

# Top quark mass standard reconstruction methods

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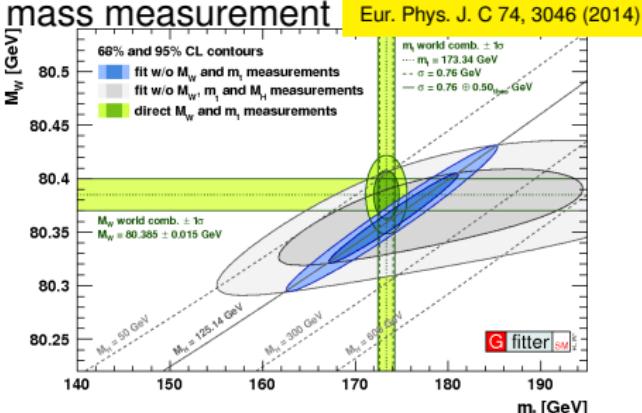


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# Top quark mass measurement : motivations

- Several motivations for top quark mass measurement



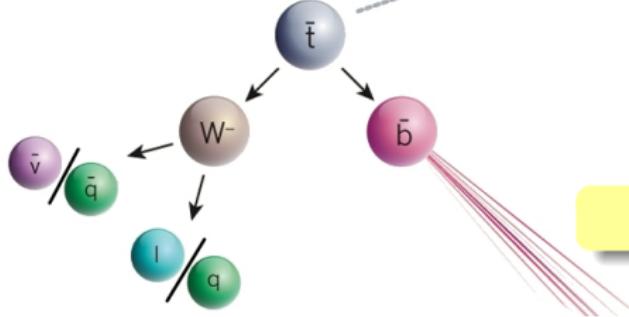
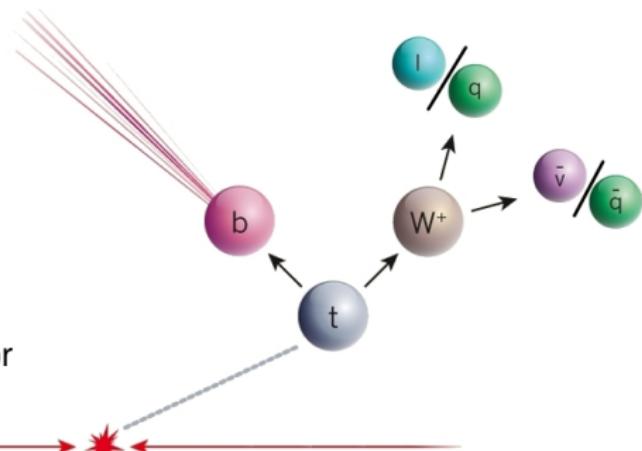
- Electroweak fit
  - Relation between  $m_{top}$ ,  $m_W$  &  $m_H$
  - Possible constraints on BSM
- Stability condition of the EW vacuum and top mass measurements

- A word of caution : we only use MC :
  - Hard matrix element : affect normalisation of the variables
  - Parton shower evolution : affect normalisation and shape of variables
  - Hadronisation model : idem
- MC mass :  $m_{top}$  propagator prior to top decay
  - This is what we measure in general
- Need also to relate  $m_{top}^{MC}$  and field theoretic masses

# Definition of decay channels

Top mass measured in  $t\bar{t}$  events :

- **$\ell + \text{jets channel}$**  : good balance between high signal rate, background and kinematic reconstruction
- **Dilepton channel** : very low background, but under-constrained kinematics for  $m_{top}$  measurement, low signal rate



- **Hadronic channel** : highest signal rate but very high backgrounds, mostly from QCD multijet production

