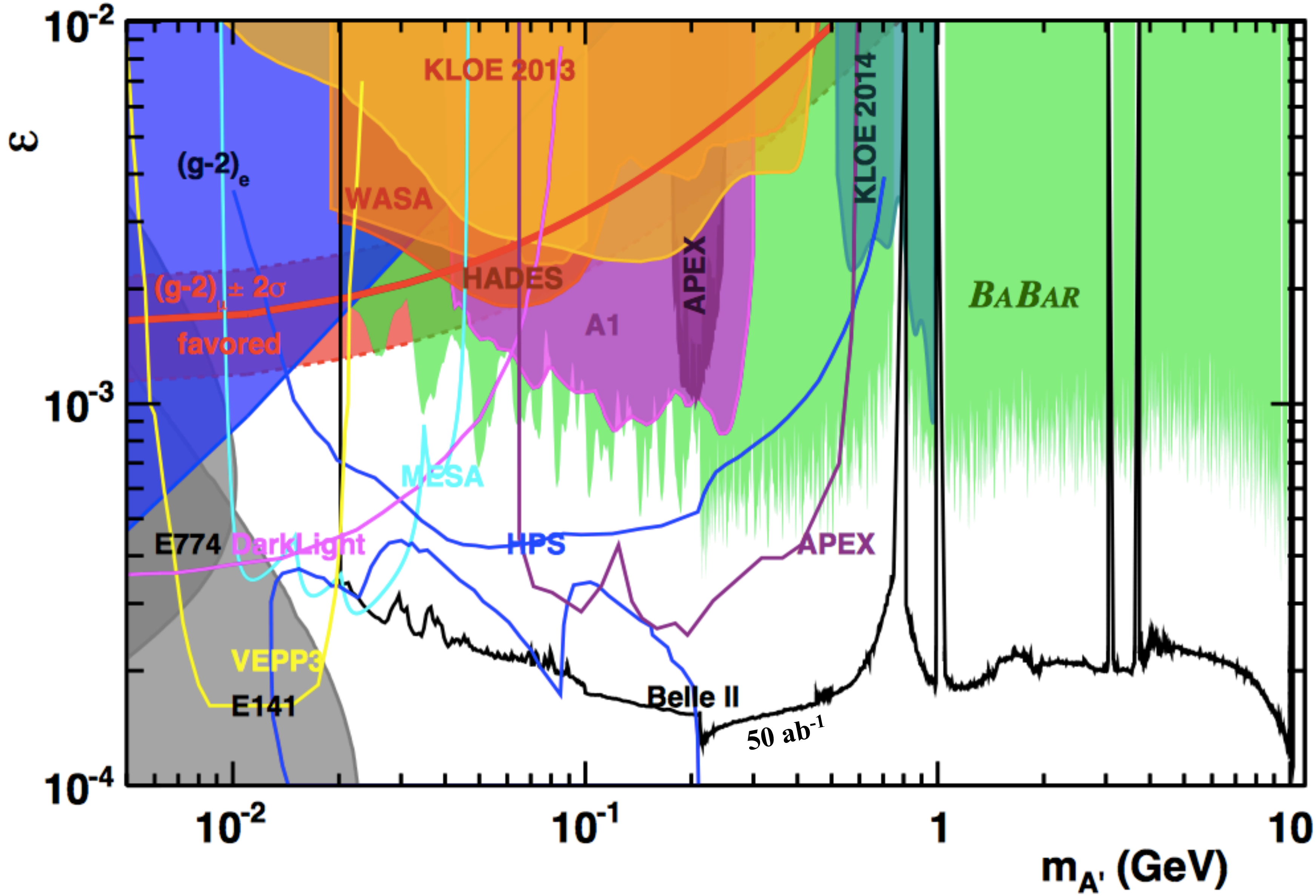
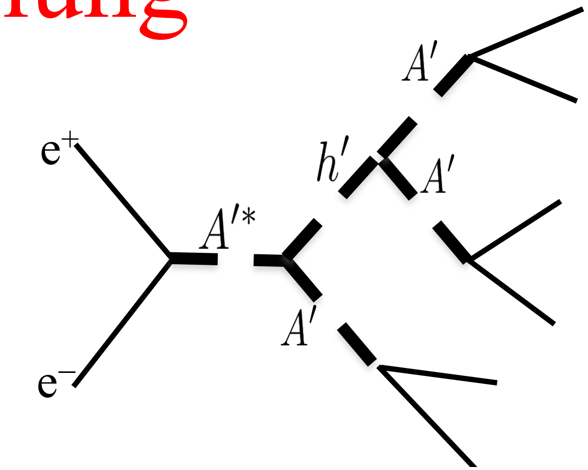


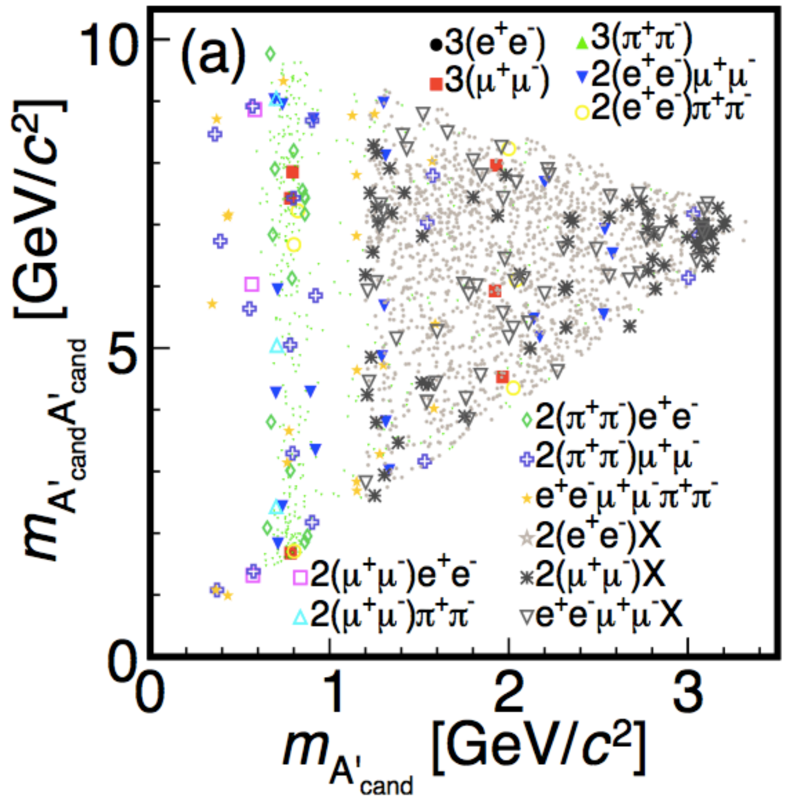
Figure: C. Hearty. (Recent PHENIX, NA48 & BESIII limits not shown.)

Dark Higgsstrahlung

Belle: arXiv:1502.00084

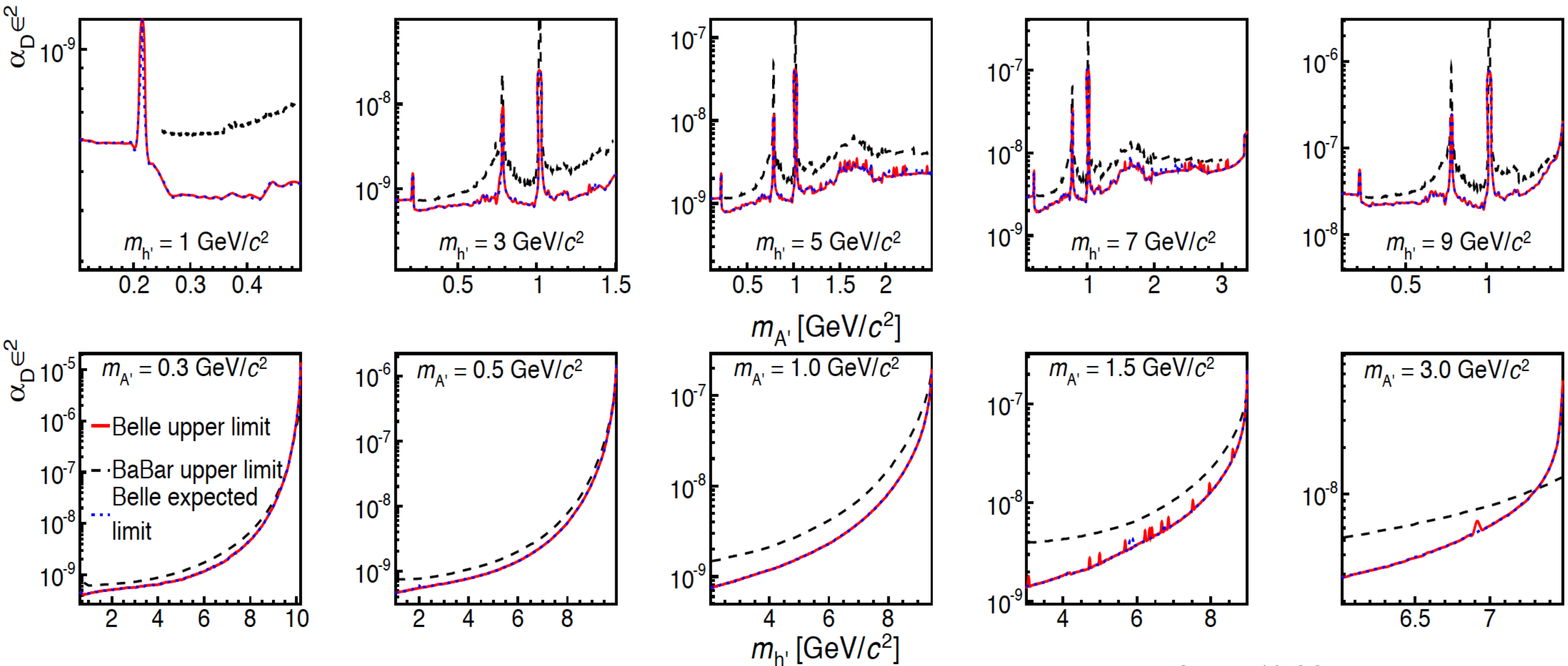


- Study the case $m_{h'} > 2\, m_{A'}$
- Look for:
  - 3 pairs of leptons and/or hadrons
  - $2(l^+l^-)$+missing
- Cut on mass difference $\Delta m_{A'}$ between the 3 A' candidates
- Background estimated from events with same-charge A' candidates, normalized in $\Delta m_{A'}$ mass-difference sideband



