BSM searches with top quarks in ATLAS

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 the early LHC potential for BSM physics, with a strong focus on tt resonances. A glimpse of some of the things we could do after 2011.

CSIC

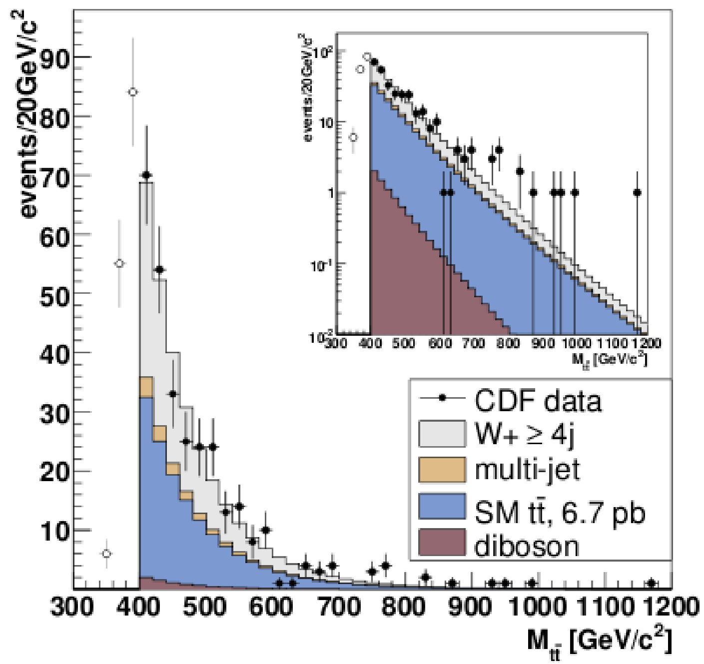
IFIC

tt resonances – from Tevatron to LHC

Tevatron has allowed a detailed study of the top quark properties *in 15 years since its discovery*

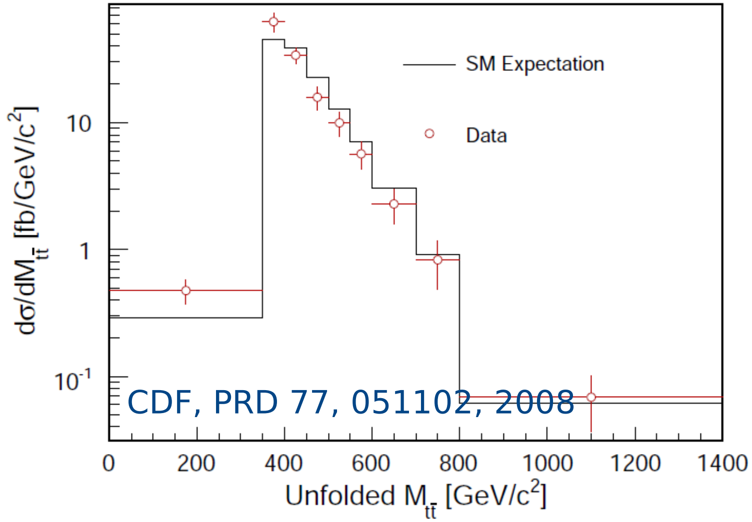
→ *8 fb^{-1} ppbar @ 1.96 TeV = 64.000 $t\bar{t}$ pairs*
→ *statistics concentrated for pairs at rest*
→ *mass reach (heaviest observed pair) ~ 1 TeV*

CDF arXiv:0709.0705



~20 papers by CDF and D0 on ***tt resonance searches***

First fully unfolded **dσ/dM$_{tt}$ measurement** (CDF, PRD77, 051102, 2008) published recently



Tevatron vs LHC

Tevatron, where the top was born

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

- tops produced ~ at rest,
- *heaviest observed pair at m_{tt} = 1 TeV*
- *Measurements of its mass to < 1 %*
- *Cross-section in good agreement with SM prediction*

LHC, the first top factory

Even if in the early days luminosity and center-of-mass energy are less than nominal design values:

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

→ *1 fb^{-1} @ 7 TeV (envisaged 2011) similar*

- Double the world's top sample
- Much larger increase in statistics for high p_T tops

Resonance searches

For an, admittedly somewhat unfair, comparison of the sensitivity of resonance searches in different di-object final states, express the sensitivity as a **lower limit on the mass of a sequential Z'**
(i.e. a heavy sister of the SM Z boson, with identical couplings to SM particles)

	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	This talk (see also Roberto Chierici's talk on the CMS potential in this workshop)

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

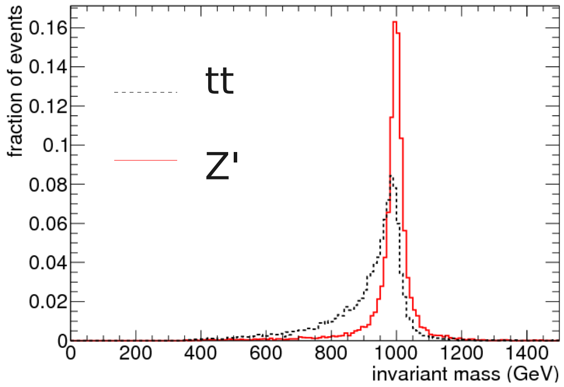
- tops produced ~ at rest,
- *heaviest observed pair ~ 1 TeV*
- *~20 papers on tt resonance searches*

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

Model-independent limit on resonances – I

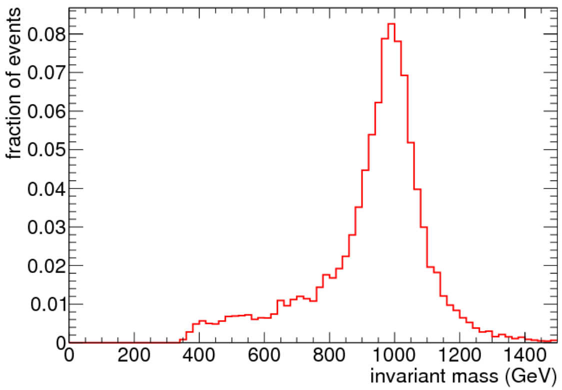
All resonances are equal, but some ....



