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Synergies in top-beauty and first look at b-tagging with exclusive decays

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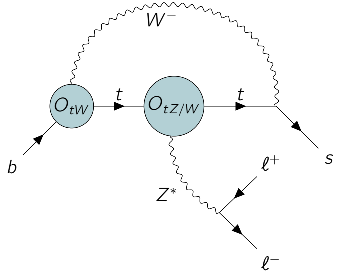
Motivation

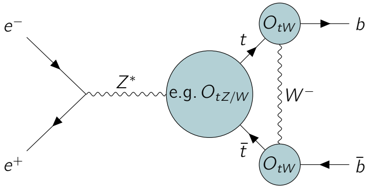
- SMEFT approach to connect modifications at top- and beauty scales with common set of operators → Anomalies at $\mathcal{O}(m_B)$ and $\mathcal{O}(m_Z)$ translate to higher energy scale

- $\mathcal{O}(m_B) \sim 5\,\text{GeV}$



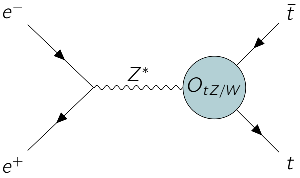
$\Rightarrow b \to s$ FCNCs

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



$\Rightarrow \approx 1\,\%$ of R_b in the SM

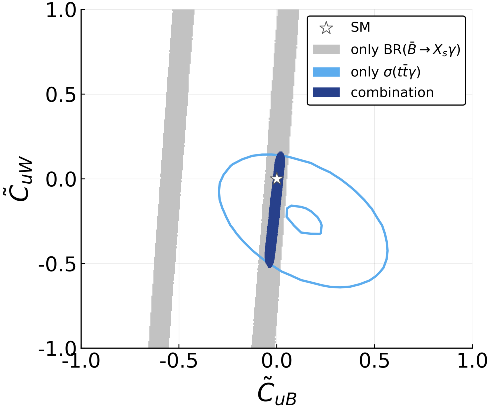
- $\mathcal{O}(m_t) \sim 350\,\text{GeV}$



$\Rightarrow$ Modification of e. g. the t forward-backward asym.

Motivation

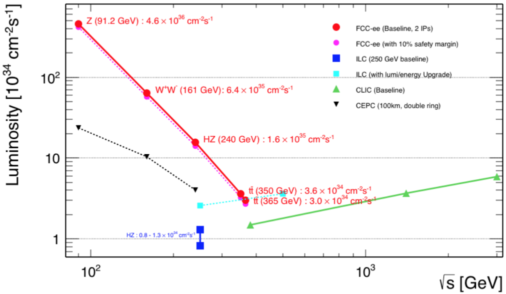
- Combination of top- and beauty observables: synergies in global SMEFT fits [1]
- More operators can be probed at once + different collider setups can be tested
- High precision and variety of observables is the key to extract tight constraints
  → To which extent can FCC-ee bring improvements?



$t + b$-observables: Removes flat directions in parameter space.

Motivation

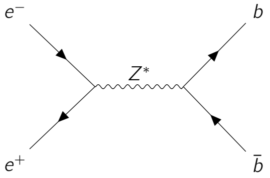
- FCC-ee (run-plan) offers ideal environment to study $Z \to b\bar{b}$ and top-observables at one machine
- Especially Z-pole run with $\mathcal{O}(10^{12})$ events offers **unrivaled precision** and possibilities
- Deviations on $Z \to b\bar{b}$ observables/scale **translate to top-energy scale**



Phase	$\sqrt{s}$ / GeV	Event statistics
Z^0	$88 - 95$	$5 \cdot 10^{12}$ $(10^6 \cdot$ LEP)
W^+W^-	$158 - 192$	$3 \cdot 10^8$ $(10^4 \cdot$ LEP)
Z^0H	240	10^6
$t\bar{t}$	$345 - 365$	10^6

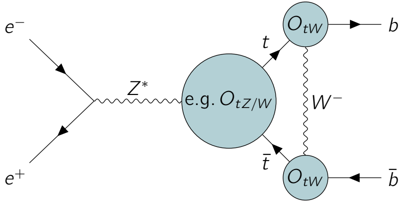
Measurements at the Z-pole: R_b

- Running down the scale to $Z \to b\bar{b}$: R_b and A_{FB}^b with the largest pull from EWPO fit
- R_b is defined as ratio of $Z \to b\bar{b}$ events wrt. to $Z \to$ hadrons
- Potential for SM-deviation in R_b: $\frac{\Delta R_b^{\mathrm{LEP}}}{R_b^{\mathrm{tree}} - R_b^{\mathrm{SM}}} \approx 40\,\%$



Tree-level contribution.

$\oplus$



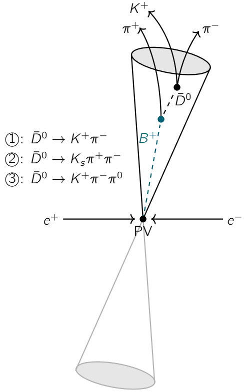
Zbb-vertex correction, contribution $\approx 1\,\%$.

