# First steps with flavour physics studies at FCC-ee

(using key4hep/EDM4hep, Delphes, EvtGen, FCCAnalyses, and awkward)

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**Donal Hill (EPFL)**

with thanks to Clement Helsens and the FCCSW team

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2nd FCC-France Workshop

# Flavour at FCC-ee

- Strong case for flavour physics at the $Z^0$-pole at FCC-ee

- Production of $3.8 \times 10^{11}$ $Z^0$'s anticipated per year per IP
  - $5.8 \times 10^{10}$ $b\bar{b}$
  - $4.6 \times 10^{10}$ $c\bar{c}$
  - $1.3 \times 10^{10}$ $\tau\tau$

- $Z^0$ production rate of ~ $100$ kHz and clean $e^+e^-$ environment put us in triggerless readout territory
  - No efficiency losses from online selection cuts

- We must identify the physics cases where FCC-ee can perform better than either LHCb Upgrade II or Belle II
  - Show a sample of mode studies today - more details here and in backup slides

# Goals: medium-term

Enable informed detector design studies with a focus on heavy flavour physics at FCC-ee

- What detector specifications are vital, and which are desirable?

# Goals: shorter-term

## Identify highest-priority heavy-flavour modes for FCC-ee

- How can FCC-ee extend physics reach beyond LHCb and Belle II?
- What modes are the most theoretically compelling?

# Goals: immediate

## Develop software tools in FCCSW to facilitate studies

- EvtGen for exclusive decay mode simulation (this talk)
- MC truth-matching (this talk)
- Particle combinations to reconstruct modes of interest (this talk)
- Reconstruction and analysis tools (flavour tagging, decay chain building with vertex fitting, isolation, full event interpretation...)

# Software and samples used

- Use key4hep/EDM4hep to simulate $e^+e^- \to Z^0 \to f\bar{f}$ processes
  - **Pythia** for generation and hadronisation
  - **EvtGen** to decay hadrons, including option to force a user-specified decay (exclusive)
  - **Delphes** for IDEA detector performance parameterisation
  - Details of samples used here
- Additional processing of EDM4hep output in **FCCAnalyses**, providing user-friendly ROOT files with MC-association info
- User-level analysis with **uproot** and **awkward array**
  - Examples and some common functions here
  - Particle combinations at 4-vector level - **full decay chain reconstruction with vertexing not yet fully implemented**

# Species yields at FCC-ee (per IP per year)

- Use these yields in combination with decay branching fractions ($\mathcal{B}$) to estimate yields for exclusive modes
- Production fractions from $e^+e^- \to Z^0 \to f\bar{f}$ Pythia
- No efficiency factors from reconstruction or selection included

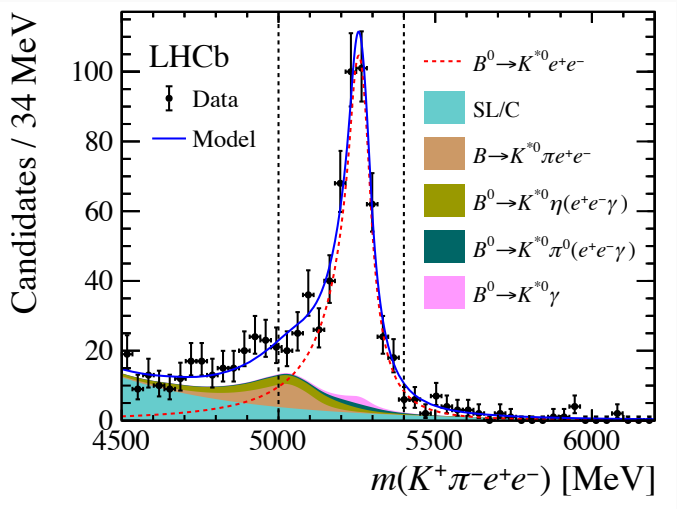
| $Z^0$ mode | Species | Production fraction | Yield |
|---|---|---|---|
| $b\bar{b}$ | $B^{\pm}$ | 0.43 | $4.9 \times 10^{10}$ |
| $b\bar{b}$ | $B^0$ | 0.43 | $4.9 \times 10^{10}$ |
| $b\bar{b}$ | $B_s^0$ | 0.098 | $1.1 \times 10^{10}$ |
| $b\bar{b}$ | $B_c^{\pm}$ | $4 \times 10^{-4}$ | $4.5 \times 10^{7}$ |
| $\tau\tau$ | $\tau$ | 1 | $2.5 \times 10^{10}$ |
| $c\bar{c}$ | $D^{\pm}$ | 0.43 | $3.9 \times 10^{10}$ |

# LHCb & Belle II estimates

- Existing Run 1 (3 $\text{fb}^{-1}$) or Run 1 + 2 (9 $\text{fb}^{-1}$) analysis yields used as baseline figures
  - If 3 $\text{fb}^{-1}$, extrapolate to 9 $\text{fb}^{-1}$ with lumi scaling plus an additional factor 2 for higher $\sqrt{s}$ and better trigger efficiency
- Scale 9 $\text{fb}^{-1}$ yields to 300 $\text{fb}^{-1}$ (full LHCb Upgrade II) with relative lumi factor
- Efficiency effects are included since real analysis yields used
- Belle II expectations from Belle II physics book [arXiv:1808.10567]

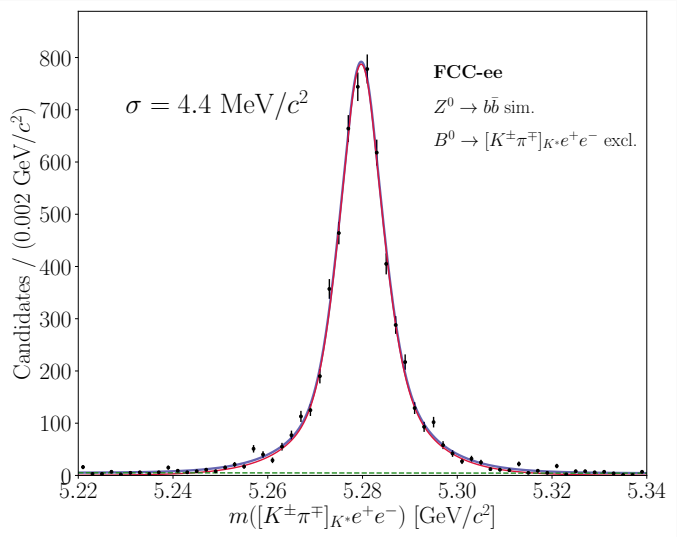
# $B^0 \to (K^{*0} \to K\pi)e^+e^-$

- Rare decay involving $b \to s$ transition ($\mathcal{B} = 3.4 \times 10^{-7}$)
  - Sensitive to NP in loop-level processes
- Significant work already from LHCb on $K^{(*)}\ell^+\ell^-$ modes:
  - Lepton universality tests via $R(K^{(*)})$
  - Differential branching fractions
  - Angular analyses
- Measurements of electron mode are challenging at LHCb due to limited Bremsstrahlung recovery (tail in $B$ invariant mass)
  - 450 events in 9 fb$^{-1}$ LHCb analysis [arXiv:2010.06011]



