B_s decays to invisibles: First limit from LEP and possibilities at FCC-ee

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based on 2310.13043
with: Gonzalo Alonso-Álvarez

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Why Now?

- **Belle II [2311.14647]** Evidence for $B^+ \to K^+\nu\bar{\nu}$ Decays
  3.5σ **evidence for** $B^+ \to K^+\bar{\nu}\nu$ **decays using an inclusive tagging. This rate is** 2.7σ **larger than the SM prediction.**

- **This would be evidence for a** $b \to s\bar{\nu}\nu$ **transition and thus** $B_s \to \bar{\nu}\nu$ **could be a key channel to help in the interpretation. In particular because** $\mathrm{BR}(B_s \to \bar{\nu}\nu)|_{\mathrm{SM}} \propto (m_\nu/m_B)^2 \simeq 0$

- **However :** when including S and P operators. Presently, no upper limit on the branching ratio of $B_s^0 \to$ invisibles exists,
  (simply because B_s are not produced in the $\Upsilon(4S)$)
  Bause, Gisbert & Hiller 2309.00075

- **Then:** The first limit on invisible decays of B_s mesons comes from LEP
  Gonzalo Alonso-Álvarez[1,2,*] and Miguel Escudero Abenza[3,†]

recast of an old ALEPH analysis:

$$\mathrm{BR}(B_s \to \bar{\nu}\nu) < 6 \times 10^{-4}$$

2310.13043

Outline

- Status of $B \to K\bar{\nu}\nu$ transitions and interpretation
- Searches for b decays with large missing energy at LEP
  - The basic elements of the analysis
  - Results
- $B \to \text{invisibles}$ at FCCee: Lessons learned from LEP
- Implications for other scenarios*:

  B-Mesogenesis

  Flavorful Axions

Belle II results

Belle II [2311.14647] has recently reported 3.5σ evidence for $B^+ \to K^+\bar{\nu}\nu$ decays using an inclusive tagging. What is intriguing is that the rate appears to be 2.7σ larger than the SM prediction.

