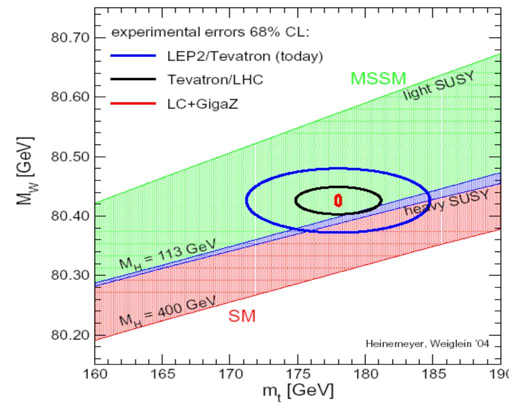
VLCW06, Vancouver, July 19-23, 2006

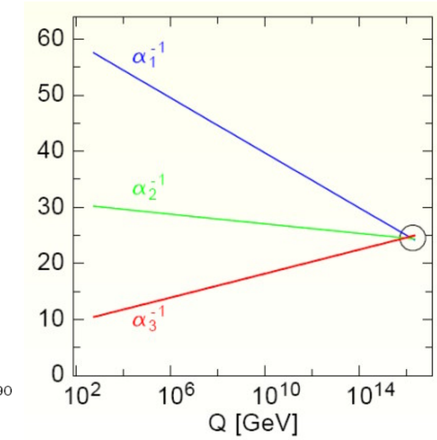
Precision Physics WG Summary

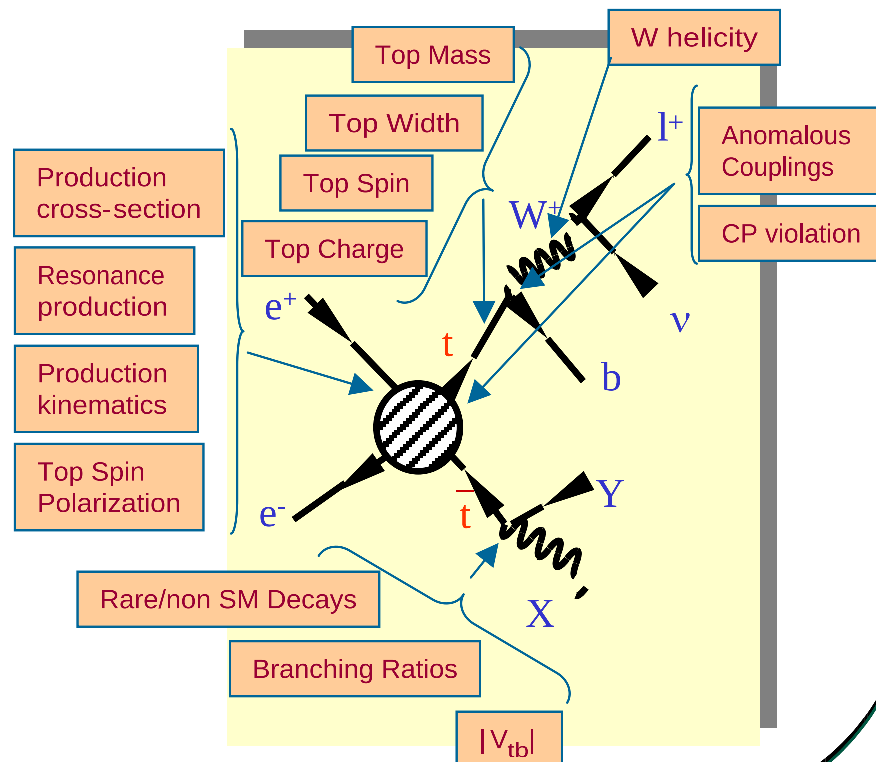
Conveners: Frank Petriello, Doreen Wackeroth, Aurelio Juste

The Power of Precision Physics

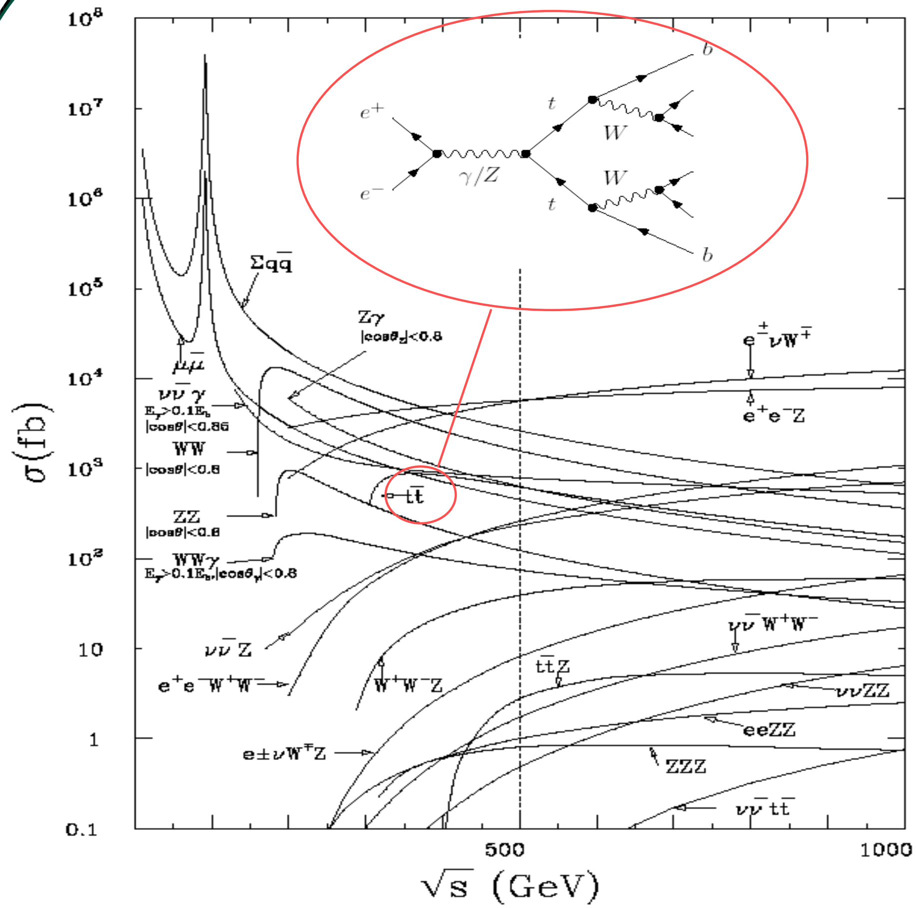
- The LHC will be probing the relevant energy scale and should definitely discover signs of the EWSB dynamics.
- The main strength of the ILC resides on its precision and model independence ⇒ will complement the LHC by providing essential information to interpret and exploit these discoveries.
- Here we cover Top, QCD and EW Physics, although at the ILC, precision measurements will extend well beyond these topics.
- Precise measurements of EW (e.g. M_W) and QCD (e.g. α_s) parameters essential to provide precise theoretical calculations, constrain models of New Physics, extrapolate to GUT scale, …
- $m_t \sim 175$ GeV $\Rightarrow \lambda_t = \sqrt{2}\, m_t/v \approx 1$
  ⇒ The top quark may either play a key role in EWSB, or serve as a window to New Physics related to EWSB.
  Fully outlining the top quark profile will be critical to unravel the secrets of EWSB.



