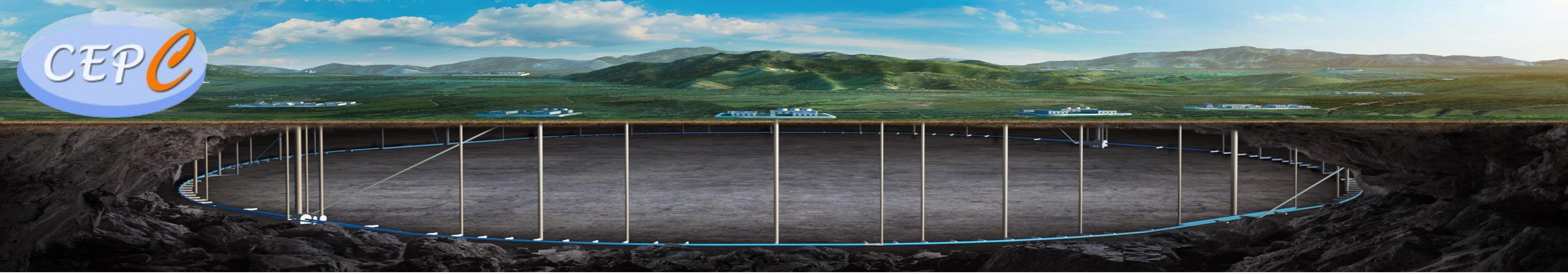

CEPC Detector and Physics Performance

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Content

- Overview of IDRC comments and main changes

- Detailed description of the changes
  - Physics performance
  - Physics benchmarks

- Research team and working plan

- Summary

(in Backup) ALL the answers to Review comments

Overview of IDRC comments and main changes

- Mingshui's summary on Detector & Physics Performance in April: link
- IDRC comments mainly includes the following aspects:
  - Refinements for object reconstruction & identification
  - Expansion of physics benchmark studies
  - Text & structure
- Main changes according to IDRC comments
  - New Missing ET reconstruction, unconverted photon ID, tau ID, other updates..
  - More physics benchmark analyses with systematic uncertainty studies
  - Rephrased performance section according to comments

Detailed description of the changes

- Physics performance updates
  - Missing ET reconstruction, unconverted photon ID, tau ID
- Physics benchmark studies

Physics Benchmarks	Process	$E_{\text{c.m.}}$(GeV)	Domain	Relevant Det. Performance
Recoil H mass	$\mu\mu H$	240	Higgs	Tracking
$H \to$ hadronic decays	$\mu\mu H$	240	Higgs	PID, Vertexing, PFA
$H \to \gamma\gamma$	ZH	240	Higgs	photon ID, EM resolution
$H \to$ invisible	ZH	240	Higgs/BSM	PFA, MET, BMR
$H \to$ LLP	ZH	240	BSM	Tracker, TOF, muon detectors
Smuon pair	$\tilde{\mu}^+\tilde{\mu}^-$	240	BSM	Tracking
A^{μ}_{FB}	$\mu^+\mu^-$	91.2	EW	Tracking, muon ID
R_b	$Z \to q\bar{q}$	91.2	EW	PFA, jet flavor tagging
CPV in $D^0 \to h^+h^-\pi^0$	$Z \to q\bar{q}$	91.2	Flavor	PID, vertex, π^0, EM resolution
Top mass & width	$t\bar{t}$	~ 345	Top	Beam energy

Detector performance changes

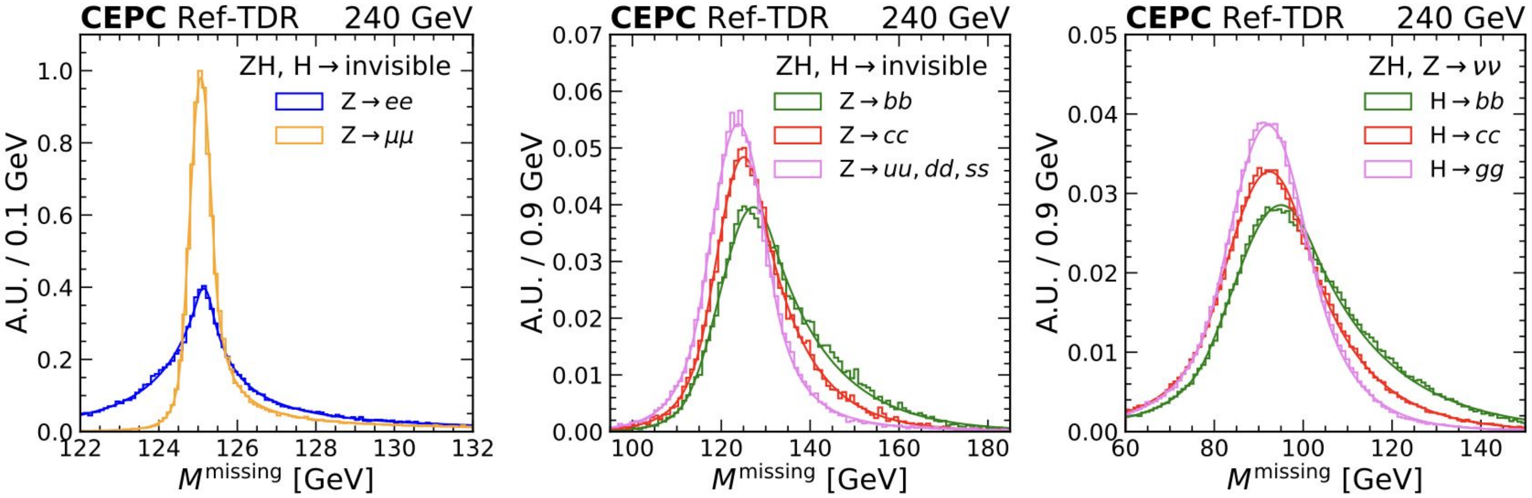
Missing momentum Reconstruction

- The missing momentum is computed by

$$p_{\text{missing}} = p_{\text{total}} - p_{\text{visible}}, \qquad p_{\text{total}} = (0, 0, 0, \sqrt{s})\text{GeV},$$

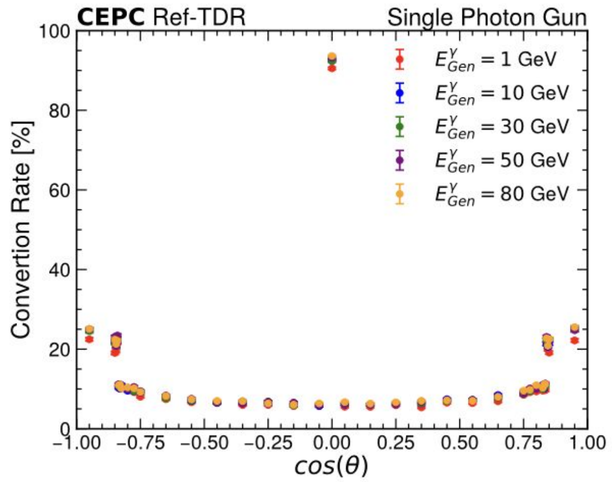
The visible momentum is by summing up all PFO

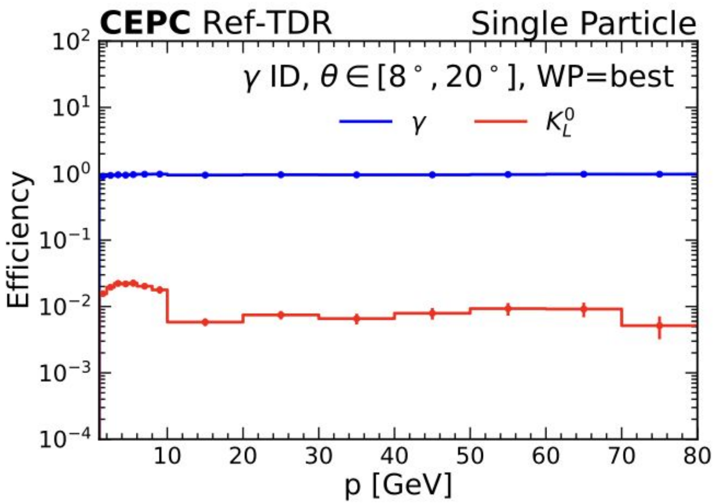
- Missing mass resolution:
  – 0.28 and 0.4 GeV for leptonic channels, 6.4 - 9.2 GeV for hadronic channels
- Beam induced background considered
  – Contributes 7 GeV additional visible energy, and increase the resolution by ~10%
  – Can be significantly suppressed by a |cos θ| < 0.98 cut

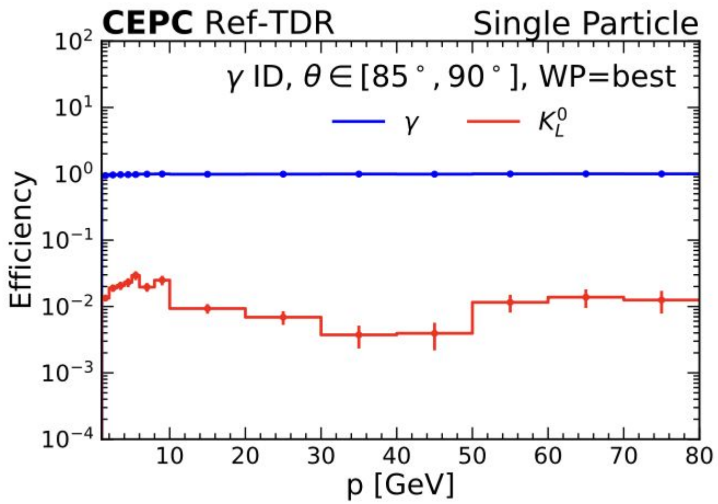


Conversion rate and Unconverted Photon ID

- The photon conversion rate is investigated:
  – ~5-25% and consistent with the material amount of the tracker
- A unconverted photon ID is developed based on XGBoost
- Performance:
  – Photon efficiency > 90%, K0L misidentification rate is up to 2%



