Physics Performance Summary

Patrizia Azzi (Padova), Emmanuel Perez (CERN), Michele Selvaggi (CERN)

8th FCC Physics Week - CERN

January 16 2025

Reaching the end of the FCC Feasibility Study

- Conclusion of a long path started in 2020!
- **Physics Performance activities exploited "Case Studies" to extract physics motivated detector requirements**
- Several experimental analyses have progressed covering new topics (taus, top, etc) and exploring new potential of the FCC-ee Physics Program

- to make this a reality:
  - developed **tools for simulation** and **reconstruction**, **MC production** in coordination with the Software group
  - developed high level tools for **physics analysis**

- A section of the Final Report is devoted to "Detector Requirement" collecting the status of the investigations up to know, with many **new contributions**

Detector Requirement Section

- Structure similar to the Mid-Term report
- Several “Next Steps” ideas have become finalized studies
- Added new section with Full Simulation and reconstruction results
- Contains answers and request from the comments received by the SAC

Requirements summary Table

	Aggressive	Conservative	Comments
Beam-pipe	$\frac{X}{X_0} < 0.5\%$	$\frac{X}{X_0} < 1\%$	$\mathrm{B} \to \mathrm{K}^* \tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15 \,/\, (p \sin^{3/2}\theta)$ µm $\frac{X}{X_0} < 1\%$	–	$\mathrm{B} \to \mathrm{K}^* \tau\tau$ R_c
	$\delta L = 5$ ppm	–	$\delta\tau_\tau < 10$ ppm
Tracking	$\frac{\sigma_p}{p} < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\frac{\sigma_p}{p} < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4$ MeV $\delta\Gamma_Z = 15$ keV $\mathrm{Z} \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1$ mrad	$\delta\Gamma_\mathrm{Z}(\mathrm{BES}) < 10$ keV
ECAL	$\frac{\sigma_E}{E} = \frac{3\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$	$\mathrm{Z} \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 5 \times 5$ mm^2	τ polarization boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100$ µm, $\delta R_{\text{min}} = 10$ µm ($\theta = 20°$)	–	alignment tolerance for $\delta\mathcal{L} = 10^{-4}$ with $\gamma\gamma$ events
HCAL	$\frac{\sigma_E}{E} = \frac{30\%}{\sqrt{E}}$	$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg, invisible HNLs
	$\Delta x \times \Delta y = 2 \times 2$ mm^2	$\Delta x \times \Delta y = 20 \times 20$ mm^2	$\mathrm{H} \to \mathrm{s\bar{s}},\ \mathrm{c\bar{c}}$, gg
Muons	low momentum ($p < 1$ GeV) ID	–	$\mathrm{B_s} \to \nu\bar{\nu}$
Particle ID	3σ K/π $p < 40$ GeV	3σ K/π $p < 30$ GeV	$\mathrm{H} \to \mathrm{s\bar{s}}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100$ µm, $\delta R_{\text{min}} = 1$ µm acceptance 50-100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$\mathrm{e^+e^-} \to \gamma\gamma$ $\mathrm{e^+e^-} \to \mathrm{e^+e^-}\tau^+\tau^-(\mathrm{c\bar{c}})$

Beyond a Higgs factory (strong non trivial requirements at the Z) …

Talks this week

- This FCC Physics Week only Joint Session of Physics Performance with Physics Programme, Software and Detectors
- Thank you to all the speakers for excellent presentations!!!

HIGGS&TOP

Higgs couplings (combination, WW/ZZ, 365, tau tau)
Speaker: Alexis Maloizel (APC, CNRS/IN2P3 and Université Paris Cité (FR))
FCC_8th

Higgs mas
Speaker: Ang Li (Brookhaven National Laboratory (US))
2025_01_14_FCC_P...

Top summary (top EW couplings, Vts, mass, exotics)
Speaker: Matteo Defranchis (CERN)
top_FCC_jan25_MD....

EWK

Rs, AFBss, RC, B->K*gamma
Speaker: Lars Rohrig (Technische Universitaet Dortmund (DE))
Flavours_EWPOs_L...

Advanced r ... ronic events using AI
Speaker: Ma ... ny of Sciences (CN))
Trilogy FCC - v2.pdf

Tau polarization and reconstruction
Speaker: Maria Cepeda (CIEMAT)
TauPolarizationFCC...

