Top quark physics and Electroweak measurements at the ILC

Roman Pöschl

... based on the work of many (!) people

ILD Meeting - Oshu City September 2014

The solid pillars of the LC phyics program

Top quark

Discovered 1995 at Tevatron

LHC and ILC are/would be
Top factories

W Boson

Discovered 1979 at SPS

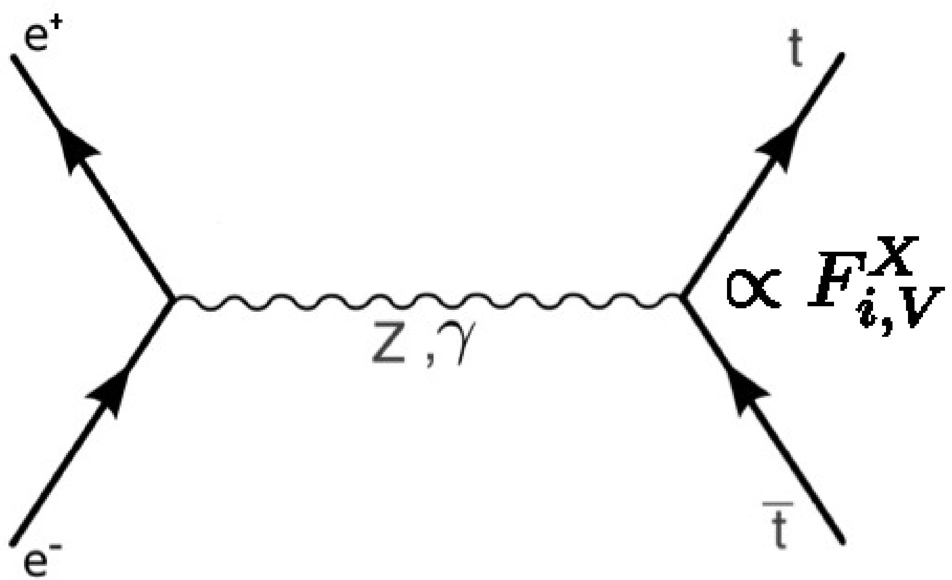
LHC and ILC are/would be
W factories

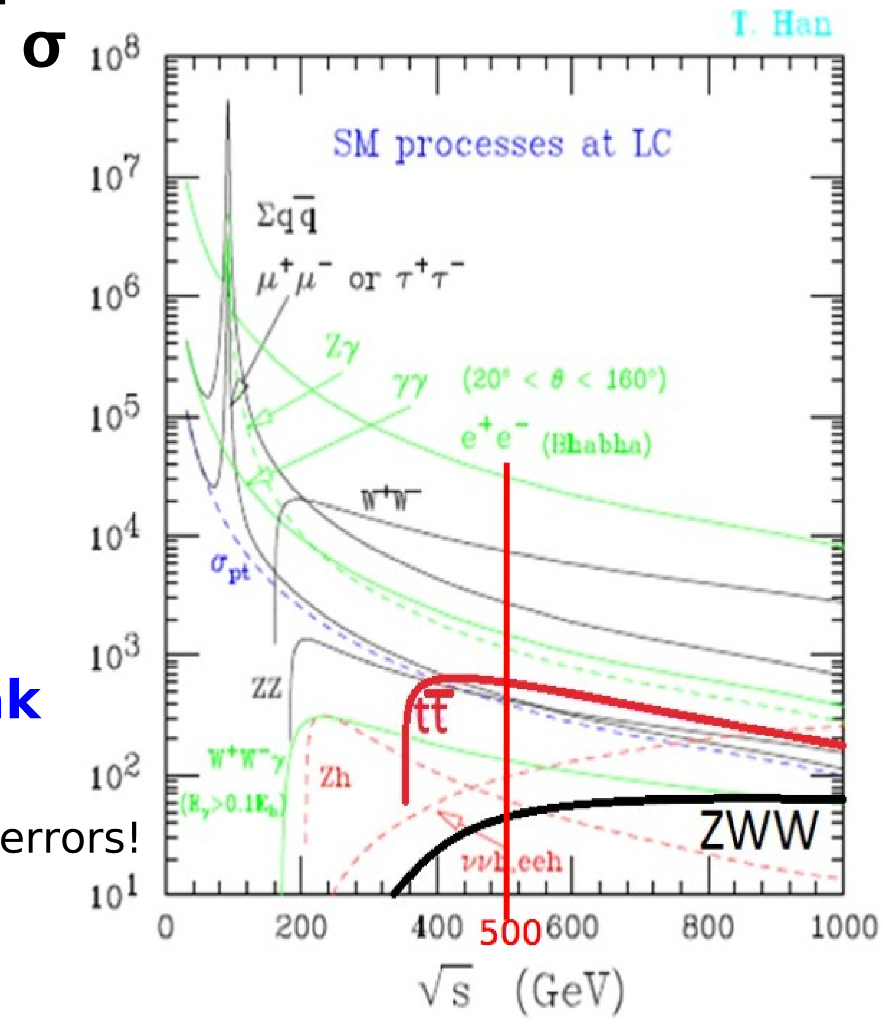
Higgs Boson

Discovered 2012 at LHC

ILC are/would be
Higgs factories
See talk by Mark

Top quark physics at electron-positron colliders





- Top quark production through **electroweak** processes,

  no competing QCD production => Small theoretical errors!

- High precision measurements

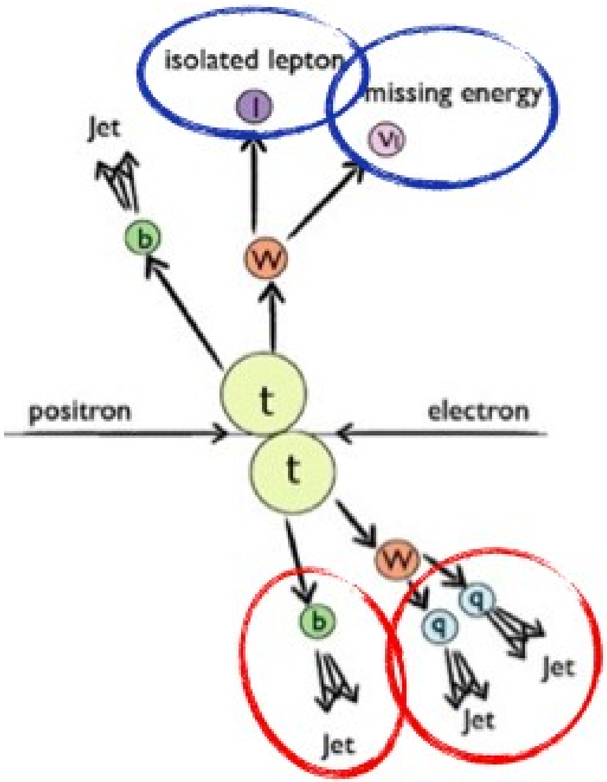
  Top quark mass at ~ 350 GeV through threshold scan

  Polarised beams allow to test chiral structure at ttX vertex

  => Precision on form factors F

Identifying and reconstructing top quarks

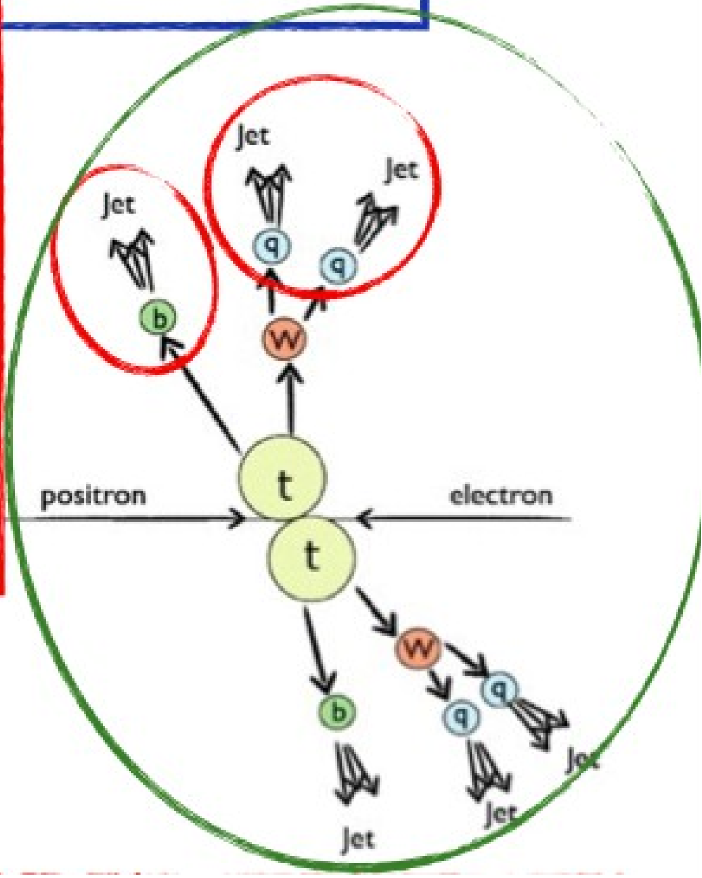
- Strategy depends on targeted ttbar final state



Semi-leptonic:
- isolated lepton ID, momentum measurement
- missing energy measurement

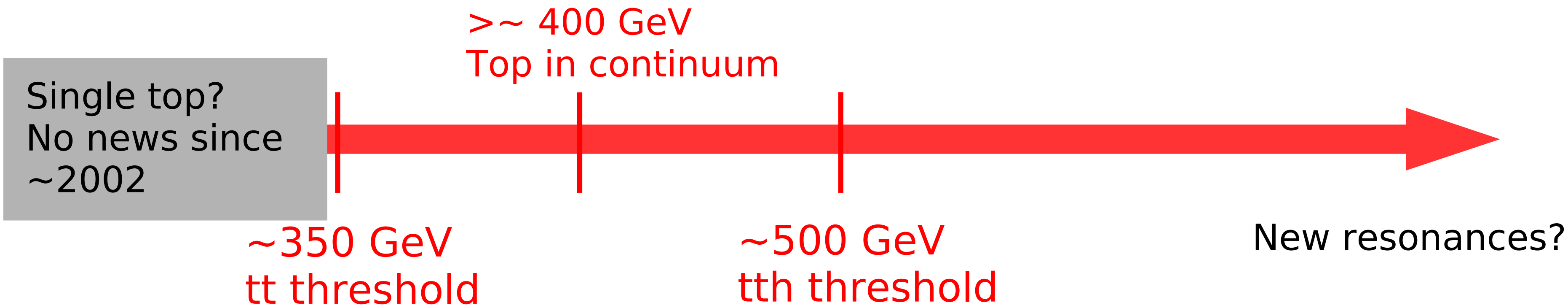
Universal
- Flavor tagging:
  - b - identification
  - b/c separation
- b-Jet energy measurement
- light Jet reconstruction & energy measurement

All-hadronic
- global hadronic energy reconstruction



Stolen from Frank Simon

Relevant scales for Top physics and LC Physics programme

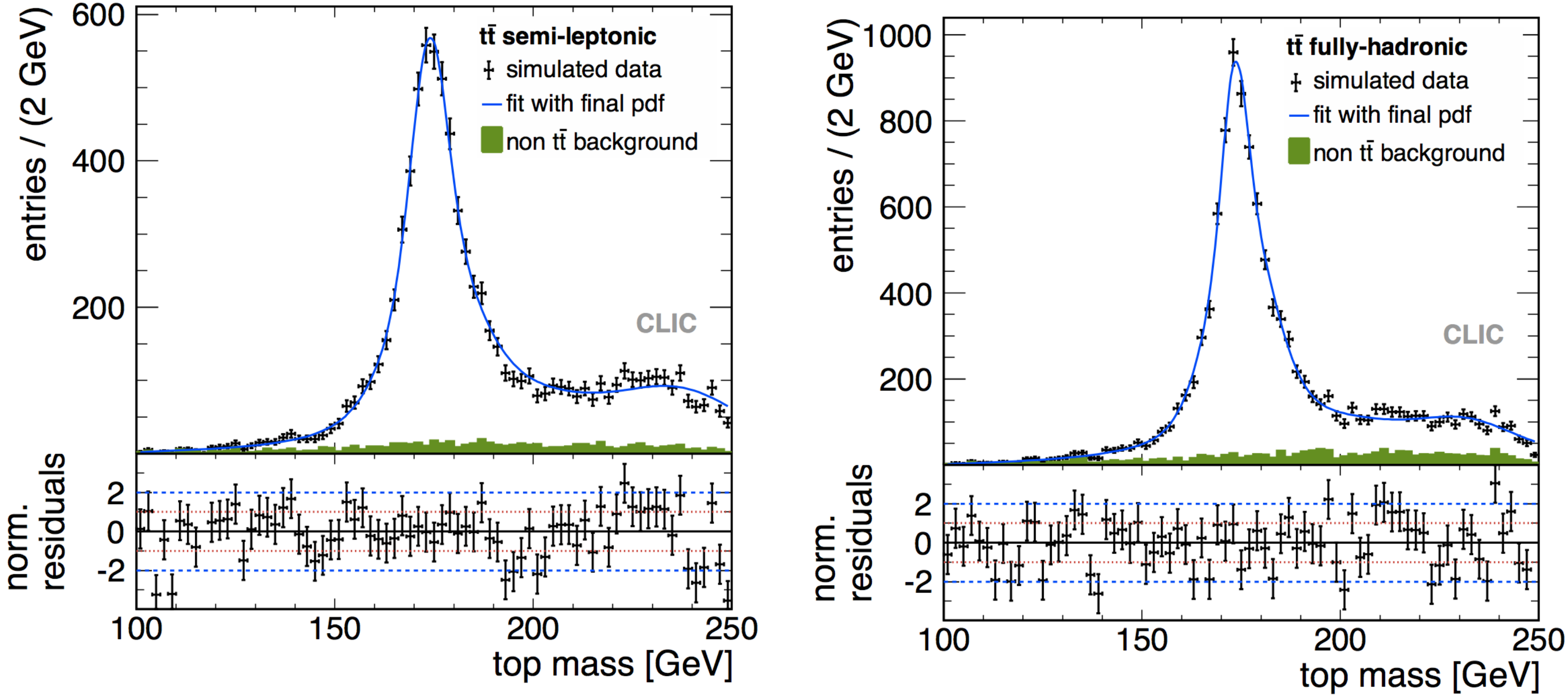


- After TDR and Japanese initiative, programme for ILC under discussion
  ILC in staged approach but which is first stage?

- Arguments to start at 350 GeV include Top physics programme

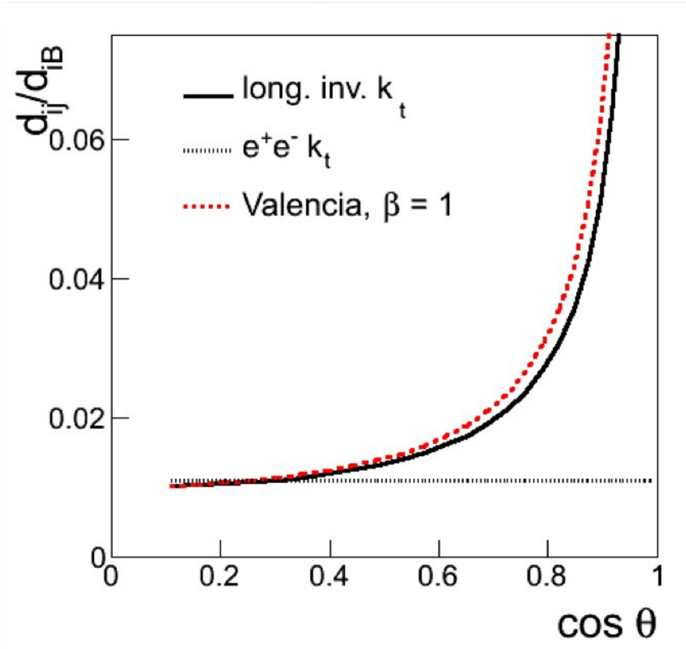
Top mass spectrum in continuum – 500 GeV

CLIC study but results very similar for ILC – L=100 fb-1



- (Almost) background free measurement of top mass
- However, continuum mass theoretically not well
  Defined (Renormalisation scheme dependent)
  Similar issues at Lepton and hadron colliders
- Still an important 'Standard Candle' in the continuum

New 'tool' – Valencia Jet Algorithm



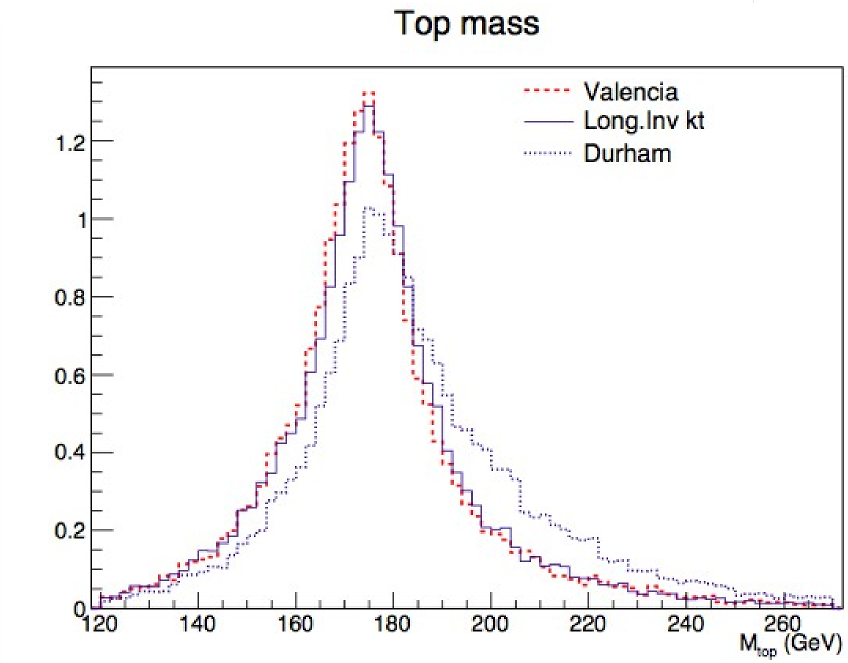
Combining Durham algorithm

$$d_{ij} = min(E_i^{2\beta}, E_j^{2\beta})(1 - \cos\theta_{ij})/R^2$$

With robustness of long. k_T against background

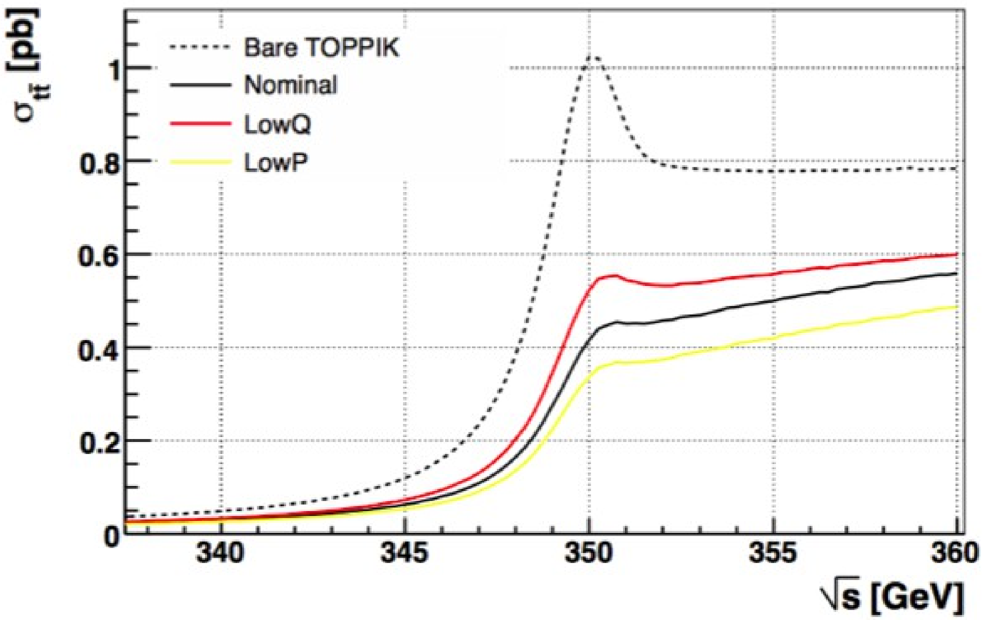
$$d_{iB} = p_T^{2\beta}$$

Exponent β to tune background Rejection level



Remark: Idea that emerges during top studies
Results in the following however still
with good old Durham and/or kt algo

ttbar cross section at threshold



Principle: m_t **from** $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood (renormalons, summations)

➢ Top decay protects from non-pert effects

Much of the discriminating power of the approach related to the strong mass-dependence (ttbar resonance).

Peak position very stable in theory predictions (threshold mass scheme).

Typical results:

$\rightarrow \delta m_t^{\text{exp}} \simeq 50$ MeV

$\rightarrow \delta m_t^{\text{th}} \simeq 100$ MeV

What mass?

