$B_c \rightarrow \tau\nu$

− an example of flavor physics at the Z pole

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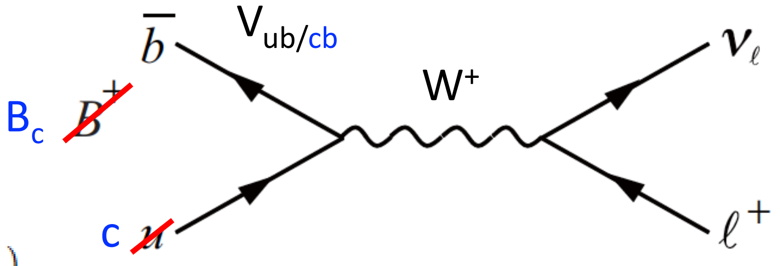
$B_{u,c} \rightarrow \tau\nu$ in the Standard Model



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

$$P^+(Q\bar{q}) \rightarrow \ell^+\nu_\ell \qquad (1)$$

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):

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

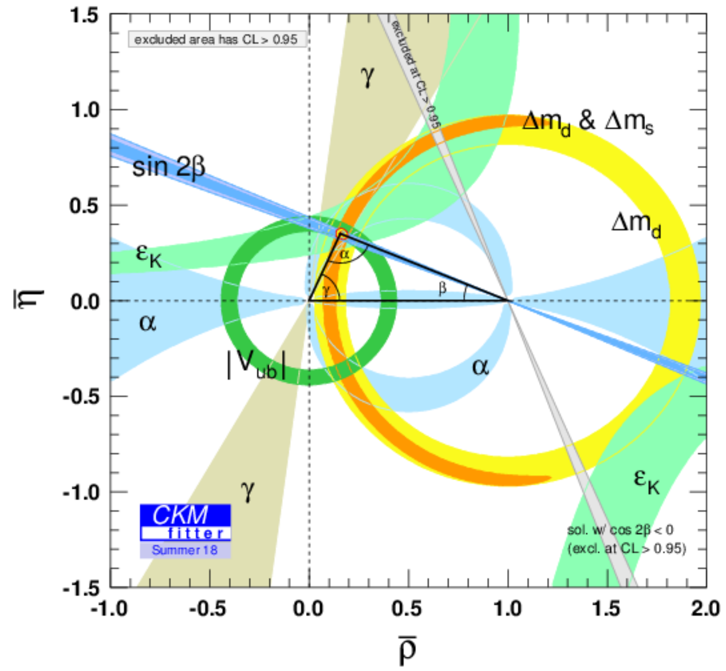
$$\Gamma_{SM}(P^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{Qq}|^2 f_P^2 M_P m_\ell^2 (1 - \frac{m_\ell^2}{M_P^2})^2 ,$$

Due to helicity suppression, τ final state has largest branching fraction

- Get f_{Bu} from LQCD, then measure BR($B_u \rightarrow \tau\nu$) to determine V_{ub}
- Get f_{Bc} from LQCD, then measure BR($B_c \rightarrow \tau\nu$) to determine V_{cb}

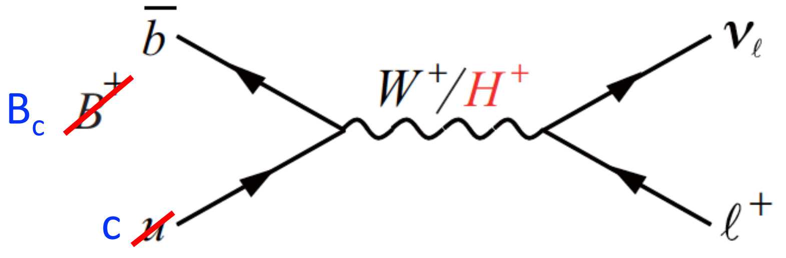
  – OR –

- Get V_{cb} from BR($B \rightarrow D(*)\, l\, \nu$) measurements and measure f_{Bc} 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

