FCC-EE SUMMARY
EXPERIMENTS & DETECTORS

Patrizia Azzi - INFN Padova (IT)
### FCC-ee PHYS&EXP CONTRIBUTIONS TO CONFERENCE

<table>
<thead>
<tr>
<th>POSTERS</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A thousand recipes to use up dimuons at the FCC-ee</td>
<td>P. Janot</td>
</tr>
<tr>
<td>CKM and beyond at the Z factory</td>
<td>S. Monteil</td>
</tr>
<tr>
<td>Detector qualification with Higgs bosons in the jets and missing energy final state</td>
<td>J. V Anhen, K. Peters</td>
</tr>
<tr>
<td>Direct W mass reconstruction at and above WW threshold</td>
<td>M. Béguin</td>
</tr>
<tr>
<td>Beam Polarization and Energy calibration at FCC-ee</td>
<td>A. Blondel</td>
</tr>
<tr>
<td>IDEA Dual-Readout calorimetry software</td>
<td>M. Dunser</td>
</tr>
<tr>
<td>Precision calculations for FCC S. Jadach</td>
<td></td>
</tr>
<tr>
<td>Searching right-handed neutrinos at the FCC</td>
<td>O. Fisher</td>
</tr>
<tr>
<td>The IDEA drift chamber (2, physics performance or software oriented)</td>
<td>F. Grancagnolo, 2 posters</td>
</tr>
<tr>
<td>The top factory</td>
<td>N. Foppiani, P. Azzi, F. Blekman</td>
</tr>
<tr>
<td>The W factory : anomalous W couplings</td>
<td>P. Azzurri</td>
</tr>
<tr>
<td>TTop FCNC at FCC-ee</td>
<td>N. Van Der Kolk</td>
</tr>
</tbody>
</table>

- **FCC-ee experiments & detectors overview - D. D'Enterria**
- CLD Detector model overview - O. Viazlo
- IDEA Detector model overview - F. Bedeschi
- IDEA Dual-Readout Calorimeter - M. Antonello
- IDEA Drift Chamber - G. F. Tassielli
- A light and compact detector solenoid - H. T. Kate
- Mitigation of synchrotron radiation from IR - A. M. Kolano
- Beam-induced backgrounds and impact in the full-Silicon Tracker - G. G. Voutsinas
- Beam-induced backgrounds and impact in the IDEA drift chamber - N. A. Tehrani
- LumiCal for FCC-ee and beam-background impact - M. Dam
- Z pole scan strategy and beam energy spread measurement - P. Janot
- FCCee as a W factory - P. Azzurri
- Top threshold scan strategy - F. Simon
- Update of Higgs studies with the CLD detector model - C. Bernet
- New results in flavour physics - S. Monteil
- Search for Heavy Right Handed Neutrinos - E. Graverini
- QCD and photon-photon physics at the FCC-ee - E. D'Enterria
POSTERS

A thousand recipes to use up dimuons at the FCC-ee - P. Janot

CKM and beyond at the Z factory - S. Monteil

Detector qualification with Higgs bosons in the jets and missing energy final state - J. V Anken, K. Peters

Direct W mass reconstruction at and above WW threshold - M. Béguin

Beam Polarization and Energy calibration at FCC-ee - A. Blondel

IDEA Dual-Readout calorimetry software - M. Dunser

Precision calculations for FCC - S. Jadach

Searching right-handed neutrinos at the FCC - O. Fisher

The IDEA drift chamber (2, physics performance or software oriented) - F. Grancagnolo, 2 posters

