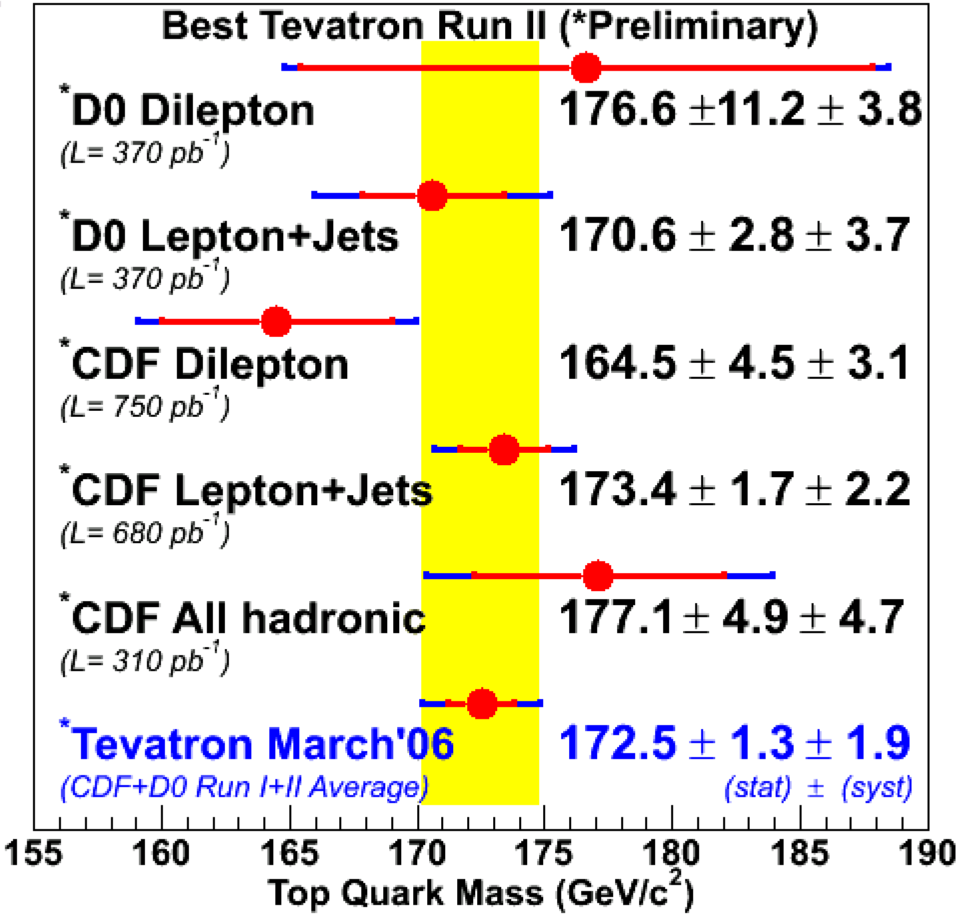
Brussels Top Quark Achievements

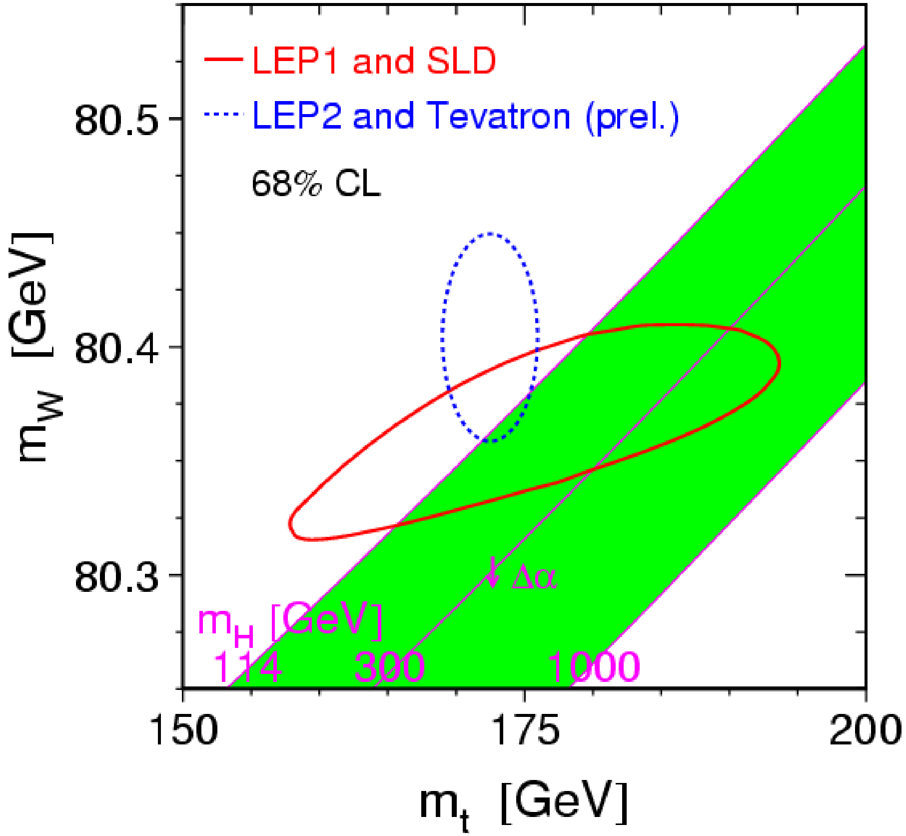
Outline

- introduction
  - top quarks physics at the LHC
- achieved results in Brussels
  - reconstruction topics
  - calibration topics
  - physics topics
- conclusions

The top quark mass is currently measured up to 1.3%!

- low top quark mass prefers low Higgs mass

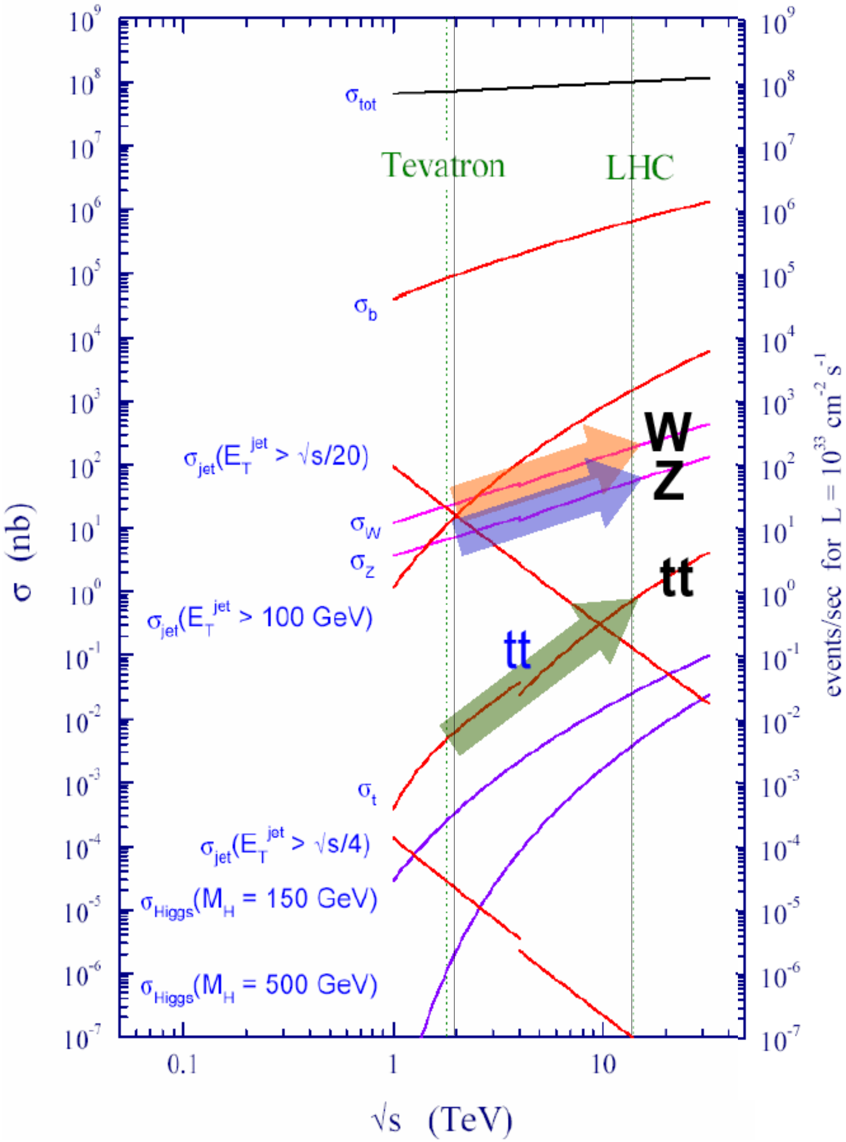




At LHC, everything is "Large"

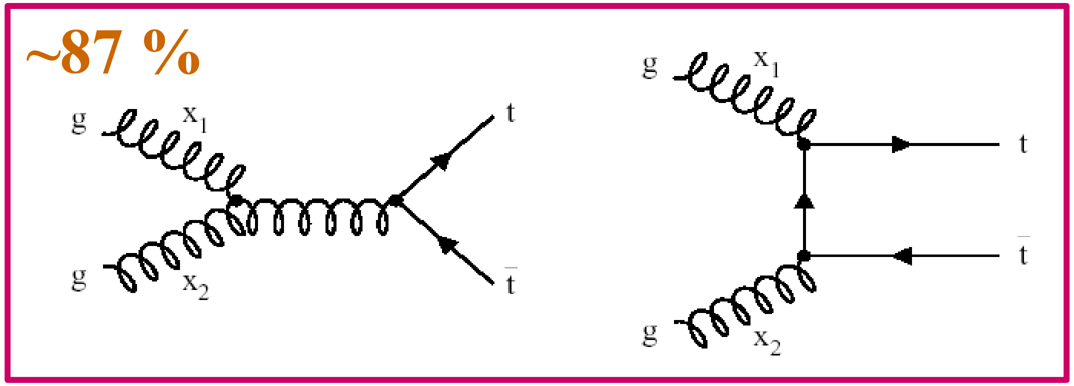
- center of mass energy 14 TeV
- luminosity up to 10^{34} cm^{-2} s^{-1}
- "standard candles" are overwhelming
  - W's: ~200/s
  - Z's: ~50/s
- top quark rate huge: 1/s
  - Tevatron: hundreds
  - LHC: millions!

