Analysis of the decay $B^+ \to \ell^+\nu\gamma, \ell^+ = e^+, \mu^+$

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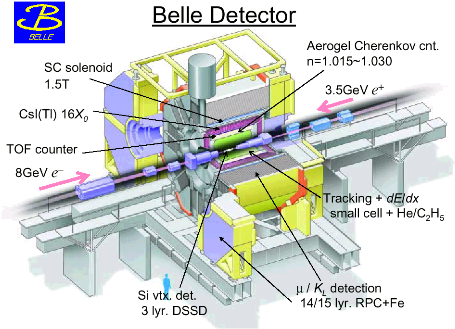
The Belle experiment

- The Belle experiment ran 1999 - 2011 at KEKB accelerator at KEK in Tsukuba, Japan
- Asymmetric e^+e^- accelerator at $Y(4S)$ energy of 10.58 GeV
  $\mathcal{B}(Y(4S) \to B\text{-}\bar{B}) \approx 96\%$
- $(771.6 \pm 10.6) \times 10^6 B\text{-}\bar{B}$ pairs measured



Helicity suppression of $B^+ \to \ell^+\nu$

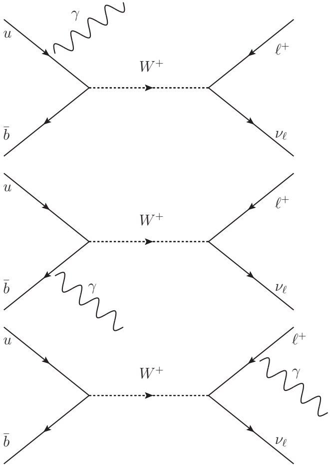
- Pure $B^+ \to \ell^+\nu$ decay is helicity suppressed
- B meson has spin 0 and decays into particle and antiparticle with opposite spin

  $\to$ Both particles are almost exclusively right- or left-handed
- A heavier lepton has a lower momentum and thus a bigger coupling to the weak current
- SM prediction: $\mathcal{B}(B^+ \to e^+(\mu^+)\nu) = 9.2 \times 10^{-12}$ (3.9×10^{-7})
- Measurement[1]: $\mathcal{B}(B^+ \to \tau^+\nu) = (1.8 \pm 0.5) \times 10^{-4}$

[1] Belle: Phys. Rev. D 82 071101, BaBar: Phys.Rev. D88 (2013) 031102

Theory of $B^+ \to \ell^+\nu\gamma$ [2]

- $B^+ \to \ell^+\nu\gamma$: Photon lifts helicity suppression but introduces additional electromagnetic coupling
- SM expectation $\mathcal{O}(\mathcal{B}(B^+ \to \ell^+\nu\gamma)) \approx 10^{-6}$
- Weak decay is precisely calculable
- Photon emission needs an approximation from heavy quark theory where $E_\gamma > 1 GeV$ is required



[2] Beneke, Rohrwild: B meson distribution amplitude from $B^+ \to \gamma\ell^+\nu$ arXiv:1110.3228 (2011)

Theory of $B^+ \to \ell^+ \nu \gamma$ [2]

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- Branching fraction depends on λ_B
  - Describes the first moment of the quark distribution amplitude inside the *B* meson
  - Theoretical calculation of the parameter unreliable
  - Important parameter for several radiative *B* meson decays

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[3] Aubert et al.: Search for the radiative leptonic decay $B^+ \to \gamma \ell^+ \nu$, arXiv:0704.1478 (2007)

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- From other measurements λ_B can be constrained
  $\to \mathcal{O}(\mathcal{B}(B^+ \to \ell^+ \nu \gamma)) \approx 10^{-6}$
- BaBar measurement of $\mathcal{B}(B^+ \to \ell^+ \nu \gamma)$ gives upper limits of $< 17 \times 10^{-6}$ (electron channel), $< 24 \times 10^{-6}$ (muon channel) [3]

