Heavy-flavour studies at FCC-ee

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Motivation

- Extremely strong physics case for FCC-ee (in my opinion)
- Beyond precision EW and Higgs there is an **unparalled opportunity** in heavy flavour
- Precision flavour measurements are a powerful discovery apparatus
  - Loops receive NP contributions
  - Consistency in flavour observables $\rightarrow$ NP unlikely at the LHC
- Heavy flavour observables have a strong history of finding new physics
  - GIM mechanism $\rightarrow$ discovery of charm
  - CP violation in K_{L}^{0} decay $\rightarrow$ CKM mechanism $\rightarrow$ discovery of bottom and top
  - EW precision fit $\rightarrow$ discovery of Higgs
- FCC-ee is a **dream** environment for heavy flavour
  - Running at Z-pole or on-shell production of $W^{\pm}$
  - Get all the benefits of both Belle II and LHCb
- *Beyond the pure physics case there are several strong sociological and long-term physics arguments (in my opinion)*

Motivation

- FCC-ee is a **dream** environment for heavy flavour
- The Monteil-Wilkinson tick-list [*EPJ+* **126** (2021) 8]

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

- **Tera-Z** run at the Z^0-pole:
  - 6×10^{12} Z^0 (across 4 experiments)

Species (both flavours)	B^0	B^+	B_s^0	Λ_b^0	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (billions)	740	740	180	160	3.6	720	200

- **Giga-W** run at W^+W^- threshold:
  - 2.4×10^8 $W^\pm$ pairs (across 4 experiments)

Heavy flavour environment at the FCC

- Huge luminosity competes with pp cross section, $10^5 Z/s$, $10^4 W/h$, $10^3 H, t/d$
- Hundreds of billions of B mesons
- Clean environment, no pile-up, controlled beam background
- E and p constraints
- Minimal trigger losses
- Do LEP in ONE MINUTE!
  $\rightarrow$ many flavour (and EW) observables are still dominanted by LEP
- Boost at the Z $\rightarrow$ $\langle E_B \rangle \approx 70\% \times E_{\text{beam}}$ $\langle \beta\gamma \rangle \approx 6$
  - b fragmentation allows topological reconstruction
  - the "other" b gives constraint on missing energy
- Large sample of W^+W^- (on-shell and boosted) will give access to all CKM element **magnitudes**

Detector requirements for flavour

Tracking

- Good p resolution is required for most physics at FCC
  - Ability to reconstruct down to low momentum important for flavour

Vertexing

- Essential for huge parts of flavour program
  - Resolve TD oscillations of B_s^0 so $\sigma_t \sim 50\,\text{fs}$
  - Semi-leptonic and decays to τ, $\sigma_v \sim 5\,\mu\text{m}$ for 3-track vertex

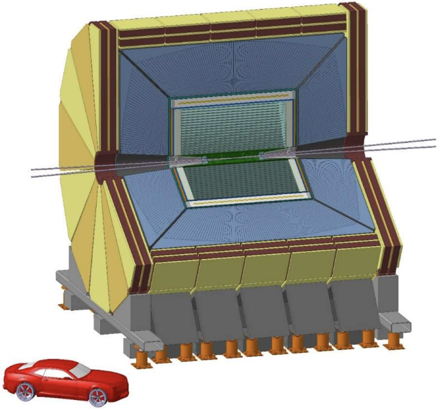
Calorimetry

- Low multiplicity allows study of flavour with neutrals
  - Anything with π^0 or γ incredibly challenging at LHCb
  - Need performance maintained at low energy

Particle ID

- Vital for any heavy flavour program
  - Need effective kaon-pion separation across wide range of momentum
  - Non-signal momenta $\sim 10\,\text{GeV}/c$, signal momenta $\sim 30\,\text{GeV}/c$

The IDEA concept



- Si vertex detector (5 layers)
- Drift chamber (~ 100 layers)
- Si strips
- Solenoid (2T, 5m)
- Preshower
- Calorimeter
- Muon chambers

- Solenoid *inside* the calorimeter (so needs to be thin)
- Large tracking volume (but needs low X_0) with low power (air cooling)
- Vertex precision $\sim 3\,\mu\text{m}$ (but $5\,\mu\text{m}$ shown by ALICE)
- **There is an IDEA card in DELPHES for simulation**
- **To what extent is this shovel ready? Can it hit desired performance targets?**

Current / foreseen activities in flavour

- Rare semi-leptonic and leptonic decays
  - $b \to s\tau^+\tau^-$, $B_s^0 \to \tau^+\tau^-$
  - $b \to s\nu\overline{\nu}$ (what I will show today)
  - $B_c^+ \to \tau^+\nu_\tau$
  - $b \to s(\overline{d})\ell^+\ell^-$
- CP violation and CKM
  - CKM angle γ with $B_s^0 \to D_s^- K^+$ and $B^+ \to D^0 K^+$
  - a_{sl} semileptonic asymmetries (CPV in mixing)
  - CKM angle α
  - Measurements of V_{ub}, V_{cb} *etc.*
- Tau physics
  - LFV and LFU in τ decay
- Charm physics
  - Rare charm *e.g.* $D \to \pi\nu\overline{\nu}$, $D^0 \to \gamma\gamma$
  - Hadronic charm

* ECFA focus topics

Contributing

How can you contribute?

- It's very easy, you would be very welcome
- There is an IDEA card in DELPHES
- MC takes about a day to produce
- There is some simple reconstruction framework
- Can quickly produce nTuples
- Perfect as the "second project" of a capable PhD student
- Perfect way to engage the early careers in FCC activities

What should I do?

