Recent Progress in Physics Analyses with the CEPC Ref-TDR Detector and Full Simulation

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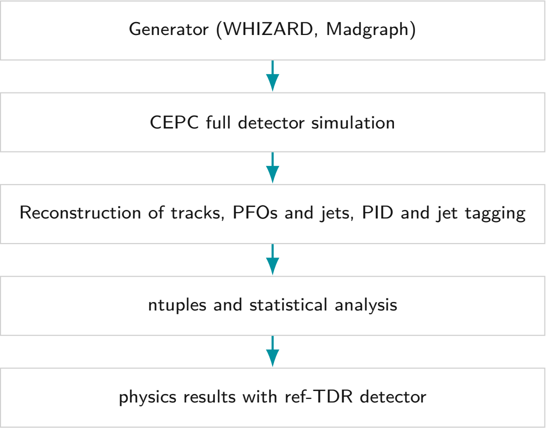
Outline

- **1:** Why TDR full-simulation analyses are important.
- **2:** Recent physics-analysis progress with the TDR full-simulation chain.
  Selected examples; more studies are listed near the end.
- **3:** Potential computing-power and CEPC software improvements.

Physics benchmark studies link detector performance to results



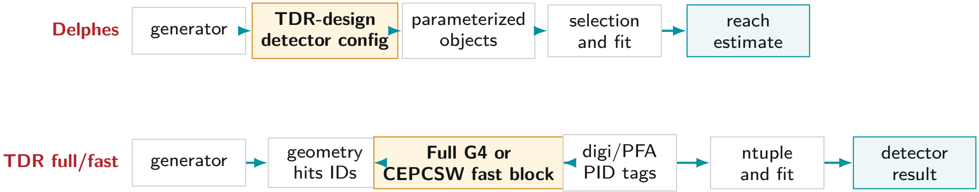
Physics benchmark studies are required because they connect detector performance to selections, migrations, nuisance terms and final physics precision.

Ref-TDR benchmark portfolio

Physics Benchmarks	Relevant Det. Performance	Expected Precision
Recoil H mass	Tracking	Δm_H=±4.0 MeV
$H \to$ hadronic decays	PID, Vertexing, PFA	relative unc. of BR = 0.3% ($b\bar{b}$) – 8.7% (ZZ^*)
$H \to \gamma\gamma$	photon ID, EM resolution	$\Delta(\sigma \times \mathrm{BR})/(\sigma \times \mathrm{BR})_{\mathrm{SM}}$=3.1%
$H \to$ invisible	PFA, missing energy, BMR	4.5σ to SM, BR<0.047% to BSM at 95% CL
$H \to$ LLP	Vertexing, TOF, muon detectors	$\mathrm{BR}(H \to \chi\chi) < 4 \times 10^{-5}$ for m_χ=10 GeVand lifetime=0.1 ns
Smuon pair	muon ID, missing energy	Discovery reach up to $m(\tilde{\mu})$=119 GeV
A^{μ}_{FB}	Tracking, muon ID	±0.000031 (stat.) ± 0.000028 (syst.)
R_b	PFA, jet flavor tagging	2.5×10^{-6} (stat. unc. only)
CPV in $D^0 \to h^+h^-\pi^0$	PID, vertex, π^0, EM resolution	Sensitivity to 0.05° (0.05%) asymmetry in phase (magnitude)
Top quark mass	Beam energy	Δm_{top}=14 MeV (optimistic syst.), 32 MeV (conservative syst.)

- **Coverage:** Higgs, Z-pole, flavor, top and BSM;
tracking, PFA, PID, tagging, missing energy and calibration.
- **Publications:** Most TDR sections or continuation studies will become papers.

Why full simulation is necessary



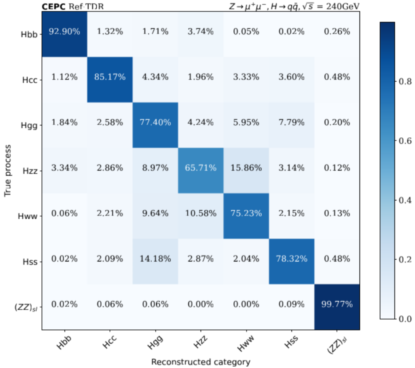
- **Delphes:** Useful fast physics analysis with parameterized detector response; it can use the TDR-design detector configuration.
- **TDR full/fast sim:** Adds geometry, hits, cell IDs, reconstruction failures and software contracts to the same physics test.
- **Full-sim task:** Validate hit-to-PFO migrations, cell-ID effects and reconstruction-driven systematics; Delphes can parameterize them but not validate them.

