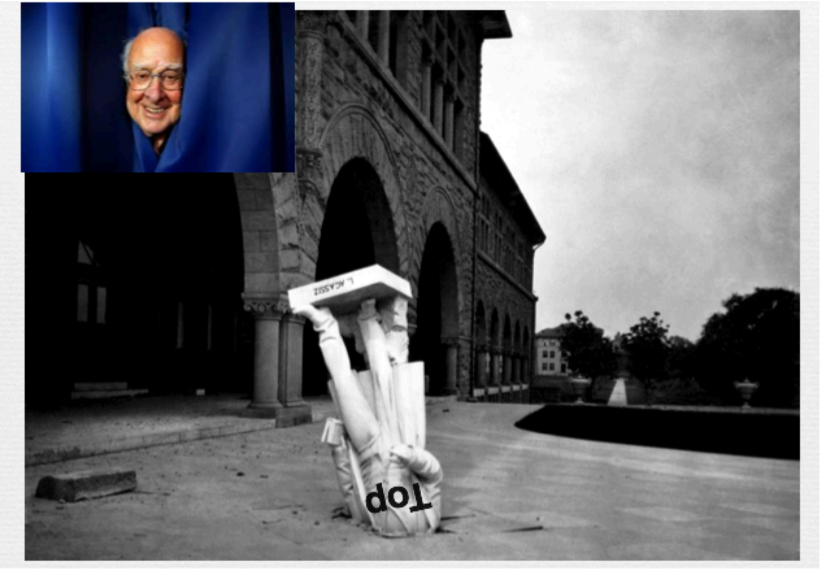
Top Theory

Ben Pecjak

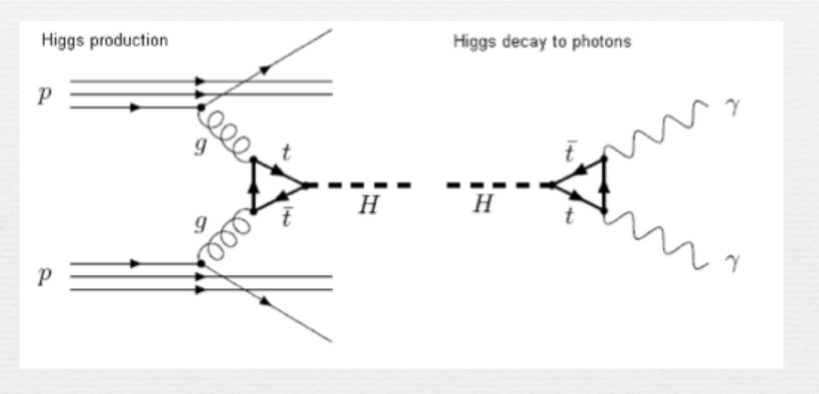
Durham University

Oxford, November 14, 2013

Top hits bottom?

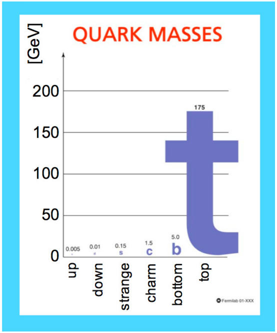


Still, top is a matter of life and death for the Higgs



Thanks/blame to Eric Laenen for graphics/puns

Why top?



Top is special because of large mass $m_t \sim 173$ GeV

- plays special role in many BSM models
- decays before hadronizing and losing spin information: "free quark" [Bigi, Dokshitzer, V.A. Khoze, Kuhn, Zerwas '86]
- $\alpha_s(m_t) \ll 1$: can use perturbation theory

Why top now?

1) Tevatron: Top is relatively unstudied ($\sigma_{t\bar{t}X} \sim 7$pb)

- discovered 20 years ago at Tevatron but limited statistics on many measurements
- 1 pair per day produced

2) LHC: Top is everywhere ($\sigma_{t\bar{t}X} \sim 160$pb at LHC7, ~ 900pb at LHC14)

- top sample at LHC already surpassed Tevatron!
- 1 pair per second at LHC14
- top-related processes significant background for new physics searches

The LHC is a top factory

Two years of LHC: the total cross section

Winter 2010

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

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

CMS: 11 top candidates in di-lepton channel

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

Winter 2012

ATLAS: combined channels with integrated luminosity 0.7-1.0 fb^{-1}

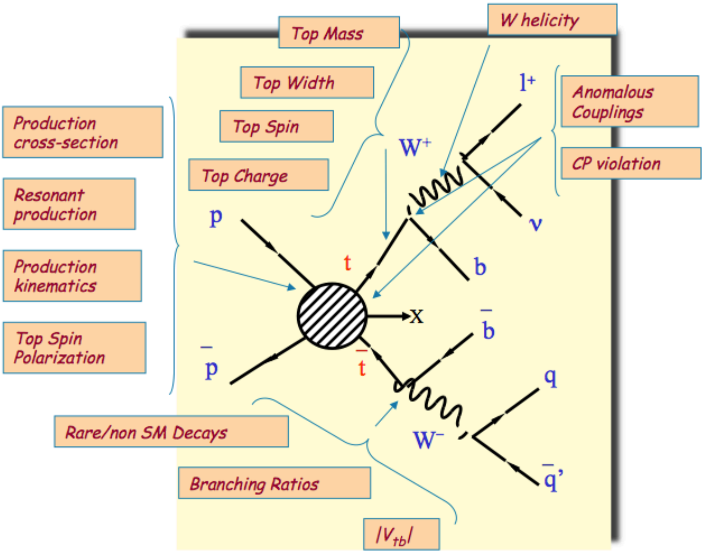
$$\sigma_{t\bar{t}} = 177 \pm 3(\text{stat.}) \pm 8(\text{syst.}) \pm 7(\text{lum.})\text{pb}$$