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

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

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

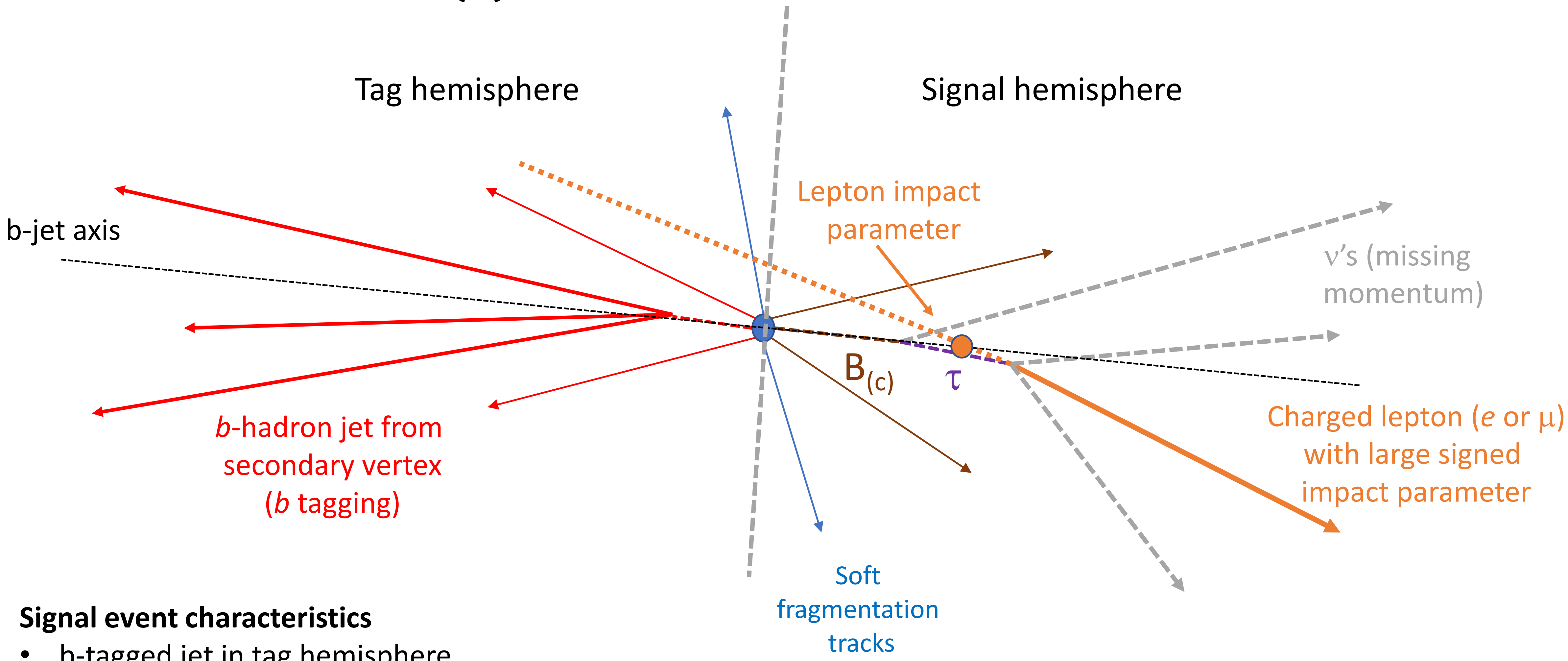
Table 84.3: Experimental results for $\mathcal{B}(D_s^+ \to \mu^+\nu)$, $\mathcal{B}(D_s^+ \to \tau^+\nu)$, and $|V_{cs}|f_{D_s^+}$. Numbers for $|V_{cs}|f_{D_s^+}$ have been extracted using updated values for masses (see text). The systematic uncertainty for correlated error on the D_s^+ lifetime is 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	$\mathcal{B}(\%)$	$\lvert V_{cs}\rvert f_{D_s^+}$ (MeV)
CLEO-c [47,48]	$\mu^+\nu$	$0.565 \pm 0.045 \pm 0.017$	$250.8 \pm 10.0 \pm 4.2$
BaBar[a] [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 ± 0.024	248.8 ± 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 ± 0.22	252.1 ± 5.2
Our average	$\mu^+\nu + \tau^+\nu$		250.9 ± 4.0