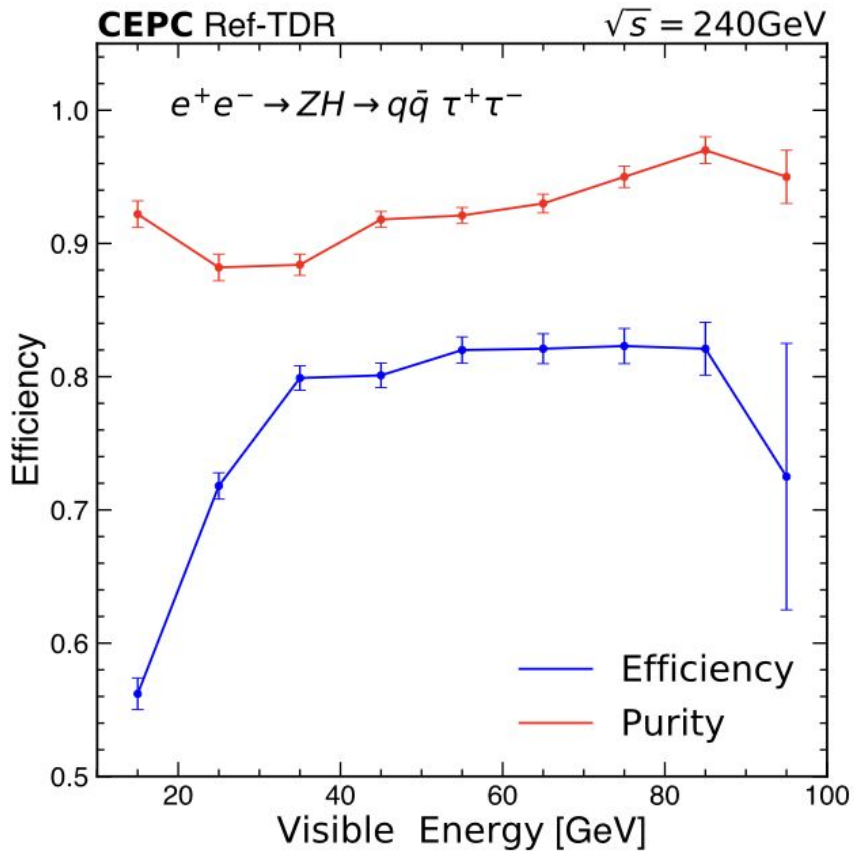




Hadronic Tau ID

- A hadronic tau ID is developed
  – start with a seed track, E > 1.5 GeV
  – reconstruct tau in a cone of 0.12
  – tau candidate mass in 0.01 - 2 GeV
  – Isolation: energy in 0.12-0.31 should be less than 8% of tau candidate

- Efficiency ~ 80%, and purity > 90% over background jets



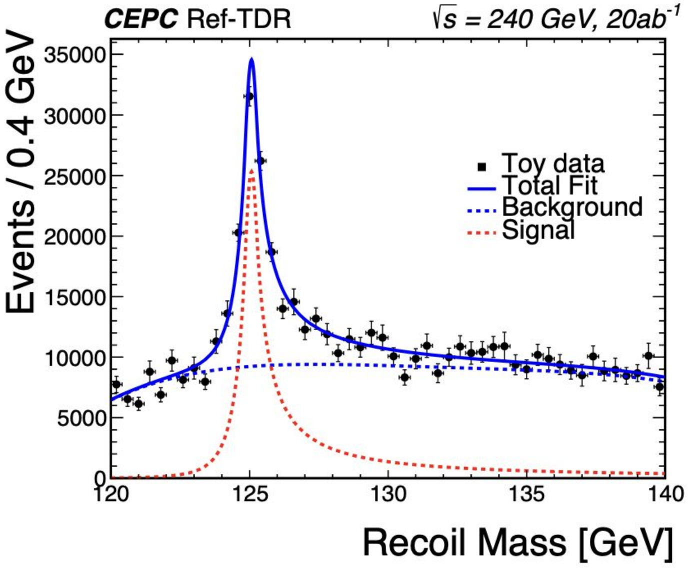
Physics benchmark studies

Recoil H mass

- Physics goal: precise measurement of Higgs boson mass
- Relevant performance: tracking
- Analysis strategy:
  - Selection of Z(μμ)H events
    - Only requires the reconstruction & identification of the muon pair
  - S+B fit on the recoil mass

$$M_{\rm rec}^2 = (\sqrt{s} - E_{\mu^-} - E_{\mu^+})^2 - |\vec{p}_{\mu^-} + \vec{p}_{\mu^+}|^2.$$

Final States	$2\nu 2\mu$	4μ	$2\mu 2e$	$2\mu 2\tau$	$2\mu 2q$	2μ	$\mu\mu H$
Events number	120000	40000	40000	40000	80000	100000	40000
Muon pair	31.4%	41.7%	6.7%	25.8%	29.5%	88.2%	95.6%
MEZ $\in [0, 50]$ GeV	26.5%	29.9%	4.7%	17.1%	25.7%	54.2%	94.4%
$E_{\mu\mu} \in [0, 110]$ GeV	12.7%	16.5%	4.1%	10.0%	15.0%	53.0%	93.8%
$p_{\mu\mu} \in [20, 60]$ GeV	7.5%	9.9%	2.1%	5.6%	8.0%	9.8%	83.7%
$m_{\mu\mu} \in [50, 120]$ GeV	5.8%	6.7%	0.4%	3.1%	3.1%	9.8%	83.6%
$M_{\rm rec} \in [120, 140]$ GeV	2.6%	3.2%	0.1%	1.6%	1.7%	6.5%	78.7%



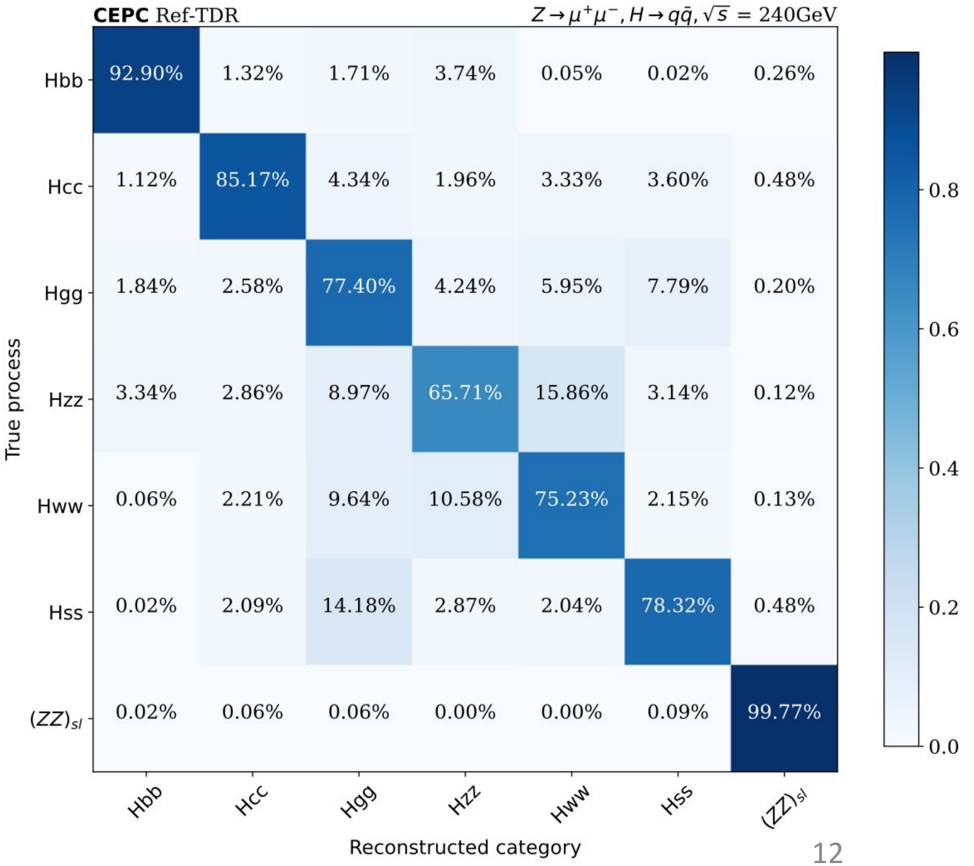
Recoil H mass

- Statistical uncertainty: ±3.2 MeV
- Systematic uncertainties: ±2.5 MeV in total
  - Muon momentum scale: 2 MeV variation, ~1 MeV impact on mH
  - Center of mass energy: 2 MeV variation, ~2 MeV impact on mH
  - Beam energy spread: 0.17% variation @ 240 GeV, negligible impact
  - ISR on/off: ~1 MeV impact on mH
  - Beam induced Bkg: recoil mass is 5 MeV wider, negligible impact on mH
- Result:
  - Total uncertainty ± 4.1 MeV
  - Much better precision than LHC: ±0.1 GeV
  - Comparable with FCC-ee: ± 4.4 MeV

Higgs Br in hadronic final states

- **Physics goal:** precise measurement of 6 Higgs boson decay modes
- **Relevant performance:** PID, vertexing, PFA
- **Analysis strategy:**
  - Selection of Z(μμ)H events
  - Multi-classification with Transformer
  - Measurement by unfolding migration matrix

Process	$b\bar{b}$	$c\bar{c}$	gg	WW^*	ZZ^*	$s\bar{s}$	$(ZZ)_{sl}$
Muon pair	96.9%	96.7%	96.7%	96.7%	96.7%	96.6%	21.1%
Isolation	90.3%	90.3%	90.5%	90.4%	90.7%	90.5%	19.7%
$\lvert\cos\theta_{\mu\mu}\rvert$ <0.996	90.0%	90.0%	90.2%	90.1%	90.4%	90.1%	3.0%
N_{tracks} >7	90.0%	90.0%	90.2%	90.1%	90.4%	90.1%	3.0%
Z mass window	86.4%	86.4%	86.5%	86.4%	86.7%	86.5%	1.4%
H mass window	82.4%	82.3%	82.5%	82.4%	82.8%	82.4%	0.7%



Higgs Br in hadronic final states

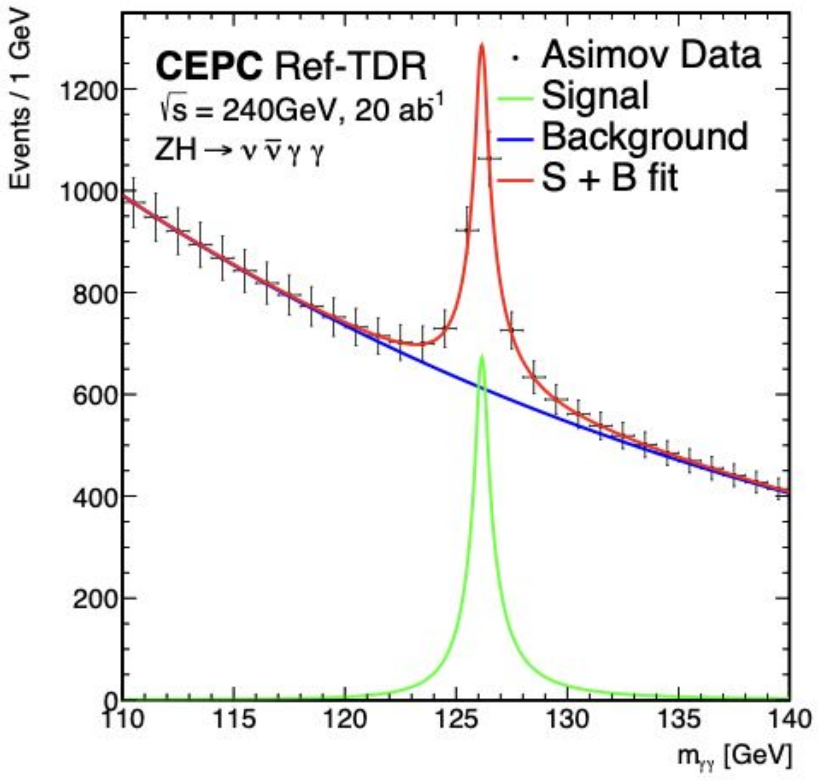
- Systematic uncertainties
  - The main systematic uncertainty is from vertexing & tracking: smearing of track spatial resolution by 20%
- Results:
  - Precise measurement in 5 channels
  - 95% CL upper limit for the Br of ss channel < 0.2%
  - Unprecedented sensitivity compared with LHC, better than FCC-ee for H-qq, comparable or slightly worse for H-WW/ZZ