Electro-weak

Z', Γ = 3.4 % M, σ x BR (X->tt) < 1 pb

tt mass distribution is affected by gluons radiated off top quarks



Coloured

KK gluon, Γ = 15.3 % M, σ x BR (X->tt) > 10 pb

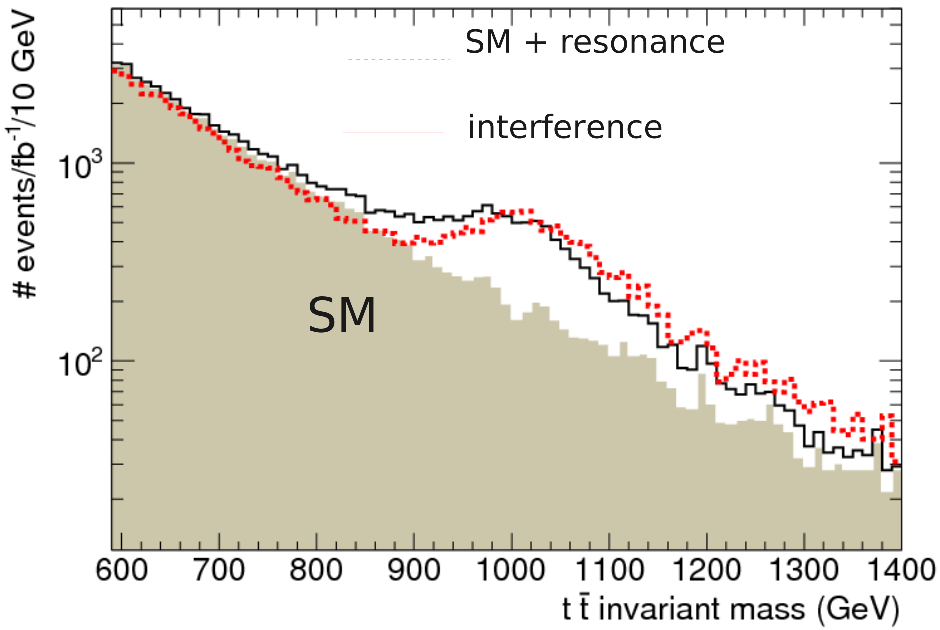
Convolution of Breit-Wigner with parton luminosity function yields low-mass tail

The numbers above are examples, but in any given model (spin, charge) the rate and width are tightly connected. In particular, for a given width the maximum σxBR (qq-> X-> tt) is obtained by setting:

$g_t = 5 \times g_{ud}$

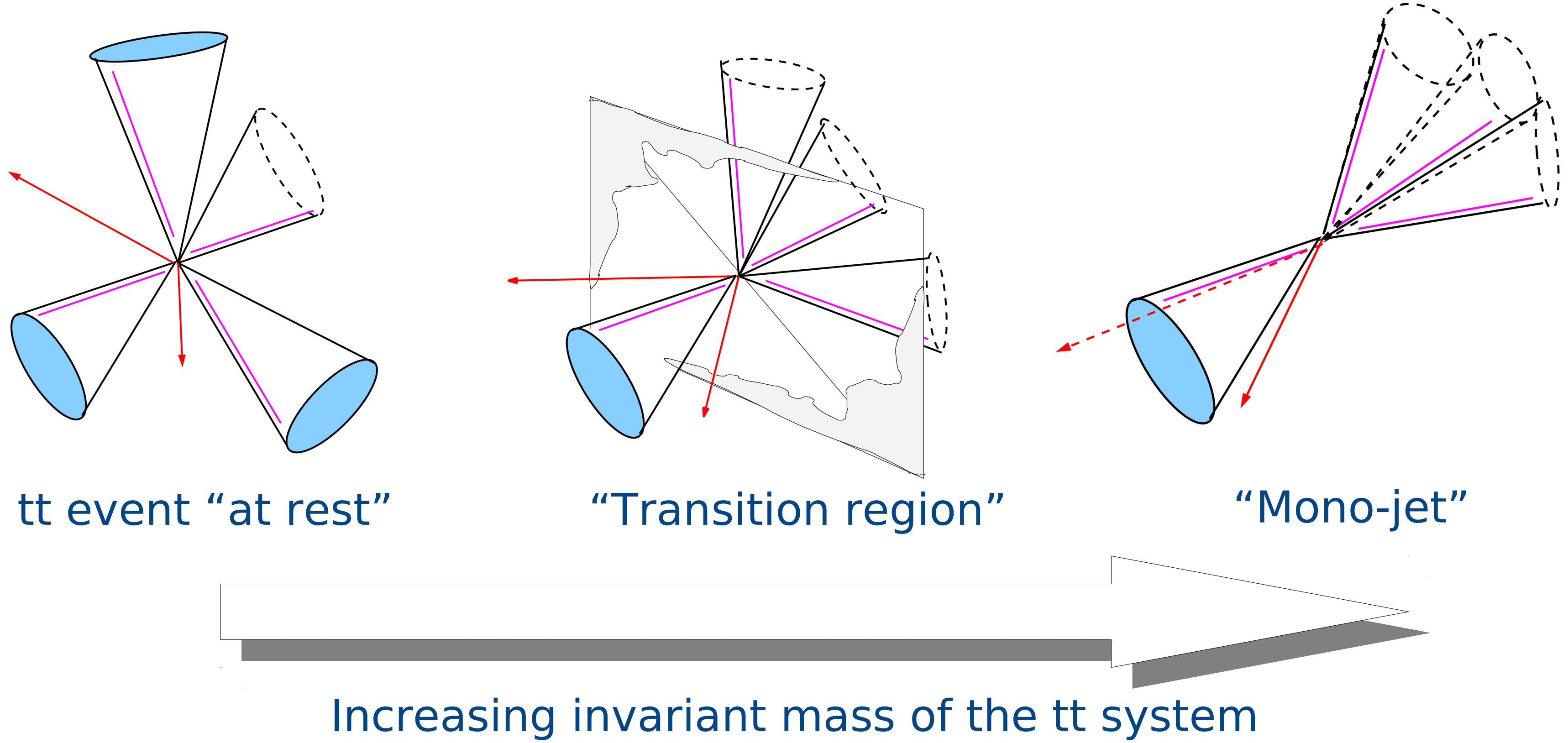
g = 0 for all other couplings

Model-indepent limits on resonances? II



Interference with SM production for coloured resonance: destructive for low mass (see Les Houches 2009, to be published)

Semi-leptonic tt event topologies

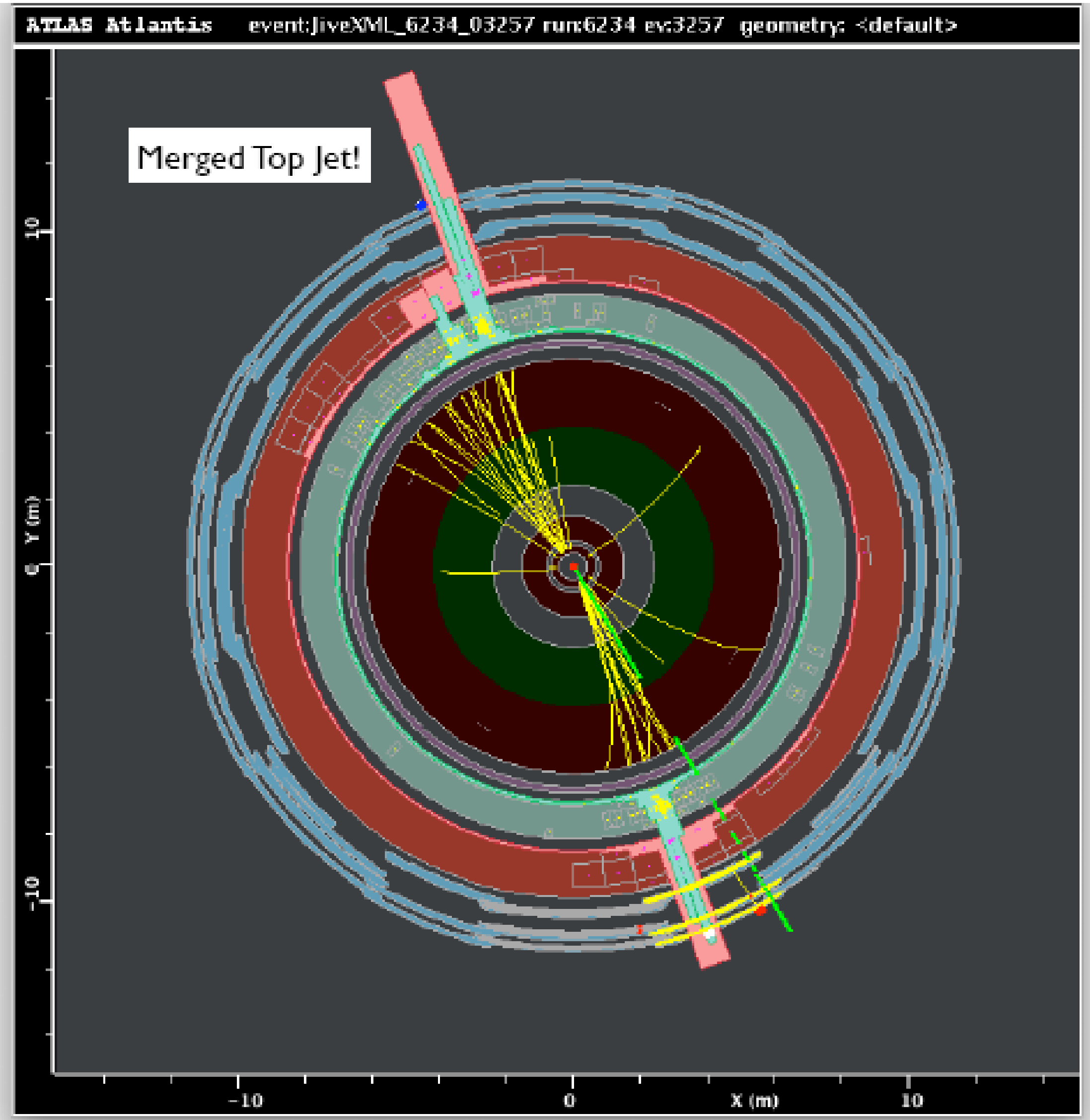


- Reconstruction of the tt mass spectrum is highly non-trivial.
  - Resolved approach: resolve all partons
  - Mono-jet: reconstruct full top decay as a single jet
- Forget about competing with di-lepton channels
  - Confirm resonances with significant BR to leptons
  - Concentrate on top-philic models

