Top physics and the top mass

Lecture 3/3

2013 CERN-Fermilab HCP Summer School

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(and this year also: LHC Physics Centre, Fermilab)

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Outline

- Wednesday:
  - Lecture 1: Intro to top physics and its jargon.
- Thursday:
  - Lecture 2: SM top physics and the top mass
- Friday:
  - Lecture 3: SM and top physics, the portal to physics searches
    - Measuring top properties
    - Searches for physics beyond the standard model using tops

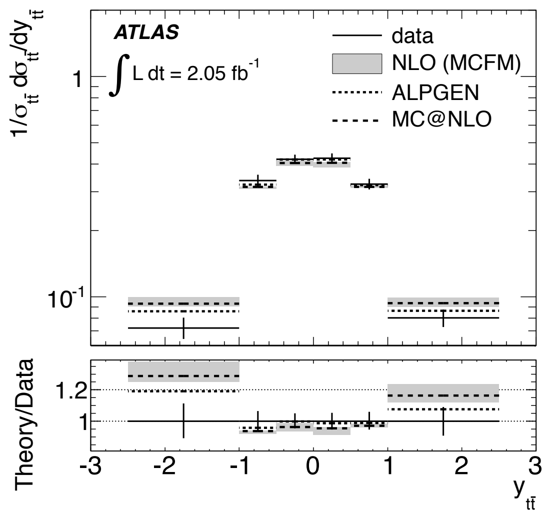
Top quark and new physics

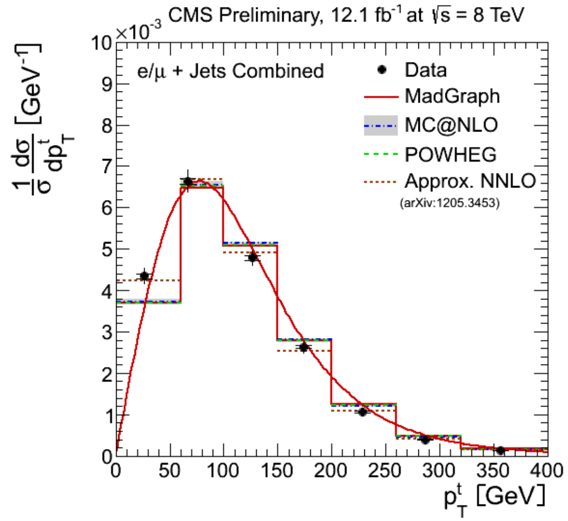
- Precise SM measurements
  - Heaviest known elementary particle (large Yukawa coupling)
    - Constraints on Higgs mass
    - Unique window on bare quarks due to short lifetime
  - Probe for QCD at scale >gauge bosons
- A window to new physics
  - New physics - many models couple preferentially to top
  - New particles may decay to top
  - Non-standard couplings
- In many new physics scenarios (e.g. SUSY) top is dominant BG
- Great tool to calibrate detector
  - Jet energy scale, b-jet efficiency

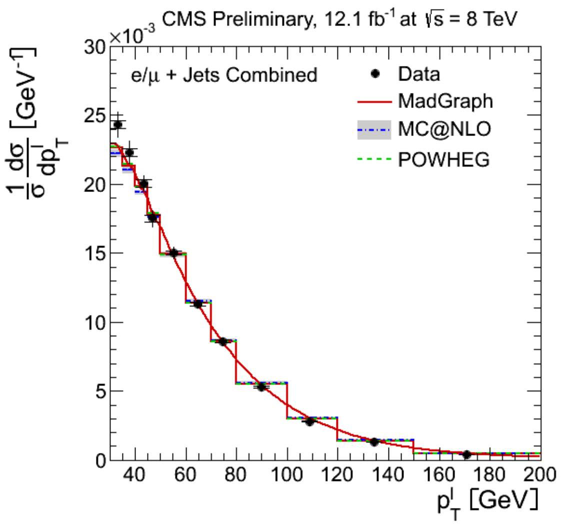
(
Top pair production rate
Top mass
Single top production rate
$B(t \to Wb)$
$|V_{tb}|$
W helicity
Top polarization
Anomalous couplings
Spin correlations
Rare decays
Top width
...
)

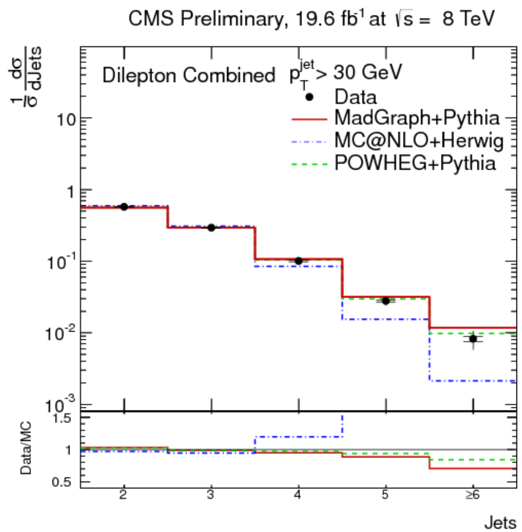
Properties of top pair production

- Very large LHC samples allow differential cross section measurements
- Most bins limited by systematic uncertainties
- Many differential kinematics examined
- Active interaction with generator and pdf community
- Improvement of models of great benefit to community for next LHC run – particularly for searches

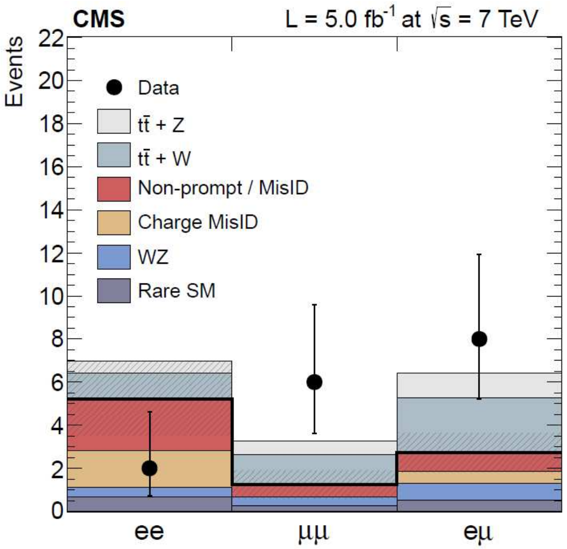


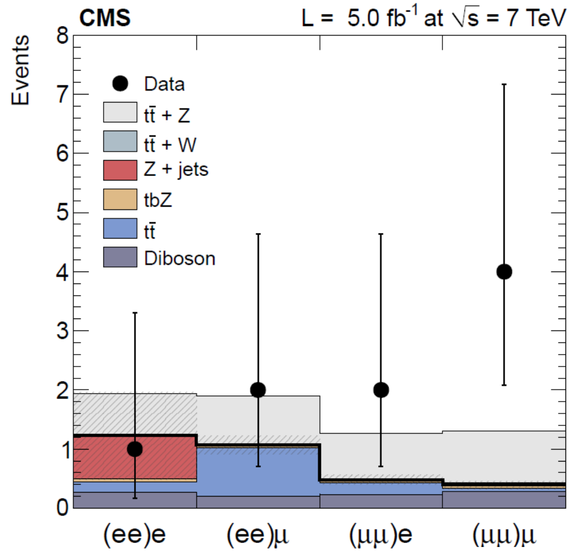


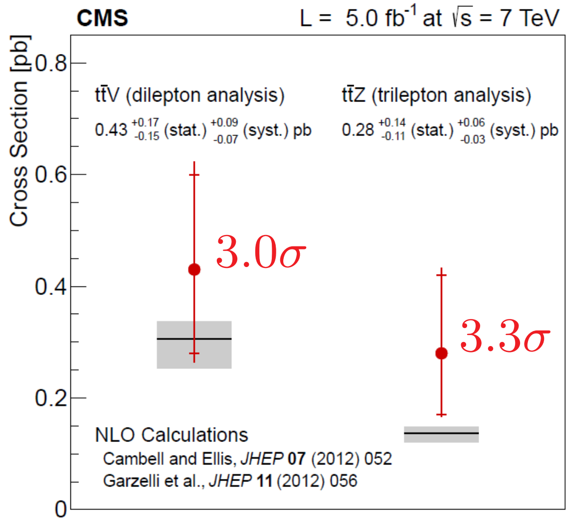


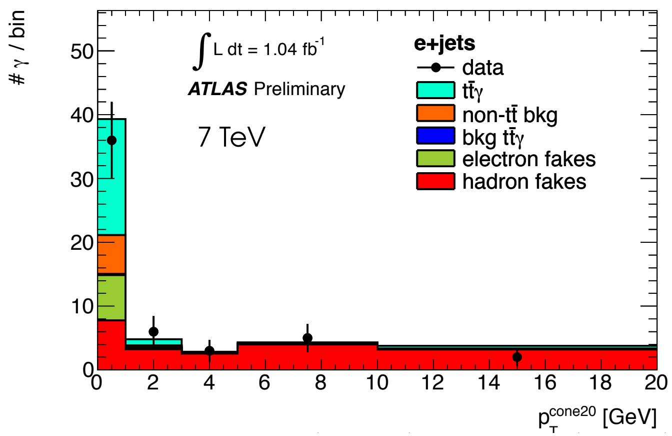


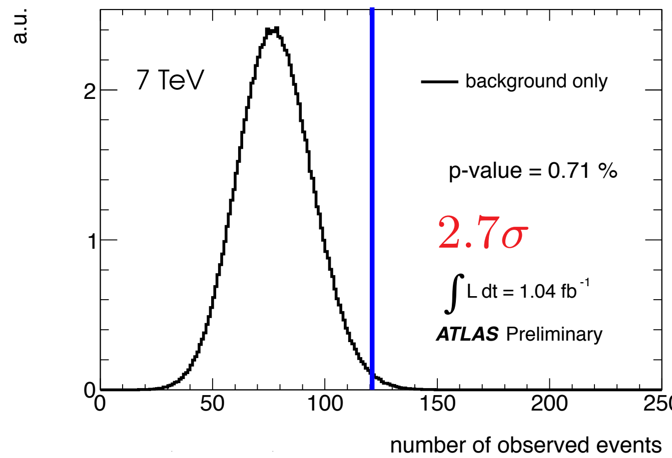
SM production of ttbar+Z/photon/W





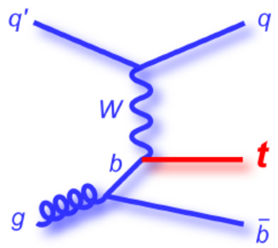




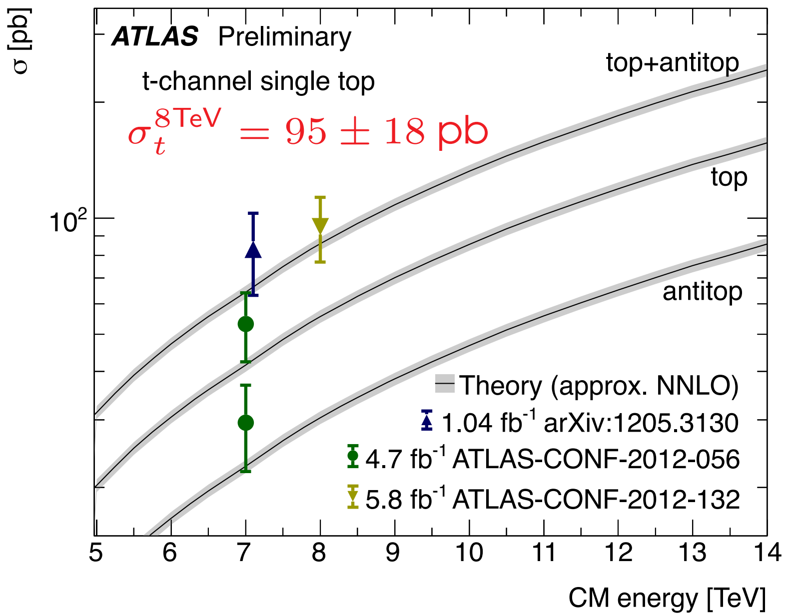


Single top production

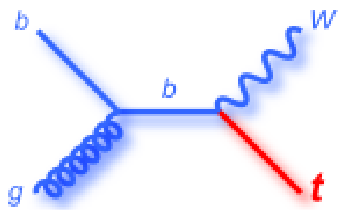
- Single top in t-channel



t-channel

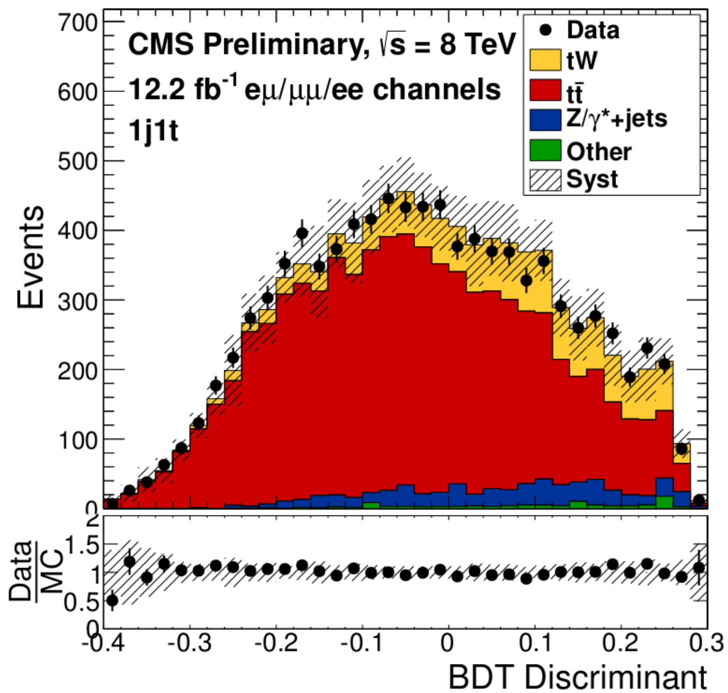


- Single top in tW-channel



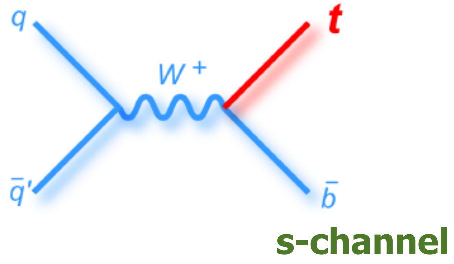
tW-channel

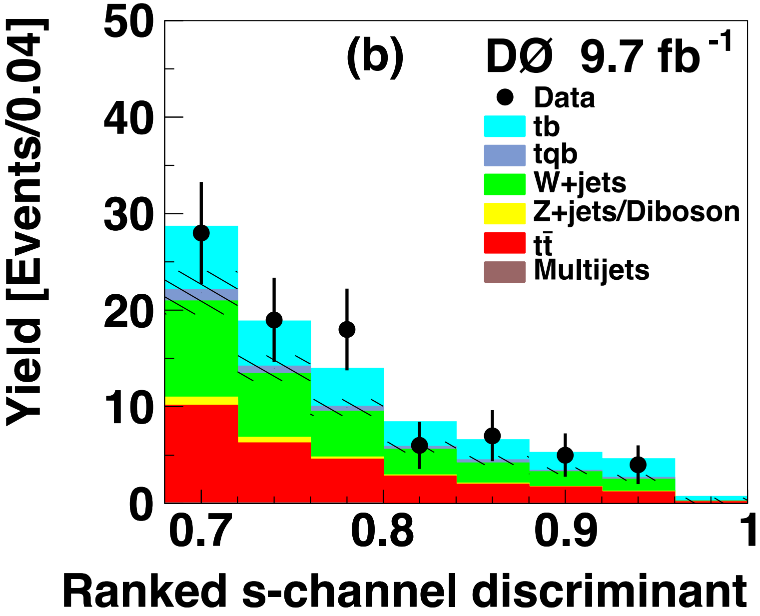
First observation
6.0 S.D. significance!
Cross section: 23.4±5.5 pb

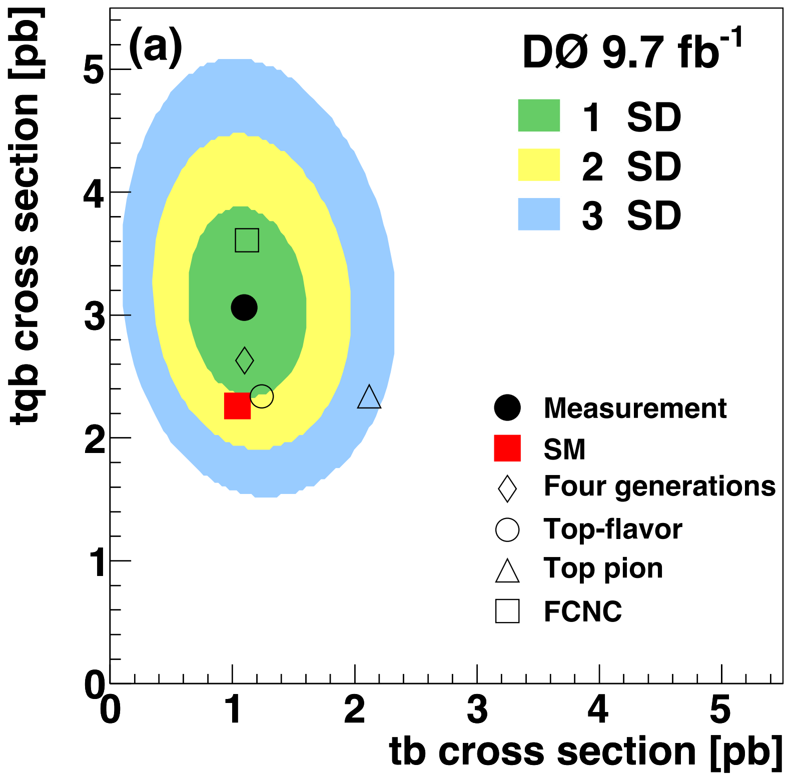


Single top in s-channel

- Tevatron legacy?
- Cross section: $1.10^{+0.33}_{-0.31}$ pb
- (A)NNLO: 1.06±0.04 pb
- Significance: 3.7 S.D.!!!





