Electroweak precision physics at the FCC-ee

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Electroweak physics at future colliders

- **Electroweak physics programme** at intensity frontier
  - Z-boson lineshape:
    - m_Z, Γ_Z, σ_0^{had} ($\rightarrow N_\nu$),
    - $R_\ell = \Gamma_{had}/\Gamma_\ell$, $R_q = \Gamma_{qq}/\Gamma_{had}$
    - A_{FB}^{ℓ}, A_{FB}^{q}, P_τ, $A_{FB}(P_\tau)$
    - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$ → direct measurement vs. lattice calculations → interpret data without having to trust lattice and test lattice calculations themselves
  - WW, ZH, tt̄ thresholds, and above:
    - m_W, Γ_W, BR($W \rightarrow \ell\nu$), $\alpha_S(m_Z)$, m_t, triple and quartic gauge couplings
- Great precision needed to interpret potential deviations in terms of new physics → many EW precision observables to explore nature of BSM candidate signals

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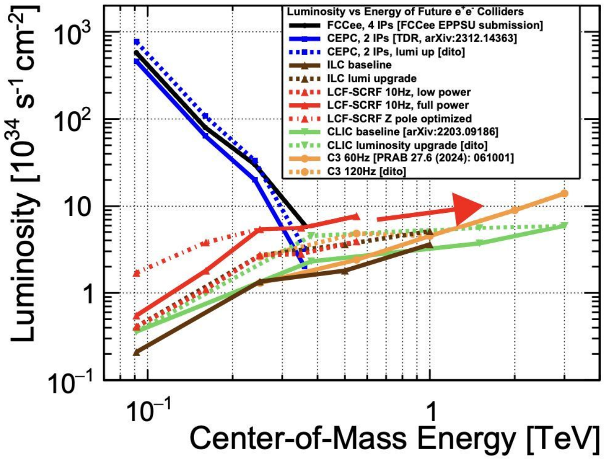
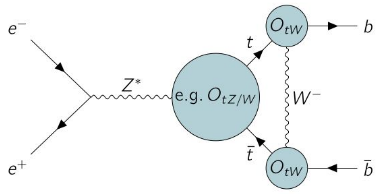
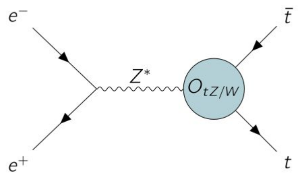


$\mathcal{O}(m_Z) \sim 90$ GeV



$\mathcal{O}(m_t) \sim 350$ GeV to 365 GeV



FCC-ee: features and operations

- **Circular**: (*e.g.* **FCC-ee**)
    - huge luminosity
    - 4 interaction points (IPs)
    - absolute beam energy calibration by continuous resonant depolarization of pilot bunches up to 160 GeV
- vs. **linear**:
    - luminosity/1000
    - 1 or 2 IP
    - longitudinally polarised beams

FCC-ee			
Energy	Physics case	Years of operation	Int. luminosity
91.2 GeV	Z pole	4	205 ab^{-1}
160 GeV	WW threshold	2	19 ab^{-1}
230-250 GeV	Higgs production at ZH threshold	3	11 ab^{-1}
365 GeV	$t\bar{t}$ threshold	5	3 ab^{-1}

FSR, 2505.00272

- 5×10^9 Z (2 years)
- 5×10^7 WW (8 years)

- 6×10^{12} Z (run-in + 3 years)
- 2.4×10^8 WW (2 years)

FCC-ee: EW flagship measurements

- **FCC-ee** is an excellent machine for a **wide physics programme**
    - $t\bar{t}$ production at threshold
    - Higgs and di-Higgs production
    - EW and *Z*-pole measurements
    - investigation on new physics
- Possible anomalies translate over a range of energy scales: from Z pole to top threshold
- Heavy-quark EW measurements as a probe for new physics
    - measurements will be dominated by the systematic uncertainty at FCC-ee (Z pole)
    - motivates novel ideas to make use of the Z pole statistics to bring down systematic uncertainty

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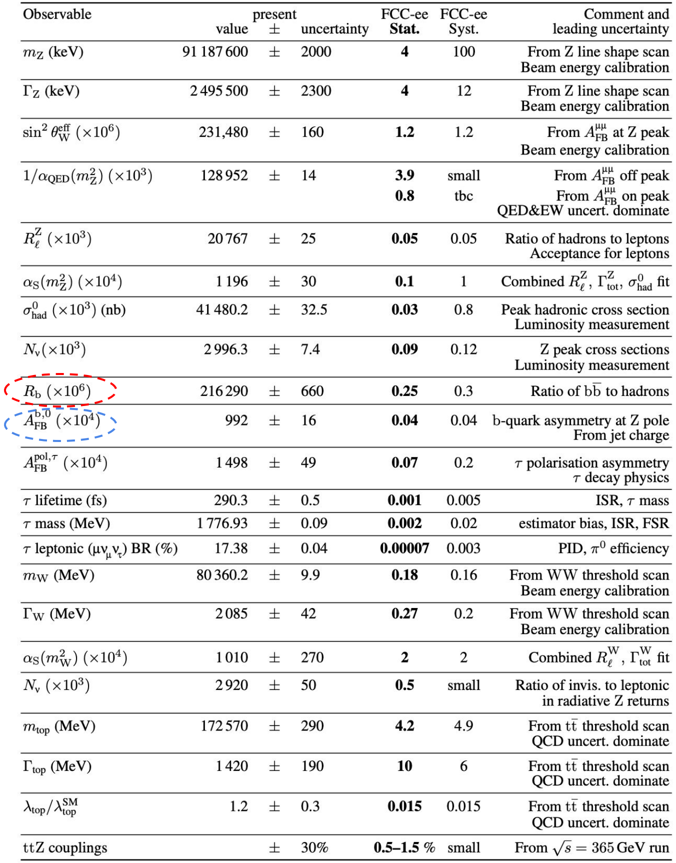


Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ $(\times 10^6)$	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ $(\times 10^3)$	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z $(\times 10^3)$	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ $(\times 10^4)$	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 $(\times 10^3)$ (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ $(\times 10^4)$	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic $(\mu\nu_\mu\nu_\tau)$ BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ $(\times 10^4)$	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν $(\times 10^3)$	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

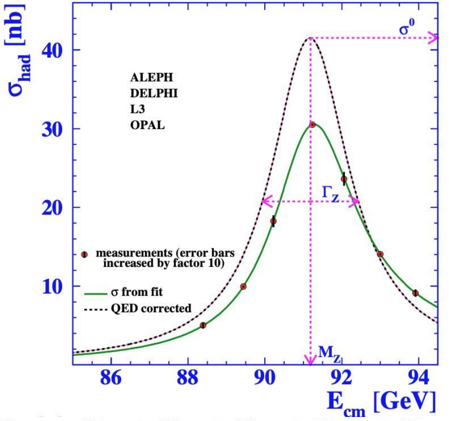
Z-boson lineshape

- feasibility studies at the Z-boson pole included in the FSR
  - Z-boson mass and width
  - asymmetries
    - focus on a few selected examples: inclusive b-quark A_{FB} and R_b measurements in $Z \rightarrow b\bar{b}$ events

Z boson features

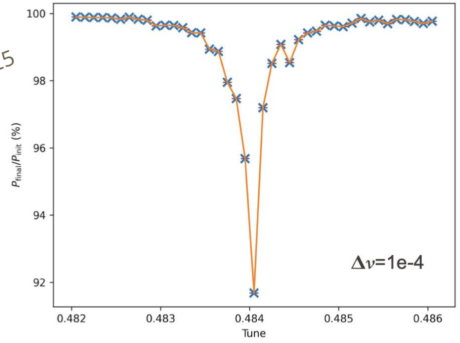
arXiv: 0509008

- **m_Z** → input to cross sections, width, branching ratios of the Z boson
    - current uncertainty Δm_Z ~ 2 MeV (LEP)
    - $\sigma_{stat} \sim \Gamma Z / 2\sqrt{(N_Z^{\text{off-peak}})}$
        - 4 keV at FCC-ee
    - dominant systematic uncertainty: **absolute point-to-point** (p.t.p.) **beam energy calibration**
        - resonant depolarisation $\Delta\sqrt{s} \sim \Delta m_Z \sim 100$ keV
- **Γ_Z** → sensitive to fermion couplings and to BSM
    - current uncertainty $\Delta\Gamma_Z$ ~ 2 MeV
    - dominant systematic uncertainty: relative absolute beam energy calibration
        - point-to-point $\Delta\sqrt{s}_{\text{p.t.p.}}$ → can be **verified in-situ** with *μμ* events
        - $\Delta\Gamma_Z$ ~ 12 keV at FCC-ee



$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

Yi Wu's talk at FCC Week 2025



spin tune ν_s using res. depolarization at FCC-ee

Asymmetries at the FCC-ee

- Forward-backward asymmetry in $e^+e^- \to Z \to b\bar{b}$ events:

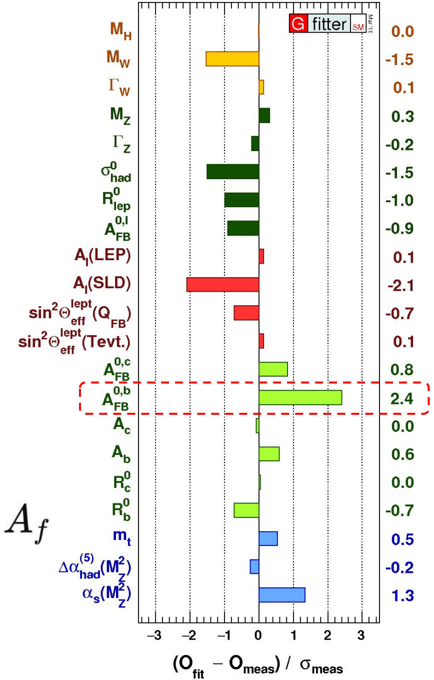
$$A^b_{FB} \equiv \frac{N_F - N_B}{N_F + N_B} \quad \text{with} \quad N_F = \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta \qquad N_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta$$

→ **>2σ deviation** with respect to global EW fits → most accurate measurement of $\sin^2\vartheta_{W,\,eff}$ at the Z pole

θ_b distribution (at LO)

$$\frac{d\sigma_{b\bar{b}}}{d\cos\theta_b} = \sigma_{b\bar{b}} \frac{3}{8}\left(1 + \cos^2\theta_b + \frac{8}{3} A^b_{\mathrm{FB}} \cos\theta_b\right) \qquad A_{\mathrm{FB}} = \frac{3}{4} A_e\, A_f$$

- **Measurement**:
  - A^b_{FB} extracted from ***cosθ(b)*** distribution
  - experimental distinction between b and $\bar{b}$ needed
    ⇒ quark **charge** determination crucial
    - via "**jet charge**" (e.g. weighted sum of charged tracks in jet, or vertex charge of MVA tagger)
    - with **soft-lepton-tagging**
    - using **machine-learning** techniques to combine all infos



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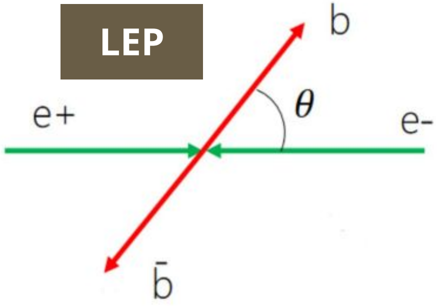


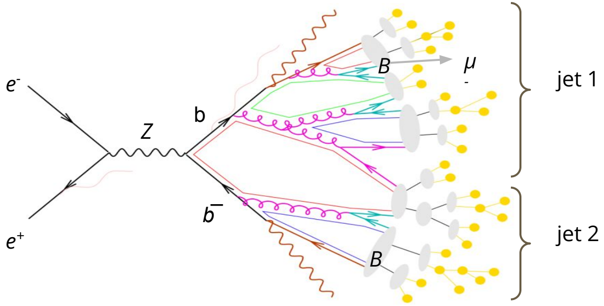
b-quark charge determination

DOI: 10.17181/dpyb5-vnc32

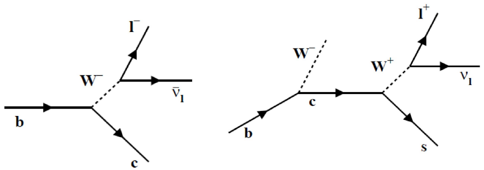
- Two classes of **methods**:

