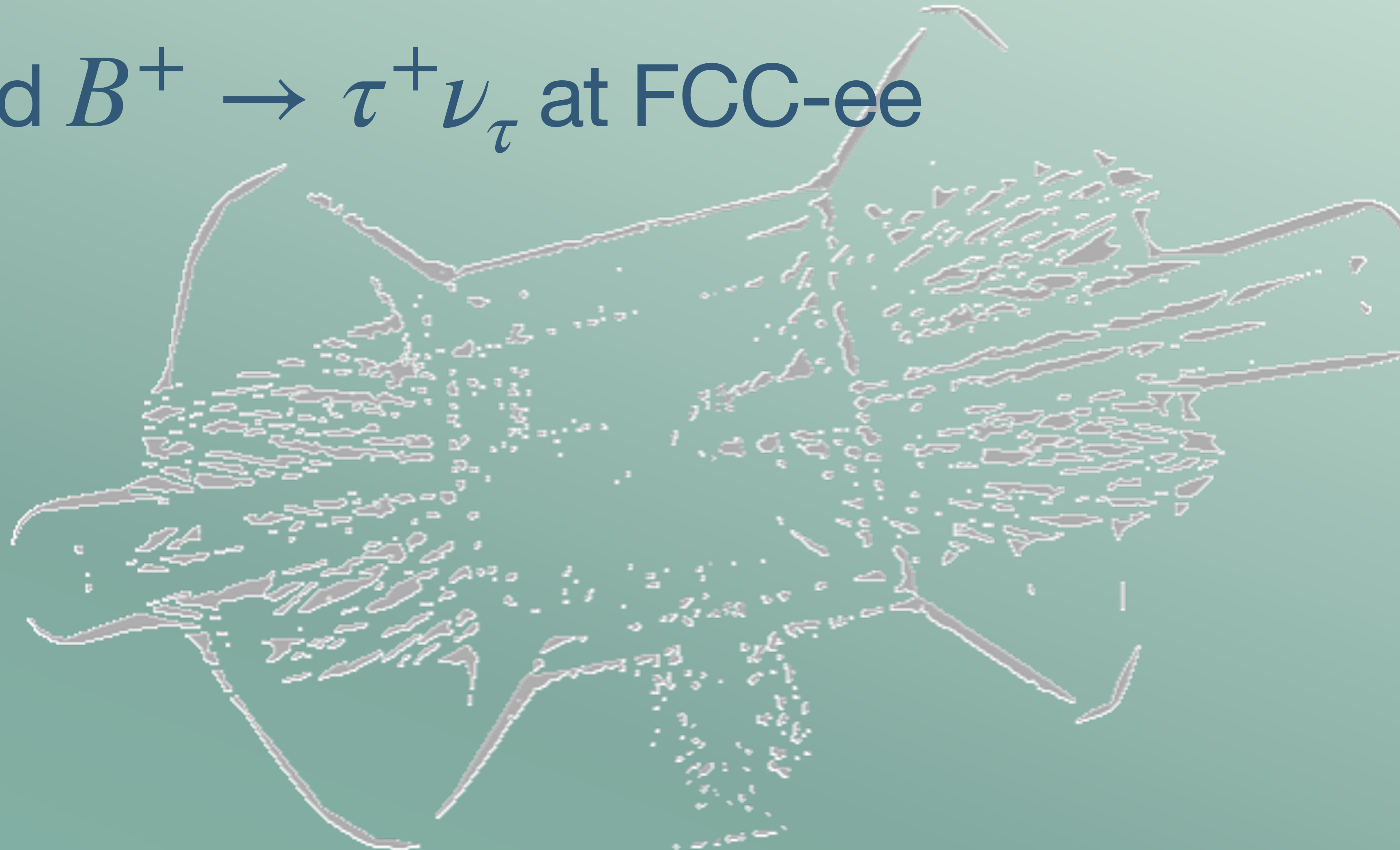


$B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ at FCC-ee

ECFA workshop, DESY
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Outline



- This set of slides is based on 2 FCC-ee performance studies
 - $B_c^+ \rightarrow \tau^+ \nu_\tau$: [https://link.springer.com/article/10.1007/JHEP12\(2021\)133](https://link.springer.com/article/10.1007/JHEP12(2021)133)
 - $B^+/B_c^+ \rightarrow \tau^+ \nu_\tau$: paper draft in preparation
- **Table of content**
 - Common analysis workflow
 - $B_c^+ \rightarrow \tau^+ \nu_\tau$ results
 - $B^+/B_c^+ \rightarrow \tau^+ \nu_\tau$ results

FCC-ee as flavor factory



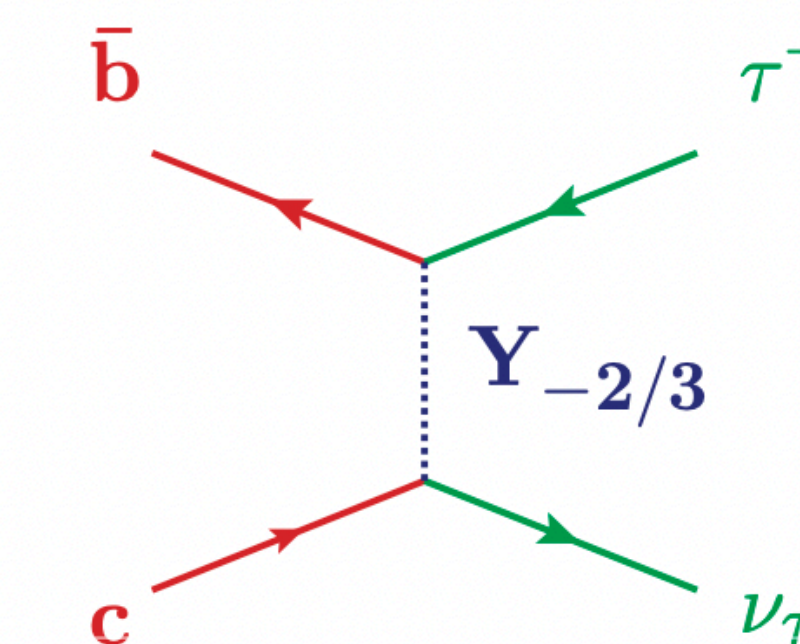
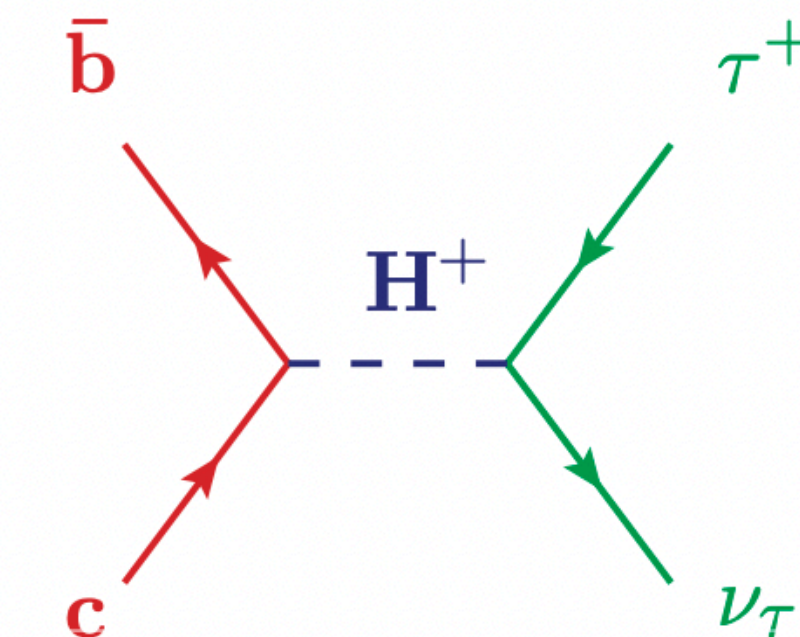
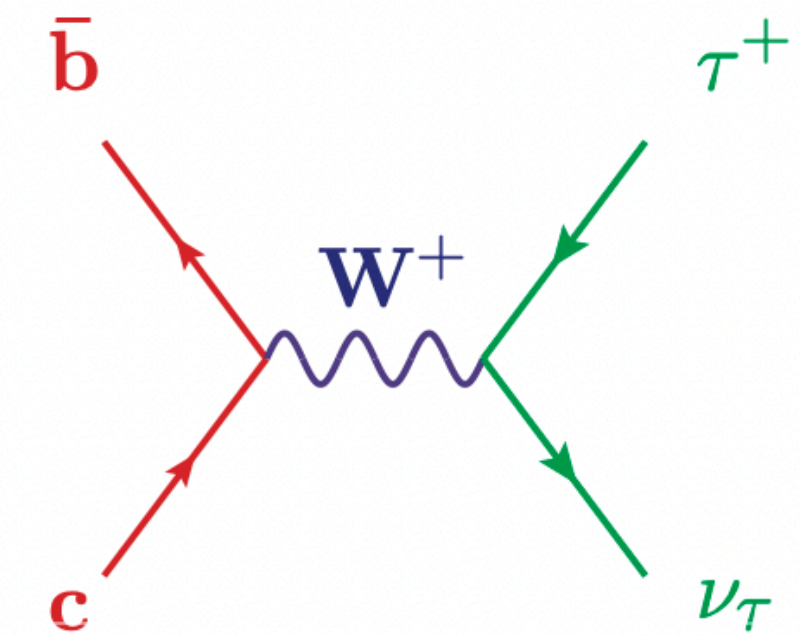
- FCC-ee expects to operate at Z-pole for 4 years, producing a total of 5×10^{12} Z bosons
 - Unparalleled opportunity for all flavor physics
- All species of b-hadrons are produced
- Decay products significantly boosted
- In particular for $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$:
 - Not possible to identify at LHCb
 - Not enough energy for B_c^+ at Belle II $\Upsilon(4S)$

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

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

$B_c^+ / B^+ \rightarrow \tau^+ \nu_\tau$ decays

- Directly related to anomalies in $b \rightarrow c \tau \nu_\tau$
- Clean probes to measure $|V_{cb}|$ and $|V_{ub}|$
- Sensitive to BSM physics, like charged Higgs and leptoquarks
- $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ are helicity and CKM-suppressed.
 - $f(B_c^+) \approx 0.04 \%$, $\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_\tau) \approx 1.94 \%$
 - $f(B^+) \approx 43 \%$, $\mathcal{B}(B^+ \rightarrow \tau^+ \nu_\tau) \approx 1.09 \times 10^{-4}$
- In the 5×10^{12} Z events scenario of FCC-ee
 - $B_c^+ \rightarrow \tau^+ \nu_\tau$ ($\pi^+ \pi^+ \pi^- \bar{\nu}_\tau$) ≈ 1 M
 - $B^+ \rightarrow \tau^+ \nu_\tau$ ($\pi^+ \pi^+ \pi^- \bar{\nu}_\tau$) ≈ 6 M

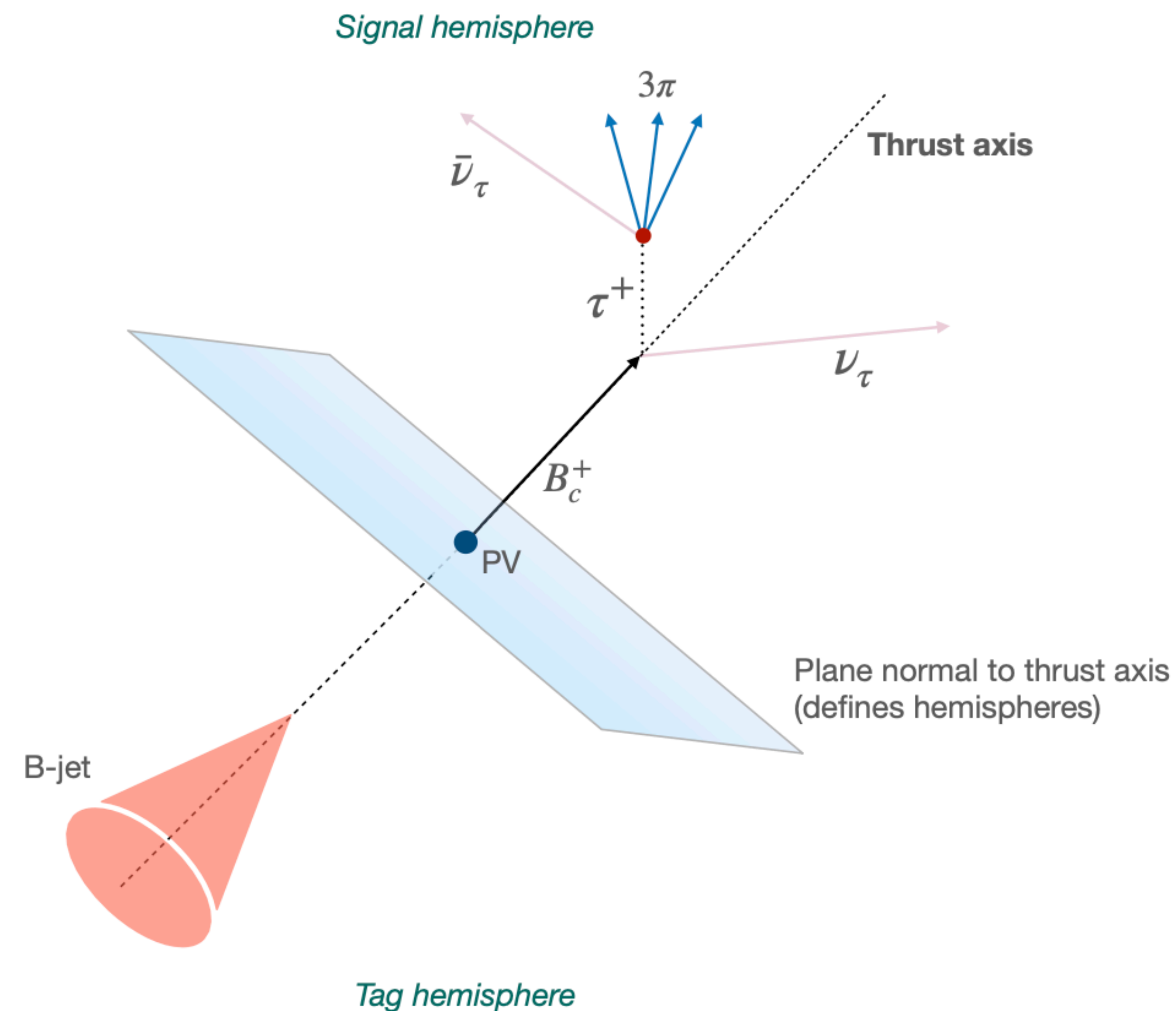


b-decay hemispheres

- Focus on three-prong $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ decay
- Thrust axis defined as the axis that aligns the most with particle momenta.

$$T_i = \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$$

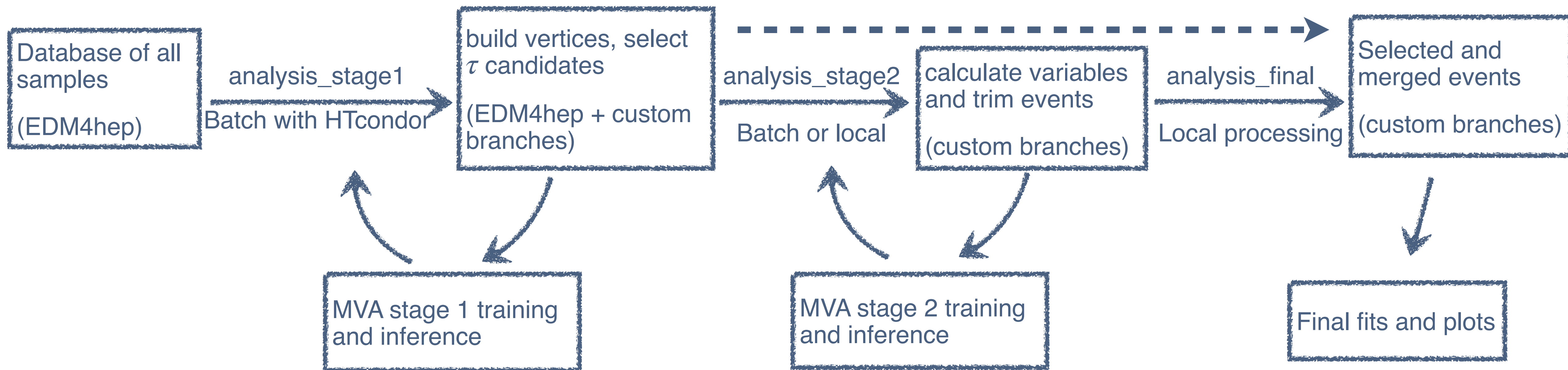
- Measures the decay axis of $Z \rightarrow b\bar{b}$
- Due to high missing energy in the signal decays
 - The thrust axis would be skewed in signal events
 - The two hemispheres would have very different energy distributions.



