Prospects for Bc →τ ν @ FCCee

arXiv:2105.13330

Y.Amhis, C.Helsens, D.Hill, O.Sumensari

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Case of flavour physics at an @e⁺e⁻ machine running at the *Z⁰* pole

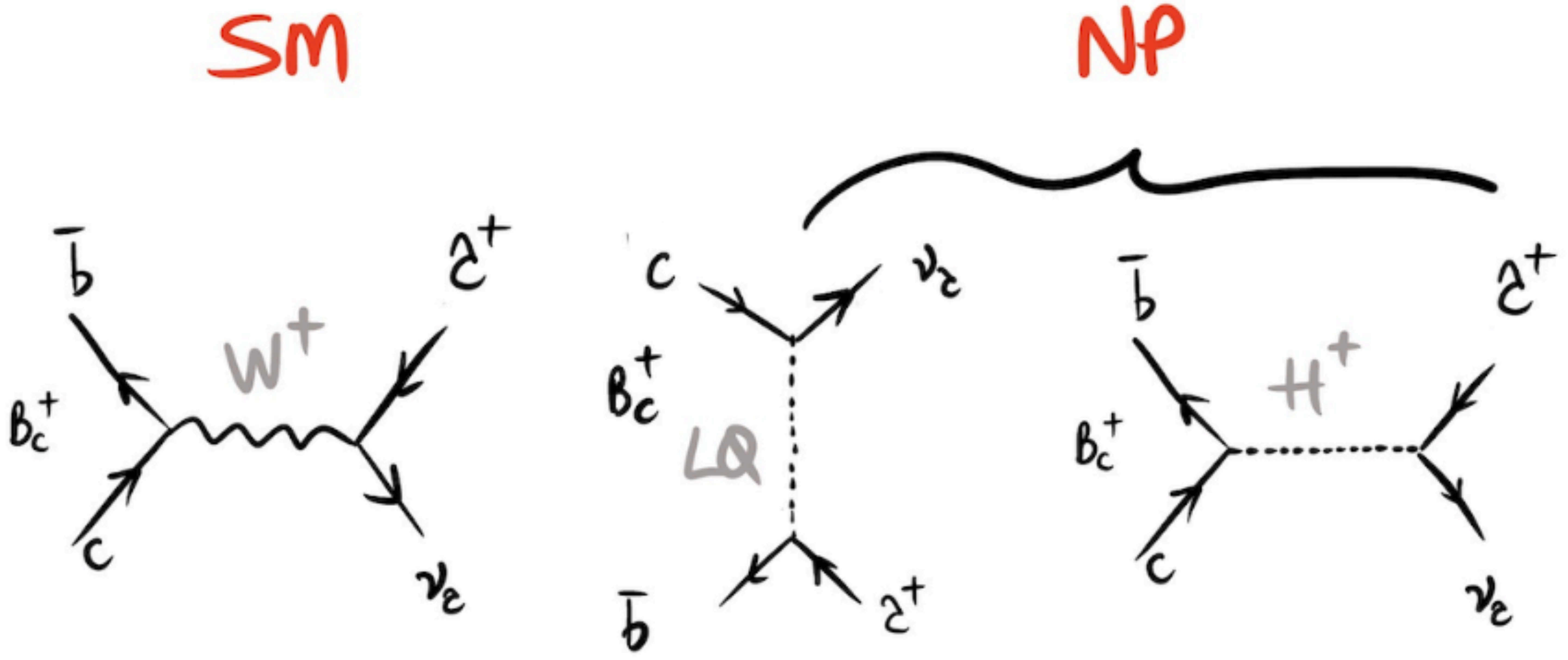
Experimentally attractive

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Very generous yields

Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

Why do we care about this decay?



- Can be used to measure the CKM element $|V_{cb}|$ and highly sensitive to scalar contributions from NP.
- No possible at LHCb due to missing energy-lack of constraints and reconstructed information.
- No B_c production at Belle II.
- A Tera-Z machine is an ideal machine to study this decay.

With an EFT at $\mu = m_b$

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

C_i are the Wilson coefficients, null in the SM using this convention.

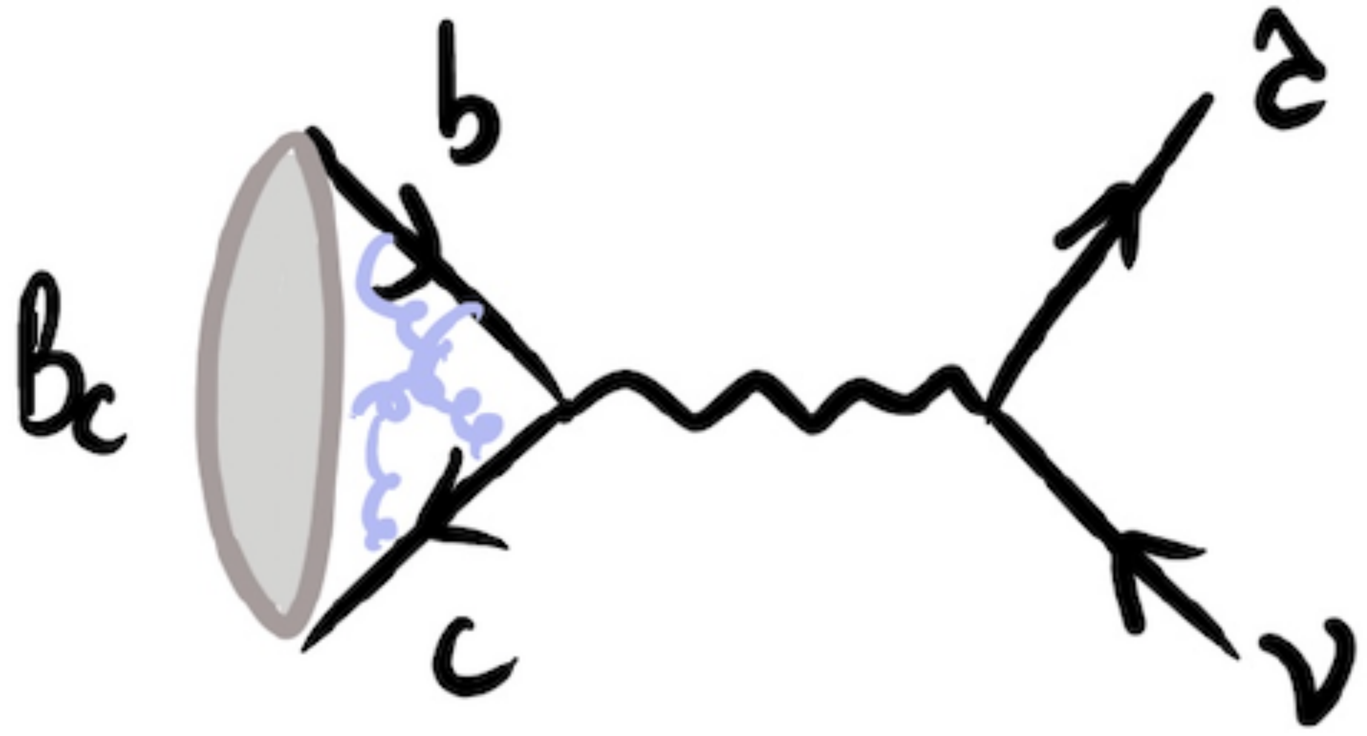
If one uses : $C_{V(A)} = C_{V_R} \pm C_{V_L}$ and $C_{S(P)} = C_{S_R} \pm C_{S_L}$.

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

C_P lifts the SM helicity suppression sizeable enhancement !

