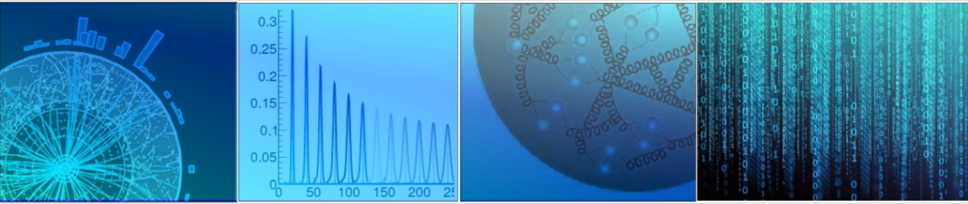
Introduction to the HU Berlin MEM toolkit

Data Science @ LHC Workshop | CERN · November 10th, 2015



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Motivation

Task

- Set of measured collision events **x** (electrons, muons, jets, ...) to be compared with theory (simulated events)
- Distinguish hypotheses regarding the p.d.f.

$$f(\mathbf{x}|N_S,\alpha) = \frac{N_S}{N_S+N_B} f_S(\mathbf{x}|N_S,\alpha) + \frac{N_B}{N_S+N_B} f_B(\mathbf{x}|N_B,\alpha)$$

  - Does a certain process occur ($N_S > 0$)?
  - What is the value of a certain parameter α?

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Challenge

- Complexity of collision events
- Similarity of signal and background processes

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Solutions

- Marginalization: reduction of $f(\mathbf{x}|N_{S_0},\alpha_0)$ to a one-dimensional function discriminating signal and background, use Machine Learning
- Approximation: simplified version of $f(\mathbf{x}|N_S,\alpha)$, known as Matrix Element Method (MEM)

Motivation

	Machine Learning	MEM
Speed	fast	slow
Requires sim. events	yes	no
Variation of α	not so easy	easy

Aim to show how to take advantage of the MEM
in a standardized way:
MEM toolkit developed at HU Berlin

Status: not yet public,
but shared upon request,
collaboration is welcome

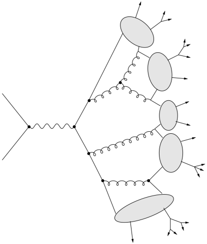
Outline

1. Concept
   - Ansatz
   - Implementation
2. Usage
   - Configuration
   - Input and output of events

Ansatz

- Approximation of the event p.d.f. by means of a factorization
  - Hard scattering - fixed (leading) order perturbation theory
  - Hadronization, detector effects: parametrizations known as transfer functions

$f(\mathbf{x}|N_S, \alpha) =$



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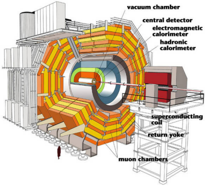
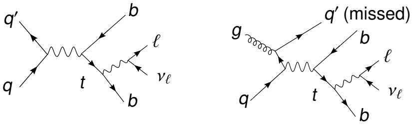


$$\approx \int \mathrm{d}\Phi \frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} W(\mathbf{x}|\Phi)$$

- Three building blocks to implement
  - Hard scattering cross sections $\mathrm{d}\sigma/\mathrm{d}\Phi$
  - Transfer functions $W(\mathbf{x}|\Phi)$
  - Phase space integration $\int \mathrm{d}\Phi$

Hard scattering

- Leading order description, $d\sigma_{ij}/d\Phi = \frac{1}{2x_1 x_2 s}|\mathcal{M}_{ij}|^2$
- Amplitudes taken from the MCFM package
  - Many processes can be implemented
  - Incorporation not automatized
- Finite transverse boosts through bremsstrahlung – additional scattering processes which constitute higher order corrections[1]



  - Example: *s*-channel single top-quark production with 2 and 3 final state partons
  - In case of two measured jets: integrating over one of the partons without matching it to a jet

