Study of the Z-boson couplings to heavy fermions at the FCC-ee

M.Cobal, G. Guerrieri, G.Panizzo, L.Toffolin

RD_FCC collaboration meeting, 15-16 December 2021

University of Udine and INFN Trieste

Outline

- Short introduction: A^b_{FB}, motivations

- Route to follow

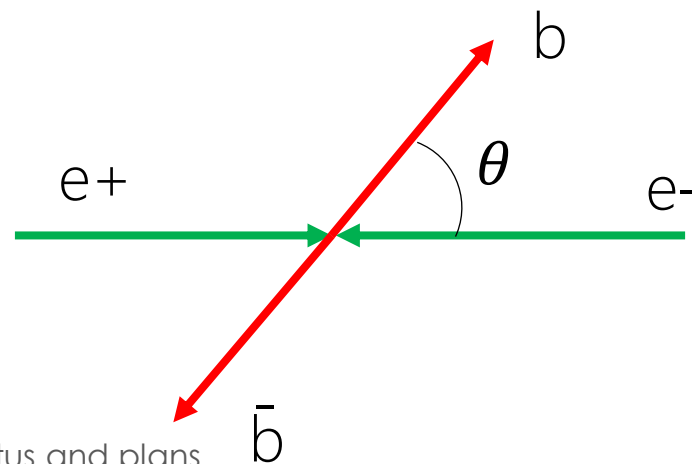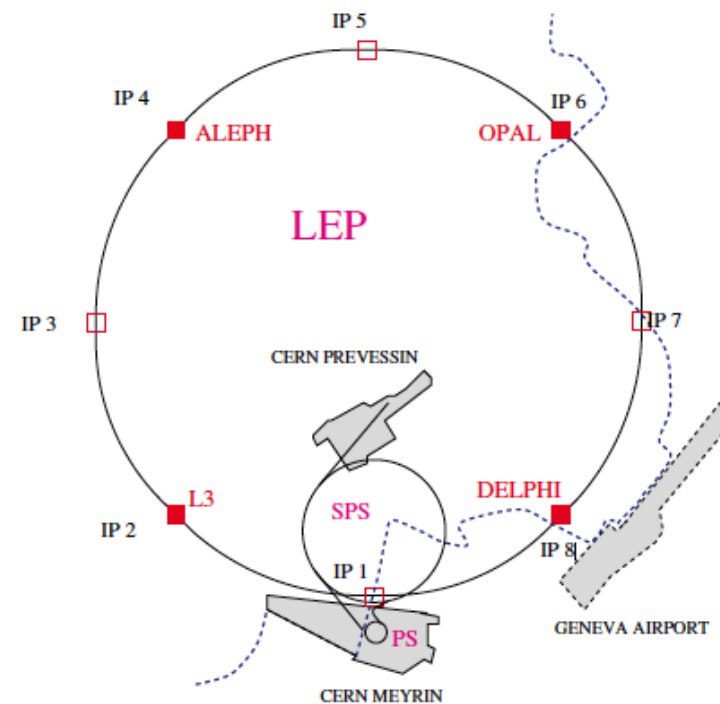- Status and plans

- Conclusions

A^b_{FB} Motivations: LEP

$$\frac{d\sigma}{d\Omega} = N_c \frac{\alpha^2}{4s} \{(1 + \cos^2\theta)[Q_f^2 - 2\chi_1 v_e v_f Q_f + \chi_2(a_e^2 + v_e^2)(a_f^2 + v_f^2)]$$

$$+ 2\cos\theta [-2\chi_1 a_e a_f Q_f + 4\chi_2 a_3 a_f v_e v_f]\}$$

$$a_f = T_3^f, \qquad v_f = T_3^f - 2\sin^2\theta_w Q_f$$

T_3^f = fermion isospin
Q_f = fermion charge

$$\sigma_B = \int_{-1}^{0} \frac{d\sigma}{d\Omega} dcos\theta, \quad \sigma_F = \int_{0}^{1} \frac{d\sigma}{d\Omega} dcos\theta$$