Analysis workflow



- Fully based on common FCC software from EDM4hep to FCCAnalysis framework
- Data processing with <https://github.com/HEP-FCC/FCCAnalyses>
- Specific studies with <https://github.com/zuoxunwu/FCCeePhysicsPerformance>

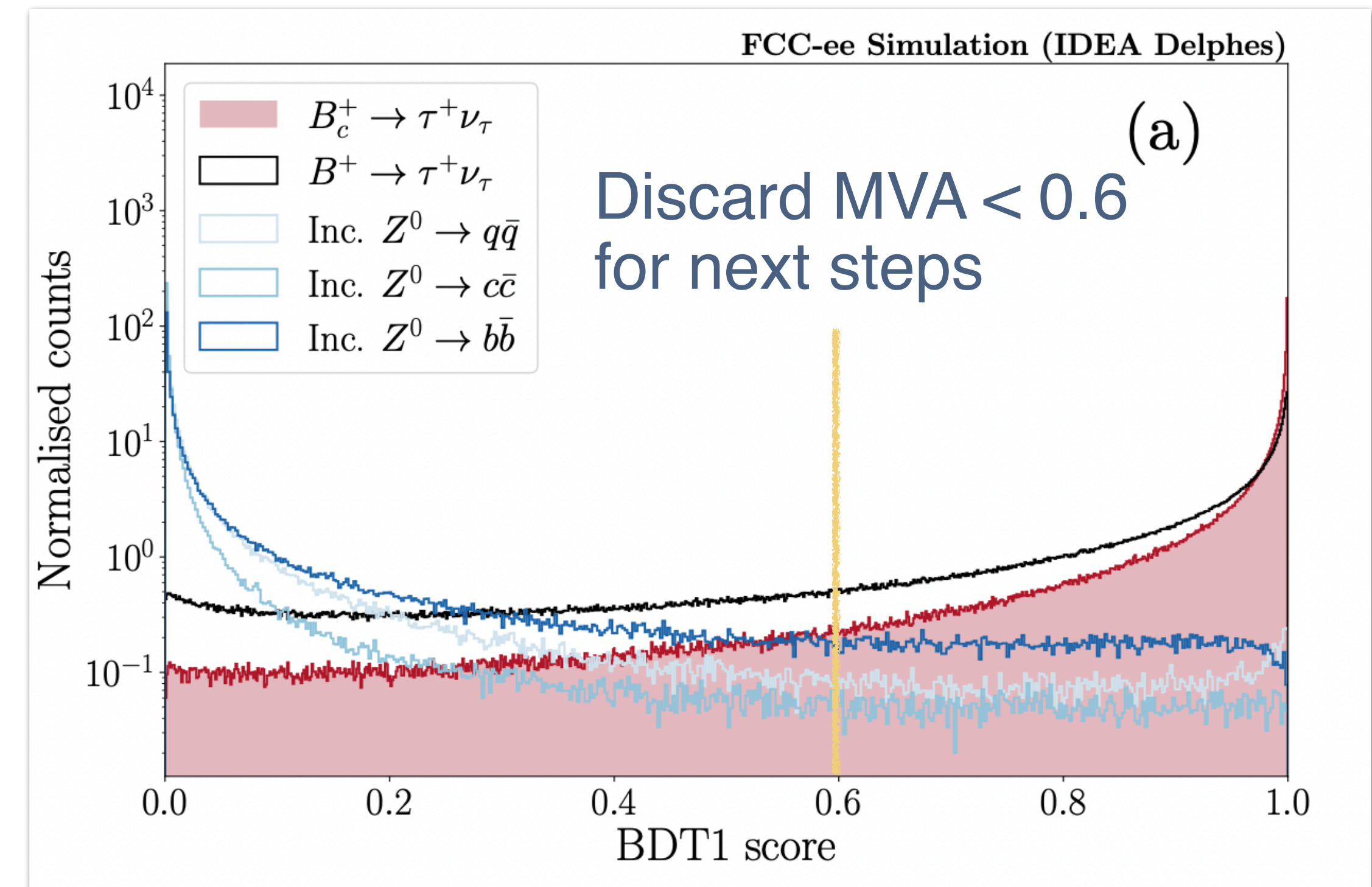
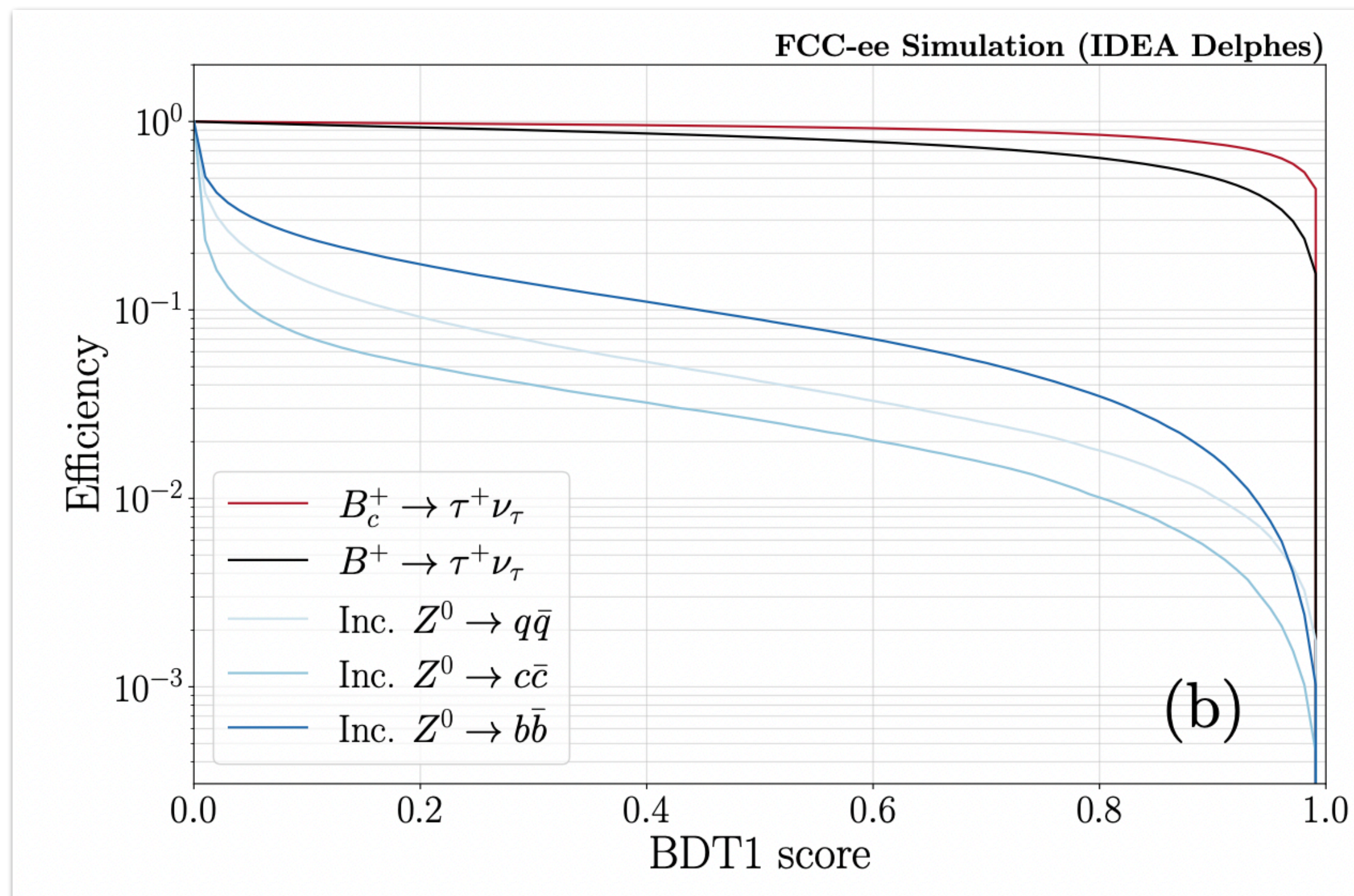


Complete workflow can be run in 1-2 days

$B_c^+ \rightarrow \tau^+ \nu_\tau$ **result**

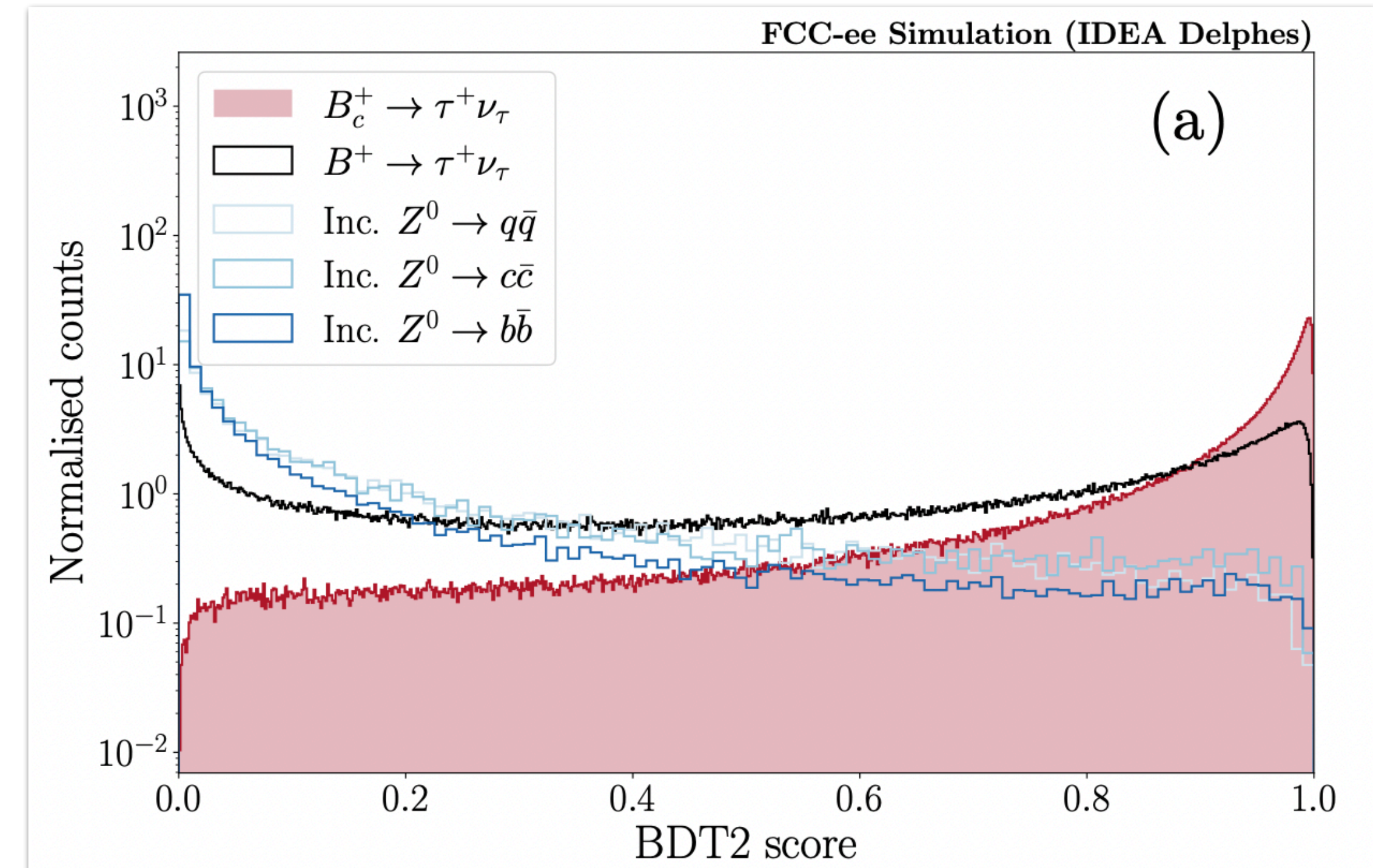
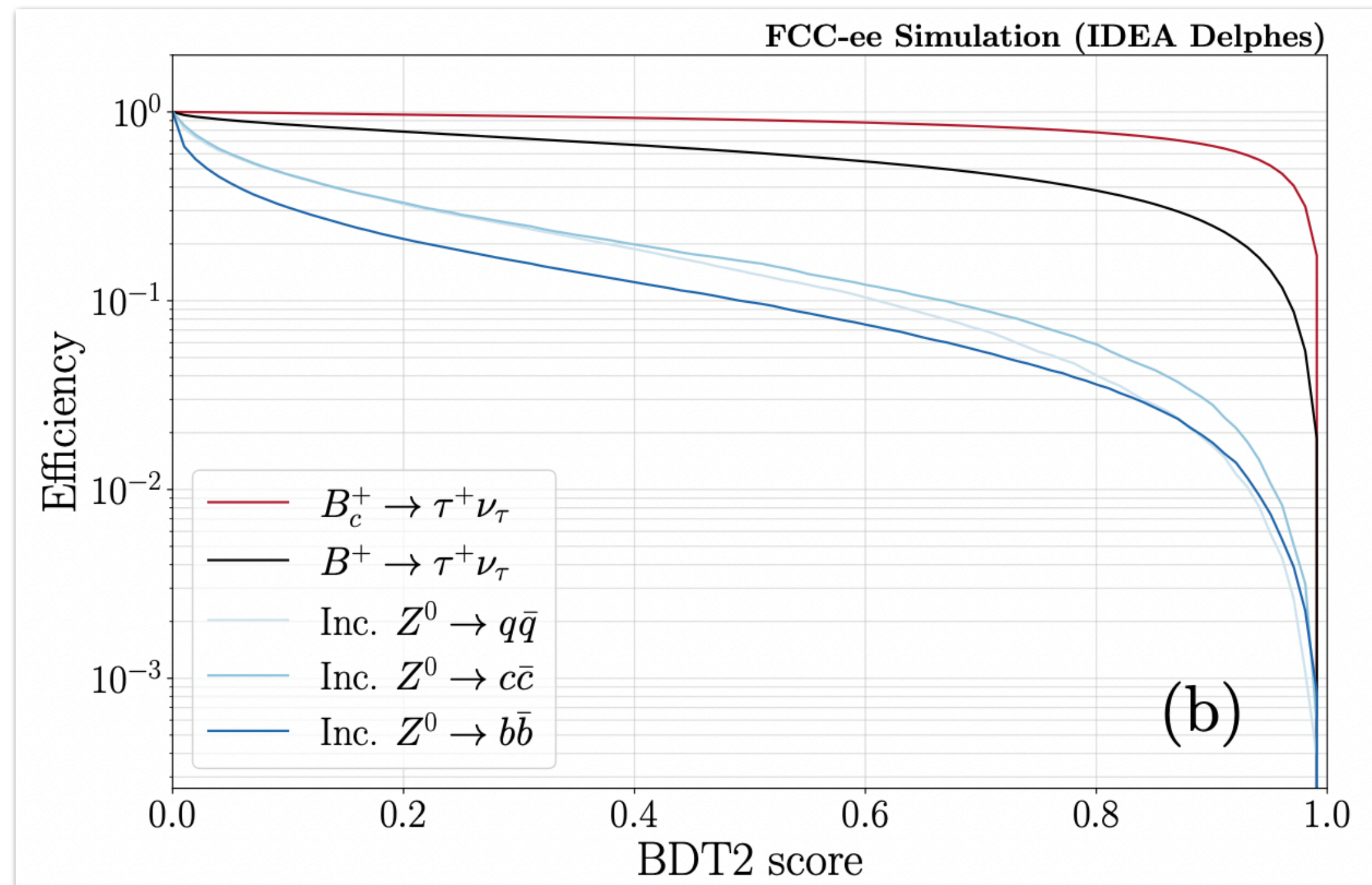
Stage1 MVA