# $B^0 \to (K^{*0} \to K\pi)e^+e^-$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(4.9 \times 10^{10}) \times (3.4 \times 10^{-7})$ = **17,000 events**
  - LHCb 300 fb$^{-1}$: 120,000 across full $q^2$ range
    - 9 fb$^{-1}$ analysis uses $0.0008 < q^2 < 0.257$ GeV$^2$ (14% of signal)
- Exclusive EvtGen sample, with IDEA Delphes and $p > 1$ GeV cuts on all tracks
  - No truth-matching applied here
  - $B^0$ peak resolution excellent
  - No brem modelled in Delphes




LHCb $\sigma = 75$ MeV/$c^2$

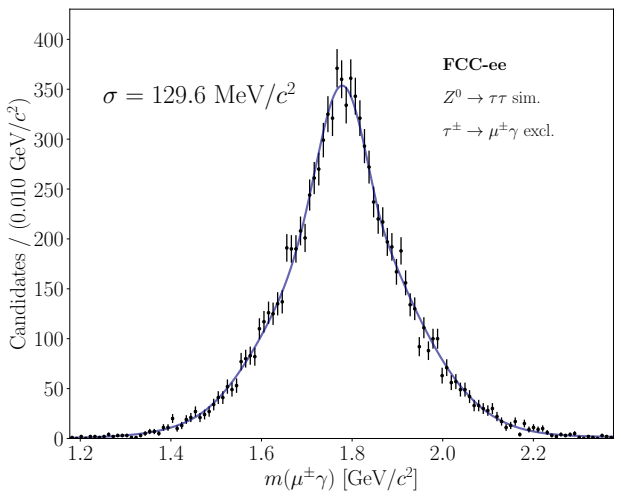
Belle $\sigma = 5$ MeV/$c^2$
[arXiv: 1904.02440]

# $\tau^+ \to \mu^+\gamma$

- Lepton flavour violating decay with unobservable rate in SM
- NP scenarios predict it to have the highest $\mathcal{B}$ of all LFV modes [arXiv:0908.2381]
- Current best limits $\mathcal{B} < 4.4 \times 10^{-8}$ from $B$-factories
- Challenging due to lack of $\tau$ vertex and presence of photon

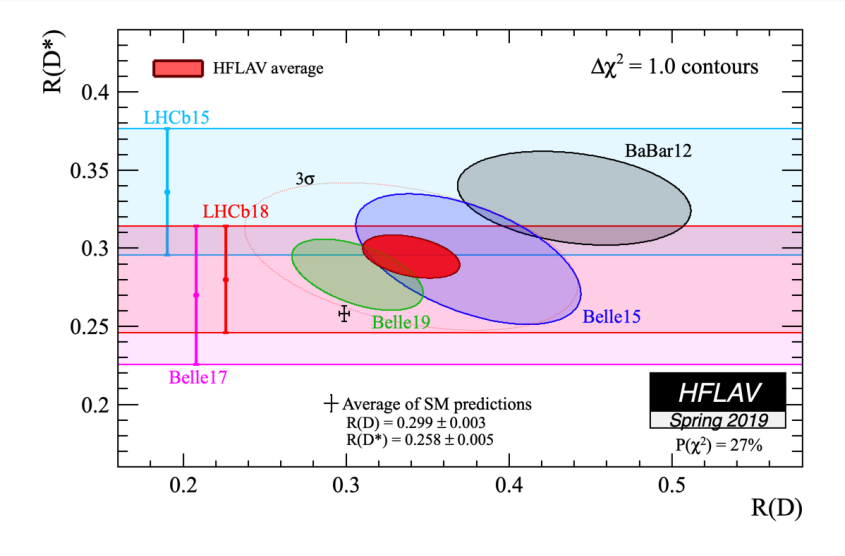
# $\tau^+ \to \mu^+\gamma$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(2.5 \times 10^{10}) \times (1 \times 10^{-9})$ = 25 events
  - With 4 IPs, observation still possible at $\mathcal{B} = 6 \times 10^{-11}$
  - Belle II 50 ab$^{-1}$ projected upper limit is $10^{-9}$ [arXiv:1808.10567]
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $\tau$ peak resolution poor due to $\gamma$ (3-vector assumed to point to PV)
  - **Tight offline selection likely required due to random photon combinatorics and lack of decay vertex - will impact upper limit**



# $B^0 \to D^{*-}(\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau)\nu_\tau$

- SM lepton universality asserts that decays to different lepton types are equally probable (aside from phase space factors)
- Branching fraction ratios of $\tau$ vs. $\ell$ in tension with SM at $3\sigma$ level
  - Could be caused by additional mediators such as charged Higgs
- Rich angular structure in $b \to c\ell\nu$ decays, with terms that are sensitive to different NP couplings (scalar, vector, tensor) [arXiv:1908.04643]

