The automated Matrix-Element reweighting and its applications at the LHC

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Overview

Introduction

The Matrix Element Method (MEM) is a multivariate analysis (MVA) method in particle physics.

- takes into account all kinematic information of an event (object 4-vectors)
- computes posterior probability that an event x is produced under a given hypothesis α : $\mathcal{P}(x|\alpha)$.

In comparison with other MVA techniques (NN, BDT), MEM is certainly the most theoretically motivated.

This method has been widely used and tested, especially for measurement in the top sector at the Tevatron and for Higgs searches/measurement at the LHC.

The Method

α :	theoretical information (signal hypothesis).
x :	experimental informations.
$P_\alpha(y)$:	probability to have a parton-level configuration y under the theoretical assumption α.
$W(x,y)$:	transfer function giving the probability that a parton-level configuration y evolves into a reconstructed event x .

The probability is then defined by :

$$P(x|\alpha) = \int dy P_\alpha(y) W(x,y)$$

In collider physics, $P_\alpha(y)$ can be re-written in terms of $|\mathcal{M}_\alpha|^2(y)$ and the *pdf's* ($f_1(q_1)$ et $f_2(q_2)$) :

$$P(x|\alpha) = \frac{1}{\sigma_\alpha \varepsilon_\alpha} \int d\phi(y) dq_1 dq_2 f_1(q_1) f_2(q_2) |\mathcal{M}_\alpha|^2(y) W(x,y) \, .$$

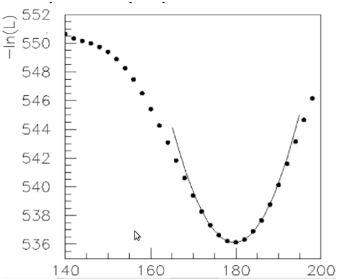
Likelihood

Given a data sample of N events, one can define a likelihood build upon the MEM probability associated with these events.

$$\mathcal{L}(\alpha) = f(N) \prod_{i=1}^{N} P(x_i|\alpha)$$

where $f(N)$ is a renormalisation factor.

If the model α provides a good description of the data set $\rightarrow$ high value of the likelihood (e.g. Top-mass measurement [1]).



- 72 events
- $M_t = 180.1 \pm 3.6_{\text{stat}} \pm 4.0_{\text{sys}}$ GeV

1. J. Estrada : Phd dissertation, University of Rochester (2001)

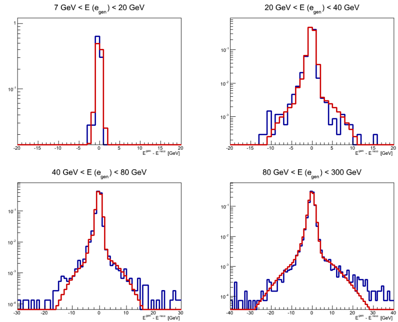
Transfer Functions : $W(x,y)$

$W(x,y)$ takes into account the evolution of a parton-level configuration y into a reconstructed event x.

$$P(x|\alpha) = \int dy P_\alpha(y) W(x,y)$$

Example : Transfer function for electrons.

- Triple-gaussian on the measured energy.
- δ-function applied for angular variables (η, ϕ)



- In blue : pseudo-data (here, simulated with *Delphes* `arXiv:0903.2225v3`)
- In Red : cross-check of the Fit.

appropriate parametrization

- core of the distribution
- overall width of the tails

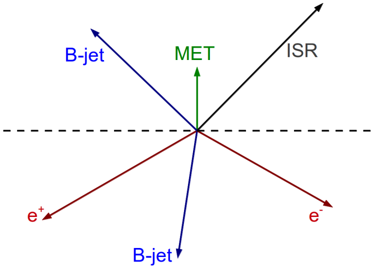
ISR treatment

1) Lorentz transformation to “boost-back” the system into a frame where the transverse momentum of the ISR is 0.

- $P(x|Zb\bar{b} \to l^+ l^- b\bar{b})$:

$$p_{ISR} = -\sum p_i$$

- $P(x|t\bar{t} \to l^+ l^- b\bar{b}\nu\bar{\nu})$:



$$p_{ISR} = -\sum p_i - \mathrm{MET}$$

$$\sum p_i = p_{b1} + p_{b2} + p_{e1} + p_{e2}$$

2) Using LO calculation that contains the extra radiation

- Good modelisation of the extra hard radiation
- time consuming

1) and 2) are **complementary**.

MadWeight : The automation at LO

The calculation of the probability entails an intricate numerical integration.
A generic module dubbed `MadWeight`[2] has been designed to perform this phase-space integration in an efficient way.

- based on MadGraph/MadEvent.
- for any process implemented in MadGraph.
- averages over all possible parton-jet assignements.
- transfer function provided by the user (no restriction).

