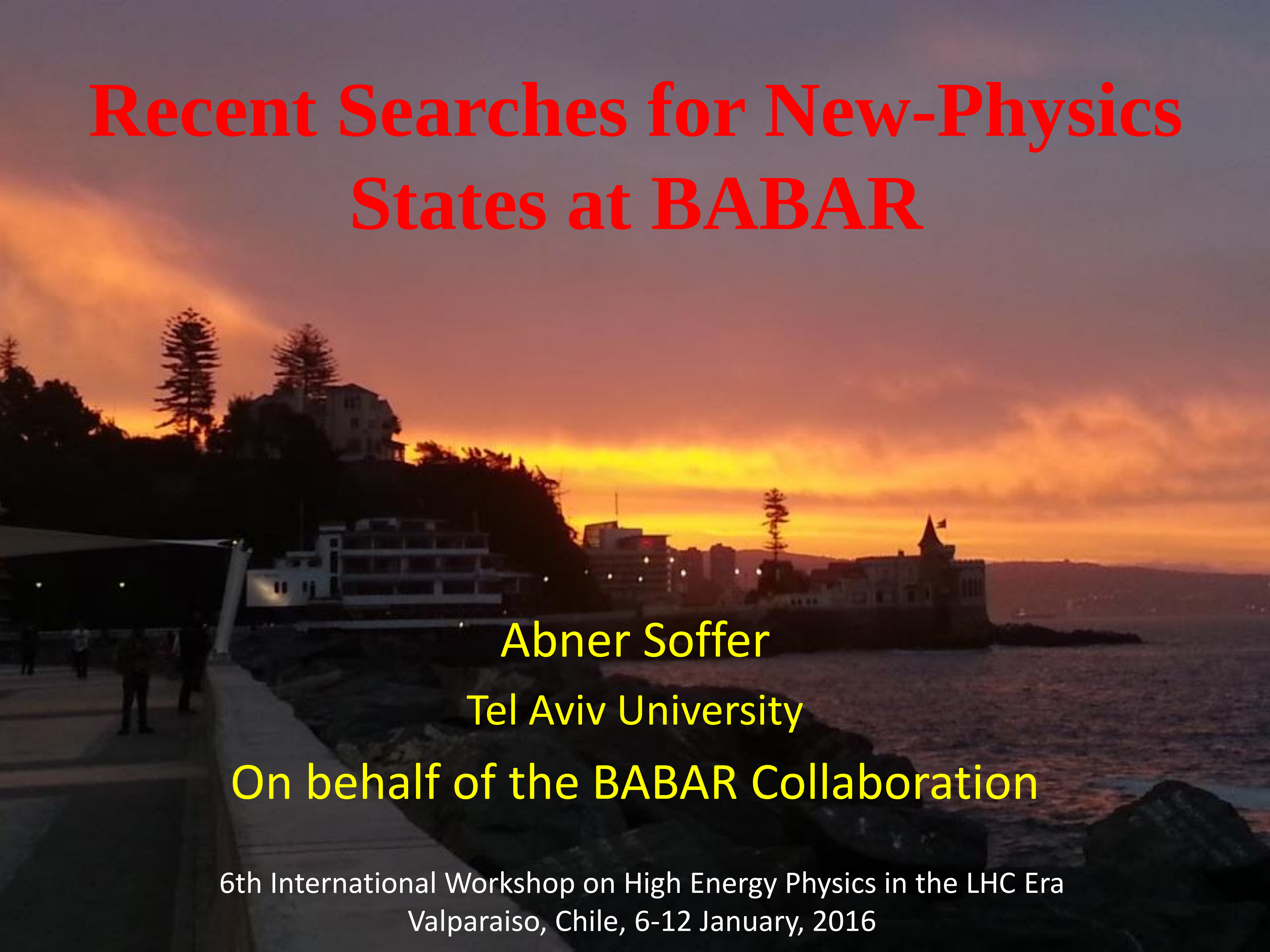


Recent Searches for New-Physics States at BABAR

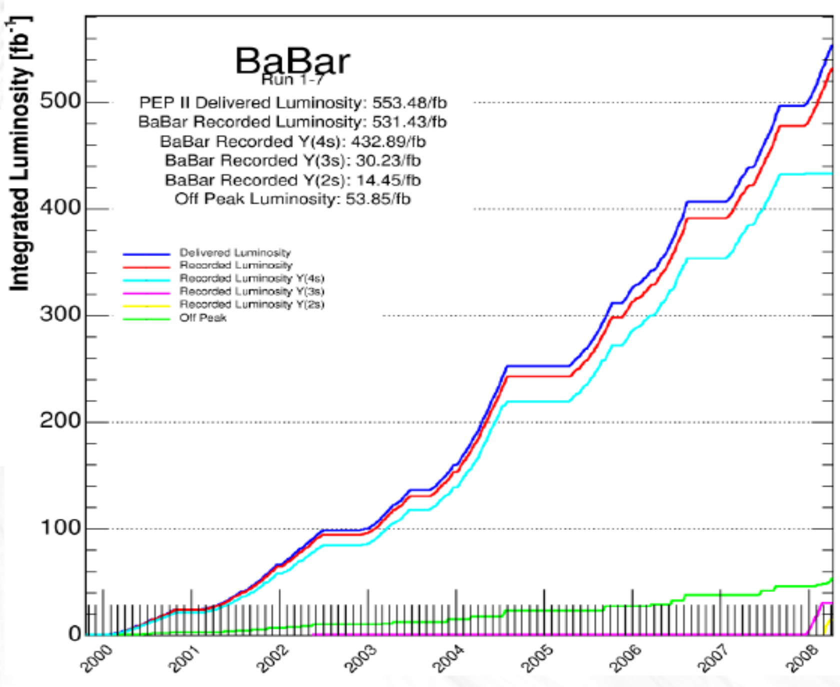
Abner Soffer
Tel Aviv University
On behalf of the BABAR Collaboration

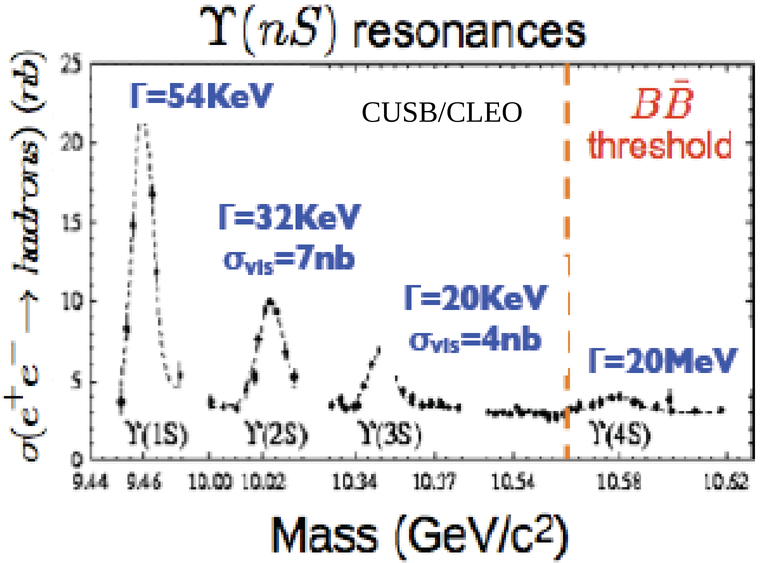
6th International Workshop on High Energy Physics in the LHC Era
Valparaiso, Chile, 6-12 January, 2016

Outline

- The BABAR experiment
- Search for new scalars decaying to $c\bar{c}$
  - PRD 91, 071102(R) (2015)
- Search for new long-lived particles
  - PRL 114, 171801 (2015)

