

$$B_c \rightarrow \tau \nu$$

– an example of flavor physics at the Z pole

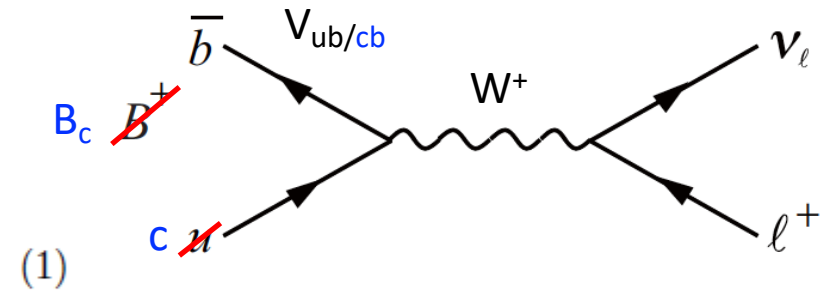
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# $B_{u,c} \rightarrow \tau\nu$ in the Standard Model

The study of purely leptonic decays of heavy charged mesons  $P^+$  (e.g.  $D^\pm, D_s^\pm, B^\pm, \dots$ )

$$P^+(Q\bar{q}) \rightarrow \ell^+\nu_\ell$$



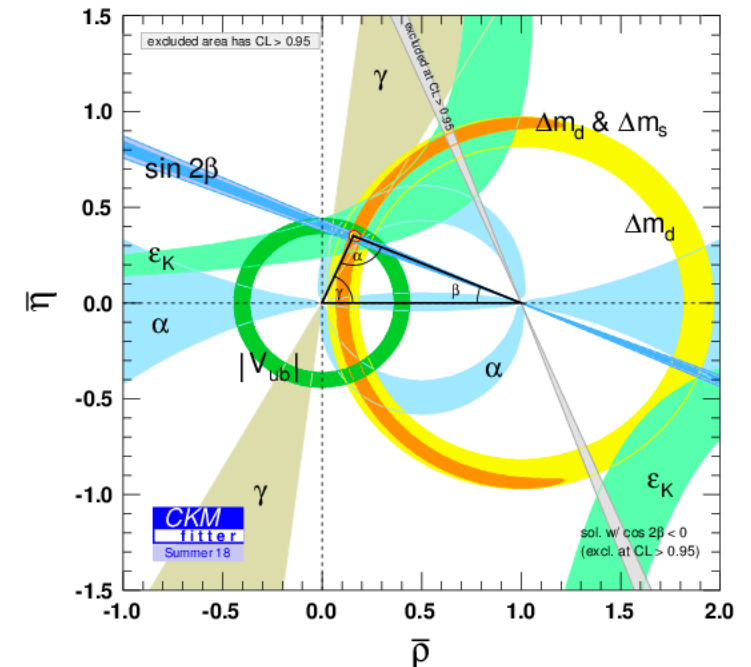
is of particular interest, due to their sensitivity to both the meson decay constants  $f_P$  and the CKM matrix elements  $V_{qQ}$ . In the Standard Model (SM) the width of the decay (1) is predicted to be (here we assume a zero value for neutrino mass):

$$\Gamma_{SM}(P^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} |V_{Qq}|^2 f_P^2 M_P m_\ell^2 \left(1 - \frac{m_\ell^2}{M_P^2}\right)^2,$$

Interpret  $f_P$  as wave function of the light quark at the location of the  $b$  quark

Due to helicity suppression,  $\tau$  final state has largest branching fraction

- Get  $f_{B_u}$  from LQCD, then measure  $\text{BR}(B_u \rightarrow \tau\nu)$  to determine  $V_{ub}$
- Get  $f_{B_c}$  from LQCD, then measure  $\text{BR}(B_c \rightarrow \tau\nu)$  to determine  $V_{cb}$   
– OR –
- Get  $V_{cb}$  from  $\text{BR}(B \rightarrow D^{(*)} | \nu)$  measurements and measure  $f_{B_c}$  and compare to LQCD predictions



$V_{ub}$  provides important constraint on SM consistency

# New Physics in leptonic $P^+$ decays

( $B_c, B_u, D_s \rightarrow \tau\nu, \mu\nu$ )

- Example 2HDM
  - $H^+$  can replace  $W^+$  propagator

$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu)_{2\text{HDM}} = \mathcal{B}(B^+ \rightarrow \ell^+ \nu)_{\text{SM}} \times r_H,$$

$$r_H = (1 - M_B^2 \tan^2 \beta / M_H^2)^2$$

- A few years ago a  $3.2\sigma$  discrepancy between the measured  $f(D_s)$  and the theoretical prediction caused a lot of excitement; the discrepancy went away