This mode at B-factories: $\bar{B}B(\to K\bar{\nu}\nu)$

a) Hadronic Tag

$\bar{B} \to$ hadrons

eff $\sim 0.4\,\%$

b) Semileptonic Tag

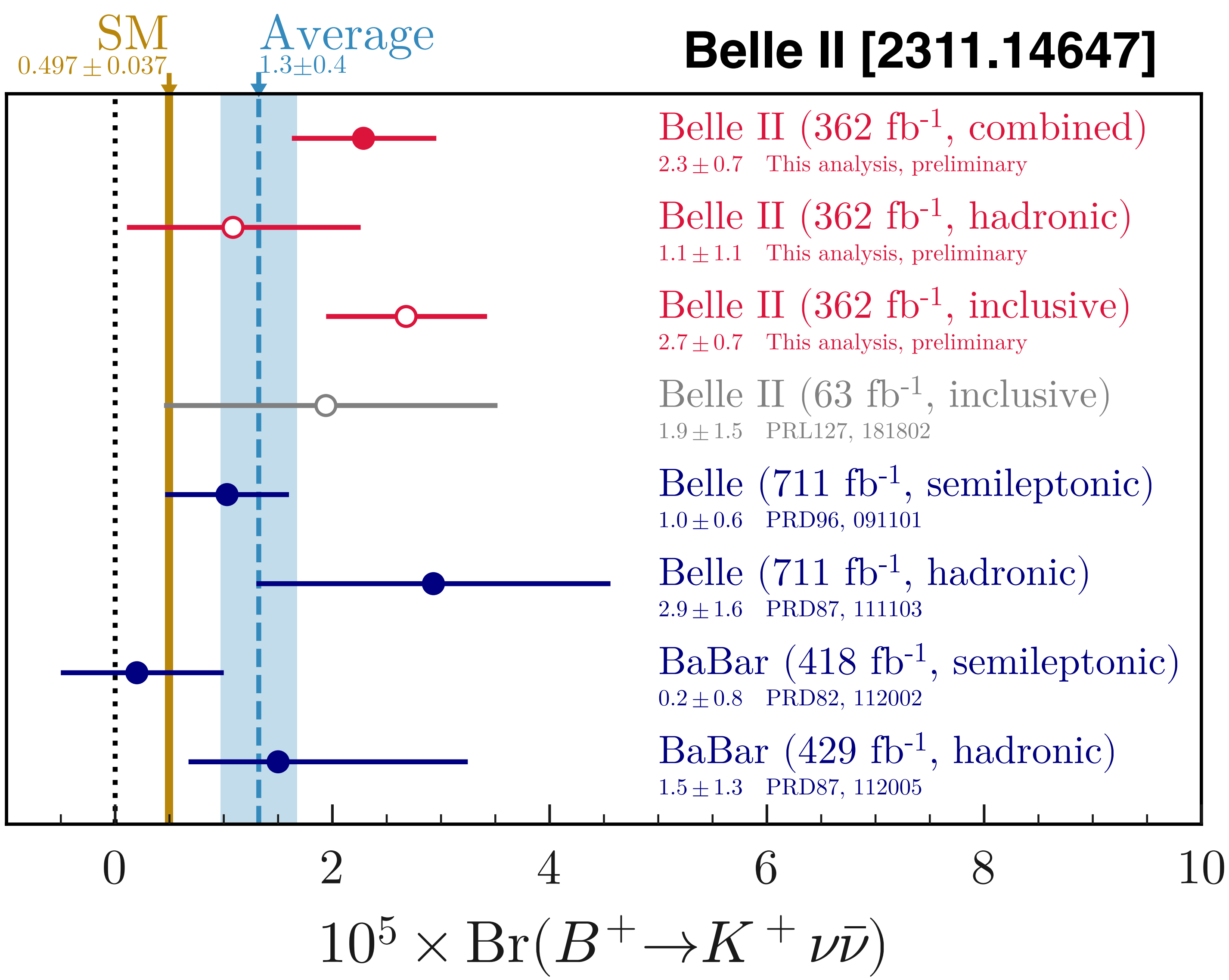
$\bar{B} \to \nu\ell^+X$

eff $\sim 1.6\,\%$

c) Inclusive Tag

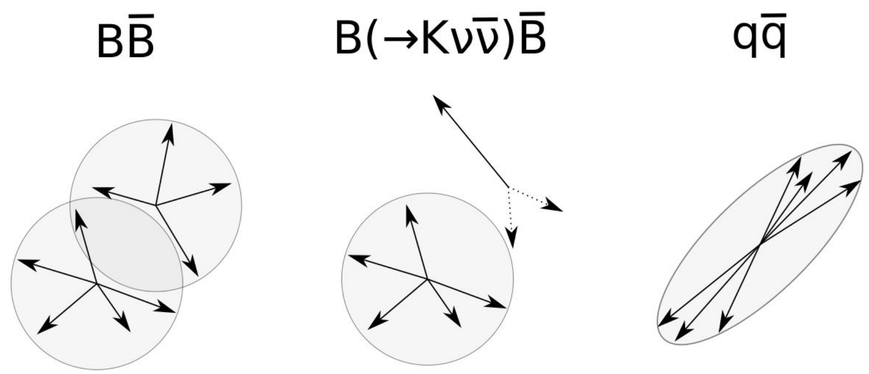
$\bar{B} \to$ anything

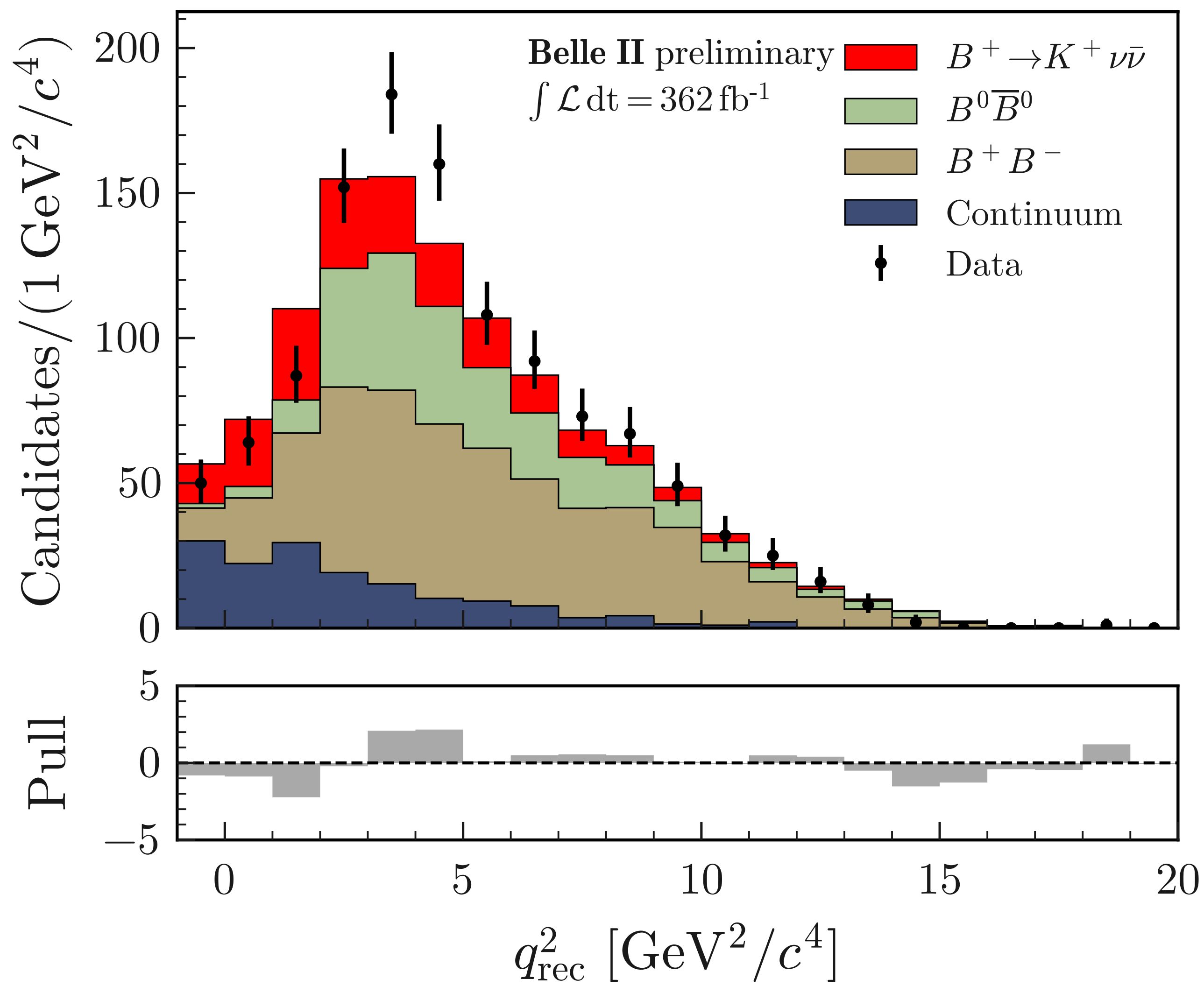
eff $\sim 8\,\%$



Belle II : Inclusive Analysis

Series of boosted decision trees on global properties of the event:





$$q^2_{\mathrm{rec}} = E_B^2 + m_K^2 - 2E_B E_K$$

Combined Result: $\mathrm{BR}(B^+ \to K^+\bar{\nu}\nu) = (2.3 \pm 0.7) \times 10^{-5}$

2.7σ **larger**

Standard Model: $\mathrm{BR}(B^+ \to K^+\bar{\nu}\nu)|_{\mathrm{SM}} = (0.51 \pm 0.03) \times 10^{-5}$

Bečirević, Piazza & Sumensari 2301.06990

Belle II BSM interpretations

1) Heavy New Physics:

2309.02246 Allwicher, Bečirević, Piazza, Rosauro-Alcaraz & Sumensari
2309.00075 Bause, Gisbert & Hiller

Models face the strong constraint of $\mathrm{BR}(B \to K^\star \bar{\nu}\nu) < 1.8\,\mathrm{BR}(B \to K^\star \bar{\nu}\nu)|_{\mathrm{SM}}$

This requires right handed couplings to quarks which imply non-minimal BSM sectors which need to be balanced to avoid flavor constraints

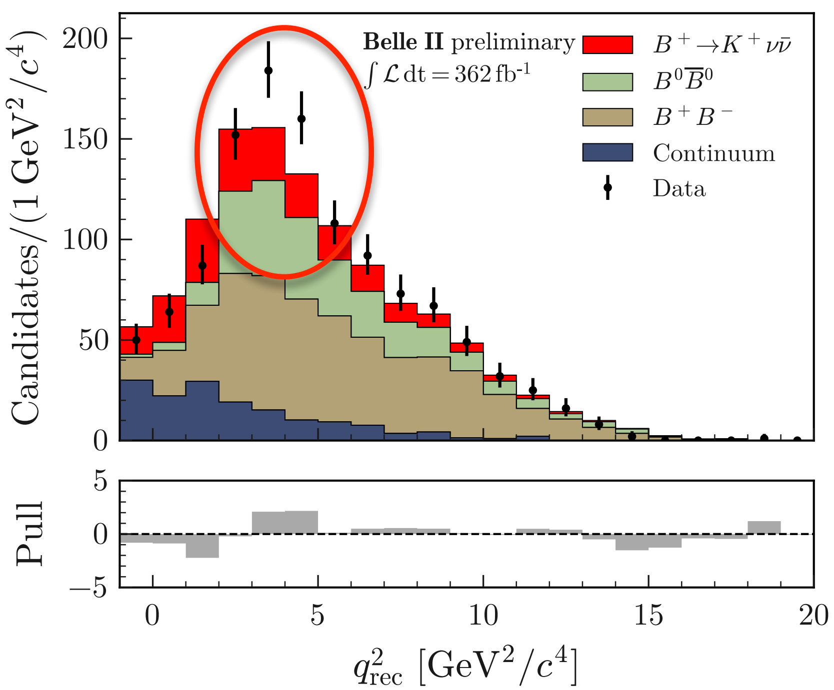
e.g., 2 leptoquarks

2) Light New Physics:

2311.14629 Altmannshofer, Crivellin, Haigh, Inguglia & Martin Camalich
2312.12507 Fridell, Ghosh, Okui & Tobioka
2312.00982 McKeen, Ng & Tuckler
2309.02940 Felkl, Giri, Mohanta & Schmidt

Decays of the type $B \to KX$ or $B \to K\chi\chi$ could explain even better the Belle II spectrum

Belle II [2311.14647]



