Top production as a window to new physics.

The experimental view

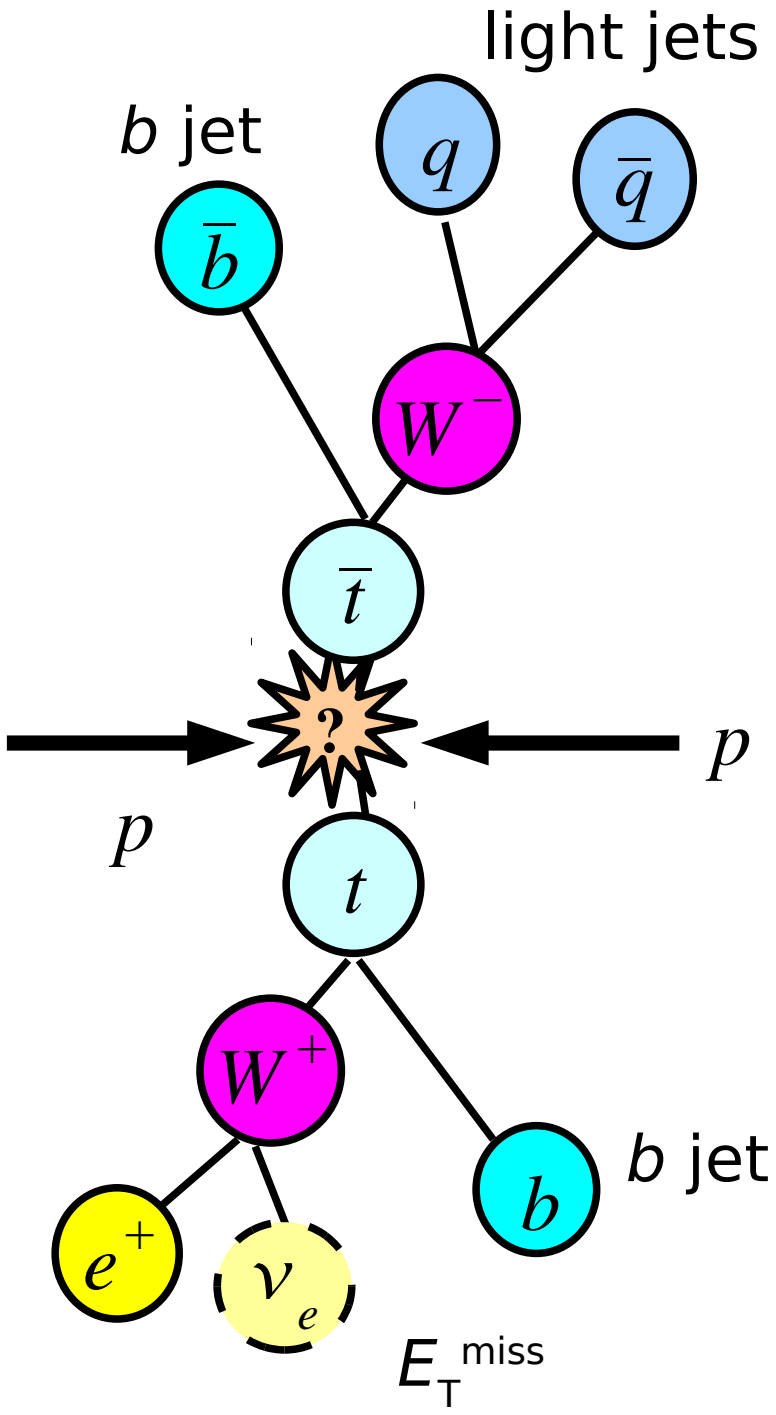
Outline:

top asymmetries
same-sign top via FCNC
M($t\bar{t}$),
$t\bar{t}$+X, Wtb vertex

Elin Bergeaas Kuutmann (ATLAS)
on behalf of the ATLAS, CMS, CDF and D0 collaborations

Why top and exotics?

- Top is heavy (M ~173 GeV/c^2), close to EW symmetry breaking scale.
- Potential interesting new physics in top events.
  - The Tevatron top forward-backward asymmetry?
  - Flavour-changing neutral currents?
  - What about top pair resonances? Like $Z^0 \rightarrow q\bar{q}$
  - Same-sign tops?
  - ....



Nomenclature:

l+jets: $t\bar{t} \rightarrow Wb+Wb \rightarrow l\nu b+bqq$ ($l = e, \mu$)

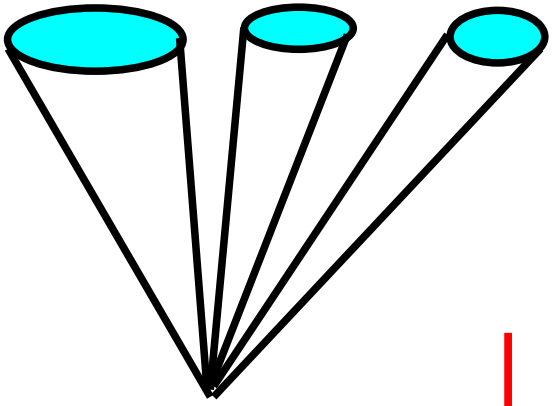
dilepton: $t\bar{t} \rightarrow Wb+Wb \rightarrow l\nu b+l\nu b$

all-had: $t\bar{t} \rightarrow Wb+Wb \rightarrow bqq+bqq$

Boosted tops

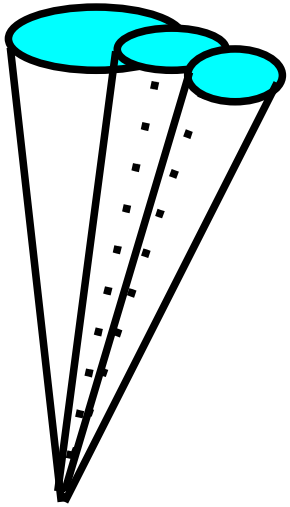
$t \to b + W$

$\hookrightarrow q\bar{q}$

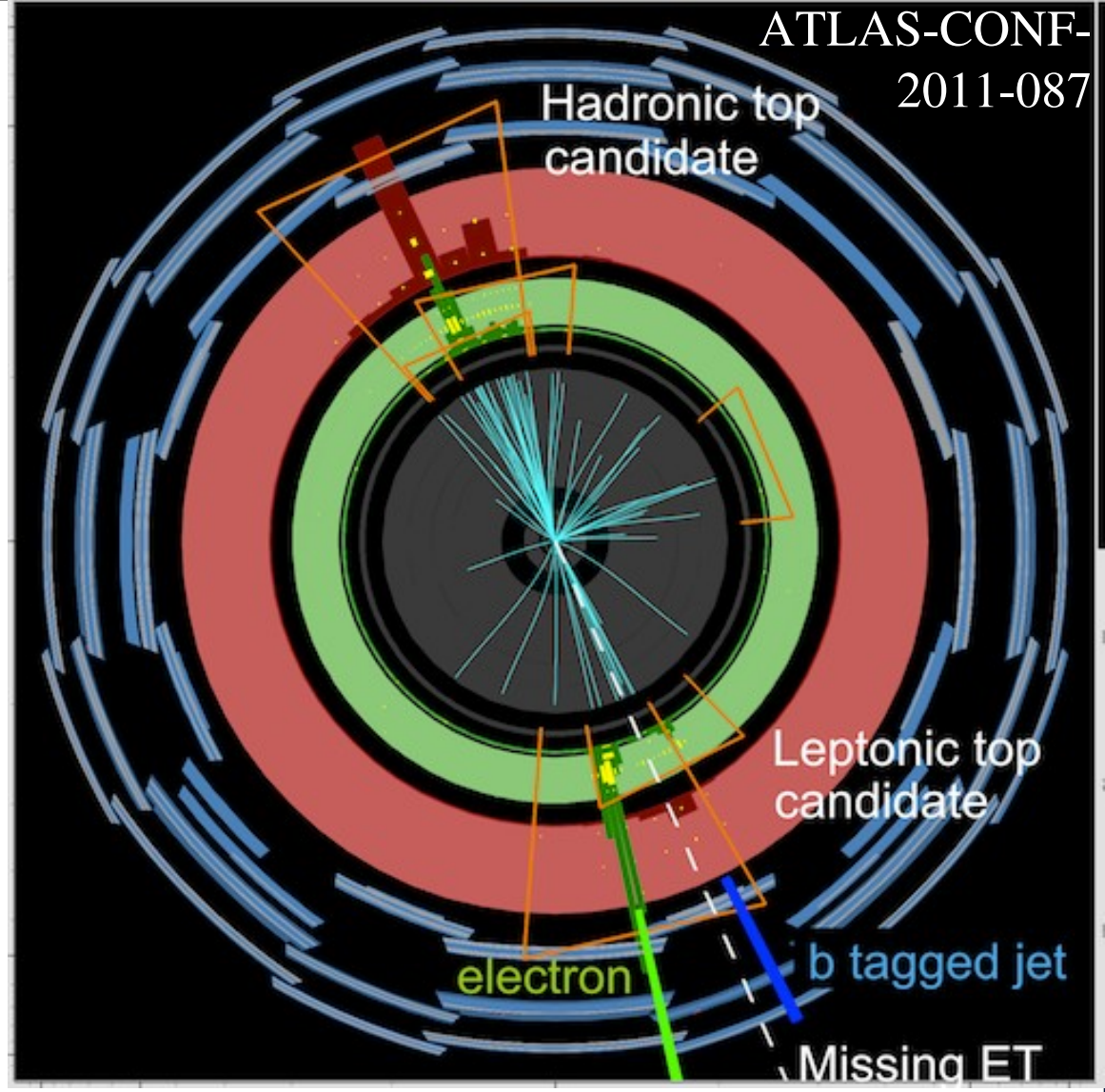


Normal (resolved) decay

High-energetic event



Boosted
Only one or two jets reconstructed



A boosted $t\bar{t}$ candidate, $M(t\bar{t}) = 1.6$ TeV

Leptonically decaying top:
b-jet, lepton and E_T^{miss} close.

Top asymmetries

or

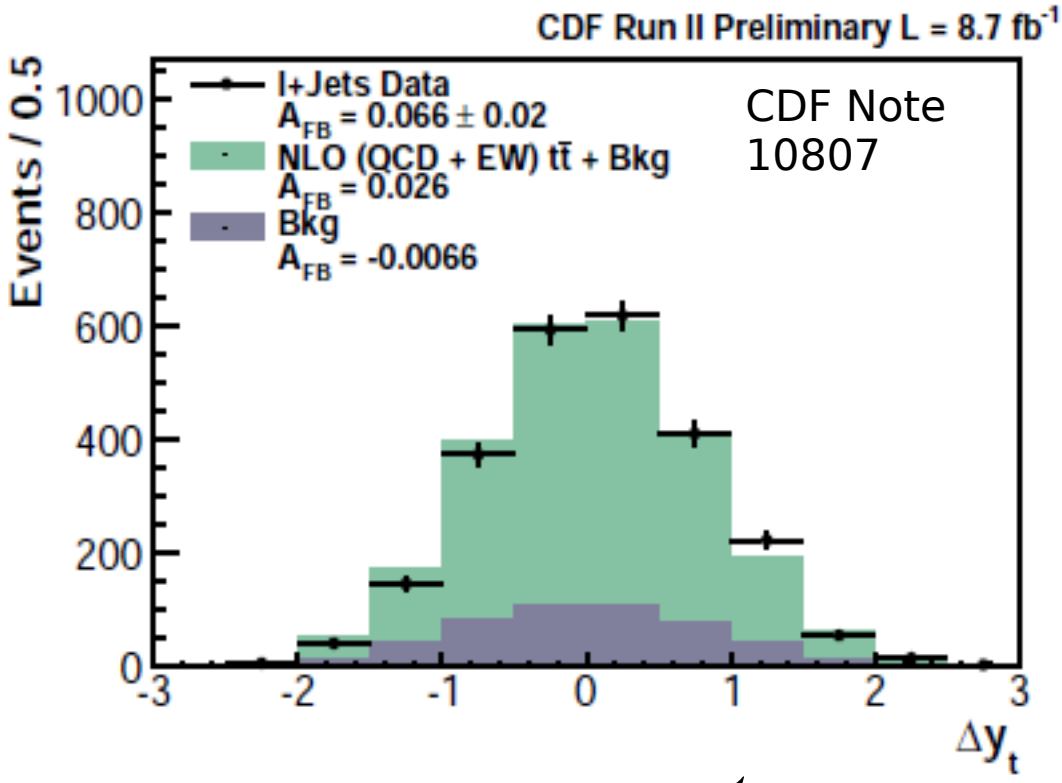
the legacy from the Tevatron

Top asymmetries

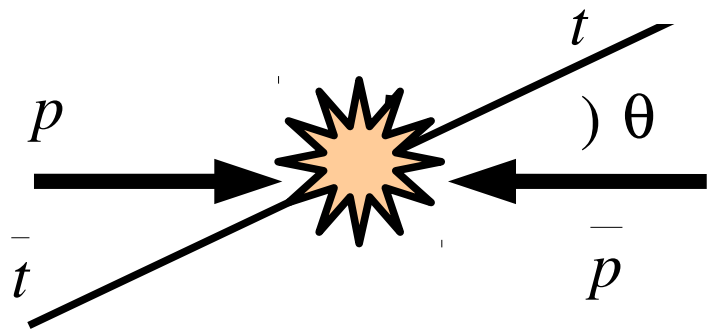
Forward-backward asymmetry between top and anti-top.
Rapidity (y) differences:

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y(t) - y(\bar{t})$$



$p\bar{p}$ collisions
=> $q\bar{q} \rightarrow t\bar{t}$ dominates
t is boosted in the u direction (and similar for $\bar{u}$ and $\bar{t}$).
An asymmetry is expected (NLO).