BSM

Higgs exotica (2HDM, H->4b, LL)
Speaker: Axel Gallen (Uppsala University (SE))
HiggsE

ALPS
Speaker: Giacomo Polesello (INFN, Sezione di Pavia (IT))

HNL latest results/summaries
Speaker: Pantelis Kontaxakis (Universite de Geneve (CH))

QCD/FLAVOR

QCD with low-sqrt(S) runs at FCC-ee
Speaker: Andrii V

Flavour at FCC-
Speaker: Joseph

Lepton number violation and heavy neutrino-antineutrino oscillations
Speaker: Jan Hajer (CFTP, IST, Universidade de Lisboa)

Measuring (g-2)_tau via gamma-gamma -> tau+tau- at the FCC-ee
Speaker: Michael Pitt (CERN)

EPOL

Point-to-point calibration with dimuons
Speaker: Emmanuel Francois Perez (CERN)

SIM&RECO

ML based flavor tagging in Fast/Full sim
Speaker: Sara Aumiller (Technische Universitat Munchen (DE))

mical Physics and B

Particle Flow at FCC
Speaker: Anna Zaborowska (CERN)

Tracking and ML based Particle Flow
Speaker: Andrea De Vita (University of Padova)

Highlights
(focusing on new stuff presented this week)

The Z width

E. Perez

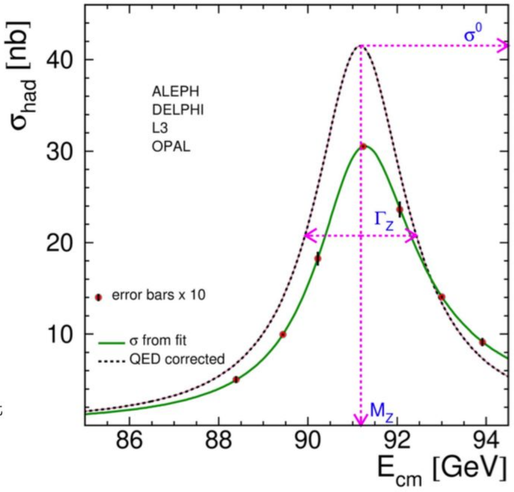
- Γ_Z is extracted from the **Z lineshape**
- **dominant** uncertainty on Γ_Z (and $A_{FB}^{\mu\mu}$) is **point-to-point uncertainty** on $\sqrt{s}$

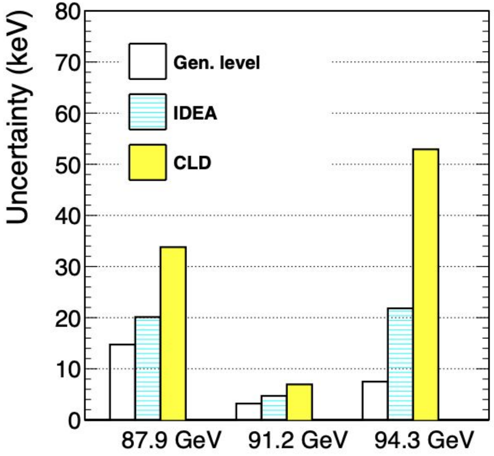
$$\left\{ \frac{\Delta\left(\sqrt{s_+} - \sqrt{s_-}\right)}{\sqrt{s_+} - \sqrt{s_-}} \right\}_{\text{ptp-syst}}$$

- can be monitored **in situ** with **di-muon** pairs
- precision scales as

  ~ (track momentum resolution)/ $\sqrt{N^{\text{off-peak}}}$

- Requires exquisite control of momentum scale stability (~ 10^{-7})

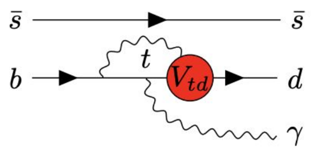




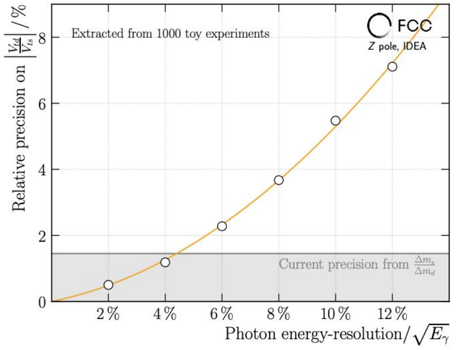
Flavour and EWPO

Lars Roehrig

Define stringent Detector Requirements (vertexing, tracking, calorimetry, PID)