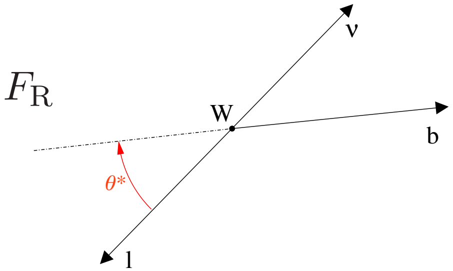


W helicity in top quark decay

- Helicity of W bosons very well-defined in standard model
- No hadronisation: coupling of top quark to W directly propagated to angular distributions of leptons in ttbar events

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R$$

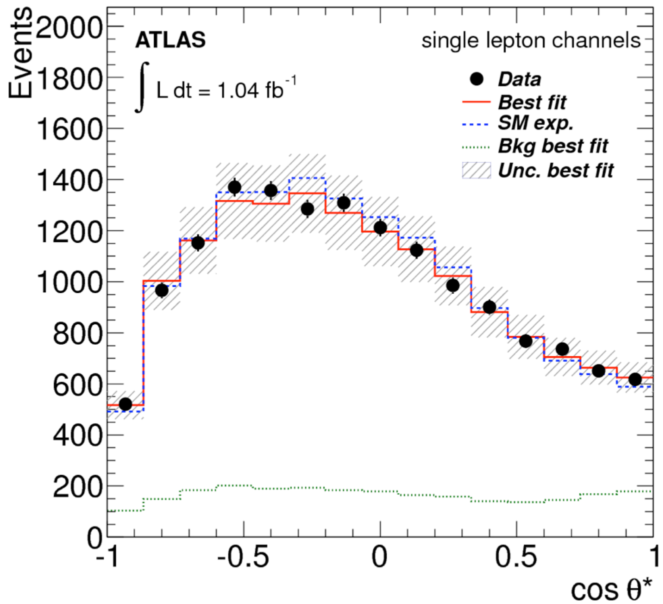
$$A_\pm = \frac{N(\cos\theta^* > z) - N(\cos\theta^* < z)}{N(\cos\theta^* > z) + N(\cos\theta^* < z)} \qquad z = \pm(1-2^{2/3})$$

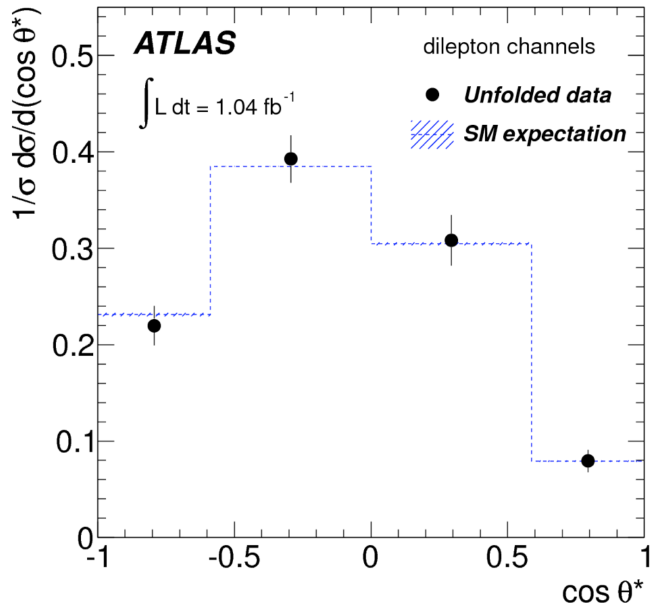


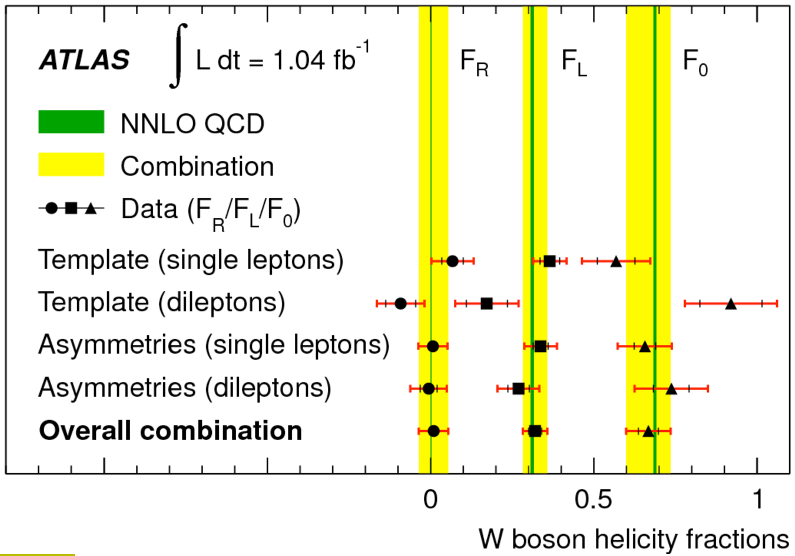
- Sensitive variable: Angle between down-type fermion in W rest frame and W momentum in top rest frame: cos(θ*)
- Measurements determine fractions of longitudinally, left, and right-handed W bosons

in SM (LO):
F_0=0.6902
F_L=0.3089
F_R=0.0009

Fitting the data

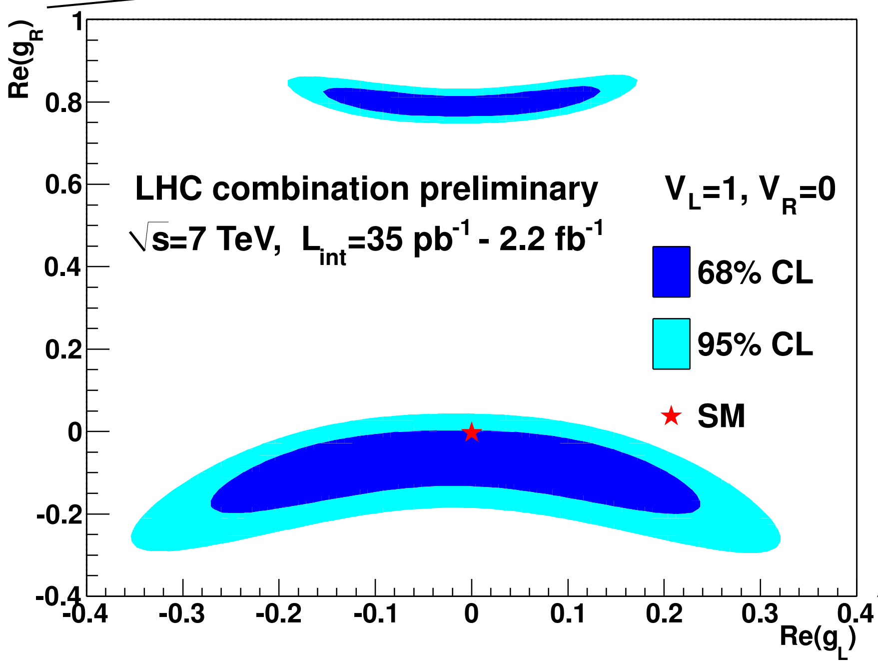






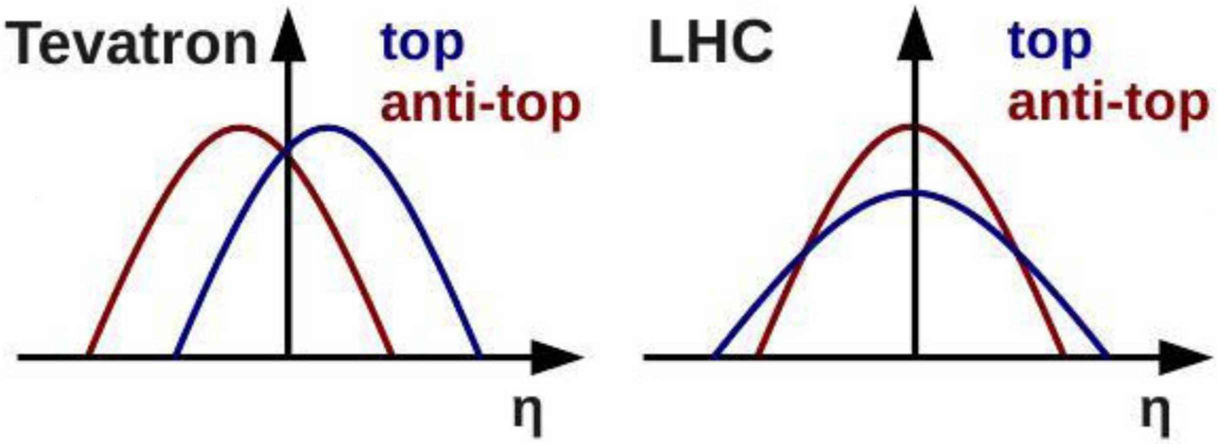
Interpret in effective lagrangean

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_{\rm L}P_{\rm L} + V_{\rm R}P_{\rm R}\right)t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\left(g_{\rm L}P_{\rm L} + g_{\rm R}P_{\rm R}\right)t\,W_{\mu}^{-} + \text{h.c.}$$



- Combination of ATLAS and equivalent CMS measurement used to constrain anomalous couplings at tWb vertex
- Very consistent with SM

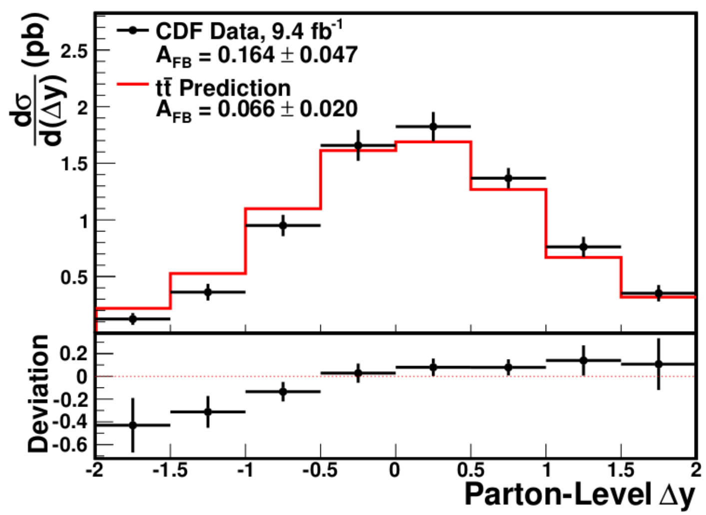
Top asymmetries: forward-backward



- New physics in production can alter angular distributions

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

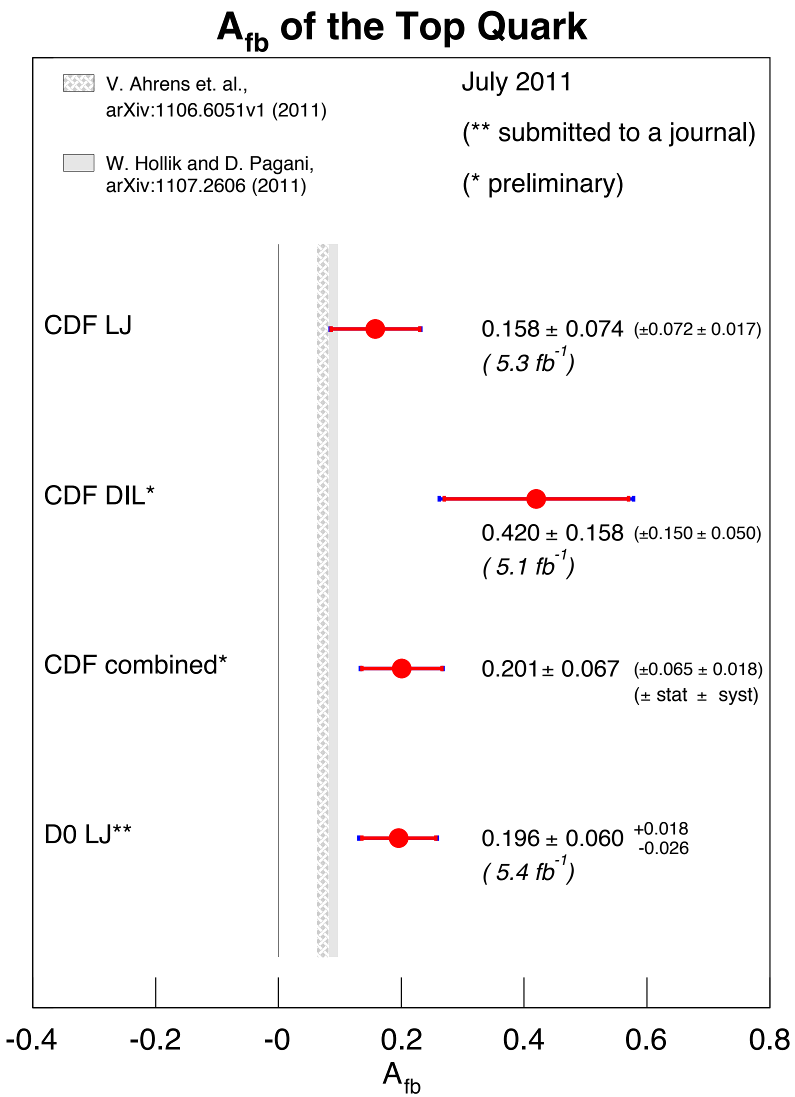
with $\Delta y = y_t - y_{\bar{t}}$

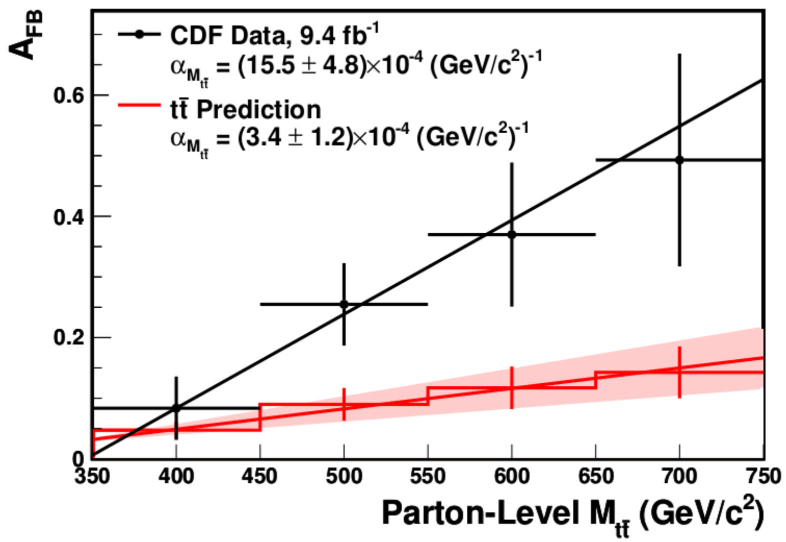


- At Tevatron:

  2.5 S.D. deviation from SM

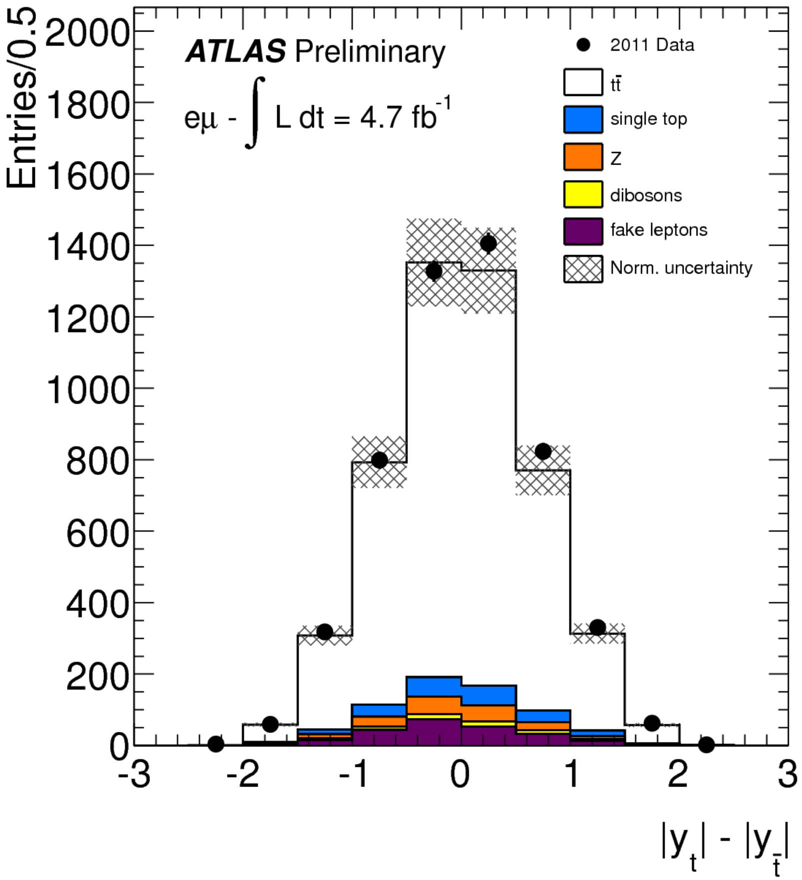
AFB details

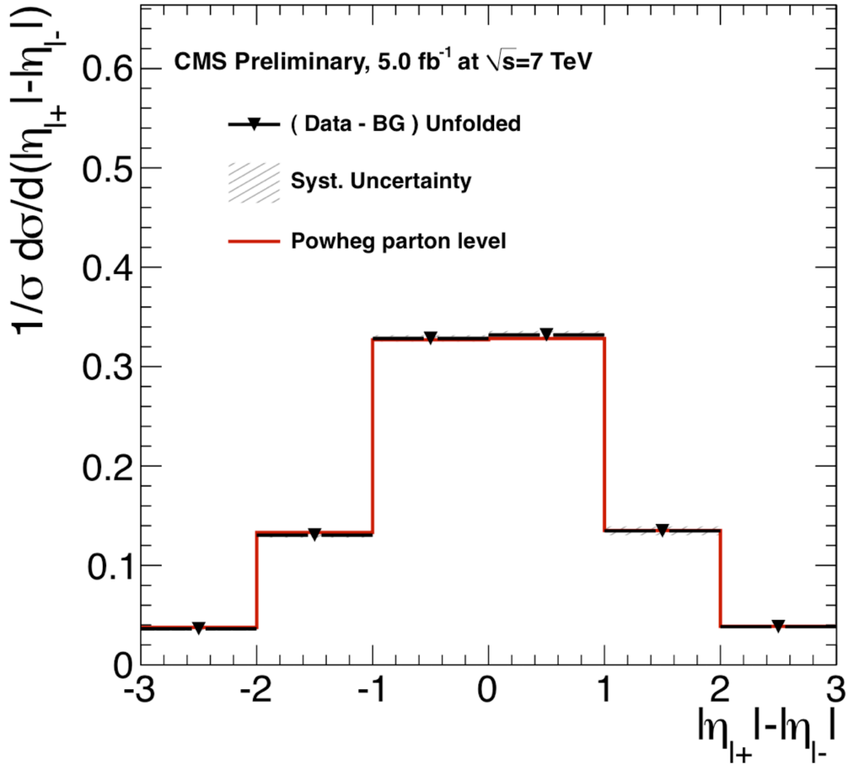




- AFB deviations largest at high m(ttbar)
- No effect at the LHC!!!

