Search for a Dark Leptophilic Scalar Φ_L in $e^+e^- \rightarrow \tau^+\tau^-\Phi_L$ with the *BABAR* detector

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On behalf of the *BABAR* Collaboration

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INSTITUTE OF PARTICLE PHYSICS

McGill

Dark sectors

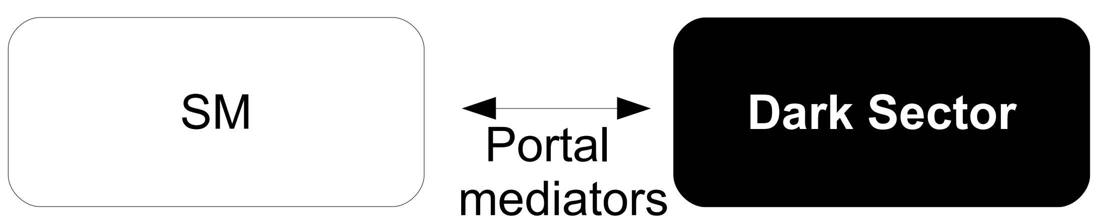
Maybe dark matter is not specifically related to solution to problems of the SM and is, in effect, a distinct "sector"

- Dark sector fermions which carry charges for non-SM gauge interactions, possibly acquiring mass via dark sector Higgs etc.
- EFT provides a number of "portals" to access this dark sector:

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= -\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu} - H^\dagger H (AS + \lambda S^2) - Y_N^{ij} \bar{L}_i H N_j + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

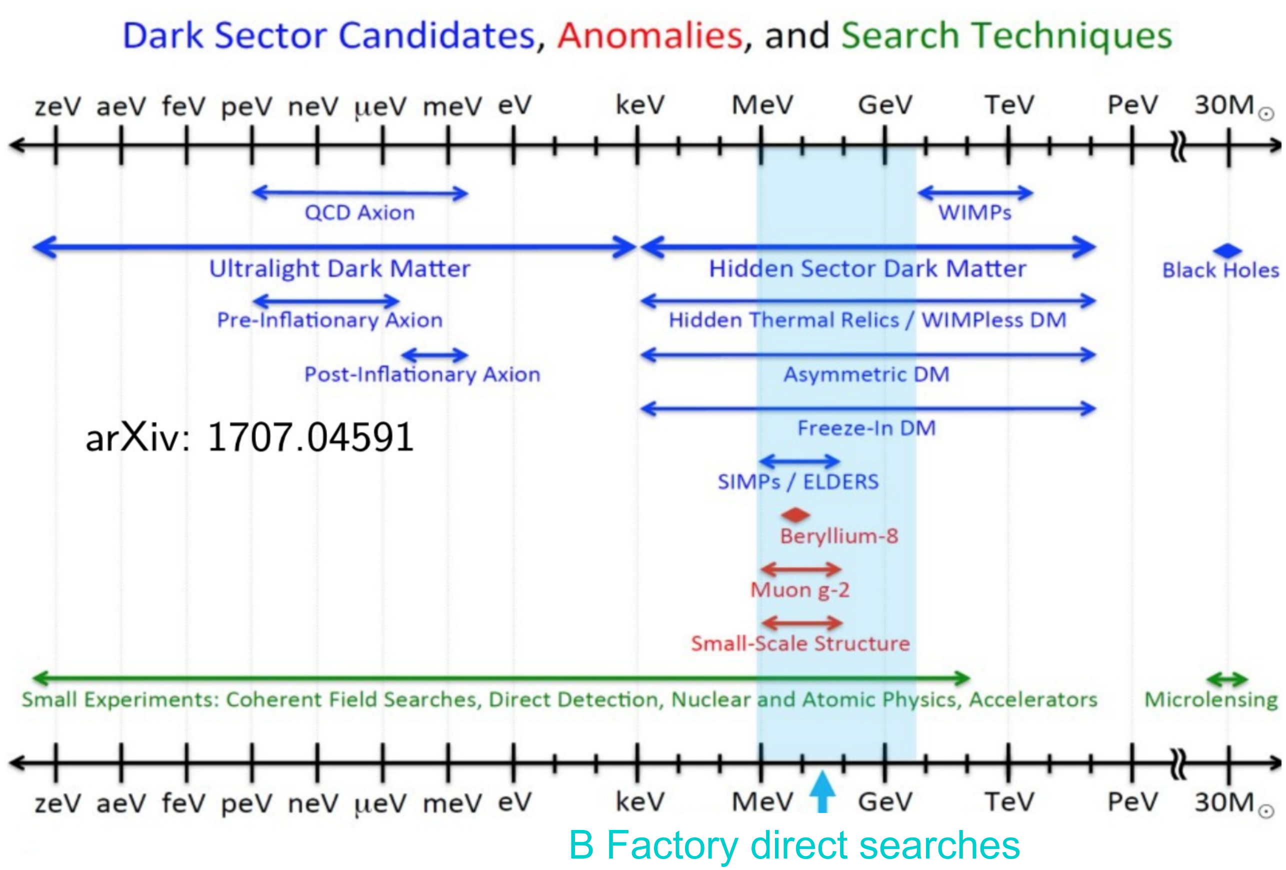
Vector portal — Higgs portal — Neutrino portal



Dark sector can be probed via mixing of the portal mediators with SM bosons

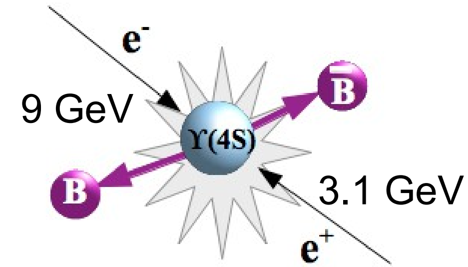
Dark Sector @ B Factories

- Clean e^+e^- environment with hermetic (near 4π) detector coverage; good missing energy reconstruction
- Potential to reconstruct displaced vertices in $\sim 1\text{mm} < c\tau < \sim 10\text{cm}$ ($\sim$100cm), with $c\tau >$ ~3m being "missing energy"
- Production of on-shell bosons via $e^+e^- \to \gamma Z'$ "radiative" and $e^+e^- \to f\bar{f}Z'$ "-strahlung" processes
- Inclusive trigger for (N_{tracks}>3) hadronic events, but low-multiplicity searches require dedicated triggers



BABAR experiment

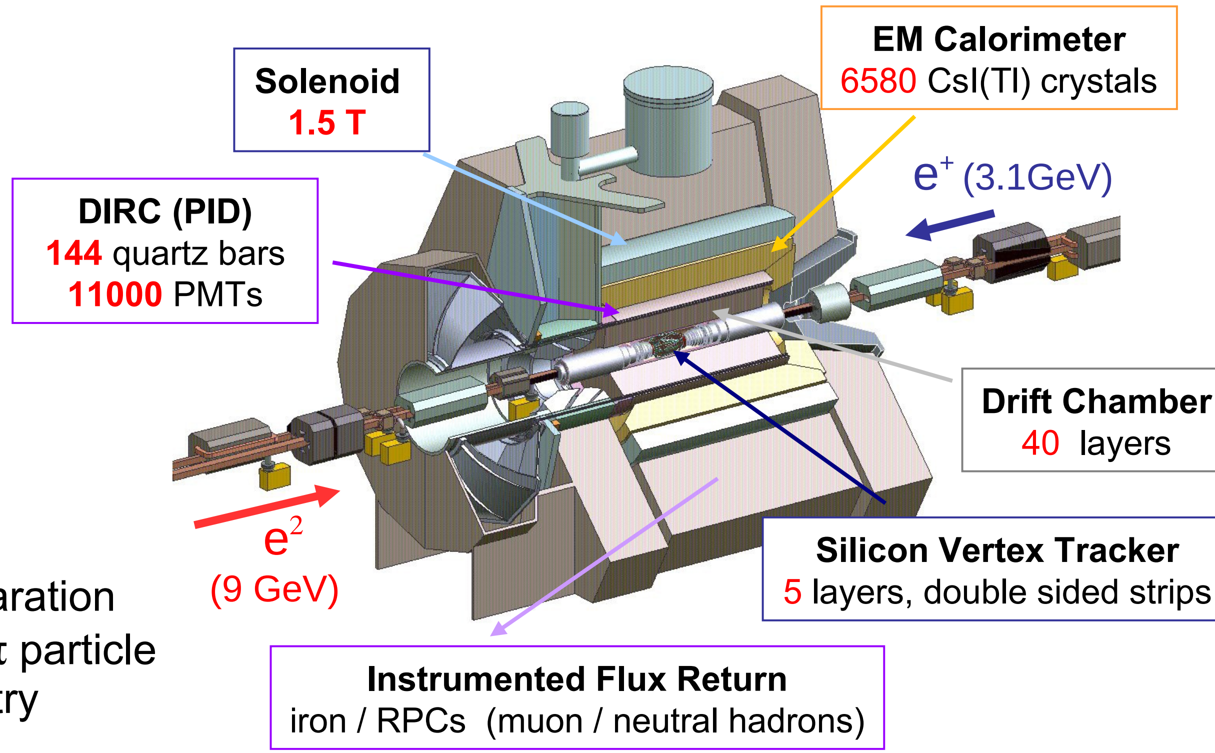
Asymmetric B Factory experiment at the SLAC National Accelerator Laboratory



