Z and W Electroweak Precision Measurements – The Z line shape

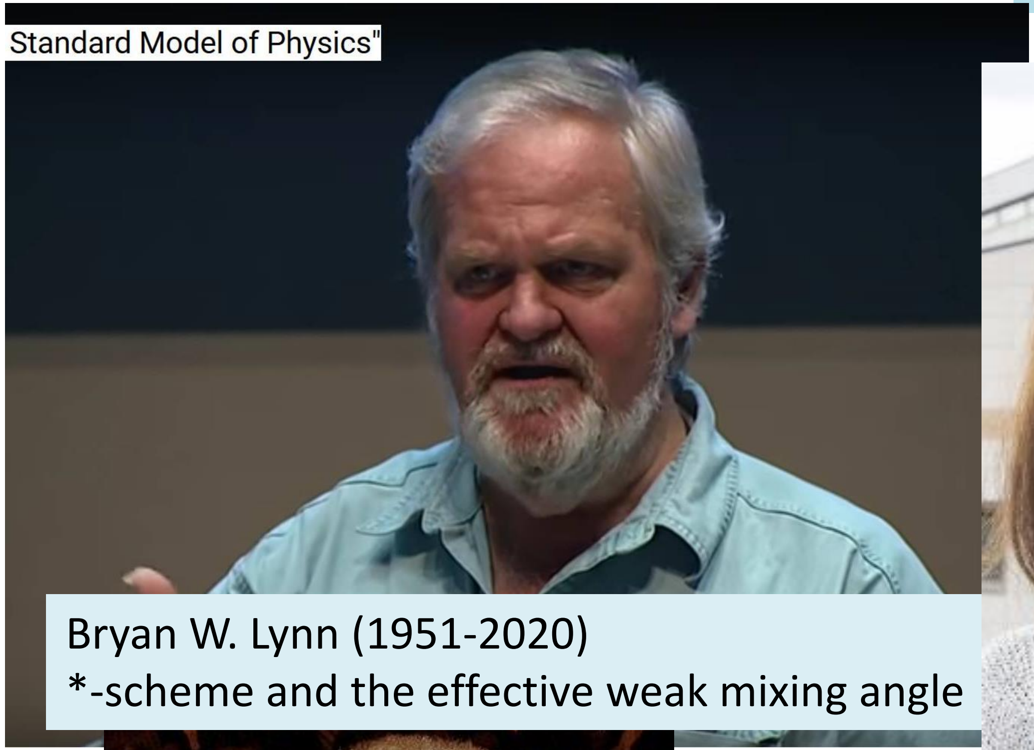
1. Motivation, framework
2. What is involved
3. (not included in this talk:ECM, Luminosity, theoretical calculations)
4. Final state selections, leading to detector requirements

   templates for analyses (Case studies)

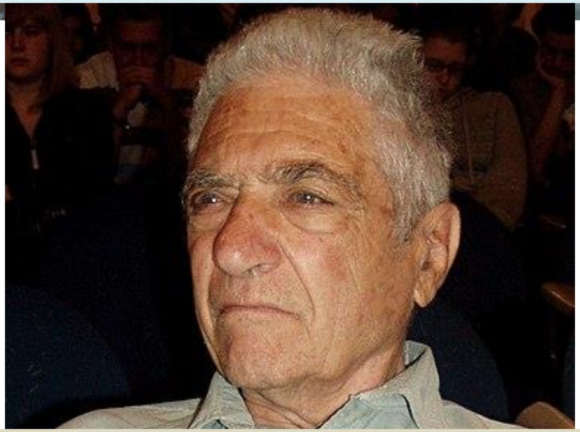
in 18 minutes + 7 minutes for questions

FCC

in Memoriam



Bryan W. Lynn (1951-2020)
*-scheme and the effective weak mixing angle



Jack Steinberger (1921-2020)
« Only the best is good enough »

Marie-Noelle Minard (1947-2022)
'She spotted the first Z boson in 1983', pilar of ALEPH supervised reference ALEPH PhD thesis on Z line shape (Lucotte, 1996)

Tord Riemann (1951-2021)
DESY-ZEUTHEN
S-matrix formalism for
Z line shape

« The Standard Model is complete »

This statement is correct in the following sense, which allows to separate 'SM' from 'BSM'

we should distinguish
A. 'Theory of particle physics'
based on Quantum Field Theory, relativity, quantum mechanics, principles of Gauge invariance etc... using in particular the SU(3)_color ⊗ SU(2)_L ⊗ U(1) gauge groups or extensions thereof.
In itself it is not necessarily predictive, but provides a wide toolset to include further discoveries.
** definitely not complete**
and
B. « the Standard Model » which is one possible model witihin the above, with a specific set of constituants (fermions and gauge bosons), their couplings, chiralities and their masses, which are all extracted from experiment
It was created (and named in ~1976) after the discovery of the Neutral Currents, Charm and the tau and ν_τ
With the discovery of the Higgs boson, the Standard Model is complete and forms a predictive and quantitative tool.
-- assumes neutrinos are massless
-- comprises 3 families of quarks and leptons and a single, elementary Higgs boson, and as such
contains no free parameter (only parametric uncertainties) ANY DEVIATION from SM is BSM DISCOVERY

-- does not explain in a unique way the neutrino masses or the Baryon Asymetry of the Universe, does not comprise a candidate DM particle, etc... for which we know for sure that BSM is needed.

Motivation for the precision measurements *and* precision calculations

1. Given that **the minimal SM is complete** with the Higgs discovery, how do we find out:
-- if the Higgs boson is exactly what is foreseen by the standard model? (→ Higgs Factory)
-- where/what are the new physics phenomena that must be present to explain:
baryon asymmetry
dark matter,
neutrino masses (and other mysteries we don't understand) (→ EW/top factory)

2. A powerful and broadly efficient method is to perform **precision EW measurements**
-- many **observables** contain sensitivity to new phenomena, either by loops, direct long distance propagator effects, or mixing with SM coupled particles.

«T»

→ are there any more weakly coupled particles?
The top quark effect at LEP was 10σ! (→ there is *not* another t-b quark system)
any custodial SU(2)-violating effect appears regardless of mass scale

$\Delta\rho = \Delta T/\alpha = \alpha/\pi \, . \, (m^2_{top} - m^2_b)/m^2_W$

«ν»

-- is there mixing ? in particular active-sterile neutrino mixing

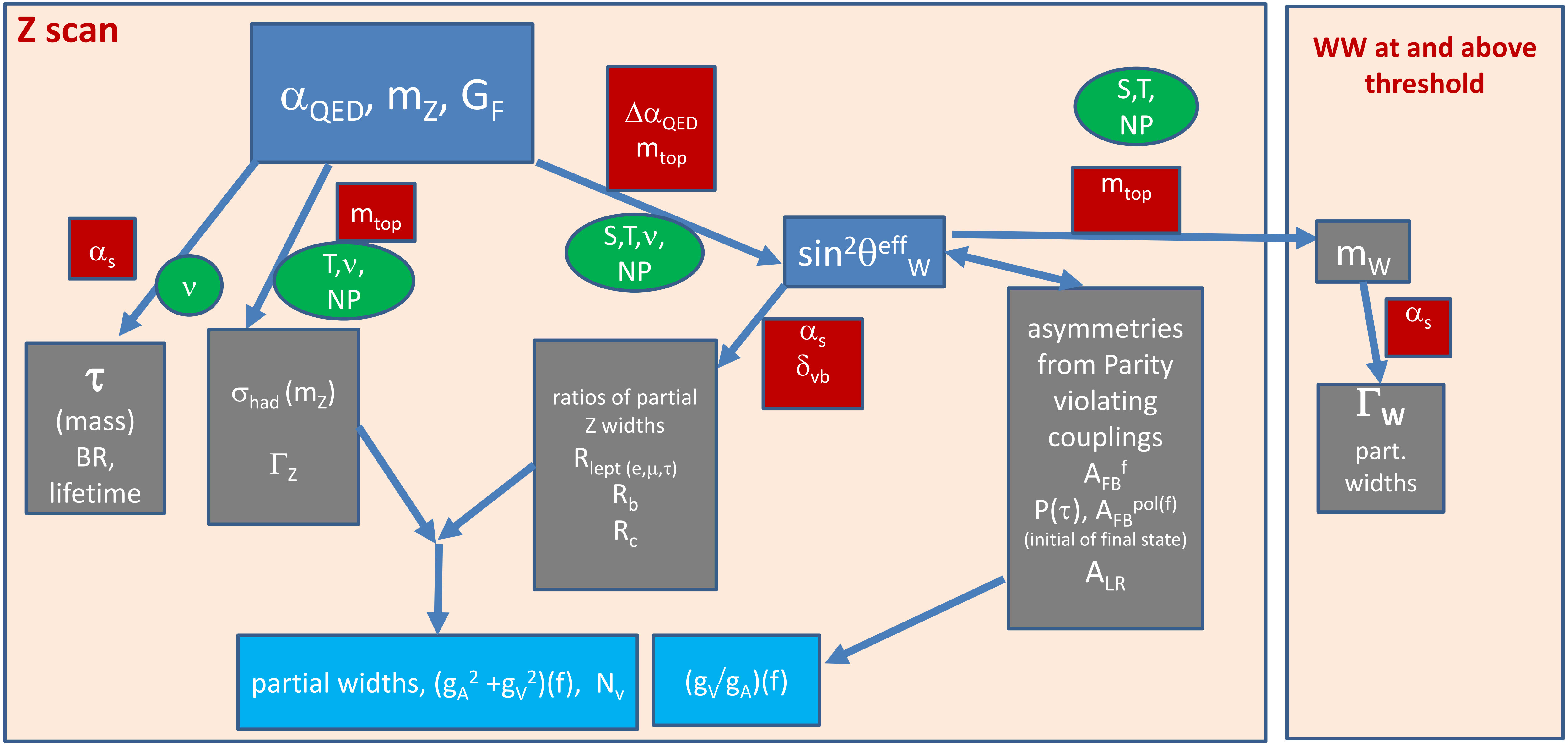
«S»