- Goal: use event-level variables to remove “easy” backgrounds from $Z \rightarrow c\bar{c}, q\bar{q}$ processes
- Signal: $B_c^+ \rightarrow \tau^+ \nu_\tau$, background: inclusive $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ decays
- Variables: energy (total, charged, neutral) in each hemisphere, particle multiplicity, number of tracks from PV, number of displaced vertices, number of 3π candidates



Stage2 MVA

- Goal: use full kinematic property of $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ decay to maximize signal purity.
- Signal: $B_c^+ \rightarrow \tau^+ \nu_\tau$, background: inclusive $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ decays
- Variables: full kinematic properties of the $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ decay, mass of the PV, impact parameters of all other vertices, Nominal B_c energy: m_Z – all reco particles except the 3π candidate



Final selection



- After the Stage2 MVA, $Z \rightarrow c\bar{c}$ and $Z \rightarrow q\bar{q}$ are reduced by a factor more than 10^9
 - All simulation events are rejected (Do not consider for further steps)
- Inclusive $Z \rightarrow b\bar{b}$ largely rejected, not enough events to estimate efficiency at high MVA scores.
 - Use a set of exclusive samples, $B \rightarrow D\tau\nu / D3\pi / DD_s$, where $B \in \{B^0, B^+, B_s^0, \Lambda_b^0\}$, to estimate background yields.
- Estimate method:
 - $N_{\text{baseline}}^{\text{bkg}}$: Bkg yield after baseline MVA cuts estimated from inclusive samples
 - $\epsilon(\text{MVA1 cut} | \text{baseline})$: Bkg cut efficiency relative to baseline estimated from exclusive samples
 - $\epsilon(\text{MVA2 cut} | \text{baseline})$: Bkg cut efficiency relative to baseline estimated from exclusive samples
 - Assuming MVA1 and MVA2 are uncorrelated,
$$N_{\text{final}}^{\text{bkg}} = N_{\text{baseline}}^{\text{bkg}} \times \epsilon(\text{MVA1 cut} | \text{baseline}) \times \epsilon(\text{MVA2 cut} | \text{baseline})$$

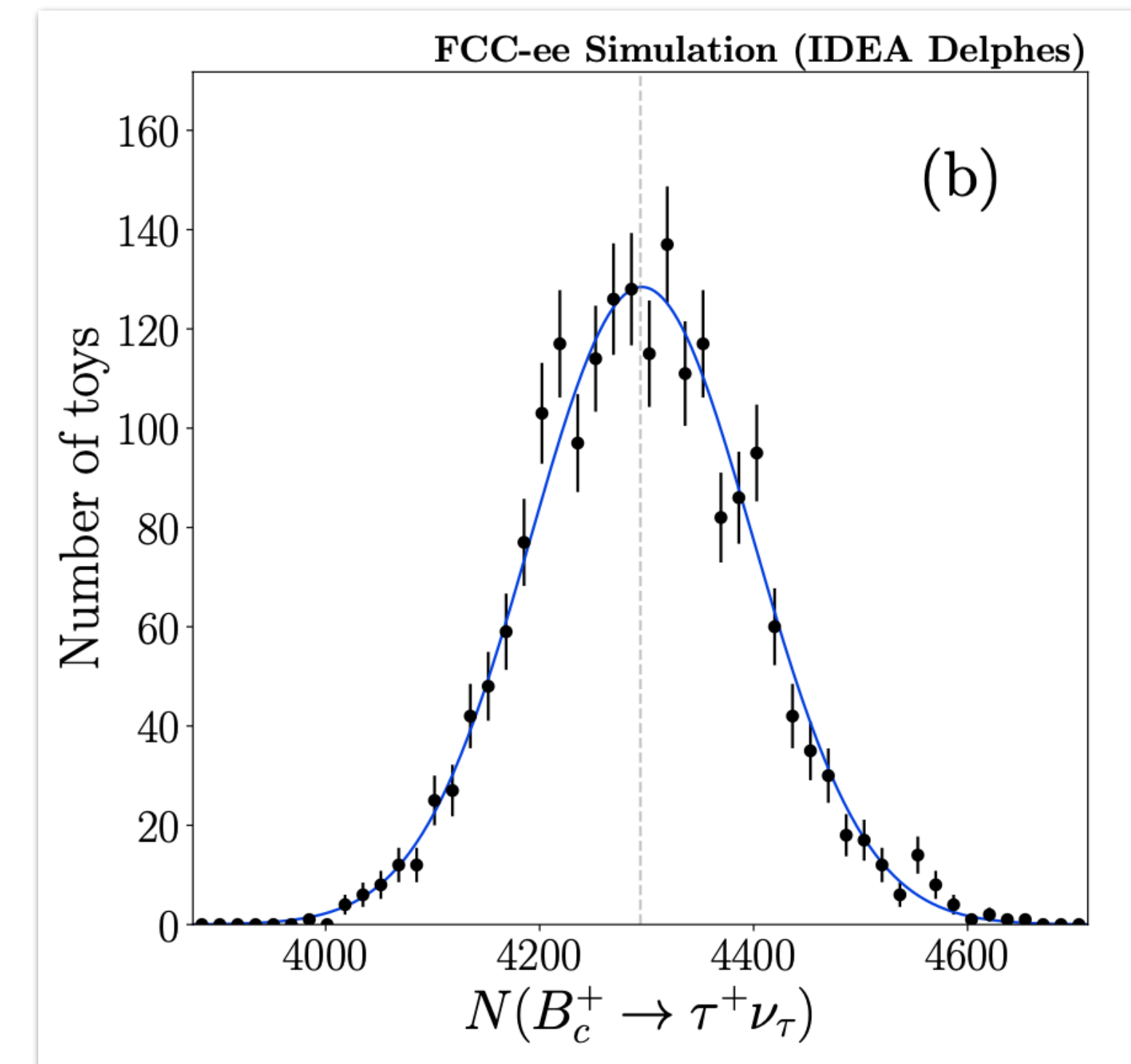
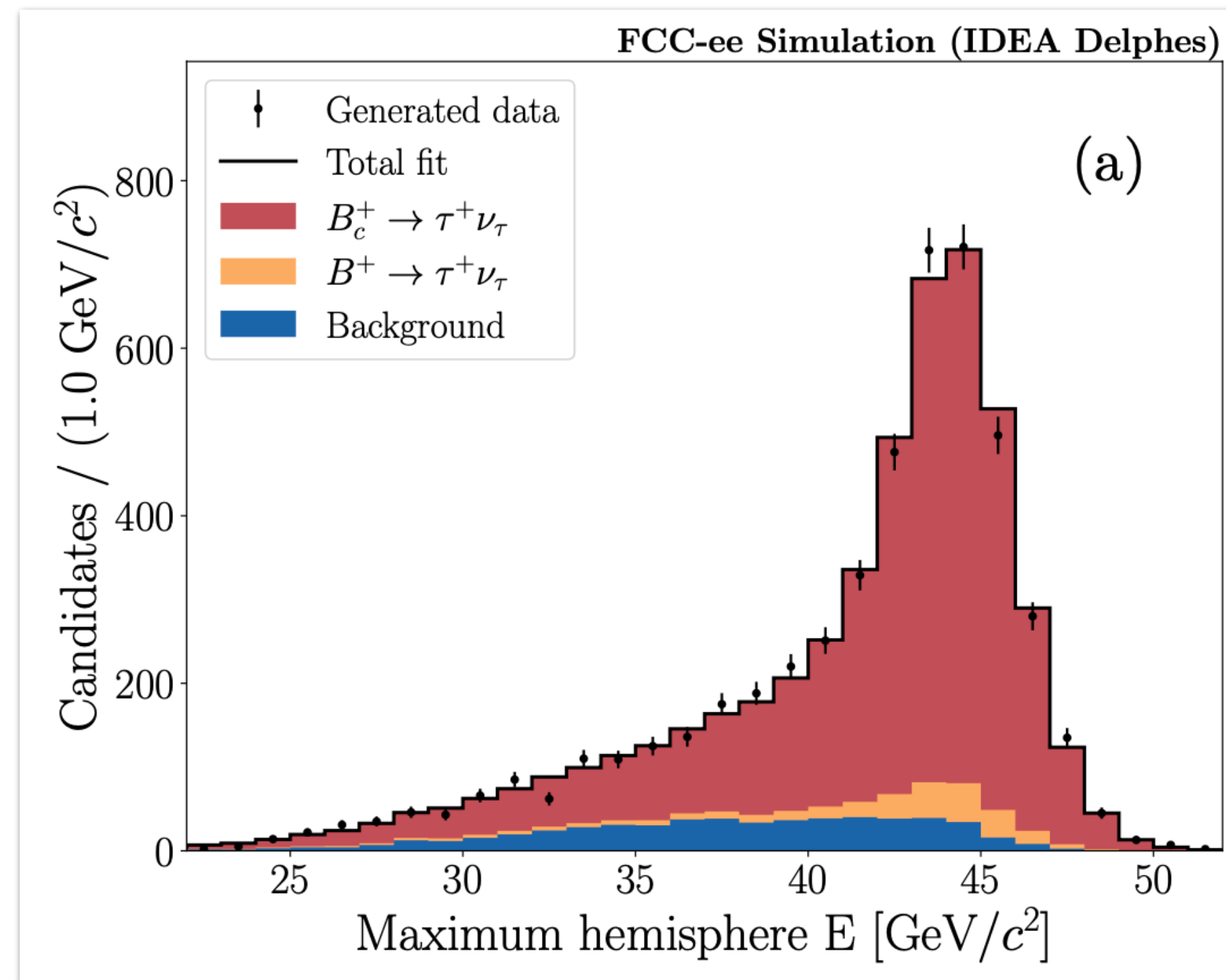
Template fit

- From 2D scan of (MVA1, MVA2) cuts, the optimal yields are:

- $B_c^+ \rightarrow \tau^+ \nu_\tau$: 4295

- $B^+ \rightarrow \tau^+ \nu_\tau$: 285

- Total bkg: 448



- Template fit on the total energy in the hemisphere with more energy
- 2000 pseudo-experiments performed with Asimov dataset.
- Statistical uncertainty on signal is about 2.4%

$B_c^+ \rightarrow \tau^+ \nu_\tau$ interpretations

Precision on $\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_\tau)$



- Using $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu$ as a normalization mode, measure the ratio

$$\begin{aligned} R_c &= \frac{\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \\ &= \frac{N(B_c^+ \rightarrow \tau^+ \nu_\tau)}{N(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} \times \frac{\epsilon(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}{\epsilon(B_c^+ \rightarrow \tau^+ \nu_\tau)} \times \frac{\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)}{\mathcal{B}(\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau)} \end{aligned}$$

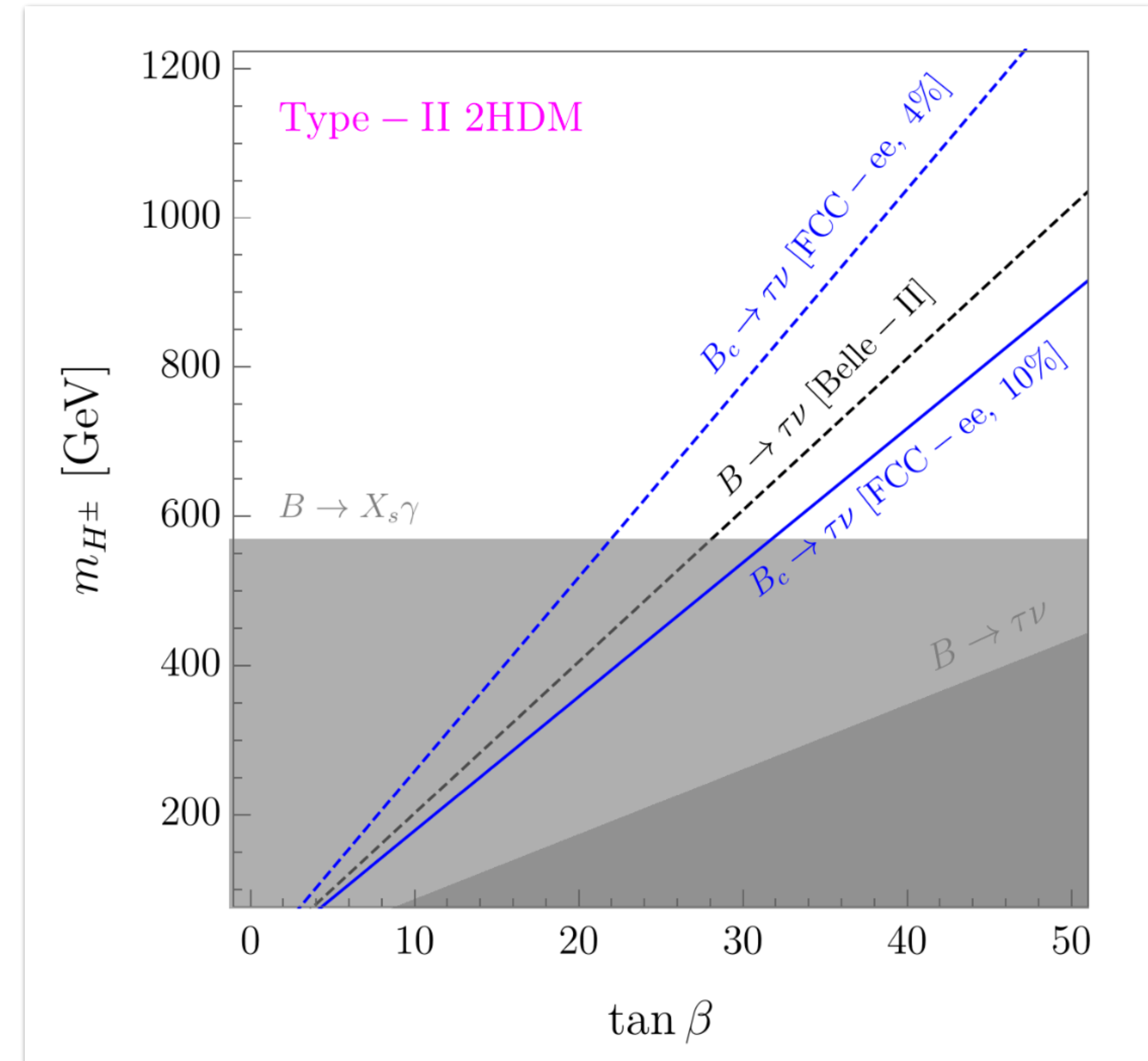
- R_c has good experimental precision $\sim 4\%$
 - Decoupled from $|V_{cb}|$ and $f(B^+)$
 - Highly sensitive to BSM
- Can be translated to a measurement on $\mathcal{B}(B_c^+ \rightarrow \tau^+ \nu_\tau)$
 - Use current best $|V_{cb}|$ [1], and form-factors calculated from lattice QCD [2, 3] for the SM value of $\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$