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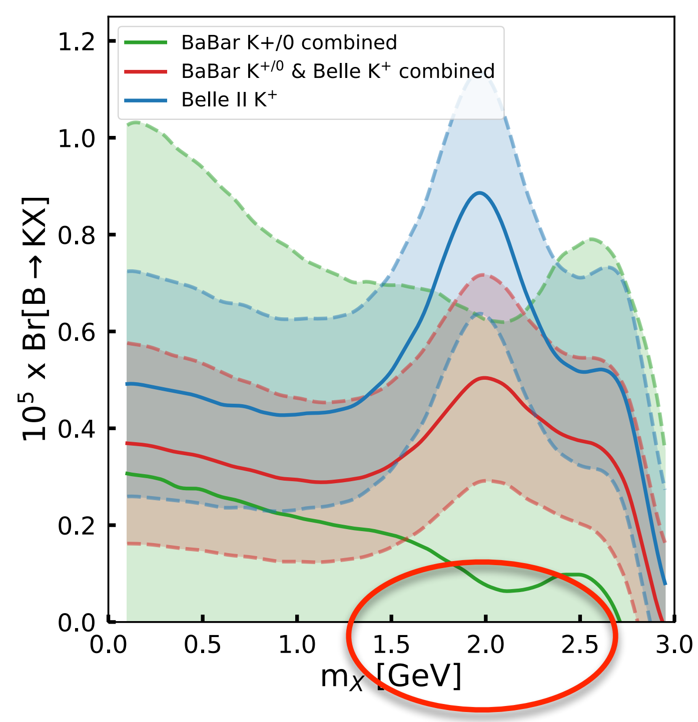
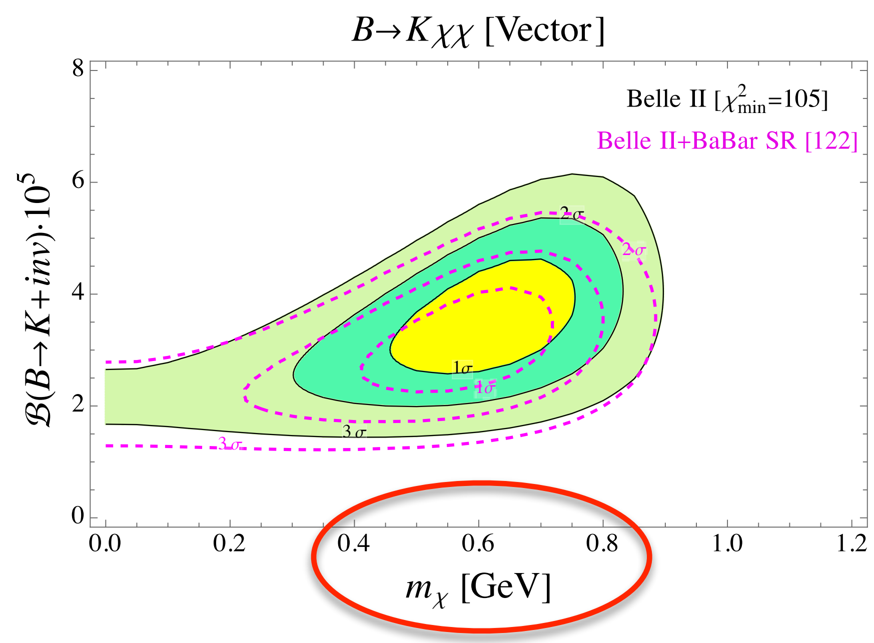


2312.12507



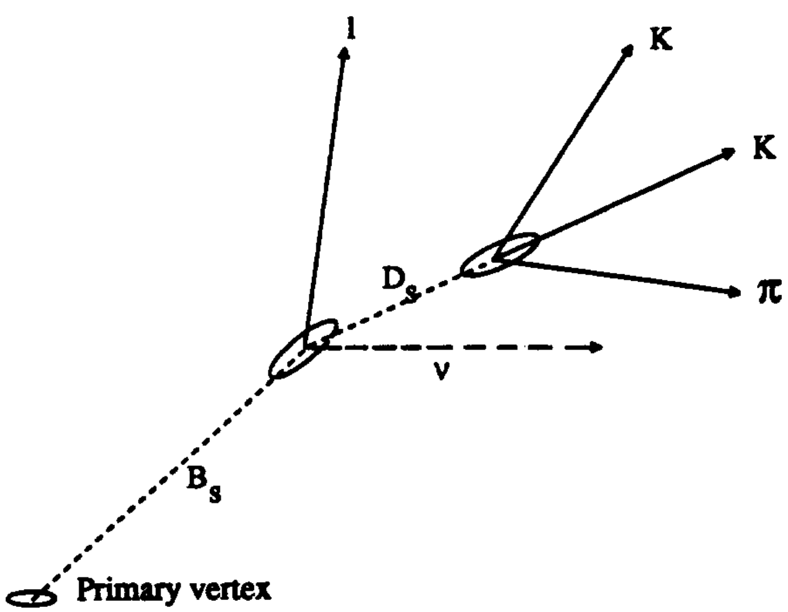
This means that $B_s \to$ invisibles decays are key to elucidate the situation $\mathrm{BR} \sim 10^{-4}$

Searches for b-decays with ME at LEP

Missing Energy was a key observable in many b-quark physics analysis at the LEP experiments:

Measurement of the B_s^0 lifetime

ALEPH Collaboration



D_s^- and the lepton respectively. The neutrino energy (E_ν) is estimated using a missing energy technique. It is given by

$$E_\nu = E_{\text{tot}} - E_{\text{vis}} ,$$

where E_{tot} and E_{vis} are the total and visible energies in the same hemisphere as the B_s^0 candidate. The vis-

Measurement of the $b \to \tau^- \bar{\nu}_\tau X$ branching ratio and an upper limit on $B^- \to \tau^- \bar{\nu}_\tau$

ALEPH Collaboration

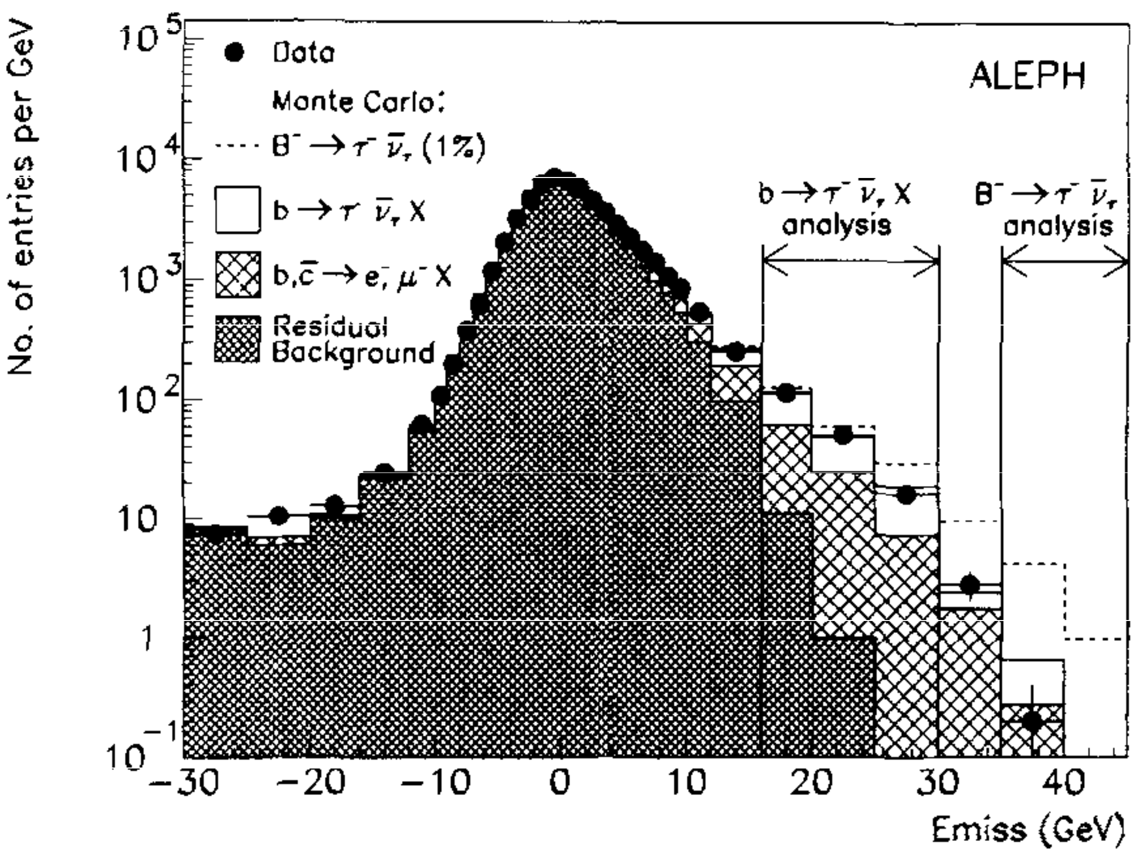


Fig. 4. E_{miss} spectrum for $B^- \to \tau^- \bar{\nu}_\tau$ exclusive analysis.

