The Top Quark as a Window on Beyond the Standard Model Physics.

The Focus of this talk will be on **experimental challenges**: analyze the subject as a source of detector requirements

Today & Tomorrow (status of top properties after 13 years at the Tevatron, plans at the LHC)

And the day after tomorrow (top physics at linear e+e- colliders)

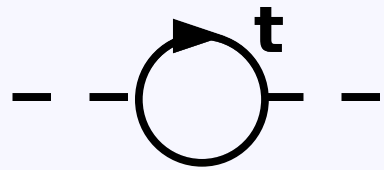
Marcel Vos, IFIC Valencia

CSIC

IFIC

Solutions to the hierarchy problem: new phenomenology

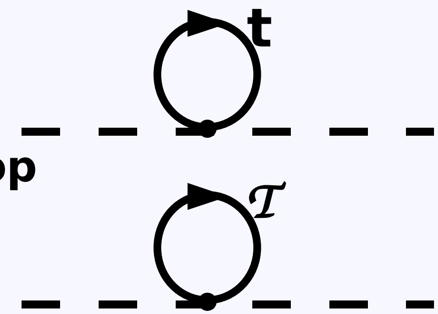
$$\underbrace{m_h^2 = m_h^2(0)}_{\text{bare mass}} + \underbrace{\delta m_h^2}_{\text{radiative corrections}}$$

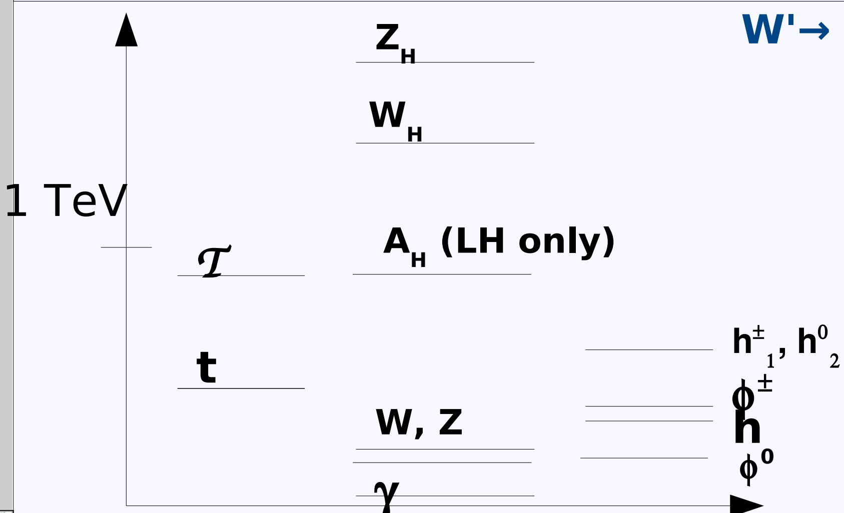


Loop cancellations λ^2 divergence

SUSY:
scalar (s)top

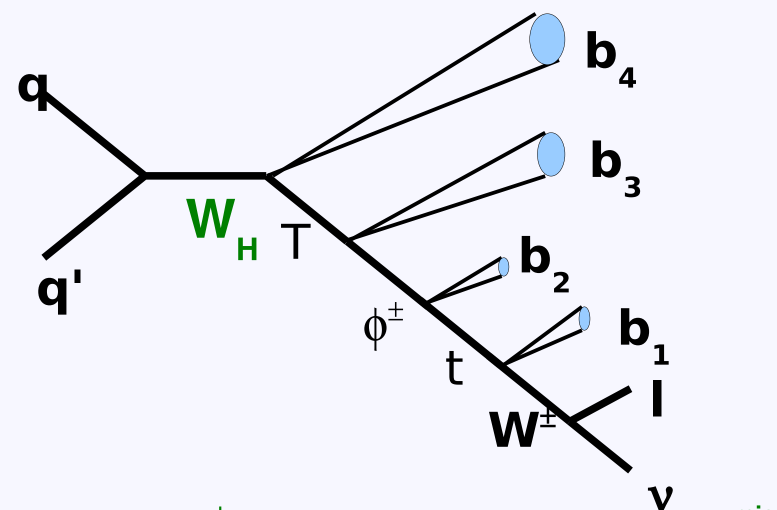
NON-SUSY:
$\mathcal{T}$ = heavy, spin ½ top





W'→ tb search @ D0: *Phys.Rev.Lett.100 (2008) 21180*

LR Twin Higgs model: cascade decay



$W_H \rightarrow Tb \rightarrow \phi^{\pm}bb \rightarrow t{+}3b \rightarrow bb + l + E_t^{miss}$

Little Higgs: Arkani-Hamed et al., Phenomenology: Han et al., LR Twin Higgs: Chacko et al. (hep-ph/0506256) Phenomenology: Goh and Su (hep-ph/0608330), Les Houches 2007

Tevatron searches

Tevatron (narrow) tt resonances

D0, FERMILAB-PUB-08-097E, arXiv:0804.3664

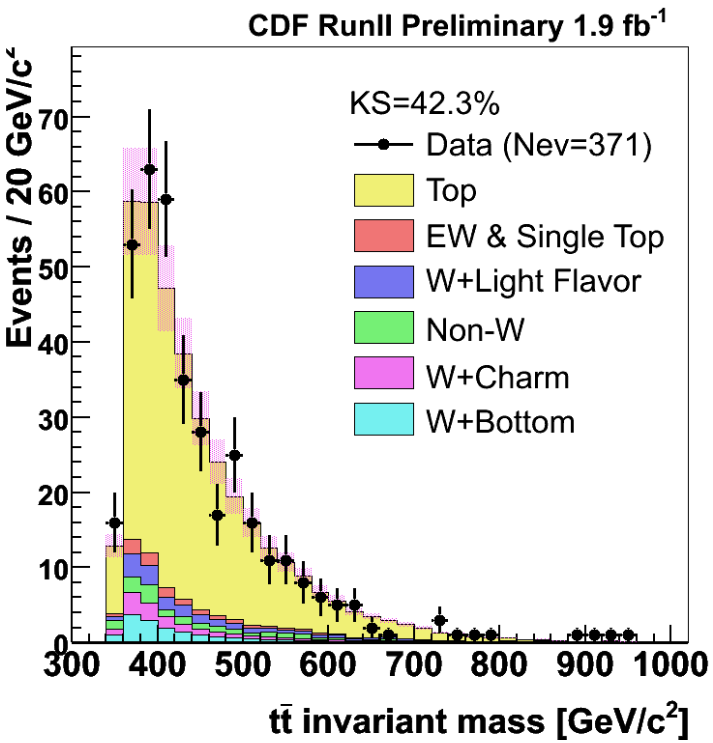
CDF, Phys.Rev.Lett.85 (2000), arXiv:0710.5335v1

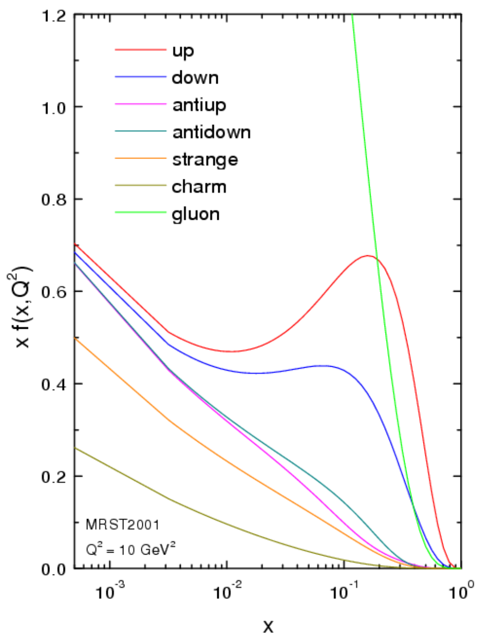
CDF totals 347 evts. In 1 fb^{-1}.