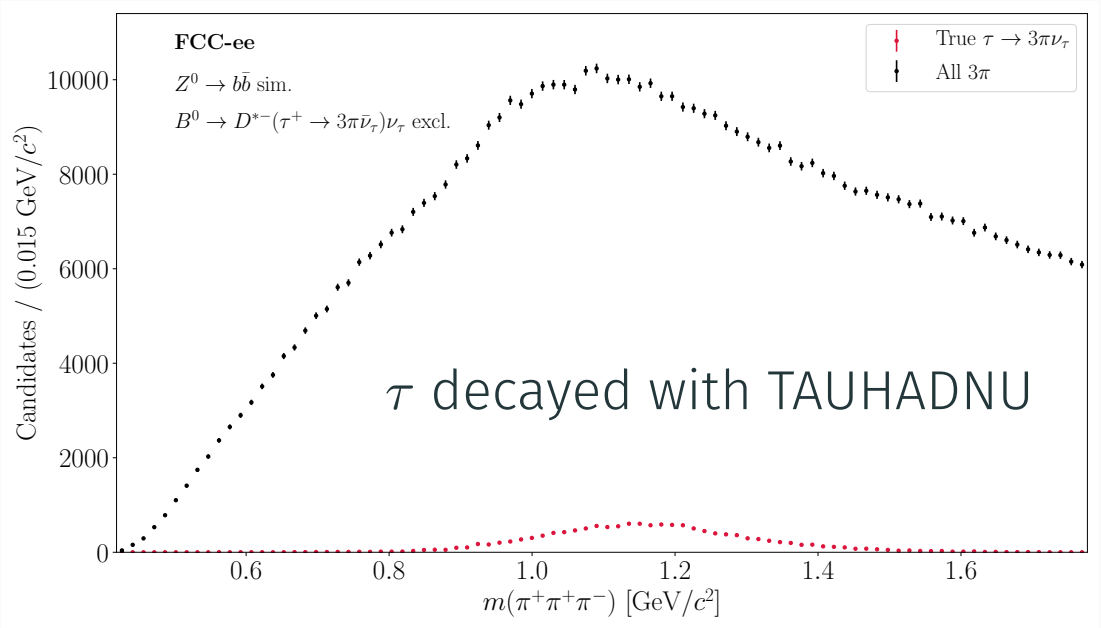


# Decay reconstruction using $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$

- Advantageous to reconstruct $\tau \to 3\pi\nu$ mode, as three pions provide $\tau$ decay vertex [arXiv:1711.02505]
- Coupled with $B$ decay vertex from $D^*$ decay, have a measurement of $\tau$ flight
  - Can be used to estimate momentum components
- Non-signal $b$-jet at FCC-ee provides $B$ direction info
- Random track combinations and backgrounds from decays involving two charm hadrons are main challenges
  - To isolate signal distributions in FCC-ee sim, use **truth matching of three pions**
  - Require that the parent PDG ID for all three pions is $\tau$ $(\pm 15)$

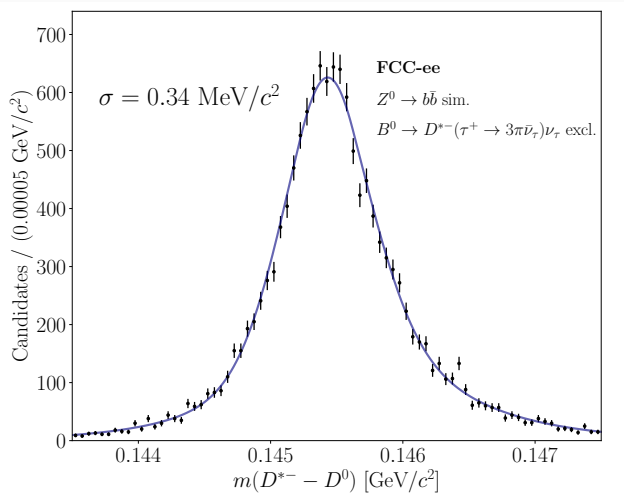
# Truth-matching in action for $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu}_\tau$

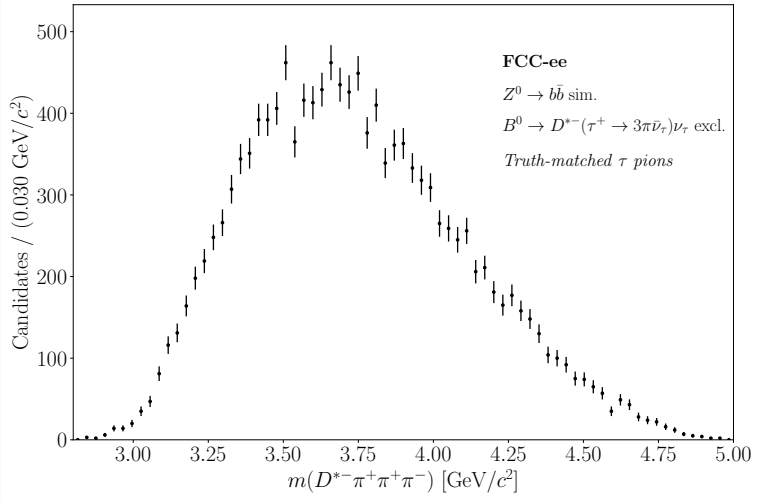
- Process exclusive $B^0 \to D^{*-}\tau^+\nu_\tau$ sample, with only a $p > 1$ GeV cut on considered tracks
  - Large background present from random combinations even in exclusive signal sample
- Much of this will be from pions produced at the PV and on the other side of the event
  - Flight, impact parameter, and direction requirements to be studied
  - **Use the truth-matched $3\pi$ + $D^*$ to create $B^0$ candidates**



# $D^*$ and $B^0$ ($D^*$ + $\tau$) candidates

- Multiple missing neutrinos, so $\tau$ and $B^0$ are not fully reconstructed
- Mass distributions all have the expected form however, and $\Delta M = m(D^* - D^0)$ has excellent resolution
  - Truth-matching of TAUOLA $\tau$ decays to be studied
- Expect **2 million** events per experiment per year
  - 600,000 in 300 fb$^{-1}$ LHCb after selection [arXiv:1908.04643]
  - A 2% efficient offline selection could match full LHCb statistics