- Think of your favourite flavour measurement/observable that has missing energy and/or neutrals
- These tend to be theoretically cleaner (leptonic, semi-leptonic decays)
- Perhaps something involving a B_s^0 to Λ_b^0 decay

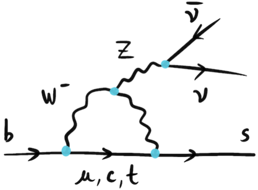
Case Study

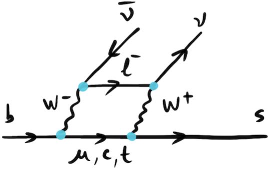
$$b \to s\nu\overline{\nu}$$

[arXiv:2309.11353]

- I don't have time to cover everything
- I tend to dislike "whistle-stop" tours
- So I will present one specific topic that demonstrates how far FCCee can go

- Considerable interest in the flavour community in $b \to s\ell^+\ell^-$ and $b \to c\ell^-\overline{\nu}$ transitions
  - $b \to s\nu\overline{\nu}$ transitions are complementary probes (ℓ^+ and ν share a weak doublet)
- **SM predictions are clean:**
  - Dominant uncertainties from hadronic form-factors and CKM elements
  - No long-distance contributions from (in)famous charm loops
  - Sensitive to a variety of NP scenarios *e.g.* Z', leptoquarks *etc.*





$$\boxed{\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{ij} (C_L^{ij} O_L^{ij} + C_R^{ij} O_R^{ij}) + h.c,}$$

- In the SM, $C_L^{ii} = -6.35(7)$ and $C_R^{ij} = 0$ [1, 2, 3, 4]

Experimental state-of-the-art

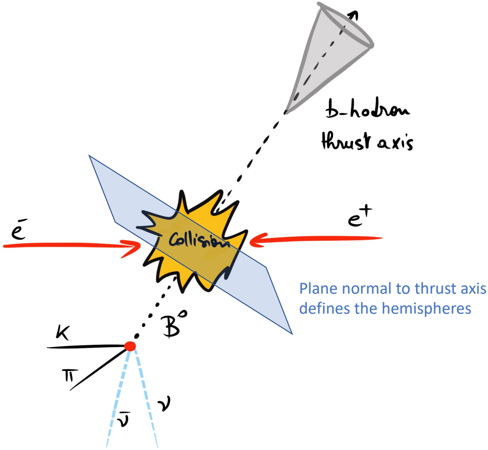
- FCC-ee provides a (possibly *unique*) opportunity for semileptonic flavour physics
- In the SM $b \to s\nu\bar{\nu}$ BF predictions are $\mathcal{O}(10^{-5})$
- $B^+ \to K^+\nu\bar{\nu}$ has just been seen by Belle II [arXiv:2311.14647] - $\mathcal{B} = (2.3 \pm 0.7) \times 10^{-5}$
  - 2.7σ enhancement from SM prediction
- From the underlying $b \to s\nu\bar{\nu}$ transition we can study:

Decay	B-factories	FCC-ee	Current Limit	SM prediction
$B^+ \to K^+\nu\bar{\nu}$	✔	✔	$< 1.6 \times 10^{-5}$	$(4.0 \pm 0.5) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	✔	✔	$< 4.0 \times 10^{-5}$	$(9.8 \pm 1.1) \times 10^{-6}$
$B^0 \to K^0_S\nu\bar{\nu}$	✔	✔	$< 2.6 \times 10^{-5}$	$(3.7 \pm 0.4) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	✔	✔	$< 1.8 \times 10^{-5}$	$(9.2 \pm 1.0) \times 10^{-6}$
$B^0_s \to \phi\nu\bar{\nu}$	✗	✔	$< 5.4 \times 10^{-3}$	$(9.9 \pm 0.7) \times 10^{-6}$
$\Lambda^0_b \to \Lambda^0\nu\bar{\nu}$	✗	✔	–	–

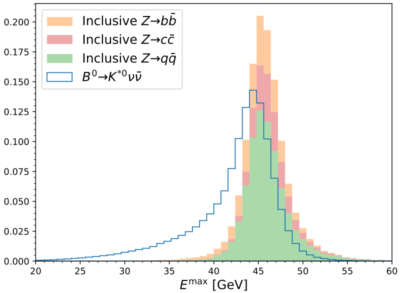
- Decays with intermediate vectors are consierably easier experimentally
  - single track is hard, final state neutral needs good $K^0_S/\ \Lambda^0$ reco
  - intermediate scalars are much cleaner for theory
- Decays with intermediate scalars are cleaner for theory
- With 2 neutrinos in the final state, decays are (probably) impossible at the LHC

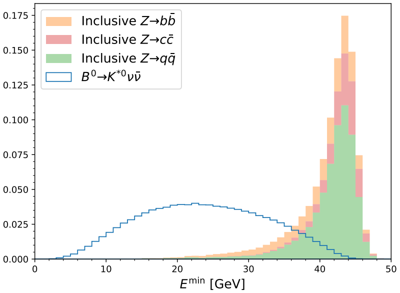
We have studied the prospects for $B^0 \to K^{*0}\nu\overline{\nu}$ and $B_s^0 \to \phi\nu\overline{\nu}$

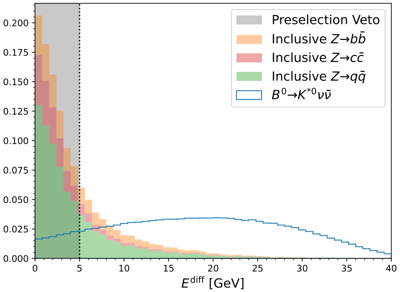
- Use the thrust axis for $Z^0 \to q\overline{q}$ to define event hemispheres
- Due to missing energy in the signal decay the two hemispheres have different energy distributions



Energy in each hemisphere

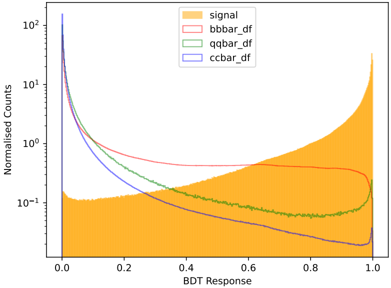


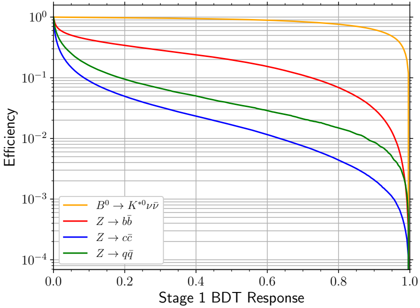




Event-level MVA

- Background sample from inclusive $Z^0 \to q\bar{q}, c\bar{c}, b\bar{b}$ using PDG branching fractions
- Input variables are the event energy distributions and vertex information

