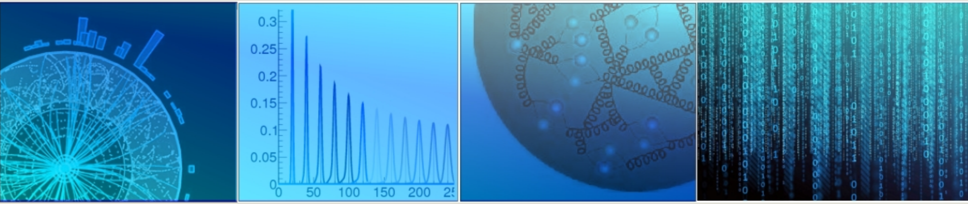
Single-Top s-Channel with MEM

ME Mini-Workshop | UCL | Louvain-la-Neuve · December 1, 2015



Oliver Maria Kind · Patrick Rieck · Sören Stamm
kind@physik.hu-berlin.de

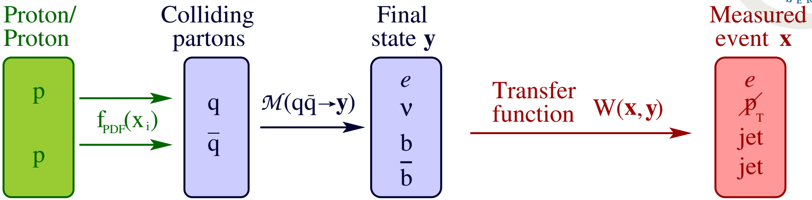
Institut für Physik
Humboldt-Universität zu Berlin
Germany

Part I

Introduction

The Matrix Element Method

Computation of event likelihoods

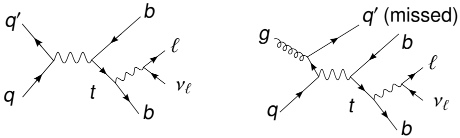


$$\mathcal{P}(\mathbf{X}|H) = \frac{1}{\sigma\epsilon}\sum_{p\in\{\text{perms}\}}\int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2)\cdot\int d\mathbf{y}\,\underbrace{\frac{\|\mathcal{M}^H_{i,j}(\mathbf{y})\|^2}{2x_1x_2s}}_{=d\sigma_{ij}/d\mathbf{y}}\cdot W_p(\mathbf{x}|\mathbf{y})$$

- Compute likelihood $\mathcal{P}$ for each measured event $\mathbf{X}$ to be of a certain process type H
- Three building blocks needed
  - Hard scattering cross-section $d\sigma_{ij}/d\mathbf{y}$
  - Transfer functions $W_p(\mathbf{x}|\mathbf{y})$
  - Phase space integration $\int d\mathbf{y}$

Hard Scattering

- Leading order description $\mathrm{d}\sigma/\mathrm{d}\mathbf{y} = \frac{1}{2x_1 x_2 s}||\mathcal{M}||^2$
- Amplitudes taken from the MCFM package
  - Many processes can be implemented
  - Incorporation not (yet) automatized
- Additional transverse boosts by ISFSR or higher order corrections[1]



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

[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 Functions

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

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

- Complete transfer functions contains:
  - Permutation sum of all matchings
  - Reconstruction efficiencies
  - Detector resolutions

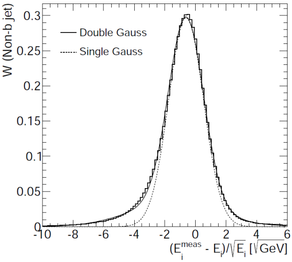
$$W(\mathbf{x}|\mathbf{y}) = \text{const.} \cdot \sum_{i\in\{\text{perms}\}} \left(\prod_{j\in\{\text{matched}\}} W_{\text{res}}(\mathbf{p}_{ij}^{\text{rec}}|\mathbf{p}_{ij}) \cdot \varepsilon(\mathbf{p}_{ij}) \cdot \prod_{k\in\{\text{unmatched}\}} (1 - \varepsilon(\mathbf{p}_{ij})) \right)$$

Transfer Functions (cont'd)