+ EW single top production

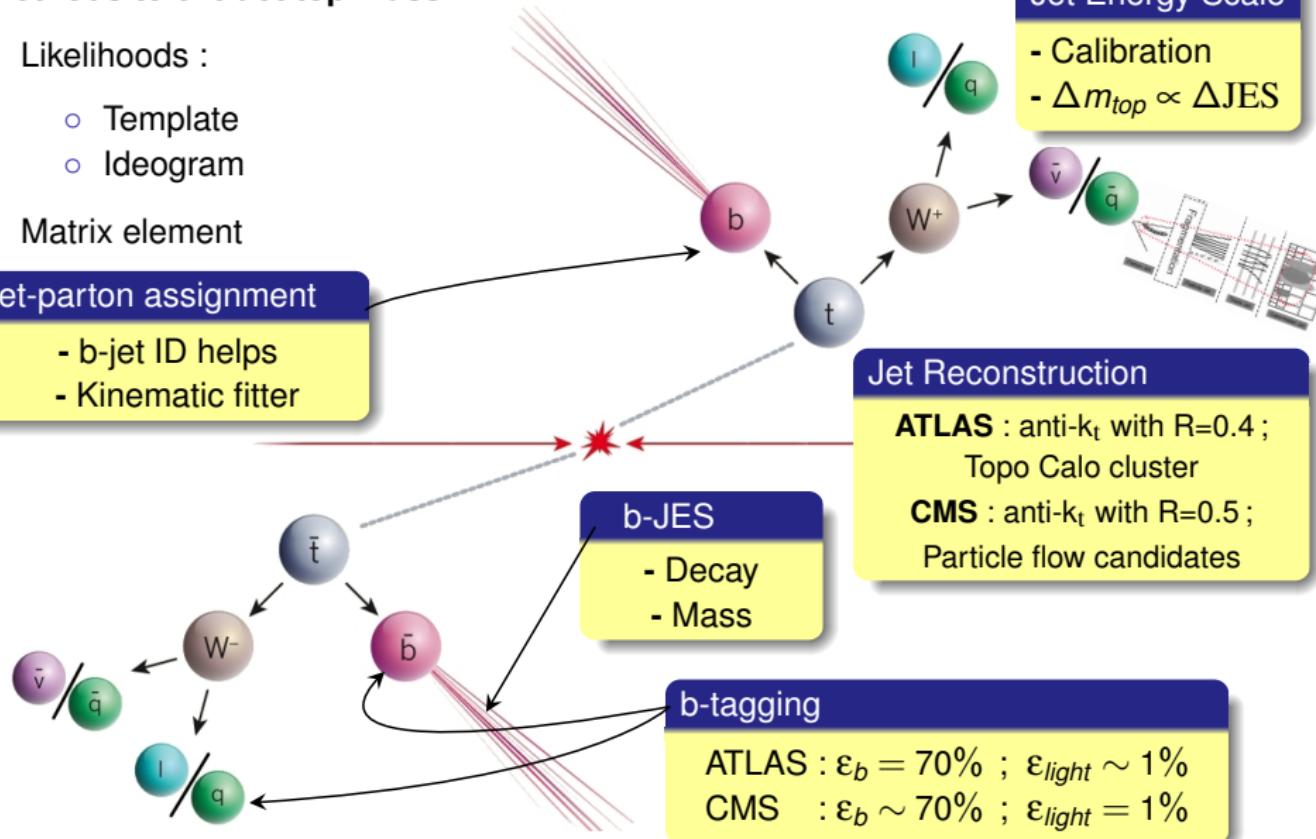
# Key ingredients to top mass measurements

## Methods to extract top mass :

- Likelihoods :
  - Template
  - Ideogram
- Matrix element

### Jet-parton assignment

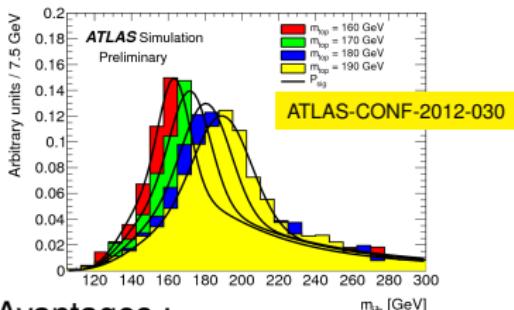
- b-jet ID helps
- Kinematic fitter



# Measurement techniques

## Template method :

- Exploit dependence of  $m_{top}$  on kinematic observables
  - Form templates using MC
  - Maximise consistency of templates with data at given  $m_{top}$  related parameter



- Avantages :
  - Robust and straight-forward
- Drawback :
  - Sub-optimal sensitivity

## Ideogram method :

- Calculates per-event probability, as MEM
- Defines probability densities from distributions in MC, as templates
- Avantages : In between the two

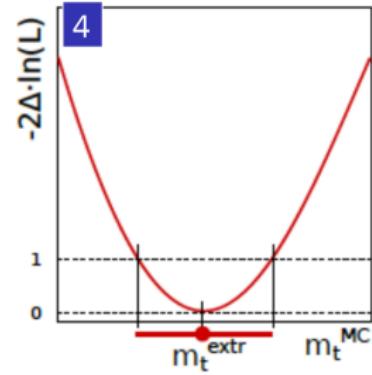
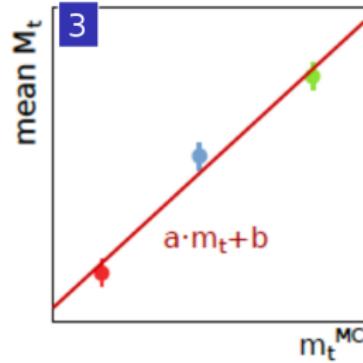
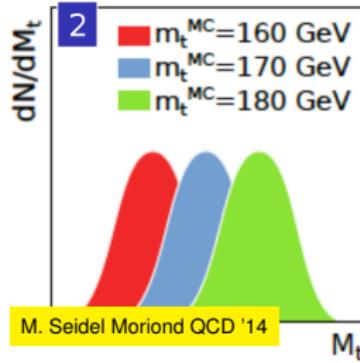
## Matrix element method :