Experimental challenges:
- Assign the decay products to the right (anti-)top
- Unfold detector effects => parton level A_{FB}

Rapidity $y = 0.5 \log[(E+p_L)/(E-p_L)]$

At high energies:

$y \rightarrow \eta = -\log[\tan(\theta/2)]$

Top asymmetries (2)

SM prediction:

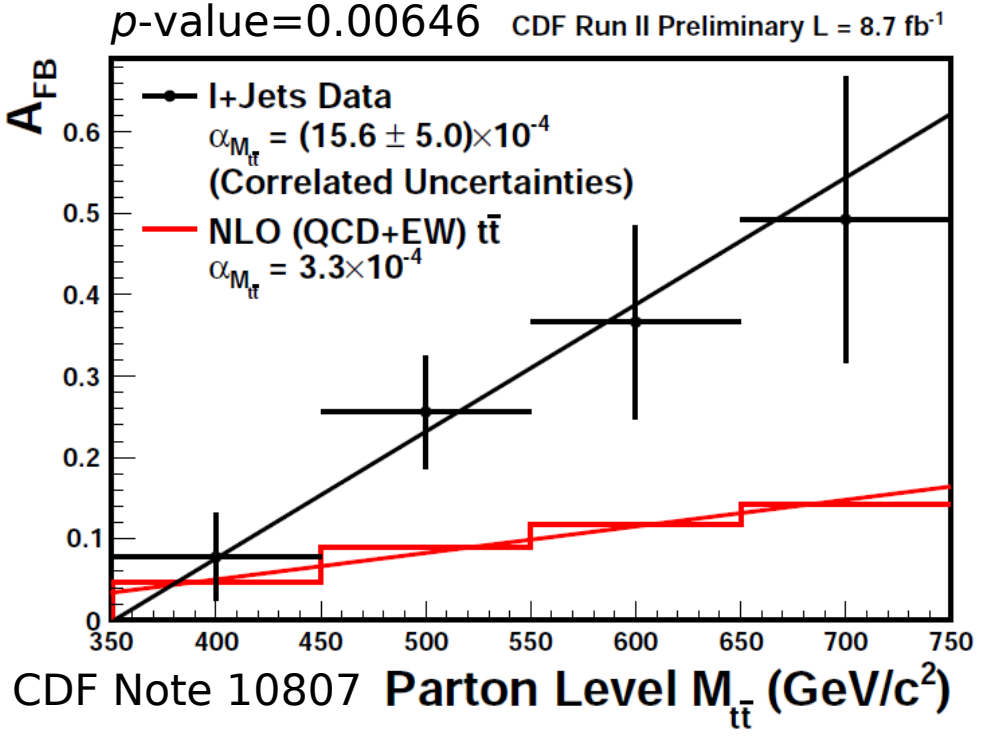
$A_{FB} = 0.074^{+0.007}_{-0.006}$ (Ahrens et al)

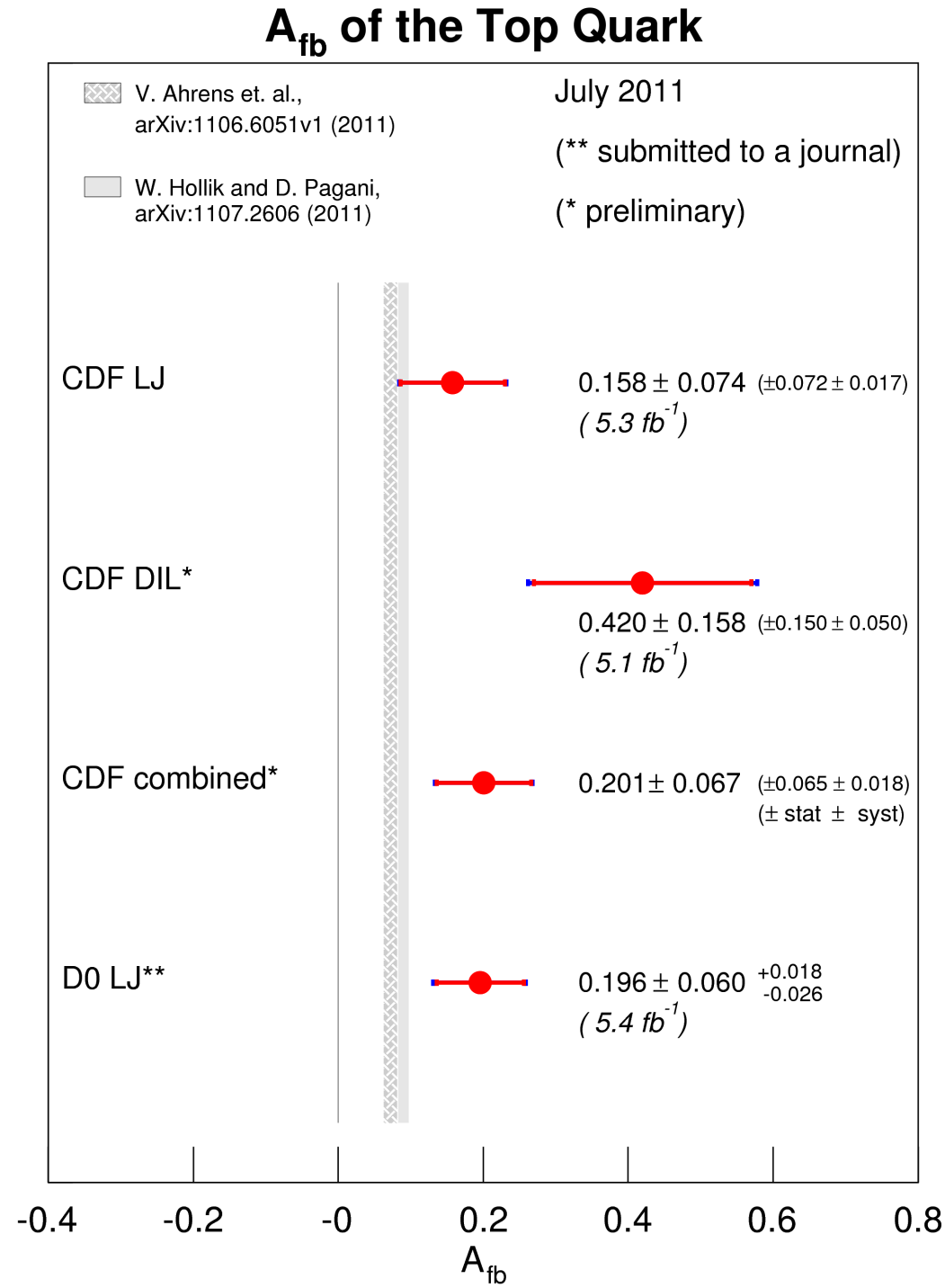
$A_{FB} = 0.089^{+0.008}_{-0.006}$ (Hollik et al)

New 8.7 fb^{-1} CDF result:

$A_{FB} = 0.162 \pm 0.047$ (CDF Note 10807)

The indicated A_{FB} is mass-dependent!





http://www-cdf.fnal.gov/physics/new/top/public_tprop.html

Top asymmetries @ LHC

pp collider => no f/b asymmetry.

Forward/central asymmetry!

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

$$\Delta|y| = |y(t)| - |y(\bar{t})|$$

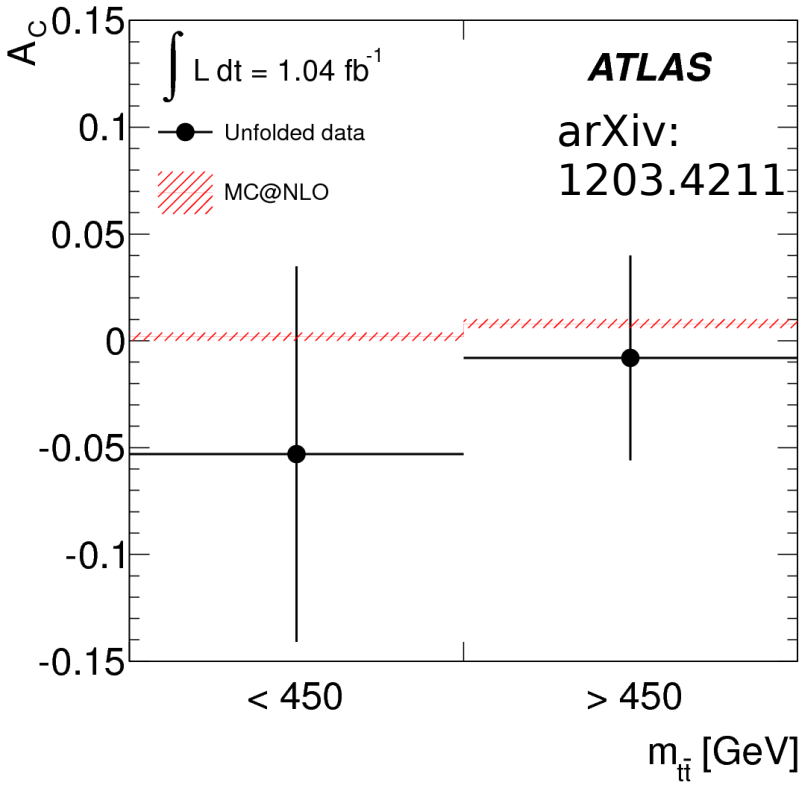
$q\bar{q} \rightarrow t\bar{t}$, q a valence quark, $\bar{q}$ a sea quark
=> t more energetic (forward-boosted) than $\bar{t}$

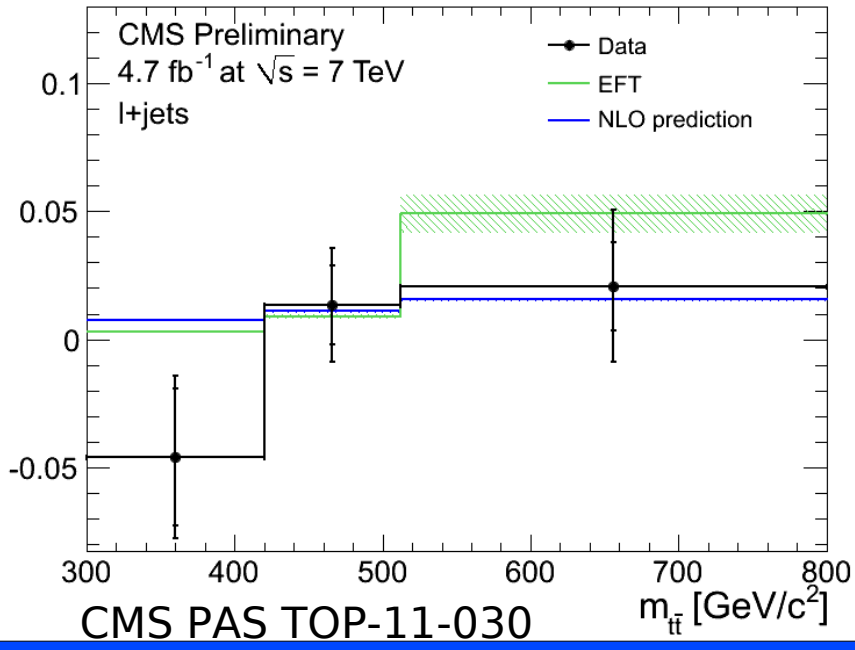
$A_C = 0.0115 \pm 0.0006$
Kühn & Rodrigo arXiv:1109.6830.

$A_C = 0.004 \quad \pm 0.010(\text{stat.}) \pm 0.012\ (\text{syst.})$
CMS 5fb^{-1} TOP-11-030

$A_C = -0.018 \quad \pm 0.028\ (\text{stat.}) \pm 0.023\ (\text{syst.})$
ATLAS 1fb^{-1} arXiv:1203.4211

Experiment and SM predictions agree.





Same-sign top via flavour-changing neutral currents (FCNC)

or

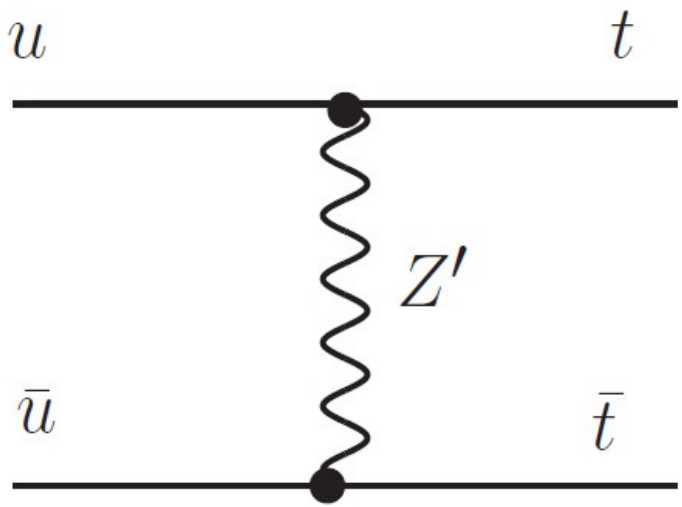
a model that could give us a forward-backward asymmetry

Same-sign top via FCNC

ATLAS 1fb^{-1} arXiv:1202.5520; CMS 5 fb^{-1} SUS-11-020-pas

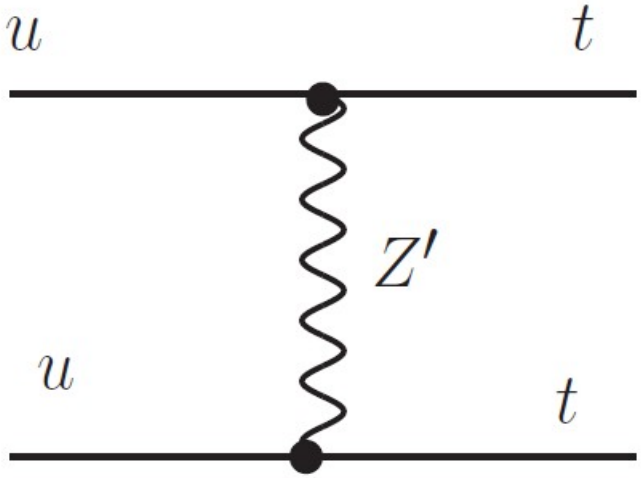
- Observation of **same-sign top** events could help us understand the F/B asymmetry observed at the Tevatron.
  (S. Jung et al PRD 81, 015004 (2010)).
- t-channel exchange of FCNC Z' in uu collisions
  → tt production
  Z': colour singlet (Z^0-like)
- tt not predicted by SM.

Selection strategy: find *same-sign* leptons (from dileptonic decay of tt).



Tevatron: $u\bar{u} \rightarrow t\bar{t}$.
A_{FB} through interference

LHC: uu → tt.
Same-sign top



Same-sign top via FCNC (cont.)

