Search for long-lived particles in e^+e^- collisions at BABAR

arXiv:1502.0258

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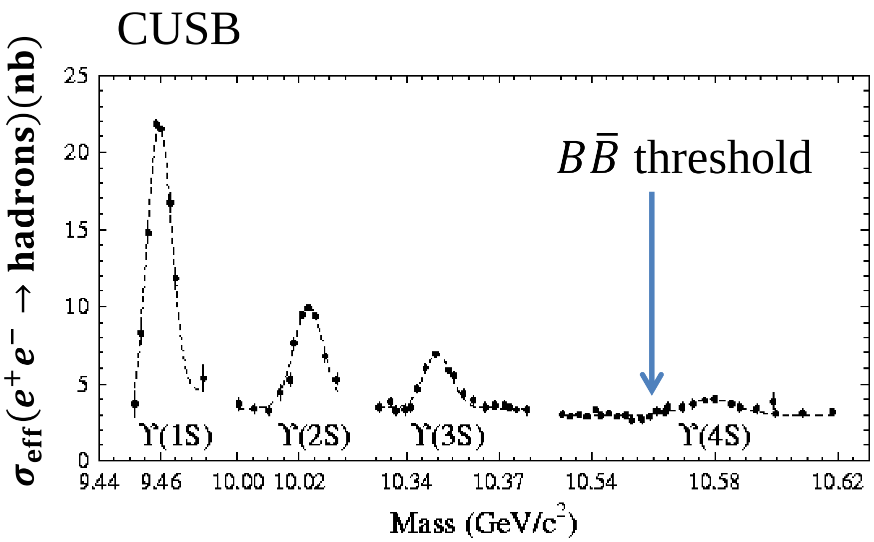
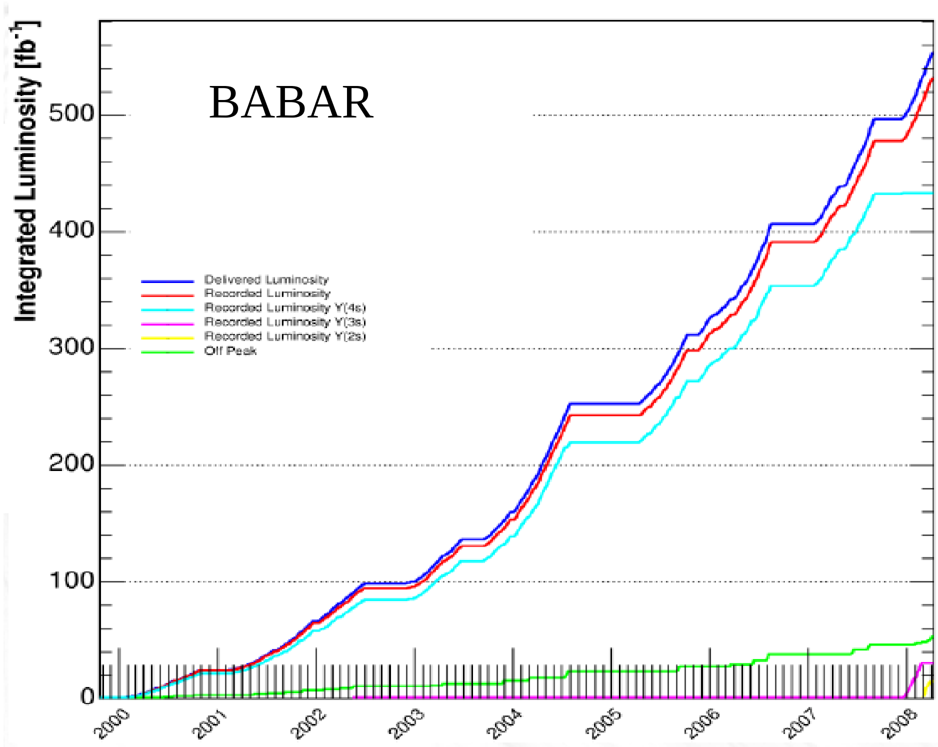
On behalf of the BABAR Collaboration

Motivation

- Searches for long-lived particles (LLPs) have been conducted for $m \ll$ GeV, e.g.,
  - Recasting beam dump experiments: Andreas, Niebuhr, Ringwald, 1209.6083
  - Recasting π^0 decays: Gninenko, 1112.5438
  - NuTeV, hep-ex/0104037
- And for $m \sim$ multi-GeV, e.g.,
  - D0: hep-ex/0607028, 0906.1787
  - CDF: hep-ex/9805017
  - ATLAS: 1210.7451, 1203.1303
  - CMS: 1409.4789, 1411.6977
  - LHCb: 1412.3021
- But not so much for $m \sim$ GeV
  - Well suited for high-luminosity B factories such as BABAR
  - Belle: long-lived heavy neutrino 1301.1105
  - So far, no generic search that uses long lifetime as main signature

