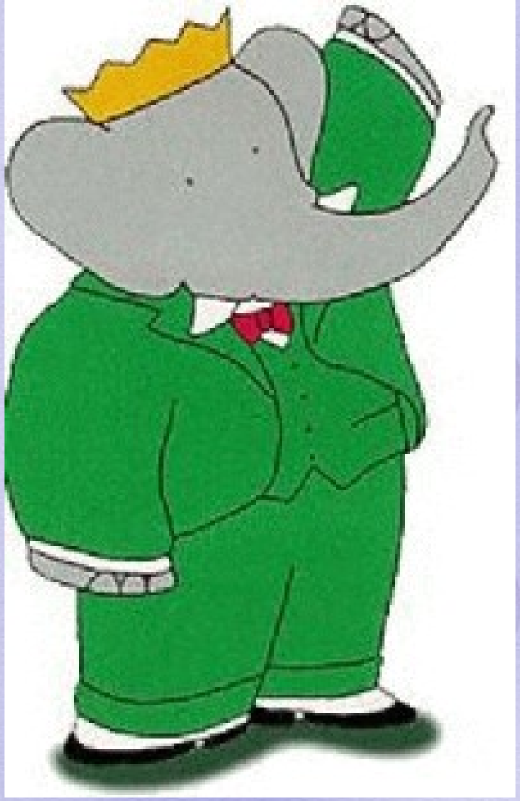
Model-Independent Search for the Decay $B^+ \to \ell^+ \nu_\ell \gamma$ at BABAR

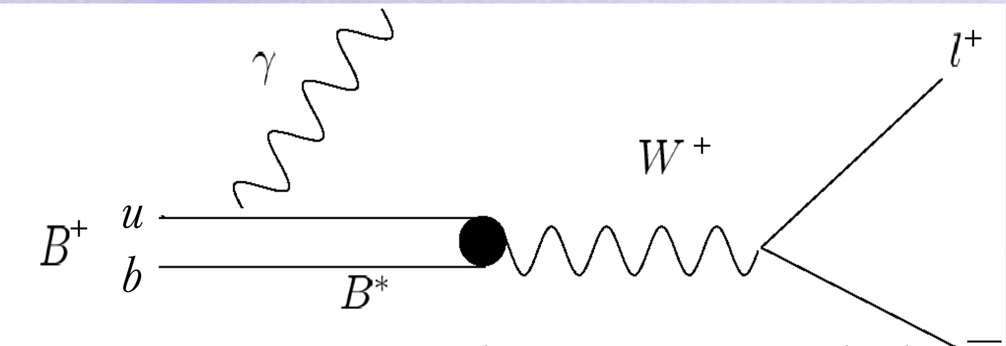
(arXiv: 0907.1681)



Dana Lindemann
Steven Robertson
McGill University, Montreal, Canada
Representing the BABAR Collaboration

APS Division of Particles & Fields
July 27, 2009

Theoretical Motivation for $B^+ \to \ell^+ \nu\gamma$

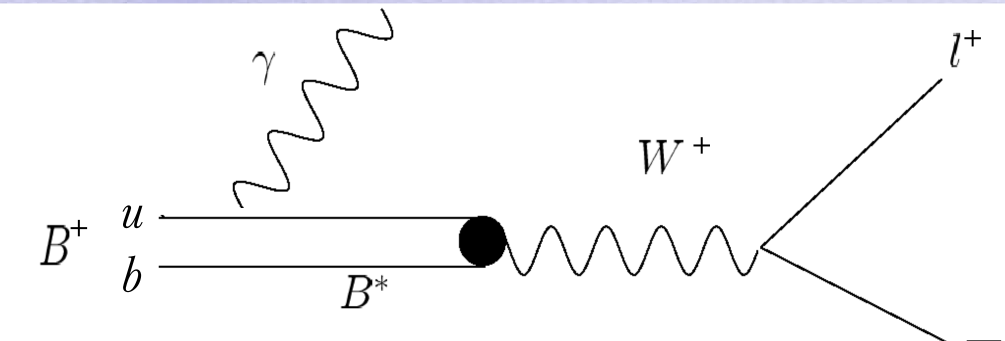


Note: $\ell = \mu$ or e, complex conjugates implied

Leptonic decay BF measurements provide clean predictions of SM parameters without hadronic (QCD) final-state uncertainties

- *BF*$(B \to \ell\nu) \propto m_\ell^2$ due to helicity suppression: *BF*$(B \to e\nu) \approx 10^{-11}$, *BF*$(B \to \mu\nu) \approx 10^{-7}$
- Radiative mode has no helicity suppression
  - Photon release causes W^+ to couple to a spin-1 virtual state

Theoretical Motivation for $B^+ \to \ell^+ \nu\gamma$



Note: $\ell = \mu$ *or* e, *complex conjugates implied*

SM prediction:

$BF(B \to \ell\nu\gamma) \approx 10^{-6}$

Published Limits (CLEO '97)

$BF(B \to e\nu\gamma) < 2.0 \times 10^{-4}$

$BF(B \to \mu\nu\gamma) < 5.2 \times 10^{-5}$

Browder, *et al.* [CLEO Collab], PRD 56, 11 (1997).

- $BF(B \to \ell\nu) \propto m_\ell^2$ due to helicity suppression: $BF(B \to e\nu) \approx 10^{-11}$, $BF(B \to \mu\nu) \approx 10^{-7}$
- Radiative mode has no helicity suppression
  - Photon release causes W^+ to couple to a spin-1 virtual state
- Branching Fraction is independent of lepton-type

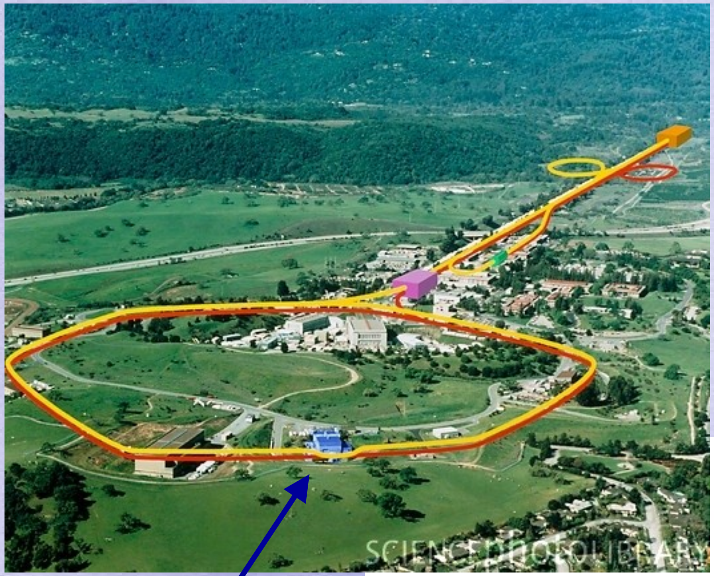
$$BF\left(B^+ \to \ell^+ \nu\gamma\right) \approx \frac{\alpha G_F^2}{288\pi^2} |V_{ub}|^2 f_B^2 m_B^5 \tau_B \left(\frac{2}{3\lambda_B} + \frac{1}{3m_b} \right)^2$$

Korchemsky, Pirjol, and Yan, PRD 61 114510 (2000).

- Only decay providing clean measurement of λ_B:
  - 1st inverse moment of the B-meson wave function
  - Theoretical significance (QCD factorization, $B \to \pi\pi$, etc.)
  - Of order Λ_{QCD} (few hundred MeV)

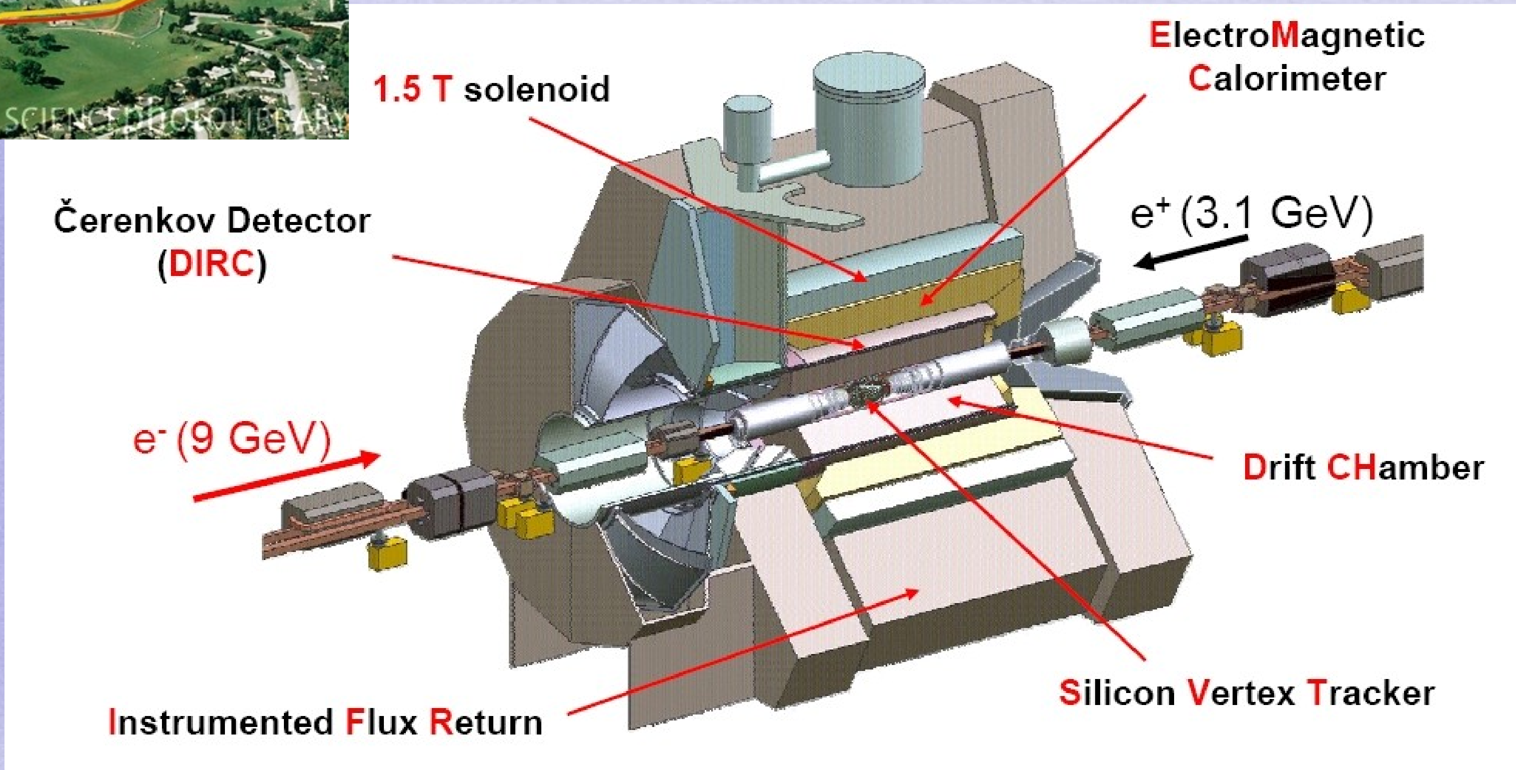
Benchmark decay for measuring angle α of the CKM Unitary Triangle