Probe of 2HDM

- Consider effective Hamiltonian for SM + BSM $b \rightarrow c\tau\nu_\tau$ transition

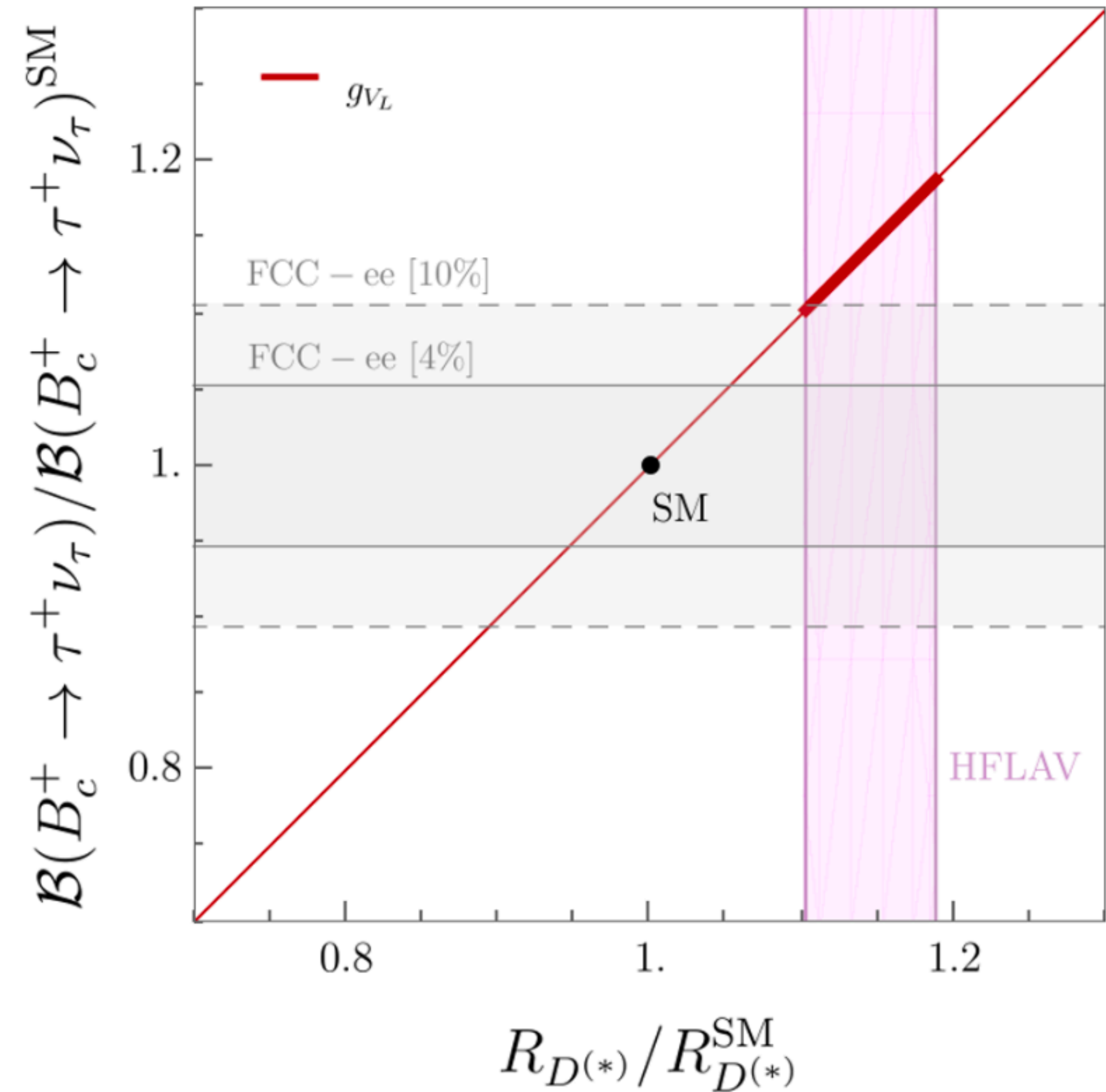
$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb} \left[(1 + g_{V_L}) (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R) (\bar{\tau}_L \gamma^\mu \nu_L) \right. \\ \left. + g_{S_L} (\bar{c}_R b_L) (\bar{\tau}_R \nu_L) + g_{S_R} (\bar{c}_L b_R) (\bar{\tau}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\tau}_R \sigma^{\mu\nu} \nu_L) \right] + \text{h.c.}$$

- Computed in two scenarios where the uncertainty of $\Gamma(B_c^+ \rightarrow \tau^+ \nu_\tau) / |V_{cb}|^2$ is 10% and 4%.
- Can be interpreted in Type-II 2HDM where the effective coefficients are determined by m_{H^\pm} and $\tan\beta$



Probe of leptoquark

- Can also be interpreted with leptoquark model and examine the current deviation of R_{D^*} from its SM expectations.
- Leptoquark implies a deviation on $\Gamma(B_c^+ \rightarrow \tau^+ \nu_\tau) / |V_{cb}|^2$ larger than 10%. Can be fully examined.

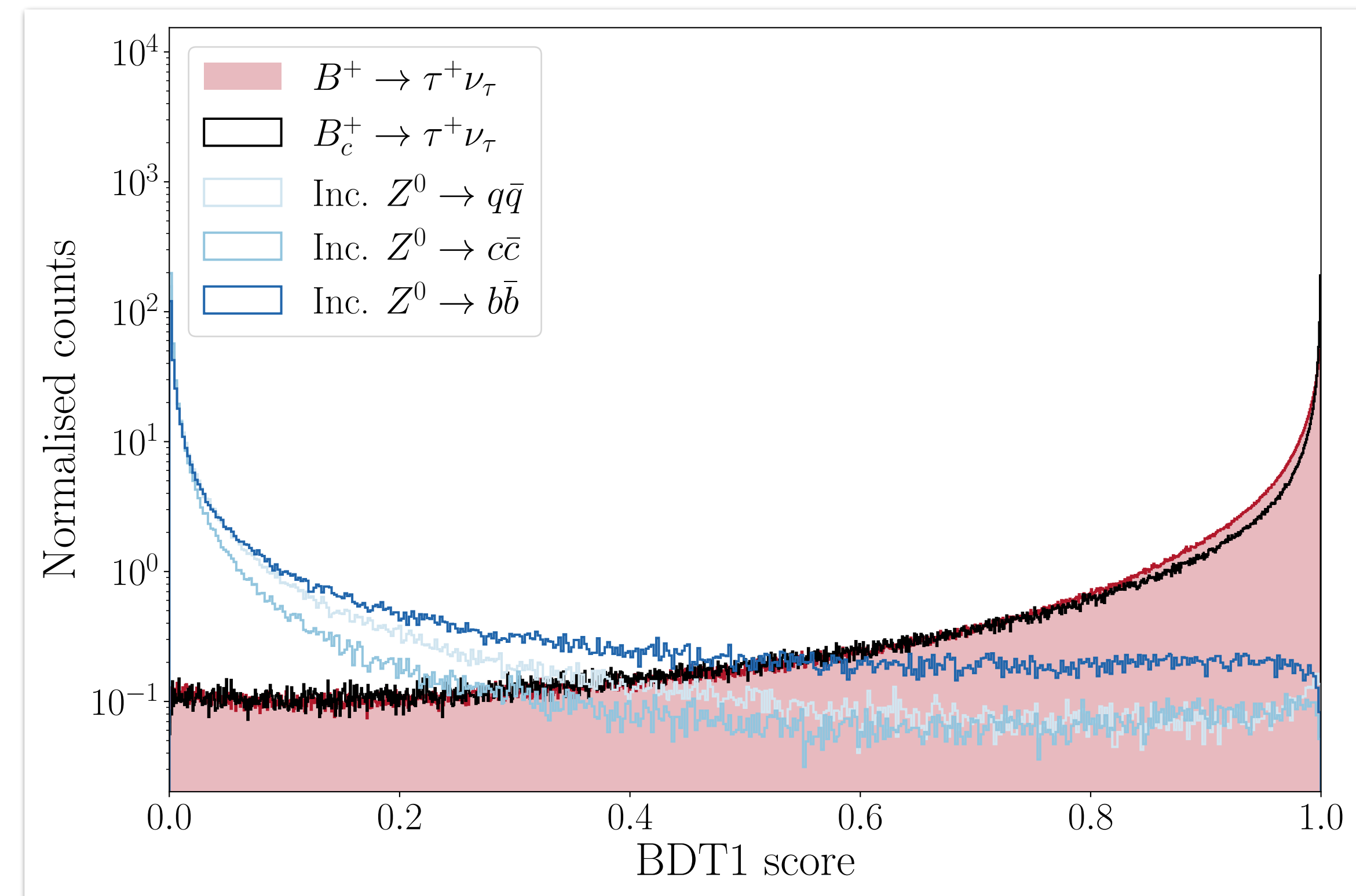
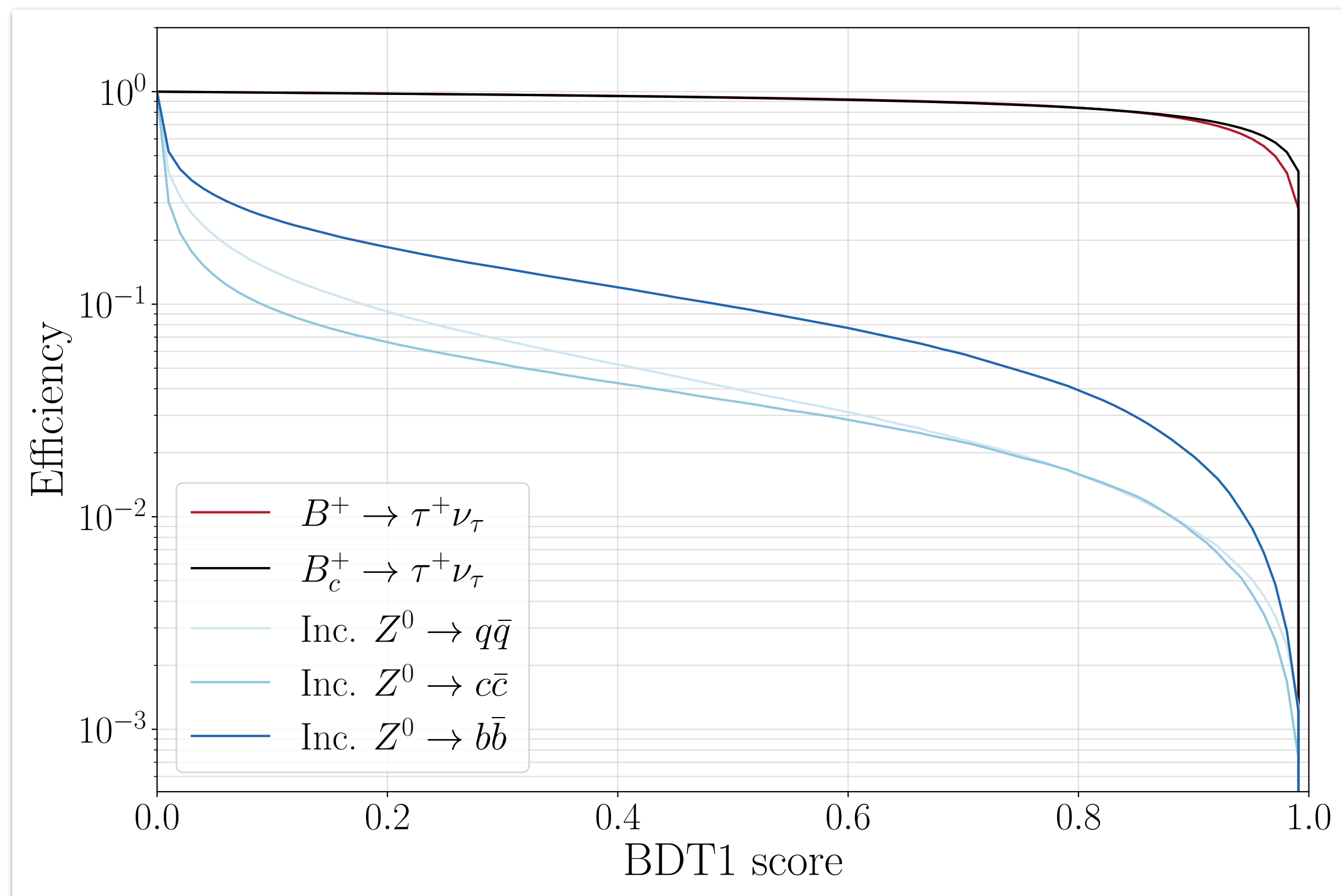