The top factory - N. Foppiani, P. Azzi, F. Blekman

The W factory: anomalous W couplings - P. Azzurri

Top FCNC at FCC-ee - N. Van Der Kolk

FCC Physics talks

QCD measurements at FCC - M. Klein

Search for BSM Phenomena 1 - A. Wulzer

Search for BSM Phenomena 2 - R. Torre

Higgs Measurements - M. Klute

EW measurements at FCC - R. Tenchini

Top Physics at FCC - C. Schwanenberger

Global fits of EW and Higgs observable - J. De Blas

FCC-EE PHYS&EXP CONTRIBUTIONS TO CONFERENCE

FCC-ee experiments & detectors overview - D. D’Enterria

CLD Detector model overview - O. Viazlo

IDEA Detector model overview - F. Bedeschi

IDEA Dual-Readout Calorimeter overview - M. Antonello

IDEA Drift Chamber - G. F. Tassielli

A light and compact detector solution - N. A. Tehrani

Mitigation of synchrotron radiation impact - G. G. Voutsinas

Beam-induced backgrounds and impact in the IDEA drift chamber - N. A. Tehrani

LumiCal for FCC-ee and beam backgrounds - G. G. Voutsinas

Z pole scan strategy and beam energy spread measurement - P. Janot

FCCee as a W factory - P. Azzurri

Top threshold scan strategy - F. Simon

Update of Higgs studies with the CLD detector model - C. Bernet

New results in flavour physics - S. Monteil

Search for Heavy Right Handed Neutrinos - E. Graverini

QCD and photon-photon physics at the FCC-ee - E. D’Enterria
FCC Physics talks

QCD measurements at FCC - M. Klein
Search for BSM Phenomena 1 - A. Wulzer
Search for BSM Phenomena 2 - R. Torre
Higgs Measurements - M. Klute
EW measurements at FCC - R. Tenchini
Top Physics at FCC - C. Schwanenberger
Global fits of EW and Higgs observable - J. De Blas

18 FCC-ee talks
13 posters
7 complementary physics talks
EXPLORE the 10-100 TeV energy scale region with precision measurements of the properties of the Z,W,Higgs and top particles
- 20-50fold improved precision on EWK observables
- 10 fold more precise and model-independent Higgs coupling measurements

DISCOVER that the Standard Model does not fit
- Existence of extra-weakly-coupled and Higgs-coupled particles
- Understanding of the underlying physics structure

DISCOVER a violation of flavour conservation/universality

DISCOVER very weakly coupled particles in the 5-100 GeV mass range
- Such as right handed neutrinos, dark photons, ...

DISCOVER dark matter as invisible decays of the Z or Higgs
DISCOVERY MACHINE AND MORE

➤ **EXPLORE** the 10-100 TeV energy scale region with precision measurements of the properties of the Z, W, Higgs and top particles
  ➤ 20-50 fold improved precision on EWK observables
  ➤ 10 fold more precise and model-independent Higgs coupling measurements

➤ **DISCOVER** that the Standard Model does not fit
  ➤ Existence of extra-weakly-coupled and Higgs-coupled particles
  ➤ Understanding of the underlying physics structure

➤ **DISCOVER** a violation of flavour conservation/universality

➤ **DISCOVER** very weakly coupled particles in the 5-100 GeV mass range
  ➤ Such as right handed neutrinos, dark photons, …

➤ **DISCOVER** dark matter as invisible decays of the Z or Higgs

« Leave no stone unturned »
no trigger and huge statistics,
FCC-ee is a physicist’s dream
PHYSICS GOAL MINIMAL NEEDS

➤ 150 ab-1 at around the Z pole ($\sqrt{s}=91.2$ GeV)
➤ 10 ab-1 at the WW threshold ($\sqrt{s}=161$ GeV)
➤ 5 ab-1 at the HZ cross section maximum ($\sqrt{s}=240$ GeV)
➤ 0.2 ab-1 at the top threshold ($\sqrt{s}=350$ GeV)
➤ 1.5 ab-1 above the top threshold ($\sqrt{s}=365$ GeV)

The FCC-ee unique discovery potential is multiplied by the presence of the four heavy particles of the standard model in its energy range

Helps shape up the FCC-hh program and detectors
PHYSICS GOAL MINIMAL NEEDS

- 150 ab$^{-1}$ at around the Z pole ($\sqrt{s}=91.2$ GeV)
- 10 ab$^{-1}$ at the WW threshold ($\sqrt{s}=161$ GeV)
- 5 ab$^{-1}$ at the HZ cross section maximum ($\sqrt{s}=240$ GeV)
- 0.2 ab$^{-1}$ at the top threshold ($\sqrt{s}=350$ GeV)
- 1.5 ab$^{-1}$ above the top threshold ($\sqrt{s}=365$ GeV)

The FCC-ee unique discovery potential is multiplied by the presence of the four heavy particles of the standard model in its energy range.

Helps shape up the FCC-hh program and detectors.