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%	7.9%
Rel. Syst. Un.	0.1%	3.7%	1.8%	0.4%	4.2%
Rel. Total Un.	0.3%	4.3%	2.2%	1.2%	8.9%

Higgs to di-photon decay

- Physics goal: measurement of Higgs to diphoton decay
- Relevant performance: photon ID, EM calorimeter resolution
- Analysis strategy:
  - Selection of μμγγ, qqγγ, ννγγ events
  - Categorization with BDT
  - S+B fit on the di-photon mass in BDT bins

	Selection efficiency	Expected yield at 20 ab^{-1}
$q\bar{q}\gamma\gamma$ signal	64.6%	4010
$q\bar{q}\gamma\gamma$ background	0.06%	658000
$\mu^+\mu^-\gamma\gamma$ signal	50.4%	155
$\mu^+\mu^-\gamma\gamma$ background	0.01%	12100
$\nu\bar{\nu}\gamma\gamma$ signal	59.0%	1250
$\nu\bar{\nu}\gamma\gamma$ background	0.002%	19700



Higgs to di-photon decay

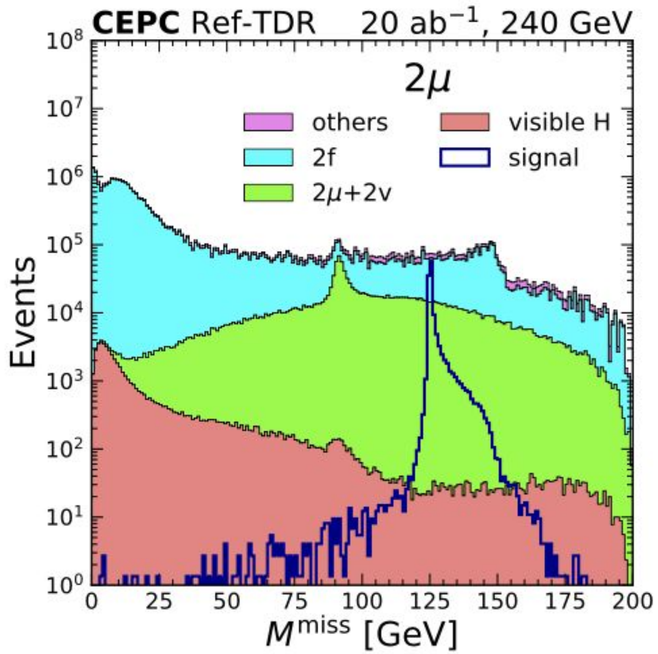
- Systematic uncertainties
  - Mainly from photon reconstruction, photon energy scale & resolution, the mis-modeling of BDT is also considered, all investigated in CDR
  - According to CDR studies, a 15% degradation on the precision is defined as a conservative total systematic variation
- Results:
  - Total uncertainty of Higgs to di-photon decay Br ~3.2%
  - Expected to be comparable with HL-LHC, and comparable with with FCC-ee result (3.6%)

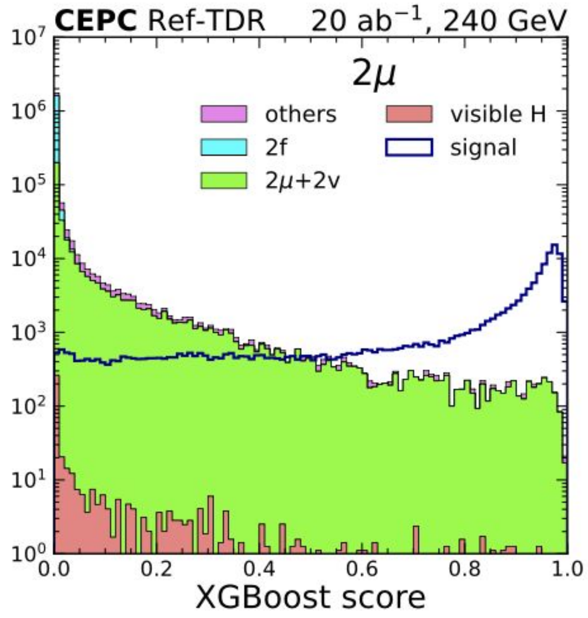
	$\Delta(\sigma \times \mathrm{Br})/(\sigma \times \mathrm{Br})_{SM}$
$q\bar{q}\gamma\gamma$	0.039
$\mu^+\mu^-\gamma\gamma$	0.160
$\nu\bar{\nu}\gamma\gamma$	0.050
Combined	0.032

Higgs to invisible decay

- Physics goal: search for the Higgs to invisible decay
- Relative performance: PFA, MET, BMR
- Analysis strategy:
  - Reconstruction of MET, selection of μμH, eeH, qqH, H->inv events
  - Classification with BDT (XGBoost)
  - S+B fit on XGBoost scores

	process	signal	$2(\mu/e/q)+2\nu$	2-fermion	visible H	others
2μ	Total yield	1.44×10^2	5.68×10^6	1.78×10^9	4.07×10^6	3.79×10^8
	Baseline sel	96.1%	32.0%	2.35%	2.55%	0.88%
	Kinematic sel	98.0%	19.8%	3.40%	0.44%	5.31%
	Selected yield	1.35×10^2	3.59×10^5	1.42×10^6	4.55×10^2	1.78×10^5
$2e$	Total yield	1.49×10^2	5.57×10^6	1.78×10^9	4.07×10^6	3.79×10^8
	Baseline sel	83.8%	41.7%	1.03%	1.96%	1.60%
	Kinematic sel	95.3%	23.0%	3.35%	2.19%	5.77%
	Selected yield	1.19×10^2	5.35×10^5	6.13×10^5	1.75×10^3	3.49×10^5
$2q$	Total yield	2.90×10^3	7.39×10^6	1.78×10^9	4.07×10^6	3.77×10^8
	Baseline sel	99.0%	66.1%	9.24%	19.8%	8.35%
	Kinematic sel	95.4%	38.1%	37.3%	37.8%	12.9%
	Selected yield	2.74×10^3	1.86×10^6	6.13×10^7	3.04×10^5	4.05×10^6





Higgs to invisible decay

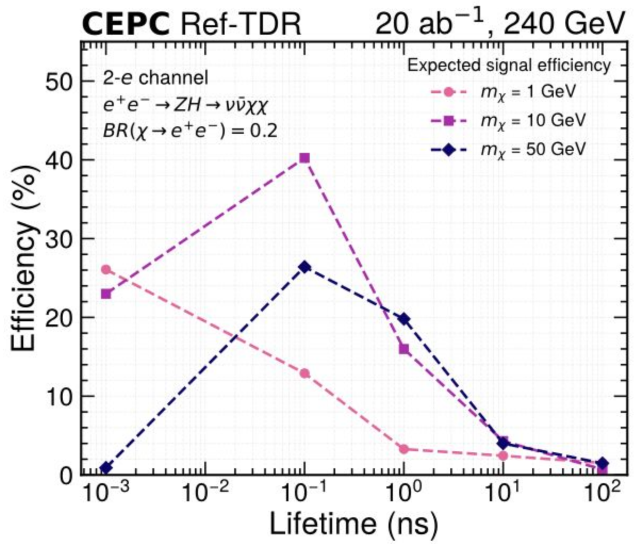
- Systematic uncertainties:
  - The impact from luminosity, beam energy measurements, efficiencies and resolution are < 1%
  - The beam induced background is studied, but its impact is eliminated with a |cosθ| < 0.98 cut
- Results
  - The combined expected significance is 4.4 σ, upper limit of BR is 0.049%
  - Better than LHC (11-15%) and FCC-ee (0.1-0.2%)

channel	uncertainties	significance of SM obs.	UL on BSM BR
2μ	−43%/+44%	2.4σ	0.093%
$2e$	−62%/+65%	1.6σ	0.14%
$2q$	−31%/+31%	3.3σ	0.064%
combine	−23%/+23%	4.4σ	0.049%

Higgs to LLP

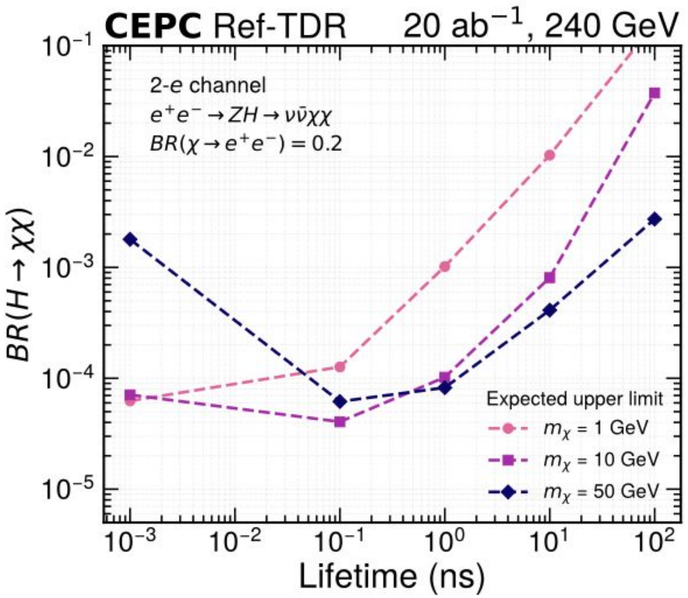
- Physics goal: search for long-live particles (LLP) in Higgs boson decays
- Relative performance: Tracking, TOF, muon detectors
- Analysis strategy:
  - Selection of ννH(χχ) events with χ-> ee or μμ
    - with large recoil mass, vertex displacement and TOF delay
  - Counting for expected number of signal with background fully suppressed

