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Top Pair Differential Cross Section - Theory

Standard Model @ LHC 2012

Overview

- Total rate versus differential predictions.
- Monte Carlo tools.
- Beyond the narrow width approximation.
- Angular correlations.

The top pair cross-section

- Total cross-section for top pair known at exact NLO level ($\sim$ 20 years).
- Resummation to NNLL level (Beneke, Falgari, Schwinn; Czakon, Mitov; Ahrens et. al., Aliev et. al.; Kidonakis).
- Allows approximate NNLO cross-section prediction; public codes are available.
- Agrees well with measured values from both Tevatron and LHC.
- Differential cross-sections are needed for more comprehensive analyses and studies.

Theory issues in top pair production

- The differential top quark cross-section is a theorist's playground:
  1. Higher order QCD radiation (parton showers, matching schemes).
  2. Spin correlations of top decay products.
  3. Corrections to narrow width approximation.
  4. Logarithmically enhanced terms / resummation.
  5. Jet substructure / top tagging.
- There are many issues which require a dialogue between theorists and experimentalists:
  1. What is the domain of applicibility of Monte Carlo tools?
  2. Can evaluation of theoretical uncertainties be more easily built into Monte Carlos?

ME + parton shower predictions

- Current state of the art: combine matrix elements at some order with a parton shower Monte Carlo.
- General purpose tools are available at LO + LL order: MadGraph, ALPGEN, Pythia, Herwig(++), Sherpa.
- However, NLO corrections known to be large for top pair production ($\sim 60\%$).
- $\Rightarrow$ Interface NLO matrix elements with a parton shower.
- Many different algorithms on the market: MC@NLO, POWHEG, Vincia. See also recent Sherpa publications.
- Not all of these implemented for top production.

Top pair production: NLO + parton shower

- Top pair production implemented in both the MC@NLO (Frixione, Webber) and POWHEG (Frixione, Nason, Ridolfi) frameworks.
- Publicly available MC@NLO is interfaced with Herwig 6 and Herwig++.
- POWHEG and aMC@NLO interfaced with Herwig(++) and PYTHIA.
- All SM single top production modes are implemented in MC@NLO (Frixione, Laenen, Motylinski, Webber, White) and POWHEG (Alioli, Nason, Oleari, Re).
- Single top production in association with a charged Higgs boson also implemented (Weydert et. al., Klasen, Kovarik, Nason, Weydert).

Which description is best?

Tree level + shower

- Good description of hard jet radiation.
- NLO corrections are large and missing.

NLO + shower

- Poor description of more than one hard jet.
- NLO corrections are large and present!

- Which description is best requires a pragmatic answer, which depends on the observable.
- For some observables, both approaches may be subject to large corrections.
- It is important to understand the uncertainties in each approach.
- Some are more understandable than others...

Uncertainties

- Naïvely, uncertainties can be split into three classes:
  1. Uncertainties in the matrix elements calculation (e.g. scale variation, PDF uncertainty, measured parameters).
  2. Uncertainties in the parton shower (e.g. scale choices, hadronisation, underlying event).
  3. Uncertainty due to the matching of the ME's with the shower (e.g. CKKW , MLM? POWHEG or MC@NLO?).
- In practice these are not independent! E.g.:
  1. Scale choices affect matching prescription (POWHEG damping term?).
  2. Correlation between scale choice in shower and matrix element?

Scale and PDF uncertainties

- It is conventional to quote theoretical uncertainties in terms of those due to renormalisation / factorisation scale variation, and PDF errors.
- Typically, this can involve rerunning Monte Carlo event generators multiple times (e.g. with different scales, PDF error sets).
- Often this is so time-consuming as to be infeasible.
- It is instead useful to present Monte Carlo tools such that uncertainties can be calculated in a single run e.g. by reweighting.
- An example of this idea can be found in aMC@NLO (Frederix et. al.).
- Dialogue between experimentalists and theorists useful?

Uncertainties due to ME choice / matching schemes

- Perhaps the hardest systematic uncertainties to investigate are those due to which approach is used to model higher order QCD effects.
- E.g. NLO or tree level (but higher order) matrix elements? Matching scheme?
- Typically, one estimates this uncertainty by comparing different predictions e.g. MC@NLO, POWHEG, ALPGEN, SHERPA, MadGraph ...
- One can also try to understand why differences occur, when they occur.
- Sometimes the spread of theoretical predictions can exceed the experimental uncertainty: e.g. top pair production with a jet veto.

Uncertainties due to ME choice / matching scheme

- For some cases, both tree level + shower and NLO + shower approaches may break down.
- Examples: jet vetoes and $\log(Q/Q_0)$ terms, non-global logs (Dasgupta, Salam), super-leading logs (Forshaw, Kyrieleis, Seymour, Marzani).
- Sometimes alternative Monte Carlo tools are available e.g. HEJ (Andersen, Smillie).
- In some cases, no single tool gives a good answer over the whole range of data.
- How does one decide which approach to use in such cases? Can one systematise these uncertainties?
- What can theorists do other than try to systemically increase the accuracy of their approaches?

