Semi-analytic MEM for ttH-multilepton

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Semi-analytic
Matrix element method

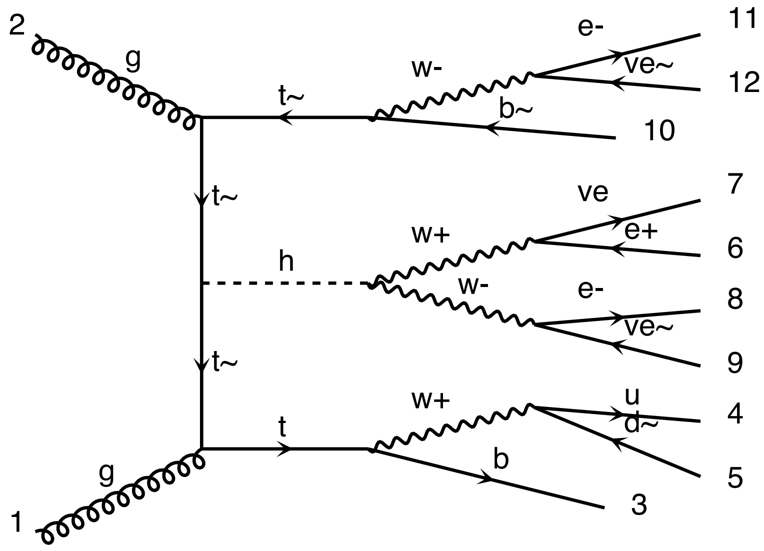


diagram 5 QCD=2, QED=8

Matrix element method:
- Integrate cross-section for a given phase-space point, to be used as a discriminant
- Includes correlations, performance should be similar to BDT

Complex final state:
- 3 leptons
- 2 b-jets
- 2 jets
- 3 neutrinos

Semi-analytic MEM and Madweight:
- **Reference : Madweight**
- **Alternative: Use standalone ME code provided by a generator, perform the integration by ourselves**
  - Will allow to consider categories with missing jets: in general a jet can easily be out of acceptance or mis-reconstructed
  - Developer control over the assumptions in the computation

At the moment, concentrate on 3 lepton 4 jets category

MEM Setup

Integration: **VEGAS** in ROOT

Matrix element: **Madgraph** C++ standalone

MEM weight

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int d\Phi_\alpha \cdot \delta^4 \Big(p_1^\mu + p_2^\mu - \sum_{k \geq 2} p_k^\mu \Big) \cdot \frac{f(x_1, \mu_F) f(x_2, \mu_F)}{x_1 x_2 s} \cdot \Big| \mathcal{M}_\alpha (p_k^\mu) \Big|^2 \cdot W(\Phi' | \Phi_\alpha)$$

Phase-space enforcing 4-momentum conservation: **analytic**

Pdf: **LHAPDF** interface

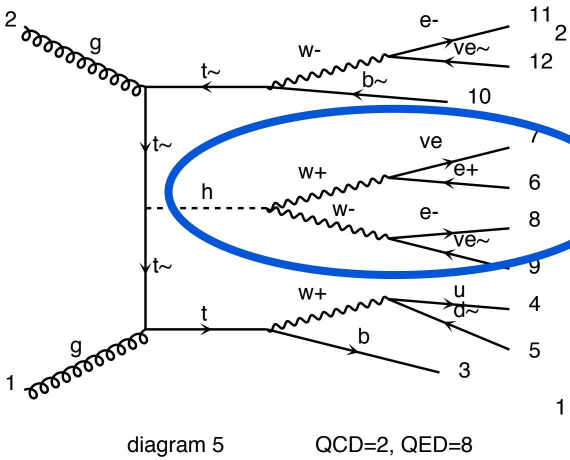
Transfer functions: Evaluated in MC samples