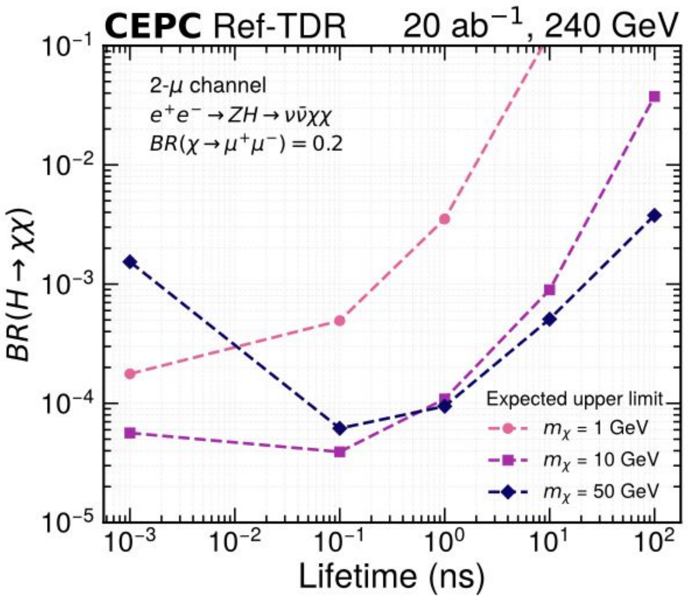
Selection	Category	Criteria
Jet veto	2-e and 2-μ channels	nPFO < 20
Lepton ID	2-e and 2-μ channels	two oppositely-charged leptons passing **BEST WP**
Lepton momentum	2-e and 2-μ channels	$P_\ell > 3$ GeV
Polar angle difference	2-e and 2-μ channels	$1^\circ < \Delta\theta_{\ell\ell} < 60^\circ$
Z-veto	2-e and 2-μ channels	$\lvert M_{\ell\ell} - 90\rvert > 5$ GeV
Recoil mass	2-e channel 2-μ channel	$M_{\rm rec} > 130$ GeV $M_{\rm rec} > 140$ GeV
Vertex displacement	$m_\chi = 1$ GeV $m_\chi = 10, 50$ GeV	$d_{vtx} > 3.5$ mm $d_{vtx} > 1$ mm
Invariant mass window	$m_\chi = 1$ GeV $m_\chi = 10, 50$ GeV	$\lvert M_{\ell\ell} - m_\chi\rvert < 0.6$ GeV $\left\lvert \frac{M_{\ell\ell}-m_\chi}{m_\chi} \right\rvert < 10\%$
Time-of-flight delay	$m_\chi = 1$ GeV and 2-μ channel	$\Delta T > 0.05$ ns



Higgs to LLP

- Statistical uncertainty should be dominant for this search
- Result:
  - 95% CL upper limits on the decay branching ratios of H->χχ
  - Comparable with LHC and ILC projection, including more Z decay modes should further improve the precision by a factor of 5

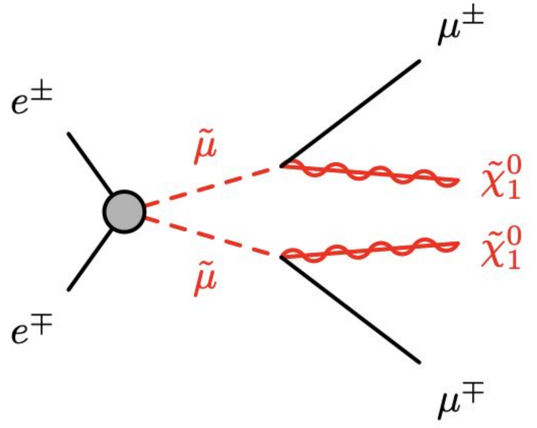




Search for Smuons

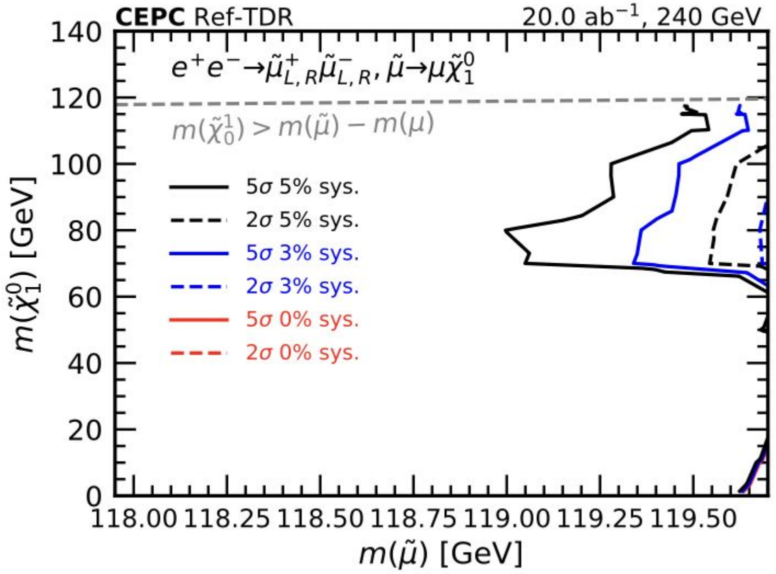
- Physics goal: search for SUSY Smuons
- Relative performance: Tracking
- Analysis strategy:
  - Selection of Smuon pair events
    - 3 signal regions with different muon kinematics, targeting different msμ - mχ0
    - Main background: ZZ, WW, ττ, μμ
  - Counting for expected signal and background events in the signal regions

SR-ΔM^h	SR-ΔM^m	SR-ΔM^l
$E_{\mu 1,2} > 40$ GeV	$9 < E_{\mu 1,2} < 48$ GeV	–
$E_{\mu 1,2} \in (40-50, >50)$ GeV	$E_{\mu 1,2} \in (9-25, 25-48)$ GeV	–
$\Delta R(\mu, \mathrm{recoil}) < 2.9$	$1.5 < \Delta R(\mu, \mathrm{recoil}) < 2.8$	$1.5 < \Delta R(\mu, \mathrm{recoil}) < 2.8$
$M_{\mu\mu} < 60$ GeV	$M_{\mu\mu} < 80$ GeV	–
$M_{\mathrm{recoil}} > 40$ GeV	–	$M_{\mathrm{recoil}} > 220$ GeV



Search for Smuons

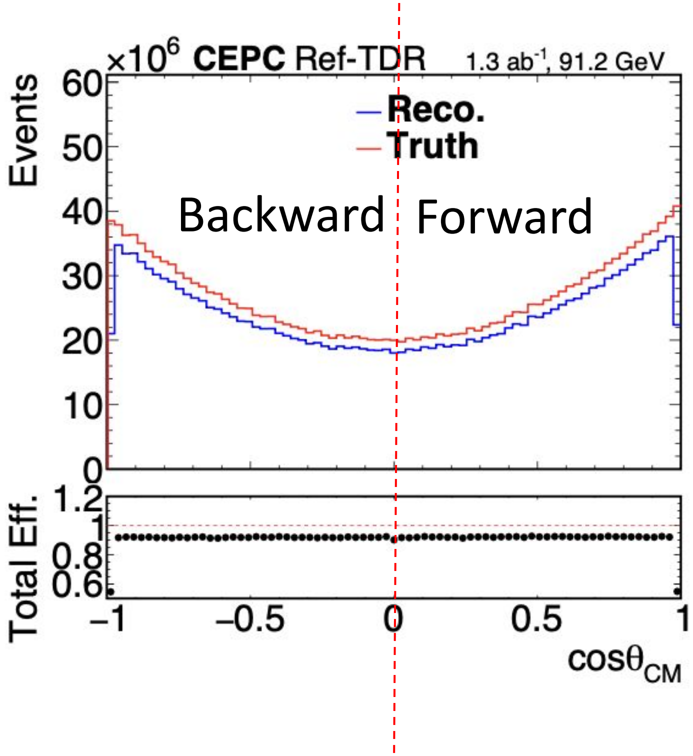
- Statistical uncertainty should be dominant
  - A 5% flat systematic uncertainty is assumed while calculating significance
- Results
  - The prospected exclusion and discovery contours on Smuon and χ0 mass
  - The exclusion limit of Smuon is ~119 GeV
    - Much better than LEP (~20 GeV), no similar result at LHC and FCC-ee so far



ee-mm forward-backward asymmetry

- Physics goal: precise EW measurement of AFB(μ) at Z pole energy
- Relative performance: Tracking, muon ID
- Analysis strategy:
  - Selection of a pair of muon from Z decay
  - Computation of μ cosθ at center-of-mass frame
  - Counting for forward / backward events

	$e^+e^- \to \mu^+\mu^-$	$e^+e^- \to \tau^+\tau^-$	$e^+e^- \to b\bar{b}$	$e^+e^- \to e^+e^-$
Cross-section	1.2 nb	1.2 nb	6.6 nb	1.2 nb
Simulated events	982476	185855	44550	32397
A pair of muons	967262	5135	1035	0
Z mass window	903640	5	0	0
Muon $\|\cos(\theta)\| > 0.05$	869450 (88.5%)	5 (0.003%)	0 (<0.002%)	0 (<0.003%)

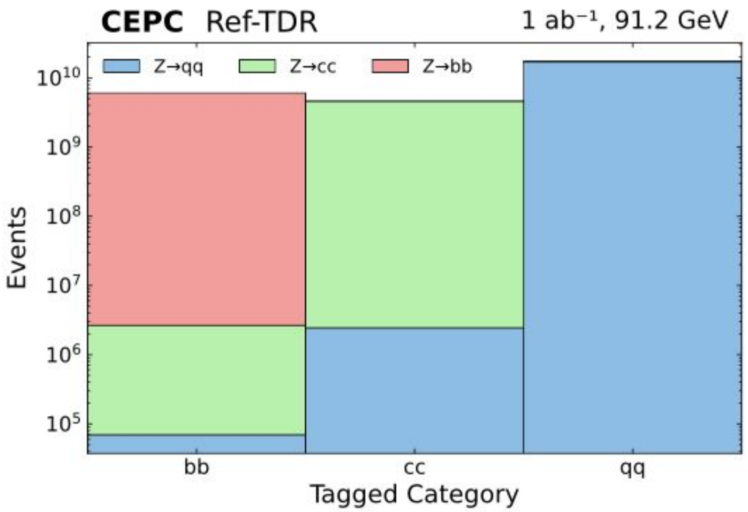


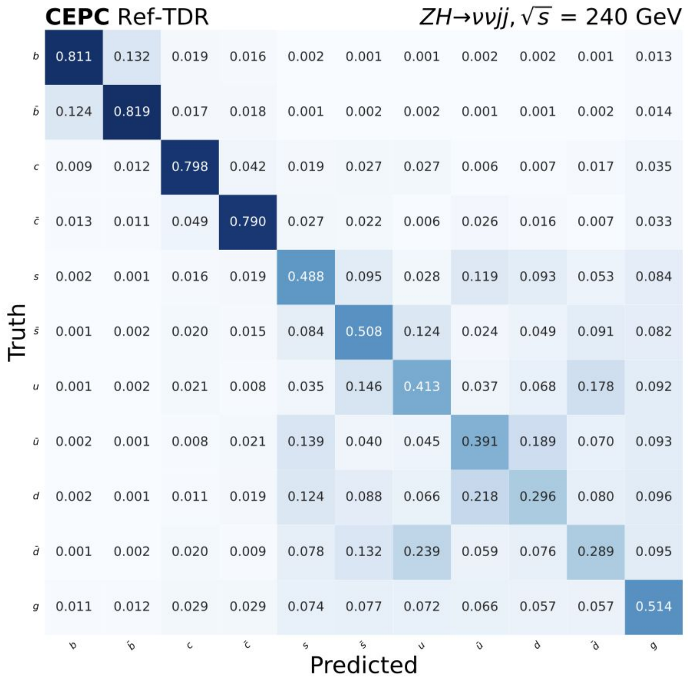
ee-mm forward-backward asymmetry

- Statistical uncertainty: ±0.000031
  - According to $4*10^{10}$ Z bosons expected during the one-month low-luminosity Z pole data taking in the first year of ZH operation
- Systematic uncertainties: total uncertainty ±0.000028
  - Background: mostly suppressed with Z mass window cut, impact is 10^{-6}
  - Detector acceptance and resolution: comparing results by MC particles and PFO, the impact is $9*10^{-6}$
  - Beam energy calibration: assuming a 300 KeV conservative uncertainty of Z pole energy calibration, the impact is ±0.000027
  - Beam energy spread: 0.13% variation at @ Z pole, impact is 10^{-6}
- Result:
  - AFB(μ) = 0.016 ±0.000031 (stat.) ±0.000028 (syst.),
  - Much better than LEP (±0.0014)
  - Comparable with FCC-ee (total uncertainty ±0.00001) with conservative assumptions