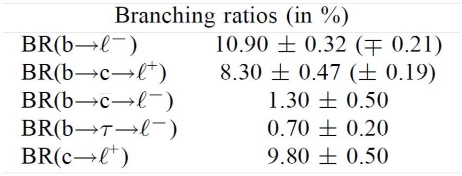
many possible variations exist, e.g. based on exclusive final states from B-hadron decays, secondary vertex reconstruction…

1. **Jet charge**:
    - weighted **sum** of charges of constituent **tracks**
    - can be applied to all jets ⇒ maximal efficiency
    - relatively low purity
    - strong dependence on jet shape and hadronization
    - “self-calibrating” à la LEP



2. **Soft lepton tagging**:
    - charge of *b* inferred from charge of *e* or *μ* in ***B*-hadron semileptonic decay**
        - crucial to minimize $b \rightarrow c \rightarrow \mu$ contribution that "fakes" charge
    - relatively low efficiency (restricted to semileptonic decays)
    - better purity
    - highly sensitive to *B*-hadron decay modelling



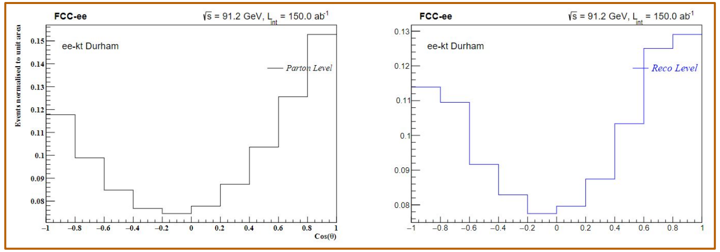


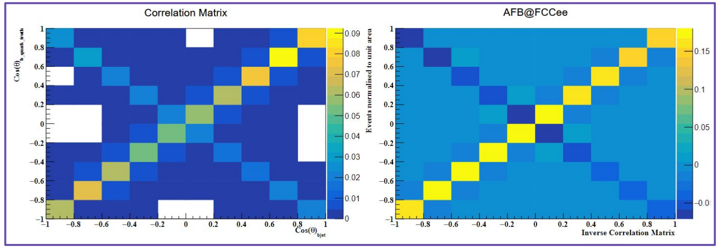
Branching ratios (in %)	
$BR(b \rightarrow \ell^-)$	10.90 ± 0.32 (∓ 0.21)
$BR(b \rightarrow c \rightarrow \ell^+)$	8.30 ± 0.47 (± 0.19)
$BR(b \rightarrow c \rightarrow \ell^-)$	1.30 ± 0.50
$BR(b \rightarrow \tau \rightarrow \ell^-)$	0.70 ± 0.20
$BR(c \rightarrow \ell^+)$	9.80 ± 0.50

$A_{FB}{}^{b}$: results

DOI: 10.17181/dpyb5-vnc32

- Event generation and selection:
    - beam energy: 45.5348 GeV (*Z*-pole)
    - signal: **2 *b*-tagged jets**
        - 1 jet with charge > 0
        - 1 jet with charge < 0
- Building **truth-level and reco-level *cosθ* distributions** for *b*-quarks and *b*-quark-jets
- **Response matrix** and efficiency correction vector built from $1 \cdot 10^{6}$ events
    - re-scaling the event number to match expected luminosity at *Z*-pole: $\mathscr{L}_{Z\text{-}pole}$ = 140 ab^{-1}
- **Unfolding with simple matrix inversion**, 10x10 matrix used
- **Statistical uncertainty** extracted from pseudo-experiments
- Different sources of systematic uncertainty investigated:
    - modelling of **heavy-quark fragmentation**
    - emission of **final-state QCD radiation**
    - **Pythia** versus **Dire** parton shower
    - *b*-tagging and *c*-mistagging rates





systematic uncertainty contribution

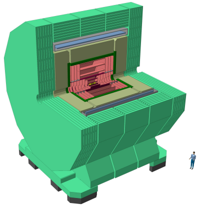
FSR, 2505.00272

$A_{\mathrm{FB}}^{\mathrm{b},0}$ $(\times 10^{4})$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge

A_{FB}^{b}: systematic uncertainties and interplays with R_b

DOI: 10.17181/dpyb5-vnc32

- **No limitation from statistical uncertainty**
  - LEP combination has nearly equal statistical and systematics contributions
  - expected ~10^5 times more statistics at FCC-ee ⇒ ~300 times smaller than statistical uncertainty
- **Systematic uncertainties** expected to be **dominant**, but many handles in data to constrain them, in particular extra radiation and gluon splitting affecting hemisphere correlations → to be measured in situ
- Special focus on **QCD corrections to A_{FB}^{b}**:
  - perturbative regime → emission of gluon final state radiation
  - non-perturbative regime → *b*-quark fragmentation modelling
- Considering **hemisphere correlations**:
  - two different approaches:
    - **inclusive measurement** → centrally generated events + IDEA fast-sim Delphes outputs
    - **exclusive *B*-hadron decays** → private simulation + tests on CLD full-sim outputs

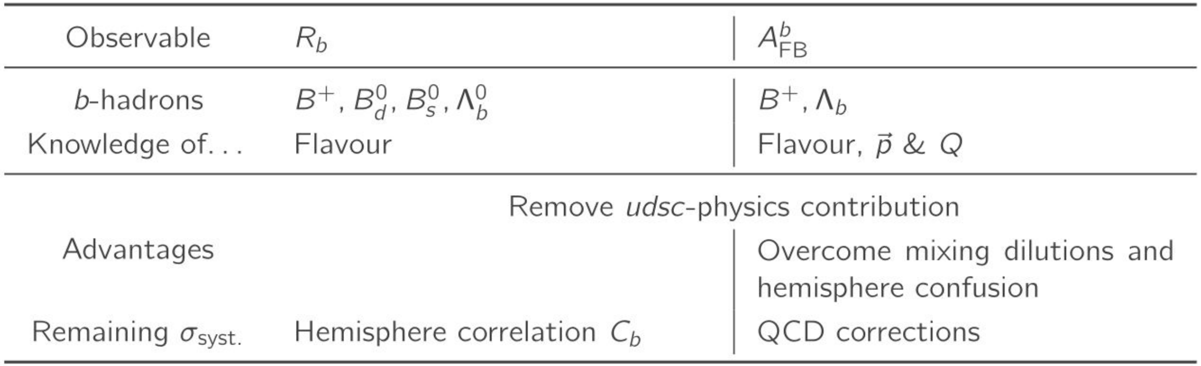


- R_b note
- Lars Röhrig's presentation

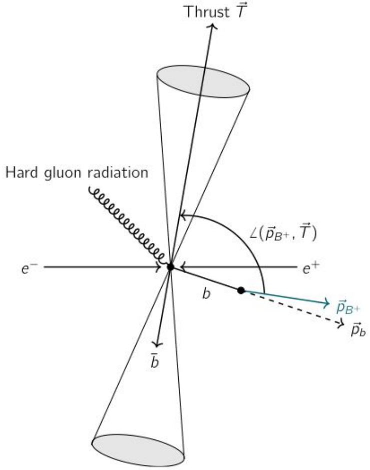
R_b in exclusive *b*-hadron decays: motivation

DOI: 10.17181/znj58-zvx36

- LEP: **σ_{syst} dominated by *udsc*-physics** and hemisphere correlations
- With **Tera-Z**: **σ_{syst} in reach** → measurement limited by systematic uncertainties
- Reconstruct exclusive *b*-hadron: determine quark-flavour with 100 % purity → stick to ultra-pure mass region to assess remaining systematic uncertainties → $\varepsilon_b = 1$
- C_b and QCD corrections evaluated on full simulation sample of 83200 Z → $[B^+ \to D^0 \pi^+]_{\bar{b}}$ $[B^- \to D^0 \pi^-]_b$ events and forced decays ($B^\pm \to [K^+ \pi^-]_{D0}\, \pi^+$)



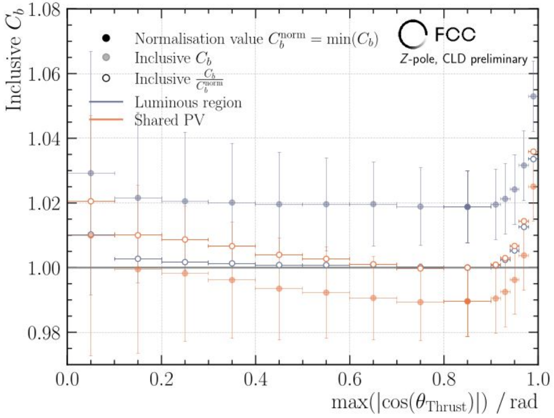
Observable	R_b	A^b_{FB}
b-hadrons	B^+, B^0_d, B^0_s, Λ^0_b	B^+, Λ_b
Knowledge of. . .	Flavour	Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	
		Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{\mathrm{syst.}}$	Hemisphere correlation C_b	QCD corrections



R_b in exclusive b-hadron decays: results

- Goal: find regions of the phase-space which increase C_b (kinematically + event-variables) → at LEP: mainly driven by PV measurement uncertainty

$$\sigma_{\mathrm{PV}} = \sqrt{\sum_{i\in[x,y,z]} \left(\mathrm{PV}_i^{\text{Object-level}} - \mathrm{PV}_i^{\text{Particle-level}}\right)}$$



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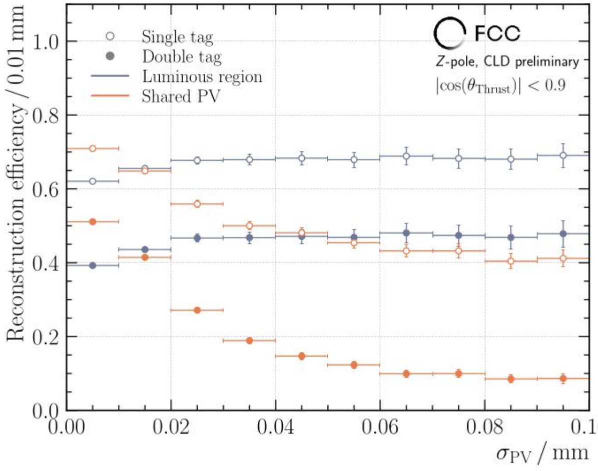

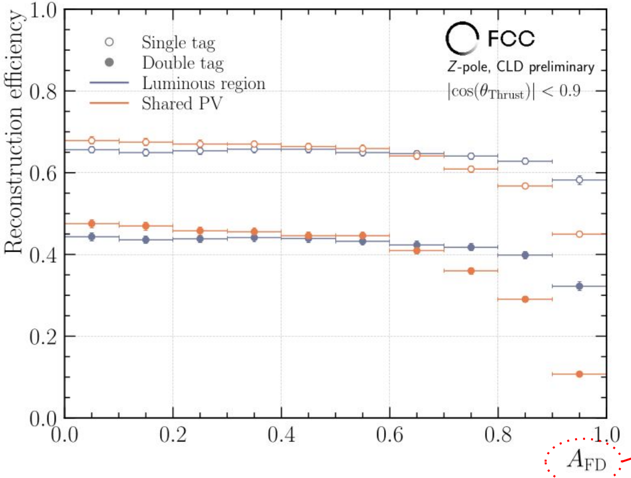

uncertainty projections for R_b: 0.25 (stat.) + 0.3 (syst.)

