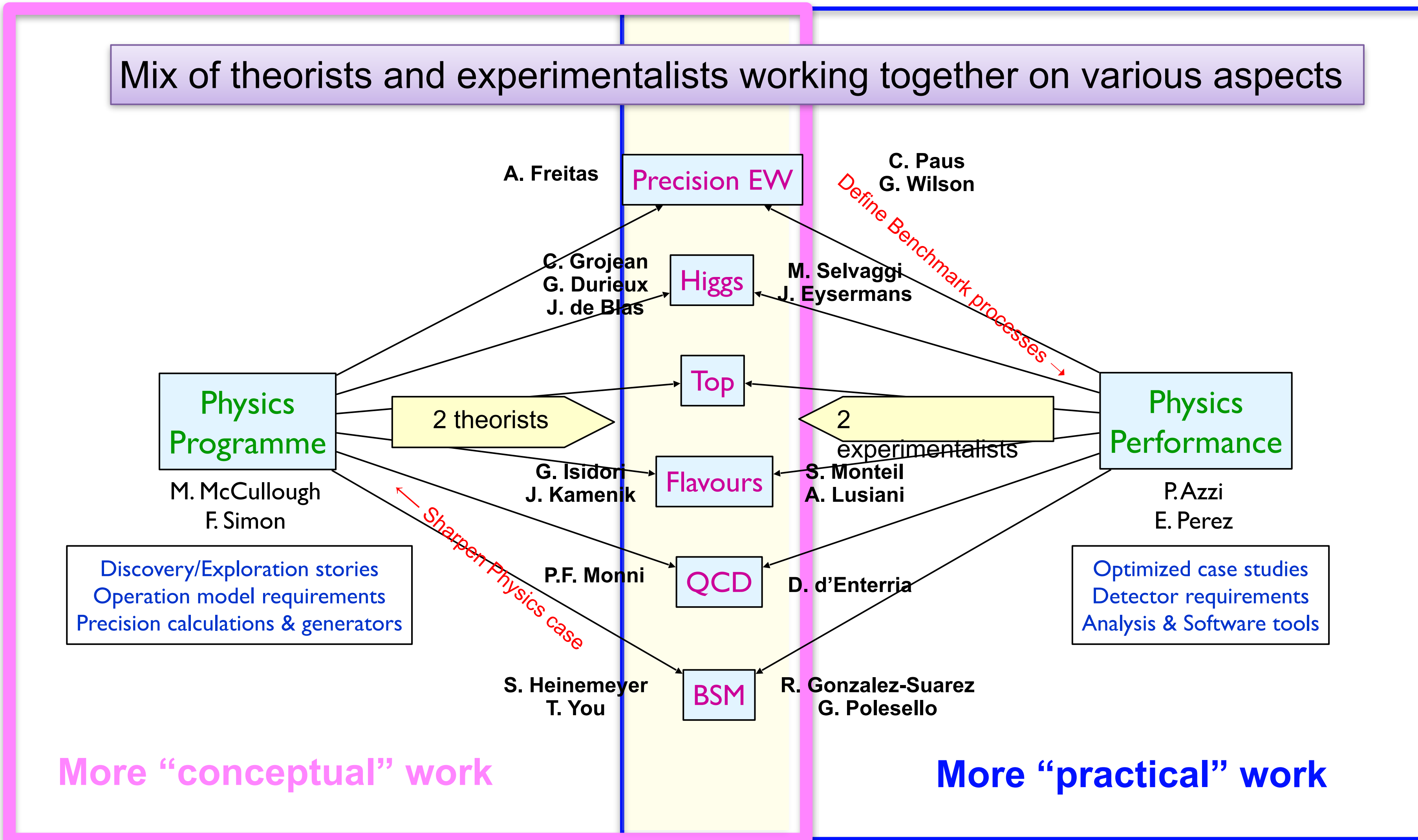
Overview of open projects

in FCC-ee Physics { **Programme** / **Performance**

6th FCC Physics Workshop
Jan 23-27, Kraków, Poland

Physics Performance Conveners: Patrizia Azzi(INFN-PD), Emmanuel Perez(CERN)
Physics Programme Conveners: Matthew McCollough(CERN), Frank Simon(KIT)

Structure of Physics groups - Who to contact!



Higgs measurements

Requirements on detector performance from Higgs physics: a priori already explored by ILC, but must be revisited :

- different environment (less beamstrahlung, no power-pulsing of electronics, etc)
- More ambitious goals on m_H (for ee → H) and on σ(ZH) (for self-coupling)
- Unique: possible run at the Higgs pole

Higgs analyses that are already covered :

- σ(ZH) and mH from Higgs recoil, Z → ll
- Higgs couplings to b, c, g, s
- Higgs to invisible
- Higgs self-coupling from precise σ(ZH) measurements at 240 and 365 GeV
- ee → H production in s-channel at 125 GeV
- *σ(ZH) in Z → qq (starting – challenge = model independent σ meas.)*

Talks at Krakow: Li, Marchiori, Metha.
Review by Selvaggi

Higgs measurements: not covered yet (or recent expression of interest)

