BSM searches with top quarks

An experimentalist's summary

Marcel Vos (IFIC Valencia)

To warm up...

The mass of the top quark is an indication of its affinity to new physics.

→ that's why it's a trouble maker in the SM

→ that's why it's special in many BSM models (Little Higgs, ED)

The top is a multi-purpose quark (from calibration to BSM searches)

→ trigger, tag, isolate, distinguish from anti-quark

Top is the new bottom (E. Laenen, CERN theory workshop 2009).

→expect a prominent role of the top quark at the LHC (and the ILC!)

This talk: evaluate some of the LHC developments for BSM physics with tops and translate to the case of a FLC. Understand requirements on detector.

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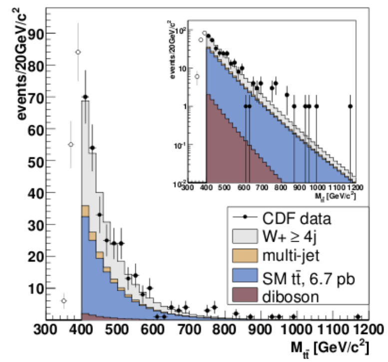
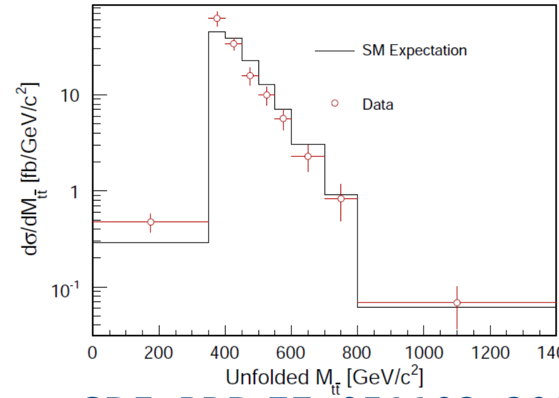
Resonance searches



CDF arXiv:0709.0705



CDF, PRD 77, 051102, 200

Exiting limits (mostly Tevatron)	
di-lepton	M_Z > 1 TeV
di-jets	M_Z > 750 GeV, limits on strongly coupled states in the range 600 GeV – 1.2 TeV
tt	No limit on sequential Z', Constrains a leptophobic state in topcolor models
LHC/ATLAS prospects (CERN-OPEN-2008-005)	
di-lepton	multi-TeV early, finally 5 TeV
di-jets	Competitive with Tevatron very early (100 pb-1)
tt	Next few slides

Tevatron → *8 fb^{-1} ppbar @ 1.96 TeV = 64.000 tt pairs*

- tops produced ~ at rest,
- *heaviest observed pair ~ 1 TeV*
- *~20 papers on tt resonance searches*

LHC early days → *200 pb^{-1} pp @ 10 TeV = 80.000 tt pairs*

- *1 fb^{-1} @ 7 TeV (envisaged 2011) similar*
- A top factory!
- especially for high p_T tops

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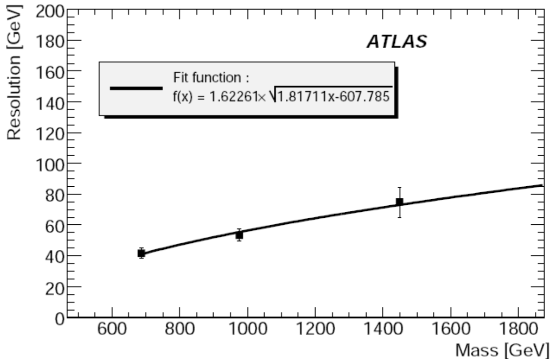
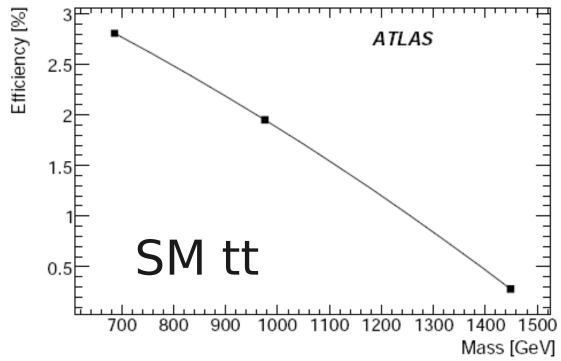
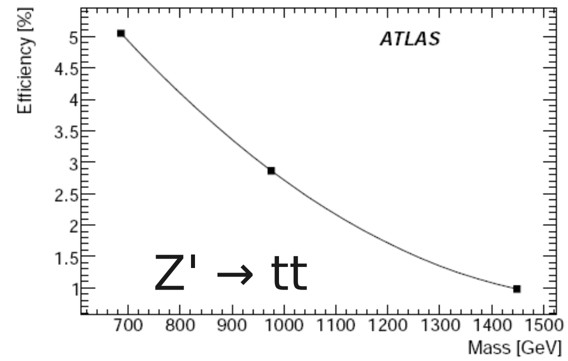
ATLAS tt resonance searches



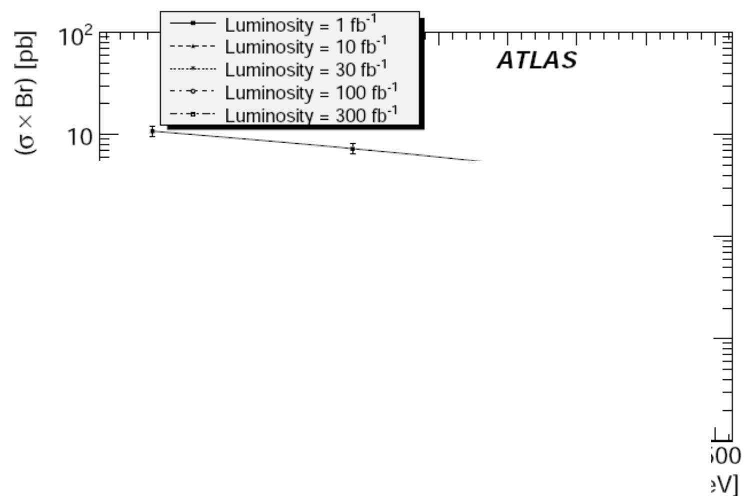




- Resonance mass resolution ~5 % in mass range from 700 to 1500 GeV.
- A sharp efficiency drop towards larger resonance mass

  5 % @ 700 GeV

  < 1 % @ 1500 GeV



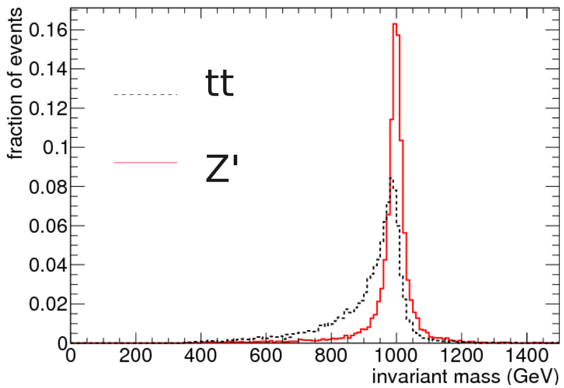
The sensitivity (σ x BR for narrow tt resonances versus mass and integrated luminosity for 14 TeV LHC operation