-- high mass SM-coupled and custodial SU(2)-respecting → (ex: Z' or degenerate Su-Sy)

not to forget:
QCD
Lepton-quark
lepton and quark family
Universality

Emphasis on different observables depending on the question asked.

Overview of loop correction relationships and examples of new physics effects



bottom line: FCCee provides both the SM inputs and the SM measurements → unprecedented exploration of BSM!

The fundamental reference

CERN-PH-EP/2005-041
SLAC-R-774
hep-ex/0509008
7 September 2005

Precision Electroweak Measurements on the Z Resonance

The ALEPH, DELPHI, L3, OPAL, SLD Collaborations,[1]
the LEP Electroweak Working Group,[2]
the SLD Electroweak and Heavy Flavour Groups

Accepted for publication in *Physics Reports*

Basic papers of the 4 LEP experiments

[41] ALEPH Collaboration, D. Decamp *et al.*, Z. Phys. **C48** (1990) 365–392;
ALEPH Collaboration, D. Decamp *et al.*, Z. Phys. **C53** (1992) 1–20;
ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. **C60** (1993) 71–82;
ALEPH Collaboration, D. Buskulic *et al.*, Z. Phys. **C62** (1994) 539–550;
ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. **C14** (2000) 1–50.

[42] DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B367** (1991) 511–574;
DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B417** (1994) 3–57;
DELPHI Collaboration, P. Abreu *et al.*, Nucl. Phys. **B418** (1994) 403–427;
DELPHI Collaboration, P. Abreu *et al.*, Eur. Phys. J. **C16** (2000) 371–405.

[43] L3 Collaboration, B. Adeva *et al.*, Z. Phys. **C51** (1991) 179–204;
L3 Collaboration, O. Adriani *et al.*, Phys. Rept. **236** (1993) 1–146;
L3 Collaboration, M. Acciarri *et al.*, Z. Phys. **C62** (1994) 551–576;
L3 Collaboration, M. Acciarri *et al.*, Eur. Phys. J. **C16** (2000) 1–40.

[44] OPAL Collaboration, G. Alexander *et al.*, Z. Phys. **C52** (1991) 175–208;
OPAL Collaboration, P. D. Acton *et al.*, Z. Phys. **C58** (1993) 219–238;
OPAL Collaboration, R. Akers *et al.*, Z. Phys. **C61** (1994) 19–34;
OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C19** (2001) 587–651.

Reference: https://inspirehep.net/literature/691576
Phys.Rept. 427 (2006) 257-454

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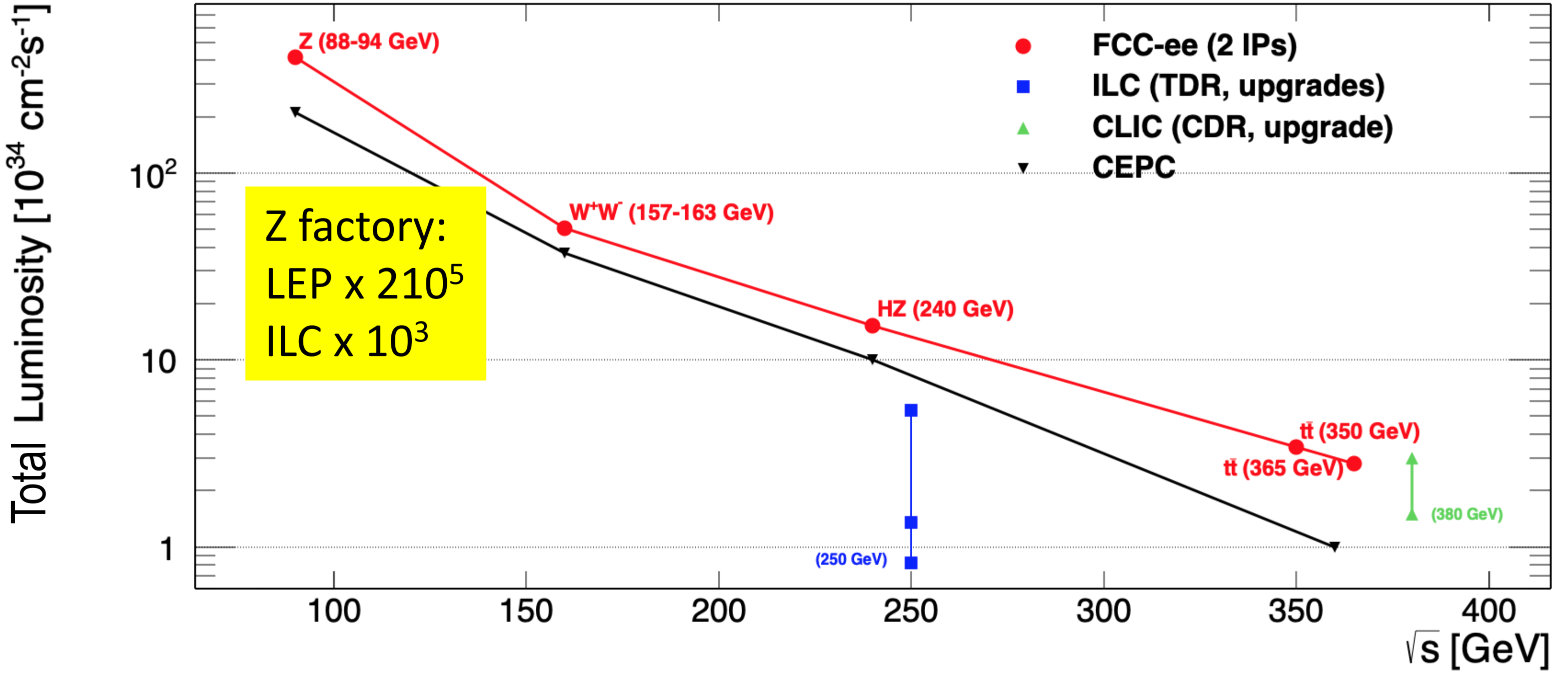
FCC-ee

Great energy range for the heavy particles of the Standard Model



notes:

-- 4IP increases Total Lumi by 1.7
-- 2IP assumed in all numbers below
-- order and duration of Z/WW/ZH can be decided at a later stage
-- ee→ H must be after both Z and ZH and before tt

see back-ups for facility comparisons

Event statistics (2IP) for typical run plan:

					E_{CM} errors:
Z peak	**E_{cm} : 91 GeV**	**4yrs**	**5 10^{12} e+e- → Z**	**LEP x 2.10^5**	<100 keV
WW threshold	**$E_{cm} \geq$ 161 GeV**	**2yrs**	**>10^8 e+e- → WW**	**LEP x 2.10^3**	<300 keV
ZH maximum	**E_{cm} : 240 GeV**	**3yrs**	**> 10^6 e+e- → ZH**	**Never done**	1 MeV
s-channel H	***E_{cm} : m_H***	***(3yrs?)***	***O(5000) e+e- → H***	***Never done***	*<< 1 MeV*
$t\bar{t}$	**E_{cm} : $\geq$ 340 GeV**	**5yrs**	**10^6 e+e- → $t\bar{t}$**	**Never done**	2 MeV

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Parenthesis

In the following I will use the ‘CDR baseline numbers’ **(2IP)**

**for the next iteration we should define a new baseline for 4IP running,
possibly giving numbers per experiment (or not)**

running at the Z peak **is.a.dream!**

it gives 3 orders of magnitude signal/background enhancement!

at FCC-ee 100 kHz event rate!

