Top Quark Physics with Early Data of CMS Detector

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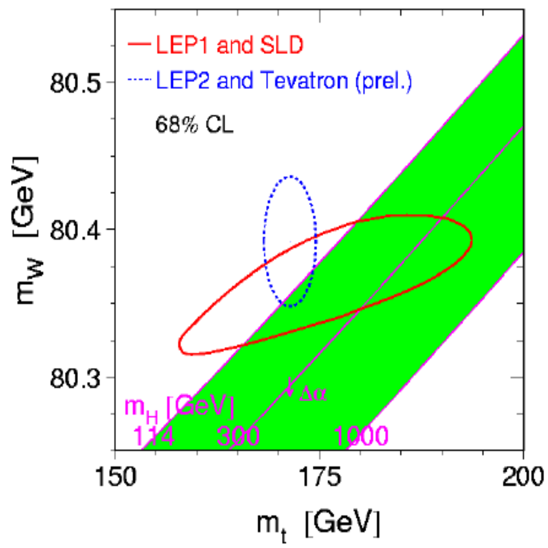
Outline

- the top quark – a peculiar particle
- from the Tevatron to the LHC
- top physics with first data
- the top quark as a calibration tool
- measuring top quark properties
- the top quark as a probe for new physics

The top quark- a peculiar particle

The top quark

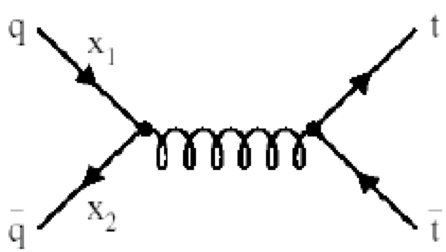
- SU(2) partner of the b-quark, heavy brother of the up and charm quark
  - → fermion, electrical charge 2/3
- discovered at the Tevatron in 1995
  - → completes the third generation of fermions in the Standard Model
  - → still the only place where the top quark was studied directly
- heaviest fundamental particle known: m_{top} = 173.1 ± 0.6 ± 1.1 GeV
  - → precision of 0.7% !
- pair production cross section ~ 7 pb
  - → only a few ten-thousands tops have been produced so far
- the top can also be produced alone
  - → single top observation (5σ) came only less than 2 months ago from both DØ (arXiv:0903.0850) and CDF (arXiv:0903.0885)

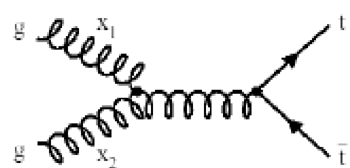


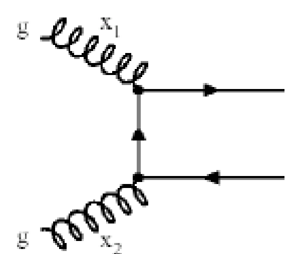
The top quark- a peculiar particle

Top pair production: the Tevatron versus the LHC

- production through the strong interaction
  - → Tevatron: ~ 7pb ; LHC (14TeV): ~ 830pb
- at the kinematic threshold for top pair production: $s_{hat} = x_1 \, x_2 \, s = (2m_t)^2$
  - → Tevatron: $x_1 x_2 = 0.034$ -> <x> ~ 0.19 -> valence quarks dominant
  - → LHC (14TeV): $x_1 x_2 = 0.0006$ -> <x> ~ 0.025 -> gluon sea dominant
- ttbar cross section is largest at the kinematic threshold
  - → Tevatron: dominated by ~ 85% qq->tt
  - → LHC (14TeV): the inverse: dominated by ~ 87% gg->tt





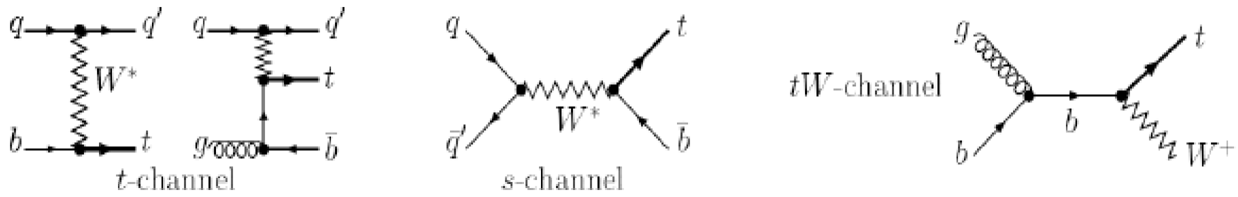


- Tevatron measurement: gg->tt / pp->tt < 0.38 (95% CL) (CDF link)

The top quark- a peculiar particle

Single top production

- produced through the weak interaction
- three distinct production modes



- LHC cross sections (14TeV)