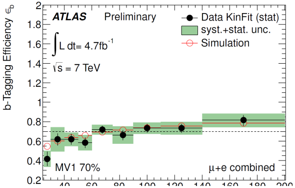
- Double Gaussian resolution functions for e, μ an jet energies, matched to partons
- Fixing of all angles
  Fixing of e or μ energies optional
- Can use $\not{E}_t$ and $\varphi_{\not{E}_t}$ transfer functions, matched to neutrino transverse mo-mentum
- Incorporate reconstruction efficiencies
  - Single-object transfer function:

$$W_{\mathrm{res}}(\mathbf{p}^{\mathrm{rec}}|\mathbf{p}) \cdot \varepsilon(\mathbf{p})$$

  - Includes b-tag efficiencies
  - $(1 - \varepsilon(\mathbf{p}))$ for non-reconstructed objects



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



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

Phase Space Integration

- Complete event likelihood:

$$\mathcal{P}(\mathbf{x}|H) = \frac{1}{\sigma\epsilon} \sum_{p\in\{\text{perms}\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \sum_{i,j} f_i(x_1) f_j(x_2) \cdot \int \mathrm{d}\mathbf{y} \frac{\|\mathcal{M}^H_{i,j}(\mathbf{y})\|^2}{2x_1 x_2 s} \cdot W_p(\mathbf{x}|\mathbf{y})$$

- Integration by means of Monte Carlo techniques using the VEGAS algorithm (importance sampling)
- Phase space integration $\int \mathrm{d}\mathbf{y}$ uses dedicated algorithms (W+n jets, single-top, $t\bar{t}$ production, ...); no generalized algorithm
- Proper likelihood normalization: $\int \mathrm{d}\mathbf{x}\mathcal{P}(\mathbf{x}|H) = 1$, useful when discriminant functions are constructed from likelihoods based on different processes

MEM Use Cases

Use case 1 : Estimation of model parameters

- m_{top} , couplings, x-sections, ...
- Also: calibration constants (JES, b-JES, ...)

➔ see next slides

Use case 2 : Signal and bkg discrimination

- x-sections & searches
- s-channel analysis

➔ see next slides

Use case 3 : Decay reconstruction

- Find correct jet permutation for complex final states (eg. $t\bar{t}$ production)
  ➔ tag & probe method for b-tag calibration etc.

Part II

Use Case 1: Parameter Estimation

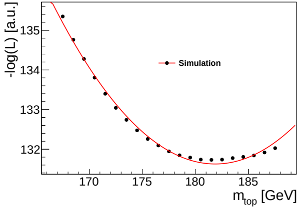
Application: top-quark mass measurement

Top-Quark Mass Measurement

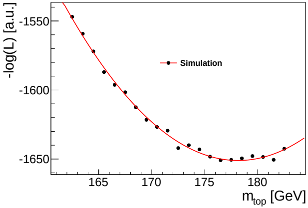
Model parameter estimation using MEM

- Idea: Compute $L_{t\bar{t}}$ for different top-quark masses
  ➔ **unbinned, event-wise ML fit** ➔ mass measurement
- Define sample likelihood $-\sum_{\text{events } X} \ln L_{t\bar{t}}(X\,|\,m_{top})$ ➔ minimize
- Results of a very preliminary small study:

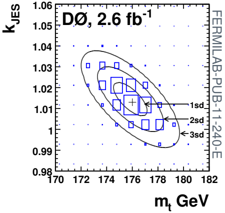
$t\bar{t}$ lepton + jets



$t\bar{t}$ di-lepton



DØ Run-II, Lepton + Jets



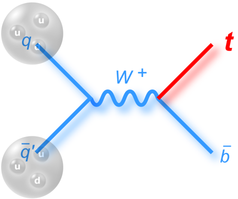
- Shift in top mass caused by higher orders and soft effects;
  known from Tevatron analyses and LHC studies (can be calibrated)
- Method can be used for other model parameters as well (couplings . . .)
- Calibration parameters (JES etc.) can be determined in the same way, or even simultaneously ➔ in situ calibration
- Problem: how to handle ~100 systematics ? — not yet implemented

Part III

Use Case 2: Discrimination

Application: single-top s-channel analysis

Motivation:



Feb 2014 | CDF & DØ @1.96 TeV, 9.7/fb
NN, BDT, ME combination ➔ 6.3σ

Dec 2013 | CMS @8 TeV, 19.3/fb
BDT analysis ➔ 0.7σ

Oct 2014 | ATLAS @8 TeV, 20.3/fb
BDT analysis ➔ 1.3σ

- First evidence in pp collisions at the LHC ?
- Search for BSM physics (anomalous Wtb couplings, V_{tb}, . . .)