Most tt-pairs produced ~ at rest:

heaviest pair: M ~950 GeV

the cross section of any narrow Z' decaying to a $t\bar{t}$ is less than 0.64 pb at 95%C.L., for Z' masses above 700 GeV





LHC will explore tops "in action"

SM tt production @ 14 TeV (MC@NLO)

~20% of events has p_T(top) > 200 GeV

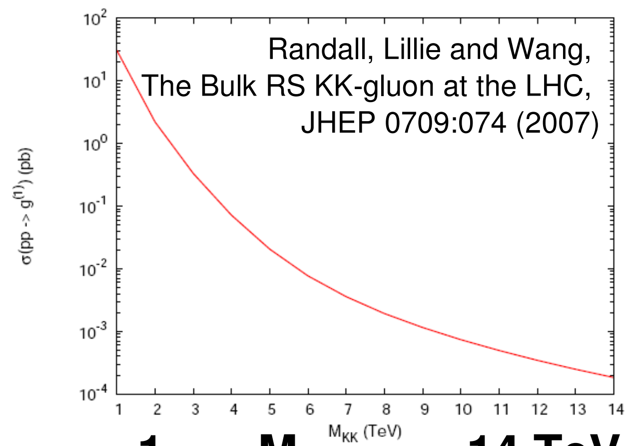
~0.1% of events has p_T(top) > 500 GeV

Assuming L =10^{34} cm^{-2}s : one event / 2.5 seconds (minute)

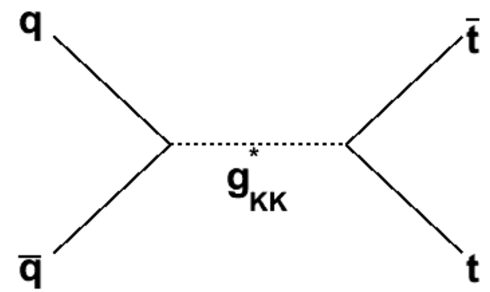
An example of a signal

RS warped extra dimensions

L. Randall, R. Sundrum, A Large Mass Hierarchy from a Small Extra Dimension. Physical Review Letters 83 (1999): 3370–3373
L. Randall, Warped Passages: Unraveling the Mysteries of the Universe's Hidden Dimensions. New York: HarperCollins (2005).
“possibly the most attractive ....”)



1.... M_{KK} .....14 TeV



When SM gauge penetrate the bulk, Kaluza Klein towers of excited states appear.

couples strongly to quarks:
large cross-section: 15 pb for $m(g^*_{KK})$ = 1 TeV @ 10 TeV

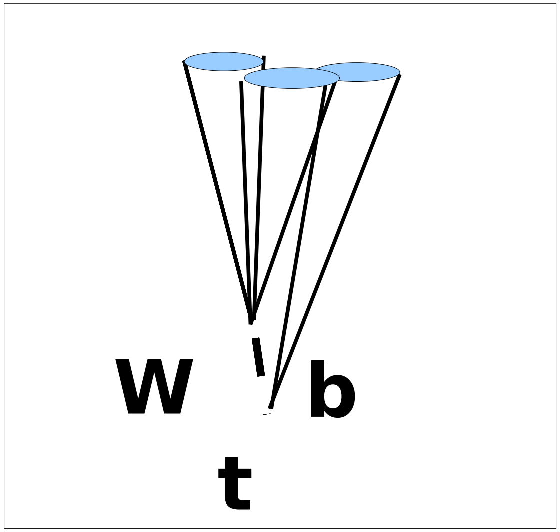
but, by the same token:
not a narrow resonance! Basic RS model: $\Gamma = 0.17$ M

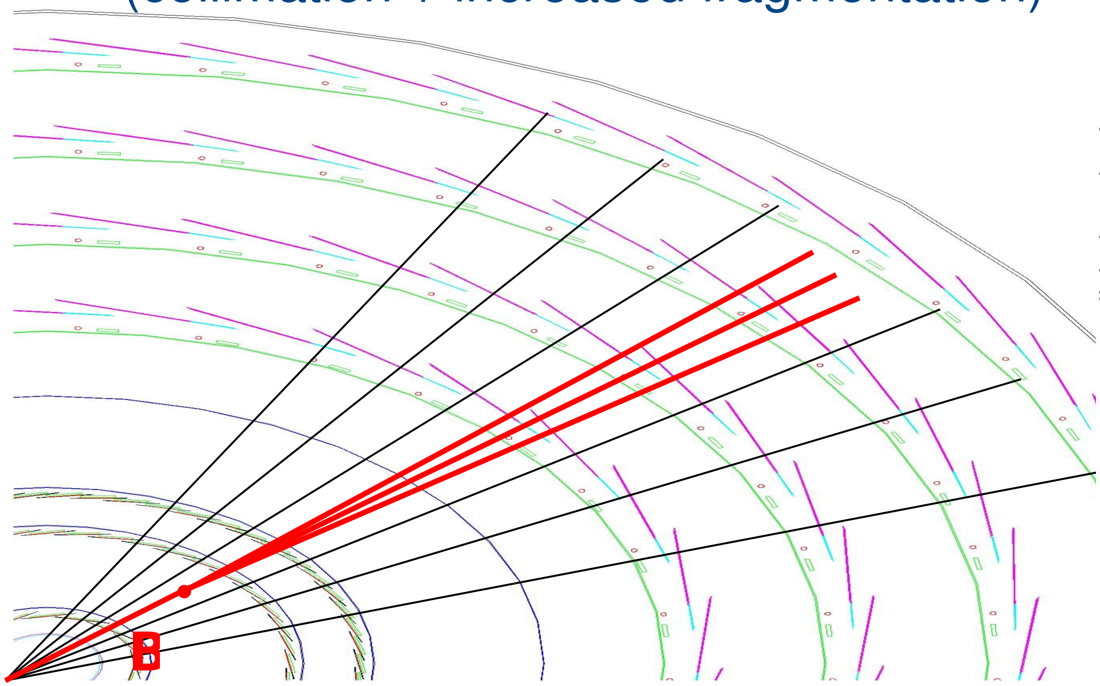
Large branching fraction into tt
Basic RS scenario: 92.6 %