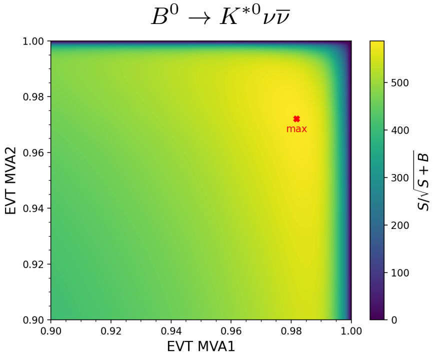


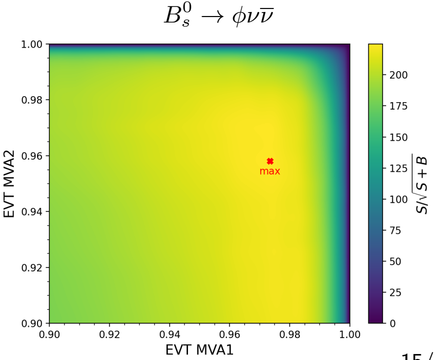


- Powerful seperation - cut at 0.6 has $> 90\%$ signal efficiency and $\sim 90\%$ background rejection
- Very similar for the $B_s^0 \to \phi\nu\bar{\nu}$ mode

Analysis-level MVA

- Train a second BDT on variables related to the candidate properties:
  - Intermediate candidate kinematics
  - Intermediate candidate topology
  - The nominal B-meson energy (Z mass minus E_{rec})
- Use multivariate splines to build efficiency maps across the (BDT1, BDT2) plane
- Then maximise the FOM, $S/\sqrt{S+B}$, as a function of the BDT cuts for a range of BF values





Signal estimate

- Signal expectation is computed as

$$\boxed{S = N_Z\,\mathcal{B}(Z \to b\bar{b})\,2\,f_B\,\mathcal{B}(B \to Y\nu\bar{\nu})\,\mathcal{B}(Y \to f)\,\epsilon^s_{\text{pre}}\,\epsilon^s_{\text{BDTs}},}$$

- Background expectation computed as

$$\boxed{B = \sum_{f\in\{b\bar{b},c\bar{c},q\bar{q}\}} N_Z\,\mathcal{B}(Z \to f)\,\epsilon^b_{\text{pre}}\,\epsilon^b_{\text{BDTs}},}$$

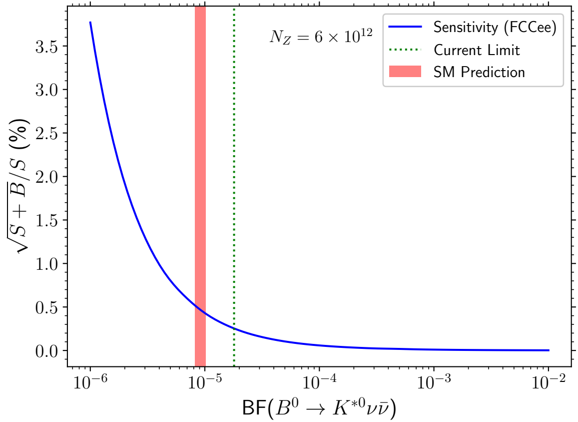
assuming

  - $6 \times 10^{12}\ Z^0$ in FCC-ee operation
  - known / predicted production fractions and branching ratios
  - analysis efficiencies

$B^0 \to K^{*0}\nu\overline{\nu}$ Efficiency and Sensitivity

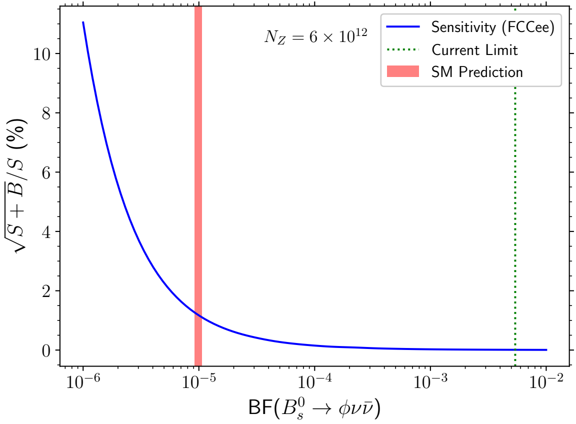
For optimal cuts at the SM prediction:

- Signal efficiency $\sim 3.7\%$
- $b\bar{b}$ efficiency $\sim 10^{-7}$
- $c\bar{c}$ efficiency $\sim 10^{-9}$
- $q\bar{q}$ efficiency $\sim 10^{-9}$
- S/B ratio $\sim 1 : 20$
- Sensitivity $\sim 0.53\%$
- For reference the current Belle II $B^+ \to K^+\nu\overline{\nu}$ has $\sim 30\%$



For optimal cuts at the SM prediction:

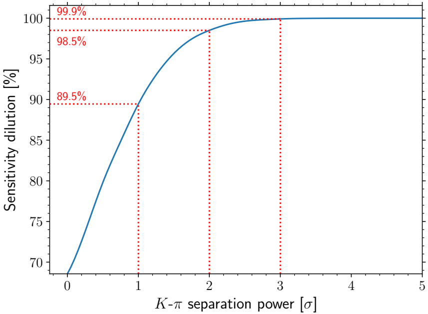
- Signal efficiency $\sim 7.4\%$
- $b\bar{b}$ efficiency $\sim 10^{-7}$
- $c\bar{c}$ efficiency $\sim 10^{-9}$
- $q\bar{q}$ efficiency $\sim 10^{-9}$
- S/B ratio $\sim 1:9$
- Sensitivity $\sim 1.20\%$
- CEPC at $\sim 1.8\%$ [arXiv:2201.07374]