- $\mathcal{O}(10^{12})$ $Z \to b\bar{b}$ events @FCC-ee: Measurements systematically limited
  Goal: reduce systematic uncertainty to scale of statistical uncertainty

New hemisphere tagging: Overview

Exclusive b-hadron tagging

Select the hemispheres by exclusively tag *b*-hadrons with a potential purity of $P = 100\,\%$ and an efficiency of $\varepsilon \approx 1\,\%$

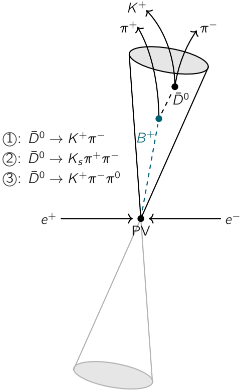


Outline

1. **Proof of principle**: run equations for R_b with FCC-ee numbers by
   - 1.1 …using the standard LEP-tagger
   - 1.2 …using exclusive *b*-hadron decays as tagger out of inclusive sample
2. Verify purity of $100\,\%$ and a potential efficiency of $1\,\%$ from simulation
3. Study of possible uncertainties

New hemisphere tagging: Proof of principles

- **Standard-tagger calculations** with measured values from Ref. [2] (ALEPH Collaboration)
- Tagging based on long lifetime of b-hadrons and b/c-hadron mass difference
- Result:
  $\rightarrow\ R_b = 0.2167 \pm 0.0011(\text{stat}) \pm 0.0013(\text{syst})$
  $\rightarrow\ \varepsilon_b = 0.2271 \pm 0.0016$
- LEP-times: Syst. unc. dominated by *udsc*-physics + MC statistics
- Machinery to test the statistical uncertainty on R_b for different scenarios:
  1. Tagging at FCC-ee à la LEP
  2. Tagging exclusively at FCC-ee



Different tagging scenarios at FCC-ee

I: À la LEP

- **Standard tagger** includes the contributions from *udsc*-physics
- Here: Numbers for $\varepsilon_{b,c,uds}$ and uncertainties provided by Ref. [2], taking all uncertainty correlations into account
- Suppose $N^{Z\rightarrow\text{had}} = 10^{12}$: $\Delta R_b(\text{stat}) = 2.022 \cdot 10^{-6}$

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- Suppose $N^{Z\to\text{had}} = 10^{12}$: $\Delta R_b(\text{stat}) = 2.022 \cdot 10^{-6}$

II: Exclusive b-hadron decays

- **Exclusive tagger** doesn't include the contributions from *udsc*-physics: $\varepsilon_{c,uds} = 0.0$
- Here: Assume $\varepsilon_b = 1\,\%$, taking all uncertainty correlations into account, equations simplify
- Suppose $N^{Z\to\text{had}} = 10^{12}$: $\Delta R_b(\text{stat}) = 4.570 \cdot 10^{-5}$

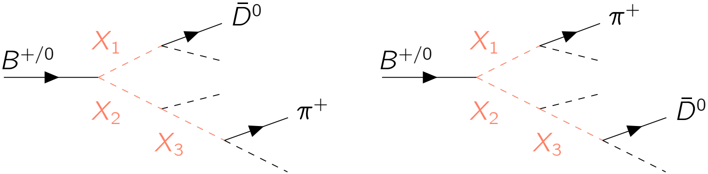
→ Reduction of major source of systematic uncertainty to the cost of statistical uncertainty (hemisphere correlation uncertainty (syst.) becomes central)

Starting point and assumptions

- 3 `spring2021` samples with 10^7 events each: $Z \to b\bar{b}$, $Z \to c\bar{c}$ and $Z \to \overline{udsuds}$
- **Event reweighting** with $R_b = 0.216$, $R_c = 0.172$ and $R_{uds} = R_u + R_d + R_s = 0.604$
- Vertex information of all charged particles is taken from MC
- Aiming for the rec. of **two representative decay modes** (generalize for more):
  1. **Fully charged:** $B^+ \to [\pi^- K^+]_{\bar{D}^0}\, \pi^+$, $\mathrm{BR}(\bar{D}^0 \to \pi^- K^+) \approx 4\,\%$
  2. **With one π^0:** $B^+ \to [\pi^- K^+ \pi^0]_{\bar{D}^0}\, \pi^+$, $\mathrm{BR}(\bar{D}^0 \to \pi^- K^+ \pi^0) \approx 14\,\%$

Including also partially reco. particles, e.g. $B^+ \to [\bar{D}^0 Y]_X\, \pi^+$ (with e.g. $X = D^*(2007)^0$ and $Y = \pi^0$), classification by number N_X of not-reco. particles X_i, $\max(N_X) = 4$

$$\boxed{\text{Here} : N_X = 3}$$

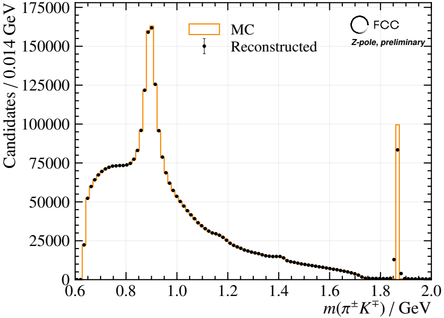


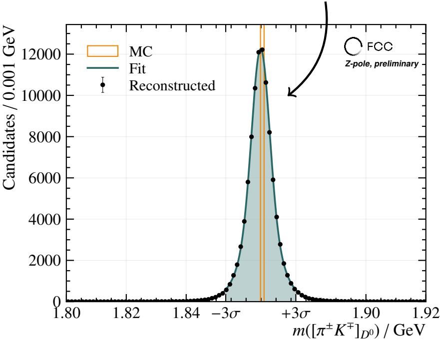
All fits on the next slides are performed using an unbinned maximum likelihood fit

Fully charged decay mode

$\bar{D}^0 \to \pi^- K^+$-reconstruction

- **Charged pion** and **kaon** collection combined with a max. distance between the vertices of 50 µm to emulate resolution effects
- Oppositely charged candidates are chosen to emerge from the **same hemisphere**
- Fit D^0 peak with **triple Gaussian**: $\mu_{\text{central}} = 1.8648\,\text{GeV}, \sigma_{\text{combined}} = 0.0039\,\text{GeV}$