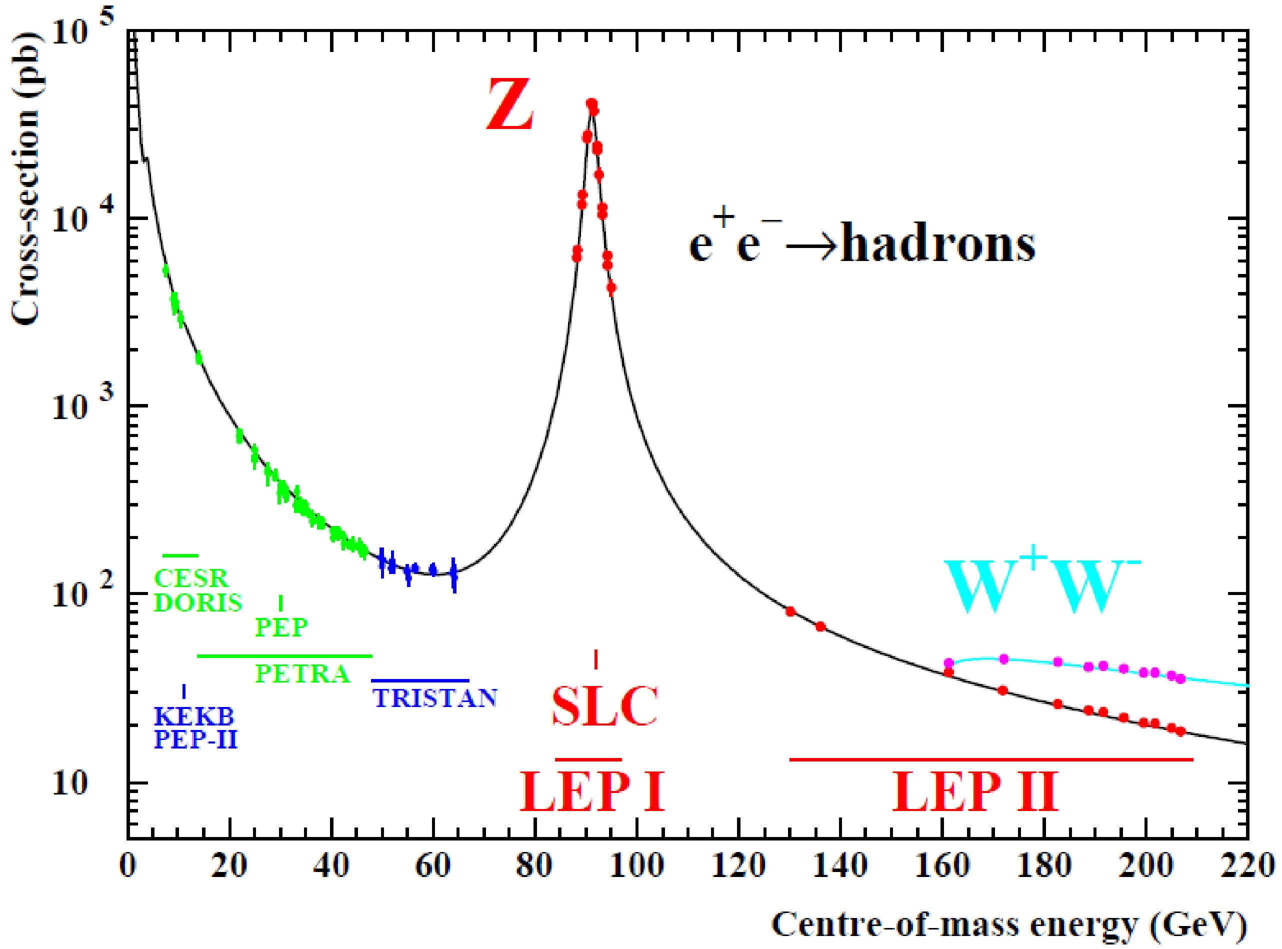

Figure 1.2: The hadronic cross-section as a function of centre-of-mass energy. The solid line is the prediction of the SM, and the points are the experimental measurements. Also indicated are the energy ranges of various e^+e^- accelerators. The cross-sections have been corrected for the effects of photon radiation.

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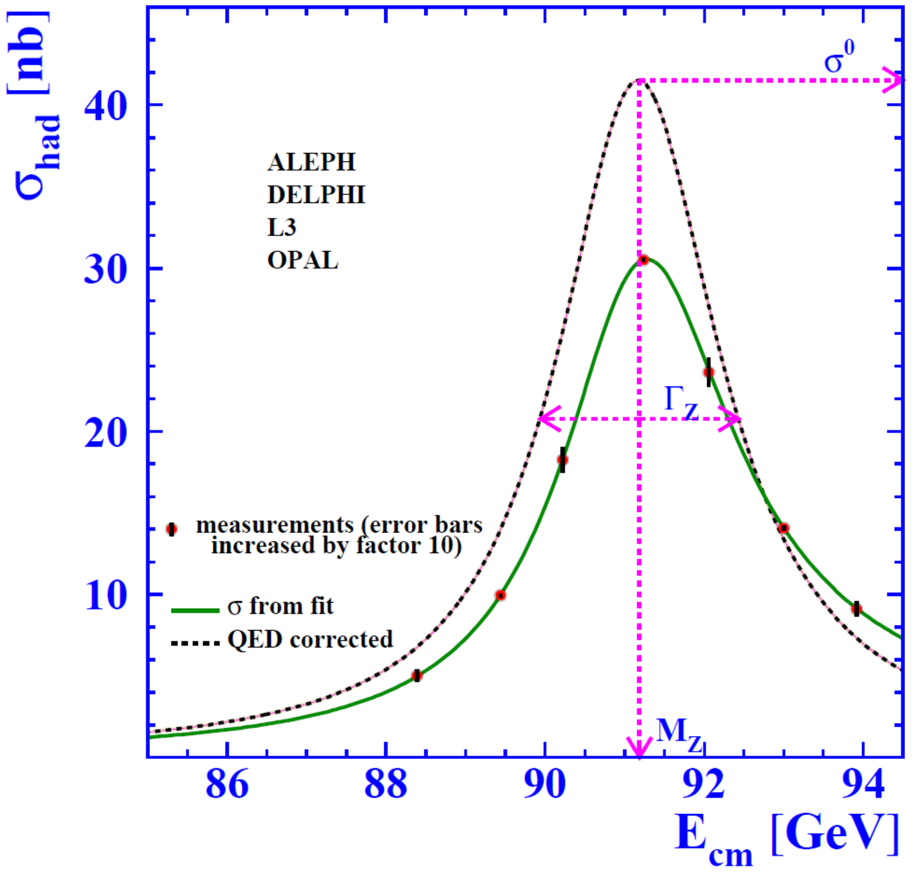
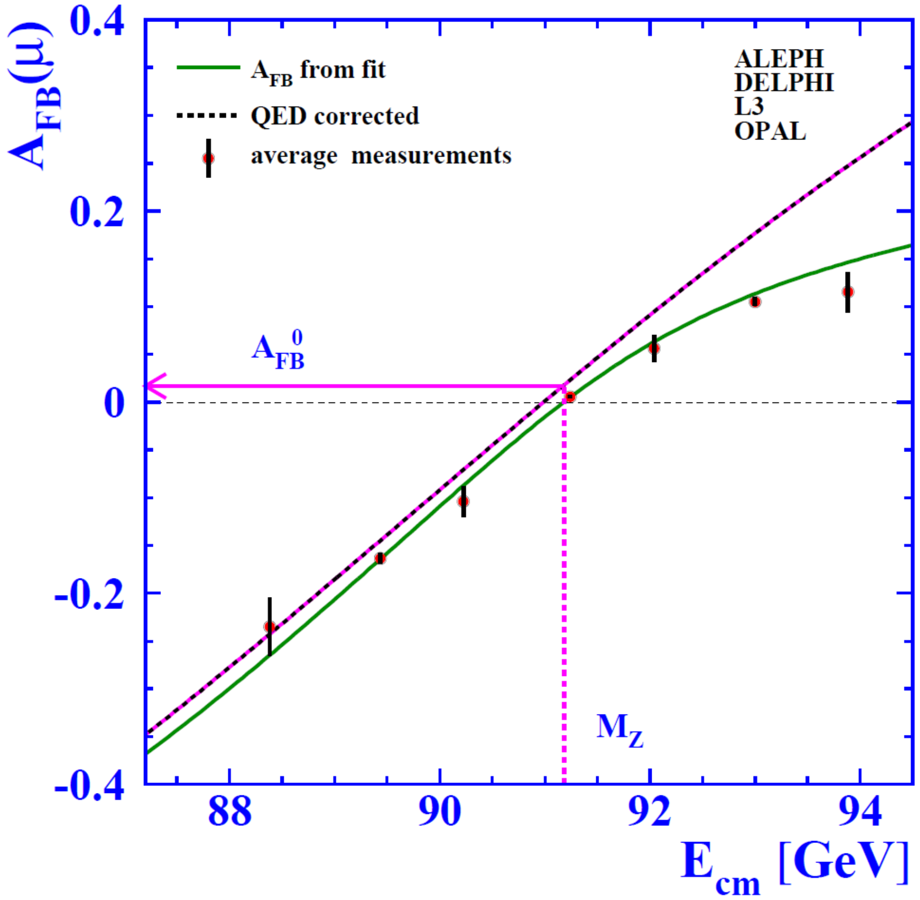
The task: extract precision observables from the measurements of hadron and lepton cross-sections and lepton forward backward asymmetries as function of E_{cm}