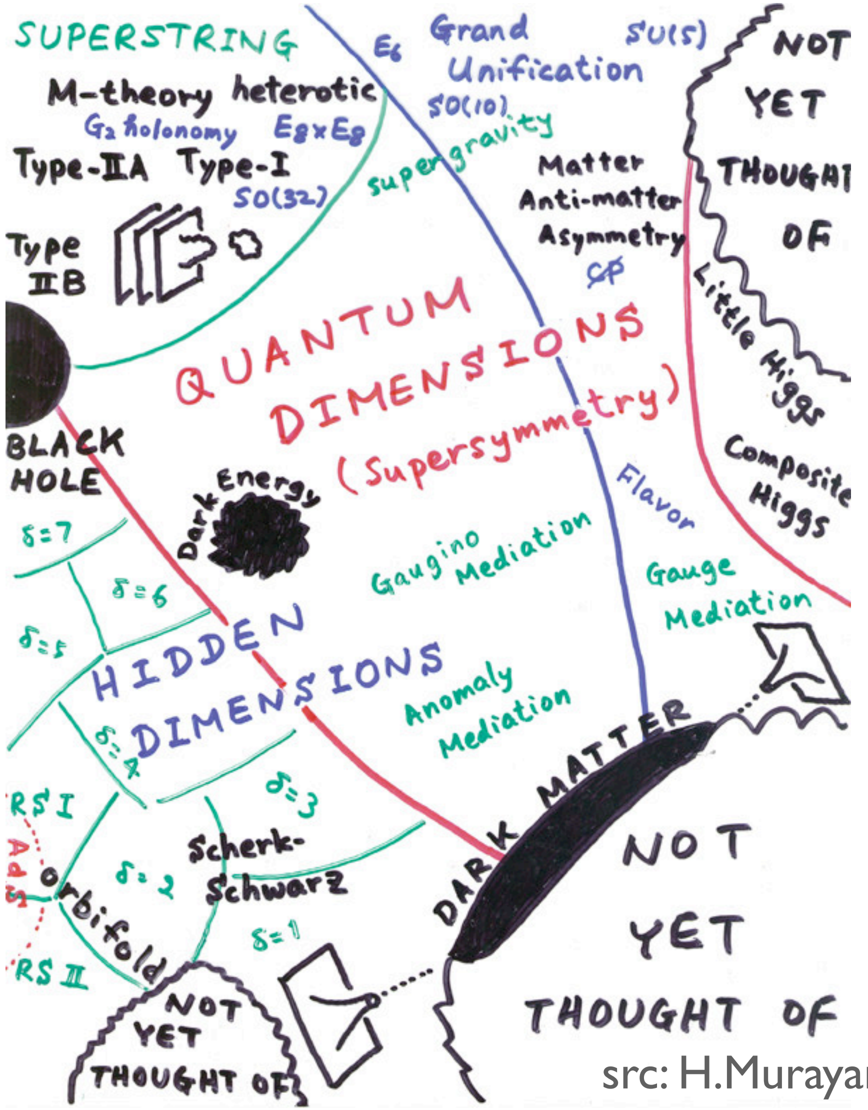
Asymmetry at the LHC?





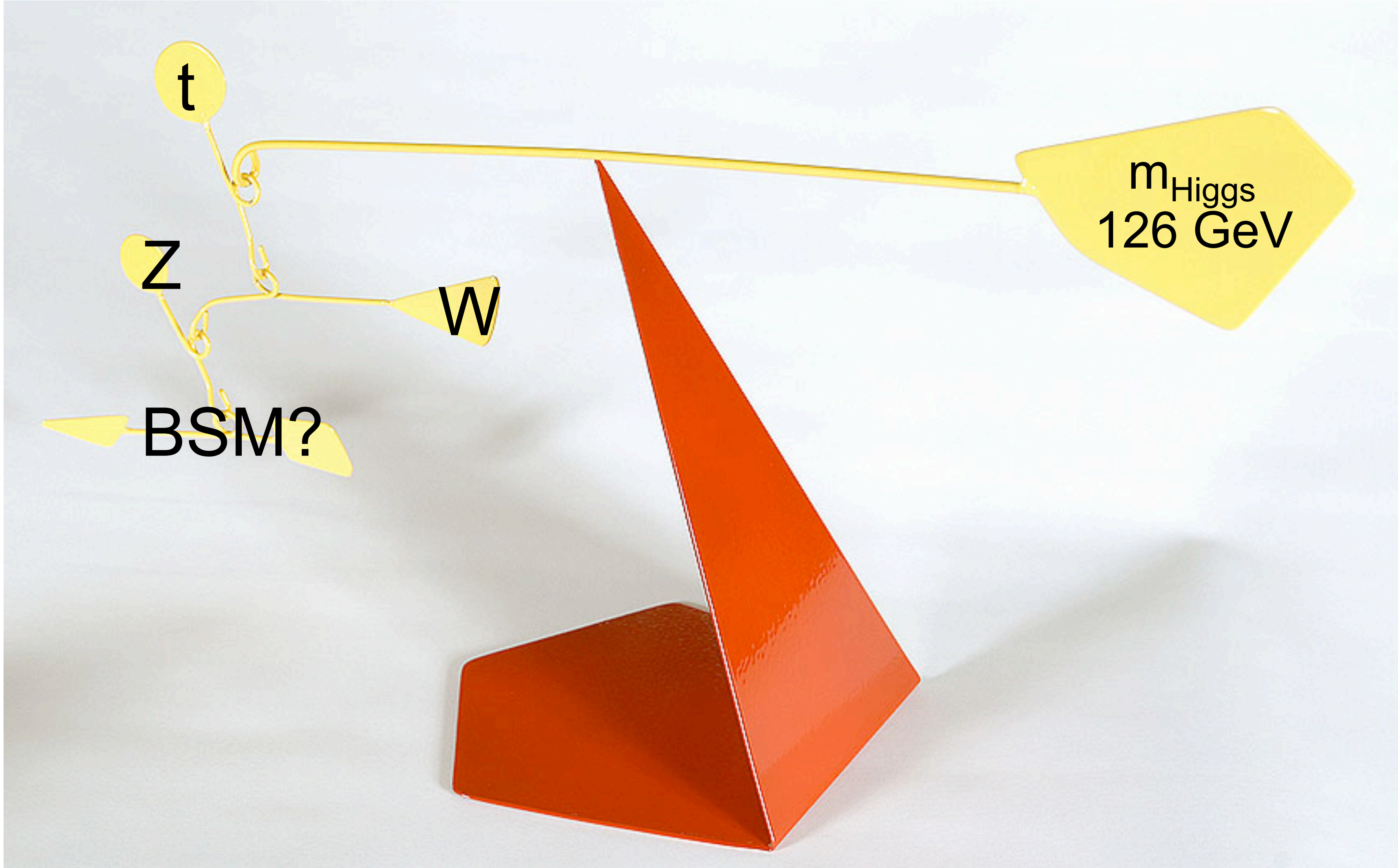
17 SM parameters do not constrain creativity

- SUSY in all it's variations
  - GMSB
  - MSSM, CMSSM etc
- New strong interactions?
  - Technicolor; excited quarks; compositeness; new "contact" interactions
- Exotica:
  - Weird stuff: leptoquarks?
  - New "forces"?
  - New resonances (W-Z-like)
  - More generations?
    - Fourth generation (b'/t')
  - Gravity descending at the TeV scale?
  - New resonances; missing stuff; black holes; SUSY-like signatures [Universal Extra dimensions]
- SUSY-inspired exotica:
  - Long-lived massive (new) particles?
- Some true inspirations: "hidden valleys"?



src: H.Murayama

Little Hierarchy problem, Naturalness



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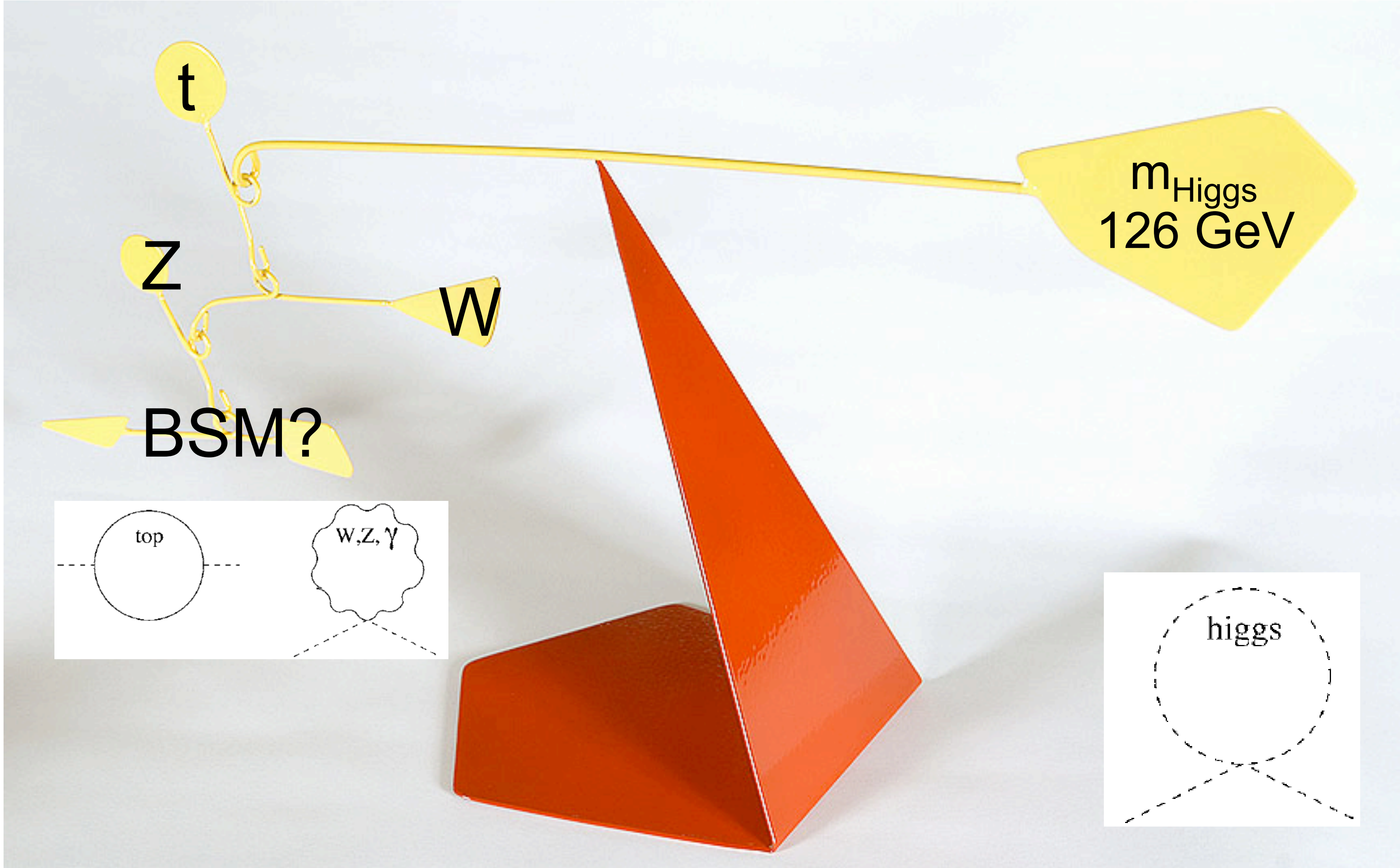

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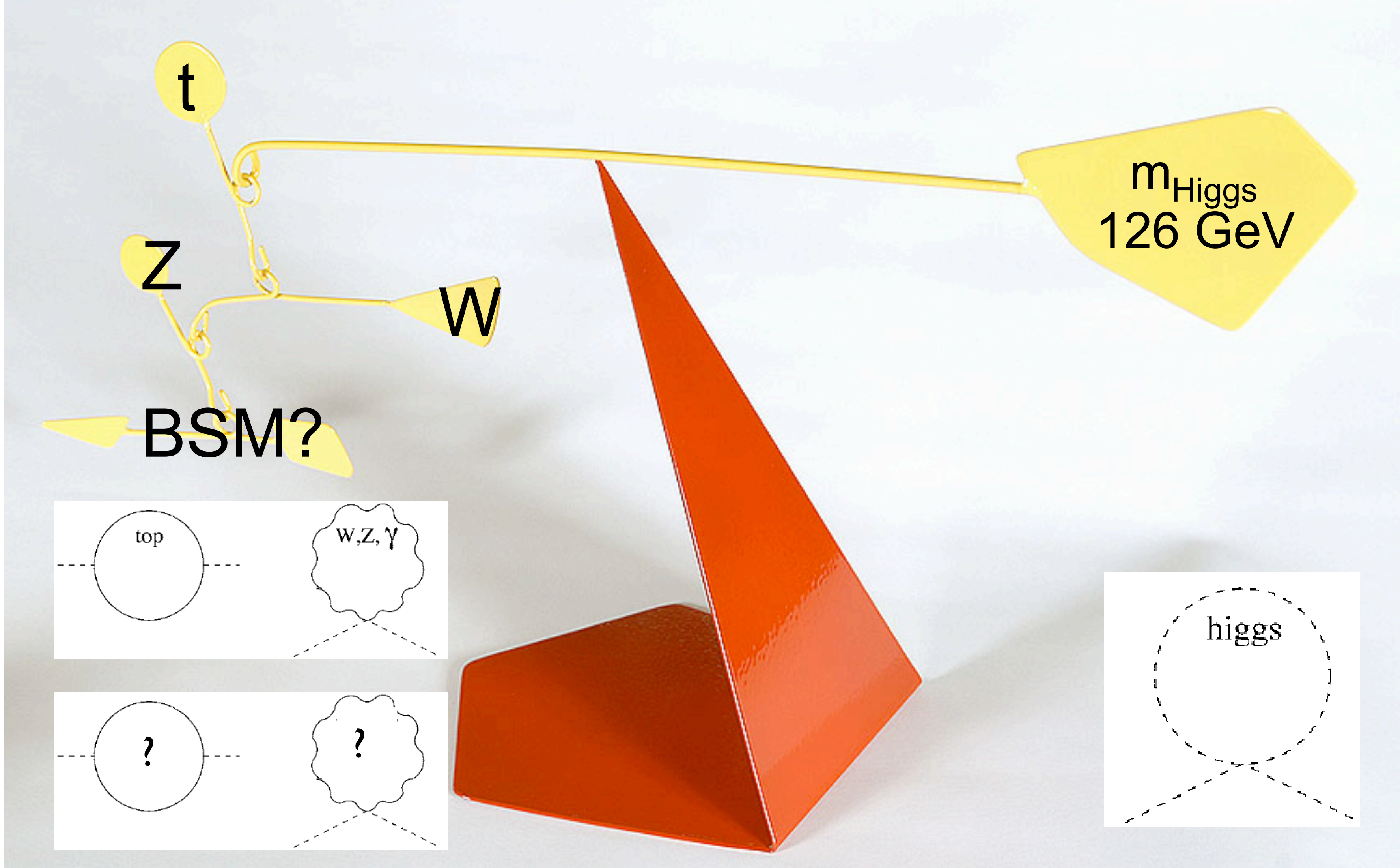