ee-bb relative branching ratio

- Physics goal: precise EW measurement of Rb at Z pole
- Relative performance: PFA, jet flavor tagging
- Analysis strategy: $\nu^{ii} = R_b N^{ii}_{bb}(\boldsymbol{\theta}) + R_c N^{ii}_{cc}(\boldsymbol{\theta}) + R_q N^{ii}_{qq}(\boldsymbol{\theta}),$
  - Selection of Z-bb/cc/qq categories by the Transformer Jet origin identification (JOI) algorithm
  - Simultaneous counting measurement for Rb





ee-bb relative branching ratio

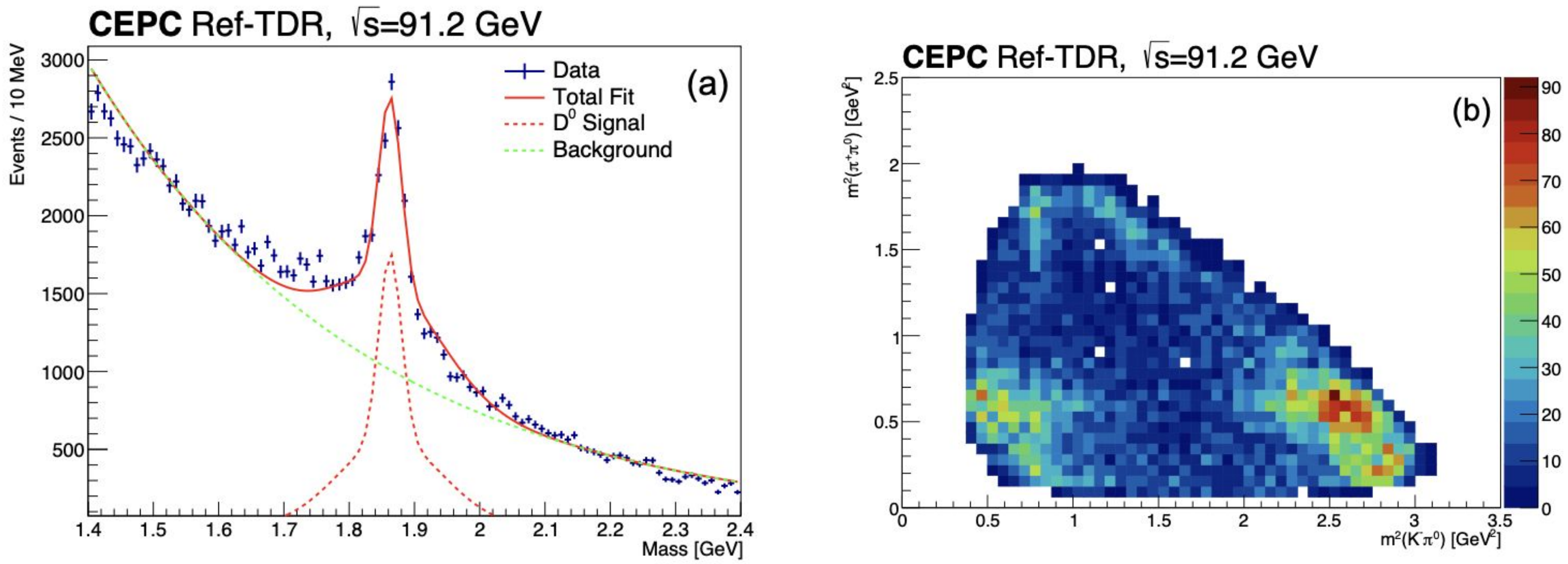
- Statistical uncertainty
  - ± $2.5*10^{-6}$ with $4*10^{10}$ Z bosons during one-month low-luminosity Z pole data taking in the first year of ZH operation
- Systematic uncertainties:
  - Main uncertainty is from JOI: 0.1% variation on tagging probabilities resulting in a 10^{-5} systematic uncertainty
- Result:
  - Slightly better statistical precision than FCC-ee

	$\sigma_{R_b}\,(10^{-6})$	$\sigma_{R_c}\,(10^{-6})$	$\sigma_{R_q}\,(10^{-6})$	**Flavor tagging method**
LEP+SLC	659	3015	–	–
FCCee	1.9 (0.25)	–	–	–
CEPC (template fit)	1.2	2.3	2.1	LCFIPlus
CEPC (ParticleNet)	1.3	1.4	–	ParticleNet
CEPC (JOI)	1.6	1.5	–	JOI

Table with statistical-only uncertainty

CP violation search

- Physics goal: CP violation searches in $D0 \rightarrow h^- h^+ \pi 0$ at Z pole
- Relative performance: PID ($\pi 0$), vertex,EM resolution
- Analysis strategies:
  - Selection of $D0 \rightarrow h^- h^+ \pi 0$ candidate, with hadron PID
  - D0 signal event extraction and Dalitz plot analysis



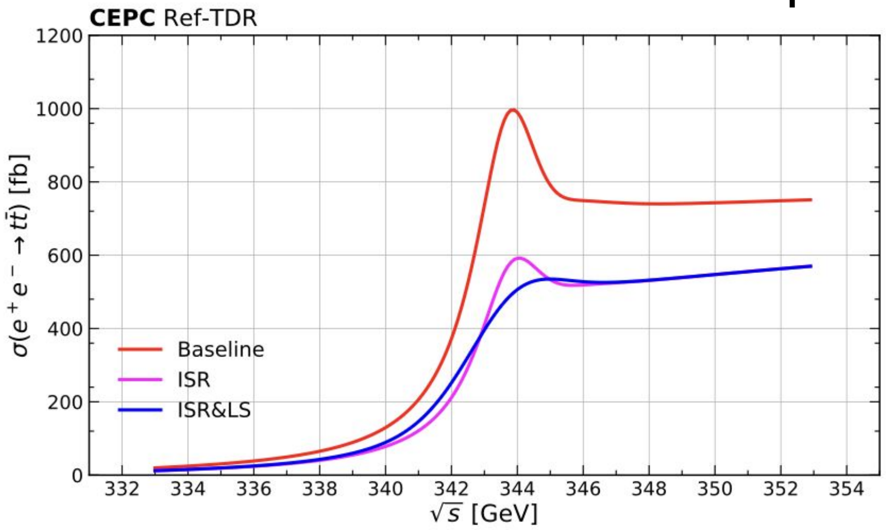
CP violation search

- Statistical uncertainty should be dominant
- Result:
  - Better sensitivity than LHCb projection in the $\pi 0$ final states

Decays	LHCb (6 fb^{-1})	LHCb (300 fb^{-1})	CEPC (4 Tera Z)
D^{*+}	4.7×10^{12}	2.4×10^{14}	4.6×10^{11}
D^0 from D^{*+}	3.2×10^{12}	1.6×10^{14}	3.1×10^{11}
$D^{*+} \to (D^0 \to K^-K^+)\pi^+$	1.6×10^{10}	6.5×10^{11}	1.3×10^{9}
$D^{*+} \to (D^0 \to \pi^-\pi^+)\pi^+$	4.6×10^{9}	2.3×10^{11}	4.5×10^{8}
$D^{*+} \to (D^0 \to K^-\pi^+)\pi^+$	1.6×10^{11}	6.3×10^{12}	1.2×10^{10}
$D^{*+} \to (D^0 \to \pi^-\pi^+\pi^0)\pi^+$	4.8×10^{10}	2.4×10^{12}	4.6×10^{9}
$D^{*+} \to (D^0 \to K^-\pi^+\pi^0)\pi^+$	4.6×10^{11}	2.3×10^{13}	4.4×10^{10}
Reco. & Sel. $D^0 \to K^-K^+$	5.8×10^{7} [56]	2.9×10^{9}	1.3×10^{8}
Reco. & Sel. $D^0 \to \pi^-\pi^+$	1.8×10^{7} [56]	9×10^{8}	4.5×10^{7}
Reco. & Sel. $D^0 \to K^-\pi^+$	5.2×10^{8} [56]	2.6×10^{10}	1.2×10^{9}
Reco. & Sel. $D^0 \to \pi^-\pi^+\pi^0$	2.5×10^{6} [57]	1.2×10^{8}	4.6×10^{8}
Reco. & Sel. $D^0 \to K^-\pi^+\pi^0$	1.9×10^{7} [57]	9.6×10^{8}	4.4×10^{9}

Top mass & width

- Physics goal: precise top measurement at higher energy (~345 GeV)
- Relative performance: beam energy
- Analysis strategy:
  - Selection of ttbar events in semi-leptonic (44% acc*eff) and hadronic (62% acc*eff) channels
  - ttbar cross section is measured at a set of beam energies around threshold. The line shape is parameterized as a function of the top mass / width



Top mass & width

- Systematic uncertainties
  - mainly from experimental efficiencies and theoretical uncertainties
- Result
  - m(top) precision is 21 MeV with optimistic assumption
  - Statistical result is 7 MeV, comparable with FCC-ee (7 MeV)

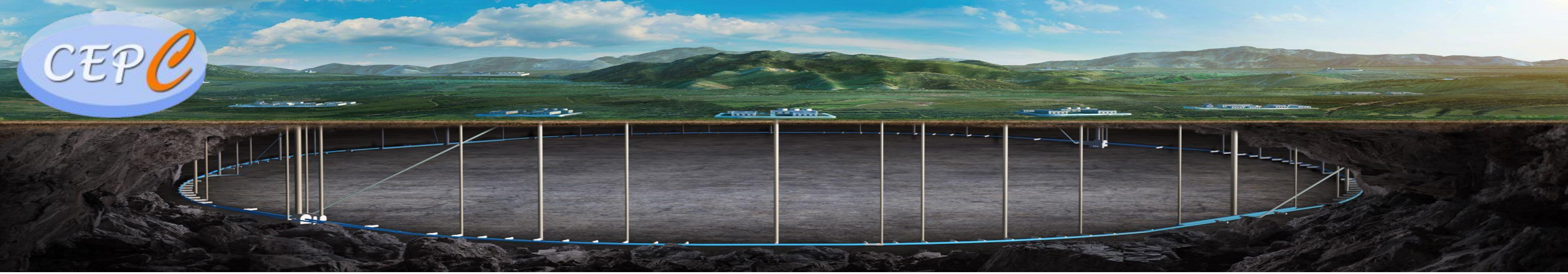
Source	m_{top} precision (MeV) Optimistic	Conservative
Statistics	7	7
Theory	8	24
Quick scan	2	2
α_S	16	16
Top width	5	5
Experimental efficiency	4	44
Background	1	3
Beam energy	2	2
Luminosity spectrum	3	6
Total (without theory)	19	48
Total	21	54

Research Team

Working plan

- Item 1
  - Sub item 1
- Item 2

Summary



Thank you for your attention!