BABAR energy and dataset

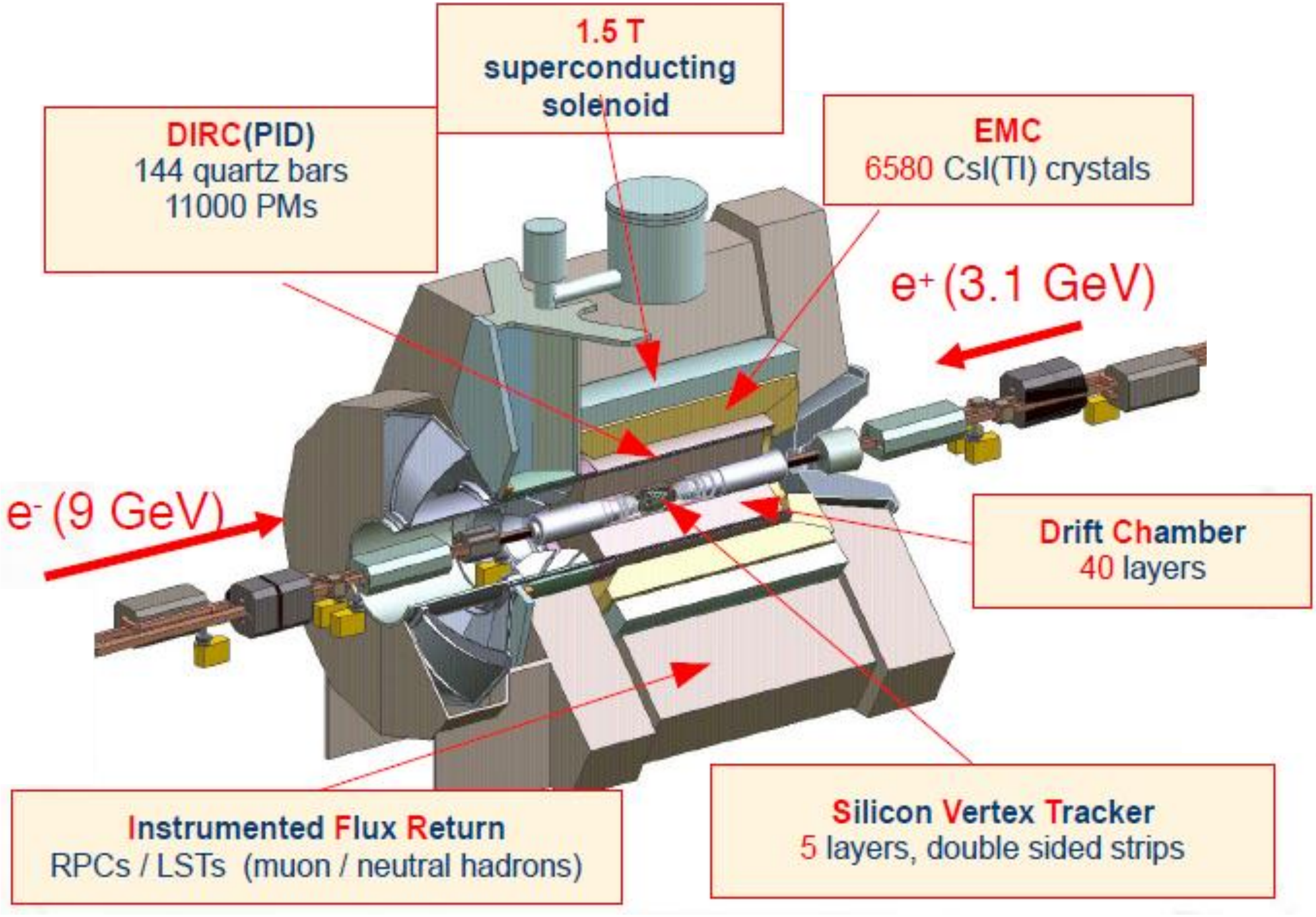




Resonance	L(fb^{-1})	#(10^6)
$\Upsilon(4S)$	424	471
$\Upsilon(3S)$	28	121
$\Upsilon(2S)$	14	99

Belle data ended mid-2010,
L(4S) = 711 fb^{-1}, L(5S) = 121 fb^{-1}

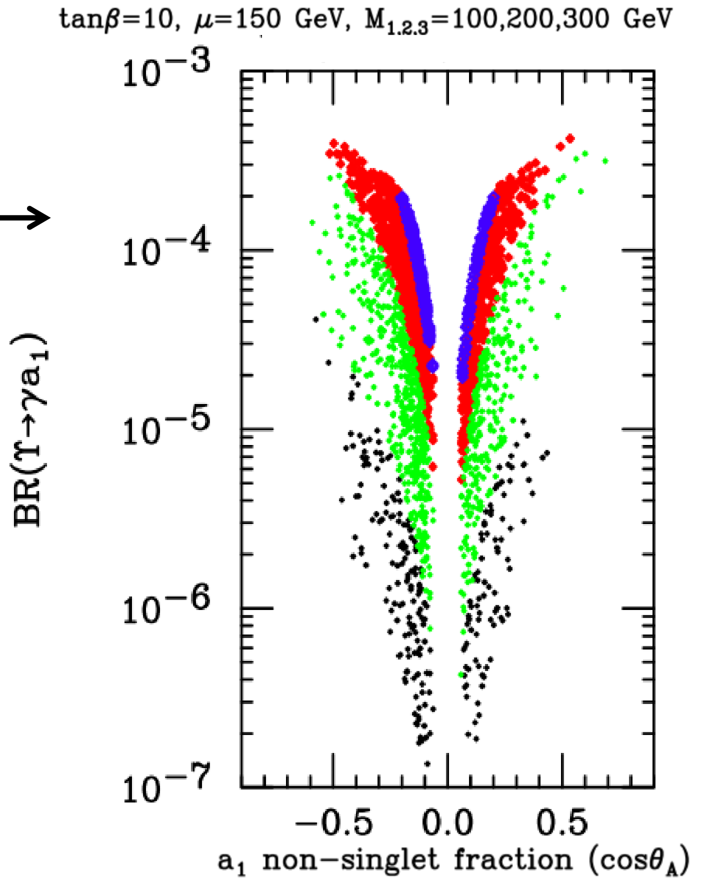
The BABAR Detector



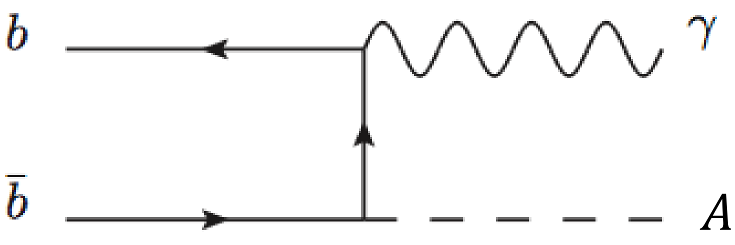
Search for new scalar A^0 decaying to $c\bar{c}$

Motivations for light scalars

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

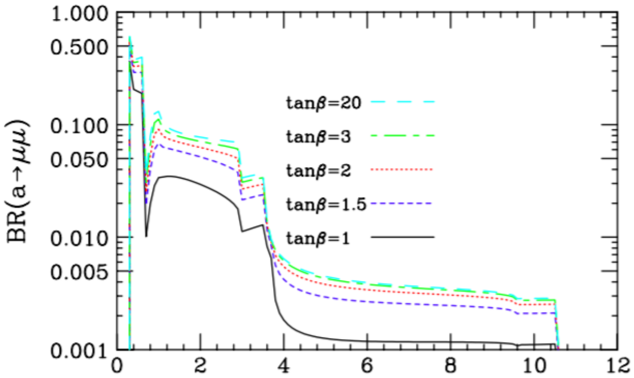


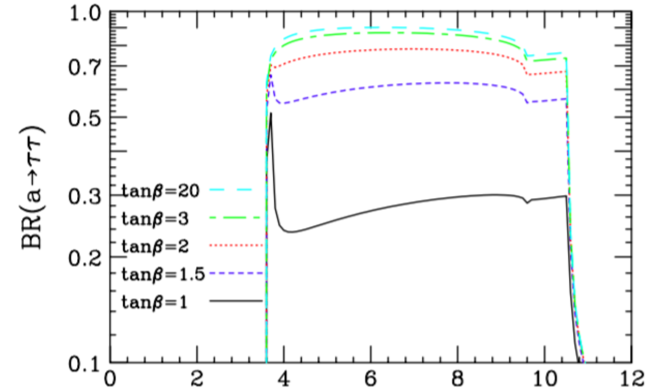
$m_{a1} < 2m_\tau$
$2m_\tau < m_{a1} < 7.5$ GeV
$7.5 < m_{a1} < 7.5$ GeV
$8.8 < m_{a1} < 9.2$ GeV