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

Particle Data Group, 2018

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 μ)
- Large lepton impact parameter

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

L3 Collaboration, PLB 396 (1997) 327

- 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 ± 0.5) %

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

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

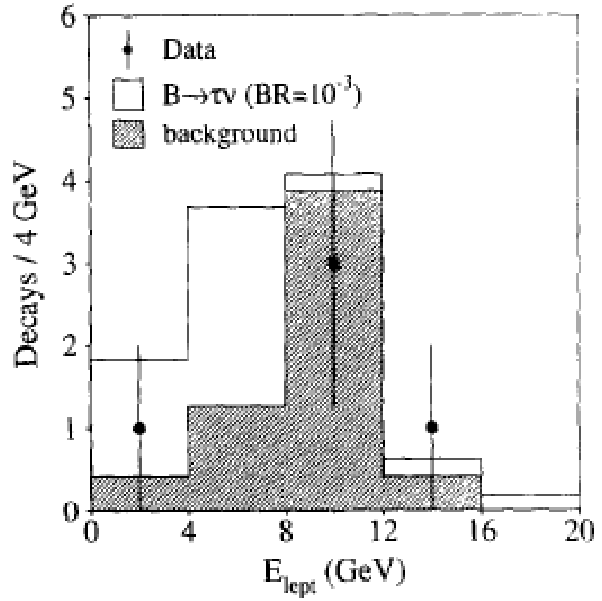


Fig. 6. Lepton energy spectrum for the selected $B^- \to \tau^- \bar{\nu}_\tau$, $\tau^- \to l^- \bar{\nu}_l \nu_\tau$ candidates. The hatched histogram represents the background, the open histogram shows the signal contribution assuming $\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau) = 10^{-3}$.

Mangano and Slabospitsky, PLB 410 (1997) 299
Deng et al., Eur.Phys.J. C70 (2010) 113

#B_c → τν and #B_u → τν are roughly the same at the Z pole

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

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

Largest uncertainty, assume here 0.1%

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

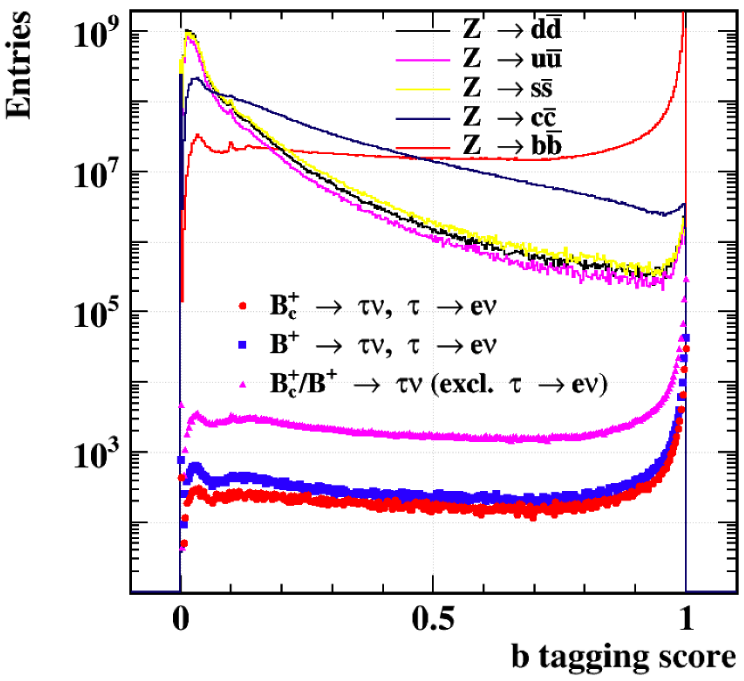
$N(B_u \rightarrow \tau\nu) = N_Z \times BR(Z \rightarrow b\bar{b}) \times 2 \times BR(b \rightarrow B_u X) \times BR(B_u \rightarrow \tau\nu)$

$= 10^{11} \times (0.1512 \pm 0.0005) \times 2 \times (0.378 \pm 0.022) \times (1.09 \pm 0.24) \times 10^{-4}$

