Top Theory: Production

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IPPP Durham

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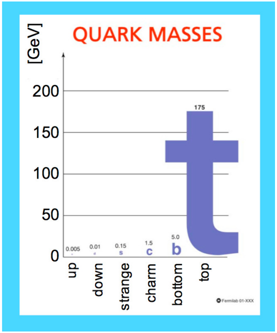
WHY TOP?



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}

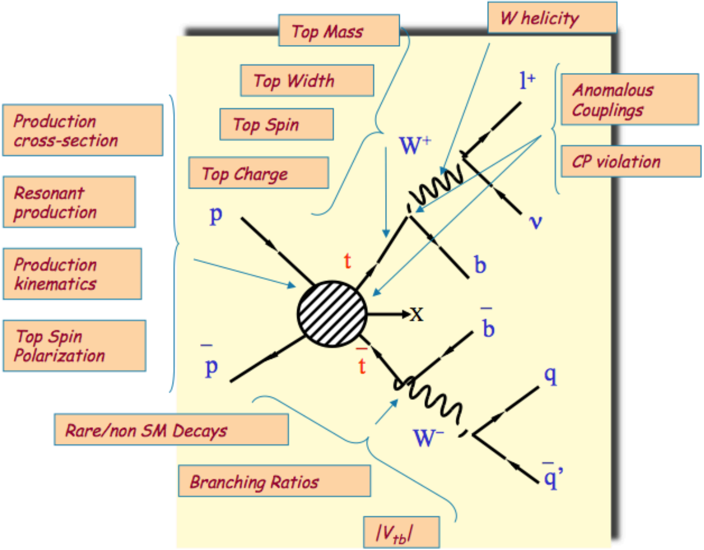
$$\sigma_{t\bar{t}} = 177 \pm 3(\text{stat.}) \pm 8(\text{syst.}) \pm 7(\text{lum.})\text{pb}$$

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

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

Factorization for inclusive production

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

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

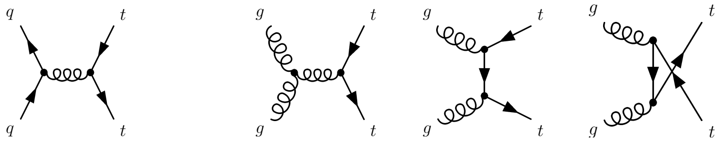
$$s = \left(p_{h_1} + p_{h_2}\right)^2 , \; \hat{s} = x_1 x_2 s$$

Strategy:

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

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

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



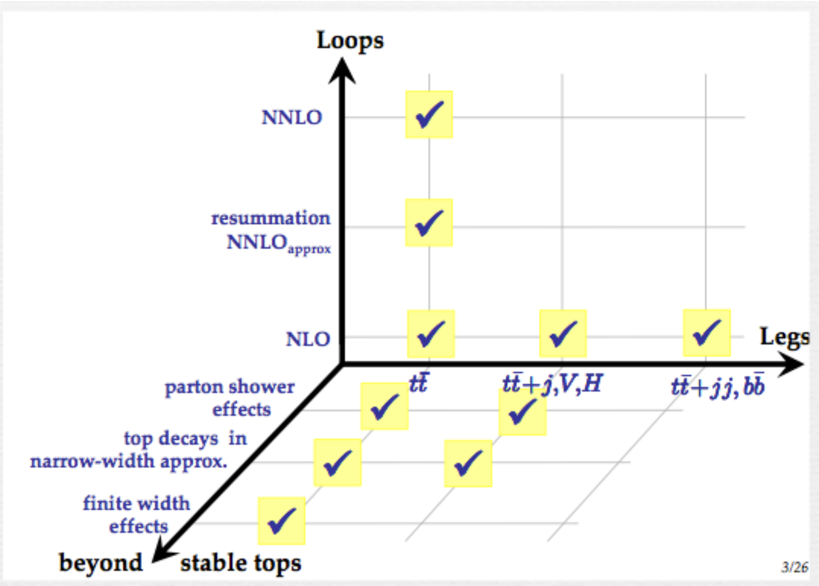
- $q\bar{q}$ dominant at Tevatron ($\sim 90\%$ of cross section)
- gg dominant at LHC ($\sim 75\%$ of cross section at 7 TeV)

Higher-order corrections:

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

NLO QCD known for 20 years, going beyond it in one way or another is active area of research

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



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

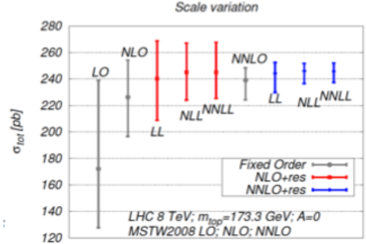
- $\hat{\sigma}^{\rm VV}$: Czakon, Mitov, Moch; Bonciani, Ferroglia, Gehrmann, Maitre, Manteuffel, Studerus; Kniehl, Korner, Merebashvili, Rogal ...
- $\hat{\sigma}^{\rm RV}$ (1-loop $t\bar{t}+j$): Dittmaier, Uwer, Weinzierl '07; Bevilacqua,Czakon, Papadolpoulos, Worek '10; Melnikov, Schulze '10; Gehrmann-De Ridder, Glover, Pires '11
- $\hat{\sigma}^{\rm RR}$: Czakon '11; Abelof, Gehrmann-De Ridder '11 + Maierhofer, Pozzorini '14