Limits on $\alpha_D\varepsilon^2$

vs. $m_{A'}$ for different $m_{h'}$



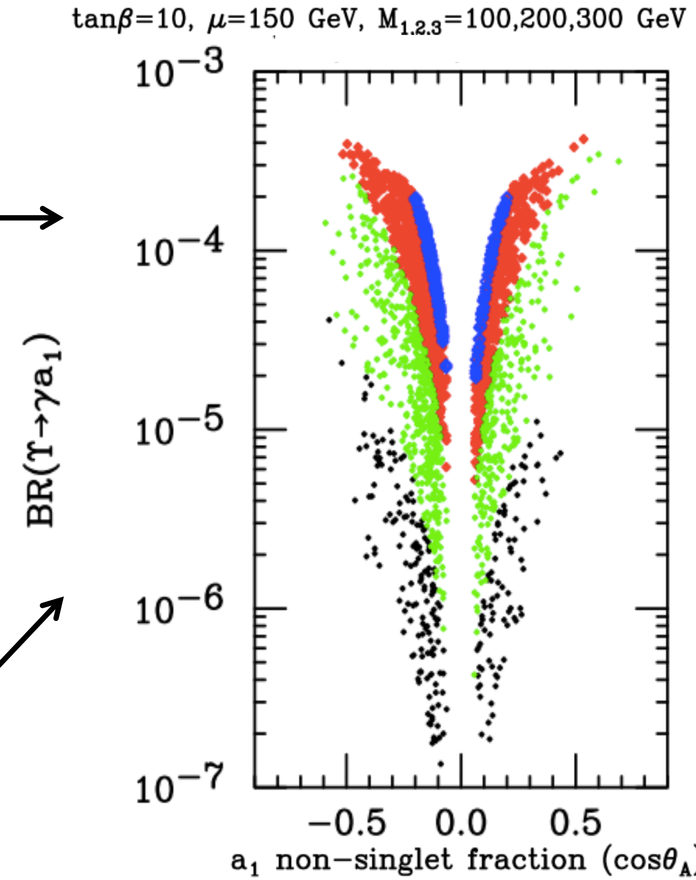
vs. $m_{h'}$ for different $m_{A'}$

Belle: arXiv:1502.00084

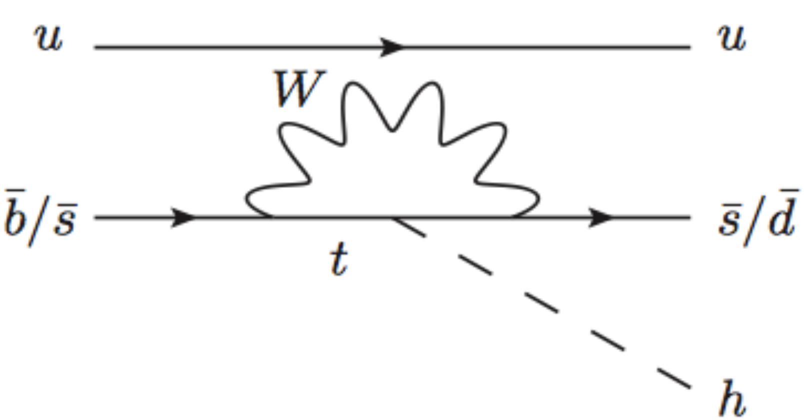
BABAR: PRL 108, 211801 (2012)

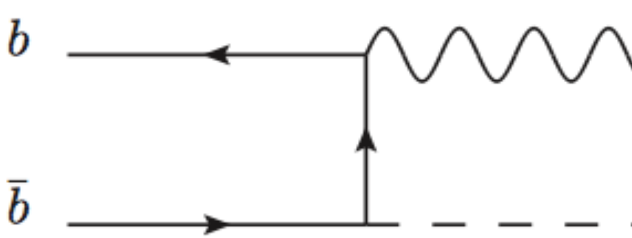
Light Higgs

- NMSSM: new light, CP-odd Higgs a_1 (or A^0)
  - Dermisek et al, PRD 76, 051105(R) (2007)
- Scalar that mixes with SM Higgs ("Higgs portal")
  - Clarke et al, JHEP 1402, 123 (2014)
  - Schmidt-Hoberg et al, PLB 727, 506 (2013)



$m_{a1} < 2m_\tau$
$2m_\tau < m_{a1} < 7.5$ GeV
$7.5 < m_{a1} < 7.5$ GeV
$8.8 < m_{a1} < 9.2$ GeV

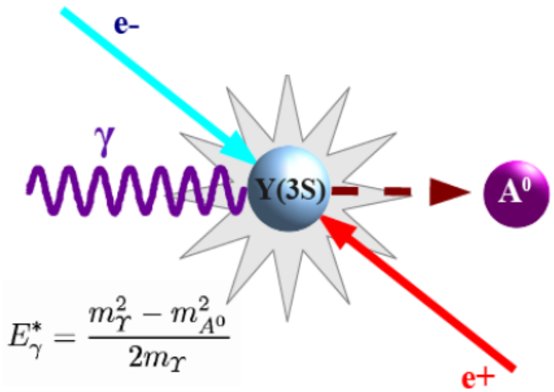




$h \rightarrow$ pair of SM or dark fermions

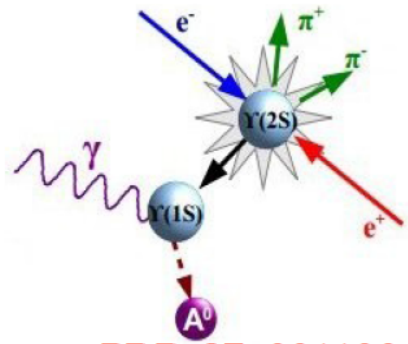
$V \rightarrow A^0 \gamma$ searches

Radiative Decays of Υ(nS)
Signature: monochromatic photon



BABAR
- $A^0 \rightarrow \mu^+\mu^-$, PRL **103**, 081803 (2009)
- $A^0 \rightarrow \tau^+\tau^-$, PRL **103**, 181801 (2009)
- $A^0 \rightarrow$ hadrons, PRL **107**, 221803 (2011)
- $A^0 \rightarrow$ invisible, arXiv:0808.0017

Additional constraints: Υ(1S) from $\Upsilon(2S,3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$ transitions
Signature: two low-momentum pions, recoiling against Υ(1S)



BABAR
- $A^0 \rightarrow \mu^+\mu^-$, PRD **87**, 031102 (2013)
- $A^0 \rightarrow \tau^+\tau^-$, PRD **88**, 071102 (2013)
- $A^0 \rightarrow$ hadrons, PRD **82**, 0317019R (2013)
- $A^0 \rightarrow$ invisible, PRL **107**, 021804 (2011)

CLEO Υ(1S) $A^0 \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$, PRL **101**, 151802 (2008)

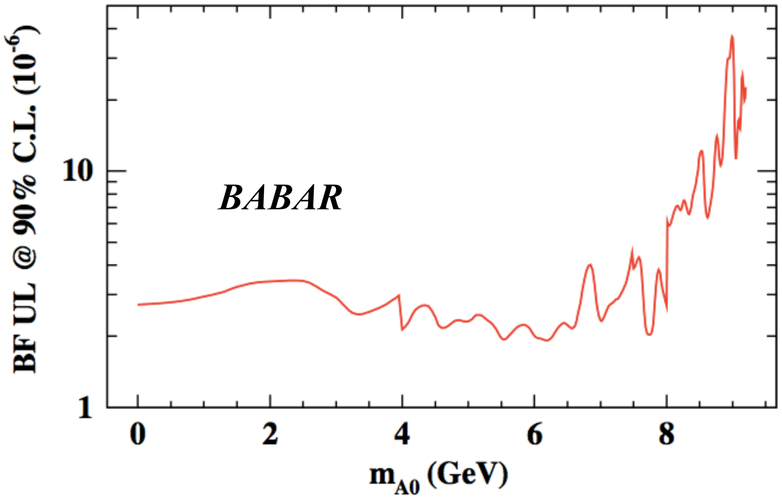
BESIII J/ψ $A^0 \rightarrow \mu^+\mu^-$, PRD **85**, 092012 (2011)

(BESIII updated expected soon)

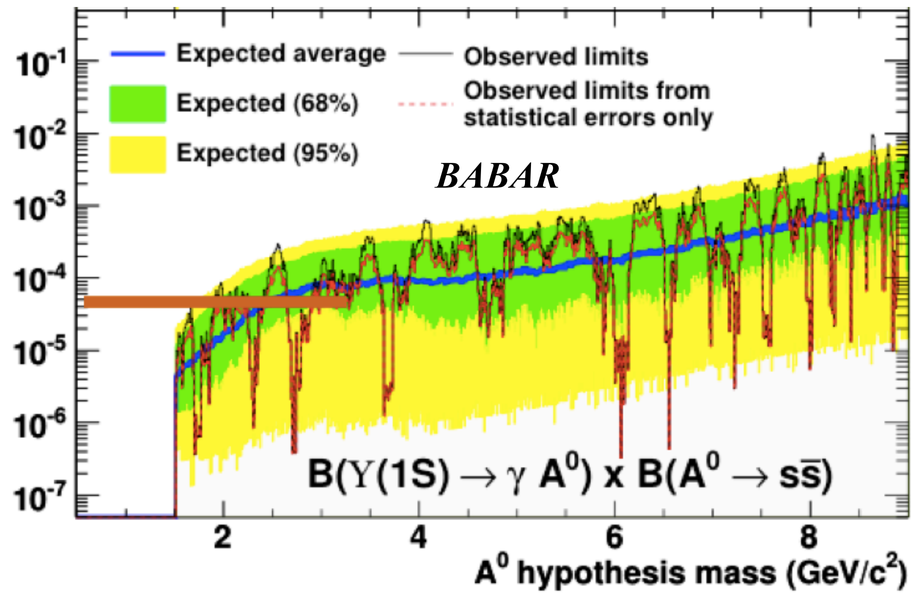
CMS inclusive $A^0 \rightarrow \mu^+\mu^-$, PRL **109**, 121801 (2012)

CMS $H(125) \rightarrow 2(A^0 \rightarrow \mu^+\mu^-)$, PLB **726**, 564 (2013)