Shortish term (1 fb^{-1}) → 8 pb @ 1 TeV

Long term (300 fb^{-1}) → 0.4 pb @ 1 TeV

It may take quite long to get to pb level

Choose your resonance carefully

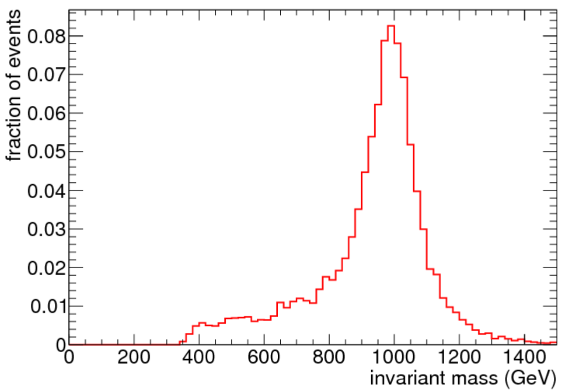


Narrow electro-weak resonance Z'

$\Gamma \sim 3$ % M

σ x BR (X->tt) ~ 1 pb

tt mass distribution is affected by gluons radiated off top quarks



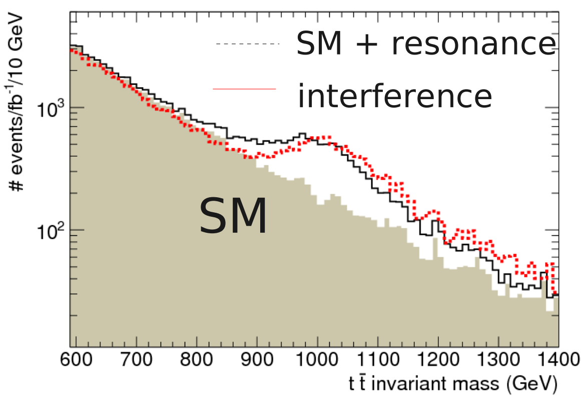
Broad coloured resonance: KK gluon

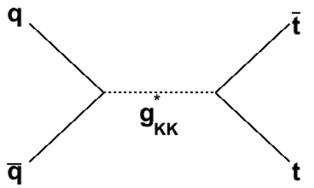
Randall, Lillie and Wang, JHEP 0709:074 (2007)

$\Gamma = 15.3$ % M

σ x BR (X->tt) > 10 pb

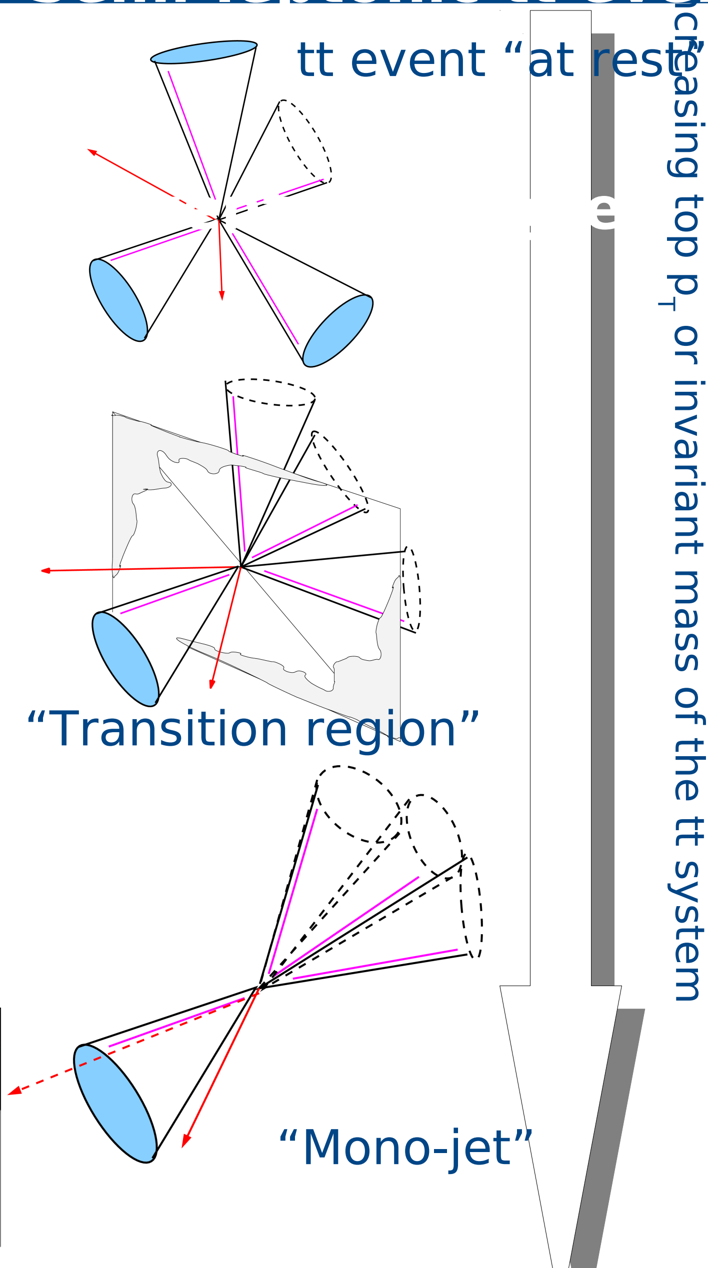
Convolution of Breit-Wigner with parton luminosity function yields low-mass tail