Similar setup with CMS ttH(bb) MEM analysis

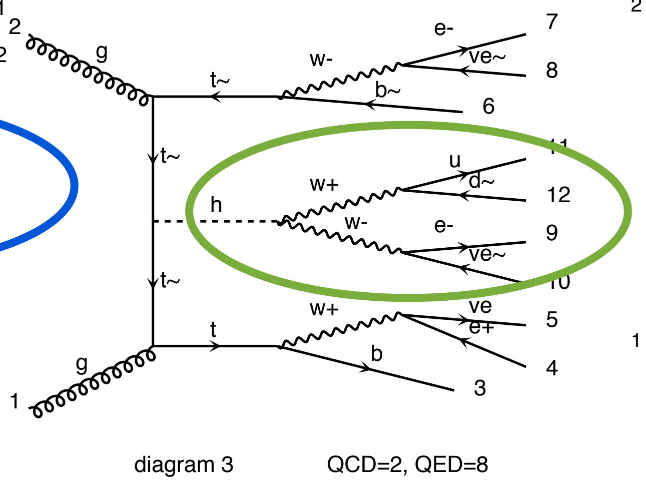
Hypotheses

- Assume **narrow-width for top and Higgs** (top not assumed narrow in default Madweight)
- Keep **full W propagator** in the ME: W mass follows a Breit-Wigner
- Do not set b-quark mass to 0 (contrary to Madweight)

ttH,H→2l2v decay semi leptonic ttbar

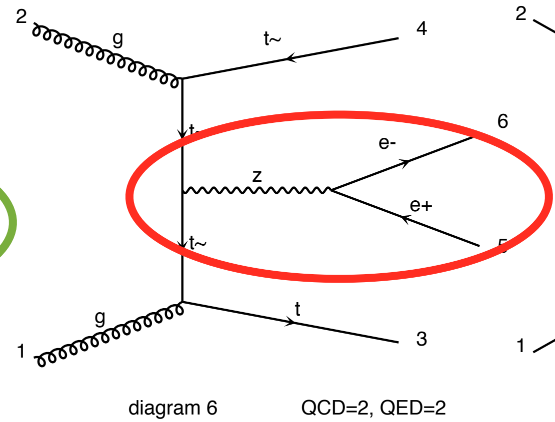


ttH,H→lvjj decay fully leptonic ttbar



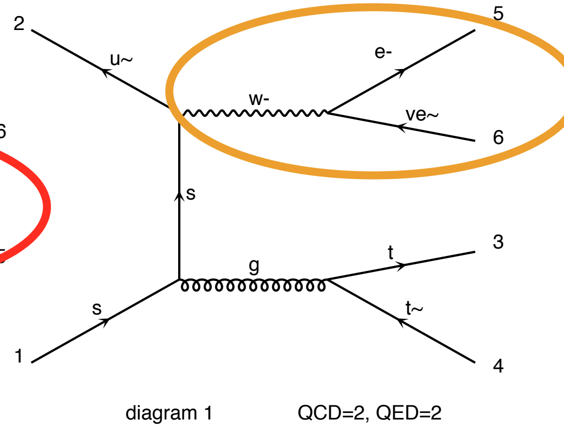
- Higgs decay to WW* considered

TTZ hypothesis



- Z/gamma* included

TTW hypothesis



- 2 jets missing
- Need sm_ckm

- Only the main diagrams are considered

Phase-space parametrization

Example of **hadronic top decay (1→3)**:

$$d\Phi_{top,had} = \frac{d^3p_b}{2E_b(2\pi)^3}\frac{d^3p_{j1}}{2E_{j1}(2\pi)^3}\frac{d^3p_{j2}}{2E_{j2}(2\pi)^3}(2\pi)^4\delta^4(p_t^\mu - p_b^\mu - p_{j1}^\mu - p_{j2}^\mu)$$

Integrating out the delta, we can choose which differential element we cancel out.
The following expression is valid in any frame:

$$d\Phi_{top,had} = \frac{1}{8(2\pi)^5}\beta_b p_b dE_b sin\theta_b d\theta_b d\phi_b \frac{E_{j2} sin\theta_{j2} d\theta_{j2} d\phi_{j2}}{(p_t cos\theta_{j2} - p_b cos(\widehat{p_t - p_b, p_{j2}}) - (E_t - E_b))}$$

