First look at $B_c^+ \to \tau^+ \nu$ with FCC-ee

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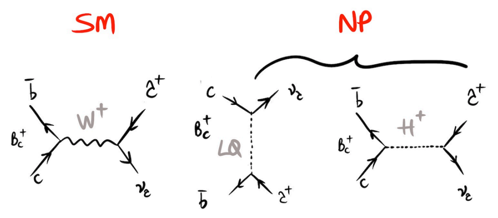
20/01/21

2nd FCC France workshop

Why do we care about $B_c^+ \to \tau^+\nu$?

Contributions in the SM and NP scenarios :



- Can be used to measure CKM matrix element $|V_{cb}|$, moreover it is highly sensitive to scalar contributions from NP (e.g. charged Higgs, leptoquarks).
- Not possible at LHCb due to missing energy – lack of constraints and reconstructed information.
- No B_c^+ mesons produced at Belle II.
- FCC-ee is an ideal machine to study this decay!

Why do we care about $B_c^+ \to \tau^+ \nu$?

Most general EFT description at $\mu = m_b$:

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1 + C_{V_L}) (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{V_R} (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L) + C_{S_L} (\bar{c}_L b_R)(\bar{\tau}_R \nu_L) + C_{S_R} (\bar{c}_R b_L)(\bar{\tau}_R \nu_L) \Big] + \text{h.c}$$

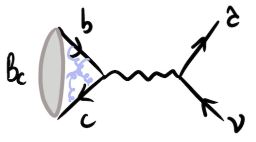
- $C_i \equiv$ Wilson coefficients induced by NP ($C_i = 0 \ \forall i$ in the SM).
- Useful definitions: $C_{V(A)} = C_{V_R} \pm C_{V_L}$ and $C_{S(P)} = C_{S_R} \pm C_{S_L}$.
- $B_c^+ \to \tau^+ \nu$ very sensitive to pseudo-scalar contributions:

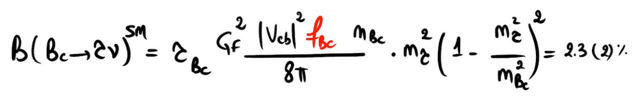
$$\mathcal{B}(B_c \to \tau\nu) = \mathcal{B}^{\text{SM}}(B_c \to \tau\nu) \left| 1 - C_A - C_P \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \right|^2$$

Hence, C_P lifts the SM helicity suppression – sizable enhancement!

SM prediction

SM contribution:





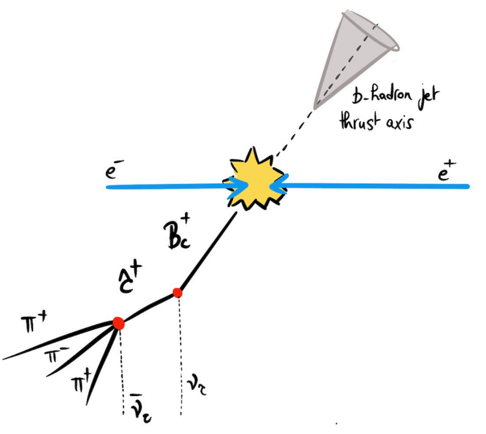
$$\mathcal{B}(B_c \to \tau\nu)^{SM} = \tau_{B_c} \frac{G_F^2 |V_{cb}|^2 f_{B_c} m_{B_c}}{8\pi} \cdot m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 = 2.3(2)\%$$

where we have used the decay constant $f_{Bc} = 434(15)$ MeV [HPQCD, 1503.05762] and $|V_{cb}|^{\text{excl}} = 39.25(56) \times 10^{-3}$ [HFLAV].

NB: Improved LQCD computations of f_{Bc} are needed to match the experimental precision expected at FCC-ee.

Decay topology – see dedicated talk by D.Hill

B_c^+ lifetime very short ~ 0.5 ps, too many degrees of freedom to fully reconstruct the decay.
Strategy based on exploring:

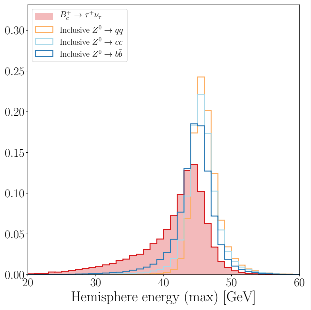


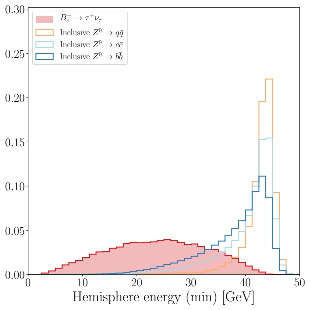
- thrust axis properties to suppress contamination from light jets.
- decay $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}$ to separate from the $B^+ \to \tau^+\nu$ events.