Photon radiation (Figure 1.11) from the initial and final states, and their interference, are conveniently treated by convoluting the electroweak kernel cross-section, $\sigma_{ew}(s)$, with a QED radiator, H^{tot}_{QED},

$$\sigma(s) = \int_{4m_f^2/s}^{1} dz\, H^{tot}_{QED}(z,s)\sigma_{ew}(zs). \quad (1.36)$$

in practice fit the measured cross-sections to σ(s, {pseudo_obs})

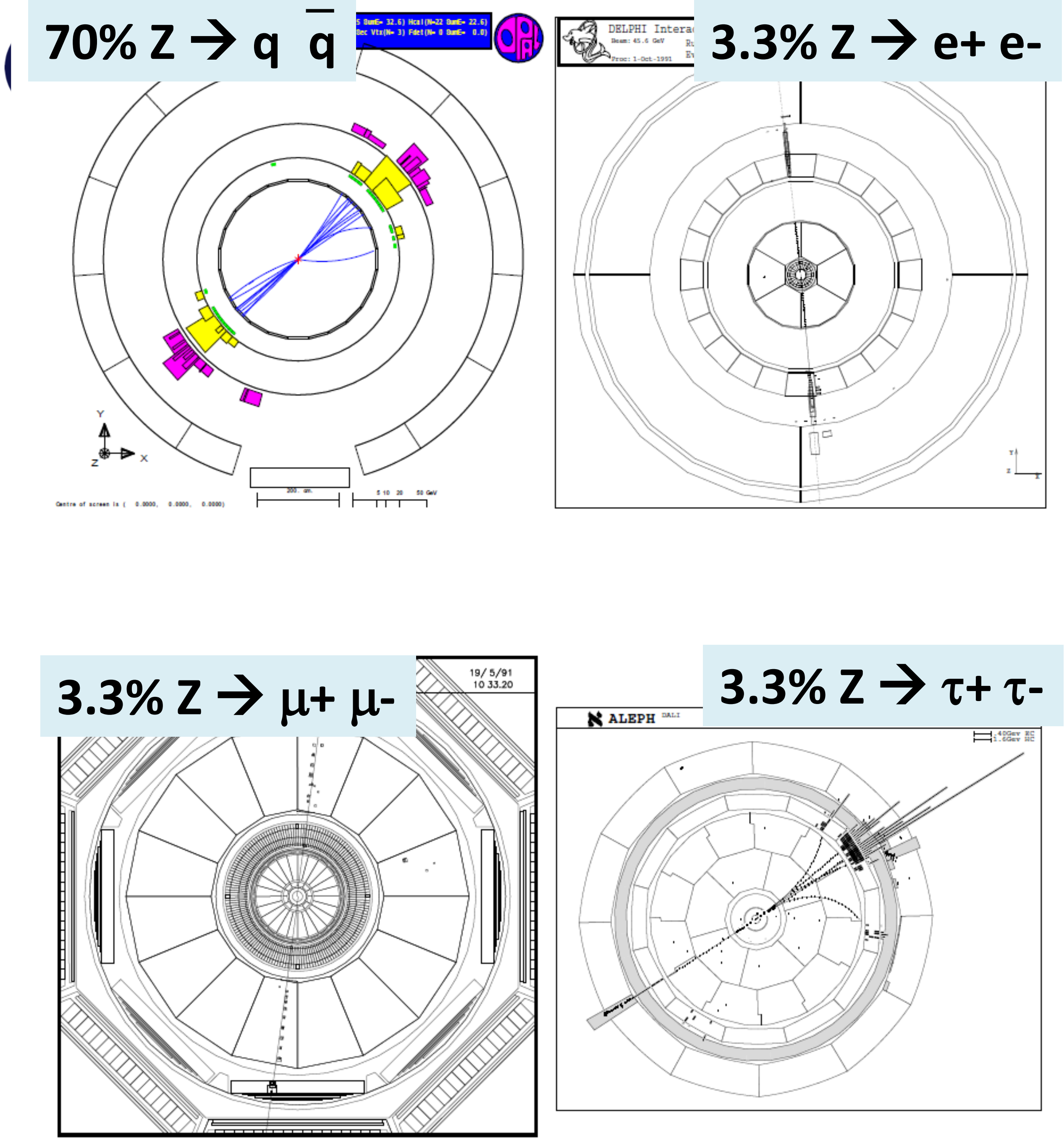


Figure 1.7: Pictures of $q\bar{q}$, e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states, visualised with the event displays of the OPAL, DELPHI, L3 and ALEPH collaborations, respectively. In all views, the electron-positron beam axis is perpendicular to the plane of the page. The stability of the electron and the long lifetime of the muon allow these fundamental Z decays to be directly observed, while the low-multiplicity products of τ decays are confined to well-isolated cones. Hadronic Z decays result in higher-multiplicity jets of particles produced in the QCD cascades initiated by the initial $q\bar{q}$ pair.

The LEP parameters and output from the Z Line Shape

Because the measured cross-sections depend on products of the partial widths and also on the total width, the widths constitute a highly correlated parameter set. In order to reduce correlations among the fit parameters, an experimentally-motivated set of six parameters is used to describe the total hadronic and leptonic cross-sections around the Z peak. These are

- the mass of the Z, m_Z;
- the Z total width, Γ_Z;
- the "hadronic pole cross-section",

$$\sigma^0_{\rm had} \equiv \frac{12\pi}{m_Z^2}\frac{\Gamma_{\rm ee}\Gamma_{\rm had}}{\Gamma_Z^2};$$

- the three ratios

$$R^0_{\rm e} \equiv \Gamma_{\rm had}/\Gamma_{\rm ee},\; R^0_\mu \equiv \Gamma_{\rm had}/\Gamma_{\mu\mu} \text{ and } R^0_\tau \equiv \Gamma_{\rm had}/\Gamma_{\tau\tau}. \quad (1.46)$$

If lepton universality is assumed, the last three ratios reduce to a single parameter:

$$R^0_\ell \equiv \Gamma_{\rm had}/\Gamma_{\ell\ell}, \quad (1.47)$$

where $\Gamma_{\ell\ell}$ is the partial width of the Z into one massless charged lepton flavour. (Due to the mass of the tau lepton, even with the assumption of lepton universality, $\Gamma_{\tau\tau}$ differs from $\Gamma_{\ell\ell}$ by about $\delta_\tau = -0.23\%$.)

Z mass
Z width
σ^o_{had}
R_ℓ
$A_{FB}^{0\ell}$
➔New: $dA_{FB}^{0\ell}/dE_{cm}$ for $\alpha_{QED}(m_Z)$

Without lepton universality		Correlations								
χ^2/dof = 32.6/27		m_Z	Γ_Z	$\sigma^0_{\rm had}$	$R^0_{\rm e}$	R^0_μ	R^0_τ	$A^{0,\rm e}_{\rm FB}$	$A^{0,\mu}_{\rm FB}$	$A^{0,\tau}_{\rm FB}$
m_Z [GeV]	91.1876 ± 0.0021	1.000								
Γ_Z [GeV]	2.4952 ± 0.0023	−0.024	1.000							
$\sigma^0_{\rm had}$ [nb]	41.541 ± 0.037	−0.044	−0.297	1.000						
$R^0_{\rm e}$	20.804 ± 0.050	0.078	−0.011	0.105	1.000					
R^0_μ	20.785 ± 0.033	0.000	0.008	0.131	0.069	1.000				
R^0_τ	20.764 ± 0.045	0.002	0.006	0.092	0.046	0.069	1.000			
$A^{0,\rm e}_{\rm FB}$	0.0145 ± 0.0025	−0.014	0.007	0.001	−0.371	0.001	0.003	1.000		
$A^{0,\mu}_{\rm FB}$	0.0169 ± 0.0013	0.046	0.002	0.003	0.020	0.012	0.001	−0.024	1.000	
$A^{0,\tau}_{\rm FB}$	0.0188 ± 0.0017	0.035	0.001	0.002	0.013	−0.003	0.009	−0.020	0.046	1.000

With lepton universality		Correlations				
χ^2/dof = 36.5/31		m_Z	Γ_Z	$\sigma^0_{\rm had}$	R^0_ℓ	$A^{0,\ell}_{\rm FB}$
m_Z [GeV]	91.1875 ± 0.0021	1.000				
Γ_Z [GeV]	2.4952 ± 0.0023	−0.023	1.000			
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	−0.045	−0.297	1.000		
R^0_ℓ	20.767 ± 0.025	0.033	0.004	0.183	1.000	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.055	0.003	0.006	−0.056	1.000