SM prediction

Tree-level Feynman diagram in the SM



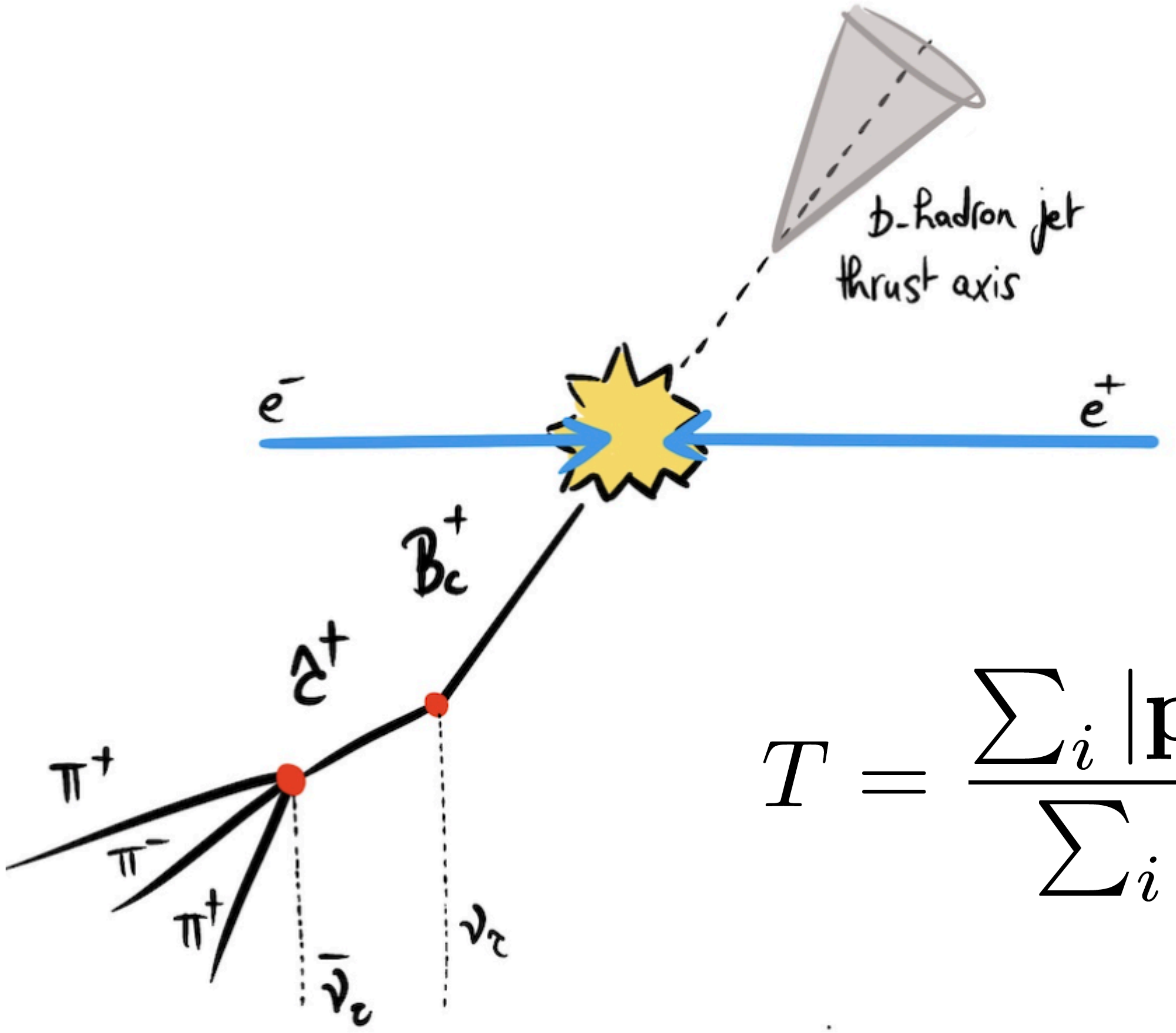
$$\mathcal{B}(B_c \to \tau\nu)^{SM} = \tau_{B_c} \frac{G_F^2 |V_{cb}|^2 f_{B_c} m_{B_c}}{8\pi} \cdot m_\tau^2 \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2$$

$$\mathcal{B}(B_c^+ \to \tau^+ \nu_\tau)^{\mathrm{SM}} = 1.95(9) \times 10^{-2}$$

Decay constant from HPQCD and V_{cb} exclusive HFLAV.
Looking forward to improvements of the decay constant computation with LQCD techniques.

Decay topology

B_c lifetime very short ~ 0.5 ps,
i.e too many degrees of freedom
to fully reconstruct the decay.
Explore the thrust axis properties
and the hadronic τ decays.



$$T = \frac{\sum_i |\mathbf{p}_i \cdot \hat{\mathbf{n}}|}{\sum_i |\mathbf{p}_i|}$$

Note : arXiv:2007.08234 explored leptonic τ decays.

Master formula

$$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau) = \frac{N(B_c^+ \to \tau^+\nu_\tau)}{N(B_c^+ \to J/\psi\mu^+\nu_\mu)} \times \frac{\epsilon(B_c^+ \to J/\psi\mu^+\nu_\mu)}{\epsilon(B_c^+ \to \tau^+\nu_\tau)} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau)} \times \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)\,,$$

How do we get to the final branching ratio?

Analysis strategy

$$\mathcal{B}(B_c^+ \to \tau^+\nu_\tau) = \frac{N(B_c^+ \to \tau^+\nu_\tau)}{N(B_c^+ \to J/\psi\mu^+\nu_\mu)} \times \frac{\epsilon(B_c^+ \to J/\psi\mu^+\nu_\mu)}{\epsilon(B_c^+ \to \tau^+\nu_\tau)} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\tau^+ \to 3\pi\bar{\nu}_\tau)} \times \mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)\,,$$

Avoid using B_c hadronisation fraction

data

simulation

PDG

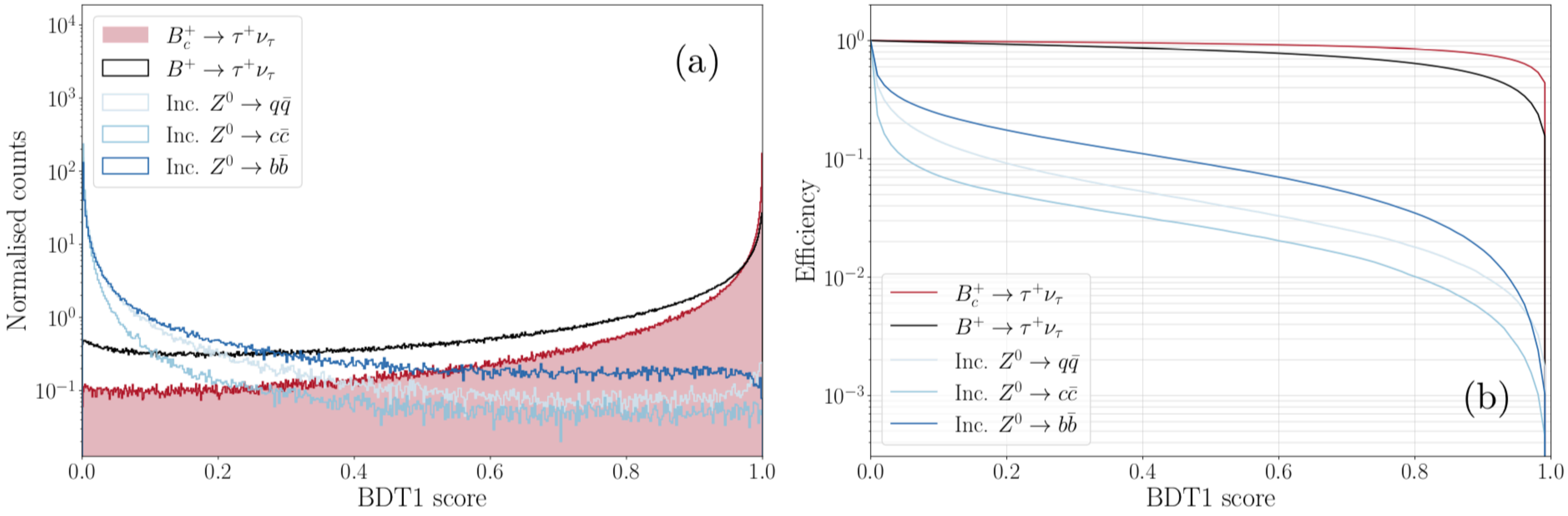
LQCD

Running at the *Z* pole.
Detector configuration using IDEA concept.
Simulation based on DELPHES with HEP-FCC
Needs : very good vertex seeding and particle identification.
Use a two staged BDT.