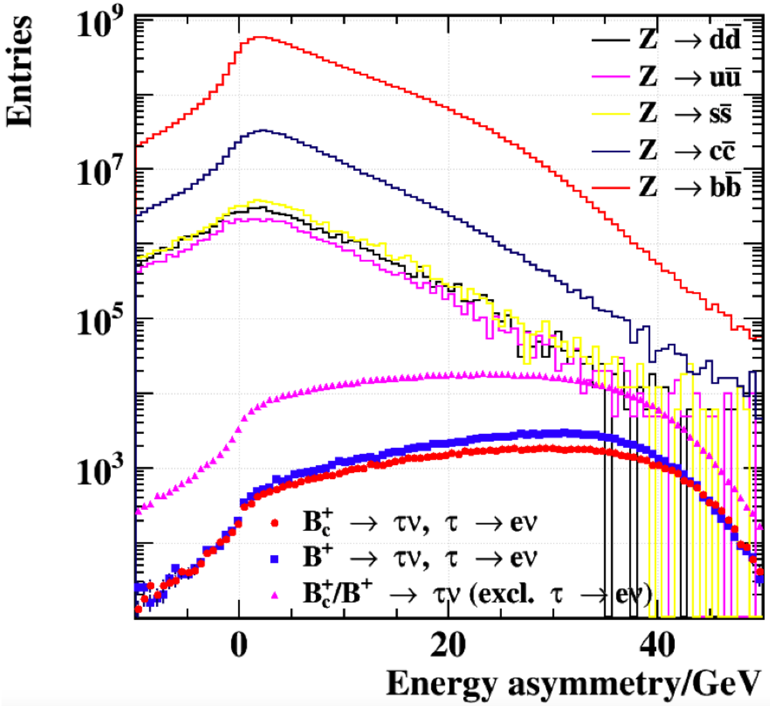
$= (1.1 \pm 0.3)$ M

- Roughly 1M each of $B_u \rightarrow \tau\nu$ and $B_u \rightarrow \tau\nu$ are produced in 10^{11} Z decays
  - Assume here: $0.75\times 10^6\ B_c^+ \rightarrow \tau^+\nu_\tau$ & $1 \times 10^6\ B^+ \rightarrow \tau^+\nu_\tau$
  - $BR(\tau \rightarrow e\nu\nu) = 17.8\%$, $BR(\tau \rightarrow \mu\nu\nu) = 17.3\%$

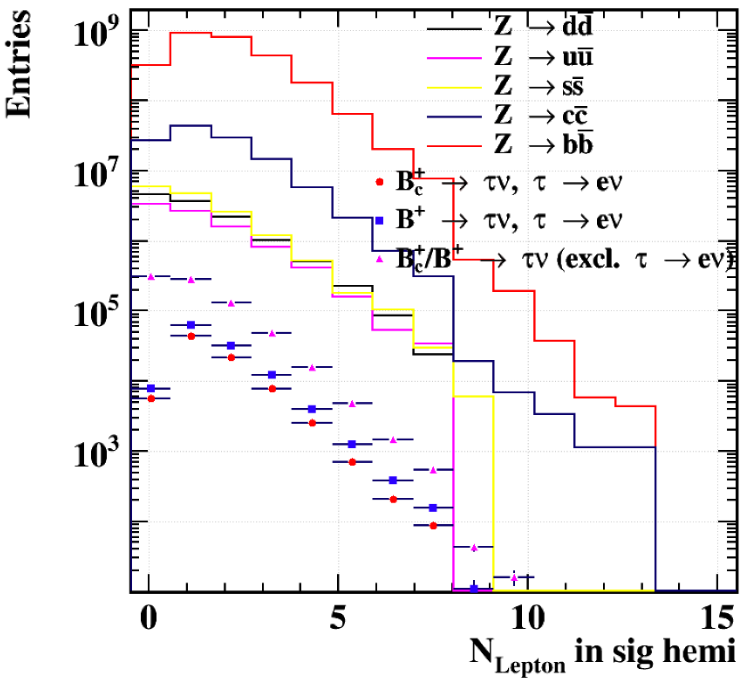
Parameter distributions ($B_c \rightarrow \tau\bar{\nu}, \tau \rightarrow e\nu\bar{\nu}$)