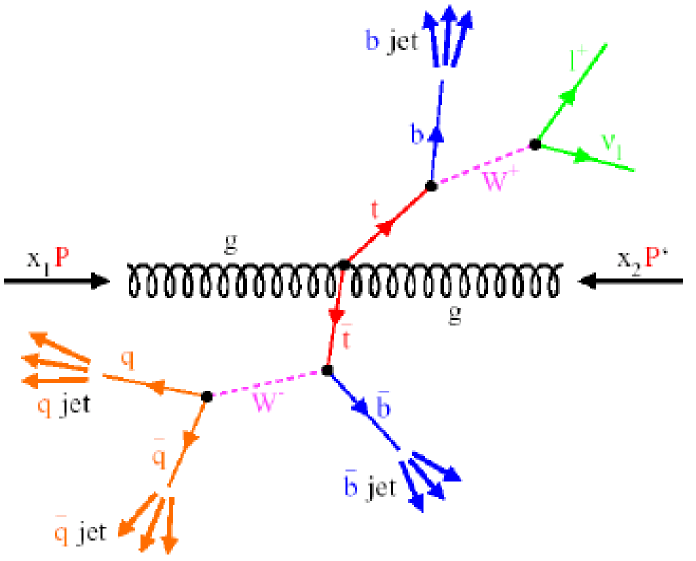
	t-channel	s-channel	tW-channel
top	σ^{NLO} = 153 pb	σ^{NLO} = 6.6 pb	σ^{NLO} = 60 pb
anti-top	σ^{NLO} = 90 pb	σ^{NLO} = 4.1 pb	σ^{NLO} = 60 pb
Tevatron	× 120	× 10	× 400

- processes with gluons in the initial state become dominant at LHC
  - → best possibilities in t-channel: large cross section + forward quark
  - → tW-channel within reach
  - → s-channel very difficult

The top quark- a peculiar particle

The top quark decay

- Standard Model prediction
  - lifetime $\tau = 0.4 \times 10^{-24}$ s
  - decay before hadronization
  - BR(t->Wb) ~ 100% ($|V_{tb}| \sim 1$)
- note: this prediction assumes
  - no additional quark families with $m_{b'} + m_W < m_t$
  - unitarity of the CKM matrix



- exploration of rare decays is a handle to new physics
- some limits set at Tevatron, often statistically limited
  - BR(t->Zq) < 3.7% (95% CL) (CDF link)
  - BR(t->H$^+$b) < 35% (95% CL) (D0 link)
  - BR(t->Wb)/BR(t->Wq) > 0.79 (95% CL) $|V_{tb}| > 0.89$ (95% CL) if 3x3 CKM is unitary (D0 link)

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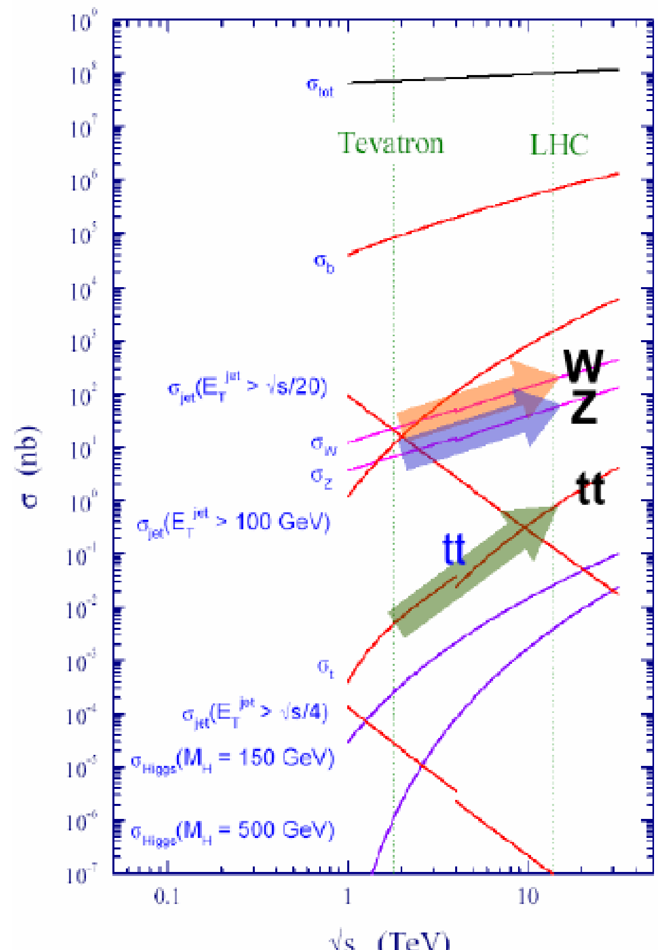
From the Tevatron to the LHC

At the LHC, everything is "Large"

- "standard candles" are overwhelming
  - → W's: ~200/s ; Z's: ~50/s
- top quark rate huge: reaching 1/s
  - → Tevatron: thousands
  - → LHC: millions!

Process	Tevatron x-sec.	LHC x-sec. (14 TeV)	Tevatron to LHC
top pairs	7 pb	830 pb	x 120
single top s-channel	0.9 pb	11 pb	x 10
single top t-channel	2.0 pb	250 pb	x 120
single top tW-channel	0.15 pb	66 pb	x 400

- top quark physics at LHC allows precision measurements
- top quark events become standard candle themselves, providing control and calibration samples



From the Tevatron to the LHC

- σ(tt) grows more rapidly than QCD, W and Z cross sections as a function of the center-of-mass energy
- so backgrounds are expected negligible?
  - → no! argument only works inclusively...