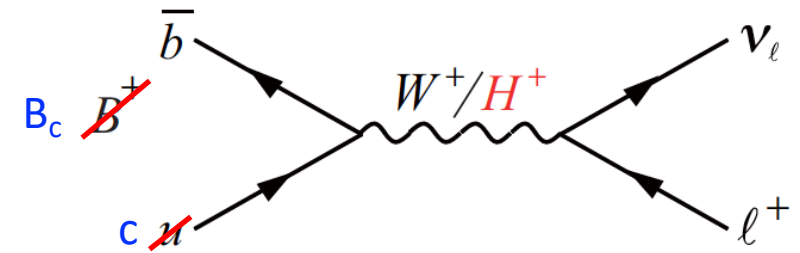
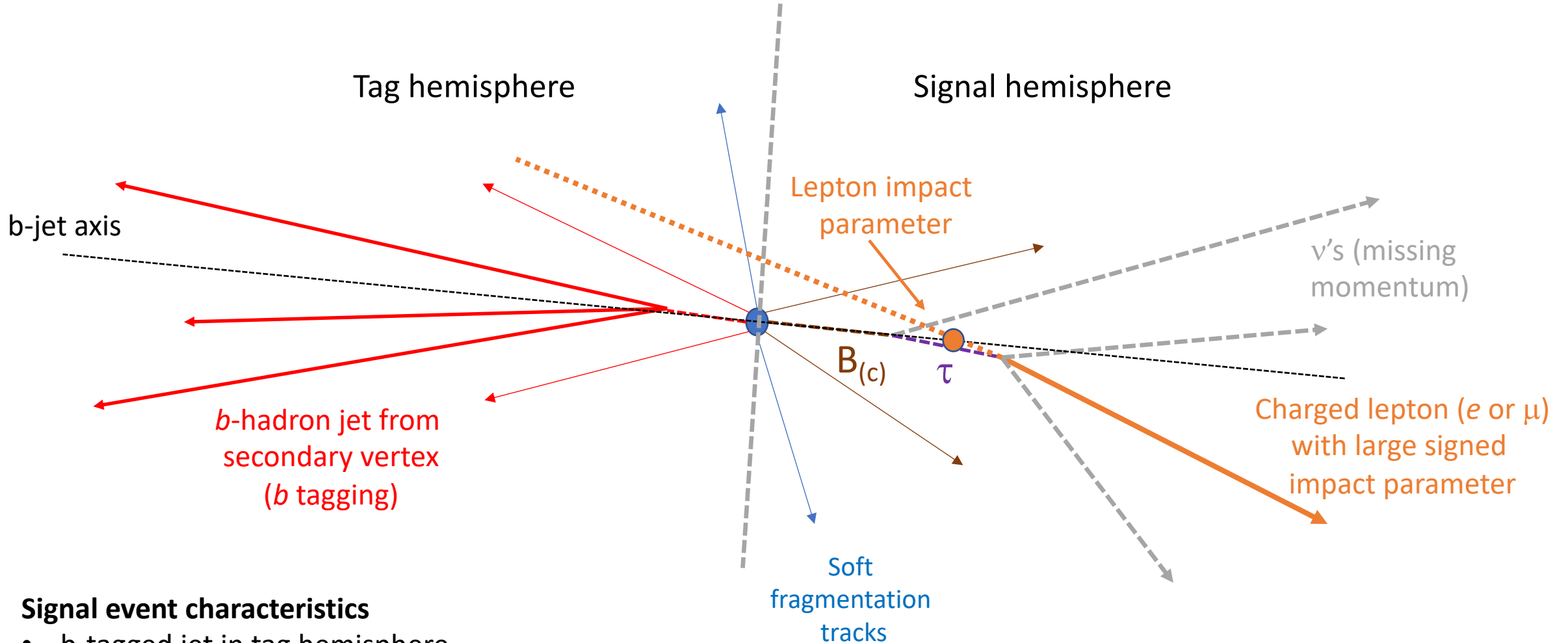


Table 84.3: Experimental results for  $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu)$ ,  $\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu)$ , and  $|V_{cs}|f_{D_s^+}$ . Numbers for  $|V_{cs}|f_{D_s^+}$  have been extracted using updated values for masses (see text). The systematic uncertainty for correlated error on the  $D_s^+$  lifetime is included. The mass uncertainties are also common, but negligible. Common systematic errors in each experiment have been taken into account in the averages.

Experiment	Mode	$\mathcal{B}(\%)$	$ V_{cs} f_{D_s^+}$ (MeV)
CLEO-c [47,48]	$\mu^+ \nu$	$0.565 \pm 0.045 \pm 0.017$	$250.8 \pm 10.0 \pm 4.2$
BaBar <sup>a</sup> [53]	$\mu^+ \nu$	$0.602 \pm 0.038 \pm 0.034$	$258.9 \pm 8.2 \pm 7.5$
Belle [49]	$\mu^+ \nu$	$0.531 \pm 0.028 \pm 0.020$	$243.1 \pm 6.4 \pm 4.9$
Our average	$\mu^+ \nu$	$0.556 \pm 0.024$	$248.8 \pm 5.8$
CLEO-c [47,48]	$\tau^+ \nu$ ( $\pi^+ \bar{\nu}$ )	$6.42 \pm 0.81 \pm 0.18$	$270.8 \pm 17.1 \pm 4.2$
CLEO-c [50]	$\tau^+ \nu$ ( $\rho^+ \bar{\nu}$ )	$5.52 \pm 0.57 \pm 0.21$	$251.1 \pm 13.0 \pm 5.1$
CLEO-c [51,52]	$\tau^+ \nu$ ( $e^+ \nu \bar{\nu}$ )	$5.30 \pm 0.47 \pm 0.22$	$246.1 \pm 10.9 \pm 5.4$
BaBar [53]	$\tau^+ \nu$ ( $e^+ (\mu^+) \nu \bar{\nu}$ )	$5.00 \pm 0.35 \pm 0.49$	$239.0 \pm 8.4 \pm 11.9$
Belle [49]	$\tau^+ \nu$ ( $\pi^+ \bar{\nu}$ )	$6.04 \pm 0.43^{+0.46}_{-0.40}$	$262.7 \pm 9.3^{+10.2}_{-8.9}$
Belle [49]	$\tau^+ \nu$ ( $e^+ \nu \bar{\nu}$ )	$5.37 \pm 0.33^{+0.35}_{-0.31}$	$247.7 \pm 7.6^{+8.3}_{-7.4}$
Belle [49]	$\tau^+ \nu$ ( $\mu^+ \nu \bar{\nu}$ )	$5.86 \pm 0.37^{+0.34}_{-0.59}$	$258.7 \pm 8.2^{+7.7}_{-13.2}$
Our average	$\tau^+ \nu$	$5.56 \pm 0.22$	$252.1 \pm 5.2$
Our average	$\mu^+ \nu + \tau^+ \nu$		$250.9 \pm 4.0$

