B Decays with Invisibles in the Final State

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Overview

- Current Status

  - $B \to h^{(*)} X_{invisble}$

  - $B^+ \to l^+ \nu$ ($l = e, \mu, \tau$)

  - $B \to D^* \tau \nu$

- Future

  - Prospective Influence of Detector and Reconstruction Mods of Belle II vs. Belle

  - Tools and Methods Outlook

$B \rightarrow h^{(*)} X_{invisble}$

▪ current measurements dominated by B factories (**Belle, Babar**) due to heavy use of production mechanism in analysis

Y(4S) meson
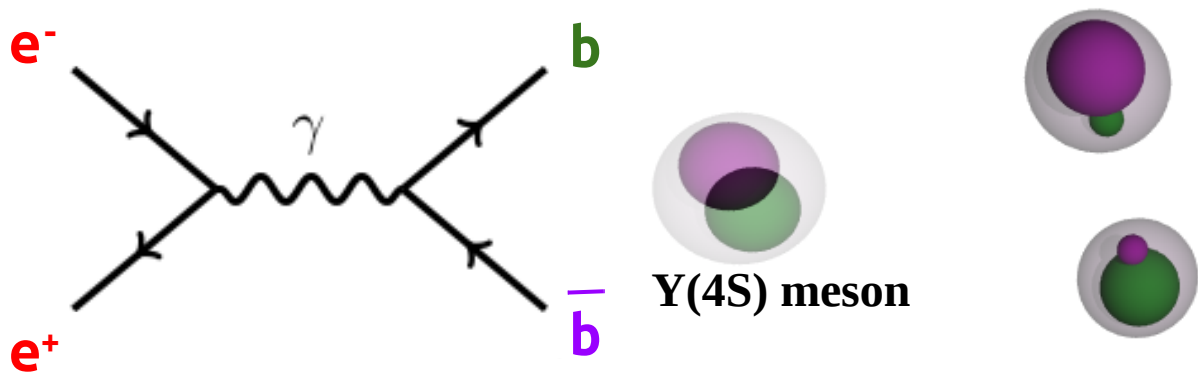
B meson pair
(+ nothing else)

B → h$^{(*)}$X$_{invisble}$

- typical basic strategy:

  - recombine one of the B mesons of the Y(4S) - currently typically divided into *semileptonic tag-side* and *hadronic tag-side* decays

  - select h$^{(*)}$ in certain momentum range
    (typically based on B → h$^{(*)}$ ν ν expectation)

  - veto any additional tracks, neutral pions/kaons

  - fit the amount of energy remaining in the calorimeter for the remaining events

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$B \rightarrow h^{(*)} X_{invisble}$

Muon case for illustrative purposes

- Momentum Selection Issues @ Belle

  - $p(B_{signal})$ about 331 (326) MeV/c
    in the (~known) Y(4S)-cms for B^+ (B^0) mesons

- Cuts on momentum to avoid

  - $b \rightarrow c \rightarrow s$ transitions

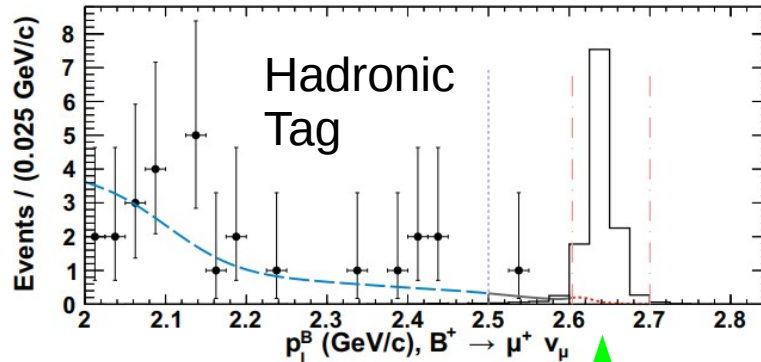 - two body decays, e.g. $B \rightarrow K^* \gamma$ (BR ~ 4 x 10^{-5})...

    in the *Hadronic Tag* analysis:
    (1.6 < p(h$^{(*)}$) < 2.5) GeV/c in B$_{sig}$ frame
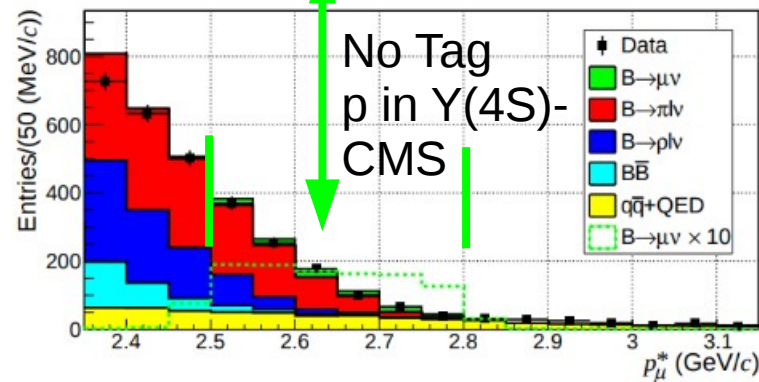