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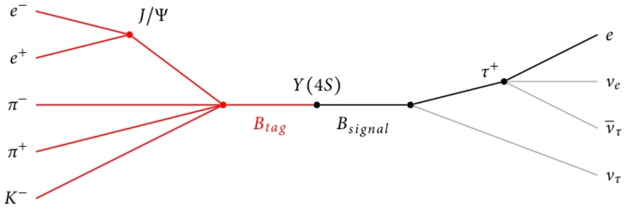
Full reconstruction[4]



- Hadronic full reconstruction covers 12% of the B^+ branching fraction
- The efficiency is in the range of 0.5%

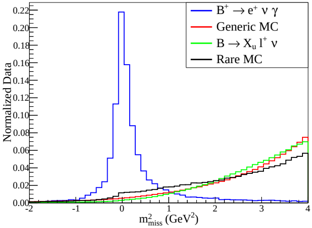
[4] Feindt et al.: A Hierarchical NeuroBayes-based Algorithm for Full Reconstruction of B Mesons at B Factories

$B^+ \to \ell^+ \nu \gamma$ analysis

- Full reconstruction of one B meson
  $\to$ Impuls des zweiten B-Mesons

  $$\to p_{B_{sig}} = (E_{Beam}/2, -\vec{p}_{B_{tag}})$$

- $m^2_{\text{miss}} = (p_{Bsig} - p_{lepton} - p_\gamma)^2$



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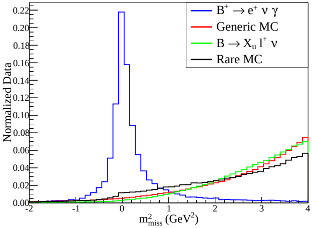


- Analysis is performed on MC (blind analysis)
- Signal branching fraction is assumed to be 5×10^{-6}
- Background simulation consists of: generic MC with $b \to c$ decays and semi-leptonic $b \to u\ell\nu$ MC with $B^+ \to \pi^0/\eta\ell^+\gamma$ processes

Pre-selection

- After full reconstruction only signal side particles are expected to be left in the detector
- Signal signature consists of a charged track and a high energetic photon

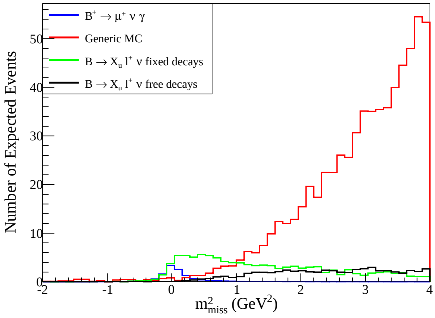
Efficient signal selection

- Highest energetic photon in the event with an energy above 1 GeV
- No charged tracks left after selection
- Lepton selection based on compounded likelihood variable
- Little remaining energy deposition in the calorimeter
- Cut on the mass of the fully reconstructed *B* meson

Signal like background

- Dominant background after pre-selection: $B^+ \to \pi^0 \ell^+ \nu$ and $B^+ \to \eta \ell^+ \nu$
- $\mathcal{B}(\pi^0 \to \gamma\gamma) \approx 99\%$, $\mathcal{B}(\eta \to \gamma\gamma) \approx 40\%$

- Decays are similar to signal if only one photon is found
- Second photon originating from the meson is searched in the detector with specific variables



Meson vetoes

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- Meson masses of π^0, η are reconstructed from signal photon candidate an the remaining photons in the calorimeter
- Meson candidate with mass closest to its nominal mass is kept

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  $\rightarrow$ Mass spectra are computed with different energy cuts on the background photons