5x10$^{12}$ Z 10$^8$ W
10$^6$ HZ 10$^6$ tt
the more the better!
NEW LUMINOSITY PLOT

➤ High integrated luminosity at the needed $E_{cm}$
➤ Clean environment
➤ Precise knowledge of the center-of-mass energy and of the luminosity
➤ Precise detectors offering plenty of redundancy (and more than one)
NEW LUMINOSITY PLOT

- High integrated luminosity at the needed $E_{cm}$
- Clean environment
- Precise knowledge of the center-of-mass energy and of the luminosity
- Precise detectors offering plenty of redundancy (and more than one)

Max $E_{cm}$ is 365 GeV!
## NEW RUN PLAN

<table>
<thead>
<tr>
<th>Working point</th>
<th>Z, years 1-2</th>
<th>Z, later</th>
<th>WW</th>
<th>HZ</th>
<th>tt threshold</th>
<th>365 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi/IP ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>100</td>
<td>200</td>
<td>31</td>
<td>7.5</td>
<td>0.85</td>
<td>1.5</td>
</tr>
<tr>
<td>Lumi/year (2 IP)</td>
<td>26 ab$^{-1}$</td>
<td>52 ab$^{-1}$</td>
<td>8.1 ab$^{-1}$</td>
<td>1.95 ab$^{-1}$</td>
<td>0.22 ab$^{-1}$</td>
<td>0.39 ab$^{-1}$</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>0.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

### Operation assumptions (10% safety margin)

- 200 physics days/year
- Hubner factor $\sim$0.75 (lower than KEKB top-up injection that reached $>80\%$)
- half the design luminosity in the first year of Z and top operation
- machine upgrades during Winter shutdown (3m/y)
- Longer shutdown to install the 196 RF
# NEW RUN PLAN

<table>
<thead>
<tr>
<th>Working point</th>
<th>Z, years 1-2</th>
<th>Z, later</th>
<th>WW</th>
<th>HZ</th>
<th>tt threshold</th>
<th>365 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi/IP ($10^{34}$ cm$^{-2}$s$^{-1}$)</td>
<td>100</td>
<td>200</td>
<td>31</td>
<td>7.5</td>
<td>0.85</td>
<td>1.5</td>
</tr>
<tr>
<td>Lumi/year (2 IP)</td>
<td>26 ab$^{-1}$</td>
<td>52 ab$^{-1}$</td>
<td>8.1 ab$^{-1}$</td>
<td>1.95 ab$^{-1}$</td>
<td>0.22 ab$^{-1}$</td>
<td>0.39 ab$^{-1}$</td>
</tr>
<tr>
<td>Physics goal</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>0.2</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

**Operation assumptions (10% safety margin)**

- 200 physics days/year
- Hubner factor ~0.75 (lower than KEKB top-up injection that reached >80%)
- half the design luminosity in the first year of Z and top operation
- machine upgrades during Winter shutdown (3m/y)
- Longer shutdown to install the 196 RF

**Total running time**

13(+1) years (~LEP)
Unique and flexible design
Crab-waist collision scheme
Synchrotron radiation driver for IR design at high energy operations
Asymmetric optics
Small emittance
Central Be beam pipe with diameter 3cm
Solenoid compensation scheme needed for large beam crossing angle

Detector solenoid dimensions $3.76m \times 4m$ (half-length)
Drift chamber at $z=2m$ with 150 mrad opening angle (IDEA design)
- Unique and flexible design
- Crab-waist collision scheme
- Synchrotron radiation driver for IR design at high energy operations
- Asymmetric optics
- Small emittance
- Central Be beam pipe with diameter 3cm
- Solenoid compensation scheme needed for large beam crossing angle

Discussion of mechanical integration brings improvements to this scheme
LUMINOSITY MEASUREMENT

- Using small angle Babha scattering, Very precise normalization needed: absolute normalization at $10^{-4}$ and relative to $5 \times 10^{-5}$
- Theory now at $2 \times 10^{-4}$!
- Can exploit also large angle Babha production of photons and/or electrons: in progress
- Basic design: Cylindrical detectors of W+Si sandwich centered around, and perpendicular to the outgoing beam line (asymmetric)
- Studied effect of:
  - synchrotron radiation: negligible with shielding
  - beam background: ee pairs soft and close to detector boundaries. $\sqrt{s}$ dependence
  - beam-gas background: negligible
  - Focusing effect of opposite beam to be studied
LUMINOSITY MEASUREMENT