$B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ results

The following results are work in progress

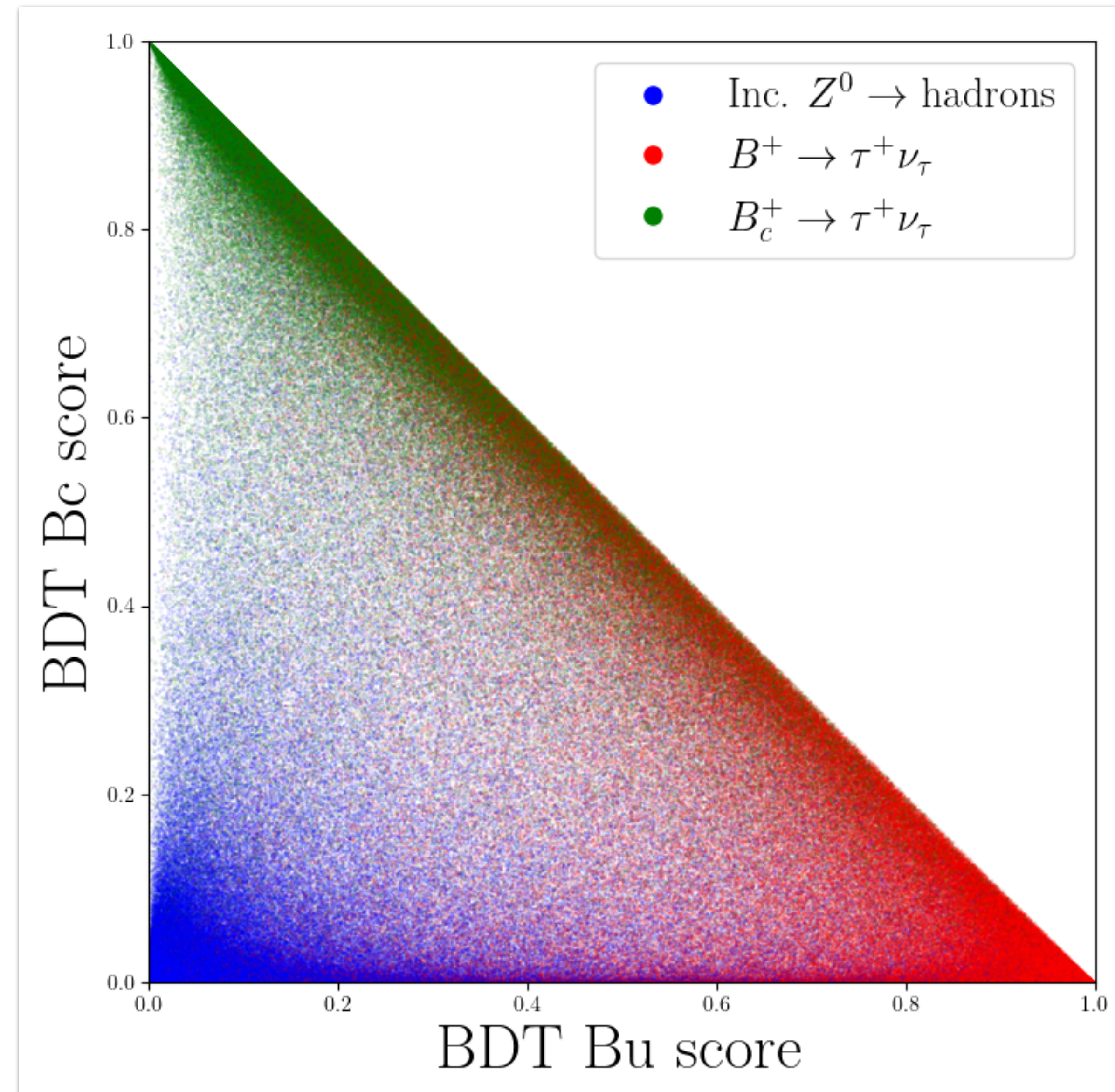
Stage1 MVA

- Goal: remove “easy” backgrounds (same as in Bc analysis)
- Same setup as in Bc analysis, just include both $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ as signals
- Better efficiency for Bu, similar performance on Bc and background as before.



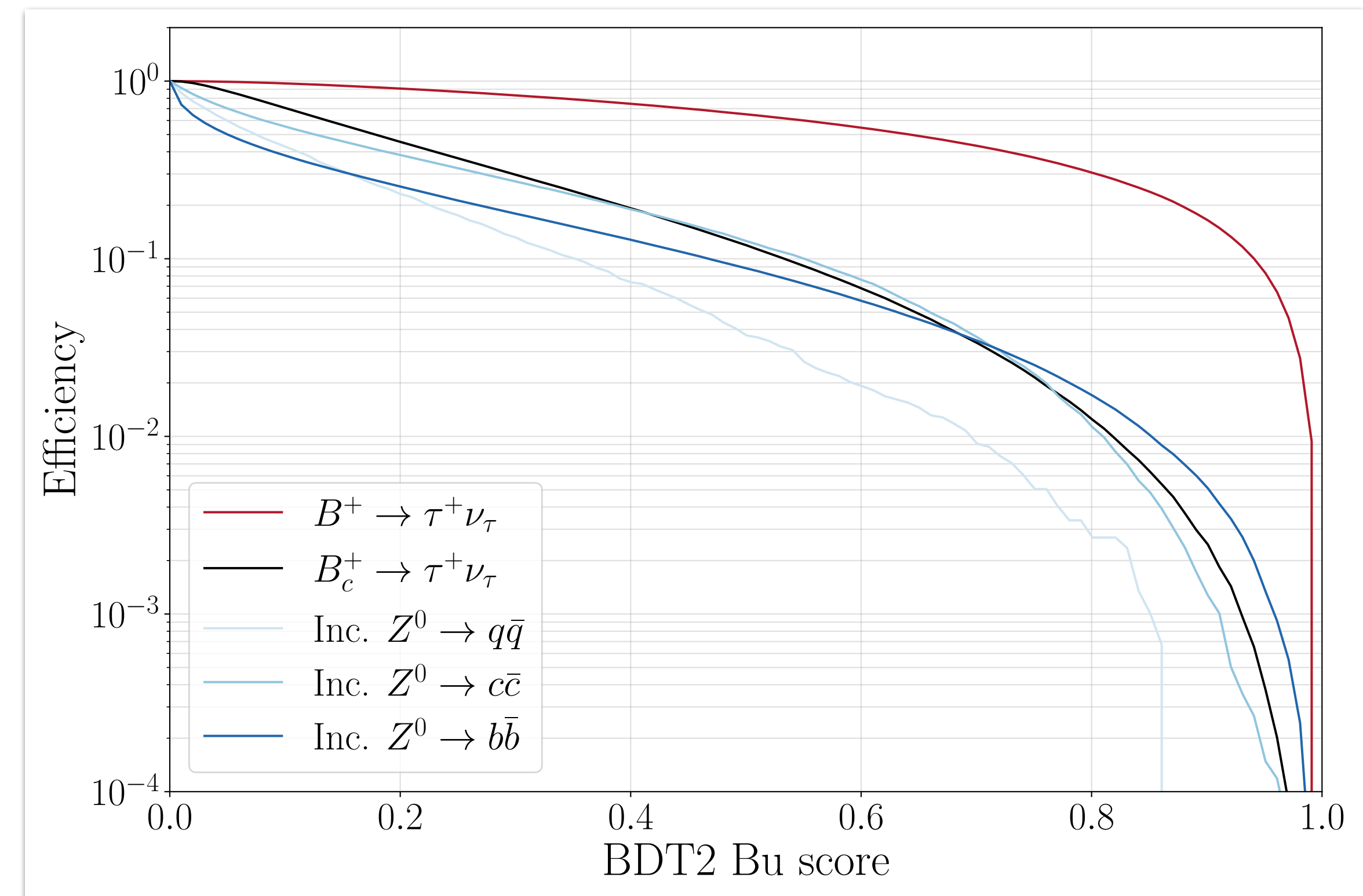
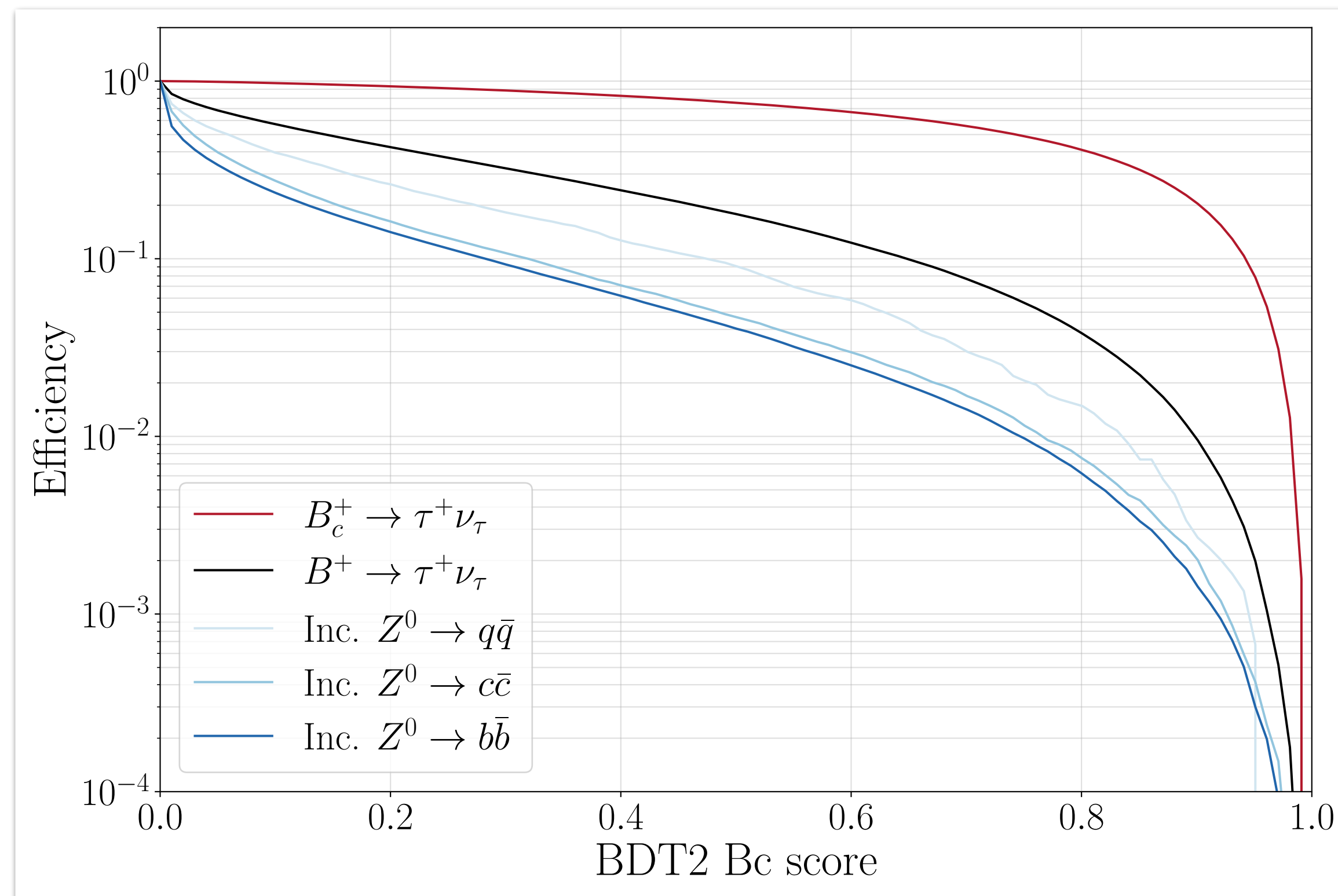
Stage2 MVA

- Goal: separate Bu from background while keeping the efficiency for Bc
- Same selection, samples, and input variables as in Bc analysis
- Multiclassifier BDT
 - label 0: $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$
 - label 1: $B^+ \rightarrow \tau^+ \nu_\tau$
 - label 2: $B_c^+ \rightarrow \tau^+ \nu_\tau$
- Good separation achieved between all 3 processes.



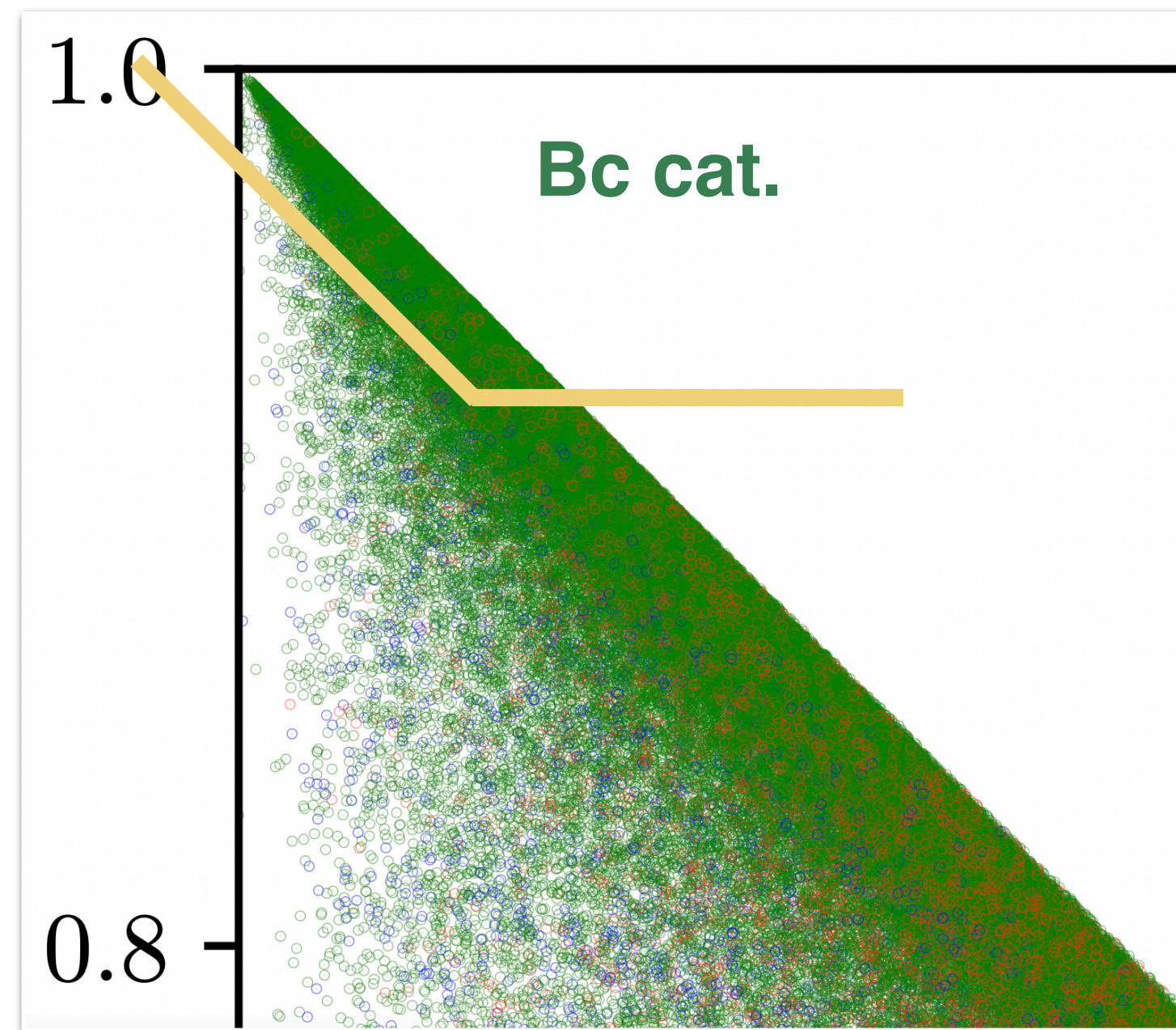
Stage2 MVA

- High purity of $B^+ \rightarrow \tau^+ \nu_\tau$ or $B_c^+ \rightarrow \tau^+ \nu_\tau$ in the corresponding high-MVA region
 - Very little cross-contamination
 - Harder to separate $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ from $B^+ \rightarrow \tau^+ \nu_\tau$, as expected