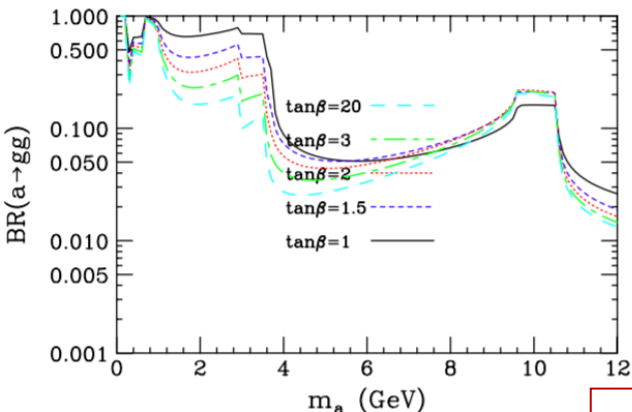


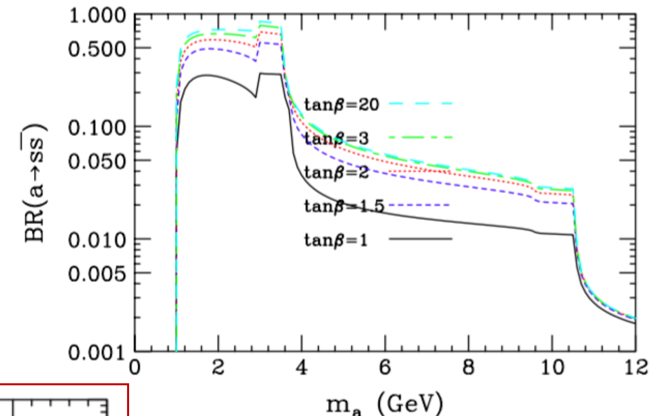
A^0 → SM/dark fermion pair

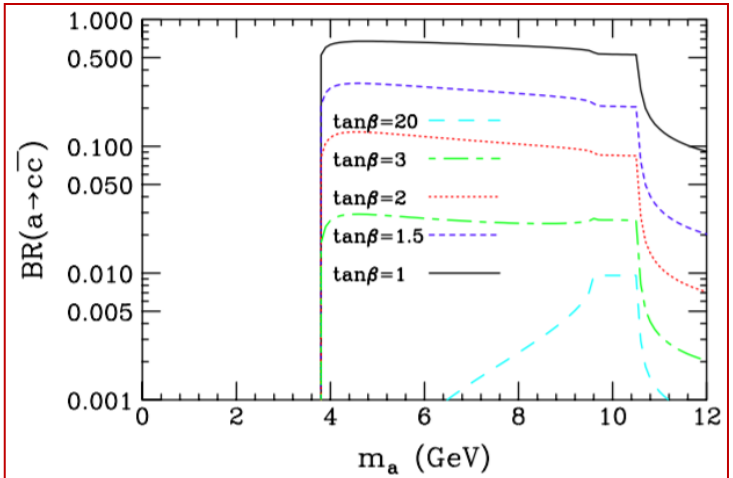
A^0 branching fractions (NMSSM)







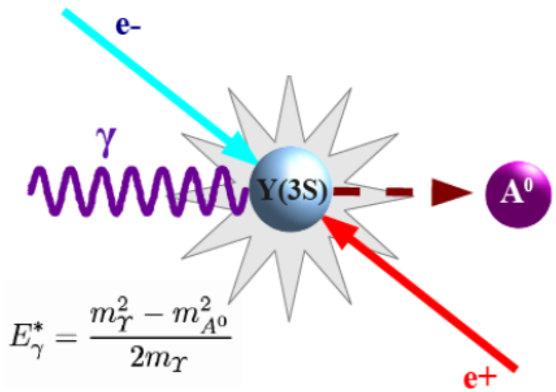




$Br(A^0 \to c\bar{c})$ dominates
at low $\tan\beta$
and $m_{A^0} > 4$ GeV

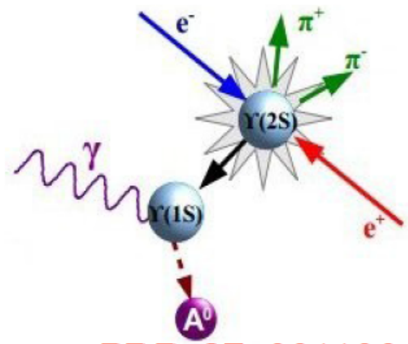
$\Upsilon(nS) \to A^0\gamma$ searches

Radiative Decays of ϒ(nS)
Signature: monochromatic photon



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

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



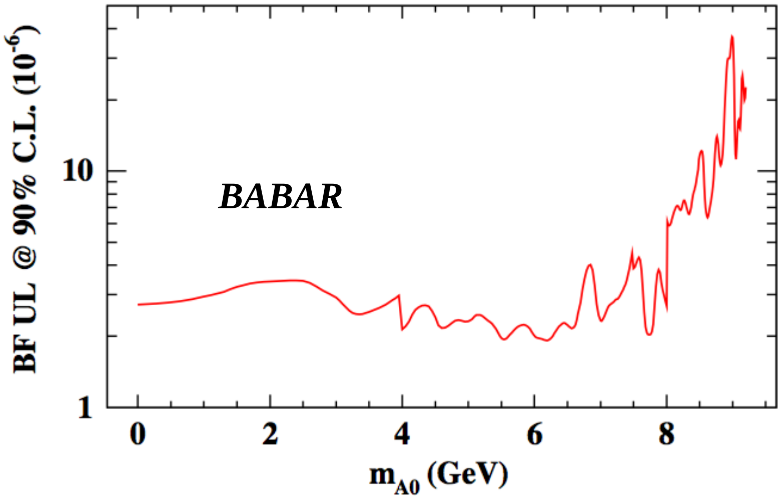
BABAR
- $A^0 \to \mu^+\mu^-$, PRD **87**, 031102 (2013)
- $A^0 \to \tau^+\tau^-$, PRD **88**, 071102 (2013)
- $A^0 \to$ hadrons, PRD **82**, 0317019R (2013)
- $A^0 \to$ invisible, PRL **107**, 021804 (2011)

CLEO ϒ(1S): $A^0 \to \mu^+\mu^-$, $\tau^+\tau^-$, PRL **101**, 151802 (2008)
BESIII J/ψ: $A^0 \to \mu^+\mu^-$, PRD **85**, 092012 (2011)
(BESIII updated expected soon)

Also searches at LHC:
CMS inclusive: $A^0 \to \mu^+\mu^-$, PRL **109**, 121801 (2012)
CMS: $h \to 2(A^0 \to \mu^+\mu^-)$, PLB **726**, 564 (2013)
ATLAS: $h \to (\mu^+\mu^-)(\tau^+\tau^-)$ PRD**92** 052002 (2015)