$$A_{FB}^{0,f} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f, \qquad \text{where} \quad A_f = \frac{2a_f v_f}{a_f^2 + v_f^2}$$
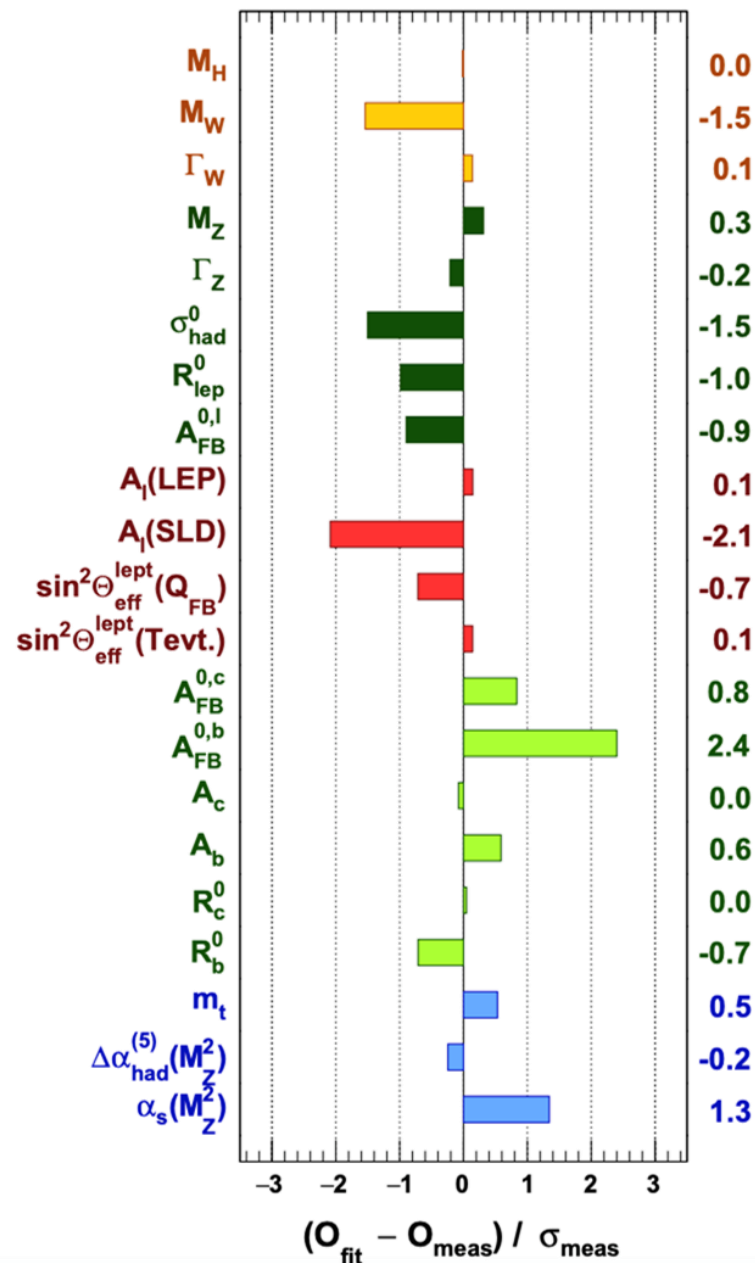
A^b_{FB} : the EW fit

- Pull value:

$$\frac{O_{fit} - O_{meas}}{\sigma_{meas}}$$

- b-quark observables →
Largest discrepancies!

- Indirect $A_b(A^{0,b}_{FB}$; A_e(SLD))
  → 2.8σ

Eur.Phys.J.C 78 (2018) 8, 675

Afb status and plans

A$^{0,b}_{FB}$: Forward or Backward?

- Thrust axis can be used to estimate the direction of the original quark. For a given event defined as:

$$T = \max_{\hat{n}} \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$

- Oriented towards the hemisphere containing the negatively charged lepton (or opposite the positively charged lepton).

- Points in the direction of the b-quark for bbbar events and in the direction of the c-quark for ccbar events.

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

Exploit:

- Decay channels with leptons (e or μ) (Soft lepton tagging)

- Non-zero lifetime of heavy flavoured particles <L> ~2.7mm

  - Hard fragmentation and large mass of the b-quark → leptons from b-quark decay with large transverse momentum, P_T , with respect to the quark direction.

  - c-quark: lower mass and softer fragmentation, produces leptons with lower P_T , but nevertheless still higher than that of leptons from the decays of the→ lighter q

- Ingredients for machine learning algorithms

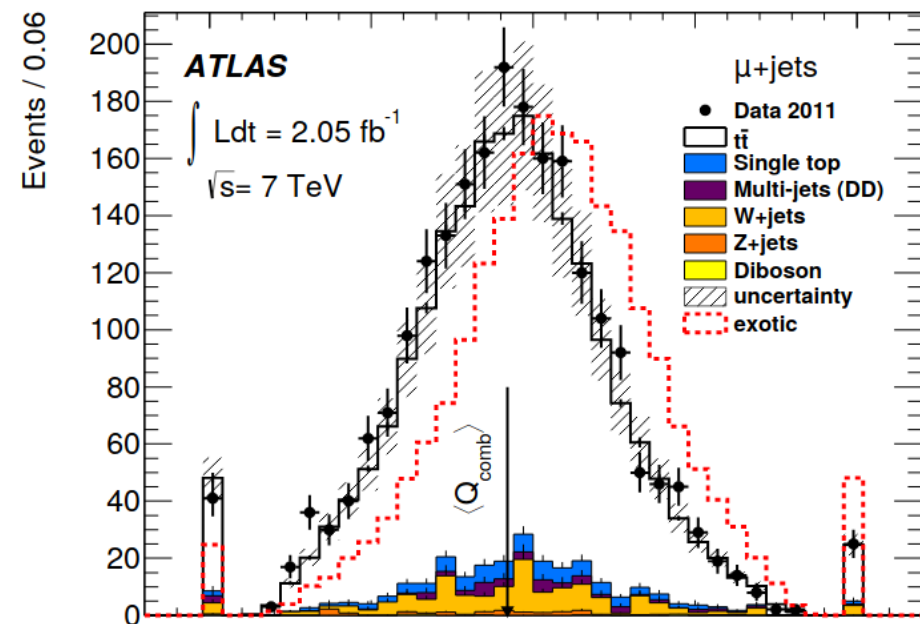# A$^{0,b}_{FB}$: b - charge ?