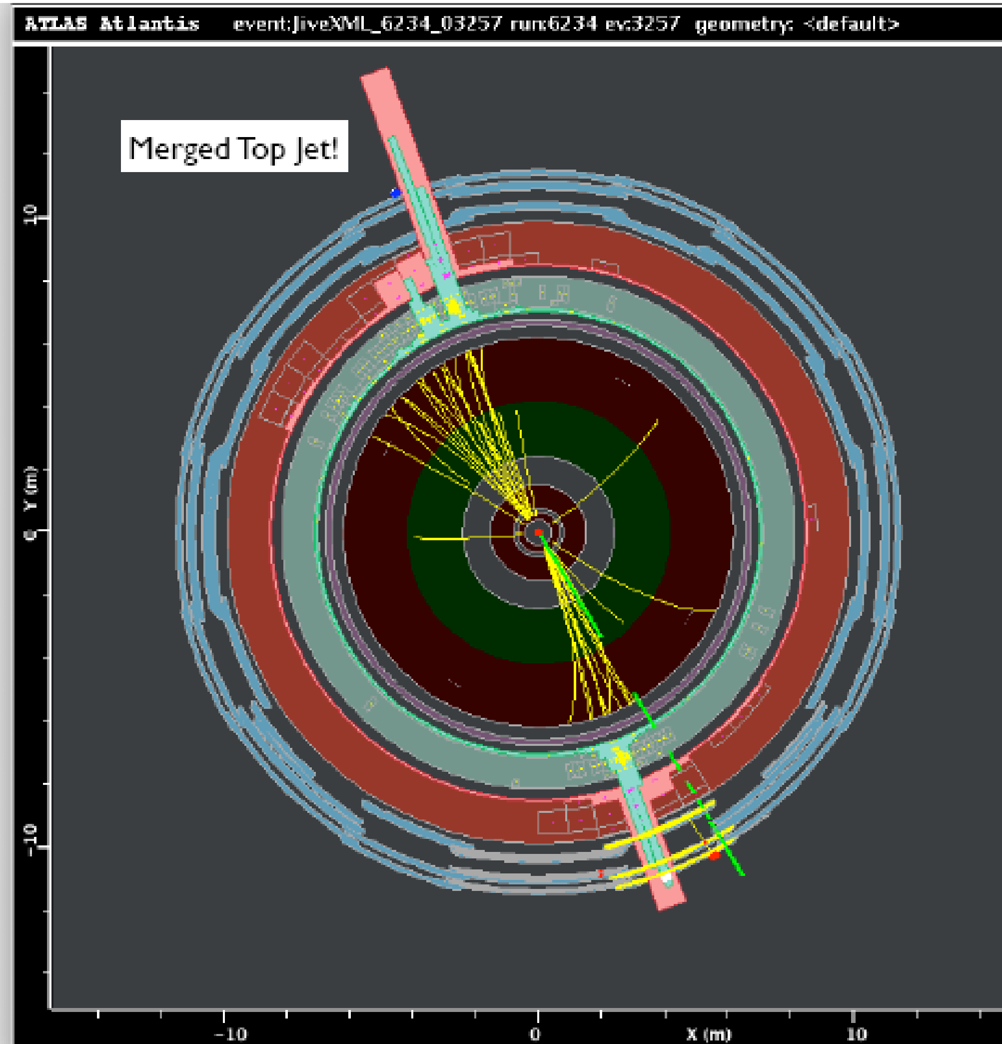




Interference with SM production for coloured resonance: destructive for low mass

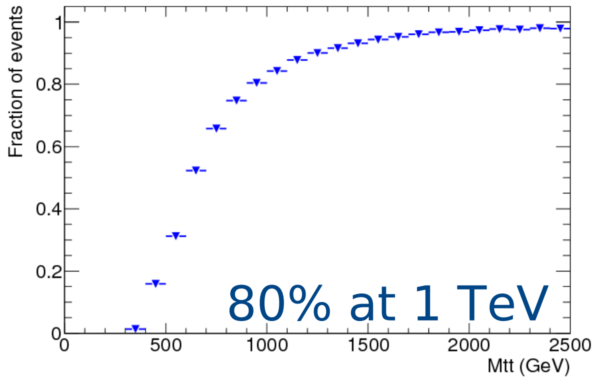
Semi-leptonic tt event topologies

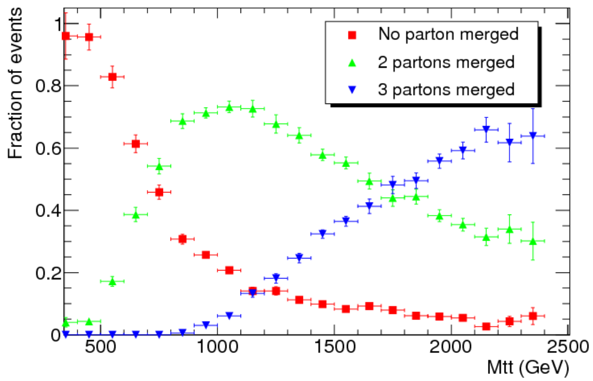


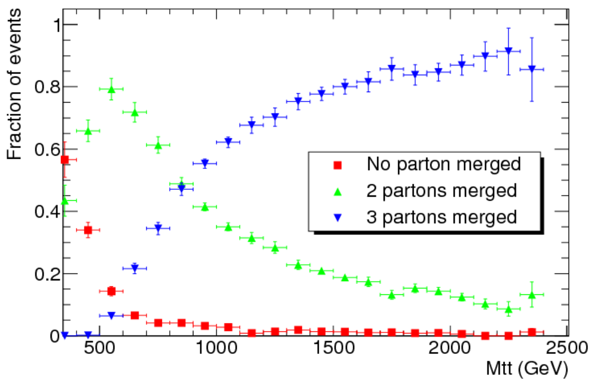


Where's the isolated lepton?
Where does the b-jet end and the W start?

tt event topologies







Probability that a simple distance criterion (k_T) yields the correct pairing of top and anti-top decay products

Probability that partons from top decay merge in a cone of a given ΔR size: 0.4 (left) or 0.8 (right)

Two effects at larger m_{tt} :

- Combinatorics trivially resolved: 50 % for m_{tt} = 700 GeV
- Mono-jets form: 50 % at m_{tt} = 900 GeV (ΔR < 0.4) - 1.8 TeV (ΔR < 0.4)

Reconstruction of the tt mass spectrum is highly non-trivial.

- Resolved approach: resolve all partons
- Mono-jet approach: reconstruct full top decay as a single jet

Top mono-jet identification

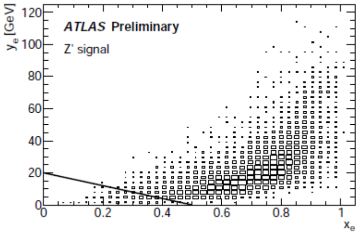
Lillie, Randall, Wang, JHEP 09 (2007) 074, hep-ph/0701166,
K. Agashe et al., Phys. Rev. D77 (2008) 015003, hep-ph/0612015,
U. Baur and L.H. Orr, Phys. Rev. D76 (2007), 094012, 0707.2066,
J. Thaler and L.T. Wang, JHEP 07 (2008) 092, 0806.0023.

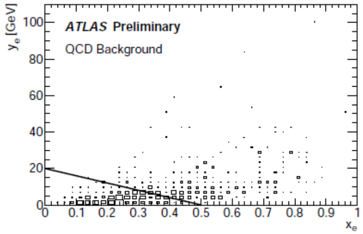
L.G. Almeida et al., Phys. Rev. D79 (2009) 074017, 0807.0234.

D.E. Kaplan et al., , Phys. Rev. Lett. 101 (2008) 142001, 0806.0848.