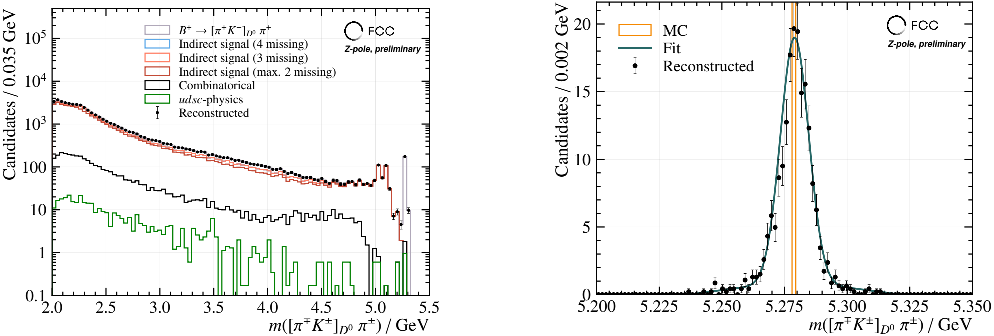


Fully charged decay mode

$B^+ \to [\pi^- K^+]_{\bar{D}^0}\ \pi^+$-reconstruction

$\mu^{B^+}_{\text{central}}$	5.279 GeV
$\sigma^{B^+}_{\text{combined}}$	0.006 GeV

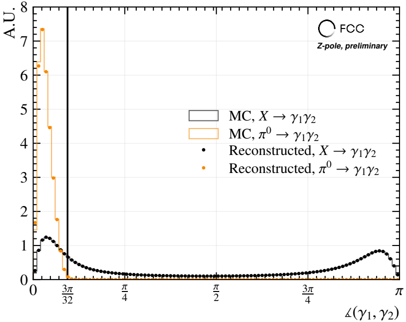
- Select D^0-candidates in $\pm 3\sigma$ range around μ_{central}
- The D^0 vertex is displaced by at least 300 µm from the PV
- D^0 and charged pion vertex with less than 50 µm displacement

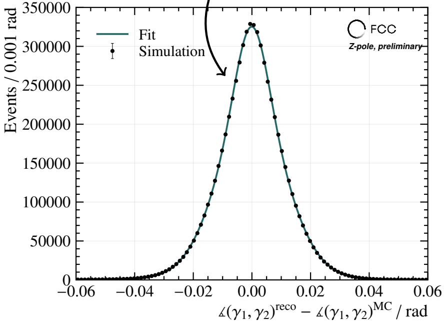


Decay mode including a neutral pion

$\bar{D}^0 \to \pi^- K^+ \pi^0$-reconstruction

- Neutral pion candidate reconstructed out of **two photons** with $\measuredangle(\gamma_1, \gamma_2) < \frac{3\pi}{32} \approx 17°$
  $\to$ **Reduces combinatorics**, e.g. from two photons in two different hemispheres
- Fit of the resolution of the angle between two photons (including all photons) with triple Gaussian model: $\mu_{\text{central}} = \mathcal{O}(10^{-5}), \sigma_{\text{combined}} = 0.0084\,\text{rad} \approx 0.48°$





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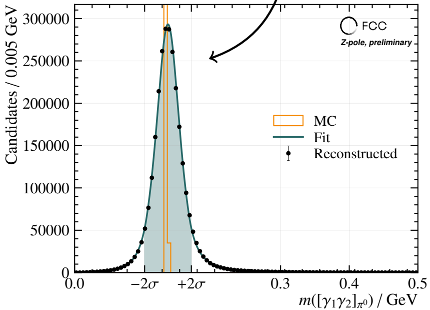
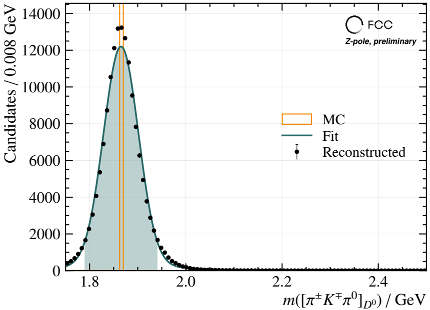
  $\to$ **Reduces combinatorics**, e.g. from two photons in two different hemispheres
- Selected candidates fitted with double-sided Crystalball + Gaussian function (82/18):
  $\mu_{\text{shared}} = 0.1359\,\text{GeV}, \sigma_{\text{combined}} = 0.0170\,\text{GeV}$



$\xrightarrow{+\,\pi^\pm K^\mp}$

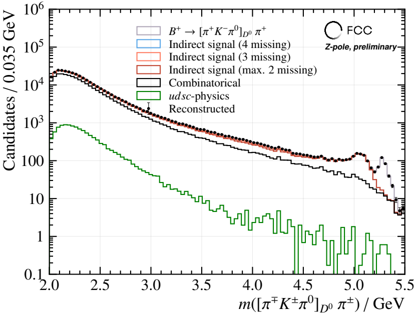


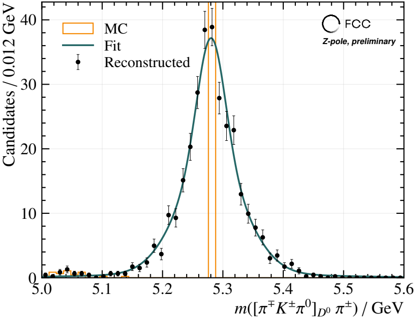
Decay mode including a neutral pion

$\mu^{B^+}_{\text{central}}$	5.280 GeV
$\sigma^{B^+}_{\text{combined}}$	0.075 GeV

