Top quark physics at lepton colliders

Input from theorists +
further studies of $e^+e^- \rightarrow$ 6 fermion composition

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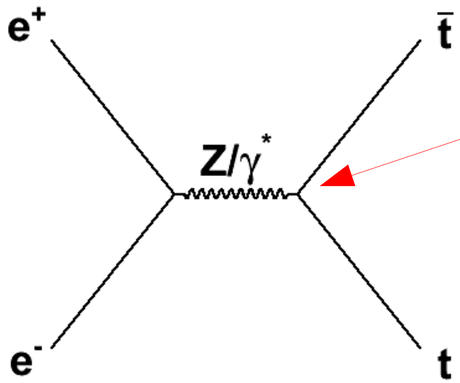
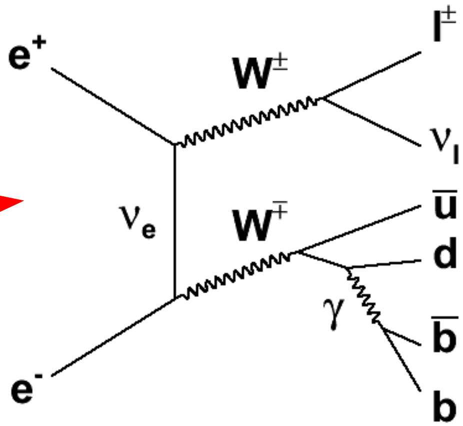
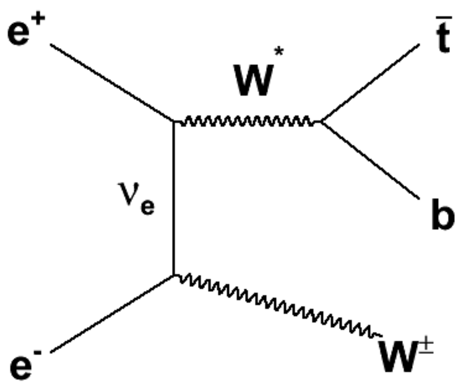
Fundamental issues:
The good, the bad and the ugly



This is the vertex we want to probe

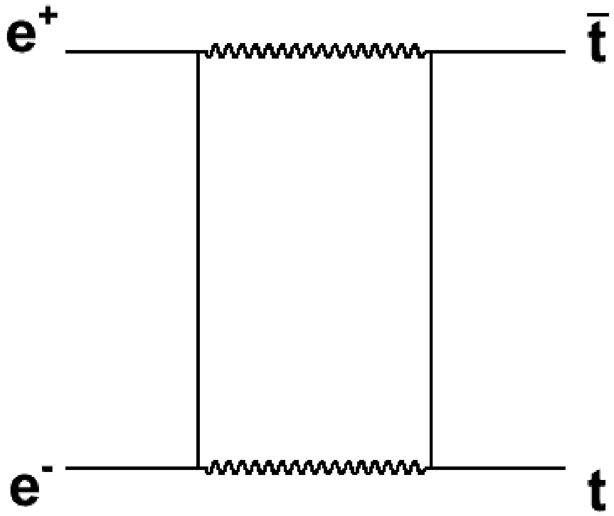


This is a background we can reduce



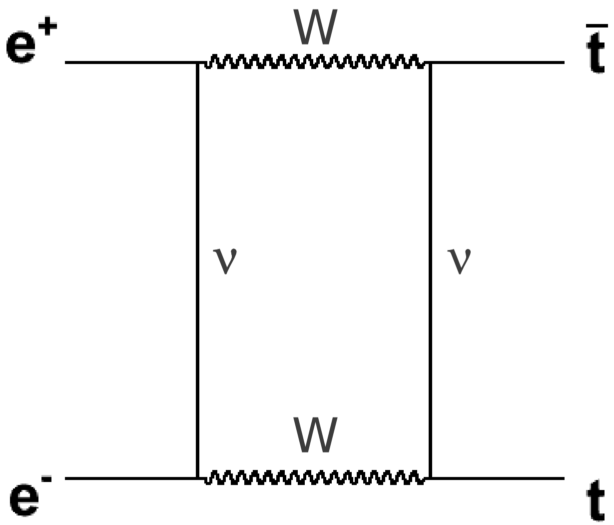
This is a problem

Fundamental issues...



German Rodrigo: at the next order further diagrams become important

These involve higher orders of the ttγ and ttZ vertices we're after... mixing the two sets of form factors for ttγ and ttZ



And, unwanted (Wtb) vertices appear...

Is it sufficient to say that the anomalous couplings are small to make the couplings squared negligible?

Pedro Ruiz Femenia (a student of Toni Pich, and with some help from Germán Rodrigo) has evaluated the existing EW and QCD corrections, trying to come up with error estimates for the current state-of-the-art calculations...

Note that: the errors he estimates do not necessarily limit the ILC potential. Often, great progress can still be made at a relatively small cost (and will certainly be made as soon as the project is approved).

1/ Axial part (of the Z) not included in cross-section estimates. If needed, they can be included; they are available at N^3LO.

2/ Results obtained last Friday. A cross-check is needed if we're to use any of these results.

3/ Pedro used a top quark mass m_t=172 GeV, defined in the on-shell scheme (pole mass).

Important sources:

Kiyo, Maier, Maierhöfer, P. Marquard, arXiv:0907.2120, 3 loops

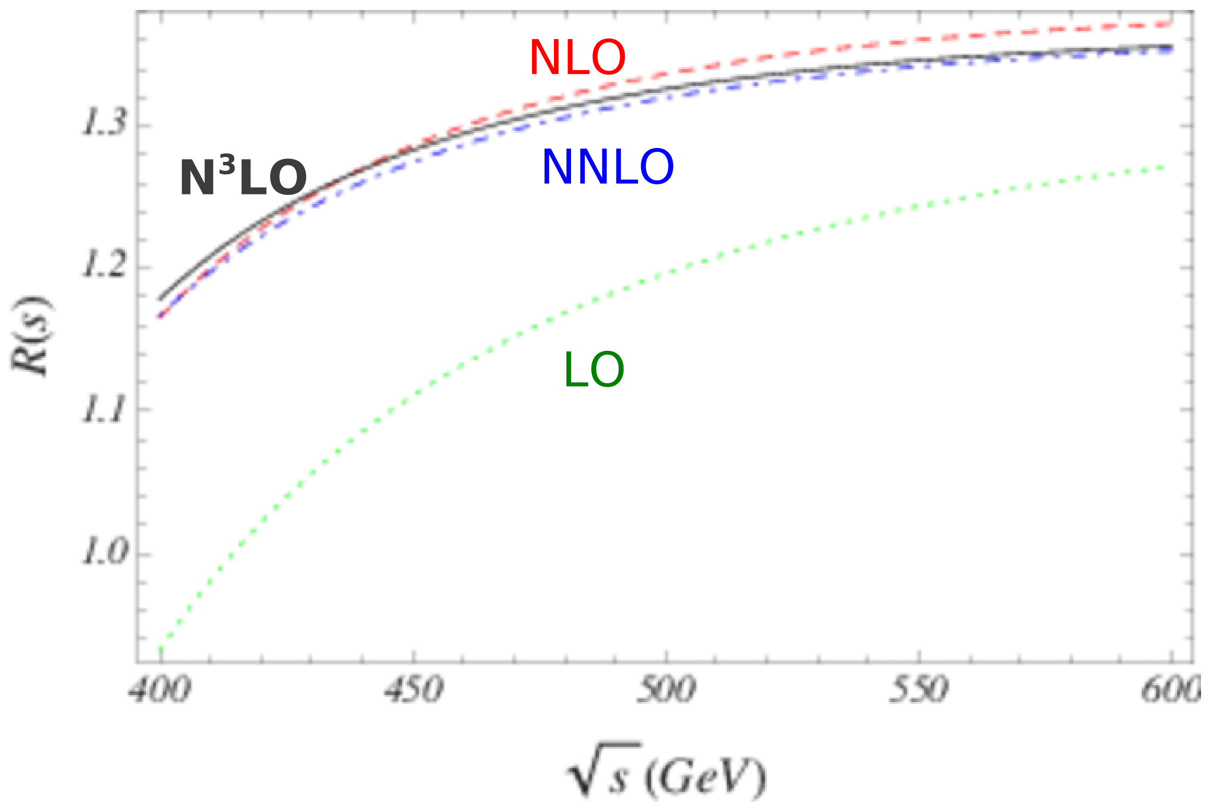
Hoang, Mateu, Zebarjad, Nucl. Phys. B 813 (2009) 349-369, 2-loops