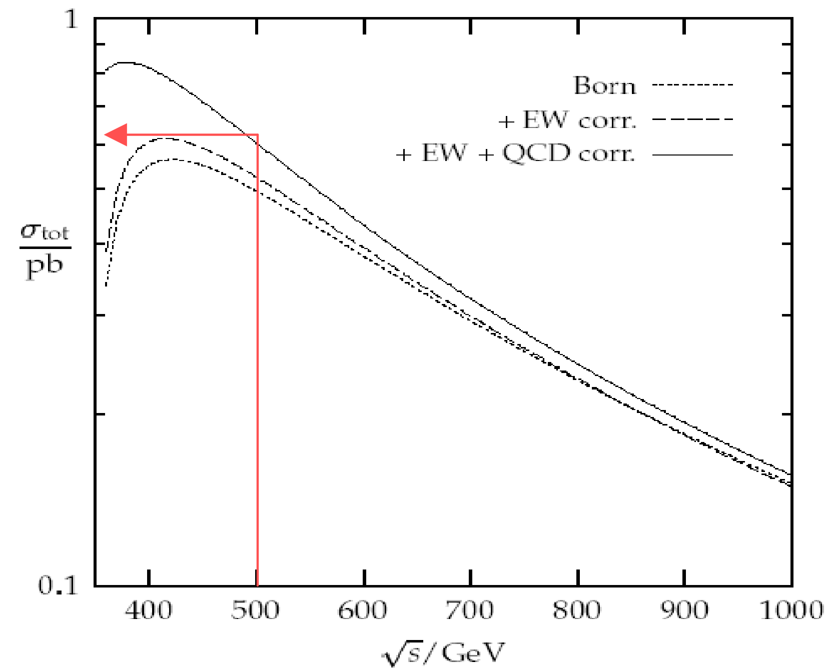




Top Production in e^+e^- Collisions



- Top pair production via γ/Z exchange dominates



σ_{tt}~0.6 pb at √s=500 GeV

⇒ ~200k events/year (L=2x10^{34}cm^{-2}s^{-1})

- The anticipated experimental accuracy must be matched with precise theoretical predictions

Available
- Total cross section
  - tt, threshold : NNLL QCD, N(LL) EW
  - continuum: O(α_s^2), O(α_{EW}), 2-loop Sudakovs
  - ttH : O(α_s), O(α_{EW}), tt threshold effects

Event generators
- $e^+e^-\rightarrow$(tt) $\rightarrow$WbWb: O(α_s)

Will be needed: $e^+e^-\rightarrow$6f (lusifer) and $e^+e^-\rightarrow$8f to O(α_s)
consistent treatment of unstable particles, non-factorizable corrections,…

Top Pair Production at Threshold (I)

- Large Γ_t: cutoff for non-perturbative QCD effects
  - Top decays before top-flavored hadrons or tt-quarkonium bound states can form.
  - Use non-relativistic pQCD to compute σ_{tt} near threshold.
- Remnants of toponium S-wave resonances induce a fast rise of σ_{tt} near threshold.

  Basic parameters: σ_{tt} (m_t, α_s, Γ_t)

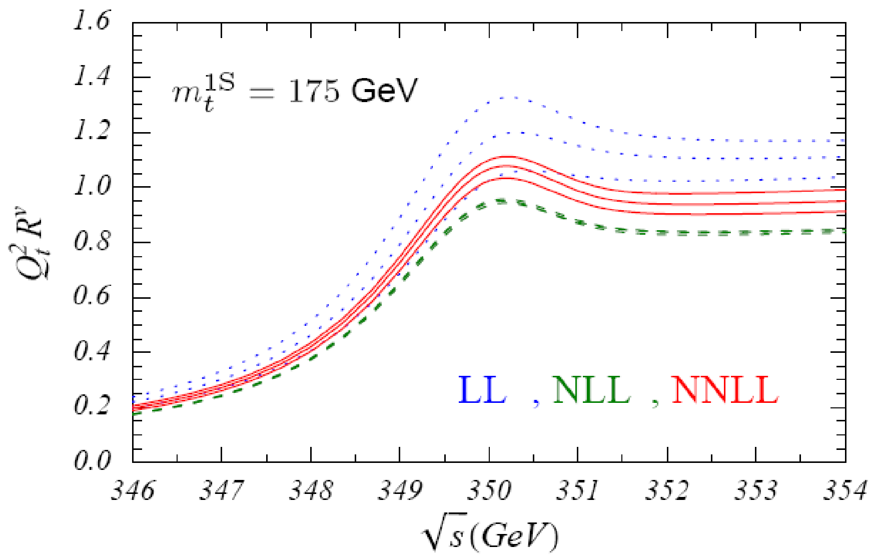
  $\Rightarrow$ high precision expected (color singlet system, counting experiment,…)
- Convergence of calculation sensitive to m_t definition used: pole mass is not IR-safe

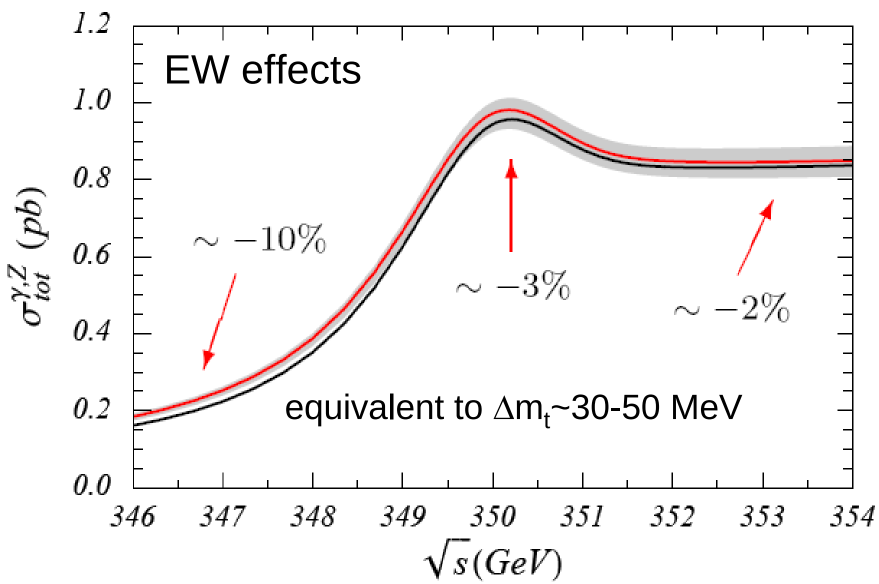
  $\Rightarrow$ σ_{tt}^{peak} not stable vs $\sqrt{s}$

  Solution is to use threshold masses: e.g. 1S mass (=1/2 the mass of the lowest tt bound state in the limit $\Gamma_t \rightarrow 0$).