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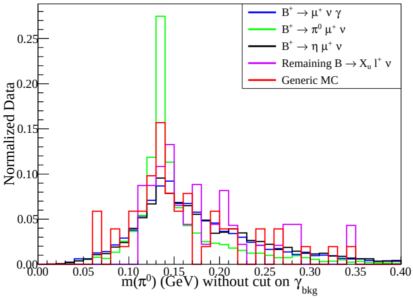
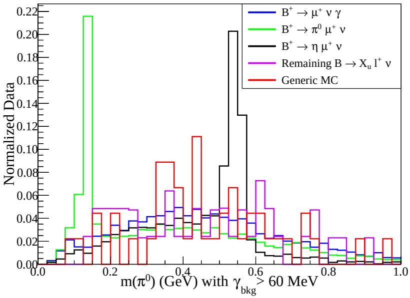
  $\rightarrow$ Mass spectra are computed with different energy cuts on the background photons

  $\rightarrow$ Leads to different mass distributions with complementary information
- Meson mass spectra are gathered in neural network which is used for selection

Meson vetoes

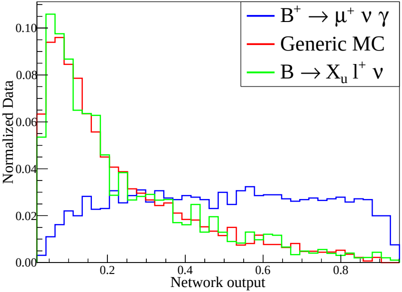




Network training

- Neural net is trained with NeuroBayes[5]
- Training: Signal-MC against $X_u \ell \nu$ MC and especially $B^+ \rightarrow \pi^0 \ell^+ \gamma$

- Additional variables in the network are the remaining energy in the calorimeter and angles among the signal candidate particles
- Signal is measured with a fit of the missing mass in 6 bins of the network output



[5] Feindt: A Neural Bayesian Estimator for Conditional Probability Densities, arXiv:physics/0402093 (2004)

Network output data-MC comparison

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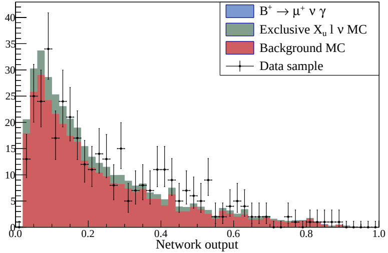
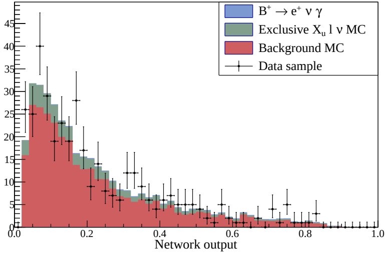
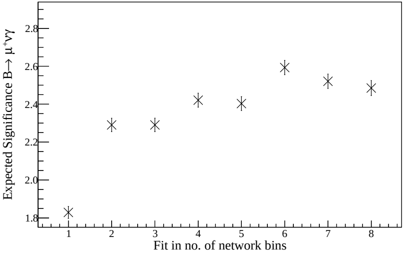