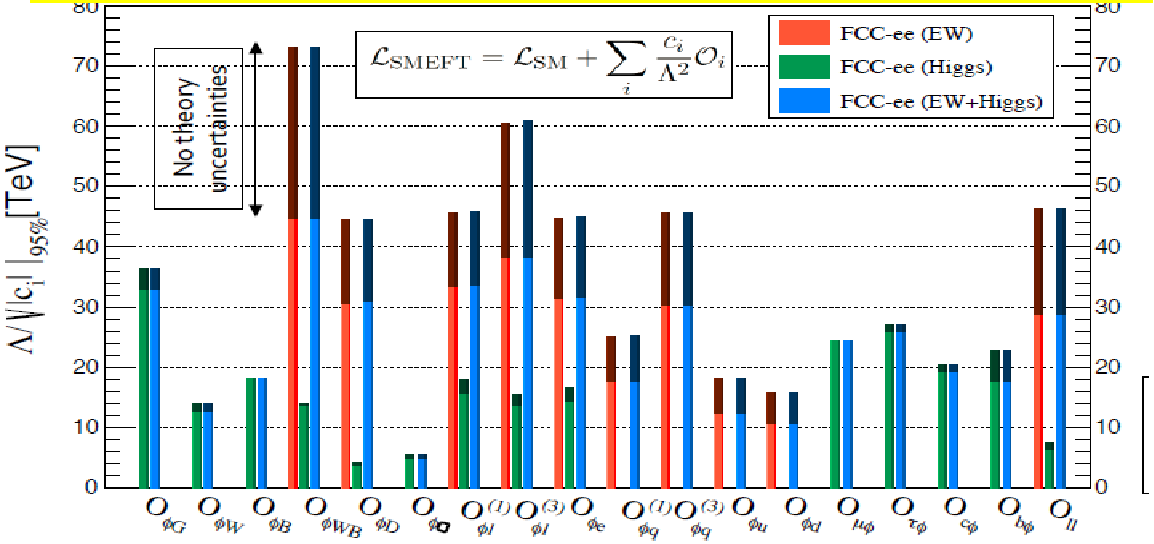
to which are added the forward backward asymmetries **$A_{FB}^{0\ell}(m_Z)$** for leptons, ~uncorrelated from the total cross-sections

For a ~symmetric scan, the slope **$A_{FB}^{0\ell}(E_{cm})$ will be independent of $A_{FB}^{0\ell}(m_Z)$**

this set of pseudo observables is chosen as it minimises the statistical and systematic correlations in addition is leads to relatively straightforward relationship with the physics effects.

Precision EW measurements: is the SM complete?

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run



NP Sensitivity by oblique/vertex loops or mixing

- ***Higgs + EWPO (+ flavours) are complementary***
- top quark mass and couplings essential!

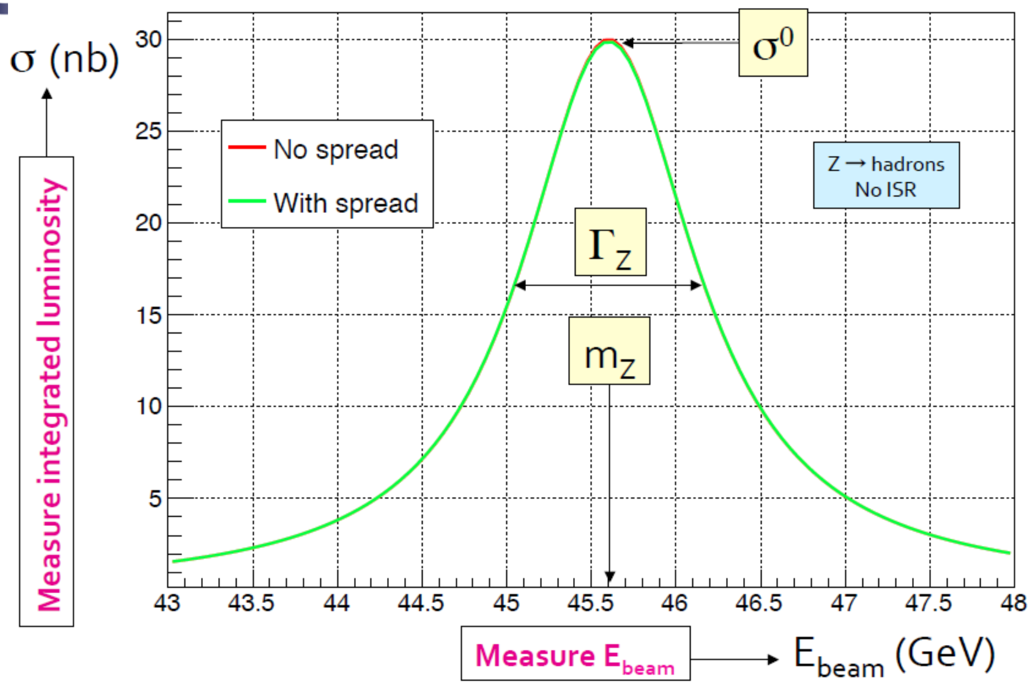
(the 91km circumference is optimal for this)

- preliminary systematics!

aim at reducing to the level of statistics

- many observables still to be added (flavours)
- complemented by high energy FCC-hh
- ***Theory work is critical and initiated*** *1809.01830*
- *see also recent physics workshop session.*

FCC scan points for m_Z and m_W



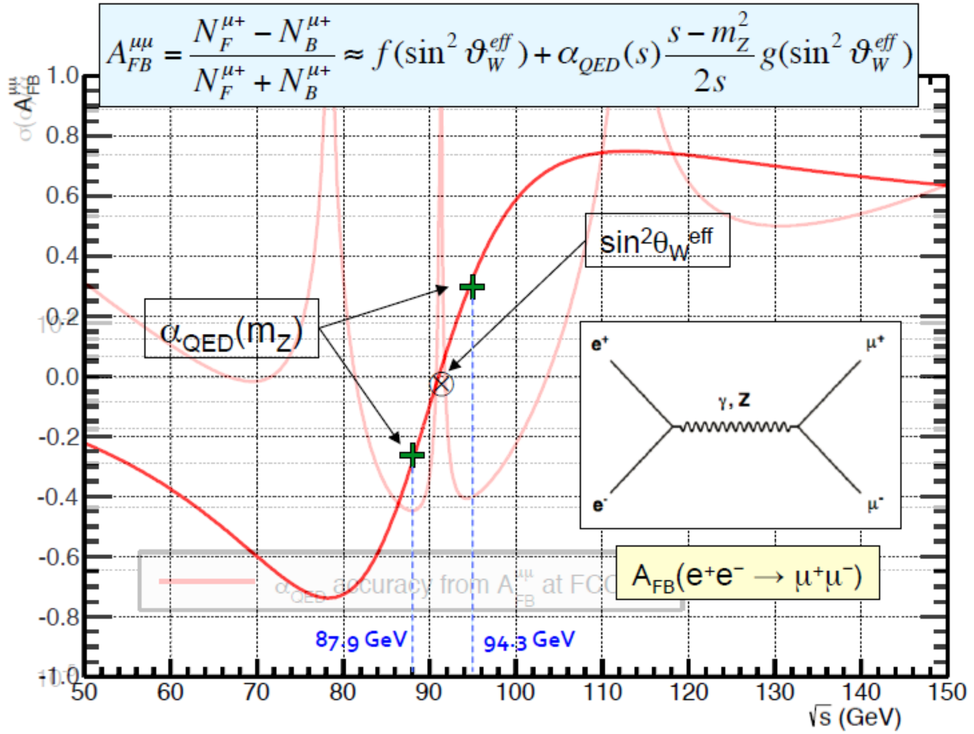
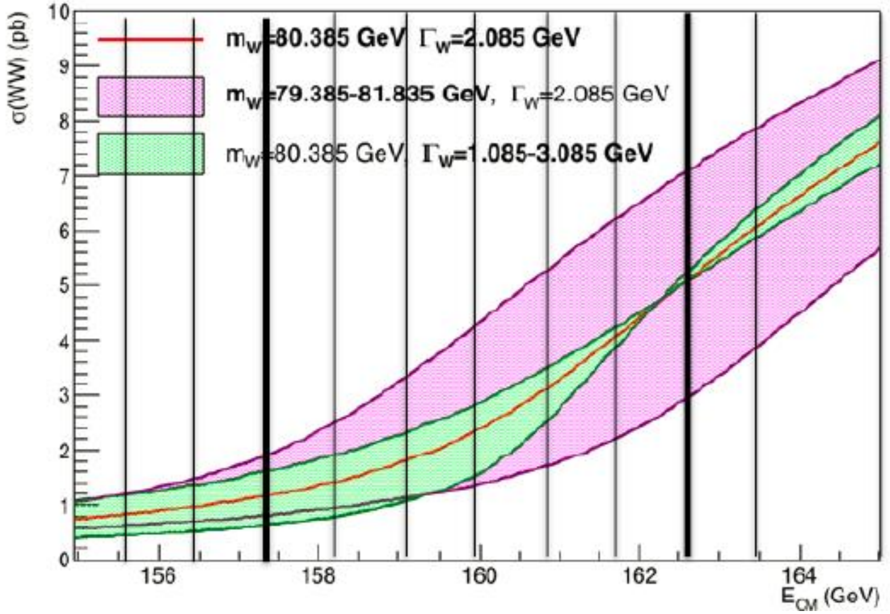


Table 3: Center-of-mass energies for the proposed Z scan. The points noted A and B are half integer spin tune points with energies closest to the requested energies.