IDRC feedback defines continuation work

- **General comment:** The physics benchmark studies and operational aspects remain at an early stage; they should be developed toward more comprehensive qualification of the Reference TDR detector with realistic operational modelling.
- **$H \to s\bar{s}$:** JOI flavour separation is promising; demonstrate its impact on $H \to s\bar{s}$ **sensitivity**, a novel channel beyond current LHC reach.
- **$Z \to s\bar{s}$:** Since charged kaons can be efficiently identified at the Z pole, explore A_{FB} **in** $Z \to s\bar{s}$.

$H \to s\bar{s}$: goal, detector link, strategy

- **Goal:** First measurement sensitivity to $H \to s\bar{s}$; highlighted by IDRC.
- **Relevant detector:** PID, vertexing, PFA and strange jet tagging.
- **Strategy:** Same baseline as the Higgs BR study in $\mu\mu H$; extend to other Z decay modes and improve strange jet tagging.
- **Current anchor:** $\mu\mu H$ full-sim status first; holistic Delphes study provides comparison for the next TDR update.



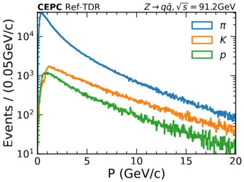
Ref-TDR $\mu\mu H$ Higgs BR classification matrix; $H \to s\bar{s}$ is the follow-up target.

$H \to s\bar{s}$: error analysis and result

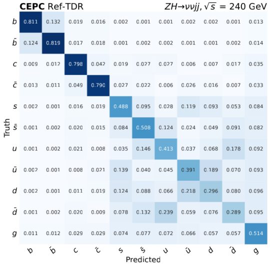
Signal	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$	$H \to ZZ^*$	$H \to WW^*$	$H \to s\bar{s}$
BR	57.7%	2.91%	8.57%	2.64%	21.5%	4.4×10^{-4}
Rel. stat. unc.	0.4%	2.2%	1.3%	7.8%	1.1%	97.2%
Rel. syst. unc.	0.1%	3.7%	1.8%	4.2%	0.4%	211.7%

- **Error analysis:** $\mu\mu H$ full sim: stat. 97.2%, syst. 211.7%.
- **Newest reference:** HiHEP article 2603003481: status report quotes 29.3% and 4–8σ in a Delphes/fast-sim-level setup.
- **TDR update:** The corresponding Ref-TDR full-simulation result will be updated.

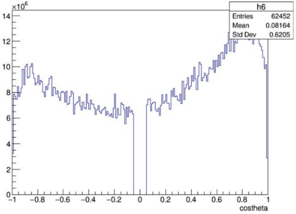
$Z \to s\bar{s}$ AFB: goal, detector link, strategy



Ref-TDR charged-hadron PID at the Z pole.



TDR Fig. 15.15: JOI jet-tagging confusion matrix.



s-jet $\cos\theta$ distribution in the current $A_{FB}(s)$ study.

- **Goal:** First precise measurement path for $A_{FB}(s)$; highlighted by IDRC.
- **Relevant detector:** Kaon ID, strange jet tagging, PFO charge and angular reconstruction.
- **Strategy:** Similar workflow as $e^+e^- \to \mu^+\mu^-$ AFB; harder because of flavor and charge mis-tagging.