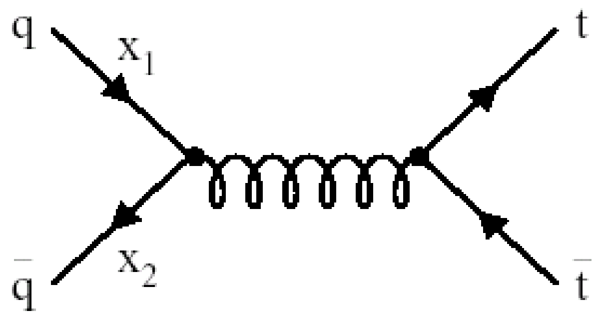
- top quark physics at LHC allows precision measurements
- top quark events become standard candle themselves as they provide interesting control and calibration samples

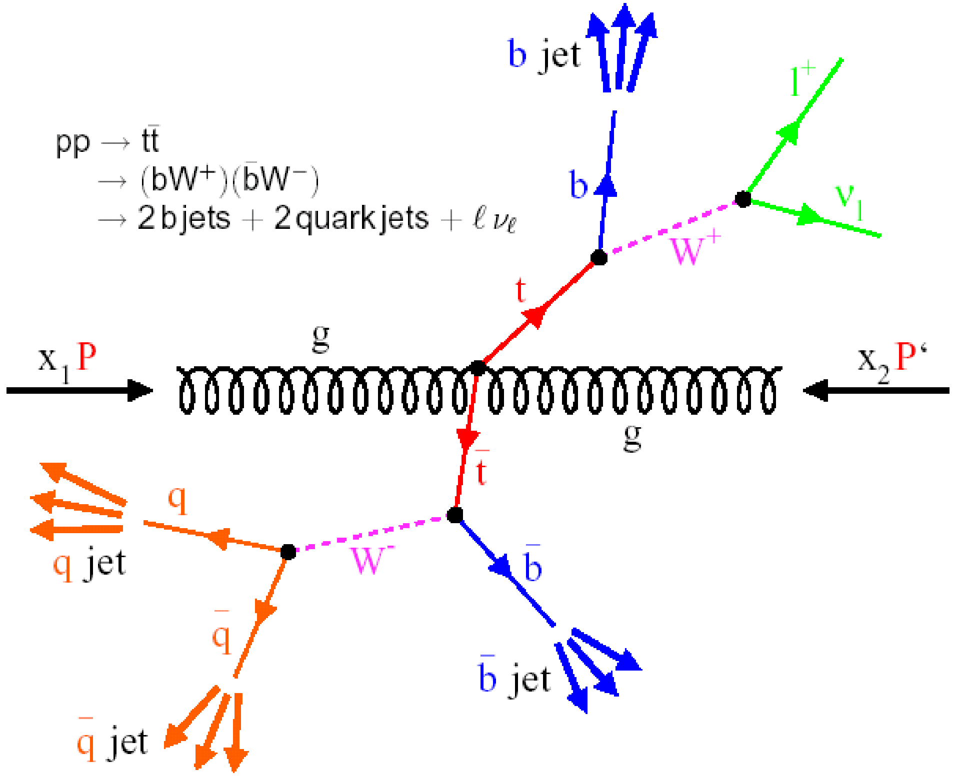


Top quark pair cross section

- high LHC energy
  - -> partons taken at low-x
  - -> gluon fusion dominates
- NLO x-sec 830pb







Top quark decay

- SM prediction: BR(t->Wb) ~1
- final state controlled by W decays

Top Quark Pair Decay Modes

Fully hadronic decay channel

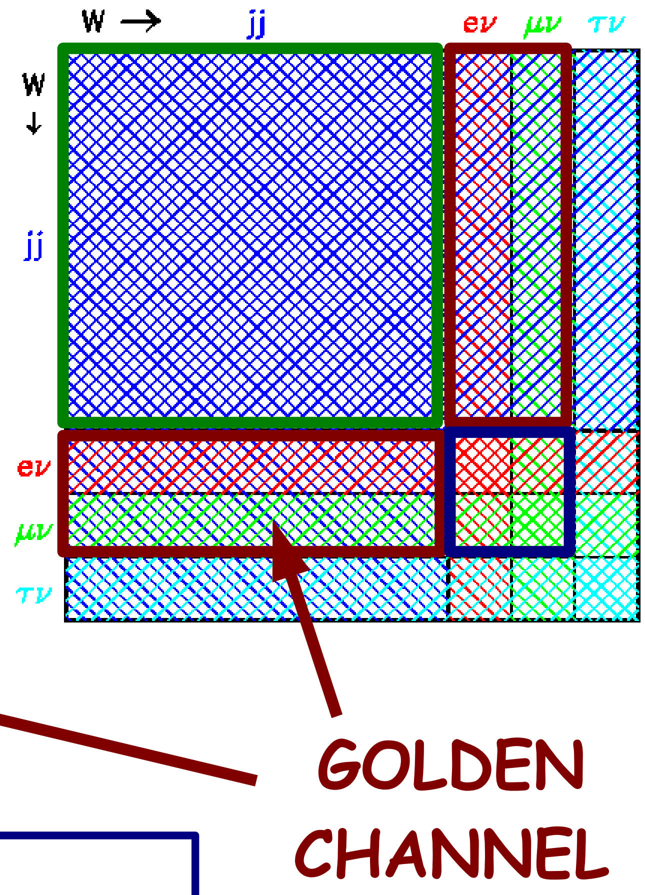
- 3.7M ev/10fb^{-1}
- main background: QCD multijet
- 6 jets E_T>40GeV, 2 b-tags

-> S/B ~ 1/19 for 2.7% eff.

Lepton + jets decay channel (e/mu)

- 2.5M ev/10fb^{-1}
- main background: W+multijet
- 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
- lepton (1|2) p_T>(35|25)GeV, MET>40GeV, 2 jets E_T>25GeV

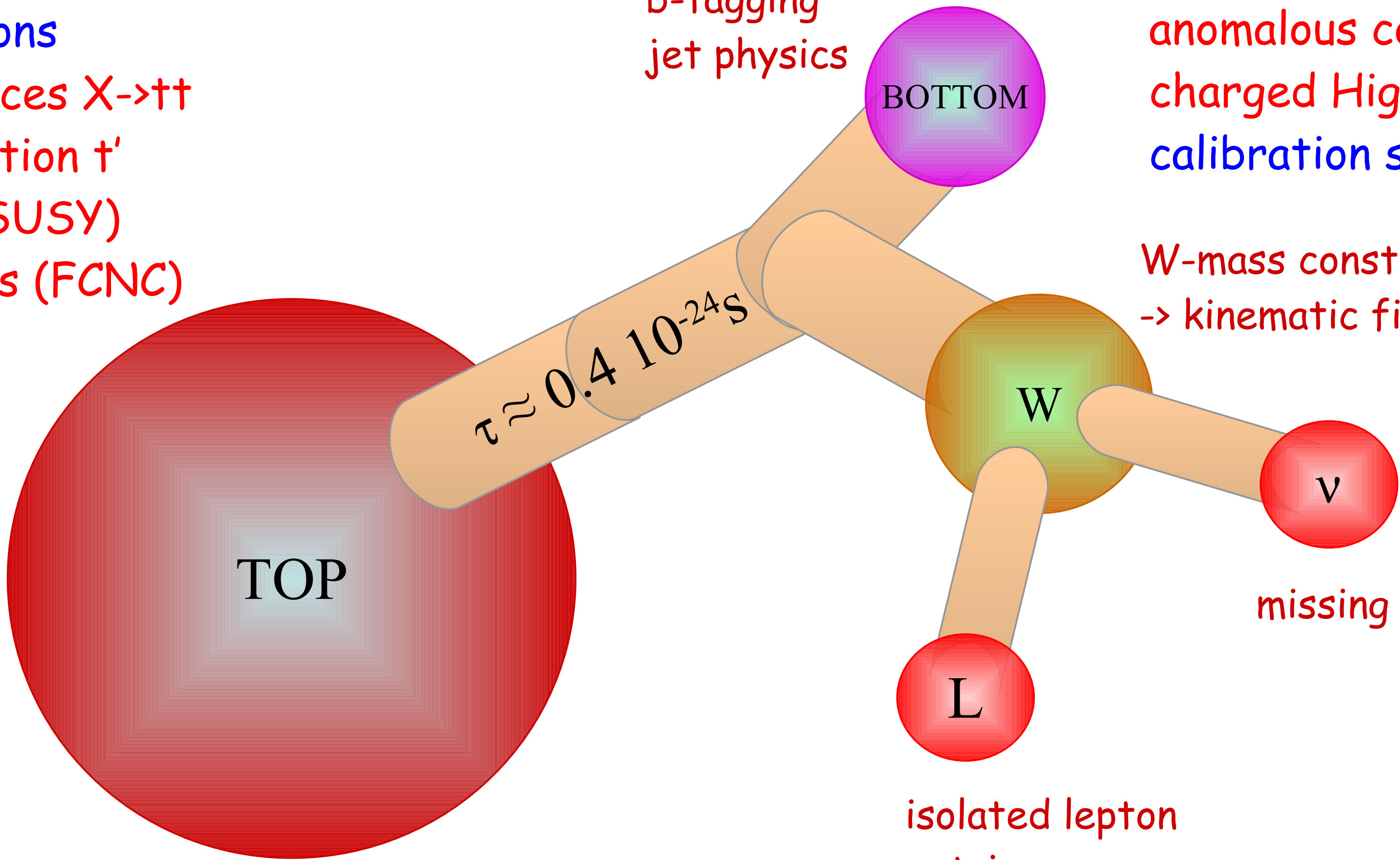
-> S/B ~ 10 for 20% eff.

Why all this Top-Fuzz?

PRODUCTION
- cross section - kinematics
- single top
- spin-correlations
- heavy resonances X->tt
- fourth generation t'
- new physics (SUSY)
- flavour physics (FCNC)

DECAY
- W helicity
- CKM matrix elements
- anomalous couplings
- charged Higgs
- calibration sample !!

b-tagging
jet physics



W-mass constraint
-> kinematic fit

missing energy

isolated lepton
-> trigger

PROPERTIES
- mass
- charge
- lifetime and width
- spin

Current CMS top results from Brussels

Reconstruction topics

- muon and electron identification in top events (CMS NOTE 2006/024)
- optimal jet reconstruction (Les Houches Proceedings hep-ph/0604120)
- kinematic fitting techniques in top events (CMS NOTE 2006/023)

Calibration topics

- jet energy scale calibration (CMS NOTE 2006/025)
- b-tag efficiency measurements on data (CMS NOTE 2006/013)

Physics topics

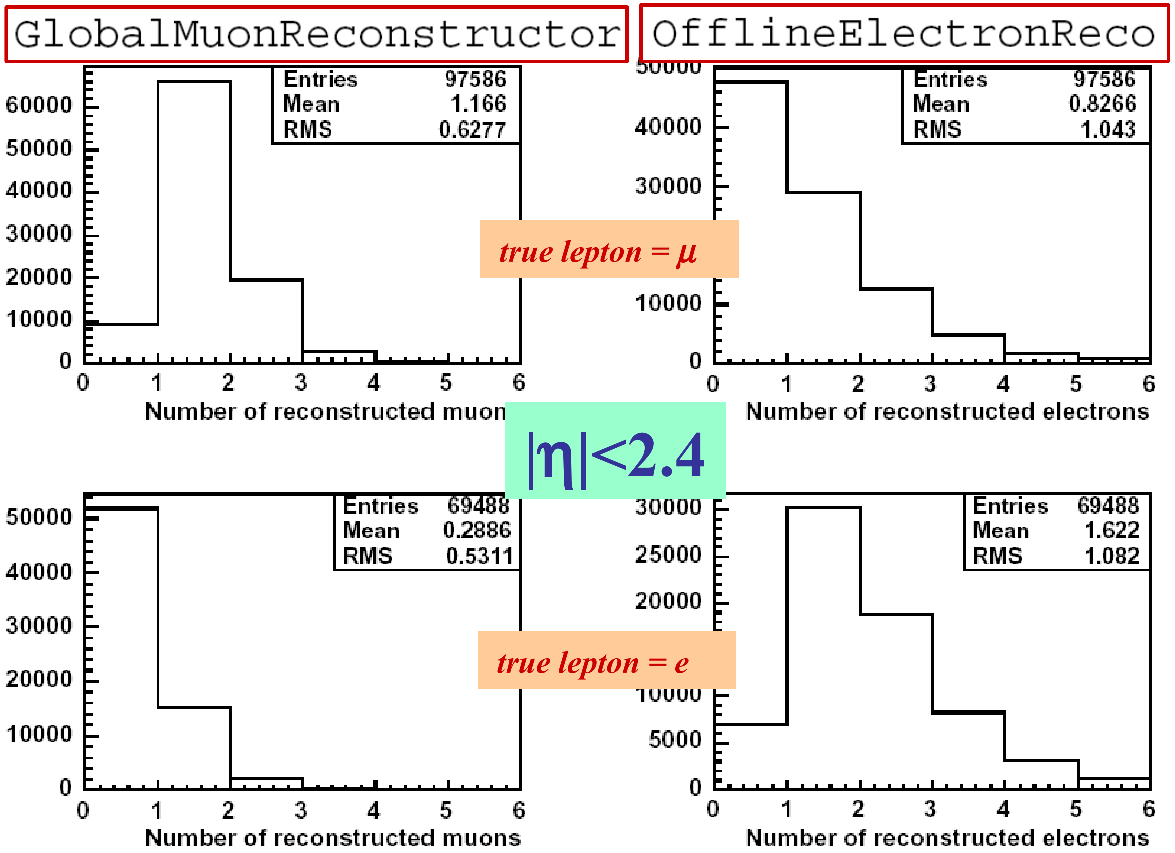
- top quark pair cross section in the lepton+jets channel (CMS NOTE 2006/064)
- top mass measurement in the lepton+jets channel (CMS NOTE 2006/066)
- same-charge top pair discovery potential (CMS NOTE 2006/065)