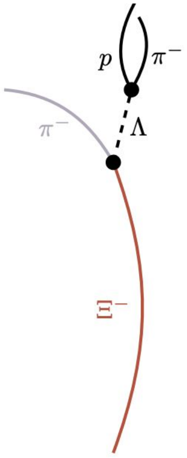


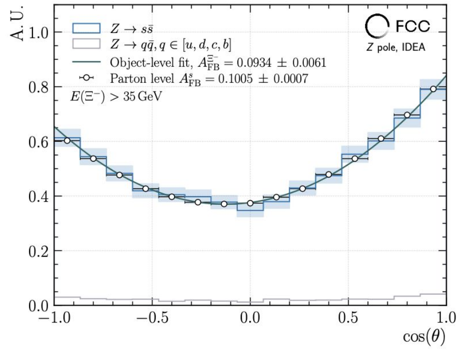
$B_s \to K^* \gamma$



$\mathcal{O}(\sigma(R_s)) = 3 \cdot 10^{-4}$ in reach

$\mathcal{O}(\sigma(A^s_{FB})) = 1.5 \cdot 10^{-4}$ in reach





→ Use exclusive $\phi(K^+K^-)$ or Ξ^- exclusive modes for R_s or A_{FB}s

→ $O(5\ \%/\sqrt{E})$ well in reach with crystals

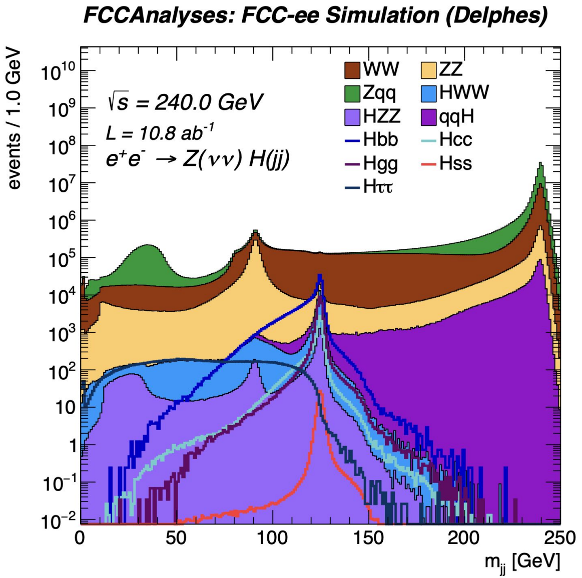
Higgs couplings

Alexis Maloizel
George Iakovidis
Sofia Giapicchini
...

Expected sensitivity (%) of σ.BR(H⟶jj) at 68% CL

240 GeV		**H⟶bb**	**H⟶cc**	**H⟶gg**	**H⟶ss**
Combined (BNL)		0.21	1.66	0.8	104.99
Combined (APC)		0.22	1.65	0.93	121
365 GeV		**H⟶bb**	**H⟶cc**	**H⟶gg**	**H⟶ss**
Combined	**ZH**	0.41	3.13	2.21	356.12
	VBF	0.67	3.49	2.66	290

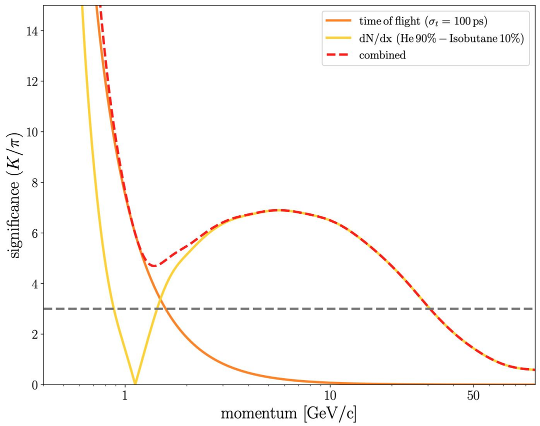
	Explicit tau reconstruction	**PNet tau reconstruction**
Cut-based analysis	±1.17 %	±0.94 %
BDT analysis 200 trees	±1.06 %	±0.85 %

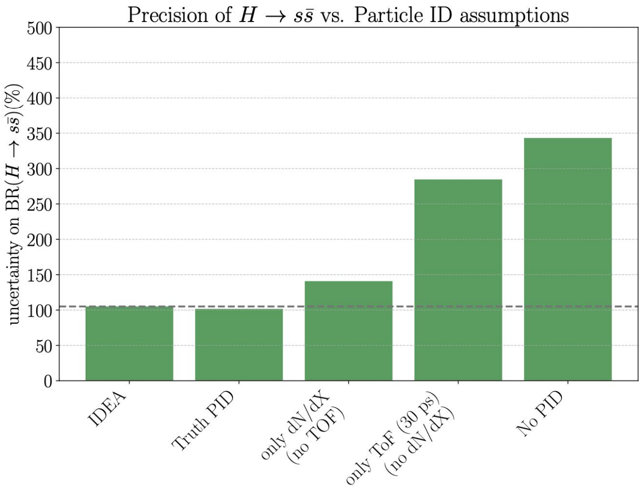


Achieved full combination of H→jj modes at both 240 and 365 GeV including split in production mode.