BABAR Energy and data

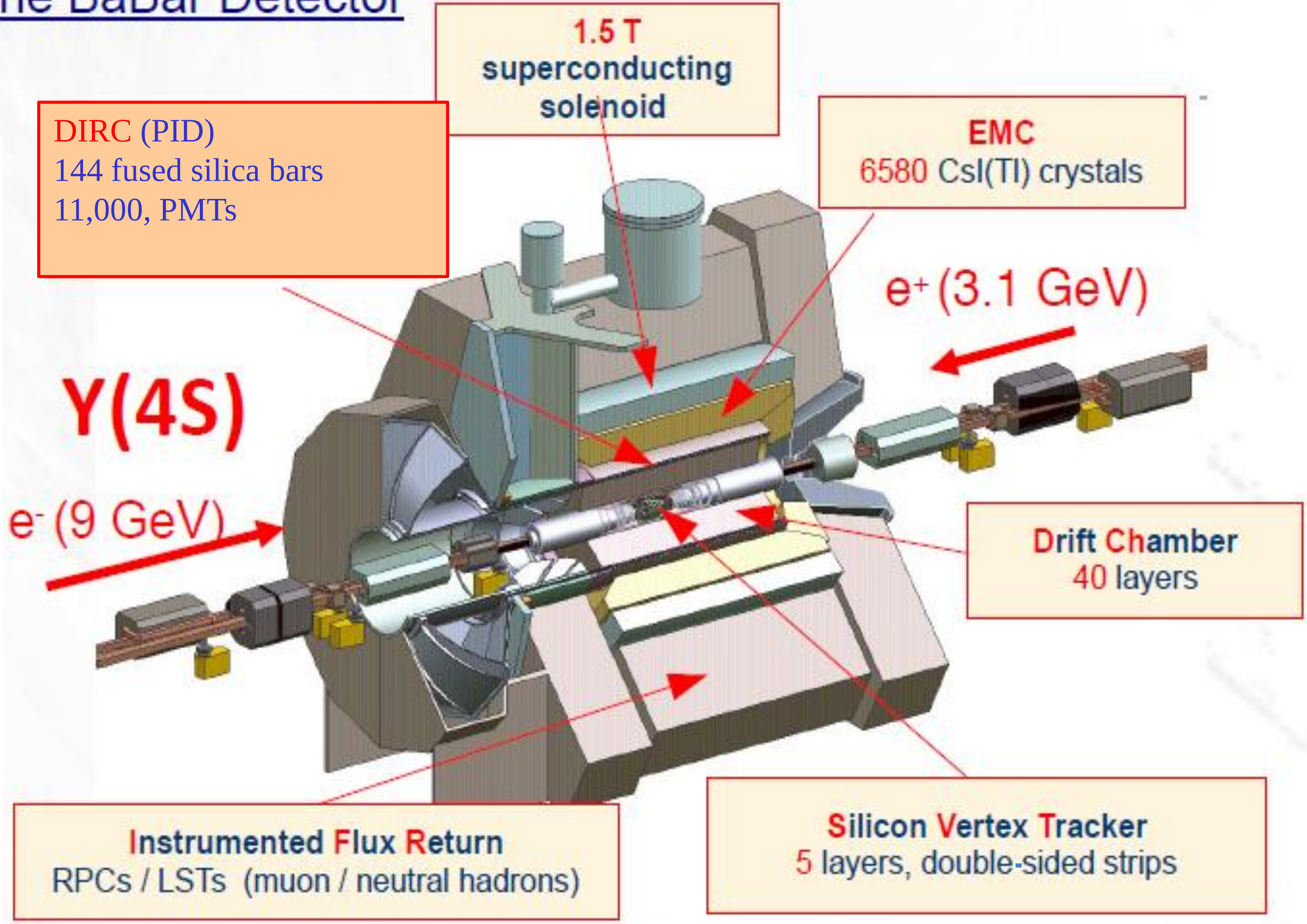




L(4S) = 424 fb^{-1} N(4S) = 471 × 10^6
L(3S) = 28 fb^{-1} N(3S) = 121 × 10^6
L(2S) = 14 fb^{-1} N(2S) = 99 × 10^6
L(off-peak) = 48 fb^{-1}

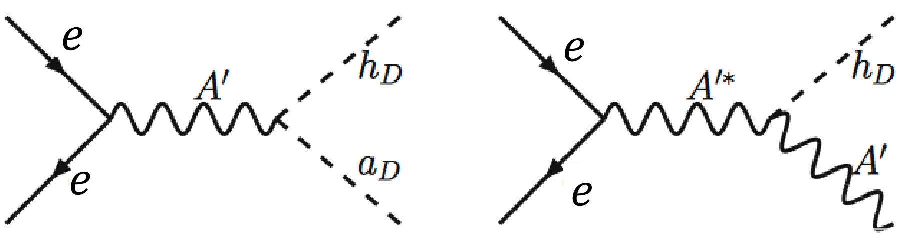
$\sim 1.3 \times 10^9\ e^+e^- \to c\bar{c}$
$\sim 0.9 \times 10^9\ e^+e^- \to \tau^+\tau^-$

The BaBar Detector

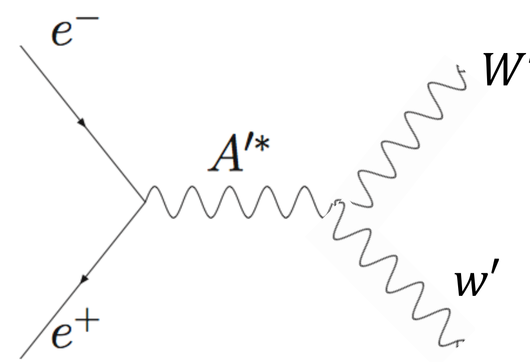


Scenarios for LLPs at B factories – Vector portal

- Produce a dark-sector photon A' via kinetic mixing with the SM photon: $\epsilon F^{\mu\nu} F'_{\mu\nu}$
- A' decays into dark (pseudo)scalar or vectors.
  One of these can be long-lived if it is the lightest dark state:



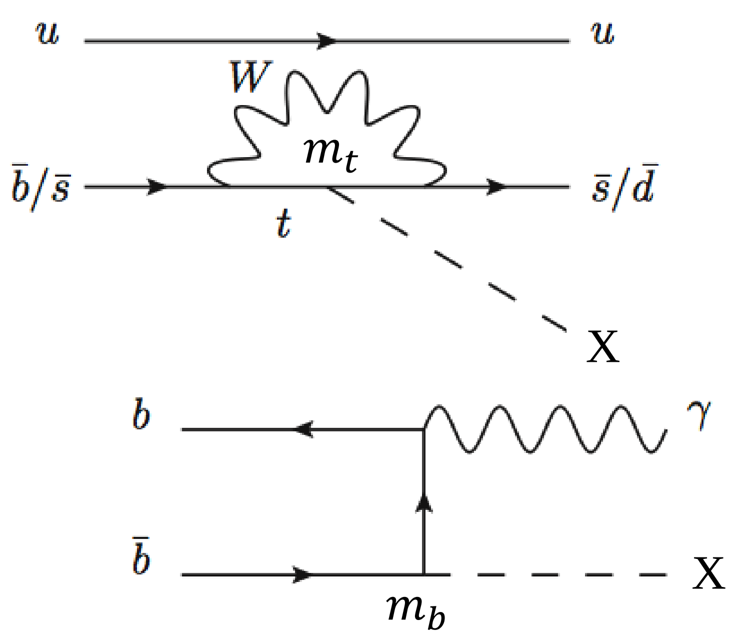
Schuster, Toro, Yavin, 0910.1602



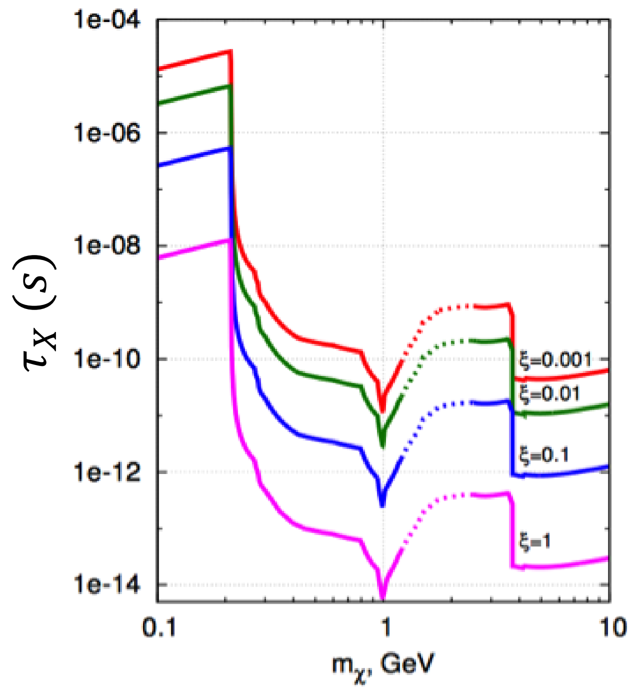
Essig, Schuster, Toro, 0903.3941

Scenarios for LLPs at B factories – Higgs portal

- A light scalar X mixes with the SM Higgs.
- Production rate $\propto m_b^2$ or m_t^2, decay rate $\propto m_f^2$



Clarke, Foot, Volkas , 1310.8042

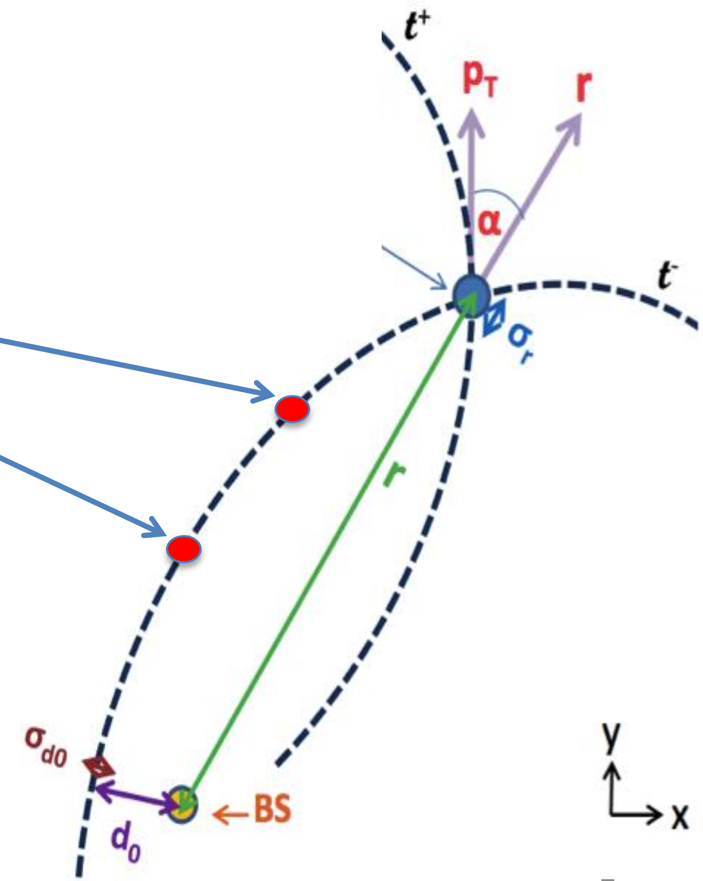


$$B(b \to Xs) \approx O(10^{-6})$$

Bezrukov, Gorbunov, 1303.4395, 0912.0390

Event selection

- Form vertex out of track pairs, loosely selected as $e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp, \pi^+\pi^-, K^+K^-, \pi^\pm K^\mp$ (allowing overlaps)
- Require
  - Track $d_0 > 3\sigma$
  - Vertex $\chi^2 < 10$
  - $r > 1$ cm, $\sigma_r < 0.2$ cm
  - No hits before the vertex
  - $\alpha < 0.01$ rad
- Remove
  - K_S, & Λ with mass cuts
  - $e^+e^- \to e^+e^-$ & cosmics with angle cuts
  - Beampipe, support tube, drift chamber wall



Signal extraction method - overview

- LLP fully reconstructed – signal appears as a mass peak
- Fit m distribution assuming background only – obtain background shape
- Scan for a signal peak on top of the background, in steps of 2 MeV
- For each scan point, determine signal significance

$$S(m_0) = \pm\sqrt{-2\log\frac{L_0}{L_1}}$$

Mass @ scan point

Sign of signal yield

Maximum likelihood with background-only hypothesis

Maximum likelihood with background+signal hypothesis

Probability density functions (PDFs)