- Directly calculate the event probability :
 
$$P_{evt}(m_{top}) = f_{top} P_{sig}(m_{top}) + (1 - f_{top}) P_{bkg}(m_{top})$$

$$P_{sig}(m_{top}) \propto |M_{t\bar{t}}(p_1, p_2; m_{top})|$$
- Avantages :
  - Use full 4-vectors → maximal use of statistical informations
- Drawbacks :
  - Computationally intensive

# Step-by-step procedure

- ① Select  $t\bar{t}$  events candidates
  - Efficient b-tag algorithms, high integrated luminosity
  - Good object reconstruction
- ② Construct best estimator for  $m_{top}$  (e.g. inv. mass of decay products)
- ③ Parametrise reconstructed mass in terms of generated mass
- ④ Perform maximum likelihood fit
  - Calibrated on MC, evaluation on data  $\Rightarrow t\bar{t}$  modelling crucial

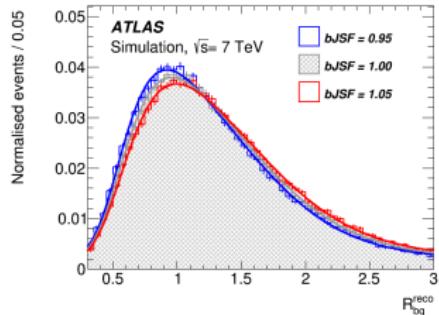
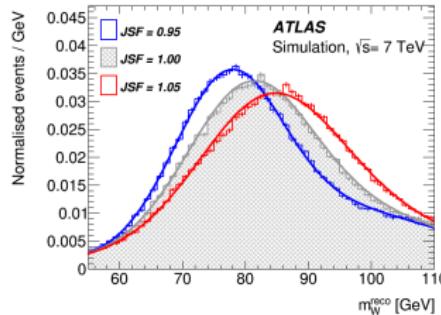
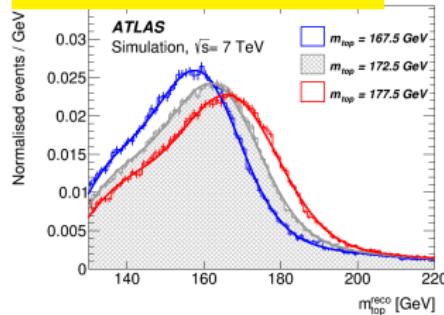


# Template method : description

⇒  $m_{top}$  by ATLAS in  $\ell + \text{jets}$  channel @7 & 8 TeV ([Ph.D. F. Balli, IRFU, 2014](#))

- Apply template method using the observable  $m_{top}^{reco}$ 
  - Signal template : parametrised by Gaussian + Landau functions
  - Background template : parametrised only with Landau
- Reconstructed top quark mass has strong dependence on JES and bJES
- *In-situ* measuring additional quantities to reduce these systematics :
  - Reconstructed mass of  $W$  boson ( $m_W^{reco}$ ) to constrain JES SF ; developed by ATLAS & CMS ( $\ell + \text{jets}$ )
  - Ratio of  $p_T^{b\text{-tag}}$  over  $p_T^W$  to constrain bJES SF : only ATLAS ( $\ell + \text{jets}$ )
  - Both templates : Two Gaussian functions

arXiv :1503.05427, submitted to EPJC



# Template method : kinematic fits

## Main challenge :

- Reconstruct  $t\bar{t}$  correctly even though :
  - Several assignments between partons and jets possible at LO
  - Additional jets coming from ISR/FSR

→ Perform kinematic fit of the event, using  $\chi^2$  minimisation : arXiv :1312.5595

$$\begin{aligned} \chi^2 = -2 & \left\{ \sum_{i=1}^4 \ln TF_{jet}(E_{jet,i}^{meas} | E_{jet,i}) + \ln TF_\ell(E_\ell^{meas} | E_\ell) + \sum_{j=x,y} \ln TF_{E_j^{\text{miss}}}(E_j^{\text{miss}} | p_j^\nu) \right\} \\ & + 8 \cdot \ln 2 \cdot \left\{ \underbrace{\frac{m_{q_4\ell\nu} - m_{top}}{\Gamma_{top}^2}}_{m_{top} \text{ extraction}} + \underbrace{\frac{m_{q_1q_2q_3} - m_{top}}{\Gamma_{top}^2}}_{\text{JES constraint}} + \underbrace{\frac{m_{q_1q_2} - m_W}{\Gamma_W^2}}_{m_{\ell\nu} \text{ constraint}} + \underbrace{\frac{m_{\ell\nu} - m_W}{\Gamma_W^2}}_{E_T^{\text{miss}} \text{ constraint}} \right\} \end{aligned}$$