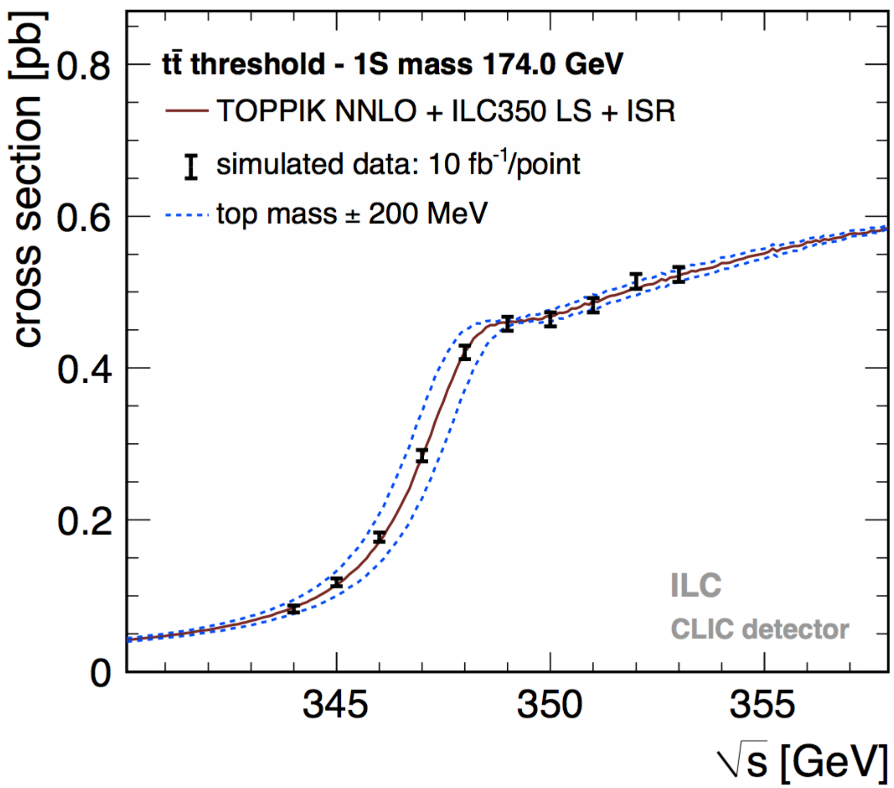
$\sqrt{s}_{\text{rise}} \sim 2m_t^{\text{thr}} +$ pert.series

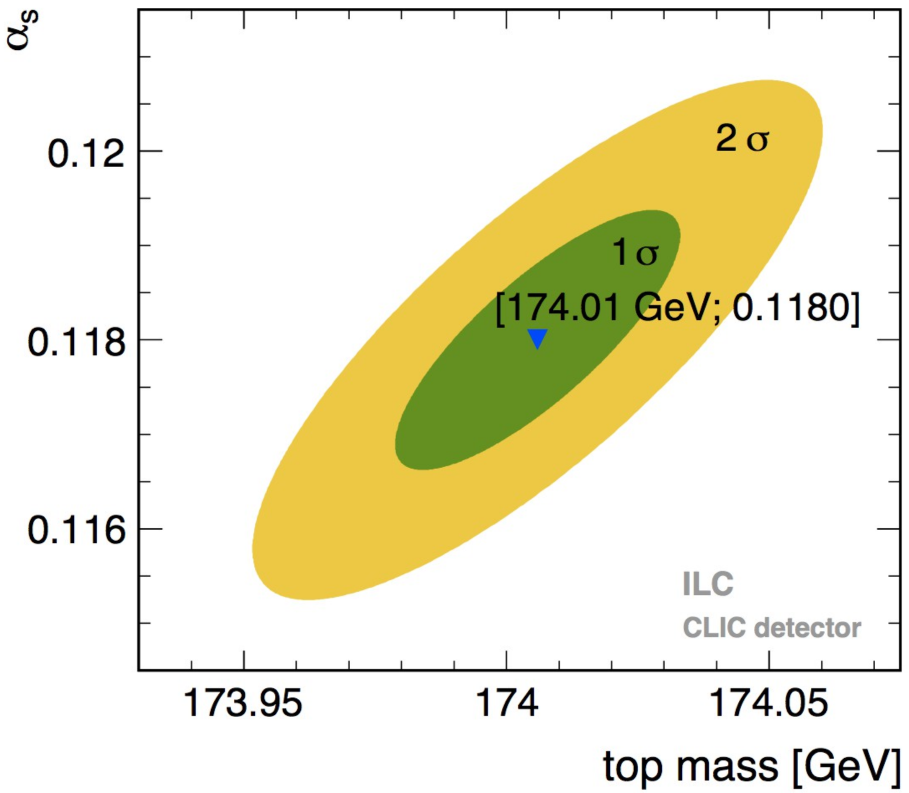
(short distance mass: 1S $\leftrightarrow \overline{\text{MS}}$)

A. Hoang

Top quark mass – Results of full simulation studies

arXiv:1303.3758





~100 MeV

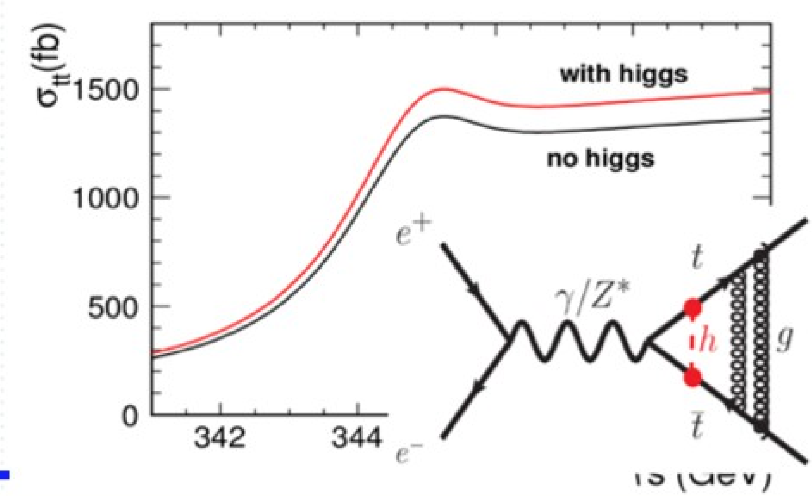
1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022

Top Yukawa coupling at threshold

The cross section is enhanced about <u>9%</u> by exchanging the Higgs boson !!

$$\sigma_{tt} \propto \left|\mathcal{M}_{w/o\ higgs} + y_t^2 \mathcal{M}_{w/\ higgs}\right|^2$$

$$\frac{\delta y_t}{y_t} \sim \frac{109 \times \frac{1}{2} \times \frac{\delta\sigma}{\sigma}}{9}$$



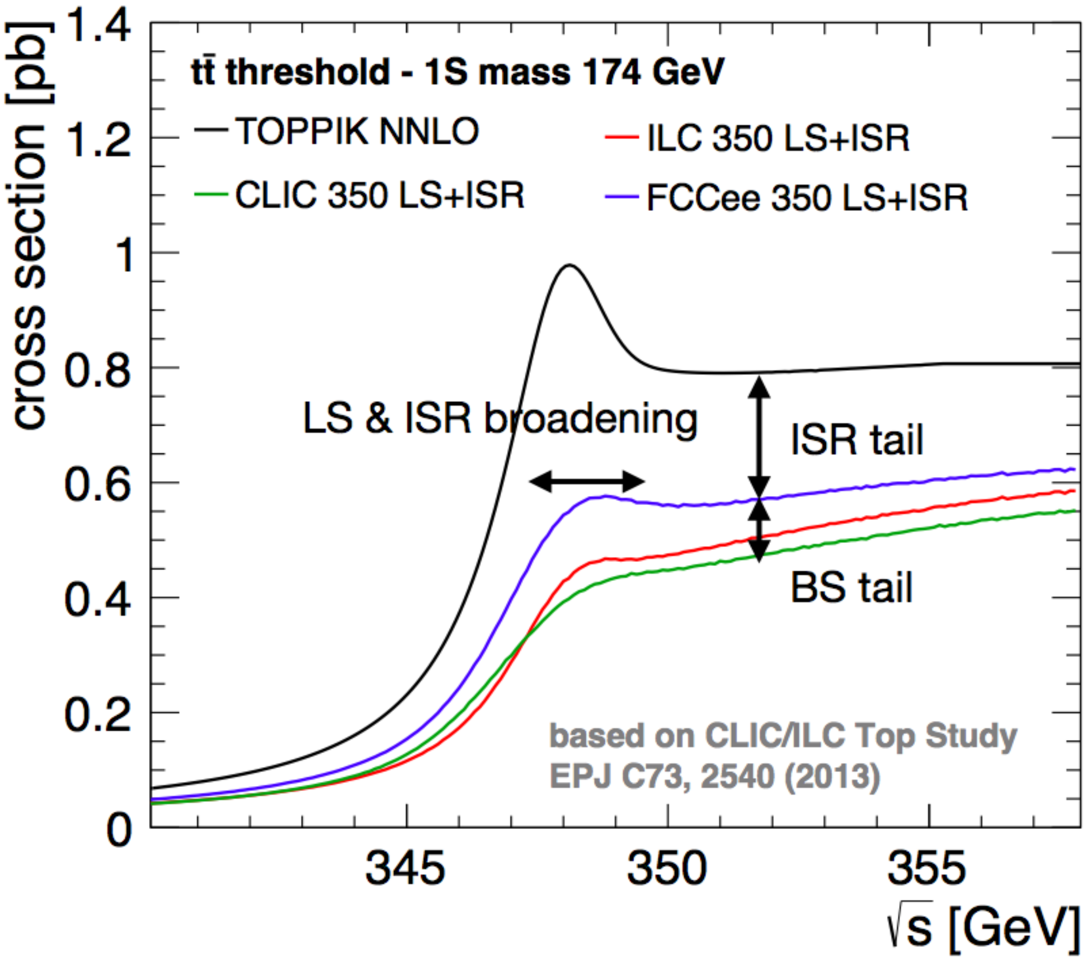
$\int \mathcal{L} dt = 100\ \mathrm{fb}^{-1}$

	(2 + 1) param fit	3 param fit
mt	19 MeV	29 MeV
Γt	38 MeV	39 MeV
yt	4.6%	5.9%

Stat. Uncertainties 'add' Theoretical uncertainties ~70 MeV

T. Horiguchi

Fighting rumours – Consequences of luminosity spectrum



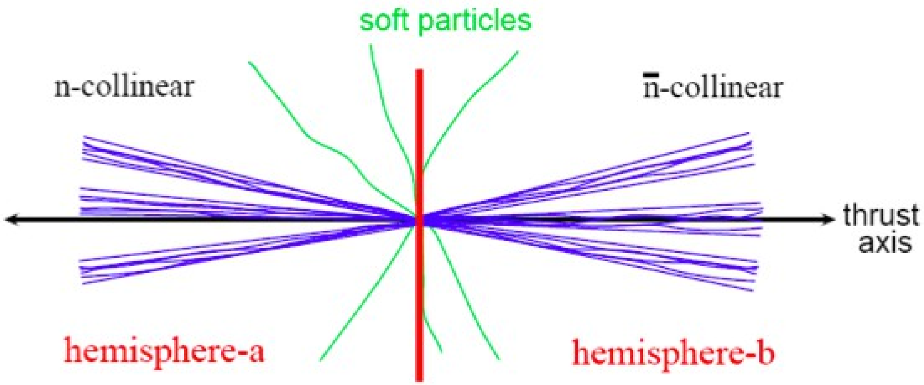
- Initial State Radiation
  Lowers effective L at top energy
- BeamStrahlung
  Lowers effective L
  at top energy
  Not at FCCee Gaussian spectrum
- Luminosity spectrum & Initial State Radiation broadening
  Smearing of cross section
  Due to beam energy spread
  ILC and FCCee comparable
  Worse at CLIC

1) Main effect on L spectrum is ISR
   => Reduces Luminosity, smears out 1s bound state peak
2) LC somewhat smaller L due to BeamStrahlung

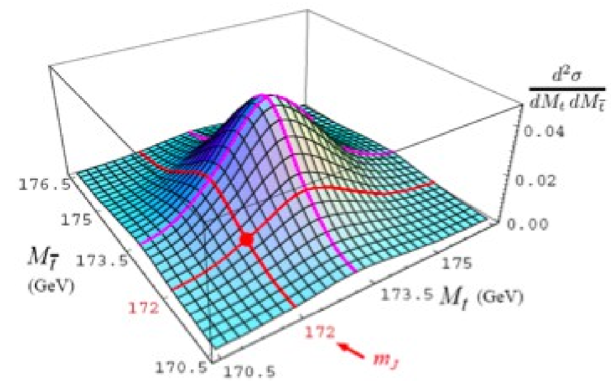
Reconstructed top jets (ILC)

Invariant mass distribution: (boosted tops)

Fleming, Mantry, Stewart, AH (2008)



- Hemisphere top jets
- Related to event-shapes



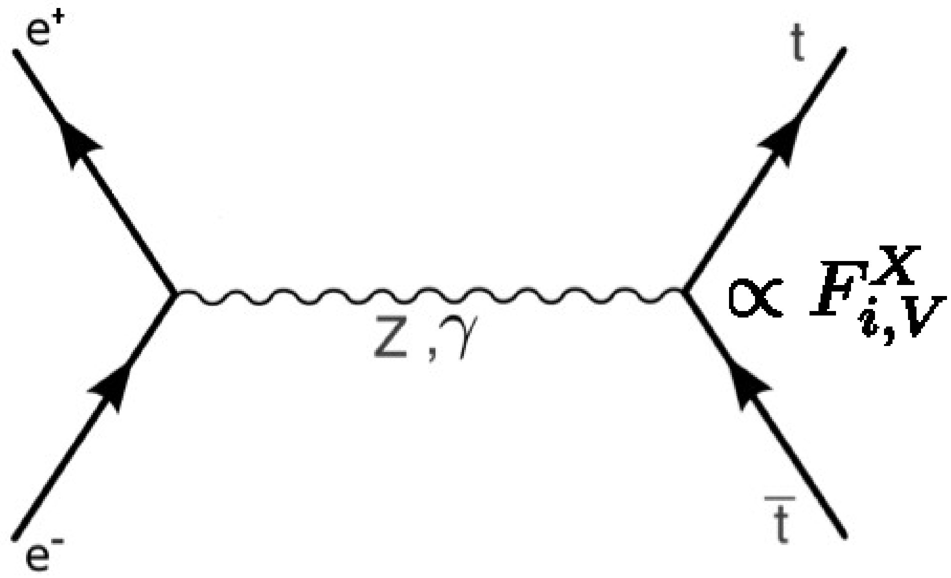
$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m) H_m\Big(m, \frac{Q}{m}, \mu_m, \mu\Big) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\Big(\hat s_t - \frac{Q\ell^+}{m}, \Gamma, \mu\Big)\, B_-\Big(\hat s_{\bar t} - \frac{Q\ell^-}{m}, \Gamma, \mu\Big)\, S_{\rm hemi}(\ell^+, \ell^-, \mu)$$

JET JET SOFT

→ Differential strongly top mass-dependent observable.

Fine print: Search/study also alternatives to threshold scan

Electroweak couplings of the top quark



$$\Gamma^{ttX}_{\mu}(k^2, q, \overline{q}) = -ie\left\{\gamma_\mu\left(F^X_{1V}(k^2) + \gamma_5 F^X_{1A}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\overline{q})^\mu\left(iF^X_{2V}(k^2) + \gamma_5 F^X_{2A}(k^2)\right)\right\}, \tag{2}$$

$$\mathcal{F}^L_{ij} = -F^\gamma_{ij} + \left(\frac{-\frac{1}{2} + s^2_w}{s_w c_w}\right)\left(\frac{s}{s - m^2_Z}\right)F^Z_{ij}$$

$$\mathcal{F}^R_{ij} = -F^\gamma_{ij} + \left(\frac{s^2_w}{s_w c_w}\right)\left(\frac{s}{s - m^2_Z}\right)F^Z_{ij} ,$$

Disentangling

At ILC **no** separate access to ttZ or ttγ vertex, but ...

ILC 'provides' two beam polarisations

$P(e^-) = \pm 80\%$ $P(e^+) = \mp 30\%$

There exist a number of observables sensitive to chiral structure, e.g.

σ_I

x-section

$$A^t_{FB,I} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

Forward backward asymmetry

$$(F_R)_I = \frac{(\sigma_{t_R})_I}{\sigma_I}$$

Fraction of right handed top quarks

⇩

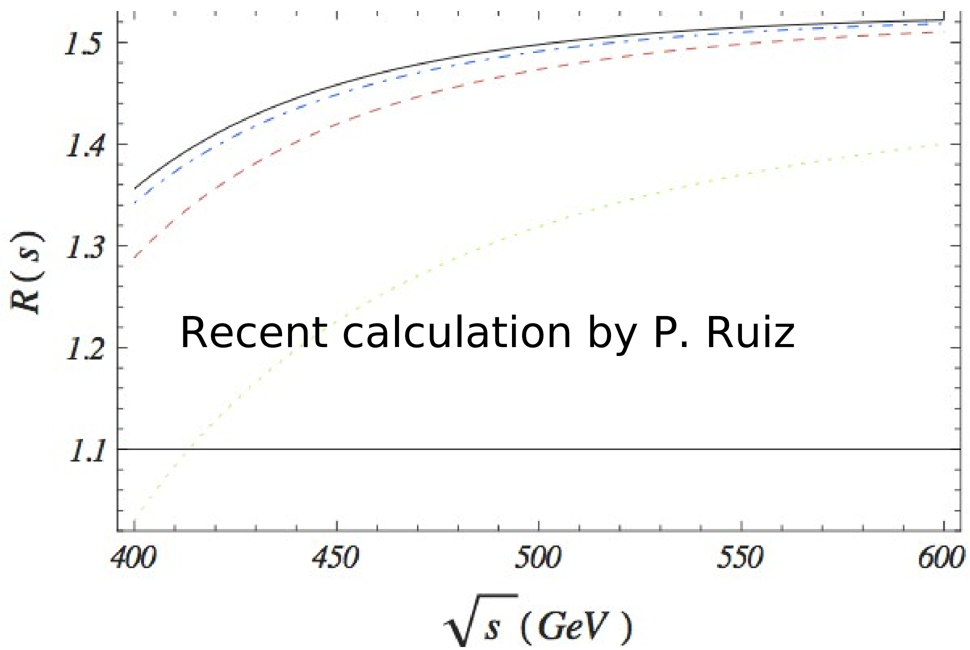
Extraction of six (five) unknowns

$$F^{\gamma}_{1V},\ F^{Z}_{1V},\ F^{\gamma}_{1A} = 0,\ F^{Z}_{1A}$$

$$F^{\gamma}_{2V},\ F^{Z}_{2V}$$

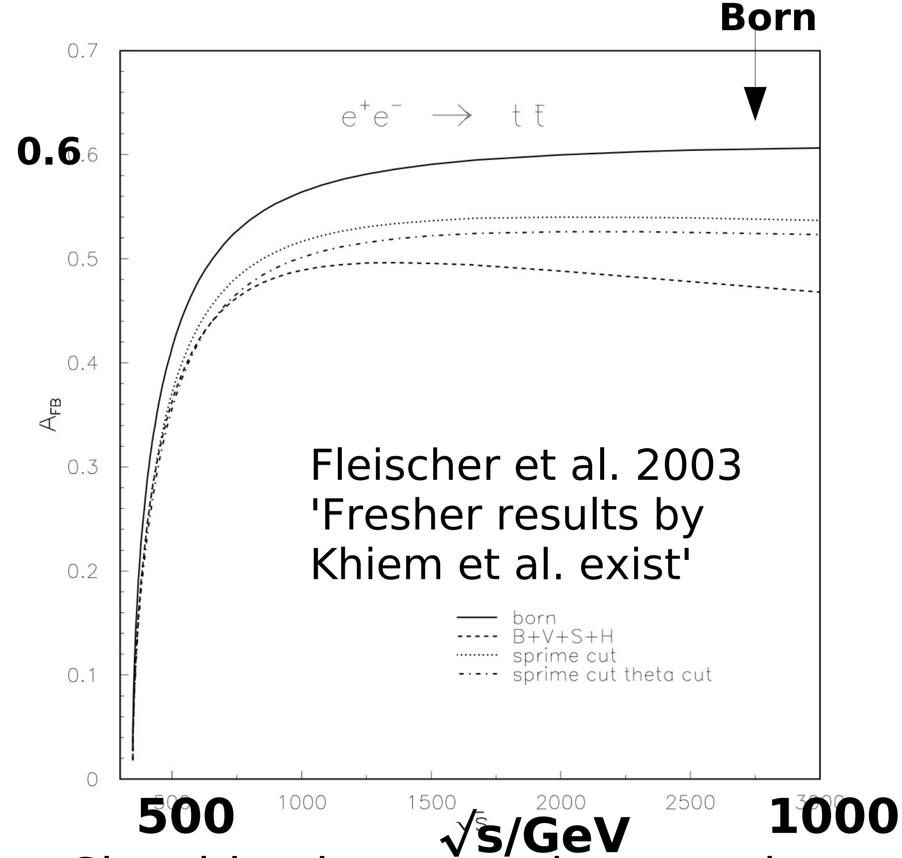
Theoretical uncertainties

QCD up to $O(a_s^3)$



- Well behaving perturbation series
- Small scale uncertainties <1%
- Size of next correction expected to be Smaller than 0.3% at 500 GeV

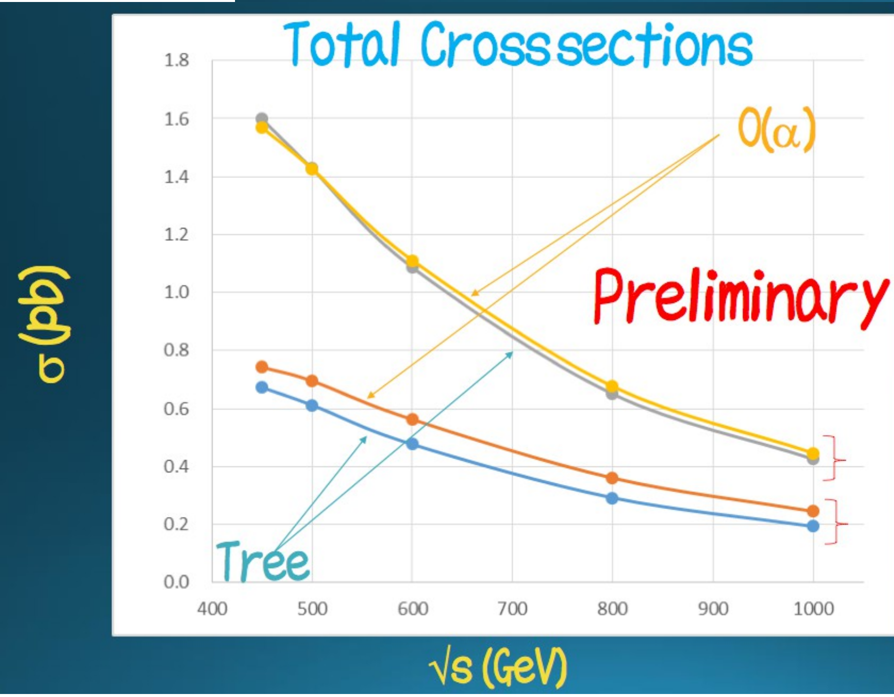
NLO electroweak



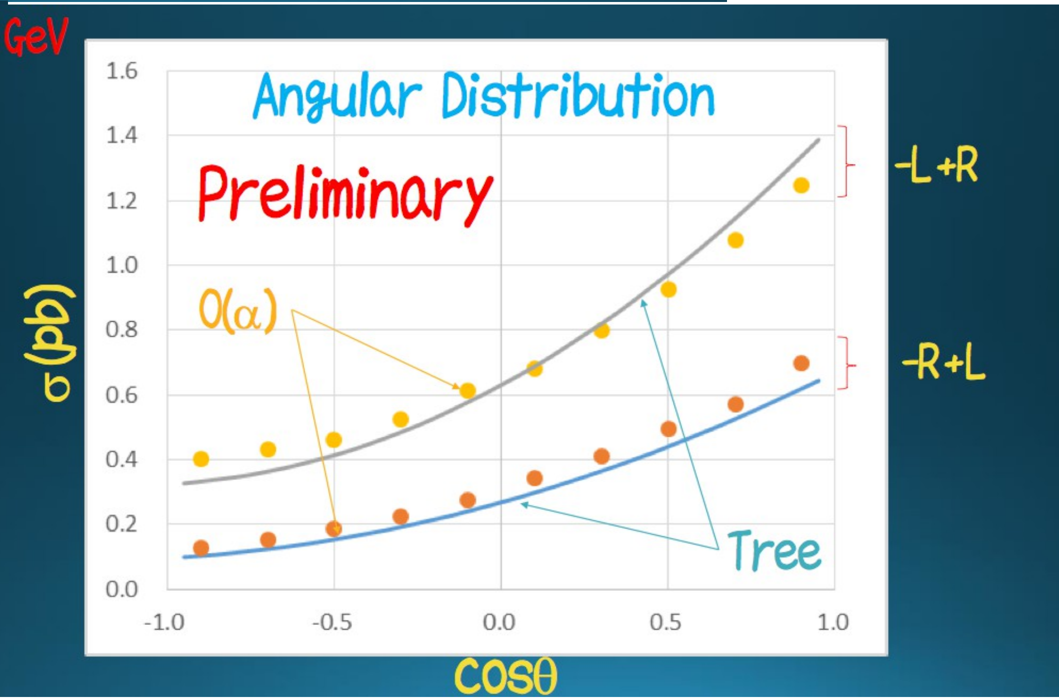
- Sizeable electroweak corrections to AFB (~15%)
- Size of NNLO correction? Answers fange from “1%” over “I think I know what to do” to “I don't know”
- Full NNLO ~ 10 years of work

Generators for top physics – e.g GRACE

- GRACE: Automatic Full o(α) ELWK correction w/ SM & MSSM
- Beam polarization is implemented in GRACE-system, but Still Preliminary.
- Polarization of "$e^-_L e^+_R$" gives smaller O(α)-corrections than "$e^-_R e^+_L$", however change A_{FB}
- SUSY signals can be seen through loop-effect.