Bernreuther, Bonciani et al., hep-ph/0604031

Theory input

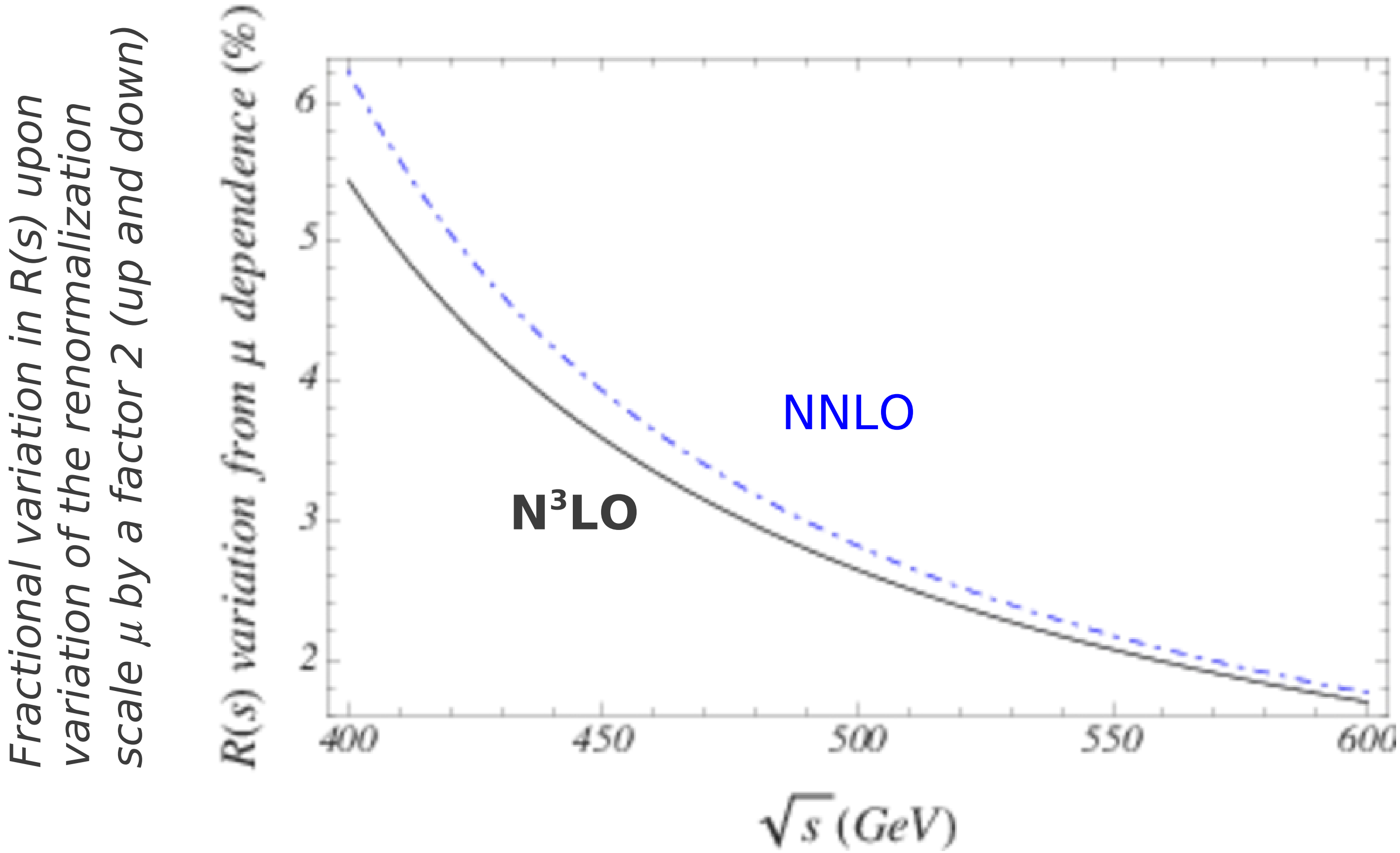
QCD corrections to $e^+e^- \rightarrow t\bar{t} + X$, known up to $O(\alpha_s^3)$ (3-loops), in an expansion in m_t^2/q^2 with enough terms to be valid at $\sqrt{s}$ = 500 GeV