Many channels to cover… lots of space to contribute

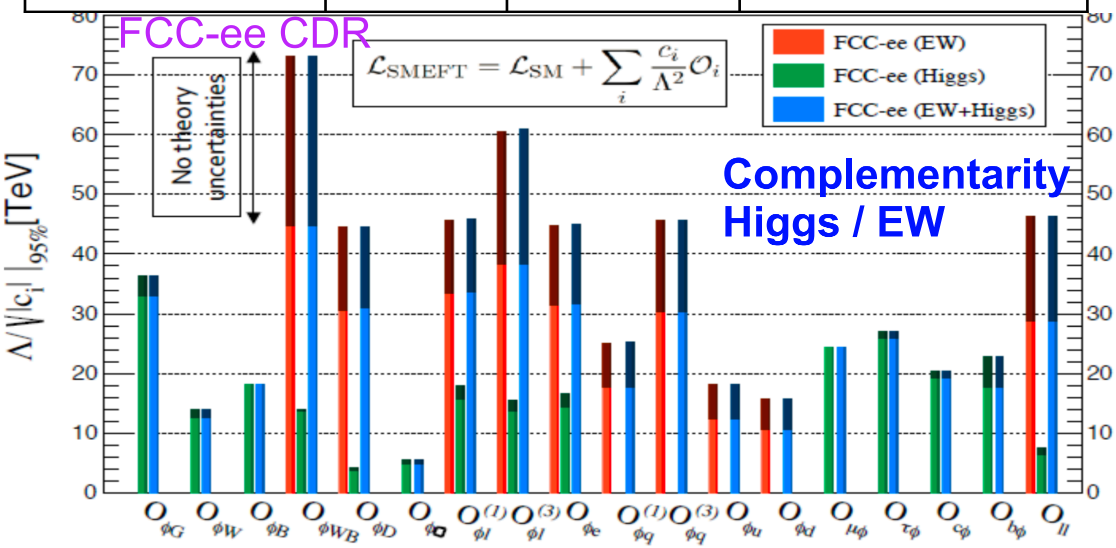
Measurement	Requirements
Direct reconstruction of mH in hadronic final states Example in Backup	jet angular resolution, kinematic fits, b-tag effi & purity *(Possible link with meas. of σ(ZH) in Z → qq)*
Γ(H) • H → ZZ • ZH(WW), ZH(bb), $\nu\nu$H(bb) Example in Backup	• Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits • Visible and missing mass resolutions
HZγ coupling (production and decay)	photon identification, energy and angular scale
Rare decays: H → $\gamma\gamma$ and H → μμ (unlikely to do better than HL-LHC..)	Photon ID and resolution, track resolution
H → $\tau\tau$ and CP studies	Tau reconstruction, Pi0 id

EW & QCD precision measurements: few examples

(*) current guess

	stat	w/ syst (*)	improvement
M_W	400 keV	500 keV	30
M_Z	4 keV	< 100 keV	> 20
Γ_Z	4 keV	< 25 keV	> 100
$\sin^2\theta_{eff}$ (τ pol)		3 10 $^{-6}$	60
$\alpha_{QED}(m^2_Z)$	3 10-5	3 10 $^{-5}$	4 (stat. lim. !)
Rb	3 10-7	2 10 $^{-5}$	30
alphaS(m2Z)	10-5	10-4	30
Mtop	20 MeV	40 MeV	12
…			

- Huge statistics: very small stat errors call for very small syst uncertainties too.
  - E.g. acceptances, should be known to 10-4 – 10-5
- Goal: σ(exp syst) ≈ σ(stat)
- Work on theo. side also critical (and initiated, 1809.01830)



One key experimental handle: knowledge of √s (exquisite at circular collider with resonant depolarisation method, at Z & WW)

In terms of weakly-coupled new physics: FCC-ee precision corresponds to sensitivity on Λ_{NP} up to 70 TeV, anticipating what FCC-pp would focus on.

EWK Precision measurements

For many measurements. :

- Early studies (CDR) for a first estimate of the stat uncertainty & main systematics
  - Often made with simple tools

- Some more evolved studies were started with simulations of an FCC-ee detector, but manpower left. E.g. :
  - Measurement of the W mass (PhD thesis)
  - Determination of EW top couplings (master thesis)

- Very large room for contributions !
  - Only one analysis currently ongoing
    - A_{FB} of b quarks (one group only) talk at Krakow Guerrieri
  - Starting point :
    - reproduce the early studies (with state of the art MCs and simulations, realistic beam conditions, with backgrounds, etc)
    - And/or reproduce the LEP analyses

- Next page: a list of “open” studies, a few being illustrated in the following slides.

EW measurements currently uncovered

talk at Krakow Blondel on Z line shape

	Measurement	Requirements
Z peak	Total width of the Z	scale (magnetic field) stability — Example in Backup
Z peak	Rb, Rc, (AFB)	Flavour tagging, acceptance, QCD corrections
Z peak	Ratio Rl = Gamma_had / Gamma_l	Geometrical acceptance for lepton pairs
Z peak	Tau polarisation	ECAL granularity — Example in Backup — talk at Krakow Brient
Z peak	AFB (muons)	QED corrections
Z peak	Luminosity from diphoton events	e/gamma separation, gamma acceptance
WW threshold	Coupling of Z to nu_e	Photon energy resolution, acceptance, track eff
WW threshold	σ(ee → WW) and MW (threshold scan ; direct reco also above threshold)	√s determination, bckgd control; angles, kinem. fits — Example in Backup — talk at Krakow Azzurri
WW threshold	Vcb via W -> cb	Flavour tagging
WW threshold	W leptonic BRs	Lepton ID, acceptance
ttbar	Meas of √s via radiative return	lepton and jet angular resolutions, acceptance
ttbar	Top properties from threshold scan	Jet reco, b-tagging, kine fits — talk at Krakow Wilson
ttbar	EW couplings of the top	Jet reco, b-tagging, kine fits

FCC-ee at the intensity frontier

15 times the BelleII anticipated statistics for B0s and B+

❑ **TeraZ offers four additional pillars to the FCC-ee physics programme**

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \to s\tau\tau$

QCD programme

- Enormous statistics with $Z \to \ell\ell$, qq(g)
- Complemented by 100,000 $H \to gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
$5 \cdot 10^{12}$ Z is a minimum

Tau physics programme

- Enormous statistics: $1.7\ 10^{11}$ $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons

Analyses in Flavour physics

Ongoing analyses in b physics :

- Bc (and Bu) to tau nu - New physics, access to Vcb, Vub
- $B \rightarrow K^*$ tau tau - very rare decay, high interest in view of LFU
- CP violation in $B \rightarrow$ Ds K ((re-) starting) - meas. of γ to < 1 degree
- b to s nu nu - sensitive to new physics
- Semi-leptonic CP asymetries - BSM contributions in mixing

Many interesting opportunities in tau physics.