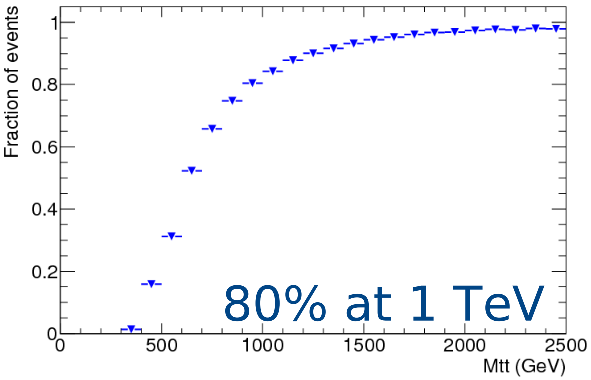
Reconstruction of high p_T tops

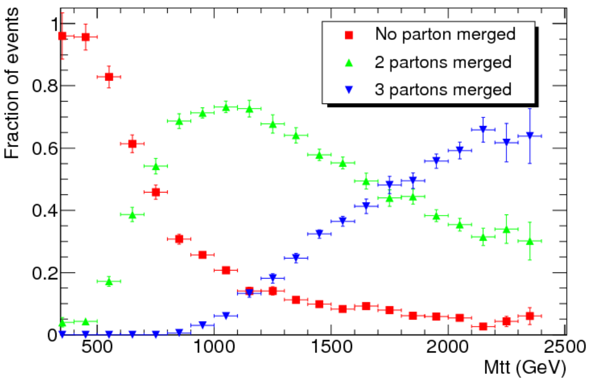
Challenges for top reconstruction at high p_T

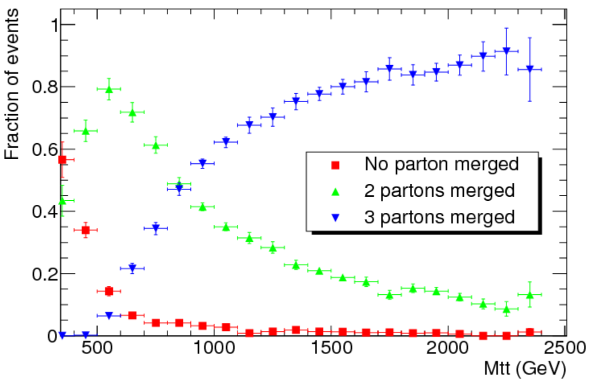
- **Partons from top decay are not resolved by jet reconstruction algorithms**
- isolation of leptons
  - Trigger & offline
- E_T^{miss} resolution i
- tracking performance in jets
  - b-tagging
- control samples
  - calibration, b-tag)



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)

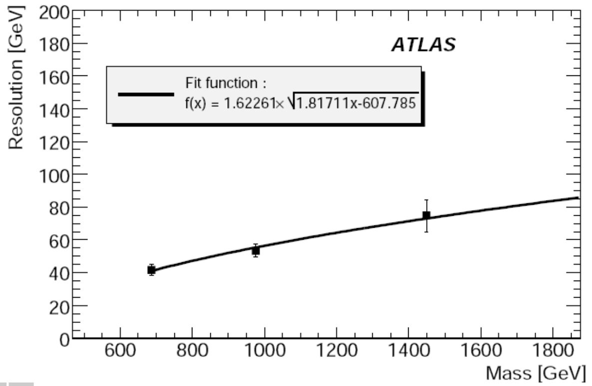
Two effects at larger m_{tt} :

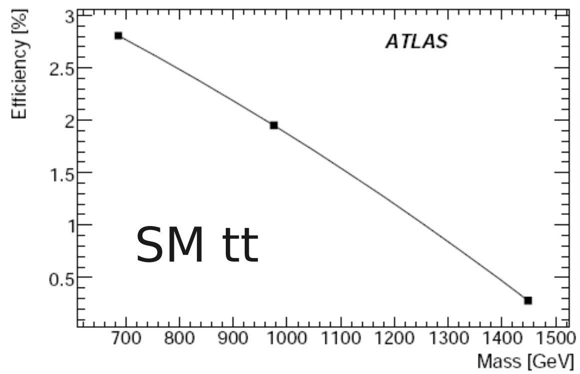
- Combinatorics trivially resolved: 50 % for m_{tt} = 700 GeV
- Mono-jets form: 50 % at m_{tt} = 900 GeV (ΔR < 0.4) - 1.8 TeV (ΔR < 0.4)

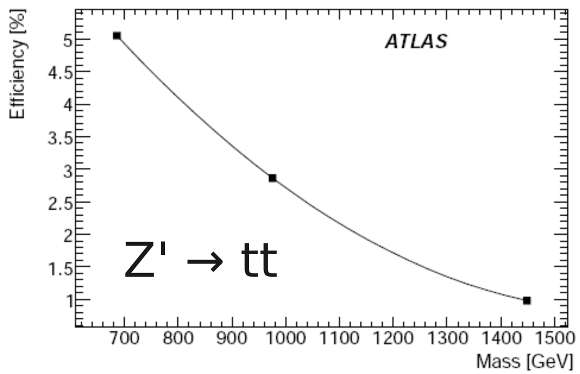
Can define two algorithms already:

- Standard-model oriented “resolved” for low mass (top x-section and mass measurements)
- Mono-jet algorithm for large mass (> 2 TeV, ATL-PHYS-INT-2009-037)

ATLAS tt resonance searches





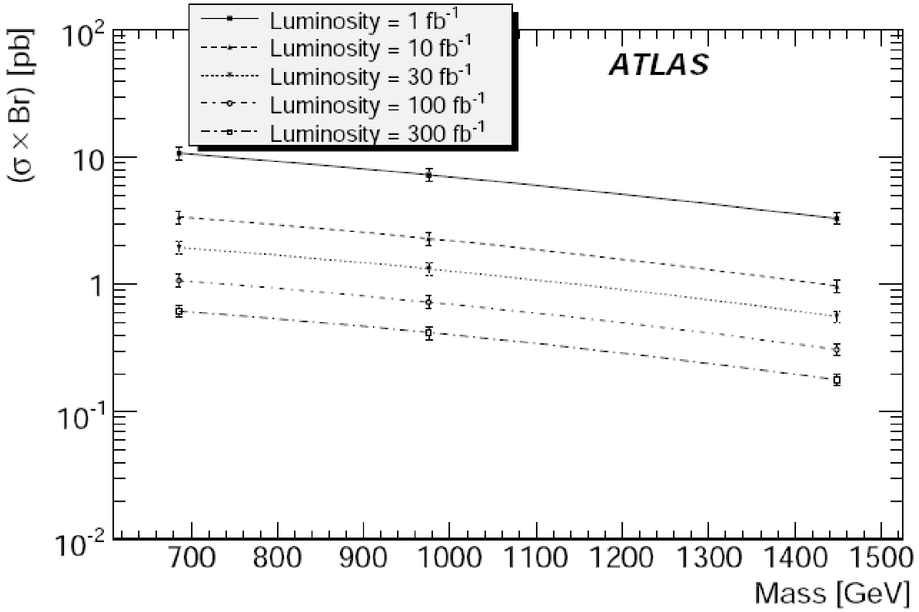


- Resonance mass resolution ~5 % in mass range from 700 to 1500 GeV.
- A sharp efficiency drop towards larger resonance mass