  High accuracy in absolute normalization requires velocity resummation.

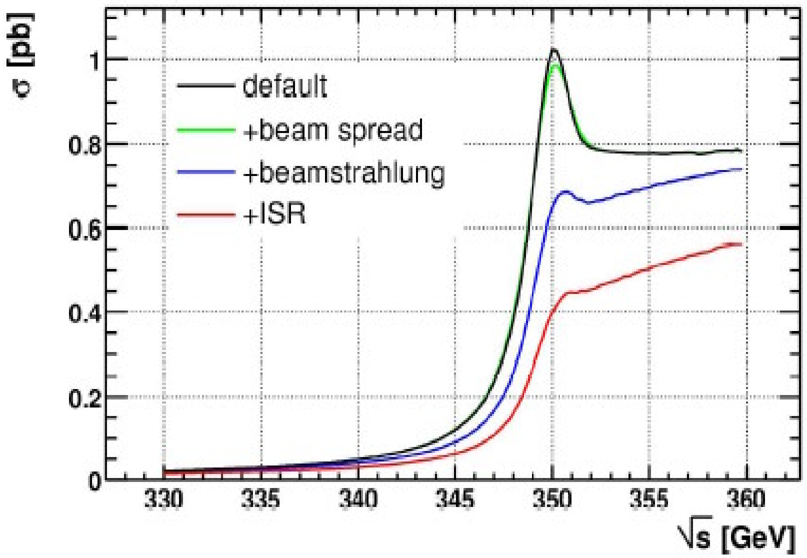
  State of the art (NNLL): $(\Delta\sigma_{tt})_{QCD}$~6%
- Goal: 3% $\Rightarrow$ important to take into account previously neglected %-level effects: EW corrections (Γ_t+non-resonant W^+bW^-b background, QED), non-factorizable QCD corrections,… $\Rightarrow$ a lot of work ahead!





$\Rightarrow$ Talk by Andre Hoang

Top Pair Production at Threshold (II)



- Lineshape significantly distorted:

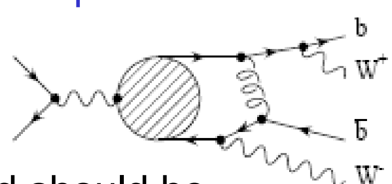
$$\sigma^{\mathrm{obs}}(\sqrt{s}) = \frac{1}{L_0}\int_0^1 L(x)\,\sigma(x\sqrt{s})\,\mathrm{d}x$$

  - Beam energy spread+Beamstrahlung: must be measured (acollinearity in Bhabha events) ⇒ detector/theory precision.
  - Bremsstrahlung (ISR): can a-priori be calculated precisely (enough?)
- Precise determination of dL/d√s and <√s> critical.

Not only σ_{tt} but also differential observables are important!

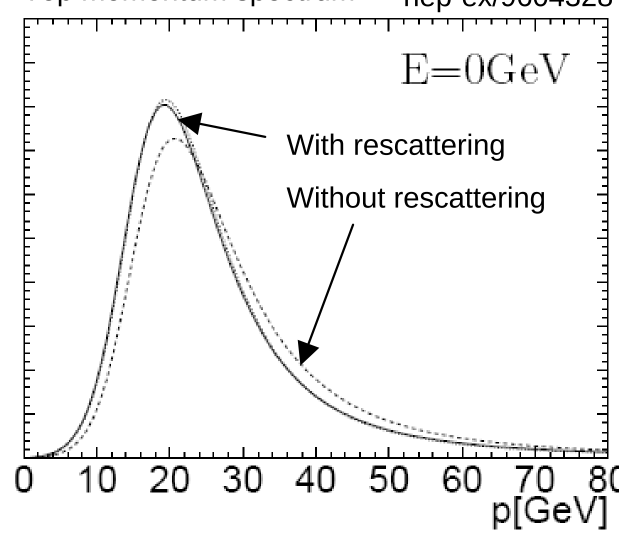
- To implement effect of experimental cuts (MC event generators)
- Exploit additional experimental information from A_{FB}, $d\sigma/dp_t$, s_t,…
  - Additional sensitivity to m_t, α_s and Γ_t
  - Reduce correlations

  ⇒ Simultaneous determination of parameters possible when using all threshold observables.
- Non-factorizable QCD (aka "rescattering") corrections important.
- N(N)LO QCD corrections are available and should be implemented in a MC event generator for more realistic experimental studies.



Top momentum spectrum

hep-ex/9604328



Experimental Threshold Scan (I)

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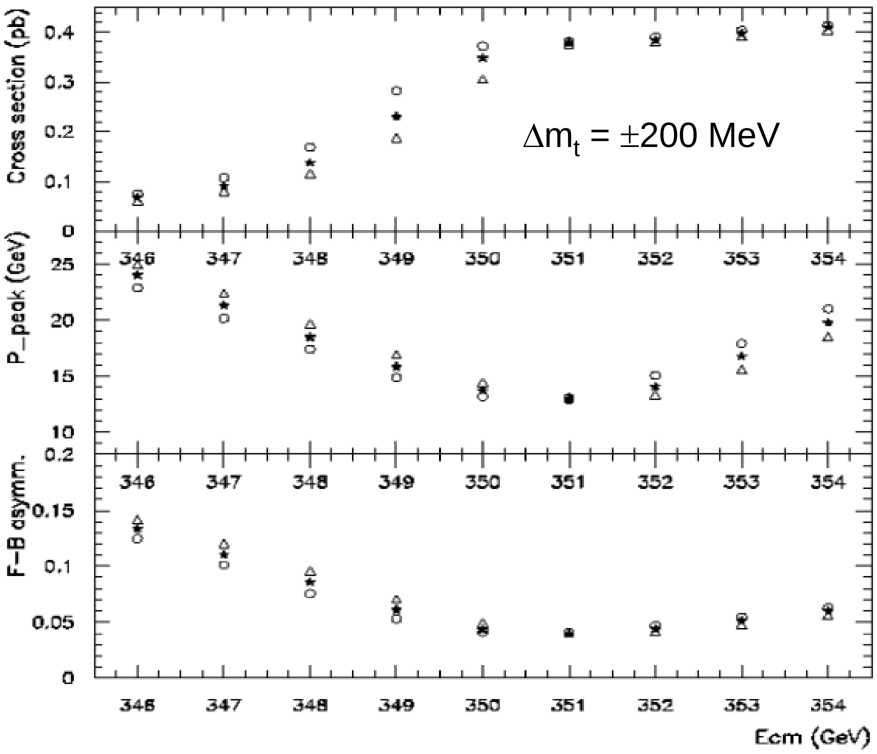