- Existing FastSim samples of limited use for several tau studies
- But fullSim is coming up

Looking for interested contributors.

talk at Krakow: Miralles

Flagship measurement, tau lifetime, work is starting by one of the conveners (A. Lusiani)

Flavour physics analyses currently uncovered

	Measurement	Requirements
Z peak	CP violation in Bs → ΦΦ	PID, vertex, track resolution
	B0 → $\pi 0 \pi 0$ (→ eeγ) Example in Backup	Low energy γ 's in jets (ECAL resolution and granularity)
	Bs → $\tau\,\tau$	Vertexing
	Meas of γ from B+ → DK+	Ks reconstruction
	τ → 3μ, τ → μγ Example in Backup	resolutions
	τ lifetime talk at Krakow Lusiani Example in Backup	Alignment, scale of vertex detector,
	τ BRs	Lepton ID, PID, e/pi separation
	τ mass	Track reco & resolution (in multi-track collimated environment)
	Charm physics	
WW	Masses, spectroscopy, exotics…	
	EW parameters, exclusive modes (Vcb,etc)	Flavour tagging

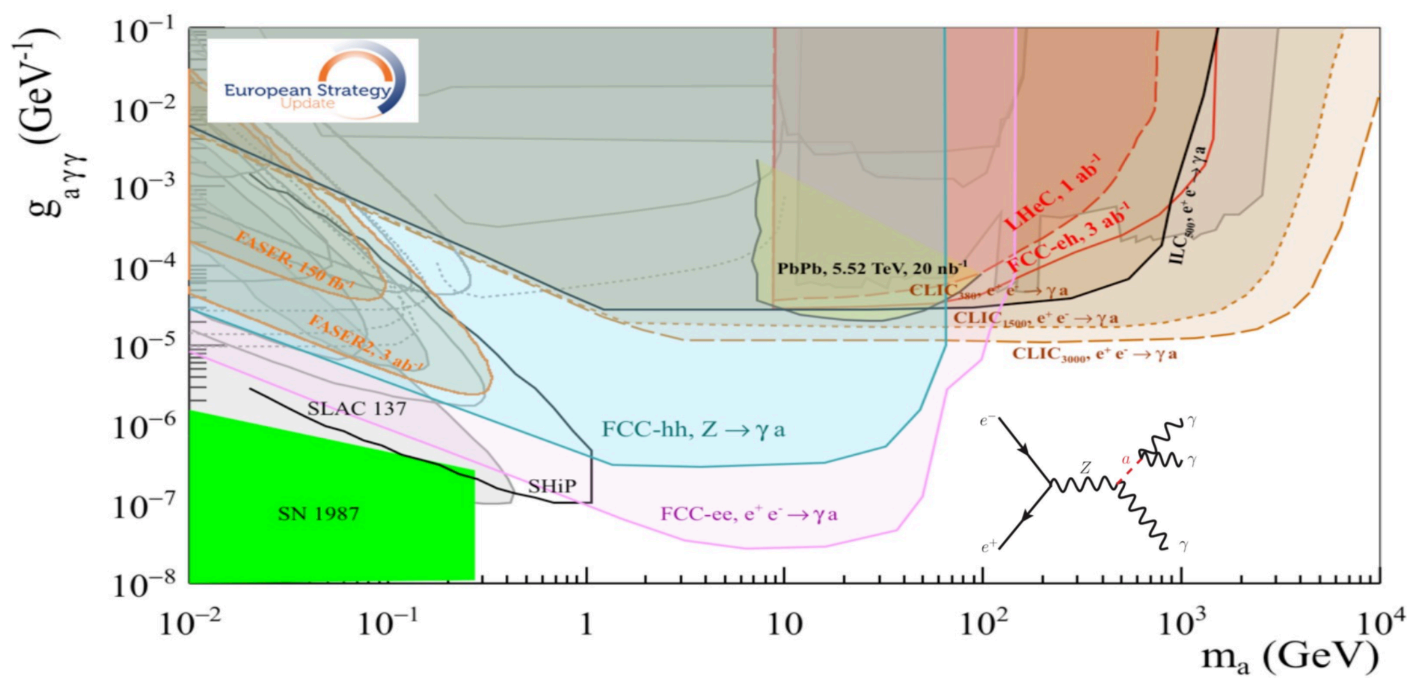
Direct searches for new particles

Areas with active analyses :

- Exotic particles produced at 91 GeV:
  - Heavy Neutral Leptons (ee $\rightarrow \nu$N)
  - Axion-like particles / dark photons (ee $\rightarrow \gamma$a or $\gamma\gamma_D$)
- Exotic Higgs decays to LLPs

Talks at Krakow:
Ripellino, Kulkarni

Large phase space to cover, different signatures, large range of decay lengths etc: ready for more people to step in !