Theory:  $f_{D_s} = 249.0(1.2)$  MeV

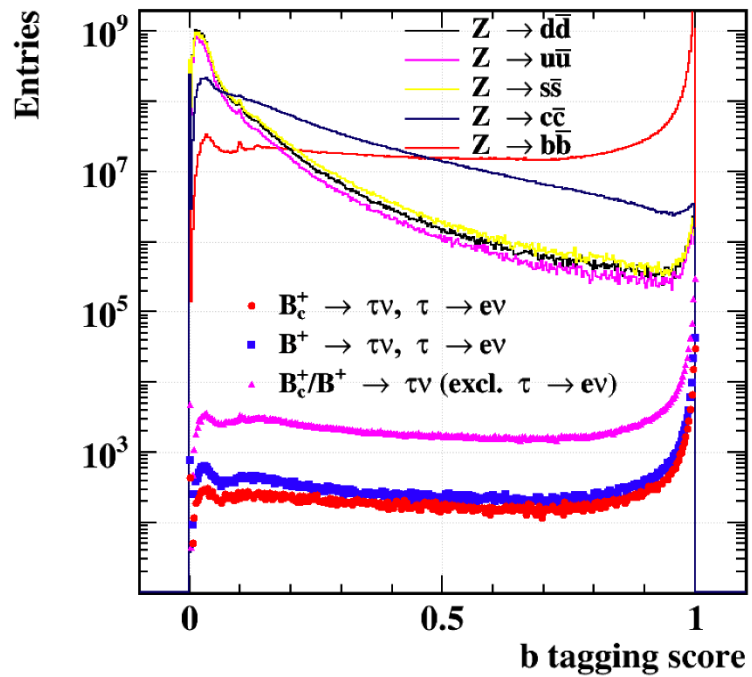
# Topology of $B_{(c)} \rightarrow \tau(\rightarrow e/\mu + \nu\bar{\nu})\bar{\nu}$ at the $Z^0$ pole



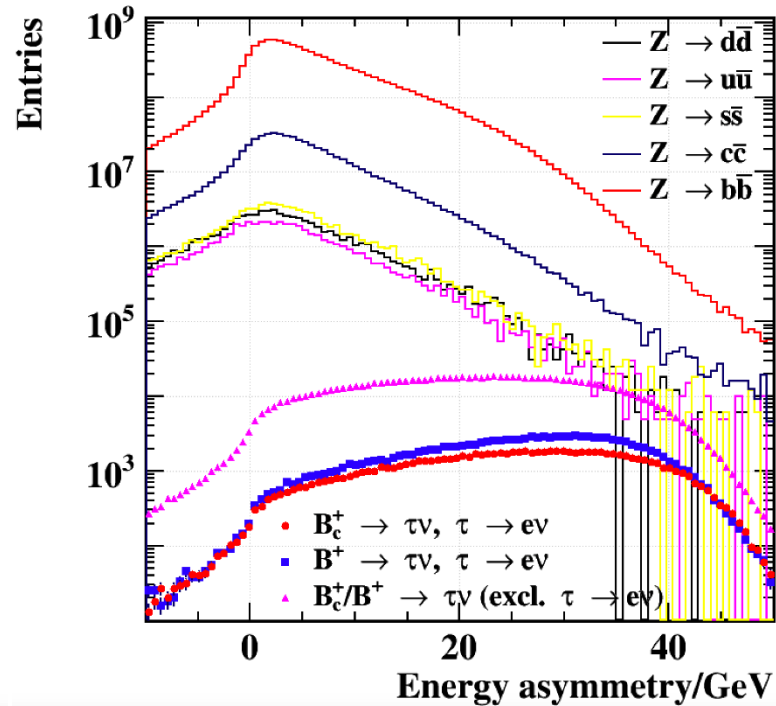
## Signal event characteristics

- $b$ -tagged jet in tag hemisphere
- Large energy-imbalance between signal and tag hemisphere
- Clean, well-reconstructed lepton ( $e$  or  $\mu$ )
- Large lepton impact parameter

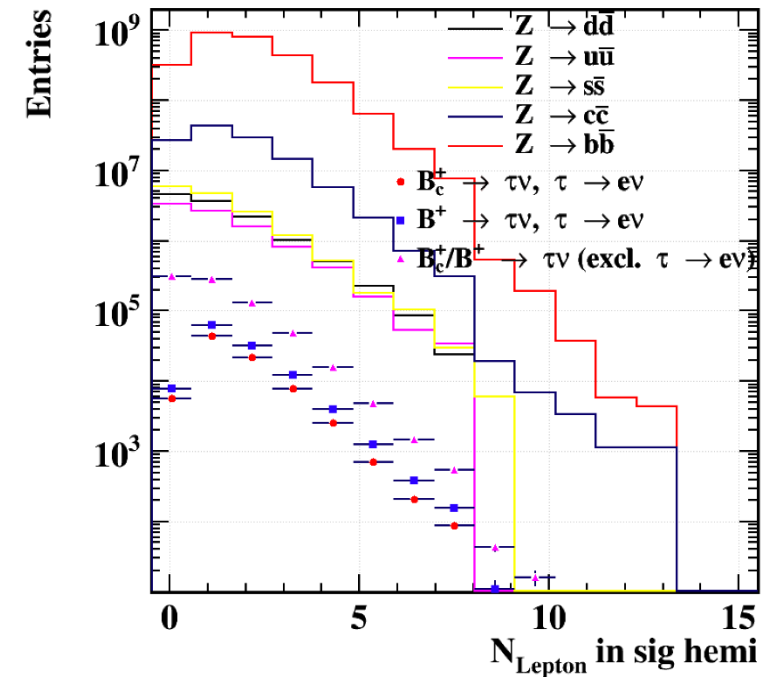
# Parameter distributions ( $B_c \rightarrow \tau \bar{\nu}, \tau \rightarrow e \nu \bar{\nu}$ )