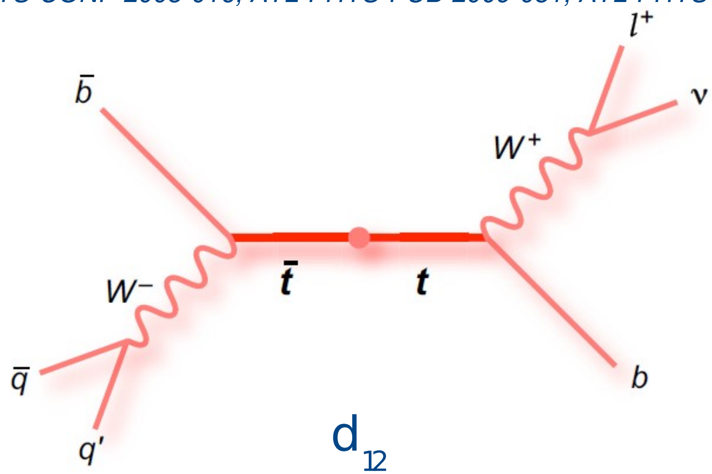
CMS-JME-09-001-PAS, CMS-TOP-09-009-PAS, CMS-EXO-09-002-PAS, CMS-EXO-09-009-PAS

ATL-PHYS-CONF-2008-008, ATL-PHYS-CONF-2008-016, ATL-PHYS-PUB-2009-081, ATL-PHYS-COM-2010-153





Leptonic side: embedded lepton

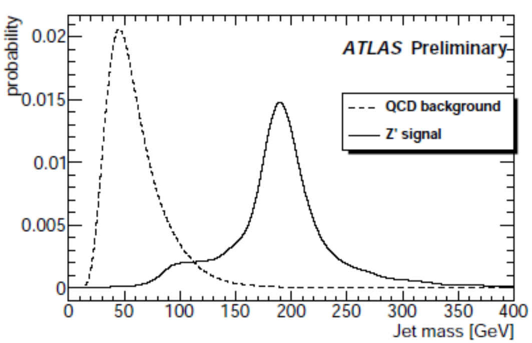


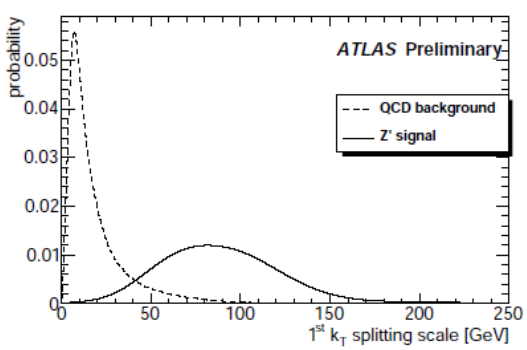
Hadronic side: jet substructure

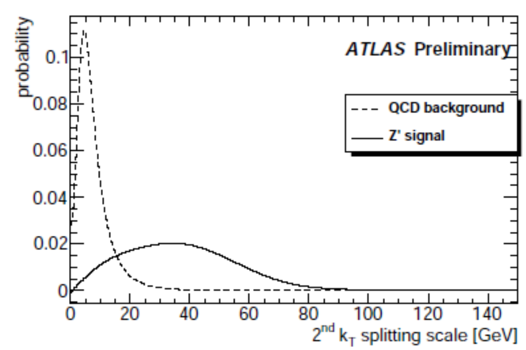
Jet mass

d_{12}

d_{23}

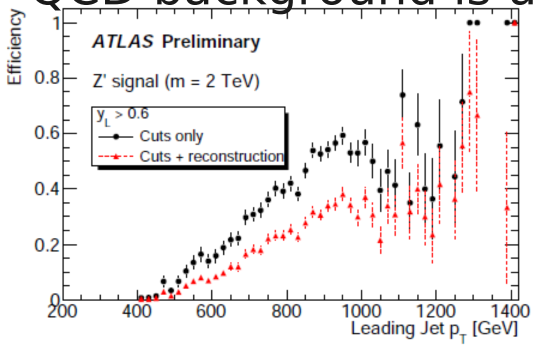




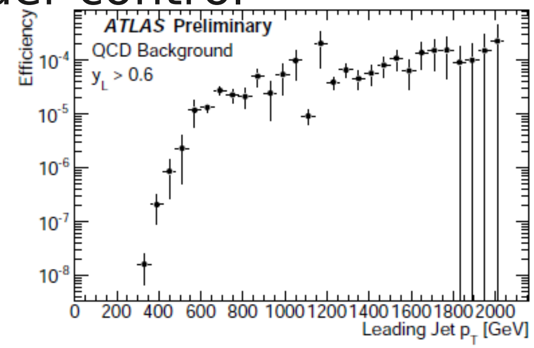


Mass resolution

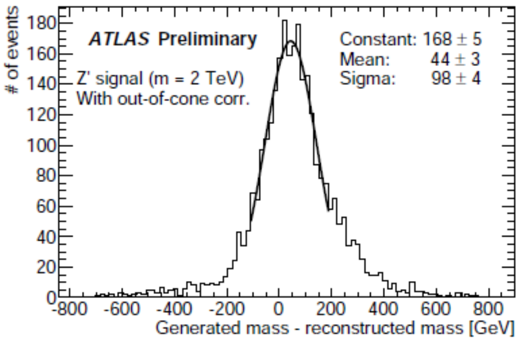
QCD background is under control



Efficiency: reconstruction + selection



QCD rejection: 10^4 stable with p_T



5 % Mass resolution @ 2 TeV

Sensitivity: 95 % C.L. Limits on the cross-section X BR of a narrow resonance After 1 fb^{-1} at 14 TeV (if there are no deviations from SM predictions)

Mono-jet approach:

550 fb	for m = 2 TeV
160 fb	for m = 3 TeV

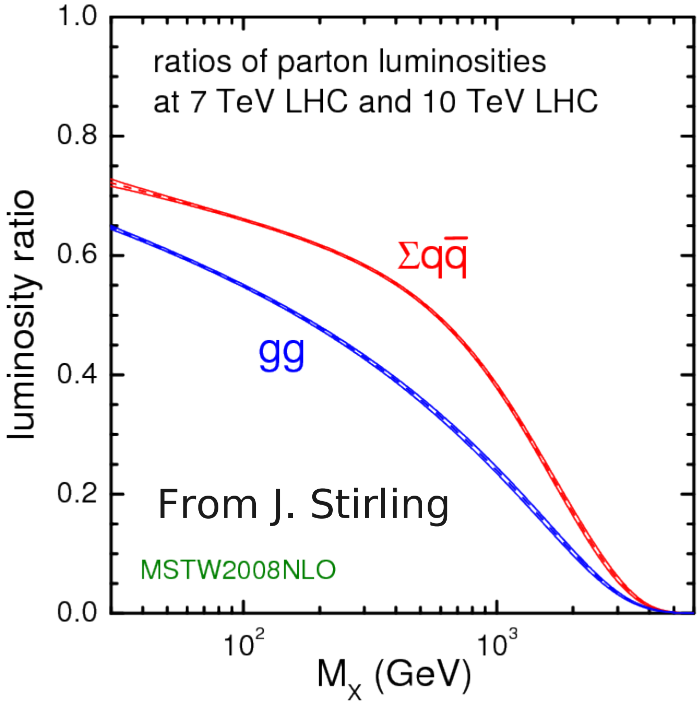
Resolved reconstruction:

8 pb	for m = 1 TeV
3.5 pb	for m = 1.5 TeV

Significantly increased sensitivity for large resonance mass

Early LHC scenarios

ATLAS study of potential of the early runs evaluated in detail for the lepton+jet final state (The ATLAS collaboration, Searching for tt resonances using early ATLAS data, ATL-COM-PHYS-2010-154, approval process ongoing)



- Reconstruction for complete tt mass spectrum, merging ideas from resolved and mono-jet approaches
- Evaluation of 1 TeV in early LHC scenarios (7, 10 TeV, 100s of pb^{-1})
- Take into account non-negligible width
- Early surprises are possible!

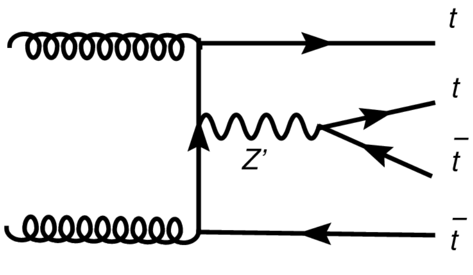
See also: CMS-PAS-TOP-09-009, CMS-PAS-JME-09-001, CMS-PAS-EXO-09-002, CMS-PAS-EXO-09-008 and Roberto Chierici's talk in this workshop

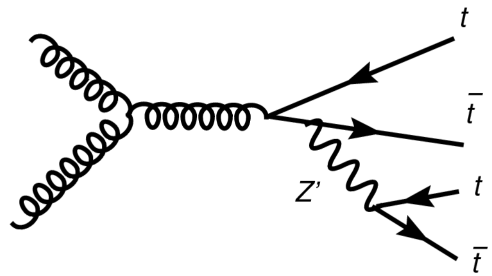
Signal x-sec for M = 1 TeV much reduced due to reduced LHC cms energy. However:

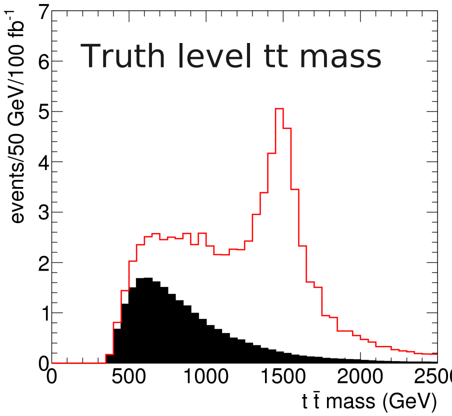
- Qq initiated processes suffer less
- Dominant background reduced even more

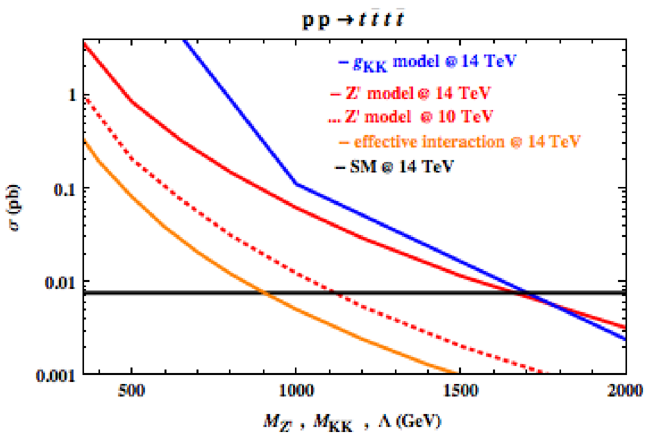
Outlook: tt+X

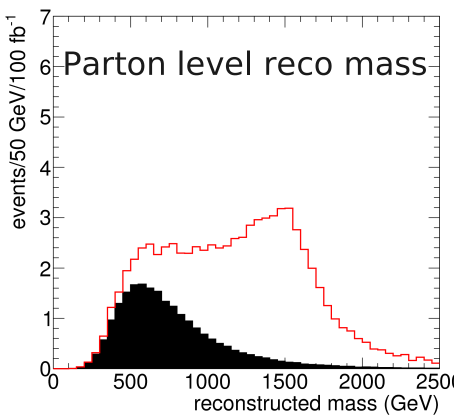
As soon as SM tt spectrum is understood, tt+X studies start











Probes a very interesting set of BSM scenarios

KK gluon (with strong preference for top quarks as in RS setup)

New states that only couple to top quarks. G. Servant (to be published)

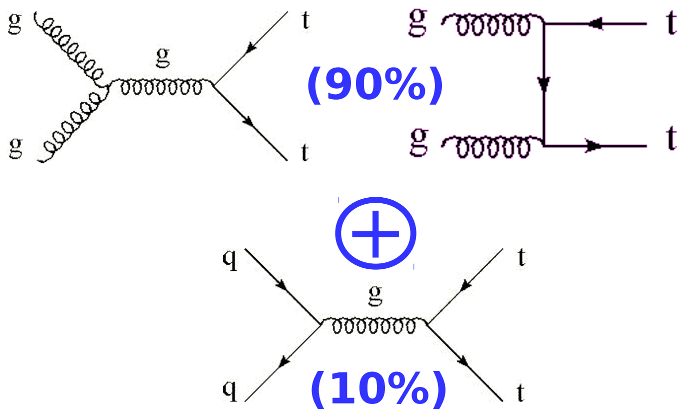
top compositeness, Lillie, Shu, Tait; Kumar, Tait, Vega-Morales; Pomarol, Serra

Relatively easy to isolate (same-sign lepton), but will we ever be able to reconstruct such events?

See proceedings Les Houches 09 (to be published) and Lea Gauthier's talk in this workshop.

LHC vs ILC

LHC



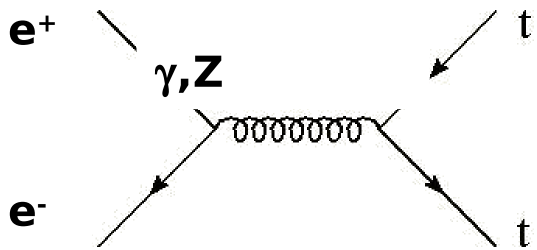
tt production cross section at LHC:

~833 pb

At √s = 14 TeV

2 tt events per second !
8 millions tt events/year
Assuming L =10³⁴ cm⁻² s

ILC



tt production cross section at ILC:

~0.6 pb

At √s = 500 GeV

120k tt events/year
Assuming L =10³⁴ cm⁻² s

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' .