Scan point	Centre-of-mass Energy	Beam Energy	Spin tune	
E_{CM}^{-} A	87.69	43.85	99.5	
E_{CM}^{-} Request	87.9	43.95	99.7	30 ab-1
E_{CM}^{-} B	88.57	44.28	100.5	
E_{CM}^{0}	91.21	45.61	103.5	90 ab-1
E_{CM}^{+} A	93.86	46.93	106.5	
E_{CM}^{+} Request	94.3	47.15	107.0	30 ab-1
E_{CM}^{+} B	94.74	47.37	107.5	



task list (or «work packages » or «case studies» as you prefer)

at each scan point we want

-- integrated luminosity

-- from e+e- → e+e- : Low angle Bhabha events **task 1**

-- from e+e- → $\gamma\gamma$: large angle two-photon events **task 2** see also task 5 (e+e-)

and correlations between these event counts and energy points (see relevant talks)

-- luminosity weighted **center-of-mass energy** (distribution) → see Guy's talk **task 3**

and correlations between the energy points (overall scale and point to point uncertainties)

-- **cross-sections for hadrons** : event selection(s), acceptance, efficiency, background(s) **task 4**

-- **cross-section for each species of lepton pair** (ee, $\mu\mu$, $\tau\tau$) event selection(s), efficiency, backgrounds **tasks 5,6,7**

-- cross-talk between channels is very low...

... but optimum must be found between efficiency, low background and cross-talk, to minimize R_ℓ uncertainty **union of tasks 5,6,7**

-- **make sure that data can be selected for which all needed detector are operating!** **task 0**

main topic today: hadronic and leptonic event selection for cross-sections and R_ℓ

a comment

The hadronic and leptonic event selections are used for the
- Z peak cross-section
- Z mass
- Z width

where other sources of errors might be limiting (luminosity, Ecm calibration)

The hadronic and leptonic cross-sections are the only ingredients in the ratio of hadrons to leptons R_ℓ which is of great interest (α_s test of lepton universality, test of quark-lepton universality)

there the statistics of $1.7\ 10^{11}$ events per lepton channel, $5\ 10^{11}$ total, is the limiting factor
➔ target is relative precision of $1.5\ 10^{-6}$ for both hadron and all leptonic channels.

Hadronic event selection

We follow the ALEPH work described in particular in Arnaud Lucotte, PhD thesis 1996.

-- based on two essentially independent selections

-- one on charged tracks only (TPC) eff=97.5 $\pm$ 0.08 %

5 tracks with $\geq$ 4hits and cosθ <0.95 (6 points in ALEPH TPC), for a total $\Sigma|p| > 0.1 \sqrt{s}$

-- one on calorimeter signals mostly eff= 99.1 $\pm$ 0.12 %

-- sum in barrel > 6 GeV, of sums in both endcaps > 1.5 GeV such that E_cal>0.2 $\sqrt{s}$

+ further selections applied for events with $\leq$ 4 tracks to eliminate taus, bhabha and two-photon backgrounds

-- comparison of the two analyses (verification of overlap > 96% and losses) allows verification of systematics at edges

-- TPC selection has smaller systematics due to easier simulation of detector response + higher redundancy of detector.

-- in a detector operated with a trigger, the two selections are based on independent triggers.

(trigger efficiencies when all detectors are working are almost perfect)

-- BUT what about the common losses, due to the events in which both jets are lost in the low angle cones? (QCD fluctuations, presumably correlated between the two hemispheres)

FCC

something to understand further: flavour dependence of efficiency

Saveur des Quarks	$< E_{TPC} >$ (GeV)	$< N_{TPC} >$	Efficacité
quark u	50.89	17.78	$97.58 \pm 0.04\%$
quark d	48.93	17.43	$97.37 \pm 0.04\%$
quark s	49.21	16.87	$97.04 \pm 0.04\%$
quark c	50.28	18.76	$97.57 \pm 0.04\%$
quark b	49.30	20.13	$97.94 \pm 0.04\%$
Toutes	50.60	18.42	$97.488 \pm 0.016\%$

Tableau IV.4: Efficacité de sélection des événements hadroniques pour la TPC.

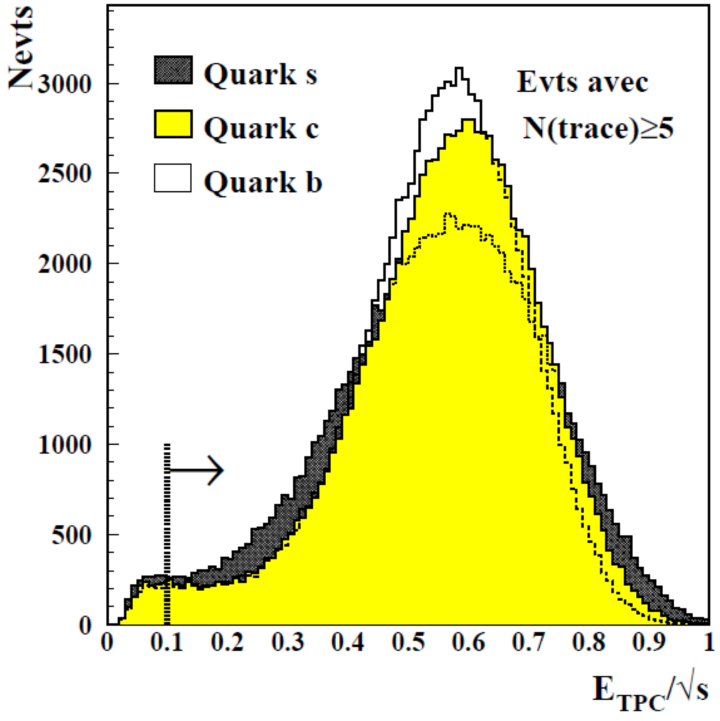


Figure IV.2.17: Effet de la coupure sur l'énergie sur des échantillons simulés $Z \to q\bar{q}$ pour différentes saveurs

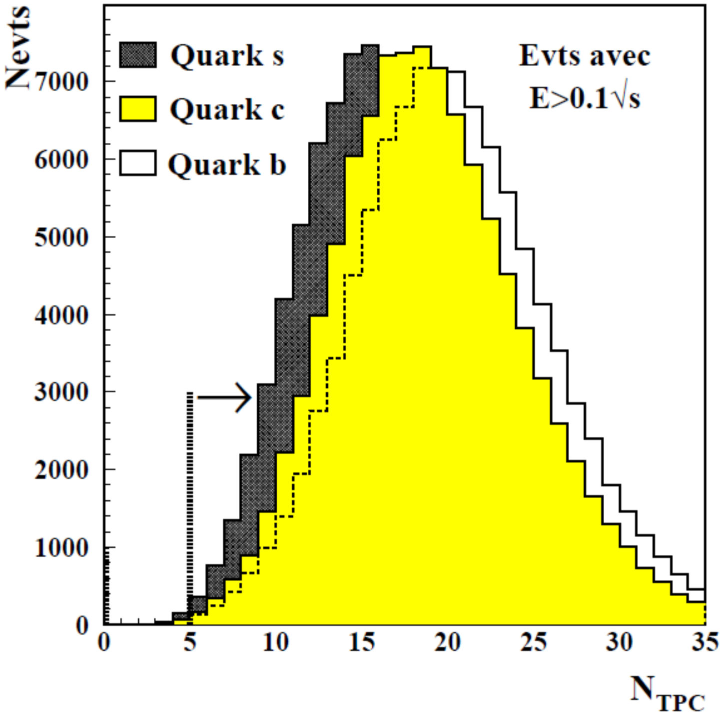
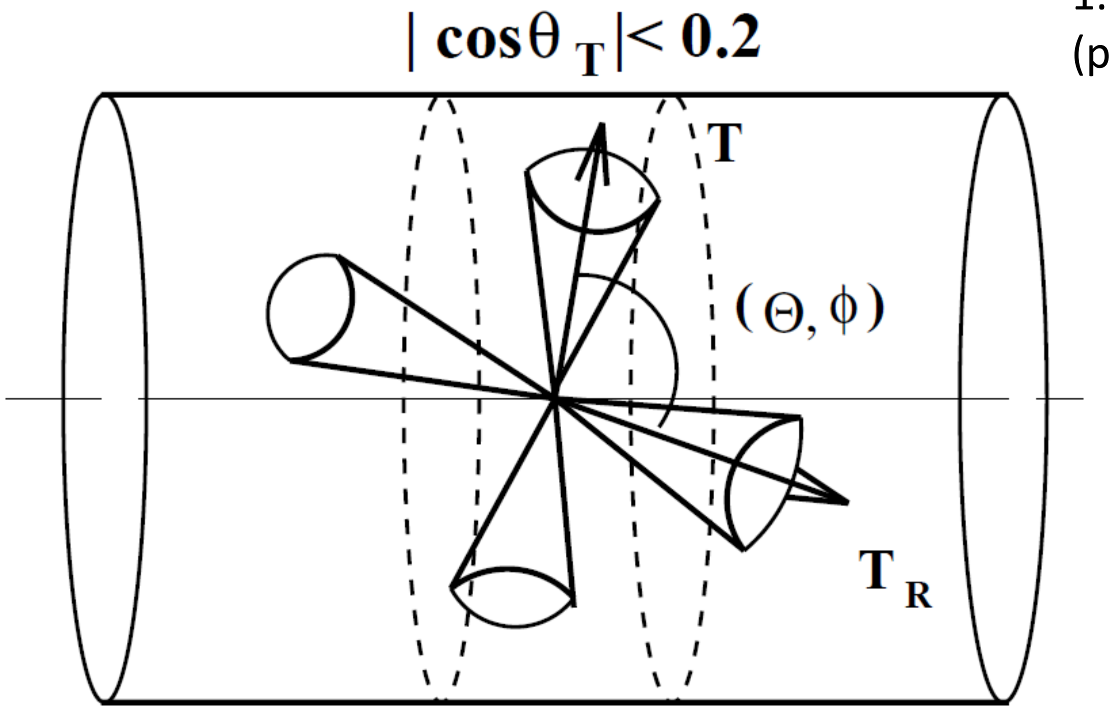