First stage BDT

Signal : B_c decays are generated with hadronic τ final states using EvtGen (SLN model for the Bc and TAUHADNU for the τ)

Backgrounds: Large sample of inclusive *Z* to *bb*, *cc*, *qq* generated with Pythia. and a collection of exclusive *b*-hadron decays to open charm.



Focuses on event topology

BDT = XGBOOST

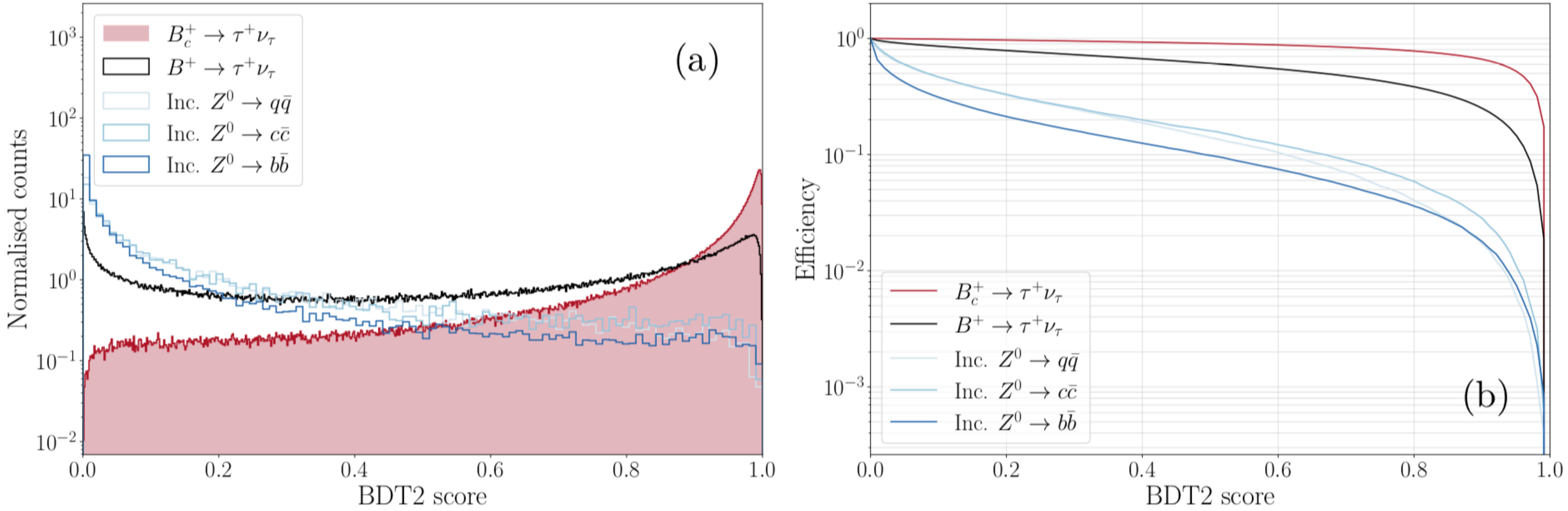
Input variables for the first BDT

- Total reconstructed energy in each hemisphere;
- Total charged and neutral reconstructed energies in each hemisphere;
- Charged and neutral particle multiplicities in each hemisphere;
- Number of tracks in the reconstructed PV;
- Number of reconstructed 3π candidates in the event;
- Number of reconstructed vertices in each hemisphere;
- Minimum, maximum, and average radial distance of all decay vertices from the PV.

Explore event level information

Second stage BDT

Similar input samples as the first stageBDT and requiring 0.6 on the first one.



Focuses on the 3π properties and other reconstructed decay vertices in the event.

Input variables for the second BDT

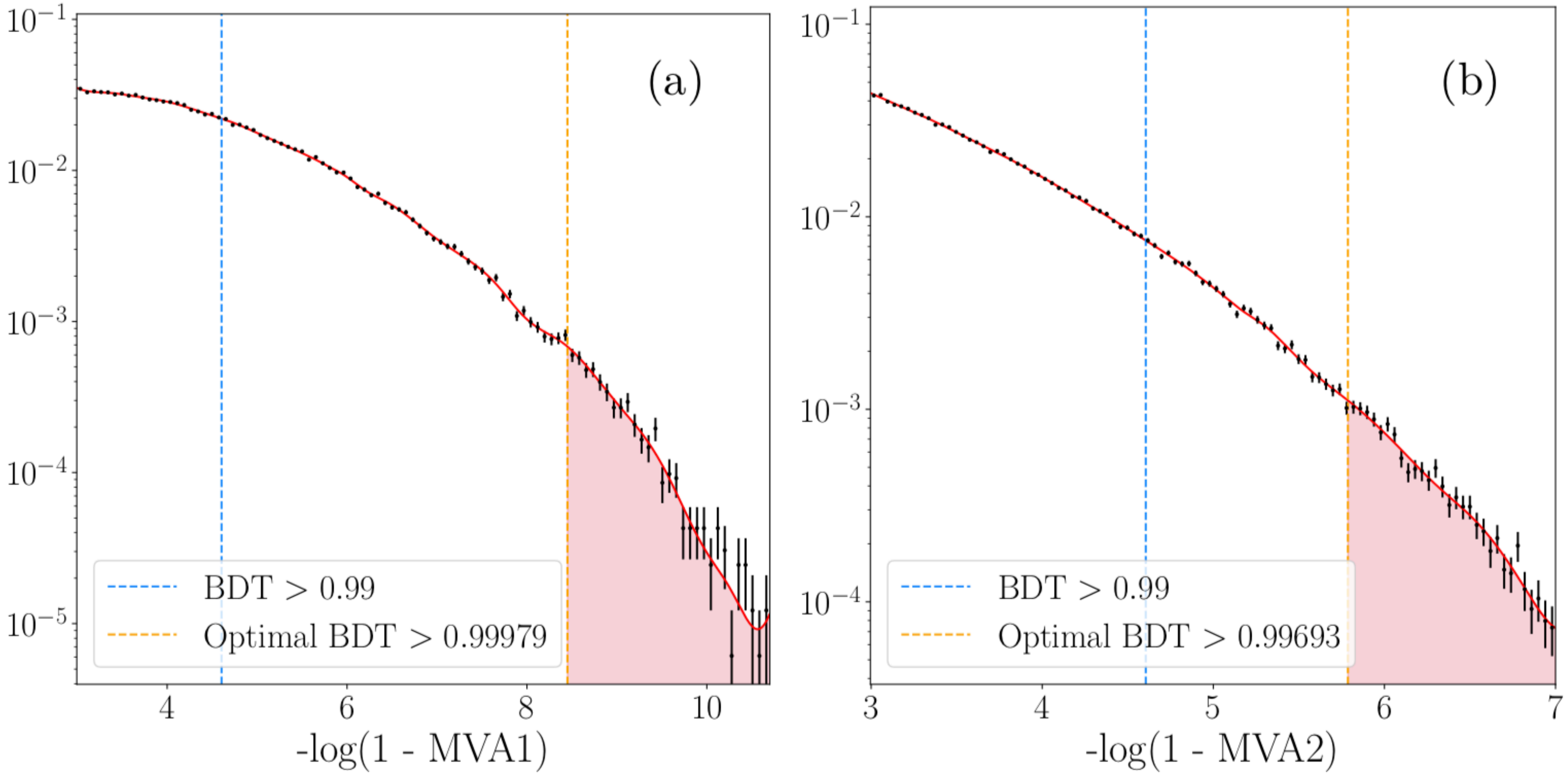
- 3π candidate mass, and masses of the two $\pi^+\pi^-$ combinations;
- Number of 3π candidates in the event;
- Radial distance of the 3π candidate from the PV;
- Vertex χ^2 of the 3π candidate;
- Momentum magnitude, momentum components, and impact parameter (transverse and longitudinal) of the 3π candidate;