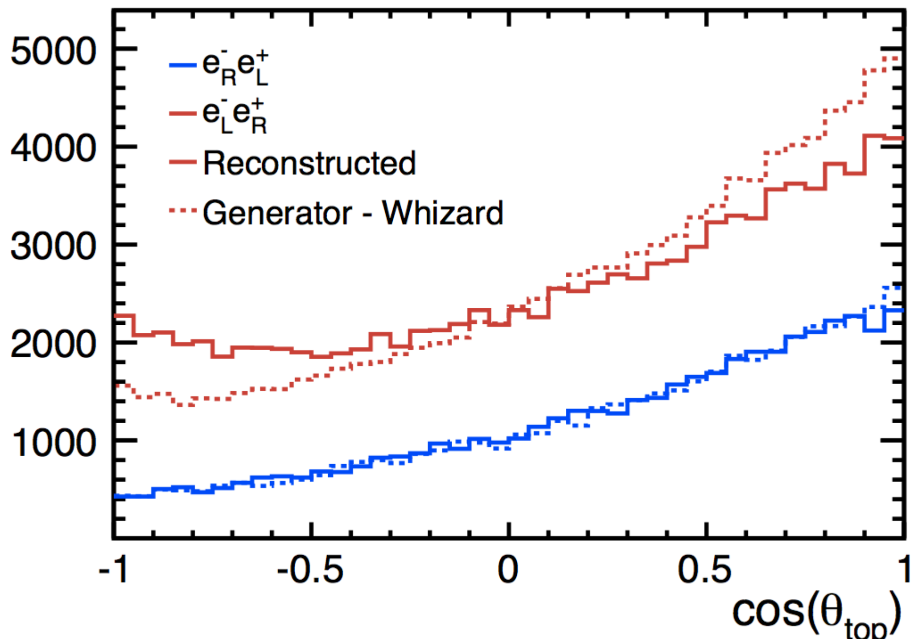


√s=500 GeV



Worth to mention
- WHIZARD is our working horse
 ... contains now suite to test anomal. top couplings

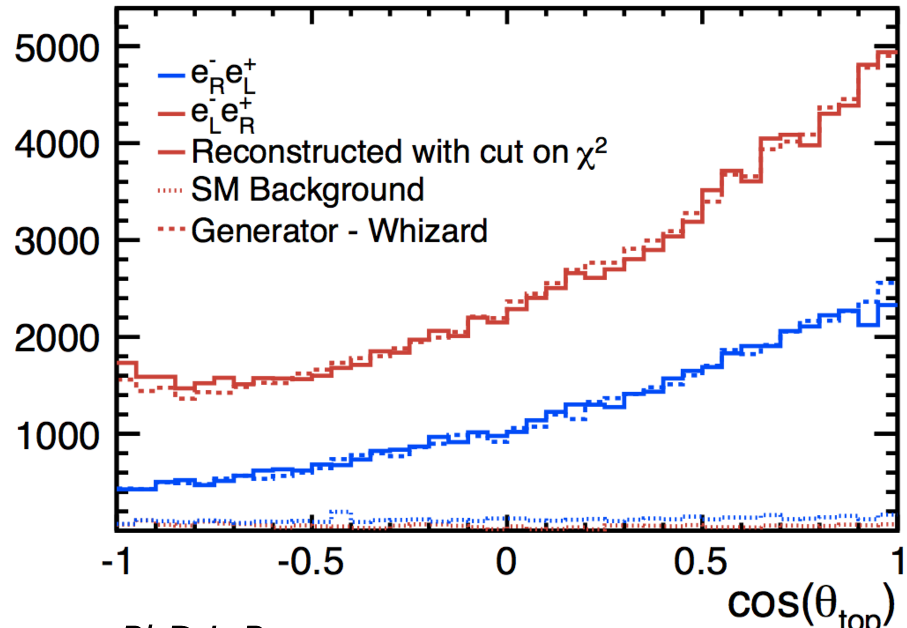
Semi Leptonic Analysis - Reconstruction of top quark production angle



Ambiguities in case of **left** handed electron beams
Due to V-A structure at ttX vertex

Precise reconstruction of θ_{top} in case of **right** handed electron beams

Remedy to address ambiguities:
Select cleanly reconstructed events by χ^2 analysis
or
Reconstruction of b quark charge



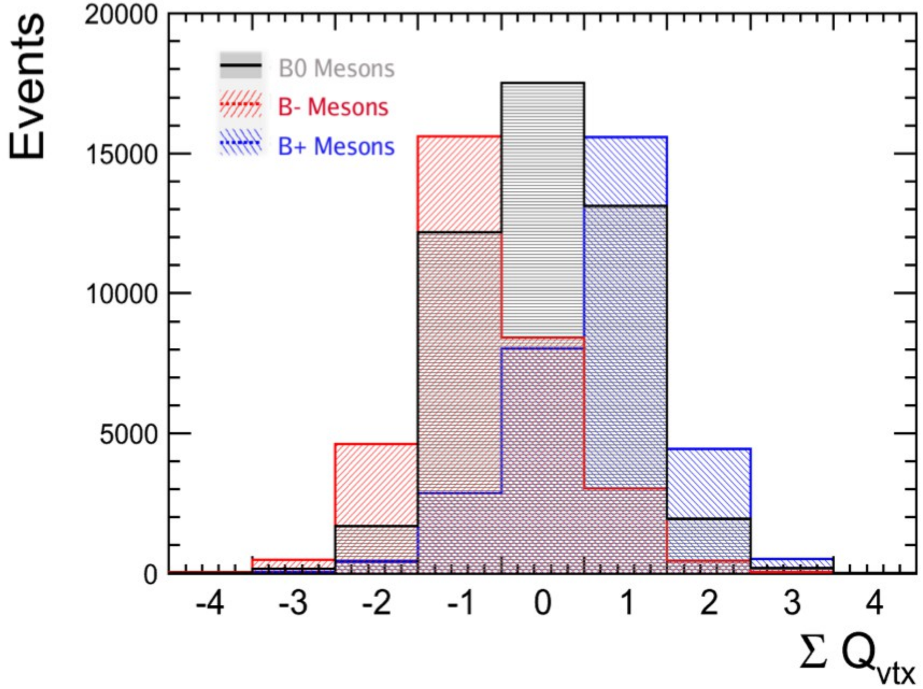
Precise reconstruction for both beam polarisations

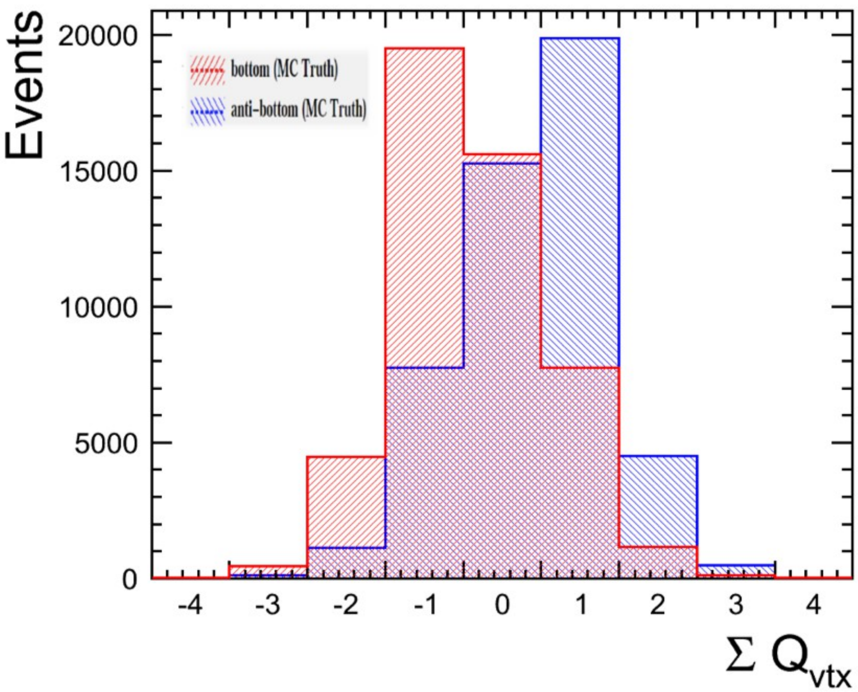
- Efficiency Penalty for e_L
- ε_{tot}: $e_R \sim 50\%$, $e_L \sim 30\%$

Precision on $A_{FB} \sim 2\%$

Measurement of b quark charge

(N.B. At example of fully hadronic analysis)





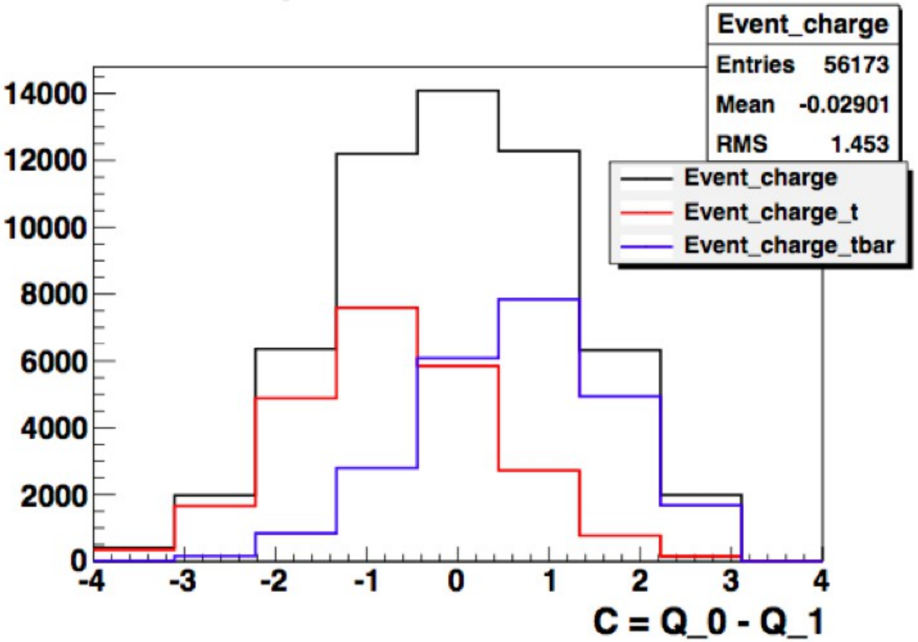
- LC vertex and tracking system allows for determination of b-meson (b-quark) charge
  B-quark charge measured correctly in about 60% of the cases

- `LCFIPlus` package not yet optimised for vertex charge measurement

  Optimisation of b-quark charge is major topic for future studies

Top polar angle using b charge

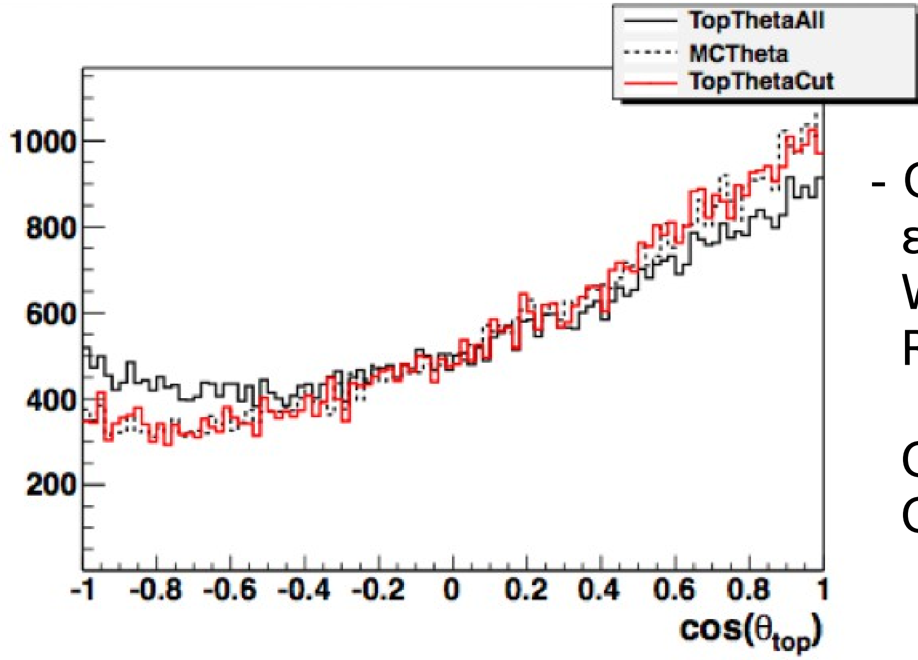
(SL Analysis)



Event charge C = b1 -b2

In SL can compare charge C with lepton charge to select clean sample

Use only events with correct C or C=0 (plus another cut on the Lorentz Factor)



- Clean reconstruction of top quark direction
  ε ~ 30%
  Will improve with improving charge Reconstruction

  Can already be considered as indpendent Cross check of existing results

B charge measurement - Potential

- b quark hadronises to about

~40% to charged B mesons
~50% to neutral B mesons
~10% to Baryons
=> 64% cases where there is at least one charged b => Should be recognisable

- neutral B mesons decay to about

~ 50% into charged D Mesons => measurable
~ 50% into neutral D mesons
~64% of these D neutral undergo prong decays => charged particles => measurable
=> Out of 36% cases remaining above ~75% can (in principle) be retrieved

=> 91% of the charges from top quark decays lead to signatures that are in principle measurable

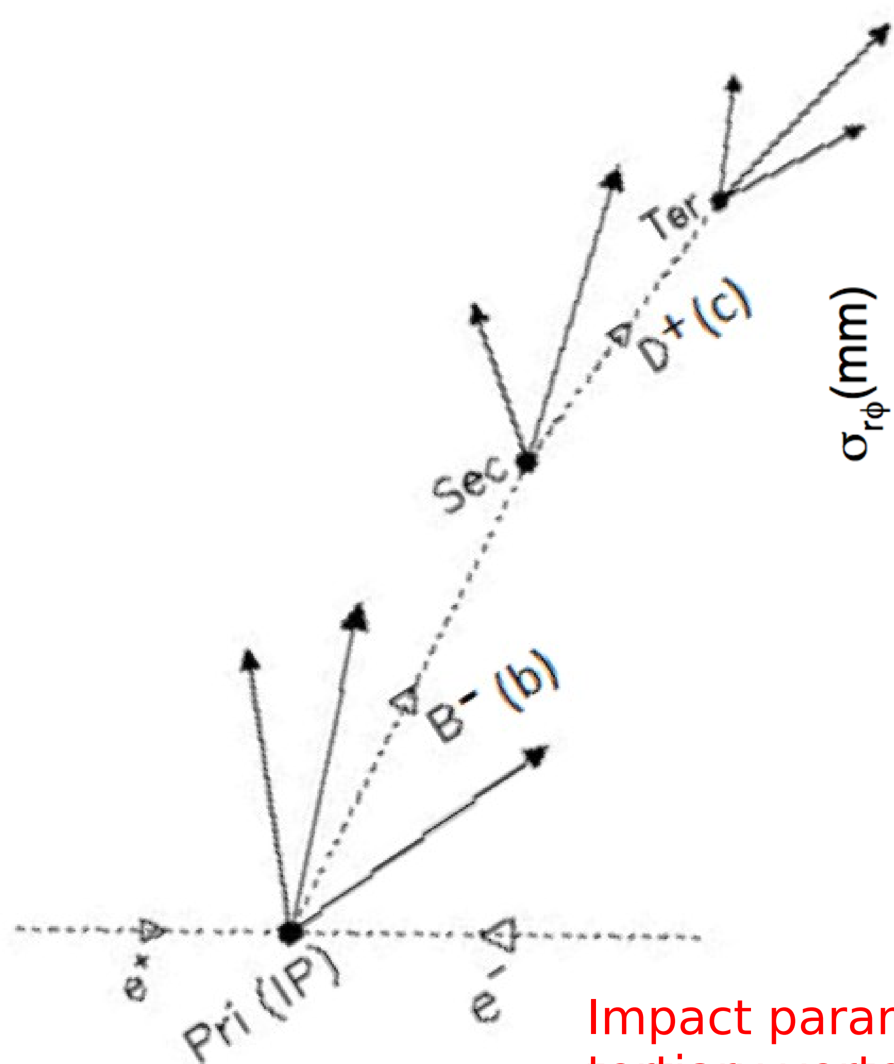
Two tasks:

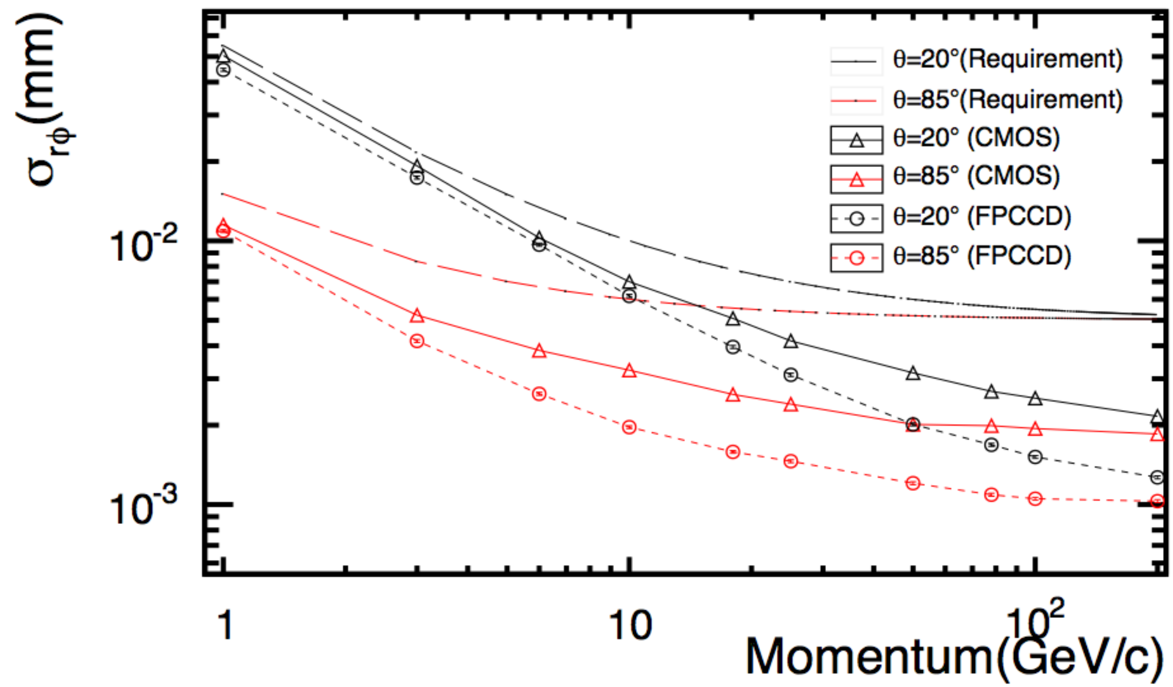
1) Short term (~6 months)
Understand why final state with charged B Meson are wrongly reconstructed
Exact fraction depends on final state, looks as if SL is somewhat easier than fully hadronic
2) Medium long term (~ 2 years)
Tertiary vertices for neutral B Mesons

Tertiary vertices – Principal considerations

Decay length of neutral D
cτ ≈ 120μm

Decay length of charged D
cτ ≈ 310 μm





Impact parameter resolution of < 10 μm should permit tertiary vertex reconstruction …
- Long lived charged particles via dE/dx central tracking

