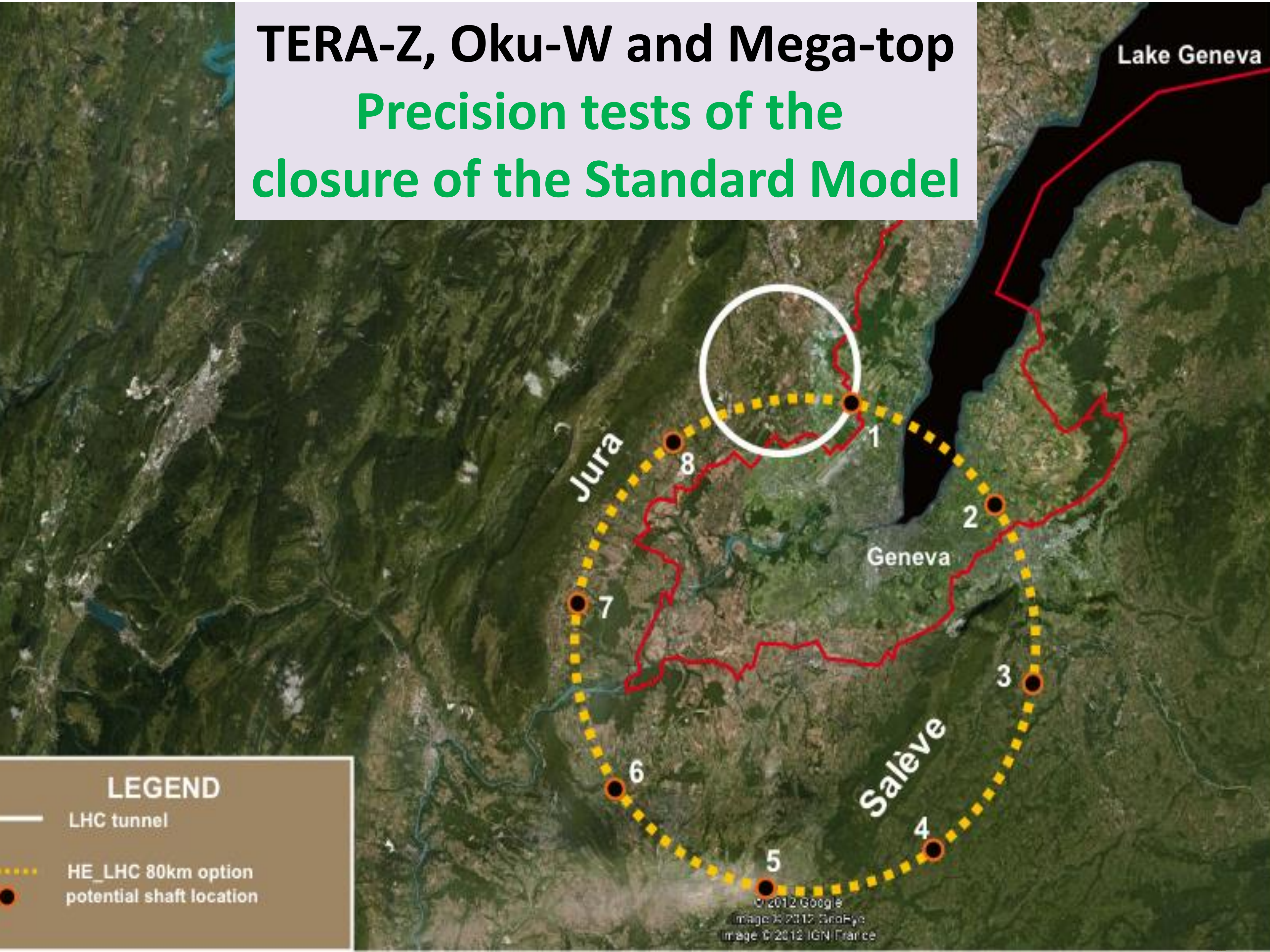
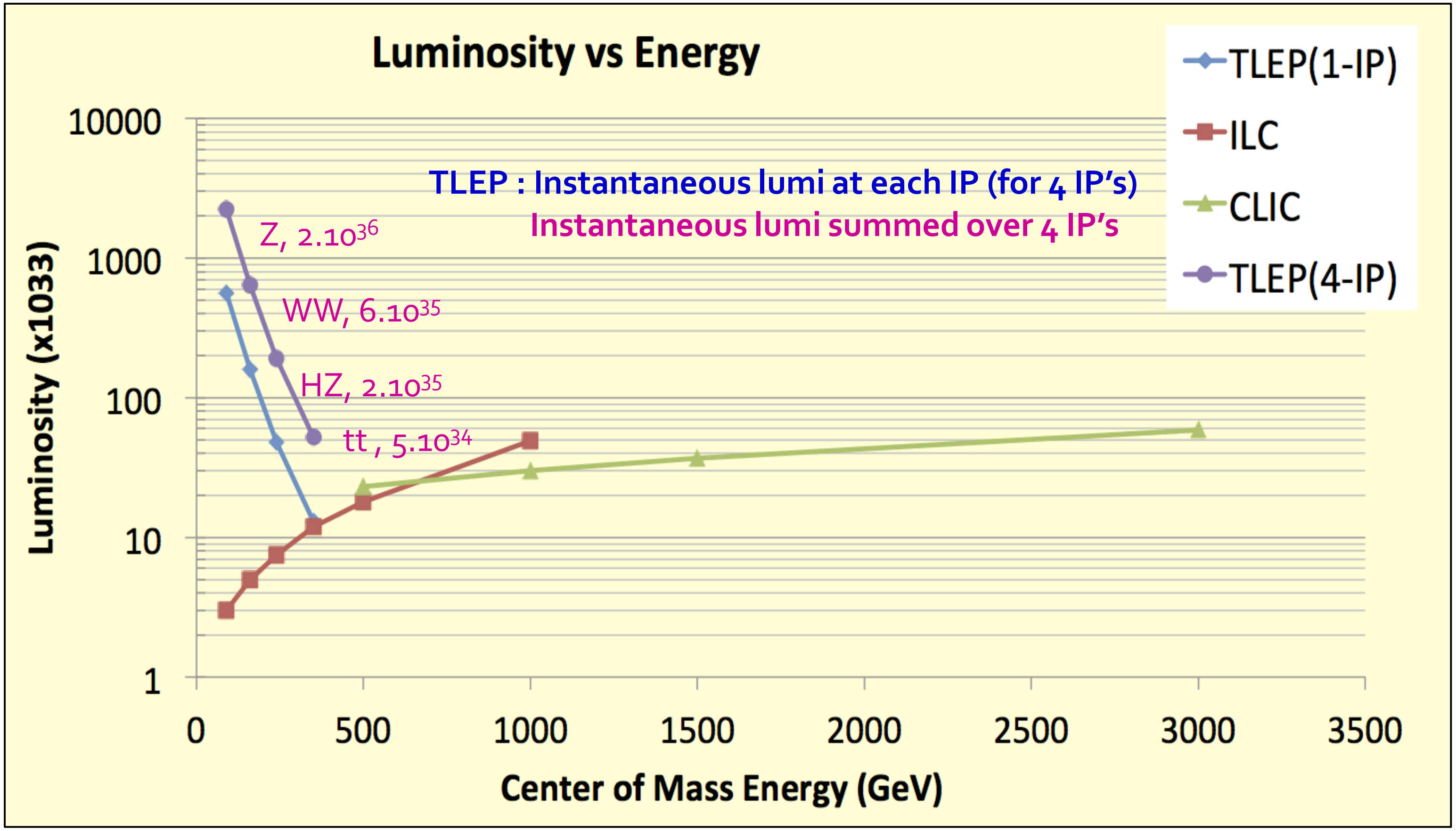
TERA-Z, Oku-W and Mega-top

