NNLO predictions for top-quark pair production with leptonic final states

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LoopFest 2018, Michigan State University

2018-07-19

Top quarks at the LHC

The LHC performance is really good.

→ large amount of top quark data.
→ Observables (XS, differential distributions, mass,. . .) at % level precision

Top quark pair production is important:

- parameter estimation
- Standard Model precision measurements
- background for many physics searches for SM . . .
- . . . and beyond

Necessity of precise theory predictions for production and decay!

$t\bar{t}$ in theory and experiment

Experiment:

- Signature: *b*-jets, leptons, missing energy (depending on the decay channel)
- top-quarks are reconstructed from decay products
- Modeling extremely important
- measurements like $t\bar{t}$ (differential) x-sections rely on extrapolation in fiducial volumes

Theory

- theory of stable on-shell tops well under control: state of the art NNLO (+EW) → good modeling of reconstructed top data
- on-shell NWA and off-shell: up to now NLO
  → more realistic final state.
  → omit systematic uncertainties
  → spin information of top accessible!

Theory - resonant top quark pair production

Stable onshell tops, spin summed:

- Total inclusive cross sections @ NNLO+NNLL accuracy

  [Czakon, Fiedler, Mitov '13]
- Fully differential distributions @ NNLO

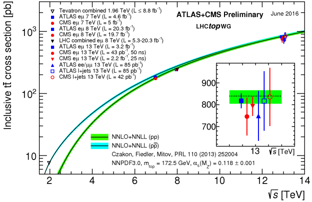
  [Czakon, Fiedler, Heymes, Mitov '16]
- + EW corrections

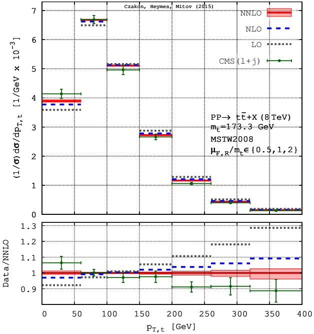
  [Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro '17]

Unstable tops + spin correlations:

- Approximate NNLO + NNLO decay

  [Gao,Papanastasiou '17]





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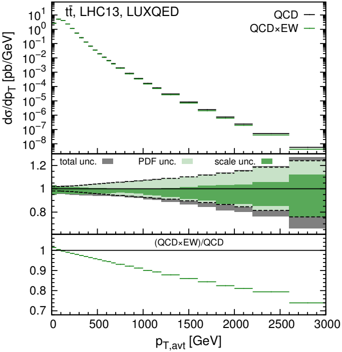

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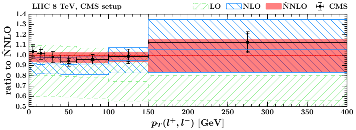
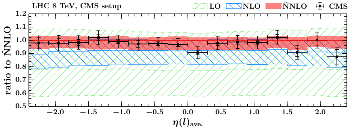
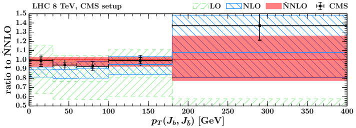






Towards realistic final states at NNLO

Best: full off-shell NNLO ← not feasible yet

Here: Narrow-Width-Approximation at NNLO

Necessary ingredients

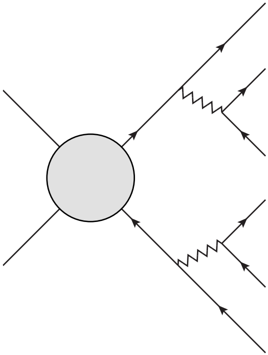
- Handling of real-radiation contribution:
    - facilitate cancellation of divergences between double-real, real-virtual, double-virtual contributions
    - difficult: double real radiation
    - → new implementation of STRIPPER algorithm
- Virtual matrix elements:
    - one-loop → no problem here
    - two-loop production and decay matrix elements
    - polarization needed

$t\bar{t}$ production and decay in NWA

Motivation: $\Gamma_t \ll m_t$

Narrow-Width-Approximation

- On-shell top-quarks
- Factorization of top-decay
- Separations of QCD corrections
- Keep spin correlations



