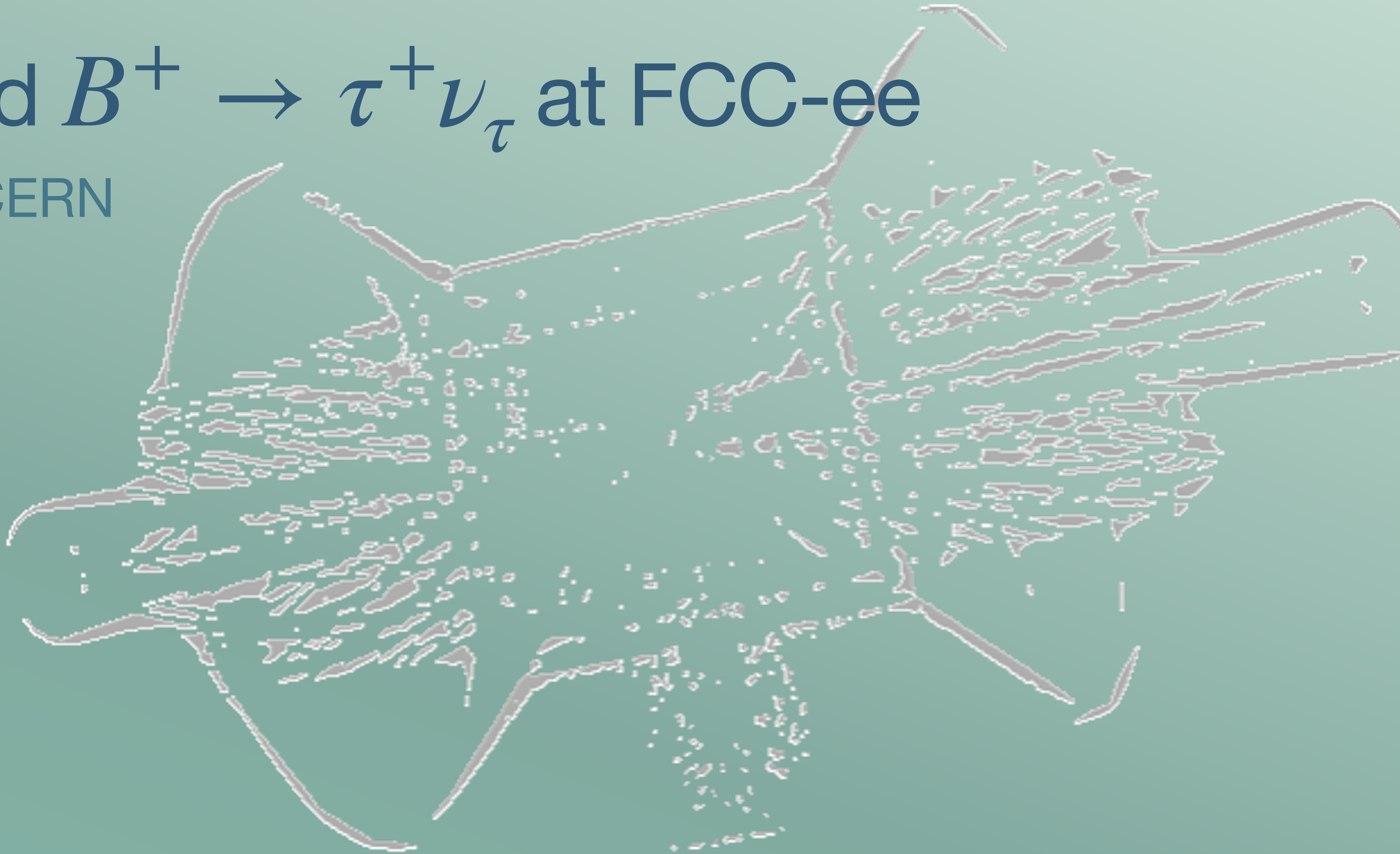
$B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$ at FCC-ee

FCC flavor workshop, CERN
September 13, 2022



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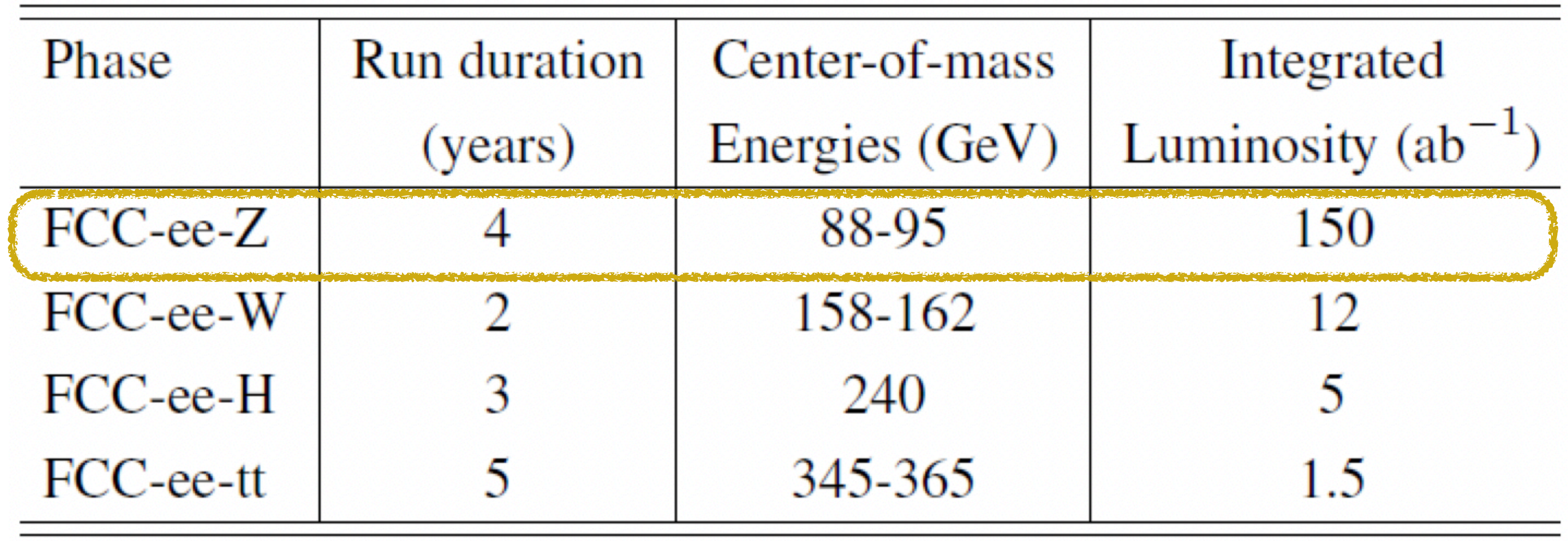
Outline

- This set of slides is based on 2 FCC-ee performance studies
  - $B_c^+ \to \tau^+\nu_\tau$: https://link.springer.com/article/10.1007/JHEP12(2021)133
  - $B^+/B_c^+ \to \tau^+\nu_\tau$: paper draft in preparation

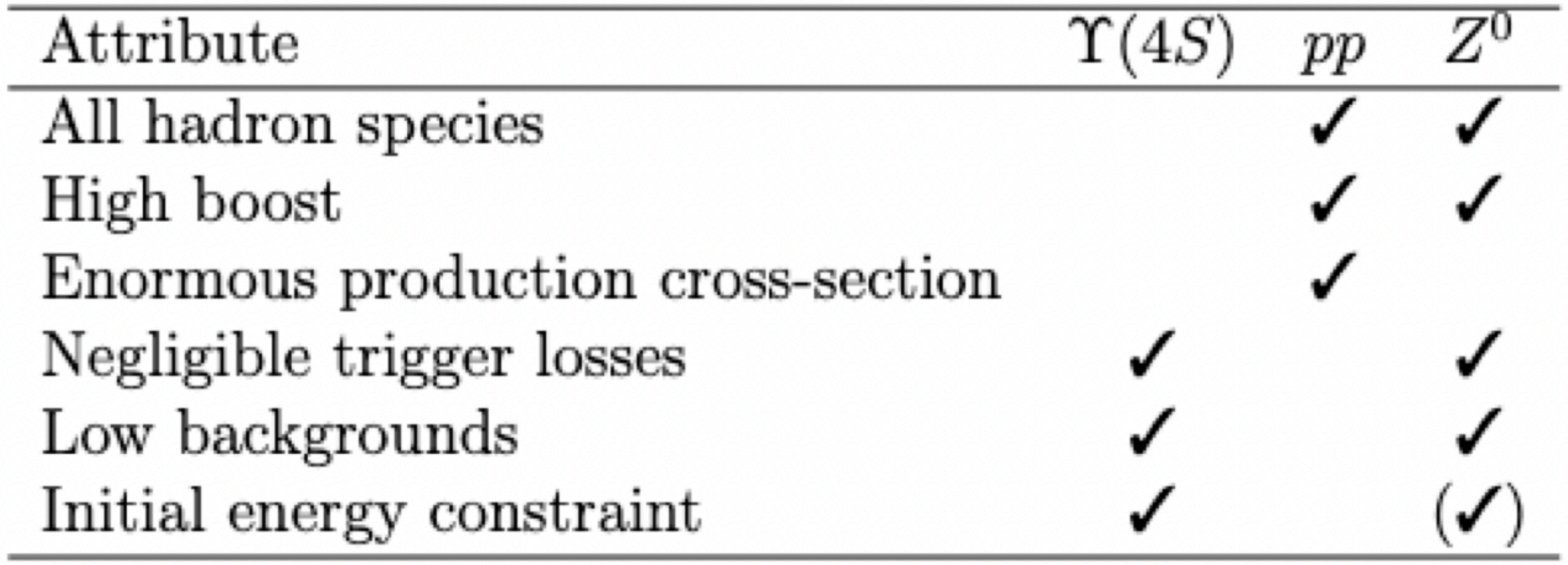
- **Table of content**
  - Common analysis workflow
  - $B_c^+ \to \tau^+\nu_\tau$ results
  - $B^+/B_c^+ \to \tau^+\nu_\tau$ results

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 $B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$:
  - 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	✓		(✓)

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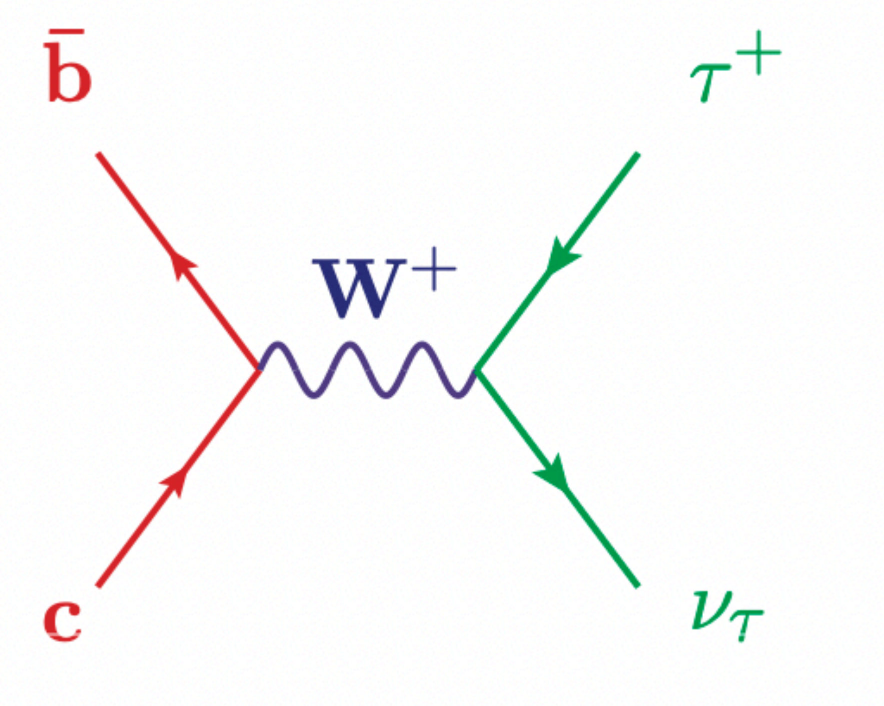
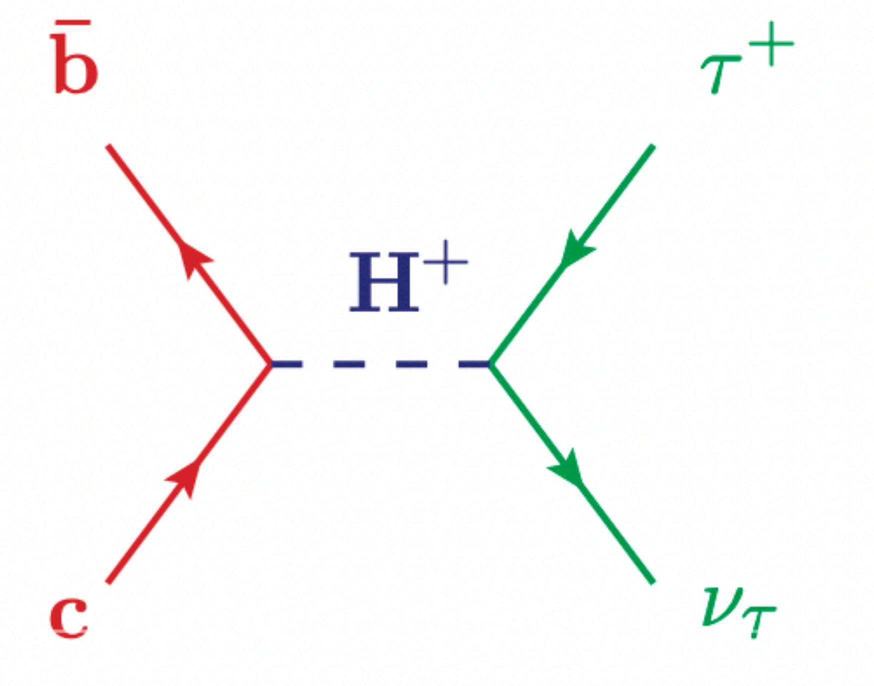
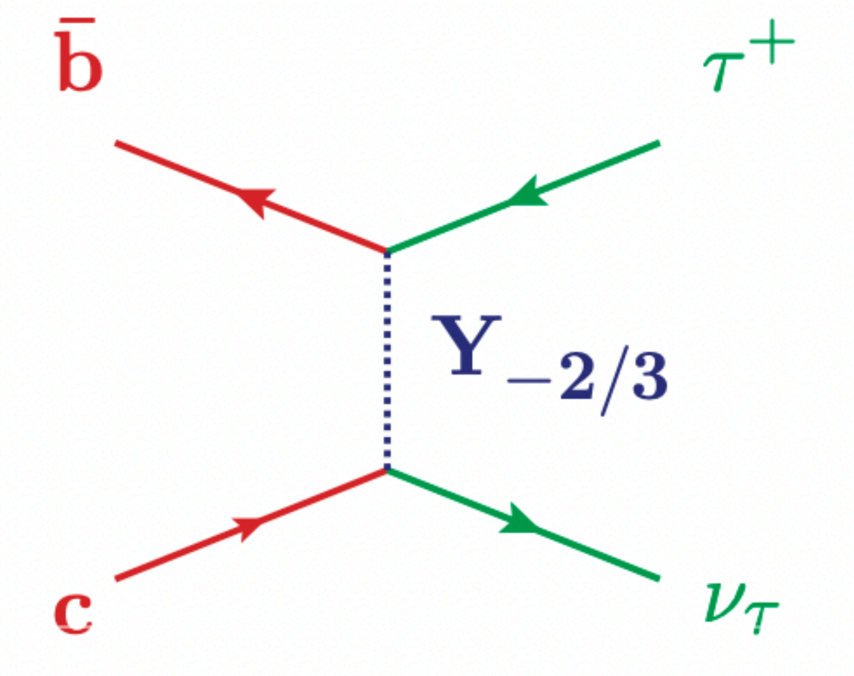
$B_c^+ / B^+ \to \tau^+\nu_\tau$ decays