Precision tests of the closure of the Standard Model



Performance of e+ e- colliders



- **Luminosity : Crossing point between circular and linear colliders ~ 4-500 GeV**

  As pointed out by H. Shopper in 'The Lord of the Rings' (Thanks to Superconducting RF…)

- **Circular colliders can have several IP's . Sum scales as $\sim(N_{IP})^{0.5-1}$**

  use 4 IP machine as more reliable predictions using LEP experience

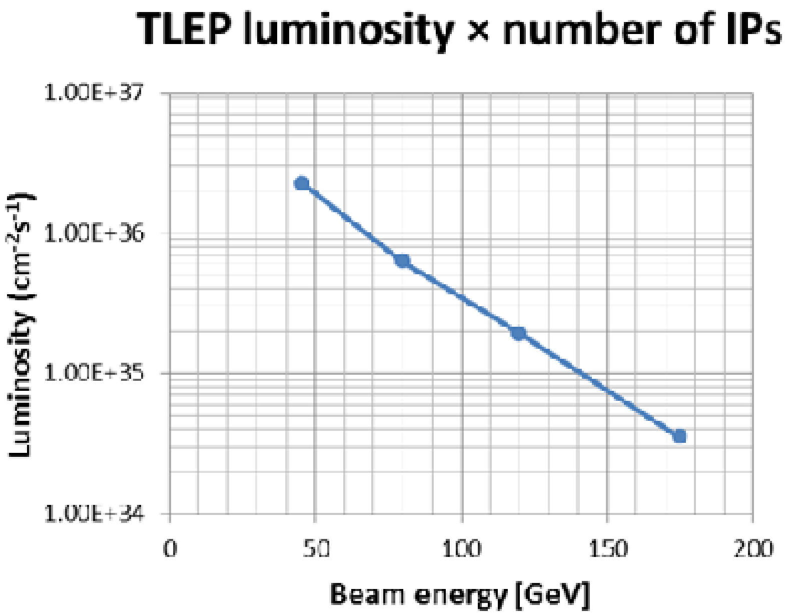
Table 1: TLEP parameters at different energies

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	45	80	120	175
circumf. [km]	80	80	80	80
beam current [mA]	1180	124	24.3	5.4
#bunches/beam	4400	600	80	12
#e−/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
$V_{RF,tot}$ [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$ /IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	67	25	16	20

TLEP: A HIGH-PERFORMANCE CIRCULAR e^+e^- COLLIDER TO STUDY THE HIGGS BOSON

M. Koratzinos, A.P. Blondel, U. Geneva, Switzerland; R. Aleksan, CEA/Saclay, France; O. Brunner, A. Butterworth, P. Janot, E. Jensen, J. Osborne, F. Zimmermann, CERN, Geneva, Switzerland; J. R. Ellis, King's College, London; M. Zanetti, MIT, Cambridge, USA.

http://arxiv.org/abs/1305.6498.