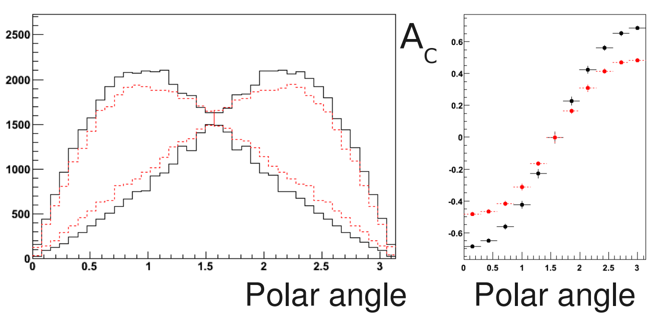
Z' mass	SM	1 TeV	2 TeV	3 TeV	4 TeV
ee --> tt Cross-section	91.7 ± 0.1	88.2 ± 0.2	93.8 ± 0.2	94.9 ± 0.2	94.9 ± 0.2
A_{FB}^{tt}	0.41 ± 0.01	0.296 ± 0.007	0.390 ± 0.007	0.395 ± 0.007	0.398 ± 0.006
$A_{FB}^{tt\,(central)}$	0.36 ± 0.01	0.263 ± 0.007	0.346 ± 0.007	0.352 ± 0.007	0.351 ± 0.007

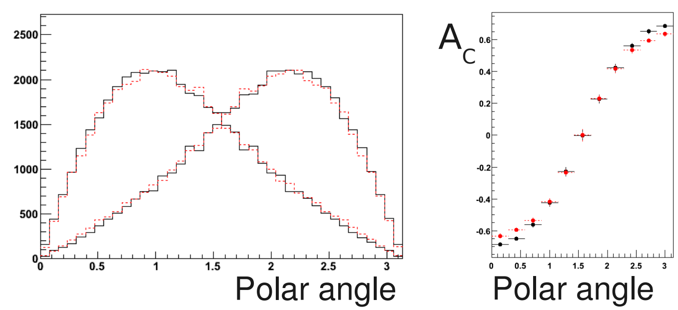
LO production cross-section (MadGraph) and top quark FB asymmetry for the ee--> tt process in the Standard Model and various sequential Z' scenarios. Errors are purely statistical, assuming 500 pb^{-1}.

Forward backward asymmetry is a very sensitive probe

Not only A_{FB}^{t}, but also A_{FB} of b from tt, A_{FB} of μ from tt

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





Michael Peskin @ Albuquerque

For the QCD strong interactions, we understood the composite structure of meson and baryons by measuring their coupling to pointlike currents.

For the top quark, the composite structure would be manifest in the form factors of vector and axial vector currents:

$$e A_\mu \, \bar{t}\gamma^\mu [F_{LA}(Q^2) P_L + F_{RA}(Q^2) P_R] t$$
$$+ \frac{e}{c_w s_w} Z_\mu \, \bar{t}\gamma^\mu [F_{LZ}(Q^2) P_L + F_{RZ}(Q^2) P_R] t$$

These form factors are constrained at $Q^2 = 0$ to be

$$F_{LA}(0) = F_{RA} = \frac{2}{3} \quad F_{LZ}(0) = (\frac{1}{2} - \frac{2}{3}\sin^2\theta_w) \quad F_{RZ}(0) = \; ?$$

At the top quark theshold, we measure them at

$$Q^2 = 4 m_t^2 \; , \; Q^2/m_R^2 = 0.1$$

Form factors to determine composite nature

We recommend that the following processes be studied in the LOI frameworks in preparation for a possible LHC discovery in 2010:

$$
\begin{aligned}
500\ \text{GeV}: & \\
e^+e^- &\rightarrow b\bar{b}, c\bar{c} \quad \sigma, A_{FB} \text{ for each } P_e \\
e^+e^- &\rightarrow t\bar{t} \quad \sigma, A_{FB} \text{ for each } P_e \\
e^+e^- &\rightarrow \chi^+\chi^-, \chi^0\chi^0, \; \chi \rightarrow \nu, \ell + \text{stable } L \\
1\ \text{TeV}: & \\
e^+e^- &\rightarrow \nu\bar{\nu}h^0, \; h \rightarrow b\bar{b} \quad m_h = 200\ \text{GeV} \\
e^+e^- &\rightarrow t\bar{t}h^0, \; h^0 \rightarrow WW, ZZ \quad m_h = 200\ \text{GeV}
\end{aligned}
$$

$e^+e^- \rightarrow$ tt @ 500 GeV included in benchmark list for early LHC discovery channels (see also Keisuke Fuji's talk in the LCWS10 plenary)

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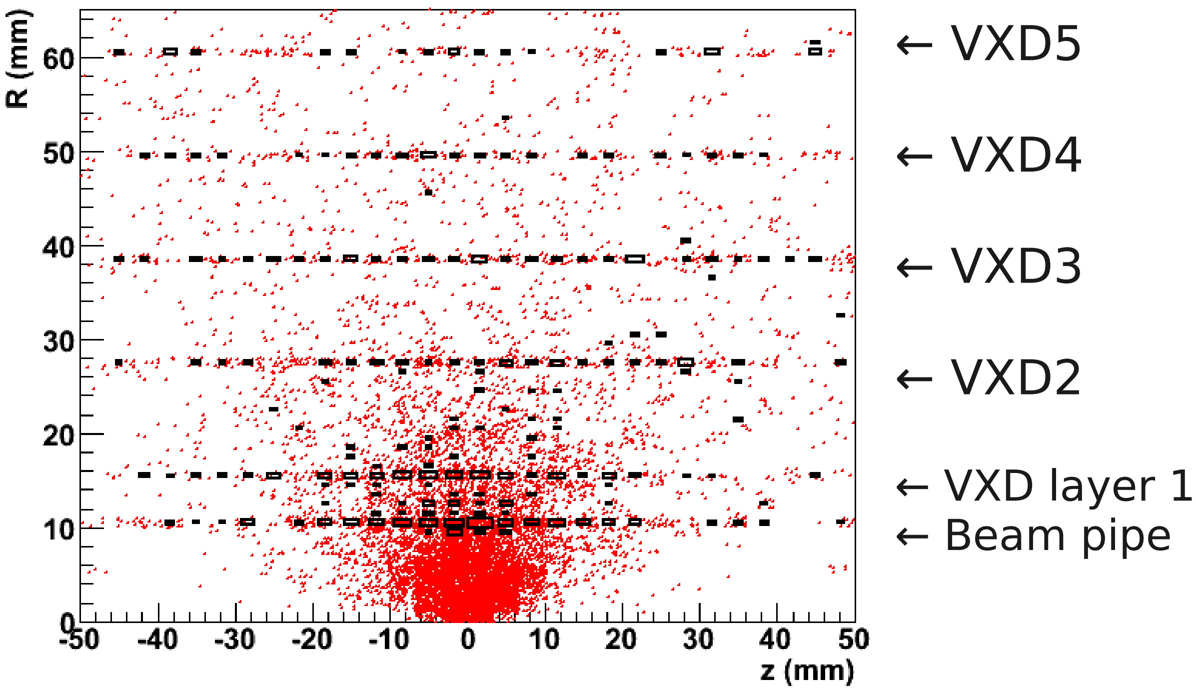
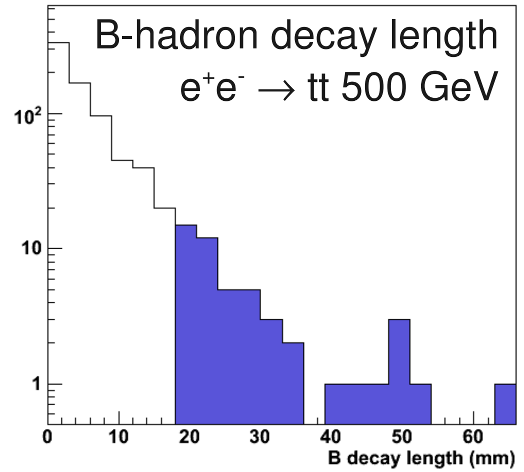
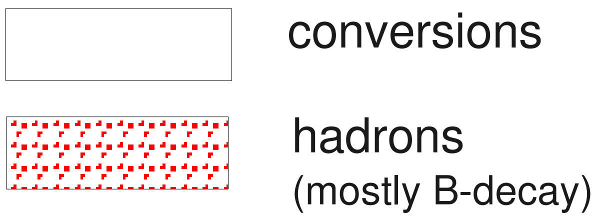
Experimental challenges II







