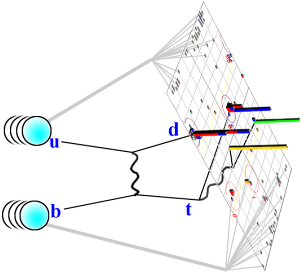
What do we learn from single top quarks?

Zack Sullivan

Illinois Institute of Technology
CTEQ Collaboration

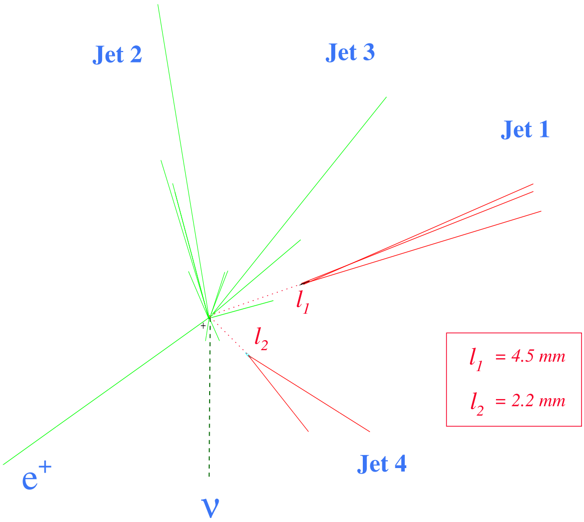
April 9, 2015



Outline

1. **What t-, s-, and Wt-channel teach us**
   - Rethinking the proton
   - Getting to NLO (and NNLO)
   - What good is spin?
   - What are we predicting, anyway?
2. **Single-top means more than it used to**
   - What is Wt production?
   - t + anything
   - Single-top for resonance searches
3. **Conclusions**

“This is the top quark!” — Bruce Barnett



$M_{top}^{Fit} = 170 \pm 10$ GeV/c^2

24 September, 1992
run #40758, event #44414

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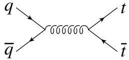
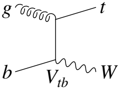
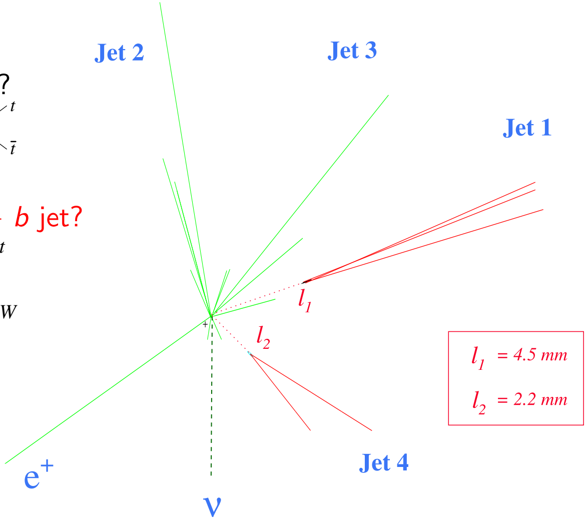
Is this $t\bar{t}$?



Or $Wt + b$ jet?





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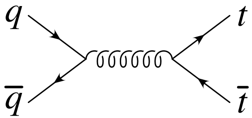
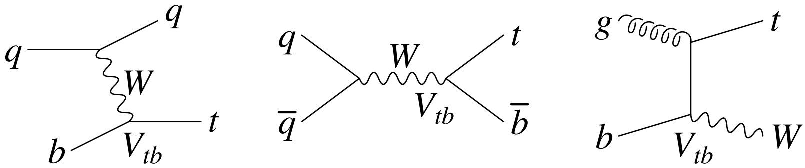
What is single-top-quark production?

Top quark pairs were discovered in 1995 via strong force production:



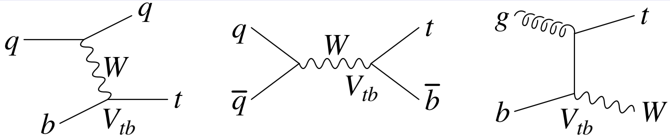
Single-top-quark production is an electroweak (EW) process:



t-channel *s*-channel *Wt*-associated

t-channel discovered in 2009 at the Tevatron
s-channel discovered in 2014 at the Tevatron
Wt-channel discovered in 2014 at the LHC

What do we want from single-top-quark production?