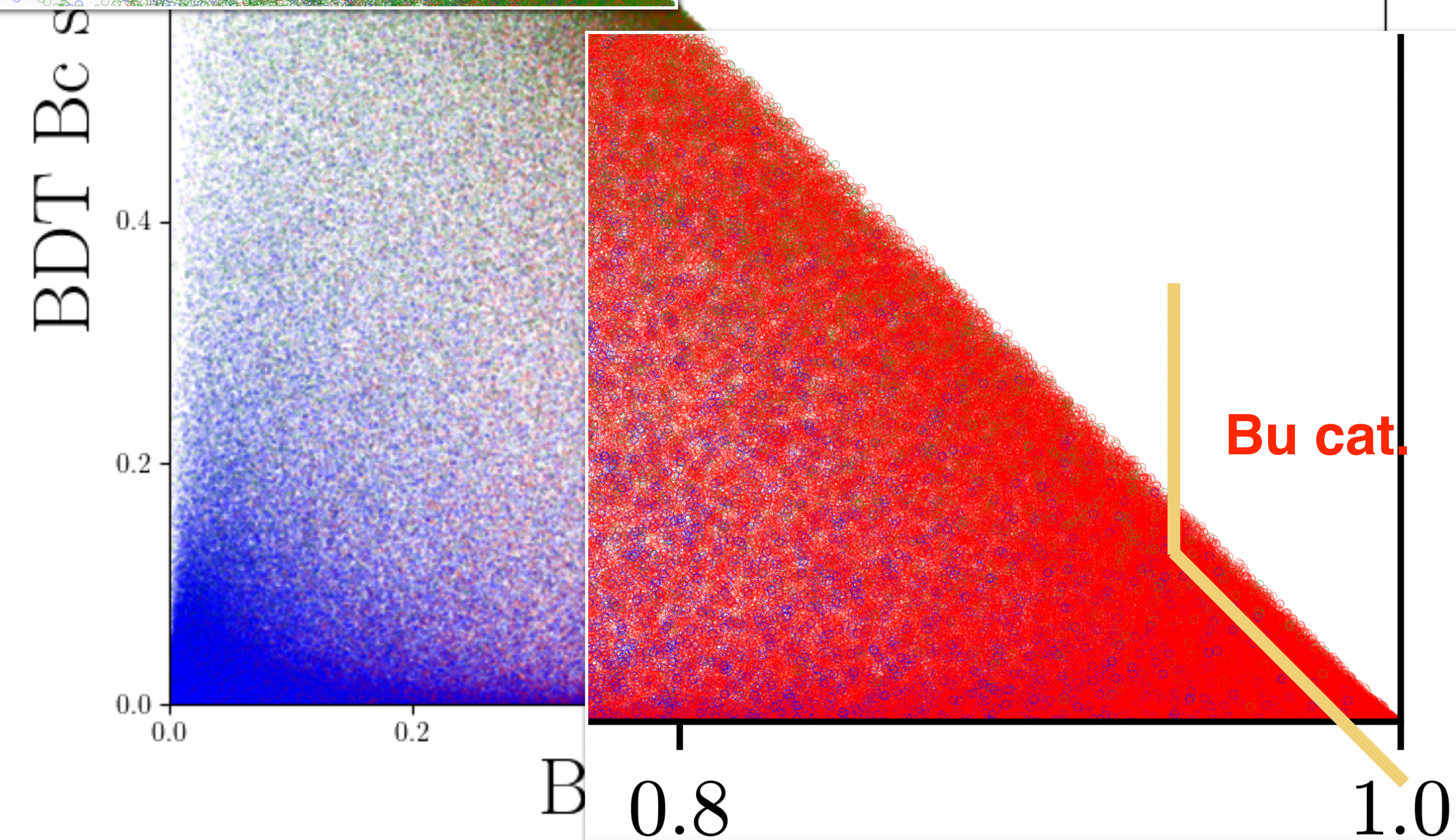
Categorization (new)

- Select a stripe close to $MVA_{\text{bkg}} \rightarrow 0$
- Orthogonality ensured by selecting different corners.



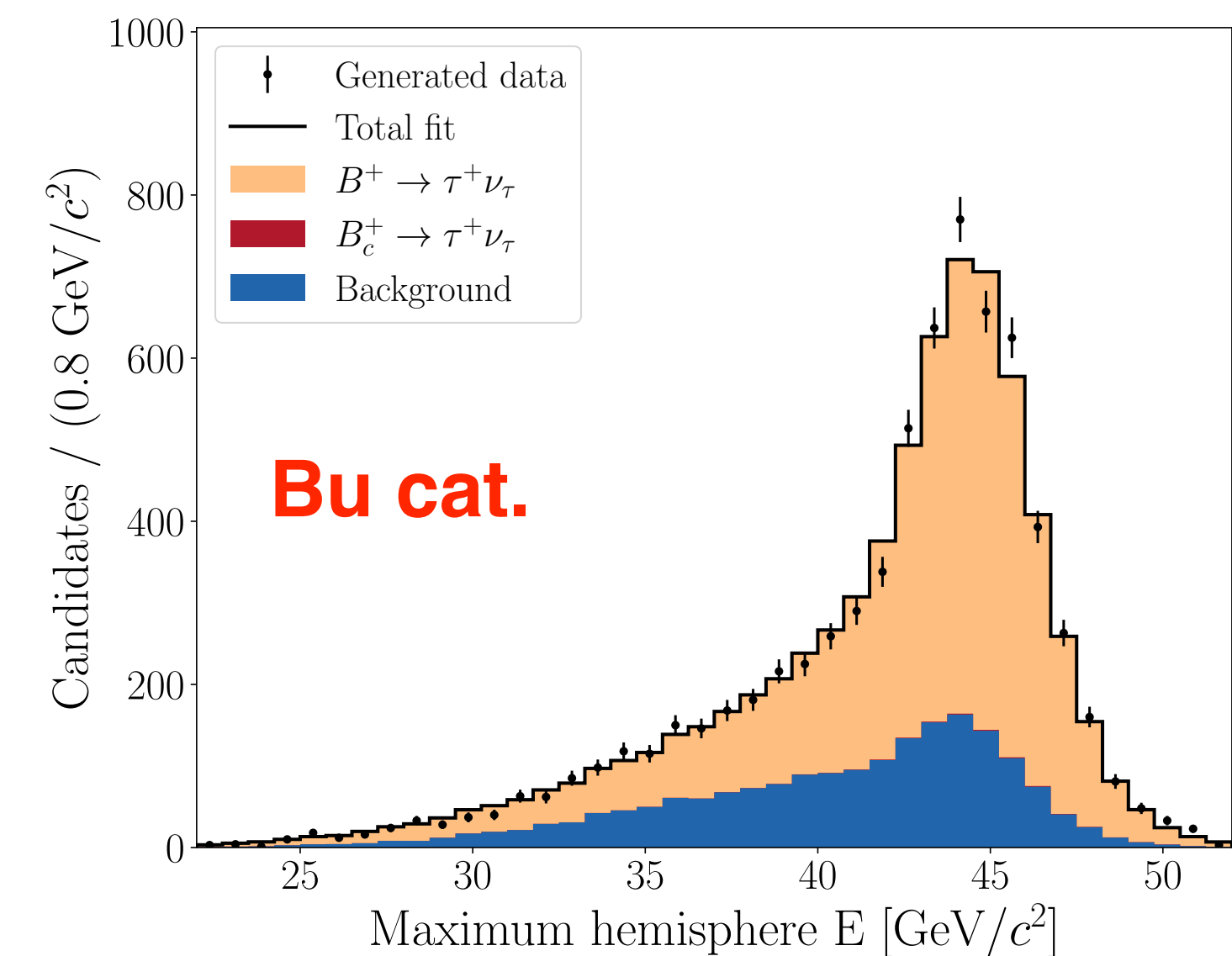
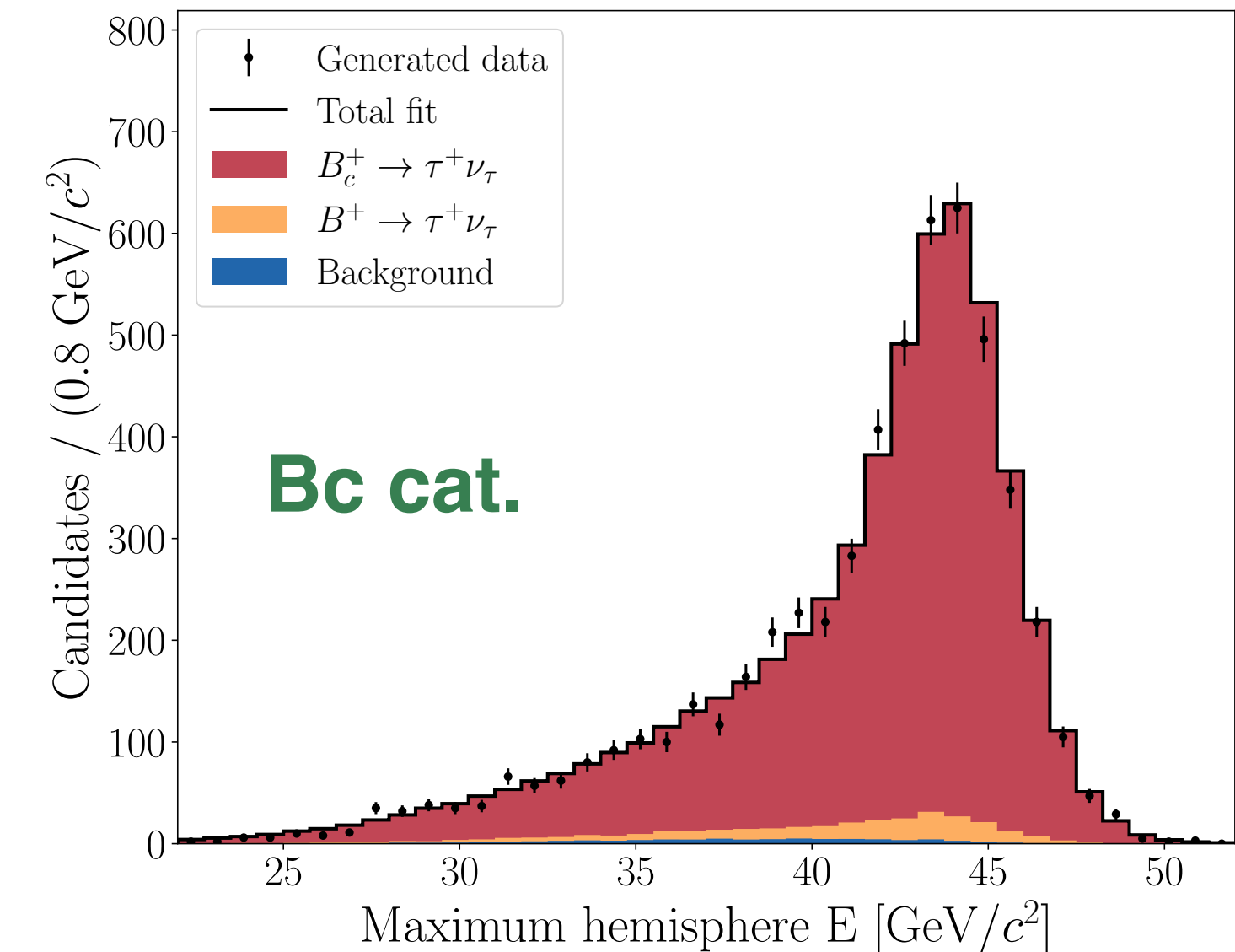
- Inc. $Z^0 \rightarrow \text{hadrons}$
- $B^+ \rightarrow \tau^+ \nu_\tau$
- $B_c^+ \rightarrow \tau^+ \nu_\tau$

	Bc category	Bu category
Exp. Bc events	5002.2	11.14
Exp. Bu events	264.6	5115.9
Exp. bkg events	190.4	1806.0
Sig. purity	92%	74%



Template fit

- Simultaneous fit of 2 categories.
- 4 free parameters (yield modifiers)
 - μ_{bc} correlated across two cats
 - μ_{bu} correlated across two cats
 - $\mu_{bkg}^{Bc\ cat}$, $\mu_{bkg}^{Bu\ cat}$ independent in each category
- Signal strength uncertainty (from 2000 pseudo experiments)
 - $\sigma(\mu_{bc}) = 2.2\%$
 - $\sigma(\mu_{bu}) = 3.9\%$
- Further work to be done on the interpretation.



Summary



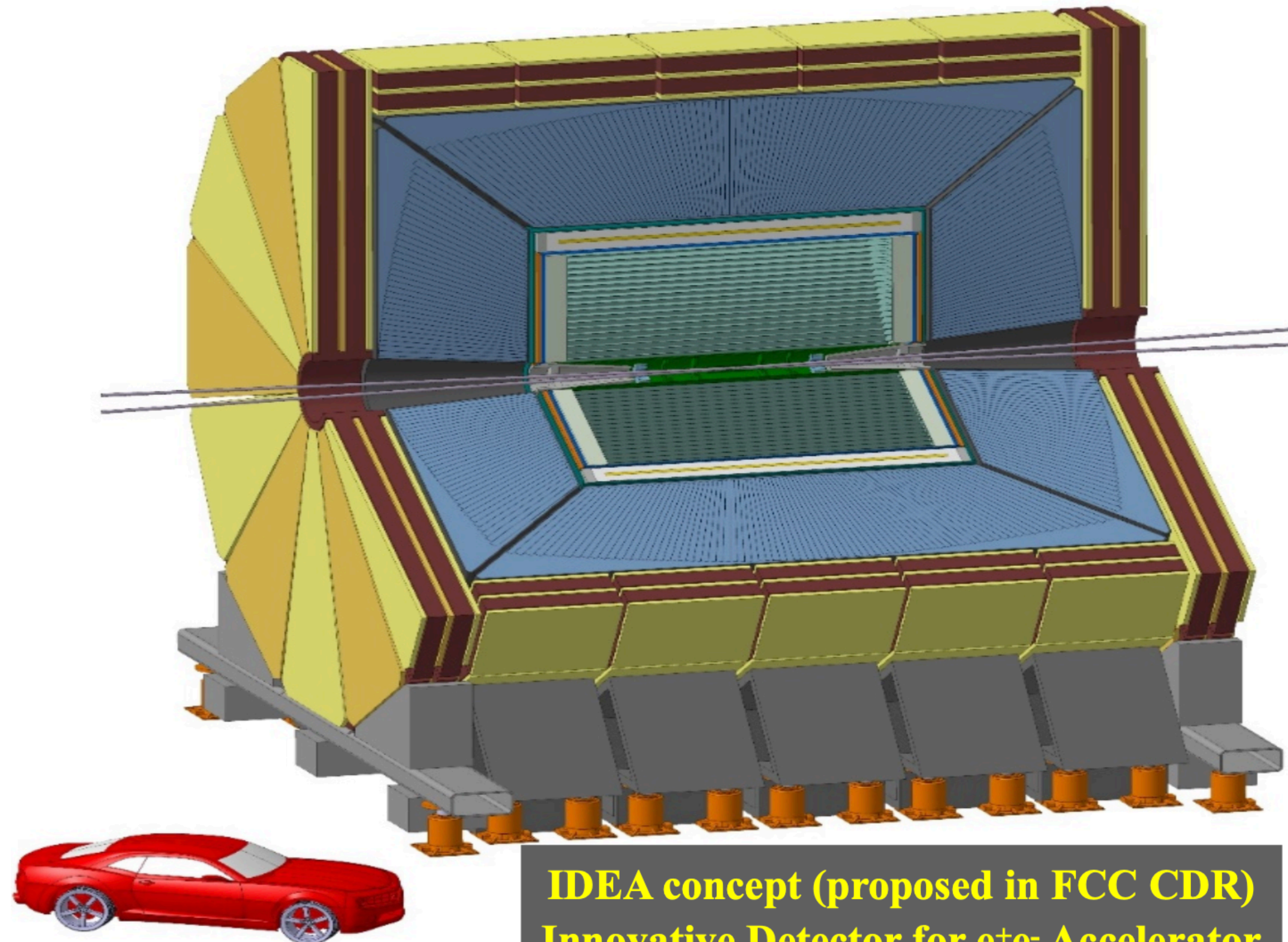
- Example of physics case study with common FCC framework
 - Analysis workflow well-factorized, easy to adapt.
- Good results expected for $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$
 - Signal yield precision $\sim 2\%$ for $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $\sim 4\%$ for $B^+ \rightarrow \tau^+ \nu_\tau$
 - Interpreted as constraints on 2HDM and leptoquark models, more work to be done on the measurement of $|V_{ub}|$ (maybe even $|V_{cb}|$)