- example: W+jets
  - → σ(W) increases with a factor ~10
  - → σ(W+4jets) with a factor ~100

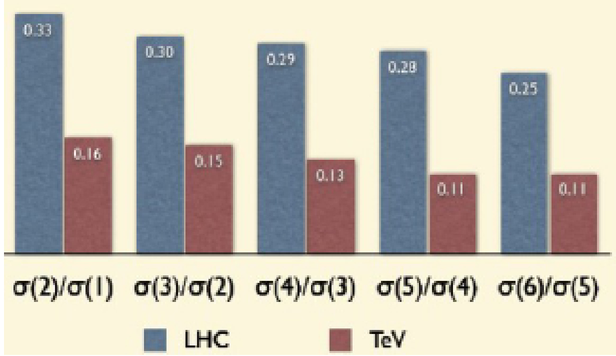
- also LHC will need to control QCD, W+jets,...

M. Mangano

W+Multijet rates

σxB(W→eν)[pb]	N jet=1	N jet=2	N jet=3	N jet=4	N jet=5	N jet=6
LHC	3400	1130	340	100	28	7
Tevatron	230	37	5.7	0.75	0.08	0.009

E_T(jets) > 20 GeV , |η|<2.5 , ΔR>0.7



- Ratios almost constant over a large range of multiplicities
- $O(\alpha_s)$ at Tevatron, but much bigger at LHC

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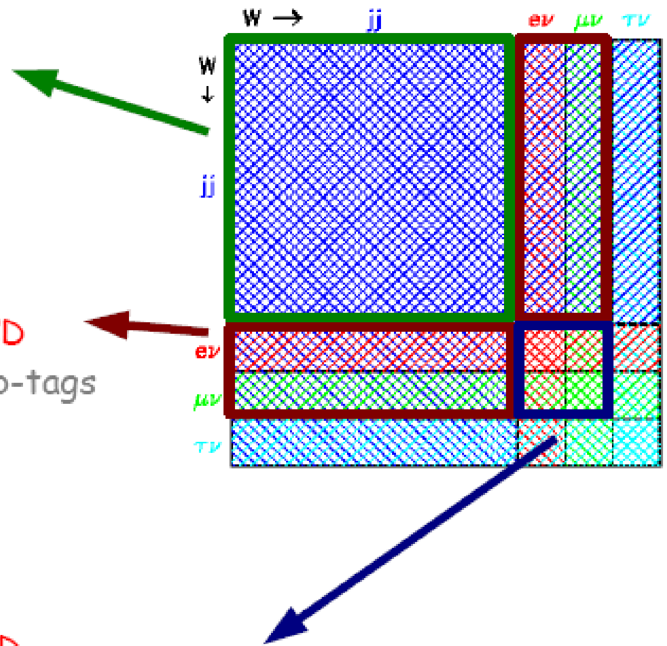
From the Tevatron to the LHC

A feeling of a 10 fb^{-1} LHC analysis with top pairs

from CMS Physics TDR Vol. II, 2006

- Fully hadronic decay channel
  - → 3.7M ev/10fb^{-1}
  - → main background: QCD multijet
  - → 6 jets E_T>40GeV, 2 b-tags
    - S/B ~ 1/19 for 2.7% eff.



- Lepton + jets decay channel (e/mu)
  - → 2.5M ev/10fb^{-1}
  - → main background: W+multijet, ~no QCD
  - → lepton p_T>20GeV, 4 jets E_T>30GeV, 2 b-tags
    - S/B ~ 26 for 6.5% eff.

- Dilepton decay channel (e/mu)
  - → 0.4M ev/10fb^{-1}
  - → main background: Z+jets, WW, no QCD
  - → lepton (1|2) p_T>(35|25)GeV, MET>40GeV, 2 jets E_T>25GeV
    - S/B ~ 10 for 20% eff.

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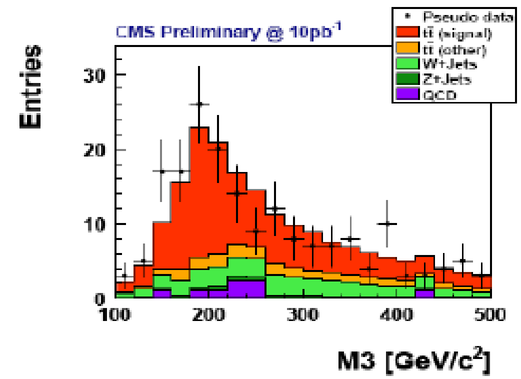
Top physics with first data

Rediscovery of the top quark

- much more statistics with 10/pb than used for the original top discovery
- but the detector and hence physics objects will not be well understood
  - → need simple, robust methods for event selection
    - e.g. high thresholds to avoid not-well controlled noise
    - MET and b-tagging will probably not be sufficiently understood
- a mass peak from lepton+jets is much easier to establish than a cross section deviation as a function of number of jets
  - → but also here no advanced kinematic methods can be employed to select which jets to combine, because JES will not be well known
  - → no mass measurement, so mass doesn't need to be at the right value
- top rediscovery with 10 pb^{-1} in lepton+jets