Polarized matrix elements

$t\bar{t}$ production and decay at NNLO QCD in NWA

Decay Production	LO	NLO	NNLO
LO	🟩	🟩 Standard NLO	🟩 [Bonciani'08] [Asatrian'08] [Beneke'08]
NLO	🟩 Standard NLO	🟩 Standard NLO	🟥
NNLO	🟩 [Long,Czakon,RP '17]	🟥	🟥

Polarised $t\bar{t}$ production amplitudes

Gluon channel

$$\mathcal{M} = \epsilon_{1\mu}(p_1)\epsilon_{2\nu}(p_2)M^{\mu\nu}$$

$M^{\mu\nu}$ is a rank-2 Lorentz tensor

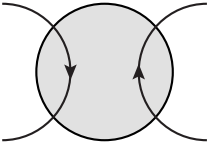
- Momentum conservation
- Transversality
- Equation of motion
- Parity conservation → no γ_5

8 independent structures

($d = 4$ dimensions)

$$M^{\mu\nu} = \sum_{j=1}^{8} M_j T_j^{\mu\nu}$$

Quark channel



- Two disconnected fermion lines
- Connection by gluons+loops

4 independent structures

$$\mathcal{M} = \sum_{i=1}^{4} M_j T_j$$

$$\text{with}\, T_j \sim \bar{v}_2 \Gamma_j u_1 \bar{u}_3 \Gamma'_j v_4$$

Two loop polarised $t\bar{t}$ production amplitudes

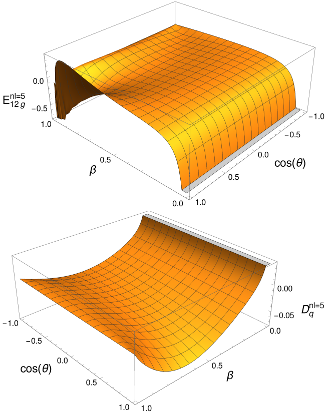
projection method → scalar coefficients with scalar integrals

Master integrals

- reduction of scalar integrals via in-house Laporta implementation
- new partially canonicalised
- numerical treatment of master with help of differential equation
  → interpolation grid

- finite remainder functions
- full color and spin information

spin-density coefficients:



Subtraction framework

NNLO subtraction schemes

Handling real radiation contribution in NNLO calculations
cancellation of infrared divergences

increasing number of available NNLO calculations with a variety of schemes

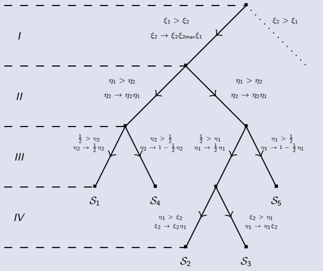
- qT-slicing [Catani,Grazzini, '07] ,[Ferrera,Grazzini,Tramontano, '11], [Catani,Cieri,DeFlorian,Ferrera,Grazzini,'12], [Gehrmann,Grazzini,Kallweit,Maierhofer,Manteuffel,Rathlev,Torre,'14-15'], [Bonciani,Catani,Grazzini,Sargsyan,Torre,'14-'15]
- N-jettiness slicing [Gaunt,Stahlhofen,Tackmann,Walsh, '15], [Boughezal,Focke,Giele,Liu,Petriello,'15-'16] , [Bougezal,Campell,Ellis,Focke,Giele,Liu,Petriello,'15], [Campell,Ellis,Williams,'16]
- Antenna subtraction [Gehrmann, GehrmannDeRidder,Glover,Heinrich,'05-'08] , [Weinzierl,'08,'09], [Currie,Gehrmann,GehrmannDeRidder,Glover,Pires,'13-'17], [Bernreuther,Bogner,Dekkers,'11,'14], [Abelof,(Dekkers),GehrmannDeRidder,'11-'15], [Abelof,GehrmannDeRidder,Maierhofer,Pozzorini,'14], [Chen,Gehrmann,Glover,Jaquier,'15]
- Colorful subtraction [DelDuca,Somogyi,Troscanyi,'05-'13], [DelDuca,Duhr,Somogyi,Tramontano,Troscanyi,'15]
- Sector-improved residue subtraction (STRIPPER) [Czakon,'10,'11] , [Czakon,Fiedler,Mitov,'13,'15], [Czakon,Heymes,'14] [Czakon,Fiedler,Heymes,Mitov,'16,'17], [Bughezal,Caola,Melnikov,Petriello,Schulze,'13,'14], [Bughezal,Melnikov,Petriello,'11], [Caola,Czernecki,Liang,Melnikov,Szafron,'14], [Bruchseifer,Caola,Melnikov,'13-'14], [Caola, Melnikov, Röntsch,'17]