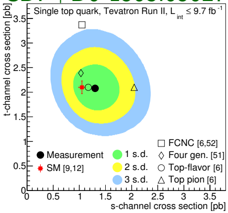


t-channel   *s*-channel   *Wt*-associated

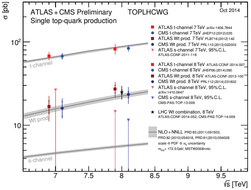
$V_{tb} = 0.998 \pm 0.038(\mathrm{exp.}) \pm 0.016(\mathrm{theo.});\ V_{tb} > 0.92\,(95\%\mathrm{C.L.})$

Experimentalists get V_{tb} and cross sections and limits on new physics

CDF+D0 1503.05027



CMS+ATLAS 1411.7521



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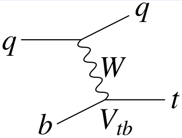

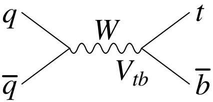

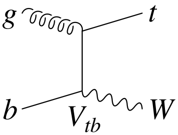

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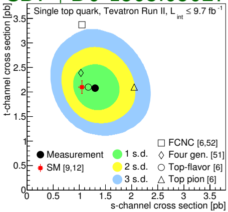

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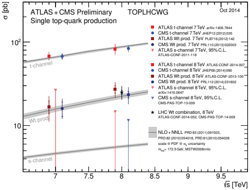
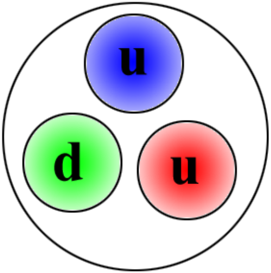


Theorists use single-top as a framework to develop new techniques and a deeper understanding of the cross section.

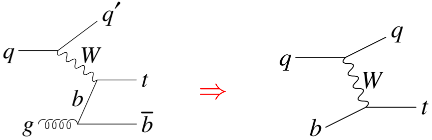
$$\sigma_{\text{obs.}} = \int f_1(x_1,\mu_1) f_2(x_2,\mu_2) \otimes \overline{|M|^2} \otimes d\text{P.S.} \otimes D_i(p_i) \ldots D_n(p_n)$$

Rethinking the proton



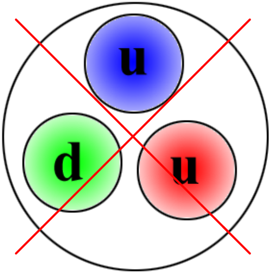
This "valence" picture is incomplete.

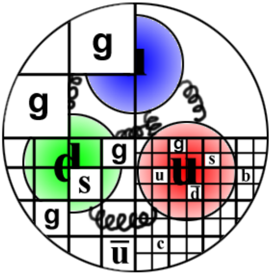
W-gluon fusion $\Rightarrow$ t-channel single top (1997)



$b\,\mathrm{prop.} \sim \alpha_s \ln\left(\frac{Q^2+m_t^2}{m_b^2}\right) + \mathcal{O}(\alpha_s) \quad m_t \approx 35 m_b$

Rethinking the proton





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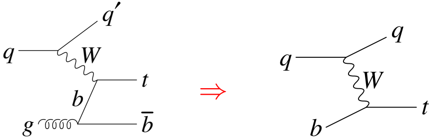
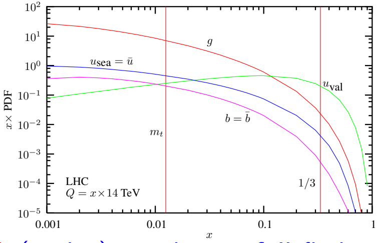


b prop. $\sim \alpha_s \ln\left(\frac{Q^2+m_t^2}{m_b^2}\right) + \mathcal{O}(\alpha_s)$ $\quad m_t \approx 35 m_b$

Larger energies resolve smaller structures.



b (and c) quarks are full-fledged members of the proton structure.

The top quark as a parton

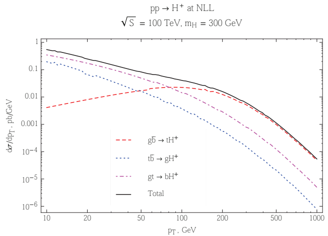
In general, we do not consider the top quark when discussing proton structure.

