Measuring tT events at the LHC

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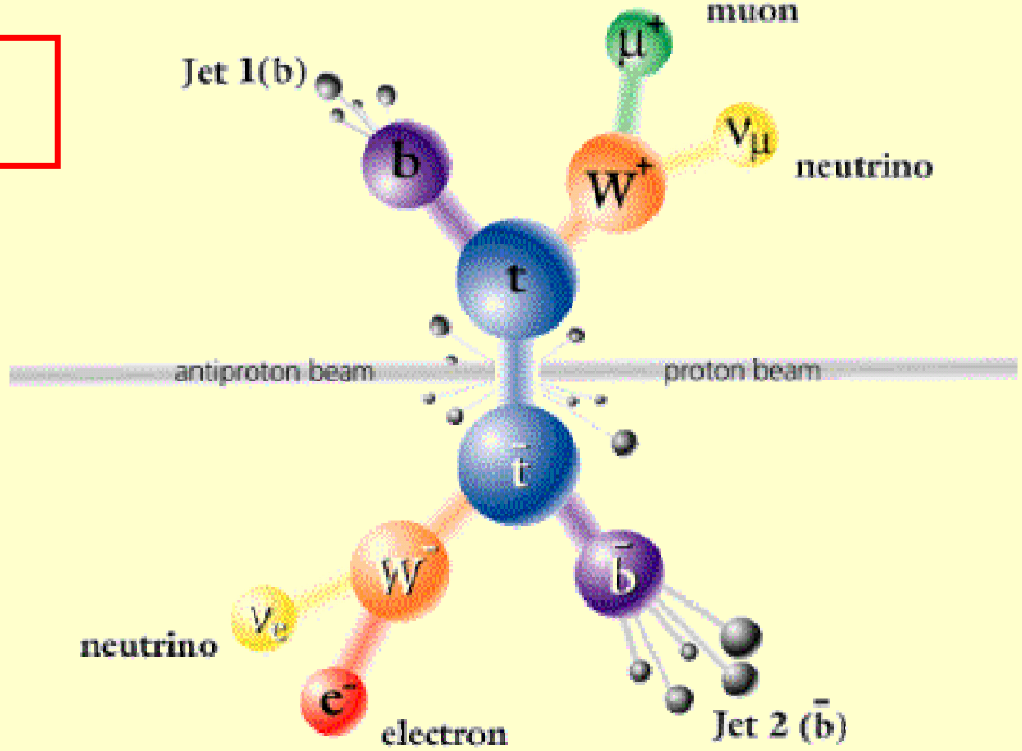
- Physics : the top quark knowledge within few (!?) years
- Method : overview of measurements in the $pp \rightarrow t\bar{T}$ channels
  - several methods with their individual features
- New ideas : LHC compared to the Tevatron
  - from statistical improvement to detailed systematics
  - could open new possibilities…
  - new measurements become possible…

Differentiate our analyses !!!



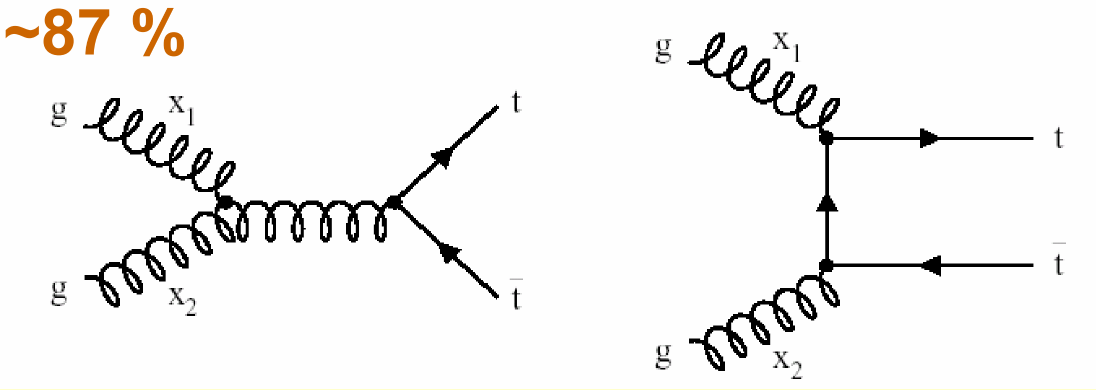
Do not concentrate on few particular analysis tools…

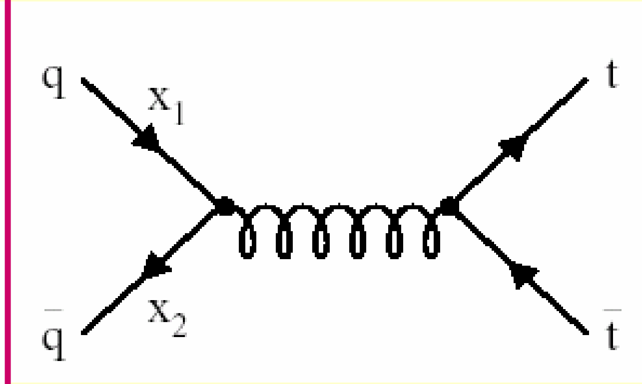
- study many different tools (for example jet clustering algorithms)
- identify their positive and negative features in the LHC environment

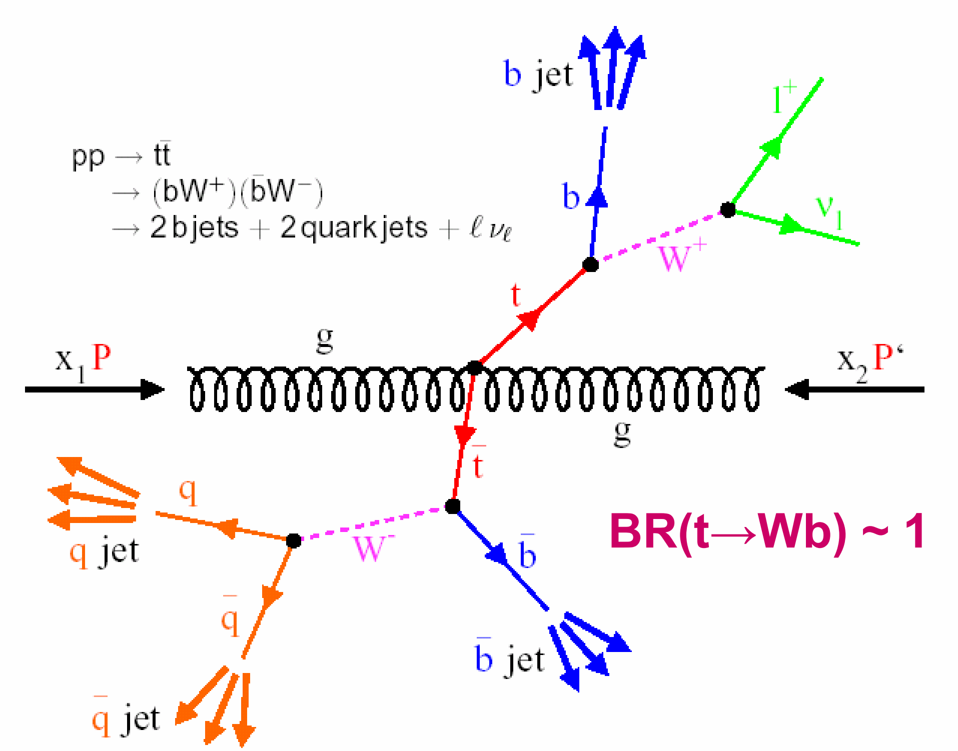
Optimize the analyses for both statistical and systematical uncertainties !!

The pp → tT process at the LHC

~87 %







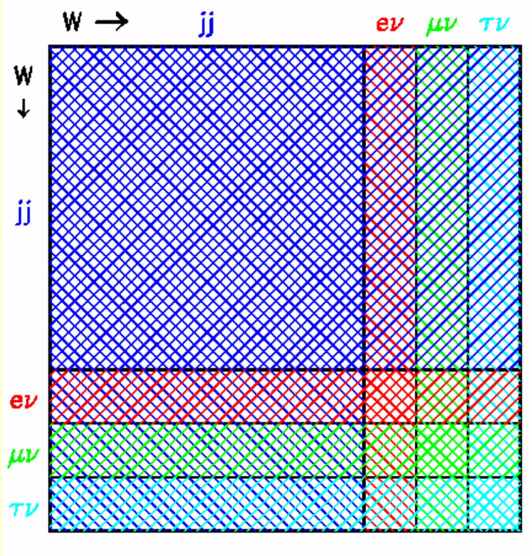
BR(t→Wb) ~ 1

- Many physics parameters to be measured with these events (hence reconstruct the ***complete*** event !)
- Also it is the main background for searches beyond the Standard Model at the LHC
- NLO cross-section for tT production σ^{NLO} = 833 pb ⇨ ~8M events for 10fb^{-1}

  (10 fb^{-1} = 1 year of LHC running at low luminosity, hence by summer 2008)

The pp → tT process at the LHC : event selection

Main background processes for pp→tT→WbWb :



❖ Fully hadronic channel : 3.7M*evnt*/10fb^{-1}
- QCD multijet (2→2 parton processes)
- 6-jets p_T>40GeV, b-tags≥2 : S/B~1/19, ε~2.7%

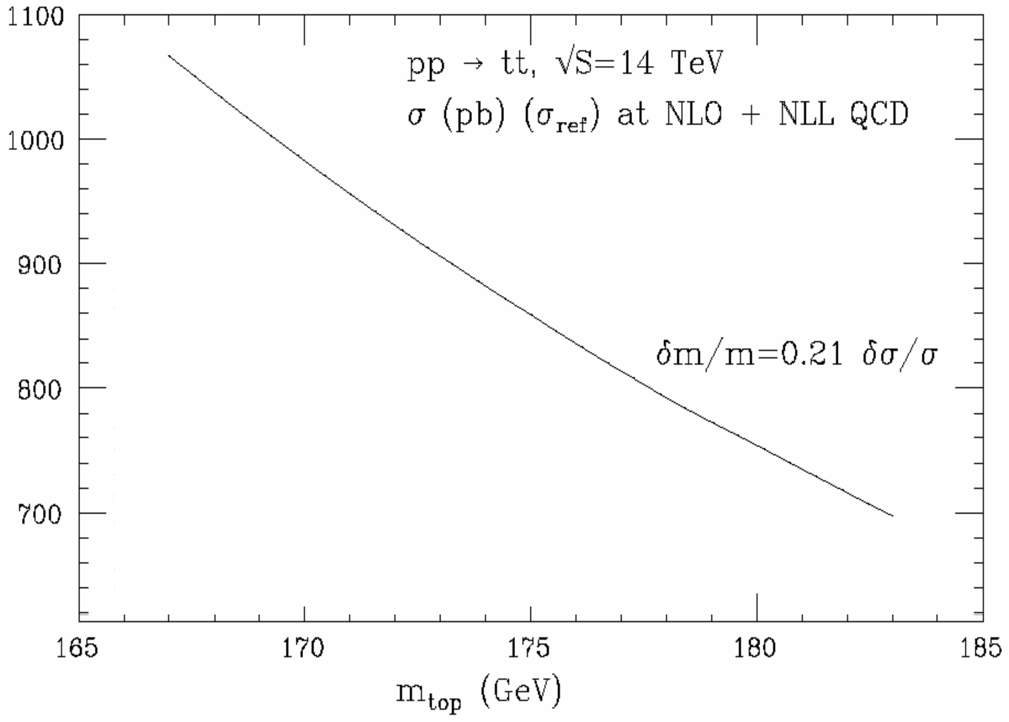
❖ Lepton + jets channel (lepton = e/μ) : 2.5M*evnt*/10fb^{-1}
- bb→lν+jets, W+jets→lν+jets, Z+jets→ll+jets,
- WW→lν+jets, WZ→lν+jets, ZZ→ll+jets
- before selection we have S/B ~ 10^{-5}
- p_T^{lepton}>20GeV, E_T^{miss}>20GeV, p_T^{jet}>40GeV, b-tags≥2 : S/B ~ 78, ε~3.5%
- p_T^{lepton}>20GeV, E_T^{miss}>20GeV, p_T^{jet}>40GeV, b-tags≥1 : S/B ~ 28, ε~14%

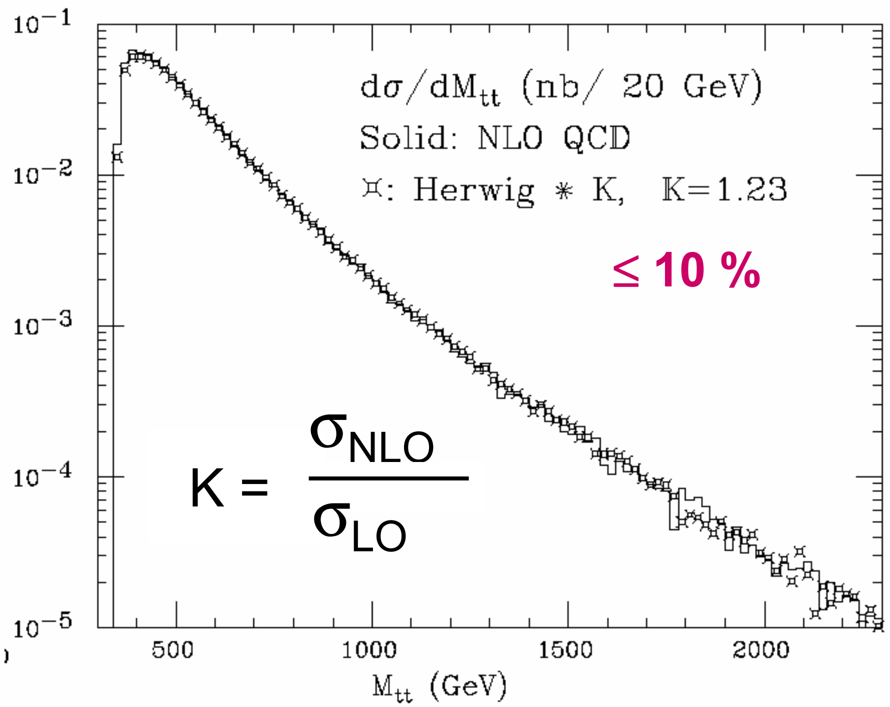
❖ Di-lepton channel : 0.4M*evnt*/10fb^{-1}
- Drell-Yan processes, Z+jets→ll+jets, WW+jets, bb
- p_T^{l+}>35GeV, p_T^{l-}>25GeV, E_T^{miss}>40GeV, p_T^{jets}>25GeV : S/B~10, ε~20%

ATLAS numbers

The pp → tT process at the LHC : cross section

❖ Sensitive to top mass : $\Delta\sigma/\sigma \sim 5\ \Delta m_t/m_t$ → 5% on σ gives 2 GeV on m_t





systematics dominated by the uncertainty on the luminosity

ATLAS preliminary

Time	Number of events at 10^{33}	$\Delta\sigma/\sigma$ (stat)
1 "week"	2×10^3	2.5%
1 "month"	7×10^4	0.4%
1 "year"	3×10^5	0.2%

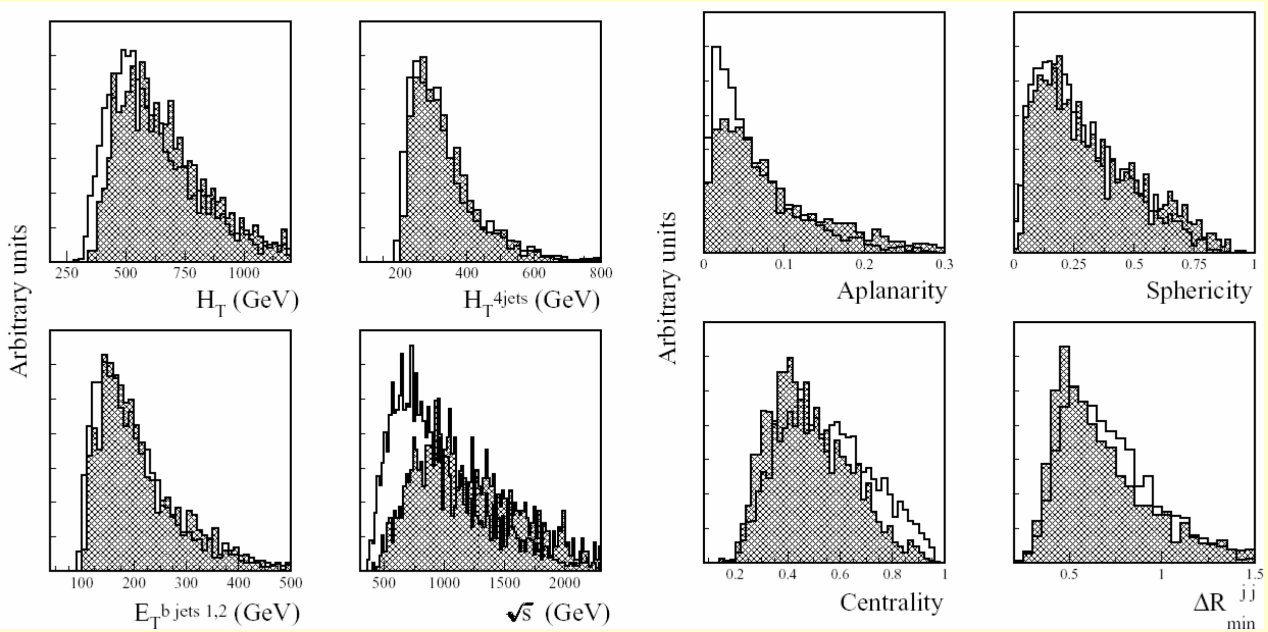
Cross-section sensitive to renormalisation and factorisation scale, and to the choice of PDF (Parton Density Function)

… influence known ??

The pp → tT process at the LHC : fully hadronic

❖ Fully hadronic channel : 3.7M*evnt*/10fb^{-1}

- 6-jets p_T>40GeV, b-tags≥2 : S/B~1/19, ε~2.7%
- discriminant variables (energy flow, additional radiation, event shape)



some based on the D0 Neural Network procedure

not as powerful as in D0

ATLAS paper hep-ex/0403021

- *hatched* : tT signal
- *open* : QCD background

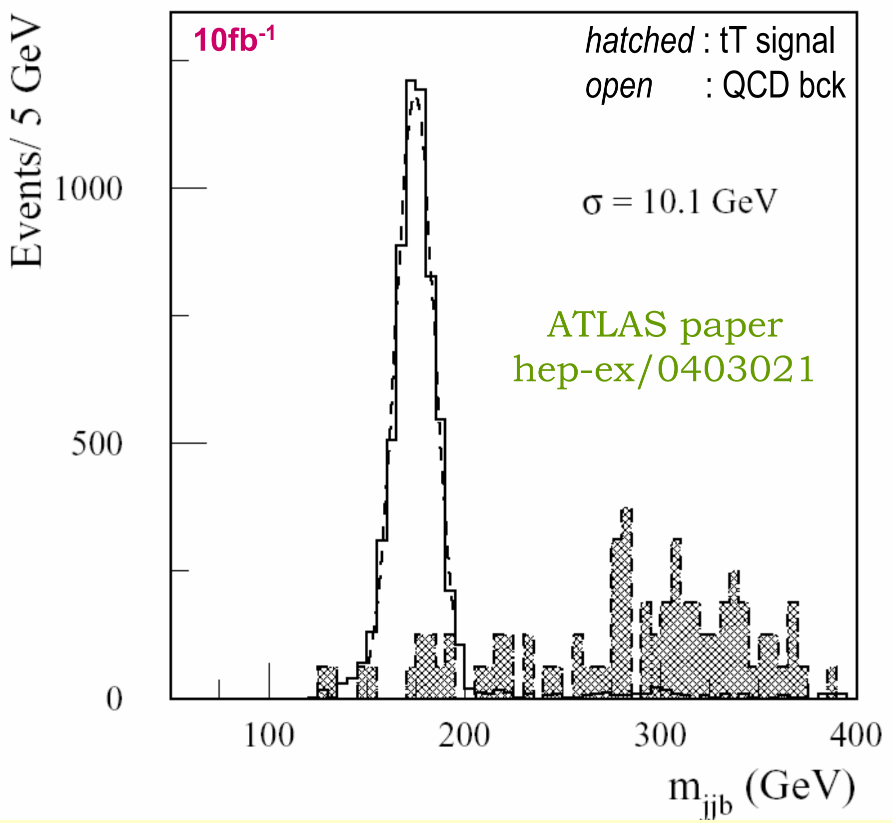
- kinematic fit (χ^2 on the jet energies) + mass window 130-200 GeV :

  S/B~6, ε~0.18% (uncertainty on remaining background B is ~40%)
- can be further improved by asking p_T^{top}>200GeV : S/B~18, ε~0.09%

A clean sample of signal events with ~3.3k*evnt*/10fb^{-1} ⇨ *for top mass estimation*

The pp → tT process at the LHC : fully hadronic

- Fully hadronic channel : 3.7M*evnt*/10fb^{-1}
  - p_T^{top}>200GeV : S/B~18, ε~0.09% ⇨ ~3.3k*evnt*/year
  - using the kinematic fit and the jet combination with the lowest χ^2



Gaussian fit in the window 130-200 GeV results in a peak width of 10.1 GeV

for 10fb^{-1} ⇨ **δm_t(stat) = 180 MeV**

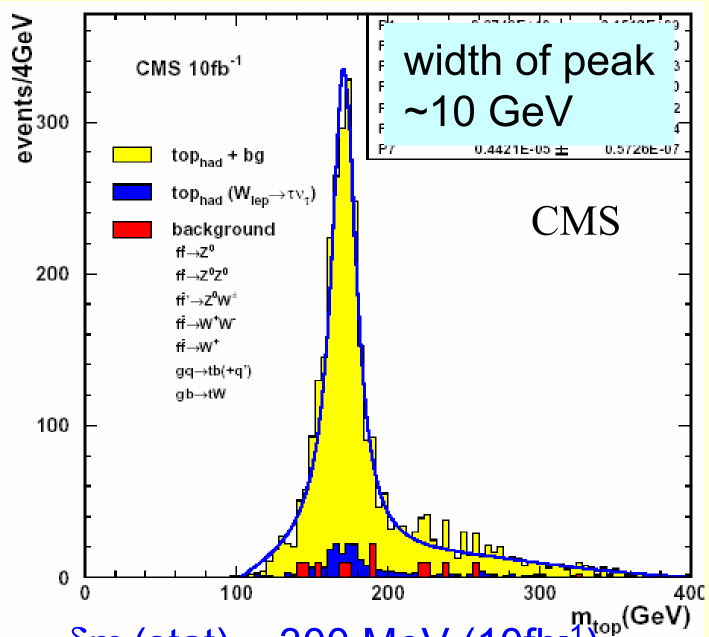
Systematics	δm_t (GeV)
Light jet energy scale	0.8
b-jet energy scale	0.7
b-quark fragmentation	0.3
Initial state radiation	0.4
Final state radiation	2.8

Total systematic uncertainty ~ 3.0 GeV

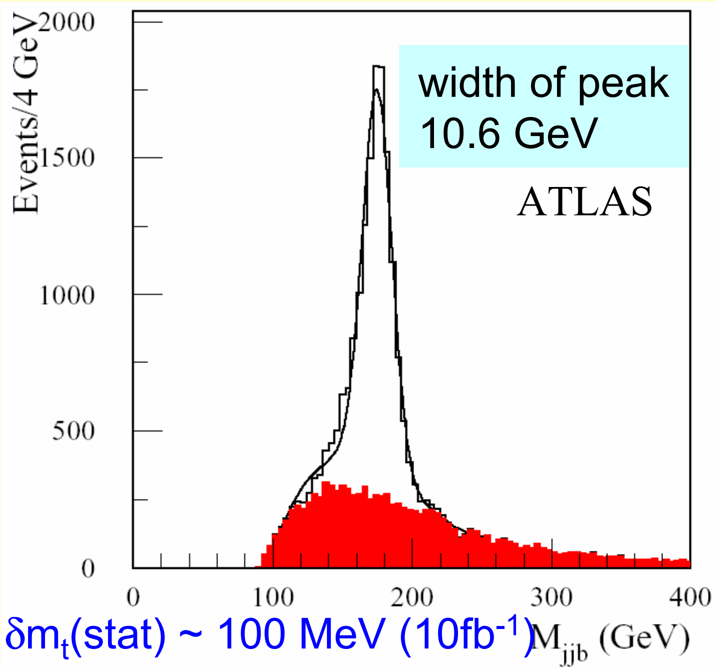
⇨ This clean sample will also be exploited for differential distributions.

The pp → tT process at the LHC : lepton+jet channel

Preliminary plots of ATLAS/CMS are similar :



δm_t(stat) ~ 300 MeV (10fb^{-1})



δm_t(stat) ~ 100 MeV (10fb^{-1})

Systematics ATLAS	δm_t (GeV)
Light jet energy scale	0.2
b jet energy scale	$0.7 \times x\%$
Initial State Radiation	0.1
Final State Radiation	1
b-quark fragmentation	0.1
Combinatorial background	0.1
Statistical error	0.1

kinematic fit →

Internal Systematics ATLAS	δm_t (GeV)
light jet energy scale	0.2
Initial State Radiation	0.1
Final State Radiation	≤ 0.5
b-quark fragmentation	0.1
Combinatorial background	0.1
Total	≤ 0.6
Statistical error	0.1
b jet energy scale	$0.7 \times x\%$

Alternative top mass estimators

- **Single lepton plus jets : High p_T sample with p_T(jjb)> 200 GeV ([Jet-Analysis])**

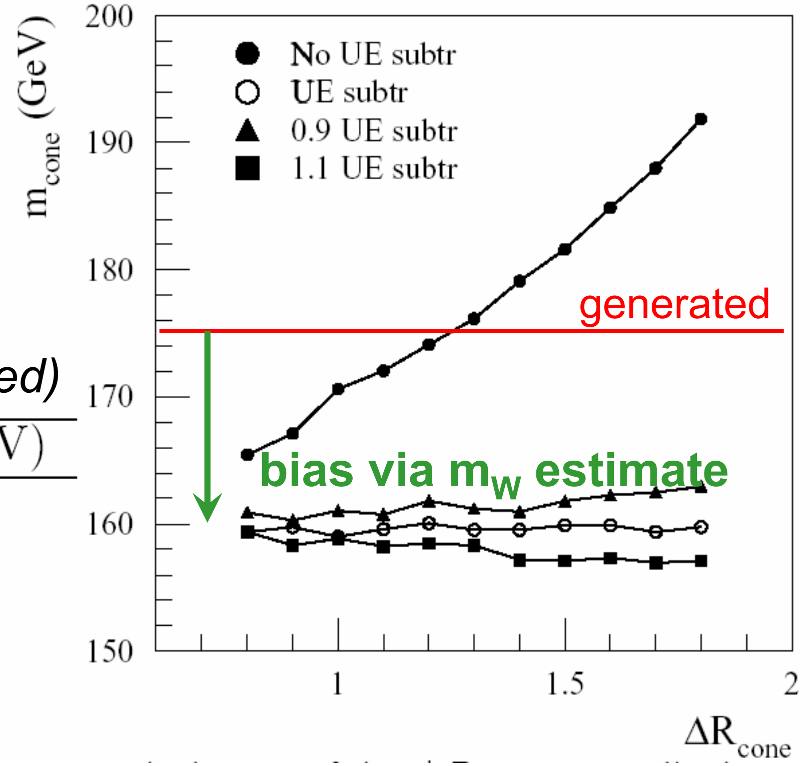
  Yellow Report LHC

  - ✓ *back-to-back top pair production (lab-frame) : hence different hemi-spheres*
  - ✓ *less combinatorial background or other background*
  - ✓ *smaller systematics from energy calibration and gluon radiation*
  - ✓ *statistical uncertainty $\Delta m_t \sim 250$ MeV/c^2*
  - *jet overlapping probability increases ⇨ affects jet calibration*

- **Single lepton plus jets : High p_T sample with p_T(jjb)> 200 GeV ([Cluster-Analysis])**

  ATLAS-COM-PHYS-99-050

  - ✓ *collect all energy in a cone around the top direction*
  - ✓ *less sensitive to jet calibration and the jet topology of the event*
  - *large dependence on cone size*
  - *should subtract underlying event energy*
  - *m_W estimate in tT→lepton+jets (data based)*



	$\|\Delta m_t\|$ (GeV)	δm_t (GeV)
Initial state radiation	0.7	0.1
Final state radiation	0.3	0.1
b-quark fragmentation	0.3	0.3
UE estimate (±10%)	1.3	1.3
mass scale calibration	0.9	0.9

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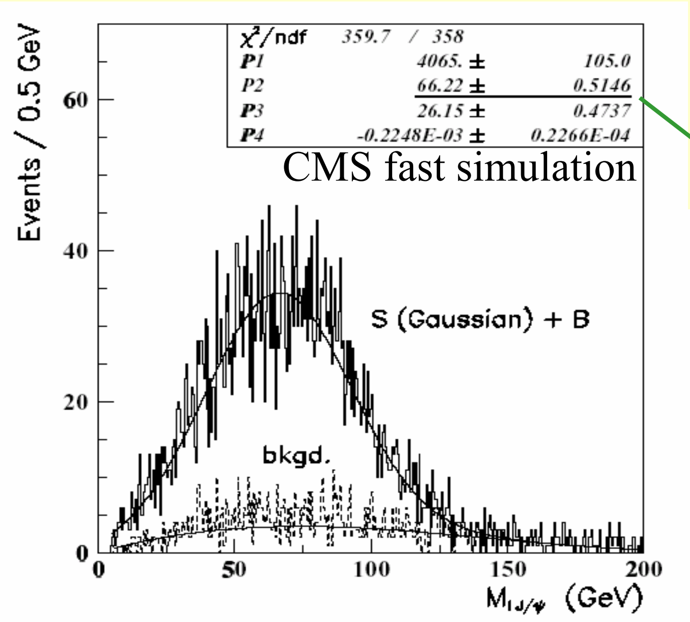
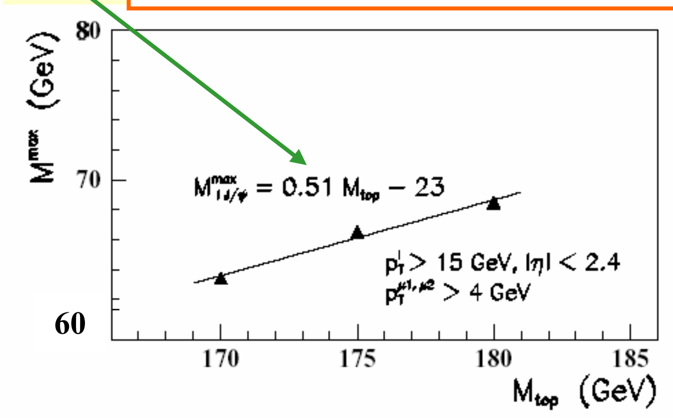
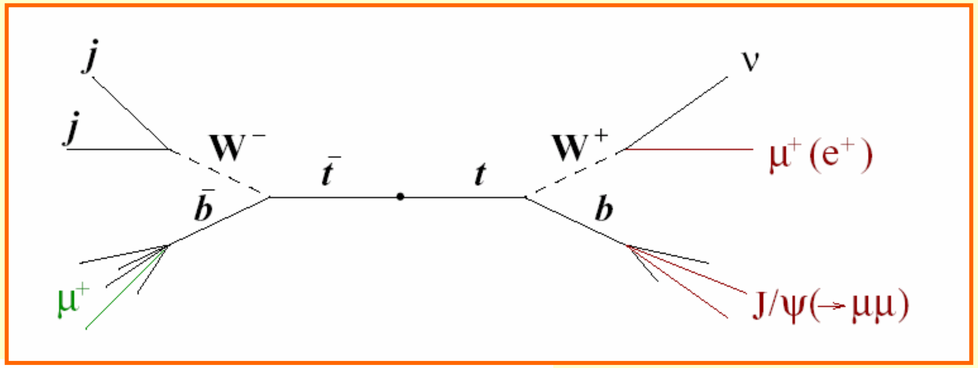
Alternative top mass estimators

- **From $t \to l + J/\psi + X$ decays :**

hep-ph/9912320







slope

⇨ *100 fb^{-1} gives after selection ~ 1,000 signal events (S/B > 100)*

✓ *the large mass of the J/ψ induces a strong correlation with the top mass*

✓ *easier to identify (extremely clean sample)*

BR(overall in tT) ~ 5.3 x 10^{-5}

✓ *no jet related systematics !!*

Systematic uncertainties	$\delta M_{\ell\text{-}J/\psi}^{peak}$ (GeV/c^2)
Final State Radiation	0.15
PDF	0.1
b-quark fragmentation	0.3
Background	0.1
Statistical error	0.5

New method : hep-ex/0501043
correlate the b transverse decay length with m_t

Alternative top mass estimators

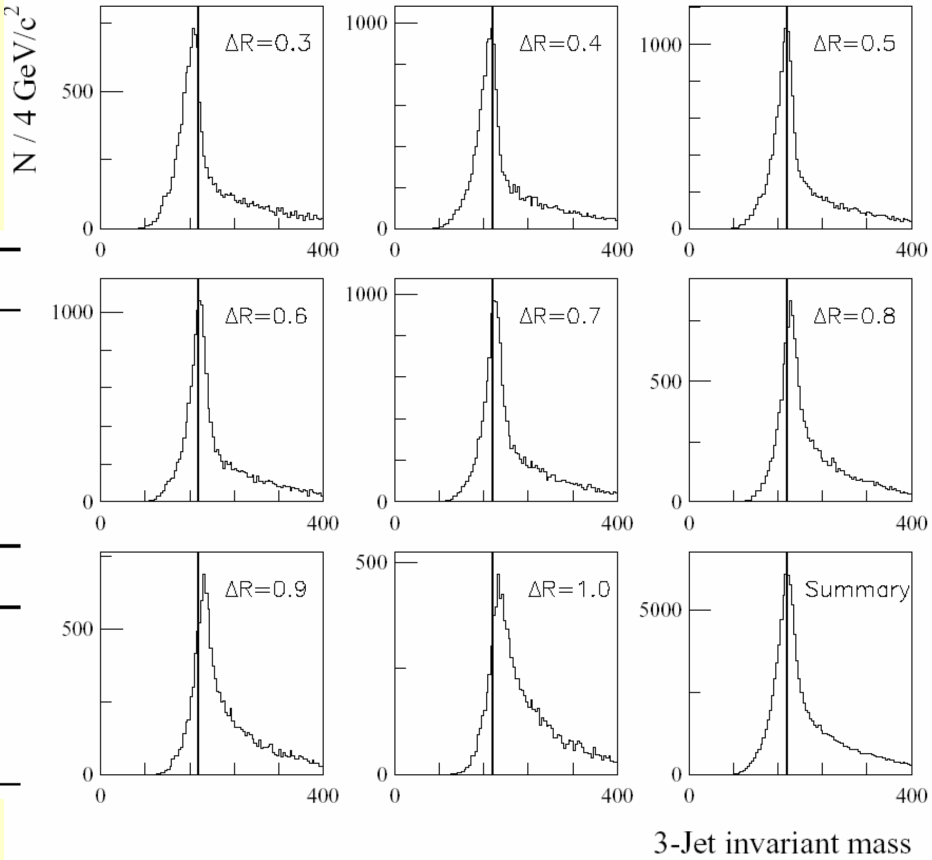
❖ Continuous jet algorithms :

ATLAS paper hep-ex/0403021

⇨ *use the same event selection as for the nominal analysis*

✓ *use the cone-based jet clustering algorithm, but scan the hole ΔR range*
✓ *for each event several m_t are determined depending on ΔR*
✓ *let the event itself choose its jet broadness… less sensitive to radiation*
✓ *statistical unc. ($10fb^{-1}$) ~ 100 MeV/c^2*
systematics : b-jet energy scale

Source	δm_t (GeV)
Range of jet cone sizes	0.25
χ^2 dependence	0.2
Signal and background shape	0.1
ISR and FSR	0.2
External b-jet calibration 1%	0.7
Internal b-jet calibration	
Physics effects	0.13
W signal shape	0.1



The pp → tT process at the LHC : di-lepton channel

❖ Di-lepton channel : 0.4Mevtn/10fb^{-1}

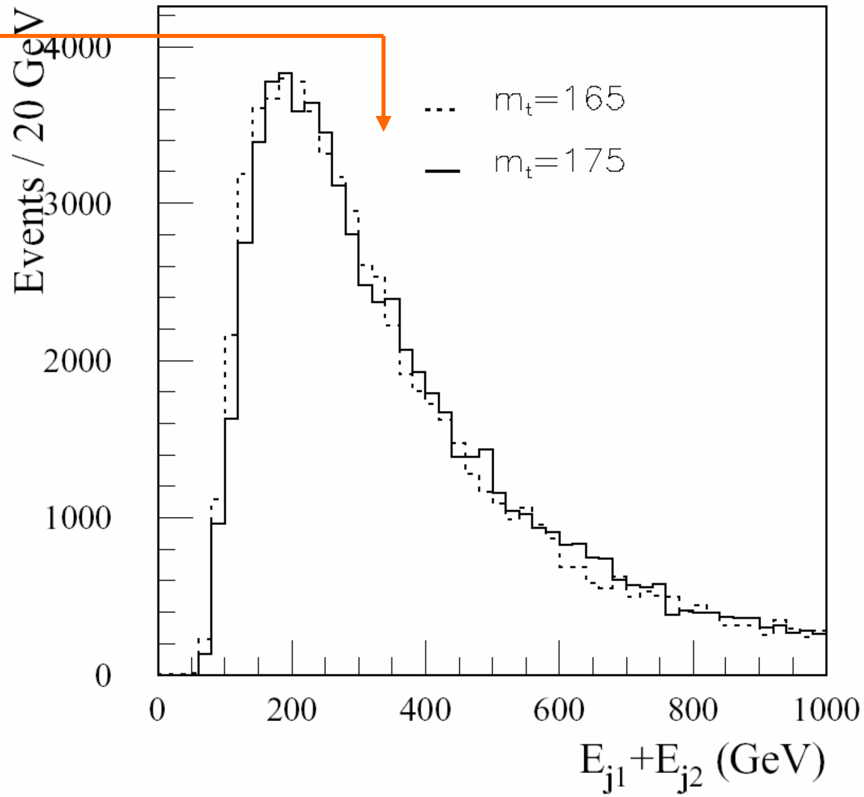
(Jet-Analysis with m_{lb}, Jet-Energies, Tri-lepton events and Full-reconstruction)

⇨ *10 fb^{-1} gives after selection ~ 80,000 signal events (S/B ~ 10)*

i.
- ✓ $m_t^2 = M_W^2 + 2 \langle m_{lb}^2 \rangle / (1 - \langle \cos\theta_{lb} \rangle)$ *(high p_T b-tagged jets → 15,000 events)*
- ✓ *statistical uncertainty ~ 900 MeV/c^2*
- 💣 *b-quark fragmentation could give large systematics*

ii.
- ✓ *energy distribution of two leading jets*
- ✓ *match with correct MC distribution*
- ✓ *statistical uncertainty ~ 400 MeV/c^2*
- 💣 *jet energy calibration ~ 1.5 GeV/c^2*

iii.
- ✓ $t \to l\nu b$ *followed by* $b \to l\nu c$
- ✓ *invariant mass distribution of the two leptons from the same top decay*
- ✓ *only about 7250 events*
- ✓ *statistical uncertainty ~ 1000 MeV/c^2*
- 💣 *systematics from b-quark and ISR and FSR up to 1.5 GeV/c^2*



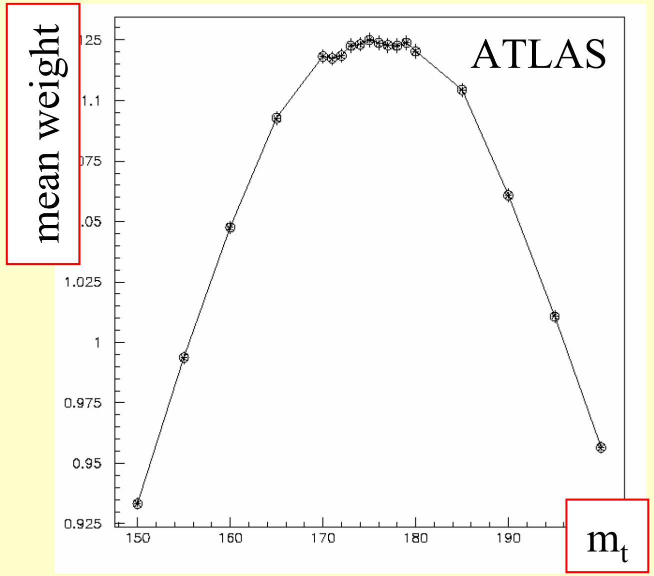
The pp → tT process at the LHC : di-lepton channel

iv.

- ✓ *full event reconstruction by assuming a fixed value for the top mass*
- ✓ *a χ^2 can be determined as a function of this value $m_t \rightarrow \chi^2(m_t)$*
- ✓ *based on solving a set of equations (kinematic constraints)*

- ✓ *solution is found in 98% of the selected events*
- ⇨ *δm_t(stat) ~ 300 MeV (10fb^{-1})*

- ✓ *small systematics due to radiation (switching on/off ISR/FSR)*



source of uncertainty	$\lvert\Delta m_t\rvert$ (GeV)	δm_t (GeV)
Statistics and reconstruction method		0.3
b-jet energy scale	0.6	0.6
b-quark fragmentation	0.7	0.7
Initial state radiation	0.4	0.1
Final state radiation	2.7	0.6
Parton distribution function	1.2	1.2

20% →

Overview of precision expected for each analysis

CMS notes [1]
ATLAS paper hep-ex/0403021 [2]
LHC Yellow Report on Standard Model Physics [3]

Analysis	Ref.	Stat.Unc. MeV	Syst.Unc. MeV
Single-lepton channel (Full-Analysis)	[1,2]	100	~1000
High p_T single-lepton sample (Jet-Analysis)	[3]	250	~1000 (?)
High p_T single-lepton sample (Cluster-Analysis)	[3]	150	~1500
Single-lepton channel (Continuous jet algorithm)	[2]	100	~1000
Di-lepton channel (Jet-Analysis with m_{lb})	[3]	900	~1300
Di-lepton channel (Energy-Analysis)	[3]	400	~2000
Di-lepton channel (Tri-lepton events)	[3]	1000	~1500
Di-lepton channel (Full-reconstruction)	[2]	300	~1300
From $t \to l + J/\psi + X$ decays (4 years high lumi)	[1,2,3]	1000	<1000
High p_T fully-hadronic channel	[2]	180	>3500

- combining all those results could lead to a more precise measurement *(correlations to be estimated !!)*
- systematic effects do not necessary overlap between analyses

Expectation : top mass determination better than 1 GeV after understanding the detector

Definition of the systematic uncertainties

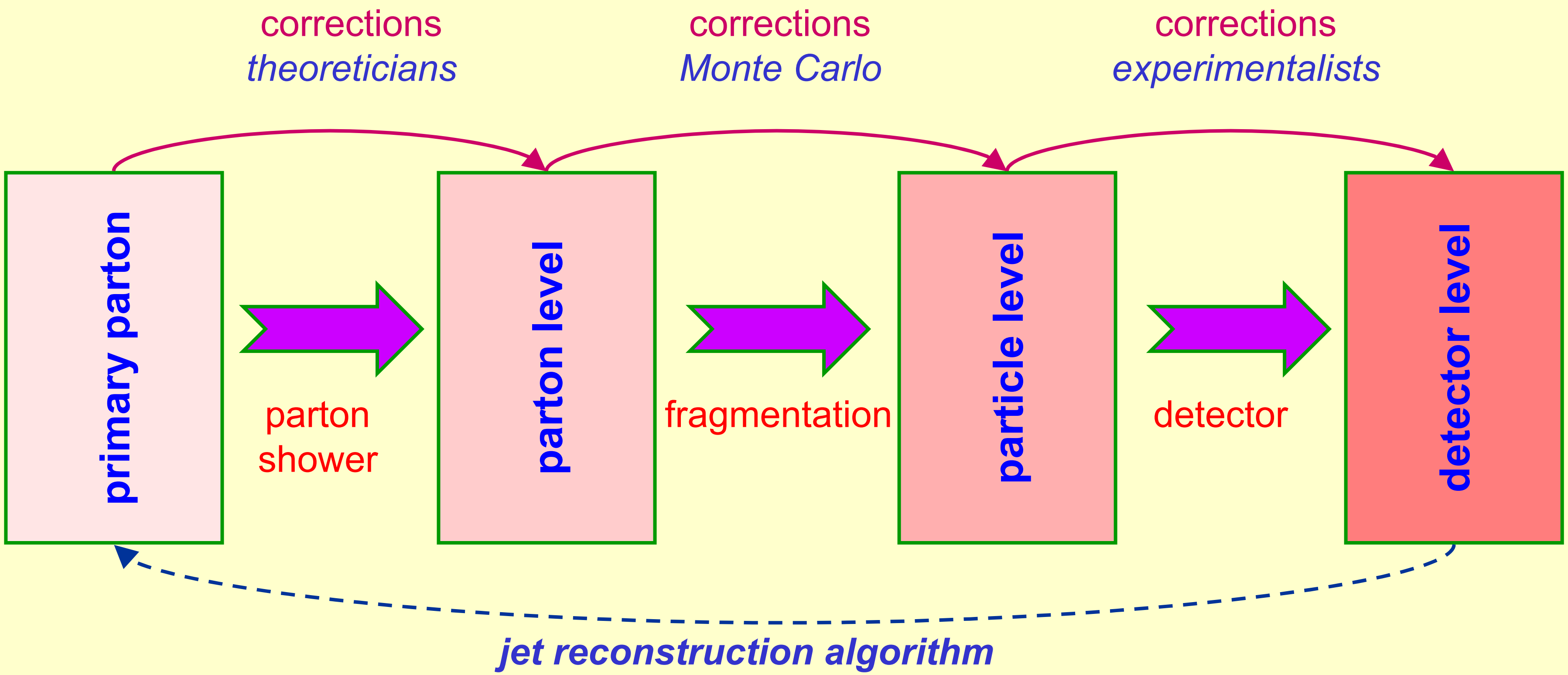
- Jet energy scale : *(underlying event, pile-up, jet definition ?)*
  - different mis-calibration coefficients were applied to the jets
  - in was assumed that the jet energy scale is known to the 1% level
  - a difference is made between light and heavy quark jets
- Radiation in the initial and final state (ISR/FSR) : *(procedure ?)*
  - it assumed that our knowledge of ISR/FSR is 10%
  - conservatively 20% of the shift between with-ISR/FSR and no-ISR/FSR was taken (linear rescaling)
- b-quark fragmentation : *(MC tuning issue ?)*
  - described in the fragmentation by the Peterson function (parameter ε_b)
  - PYTHIA default ε_b=-0.006 with an uncertainty of 0.0025
  - the shift between ε_b(default) and ε_b(0.0019) was taken
- Background :
  - dominated by combinatorial background (S/B is high)
  - estimated by changing the assumed shape in the fit

list to be updated, refined, unified between experiments, … discussion !!

Key issue : jet reconstruction

Tevatron paper hep-ex/0005012

- A jet of particles is a very complex object !!
  - *and we will see many of these particles*
  - *jet algorithms can have both theoretical and experimental difficulties*



- <u>Aim :</u> optimize the resolution on the reconstructed primary parton kinematics
  - *use several jet clustering algorithms and study their features (cut on differences !!)*
  - *understand the influence of each step in the production of the detected jet*
  - *important steps : input object → clustering algorithm → calibration*

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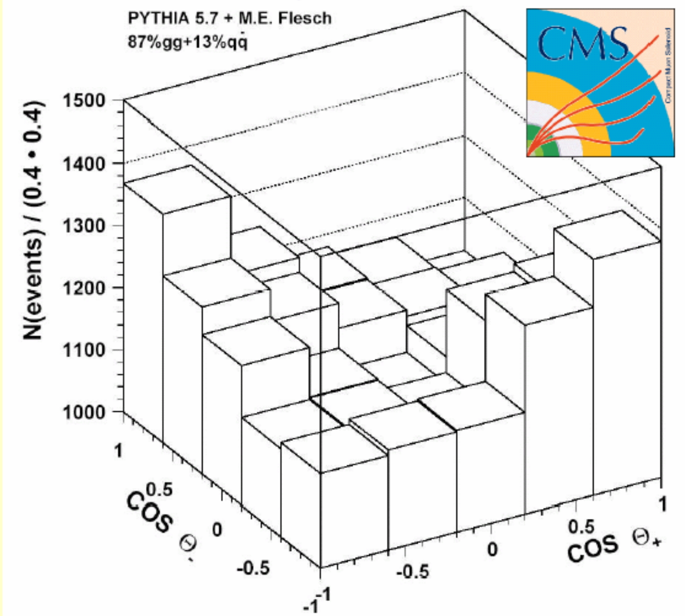
New topics

- <u>Spin correlations</u>
  - ⇨ the top quark does not loss its spin information before it is decaying into W and b
  - ⇨ $$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$ with $\mathcal{A}$=0.431 (gg) and $\mathcal{A}$=-0.469 (qQ)
  - ⇨ two observables $\theta^+(\theta^-)$: angle between t(T) direction in the tT c.m. frame and the $\ell^+(\ell^-)$ direction of flight in the t(T) rest frame
  - ⇨ fit to double differential distribution

$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-})$$

  - ⇨ result (30fb^{-1}) : $\mathcal{A}$ (stat) = 0.035 and $\mathcal{A}$ (syst) = 0.028

    ATL-PHYS-2003-012 : similar results from ATLAS



- Measuring the <u>difference between m_t and m_T</u>
  - ⇨ almost all systematics cancel when taking the difference between both
  - ⇨ after several years the precision could be around 50 MeV
  - ⇨ get theorist to work what we could learn from that ?
  - ⇨ differences between t and T can learn us something about the PDF's (rapidity distributions)

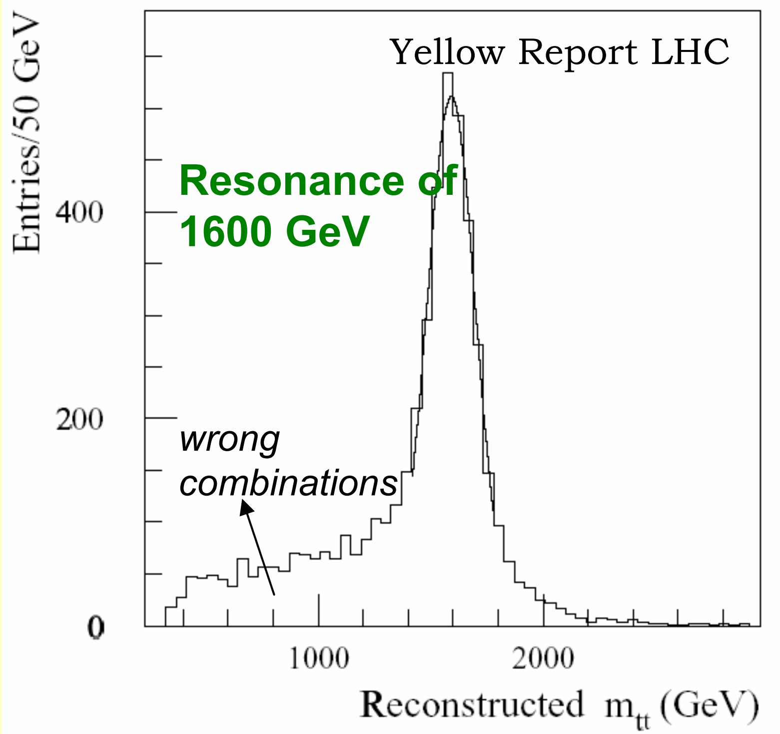
  - ⇨ other differences between t and T (CP violation ?) …. *identify them !!!*

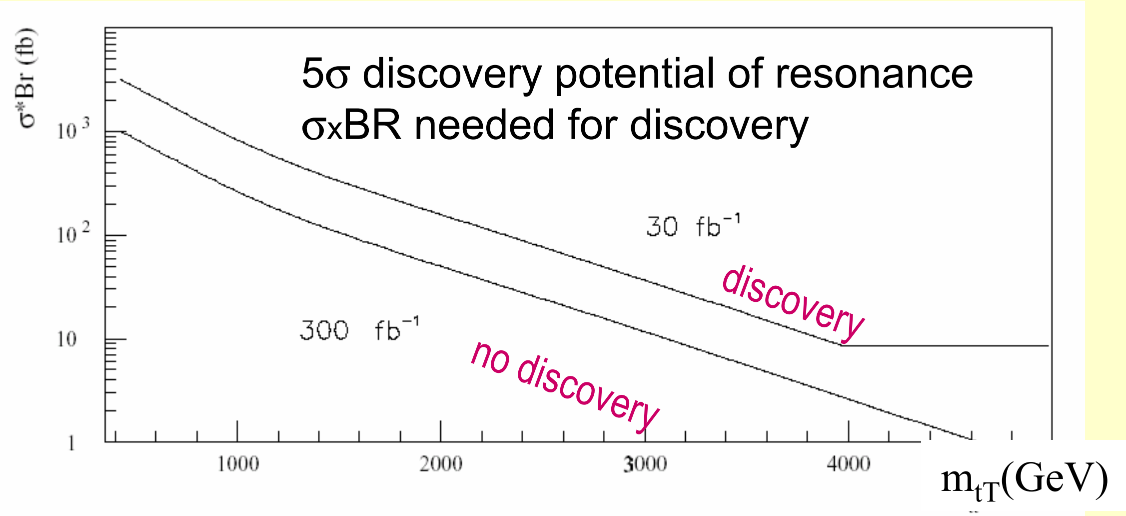
New topics

- A lot more when we differentiate the selected events in phase-space !!
  - ⇨ search for resonances in the $d\sigma_{tT}/dM_{tT}$ spectrum
    - SM : BR(H → tT) to small to be visible above continuum tT production (Γ_H too large)
    - MSSM : if $M_{H,A} > 2m_t$ then BR(H/A → tT) ≈ 100 % for tanβ ≈ 1
    - Technicolor models : in some models heavy particles decaying to tT

    - selection of lepton plus jets channel
    - precise kinematic reconstruction : $\delta m_{tT}/m_{tT} \sim 6.6\%$

For a random resonance :
(choose jet combination which match best the tT event kinematics)





New topics

❖ If extra-dimensions exist and TeV-scale gravity models are correct

- top quarks will be produced from the decay of black holes via Hawking Radiation hep-ph/0205199
- Δm_t = 0.28 (stat) ⊕ 0.5 (syst) = 0.57 GeV (LHC using 10 fb^{-1})
- Yukawa coupling via single top production
  $BR(t \to tH) = 0.046\, y_t^2 / |V_{tb}|^2$
  improvement (30 fb^{-1}) from 16.2% till 2.7%
- … but mixing up a lot of unknowns

Provide reconstruction information

❖ **Get <u>jet calibration</u> from W mass constraint**

- **the selected event sample can be very clean**
- **the jets assigned to the W can be associated in a clean way**
- **a kinematic fit of the full event can be exploited**
- **enough jets left to estimate E^{rec}/E^{gen} as a function of observables**

- **use half of the events for calibration and the other half for measurements**

⇨ ***first results by ATLAS, soon expected by CMS***

❖ **Get <u>b-tag efficiency</u> out of data rather than MC**

- **extremely interesting for $H \rightarrow bb$ searches**
- **a clean b enriched jet sample can be extracted from data (purity>95%)**
- **apply the b-tag method and count how much jets remain…**

⇨ ***first analysis by CMS, preliminary results soon***

Summary

- ***standard and alternative methods have been exploited for mass measurement***
  - *dominated by systematic uncertainties → definition of systematic uncertianties*
  - *optimize the analysis results by reducing systematic uncertainties*
  - *design procedures to combine and compare results between CMS/ATLAS*
- ***other standard physics parameters to be measured***
  - *cross-section and differential cross-sections: MC@NLO*
  - *spin correlations : which generators are applicable*
  - *top quark width… any interest ? can we use MC@NLO for this ?*
- ***new ideas***
  - *differences between top and anti-top quark $t \leftrightarrow T$ (reduced systematics)*
  - *more alternative methods… ?*
  - *signals of models beyond the Standard Model and rare decays*
- ***providing information for general reconstruction tools***
  - *b-tagging efficiency and jet energy calibration (light quark jets)*
- ***key issues to be successful*** *(almost clean samples)*
  - *definition of the jet, radiation effects, jet combinations, …*
- ***possibly much more…***