- *BABAR* collected data from1999 until 2008:
  - data samples recorded at the $\Upsilon(4S)$ resonance "on peak" as well as at the $\Upsilon(2S)$ and $\Upsilon(3S)$ energies
  - non-resonant "off peak" data recorded just below the $\Upsilon(4S)$

Process	σ (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
Light quark $q\bar{q}$	~2.1
$\tau^+\tau^-$	0.9
e^+e^-	~40

Detector optimized for B vertex separation and momentum measurement, K - π particle identification and precision calorimetry



Leptophilic scalar

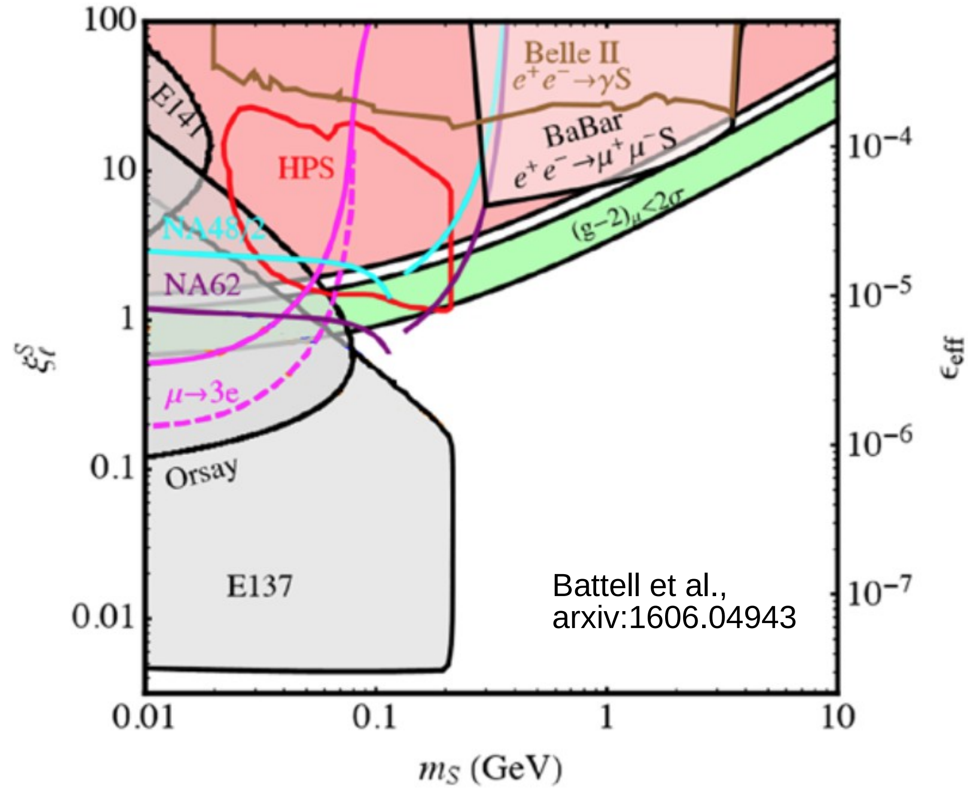
Many BSM models predict an extended Higgs sector with additional light gauge singlets that mix with the Higgs boson (e.g. NMSSM, but more generally singlet-extended scalar sectors)

- scalar could mediate interactions between the SM and dark matter
- generic scenarios strongly constrained by heavy flavour FCNC decays (e.g. $B \to K\varphi$, $K \to \varphi\pi$)

If this new scalar interacts predominantly with leptons rather than quarks, then experimental bounds can be evaded

- couplings proportional to mass, hence interact preferentially with heavy-flavour leptons
- such a scalar could explain the g-2 anomaly

Previous BABAR search for muonic dark force provides model-independent constraints Phys. Rev. D94 011102 (2016)



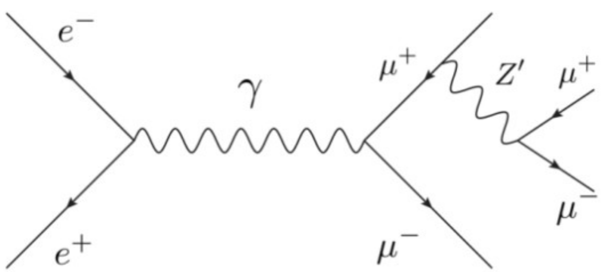
Battell et al., arxiv:1606.04943

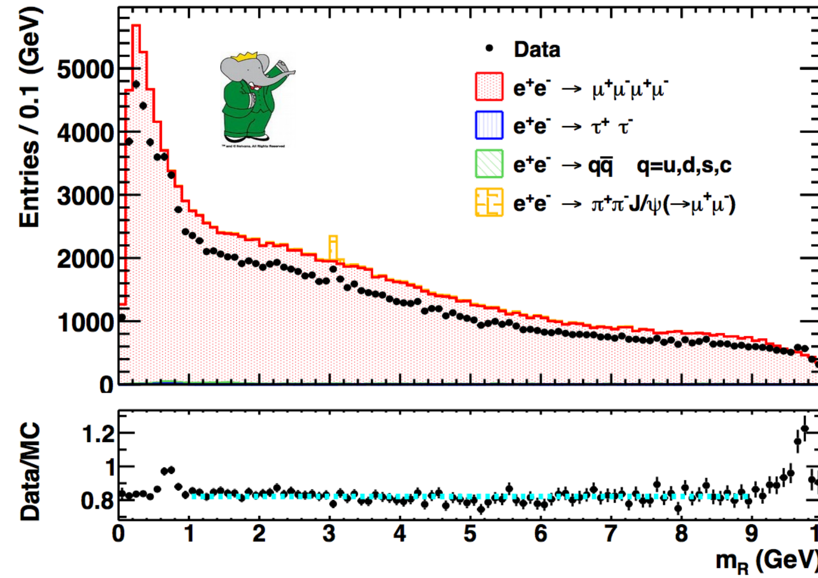
Muonic dark force

Phys. Rev. D94 011102 (2016)

Dark boson Z' which couples only to second and third generation leptons (i.e. SM fields are directly charged under dark force)

He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991).
B. Batell, D. McKeen and M. Pospelov, Phys. Rev. Lett. B.107, 011803 (2011).



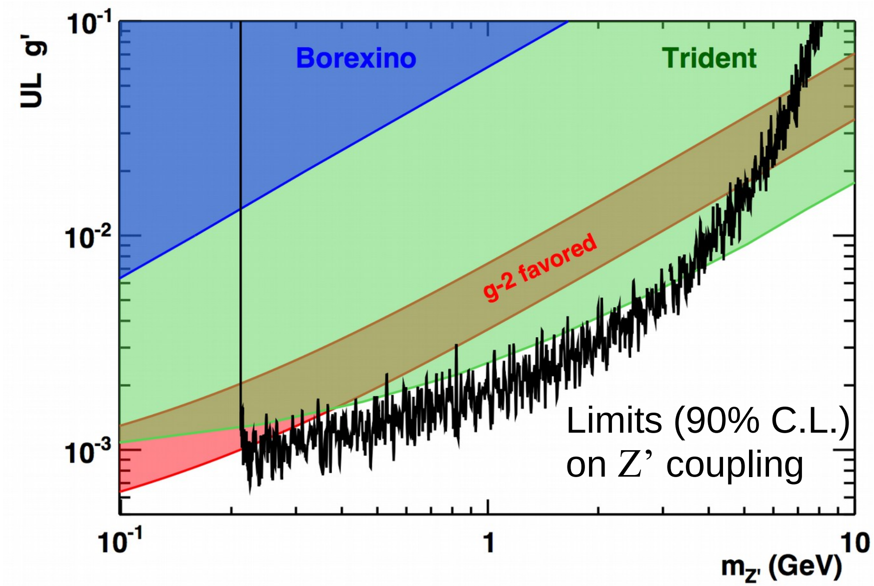


Di-muon reduced mass: $m_R = (m_{\mu\mu}^2 - 4m_\mu^2)^{1/2}$

"Z'-strahlung" production of Z' :

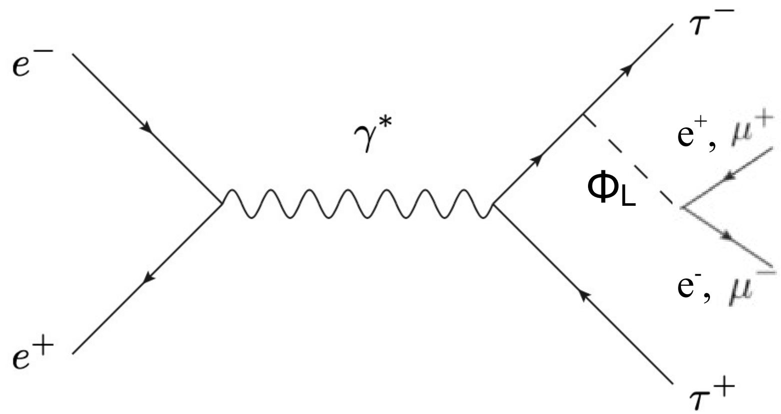
$$e^+e^- \to \mu^+\mu^- Z' , \; Z' \to \mu^+\mu^-$$

- Search for a di-muon mass peak in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
- No signal observed; cross section limits obtained at 90% C.L. at level of ~0.2 fb below $m_{Z'}$ of 10 GeV