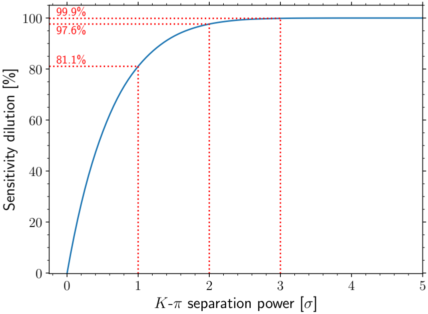
PID requirements of the detector

- For serious flavour analysis at FCC-ee - hadronic PID separation is vital
- Our analysis assumes *perfect* PID
- Naively investigate this by making random swaps (no momentum dependence)

$B^0 \to K^{*0}\nu\overline{\nu}$



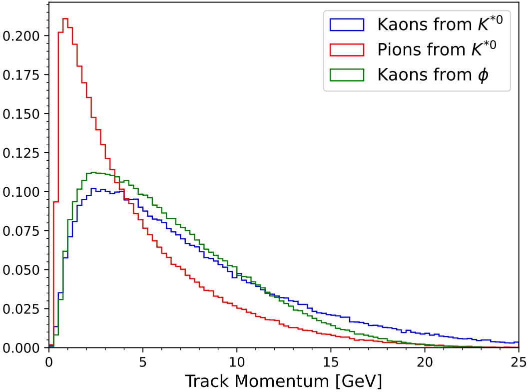
$B_s^0 \to \phi\nu\overline{\nu}$



- K-π separation of 2σ would have negligible impact on the sensitivity

PID requirements of the detector

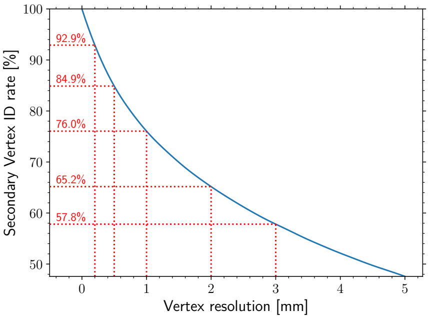
- Pion from the K^{*0} is down in the *difficult* region of ~ 1 GeV/c for dN/dx
- PID detector requirement perhaps need timing



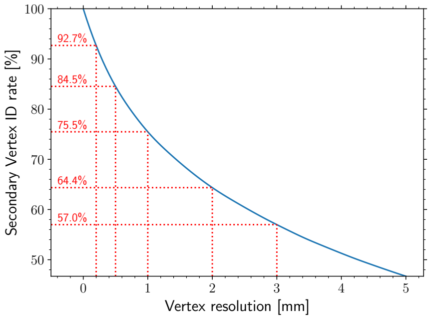
Vertexing requirements of the detector

- For serious flavour analysis at FCC-ee - precision vertexing is essential
- Our analysis assumes *perfect* vertex seeding
- Naively investigate this by making random swaps

$B^0 \to K^{*0}\nu\bar{\nu}$

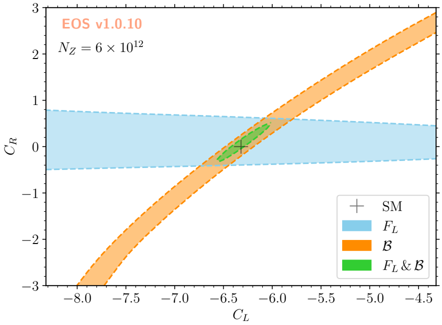


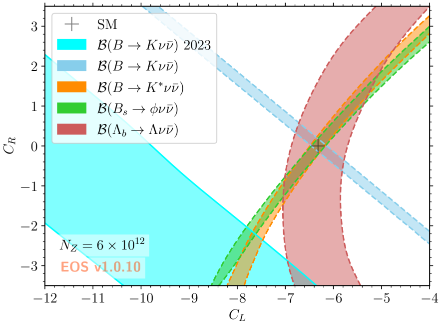
$B_s^0 \to \phi\nu\bar{\nu}$



- Need < 0.2 mm resolution to mitigate vertex mis-id
  - But this is already above the requirements for vertex precision anyway

- Shown here for the $B^0 \to K^{*0}\nu\overline{\nu}$ mode
- Sensitivity to BF should be sufficient to fit as a function of q^2
- Expect direct measurements of F_L could get to $\sim 2.5\%$ ($\sim 5\%$) for $B^0 \to K^{*0}\nu\overline{\nu}$ ($B_s^0 \to \phi\nu\overline{\nu}$)





Summary

- Precision flavour measurements set powerful constraints on NP
- Explaining flavour anomalies is how we built the SM
- FCC-ee offers an unparalled opportunity in heavy flavour measurements
  - Beauty, charm and tau physics
  - Operating at the Z-pole and W^+W^-
  - It is the perfect environment for flavour physics
- FCC-ee will improve on almost all key flavour observables
  - In certain sectors by orders of magnitude
- Pushes NP reach up to $10^2 - 10^4$ TeV
- **We need to build this machine!**

[1] J. Brod, M. Gorbahn, and E. Stamou, *Two-Loop Electroweak Corrections for the $K \to \pi\nu\bar{\nu}$ Decays*, Phys. Rev. D **83** (2011) 034030, arXiv:1009.0947.

[2] G. Buchalla and A. J. Buras, *The rare decays $K \to \pi\nu\bar{\nu}$, $B \to X\nu\bar{\nu}$ and $B \to l^+l^-$: An Update*, Nucl. Phys. B **548** (1999) 309, arXiv:hep-ph/9901288.

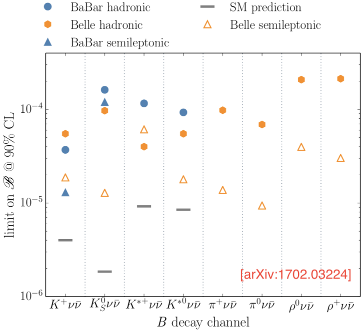
[3] A. J. Buras, J. Girrbach-Noe, C. Niehoff, and D. M. Straub, *$B \to K^{(*)}\nu\overline{\nu}$ decays in the Standard Model and beyond*, JHEP **02** (2015) 184, arXiv:1409.4557.