# Event-level information

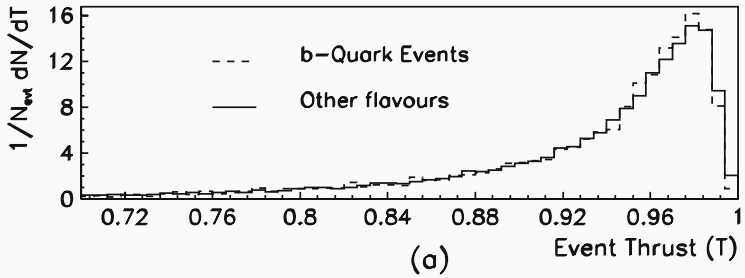
# Thrust

$$T = \frac{\Sigma_i |\vec{p}_i \cdot \hat{n}|}{\Sigma_i |\vec{p}_i|}$$

- Thrust axis of an event given by direction of unit vector $\hat{n}$
- The direction of $\hat{n}$ is chosen to maximise the thrust $T$
- A two-jet event will have $T = 1$ (perfectly back-to-back) while a spherically symmetric event has $T = 0.5$
- Useful method to determine event **hemispheres**
  - Use angle of particles relative to the thrust axis
  - Allows calculation of energy in each hemisphere, which is important for missing momentum studies

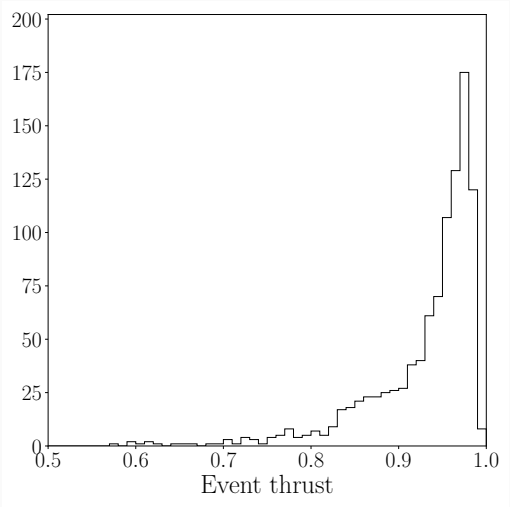
# Thrust in inclusive $Z^0 \to b\bar{b}$ events

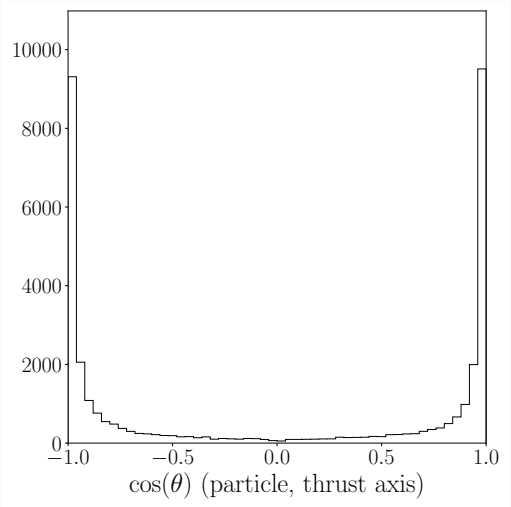
- Thrust values are peaked close to 1 in $Z^0 \to b\bar{b}$ - similar shape to LEP data




LEP OPAL data

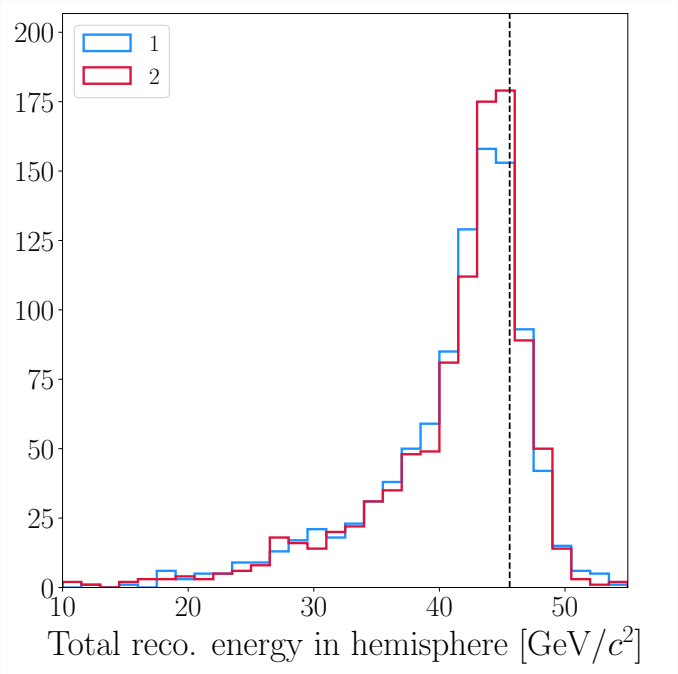
- Angle of particles with respect to the thrust axis provides clear separation into hemispheres ($> 0$ and $< 0$)

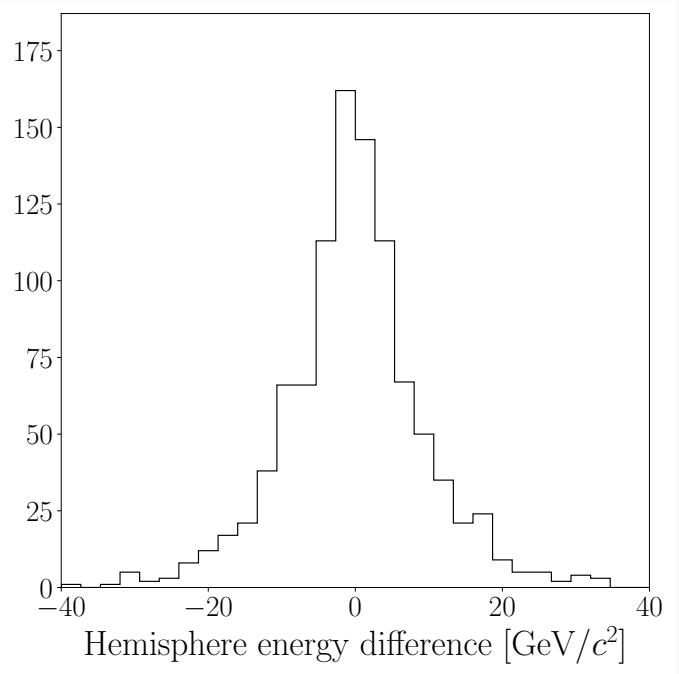


# Hemisphere energies in $Z^0 \to b\bar{b}$ events

- Each hemisphere sums to $\sim m(Z^0)/2$, with resolution visible plus tails due to missing energy (neutrinos)
- Energy difference between hemispheres can be used for missing momentum modes
  - The signal side should have less energy
- See Yasmine's talk on $B_c^+ \to \tau^+ \nu_\tau$ for an example use case