- Angle between the 3π candidate and the thrust axis;
- Minimum, maximum, and average impact parameter (longitudinal and transverse) of all other reconstructed decay vertices in the event;
- Mass of the PV;
- Nominal B energy, defined as the Z mass minus all reconstructed energy apart from the 3π candidate.

Optimisation

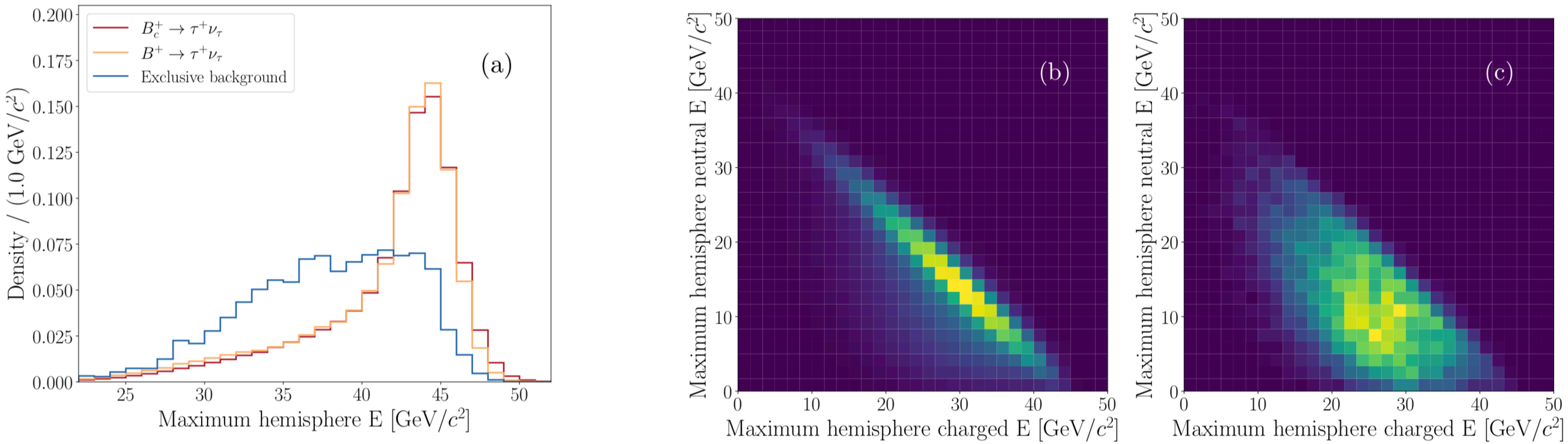
Perform a two dimensional optimisation on the BDT cuts (2500 points in total) maximise S/(S+B)

$$N(B_c^+ \to \tau^+\nu_\tau) = N_Z \times \mathcal{B}(Z \to b\bar{b}) \times 2 \times f(B_c^+) \times \mathcal{B}(B_c^+ \to \tau^+\nu_\tau) \times \mathcal{B}(\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau) \times \epsilon,$$



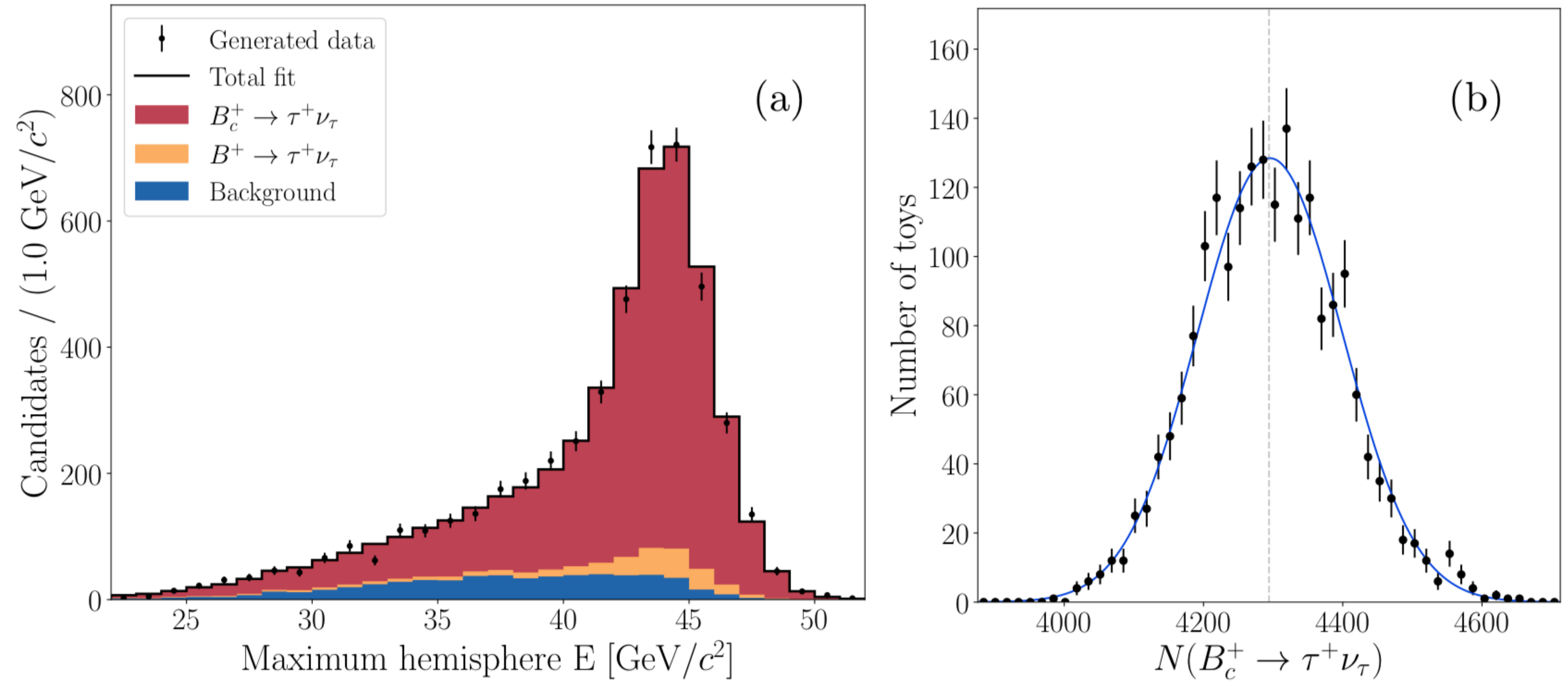
Towards the fit

Compare signal and background distributions after tight BDT cut
and identify most discriminating ones



Use these histograms to build the PDF for the template fits.