CONSISTENT SET OF PARAMETERS FOR TLEP TAKING INTO ACCOUNT BEAMSTRAHLUNG

TLEP: PARAMETERS & STATISTICS

($e^+e^- \to ZH$, $e^+e^- \to W^+W^-$, $e^+e^- \to Z$,[$e^+e^- \to t\bar{t}$])

	TLEP-4 IP, per IP	statistics
circumference	80 km	
max beam energy	175 GeV	
no. of IPs	4	
Luminosity/IP at 350 GeV c.m.	$1.3 \times 10^{34}\ cm^{-2}s^{-1}$	10 ILC
Luminosity/IP at 240 GeV c.m.	$4.8 \times 10^{34}\ cm^{-2}s^{-1}$	40 ILC
Luminosity/IP at 160 GeV c.m.	$1.6 \times 10^{35}\ cm^{-2}s^{-1}$	100 ILC
Luminosity/IP at 90 GeV c.m.	$5.6\ 10^{35}\ cm^{-2}s^{-1}$	1000 ILC

2.5

at the *Z* pole repeat the LEP physics programme in a few minutes…

A possible TLEP running programme

1. ZH threshold scan and 240 GeV running (200 GeV to 250 GeV)
   5+ years @2 10^35 /cm2/s => 210^6 ZH events
   ++ returns at Z peak with TLEP-H configuration
   for detector and beam energy calibration

Higgs boson HZ studies
+ WW, ZZ etc..

2. Top threshold scan and (350) GeV running
   5+ years @2 10^35 /cm2/s ➔ 10^6 ttbar pairs ++Zpeak

Top quark mass
Hvv Higgs boson studies

3. Z peak scan and peak running , TLEP-Z configuration ➔ 10^12 Z decays
   ➔ transverse polarization of 'single' bunches for precise E_beam calibration
   2 years

M_Z, Γ_Z R_b etc…
Precision tests and rare decays

4. WW threshold scan for W mass measurement and W pair studies
   1-2 years ➔ 10^8 W pairs ++Zpeak

M_W, and W properties etc…

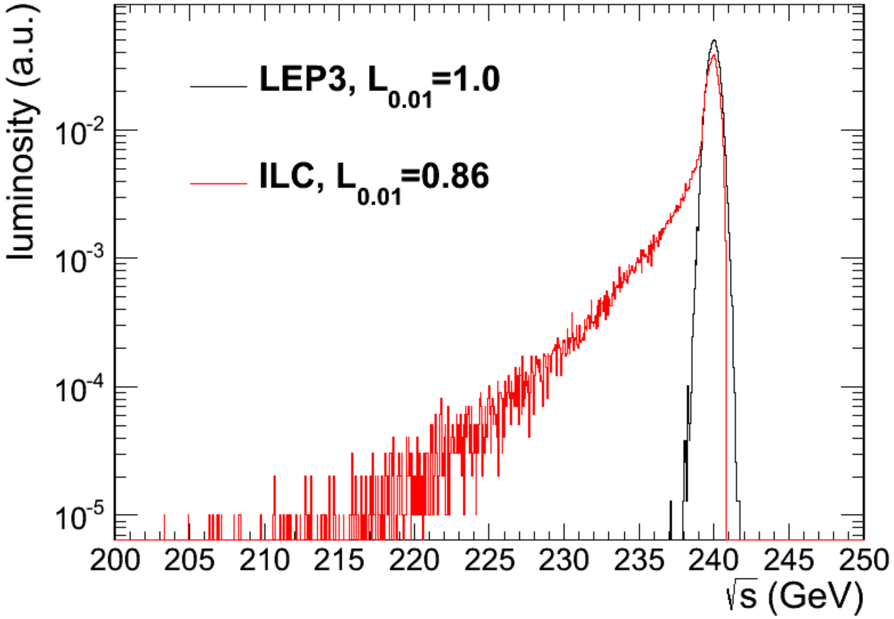
5. Polarized beams (spin rotators) at Z peak 1 year at BBTS=0.01/IP => 10^{11} Z decays.

A_{LR}, A_{FB}^{pol} etc

NB accelerator configuration possibly different for TLEP-Z , W vs TLEP-H and TLEP-t

