The new DIS and Drell Yan: single top quarks and W-prime bosons

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CTEQ Collaboration

C T E Q

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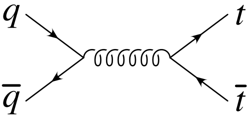
Thanks

Theory collaborators	Experimental collaborators
Brian Harris	CDF single-top group
Eric Laenen	DØ single-top group
Pavel Nadolsky	ATLAS top group
Lucas Phaf	CMS top group
Tim Stelzer	
Stefan Weinzierl	
Scott Willenbrock	
Daniel Duffty (grad student)	
Hao Zhang (postdoc)	

Department of Energy for funding much of this research
Jefferson Lab for the kind invitation, and for adding to the story

What is single-top-quark production?

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



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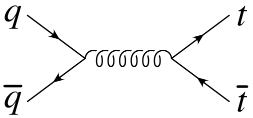
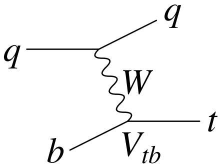
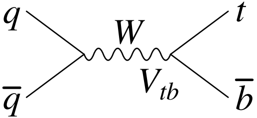


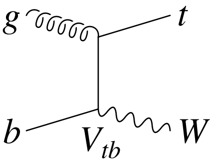
Single-top-quark production is an electroweak (EW) process:



t-channel



s-channel

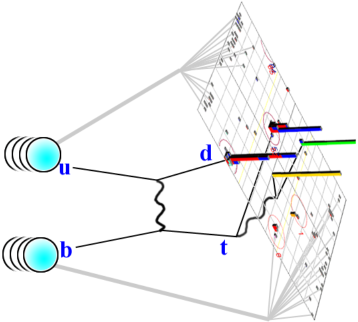


Wt-associated

Discovered in 2009 at the Tevatron

What is single-top-quark production?

Experimentalist: Single top quark production is the observation of $b\,\ell^{\pm}\not\!\!E_T$ that reconstruct to a top quark mass, plus an extra jet (or two).



Theorist: Single top quark production is a playground in which we refine our understanding of perturbative QCD.

Outline

1. **Understanding the cross section**
   - Single top goes beyond DIS and Drell Yan
   - Interpreting the initial state
   - Matrix elements
   - Interpreting the final state

2. **W' bosons and single top quarks**
   - Models of W' bosons
   - Model independent searches for W' bosons
   - Investigating the initial state
   - Investigating the final state

3. **Conclusions**

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Structure of an observable cross section

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

Theorists factorize (break) the cross section into:

- Initial-state IR singularities swept into parton distribution "functions".
  These are not physical, but include scheme dependent finite terms:
  $\overline{\mathrm{MS}}$ — the current standard
  DIS — ill-defined in all modern PDF sets, could be fixed, but why?

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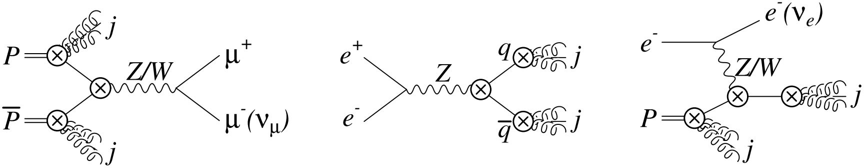
- Fragmentation functions or jet definitions.
  These provide the coarse graining to hide final-state IR singularities.

Drell-Yan and DIS

The traditional testbed of perturbative QCD have been restricted to Drell-Yan production, e^+e^- to jets, or deep inelastic scattering (DIS).

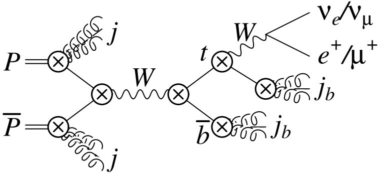


A key property that all three processes share is a complete factorization of QCD radiation between different parts of the diagrams.

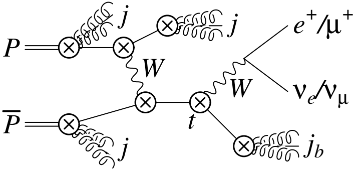
- Drell-Yan $\rightarrow$ Initial-state (IS) QCD radiation only.
- $e^+e^- \rightarrow$jets $\rightarrow$ Final-state (FS) QCD radiation only.
- DIS $\rightarrow$ Proton structure and fragmentation functions probed. Simple color flow.

s-/t-channel single-top-quark production (A generalized Drell-Yan and DIS)

A perfect factorization through next-to-leading order (NLO) makes single-top-quark production mathematically *identical*† to DY and DIS!



Generalized Drell-Yan.
IS/FS radiation are independent.



Double-DIS (DDIS) w/ 2 scales:
$\mu_l = Q^2$, $\mu_h = Q^2 + m_t^2$

Color conservation forbids the exchange of just 1 gluon between the independent fermion lines.