- Directly related to anomalies in $b \to c\tau\nu_\tau$
- Clean probes to measure $|V_{cb}|$ and $|V_{ub}|$
- Sensitive to BSM physics, like charged Higgs and leptoquarks

- $B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$ are helicity and CKM-suppressed.
  - $f(B_c^+) \approx 0.04\,\%\,,\quad \mathscr{B}(B_c^+ \to \tau^+\nu_\tau) \approx 1.94\,\%$
  - $f(B^+) \approx 43\,\%\,,\quad \mathscr{B}(B^+ \to \tau^+\nu_\tau) \approx 1.09 \times 10^{-4}$
- In the 5×10^{12} Z events scenario of FCC-ee
  - $B_c^+ \to \tau^+\nu_\tau\ (\pi^+\pi^+\pi^-\bar{\nu}_\tau) \approx$ 1M
  - $B^+ \to \tau^+\nu_\tau\ (\pi^+\pi^+\pi^-\bar{\nu}_\tau) \approx$ 6M





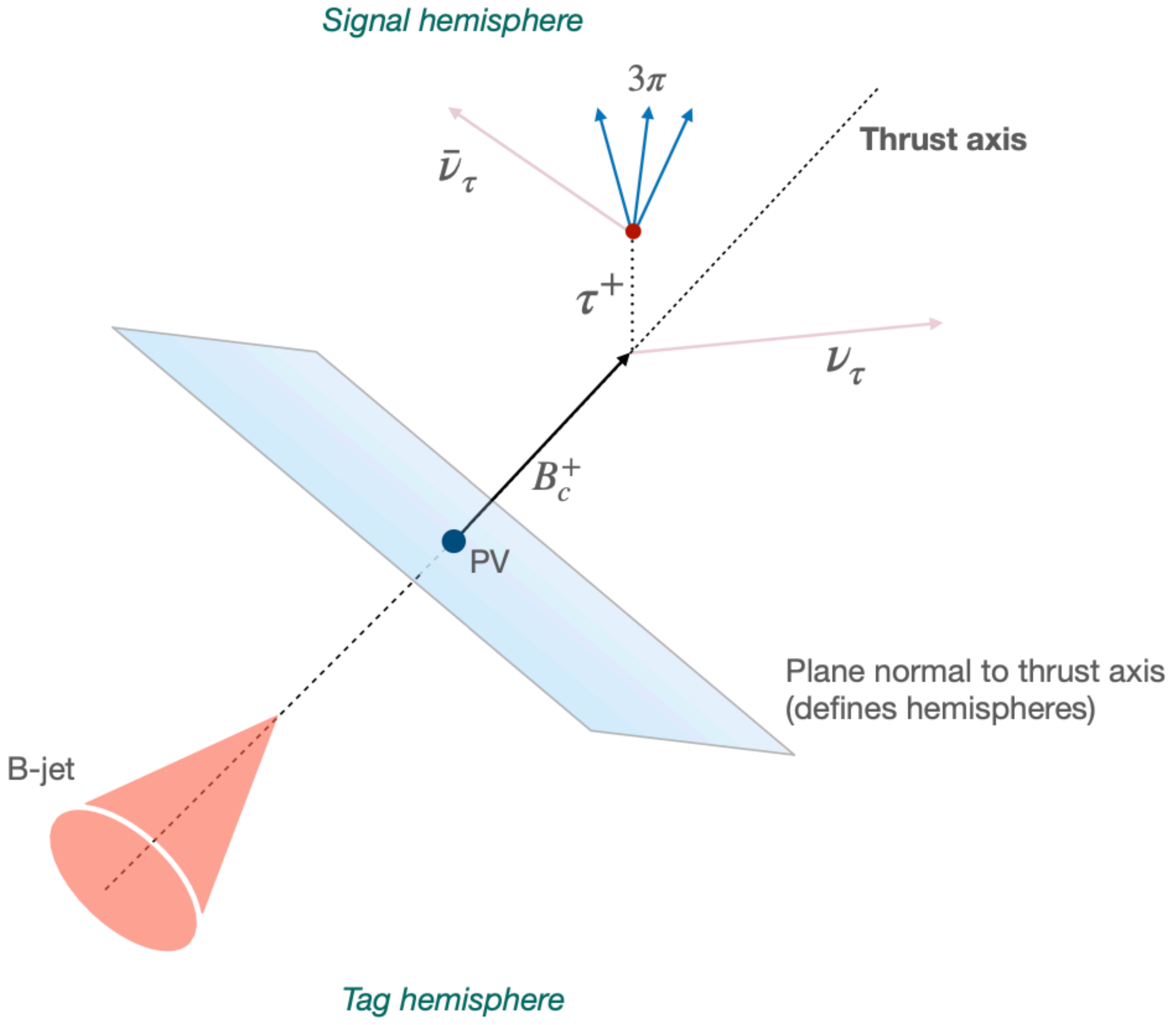


b-decay hemispheres

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

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

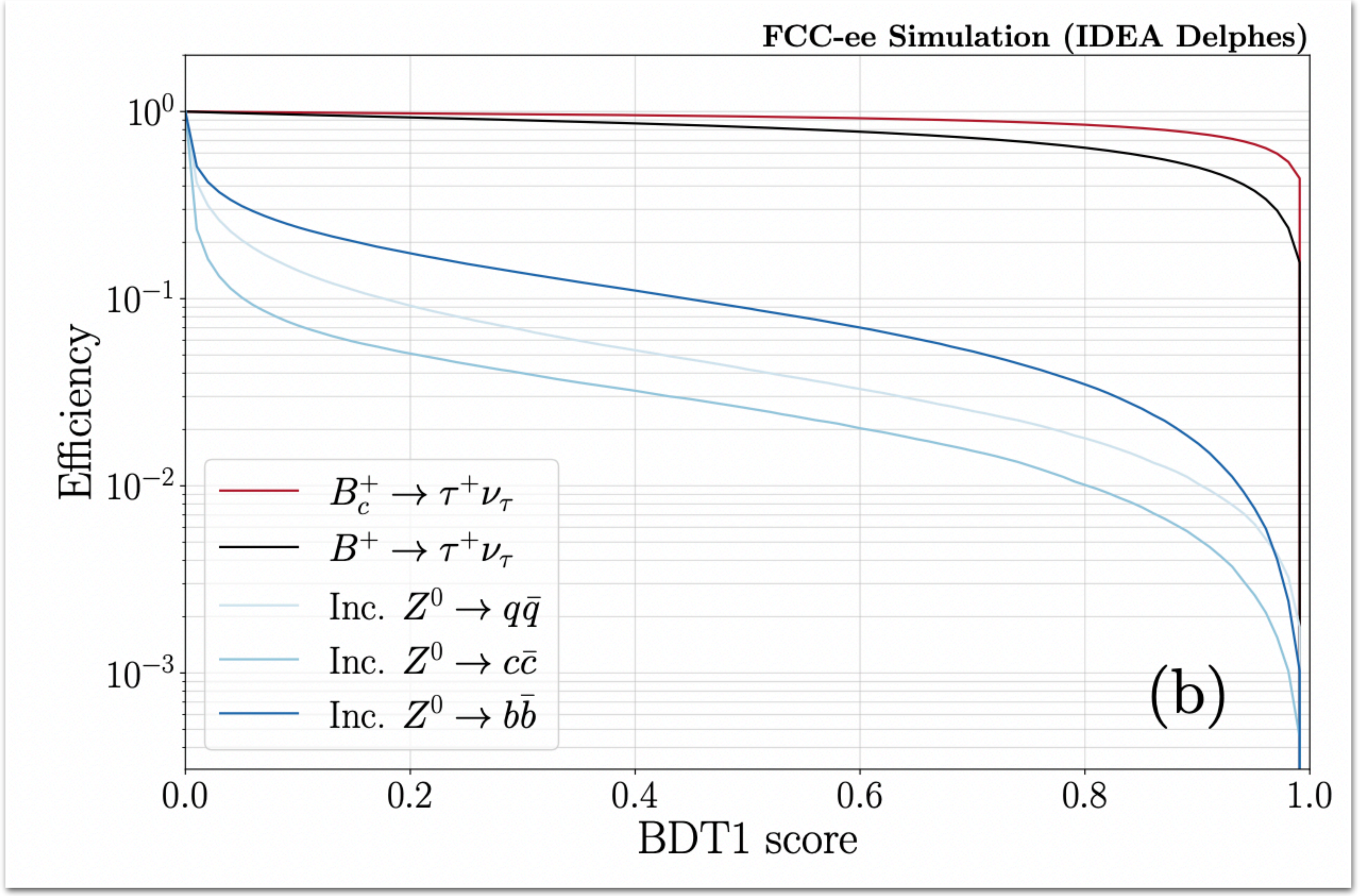
- Measures the decay axis of $Z \to b\bar{b}$
- Due to high missing energy in the signal decays
  - The thrust axis would be skewed in signal events
  - The two hemispheres would have very different energy distributions.

