The Matrix Element Method as a tool for precision and accuracy

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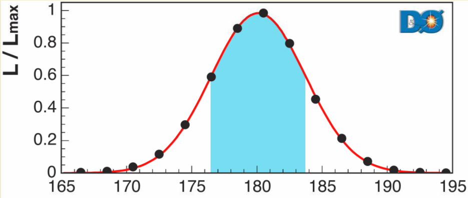
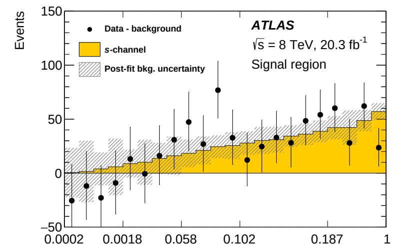
The power of the The Matrix Element Method [Kondo '88,'91]

- Multivariate Maximum Likelihood method
  - Can be used for signal searches and parameter estimation
  - Allows for unambiguous statistical interpretation
- Likelihood is calculated in QFT: $$\mathcal{L}(\Omega|\{\vec{x}^{(i)}\}) \propto \prod_i \frac{1}{\sigma(\Omega)} \frac{d\sigma(\Omega)}{dx_1^{(i)} \ldots dx_r^{(i)}}$$
  - Derived from first principles
  - Transparent connection between theory and experiment
  - No training needed
- Optimal use of information
  - Most efficient inference



[DØ 2004: Nature 429, 638] **Top quark mass (GeV/c²)**



[ATLAS 2016: Phys.Lett. B756, 228-246] P(S|X)

The status quo of the Matrix Element Method

Very powerful method! — THE method to analyse data?

✗ Calculation of the likelihood in perturbative QCD has been restricted to the Born approximation!

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Steps towards the MEM at NLO accuracy

- Effects of real radiation only [Alwall,Freitas,Mattelaer '11]
- Uncolored final states only [Campbell,Giele,Williams '12], [Campbell,Ellis,Giele,Williams '13]
- Steps towards colored final states [Campbell,Giele,Williams '13]
- LO matrix element and parton shower [Soper,Spannowsky '11 '13 '14]

The MEM at NLO accuracy

- First consistent, universal extension to NLO accuracy [TM,Uwer '15]
- Proposed generalisation [Baumeister,Weinzierl '17]
- First realistic example application for LHC [TM,Uwer '17]
- Special formulation for conv. jet algorithms [Kraus,TM,Uwer '18]

The importance of higher-order corrections

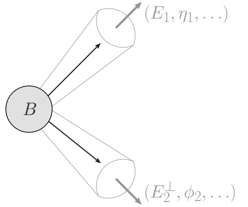
- Next-to-leading order QCD corrections typically not small
  - Better approximation of the full theory
- Reduced dependence on unphysical scales
  - Reduction of the associated theoretical uncertainties
- Non-trivial modelling of jet structure and additional jet activity
  - Description of kinematics not fitting the LO picture
- Renormalisation scheme uniquely defined
  - Unambiguous interpretation of the model parameters

Differential jet cross section at NLO accuracy

Given: Fixed values of jet variables (e.g. $E_1, \eta_1, E_2^{\perp}, \phi_2, \ldots$)

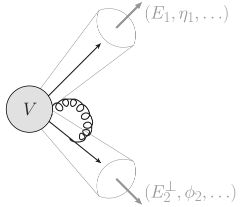
Aim: Define event weight at NLO accuracy:

$$\frac{d\sigma^{\mathrm{B}}}{dE_1\, d\eta_1\, dE_2^{\perp}\, d\phi_2 \ldots} + \frac{d\sigma^{\mathrm{V}}}{dE_1\, d\eta_1\, dE_2^{\perp}\, d\phi_2 \ldots} + \frac{d\sigma^{\mathrm{R}}}{dE_1\, d\eta_1\, dE_2^{\perp}\, d\phi_2 \ldots}$$