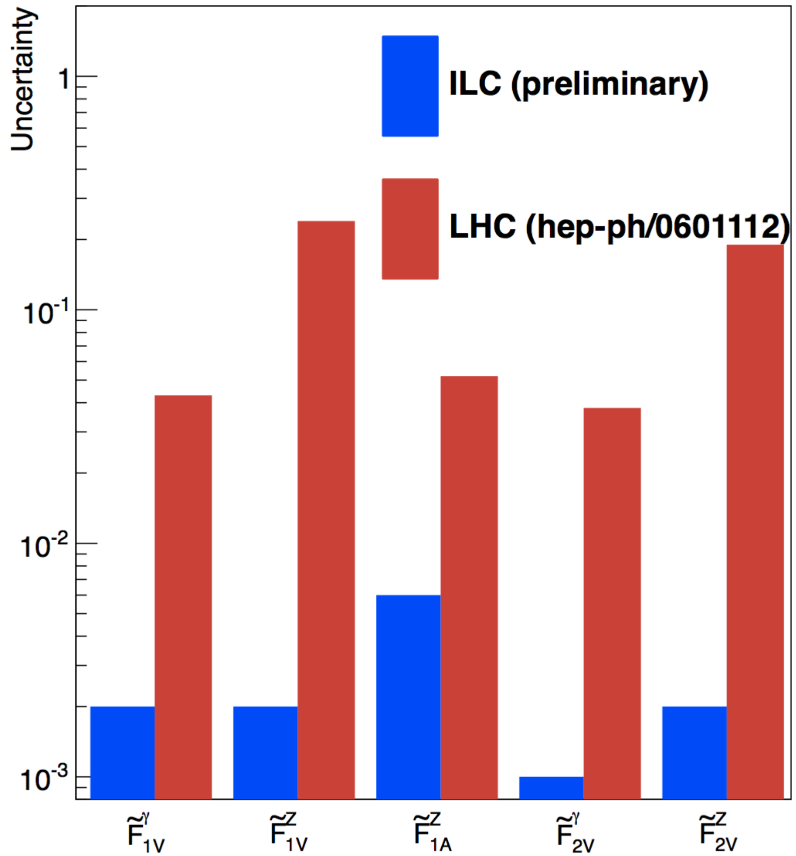
N.B.: Both measurements are not part of ILD DBD

Results of full simulation study for DBD at $\sqrt{s}$ = 500 GeV

IFICLAL ArXiv: 1307.8102

Precision: cross section ~ 0.5%, Precision A_{FB} ~ 2%, Precision λ_t ~ 3-4%

Accuracy on CP conserving couplings



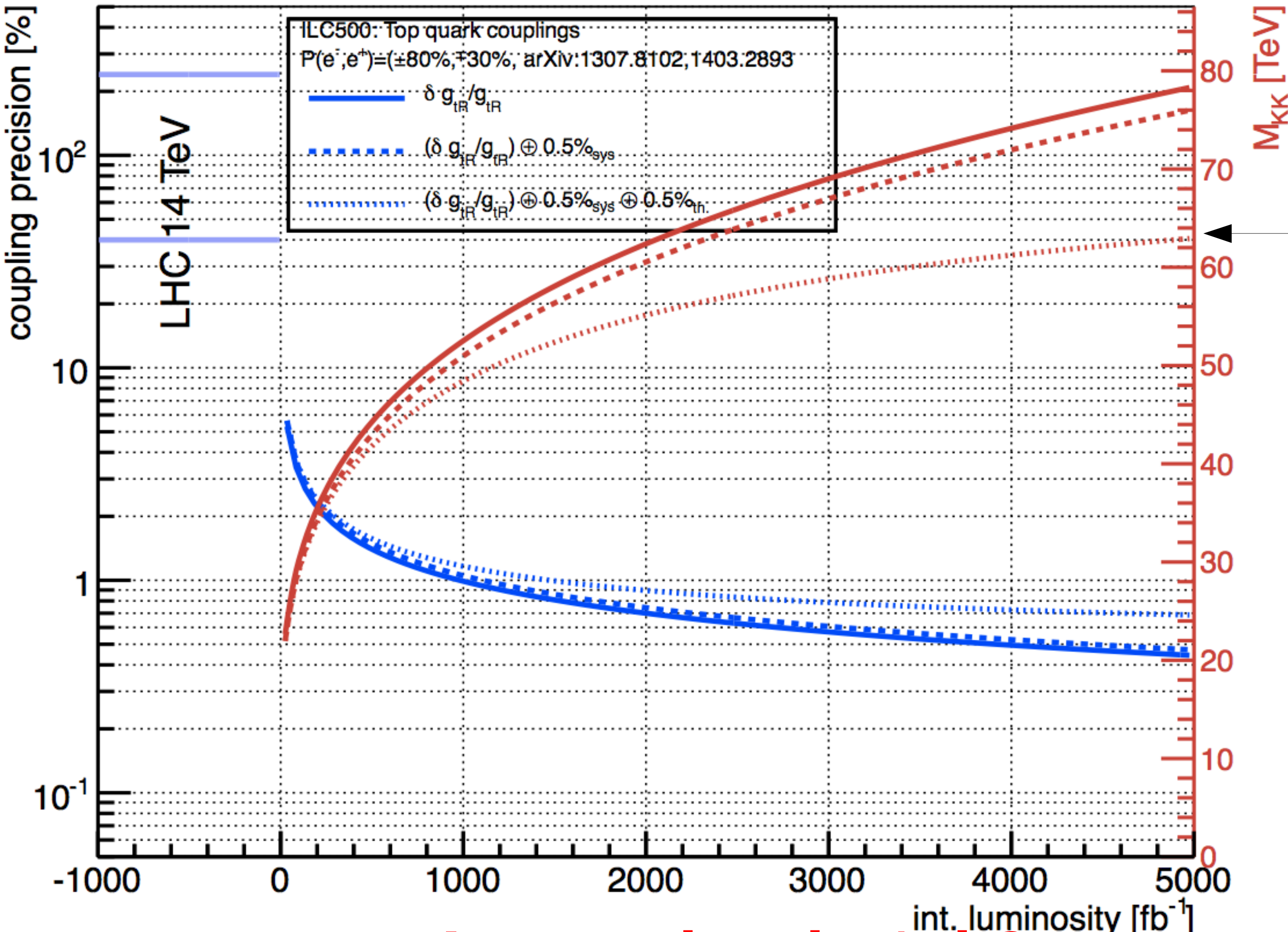
- ILC might be up to two orders of magnitude more precise than LHC ($\sqrt{s}$ = 14 TeV, 300 fb^{-1})
  Disentangling of vector/axial vectol couplings for ILC
  One variable at a time For LHC
  However LHC projections from 8 years old study
- Need to control experimental (e.g. Top angle) and theoretical uncertainties (e.g. Electroweak corrections)
  -> Dedicated work has started
- Potential for CP violating couplings at ILC under study
  (However CP violation would rather show up at threshold)

ILC will be indeed high precision machine for electroweak top couplings

Example for physics reach

Kaluza-Klein masses in Randall-Sundrum model in extra dimensions

A la Richard, Djouadi et al.



0.5% error that doesn't scale with lumi

Impressive, isn't it?

Discussion of potential systematic uncertainties

Experimental

- Luminosity: Critical for cross section measurements
  Expected precision 0.1% @ 500 GeV

- Beam polarisation: Critical for asymmetry measurements
  Expected to be known to 0.1% for e- beam
  and 0.35% for e+ beam

- Migrations/Ambiguities: Critical for AFB:
  Need further studies but expect to control them better than the theoretical error

- Jet energy scale: Critical for top mass determination
  Systematic study CLIC states systematic error ~ statistical error

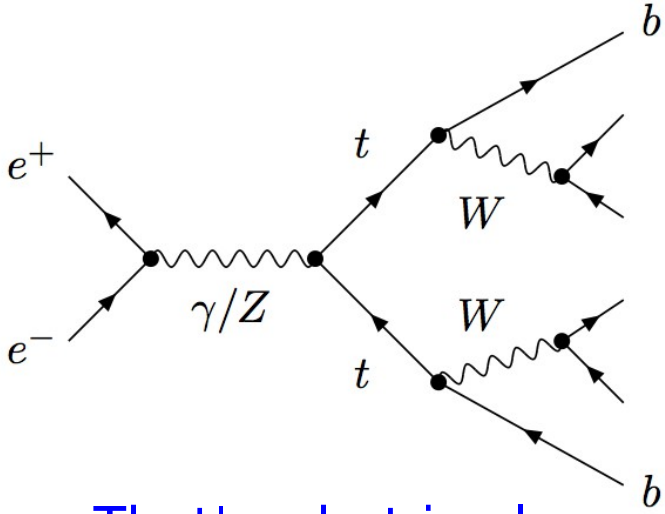
- Other effects: B-tagging, passive material etc.
  LEP claims 0.2% error on R_b -> guiding line for LC

Theory:

- see above and in the following

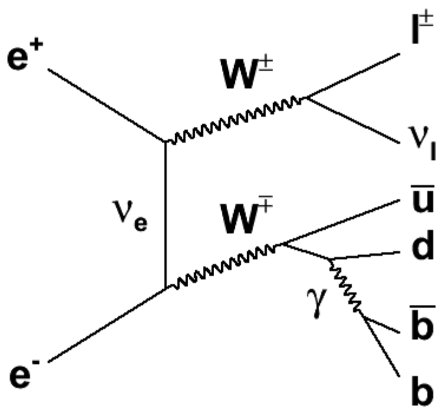
Closer look at ttbar production

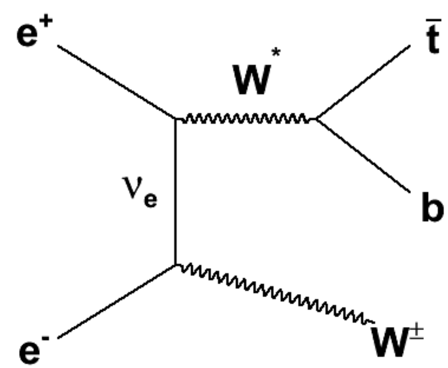
That's what we are interested in



Top pair production is effectively ee->6f process

That's what is also contributing to final state!





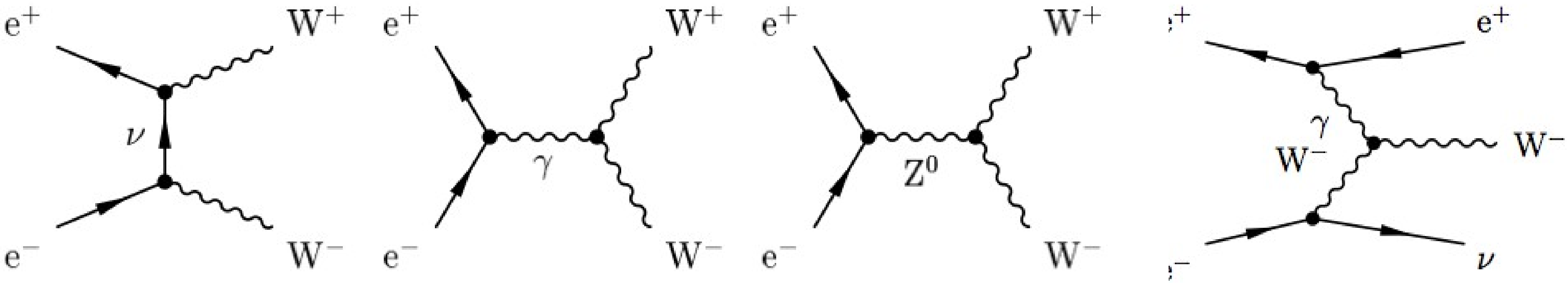
+ s-channel, t-channel only relevant for eL

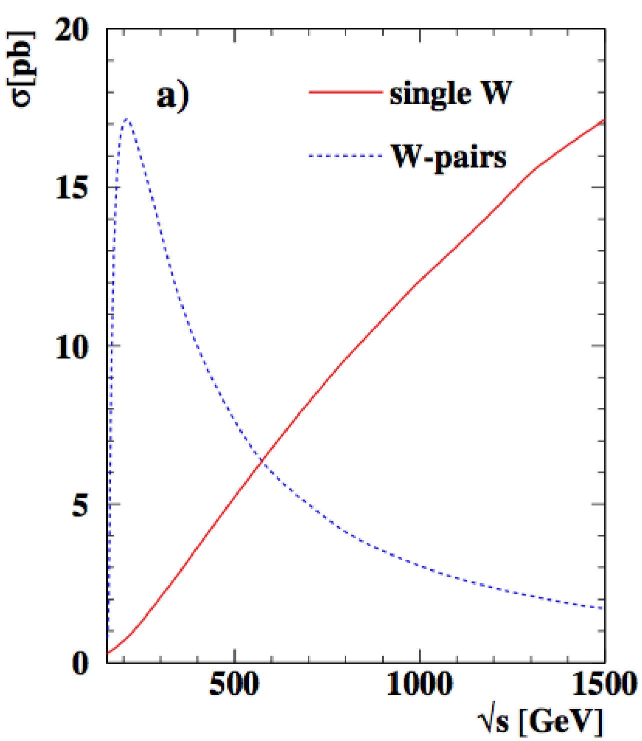
- Can one really speak about a ttbar cross section?
- If only 6f is relevant: What are relations to ttX couplings?
- What selection cuts are (theoretically) save?

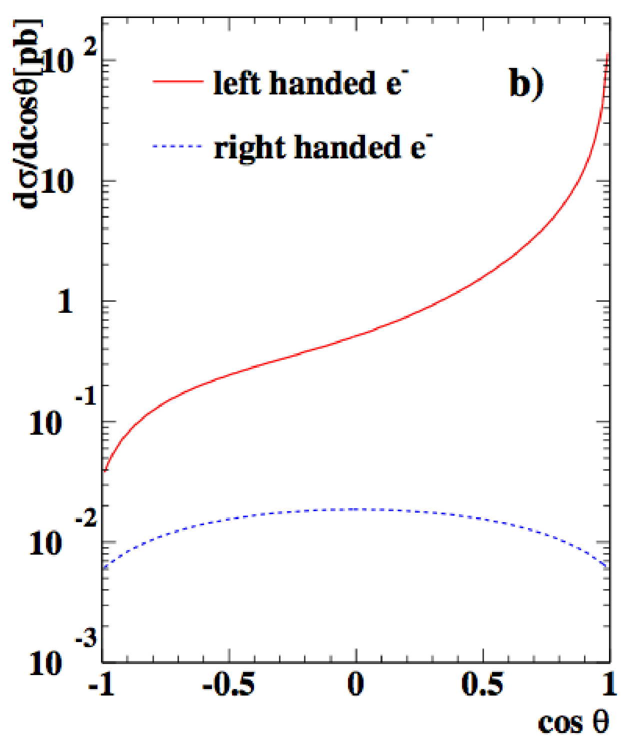
W physics

W pair production

Single W production





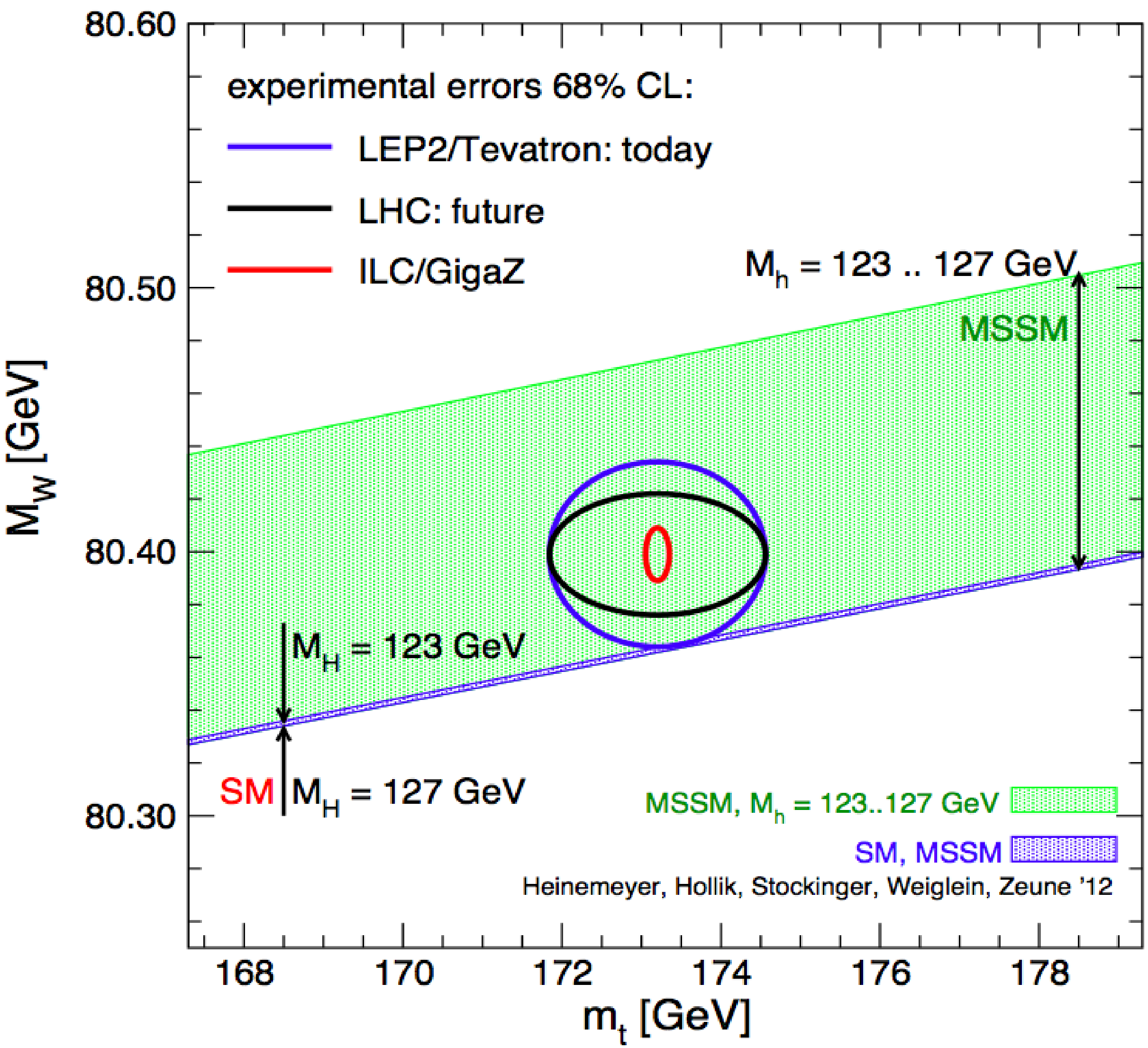


- Important SM parameter

- Sensitivity to Triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

=> Enrich different helicity modes of W
=> in situ measurement of beam polarisation

Top mass Higgs Mass and BSM – SM vs. MSSM



Precise Top **(and W)** mass crucial to test compatibility of measured Higgs mass

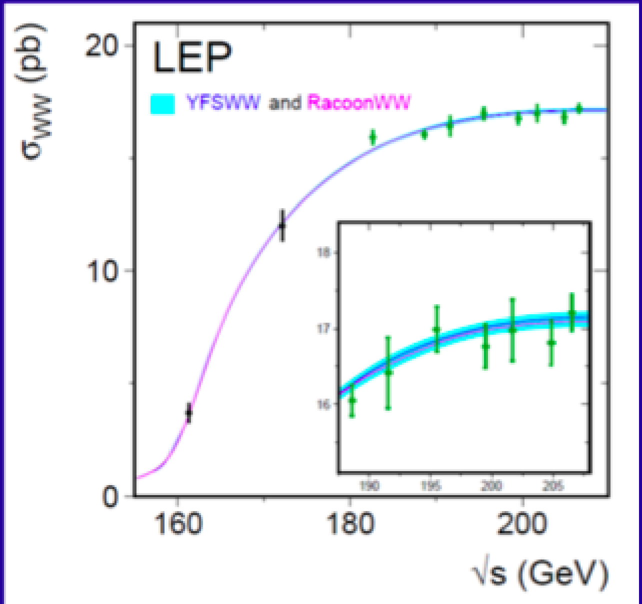
MS might not be sufficient to explain Higgs mass

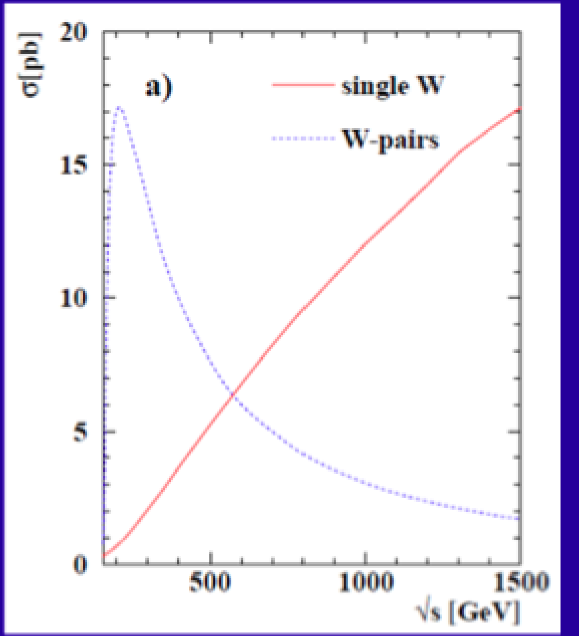
LHC may not reach sufficient discriminative power

A lepton collider will

W Mass Measurement Strategies

- W^+W^-
  - 1. Threshold Scan ($\sigma \sim \beta/s$)
    - Can use all WW decay modes
  - 2. Kinematic Reconstruction
    - Apply kinematic constraints
- W e ν (and WW → qqτν)
  - 3. Directly measure the hadronic mass in W → q q' decays.
    - e usually not detectable





Methods 1 and 2 were used at LEP2. Both require good knowledge of the absolute beam energy.

Method 3 is novel (and challenging), very complementary systematics to 1 and 2 if the experimental challenges can be met.

G.W. Wilson

m_W Prospects

1. Polarized Threshold Scan
2. Kinematic Reconstruction
3. Hadronic Mass

Method 1: Statistics limited.

Method 2: With up to 1000 the LEP statistics and much better detectors. Can target factor of 10 reduction in systematics.

Method 3: Depends on di-jet mass scale. Plenty Z's for 3 MeV.