Score of the  $b$ -tagging algorithm for tag-side jet:  
 $b\text{-tag} > 0.6$

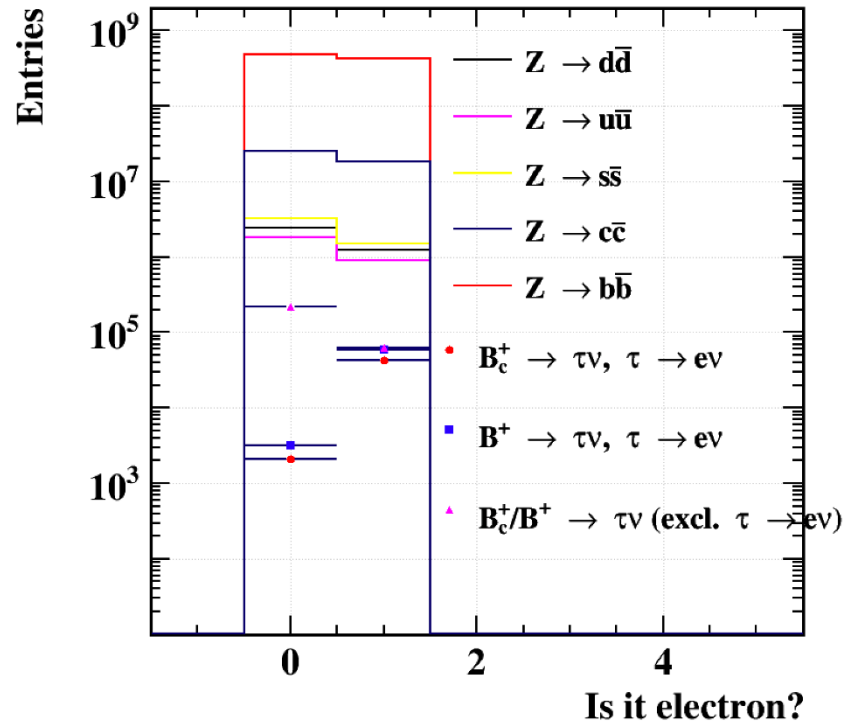


Energy asymmetry between the two hemispheres  
 $\Delta E = E_{\text{Recoil}} - E_{\text{signal}} > 10 \text{ GeV}$

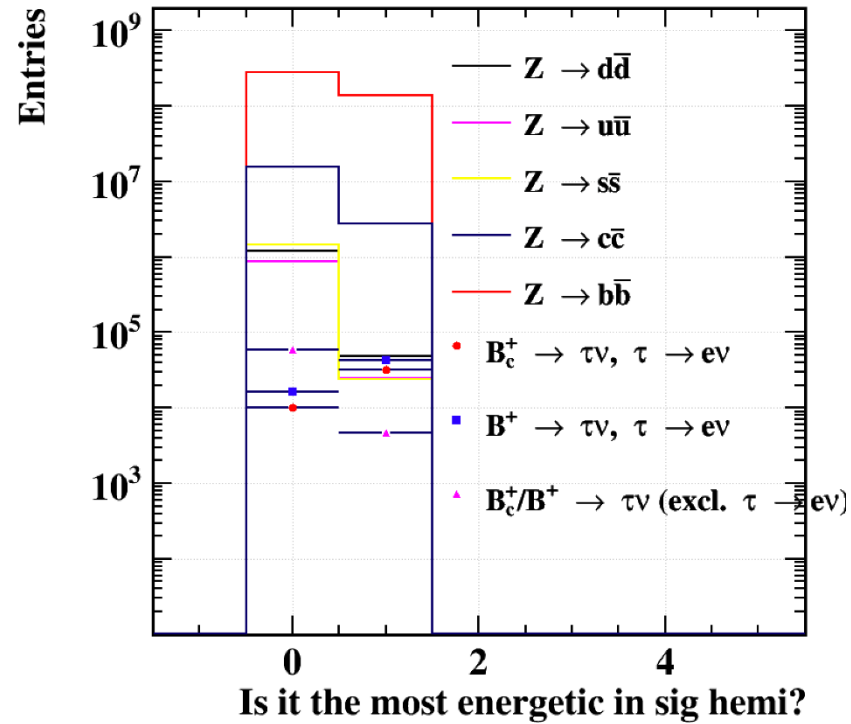


Exactly one lepton in the signal hemisphere

# Parameter distribution ( $B_c \rightarrow \tau \bar{\nu}, \tau \rightarrow e \nu \bar{\nu}$ )



Require lepton candidate to pass electron ID



Electron is most energetic particle in signal hemisphere

# Pre-selection cut flow ( $B_c \rightarrow \tau \bar{\nu}, \tau \rightarrow e \nu \bar{\nu}$ )

Large event weights required  
to scale MC to  $10^{11}$  Z decays

1/6100

1/4900

1/6100

1/1100

1/1500

	$B_c^+ \rightarrow \tau^+ \nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	$B^+ \rightarrow \tau^+ \nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	dd	uu	ss	cc	bb
All	625177/134681	797230/195570	2530406	2415827	2531430	10414223	10532756
$b$ -tag > 0.6	437048/94370	536144/133336	12495	11559	14920	590417	7885422
$\Delta E > 10$ GeV	361063/83338	433750/119520	2048	1857	2525	108464	1892666
One lepton in signal hemisphere	127468/44500	153697/61805	610	549	784	38263	623432
Electron ID	32044/42386	30916/58652	206	181	245	16107	287334
Electron is the most energetic particle	2569/32458	2173/42475	8	5	4	2449	93945