- Using small angle Babha scattering, very precise normalization needed: absolute normalization at $10^{-4}$ and relative to $5 \times 10^{-5}$
- Theory now at $2 \times 10^{-4}$!
- Can exploit also large angle Babha production of photons and/or electrons: in progress
- Basic design: Cylindrical detectors of W+Si sandwich centered around, and perpendicular to the outgoing beam line (asymmetric)
- Studied effect of:
  - synchrotron radiation: negligible with shielding
  - beam background: ee pairs soft and close to detector boundaries. $\sqrt{s}$ dependence
  - beam-gas background: negligible
  - Focusing effect of opposite beam to be studied

Preliminary design of LumiCal now exists!
Moving on to technical challenges
 Requirement from physics

- Center-of-mass energy determination with precision of ±100keV around the Z peak
- Center-of-mass energy determination with precision of ±300keV at W pair threshold
- For Z peak cross-section and width energy spread uncertainty: \( \Delta\sigma/\sigma = 0.2\% \)

- Use resonant depolarization as main measurement method
- use pilot bunches to calibrate during physics data taking
- take data at points where self-polarization is expected: easy to accommodate for Z and W
- defining scan strategy to minimize loss of statistics
- Hardware requirements: wigglers (@Z), polarimeters and kickers for depolarization:
  - studies in progress to find the optimal sweep (different for Z and W)
- Systematics studies ongoing
Requirement from physics

- Center-of-mass energy determination with precision of ±100keV around the Z peak
- Center-of-mass energy determination with precision of ±300keV at W pair threshold
- For Z peak cross-section and width energy spread uncertainty: \( \Delta\sigma/\sigma = 0.2\% \)

- Use resonant depolarization as main measurement method
- Use pilot bunches to calibrate during physics data taking
- Take data at points where self-polarization is expected: easy to accommodate for Z and W
- Defining scan strategy to minimize loss of statistics
- Hardware requirements: wigglers (@Z), polarimeters and kickers for depolarization:
  - Studies in progress to find the optimal sweep (different for Z and W)
- Systematics studies ongoing

Preliminary estimate of systematics range from \( \Delta E/E = 10^{-14} \) to \( 10^{-6} \)

Precision needed requires to take into account all effects specific to the machine
The beam energy spread affects the lineshape changing the cross section.

The size of the energy spread and its impact on $\Gamma_Z$ is similar to LEP but systematic shave to be controlled in a different way.

FCC-ee asymmetric optics with a beam crossing angle $\alpha$ of 30 mrad.

Using $10^6$ dimuon events (4 min @FCC-ee) can measure the energy spread at 0.1% of its value.

Detector requirement on muon angular resolution of 0.1 mrad.

$\gamma$ Longitudinal Boost, $x_{\gamma} = -\frac{x_+ \cos \theta^+ + x_- \cos \theta^-}{\cos(\alpha/2) + |x_+ \cos \theta^+ + x_- \cos \theta^-|}$

Can keep related systematic uncertainty on $\Gamma_Z$ at less than 30 keV.
MEASUREMENT OF ENERGY SPREAD

➤ The beam energy spread affects the lineshape changing the cross section

➤ The size of the energy spread and its impact on $\Gamma_Z$ is similar to LEP but systematic shake to be controlled in a different way

➤ FCC-ee asymmetric optics with a beam crossing angle $\alpha$ of 30 mrad

➤ Using $10^6$ dimuon events (4 min @FCC-ee) can measure the energy spread at 0.1% of its value

➤ Detector requirement on muon angular resolution of 0.1 mrad

\[
x_{\gamma} = \frac{x_+ \cos \theta^+ + x_- \cos \theta^-}{\cos(\alpha/2) + |x_+ \cos \theta^+ + x_- \cos \theta^-|}
\]

New technique using dimuons events does the job!
Inspired by the CLIC detector model and adapted for the FCC-ee running conditions

- Full silicon tracking system - provides ≥12 hits per track
- Fine-grained ECAL and HCAL optimised for particle flow reconstruction
- Superconducting solenoid is outside of the calorimeter
- Steel return yoke with muon chambers
- Forward detector region (< 150 mrad) is reserved for Machine-Detector Interface (accommodates LumiCal)
- Support structures, cables and services are included in the model

Jet energy resolution in barrel region:

\[
\sigma_{T}\left(\frac{\Delta p}{p}\right) \quad \text{[GeV RMS]} 
\]

Achieved resolutions for 100 GeV muons in the barrel:

- 380 GeV: 376.4 GeV
- 91 GeV: 90.4 GeV
- Jet energy resolution in barrel region:

\[
\frac{T_{\text{true}}}{T} \quad \text{[GeV]} 
\]

Jet energy resolution in barrel region:

\[
\sigma_{\Delta p}/p \quad \text{[GeV]} 
\]

Jet energy resolution in barrel region:

\[
\frac{T_{\text{true}}}{T} \quad \text{[GeV]} 
\]

Jet energy resolution in barrel region:

\[
\sigma_{\Delta p}/p \quad \text{[GeV]} 
\]
CLD DETECTOR PERFORMANCE

- Inspired by the CLIC detector model and adapted for the FCC-ee running conditions

- CLD detector layout
  - Full silicon tracking system - provides $\geq 12$ hits per track
  - Fine-grained ECAL and HCAL optimised for particle flow reconstruction
  - Superconducting solenoid is outside of the calorimeter
  - Steel return yoke with muon chambers
  - Forward detector region ($<15$ mrad) is reserved for Machine-Detector Interface (accommodates LumiCal)
  - Support structures, cables and services are included in the model

- CLD model
  - Steel return yoke with muon chambers
  - Interface (accommodates LumiCal)
  - Forward detector region ($<15$ mrad)
  - Superconducting solenoid is outside of the calorimeter
  - Fine-grained ECAL and HCAL optimised for particle flow reconstruction

- CLD detector performance
  - Tracking efficiency
    - Fully efficient tracking from 1 GeV
    - Tracking fully efficient from 700 MeV
    - Pt Resolution of $4 \times 10^{-5} \text{GeV}^{-1}$ for 100 GeV muons
    - >95% Photon and electron efficiency
  - Energy resolution in barrel region 3-5%
  - Similar to original CLIC detector

- Work in progress
IDEA DETECTOR STUDIES

- Beam pipe (R~1.5 cm)
- VTX: 4-7 MAPS layers
- DCH: 4 m long, R 30-200 cm
- Outer Silicon Layer
- SC Coil: 2 T, R~2.1 m
- Preshower: ~ 1-2 $X_0$
- DR calorimeter: 2 m/7 $\lambda_{int}$
- Yoke + muon chamber

➤ Significant steps in the simulation of the subdetectors in the FCC-SW. Validation in progress with standalone software
➤ More detector R&D in progress in all sub-components
➤ Study of the background effects in the drift chamber ongoing
➤ Next completing simulation of the overall detector
IDEA DETECTOR STUDIES

- Beam pipe (R~1.5 cm)
- VTX: 4-7 MAPS layers
- DCH: 4 m long, R 30-200 cm
- Outer Silicon Layer
- SC Coil: 2 T, R~2.1 m
- Preshower: ~1-2 $X_0$
- DR calorimeter: 2 m/7 $\lambda_{\text{int}}$
- Yoke + muon chamber

Significant steps in the simulation of the subdetectors in the FCC-SW. Validation in progress with standalone software

- More detector R&D in progress in all sub-components
- Study of the background effects in the drift chamber
- Next completing simulation of the overall detector

IDEA detector concept becoming a reality in FCC-SW
Test beam planned in Fall 2018!
➤ Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.

➤ Model independent determination of the total Higgs decay width

➤ New estimates of Higgs coupling precision made with custom simulation (PAPAS)
  - CLD performs 10-35% better compared to results with CMS simulation
  - now ready to study variation in detector design cost/performance

ZH → ℓℓbb

ZH → qqbb
HIGGS

➤ Ultimate precision on Higgs couplings below 1% (and measurement of the total width) a milestone of the FCC physics program.
➤ Model independent determination of the total Higgs decay width
➤ New estimates of Higgs coupling precision made with custom simulation (PAPAS)
  ➤ CLD performs 10-35% better compared to results with CMS simulation
  ➤ now ready to study variation in detector design cost/performance

ZH → ℓℓbb
ZH → qqbb

Precision estimates on Higgs couplings confirmed AND improved by 10-35%
Integrated luminosity goals for Z and W physics

- 150 ab$^{-1}$ around the Z pole (≈ 25 ab$^{-1}$ at 88 and 94 GeV, 100 ab$^{-1}$ at 91 GeV)
- 10 ab$^{-1}$ around the WW threshold (161 GeV with ± few GeV scan)
- Runs at 240 and at 350-365 GeV very important for WW physics as well

FCC-ee program will bring improvement of 1 to 2 orders of magnitude in precision of EWPO

New at this collaboration meeting:

- Direct M(W) reconstruction in the 4-jet channel to be used above the WW threshold region. $\Delta M(W)=0.5\text{MeV (stat)}$ with 5ab$^{-1}$ at $\sqrt{s}=240$ GeV
- Study of TGC (leptonic mode only) shows a precision achievable of $O(10^{-3})$!

