A_{FB}^{b}

(*with a focus on discussion of systematics control and evaluation*)

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Outline

- 'Short' introduction: $A^{0,b}_{FB}$, motivations, status
- Systematic uncertainties
- Future plans and conclusions

$A^{0,b}_{FB}$

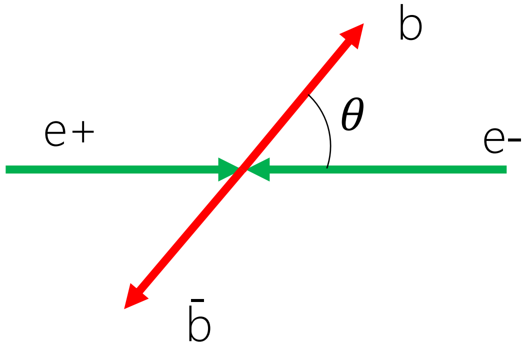
Goal

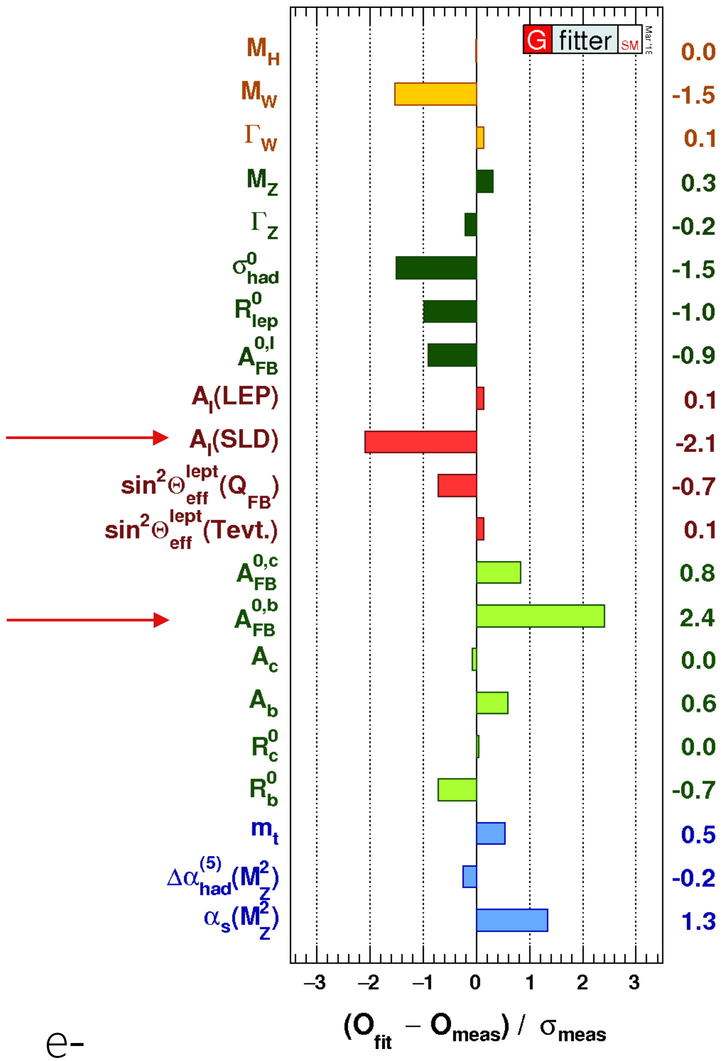
- Precise measurement of the forward-backward asymmetry of $b\bar{b}$ in $e^+e^- \rightarrow Z \rightarrow b\bar{b}$
- >2σ deviation between LEP combination and EW fits
- Ideal benchmark measurement for FCC-ee @m_Z

Measurement

- $A^{0,b}_{FB}$ can be extracted from the distribution of $\cos\theta(b)$
- experimental distinction between b and $\bar{b}$ needed
  - ⇒ quark charge determination

$$\frac{d\sigma}{d\cos\theta} = \sigma^{\rm tot}_{b\bar{b}} \left(\frac{3}{8}(1+\cos^2\theta) + (A^b_{\rm FB})_{\rm obs}(1-2\chi_B)\cos\theta \right)$$





