Precision Top-Quark Physics with Leptonic Final States

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PhD defence talk

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Introduction

Top-quark pair production

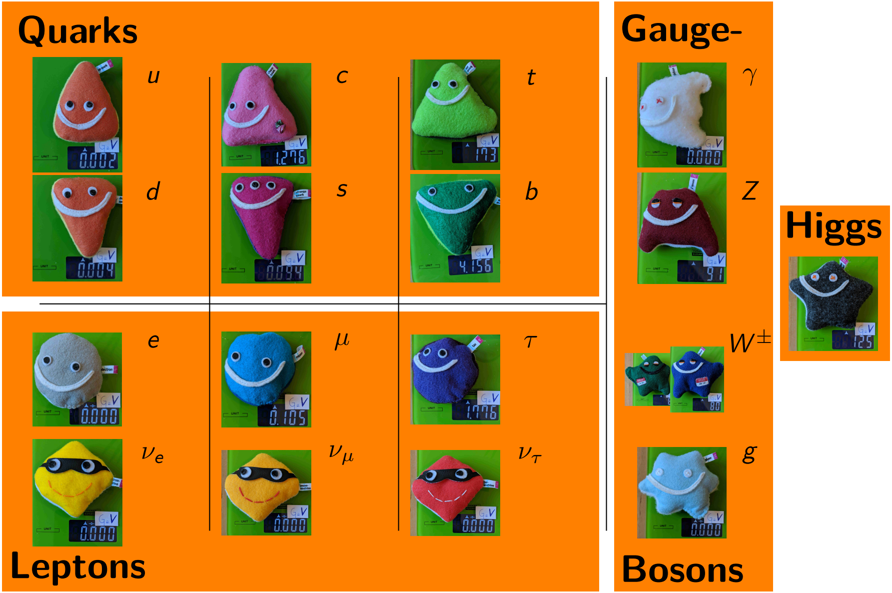
- Virtual amplitudes
- Real radiation
- Subtraction framework

Application

- Differential measurements

Summary and Outlook

The Standard Model of Particle Physics



The Standard Model of Particle Physics

Quarks

u c t

Gauge-

γ

The top quark

- Mass: $m_t \approx 173$ GeV
  $\rightarrow$ heaviest known particle
- Yukawa coupling $y_t \sim 1$
  Higgs-Top connection
- Short lifetime: 10^{-25} s
  $\rightarrow$ decays before hadronization

Higgs

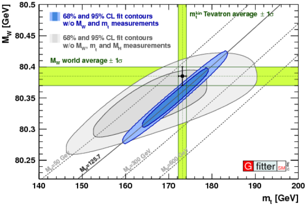
Leptons

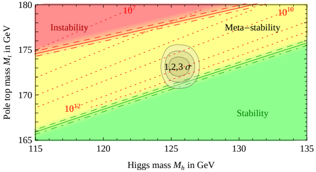
Bosons

Top-quarks and the Standard Model

Electroweak (EW) Precision

- Loop-corrections
  $\rightarrow$ Relations among SM parameters
  $\rightarrow$ EW precision measurements:
  - Gauge boson and Higgs mass
- Consistency check of SM
- Vacuum stability
- Rare meson decays

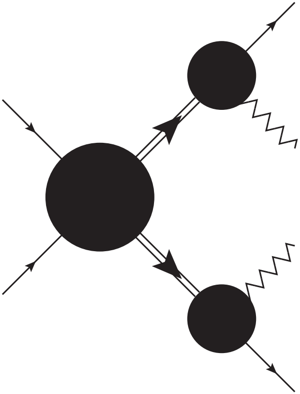


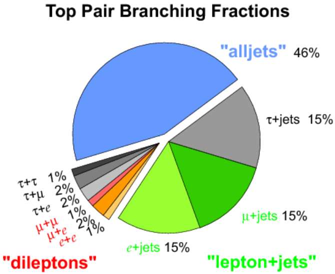


Beyond the Standard Model

- Higgs sector extensions
- Top-quark partner
- . . .