Figure IV.2.18: Effet de la coupure sur la mutliplicité sur des échantillons simulés $Z \to q\bar{q}$ pour différentes saveurs

to which extend can these differences be trusted?

➔ should study wrt calorimetric efficiency

Calculation of the selection efficiency **using data** (in ALEPH, used for TPC selection) or **how to beat the stats**



0. assume(verify) that hadronization is independent of polar angle

1. consider an extremely pure sample of events
(purity is 99.95 ±0.003 % contaminated by 0.05% of tau pairs)

$$\frac{E_{TPC}}{\sqrt{s}} > 0.1$$

$$N_{TPC} \geq 5$$

$$et \quad |cos\theta_T| < 0.2$$

T = thrust axis

2. **Rotate these events around the detector**
   with a 1+ $\cos^2\theta$ distribution
   calculate the resulting detection efficiency $\varepsilon^{data,rot}$

3. do the same with the full monte-carlo events

4. evaluate the precision of the method in MC $\varepsilon^{MC,rot}$

5. compare $\varepsilon^{data,rot}$ $\varepsilon^{MC,rot}$ and $\varepsilon^{MC,true}$ and conclude

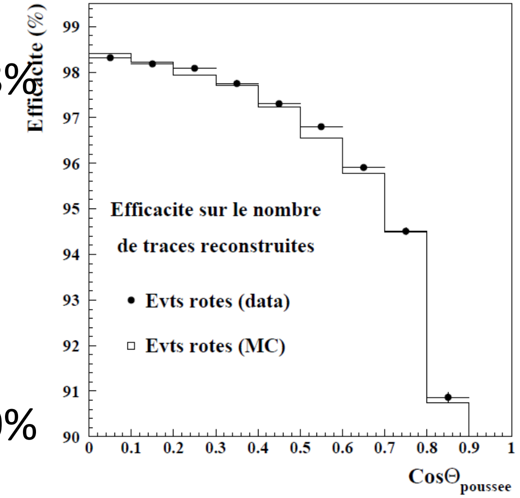


Figure IV.4.40: Nombre de traces reconstruites après rotation sur le nombre de traces initial en fonction du cosinus de l'angle de l'axe de poussée de l'événement, pour les données et la simulation.

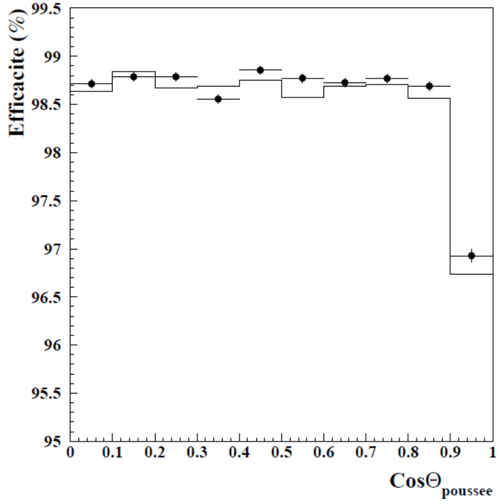


Figure IV.4.41: Efficacité de sélection après rotation en fonction du cosinus de l'angle de l'axe de poussée de l'événement pour les données et la simulation.

note that the statistical errors of the method are smaller than that given by the number of events (and could have been even much smaller)

Années	Données	Simulation	Différence	Systématique
1990	$97.73 \pm 0.05\%$	$97.80 \pm 0.05\%$	$0.07 \pm 0.07\%$	0.10%
1991	$97.71 \pm 0.04\%$	$97.84 \pm 0.04\%$	$0.13 \pm 0.06\%$	0.14%
1992	$97.73 \pm 0.03\%$	$97.778 \pm 0.03\%$	$0.05 \pm 0.04\%$	0.06%
1993	$97.73 \pm 0.03\%$	$97.78 \pm 0.02\%$	$0.05 \pm 0.03\%$	0.06%
1994	$97.72 \pm 0.03\%$	$97.78 \pm 0.02\%^*$	$0.06 \pm 0.03\%$	0.07%
1995	$97.72 \pm 0.03\%$	$97.78 \pm 0.02\%^*$	$0.06 \pm 0.03\%$	0.07%

Tableau IV.13: Erreurs systématiques associées à la modélisation de l'hadronisation pour les années de 1993 à 1995 pour les événements au pic du Z.($*$: résultats obtenus avec le Monte Carlo 1993).

a number of other tests to be performed and ways to assign systematics

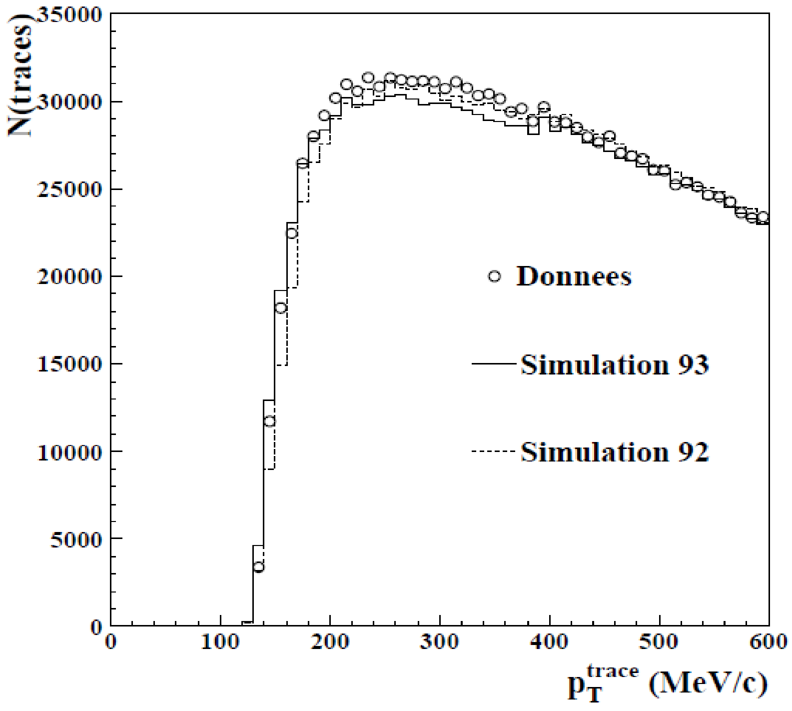


Figure IV.4.46: Spectre d'impulsion transverse des traces chargées pour les valeurs $p_T < 600$ MeV/c pour les Monte Carlo 92 et 93. Les données y sont superposées.

For the tracking system, a critical issue is the reconstruction of low transverse momentum (not always so low momentum) tracks, where the number of detector points is difficult to simulate

Note that 4 TPC hits was equivalent to a ~200 MeV/c P_t cut.

more generally the low angle cut is critical.