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2. P. Artoisenet, V. Lemaitre, F. Maltoni and O. Mattelaer, JHEP 1012, 068 (2010), 1007.3300

Overview

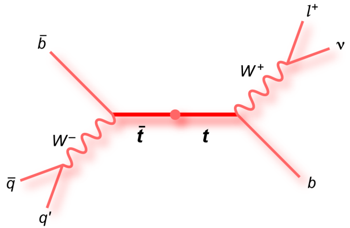
b-Charge association [3]

3. *Gedalia et al., Top B Physics at the LHC, arXiv :1212.4611*

b-Charge association

Measuring CP violation with $t\bar{t}$ at LHC :

- **mixing** :
  $N(b \to \bar{b} \to \ell^+) - N(\bar{b} \to b \to \ell^-)$
- **direct** :
  $N(b \to \ell^-) - N(\bar{b} \to \ell^+)$



<u>Goal :</u> find out which are b and $\bar{b}$ initially $\to$ **b-Charge Association**

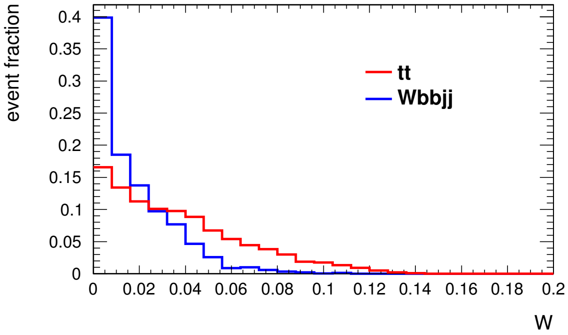
<u>How ?</u>

- MadWeight can averages over parton-jet assignements (standard way)
- Or computes the probability of each permutation :
  - b-jets ($\times$2)

For each event, probabilities P_1 and P_2 of two possible choices of the b-charge can be computed.

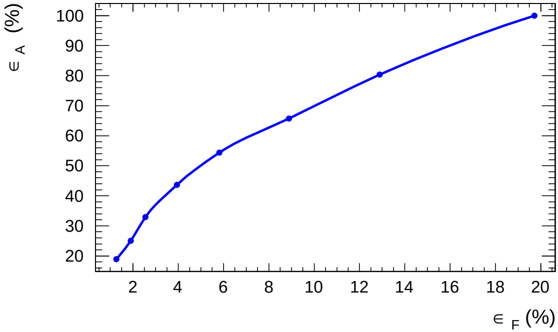
W variable

$$\text{define } W = \left|\frac{P_1 - P_2}{P_1 + P_2}\right|$$



- large values of W correspond to good discrimination between the two association hypothesis
- sample with correct association can be selected.
- bonus : background rejection ! !

Efficiency vs. charge mis-association rate



Can achieve $\leq$ 10% mis-association rate with $\approx$ 70% signal efficiency.

Differential cross-section measurement (DNEM) [4]

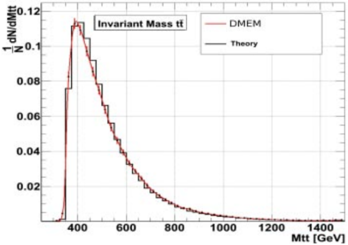
4. *A. Pin & O. Mattelaer, Determination of differential cross sections from ttbar fully leptonic, using the matrix element method, Il Nuovo Cimento C, Top 2011 Conference Proceedings*

$t\bar{t}$ differential cross section measurement.

It is possible to adapt the MadWeight program to estimate the pdf of arbitrary variable (e. g. $t\bar{t}$ invariant mass)

$$\frac{\partial \mathcal{P}}{\partial m}\Big|_{m=m_0} = \frac{1}{\sigma}\int d\phi(y)dq_1 dq_2 f_1(q_1)f_2(q_2)|\mathcal{M}_\alpha|^2(y)W(x,y)\times\delta(m-m_0)$$

For each event, a $\frac{1}{\mathcal{P}}\frac{\partial \mathcal{P}}{\partial m_{tt}}$ curve is computed. Then the sum of the curves provides $\frac{\partial \sigma}{\partial m_{tt}}$

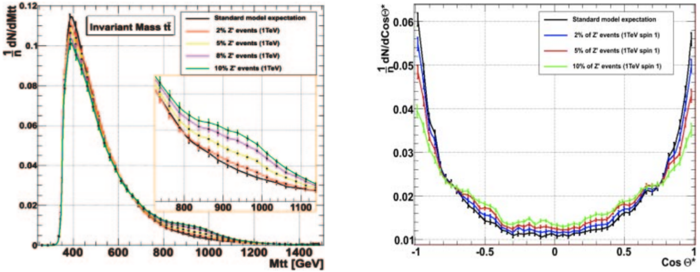


Comparison between

- theory : parton-level $t\bar{t}$-mass
- DNEM : reconstructed distribution using MEM

$t\bar{t}$ differential cross section measurement : search for resonnances

A prospect developped for the LHC was the search for resonnant productions of $t\bar{t}$ pairs decaying leptonically.



- Good discrimination
- possibility to measure the spin of the resonance using the angular variable $\cos(\theta^*_{tt})$
- sensitive to the transfer function.