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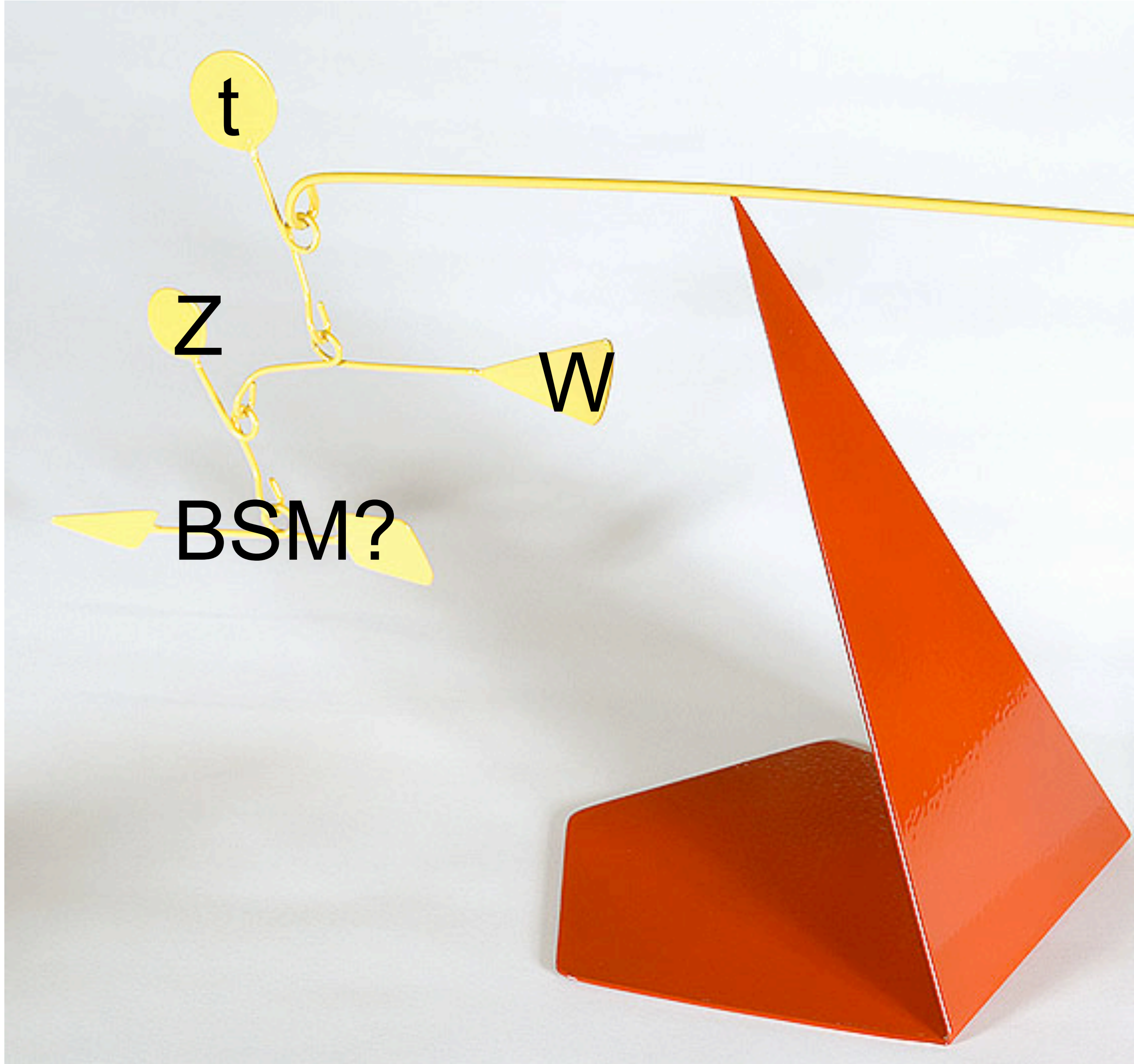
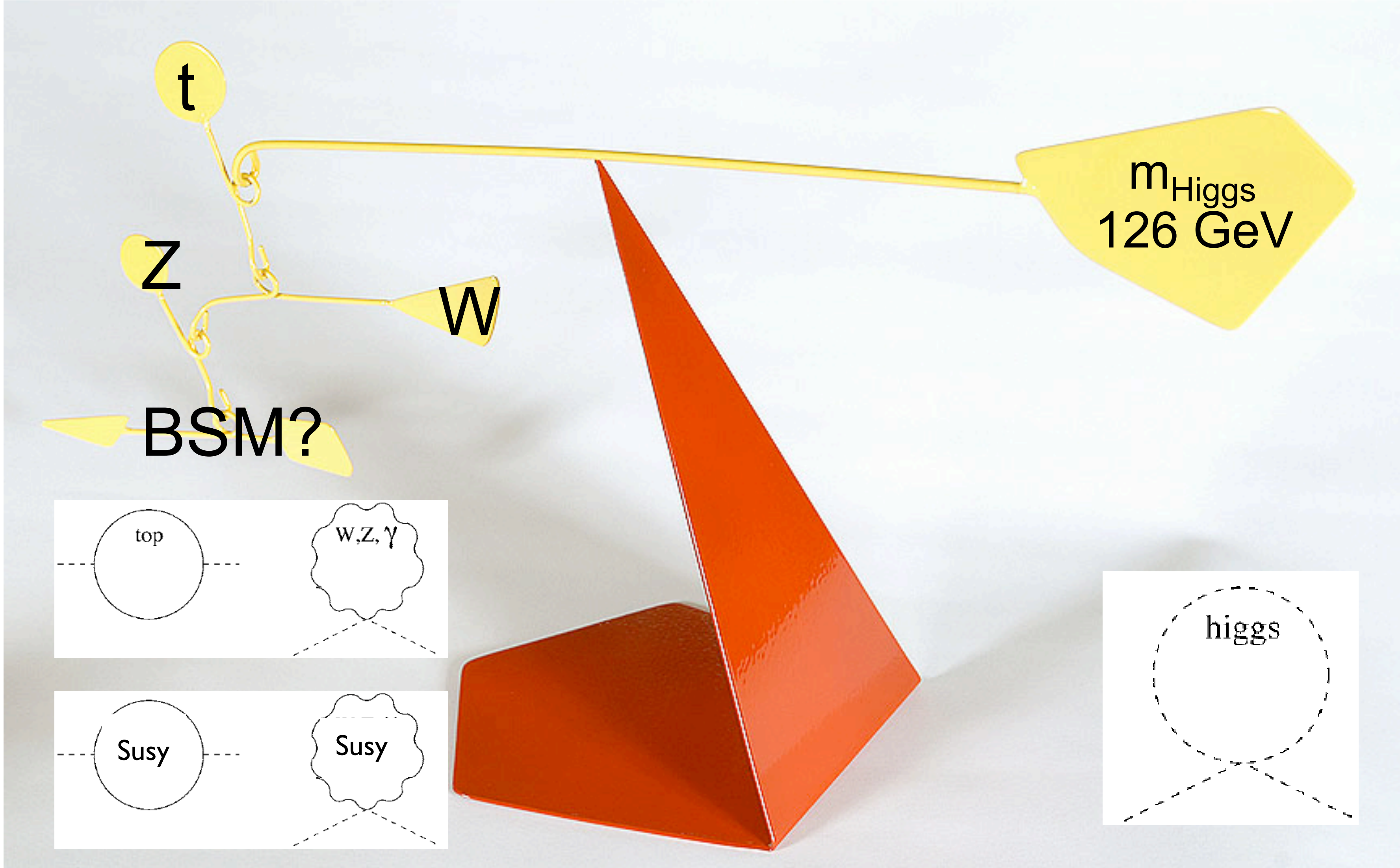


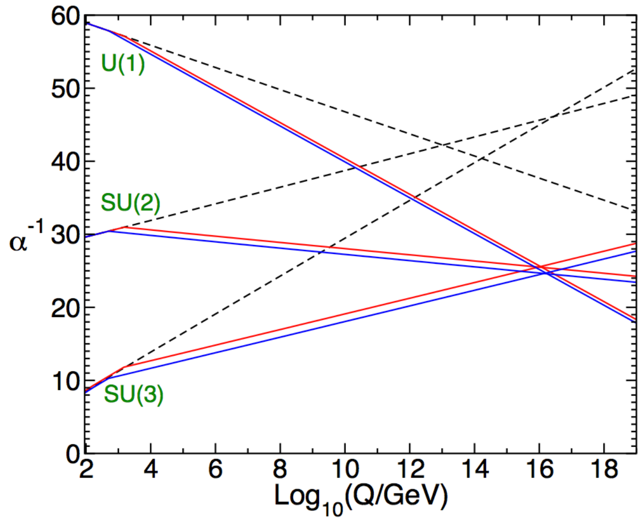
If fine tuning <=10%:
Restrictions:
Λ_{quarks} ~< 2 TeV
Λ_{gauge} ~< 5 TeV

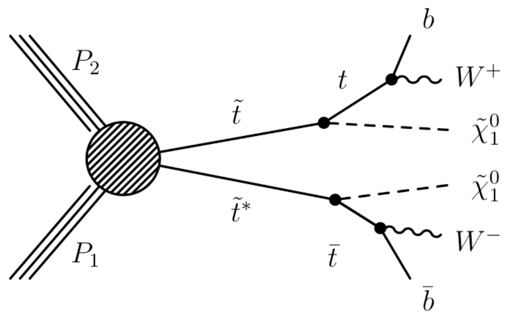
Little Hierarchy problem, Naturalness



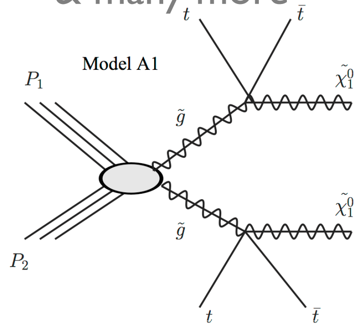
Supersymmetry - in top sector?

- Solves hierarchy problem, GUT convergence and can add CP violation
- Dark Matter candidates available
- Naturalness motivations can be interpreted to favor light stop
  - ttbar+MET, ttbar+X+MET signatures

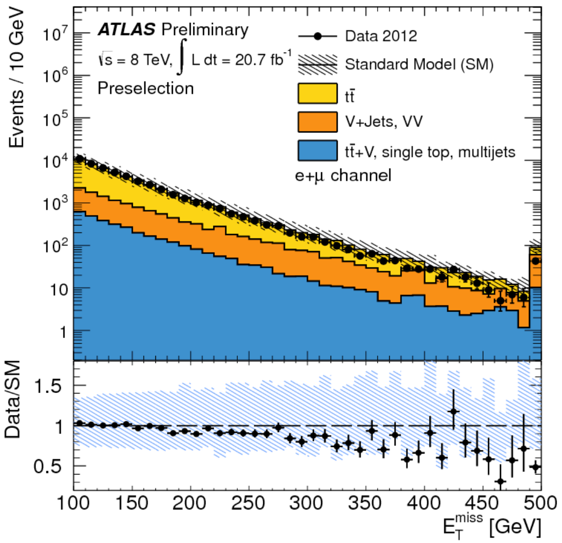


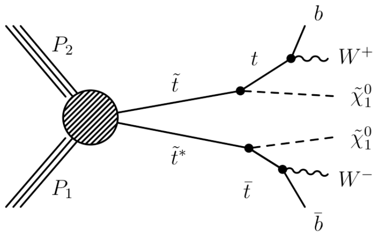


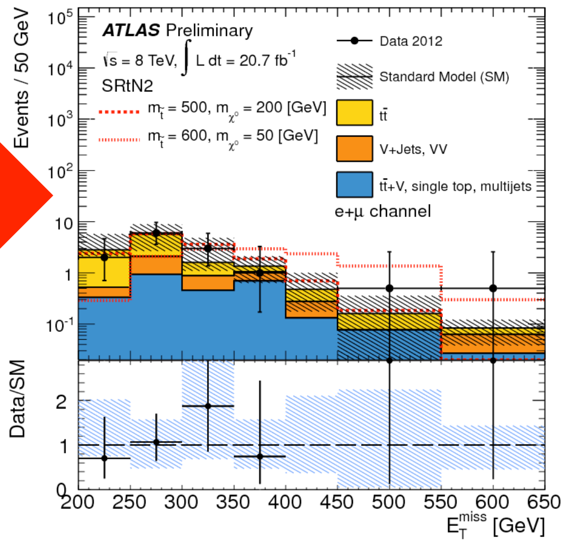
& many more



Example stop search in l+jets+MET







One signal region

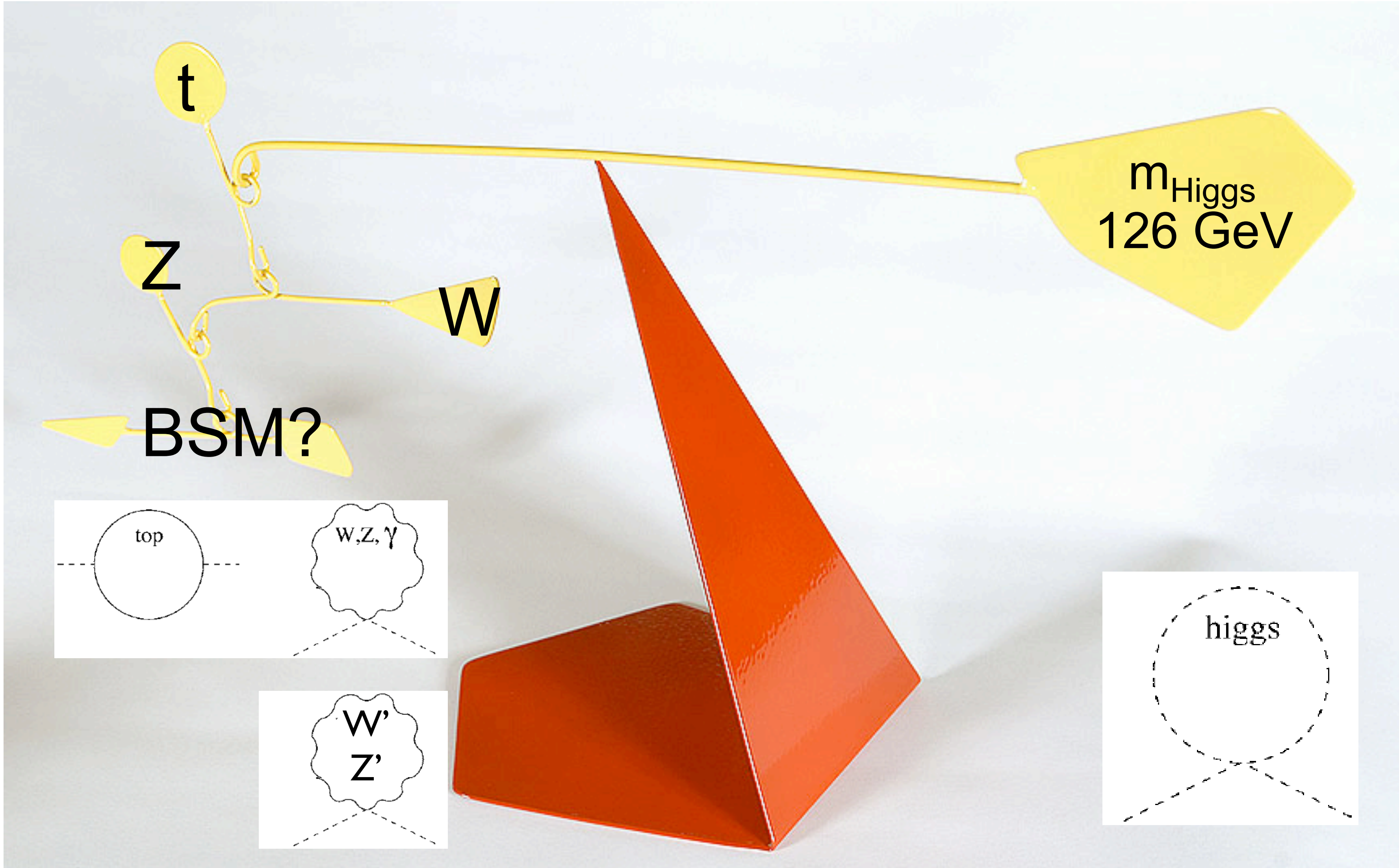
ATLAS-CONF-2013-037

requires detailed understanding of top quark pair production at high missing ET

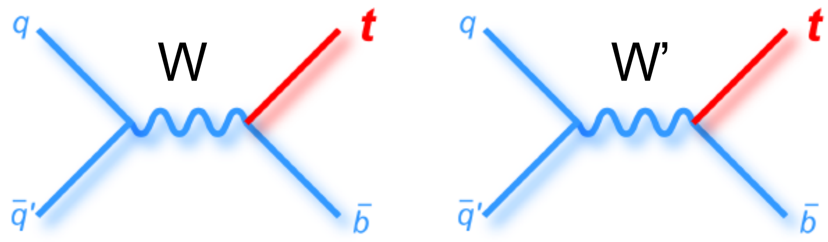
- Analysis works in many signal regions, looking in boxes constrained by number of b-tags, transverse mass, MET, etc
- Sensitivity for stop depends on scenario considered, each region has strengths/ weaknesses
- Strong limits on stop mass

• Can exclude direct stop production with masses lower than 600 GeV (with some caveats on neutralino mass, etc)

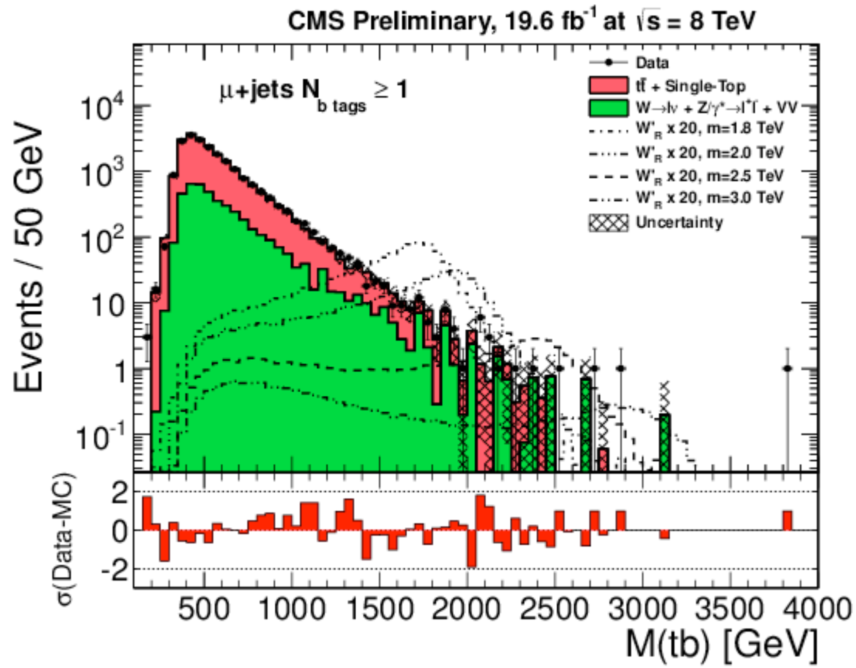
Little Hierarchy problem, Naturalness



W' to tb



- analogue to single top s-channel production
- Leptonic top decay:
  - Final state of lepton+MET+2 b jets
- Mass reconstruction also used in SM top physics, using W boson mass to constrain MET
  - With additional top mass constraint