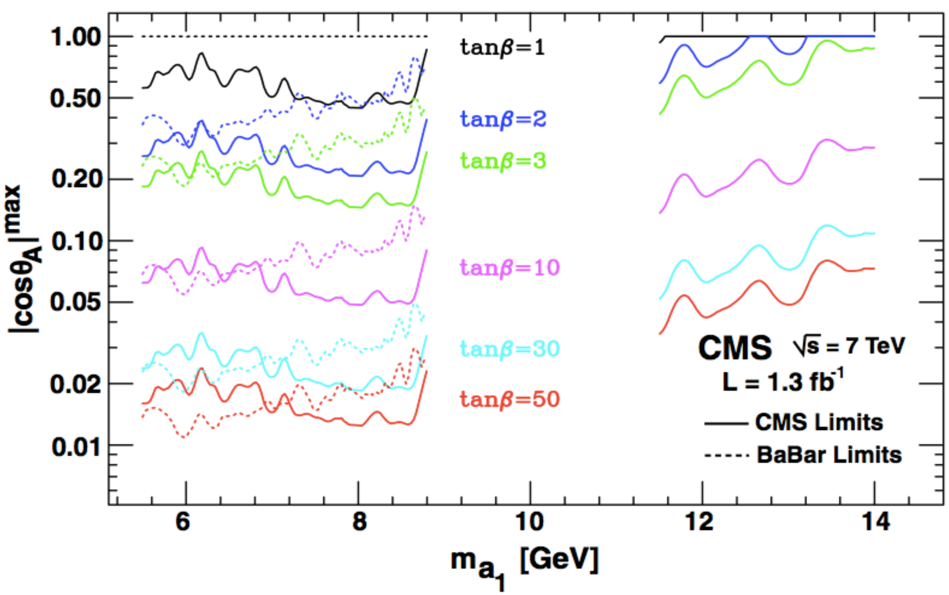
Invisible



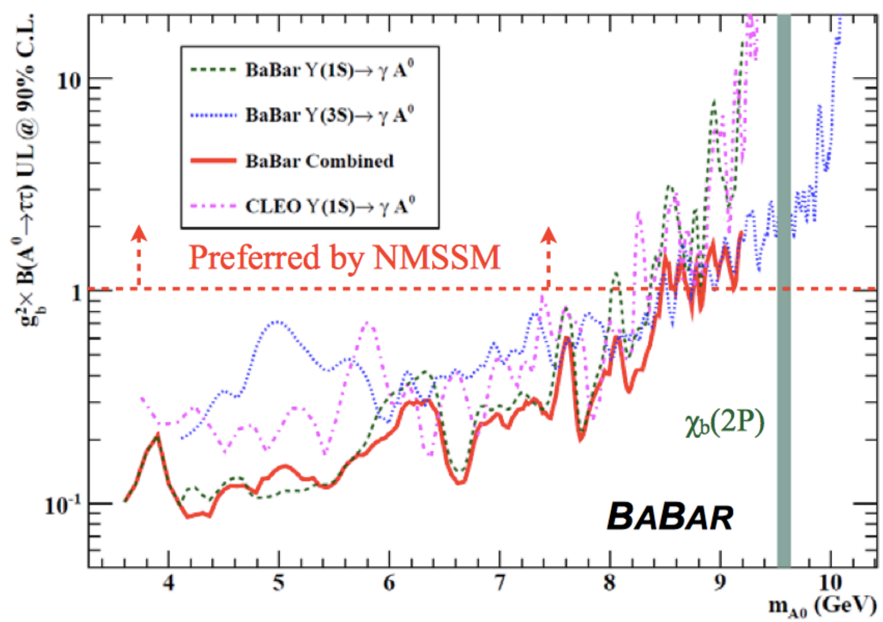
Hadrons



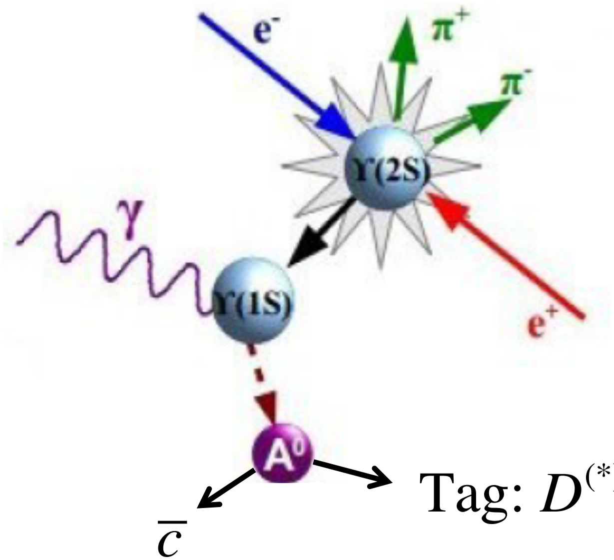
$\mu^+\mu^-$



$\tau^+\tau^-$



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

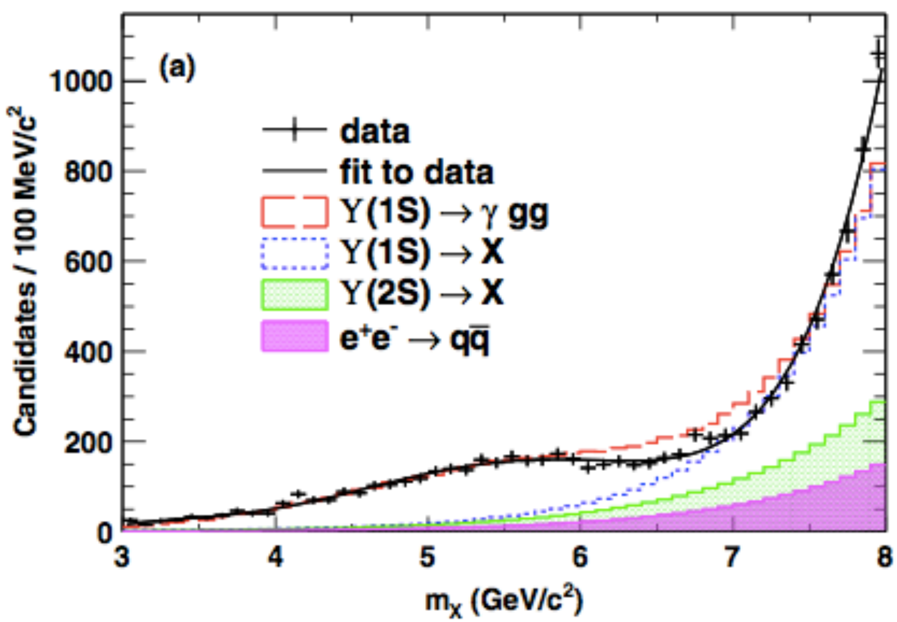


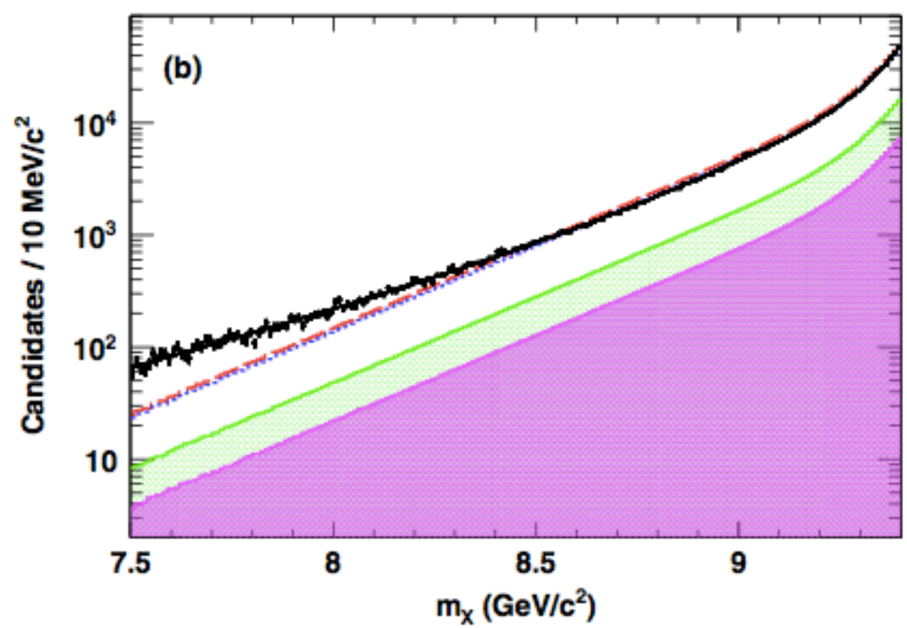
$\bar{c}$ Tag: $D^{(*)}$

BABAR: PRD 91, 071102(R) (2015)

$\left(p_{e^+e^-} - p_{\pi^+\pi^-}\right)^2$ consistent with $m^2_{\Upsilon(1S)}$

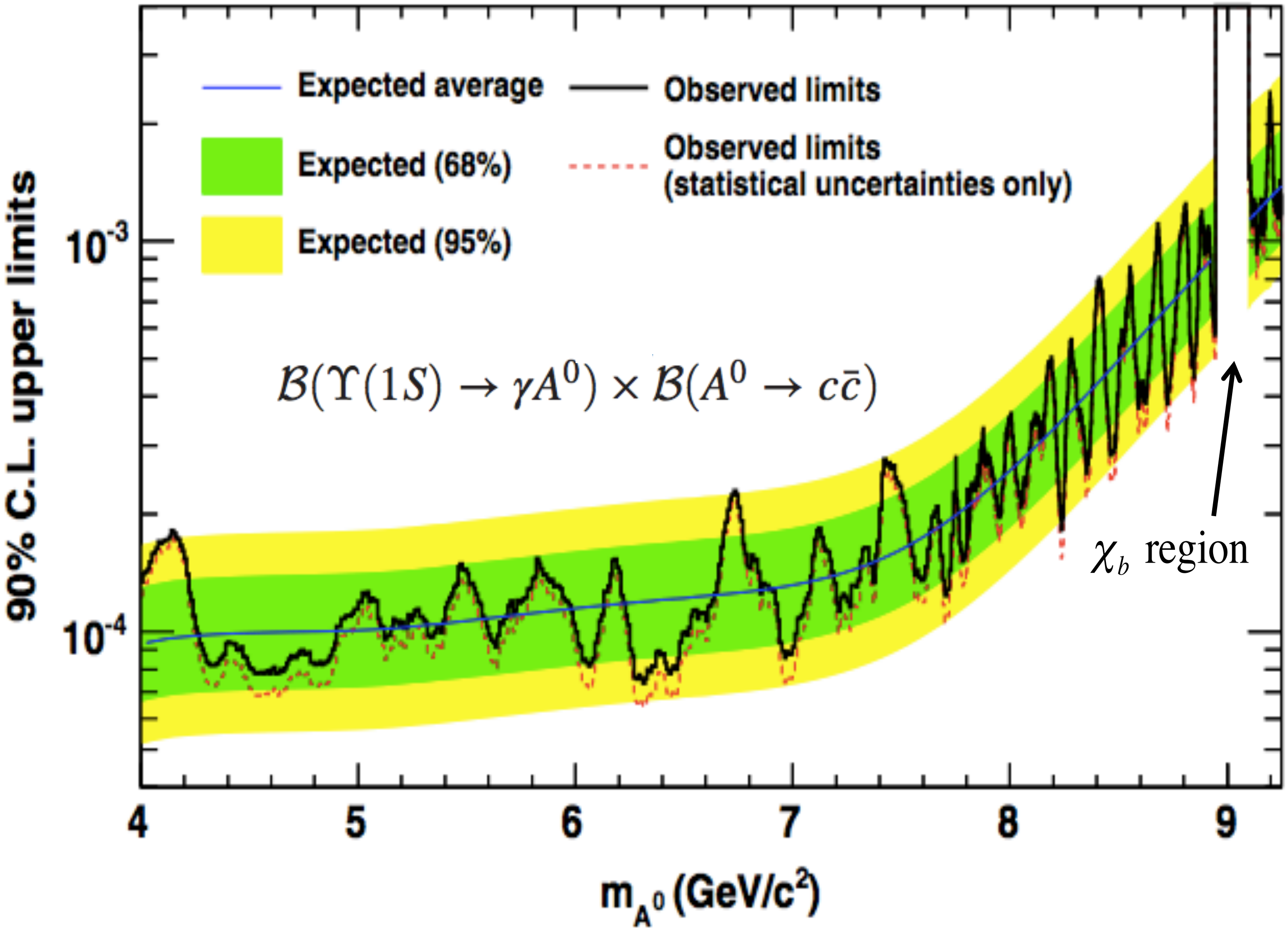
Obtain $m^2_{A^0}$ from $\left(p_{e^+e^-} - p_{\pi^+\pi^-} - p_\gamma\right)^2$