Searches for b-decays with ME at LEP

In fact: the first limit on $b \to s\bar{\nu}\nu$ comes from LEP:

hep-ph/9510378

First limit on inclusive $B \to X_s \nu\bar{\nu}$ decay and constraints on new physics

Yuval Grossman [a,1], Zoltan Ligeti [b,2], Enrico Nardi [a,3]
[a] *Department of Particle Physics, Weizmann Institute of Science, Rehovot 76100, Israel*
[b] *California Institute of Technology, Pasadena, CA 91125, USA*

Received 2 November 1995; accepted 29 January 1996

Subsequent analysis by ALEPH (hep-ex/0010022) lead to:

$$\mathrm{Br}(b \to s\bar{\nu}\nu) < 6.4 \times 10^{-4}$$ **at 90% CL**

$$\mathrm{Br}(b \to s\bar{\nu}\nu)\,|_{\mathrm{SM}} = (2.7 \pm 0.2) \times 10^{-5}$$

0902.0160: Altmannshofer, Buras, Straub & Wick

Also Grossman, Ligeti and Nardi (hep-ph/9607473) $B \to \tau\tau$ $B \to \nu\nu\gamma$

There is no b-decay that can lead to more ME than $B \to \mathrm{invisibles!}$

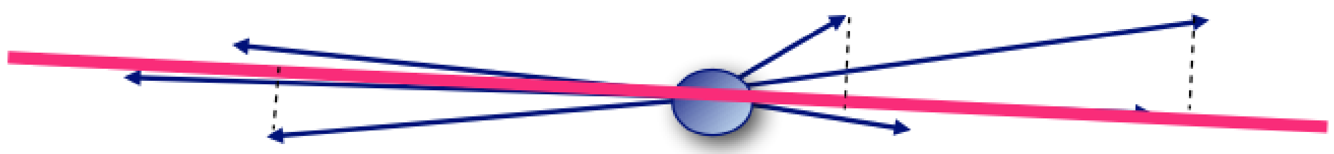
Our study: $$\mathrm{Br}(B_s \to \mathrm{invisibles}) < 5.9 \times 10^{-4}$$ **at 90% CL**

The Process

Essence of the analyses at ALEPH

1) Look at 2-jet events, $Z \to \bar{q}q$: $T > 0.85$ and $|\cos\theta| < 0.7$

2) Separate events in two hemispheres defined by the thrust axis



$$T = \max_{\vec{n}} \frac{\sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$$

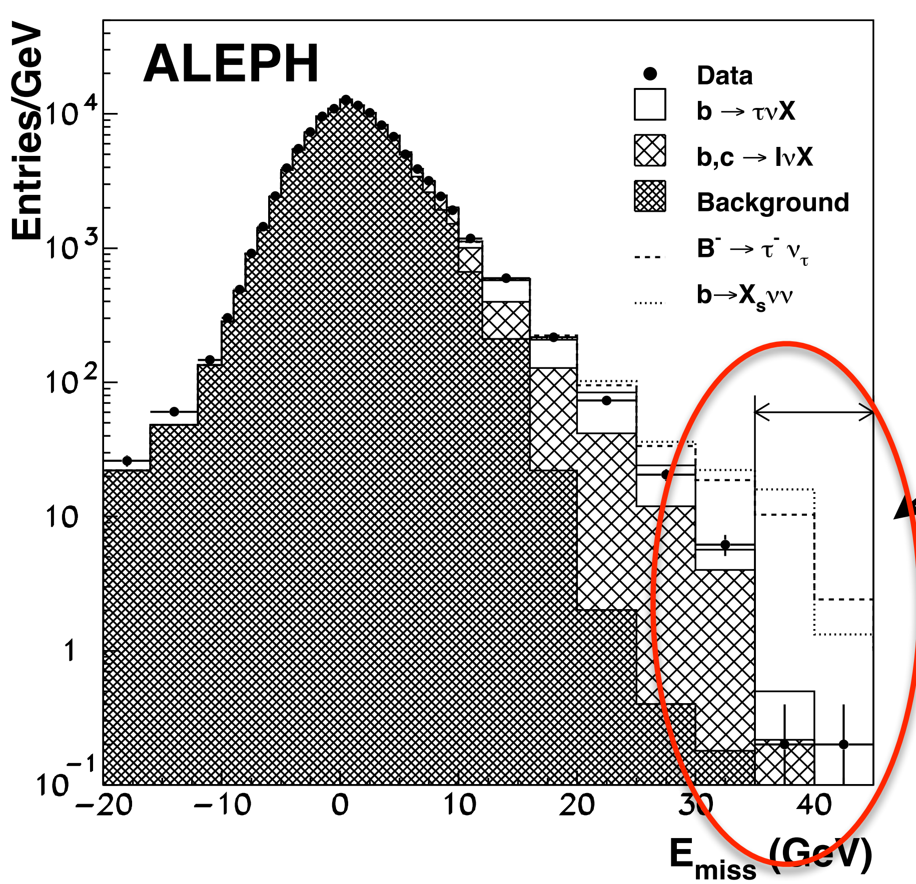
3) Measure missing energy as $E_{\rm miss} \simeq M_Z/2 - E_{\rm vis}$

4) Only use opposite hemispheres with $E_{\rm miss} < 25\,{\rm GeV}$ and $\geq$ 6 charged tracks

5) Apply b-tagging in the hemisphere without large missing energy

6) Use e/μ rejection algorithms to remove $b, \bar{c} \to \ell\nu X$ events

Result:
hep-ex/0010022



Prediction of the spectrum

1) What is the fraction of the beam energy carried out by the B_s?

~ 70%

DELPHI 1102.4748

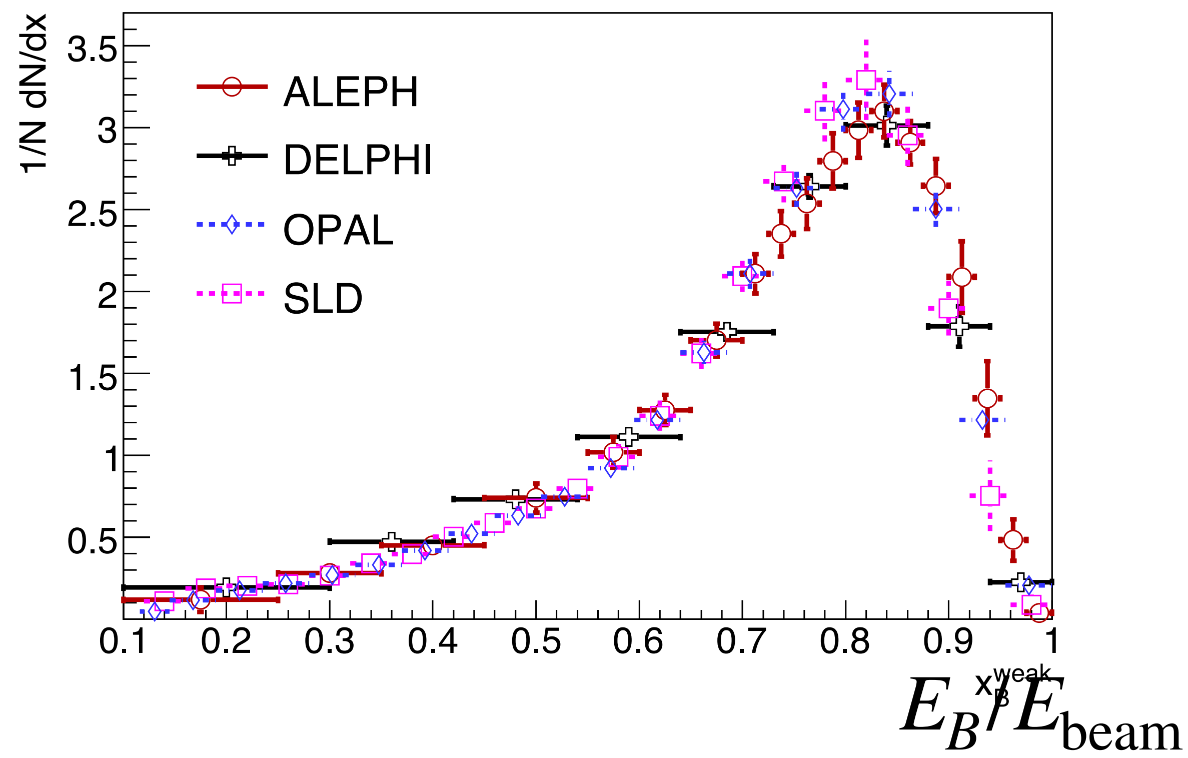


Figure 13: Comparison between the various measurements of the b-quark fragmentation distribution versus $x_{\rm B}^{\rm weak}$.