$Z \to s\bar{s}$ AFB: error analysis and result

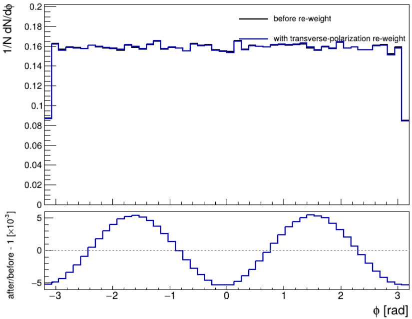
$$A_{FB}^{s} = \frac{A_{FB}^{obs} - A_{FB}^{\bar{s}} \cdot f_2 - A_{FB}^{bkg} \cdot f_3}{f_1},$$

Truth category	Tagged $s\bar{s}$	Charge mis-ID	Other
$s\bar{s}$	22.247%	1.024%	76.728%
other	0.484%	0.674%	98.842%

- **Error analysis:** 1 ab^{-1}: stat. 2.8×10^{-5}; detector-resolution estimate 3.7×10^{-5}.
- **Result:** $A_{FB}(s) = 0.154499 \pm 0.000028$; PFO-corrected value 0.154499.
- **Next focus:** Study strange jet tagging and Kaon ID.
- **Systematics:** Control flavor and charge mis-tagging systematics at the 10^{-4} scale.

Transverse-polarization Z width: goal and strategy

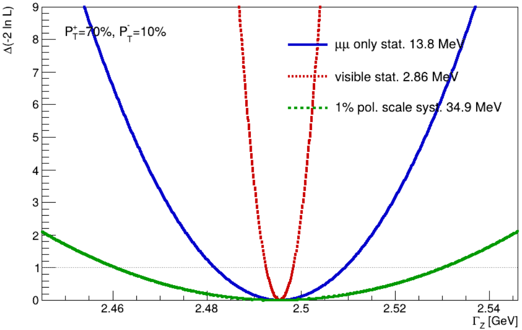
$$F(\theta,\phi) \propto (1+\cos^2\theta) + 2A_eA_f\cos\theta$$
$$- A_f P_T^- P_T^+ (1-\cos^2\theta)\cos 2\phi$$
$$+4A_e P_T^- P_T^+ \frac{\Gamma_Z}{M_Z}(1-\cos^2\theta)\sin 2\phi.$$



2D re-weighting check for the transverse-polarization ϕ asymmetry.

- **Goal:** A new Γ_Z method from controlled transverse polarization.
- **Strategy:** $e^+e^- \to \mu^+\mu^-$ sample; $P_T^+ = 70\%$, $P_T^- = 10\%$; 2D re-weighting of the ϕ asymmetry.
- **Width handle:** The red $\sin 2\phi$ interference term carries the Γ_Z/M_Z dependence.

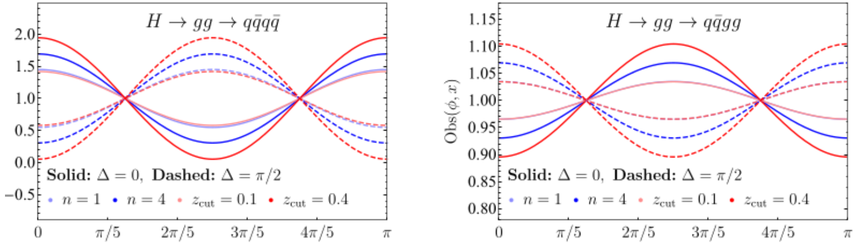
Transverse-polarization Z width: error analysis and result



Configuration	$\sigma(\Gamma_Z)$
$\mu\mu$ only, stat.	13.8 MeV
Visible channels, stat.	2.86 MeV
1% pol. scale syst.	34.9 MeV

- **Error analysis:** 1% polarization-scale uncertainty gives $\sigma_{\text{syst}}(\Gamma_Z) \simeq 34.9$ MeV.
- **Result:** $\Gamma_Z = 2.495 \pm 0.014$ GeV ($\mu\mu$); 2.495 ± 0.0029 GeV (visible), stat. only.

$H \to gg$ CP: spin correlation and quantum-simulation link



Angular observables for $H \to gg$ spin correlation; solid/dashed curves denote CP-even/CP-odd cases.

Decay channels	$b\bar{b}$	$c\bar{c}$	gg	WW^*	ZZ^*
BR	57.7%	2.9%	8.6%	21.5%	2.6%
Rel. Stat. Un.	0.3%	2.2%	1.3%	1.1%	7.6%
Rel. Syst. Un.	0.1%	3.6%	1.8%	0.4%	4.3%
Rel. Total Un.	0.3%	4.2%	2.2%	1.2%	8.7%

Ref-TDR Higgs branching-ratio precision anchor.