- Jet charge can be measured with two classes of methods
  - Here naive examples (from LHC feasibility study experience):
  - Q$_{jet}$ variable (with > 6 charged tracks sum, each weighted)

$$Q_{jet} \equiv \sum q_{tr} w_{tr}, \qquad w_{tr} \equiv \frac{\left(p_{tr}^{\parallel}\right)^r}{\Sigma \left(p_{tr}^{\parallel}\right)^r}$$

- Soft µ charge (here in a simplified variant "Q$_{jet}$ ")

$$p_{T\mu}^{lab} > 4\,\text{GeV}, \qquad p_{T\mu}^{rel} > 0.8\,\text{GeV}, \qquad Q_{\mu,jet} \equiv q_\mu \left(\frac{p_{T\mu}^{rel}}{m_b}\right)^r$$

Complete expression for $A^{0,b}_{FB}$

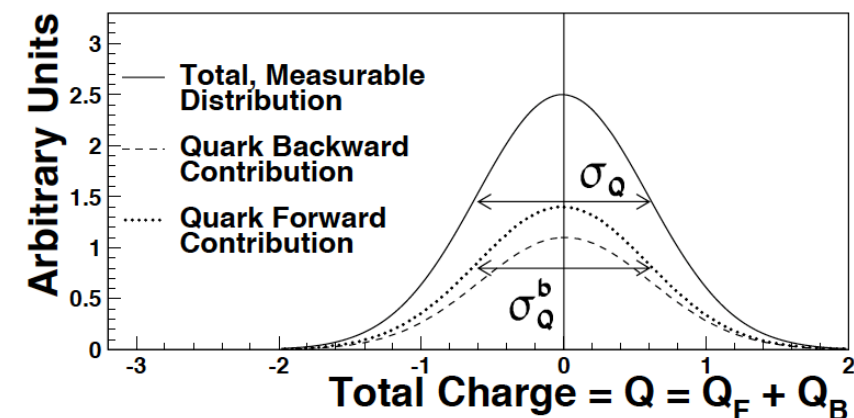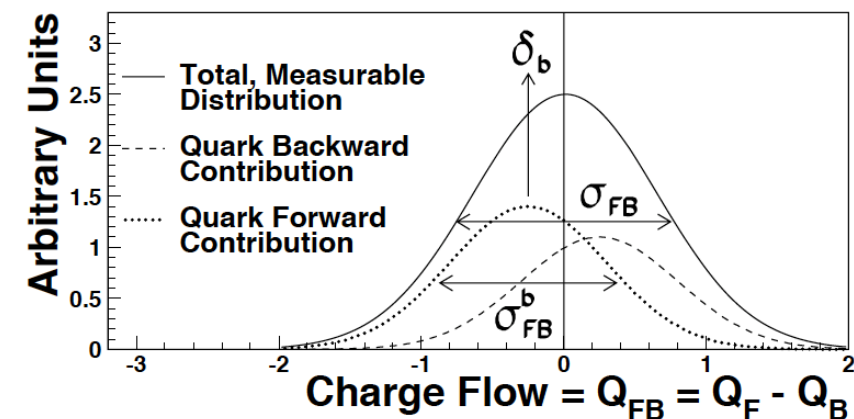- With both methods, ideal case: $\varepsilon_b = 1$, $\varepsilon_{c,l} = 0$:

$$2\langle Q^b \rangle \equiv \delta^b$$

$$Q^b_{FB} \equiv \langle Q^b_F - Q^b_B \rangle = \delta_b A^b_{FB}$$

- In real life one measures together:

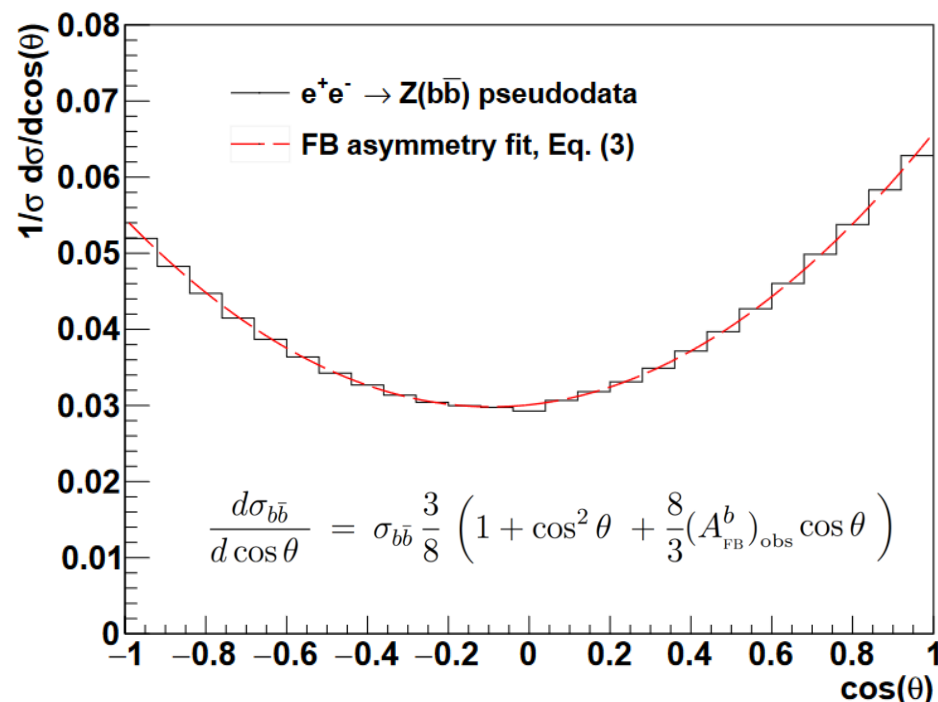$$\langle Q_{FB} \rangle^b = \sum_f c_f \delta^f A^f_{FB}$$