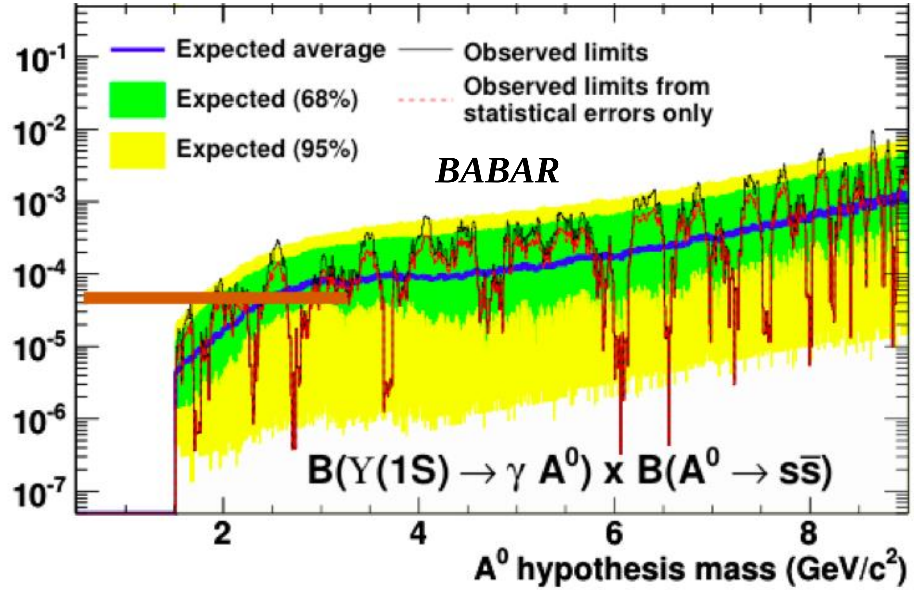
PRL **107**, 021804

Invisible



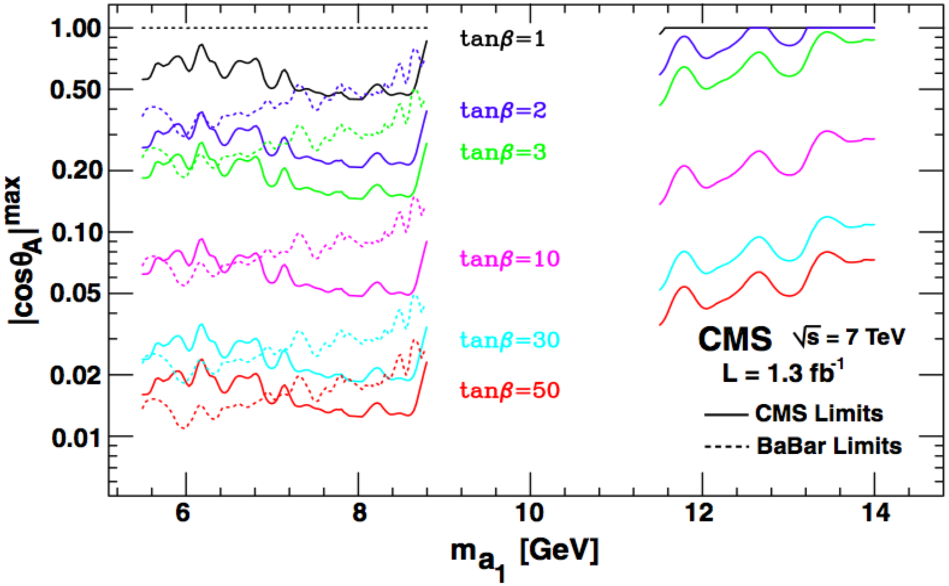
Hadrons

PRD **82**, 0317019R



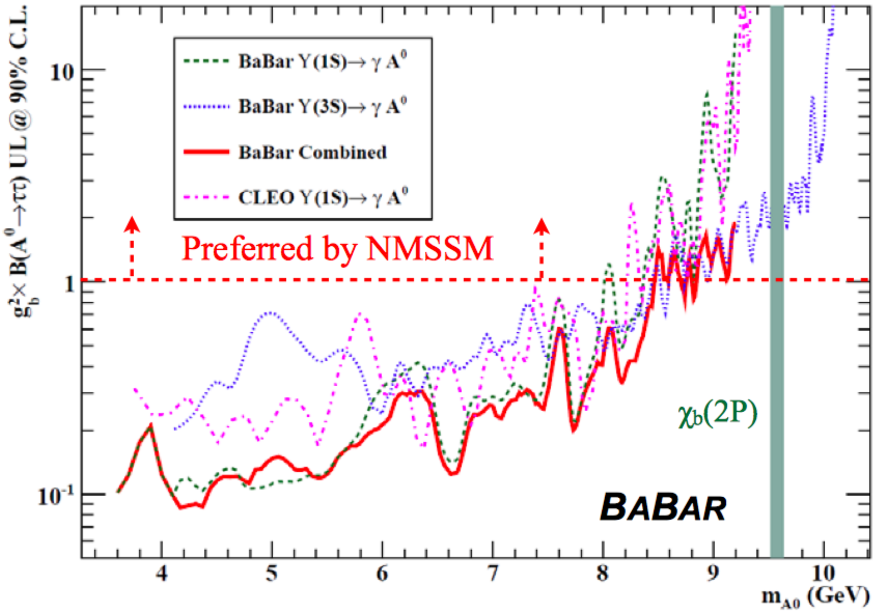
PRL **109**, 121801

$\mu^+\mu^-$

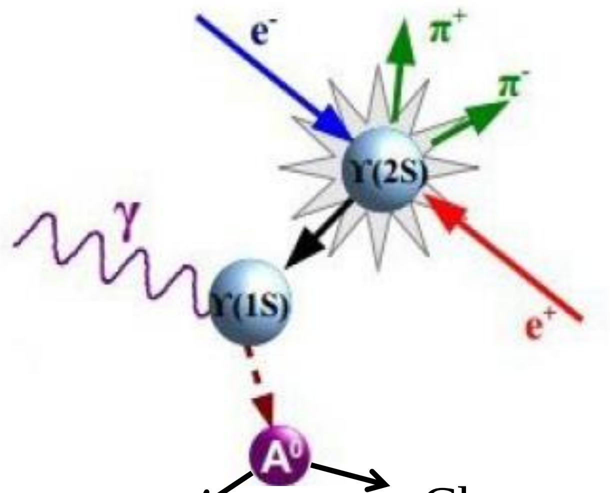


$\tau^+\tau^-$

PRD **88**, 071102



Event selection



$\overline{c}$

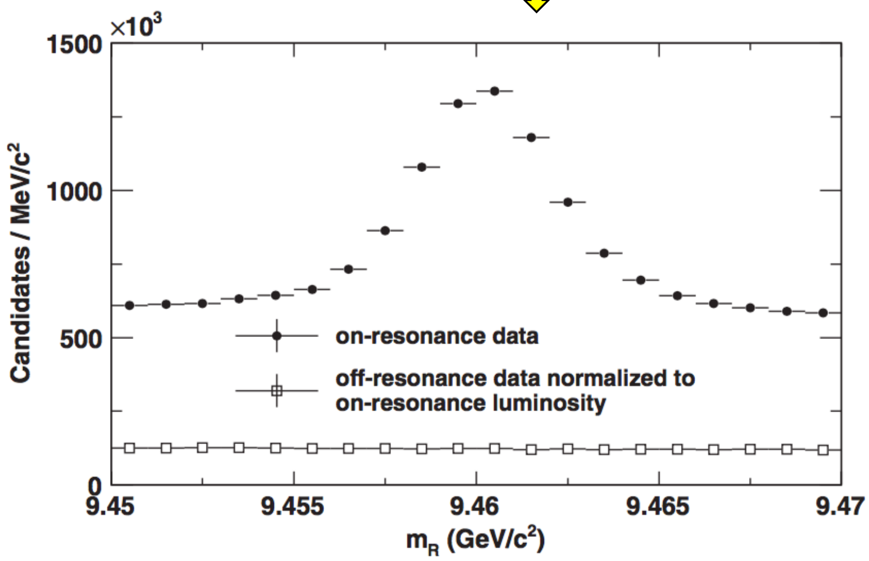
Charm tag:

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

Cut on mass recoiling against $\pi^+\pi^-$ pair

$$m_R^2 = (p_{e^+e^-} - p_{\pi^+\pi^-})^2$$

$p_{e^+e^-} = (M_{\Upsilon(2S)}, 0, 0, 0)$
in CM frame



Calculate light Higgs candidate mass:

$$m_X^2 = \left(p_{e^+e^-} - p_{\pi^+\pi^-} - p_\gamma\right)^2$$

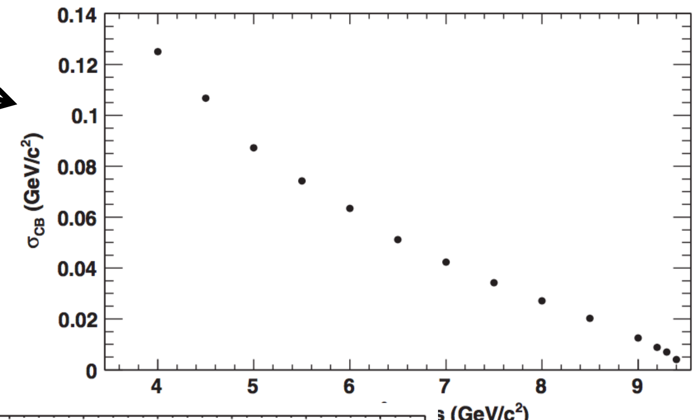
Backgrounds

- Suppressed using a 24-variable boosted decision tree
- Calculated separately in 10 cases:
  - 5 tag-charm modes
  - 2 m_X regions
- in low-mass region:
  - $4 < m_X < 8$ GeV
- and high-mass region:
  - $7.5 < m_X < 9.25$ GeV

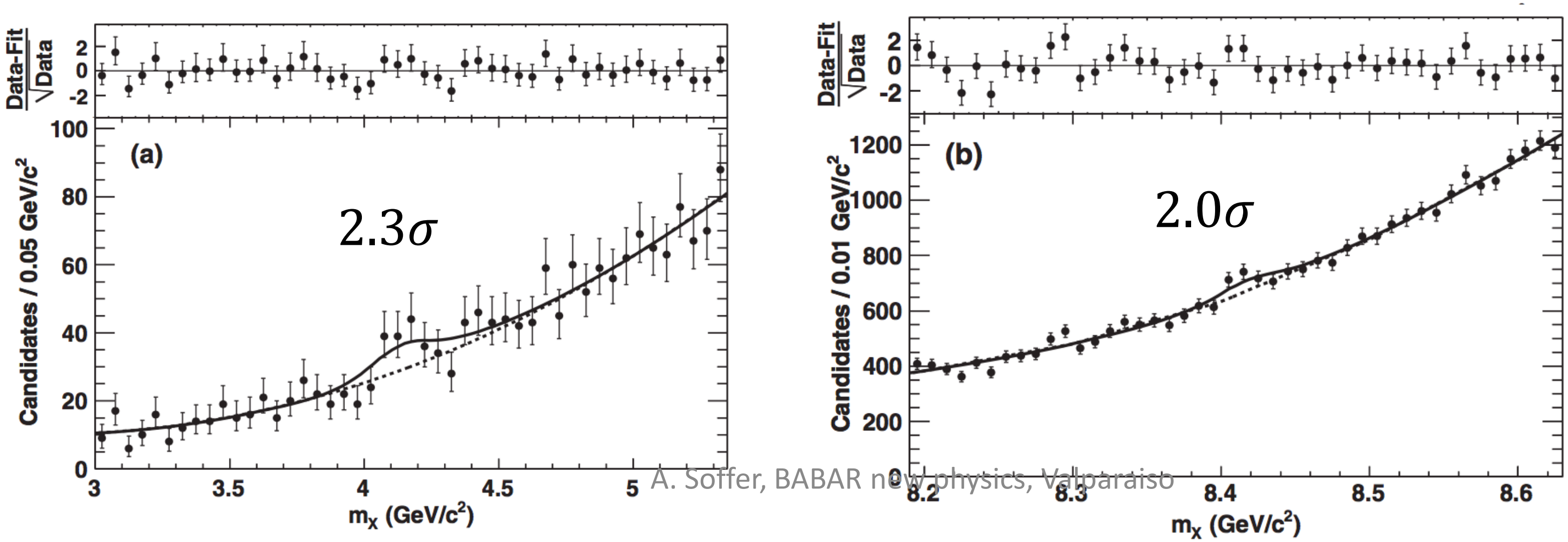
Background source	Low-mass	High-mass
$\Upsilon(1S) \to \gamma g g$	35%	1%
$\Upsilon(1S) \to$ other	34%	66%
$\Upsilon(2S) \to$ other	15%	18%
$e^+e^- \to q\bar{q}$	16%	15%