Top-quark pair production - Event signature





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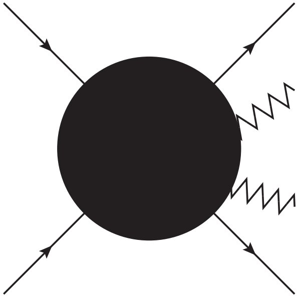

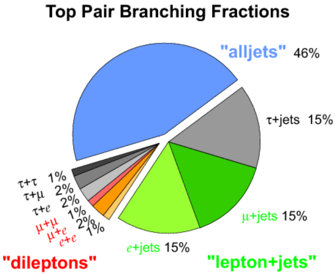

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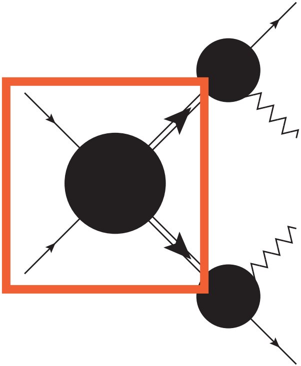
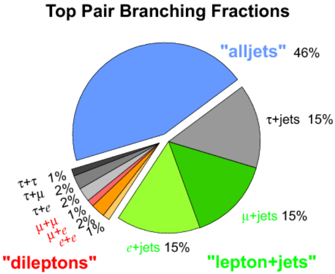


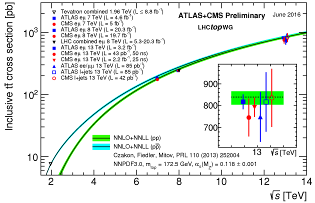


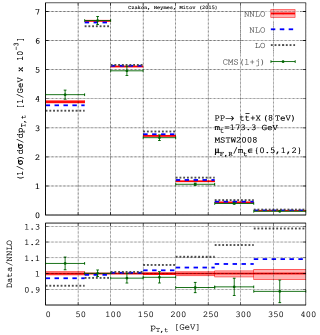
Top-quark pair production - Theory

Stable top-quark @ NNLO QCD and beyond

Stable onshell and spin-summed Top-quark pair-production

- 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]





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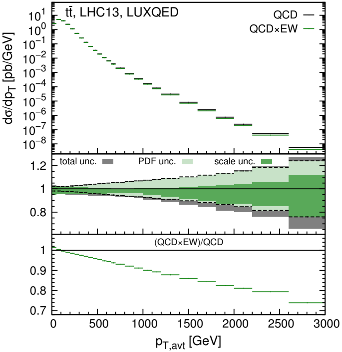

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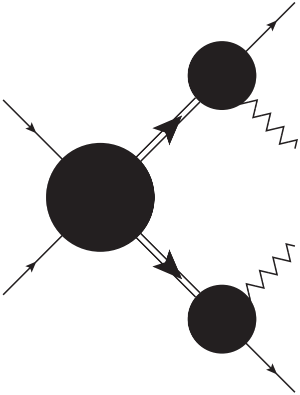

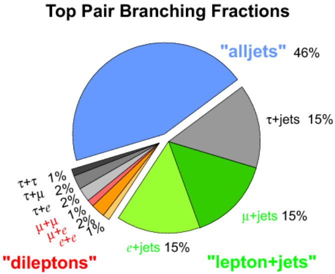

Offshell/NWA calculations

Next-to-leading order

- Narrow-Width-Approximation (NWA) [Berneuther et al; Melnikov, Schulze; Campbell,Ellis]
- Offshell [Bevilaqua et al; Denner et al; Falgari et al; Heinrich et al; Frederix et al]
- NWA + Parton Shower [Campbell,Ellis; Nason,Re]
- Offshell + Parton Shower [Jezo, Nason et al; Frederix et al]

Next-to-next-to-leading order

- NWA with approximate N$\hat{\text{N}}$LO [Gao,Papanastasiou]

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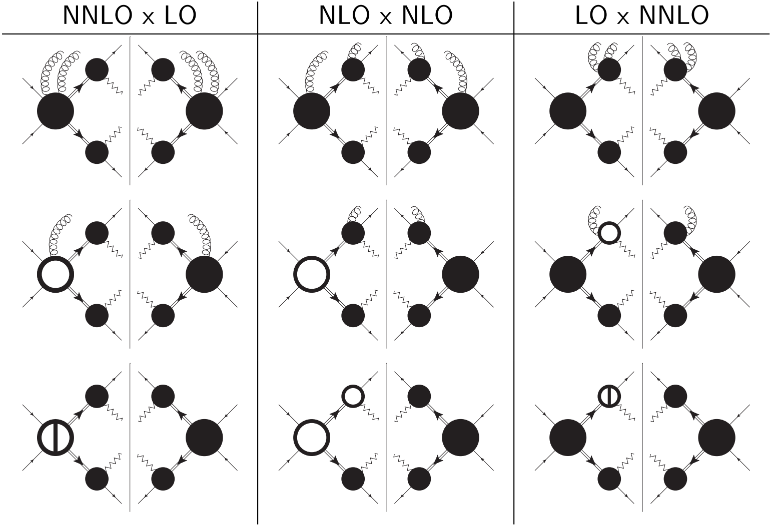
This thesis:

NWA with full NNLO corrections to production and decay!