R(s) = cross-section normalized to x-sec for massless fermion



Theory input

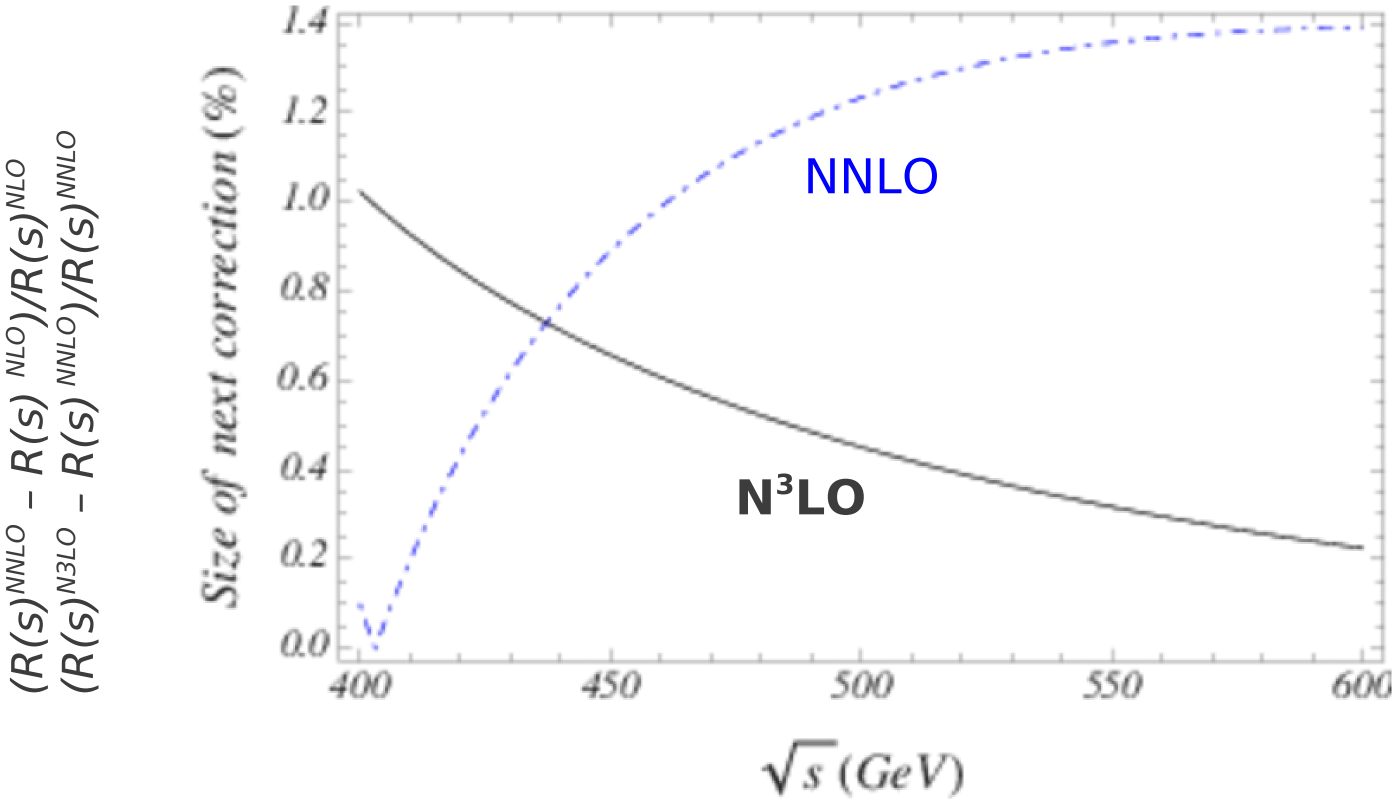
Error estimate from scale variations: 2-3 %
(less if we run at larger center-of-mass energy)
Assigning this as the x-sec error would be very conservative...



Theory input

Error estimate by comparing size of subsequent corrections in the perturbative series

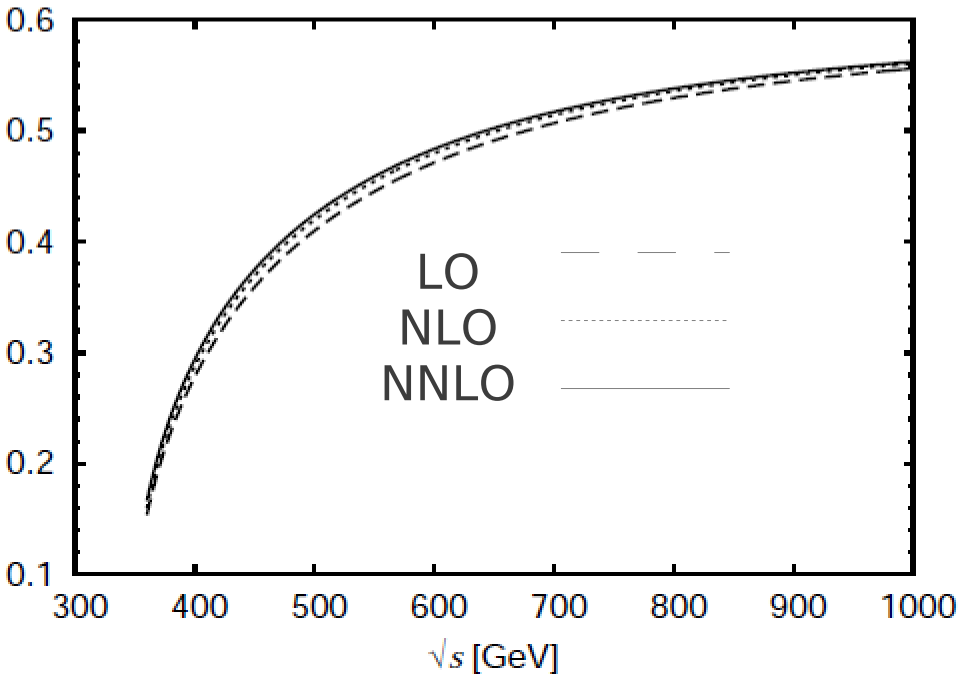
LO → NLO: ~13 %
NLO → NNLO: ~1.5 %
NNLO → N^3LO: ~0.5 %



Theory input

What about A_{FB} ?

Order α_s^2 results in Bernreuther, Bonciani et al., hep-ph/0604031

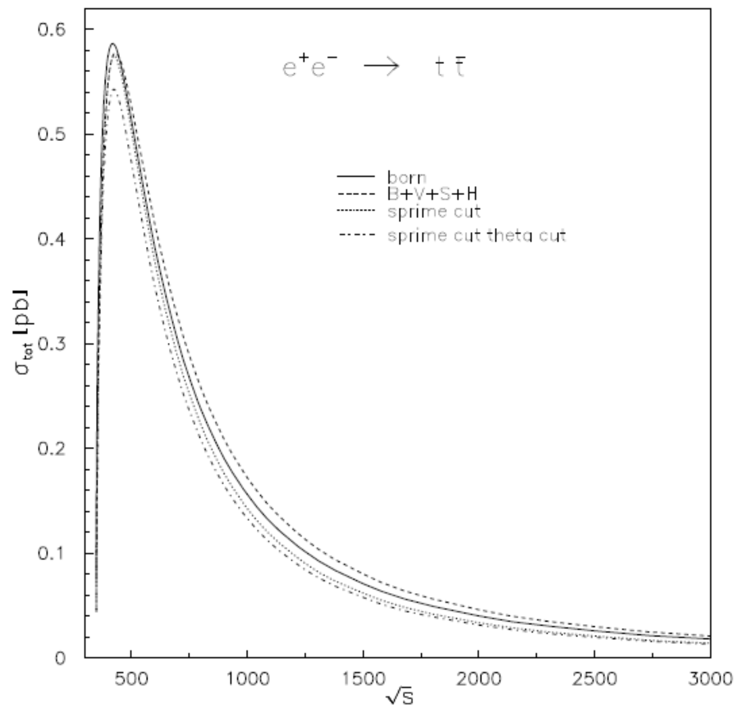


"… we conclude that the 2-parton QCD corrections to the lowest order asymmetry are moderate to small for √s > 400 GeV"