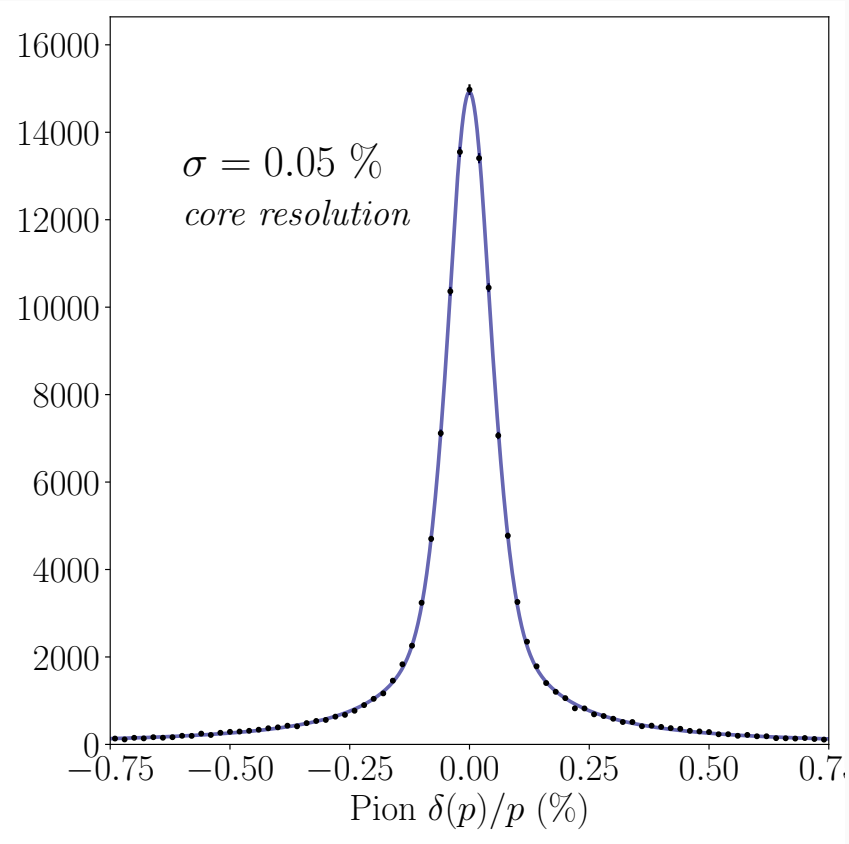
# Summary

- First steps taken in flavour physics studies at FCC-ee
  - Early adoption of key4hep/EDM4hep
  - FCCAnalyses providing user-level ROOT files
  - uproot and awkward array for particle combinations
- Exclusive samples generated and analysed for a set of interesting heavy flavour modes
  - Yield expectations compare favourably to LHCb UII and Belle II
  - **We must ask: where can FCC-ee really shine?**
- Move towards detector design studies which are informed by physics performance on key decay modes

# Backup

# Track momentum resolution in Delphes

- Pions from $B^0 \to D^{*-}\tau^+\nu_\tau$ exclusive sample
- Core resolution is excellent
- Resolution includes component from track covariance module



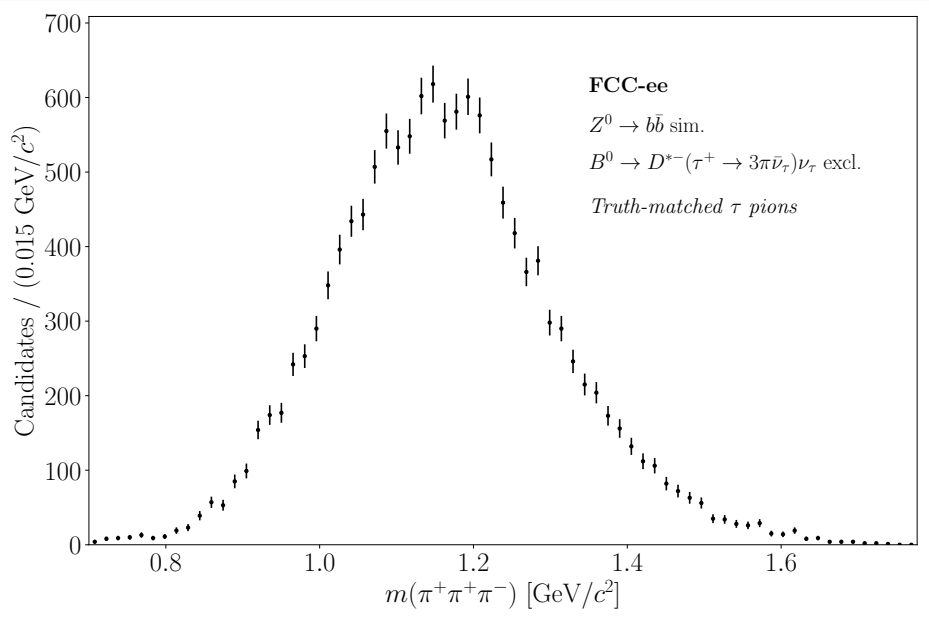
# $B$-hadron production fractions

- Values measured in inclusive $Z^0 \to b\bar{b}$ sample produced with Pythia in FCCSW
- Use these values in yield estimations where applicable

| $B$-hadron | Production fraction (%) |
|---|---|
| $B^0$ | 43.0 |
| $B^{\pm}$ | 43.0 |
| $B_s^0$ | 9.6 |
| $B_c^{\pm}$ | 0.04 |
| $\Lambda_b^0$ | 3.7 |

# Truth-matched $m(3\pi)$ distribution in $B^0 \to D^{*-}\tau^+\nu_\tau$

- Same distribution as shown in red in main slides
- Consistent with $a_1(1260)^+ \to 3\pi$ production in TAUHADNU
- TAUOLA generation also working, but MC-truth needs to be understood for matching
- Will make use of this matching for various tauonic decay modes