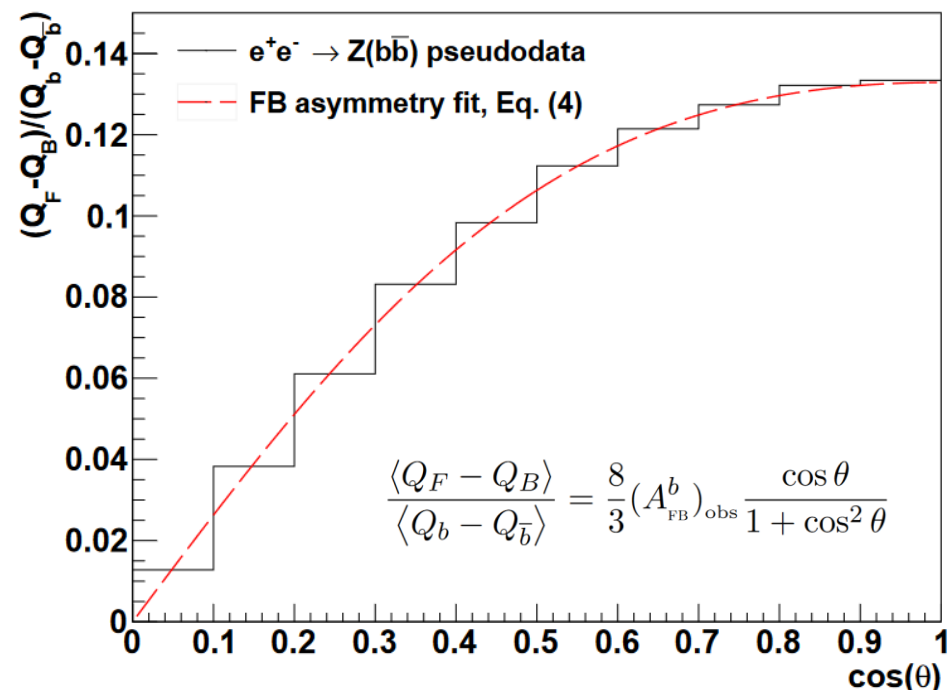$$c_f = \frac{\sigma_f \, \epsilon_f}{\sum_i \sigma_i \, \epsilon_i}$$

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

Fitting the distribution of polar angles θ between the e$^-$ and the thrust axis.

Fitting the charge flow distribution wrt $\cos\theta$.

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

$$\frac{\langle Q_F - Q_B \rangle}{\langle Q_b - Q_{\bar{b}} \rangle} = \frac{8}{3}(A^b_{FB})_{obs}\frac{\cos\theta}{1 + \cos^2\theta}$$

Systematics

- Mixing parameters

- Showering model and b-tagging algorithm implementation
  - Need detailed studies

- B and c semileptonic branching ratios and fragmentation parameters

- Fraction of fake or non-prompt leptons selected

- Need to check JES impact, expected to be negligible (for our current analysis)

- QED ISR: should be included in the theoretical definition

- FSR: need to recheck that it should not influence the measure

- c_f : should be estimated using NLO predictions on σ_f

Tools and algorithms: FCCAnalyses*

- Very recently tried to join the effort for a common software:

    - Tools in: FCCAnalyses : https://github.com/HEP-FCC/FCCAnalyses/
    - EDM4Hep: common event data model