Some references and useful reading

- **FCC Conceptual Design Reports**
  - Vol. 1 – Physics; Vol. 2 – FCC-ee; Vol. 3 – FCC-hh : 1338 authors
    - Preprints (Jan. 2019) on http://fcc-cdr.web.cern.ch
    - Published in EPJ C (Vol. 1) and EPJ ST (Vol. 2 & 3)
- **Symposia and workshops, with many further details**
  - Public presentation of the CDR, 4-5 March 2019: https://indico.cern.ch/event/789349/
  - Physics workshops (Jan. 20, Nov. 20), FCC Week 2019: https://indico.cern.ch/category/5225/
- **Other useful documentation, to extend and deepen knowledge**
  - FCC-ee: Your questions answered – https://arxiv.org/abs/1906.02693
  - Circular vs Linear colliders: Another story of complementarity – https://arxiv.org/abs/1912.11871
  - Theory calculations for FCC-ee – https://arxiv.org/abs/1809.01830 & https://arxiv.org/abs/1905.05078
  - Polarization and centre-of-mass energy calibration at FCC-ee - https://arxiv.org/abs/1909.12245

Some useful reading beyond the CDR

- **EPJ+ special issue "A future Higgs and EW Factory: Challenges towards discovery"**

All 34 references in this Overleaf document:
https://www.overleaf.com/read/xcssxqyhtrgt

MDI, $\sqrt{s}$

Challenges to match statistical precision

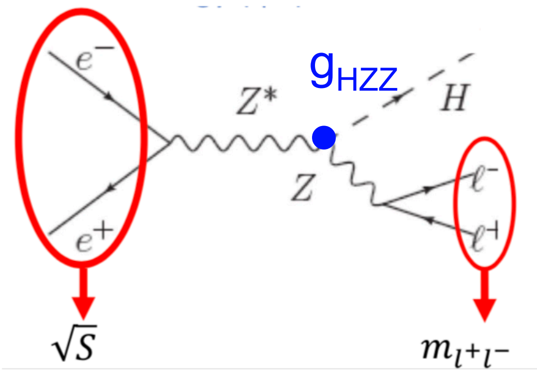
Detector requirements & possible solutions

Theory challenges

Software and computing challenges

BACKUP MATERIAL

FCC-ee as a Higgs factory



Key process: Higgsstrahlung σ (ZH) α g^2_{HZZ}

√s well known: ZH events tagged by the Z, without reconstructing the Higgs decay (recoil mass). Unique to lepton colliders.

Hence an absolute deterrmination on g_{HZZ} (indep. of Higgs decay mode).

Once g_{HZZ} is known: measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{X\overline{X}}) \propto \frac{g^2_{\mathrm{HZZ}} \times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

Hence a model-indep determination of all Higgs couplings.

FCC-ee prospects :

- HZZ coupling to the per-mil level, most other couplings < 1%
- Ultimate precision on $H\gamma\gamma$, Hμμ and $HZ\gamma$ from FCC-hh (synergy with FCC-ee)
- Self-coupling from precise measurement of σ(ZH) at 240 and 365 GeV
  - precision on λ of ~ 25% with 4 IPs at FCC-ee [to 3-8% at FCC-hh]
- $\sqrt{s} = m_H$: Electron Yukawa coupling: sensitivity close to the SM is at reach

Example: direct measurement of m_H

For a run at the Higgs pole: m_H must be known with a precision < 4 MeV (Γ_H).
mH from a fit to the recoil mass in Z(ll)H may not reach that precision.
→ complement with direct reconstruction of ZH → 4 jets

Z (and H) → hadrons or taus: cluster events to four jets and fix all jet velocities $\beta_i = p_i/E_i$

➔ **Determine all jet energies by solving (with a matrix inversion):**

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

followed by $m_H^{est} = m_{12} + m_{34} - m_Z$

+ template fits, bias understanding, combination, etc .

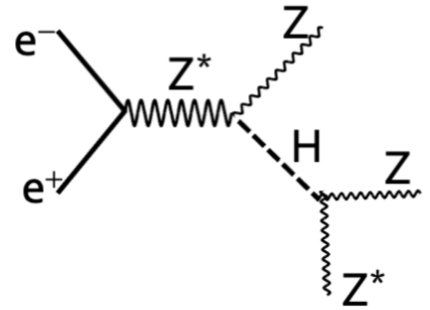
➔ **Can/should also try a full 5C kinematic fit (with E, p, m_Z constraints)**

Calibration of the method on ee → ZZ → qqbb

- ➢ requirements on the jet angular resolutions, on the b-tagging efficiency and purity (and on the determination of the beam energy spread)
- ➢ Code for kinematic fits, could be used in other analyses.

Example: Higgs width

- From ZH(ZZ) i.e. ZZZ* : $\sigma(ZH) \times BR(H \rightarrow ZZ) \propto g^4_{HZZ} / \Gamma_H$



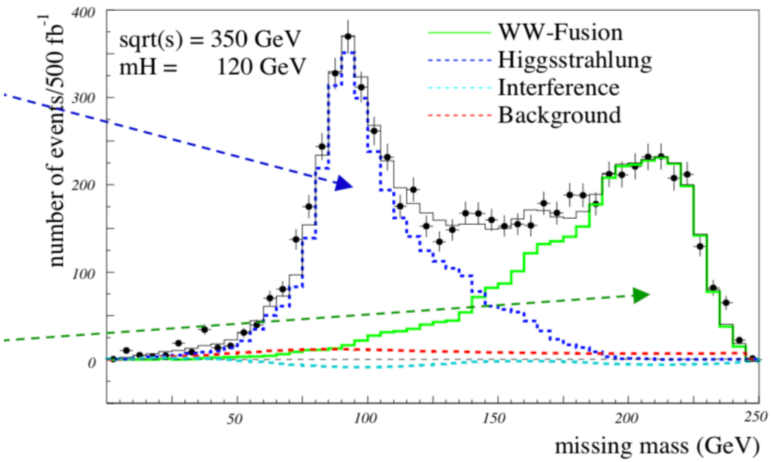
  - 3 or 4 leptons: ~ bckgd free but low stat
  - ≤ 2 leptons : key = jet clustering and kinematic fits
    - Many constraints: (E, p), M(H), M(Z) x2
    - Angles very well measured → Over-constrained fit for final state with 6 partons
    - Separation of signal from ZH(WW) background will set detector requirements