Backup

Detector concept

- Silicon vertex detector
- Short-drift wire chamber
- 2T solenoid magnet
- Dual readout calorimeter
- Iron yoke + muon chambers

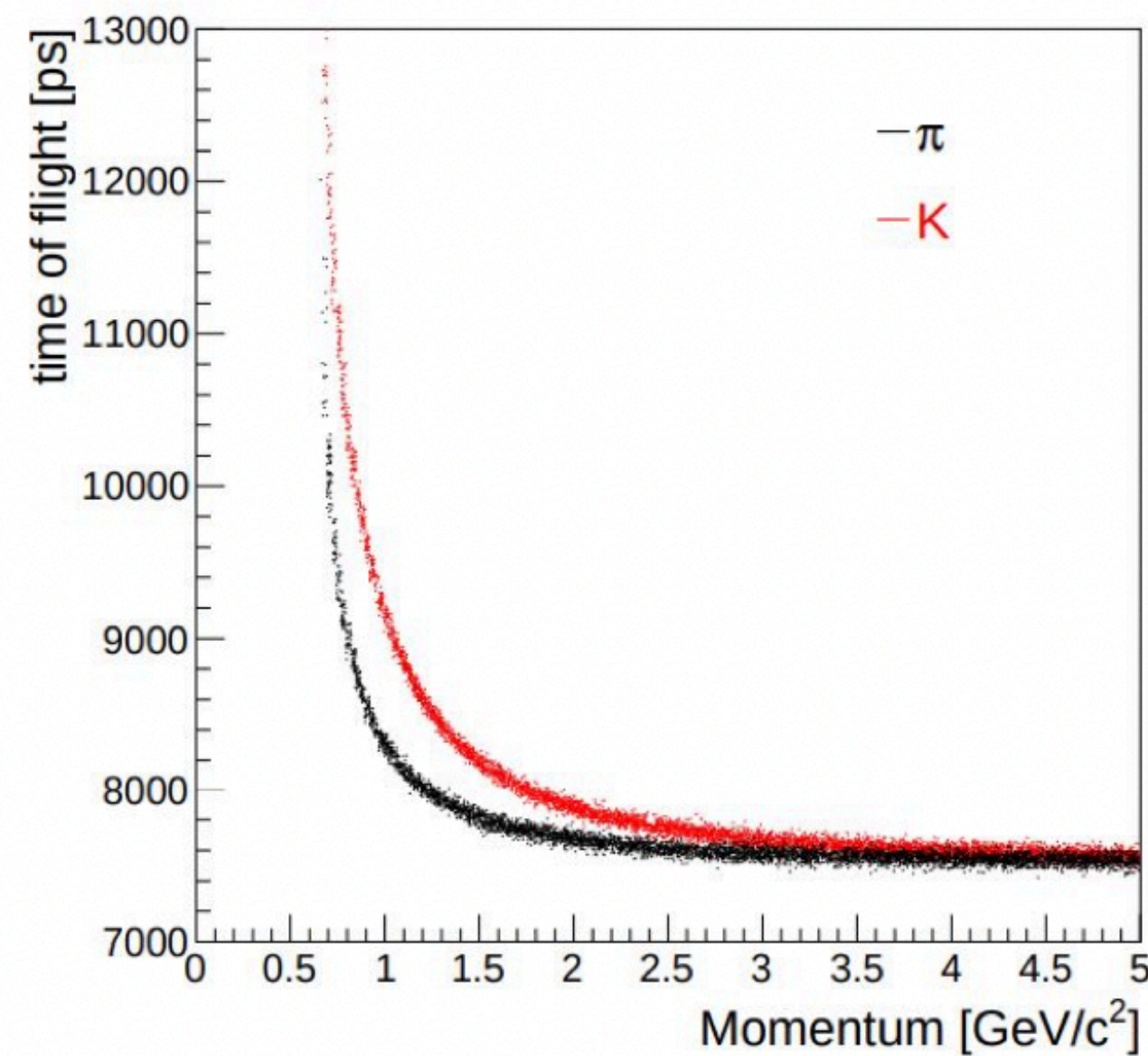


**IDEA concept (proposed in FCC CDR)
Innovative Detector for e^+e^- Accelerator**

Kaon vs Pion ID

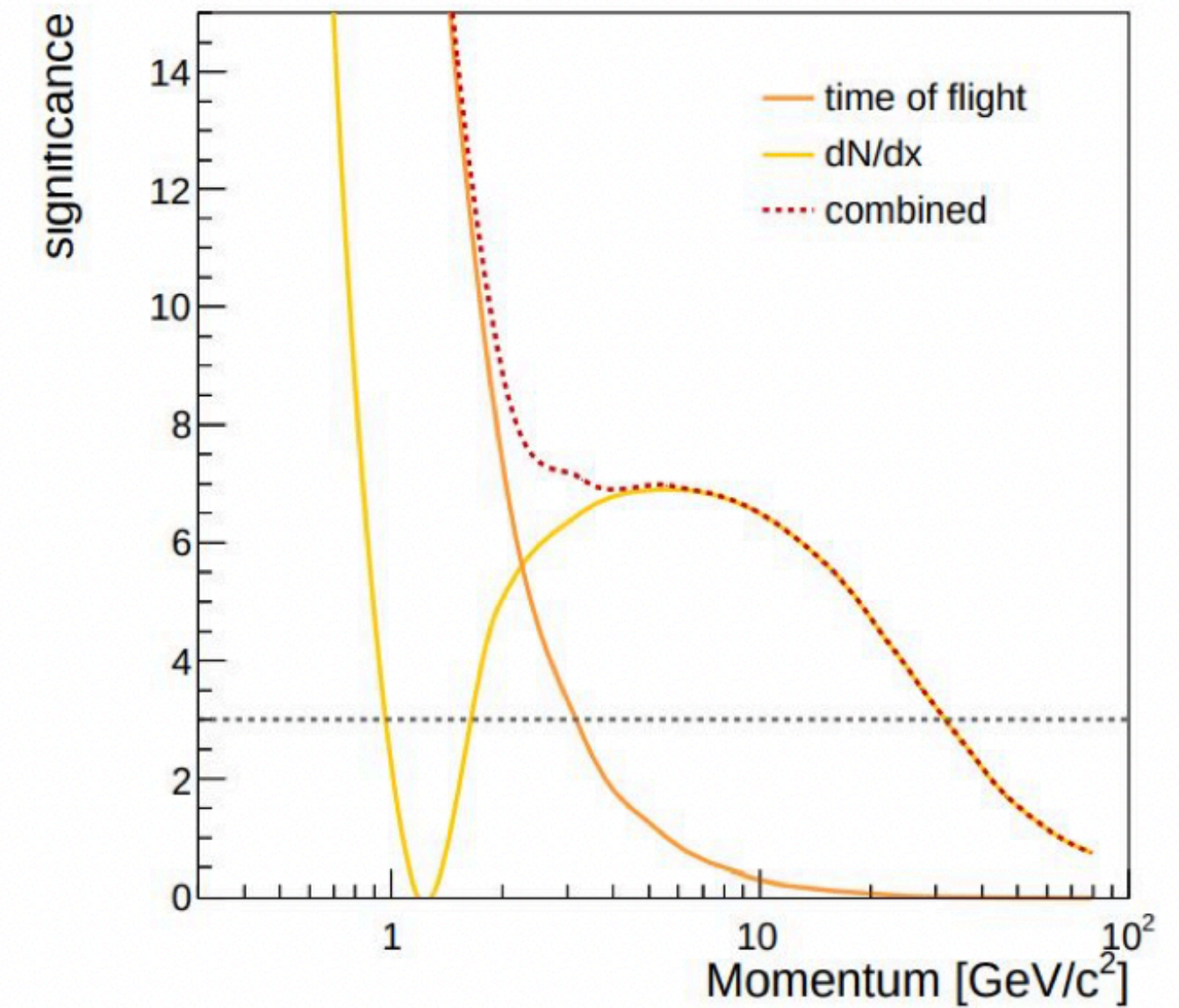
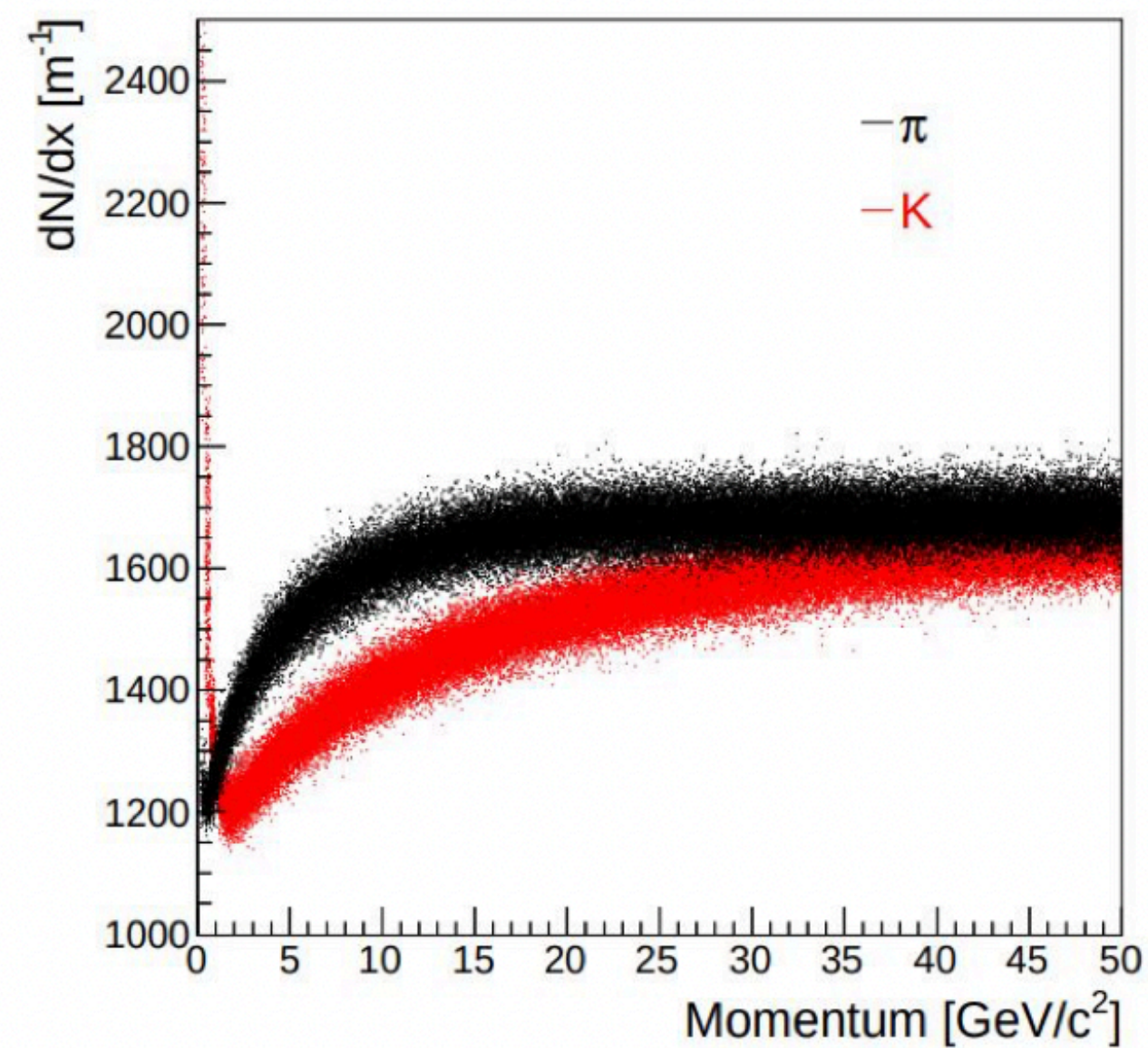
Time of Flight

- Good K/π separation at low momenta



Cluster Counting

- Count number of primary ionization clusters along track path



3-sigma separation for tracks with $p < 30\text{GeV}$

Assume perfect ID in the kinematic region ($p < 30\text{ GeV}$) of study.

Theory predictions



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

- $|V_{cb}| = 39.09(68) \times 10^{-3}$ from $B \rightarrow D^{(*)} l \nu$
- $f_{B_c} = 427(6)$ MeV from LQCD

Samples



- $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ signals, 10M each
- Inclusive $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ processes, 1B each
- Exclusive B decays backgrounds, 200M each
- All events generated with Pythia and simulated in DELPHES with IDEA detector

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

Stage1 MVA



- Goal: remove “easy” backgrounds from $Z \rightarrow c\bar{c}, q\bar{q}$ processes
- Binary BDT classifier
 - signal: $B_c^+ \rightarrow \tau^+ \nu_\tau$
 - background: inclusive $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ decays
- Pre-selection for training:
 - A primary vertex (PV) is reconstructed
 - At least one 3π secondary vertex (SV) is reconstructed
 - At least one 3π candidate in the hemisphere with less energy
- Use general event properties as **input variables**:
 - Energy (charged, neutral, total) in each hemisphere
 - Particle multiplicity (charged, neutral, total) in each hemisphere
 - Number of tracks associated to the PV
 - Number of secondary vertices and their displacements
 - Number of 3π candidates