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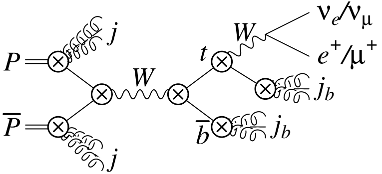

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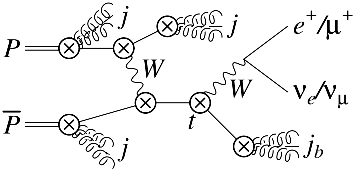

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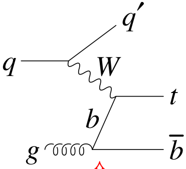
† Massive forms: m_t, m_b, and m_t/m_b are relevant.

Rethinking the initial state: W-gluon fusion $\longrightarrow$ t-channel single-top

W-gluon fusion (circa 1996)



$\Uparrow$

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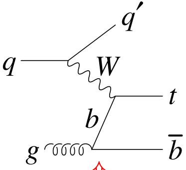

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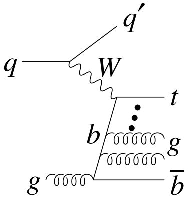

Each order adds

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Looks bad for perturbative expansion...

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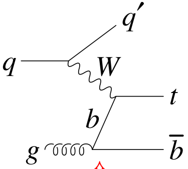

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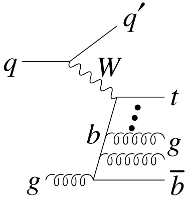

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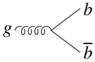
Solution: Use a "math trick"

The Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation sums large logs from collinear singularities in gluon splitting to quarks.

$$\frac{db(\mu^2)}{d\ln(\mu^2)} \approx \frac{\alpha_s}{2\pi} P_{bg} \otimes g$$



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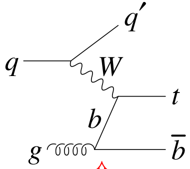

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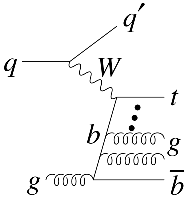

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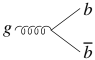

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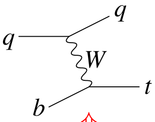
$$b(x,\mu^2) = \frac{\alpha_s(\mu^2)}{2\pi} \ln\left(\frac{\mu^2}{m_b^2}\right) \times \int_x^1 \frac{dz}{z} P_{bg}(z) g\left(\frac{x}{z},\mu^2\right)$$

$$b \propto \alpha_s \ln(\mu^2/m_b^2) \times g$$

Barnett, Haber, Soper, NPB 306, 697 (88)
Olness, Tung, NPB 308, 813 (88)
Aivazis, Collins, Olness, Tung, PRD 50, 3102 (94)
Stelzer, Z.S., Willenbrock PRD 56, 5919 (97)

New nomenclature and classification

New Leading Order



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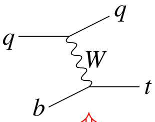

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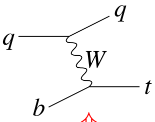

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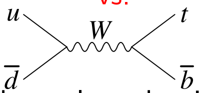

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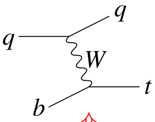

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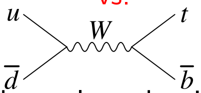

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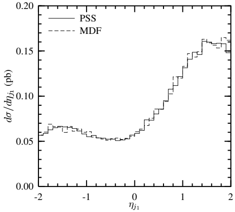
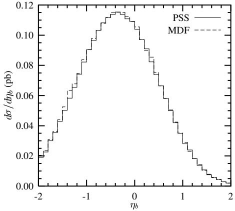
Classifying processes by analytical structure leads directly to kinematic insight:

Jets from t-channel processes are more forward than those from s-channel.

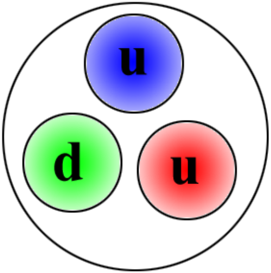


jet from t-channel



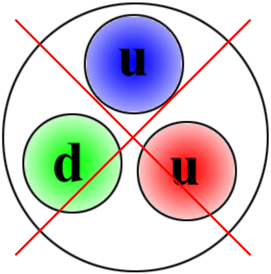
b jet from s-channel

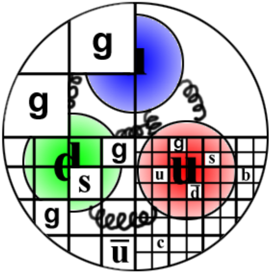
Rethinking the proton



Using DGLAP was NOT just a math trick!

This "valence" picture of the proton is not complete.