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[1] First NLO implementation of the MEM published as a proof of principle – T. Martini, P. Uwer, JHEP 09, 083, 2015, arXiv:1506.08798

Transfer Function

- $W(\mathbf{x}|\Phi)$: p.d.f. of reconstruction of momenta $\mathbf{x} = \{\mathbf{p}_i^{\text{reco}}\}$ given particle momenta $\{\mathbf{p}_j\}$
- Matching particles to measured objects (electrons $\leftrightarrow$ electron candidates, partons $\leftrightarrow$ jets etc.)
- Single particle resolution function (if matched) with approx. flawless angular resolutions:

$$W_{\text{res}}(\mathbf{p}^{\text{reco}}|\mathbf{p}) = W_{\text{res}}^{E}(E^{\text{reco}}|E) \cdot \delta\left(\cos\vartheta^{\text{reco}} - \cos\vartheta\right) \cdot \delta\left(\varphi^{\text{reco}} - \varphi\right)$$

- Complete transfer functions including
  - Matching permutations
  - Reconstruction efficiencies
  - Resolutions

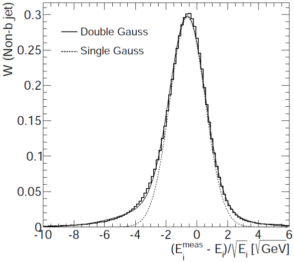
$$W(\mathbf{x}|\Phi) = \text{const} \cdot \sum_{i \in \{\text{permutations}\}} \prod_{j \in \{\text{matched}\}} W_{\text{res}}\left(\mathbf{p}_{ij}^{\text{reco}}|\mathbf{p}_{ij}\right) \varepsilon(\mathbf{p}_{ij}) \prod_{k \in \{\text{unmatched}\}} \left(1 - \varepsilon\left(\mathbf{p}_{ik}\right)\right)$$

Transfer Functions

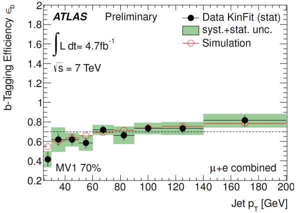
- Double Gaussian resolutions for *e*, μ and jet-energies, matching to LO parton level
- Fixing all angles,
  fixed *e* and μ-energies optional
- Can use $\not{E}_t$ and $\varphi_{\not{E}_t}$ transfer functions, matched to neutrino transverse momentum
- Incorporating reconstruction efficiencies
  - Single object transfer function:

    $$\varepsilon(\mathbf{p}) \cdot \mathbf{W}_{\text{res}}(\mathbf{p}^{\text{reco}}|\mathbf{p})$$

  - Includes *b*-tag efficiencies
  - $1 - \varepsilon(\mathbf{p})$ for objects not reconstructed



[J. Erdmann et al., NIM A748, 2014, arxiv:1312.5595]



[ATLAS Collaboration, ATLAS-CONF-2012-097 (2012)]

Integration

- Complete event likelihood:

$$f(\mathbf{x}) = \frac{1}{\sigma'} \sum_{p \in \{\text{permutations}\}} \int dx_1 dx_2 d\Phi \sum_{i,j} \frac{f_i(x_1) f_j(x_2)}{2 x_1 x_2 s} |\mathcal{M}_{ij}|^2 W_p(\mathbf{x}|\Phi)$$

- Integration by means of Monte Carlo techniques
  using the VEGAS algorithm (importance sampling)

- Phase space integration $\int d\Phi$ using dedicated algorithms
  (W+n jets, single top, top pair production, ...),
  no general algorithm

- Proper likelihood normalization $\int d\mathbf{x}\, f(\mathbf{x}) = 1$,
  useful when discriminant functions are constructed
  from likelihoods based on different processes

Software Design

- Designed from scratch using C++, dependencies:
  - ROOT
  - LHAPDF
  - CUBA (MC integration)
- Easy to extend due to modular code structure and inheritance from base classes for
  - Physics objects
  - Scattering processes
  - Phase space generations
  - Transfer functions
- Easy to use
  - Likelihood computation and I/O setup using simple ROOT C-scripts (see next part)
  - Simplicity of I/O due to usage of common file format (ROOT ntuples, see next part)
- Not ATLAS specific