→ Perform kinematic fit of the event, using likelihood maximisation : arXiv :1312.5595

$$\begin{aligned} \mathcal{L} = -2 & \left\{ \prod_{i=1}^4 \ln TF_{jet}(E_{jet,i}^{meas} | E_{jet,i}) \cdot \ln TF_\ell(E_\ell^{meas} | E_\ell) \cdot \prod_{j=x,y} \ln TF_{E_j^{\text{miss}}}(E_j^{\text{miss}} | p_j^\nu) \right\} \\ & \times \underbrace{\mathcal{B}(m_{q_1q_2q_3} | m_{top}, \Gamma_{top})}_{m_{top} \text{ extraction}} \cdot \underbrace{\mathcal{B}(m_{q_4\ell\nu} | m_{top}, \Gamma_{top})}_{\text{JES constraint}} \cdot \underbrace{\mathcal{B}(m_{q_1q_2} | m_W, \Gamma_W)}_{m_{\ell\nu} \text{ constraint}} \cdot \underbrace{\mathcal{B}(m_{\ell\nu} | m_W, \Gamma_W)}_{E_T^{\text{miss}} \text{ constraint}} \end{aligned}$$

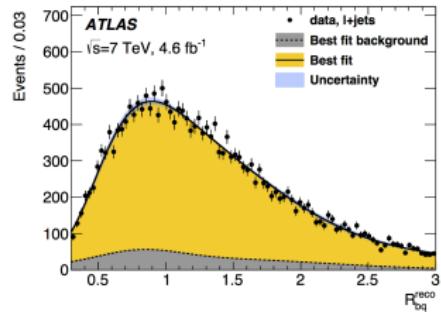
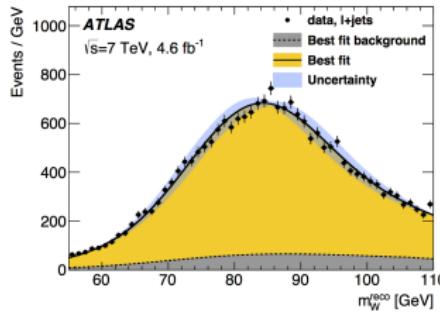
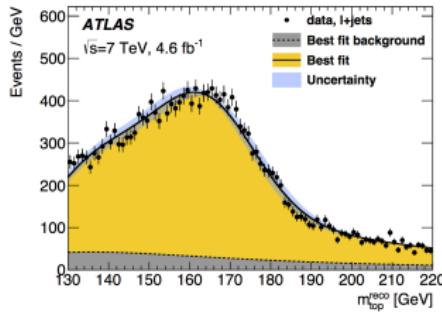
⇒ In both cases implementation of Transfer Functions (TF) ; enable to parametrise detector resolutions

# Template method : $\ell$ +jets @ 7 TeV

Analysis lead by F. Balli and IRFU

- Signature : 2 b-jets, 1 lepton, 2 jets,  $E_T^{miss}$  (1ν)
  - Use of likelihood kinematic fit for jet-parton assignment
- ⇒ 3D vs 2D analysis reduces systematics by ∼ 40%
- ATLAS @ 7 TeV :  $172.3 \pm 0.8(\text{stat.}) \pm 1.0(\text{syst.})$  GeV
  - Main uncertainties : stat. comp. bJSF (0.67) ; JES (0.58) ; b-tagging (0.50)

arXiv :1503.05427, submitted to EPJC

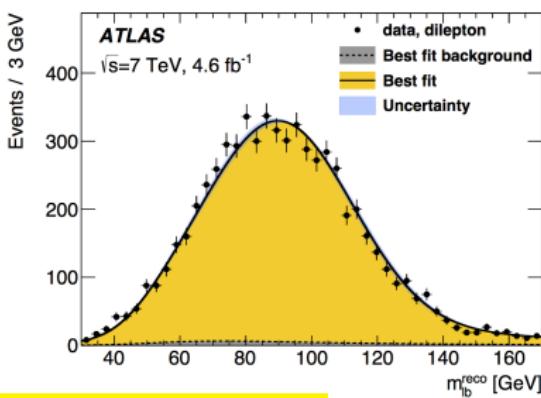


# Template method : dilepton @ 7 TeV and @ 8TeV

- Signature : 2 b-jets, 2 leptons,  $E_T^{\text{miss}} (2\nu)$
- ⇒ Use of  $m_{\ell b}$  estimator, defined as invariant mass of lepton and b-jet
- Reconstruction of the estimator and event fit :
  - Choose permutation that minimise  $m_{\ell b}$
  - ~ 75–80% correct assignments