- *Semileptonic Tag* analysis uses (0.5 < p(h$^{(*)}$) < 2.96) GeV/c in the Y(4S)-rest frame,
  and then this variable is used in a **multi-variate method with SM**
  B $\rightarrow$ h$^{(*)}$ ν ν simulation
  ==> this is somewhat more difficult to interpret for other purposes

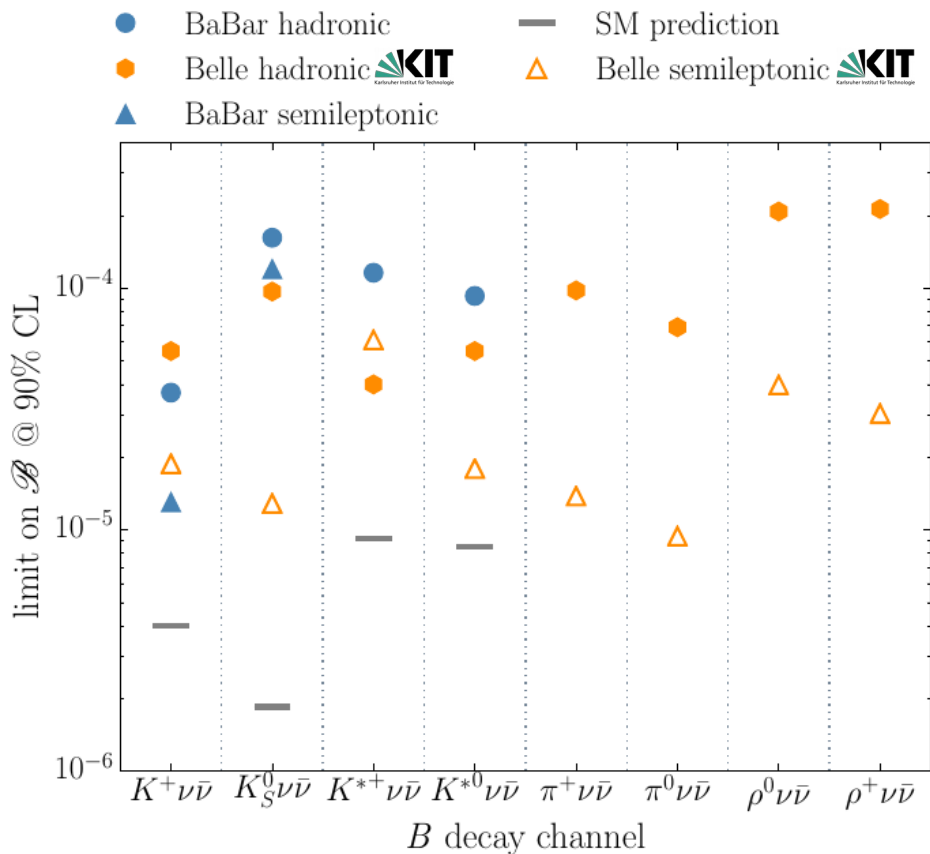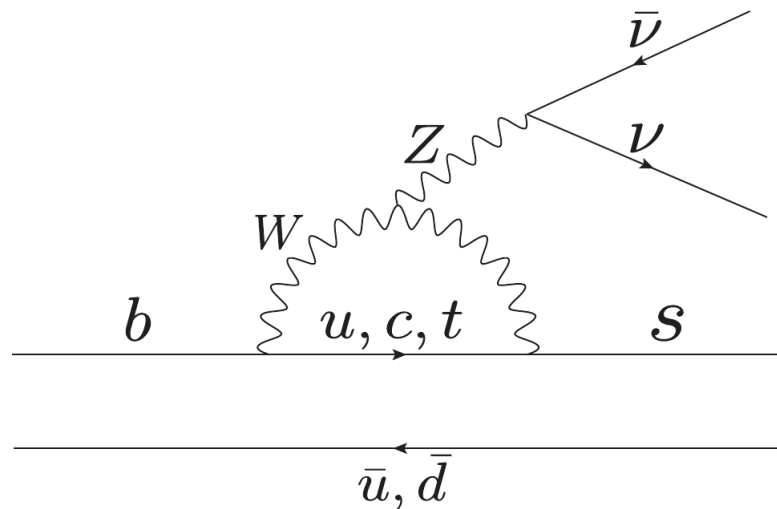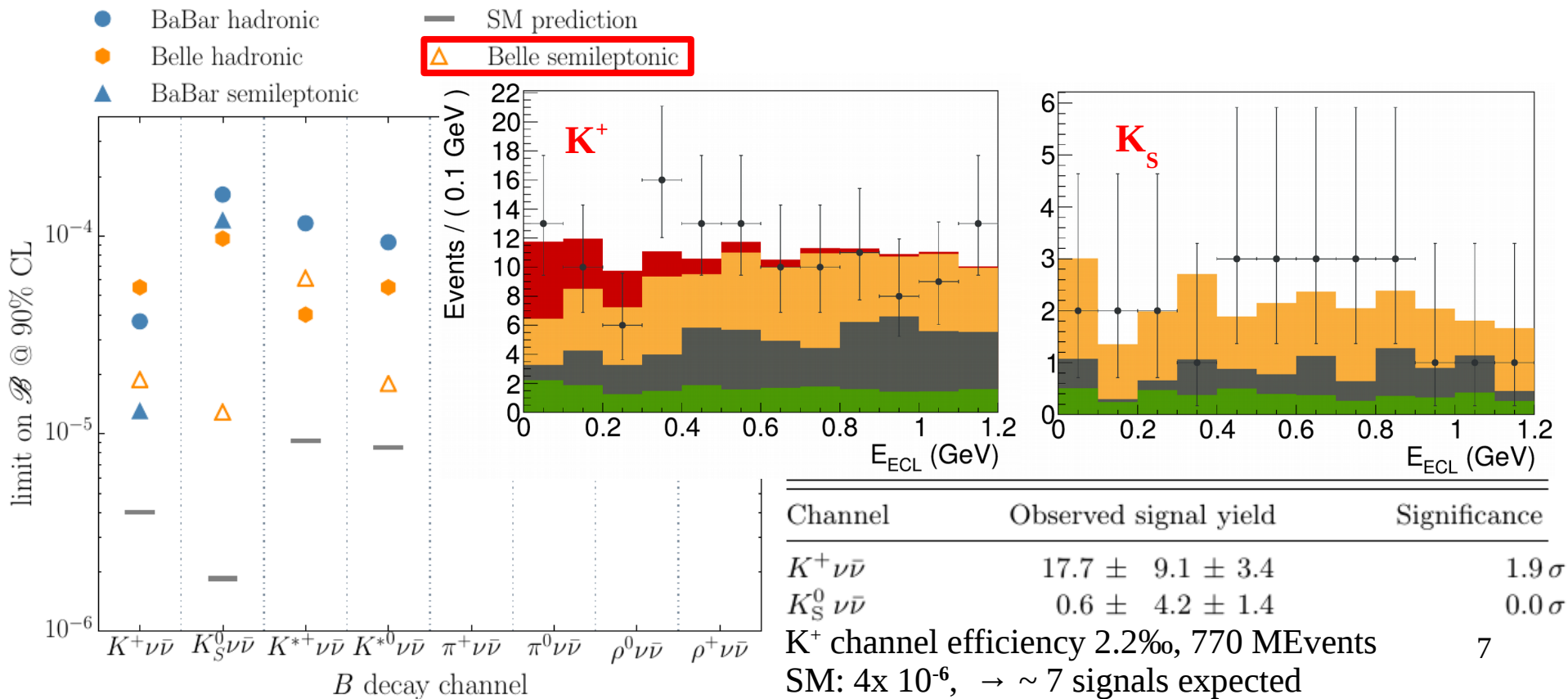Let's have a look at
current B $\rightarrow$ h$^{(*)}$ ν ν
analyses!