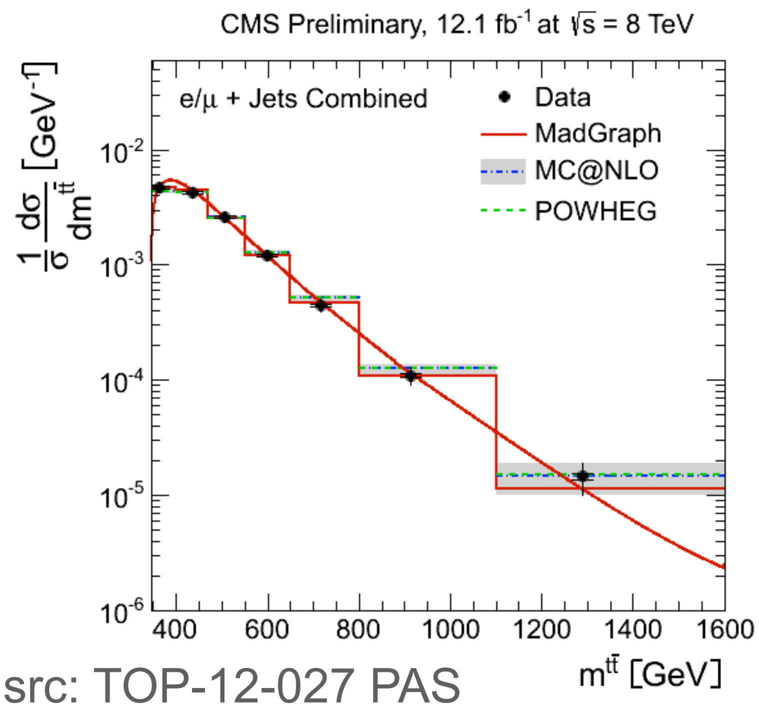


- Interpret in left and right handed W' scenarios

src: B2G-12-010 PAS

Investigating ttbar invariant mass distribution

- Differential cross sections now available for 8 TeV sub-set
- Searches in tails of distributions ongoing for 8 TeV full sample



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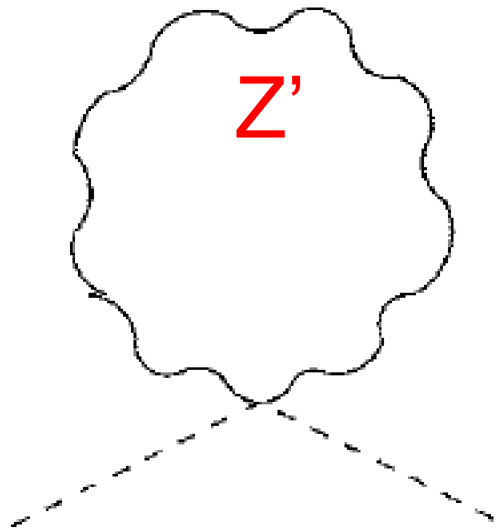
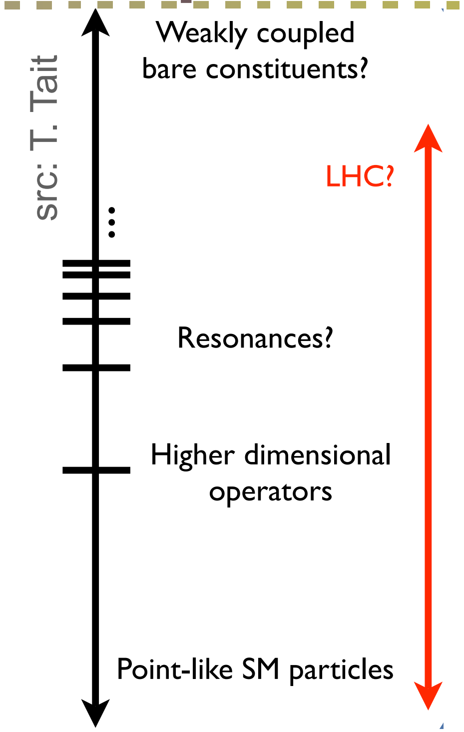
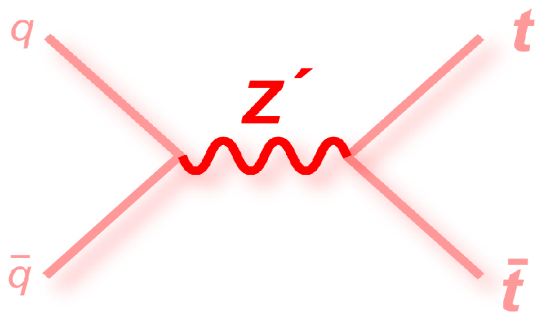


- Z' scenarios interwoven with natural EXO solutions and A_{FB}-explaining models
- M_{ttbar} distribution sensitive to many new physics scenarios

Top resonaces physics motivation

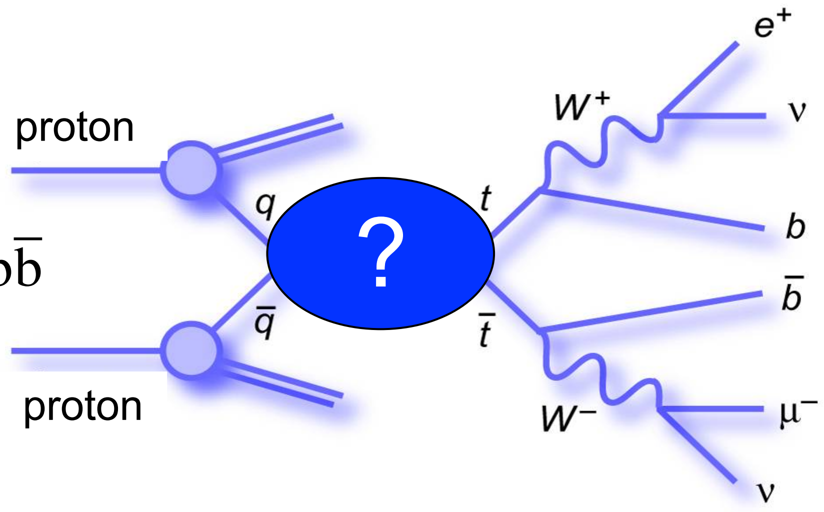




- Many new physics models predict extra exchange of massive particles in top quark production
  - Would be observed in a peaked or general excess/dip in the top-antitop invariant mass spectrum
  - Substantial number of theoretical models
  - Z', colorons, axigluons, Randall-Sundrum/ADD gravitons, Pseudo-scalar Higgs to ttbar
    - And many more
- Searches presented can be interpreted in any of these
  - For general comparison,"Topcolor-assisted technicolor" model: hep-ph/991.1288: Hill, Parke, Harris

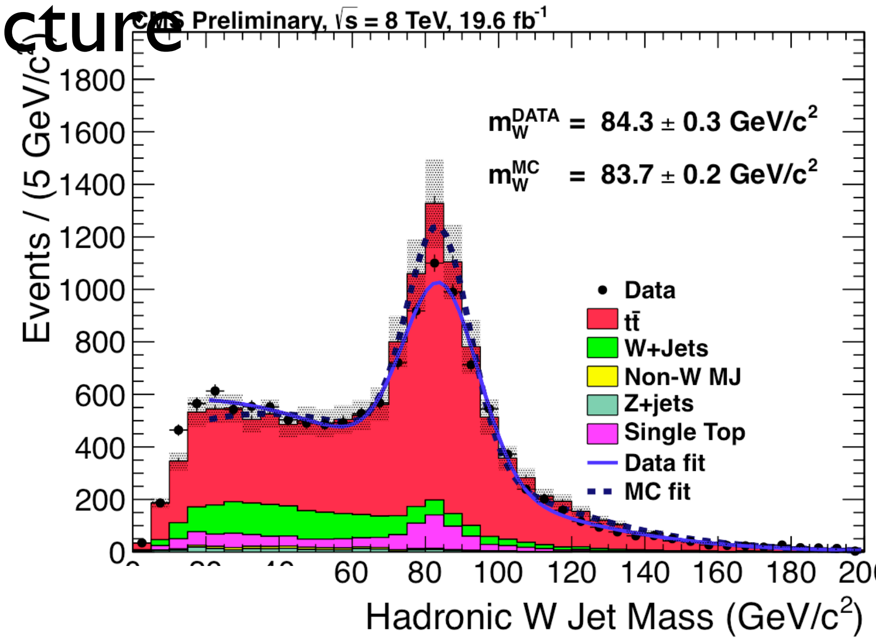
analysis strategy

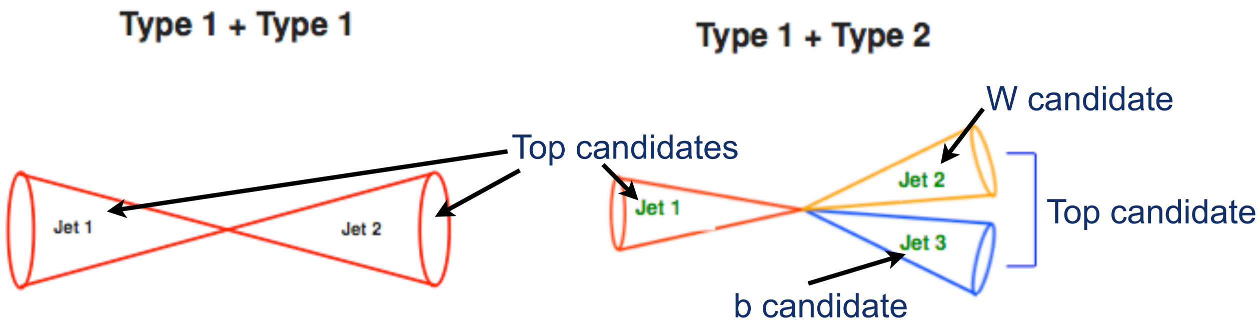
- Searches in all available top decay channels
  - Dileptons $t\bar{t} \rightarrow \ell^{-}\ell^{+}\nu\bar{\nu}b\bar{b}$
  - Semileptonic ≡ lepton+jets $t\bar{t} \rightarrow \ell\nu q\bar{q}b\bar{b}$
  - Hadronic ≡ alljets $t\bar{t} \rightarrow q\bar{q}q\bar{q}b\bar{b}$
- And in different regimes
  - Close to 2x(top mass) threshold
    - Sensitive to shape of SM M(ttbar) distribution
    - Conventional top physics techniques may be used
  - More boosted
    - Sensitive to more massive M(ttbar) BSM physics
    - Dedicated reconstruction techniques may be necessary



All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - 'top jets'
  - 'W boson jets'

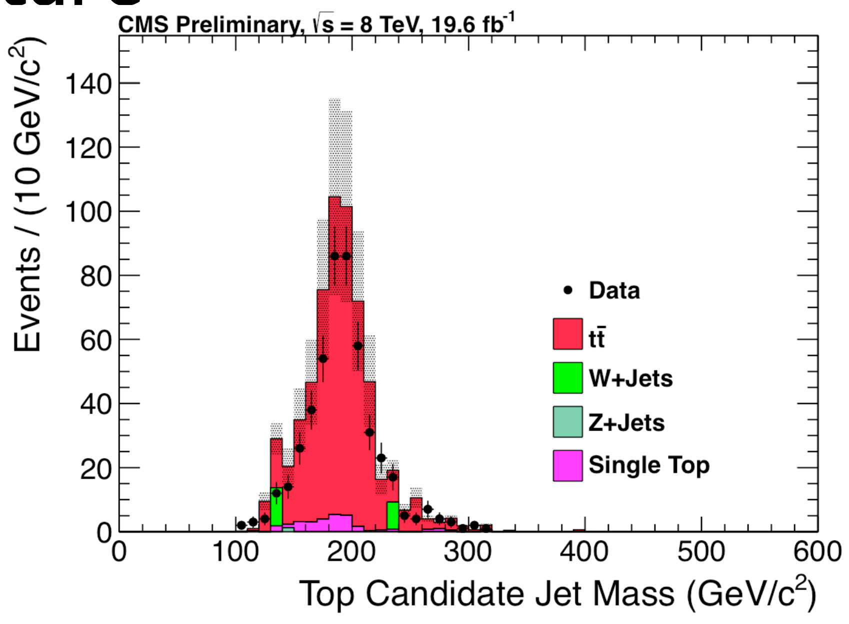


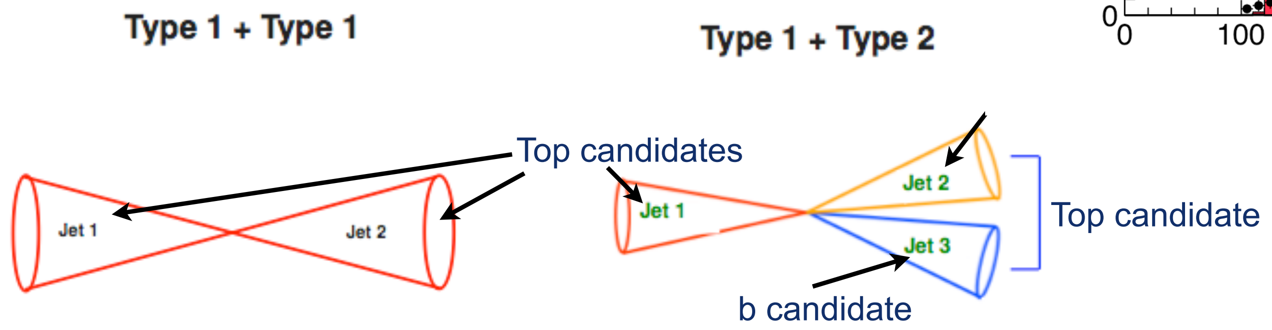


src: CMS-B2G-12-005

All hadronic, boosted, 8 TeV

- Using boosted objects and jet pruning to identify substructure
  - Full merged topology
- Cambridge-Aachen jets
  - 'top jets'
  - 'W boson jets'





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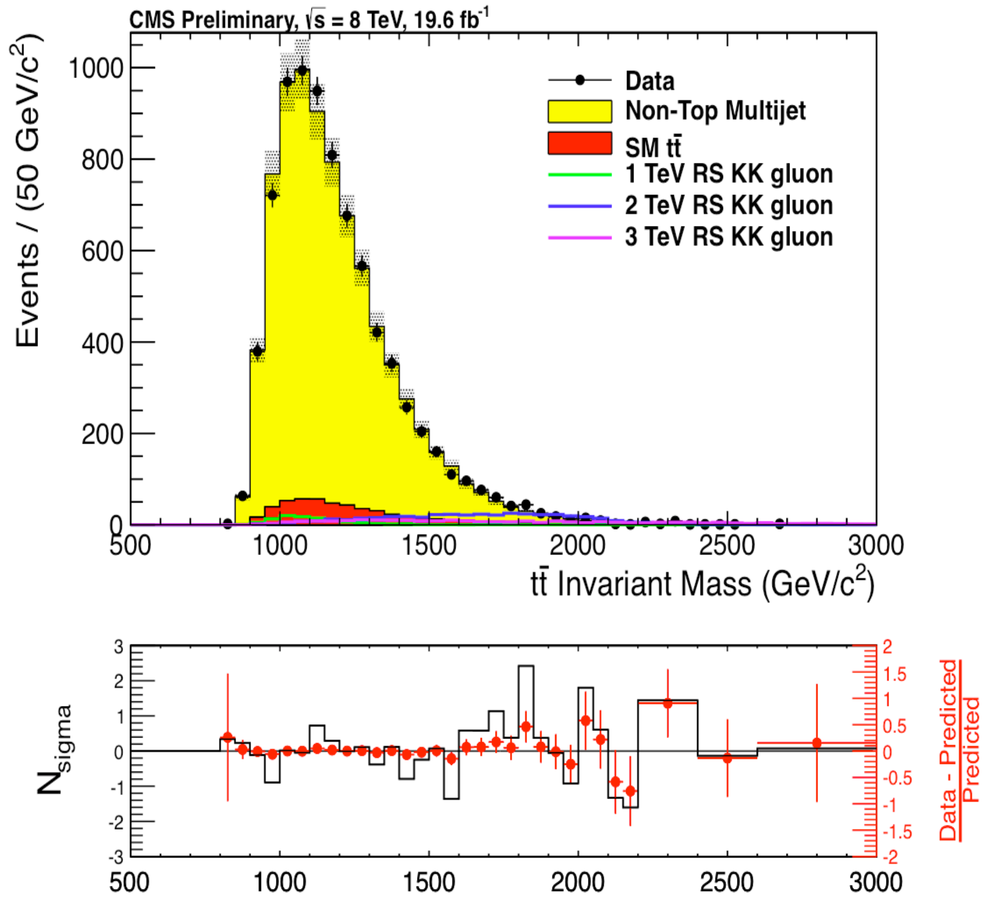
All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits



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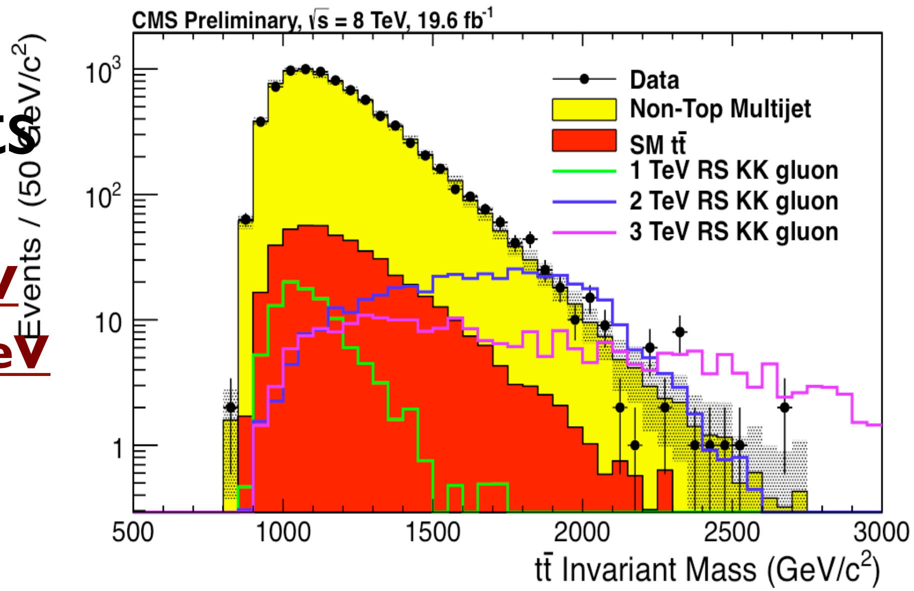
All hadronic, boosted, 8 TeV