CMS: combined channels with integrated luminosity 0.8-1.1 fb^{-1}

$$\sigma_{t\bar{t}} = 166 \pm 2(\text{stat.}) \pm 11(\text{syst.}) \pm 8(\text{lum.})\text{pb}$$

- Progress happens fast for bread and butter measurements, and quickly extending beyond...!!
- Goal for talk: give snapshot of selected topics, shaped by my interests/knowledge/IPPP colleagues

The assembly line of top properties



Outline

1) Top-quark pair production: some basics and the total cross section

2) Boosted top production: exploring a new regime at LHC

3) FB and charge asymmetries at the Tevatron and LHC

- observables and SM calculations
- new physics

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

$$d\sigma^{t\bar{t}X}_{h_1,h_2} = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i^{h_1}(x_1,\mu_F) f_j^{h_2}(x_2,\mu_F) d\hat{\sigma}_{ij}\left(\hat{s}, m_t, \ldots, \alpha_s(\mu_R), \mu_F, \mu_R\right) + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_t}\right)$$

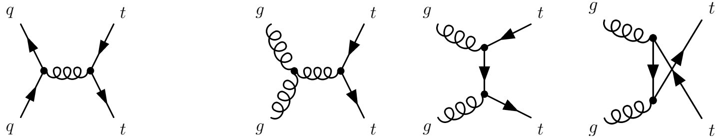
$$s = \left(p_{h_1} + p_{h_2}\right)^2 \,,\; \hat{s} = x_1 x_2 s$$

Strategy:

- take PDFs from data (PDF set collaborations)
- calculate partonic cross sections $d\hat{\sigma}_{ij}$ in QCD (Feynman diagrams)

$$d\hat{\sigma}_{ij} = \alpha_s^2 d\hat{\sigma}^{(0)}_{ij} + \alpha_s^3 d\hat{\sigma}^{(1)}_{ij} + \ldots$$

FEYNMAN DIAGRAMS FOR $d\hat{\sigma}_{ij}$



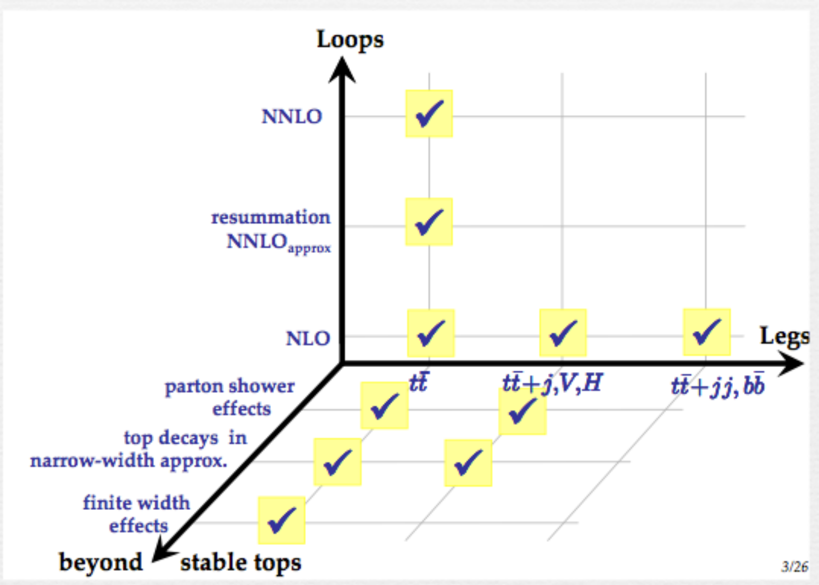
- $q\bar{q}$ dominant at Tevatron ($\sim$ 90% of cross section)
- gg dominant at LHC ($\sim$ 75% of cross section at 7 TeV)

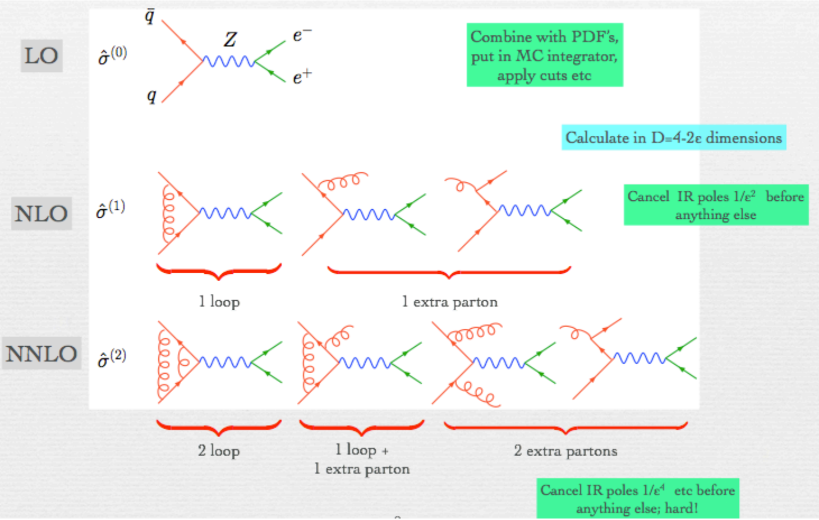
Higher-order corrections:

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

NLO known for 20 years, has been much recent progress in higher-orders. Relevant framework and status (fixed-order, parton showers, analytic resummation, etc.) depends on observable.