Fit in 20σ-wide intervals with a polynomial background & a signal peak

Branching-fraction limits



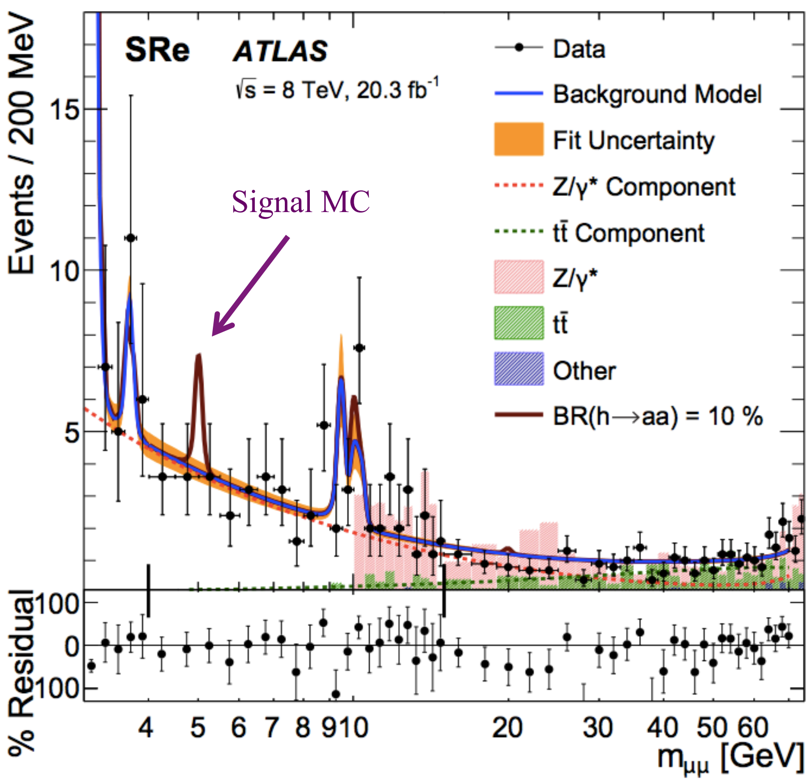
NMSSM in H(heavy) → $a_1 a_1$

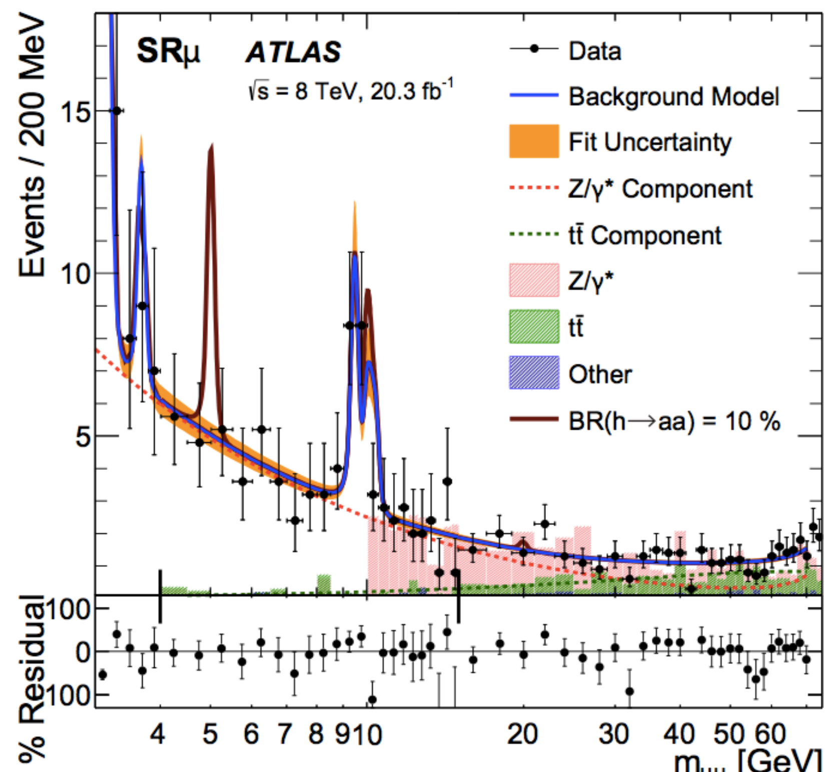
ATLAS: 1505:01609
(See Peter Onyisi's talk)

$a_1 \to \mu\mu$

$a_1 \to \tau\,(\to e/\mu)\;\tau\,(\to\text{hadrons})$

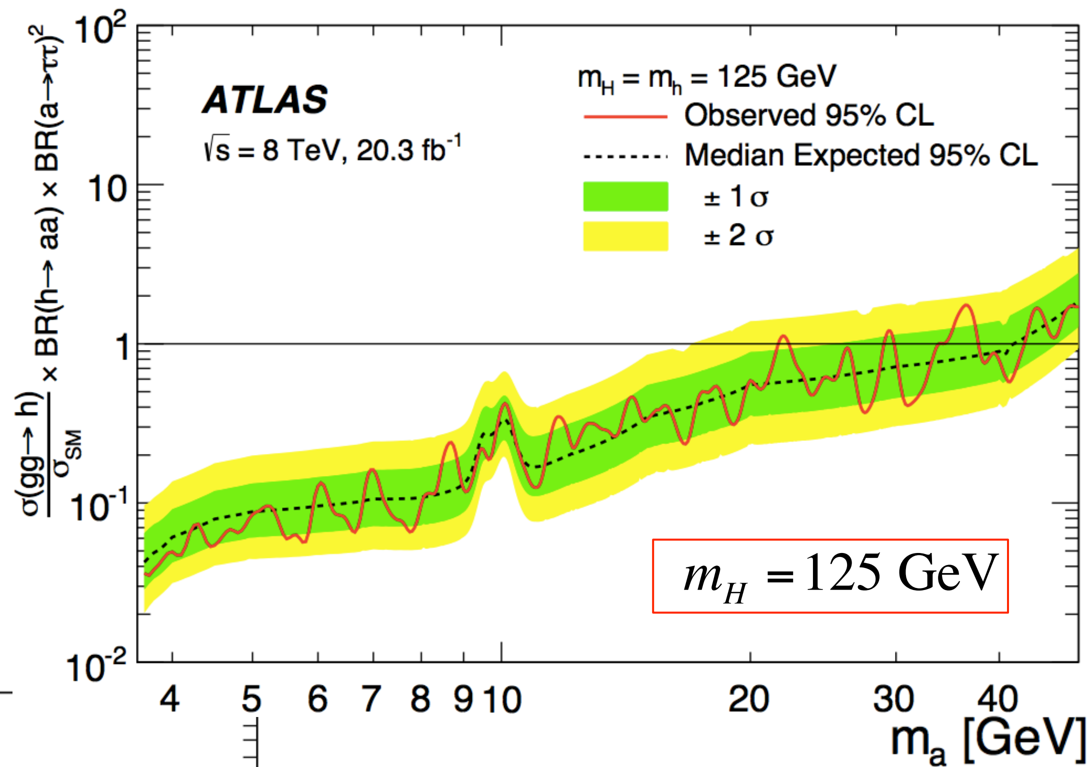
- Apply cuts on $\tau\tau$ side, fit $\mu\mu$ side (background model from control regions)

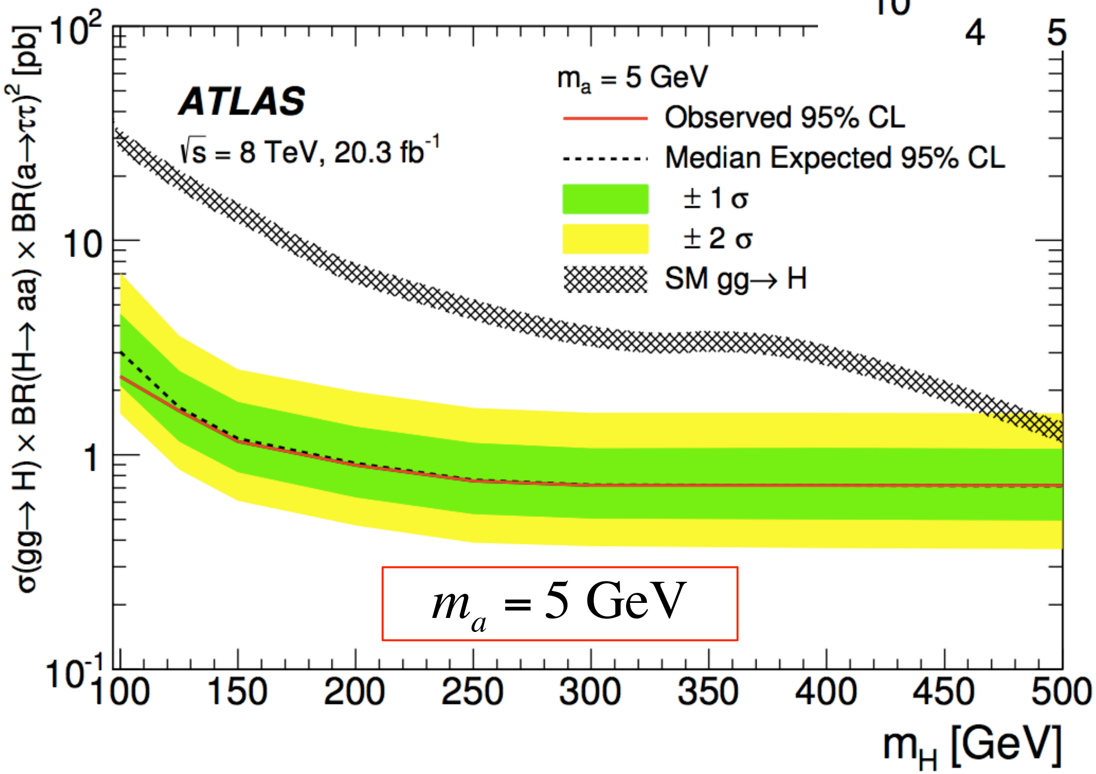




Limits

Scaled by $Br(a \to \tau\tau) \sim 1$





Light long-lived particles

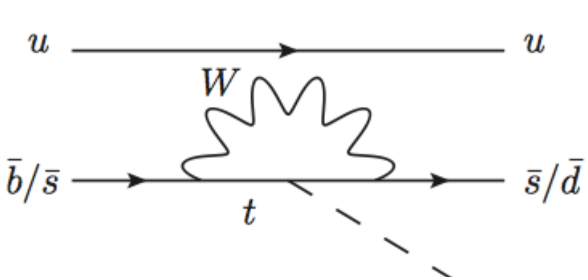
E.g., Higgs portal scenario: inflaton mixes with the SM Higgs