Example of attainable precision:

- 9+1 point scan with 30 fb^{-1}/point.
- Lepton+jets and alljets final states.
- Assumptions:
  - Theoretical uncertainties: $\Delta\sigma_{tt}$=3%, $\Delta p_t^{peak}=\Delta A_{FB}$=0
  - Perfect knowledge of luminosity spectrum
  - SM top couplings
- Simultaneous determination of m_t, α_s and Γ_t (experimental uncertainties only):

  Δm_t(1S)=19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 MeV ,ρ_{ij}<0.5
- Theoretical uncertainty on m_t ~ O(100 MeV). More work needed for a precise estimate.

- Experimental analysis should be repeated with increased level of realism:
  - Run parameter optimization (beamstrahlung, integrated luminosity/point, beam polarization, …)
  - Current detector concepts: event reconstruction and selection
  - Realistic energy and luminosity spectrum uncertainties
  - Improved Monte Carlo event generator (including rescattering corrections)
  - Realistic theoretical uncertainties
  - Simultaneous determination of top anomalous couplings and/or implementation of external constraints for a model-independent determination of threshold parameters
  - …

Experimental Threshold Scan (II)

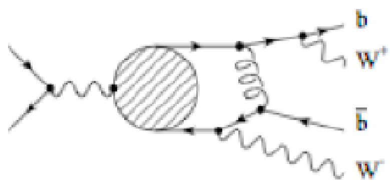
- Ongoing work to build a MC event generator for precise tt threshold studies, including:
  - State of the art theoretical calculations for inclusive cross section and differential distributions
  - Top polarization
  - Realistic luminosity spectrum

NLO rescattering corrections

Modify Green's functions

NNLL renormalization group improved total Cross section (only)

Scale total Cross section reduces theoretical uncertainty



NNLO Cross section + differential quantities $d\sigma/dp$, A_{FB} etc

⇒ Talk by Filimon Gournaris

Include Beam Effects !!

Top quark pair 4-momenta → Decay top quarks

Give decay products to Pythia / Herwig for further decays and hadronization

Event Generator

- Important requirement: speed (NNLO calculation in TOPPIK takes >1.5s/event)
  ⇒ pre-compute Green functions with TOPPIK and perform fast 4D interpolation in (m_t,Γ_t, α_s,$\sqrt{s}$)
- Powerful tool for the next generation of threshold studies: top spin physics at threshold, optimization of scan strategy, additional observables, meaningful systematic uncertainties,…

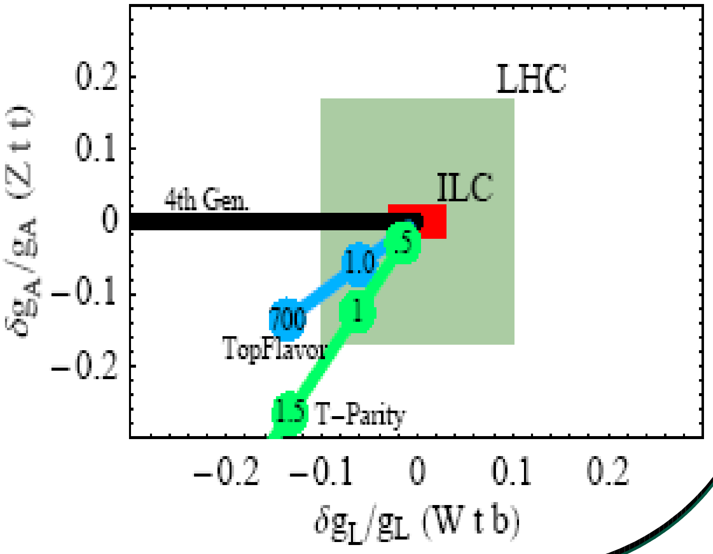
Top Quark and New Physics

- The top quark plays a prominent role in many models of New Physics.
  - Radiative effects in the top sector drive EWSB (e.g. Little Higgs)
  - New particles preferentially coupled to the top quark:
    - Vector gauge bosons (e.g. g_t in Topcolor, V_{KK} in Randall-Sundrum extra-dimensions,..)
    - Charged scalars (e.g. $H^{\pm}$ in generic 2HDMs)
    - Neutral scalars (e.g. η_T in Technicolor)
  - Mixing with the top quark (e.g. TopFlavor)
  - …
- In many instances the new states can be sufficiently heavy that they are not produced directly at the ILC (or even the LHC).

$\Rightarrow$ The first indication for New Physics might be in the form of modified top quark interactions.

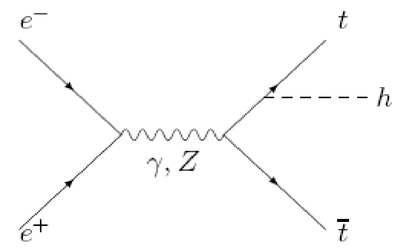
- Anomalous top couplings can manifest themselves affecting many observables:
  - total cross-sections,
  - tt invariant mass distribution,
  - angular distributions of decay products,
  - rare decays,
  - ...

hep-ph/0606068



- Several operators can contribute to a given observable. Must disentangle the effect of different operators. Beam polarization will be a crucial tool.
- High precision and model independence critical to be able to rule/figure out specific models of New Physics.