$B^+ \to [\pi^- K^+ \pi^0]_{\bar{D}^0}\ \pi^+$-reconstruction

- Same requirements on vertexing of the D^0 and the additional charged pion
- **More statistics**, but less pronounced signal peak + more combinatorical and *udsc*-physics background
- Smeared signal peak due to the π^0 reconstruction





. . . back to the motivation

- Motivation: show that a purity of ≈ 100 % and a total efficiency of 1 % can be reached
- Apply **mass cut** to the $B^{\pm}$-mass fit ($\pm 3\sigma$ for charged mode, not optimized so far)

Process	mass window	Purity / %	Efficiency / %
$B^+ \to [\pi^- K^+]_{\bar{D}^0}\, \pi^+$	$[5.258, 5.301]$	99.50	$8.34 \cdot 10^{-3}$
$B^+ \to [\pi^- K^+ \pi^0]_{\bar{D}^0}\, \pi^+$	$[5.217, \infty]$	99.00	$1.27 \cdot 10^{-2}$

- First reconstruction seems promising, now: sum up possible b-hadron decay modes including also neutral pions
  - $B^+ \to \bar{D}^0\, X,\ D^-\, X,\ D_s^-\, X,\ \eta_c\, X,\ J/\psi\, X,\ \chi_c\, X,\ \ldots$
  - $\Lambda_b \to \Lambda_c\, \pi^-,\ \Lambda_c\, D_s^-,\ \Lambda_c^*\, X,\ \ldots$
  - B^0 and B_s . . .

→ Librarian work to be done

Conclusions and Outlook

- Anomalies at m_B and m_Z-energy scale: **modifications at top-energy scale** → SMEFT approach provides a common set of operators to connect both
- **Combination** of different scales showed synergies in global interpretations: **to which extent can FCC-ee improve?**
- Bringing systematic uncertainties down to the scale of the statistical uncertainty is key for measurements @FCC-ee (especially at Z-pole!)
- Proposal for R_b (further application for A^b_{FB}) measurement: **exclusively reconstruct** b-hadrons to tag hemispheres without light-physics contamination
- **Very pure reconstruction** possible in FCC-ee environment
- Remaining systematic uncertainty: correlation between the hemispheres (needs to be $< 10^{-4}$)

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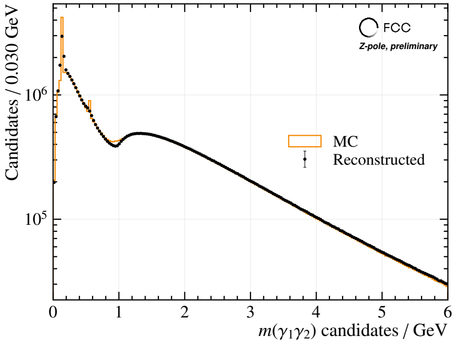
Thank you for your attention!

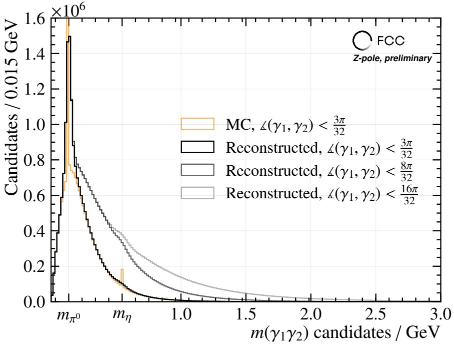
Backup

Impact of the photon-angle on π^0 reconstruction

- Impact of the angle between the two photons on the π^0 invariant mass distribution
- Reduction of large fraction of combinatorical background by keeping the signal peak significance



$m(\gamma_1\gamma_2)$ full invariant mass distribution.



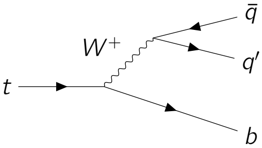
$m(\gamma_1\gamma_2)$ invariant mass distribution with $\measuredangle$-cuts.

Estimation of top observables at FCC-ee

- Use official FCC-ee simulated samples of $\sqrt{s} = 365\,\text{GeV}$ $e^+e^- \to t\bar{t} \to$ *all* collisions
- Focus on semileptonic and dileptonic decay on parton & reconstructed level

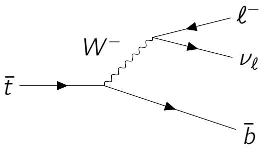
Semileptonic

- 1 isolated lepton $\ell \in [e, \mu]$ with $p_\ell > 20\,\text{GeV}$
- Missing energy
- Exactly 4 jets, 2 of them b-tagged (80 % efficiency each)



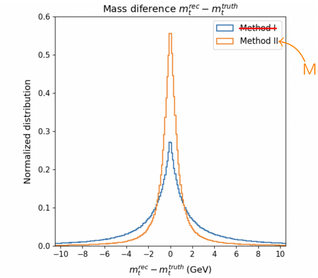
Dileptonic

- 2 isolated leptons $\ell \in [e, \mu]$ with $p_\ell > 20\,\text{GeV}$
- Missing energy
- Exactly 2 jets, both b-tagged (80 % efficiency each)