- Signal:
  - $P_S \propto R\left[\frac{(m - m_0)}{\sigma_m}\right]$

The event's measured mass

Scan point hypothesized mass

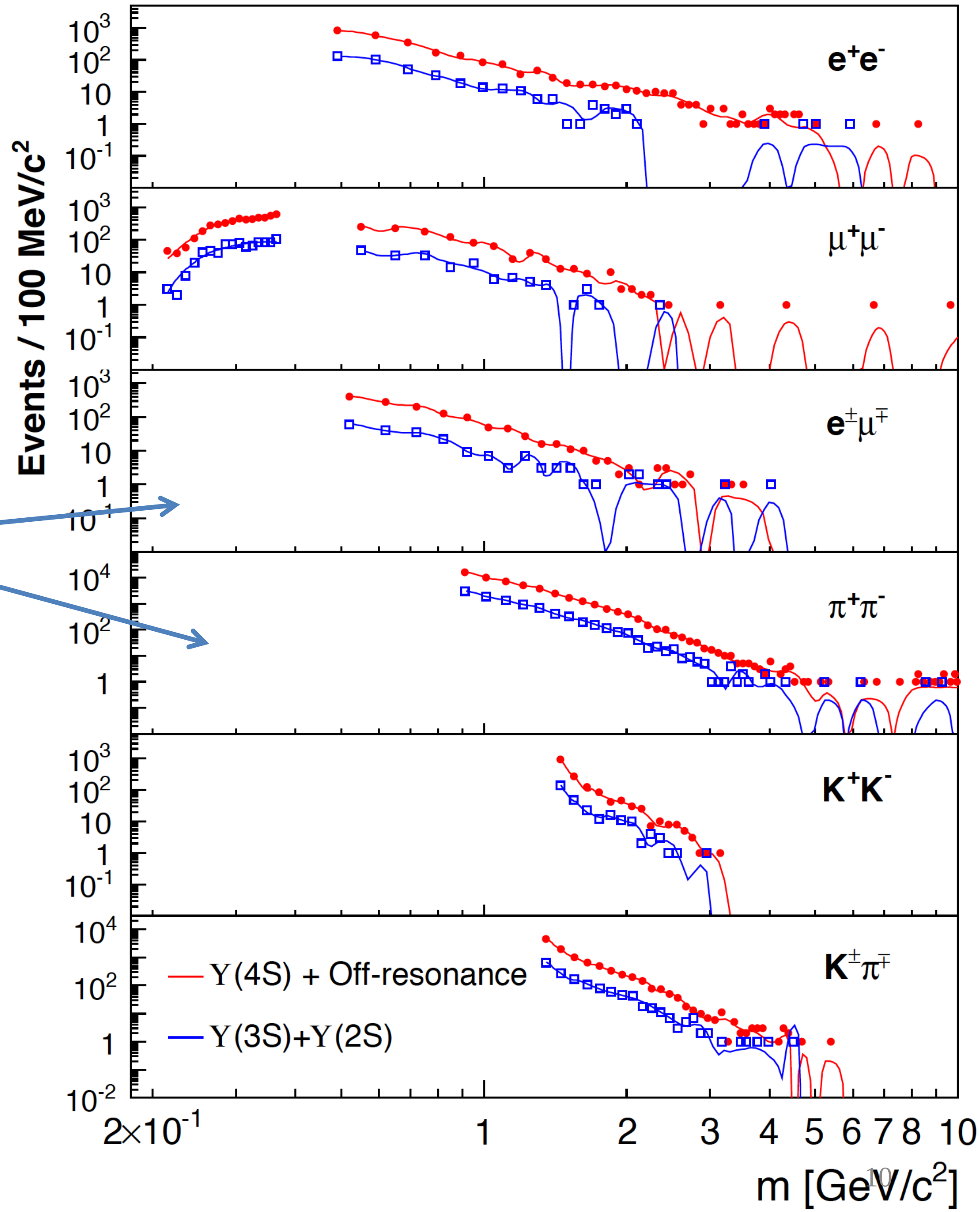
The event's mass uncertainty

Resolution function from signal simulation, evaluated at 12 masses for each mode

- Background:
  - P_B = 2nd-order polynomial spline with knots separated by 15 times the signal mass resolution (mass-dependent)
    - Gives optimal balance b/w signal sensitivity and low fake-signal rate
    - At low mass, optimum found only in $\mu^+\mu^-$ mode.
      Low-mass regions discarded in other modes

Mass fits

Low-mass discarded regions



$S(m_0) < 3$ everywhere but at two points in the $\mu\mu$ mode:

Highest-significance points

- $m_{\mu\mu} = 0.212$ GeV:
  - $S = 4.7$
  - 13 signal events
  - P-value $= 4 \times 10^{-4}$ with look-elsewhere effect in $m_{\mu\mu} < 0.37$ GeV

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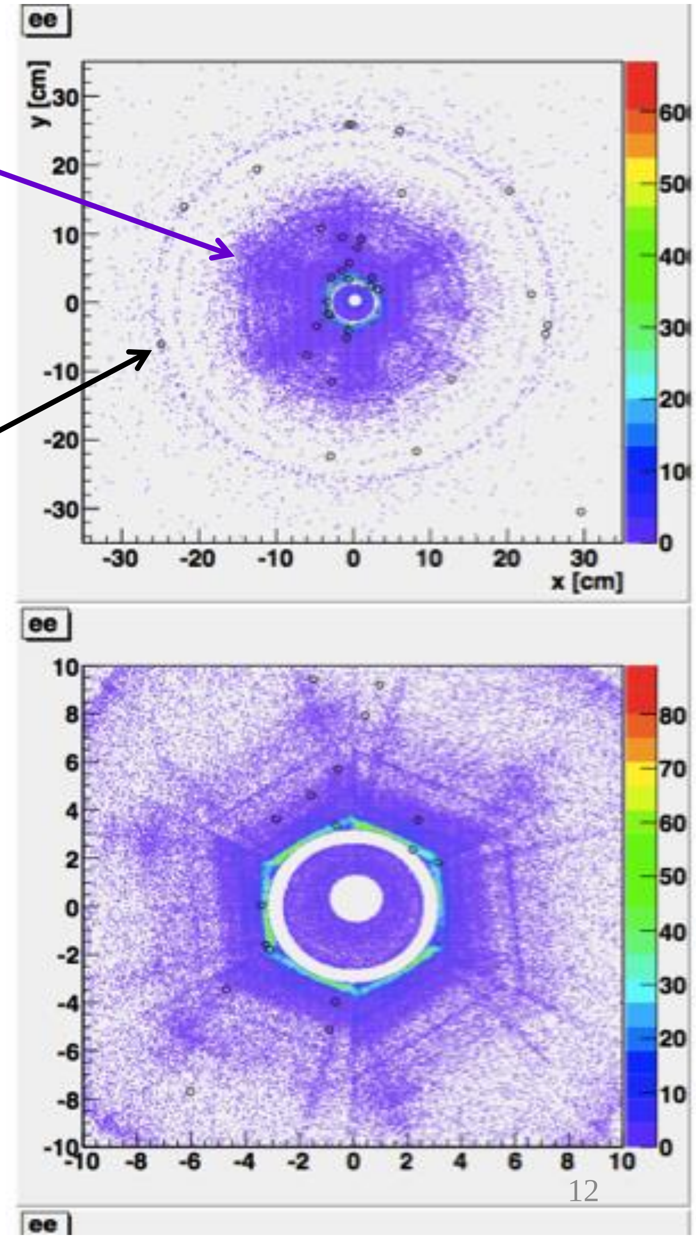
  - More than 50% of the candidates are in or near material regions
  - All have $0.2 < p < 0.3$ GeV, where $e - \mu$ discrimination is small.
  - Look like γ conversions