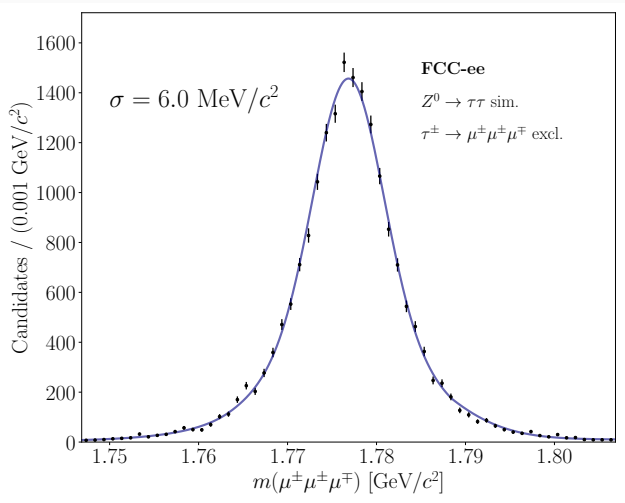


# $\tau^+ \to \mu^+\mu^+\mu^-$

- Lepton flavour violating (LFV) decay - violation of lepton universality (see $B$ anomalies) would also imply LFV
- Unambiguous sign of NP, with a clear signal peak at $m(\tau)$
- Current best limit $\mathcal{B} < 2.1 \times 10^{-8}$ from Belle
  - NP can enhance decay to $10^{-10} < \mathcal{B} < 10^{-8}$ level
- Other similar modes e.g. $\tau^+ \to \mu^+e^+e^-$, $\tau^+ \to \mu^+e^-$ can also be considered

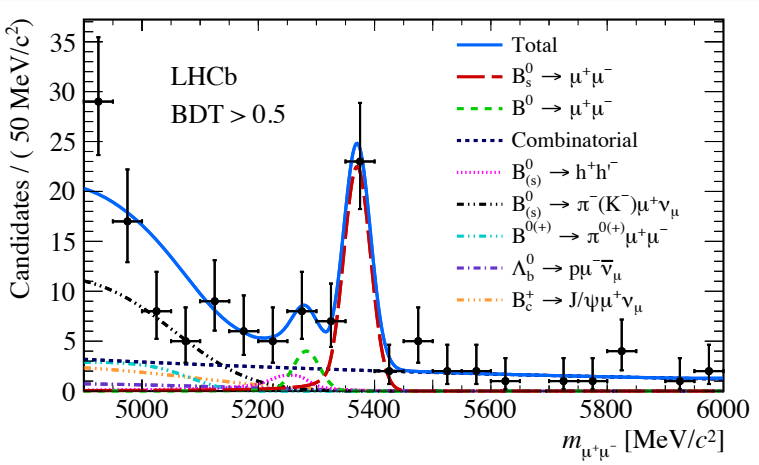
# $\tau^+ \to \mu^+\mu^+\mu^-$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - 3 events assuming $\mathcal{B} = 10^{-10}$ and $Z^0 \to \tau\tau$ production
  - With good background suppression at 50% signal efficiency, observation possible (across experiments) at $\mathcal{B} \sim 10^{-10}$
  - Belle II 50 ab$^{-1}$ projected upper limit is $3.3 \times 10^{-10}$ [arXiv:1808.10567]
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $\tau$ peak resolution very good
  - $\tau$ flight and excellent vertexing would help fight background



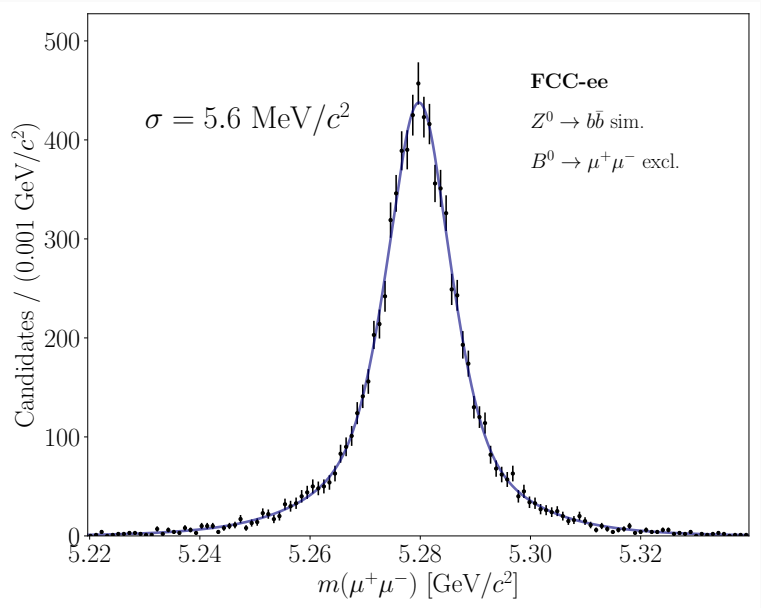
# $B^0 \to \mu^+\mu^-$

- Very rare decay ($\mathcal{B} = 1.07 \times 10^{-10}$ in SM) which is sensitive to NP contributions
- Not observed yet, but $\mathcal{B}$ measurements by LHC experiments
- PDG combination $\mathcal{B} = (1.1 \pm 1.4) \times 10^{-10}$
  - In agreement with SM, but theory error is $0.1 \times 10^{-10}$ [arXiv:1208.0934]
- Well-motivated to push for observation and $< 10\%$ $\mathcal{B}$ precision



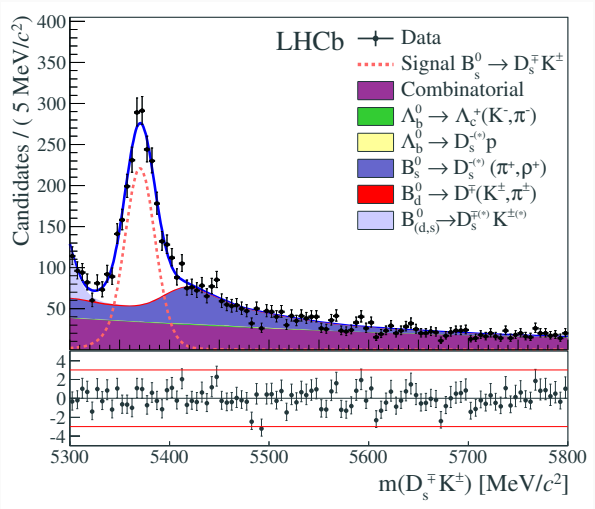
# $B^0 \to \mu^+\mu^-$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(4.9 \times 10^{10}) \times (1.07 \times 10^{-10})$ = 5 events
  - Anticipate ~ 80 events with 4 IPs
  - 300 fb$^{-1}$ LHCb: ~ 700 events based on 7 observed in 4.4 fb$^{-1}$
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $B^0$ peak resolution excellent