Score of the b-tagging algorithm for tag-side jet: b-tag > 0.6

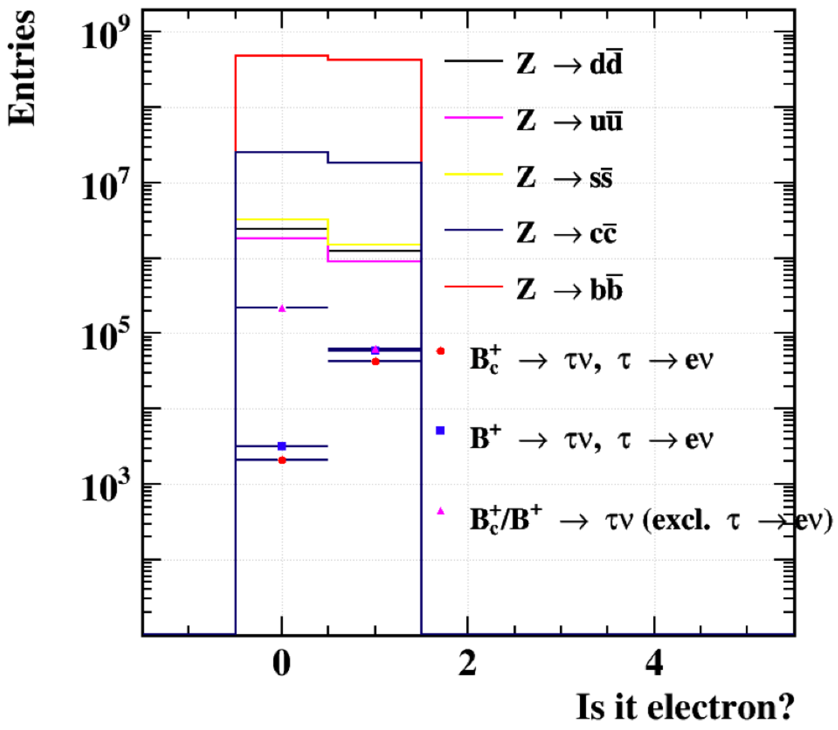


Energy asymmetry between the two hemispheres $\Delta E = E_{Recoil} - E_{signal} > 10$ GeV