RECONSTRUCTION TOPICS

Muon and Electron Identification

Reconstruction of muons and electrons

- offline CMS reconstruction (ORCA) does not yield "physics quality" objects



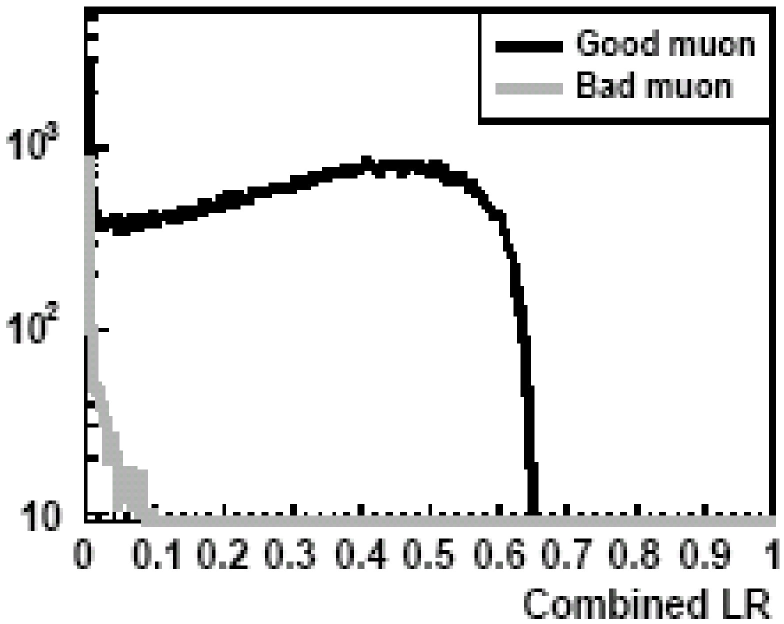
- aim 1: identify the 'true' lepton
- aim 2: build discriminator between W-like and QCD/fake leptons

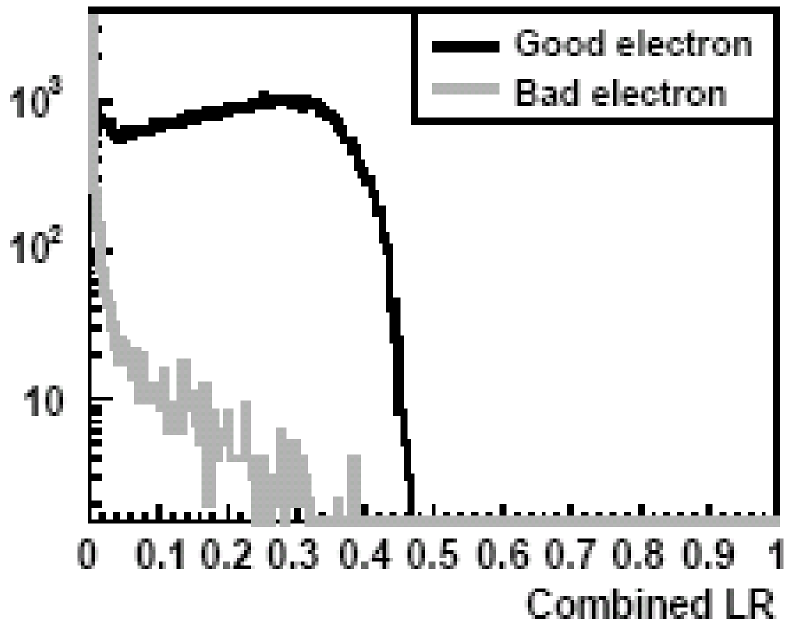
Identification of muons and electrons

- CMS NOTE 2006/024
- likelihood ratio method to distinguish between 'W-like' and QCD/fake electrons and muons
- sample dependent method: performed in lepton+jets $t\bar{t}$ events
- combination of likelihood ratio S/(S+B) of several observables into a global discriminator
    - transverse momentum
    - isolation energy (calo-towers)
    - isolation p_T (tracks)
    - isolation angle (minimum angle to jet)
    - association significance primary vertex
    - for electrons: reconstruction quality variable

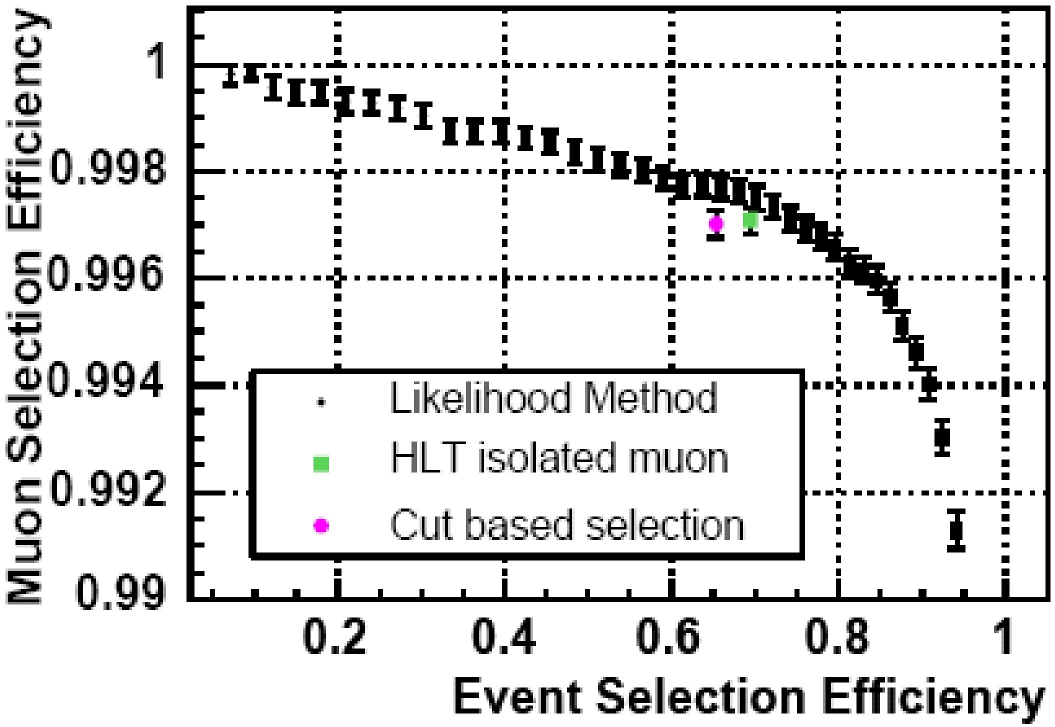
} backup slides for detail

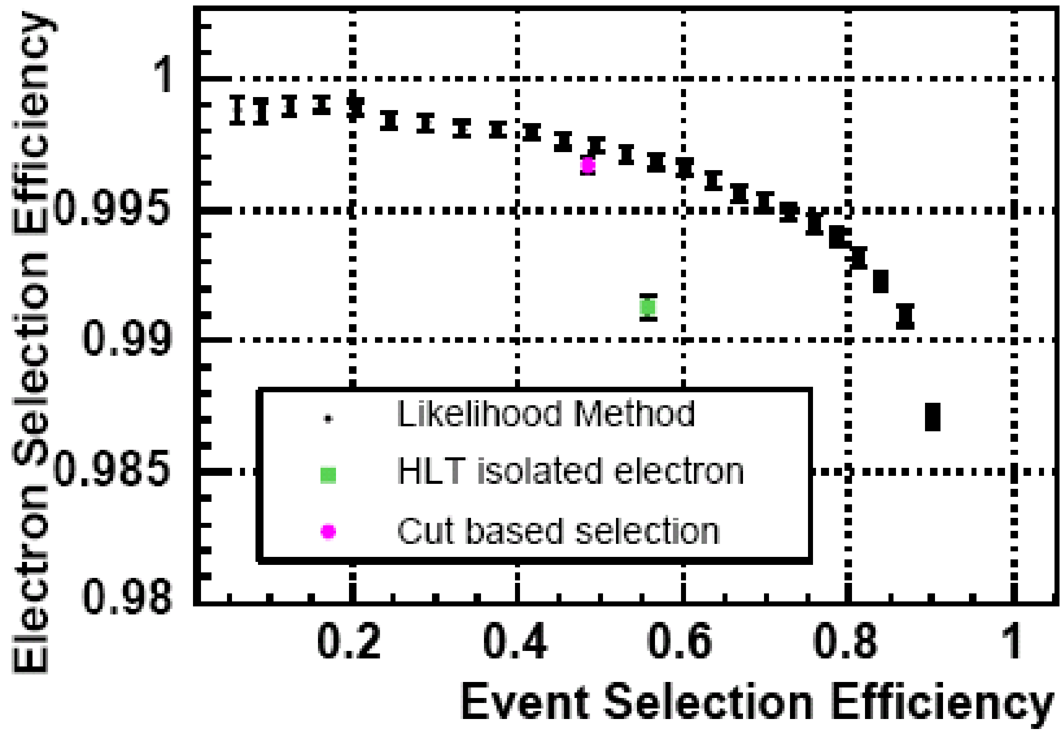
Combined likelihood ratio





Lepton identification efficiencies





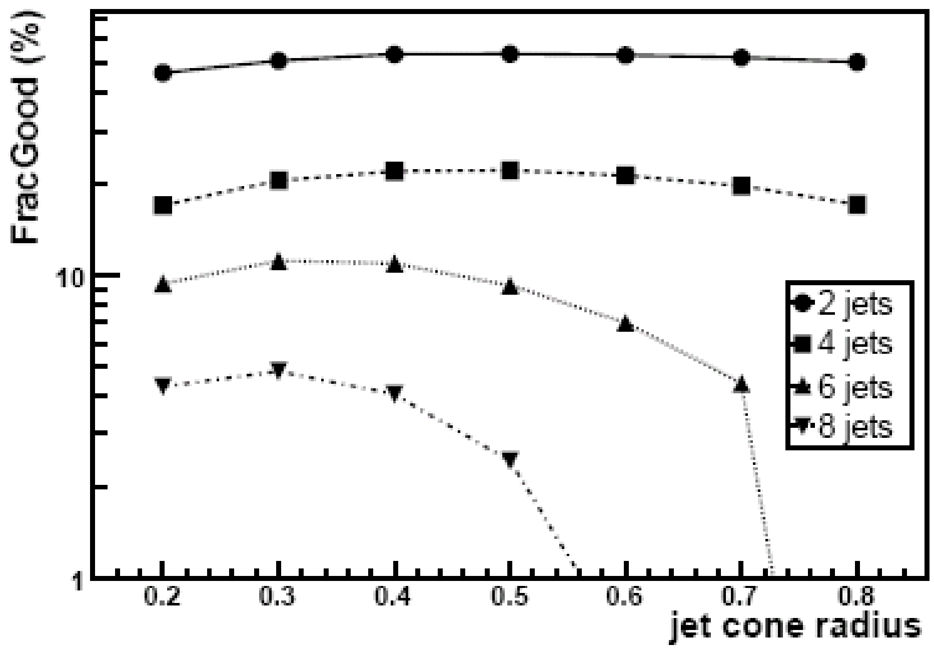
(cut based selection: set of hard cuts on previously defined variables)