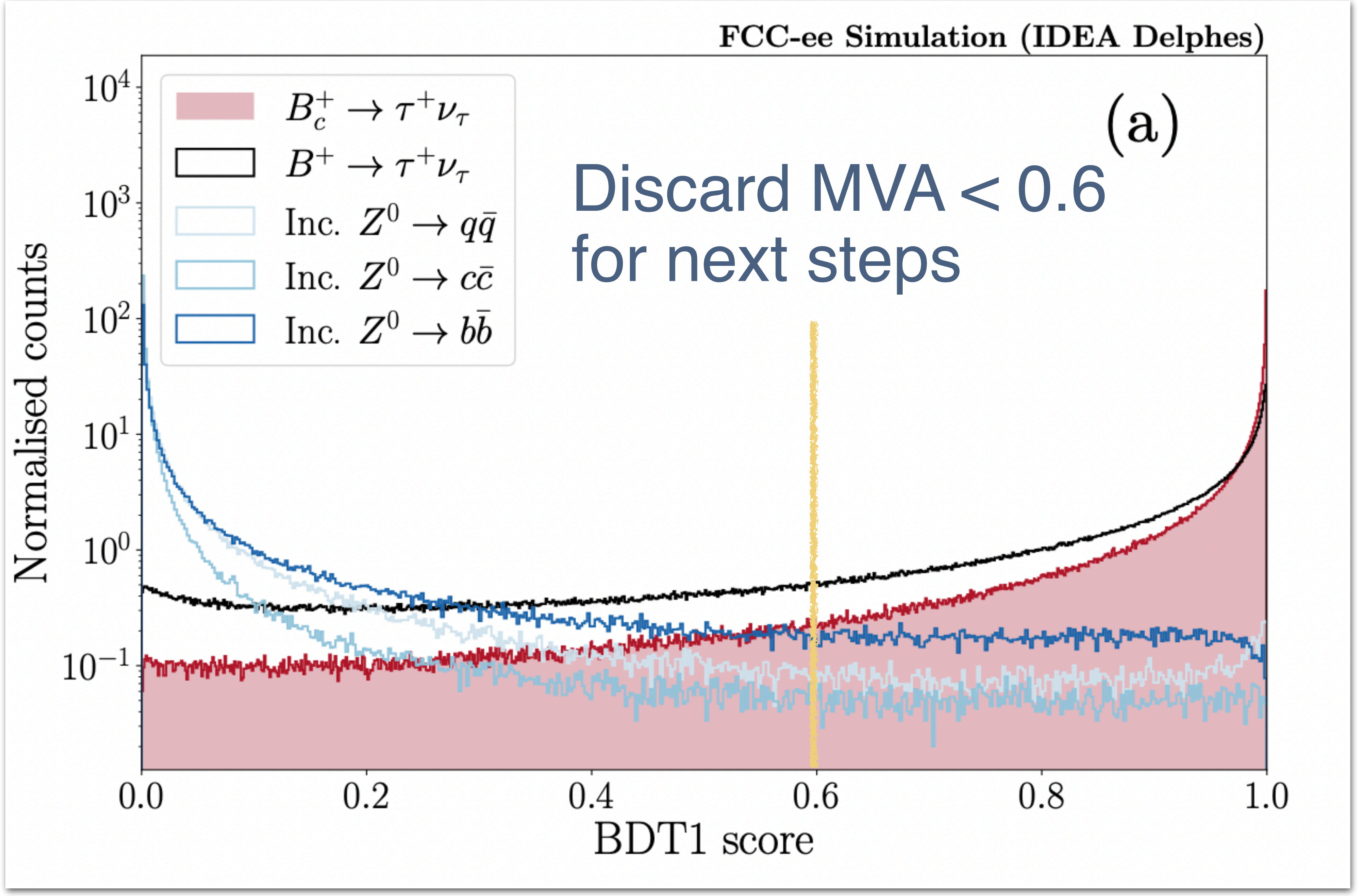


$B_c^+ \to \tau^+ \nu_\tau$ result

Stage1 MVA

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





Discard MVA < 0.6 for next steps

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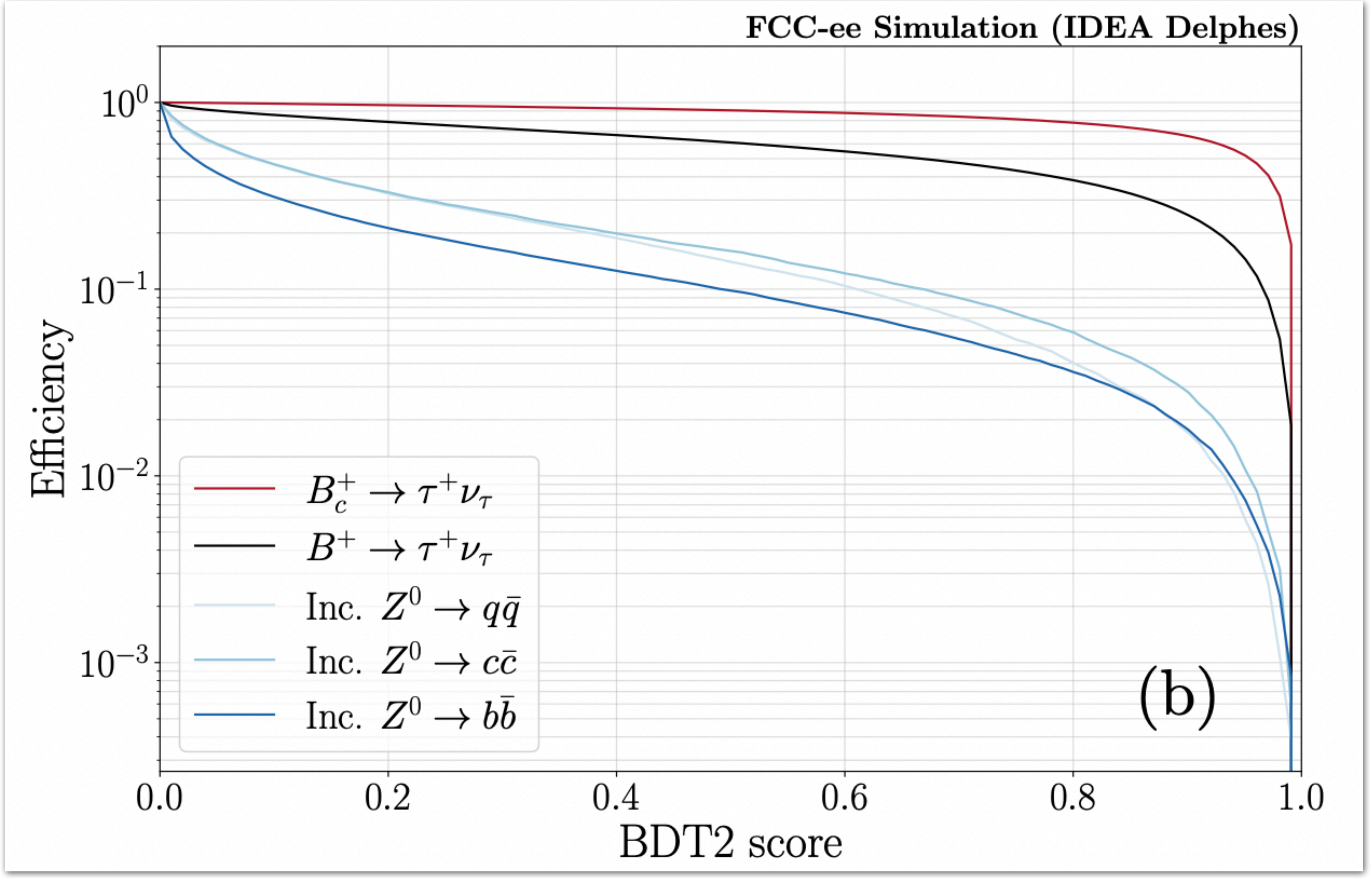
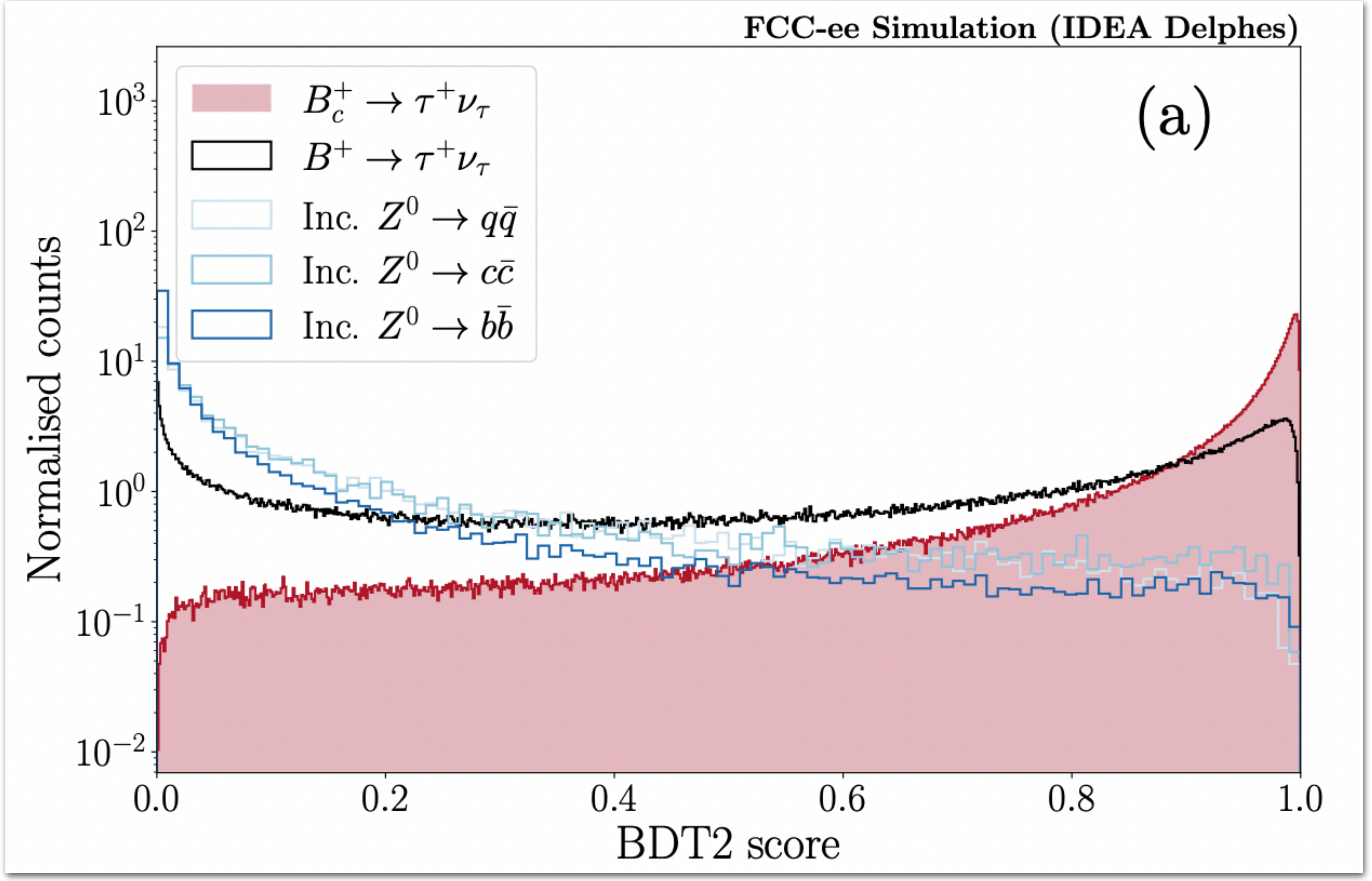
Stage2 MVA

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





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Final selection

- After the Stage2 MVA, $Z \to c\bar{c}$ and $Z \to q\bar{q}$ are reduced by a factor more than 10^9
  - All simulation events are rejected (Do not consider for further steps)
- Inclusive $Z \to b\bar{b}$ largely rejected, not enough events to estimate efficiency at high MVA scores.
  - Use a set of exclusive samples, $B \to D\tau\nu$ / $D3\pi$ / DD_s, where $B \in \{B^0, B^+, B_s^0, \Lambda_b^0\}$, to estimate background yields.

- Estimate method:
  - $N^{\text{bkg}}_{\text{baseline}}$: 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,

$$N^{\text{bkg}}_{\text{final}} = N^{\text{bkg}}_{\text{baseline}} \times \epsilon(\text{MVA1 cut}\,|\,\text{baseline}) \times \epsilon(\text{MVA2 cut}\,|\,\text{baseline})$$

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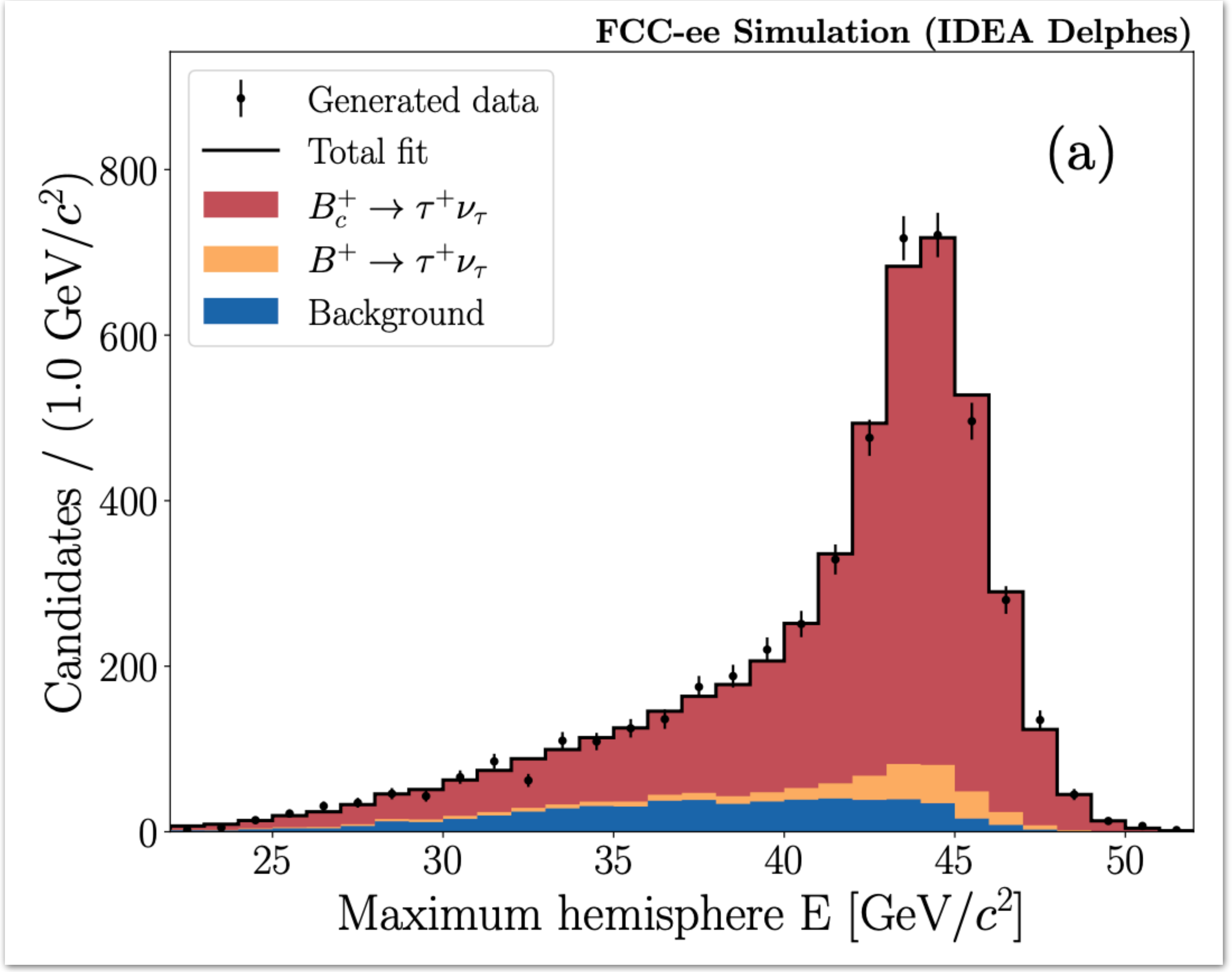
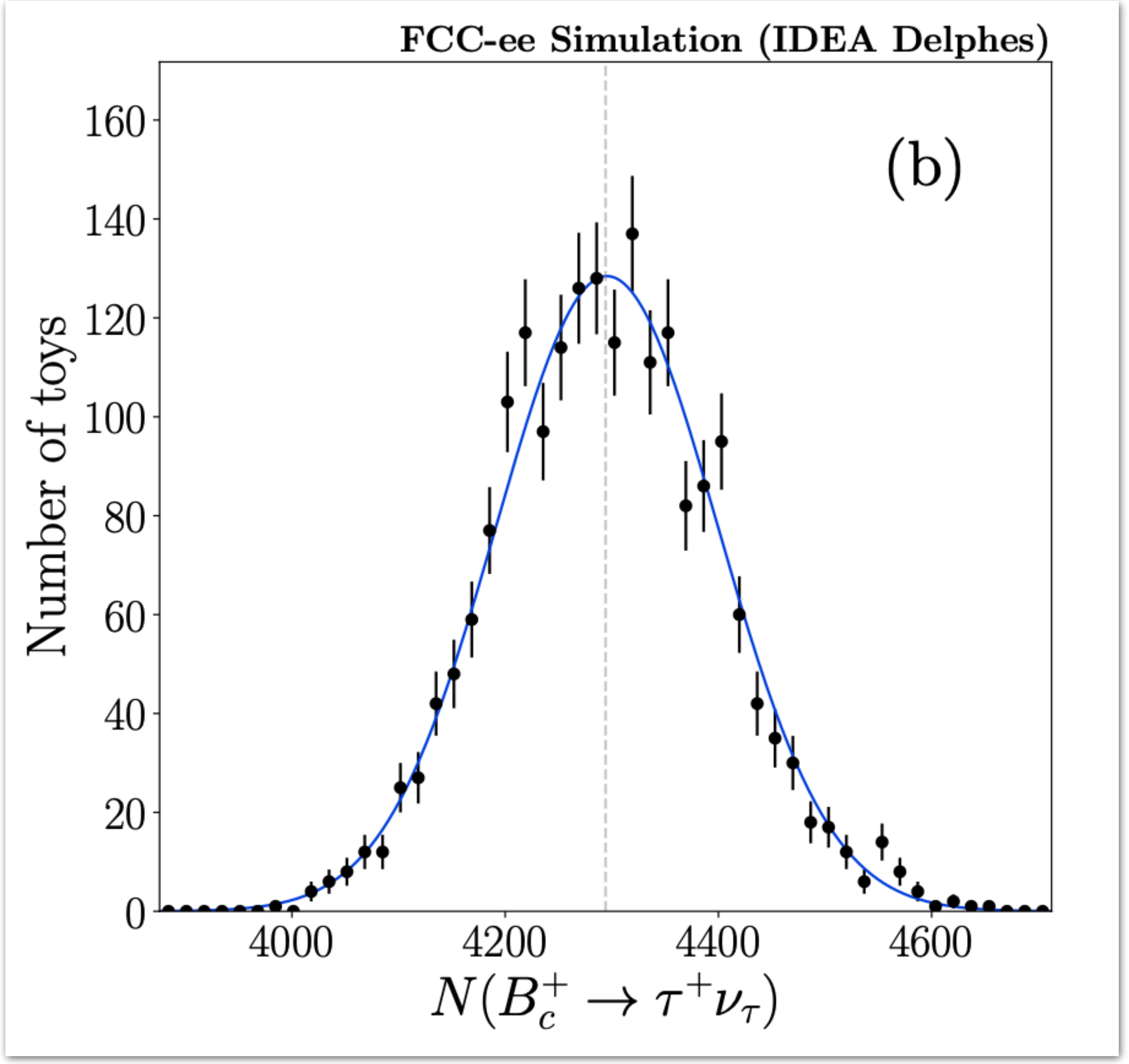
Template fit

- From 2D scan of (MVA1, MVA2) cuts, the optimal yields are:
  - $B_c^+ \to \tau^+\nu_\tau$: 4295
  - $B^+ \to \tau^+\nu_\tau$: 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%

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

Precision on $\mathscr{B}(B_c^+ \to \tau^+\nu_\tau)$

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

$$R_c = \frac{\mathscr{B}(B_c^+ \to \tau^+\nu_\tau)}{\mathscr{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