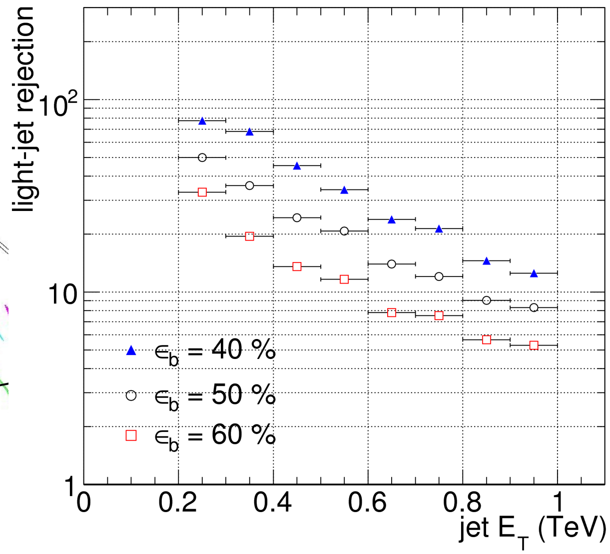
Strongly interacting tt resonances could be part of “early LHC physics”
Accompanied by Z_{KK}, graviton. See Shrihari Gopalakrishna in the NP at the Tera scale session

TeV top quarks

- boosted (hadronic) decay products cannot be resolved
- $L = c\,\tau\,\gamma \Rightarrow$ strongly enhanced for high p_T b-jets
- Particle density increases strongly (collimation + increased fragmentation)



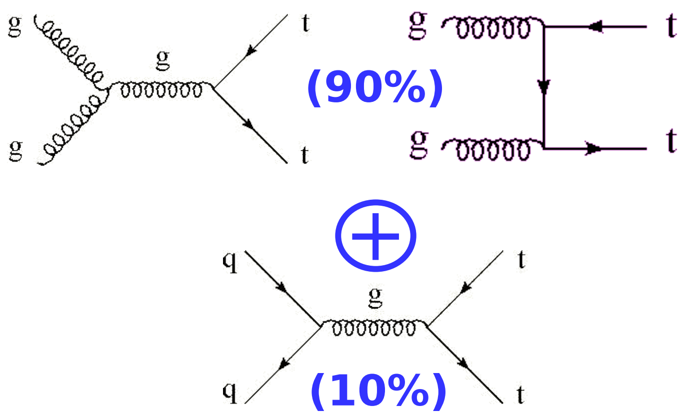




CERN-OPEN-2008-020, Geneva, 2008, to appear

LHC vs ILC

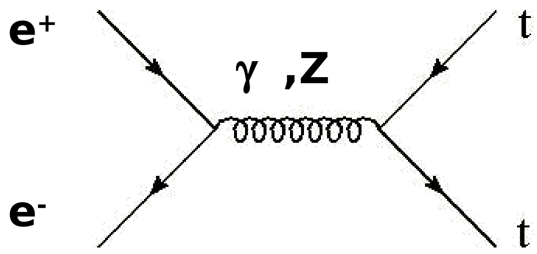
LHC



tt production cross section at LHC:
~833 pb
At √s = 14 TeV

2 tt events per second !
8 millions tt events/year
Assuming L =10^{34} cm^{-2}s

ILC



tt production cross section at ILC:
~0.6 pb
At √s = 500 GeV

120k tt events/year
Assuming L =10^{34} cm^{-2}s

LHC vs ILC

- ILC clearly the place to measure Z-t-t coupling
- ILC definitely better for top mass measurement
- ILC reach for FCNC searches limited by statistics, while lower background allows to compete with LHC expectation

BR 5σ sensitivity	$t \to qZ$	$t \to q\gamma$
LHC, L = 100 fb^{-1}	1.6×10^{-4}	3.8×10^{-5}
ILC, 500 GeV	2×10^{-4}	4×10^{-6}

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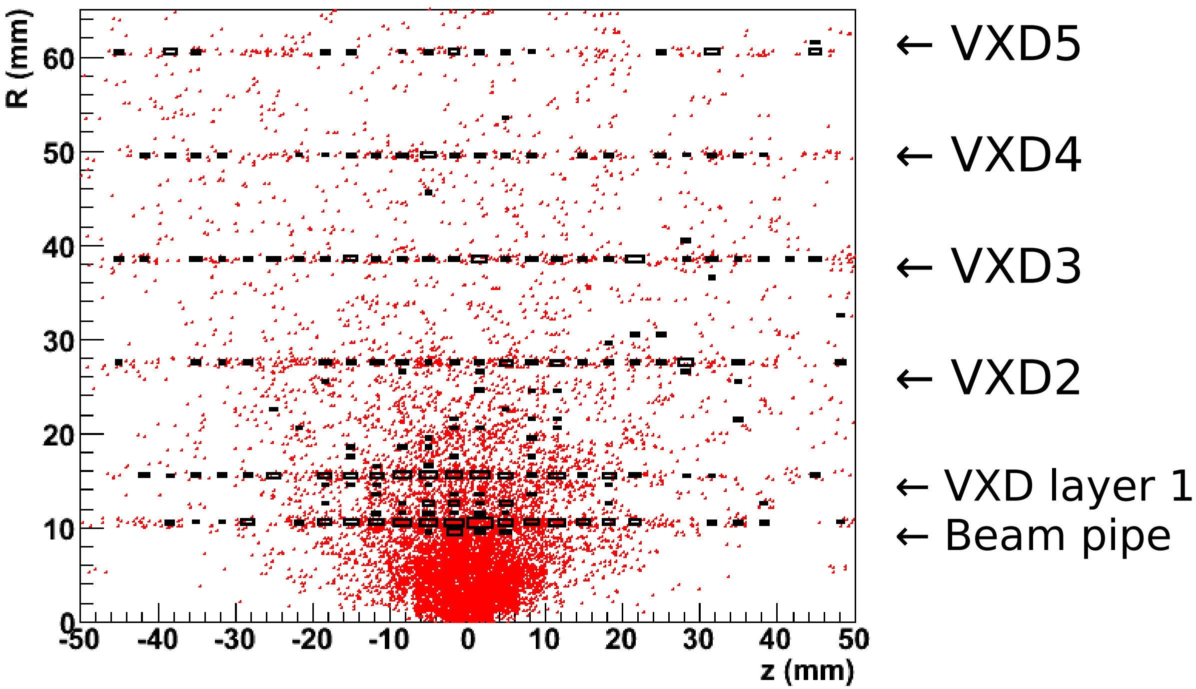
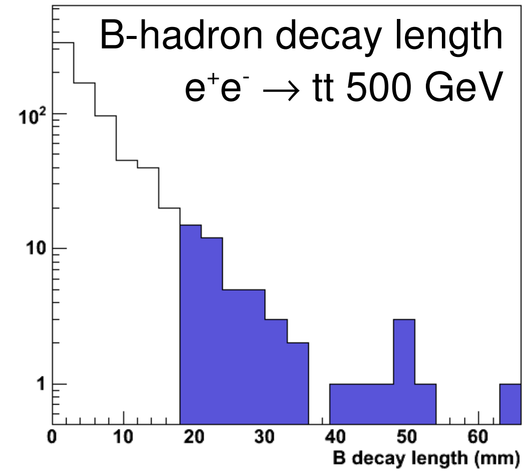




conversions

hadrons
(mostly B-decay)