The future of Monte Carlo tools

- Several recent developments pave the way for broad improvements to the accuracy of Monte Carlo tools.
- New methods for NLO calculations e.g. generalized unitarity (BlackHat, Rocket), Integrand Reduction / OPP (CutTools, Samurai).
- Increased automation of all stages from Lagrangian / Feynman Rules (FeynRules) to NLO + parton shower Monte Carlo (POWHEG-BOX, Sherpa, POWHEL, aMC@NLO) !
- Other automated NLO parton level programs (GoSam, HELAC-NLO).
- Combination of NLO matrix elements with higher order tree level matrix elements (MENLOPS): Hamilton, Nason; Hoeche et. al.; Alioli, Hamilton, Re.
- Calculating both SM and BSM corrections to top pair production, at NLO + shower level, will soon be a lot easier.
- A new era of Monte Carlo event generation has begun!

Beyond the narrow width approximation

- I have assumed for most of the talk that the top quark is produced in the narrow width approximation i.e. production and decay are explicitly disentangled.
- In fact there are non-factorisable contributions $\sim \Gamma_t/m_t$, which can be significant in some distributions.
- Such effects can effect e.g. the extraction of the top quark mass.
- There are also subtle interference issues involving some processes (e.g. Wt and top pair production).
- Recently, corrections to the narrow width approximation in single top have been studied in an effective field theory approach (Falgari, Giannuzzi, Mellor, Signer).
- There have also been impressive NLO calculations of $WWb\bar{b}$ (Denner, Dittmaier, Kallweit, Pozzorini; Bevilacqua et. al.), which allow detailed studies of off-resonance effects in top pair production.

Angular correlations

- So far we have examined possible uncertainties in top pair production.
- From now on, will focus on what can be done with the differential cross-section!
- A huge amount of work is being done on top pair production e.g.
  1. Corrections to top pair invariant mass distribution.
  2. Tevatron forward-backward asymmetry (e.g. W' and Z' models).
  3. Jet substructure studies and top tagging.
  4. Angular correlations.
  5. ...
- Here will focus on angular correlations.

Angular correlations

- One may define a degree of (longitudinal) polarisation for a produced top quark:

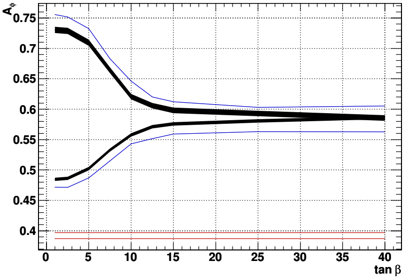
$$P_t = \frac{\sigma(+,+) - \sigma(-,-)}{\sigma(+,+) + \sigma(-,-)},$$

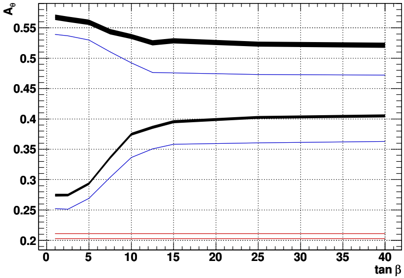
  where $\sigma(\pm,\pm)$ is the cross-section for a positively or negatively polarised top.
- In SM top pair production, the top quark is unpolarised on average ($P_t = 0$), but there is a mutual spin correlation between the decay products of the t and $\bar{t}$ (Mahlon, Parke; Bernreuther et. al.).
- Top quark polarisation can be non-zero if new resonances are present.

Lab frame observables for top polarisation

- Decay lepton spins are almost 100% correlated with top quark spin.
- Then can use lab frame leptonic angular distributions as markers of top polarisation.
- Example observables have been considered in top pair production (Godbole,Rao,Rindani,Singh), and can be used to infer the properties of the relevent new physics particles.
- Such observables are also useful in single top associated production e.g. in charged Higgs boson production (Huitu et. al., Godbole et. al.).
- Angular asymmetry parameters can be used to efficiently infer the coupling of new physics particles to the top.

Angular Observables - example results





- Here shown for a $H^- t$ production.
- Energy-related observables can also be considered in the boosted top case (Shelton; Godbole et. al.).
- Useful in a number of contexts, and seemingly robust against detector effects (Papaefstathiou, Sakurai).
- This is a very active area!

Conclusions

- Significant advances in the calculation of differential cross-sections (new NLO methods, Monte Carlo developments, automation).
- Particularly useful for top production will be increased automation of new physics models.
- There have been interesting new developments in the study of off-resonance effects.
- A lot of exciting top phenomenology still to be done e.g. polarisation studies, top tagging / jet substructure ...

Three topics for discussion

- How best can the emerging next generation of Monte Carlo tools be packaged so as to be most useful for experimentalists?
- What observables in top pair production show most disagreement between different approaches? In particular between (tree level + shower) and (NLO + shower)? Or between different examples of the former and latter? Do we understand why?
- When should we worry about corrections to the narrow width approximation in top pair production?