In a 500 GeV ILC the top quarks are "at rest" and the B-hadron boost small ($<p_B>$ = 67 GeV)

But, then again, VXD is much closer:

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

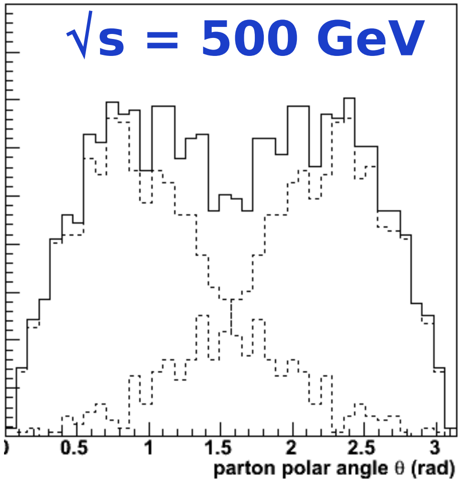
1 TeV ILC?, CLIC, see M. Battaglia's talk in the plenary

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

Experimental challenge I

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

$e^+e^- \rightarrow Z \rightarrow$ cc/bb/tt



See Alberto Ruiz' presentation in VXD/TRK session of this workshop

J. Fuster et al. Forward tracking at the next e+ e- collider. Part I. The Physics Case, JINST 4:P08002,2009, arXiv:0905.2038 [hep-ex]

and Part II on instrumental challenges of the forward region (to be submitted soon)

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

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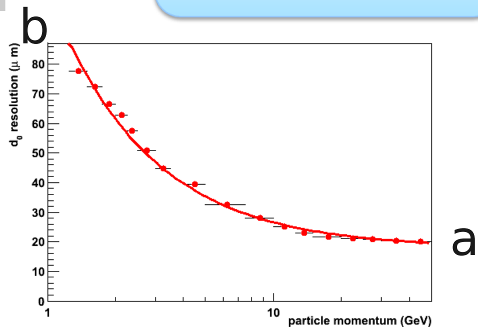
Impact parameter resolution

VXD: impact parameter resolution 5 – 10 μm.

This precision is required to achieve excellent heavy flavour tagging, particularly for couplings of the Higgs boson to charm (cτ ~150 μm) and bottom (cτ ~ 450 μm)

	a (μm)	b (μm GeV)
LEP	25	70
SLD	8	33
LHC	12	70
ILC	5	10

$$\sigma_{IP} = a \oplus \frac{b}{p\sin^{3/2}\theta}$$

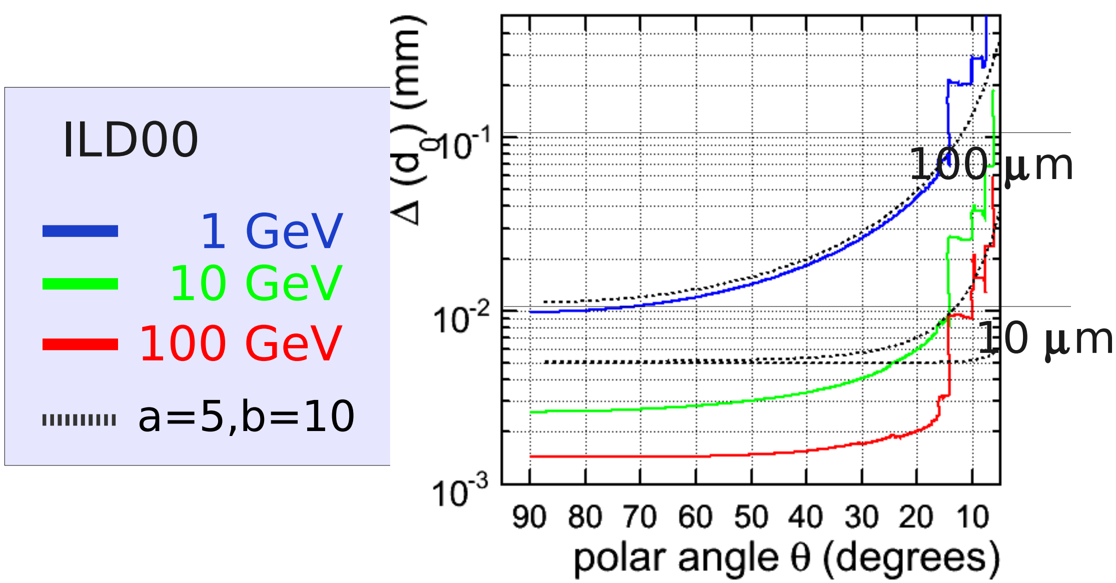


Unprecedented precision
(small pixels, 20x20 μm²)