FSR, 2505.00272

flight distance asymmetry

$$A_{\mathrm{FD}} = \frac{\mathrm{FD}_{B\mathrm{max}} - \mathrm{FD}_{B\mathrm{min}}}{\mathrm{FD}_{B\mathrm{max}} + \mathrm{FD}_{B\mathrm{min}}}$$

Above WW threshold

- W boson properties
- Triple/quadruple gauge couplings

W mass via threshold scan

- At lepton colliders, direct measurement possible via **W-pair threshold scans** (cross section vs. beam energy), simultaneous extraction of m_W and Γ_W

$$\Delta m_W(\text{stat}) = \left(\frac{d\sigma_{WW}}{dm_W}\right)^{-1}\frac{\sqrt{\sigma_{WW}}}{\sqrt{\mathcal{L}}}$$

  - dominant role of **systematic uncertainties**
    a) absolute energy calibration:
      i) Δm_W (syst) ~ 150 keV (FCC-ee) (300 keV on √s) → via resonant depolarisation (only at FCC-ee)
      ii) Δm_W (syst) ~ 700 keV (LEP3) → via radiative return Z (at LEP3)

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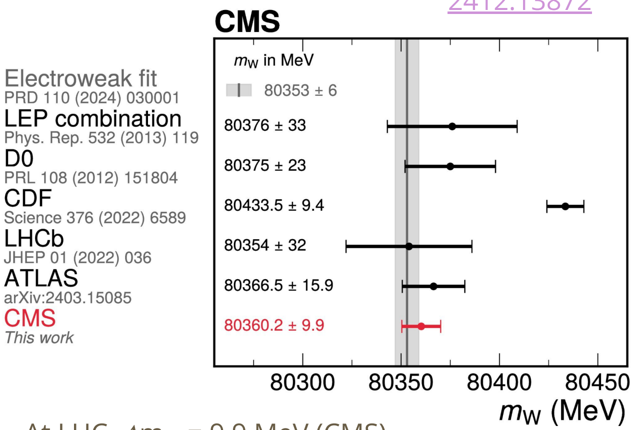
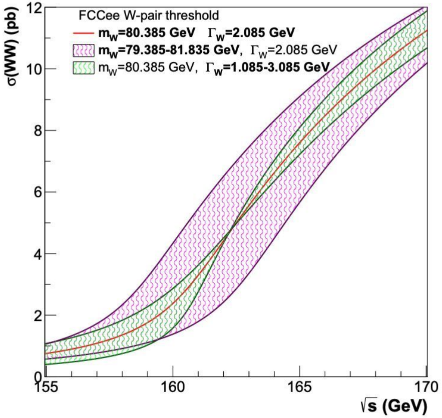


At LHC, Δm_W = 9.9 MeV (CMS)



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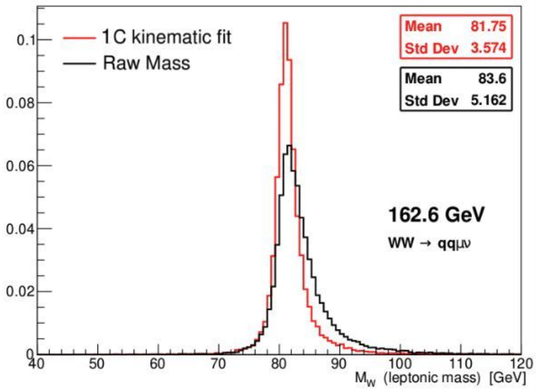
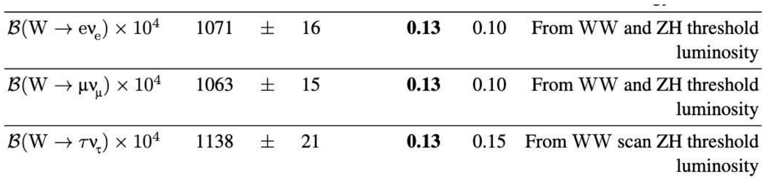
W mass via kinematic fit

- Alternative for the W mass reconstruction: **kinematic fit**
  - direct **reconstruction of decay products**, à la LEP2
    - WW threshold (160 GeV) → FCC-ee, LEP3
    - boosted regime (~ 240 GeV) → linear colliders, FCC-ee, LEP3
- Large *W* production rate to constrain leptonic branching ratios (BRs)
  - absolute measurement limited by luminosity determination → from $\gamma\gamma$/Bhabha scattering at FCC-ee: $\delta\mathscr{L}/\mathscr{L} \sim 10^{-4}$
- Bonus: **triple/quartic gauge couplings**
  - through WW/VBS production
  - full 5D angular information of WW decays in the semileptonic channel

M. Beguin's thesis





$\mathcal{B}(W \to e\nu_e) \times 10^4$	1071	±	16	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \mu\nu_\mu) \times 10^4$	1063	±	15	**0.13**	0.10	From WW and ZH threshold luminosity
$\mathcal{B}(W \to \tau\nu_\tau) \times 10^4$	1138	±	21	**0.13**	0.15	From WW scan ZH threshold luminosity

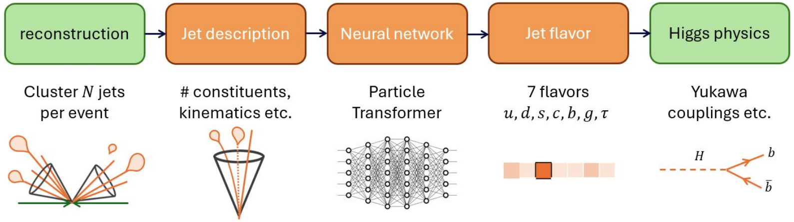
Jet flavour tagging improvements

- Jet flavour tagging improvements for EWK measurements at FCC-ee

Jet flavor tagging performance at FCC-ee - I

- All the **EW precision measurements** in general require good **jet flavour tagging** performance
  - need to minimize contribution from light-jets and charm-jets
  - in addition, $\boldsymbol{b}$ to $\boldsymbol{\bar{b}}$ **discrimination** would be beneficial
- Process used for training: $e^+ e^- \rightarrow$ ZH at 240 GeV, with H $\rightarrow jj$ and Z $\rightarrow \nu\bar{\nu} \rightarrow$ two jets as event signature, done jet by jet

ParticleNetIdea: current *b*-tagging baseline for FCC-ee



reconstruction → Jet description → Neural network → Jet flavor → Higgs physics

Cluster N jets per event

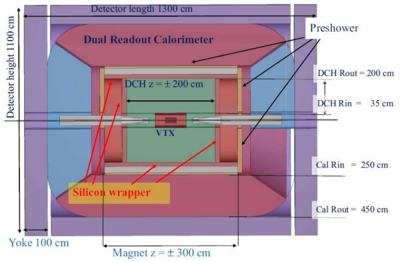
constituents, kinematics etc.

Particle Transformer

7 flavors u, d, s, c, b, g, τ

Yukawa couplings etc.

- Preliminary projections with IDEA detector concept:
  - drift chamber tracker (*dE/dx*)
  - silicon vertex detector and wrapper
    - uses the vertex detector and wrapper as TOF with resolution O(30ps)
  - *coupling* with small beam size and beam pipe
  - fully tested on fast simulation outputs

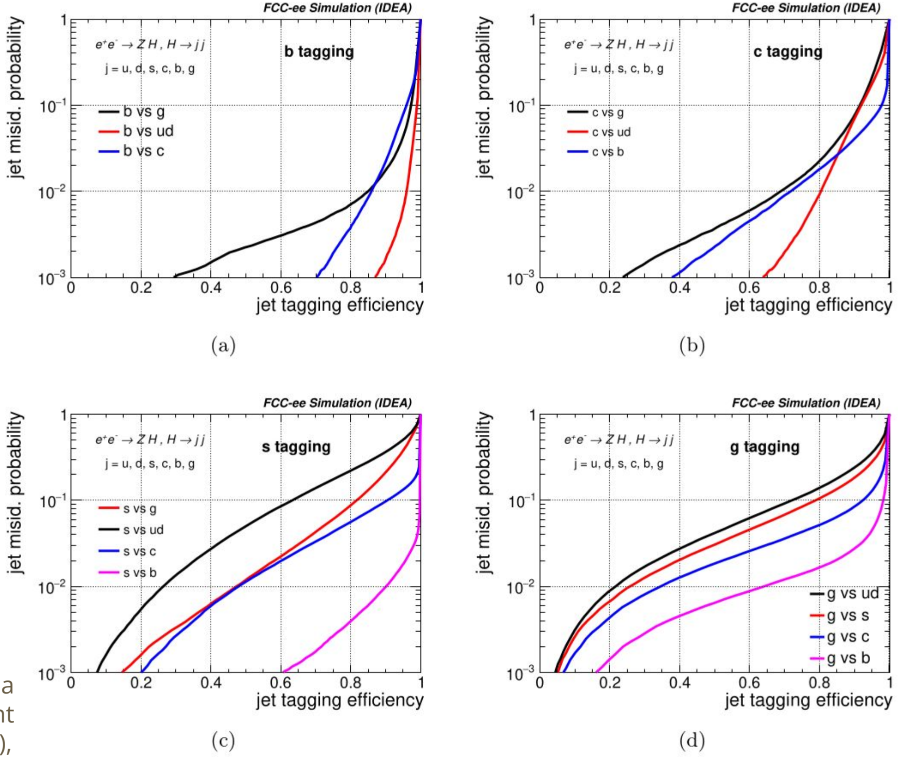


Jet flavor tagging performance at FCC-ee - II

Preliminary projections: → full list in doi:10.17181/0zn0c-3xe20

achieve e.g.
b tagging with 75% efficiency for 10^{-3} charm contamination (single jet)
c 60% $2\ 10^{-3}$ b contamination
s 10% efficiency $2\ 10^{-3}$ u,d contamination

- Possibility to achieve high purity (99%) for *s* quarks with an efficiency of more than 10%
- Given such tagging performance, at m_Z:
    - $R_b \to [\pm 1.2\ (\text{stat.}) \pm 1.6\ (\text{syst.})] \cdot 10^{-6}$
    - $A^b_{FB} \to [\pm 7.8 (\text{stat.}) \pm 1.8\ (\text{syst.})] \cdot 10^{-6}$
    - see full table in spares
- Complete information in A. Blondel's report at FCC Performance Meeting on 13 May 2025



(a) (b)

(c) (d)

ParticleNetIdea performance in terms of a ROC curve for the identification of different *b*-quarks (upper left), *c* quarks (upper right), *s*-quarks (lower left), and *g* (lower right) jets

arXiv:2202.03285v1

Conclusions

- FCC-ee is an excellent machine for **EW precision measurements**
  - **linear colliders**: advantage of chiral observables (asymmetries) per unit of luminosity → possibility of longitudinal polarisation
  - **circular colliders**: 300 (LEP3) - 1000 (FCC-ee) advantage of luminosity → better precision in overall measurements with respect to **linear collider facilities**, factors of:
    - $\sin^2\theta_W$, leptonic asymmetries → 5:1
    - lepton couplings, $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$ → 30:1
    - electromagnetic and strong coupling: only at FCC-ee (or circular machines)
    - m_W → 4:1 (resonant depolarisation helps with FCC-ee)
    - di-fermion and multi-boson production → uniquely probed by:
      - linear colliders (ILC, CLIC, …) up to 500 GeV - 3 TeV
      - muon collider up to 10 TeV
      - FCC-hh up to 40-50 TeV
- Improvements in **Monte Carlo generators** and **flavour tagging performance** can help a lot
  - possibility to go **beyond pure *b*-tagging**

checkout *Electroweak inputs* at the Open Symposium on the EU Strategy (Venice, 2025) for complete information

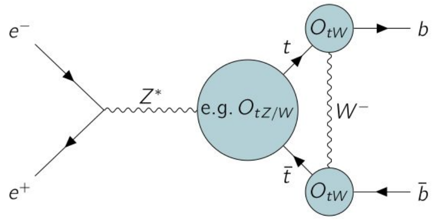
THANK YOU FOR YOUR ATTENTION!

BACKUP

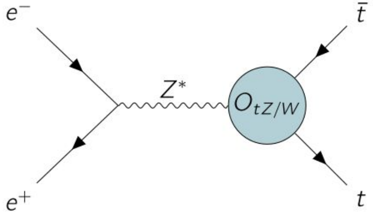
FCC-ee as a precision machine

- FCC-ee is an excellent machine for **Standard Model precision measurements**
    - ttbar production at threshold
    - Higgs and di-Higgs production
    - Z-pole measurements: Z-boson mass and width, asymmetries
- Possible anomalies translate over a range of energy scales: from Z pole to top threshold
- Heavy-quark EW measurements as a probe for new physics with a common set of dimension-6 operators
    - heavy-quark electroweak observables under study: A_{FB}^{b} and R_b
    - measurements will be dominated by the systematic uncertainty at FCC-ee (Z pole) → dominant contribution to uncertainty from light- and *c*-quark physics
    - motivates novel ideas to make use of the Z pole statistics to bring down systematic uncertainty

$\mathcal{O}(m_Z) \sim 90$ GeV



$\mathcal{O}(m_t) \sim 350$ GeV to 365 GeV



FCC-ee EWK projections at the Z pole

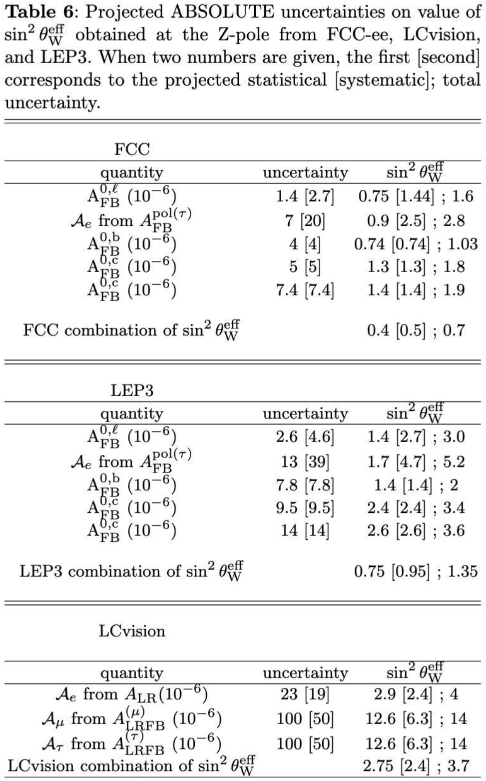


Table 6: Projected ABSOLUTE uncertainties on value of $\sin^2\theta_W^{\rm eff}$ obtained at the Z-pole from FCC-ee, LCvision, and LEP3. When two numbers are given, the first [second] corresponds to the projected statistical [systematic]; total uncertainty.