2) Hadronization fractions [HFLAV]

$$f_{B_s} = 0.101 \pm 0.008\,,$$
$$f_{B_d/B^\pm} = 0.407 \pm 0.007\,,$$
$$f_{\rm b-baryons} = 0.085 \pm 0.011\,.$$

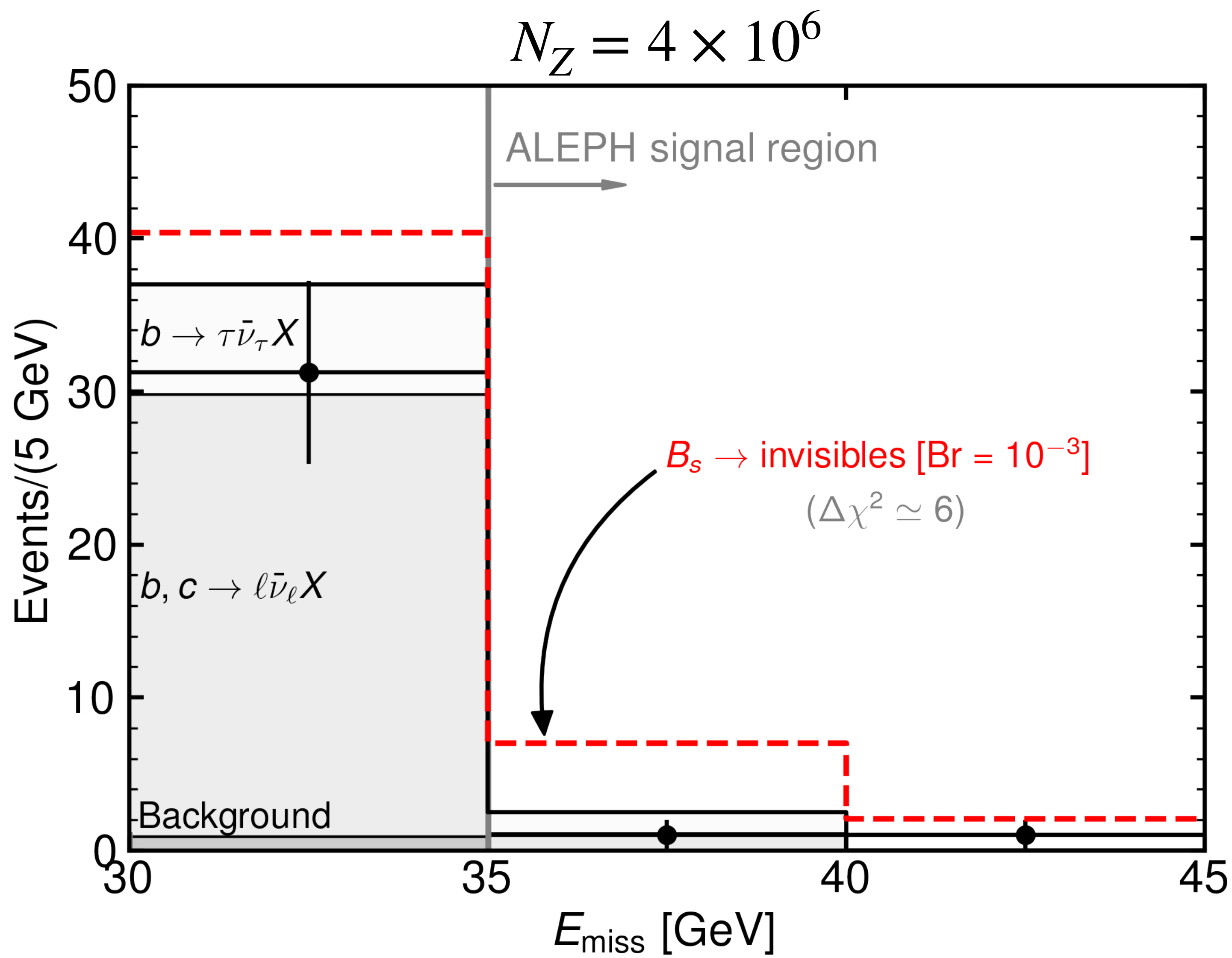
3) Number of events: $N(Z \to \text{hadrons}) = 4 \times 10^6$

$$\text{Br}(Z \to b\bar{b})/\text{Br}(Z \to \text{hadrons}) \simeq 22\,\%$$

4) The efficiency after all of the cuts are performed is $8\,\%$:

$$\text{efficiency}(B^- \to \tau^- \bar{\nu}_\tau) = 8.1\,\%$$
$$\text{efficiency}(b \to s\bar{\nu}\nu) = 8.8\,\%$$

Results



$$\mathrm{Br}(B_s \to \text{invisibles}) < 5.9 \times 10^{-4}$$ **at 90% CL**

$$\mathrm{Br}(B_d \to \text{invisibles}) < 1.4 \times 10^{-4}$$ **at 90% CL**

Power of the searches and outlook

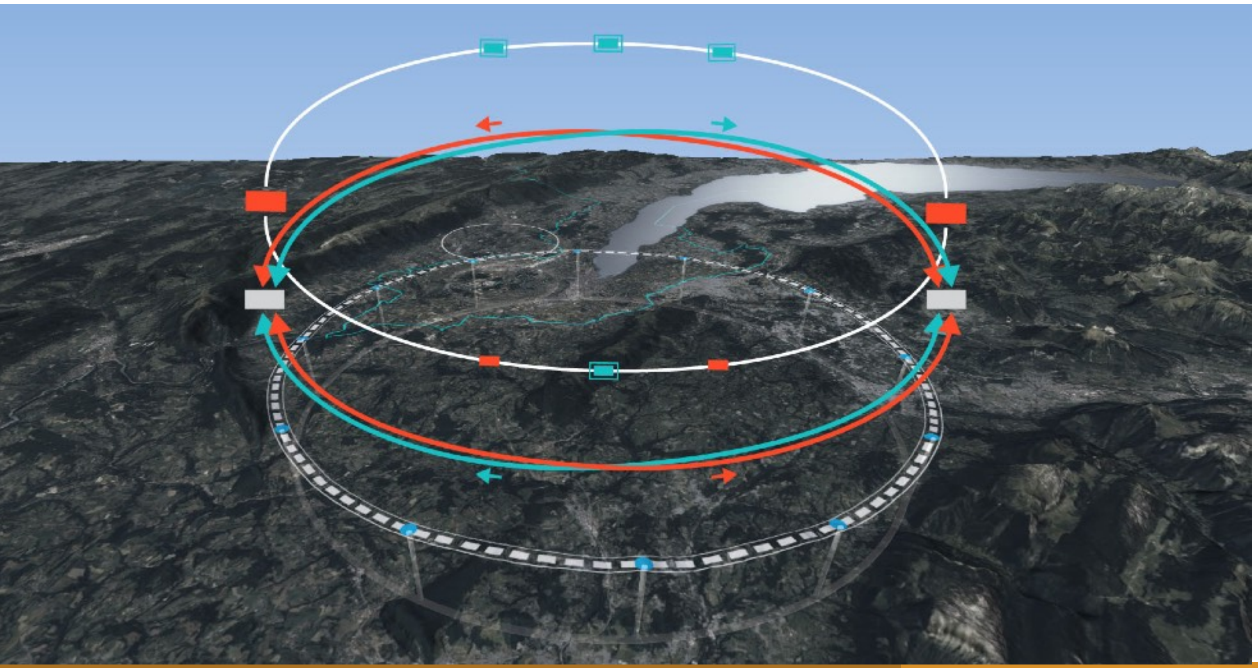
	Limit at 90% CL	$N_{b\bar{b}}$
LEP:	$\mathrm{Br}(B_d \to \text{invisibles}) < 1.4 \times 10^{-4}$	$0.9\,\mathrm{M}$
BaBar: 1206.2543	$\mathrm{Br}(B_d \to \text{invisibles}) < 2.4 \times 10^{-5}$	$471\,\mathrm{M}$

Belle II with $\mathscr{L} = 5\,\mathrm{ab}^{-1}$ at the $\Upsilon(5S)$ resonance:

$\mathrm{Br}(B_s \to \text{invisibles}) < 10^{-5}$ **1808.10567**

and improve our limit by a factor of 40!