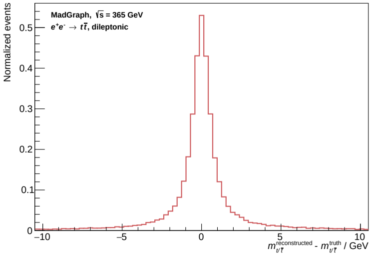
Reconstructing the dileptonic final state

- Ex. methods to fully reconstruct $t\bar{t}$-system [4]→ only verified on generator-level
- Based on 4-momentum conservation: $P_0 = P_{\ell_1} + P_{\ell_2} + P_\nu + P_{\bar{\nu}} + P_{j_1} + P_{j_2}$, P_i: input 4-vector, $P_0 = (\sqrt{s}, 0, 0, 0)^\top$
- Not enough to fix six ν-momentum components: Minimisation w.r.t. m_t and m_W
- *Generator-level*: Event energy $\Sigma E_i = \sqrt{s_i} = 365\,\text{GeV}$ known → Reproduce results



Method II applied

Publication reference.



Generator-level: Feasibility tests.

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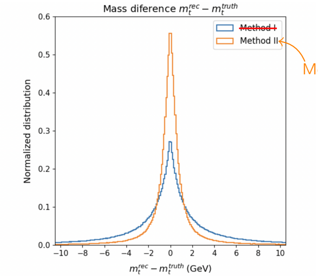
  P_i: input 4-vector, $P_0 = (\sqrt{s}, 0, 0, 0)^\top$
- Not enough to fix six ν-momentum components: Minimisation w.r.t. m_t and m_W
- *Reco-level*: Event energy not known $\Sigma E_i \neq \sqrt{s_i}$, because ME $\neq E_{\nu_1} + E_{\nu_2}$



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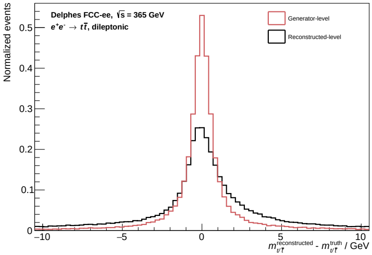
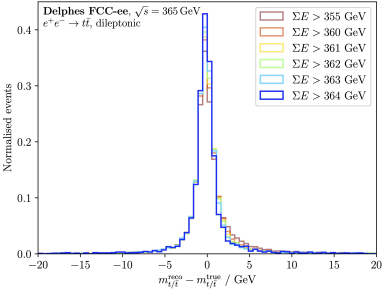


Reco-level: Naively assume $P_0 = 365$ GeV.

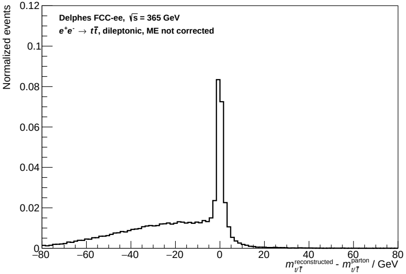
Reconstructing the dileptonic final state

- Reason for asymmetry: Total event energy not exactly determinable
- Cross-check: Cuts during reconstruction on ΣE remove asymmetries (left plot)
- Use event-wise knowledge: $P_0 = P_{\ell_1} + P_{\ell_2} + P_{\text{ME}} + P_{j_1} + P_{j_2}$

  $\rightarrow$ Asymmetry gets worse, too less energy for reconstruction



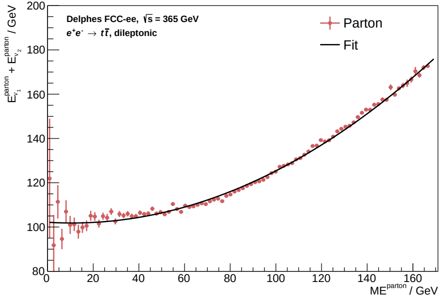
Cuts on the total event energy.



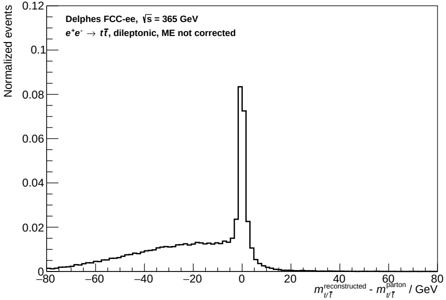
Reco-level: Use accessible event energy for P_0.

Reconstructing the dileptonic final state

- Ansatz: Find correlation between ME and $E_{\nu_1} + E_{\nu_2}$ with parton-level information
- Correct reconstructed ME with fitted dependence: $\mathrm{ME}^{\mathrm{corr.}} = p_0^{\mathrm{fit}} \cdot \mathrm{ME}^2 + p_1^{\mathrm{fit}} \cdot \mathrm{ME} + p_2^{\mathrm{fit}}$
- Use corrected, event-wise knowledge: $P_0^{\mathrm{corr.}} = P_{\ell_1} + P_{\ell_2} + P_{\mathrm{ME}^{\mathrm{corr.}}} + P_{j_1} + P_{j_2}$



Fit 2nd degree polynom.

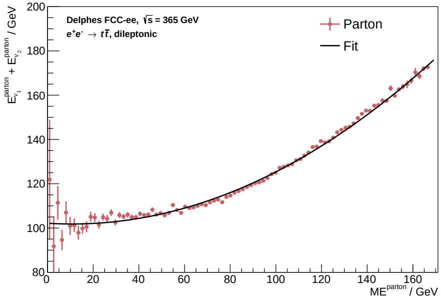


Reco-level: Uncorrected P_0.