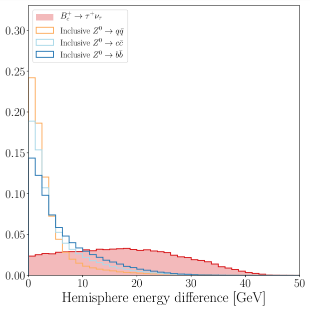
Information about simulation

- Samples produced with Pythia, EvtGen and Delphes in EDM4hep, with post-processing in FCCAnalyses to calculate thrust and hemisphere energy information
- 30,000 $B_c^+ \to \tau^+ \nu_\tau$ after filtering (filter keeps events with a B_c^+ produced in hadronisation)
    - $\tau^+ \to 3\pi\bar{\nu}_\tau$ generated via TAUHADNU model
- Inclusive $Z^0 \to q\bar{q}, c\bar{c}, b\bar{b}$ - 10, 5, 10 million respectively
    - MVA studies (see later) combine these into a single 1 million event training sample using Z^0 branching fractions
    - Background rejection then tested using full samples

$E^{\text{max/min/diff}}$ - clear separation for $B_c^+ \to \tau^+ \nu_\tau$

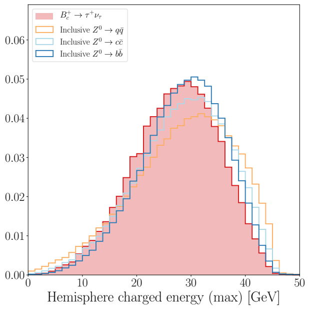


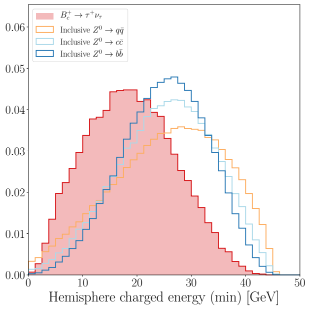




$E_c^{\text{max/min}}$

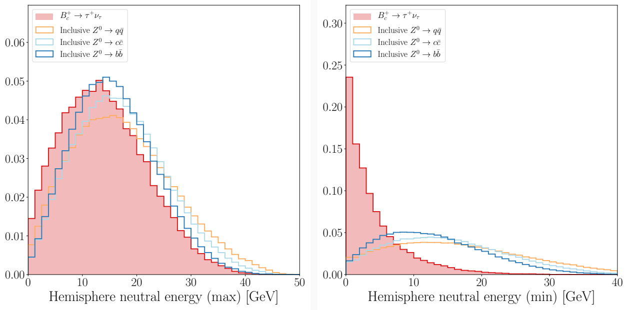
- More separation power in the minimum energy hemisphere
- This side is predominantly signal due to missing neutrinos
- In inclusive background, hemispheres have similar energy on average





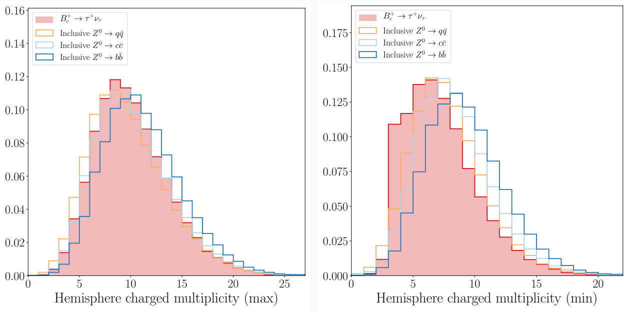
$E_n^{\mathrm{max/min}}$ - more power in min. E hemisphere (mostly signal side)

- More separation power in the minimum energy hemisphere
- This side is predominantly signal due to missing neutrinos
- In inclusive background, hemispheres have similar energy on average