Jet Clustering Optimization

Search for jet definition yielding optimal reconstruction

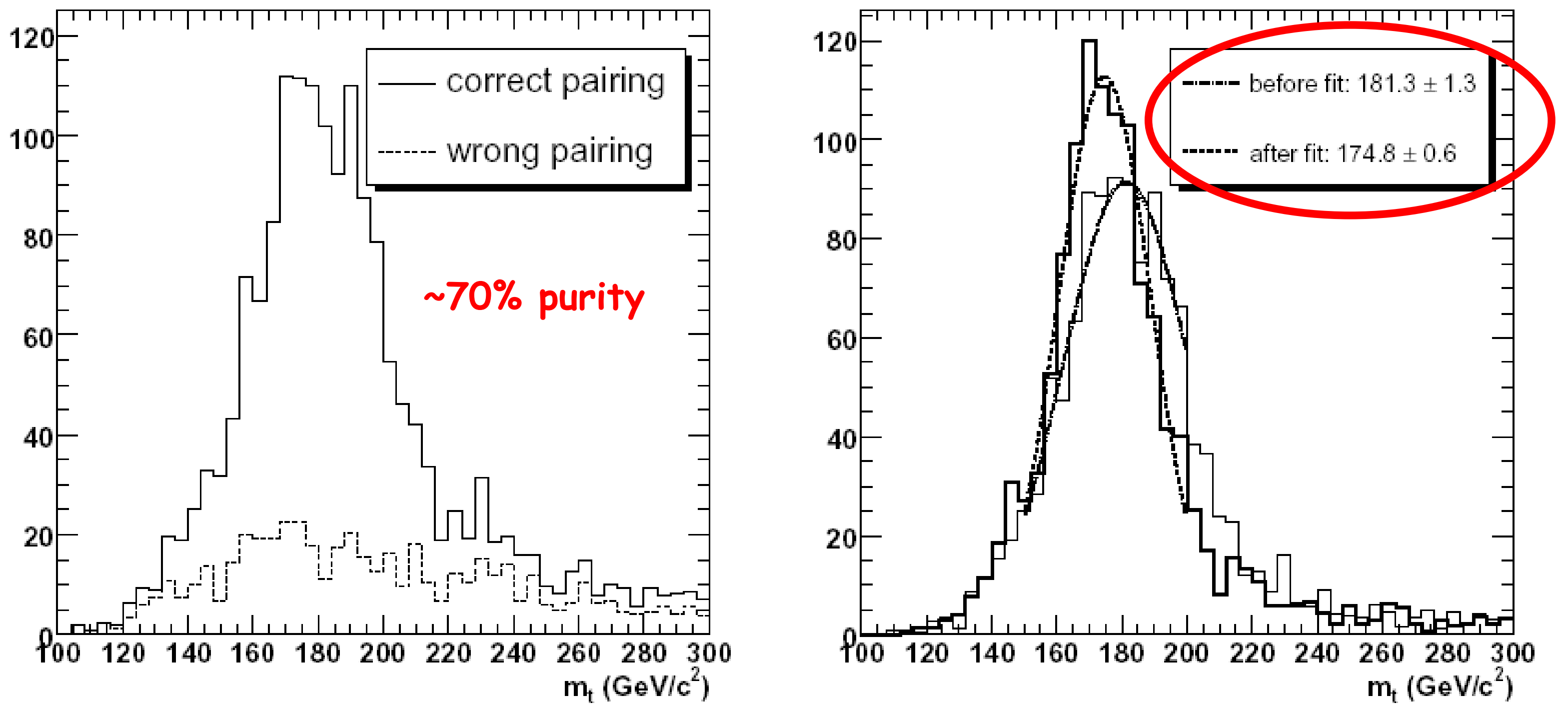
- Les Houches 2005 QCD, EW & Higgs Proceedings: hep-ph/0604120
- optimal jet clustering is looked for from an analysis point of view
  -> reconstruction efficiency is maximized
- optimization versus main algorithm parameters
- iterative cone, kT and midpoint cone algorithms considered
- top-like events with different jet environments considered:
  -> 2, 4, 6 and 8 jets

- example:
  fraction well clustered
  and selected jets versus
  cone ΔR for IC algorithm



Fitting event topologies applying kinematical constraints

- CMS NOTE 2006/023
- using kinematic fit techniques mass constraints can be enforced to the reconstructed event topology
- we used linearized Least-Square method with Lagrange multipliers
- example: top mass when W mass enforced in the t -> Wb -> qq'b decay

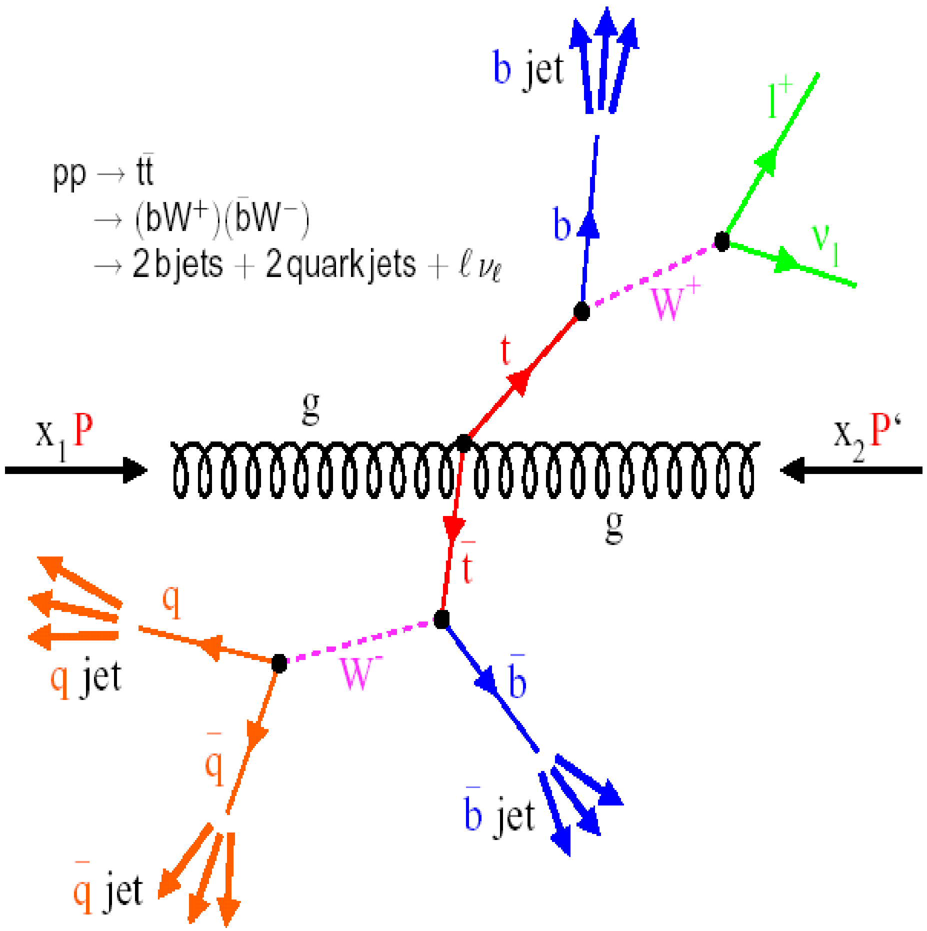


- to obtain the same precision without the fit, 5 times more data is needed!

CALIBRATION TOPICS

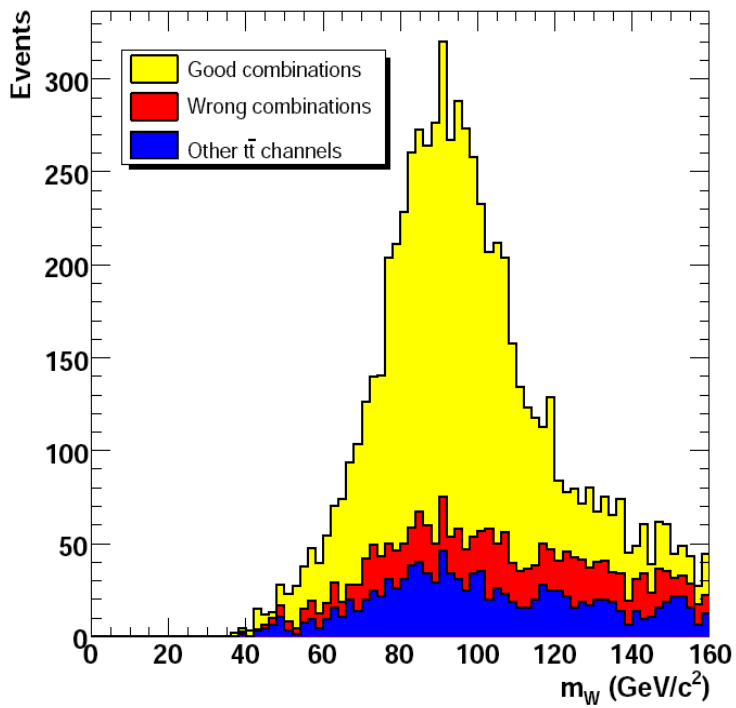
Why calibration with top events

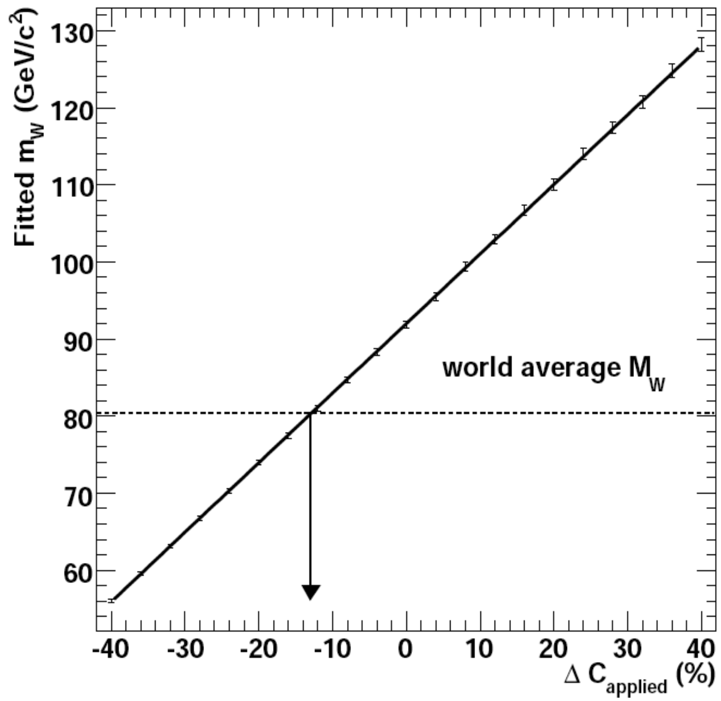
- lots of events + first day physics!
- controllable background
- many interesting objects
  - isolated muons and electrons
  - light and heavy flavour jets
  - missing energy
- constraints from W and top mass
- uses all parts of the detector
- interesting kinematical range



JES calibration with W-mass constraint in $t\bar{t}$ events

- CMS NOTE 2006/025 and Physics TDR Vol.I p. 428-431
- selection of muon/electron + 4 jets final state
- jets are (anti) b-tagged to identify jets from W decay without ambiguity
- reconstructed W mass from these jets is sensitive to Jet Energy Scale
- needed correction for true W mass scales linearly with initial miscalibration





Jet Energy Scale Calibration

JES calibration with W-mass constraint: results

- very small statistical uncertainty
  - 1 fb^{-1} : 0.6%
- very few systematic uncertainties
  - pile-up on-off: 3.08%
  - combinatorial background on-off: 0.13%
  - background from other tt-decays on-off: 0.17%
- in real life we will know systematics much better than on-off!