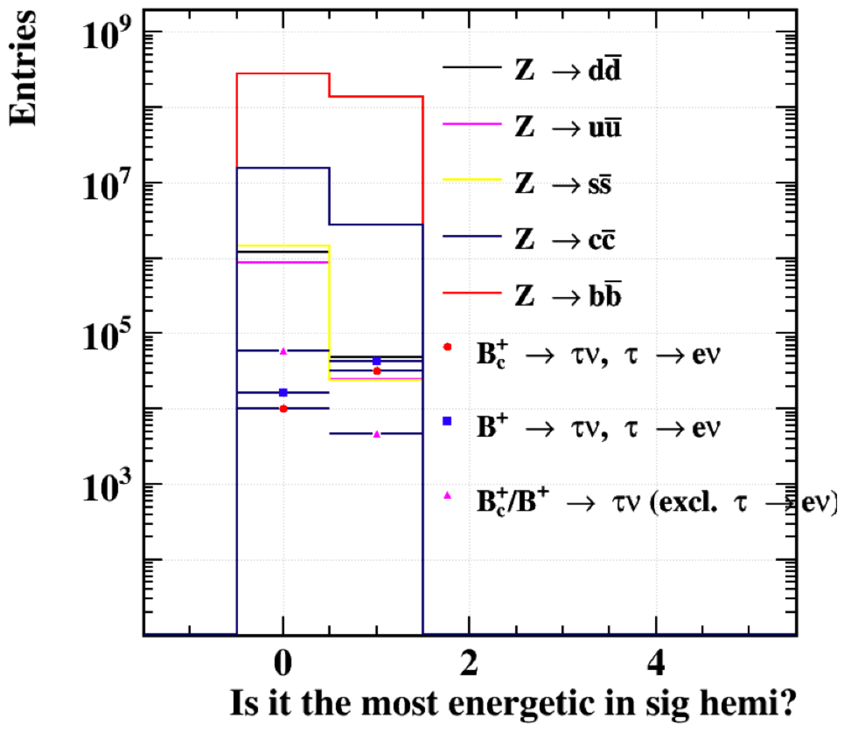


Exactly one lepton in the signal hemisphere

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



Require lepton candidate to pass electron ID



Electron is most energetic particle in signal hemisphere

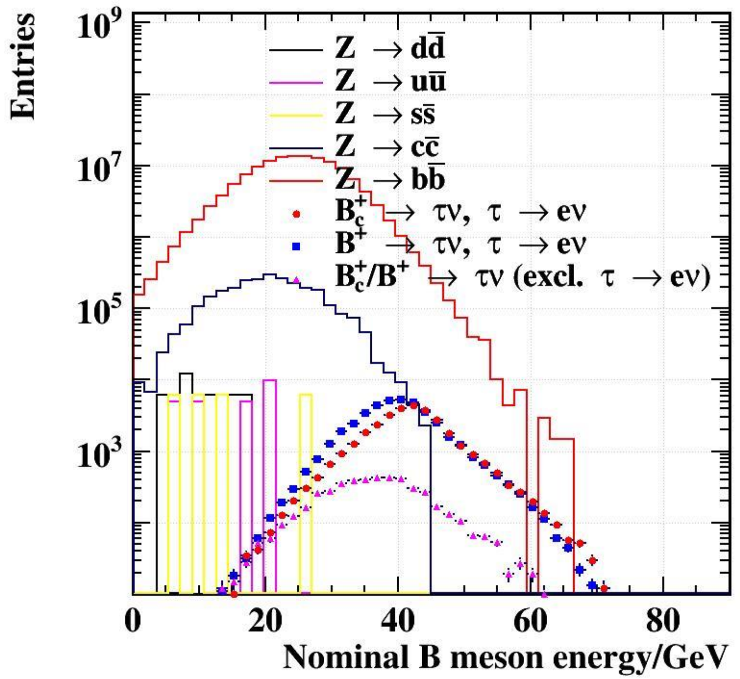
Pre-selection cut flow ($B_c \to \tau\bar{\nu}, \tau \to e\nu\bar{\nu}$)

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

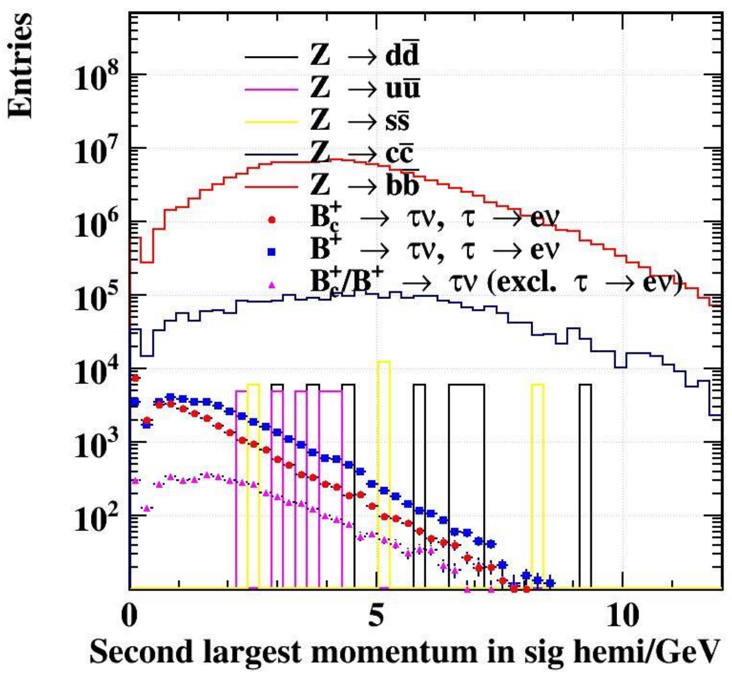
	$B_c^+ \to \tau^+\nu_\tau$ excl. $\tau \to e/\tau \to e$	$B^+ \to \tau^+\nu_\tau$ excl. $\tau \to e/\tau \to e$	dd (1/6100)	uu (1/4900)	ss (1/6100)	cc (1/1100)	bb (1/1500)
All	625177/134681	797230/195570	2530406	2415827	2531430	10414223	10532756
b-tag > 0.6	437048/94370	536144/133336	12495	11559	14920	590417	7885422
ΔE > 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