H->ss

- **H→ ss** evidence within reach at the FCC-ee
- need Kaon identification:
  - dE/dx (**dN/dx**) - Cherenkov detectors (**RICH**)
  - Low momentum: **Time of flight**
- need powerful **jet tagging**
- need excellent **mass resolution** (through **particle-flow**)



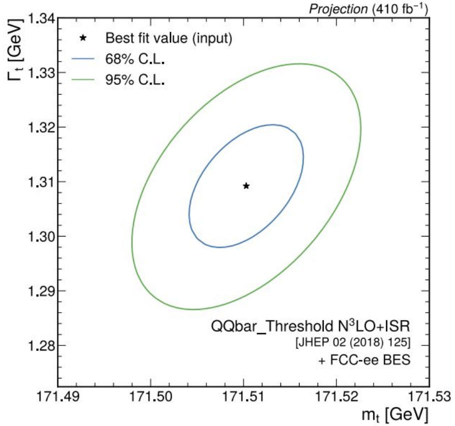


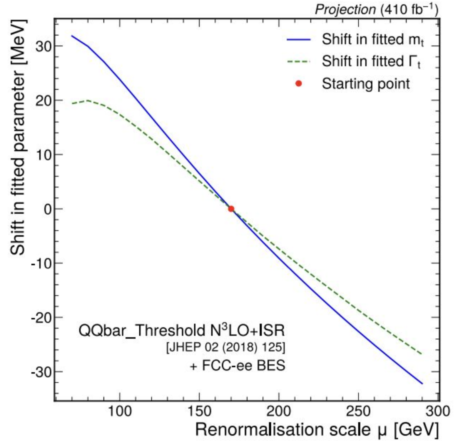
100 ps timing resolution sufficient for low momentum PID

Top mass & threshold studies

de Franchis, Mehta

uncertainty	m_t^{PS} [MeV]	Γ_t [MeV]	comment
statistical	3.7	9.6	FCC-ee, 410 fb^{-1}
luminosity calibration (uncorr.)	0.6	1.1	$\delta L/L = 1 \times 10^{-3}$
luminosity calibration (corr.)	0.3	0.5	$\delta L/L = 0.5 \times 10^{-3}$
beam energy calibration (uncorr.)	1.2	2.0	$\delta\sqrt{s} = 5$ MeV [16, 17]
beam energy calibration (corr.)	1.2	0.1	$\delta\sqrt{s} = 2.5$ MeV
beam energy spread (uncorr.)	0.6	1.1	$\delta\Delta E = 1\%$ [16]
beam energy spread (corr.)	< 0.1	1.5	$\delta\Delta E = 0.5\%$
parametric (α_s)	2.0	1.9	$\delta\alpha_s = 1 \times 10^{-4}$
parametric (y_t)	3.8	4.5	$\delta y_t = 3\%$
total profiled	6.2	11.3	
b-tagging, background	0.2 – 0.5	0.6 – 1.2	controlled in-situ
theory, unprofiled (scale)	35	25	N^3LO NRQCD [7]





top mass (width) precision (stat) ≃ 3.7 (9.6) MeV (stat.)

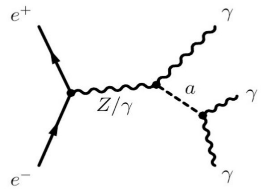
Dominant uncertainty : THEORY

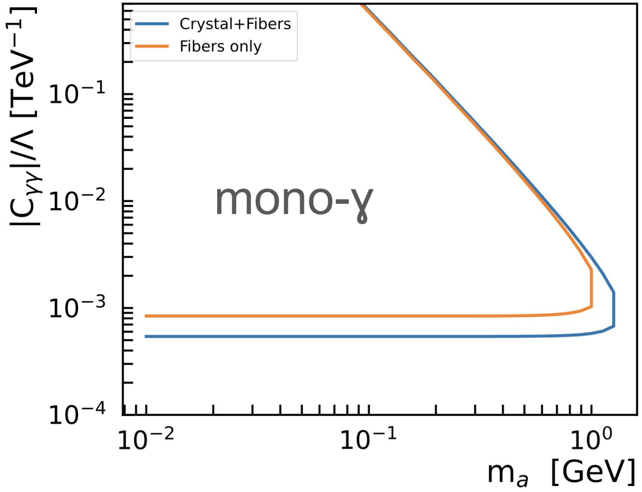
Large sensitivity to top yukawa above threshold