FCC

quantity	uncertainty	$\sin^2\theta_W^{\rm eff}$
$\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ (10^{-6})	1.4 [2.7]	0.75 [1.44] ; 1.6
$\mathcal{A}_e$ from $A_{\mathrm{FB}}^{\mathrm{pol}(\tau)}$	7 [20]	0.9 [2.5] ; 2.8
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{b}}$ (10^{-6})	4 [4]	0.74 [0.74] ; 1.03
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{c}}$ (10^{-6})	5 [5]	1.3 [1.3] ; 1.8
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{c}}$ (10^{-6})	7.4 [7.4]	1.4 [1.4] ; 1.9
FCC combination of $\sin^2\theta_W^{\rm eff}$		0.4 [0.5] ; 0.7

LEP3

quantity	uncertainty	$\sin^2\theta_W^{\rm eff}$
$\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ (10^{-6})	2.6 [4.6]	1.4 [2.7] ; 3.0
$\mathcal{A}_e$ from $A_{\mathrm{FB}}^{\mathrm{pol}(\tau)}$	13 [39]	1.7 [4.7] ; 5.2
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{b}}$ (10^{-6})	7.8 [7.8]	1.4 [1.4] ; 2
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{c}}$ (10^{-6})	9.5 [9.5]	2.4 [2.4] ; 3.4
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{c}}$ (10^{-6})	14 [14]	2.6 [2.6] ; 3.6
LEP3 combination of $\sin^2\theta_W^{\rm eff}$		0.75 [0.95] ; 1.35

LCvision

quantity	uncertainty	$\sin^2\theta_W^{\rm eff}$
$\mathcal{A}_e$ from $A_{\mathrm{LR}}(10^{-6})$	23 [19]	2.9 [2.4] ; 4
$\mathcal{A}_\mu$ from $A_{\mathrm{LRFB}}^{(\mu)}$ (10^{-6})	100 [50]	12.6 [6.3] ; 14
$\mathcal{A}_\tau$ from $A_{\mathrm{LRFB}}^{(\tau)}$ (10^{-6})	100 [50]	12.6 [6.3] ; 14
LCvision combination of $\sin^2\theta_W^{\rm eff}$		2.75 [2.4] ; 3.7

M. Selvaggi, *Electroweak inputs*, Open Symposium on the EU Strategy for Particle Physics, Venice, 2025

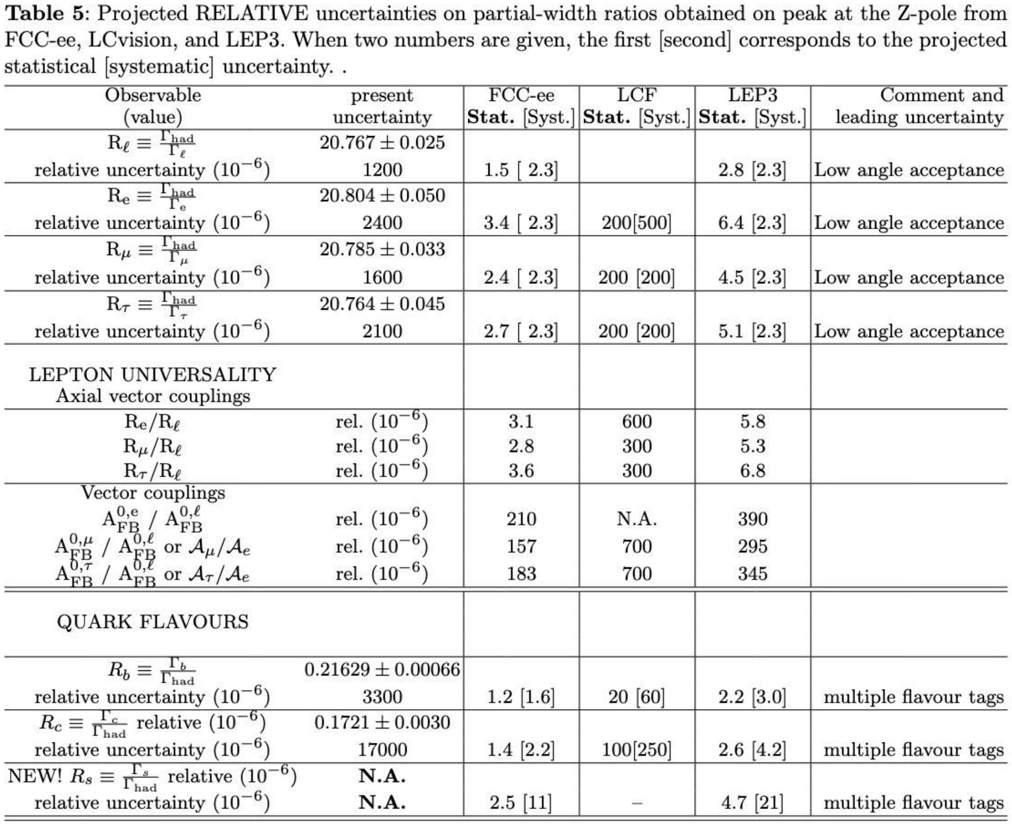


Table 5: Projected RELATIVE uncertainties on partial-width ratios obtained on peak at the Z-pole from FCC-ee, LCvision, and LEP3. When two numbers are given, the first [second] corresponds to the projected statistical [systematic] uncertainty. .

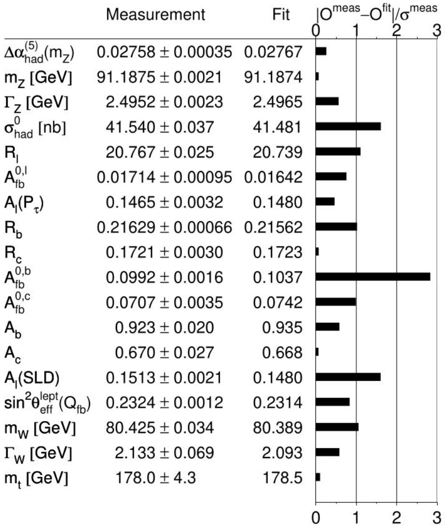
Observable (value)	present uncertainty	FCC-ee **Stat.** [Syst.]	LCF **Stat.** [Syst.]	LEP3 **Stat.** [Syst.]	Comment and leading uncertainty
$\mathrm{R}_\ell \equiv \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell}$	20.767 ± 0.025				
relative uncertainty (10^{-6})	1200	1.5 [2.3]		2.8 [2.3]	Low angle acceptance
$\mathrm{R}_e \equiv \frac{\Gamma_{\mathrm{had}}}{\Gamma_e}$	20.804 ± 0.050				
relative uncertainty (10^{-6})	2400	3.4 [2.3]	200[500]	6.4 [2.3]	Low angle acceptance
$\mathrm{R}_\mu \equiv \frac{\Gamma_{\mathrm{had}}}{\Gamma_\mu}$	20.785 ± 0.033				
relative uncertainty (10^{-6})	1600	2.4 [2.3]	200 [200]	4.5 [2.3]	Low angle acceptance
$\mathrm{R}_\tau \equiv \frac{\Gamma_{\mathrm{had}}}{\Gamma_\tau}$	20.764 ± 0.045				
relative uncertainty (10^{-6})	2100	2.7 [2.3]	200 [200]	5.1 [2.3]	Low angle acceptance
LEPTON UNIVERSALITY Axial vector couplings					
$\mathrm{R}_e/\mathrm{R}_\ell$	rel. (10^{-6})	3.1	600	5.8	
$\mathrm{R}_\mu/\mathrm{R}_\ell$	rel. (10^{-6})	2.8	300	5.3	
$\mathrm{R}_\tau/\mathrm{R}_\ell$	rel. (10^{-6})	3.6	300	6.8	
Vector couplings					
$\mathrm{A}_{\mathrm{FB}}^{0,\mathrm{e}}$ / $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$	rel. (10^{-6})	210	N.A.	390	
$\mathrm{A}_{\mathrm{FB}}^{0,\mu}$ / $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ or $\mathcal{A}_\mu/\mathcal{A}_e$	rel. (10^{-6})	157	700	295	
$\mathrm{A}_{\mathrm{FB}}^{0,\tau}$ / $\mathrm{A}_{\mathrm{FB}}^{0,\ell}$ or $\mathcal{A}_\tau/\mathcal{A}_e$	rel. (10^{-6})	183	700	345	
QUARK FLAVOURS					
$R_b \equiv \frac{\Gamma_b}{\Gamma_{\mathrm{had}}}$	0.21629 ± 0.00066				
relative uncertainty (10^{-6})	3300	1.2 [1.6]	20 [60]	2.2 [3.0]	multiple flavour tags
$R_c \equiv \frac{\Gamma_c}{\Gamma_{\mathrm{had}}}$ relative (10^{-6})	0.1721 ± 0.0030				
relative uncertainty (10^{-6})	17000	1.4 [2.2]	100[250]	2.6 [4.2]	multiple flavour tags
NEW! $R_s \equiv \frac{\Gamma_s}{\Gamma_{\mathrm{had}}}$ relative (10^{-6})	**N.A.**				
relative uncertainty (10^{-6})	**N.A.**	2.5 [11]	–	4.7 [21]	multiple flavour tags

Z pole asymmetries at the FCC-ee

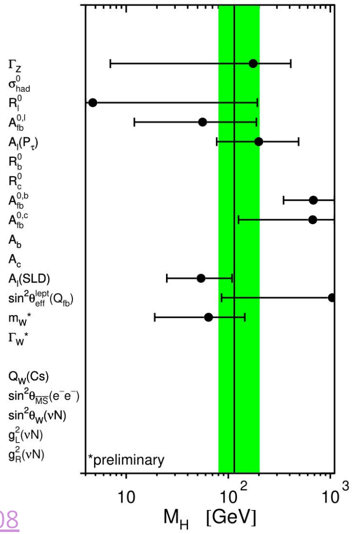
- A^{b}_{FB} : forward-backward asymmetry in $e^{+}e^{-} \rightarrow Z \rightarrow b\bar{b}$ events

$$A^{b}_{\mathrm{FB}} \equiv \frac{N_F - N_B}{N_F + N_B} \quad \text{with} \quad N_F = \int_0^1 \frac{d\sigma}{d\cos\theta}\, d\cos\theta \qquad N_B = \int_{-1}^0 \frac{d\sigma}{d\cos\theta}\, d\cos\theta$$

- most statistically accurate measurement of $\sin^2\vartheta_{W,\,eff}$ at the Z pole
- most constraining term on the Higgs mass