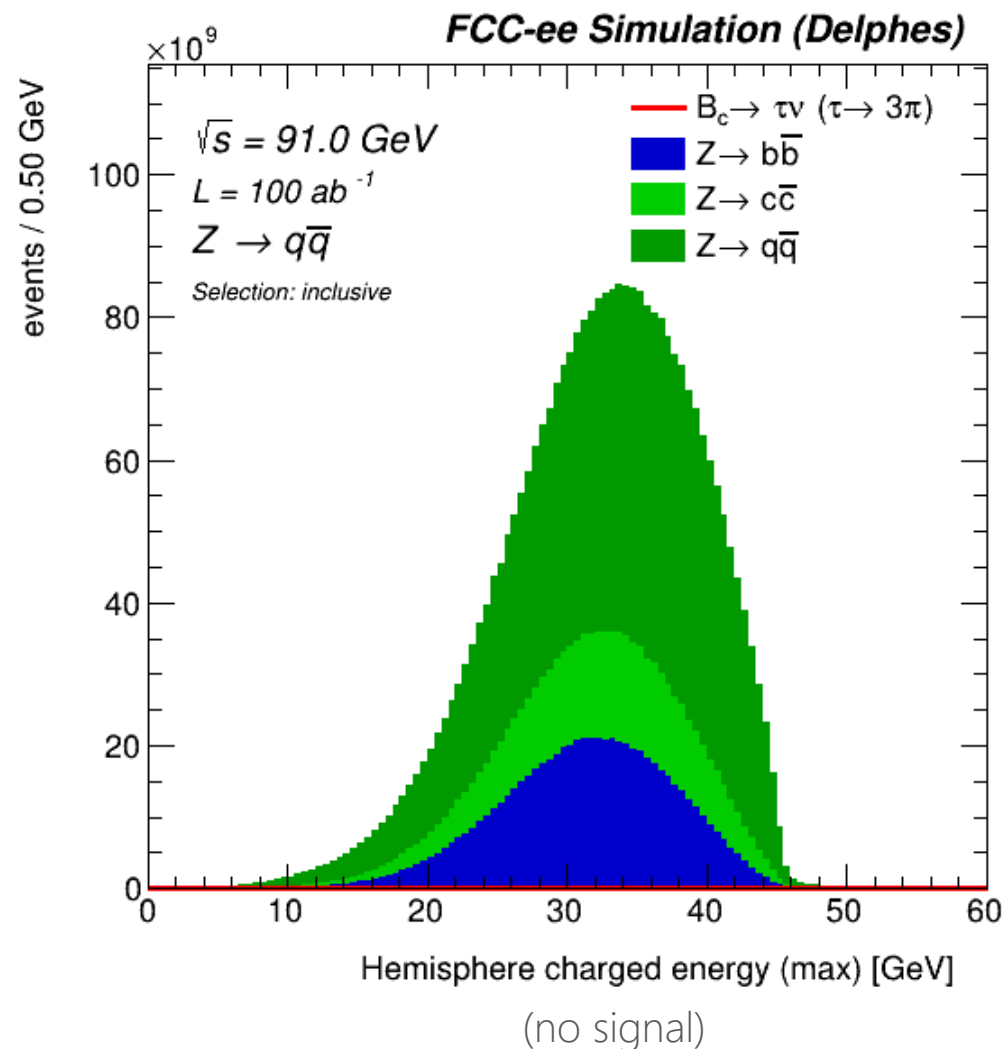- Getting acquainted not to use Delphes alone!

Tools and algorithms: FCCAnalyses*

- ROOT files at:
    - /eos/experiment/fcc/ee/generation/DelphesEvents/spring2021/IDEA/p8_ee_Zbb_ecm91/
    - 10 samples of 10^5 inclusive Zbb events

- Samples produced with Pythia, EvtGen and Delphes in EDM4hep with post – processing in FCCAnalyses to calculate thrust and hemisphere energy info

- Selection:
    - EVT_thrutshemis_emax<48. && EVT_thrutshemis_emin<35. && EVT_Ediff>10.

Status

Really preliminary stage:

- Starting to practice with Key4HEP and the EDM4HEP event data model

- Running out-of-the-box

- Modifying basic analysis FCCAnalyses-master/examples/FCCee/flavour/generic-analysis

FCC-ee Simulation (Delphes)

$\times 10^9$

events / 0.50 GeV

$\sqrt{s} = 91.0$ GeV

$L = 100$ ab^{-1}

$Z \rightarrow q\bar{q}$

Selection: inclusive

Legend:
- $B_c \rightarrow \tau\nu$ ($\tau \rightarrow 3\pi$)
- $Z \rightarrow b\bar{b}$
- $Z \rightarrow c\bar{c}$
- $Z \rightarrow q\bar{q}$

Hemisphere charged energy (max) [GeV]

(no signal)

Status

Really preliminary stage:

- Starting to practice with Key4HEP and the EDM4HEP event data model

- Running out-of-the-box

- Modifying basic analysis FCCAnalyses-master/examples/FCCee/flavour/generic-analysis
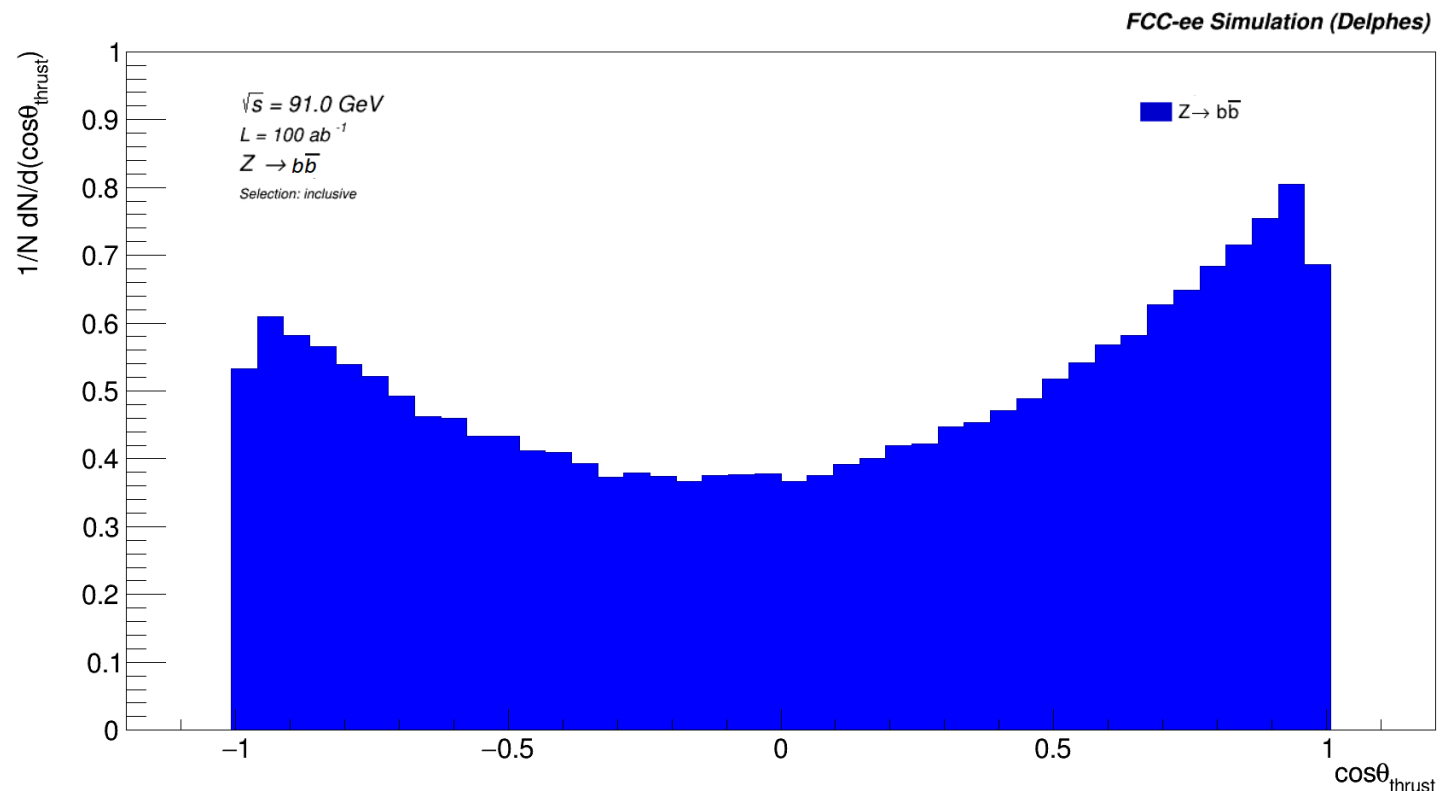
Plans

One PhD part-time and a Master thesis student working on the subject.
Collaboration with Grenoble (Dr. Fairouz Malek's group) expected.

- First step: fast MC studies

  - e.g.: framework already saves the thrust axis (variables
    EVT_thrust_z.).

  - Check b/b directions vs thrust axis, to confirm everything is
    working

  - Look at $\delta_{b,c}$ distributions

- Second step: complete EDM4HEP analysis for AbFB only on signal.

  - focus on the two methods Jet charge, soft muon pTrel
  - Check AFB = 2dbQFB relation
  - Add backgrounds from c, light jets
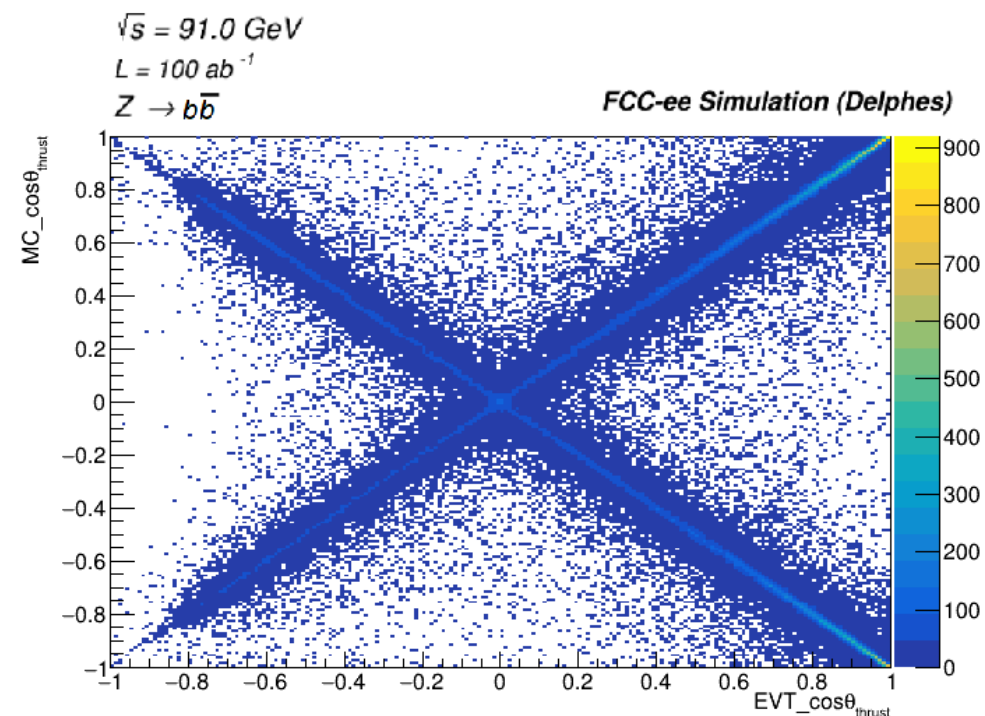
Conclusions

- The presented study is under way

- Already started looking into the codes, new framework. Ramping up.