- Now **connecting with TTH phase-space** one can redo the computation, including the top quark phase-space (thanks to top quark narrow-width approximation)
- It leads to a similar expression

- Same method applies to the **Higgs decay** phase-space **(1→4)**

- Remains to workout the **incoming particle phase-space:**

$$dx_1 dx_2 \delta(p^z_{tot} - p^z_{top} - p^z_{antitop} - p^z_{higgs})\delta(E_{tot} - p^z_{top} - E_{antitop} - E_{higgs}) = \frac{2}{s}$$

Phase space summary

Top hadronic decay:

$$d\Phi_{top,had} \propto dE_b d\theta_b d\phi_b dE_{j1} d\theta_{j1} d\phi_{j1} d\theta_{j2} d\phi_{j2}$$

Top leptonic decay:

$$d\Phi_{top,lep} \propto dE_b d\theta_b d\phi_b dE_l d\theta_l d\phi_l d\theta_\nu d\phi_\nu$$

Boson decay:

$$d\Phi_{H\to 2l2\nu} \propto dE_{l1} d\theta_{l1} d\phi_{l1} dE_{l2} d\theta_{l2} d\phi_{l2} dE_{\nu 1} d\theta_{\nu 1} d\phi_{\nu 1} d\theta_{\nu 2} d\phi_{\nu 2}$$

$$d\Phi_{H\to l\nu jj} \propto dE_{l1} d\theta_{l1} d\phi_{l1} d\theta_{\nu 1} d\phi_{\nu 1} dE_{j2} d\theta_{j1} d\phi_{j2} dE_{j1} d\theta_{j2} d\phi_{j2}$$

$$d\Phi_Z \propto dE_{l1} d\theta_{l1} d\phi_{l1} dE_{l1} d\theta_{l2} d\phi_{l2}$$

$$d\Phi_W \propto dE_l d\theta_l d\phi_l dE_\nu d\theta_\nu d\phi_\nu$$

Integrate over **jet and b-jet energy**, constrained by a **transfer function**

b-jet/jet angles, and **lepton energy and angles** assumed to be **known**

Full integration on **neutrino variables**, completely **unknown**

Integration variables	Top lep	Top had	Boson	Total variables	VEGAS calls
TTH,H→2l2v	3	2	5	**10**	**300k**
TTH,H→lvjj	2x3	0	4	**10**	**300k**
TTZ,Z→ll	3	2	0	**5**	**100k**
TTW,W→lv	2x3	0	3	**9**	**300k**

Total momentum conservation

Incoming partons: -

- Integration on both bjorken x are cancelled with total **momentum conservation in z and E**

The TTH system is boosted in x-y plane, because of showering + ISR at ME level

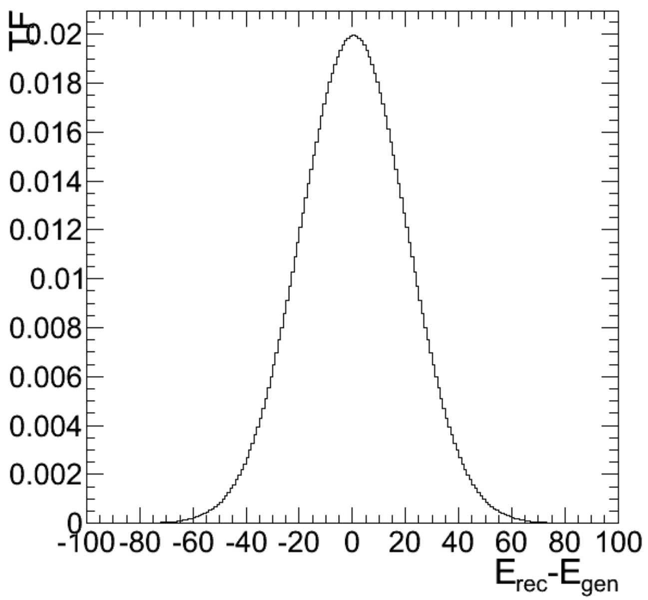
- The **ME** used to evaluate the weight is **LO**: the **recoil needs to be corrected**
- Recoil = system **transverse momentum at parton level**
- First **boost back the TTH system** with the Recoil Pt, then evaluate the ME

