Kinematic Fit in CMS & the Use of Top Quarks for Calibration

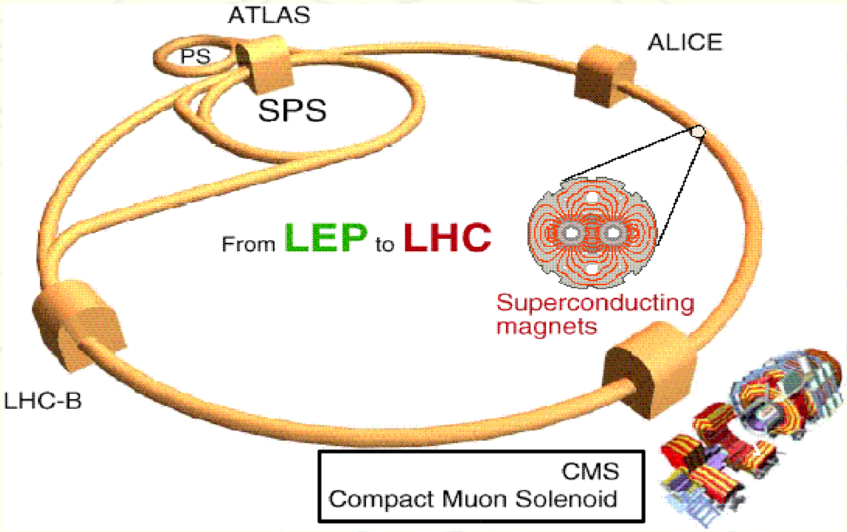
Jan Heyninck (Vrije Universiteit Brussel)
(on behalf of the CMS collaboration)

- ✓ short introduction to CMS and LHC
- ✓ Fitting of Event Topologies with External Kinematic Constraints in CMS
- ✓ Offline Calibration of b-Jet Identification Efficiencies
- ✓ Light quark jet energy scale calibration using the W-mass constraint in single-leptonic tt-events

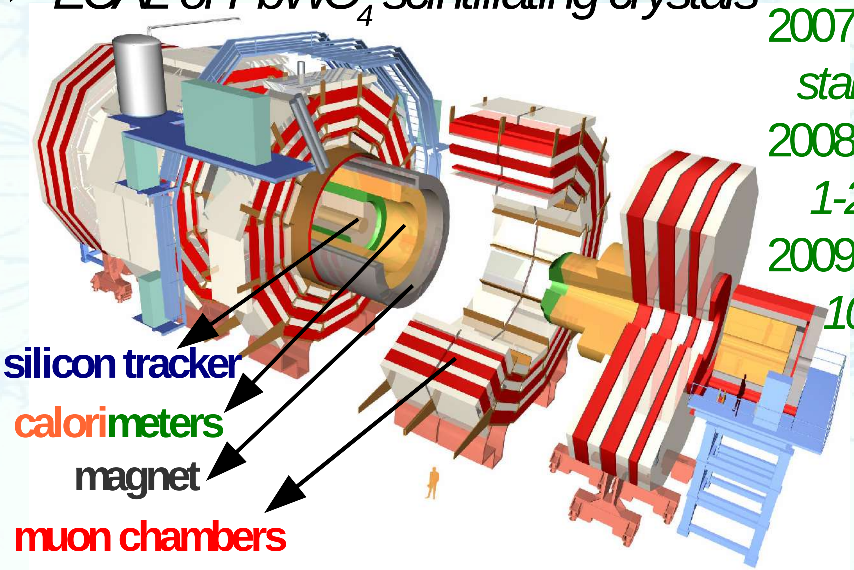
Introduction

All the results presented here contribute to the Compact Muon Solenoid (CMS) experiment, which will be one of the four new detectors of the Large Hadron Collider (LHC), currently under construction at CERN.

- ✓ *in the 27km long LEP tunnel,*
- ✓ *14 TeV centre of mass energy*
- ✓ *each 25ns a proton-proton collision*
- ✓ *first beam in mid 2007*



- ✓ *superconducting solenoid of 4T*
- ✓ *12500 ton; Ø=15m; length=21m*
- ✓ *full silicon tracker & calorimeters in magnet*
- ✓ *ECAL of $PbWO_4$ scintillating crystals*



2007: *start-up*
2008: *1-2 fb^{-1}*
2009: *10 fb^{-1}*

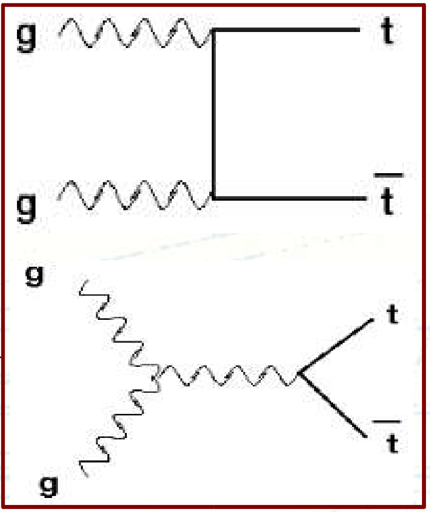
Introduction

Top quark production @ LHC

- due to enormous statistics, $t\bar{t}$-pairs can be used both for signal and calibration purpose

Center of Mass Energy	1.96 TeV	14 TeV	
cross-section (NLO)	$5.06^{+0.13}_{-0.36}$ pb	833^{+52}_{-39} pb	(x 170)
expected nr. of events	10 tt pairs/day	1 tt pair/s	
production channel	85% quarkfusion	87% gluonfusion	