Performances



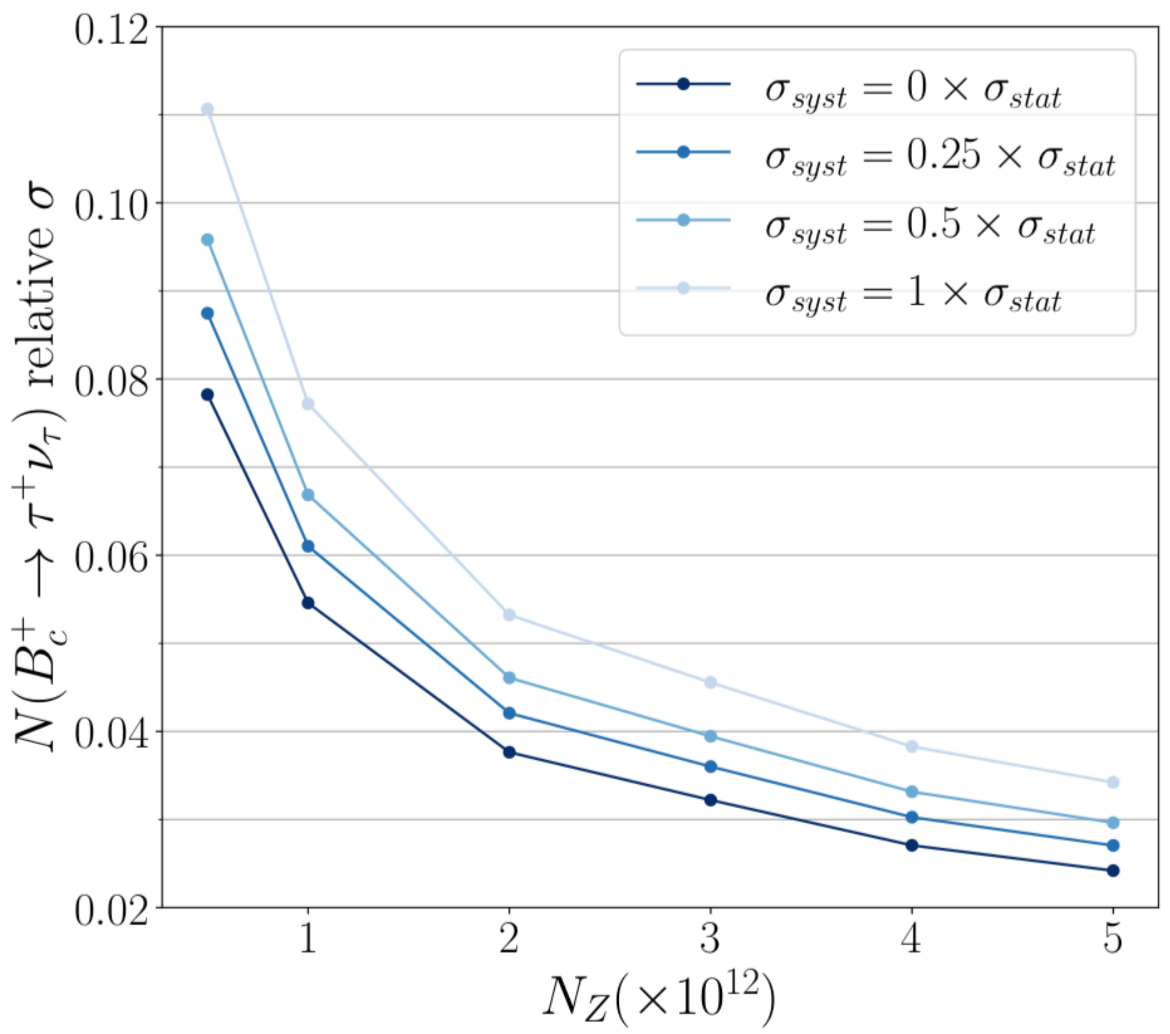
Example of one pseudo-experiment

Evolution of the sensitivity

with :

$N_Z = 5 \times 10^{12}$

2000 toys

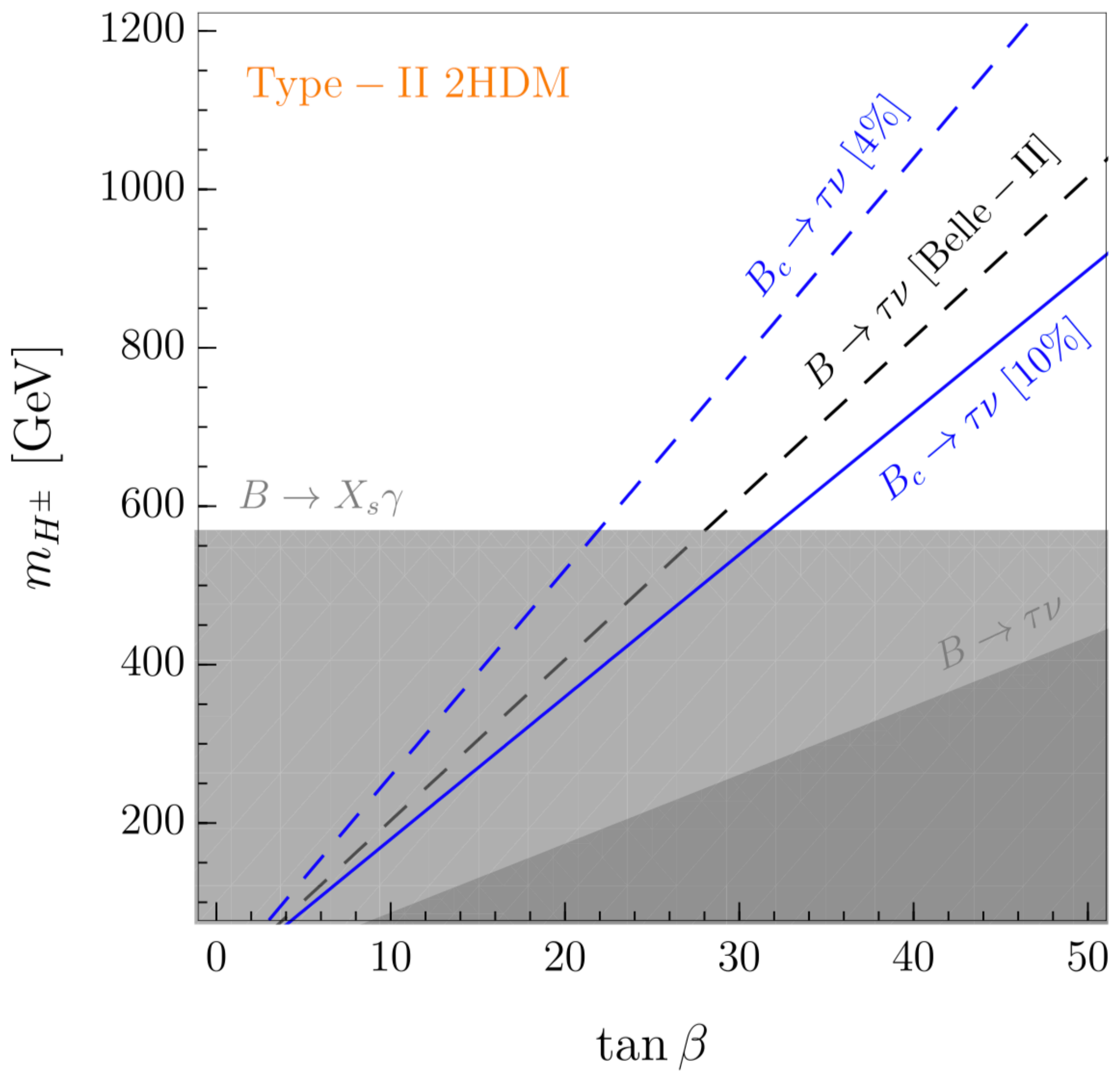


$N_Z(\times 10^{12})$	$N(B_c^+ \to \tau^+\nu_\tau)$	Relative σ (%)
0.5	430 ± 33	7.8
1	858 ± 46	5.5
2	1717 ± 64	3.8
3	2578 ± 83	3.2
4	3436 ± 93	2.7
5	4295 ± 103	2.4