In a 500 GeV ILC the top quarks are “at rest” and the B-hadron boost small ($\langle p_B \rangle$ = 67 GeV)

But, then again, VXD is much closer:

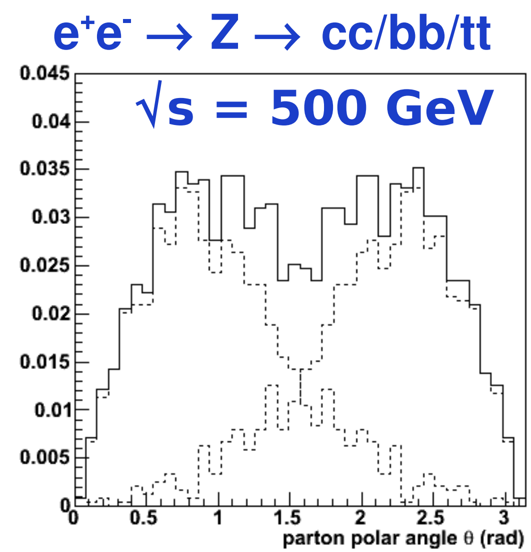
ATLAS 55 mm vs. ILD 16 mm / SiD 12.5 mm

1 TeV ILC?, CLIC, see M. Battaglia's talk in the plenary

bb/cc production? A_{FB}^{b}, A_{FB}^{c}

Multi-fermion final states

Final states with many fermions (like ordinary SM tt-events) are hardly ever contained in the central detector

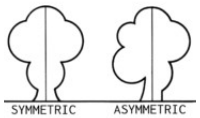


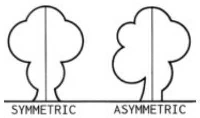
P (θ < 30)	√s = 500 GeV	√s = 1 TeV	√s = 3 TeV
at least one top	0.15	0.17	0.22
at least one b	0.22	0.25	0.25
any fermion	0.59	0.51	0.4

The probability in tt events to find at least one top, b-quark or fermion in the forward detector

Tag a forward b-jet in 1 out of 4 events: requires vertexing

Heavy resonances at the ILC: asymmetry



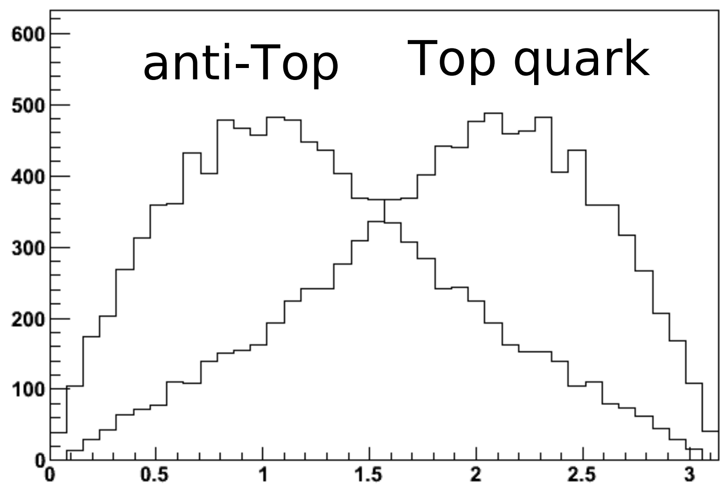


a forward-backward asymmetric distribution originates in e+e- → tt production from an interference of the vector and axial-vector fermion anti-fermion production vertices at tree level of electroweak interaction.

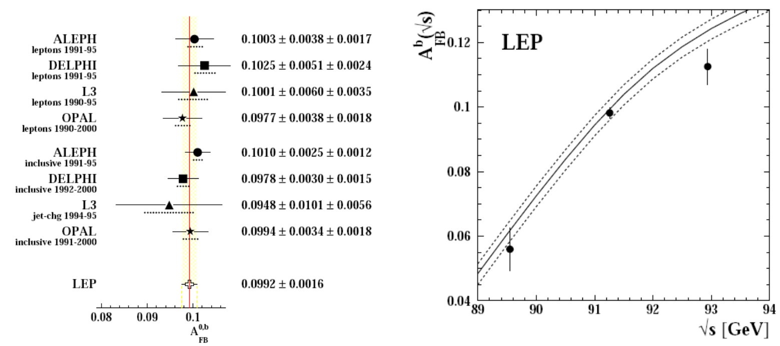
Compared to LEP: asymmetry much larger, top quark accessible

Compared the LHC: p-p collissions and dominant gg initiated processare intrinsically symmetric

is i



e^+e^- → tt production at a 500 GeV ILC
MadGraph Standard Model Leading Order



From A. Schael et al., precision electroweak measurements at the Z-resonance, hep-ex/0509008

A_{FB}^{tt}

ILC has a sensitivity to Z' resonances with masses that are well beyond it's direct reach due to interference of γ/Z/Z' .

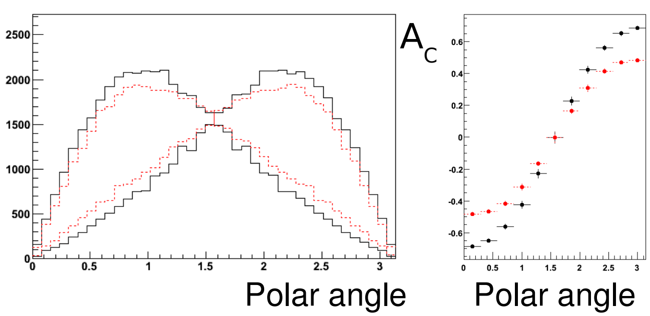
Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV
ee --> tt Cross-section	91.7 ± 0.1	88.2 ± 0.2	93.8 ± 0.2	94.9 ± 0.2	94.9 ± 0.2
A_{FB}^{tt}	0.41 ± 0.01	0.296 ± 0.007	0.390 ± 0.007	0.395 ± 0.007	0.398 ± 0.006
$A_{FB}^{tt\ (central)}$	0.36 ± 0.01	0.263 ± 0.007	0.346 ± 0.007	0.352 ± 0.007	0.351 ± 0.007

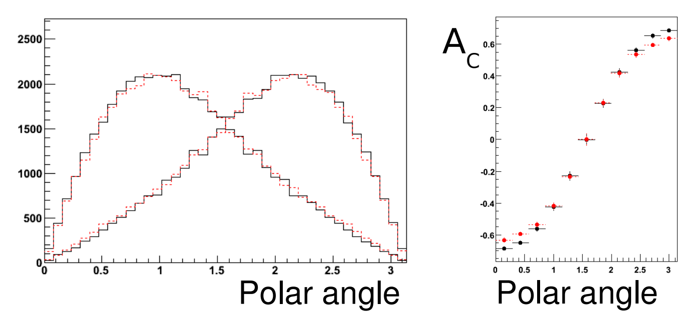
LO production cross-section (MadGraph) and top quark FB asymmetry for the ee--> tt process in the Standard Model and various sequential Z' scenarios. Errors are purely statistical, assuming 500 pb^{-1}.