- From measurement of $\nu\nu$H(bb) events at 365 GeV :

$$\frac{\sigma_{WW\rightarrow H} \times BR(H\rightarrow bb) \times \sigma^2_{HZ}}{\sigma_{ZH} \times BR(H\rightarrow bb) \times \sigma_{ZH} \times BR(H\rightarrow WW^*)}$$

  - Background esp. from Z($\nu\nu$)H(bb)
    - Sig. & back: hadronic mass peaks at mH
    - Background: missing mass peaks at mZ

From early ILC studies

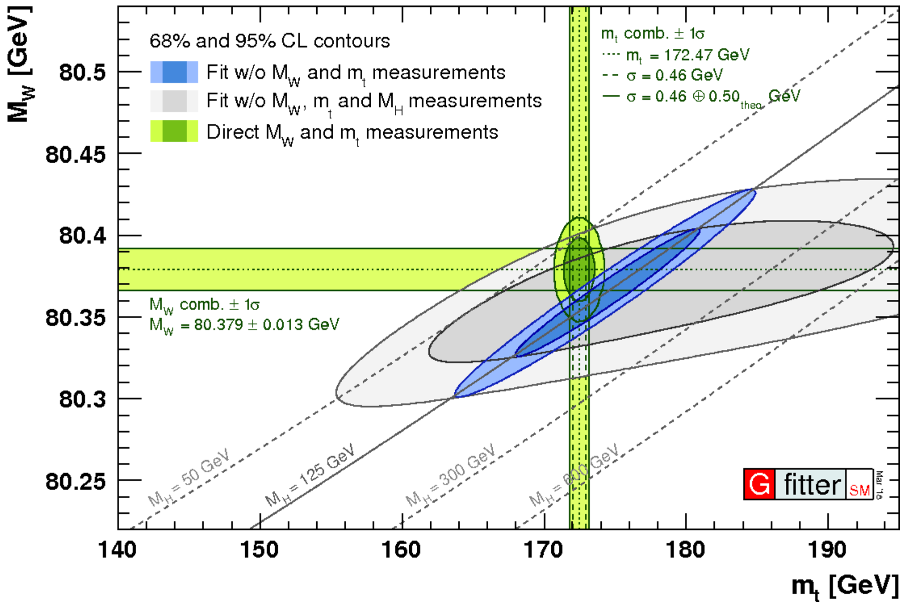


- Will set requirement on resolutions of hadronic mass, missing mass, Particle Flow reco, calorimeter granularity

FCC-ee as an Electroweak factory

With highest luminosities at 91, 160 and 350-365 GeV: complete set of EW observables can be measured with a precision dramatically improved w.r.t. today.

With m_{top}, m_W and m_H fixed by measurements: the SM has nowhere to go !



Increased precision could show first hints of physics beyond the SM.

- Improve the direct determination of MW and Mtop
  - PDG 2020: MW to 12 MeV
- And the SM fit prediction for these quantities, e.g. :

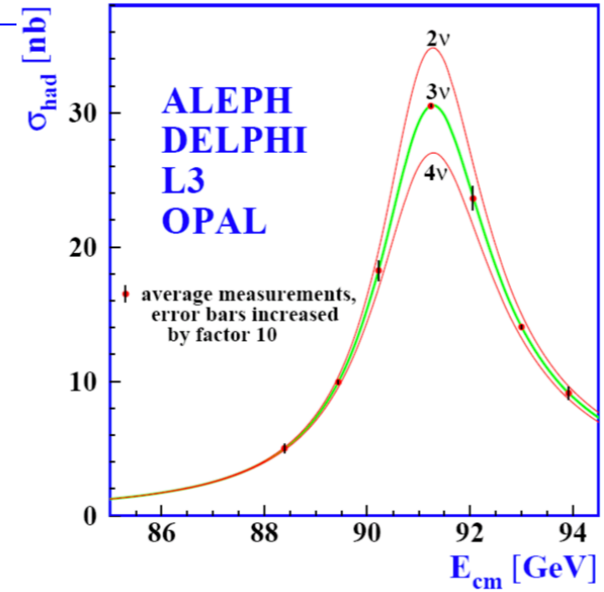
$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{theory} \text{ GeV} = 80.358 \pm 0.008_{total} \text{ GeV},$$

Estimates from S.

Requires improved measurements of m_{top}, m_Z, $\alpha_{QED}(m^2_Z)$, α_S… and more generally all usual EWPO included in the EW fits.

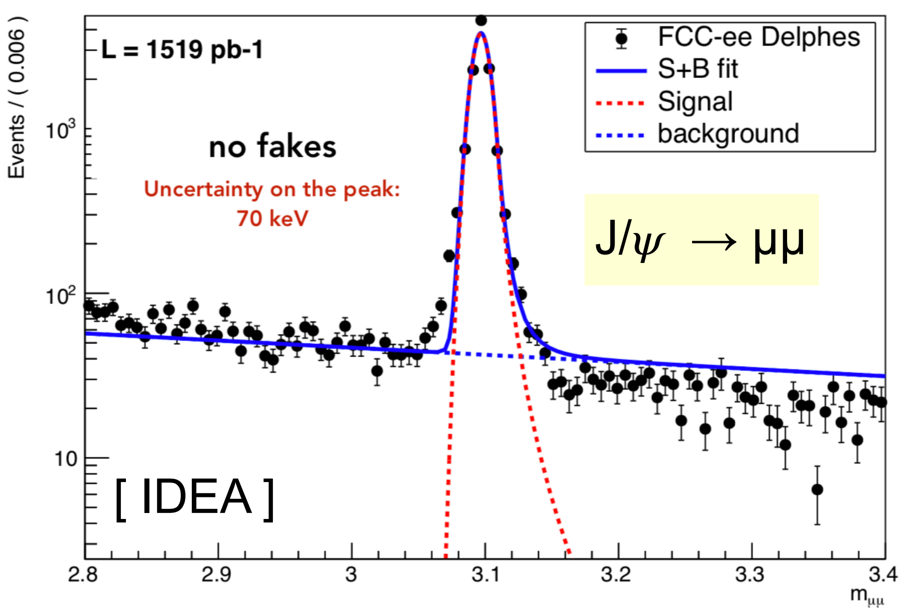
Example: Determination of the Z width

Key = Relative uncertainty of √s between the different energy points of the lineshape scan.