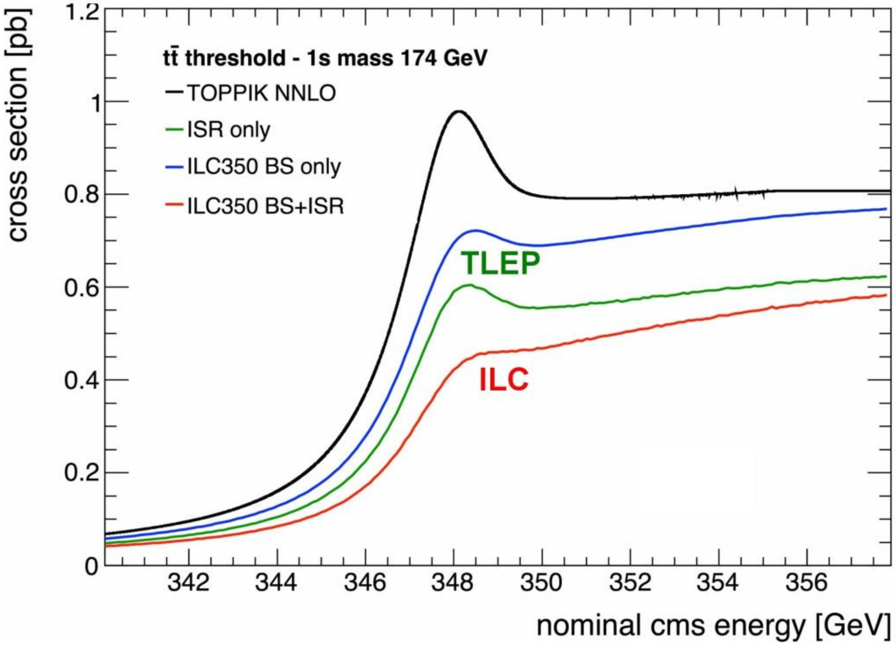
BEAMSTRAHLUNG

Luminosity *E* spectrum



➔

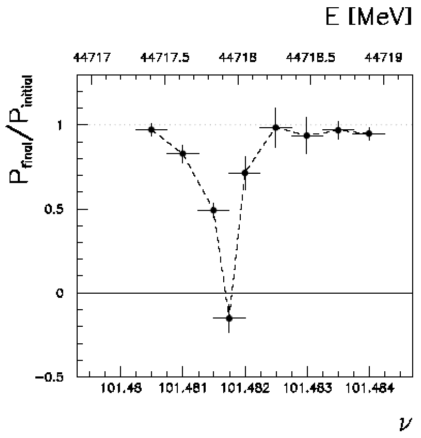
Effect on top threshold



Beamstrahlung @TLEP is benign: particles are either lost or recycled on a synchrotron oscillation

➔ some increase of energy spread
but no change of average energy
Little EM background in the experiment.

Beam polarization and E-calibration @ TLEP



Precise meast of E_{beam} by resonant depolarization
~100 keV each time the meast is made

At LEP transverse polarization was achieved routinely at Z peak.
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

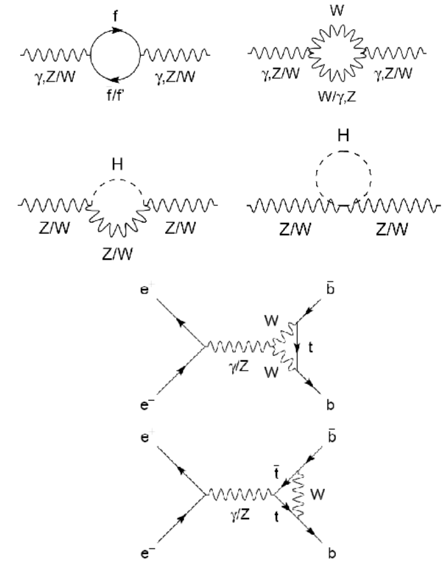
Polarization in collisions was observed *(40% at BBTS = 0.04)*

At LEP beam energy spread destroyed polarization above 60 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ *At TLEP transverse polarization up to at least 80 GeV*
to go to higher energies requires spin rotators and siberian snake

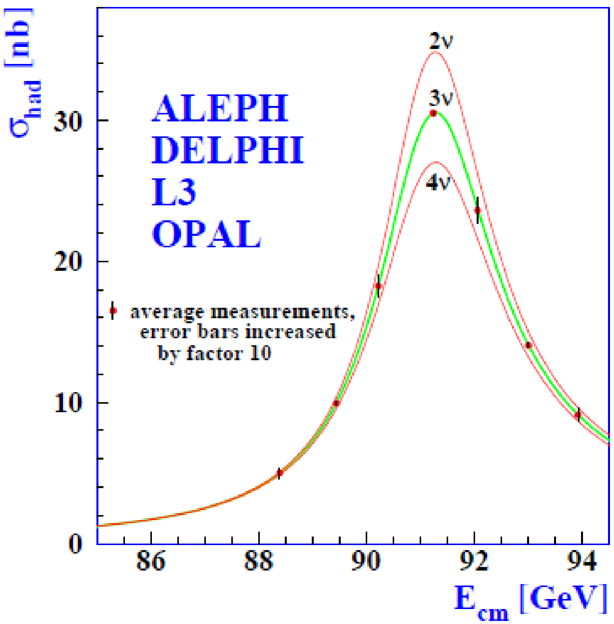
TLEP: use 'single' bunches to measure the beam energy continuously
no interpolation errors due to tides, ground motion or trains etc…

<< 100 keV beam energy calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

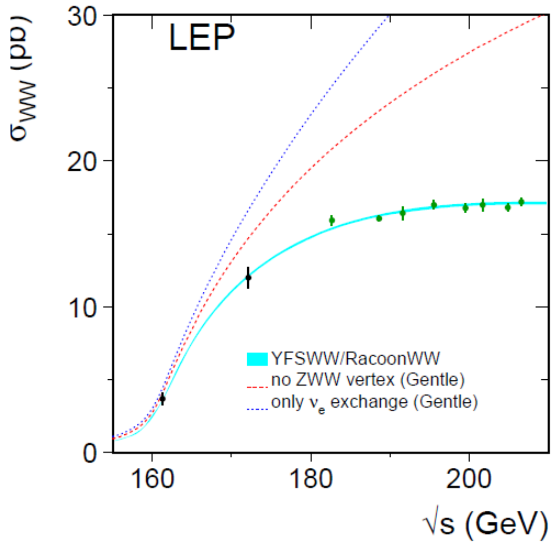
Precision measurements of EW observables

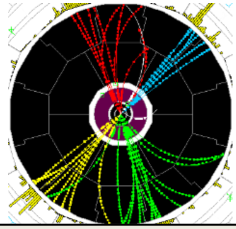


Z pole asymmetries, lineshape

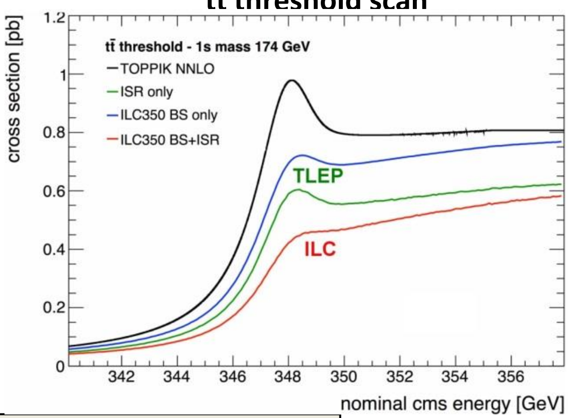


WW threshold scan





tt threshold scan



TLEP : Repeat the LEP1 physics programme every 15 mn

STATISTICS!