1

ΔM_W [MeV]	LEP2	ILC	ILC
$\sqrt{s}$ [GeV]	161	161	161
$\mathcal{L}$ [fb^{-1}]	0.040	100	480
$P(e^-)$ [%]	0	90	90
$P(e^+)$ [%]	0	60	60
statistics	200	2.4	1.1
background		2.0	0.9
efficiency		1.2	0.9
luminosity		1.8	1.2
polarization		0.9	0.4
systematics	70	3.0	1.6
experimental total	210	3.9	1.9
beam energy	13	0.8	0.8
theory	-	(1.0)	(1.0)
total	210	4.0	2.1

2

ΔM_W [MeV]	LEP2	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	172-209	250	350	500
$\mathcal{L}$ [fb^{-1}]	3.0	500	350	1000
$P(e^-)$ [%]	0	80	80	80
$P(e^+)$ [%]	0	30	30	30
beam energy	9	0.8	1.1	1.6
luminosity spectrum	N/A	1.0	1.4	2.0
hadronization	13	1.3	1.3	1.3
radiative corrections	8	1.2	1.5	1.8
detector effects	10	1.0	1.0	1.0
other systematics	3	0.3	0.3	0.3
total systematics	21	2.4	2.9	3.5
statistical	30	1.5	2.1	1.8
total	36	2.8	3.6	3.9

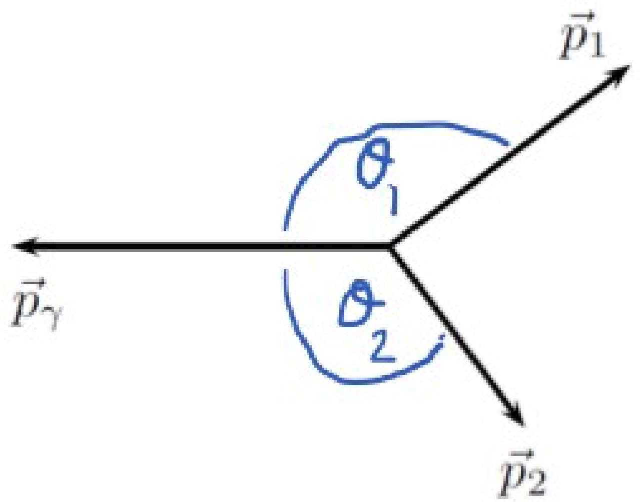
3

ΔM_W [MeV]	ILC	ILC	ILC	ILC
$\sqrt{s}$ [GeV]	250	350	500	1000
$\mathcal{L}$ [fb^{-1}]	500	350	1000	2000
$P(e^-)$ [%]	80	80	80	80
$P(e^+)$ [%]	30	30	30	30
jet energy scale	3.0	3.0	3.0	3.0
hadronization	1.5	1.5	1.5	1.5
pileup	0.5	0.7	1.0	2.0
total systematics	3.4	3.4	3.5	3.9
statistical	1.5	1.5	1.0	0.5
total	3.7	3.7	3.6	3.9

G.W. Wilson

How to reach ~10ppm on $\sqrt{s}$?

(New) In situ beam energy method: $e^+e^- \rightarrow \mu^+\mu^- (\gamma)$



$$(\sqrt{s})_P = E_1 + E_2 + |p_1 + p_2|$$

$$\approx$$

$$\sqrt{s}_P \approx (p_T)_1 \left(\frac{1+\cos\theta_1}{\sin\theta_1}\right) + (p_T)_2 \left(\frac{1+\cos\theta_2}{\sin\theta_2}\right)$$

- (New) method depends of angles and p_T

- Main question: How to control momentum scale?

Control of momentum measurement

- Which reference?

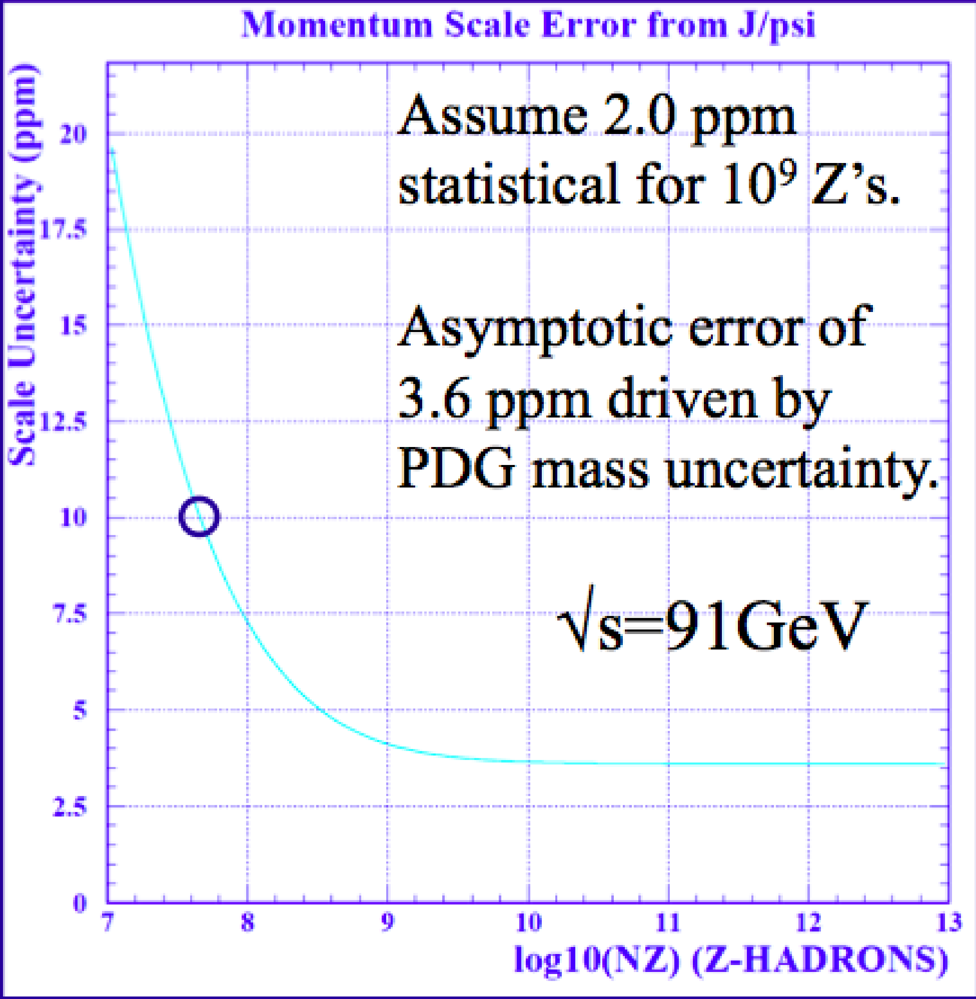
Particle	ΔM/M (PDG) (ppm)
J/psi	3.6
Upsilon	27
Z	23
W	190
H	2400

- Traditionally
  Calibration on Z ~23 ppm uncertainty, Z width is an issue

- Alternative
  Calibration on J/Psi ~3.6 ppm uncertainty

"Calibration" Run at $\sqrt{s}=m_Z$ for detector p-scale calibration

If detector is stable and not pushed, pulled and shaken, one could hope that such a calibration could be maintained long term at high energy.



Plot assumes negligible systematics from tracking modeling …

⇒ Need at least 40 M hadronic Z's for 10 ppm

⇒ Corresponds to $\geq 1.3\ fb^{-1}$ ($L \geq 1.3 \times 10^{33}$ for 10^6s) assuming unpolarized beams

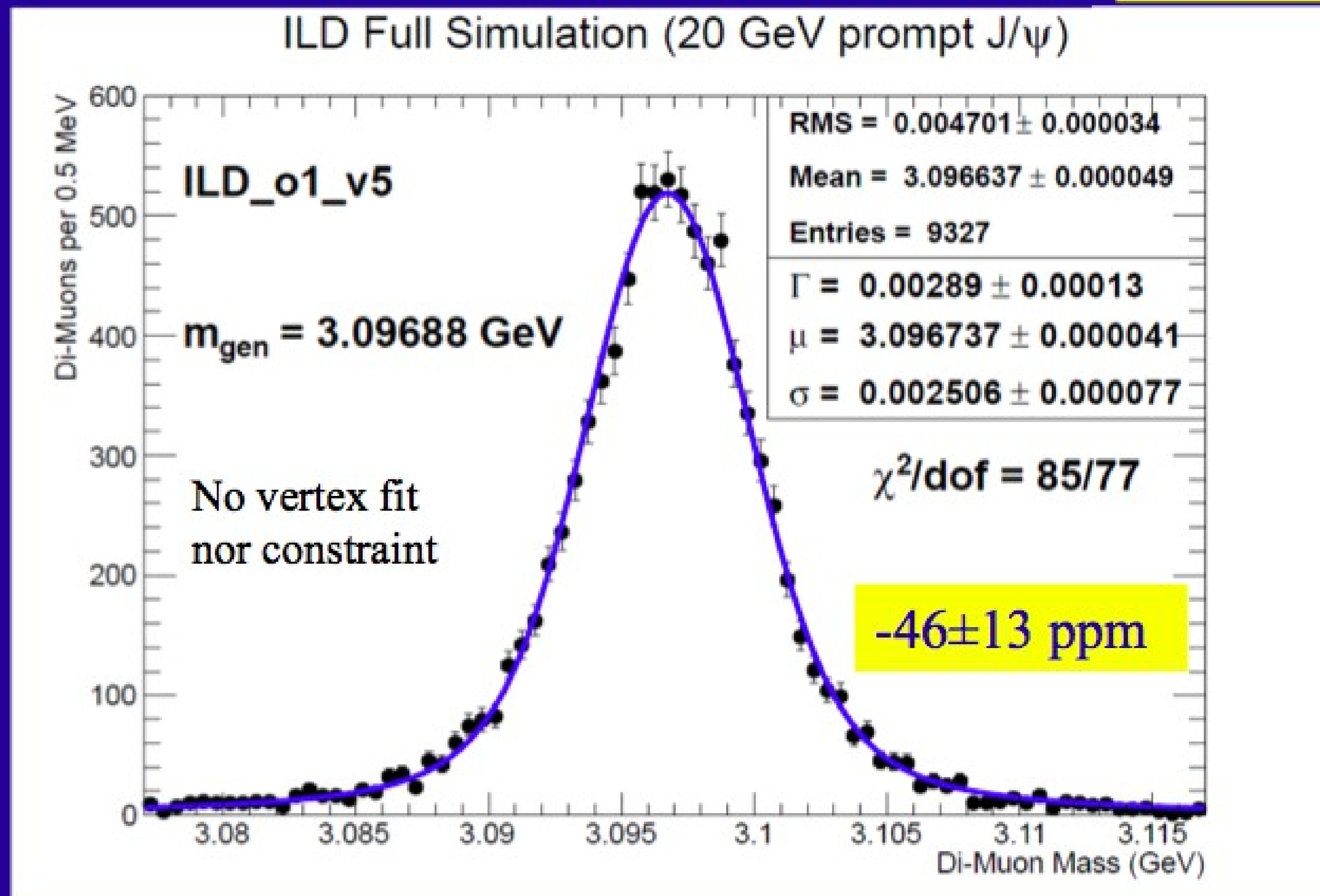
G.W. Wilson

Full Simulation + Kalman Filter

10k "single particle events"

$\sqrt{s}=m_Z$

Work in progress – likely need to pay attention to issues like energy loss model and FSR.



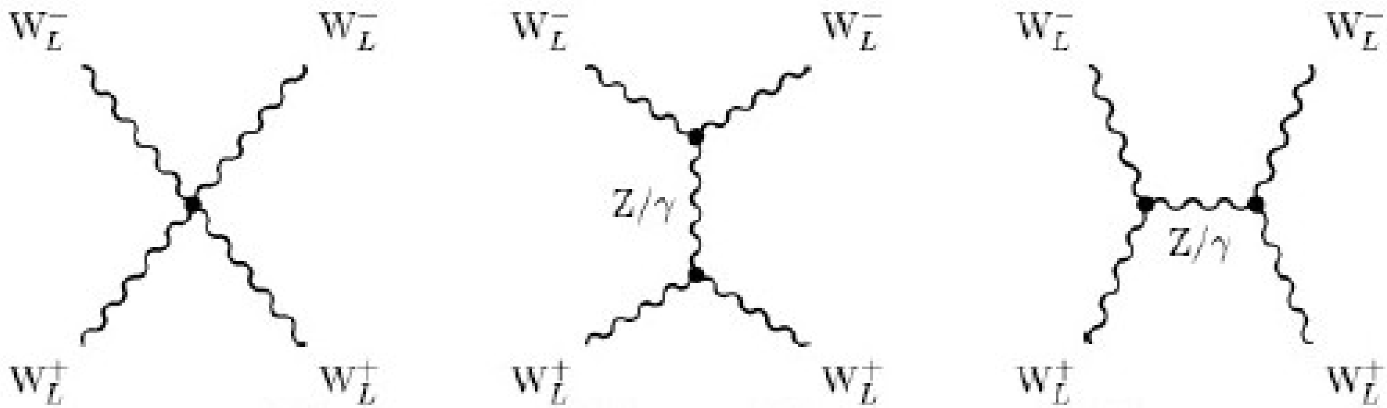
Preliminary statistical precision similar.

More realistic material, energy loss and multiple scattering.

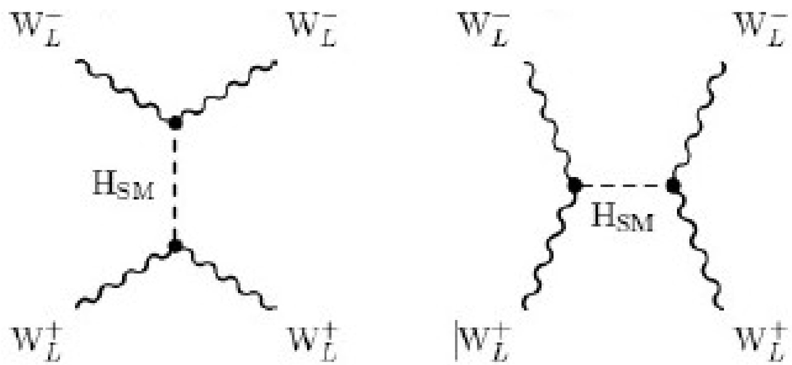
Empirical Voigtian fit.

G.W. Wilson

Scattering of (longitudinally polarised) W Bosons



Violation of unitarity @ √s≈1 TeV

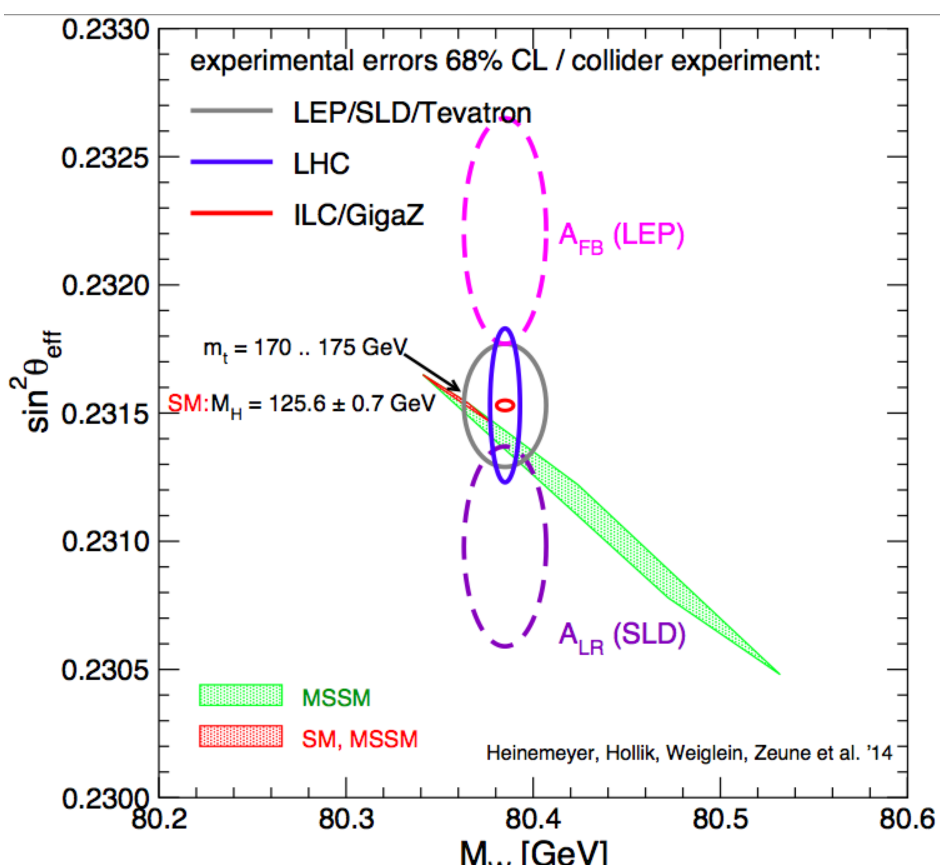


Counter terms

- **Before 4th of July 2012 one of the strongest motivations for a light Higgs**
- **Still "one of the most important physical observables in the EW sector"**
  - **→ Search for deviations from the electroweak structure of the SM**
  - **→ Sensitive to new physics, i.e. Strongly interaction light Higgs**

  No activity since 2006!

(Last but not least) GigaZ



- Final word on $\sin\theta^{l}_{eff}$!

  Needs polarised positrons!

- Clarify a standing discrepency between AFB and ALR

  both are the most precise measurements of their kind

- Important/Crucial consistency Test of SM

  (in presence and absence of new physics)

- Opportunity to improve Z mass

Shopping list ...

- Top Physics
  - Vertex charge for A_{FB} (beneficial to other studies)
  - Control of relevant parameters (lumi, polarisation)
  - Influence of higher order correction (Close collaboration with theory)
    - Uncertainty of 0.5% that you can't improve renders lumi above 1ab-1 at 500 GeV rather useless (at the example of mass reach in ED scenario)
  - More on interpretation of results
    - We have beautiful prospects to strengthen the physics case of the ILC
- Mass measurement at threshold mostly influenced by machine parameters
  - however Influence of BS overestimated in the past
  - ISR you can't change
- Make sure that we don't miss something
  - Coherent effort has started (1st top workshop)
- Synchronise event selection/background suppression
  - Several analyses with each a different cut scenario

- W Physics and beyond
  - Obvious benefits from ultimate precision
  - Needs excellent control of momentum
  - Proposal to measure J/Psi beneficial for other detectors
  - **W/Z physics requires the strategic decision on low energy running!**
    - Potential is there but requires machine adjustments

Who is working on top quark physics?

Group	Topic	Midterm goals
University of Vienna	Top mass theory	Elw./unstable particle for σ_{tot}.
MPI Munich	Top mass experiment	
University Tohoku	$t\bar{t}$ threshold	A_{FB} at threshold
WHIZARD [1]	$t\bar{t}$ threshold Anomalous couplings	Correct NLL/NLO matching
GRACE	Elw. corrections	Elw. NLO for polarised beams
KEK	Japanese contact for top studies within TYL[1]	
LAL	Top couplings experiment Elw. corrections Phenomenology French contact for top studies within TYL	b charge determination Collab. with GRACE/New observables Interpretation of results
IFIC	Top couplings experiment Elw. corrections Phenomenology	Role of single top Collab. with Spanish theory groups Interpretation of results
DESY Zeuthen	Top couplings theory	"Resurrection" of NLO calculations

[1] French-Japanese virtual laboratory

'Stock taking' at Top@LC Workshop at LPNHE (March 2014)
https://agenda.linearcollider.org/conferenceProgram.py?confId=6296
First one of a series
Coherent approach within LC, contact to theory and LHC

Backup

Summary and outlook

- The ILC is the right machine for precision physics in the range m_Z – 1 TeV

- Rich program of top quark physics with 'exciting' prospects
  - Precision on top mass ~50 MeV =>
    'Final word' on vacuum stability of the universe
  - Test of models with extra dimensions and/or compositeness
    Btw.: Composite top (or Higgs) would be new physics

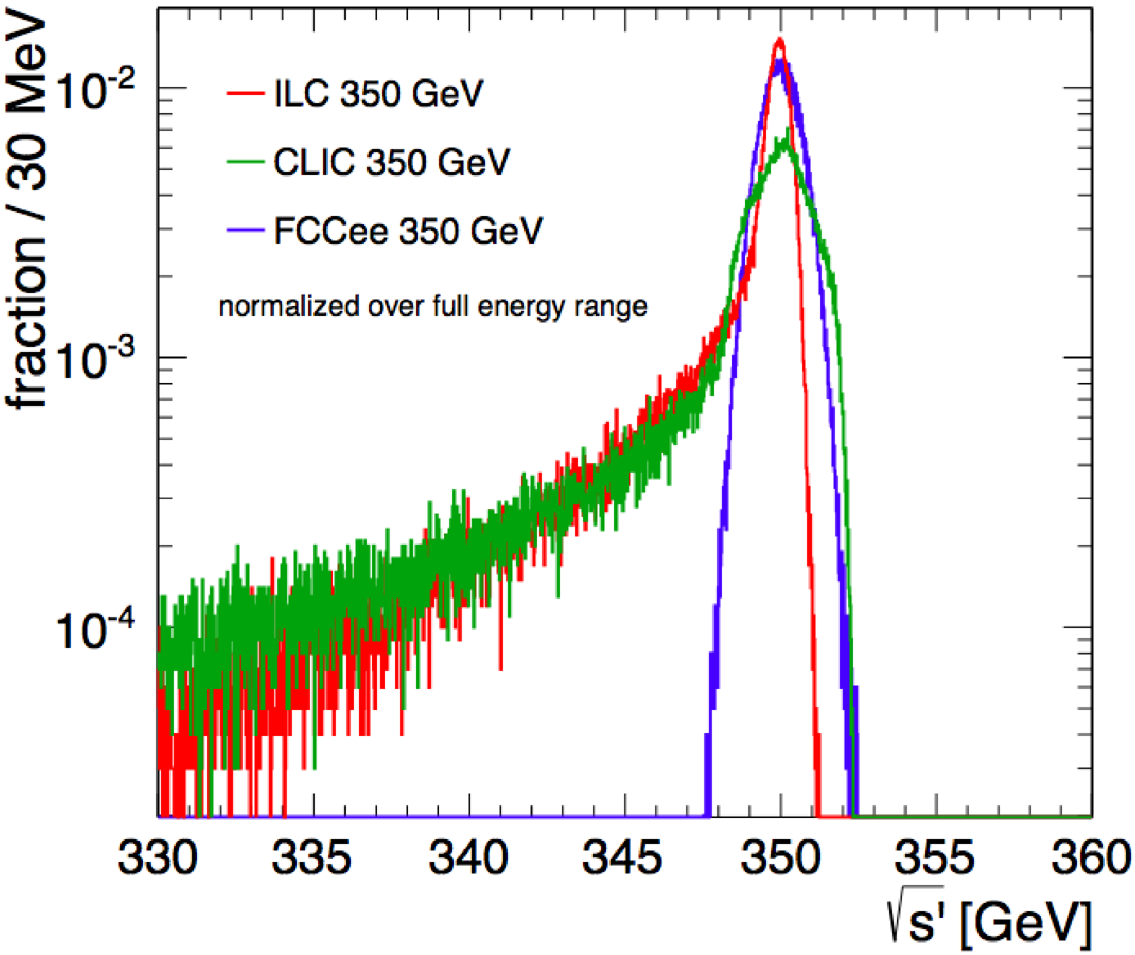
- W physics is essential part of electroweak tests
  - Important SM parameter
    Needs control of beam energy (→ benefit for entire physics programme)
  - New resonances or (not discussed here) extra dimensions
    Sensitivity up to 5 TeV
  - WW->WW studies need update with full simulation

- Both, top and W programme would benefit from running at 1 TeV

- Both programmes need consistent work on experimental but also on theoretical side !!!