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$A^{0,b}_{FB}$: b-jet charge

Two classes of methods:

- Jet-charge based studies
  - 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

- Lepton-charge based studies
  - charge of b inferred from charge of e or μ in B-hadron semileptonic decay
  - relatively low efficiency (restricted to semileptonic decays)
  - better purity
  - highly sensitive to B-hadron decay modelling

$A^{0,b}_{FB}$: LEP measurements

Reference	Measurement: Experiment	$(A^{0,b}_{FB}) \pm \delta(\text{stat}) \pm \delta(\text{syst})$	relative uncertainties: 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	$0.0992 \pm 0.0015 \pm 0.0007$	1.5%	0.5%	0.7%

stat. syst.

Analysis strategy

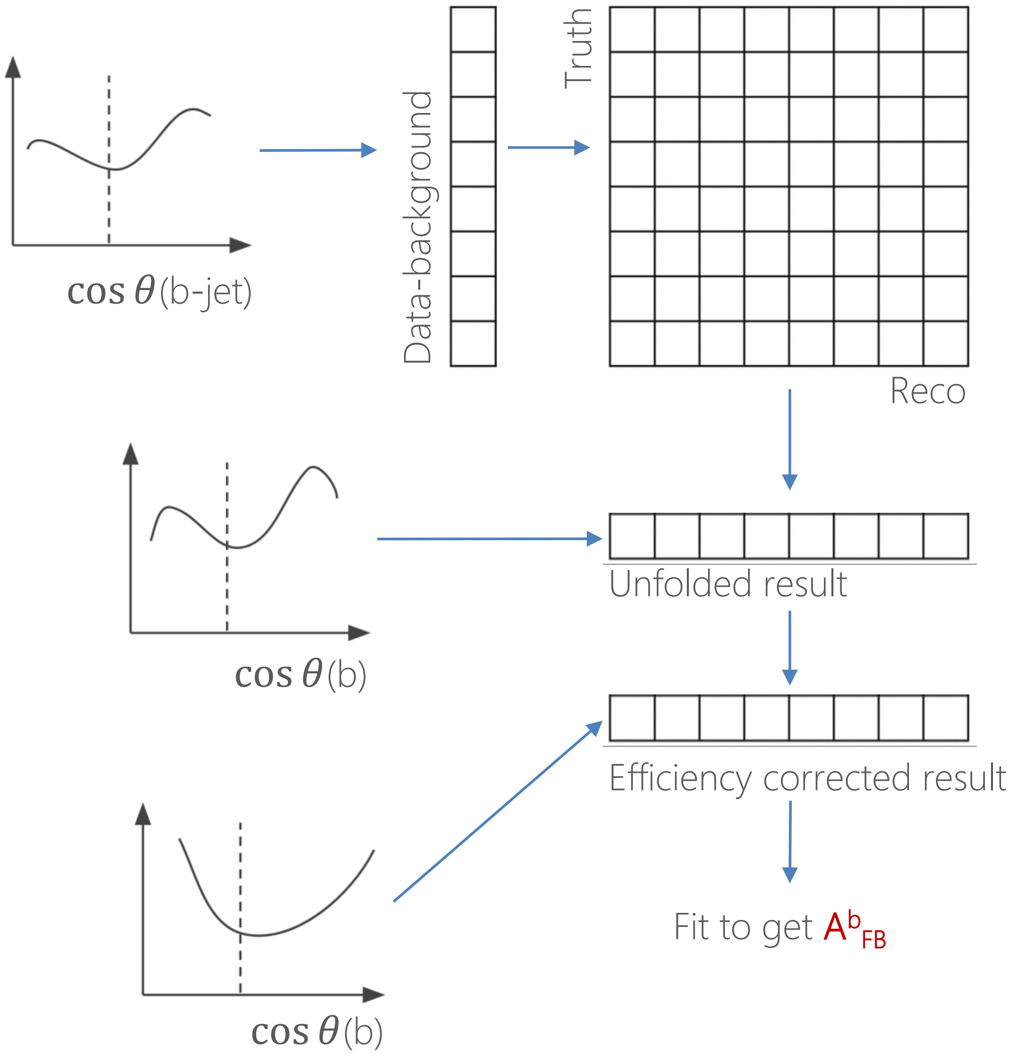
Workflow

1. Build reco-level observable exploiting:
   - Jet direction
   - Jet-charge (determined with one of the two methods)
2. Perform unfolding from reco-level to parton-level
3. Extract $A^{0,b}_{FB}$ from the unfolded distribution

Framework

- Using both HEP-FCC/FCCAnalyses framework and stand-alone Madgraph+Delphes
- Investigating usage of thrust axis, jets with different algorithms, leptons…

Considering for the future: secondary vertex reconstruction, exclusive B-hadron decays, interplay with b-tagging…