Muon channel



Electron channel

Network bin optimization



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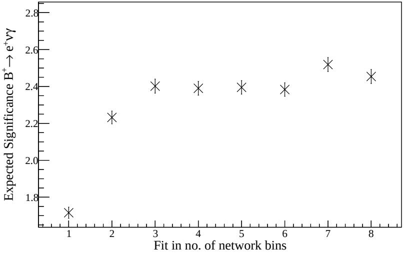
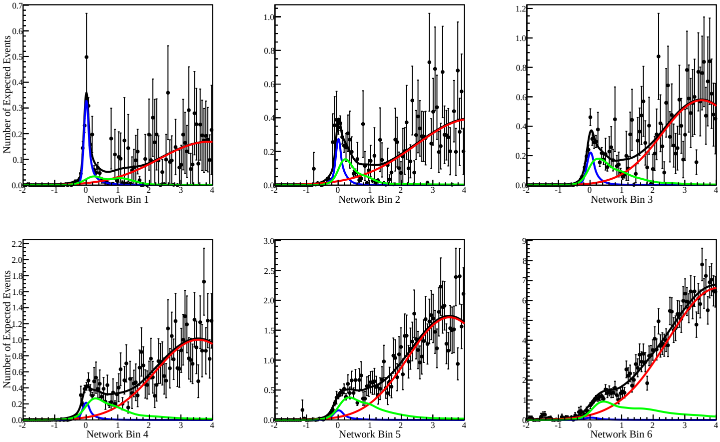
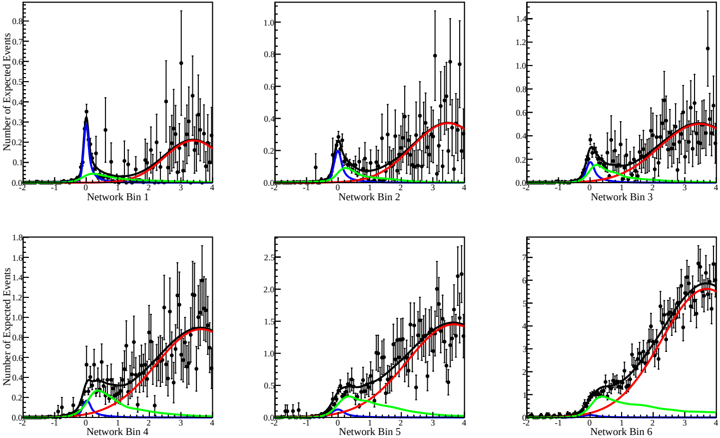


Electron channel

Fit shapes, muon channel



Fit shapes, electron channel



Signal extraction

- Yield of the dominant $B^+ \to X_u \ell^+ \nu$ backgrounds is fixed to MC prediction

  $\to$ Two free fit parameters are the signal and one background yield

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  $\to$ Two free fit parameters are the signal and one background yield
- Electron and muon channel are fitted separately and simultaneously
- Several tests are performed with toy MC studies: linearity test, confidence interval coverage, bootstrapped toy MC

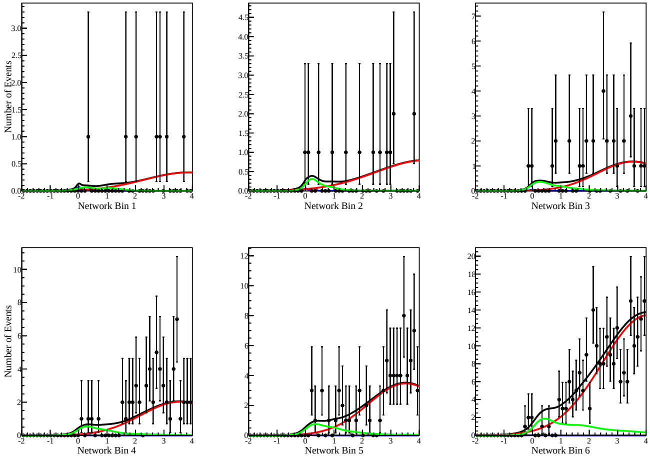
  $\to$ No bias is found for significant measurements

  $\to$ Confidence interval coverage is too large

Systematic error

Sample	muon channel	electron channel
Meson veto network	-0.58	-0.66
Fit shapes	$^{+0.75}_{-1.34}$	$^{+0.64}_{-1.06}$
Fixing of $B \to X_u \ell^+ \nu$	± 0.18	± 0.24
$B^+ \to \ell^+ \nu \gamma$ model	-0.01	-0.05
Tag side efficiency	± 0.35	± 0.34
Continuum suppression	-0.13	-0.4
Tracking efficiency	-0.01	-0.01
Lepton ID	± 0.42	± 0.18
$N_{B\bar{B}}$	± 0.11	± 0.11
Sum	$^{+1.14}_{-1.59}$	$^{+1.10}_{-1.39}$
	Simultaneous fit	
Sum	$^{+1.81}_{-2.29}$	