Total momentum Px and Py is conserved: no integration

- But can be constrained with **Transfer function**
- Use **mET TF** (not "aligned" the with integration variables)
- Highly correlated with total momentum (up to neutrinos)

Transfer functions

- Measured **transfer functions** in **ttbarH sample** (cross-checked with ttbar), separately for jets and b-jets, in 3 η bins and 6 energy ranges
- **6 Transfer functions** are used:
  - **2 Bjet energies,** for top and antitop
  - **2 Jet energy** from W(*) in TTH/TTZ, or from ISR (TTWjj)
  - **Recoil Px and Py**: **use mET TF** (helps against TTZ).



Simple exemple of Gaussian TF with width 0.2*E, for a jet with E=100 GeV

Choice of the integration range:

- Started with [0.65*E, 2.0*E], was fine with gaussian TF
- Now using [0.2*E, 5.0*E]:
  - less events with weight=0
  - but can degrade slightly the performance
  - depends on the TF which are used
- Ideally: make the TF flat by change of variable

Jet choice and combinatorics

Non B-quarks can have different origin:
- **minimum |Mjj-Mw|:** aims selecting jets from **W** (arising from Higgs or hadronic top)
- **minimum Mjj:** aims selecting jets from **W*** (arising from Higgs)
- **highest pT:** aims at selecting jets being **ISR/FSR** (TTW) - not used since we don't use by the default the TTWJJ hypothesis

B-quarks choice:
Simplest option: select two jets with the highest b-tag discriminant value

Permutations: **Jets (2)**, **B-jets (2)** (no jet / b-jet cross-permutation), **Leptons (2)** in general (ME Boson decay has +/- assignment)

Hypothesis	Permutations
TTH (2 hyp)	2x8=16
TTZ	4 (if only one SFOS) or 8
TTW	4 (no jet)

Combining permutations:

$$\begin{cases} w_\alpha = 10^{-300} & \text{if } \sum w_i = 0 \\ w_\alpha = \frac{1}{N_{w_i \neq 0}} \sum_{w_i \neq 0} w_i & \text{else} \end{cases}$$

Likelihood discriminant

$$L_{\mathrm{TTHvsTTW}} = -log\Big(\frac{\sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + \sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}\Big)$$

$$L_{\mathrm{TTHvsTTZ}} = -log\Big(\frac{\sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + \sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}}}\Big)$$

- Rescale TTW hypothesis by an effective factor, to account for the 2 missing jets phase space, and get wTTW shape more similar to wTTZ (otherwise their mean value in the weight is different by 15 orders of magnitude)

$$\begin{cases} -log\Big(\frac{\sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}} + k \cdot \sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + \sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}} + k \cdot \sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}\Big) & \mathrm{SFOS} \\ -log\Big(\frac{k \cdot \sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + k \cdot \sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}\Big) & \mathrm{no} \quad \mathrm{SFOS} \end{cases}$$

- Categories : will decide which sub-categories to use on the basis of expected sensitivities

Comparison with Madweight

Performance:
- Checked on events with one SFOS pair only, TTH against TTZ
- Performance is comparable, Madweight has slightly better background rejection (by 5%) for 80% signal efficiency
  - Probably has to do with convergence
  - Could also be due to top quark BW neglected (although we do it coherently for signal and background)

Timing (lacks real comparison):
- Madweight: needs several iterations of one night-long, for each process
- Private code: able to run all hypotheses/permutations on ~20000 events in one night with lxbatch

Events with weight=0:
- Madweight: TTH 3-6%, TTZ 2 per mille
- Private code: TTH 4-5%, TTZ 3%

Uncertainty on the weight:
- Madweight: TTH bulk at < 5 per mille, TTZ < 2 per mille
- Private code: TTH 2.5%, TTZ 5 per mille, long tails

Automation

Up to now, focused on TTH multi lepton analysis.