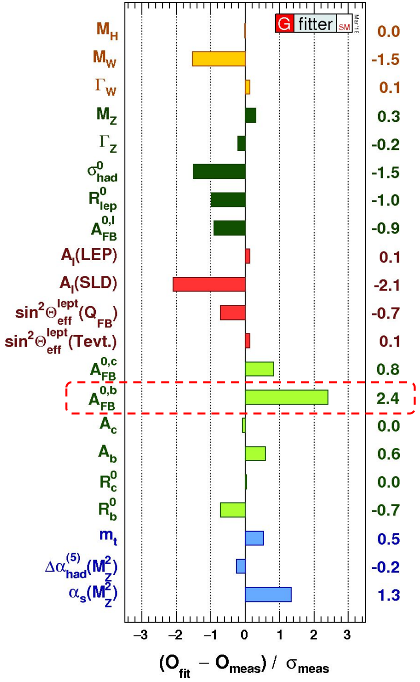


	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



arXiv: 0509008

2018 update



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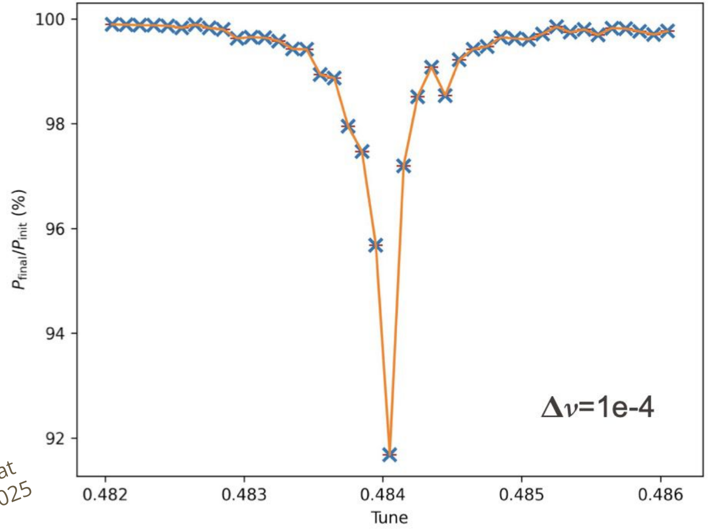
ν_s via resonant depolarization

- FCC-ee simulation of a determination of the **spin tune** $\nu_s = E_{beam}$ (GeV)/0.440648 using **resonant depolarization**
  - *y*-axis: polarization level (after/before)
  - *x*-axis: spin tune ν_s around which a RF kicker is applied on the beam.
  - precision of $\Delta\nu_s = 0.0001$

  → corresponds to an interval of 44 keV in which the resonance is equivalent to a RMS of:

  ± 44.0648 keV/√(12) = ±13 keV

"Progress in the center-of-mass energy calibration at FCC-ee" talk by A. Martens at EPS-HEP 2025



Yi Wu's talk at FCC Week 2025

spin tune ν_s using res. depolarization at FCC-ee

Hemisphere analysis principles

- Important principles of e^+e^-: (none of them true in *pp* collisions)
    - event-by-event conservation of
        - 4-momentum
        - all 0 charges electric, color, flavour and baryon number
        - little and identifiable pile-up (0.002 at most)
- Analysis based on full event → no jet algorithm
    - thrust axis defines forward and backward hemispheres
    - hemisphere charges Q_F, Q_B

      $\rightarrow Q_F - Q_B = Q_{FB}$ and $Q_F + Q_B = Q_{tot}$

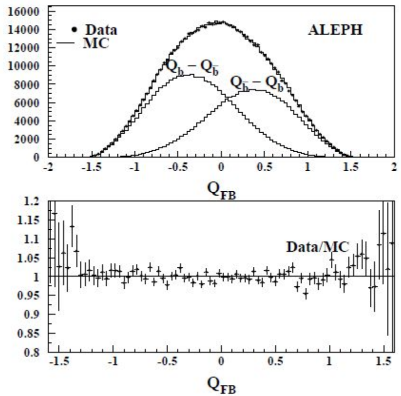


Fig. 2. The charge difference between forward and backward hemispheres measured in the selected event sample labelled **E** in Fig. 3. The MC distribution corresponds to an asymmetry of $A^b_{\rm FB} = 0.0967$

Alain Blondel's presentation at FCC Physics Performance meeting

hemisphere charge separation

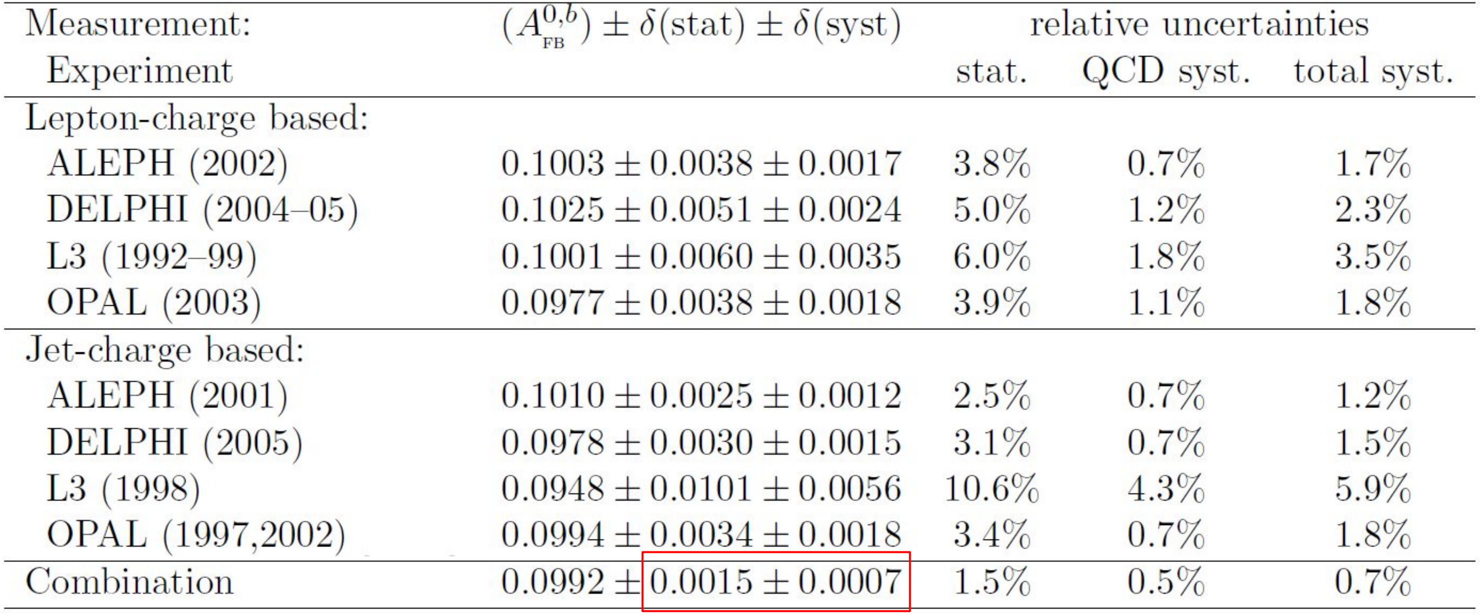
$$\begin{aligned}\langle Q^f_{{\rm F}B}\rangle &= \langle Q^f_{\rm F} - Q^f_{\rm B}\rangle \\ &= \frac{1}{n^f_{\rm tot}}\left(n^f_{\rm F}\langle Q_f - Q_{\bar{f}}\rangle + n^f_{\rm B}\langle Q_{\bar{f}} - Q_f\rangle\right) \\ &= \delta_f\, A^f_{{\rm F}B}\,\frac{8}{3}\,\frac{\cos\theta}{1+\cos^2\theta}\,, \qquad (1)\end{aligned}$$

hemisphere charge separation from data:

$$\begin{aligned}\bar{\delta}^2_f &= \sigma^2(Q^f_{{\rm F}B}) - \sigma^2(Q^f_{\rm tot}) \\ &= \delta^2_f - 4\,\langle \mathcal{R}_f \mathcal{R}_{\bar{f}}\rangle - \langle Q^f_{{\rm F}B}\rangle^2 + \langle Q^f_{\rm tot}\rangle^2 \\ &= [\delta_f\,(1+k_f)]^2\;,\end{aligned}$$

A^b_{FB}: LEP measurements

- Jet charge and soft lepton tagging methods for the A^b_{FB} measurement already implemented at LEP



	Measurement:	$(A^{0,b}_{\mathrm{FB}}) \pm \delta(\mathrm{stat}) \pm \delta(\mathrm{syst})$	relative uncertainties		
	Experiment		stat.	QCD syst.	total syst.
	Lepton-charge based:				
Eur.Phys.J.C24	ALEPH (2002)	$0.1003 \pm 0.0038 \pm 0.0017$	3.8%	0.7%	1.7%
Eur.Phys.J.C34	DELPHI (2004–05)	$0.1025 \pm 0.0051 \pm 0.0024$	5.0%	1.2%	2.3%
Phys.Lett.B448	L3 (1992–99)	$0.1001 \pm 0.0060 \pm 0.0035$	6.0%	1.8%	3.5%
Phys.Lett.B577	OPAL (2003)	$0.0977 \pm 0.0038 \pm 0.0018$	3.9%	1.1%	1.8%
	Jet-charge based:				
Eur.Phys.J.C22	ALEPH (2001)	$0.1010 \pm 0.0025 \pm 0.0012$	2.5%	0.7%	1.2%
Eur.Phys.J.C40	DELPHI (2005)	$0.0978 \pm 0.0030 \pm 0.0015$	3.1%	0.7%	1.5%
Phys.Lett.B439	L3 (1998)	$0.0948 \pm 0.0101 \pm 0.0056$	10.6%	4.3%	5.9%
Phys.Lett.B546	OPAL (1997,2002)	$0.0994 \pm 0.0034 \pm 0.0018$	3.4%	0.7%	1.8%
	Combination	$0.0992 \pm \boxed{0.0015 \pm 0.0007}$	1.5%	0.5%	0.7%

stat syst

b-quark charge determination

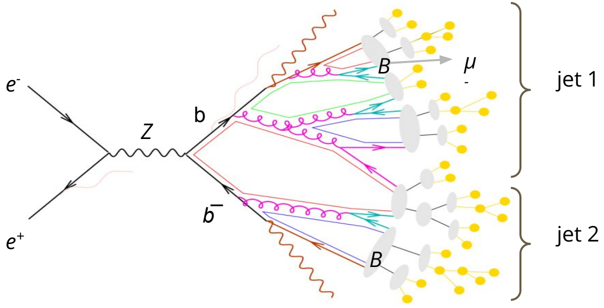
DOI: 10.17181/dpyb5-vnc32

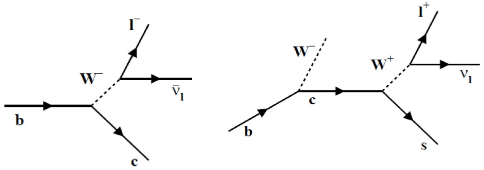
- Two classes of **methods**:

  1. **Jet charge**:
     - charge of jet obtained as weighted **sum** of charges of constituent **tracks**
     - can be applied to all jets ⇒ maximal efficiency
     - relatively low purity
     - strong dependence on jet shape and hadronization

  2. **Soft lepton tagging**:
     - charge of *b* inferred from charge of *e* or *μ* in ***B*-hadron semileptonic decay**
       - crucial to minimize ***b* → *c* → *μ*** contribution that "fakes" charge
     - relatively low efficiency (restricted to semileptonic decays)
     - better purity
     - highly sensitive to *B*-hadron decay modelling

many possible variations exist, e.g. based on exclusive final states from B-hadron decays, secondary vertex reconstruction...