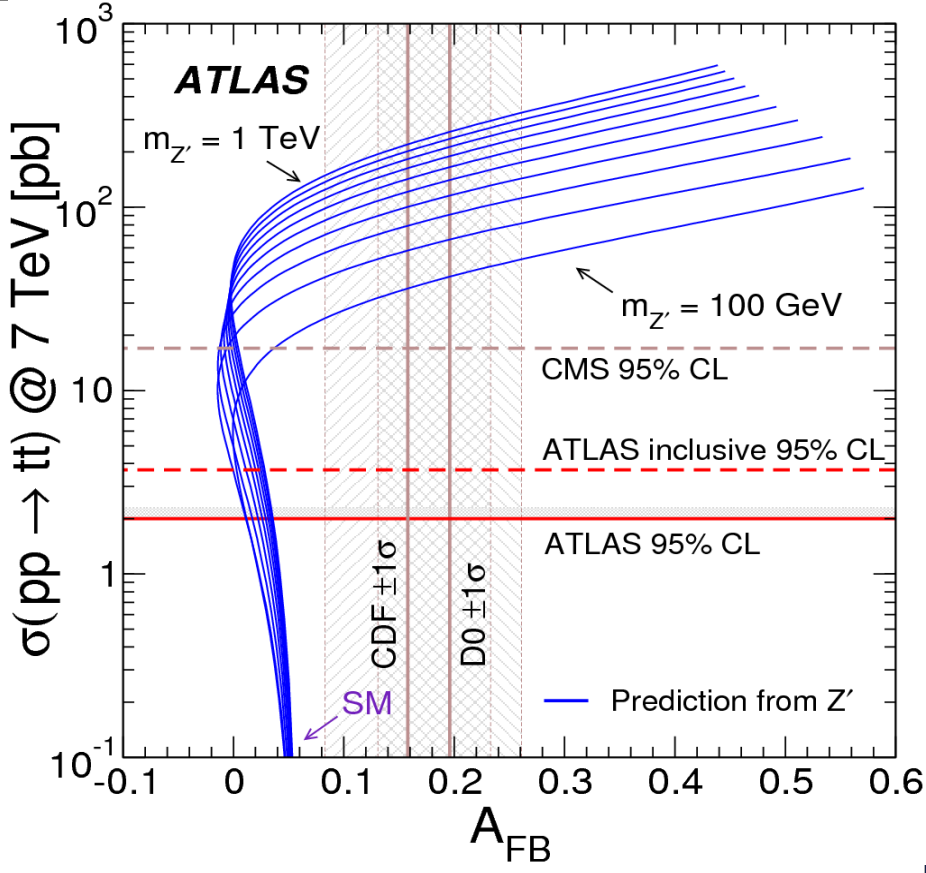
arXiv:1202.5520; CMS SUS-11-020-pas

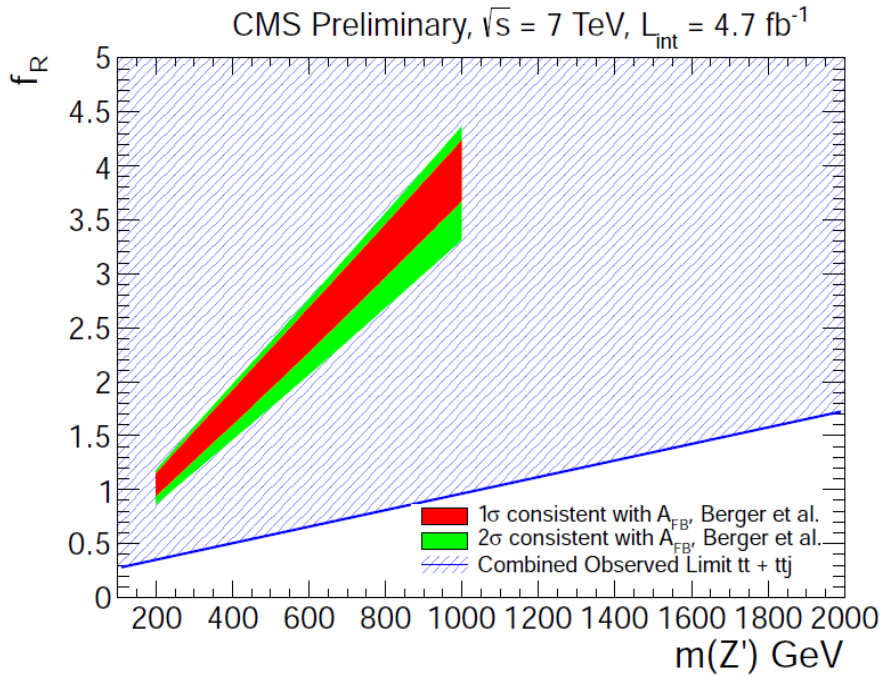
No deviation from SM observed.

Top plot: Upper limits on the tt production with the forward-backward asymmetry from the Tevatron and limits on *Z*' production (ATLAS).

Bottom plot: upper limit on the coupling f_R as a function of *Z*' mass (CMS).

Both studies disfavour FCNC *Z*' as the cause of the Tevatron A_{FB} (but do not exclude them completely)





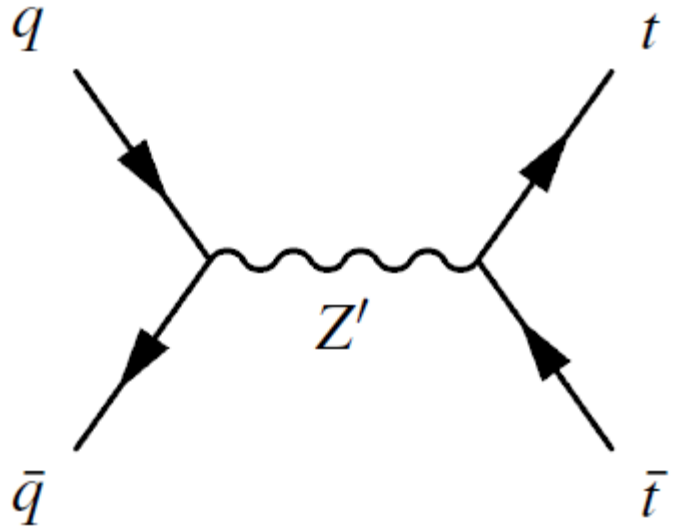
M($t\bar{t}$) searches: $t\bar{t}$ resonances

or

are there any bumps out there?

$t\bar{t}$ resonances

- Strategy: search the $M_{t\bar{t}}$ spectrum for bumps that could indicate a resonance (like $Z^0 \rightarrow q\bar{q}$)
- Physics models often considered:
  - *Colour singlet: leptophobic topcolor Z'* (heavy Z^0-like boson), Γ/M ~1%
  - *Colour octet:* g_{KK} from a RS extra dimension, Γ/M ~15%

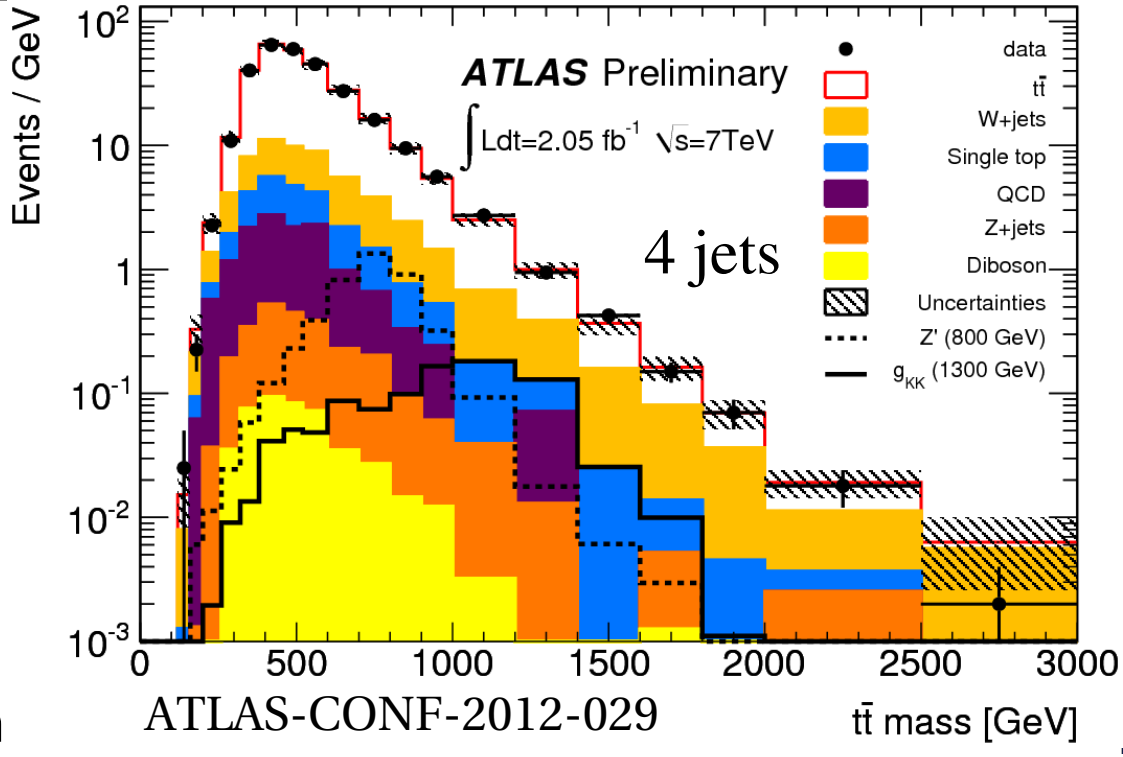


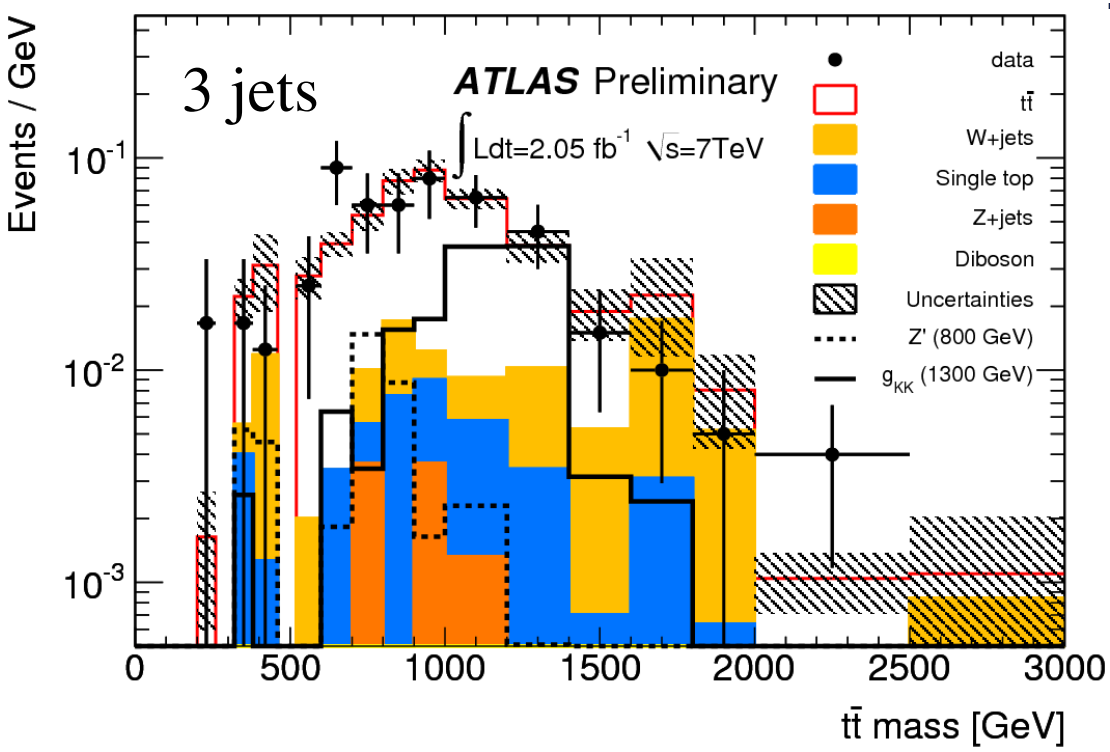
Generic models, and a generic search to find *any* bump in the $M_{t\bar{t}}$ spectrum.

CMS and ATLAS have similar approaches.
Will show l+jets results.

$t\bar{t}$ resonances (cont.)

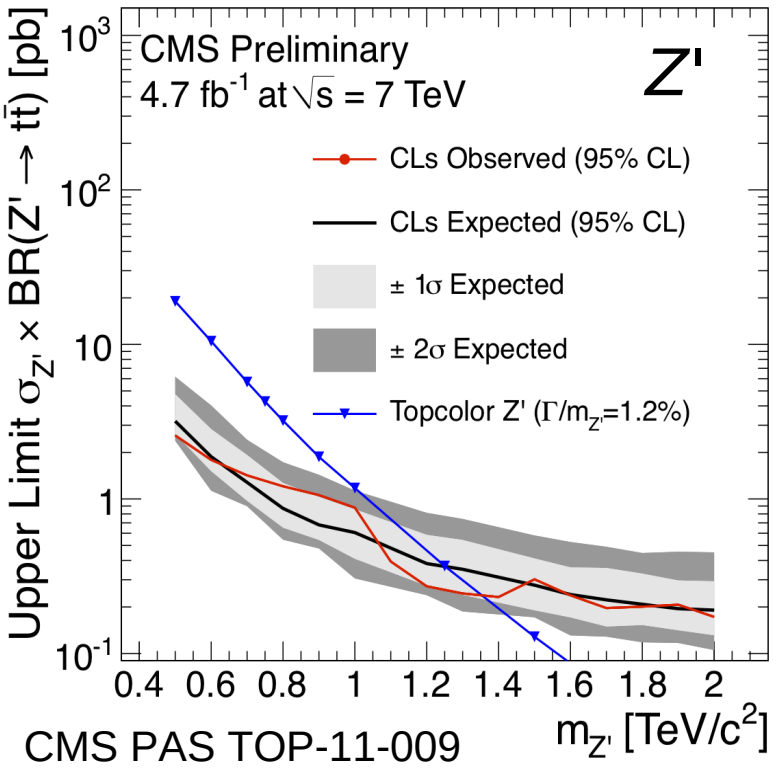
- ATLAS l+jets strategy (ATLAS-CONF-2012-029):
- Selection: 1 lepton (e or μ), 4 jets, at least 1 b-tag, E_T^{miss}.
- Compute $M_{t\bar{t}}$ using a W mass constraint on the l+E_T^{miss} system
- Account for **boosted** tops: if m_j>60 GeV, require only 3 jets (bottom plot).
  Better S/B despite worse statistics!
- Search for bumps or dips with the BumpHunter (arXiv:1101.0390)
  No deviation found
  → Set limits



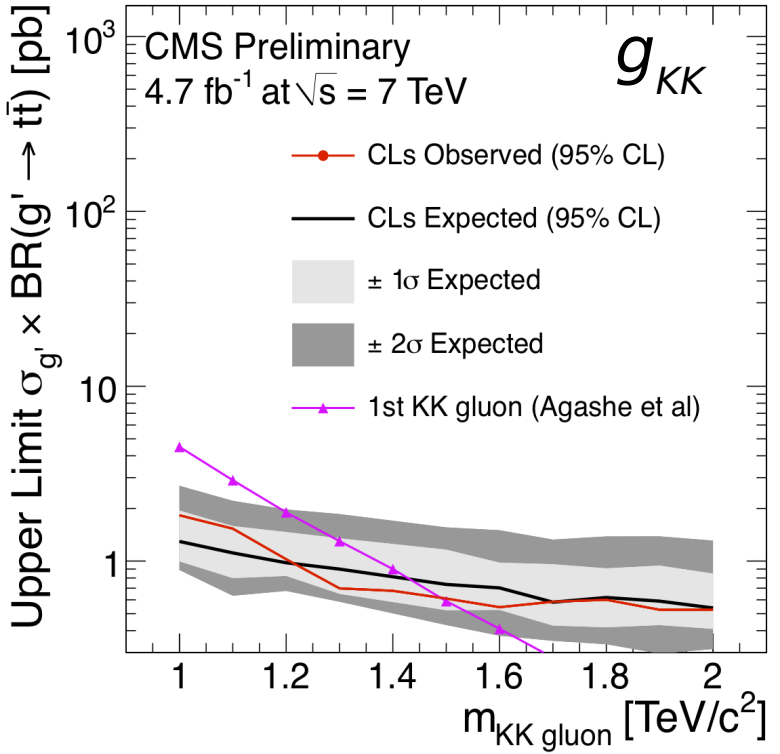


$t\bar{t}$ resonances (cont.)