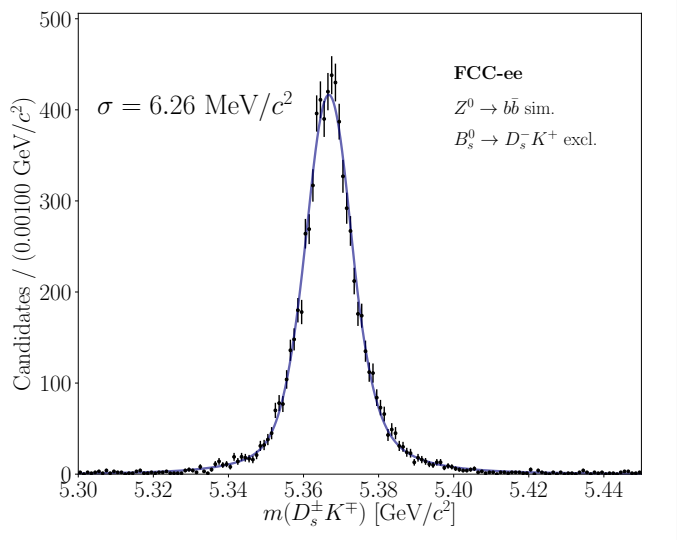
# $B_s^0 \to (D_s^- \to K^+K^-\pi^-)K^+$ (also see here from Roy)

- Time-dependent $CP$ violation due to interference between mixing and decay amplitudes
- Measures $\gamma - 2\beta_s$ at tree-level, which can be compared to $\phi_s = -2\beta_s$ measured in charmonium ($B^0 \to J/\psi K_s^0$ e.t.c.)
  - Comparison sensitive to NP, as measured $\phi_s$ may not be $\phi_s^{SM}$
- An interesting mode for FCC-ee because:
  - Belle-II does not resolve $B_s^0$ time-dependence
  - LHCb flavour-tagging efficiency is poor



# $B_s^0 \to D_s^- K^+$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(1.1 \times 10^{10}) \times (1.2 \times 10^{-5})$ = 135,000 events
  - Anticipate ~ 2 million events with 4 IPs
  - 300 fb$^{-1}$ LHCb: $340,000$ events based on 1770 observed in 3 fb$^{-1}$
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $B_s^0$ peak resolution excellent
  - Would PID selections be needed to separate from $B_s^0 \to D_s^- \pi^+$?



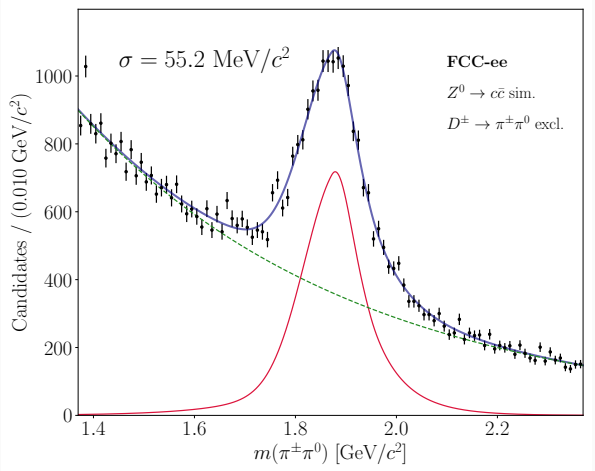

LHCb $\sigma$ = 17 MeV/$c^2$

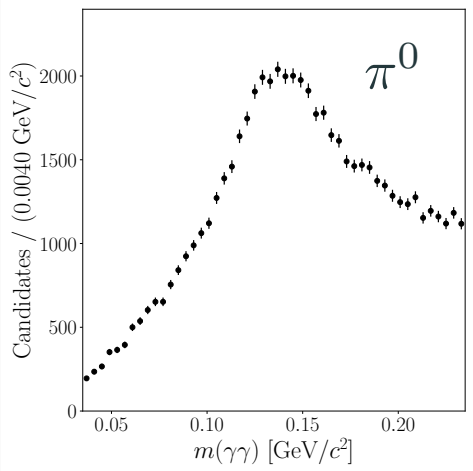
# $D^+ \to \pi^+\pi^0$

- In SM, decay is dominated by two singly Cabibbo-suppressed tree-level diagrams
- Other diagrams?
  - Gluonic penguin forbidden from isospin conservation
  - Electroweak penguin suppressed by $\alpha$, $\sim 10^{-6}$ contribution
- No $CP$ asymmetry expected in SM as a result, as no comparably sized amplitudes can interfere
  - Measurement of $CP$ asymmetry is thus a clear signal of NP
- Efforts at LHCb ongoing, but made difficult by lack of decay vertex and limited $\pi^0$ reconstruction efficiency

# $D^+ \to \pi^+\pi^0$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(3.9 \times 10^{10}) \times (1.2 \times 10^{-3})$ = **48 million** events
  - $\sim 5 \times 10^{-5}$ precision on $A_{CP}$, if systematics can be controlled
  - $2 \times 10^{-3}$ precision predicted at Belle II [arXiv:1808.10567]
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $D^+$ and $\pi^0$ peaks limited in resolution due to photons
  - Background in $\pi^0$ distribution from random photon combinatorics, leading to background in $D^+$