New resonance at 125 GeV/c^2 : parity measurement [5]

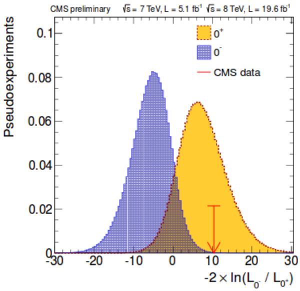


FIGURE: CMS results (Moriond)

- Background discrimination
- hypothesis testing
- Following an approach defined in [6]

5. *Work under progress*
6. On the spin and parity of a single-produced resonance at the LHC - Bolognesi, Sara et al. Phys.Rev. D86 (2012) 095031 arXiv :1208.4018 [hep-ph]

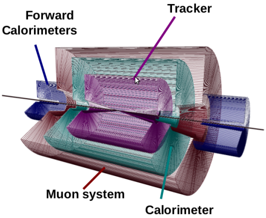
Generation and Detector simulation

Generation :

- Implementation of an effective model in MadGraph using FeynRules [7] :

$$\mathcal{L}_{eff} = \frac{g}{\Lambda} 0^- Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

- $M_{0^+} = M_{0^-} = 125 GeV$
- Events generation with MadGraph :
  - $pp \to 0^+ \to e^+ e^- \mu^+ \mu^-$
  - $pp \to 0^- \to e^+ e^- \mu^+ \mu^-$
  - $pp \to e^+ e^- \mu^+ \mu^-$
- Pythia is used for the showering
- Fast Detector simulation (*Delphes*).



7. *N. D. Christensen and C. Duhr, Comput. Phys. Commun. 180 (2009) 1614*

The selection

The selection is as close as possible to CMS selection :

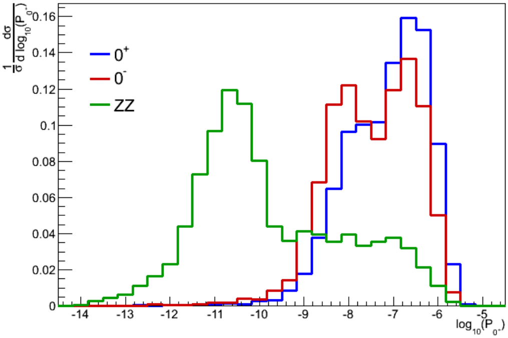
Charged leptons selection :

- $PT > 7$ GeV & $|\eta| < 2.4$

Event selection :

- $p_{T1} \geq 20$ GeV
- $p_{T2} \geq 10$ GeV
- $50 \text{ GeV} \leq M(Z1) \leq 120$ GeV
- $12 \text{ GeV} \leq M(Z2) \leq 120$ GeV
- $110 \text{ GeV} \leq M(X) \leq 160$ GeV

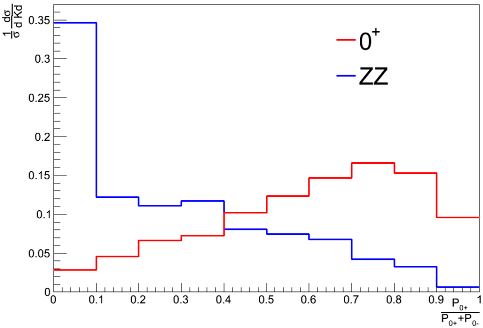
Example : P_{0^+} from MadWeight ($110 \leq m_{ee\mu\mu} \leq 160$)



Kinematic Discriminant Variable

Let's define a simple kinematic discriminant :

$$KD = \frac{P_{0^+}}{P_{0^+} + P_{ZZ}}$$



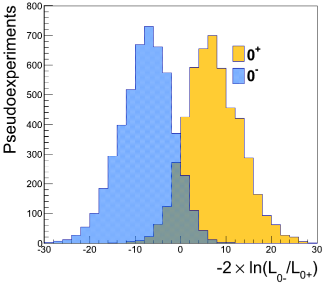
This quantity is ideal to cut on in order to increase the purity of the sample.

Higgs parity measurement

extended Likelihood :

$$\mathcal{L}_k = e^{-n_s-n_b} \prod_i \left(n_s \times P_s^k(x_i) + n_b \times P_b(x_i) \right) \tag{1}$$

where k is represents the different spin-parity signal hypothesis for the new resonance (0^+, 0^-, 2^+, etc...).



- assuming $\approx 25\ \text{fb}^{-1}$
- only ZZ background considered
- statistical errors only
- expected separation : $\approx 3\sigma$

While similar to CMS and ATLAS approaches for the 4 leptons topology, this method can be **easily extended** to channels with neutrinos or jets.

Conclusion

- MadWeight is a program aimed at **automating** the calculation of the Matrix element Method
- effective treatment for ISR
- can be used to test any hypothesis in the Standard Model or beyond (provided that the corresponding model is available in madgraph 5)
- Providing a wide range of applications.
  - precision measurement (top mass)
  - hypothesis testing
  - disentangle sub-configurations (b-charge association)
  - search for new resonances $\frac{\partial\sigma}{\partial m_{tt}}$

Next step

- Matrix element method at NLO ?

Thanks for your attention !