  CMS PAS TOP-08-005

  - → hard isolated muon
  - → 4 hard jets
  - → angular muon-jet separation
  - → top mass from 3 jets with highest ΣE_T
    - yields ~35% correct assignment



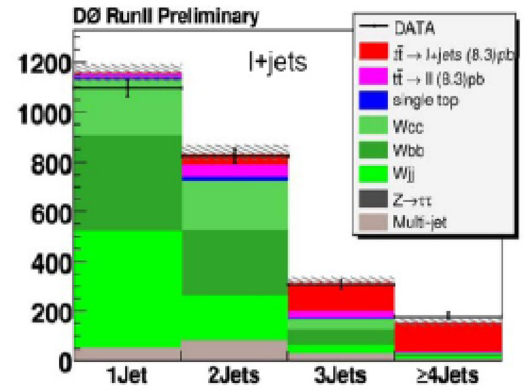
Top physics with first data

measuring cross sections

- cross section measurements seem easy in principal
  - → select events with some cuts
  - → subtract your expected background contribution
  - → count the obtained number of events
  - → extract cross section folding in selection and trigger eff.'s and luminosity
- event selection: not just a set of random cuts
  - → needs to be simple -> avoid unnecessary uncertainties
  - → but needs to efficiently reduce backgrounds and systematics
- estimating backgrounds: the difficult part
  - → one should always aim for data-driven techniques
  - → defining and understanding control samples can be difficult, extrapolation to signal region must be proved to work, uncertainties must be assessed
- translating back to cross section
  - → less difficult as long as you stick to default cuts -> efficiencies and uncertainties will be obtained for you
  - → otherwise there's a lot of work in this as well, for instance in the trigger

Top physics with first data

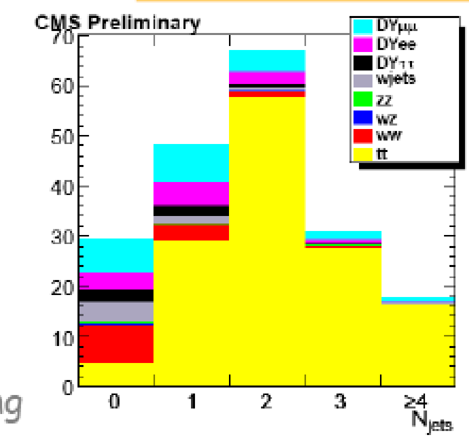
- the result of a cross section analysis can typically be summarized in 1 plot
  - → # events as a function of # jets, comparing MC expectations to data
  - → proving signal, backgrounds and control regions are well understood
  - → a lot of work in 1 number and 1 plot!



Cross section measurements in early data

- example: ttbar dilepton cross section with 10/pb
  - → ee, μμ and eμ channels each an analysis themselves
  - → Z->dilepton is the main background
  - → 0 and 1 jet bins crucial to prove understanding of backgrounds in control region
  - → expected statistical uncertainty O(10%)
  - → comparable systematics anticipated; work ongoing

CMS PAS TOP-08-001



Top physics with first data

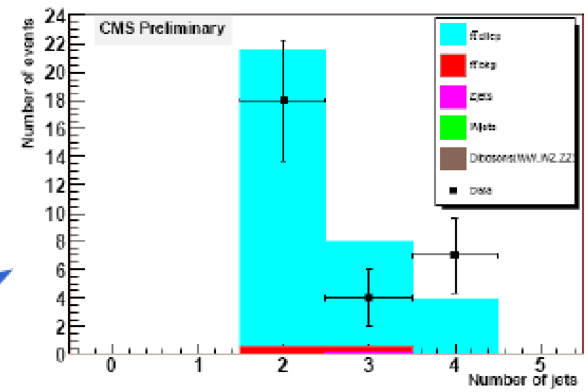
Control of the QCD background

- example of one background study as part of a cross section measurement
- QCD multijet events can look like top events
  - → when a real lepton within a jet looks as if it is isolated
  - → when weird jet or misreconstruction "fake" a lepton (esp. electrons)
- both effects are rare (but QCD cross section is huge!)
  - → impossible to model reliably in simulations
  - → need to estimate from data the amount of QCD passing the selection cuts
- several methods being developed
  - → "ABCD": use low MET and/or bad Iso to predict high MET, low Iso
  - → similar: isolation vs $p_{T,lepton}$ or $d_{0,muon}$
  - → ad-hoc method of extrapolation of the Iso variable in the signal region
  - → all these methods have their drawbacks and limits, but can probably be sufficient for this small QCD contamination, allowing large uncertainties
- area of large activity! [also as part of the CMS V+jets group]