Can be controlled via the direct measurement of $M_{\mu\mu}$ in dimuon events : compare the peak positions at the different √s points.

- σ($M_{\mu\mu}$) : statistical potential to control relative δ(√s) to O(40 keV)
- Requires the stability of the momentum scale, esp. of B, to that level, i.e. 40 keV / 90 GeV < 10^{-6}



In-situ, using the large statistics of well-known resonances, e.g. J/ψ → μμ

First studies: Target seems close to be within reach with an IDEA-like resolution.

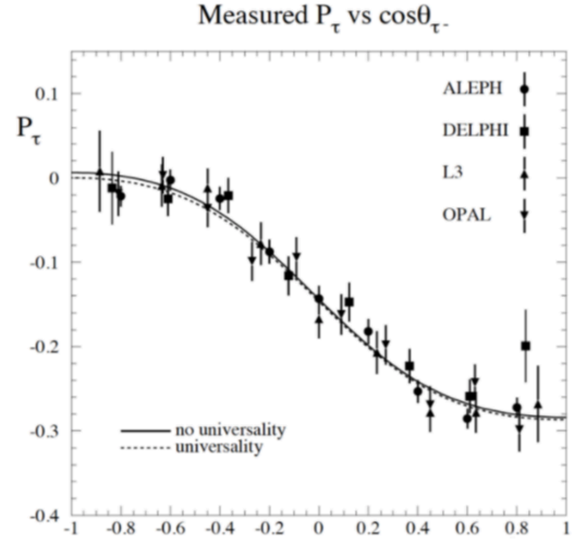
post-doc left, but code in place, should be easy to take over !

Example: Tau polarisation

Dedicated talk at Krakow, from JC Brient (ALEPH expert)

- Tau polarisation has a central role at the FCC-ee: crucial ingredient for $A_e, sin^2\theta_{eff}$ at a circular collider
  - Desired precision of few x10-6 on $sin^2\theta_{eff}$, similar to that from $A_{FB}^{\mu\mu}$ but model independent
- Very large tau statistics ($\approx 1.5 \times 10^{11}$). Not only leptonic decays. Can profit of hadronic decays and choose the best channels (avoiding modelling issues).
  - For instance use best decay channels such as τ→ρντ
- Fit of $\mathscr{P}(\tau)$ vs cosθ : Ae much less affected by syst. than A. Could achieve $\Delta(sin^2\theta_{eff}) \sim 3 \cdot 10^{-6}$

$$P_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + \mathcal{A}_e(2\cos\theta)}{(1+\cos^2\theta) + \frac{4}{3}\mathcal{A}_{fb}(2\cos\theta)}$$



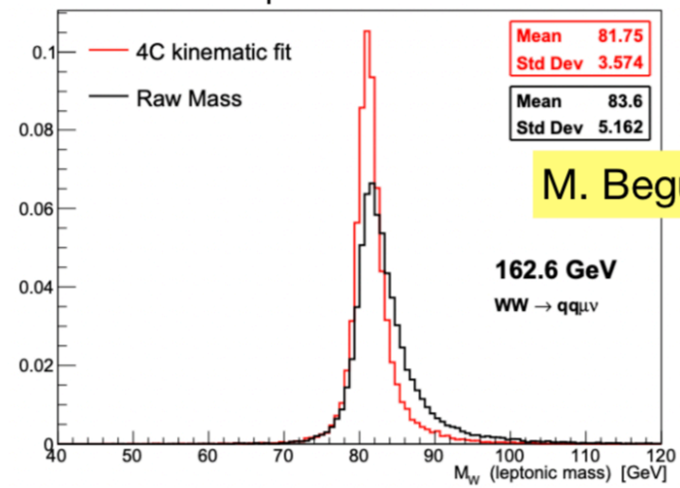
Crucial to have excellent $\pi^\pm/\pi^0$ separation (for the rho channel), hence ECAL granularity requirement

Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

Example: W mass direct reco

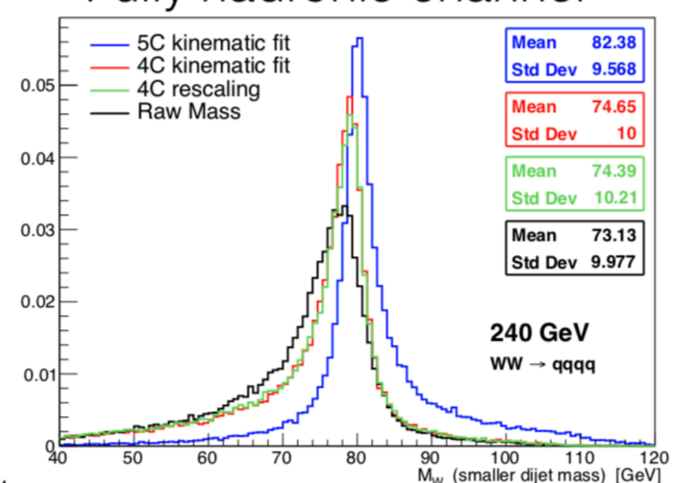
- Precise M(W) from threshold run ~400keV (stat)
- **M(W) direct reconstruction from decay products useful at any $\sqrt{s}$>threshold**
- Competitive as statistical uncertainty but different challenges to be considered:
  - Event reconstruction, choice of jet algorithms
  - Lepton momentum scale and resolution
  - Kinematical fitting