STRIPPER

Outline of the scheme

- decomposition of phase space to disentangle overlapping singularities
- simple extraction of Laurent series in ϵ
- provides a general set of subtraction terms
- numerical treatment of integrated subtraction terms $\rightarrow$ numerical cancellation of ϵ poles
- defined in *d*-dimensions $\rightarrow$ numerical evaluation not efficient
  $\Rightarrow$ four-dimensional formulation

Triple collinear factorization



originally: 5 sub-sectors

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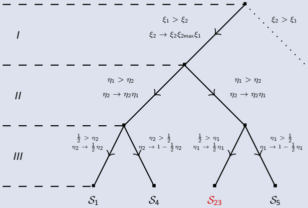
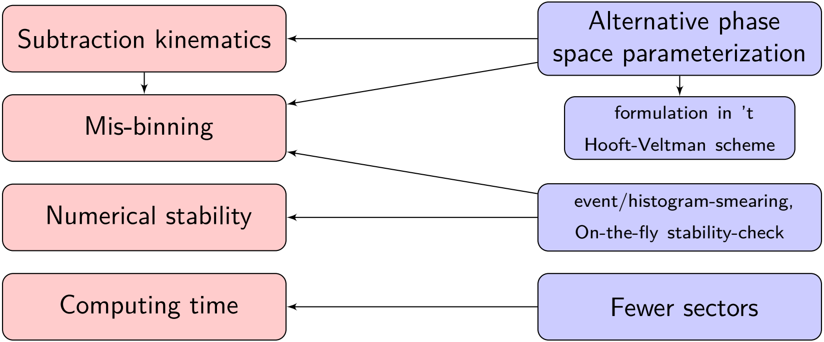


Caola, Melnikov, Röntsch [hep-ph:1702.01352v1]

now: 4 sub-sectors

How to improve the STRIPPER subtraction scheme?



Subtraction kinematics

Mis-binning

Numerical stability

Computing time

Alternative phase space parameterization

formulation in 't Hooft-Veltman scheme

event/histogram-smearing, On-the-fly stability-check

Fewer sectors

New phase space construction: Idea

Goal

Phase space construction with a minimal # of subtraction kinematics

Old construction

- Start with unresolved partons
- Fill remaining phase space with Born configuration

→ Non-minimal # kinematic configurations
(e.g. single soft and collinear limits yield different configurations)

New construction

- Start with Born configuration
- Add unresolved partons (u_i)
- Cleverly adjust Born configuration to accommodate the u_i

Consequences

Features

- Minimal number of subtraction kinematics
- Only one DU configuration
  → pole cancellation for each Born phase space point
- Expected improved convergence of invariant mass distributions, since $\tilde{q}^2 = q^2$

Unintentional features

- Construction in lab frame
- Original construction of 't Hooft Veltman corrections [Czakon,Heymes'14] is spoiled

NWA within STRIPPER

Implementation

- general (process-independent) STRIPPER implementation
  - new parameterization
  - new four-dimensional construction
- additional input: 1- and 2-loop finite remainder functions
- modifications for NWA:
  - onshell phase spaces
  - additional CS like dipole subtraction for decay part of NLOxNLO contributions (mixed subtractions)

$pp \to t\bar{t} \to b\bar{b}ll'vv'$

differential cross section:

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{t\bar{t}} \times \frac{\mathrm{d}\Gamma_t}{\Gamma_t} \times \frac{\mathrm{d}\Gamma_{\bar{t}}}{\Gamma_t}$$

decays - total width:

$$\Gamma_t = \Gamma(t \to bW^+) \sum_{ff'} \frac{\Gamma(W^+ \to ff')}{\Gamma_W}$$

decays - differential decays:

$$\mathrm{d}\Gamma_t = \mathrm{d}\Gamma(t \to bW^+) \sum_{f \in \{e,\mu\}} \frac{\mathrm{d}\Gamma(W^+ \to f\nu_f)}{\Gamma_W}$$