However, no model-specific assumptions in analysis; results are more generally applicable

Leptophilic scalar



Experimental signature is a narrow resonant peak in m($l^+ l^-$) ($l = $ e, μ) with width limited by detector resolution

$$e^+e^- \rightarrow \tau^+\tau^- \Phi_L \,,$$
$$\Phi_L \rightarrow l^+ l^- \quad (l = e, \mu)$$

Search for a dark scalar Φ_L which is radiated from a tau lepton

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

- Φ_L preferentially decays to kinematically accessible final states (depends on mass)
- For low Φ_L mass and coupling, Φ_L can be non-prompt

- Consider 1-prong tau final states, i.e. two charged tracks (e, μ, π) accompanied by two oppositely charged leptons
- 4-track topologies (plus additional neutrals)
- For $2m_e < m_\Phi < 2m_\mu$ permit Φ_L to be non-prompt
- Analysis is optimized and validated using a small sample (~5%) of data, which is subsequently discarded

Background suppression

Multivariate selectors (BDT) trained for each channel and $c\tau_{\Phi L}$ (1 mm, 10 mm, 100 mm)

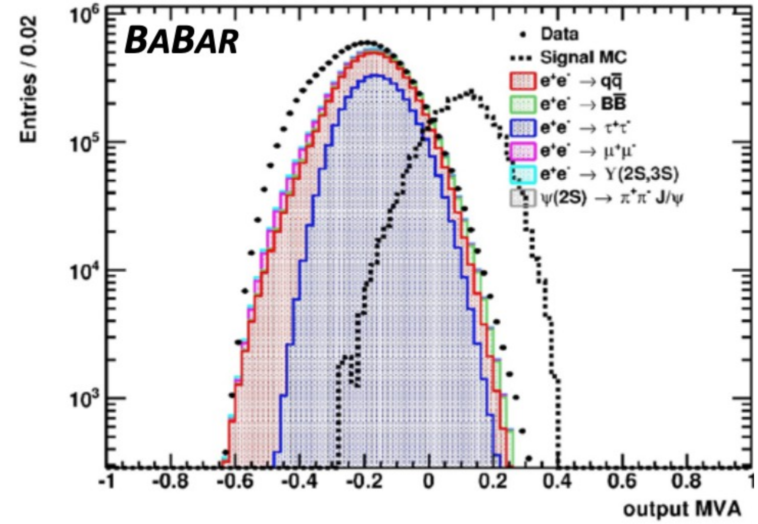
- vertex quality
- missing energy and momentum
- track momenta
- neutral particle multiplicity
- particle ID

(details in backup slides)

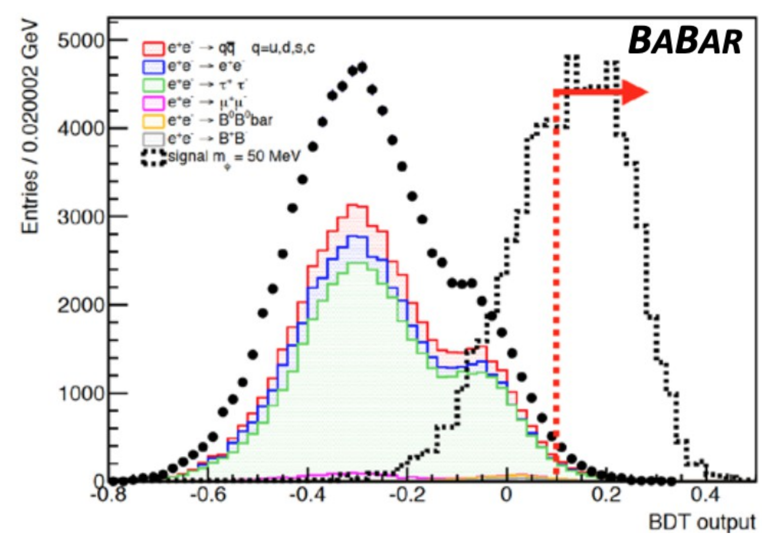
Backgrounds arise predominately from generic continuum $q\bar{q}$ and di-leptons

- Bhabhas suppressed by dedicated kinematic and angular cuts
  - $N_{elec}<4$, $E_{vis}>9$ GeV, $E_{miss}>0.3$ GeV and $\cos\theta_{\Phi\text{-track}} < 0.98$
- Resonant contributions at specific $m(\mu^+\mu^-)$ masses e.g. $\psi(2S) \to \pi^+\pi^- J/\psi(\to\mu^+\mu^-)$
- Missing contributions from un-modelled 2-photon mediated processes and ISR in generic simulation

Di-muon (prompt)



Di-electron (prompt)



Di-lepton mass

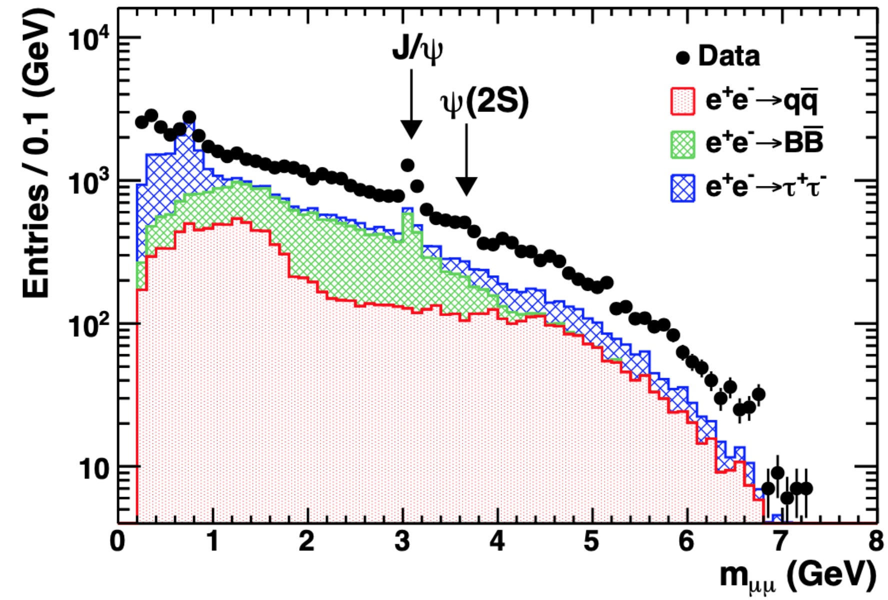
"Data driven" approach mitigates impact from known simulation deficiencies

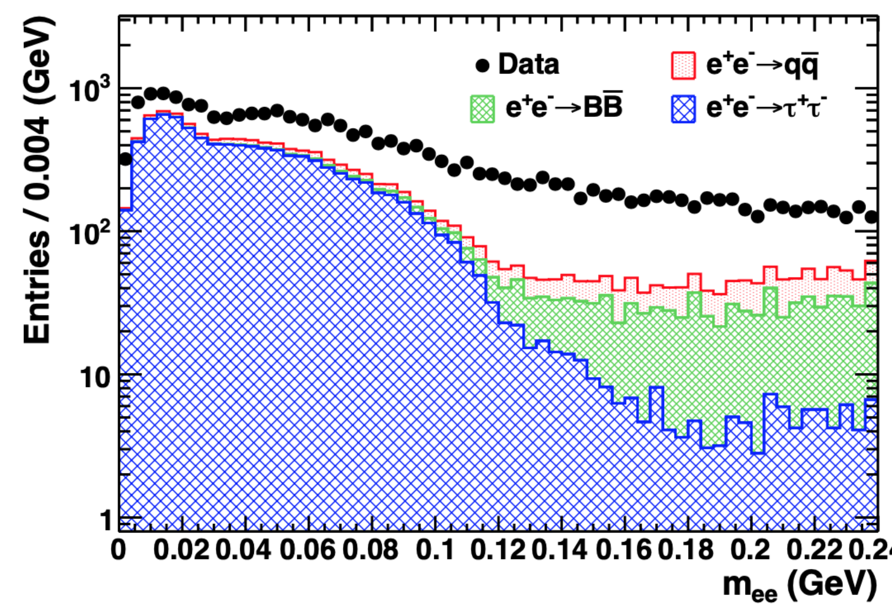
- Signal MC simulates 36 Φ_L mass points for prompt decays, plus $c\tau_{\Phi L}$ values up to 300 mm for $m_{\Phi L}$ < 0.3 GeV

Φ_L candidates are kinematically fit including vertex constraints

- $\Phi_L(\mu^+\mu^-)$ required to be compatible with beam interaction region, while $\Phi_L(e^+e^-)$ is only required to point back to interaction region

Signal mass resolution varies from 1 MeV – 50 MeV over full range of $m_{\Phi L}$