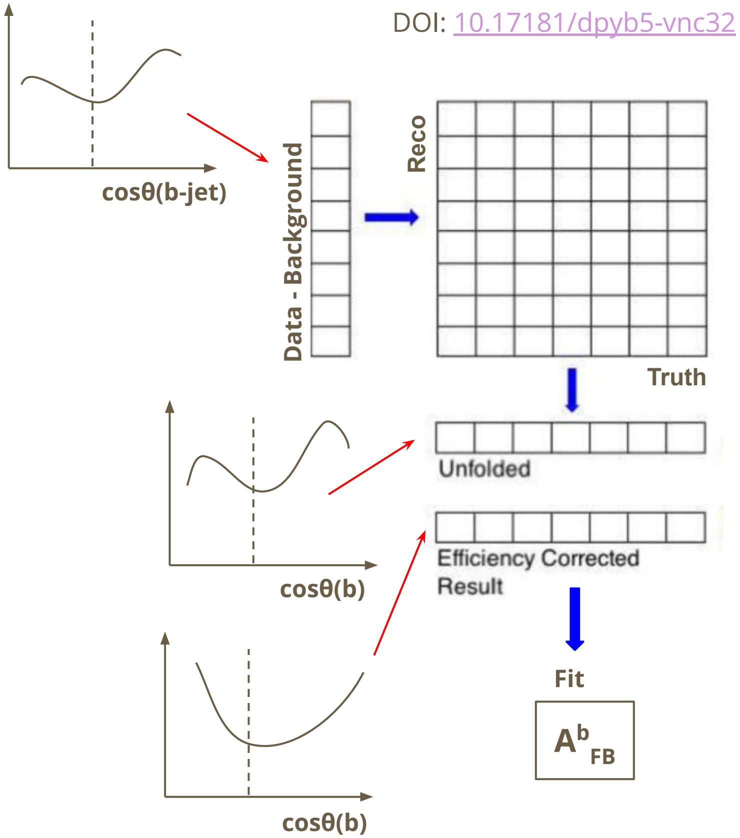


Branching ratios (in %)	
BR($b \to \ell^-$)	10.90 ± 0.32 (∓ 0.21)
BR($b \to c \to \ell^+$)	8.30 ± 0.47 (± 0.19)
BR($b \to c \to \ell^-$)	1.30 ± 0.50
BR($b \to \tau \to \ell^-$)	0.70 ± 0.20
BR($c \to \ell^+$)	9.80 ± 0.50

Analysis strategy

DOI: 10.17181/dpyb5-vnc32

- **Analysis framework**:
  1. **feasibility study** with **Key4hep-FCCAnalyses** framework and **standalone Madgraph private** simulation
     - ■ **EDM4hep** for event generation
     - ■ **Pythia8** for parton shower simulation
     - ■ **Delphes** for detector fast-simulation
  2. Software features:
     - ■ **IDEA detector** concept
     - ■ **Durham ee-kT** jet algorithm used, ***R*****=0.4**
     - ■ simplified Delphes ***b*****-tagging** (flat 80% efficiency, 10%/1% *c*/light-mistagging)
- **Investigated workflow**:
  1. build **reco-level observable** using:
     - ■ jet direction
     - ■ charge determined with one of the two methods (studies in parallel)
  2. perform **unfolding** from reco-level to parton-level
  3. extract A_{FB}^{b} from **fit** to unfolded distribution



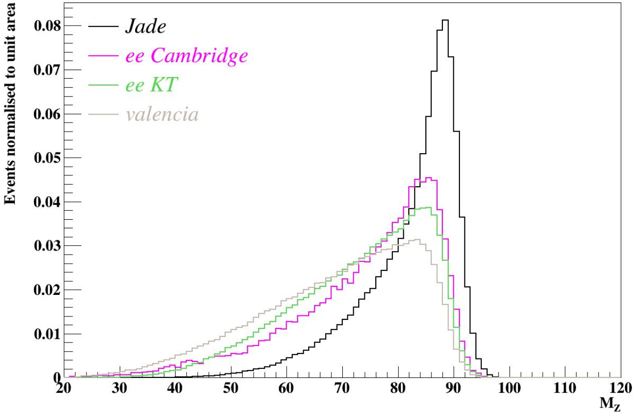
Alternative workflow:
starting to consider also template fit at reco-level (with templates obtained via "folding" or reweighting)

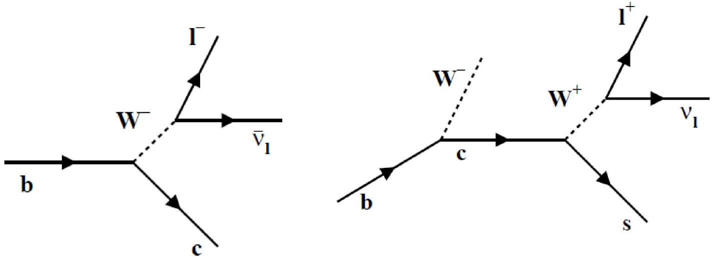
Soft muon based studies - I

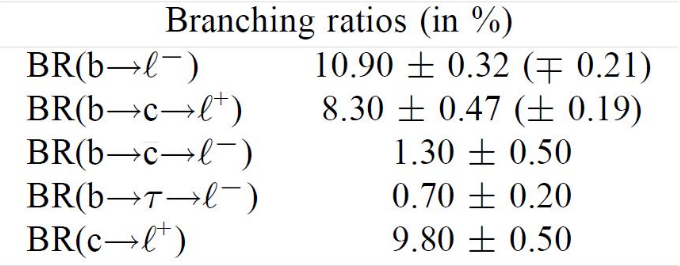
- Using **central FCC analysis software** and centrally produced samples
- **Jets** reconstructed by Durham **ee-kT** algorithm
- Focusing on **soft muon tagging** method

- Investigating optimal **selection** to minimize contribution from "charge flips" due to $b \rightarrow c \rightarrow \mu$ decays:
  - μ with ΔR (jet) < 0.4 (non-isolate) used to *tag* jets
  - $p(\mu) > 10$ GeV cut applied
  - investigating cuts on other quantities (e.g. $p_T^{rel}(\mu,jet)$)

DOI: 10.17181/dpyb5-vnc32







Branching ratios (in %)	
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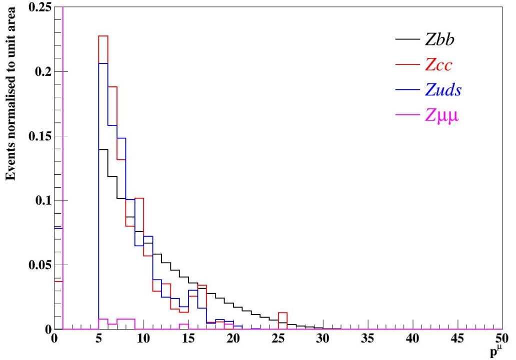
$BR(b \to c \to \ell^+)$	$8.30 \pm 0.47\ (\pm 0.19)$
$BR(b \to c \to \ell^-)$	1.30 ± 0.50
$BR(b \to \tau \to \ell^-)$	0.70 ± 0.20
$BR(c \to \ell^+)$	9.80 ± 0.50

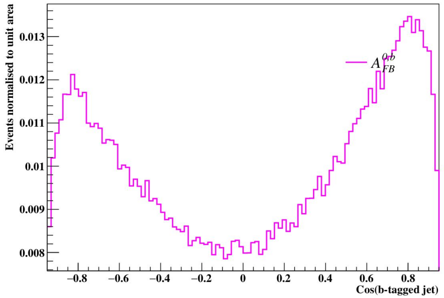
Soft muon based studies - II

DOI: 10.17181/dpyb5-vnc32

- Background studies:
  - $Z \rightarrow c\bar{c}$
  - $Z \rightarrow light$
  - $Z \rightarrow \mu\mu$
- Jet selection rejects most of $Z \rightarrow \mu\mu$
- *b*-tagging cut will reduce the rest
  - cut on $p_\mu > 10$ GeV will further reduce them



- Unfolding implemented:



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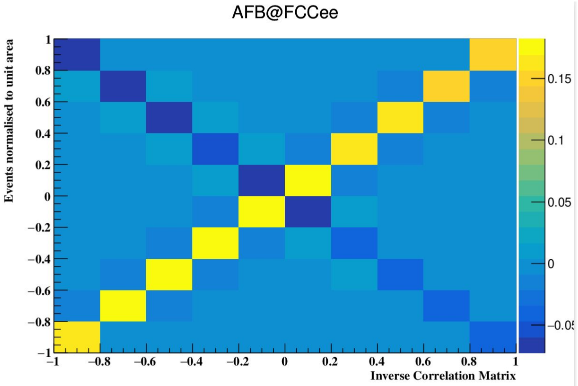

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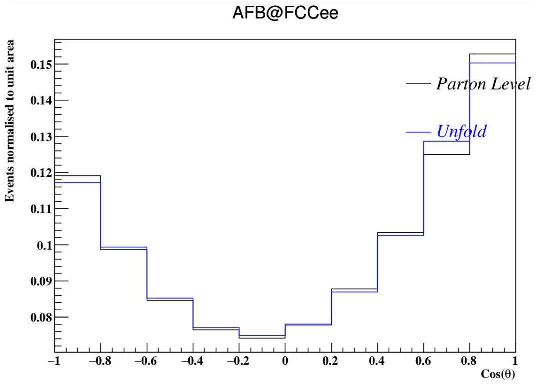
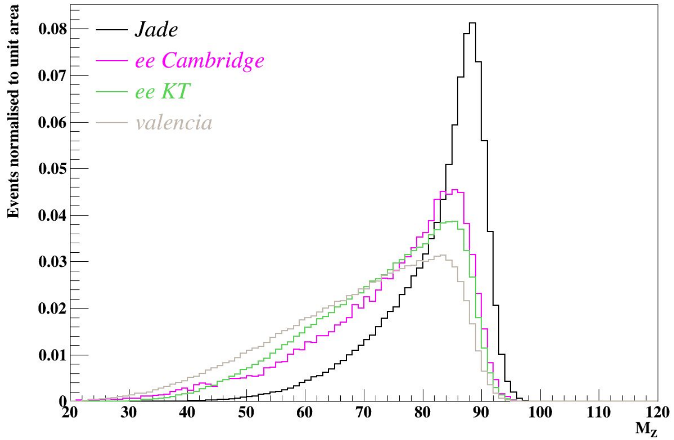


- Extraction of statistical and systematic uncertainty

Soft muon tagging optimisation and unfolding

- Backgrounds: $Z \rightarrow c\bar{c}$, $Z \rightarrow light$, $Z \rightarrow \mu\mu$
- Optimal **selection** to minimize contribution from "charge flips" due to $\boldsymbol{b \rightarrow c \rightarrow \mu}$ decays:
  - μ with ΔR (jet) < 0.4 (non-isolate) used to *tag* jets
  - $p(\mu) > 10$ GeV cut
- Unfolding implemented



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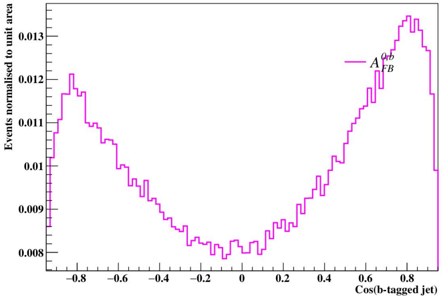
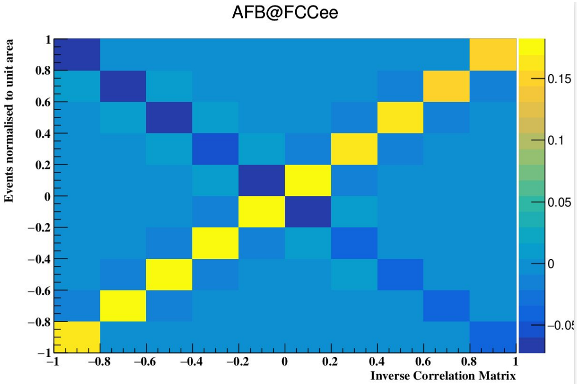
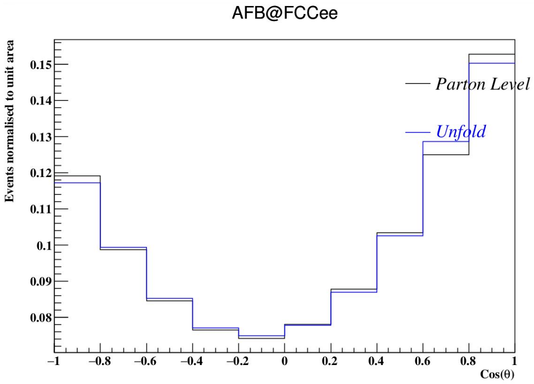


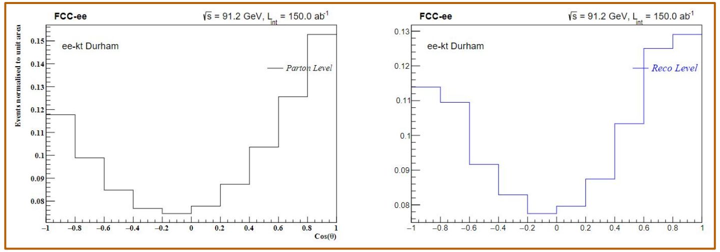


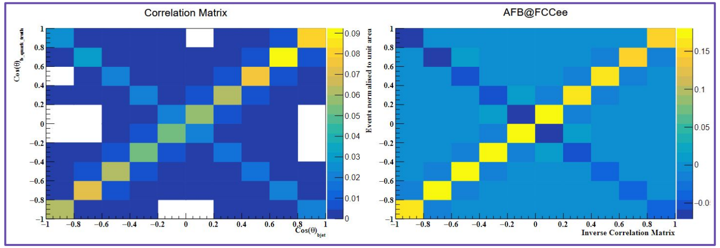


Results on the A_{FB}^{b} feasibility study

DOI: 10.17181/dpyb5-vnc32

- Event generation and selection:
    - beam energy: 45.5348 GeV (*Z*-pole) from **"Spring2021"**
    - signal: **2 *b*-tagged jets**
        - 1 jet with charge > 0
        - 1 jet with charge < 0
- Building **truth-level and reco-level *cosθ* distributions** for *b*-quarks and *b*-quark-jets
- **Response matrix** and efficiency correction vector built from $1 \cdot 10^6$ events
    - re-scaling the event number to match expected luminosity at *Z*-pole: $L_{Z\text{-}pole} = 140\ \text{ab}^{-1}$
- **Unfolding with simple matrix inversion**, 10x10 matrix used
- **Statistical uncertainty** extracted from pseudo-experiments
- Different sources of systematic uncertainty investigated:
    - modelling of **heavy-quark fragmentation**
    - emission of **final-state QCD radiation**
    - **Pythia** versus **Dire** parton shower
    - *b*-tagging and *c*-mistagging rates