The BaBar Detector

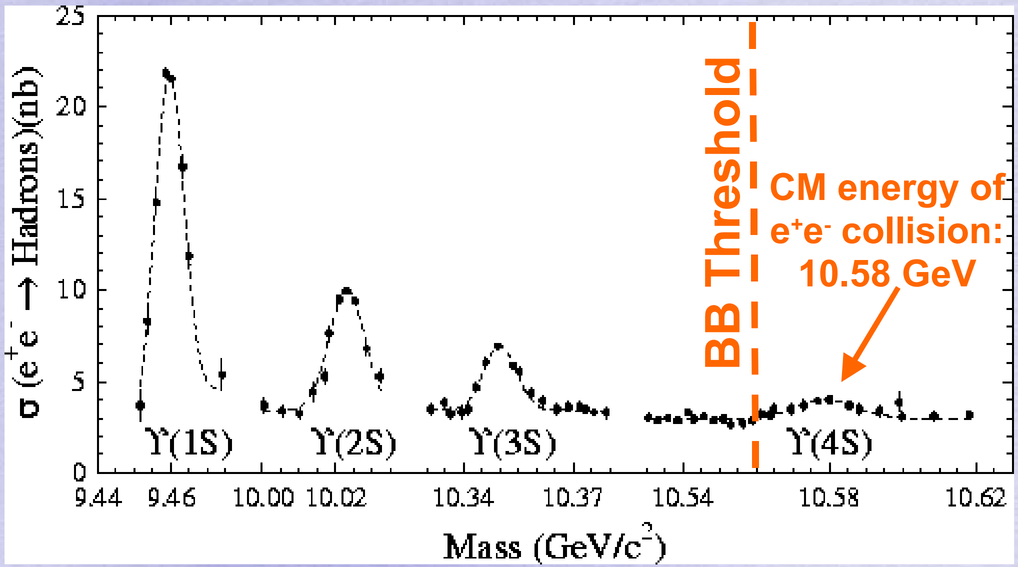


BaBar Detector

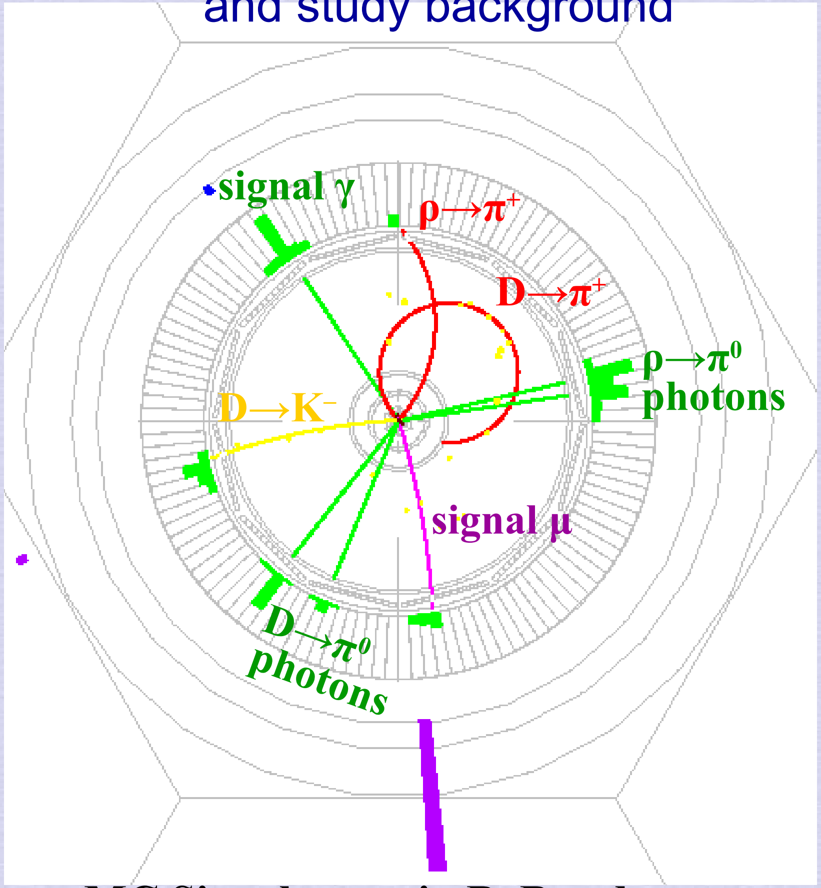
- Babar Collaboration:
  ~350 physicists from 12 nations
- Data-taking from 1999 to April 2008
- Located at SLAC, California
  - 2 mile long linear accelerator
  - Asymmetric PEP-II e+e- storage ring



ϒ(4S) at the B-Factory



GEANT4-based Monte Carlo (MC) simulations model the detector response. Used to determine signal efficiency and study background



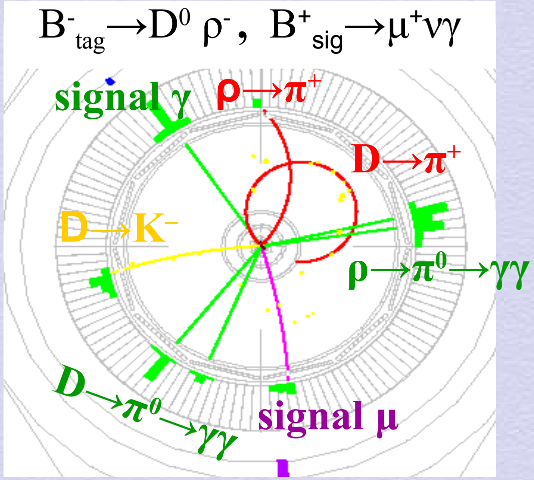
MC Signal event in BaBar detector:

$B^+_{sig} \to \mu^+ \nu \gamma$ *and* $B^-_{tag} \to D^0 \rho^-$

- ϒ(4S) is a $b\bar{b}$ quarkonium resonance whose mass is just above the threshold for $B\bar{B}$ meson pair production
- ϒ(4S) decays to $B\bar{B}$ 99% of the time
- ~1.1 million $B\bar{B}$ pairs produced per fb^{-1}
- Full BaBar data set used: 465 million $B\bar{B}$ pairs (423 fb^{-1} integrated luminosity)

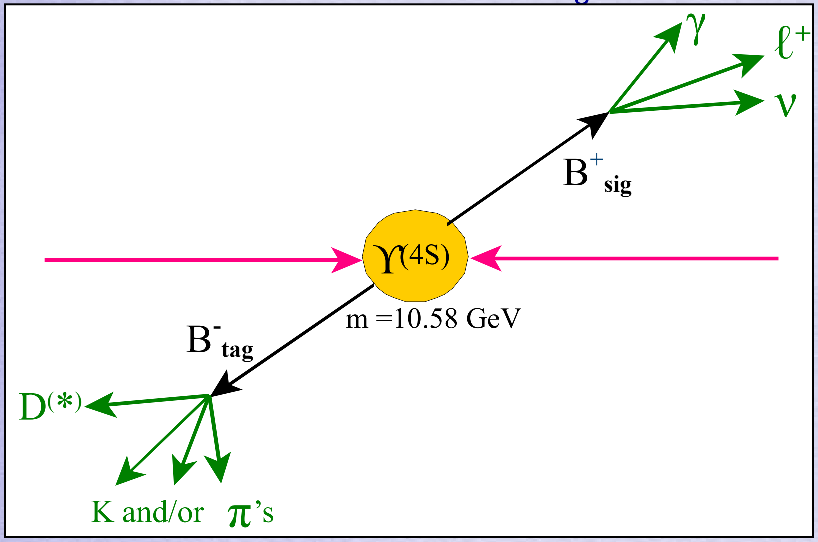
Hadronic Tag Reconstruction

- **How?**
  - Find $B_{tag} \rightarrow D^{(*)}X_{had}$ events (X_{had} is combination of kaons and/or pions)
  - Choose combo with a B_{tag} energy closest to $E_{CM}/2$
  - Remaining particles are assigned to B_{sig}



This technique has never been used for this signal decay!

All previous analyses used inclusive methods



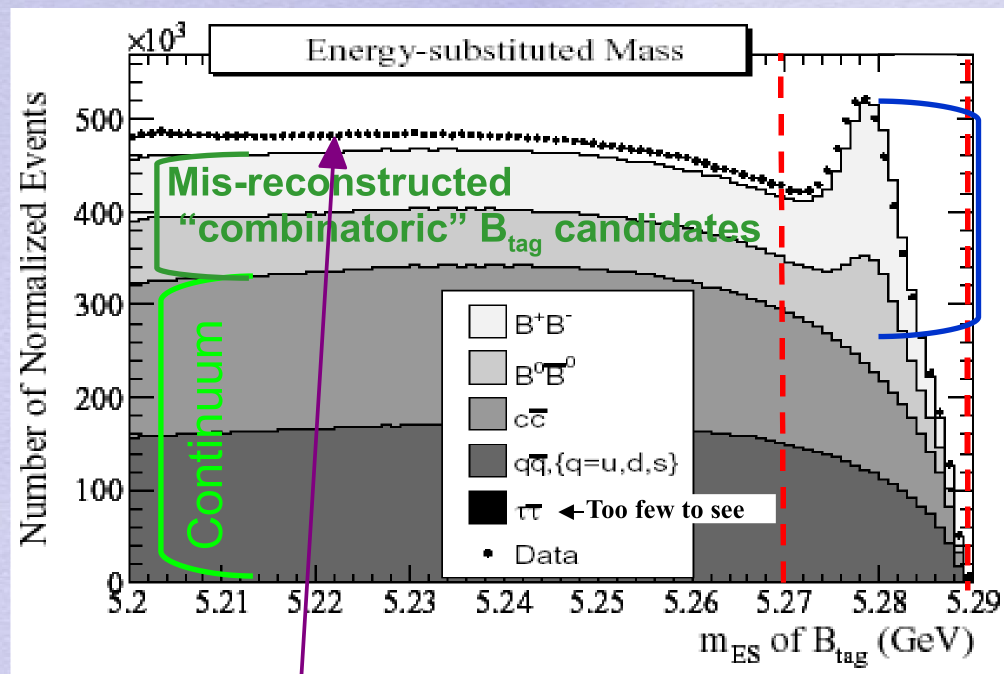
- **Why?**
  - High B purity, removing much of the non-$B\bar{B}$ background
  - B 4-momentum is determined, giving excellent momentum resolution on the B_{sig} daughters (including the undetectable neutrino!)
- **The Challenge**
  - Low reco efficiency (~0.3% for signal) so statistically limited sample
  - We aim to avoid any kinematic or model-dependent constraints