Top pairs (plus stuff) in 3D [Schulze]




LO
$\hat{\sigma}^{(0)}$
$\bar{q}$
Z
e^-
e^+
q
Combine with PDF's, put in MC integrator, apply cuts etc
Calculate in D=4-2ε dimensions
NLO
$\hat{\sigma}^{(1)}$
Cancel IR poles $1/\varepsilon^2$ before anything else
1 loop
1 extra parton
NNLO
$\hat{\sigma}^{(2)}$
2 loop
1 loop + 1 extra parton
2 extra partons
Cancel IR poles $1/\varepsilon^4$ etc before anything else; hard!

Total cross section at NNLO in fixed order: steps forward

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

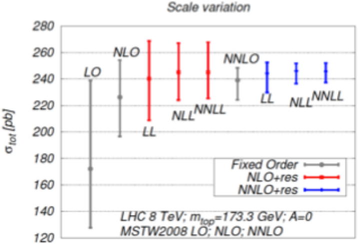
Many partial results in fixed order

- $\hat{\sigma}^{\rm VV}$: Czakon, Mitov, Moch; Bonciani, Ferroglia, Gehrmann, Maitre, Manteuffel, Studerus; Kniehl, Korner, Merebashvili, Rogal ...
- $\hat{\sigma}^{\rm RV}$ (1-loop $t\bar{t}+j$): Dittmaier, Uwer, Weinzierl '07; Bevilacqua,Czakon, Papadolpoulos, Worek '10; Melnikov, Schulze '10; Gehrmann-De Ridder, Glover, Pires '11
- $\hat{\sigma}^{\rm RR}$: Czakon '11; Abelof, Gehrmann-De Ridder '11

Total cross section at NNLO

Total cross inclusive cross section now known at NNLO!!!

[Baernreuther, Fiedler, Mitov, Czakon '13]



Concurrent uncertainties:

Scales	~ 3%
pdf (at 68%cl)	~ 2-3%
α_s (parametric)	~ 1.5%
m_{top} (parametric)	~ 3%

Soft gluon resummation makes a difference:

5% -> 3%

- first ever NNLO calculation for 2→2 process
- allows full use of impressive precision on experimental cross section
- many applications possible: m_t extraction, α_s extraction, PDFs, etc...
- expect NNLO differential cross sections and A_{FB} sometime in near future...

Outline

1) Top-quark pair production: some basics and the total cross section

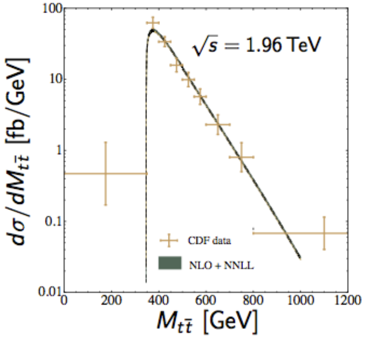
2) Boosted top production: exploring a new regime at LHC

3) FB and charge asymmetries at the Tevatron and LHC

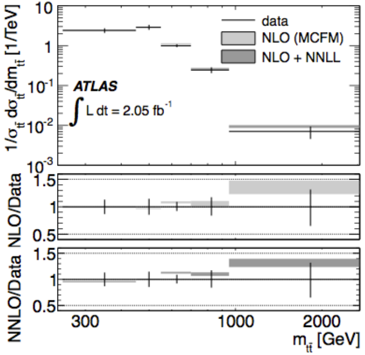
- observables and SM calculations
- new physics

Tevatron vs. LHC: differential cross sections

Tevatron $\sqrt{s} \approx 2 \; TeV$



LHC: $\sqrt{s} = 7 \; TeV$



- LHC has data in "boosted regime" $M_{t\bar{t}} \gg m_t$, $p_T^t \gg m_t$, etc
- not just "corner of phase space": important for new physics searches

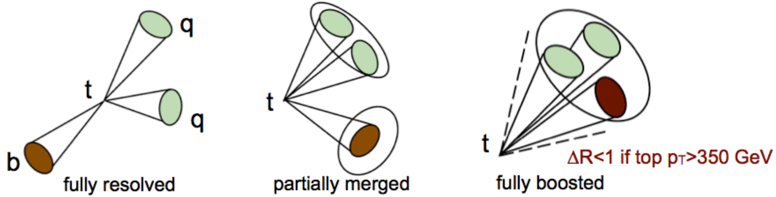
Boosted top production: the complications

Two problems arise for boosted production

1) how to find the boosted tops in the first place
2) how to calculate the production cross sections reliably

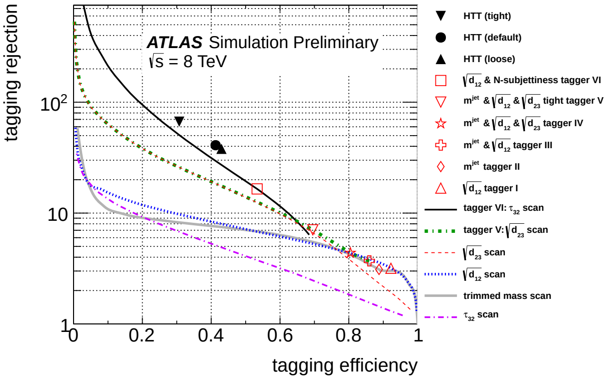
Finding boosted tops: jet substructure and tagging

- In high p_T regime, decay products of top are collimated
  (overlapped objects, reduced combinatorics, large-area jets wi
- New techniques of identifying/reconstructing top are needed



- To the observer, a high-p_T top is a fat jet
- Inside, we can see substructure specific to top decays, use as tagger
- Many methods available, some of which are now being used/studied at LHC

Results from taggers (they work)



- signal is top jet created from Z' decay, background is QCD jets
- methods work to varying degrees of efficiency (in this plot top-right is "good", so in this example HTT = HEP tagger [Plehn, Spannowsky, Takeuchi, D. Zerwas] is best)