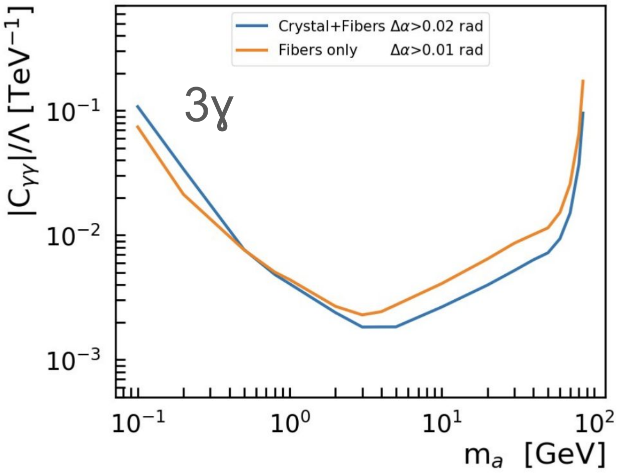
Calorimetry and ALPs

Polesello

- Low mass ALPs produced copiously at Tera Z
- If ALP decays within detector volume
  - 3 photon signature
- If ALPs very long-lived signature is a single mono-chromatic photon
  - Key handle for irreducible e+ e- → ν ν γ background is EM resolution