- Statistics, statistics: 10^{10} tau pairs, 10^{11} bb pairs, QCD and QED studies etc…

Transverse polarization up to the WW threshold

- Exquisite beam energy determination (100 keV each time) for M_Z Γ_Z M_W

Longitudinal polarization at the Z pole

- Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

EWRCs

$\Delta\rho$: $\equiv \varepsilon_1$ $\quad \Gamma_\ell = (1+\Delta\rho)\,\frac{G_F\, m_Z^3}{24\pi\sqrt{2}}\left(1+\left(\frac{g_{V\ell}}{g_{A\ell}}\right)^2\right)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$

ε_3 $\quad \sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\, m_Z^2}\;\frac{1}{1+\Delta\rho}\;\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$

δ_{vb} $\quad \Gamma_b = (1+\delta_{vb})\,\Gamma_d\left(1 - \text{mass corrections } \alpha\, m_b^2/M_Z^2\right)$

ε_2 $\quad M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F \sin^2\theta_W^{eff.}}\cdot\frac{1}{\ldots}$

$\sin^2\theta_W^{eff}$ is defined fr...

$\sin^2\theta^{eff}$ ... g_{Ae} ... $= \sin^2\theta_W{}^{eff}_{lept}$

...ed from asymmetries at the Z.

also $\quad \ldots = \frac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\;\frac{1}{(1-\Delta r)}$

Δr

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2$$

There is much more than M_W and $\sin^2\theta_W^{eff}$

relations to the well measured

$G_F \; m_Z \; \alpha_{QED}$

at first o...

... $(m_{top}/m_Z)^2$

... $\alpha/4\pi \log(m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_w\, \alpha/9\pi \log(m_h/m_Z)^2$

$\delta_{vb} = 20/13\; \alpha/\pi\; (m_{top}/m_Z)^2$

complete formulae at 2d order including strong corrections are available in fitting codes

e.g. ZFITTER , GFITTER

Will need to be improved for TLEP!

Example (from Langacker& Erler **PDG 2011**)

$\Delta\rho = \varepsilon_1 = \alpha(M_Z)\ .\ T$

$\varepsilon_3 = 4\sin^2\theta_W\ \alpha(M_Z)\ .\ S$

$\Delta\rho$ today = 0. 0004+0.0003−0.0004

-- is consistent with 0 at 1σ

-- is sensitive to non-conventional Higgs bosons (… ith 'funny v.e.v.s)

-- is sensitive to Isospin violation such as m …

$$\rho_0 = 1 + \frac{3\,G_F}{8 \ldots} \qquad (10.63)$$

where the sum includes fourt… …n doublets, $\binom{t'}{b'}$ or $\binom{E^0}{E^-}$, right-handed (mirror) doublets, non-d… …ermion doublets (with an extra factor of 2), and scalar doub… …ersymmetry (in the absence of L–R mixing).

There is no decoupling in $(m/\Lambda)^n$ for particles which do not respect the SM symmetries

Present m…

$$\sum_i \frac{C_i}{3}\Delta m_i^2 \le (52\ \mathrm{GeV})^2.$$

Most e.g. SUSYmodels have these symmetries embedded from the start (natural?)

Similarly:

$$S = \frac{C}{3\pi}\sum_i \left(t_{3L}(i) - t_{3R}(i)\right)^2,$$

Quantity	Physics	Present precision		TLEP Stat errors	Possible TLEP Syst. Errors	TLEP key	Challenge
M_Z (keV)	**Input**	91187500 ±2100	Z Line shape scan	5 keV	<100 keV	E_cal	QED corrections
Γ_Z (keV)	**$\Delta\rho$ (T)** (no $\Delta\alpha$!)	2495200 ±2300	Z Line shape scan	8 keV	<100 keV	E_cal	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.0001	<0.001	Statistics	QED corrections
N_ν	**PMNS Unitarity sterile ν's**	2.984 ±0.008	Z Peak	0.00008	<0.004		Bhabha scat.
N_ν	**PMNS Unitarity sterile ν's**	2.92 ±0.05	(γ+Z_inv) (γ+Z$\rightarrow \ell\ell$)	0.001 (161 GeV)	<0.001	Statistics	
R_b	δ_b	0.21629 ±0.00066	Z Peak	0.000003	<0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	**$\Delta\rho$, ε_3, $\Delta\alpha$ (T, S)**	0.1514 ±0.0022	Z peak, polarized	0.000015	<0.000015	4 bunch scheme, > 2exp	Design experiment
M_W MeV/c2	**$\Delta\rho$, ε_3, ε_2, $\Delta\alpha$ (T, S, U)**	80385 ± 15	Threshold (161 GeV)	0.3 MeV	<0.5 MeV	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	10 MeV	<10MeV	E_cal & Statistics	Theory interpretation 40 MeV?

Words of caution:

1. TLEP will have 5.10^4 more luminosity than LEP at the Z peak, 5.10^3 at the W pair threshold.
Predicting achievable accuracies with statistical errors decreasing by 250 is very difficult. The study is just beginning.