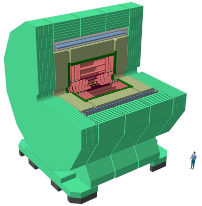
systematic uncertainty contribution

$A_{FB}^{b,0}$ $(\times 10^4)$	992	±	16	0.04	0.04	b-quark asymmetry at Z pole From jet charge

A_{FB}^{b}: systematic uncertainties and interplays with R_b

DOI: 10.17181/dpyb5-vnc32

- **Statistical uncertainty will not be an issue**:
  - LEP combination has ~equal stat and syst contributions
  - expected ~10^5 times more statistics at FCC-ee ⇒ ~300 times smaller than statistical uncertainty
- **Systematic uncertainties** expected to be **dominant**, but many handles in data to constrain them, in particular extra radiation and gluon splitting affecting hemisphere correlations → to be measured in situ
- Special focus on **QCD corrections to A_{FB}^{b}**:
  - perturbative regime → emission of gluon final state radiation
  - non-perturbative regime → *b*-quark fragmentation modelling
- Considering **hemisphere correlations** → effort held by **LPC (Clermont-Ferrand)-TU Dortmund FCC group**
  - two different approaches:
    - **inclusive measurement** → centrally generated events + IDEA fast-sim Delphes outputs
    - **exclusive *B*-hadron decays** → private simulation + tests on CLD full-sim outputs

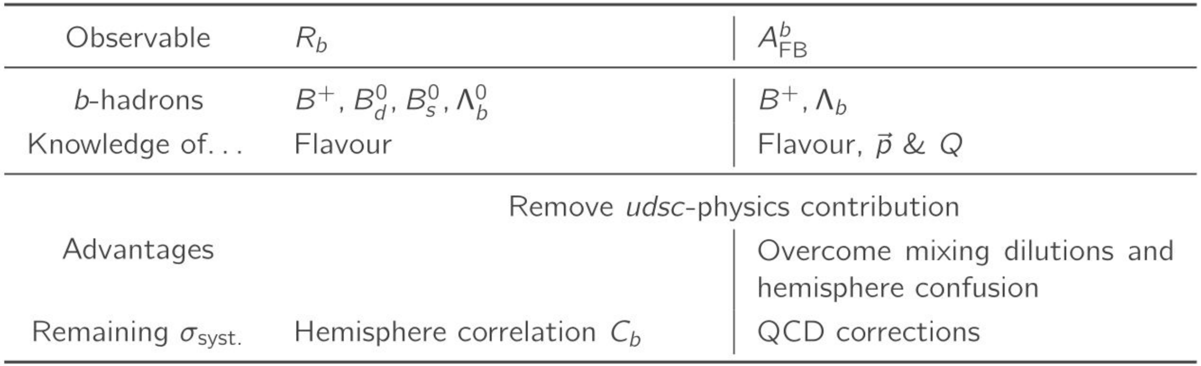


- R_b (inclusive) note
- Lars Röhrig's presentation

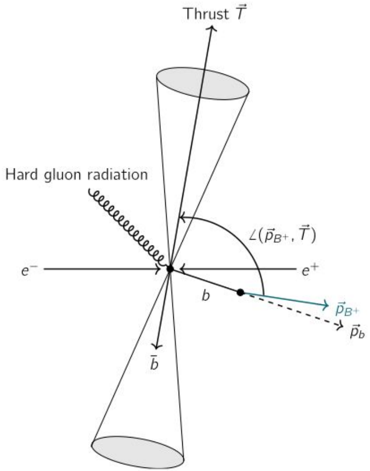
R_b in exclusive *b*-hadron decays: motivation

DOI: 10.17181/znj58-zvx36

- LEP: σ_{syst} dominated by *udsc*-physics and hemisphere correlations
- With Tera-*Z*: σ_{syst} in reach → measurement limited by systematic uncertainties
- Reconstruct exclusive *b*-hadron: determine quark-flavour with 100 % purity → stick to ultra-pure mass region to assess remaining systematic uncertainties → $\varepsilon_b = 1$
- C_b and QCD corrections evaluated on full simulation sample of 83200 $Z \to [B^+ \to D^0 \pi^+]_{\bar{b}} [B^- \to D^0 \pi^-]_b$ events and forced decays ($B^\pm \to [K^+ \pi^-]_{D0} \pi^+$)



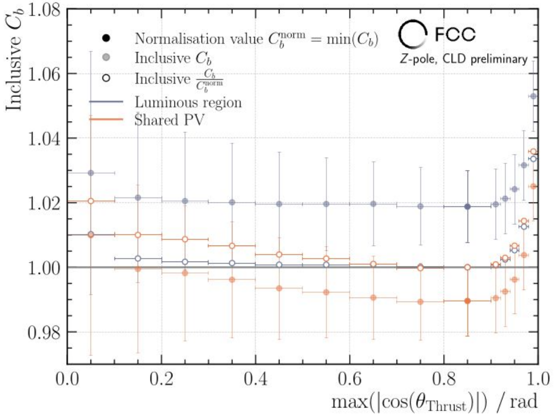
Observable	R_b	A^b_{FB}
b-hadrons	$B^+, B^0_d, B^0_s, \Lambda^0_b$	B^+, Λ_b
Knowledge of. . .	Flavour	Flavour, $\vec{p}$ & Q
Advantages	Remove *udsc*-physics contribution	
		Overcome mixing dilutions and hemisphere confusion
Remaining $\sigma_{syst.}$	Hemisphere correlation C_b	QCD corrections

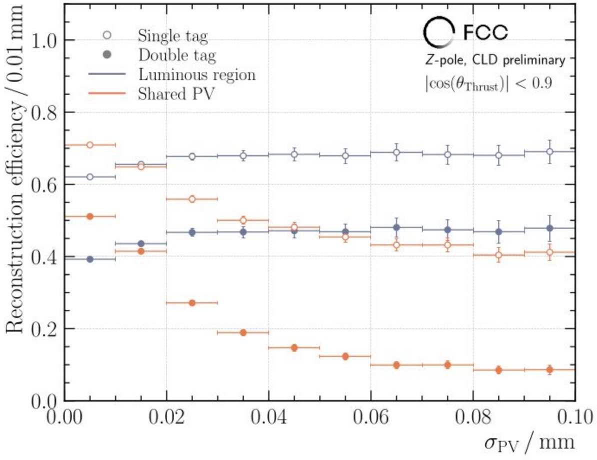


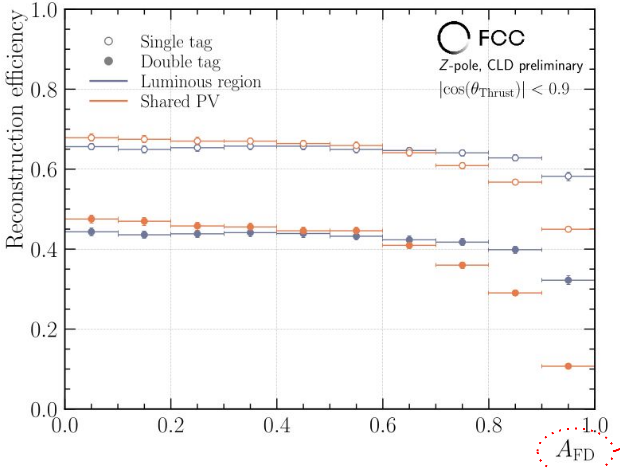
R_b in exclusive *b*-hadron decays: results

- Goal: find regions of the phase-space which increase C_b (kinematically + event-variables) → at LEP: mainly driven by PV measurement uncertainty

$$\sigma_{\mathrm{PV}} = \sqrt{\sum_{i\in[x,y,z]} \left(\mathrm{PV}_i^{\text{Object-level}} - \mathrm{PV}_i^{\text{Particle-level}}\right)}$$







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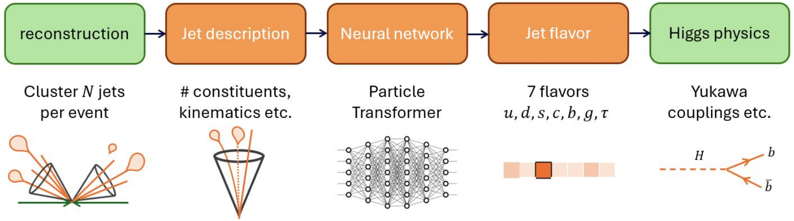
flight distance asymmetry

$$A_{\mathrm{FD}} = \frac{\mathrm{FD}_{B_{\max}} - \mathrm{FD}_{B_{\min}}}{\mathrm{FD}_{B_{\max}} + \mathrm{FD}_{B_{\min}}}$$

Jet flavor tagging performance at FCC-ee - I

- A_{FB}^{b} and R_b measurements (as well as **EW precision measurements** in general) require good **jet flavour tagging** performance
  - need to minimize contribution from light-jets and charm-jets
  - in addition, ***b*** **to** $\boldsymbol{\bar{b}}$ **discrimination** would be beneficial
- Process used for training: $e^+ e^- \rightarrow$ ZH at 240 GeV, with H $\rightarrow jj$ and Z $\rightarrow \nu\bar{\nu} \rightarrow$ two jets as event signature, done jet by jet

ParticleNetIdea: current *b*-tagging baseline for FCC-ee


reconstruction → Jet description → Neural network → Jet flavor → Higgs physics

Cluster N jets per event

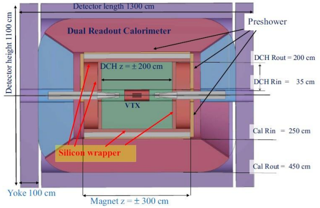
constituents, kinematics etc.

Particle Transformer

7 flavors u, d, s, c, b, g, τ

Yukawa couplings etc.