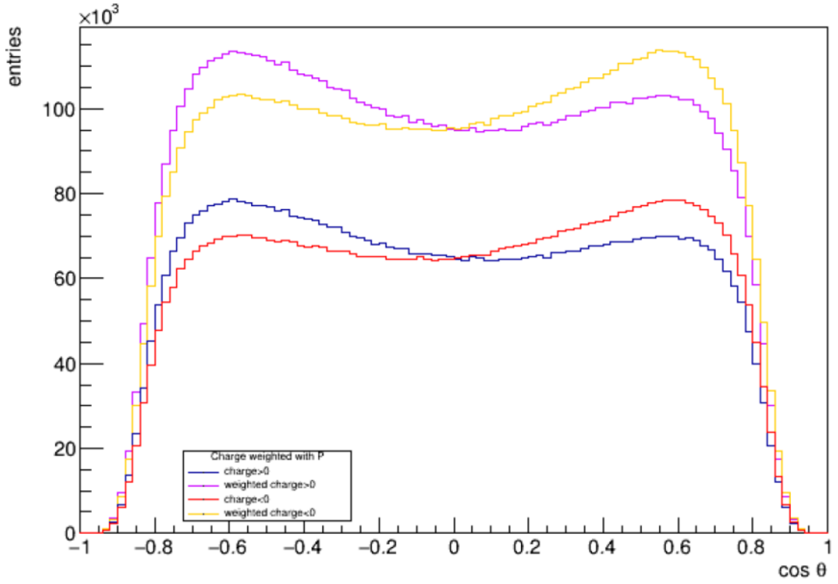


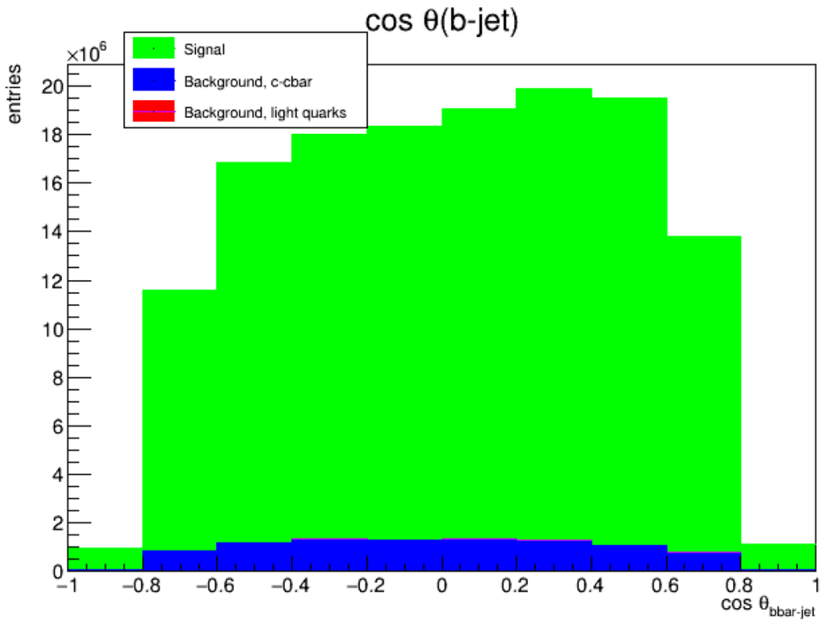
Jet-charge study

- Based on private MadGraph+Delphes simulation (with IDEA card)
- Durham jet algorithm used
- Simplified b-tagging (flat 80% eff., 10%/1% c/light-mis-tagging)
- Jet charge built with weighted sum of charges of tracks (as saved by Delphes)
  - $\Delta R<0.4$ from jet axis
  - weight = p_L (track) w.r.t. jet axis