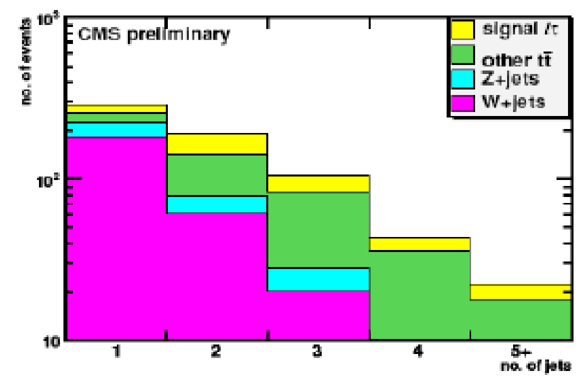
Top physics with first data

Cross section measurements with 100/pb

- detector will be a bit better understood
  - → alignment and calibrations, MET cleanup, first b-tag efficiency measurements
- and 10x more statistics!
- both allow a much cleaner selection of the signal events of interest



- example 1: **CMS PAS TOP-08-002**
  - → top -> dilepton, using b-tagging
- example 2: **CMS PAS TOP-08-004**
  - → top -> tau-jet + electron/muon + large MET



- differentiation of larger jet multiplicities is interesting for MC tuning and searches with multi-jets, like in SUSY

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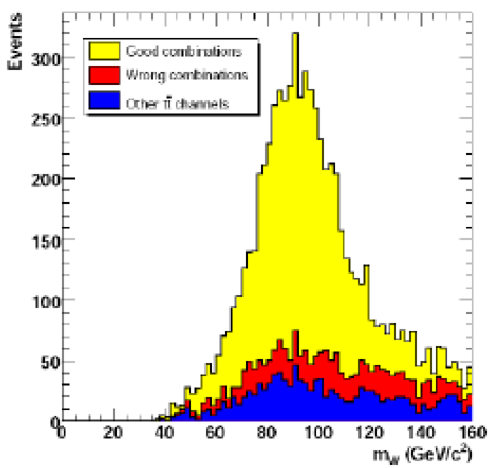
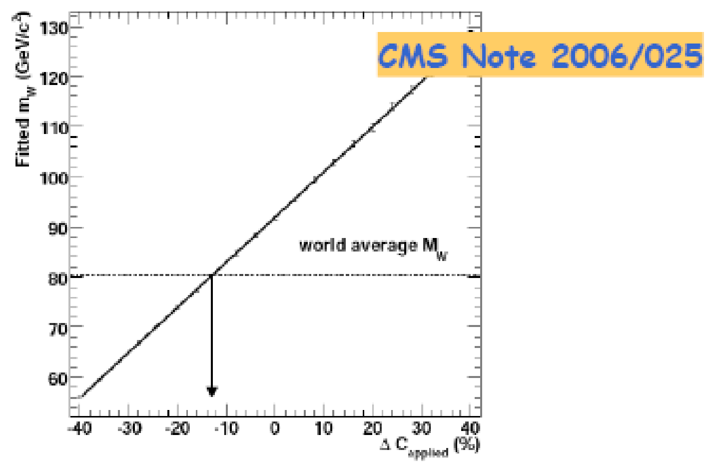
The top quark as a calibration tool

Jet energy scale calibration using the W-mass constraint

- reconstructed hadronic W mass in lepton+jets events is sensitive to jet energy scale of light quark jets
- imposing the W-mass it is possible to determine the JES corrections down to the parton level
- needed correction for true W mass scales linear with initial miscalibration





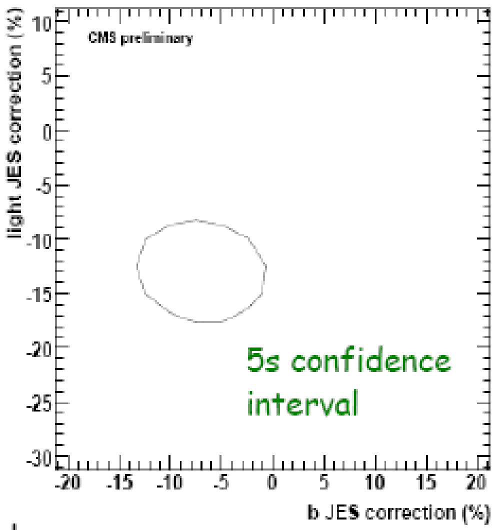
- top quarks will be the most important JES calibration sample at the LHC

The top quark as a calibration tool

Extension to calibration of b-jet energy scale

CMS PAS TOP-08-002

- full kinematic fit imposes W and top mass on 3 well-paired jets
- miscalibrations are applied on all 3 jets to scan for the JES corresponding to the true W and top mass
- closure test on MC ok, no significant bias expected
- systematics
  - pile-up -> can be monitored via primary vertex count
  - effect combinatorial and non-ttbar background negligible
  - effect from jet energy resolution negligible
- expected performance
  - ~1% statistical uncertainty on JES for light and b-jets
- this is inclusive, can be differentiated versus p_T, $|\eta|$
- detailed understanding of pile-up - JES interplay crucial