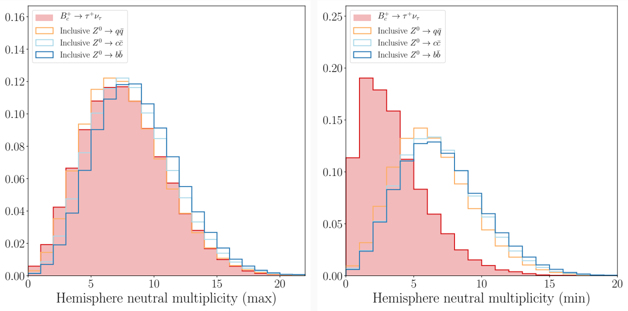
$M_c^{\text{max/min}}$

- Non-signal sides are similar in terms of charged particle content
- Signal side slightly lower in multiplicity, since we only have three charged tracks in signal decay



$M_n^{\text{max/min}}$

- Non-signal sides are similar in terms of neutral particle content
  - Neutral particles are charge-zero objects reconstructed in PFlow
- Signal side quite a bit more quiet



Multivariate analysis

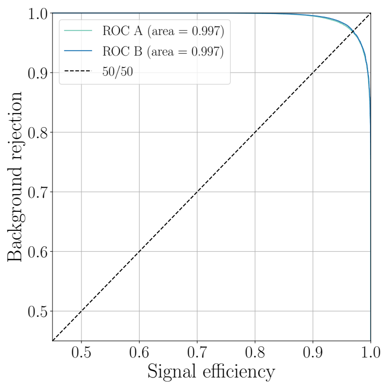
- Use hemisphere energy information to distinguish $B_c^+ \to \tau^+ \nu_\tau$ from $Z^0 \to q\bar{q}, c\bar{c}, b\bar{b}$

- Create combined background sample of 1 million events using Z^0 PDG branching fractions

- Use *`XGBClassifier`* from *`xgboost`* package with:
  - *`n_estimators`* = 400
  - *`learning_rate`* = 0.3
  - *`max_depth`* = 3
  - All other hyper-parameters set to defaults

- Split samples into A and B, and train two BDTs (A and B)
  - Apply BDT A (B) to sample B (A) to get predictions for full sample

ROC AUC and feature ranking



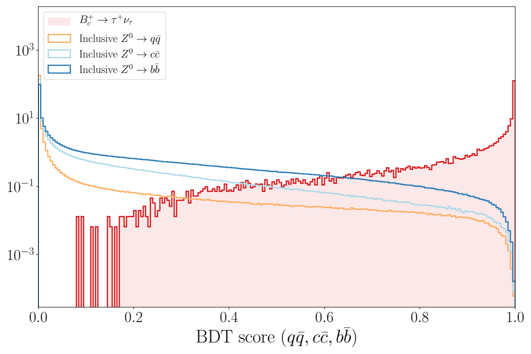
Variable	Feature importance
E^{min}	0.419
E_n^{min}	0.159
E_c^{min}	0.142
E^{max}	0.097
E_c^{max}	0.0473
M_c^{min}	0.036
E_n^{max}	0.035
M_c^{max}	0.025
M_n^{min}	0.024
M_n^{max}	0.016

- Lower energy hemisphere dominates, but also contributions from charged and neutral sub-totals and the maximum hemisphere energy

BDT score distributions

- Reject all $q\bar{q}$, $c\bar{c}$, and $b\bar{b}$ background events (in their respective samples) with BDT > 0.997 cut
  - 10^7-level rejection, as samples are 5-10 million in size
  - $q\bar{q}$ > $c\bar{c}$ > $b\bar{b}$ in terms of rejection power

- The same BDT cut is 60% efficient on $B_c^+ \to \tau^+\nu_\tau$ signal



Signal purity estimate

- Assume 5×10^{12} Z^0 in FCC-ee operation
- With $\mathcal{B}(Z^0 \to \text{hadrons})$ = 69.9%, leads to 7.0×10^{12} inclusive background decays
- $N(B_c^+ \to \tau^+ \nu_\tau)$ = $237,000$ using the following factors

Factor	Value
$N(Z^0)$	5×10^{12}
$\mathcal{B}(Z^0 \to b\bar{b})$	0.1512
B_c^+ production rate	7.9×10^{-5} [1501.00338(NRQCD)]
$\mathcal{B}(B_c^+ \to \tau^+ \nu_\tau)$	0.0236
$\mathcal{B}(\tau^+ \to \{3\pi, 3\pi\pi^0\}\bar{\nu}_\tau)$	0.14

- Signal purity before any selection is thus 3×10^{-8}.
- The Input marked in orange has to be carefully looked at.