Event Selection

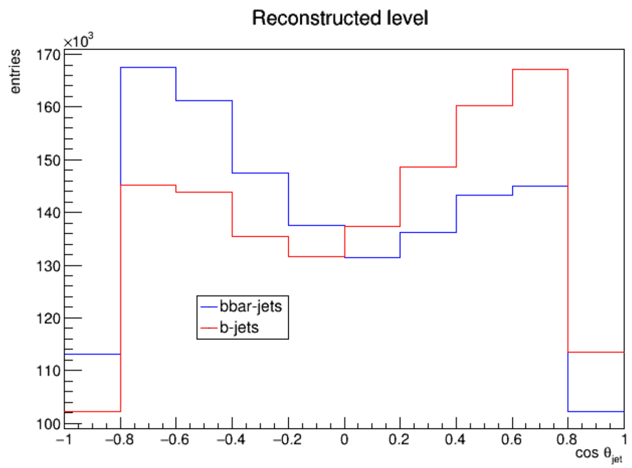
- $\geq$ 2 b-tagged jets
- $\geq$ 1 jet with charge > 0
- $\geq$ 1 jet with charge < 0





Jet-charge study

- Response matrix and efficiency correction vector built from 6M $b\bar{b}$ events.
- Unfolding with simple Matrix inversion, 10x10 matrix used.



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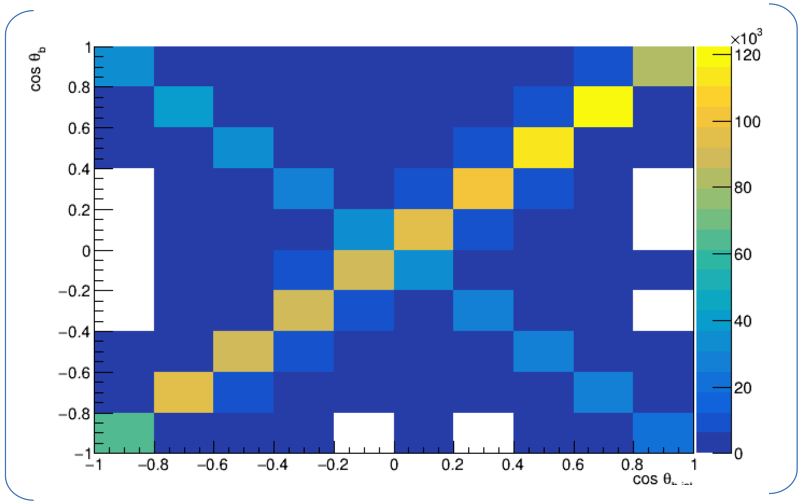