Forward backward asymmetry is a very sensitive probe

Not only A_{FB}^{tt}, but also A_{FB} of b from tt, A_{FB} of μ from tt, see E. Devetak, this session

A forward signal by construction: the (exact) center of the detector does not contribute



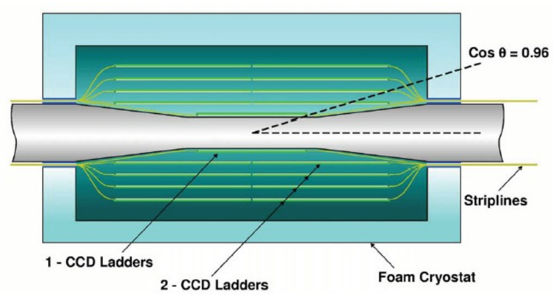


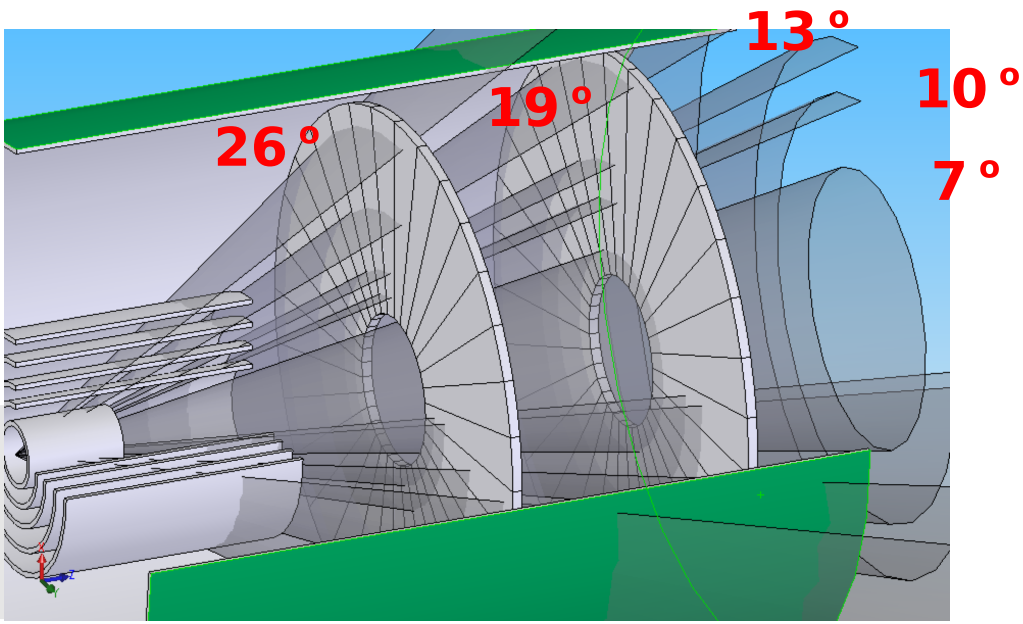
ILD: vertex detector

Concept	Magnetic Field	Angular Coverage 5-point	3-point
SiD	5 T	12.5 (43 barrel)	9
LDC	4 T	26	19
GLD	3T	26 (6 points)	18 (4 barrel + 2 disk)

Long barrel layout (LDC, GLD, ILD) has limited coverage for angular region from 7º to 25º

forward tracking in the case of a "long barrel" vertex detector

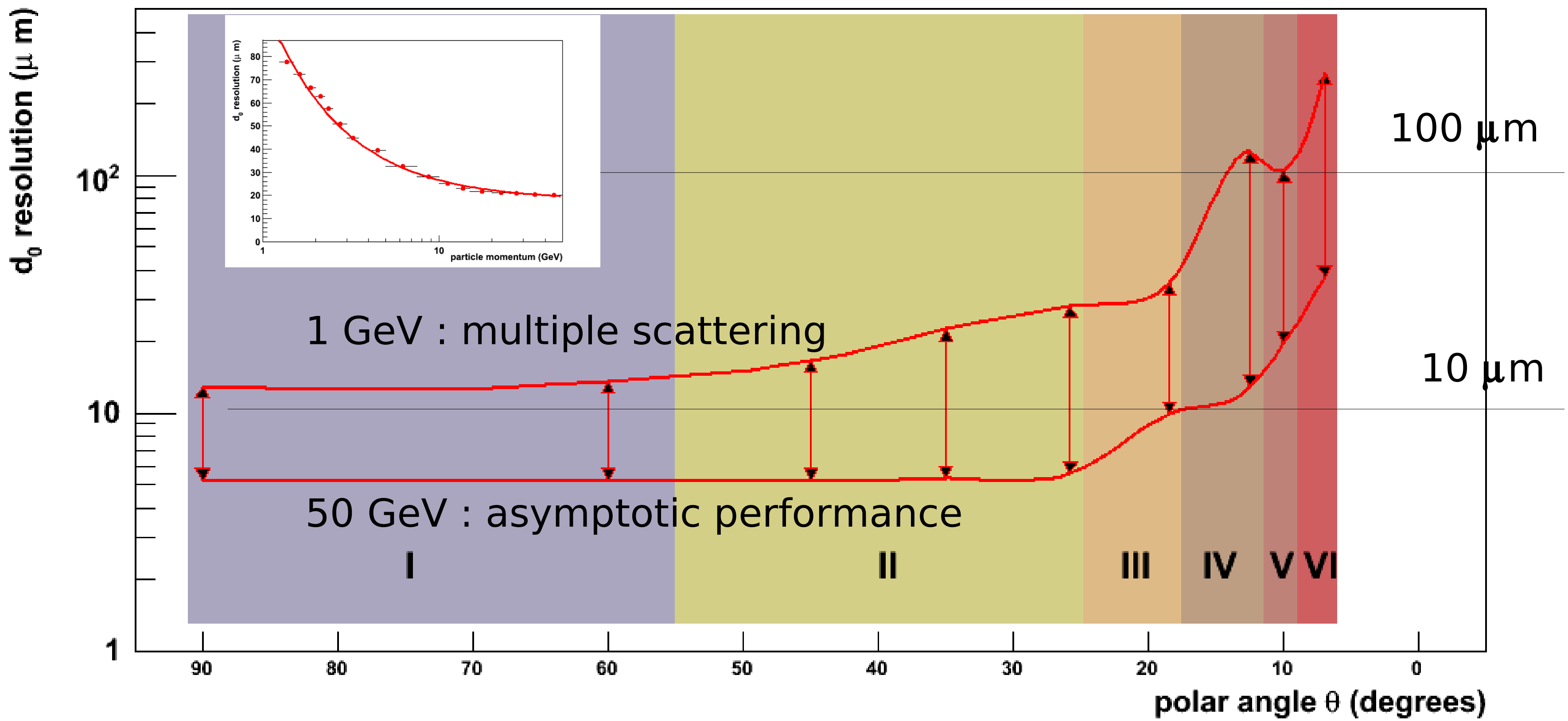




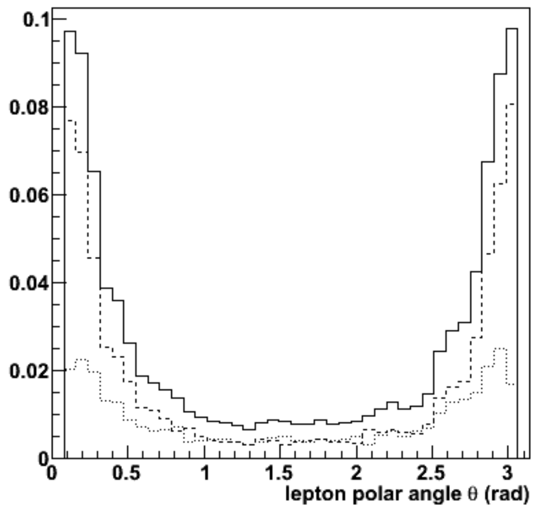
ILD inner tracker layout:
- VXD (cylinders)
- SIT (green)
- FTD disk 1 and 2