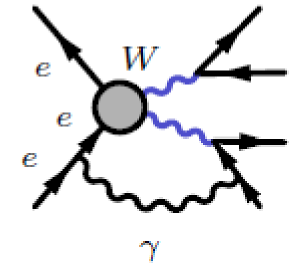
2. The following table are 'plausible' precisions based on my experience and knowledge of the present limitations, most of which from higher order QED corrections (ex. production of additional lepton pairs etc..).
Many can have experimental cross-checks and errors may get better.

3. The most serious issue is the luminosity measurement which relies on the calculations/modeling of the low angle Bhabha scattering cross-section.
This dominates the measurement of the hadronic cross section at the Z peak thus the determination of N_ν (test of the unitarity of the PMNS matrix)

4. The following is only a sample of possibilities. With 10^{12} Z decays, there are many, many more powerful studies to perform at TERA-Z
e.g. flavour physics with 10^{11} $b\bar{b}$, $c\bar{c}$, 10^{10} $\tau\tau$ etc…

W-O-W!

ΔM_W **= 0.5 MeV ?**



Future improvements of theory predictions?

Doable in principle:

- NNLO $\log\beta$, $\log(s/m_e^2)$ terms
- NNLO Coulomb corrections near threshold for distributions

Major effort, several years:

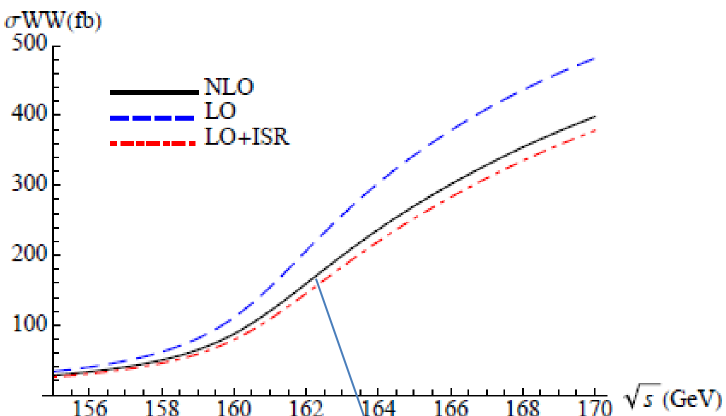
- NNLO EW corrections to on-shell $e^+e^- \to W^+W^-$

  (current frontier: first NNLO QCD $2 \to 2$ processes)

$\Rightarrow$ Input to full NNLO EFT calculation
Naive estimate for remaining uncertainty from cross-section calculation
$\Delta\sigma \sim \mathcal{O}(0.1‰)$, $\Delta M_W < 1$ MeV
ISR uncertainty?

Completely new methods needed:

- NNLO EW corrections to $e^+e^- \to 4f$



maximum sensitivity :
near threshold's inflexion point.

SUMMARY

Hans Kuehn
"Precision calculations for TLEP"

- theory predictions do not (yet?) fulfill TLEP requirements,
- missing corrections are presumably feasible (QCD),
- important experimental input from low-energy e^+e^- annihilation:

  $m_b, m_c, \Delta\alpha, (\alpha_s?)$, **(SuperKEKb, TLEP – guidance needed for $\Delta\alpha$)**
- m_b determiantion $\Rightarrow \Gamma(H \to bb)$

  usage of $m_b(pole)$ is strongly disfavoured compared to $m_b(10\text{ GeV})$

perspectives: (assume $\delta\alpha_s = 2 \times 10^{-4}$)

$\delta m_b(10\text{GeV})/m_b \sim 10^{-3}$ conceivable (dominated by $\delta\Gamma(\Upsilon \to e^+e^-)$)

$$\Rightarrow \frac{\delta\Gamma_b}{\Gamma_b} = \pm 2 \times 10^{-3}|_{m_b} \pm 1.3 \times 10^{-3}|_{\alpha_s,\text{running}} \pm 1 \times 10^{-3}|_{\text{theory}}$$

Aim at $\Delta\kappa_b$ ~ 0.4% at TLEP

The marvels of statistics

many tricks to explore:

- measure $m_b\,(Q^2)$ from $Z \rightarrow \bar{b}b\gamma$ etc...

- measure $\alpha_s\,(Q^2)$ from

i) $R_h = (\Gamma_{had}\ /\ \Gamma_{\ell\ell}\ )\_Z$

ii) $B_h = (\Gamma_{had}\ /\ \Gamma_{\ell\nu}\ )\_W$

iii) tau decays (spectral functions)

-- measure $\alpha_{QED}\,(Q^2)$ from e+e- → e+e- (t)

etc. etc... Not all will work.

-

NEUTRINO CONNECTIONS

The only known BSM physics at the particle physics level is the existence of neutrino masses

-- There is no unique solution for mass terms: Dirac only? Majorana only? Both?

-- if Both, the existence of (2 or 3) families of massive right-handed (sterile) N_i , $\bar{N}_i$ neutrinos is predicted («see-saw» models) but masses are unknown (eV to 10^{10}GeV)

-- mixing with active neutrinos leads to various observable consequences

-- if very light (eV) , possible effect on neutrino oscillations

-- if mixing in % or permil level, possibly measurable effects on

-- PMNS matrix unitarity violation and deficit in Z invisible width

-- occurrence of Higgs invisible decays $H \rightarrow \nu_i \bar{N}_i$

-- violation of unitarity and lepton universality in W or τ decays

-- etc etc..