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B → h$^{(*)}$ ν ν̄   - Limits Overview

- highest sensitivity currently for the semileptonically tagged (more model dependent) Belle analysis
  https://arxiv.org/pdf/1702.03224.pdf , PRD accepted

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B → h$^{(*)}$ ν ν̄   - Limits Overview

Legend:
- ● BaBar hadronic
- ⬡ Belle hadronic
- ▲ BaBar semileptonic
- — SM prediction
- △ Belle semileptonic

Channel	Observed signal yield	Significance
$K^+ \nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K_S^0 \nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$

K^+ channel efficiency 2.2‰, 770 MEvents

SM: 4x 10^{-6}, → ~ 7 signals expected

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B → h$^{(*)}$ ν ν̄ - Limits Overview

BaBar hadronic
Belle hadronic
BaBar semileptonic
SM prediction
Belle semileptonic

K*$^+$

K*^{0}

Channel	Observed signal yield	Significance
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$

K*$^+$ channel efficiency 0.57‰, 770 MEvents
SM: 9x 10^{-6}, → ~ 4 signals expected

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B → h$^{(*)}$ ν ν̄ - Limits Overview

For comparison:
Hadronically tagged analysis
(Phys. Rev. D 87 (2013) 111103)

| Mode	N_{tot}	N_{sig}	Significance	$\epsilon, 10^{-4}$	Upper limit	Expected limit
$B^+ \to K^+ \nu\bar{\nu}$	43	$13.3^{+7.4}_{-6.6}(\text{stat}) \pm 2.3(\text{syst})$	2.0σ	5.68	$< 5.5 \times 10^{-5}$	2.2×10^{-5}
$B^0 \to K_s^0 \nu\bar{\nu}$	4	$1.8^{+3.3}_{-2.4}(\text{stat}) \pm 1.0(\text{syst})$	0.7σ	0.84	$< 9.7 \times 10^{-5}$	7.3×10^{-5}
$B^+ \to K^{*+} \nu\bar{\nu}$	21	$-1.7^{+1.7}_{-1.1}(\text{stat}) \pm 1.5(\text{syst})$	–	1.47	$< 4.0 \times 10^{-5}$	5.8×10^{-5}
$B^0 \to K^{*0} \nu\bar{\nu}$	10	$-2.3^{+10.2}_{-3.5}(\text{stat}) \pm 0.9(\text{syst})$	–	1.44	$< 5.5 \times 10^{-5}$	4.6×10^{-5}