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

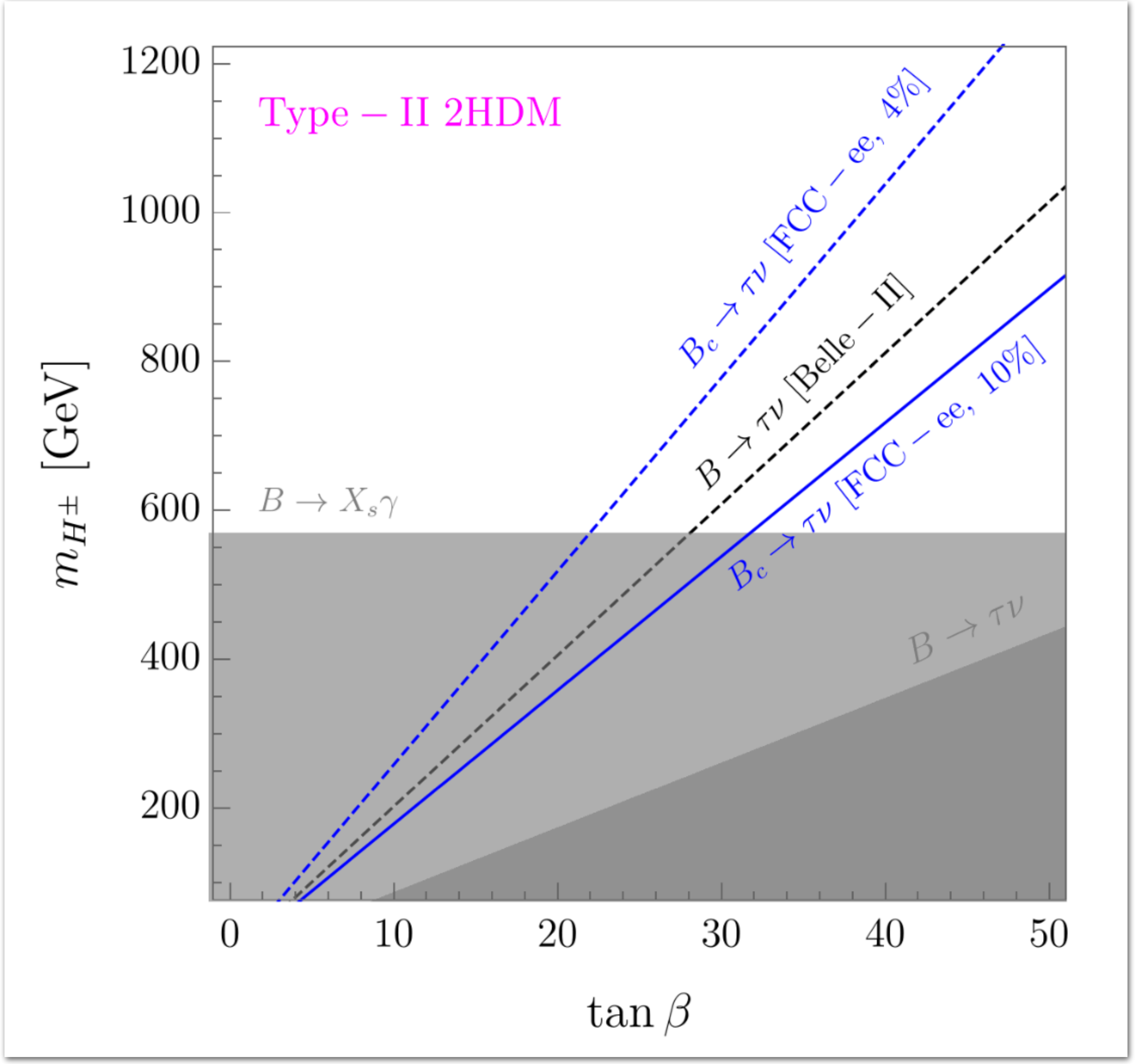
- R_c has good experimental precision ~4%
  - Decoupled from $|V_{cb}|$ and $f(B^+)$
  - Highly sensitive to BSM
- Can be translated to a measurement on $\mathscr{B}(B_c^+ \to \tau^+\nu_\tau)$
  - Use current best $|V_{cb}|$[1], and form-factors calculated from lattice QCD [2, 3] for the SM value of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

Probe of 2HDM

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

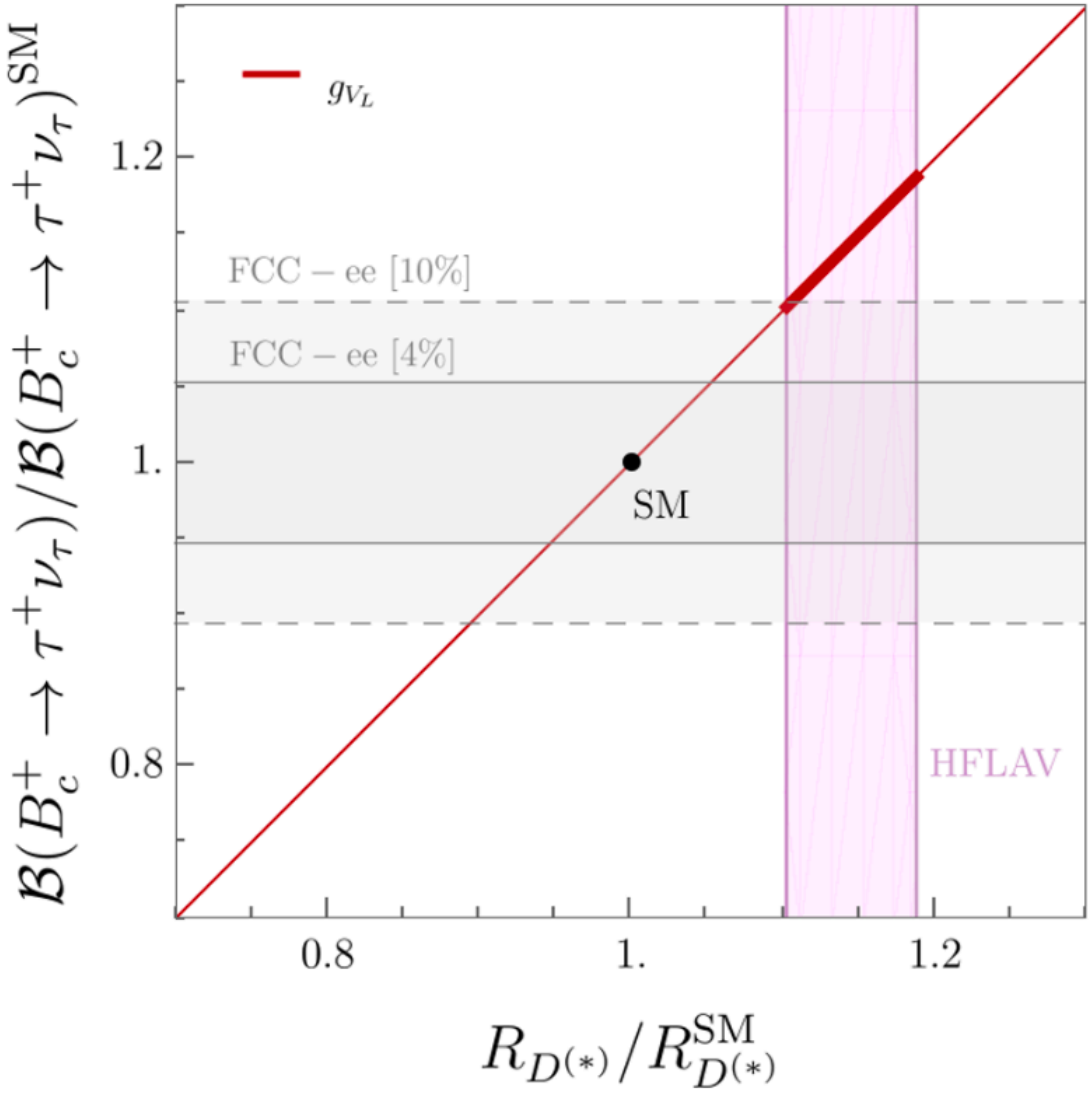
$$\mathcal{H}_{\text{eff}} = 2\sqrt{2}G_F V_{cb}\Big[(1+g_{V_L})\left(\bar{c}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma^\mu\nu_L\right) + g_{V_R}\left(\bar{c}_R\gamma_\mu b_R\right)\left(\bar{\tau}_L\gamma^\mu\nu_L\right) + g_{S_L}\left(\bar{c}_R b_L\right)\left(\bar{\tau}_R\nu_L\right) + g_{S_R}\left(\bar{c}_L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

- Computed in two scenarios where $\Gamma(B_c^+ \to \tau^+\nu_\tau)/|V_{cb}|^2$ 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 $\Gamma(B_c^+ \to \tau^+\nu_\tau)/|V_{cb}|^2$ larger than 10%. Can be fully examined.



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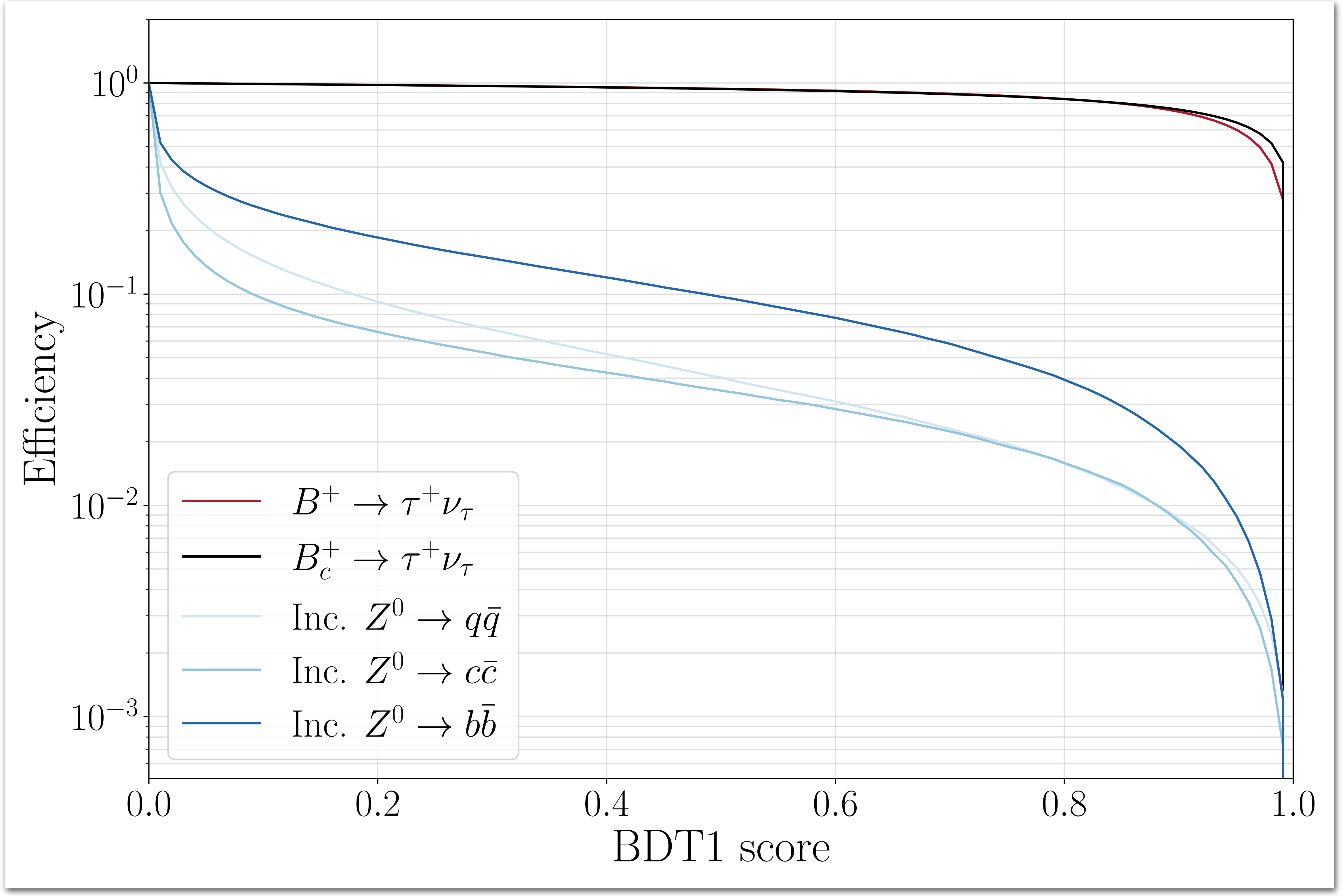
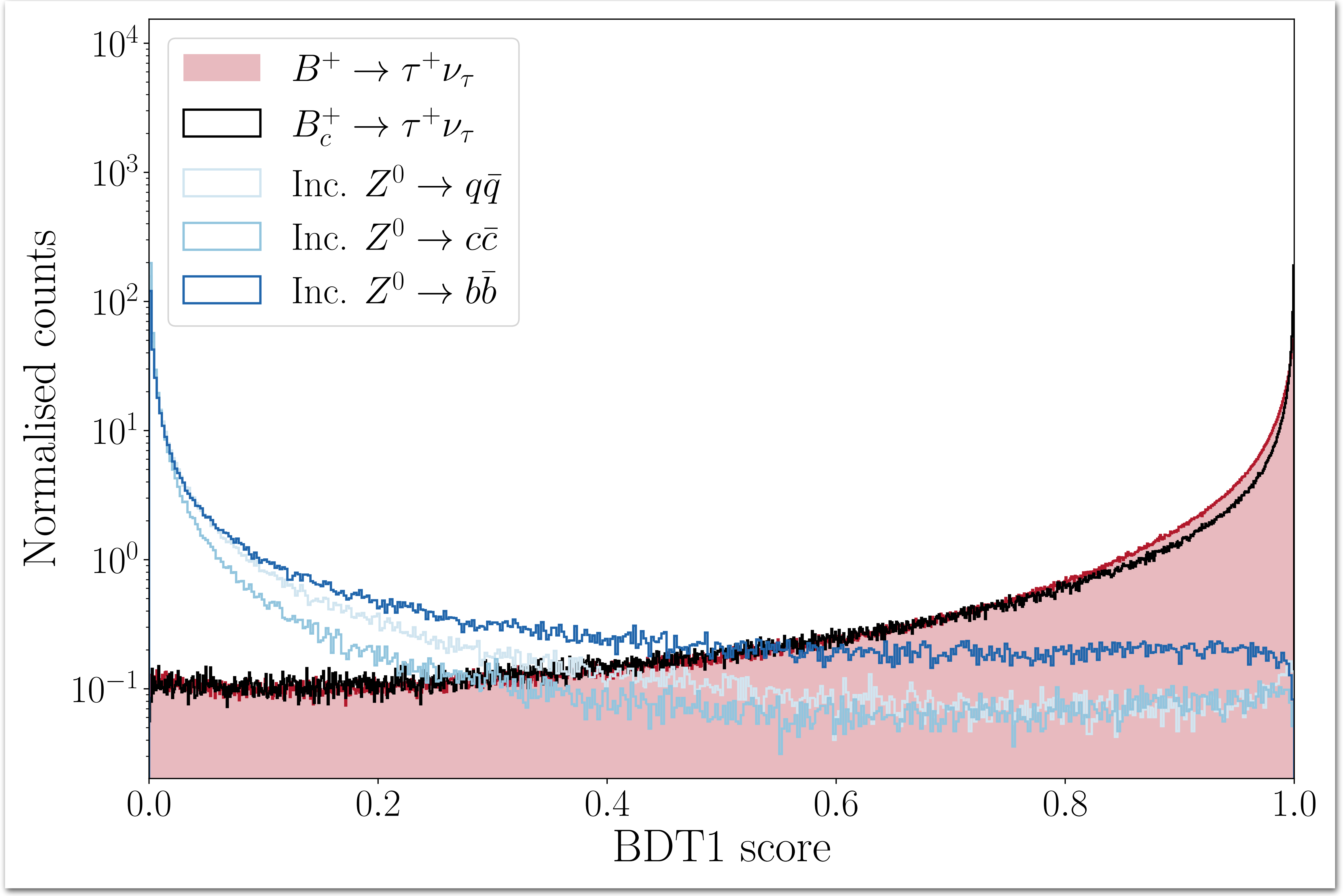
$B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$ results