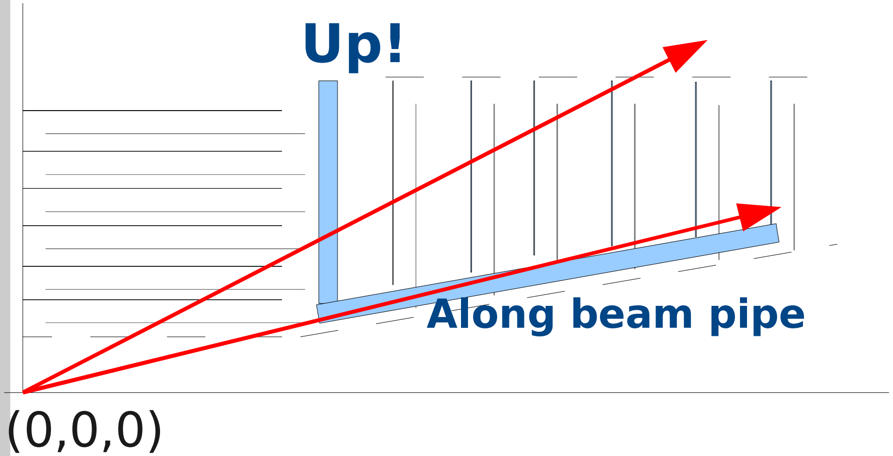
Strongly reduce the multiple Coulomb scattering term
(material: 0.1 % X_0 / layer ~ 100 μm Si)

ILD vertexing performance

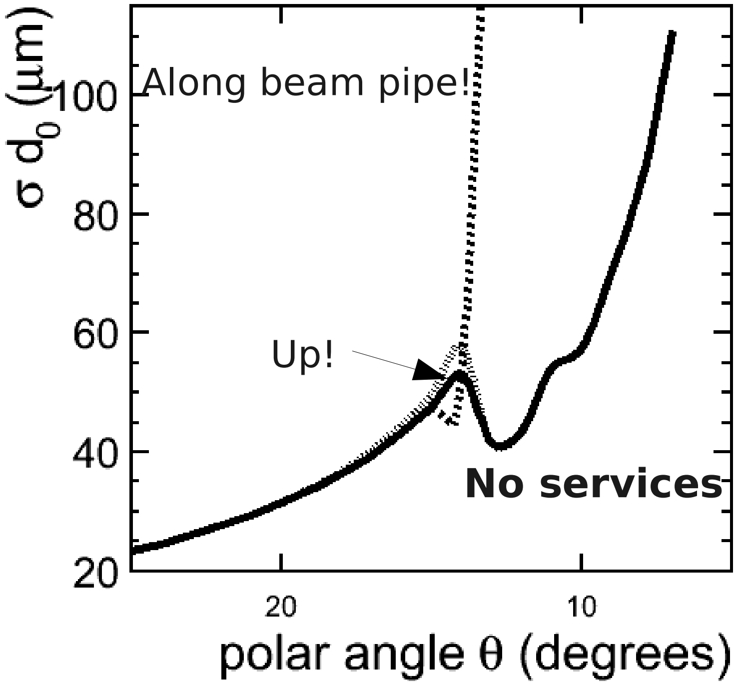
central:
a~1.7 μm
forward:
performance significantly worse than extrapolation of barrel formula with a=5,b=10



Choosing a toy geometry

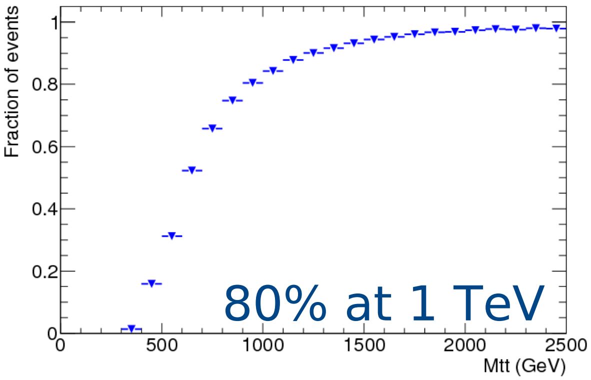


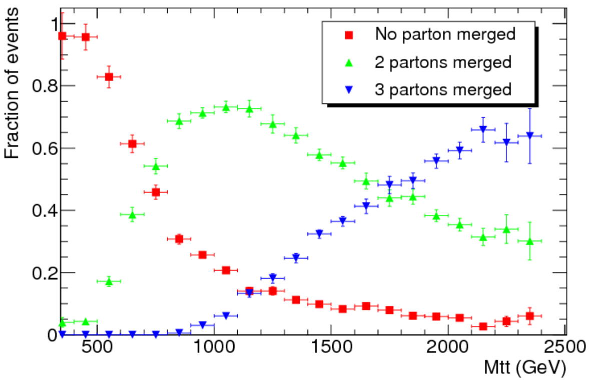
Impact parameter resolution of shallow tracks with $p_T = 1$ GeV



Add 3 % X_0 (on perpendicular crossing) of barrel VXD services to fast simulation. Consider two routing options

Experimental challenges II



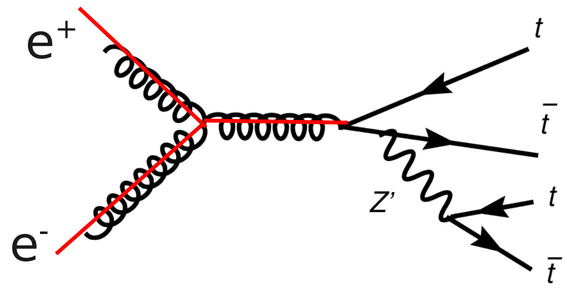


If you remember these two plots for the LHC, the ILC takes us right through the transition from fully resolved tt topology to the top mono-jet regime

From Keisuke Fuji's talk:
350 GeV threshold scan benchmark channel is generated
500 GeV tt is an early LHC benchmark channel
1 TeV tt is not
CLIC carries on at very high energy

4 top production (one last time)

Looking for a challenging scenario, consider some of the new physics that feeds into the 4 top final state is discovered at the LHC. Production of heavy gluons, a new state that only couples to top and four top contact interactions in an e^+e^- machine is not the first thing one thinks of.



Geraldine Servant, Marco Battaglia looking into CLIC potential for one of the models of slide 13

Here, consider the following preliminary numbers for signal

- σ(contact interaction) ~ 0.01 fb
- σ(1 TeV KK gluon) ~ 1.5 fb
- σ(360 GeV Z') ~ 5 fb (G. Servant, Higgs in space)

And backgrounds:

- σ(SM tttt) = 0.02 fb
- σ(ttWjj) = 0.4 fb
- σ(ttWW+Nj) = 0.6 fb

BSM with tops: take-away

BSM with tops at the LHC is very exciting

Translation of discovery into physics case for the ILC had received little attention, but this going to change (i.e. benchmark list from the physics panel)

Whole set of detector requirements to be derived:
- forward vertexing
- jet substructure analyses

Can we include a tt sample at 1 TeV to complete the series 350, 500, ..., multi-TeV?

If you're looking for a challenge: BSM with 4 tops at FLC