Scale variations yield <1% error @ NNLO

Theory input

EW correction to cross-section are ~3% at √s = 500 GeV

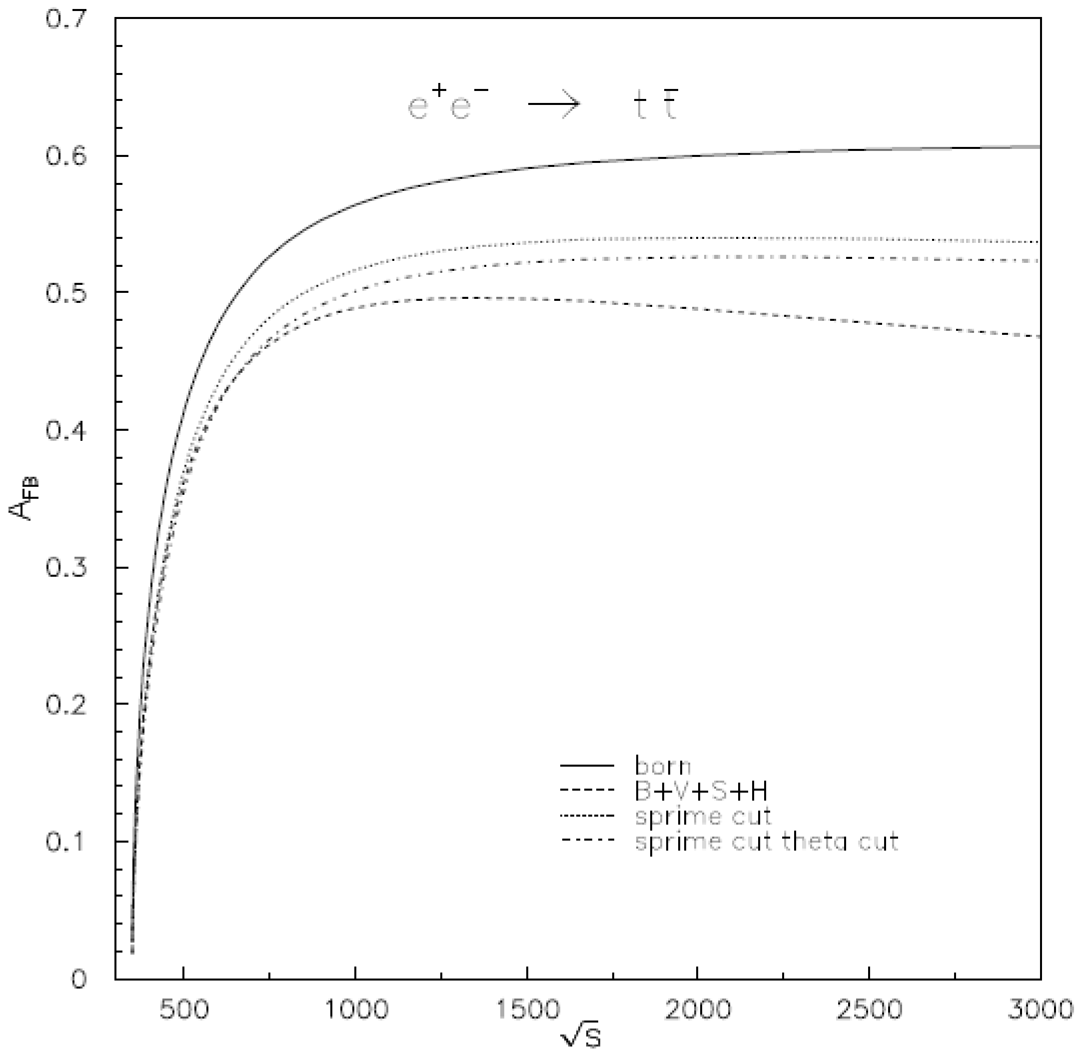


EW corrections from the decay
tt → bWbW → six fermions
are expected to be order Γ_t/m_t~1%
Not calculated for e^+e^-, but they do exist for (the more complicated case of) hadron collider production

Electroweak corrections
Glover et al. hep/ph04010110
Fleischer et al. hep/ph0302259

Theory input

EW correction to forward-backward asymmetry are ~20% at √s = 500 GeV



Theory input: conclusions

Summarizing:

- Form factors are well-defined for LO. A more complex situation arises when interfering diagrams for the same six-fermion final states are considered, or higher orders are included...

- QCD calculations are available to α_s^3. For x-sec and α_s^2 for A_{FB}.
A ~ rigorous error estimate yields acceptably small errors.

- Electroweak corrections are available. Effects are sizable, but expect next order correction to be much smaller... Contacted Jos Vermaseren to see if we can get an error estimate.

- Corrections to decay have been calculated, but not yet evaluated. Error order 1%.

Proposal: get Pedro Ruiz to write a section “Theory state-of-the-art”

Problem I

WHIZARD generates $e^+ e^- \to b \bar{b} l \nu j j$
Includes the good, the bad and the ugly
Interference taken into account

Unpolarized cross-sections according to MadGraph
tt production (2 diagrams) : 29 fb
6-fermion production (250 diagrams) : 30 fb

The Barklow criterion allegedly considers events with two on-shell top quarks only ($| m_{bW} – m_t | < 5 \Gamma_t$) mt = 174, Gt = 1.5...

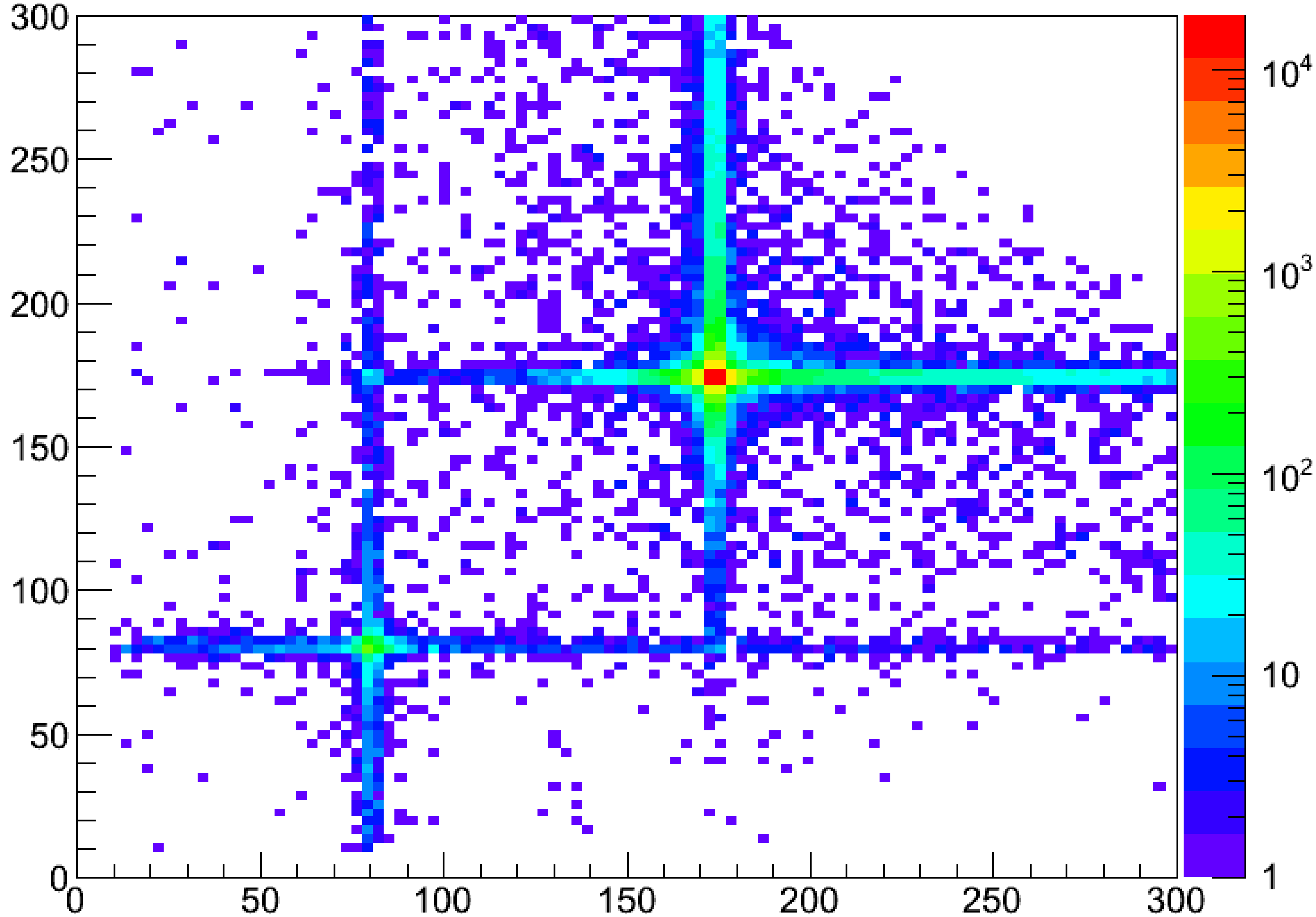
According to Nacho we discard:

30 % of L-handed events
24 % of R-handed events

Disclaimer: what we call the Barklow criterion was never intended to be used as such by Tim Barklow!!!

Top candidate mass distributions

Running over 108.800 Left-handed events



Problem I

A practical issue: how do we define our $e^+e^- \rightarrow t\bar{t}$ sample?

Running over 108.800 Left-handed events

Apply criterion on N-tuple: $| m_{bW} - m_t | < 5\ \Gamma_t$

Loose definition: $| m_{bW} - m_t | < 10\ \Gamma_t$

Barklow/IsTTbarEvent:	75635	→	69.5%
Mass criterion on N-tuple:	86721	→	79.7%
Loose criterion:	93081	→	85.6%

I create a cleaner criterion based on:

- the loose mass constraints
- energy of top and anti-top < 251 GeV
- E_b in top frame < 90 GeV

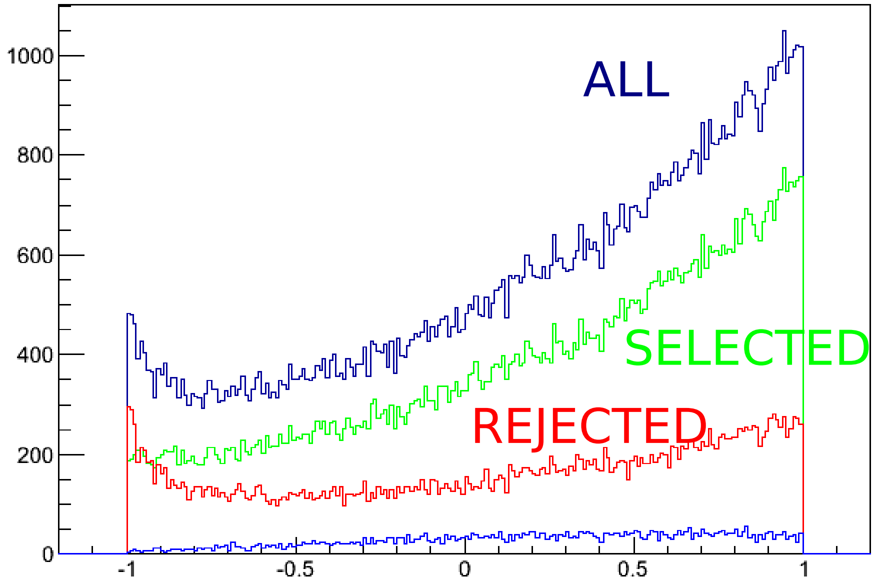
This select 76% of events

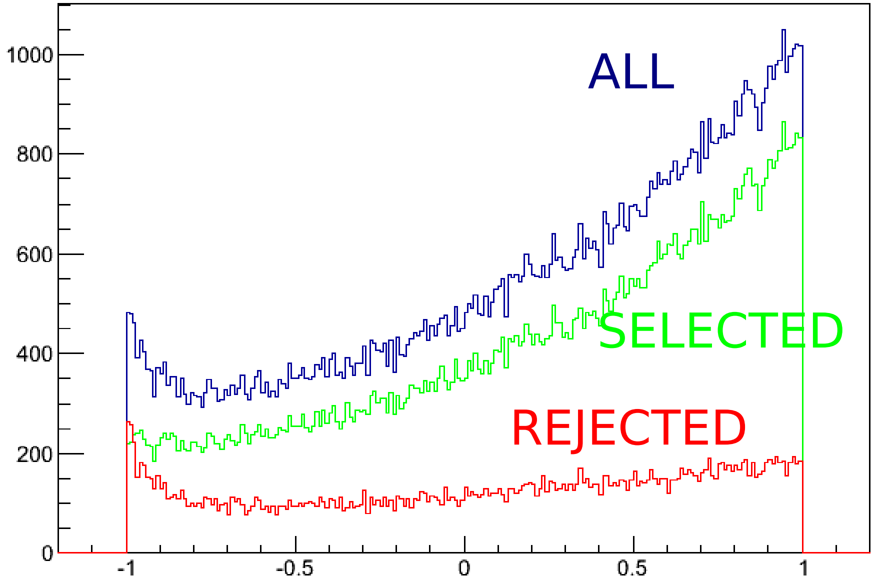
I find that the overlap with Barklow is imperfect... only 93% of events that meet the isTTbarEvent also make the new criterion → is the sample contaminated with non-ttbar events?