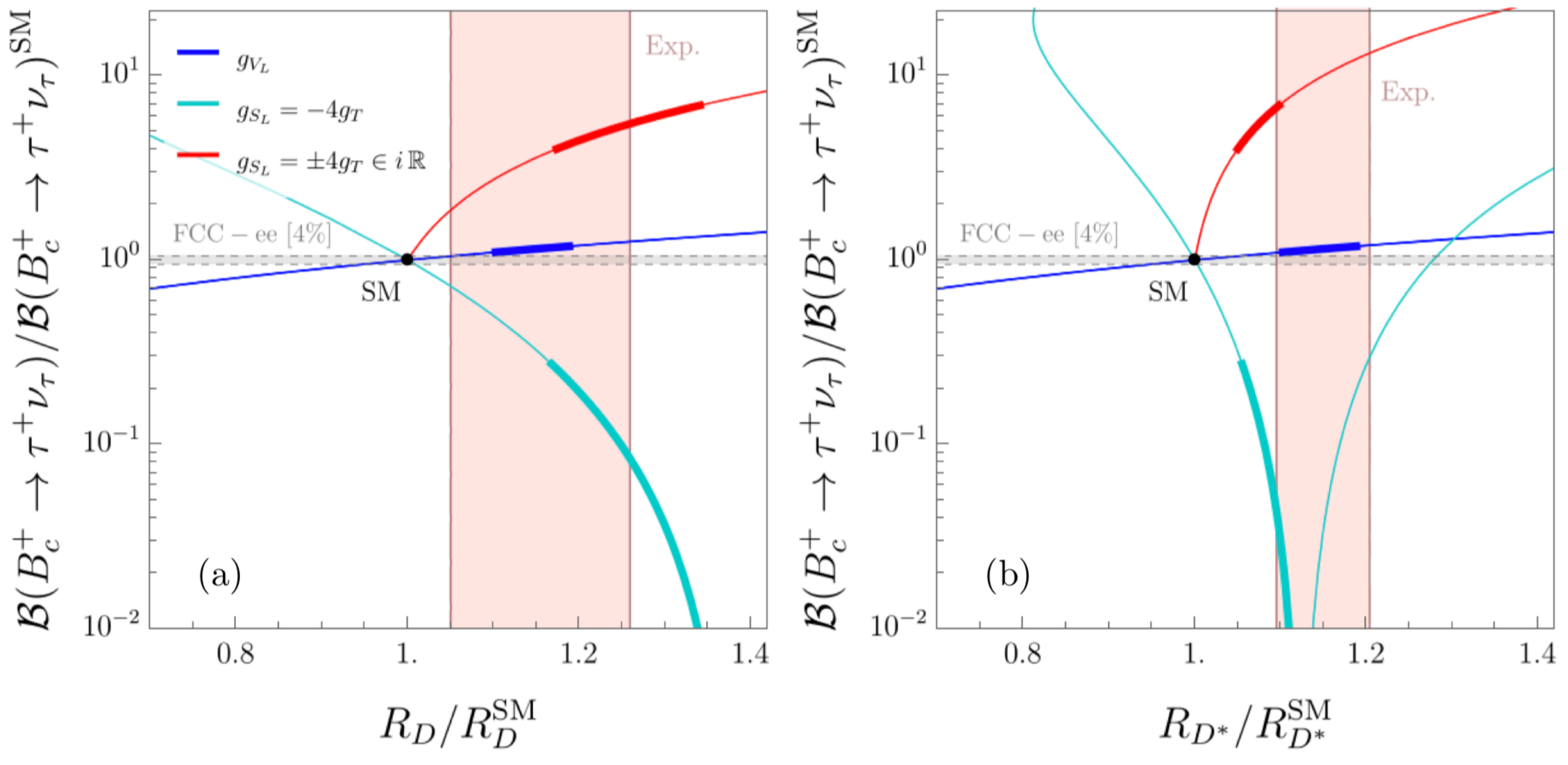
Phenomenology

Models considered taking into account the current experimental landscape from flavour physics.

2HDM



Leptoquarks



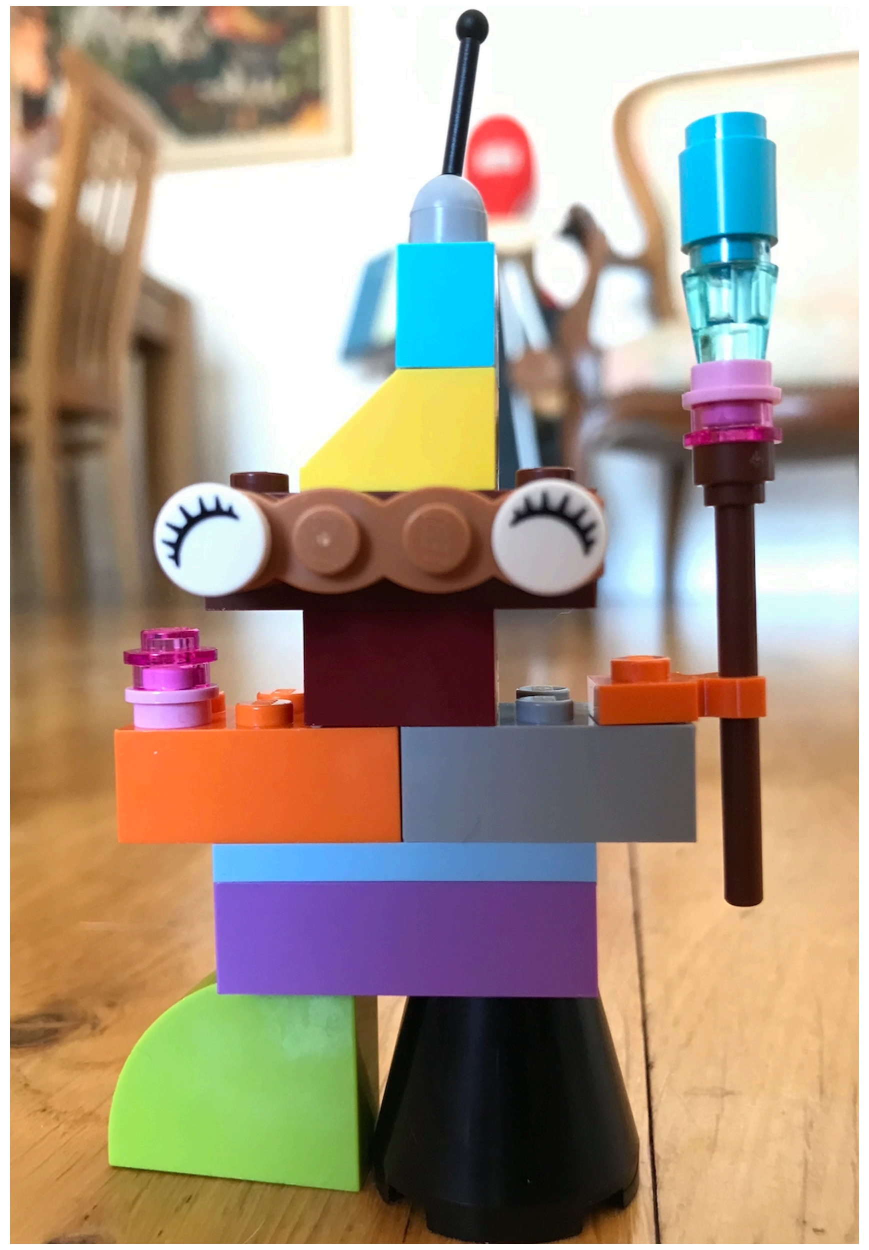
Determination of the range of Wilson coefficients assuming real values are provided.