NWA @ NNLO QCD



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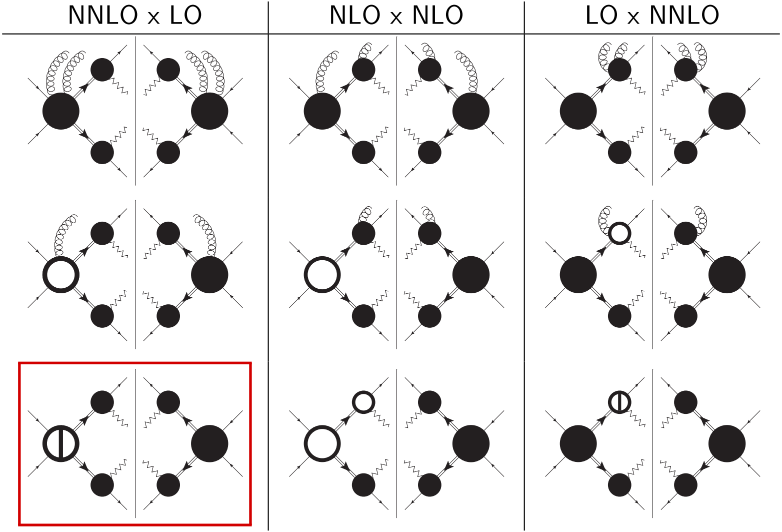


Polarised $t\bar{t}$ production amplitudes

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

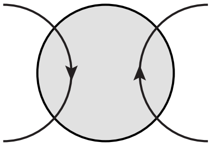
- Momentum conservation
- Transversality
- Equation of motion
- Parity conservation $\rightarrow$ no γ_5

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

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

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

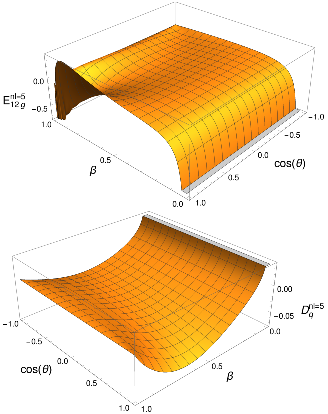
Projection method $\rightarrow$ scalar coefficients with scalar integrals

Master integrals

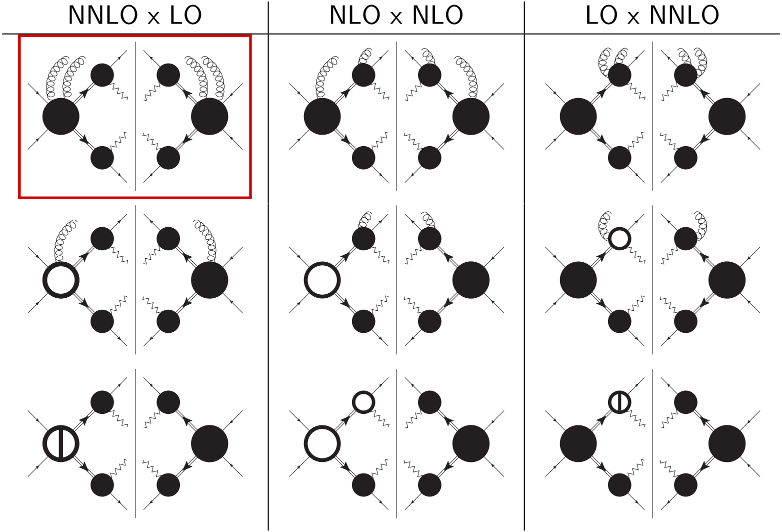
- Reduction of scalar integrals via in-house Laporta implementation
- New partially canonicalised
- Numerical treatment of master with help of differential equation
  $\rightarrow$ interpolation grid

- Finite remainder functions
- Full color and spin information

spin-density coefficients:



NWA @ NNLO QCD



Real radiation contributions

- (Infrared) Divergences due to inclusive integration of additional radiation

Sketch: $\mathrm{d}\Phi\times$  $\sim \int_0 \underbrace{\frac{\mathrm{d}E\mathrm{d}\theta}{E(1-\cos\theta)}}_{\text{divergent}} f(E,\theta)$

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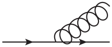
Sketch: $\mathrm{d}\Phi \times$  $\sim \int_0 \underbrace{\frac{\mathrm{d}E\mathrm{d}\theta}{E^{1+2\varepsilon}(1-\cos\theta)^{1+\varepsilon}}}_{\text{CDR}} f(E,\theta) \sim \frac{1}{\varepsilon^2} + \ldots$

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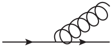
  Sketch: $\mathrm{d}\Phi \times$  $\sim \int_0 \underbrace{\frac{\mathrm{d}E\mathrm{d}\theta}{E^{1+2\varepsilon}(1-\cos\theta)^{1+\varepsilon}}}_{\text{CDR}} f(E,\theta) \sim \frac{1}{\varepsilon^2} + \dots$

- How to solve this kind of problem? $\rightarrow$ Subtraction!

  Sketch: $\int_0 \frac{\mathrm{d}E\mathrm{d}\theta}{E^{1+2\varepsilon}(1-\cos\theta)^{1+\varepsilon}}(f(E,\theta) - S) + \int_0 \frac{\mathrm{d}E\mathrm{d}\theta}{E^{1+2\varepsilon}(1-\cos\theta)^{1+\varepsilon}} S$

- NLO subtraction schemes: Catani-Seymour(CS), FKS, ...

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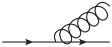
  Sketch: $\mathrm{d}\Phi \times$  $\sim \int_0 \underbrace{\frac{\mathrm{d}E\mathrm{d}\theta}{E^{1+2\varepsilon}(1-\cos\theta)^{1+\varepsilon}}}_{\text{CDR}} f(E,\theta) \sim \frac{1}{\varepsilon^2} + \ldots$

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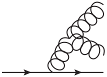
- @ NNLO business becomes harder:



$\leftarrow$ Overlapping singularities

NNLO subtraction schemes

increasing number of available NNLO calculations with a variety of schemes

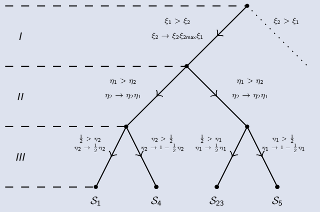
- qT-slicing [Catani,Grazzini, '07] ,[Ferrera,Grazzini,Tramontano, '11], [Catani,Cieri,DeFlorian,Ferrera,Grazzini,'12], [Gehrmann,Grazzini,Kallweit,Maierhofer,Manteuffel,Rathlev,Torre,'14-15'], [Bonciani,Catani,Grazzini,Sargsyan,Torre,'14-'15]
- N-jettiness slicing [Gaunt,Stahlhofen,Tackmann,Walsh, '15], [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]
- Projection-to-Born[Cacciari et al.'15], 'Torino'-subtraction [Magnea et al.'17/'18], Geometric subtraction [Herzog '18]

Sector-improved residue subtraction - 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 [Czakon,'10] $\rightarrow$ numerical evaluation not efficient $\Rightarrow$ four-dimensional formulation [Czakon,Heymes,'14]

Triple collinear factorization



Stripper - Updates

Phase space parameterization

- Minimal number of subtraction kinematics
  $\rightarrow$ improvements on mis-binning
- Only one double unresolved configuration
  $\rightarrow$ pole cancellation for each Born phase space point
- Expected improved convergence of invariant mass distributions, since $\tilde{q}^2 = q^2$

4 dimensional formulation

- Takes advantage of the finiteness of NLO calculations
- Uses 'slicing' to extract unmatched poles
- Cancel slicing parameter dependence analytically

NWA within STRIPPER

Implementation

- General (process-independent) STRIPPER implementation
  - New parameterization
  - New four-dimensional construction
- Additional input: 1- and 2-loop polarized finite remainder functions
- Modifications for NWA:
  - Onshell phase spaces
  - Additional CS-like dipole subtraction for decay part of NLOxNLO contributions (mixed subtractions)

Application

Application: Differential measurements @LHC13

New differential top-quark measurements at 13 TeV

CMS and ATLAS:

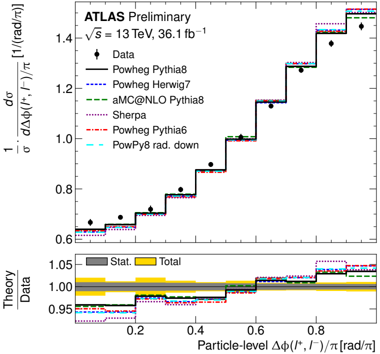
- %-level bin-wise uncertainties
- Differential distributions:
  - Decay products
  - Reconstructed t-quarks
- Observables sensitive to spin-correlation

NWA@NNLO: Fiducial region

- 2 b-jets with $p_T > 30$ GeV, $|\eta| > 2.4$
- 2 opposite sign leptons with 25 (20) GeV, $|\eta| > 2.4$
- $m_{\ell\bar{\ell}} > 20$ GeV
- anti-k_T with $R = 0.4$

Example: Spin Correlation in $\Delta\phi(\ell, \bar{\ell})$

ATLAS-CONF-2018-027



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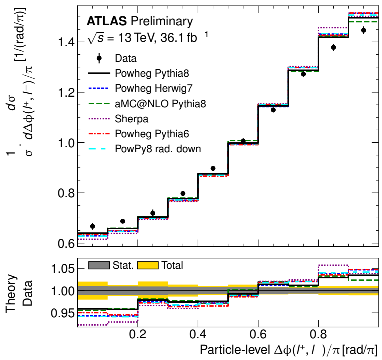
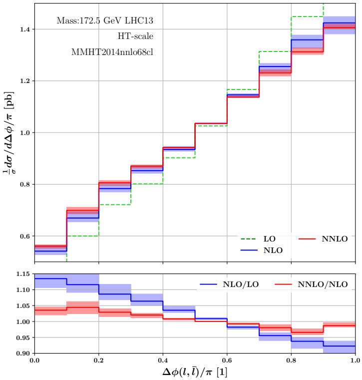


NWA @ NNLO predictions



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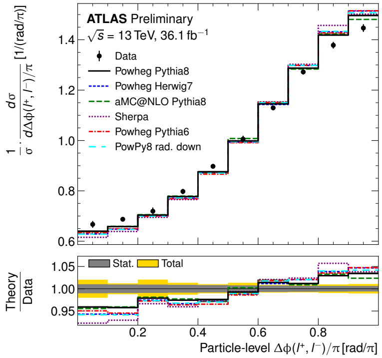

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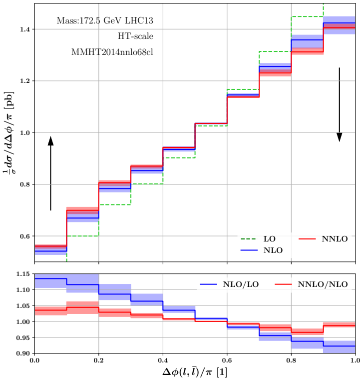
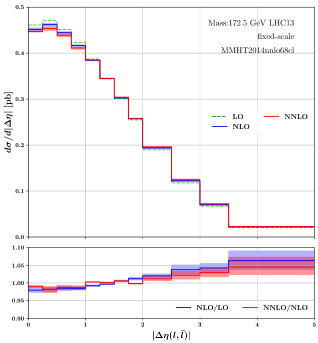