Measurement on data, muon channel



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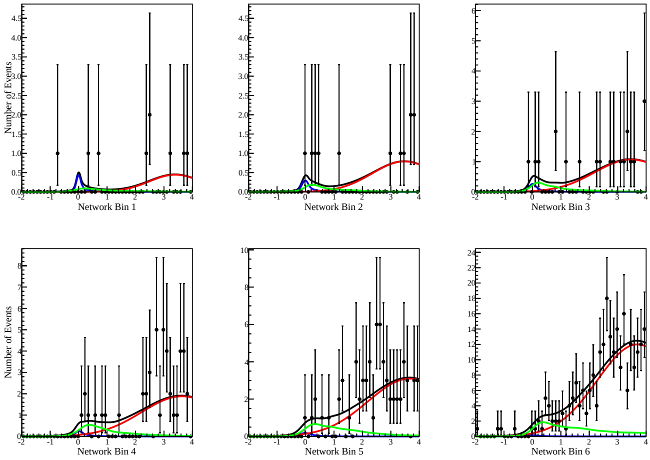
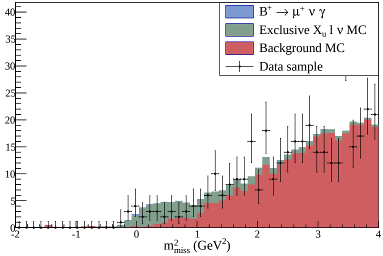
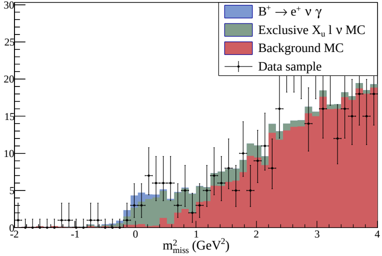


Fit results on data one bin



Muon channel



Electron channel

Measurement on data

Default analysis E(γ_{sig}) $>$ 1 GeV

Sample	Yield	significance in σ	BR limit $\times 10^6$ (90% CL)
$B^+ \to e^+\nu\gamma$	$6.1^{+4.9+1.1}_{-3.9-1.4}$	1.4	13.2
$B^+ \to^+ \nu\gamma$	$0.9^{+3.6+1.1}_{-2.6-1.6}$	0.4	7.1
$B^+ \to \ell^+\nu\gamma$	$6.6^{+5.7+1.8}_{-4.7-2.3}$	1.4	7.3

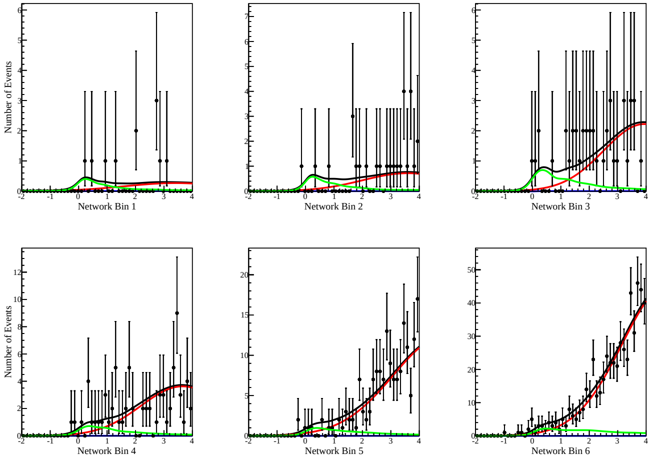
Secondary analysis with E(γ_{sig}) $>$ 400 MeV

Sample	Yield	significance in σ	BR limit $\times 10^6$ (90% CL)
$B^+ \to e^+\nu\gamma$	$11.9^{+7.0+1.9}_{-6.0-2.4}$	2.0	14.4
$B^+ \to \mu^+\nu\gamma$	$-0.1^{+5.2+1.9}_{-4.1-2.3}$	-	6.3
$B^+ \to \ell^+\nu\gamma$	$11.3^{+8.4+3.1}_{-7.4-3.6}$	1.5	7.6

For the yields the first error is statistical, the second error is systematic.
Significances and upper limits contain systematic errors.