Semi-leptonic channel



M. Beguin

Fully hadronic channel

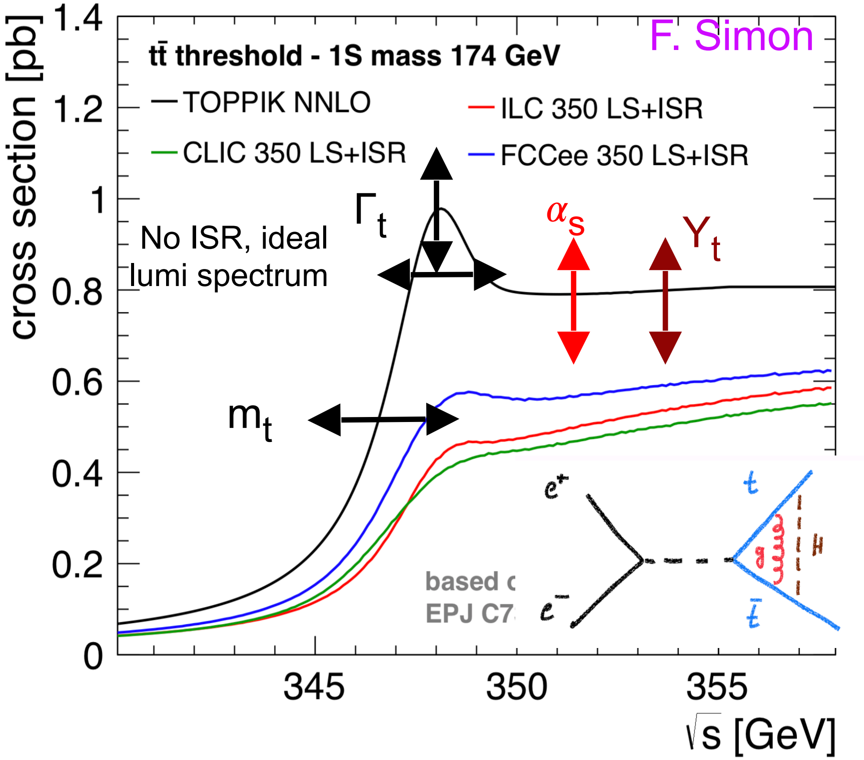


Definition of W mass estimators and study and optimisation of:

- Statistical and systematic uncertainties with templates fit
- W hadronic decay modelling systematics
- Exploiting also ZZ and Zγ events for constraints and calibration
- Thesis of M. Beguin available as starting point

Example: Top mass and width, Yukawa coupling

Short scan at the tt threshold. Determines m_{top} in a theoretically clean way, Γ_{top}, and the Yukawa coupling of the top.



Threshold shape affected by ISR & lumi spectrum (= main difference between the ee colliders).

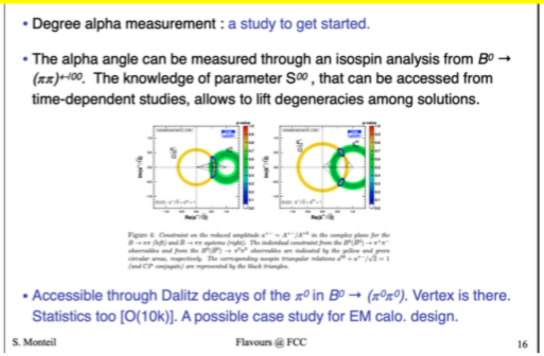
Measure σ at a few points around $2m_{top}$, e.g. 200 fb^{-1}

- M_{top} determined with a stat uncertainty of 15-20 MeV (theory syst ~ 40 MeV)
- y_{top} to about 10% - 20%

Possible project:
Optimise the scan, i.e. √s points & luminosity at each point) - re-optimisation of the scan made recently for CLIC conditions showed a sizable improvement !)

Example: CP study of B $\rightarrow \pi 0 \pi 0$

Monteil @FCCWeek



- Relevant for the angle α is the measurement of the time-dependent CP asymmetries in $B^0 \rightarrow \pi^0\pi^0$. It can be achieved with Dalitz decays.

- We expect 2500 $B^0 \rightarrow \pi^0(\rightarrow \gamma\gamma)\pi^0(\rightarrow e^+e^-\gamma)$ with efficiency for $\pi^0 \rightarrow \gamma\gamma$ reco such as LEP -> improve efficiency with ECAL design
- Use the electron for the vertex information to extract the time dependence

A very interesting study that needs to get started !

Example: Tau lifetime, BRs (and mass)

Example of precision challenge: Universality of Fermi constant

Andreas Crivellin and John Ellis.

EXOTIC FLAVOURS AT THE FCC

CERN COURIER — Volume 62 Number 1 January/February 2022

Here, a new-physics effect at a relative sub-per-mille level compared to the SM would suffice to explain the anomaly. This could be achieved by a heavy new lepton or a massive gauge boson affecting the determination of the Fermi constant that parametrises the strength of the weak interactions. As the Fermi constant can also be determined from the global electroweak fit, for which Z decays are crucial inputs, FCC-ee would again be the perfect machine to investigate this anomaly, as it could improve the precision by a large factor (see "High precision" figure). Indeed, the Fermi constant may be determined directly to one part in 10^5 from the enormous sample ($>10^{11}$) of Z decays to tau leptons.