- GigaZ would be ideally complement to precision physics at higher energies

Fighting rumours - The luminosity spectrum at different colliders



- The luminosity spectrum at different e+e- colliders
  - ILC & CLIC – Full machine simulations (Guinea Pig)
  - FCCee (TLEP) Gaussian, 0.19% sigma (including BS)

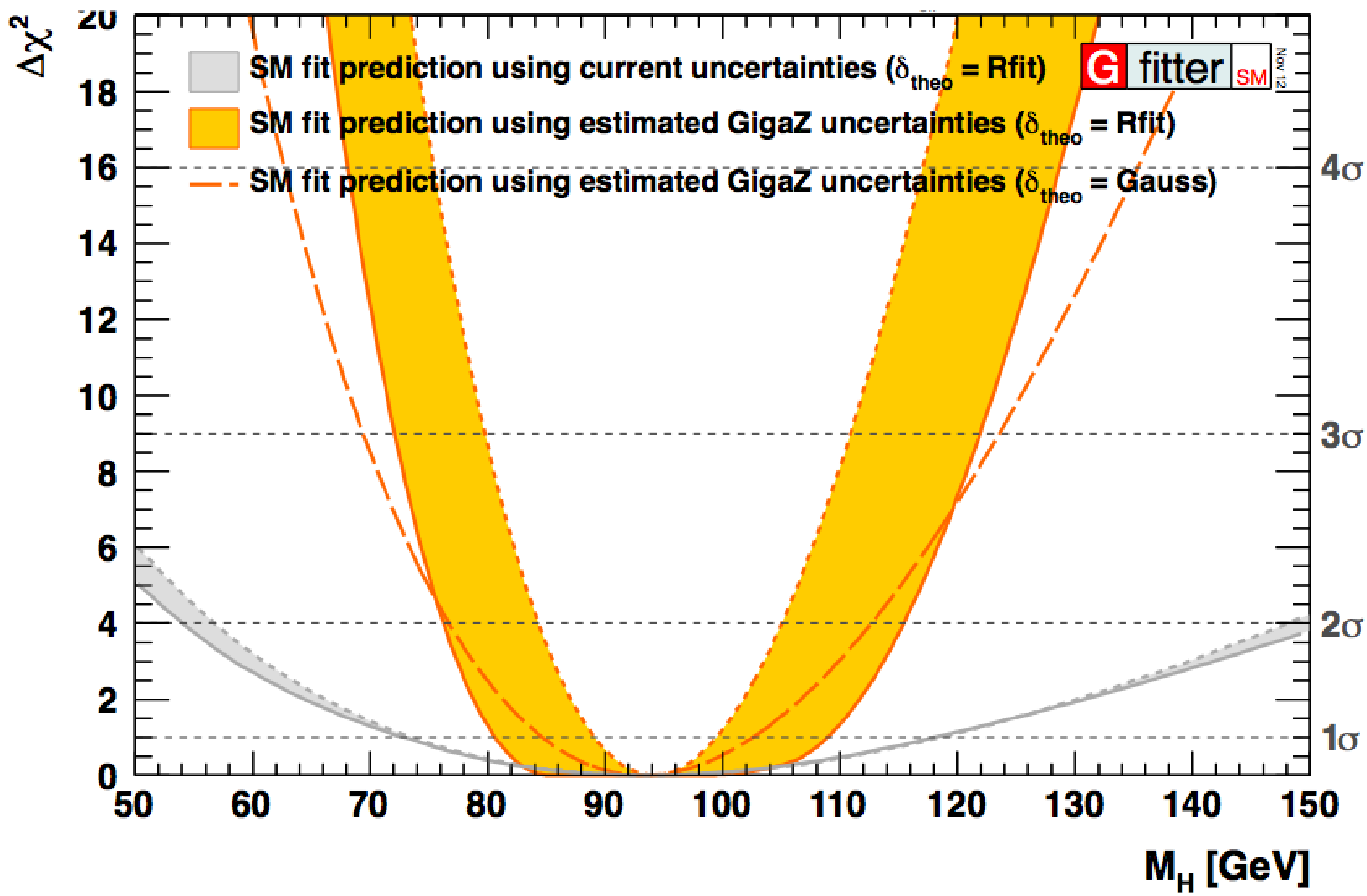
F. Simon
AWLC14

Giga Z

Running on Z-pole would allow for 'LEP/SLD' within a couple of days
Again polarised beams

Example I: W mass could be determined to about 6 MeV

Example II: Electroweak fit based on GigaZ



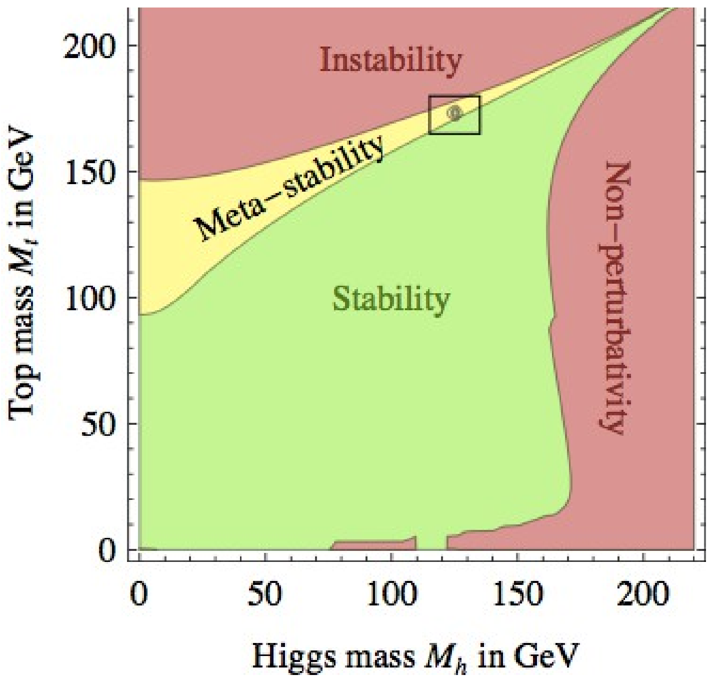
$$m_h = 92.3^{+16.6}_{-11.6}\,\mathrm{GeV}$$

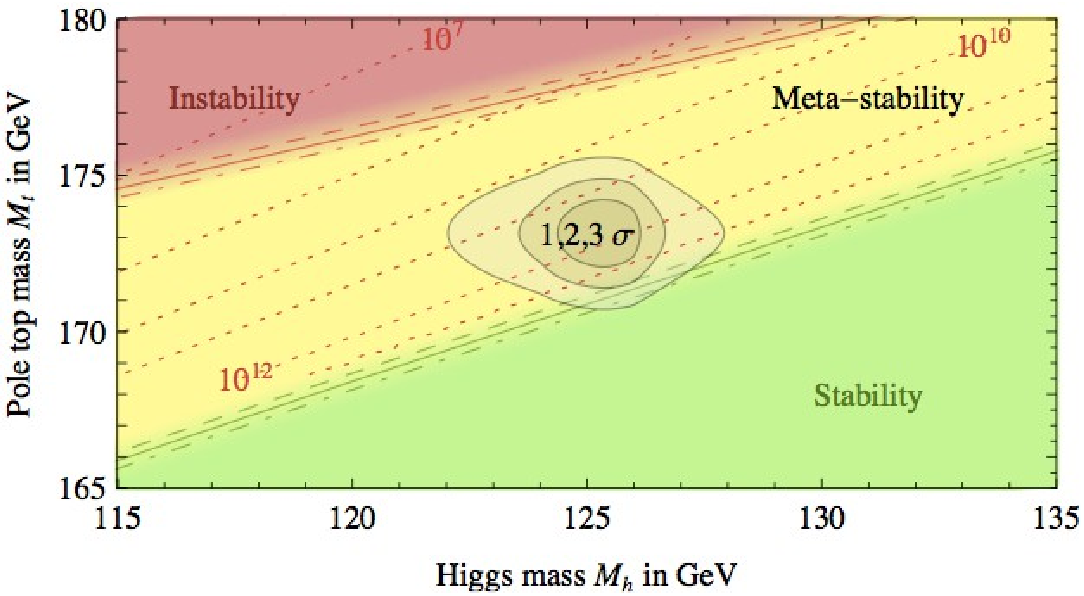
=> Nearly 4σ deviation
From mass of scalar
Resonance discovered
At LHC

Vacuum stability and top quark mass

Degrassi et al.
arXiv:1205.6497

$$M_h\ [\text{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\text{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\text{th}}\ .$$

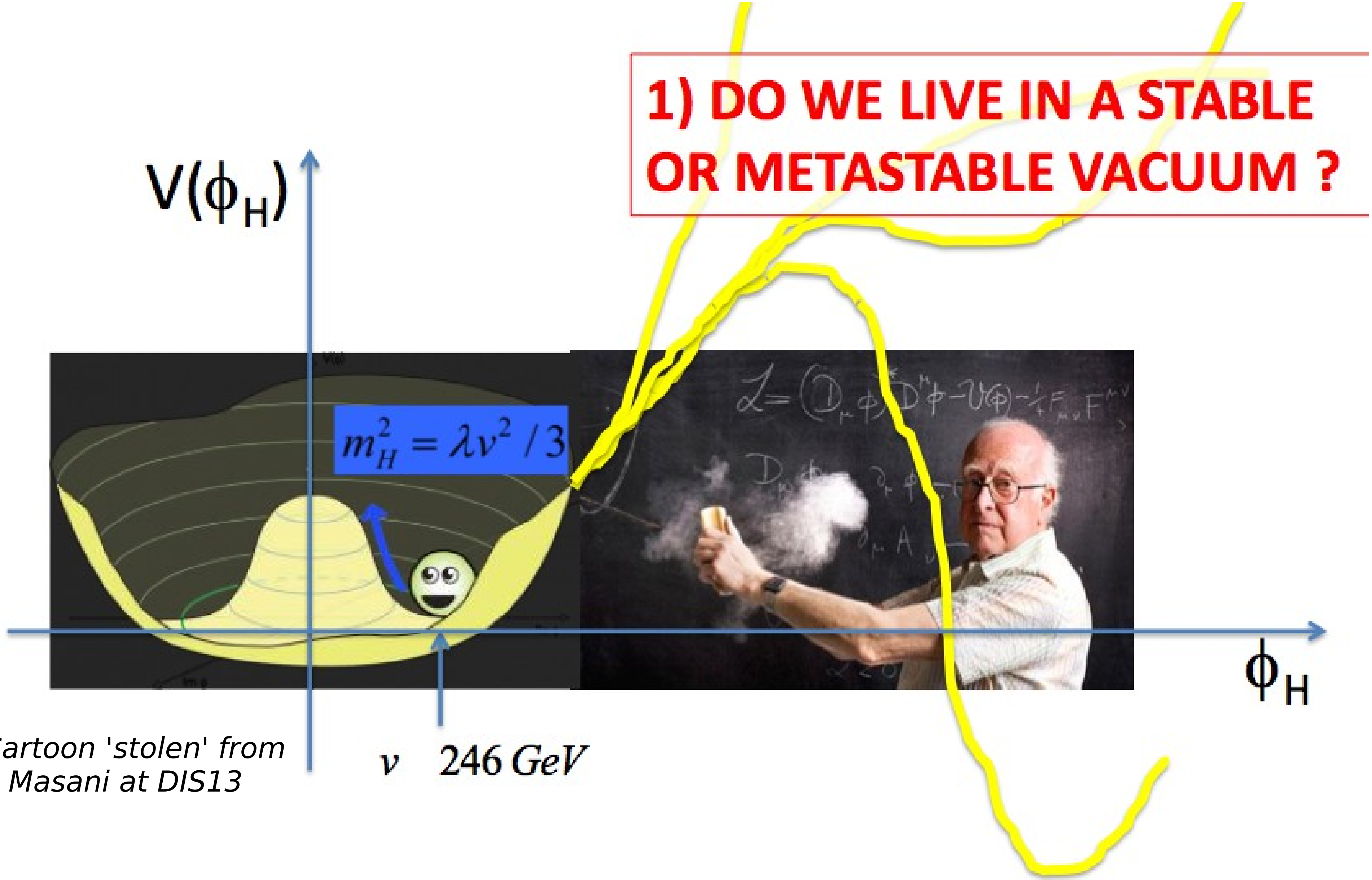




Type of error	Estimate of the error	Impact on M_h
M_t	experimental uncertainty in M_t	±1.4 GeV
α_s	experimental uncertainty in α_s	±0.5 GeV
Experiment	**Total combined in quadrature**	**±1.5 GeV**
λ	scale variation in λ	±0.7 GeV
y_t	$\mathcal{O}(\Lambda_{\text{QCD}})$ correction to M_t	±0.6 GeV
y_t	QCD threshold at 4 loops	±0.3 GeV
RGE	EW at 3 loops + QCD at 4 loops	±0.2 GeV
Theory	**Total combined in quadrature**	**±1.0 GeV**

Uncertainty on **(pole)** top quark mass dominates uncertainty on stability conditions

Motivation for precise top quark mass



Cartoon 'stolen' from I. Masani at DIS13

Equations for cross section, A_{FB} and F_R

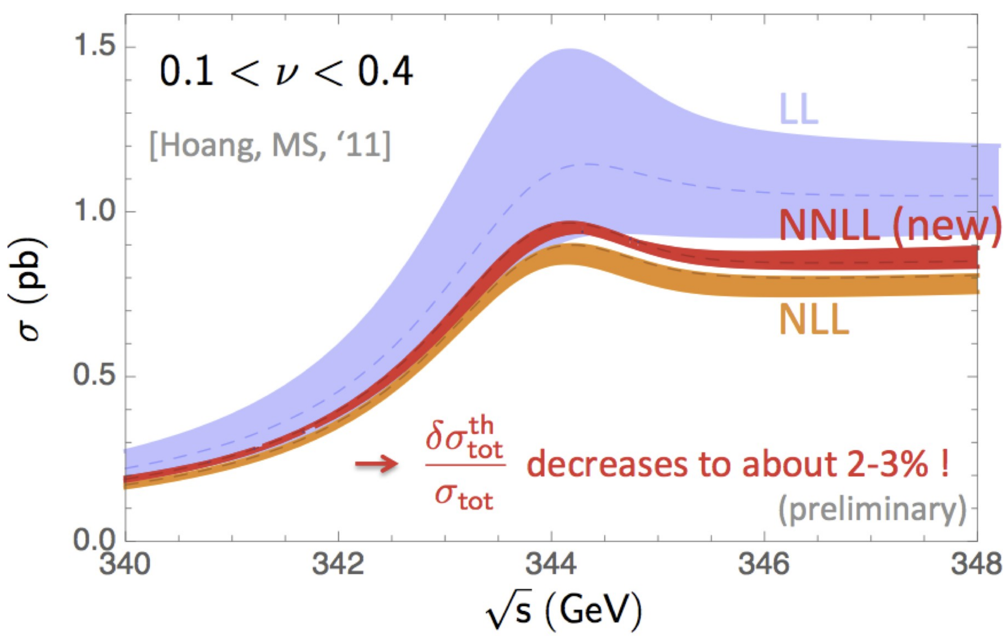
$$\sigma_I = 2\mathcal{A}N_c\beta\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right],$$

$$(A^t_{FB})_I = \frac{-3\mathcal{F}^{I'}_{1A}(\mathcal{F}^I_{1V}+\mathcal{F}^I_{2V})}{2\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right]},$$

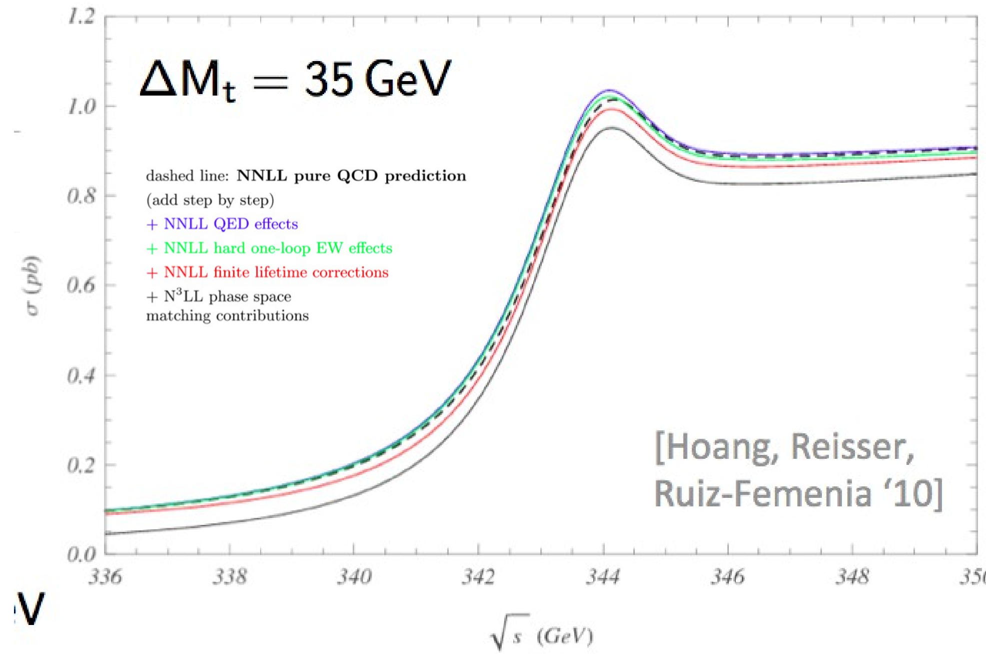
$$(F_R)_I = \frac{(\mathcal{F}^I_{1V})^2(1+0.5\gamma^{-2}) + (\mathcal{F}^{I'}_{1A})^2 + 2\mathcal{F}^I_{1V}\mathcal{F}^{I'}_{1A} + \mathcal{F}^I_{2V}(3\mathcal{F}^I_{1V}+2\mathcal{F}^{I'}_{1A}) - \beta\mathcal{F}^I_{1V}\mathfrak{Re}(\mathcal{F}^I_{2A})}{2\left[(1+0.5\gamma^{-2})(\mathcal{F}^I_{1V})^2 + (\mathcal{F}^{I'}_{1A})^2 + 3\mathcal{F}^I_{1V}\mathcal{F}^I_{2V}\right]}.$$

Top quark mass – Theoretical accuracies

QCD



QCD + electroweak

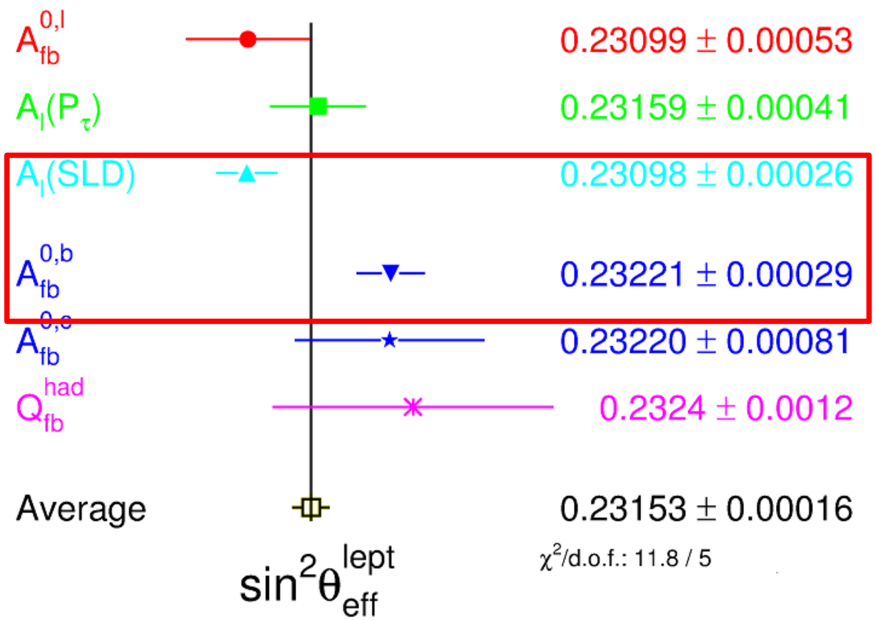


Correct resummation of
Non relativistic logs ~v

Theoretical uncertainties at the 2-3% level
=> Threshold scan theoretically well understood

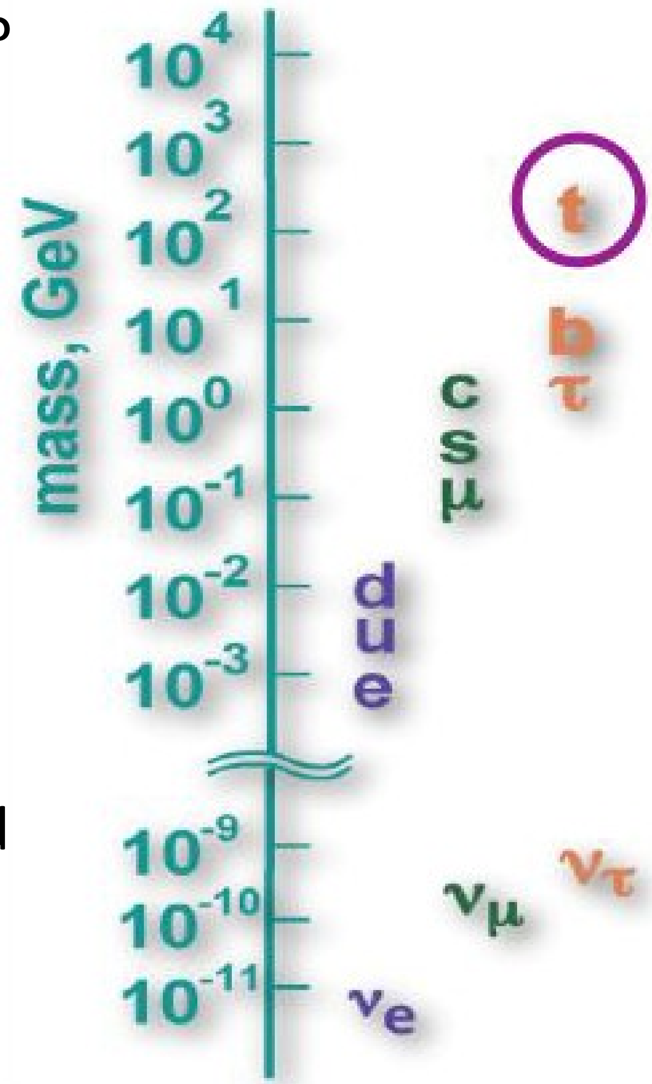
The top quark and flavor hierarchy

- Flavor hierarchy ? Role of 3rd generation ?