- LLH fit to bumps in mass spectrum used to set limits
  - Narrow (1.2%) Z' limit: **M(Z') > 1.7 TeV**
  - Wide (10%) Z' limit: **M(Z') > 2.35 TeV**
  - RS Kaluza-Klein gravitons: **M(KKG) > 1.8 TeV**



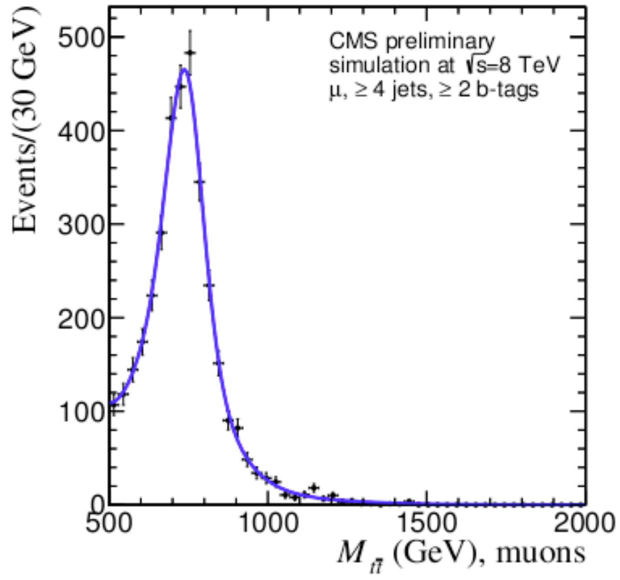
- 95% CL upper limits on increased cross section at high mass:

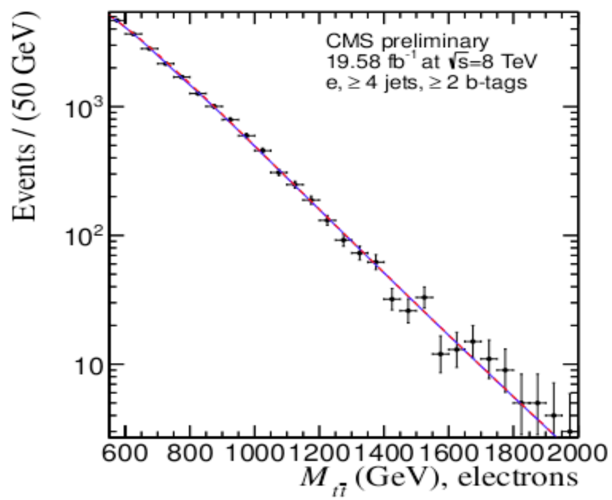
  $\sigma_{NP+SM} < 1.79\ \sigma_{SM}$ for masses above 1 TeV

src: CMS-B2G-12-005

Semileptonic, threshold

- Require only one lepton, >= 4 jets and split in b-tag multiplicity
- χ^2 sorting used to select best jet combination
- Using data-driven estimates for falling distribution of top pair mass spectrum above 500 GeV/c^2
- Systematic uncertainties take into account rate and shape changes for signal and background model

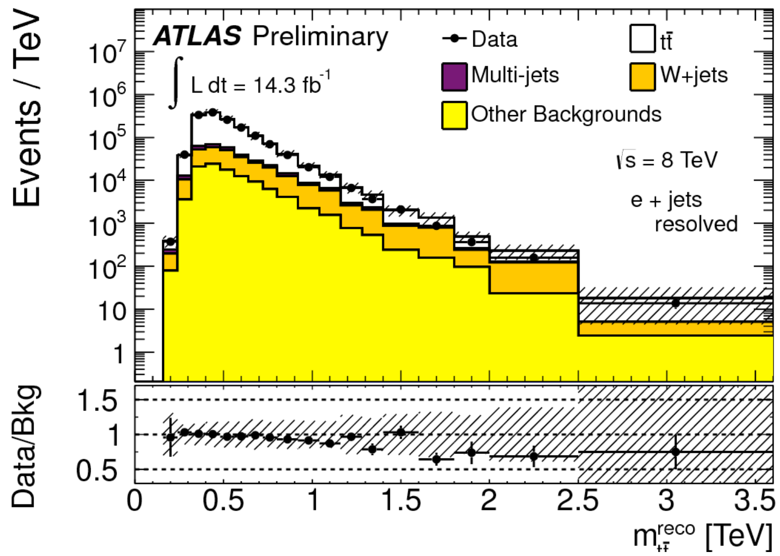


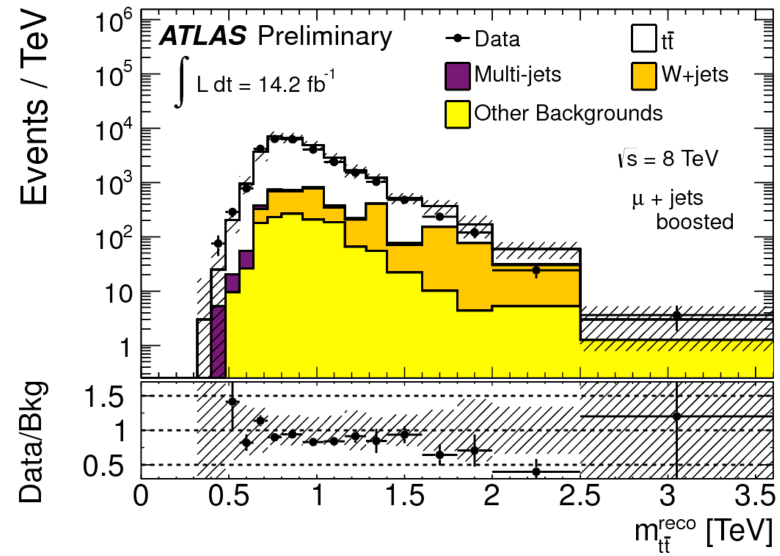


src: CMS PAS B2G-12-006

Semileptonic, boosted

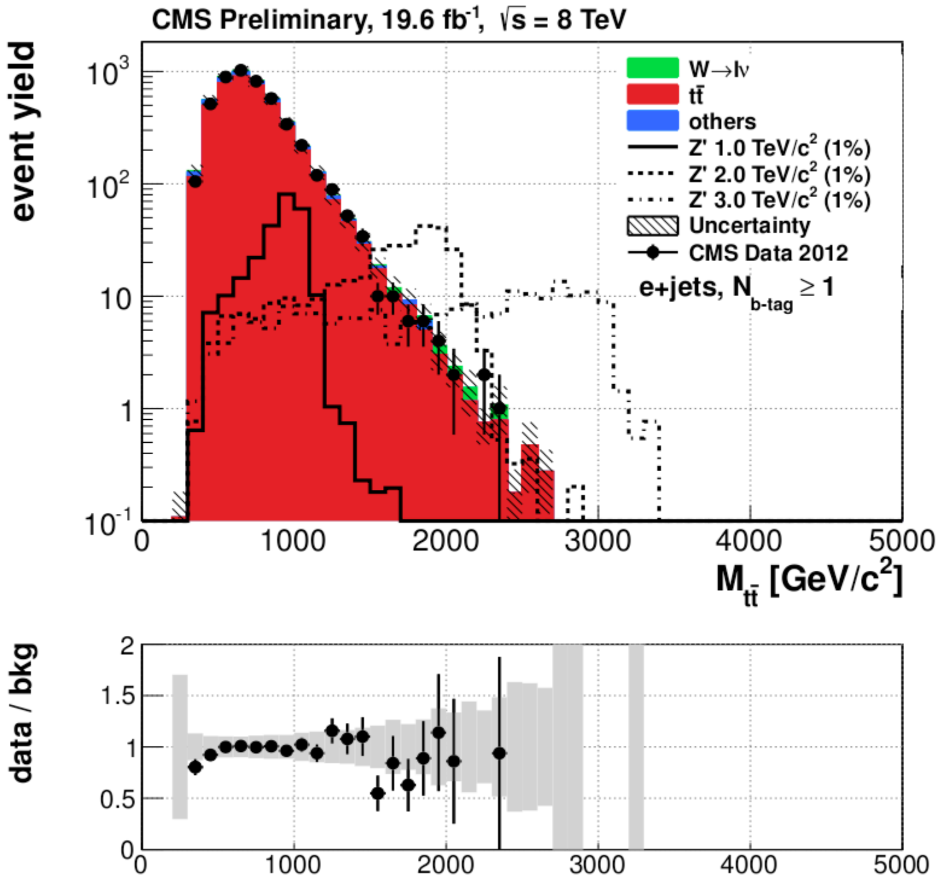
- Resolved topologies
  - use standard lepton+jets selection (lepton, MET, 4 jets, b-tag)
  - with χ^2 sorting
  - and constraints from top and W boson mass (including pT balance of tops)
- Boosted topologies
  - uses wide jet (r=1) as top candidate
    - With selection on substructure to optimise for top quarks
  - other side 'normal' ak5 jet, lepton, missing ET





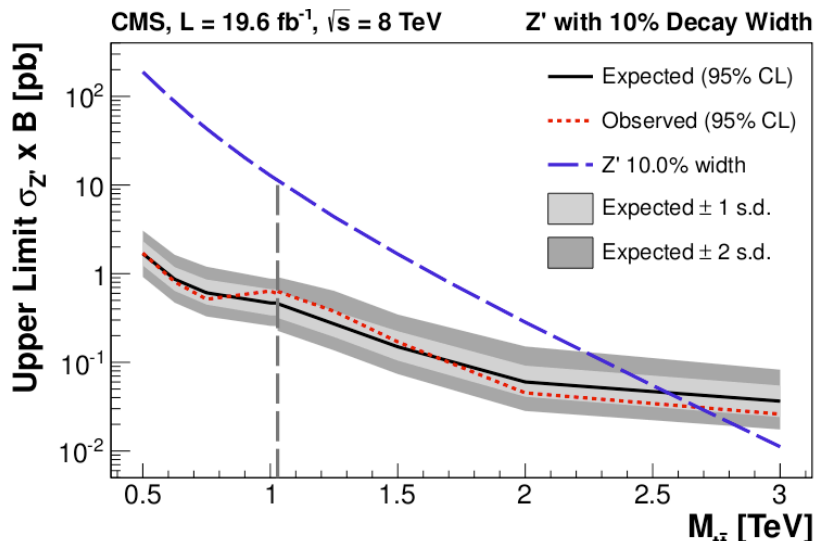
src: ATLAS-CONF-2013-052

Semileptonic, non-isolated



- Multiple scenarios considered
  - Worlds best limit on production of resonant ttbar:
    - Z' (width 1.2%): m > 2.10 TeV
    - Z' (width 10%): m > 2.68 TeV
    - KK gluons: m > 2.69 TeV
    - Resonances in low-mass region:

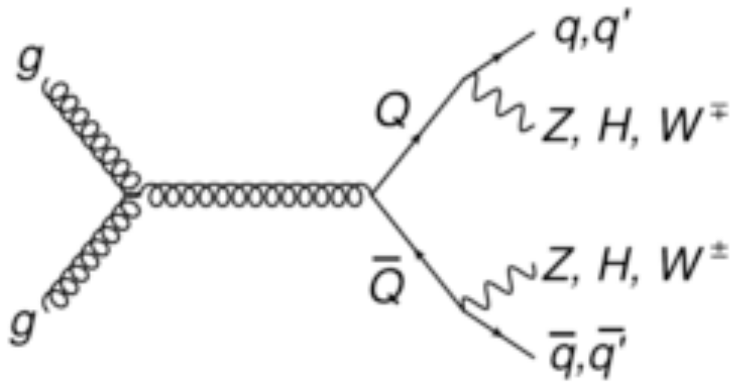
      excluded with xsec > 1-2 pb!!



src: CMS PAS B2G-12-006

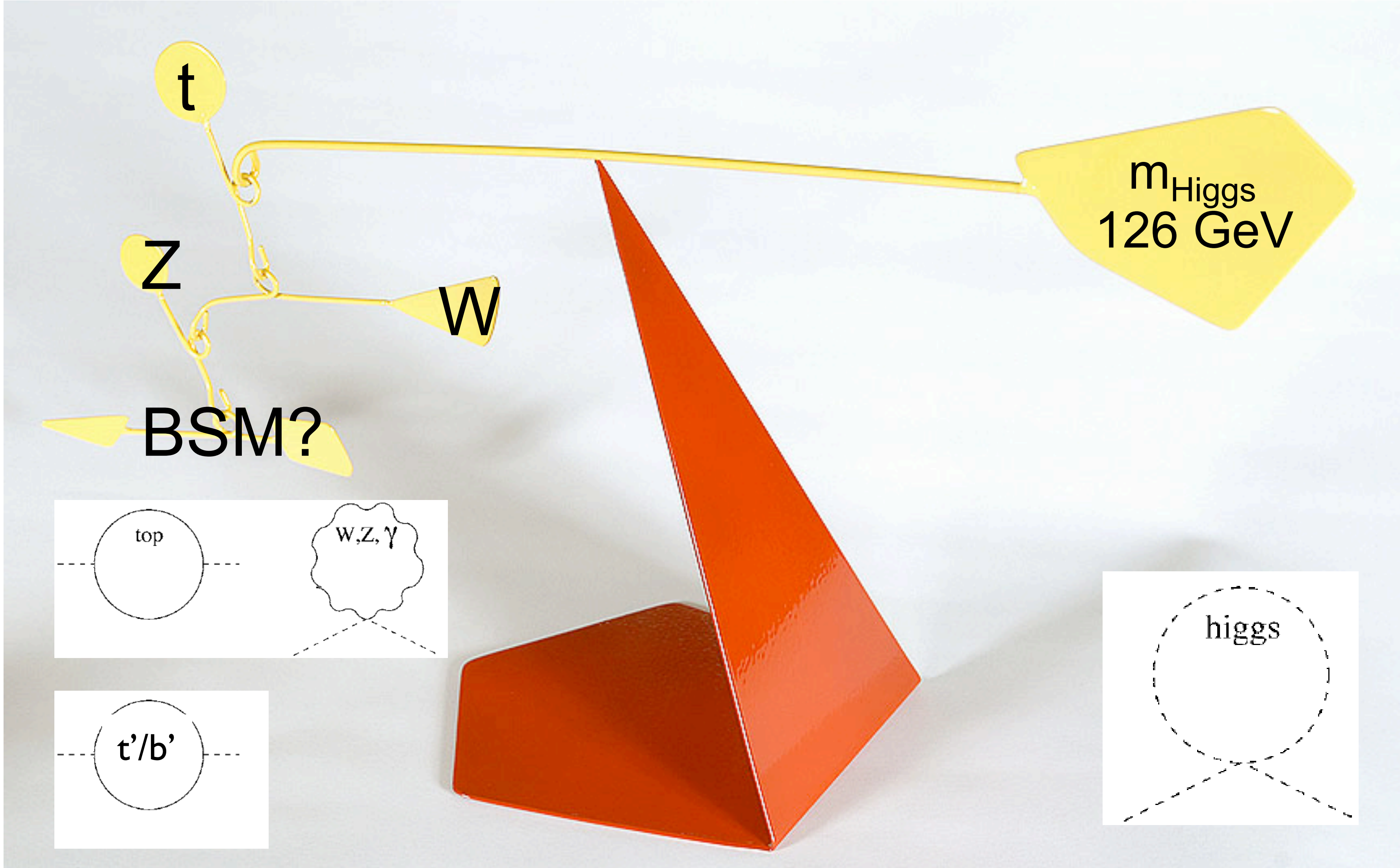
Vector like quarks intro

- Non- SM fourth generation
  - Can enhance CP violation
  - Heavy neutrino as DM candidate
- Vector-like fermions (non-chiral fermions):
  - Typical: exotic 4th generation top/bottom partner
    - 2HDM models
    - Little Higgs models
    - Warped extra dimensions
  - Not excluded by Higgs mass constraints/branching ratios
- Models benchmark for new physics decaying top-like:
  - Extremely rich phenomenology with final states with multiple gauge bosons, b and t quarks:



  - Current searches mostly pair production

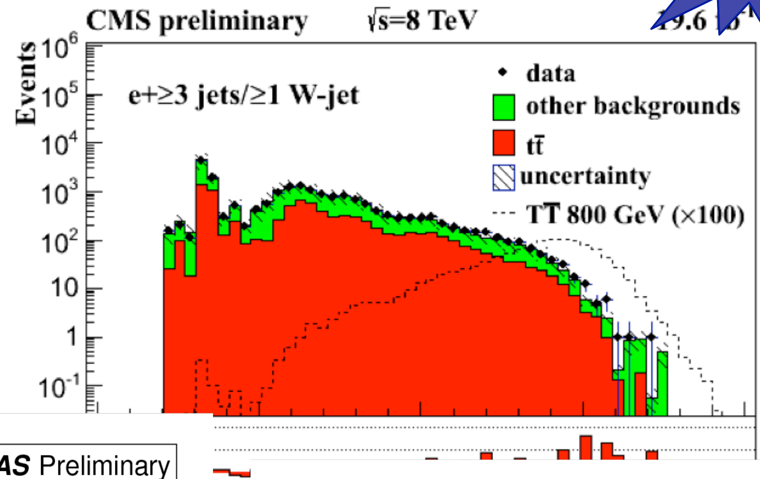
Little Hierarchy problem, Naturalness

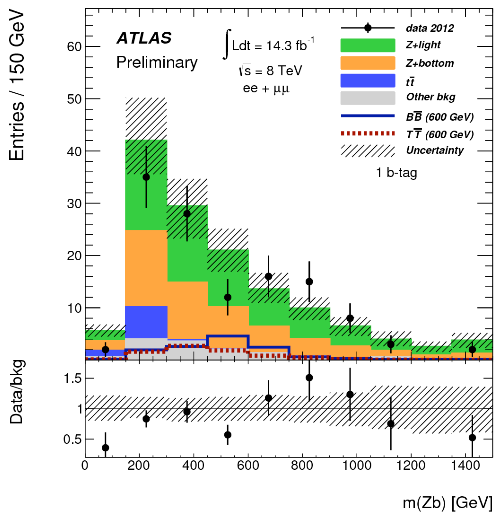


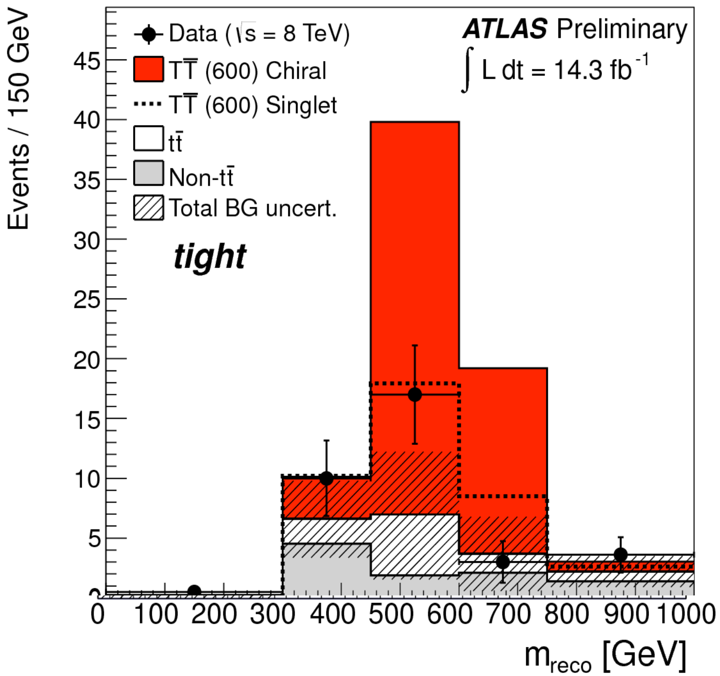
Vector-like quark partners

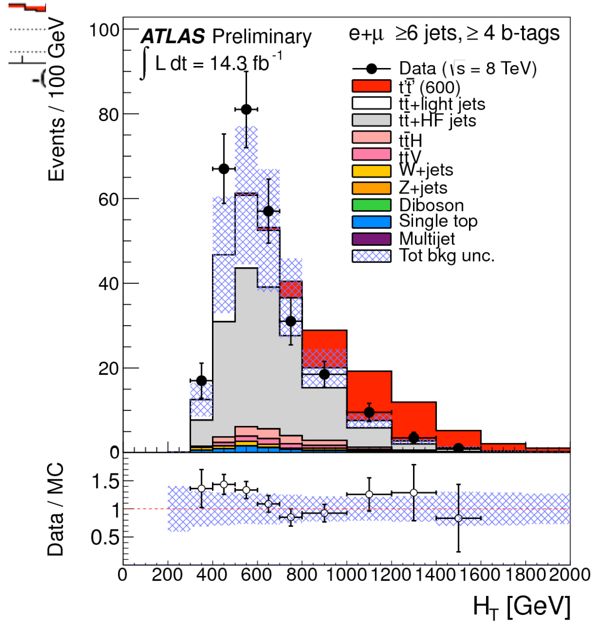
new

- CMS: 1,2,3 lepton channels combined
  - 1-lepton top quark partner analysis includes tagging of hadronic W bosons
- ATLAS: 4 separate channels including Z+b, multileptons and T to bW 1-lepton+jets with high b jet multiplicity (incl W tagging)





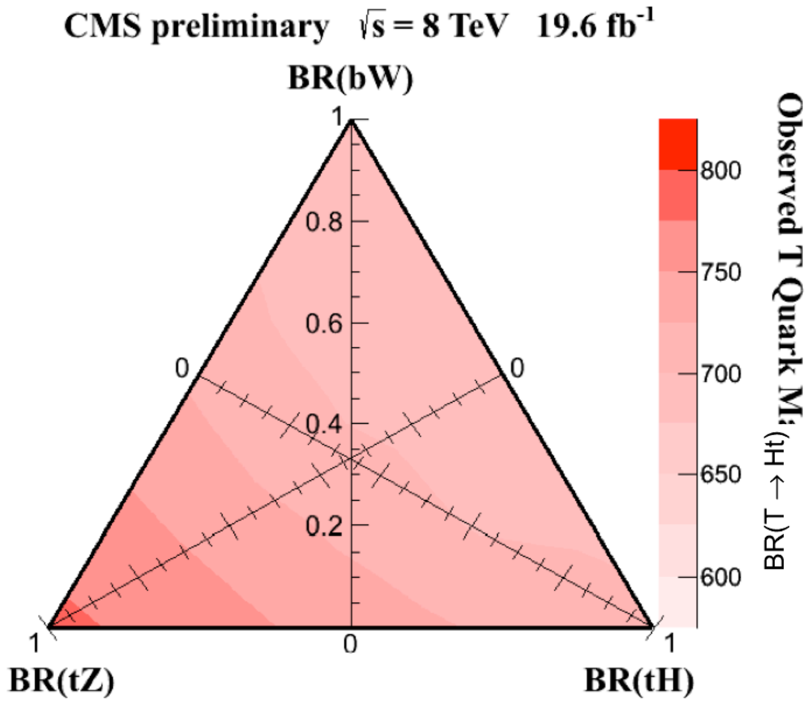




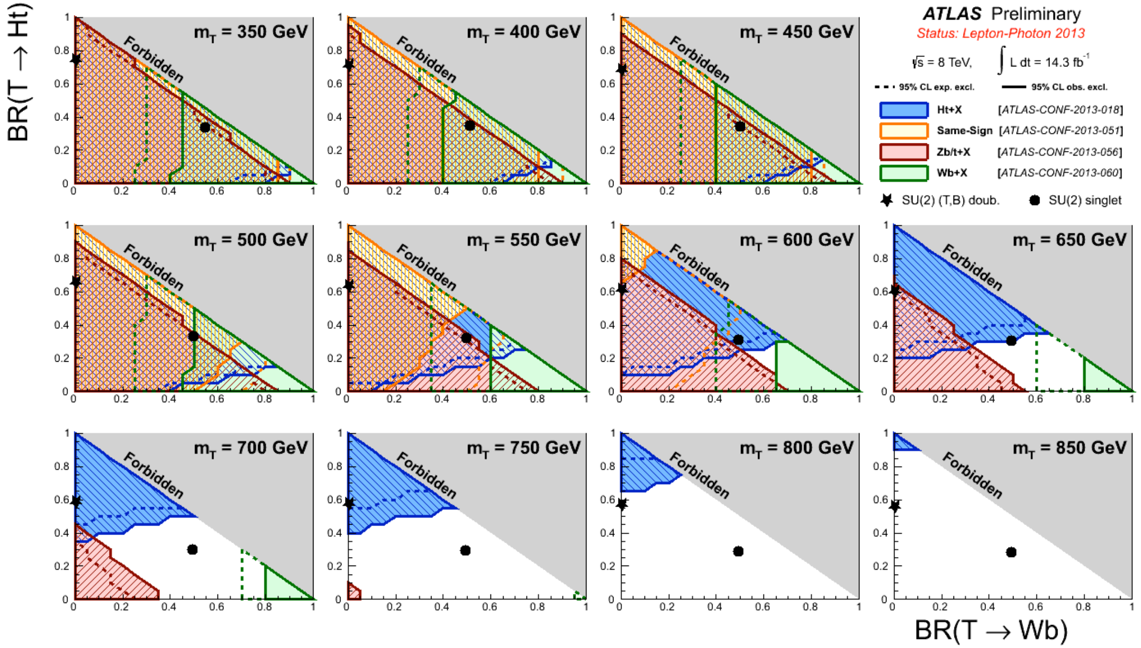
CMS PAS B2G-12-015
ATLAS-CONF-2013-060/018/051/056

Vector-like quark partners

new



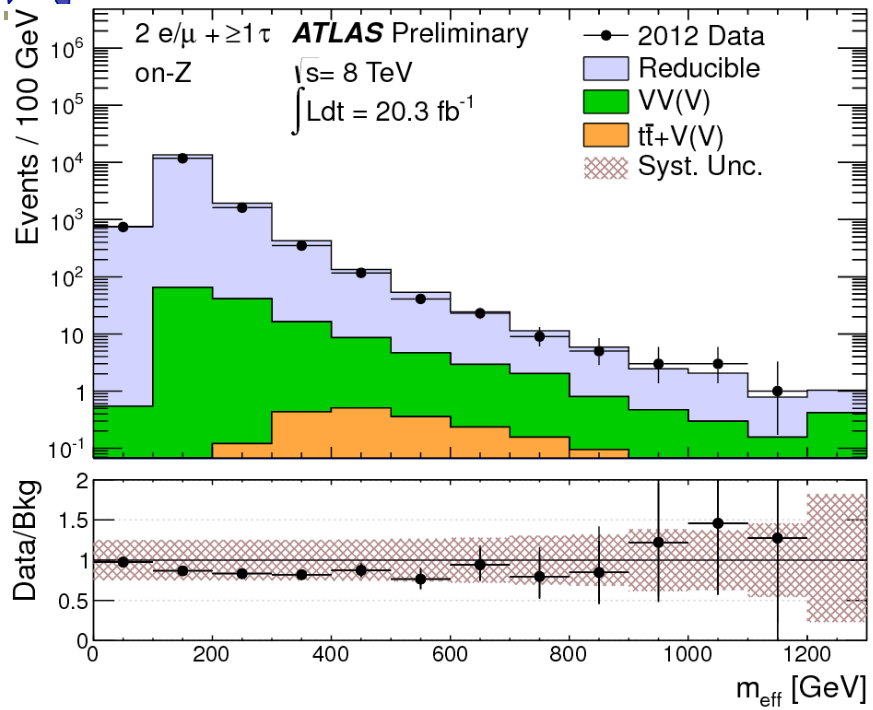
- CMS and ATLAS set limits in same space – presentation different but same message
- ATLAS also sets limit on bottom partners



For full LHC 8 TeV dataset typical 95% CL exclusion for masses are 650-800 GeV, depending on the decay channel

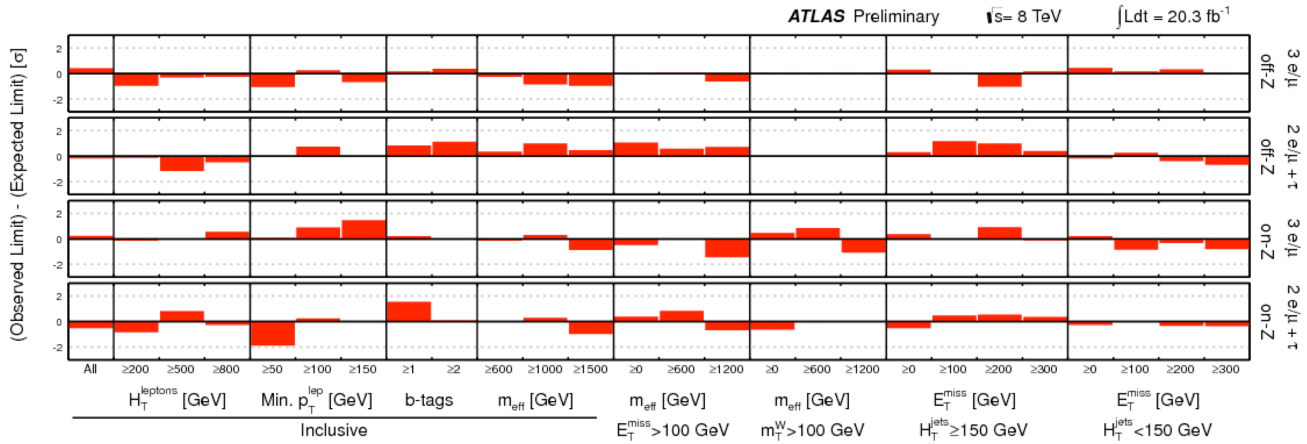
CMS PAS B2G-12-015
ATLAS-CONF-2013-060/018/051

General search multi-leptons



- Full ATLAS 8 TeV dataset examined in 3-lepton final states
  - On- and off-Z boson regions
  - Maximally one hadronic tau
  - Several kinematic variables examined
  - split by number of b tagged jets
- No excess above SM predictions

Limits on fourth generation, doubly charged Higgs (including Higgs triplets), various exotic neutrino models



ATLAS CONF-2013-070

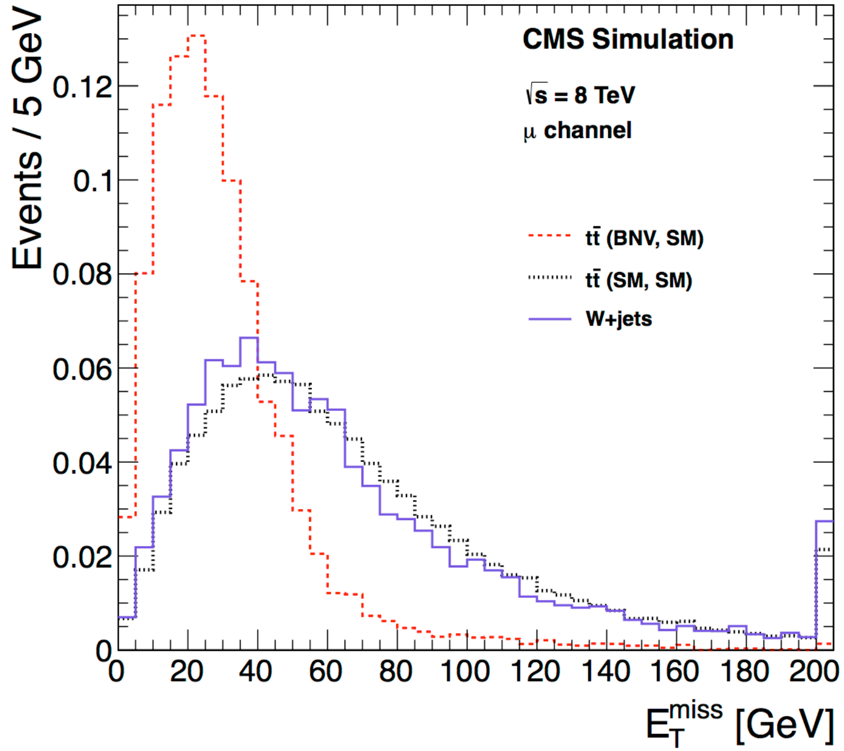
Baryon Number Conservation

- Baryon number conserved in Standard Model
  - Small violation possible from non-perturbative effects

- Supersymmetry, Grand Unified Theories and black-hole physics naturally allow Baryon Number violation (**BNV**).
  - stringent limits from precision measurements in nucleon, tau, HF mesons and Z bosons
  - Top decay (small BR) of type t to μbc not excluded

Search for BNV in tops

- Idea: should be visible as subtle increase of top events in lepton+jets with very low missing transverse energy
- Experimentally extremely challenging regime
  - Lepton
  - 5 jets
  - No MET



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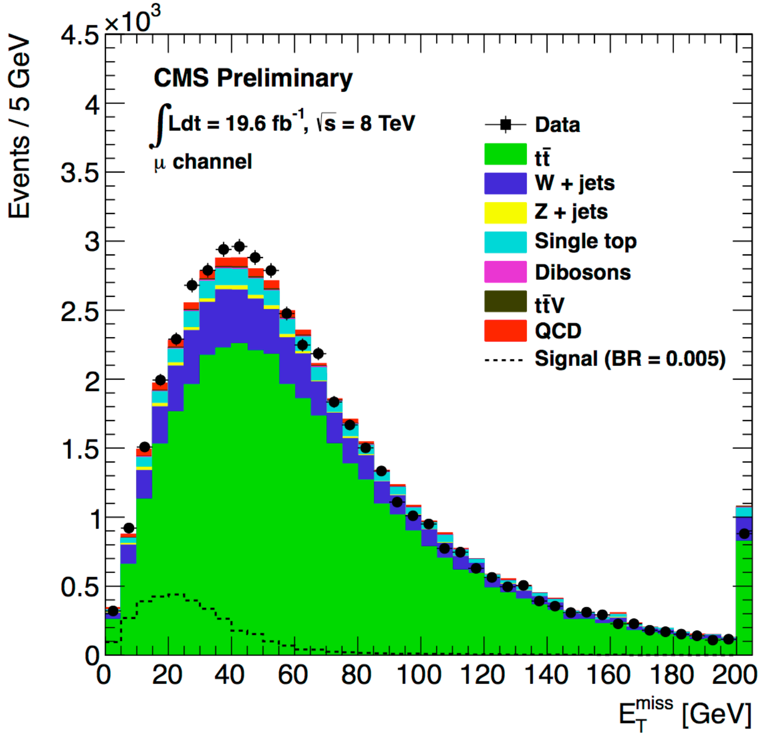
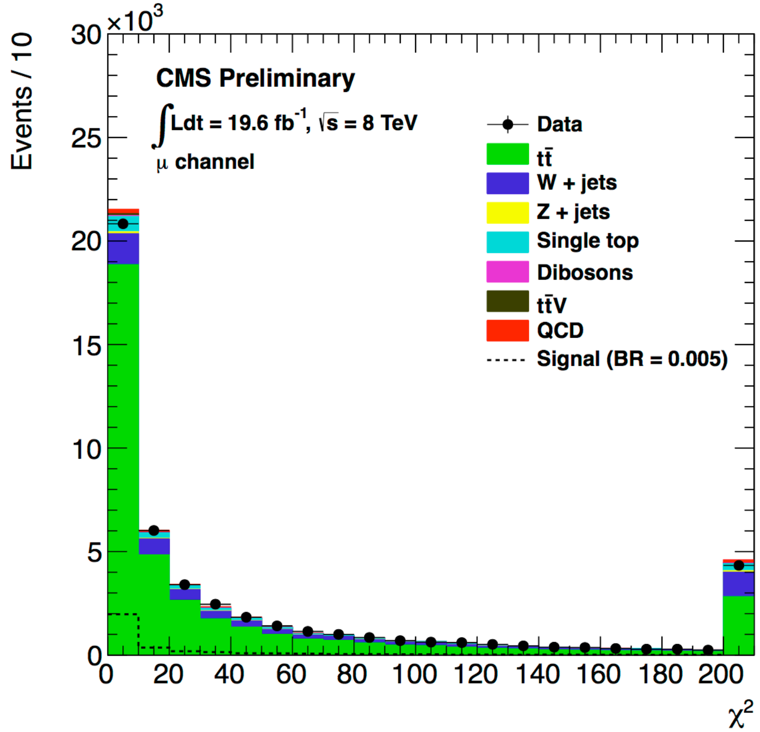
Search for BNV tops