When fixed order fails: boosted tops and large logarithms

Consider very large pair invariant mass where $\tau = M_{t\bar{t}}^2/s \to 1$

$$\frac{d\sigma}{dM_{t\bar{t}}}(s, m_t, M_{t\bar{t}}) = \sum_{i,j} \int_\tau^1 \frac{dz}{z}\, ff_{ij}(\tau/z, \mu_f)\, \frac{d\hat{\sigma}_{ij}}{dM_{t\bar{t}}}(z, m_t, M_{t\bar{t}}, \mu_f)$$

$$ff_{ij}(y, \mu_f) = \int_y^1 \frac{dx}{x}\, f_{i/h_1}(x, \mu_f)\, f_{j/h_2}(y/x, \mu_f)$$

Two kinds of large logarithms appear:

- soft logs: $\ln(1-z)$ $\quad (z \equiv M_{t\bar{t}}^2/\hat{s})$
- small-mass (collinear) logs: $\ln m_t/M_{t\bar{t}}$

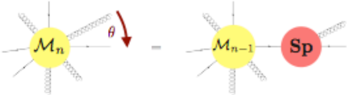
Fixed-order perturbation theory fails if, e.g. $\alpha_s \ln(m_t/M_{t\bar{t}}) \sim 1$

Can use effective field theory to factorize scales and resum large logarithms

QCD made simple

Interplay of soft and collinear emissions is characteristic for high-energy processes. In both limits interactions simplify:

- Collinear limit, where multiple particles move in a similar directions



- Soft limit, in which particles with small energy and momentum are emitted. Eikonal interactions.

At the same time the cross sections are enhanced in these regions.

All resummations rely in one way or another on these simplifications

Factorization for boosted top production

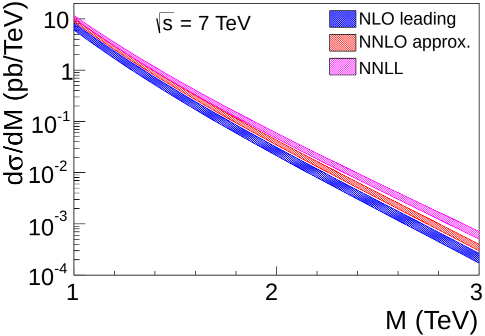
[Ferroglia, BP, Yang '12]

When $m_t \ll M$ and $(1-z) \ll 1$

$$\frac{d\hat{\sigma}}{dM} \sim \mathrm{Tr}[H(M,\mu)S(M(1-z),\mu)] \otimes C_D^2(m_t,\mu)S_D^2(m_t(1-z),\mu) + \mathcal{O}(1-z) + \mathcal{O}\left(\frac{m_t^2}{M^2}\right)$$

- cross section completely factorized into one-scale functions
- starting point for NNLL resummation of both types of logs
- all functions are known to NNLO: most complete approximation to date
- factorization and resummation for $p_T \gg m_t$ has also been worked out [Ferroglia, Marzani, BP, Yang '13]

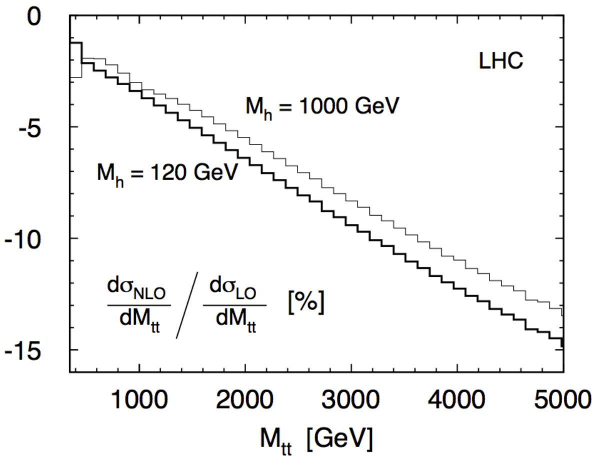
Fixed order vs. soft gluon resummation



- fixed order converges well at smaller M
- fixed order does not converge at higher M and resummation is mandatory
- NNLL is soft-gluon resummation only, resummation of $\ln m_t/M$ terms can be included using results of [Ferroglia, BP, Yang '12]

Electroweak corrections

- electroweak corrections to total cross section are small: $\sim 1-2\%$.
- but can have sizable effect on boosted production [Kuhn,Sharf,Uwer '06]



NLO MC Event generators

[Frederix Top2013]

- The most important development is that NLO computations, matched to parton showers, are now completely automated:
  - **Sherpa** + external tools and
  - **aMC@NLO** (based on madgraph5)
  - (In POWHEL many ttbar+X (X=W,Z,j,bb~) implemented by hand)

Comments

- obviously an invaluable tool for experiment
- an important element of generators is parton shower resummation (LL). would be interesting to compare in more detail with the NNLL analytic resummations for boosted top production.

Outline

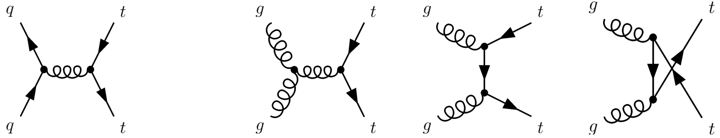
1) Top-quark pair production: some basics and the total cross section

2) Boosted top production: exploring a new regime at LHC

3) FB and charge asymmetries at the Tevatron and LHC

- observables and SM calculations
- new physics

Born level QCD graphs for $pp(\bar{p}) \to t\bar{t}X$



$$\frac{d\sigma^{\text{Born}}_{q\bar{q}}}{d\cos\theta_t} = f_{q\bar{q}}(\cos^2\theta_t); \qquad \frac{d\sigma^{\text{Born}}_{gg}}{d\cos\theta_t} = f_{gg}(\cos^2\theta_t)$$