Unique opportunities are offered here for this decay.

Conclusion

In summary, this work demonstrates why FCC-ee is the most well-suited environment for a measurement of the branching fraction of the $B_c^+ \to \tau^+ \nu_\tau$ decay, and represents the first FCC-ee analysis to use common software tools from EDM4HEP through to final analysis.

That's it !



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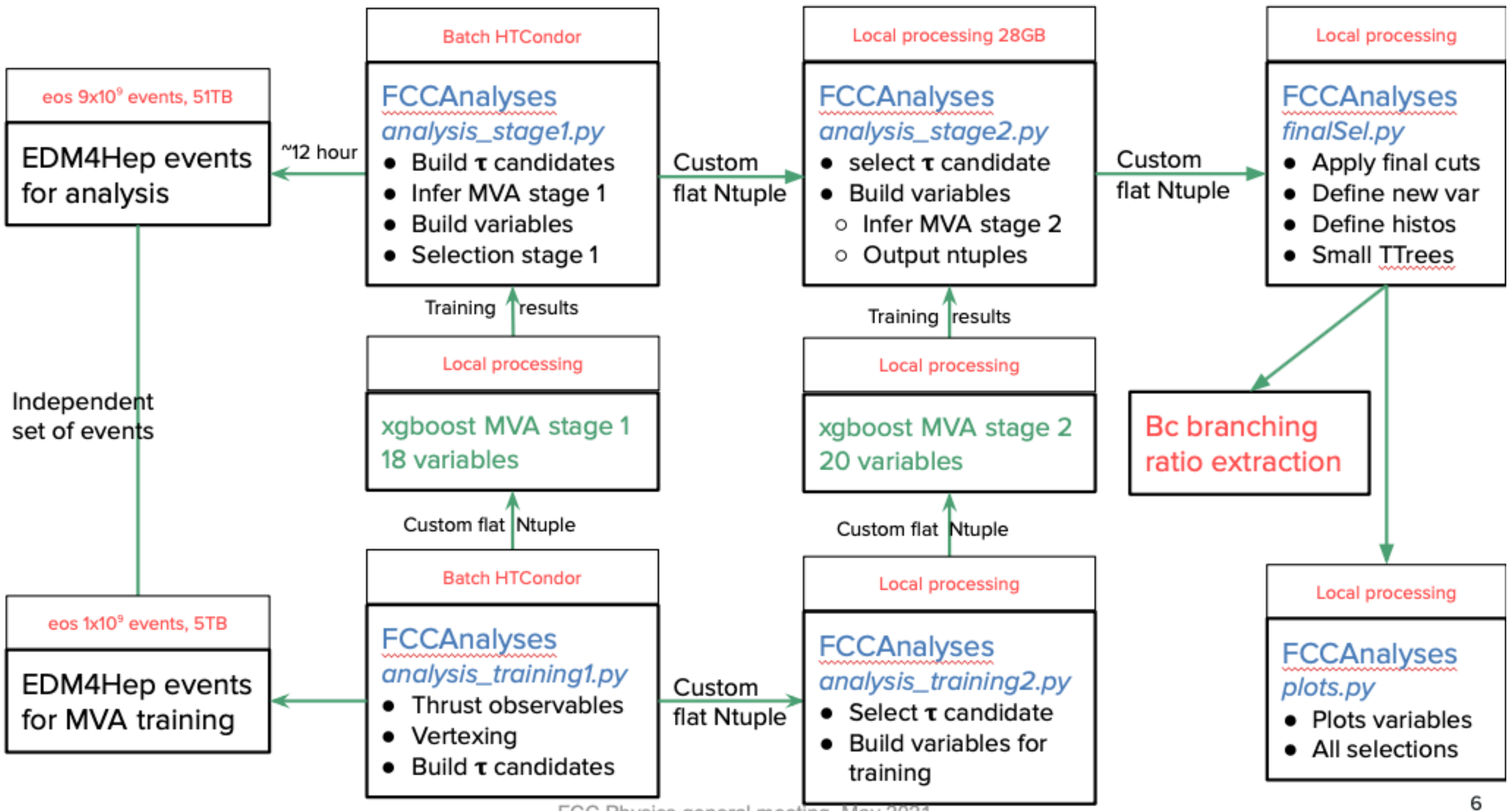
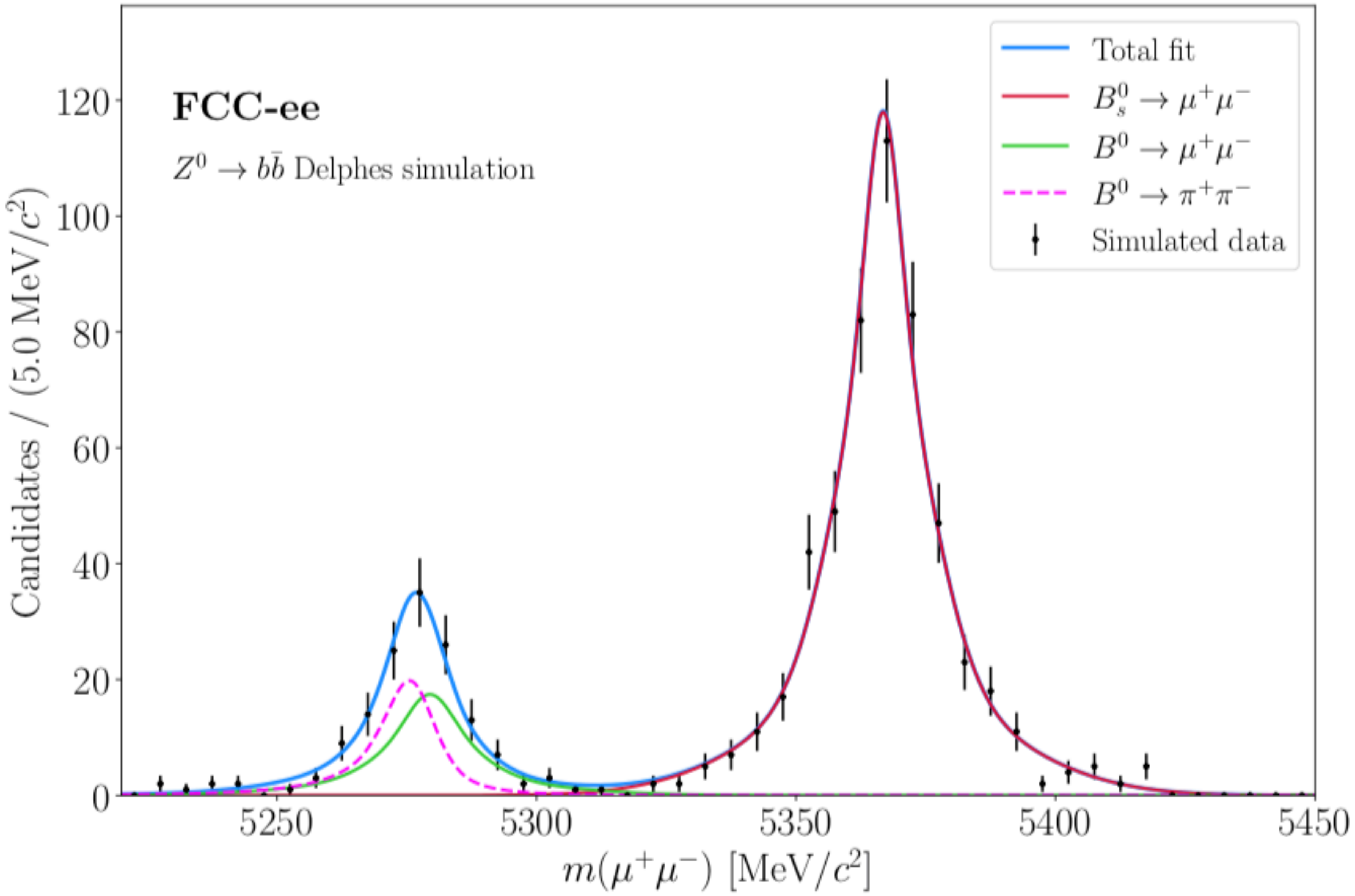
Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
$S_1 = (3,1)_{-1/3}$	✖	✔	✖
$R_2 = (3,2)_{7/6}$	✖	✔	✖
$\widetilde{R}_2 = (3,2)_{1/6}$	✖	✖	✖
$S_3 = (3,3)_{-1/3}$	✔	✖	✖
$U_1 = (3,1)_{2/3}$	✔	✔	✔
$U_3 = (3,3)_{2/3}$	✔	✖	✖