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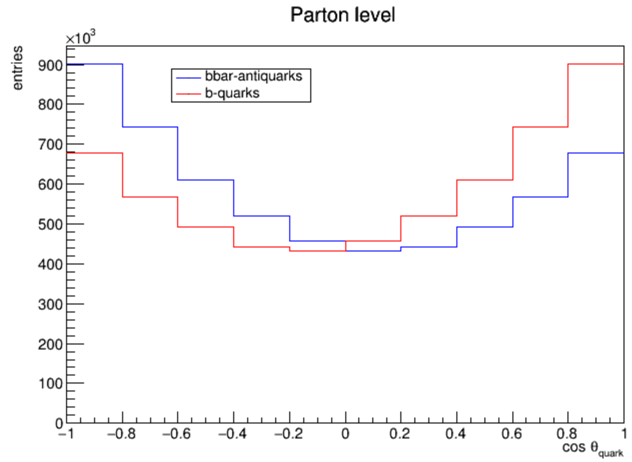
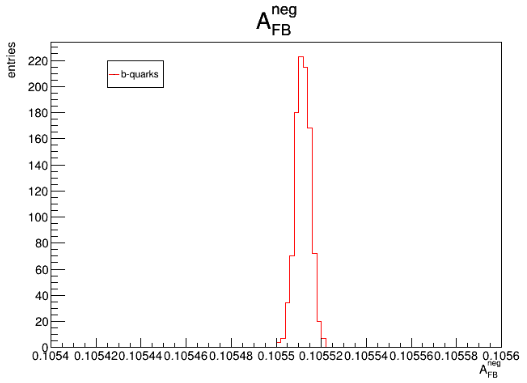


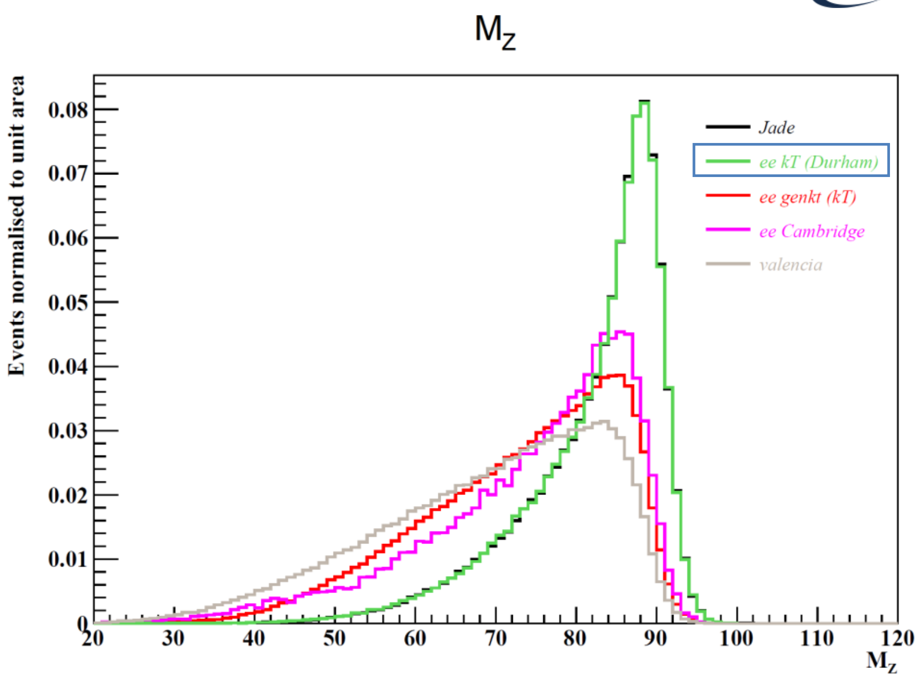
- Statistical uncertainty obtained from pseudo-experiments
  - 0.7 fb^{-1}: ± 0.1%
  - 150 ab^{-1}: ± 0. 004%

$$A^b_{FB} = 0.105700 \pm 0.000004(\text{stat.})$$



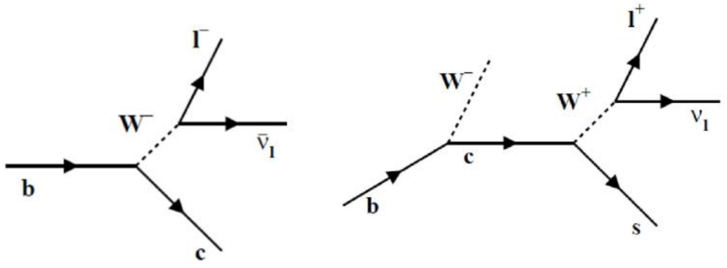
Lepton-charge study

- Based on private HEP-FCC/FCCAnalyses (with centrally produced samples)
- IDEA detector concept
- Jets reconstructed by Durham algorithm