- Z' is narrow, weakly interacting: better upper limit, lower theory x-sec
  g_{KK} is broad, strongly interacting: worse upper limit, higher theory x-sec.
- Results from a similar CMS study
  CLs limits, 5fb^{-1} (PAS-TOP-11-009):
  $m_{Z'}$>~1.3 TeV
  m_{gKK}>~1.5 TeV
- ATLAS mass exclusions, 2 fb^{-1}, Bayesian limits (ATLAS-CONF-2012-029):
  $m_{Z'}$ > 860 GeV (different K-factor)
  m_{gKK}> 1025 GeV
- Tevatron limits:
  $m_{Z'}$> 835 GeV (D0 PRD85,051101(R)(2012) 5fb^{-1})
  $m_{Z'}$> 900 GeV (CDF PRD84,072004(2011) 5fb^{-1})
  No heavy gluon 400 < m < 800 GeV (CDF arXiv:0911.3112, 2fb^{-1})
- No hint of resonant production (yet...)



CMS PAS TOP-11-009

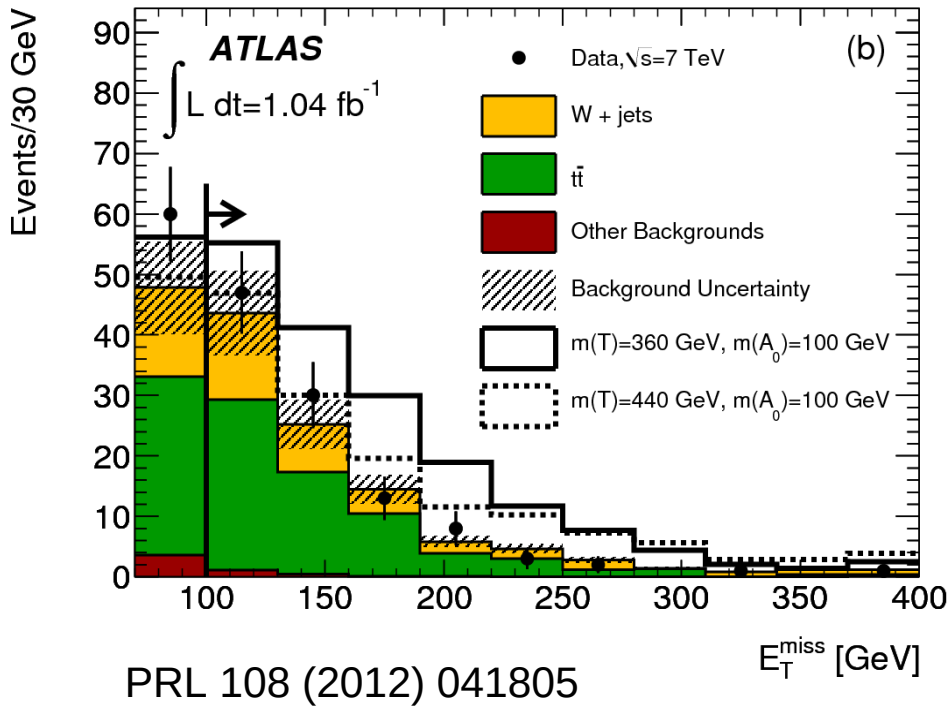


$t\bar{t}$+X, Wtb vertex

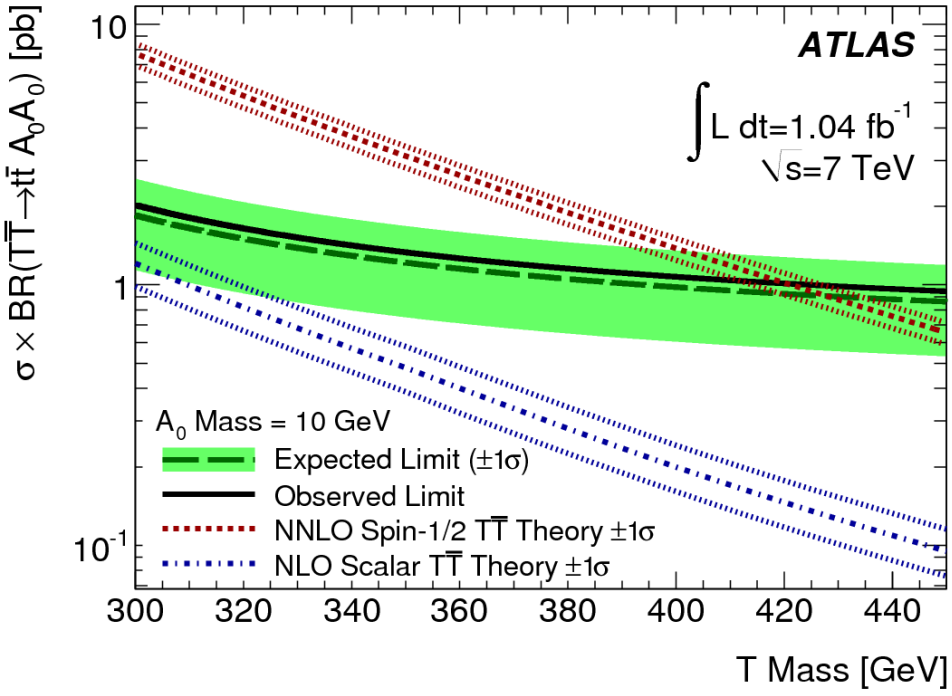
other searches for new physics

$t\bar{t} + E_T^{miss}$

- Search for $T\bar{T} \rightarrow tA_0\bar{t}A_0$ (A_0 weakly interacting) Accounts for a number of new models, e.g. SUSY
- l+jets channel, high amount of E_T^{miss}
- No deviation from SM
- Assuming BR($T\bar{T} \rightarrow t\bar{t}A_0A_0$)=100% and M($A_0$)=10 GeV, T is excluded for M<420 GeV at 95% CL.



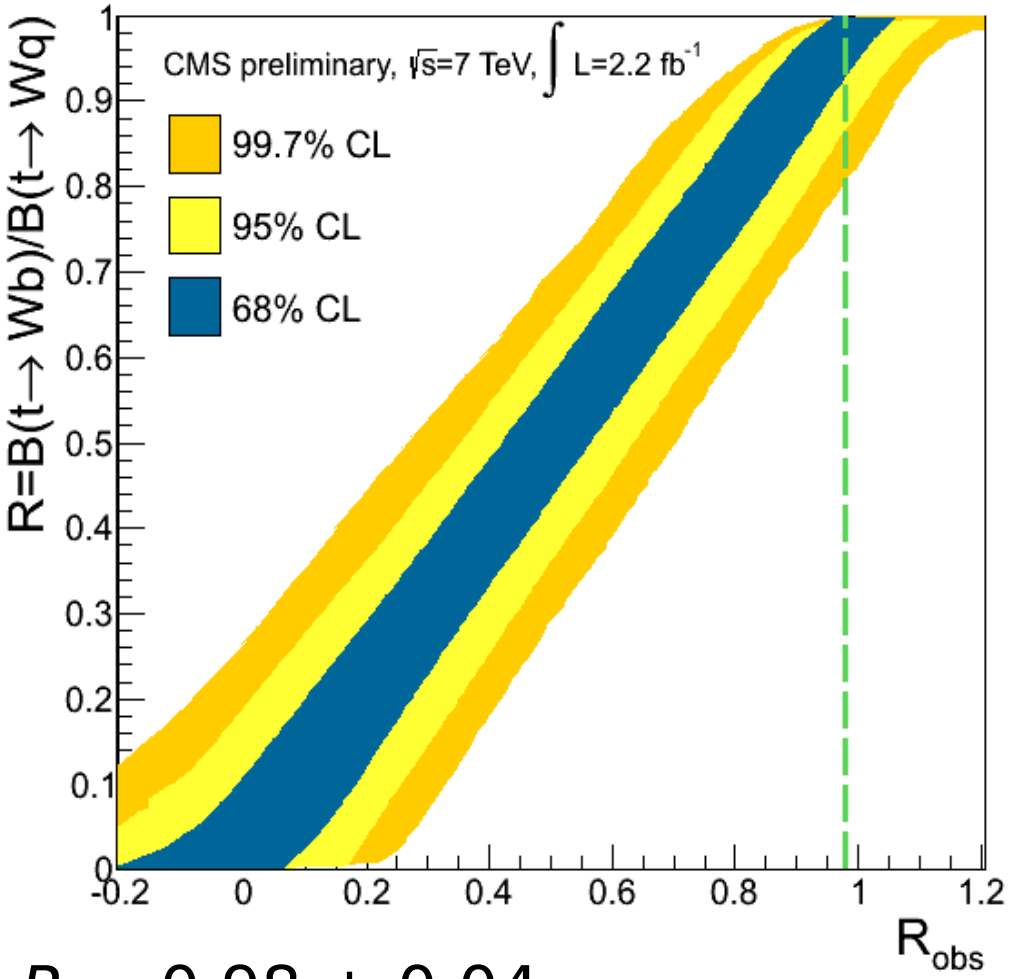
PRL 108 (2012) 041805



$B(t \to Wb) / B(t \to Wq)$

CMS PAS TOP-11-029

- We often assume
  $B(t \to Wb)=100\%$
  $|V_{tb}|$, CKM matrix unitary
- Deviation could indicate a fourth generation of quarks.
- Dilepton channel
  => 2 jets
- Measure
  $R=B(t \to Wb)/B(t \to Wq)$
  q=d,s,b
- Experimental challenges: evaluating *b*-tagging efficiency and mistag rate.



$R = 0.98 \pm 0.04$

$R > 0.85$ at 95% C.L. if $R \leq 1$.

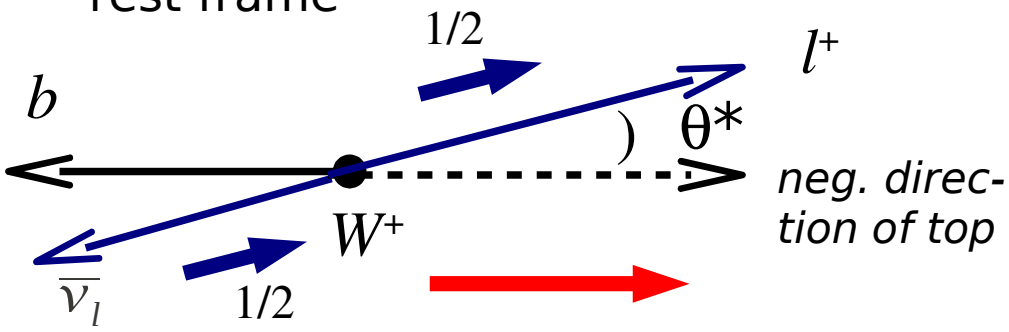
D0: PRL. 107, 121802 (2011) 5.4 fb^{-1}
$R = 0.90 \pm 0.04$

CDF: PRL 95 102002, 160 pb^{-1}
$R = 1.12^{+0.21}_{-0.19}$ (stat) $^{+0.17}_{-0.13}$ (syst)

W polarisation: probing Wtb

ATLAS-CONF-2011-122, CMS TOP-11-020-pas

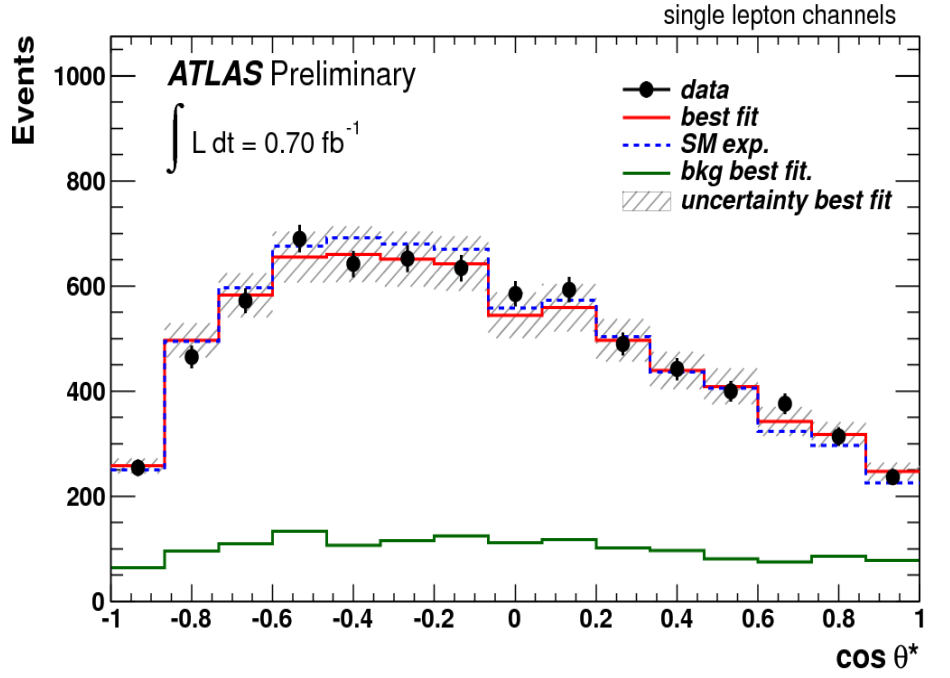
- Look at the helicity of the lepton in $t \to Wb \to l\nu b$ decays. (longitudinal, left- or right-handed)
- ATLAS: 0.7 fb^{-1}, l+jets, dilepton
- CMS: 2 fb^{-1}, μ+jets
- Measure θ^*: angle between the charged lepton in the W rest frame and the W momentum in the top rest frame