Reconstructing the dileptonic final state

- Ansatz: Find correlation between ME and $E_{\nu_1} + E_{\nu_2}$ with parton-level information
- Correct reconstructed ME with fitted dependence: $\mathrm{ME}^{\mathrm{corr.}} = p_0^{\mathrm{fit}} \cdot \mathrm{ME}^2 + p_1^{\mathrm{fit}} \cdot \mathrm{ME} + p_2^{\mathrm{fit}}$
- Use corrected, event-wise knowledge: $P_0^{\mathrm{corr.}} = P_{\ell_1} + P_{\ell_2} + P_{\mathrm{ME}^{\mathrm{corr.}}} + P_{j_1} + P_{j_2}$

→ Does not lead to hoped improvements



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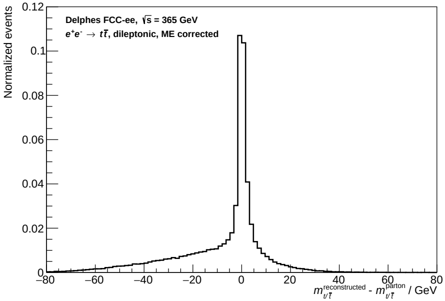
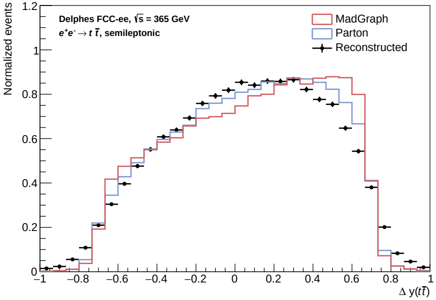


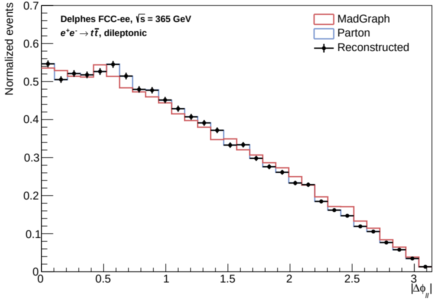
Reco-level: Corrected $P_0^{\mathrm{corr.}}$.

Observables

- Examples: $\Delta y_{t\bar{t}}$- and $|\Delta\phi_{\ell\ell}|$-distributions to extract A_{FB} and $A_{|\Delta\phi_{\ell\ell}|}$ resp.
- Distributions compared for `MadGraph` and FCC-ee samples on parton- and reco-level
- For `MadGraph`: No ISR and BES taken into account
- Prepare ground to draw similar conclusions as on generator level



$\Delta y_{t\bar{t}}$-distribution to compute A_{FB}.

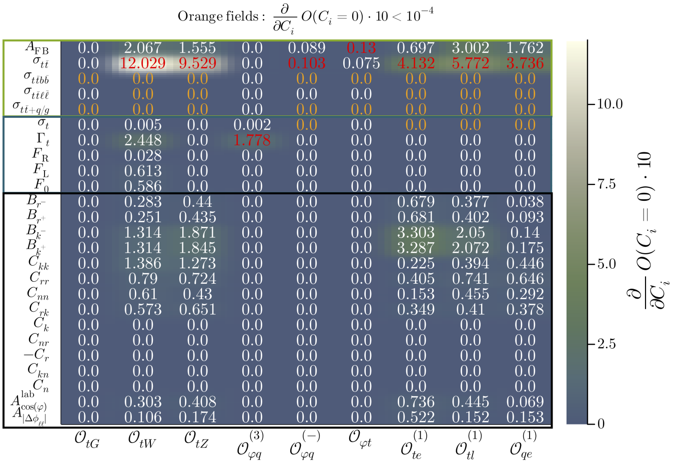


$|\Delta\phi_{\ell\ell}|$-distribution.

Summary: sensitivites from gradients

- Gradient sensitivites in matrix and most sensitive observable per operator highlighted

- Several processes dominated by $t\bar{t}$ production
- Decay predominantly via Wtb vertex with O_{tW} and $O_{\varphi q}^{(3)}$
- Both: Composition of production and decay



Orange fields : $\frac{\partial}{\partial C_i} O(C_i = 0) \cdot 10 < 10^{-4}$

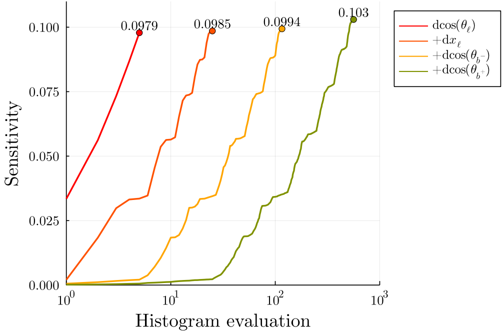
	$\mathcal{O}_{tG}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{tZ}$	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi q}^{(-)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{te}^{(1)}$	$\mathcal{O}_{tl}^{(1)}$	$\mathcal{O}_{qe}^{(1)}$
A_{FB}	0.0	2.067	1.555	0.0	0.089	0.13	0.697	3.002	1.762
$\sigma_{t\bar{t}}$	0.0	12.029	9.529	0.0	0.103	0.075	4.132	5.772	3.736
$\sigma_{t\bar{t}b\bar{b}}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$\sigma_{t\bar{t}\ell\bar{\ell}}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$\sigma_{t\bar{t}+q/g}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
σ_t	0.0	0.005	0.0	0.002	0.0	0.0	0.0	0.0	0.0
Γ_t	0.0	2.448	0.0	1.778	0.0	0.0	0.0	0.0	0.0
F_{R}	0.0	0.028	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F_{L}	0.0	0.613	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F_0	0.0	0.586	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B_{r^-}	0.0	0.283	0.44	0.0	0.0	0.0	0.679	0.377	0.038
B_{r^+}	0.0	0.251	0.435	0.0	0.0	0.0	0.681	0.402	0.093
B_{k^-}	0.0	1.314	1.871	0.0	0.0	0.0	3.303	2.05	0.14
B_{k^+}	0.0	1.314	1.845	0.0	0.0	0.0	3.287	2.072	0.175
C_{kk}	0.0	1.386	1.273	0.0	0.0	0.0	0.225	0.394	0.446
C_{rr}	0.0	0.79	0.724	0.0	0.0	0.0	0.405	0.741	0.646
C_{nn}	0.0	0.61	0.43	0.0	0.0	0.0	0.153	0.455	0.292
C_{rk}	0.0	0.573	0.651	0.0	0.0	0.0	0.349	0.41	0.378
C_k	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{nr}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$-C_r$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_{kn}	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C_n	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
$A^{\mathrm{lab}}_{\cos(\varphi)}$	0.0	0.303	0.408	0.0	0.0	0.0	0.736	0.445	0.069
$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	0.0	0.106	0.174	0.0	0.0	0.0	0.522	0.152	0.153