QCD amplitudes are forward-backward symmetric at LO in α_s

- FB asymmetries are small in SM, so the Tevatron measurements are a legitimate hint at new physics
- quantifying "small in SM" is challenging but important

FB asymmetry definitions for Tevatron

1) Top-quark asymmetry in frame i

$$A^i_{\mathrm{FB}} = \frac{N_t(y^i_t > 0) - N_t(y^i_t < 0)}{N_t(y^i_t > 0) + N_t(y^i_t < 0)}$$

- frame-dependent quantity, usually measured in $p\bar{p}$ frame
- at Tevatron $N_t(y) = N_{\bar{t}}(-y)$ so FB asymmetry = charge asymmetry

2) Pair asymmetry (observe $t\bar{t}$ pair with $\Delta y = y_t - y_{\bar{t}}$)

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

- Boost invariant, but same as top-quark asymmetry in $t\bar{t}$ frame

Components of A_{FB} calculations within SM

1) leading QCD contributions calculated in [Kuhn,Rodrigo 1998]

2) (mixed QCD)-electroweak corrections dealt with in [Kuhn, Rodrigo 1998], [Bernreuther, Si 2010], [Hollik, Pagani 2011], [Bernreuther, Si 2012], [Kuhn, Rodrigo 2011]

3) higher-order QCD contributions estimated with soft-gluon resummation

- [Almeida, Sterman, Vogelsang 2008] at NLL for $A_{\mathrm{FB}}^{t\bar{t}}$
- [Ahrens, Ferroglia, Neubert, BP, Yang 2010, 2011] at NNLL for $A_{\mathrm{FB}}^{t\bar{t}}$, $A_{\mathrm{FB}}^{p\bar{p}}$
- [Kidonakis 2011] at NNLL for $A_{\mathrm{FB}}^{p\bar{p}}$

SM results for total FB asymmetries

Theory: (NLO and NLO+NNLL use $\mu = m_t = 173.1$ GeV, MSTW2008 90% CL)

	$A_{\mathrm{FB}}^{t\bar{t}}$ [%]	$A_{\mathrm{FB}}^{p\bar{p}}$ [%]
NLO	$7.32^{+0.69+0.18}_{-0.59-0.19}$	$4.81^{+0.45+0.13}_{-0.39-0.13}$
NLO+NNLL [Ahrens et. al.'11]	$7.24^{+1.04+0.20}_{-0.67-0.27}$	$4.88^{+0.20+0.17}_{-0.23-0.18}$
$\mathrm{NNLO_{approx}}$ [Kidonakis '11]		$5.2^{+0.0}_{-0.6}$
EW'/NLO' ($\mu = m_t$) [Bernreuther, Si '10]	0.05	0.04
EW/NLO ($\mu = m_t$) [Hollik, Pagani '10]	0.22	0.22

- soft-gluon resummation moderate effect for $\mu_f = m_t$
- EW corrections turned out to be quite large!!
- NNLO will be interesting...

Leptonic observables

In real life, the top quarks decay (take dilepton as an example)

$$p\bar{p} \to t\bar{t}X \to \ell^+\ell^- + j_b + j_{\bar{b}} + \cdots + E_T^{\mathrm{miss}}$$

Can also define lepton asymmetries

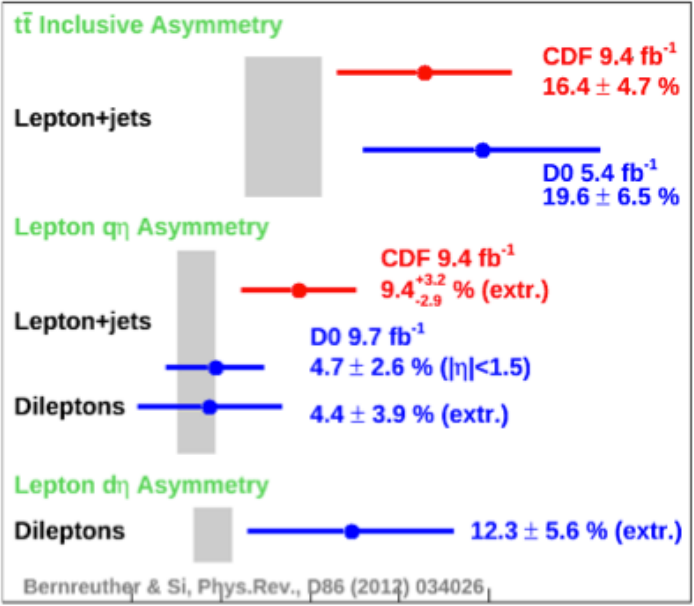
$$A^i_{\mathrm{FB}} = \frac{N_{\ell^+}(y^i_{\ell^+} > 0) - N_{\ell^+}(y^i_{\ell^+} < 0)}{N_{\ell^+}(y^i_{\ell^+} > 0) + N_{\ell^+}(y^i_{\ell^+} < 0)}$$

The asymmetries (with acceptances) can be obtained with NLO+EW calculations [Bernreuther, Si '12] (in on-shell approx.)

$$A^{\ell}_{\mathrm{FB}} = 3.8(3)\%, \quad A^{\ell^+\ell^-}_{\mathrm{FB}} = 4.8(4)\%$$

- full NLO calculation with off-shell top-quarks shows corrections to on-shell approx. are small [Bevilacqua et. al. 2010]
- measurement of leptonic asymmetries with acceptances is a good consistency check on $t\bar{t}$-level results