The top quark as a calibration tool

B-Tagging Efficiency Measurement

CMS Note 2006/013

- b-jet-rich samples are selected in ttbar e+mu, mu+jets and e+jets events
  - → challenges in selecting a pure b-jet sample come from both process backgrounds and combinatorial background
- extraction of b-tagging efficiencies from b-jet samples
  - → apply any b-tag algorithm on a selected data sample -> fraction x_{tag} tagged
  - → estimate sample's b-tag purity x_b and mistag probability ε_0 from MC

$$\epsilon_b = \frac{1}{x_b}\left[x_{tag} - \epsilon_o(1 - x_b)\right]$$

from data, contributes statistical uncertainty

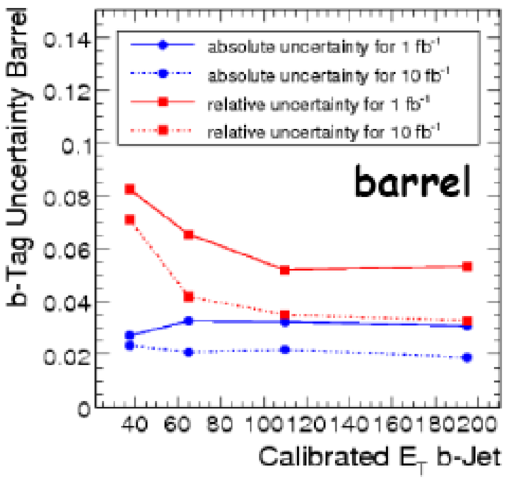
from MC shown not to contribute additional systematics

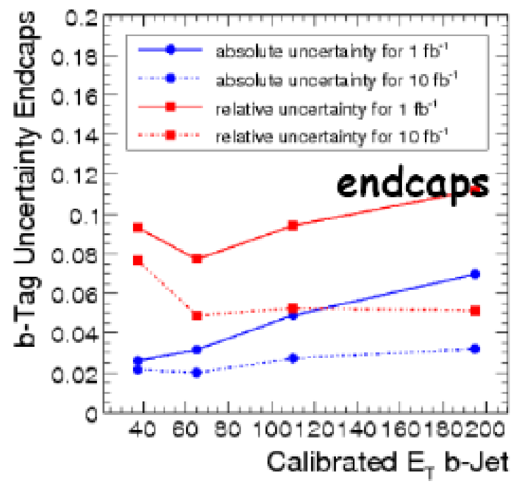
from MC, systematics determined as function of likelihood ratio cut

- systematics
  - → by far dominated by uncertainties on initial state gluon radiation
  - → we will need LHC data or better Monte-Carlo to improve
  - → no systematics from misalignment -> this is in fact measured
  - → systematics decrease as the purity of selected samples is increased!

The top quark as a calibration tool

- differentiation versus p_T and η possible with $1 fb^{-1}$ of data
- three samples are exclusive and similar -> can be combined





- top events will provide the most important b-tagging efficiency calibration samples at the LHC
- new methods are in the works, especially to measure c-jet and possibly light jet efficiencies simultaneously

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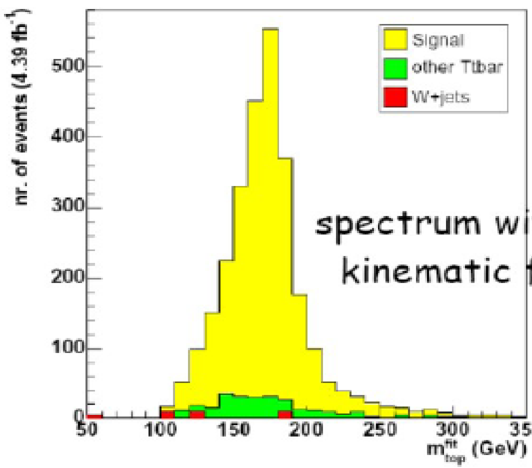
Measuring top quark properties

Top mass strategies in the golden channel

CMS Note 2006/066

- lepton + jets event selection: efficiency ~6%
  - → 1 isolated lepton and 4 jets, of which 2 b-tagged
  - → extra cuts on kinematic fit, jet combination likelihood and signal/background separation likelihood
- mass reconstruction performed for the hadronically decaying top
  - → leptonic side used for determination of the best jet association
- estimators studied:
  - → Gaussian fit on the reconstructed top mass peak
  - → parameterized ideogram
    - an event-by-event pdf as a function of the top mass, with top mass uncertainty calculated from fit and assumed Gaussian
  - → full scan ideogram
    - the event-by-event top mass resolution function is now built by scanning with an additional top mass constraint in the kinematic fit
  - → details in the backup



spectrum with kinematic fit

Measuring top quark properties

Systematics for the top mass in the golden channel

- most of the following table consists of ambitious detector systematics

	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up *(5% On-Off)*	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale *(1.5%)*	2.90	1.05	0.96
Radiation (pQCD)	0.80	0.27	0.22
Fragmentation	0.40	0.40	0.30
b-tagging *(2%)*	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty ($10 fb^{-1}$)	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

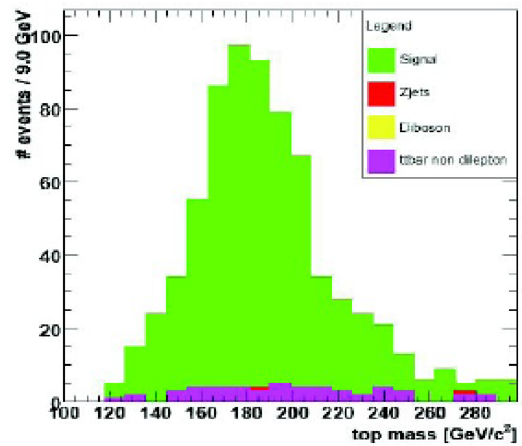
- main uncertainty from the b-jet energy scale
- to reach 1 GeV uncertainty we need a very good detector understanding
  - → the more recent CMS studies indicate that this should indeed be possible