Has been fruitful calculational laboratory for higher-order QCD community

Total cross section at NNLO

Total inclusive cross section now known (numerically) 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:

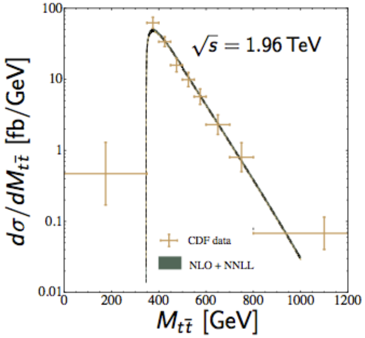
5% -> 3%

- 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...

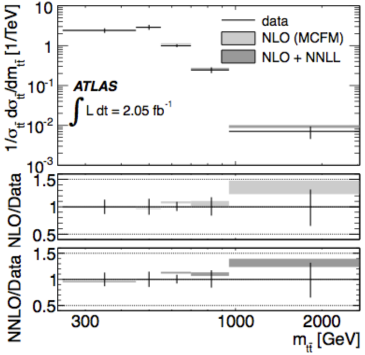
1) Top-quark pair production: some basics and the total cross section

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

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

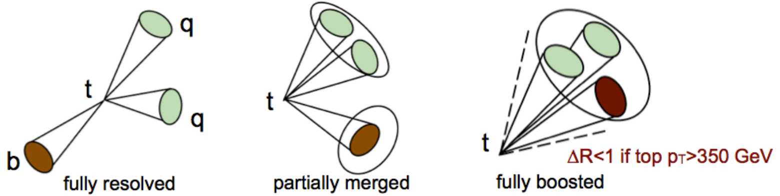
1) how to find the boosted tops in the first place
2) how to calculate the production cross sections reliably

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 (grooming, pruning, trimming, etc.), some of which are now being used/studied at LHC (they work!)

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: $[\ln(1-z)/(1-z)]_+ \qquad (z \equiv M_{t\bar{t}}^2/\hat{s})$
- small-mass (collinear) logs: $\ln m_t/M_{t\bar{t}}$

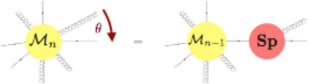
Fixed-order perturbation theory fails if, e.g. $\alpha_s \ln(m_t/M_{t\bar{t}}) \sim 1$

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
- Modern tool is soft-collinear effective theory (SCET)
  [Bauer, Fleming, Pirjol, Stewart '01]

Resummation for boosted top production

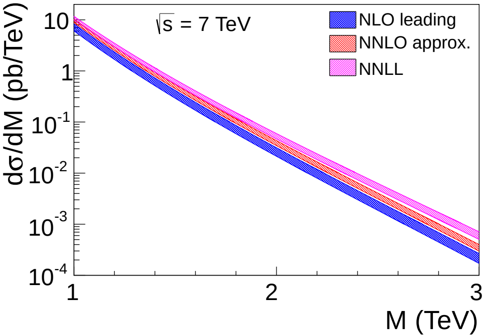
[Ferroglia, BP, Yang '12, '13]

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]

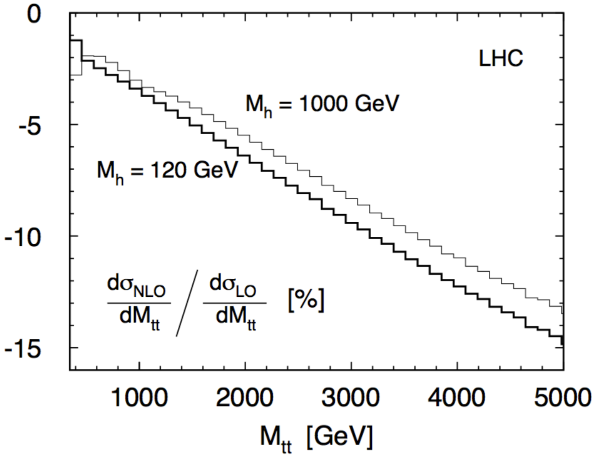
Fixed order vs. soft gluon resummation



- 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

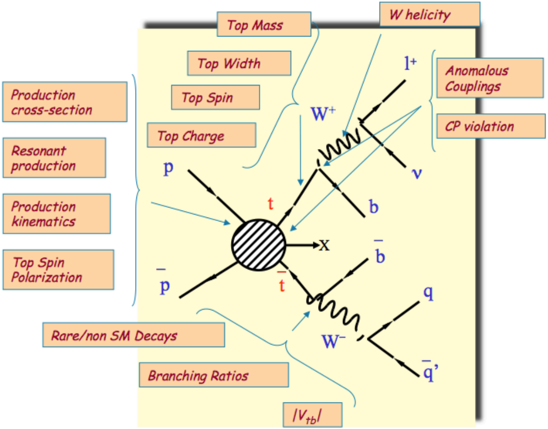
[Frederix Top2013]

- 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.

Summary



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