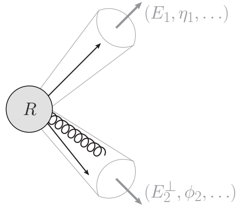
Born approximation

- IR finite
- Mapping partonic $\rightarrow$ jet momenta trivial



Virtual corrections

- IR divergent
- Mapping partonic $\rightarrow$ jet momenta trivial



Real corrections

- IR divergent
- Mapping Partonic $\rightarrow$ jet momenta non-trivial

Need:
- 1-to-1 correspondence of virtual and real corrections
- Efficient integration of unresolved partonic configurations

Differential jet cross section at NLO accuracy

Solution: Factorization of phase space in terms of the jet variables

For the Born and virtual contributions:

$$d\text{LIPS}_n = dE_1 d\eta_1 dE_2^\perp d\phi_2 \ldots \times \frac{d\text{LIPS}_n}{dE_1 d\eta_1 dE_2^\perp d\phi_2 \ldots}$$

For the real corrections:

$$d\text{LIPS}_{n+1} = dE_1 d\eta_1 dE_2^\perp d\phi_2 \ldots \times \frac{d\text{LIPS}_n}{dE_1 d\eta_1 dE_2^\perp d\phi_2 \ldots} \times d\Phi_{\text{unres}}$$

Possible for sensible choice of the jet variables:

Jet variables cannot allow to reconstruct

- Invariant jet masses
- Overall transverse momentum

[TM '18], [Kraus,TM,Uwer '18]

Allows to define weight at NLO accuracy for events given in terms of jet variables:

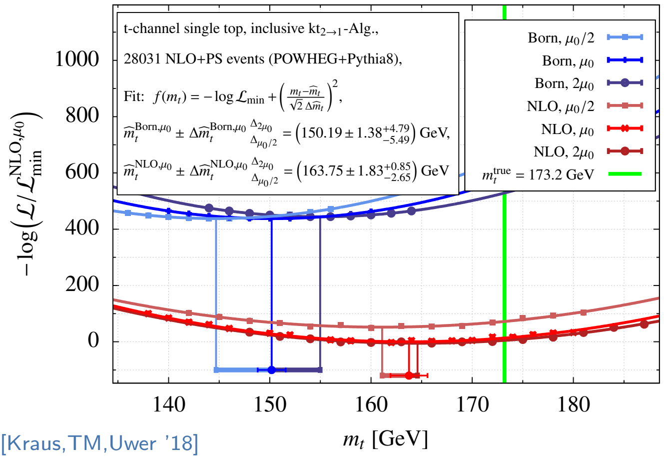
$$w(E_1, \eta_1, E_2^\perp, \phi_2, \ldots) = \frac{1}{\sigma^{\textbf{NLO}}} \frac{d\sigma^{\textbf{NLO}}}{dE_1 d\eta_1 dE_2^\perp d\phi_2 \ldots}$$

Studying parton-shower effects in the MEM@NLO

Single top-quark events generated with POWHEG+Pythia8

Top-quark mass extraction with the MEM

Likelihood in the Born approximation and at NLO accuracy

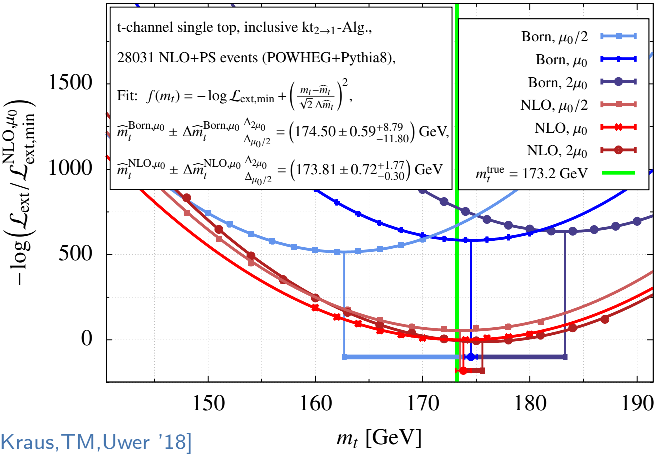


[Kraus,TM,Uwer '18]