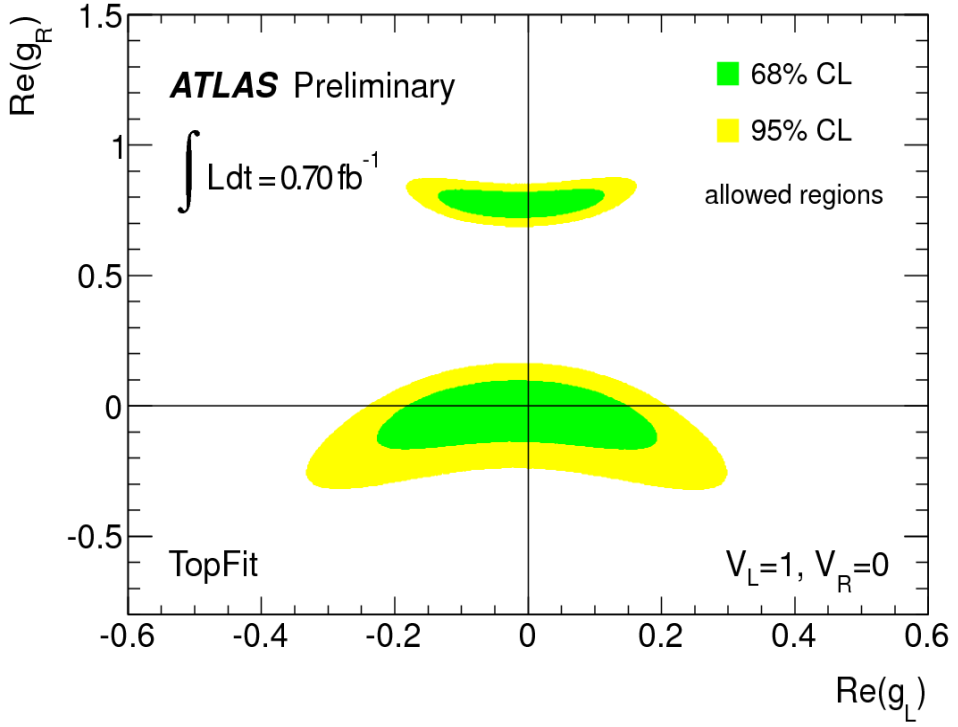
- Set limits on anomalous couplings to Wtb:

$$g_L = \sqrt{2} C_{dW}^{33*} \frac{v^2}{\Lambda^2} \qquad g_R = \sqrt{2} C_{uW}^{33} \frac{v^2}{\Lambda^2}$$

v: EWSB scale (246 GeV)
Λ: scale of new physics
SM: $g_L = g_R = 0$

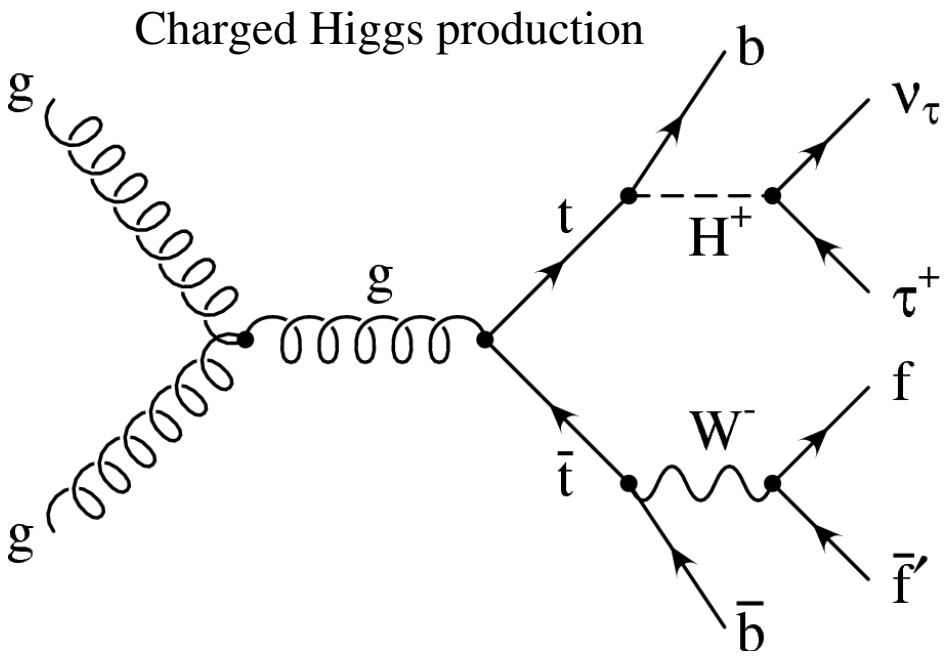


ATLAS-CONF-2011-122



Other searches (not covered here)

- FCNC in top decays
  ATLAS-CONF-2011-061
  CMS PAS TOP-11-028
- FCNC in single top production
  ATLAS: arXiv:1203.0529
- $t\bar{t} + \gamma$ cross section
  ATLAS-CONF-2011-153
- New heavy quarks
  CDF: arXiv:1203.3894 ($p\bar{p} \rightarrow tM \rightarrow t\bar{t}q$)
- Spin correlations in $t\bar{t}$ events
  ATLAS: arXiv:1203.4081 (Zero correlation excluded at 5.1σ!)
  CDF: Conf. Note 10719
  D0:Phys. Rev. Lett. 108, 032004 (2012)
- Fourth generation quarks (tt+WW events)
  ATLAS: arXiv:1202.6540, arXiv:1202.5520 (b')
  ATLAS: arXiv:1202.3076, arXiv:1202.3389 (t')
  CMS: PAS EXO-11-054 (t', b')



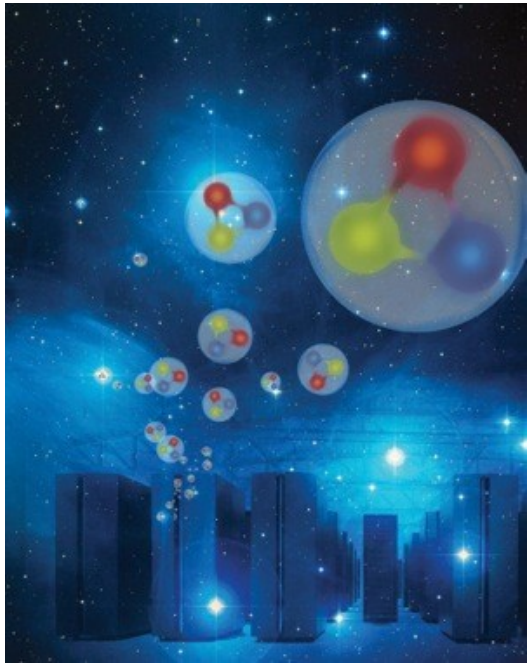
- Charged Higgs in top events
  ATLAS-CONF-2012-011
  CMS-PAS-HIG-11-007
- Top and SUSY (a selection)
  ATLAS: 1203.6193, 1203.5763, ATLAS-CONF-2012-037
  CMS: SUS-11-020-pas

Summary, Conclusions & Outlook

- The Tevatron FB asymmetry is the one measurement which hints at a deviation from the SM in the top sector.
- LHC top searches have not shown any signs of new physics so far...
  - Charge asymmetry, FCNC, same-sign top, M($t\bar{t}$) spectrum, $t\bar{t}$+X, Wtb vertex, spin correlations, fourth generation quarks... investigated.
- ... but now we have 8 TeV collisions!

  $\sigma(t\bar{t})$ is ~40% larger at 8 TeV than at 7 TeV *

  $\sigma(Z' \rightarrow t\bar{t})$ is *twice* as large for $M(Z') = 2$ TeV! **
  - Main experimental challenge: boosted top Merging hadronic top, non-isolated leptons, b-tagging of subjets, pile-up, triggers...



scientificamerican.com

* Approx NNLO with Hathor MSTW2008 NNLO PDF. (J Ferrando)
** pythia8 SSM Z'->ttbar MSTW2008 LO PDF. (J Ferrando)

Questions to theorists

- In the light of recent findings, what model would you propose (or advocate) that explain both Tevatron and LHC results?
- Is there any search or measurement we didn't do, but should?

Thank you!

Funding agencies of ATLAS, CDF, CMS and D0.

My personal thanks to James Ferrando, Tobias Golling, Dominic Hirschbühl, Maria Jose Costa, Uta Klein, Kevin Kröninger, Klaus Mönig, Sanjay Padhi, Viatcheslav Sharyy, Marcel Vos and Stephane Willocq for help with compiling these slides.

Backup

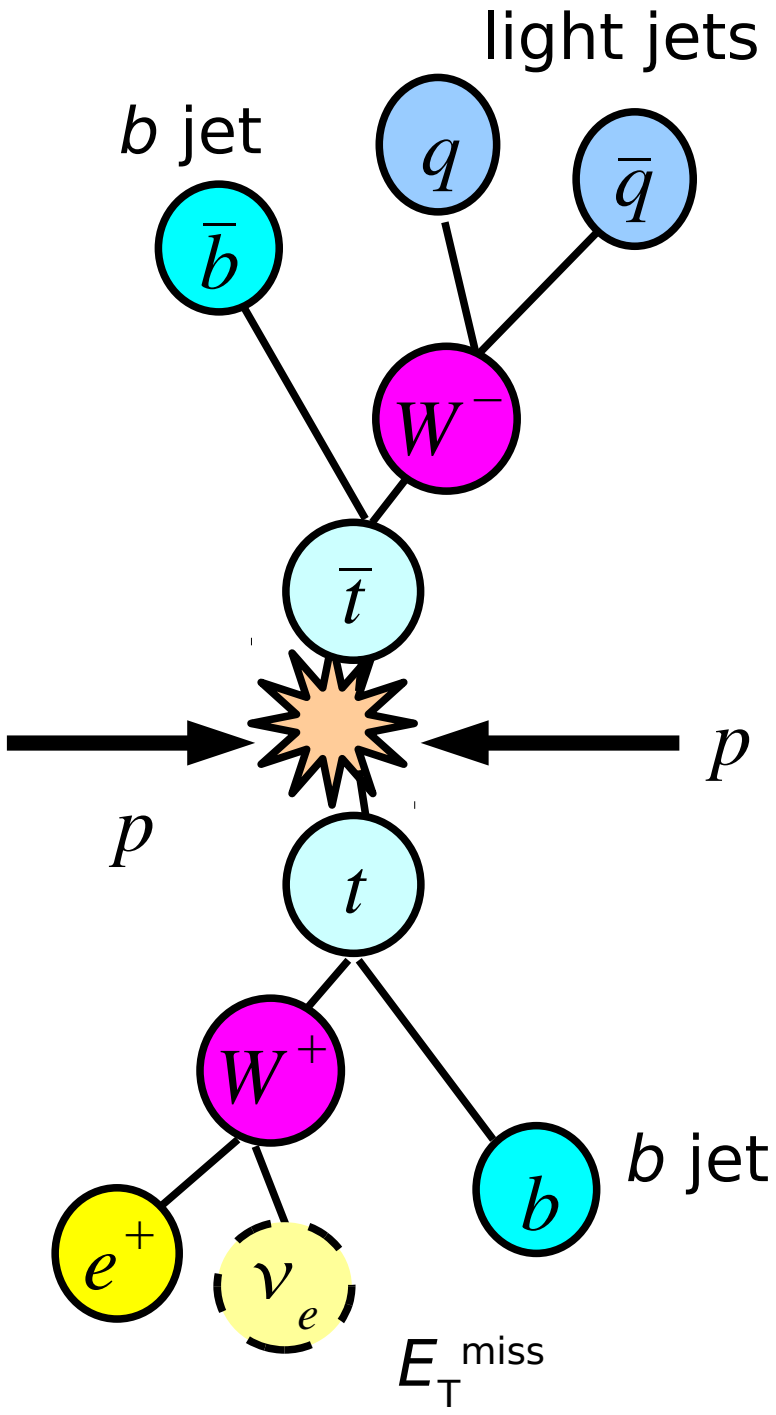
other things to talk about

Top reconstruction strategies

- dilepton (BR ~6%):
  - Trigger on one of the leptons
  - Exactly two leptons
  - Require E_T^{miss} from the ν's
  - 2 jets from b quarks
  - $m_{ll} \sim m_Z$ mass veto
- l+jets (BR ~38%):
  - Trigger on the lepton
  - Exactly one lepton
  - Require E_T^{miss} from ν
  - 4 jets (2 from b quarks)
- All-hadronic (BR ~56%):
  - Trigger on multi-jets
  - 6 jets (2 from b quarks)

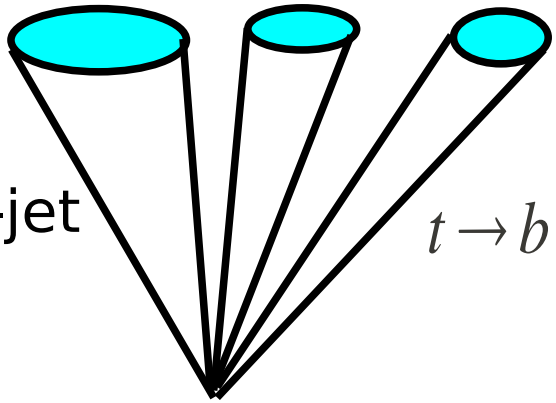
b-tagging to ID b-jets:
typically ~60% efficient