Fermi constant is measured in μ decays and defined by

$$G_F^{(e)} G_F^{(\mu)} = \frac{192\pi^3}{m_\mu^5 \tau_\mu}$$

Assuming (e,μ) universality, the Fermi constant then is

$$G_F \equiv G_F^{(e)} = G_F^{(\mu)} = \sqrt{\frac{192\pi^3}{m_\mu^5 \tau_\mu}}$$

Experimentally known to 0.5 ppm (μ lifetime)

Similarly can define Fermi constant measured in τ decays

$$G_F^{(e)} G_F^{(\tau)} = \frac{192\pi^3 \mathcal{B}(\tau \to e\nu\nu)}{m_\tau^5 \tau_\tau}$$

Compare τ and μ based Fermi consants

$$\frac{G_F^{(e)}}{G_F^{(\mu)}} = \frac{m_\mu^5 \tau_\mu}{m_\tau^5 \tau_\tau} \mathcal{B}(\tau \to e\nu\nu)$$

Current precision:	67 ppm BES	1700 ppm Belle	2200 ppm LEP

FCC-ee: Will see 3×10^{11} τ decays
Statistical uncertainties at the 10 ppm level
How well can we control systematics?

m_τ	Use J/ψ mass as reference (known to 2 ppm)	tracking
τ_τ	Laboratory flight distance of 2.2 mm ⇒ 10 ppm corresponds to 22 nm (!!)	vertex detector
$\mathcal{B}$	No improvement since LEP (statistics limited) Depends primarily e^-/π^- (& e^-/ρ^-) separation	ECAL dE/dx

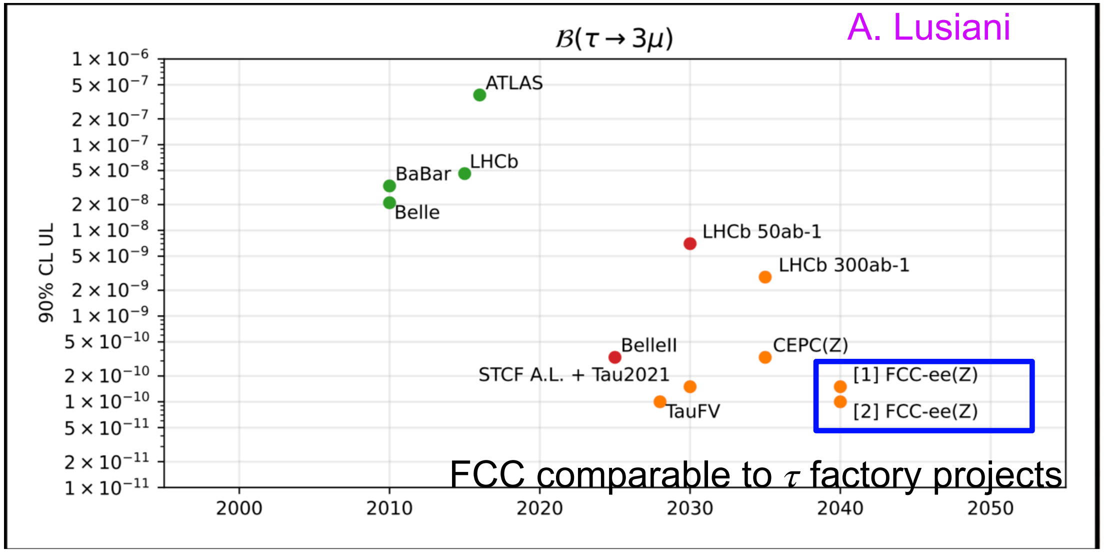
Example: Lepton Flavour Violating decays with taus

$\tau \rightarrow 3\mu$

Remember: about 1.7 10^{11} $Z \rightarrow \tau\,\tau$ decays !

Present bound ~ 10^{-8} (B factories). FCC could bring 2 orders of magnitude.

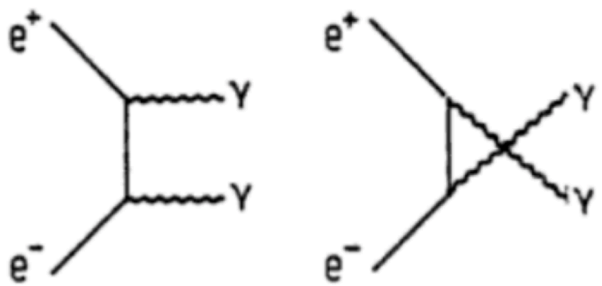
Channel also tests the reco of collimated tracks and purity of muon-ID.



Consolidate the guessed sensitivity shown above by a full analysis, including simulated backgrounds (mostly fakes from tau -> 3pi nu decays).

Starting point: an exercise was set up for this study in the last SW tutorial, see
https://hep-fcc.github.io/fcc-tutorials/fast-sim-and-analysis/fccanalyses/doc/starterkit/FccFastSimVertexing/

Alternative measurement of the luminosity : ee $\longrightarrow \gamma\gamma$ at large angles



- Pure QED process (at LO)
- Well controlled theoretically

Much smaller σ than small angle Bhabhas, but statistics still adequate for a precision of 10^{-4}

Example:

θ_{min} = 20 deg

Huge contamination from $e^+e^- \longrightarrow e^+e^-$ before any id cut (20 - 100x signal)

Energy	Process	Cross Section	Large angle $e^+e^- \to \gamma\gamma$	Large angle $e^+e^- \to e^+e^-$
90 GeV	$e^+e^- \to Z$	40 nb	0.039 nb	2.9 nb
160 GeV	$e^+e^- \to W^+W^-$	4 pb	15 pb	301 pb
240 GeV	$e^+e^- \to ZH$	0.2 pb	5.6 pb	134 pb
350 GeV	$e^+e^- \to tt$	0.5 pb	2.6 pb	60 pb

Need a good control of the e/γ separation (γ conversions, e $\longrightarrow \gamma$ fake rate).

e.g. with ε (γ id) = 99% and fake(e $\longrightarrow \gamma$) = 1%, would need to know the γ id inefficiency to the % level and the fake rate to a few per-mille.

Worth to take a closer look – systematics completely different from small angle Bhabhas (and no beam induced effect !)