γ conversion,
$m_{ee} < 10$ MeV



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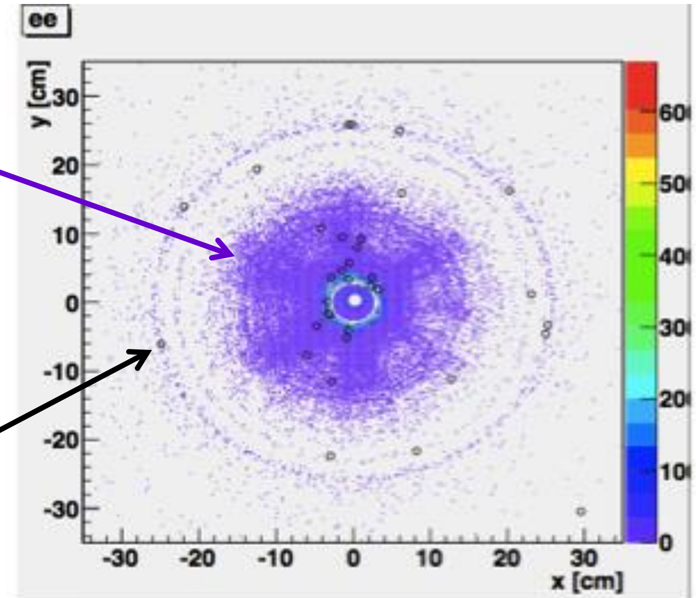
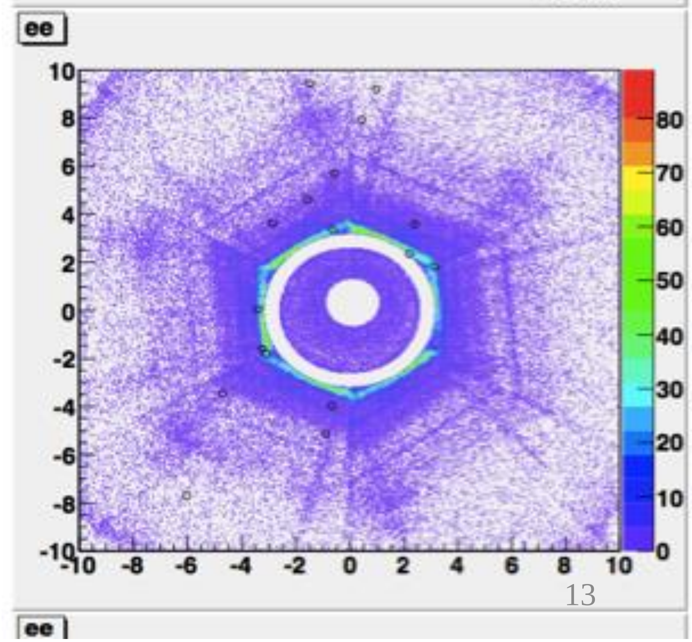
  - Look like γ conversions
- $m_{\mu\mu} = 1.24$ GeV:
  - $S = 4.2$
  - 10 signal events
  - P-value $= 8 \times 10^{-3}$ with look-elsewhere effect in $m_{\mu\mu} > 0.5$ GeV