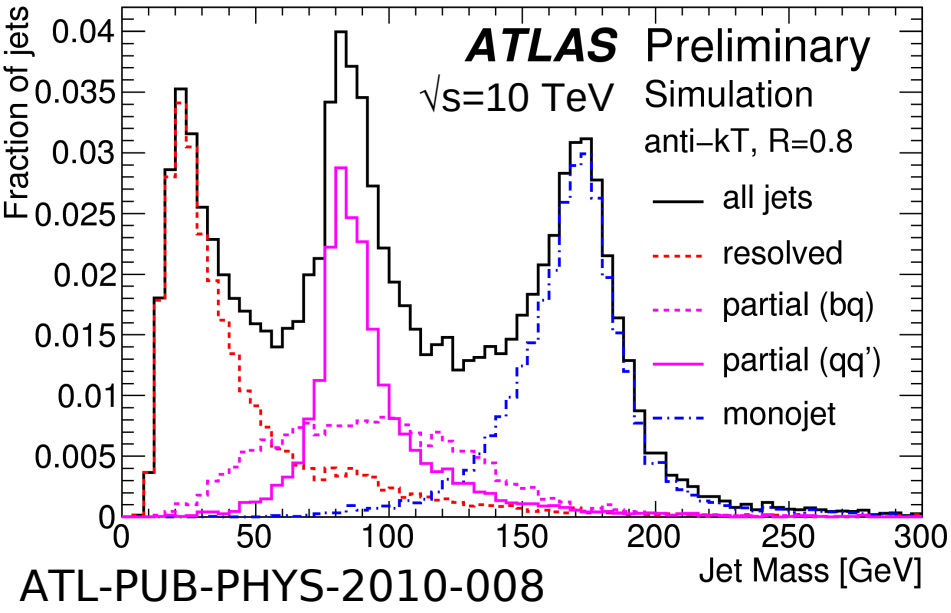
Boosted tops: the decay products merge in the detector



Motivation – boosted top

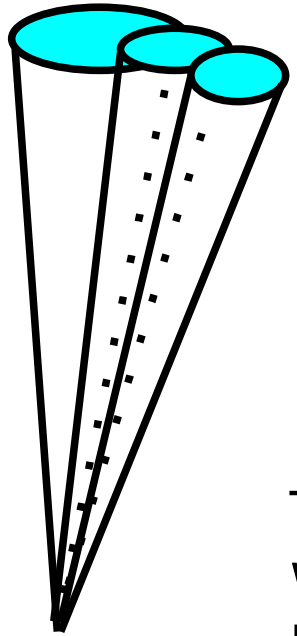
Normal (hadronic) top decay.





ATL-PUB-PHYS-2010-008

If a lot of energy is available in the system, the top decay can be **boosted** and the jets from the decay products overlap.



The jet algorithms see only one jet (also for small dR).

=> Normal top reconstruction impossible.

This problem is evident when the (narrow) jet mass m>~60 GeV, indicating W->$q\bar{q}$ in one jet.

Analyses with boosted top

- CDF note 10234: search for boosted $t\bar{t}$
- ATL-PUB-PHYS-2010-008: boosted $t\bar{t} \rightarrow$ l+jets resonances, $\sqrt{s}$=10 TeV MC simulation
- CMS-EXO-11-092-pas: boosted $t\bar{t} \rightarrow$ e+jets resonances, 4 fb^{-1}
- CMS-EXO-11-055-pas: boosted $t\bar{t} \rightarrow \mu$+jets resonances, 1 fb^{-1}

http://www-cdf.fnal.gov/physics/new/top/public_tprop.html

Top asymmetries (2)

Observed:

$A_{FB} = 0.158 \pm 0.074$
(CDF 5 fb^{-1} l+jets
PRL 83, 112003)

$A_{FB} = 0.42 \pm 0.16$
(CDF 5 fb^{-1} dilepton
Note 10436)

$A_{FB} = 0.201 \pm 0.067$
(CDF 5 fb^{-1} combined
Note 10584)

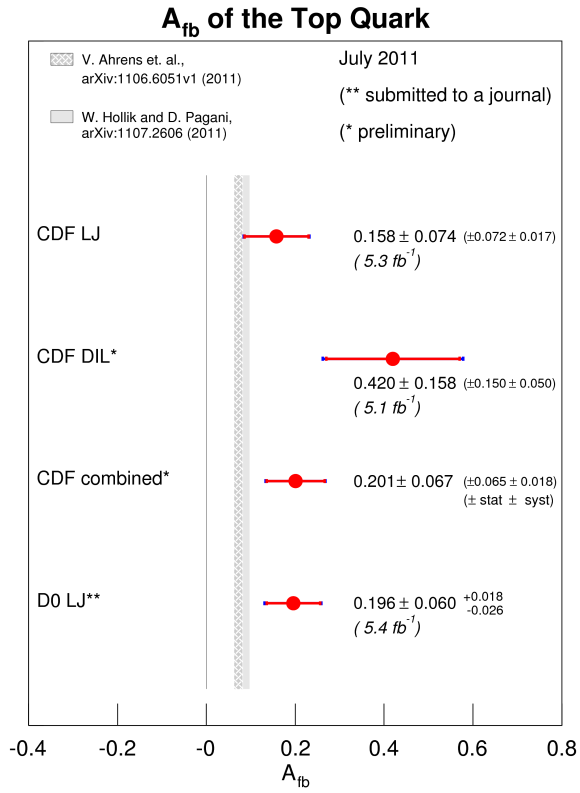
$A_{FB} = 0.196 \pm 0.065$
(D0 5 fb^{-1}
PRL 84, 112005)

$A_{FB} = 0.162 \pm 0.047$
(CDF 9 fb-1, l+jets
Note 10807)

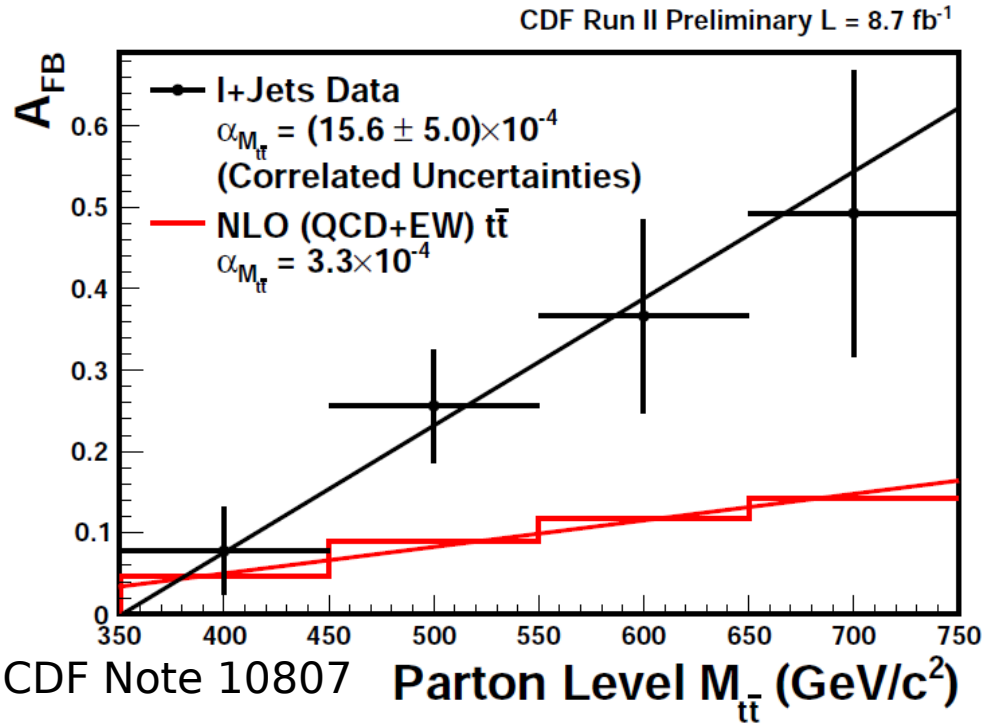
Predicted from SM:

$A_{FB} = 0.074^{+0.007}_{-0.006}$
(Ahrens et al
arXiv:1106.6051)

$A_{FB} = 0.089^{+0.008}_{-0.006}$
(Hollik, Pagani
arXiv:1107.2606)

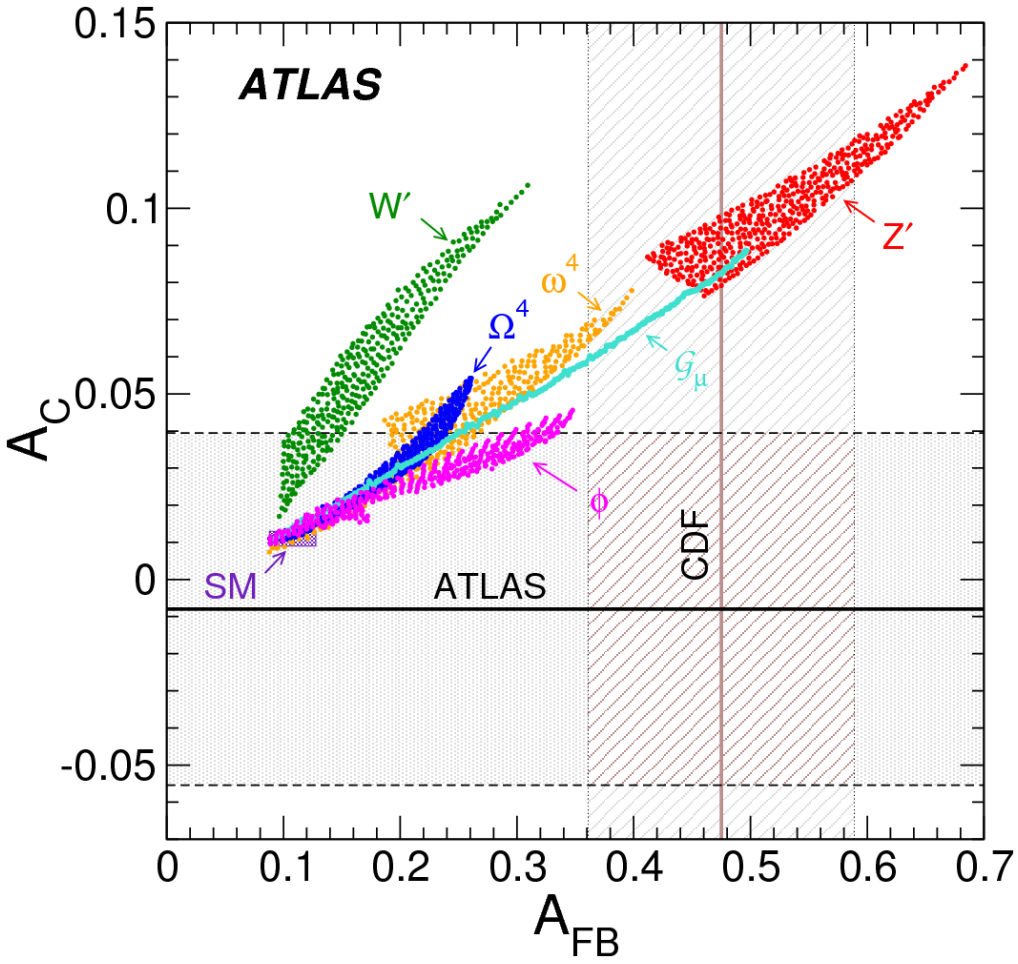


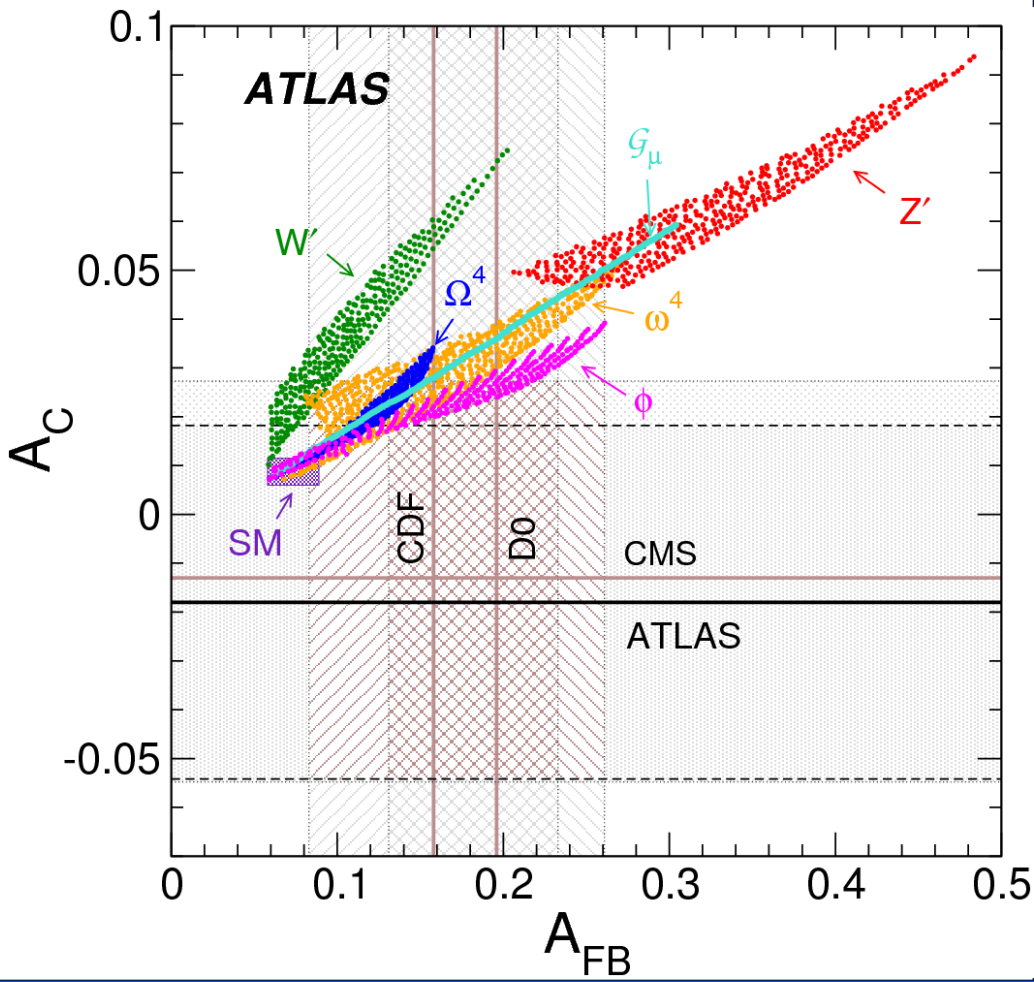
The observed A_{FB} is mass-dependent!