# Search for $B_u \rightarrow \tau \nu$ at the Z pole (L3)

- 1.475M hadronic Z decays
- Main selection criteria
  - Large missing energy
  - One low-multiplicity hemisphere that contains a track consistent with coming from a tau, but not consistent with coming from the primary vertex
- Total efficiency  $(2.8 \pm 0.5) \%$

$$\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) < 5.7 \times 10^{-4} \text{ at 90\% CL}$$

- L3 did not consider  $B_c$  contribution ( $B_c$  had not been discovered at the time)

L3 Collaboration, PLB 396 (1997) 327

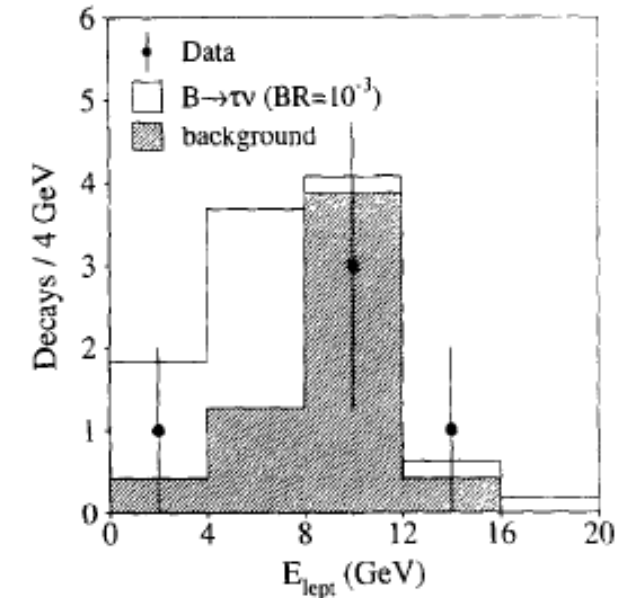


Fig. 6. Lepton energy spectrum for the selected  $B^- \rightarrow \tau^- \bar{\nu}_\tau$ ,  $\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau$  candidates. The hatched histogram represents the background, the open histogram shows the signal contribution assuming  $\mathcal{B}(B^- \rightarrow \tau^- \bar{\nu}_\tau) = 10^{-3}$ .



#B<sub>c</sub> → τν and #B<sub>u</sub> → τν are roughly the same at the Z pole

$$\frac{N_{B_c}}{N_{B_u}} = \frac{f(b \rightarrow B_c)}{f(b \rightarrow B_u)} \left| \frac{V_{cb}}{V_{ub}} \right|^2 \left( \frac{f_{B_c}}{f_{B_u}} \right)^2 \frac{m_{B_c}}{m_{B_u}} \frac{\tau_{B_c}}{\tau_{B_u}} \frac{\left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2}{\left(1 - \frac{m_\tau^2}{m_{B_u}^2}\right)^2} \sim O(1)$$

- $\frac{\tau_{B_c}}{\tau_{B_u}} \sim 0.31$  ( $\pm 2\%$ )
- $\frac{m_{B_c}}{m_{B_u}} \frac{\left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2}{\left(1 - \frac{m_\tau^2}{m_{B_u}^2}\right)^2} \sim 1.3$  ( $\ll \pm 0.1\%$ )
- $\left(\frac{f_{B_c}}{f_{B_u}}\right)^2 \sim 6.2$  ( $\pm 10\%$ ;  $\pm 3.5\%$  each  $f_{B_c}$  and  $f_{B_u}$  each, correlated?)
- $\left|\frac{V_{cb}}{V_{ub}}\right|^2 \sim 120$  ( $\pm 20\%$ ;  $\pm 9\%$   $V_{ub}$ ,  $\pm 2\%$   $V_{cb}$ , BELLEII expects to measure  $V_{ub}$  with 1% precision)
- $\frac{f(b \rightarrow B_c)}{f(b \rightarrow B_u)} \sim O(1/400)$  ( $f(b \rightarrow B_c) = 0.008\% - 0.1\%$ ,  $\pm 5.8\%$   $f(b \rightarrow B_u)$ )

 Largest uncertainty, assume here 0.1%

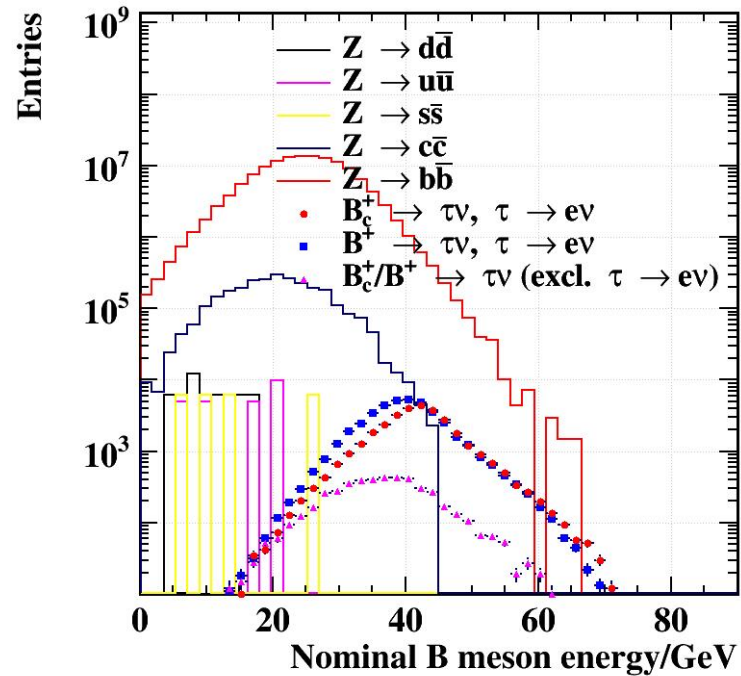
# How many $B_{u,c} \rightarrow \tau\nu$ @ CEPC Z pole?