- Preliminary projections with IDEA detector concept:
  - drift chamber tracker (*dE/dx*)
  - silicon vertex detector and wrapper
    - uses the vertex detector and wrapper as TOF with resolution O(30ps)
  - *coupling* with small beam size and beam pipe

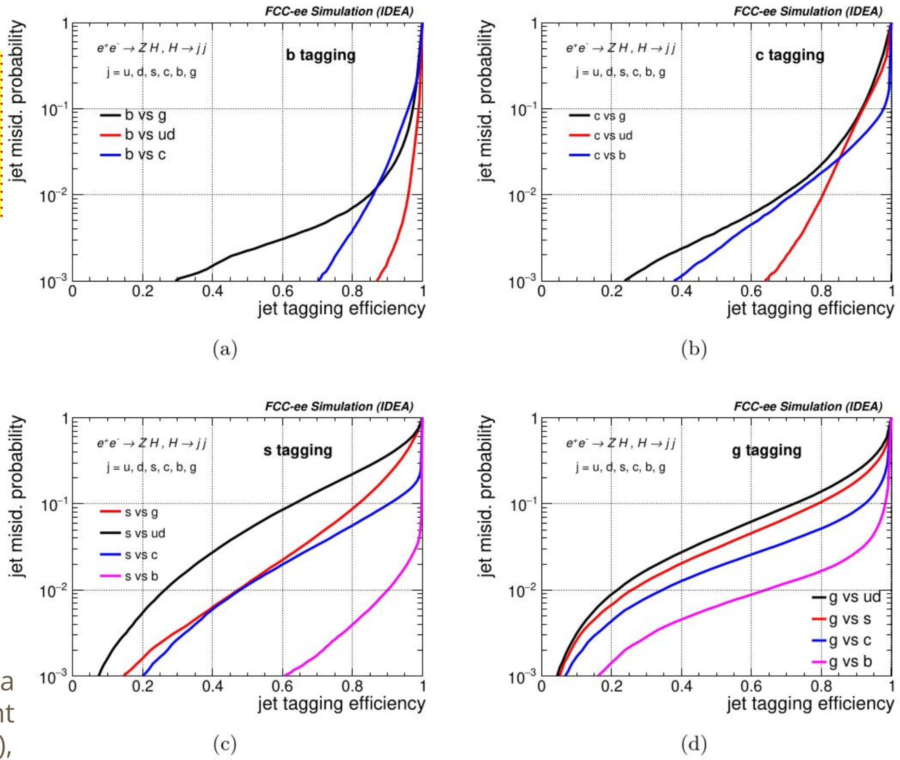


Jet flavor tagging performance at FCC-ee - II

Preliminary projections:

achieve e.g.
b tagging with 75% efficiency for 10^{-3} charm contamination (single jet)
c 60% $2\ 10^{-3}$ b contamination
s 10% efficiency $2\ 10^{-3}$ u,d contamination

- Possibility to achieve high purity (99%) for *s* quarks with an efficiency of more than 10%
- More information available in:
  - A. Blondel's report at FCC Performance Meeting on 13 May 2025
  - F. Bedeschi, L. Gouskos, M. Selvaggi, arXiv:2202.03285v1



(a) (b)

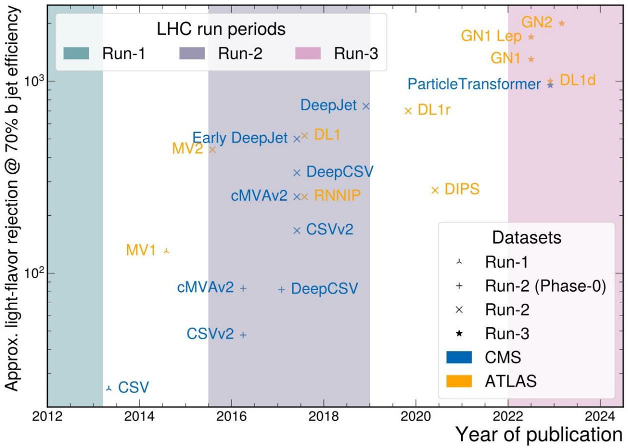
(c) (d)

ParticleNetIdea performance in terms of a ROC curve for the identification of different *b*-quarks (upper left), *c* quarks (upper right), *s*-quarks (lower left), and *g* (lower right) jets

arXiv:2202.03285v1

Jet flavor tagging: a look at ATLAS & CMS

- EW precision tests at FCC-ee can benefit from the long story of improvement in jet flavour identification at the LHC
    - ATLAS and CMS share very similar directions, however with different approaches
        - combination of output probabilities of the tagger (i.e. GN2 - or its ancestor GN1) into a 1D discriminant defined as likelihood ratio:
        - regress the energy correction and resolution of the jet with the same algorithm to define a per-jet flavour aware jet energy regression and resolution estimation



arXiv:2404.01071

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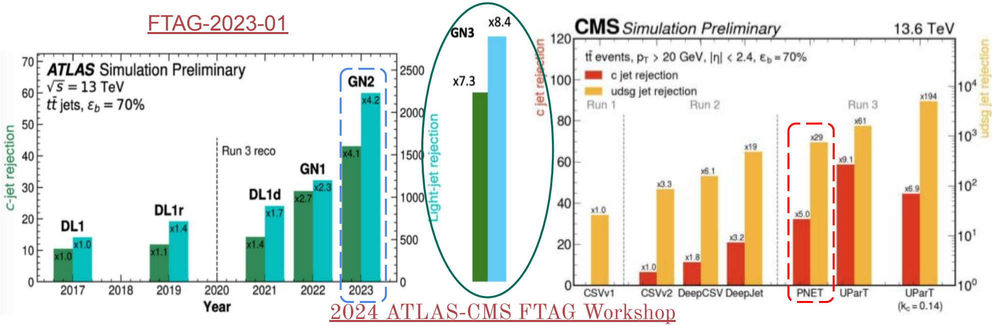

2024 ATLAS-CMS FTAG Workshop

→ moving to **GNN-based approaches** and transformers architecture!

Electroweak physics at future colliders

- Electroweak physics programme at intensity frontier
    - *Z*-boson lineshape:
        - m_Z, Γ_Z, σ_0^{had} ($\rightarrow N_\nu$),
        - $R_\ell = \Gamma_{had}/\Gamma_\ell$, $R_q = \Gamma_{qq}/\Gamma_{had}$
        - A_{FB}^{ℓ}, q, P_τ, $A_{FB}(P_\tau)$
        - $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$ → direct measurement vs. lattice calculations → interpret data without having to trust lattice and test lattice calculations themselves
    - *WW*, *ZH*, $t\bar{t}$ thresholds, and above:
        - m_W, Γ_W, BR($W \rightarrow \ell\nu$), $\alpha_S(m_Z)$, m_t, triple and quartic gauge couplings
- Great precision needed to interpret potential deviations in terms of new physics → many EW precision observables to explore nature of BSM candidate signals

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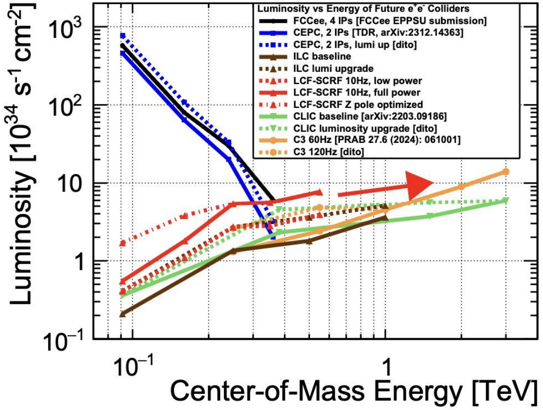
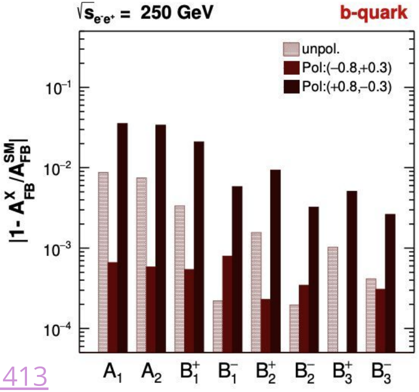




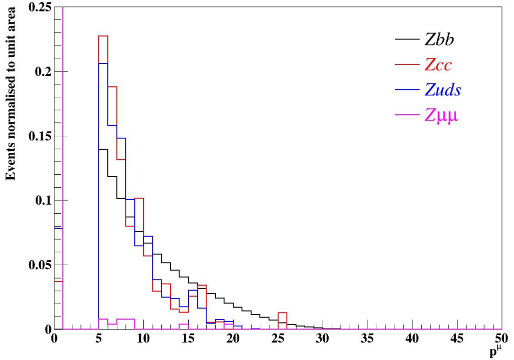
2306.11413

Soft muon based studies

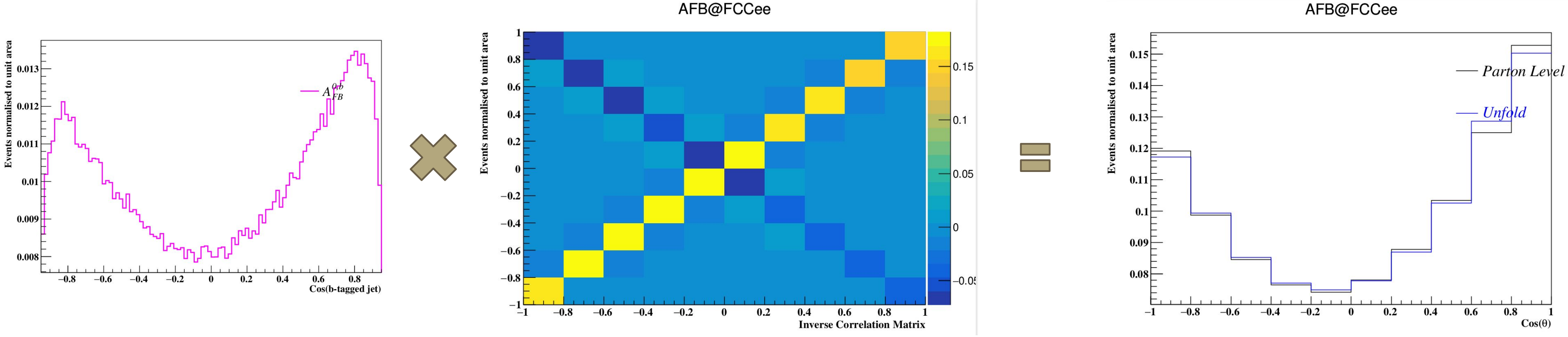
DOI: 10.17181/dpyb5-vnc32

- Background studies:
    - $Z \rightarrow c\bar{c}$
    - $Z \rightarrow light$
    - $Z \rightarrow \mu\mu$
- Jet selection rejects most of $Z \rightarrow \mu\mu$

- *b*-tagging cut will reduce the rest
    - cut on $p_\mu > 10$ GeV will further reduce them



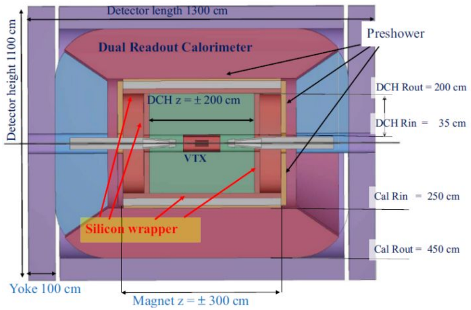
- Unfolding implemented:

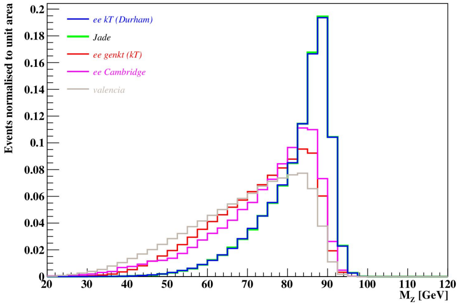


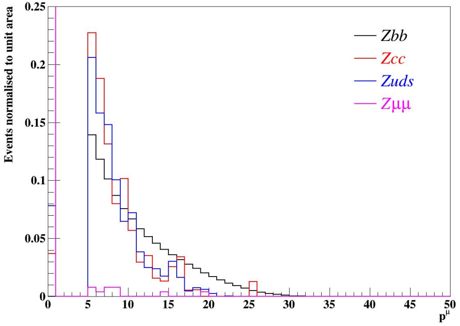
- Extraction of statistical and systematic uncertainty

A_{FB}^b measurement at FCC-ee

- A_{FB}^b measurement may be performed at the **FCC-ee**
  - 91.8 km circumference
  - 2045-2060 as e^+e^-, 2070-2090 as *pp* collider
  - feasibility study phase ongoing until 2027
- **Feasibility study on A_{FB}^b at FCC-ee** based on **HEP-FCC/FCCAnalyses** framework
  - **EDM4HEP** for event generation
  - **Pythia8** for parton shower simulation
  - **Delphes** for detector fast-simulation
- Software features:
  - **IDEA detector** concept
  - **Durham ee-kT** jet algorithm used, Dire parton shower
  - Simplified Delphes ***b*-tagging** (flat 80% efficiency, 10%/1% *c*/light-mistagging)
  - ***b*-quark charge** determined with:
    - **jet charge** built with weighted sum of charges of tracks (as saved by Delphes)
    - **soft lepton** (muon) tagging







Conclusions

- **FCC-ee** is not just a Higgs factory, but also an **EW** and Top laboratory
- Measurements of A_{FB}^{b} (inclusive) and R_b (and A_{FB}^{b}) in exclusive *b*-hadron decays show encouraging results
    - negligible contribution from statistical uncertainty
    - systematic uncertainties dominating
        - discrimination between $\boldsymbol{b}$ and $\boldsymbol{\bar{b}}$ would be of high importance
- Improvements in **Monte Carlo generators** and **flavour tagging performance** can help a lot
    - first look at jet tagger performance is promising
        - ParticleNet-based (by CMS)
        - IDEA detector concept
    - possibility to go **beyond pure *b***-tagging
        - prospect of high purity (99%) in *s*-tagging for $\varepsilon_b = 0.1$