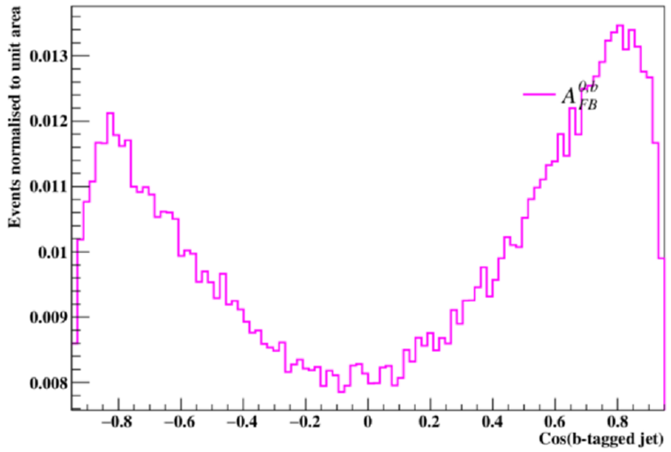
Event Selection

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



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

Lepton-charge study



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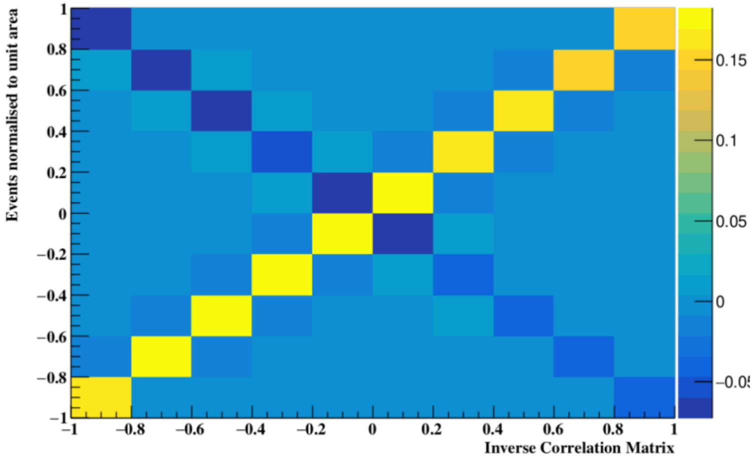

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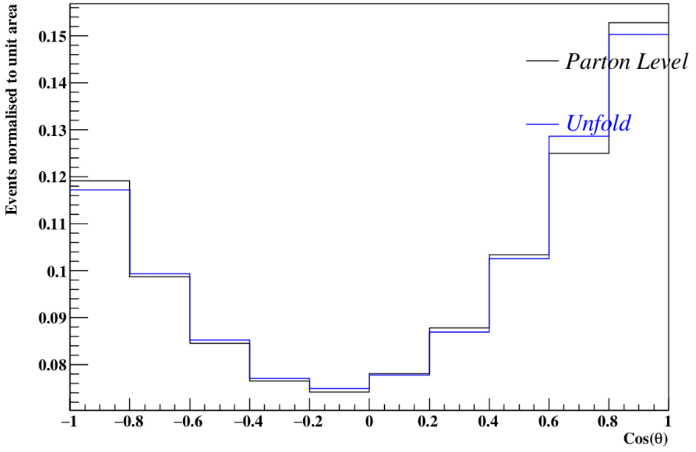