$$\begin{aligned} N(B_u \rightarrow \tau\nu) &= N_Z \times \text{BR}(Z \rightarrow b\bar{b}) \times 2 \times \text{BR}(b \rightarrow B_u X) \times \text{BR}(B_u \rightarrow \tau\nu) \\ &= 10^{11} \times (0.1512 \pm 0.0005) \times 2 \times (0.378 \pm 0.022) \times (1.09 \pm 0.24) \times 10^{-4} \\ &= (1.1 \pm 0.3) \text{ M} \end{aligned}$$

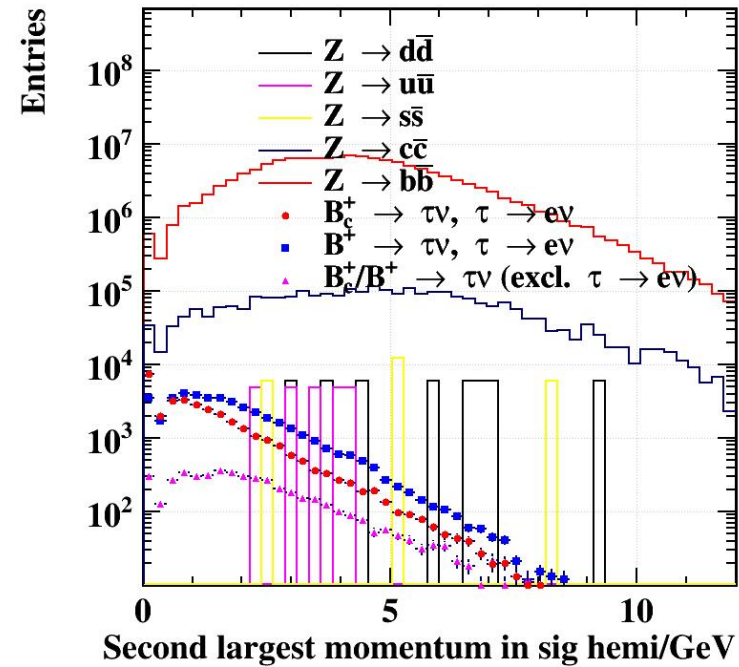
- Roughly 1M each of  $B_u \rightarrow \tau\nu$  and  $B_c \rightarrow \tau\nu$  are produced in  $10^{11}$  Z decays
  - Assume here:  $7.5 \times 10^5 B_c^+ \rightarrow \tau^+ \nu_\tau$  &  $1 \times 10^6 B^+ \rightarrow \tau^+ \nu_\tau$
  - $\text{BR}(\tau \rightarrow e\nu\nu) = 17.8\%$ ,  $\text{BR}(\tau \rightarrow \mu\nu\nu) = 17.3\%$

# Signal selection

- Use a 7-parameter BDT to isolate  $B_{u,c} \rightarrow \tau\nu$  events



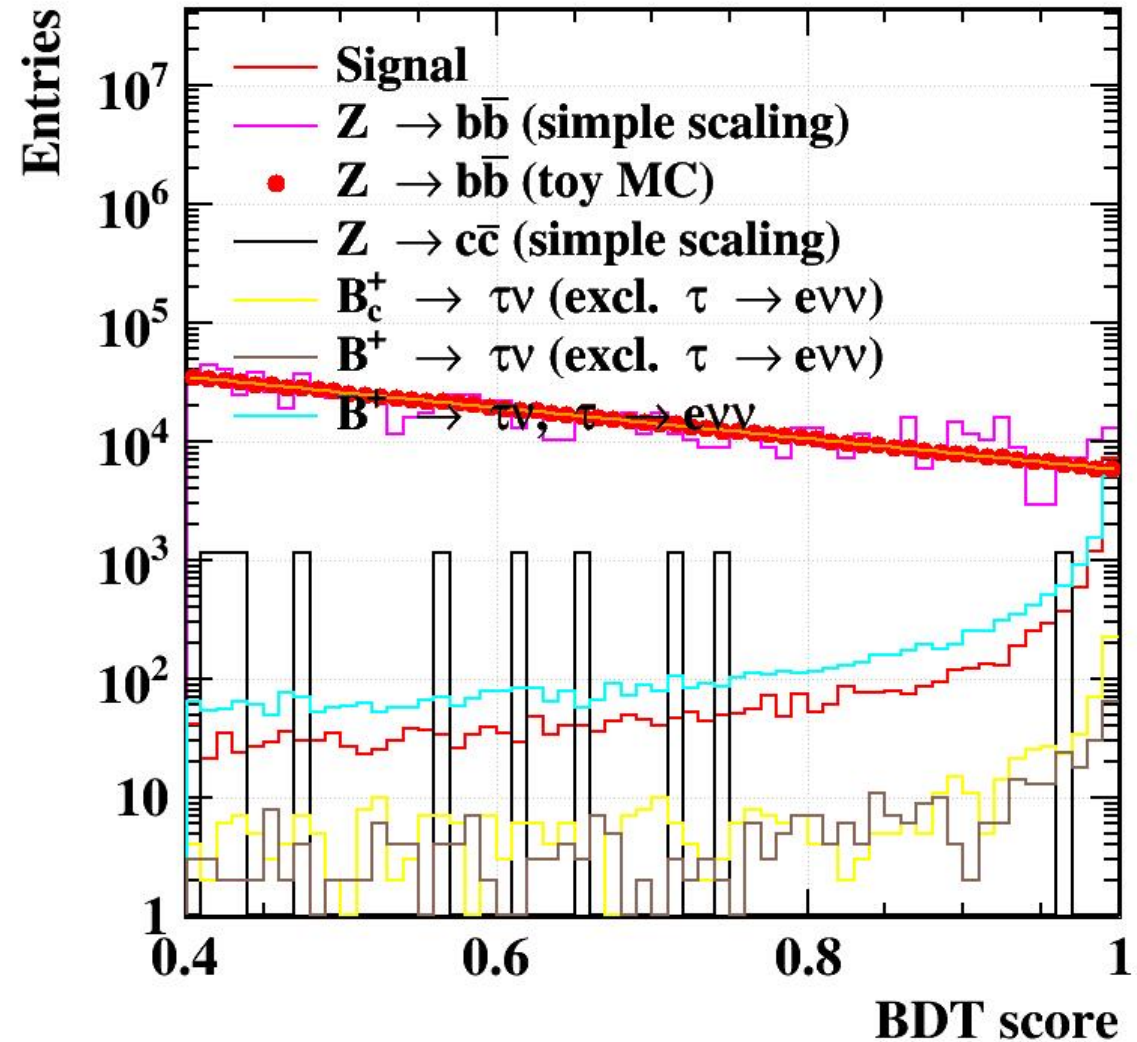
$E_B = 91.2$  GeV – all visible energy  
(except the signal electron)