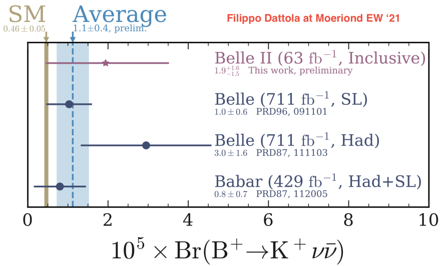
[4] M. Misiak and J. Urban, *QCD corrections to FCNC decays mediated by Z penguins and W boxes*, Phys. Lett. B **451** (1999) 161, arXiv:hep-ph/9901278.

BACK UP

Searches at B-factories

- Searches at B-factories use B-mesons produced via $e^+e^- \to \Upsilon(4S) \to B^+B^-$
- Event is *tagged* either *inclusively* or using specific hadronic or semileptonic decays of the other B.
- Belle II results: BR($B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5}$ at 90% C.L. [arXiv:2104.12624].
- Expect to reach $\sim 10\%$ precision on B^+/B^0 with 50 ab^{-1} [arXiv:1808.10567]





- **FCC-ee** is the **only foreseen experiment** that **can improve Belle-II measurement** in the (far) future (apart from maybe CEPC)!

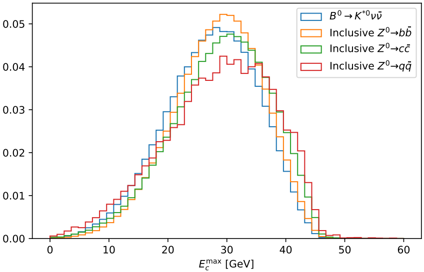
Relevant for detector design

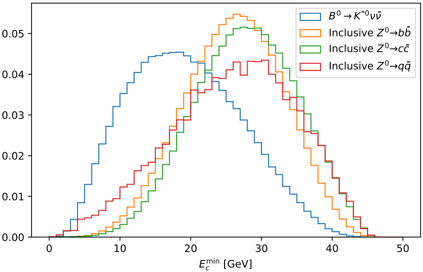
- Use the same vertexing procedure developed for $B_c^+ \to \tau^+ \nu_\tau$ (see this talk for details) which assumes *perfect* vertex seeding
  $\to$ implies we will have **excellent vertex resolution**
- We also truth match the kaon and pion daughters to have the correct mass hypothesis (with the reconstructed momentum)
  $\to$ implies we will have **excellent PID**
- When we get a bit more advanced it would be nice to understand the impact of relaxing these requirements.
- Also assume the K^{*0} in the signal mode is pure $K^*(892)^0$

None of this is particularly relevant for the event level MVA we have trained so far (and show today) but it will be important for the next stage MVA

Charged energy in each hemisphere

- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay





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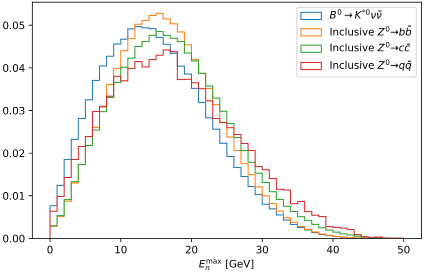

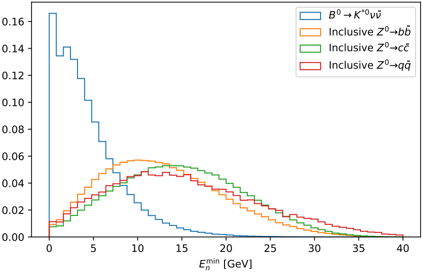

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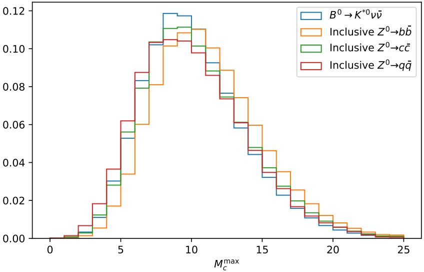
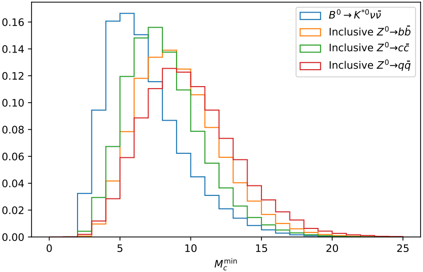
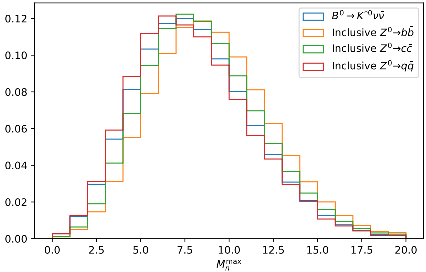
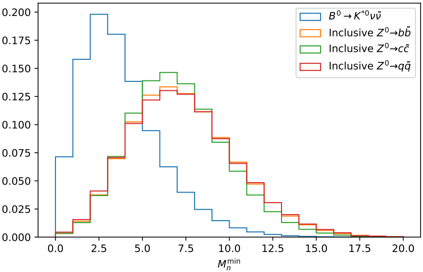




Neutral multiplicity in each hemisphere

- More discrmination power in the minimum energy hemisphere (signal side) due to missing energy in the signal decay

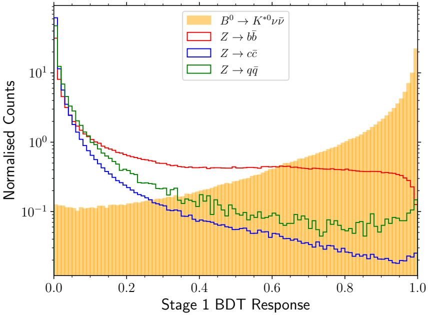




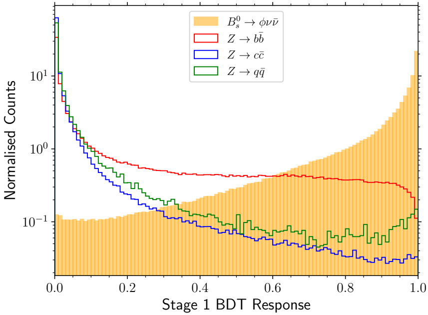
Stage 1 Inputs

- The total reconstructed energy in each hemisphere,
- The total charged and neutral reconstructed energies of each hemisphere,
- The charged and neutral particle multiplicities in each hemisphere,
- The number of charged tracks used in the reconstruction of the primary vertex,
- The number of reconstructed vertices in the event,
- The number of candidates in the event
- The number of reconstructed vertices in each hemisphere,
- The minimum, maximum and average radial distance of all decay vertices from the primary vertex.