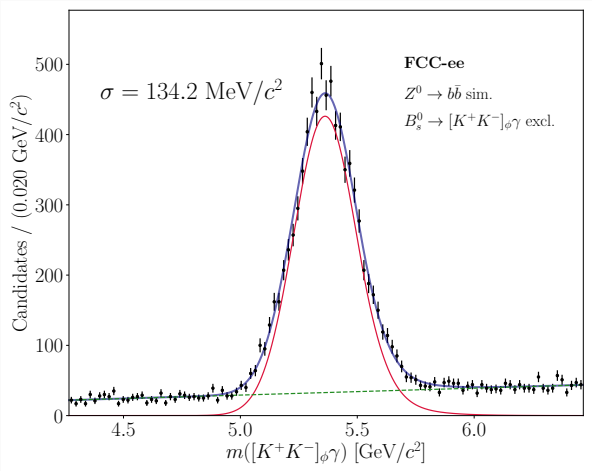



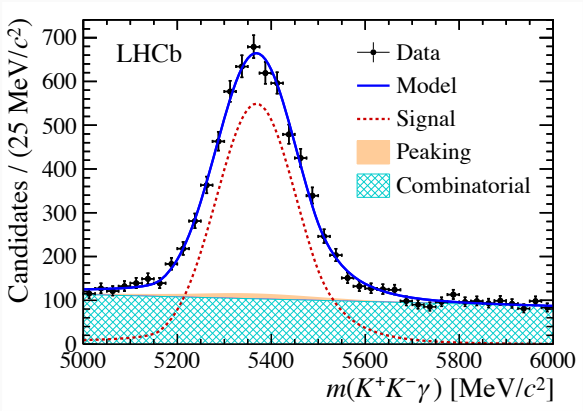
# $B_s^0 \to (\phi \to K^+K^-)\gamma$

- Decay involves $b \to s\gamma$ loop-level transition
- Decay rate is well-measured, but **photon polarisation** in the decay is sensitive to NP
- Predominantly left-handed in SM, but NP models can introduce a sizeable right-handed component
  - Polarisation can be affected by NP without altering rate
- Polarisation observable $\mathcal{A}^\Delta$ has been studied at LHCb: $\mathcal{A}^\Delta = -0.67^{+0.37}_{-0.41} \pm 0.17$ [arXiv:1905.06284]
  - Sensitive to ratio of right and left polarisation amplitudes
  - SM prediction $\mathcal{A}^\Delta_{\mathrm{SM}} = 0.047^{+0.029}_{-0.025}$, agreement at $1.7\sigma$

# $B_s^0 \to (\phi \to K^+K^-)\gamma$

- FCC-ee yield (per experiment, per year, no selection cuts):
  - $(1.1 \times 10^{10}) \times (1.7 \times 10^{-5})$ = **190,000 events**
  - Anticipate ~ $3$ million events with 4 IPs
  - LHCb 3 fb$^{-1}$ yield ~ $4000$, so ~ $800,000$ with 300 fb$^{-1}$
  - Precision below theory error on $\mathcal{A}^{\Delta}$ possible
- Exclusive EvtGen sample with IDEA Delphes
  - No truth-matching applied
  - $B_s^0$ peak resolution limited due to photon
  - Background even in exclusive signal MC sample from random photon combinatorics



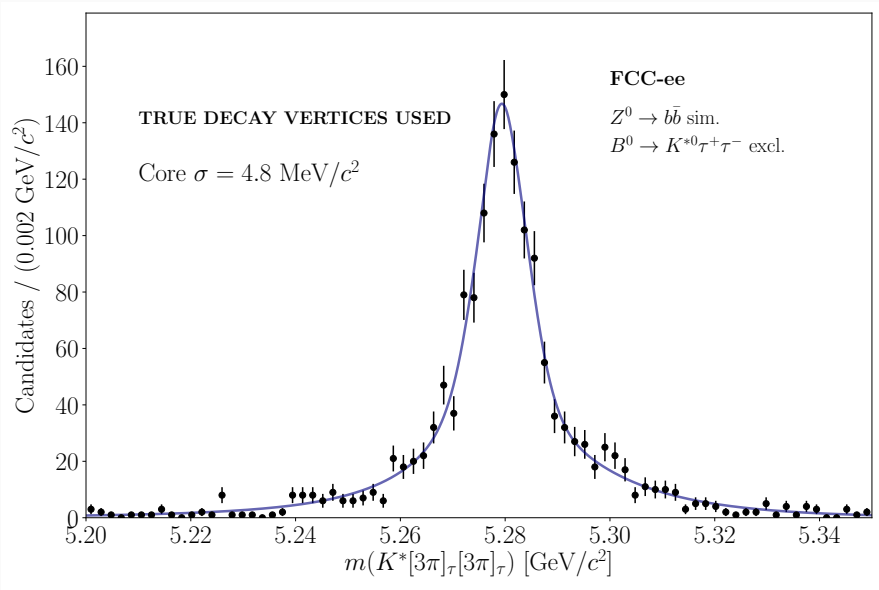

LHCb $\sigma$ = 100 MeV/$c^2$

# $B^0 \to K^{*0}\tau^+\tau^-$ (see Lingfeng Li's talk at November workshop)

- Tauonic equivalent of $K^{*0}\ell^+\ell^-$, critical to extend the $b \to sll$ lepton universality picture
- Total $\mathcal{B} = 3.2 \times 10^{-10}$, assuming $B^0$ decay $\mathcal{B} = 10^{-7}$ and reconstruct only $K^* \to K\pi$ and $\tau \to 3\pi\nu$
- $(4.9 \times 10^{10}) \times (3.2 \times 10^{-10})$ = 16 events per exp. per year
  - Considering sub-decays with neutrals can boost this to $\sim 1000$
- Very large SM backgrounds from decays where charm meson fakes $\tau \to 3\pi$ signal

# $B^0 \to K^{*0}\tau^+\tau^-$

- Using truth-matched $K^*$ and $\tau$'s to build $B^0$
- $\tau$ momentum reconstruction technique from CDR has been successfully applied to key4hep/EDM4hep output
- Perfect vertex knowledge for now
  - Resolution from momentum measurement ($\sim 5$ MeV/$c^2$) will be degraded further by finite vertex precision



# Other important missing momentum modes

- $B_s^0 \to \tau^+\tau^-$
  - Not yet observed, with only weak $\mathcal{B}$ limits ~ $10^{-2}$
  - Significant NP enhancements possible due to larger $\tau$ mass
  - With SM $\mathcal{B} \sim 10^{-6}$ and $\tau \to 3\pi\nu$, 80 events per exp. per year

- $B_c^+ \to \tau^+\nu_\tau$ (no chance at LHCb, no $B_c^+$ at Belle II)
  - Same vertex factors as $B^0 \to D^{(*)}\tau\nu_\tau$, so an important crosscheck of $b \to cl\nu$ lepton universality measurements
  - Measurement of $|V_{cb}|$ possible
  - CEPC studies exist, which we should aim to match and extend [arXiv:2007.08234]
  - See talk from Yasmine here for details