Second largest track momentum  
in signal hemisphere

# BDT( $B_{u,c} \rightarrow \tau\nu, \tau \rightarrow e\nu\nu$ )

Variable	Importance
Nominal Bc energy	0.201
Second largest momentum in signal hemisphere	0.151
Maximum neutral cluster energy inside 30 deg cone	0.151
Energy asymmetry	0.148
Electron energy	0.123
Second largest IP in signal hemisphere	0.120
Number of tracks in signal hemisphere	0.106



# Cut chain ( $B_{u,c} \rightarrow \tau \nu, \tau \rightarrow e \nu \nu$ )

	$B_c^+ \rightarrow \tau^+ \nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	$B^+ \rightarrow \tau^+ \nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	$\frac{1}{6100}$ ↓ dd	$\frac{1}{4900}$ ↓ uu	$\frac{1}{6100}$ ↓ ss	$\frac{1}{1100}$ ↓ cc	$\frac{1}{1500}$ ↓ bb
All	625177/134681	797230/195570	2530406	2415827	2531430	10414223	10532756
$b$ -tag > 0.6	437048/94370	536144/133336	12495	11559	14920	590417	7885422
$\Delta E > 10$ GeV	361063/83338	433750/119520	2048	1857	2525	108464	1892666
One lepton in signal hemisphere	127468/44500	153697/61805	610	549	784	38263	623432
Electron ID	32044/42386	30916/58652	206	181	245	16107	287334
Signal $e$ candidate is most energetic $e$	2569/32458	2173/42475	8	5	4	2449	93945
BDT > 0.99 (training data)	226/7226	65/5150	0	0	0	0	9 (5884)
BDT > 0.99 (test data)	223/7142	87/5178	0	0	0	1	8 (7441)

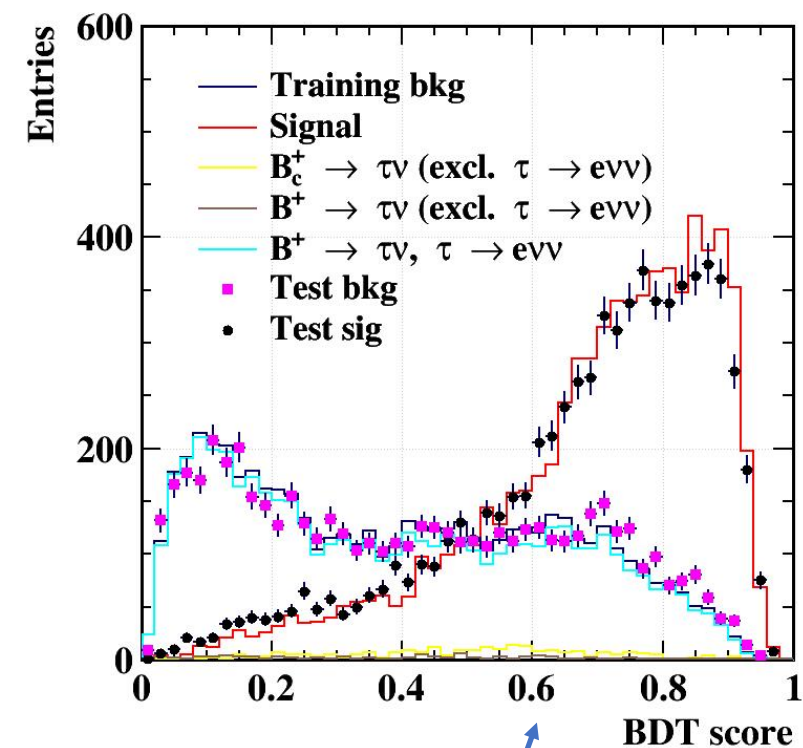
50/50 split between test and train samples