Event selection:

- Isolated high-p_t e|μ & 2 b-jets & large $\not{E}_t$
- Main backgrounds: $t\bar{t}$, W+jets, single-top *t*-channel

Single-Top *s*-Channel Production
ME discriminant

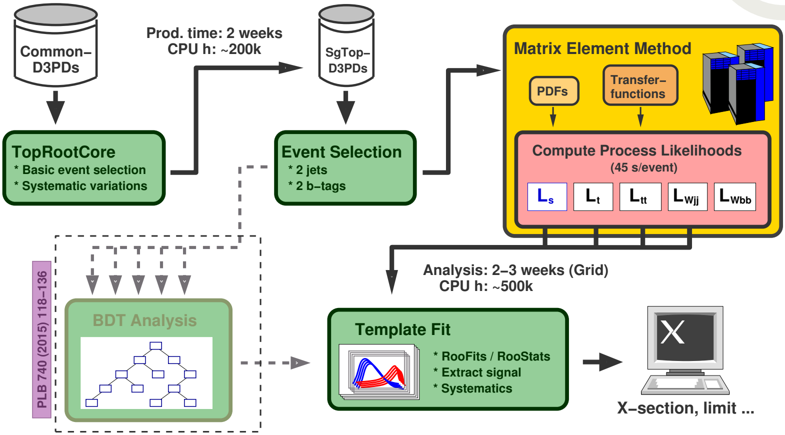
- Build ME discriminant for each selected event
  Discriminate *s*-channel against *t*-channel, $t\bar{t}$, W+$b\bar{b}$, W+c + jet, W+jets light-flavour
- Signal probability for given event X:
  (Bayes' theorem)

$$P(S|X) = \frac{\sum_S P(S)\mathcal{P}(X|S)}{\sum_S P(S)\mathcal{P}(X|S) + \sum_B P(B)\mathcal{P}(X|B)}$$

- Process likelihoods, $\mathcal{P}(X|H)$:
  - *s*-channel, 2 outgoing partons
  - *s*-channel, 3 outgoing partons
  - *t*-channel (2→3)
  - $t\bar{t}$, single lepton | di-lepton
  - W + 2 outgoing light partons
  - W + $b\bar{b}$
  - W + c + 1 outgoing parton
- P(H): *a priori* probabilities given by relative MC event yields
- Signal shape differs from background shapes

➔ signal extraction: template fit of ME discriminant distributions

Single-Top s-Channel Production
Analysis outline



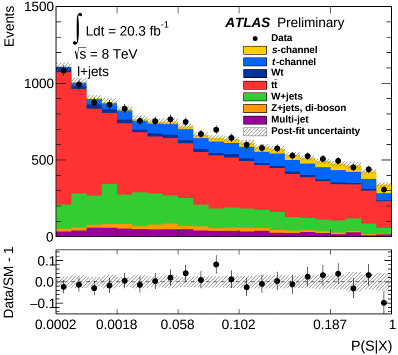
- Compute all event probabilities for all systematics in parallel ➔ GRID
- Total computing time for all processes per event: $\sim$45s only

  (Achieved by random number transformations, MC integration optimization, exploiting crossing symmetries, smart caching etc.)
- Analysis can be run on a feasible time scale

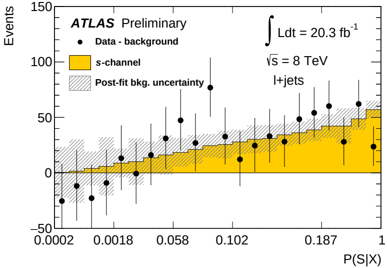
Single-Top *s*-Channel Production

Results

Post-fit ME discriminant



ME discriminant, signal only



Cross-section measurement:

$$\sigma_s = 4.8 \pm 1.1(\text{stat.})^{+2.2}_{-2.0}(\text{syst.})\,\text{pb}$$

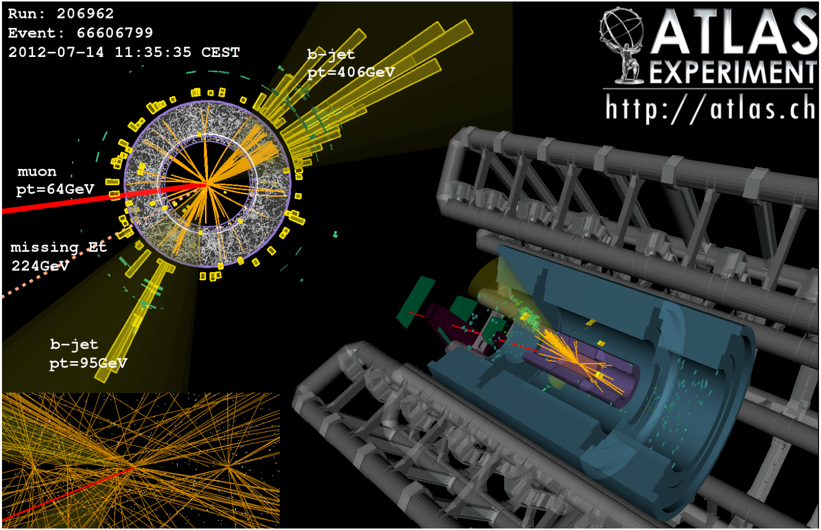
- Observed significance 3.2σ
- Expected significance 3.9σ

First evidence for single-top *s*-channel production at the LHC

arXiv:1511.05980 (submitted to PLB)

Single-Top *s*-Channel Production

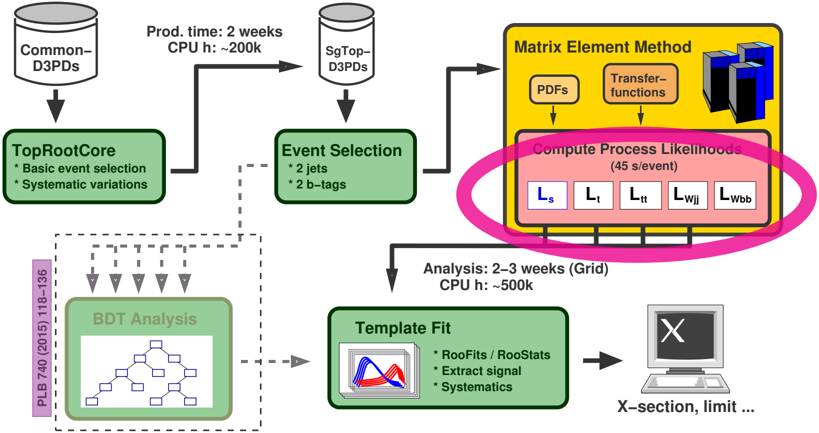
Golden candidate event



Part IV

The MEMTK Software

Computation of Process Likelihoods



MEMTK Fact Sheet

Purpose:

- A C++ package for the computation of ME event likelihoods

Dependencies: ROOT, CUBA, LHAPDF

Input / output: ROOT-based ntuples (generic or user-defined)

Processes:

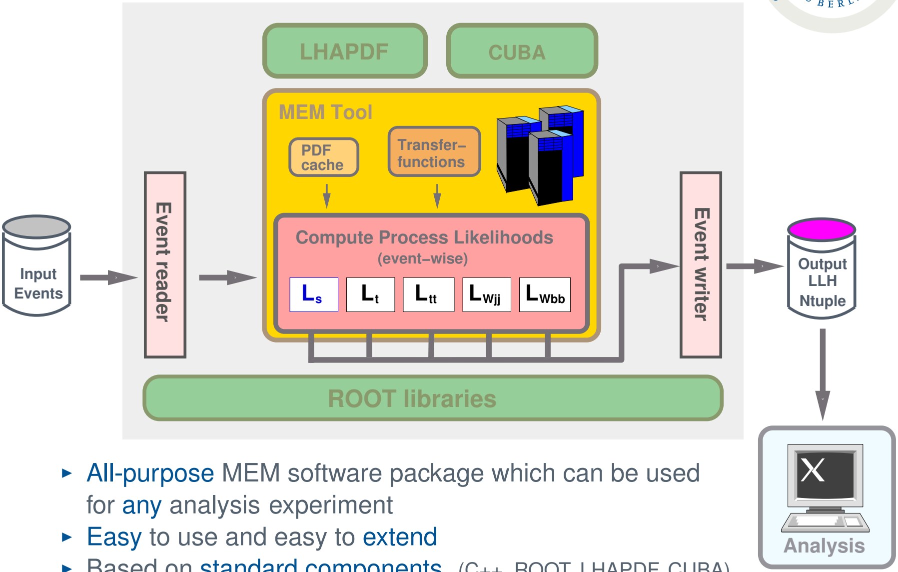
- Already implemented: (based on MCFM ME codes)
  - single-top: *s*-channel $2\to2|3$, *t*-channel $2\to2|3$
  - $t\bar{t}$: single lepton | di-lepton
  - $W+qq$, $W+qqq$, $W+cq$, $W+\bar{b}$, $W+b\bar{b}q$, $WH\to b\bar{b}$, $WqH\to b\bar{b}$
- Adding more processes possible (not automatized ☹)