B → h$^{(*)}$X$_{\text{invisble}}$ – Conclusion

- sensitivity for SM decay involving neutrinos is very close

- future analyses should potentially consider in early stages effects of alternative h-momentum distributions (e.g. has P'$_5$ anomaly consequences (?)) and/or extract yield in bins of h-momentum

- single particle X, like light axi-flavons require special searches, that don't cut away interesting momentum range

- Belle analysis reference:
  semileptonic tag: **https://arxiv.org/pdf/1702.03224.pdf , PRD accepted**
  hadronic tag: **https://arxiv.org/pdf/1303.3719.pdf , Phys. Rev. D 87 (2013) 111103**

B⁺ → l⁺ ν (l = e, μ, τ)

- for τ case analysis strategy is almost identical as for the B → h$^{(*)}$ ν ν, only momentum, PID is different

- due to helicity suppression τ branching fraction much higher than for light leptons

- however, search for possible heavy invisible particle fairly difficult due to unprecise tau momentum knowledge
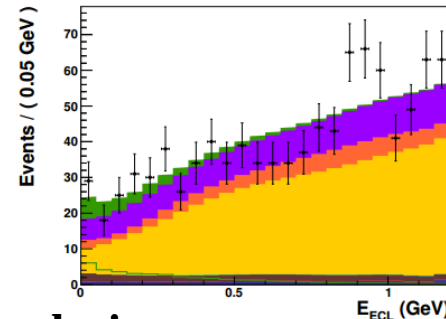
Example from Belle semileptonically tagged B → τν analysis Phys. Rev. D 92, 051102(R)
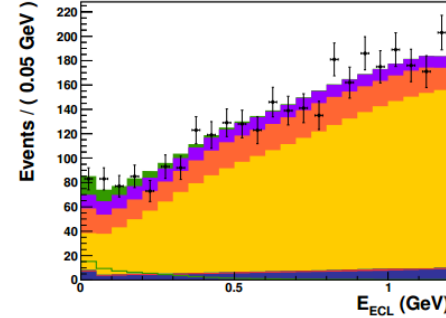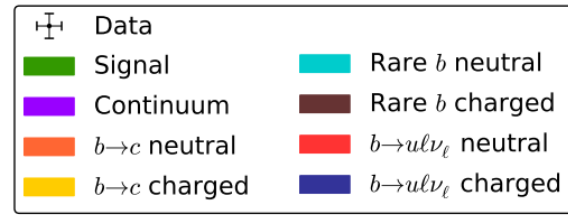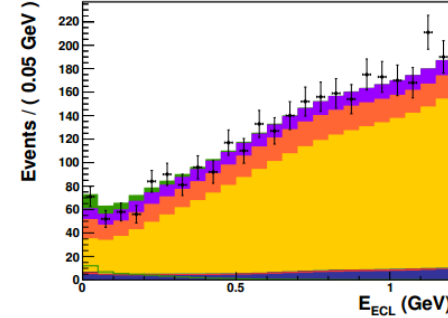
Figure 7.8: Result of the fit on the real data sample in E_{ECL}.
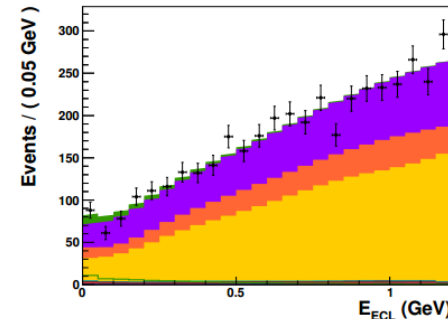
(a) $\tau^+ \to e^+ \bar{\nu}_\tau \nu_e$