Another point to improve : non-resonant (NR) background

In ALEPH it was obtained from a study of the energy dependence of the low visible energy events. The two photon process is not so well known (it is similar in many ways to a low E hadronic cross-section, as e.g. in neutrino interactions)

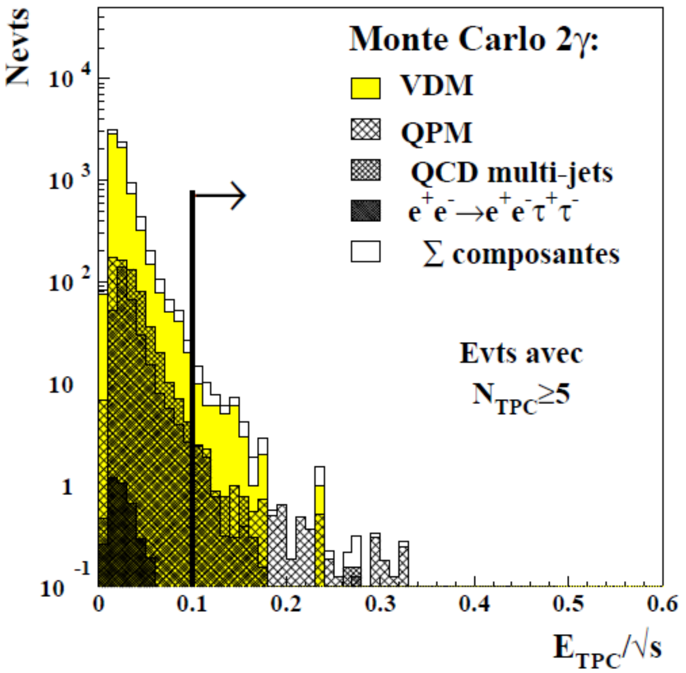
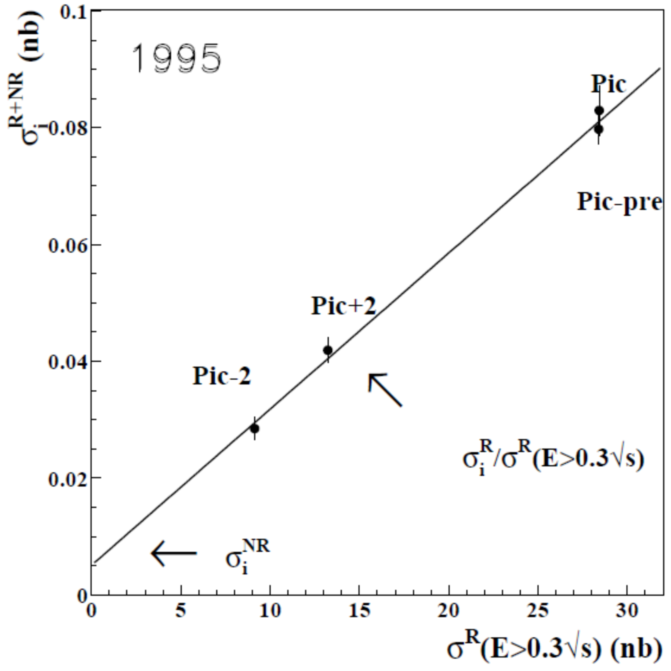


Figure IV.3.23: Distribution de l'énergie totale chargée d'événements 2γ simulés. La coupure est indiquée par une flèche.



the residual NR part is estimated rom a fit to the E_{TPC}/Ecm situated btw 10 and 30% to the sum of resonant and non-resonant parts. Per se it is statistically limited (except that at some point the non-resonant is not be Energy independent or even linearly!)

Definitely the situation should be improved by better modeling of these NR processes, with lower angle acceptance, etc.

Hadronic selection for total cross-sections at FCC

Target : precision on event count at ~10^{-6} level

NEW no trigger -- but still need flag that all detectors are working!

NEW pile up with 70kHz of Z→ hadron rate one has to worry about pile up of 2. 10^{-3}

-- separate vertices within luminous region in x,z,t ? *→

-- cut or do not cut?

NEW much better detectors but **keep things simple!**

-- lower limit of acceptance (O(110mrad =7°) cos(7°) = 0.993 -- fantastic! *(too small a hole for a jet)*

hadonic event efficiency should be very very close to 100%

-- consider that collisions are not head on, both transverse and longitudinal boosts

-- tracks only /calorimeter only/ full energy flow selection?

full energy flow has probably better performance, but assessment of detector effects should be evaluated

➔ suggest to keep "tracks only" as back-up/cross-check and tool for systematics.

NEW Issues to be addressed :

-- non resonant background (two-photon) → must be simulated, eliminated/subtracted at desired level of precision

-- flavor dependence of selection (probably easier with better closure of acceptance)

-- tau pair background contribution: no problem for width or mass, serious issue for $\mathbf{R_\ell}$ and peak cross-section

Luminous region 'vertex size' in x,y,z,t for various ECM points at FCC-ee

Ebeam (GeV)	45.6	80	120	175	182.5
σ_x (μm)	6.4	13.0	13.7	36.6	38.2
σ_y (nm)	28.3	41.2	36.1	65.7	68.1
σ_z (mm)	12.1	6.0	5.3	2.62	2.54
Vtx σ_x(μm)	**4.5**	9.2	9.7	25.9	27.0
Vtx σ_y(μm)	0.02	29.2	25.5	46.5	48.2
Vtx σ_z(μm)	**300**	0.60	0.64	1.26	1.27
Vtx σ_t (ps)	**30**	14.1	12.5	6.2	6.0

precision of vertex reconstruction in x,z,t : O(2μm, 2μm, 3ps)

Courtesy of Emmanuel Perez
https://github.com/HEP-FCC/FCCeePhysicsPerformance/tree/master/General#vertex-distribution

Hadronic selection for total cross-sections at FCC (II)

Target : precision on event count at ~10^{-6} level looks daunting but statistics is huge and Z peak conditions are ideal

Detector performance is paramount for this precision and probably the most demanding

-- **track reconstruction efficiency** (was 99.9% with ALEPH TPC) ... what of drift chamber or silicon tracker?
- -- to which precision do we need to know it?
- -- how can it be measured
- -- down to which angle is track reconstruction of sufficient quality?
- -- down to which momentum? how important is it to achieve 200 MeV transverse momentum?

-- **reliability of reconstruction of energy flow objects** (or total energy going into calorimeters)?
- -- same questions as above

-- Evaluation of detection efficiency systematics
- --- using event rotation
- --- and other tricks data/MC comparison etc...

-- NB a priori no need of ‘jet’ reconstruction – only ‘thrust axis‘ and the two hemispheres of a hadronic Z decay

Hadronic event selection is the workhorse of a large variety of analyses -- it must be fully inclusinve !

Leptonic event selection

-- statistics 1.7 10^{11} events in each channel ➔ 5 10^{11} leptonic events provide $1/\sqrt{N} = 1.4\ 10^{-6}$

Paradoxically leptonic event selection is much more prone to systematics than the hadronic selection
The main reason is that it is much easier to lose one track than a whole jet.

For instance if two tracks are required the loss of efficiency is twice the track reconstruction inefficiency $\varepsilon(\theta)$

➔ selection might start with single track selection, second track to be used to ensure both

-- high efficiency
-- measurement of efficiency (2 tracks vs 1 track)

Also low angle definition is essential, as it is not compensated by the wider 'jet' structure

Typical dilepton selection

-- define a inclusive dilepton selection (goal to measure number of leptons pairs with highest precision)

-- within this sample evaluate ee/ mumu/ tautau fractions

-- e/mu/tau separation requires **dedicated tau analysis**

-- ee channel comprises both Z decays, t-channel (Bhabha scattering, non resonant) and their interference required **dedicated treatment of e+e- channel**

must impose a low angle limit of selection (necessary because of low angle bhabha scattering)

sensitivity to low angle cut

-- a cut such as $|\cos\theta|<0.95$ has a typical efficiency of 0.9 for a process with angular distribution $(1 + \cos^2\theta)$

-- what is the precision required on this angle to ensure a overall precision matched with the statistical precision?

-- this cut is correlated between channels and must be considered globally.

-- as for luminosity measurement one could consider a tight-lose method (switch on event by event basis) requirement applies to tight cut.

Answer: at an angle of 20 degrees, a 2mrad change of polar angle → 10^{-3} change of acceptance.

a precision of 1.4 10^{-6} will require a (hardware or alignment) with precision of 3 μrad (i.e. 6 microns at 2m)

For an angle of 10 degrees the precision required is relaxed by 2 – 6 μrad or 12 microns at 2m

This question is synergetic with the luminosity measurement from e+e- → $\gamma\gamma$ events

Conclusions on Z hadronic and leptonic event selections

Cornerstones of precision measurements these selections are also the workhorse of a large variety of analyses
-- not very sophisticated from the side of analysis, but demanding on detector design/construction/alignment and understanding of analysis – detector relationship

A lot to learn (tricks) and improve from LEP analyses.

Much better detectors should lead to great improvements in efficiency and precision (Energy flow)

New issues have been identified for FCCee:

-- no trigger, but pile-up!
-- much better detector should lead to better performance/precision
-- non resonant background
-- flavour dependence of selection
-- tau pairs both in hadronic and leptonic selections
-- leptonic selection is probably the most demanding on the hardware construction of the endcaps.

Great physics payoff and great opportunity to be clever for detector design/construction/alignment/analysis