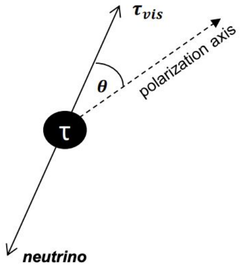


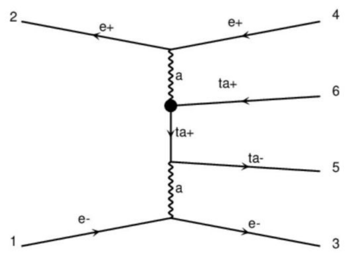


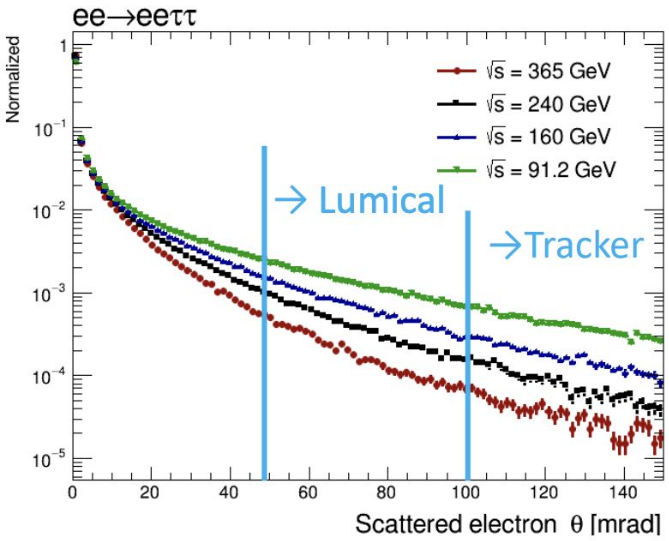
Dual Readout vs Dual Readout + crystals

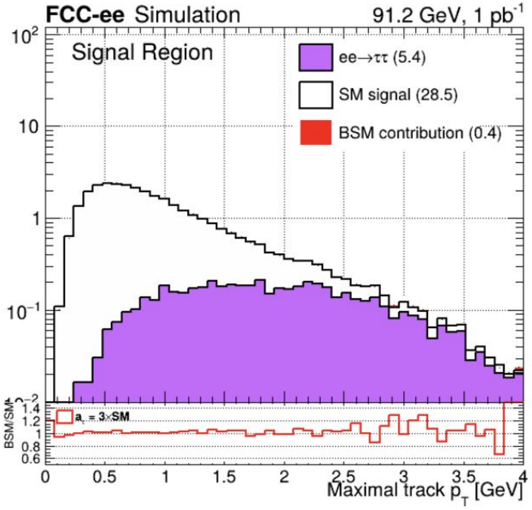
Tau g-2

Michael Pitt







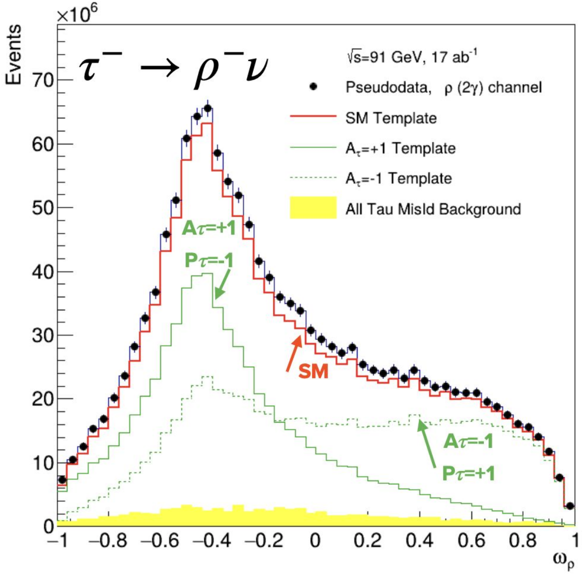


- FCC-ee could measure tau g-2 at the level of CMS in ~ hours
- tagging forward electrons might help with reconstructing tau polarisation

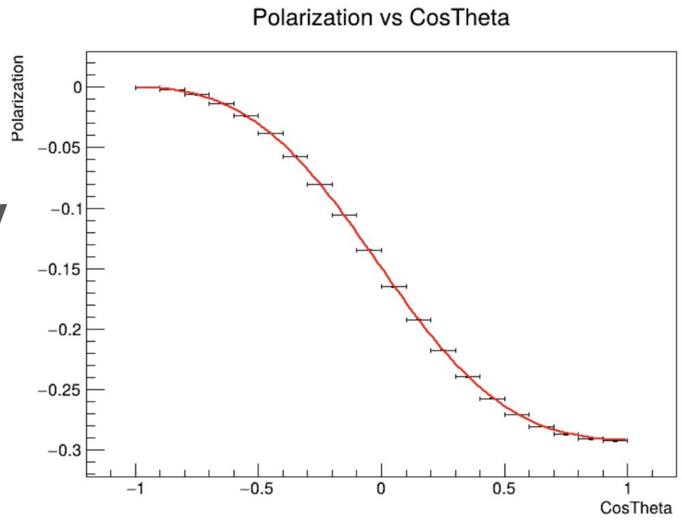
Tau polarisation

Maria Cepeda

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+2\mathcal{A}_e\mathcal{A}_\tau\cos\theta}$$



first full sim study

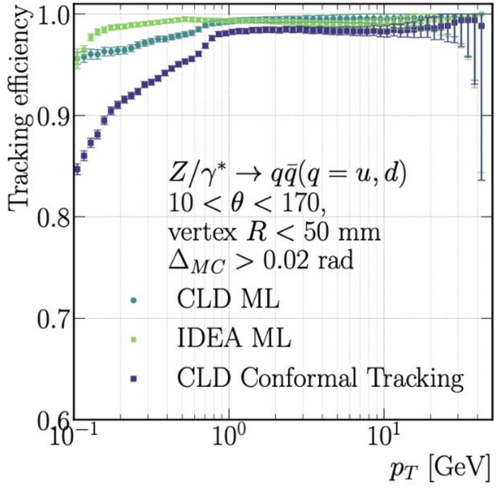


Statistical uncertainty from t for 17 ab^{-1} (just 1 exp, 1 year, only one decay mode): (15.000 +- 0.007)%
Extrapolating to full statistics, full set of final states and decay modes: <<0.01%

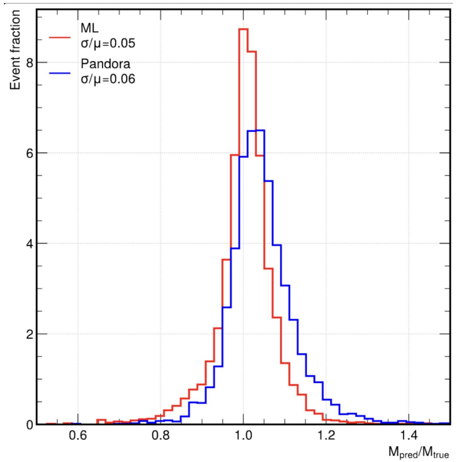
→ Machinery in place, next systematics (and detector requirements)!