-+- many more examples

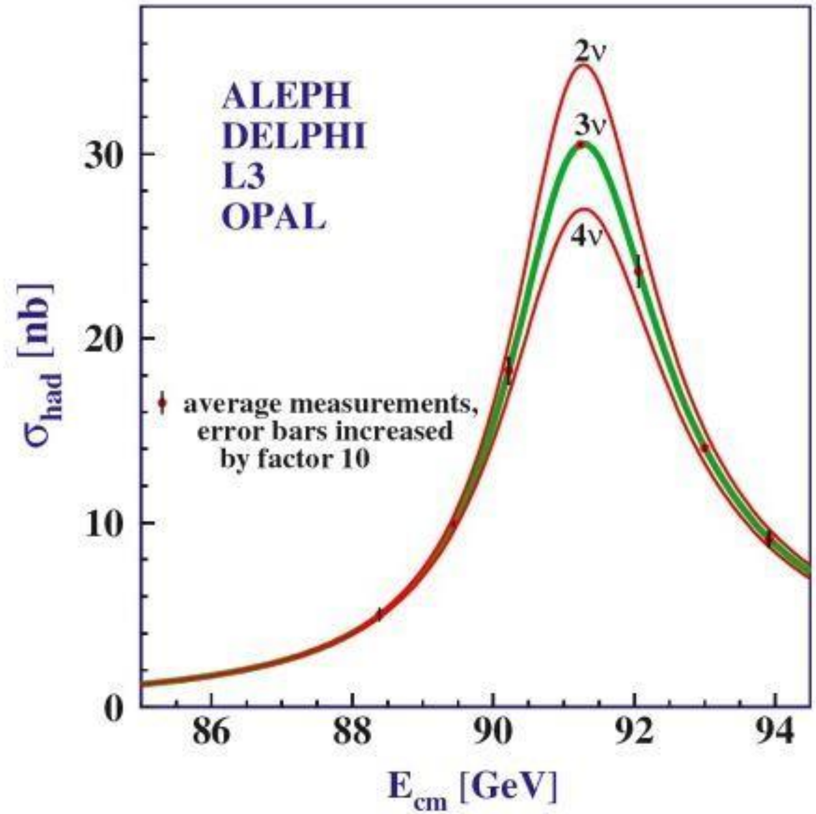
At the end of LEP:

Phys.Rept.427:257-454,2006

N_ν = 2.984 ±0.008

- 2 σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔



The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ±0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_v = \frac{\frac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\frac{\Gamma_\nu}{\Gamma e,\mu}\ (SM)}$$

The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of O(10^{12}) Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma e}\ (SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_\gamma| < 0.95$

161 GeV (10^7 s) running at $1.6\times10^{35}/cm^2/s$ x 4 exp ➔ 3×10^7 γ Z(inv) evts, $\Delta N_\nu = 0.0011$
adding 5 yrs data at 240 and 350 GeV .... $\Delta N_\nu = 0.0008$

A better point may be 105 GeV (20pb and higher luminosity) may allow $\Delta N_\nu = 0.0004$?

EXPERIMENTS ON BEAM-BEAM DEPOLARIZATION AT LEP

R. Assmann*, A. Blondel*, B. Dehning, A. Drees°, P. Grosse-Wiesmann, H. Grote, M. Placidi, R. Schmidt, F. Tecker†, J. Wenninger

PAC 1995

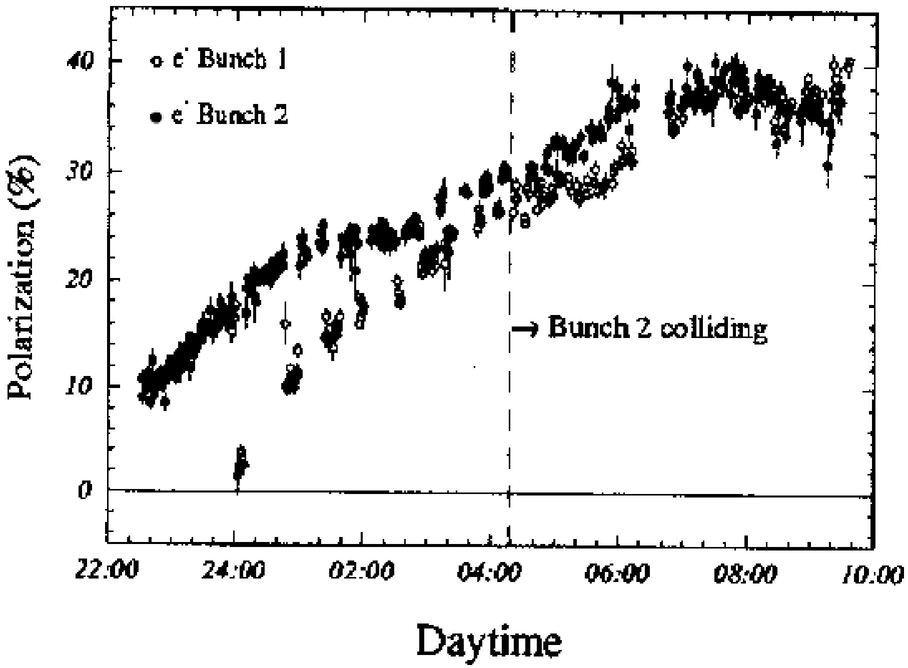


Figure. 3. Polarization level during third experiment

- With the beam colliding at one point, a polarization level of 40 % was achieved. The polarization level was about the same for one colliding and one non colliding bunch.
- It was observed that the polarization level depends critically on the synchrotron tune : when Q_s was changed by 0.005, the polarization strongly decreased.

experiment performed at an energy of 44.71 GeV the polarization level was 40 % with a linear beam-beam tune shift of about 0.04/IP. This indicates, that the beam-beam depolarization does not scale with the linear beam-beam tune shift at one crossing point. Other parameters as spin tune and synchrotron tune are also of importance.