FB asymmetry

Both criteria reject the background with the obviously wrong shape

Barklow accepts some more (light blue) and rejects some more

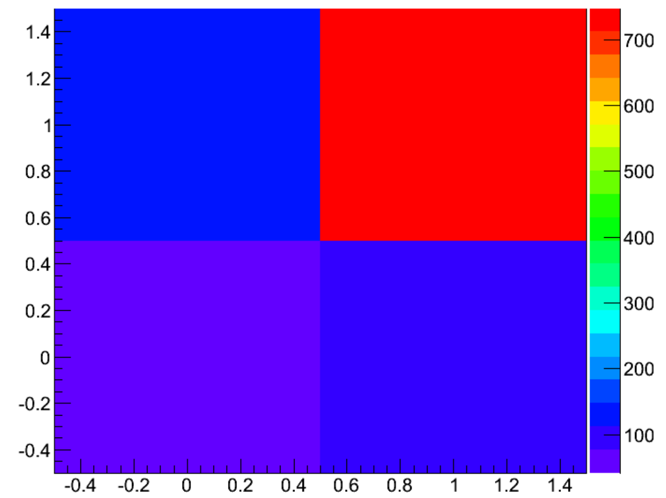




MadGraph unpolarized

Ttbar : 75 %
Single top : 20 %
Others : 4.2 %

Not too dissimilar from the previous results



Polarized x-sections

Unpolarized:			
total	->	564.2 fb	
ttbar through gamma	->	422.5 fb	
ttbar through Z	->	96.1 fb	
WW* nu-exchange	->	24.7 fb	92%
WW* through Z	->	11.5 fb	
WW* through gamma	->	9.1 fb	
P: +30%, -80%			
total	->	957.9 fb	
ttbar through gamma	->	669.3 fb	
ttbar through Z	->	208.2 fb	92%
WW* nu-exchange	->	58.3 fb	
WW* through Z	->	13.3 fb	
WW* through gamma	->	8.3 fb	
P: -30%, +80%			
total	->	441.5 fb	
ttbar through gamma	->	376.2 fb	
ttbar through Z	->	32.5 fb	93%
WW* nu-exchange	->	3.4 fb	
WW* through Z	->	15.0 fb	
WW* through gamma	->	14.2 fb	

Strategy...

Attempts to disentangle single top and $t\bar{t}$ production seem to show this is difficult (maybe not impossible)
In any case the processes are entangled at the theory level by the interference term

Solution: measure and rate and differential distributions for the full six-fermion final state → compare this to prediction
Complicates matters:

- less experimental handles (top mass constraint)
- theory now depends on Wtb vertex in production as well
- definition of form factors

Problem II

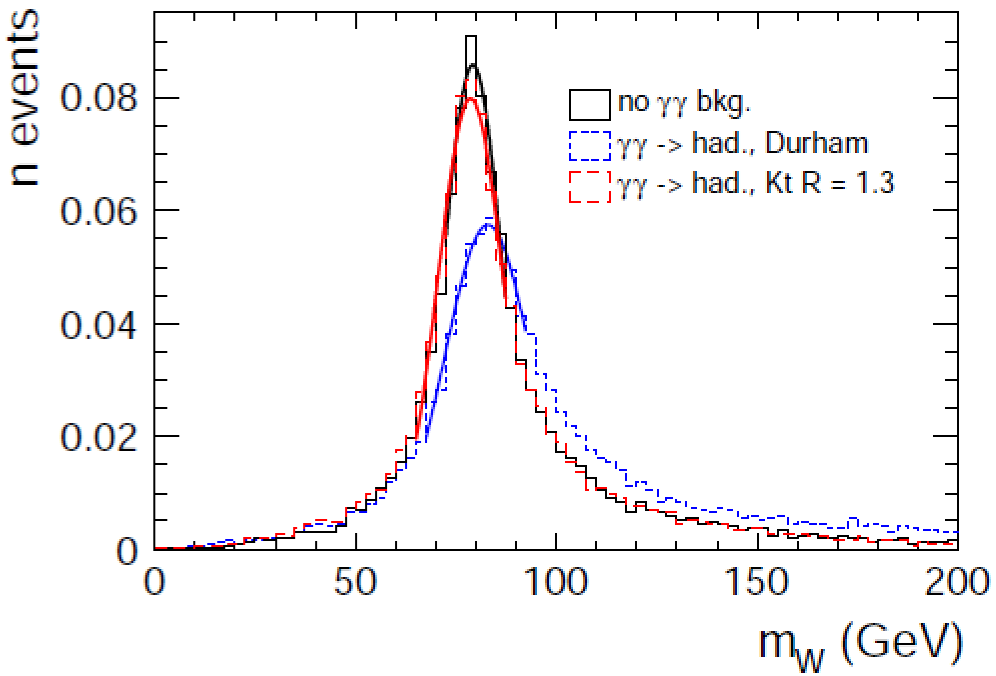
François Richard: The gamma-gamma background is not innocuous since Jeremy finds that the top angular distribution suffers from the presence of this component for P=-.

Quoting the DBD:
At lepton colliders exclusive jet algorithms, in which every particle is assigned to a jet have been favoured. However, at the ILC such algorithms work poorly […] the large cross section for $\gamma\gamma \rightarrow$ hadrons implies that most interesting events will be accompanied by several unrelated "pile-up" events in the same bunch crossing.

Problem II: DBD solution

Still from the DBD:
This problem was studied at CLIC, where the pile-up conditions are much more challenging than at ILC. It was concluded that the use of inclusive algorithms, developed for hadron colliders, was well-suited to mitigate this problem.

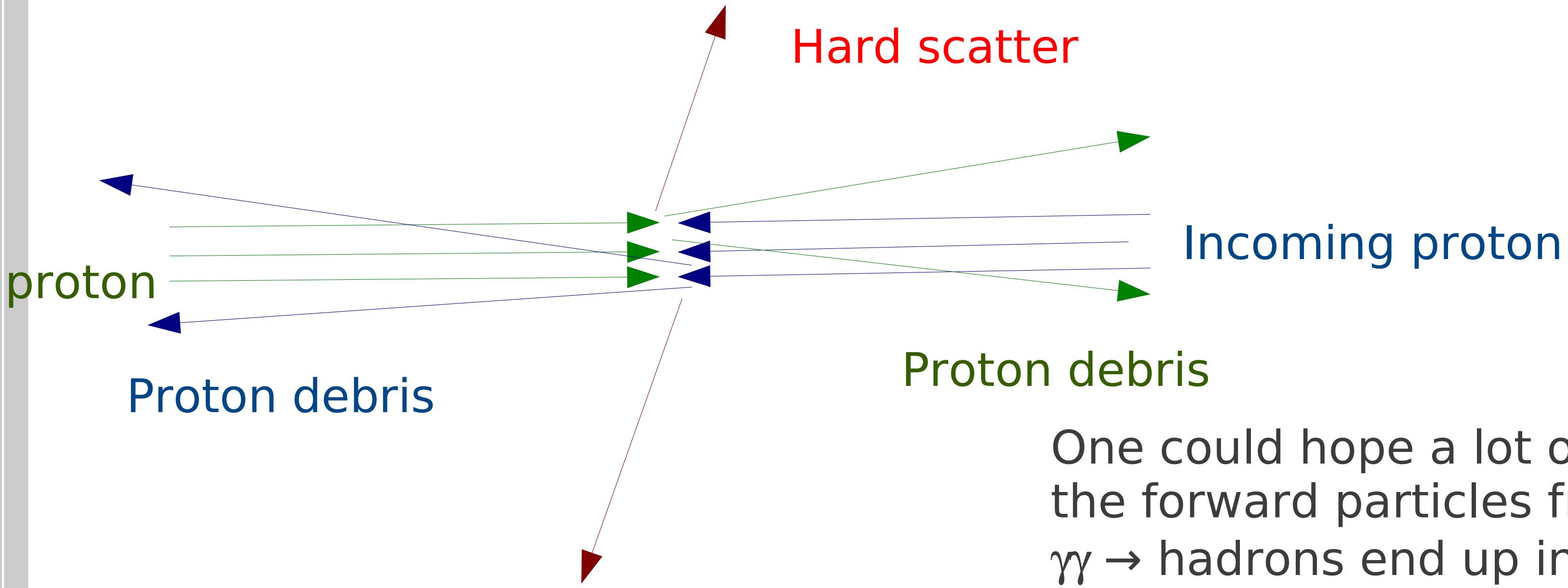
Reconstructed di-jet mass distribution in $e^+e^- \rightarrow W^+W^- \rightarrow l\nu q\bar{q}$.