- Top quark : no hadronisation → clean and detailed observations

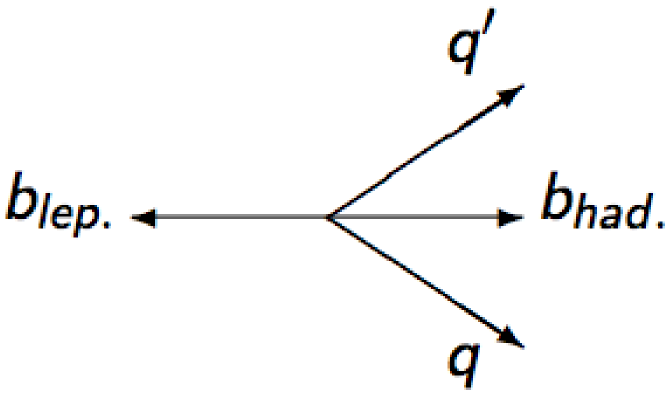
- Redo measurements of A_{LR} and A_{FB} with the top



Experimental challenge b-charge reconstruction - Motivation

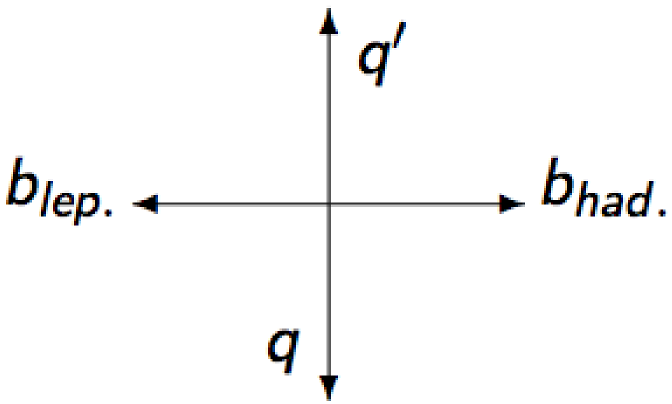
- To measure A_{FB} in fully hadronic decays there is no choice

- In semi-leptonic decays there is the charged lepton but ....



Right handed electron beam:

- mainly right handed tops In final state (V-A)
- <u>Hard W</u> in flight direction of Top and soft b's
- Flight direction of t from flight direction of W



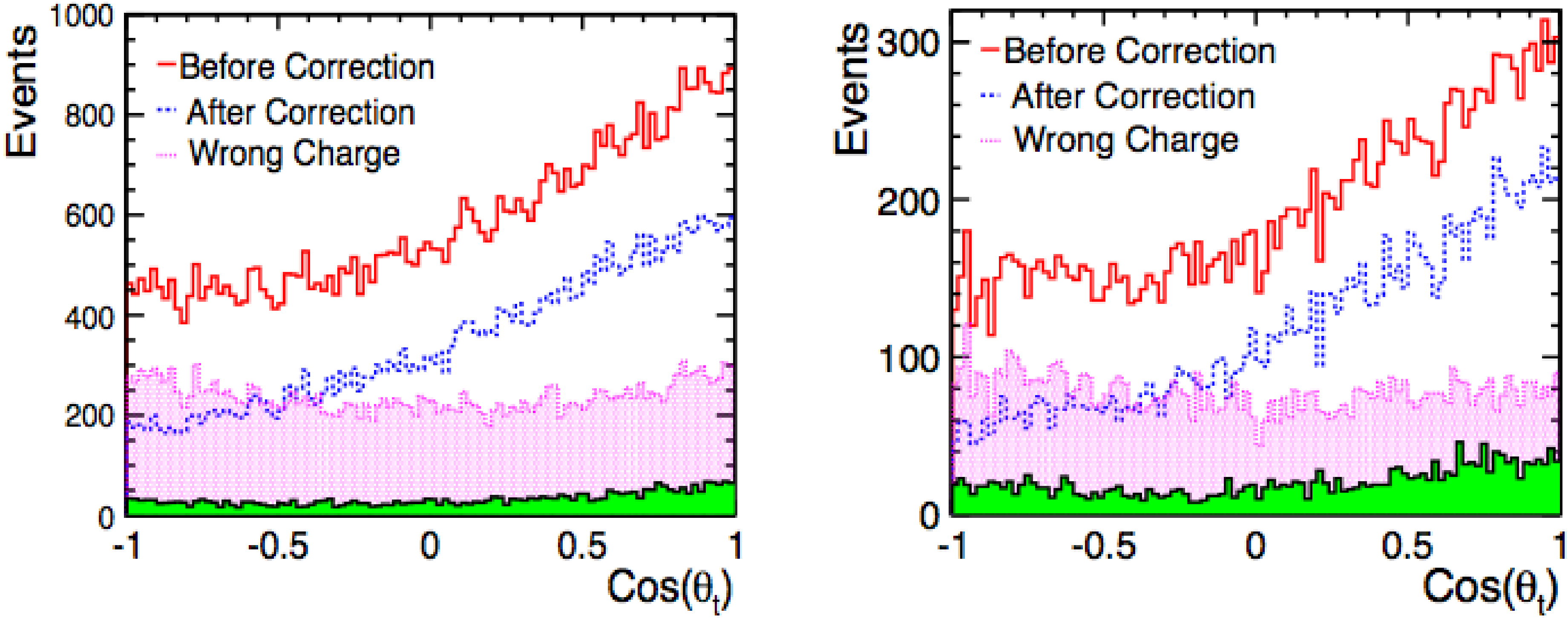
Left handed electron beam:

- mainly left handed tops
- <u>Hard b</u> in flight direction of Top and soft W's
- Flight direction of t from flight direction of b

=> Wrong association ↔ top flip

Measurement of b-charge to resolve ambiguities

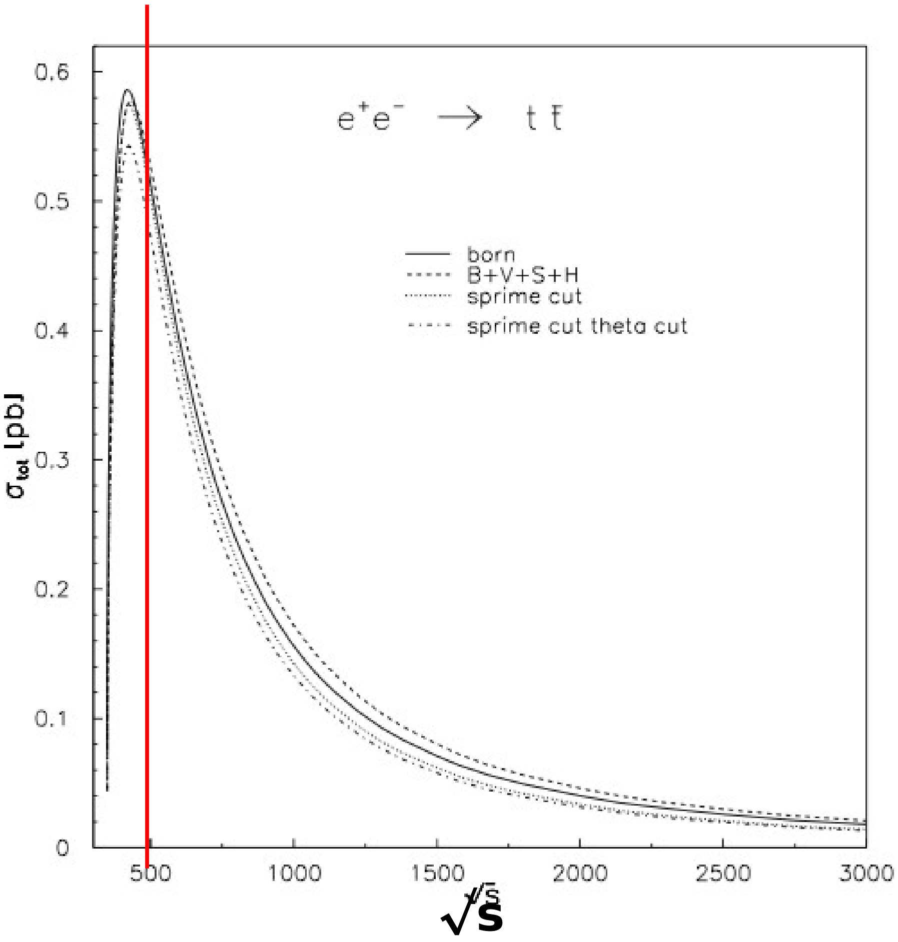
Top polar angle In fully hadronic top decays

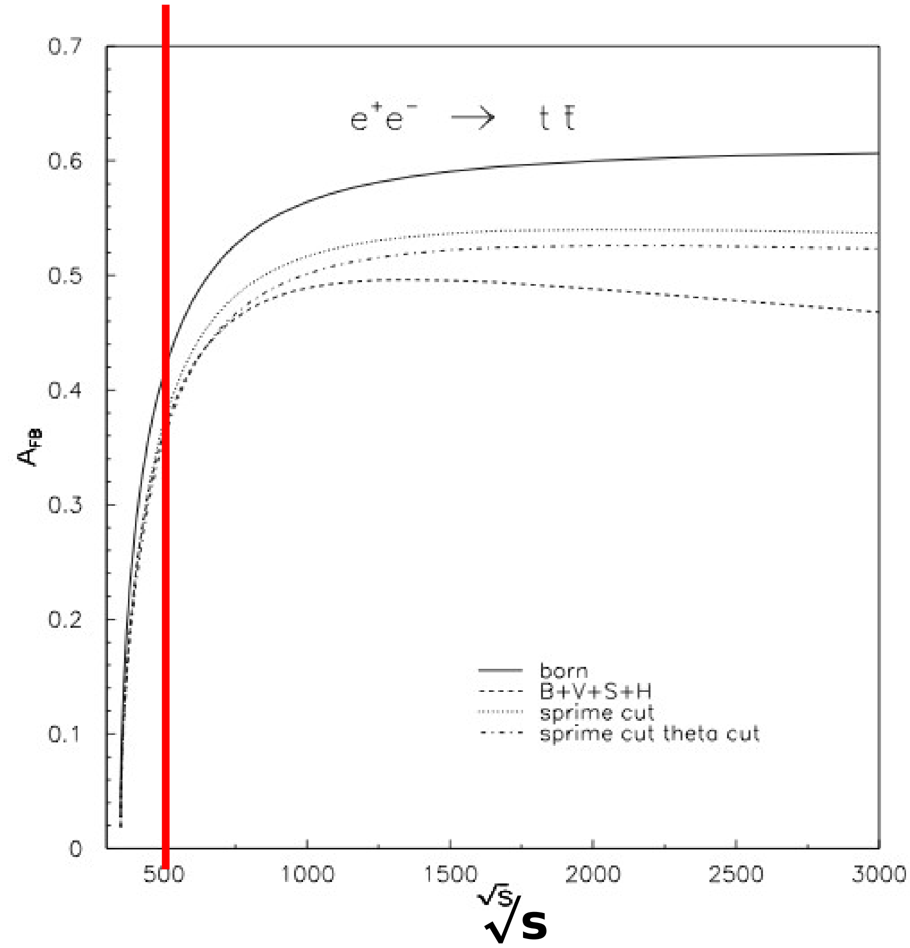


- In SL one has the lepton as handle and/or one can get along with harsh kinematic cuts (penalty on statistics)
- In fully hadronic on starts with harsh cuts but level of confusion is still not acceptable

  One could correct but would rely heavily on MC
- For combining SL and fully hadronic vertex charge measurement has to make a significant leap

500 GeV – Answers to yesterday's questions



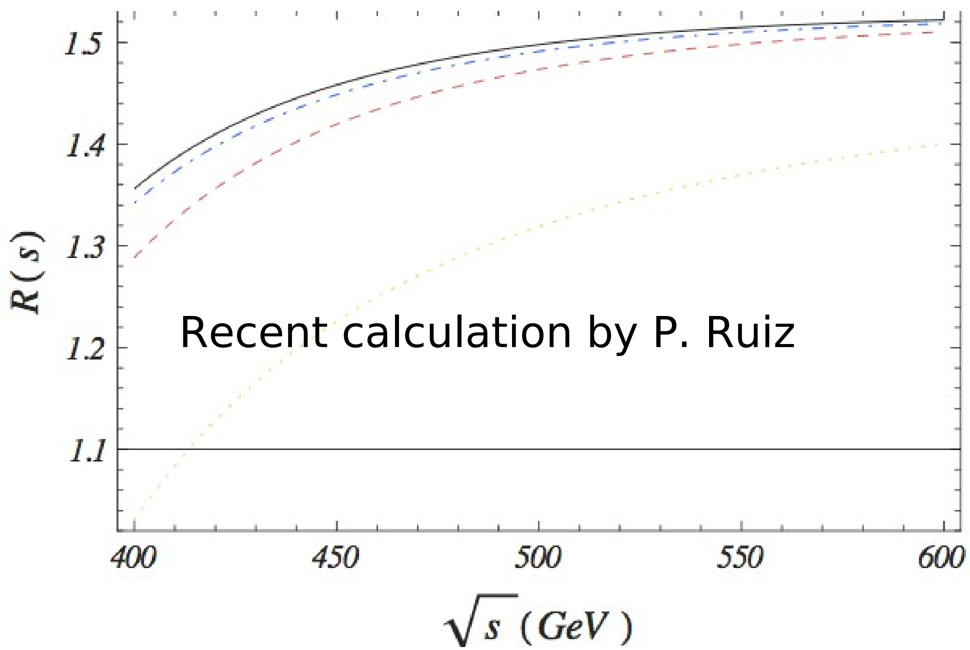


- Cross section close to maximum, A_{FB} well developed

- Other remarks: Need some velocity to get sensitive to chiral obervables (see backup slides)

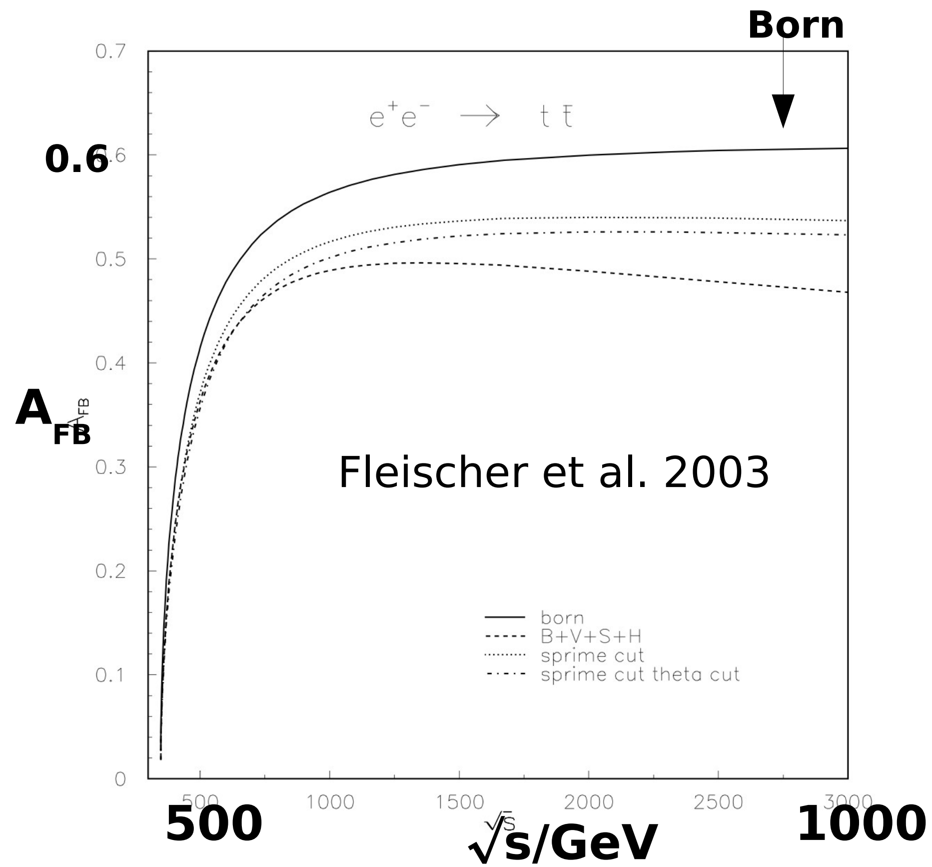
SM correction to Born process

QCD up to $O(a_s^3)$



- Well behaving perturbation series
- Small scale uncertainties <1%
- Size of next correction expected to be Smaller than 0.3% at 500 GeV

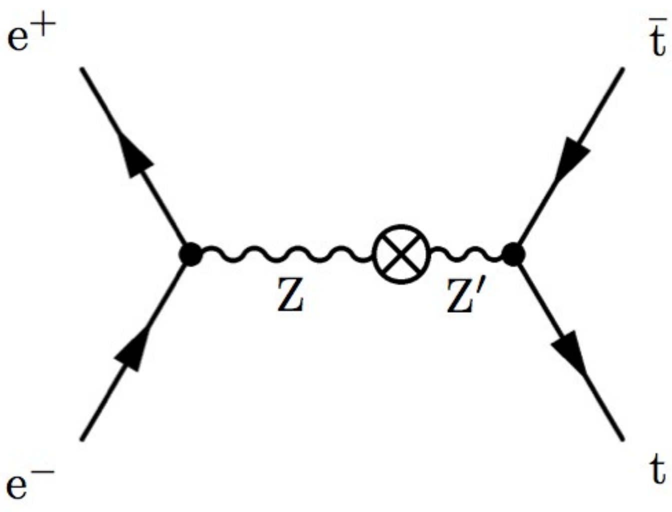
NLO electroweak

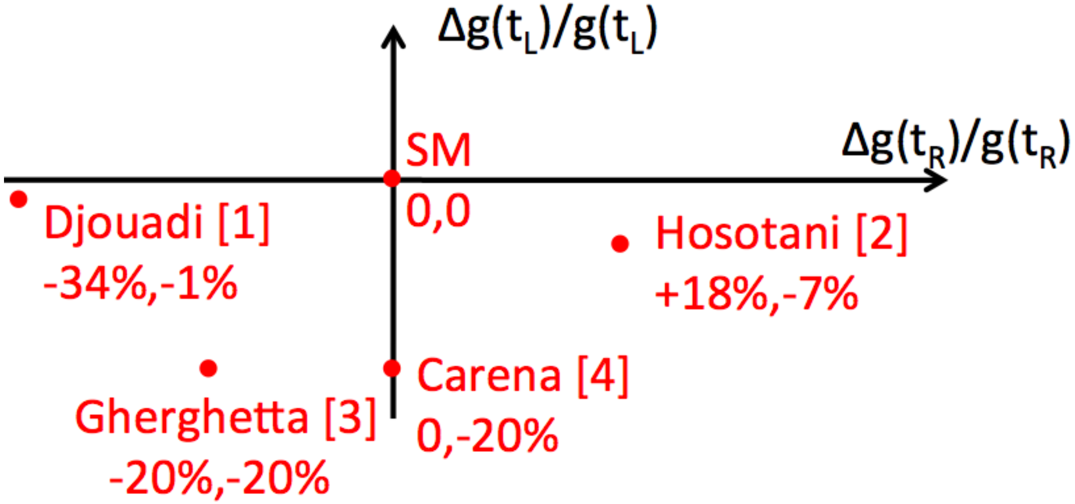


- Sizeable electroweak corrections to AFB (~15%)
- (To my knowledge) no estimation of size of next (i.e. NNLO correction) Needed for precision physics !(?)