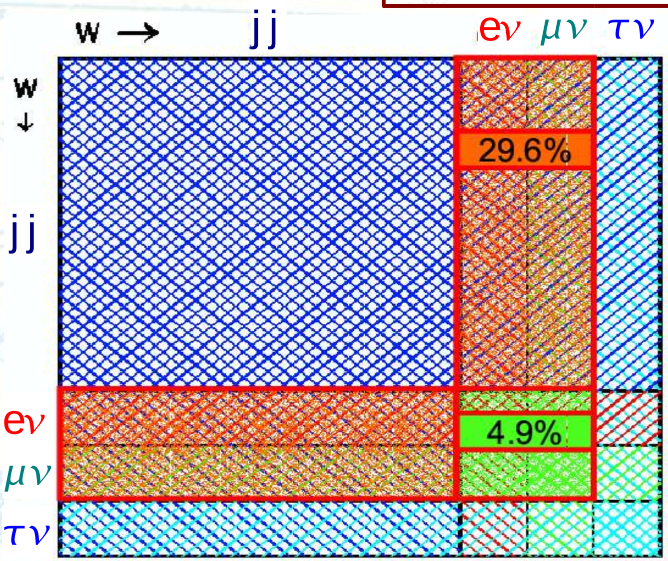
(Belyaev, Boos, Dudko [hep-ph/9806332])



Top quark decay

- Nearly 100% on-diagonal CKM decay $t \rightarrow Wb$
- P(hadronic W decay) = 6/9, P(leptonic) = 3/9

$\rightarrow$ for $t\bar{t}$-pair:
- 4/9 full hadronic
- 4/9 semi-leptonic
- 1/9 full leptonic



Remark

all events were generated with PYTHIA, passed to full GEANT4 detector simulation, and analyzed using the LCG, the LHC Computing Grid.

Kinematic Fitting: What and why?

The aim of a kinematic fit is ...

... to fit the measured quantities (e.g. particles' four-vectors) within their uncertainty to a certain event hypothesis. This hypothesis often translates in certain kinematic constrains (e.g. energy conservation, mass-constraint).

More precisely, a kinematic fit will determine the corrections $\Delta\bar{y}$ on the measured parameters $\bar{y}$, such that :

1. $S(\vec{y}) = \Delta\vec{y}^T \mathcal{V}^{-1} \Delta\vec{y} = \chi^2$ is minimal
2. all constraints are fulfilled: (with $\bar{a}_i$ unmeasured parameters)

$$\begin{aligned} f_1(\bar{a}_1,\bar{a}_2,\ldots,\bar{a}_p,\bar{y}_1,\bar{y}_2,\ldots,\bar{y}_n) &= 0 \\ f_2(\bar{a}_1,\bar{a}_2,\ldots,\bar{a}_p,\bar{y}_1,\bar{y}_2,\ldots,\bar{y}_n) &= 0 \\ &\vdots \\ f_m(\bar{a}_1,\bar{a}_2,\ldots,\bar{a}_p,\bar{y}_1,\bar{y}_2,\ldots,\bar{y}_n) &= 0 \end{aligned}$$

Output:

- ✓ χ^2-value for each event = P(event hypothesis == true)
- ✓ lower resolutions on reconstructed physical properties as e.g. the top mass

Kinematic Fit Package in CMS

- *Basically C++ implementation of the package used in Aleph & BaBar*

- *To determine the optimal $\Delta\bar{y}$ this method uses Lagrange Multipliers $\bar{\lambda}$:*

$$L(\vec{y},\vec{a},\vec{\lambda}) = S(\vec{y}) + 2\sum_{k=1}^{m} \lambda_k f_k(\vec{y},\vec{a})$$

(one multiplier for each constraint)

function $L(\bar{y},\bar{a},\bar{\lambda})$ minimal when $S(\bar{y})$ = minimal and $f_k(\bar{y},\bar{a}) = 0$

If all $f_k(\bar{y},\bar{a})$ linear → minimization in one step,

otherwise iteratively using a Taylor expansion to linearize the constraint functions.

In this case, a fit is defined as converged if:

$$\frac{S(\vec{y})_{n-1} - S(\vec{y})_n}{ndf} < \epsilon_S \quad \text{and} \quad F = \sum_{k=1}^{m} f_k^{(n)}(\vec{y},\vec{a}) < \epsilon_F$$