γ conversion, $m_{ee} < 10$ MeV

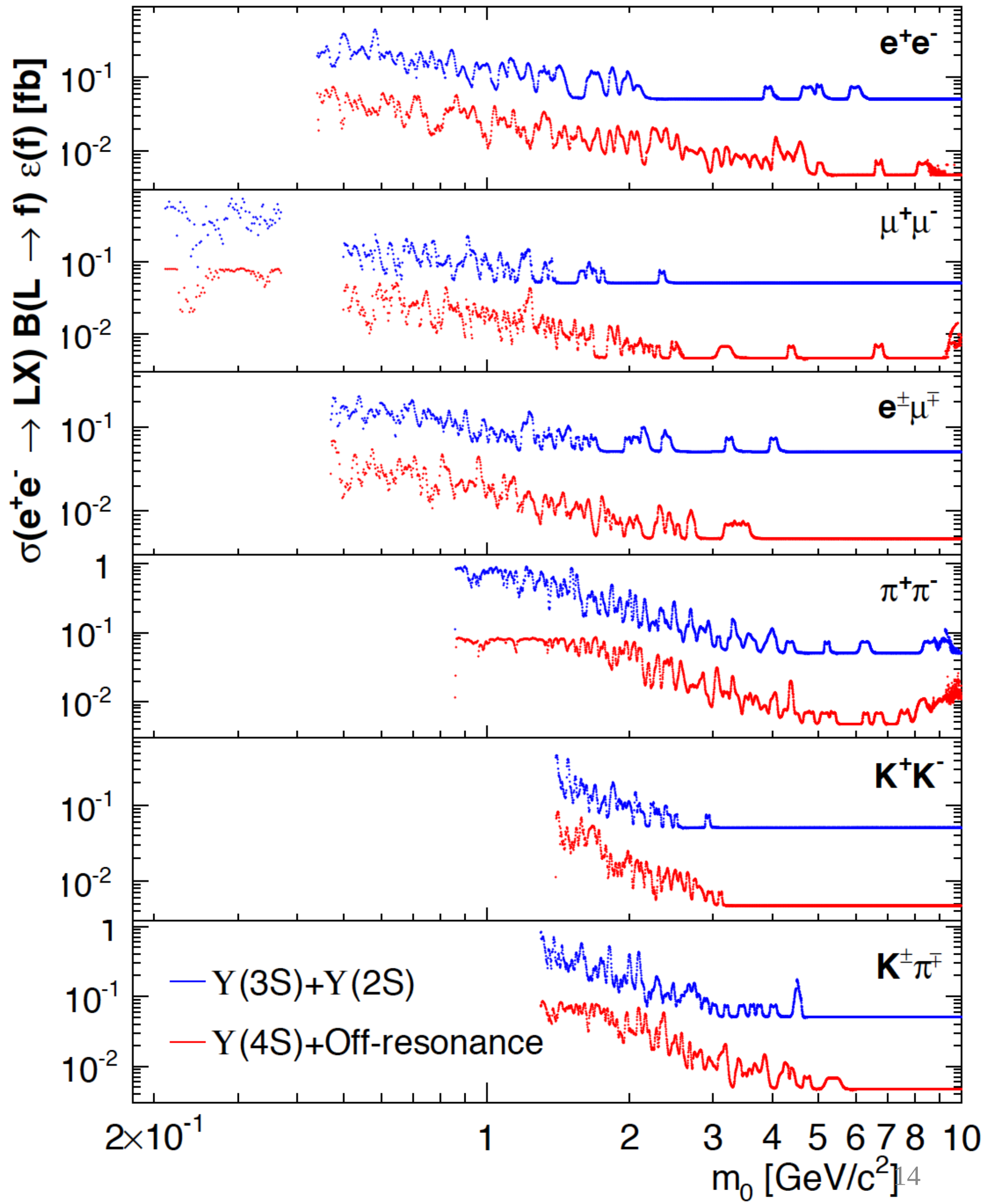




Model-independent upper limits on $\sigma B \epsilon$ @ 90% CL

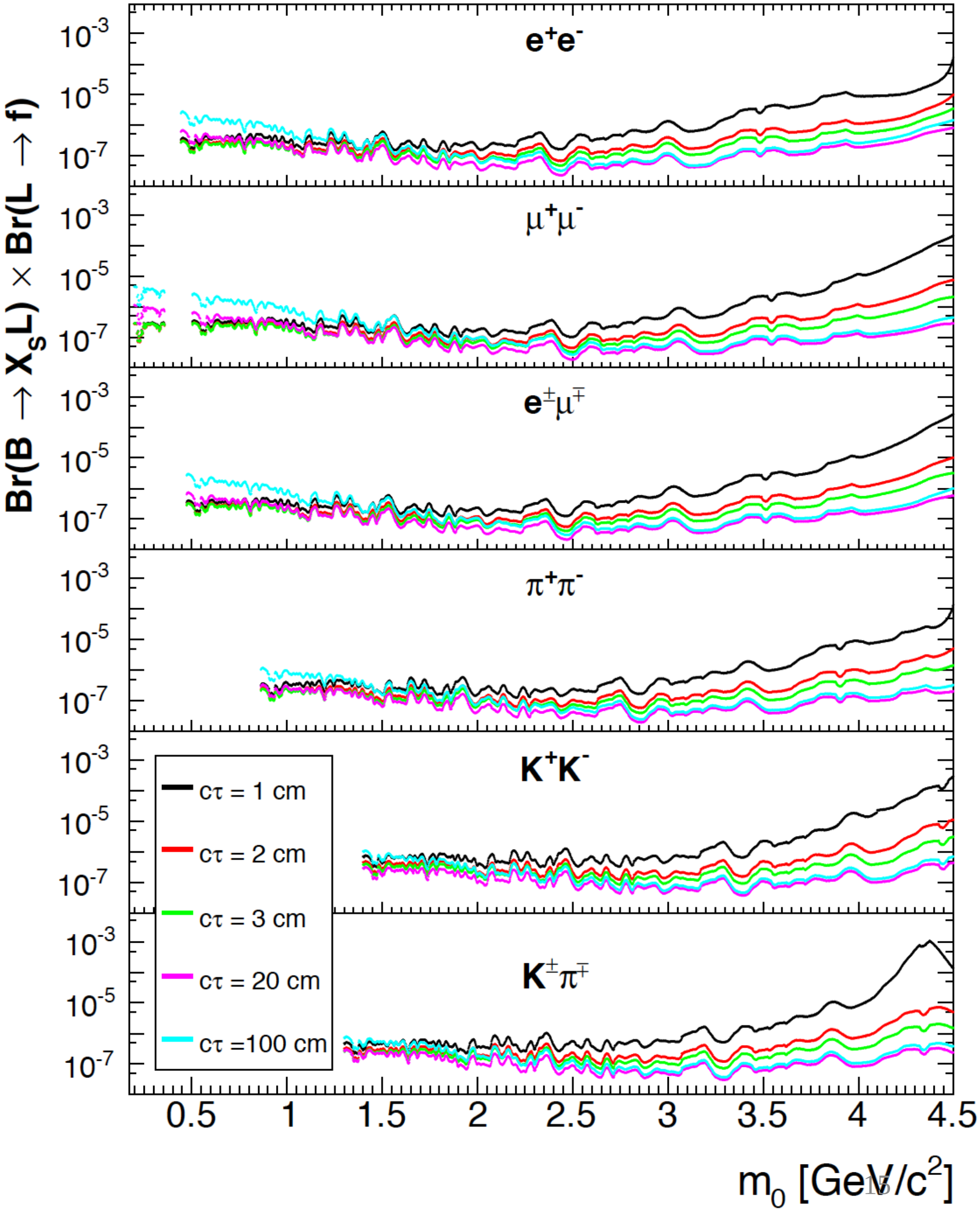
Include systematic errors on

- P_B spline binning
- P_S dependence on r, m, p_T
- Signal mass resolution



- Provide an efficiency table for each channel as a function of m, $c\tau$, p_T,
- Limits can be recast for any model one simulates