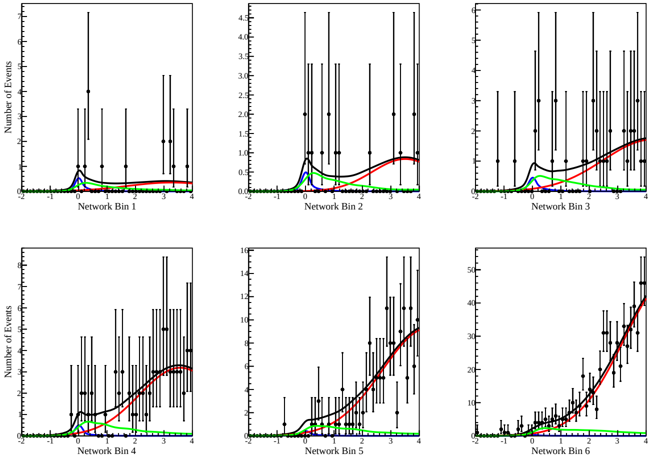
Backup Slides

Measurement on data, muon channel, secondary analysis



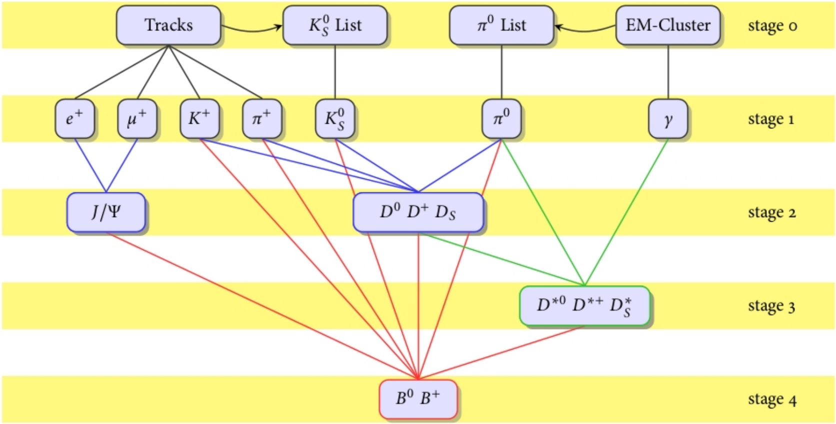
Muon channel with E(γ_{sig}) $>$ 400 MeV.

Measurement on data, electron channel, secondary analysis



Electron channel with E(γ_{sig}) $>$ 400 MeV.

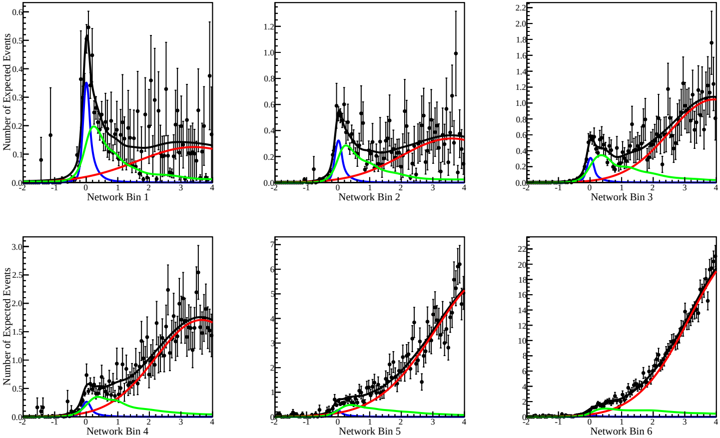
Hierarchische Ansatz der vollständigen Rekonstruktion