Top asymmetries – exclusions

arXiv:1203.4211





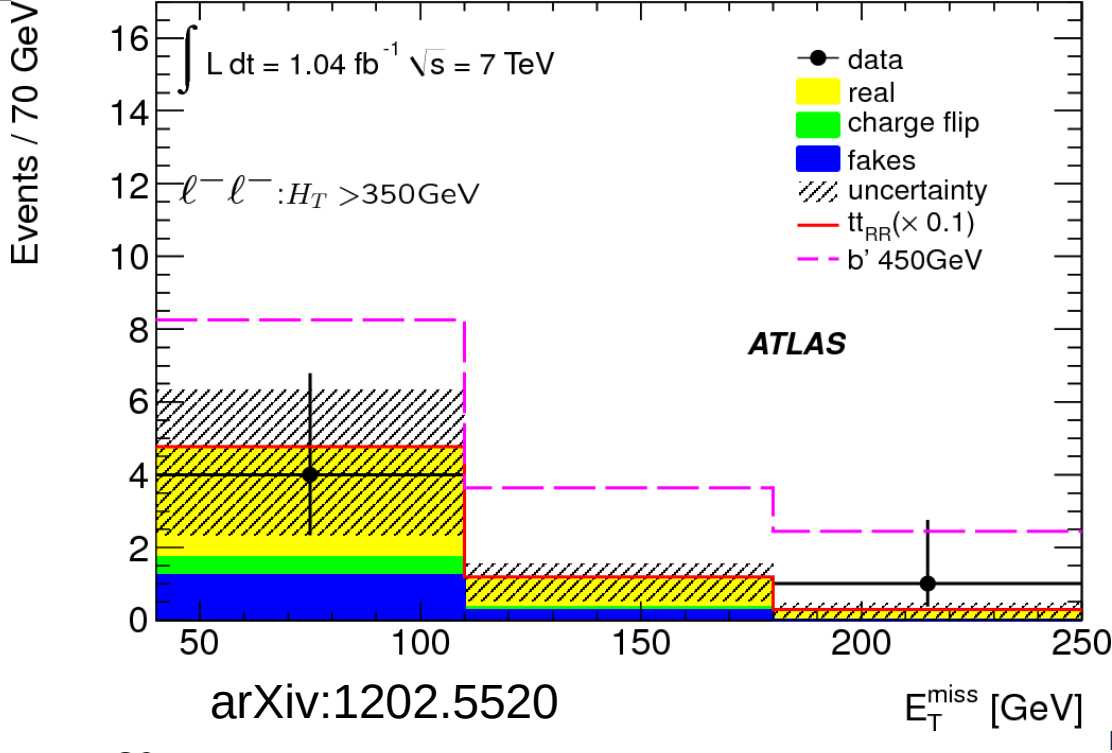
Same-sign top via FCNC (cont)

arXiv:1202.5520; JHEP 8 (2011) 5

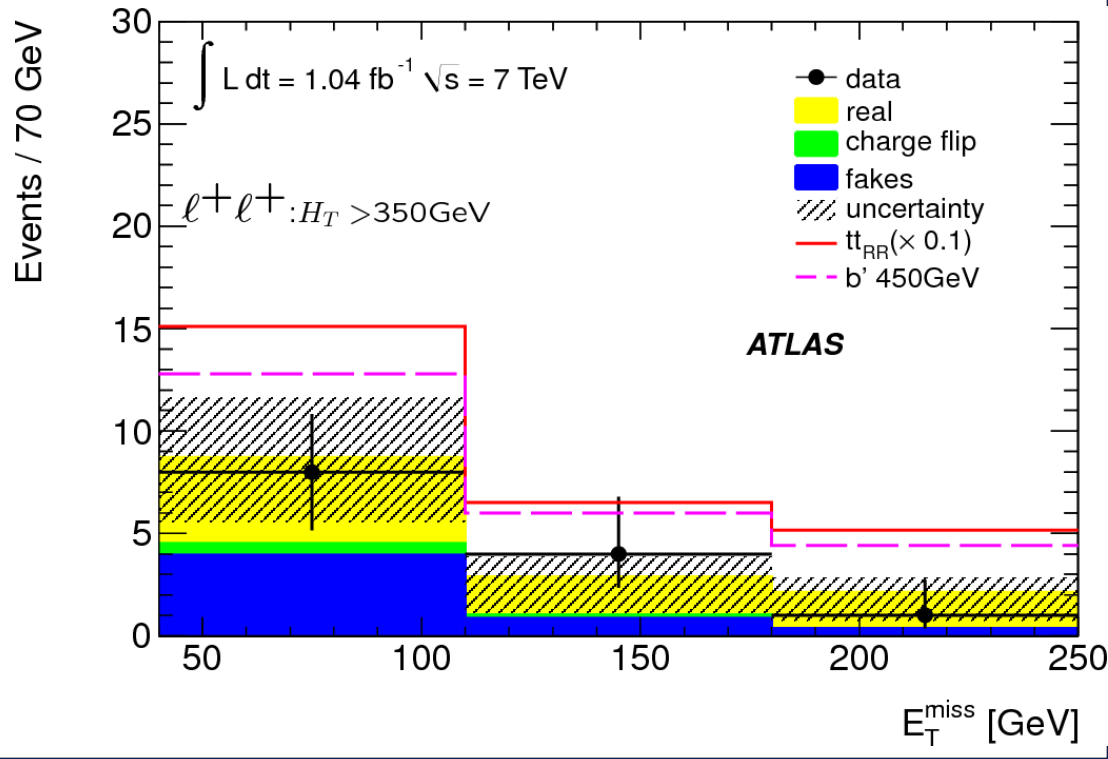
- *pp* collider → ++ background more common.
- Event selection :
  - 2 same-sign leptons
    ee, *eμ* or *μμ*
    (CMS: ++ only)
  - E_T^{miss}, 2 jets (CMS: 2+ jets)

- "real": true same-sign lepton events from e.g. dibosons
- "charge flip": one misidentified charge
- "fake": misidentified jets or γ

No evidence for same-sign tt production found...



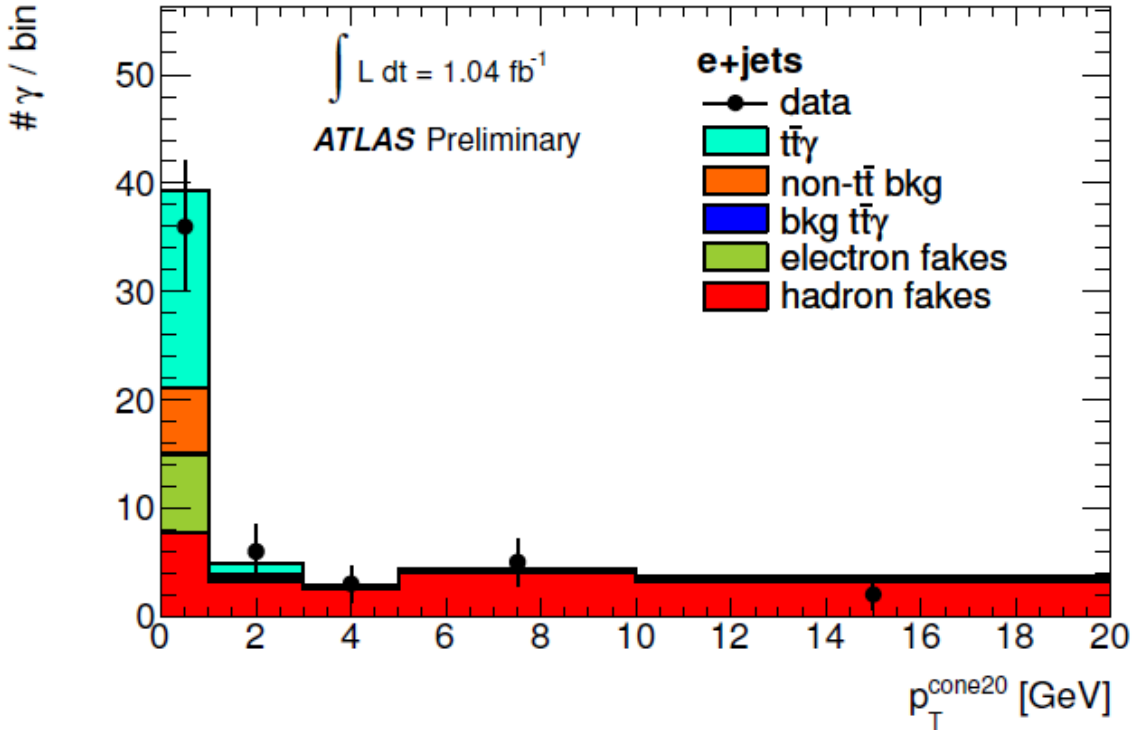
arXiv:1202.5520



$t\bar{t}+\gamma$

ATLAS-CONF-2011-153

- EW couplings to the top quarks
- Experimental challenges:
  - identifying the photon (and not e.g. $\pi^0 \rightarrow \gamma\gamma$)
  - estimating the background



p_T^{cone20}: track isolation;
p_T sum in $\Delta R<0.2$

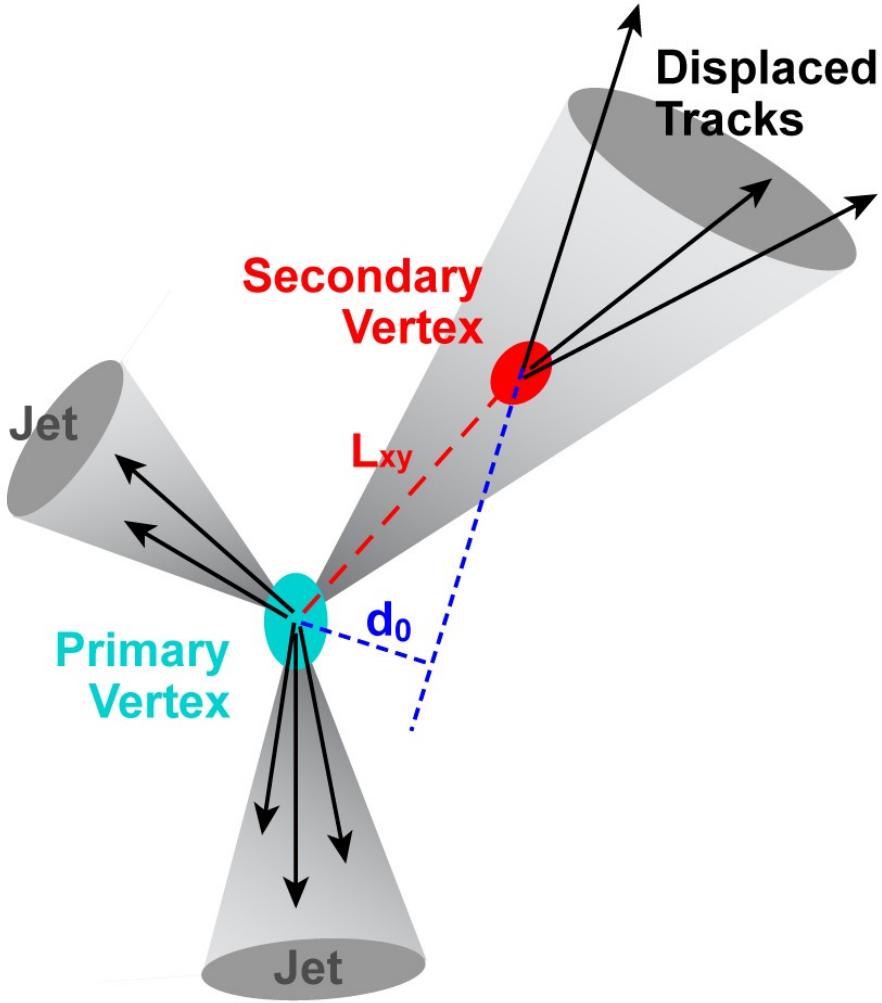
- $\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5$ (stat.) ± 0.7 (syst.) ± 0.08 (lumi.) pb
  ($t\bar{t} \rightarrow$ l+jets or dileptonic)
- SM prediction:
  $\sigma_{t\bar{t}\gamma} = 2.1 \pm 0.4$ pb

b-tagging for $B(t \to Wb) / B(t \to Wq)$

CMS PAS TOP-11-029

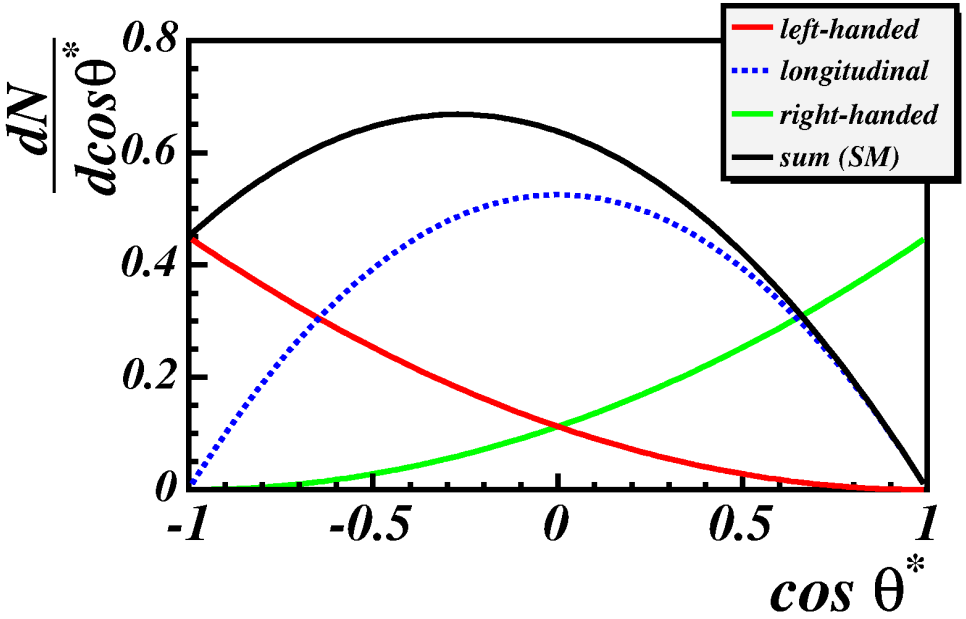
- CMS b-tagging
  CMS BTV-11-002-pas
  CMS BTV-11-003-pas
  CMS BTV-11-004-pas
- "Track counting high efficiency" TCHE algorithm used
- Tag uncert 3%
- Mistag eff (light quarks) 14%
- Misassignment of jets an additional uncertainty.
- Heavy flavour content also determined from data.