Higgs-portal upper limits for $B \to X_S L$ with different L lifetimes



Include also systematic errors on

- Luminosity
- Reconstruction efficiency
- Monte Carlo statistics

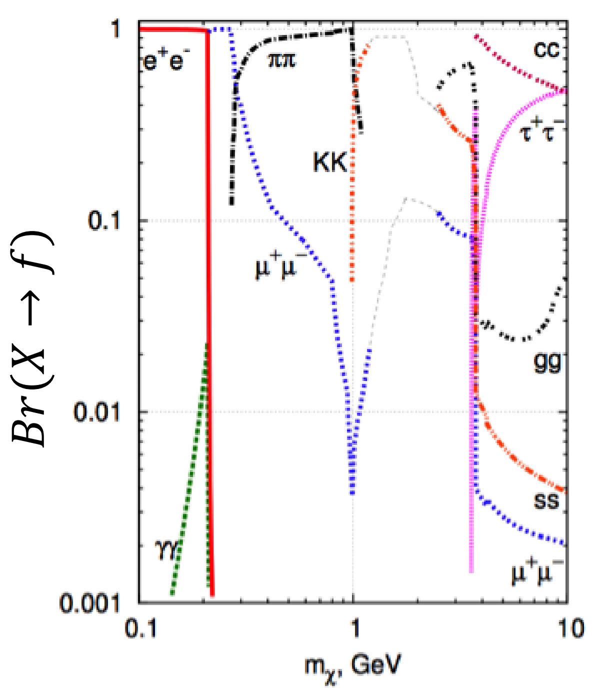
Summary

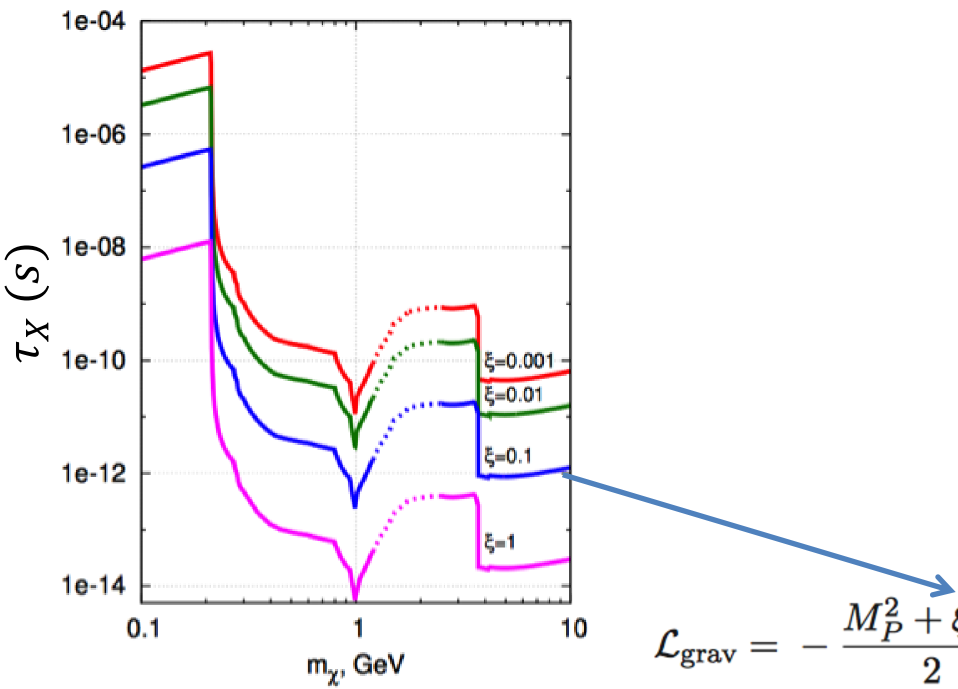
- First O(GeV) mass-range search to use the long lifetime as the main signature
- Model-independent limits + efficiency tables for application to any model
- Model-dependent limits for Higgs-portal scenario
- Outlook:
  - Similar measurements can be done at Belle with ~twice the integrated luminosity
  - Belle-II will have ~ 30 times the BABAR+Belle luminosity

Backup

More about the inflaton model

- The inflaton mixes with the SM Higgs via $-\lambda\left(H^{+}H-\frac{\alpha}{\lambda}X^{2}\right)^{2}$ Lagrantian term
- Sizable production rate: $B(B\rightarrow XX_s)\approx 4.8\times 10^{-6}\left(1-\frac{m_X^2}{m_b^2}\right)\left(\frac{2\alpha/\lambda}{10^{-6}}\right)$





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

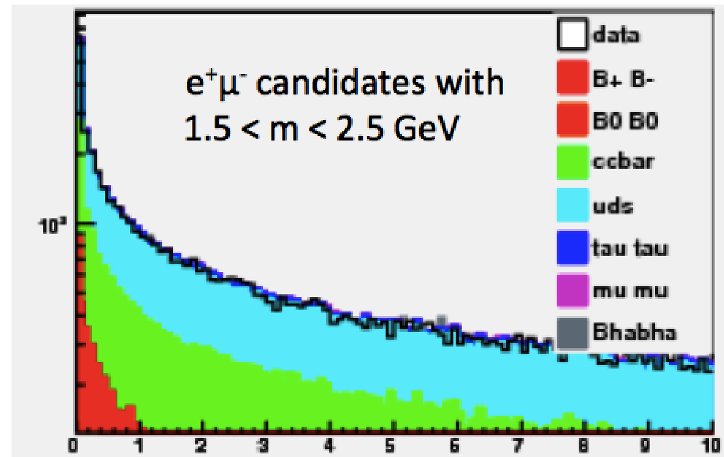
Bezrukov, Gorbunov, 1303.4395, 0912.0390

Data-MC comparison

- Used loose-cut skim as a control sample

- Generally see good data-MC agreement in all variables, modes, mass ranges.

- Note: analysis does not depend on data-MC agreement



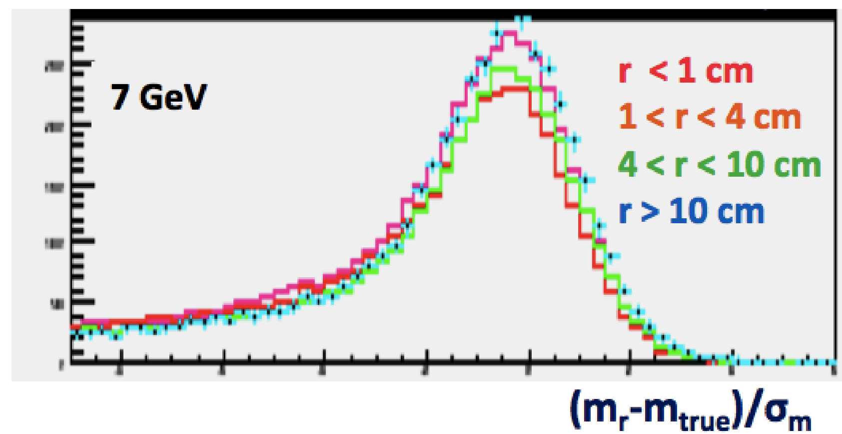
χ^2

r (cm)

Signal PDF

- Mass uncertainty σ_m changes greatly with vertex m, r, boost

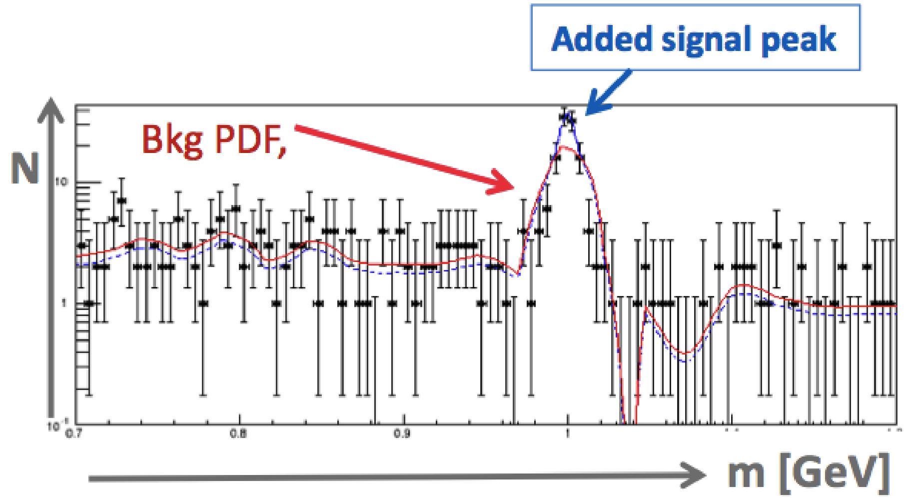
- But mass resolution function is quite stable wrt. the candidate's estimated σ_m