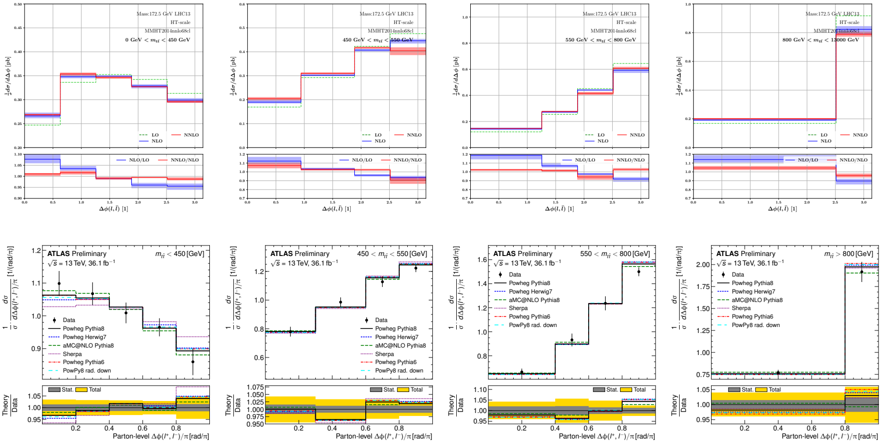
Differential distributions @ NNLO QCD

endless possibilities: $|\Delta\eta(\ell, \bar{\ell})|$



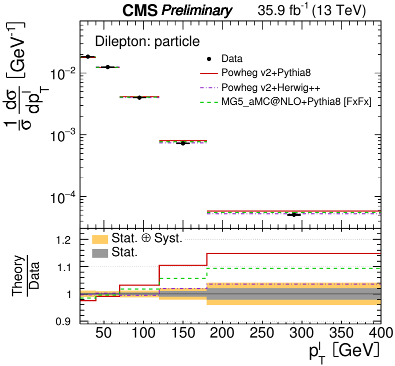
Differential distributions @ NNLO QCD

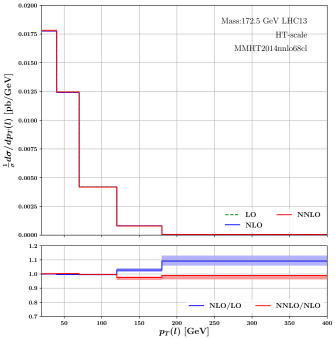
endless possibilities: double differential: $\Delta\phi$ x $m_{t\bar{t}}$



Differential distributions @ NNLO QCD

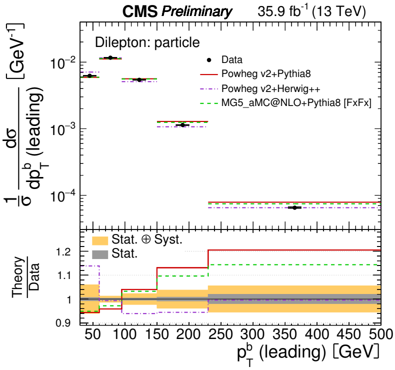
endless possibilities: p_T of lepton.

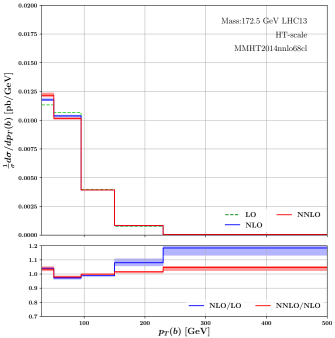




Differential distributions @ NNLO QCD

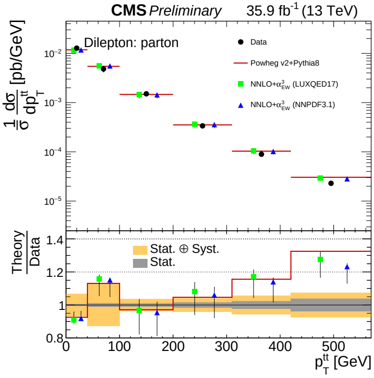
endless possibilities: p_T of leading b-jet.

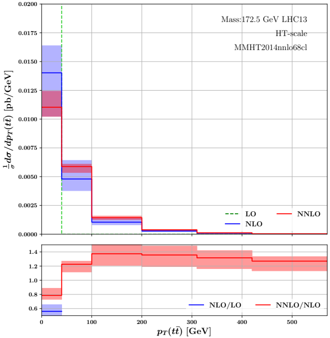




Differential distributions @ NNLO QCD

endless possibilities: p_T of $t\bar{t}$ pair.





Summary

Goal achieved: NWA @ NNLO QCD

- Calculation of polarized double virtual $t\bar{t}$ - production amplitudes
- Improvements on Stripper framework:
  - Phase space parameterization
  - 4 dimensional formulation
  - NWA decays!
- First novel NNLO QCD results!
  - $\Delta\Phi(l,\bar{l})$ distributions
  - Differential distributions in fiducial phase space
  - Fiducial cross section for $t\bar{t}$ production in the di-lepton channel

Outlook

NWA $t\bar{t}$ @ NNLO QCD

- Comparison with data!
- Improved measurements of m_t from leptonic observables (less modelling depend)
- More decay channels: Hadronic W decays in NWA

STRIPPER

- Go beyond $t\bar{t}$ - first steps have been done ...
- fastNLO tables
- Automated 1-Loop input