  5 % @ 700 GeV

  < 1 % @ 1500 GeV

The sensitivity of the standard approach for tt resonances versus mass and integrated luminosity



Top mono-jet identification

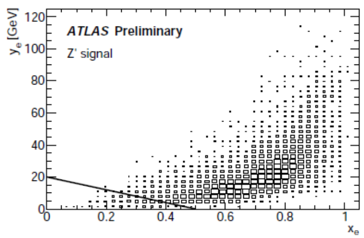
Lillie, Randall, Wang, JHEP 09 (2007) 074, hep-ph/0701166,
K. Agashe et al., Phys. Rev. D77 (2008) 015003, hep-ph/0612015,
U. Baur and L.H. Orr, Phys. Rev. D76 (2007), 094012, 0707.2066,
J. Thaler and L.T. Wang, JHEP 07 (2008) 092, 0806.0023.

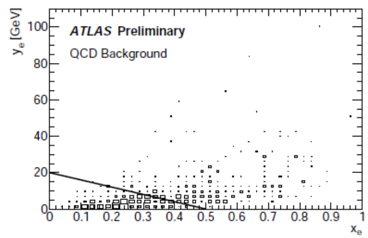
L.G. Almeida et al., Phys. Rev. D79 (2009) 074017, 0807.0234.