Ideal place to look at these decays: FCCee



Sensitivity beyond $\sim 10^{-5}$ dependent upon further tagging methods since, e.g. $\mathrm{Br}(b \to s\bar{\nu}\nu)|_{\mathrm{SM}} = (2.7 \pm 0.2) \times 10^{-5}$.

see Amhis et al. 2105.13330, 2309.11353 and Fedele et al. 2305.02998

and talk this morning by Matthew Kenzie

FCCee: lessons learned

see: CDS-link '94

Measurement of the $b \rightarrow \tau^- \overline{\nu}_\tau$ X Inclusive/Exclusive Branching Ratios

I.R. Tomalin
C.E.R.N.

- **Muon and electron detection efficiencies are key to reduce background. In particular, muon efficiencies at low momentum**

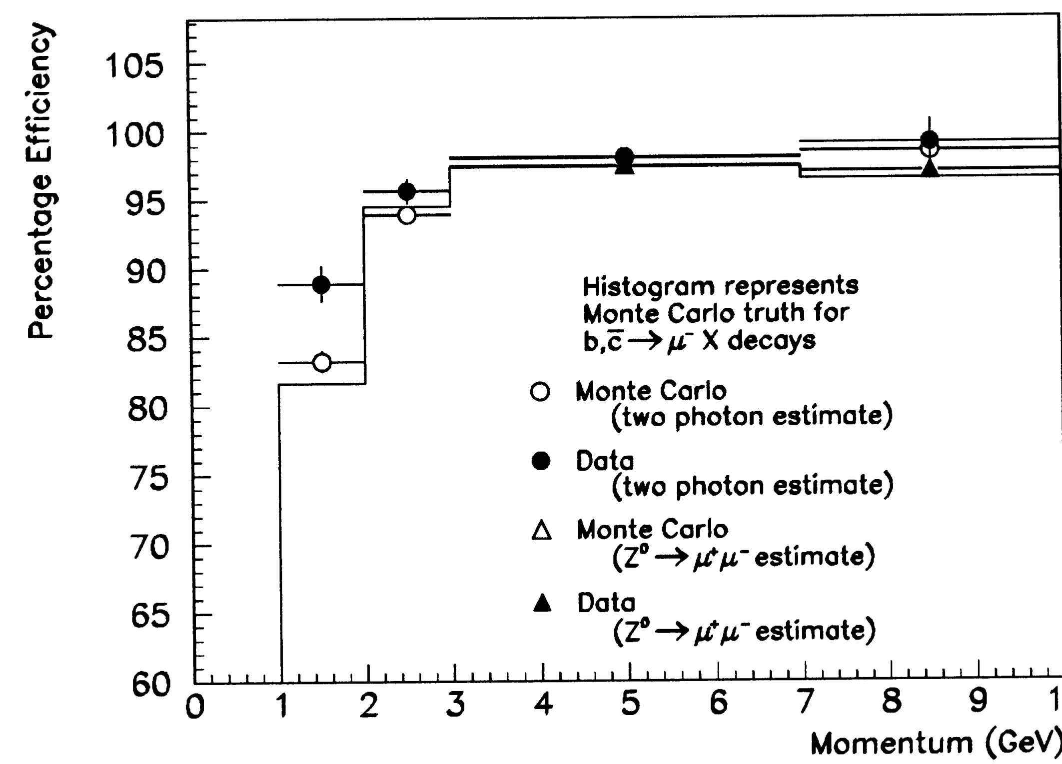


Figure 5b: $\mu^{\pm}$ identification efficiency.

- **There were considerable systematics arising from inaccurate neutral energy deposition modeling in the HCAL. In particular by high energy neutrons & K_L**

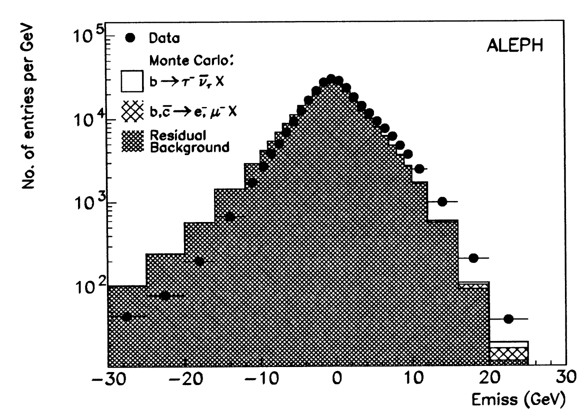


Figure 1a: E_{miss} before recalibration, using light quark tag and $e^{\pm}/\mu^{\pm}$ rejection.

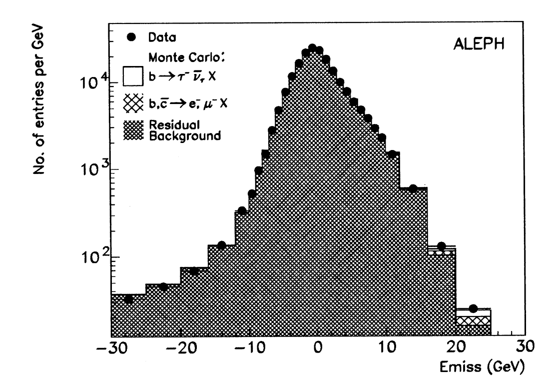


Figure 1b: E_{miss} after recalibration, using light quark tag and $e^{\pm}/\mu^{\pm}$ rejection, and $E_{neut} < 7$ GeV cut.

Conclusions

- **Revisited and old search for b-decays with large missing energy at LEP. Found the first constraint on $B_s \to \text{invisibles}$**

$$\text{Br}(B_s \to \text{invisibles}) < 5.9 \times 10^{-4}$$ **90% CL**

Not yet able to test the parameter space of light BSM models capable of explaining the Belle II signal, but we thought it was interesting

As a search strategy it is really powerful as shown by comparison with dedicated BaBar search for $B_d \to \text{invisibles}$

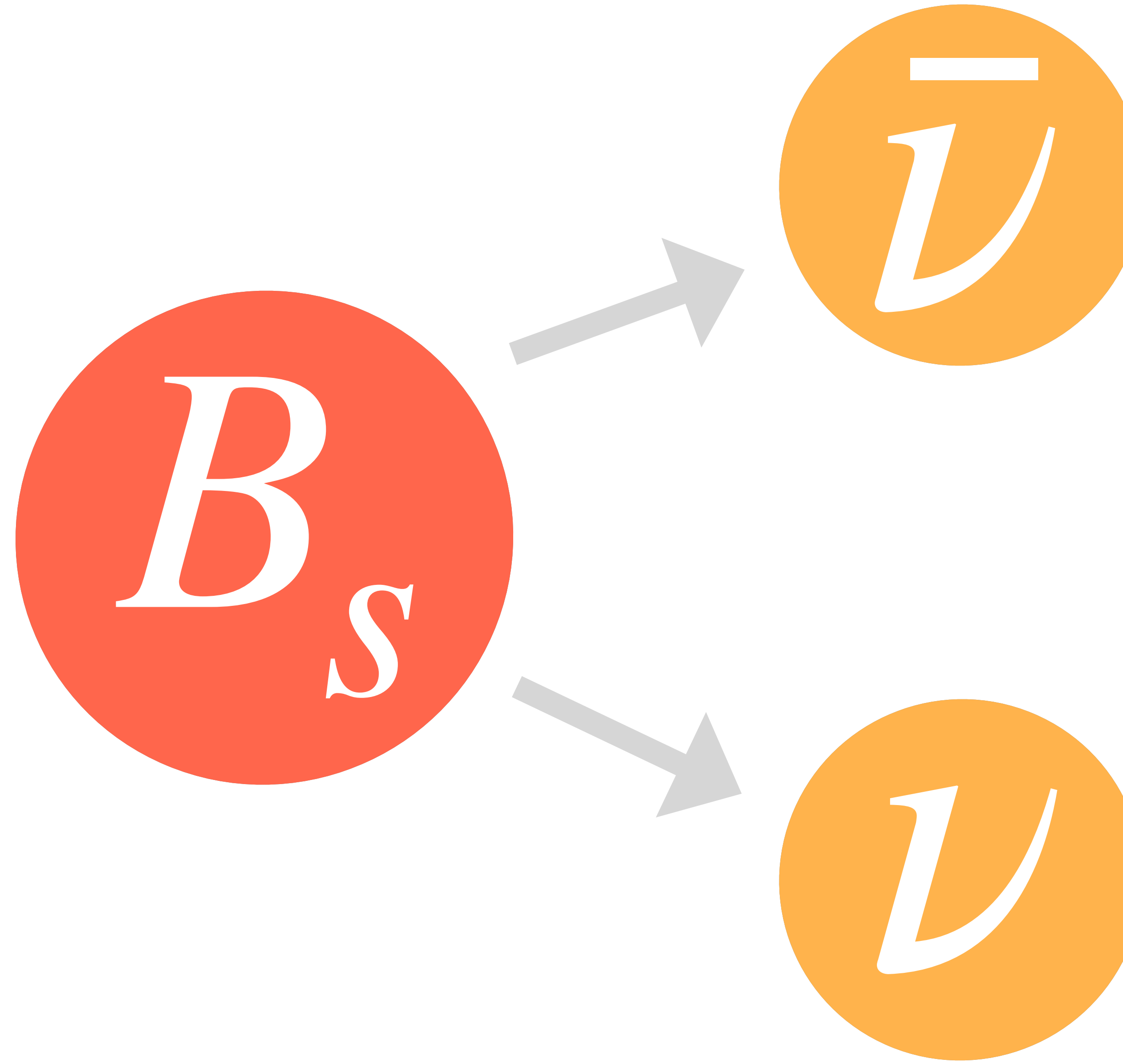
- **Something interesting to do:** **Actual full reanalysis of the old data**