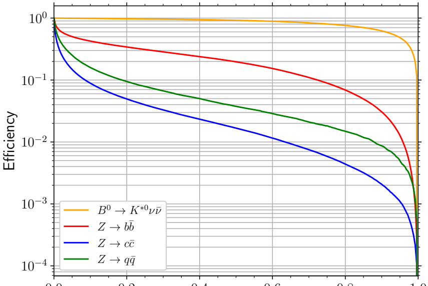
Stage 1 BDT



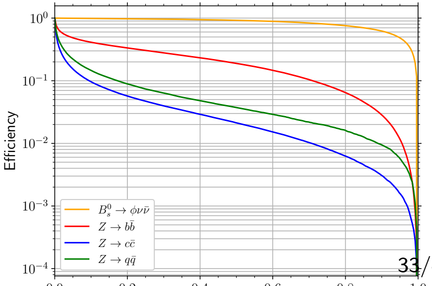
$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 1 BDT Response



$B_s^0 \to \phi\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 1 BDT Response

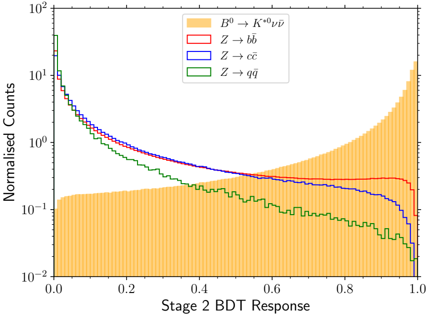


Efficiency
$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$

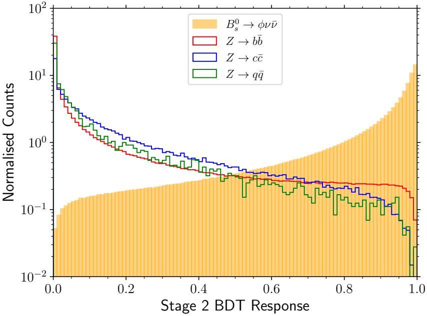


Efficiency
$B_s^0 \to \phi\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$

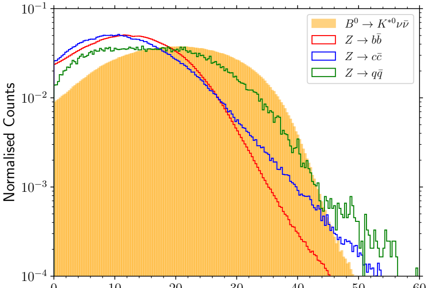
Stage 2 BDT



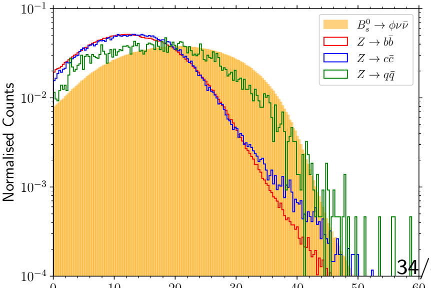
$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 2 BDT Response



$B_s^0 \to \phi\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts
Stage 2 BDT Response



$B^0 \to K^{*0}\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts

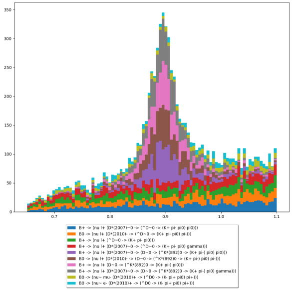


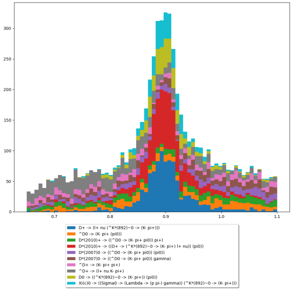
$B_s^0 \to \phi\nu\bar{\nu}$
$Z \to b\bar{b}$
$Z \to c\bar{c}$
$Z \to q\bar{q}$
Normalised Counts

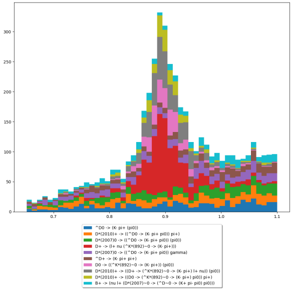
Stage 2 Inputs

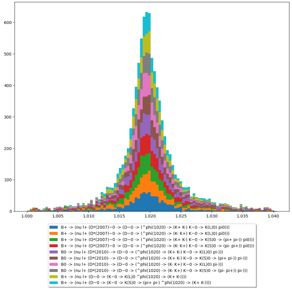
- The intermediate candidate's reconstructed mass
- The number of intermediate candidates in the event
- The candidate's flight distance and flight distance χ^2 from the primary vertex
- The x, y and z components of the reconstructed candidate's momentum
- The scalar momentum of the candidate
- The transverse and longitudinal impact parameter of the candidate
- The minimum, maximum and average transverse and longitudinal impact parameters of all other reconstructed vertices in the event
- The angle between the intermediate candidate and the thrust axis
- The mass of the primary vertex
- The nominal B candidate energy, defined as the Z mass minus all of the reconstructed energy apart from the candidate children