Top-Higgs Yukawa Coupling

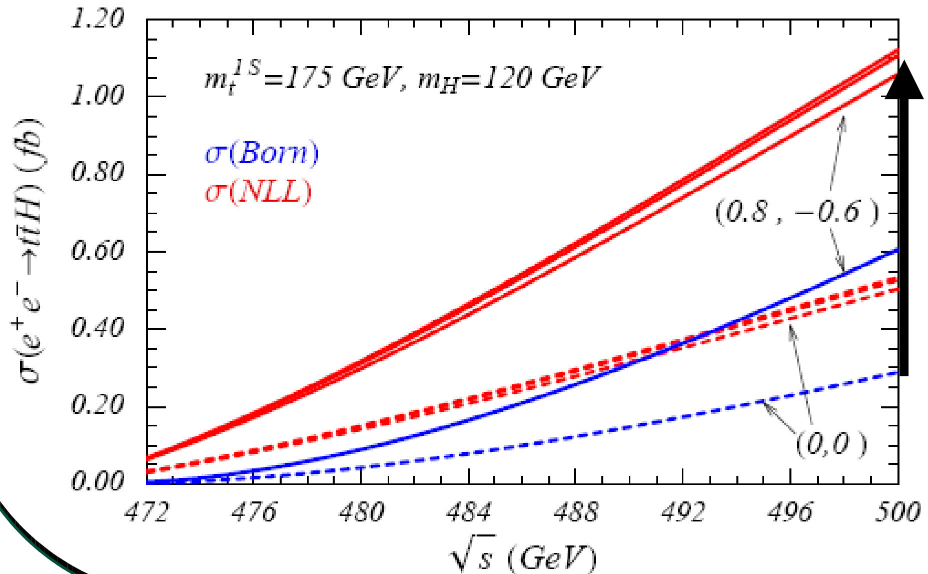


- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions. Precise measurement important since the top quark is the only "natural" fermion from the EWSB standpoint.
- Can be determined via cross section measurement: $\sigma_{tth} \propto g^2_{tth}$
- σ_{tth}(Born) ~ 0.2(2.5) fb at $\sqrt{s}$=500(800) GeV for m_h=120 GeV
- Previous study:
  $\sqrt{s}$=800 GeV, L=1 ab^{-1}, $\Delta g_{ttH}/g_{tth}$ ~ 6(10)% for m_H=120(190) GeV
  $\Rightarrow$ What are the prospects at $\sqrt{s}$=500 GeV?
  First estimate: $\Delta g_{ttH}/g_{tth}$~23% for m_H=120 GeV, L=1 ab^{-1} [AJ, 2002]

hep-ph/9910301
hep-ph/0604034

- However, at $\sqrt{s}$=500 GeV the tt dynamics is non-relativistic
  $\Rightarrow$ must use vNRQCD as in the tt threshold

$\Rightarrow$ Talk by Andre Hoang



Considering σ_{tth} enhancement due to:

- Large QCD resummation effect:
  ~x2.4 for m_h=120 GeV
- Use of beam polarization:
  ~x2.1 for $(P(e^-),P(e^+))$ = (-0.8,+0.6)

Anticipate:

$(\Delta g_{ttH}/g_{tth})_{stat}$~10% for m_H=120 GeV, L=1 ab^{-1}

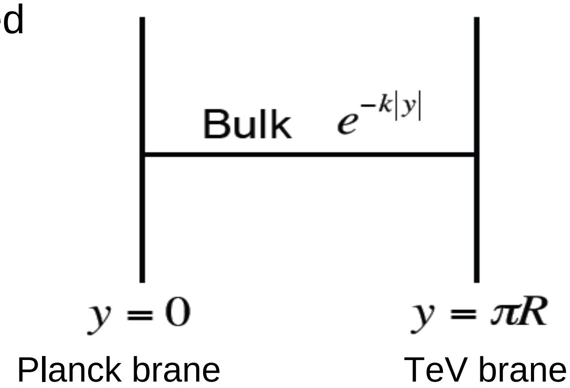
Top Quark and Extra-Dimensions (I)

- Solving the hierarchy problem is one of the main focus of models of New Physics (e.g. SUSY, Technicolor, extra-dimensions,..)
- Randall-Sundrum extra-dimensions:
  - 5D spacetime w/ one dimension (y) compactified on a S_1/Z_2 orbifold (AdS_5 geometry)
  - Bounded by Planck and TeV branes

    $M_P^* = M_P e^{-\pi kR} \sim TeV$ (if kR ~ 12)

    $\Rightarrow$ solution to hierarchy problem
  - Higgs on TeV brane
  - Gauge bosons in 5D bulk $\Rightarrow$ KK excitations

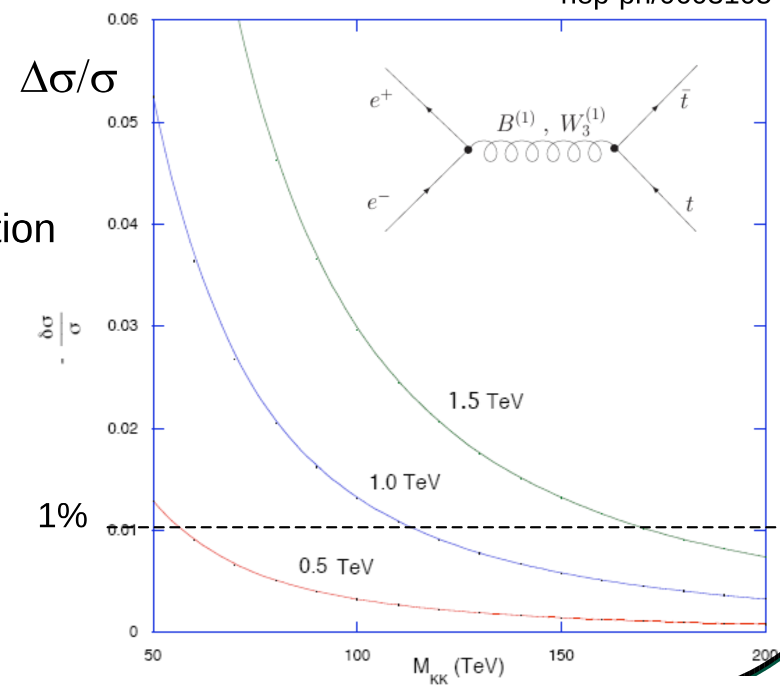
$$ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2$$



- CASE 1: fermions on TeV brane
  - Enhanced coupling to KK-gauge bosons

    $\Rightarrow$ significant corrections to fermion pair production (here the top quark is not special)
  - Severe constraints from precision EW data: M_{KK}>20 TeV (inaccessible to LHC)
  - Precise measurements at the ILC sensitive to very high mass.