JES calibration: outlook

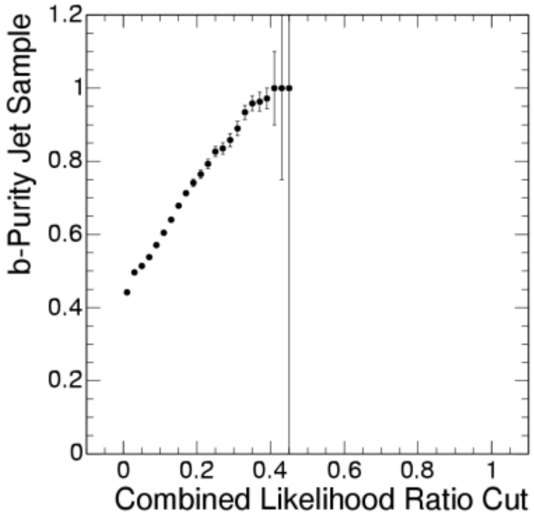
- inclusive results need to be differentiated
- robustness of the method: dependence on jet environment, jet definition?
- detailed understanding needed of pile-up and of interplay with JES
- get this method data-ready to deliver calibrations to CMS community

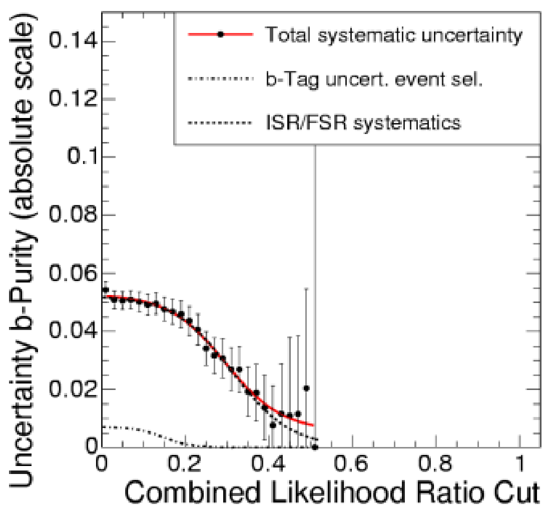
This will be the most important JES calibration method in CMS

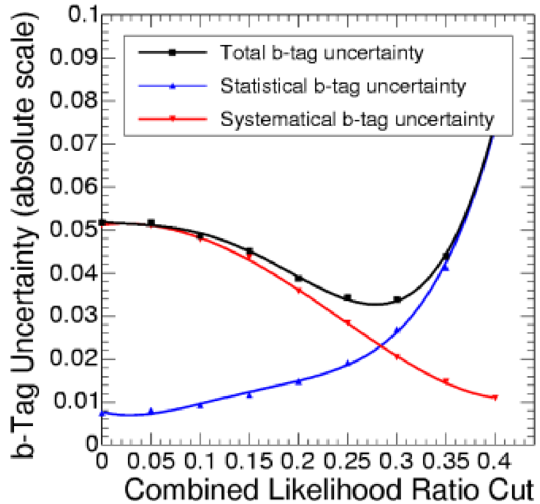
B-Tag Efficiency Measurement

b-Tagging efficiency measurement with $t\bar{t}$ events

- CMS NOTE 2006/013 and Physics TDR Vol.I p. 478-481
- method designed to measure b-jet tagging efficiency in jet samples from fully leptonic (e+mu) and semileptonic (e+jets and mu+jets) $t\bar{t}$ decays
- no use of tracker information for jet sample selection!
- minimization of total error by selecting a jet sample as pure in b jets as possible with given statistics
- b-, c- & udsg-content of the enriched jet sample is obtained from MC
- mistag rates also obtained from MC
- systematics currently dominated by initial/final state gluon radiation

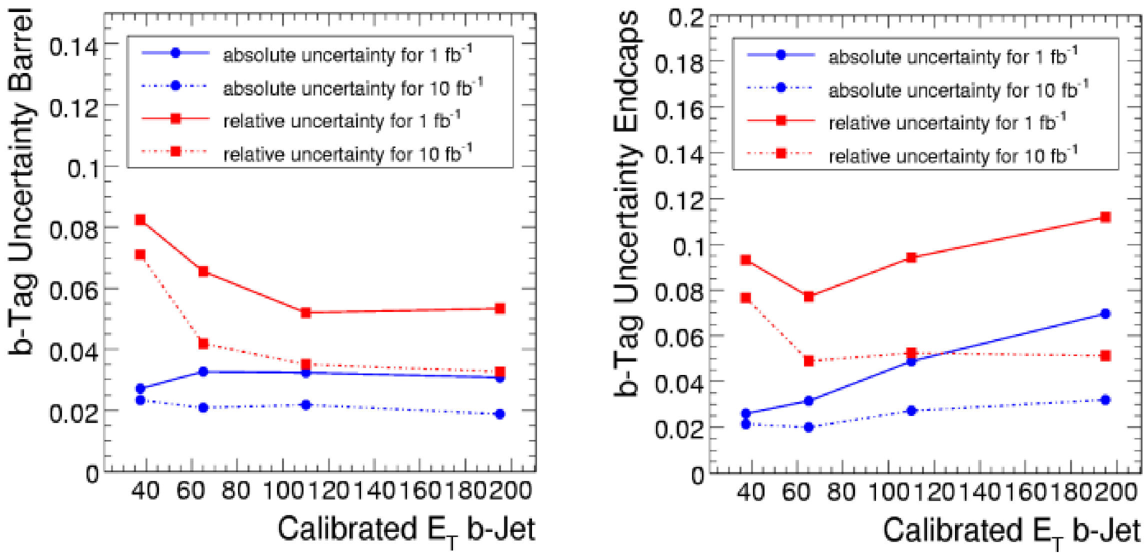






b-Tagging efficiency measurement with $t\bar{t}$ events: results

- differentiation performed vs. jet E_T and eta
- combined expected accuracies in barrel and endcaps:



b-Tagging calibration: outlook

- systematics are the difficulty: needs more “theoretical” understanding
- difficult work on interpretation of results has yet to start
- get this method data-ready to deliver calibrations to CMS community

This will be the most important b-tag calibration method in CMS

PHYSICS TOPICS

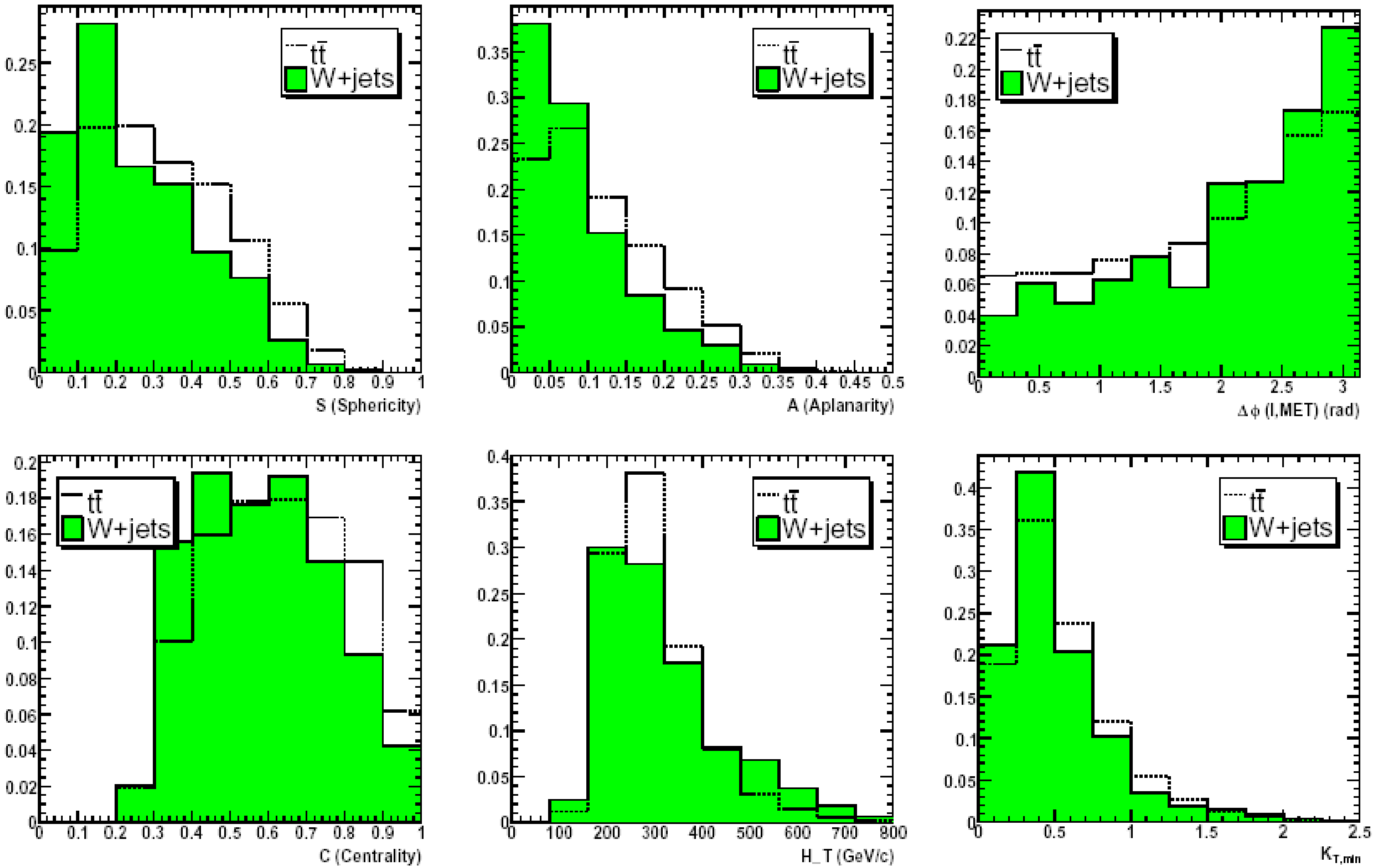
Event selection for cross section measurement

- CMS NOTE 2006/064 and Physics TDR Vol.II
- signal simulated with PYTHIA (+ full sim.)
- main background is W+jets
  - -> generated with AlpGen + ME/PS matching (+ fast sim.)
  - -> several exclusive final states taken into account
- QCD background is a difficult one to estimate... but can be neglected
- event selection kept simple, as every cut introduces extra systematics

	Signal	Other $t\bar{t}$	W+4j	Wbb+2j	Wbb+3j	S/N
Before selection	365k	1962k	82.5k	109.5k	22.5k	5.9
L1+HLT Trigger	62.2%	5.30%	24.1%	8.35%	8.29%	7.8
Pre-selection	45.8%	2.68%	11.7%	3.94%	5.91%	9.1
Four jets E_T >30 GeV	25.4%	1.01%	4.1%	1.48%	3.37%	9.9
p_T^{lepton} >20 GeV/c	24.8%	0.97%	3.9%	1.41%	3.14%	10.3
b-tag criteria	6.5%	0.24%	0.064%	0.52%	0.79%	25.4
Kinematic fit	6.3%	0.23%	0.059%	0.48%	0.72%	26.7
Selected cross section (pb)	5.21	1.10	0.10	0.08	0.05	26.7
Scaled L=1fb^{-1}	5211	1084	104	82	50	26.7