Signal purity estimate

- Let's target 10,000 signal events with 10,000 background (50% purity) for a $\sim 1\%$ precision $\mathcal{B}$ measurement

- Total background rejection required: 7.0×10^8

- Total signal efficiency required: 4.2%

- BDT achieves 10^7 rejection for 60% signal efficiency:
    - Brings us from 3×10^{-8} to 20% purity (**another factor 2.5 in purity needed**)
    - Further factor of 70 in background rejection needed
    - Can tolerate an additional signal efficiency of 7%

- Selections based on specific signal properties (3π vertex quality, resonant structure, PV separation) to be studied to understand additional background rejection capabilities

Conclusion & next steps

- Event-level hemisphere energy information provides good discrimination for missing energy mode $B_c^+ \to \tau^+\nu_\tau$

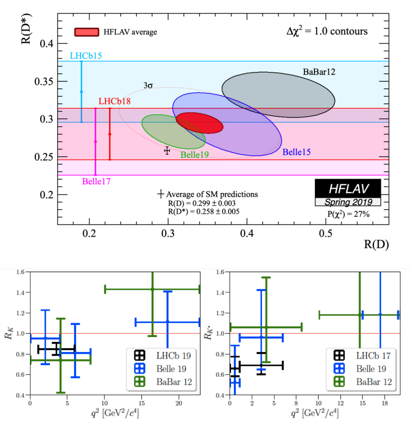
- Larger background and signal samples to be generated, allowing rejection to be better understood

- Most dangerous physics background is $B^+ \to \tau^+\nu_\tau$ - will study this vs. signal in dedicated manner
  - B^+ lifetime is 3 times larger than B_c^+, so τ vertex separation from PV will be an important discriminator
- Investigate the best way to normalise the measurement.
- Investigation of possible improvements to the theory inputs.
- Preparation of the phenomenology interpretation.

~~Panic~~ Backup slides

Flavour anomalies

Tensions observed in the data in both neutral currents $b \to s\ell^+\ell^-$ and charged ones $b \to c\ell^+\nu$. Not clear yet if this is a sign of NP or not. Yet...



Note : tensions seen in both LU tests + angular analyses.

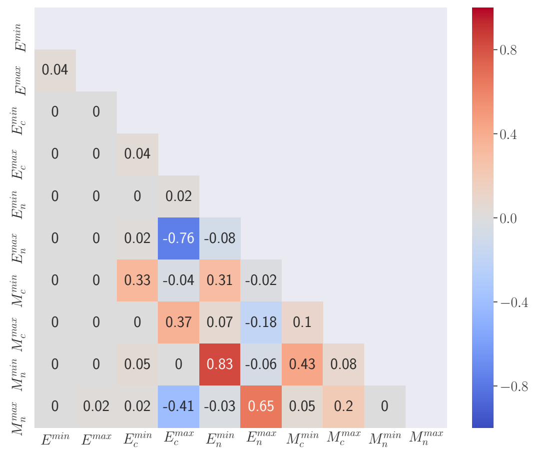
Lepto-quarkology

Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
$S_1 = (3,1)_{-1/3}$	✖	✔	✖
$R_2 = (3,2)_{7/6}$	✖	✔	✖
$\widetilde{R}_2 = (3,2)_{1/6}$	✖	✖	✖
$S_3 = (3,3)_{-1/3}$	✔	✖	✖
$U_1 = (3,1)_{2/3}$	✔	✔	✔
$U_3 = (3,3)_{2/3}$	✔	✖	✖

Table 1: Summary of LQ models which can accommodate $R_{K^{(*)}}$, $R_{D^{(*)}}$ and both. Table based work from 1808.08179..

Variable correlations - $B_c^+ \to \tau^+\nu_\tau$

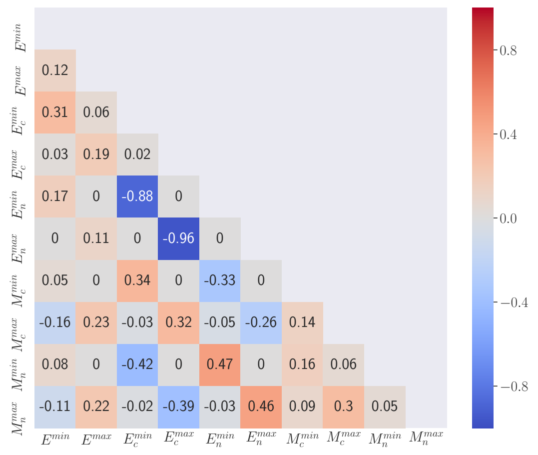
- Some strong correlations but also quite a lot of mutual information