The following results are work in progress

Stage1 MVA

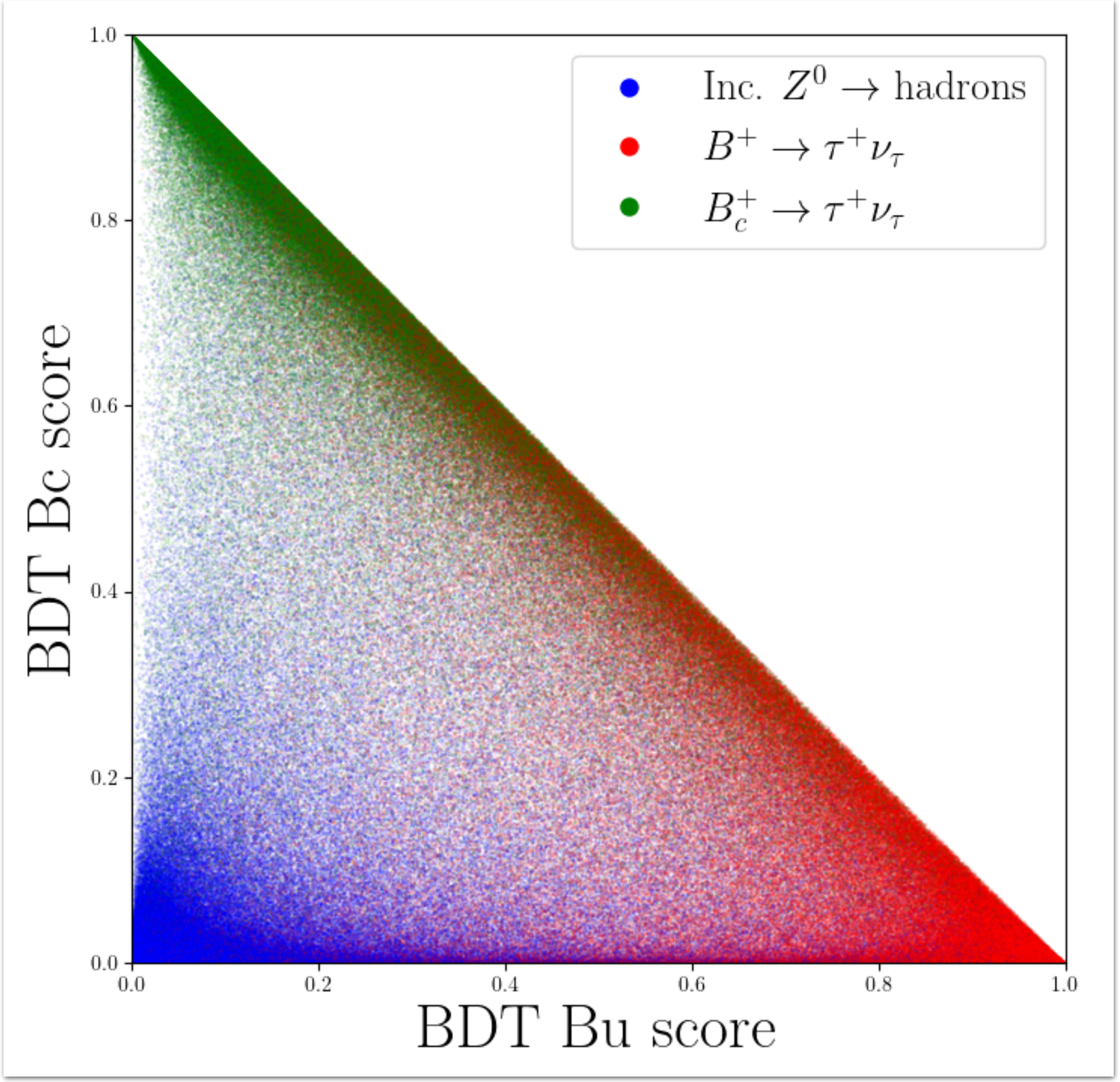
- Goal: remove "easy" backgrounds (same as in Bc analysis)
- Same setup as in Bc analysis, just include both $B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$ as signals
- Better efficiency for Bu, similar performance on Bc and background as before.





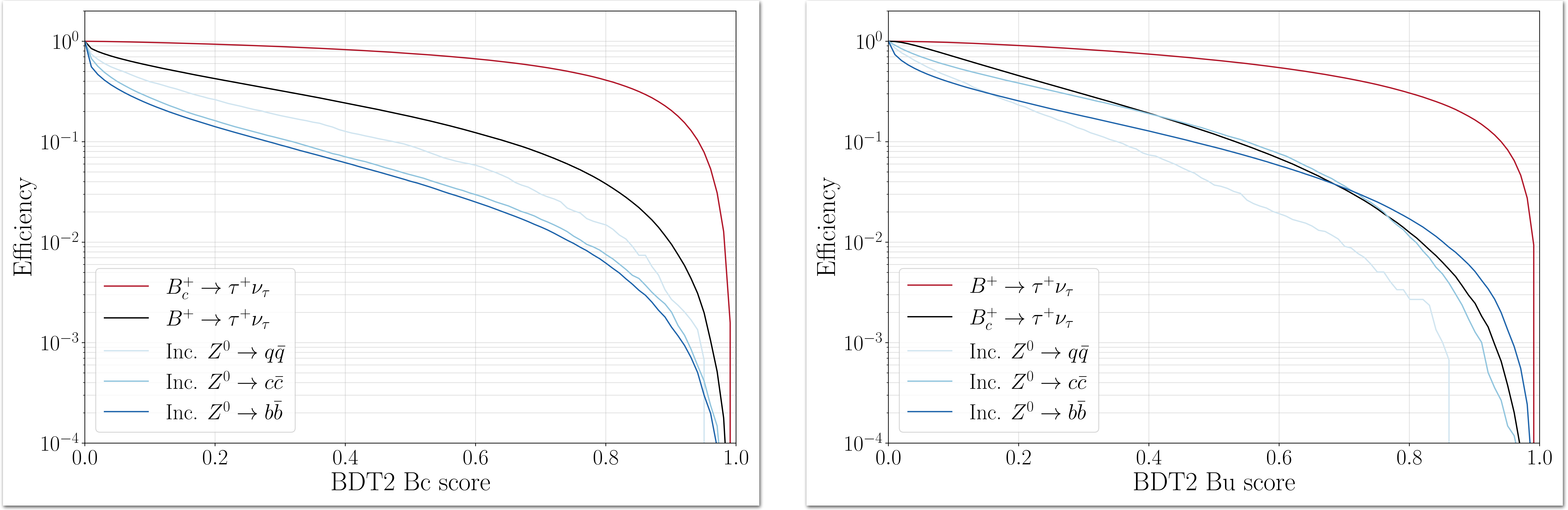
Stage2 MVA

- 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: $Z \to b\bar{b}, c\bar{c}, q\bar{q}$
  - label 1: $B^+ \to \tau^+\nu_\tau$
  - label 2: $B_c^+ \to \tau^+\nu_\tau$
- Good separation achieved between all 3 processes.



Stage2 MVA

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



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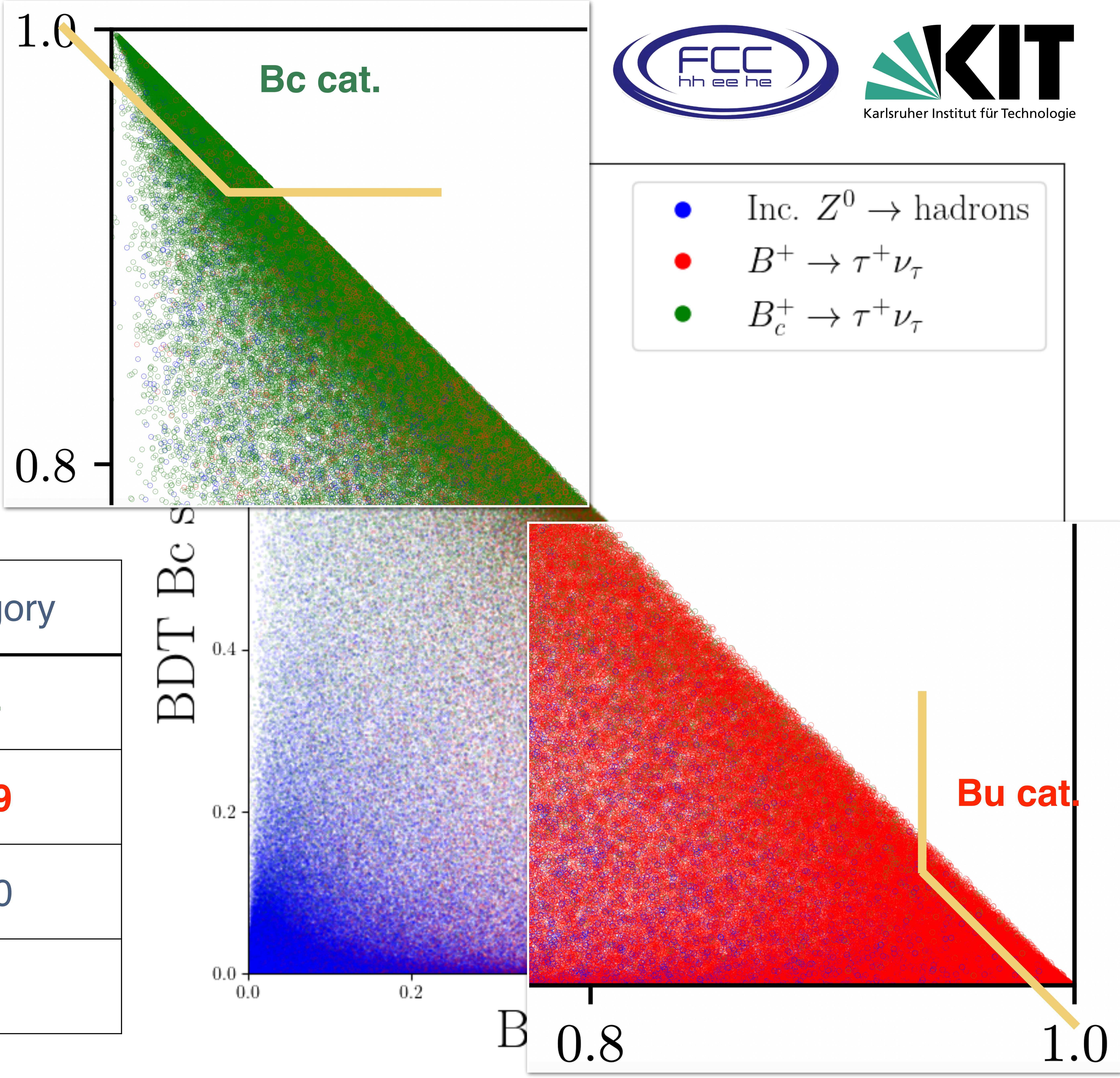
Categorization (new)

- Select a stripe close to $\mathrm{MVA}_{\mathrm{bkg}} \to 0$
- Orthogonality ensured by selecting different corners.