Single top-quark events generated with POWHEG+Pythia8

Top-quark mass extraction with the MEM

Extended Likelihood (Born approximation and at NLO accuracy)

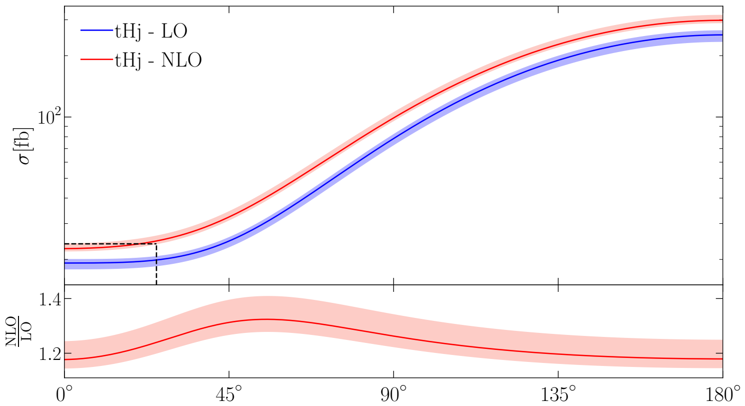


[Kraus,TM,Uwer '18]

BSM parameter determination with the MEM@NLO

Single top-quark+Higgs production with a CP-Mixing phase:

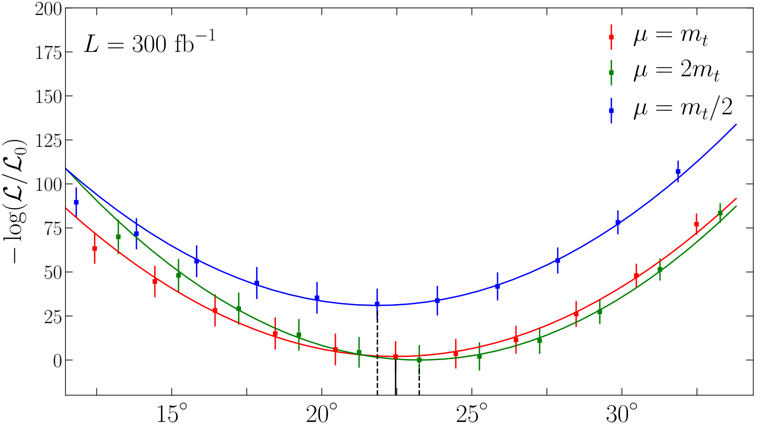
$\mathcal{L}^t = -\frac{y_t}{\sqrt{2}}\ \bar{t}\left(\cos\alpha + i\frac{2}{3}\sin\alpha\ \gamma_5\right) t\ H$ [Demartin,Maltoni,Mawatari,Zaro '15]



[Kraus,Peitzsch,TM,Uwer (in prep.)]

NLO corrections are important and dependent on α!

Single top-quark+Higgs events generated at NLO accuracy ($\alpha = 22.5^\circ$)



[Kraus,Peitzsch,TM,Uwer (in prep.)]

Extracted estimator for CP-mixing phase: $\hat{\alpha}^{\mathrm{NLO}} = 22.5^\circ \pm 0.9^\circ{}^{+0.7^\circ}_{-0.6^\circ}$

Statistical and theoretical uncertainty comparable

Conclusions & outlook

Conclusions

- Elevation of the powerful MEM to a sound theoretical footing at NLO accuracy
- Readily applicable to experimental data
- Parton shower effects can be important
- MEM@NLO is a promising tool for precise parameter extraction at the LHC
- Higher-order corrections crucial to improve the reliability of the analyses

Outlook — only the starting point of the MEM@NLO machinery

- Study of more realistic final states (decays, ...)
- Investigation of the impact of non-trivial transfer functions
- Inclusion of parton shower effects
- Publication of an automation of the algorithm as a software package/library