Impact parameter

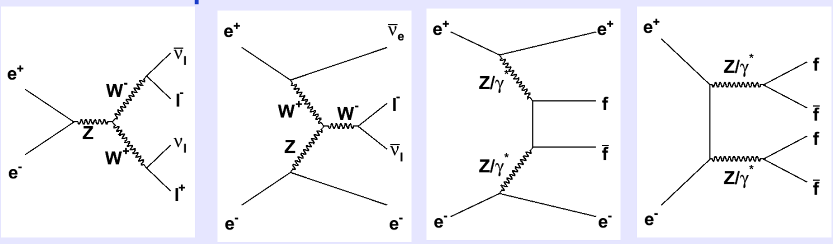
* I	$35 < \theta < 90$	5 VXD + SIT	
* II	$25.8 < \theta < 35$	5 VXD + FTD1	
* III	$18.5 < \theta < 25.8$	3 VXD + FTD1+2	
* IV	$12.5 < \theta < 18.5$	VXD2 + FTD	
* V	$10 < \theta < 12.5$	FTD1,...	
* VI	$6.5 < \theta < 10.0$	FTD2,...	



The list: physics that prefers forward



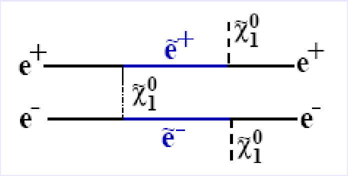
SM: di-boson productions

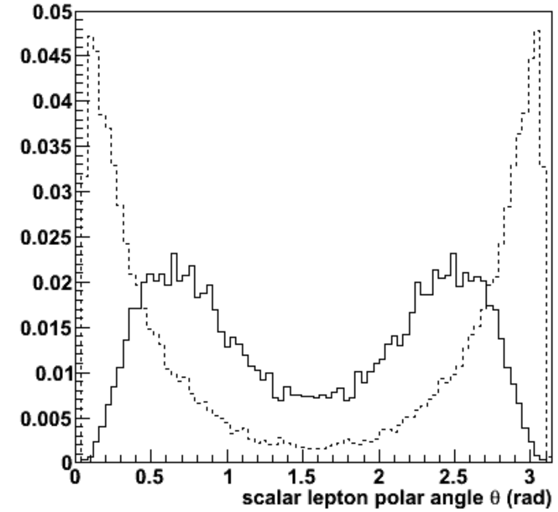


Di-boson production: leptons from WW production @ 500 GeV: electrons (dashed) and muons (dotted)

SUSY: SPS1a t-channel s-lepton production @ 500 GeV (full) and 3 TeV (dashed)

SUSY: s-electrons





Products from t-channel prefer the forward region (and increasingly so with higher center-of-mass energy)

Fraction of forward s-electrons ($\theta < 30^o$) for s-electron pair production in SPS1a

@ 500 GeV **24 %**

@ 1 TeV **50 %**

Conclusions

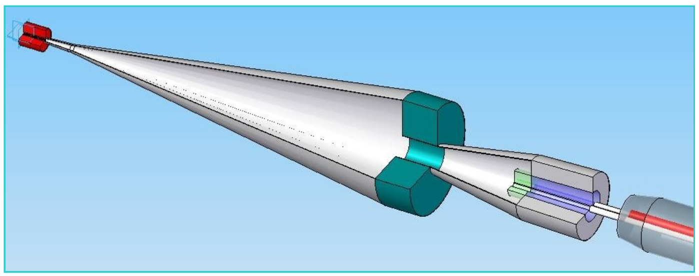
High p_T top at the LHC is an excellent window to new physics and an experimental challenge

a corner of the LHC “early physics space” that would a priori not seem very favourable to a 500 GeV ILC, but that may provide important input to detector optimizat

Exotic physics with top quarks at the ILC requires excellent forward flavour tagging

TPC

TPC active inner radius ~ 40 cm
envelope down to ~ 30 cm



Beam Pipe

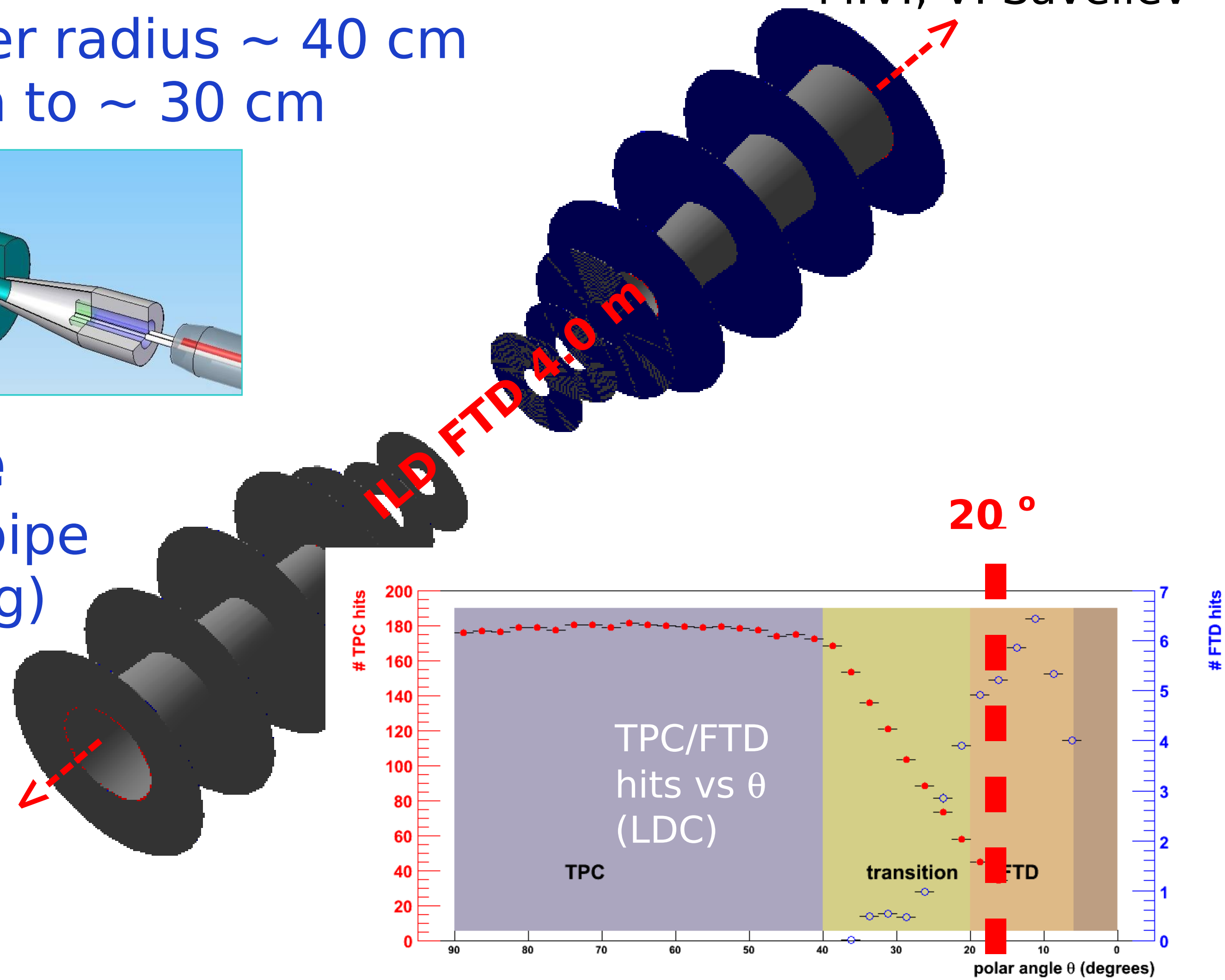
conical beam pipe
(beamstrahlung)