Performance:

Per process (depending on precision)	1 – 10 s
For a typical single-top event (7 processes)	40 – 50 s
$20\,\text{fb}^{-1}$ including $\sim$90 systematics	2 weeks

Availability: will be public soon – currently upon request only

MemTk Layout



- All-purpose MEM software package which can be used for any analysis experiment
- Easy to use and easy to extend
- Based on standard components (C++, ROOT, LHAPDF, CUBA)

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 ($N^{\mathrm{rec}}_{e,\mu} \in \{1, 2\}$)	2
WH, H→bb	2
WHq, H→bb	3
W+qq	2
W+qqq	3
W+cq	2
W+bq	2
W+bbq	3

Main Configuration Script

- **Here:** example for a **single** process only (W+$b\bar{b}$)
- More processes can be **added easily** in the same fashion

```
MemMgr *mgr = new MemMgr;
mgr->SetCollider(MemMgr::kPP, 8000.);
mgr->SetPdfMgr("cteq66");

MemTFcnSet *tfcn = new MemTFcnSet(MemTFcnAtlasBase::kMC12);

MemProcWbb *proc_Wbb =
    new MemProcWbb("Wbb", "W + b bbar", 80.4);
proc_Wbb->GetMCMgr()->SetEpsRel(0.05); // Precision of MC integration
proc_Wbb->SetTFcnSet(tfcn);

mgr->AddProcess(proc_Wbb);

mgr->SetEvtReader(new MemEvtReaderGeneric);
mgr->SetInputTreeName("t_mem");
mgr->AddInputFile("MyMemInput.root");

mgr->SetEvtWriter(new MemEvtWriterGeneric);
mgr->SetOutputFile("MyMemOutput.root");
mgr->SetOutputTree("t_llh", "MEM Likelihodd Tree");

mgr->Run();
```

Manager Classes

MemMgr

- Main interface
  - Handles processes
  - I/O management:
    Input/output files, event loop, etc.

MemPdfMgr

- Interface for computing PDFs
  - Uses LHAPDF
  - Caching of PDFs available
    for faster access

```
MemMgr *mgr = new MemMgr;
mgr->SetPdfMgr("cteq66", UseCache);

[...]

mgr->AddProcess(proc_Wbb);

mgr->SetEvtReader([..]);
mgr->SetInputTreeName([..]);
mgr->AddInputFile([..]);

mgr->SetEvtWriter([..]);
mgr->SetOutputFile([..]);
mgr->SetOutputTree([..]);

mgr->Run();
```

EvtReader

- MemEvtReaderGeneric:
  flat ROOT ntuple
- Customizable event reader class
- Any input format possible

Example input ntuple layout:

el_chg	el_e	el_eta	el_n
el_phi	el_pt	evt_nr	evt_weight
jet_btagged	jet_btagw	jet_e	jet_eta
jet_flav	jet_n	jet_phi	jet_pt
met_et	met_phi	mu_chg	mu_e
mu_eta	mu_n	mu_phi	mu_pt
run_nr			

EvtWriter

- MemEvtWriterGeneric:
  4-momenta + ME likelihoods
- MemEvtWriterCloneTree:
  cloned input tree + ME likelihoods
- User-defined output format

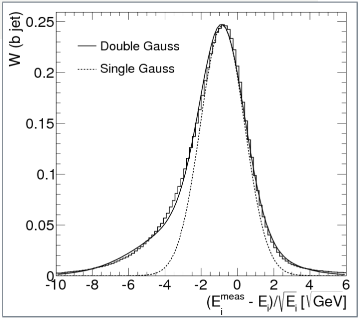
Transfer Functions

- Transfer functions are organized in sets
- A set defines transfer functions for all objects
  (electrons, muons, jets, missing transverse momentum)

```
// Pre-defined set for ATLAS analyses
MemTFcnSet *tfcn = new MemTFcnSet(MemTFcnAtlasBase::kMC12);

// Transfer functions can be changed by setter functions
tfcn->SetElectronTFcnMagnitude(new MemTFcnDelta(MemTFcnBase::kEnergy);
tfcn->SetMuonTFcnMagnitude([..]);
tfcn->SetLightJetMagnitude([..]);
```