hep-ph/0603105



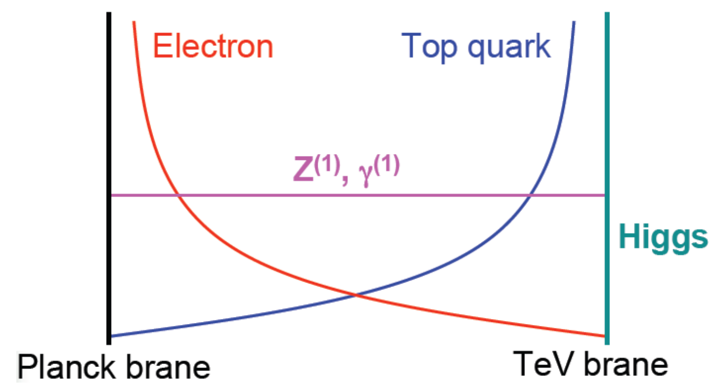
M_{KK} (TeV)

$\Rightarrow$ Talk by Erin De Pree

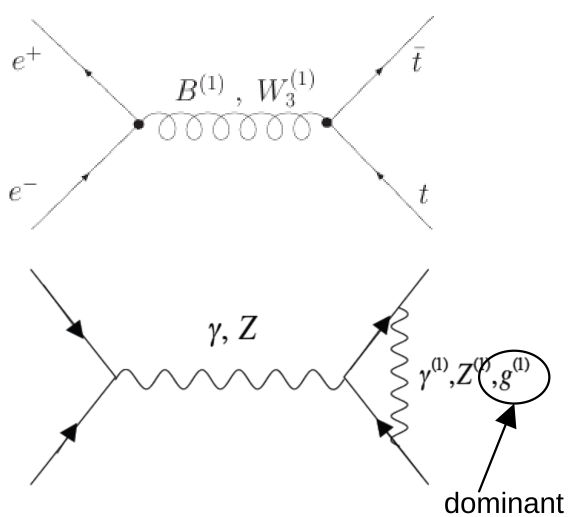
Top Quark and Extra-Dimensions (II)

- CASE 2: fermions in the bulk
  - Precision EW constraints less severe: M_{KK}>10 TeV
  - Fermion mass hierarchy explained by "geography"
  - Top quark is special: stronger coupling to KK-gauge bosons than the rest of fermions

5 dimensional wavefunctions



- Different observables would be affected:



$$\frac{\delta\sigma}{\sigma} = (0.24\alpha_L + 0.14\alpha_R)\frac{s}{M_{KK}^2}$$

$$\delta A_{LR} = (0.26\alpha_L - 0.19\alpha_R)\frac{s}{M_{KK}^2}$$

Negligible effect on A_{FB} (distinct from other extra-Z models)

Anomalous t-t-γ and t-t-Z couplings (also possibly due to top/KK-top mixing effects)

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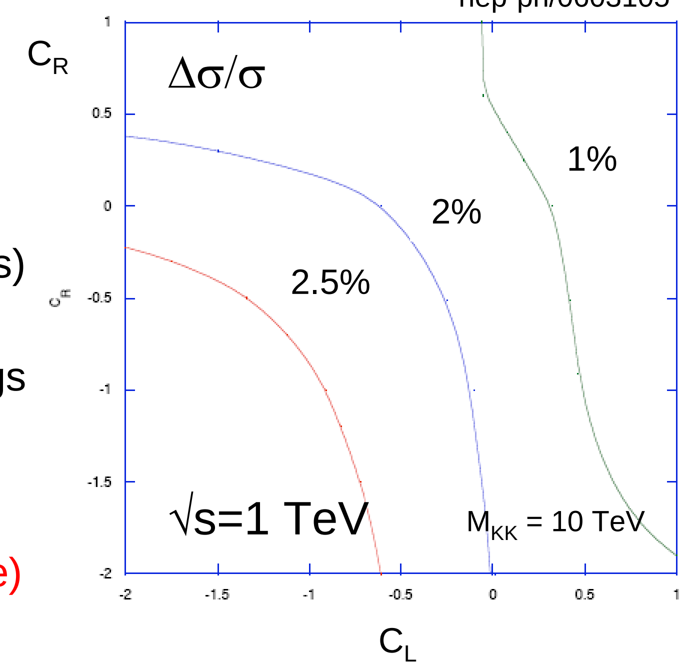


- In summary, probe M_{KK}>50-150 TeV (fermions on the brane) or up to M_{KK}~10 TeV in large regions of parameter space (fermions off the brane).
- Future improvements: P(e+), top polarization observables,..

⇒ Talk by Erin De Pree

The Role of Precision Observables

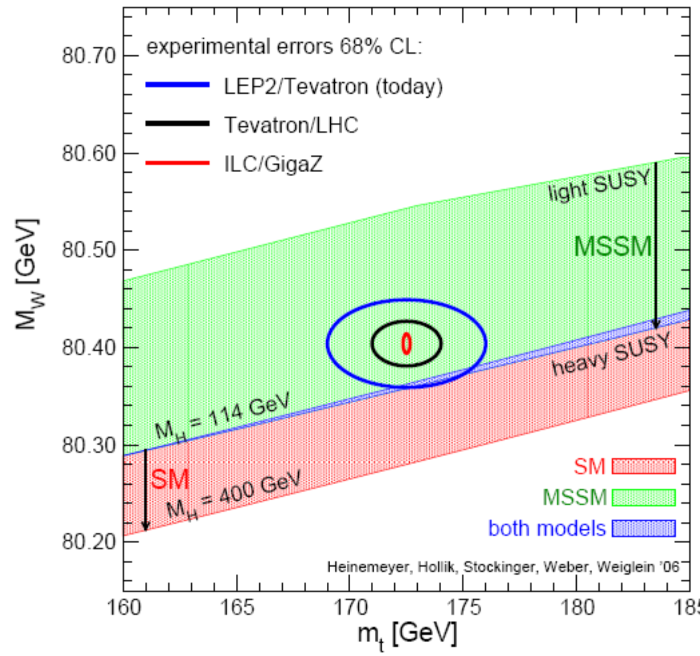
- Important ingredient for EW precision analyses at the quantum level.
  - ⇒ incisive consistency checks
  - ⇒ constrain/rule out models of New Physics
  - ⇒ provide valuable information on the parameters of the Lagrangian
- Two prominent examples: M_W and m_t
- Experimental uncertainties:

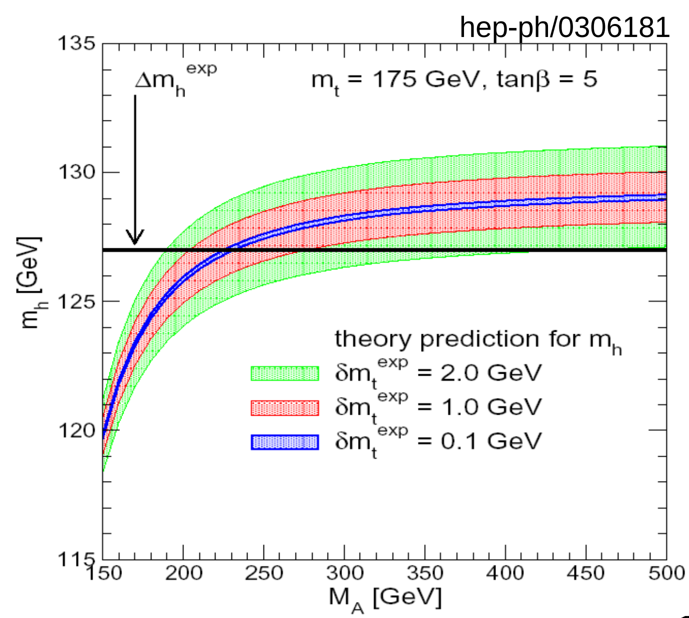
	Today	Tevatron/LHC	ILC	"GigaZ"
ΔM_W [MeV]	32	20/15	10	7
Δm_t [GeV]	2.3	1.5	0.1	

- Theoretical uncertainties (within the SM):
  - Intrinsic: $\Delta M_W^{intr} \sim 4$ MeV (2 MeV future?)
  - Parametric (due to Δm_t):

Today: $\Delta m_t = 2.3$ GeV $\Rightarrow \Delta M_W^{para,mt} = 14$ MeV
LHC : $= 1.5$ GeV $\Rightarrow \Delta M_W^{para,mt} = 9$ MeV
ILC : $= 0.1$ GeV $\Rightarrow \Delta M_W^{para,mt} = 1$ MeV

- Need ILC precision on m_t:
  - Top match future accuracy on M_W (and $\sin^2\theta_{eff}$)
  - To exploit LHC (and ILC) precision on Higgs measurements
  - …





Precise M_W Prediction in the MSSM

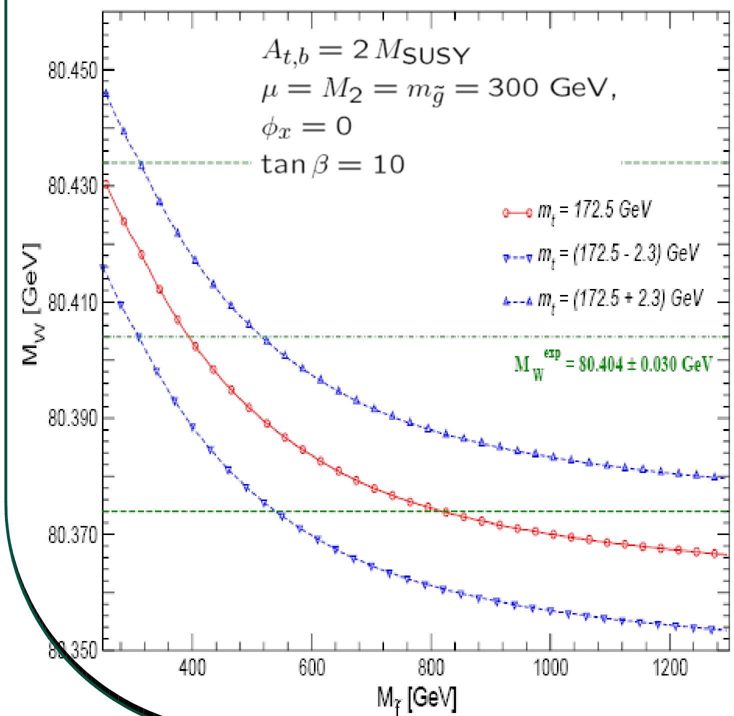
- Precise theoretical predictions for electroweak observables required to fully exploit anticipated experimental accuracy.
- M_W prediction in terms of M_Z, α, G_μ and Δr:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

Loop corrections

- Current intrinsic theoretical uncertainty within the SM (ΔM_W^{intr}~4 MeV): ~ok
- What about within the MSSM? Obtain best prediction possible by:
  - Using best available SM result
  - Implementing all available MSSM corrections

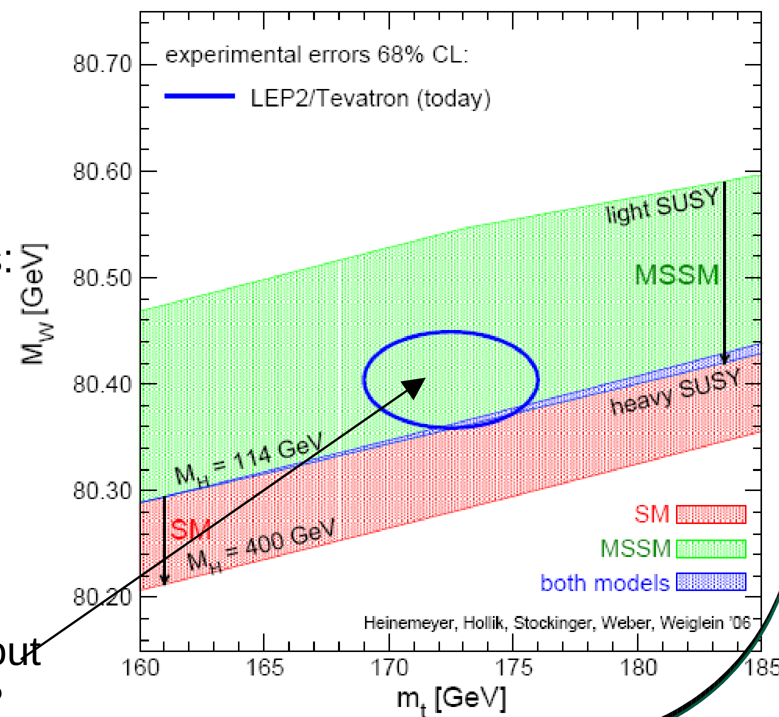
⇒ Talk by Sven Heinemeyer



Result:
ΔM_W^{intr} ~5-11 MeV
(must be improved)

Effect of different sectors:
$\tilde t$ / $\tilde b$: ΔM_W>20 MeV
$\tilde\chi^o$/ $\tilde\chi^\pm$: ΔM_W>20 MeV
…

What can be learned about SUSY parameter space?