Netwerkvariablen

- Extraenergie im ECL
- Winkel zwischen Signal γ und ν
- m(π^0) mit E(γ_{rem}) $>$ 40 MeV
- m(π^0) ohne Schnitt auf E(γ_{rem})
- m(η) mit E(γ_{rem}) $>$ 300 MeV
- Winkel zwischen Signal γ und Lepton
- m(η) mit E(γ_{rem}) $>$ 100 MeV
- m(π^0) mit E(γ_{rem}) $>$ 60 MeV
- m(π^0) mit ECL-Schnitten skaliert um 0.6

Fitformen: Myonkanal für Sekundäranalyse E(γ_{sig}) $>$ 400 MeV



Fitformen: Elektronkanal für Sekundäranalyse E(γ_{sig}) $>$ 400 MeV

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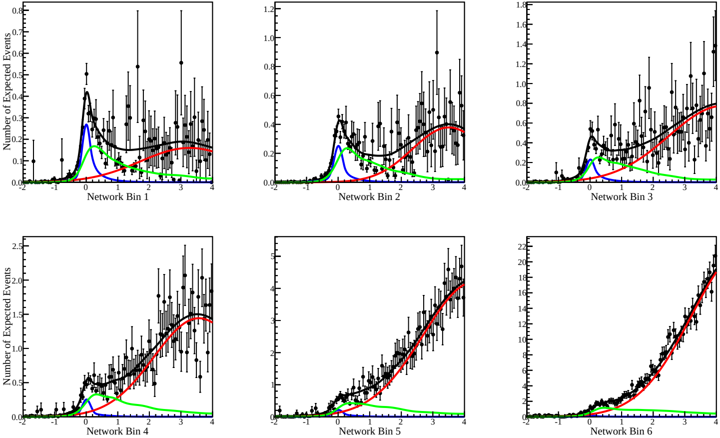
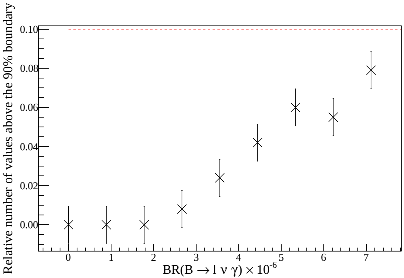
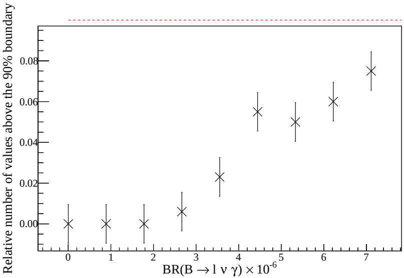


Übergroßes Konfidenzintervall für oberes Limit



Muon channel



Electron channel

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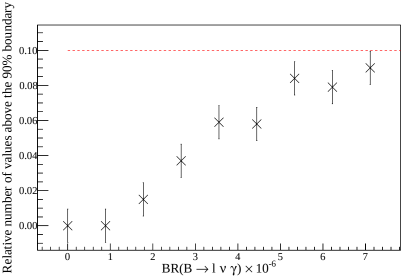
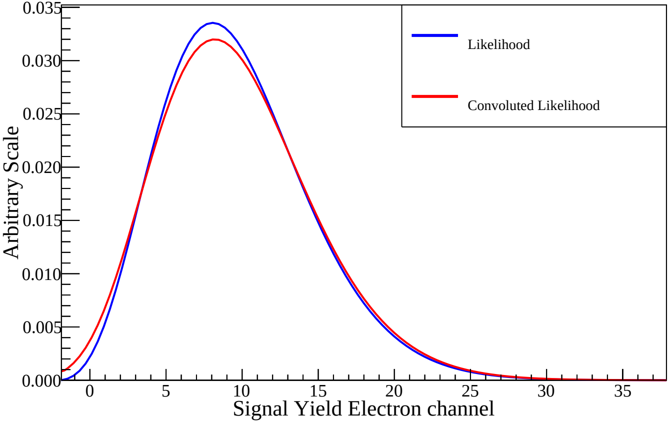