Current status: theory vs. experiment



- Definition of forward-backward asymmetry of an observable $\mathcal{O}$

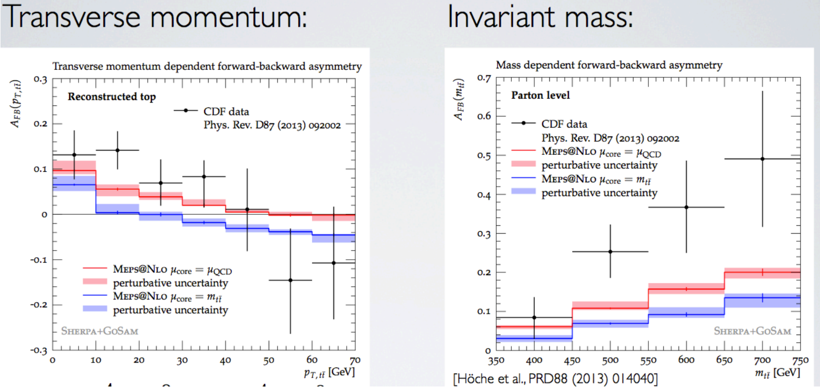
$$A_{\mathrm{FB}}^{t\bar{t}}(O) = \frac{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y>0} - \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}{\left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0} + \left.\frac{\mathrm{d}\sigma_{t\bar{t}}}{\mathrm{d}O}\right|_{\Delta y<0}}$$

- A_{FB} is ratio of expectation values
  $\rightarrow$ conventional scale variations by factor 2 will largely cancel for uncertainty on A_{FB}

$\Rightarrow$ use different functional forms of the scale definition that behave differently in $\Delta y > 0$ and $\Delta y < 0$ for a realistic estimate of uncertainty

- applies to other ratio observables, e.g. normalized observables, as well

MePS@NLO vs. data for differential asymmetries [Hoeche, Huang, Luisoni, Schoenherr, Winter 2013]



- longstanding $2-3\sigma$ discrepancy at high $M_{t\bar{t}}$ remains
- note importance of estimating scale variations with different functional forms

Charge asymmetry at LHC

At LHC pp initial state is symmetric so $A_{\mathrm{FB}} = 0$

But $N_t(y) \neq N_{\bar{t}}(-y)$, so charge asymmetry is not A_{FB}, and even though

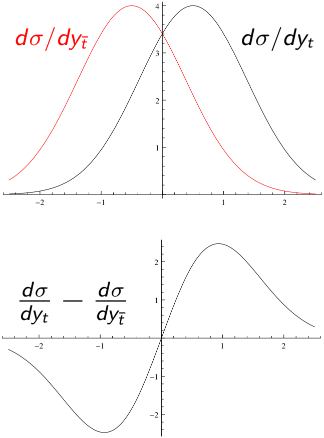
$$A^{pp}_{\mathrm{charge}} = \frac{N_t(y_t > 0) - N_{\bar{t}}(y_{\bar{t}} > 0)}{N_t(y_t > 0) + N_{\bar{t}}(y_{\bar{t}} > 0)} = 0$$

rapidity-distributions of t and $\bar{t}$ not the same locally, due to same partonic graphs which generate A_{FB} at Tevatron

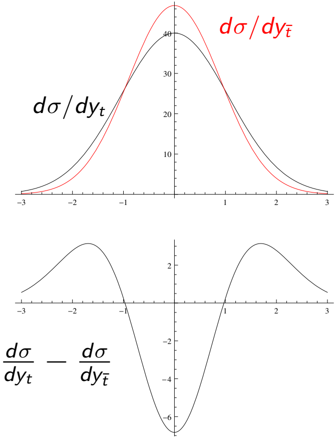
- simplest way to study LHC charge asymmetries is with rapidity cuts (intuitive picture in next two slides)
- optimal way to study LHC charge asymmetry depends on theory model, integrated luminosity and/or $\sqrt{s}$, and systematic errors in different regions of phase space

Rapidity distributions at Tevatron and LHC (schematic)

Tevatron



LHC

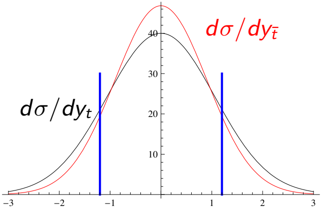


- total charge asymmetry vanishes at LHC, but asymmetry with cuts doesn't because t-quarks are more forward than $\bar{t}$ quarks [Kuhn, Rodrigo '98]

Central and forward charge asymmetries at LHC

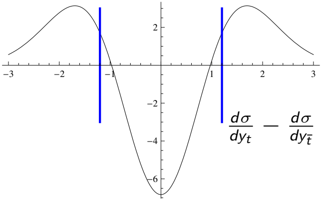
Central charge asymmetry

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



Forward charge asymmetry

$$A_F(y_{\rm cut}) = \frac{N_t(|y| > y_{\rm cut}) - N_{\bar{t}}(|y| > y_{\rm cut})}{N_t(|y| > y_{\rm cut}) + N_{\bar{t}}(|y| > y_{\rm cut})}$$

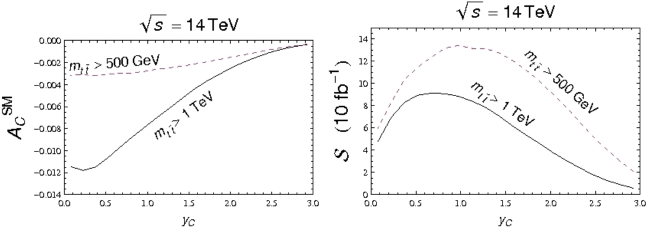


Reducing gg background

Can enhance charge asymmetries by making cuts which probe large x, where $q\bar{q}$ luminosity is higher compared to gg (high $M_{t\bar{t}}$, p_T, etc)

Two examples

- central charge asymmetry ($y < y_C$) with cut $M_{t\bar{t}} > M_{t\bar{t}}^{\min}$ [Ferrario and Rodrigo 2008]