Signal extraction

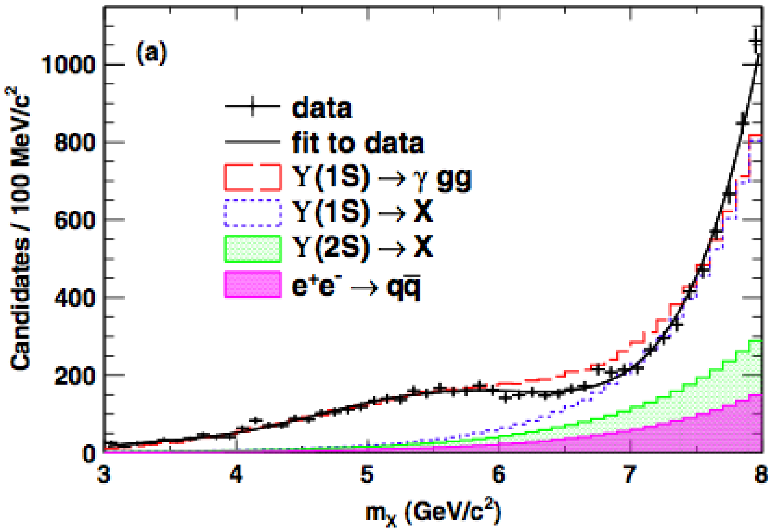
- Fit candidate-mass spectrum for a smooth background (2^{nd}-order polynomial) + a signal peak (Crystal-Ball function)
- Signal peak moved in steps of 10 (2) MeV in the low (high) mass region.
- Fit range is 20 times the Crystal-Ball width (dominated by γ resolution)

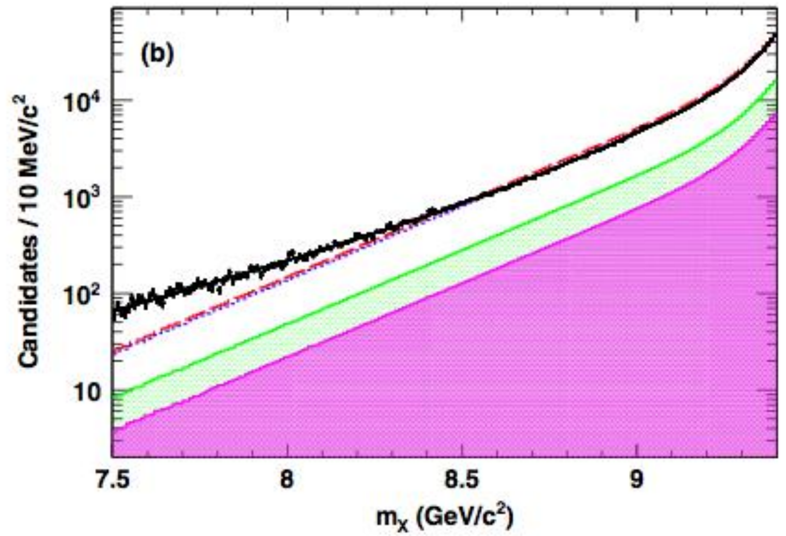


- Highest local-significance fits in each region:

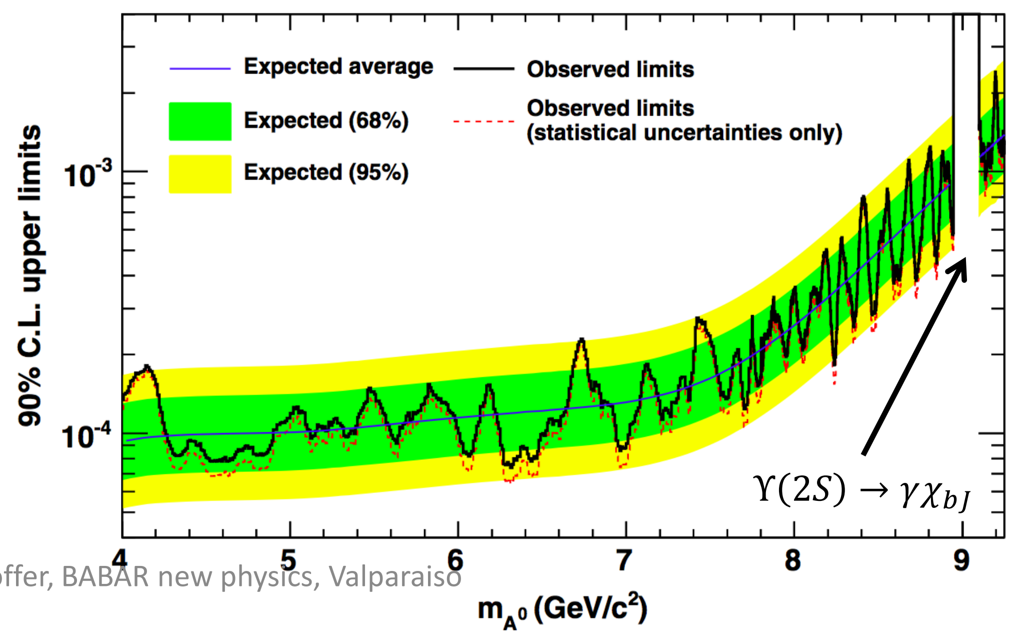


Results





$$\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}(A^0 \to c\bar{c})$$



Search for new long-lived particle *L*

Motivation 1

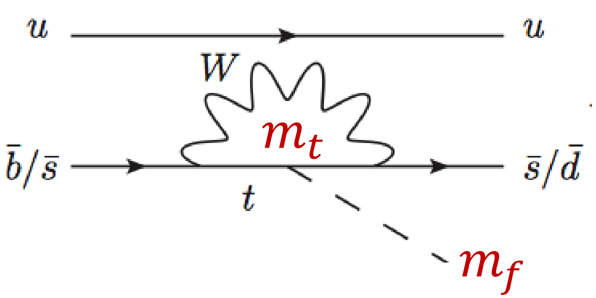
E.g., Higgs portal scenario: inflaton mixes with the SM Higgs

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

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

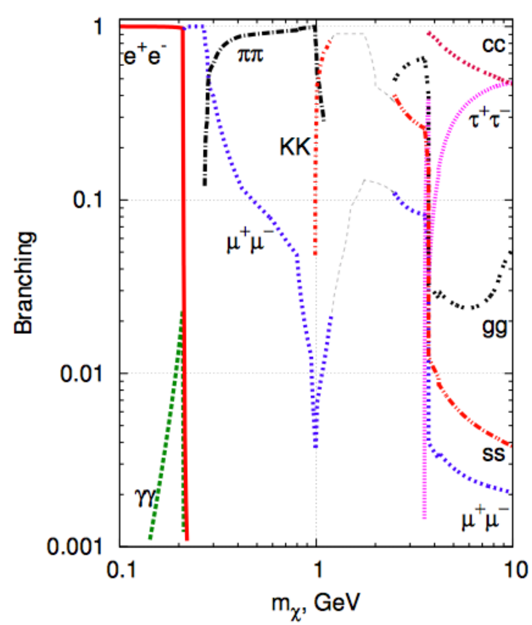
Bezrukov, Gorbunov,
JHEP 1307 (2013) 140

Parameters are well suited for colliders:

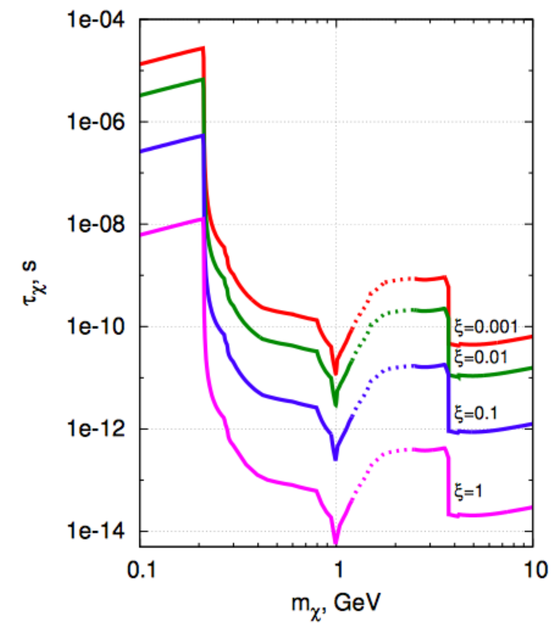


– Br($b \rightarrow sX$) ~ 10^{-6}

Large 2-track BRs

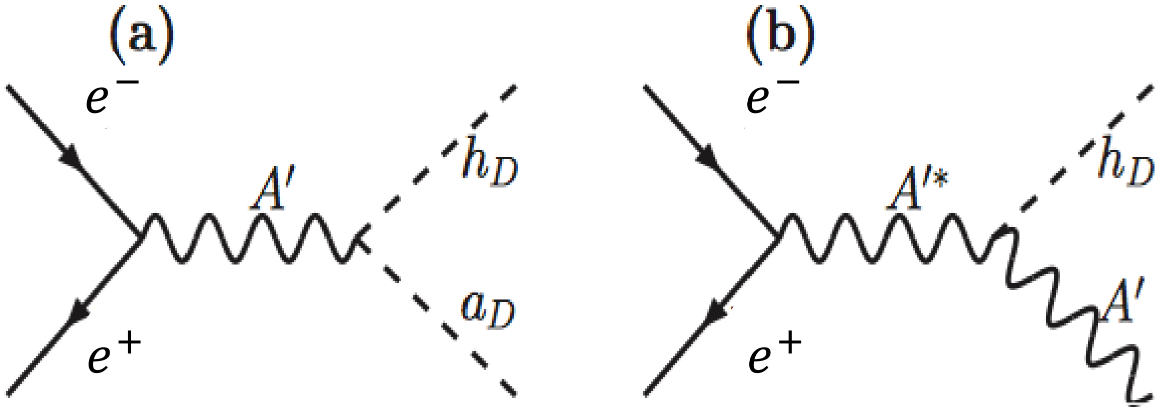


Measurable lifetimes



Motivation 2

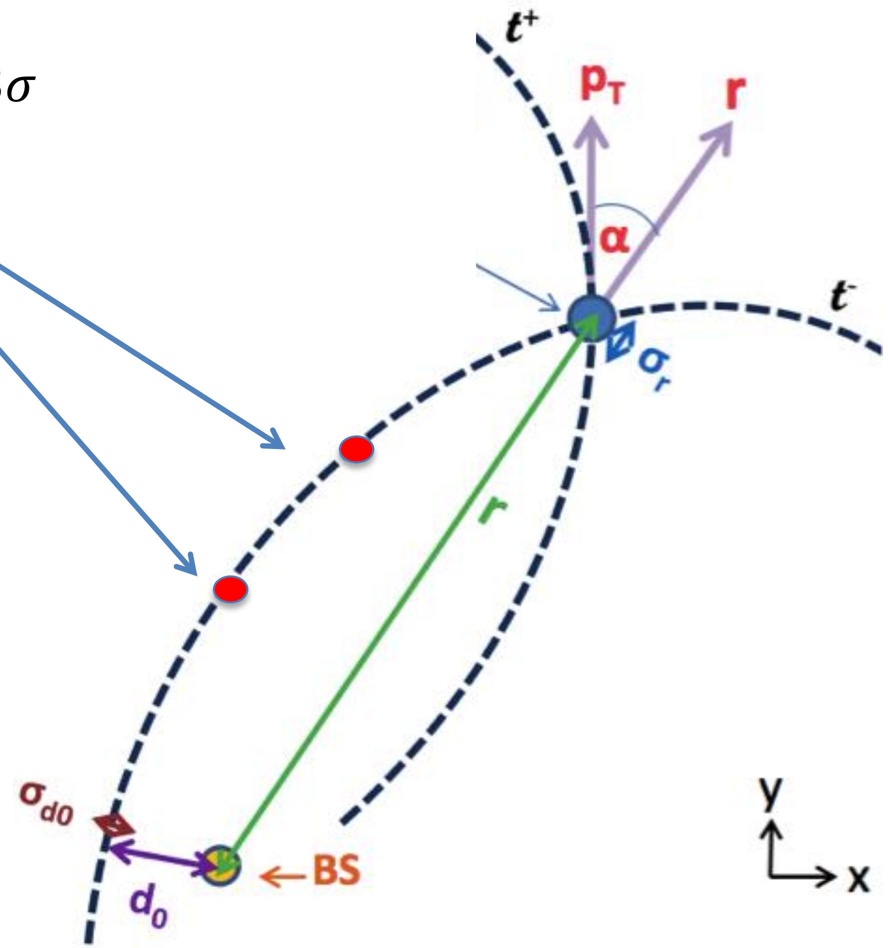
- Dark photon production (e.g., 0910.1602, 0903.3941)
  - A' decays promptly into hidden-sector scalars that decay as DV
  - A' is stable but undergoes dark-Higgsstrahlung with subsequent DV



- Our search assumes only that the long-lived particle (L):
  - is produced promptly
  - decays in a displaced vertex to 2 tracks

Event selection

- Vertex track pairs:
  - $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$
- Require
  - Track impact parameter $d_0 > 3\sigma$
  - No hits before the vertex
  - $1 < r < 50$ cm
  - $\alpha < 0.01$
  - Remove Bhabhas & cosmics with angle cuts
  - Crude veto of dense material regions



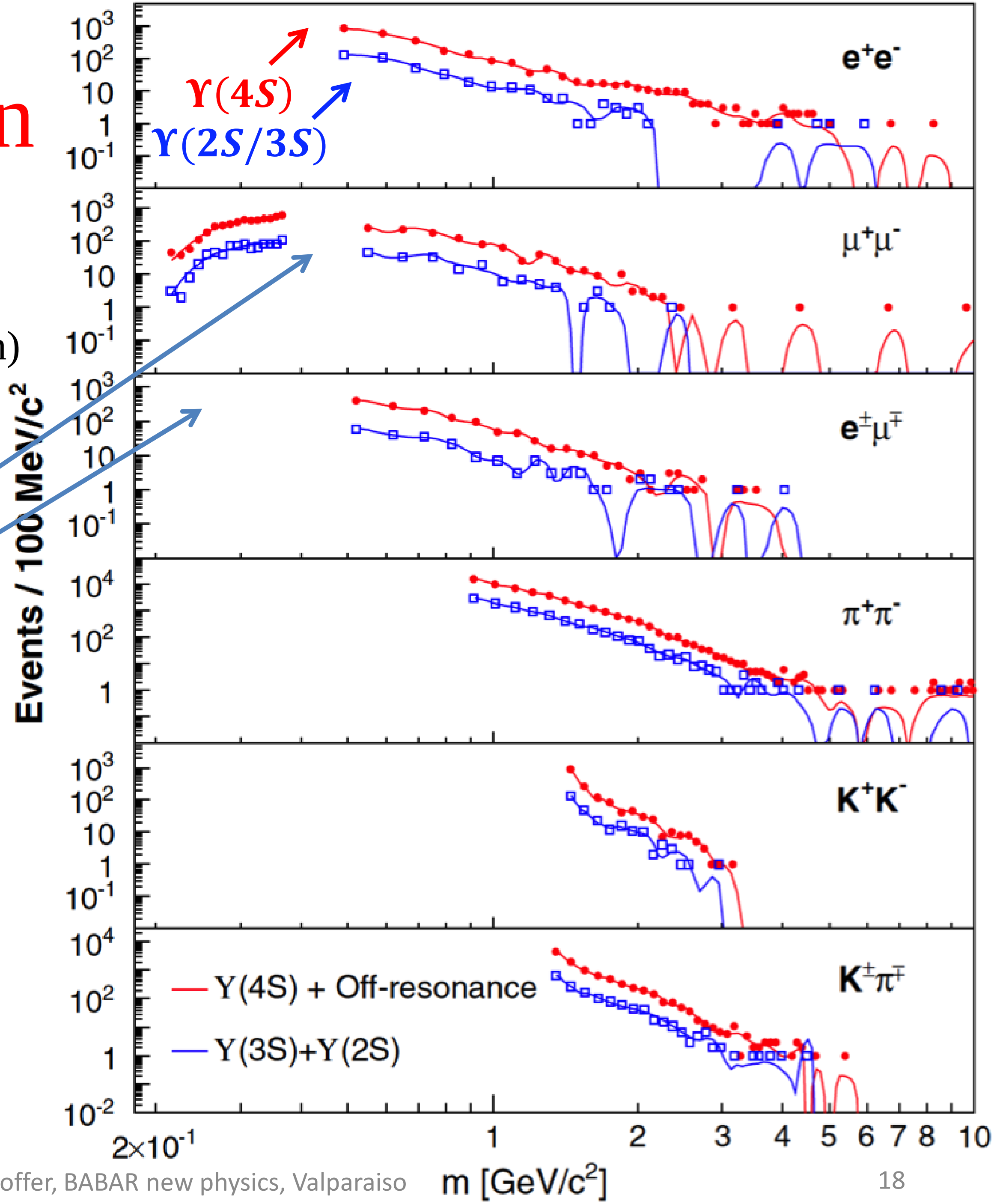
- Remaining background:
  - Mostly truly displaced tracks (K_S, material interactions)