Simultaneous fit

Systematische Fehler für die Sekunäranalyse mit E(γ_{sig}) $>$ 400 MeV

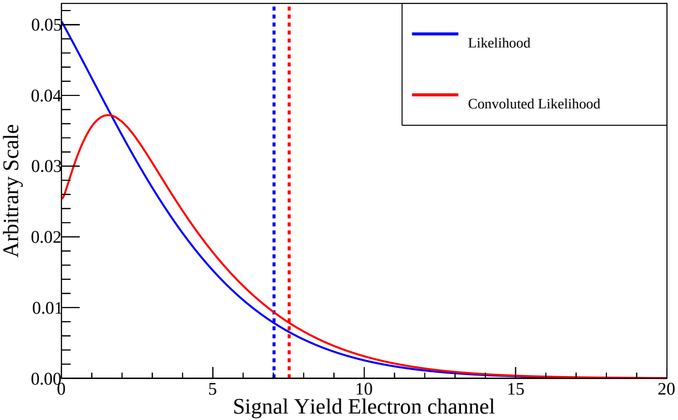
Datensatz	Myonkanal	Elektronkanal
Mesonveto Netzwerk	-0.91	-1.08
Fitformen	$^{+1.18}_{-1.69}$	$^{+1.27}_{-1.9}$
$B \rightarrow X_u \ell^+ \nu$ Normierung	± 0.31	± 0.41
$B^+ \rightarrow \ell^+ \nu \gamma$ Modell	+0.8	+0.4
Tagseiteneffizienz	± 0.52	± 0.51
Kontinuumsunterdrückung	+0.19	-0.48
Trackingeffizienz	-0.02	-0.02
Lepton ID	± 0.62	± 0.27
$N_{B\bar{B}}$	± 0.17	± 0.17
Summe	$^{+1.92}_{-2.27}$	$^{+1.92}_{-2.39}$
	Simultanfit	
Summe	$^{+3.05}_{-3.58}$	

Faltung eines signifkanten Likelihoods



Likelihood für den Elektronkanal

Faltung eines signifkanten Likelihoods



Likelihood für den Elektronkanal

Erwartete Signifikanz

Primäranalyse mit E(γ_{sig}) $>$ 1 GeV			
Datensatz	Erwartete Messung	Signifikanz in σ	Erwartetes Limit $\times 10^6$ (90% CL)
Elektron	$8.0 \pm 4.5\,^{+1.1}_{-1.4}$	2.4 (2.1)	7.02 (7.46)
Myon	$8.7 \pm 4.6\,^{+1.1}_{-1.6}$	2.5 (2.2)	6.50 (6.93)
Simultanfit	$16.5 \pm 6.5\,^{+1.8}_{-2.3}$	3.6 (2.9)	4.35 (4.76)

Sekundäranalyse mit E(γ_{sig}) $>$ 400 MeV			
Datensatz	Erwartete Messung	Signifikanz in σ	Erwartetes Limit $\times 10^6$ (90% CL)
Elektron	$12.4 \pm 6.2\,^{+1.9}_{-2.4}$	2.4 (2.1)	6.54 (6.78)
Myon	$11.9 \pm 6.0\,^{+1.9}_{-2.3}$	2.5 (2.2)	5.98 (6.23)
Simultanfit	$24.9 \pm 8.7\,^{+3.1}_{-3.6}$	3.4 (2.9)	4.08 (4.30)

Erwartete Messung und Signifikanz für Signal mit BR = 5×10^6 und erwartetes oberes Limit ohne Signal. Werte in Klammern beinhalten systematische Fehler.

- Signifikanzen werden durch eine Likelihoodverhältnis bestimmt
- Obergrenzen werden durch Integration eines Likelihoods bestimmt, wobei nur der positive Teil berücksichtigt wird