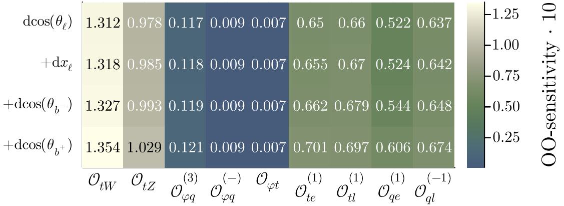
Method II: Sensitivities from optimal observables

Preliminary

- Sensitivity follows as $S_{ii} = \frac{w_i^2}{w_{\mathrm{SM}}\left(\sigma_i^{\mathrm{MG}}\right)^2} \sum_{m=1}^{n_{\mathrm{bins}}} \left(\frac{\mathrm{d}\sigma_i}{\mathrm{d}\Omega_m}\right)^2 \Big/ \frac{\mathrm{d}\sigma_{\mathrm{SM}}}{\mathrm{d}\Omega_m}$
- Each dimension of the phase-space adds up information, but: curse of dimensionality
- Tradeoff between number of bins and number of entries, here: $N_{\mathrm{bins}}/\mathrm{dimension} = 5$

Here: Dimension-dependent evaluation for C_{tZ}



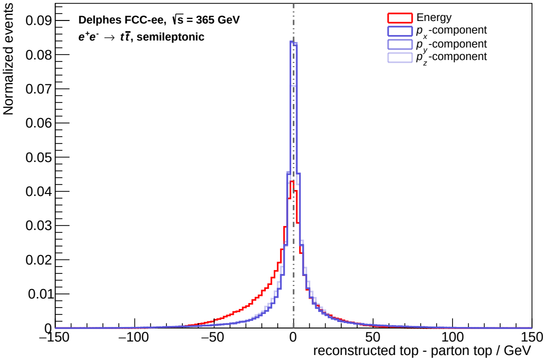


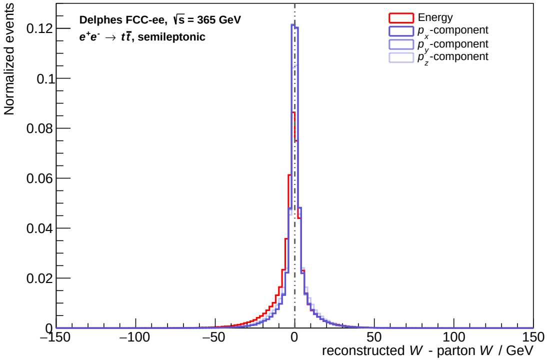
	$\mathcal{O}_{tW}$	$\mathcal{O}_{tZ}$	$\mathcal{O}_{\varphi q}^{(3)}$	$\mathcal{O}_{\varphi q}^{(-)}$	$\mathcal{O}_{\varphi t}$	$\mathcal{O}_{te}^{(1)}$	$\mathcal{O}_{tl}^{(1)}$	$\mathcal{O}_{qe}^{(1)}$	$\mathcal{O}_{ql}^{(-1)}$
$\mathrm{dcos}(\theta_\ell)$	1.312	0.978	0.117	0.009	0.007	0.65	0.66	0.522	0.637
$+\mathrm{d}x_\ell$	1.318	0.985	0.118	0.009	0.007	0.655	0.67	0.524	0.642
$+\mathrm{dcos}(\theta_{b^-})$	1.327	0.993	0.119	0.009	0.007	0.662	0.679	0.544	0.648
$+\mathrm{dcos}(\theta_{b^+})$	1.354	1.029	0.121	0.009	0.007	0.701	0.697	0.606	0.674

Collection of the OO-sensitivities S_{ii} for the different operators i.