EWK

$\Delta M_W$ (stat) summary with data at different $E_{\text{CM}}$

- Raw dijet mass
- 4C kinematic rescaling
- 4C kinematic Fit

$\Delta M_W$ (stat) summary with data at different $E_{\text{CM}}$

- Precision reach of aTGCs at FCC-ee (68% CL)

- 240 GeV 5ab only
- 365 GeV 1.5ab only
- FCC Full program

Light shade: global fit
Dark shade: individual fit
Integrated luminosity goals for Z and W physics

- 150 ab\(^{-1}\) around the Z pole (~ 25 ab\(^{-1}\) at 88 and 94 GeV, 100 ab\(^{-1}\) at 91 GeV)
- 10 ab\(^{-1}\) around the WW threshold (161 GeV with ± few GeV scan)
- runs at 240 and at 350-365 GeV very important for WW physics as well

FCC-ee program will bring improvement of 1 to 2 orders of magnitude in precision of EWPO

New at this collaboration meeting:

- Direct M(W) reconstruction in the 4-jet channel to be used above the WW threshold region. \(\Delta M(W)=0.5\text{MeV (stat)}\) with 5ab\(^{-1}\) at \(\sqrt{s}=240\text{ GeV}\)
- Study of TGC (leptonic mode only) shows a precision achievable of \(O(10^{-3})\)!
TOP

- Precise measurements of top quark properties at the FCC-ee, coupled with precise theoretical calculation provide excellent discovery potential.
- Threshold region allows most precise measurements of mass, width, and estimate of Yukawa coupling. NEW Study of optimizing the scan strategy.
- Running at 365 GeV to be used for other measurements such as top couplings, FCNC etc.

- Mass only: **8.8 MeV** (stat), **5.4 MeV** ($\alpha_s$ [2 x 10^{-4}]),
- **44 MeV** (theo)

sensitivity to:
- mass
- width
- Yukawa

February 2018

January 2018
TOP

- Precise measurements of top quark properties at the FCC-ee, coupled with precise theoretical calculation provide excellent discovery potential.

- Threshold region allows most precise measurements of mass, width, and estimate of Yukawa coupling. NEW Study of optimizing the scan strategy.

- Running at 365 GeV to be used for other measurements such as top couplings, FCNC etc.

- Mass only: **8.8 MeV** (stat), **5.4 MeV** ($\alpha_s [2 \times 10^{-4}]$), **44 MeV** (theo)

**Significant increase in precision of top mass, $\Gamma$, $Y$ (w/ reduction of theory uncertainties) with an optimized scan strategy**
BSM DIRECT SEARCHES

- Axion Like Particles (ALPS) appear in several extensions of the SM
- if no coupling with gluons FCC-ee could reach $f_a \lessgtr 100$ TeV

For Tera Z $\text{BR}[Z \rightarrow \gamma a(\gamma\gamma)] \lessgtr 3 \times 10^{-9}$
[current LEP limit $\lessgtr 5 \times 10^{-6}$]

Long Lived Particles: recent study with a SiD inspired detector and $110ab^{-1}$ at Z pole 1710.03744

For Giga Z $\text{BR}[Z \rightarrow \gamma a(\gamma\gamma)] \lessgtr 3 \times 10^{-9}$
[current LEP limit $\lessgtr 5 \times 10^{-6}$]

Probing Leptogenesis

\[ \Lambda_{a\BB} \]

$\frac{1}{4} \Lambda_{a\BB} B_{\mu\nu} \tilde{B}^{\mu\nu}$

$\gamma_{1a} = 6 \text{ m}$

$\text{Tera Z (3\gamma)}$

$\text{Giga Z (3\gamma)}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (2\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$m_a [\text{GeV}]$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^0$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$10^7$

$10^8$

$10^9$

$10^{10}$

$10^{11}$

$10^{12}$

$\text{Tera Z (3\gamma)}$

$\text{Giga Z (3\gamma)}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (2\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Giga Z (3\gamma)}$