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

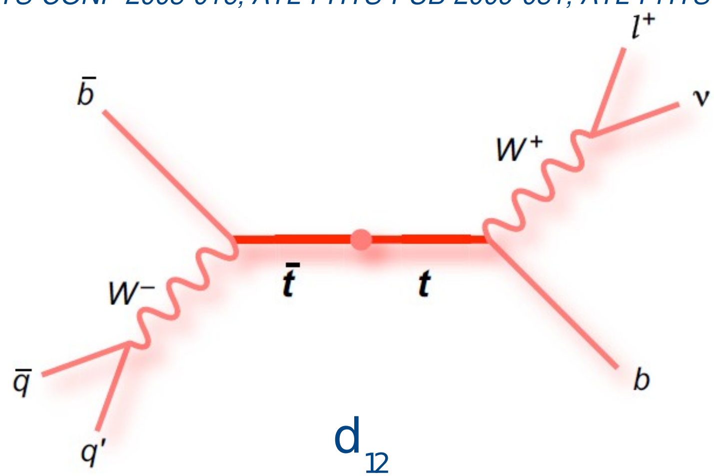
CMS-JME-09-001-PAS, CMS-TOP-09-009-PAS, CMS-EXO-09-002-PAS, CMS-EXO-09-009-PAS

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



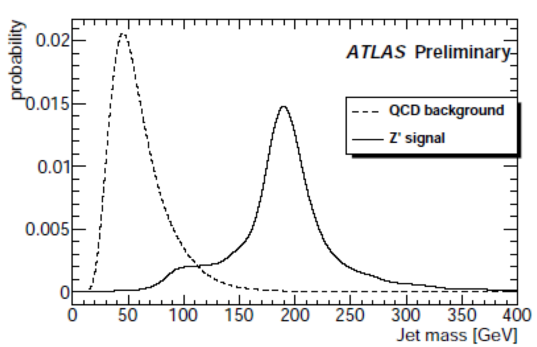


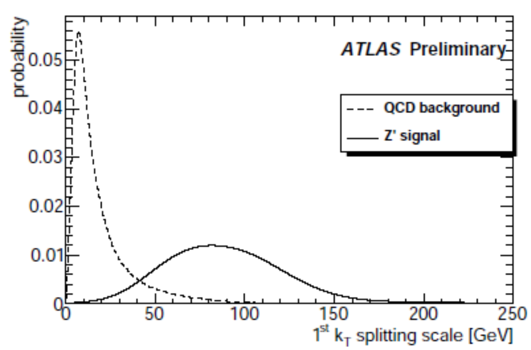
Leptonic side: embedded lepton

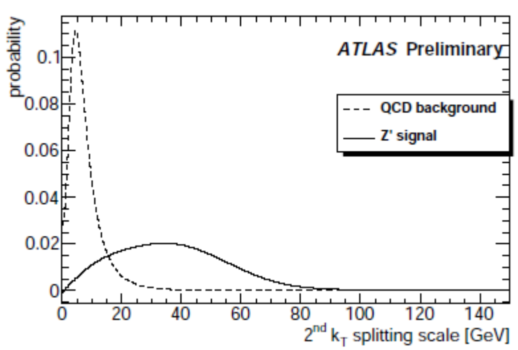


Hadronic side: jet substructure

Jet mass $\quad d_{12} \quad d_{23}$

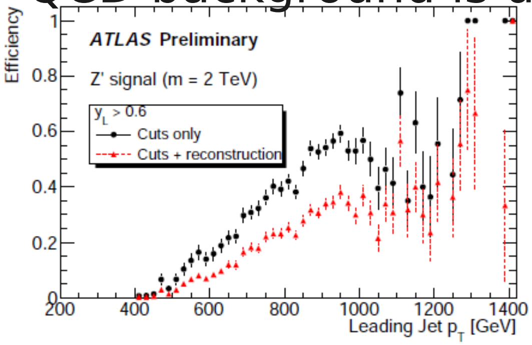


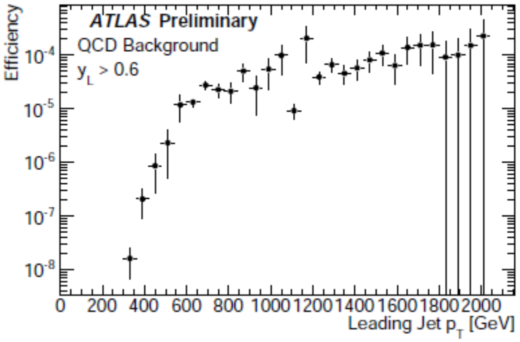


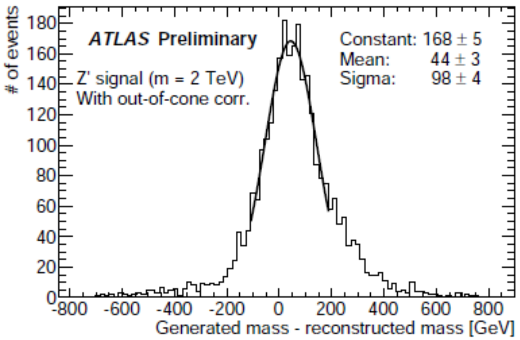


Mass resolution

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

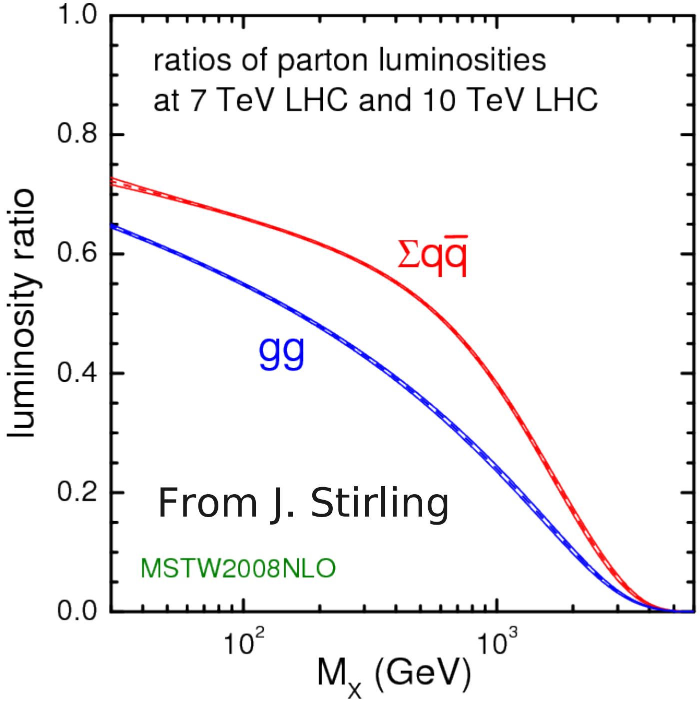
Resolved reconstruction:

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 semi-leptonic final state (The ATLAS collaboration, Searching for tt resonances using early ATLAS data, ATL-COM-PHYS-2010-153, 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

A bit further...

Smarter analysis may increase sensitivity

Paola Ferrario, German Rodrigo, Charge asymmetries of top quarks: A Window to new physics at hadron colliders, J.Phys.Conf.Ser.171 (2009) 012091

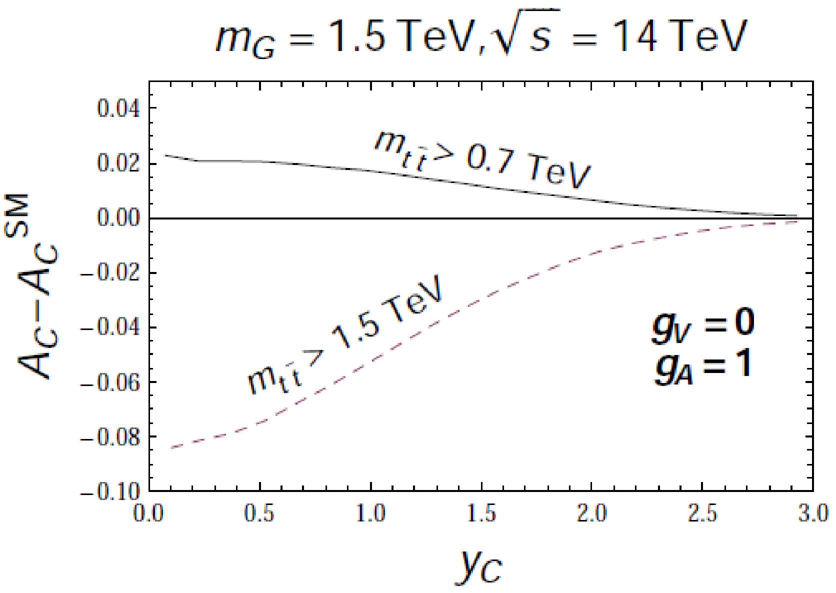
Analysis of A_{FB} at the Tevatron

(Kuhn, Rodrigo, 1998, Antuñano, Kuhn, Rodrigo, 2008)
m-dependent measurement performed by CDF (Conf. Note 9724, PRL101 (2008) 202001) and D0(PRL101 (2008) 202001)

An asymmetry can also be defined at the LHC:

$$A_C(y_C) = \frac{N_t(|y| \leq y_C) - N_{\bar{t}}(|y| \leq y_C)}{N_t(|y| \leq y_C) + N_{\bar{t}}(|y| \leq y_C)}$$

Good to get a grip on the background for very broad resonances
Requires efficiency versus η to be understood to some level