Measuring top quark properties

Top mass from the di-lepton decay channel

CMS Note 2006/077

- event selection similar to cross section
- kinematics underconstrained, but indirect mass reconstruction possible
- most important systematic from jet energy scale (also neutrino modeling)
  - → expected 4.2/2.9/1.0 GeV for 1/10/>10 fb^{-1}
- systematics dominated already for 1 fb^{-1}



Top mass from the fully hadronic decay

- all kinematics measured
- needs to trigger on b-jets
- jet pairing: 6 possible combinations after b-tag
- need to deal with multi-jet background
- systematics the main problem, again...
- needs very good detector understanding and advanced analysis techniques

	$\Delta m_t [GeV/c^2]$
Pile Up	0.4
Underlying Event	0.6
PDF	1.4
IS/FS Radiation	2.3
Fragmentation	0.9
Jet Energy Scale	2.3
b-Tagging	0.3
Background	2.0
Statistical (1fb^{-1})	0.6

due to pairing ambiguities (IS/FS Radiation)

mainly from b-jet scale (Jet Energy Scale)

Measuring top quark properties

Top mass from $b \to J/\Psi \to \mu\mu$ decays

CMS Note 2006/058

- top mass is correlated to $m_{J/\Psi\ell}$, for J/Ψ and lepton from same top
- "only" involving leptons
  - → very good mass resolution
  - → orthogonal systematics, mostly theoretical: fragmentation, Λ_{QCD},...
- but low statistics this time! $BR(tt \to J/\Psi \ell X) \sim 5.5\ 10^{-4}$ -> 4500 per $10fb^{-1}$
  - → and don't forget trigger, reconstruction and pairing efficiencies
- this mass determination only becomes useful at high luminosity

Top mass from b decay length

hep-ex/0501043

- top mass is correlated to decay length of the B-meson decay in the b-jet
- currently gaining importance at the Tevatron
- "only" involving tracks
  - → orthogonal systematics, mostly theoretical: fragmentation, Λ_{QCD},...
- not explored yet for CMS! statistics no problem, best at low luminosity

Measuring top quark properties

CMS PAS in preparation

Constraining V_{tb} through the R = t->Wb / t->Wq ratio

- test of the standard model (unitarity of the CKM matrix)
  - → sensitive to anomalous decays or a 4th fermion generation
- complement of the b-tagging efficiency measurement in ttbar events
- analysis strategy
  - → standard event selection for ttbar lepton + 4 jets
  - → choose a working point for b-tagging
  - → determine the distribution of the number-of-b-tags (0 up to 4)
  - → fit this distribution to the expectation, with R and mistag rate as free parameters and b-tag efficiency from an independent measurement
- background subtraction can be made data-driven
- main systematics expected from the b-tagging efficiency and the jet energy scale and resolution
- analysis under review, public results expected soon

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New physics in rare top decays

CMS Note 2006/093

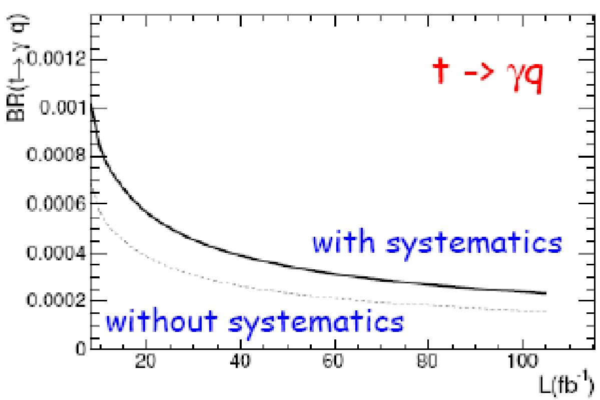
- beyond the SM, rare top decays through loops can become sizable

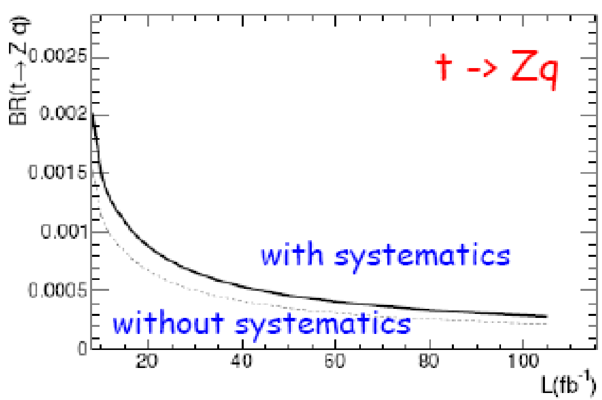
Decay	SM	two-Higgs	SUSY with $\not{R}$	Exotic Quarks	Exper. Limits(95% CL)
$t \to gq$	5×10^{-11}	$\sim 10^{-5}$	$\sim 10^{-3}$	$\sim 5 \times 10^{-4}$	< 0.29 (CDF+TH)
$t \to \gamma q$	5×10^{-13}	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$	< 0.0059 (HERA)
$t \to Zq$	$\sim 10^{-13}$	$\sim 10^{-6}$	$\sim 10^{-4}$	$\sim 10^{-2}$	< 0.14 (LEP-2)