Problem II: discussion

The DBD actually uses three solutions in one go:

- Exclusive jets → inclusive jets
- Durham without beam jets → hadron collider algorithm
- Distance criterion → k_t

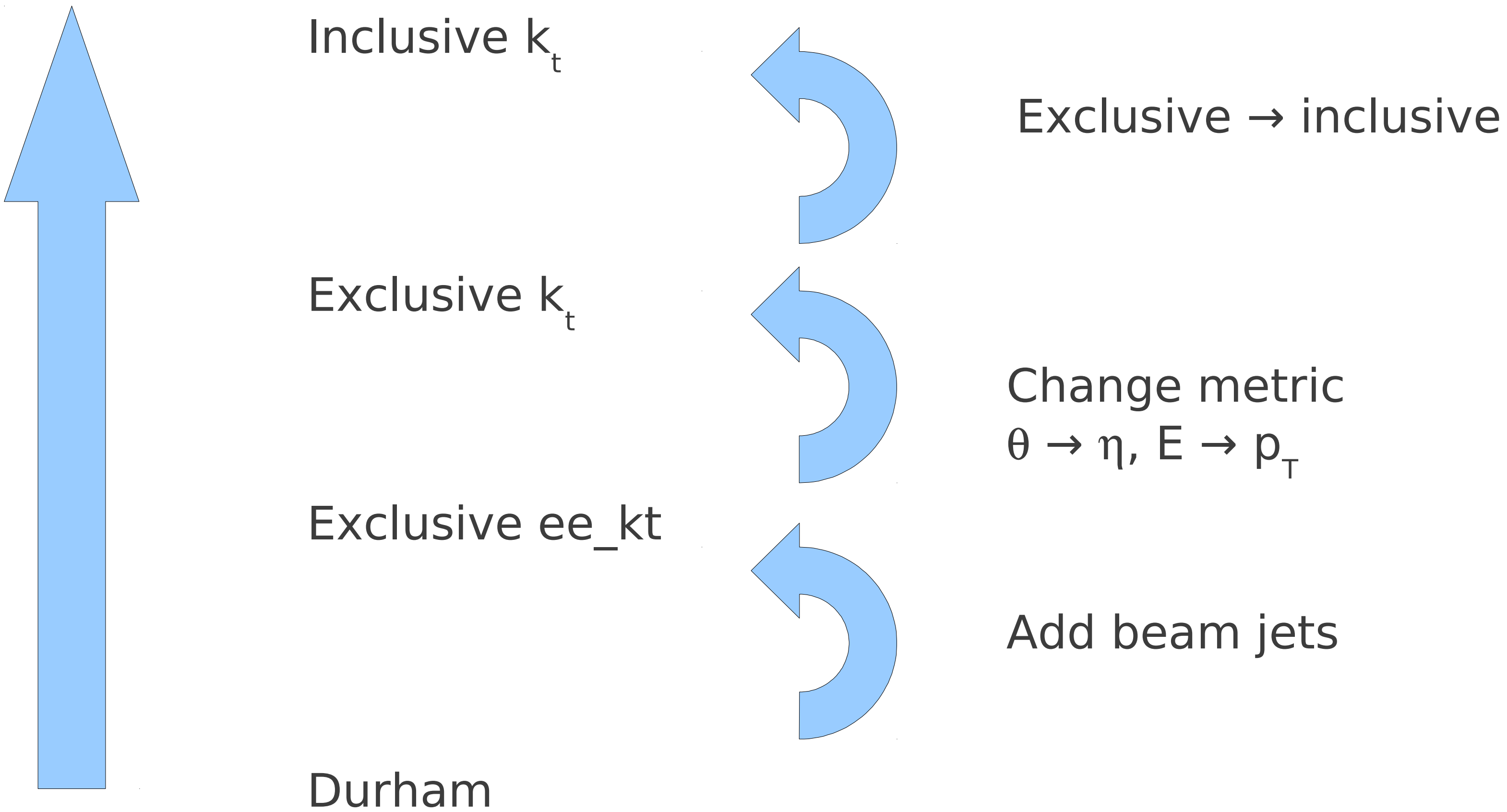


One could hope a lot of the forward particles from $\gamma\gamma$ → hadrons end up in "beam jets"

See: FastJet user manual http://arxiv.org/pdf/1111.6097.pdf

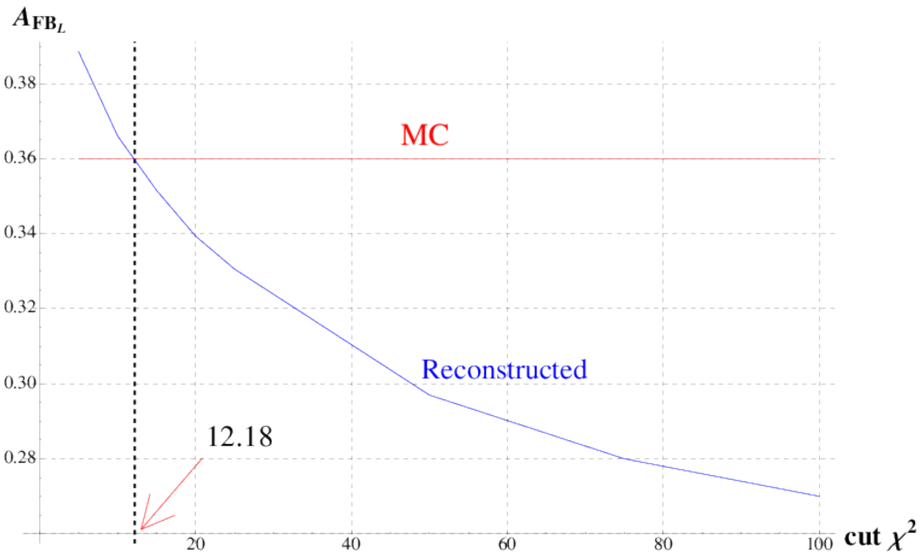
Problem II: inclusive vs. exclusive jet reco

Background resilience



Problem III

Nacho confirms the observation by François: there is a “lucky” value for The chi-squared cut



Some things that have kept us “honest” so far:
- we didn't know
- is the “lucky” chi-squared the same for both polarizations?

François proposes: What should be optimized is the differential agreement between the MC and the reconstructed angular distributions..

I'd like to know why this there is no plateau... Probably the chi2 we find depends on the polar angle of the top quark. Is it related to problem II?