Scattering processes

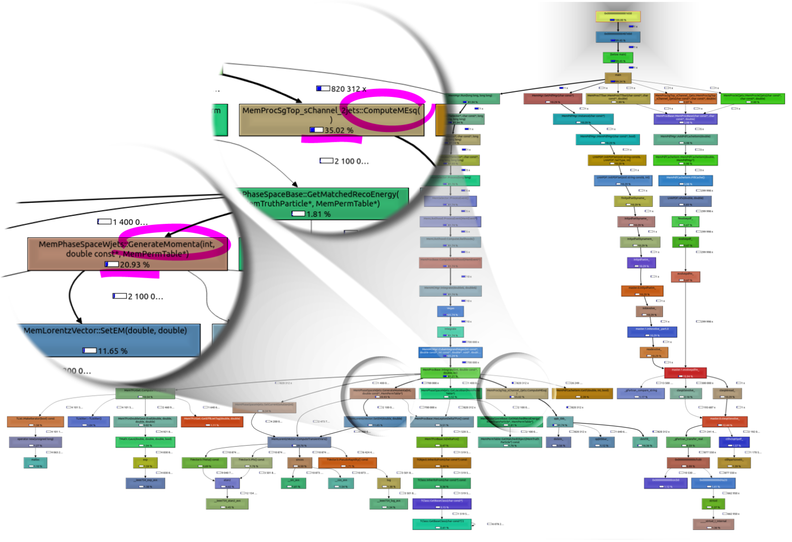
Process	**Max. jet multiplicity**
Single top s-channel $2 \to 2$	2
Single top s-channel $2 \to 3$	3
Single top t-channel $2 \to 2$	2
Single top t-channel $2 \to 3$	3
$t\bar{t}$, single lepton	4
$t\bar{t}$, di-lepton ($N_{e,\mu}^{\text{reco}} \in \{1, 2\}$)	2
WH, $H \to bb$	2
WHq, $H \to bb$	3
$W+qq$	2
$W+qqq$	3
$W+cq$	2
$W+bb$	2
$W+bbq$	3

MEM Speed-Up
Overview

Means	Explanation
Compilation	Compiler options and version
Profiling	Examine program execution (see next slide)
Reduction of permutations	Use b-tag information
Symmetrization of $\|\mathcal{M}\|^2$	For decays like $W \to qq$, $H \to bb$ instead of extra permutations
Fast amplitude evaluation	Neglect spin correlations whenever reasonable, narrow width approximation
PDF caching	Faster than continuous access to LHAPDF
δ functional resolutions	Simplifies integral (whenever reasonable)
Phase space generation	Appropriate parameterization
MC integration setup	Iteration frequency of importance sampling, quasi-random vs. pseudo-random numbers

MEM Speed-Up

Profiling (Valgrind)



MEM computation time

Process	Precision [%]	Time per event [s]
Single top s-channel $2 \to 2$	10	2
Single top s-channel $2 \to 3$	30	8
Single top t-channel $2 \to 3$	60	9
$t\bar{t}$, single lepton	20	9
$t\bar{t}$, di-lepton	20	9
$W+qq$	9	3
$W+cq$	9	5
$W+bb$	10	1

- Compromise between precision of MC integration and comp. time
- Analysis turn-around time in practice: $\mathcal{O}$(2 weeks)
  (see lightning talk at the end of the session)

Summary

- MEM toolkit for various (top-quark) processes

Advantages

- Easy to use (configuration, I/O)
- Transfer function efficiencies
- Different jet and lepton multiplicities
- Proper likelihood normalizations
- Sufficiently fast

Limitations

- Inclusion of scattering processes not automatized

- Aim for a proper publication in the next months, private communication welcome at any time