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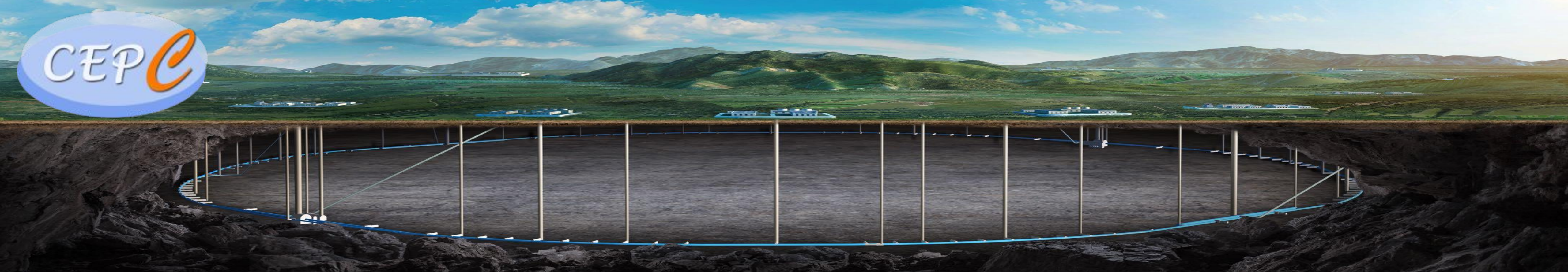

BACKUP

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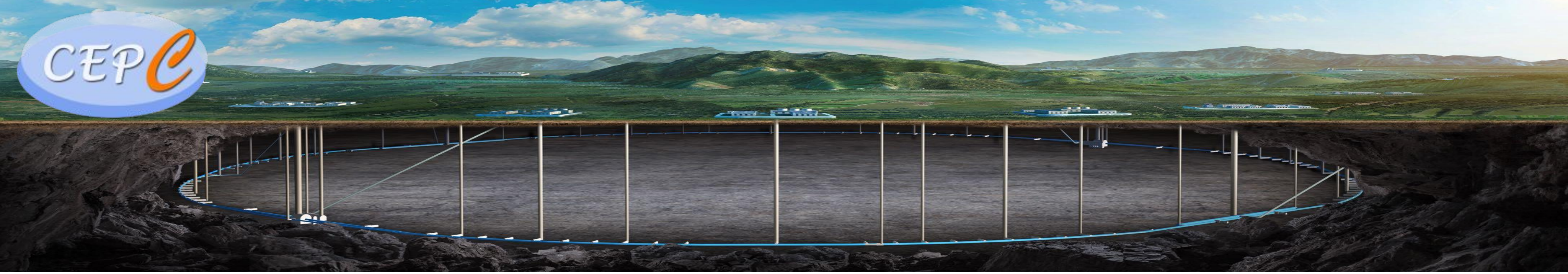
Performance

- Item 1
  - Sub item 1
- Item 2

(Please put this text box in proper pages to highlight the answer to a certain review comment)

- This study is to address the IDRC comment:
  - (Example)The mechanical interface between the detector structure—including the large magnet system—and the final focusing magnet is critical. Close collaboration with the accelerator group is necessary to assess both magnetic field interactions and potential mechanical vibrations…..



Feedback to IDRC comments

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Findings

Although further improvements are possible and recommended, the collaboration's response to the previous evaluation has been excellent and deserves recognition. The detector software, particularly the simulation component, now enables comprehensive studies of detector performance and physics benchmarks. Several design decisions have been made based on both detector and physics performance criteria. This progress has allowed the definition of a baseline detector concept. While still perfectible and requiring further detailed investigation, this is a significant and commendable step forward. The scope of physics performance studies has broadened considerably since the last assessment. The range of channels explored and the methodologies employed respond well to previous recommendations and collectively address key detector areas and primary physics topics.

Comments

- The Ref-TDR text could be improved and shortened by presenting certain aspects (e.g., particle identification, jet studies) more concisely, while still ensuring that the algorithms are described clearly and transparently.
- *Shortened and restructured: PID inputs and algorithms mainly described in Sec. 15.1.2, with properly reference to TPC chapter; Jets studies rewritten in Sec. 15.1.7 and 15.1.8, the JOI flavor tagging now chosen as default, and text on the BDT method reduced.*
- Many additional physics analyses are planned. Their presentation and motivation should be aligned with the main purpose of this document: demonstrating the feasibility and physics potential of the reference detector.
- *10 analyses conducted and documented in Sec. 15.2*
- Algorithms for particle identification, jet tagging, etc., are mentioned in multiple places and are still evolving. A systematic approach should be adopted to define and refer to these algorithms consistently across the document.
- *Restructured: XGBoost BDT approach is adopted for all PIDs, JOI chosen as default jet tagging method.*

Recommendations

- The studies encompass both physics benchmarks and detector performance metrics. A clearer distinction between these two aspects would be beneficial. The editorial team is encouraged to organize the content into:
  - Sub-detector technical performance — technical performance figures (used for sub-detector configuration decisions) should be placed in the relevant sub-detector chapters.
    - *Single photon reconstruction efficiency and resolutions now only shown in* Section 7.3.4 *(ECAL chapter)*
    - *Track impact parameters now appear only in Section 4.7 (Vertex chapter)*
    - *Plots for separation power of tof and dn/dx moved to Section 4.5 (Silicon Tracker chapter) and Section 6.4 (TPC chapter)*
  - Physics-related performance — to demonstrate baseline detector capabilities for physics analyses (e.g., particle identification, global variables like ETmiss), and to present the physics analyses themselves. This should be the main focus of the performance chapter.
    - *Sec 15.1 restructured to focus on physics-related performance*
    - *Now Tau leptons (15.1.5) and Missing E/p/m (15.1.9) also included.*

Recommendations

- The physics benchmarks listed in Table 15.3 are intended to demonstrate the performance of the reference detector. Each listed study should be discussed explicitly, explaining the role of the detector performance in achieving the result. Currently, only a subset (e.g., Higgs recoil mass, Higgs branching ratios, weak mixing angle from Z→μμ) are covered. Other channels (exotic Higgs decays, LLPs, CVP in D-meson decays) should also be summarized, possibly in a summary table.
- *Sections 15.2.2 – 15.2.11 discuss and cover 10 analyses listed in the Table 15.3, and Table 15.20 summarizes the achieved sensitivities for all those channels.*

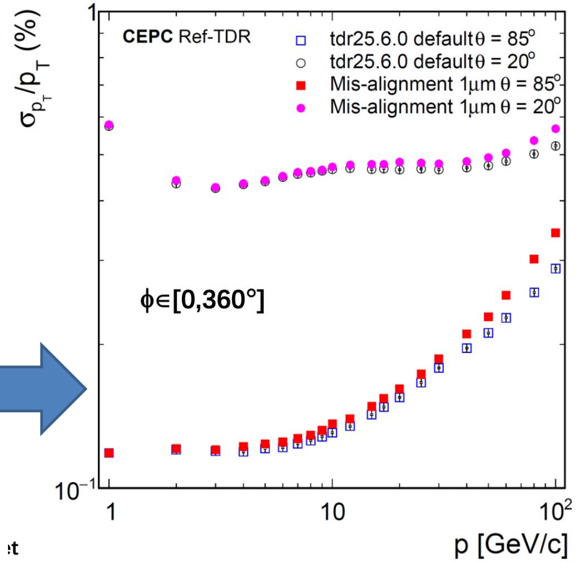
Table 15.20: Physics benchmarks, relevant detector performances and expected precision.

Physics Benchmarks	Relevant Det. Performance	Expected Precision
Recoil H mass	Tracking	Δm_H=±4.1 MeV
$H \to$ hadronic decays	PID, Vertexing, PFA	relative unc. of BR = 0.3% ($b\bar{b}$) – 8.9% (ZZ^*)
$H \to \gamma\gamma$	photon ID, EM resolution	$\Delta(\sigma \times \text{BR})/(\sigma \times \text{BR})_{\text{SM}}$=3.2%
$H \to$ invisible	PFA, MET, BMR	4.4σ to SM, BR<0.049% to BSM at 95% CL
$H \to$ LLP	Tracker, TOF, muon detectors	BR($H \to \chi\chi$) $< 4 \times 10^{-5}$ for m_χ=10 GeVand lifetime=0.1 ns
Smuon pair	Tracking	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 mass & width	Beam energy	Δm_{top}=21 MeV (optimistic syst.), 54 MeV (conservative syst.)

Recommendations

- The technical improvements planned for more detailed simulation (noise, event overlap, misalignments, calibration effects) should be pursued, and their impact on physics performance carefully demonstrated.
  - *Noise are included by default.*
  - *Preliminary studies on beam induced background through event overlap, including incoherent pairs creation (dominant)*
    - *No significant impact on tracking efficiency*
    - *5% worse resolution – negligible impact*
    - *Significant impact on missing energy/mass documented in 15.1.9, which can be mitigated by a requirement of |cosθ|<0.98 for neutral objects*

> The missing energy and mass is sensitive to BIBs. The BIBs induce additional neutral objects in calorimeters, and lead to an increase of around 7 GeV to the visible energy. With $Z \to q\bar{q}$, $H \to 4\nu$, the mean value of the missing mass distribution decreases to around 118 GeV, whereas the resolution rises to 7.2 GeV. Most neutral objects from BIBs lie in very forward and backward regions. By discarding neutral objects with $|\cos\theta| > 0.98$, the effect can be cleared, with the missing mass mean value back to around 125 GeV, and the resolution restored to 6.4 GeV.