Full Fast sim Tracking/Tagger/MLPF

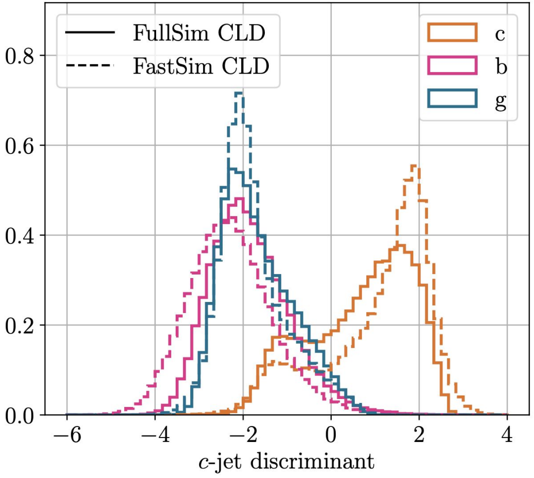
Tracking



Particle-Flow



Jet flavor tagging on-going work in full sim



Andrea de Vita

Dolores Garcia
Gregor Krzmanc

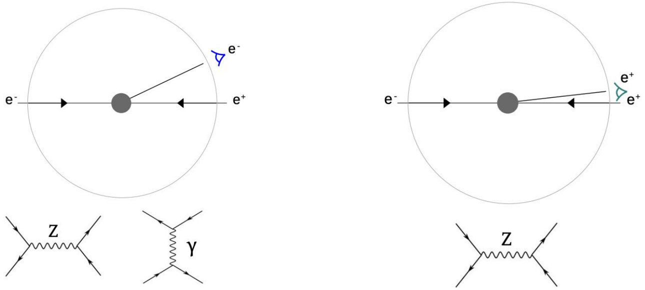
S. Aumiller

high level object reconstruction with ML

See also Manqi Ruan

New ideas at the Z pole

Marc Riembau



α_{EM} (m_Z^2) alternative method

$$\mathcal{R}_{e^-/e^+}(\theta) = \frac{\sigma(e^-e^+ \to e^-(\theta) + X)}{\sigma(e^-e^+ \to e^+(\theta) + X)}$$

<u>To be studied:</u>

control (e^+ vs e^- acceptance) systematics at 10^{-5}
beam energy spread ? charge mis Id ?

Joe Davighi

Flavor physics wishlist:

1. Extend the $bs\tau\tau$ and $bc\tau\nu$ to include leptonic tau decays
2. $B \to K^{(*)}\tau\tau \Rightarrow B \to K^{(*)}\mu\mu$ estimate [preliminary: ~80k in central bin], and other $b \to s\mu\mu$? Muons constructed perfectly, but lose vertices
3. Rare decays with electrons e.g. $B \to K^{(*)}ee$;
   a) Can presumably make big gains w.r.t. LHCb, for processes that are too rare for Belle II. A new frontier?
4. To complement $B_c \to \tau\nu$ study: estimate $B \to D^*\tau\nu$?
   a) Likewise for $B \to \tau\nu$, estimate $B \to \pi\tau\nu$
5. The above $b \to c$ processes but with $\tau \to \mu$ (could provide competitive V_{cb} measurement)
6. B_s mixing – study at FCC-ee is so far limited to V_{cb} improvement Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, Vale Silva, 2006.04824
7. LFUV R-ratios like in LHCb? Theoretically clean, this time without experimental electron challenges
8. LFUV R-ratios involving taus?
9. ...

Towards the European Strategy

- Physics Performance group in contributing in a significant way to the documents input for the European Strategy
  - Chapter 5 on "Detector Requirements" of the Final Feasibility Status Report
  - Contributions to Chapter 2 "Physics Case" with several analysis results
  - Individual CDS Notes (~30) that can be made public as supplementary material: https://repository.cern/communities/fcc-ped-sub/records?q=&l=list&p=1&s=10&sort=newest
    - Journal Publications: some papers submitted, but many to be even written up.
    - Review on-going (volunteers?)

…and what's next?

- As of now we are all extremely busy finalizing the documents for the EPPSU
- But next steps are quite obvious, and needed to keep the emphasis on having a complete reconstruction of the Full Simulation events:
    - Perform "case studies" with Full Simulation and evaluate the differences
        - help refine high-level reconstruction algorithms (PF, Tagging)
        - design ancillary analyses for calibrations (lumi, ..)
    - Extend the studies to new detector concepts and their variations
    - Extend the processes studied to cover more finely the vaste physics program of the FCC-ee.