<0.037 (CDF)

- selections devised to isolate ttbar events with one top in a rare decay
  - → need to select as little ttbar, single top,... as possible

- expected sensitivity:





- statistically limited in the beginning, but great potential in the long run

Top Physics Timeline at LHC

	Top for commissioning: The first observation of the top quark is a landmark event for the initial detector commissioning.
$10pb^{-1}$	**Early Measurements:** tT cross section will be among the first top physics measurements to be made.
$100pb^{-1}$	**Top for calibration:** The top mass and the tT topology are strong tool for understanding the detector.
$1fb^{-1}$	**Top as background:** Good understanding of the top is crucial to the discovery of new physics.
$10fb^{-1}$	**Precision measurements:** Precision-measurement of top properties and single top can be performed with accumulated data.
$100fb^{-1}$	**Discovery through top:** Study of the top quark may itself lead to the discovery of new physics.

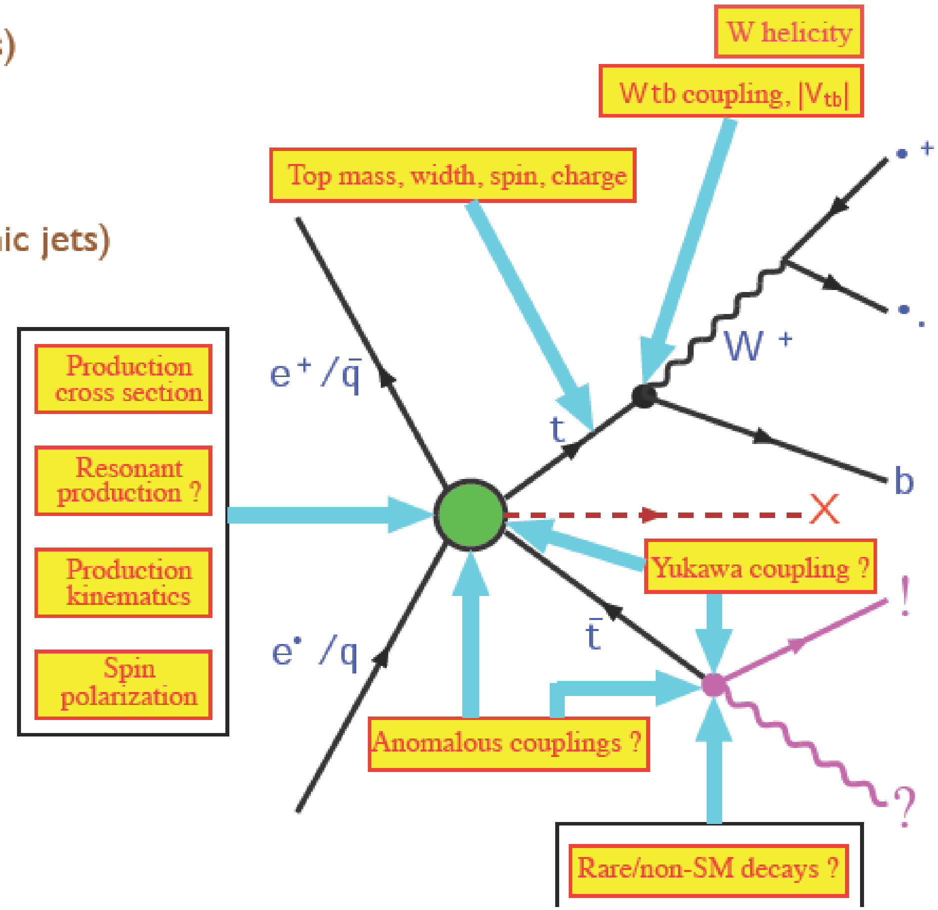
Top Physics Topics of Interest

tT cross section :
- tT semileptonic (lepton + jets)
- tT dileptonic
- tT fully hadronic

Top mass:
- tT semileptonic (using hadronic jets)
- tT dileptonic (using leptons)

Top property:
- top charge
- top width
- tT spin correlation
- W helicity
- Yukawa coupling
- anomalous coupling
- resonance production

Single top measurement:
- s-, t-, Wt cross section
- Vtb measurement
- top polarization



Conclusion

Conclusions

- top quarks provide a very rich physics program at the LHC
  - → SM measurements in the top sector
  - → calibrations
  - → beyond the SM searches
- early day top physics will be exciting
  - → many analyses become accessible in the first LHC year, some immediately
  - → ideal playground to acquire understanding of the complete CMS detector
- top quark physics should be seen as an essential part of an global CMS discovery program
  - → top physics is omnipresent in CMS, as a signal, as a background or as a playground for tools and calibrations