T.A.P.A.S. at Giga-Z

a **T**errific **A**ccuracy **P**rediction on **A**lpha **S**trong

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OUTLINE

- Introductory remarks :
  - Why remeasuring α_s ?
  - Sensitivity of Z parameters to $\alpha_\mathrm{s}(M_\mathrm{Z})$
- Achievements of A.D.L.O. :
  - Precision achieved
  - Discussion on sources of uncertainty
- Precision forecasts at Giga-Z :
  - Discussion on uncertainty reduction
  - Precision achievable in various scenarios
- Summary

Reminder

- Why (re)measuring $\alpha_s(M_Z)$?
  - Refine tests of non-Abelian structure of QCD
    - Refine SM predictions to extract SM unknowns : e.g. m$_t$ at $t\bar{t}$ threshold
      - Refine SM predictions to study its limits : e.g. evolution of α_1, α_2, α_3 $\rightarrowtail$ GUT
        - Refine predictions of new theoretical models

- Advantages of the measurement based on the Z-parameters :
  - Inclusive final state $\rightarrowtail$ rigorous QCD handling (how rigorous ?)
    - Knowledge of SM free parameters (e.g. M$_H$) will improve at required accuracy
      - Extended experience from LEP analyses $\rightarrowtail$ 2nd generation measurement at ILC

- Advantages of Giga-Z :
  - 100 times more events than at LEP-1 $\rightarrowtail$ 10 times smaller Δ_{stat} and $>$ 3–5 times smaller Δ_{syst}
    - Outstanding apparatus : accuracy and hermeticity

Sensitivity of Z Parameters to $\alpha_s(M_Z)$

- $\Gamma_h = \Gamma_h^0 \cdot (1 + \delta_{QCD})$ **with** $\delta_{QCD} \approx 1.06\,\frac{\alpha_s}{\pi} + 0.9\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3 + \ldots$

  $\hookrightarrow$ **1st term dominates and amounts typically to 4 % for $\alpha_s(M_Z) \sim$ 0.12**

- $R_l = \Gamma_h/\Gamma_l \rightarrowtail$ **QCD corr. $\sim$ 4 %**

- $\Gamma_Z = \Gamma_Z^0 + \Gamma_h^0 \cdot \delta_{QCD} \approx \Gamma_Z^0 \cdot (1 + 0.7 \cdot \delta_{QCD}) \rightarrowtail$ **QCD corr. $\sim$ 2.8 %**

- $\sigma_0^l = \frac{12\pi\Gamma_l^2}{M_Z^2\Gamma_Z^2} \approx \frac{12\pi\Gamma_l^2}{M_Z^2\Gamma_Z^{0\,2}} \cdot \frac{1}{(1+0.7\cdot\delta_{QCD})^2} \approx \sigma_0^{l\,0} \cdot (1 - 1.4 \cdot \delta_{QCD}) \rightarrowtail$ **QCD corr. $\sim$ 5.5 – 6 %**

- $\sigma_0^h = \frac{12\pi\Gamma_l\Gamma_h}{M_Z^2\Gamma_Z^2} \approx \frac{12\pi\Gamma_l\Gamma_h^0}{M_Z^2\Gamma_Z^{0\,2}} \cdot \frac{1+\delta_{QCD}}{(1+0.7\cdot\delta_{QCD})^2} \approx \sigma_0^{h\,0} \cdot (1 - 0.4 \cdot \delta_{QCD}) \rightarrowtail$ **QCD corr. $\sim$ 1.5 %**

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\begin{aligned}
R_l :&\quad \Delta\alpha_s(M_Z) &\approx&\quad 3.1 \cdot \Delta R_l/R_l \\
\sigma_0^l :&\quad \Delta\alpha_s(M_Z) &\approx&\quad 2.2 \cdot \Delta\sigma_0^l/\sigma_0^l \\
\sigma_0^h :&\quad \Delta\alpha_s(M_Z) &\approx&\quad 7.4 \cdot \Delta\sigma_0^h/\sigma_0^h \\
\Gamma_Z :&\quad \Delta\alpha_s(M_Z) &\approx&\quad 4.4 \cdot \Delta\Gamma_Z/\Gamma_Z
\end{aligned}
$$

LEP Measurements

- A.D.L.O. extracted the experimental values of R_l, σ_0^l, σ_0^h and Γ_Z essentially from multi-hadron, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states