(b) $\tau^+ \to \mu^+ \bar{\nu}_\tau \nu_\mu$

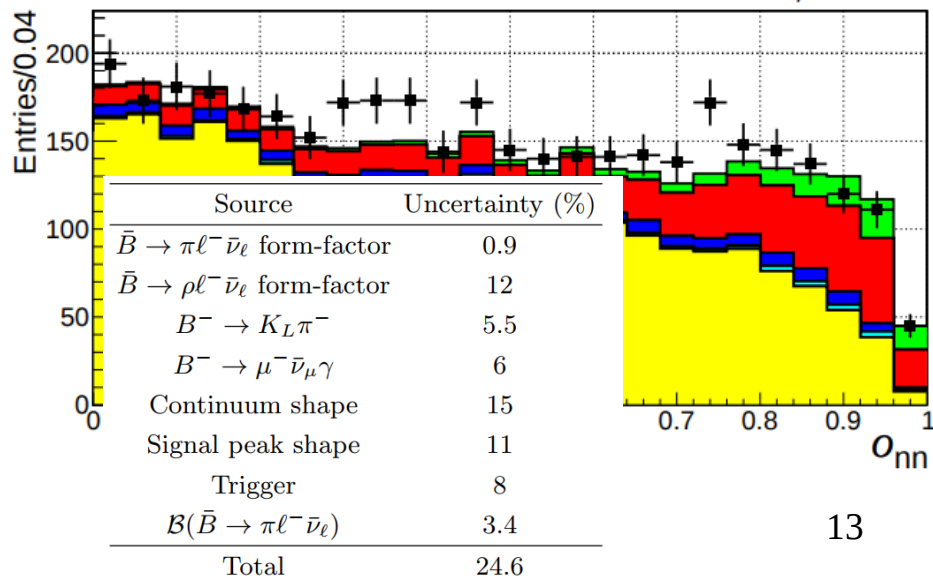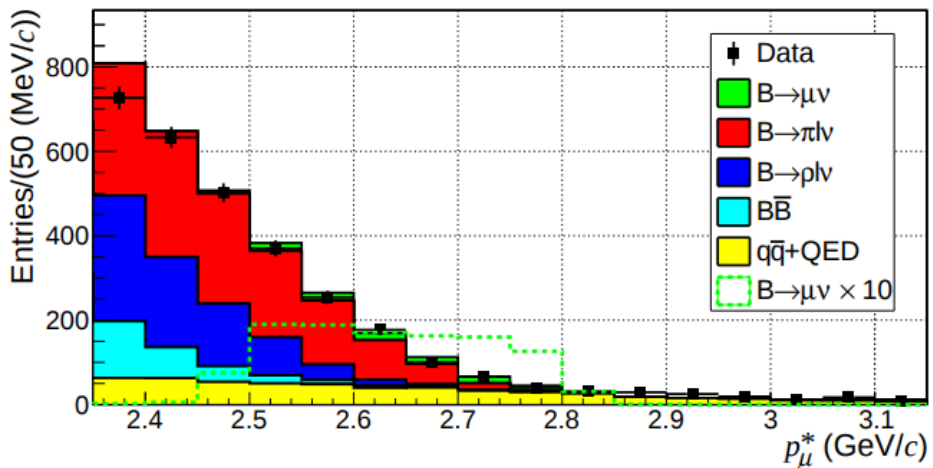(c) $\tau^+ \to \pi^+ \bar{\nu}_\tau$

(d) $\tau^+ \to \rho^+ \bar{\nu}_\tau$

$B^+ \rightarrow \mu^+ \nu$

- Strategy 1 (Belle, lead authors Sibidanov, Varvell):

  - Identify a muon

  - Fit the muon momentum in the Y(4S) rest frame and the output of an multivariate classifier

- Strategy 2 (Belle, lead authors Yook, Kwon):
  Phys. Rev. D 91, 052016

 - again use the tag side recombination and veto additional particles

B$^+$ → μ$^+$ ν (1)

- 2.4 σ significance,

$\mathcal{B}(B^- \rightarrow \mu^- \bar{\nu}_\mu) \in [2.9, 10.7] \times 10^{-7}$ at the 90% C.L.

- Two sided limit compatible with SM value of ~4 x 10^{-7}

| Source	Uncertainty (%)
$\bar{B} \rightarrow \pi \ell^- \bar{\nu}_\ell$ form-factor	0.9
$\bar{B} \rightarrow \rho \ell^- \bar{\nu}_\ell$ form-factor	12
$B^- \rightarrow K_L \pi^-$	5.5
$B^- \rightarrow \mu^- \bar{\nu}_\mu \gamma$	6
Continuum shape	15
Signal peak shape	11
Trigger	8
$\mathcal{B}(\bar{B} \rightarrow \pi \ell^- \bar{\nu}_\ell)$	3.4
Total	24.6

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B$^+$ → μ$^+$ ν (2)