Prospects for SUSY at the ILC

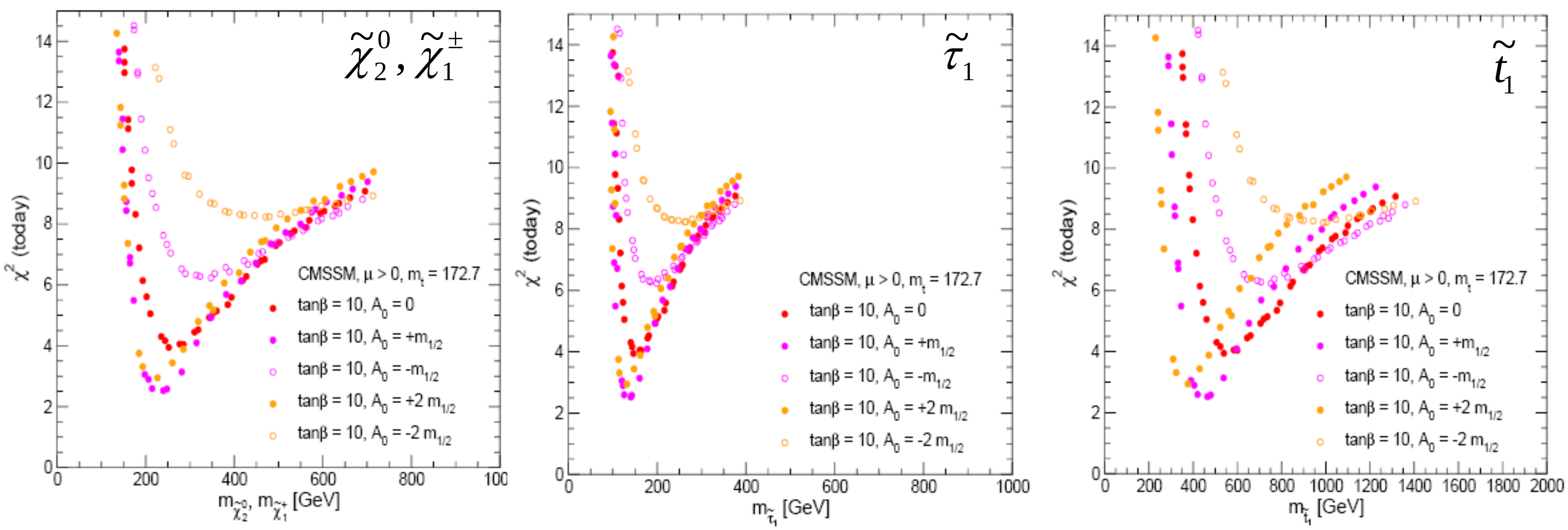
- Idea: combine different precision observables and look for favored regions of parameter space.
- Observables: M_W, $\sin^2\theta_{eff}$, $B(b\to s\gamma)$, $(g-2)_\mu$, M_H
  - Build χ^2 taking into account experimental and theoretical (parametric+intrinsic) uncertainties
  - Obtain best fit for masses.
- Too many free parameters in MSSM.

  ⇒ Talk by Sven Heinemeyer

  ⇒ Consider a number of scenarios with reduced # free parameters:

  CMSSM (mSUGRA): 5 parameters (m_0, $m_{1/2}$, A_0, $\tan\beta$, sign(μ))
- Impose hard constraint: LSP gives right amount of Cold Dark Matter.
- Rather good fit to current data (χ^2~O(2)).

tanβ = 10



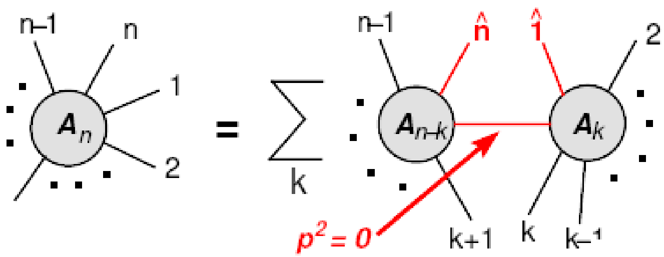
- Similar conclusion regarding ILC reach in different scenarios:
  - tanβ = 10: sleptons, charginos, neutralinos (partially) in reach. Some chance for light stop.
  - tanβ = 50: sleptons, charginos, neutralinos (partially) in reach. Hardly any chance for light stop or gluinos.

⇒ Rather good prospects for the ILC

New Approaches to Higher Order Calculations

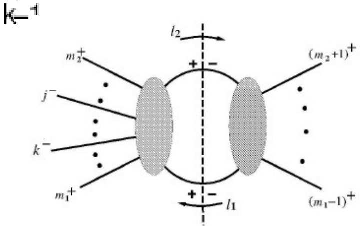
- Many physics processes at the ILC involve a large number of final state particles.
- Feynman diagram method is not optimized for multi-leg processes.
- More efficient methods have been developed that exploit symmetries in QCD leading to "recursion relations"

⇒ Talk by Carola Berger



- *"Trees are recycled into trees"*
  - 6 gluon amplitude in agreement w/ previous calculations [Giele et al]
  - Many applications: massive particles, SUSY,..
- Method also works at one-loop level and remains "sustainable":
  - Some results for parts of Higgs+gluons @ NNLO
  - A-priori no obstacles towards phenomenology

"Trees are recycled into loops"
"Loops are recycled into loops"



- In certain kinematic regions, precise theoretical calculations involve resummation of large logs.
- Exploring application of Soft Collinear Effective Theory (SCET; developed for b-physics) for resummation in collider physics.
- Application: large momentum transfer Q^2, but hadronic final states with small M_X ($\alpha_s^n \ln^{2n}(M_X/Q) \uparrow$)
- Traditionally, resummation is performed in moment space.
  Caveats: Landau poles, Mellin inversion only numerically
- Solving Renormalization Group equations in SCET, one obtains resummed expressions directly in momentum space.
  - Clear scale separation. No Landau pole ambiguities.
  - Analytic expressions for resummed rates.
  - Simple connection with fixed order expressions.

⇒ Talk by Thomas Becher

Conclusions

- After the first signs of New Physics at the LHC, precision measurements at the ILC will likely catalyze the next revolution in Physics by helping answer truly fundamental questions.

- Important to keep a dynamic and active Precision Physics Working Group:
  - The physics case needs to keep being sharpened all the time;
  - An increased involvement of experimentalists crucial to establish a feedback loop between the detector and its physics (an existing gap that needs to be bridged);
  - Theorists must find enough incentives to work on the precise theoretical predictions/tools that will be required to carry out the ILC physics program (in many cases involve multi-year projects).

- Finally, many thanks to our speakers: Thomas Becher, Carola Berger, Erin De Pree, Filimon Gournaris, Sven Heinemeyer, Andre Hoang,

  and the rest of participants, for contributing to very productive and stimulating sessions.