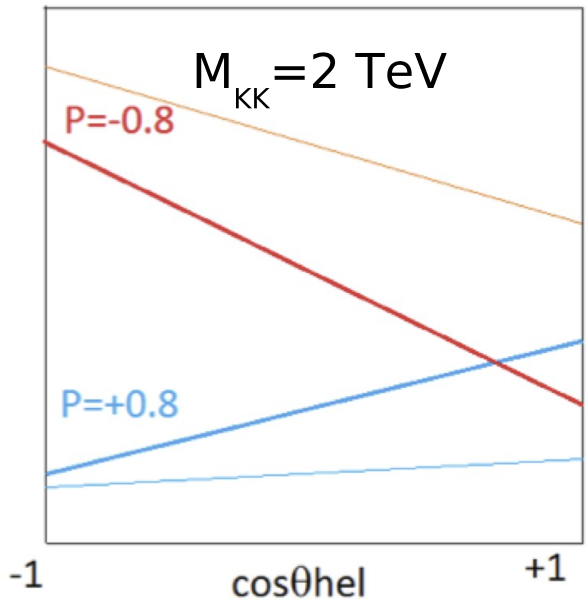
Top quark and new physics

New physics modify electroweak couplings to Z





Example: RS models with extra dimensions



ILC sensitive to M_{KK} masses up to 50 TeV

$(g\text{-}2)_t$

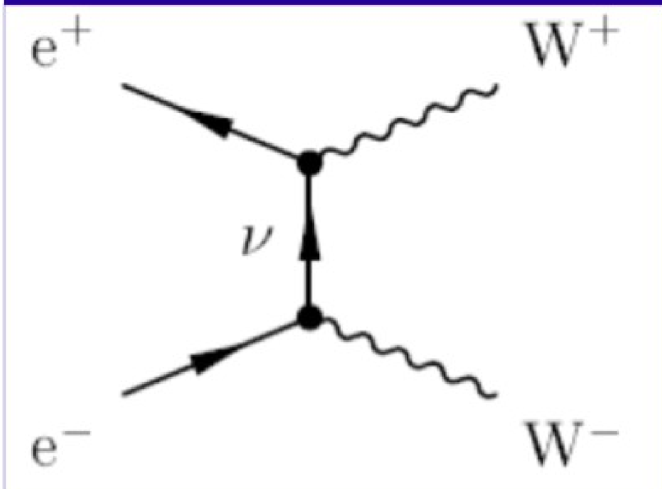
$$F_{2V}^{\gamma} = Q_t(g-2)_t/2$$

$$\delta F_{2V}^{\gamma} = \delta(g-2)_t \approx 0.1$$

$$\delta(g-2)_t \approx 0.1\% \propto m_t/M$$

=> Test of compositeness scale M up to 100 TeV

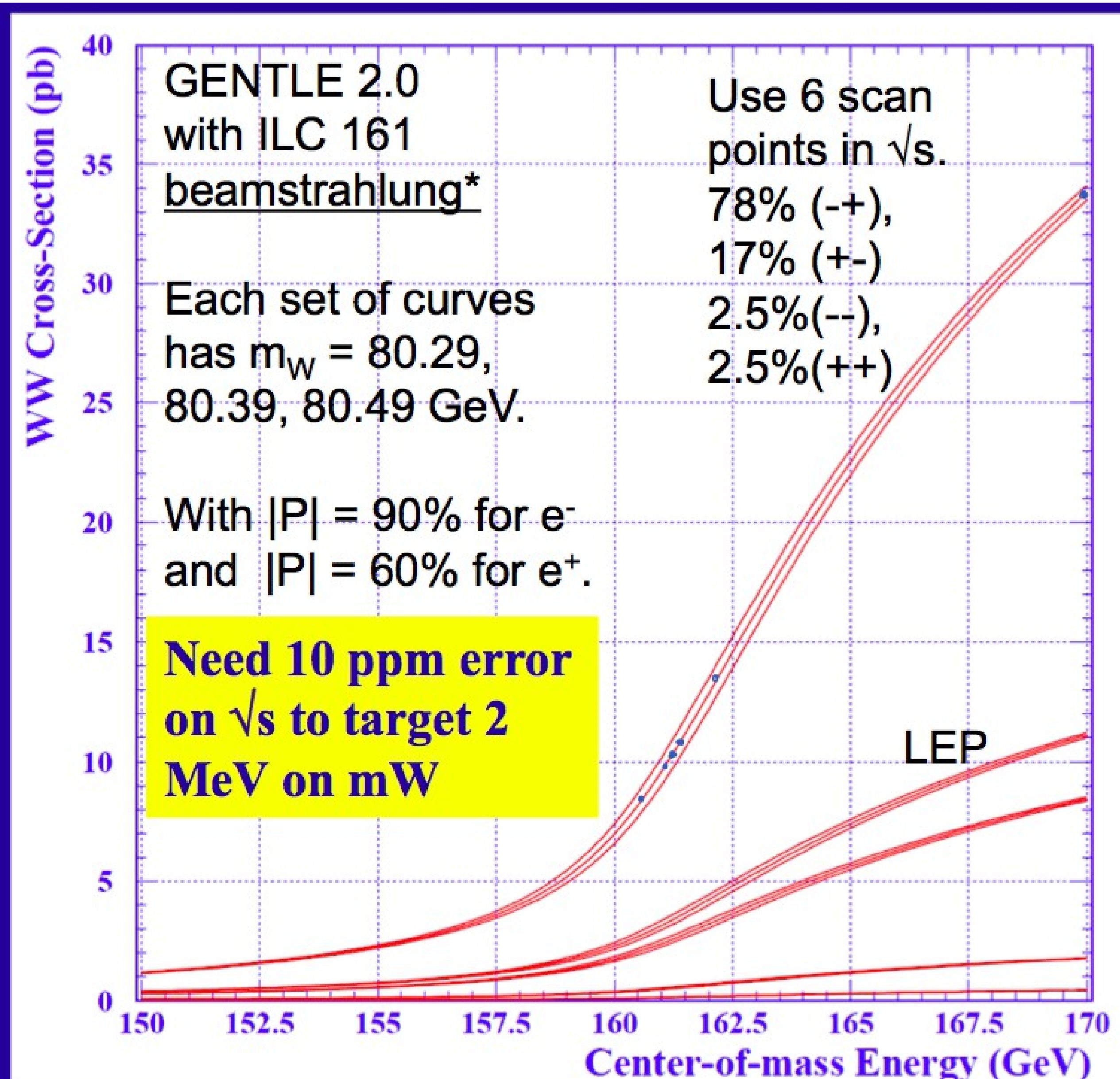
W mass through threshold scan



Use (-+) helicity combination of e- and e+ to enhance WW.

Use (+-) helicity to suppress WW and measure background.

Use (--) and (++) to control polarization (also use 150 pb qq events)



- +

0 0

- -

++

+-

Experimentally very robust. Fit for eff, pol, bkg, lumi

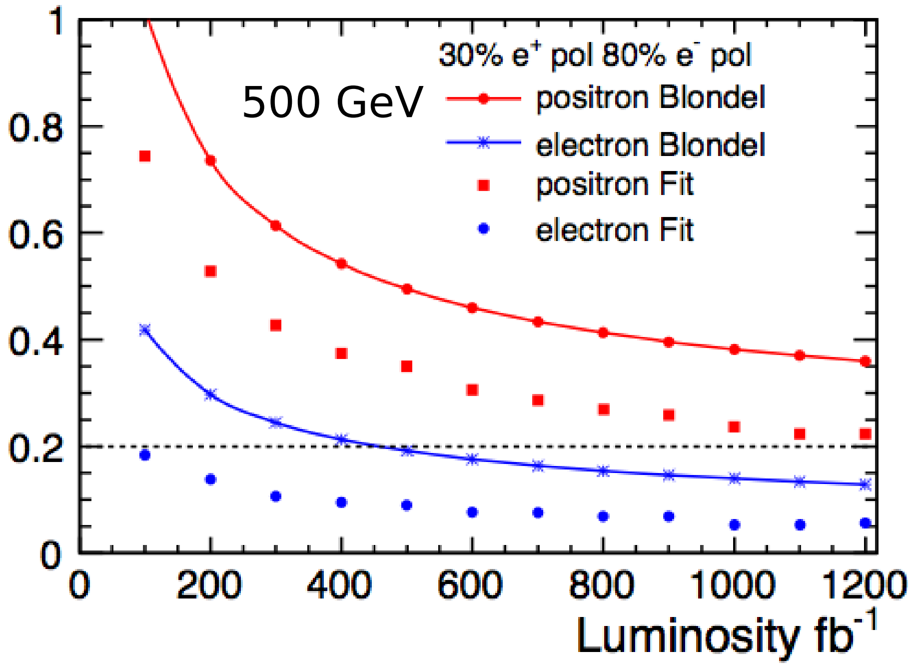
W production and beam polarisation

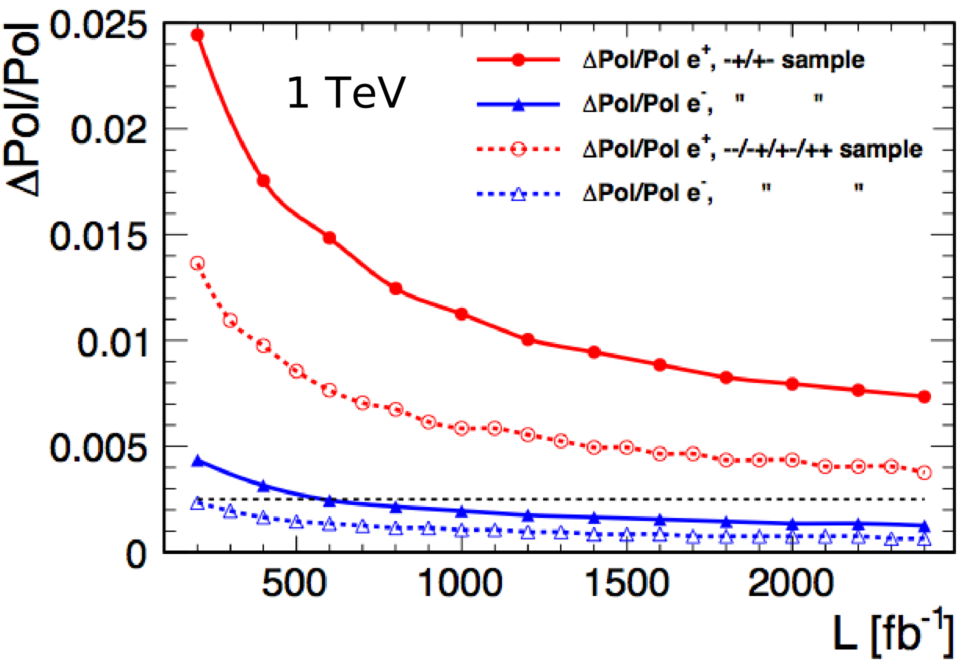
Polarisation measurement requires running at all combinations of beam polarisation: **++, +-,-+,--**

'Traditionally' – Blondel scheme

$$| P_{e^\pm} | = \sqrt{\frac{(\sigma_{-+} + \sigma_{+-} - \sigma_{--} - \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} + \sigma_{--} - \sigma_{++})}{(\sigma_{-+} + \sigma_{+-} + \sigma_{--} + \sigma_{++})(\pm\sigma_{-+} \mp \sigma_{+-} - \sigma_{--} + \sigma_{++})}},$$

Alternative: Fit to angular distributions (see PhD thesis I. Marchesini or LC-REP-2013-009)

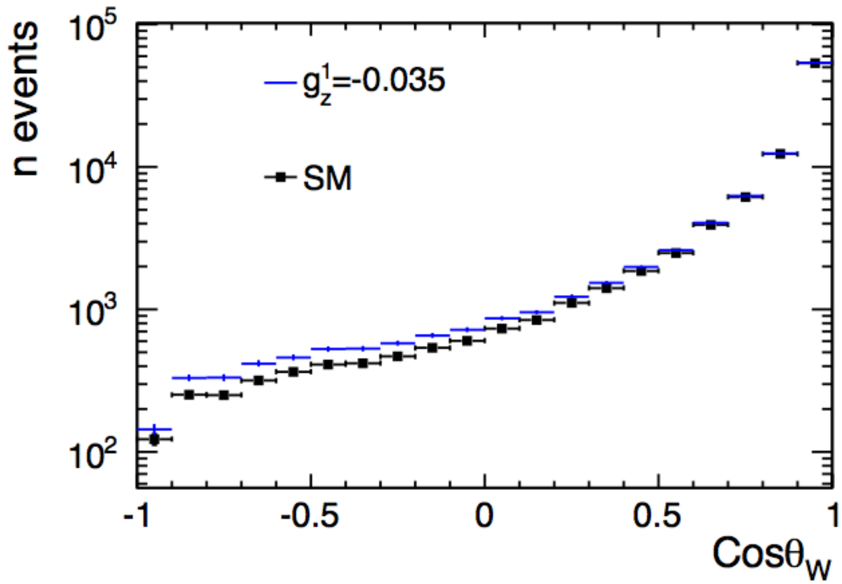




- Precisions: <0.2% for P(e-), ~0.35% for P(e+)
- Angular fit superior to Blondel scheme

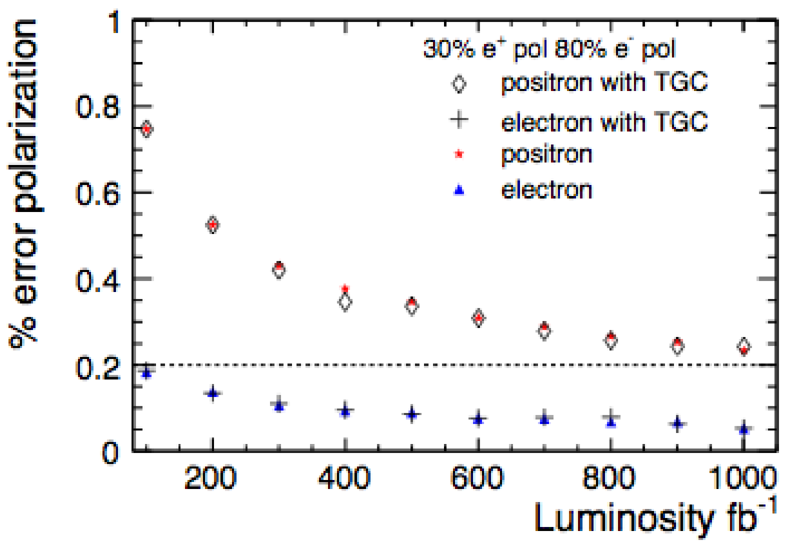
Angular fit scheme does not need running at ++,-- (albeit it benefit from it)

W production and TGCs

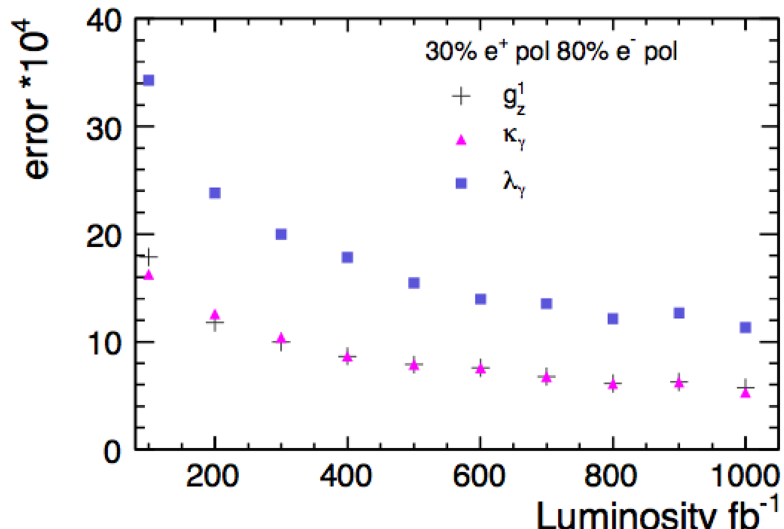


Example: Influence of **anomalous WZ coupling** on W scattering angle

Impact on P-measurement



Precisions on TGC

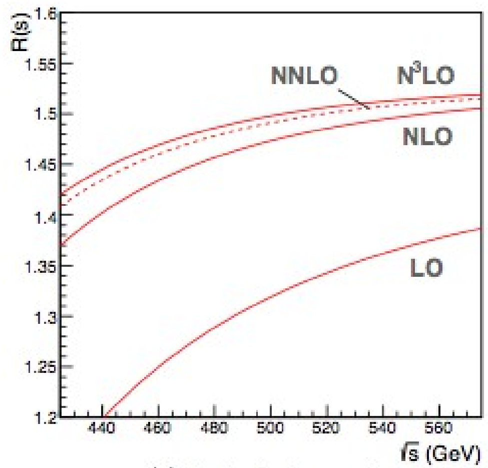


Uncertainty ~10^{-3}

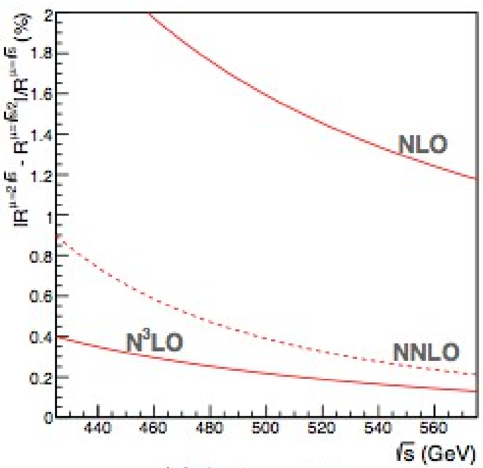
Anomalous TGC do not compromise precision

Theoretical uncertainties

✳QCD corrections are known up to N³LO



(a) Perturbation series

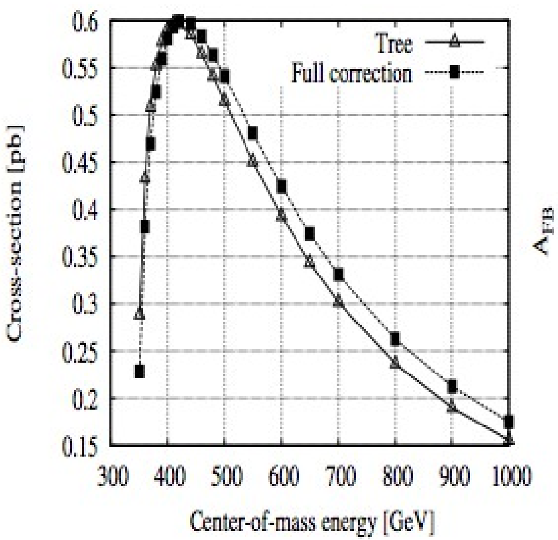


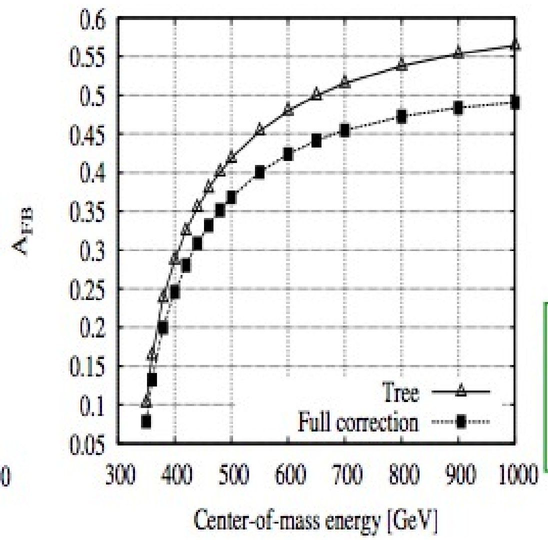
(b) Scale variations

QCD correction (N^3LO) is at the per mil level

Kiyo, Maier, Maierhofer, Marquard, NCP B823 ('09)
Bernreuther, Bonciani, Gehrmann, Heinesch, Leineweber. NPB750 ('06)
Hoang, Mateu, Zebarjad, NPB813 ('09)

✳Electroweak corrections are known at one-loop level





EW correction at one-loop is
~5% for cross section
~10% for A_{FB}

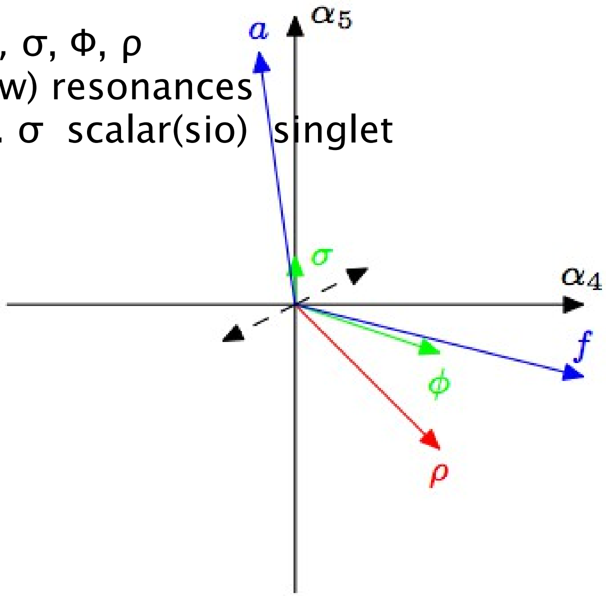
Fleischer, Leike, Riemann, Werthenbach, EJPC31 ('03)
Kheim, Fujimoto, Ishikawa, Kaneko, Kato, arXive:1211.1112

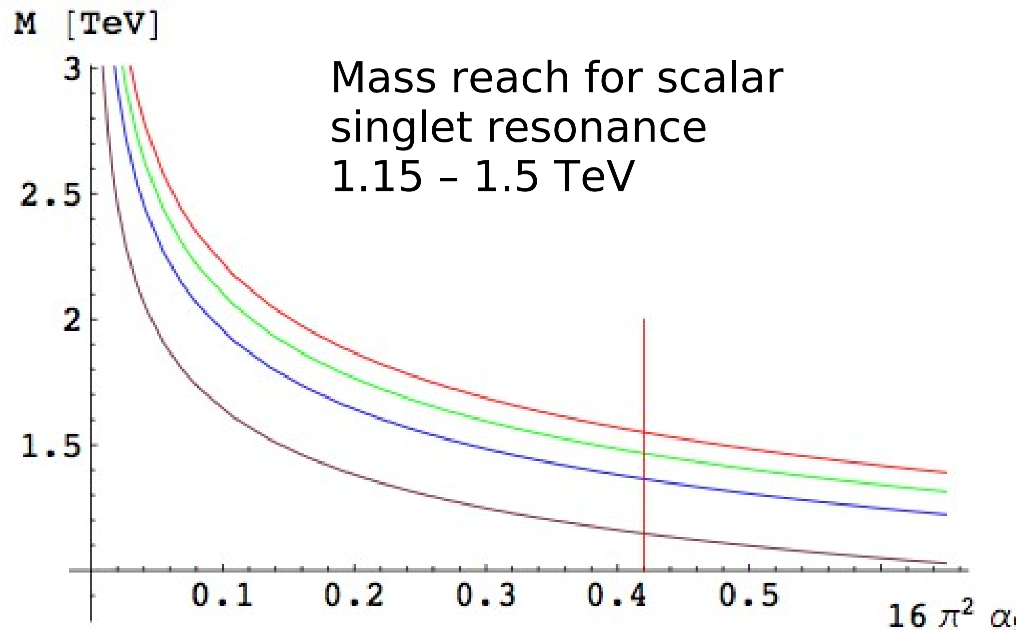
Analyses WW -> WW scattering

Existing analysis in terms of chiral Lagrangian
No Higgs but can be easily added

Deviation from
SM couplings expressed as ai

a, f, σ, Φ, ρ
(New) resonances
e.g. σ scalar(sio) singlet





Mass reach for scalar
singlet resonance
1.15 – 1.5 TeV

Up to ~ 5 TeV for other types of resonances

General remarks:

- Study most important to unveil electroweak structure
- Analysis at 1 TeV
- Results taken from hep-ph/0604048 (fast simulation)
- Analysis made no attempt to isolate W_L bosons