  see talk by Marcello Maggi on Tuesday

- **What can FCC-ee do? A sensitivity analysis is still missing but:**
  - **1) Have as good as possible e/μ ID, particularly at low momenta**
  - **2) Be mindful of MC simulations of neutral energy deposition (n, K_L)**
  - **3) Probably have a very good understanding of the b fragmentation function will be useful as well**

Thank you!

Gonzalo Alonso-Álvarez, U. Toronto



Questions, Comments and Criticism are most welcome!

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Back up

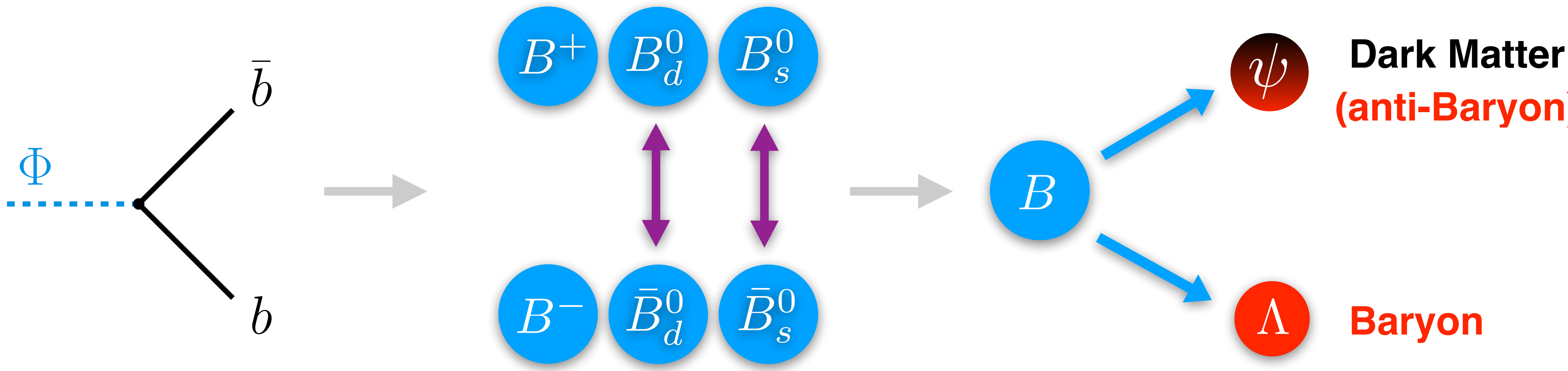
B-Mesogenesis

B-Mesogenesis: Baryogenesis and Dark Matter from B-Mesons

Elor, M.E.A., Nelson 1810.00880
Alonso-Álvarez, Elor, M.E.A., 2101.02706

see also: Aitken, McKee, Neder, Nelson 1708.01259
Nelson & Xiao 1901.08141, Alonso-Álvarez, Elor, Nelson, Xiao 1907.10612

Low Reheating Temperature | **CP violating oscillations** | **B-mesons decay into Dark Matter and hadrons**



$T_R \sim 15\,\mathrm{MeV}$ | $A_{\mathrm{SL}}^d \; A_{\mathrm{SL}}^s$ | $\mathrm{Br}\,(B \to \psi + \mathcal{B} + \mathcal{M})$

With:

$$Y_B \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}(B \to \psi + \mathcal{B} + \mathcal{M})}{10^{-2}} \sum_q \alpha_q \frac{A_{\mathrm{SL}}^q}{10^{-4}}$$

Key Prediction:

$$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) > 10^{-4}$$

B-Mesogenesis

4 Flavourful variations exist*: (All work equally well for Baryogenesis)

$\psi\, b\, u\, s$

$$B_d \to \psi + \Lambda\,(usd)$$
$$B_s \to \psi + \Xi^0\,(uss)$$
$$B^+ \to \psi + \Sigma^+\,(uus)$$
$$\Lambda_b \to \bar{\psi} + K^0$$

$\psi\, b\, u\, d$

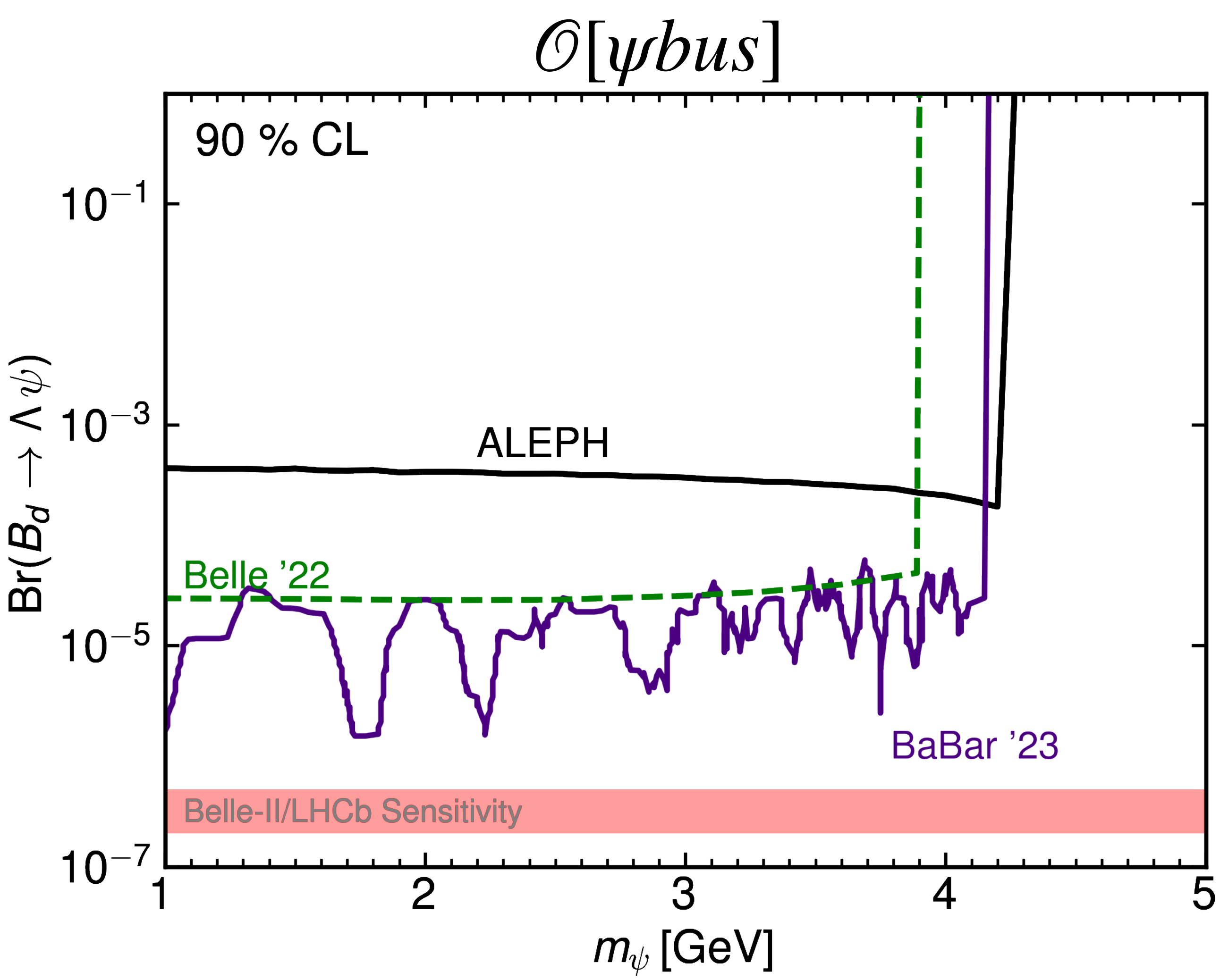
$$B_d \to \psi + n\,(udd)$$
$$B_s \to \psi + \Lambda\,(uds)$$
$$B^+ \to \psi + p\,(duu)$$
$$\Lambda_b \to \bar{\psi} + \pi^0$$