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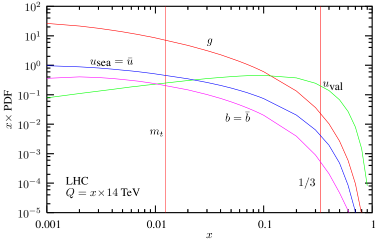
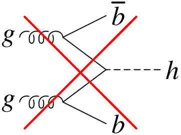
Larger energies resolve smaller structures.

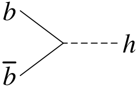
The probability of finding a particle inside the proton is given by PDFs (Parton Distribution Functions)



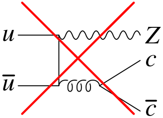
b (and c) quarks are full-fledged members of the proton structure.

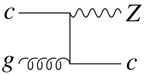
Rethinking several physical processes





Why is this important?





Starting with a c/b gives us:

$b\bar{b} \to h$	Largest SUSY Higgs cross section
Zb/Zc	Affects LHC luminosity monitor
Zbj/Zcj	Higgs background
Wbj	Largest single-top background

etc.

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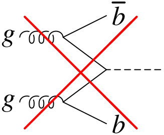

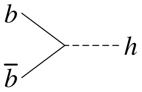

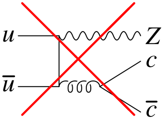

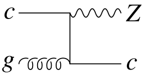

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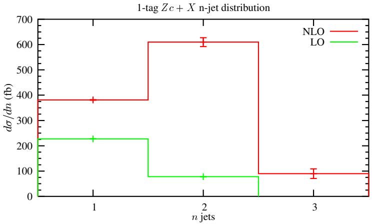
Zc at Tevatron



Parton luminosity can be more important than counting powers of α_s!

This is exaggerated at LHC:

$Z \approx Z + 1\,\text{jet} \approx Z + 2\,\text{jets}!$

(True of $W + X$ as well!)

Is jet counting poorly-defined (theoretically) at LHC?

Rethinking the matrix element: A practical problem for experiments

The same large logs that lead to a reordered perturbation for t-channel single-top, implied a potentially large uncertainty in measurable cross sections when cuts were applied.

Recall: t-channel and s-channel are distinguished by the number of b-jets.

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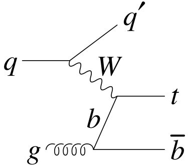
A problem: About 20% of the time, the extra $\bar{b}$-jet from the t-channel process is hard and central.

Real problem: Is the b contamination 20%, 30%, 10%?



Rethinking the matrix element: A practical problem for experiments

The same large logs that lead to a reordered perturbation for t-channel single-top, implied a potentially large uncertainty in measurable cross sections when cuts were applied.

Recall: t-channel and s-channel are distinguished by the number of b-jets.

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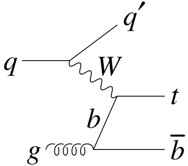

Another problem: To distinguish from $t\bar{t}$, the cross section in the $W + 2$ jet bin has to be known.

Counting jets is IDENTICAL to performing a jet veto.

Inclusive cross sections are not enough, we need to calculate exclusive cross sections

Fully Differential NLO Techniques

- In 2001, there were few matrix-element techniques or calculations that could deal IR singularities in processes with massive particles.
- Experiments were mostly stuck using LO matrix elements to predict semi-inclusive or exclusive final states.
- We needed methods to provide the 4-vectors, spins, and corresponding weights of exclusives final-state configurations.

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- We needed methods to provide the 4-vectors, spins, and corresponding weights of exclusives final-state configurations.

These needs led to work on 3 techniques:

- Phase space slicing method with 2 cutoffs.

  L.J. Bergmann, Ph.D. Thesis, FSU (89)
  cf. H. Baer, J. Ohnemus, J.F. Owens, PRD 40, 2844 (89)
  B.W. Harris, J.F. Owens, PRD 65, 094032 (02)

- Phase space slicing method with 1 cutoff.

  W.T. Giele, E.W.N. Glover, PRD 46, 1980 (92)
  cf. W.T. Giele, E.W.N. Glover, D.A. Kosower, NPB 403, 633 (93)
  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.

  cf. L. Phaf, S. Weinzierl, JHEP 0104, 006 (01)
  S. Catani, S. Dittmaier, M. Seymour, Z. Trocsanyi, NPB 627,189 (02)

Rethinking jet definitions and phase space: Experiments need exclusive $t+1$ jet at NLO

ZTOP, Z.S., PRD 70, 114012 (2004) [hep-ph/0408049]

	# b-jets	tj (Wbj)	tjj ($Wbjj$)
s-channel	$=2$	0.620 pb $^{+13}_{-11}\%$	0.168 pb $^{+24}_{-19}\%$
	$=1$	0.022 pb $^{+24}_{-19}\%$	(NNLO)
t-channel	$=1$	0.950 pb $^{+16}_{-15}\%$	0.152 pb $^{+17}_{-14}\%$
	$=2$	0.146 pb $^{+21}_{-16}\%$	0.278 pb $^{+21}_{-16}\%$

Cuts: $p_{Tj} > 15$ GeV, $|\eta_j| < 2.5$, no cuts on t
Jet definition: $\Delta R_{k_T} < 1.0$ ($\approx \Delta R_{\rm cone} < 0.74$)

Breakdown of *shape-independent* uncertainties

Process		$\times\delta m_t$(GeV)	$\mu/2$–2μ	PDF	b mass	$\alpha_s(\delta_{\rm NLO})$
s-channel	$p\bar{p}$	$^{-2.33}_{+2.71}\%$	$^{+5.7}_{-5.0}\%$	$^{+4.7}_{-3.9}\%$	$<0.5\%$	$\pm1.4\%$
	pp	$^{-1.97}_{+2.26}\%$	$\pm2\%$	$^{+3.3}_{-3.9}\%$	$<0.4\%$	$\pm1.2\%$
t-channel	$p\bar{p}$	$^{-1.6}_{+1.75}\%$	$\pm4\%$	$^{+11.3}_{-8.1}\%$	$<1\%$	$\pm0.01\%$
	pp	$^{-0.73}_{+0.78}\%$	$\pm3\%$	$^{+1.3}_{-2.2}\%$	$<1\%$	$\pm0.1\%$

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Every number here, even the concept of t-channel single-top, required a new or revised understanding of QCD.

- b PDFs $\to$ t-channel
- PDF uncertainties
- multiple scales: m_t/m_b
- 2 expansions: α_s, 1/ ln
- Fully differential NLO jet calculations

. . .

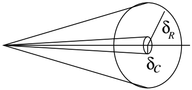
How do we interpret exclusive NLO calculations?

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

"Paradigm of jet calculations"

- We are calculating extensive objects,
  i.e., jets not "improved quarks."
- Unlike inclusive NLO calculations, exclusive NLO calculations are only well-defined in the presence of a jet definition or hadronization function. ($D_i(p_i)$)

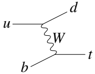
  $\Rightarrow$ The mathematics of quantum field theory tells us we cannot resolve the quarks inside of these jets!



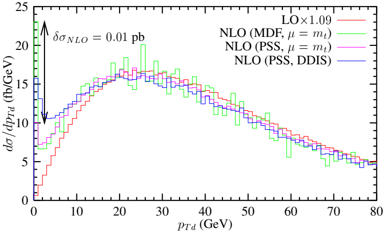
- "Bad things" happen if you treat jets as NLO partons. . .

Transverse momenta distributions at NLO

At LO, a d-quark recoils against the top quark in t-channel.



NLO "d-jet" (no cuts)



- Perturbation theory is not terribly stable at low p_{Td} (or even high p_{Td}).
- This is not what we want.
  Be careful what you ask for!

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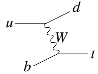

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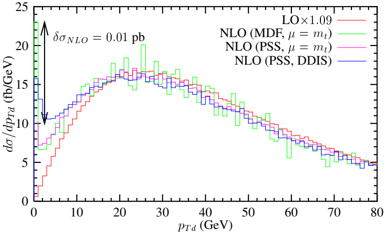
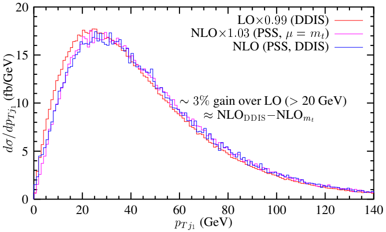


We measure the highest E_T jet



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- This is not what we want.

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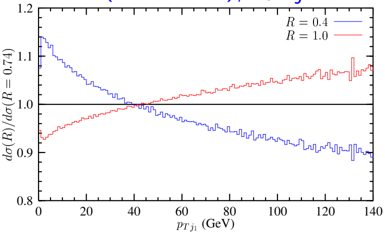
The highest E_T jet recoils against the top. The measurable change in shape is comparable to the scale uncertainty.

Jet distributions depend on jet definition

Just like the experimentalists, theorists must study the effect jet algorithms with different cone sizes R will have on measurable properties.

Ratio of $d\sigma(R)/dp_{Tj}$ to $d\sigma(R = 0.74)/dp_{Tj}$



For "reasonable" values of R the variation is $< 10\%$, but this must be checked for all observables. (Note: theoretical uncertainty $< 5\%$)

Upshot: NLO exclusive calculations give jets not partons.

Without some thought, mismatches between theory and experiment can be larger than the theory error alone would indicate.


THEORY
Experiment


THEORY
Event Generators
Experiment

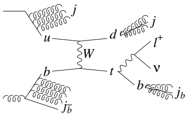

THEORY
Experiment

Event generators vs. NLO t-channel $t\bar{b}$ ($Wb\bar{b}$)

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

Initial-state radiation (ISR) is generated by backward evolution of angular-ordered showers.

$\Rightarrow$ The jet containing the extra $\bar{b}$ comes from soft ISR.



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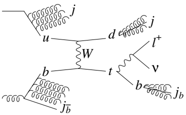
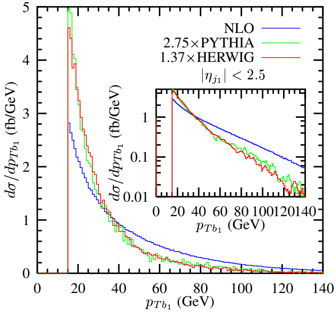
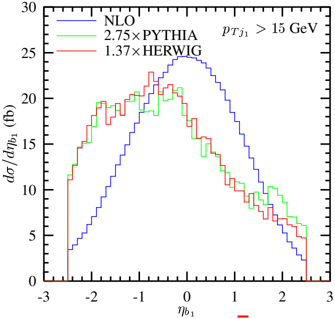






- PYTHIA/HERWIG completely underestimate the $Wb\bar{b}$ final state.
- Lesson: n-jets+showers $\neq n+1$ jets. $\Rightarrow$ Need NLO matching. (Schemes have since proliferated: MLM, CKKW, SCET, ...)

Outline

What is a W' boson?

Working definition: A W' boson is any particle that mediates a flavor-changing charged vector or axial-vector current.

Some model classes

Left-right symmetric models: Broken $SU(2)_L \times SU(2)_R$

- Generic mixing of W_L–W_R
  R. N. Mohapatra, J. Pati, A. Salam, G. Senjanovic, ...
- Orbifold-breaking — suppressed mixing, enhanced couplings
  Y. Mimura, S. Nandi, ...
- Supersymmetric L–R models
  M. Cvetic, J. Pati, ...

Models with additional left-handed W'

- Little Higgs: SU(5)/SO(5), SU(6)/SP(6), SU(N)/SU(N–1), ...
  T. Gregoire, N. Arkani-Hamed, S. Chang, H. C. Cheng, A. Cohen, I. Low, D. E. Kaplan, E. Katz, O. C. Kong, A. Nelson, M. Schmaltz, W. Skiba, D. Smith, J. Terning, J. Wacker, ...
- Topcolor — topflavor, leptophobic topflavor seesaw, generic mixing
  H. Georgi, H. J. He, E. Jenkins, X. Li, E. Ma, E. Malkawi, D. Muller, S. Nandi, E. Simmons, T. Tait, C. P. Yuan, ...
- Extra dimensions: Kaluza-Klein modes of the W
  A. Datta, P. O'Donnell, T. Huang, Z. Lin, X. Zhang, ...
- Non-commuting extended technicolor
  R. Chivukula, E. Simmons, J. Terning, ...

+ 1000's more

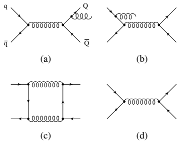
Example: Tevatron $t\bar{t}$ forward-backward asymmetry

- In proton-antiproton collisions, top quark production exhibits a forward-backward asymmetry ($\Delta y = y_t - y_{\bar{t}}$)

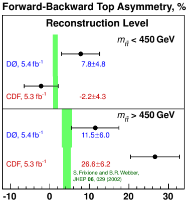
$$A_{FB}^{\rm lab} = \frac{N_t(y_t>0)-N_t(y_t<0)}{N_t(y_t>0)+N_t(y_t<0)} \qquad A_{FB}^{\rm rest} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$

- The asymmetry first appears at one loop in QCD Kuhn, Rodrigo

$$\begin{aligned} A_{FB}^{\rm rest} &= 0.05 \pm 0.006 \text{ Theory} \\ A_{FB}^{\rm rest} &= 0.164 \pm 0.045 \text{ CDF} \\ A_{FB}^{\rm rest} &= 0.196 \pm 0.065 \text{ DØ} \end{aligned}$$



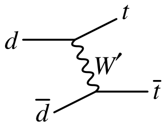
- The discrepancy w/ NLO is about 2σ
- CDF finds a larger discrepancy at large invariant mass and rapidity
- DØ does not confirm this effect



W' bosons and $A_{FB}^{t\bar{t}}$ vs. early LHC data

NOTE: There are 100's of models to explain $A_{FB}^{t\bar{t}}$, most were quickly ruled out

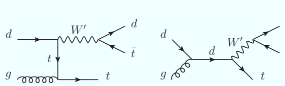
A large $V'_{td} > 1$ coupling *could* explain $A_{FB}^{t\bar{t}}$ if $M_{W'}$ is small enough.

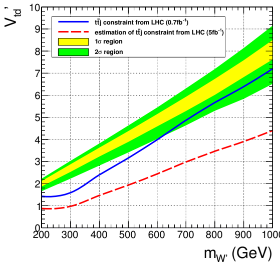


Cheung, W.Y. Keung, T.-C. Yuan; Bhattacherjee, Biswal, Ghosh; Barger, W.Y. Keung anf C.-T. Yu, Craig, Kilic, Strassler; C.H. Chen, Law, R.H. Li; Yan, Wang, Shao, C.S. Li; Knapen, Zhao, Strassler

These models were constructed to avoid constraints shown later.

W' bosons this light would have modified $t\bar{t}j$ at LHC.

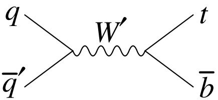




Directly excluded (>97% C.L.)

Duffty, Z.S., Zhang, PRD 85, 094027 (2012)

Model independent searches for W'



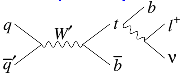
For an arbitrary Lagrangian with coupling to fermions

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

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:
$\sigma_{\mathrm{N}LO} = (g'/g_{SM})^4 \times \sigma^{\mathrm{SM}}_{\mathrm{N}LO}$ $(g' \sim g\sqrt{|V'_i||V'_f|})$
This holds for any final state, but s-channel single-top is special...

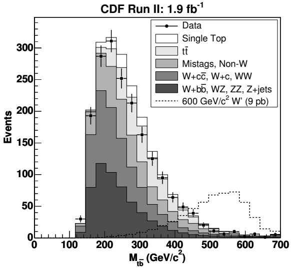
The final state is fully reconstructable!



A limit on a cross section $\times$ BR $=$ a limit on $(g')^4$!
It takes very little data to get close to the world's best limit on g'

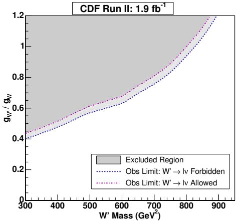
Model-independent W' searches at the Tevatron

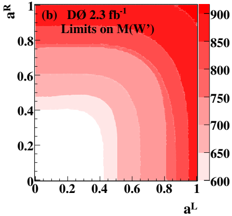
Search strategy developed in
Z.S., PRD 66, 075011 (2002)
Simple bump hunt in t-b invariant mass



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)

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





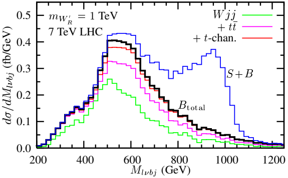
If perturbative, symmetry breaking w/ G_F

Most models have $g'/g_{SM} \sim 1$.
constrain $0.2 < g'/g_{SM} < 5$

Model-independent W' searches at the LHC

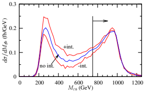
Search strategy updated to LHC

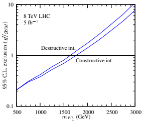
Duffty, Z.S., PRD 86, 075018 (2012)



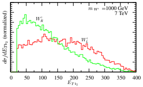
Many new issues arise at LHC:

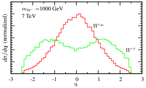
- Interference more complicated



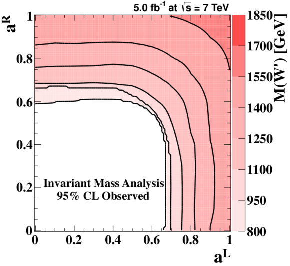


- More structure in W'_L vs. W'_R or W'^+ vs. W'^-





Initial LHC searches (Tevatron-like)



CMS 1208.0956

ATLAS has a similar study

Initial measurements used our updated NLO calculations

The next analyses will use this updated kinematic information

Investigating the initial state: PDF uncertainties

Single top and W' motivated the Modified Tolerance Method
(what you use for PDF errors on observables)

$$\delta O_{+} = \sqrt{\sum_{i=1}^{20}\left(\max[\,O(z_i^0+t)-O(z_i^0),O(z_i^0-t)-O(z_i^0),0]\right)^2}$$
$$\delta O_{-} = \sqrt{\sum_{i=1}^{20}\left(\max[\,O(z_i^0)-O(z_i^0+t),O(z_i^0)-O(z_i^0-t),0]\right)^2}$$

Z.S., PRD 66, 075011 (2002);
Z.S., P. Nadolsky, eConf C010630, P511 (2002);
eConf C010630, P510 (2002)

- In t-channel single top production, the b PDF uncertainty is $3\times$ any other theory error
- Large W' masses means large-x/large-Q^2

Mass (GeV)	$\sigma^t_{\rm LO}$ (fb)	$\sigma^{\bar t}_{\rm LO}$ (fb)	$\sigma^t_{\rm NLO}$ (fb)	$\sigma^{\bar t}_{\rm NLO}$ (fb)
500	27000	12800	$35300\ ^{+1300}_{-2300}$	$16800\ ^{+910}_{-1200}$
750	6230	2510	$7780\ ^{+600}_{-380}$	$3260\ ^{+230}_{-290}$
1000	1890	667	$2320\ ^{+170}_{-200}$	$860\ ^{+96}_{-78}$
1250	668	212	$800\ ^{+52}_{-79}$	$273\ ^{+37}_{-26}$
1500	259	75.5	$302\ ^{+29}_{-30}$	$98.0\ ^{+16.2}_{-10.9}$
1750	106	29.3	$122\ ^{+11}_{-14}$	$38.8\ ^{+6.1}_{-5.6}$
2000	45.5	12.2	$50.9\ ^{+5.7}_{-6.5}$	$16.5\ ^{+2.7}_{-2.8}$
2250	20.1	5.34	$22.1\ ^{+3.0}_{-2.9}$	$7.41\ ^{+1.45}_{-1.26}$
2500	9.17	2.49	$10.0\ ^{+1.5}_{-1.5}$	$3.55\ ^{+0.71}_{-0.66}$
2750	4.37	1.24	$4.79\ ^{+0.81}_{-0.67}$	$1.80\ ^{+0.38}_{-0.33}$
3000	2.20	0.66	$2.48\ ^{+0.41}_{-0.35}$	$0.98\ ^{+0.19}_{-0.18}$
3250	1.19	0.38	$1.40\ ^{+0.21}_{-0.20}$	$0.57\ ^{+0.11}_{-0.09}$

8 TeV

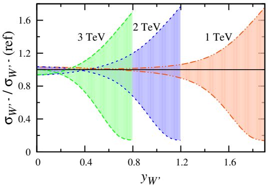
+-9% PDF

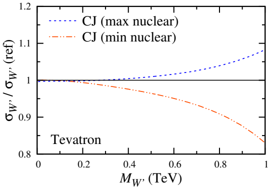
+-23% PDF

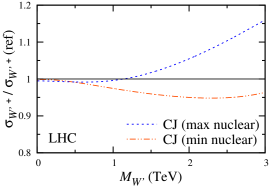
Investigating the initial state: Nuclear corrections

L.T. Brady, A. Accardi, W. Melnitchouk, J.F. Owens, JHEP 1206, 019 (2012)

- $x \sim \frac{M_{W'}}{\sqrt{S}} e^{|y|}$
- Uncertainties are not uniform in the detector.







- This leads to *additional* uncertainty in the extraction of g'/g_{SM}.

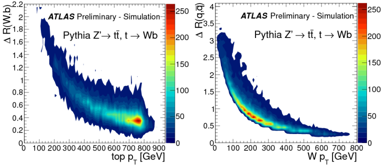
Uncertainties in *nuclear* corrections to deuterium DIS affect the large-x d PDF. Even at $\sqrt{S} = 8$ TeV!

Constraining nuclear uncertainties in large-x F_2^n at Jefferson Lab will have an important impact on LHC searches.

Investigating the final state: boosted top jets

For large W' mass the top quark is highly boosted

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



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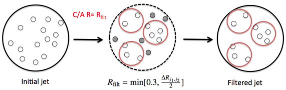
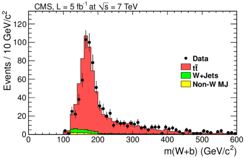
Many "boosted top" algorithms have been developed:

Filtering	Butterworth et al. PRL 100 (2008)
Pruning	Ellis et al. PRD 80 (2009)
Trimming	Krohn et al. JHEP 1002 (2010)
Mass-drop	Butterworth et al. PRL 100 (2008)
JHU tagger	Kaplan et al. PRL 101 (2008)
HEP tagger	Plehn et al. JHEP 1010
tree-less	Jankowiak et al. JHEP 1106
y-splitter	Butterworth et al. PRD 55 (2002)
energy flow	Thaler, Wang JHEP 0807
N-subjettiness	Kim PRD 83 (2011), Thaler et al. JHEP 1103
Shower decon.	Soper et al. 1102.3480
Multivariate	Gallicchio et al. JHEP 1104
Template	Almeida et al. PRD 82 (2010)

The basic idea is to create a fat (large ΔR) jet, and find identifiable clustered substructure we can associate with hadronic top decays.

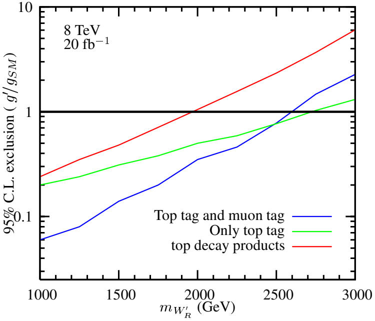




Can we improve W' searches with boosted tops?