$$\mathcal{L}_{XN} = \frac{1}{2}\partial_\mu X \partial^\mu X + \frac{1}{2}m_X^2 X^2 - \frac{\beta}{4}X^4 - \lambda\left(H^\dagger H - \frac{\alpha}{\lambda}X^2\right)^2$$

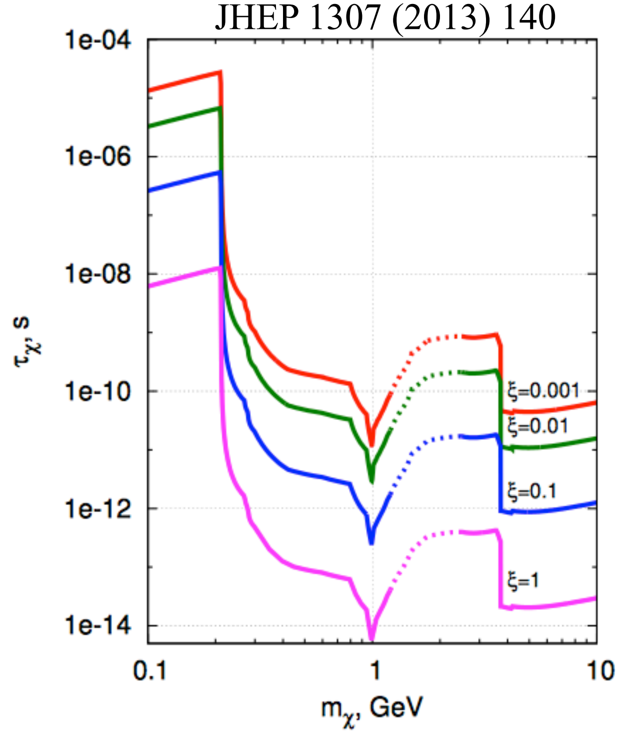
$$\mathcal{L}_{\rm grav} = -\frac{M_P^2 + \xi X^2}{2}R,$$

Parameters well suited for colliders:

- Br($b \rightarrow sX$) ~ 10^{-6}
- Lifetime:

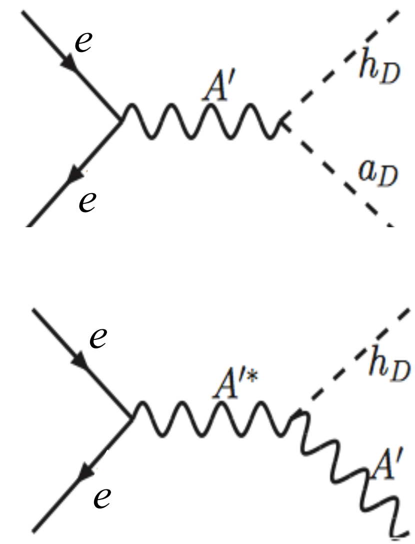


Bezrukov, Gorbunov, JHEP 1307 (2013) 140



Long-lived scalar from dark photon

Schuster et al, PRD 81, 016002 (2009)
Essig et al, PRD 80, 015003 (2009)



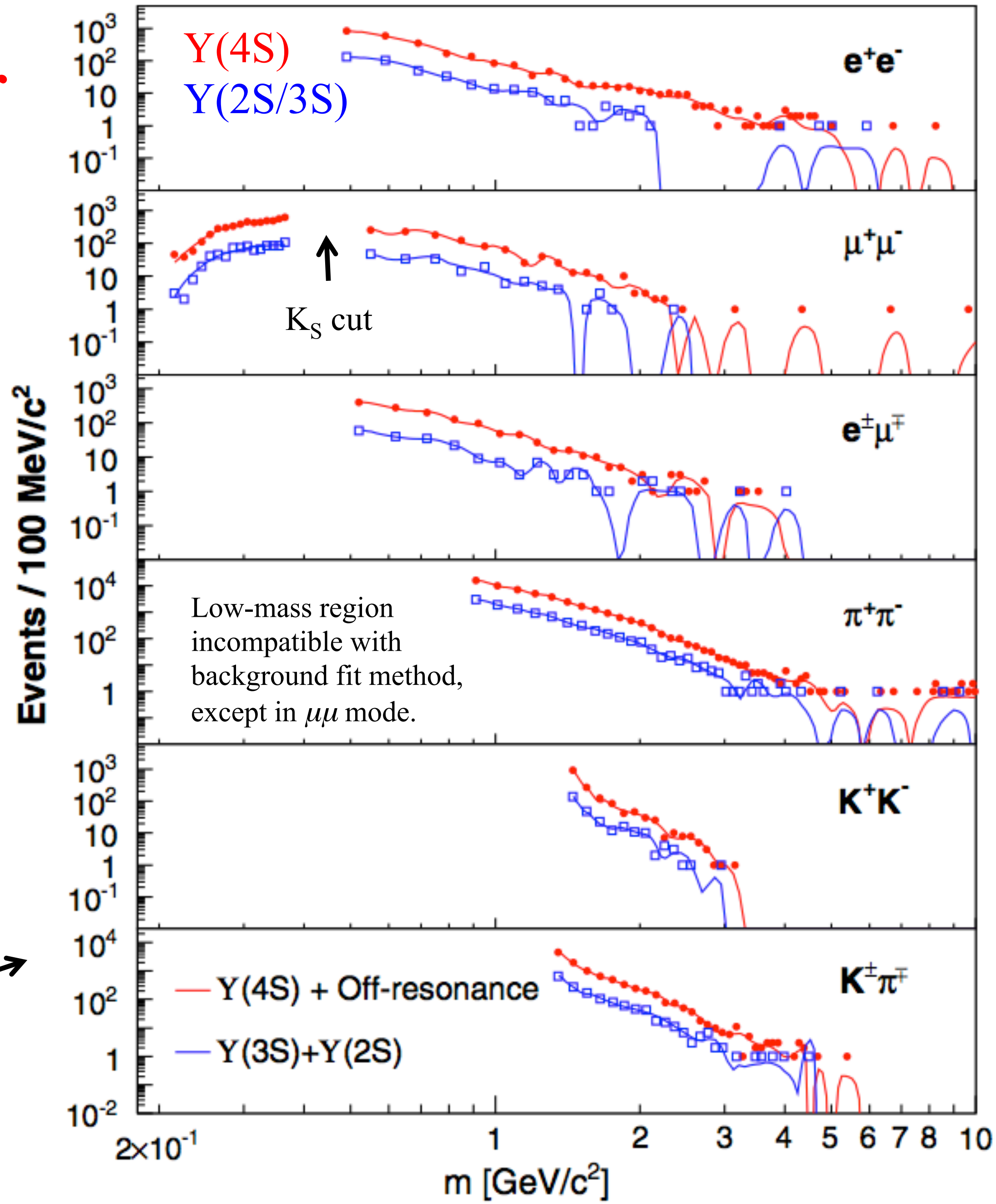
Inclusive search for long-lived particle

BABAR: PRL 114, 171801 (2015)

- Two-track final states loosely identified as:

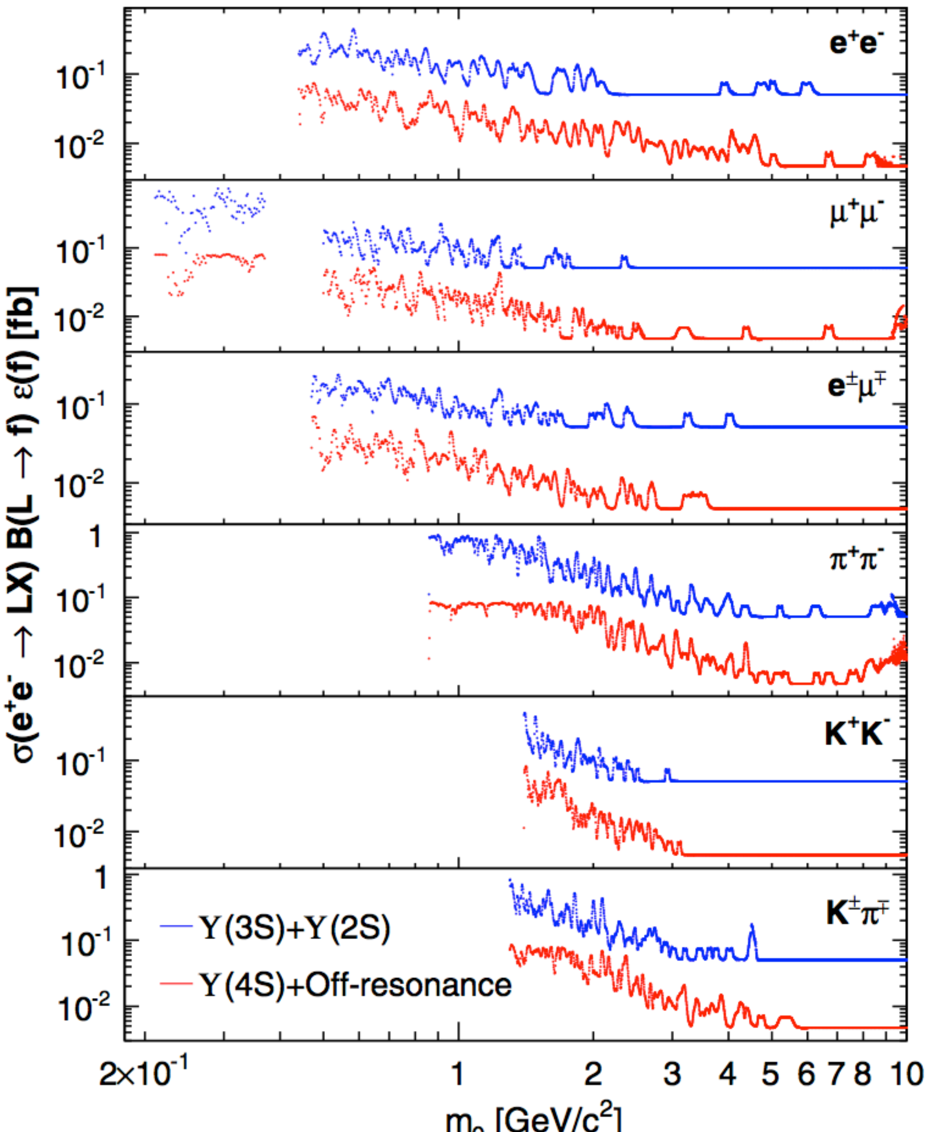
$$e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$$
$$\pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$$