Final state objects – semileptonic

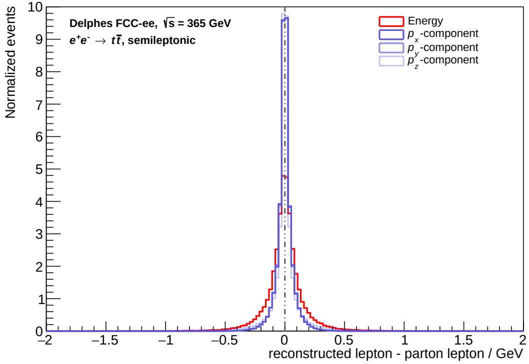
- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}, \ x \in [E, p_x, p_y, p_z]$
- Here: $t/\bar{t}$ and $W^{\pm}$

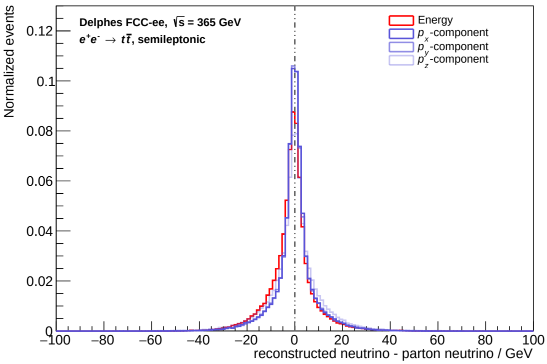




Final state objects – semileptonic

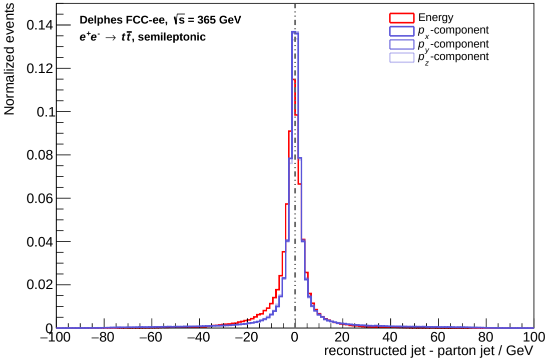
- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}$, $x \in [E, p_x, p_y, p_z]$
- Here: ℓ and ν_ℓ

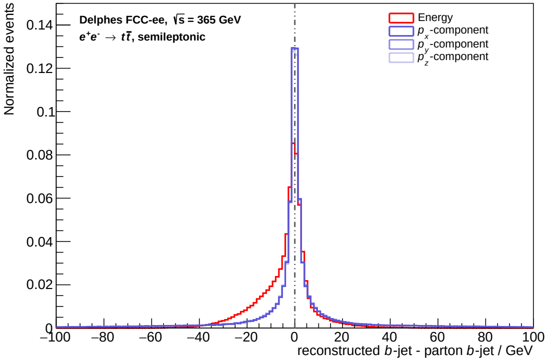




Final state objects – semileptonic

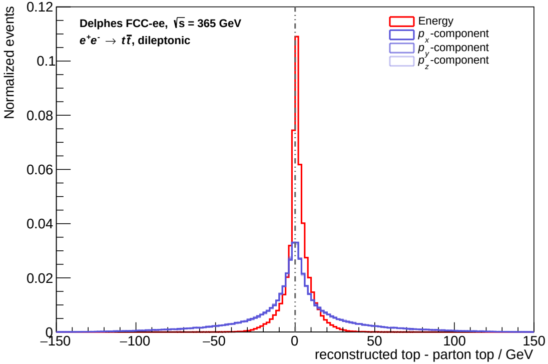
- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}, \ x \in [E, p_x, p_y, p_z]$
- Here: light jets and b-jets

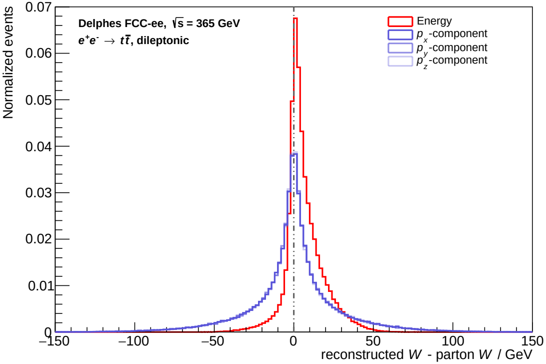




Final state objects – dileptonic

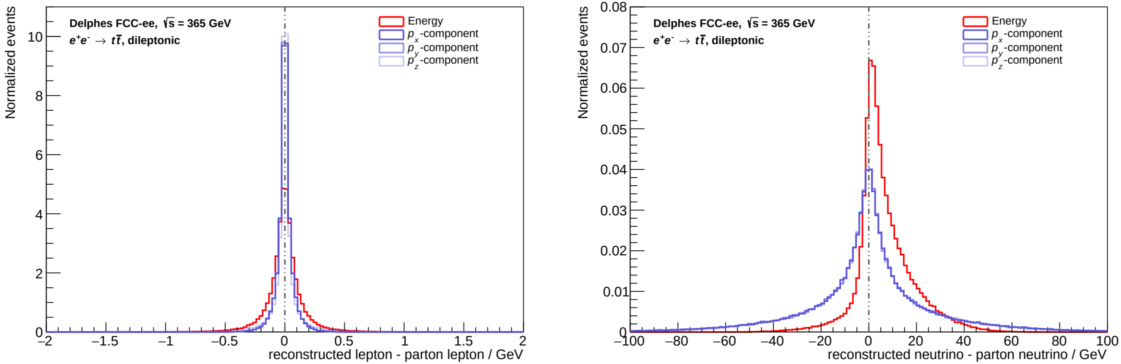
- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}, \; x \in [E, p_x, p_y, p_z]$
- Here: $t/\bar{t}$ and $W^{\pm}$





Final state objects – dileptonic

- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}, \; x \in [E, p_x, p_y, p_z]$
- Here: ℓ and ν_ℓ



Final state objects – dileptonic

- Final state object resolution plots, showing $x^{\text{reco}} - x^{\text{parton}}$, $x \in [E, p_x, p_y, p_z]$
- Here: *b*-jets