- Measurement accuracies of different experiments differ substantially :

$\frac{\Delta\epsilon_h}{\epsilon_h} \oplus \frac{\Delta bg_h}{bg_h}$	$\frac{\Delta\epsilon_\mu}{\epsilon_\mu} \oplus \frac{\Delta bg_\mu}{bg_\mu}$	$\frac{\Delta\epsilon_\tau}{\epsilon_\tau} \oplus \frac{\Delta bg_\tau}{bg_\tau}$	$\frac{\Delta L_{syst}^{exp}}{L}$	$\frac{\Delta L_{syst}^{theo}}{L}$
0.04 – 0.10 %	0.09 – 0.31 %	0.18 – 0.65 %	0.033 – 0.09 %	0.054 %

- Most accurate measurements :
  - Hadronic final state selection : L3 most accurate
    - Lepton-pair final state selection : ALEPH most accurate
      - Luminosity determination (Bhabha events) : OPAL most accurate

Quark-Pair Selection of L3

- Syst. uncertainties of the quark-pair selection entering the hadronic x-section determination (1994 data)

source of uncertainty	relative uncertainty [%]
Acceptance	0.021
Selection cuts	0.030
Trigger efficiency	0.012
Non-resonant background	0.010
Monte-Carlo statistics	0.004
Total	0.040

- Some dominant acceptance uncertainty components :
  - Geometrical acceptance control ($\gtrsim$ 0.5 % events inside forward aperture)
    - Fragmentation uncertainties $\longrightarrow$ low charged multiplicity final states at shallow angle
      - Radiative return : resonant spectrum modeling
- Major contributions to Δ_{syst} on selection cuts :
  - Cut variations around nominal cut value
  - Background subtraction (accuracy of modeling)

$\Rrightarrow$ IMPROVEMENTS PROVIDED BY ILC :

better hermiticity, rad. return & QCD modeling (stat.), background control, higher stat. for cut variations, etc.

Lepton-Pair Preselection of ALEPH

- Syst. uncertainties of the $\mu^+\mu^-$ & $\tau^+\tau^-$ preselection entering the x-section determination (1994 data)

source of relative uncertainty [%]	$\mu^+\mu^-$	$\tau^+\tau^-$
TPC tracking	0.03	0.03
$cos\theta*$	0.01	0.01
ISR/FSR simulation	0.03	0.03
total acceptance	0.04	0.04
Monte-Carlo statistics	0.06	0.07

- Main sources underlying systematic uncertainties :
  - **tracking inefficiencies $\longrightarrow$ estimated from MC / data comparison**
    - **mismeasured angles (prod. angle, acol.) $\longrightarrow$ TPC end-plates positions (toy MC to simul. the effect)**
      - **ambiguities in $l^+l^-q\overline{q}$ final states (limited understanding of 4-fermion final states)**
        - **important contribution from Monte-Carlo statistics**

$\mu^+\mu^-$-Pair Selection of ALEPH

- Syst. uncertainties of the $\mu^+\mu^-$ & selection entering the x-section determination (1994 data)

source	$\Delta\sigma/\sigma$ [%]
acceptance	0.04–0.05
momentum calibration	0.006
momentum resolution	0.005
photon energy	0.05
radiative events	0.05
muon identification	$\approx$ 0.001
Monte-Carlo statistics	0.06
TOTAL	0.09 ($\sim$ 5 X Δ_{stat})

- Dominant contributions :
  - Photon energy : adjust simulated photon energy of $\mu^+\mu^-\gamma$ events to observed distribution
  - Radiative events : difference between cross-sections computed with tight and loose cuts
  - Important contribution from Monte-Carlo statistics

⇛ IMPROVEMENTS PROVIDED BY ILC :

better hermiticity, calorimetry and tracking, radiative events modeling (stat., less material),

4-lepton understanding, higher stat. for cut variations, etc.