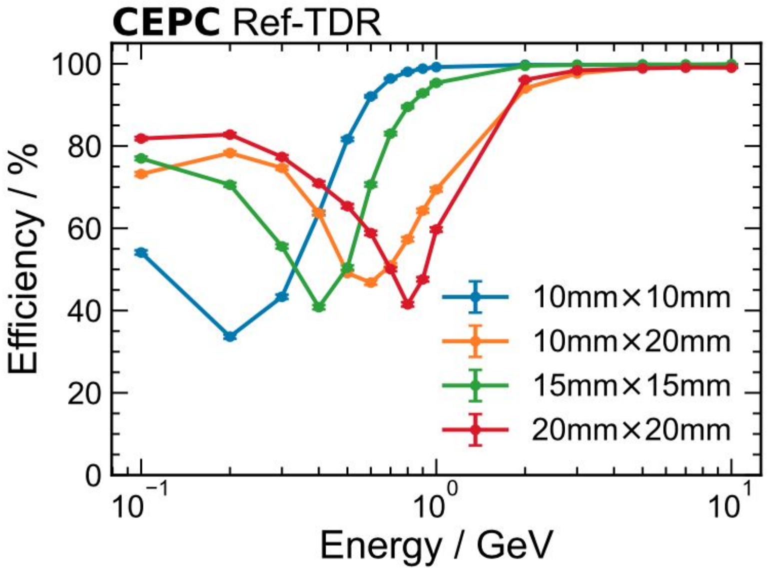


- *With alignment precision expected (1 μm), no significant misalignment effects expected on tracking*
  - *the effect can be further reduced by correcting the bias according to angle (post-TDR development)*
- *Calibration: PFA reconstruction includes preliminary simple calibration on ECAL/HCAL clusters*
  - *Figure 7.18 shows the ECAL energy resolution for 5 different calibration precision ranging from 1 % to 10 %, indicates that the calibration precision of 1 % yields around a 0.3 % degradation on the constant term*

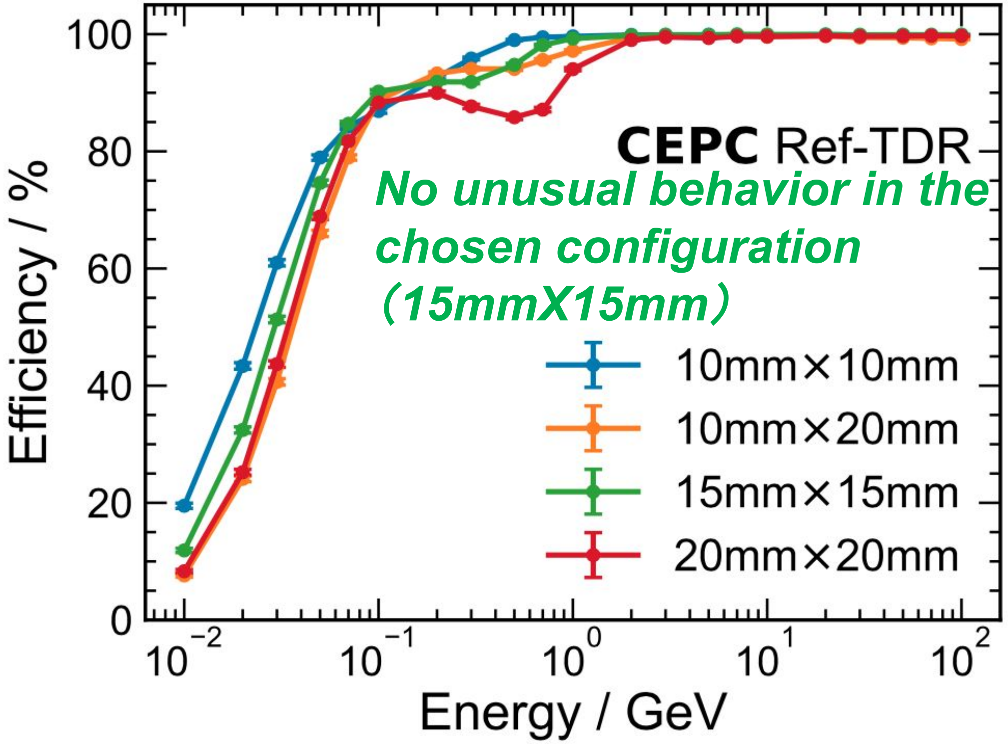
Recommendations

Several specific technical issues should be clarified and potentially improved:

- The photon efficiency behaviour around E = 1 GeV appears unusual and should be either justified or corrected, as it could impact EM/hadronic separation in PFA and influence missing energy and mass resolution.
  corrected and shown in ECAL chapter, Figure 7.21(a).



corrected



Recommendations

- Jet energy resolution for light quarks should be studied more systematically and used as a benchmark metric.

JER now made with u/d light quarks, similar performance seen as previous with b quarks

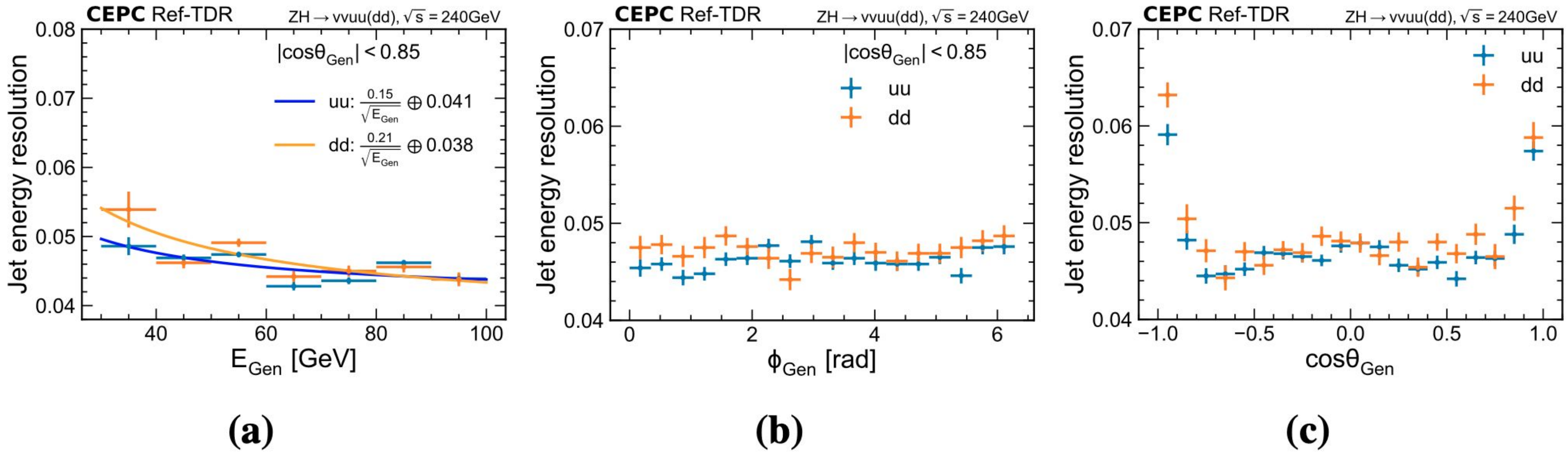


Figure 15.12: Jet energy resolution as a function of the (a) GenJet energy, (b) azimuth angle, and (c) $\cos\theta_{Gen}$ for the $ZH \to \nu\nu uu$ and $ZH \to \nu\nu dd$ processes. Only the statistical uncertainty is presented.

Recommendations

- Missing energy reconstruction should be further investigated, particularly in b- and c-jet events with tagged leptons and in BSM channels with large ETmiss.
  New section 15.1.9 shows performance on " Missing energy, momentum, mass"
  Section 15.2.5 documents studies of the H->invisible channel
- (Longer term) Tracking performance should be tested in exotic scenarios, such as long-lived particles.
  Currently Section 15.2.6 shows studies on long-lived particles.
- (If possible) Include photon conversions in tracking studies as a material probe and describe their treatment in PFA.
  Figure 15.5 shows material budget and conversion rate vs. cos(theta).
  Currently converted photon treated as two charged tracks in PFA, further improvement planed in post-TDR development.
- Particle identification needs further organization and development:
  - Currently, simple cuts are applied; more sophisticated algorithms (including ML-based methods) should be considered, balancing the ambition against available time and resources. A simpler multivariate approach could serve as an intermediate step.
    XGBoost is default now
  - Different working points ("tight" for high purity, "loose" for high efficiency) should be defined and used consistently across analyses (e.g., Figure 15.7, where a 90% WP for muon/electron ID is mentioned). Coherence with PFA must be ensured (avoiding double-counting residual energy, etc.)
    BEST WP are now used consistently across analyses.

Recommendations

- The description of jet flavor identification needs to be streamlined. Currently, information is dispersed across sections (vertexing, tracking, PFA). A concise but complete description should be provided in one place
  Now it's all in Section 15.1.8
  - A brief overview of standard Jet Flavour Tagging (JFT) is given in Section15.2.6, while Jet Origin Identification (JOI) is discussed in 15.2.7. However, it is unclear what performance gains are achieved by moving from JFT to JOI.
    Figure 15.17 shows the improvement from standard JFT to JOI: 1-2 orders of magnitude lower mis-ID rate

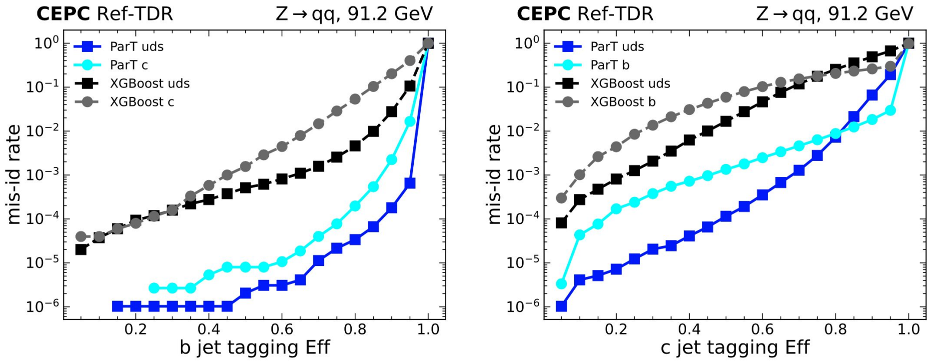


Figure 15.17 compares the JOI performance with XGBoost method. Generally, JOI performance has lower mis-identification rates than the BDT method by one to two orders of magnitude for the fixed efficiencies. Remarkably, current JOI achieves a b-jet tagging efficiency of 94% with a mis-identification rate of only 0.2% for light-quark jets.

  - Benchmark comparisons (b/c-tagging efficiency versus misidentification rates at Z-pole and ZH 240 GeV) should be provided to evaluate performance systematically.
    When JOI model trained with Higgs sample, and performance evaluated at ZH and Z-pole, no significant difference seen.

This JOI model, optimized within a Higgs-boson production environment, demonstrates sufficient universality and capability across diverse kinematic energy scales. Its application to $Z \rightarrow q\bar{q}$ final states reveals no significant performance degradation when compared against JOI models tailored explicitly for $Z \rightarrow q\bar{q}$ data. Furthermore, consistent performance of JOI is validated for $e^+e^- \rightarrow q\bar{q}$ jet samples at $\sqrt{s}$ = 240 and 360 GeV, highlighting its energy-independent robustness beyond the training environment.

Recommendations

- The offline software environment is evolving rapidly. Performance studies should be conducted with synchronized and version-controlled frameworks, especially as CyberPFA depends critically on tracking, particle ID, calibration, and alignment inputs.

  yes, all performance shown have been obtained with CEPCSW-25.3.7

- A centralized database tracking the produced samples and their statistics should be maintained and updated (extending Table 15.4). Technical samples (e.g., single electrons, muons, decaying kaons for PFA studies) should be included and documented similarly for use in detector performance validation.

  a centralized database created and maintained with IHEP gitlab service (in CEPCSW code repository)

Recommendations

- Longer-Term Considerations (for post-TDR development)
  - Consider a dedicated chapter for jet flavour tagging, especially given the comprehensive nature of JOI (which involves many sub-detectors). Comparative studies between "ideal" and "compromised" performance would also help derive systematic uncertainties in the AI-based approach.
    - *Section 15.1.8 now focuses on JOI, and also show the comparative studies in Figure 15.16*
  - The confusion matrix (Fig. 15.22) suggests JOI could distinguish quarks from antiquarks. If validated, this could significantly improve flavour-specific AFB measurements. Physics benchmarks involving b/c-quark AFB (or even strange quarks) should be added if feasible.
    - *Study already ongoing, but not mature yet, no plan to include it in TDR*
  - Organizing "data challenges," as mentioned in the "Offline Software and Computing" section, could be valuable. These would serve both as benchmarks for detector performance and stress tests for computing models (through massive production, analysis, and quality checks)
    - *From the experience of March exercise, it will take ~2 months for full sample production and another 1-2 months for updating all results. We will organize such data challenges post-TDR*

Comments on Draft v0.4.1

- The particle ID section 15.1 are now readable and well structured It would be nice if the section 15.1 ends up with a conclusion summarizing the salient performance features observed in these studies. I suggest a table of this type.