Top polarization: top decay products retain memory of top polarisation. Yukawa interactions and gauge interactions have opposite handedness. Correlated polarisation of t and anti-t (revealed through lepton angular distributions) are an indication of new physics (or Higgs boson)

Godbole, Rindani, Rao, Singh, AIP Conf.Proc.1200:682-685,2010,

arXiv:0911.3622 [hep-ph], R. Singh, Les Houches 09

Anomalous couplings: General tbW vertex can be written as

$$\Gamma^\mu = \frac{g}{\sqrt{2}} \left[\gamma^\mu (f_{1L} P_L + f_{1R} P_R) - \frac{i\sigma^{\mu\nu}}{m_W} (p_t - p_b)_\nu \, (f_{2L} P_L + f_{2R} P_R)\right]$$

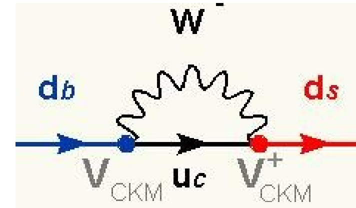
In SM, $f_{1L} = 1$, $f_{1R} = f_{2L} = f_{2R} = 0$.

Deviations from these values will denote “anomalous” couplings. Current liimits: Bernreuther, J. Phys. G., Nucl. Part. Phys. 35 (2008)

SN-ATLAS-2007-064

Searches for rare top 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} or new radiative contributions

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

Process	SM	QS	2HDM	MSSM	RPV SUSY
$t \to uZ$	8×10^{-7}	1.1×10^{-4}	x	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	x	2×10^{-6}	1×10^{-6}
$t \to uZ$	3.7×10^{-14}	1.5×10^{-7}	x	8×10^{-5}	2×10^{-4}
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim10^{-7}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim10^{-6}$	2×10^{-6}	1×10^{-6}
$t \to cZ$	4.6×10^{-12}	1.5×10^{-7}	$\sim10^{-4}$	8×10^{-5}	2×10^{-4}

Are these extremely small branching ratios accessible experimentally?

We haven't gotten very close, so far.
But, the LHC is the first top factory!

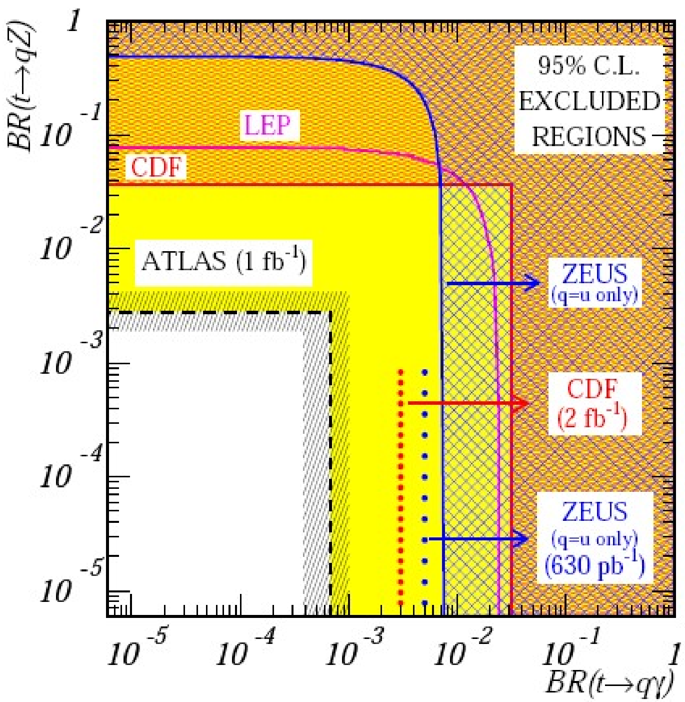
	LEP	HERA	Tevatron
BR($t \to qZ$)	7.8%	49%	3.7%
BR($t \to q\gamma$)	2.4%	0.75%	3.2%
BR($t \to qg$)	17.0%	13%	0.1-1%

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

Rare FCNC top decays

Derive 95 % CL limits using the modified fequentist likelihood method (A.L. Read, Modified frequentist analysis of search results (The Cls Method), 2000, CERN Report 2000-005)

Convert limits into limits on branching ratios using SM tt cross-section

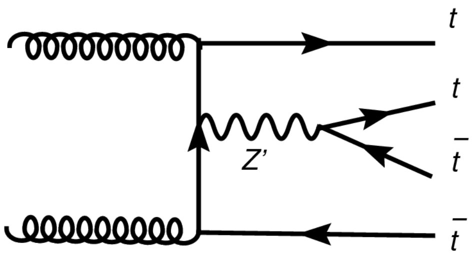


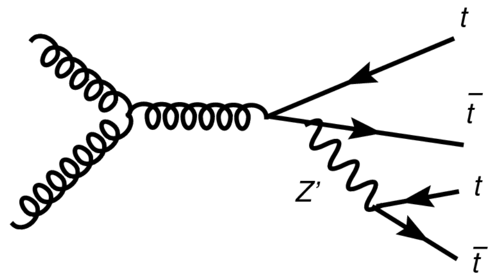
-1s	Expected	1σ
4.3×10^{-3}	1.1×10^{-3}	1.9×10^{-3}
4.5×10^{-4}	8.3×10^{-4}	1.3×10^{-3}
3.8×10^{-4}	6.8×10^{-4}	1.0×10^{-3}
1.3×10^{-2}	2.1×10^{-2}	3.0×10^{-2}
1.0×10^{-2}	1.7×10^{-2}	2.4×10^{-2}
7.2×10^{-3}	1.2×10^{-2}	1.8×10^{-2}
5.5×10^{-3}	9.4×10^{-3}	1.4×10^{-2}
2.4×10^{-3}	4.2×10^{-3}	6.4×10^{-3}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