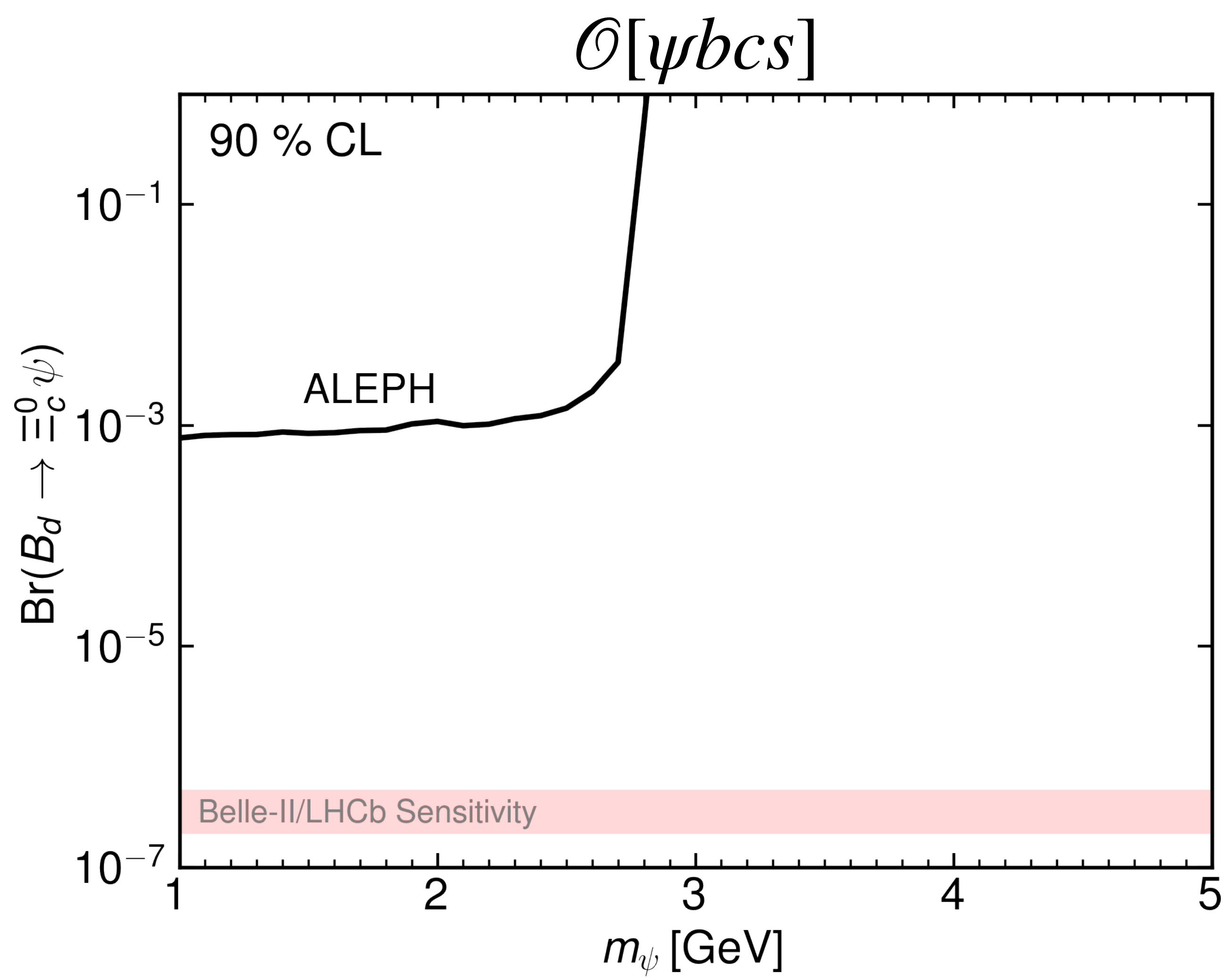
$\psi\, b\, c\, s$

$$B_d \to \psi + \Xi_c^0\,(csd)$$
$$B_s \to \psi + \Omega_c\,(css)$$
$$B^+ \to \psi + \Xi_c^+\,(csu)$$
$$\Lambda_b \to \bar{\psi} + D^- + K^+$$

$\psi\, b\, c\, d$

$$B_d \to \psi + \Lambda_c + \pi^-\,(cdd)$$
$$B_s \to \psi + \Xi_c^0\,(cds)$$
$$B^+ \to \psi + \Lambda_c\,(dcu)$$
$$\Lambda_b \to \bar{\psi} + \overline{D}^0$$





Light new scalars

Light new scalars coupled to quarks can also lead to Missing Energy in B decays:

2002.04623 Martin Camalich, Pospelov, Hoa Vuong, Ziegler & Zupan
2201.06580 Ferber, Filimonova, Schafer & Westhoff
2306.09508 Ovchynnikov, Schmidt & Schwetz

$$B \to Ka$$

Strategy employed is to recast the old searches by BaBar:

1303.7465

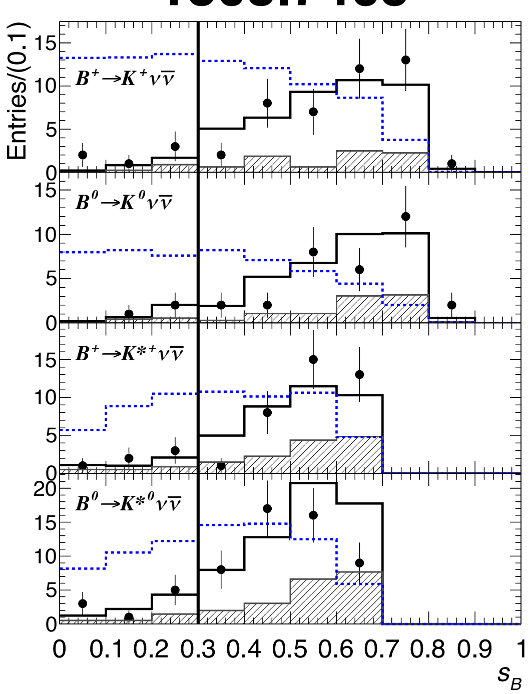


FIG. 5: (color online) The s_B distribution for (from top to bottom) $B^+ \to K^+\nu\bar{\nu}$, $B^0 \to K^0\nu\bar{\nu}$, $B^+ \to K^{*+}\nu\bar{\nu}$, and $B^0 \to K^{*0}\nu\bar{\nu}$ events after applying the full signal selection. The expected combinatorial (shaded) plus $m_{\rm ES}$-peaking (solid) background contributions are overlaid on the data (points). The signal MC distributions (dashed) are normalized to branching fractions of 20×10^{-5} for $B^+ \to K^+\nu\bar{\nu}$ and 50×10^{-5} for the other channels. Events to the left of the vertical lines are selected to obtain SM-sensitive limits, while the full spectra are used to determine partial branching fractions.

$$N_B \sim 4.7 \times 10^8$$

$$\text{efficiency} \sim 10^{-3}$$

$$\text{Br}(B \to Ka) \lesssim 10^{-5}$$

To be compared with: