Top-quark production at the LHC

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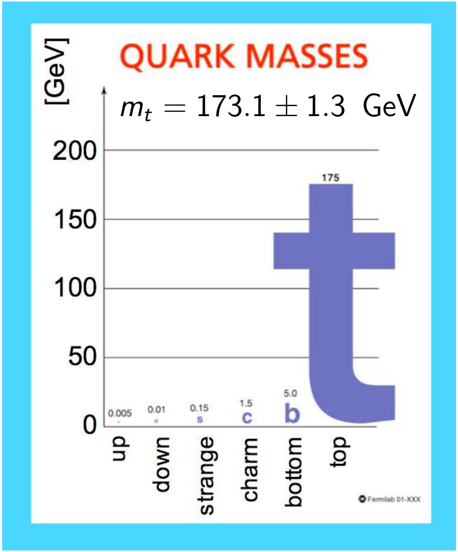
Les Houches, February 17, 2011

The Top Quark



A particle which tends to stick out...

- elementary particle according to SM, but almost as heavy as a gold atom
- because of its large mass, the top quark couples strongly to the electroweak breaking sector $\Rightarrow$ important in many BSM scenarios
- m_t an important input in electroweak fits
- decays before hadronizing, can be studied as a "bare" quark

The Tevatron and the LHC

Top physics mature, thanks to Tevatron

- discovered in 1995, few thousand top-pairs analyzed ($\sigma^{t\bar{t}} \sim$ 7pb)
- many measurements: m_t, $\sigma^{t\bar{t}}$, differential distributions
- single top production observed in 2009
- experimental errors statistics limited

At the LHC millions of top quarks will be produced

- $\sigma(s = 7\ \mathrm{TeV}) \sim 150$ pb, $\sigma(s = 14\ \mathrm{TeV}) \sim 900$ pb
- top sample at LHC will surpass Tevatron in 2011
- expect single top discovery in 2011
- in long run, top-quark properties will be precision physics

First LHC measurements now published

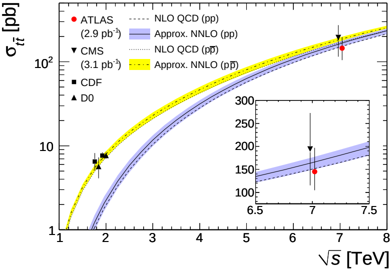


Figure from ATLAS, arXiv:1012.1792v2

ATLAS: 37 top candidates in semi-leptonic/di-lepton channels

$$\sigma_{t\bar{t}} = 145 \pm 31^{+43}_{-27}\mathrm{pb}$$

CMS: 11 top candidates in di-lepton channel

$$\sigma_{t\bar{t}} = 194 \pm 72 \pm 24 \pm 21\mathrm{pb}$$

LHC goal: $\delta\sigma/\sigma \sim 5\%$

Outline

1) Top-quark pair production

- status of QCD calculations
- some measurements and physics implications

2) Single top production

Production and decay

Almost immediately after production, decays as $t \to bW^+$ (99% of time).

$$p\bar{p}, pp \to t\bar{t}\,X \to \begin{cases} \ell^+ + \ell'^- + j_b + j_{\bar{b}} + p_T^{miss} + n \geq 0 \text{ jets} \\ \ell^\pm + j_b + j_{\bar{b}} + p_T^{miss} + n \geq 2 \text{ jets} \\ j_b + j_{\bar{b}} + n \geq 4 \text{ jets} \end{cases}$$

- can factorize $\sigma = \sigma_{\text{prod}}^{t\bar{t}X} \times \sigma_{\text{decay}}$, corrections are order $\Gamma_t/m_t \sim 0.01$

Will focus on production, but decay is important, and must include it to compare theory and experiment

Factorization for inclusive production

Factorization for $h_1 h_2 \to t\bar{t}X$:

$$d\sigma_{h_1,h_2}^{t\bar{t}X} = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i^{h_1}(x_1,\mu_F) f_j^{h_2}(x_2,\mu_F) d\hat{\sigma}_{ij}(s, m_t, \alpha_s(\mu_R), \mu_F, \mu_R)$$

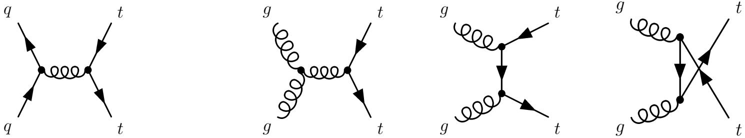
$$s_{\text{had}} = (p_{h_1} + p_{h_2})^2 \ , \ s = x_1 x_2 s_{\text{had}}$$

Strategy:

- take PDFs from data
- calculate partonic cross sections $d\hat{\sigma}_{ij}$ in QCD

Feynman diagrams for $d\hat{\sigma}_{ij}$

Born level:



- $q\bar{q}$ dominant at Tevatron ($\sim$ 90% of cross section)
- gg dominant at LHC ($\sim$ 75% of cross section at 7 TeV)

Higher-order corrections:

- virtual corrections and real emission
- $(qg, \bar{q}g) \to t\bar{t}X$ (numerically small)

NLO calculations

NLO calculations of total and differential cross sections known for 20 years
Nason, Dawson, Ellis ('88-'90); Beenakker, Kujif, van Neerven, Smith, Schuler ('89-'91); Mangano, Nason, Ridolfi ('92), Czakon and Mitov ('08)

- implemented in numerical parton MC programs; MCFM, MadGraph
- or including parton showers; MC@NLO, etc.

NLO calculations have roughly 15% factorization and renormalization scale uncertainties, to make full use of LHC data should go beyond them

Beyond NLO I: soft gluon resummation

An "easy" way to improve on NLO is soft gluon resummation

Key quantity for NNLL resummation is 2-loop soft anomalous dimension matrix, obtained from UV poles in collinear and soft Wilson line operators in SCET (see e.g. Ferroglia, BP, Neubert, Yang '09)

(Differential) cross sections known to NLO+NNLL$\leftrightarrow$NNLO$_{\rm approx}$ for three different soft limits:

- $d^2\sigma/dM_{t\bar{t}}d\cos\theta$: $(1 - M_{t\bar{t}}^2/\hat{s} \to 0)$
  Ahrens, Ferroglia, BP, Neubert, Yang '10
- $d^2\sigma/dp_T dy$: $(s_4 = \hat{s} + \hat{t}_1 + \hat{u}_1 \to 0)$
  Kidonakis '10
- σ: $(\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0)$
  Langenfeld, Moch, Uwer '08, '09; Beneke et. al. '09

These calculations favor upper range of NLO error band for σ, with reduced scale uncertainties

BEYOND NLO II: NNLO IN FIXED ORDER

$$d\sigma^{\rm NNLO}_{t\bar{t}+X} = d\sigma^{\rm VV} + d\sigma^{\rm RV} + d\sigma^{\rm RR}$$

Many partial results in fixed order

- $d\sigma^{\rm VV}$: Czakon, Mitov, Moch; Bonciani, Ferroglia, Gehrmann; Neubert, BP, Yang; Kniehl, Korner, Merebashvili, Rogal ...
- $d\sigma^{\rm RV}$ (1-loop $t\bar{t}+j$): Dittmaier, Uwer, Weinzierl '07; Bevilacqua,Czakon, Papadolpoulos, Worek '10; Melnikov, Schulze '10
- $d\sigma^{\rm RR}$: Czakon '11

Need to combine the different pieces, now looks feasible!

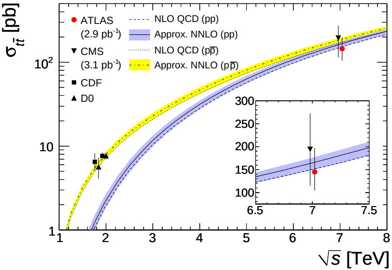
Top production: some key observables

This talk

- total cross section
- $t\bar{t}$ invariant mass distribution
- charge asymmetry

Will skip many others

- p_T, rapidity distributions, ...
- spin correlations



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How can this be used (other than subtracting $t\bar{t}$ background)?

THE TOTAL CROSS SECTION $\sigma^{t\bar{t}X}(s = 7\ \mathrm{TeV})$ AND PDF UNCERTAINTIES

	σ (pb)	δσ (pb)	comment
ABKM09	139.55	7.96	combined PDF and α_s
CTEQ6.6	156.2	8.06	combined PDF and α_s *
GJR08	169	6	PDF only
HERAPDF1.0	147.31	+5.18 -13.76	combined PDF and α_s**
MSTW08	168.1	+7.2-6.0	combined PDF and α_s***
NNPDF2.0	169	7	combined PDF and α_s****

m_{top}= 171.3 GeV
zero width approximation,
no branching ratios
68% cl uncertainties
scales $\mu_F = \mu_R = m_{top}$

* ±6.63 (PDF) ±4.59 (α_s)
** expt.+model+param.+α_s, see report for details
*** +4.7-5.6 (PDF) +3.8-4.6 (α_s)
**** ±6 (PDF) ±4 (α_s)

PDF4LHC Working Group Interim Report, arXiv:1101.0536 (January 2011) 37

Stirling, Heavy Particles at LHC, Zurich '11

- predictions range between 131-175pb at 68% CL (difference due mainly to gluon distribution at $x \sim 2m_t/\sqrt{s}$)
- measurement of $\sigma^{t\bar{t}X}(s = 7\ \mathrm{TeV})$ important for discriminating PDF sets

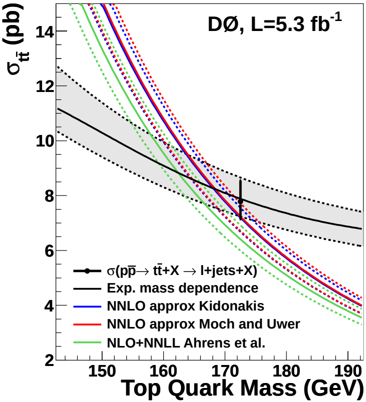


Figure from D0 in lepton+jets, arXiv:1101.0124

Can extract pole mass through cross section, but ...

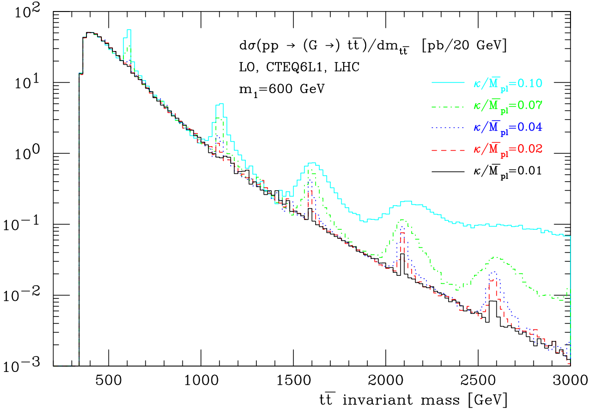
- NNLO would be very useful
- better to use a short-distance mass such as $\overline{\mathrm{MS}}$ (improved convergence of perturbative series, no renormalon ambiguity)

  Langenfeld, Moch, Uwer '09

- total cross section
- $t\bar{t}$ invariant mass distribution
- charge asymmetry

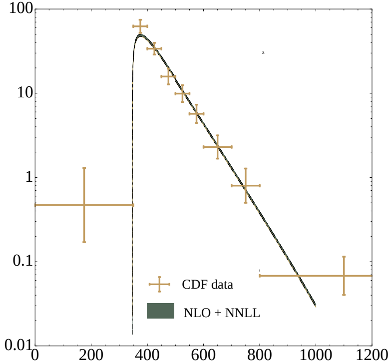
Invariant mass distribution

The distribution in the invariant mass $M_{t\bar{t}}^2 = (p_t + p_{\bar{t}})^2$ can be used to search for *s*-channel heavy resonances



Frederix and Maltoni ('07)

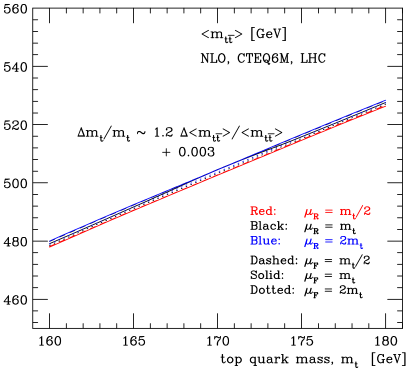
Invariant mass distribution at Tevatron



- good agreement with between theory and data at Tevatron

- Tevatron result: no $t\bar{t}$ resonances to 900 GeV
- LHC will extend reach to higher energies

Invariant mass distribution and m_t



Frederix and Maltoni ('07)

Mean invariant mass

$$\langle M_{t\bar{t}} \rangle = \int^{M_{\rm cutoff}} \mathrm{d}M_{t\bar{t}}\, M_{t\bar{t}} \frac{d\sigma}{dM_{t\bar{t}}}\bigg|_{\rm norm.}$$

- theory errors can be reduced compared to total cross section
- example: 1% measurement of $\langle M_{t\bar{t}} \rangle \Rightarrow \delta m_t / m_t \sim 1.3\%$

- total cross section
- $t\bar{t}$ invariant mass distribution
- charge asymmetry

CHARGE ASYMMETRY IN $pp(\bar{p}) \to t\bar{t}X$

Charge asymmetry:

$$A^c = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)}$$

- Tevatron: $N_{\bar{t}}(y) = N_t(-y)$, so is a forward-backward symmetry
- asymmetry depends on the frame

QCD predictions:

- Tevatron: $A^c \sim 5\%$ is NLO (α_s^3) effect from $q\bar{q}$ channel
- LHC: $A^c = 0$, since initial pp state is symmetric

Inclusive charge asymmetry at the Tevatron

DO, 4.3fb^{-1}

$$A_c(\mathrm{t\bar{t}}) = 0.08 \pm 0.08 \text{ stat} \pm 0.01 \text{ syst}$$

CDF, 5.3fb^{-1}

$$A_c(\mathrm{t\bar{t}}) = 0.158 \pm 0.072 \text{ stat} \pm 0.017 \text{ syst}$$
$$A_c(\mathrm{lab}) = 0.150 \pm 0.050 \text{ stat} \pm 0.024 \text{ syst}$$

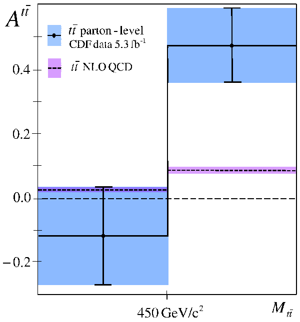
Theory

$A_c(\mathrm{lab}) = 0.051 \pm 0.006$ (NLO+EW, Kuhn, Rodrigo '98)

$A_c(\mathrm{t\bar{t}}) = 0.078 + 0.011 - 0.007$ (NLO+NNLL, Ahrens et. al. '10)

Theory and experiment agree at about 2σ

Invariant mass dependent asymmetry at Tevatron (CDF arXiv:1101:0034)



- $M_{t\bar{t}} < 450$ GeV: compatible with NLO within 1σ
- $M_{t\bar{t}} > 450$ GeV: disagrees with NLO at 3.4σ

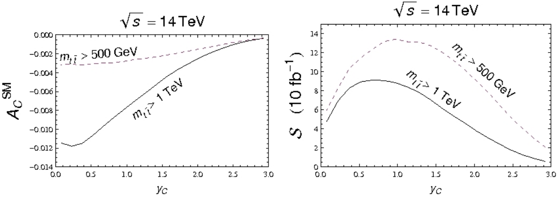
Charge asymmetry at the LHC

Integrated asymmetry vanishes.

Use cuts on y

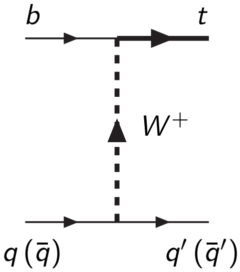
$$A_C(y_C) = \frac{N_t(|y| < y_C) - N_{\bar{t}}(|y| < y_C)}{N_t(|y| < y_C) + N_{\bar{t}}(|y| < y_C)}$$

To reduce gg contribution to denominator (charge symmetric), also use cuts on $M_{t\bar{t}}$

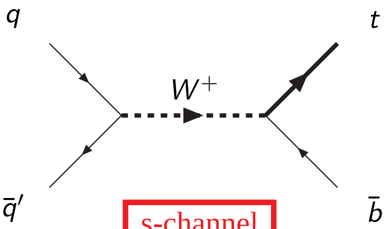


Ferrario and Rodrigo ('08)

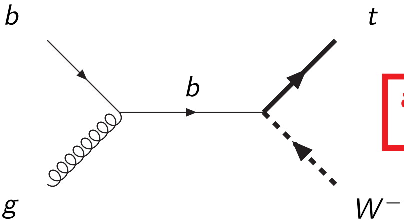
Single Top Quark Production



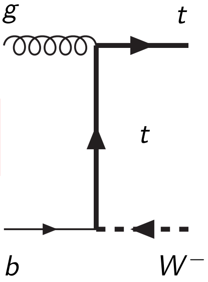
t-channel



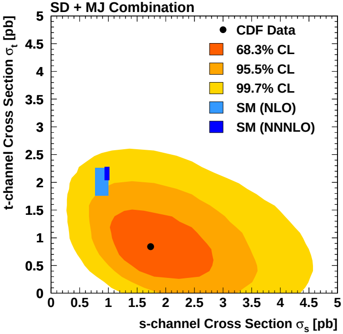
s-channel

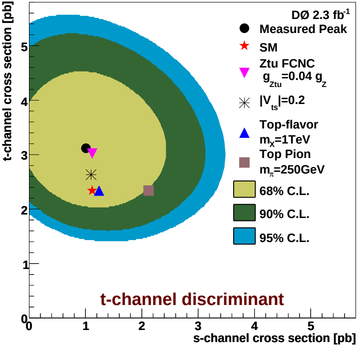


associated tW production



Single top production at the Tevatron II: separate s and t channel





- Good overall agreement with SM, although CDF has 2σ discrepancy in t channel
- can extract $|V_{tb}| = 0.88 \pm 0.07$ ($|V_{tb}| = 0.999$ from unitarity of CKM matrix)

Summary

Top physics mature field due to Tevatron

- many measurements, many agreements with SM
- couple $2-3\sigma$ deviations
  - FB asymmetry (especially with cut $M_{t\bar{t}} > 450$GeV)
  - t-channel single top at CDF
- most measurements statistics limited

At LHC statistics will not be a factor, many interesting measurements to come ...