- Require $r > 1$ cm
- Fit to background spline +signal peak:

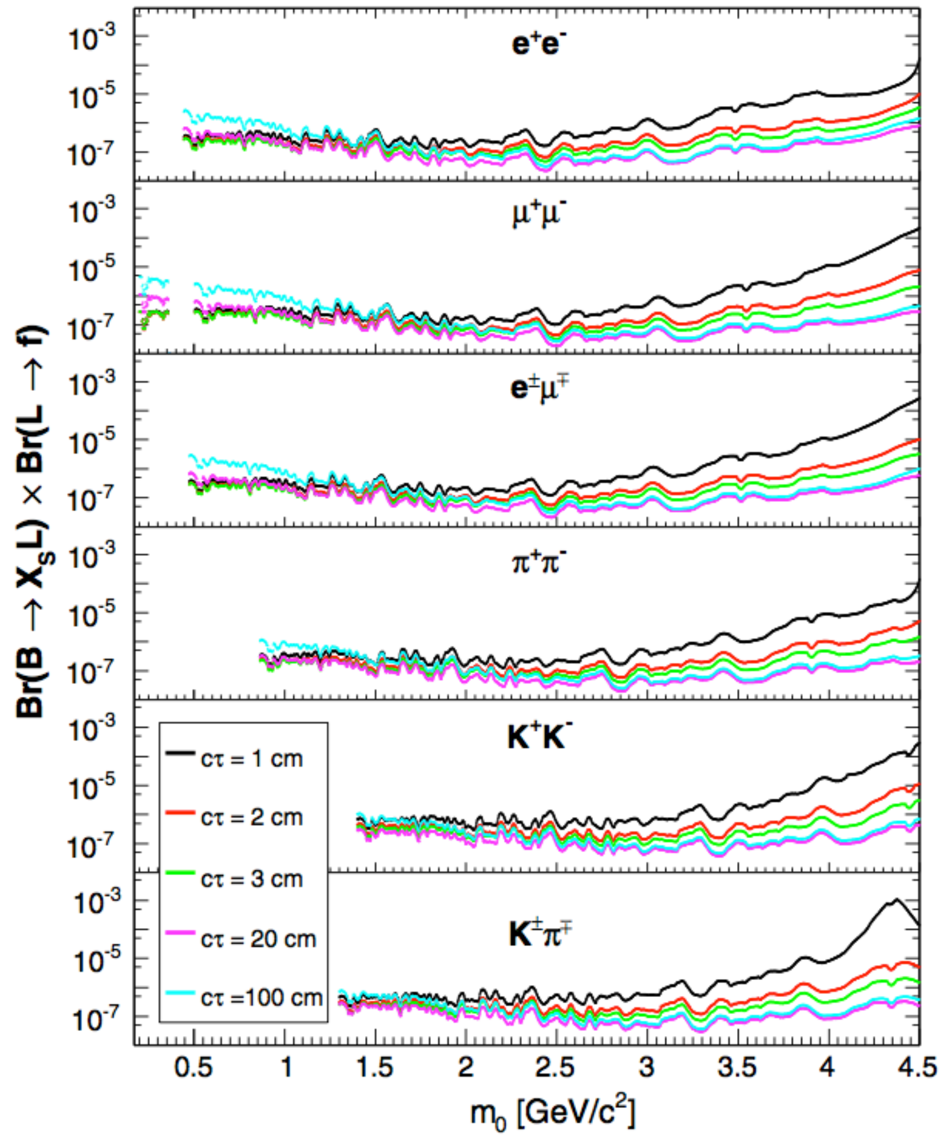


Model-independent limits on $\sigma(ee \to LX)\,\mathrm{Br}(L \to f)\,\varepsilon(f)$

Give tables of $\varepsilon(m, c\tau, p_T)$ for recasting

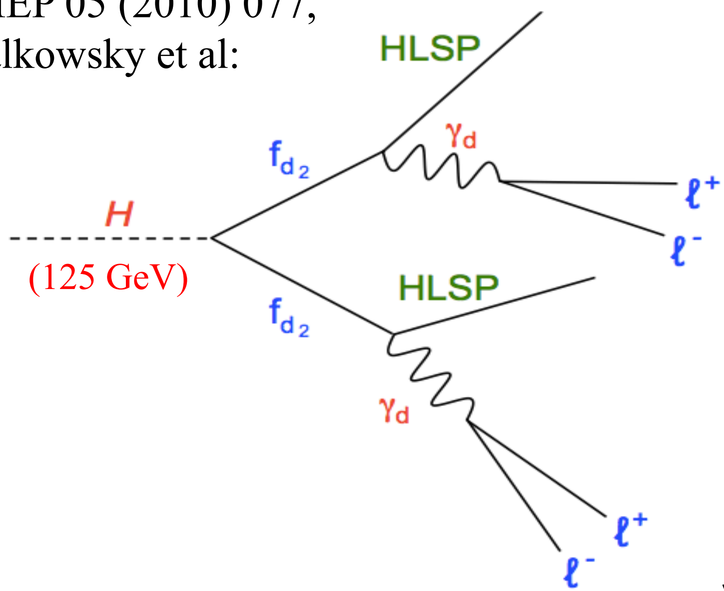


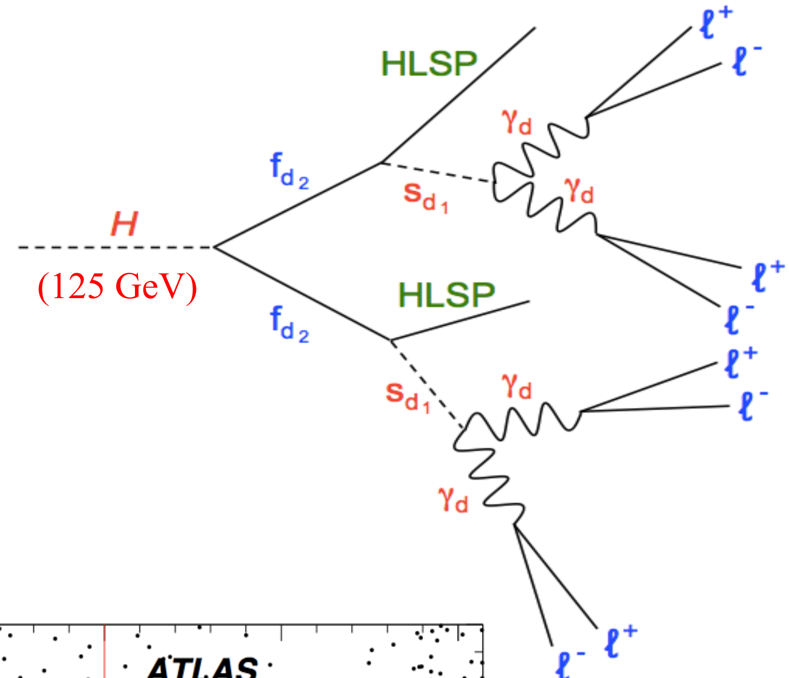
Higgs-portal limits on $\mathrm{Br}(B \to LX_s)\,\mathrm{Br}(L \to f)$ constrain inflaton model



Long-lived dark photons @ LHC

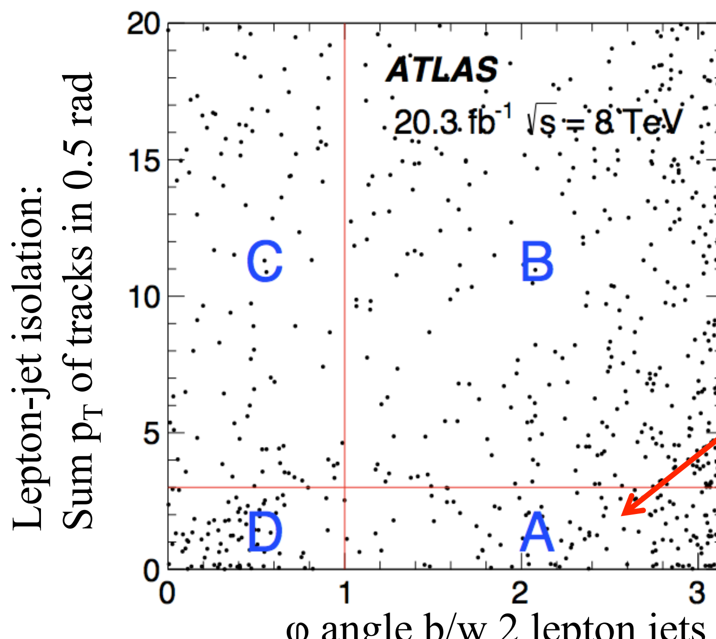
JHEP 05 (2010) 077,
Falkowsky et al:





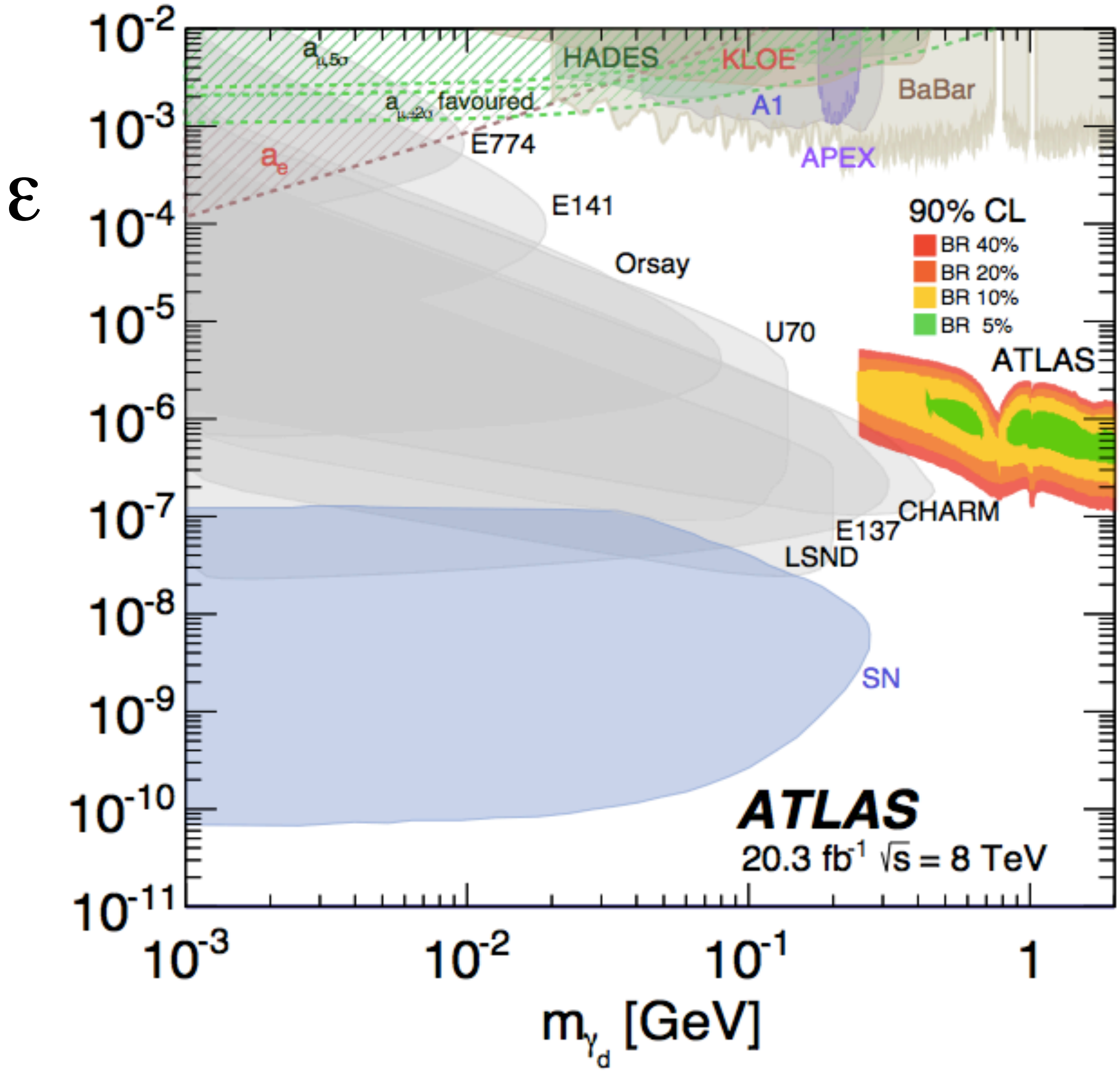
ATLAS: JHEP11 (2014) 088.

Small ε: A’ is long-lived.
Lepton-jets identified in
calorimeter/muon spectrometer



Signal region

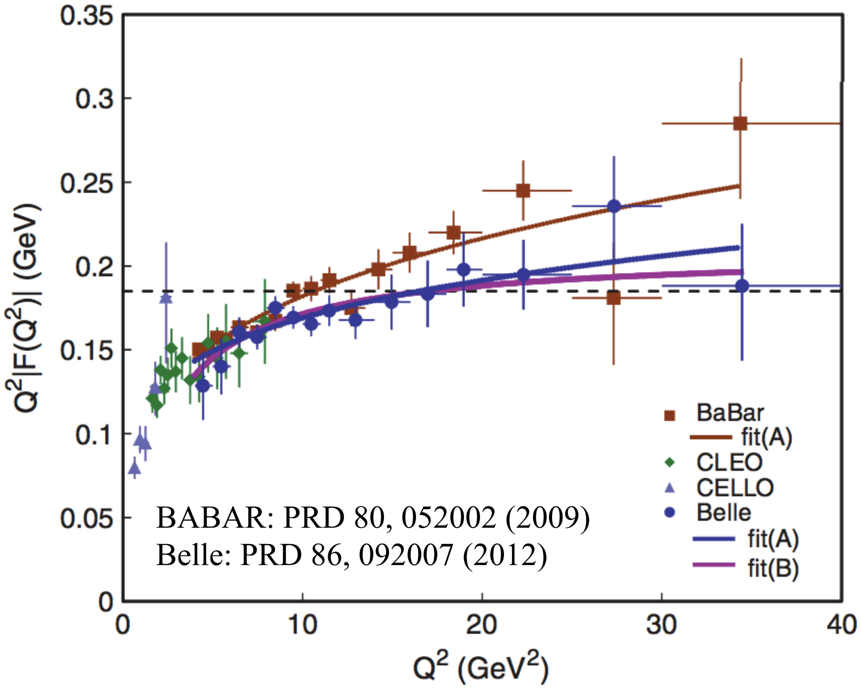
ε Limits



ε
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$a_{\mu,5\sigma}$
$a_{\mu,\pm2\sigma}$ favoured
HADES
KLOE
A1
BaBar
E774
APEX
a_e
E141
90% CL
BR 40%
BR 20%
BR 10%
BR 5%
Orsay
U70
ATLAS
CHARM
E137
LSND
SN
ATLAS
20.3 fb^{-1} $\sqrt{s}$ = 8 TeV
10^{-3}
10^{-2}
10^{-1}
1
m_{γ_d} [GeV]

π^0 impostor

Motivated by anomalous BABAR results for the $\gamma\gamma^* \rightarrow \pi^0$ transition form factor:

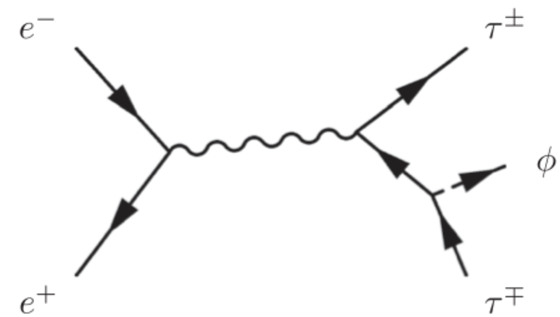


Belle results consistent with expectation as well as with the BABAR results

Proposed NP reason for anomaly:

- A π^0 "impostor" ϕ with $m \sim m_{\pi^0}$ and decays to $\gamma\gamma$ (McKeen et al, PRD 85, 053002 (2012))
- Couples strongly to τ (not well constrained)

Search via:



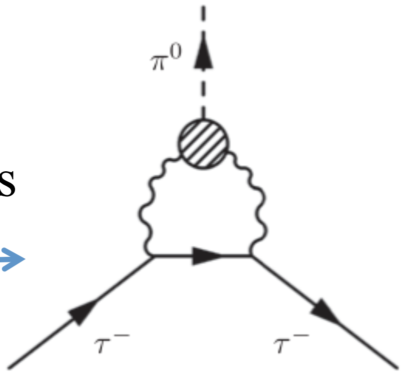
Predicted cross sections:

- Scalar ϕ_S: ~90 pb
- Pseudoscalar ϕ_P: ~3 pb
- Pseudoscalar π^0_{HC} with u/d coupling (mixes with π^0): ~0.4 pb

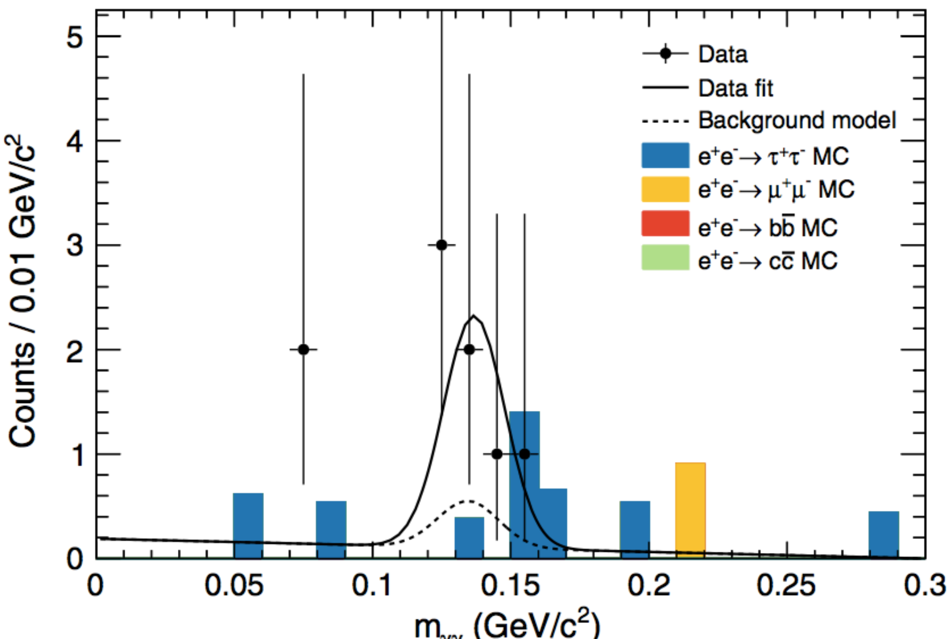
Search for a π^0 impostor

BABAR: PRD 90, 112011 (2014)

- Require $\tau^+\tau^- \rightarrow \mu e + \nu$'s, $\phi \rightarrow \gamma\gamma$
- Hadronic τ-decay background suppressed with kinematic cuts
- Irredicible SM background from $e^+e^- \rightarrow \tau^+\tau^-\pi^0$, e.g., estimated to be < 0.01 events