$\text{Tera Z (3\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$

$\Lambda_{a\BB}$

$\text{Tera Z (2\gamma)}$

$\text{Giga Z (2\gamma)}$

$\text{L3 (\gamma)}$

$\text{LEPI (2\gamma)}$

$\text{ATLAS (3\gamma)}$

$\text{ATLAS (2\gamma)}$

$\text{OPAL (2\gamma)}$
FCC-ee large statistics and clean environment is the exceptional place to search for unusual signatures.
NEW PHYSICS SENSITIVITIES

- Fit to new physics effects parameterized by dim 6 SMEFT operators
- single operator fit can be informative
- model independent result only for global fit

The dimension 6 SMEFT
What do we mean by “Sensitivity to NP up the scale of N TeV?” e.g.

\[
\frac{c}{\Lambda^2} \sim \frac{g_{NP}^2}{M_{NP}^2} < 0.01 \text{ TeV}^{-2} \quad \rightarrow \quad M_{NP} > 10 \, g_{NP} \, \text{TeV} \quad \text{(Weakly coupled NP)}
\]
\[
M_{NP} > 10 \, \text{TeV} \quad (g_{NP} \sim 1)
\]

What do we mean by “Sensitivity to NP up the scale of N TeV?” e.g.

\[
\frac{c}{\Lambda^2} \sim \frac{g_{NP}^2}{M_{NP}^2} < 0.01 \text{ TeV}^{-2} \quad \rightarrow \quad M_{NP} > 10 \, g_{NP} \, \text{TeV} \quad \text{(Weakly coupled NP)}
\]
\[
M_{NP} > 10 \, \text{TeV} \quad (g_{NP} \sim 1)
\]
NEW PHYSICS SENSITIVITIES

➤ Fit to new physics effects parameterized by dim 6 SMEFT operators
➤ single operator fit can be informative
➤ model independent result only for global fit

What do we mean by “Sensitivity to NP up the scale of N TeV”?

\[
\frac{c}{\Lambda^2} \sim \frac{g_{NP}^2}{M_{NP}^2} < 0.01 \text{ TeV}^{-2} \quad \rightarrow \quad M_{NP} > 10 g_{NP} \text{ TeV}
\]

FCC-ee program sensitive to (weakly coupled) new physics up to scales of tens of TeV
HIGHLIGHTS OF NEXT STEPS

➤ Preparing the CDR and beyond!
➤ Detailed design and integration of: interaction region, polarization system, luminosity calorimeter
➤ Study of backgrounds and reachable precision
➤ R&D of detectors toward experimental collaborations
➤ Detector performance with full simulation & event reconstruction
➤ Develop new experimental paths to consolidate sensitivity to new physics
➤ Develop new methods for theory computation to match and exceed experimental capabilities
RECAP

- There must be something beyond the Standard Theory (or totally different!)
- Experimental proofs: Cosmological Dark Matter, Baryon Asymmetry of the Universe, non-zero neutrino masses
- Which way to go?
  - Direct observation of new particles
  - New phenomena
  - Deviations from precise predictions
- Physics absolutely needs an e+e- factory that covers the whole range: Z, W, H and top at the highest luminosities
- FCC-ee is the best first step to pave the way for FCC-hh:
  - preview of new physics to be searched for
  - brings a significant reduction of systematics measurements
  - handles to understand underlying theory in case of discovery
COMPLEMENTARITIES IN FCC PROGRAM

- All three FCC options complement each other very well and are useful to complete the whole picture:

  **FCC-ee**
  - Z-pole: EW precision NC
  - WW threshold: EW precision CC
  - Higgs: General measurements
  - Ztt: EW Top couplings

  **FCC-eh**
  - EWPO: first quark families
  - Higgs: General measurements
  - PDFs

  **FCC-hh**
  - Higgs: Rare decays
  - Higgs: Top coupling
  - Higgs: Self-coupling
  - High $q^2$
COMPLEMENTARITIES IN FCC PROGRAM

- All three FCC options complement each other very well and are useful to complete the whole picture:

  **FCC-ee**
  - Z-pole: EW precision NC
  - WW threshold: EW precision CC
  - Higgs: General measurements
  - Ztt: EW Top couplings
  - EW bosons properties