Signal extraction

Fit vertex mass spectrum to smooth background (spline) + signal peak (MC, including per-event resolution) in 2-MeV steps

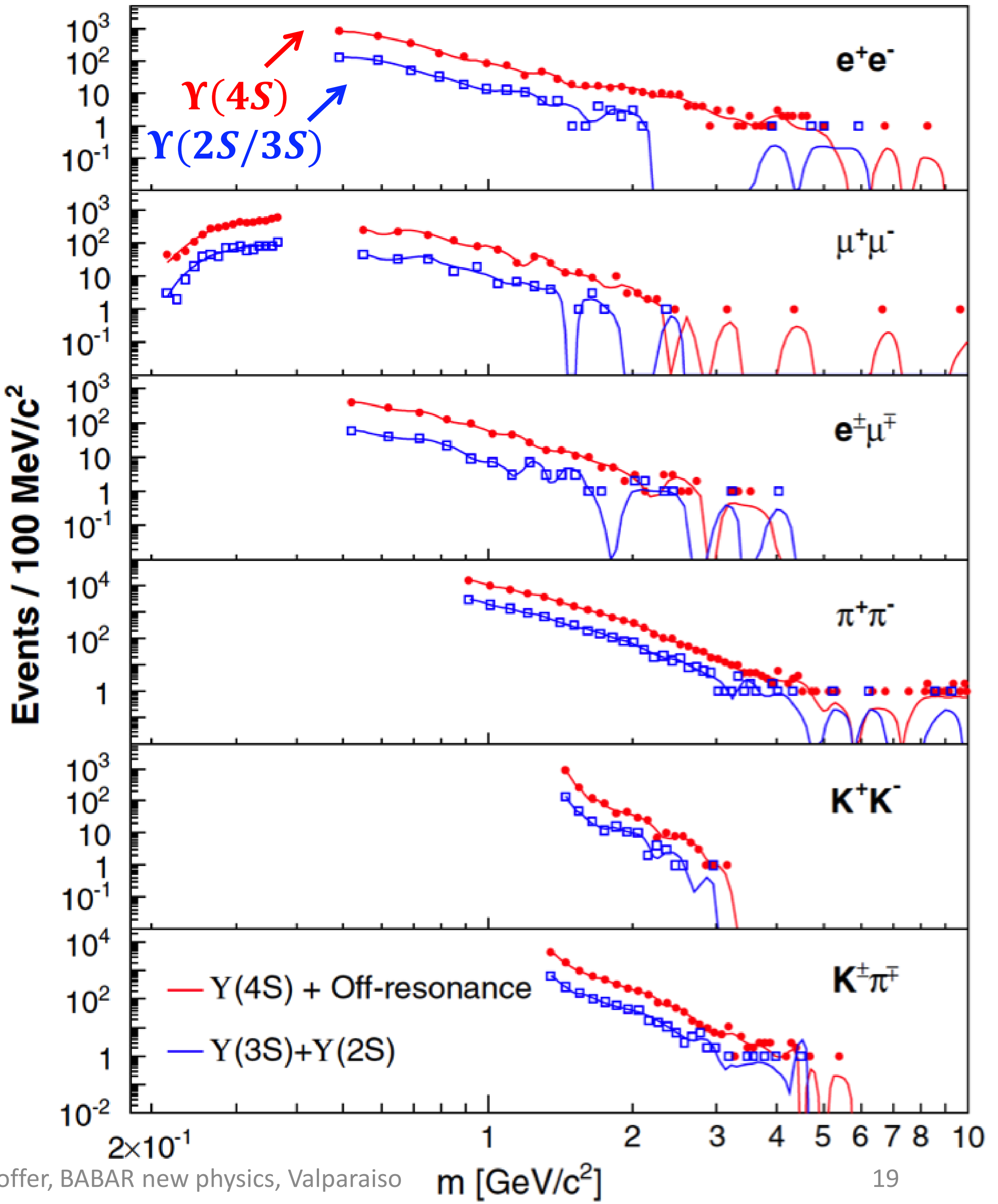
Exclude from search: K_S and low-mass regions incompatible with background fit method (determined using MC)

Dominant systematic uncertainty is due to background modeling – spline bin width.



Results

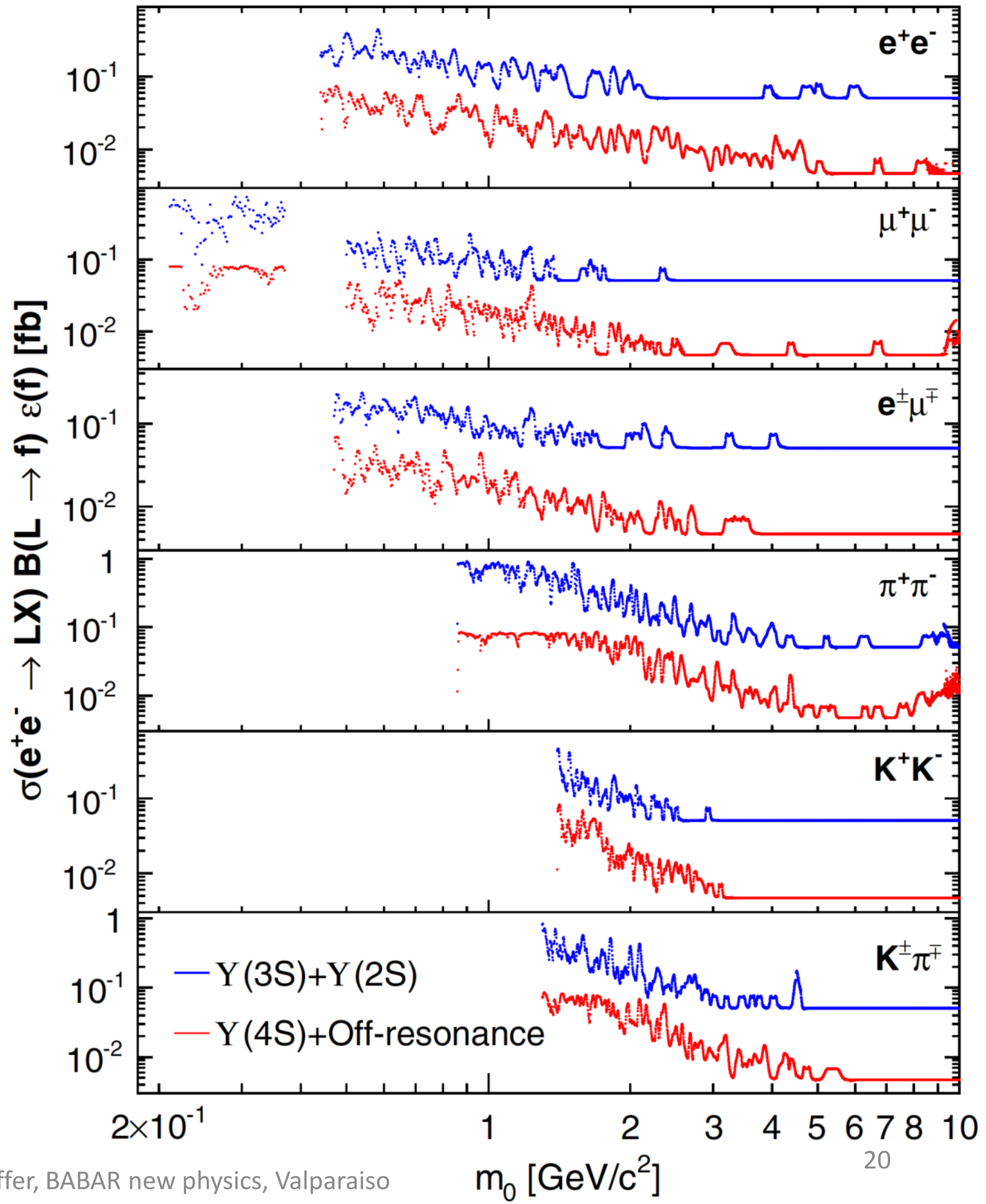
- Local significance of $4.7\,\sigma$ at $\mu\mu$ threshold, $m = 0.212$ GeV, 13 signal events.
- Background fluctuation probability $= 4 \times 10^{-4}$
- But consistent with mis-simulated material interactions:
- Of the 34 events with $m < 0.215$, most are in or near detector material.
- All low momentum tracks – poor particle identification.
- 10 events pass e^+e^- criteria
- 10 events pass $\pi^+\pi^-$ criteria