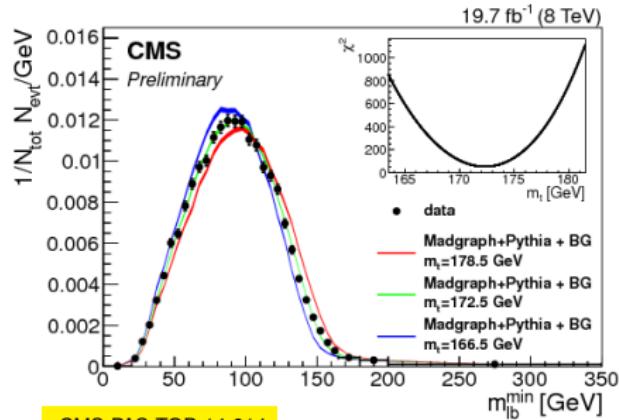
## ATLAS @ 7 TeV

- $173.8 \pm 0.5(\text{stat.}) \pm 1.3(\text{syst.}) \text{ GeV}$
- Main uncertainties : JES (0.75) ; bJES (0.68) ; hadronisation (0.53)



## CMS @ 8 TeV (only $e\mu$ channel)

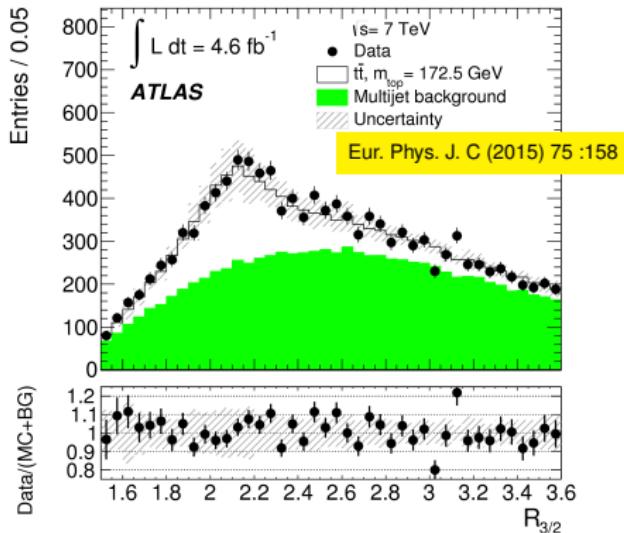
- $172.3 \pm 0.3(\text{stat.}) \pm 1.3(\text{syst.}) \text{ GeV}$
- Main uncertainties : JES (0.4) ; b-frag. (0.6) ; scale (0.55) ; top  $p_T$  (0.66)



# Template method : All-jets @ 7 TeV

- Signature : 2 b-jets, 4 jets
- Use of likelihood kinematic fit for jet-parton assignment
- Multijet background : estimated from control regions in data :
  - Divide into 6 regions by using two observables with minimal correlation : number of b-tagged jets and the 6<sup>th</sup> jet  $p_T$
  - Purity close to 17%

⇒  $m_{top}$  estimator :  $R_{3/2} = m_{jjj}/m_{jj}$



- ATLAS @ 7 TeV :  $175.1 \pm 1.4(\text{stat.}) \pm 1.2(\text{syst.})$  GeV
- Main uncertainties : bJES (0.62) ; JES (0.51) ; hadronisation (0.50)

# Ideogram : description

- Conceptually in between MEM and template method
  - Calculates per-event probability as MEM
  - Defines probability densities from distributions in MC as template methods
  - Use several approaches applied in template methods, as  $\chi^2$  kinematic 2D fit
- Multiple permutation per event
- Combine event-per-event likelihood
- Construct likelihood from event probabilities

$$\mathcal{L}(\text{sample} \mid m_{top}, JSF) = \prod_{\text{events}} \left\{ \sum_{i=1}^n P_{gof}(i) \left( \underbrace{\sum_j f_j P_j(m_{top,i}^{fit} \mid m_{top}, JSF)}_{\text{PD in } m_{top}^{fit}} \times \underbrace{P_j(m_{W,i}^{reco} \mid m_{top}, JSF)}_{\text{PD in } m_W^{reco}} \right) \right\}^{w_{\text{event}}}$$

$P_{gof} \leftarrow \exp(-0.5\chi^2)$

- $m_{top}^{fit} \leftrightarrow (m_{top}, JSF)$ ;  $m_W^{reco} \leftrightarrow JSF$

→ Used by CMS for All-jets &  $\ell + \text{jets}$

# Ideogram : All-jets & $\ell + \text{jets}$ @ 8 TeV

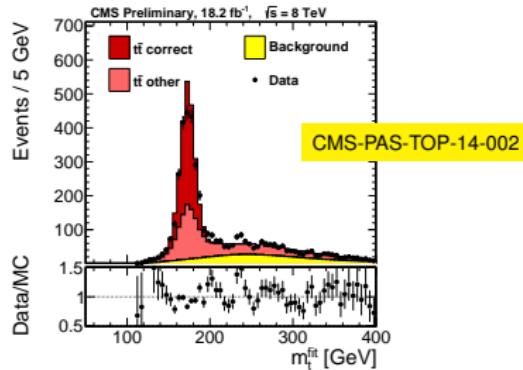
## All-jets @ 8 TeV

- Signature :  $\geq 4$  light jets, 2b-tagged jets
- Use of  $\chi^2$  kinematic fit for jet-parton assignment
- Multijet background : estimated from data-driven estimate
  - Purity close to 16%