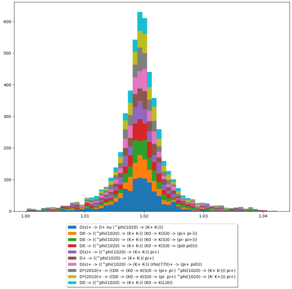
Backgrounds

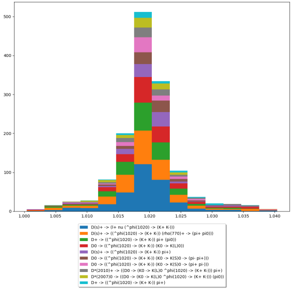




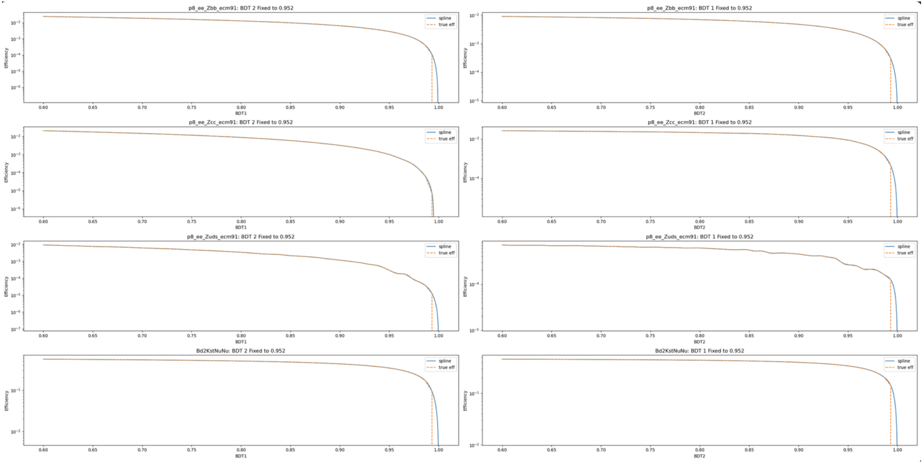








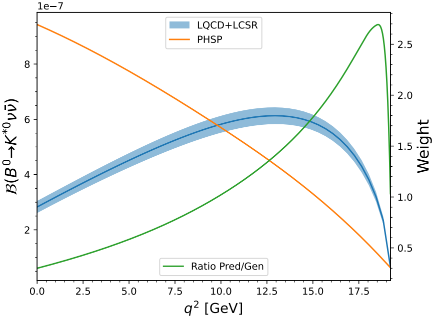
Spline Drop Off



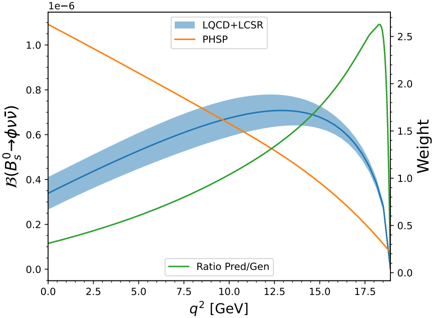
q^2 distribution reweighting

- Our simulation uses phase space (PHSP) generation models
- We reweight the q^2 distribution to match the latest theory predictions (from MR and OS)

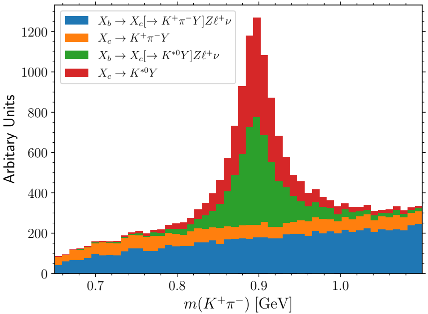
$B^0 \to K^{*0}\nu\bar{\nu}$

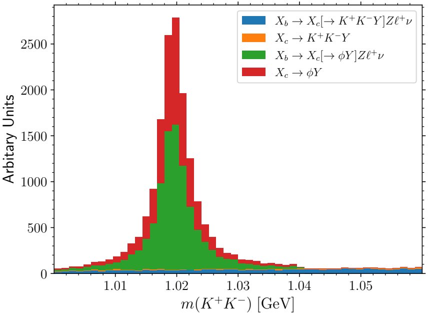


$B_s^0 \to \phi\nu\bar{\nu}$



Backgrounds





V_{ub} and V_{cb}

David Marzocca: 2nd ECFA Workshop 2023

Crucial inputs for constraining new physics from rare meson decays and meson mixing - the largest source of uncertainty

Systematic uncertainties will eventually dominate the semileptonic V_{cb} measurements

Present Day		Full LHCb and Belle II datasets
$\sigma(V_{cb}) \sim 1.4\,\%$	$\longrightarrow$	$\sigma(V_{cb}) \sim 1.0\,\%$
$\sigma(V_{ub}) \sim 6.2\,\%$		$\sigma(V_{ub}) \sim 0.9\,\%$

Can we improve on this?

V_{cb} from on-shell $W^{\pm}$ decays

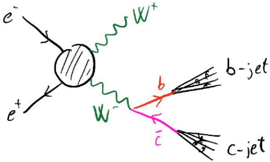
David Marzocca: 2nd ECFA Workshop 2023

- Independent of the semileptonic measurements
- Independent of Lattice QCD inputs

  $\Longrightarrow$ improved precision

- For 10^8 $W^{\pm}$ pairs $\boxed{\sim 0.14\,\%\text{ relative uncertainty}}$

  with perfect jet flavour tagging



	b	c	uds
Eff b-jet tagger	25%		
Eff c-jet tagger	10%	50%	2%

Marie-Hélène Schune: 3rd FCC Workshop 2020

Numbers inspired by:

ILD@ILC
Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging
Tomohiko Tanabe (U Tokyo)
IAS Program on High Energy Physics 2017, HKUST

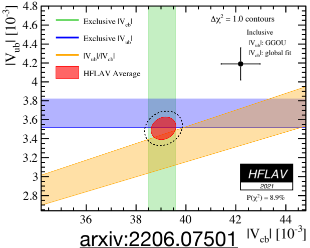
$\Longrightarrow$ $\boxed{\sim 0.4\,\%\text{ relative uncertainty}}$

Can even be slightly more optimistic given there may be twice as many $W^{\pm}$ pairs in the nominal running plan