Section 15.1.10 is added to summarize the performance with a table with objects ordered consistently with the subsection structure.

Table 15.2: Performance of physics object reconstruction and identification

Physics Object	Processes considered	$E_{\text{c.m.}}$ (GeV)	Performance
Track efficiency	$ZH \to q\bar{q}jj$	240	99.7% for track p >1 GeV
Track p resolution	Single muon gun	–	$\sigma_{1/p_T} = 2.9 \times 10^{-5} \oplus 1.2 \times 10^{-3}/(p \cdot \sin^{3/2}\theta)$
Electron ID	ZH inclusive	240	eff.>90% for p_T> 2 GeV, misID <1% (BEST WP)
Muon ID	ZH inclusive	240	eff.>90% for p_T> 2 GeV, misID <0.1% (BEST WP)
Photon ID	Single photon gun	–	eff.~100% for $E > 3$ GeV, misID $\lesssim$2% (BEST WP)
Charged hadron ID	$Z \to q\bar{q}$	91.2	overall kaon eff.=92% and purity=90.7%
Tau ID	$ZH \to q\bar{q}\tau^+\tau^-$	240	eff.~80% and purity$\gtrsim$90 GeV (visible E=30–90 GeV)
Vertex reconstruction	b^+b^-	91.2	eff.>90% for number of tracks ≥ 4
Primary vertices	$ZH \to \ell^+\ell^- b\bar{b}$	240	resolution < 3μm
Secondary vertices	b^+b^-	91.2	longitudinal (transverse) resolution $\lesssim$ 25(5)μm
JER	$ZH \to \nu\bar{\nu}b\bar{b}$	240	$0.22\sqrt{E_{\text{Gen}}} \oplus 0.043$ GeV ($\|\cos(\theta)_{\text{truth}}\| < 0.85$)
JAR	$ZH \to \nu\bar{\nu}b\bar{b}$	240	0.01 radian (θ) and 0.012 radian (ϕ)
BMR	$ZH \to \nu\bar{\nu}gg$	240	3.87% (barrel), approximately 6% (endcap)
Jet flavor tagging	$ZH \to \nu\bar{\nu}jj$, $Z \to q\bar{q}$	240, 91.2	b-tag eff.=95% with mis-ID rate=0.1% for uds
Missing mass resolution	ZH	240	0.288 GeV ($e^+e^-4\nu$), 0.40 GeV ($\mu^+\mu^-4\nu$) 6.4 GeV ($q\bar{q}4\nu$), 9.2 GeV ($\nu\bar{\nu}q\bar{q}$)

Comments on Draft v0.4.1

- The physics benchmarks in section 15.2 should be listed by physics domain and in the same order as introduced in table 15.3
    - We have updated the table based on the physics domain and center-of-mass energies. The subsections are ordered consistently now.
- in table 15.3 W fusion appears out of order (the domain is "Higgs"). Maybe move it up together with "Higgs".
    - We have decided to remove the W fusion, as the analysis did not converge on time & is unlikely to do so in a short time scale.

Table 15.3: Physics benchmarks and relevant detector performances

Physics Benchmarks	Process	$E_{c.m.}$ (GeV)	Domain	Relevant Det. Performance
Recoil H mass	$\mu\mu H$	240	Higgs	Tracking
$H \to$ hadronic decays	ZH	240	Higgs	PID, Vertexing, PFA
$H \to \gamma\gamma$	ZH	240	Higgs	photon ID, EM resolution
$H \to$ invisible	ZH	240	Higgs/BSM	PFA, MET, BMR
$H \to$ LLP	ZH	240	BSM	Tracker, TOF, ~~muon detectors~~
Smuon pair	$\tilde{\mu}^+\tilde{\mu}^-$	240	BSM	Tracking
A^{μ}_{FB}	$\mu^+\mu^-$	91.2	EW	Tracking, muon ID
R_b	$Z \to q\bar{q}$	91.2	EW	PFA, jet flavor tagging
CPV in $D^0 \to h^+h^-\pi^0$	$Z \to q\bar{q}$	91.2	Flavor	PID, vertex, π^0, EM resolution
Top mass & width	$t\bar{t}$	Threshold scan ~ 345	Top	Beam energy

Comments on Draft v0.4.1

- 15.2 please make sure that each analysis presented have 1-2 phrases at the end to compare with a reference analysis (for instance present state of the art, limits from LHC or previous LEP results etc) This exists in some places but not everywhere.
  - Sentences are added at the end of each analysis subsections.

In summary, the uncertainty of A^{μ}_{FB} measurement is ±0.000031 (stat.) ±0.000028 (syst.), based on the dataset from the one-month low-luminosity Z-pole data taking during the first year of ZH operation. The CEPC result improves the precision of the LEP result (±0.0013) [34] by two orders of magnitude.

- -This is not necessarily for this document, but on a few benchmarks items (MHiggs, MTop etc.) it would be good to have a direct comparison with FCCee studies. (and good answers if significant differences are observed) We don't include in the document, but a direct comparison to FCCee are provided in the final review talk

Mhiggs

These systematic uncertainties contribute to an additional 2.5 MeV to Δm_H, resulting in a final precision $\Delta m_H = \pm$ 4.1 MeV, which is a significant improvement from the current

Assuming the same integrated luminosity, the statistical uncertainty obtained in this analysis is comparable with the latest Future Circular Collider (FCC) result [16]. The slight difference between the two results can be attributed to the FCC analysis employing a different fitting strategy, where the signal modelling is performed separately for event categories defined by the polar angle of the leptons. In both analyses, the dominant sources of systematic uncertainty arise from the center-of-mass energy and the lepton momentum scale, with comparable impacts reported.

MTop

In summary, the top quark mass precision is expected to be 7 MeV, considering only the statistical uncertainty. Taking into account the systematic uncertainties, the top quark mass can be measured at the precision of 21 MeV optimistically and 54 MeV conservatively at CEPC. The statistical uncertainty is equivalent to the latest FCC-ee result (quoted as experimental in Table 3 from Ref. [66]) after scaling to the same luminosity. FCC-ee scans over 10 energy points with a step of 0.5 GeV and applies a total integrated luminosity of 410 fb^{-1}. Both the CEPC and FCC-ee studies adequately discussed the impact of systematic uncertainties. Differences mainly originate from the input uncertainty of α_S. CEPC takes 7×10^{-4} based on the world summary of α_S in 2015 [74], while FCC-ee adopts 1×10^{-4} that is evaluated from a projection using the FCC-ee measurements [75]. The two studies show a comparable level of precision on the top quark mass measurement.

Comments on Draft v0.4.1

- Table 15.18: maybe having the cell limits would help readability?
  - Added a vertical line and made a few minor cosmetic changes (e.g. avoided merging cells)

V0.4.1

SR-ΔM^h	SR-ΔM^m	SR-ΔM^l
$E_{\mu 1,2} > 40$ GeV	$9 < E_{\mu 1,2} < 48$ GeV	–
$E_{\mu 1,2} \in (40-50, > 50)$ GeV	$E_{\mu 1,2} \in (9-25, 25-48)$ GeV	
$\Delta R(\mu, \text{recoil}) < 2.9$	$1.5 < \Delta R(\mu, \text{recoil}) < 2.8$	
$M_{\mu\mu} < 60$ GeV	$M_{\mu\mu} < 80$ GeV	–
$M_{\text{recoil}} > 40$ GeV	–	$M_{\text{recoil}} > 220$ GeV

Table 15.18: Summary of selection requirements for the direct smuon production signal region. ΔM means difference of mass between $\tilde{\mu}$ and $\tilde{\chi}_1^0$.

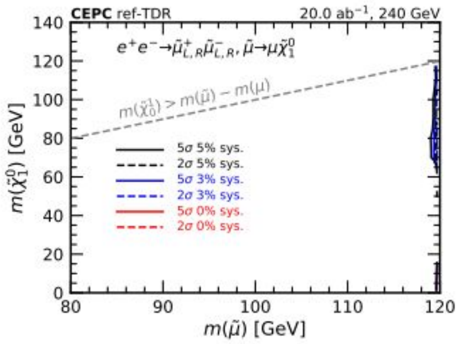
New

Table 15.14: Summary of selection requirements for the signal regions to search for the direct smuon production.

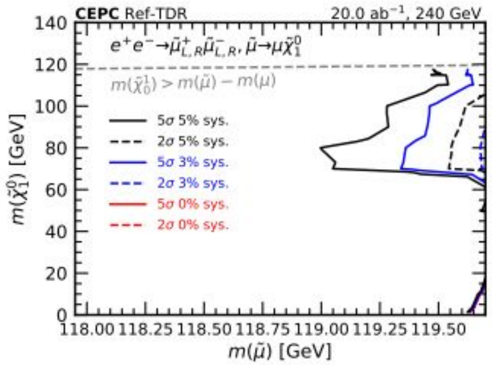
SR-ΔM^h	SR-ΔM^m	SR-ΔM^l
$E_{\mu 1,2} > 40$ GeV	$9 < E_{\mu 1,2} < 48$ GeV	–
$E_{\mu 1,2} \in (40-50, > 50)$ GeV	$E_{\mu 1,2} \in (9-25, 25-48)$ GeV	–
$\Delta R(\mu, \text{recoil}) < 2.9$	$1.5 < \Delta R(\mu, \text{recoil}) < 2.8$	$1.5 < \Delta R(\mu, \text{recoil}) < 2.8$
$M_{\mu\mu} < 60$ GeV	$M_{\mu\mu} < 80$ GeV	–
$M_{\text{recoil}} > 40$ GeV	–	$M_{\text{recoil}} > 220$ GeV

- -Figure 15.33 : are the contours right? They seem to be confined at the right of the figure and are not readable.
  - The contours are correct, but indeed were not readable. We zoomed in the figure. The left side of the contours are fully excluded.

V0.4.1



New



Comments on Draft v0.4.1

- - The section 15.3 : I suggest to move the subsection 15.3.4 as a part of the final section, to be renamed as “Summary and future plans”.
- - I suggest to rename the section 15.3 as: “Further performance aspects”
  - The new structure is as below.

V0.4.1

New

- -I suggest a proof reading, there are a few editorial minute errors left in the text. (make the references uniform etc.) But in general the text is OK.
  - We went through the chapter again and made detailed updates to improve readability.