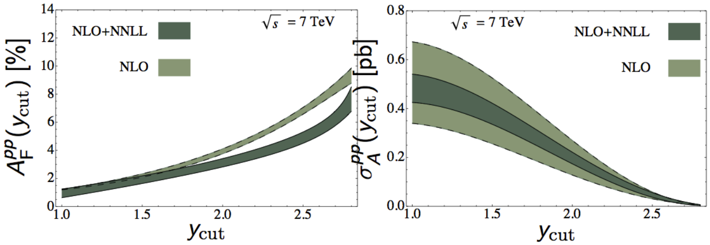


- forward asymmetry ($y_C < y < y^{\max}$) with large y_C [Xiao et. al. 2011]

QCD corrections to the forward asymmetry

$$A_F(y_{\rm cut}) = \frac{N_t(|y| > y_{\rm cut}) - N_{\bar{t}}(|y| > y_{\rm cut})}{N_t(|y| > y_{\rm cut}) + N_{\bar{t}}(|y| > y_{\rm cut})}$$

- QCD corrections can become important in corners of phase space



- NLO very sensitive to whether σ^A/σ^S expanded in α_s, NLO+NNLL more stable [Ahrens et. al. 2011]

ATLAS/CMS definition

$$A_C = \frac{N(|y_t| > |y_{\bar{t}}|) - N(|y_t| < |y_{\bar{t}}|)}{N(|y_t| > |y_{\bar{t}}|) + N(|y_t| < |y_{\bar{t}}|)}$$
$$= \frac{1}{\sigma} \times \int_0^{y_{\max}} d|y_t| \int_0^{|y_t|} d|y_{\bar{t}}| \left\{ \frac{d^2\sigma}{d|y_t|d|y_{\bar{t}}|} - \left. \frac{d^2\sigma}{d|y_t|d|y_{\bar{t}}|} \right|_{|y_t| \leftrightarrow |y_{\bar{t}}|} \right\}$$

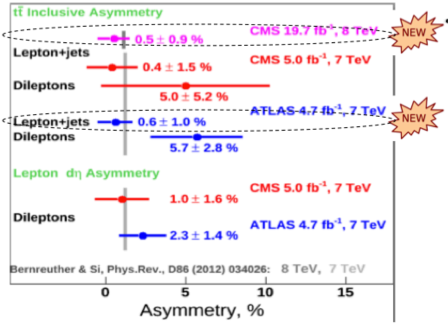
- probes antisymmetric part of cross section under $|y_t| \leftrightarrow |y_{\bar{t}}|$
- asymmetry is diluted by the gluon channel

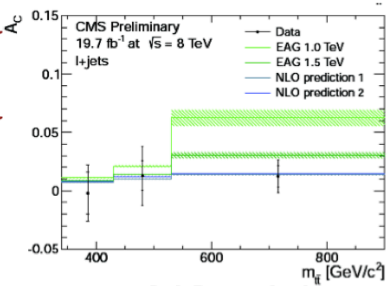
$$\Rightarrow A_C^{\mathrm{SM}} \approx 1\%$$

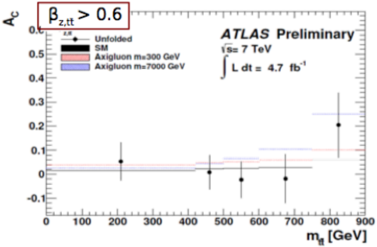
- can enhance A_C with cuts to reduce gg background (high $M_{t\bar{t}}$, etc..)

V. Shary

Charge Asymmetry Summary: LHC







LHC: no deviation from the SM prediction is seen up to now, but precision is start to be limited by the systematic uncertainties (could be improved with more statistics?).

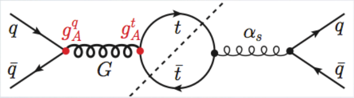
Further progress may be seen in measuring asymmetries in the specific regions of phase space (high velocity, high invariant $t\bar{t}$ mass, ...).

Two routes:

1) Focus on particular contributions/models: axigluons, Z', etc.
2) Model independent EFT approach

Axigluons [Westhoff, Top2013]

NEW PHYSICS IN S-CHANNEL: AXIGLUONS



Constructive interference for

- 🟥 $M_G < 2m_t: \ g_A^q \cdot g_A^t > 0$

[Tavares, Schmaltz, PRD84 (2011) 054008]

- 🟩 $M_G > 2m_t: \ g_A^q \cdot g_A^t < 0$

[Frampton, Shu, Wang, PLB683 (2010) 294]

Towards UV completion:

Chiral color breaking $SU(3)_L \times SU(3)_R \xrightarrow{\langle\Phi\rangle} SU(3)_C$

[Frampton, Glashow, PLB190 (1987) 157]

Anomaly cancellation and coupling textures imply new fermions.