  **FCC-eh**
  - EWPO: first quark families
  - Higgs: General measurements
  - PDFs

  **FCC-hh**
  - Higgs: Rare decays
  - Higgs: Top coupling
  - Higgs: Self-coupling
  - High q^2

**FCC-ee essential part of the FCC program!**
### FCC-EE TAKE AWAY MESSAGE

<table>
<thead>
<tr>
<th>known knowns</th>
<th>known unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Model</td>
<td>“known” new physics</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>unknown knowns</th>
<th>unknown unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>new physics modifies known physics</td>
<td>surprises</td>
</tr>
<tr>
<td>and maybe we already measured it!</td>
<td></td>
</tr>
</tbody>
</table>
### FCC-EE TAKE AWAY MESSAGE

<table>
<thead>
<tr>
<th>known knowns</th>
<th>known unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;known&quot; new physics</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>unknown knowns</th>
<th>unknown unknowns</th>
</tr>
</thead>
<tbody>
<tr>
<td>new physics modifies known physics</td>
<td></td>
</tr>
<tr>
<td>and maybe we already measured it!</td>
<td>surprises</td>
</tr>
</tbody>
</table>
unknown knowns
new physics modifies known physics
and maybe we already measured it!

unknown unknowns
surprises

Figure 1. Physics reach in the nMSM for SHiP and two realistic FCC-ee configurations (see text). Previous searches are shown (dashed lines), as well as the cosmological boundaries of the model (greyed-out areas) [3, 9].

Figure 2. SHiP sensitivity to dark photons produced in proton bremsstrahlung and secondary mesons decays. Previous searches explored the greyed-out area. Low-coupling regions are excluded by Big Bang Nucleosynthesis.

A method similar to the one outlined in Section 2 was used to compute the expected number of events. HNL production is assumed to happen in Z to n bar n decays with one neutrino kinematically mixing to an HNL. If the accelerator is operated at the Z resonance, Z bosons decay in place and the HNL lifetime is boosted by a factor

$$g = \frac{m_Z^2}{m_N + m_N^2} m_Z.$$  

(3.1)

All `+ ` final states are considered detectable with a CMS-like detector with spherical symmetry. Backgrounds from W*W*, Z*Z* and Z*g* processes can be suppressed by requiring the presence of a displaced secondary vertex.

Figure 1 shows SHiP’s and FCC-ee’s sensitivities in the parameter space of the nMSM, for two realistic FCC-ee configurations. The minimum and maximum displacements of the secondary vertex in FCC-ee, referred to as r in Figure 1, depends on the characteristics of the tracking system. Inner trackers with resolutions of the order of 100 µm and 1 mm, and outer trackers with diameters of 1 m and of 5 m have been considered. Figure 2 shows SHiP’s sensitivity to dark photons, compared to previous searches.

This work shows that the SHiP experiment can improve by several orders of magnitude the current limits on Heavy Neutral Leptons, scanning a large part of the parameter space below the B meson mass. Similarly, SHiP can greatly improve present constraints on dark photons. Right-handed neutrinos with larger mass can be searched for at a future Z factory. The synergy between SHiP and a future Z factory would allow the exploration of most of the nMSM parameter space for sterile neutrinos.

Acknowledgments
This work would not have been possible without the precious theory support by M. Shaposhnikov. We thank A. Blondel for useful discussions about the FCC-ee project. We are indebted to all our
FCC-EE TAKE AWAY MESSAGE

- **Standard Model**
- **New Physics**

- **Knows**
- **Unknowns**
- **Surprises**

**Diagram:**
- Graph showing the relationship between HNL mass and the mixing parameter.
- Curves indicating different search sensitivities.
- Legend with models and experiments.

**Acknowledgments:**
This work would not have been possible without the precious theory support by M. Shaposhnikov. We are indebted to all our colleagues for useful discussions about the FCC-ee project.
FCC-EE TAKE AWAY MESSAGE

- Knows
- Knowns
- Unknown
- Unknowns

...and

Patrizia Azzi (INFN/PD) FCC-Week Amsterdam 2018
FCC-EE TAKE AWAY MESSAGE

- **Known knowns**
  - Standard Model
  - Measured physics
  - CRAB schemes

- **Known unknowns**
  - Inverted hierarchy
  - BAU vs. BAU
  - SHiP and a future factory

- **Unknown knowns**
  - TLRs, D/H production
  - Low-coupling regions

- **Unknown unknowns**
  - Sterile neutrinos
  - SHiP sensitivity to dark photons

...ready for the unexpected!