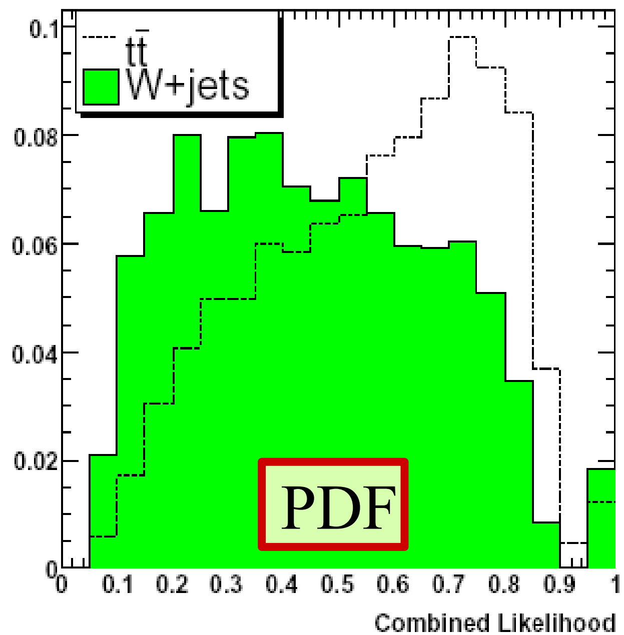
Method 1: use topological observables

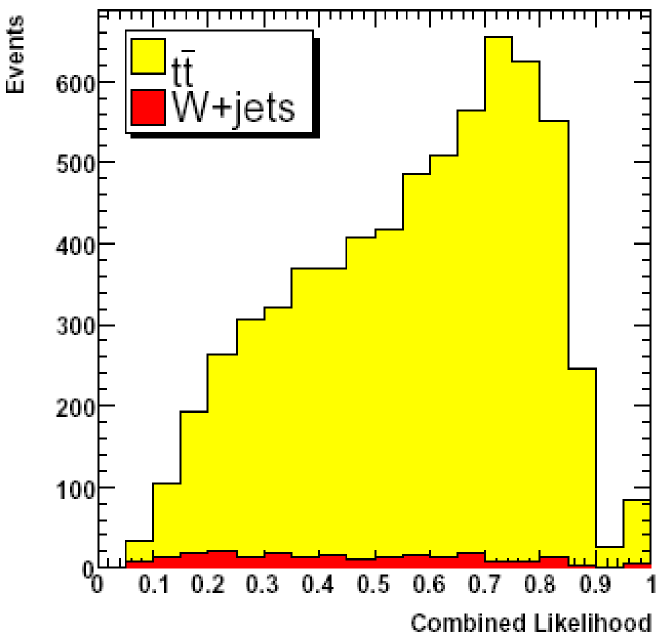
- choice of observables à la DØ...

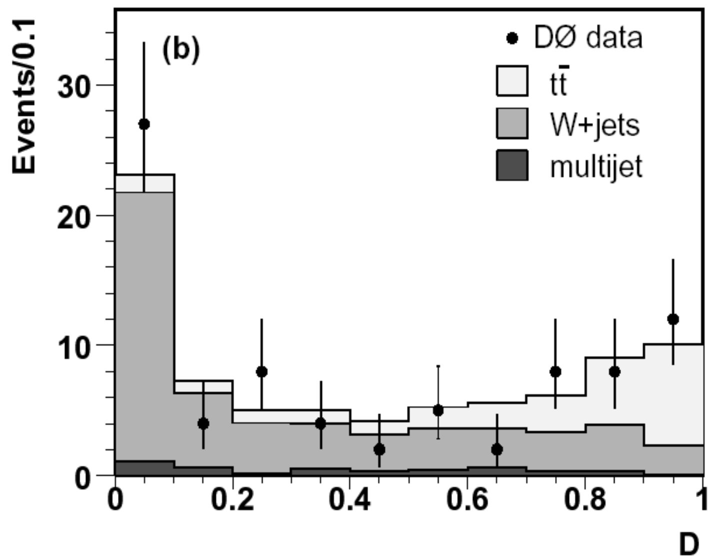


Method 1: construct discrimination variable

- combination of observables with likelihood ratio method
- idea of the method: fit signal & background simultaneously



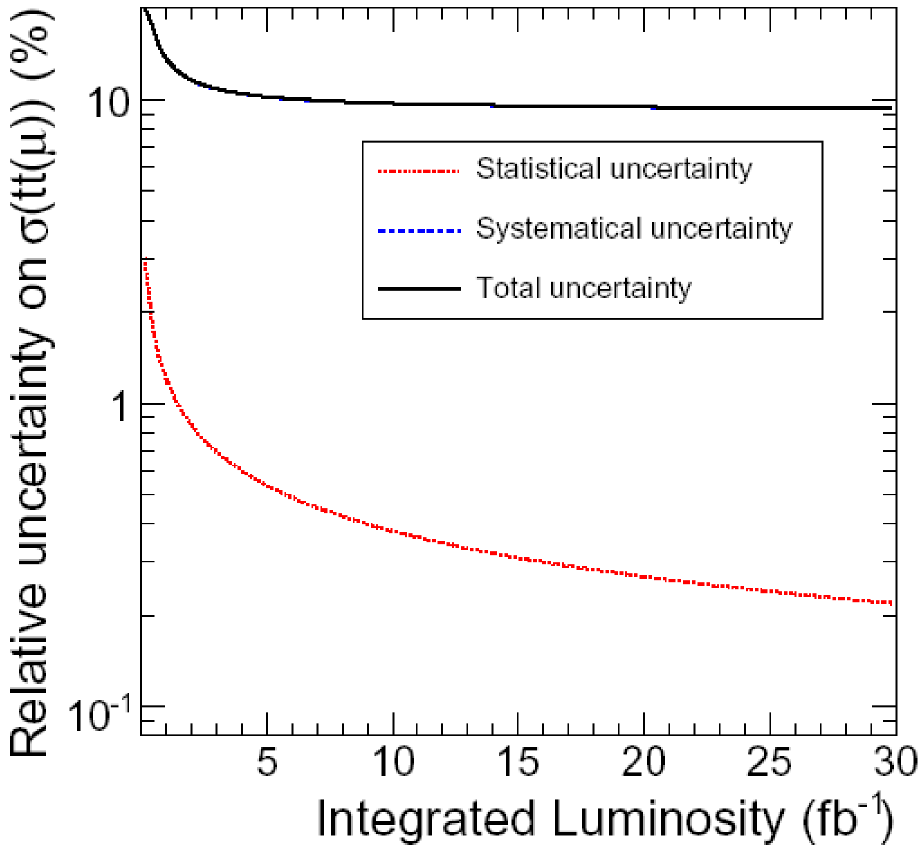




- not as much separation power as in DØ...
- not enough background to make simultaneous fitting idea work

Method 2: event counting

- systematics by far dominating
- CMS prescriptions applied



	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$
Simulation samples (ϵ_{sim})	0.6%
Simulation samples (F_{sim})	0.2%
Pile-Up	3.2%
Underlying Event	0.8%
Jet Energy Scale (light quarks)	1.6%
Jet Energy Scale (heavy quarks)	1.6%
Radiation	2.6%
Fragmentation	1.0%
b-tagging	7.0%
Parton Density Functions	3.4%
Integrated luminosity (1fb^{-1})	10%
Integrated luminosity (5fb^{-1})	5%
Integrated luminosity (10fb^{-1})	3%
Background level	0.9%
Statistical Uncertainty (1fb^{-1})	1.2%
Statistical Uncertainty (5fb^{-1})	0.6%
Statistical Uncertainty (10fb^{-1})	0.4%
Total Systematic Uncertainty (1fb^{-1})	13.6%
Total Systematic Uncertainty (5fb^{-1})	10.5%
Total Systematic Uncertainty (10fb^{-1})	9.7%
Total Uncertainty (1fb^{-1})	13.7%
Total Uncertainty (5fb^{-1})	10.5%
Total Uncertainty (10fb^{-1})	9.7%

Event selection for mass measurement

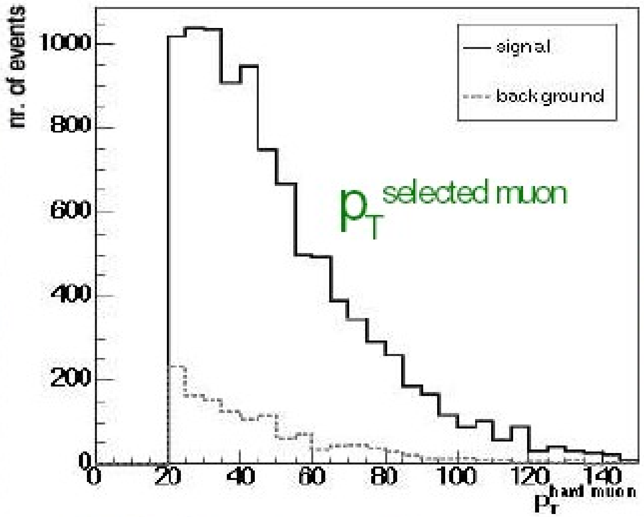
- CMS NOTE 2006/066 and Physics TDR Vol.II
- signal simulated with PYTHIA (+ full sim.)
- main background is W+jets
  - -> generated with AlpGen + ME/PS matching (+ fast sim.)
  - -> several exclusive final states taken into account
- more severe selection than for cross section

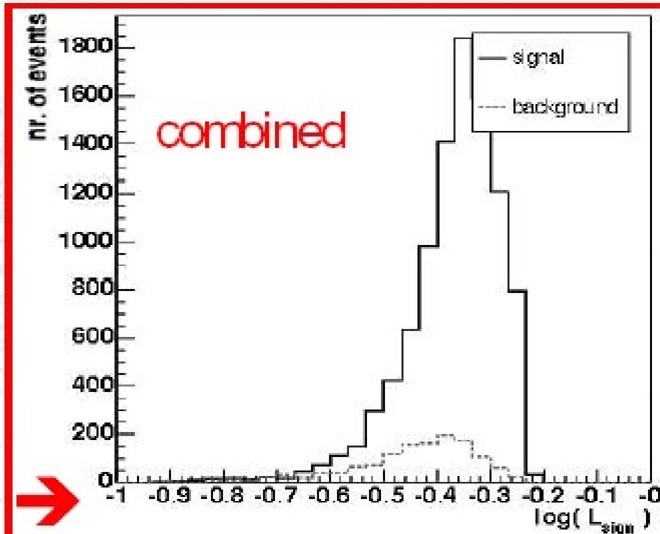
	Signal	Other $t\bar{t}$	W+4j	Wbb+2j	Wbb+3j	S/N
Before selection	365k	1962k	82.5k	109.5k	22.5k	0.032
L1+HLT Trigger	62.2%	5.30%	24.1%	8.35%	8.29%	0.74
Pre-selection	45.8%	2.68%	11.7%	3.94%	5.91%	1.10
Four jets E_T >30 GeV	25.4%	1.01%	4.1%	1.48%	3.37%	1.69
p_T^{lepton} >20 GeV/c	24.8%	0.97%	3.9%	1.41%	3.14%	1.72
b-tag criteria	5.5%	0.21%	0.052%	0.47%	0.70%	3.73
No jet overlap	3.0%	0.11%	0.027%	0.25%	0.44%	3.87
P_{χ^2}-cut 20%	1.4%	0.039%	0.0097	0.061	0.07	5.3
P_{sign}-cut 80%	1.2%	0.025%	0.0085	0.052	0.05	6.8
P_{comb}-cut 50%	0.7%	0.013%	0.0036	0.013	0.	8.2
Scaled L=1fb^{-1}	588	64	6	2	0	8.2