Signal extraction

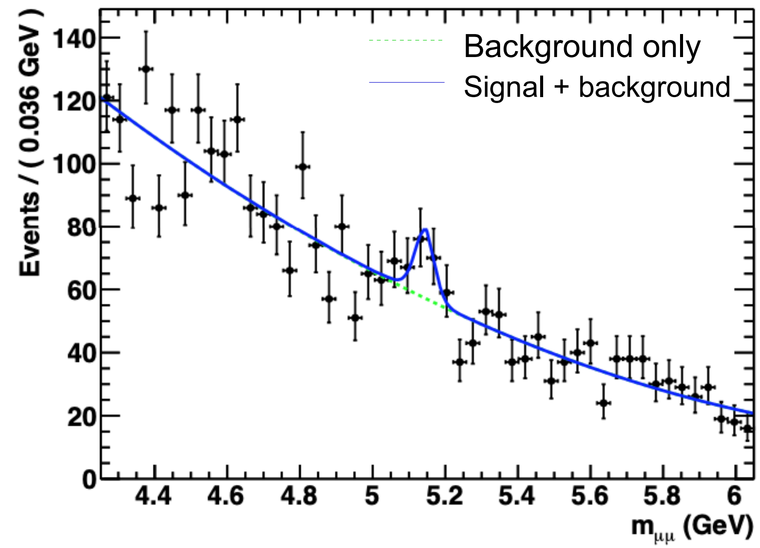
Signal extracted by fitting for a narrow di-lepton peak over sliding interval in the reconstructed dark scalar candidate mass

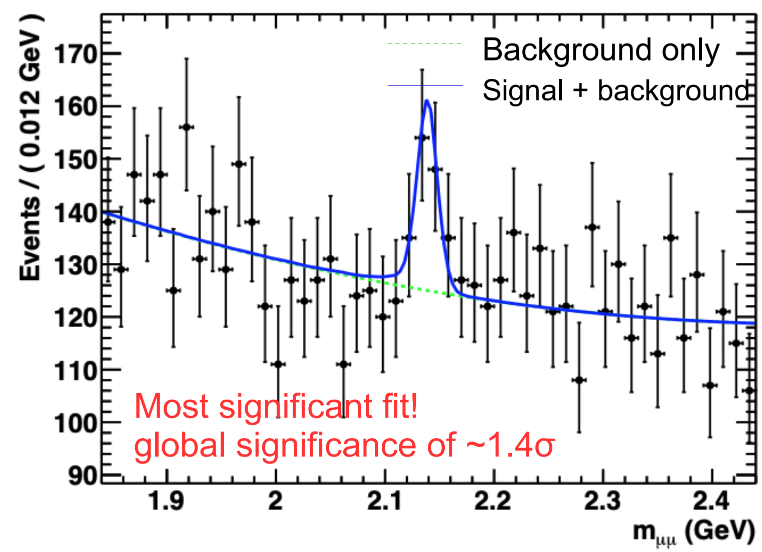
- Unbinned likelihood fit over intervals spanning 20σ-50σ (60σ) around the signal candidate mass for e (μ) mode
- Fit for signal, continuum and resonant (i.e. peaking) background components
  - Signal: non-parametric kernel density function (interpolated between simulated mass points)
  - Background: combination of polynomial, exponential and peaking (where appropriate)

Signal efficiency ranges from 0.2 – 26%

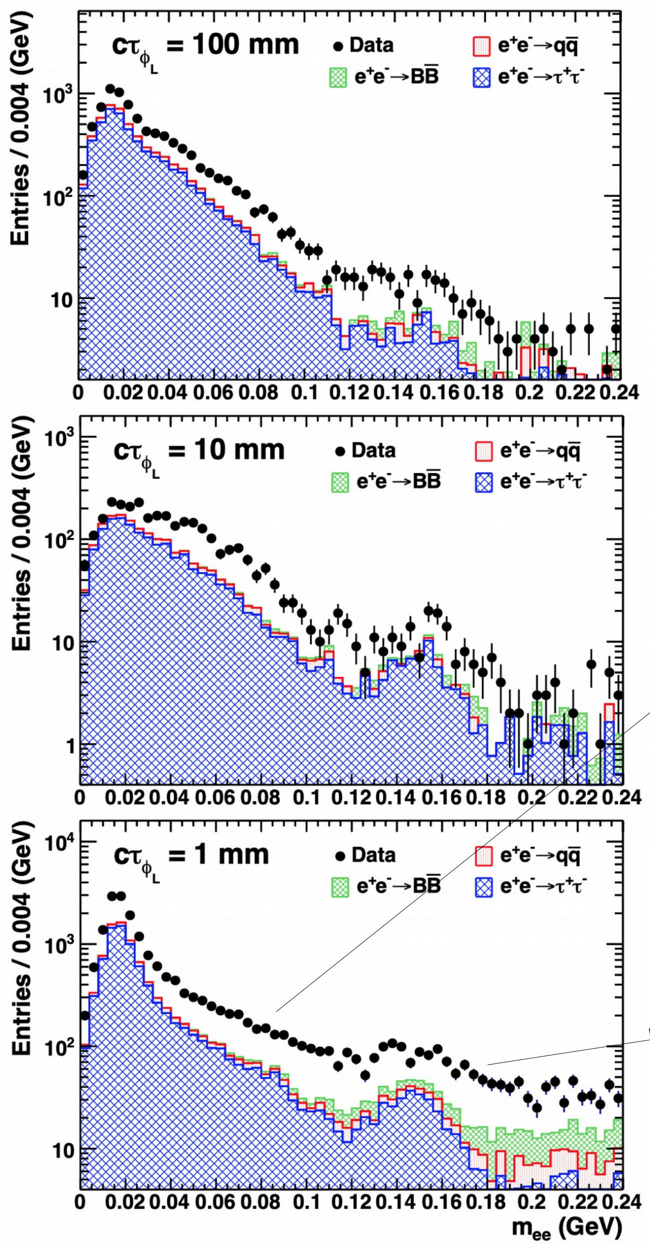
- validated from data/MC comparisons in sidebands, with correction factors of 2-7%

Example fits (di-muon):



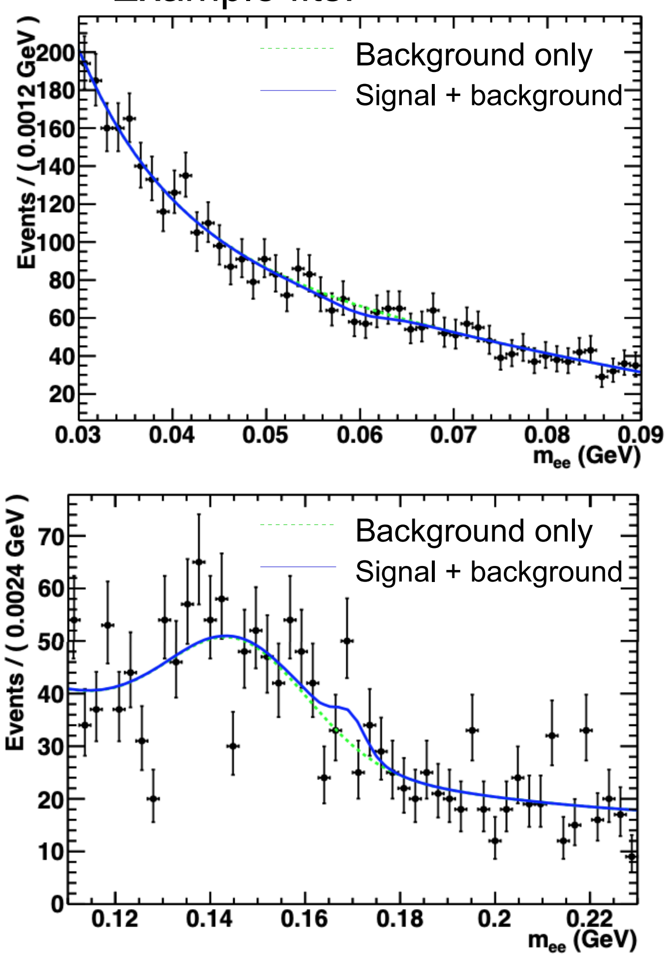


Non-prompt $\Phi_L \to e^+e^-$



For $\Phi_L(e^+e^-)$ channel, fits performed separately for three representative $c\tau_{\Phi L}$ values

Example fits:



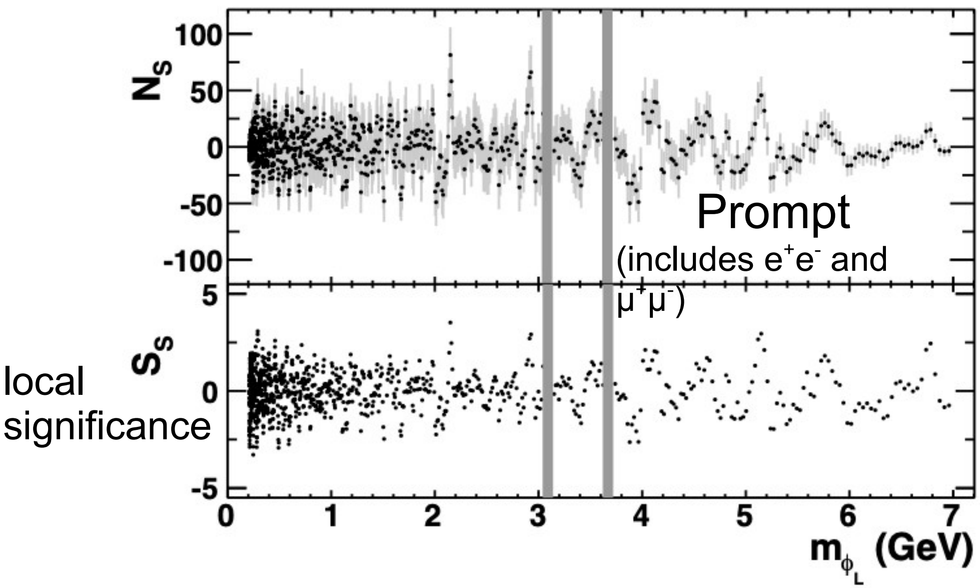
Broad structure visible in vicinity of $m(\pi^0)$ due to photon conversions $\gamma \to e^+e^-$