The reason is simple: We do not tend to measure at scales far enough above m_t to ignore its mass.

Recently this issue has been revisited in the context of single-top and Higgs production at 100 TeV.

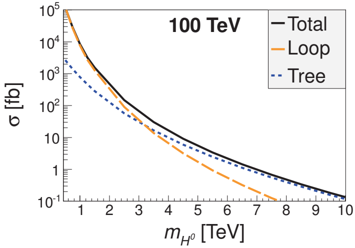
The p_T distributions for some processes, such as $H^+ + X$ and tH^0 production need a top PDF to get the correct result.

$pp \to H^+$



Dawson, Ismail, Low 1405.6211

$tg \to tH^0$



Han, Sayre, Westhoff 1411.2588

Fully differential NLO techniques for single top

$$\sigma_{\mathrm{obs.}} = \int f_1(x_1,\mu_1) f_2(x_2,\mu_2) \otimes \overline{|M|^2} \otimes d\mathrm{P.S.} \otimes D_i(p_i) \ldots D_n(p_n)$$

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In 2001, there were few matrix-element techniques or calculations that could deal w/ IR singularities in processes with massive particles.

To dig single-top out of backgrounds required accurate jet rates and angular correlations. 3 matrix element methods came to the rescue:

— Phase space slicing method with 2 cutoffs, and 1 cutoff.

B.W. Harris, J.F. Owens, PRD 65, 094032 (02)

E. Laenen, S. Keller, PRD 59, 114004 (99)

— Massive dipole formalism (a subtraction method) coupled with a helicity-spinor calculation. Invented to solve single-top production.

L. Phaf, S. Weinzierl, JHEP 0104, 006 (01)

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After discovery, precision measurements require refined matrix elements:

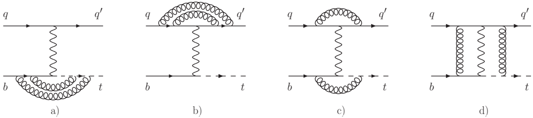
— Threshold resummation by Kidonakis (2010–13, 1306.3592...)

— NLO matched matrix elements in showering event generators for POWHEG, MC@NLO (cf. Falgari, 1302.3699 for summary)

	LHC 13 TeV				Tevatron	
	σ_t^{LO}	$\sigma_{\bar{t}}^{\mathrm{LO}}$	σ_t^{NLO}	$\sigma_{\bar{t}}^{\mathrm{NLO}}$	$\sigma_{t,\bar{t}}^{\mathrm{LO}}$	$\sigma_{t,\bar{t}}^{\mathrm{NLO}}$
t	135	79.8	$137\,^{+4.0}_{-2.3}\,^{+1.0}_{-0.9}$	$82.1\,^{+2.5}_{-1.3}\,^{+0.6}_{-0.8}$	1.03	$0.998\,^{+0.025}_{-0.022}\,^{+0.029}_{-0.032}$
s	4.27	2.63	$6.25\,^{-0.06}_{+0.09}\,^{+0.12}_{-0.09}$	$3.97\,^{-0.04}_{+0.05}\,^{+0.08}_{-0.07}$	0.28	$0.442\,^{-0.023}_{+0.025}\,^{+0.015}_{-0.011}$
tW	29.1	29.1	$29.3\,^{+1.0}_{-1.3}\,^{+0.7}_{-0.8}$	$29.2\,^{+1.0}_{-1.3}\,^{+0.7}_{-0.8}$	0.069	$0.070\,^{-0.002}_{-0.001}\,^{+0.008}_{-0.009}$

"The future is (almost) now"... NNLO

NNLO corrections are useful for kinematic variables at LHC.



Brucherseifer, Caola, Melnikov 1404.7116

8 TeV t-channel top cross sections vs. cuts on p_{Tt} ($\bar{t}$ about 1/2 size)

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	+2.4%	$54.2^{+0.5}_{-0.2}$	−1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	+4.9%	$48.3^{+0.3}_{-0.02}$	−1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	+9.3%	$36.5^{+0.1}_{+0.1}$	−0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	+13.6%	$25.4^{-0.1}_{+0.2}$	+1.6%

The above calculation ignores small box diagrams (d).