Backgrounds

σ(tt) ≈ 600 fb at 500 GeV

L=500 fb^{-1} → N_{total} ~ 570 K

Semileptonic ~ 34%

Reducible backgrounds

WW → no b quark

bb → simple topology

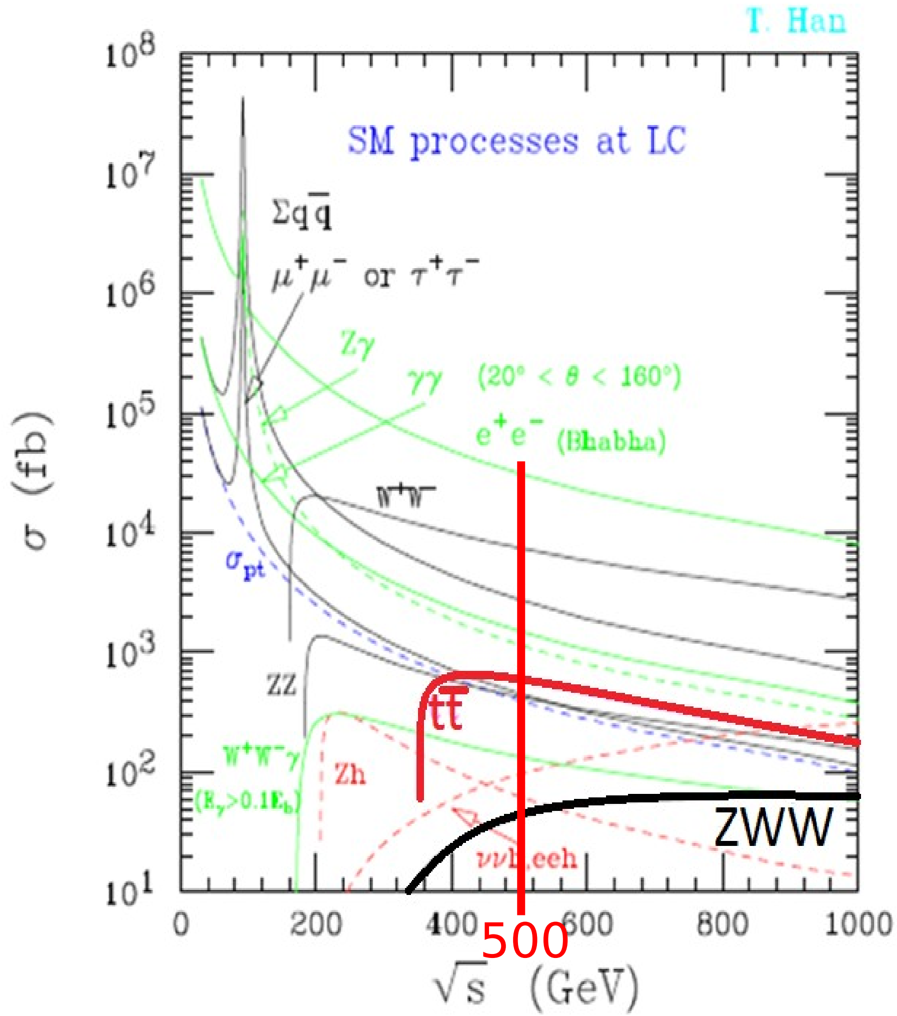
Other top decays (τ)

Irreducible:

Small but need to be subtracted

Other top decays (τ)

ZWW (Z → bb) → 8 fb



Process	tt	bb	WW	ZZ	ZWW
A_{LR} (%)	36.7	62.9	98.8	31.0	89

CP violating Form Factors

Nachtmann et al. gives the receipt used for the TESLA TDR

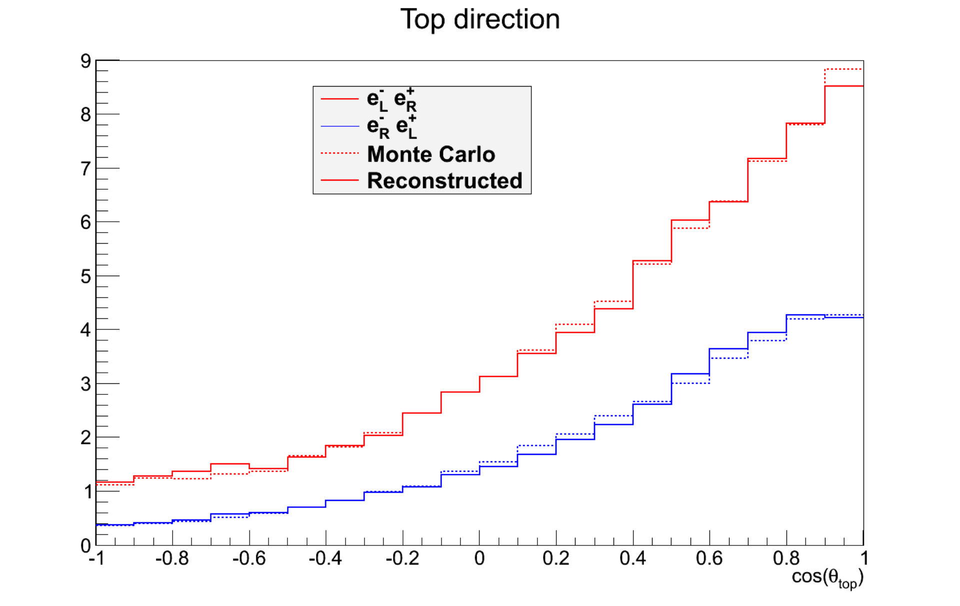
Toni Pich claims the Nachtmann paper is understandable

German Rodrigo has some orthogonal ideas

German Valencia (Iowa) has prepared a MadGraph UFO model that allows to generate events with an anomalous CP violating FF (electric dipole moment for the top quark) → unpacking later today

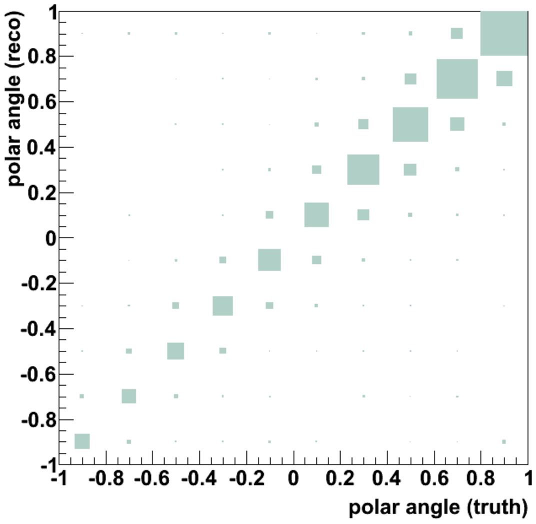
Try to reproduce TESLA numbers...

The FB asymmetry @ 1 TeV



reco = truth within 2 %

ILC1000



Mapping ÖK

> 90 % of events is correctly reconstructed

Off-diagonal elements disappear

I'm also interested to explore how the sensitivity evolves with center-of-mass energy (250-3000 GeV)

Summary

Three immediate problems + two optional ones

Proposal:

- Single top → MV
- Kt vs Durham → Nacho
- Chi-squared → Jeremy
- Paper draft → Roman

Future directions:

- different center-of-mass energy
- CP violating observables