$\Rightarrow m_{top}$  estimator :  $P_{gof} > 0.1$

CMS @ 8 TeV :  $172.1 \pm 0.4(\text{stat.}) \pm 0.8(\text{syst.})$

$\rightarrow$  Main uncertainties : bJSF (0.36) ; JES (0.28) ; signal modelling (0.29)



## $\ell + \text{jets}$ @ 8 TeV

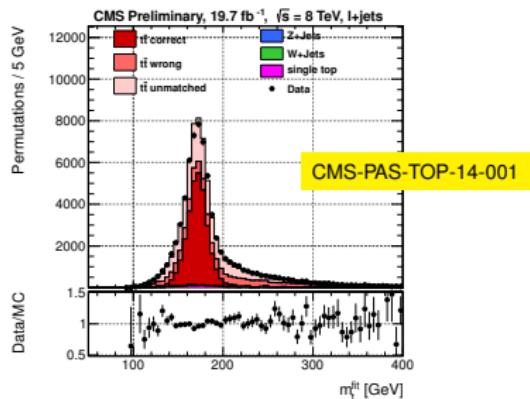
- Signature : = 1 lepton,  $\geq 4$  jets with 2b
- Use of  $\chi^2$  kinematic fit for jet-parton assignment

$\Rightarrow m_{top}$  estimator :  $P_{gof} > 0.2$

CMS @ 8 TeV :  $172.0 \pm 0.2(\text{stat.}) \pm 0.8(\text{syst.})$

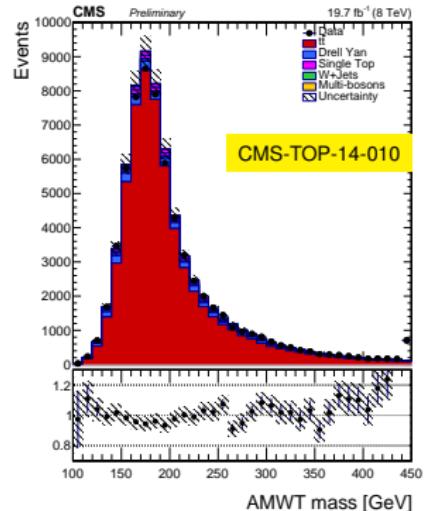
$\rightarrow$  Main uncertainties : bJSF (0.41) ; JER (0.26) ; signal modelling (0.35)

Most precise LHC measurement : 0.77 (0.45%)



# Analytical Matrix Weighting Technique (AMWT)

- Used by CMS for dilepton @ 8 TeV
  - Under-constrained system due to 2 v
  - Constraining with help of  $m_W$ ,  $m_{top}$
  - Up to 8 possible solutions per event
    - One degree of freedom in the kinematics
- Reconstruct most likely mass for the event
- Scan  $m_{top}$  hypotheses
  - Solve using smeared jets
  - Assign weight for each solution
  - Highest weight →  $m_{top}$



CMS @ 8 TeV :  $172.5 \pm 0.2(\text{stat.}) \pm 1.4(\text{syst.})$

- Main uncertainties : JES (0.61) ; b-frag (0.67) ; renormalisation and factorisation scales (0.87)

# Matrix Element Method : description

- For each event a probability is defined as a function of the probabilities to be signal like ( $P_{sig}$ ) or background like ( $P_{bkg}$ ) :

$$P_{evt}(m_{top} | x) = f_{top} P_{sig}(m_{top} | x) + (1 - f_{top}) P_{bkg}(m_{top} | x)$$

$$f_{top} \equiv \frac{N_{sig}}{N_{sig} + N_{bkg}}$$

- The probability to be signal or background like is related to the differential cross section  $\frac{d\sigma}{dx}(m_{top})$  through :

$$P_i(m_{top} | x) = \frac{1}{\sigma_{obs}^i(m_{top})} \frac{d\sigma^i}{dx}(m_{top} | x) \quad \text{with } i = \text{signal or background}$$

$$\sigma_{obs}^i(m_{top}) = \epsilon^i(m_{top}) \sigma_{th}^i(m_{top})$$

- Computing the differential cross section is the heart of the method :

$k$  : observables of the final state at the reconstructed level

$|M_{t\bar{t}}(p_1, p_2, x, m_{top})|$  : Matrix element  
e.g.  $p_1 p_2 \rightarrow t\bar{t} \rightarrow b\bar{b} e\mu\nu_e\nu_\mu$

$f_{pdf}$  : parton density function

$$\frac{d\sigma^i}{dx}(m_{top} | k) \propto \sum_i \int dp_1 dp_2 d\Phi |M_i(p_1, p_2, x, m_{top})|^2 f_{pdf}(p_1) f_{pdf}(p_2) TF(x | k)$$