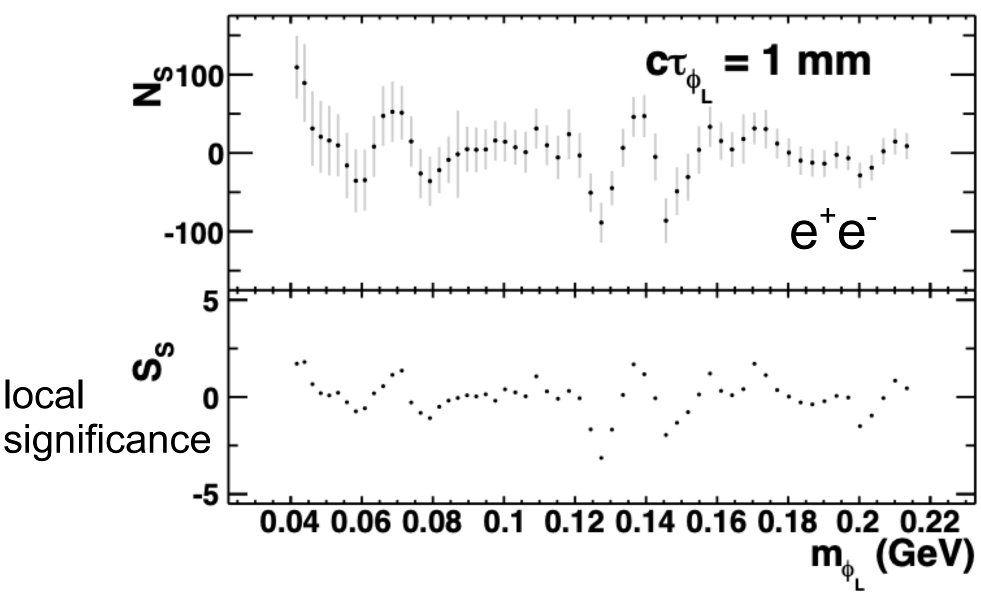
- explicitly included in background model for $c\tau_{\Phi L}$ = 1 mm

Signal yields

No significant excesses observed in $\mu^+\mu^-$ or e^+e^- modes, or in the non-prompt samples

- total of 966 mass hypotheses
- maximum local significance at m(μμ) ~2.14 GeV has global significance of 1.4σ
- J/ψ and ψ(2S) regions excluded from results, but included in fits and used for validation of signal shapes



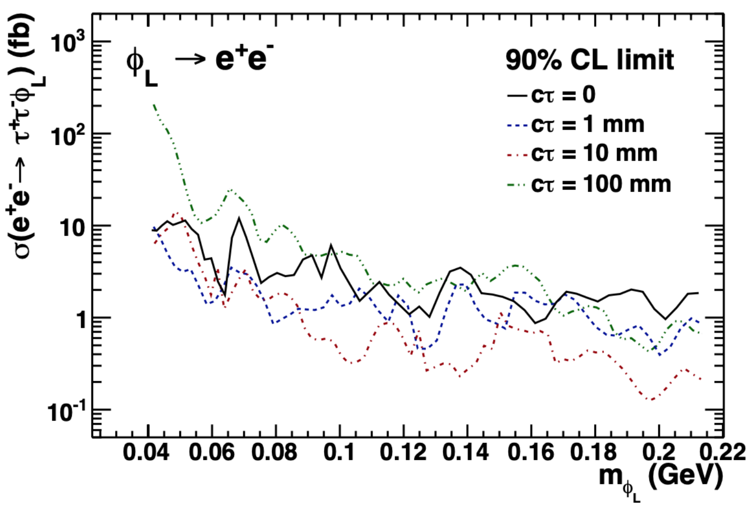


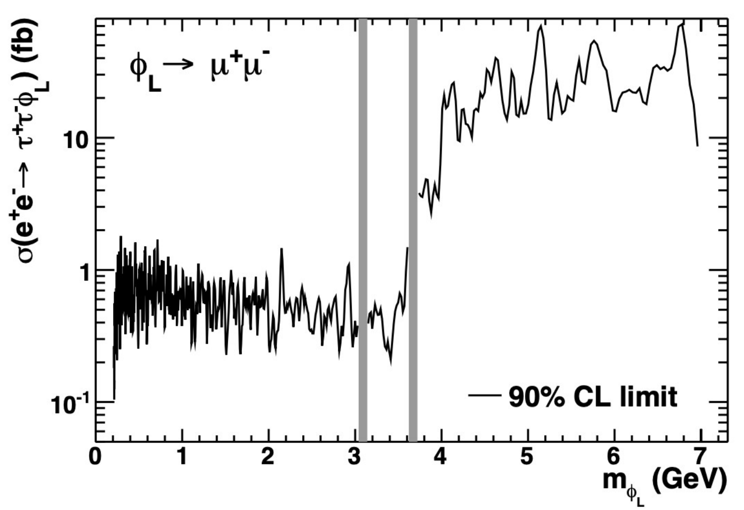
Results

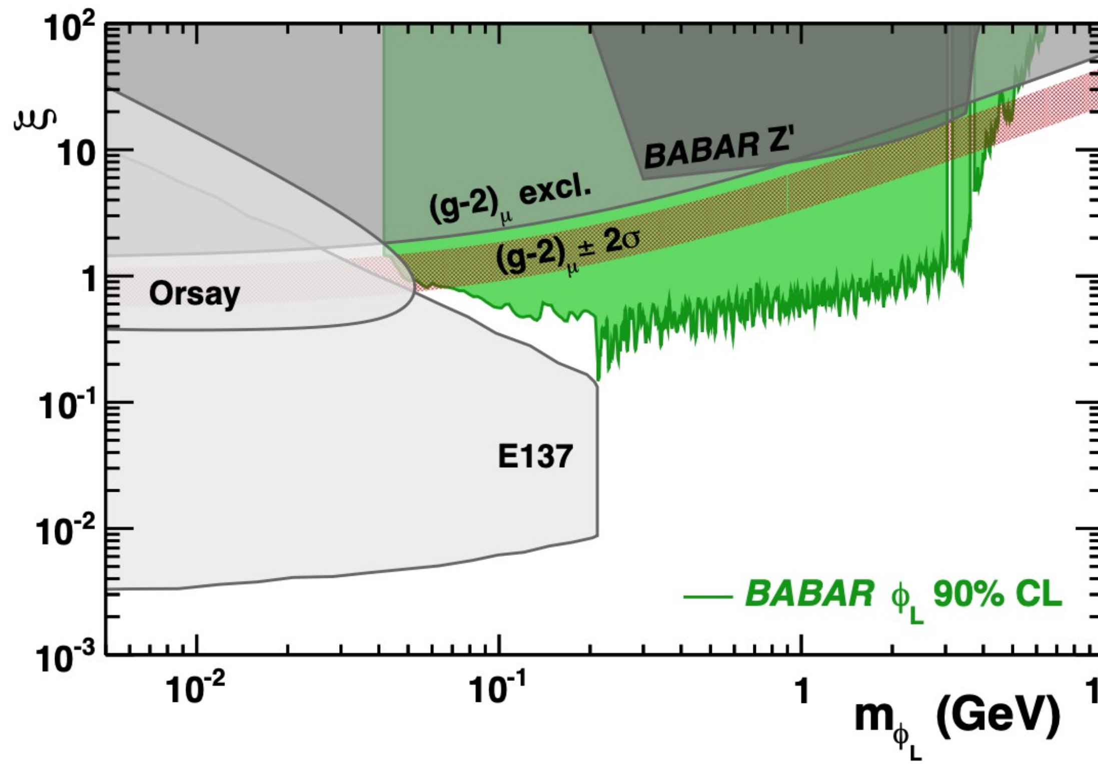
Phys. Rev. Lett. 125, 181801
514 fb^{-1}

Limits on the scalar coupling are derived using an iterative procedure, to account for impact of Φ_L lifetime:

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$$





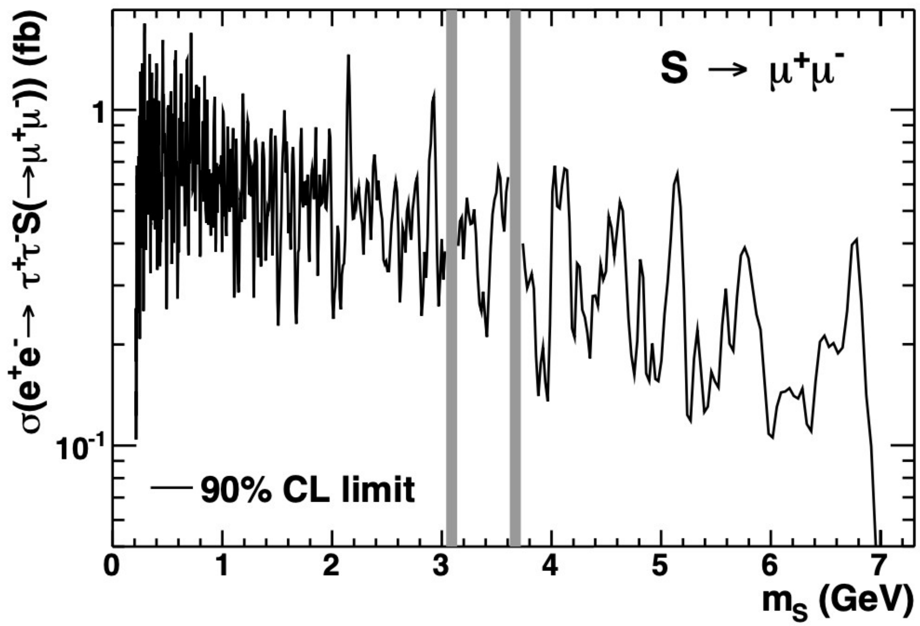


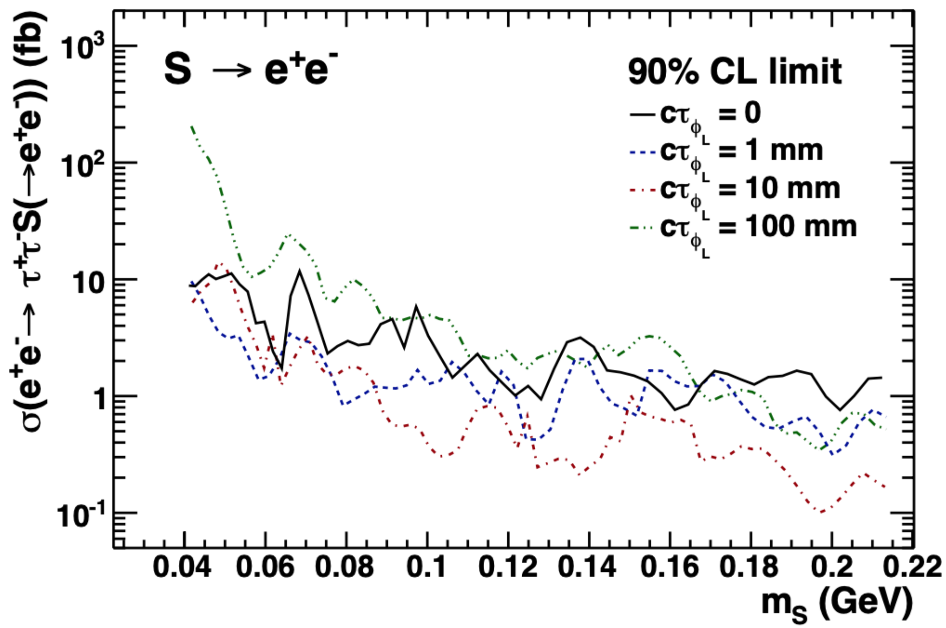
- Limits on ξ for the di-electron channel at the level of ~[0.5 – 1], corresponding to $c\tau_{\Phi L}$ ~ 10mm, and $c\tau_{\Phi L}$ ~ 2mm for di-muon channel
- $(g-2)_\mu$ region mostly excluded below di-tau threshold

Model-independent limits

Phys. Rev. Lett. 125, 181801
514 fb^{-1}

Alternatively, limits can be derived on the production cross section of a scalar S, without model assumptions on other decay modes:





Summary

Ongoing *BABAR* program to search for dark sector new physics

- Large data set obtained with inclusive triggers and hermetic detector has enabled substantial sensitivity across a variety of signatures
- Most recently, stringent limits have been set on the existence of a leptophilic dark scalar in $e^+e^- \to \tau^+\tau^- \Phi_L$, with $\Phi_L \to l^+ l^-$ $(l = e, \mu)$

Phys. Rev. Lett. 125, 181801

More results to follow very soon!

Backup Material

BDT inputs

TABLE I: List of variables used as input to the dimuon boosted decision trees.

Ratio of second to zeroth Fox-Wolfram moment of all tracks and neutrals.
Invariant mass of the four track system, assuming the pion (muon) mass for the tracks originating from the tau (ϕ_L) decays.
Invariant mass and transverse momentum of all tracks and neutrals.
Invariant mass squared of the system recoiling against all tracks and neutrals.
Transverse momentum of the system recoiling against all tracks and neutrals.
Number of neutral candidates with an energy greater than 50 MeV.
Invariant masses of the three track systems formed by the ϕ_L and the remaining positively or negatively charged tracks.
Momentum of each track from ϕ_L decays.
Angle between the two tracks produced by the tau decay.
Variable indicating if a track has been identified as a muon or an electron by PID algorithm for each track.

TABLE II: List of variables used as input to the dielectron boosted decision trees.

Transverse momentum of the system recoiling against all tracks and neutrals.
Energy of the system recoiling against all tracks and neutrals.
Number of tracks identified as electron candidates by a PID algorithm applied to each track.
Angle between ϕ_L candidate momentum and closest track produced in tau decay.
Angle between ϕ_L candidate momentum and farthest track produced in tau decay.
Angle of ϕ_L candidate relative to the beam in the center-of-mass frame.
Angle between the two tracks produced by the tau decay.
Angle between ϕ_L candidate and nearest neutral candidate with $E > 50$ MeV.
Energy of nearest neutral candidate (with $E > 50$ MeV) to ϕ_L candidate.
Total energy in neutral candidates, each of which has an energy greater than 50 MeV.
Distance between beamspot and ϕ_L candidate vertex.
Uncertainty in the distance between beamspot and ϕ_L candidate decay vertex.
ϕ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty.
Angle between the ϕ_L candidate momentum, and line from beamspot to ϕ_L decay vertex.
Distance of closest approach to beamspot of e^- in ϕ_L candidate.
Distance of closest approach to beamspot of e^+ in ϕ_L candidate.
Transverse distance between ϕ_L decay vertex and best-fit common origin of τ candidates and ϕ_L candidate.
χ^2 of the kinematic fit to the ϕ_L and τ candidates constraining their origin to the same production point.
χ^2 of the kinematic fit of the ϕ_L candidate with the constraint that the e^+e^- pair is produced from a photon conversion in detector material.
Dielectron mass for ϕ_L candidate when re-fit with the photon conversion constraint.

Leptonic Higgs Portal

Battell et al.,
arxiv:1606.04943

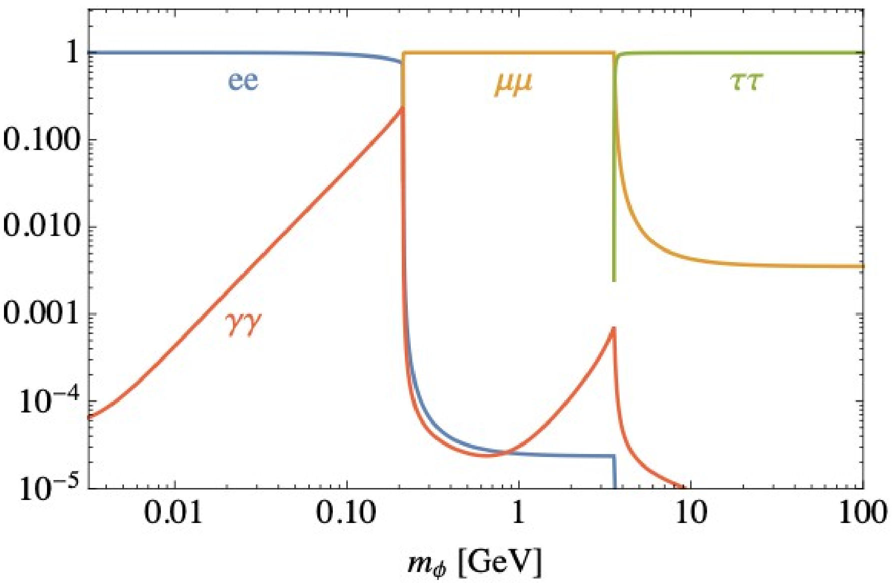
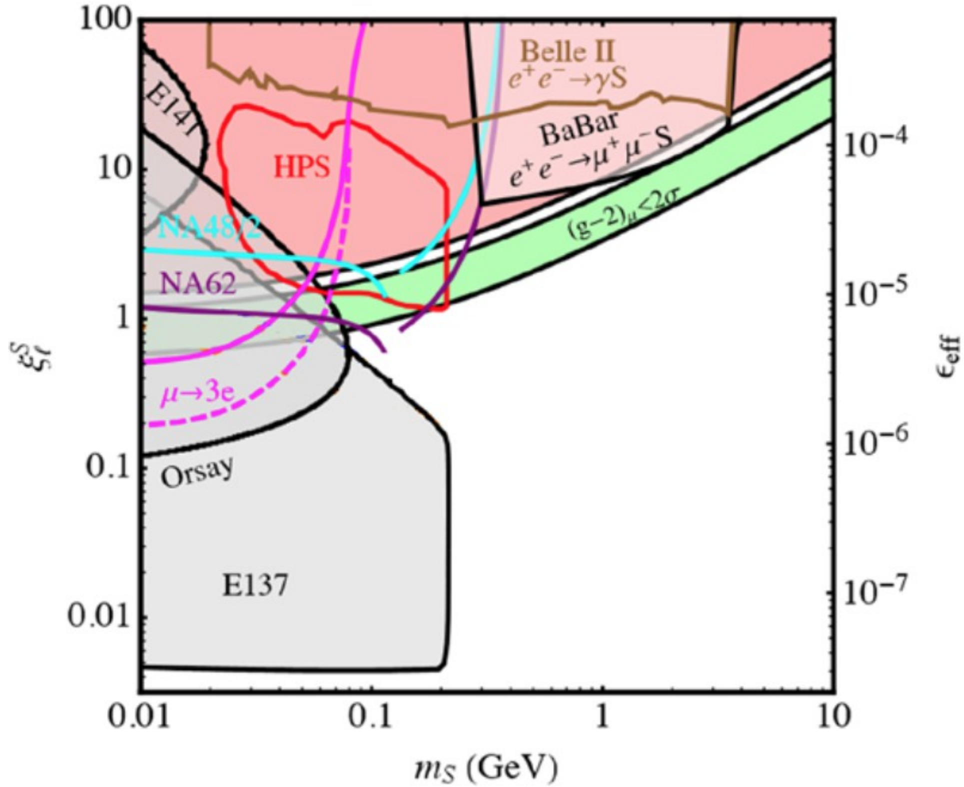