- limit on BR of
  less than 3.5 x 10^{-6}

- in this case, no tagging
  is more powerful
  → probably should be tried for things like axi-flavon, too, but as leptons are rare in
  continuum, there is no guarantee, that this works out better
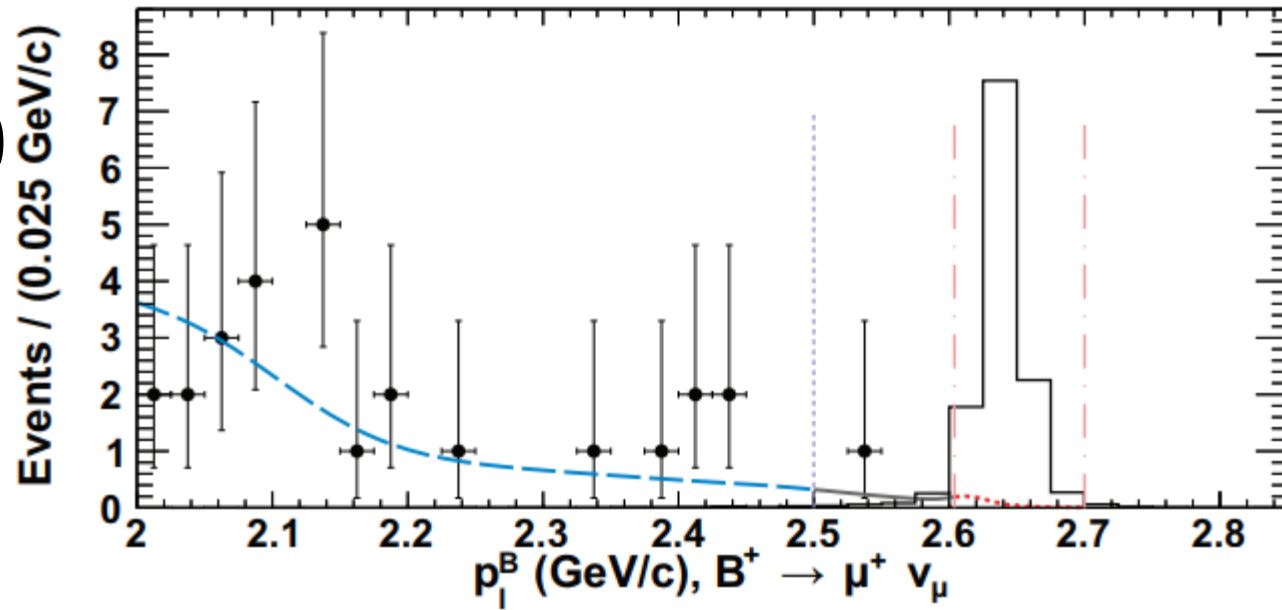
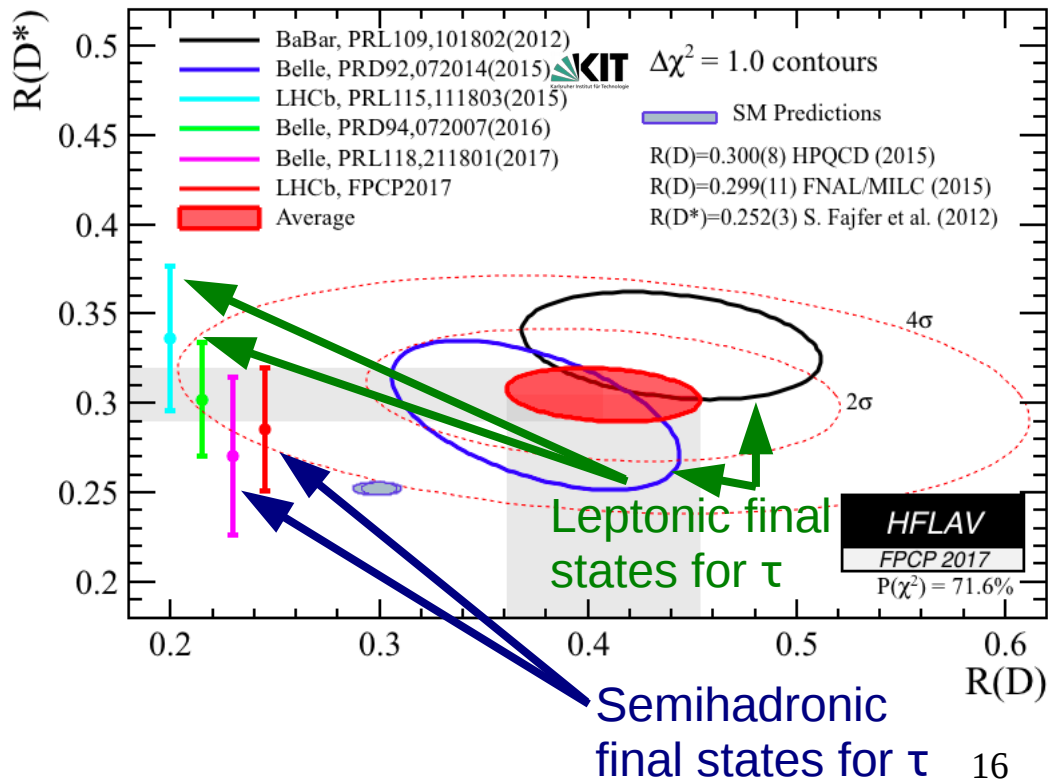 For heavy neutrinos, hadronic tag potentially competitive