- Possible parametrisations:
  - Single Gauss
  - Double Gauss
  - δ distribution
- Parameters can be set | changed using text files
- ATLAS: KLfitter sets available



Erdmann, J. et al. Nucl. Instrum. Meth. A748 (2014)

Process & Phase Space Generation

Processes

- Several processes are already built-in
  such as W+jets, single-top processes and $t\bar{t}$

```
MemProcSgTop_sChannel_2j *proc_sChannel_2j
    = new MemProcSgTop_sChannel_2j("sChannel2j",
                                   "SgTop s-channel, 2 jets",
                                   172.5);
...
MemProcWbb *proc_Wbb
     = new MemProcWbb("Wbb", "W + b bbar", 80.4);
```

- Each process inherits from the process base class
- New processes can be added by means of inheritance
  (ME computation and wrapper functions are required)
- Process class connects four-momenta with the matrix element

Phase space

- Suitable transformations of initial and final state momenta
  (plus Jacobian)
- Needs to be added for each newly added process

Monte Carlo Integration

MemMCMgr

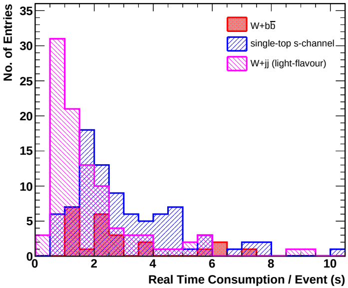
- Interface to CUBA
- Available Monte Carlo integration algorithms:
  - VEGAS (importance sampling)
  - DIVONNE (stratified sampling)
- Random number generation: pseudo or quasi random numbers
- Individual configuration of MC integration for each process
  ➔ runtime optimization

```
MemProcWbb *proc_Wbb =
    new MemProcWbb("Wbb", "W␣+␣b␣bbar", 80.4);
proc_Wbb->GetMCMgr()->SetEpsRel(0.05);     // 5% accuracy
proc_Wbb->GetMCMgr()->SetMaxEval(1.e6);    // Max. integrand evaluations
proc_Wbb->GetMCMgr()->SetNStart(1.e4);     // Vegas parameters
proc_Wbb->GetMCMgr()->SetNIncrease(1.e4);  // Vegas parameters
```

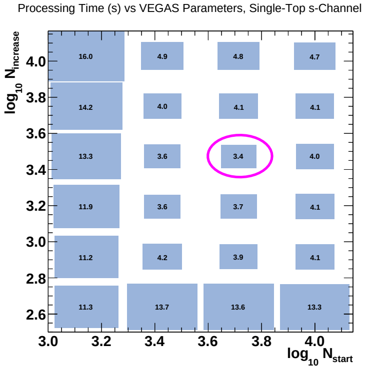
Monte Carlo Integration (cont'd)

Further reduction of computation time

- Different computation time for different processes
  ➔ focus efforts on major ones
- Investigation of computation time vs. importance sampling frequency



Computation time for different processes



MEM Speed-Up

Means	Explanation
Compilation	Compiler options and version
Profiling	Examine program execution
Reduction of permutations	Use b-tag information
Symmetrization of $\lvert\mathcal{M}\rvert^2$	For decays like W→qq, H→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 trannsformations
MC integration setup	Iteration frequency of importance sampling, quasi-random vs. pseudo-random numbers

Summary

- Development of C++ based MEM toolkit
- Several processes already implemented
- Can be extended
- First successful application:
  Evidence for single-top *s*-channel at the LHC
- MEMTK source code still private
  — publication soon

Part V

Appendix

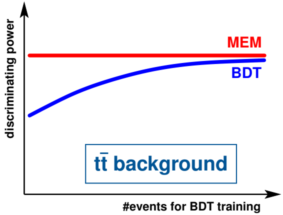
ME vs. BDT Comparison

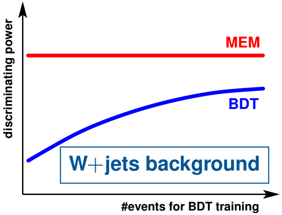
Single-Top *s*-channel analysis

- Performed detailed comparison between (old) BDT and ME analysis
- Partial improvement by better calibration, improved/larger MC samples and improved event selection

MC statistics:

- The BDT suffers from an insufficient number of training events for some of the main backgrounds





Systematic uncertainties:

- The BDT requires the reconstructed $t\bar{t}$ kinematics as input variables
  - explicit $\not{E}_t$ dependence
  - $p_z(\nu)$ ambiguity