Full two-loop calculations recently completed and coded for use in HATHOR

Assadsolimani, Kant, Tausk, Uwer 1406.4403; 1409.3654

The complete NNLO in HATHOR is not fully implemented or vetted for the public yet (March 2015), but should be usable soon

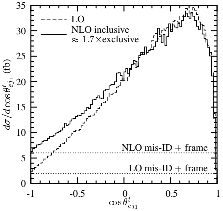
Angular correlations in single-top (selective phase space)

$$\sigma_{\text{obs.}} = \int f_1(x_1,\mu_1) f_2(x_2,\mu_2) \otimes |M|^2 \otimes d\text{P.S.} \otimes D_i(p_i)\ldots D_n(p_n)$$

$V-A$ nature of production AND decay leads to large angular correlations

Angle between e and lead jet

Mahlon, Parke ph/9611367;
ZS ph/0510224



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What if couplings were not pure $V-A$?

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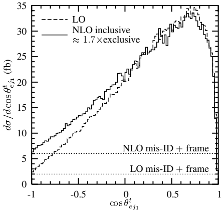

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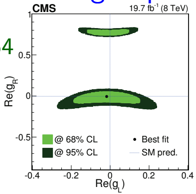
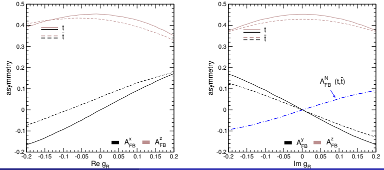
Is new physics hiding in polarization?

CMS 1410.1154



Boudreau, Escobar, Mueller, Sapp, Su 1304.5639
Aguilar-Saavedra, Amor dos Santos 1404.1585

Alternate spin axes may enhance sensitivity to new physics



"Paradigm of jet calculations"

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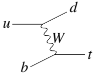
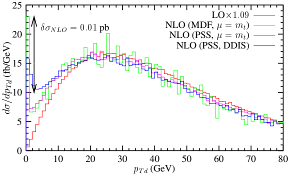
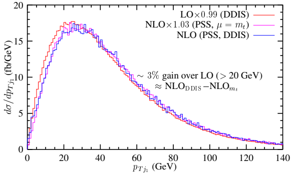


NLO "d-jet"?



We measure the highest E_T jet



Z.S., PRD 70, 114012 (2004)

The mathematics of quantum field theory tells us we cannot resolve the quarks inside of these jets! Don't take Feynman diagrams so literally.

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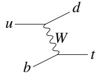

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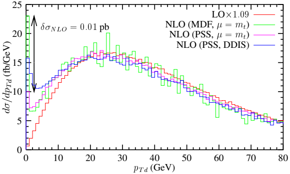

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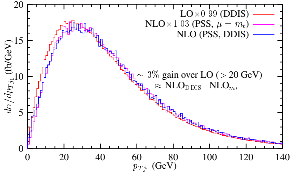

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At high Lorentz boosts, the top quark decay products may not be isolated. Significant attention has gone into understanding these "boosted top jets"

We'll come back to this...

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   - What good is spin?
   - What are we predicting, anyway?

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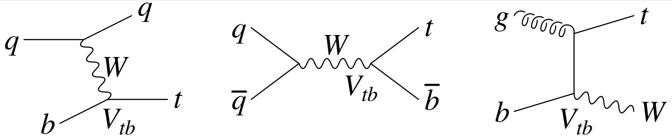
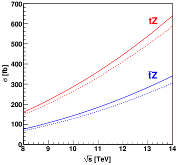
3. **Conclusions**

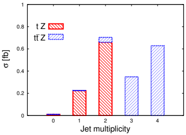
Single-top-quark production is more than it was



t-channel | *s*-channel | *Wt*-associated

— Trileptons in tZ vs. $t\bar{t}Z$



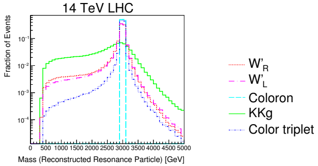


Campbell, Ellis, Rontsch 1302.3856

— tH, tZ, $t\gamma$ in MG5_aMC@NLO

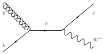
Degrande, Maltoni, Wang, Zhang 1412.5594

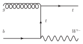
— Resonant tb production (W')



Drueke, Nutter, Schwienhorst, Vignaroli, Walker, Yu 1409.7607

— $W't$ associated ($100+$ fb^{-1})





Gong, Li, Qiao, Si, Yang 1403.0347

Zeng, Yang, Yue, Yu 1403.3144

Now that Wt is found — what is it (not)?