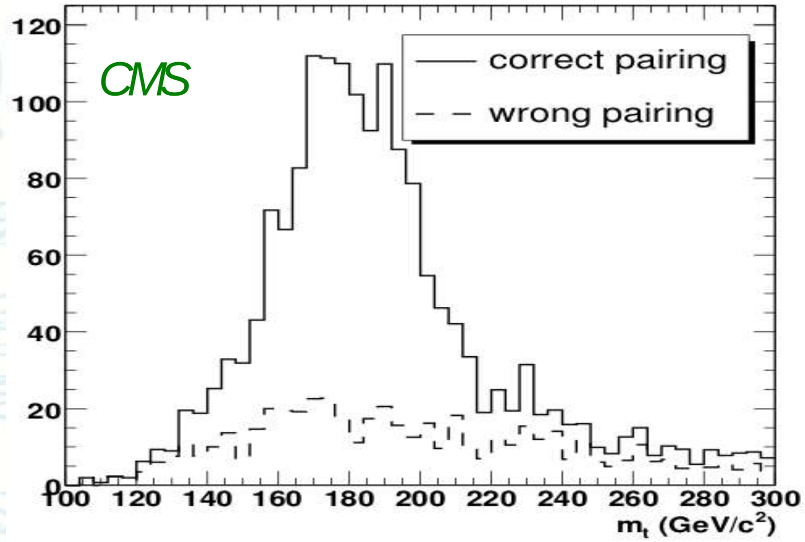
with

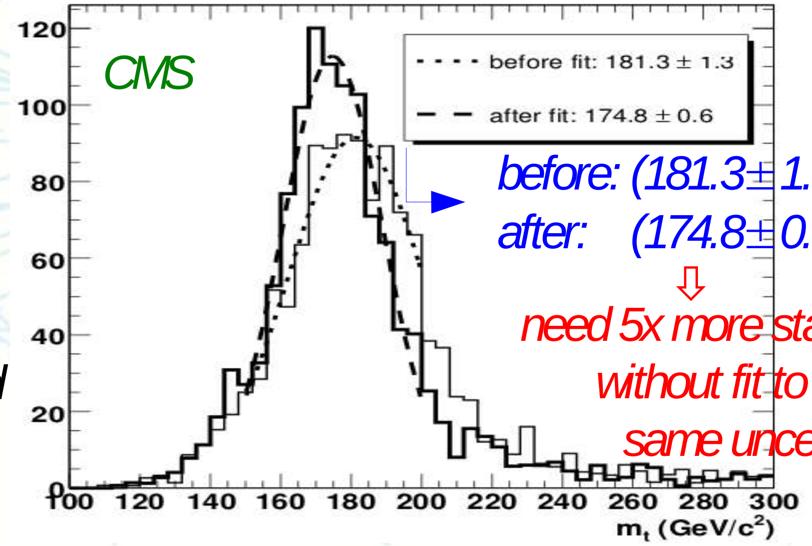
ndf = #constraints - #unmeasured quantities and ϵ_S and ϵ_F given input parameters

Importance of a KinFit for top physics

Improvement in the reconstructed top mass in semi-leptonic ttbar decay

- *event selection:*
  - ✓ *4 jets with $E_T > 30$GeV & $|\eta| < 2.4$*
  - ✓ *no jet overlap*
  - ✓ *2 b-tags*
  - ✓ *p_T muon > 20 GeV*
- *kinematic fit*
  - ✓ *2 constraints: $M(jj) = M_W$ & $M(l\nu) = M_W$*
  - ✓ *p_Z neutrino unmeasured, p_T estimated from event, so "measured"*
  - ✓ *variances on four-vectors differentiated in E_T*
  - ✓ *muon constant $E/|\bar{p}|$; jets free floating energy*
- *considered jet combination*
  - ✓ *chosen with combined likelihood ratio method*
  - ✓ *$Prob(\chi^2) > 0.2$; $|m_W^{rec} - m_W^{fit}| < 35$ GeV; $m_{top}^{lept} > 125$ GeV*





before: (181.3±1.3)GeV
after: (174.8±0.6)GeV

⇩

need 5x more statistics without fit to obtain same uncertainty!

b-tag Efficiency Measurement

- *completely new method to calibrate b-tag algorithms on data, using large tt-statistics @LHC*

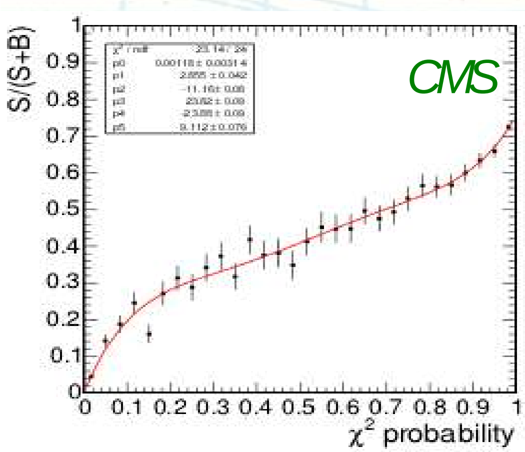
- *b-tag efficiency uncertainty very important systematic to many analyses (e.g. H→ bb)*

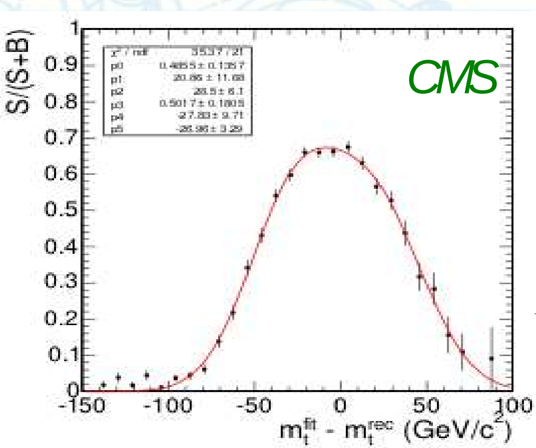
- *Principle of the method:*
  - ✓ *enrich b-content of a jet sample*
  - ✓ *estimate the b-purity x_b as accurate as possible (using MC)*
  - ✓ *apply any b-tagging algorithm on sample & estimate efficiency*
  - ✓ *differentiate this efficiency measurement in E_T and $|\eta|$-bins*

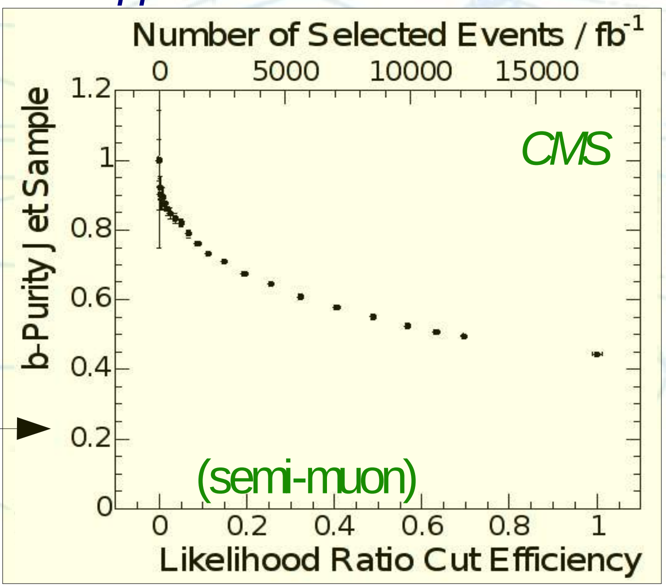
- *Used samples:*
  - ✓ *semi-leptonic decaying tt-pairs (μ or e) → difficulty combinatorial background (2/4 b-jets)*
  - ✓ *fully-leptonic decaying tt-pairs → cleaner (after suppression WW&Z+jets background), but lower statistics*

Making *b*- enriched jet samples

- *Semi-leptonic decay*
  - *Event Selection*
    - *isolated lepton*
    - *event through High Level e or μ Trigger*
    - *4 jets with $E_T > 25GeV$*
    - *1 b-tagged jet*
  - *Combined Likelihood Ratio for Event Reconstruction & Background suppression*
    - *12 observables: Prob χ^2, $|m_t^{fit}-m_t^{rec}|$, $p_T(t_{hadr})$, $\Delta\theta(b,l)$, ...*

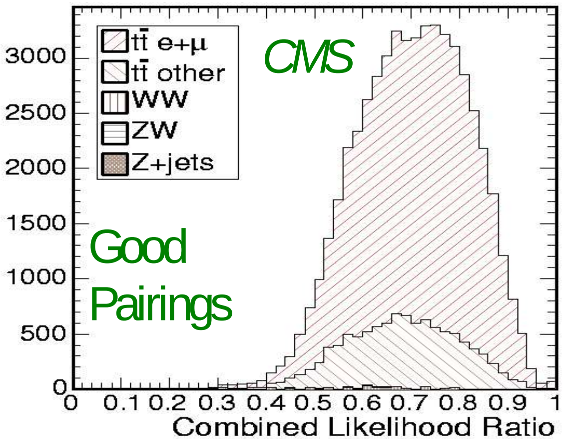


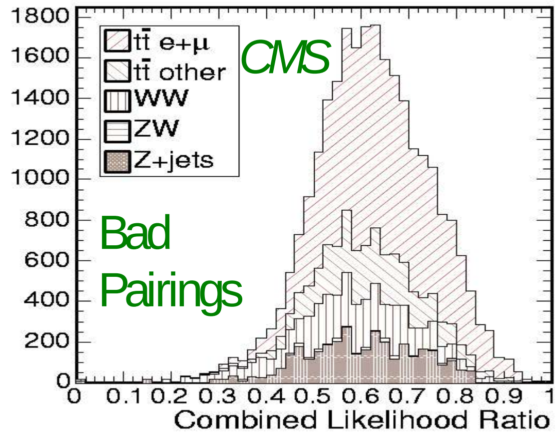


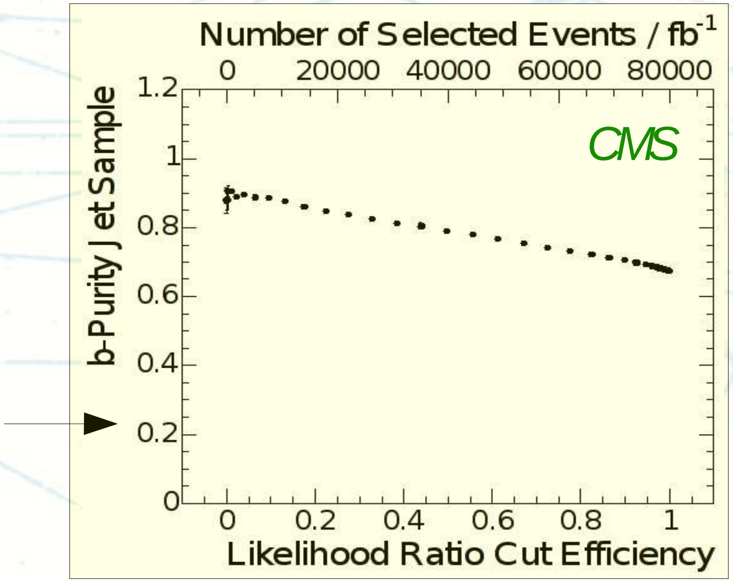


Making *b*- enriched jet samples

- ✓ *Fully-leptonic decay*
  - *Event Selection*
    - ✓ *isolated leptons*
    - ✓ *event through High Level e and μ Trigger*
    - ✓ *1 μ & 1 e with opposite sign*
    - ✓ *2 jets with $E_T > 25GeV$*
  - *Combined Likelihood Ratio for Event Reconstruction & Background suppression*
    - ✓ *14 observables:* $p_T(b)_{min}$, $pT(b)_{max}$, $\Delta\theta(b,l)_{max}$, $\Delta\varphi(b,l)_{max}$, $E_{T,\,jet\,3}/E_{T,\,jet\,2}$, ...





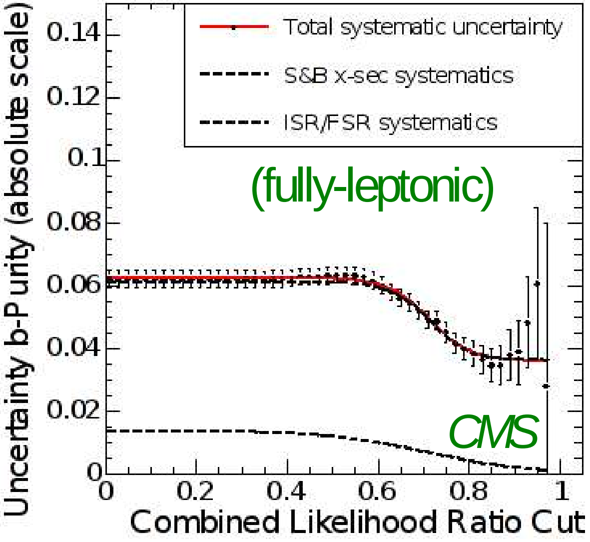


Systematics on the samples' *b*-purity

A whole list of possible systematic uncertainties on the b-purity where checked:

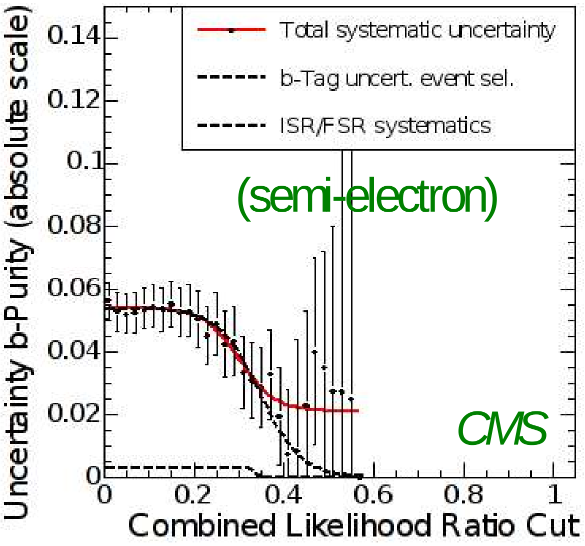
- ***Initial and Final State Radiation***
  - ✓ *gives rise to extra jets and distorted kinematics...*
  - ✓ Q^2_{max} *and* Λ_{QCD} *simultaneously varied between their uncertainty, and half of difference taken as systematic*

(CMS note 2005/025 was followed)



- ***b-tag uncertainty in semi-leptonic event selection***
  - ✓ *varied efficiency b-tag by 10%*

- ***Signal & Background cross section***
  - ✓ *W+Jets in semi-leptonic channel negligible*
  - ✓ *uncertainty fully-leptonic WW & Z+jets-background taken 20%*



- ***other effects found to be negligible***
  - ✓ *pile-up, underlying event, PDF's, jet energy scale,* m_{top}*, light- and b-quark fragmentation*

Measuring the b-tagging efficiency

Principle:

- Choose a b-enriched sample
- Assume fractions x_b, x_c , x_l for the b-,c- and light quark content of the sample
- Define ϵ_c and ϵ_l as mistag efficiencies (can come from another measurement on data)
- Apply any b-tagging algorithm A on the sample, then

$$x_{tag} = \epsilon_b x_b + \epsilon_c x_c + \epsilon_l x_l \Rightarrow \epsilon_b = (x_{tag} - \epsilon_c x_c + \epsilon_l x_l) / x_b$$

- Define

$$\epsilon_0 x_0 = \epsilon_c x_c + \epsilon_l x_l \text{ with } x_0 = x_c + x_l$$

- so that:

$$\epsilon_b = (x_{tag} - \epsilon_0 x_0) / x_b$$

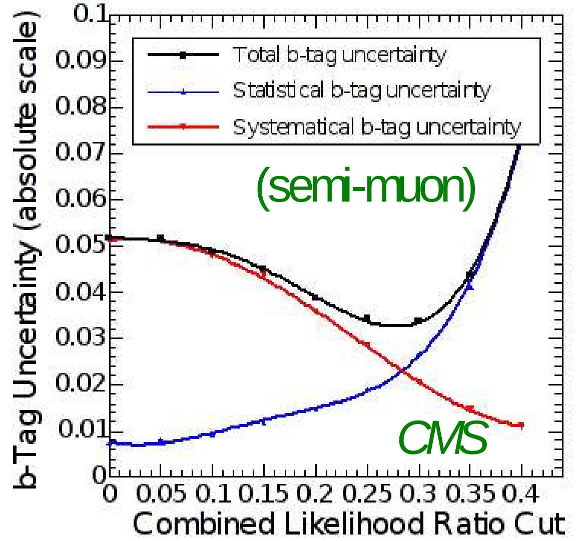
or

$$\epsilon_b = [x_{tag} - \epsilon_0 (1 - x_b)] / x_b$$

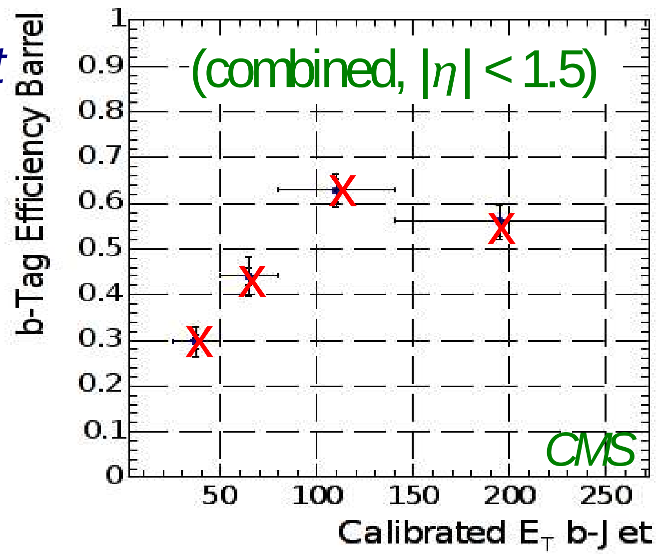
Mistag rate ϵ_0 estimated from MC, uncertainty taken as 20%

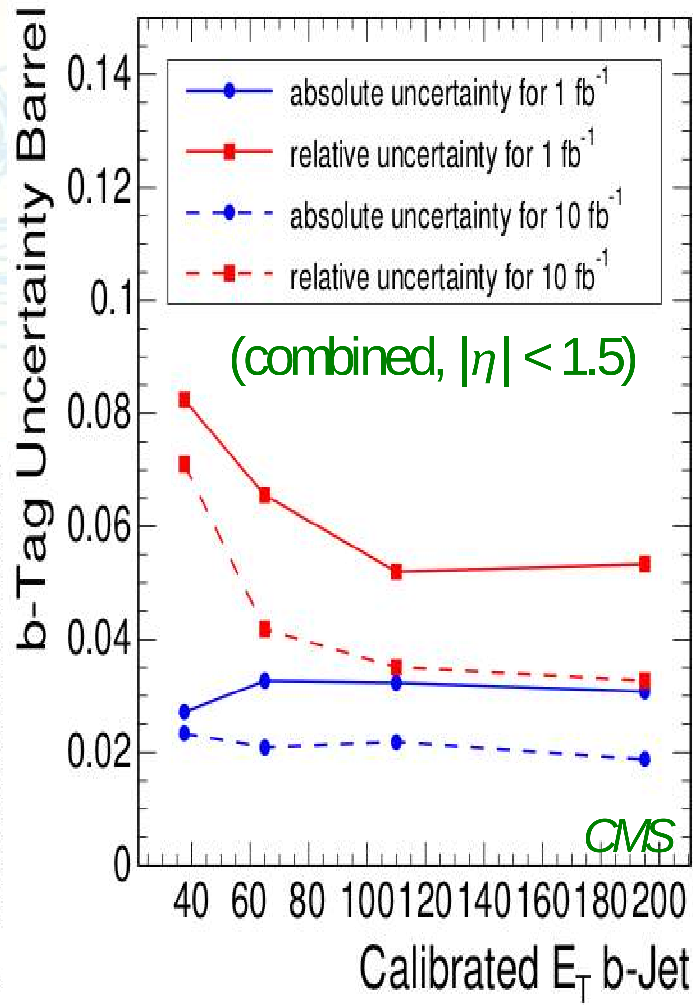
Measuring the b-tagging efficiency

- *Likelihood Ratio is observable, so what LR-cut is optimal to make the measurement? (1 fb^{-1})*



- *Differentiate measurement in b-jet E_T and b-jet $|\eta|$*
  ‖
  making measurement less channel dependent





Light quark Jet Energy Scale Calibration

✓ *Aim:*

determine the absolute light quark jet energy scale from data itself using the well known W-mass, using the abundantly produced tt-pairs

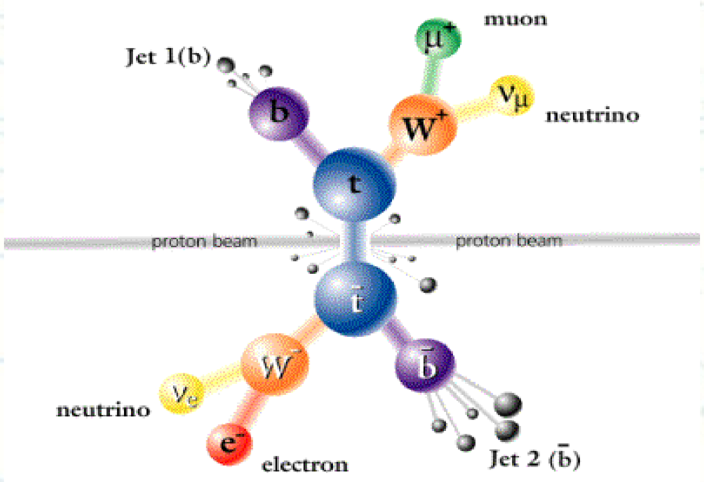
- *optimize the resolution on the primary parton kinematics:*

  - *Data driven way preferred to reduce systematics*
  - *W-bosons in top events good candidate, because large S/N & tight mass constraint*

✓ *Use cases:* *All analyses using jets*

✓ *Used samples:*

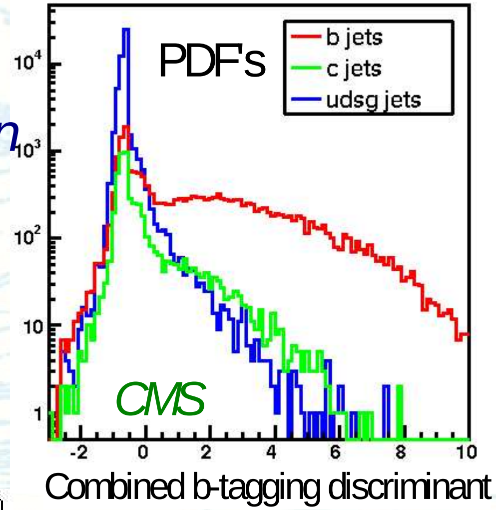
- *signal: semi-leptonic decaying tt-events (only muon)*
- *background:* - *all other tt-decays*
  - *W+jets*
- *all samples have low luminosity pile-up included*

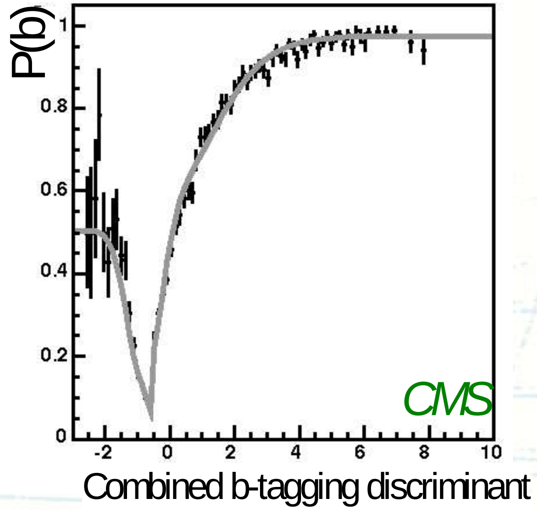


Event Reconstruction towards m_W-spectrum

✓ *Event Selection*

- *almost all W+jets events cut away*
  → should be reconsidered with AlpGen
- *Iterative Cone 0.5 jets were precalibrated with the "MCJet"-calibration*
- *b-tag criteria: exactly 2 jets with P(b)>0.6 and two jets with P(b)<0.3*

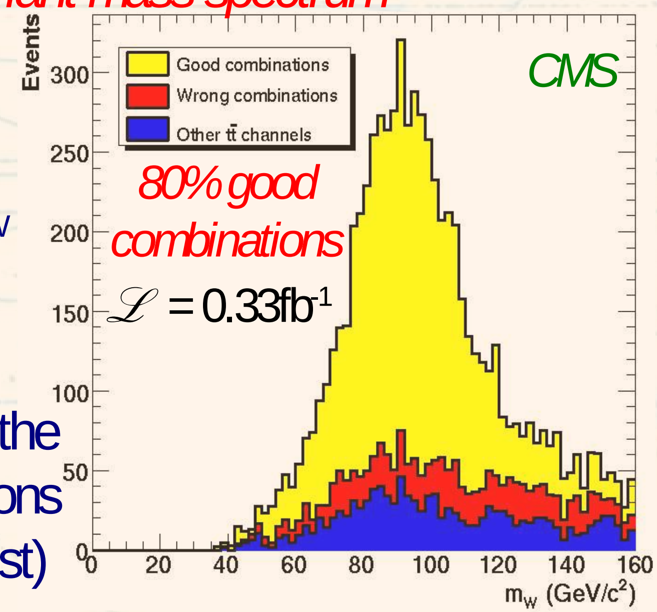




	Signal	Other $t\bar{t}$	S/N
Before selection	448k	1672k	0.005
Trigger + pre-selection	188125	50641	0.16
Four jets E_t >30 GeV	101026	21173	1.5
p_T^{lepton} >20 GeV/c	98657	16522	1.7
b-tag criteria	22727	3627	3.7
No jet overlap	12627	2067	3.5
Exactly 4 jets	7610	1248	3.4
m_t < 350 GeV/c^2	7048	1072	3.8
p_T < 120 GeV/c	6513	963	3.9
m_W < 160 GeV/c	5872	736	4.6
Ω_W > 1 rad	3858	533	4.4
Scaled L=1fb^{-1}	713	152	4.7

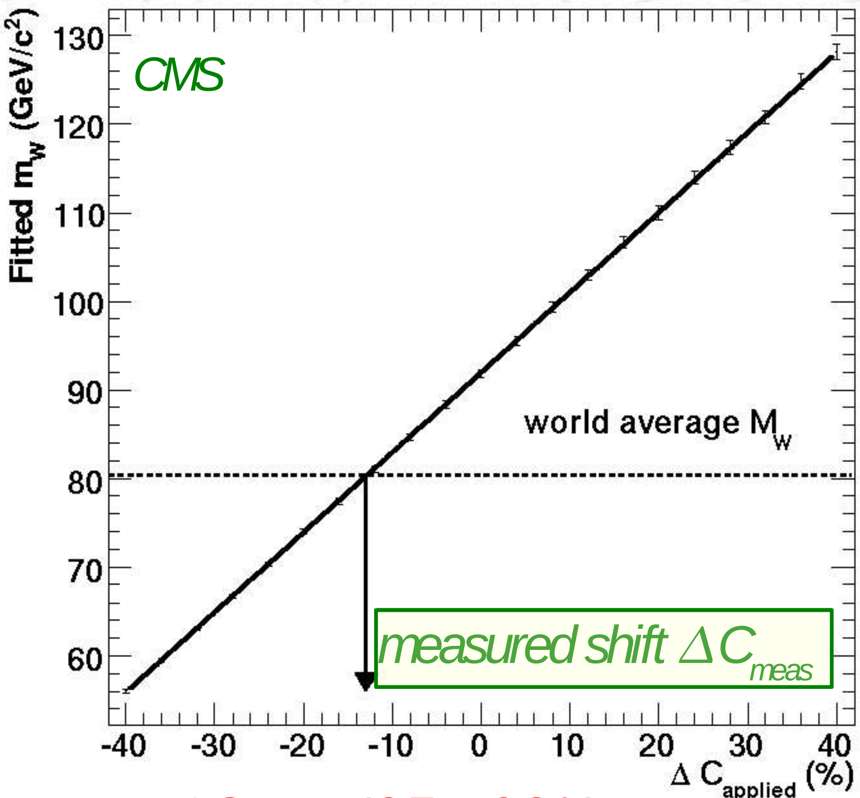
✓ *W-boson invariant mass spectrum*

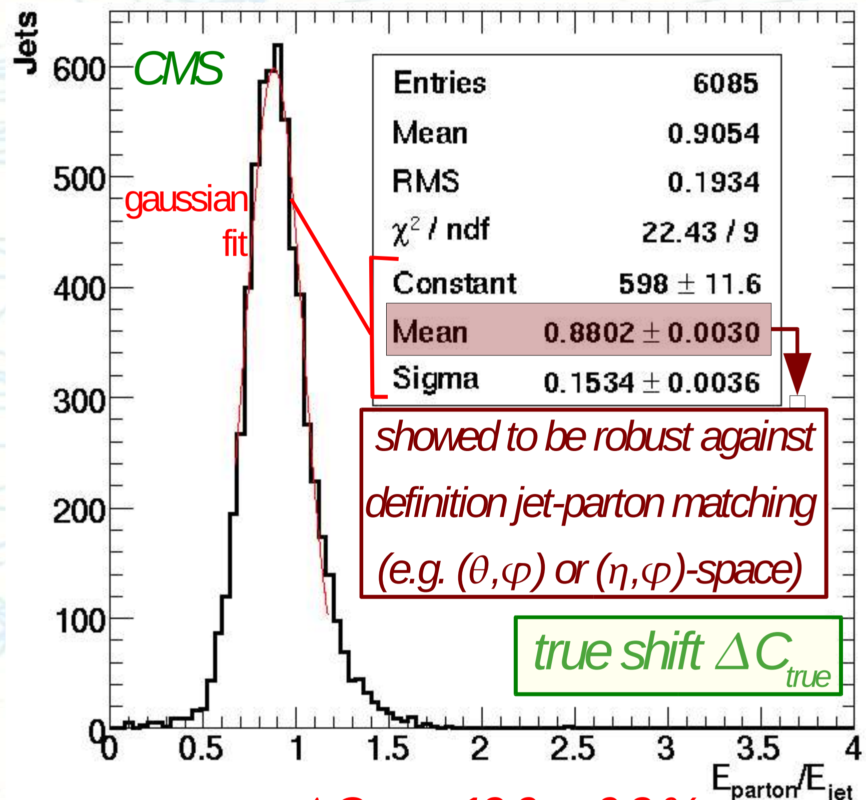
- *Gaussian Fit*
  (range 50-110 GeV)
  $\rightarrow m_W \pm \delta m_W$
- inclusive
- extra criteria for the light quark solutions (to be more robust)



Estimator for the absolute Jet Energy Scale

1. rescale each light jet energy with a relative scaling factor ΔC keeping the $E/|\overline{p}|$-ratio constant
2. Remake/refit the obtained W mass spectrum $\rightarrow m_W(\Delta C)$
3. Solve simple equation $m_W(\Delta C_{meas} \mid data) = m_W^{PDG} \rightarrow$ best estimate for ΔC
4. Compare this shift with the true one from MC ΔC_{true}





$\Delta C_{meas} = -12.7 \pm 0.3\,\%$ ← bias ~0.7 % → $\Delta C_{true} = -12.0 \pm 0.3\,\%$

Systematics & outlook for this study

✓ Systematics

- *The bias on ΔC_{meas} due to pile-up, combinatorial and channel background was evaluated:*

	Uncertainty ΔC (in %)
Pile-up	3.08
Combinatorial background	0.13
Process background	0.17
Total	3.09

→ might be reduced with pile-up subtraction methods

→ (difference ΔC with and without combinatorial / channel background)

✓ Outlook

- *Differentiate measurement of ΔC as a function of the jet E_T & jet pseudorapidity*
- *use the top mass world average to measure the b-jet energy scale*

Final Conclusion & Acknowledgement

- *Abundantly produced top quarks showed to be useful for unexploited calibration tasks!*

- *Kinematic Fitting:* *measurement without Kinematic Fitting needs 5 times more statistics to obtain same top mass uncertainty*

- *b-identification efficiency measurement:* *accuracy on measured efficiency:*
  - *$1 fb^{-1}$: 6% barrel; 10% endcaps*
  - *$10 fb^{-1}$: 4% barrel; 5% endcaps*

- *light Jet Energy Scale Calibration:* *for $1 fb^{-1}$, statistical uncertainty < 1%, systematics (pile-up) ~3%*

- *Thanks to all CMS-colleagues who gave input and feed-back on this talk!*