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

See talk at FCC general meeting May 2021



Example of a very rare decay



Can be achieved with excellent mass resolution

Decay mode	N(expected)	N(generated)	Expected / Generated	Final ϵ
$B^+ \to \bar{D}^0\tau^+\nu_\tau$	5.01×10^9	2×10^8	25.0	1.46×10^{-9}
$B^+ \to \bar{D}^{*0}\tau^+\nu_\tau$	1.22×10^{10}	2×10^8	61.1	1.1×10^{-9}
$B^+ \to \bar{D}^0 3\pi$	3.64×10^9	1.9×10^8	19.2	1.56×10^{-9}
$B^+ \to \bar{D}^{*0} 3\pi$	6.7×10^9	2×10^8	33.5	1.04×10^{-9}
$B^+ \to \bar{D}^0 D_s^+$	5.85×10^9	2×10^8	29.3	2.52×10^{-10}
$B^+ \to \bar{D}^{*0} D_s^+$	4.94×10^9	1.75×10^8	28.2	2.72×10^{-10}
$B^+ \to \bar{D}^{*0} D_s^{*+}$	1.11×10^{10}	2×10^8	55.6	2.42×10^{-10}
$B^0 \to D^-\tau^+\nu_\tau$	7.02×10^9	2×10^8	35.1	2.69×10^{-9}
$B^0 \to D^{*-}\tau^+\nu_\tau$	1.02×10^{10}	2×10^8	51.0	1.25×10^{-9}
$B^0 \to D^- 3\pi$	3.9×10^9	2×10^8	19.5	3.4×10^{-9}
$B^0 \to D^{*-} 3\pi$	4.69×10^9	2×10^8	23.4	9.84×10^{-10}
$B^0 \to D^- D_s^+$	4.68×10^9	2×10^8	23.4	3.23×10^{-10}
$B^0 \to D^{*-} D_s^+$	5.2×10^9	2×10^8	26.0	2.32×10^{-10}
$B^0 \to D^{*-} D_s^{*+}$	1.15×10^{10}	2×10^8	57.5	2.35×10^{-10}
$B_s^0 \to D_s^-\tau^+\nu_\tau$	3.53×10^9	2×10^8	17.6	3.71×10^{-9}
$B_s^0 \to D_s^{*-}\tau^+\nu_\tau$	2.35×10^9	2×10^8	11.8	2.27×10^{-9}
$B_s^0 \to D_s^- 3\pi$	8.85×10^8	2×10^8	4.4	5.53×10^{-9}
$B_s^0 \to D_s^{*-} 3\pi$	1.05×10^9	2×10^8	5.2	3.38×10^{-9}
$B_s^0 \to D_s^- D_s^+$	6.39×10^8	2×10^8	3.2	4.09×10^{-10}
$B_s^0 \to D_s^{*-} D_s^+$	2.02×10^9	2×10^8	10.1	3.17×10^{-10}
$B_s^0 \to D_s^{*-} D_s^{*+}$	2.09×10^9	2×10^8	10.5	2.56×10^{-10}
$\Lambda_b^0 \to \Lambda_c^-\tau^+\nu_\tau$	1.83×10^9	2×10^8	9.1	1.36×10^{-9}
$\Lambda_b^0 \to \Lambda_c^{*-}\tau^+\nu_\tau$	1.83×10^9	2×10^8	9.1	9.44×10^{-10}
$\Lambda_b^0 \to \Lambda_c^- 3\pi$	4.31×10^8	2×10^8	2.2	5.58×10^{-9}
$\Lambda_b^0 \to \Lambda_c^{*-} 3\pi$	4.31×10^8	2×10^8	2.2	9.21×10^{-10}
$\Lambda_b^0 \to \Lambda_c^- D_s^+$	6.15×10^8	2×10^8	3.1	3.46×10^{-10}
$\Lambda_b^0 \to \Lambda_c^{*-} D_s^+$	6.15×10^8	2×10^8	3.1	2.72×10^{-10}
$\Lambda_b^0 \to \Lambda_c^{*-} D_s^{*+}$	6.15×10^8	2×10^8	3.1	2.5×10^{-10}

$N_Z(\times 10^{12})$	Relative σ ($\sigma^N_{syst} = [0, 0.25, 0.5, 1] \times \sigma^N_{stat}$)
0.5	[0.078, 0.087, 0.096, 0.111]
1	[0.055, 0.061, 0.067, 0.077]
2	[0.038, 0.042, 0.046, 0.053]
3	[0.032, 0.036, 0.039, 0.046]
4	[0.027, 0.03, 0.033, 0.038]
5	[0.024, 0.027, 0.03, 0.034]

Table 3: Estimated relative precision on $N(B_c^+ \to \tau^+\nu_\tau)$ as a function of N_Z, where four different levels of systematic uncertainty on the signal yield are shown.

$N_Z(\times 10^{12})$	Relative σ ($\sigma^N_{syst} = [0, 0.25, 0.5, 1] \times \sigma^N_{stat}$)
0.5	[0.081, 0.09, 0.098, 0.113]
1	[0.058, 0.064, 0.07, 0.08]
2	[0.042, 0.046, 0.05, 0.056]
3	[0.037, 0.04, 0.043, 0.049]
4	[0.032, 0.035, 0.037, 0.042]
5	[0.03, 0.032, 0.034, 0.038]

Table 4: Estimated relative precision on R_c as a function of N_Z, where four different levels of systematic uncertainty on the signal yield are shown.

$N_Z (\times 10^{12})$	Relative σ ($\sigma^N_{syst} = [0, 0.25, 0.5, 1] \times \sigma^N_{stat}$)
0.5	[0.115, 0.122, 0.128, 0.139]
1	[0.1, 0.104, 0.107, 0.114]
2	[0.092, 0.093, 0.095, 0.099]
3	[0.089, 0.091, 0.092, 0.095]
4	[0.088, 0.089, 0.09, 0.092]
5	[0.087, 0.088, 0.088, 0.09]

Table 5: Estimated relative precision on $\mathcal{B}(B_c^+ \to \tau^+ \nu_\tau)$ as a function of N_Z, where four different levels of systematic uncertainty on the signal yield are shown.