Various methods have been developed to selectively identify part of the cross section Wt+jet and part $t\bar{t}$.
Tait, ph/9909352; Kersevan, Hinchliffe, ph/0603068; ...

Frixione, Laenen, Motylinski, Webber, White 0805.3067

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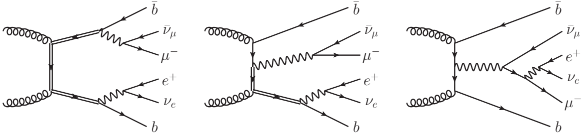
However, it is not gauge invariant.

Recent full NLO treatments w/ interference exist using MG5_aMC@NLO



Frederix 1311.4893

	μ_0	σ[fb]	σ_0[fb]	σ_1[fb]	σ_{2+}[fb]
LO	μ_{WWbb}	$1232^{+34\%}_{-24\%}$	$37^{+38\%}_{-25\%}$	$367^{+36\%}_{-24\%}$	$828^{+33\%}_{-23\%}$
NLO	μ_{WWbb}	$1777^{+10\%}_{-12\%}$	$41^{+3\%}_{-8\%}$	$377^{+1\%}_{-6\%}$	$1359^{+14\%}_{-14\%}$
K	μ_{WWbb}	1.44	1.09	1.03	1.64

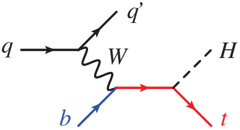
$P_{T_j} > 30$ GeV
pick your jet bin

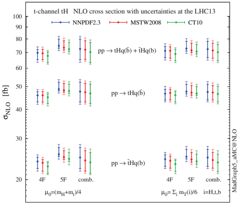
Casciolia, Kallweitb, Maierhferc, Pozzorinid 1312.0546

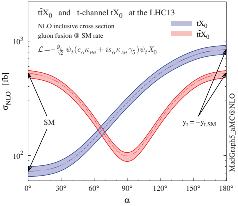
Upshot: Just use the exact predictions including interference.
"Discovery of Wt" was a firm test of QCD + Electroweak physics.

Higgs and single top

(Pseudo)scalar Higgs–top couplings are a top priority for LHC ($A^0 t\bar{t}$) $H^0 t\bar{t}$
Chang, Cheung, Lee, Lu 1403.2053; Yue 1410.2701
Hot off the presses. . . full $H^0 t / A^0 t$ NLO available in MG5_aMC@NLO
Demartin, Maltoni, Mawatari, Zaro 1504.00611
s-channel $Ht = 2.81 \pm 0.07$ fb

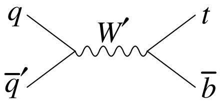






Run I LHC data limit $\sim 5 \times \sigma(Ht)$ CMS and ATLAS
Significant interest in alternate models is also picking up:
FCNC, Little Higgs, $H^+ \to tb$, etc.
Wu 1407.6113; Kobakhidz, Wu, Yue 1406.1961; Hashemi 1305.2096;
Yang, Han, Liu 1412.2927

Model independent searches for W'



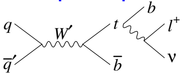
For an arbitrary Lagrangian with coupling to fermions

$$\mathcal{L}=\frac{1}{\sqrt{2}}\overline{f}_i\gamma_\mu\left(g_R e^{i\omega}\cos\zeta\, V^R_{f_if_j}P_R+g_L\sin\zeta\, V^L_{f_if_j}P_L\right)W'f_j+\mathrm{H.c.}$$

Complete factorization of couplings proved through NLO for ALL models.
Z.S., PRD 66, 075011 (2002) [hep-ph/0207290].

The differential NLO cross section looks like:
$\sigma_{\mathrm{NLO}} \times \mathrm{BR}(W'\to tb) = (g'/g_{SM})^2 \times \sigma^{\mathrm{SM}}_{\mathrm{NLO}}$ (where $g' \sim g\sqrt{|V'_i||V'_f|}$)
This holds for any final state, but s-channel single-top is special...

The final state is fully reconstructable!
For low enough mass ...