Consistent treatment of top width

Expansion in α_S:

$$\mathrm{d}\sigma_{t\bar{t}} = \mathrm{d}\sigma^{(0)}_{t\bar{t}} + \alpha_s \mathrm{d}\sigma^{(1)}_{t\bar{t}} + {\alpha_s}^2 \mathrm{d}\sigma^{(2)}_{t\bar{t}}$$

$$\mathrm{d}\Gamma_{t(\bar{t})} = \mathrm{d}\Gamma^{(0)}_{t(\bar{t})} + \alpha_s \mathrm{d}\Gamma^{(1)}_{t(\bar{t})} + {\alpha_s}^2 \mathrm{d}\Gamma^{(2)}_{t(\bar{t})}$$

$$\Gamma_t = \Gamma^{(0)}_t + \alpha_s \Gamma^{(1)}_t + {\alpha_s}^2 \Gamma^{(2)}_t$$

Consistent expansion in α_s:

$$\mathrm{d}\sigma^{\mathrm{LO}} \equiv d\sigma^{\mathrm{LO \times LO}}$$

$$\mathrm{d}\sigma^{\mathrm{NLO}} = \mathrm{d}\sigma^{\mathrm{NLO \times LO}} + \mathrm{d}\sigma^{\mathrm{LO \times NLO}} - \frac{2\Gamma^{(1)}_t}{\Gamma^{(0)}_t} \mathrm{d}\sigma^{\mathrm{LO}}$$

$$\mathrm{d}\sigma^{\mathrm{NNLO}} = \mathrm{d}\sigma^{\mathrm{NNLO \times LO}} + \mathrm{d}\sigma^{\mathrm{NLO \times NLO}} + \mathrm{d}\sigma^{\mathrm{LO \times NNLO}} - \frac{2\Gamma^{(1)}_t}{\Gamma^{(0)}_t} \mathrm{d}\sigma^{\mathrm{NLO}} + \left(\frac{3\Gamma^{(1)2}_t}{\Gamma^{(0)2}_t} - \frac{2\Gamma^{(0)}_t \Gamma^{(2)}_t}{\Gamma^{(0)2}_t} \right) \mathrm{d}\sigma^{\mathrm{LO}}$$

Considerations:

- treatment ensures after full incl. integration:

  $$\sigma = \sigma_{t\bar{t}} BR(W \to l\nu)$$

- practice: just rescaling lower order contributions

First results

Setup

Setup: CMS

m_t	173.3 GeV
m_W	80.385 GeV
m_Z	91.1876 GeV
Γ_W	2.0928 GeV
G_F	$1.16379 \cdot 10^{-5}$ Gev^2

- comparison to approximate $N\hat{N}LO$ calculation
- comparison to data provided by CMS [CMS '15]

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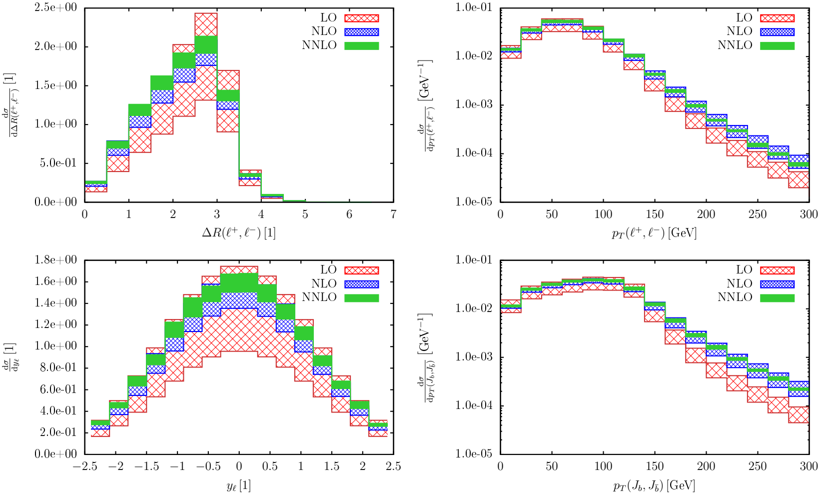
Ceveat:

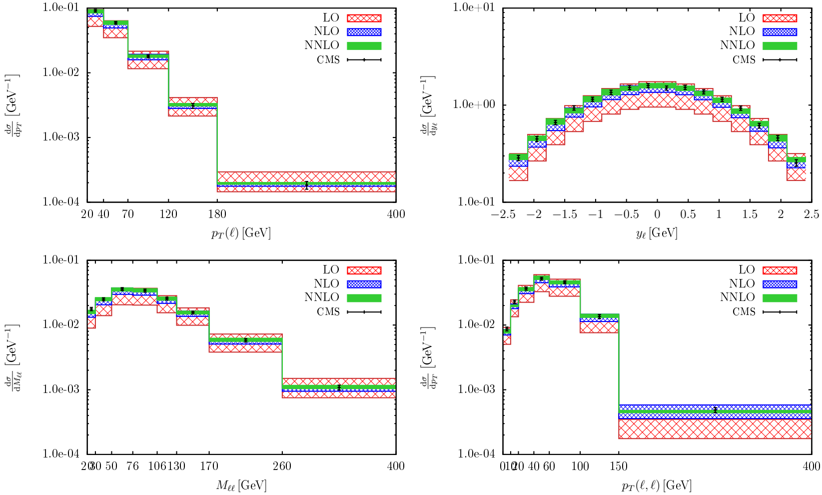
preliminiary results!

Differential distributions



scale variations: $\mu = \mu_R = \mu_F \in [m_t/2, 2m_t]$

Comparison to CMS data - Leptons



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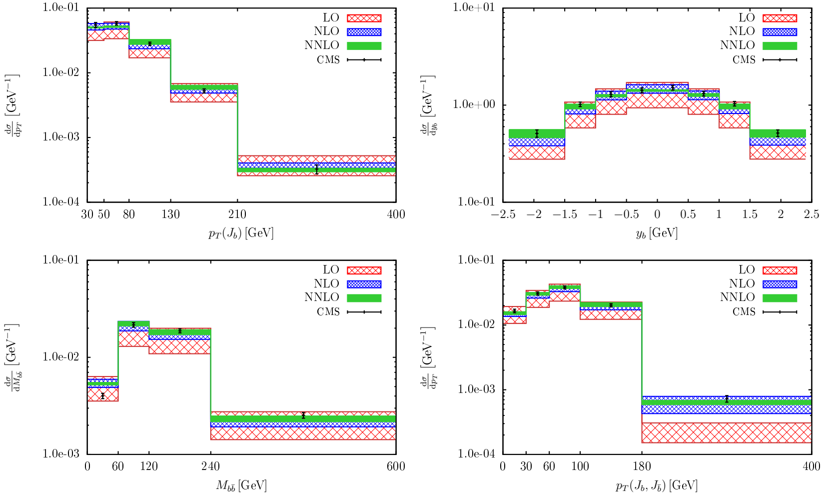
Comparison to CMS data - *b*-jets



scale variations: $\mu = \mu_R = \mu_F \in [m_t/2, 2m_t]$

Summary of progress

Summary

- STRIPPER: fully automated subtraction framework
- with Narrow-Width-Approximation implementation for t and leptonic W decays
- Polarized two-loop matrix elements
- first results for $t\bar{t}$ with leptonic final states

Outlook

- Phenomenological studies:
    - Spin correlations
    - fiducial cross sections
- hadronic W-decays $\rightarrow$ all-jet, lepton $+$ jets channels

Four dimensional formulation

Treat resolved particles in 4 dimensions (momenta and polarisations)

- Avoid unnecessary ϵ-orders of the matrix elements
- Avoid growth of dimensionality of phase space integrals

Make resolved phase space 4-dim. using measurement function, e.g.

$$F_n \to F_n \mathcal{N}^{-(n-1)\epsilon} \prod_{i=1}^{n-1} \delta^{(-2\epsilon)}(q_i)$$

This introduces errors of $\mathcal{O}(\epsilon)$ in all contributions!
Needed: Separately finite single and double unresolved contributions

- using finiteness of NLO calculation
- shifting terms from single-unresolved to double-unresolved contributions
- corrections calculated in full generality