This was only tried 3 times!
Best result: P = 40% , ξ^*_y= 0.04 , one IP
Assuming 4 IP and ξ^*_y= 0.01 ➔

reduce luminositiy somewhat, 10^{11} Z @ P=40%

Measurement of A_{LR}

electron bunches	$1\Leftarrow$	2	3	$4\Leftarrow$
positron bunches	1	$2\Rightarrow$	3	$4\Rightarrow$
cross sections	σ_1	σ_2	σ_3	σ_4
event numbers	N_1	N_2	N_3	N_4

$$\sigma_1 = \sigma_u (1 - P^-_e A_{LR})$$

$$\sigma_2 = \sigma_u (1 + P^+_e A_{LR})$$

$$\sigma_3 = \sigma_u$$

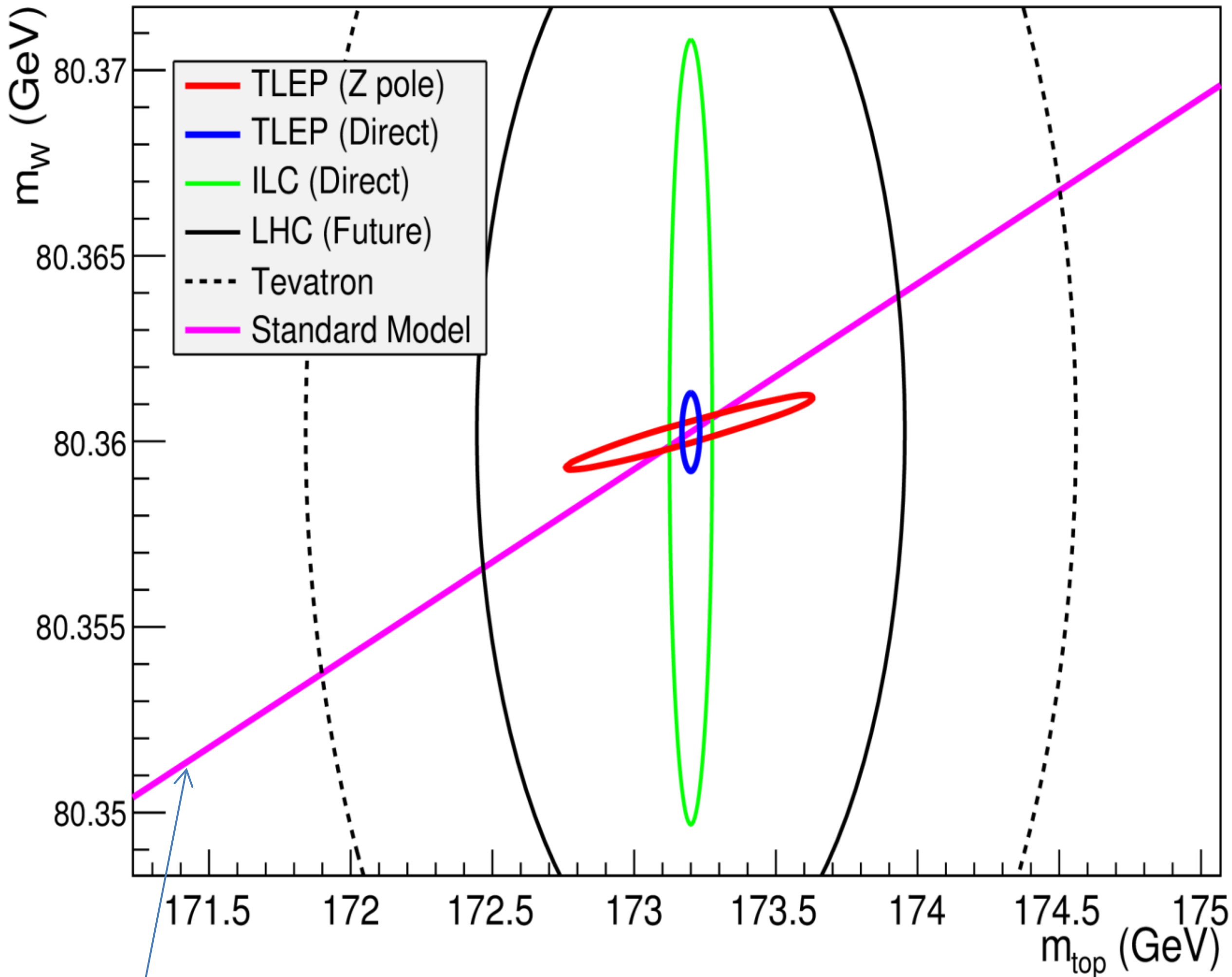
$$\sigma_4 = \sigma_u [1 - P^+_e P^-_e + (P^+_e - P^-_e) A_{LR}]$$

Verifies polarimeter with experimentally measured cross-section ratios

statistics $\Delta A_{LR} =$ 0.0025 with about 10^6 Z^0 events,

ΔA_{LR} = 0.000015 with 10^{11} Z and 40% polarization in collisions.

$\Delta \sin^2\theta_W^{eff}$ (stat) = O(2.10^{-6})



Janot

NB without TLEP the SM line would have a 2.2 MeV width

Conclusions

The search for the new phenomena
(required to e.g. explain dark matter or neutrino masses)

can go either to higher energies or smaller couplings.

With the mind-boggling statistics available, TLEP should be able to provide great sensitivity to new physics in an indirect, but global, way.

The statistics and experimental precisions need to be matched by corresponding improvements in theoretical calculations .. and smart ideas.

This is only a beginning!