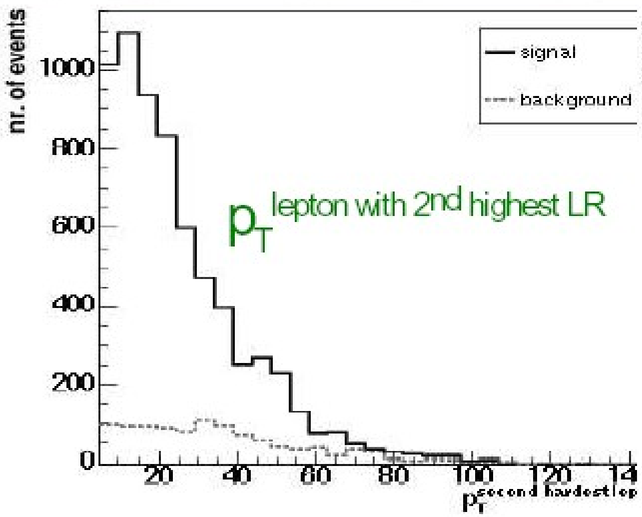
Top Quark Mass Measurement

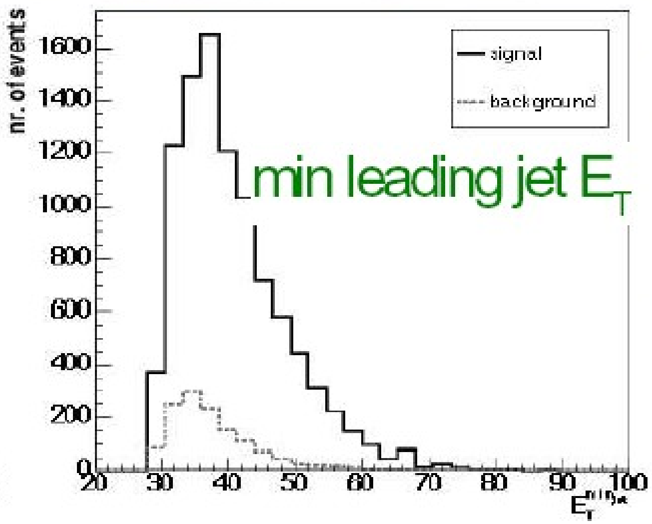
A likelihood ratio method was constructed to define a probability that a certain event is the result of a semi-leptonic muon decay (signal) compared to other ttbar-decay channels.

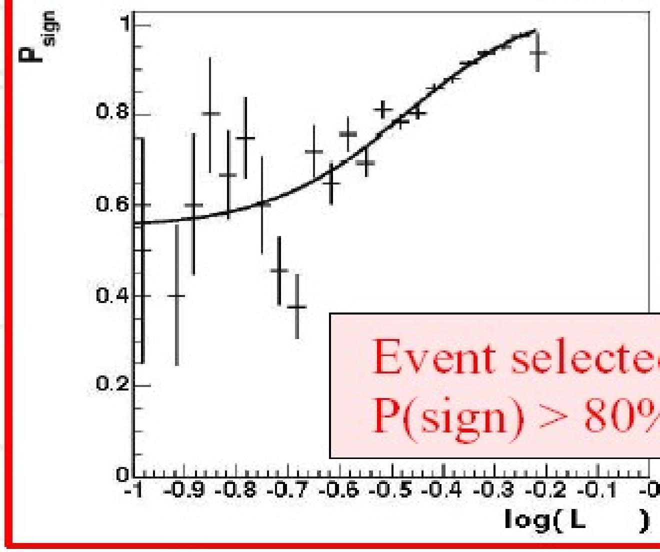
The information of 3 observables was combined











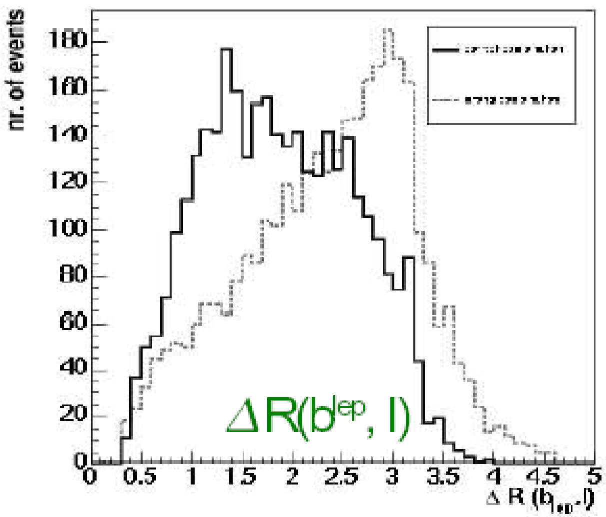
Event selected if P(sign) > 80%

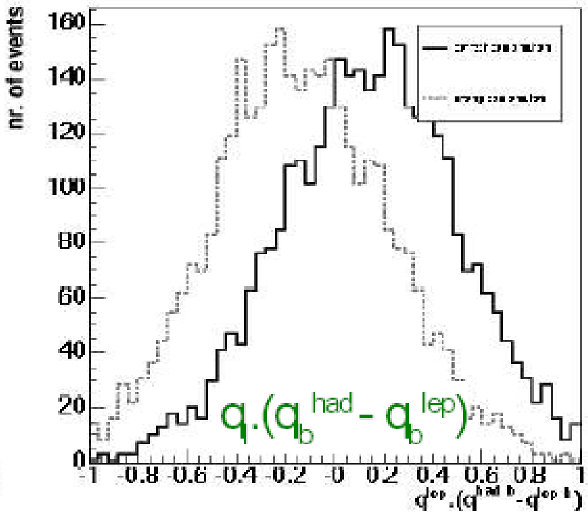
Top Quark Mass Measurement

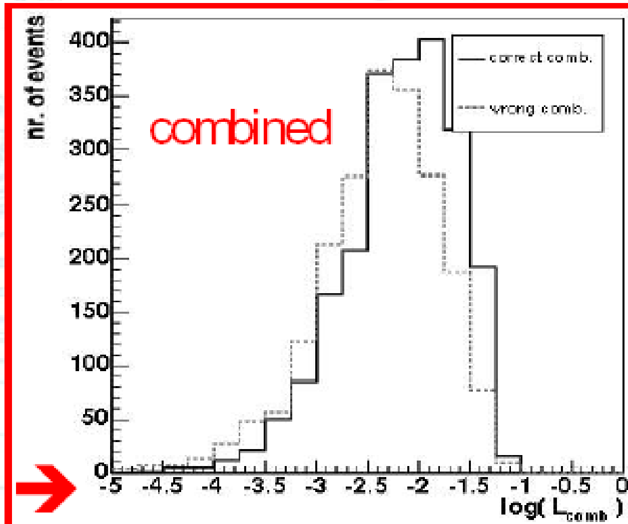
only 2 jet combinations left after hard b-tag criteria: which b-jet is the hadronic top one?

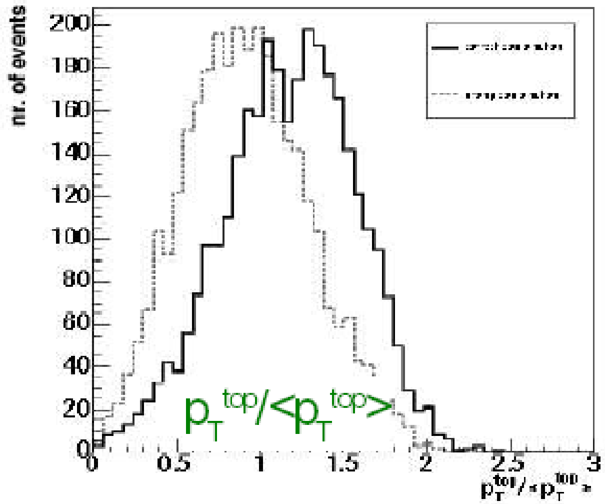
⇨ Likelihood Ratio discriminant developed with four observables:

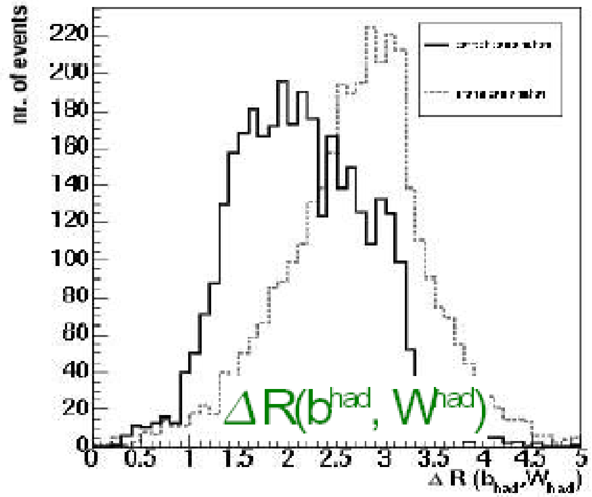
(solutions of events without good jet-parton matching considered as comb. bgr.)

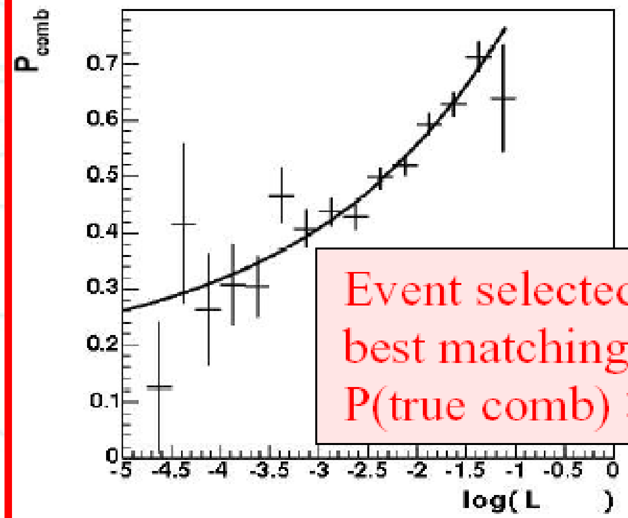












Event selected if best matching has P(true comb) > 50%

Top Quark Mass Measurement

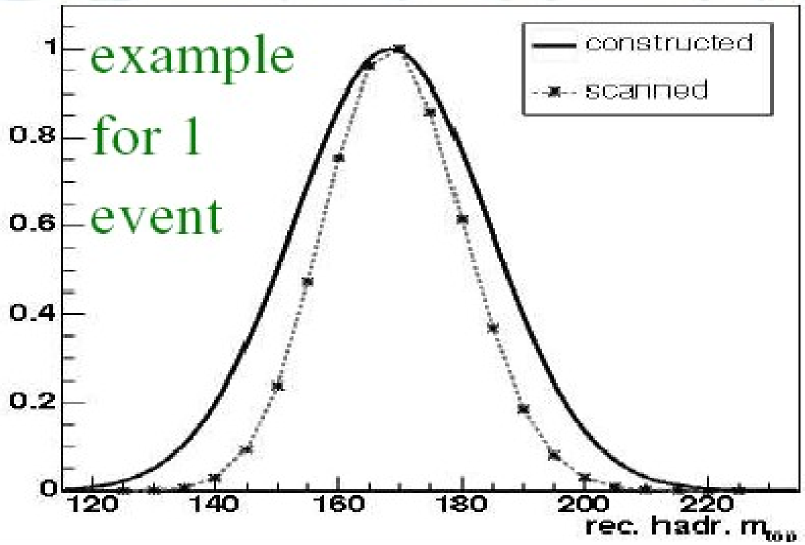
For each event one can define an ideogram $I(\{p_i\}|m_{top})$ as a probability function to observe the measured parameters $\{p_i\}$ given a certain mass m_{top}.