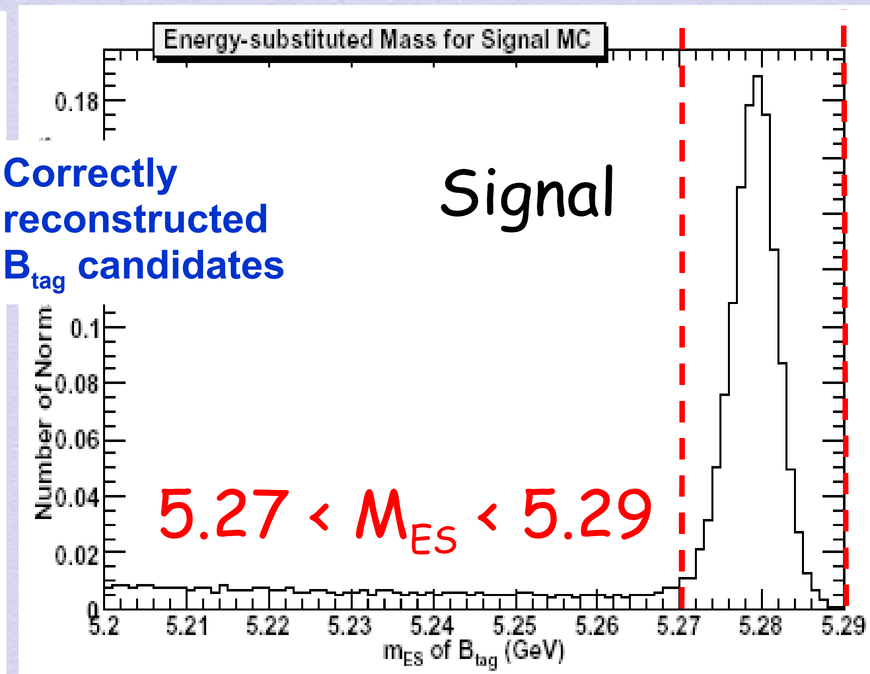
Validating the B_{tag}

We require:

- A reconstructed charged B_{tag} candidate
- Mass of B_{tag} (m_{ES}) matches B mass of 5.279 GeV

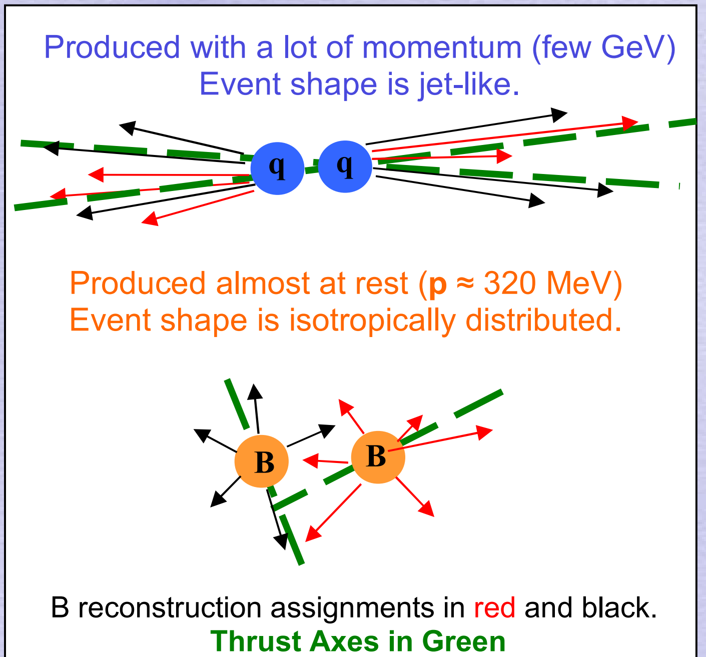
$$m_{ES} \equiv \sqrt{E^2_{CM/2} - \vec{p}^{\,2}_B}$$

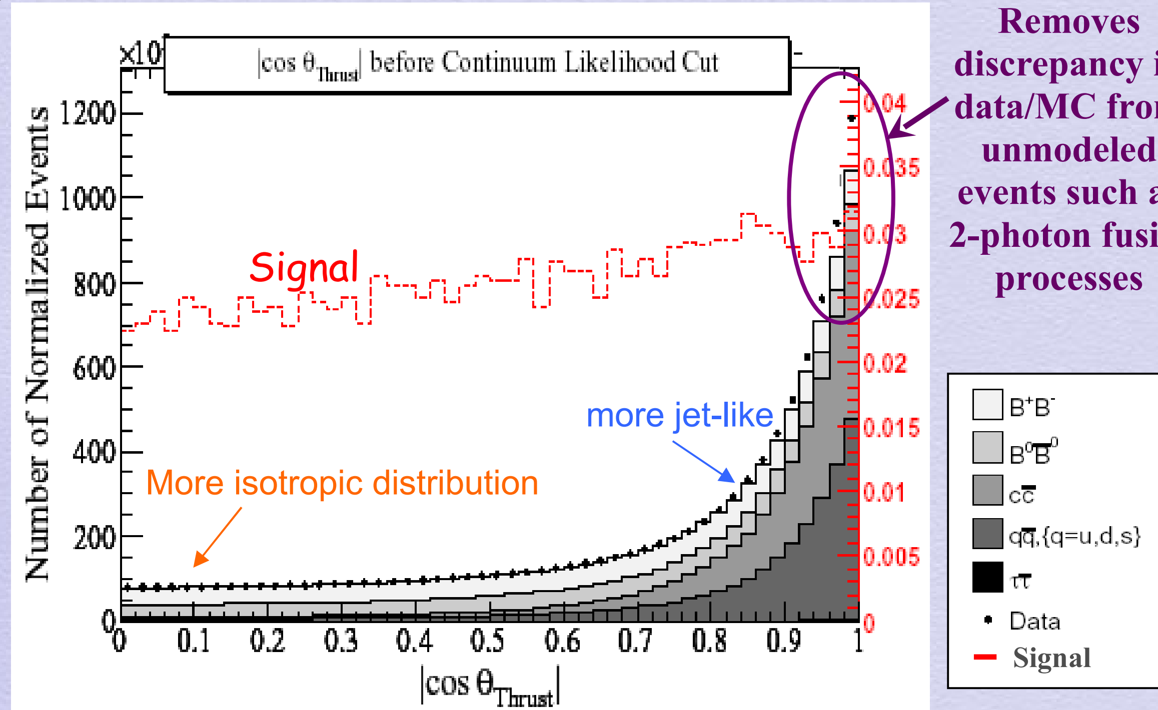




Discrepency between data/MC: avoided by scaling MC to data and estimating non-peaking background from data

Suppressing non-BB events





Removes discrepancy in data/MC from unmodeled events such as 2-photon fusion processes

Continuum Multivariate Likelihood

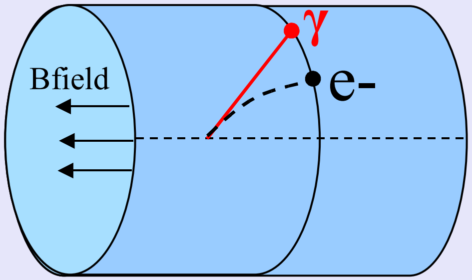
- Continuum ($q\bar{q}$ or $\tau\tau$) events are more likely to be jet-like decays, where B_{tag} candidate has a highly linear thrust and a momentum along the beam-pipe
- Discriminate continuum and $B\bar{B}$ events using 5 event-shape variables

Signal Selection

Remaining neutral EMC clusters and charged tracks assigned to B_{sig}.

- Require exactly 1 B_{sig} track
  - With a charge opposite the B_{tag}'s charge
  - Satisfies particle ID criteria for electron *or* muon, and *not* a kaon
- Bremsstrahlung photon candidates identified to correct electron's 4-vector

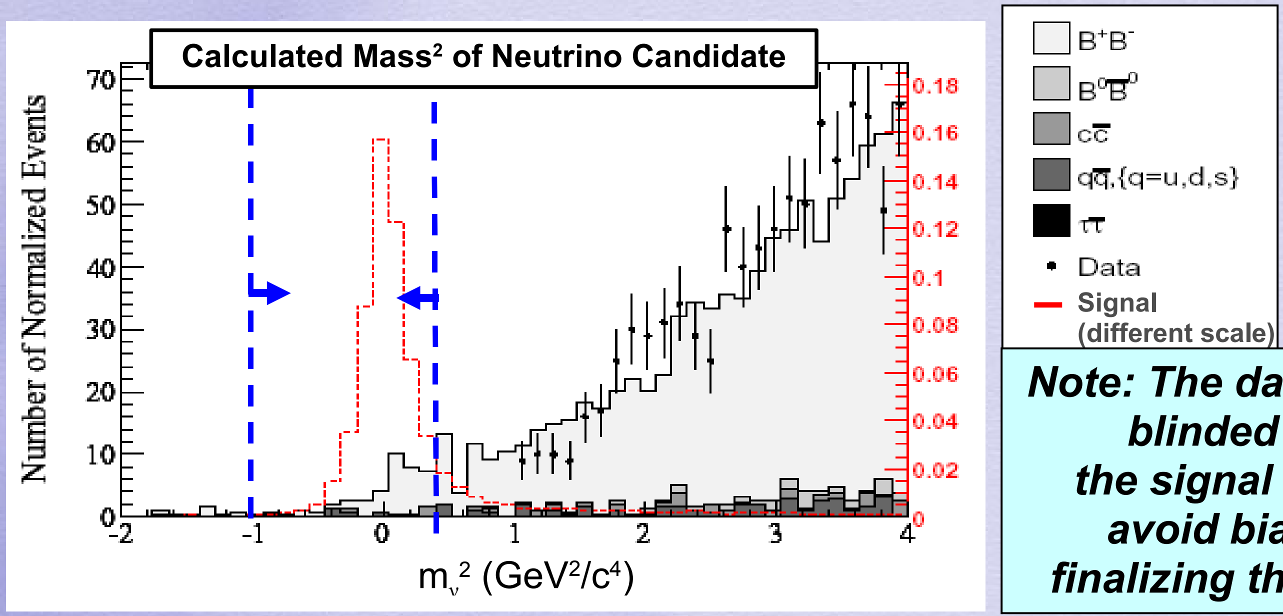
Bremsstrahlung photon candidates are any B_{sig} clusters near lepton's EMC cluster



- Signal Photon candidate chosen as highest energy (non-Brem) cluster
- Missing Momentum within detector's fiducial acceptance
  - To ensure missing E is not from a detectable particle "lost down beam-pipe"