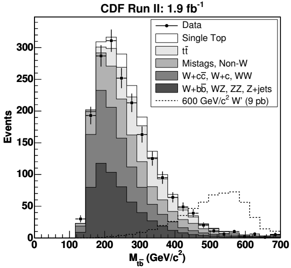


A limit on a cross section $\times$ BR = a limit on $(g'/g_{SM})^2$!
It takes very little data to get close to the world's best limit on g'/g_{SM}

Search strategy developed in

Z.S., PRD 66, 075011 (2002)

Simple bump hunt in t-b invariant mass



Run I: CDF set bound (SM-like)

$M_{W'} > 536(566)$ GeV. PRL 90, 081802 (03)

Run II:

$M_{W'} > 800(825)$ GeV. CDF, PRL 103, 041801 (09)

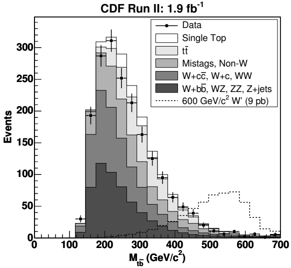
$M_{W'} > 863(890)$ GeV. DØ, PLB 699, 145 (11)

Model-independent W' searches

Search strategy developed in

Z.S., PRD 66, 075011 (2002)

Simple bump hunt in t-b invariant mass



Run I: CDF set bound (SM-like)
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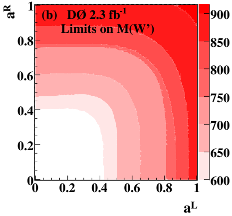
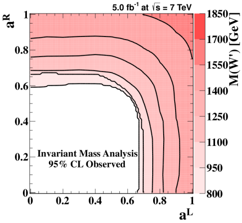
Run II:
$M_{W'} > 800(825)$ GeV. CDF, PRL 103, 041801 (09)
$M_{W'} > 863(890)$ GeV. DØ, PLB 699, 145 (11)

The important constraint is for g'/g_{SM} vs. $M_{W'}$



Initial LHC searches

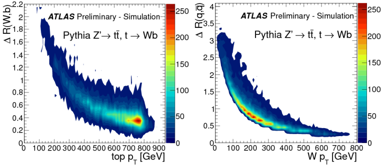


CMS PLB 718, 1229 (13)
ATLAS PRL 109, 081801 (12)

Looking for W' bosons using boosted top jets

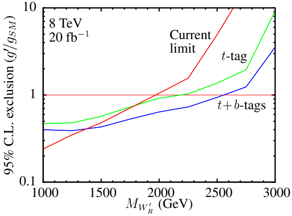
For large W' mass (> 1.5 TeV) the top quark is highly boosted

It becomes difficult to reconstruct isolated jets from $t \to bW \to bjj$



ATLAS-CONF-2012-065

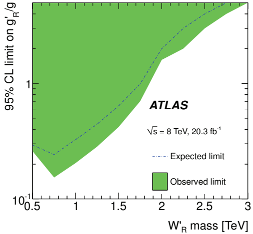
Using boosted tops improves reach

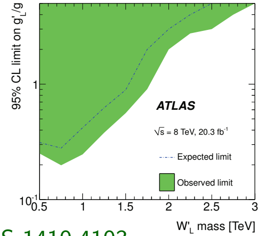


If you use "boosted bottom" tags.

Duffty, ZS 1307.1820

ATLAS has now used boosted tops (no boosted bottoms yet)



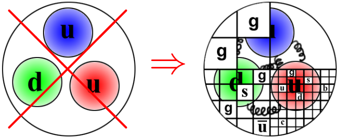


ATLAS 1410.4103

Conclusions — they're still coming

Single-top-quark production is the DIS and Drell-Yan of the 21st century

$$\sigma_{\rm obs.} = \int f_1(x_1,\mu_1) f_2(x_2,\mu_2) \otimes |M|^2 \otimes d\mathrm{P.S.} \otimes D_i(p_i) \ldots D_n(p_n)$$

- 

  — $c/b/t$ are inside the proton
  — Large $\ln(m_t^2/m_b^2)$ terms stress-test our perturbative theory ⇒ NNLO
  — Angular correlations ⇒ new physics
- The "paradigm of jet calculations"
  Exclusive NLO calculations intrinsically describe jets, not quarks.

t-channel, s-channel, and Wt have now been found — now what?

- Wt and $t\bar{t}$ can now be considered at the same time — let's do that
- Zt, Ht, At, etc. will provide the next round of discoveries
- Single-top will continue to push the limits in the search for W' and other resonances

THANK YOU