- As before, statistical uncertainty of the order of:
  - 150 ab^{-1}: ± 0. 004%

$$A^b_{FB} = 0.091100 \pm 0.000004(\text{stat.})$$

Systematic uncertainties

We know that statistical uncertainty will not be an issue

- LEP combination has ~equal stat and syst contributions
- We expect ~10^5 times more statistics at FCC-ee ⇒ ~300 times smaller stat. uncertainty

Systematic uncertainties expected to be dominant

- Modelling b-fragmentation
  - Affecting B-hadron kinematics
- Final-state QCD radiation effects
  - Affecting jet shapes, distribution of charge, B-hadron kinematics…
- b-tagging efficiency:
  - Uncertainty on mis-tag rate affecting background prediction
  - p_T and η dependency of b-tagging eff. for signal

Systematic uncertainties

Jet-charge based analysis

- b-fragmentation: ± 0.2% changing r_b value in Lund-Bowler fragmentation function in Pythia
- α_S^{FSR}: ± 6.4% Indirectly changing α_S^{FSR} value by a factor of $\sqrt{2}$

$$f(z) = \frac{1}{z^{1+br_b m_b^2}}(1-z)^a \exp(-bm_T^2/z)$$

Total syst. uncertainty of: ~6.4%

Lepton-charge based analysis

- b-fragmentation: ± 0.3%
- α_S^{FSR}: ± 3.7%

Total syst. uncertainty of: ~3.7%

These uncertainties are NOT yet meant to be comparable with a LEP result

Systematic uncertainties

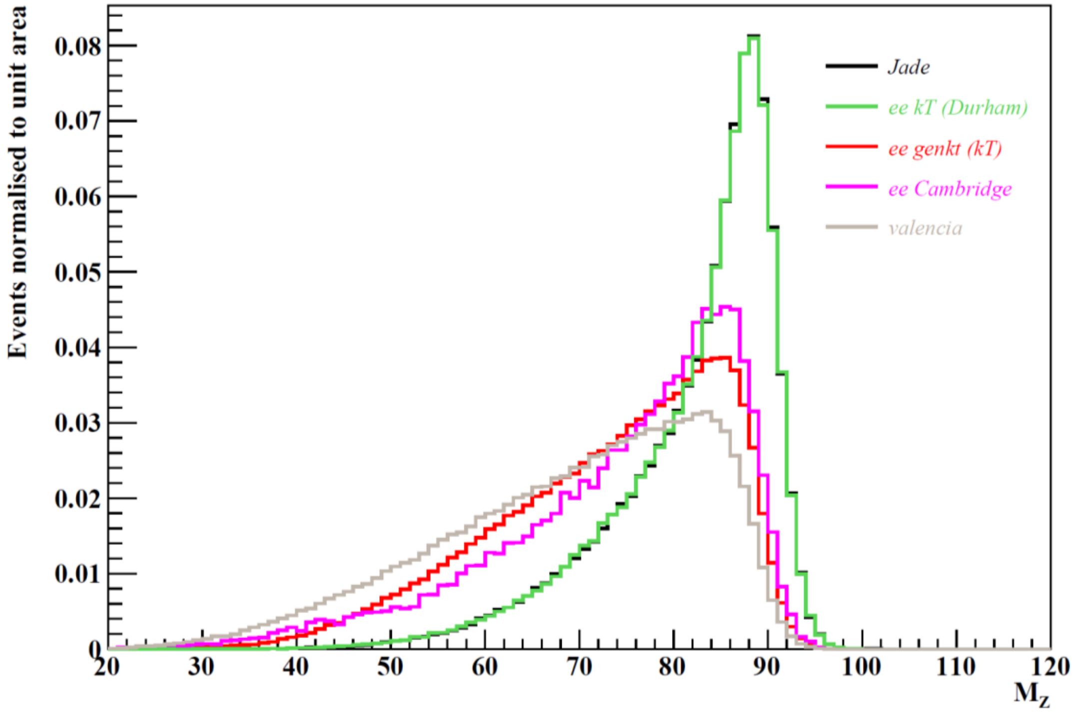
How to reduce the systematic uncertainty?