- $\phi \rightarrow \gamma\gamma$ mass distribution:
- Scan for a signal peak



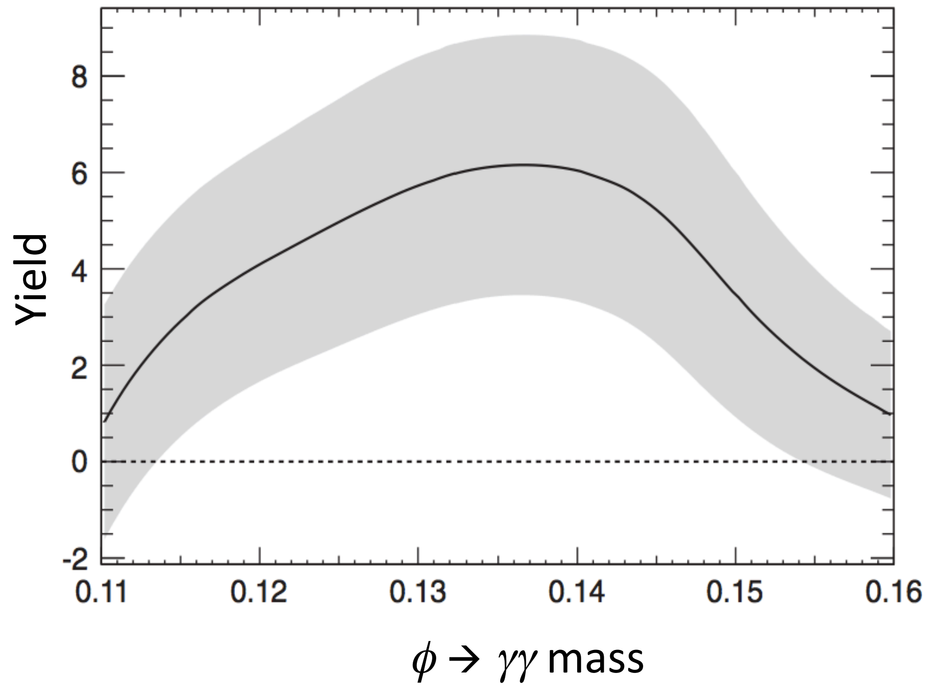
π^0 impostor results

- Subtract 1.24 ± 0.37 peaking-background events from the highest-yield point at 136 MeV
- Cross-section limits:

$$\sigma \leq \begin{cases} 73\ \text{fb} & \text{for the } \phi_P \text{ and } \pi^0_{\text{HC}} \text{ models} \\ 370\ \text{fb} & \text{for the } \phi_S \text{ model.} \end{cases}$$

- Model excluded with p values:

π^0_{HC}	5.9×10^{-4}
ϕ_P	8.8×10^{-10}
ϕ_S	2.2×10^{-9}



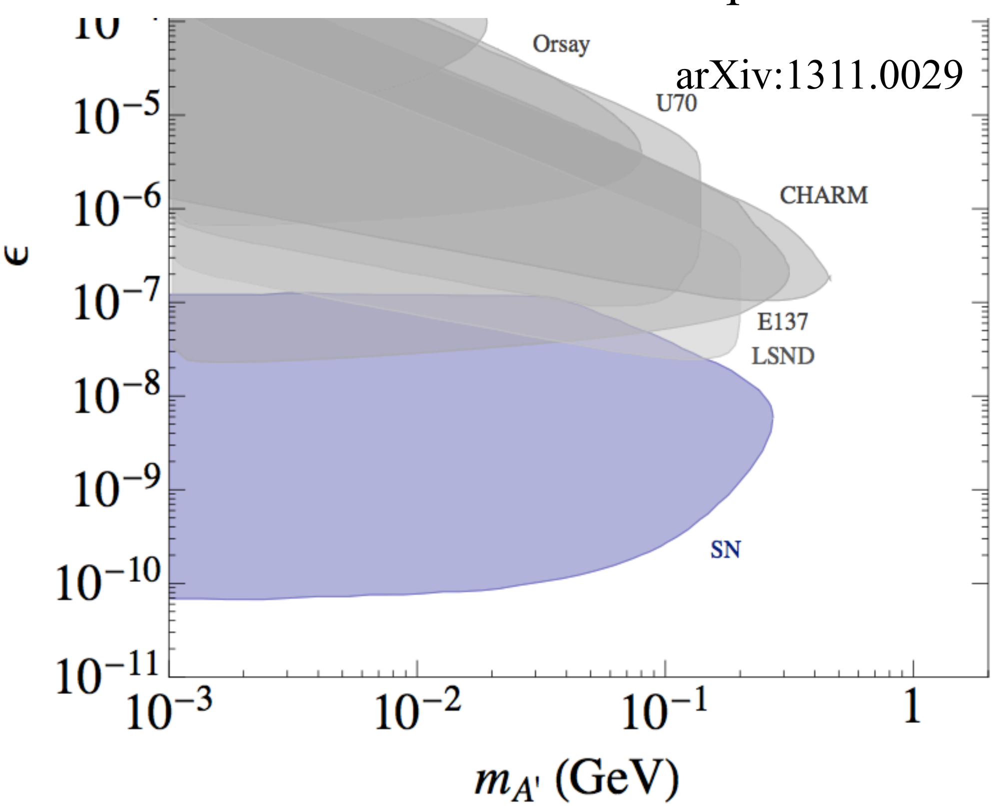
Conclusions

- Much interest in exploring GeV-scale hidden-sector vectors and scalars.
- Complementary searches:
  - Direct, low-energy production @ in e^+e^- machines & fixed-target experiments
  - Production in decays of heavier states at LHC
- Near future sensitivity improvement from:
  - ATLAS, CMS, LHCb
  - Belle-II, HPS

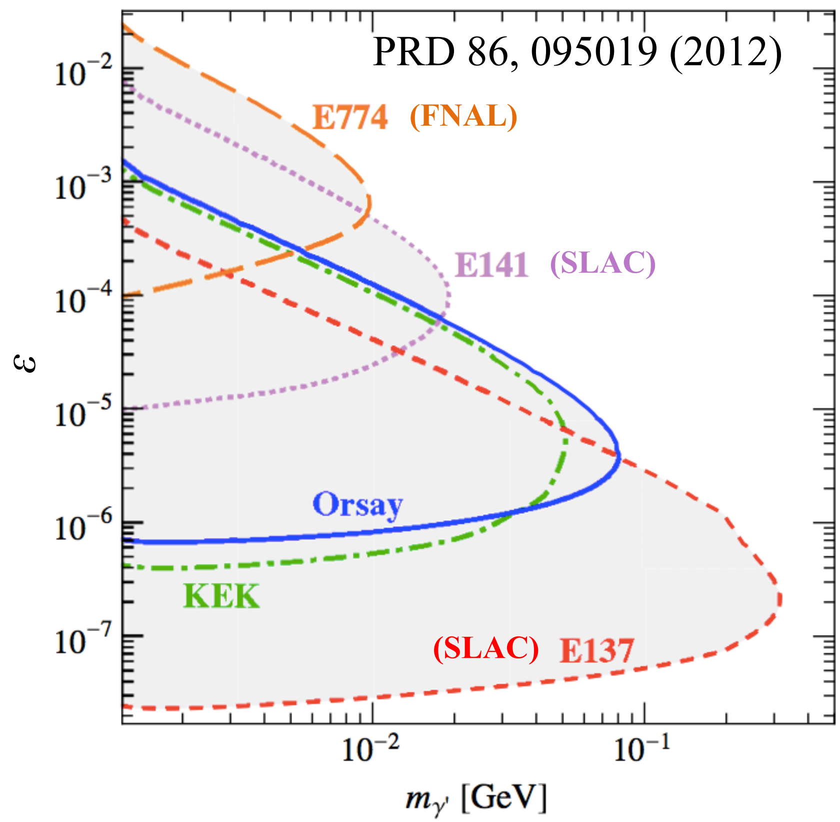
Backup slides

Long-lived *A'* @ fixed target expts.

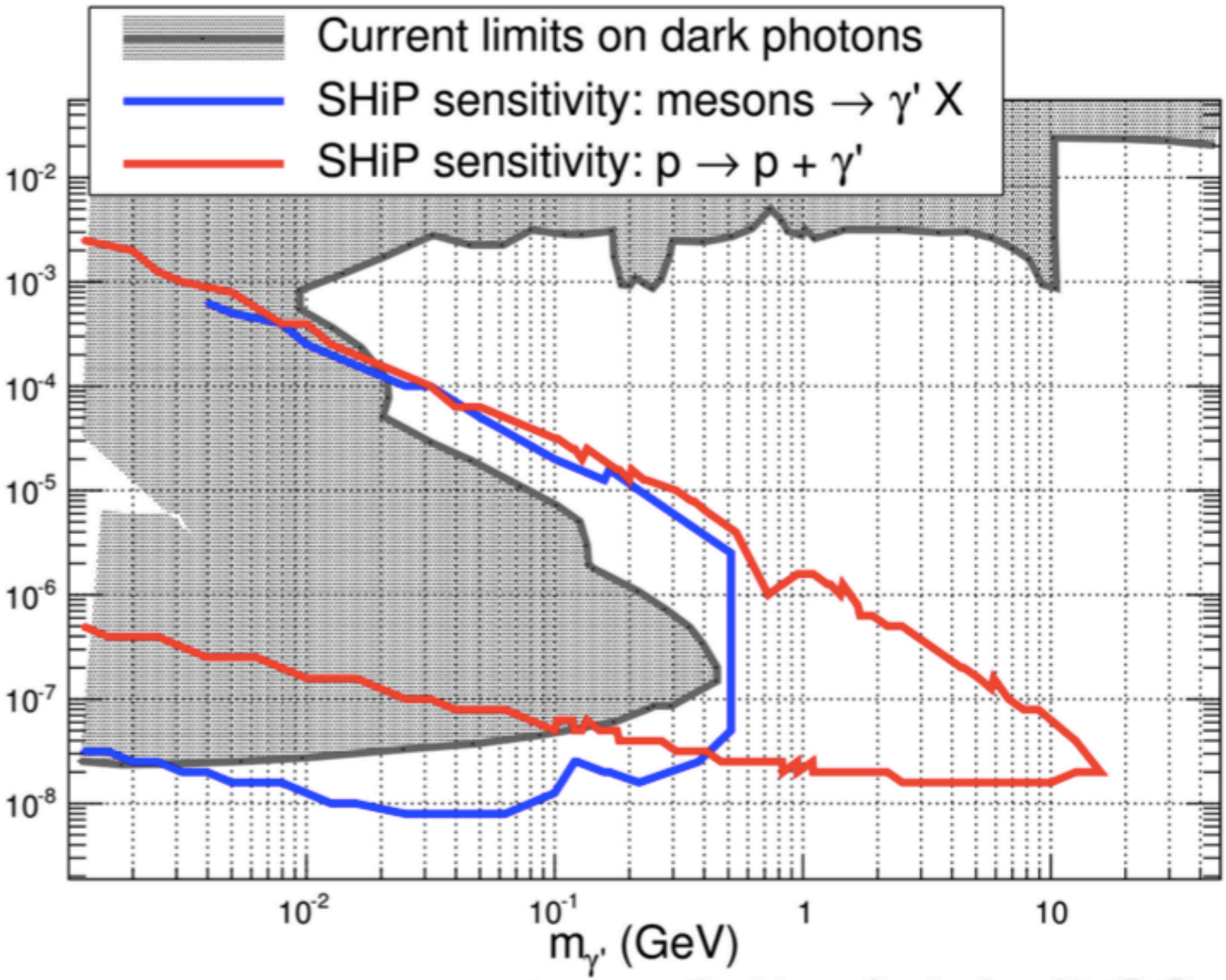
Proton beam dumps



Electron beam dumps



SHiP sensitivity



M. Patel, IPA 2014, https://indico.ph.qmul.ac.uk/indico/conferenceDisplay.py?confId=1