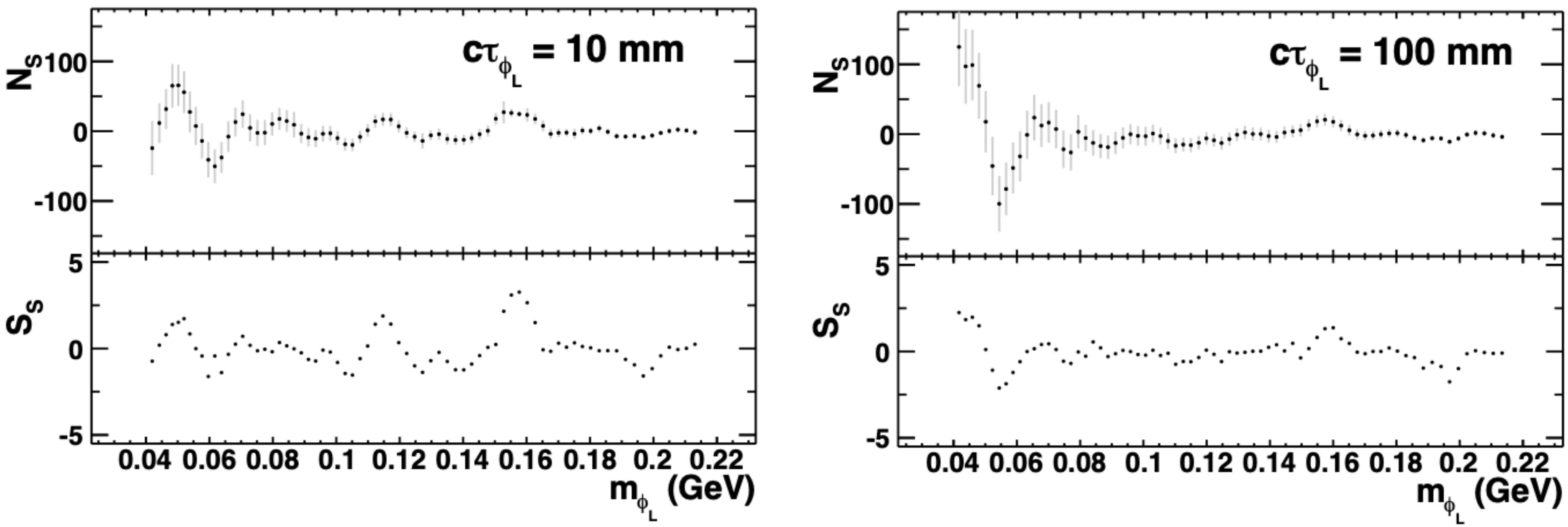
FIG. 2. Branching ratios for $S \to \gamma\gamma$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$ as a function of m_S.



$$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 + \sum_{l=e,\mu,\tau} g_\ell S \bar{\ell}\ell$$

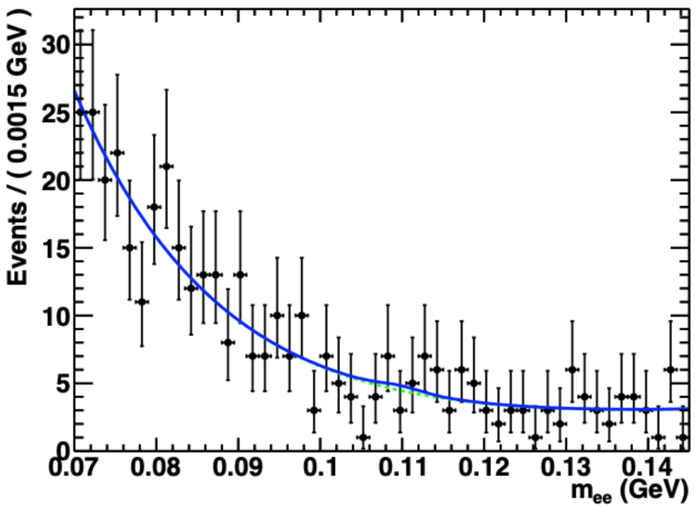
$$g_\ell = \frac{m_\ell}{v} \times \tan\beta \times \theta_\ell$$

Non-prompt yields

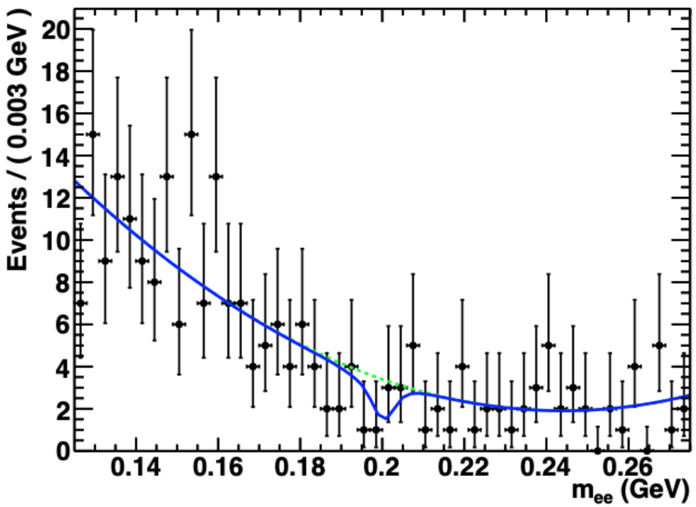


More example fits

$c\tau_{\Phi L}$ = 10 mm



$c\tau_{\Phi L}$ = 100 mm



Validation

Control samples are used to validate signal eff ciencies and to derive corrections

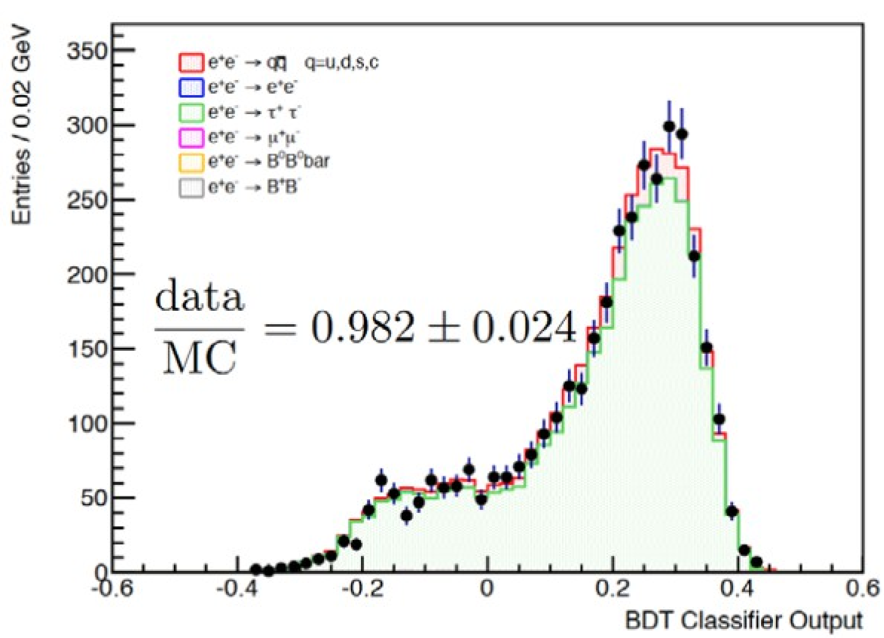
- Data globally well reproduced by MC in control samples; corrections between 2-7%