Stage2 MVA

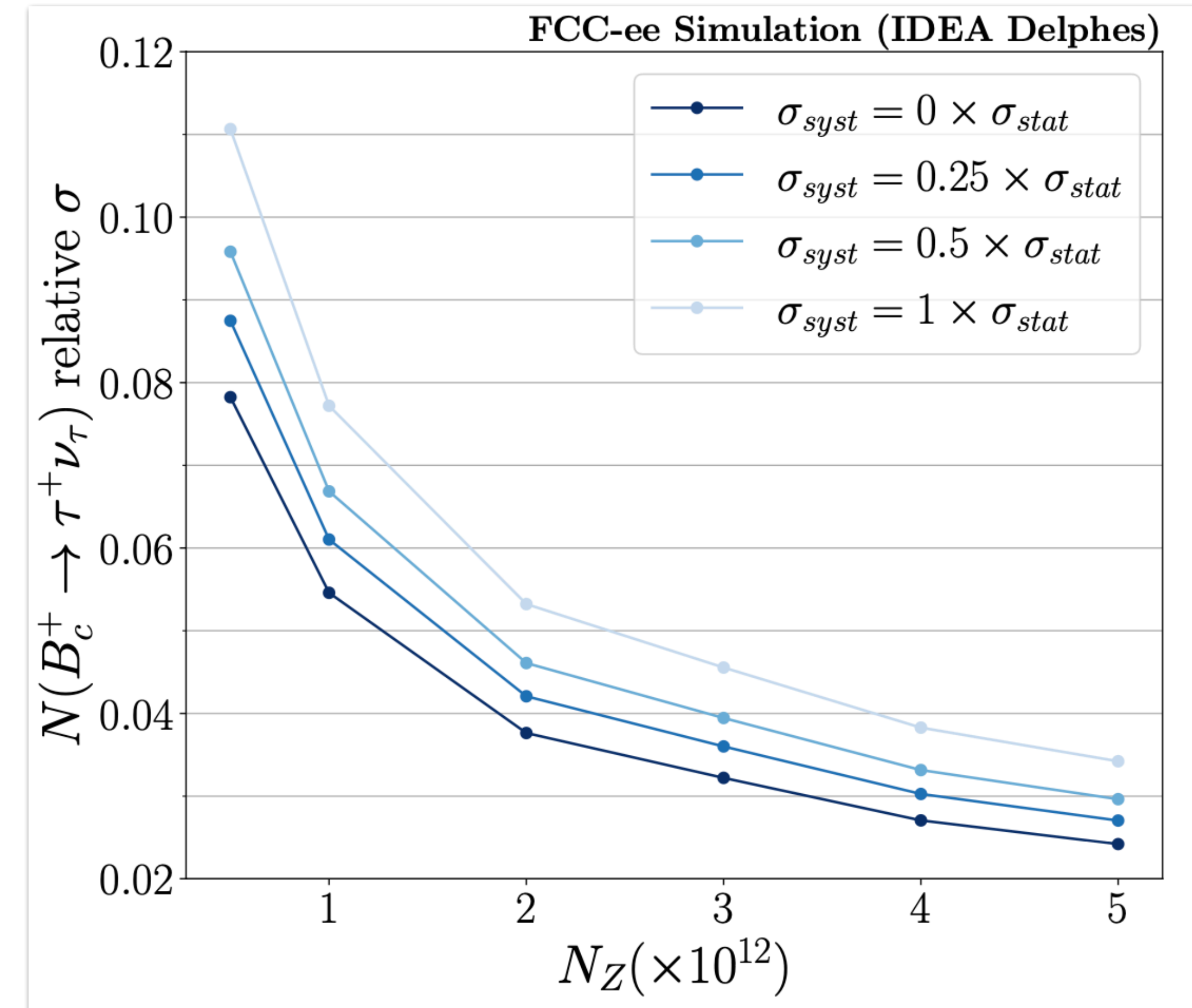


- Goal: use full kinematic property of $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ decay to maximize signal purity.
- Binary BDT classifier
 - signal: $B_c^+ \rightarrow \tau^+ \nu_\tau$
 - background: inclusive $Z \rightarrow b\bar{b}, c\bar{c}, q\bar{q}$ decays
- Selection before Stage2
 - Stage1 MVA > 0.6
 - Choose the 3π candidate with the least vertex fit χ^2
 - $m(\pi^+ \pi^-)$ compatible with ρ^0 , $m(\pi^+ \pi^+ \pi^-) < m_\tau$
 - Significant energy difference between two hemispheres, selected vertex in the hemisphere with less energy
- **Input variables:**
 - $\tau^+ \rightarrow \pi^+ \pi^+ \pi^- \bar{\nu}_\tau$ decay: mass, momentum, impact parameter, angle to the thrust axis
 - Impact parameters of all other secondary vertices
 - Mass of the PV
 - Nominal B_c energy: m_Z – all reco particles except the 3π candidate

Systematic uncertainty

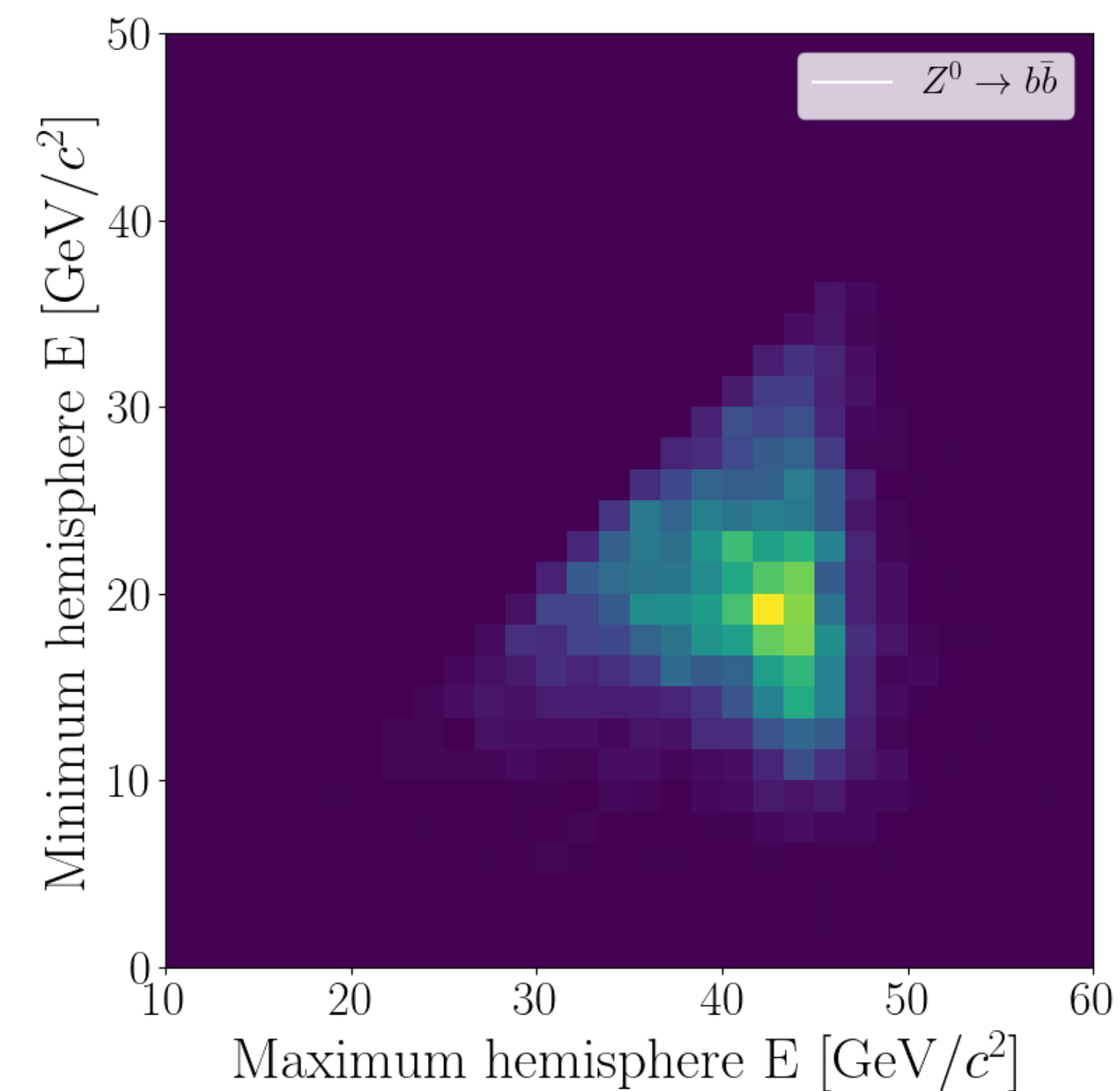
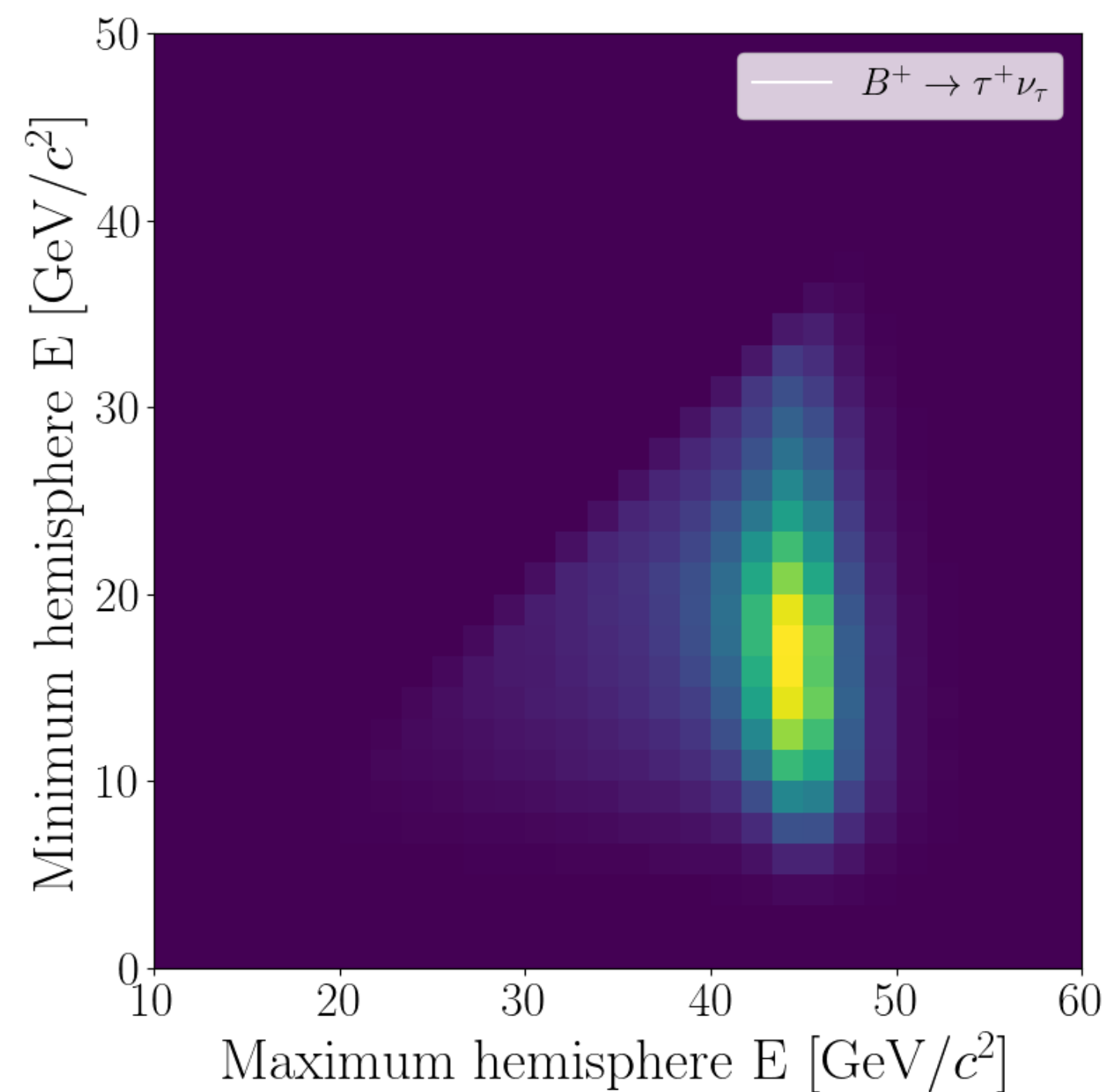
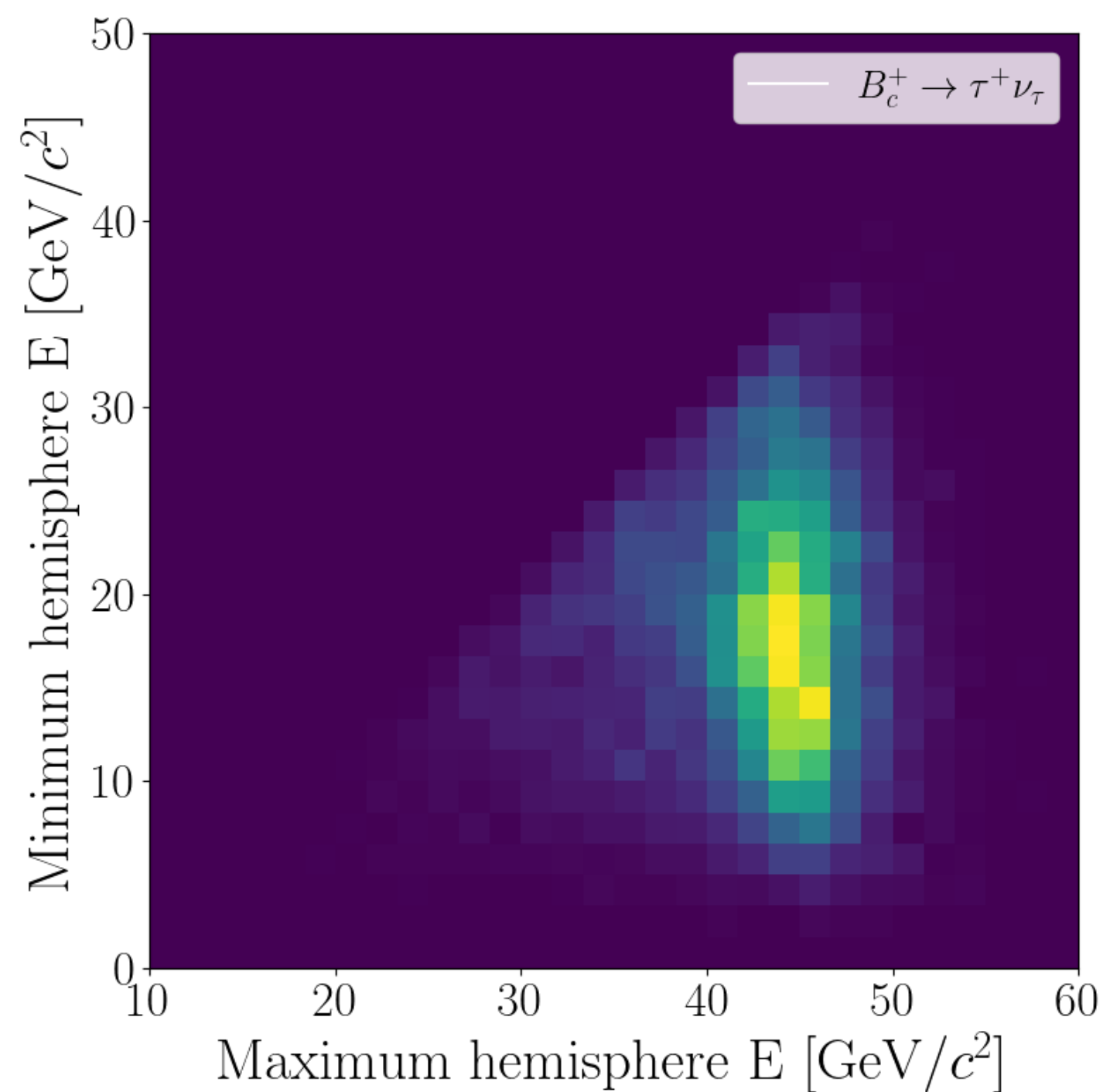


- By design, syst. uncert. at FCC-ee is expected to be constrained to the level comparable to stat. uncert. of EW precision measurements, and not a major concern for this result.
- Current analysis relies on strong assumptions in the background estimate method. Hard to estimate the uncertainty from these assumptions.
- Consider a few scenarios
 $\sigma_{syst} = [0, 0.25, 0.5, 1.0] \times \sigma_{stat}$



Variables for final fit

- No strong correlation between ThrustE_{max}_E and ThrustE_{min}_E



$|V_{cb}|$ and $|V_{ub}|$



- By taking leptonic decay constant f_B as input, the $B_c^+ \rightarrow \tau^+ \nu_\tau$ and $B^+ \rightarrow \tau^+ \nu_\tau$ results can be used to determine $|V_{cb}|$ and $|V_{ub}|$
- Clean measurement with high experimental precision
- Theoretical uncertainty (from lattice QCD) to be studied

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