- **Physics:** Spin correlation gives the angular modulation; CP mixing changes its phase and shape.
- **Detector / strategy:** PFA, gluon jets, jet substructure; $H \to gg$ classification plus $g \to gg/q\bar{q}$ sub-jet tagging.
- **Expected result:** 20 ab^{-1} ideal estimate: spin correlation 5.44σ; CP mixing angle 45°: 16.7σ.

Other analysis lines not covered today

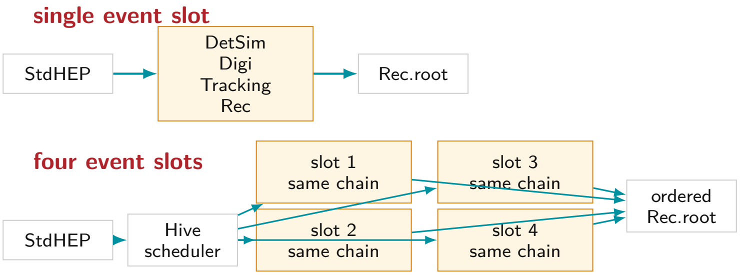
Analysis	Goal	Strategy	Expected result
$e^+e^- \to H \to gg$	Electron Yukawa, resonant Higgs.	125 GeV dijet resonance with $q\bar{q}$ control.	Feasibility line; S/B $\sim 10^{-6}$ after simple selection.
$t\bar{t}$ EW	Top EW form factors.	Leptonic angular spectra and template fit.	Percent to sub-percent reach; theory floor 0.3–1%.
Top threshold	m_t, Γ_t, α_s, y_t.	Optimized 5-point threshold scan.	$\sigma(m_t) \sim 7.5$ MeV before theory.
2HDM+a DM	Missing-energy BSM reach.	250 GeV signal grid and SM background closure.	fb-level reach in favorable low-mass points.
BIB	Operational background for detector studies.	Accelerator tracking plus CEPCSW overlay.	Flow-matching prototype ready; CEPCSW integration remains.
LumiCal / HZZ	Luminosity and forward response.	LumiCal Delphes module plus HZZ forward check.	Target: $\Delta L/L \leq 10^{-4}$; prototype and alignment remain.

Full-simulation time and resource pressure

- **Timing scale:** CEPCSW ZH full chain: 6–15 s/event. Delphes: 10^{-2}–10^{-1} s/event.
- **Scale gap:** Full sim / Delphes $\sim 10^2$–10^3.
- **Queue snapshot:** 2026-05-27 13:34 CST, lxlogin.

Group	total jobs	running jobs	running fraction
CEPC higgs group	13784	75	0.54%
All groups	140982	19559	13.9%

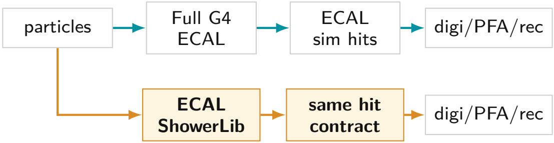
Potential speed up of CEPCSW : multi-thread processing



- **Implementation:** Upgraded key4hep/k4heap stack with GaudiHive/HiveWhiteBoard, slot-aware clonable algorithms, G4MT master-worker DetSim and OrderedPodioWriter.

Measured result $H \to b\bar{b}$, 1000-event full chain: hive1 841 s; hive4 384 s; speedup 2.19$\times$.

Potential speed up of CEPCSW: Calorimeter fast-simulation



ZH full chain	Full G4	ShowerLib
hive1	2.29 s/evt	0.74 s/evt
hive4	0.71 s/evt	0.31 s/evt

- **Design:** A G4 fast-simulation model replaces ECAL shower tracking by template lookup, transform and cell mapping while preserving the ECAL sim-hit output contract.

Combined example ZH full chain: $2.29 \to 0.31$ s/event $= 7.4\times$.

Summary

- **Full simulation:** TDR full-simulation analyses have a special role: they connect physics results to detector performance and software validity.
- **TDR continuation:** The TDR already contains many benchmark analyses; polarization-related studies and most continuation lines will become papers.
- **Recent progress:** Today covered $H \to s\bar{s}$, $A_{FB}(s)$, transverse-polarization Z width, $H \to gg$ CP and other active lines.
- **Computing:** CEPC physics-analysis workflow and computing resources still need substantial improvement.