Processes:

- 3l final state for TTH (H fully-lep and semi-lep), TTZ/γ^*, TTW, TTWJJ
- Simple bash script to **create code for new ME evaluation from MG standalone C++** (insertion not completely automated)
- Select manually the most contributing subprocesses (to speed up the integration)
- Configuration file with number of VEGAS calls, which hypothesis to run

Phase space:

- At the moment, implementation of **2→3-6 core** phase space, with **narrow-width 1→3,4 decay** is available
- Easy to extend to any 2→N core and 1→N decays
- Do not use the best change of variables from Madweight

Conclusions

- Semi-analytic MEM in C++, uses Madgraph stand-alone code

- **Focused on TTH multi lepton analysis,** discriminating TTH against TTW and TTZ, at the moment **3 leptons 4 jets category, but can** easily be extended to other processes

Future MEM developments:

- Add **new categories**: 3 leptons 2j, 3j, and same sign dilepton categories

- Try a **kinematic fit** to reduce combinatorics

- **Speed up the integration** via change of variables: mW, TF

Back-up slides

Comparing ways of handling permutations

The event weight for a given hypothesis is computed from **permutations**

- **Baseline**: remove permutation with 0 weights when computing the mean

- **Max**: use only maximum weight

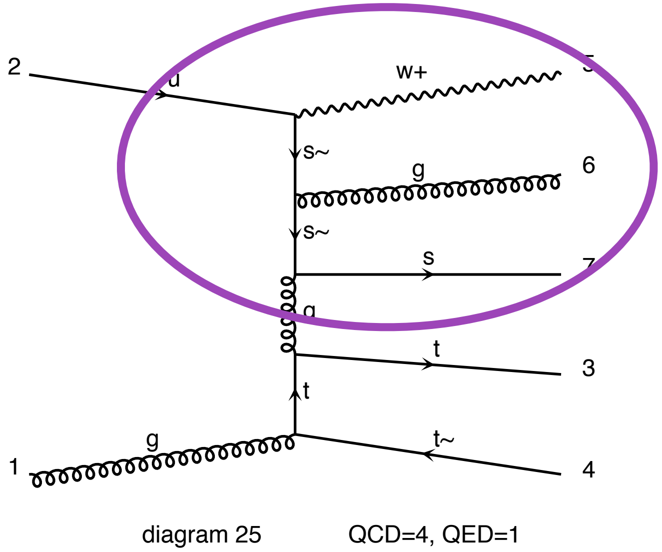
- **Average**: do not remove permutation, even if giving weight 0

Results are similar

- Motivates kinematic fit studies: if we would be able to compute only the maximum weight, performance would be preserved while speed improved by a big factor

TTWJJ hypothesis ?

TTWjj hypothesis



- **TTWJJ** hypothesis (11 variables) has many events with weight 0, **needs more time**
- **Time needed is 10x** the time for TTW (ME evaluation 2→6)
- Not used yet, but can be useful for the final discriminant

- W Breit-Wigner used
- Use jets (much slower)

$$d\Phi_{Wjj} \propto dE_l d\theta_l d\phi_l dE_\nu d\theta_\nu d\phi_\nu dE_{j1} d\theta_{j1} d\phi_{j1} dE_{j2} d\theta_{j2} d\phi_{j2}$$

TTWjj: 2x3(top lep)+3(W)+2(jets)=11 integration variables

Tuning TTW hypothesis

$$\begin{cases} -log\left(\frac{\sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}} + k\cdot\sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + \sigma_{\mathrm{TTZ}} w_{\mathrm{TTZ}} + k\cdot\sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}\right) & \mathrm{SFOS} \\ -log\left(\frac{k\cdot\sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}{\sigma_{\mathrm{TTH}} w_{\mathrm{TTH}} + k\cdot\sigma_{\mathrm{TTW}} w_{\mathrm{TTW}}}\right) & \mathrm{no\quad SFOS} \end{cases}$$