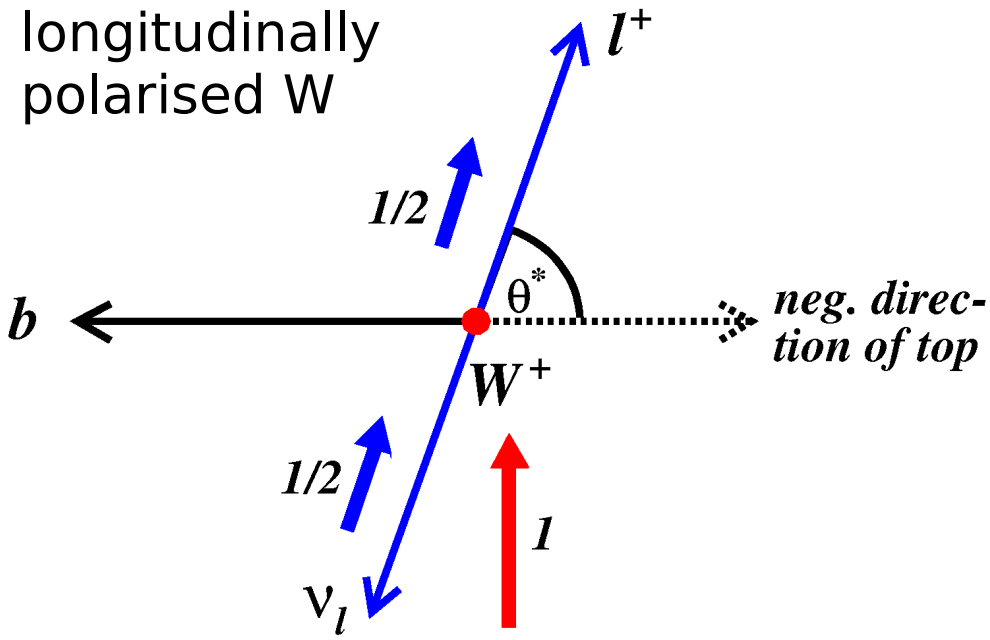
Principle: find the displaced vertex.

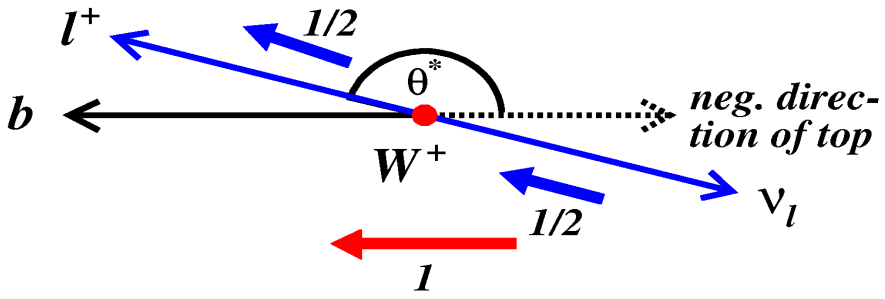


PRL 103, 092001 (2009)

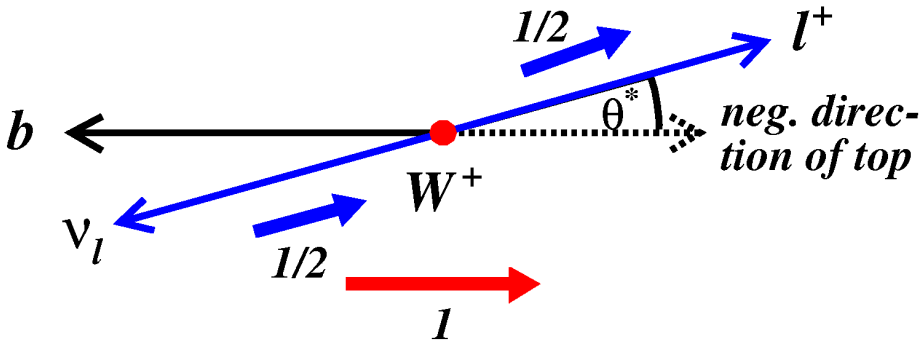
W polarisation overview CDF note 8380







left-handed polarised W



right-handed polarised W

W polarisation

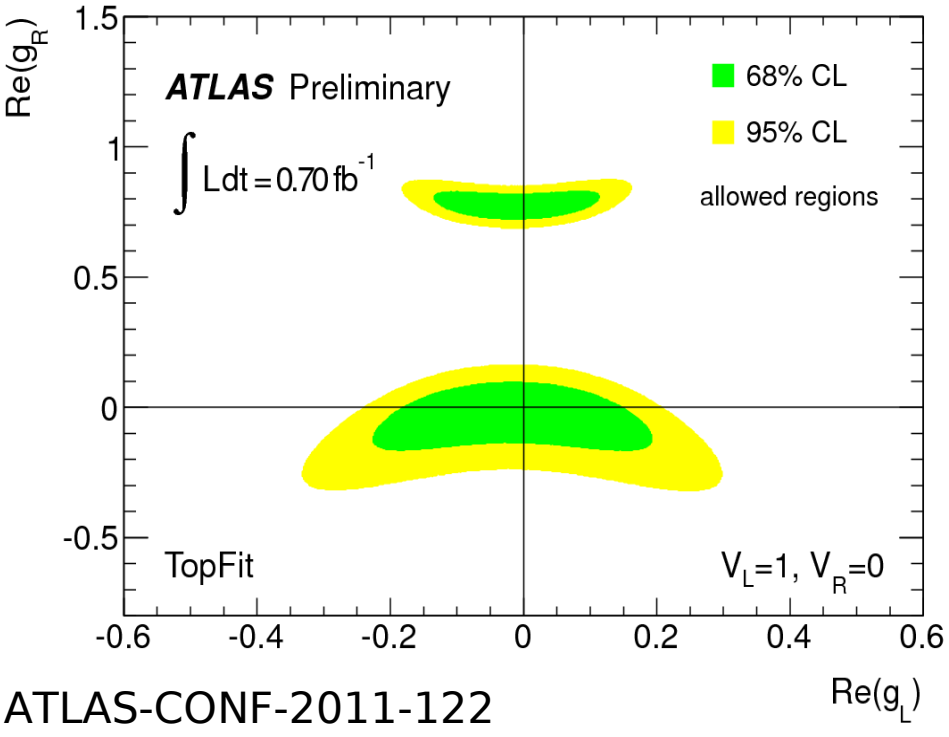
Aguilar-Saavedra:
Nucl.Phys.**B812**(2009)181-204
Nucl.Phys.**B821**(2009)215-227

$$L_{Wtb} = \frac{-g}{\sqrt{2}} \bar{b} \gamma^{\mu} (V_L P_L + V_R P_R) t W^-_{\mu} - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_{\nu}}{M_W} (g_L P_L + g_R P_R) t W^-_{\mu} + \text{h.c.}$$

$$V_L = V_{tb} + C^{(3,3+3)}_{\phi q} \frac{v^2}{\Lambda^2} \qquad V_R = \frac{1}{2} C^{33*}_{\phi\phi} \frac{v^2}{\Lambda^2}$$

$$g_L = \sqrt{2} C^{33*}_{dW} \frac{v^2}{\Lambda^2} \qquad g_R = \sqrt{2} C^{33}_{uW} \frac{v^2}{\Lambda^2}$$

C: eff. operator coefficients
v: EWSB scale (246 GeV)
Λ: scale of new physics



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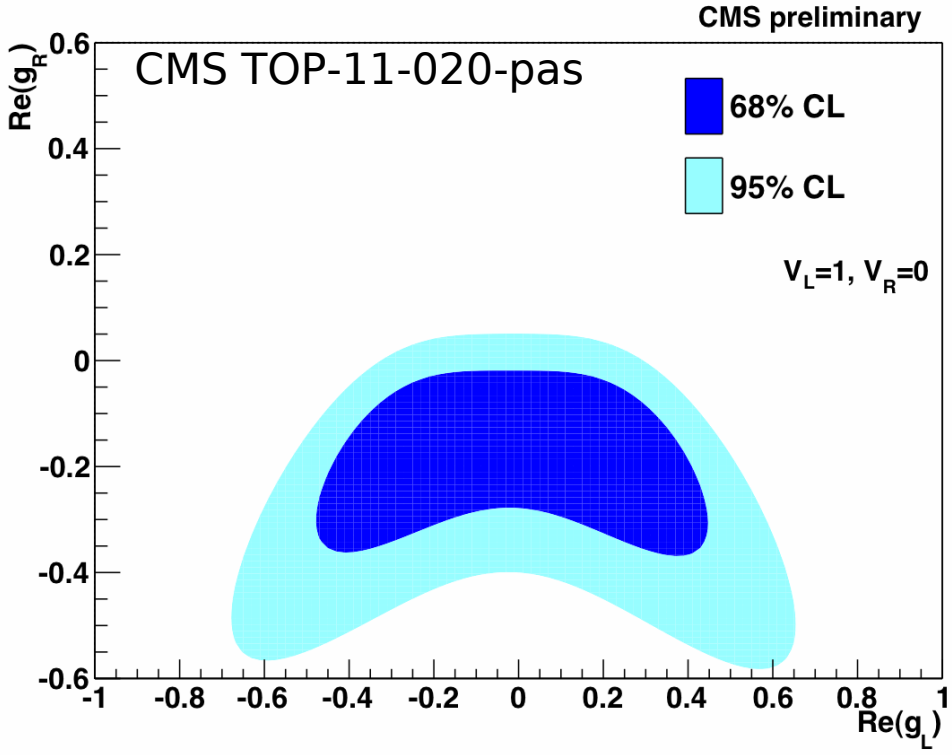
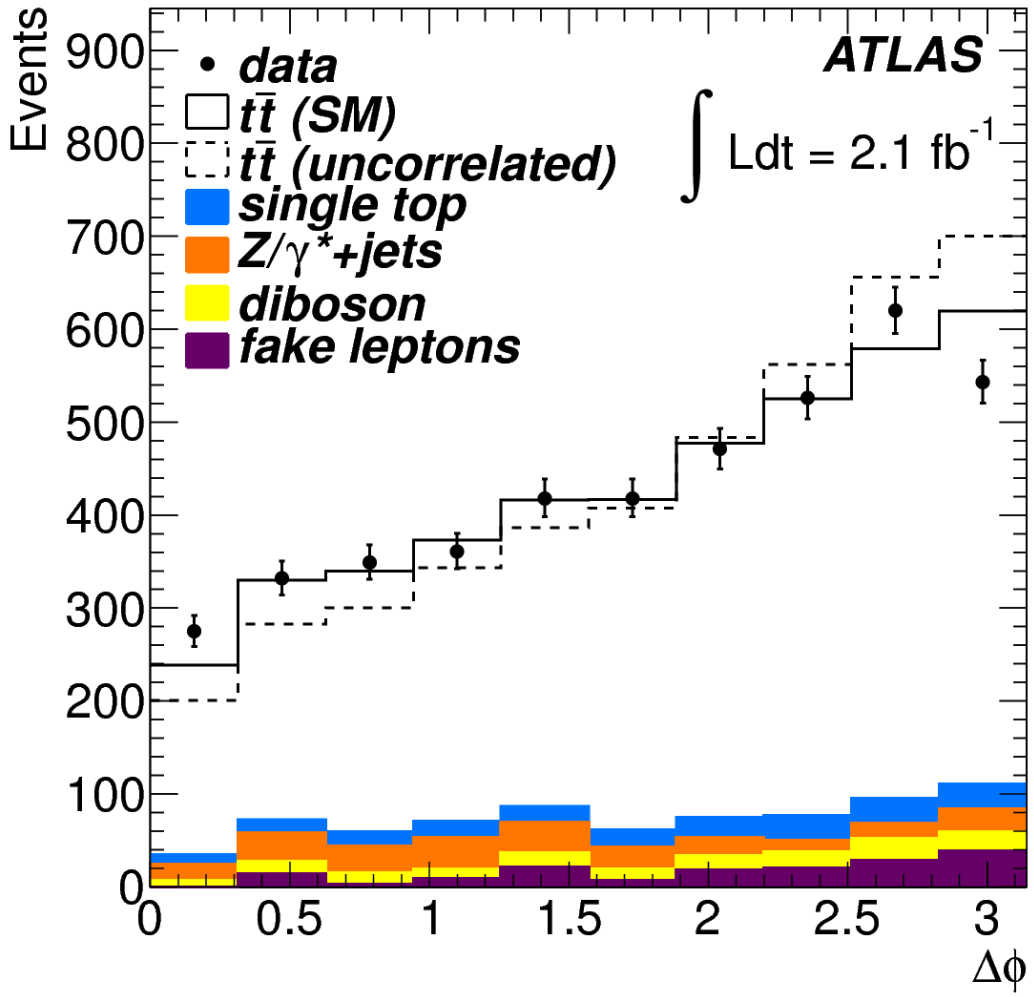


Spin correlations in ATLAS

arXiv:1203.4081 (2 fb^{-1})

- Top decays before hadronisation – unlike all other quarks.
- The spins of the top and anti-top are expected to be correlated.
- The level of correlation can be used to probe the $t\bar{t}$ production mechanism and their decays.
- Analysis strategy:
  Dilepton channel
  Azimuthal angle between the leptons: $\Delta\phi$
  sensitive to spin correlation
- Fit level of correlation:
  $f = 1$ (expected correlation)
  $f = 0$ (Zero correlation case)
- Measured:
  $f = 1.30 \pm 0.14(\text{stat})^{+0.27}_{-0.22}(\text{syst})$
- Zero correlation excluded at 5.1σ (4.2σ expected)

$\Delta\phi$ distribution: SM-like correlations clearly favoured.



Charged Higgs searches

ATLAS-CONF-2012-011, CMS-PAS-HIG-11-007

- Search for $t \to bH^+$, $H^+ \to \tau\nu$ in $t\bar{t}$ events
- Set upper limits on $BR(t \to bH^+)$