	E^{min}	E^{max}	E_c^{min}	E_c^{max}	E_n^{min}	E_n^{max}	M_c^{min}	M_c^{max}	M_n^{min}	M_n^{max}
E^{min}										
E^{max}	0.04									
E_c^{min}	0	0								
E_c^{max}	0	0	0.04							
E_n^{min}	0	0	0	0.02						
E_n^{max}	0	0	0.02	-0.76	-0.08					
M_c^{min}	0	0	0.33	-0.04	0.31	-0.02				
M_c^{max}	0	0	0	0.37	0.07	-0.18	0.1			
M_n^{min}	0	0	0.05	0	0.83	-0.06	0.43	0.08		
M_n^{max}	0	0.02	0.02	-0.41	-0.03	0.65	0.05	0.2	0	

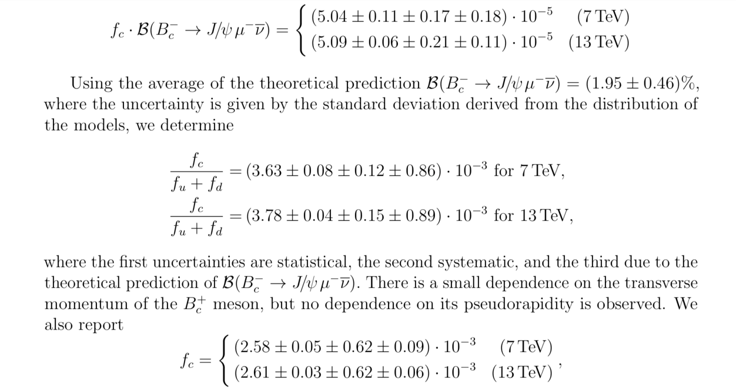
Variable correlations - inclusive $Z^0 \to q\bar{q}$ ($q = u, d, s$)

- Differences in correlation structure compared to signal (similar in $c\bar{c}$ and $b\bar{b}$, see backup slides)



	E^{min}	E^{max}	E_c^{min}	E_c^{max}	E_n^{min}	E_n^{max}	M_c^{min}	M_c^{max}	M_n^{min}	M_n^{max}
E^{min}										
E^{max}	0.12									
E_c^{min}	0.31	0.06								
E_c^{max}	0.03	0.19	0.02							
E_n^{min}	0.17	0	-0.88	0						
E_n^{max}	0	0.11	0	-0.96	0					
M_c^{min}	0.05	0	0.34	0	-0.33	0				
M_c^{max}	-0.16	0.23	-0.03	0.32	-0.05	-0.26	0.14			
M_n^{min}	0.08	0	-0.42	0	0.47	0	0.16	0.06		
M_n^{max}	-0.11	0.22	-0.02	-0.39	-0.03	0.46	0.09	0.3	0.05	

f_c @ measurement at LHCb arXiv:1910.13404



$$f_c \cdot \mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu}) = \begin{cases} (5.04 \pm 0.11 \pm 0.17 \pm 0.18) \cdot 10^{-5} & (7\,\text{TeV}) \\ (5.09 \pm 0.06 \pm 0.21 \pm 0.11) \cdot 10^{-5} & (13\,\text{TeV}) \end{cases}$$

Using the average of the theoretical prediction $\mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu}) = (1.95 \pm 0.46)\%$, where the uncertainty is given by the standard deviation derived from the distribution of the models, we determine

$$\frac{f_c}{f_u + f_d} = (3.63 \pm 0.08 \pm 0.12 \pm 0.86) \cdot 10^{-3} \text{ for } 7\,\text{TeV},$$

$$\frac{f_c}{f_u + f_d} = (3.78 \pm 0.04 \pm 0.15 \pm 0.89) \cdot 10^{-3} \text{ for } 13\,\text{TeV},$$

where the first uncertainties are statistical, the second systematic, and the third due to the theoretical prediction of $\mathcal{B}(B_c^- \to J/\psi\, \mu^- \overline{\nu})$. There is a small dependence on the transverse momentum of the B_c^+ meson, but no dependence on its pseudorapidity is observed. We also report

$$f_c = \begin{cases} (2.58 \pm 0.05 \pm 0.62 \pm 0.09) \cdot 10^{-3} & (7\,\text{TeV}) \\ (2.61 \pm 0.03 \pm 0.62 \pm 0.06) \cdot 10^{-3} & (13\,\text{TeV}) \end{cases},$$