VXD

R = 1.6 – 6 cm

SIT

R = 16 cm

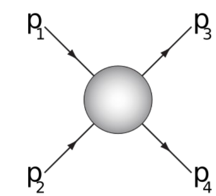


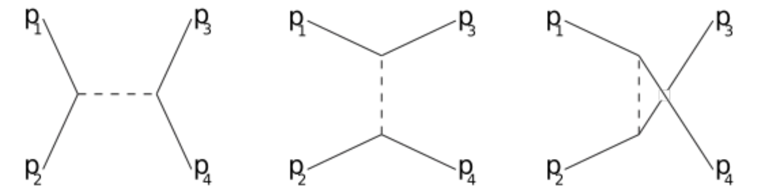
The importance of the t-channel

With increasing center-of-mass energy
(from LEP-I to to LEP-II to ILC to CLIC)
the importance of the t-channel increases

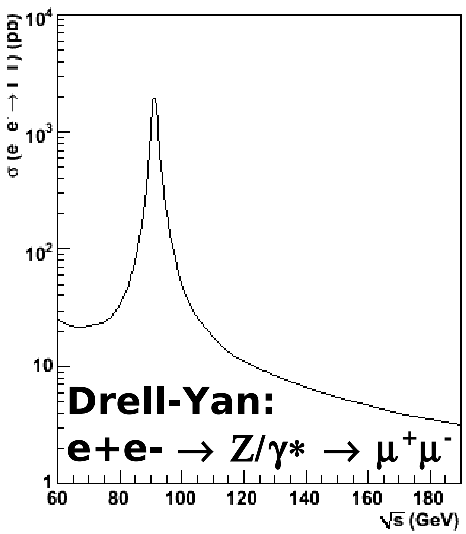
Example: scalar lepton production in SUSY (SPS benchmark point 1a)

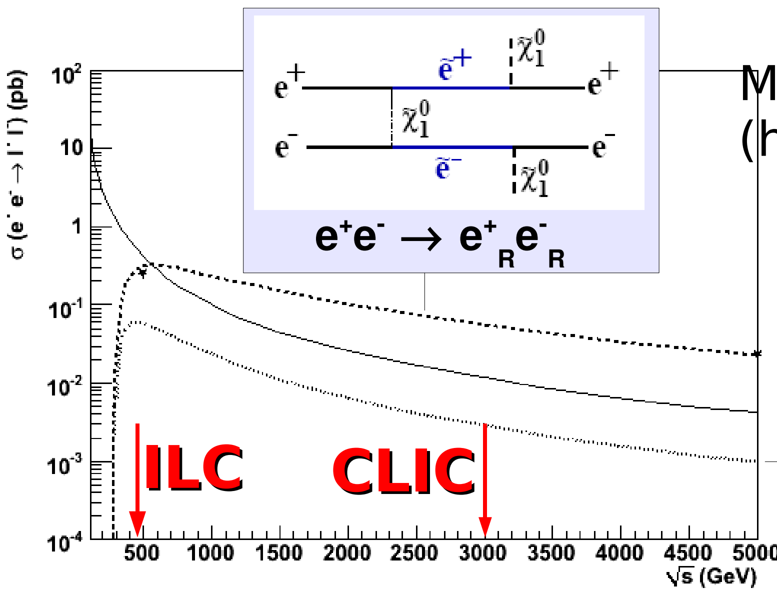
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$



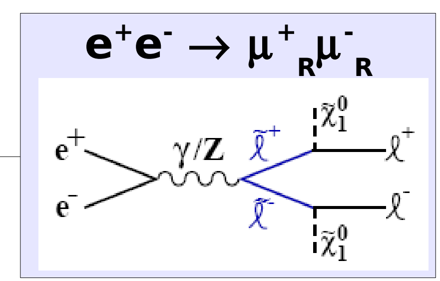


s-channel **t-channel** **u-channel**



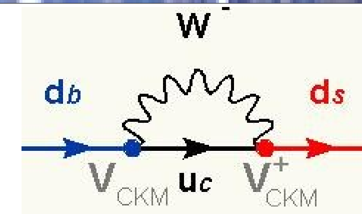


MadGraph/MadEvent
(hep-ph/0208156)



Searches for rare decays

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} \qquad V_{ij} = \begin{bmatrix} 0.97383 & 0.2272 & 0.00396 \\ 0.2271 & 0.97296 & 0.04221 \\ 0.00814 & 0.04161 & 0.999100 \end{bmatrix}.$$



Standard Model: the Wtb coupling is purely left-handed at the tree level and its strength governed by **V_{tb} ~ 0.999**

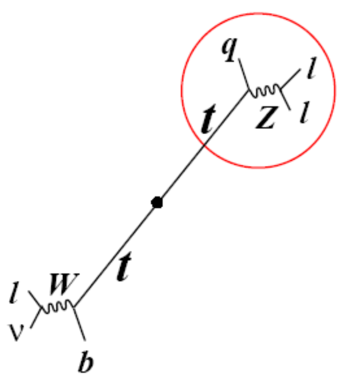
(assuming three generations of quarks and the unitarity of CKM matrix)

New physics may lead to:

- departure from the SM value for V_{tb}
- new radiative contributions

$t \to qZ$

(2jets+3l+missing)



Flavor Changing Neutral Current (FCNC) are strongly suppressed in the SM by the Glawhow-Iliopoulos-Maiani (GIM) mechanism, but may appear at tree-level in SUSY, 2 Higgs Doublet Models and models with exotic vector-like quarks

ss	SM	QS	2HDM	MSSM	RPV SUSY
Z	8×10^{-7}	1.1×10^{-4}	x	2×10^{-6}	3×10^{-5}
,	3.7×10^{-16}	7.5×10^{-9}	x	2×10^{-6}	1×10^{-6}
Z	3.7×10^{-14}	1.5×10^{-7}	x	8×10^{-5}	2×10^{-4}
Z	1×10^{-14}	1.1×10^{-4}	$\sim10^{-7}$	2×10^{-6}	3×10^{-5}
,	4.6×10^{-14}	7.5×10^{-9}	$\sim10^{-6}$	2×10^{-6}	1×10^{-6}
Z	4.6×10^{-12}	1.5×10^{-7}	$\sim10^{-4}$	8×10^{-5}	2×10^{-4}

Are these extremely small branching ratios accessible experimentally?