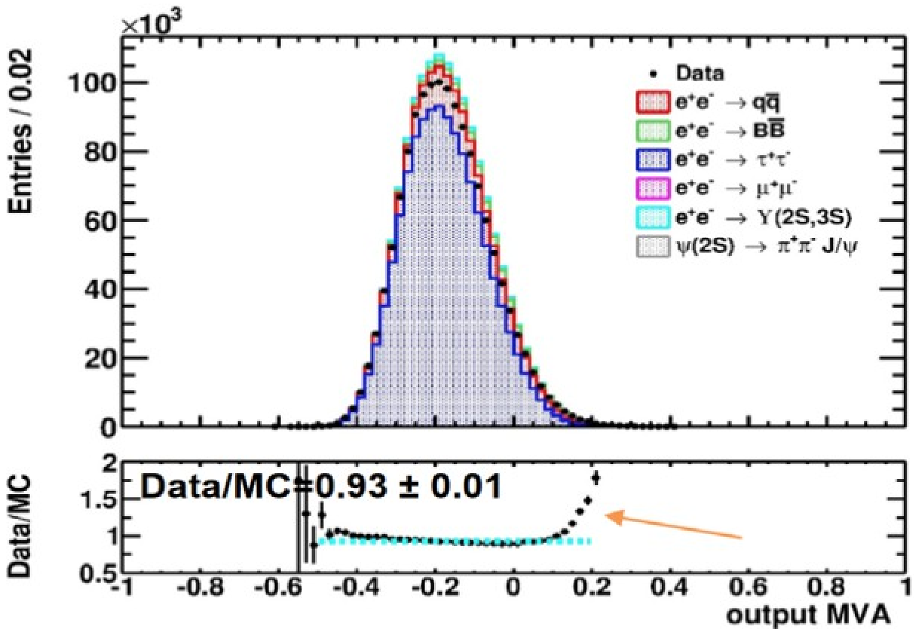
Dielectron:

- Use sample of $K_s \to \pi^+\pi^-$ in τ decays obtained with a selection procedure similar to the nominal signal selection

Dimuon:

- BDT response for data with recoil p_T > 2 GeV to suppress non-modelled components





Muonic dark force

Phys. Rev. D94 011102 (2016)
arXiv:1606.03501 [hep-ex]

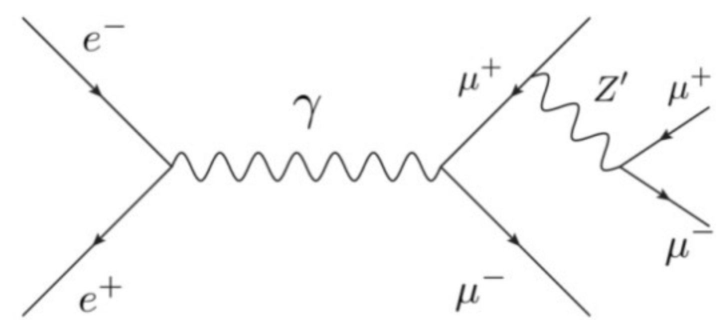
Non-minimal dark sector models can permit additional interactions between dark boson and SM particles

- Dark boson Z' which couples only to second and third generation leptons (SM fields are directly charged under dark force)

Motivated by various anomalies in the muon sector

He, Joshi, Lew, Volkas, Phys. Rev. D 43, R22 (1991).
B. Batell, D. McKeen and M. Pospelov, Phys. Rev. Lett. B.107, 011803 (2011).

- g-2 discrepancy
- could also account for dark matter as sterile neutrinos by increasing their cosmological abundance via new interactions with SM neutrinos.



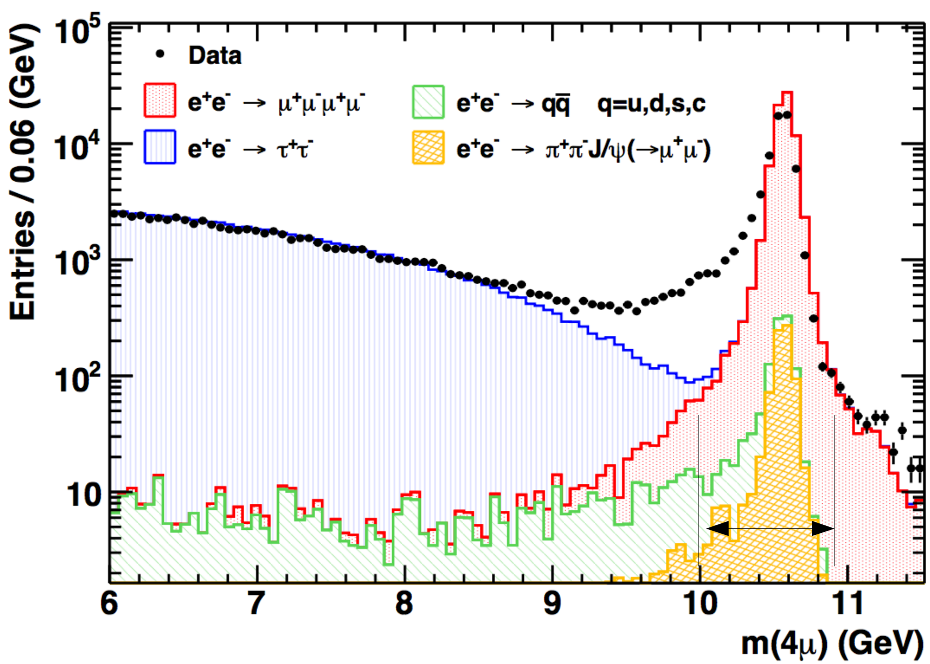
However, no model assumptions in analysis; results are more generally applicable

"Z'-strahlung" production of Z' in $e^+e^- \to \mu^+\mu^-$

$$e^+e^- \to \mu^+\mu^- Z' \,,\ Z' \to \mu^+\mu^-$$

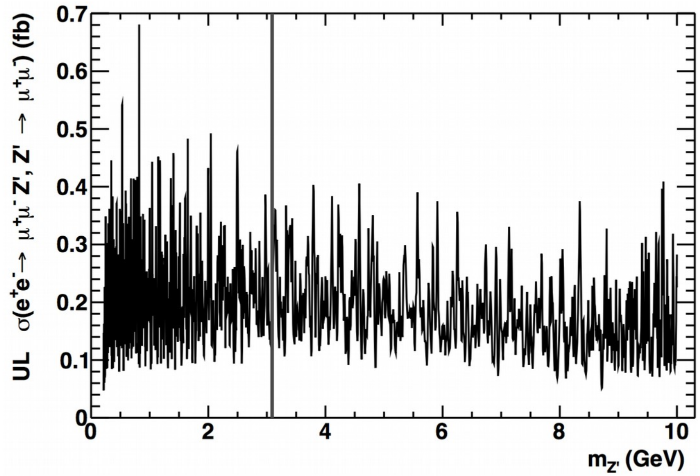
Muonic dark force

- Background is primarily from QED processes, in particular
  $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$
- Select events with 4 tracks, including two same-sign identified muons; veto events with additional calorimeter energy exceeding 200 MeV
- $\Upsilon(3S), \Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$ backgrounds rejected by vetoing events with a di-track mass combination within 100 MeV of the $\Upsilon(1S)$

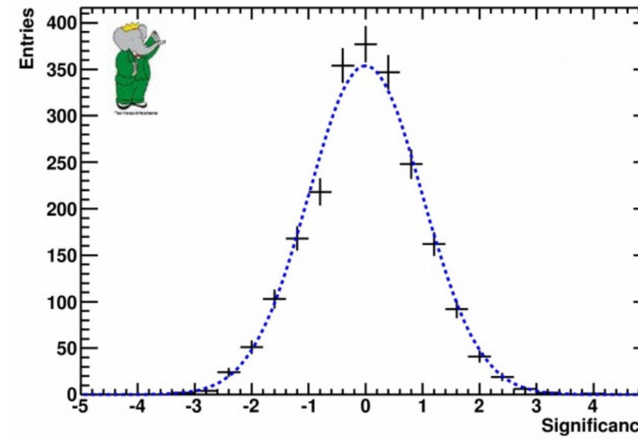


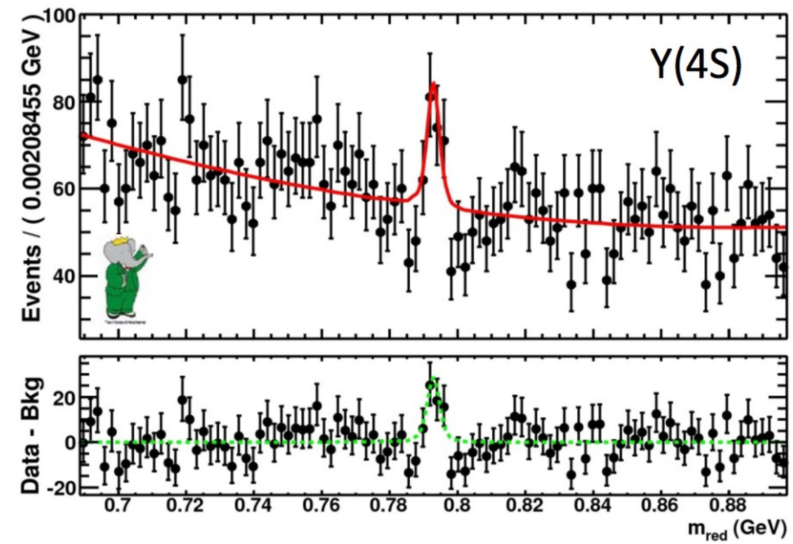
- ISR not modelled in simulation; corrected at analysis level
- Retain events with $m(4\mu)$ within 500 MeV of nominal CM energy
- Kinematic fit of 4μ mass to CM energy and interaction point imposed
  - no rejection applied; improves di-muon resolution

Muonic dark force results



Limit on $\sigma(e^+e^- \rightarrow \mu^+\mu^- Z', Z' \rightarrow \mu^+\mu^-)$





Most significant fit

Local significance: 4.3σ
Global significance: 1.6σ