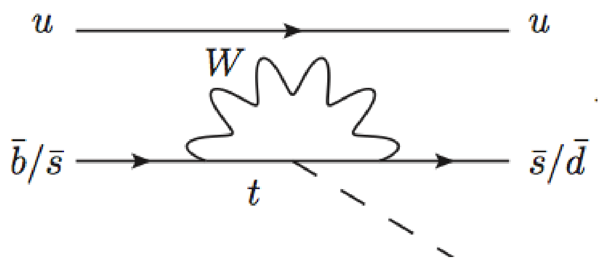
“Model-independent” upper limits on $\sigma(L)\mathrm{B}(L \to f)\epsilon$

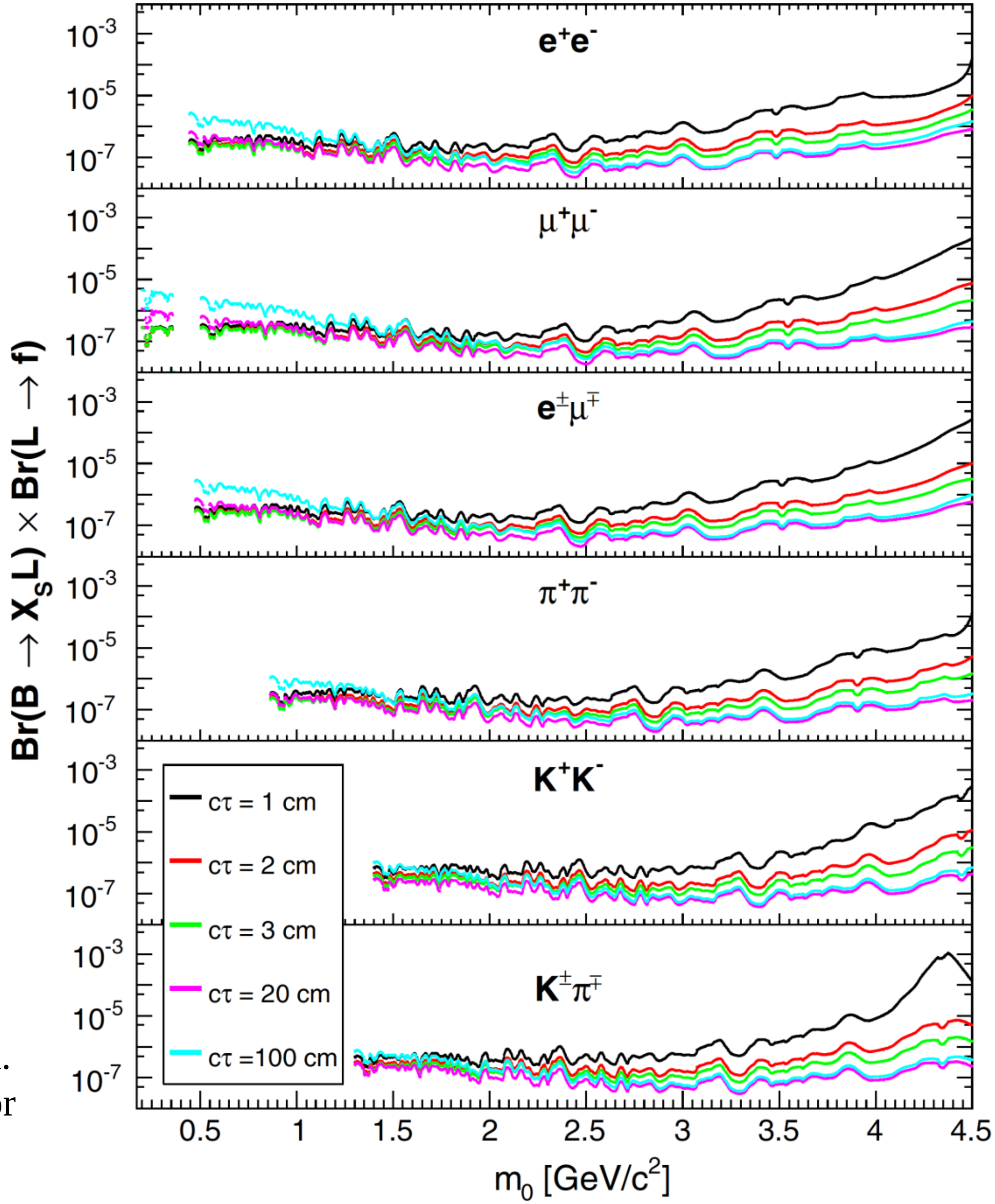
Provide efficiency table as a function of m, $c\tau$, p_T, so results can be applied to any specific model.
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.171801#supplemental

Efficiency dominated by $1 < r < 50$ cm cut



Higgs-portal model-dependent upper limits on $\mathcal{B}(B \to X_S L)\mathcal{B}(L \to f)$

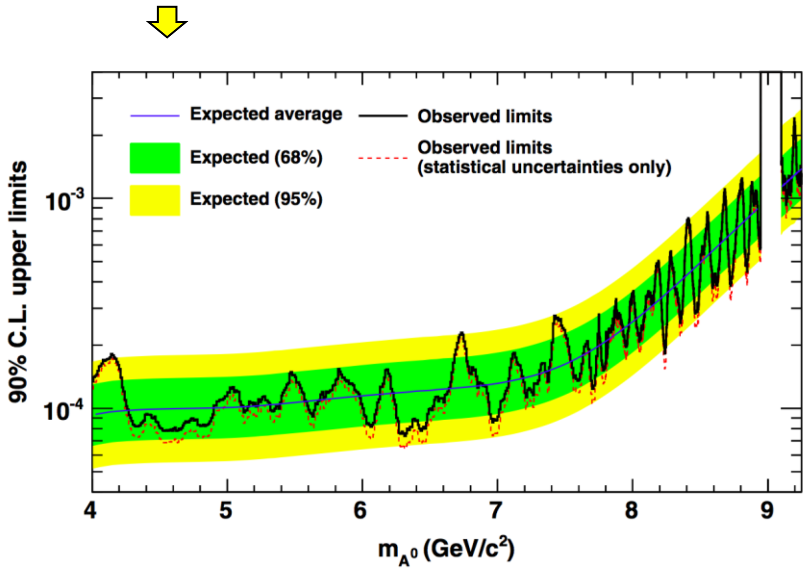


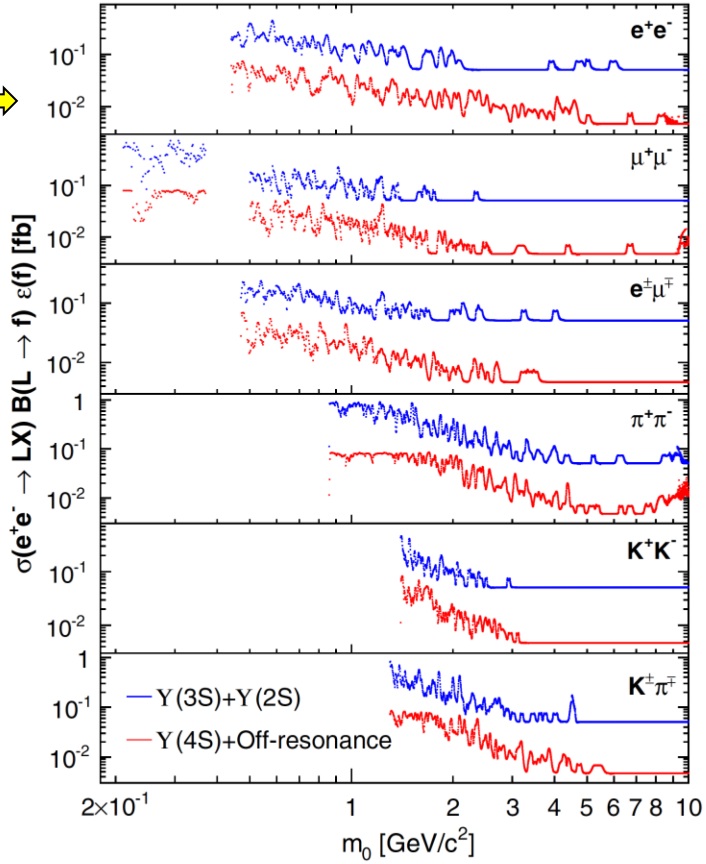


- For generic scalar couplings, LHCb (PRL 115, 161802) has much tighter limits from a $B \to K^* \mu^+ \mu^-$ search.
- BABAR more sensitive for leptophobic or hadrophobic long-lived particle.

Summary

- BABAR continues to be productive, with unique new-physics searches in ~GeV mass region:
  - Model-independent long-lived particle
  - Light Higgs $\rightarrow c\bar{c}$





http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.114.171801#supplemental

- Similar searches can be done at Belle ($1.6 - 2 \times L$) and then Belle-II ($\sim 100 \times L$)