· · · Similar remarks apply to $\tau^+\tau^-$ selection

Potential of a Virtual LEP Detector at Giga-Z

- Potential of a virtual LEP detector combining quark-pair selection of L3, lepton-pair selection of ALEPH and luminosity determination of OPAL, running one year at Giga-Z

uncertainty	Δ_{syst} [%]	Δ_{stat} [%]
$\Delta q\bar{q}$	0.040	0.003
$\Delta\mu^+\mu^-$	0.090	0.015
$\Delta\tau^+\tau^-$	0.170	0.015
ΔL_{exp}	0.033	0.002
ΔL_{theo}	0.054	–

observable	relative uncertainty [%]	$\Delta\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$
$\mathrm{R_l}$	0.09	0.0027
Γ_{Z}	0.04	$<$ 0.002
σ_0^h	0.07	0.0055
σ_0^l	0.10	0.0022

- Accuracy achievable on $\alpha_{\mathrm{s}}(M_{\mathrm{Z}})$: $\pm$ **0.0013**
  - **to be compared to present accuracy : $\pm$ 0.0027**

Improvements on Fermion-Pair Selection Expected at ILC

IMPROVEMENTS ON QUARK-PAIR SELECTION :

- **More hermetic detector**
- **Larger statistics :**
  - ⟼ **more accurate Monte-Carlo simulation**
  - ⟼ **smaller systematic uncertainty coming from cut variations**
- **More realistic generators for signal selection and background determination**

IMPROVEMENTS ON LEPTON-PAIR SELECTION :

- **Better controlled tracking efficiency (larger stat., better track finding due to lighter and more hermetic detector)**
- **Improved simulation of ISR-FSR interference (direct study)**
- **Better understanding of radiative events (improved generators, reduced detector material, high resolution tracking & calorimetry)**

Potential of the ILC Detector at Giga-Z

- 3–5 times smaller experimental (& modeling) syst. uncertainties running one year at Giga-Z

$\Delta^{q\bar{q}}_{stat}$ [%]	$\Delta^{q\bar{q}}_{syst}$ [%]	$\Delta^{l^+l^-}_{syst}$ [%]	$\Delta^{l^+l^-}_{stat}$ [%]	$\Delta R_l/R_l$ [%]	$\Delta\alpha_s(M_Z)$
0.003	0.04	0.08	0.011	0.09	0.0027
0.003	0.013	0.02	0.011	0.03	0.0008
0.003	0.009	0.015	0.011	0.02	0.0006

$\Delta^{l^+l^-}_{syst}$ [%]	$\Delta^{l^+l^-}_{stat}$ [%]	ΔL^{exp}_{syst} [%]	ΔL^{theo}_{syst} [%]	$\Delta\sigma^l_0/\sigma^l_0$ [%]	$\Delta\alpha_s(M_Z)$
0.08	0.011	0.033	0.054	0.10	0.0022
0.03	0.011	0.03	0.05	0.066	0.0014
0.02	0.011	0.02	0.03	0.043	0.0009

$\Delta^{q\bar{q}}_{stat}$ [%]	$\Delta^{q\bar{q}}_{syst}$ [%]	ΔL^{exp}_{syst} [%]	ΔL^{theo}_{syst} [%]	$\Delta\sigma^h_0/\sigma^h_0$ [%]	$\Delta\alpha_s(M_Z)$
0.003	0.04	0.033	0.054	0.075	0.0055
0.003	0.013	0.03	0.05	0.059	0.0044
0.003	0.009	0.02	0.03	0.037	0.0027

⇒ **Total uncertainty of combined value (including Γ_Z) : $\Delta\alpha_s(M_Z)$ = 0.0007-0.0005**

(depends on assumptions on Δ_{syst} reduction : factor 3 or 5)

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SUMMARY

- **Precision on $\alpha_s(M_Z)$ can be significantly improved at Giga-Z w.r.t. LEP-1 (factor $\sim$ 4–5) using the Z observables (R_l, σ^l, σ^h and Γ_Z) $\rightarrowtail$ $\Delta\alpha_s(M_Z)$ = 0.0007 – 0.0005**

- **Improvements originate from :**
  - **1) Statistics ($\sim$ 100 times more events) :**
    - **10 times less stat. uncertainty on sensitive observables**
    - **at least 3–5 times less syst. uncertainty on fermion-pair selection**
  - **2) Outstanding detector performances :**
    - **material budget**
    - **tracking**
    - **calorimetry**
    - **hermeticity**
  - **3) Steady improving theoretical calculations (H.O. corrections, SM input param.)**
  - **4) Steady improving signal and background generators (partly because of 1) and 2))**

- **Improvements profit mainly to R_l (luminosity determination expected to be limited by beamstrahlung and Γ_Z limited to LEP-1 accuracy)**

- **Study presented here should be repeated in more detail (MC, reconstruction, ...)**