Signal selection

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



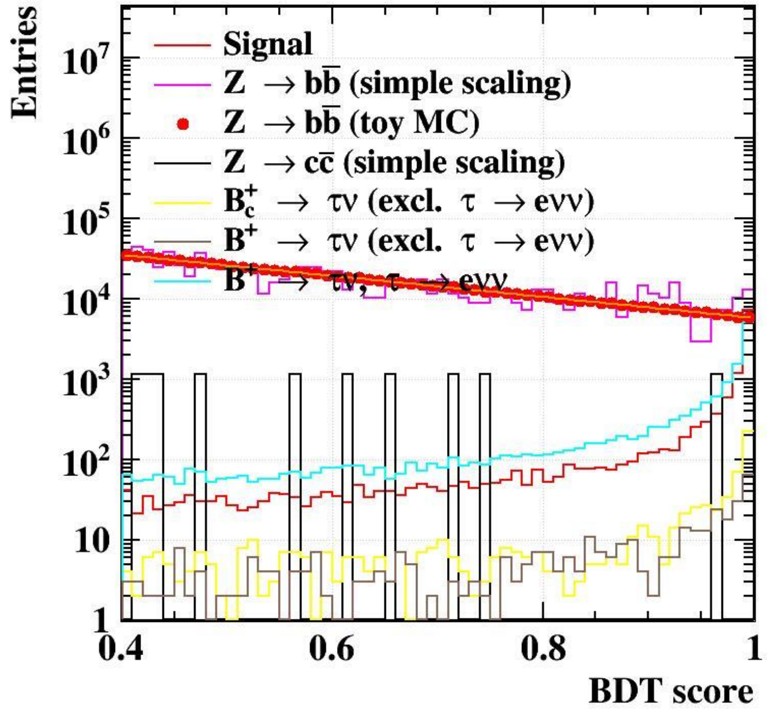
E_B = 91.2 GeV – all visible energy (except the signal electron)



Second largest track momentum in signal hemisphere

BDT($\tau \to e\nu\nu$)

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



root 5.34.07

Set the weight to corresponding luminosity

Cut chain ($\tau \rightarrow e\nu\nu$)

	$B_c^+ \rightarrow \tau^+\nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	$B^+ \rightarrow \tau^+\nu_\tau$ excl. $\tau \rightarrow e/\tau \rightarrow e$	dd (1/6100)	uu (1/4900)	ss (1/6100)	cc (1/1100)	bb (1/1500)
All	625177/134681	797230/195570	2530406	2415827	2531430	10414223	10532756
b-tag > 0.6	437048/94370	536144/133336	12495	11559	14920	590417	7885422
Energy asymmetry > 10 GeV	361063/83338	433750/119520	2048	1857	2525	108464	1892666
One lepton in sig hemi	127468/44500	153697/61805	610	549	784	38263	623432
Which is electron	32044/42386	30916/58652	206	181	245	16107	287334
And it's the most energetic one	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)