	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%



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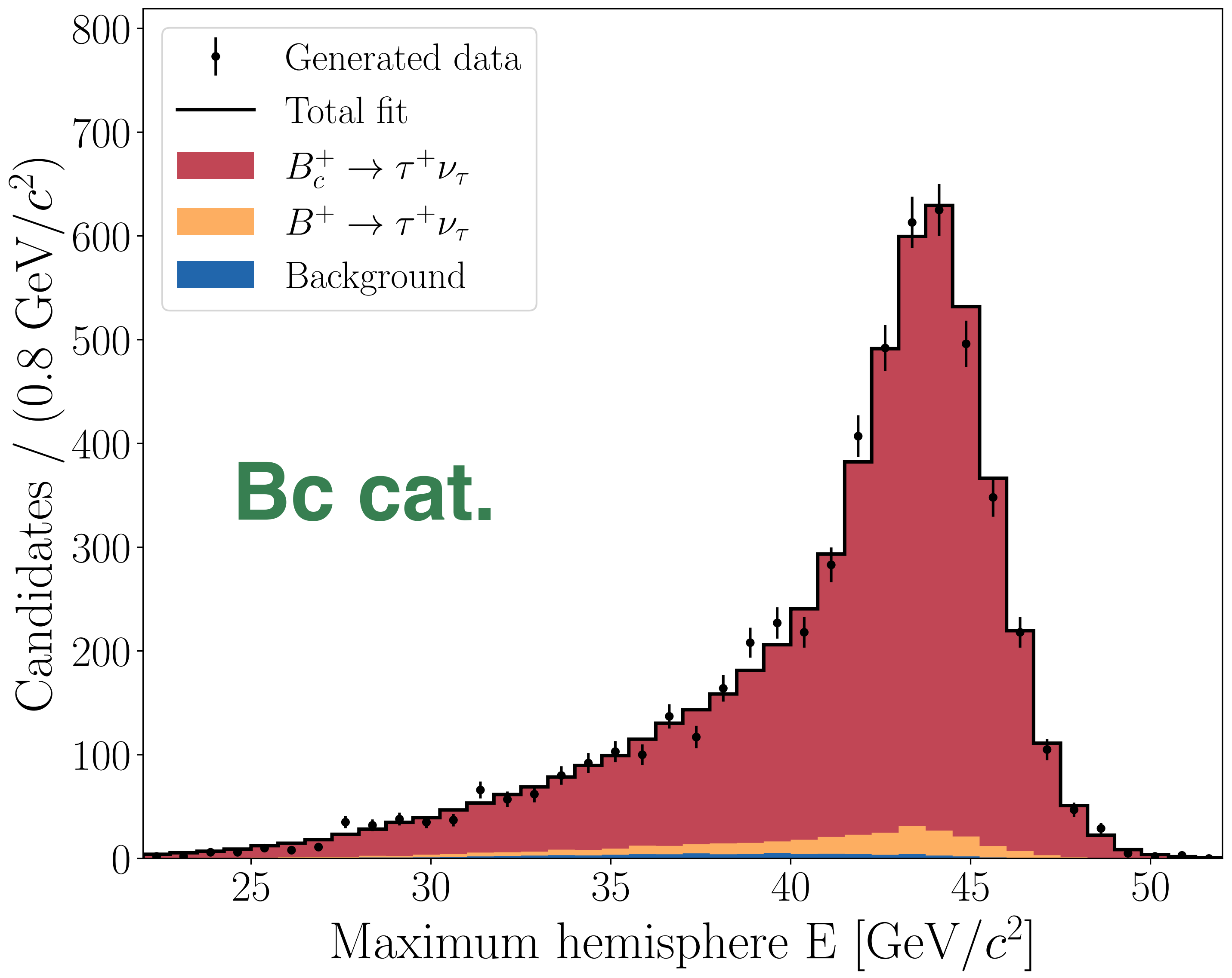
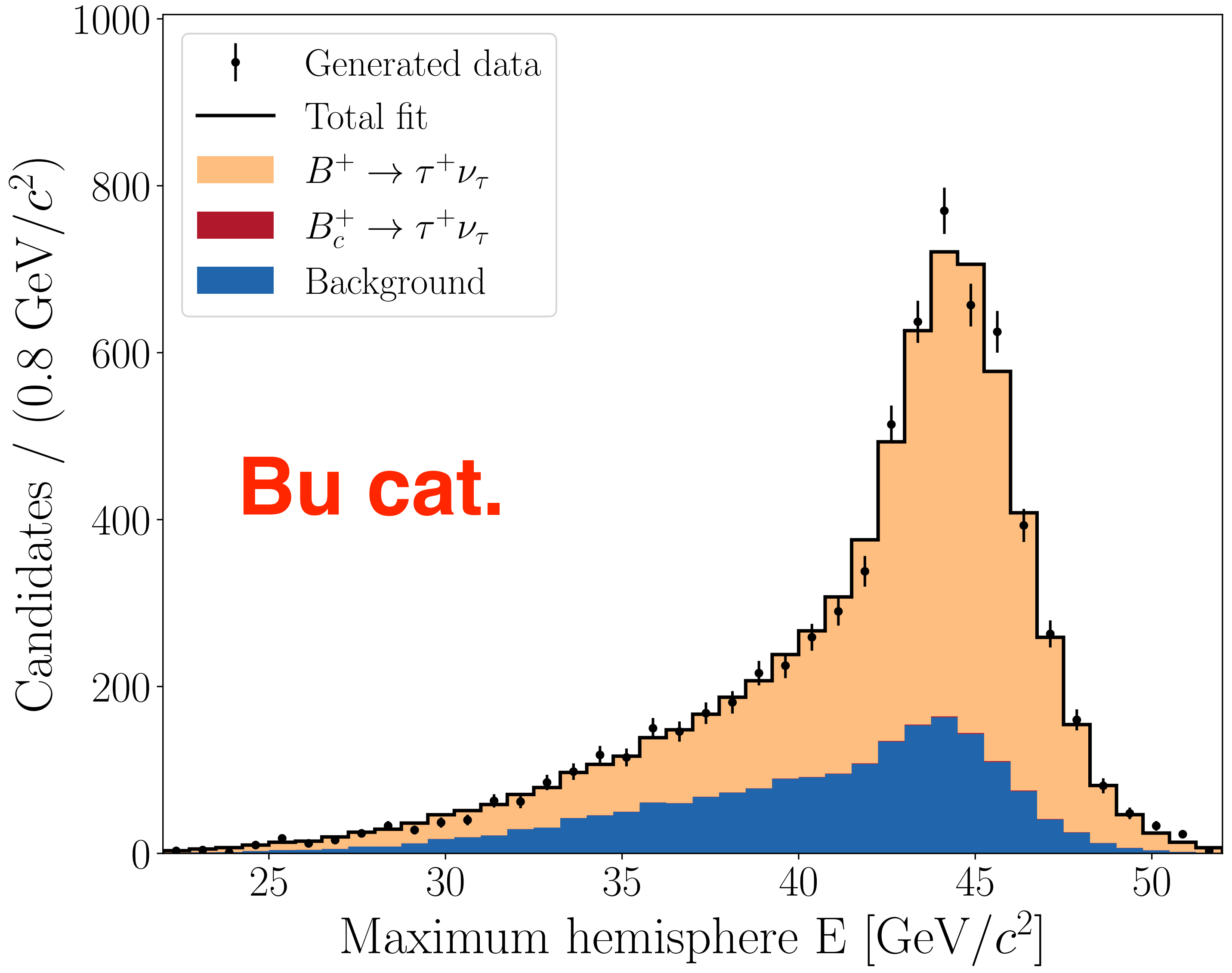
Template fit

- 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%





Summary

- Good results expected for $B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$
  - Signal yield precision ~2% for $B_c^+ \to \tau^+\nu_\tau$ and ~4% for $B^+ \to \tau^+\nu_\tau$
  - Interpreted as constraints on 2HDM and leptoquark models, more work to be done on the measurement of $|V_{ub}|$ (maybe even $|V_{cb}|$)

- Next steps:
  - Further improvements: extra variables for MVA training, 2D distribution for final fit, and more exclusive samples for background modeling.
  - Theory interpretation of new results: in collaboration with the theory group at KIT.
  - Plan for publication: preprint in October

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Backup

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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

Database of all samples

(EDM4hep)

analysis_stage1

Batch with HTcondor

build vertices, select τ candidates

(EDM4hep + custom branches)

analysis_stage2

Batch or local

calculate variables and trim events

(custom branches)

analysis_final

Local processing

Selected and merged events

(custom branches)

MVA stage 1 training and inference

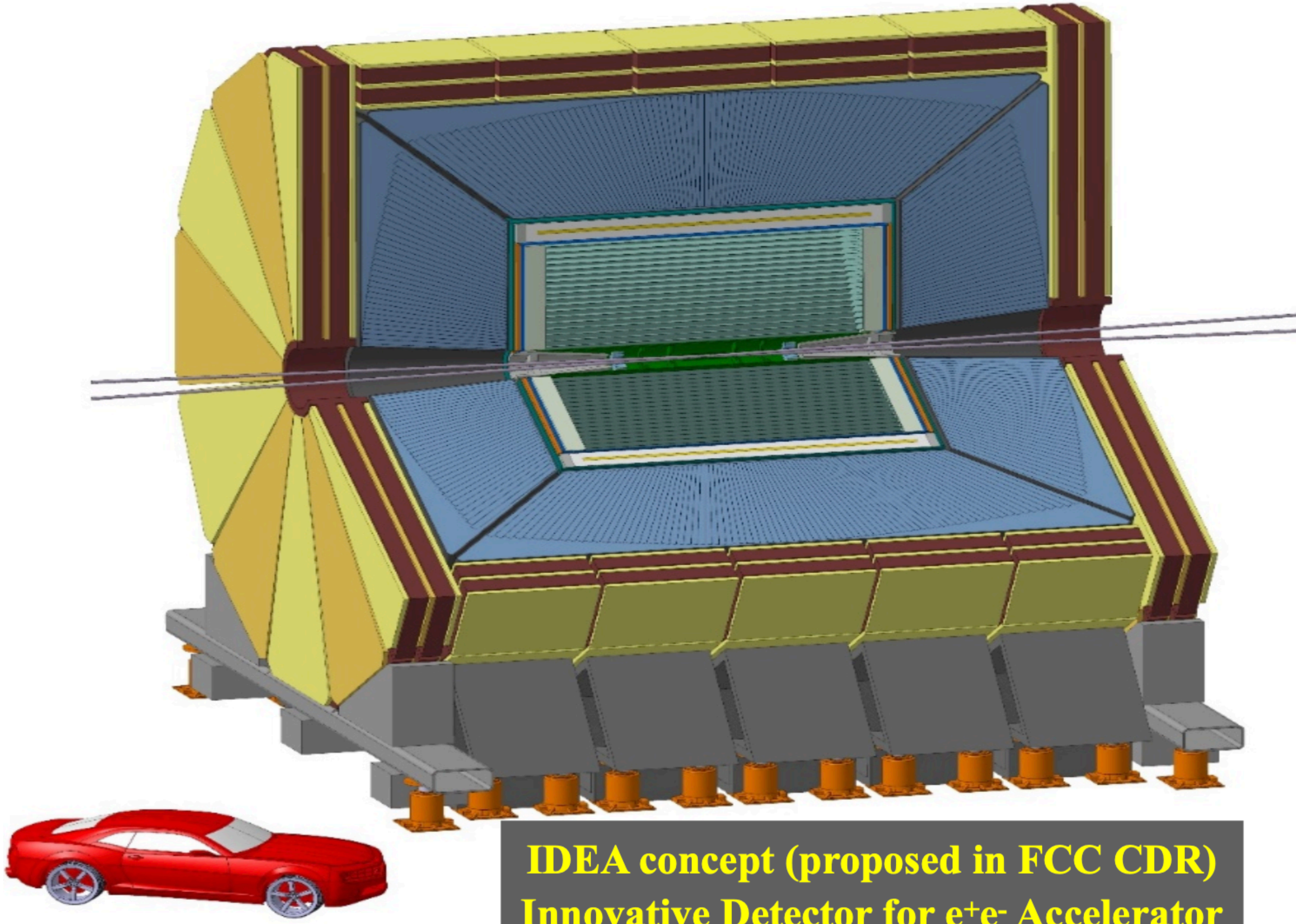
MVA stage 2 training and inference

Final fits and plots

Complete workflow can be run in 1-2 days

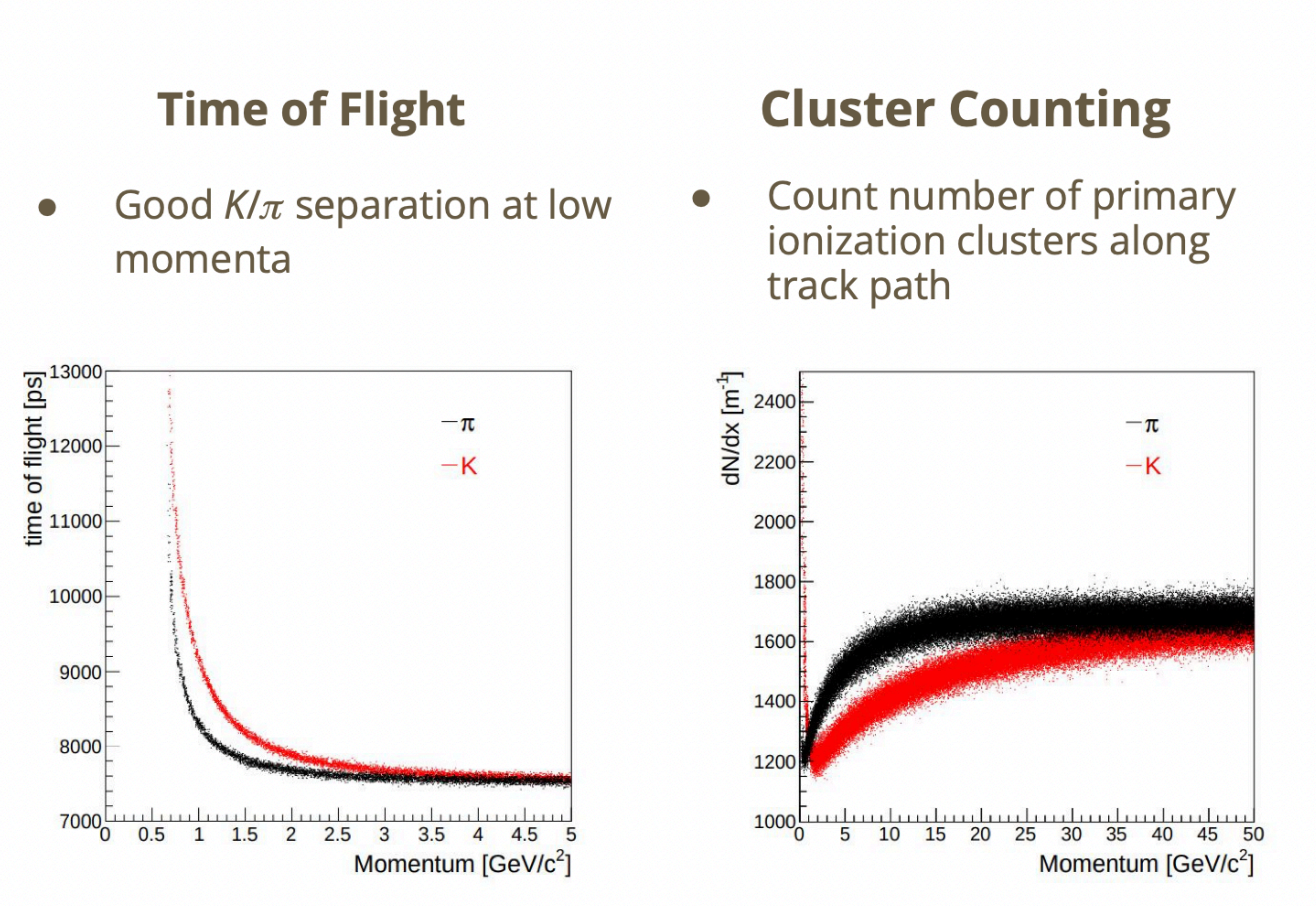
Detector concept

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



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

Kaon vs Pion ID

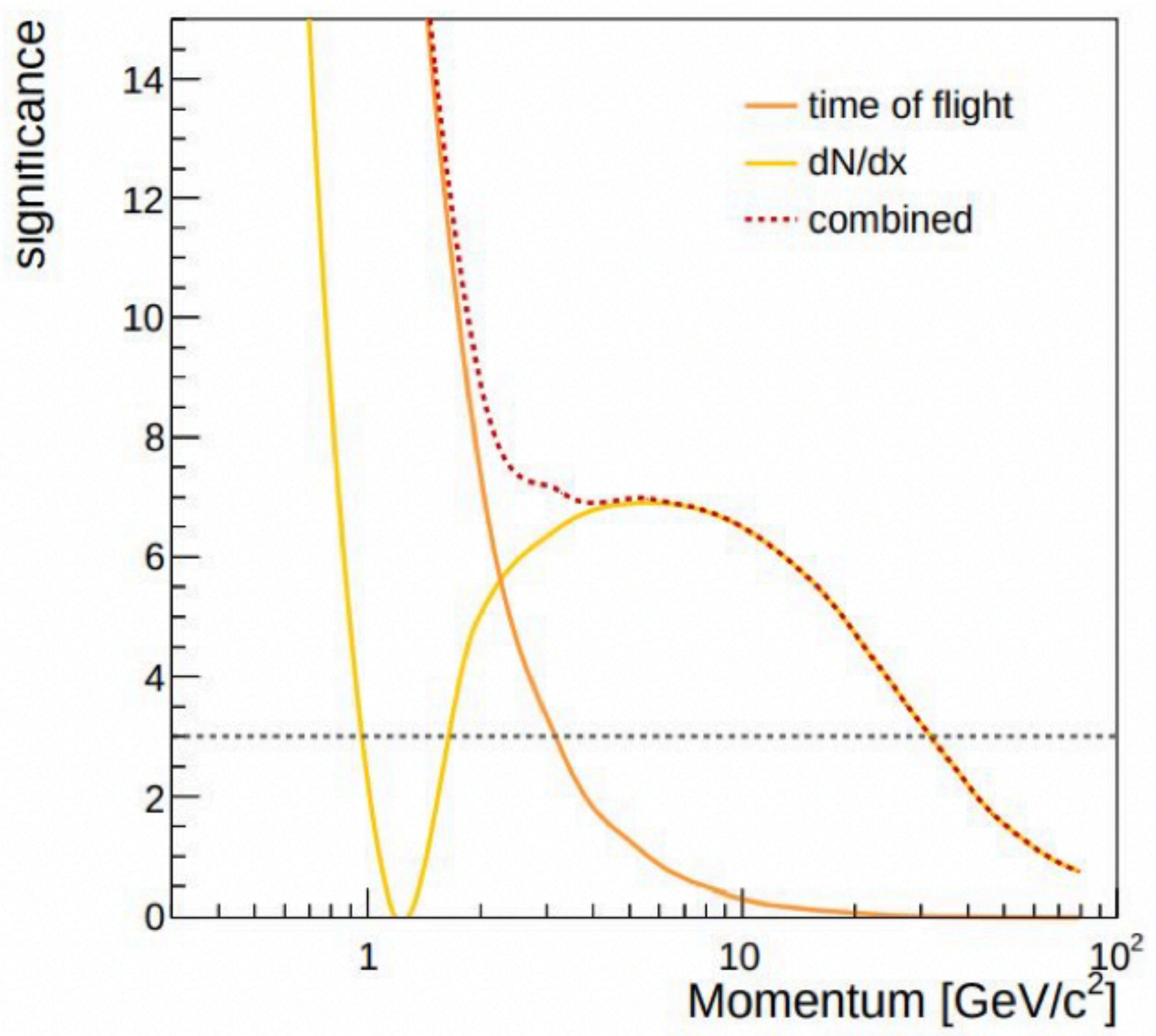


Time of Flight

- 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 < 30GeV**

Assume perfect ID in the kinematic region (p < 30 GeV) of study.