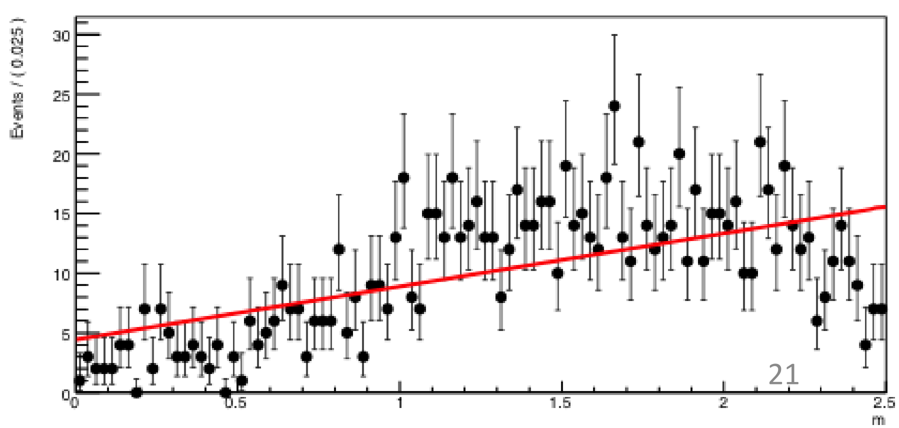
- So construct each event's PDF from its σ_m and the signal-MC resolution function histogram (obtained @ 12 mass points)

Background PDF

- Taken from the data (and validated on MC)
- Spline bin width W has to be
  - Large enough not to hide true signal peaks:



  - Small enough not to cause large fake-signal peaks



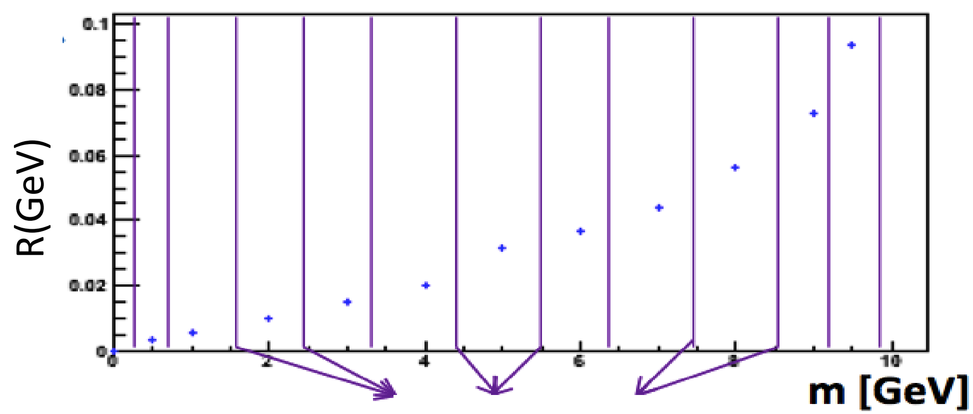
Background PDF

- Mass-dependent bin width set to

$$W = nR$$

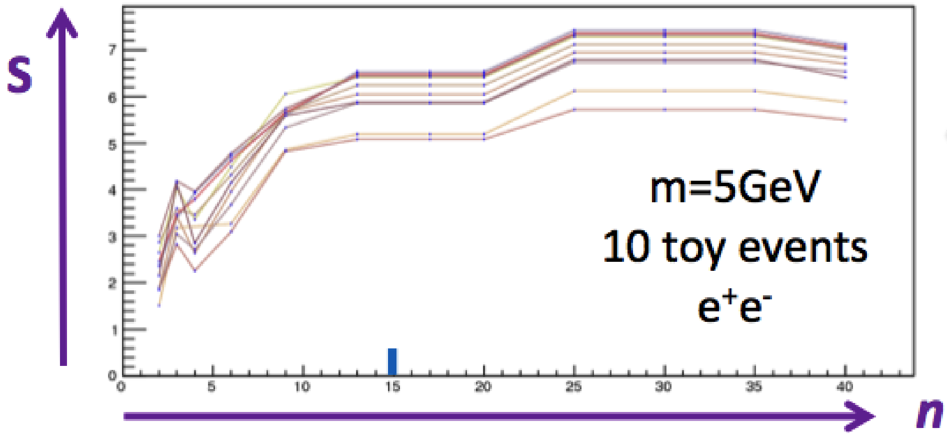
Scale factor chosen to be 15

RMS width of the signal m distribution



Mass regions

Optimal n determination, examples



n large enough
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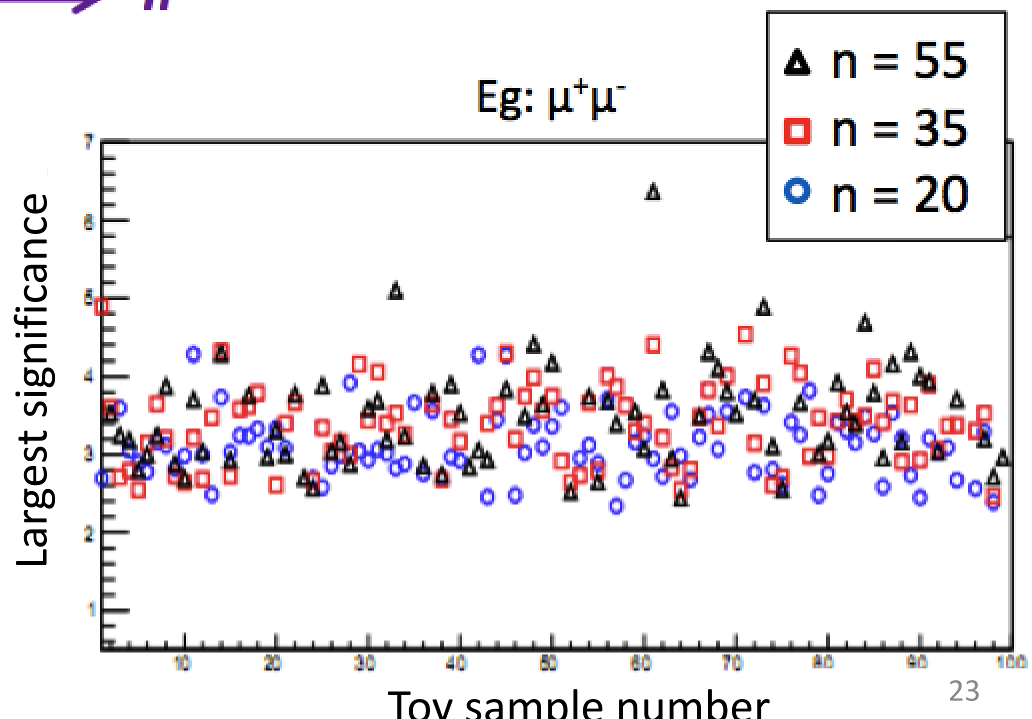

Except for $\mu^+\mu^-$ mode, method not appropriate for masses below Ks veto, due to fine structure seen in MC.