Predicted by toy MC

# A second BDT to separate $B_c \rightarrow \tau\nu$ from $B_u \rightarrow \tau\nu; \tau \rightarrow e\nu\nu$

Using all of the previous variables + electron IP

Variable	Importance
Electron IP	0.164
Electron energy	0.138
Nominal $B_c$ energy	0.137
$\Delta E$	0.134
Maximum neutral cluster energy inside 30 deg cone	0.133
Second largest momentum in signal hemisphere	0.127
Second largest IP in signal hemisphere	0.086
Number of tracks in signal hemisphere	0.082



Cut at 0.6

# Signal sensitivity of $B_c \rightarrow \tau\nu$

- $10^{11}$  Z decays
  - 5200  $B_c \rightarrow \tau\nu$  ( $\tau \rightarrow e\nu\nu$ ) events and 1400  $B_u \rightarrow \tau\nu$  ( $\tau \rightarrow e\nu\nu$ ) pass cut on 2<sup>nd</sup> BDT  $> 0.6$
  - About 7400 bb background events (will be less since some won't pass the 2<sup>nd</sup> BDT cut)
  - Total background statistical uncertainty  $\sim 100$  events, gives stat. significance of  $\sim 50\sigma$
- $10^9$  Z decays
  - 52  $B_c \rightarrow \tau\nu$  ( $\tau \rightarrow e\nu\nu$ ) events and 14  $B_u \rightarrow \tau\nu$  ( $\tau \rightarrow e\nu\nu$ ) pass cut on 2<sup>nd</sup> BDT  $> 0.6$
  - About 74 bb background events (will be less since some won't pass the 2<sup>nd</sup> BDT cut)
  - Total background stat. uncertainty  $\sim 10$  events, gives statistical significance of  $\sim 5\sigma$
- $\tau \rightarrow \mu\nu\nu$  channel has about the same sensitivity
- $B_c \rightarrow \tau\nu$  could be discovered with  $5 \times 10^8$  Z decays
  - Assuming  $f(b \rightarrow B_c) = 0.1\%$ , but could be 10x smaller
- $B_u \rightarrow \tau\nu$  sensitivity will be similar with a reversed 2<sup>nd</sup> BDT cut
  - Negligible uncertainty in production rate
- Results with both BDTs combined in one look very promising, even better signal sensitivity

# Other (experimentally) similar measurements

- EW loop/ box decays with 2  $\nu$ 's in the final state have a similar signature as  $B_{u(c)} \rightarrow \tau\nu$ : one easily identifiable particle plus large missing energy
  - Measurements unique to the Z pole
    - $\text{BR}(B_s \rightarrow \phi \nu\bar{\nu})$ ,  $\text{BR}(\Lambda_b \rightarrow \Lambda \nu\bar{\nu})$
  - Measurements that could also be done at BELLE II
    - $\text{BR}(B_d \rightarrow K_s \nu\bar{\nu})$ ,  $\text{BR}(B_u \rightarrow K^+ \nu\bar{\nu})$

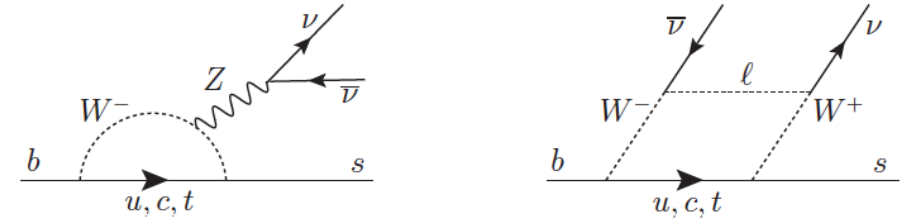


FIG. 1: Lowest-order SM Feynman diagrams for  $b \rightarrow s\nu\bar{\nu}$  transitions. The virtual top quark provides the dominant contribution in each case.

Prediction:  $\text{BR}(B_u \rightarrow K^+ \nu\bar{\nu}) = \text{BR}(B_d \rightarrow K^0 \nu\bar{\nu}) = (4.5 \pm 0.7) \times 10^{-6}$

*W. Altmannshofer et al., JHEP 0904, 022 (2009)*

- Wide variety of NP scenarios can modify the expected branching fractions and  $q^2$  ( $q$  = lepton pair mass) distribution
  - Particles contributing to additional loop diagrams (non-standard Z couplings with SUSY particles, 4<sup>th</sup> generation quarks, anomalous top-charm transitions, or a massive U(1) gauge boson Z)
  - NP can also contribute to the experimental signature of a kaon plus missing four-momentum, such as low-mass dark-matter candidates, unparticles, right-handed neutrinos, or SUSY particles
  - Models with universal extra dimension also predict higher BRs

$$\mathcal{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) < 1.6 \times 10^{-5},$$

$$\mathcal{B}(B^0 \rightarrow K^0 \nu\bar{\nu}) < 4.9 \times 10^{-5},$$

*BaBar Collaboration, PRD 87, 112005 (2013)*  
*(with  $\sim 1/100$  of expected Belle II data sample)*



# Conclusions

- $B_c \rightarrow \tau \nu$  can be discovered with about a  $\sim 5 \times 10^8$  Z if  $f(b \rightarrow B_c) = 0.1\%$ , but need  $\sim 5 \times 10^{10}$  Z if  $f(b \rightarrow B_c) = 0.01\%$ ,
- $\text{BR}(B_u \rightarrow \tau \nu)$  can be measured with about 1% precision with  $10^{11}$  Z
- Rare loop/box decays of  $B_s$ ,  $B_c$ , or b baryons with 2 neutrinos in the final state can be studied best or even exclusively at the Z pole
  - Sensitivity can now relatively easily be estimated using the existing analysis where e or  $\mu$  is replaced with  $\Lambda$ ,  $\phi$ , or K and the corresponding signal MC simulated events