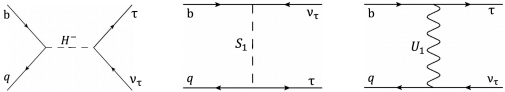
$B_{(c)} \rightarrow \tau^+ \nu_\tau$

[arxiv:2105.13330, arxiv:2305.02998]

- $\sim 2\,\%$ precision on BFs
- Independent clean probes of V_{ub} and V_{cb}
  - May help resolve the tension between exclusive and inclusive measurements
- Can also probe various NP models
  - Charged Higgs
  - Scalar leptoquarks
  - Vector leptoquarks



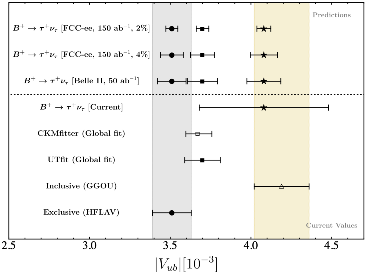
arxiv:2206.07501



Feynman diagrams for tree-level contributions from: charged Higgs (left), scalar leptoquarks (middle) and vector leptoquarks (right)

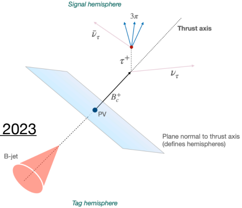
$B_{(c)} \to \tau^+\nu_\tau$

- Reconstruct $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$ decay
- Decay topology split into high- and low-energy hemispheres
- 2-stage BDT selection: Hemisphere properties followed by candidate properties
- Determine ideal and pessimistic BF uncertainties
  - 2% and 4% respectively



Comparison between current determinations of $|V_{ub}|$ and predicted determinations from Belle II and FCC-ee, where the FCC-ee values correspond to 2% and 4% uncertainty on $\mathscr{B}(B^+ \to \tau^+\nu_\tau)$. Different central values are taken from the current Exclusive, Global and $B^+ \to \tau^+\nu_\tau$ values.

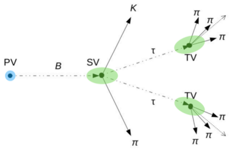
Xunwu Zuo: EPS-HEP 2023



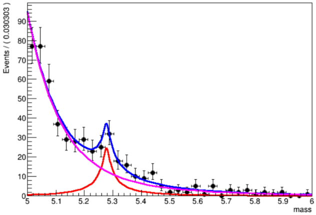
This study assumes 5×10^{12} Z^0s so we could actually push it a little further!

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

- Yet to be observed - $\mathcal{O}(10^{-7})$ BF
  - Current limit $\mathcal{O}(10^{-4}) - \mathcal{O}(10^{-3})$
- Many NP models expect NP to couple primarily to the Higgs and the third generation Ben Stefanek: 2nd ECFA Workshop 2023
- Focus again on the the 3-prong $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}$ decay
- Use energy-momentum conservation to resolve ν kinematics
- BDT trained with candidate kinematics to reduce backgrounds
- Signal yield extracted with an unbinned ML fit to the candidate B mass



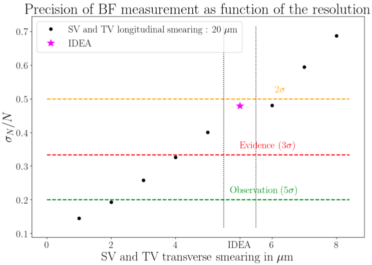
Schematic of the signal decay



B^0 candidate invariant mass fit to rescaled signal and background MC

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

- Current FCC-ee and IDEA would not allow for discovery of this mode
- Clearly some work to do!
  - Better vertexing?
    - Easier said than done
  - Higher luminosity/longer run period?
    - Difficult/competition with other runs
  - Consider other τ decays?
    - Leptonics harder to handle but would produce $\mathcal{O}(10)$ times the data



Dependence of the relative signal yield uncertainty on the vertex resolution of the IDEA detector

Motivations for precise τ measurements

Alberto Lusiani: FCC Week 2023

- m_τ is a SM parameter - must push experimental sensitivity as far as possible
  - Required for predictions of τ BF predictions
  - Necessary to determine strong-coupling, α_s, at the m_τ scale
  - Enters LFU tests at the fifth power
- A recent Belle II analysis, arxiv:2305.19116, gives the precise measurement $m_\tau = 1777.09 \pm 0.08 \pm 0.11$ MeV/c^2
  - systematically limited!
- Can also directly measure lifetime and BFs

m_τ systematics

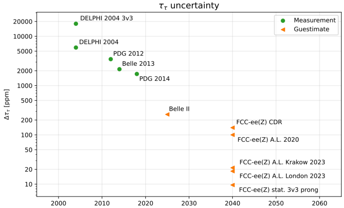
- Belle II primarily suffers due to
  - Knowledge of the beam energy
  - Momentum corrections due to scale factor dependence on p_T
- FCC-ee should be able to significantly reduce these effects
  - Beam energy should be known to within 1ppm
  - ~2ppm momentum scale calibration should be possible using $m_{j/\psi}$
- Baseline IDEA should be sufficient to obtain 14ppm measurement of $m_\tau \sim 0.02$ MeV/c^2

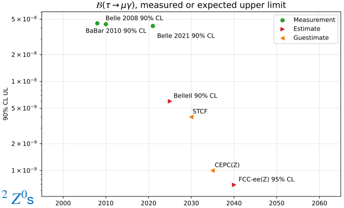
Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	< 0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

Systematic uncertainties in the Belle II m_τ measurement
arxiv:2305.19116

$\tau^{\pm}$ lifetime and BFs

- FCC-ee should provide the most precise measurements of τ lifetimes and BFs
- For lifetime
  - Impact parameter resolution for τ decay tracks $\leq 61\mu$m
  - Uncertainty on the average length scale of vertex detector elements ≤ 4.8ppm
- For BFs
  - Good EM energy resolution, $< 20\,\%/\sqrt{E(\text{GeV})}$ (LEP)
  - Granular EM calorimeter $> 15 \times 15$ mrad^2 (LEP)





Should temper expectations a little as these plots assume 8×10^{12} Z^0s