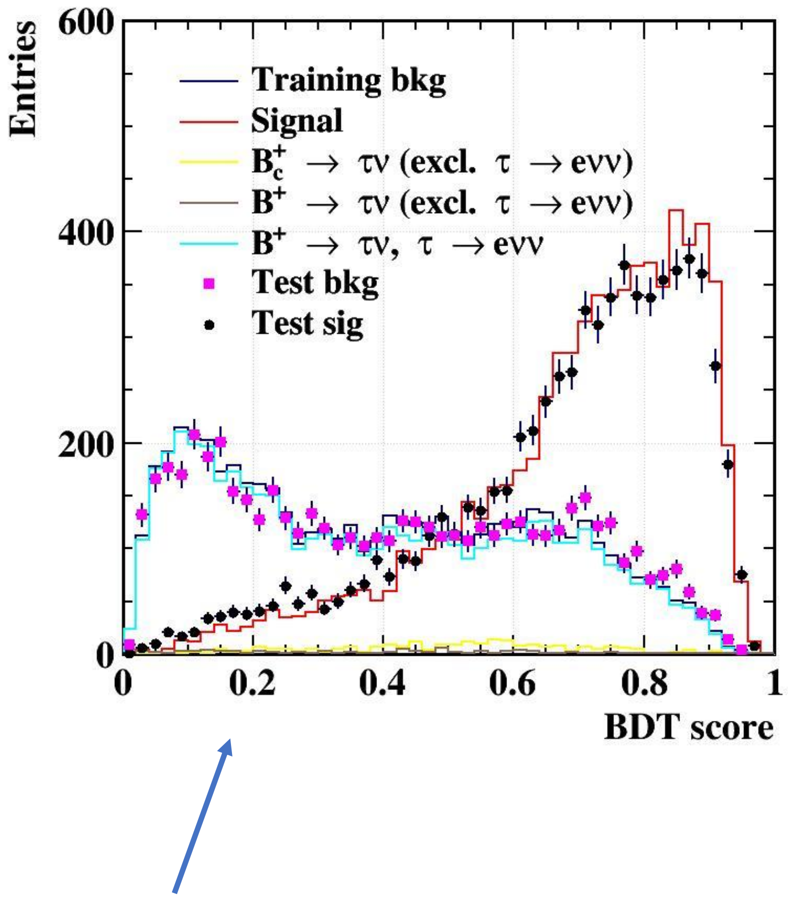
50/50 split between test and train samples

Predicted by toy MC

Second BDT($\tau \to e\nu\nu$)

Using all of the previous variables + electron IP to do BDT again (ignore bb)

Variable	Importance
Electron IP	0.164
Electron energy	0.138
Nominal Bc energy	0.137
Energy asymmetry	0.134
Maximum neutral cluster energy inside 30 deg cone	0.133
The second largest momentum in sig hemi	0.127
Second largest IP in sig hemi	0.086
Number of tracks in sig hemi	0.082



Cut at 0.6

Second BDT($\tau \to e\nu\nu$)

	$B_c^+ \to \tau^+\nu_\tau$ excl. $\tau \to e/\tau \to e$	$B^+ \to \tau^+\nu_\tau$ excl. $\tau \to e/\tau \to e$
BDT > 0.6 (training data)	76/5444	17/1300
BDT > 0.6 (test data)	107/5201	13/1434

Signal sensitivity of $B_c \to \tau\nu$

- 10^{11} Z decays
  - 10k $B_c \to \tau\nu$ ($\tau \to e\nu\nu$) events and 2.8k $B_u \to \tau\nu$ ($\tau \to e\nu\nu$) pass cut on 2nd BDT > 0.6
  - About 13k bb background events (will be less since some won't pass the 2nd BDT cut)
  - Total background statistical uncertainty ~100 events, gives stat. significance of ~100σ
- $7\text{x}10^8$ Z decays
  - 70 Bc → τν ($\tau \to e\nu\nu$) events and 20 Bu → τν ($\tau \to e\nu\nu$) pass cut on 2nd BDT > 0.6
  - About 92 bb background events (will be less since some won't pass the 2nd BDT cut)
  - Total background stat. uncertainty ~13 events, gives statistical significance of ~5σ
- $\tau \to \mu\nu\nu$ channel has about the same sensitivity

- $B_c \to \tau\nu$ could be discovered with 3.5 x 10^8 Z decays
  - Assuming f($b \to B_c$) = 0.1%, but could be 10x smaller
- $B_u \to \tau\nu$ sensitivity will be similar with a reversed 2nd BDT cut
  - Negligible uncertainty in production rate

- Results with both BDTs combined in one look very promising, even better signal sensitivity