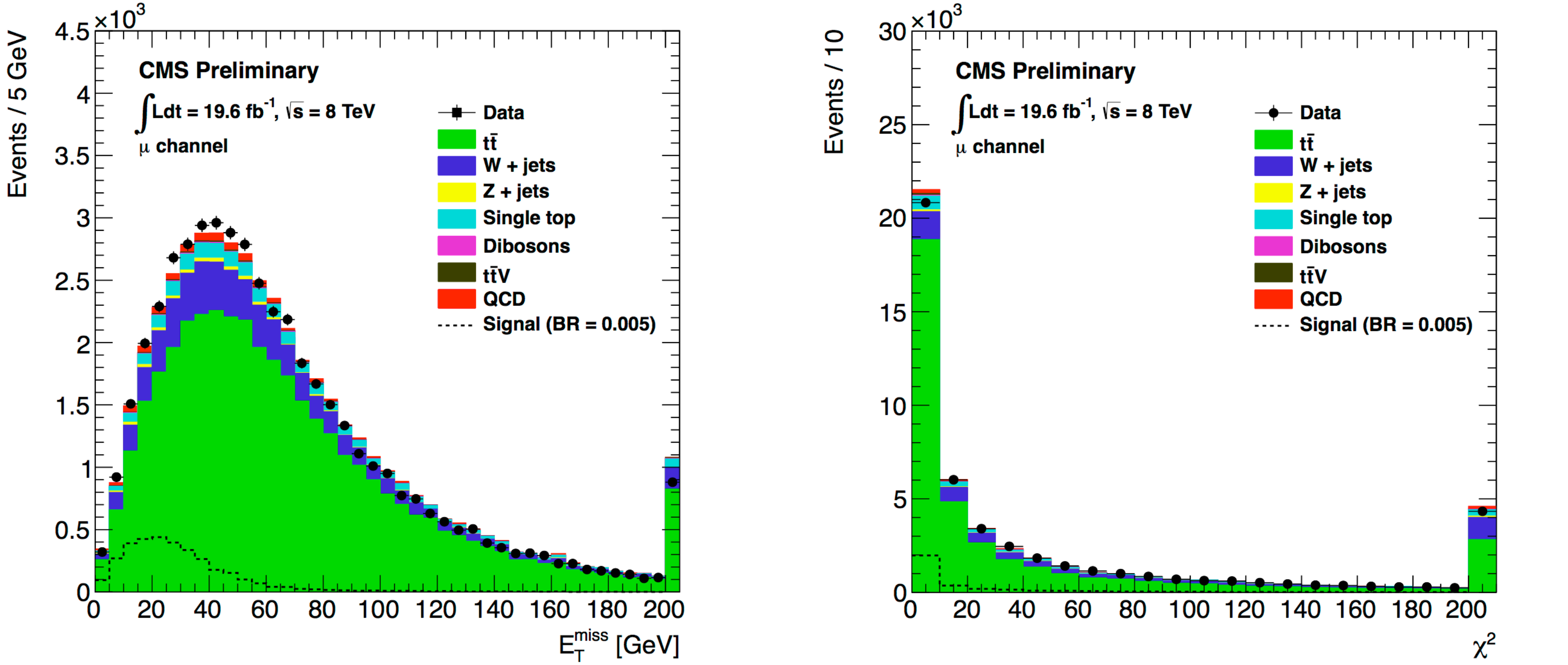




- Construct chi2 requirement on hadronic top system and make tight cut on chi2 (<20) and MET (<20) Constrain low MET, low chi2 region from bulk
- Fit to BR and selection efficiency instead of event counts

CMS PAS B2G-12-023

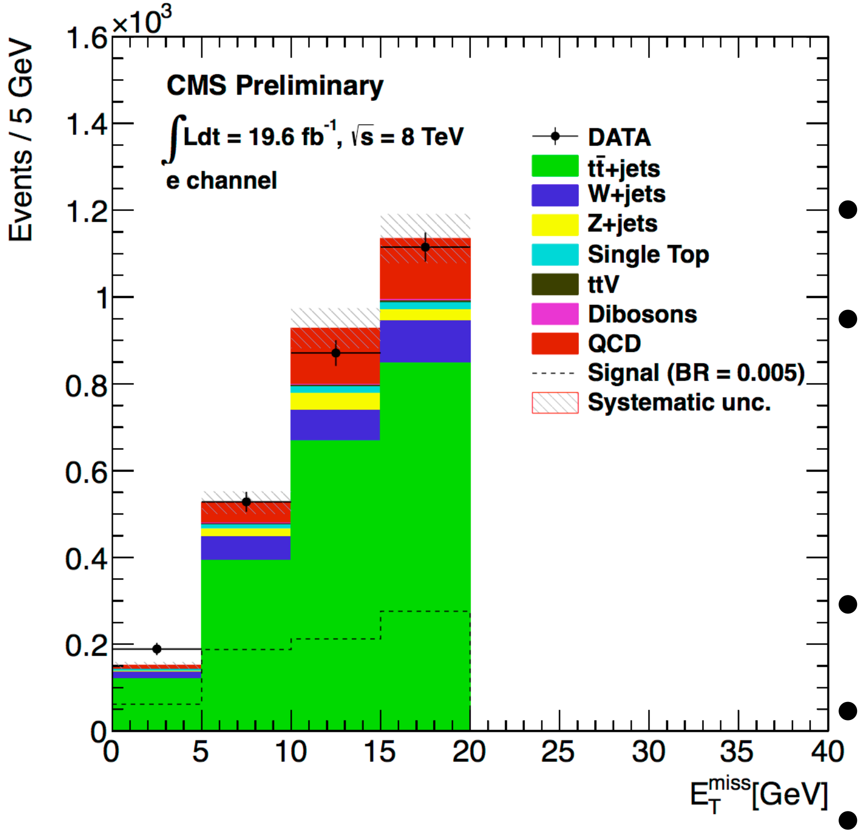
Search for BNV tops



$$N^T_{exp} = \left(N^B_{obs} - N^B_{bck}\right)\left[\frac{1}{1+\frac{\sigma_{tW}\epsilon^B_{tW}(BR)}{\sigma_{t\bar{t}}\epsilon^B_{t\bar{t}}(BR)}} \times \frac{\epsilon^T_{t\bar{t}}(BR)}{\epsilon^B_{t\bar{t}}(BR)} + \frac{1}{1+\frac{\sigma_{t\bar{t}}\epsilon^B_{t\bar{t}}(BR)}{\sigma_{tW}\epsilon^B_{tW}(BR)}} \times \frac{\epsilon^T_{tW}(BR)}{\epsilon^B_{tW}(BR)}\right] + N^T_{bck}$$

CMS PAS B2G-12-023

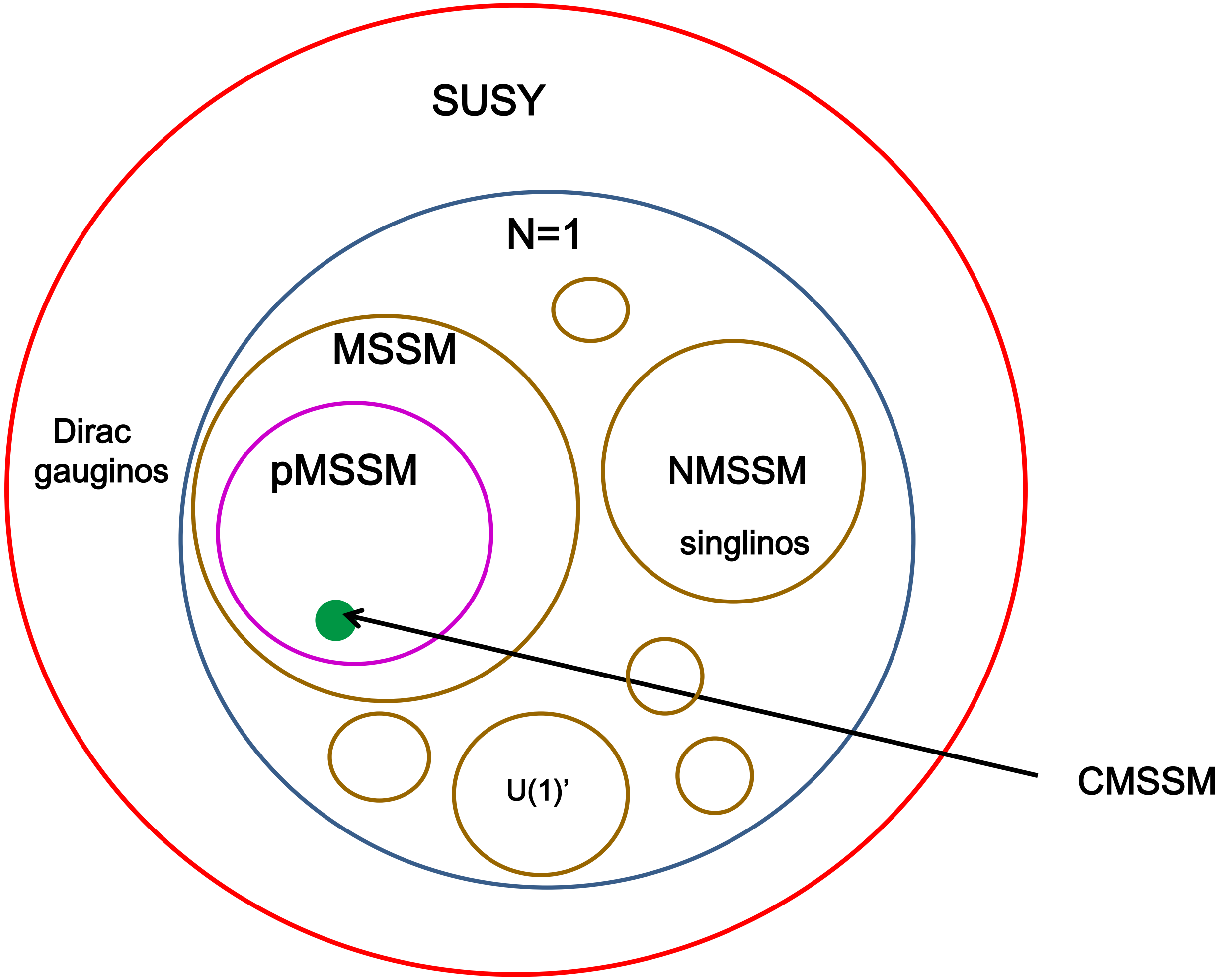
Search for BNV tops



- Modeling of QCD multijet background derived in Z+jets events
- Fit to efficiencies and BR
- Even in challenging e+jets channel decent data-MC agreement
- Limits on in μ (e) channels:
- BF< 0.016 (0.017)
- First limit ever on BNV in top sector!

End of lecture three – questions?

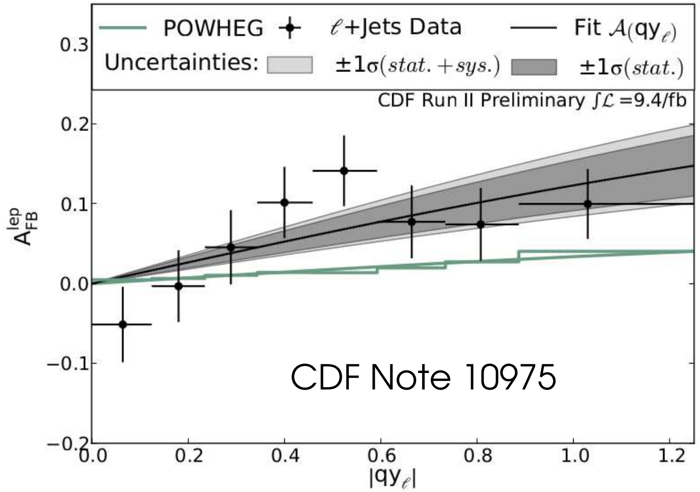
MSSM vs SUSY



- $A_{FB}^{t\bar{t}}$ measurement requires full reconstruction of $t\bar{t}$ system.
- Alternative method based on y of lepton from leptonic W decay.

$$A_{FB}^{\ell} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}$$

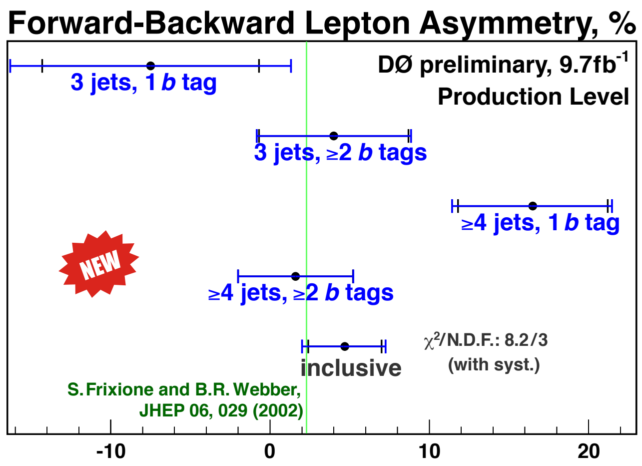
- $A_{FB}^{\ell} \approx 0.5 \cdot A_{FB}^{t\bar{t}}$ if no t polarization.
- Can also use events with jets out of acceptance (3-jet bin).



CDF Note 10975

CDF: $A_{FB}^{\ell} = 0.094^{+0.032}_{-0.029}$

D0: $A_{FB}^{\ell} = 0.047 \pm 0.023(\text{stat})^{+0.011}_{-0.014}(\text{syst})$



D0 note 6394-CONF

- CDF result approximately 2σ above SM prediction.
- D0 measurement consistent with SM (and CDF) within errors.

Top Forward-Backward and Charge Asymmetries

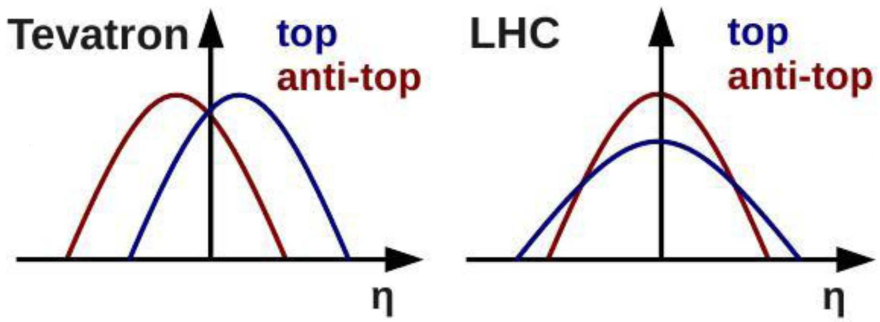
- New physics in top sector can alter angular distributions.
- Study forward-backward and charge asymmetries.

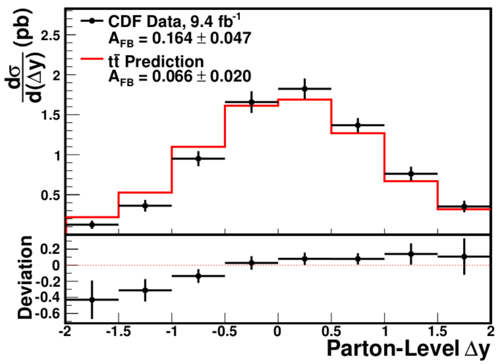
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

with $\Delta y = y_t - y_{\bar{t}}$

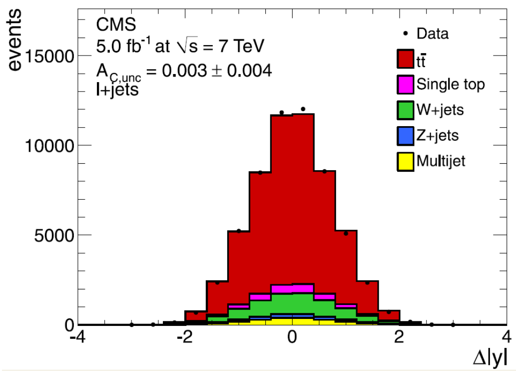
$$A_{C}^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

with $\Delta|y| = |y_t| - |y_{\bar{t}}|$

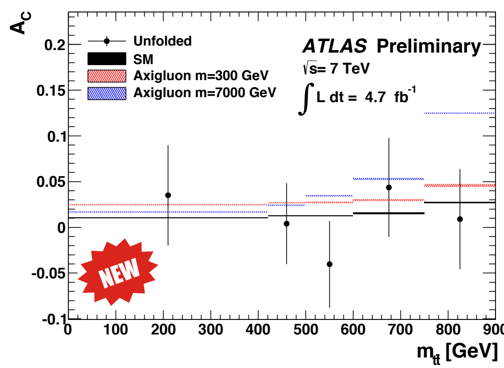




Phys. Rev. D 87 092002 (2013)



Phys. Lett. B 717, 129 (2012)



ATLAS-CONF-2013-078

- Tevatron $A_{FB}^{t\bar{t}}$ measurements in tension with SM at $\sim 2.5\sigma$.
- LHC $A_{C}^{t\bar{t}}$ measurements consistent with SM.