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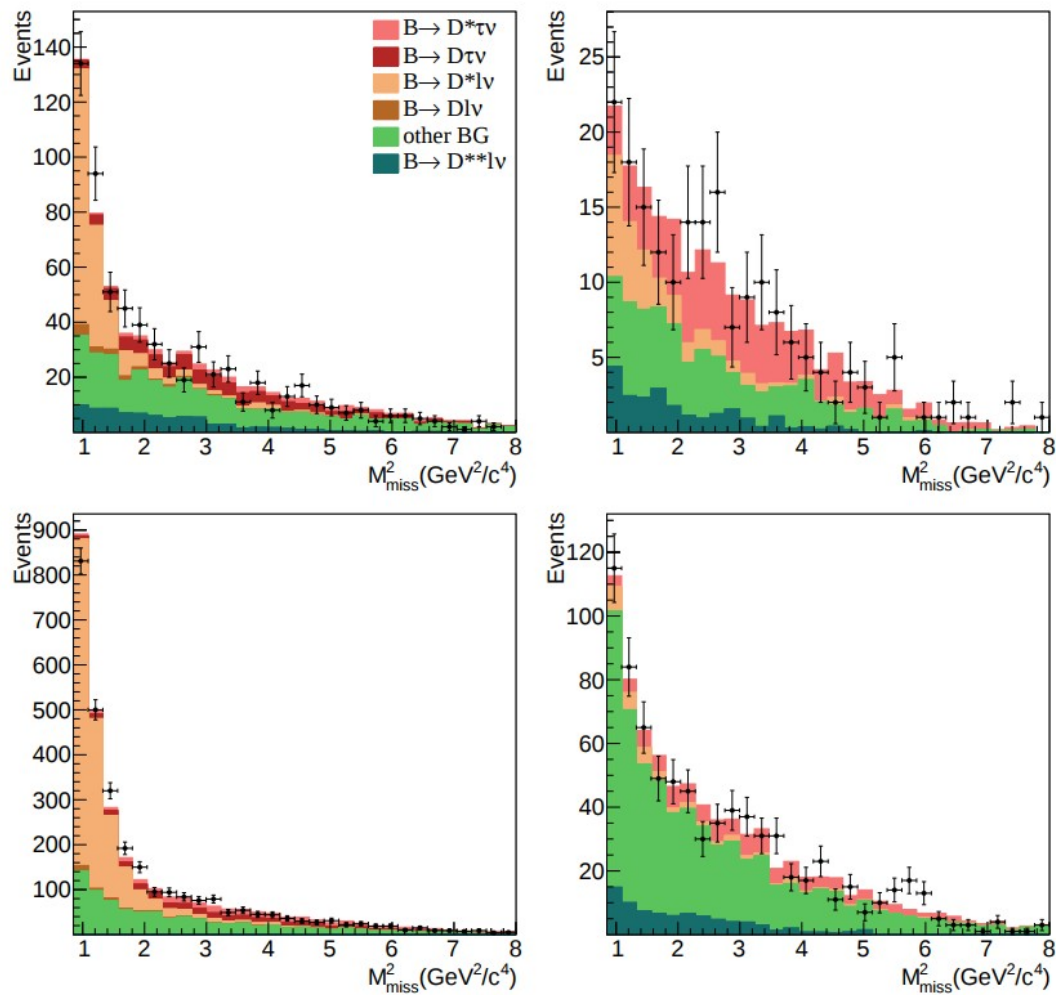# Hadronically tagged heavy neutrino search
(Belle, lead authors Park, Kwon, Phys. Rev. D 94, 012003)
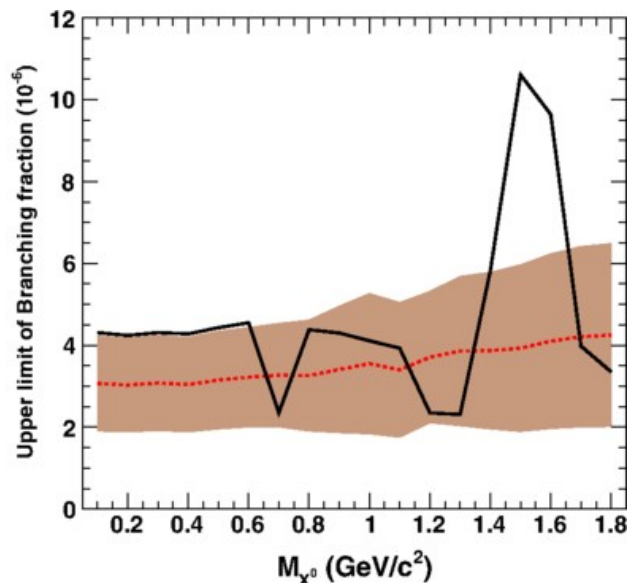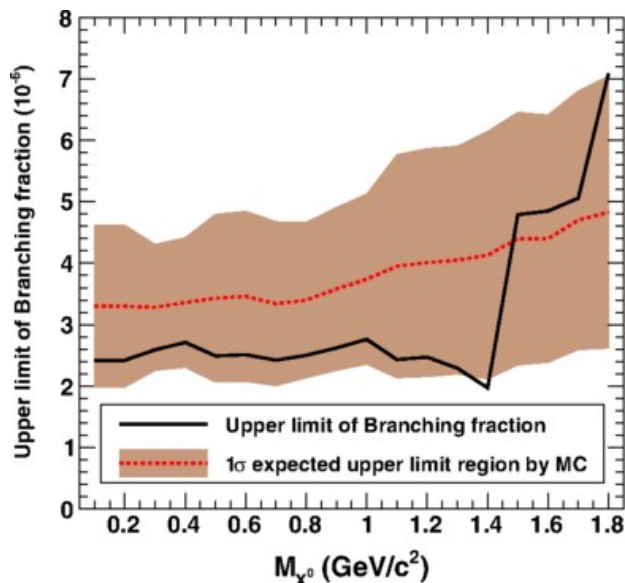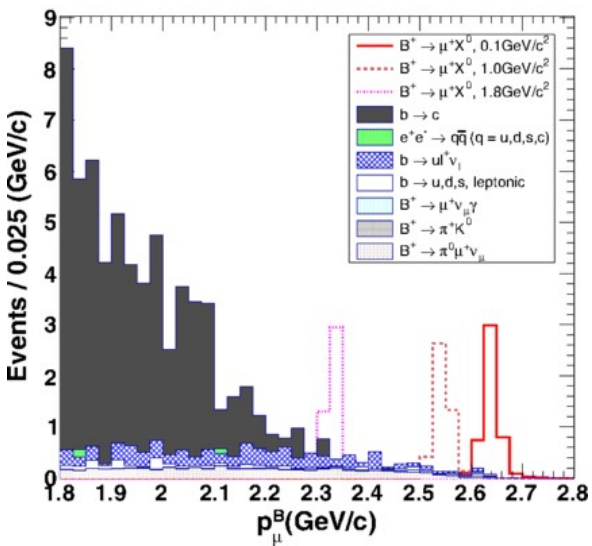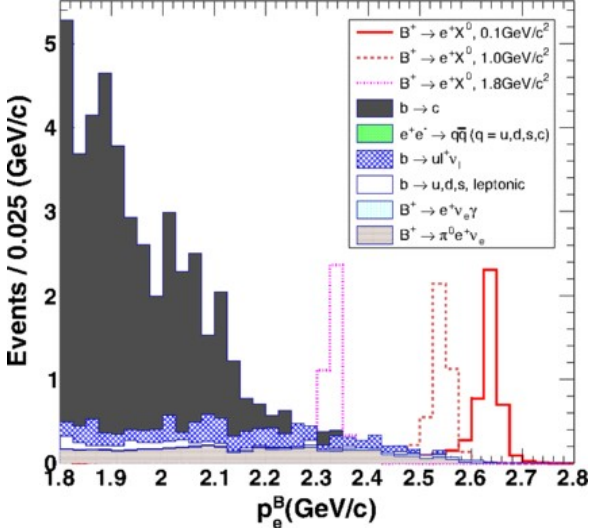
B → D* τ ν   - BR Overview