Theory predictions

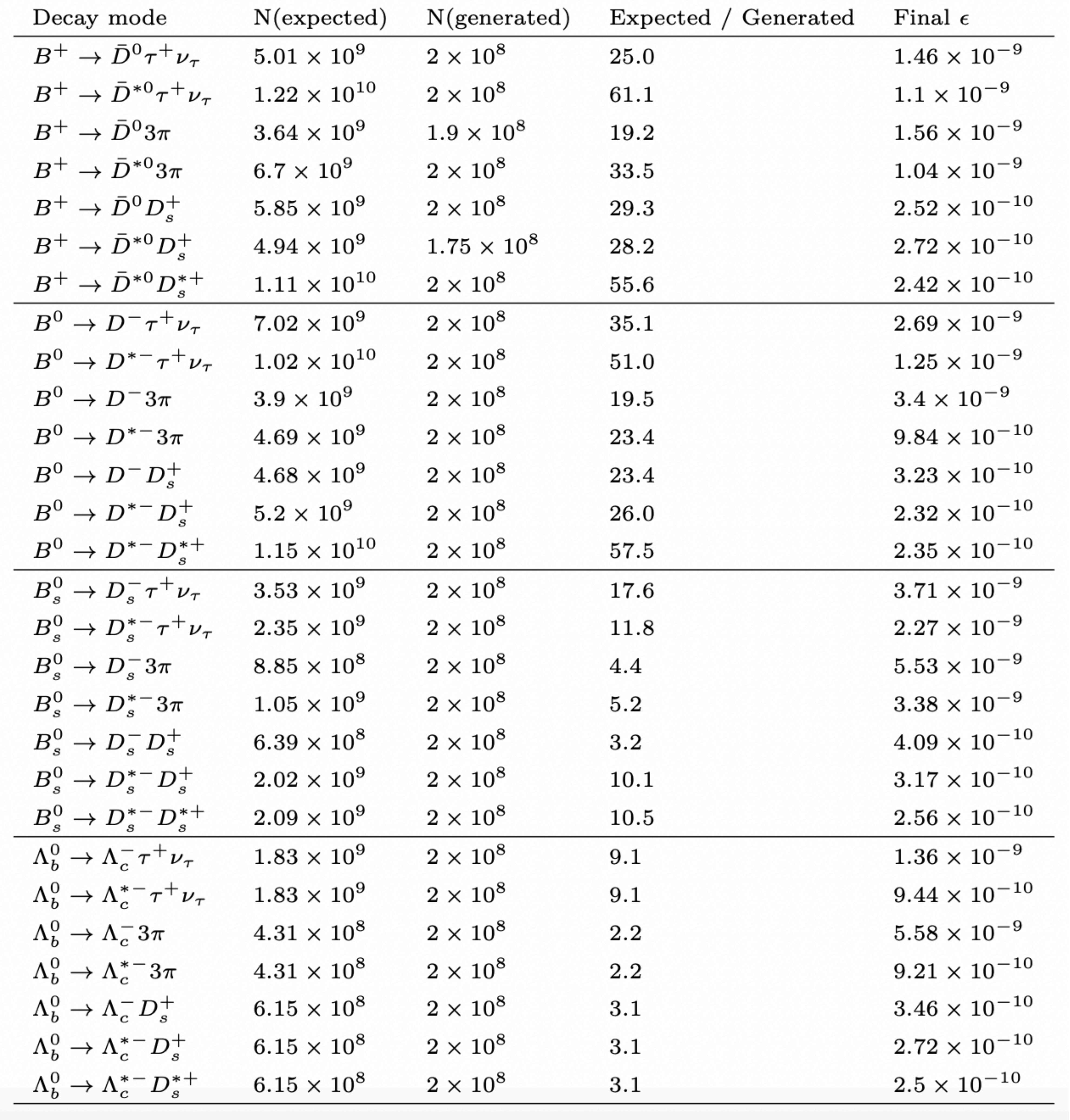
$$\mathcal{B}(B_c^+ \to \tau^+ \nu_\tau)^{\rm SM} = \tau_{B_c} \frac{G_F^2 |V_{cb}|^2 f_{B_c}^2 m_{B_c} m_\tau^2}{8\pi} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2$$

- $|V_{cb}| = 39.09(68) \times 10^{-3}$ from $B \to D^{(*)} l\nu$
- $f_{B_c} = 427(6)$ 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
$B^+ \to \bar{D}^0\tau^+\nu_\tau$	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}

Stage1 MVA

- Goal: remove “easy” backgrounds from $Z \to c\bar{c}, q\bar{q}$ processes
- Binary BDT classifier
  - signal: $B_c^+ \to \tau^+\nu_\tau$
  - background: inclusive $Z \to b\bar{b}, c\bar{c}, q\bar{q}$ 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

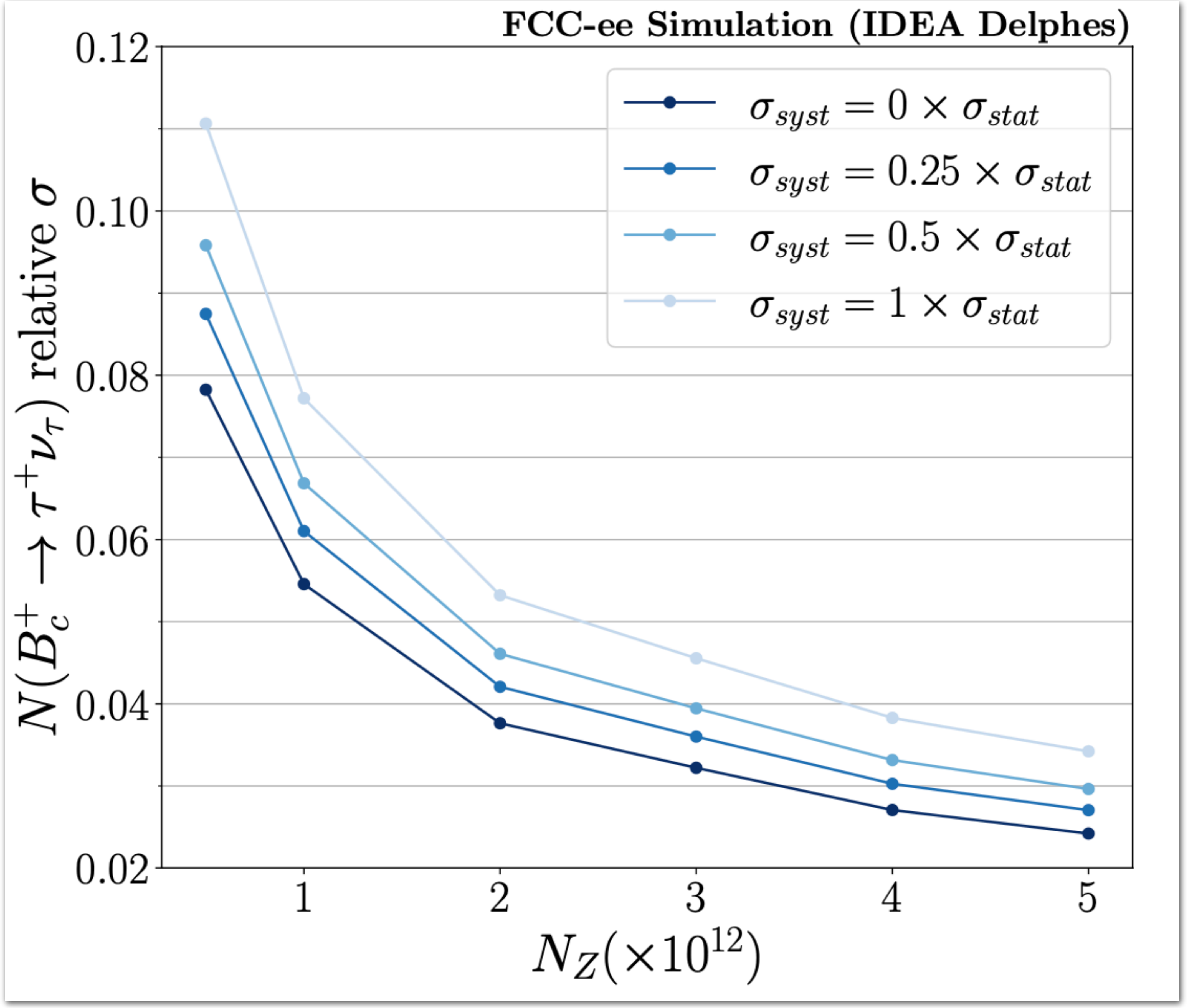
Stage2 MVA

- Goal: use full kinematic property of $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$ decay to maximize signal purity.
- Binary BDT classifier
  - signal: $B_c^+ \to \tau^+\nu_\tau$
  - background: inclusive $Z \to b\bar{b}, c\bar{c}, q\bar{q}$ 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:
  - $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$ 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