Axigluon constraints:

[Bai et al., JHEP1103 (2011) 003]
[Haisch, Westhoff, JHEP1108 (2011) 088]
[Gresham, Shelton, Zurek, JHEP1303 (2013) 008]

- Dijet and top pair production 🟥🟩, dijet pair production 🟥
- LHC charge asymmetry 🟥🟩
- Electroweak precision observables (EWP) 🟥

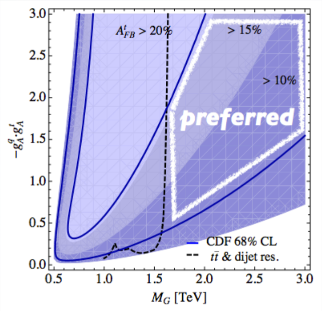
AXIGLUON SURVIVORS

Heavy, flavor-sensitive:

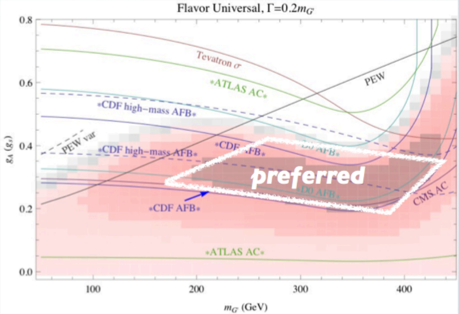
$$M_G \approx 2\,\mathrm{TeV}$$
$$g_A^q = -g_A^t \sim 1.0\, g_s$$

Light, broad, flavor-universal:

$$200 \lesssim M_G \lesssim 450\,\mathrm{GeV}$$
$$g_A^q = g_A^t \sim 0.3\, g_s$$



[Haisch, Westhoff, JHEP1108 (2011) 088 updated]



[Gresham, Shelton, Zurek, JHEP1303 (2013) 008]

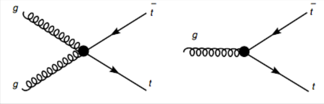
9

[Thanks to Celine Degrande]

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$|M|^2 = |M_{SM}|^2 + 2\Re\left(M_{SM}M^*_{dim6}\right) + \mathcal{O}\left(\Lambda^{-4}\right)$$

$$\mathcal{O}_{hG} = \bar{Q}\sigma_{\mu\nu}T^a t\tilde{\phi}G^{\mu\nu}_a$$



No asymmetry from top-gluon interaction

octet to interfere with the SM

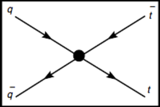
$$\mathcal{O}_{Rv} = \bar{t}\gamma_\mu T^a t \sum_{u,d,s,c} \bar{q}\gamma^\mu T^a q$$

$$\mathcal{O}_{Ra} = \bar{t}\gamma_\mu T^a t \sum_{u,d,s,c} \bar{q}\gamma^\mu \gamma_5 T^a q$$

$$\mathcal{O}_{Lv} = \bar{Q}\gamma_\mu T^a Q \sum_{u,d,s,c} \bar{q}\gamma^\mu T^a q$$

$$\mathcal{O}_{La} = \bar{Q}\gamma_\mu T^a Q \sum_{u,d,s,c} \bar{q}\gamma^\mu \gamma_5 T^a q$$

Odd (even) under $q \leftrightarrow \bar{q}$



C.D., J.-M. Gerard, C. Grojean, F. Maltoni, G. Servant, JHEP 1103 (2011) 125

FB asymmetry

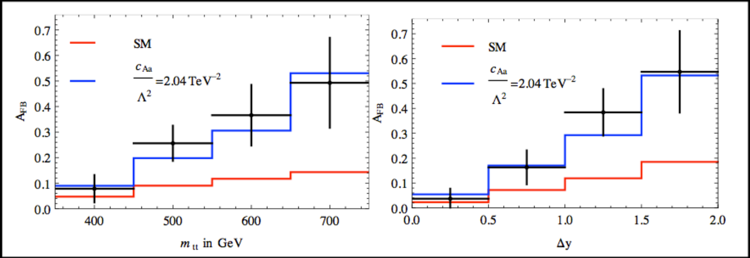
$$c_{Aa} = c_{Ra} - c_{La}$$

$$A_{FB}^{obs} = 0.162 \pm 0.047$$

$$A_{FB}^{SM} = 0.066 \pm 0.007$$

Only 1 parameter and affects A_{FB} only

$$\delta A_{FB} = 0.047^{+0.016}_{-0.011} c_{Aa} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \Rightarrow c_{Aa} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 = 2.04^{+2.12}_{-1.38}\mathrm{TeV}^{-2}$$



LHC Charge Asymmetry: $c_{Aa} \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 = -1.3^{+2.8}_{-1.3}\mathrm{TeV}^{-2}$

Prospects

[Westhoff, Top2013]

TOP CHARGE ASYMMETRY GOING FORWARD

-- Asymmetry in QCD at NNLO

cross section complete [Czakon, Fiedler, Mitov, PRL 110 (2013) 252004]

-- Rule out new-physics explanations

axigluons: dijet angular distributions, Z´: semi-inclusive top observables

-- Measure charge asymmetry at LHC

need higher luminosity or/and new observables [Berge, Westhoff, JHEP1307 (2013) 179]

-- Top charge asymmetry at LHCb

probe asymmetry in forward region [Kagan et al., PRL107 (2011) 082003]

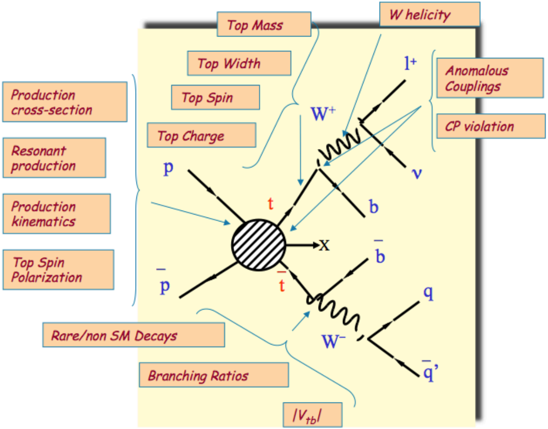
-- Asymmetries of leptons from top pair production

exp. clean and sensitive to NP [Krohn et al., PRD84 (2011) 074034][Falkowski et al., PRD87 (2013) 034039]

-- Bottom-quark charge asymmetry

probe flavor structure of NP models [Grinstein, Murphy, PRL111 (2013) 062003]

Summary



Top physics is multifaceted, look forward to new results from LHC14