Kinematic Requirements

- Kinematics of photon and lepton candidates are consistent with a 3rd massless daughter (neutrino)
  - $m_\nu^2 \equiv -|p_B - p_\gamma - p_\ell - p_{brem}|^2$
  - Requires B_{sig} 4-vector (p_B), determined from B_{tag} reconstruction



Note: The data was kept blinded within the signal region to avoid bias while finalizing the analysis

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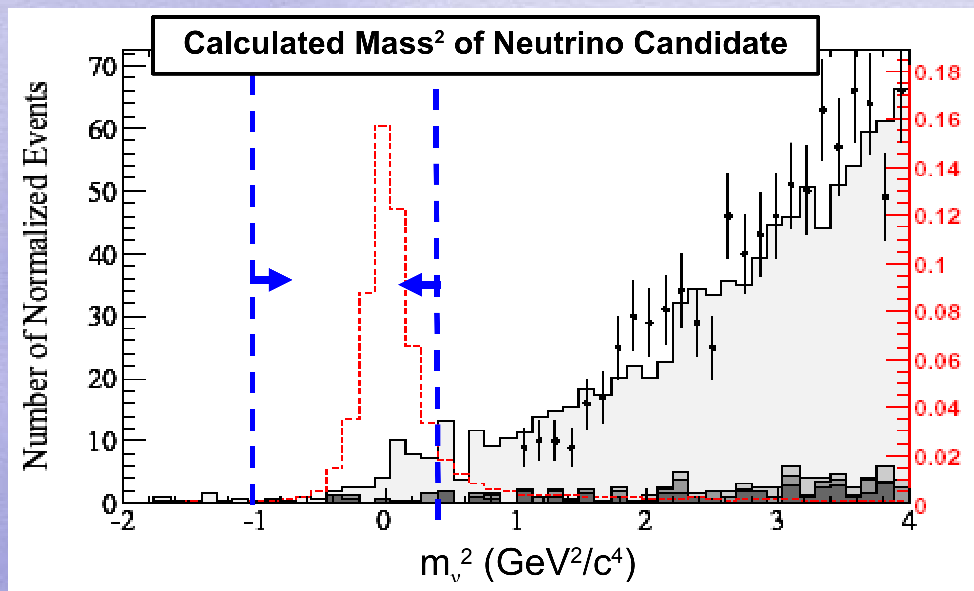

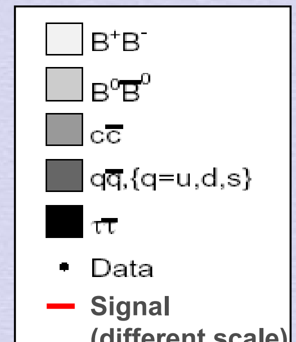

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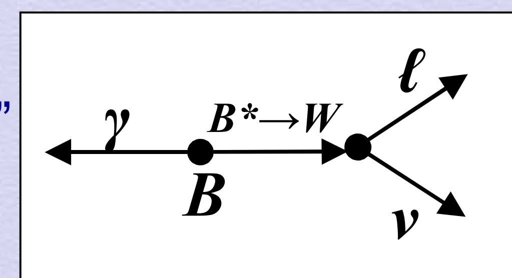
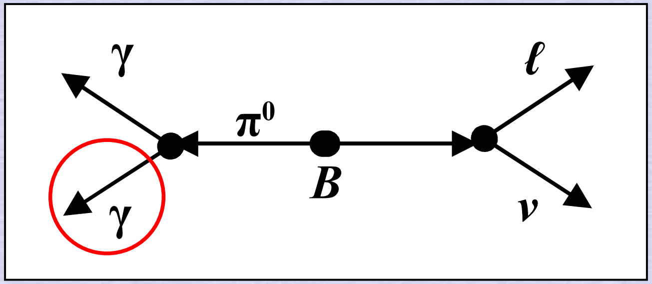
- Lepton's momentum and event's missing momentum are back-to-back ($\cos\theta_{\ell\nu} < -0.93$) in the “B* rest frame”
  - Rest frame recoiling from photon release $\equiv p_B - p_\gamma$



$B^+ \to X_u^0 \ell^+ \nu$ Suppression

The primary background is from $B^+ \to X_u^0 \ell^+ \nu$ events, where X_u^0 is a neutral meson containing an up-quark.

For example,
since 99% of π^0's decay to 2 photons,
a $B \to \pi^0 \ell \nu$ decay with a "missing" photon
resembles signal $B \to \ell \nu \gamma$ decay.



To reduce this background, we:

- Reject events with π^0 or η candidates (signal γ + unassigned cluster)
- Reject events with a $\omega \to \pi^0 \gamma$ candidate (signal $\gamma + \pi^0$ candidate)

- Reject events where the signal γ has a large calorimeter cluster width
  - Reduces $B \to \pi^0 \ell \nu$ events in which the 2 photons are reconstructed as a single merged photon

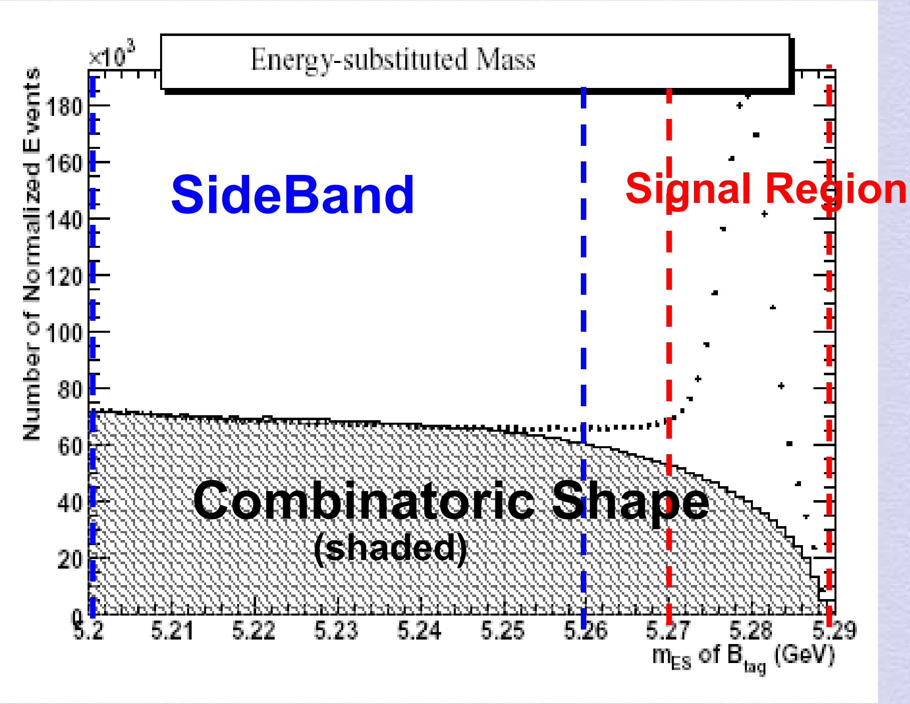
mimics signal kinematics! π^0 → 2 γ's

Background Estimation

Number of expected background events (N_{bkg}) is split into:

- N_{peak}: well-reconstructed events that peak within m_{ES} signal region

- N_{comb}: "combinatoric" events

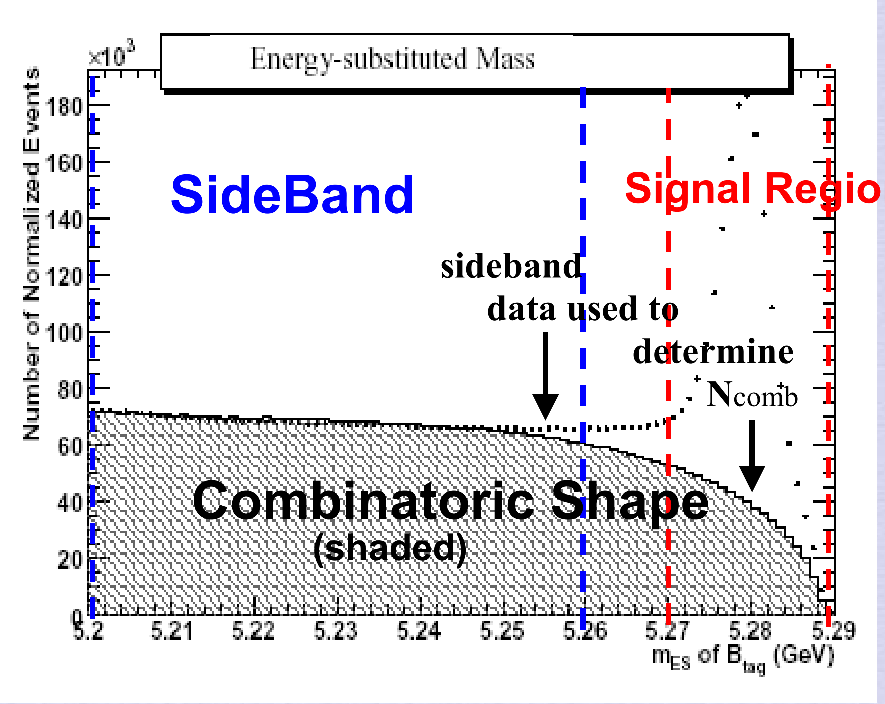


Background Estimation

Number of expected background events (N_{bkg}) is split into:

- N_{peak}: well-reconstructed events that peak within m_{ES} signal region
  - According to generically-decaying $B\bar{B}$ MC, only $B^+ \to X_u^0 \ell^+ \nu$ events contribute
  - We estimate N_{peak} from exclusive $B^+ \to X_u^0 \ell^+ \nu$ MC for higher statistics

- N_{comb}: "combinatoric" events
  - B_{tag} is mis-reconstructed from continuum or using particles from both B mesons
  - Extrapolated from m_{ES} sideband in data



Branching Fractions

Branching fraction (BF) defined as:

$$\frac{N_{obs} - N_{bkg}}{N_{B\pm} \cdot \varepsilon_{sig}}$$

Estimated $B^{\pm}$ mesons in data sample = 465 x 10^6

uncertainties: stat. ± syst.

	B→eνγ	**B→μνγ**
N_{peak}	2.4 ± 0.3 ± 0.4	2.1 ± 0.3 ± 0.3
N_{comb}	0.3 ± 0.3 ± 0.2	1.2 ± 0.6 ± 0.6
ε_{sig} (x10^{-4})	7.8 ± 0.1 ± 0.3	8.1± 0.1 ± 0.3

Within the SM range, ε_{sig} corresponds to ~1 signal events per mode!