$x$  : observables of the final state at the parton level

$p_1$  and  $p_2$  : incoming parton

$d\Phi$  : phase space for process

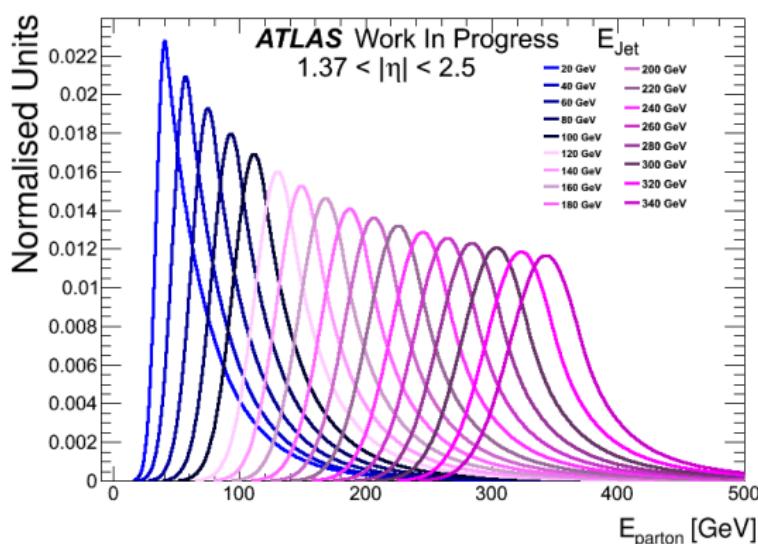
$TF(x | k)$  : Transfer Function from  $k$  to  $x$

# MEM : Transfer Functions

- Transfer Functions,  $TF(x | k)$ , relate parton-level quantities to detector-level ones

- Parametrise the jets' energy detector response :

- Typically two Gaussians are used :
  - One for the core of the distribution
  - One for the tails
- Developed Crystal Ball @LPNHE :
  - Better description of the tails
  - Correct observed data/MC discrepancy



- The jets and leptons directions ( $\eta, \phi$ )
  - Well-measured, use of  $\delta$ -functions

- Parametrise the leptons' energy detector response
  - Well-measured too, use of  $\delta$ -functions

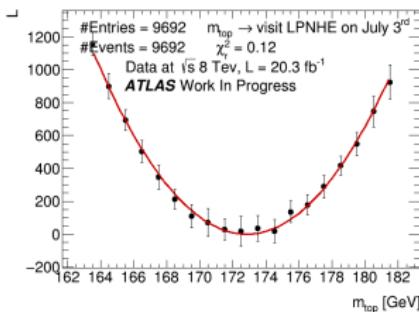
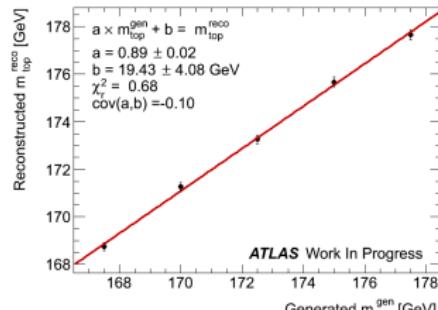
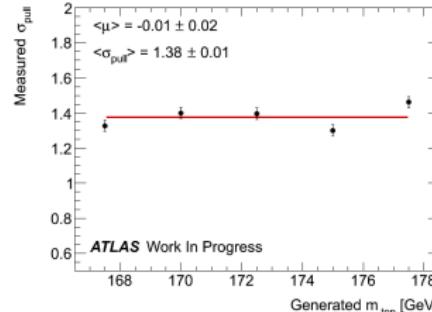
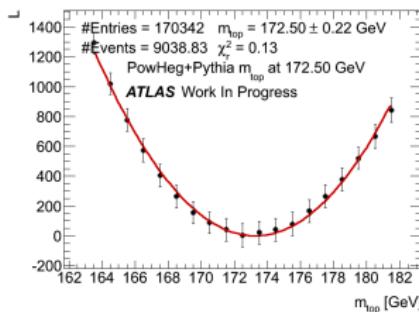
## MEM : dilepton @ 7 TeV and @ 8 TeV

Analyses on which A. Demilly, S. Pires and LPNHE contributed

- Calibrate the method with Monte-Carlo events

- $P_{evt}$  obtained with LO Matrix Element (MG4)
- Parametrise detector response