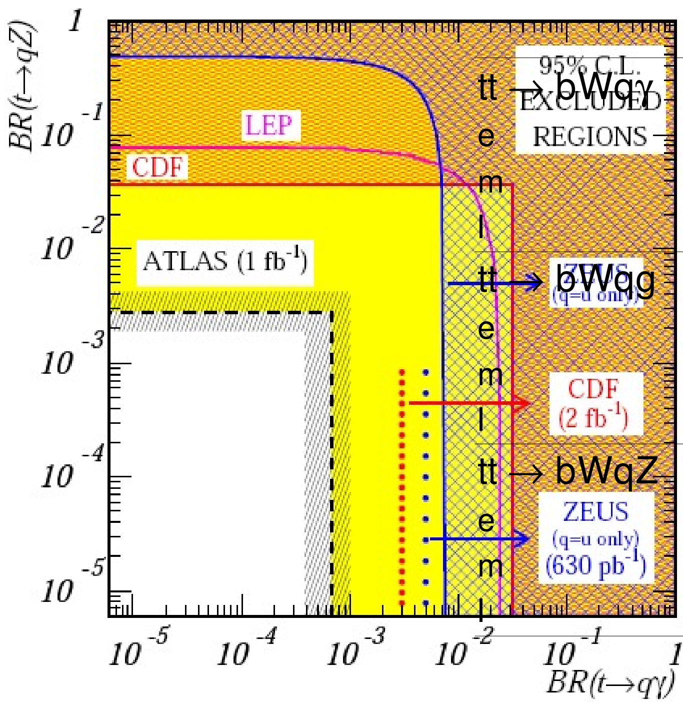
Study of ATLAS sensitivity to FCNC top decays, SN-ATLAS-2007-059

Rare FCNC top decays

	LEP	HERA	Tevatron
BR (t → qZ)	٧.٨%	٤٩%	٣.٧%
BR (t → qγ)	٢.٤%	٠.٧٥%	٣.٢%
BR (t → qg)	١٧.٠%	١٣%	٠.١-١%

Need a top factory!

Expected 95 % C.L. limits in ATLAS after 1 fb^{-1} (converted into limits on branching ratios using SM tt cross-section)



	-1s	Expected	1σ
tt → bWqγ			
e	4.3×10^{-3}	1.1×10^{-3}	1.9×10^{-3}
m	4.5×10^{-4}	8.3×10^{-4}	1.3×10^{-3}
l	3.8×10^{-4}	6.8×10^{-4}	1.0×10^{-3}
tt → bWqg			
e	1.3×10^{-2}	2.1×10^{-2}	3.0×10^{-2}
m	1.0×10^{-2}	1.7×10^{-2}	2.4×10^{-2}
l	7.2×10^{-3}	1.2×10^{-2}	1.8×10^{-2}
tt → bWqZ			
e	5.5×10^{-3}	9.4×10^{-3}	1.4×10^{-2}
m	2.4×10^{-3}	4.2×10^{-3}	6.4×10^{-3}
l	1.9×10^{-3}	2.8×10^{-3}	4.3×10^{-3}

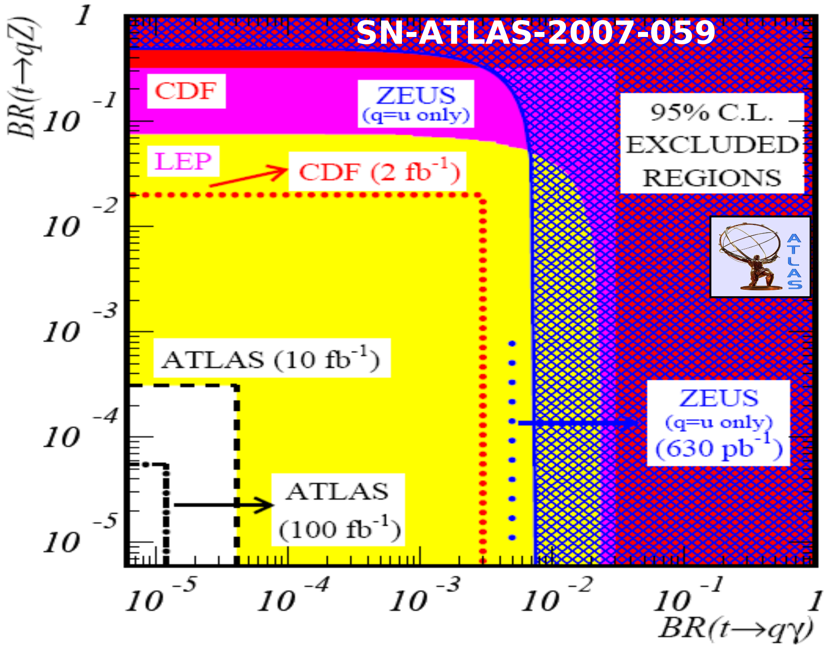
+/- 1 σ includes statistical error and systematic effect of jet energy calibration, luminosity, top quark mass, background cross-section, ISR/FSR, Pile-up, Generator, χ^2

Rare FCNC top decays

	LEP	HERA	Tevatron
BR ($t \to qZ$)	7.8%	49%	3.7%
BR ($t \to q\gamma$)	2.4%	0.75%	3.2%
BR ($t \to qg$)	17.0%	13%	0.1-1%

Need a top factory!

Expected 95 % C.L. limits in ATLAS after 1 fb^{-1} (converted into limits on branching ratios using SM tt cross-section)



-1s	Expected	1σ
4.3×10^{-3}	1.1×10^{-3}	1.9×10^{-3}
4.5×10^{-4}	8.3×10^{-4}	1.3×10^{-3}
3.8×10^{-4}	6.8×10^{-4}	1.0×10^{-3}
1.3×10^{-2}	2.1×10^{-2}	3.0×10^{-2}
1.0×10^{-2}	1.7×10^{-2}	2.4×10^{-2}
7.2×10^{-3}	1.2×10^{-2}	1.8×10^{-2}
5.5×10^{-3}	9.4×10^{-3}	1.4×10^{-2}
2.4×10^{-3}	4.2×10^{-3}	6.4×10^{-3}
1.9×10^{-3}	2.8×10^{-3}	4.3×10^{-3}

+/- 1 σ includes statistical error and systematic effect of jet energy calibration, luminosity, top quark mass, background cross-section, ISR/FSR, Pile-up, Generator, χ^2