- BF interval determined using the Feldman-Cousins method [Phys. Rev. D57 3873 (1998).]
- Systematic uncertainties are incorporated using Gaussian distributions

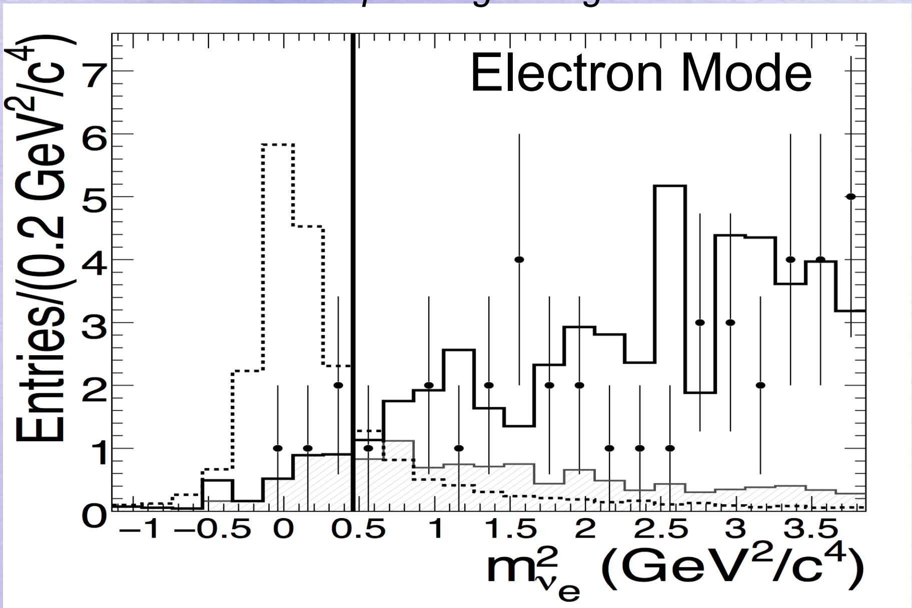
Unblinded Data

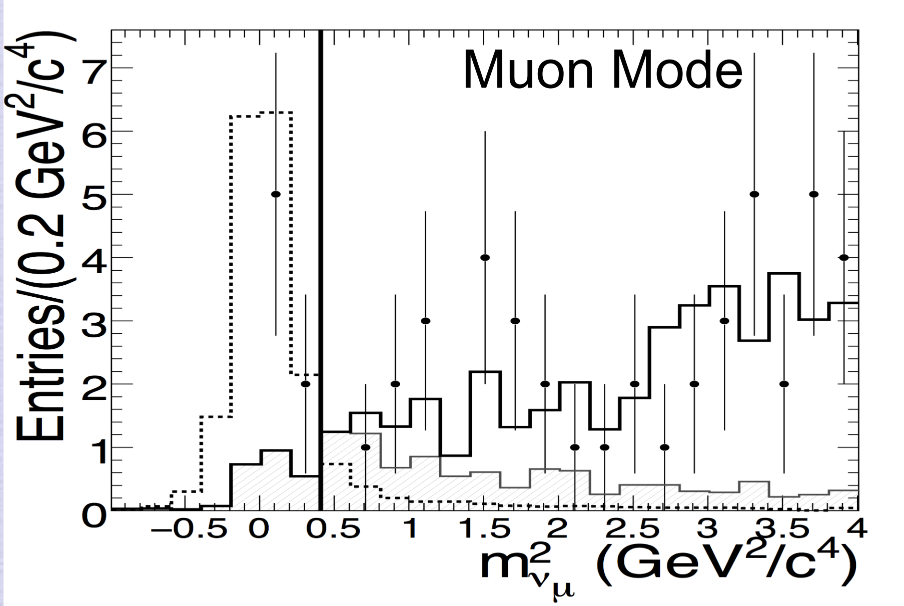
SM prediction: $BF(B\to\ell\nu\gamma) \approx 10^{-6}$
Published Limits:
$BF(B\to e\nu\gamma) < 200 \times 10^{-6}$
$BF(B\to \mu\nu\gamma) < 52 \times 10^{-6}$
Browder, *et al*. [CLEO Collab], PRD 56, 11 (1997).

$$BF = \frac{N_{obs} - N_{bkg}}{N_{B\pm} \cdot \varepsilon_{sig}}$$

	$B\to e\nu\gamma$	$B\to \mu\nu\gamma$
N_{peak}	2.4 ± 0.3 ± 0.4	2.1 ± 0.3 ± 0.3
N_{comb}	0.3 ± 0.3 ± 0.2	1.2 ± 0.6 ± 0.6
ε_{sig} ($\times 10^{-4}$)	7.8 ± 0.1 ± 0.3	8.1± 0.1 ± 0.3
N_{obs}	4	7
BF Limits	$< 17 \times 10^{-6}$	$< 26 \times 10^{-6}$

Dashed: Signal MC at BF = 40 x 10^{-6}
Grey: M_{ES}-peaking background
Black: Non-peaking background





Combined, Model-Independent Results

Since BF is expected to be independent of lepton type, we combine both modes using a maximum likelihood function

	$B\to e\nu\gamma$	$B\to\mu\nu\gamma$
N_{peak}	2.4 ± 0.3 ± 0.4	2.1 ± 0.3 ± 0.3
N_{comb}	0.3 ± 0.3 ± 0.2	1.2 ± 0.6 ± 0.6
ε_{sig} ($\times 10^{-4}$)	7.8 ± 0.1 ± 0.3	8.1± 0.1 ± 0.3
N_{obs}	4	7
BF Limits	$< 17 \times 10^{-6}$	$< 26 \times 10^{-6}$

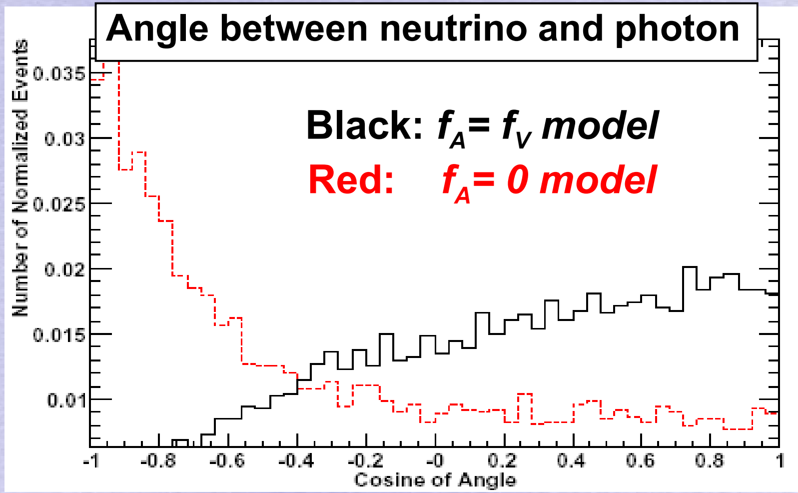
- $BF(B\to\ell\nu\gamma) = (6.5\ ^{+7.6+2.8}_{-4.7-0.8}) \times 10^{-6}$
- $BF(B\to\ell\nu\gamma) < 15.6 \times 10^{-6}$
- Signal Significance: 2.1σ
- $\lambda_B > 0.3$ GeV (using eq. on slide 3)

These results are:

- Valid over the full kinematic phasespace
- Independent of theoretical $B\to\gamma$ form-factor models because ε_{sig} is independent of the decay kinematics

Model-Dependent Limits

- Theoretically uncertain B→γ form factors affect kinematics



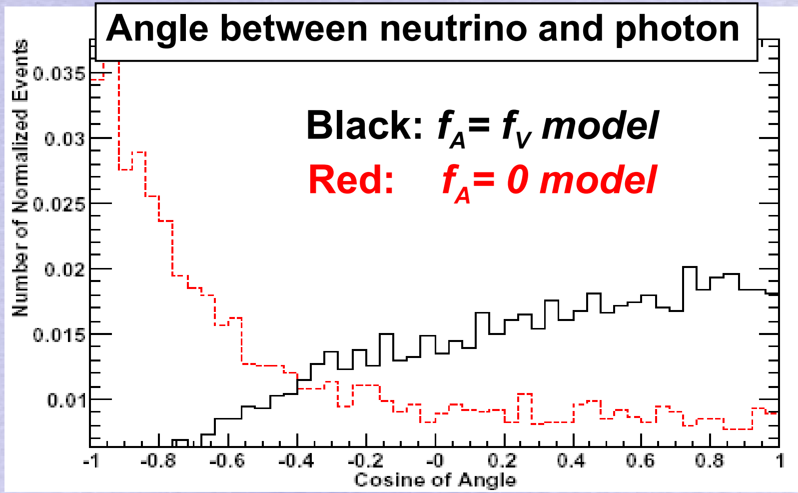
$$\frac{d\Gamma(B^+ \to \ell^+\nu\gamma)}{dE_\gamma} = \frac{\alpha G_F^2 |V_{ub}|^2 m_B^4}{48\pi^2}\left[f_V^2(E_\gamma) + f_A^2(E_\gamma)\right] x(1-x)^3$$

$$x \equiv 1 - 2E_\gamma/m_B$$

- Model-dependent limits found using the angles between the 3 daughters:
  - $f_A = f_V$ model: BF(B→ℓνγ) < 3.0 x 10^{-6}
  - $f_A = 0$ model: BF(B→ℓνγ) < 18 x 10^{-6}

Model-Dependent Limits

- Theoretically uncertain B→γ form factors affect kinematics



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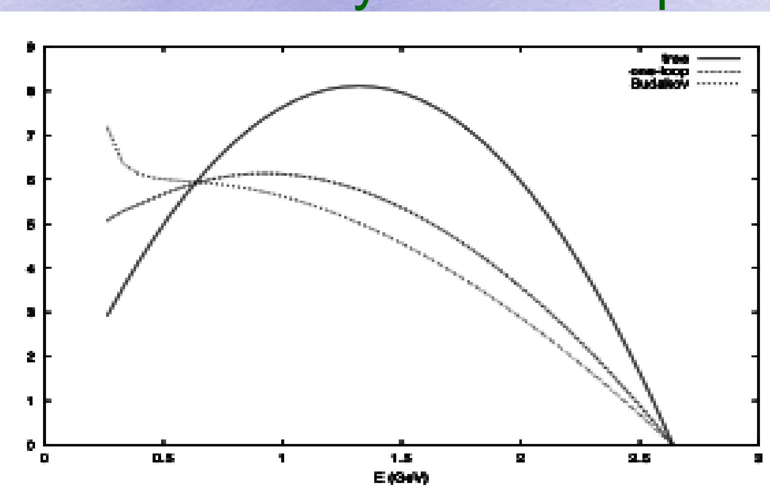
- Theoretically uncertain photon energy spectrum below Λ_{QCD}



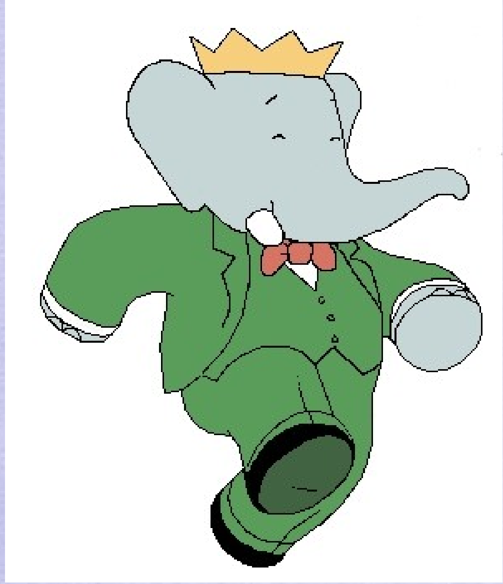
[Korchemsky, Pirjol, and Yan, PRD 61 114510 (2000).]