- First (easy, general) plots are good checks that our plans are realistic

- Plans:
  - Dedicate efforts to use full features of Key4HEP/EDM4HEP
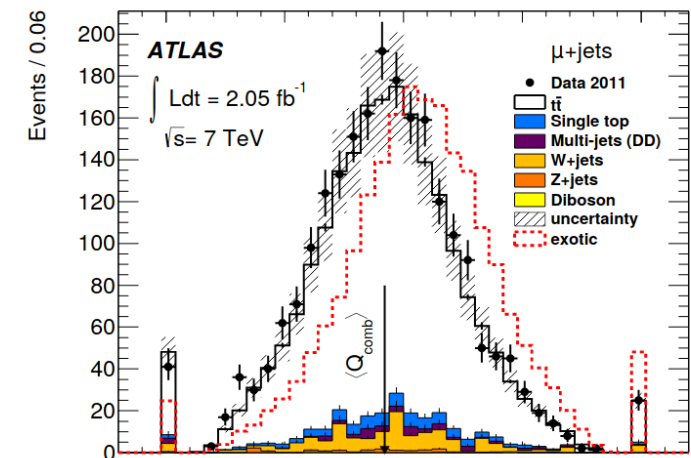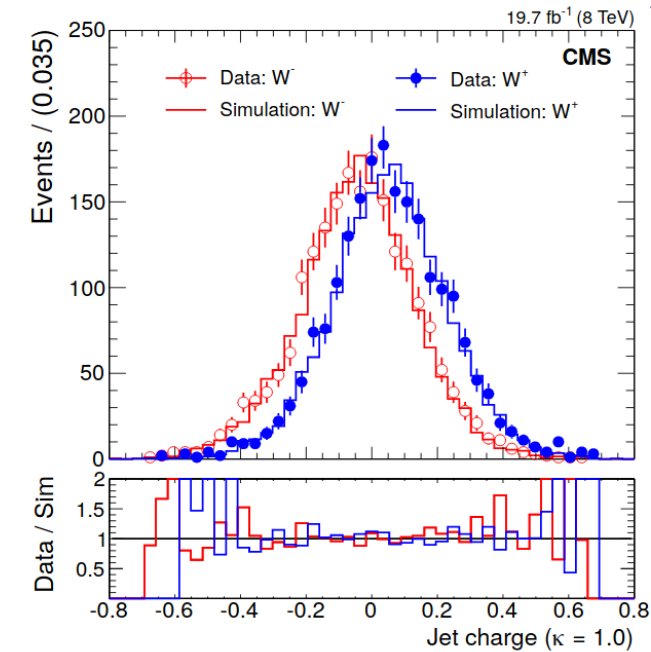 - Adapt old C++ (LHC oriented) analysis in Delphes to new framework

Backup

Analysis assumptions

- As a first attempt, will use simplified assumptions:

- Only b/c events, no background (that otherwise should affect only the c_f determination)

$$\langle Q_{FB} \rangle = \sum_{f=b,c} c_f \delta^f A_{FB}^{f,LHC}$$

- δ^b taken from simulations (but it can be measured in principle)

τ–polarization

- polarization vs polar angle:

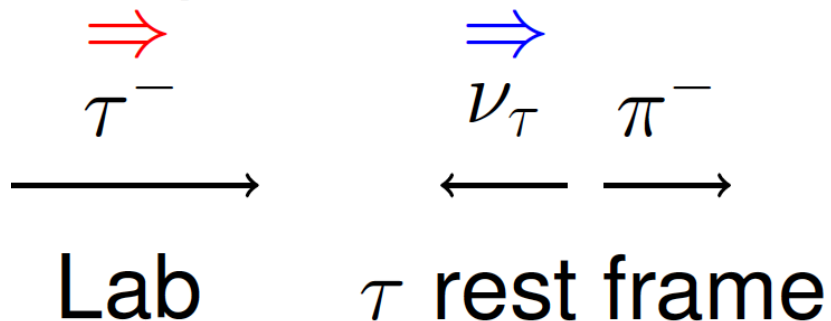$$P_\tau(\cos\theta) = -\frac{A_\tau(1+\cos^2\theta)+2A_e\cos\theta}{(1+\cos^2\theta)+\frac{8}{3}A_{0,\tau}^{FB}\cos\theta}$$

  - measuring P_T gives access to A^i

- . . . but how to determine P_T ?

P$_T$ determination
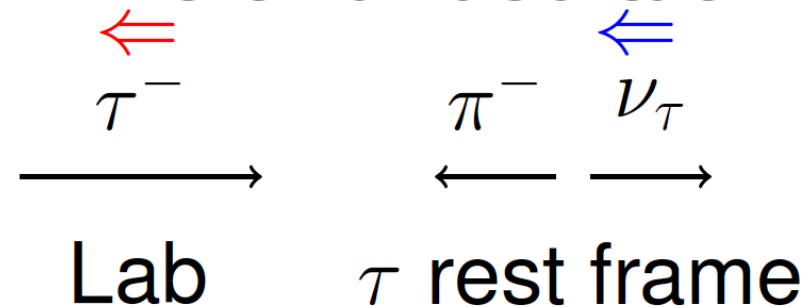
- Simplest example from easiest $\tau \to \pi \nu$ decay:

Right handed tau

τ^- ν_τ π^-

Lab τ rest frame

π boosted in τ direction

Assumption

Physics

Left handed tau

τ^- π^- ν_τ

Lab τ rest frame

π boosted in opposite direction

P$_T$ observable

- Then it is (hopefully) more clear that, defining $x_\pi = \dfrac{E_\pi}{E_{beam}}$ one has:

$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1 + P_\tau(2x_\pi - 1)$$

- Started looking at particle level distributions OUTSIDE key4Hep framework (our plan is to fix this)
- Need to carefully study new tools features for tau decays (e.g. Pythia 8 related switches)
- A lot to do here from the analysis side!
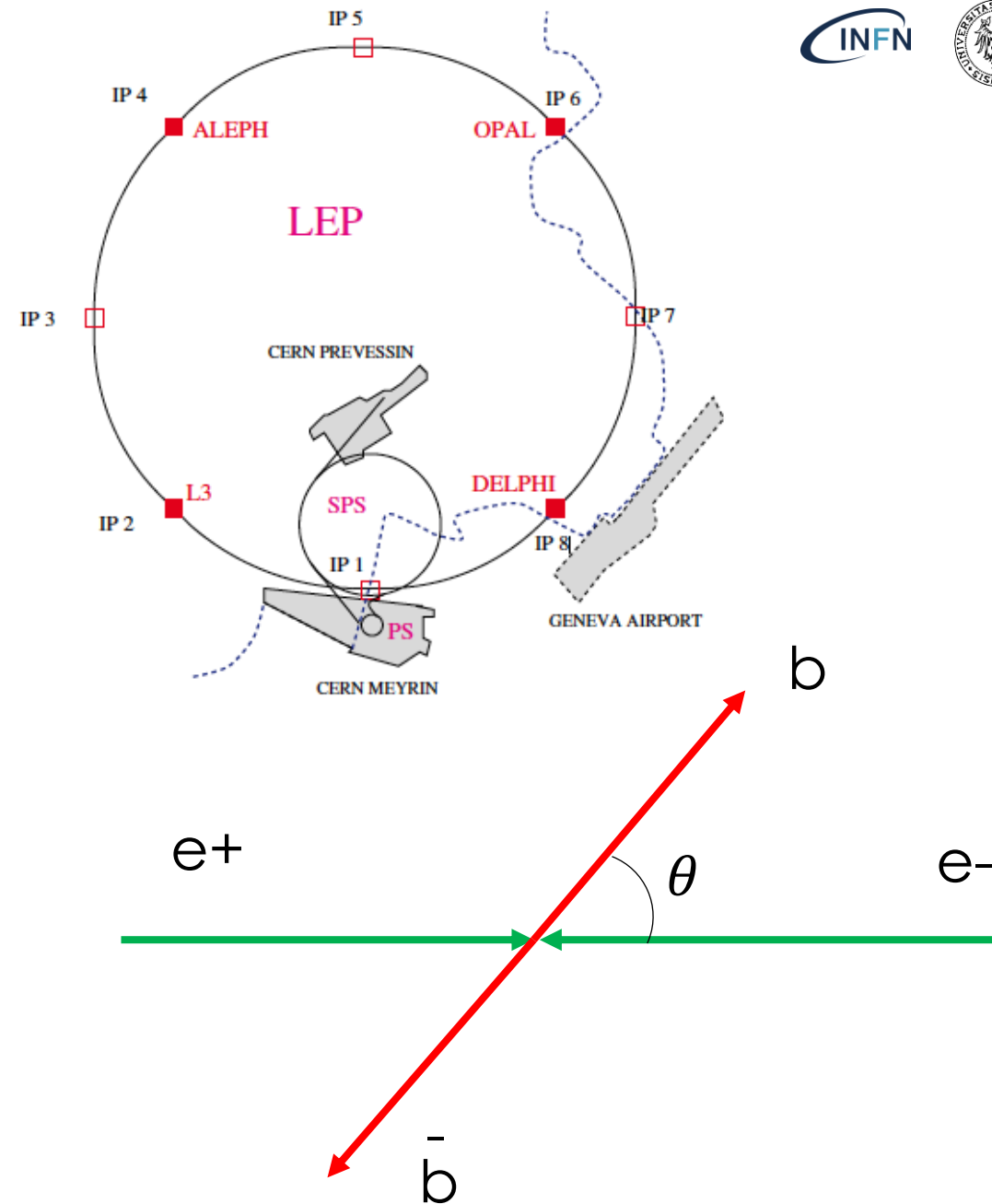
A^b_{FB} Motivations: LEP

- Definition:

$$A^b_{FB} \equiv \frac{\sigma_{bF} - \sigma_{bB}}{\sigma_{bF} + \sigma_{bB}}$$

- Tree level prediction:

$$A^b_{FB} = \frac{3}{4} A_b A_e$$

$$A_f \equiv \frac{g^2_{Lf} - g^2_{Rf}}{g^2_{Lf} + g^2_{Rf}}$$

What can be done at LHC?

- At LHC, b+ll production, ll rest frame:

$$A_{FB}^{b,LHC} \equiv \frac{\sigma_{bF} - \sigma_{bB}}{\sigma_{bF} + \sigma_{bB}}$$

where F is the lepton versus

s-channel   u-channel

- Tree level prediction:

$$A_{FB}^{b,LHC} = k \, A_b A_e$$

with k nearly scale independent