Systematic uncertainties: clustering

Jet Clusering algorithms: Jade vs Durham

Jade $A^b_{FB} = 0.0911 \pm 0.0039$

Durham* $A^b_{FB} = 0.0911 \pm 0.0034$



*Exclusive algorithms are expected to be a good all-round default.

Systematic uncertainties: QCD FSR

Parton Shower Models: Dire Showers

arXiv:1506.05057v2

- Leading order evolution kernels, and NLO corrections to collinear evolution from NLO DGLAP kernels.

Pythia $A^b_{FB} = 0.0911 \pm 0.0034$

↓ New samples are generated and analyzed

Dire $A^b_{FB} = 0.0927 \pm 0.0012$

Systematic uncertainties: *b*-tagging

Flavour tagging efficiencies

$$A^b_{FB} = 0.0927 \pm 0.0012$$

Before: flat 80% b-tagging efficiency: no fake b-jets

$$A^b_{FB} = 0.0927 \pm 0.0009$$

After: Updates in FCCAnalysis framework **`mistag_c`**, **`mistag _l`**, **`mistag_ g`***

b-tag $\varepsilon_b, \varepsilon_c, \varepsilon_l, \varepsilon_g$	c-tag $\varepsilon_b, \varepsilon_c, \varepsilon_l, \varepsilon_g$
80 / 0.4 / 0.05 / 0.7	2.0 / 80 / 0.9 / 2.5

*Franco Bedeschi, Loukas Gouskos, Michele Selvaggi, *Jet FlavourTagging for Future Colliders with Fast Simulation*, arXiv:2202.03285.
[Higgs Performance at FCC-ee, FCC Week 2022]

Ongoing studies and future plans

- Need to complete the two studies based on simple methods for b-quark charge determination, before investigating more complex methods
  - Currently implementing jet-charge study with HEP-FCC/FCCAnalyses.
  - Refining systematics evaluation.
  - Have a detailed comparison with one/more of the LEP results.

Systematic uncertainties

- Refining current systematics evaluation.
- Including additional systematics
  - tracking efficiency & resolution
  - jet energy uncertainties expected to be negligible

Planning usage of advanced techniques

- General machine-learning method for b-quark charge determination
- Possibly in a joint effort with flavour-tagging algorithm development studies

Conclusions

Carrying on two strategies in parallel

- Already starting to converge on a combined result

Studying systematics uncertainties

- Are jets effectively the best way to measure $A^{0,b}_{FB}$?
- Already clear that parton shower systematics can kill the precision

  ⇒ ad-hoc calibrations / auxiliary measurements needed

Staying up to date

- Embedding new analysis techniques
- Exploiting and benchmarking new features in the software releases.
- Looking forward to the FCC week in London to present new results.

Thank you!

Backup

Tuning α_S^{FSR}

The default pT^2 renormalization scale is multiplied by this prefactor.

For QCD this is equivalent to a change of Lambda^2 in the opposite direction, i.e. to a change of alpha_strong(M_Z^2) (except that flavour thresholds remain at fixed scales).

```
TimeShower:renormMultFac=0.707  &&  TimeShower:factorMultFac=0.707

TimeShower:renormMultFac=1.414  &&  TimeShower:factorMultFac=1.414
```

Parton Shower Models: Dire Showers arXiv:1506.05057v2

- Defining which higher order corrections are applied to the parton shower splitting functions used for timelike (i.e. final state) evolution

```
mode  DireTimes:kernelOrder  (default = 1; minimum = -1; maximum = 4)
```

- Defining which higher order corrections are applied to the parton shower splitting functions used for spacelike (i.e. initial state) evolution

```
mode  DireSpace:kernelOrder  (default = 1; minimum = -1; maximum = 4)
```

By choosing the Dire Shower Model

- Leading order evolution kernels, and NLO corrections to collinear evolution from NLO DGLAP kernels.