- B→ℓνγ with low Eγ: B→ℓν background? [Becirevic, Hass, and Kou, arXiv:0907.1845 (2009).]

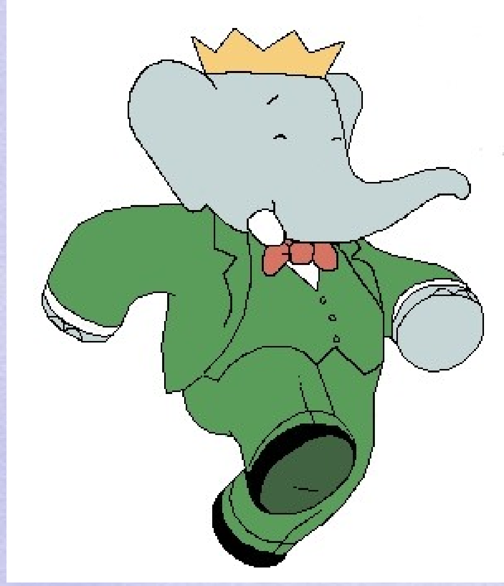
- High photon energy cut-off useful for calculation of λ_B: [Ball and Kou, JHEP04, 29 (2003).]
    - Eγ> 1GeV: ΔBF(B→ℓνγ) < 14 x 10^{-6}

Conclusion

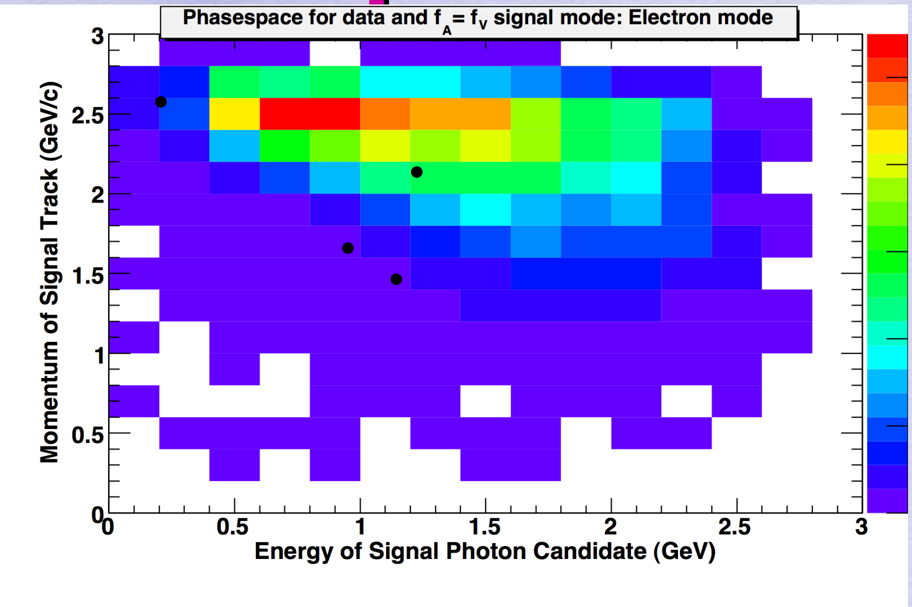
- The branching fraction measurement of $B\to\ell\nu\gamma$ is of theoretical interest for the extraction of λ_B and other SM parameters, QCD factorization, etc.
- Using the full BaBar dataset, we completed our analysis with:
  - Exclusive B reconstruction: a technique never used for this decay
  - No theoretical model dependencies and kinematic constraints
- Submitted our paper to Phys. Rev. Lett. (just last week!)
  - E-print accessible at: [arXiv: 0907.1681]