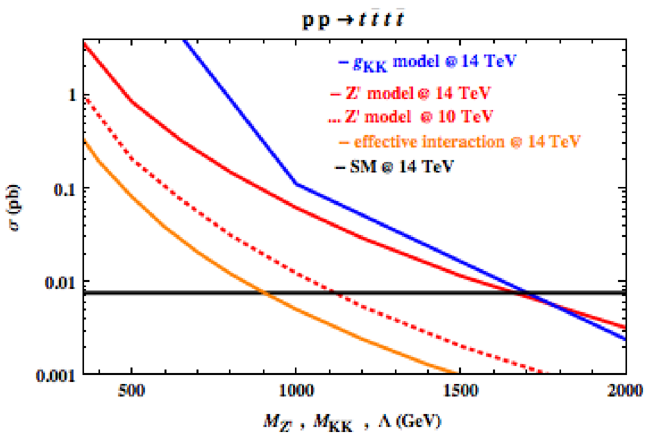
+/- 1 σ includes statistical error and systematic effect of jet energy calibration, luminosity, top quark mass, background cross-section, ISR/FSR, Pile-up, Generator, χ^2

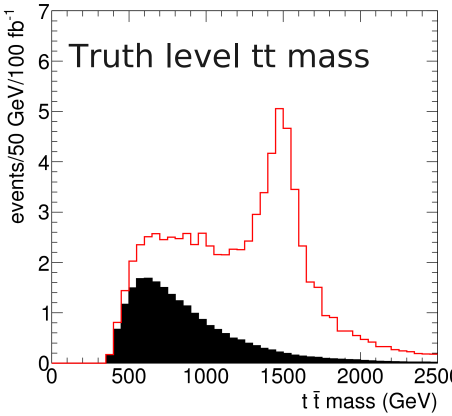
Outlook: tt+X, where X=q,H, ...

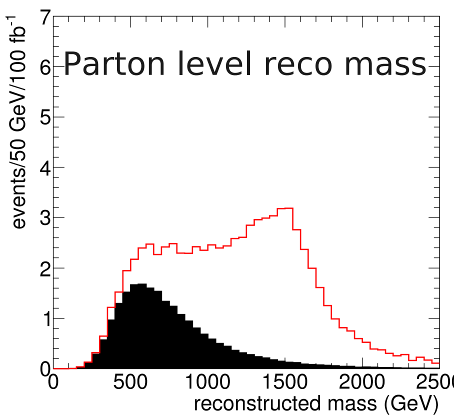
Here: tt+tt











Probes a very interesting set of BSM scenarios

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

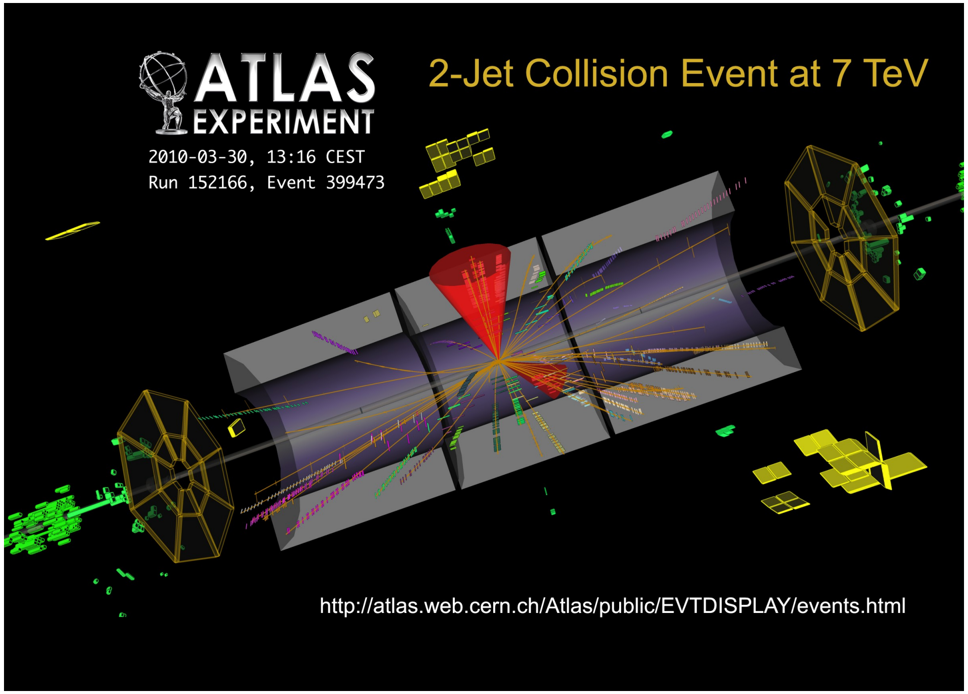
New states that only couple to top quarks. G. Servant (to be published)

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.

The top quark may prove to be the "gateway" to new physics. Resonance searches in tt final states complement searches in di-lepton, di-jet and di-boson final states. Comprehensive Monte Carlo study confirms early sensitivity to very relevant BSM scenarios (available soon).

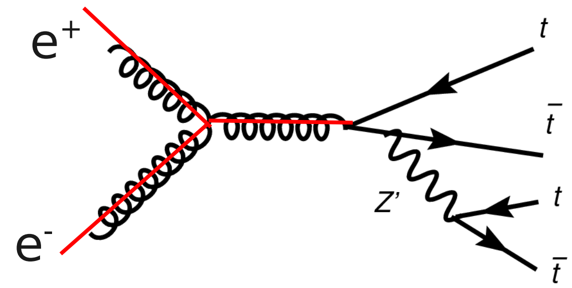


My personal projection (known to be wrong sometimes):

2009 → top properties and exotics form a joint
→ basic top reconstruction tools in place
2010 → first 7 TeV collisions
→ commission tools on data, top rediscovery
2011 → first sensitivity beyond existing limits
Beyond → tt+X and top properties programme.

4 top production at FLC (backup slide)

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

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') ~ 4 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