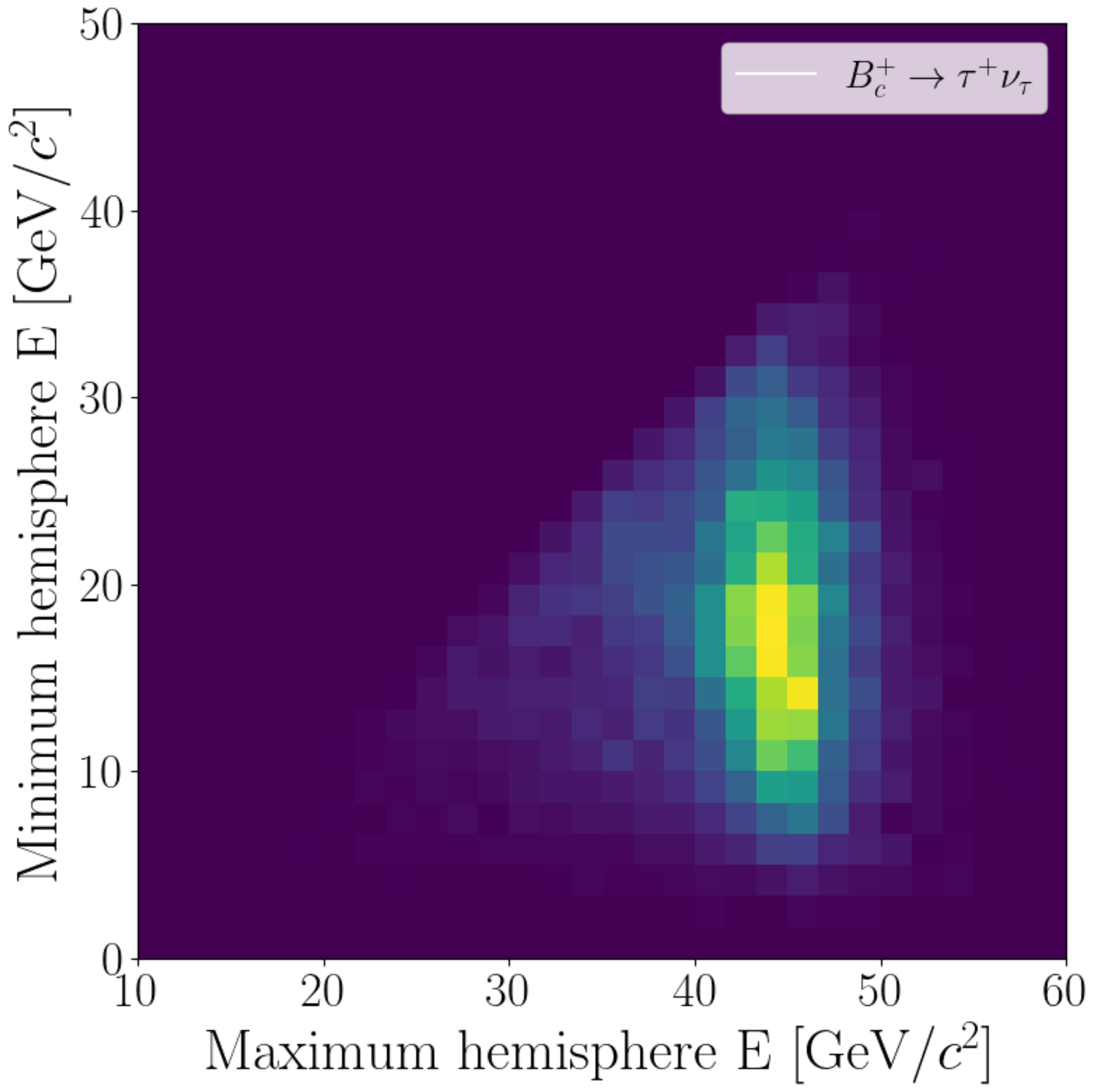
Systematic uncertainty

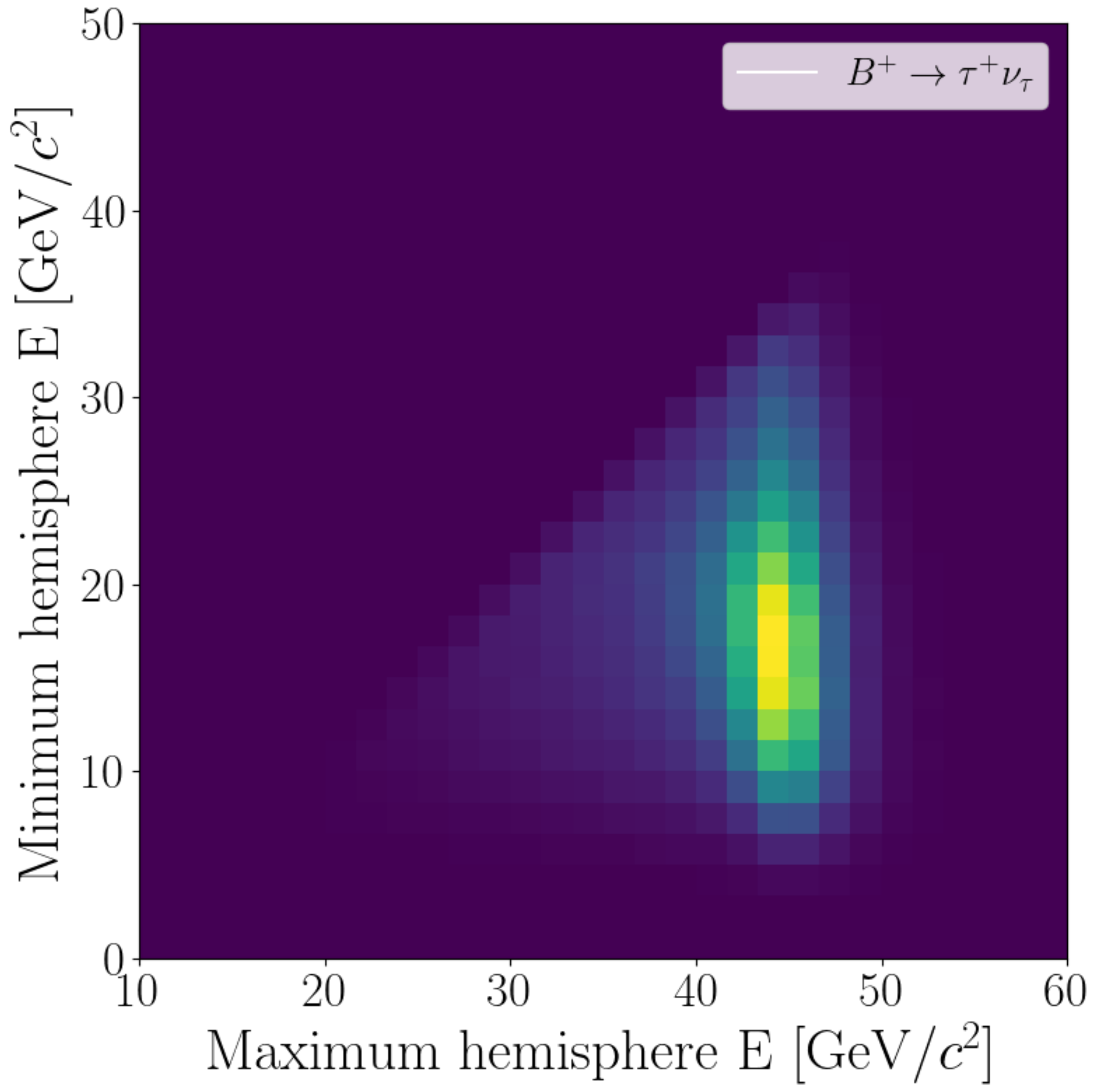
- By design, syst. uncert. at FCC-ee is expected to be constrained to the level comparable to stat. uncert. of EW precision measurements, and not a major concern for this result.
- Current analysis relies on strong assumptions in the background estimate method. Hard to estimate the uncertainty from these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

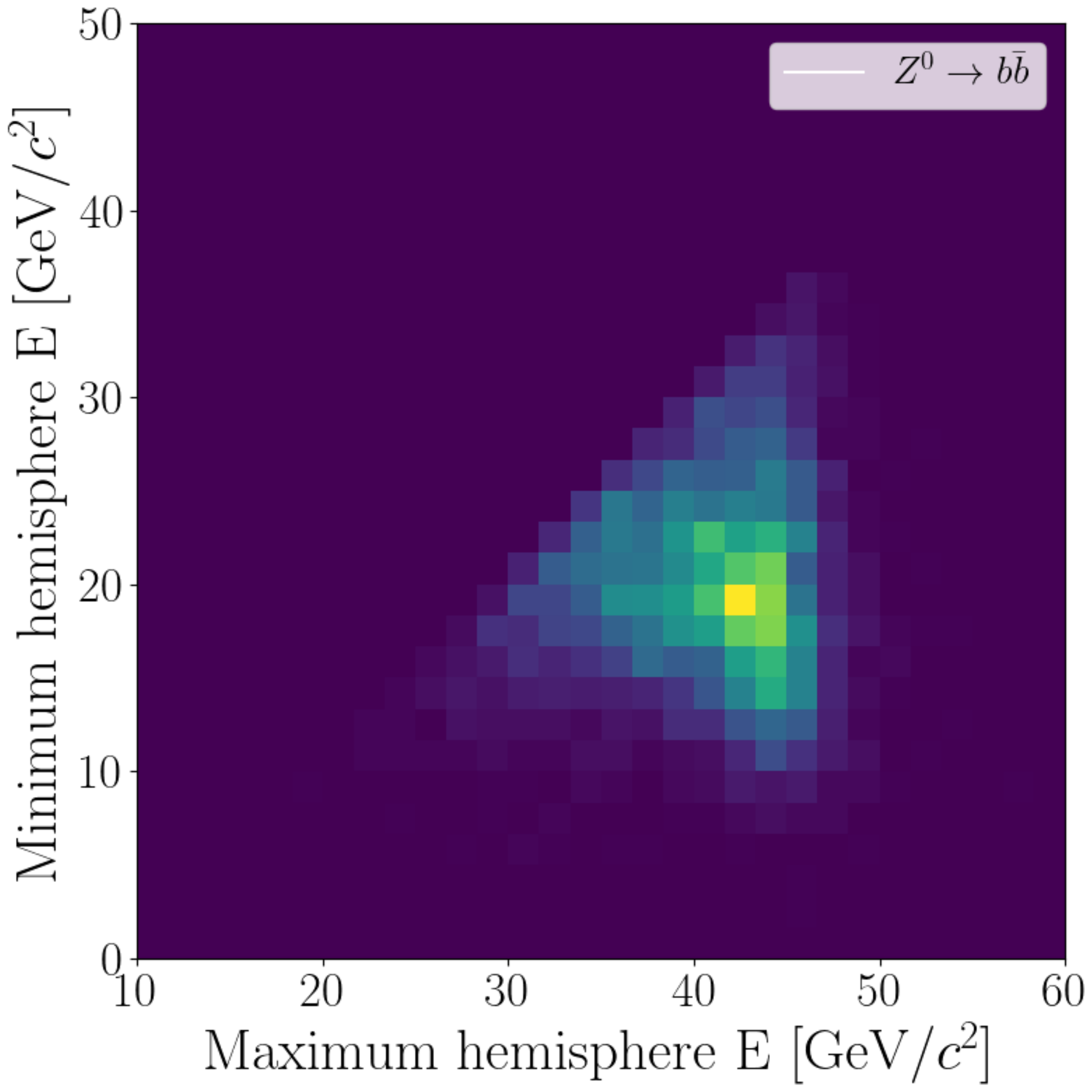


Variables for final fit

- No strong correlation between ThrustEmax_E and ThrustEmin_E







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

- By taking leptonic decay constant f_B as input, the $B_c^+ \to \tau^+\nu_\tau$ and $B^+ \to \tau^+\nu_\tau$ 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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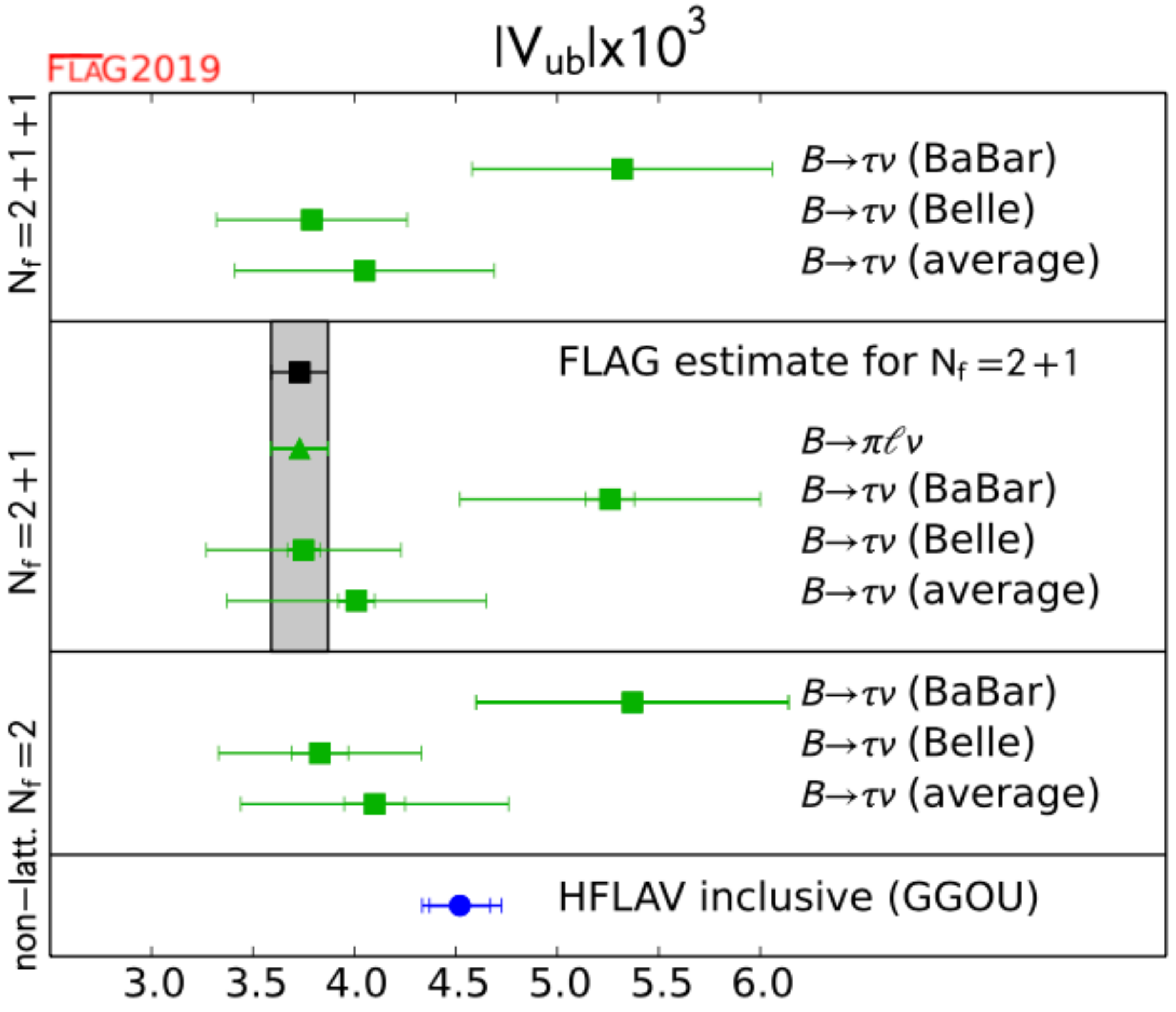
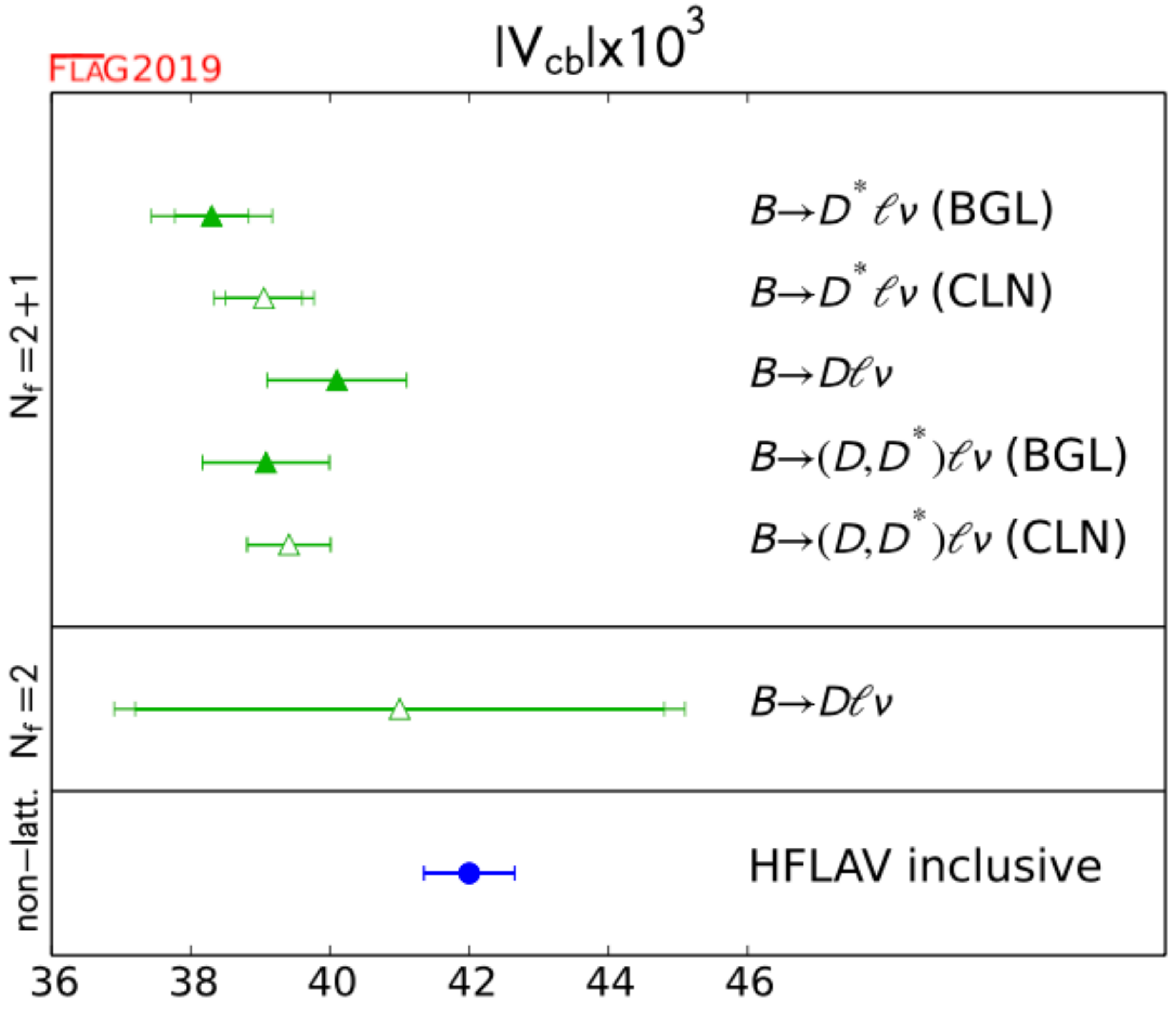


$\sigma \sim 4\%$



$\sigma \sim 2\%$