We want to thank all the speakers and all the analysts that have been part of the Physics Performance for a great show at this workshop and great content in the Final Report.

Backup

Physics landscape at the FCC-ee

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/𝝉 factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
𝝉 properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ, R_b, R_c

$A_{FB}^{b,c}$, 𝝉 pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

Detector requirements at the FCC-ee

Higgs
factory

track momentum resolution (low X_0)

IP/vertex resolution for flavor tagging

PID capabilities for flavor tagging

jet energy/angular resolution (stochastic and noise) and PF

Flavor
"boosted" B/D/τ factory:

track momentum resolution (low X_0)

IP/vertex resolution

PID capabilities

Photon resolution, pi0 reconstruction

QCD - EWK
most precise SM test

acceptance/alignment knowledge to 10 μm

luminosity

Momentum resolution

BSM
feebly interacting particles

Large decay volume

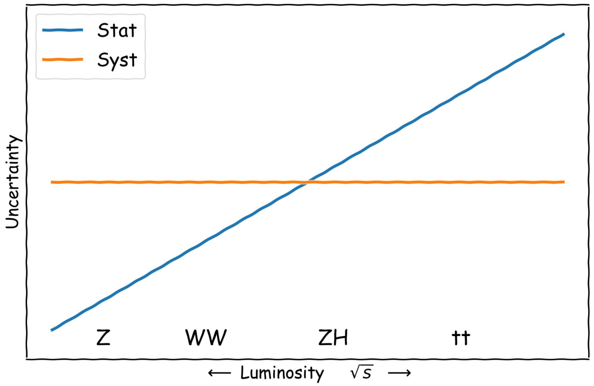
High radial segmentation
- tracker
- calorimetry
- muon

impact parameter resolution for large displacement

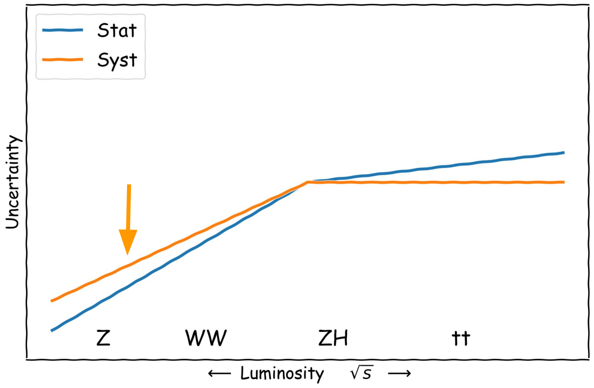
timing

triggerless

Requirements to maximise physics output



Requirements to maximise physics output

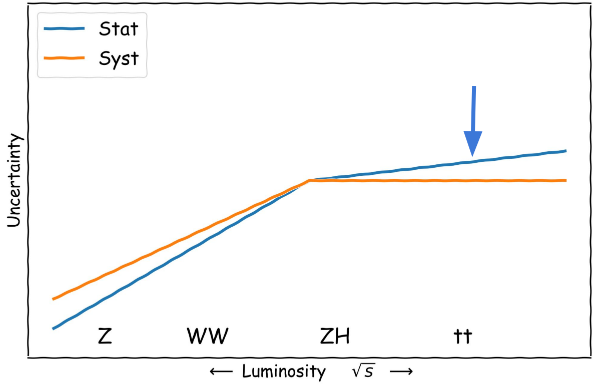


- **match systematic uncertainties to statistical errors**
  - beam energy and spread calibration (absolute, relative)
  - geometrical acceptance
  - absolute luminosity determination
  - momentum scale stability
  - momentum resolution
  - …

for each observable to measure, need:

→ specific ancillary analyses
→ beyond state-of-the-art analysis tools to be developed

Requirements to maximise physics output



- make optimal use of all available statistics
  - hermeticity, efficiency
  - particle ID
  - energy/momentum/angular resolution

- **match systematic uncertainties to statistical errors**
  - beam energy and spread calibration (absolute, relative)
  - geometrical acceptance
  - absolute luminosity determination
  - momentum scale stability
  - momentum resolution
  - …

Disclaimer:

- not a complete review
  - no feebly interacting particle searches discussed (see backup)
- focus on a few benchmarks that:
  - present new challenges
  - not a mere repetition of LEP/LHC

Summary report

Summary report