- world average differs by
  ~4 σ from theory predictions

- Slightly different analysis strategie
  for different experiments (Babar,
  LHCb, Belle), tagging methods

- when thinking about New
  Physics solutions to the
  discrepancy, take into account,
  that we might not actually see
  τ leptons, but perhaps light leptons
  + missing mass/energy

Leptonic final
states for τ

Semihadronic
final states for τ

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Example distributions from Belle hadronically tagged analysis with leptonic final state for tau

FIG. 3. Projections of the fit results and data points with statistical uncertainties for the high M_{miss}^2 region. Top left: $D^+\ell^-$; top right: $D^{*+}\ell^-$; bottom left: $D^0\ell^-$; bottom right: $D^{*0}\ell^-$.

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Prospective Influence of Detector and Reconstruction Mods of Belle II vs. Belle

- Integrated Lumonosity goal: x50

- Much better particle identification, especially at high momenta for pion/kaon separation, at low momenta for lepton ID

- Better Momentum Resolution of Tracks, higher tracking efficiency

- At full luminosity, potentially more fake tracks, background energy in the calorimeter → especially for analyses reliant on vetos of additional particles, early data probably will be more valuable than later data

Tools and Methods Outlook

- development of tagging techniques is going on (hadronic tagging at Belle currently has an efficiency of ~ 0.5% for single track signals), substantial improvement seems feasible

- improved momentum resolution without tagging or semileptonic tagging is studied, some success is very likely
  → reanalysis of B → μν even in Belle under way

Summary & Outlook

- B Meson analysis at Y(4S)-machines with invisible particles in the final state have sensitivities from $10^{-5} - 10^{-7}$ depending on the visible particles in the common decay

- To improve sensitivities for potential axion-like particles, heavy neutrinos, etc. an increased awareness during the performance of the analyses can be helpful in the future

- While x50 luminosity increase will be the dominant improvement for the presented analyses, reconstruction and analysis tools developments can play an additional role