D. Duffty, ZS, arXiv:1301.xxxx

Preliminary



Factor 2 improvements in g'/g_{SM}!

Challenges

- Full detector simulations are too optimistic for top tagging efficiency, and fake rates

  Here we use the top tagging efficiency *measured* by CMS

- Muon tagging the b jet $\Rightarrow$ great S/B

  What control sample should be used to normalize B?

- Wjj/Zjj fixed order matrix elements may be insufficient to model kinematics

  We are checking this last point now

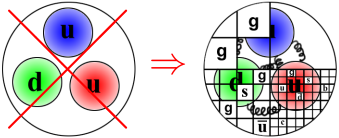
If this holds, we may be able to rule out most perturbative models with $M_{W'}$ below 2 TeV!

We will also learn about backgrounds to these substructure measurements.

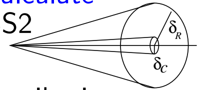
Conclusions

Single-top-quark production is the new DIS and Drell-Yan

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

- 

  — b/c are inside the proton
  — Analytic structure gives direct kinematical insight
  ⇒ New processes & new questions
- 3 mathematical techniques developed to calculate exclusive jet observables: MDF, PSS1, PSS2



- The "paradigm of jet calculations"
  Exclusive NLO calculations intrinsically describe jets, not quarks.

The search for W' production pushes our understanding

- Jet substructure (e.g., top-jets) and its backgrounds will need much deeper investigation
- Large-x physics (e.g., at JLAB) will provide increasingly important constraints on LHC physics reach

THANK YOU

ISMD2013

XLIII International Symposium on Multiparticle Dynamics

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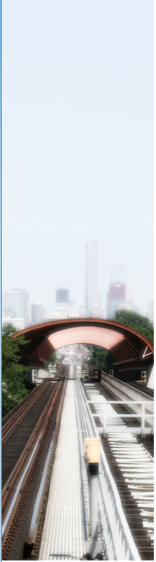

The International Symposium on Multiparticle Dynamics (ISMD) is a major international high-energy conference which attracts participants (theorists and experimentalists) with a common interest in reactions involving a large number of particles. The XLIII International Symposium on Multiparticle Dynamics will be organized in September 2013 by the HEP ANL division together with the Illinois Institute of Technology (IIT, Chicago) and Northwestern University (Chicago). The goal is to provide a truly international forum for discussion and presentations of recent experimental results from the LHC, Tevatron and other experiments as well as new developments in theory. ISMD symposiums typically involve about 120 participants and include about 100 plenary presentations with a good balance between experimental and theoretical talks spread over 5 1/2 days. The Symposium will comprise several sessions, with each session started by an overview talk and followed by topical contributions. The following sessions are planned: "High-pT QCD", "High-pT electroweak physics" (including Higgs), "Soft QCD", "Diffraction" and "Heavy-ion collisions". Special session will be held with overview talks on the "Intensity Frontier" and Snowmass2013

September 15-20, 2013

at

The Illinois Institute of Technology

I hope to hear more from Jefferson Lab about your impressive program

(http://atlaswww.hep.anl.gov/ismd13/)

W' bosons are a general prediction

For each [SU(2)⊗U(1)] that is broken, there will be a new massive charged vector W'.
$M_{W'} \approx \frac{f}{2}\sqrt{g_i^2+g_j^2}$ with $f < 1$ TeV$\left[\frac{m_H}{200\mathrm{GeV}}\right]^2$.

Couplings to fermions

The Lagrangian $\mathcal{L} = -i\frac{g'}{2\sqrt{2}} V_{ij} W'_\mu \bar{q}^i_L \gamma^\mu (1-\gamma_5) q^j_L$,
where $g' =$ is $g_{SM} F(g_1, g_2, \ldots, g_n)$.
For [SU(2)⊗U(1)]^2 (a.k.a. Littlest Higgs), $F = \frac{g_1}{g_2}$.
Note: The coupling $W' \bar{T}_L b_L$ has $F = \frac{g_1}{g_2}\frac{vx_L}{f}$, where $\frac{vx_L}{f} = \sqrt{2(1-V_{tb}/V_{tb}^{SM})}$.
Single-top tells us this is small.

An important constraint is the measured $g_{SM} = 0.6529$.

$$\frac{1}{g_1^2} + \frac{1}{g_2^2} + \cdots + \frac{1}{g_n^2} = \frac{1}{g_{SM}^2} \approx \frac{1}{0.426}$$

Thus, $g_{SM} < g_{1,2,\ldots} < 4\pi$ (upper limit of effective theory).
$\Rightarrow$ For all Little Higgs models there will be at least 1 W' with $0.184 < g'/g_{SM} < 5.43$, and preferentially $g'/g_{SM} \sim 1$.