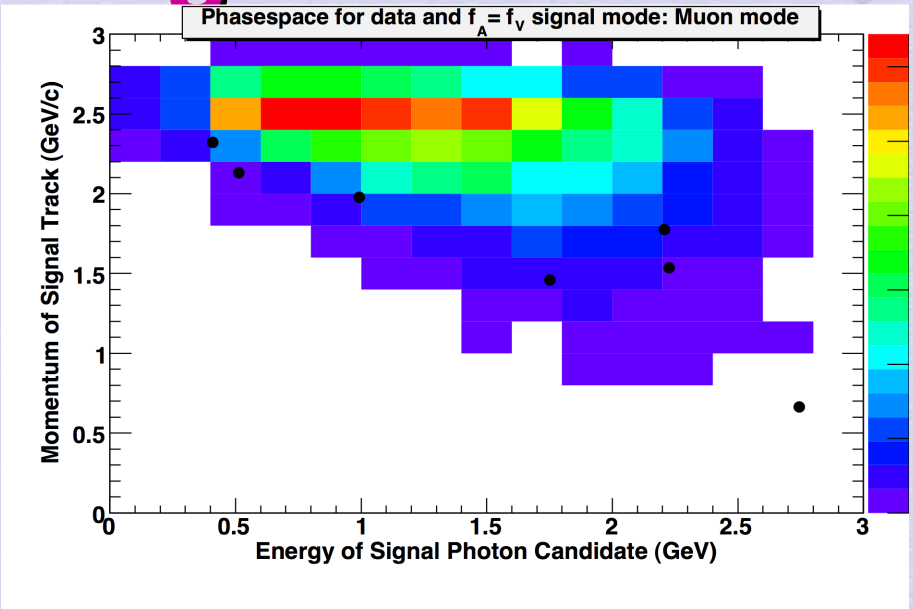


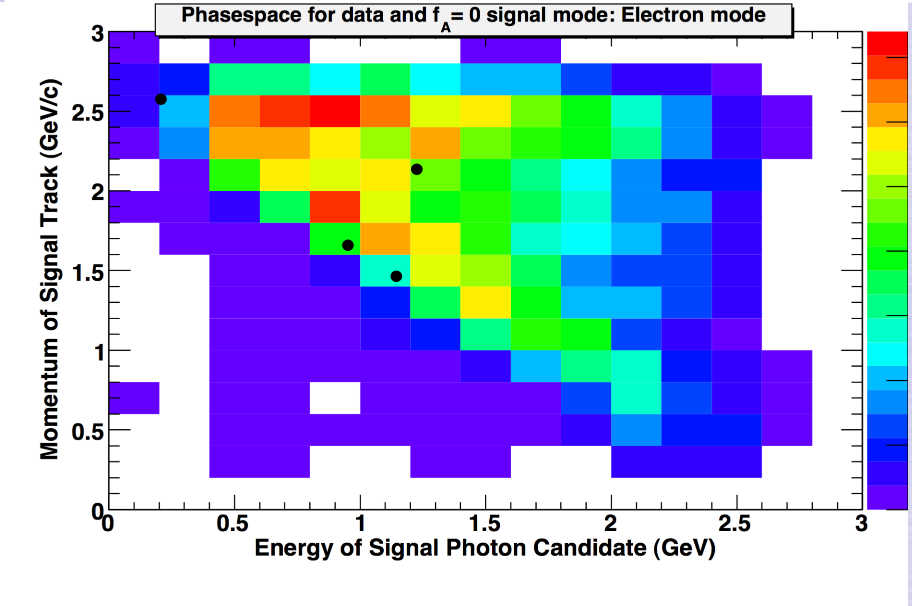
Extra Slides

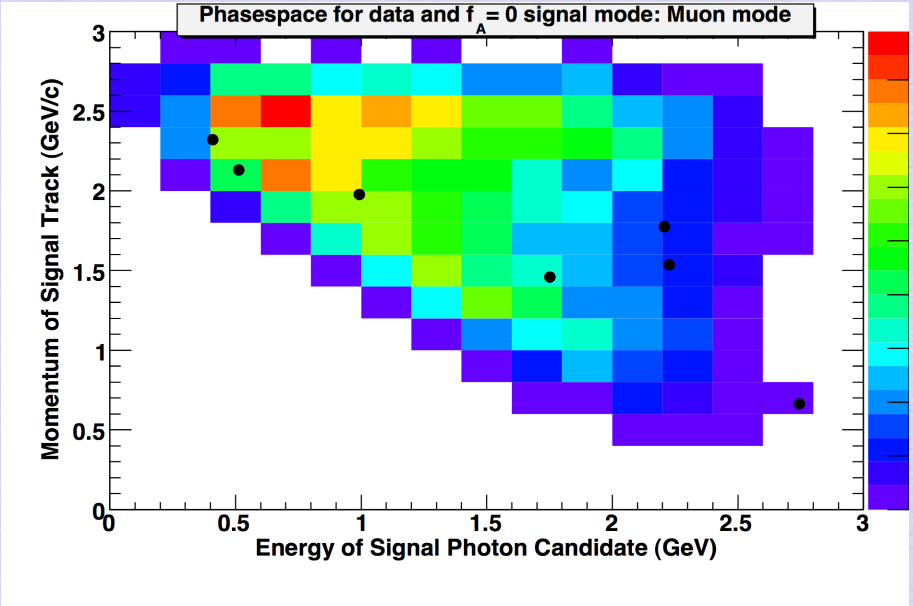


Phasespace Plots – Signal Models

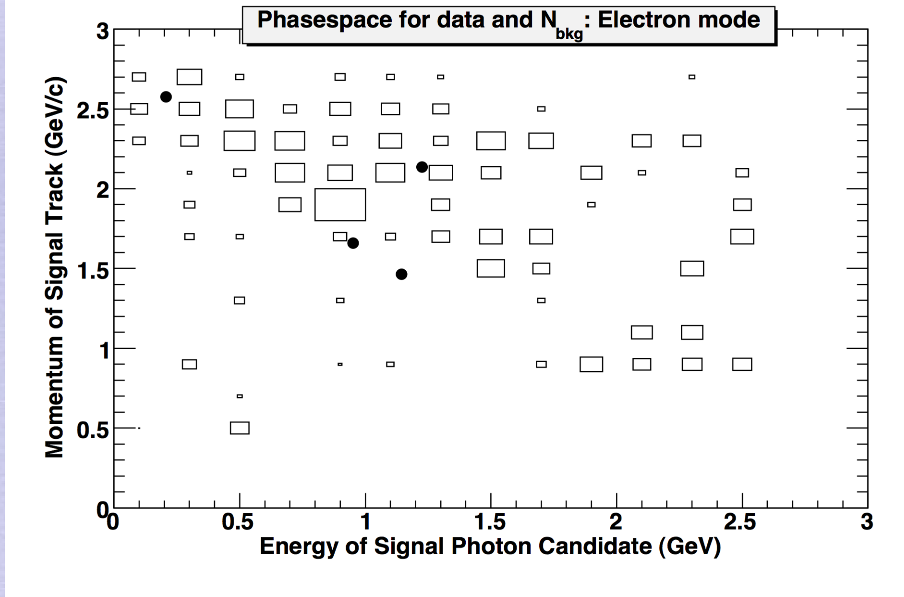


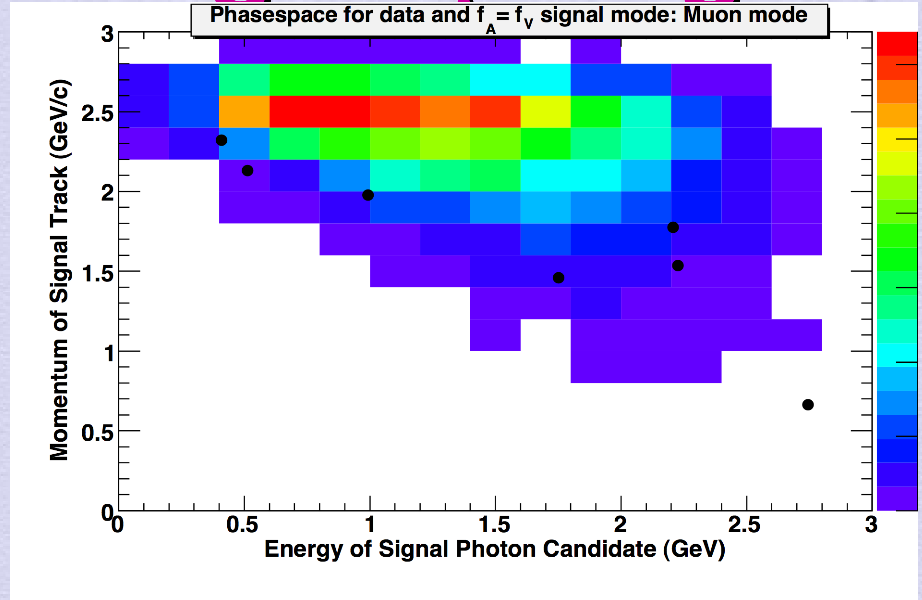


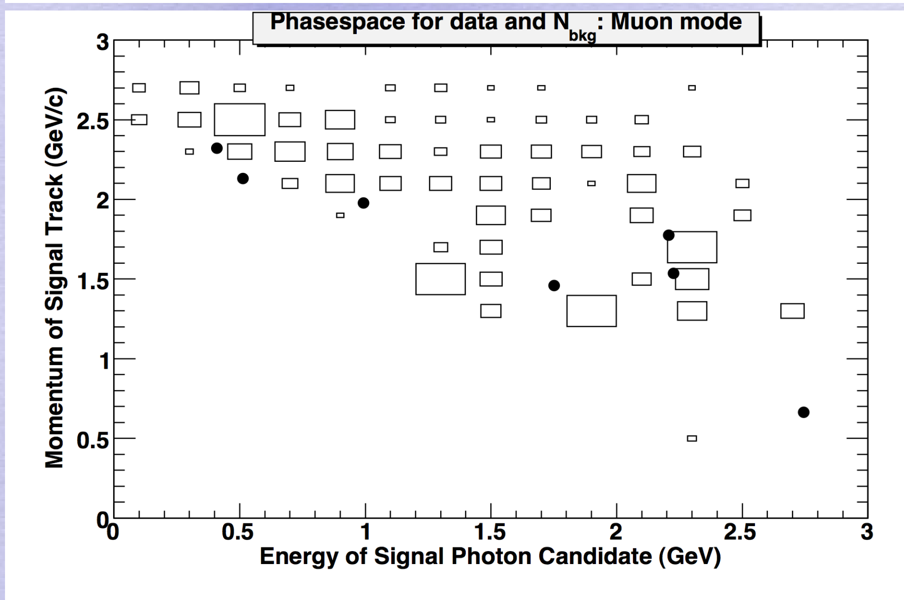


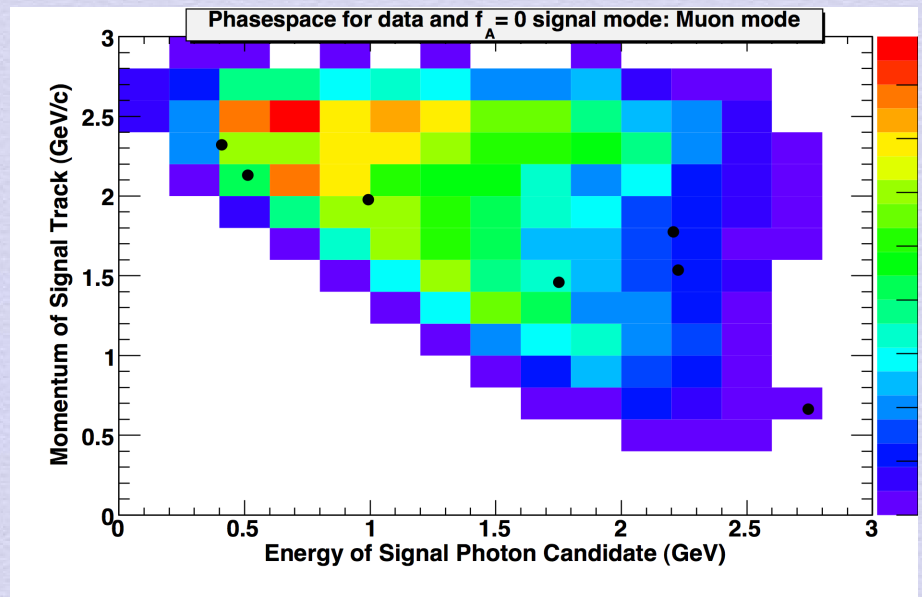


Phasespace Plots – Bkg vs μ^+ Signal

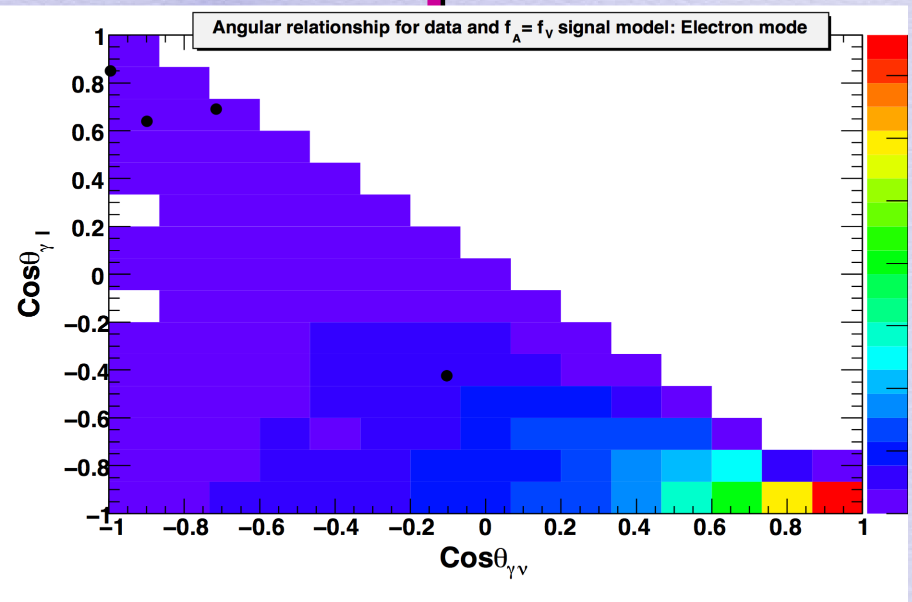


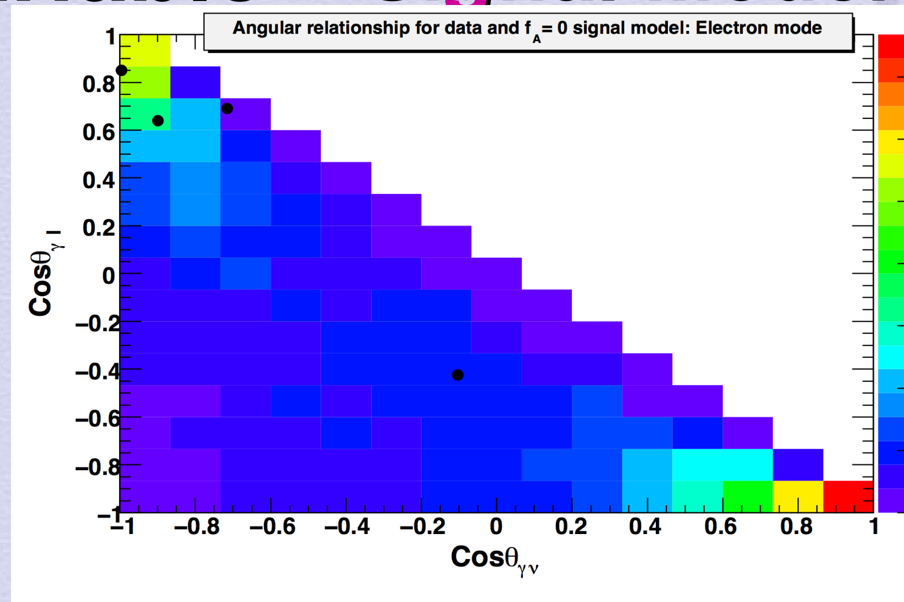


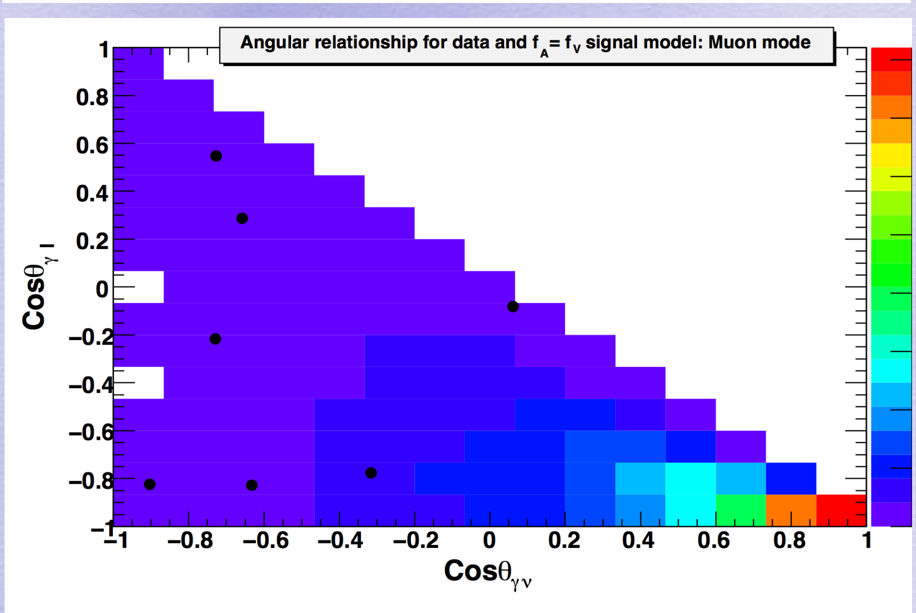


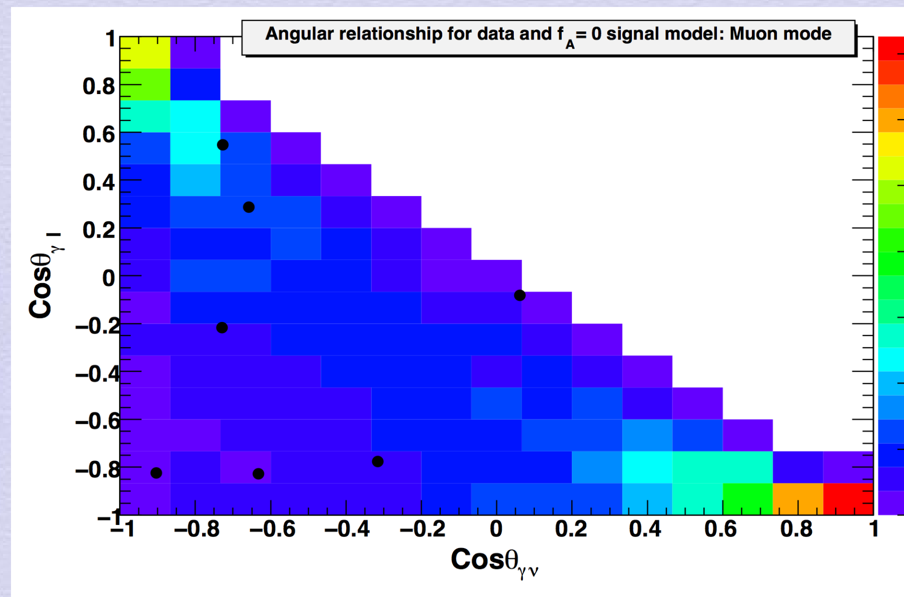


Model-Dependent Variable – Signal Models

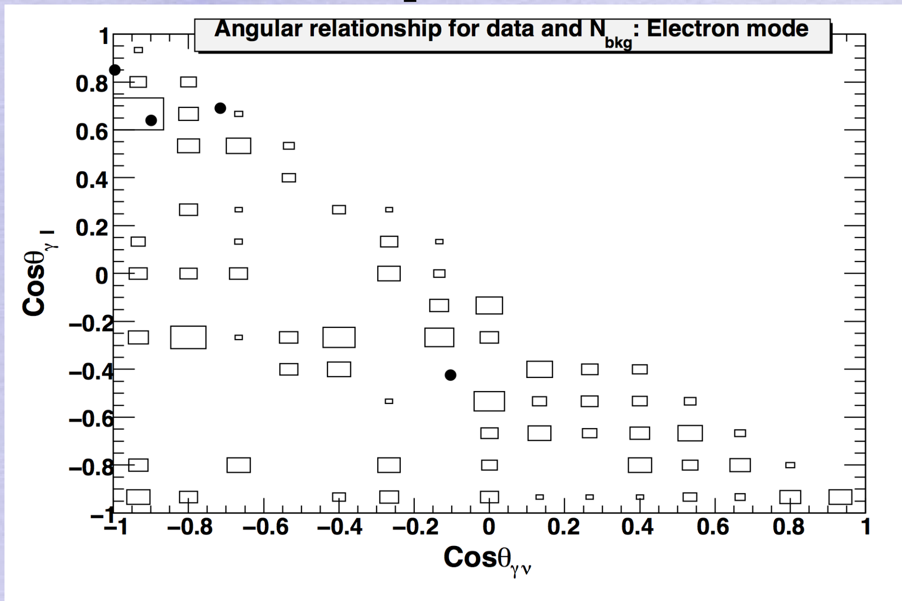


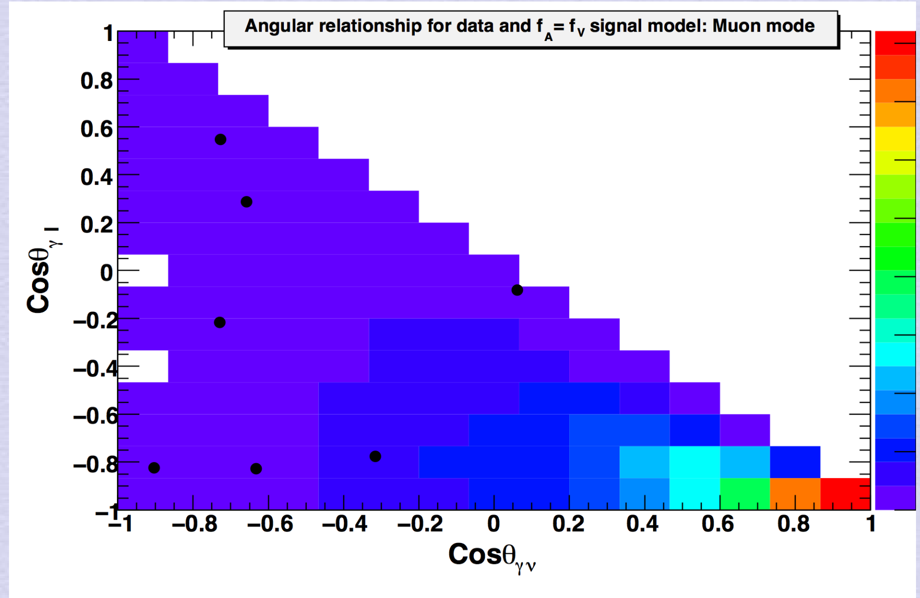


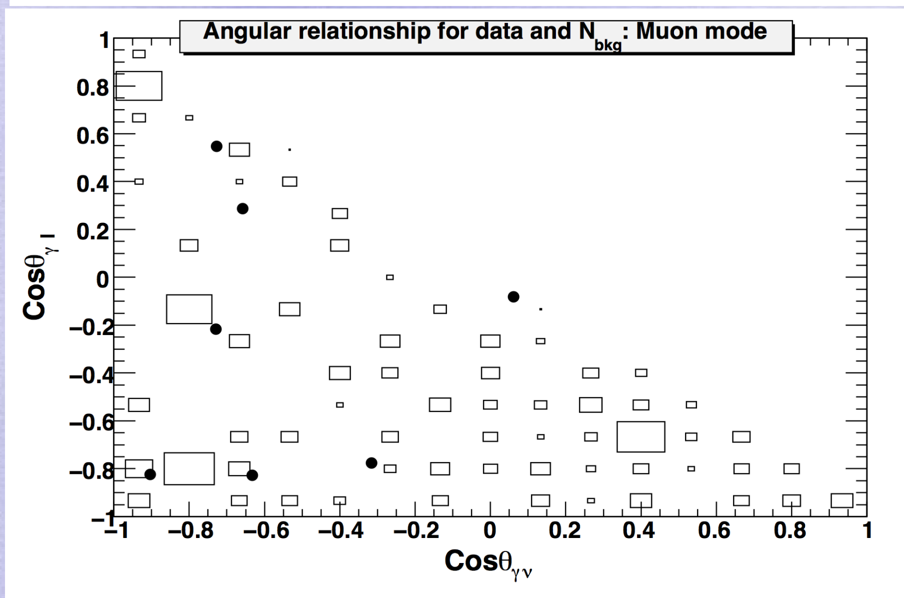


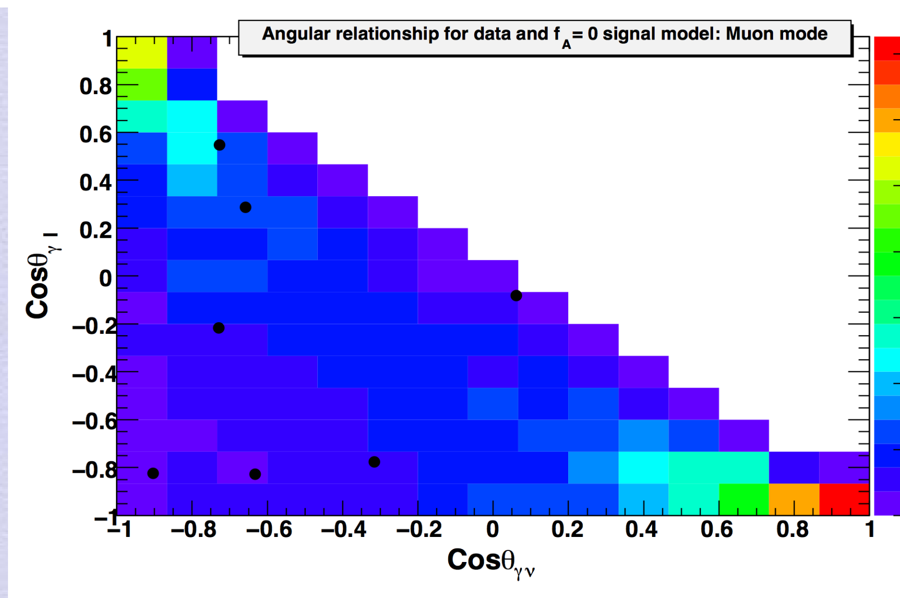


Model-Dependent Variable - Bkg vs μ^+ Signal









Uncertainties

- MC-based errors (N_{peak} and signal efficiency ε_{sig})
  - Statistical uncertainty from limited MC (signal: 1.2%, N_{peak}: 13%)
  - Efficiency disagreement between data and MC from:
    - B_{tag} reconstruction (3.1 %)
    - Tracking (0.4%)
    - Particle Identification criteria (electron: 0.9%, muon: 1.3%)
    - Reconstruction of photon candidate's energy (1.8 %)
    - m_ν^2 (signal: 0.5%, N_{peak}: 1.4%)
    - Continuum multivariate likelihood (1.4 %)

- N_{peak} also has:
  - Branching fraction and form factor uncertainties (13.6 %)

- N_{comb}
  - Dominated by sideband data statistics (electron: 100%, muon: 50.0%)
  - Combinatoric background shape uncertainty (47.4 %)