- Calibration improved by pseudo-experiments



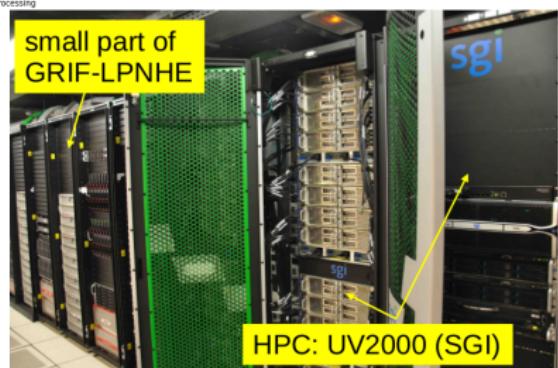
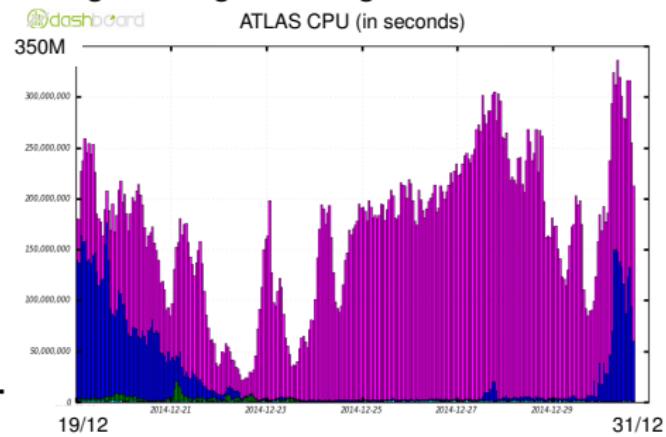
- ATLAS @ 7 TeV (only  $e\mu$  channel) : [Ph.D. A. Demilly, LPNHE, 2014](#)
- ATLAS @ 8 TeV (only  $e\mu$  channel) : S. Pires, LPNHE, Ph.D. defence 3<sup>rd</sup> July 2015

# MEM : Computational challenge merged

- Numerical calculation of an N-dimensional integral using MC integrator VEGAS.
- Use of MadWeight4 (only LO) :
  - Typically 15 mn / event → 800 days / MC
  - Production : ~ 400 variations (3 proba., Syst.)
  - ⇒ ~ 15M hours for 8 TeV results
- Tested new tools
  - MadWeight5 : x60 faster, NLO
  - MemTk : x100 faster, NLO

## • New calculation techniques

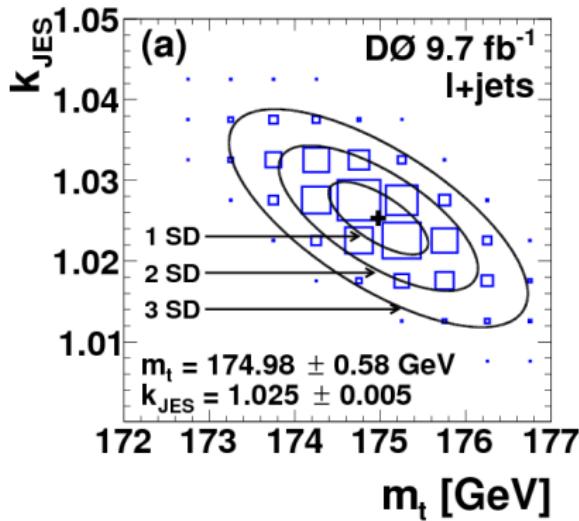
- Parallel calculus : @LPNHE/UPMC : SGI UV2000, 19 Tflop/s, 1024 cpu, 16TB shared memory
  - MemTk : ~ x20 faster w. 32cores
- GPU calculation
  - MEM : x150 faster (arXiv :1407.7595)
  - @LLR :  $H \rightarrow \tau\tau$  (CHEP'15 talk)
  - @LPNHE : buy XeonPhi & GPU for tests
- On going collaboration in Ile de France labs (LAL/LLR/LPNHE) for ATLAS/CMS/LHCb software
- ANR LPaSo not accepted, but try to continue...



MEM : D0 results :  $\ell + \text{jets}$ 

Phys.Rev.Lett. 113 (2014)

- Lepton + jets : = 4 jets &  $\geq 1$  b-tag
- 2D measurement of  $k_{JES}$  and  $m_{top}$
- Calibrations and pulls apply on both
- Factorise systematic uncertainties
  - Avoid double counting
- $m_{top} = 174.98 \pm 0.58(\text{stat.}) \pm 0.49(\text{syst.})$
- $m_{top} = 174.98 \pm 0.77(\text{tot.}) \text{ GeV}$



⇒ Most precise systematics measurement

# Conclusion

- Diversity of measurements at the LHC
  - Direct kinematic measurements
  - ATLAS and CMS French groups are involved
  - Alternative measurements too (see next presentation)
- Final Run-I measurements still to come !
- Run-II data should give access to even better precision
- On going work in Top LHC WG for harmonisation of the systematic uncertainties (ATL-PHYS-PUB-2014-020, CMS-PAS-JME-14-003)
  - French implication (R. Chierici, F. Deliot, J. Donini, B. Malescu, T. Theveneaux-Pelzer, D. Varouchas )
  - (TOP LHC WG meeting), this Wednesday !

# Summary of main results