This ideogram can be assumed gaussian, with δm_{fit} calculated from the (fitted) jet covariance matrices:

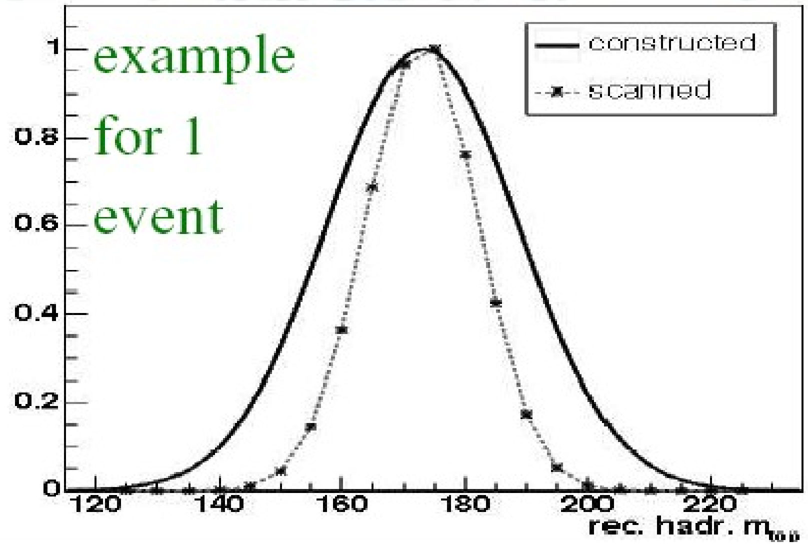
$$I(\{p_i\}|m_{top}) \sim \exp[-0.5\ (m_{fit} - m_{top})^2/(\delta m_{fit})^2]$$

or can be scanned imposing different m_{top} hypotheses as an extra constraint in the fit:

$$I(\{p_i\}|m_{top}) \sim \{P_{mtop}(\chi^2)\} \quad \text{with } m_{top} = 125, 130, \ldots, 225\ \text{GeV/c}^2$$



inclusion of b-jet kinematics in kinfit results in better ideogram resolution



Top Quark Mass Measurement

To change from the experimental space of m_{top} to the theoretical space of M_{top}, the ideogram of an event is convoluted with a theoretically expected template function $T(m_{top}|M_{top})$:

$$L_i(M_{top}) = \int I(\{p_i\}|m_{top}) \, . \, T(m_{top}|M_{top}) \, dm_{top}$$

with

$$T(m_{top}|M_{top}) = P^{signal} \, . \, [\, P^{comb}.BW(m_{top}|M_{top}) + (1-P^{comb}).B^{comb}(m_{top}) \,] + (1 - P^{signal}) \, . \, B^{channel}(m_{top})$$

where

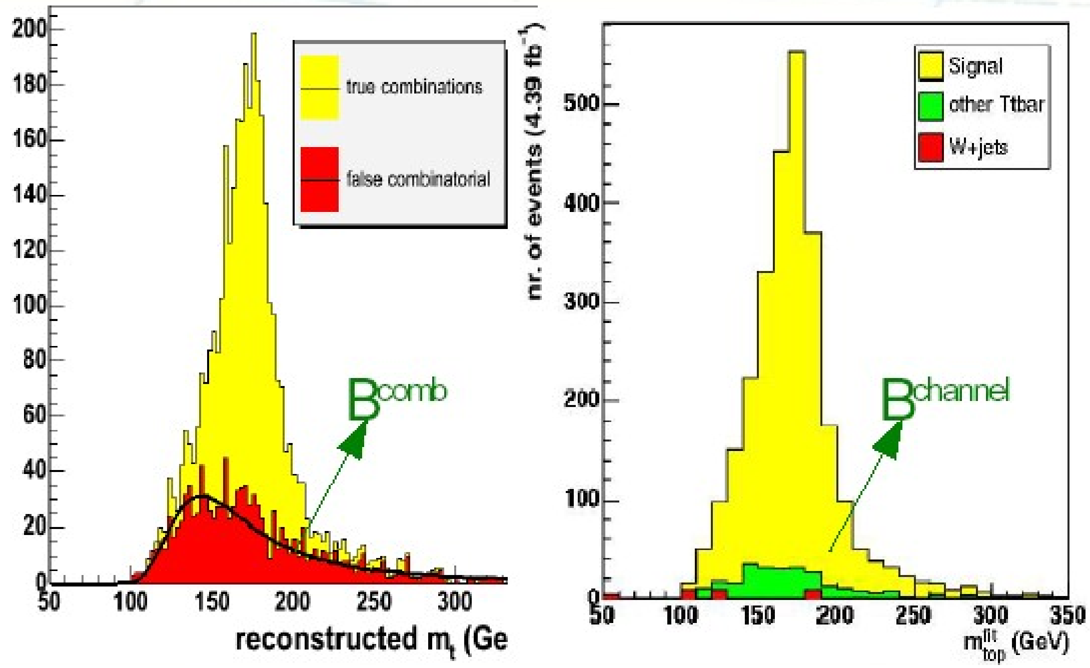
P^{signal} = P(signal event)

P^{comb} = P(true jet combination)

Finally, all event Likelihoods are combined

$$L_{tot}(M_{top}) = \Pi_i \, L_i(M_{top})$$

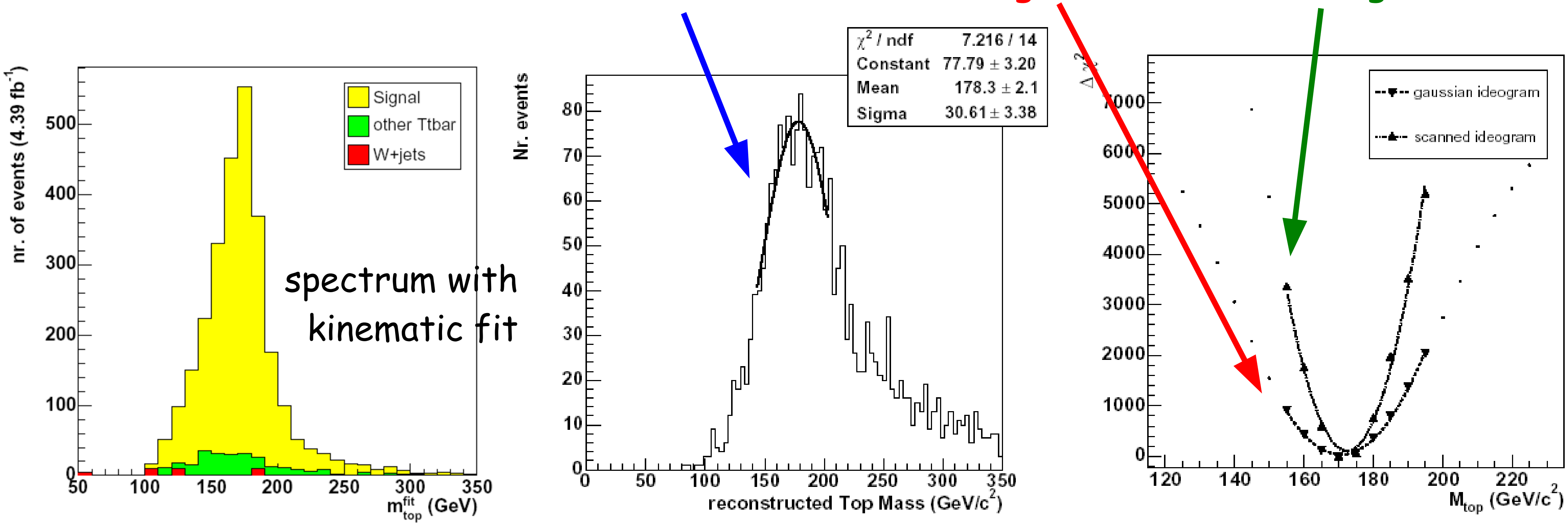
and the minimum of $-2 \ln L = \chi^2$ extracted...



Top mass estimators

- three estimators compared:

-> Gaussian fit, Gaussian ideogram, full scan ideogram



	Gaussian Fit	Gaussian Ideogram	Full Scan Ideogram
Bias (GeV/c^2)	-0.84±0.59	-4.35±0.54	-2.58±0.31
Pull	0.82	1.01	1.01
Expected uncertainty for 1fb^{-1} (GeV/c^2)	1.01	1.14	0.66
Expected uncertainty for 10fb^{-1} (GeV/c^2)	0.32	0.36	0.21

Systematic uncertainties

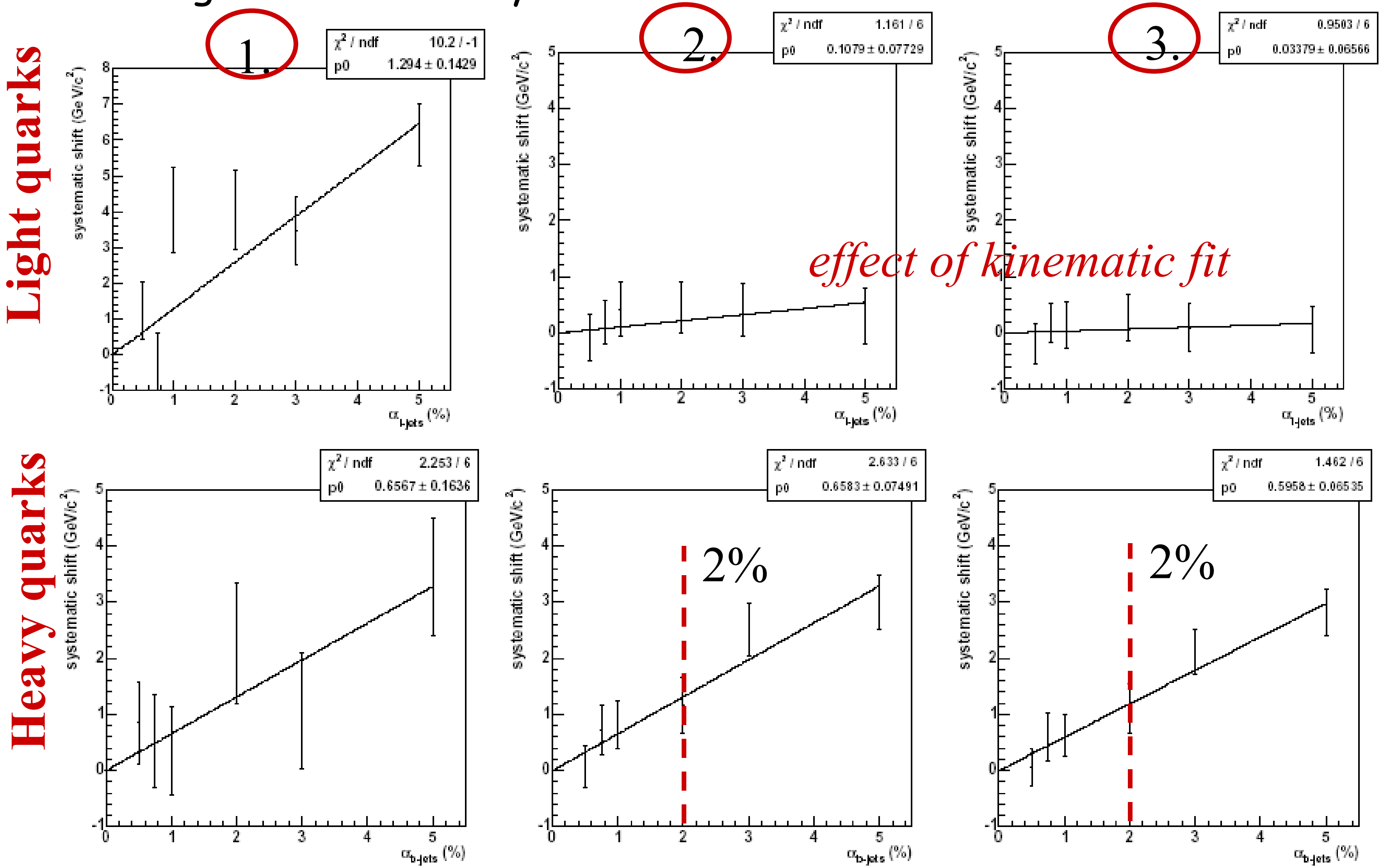
- many systematic influences were checked according to CMS prescriptions
- effect of light and b-jet energy scale added linearly
- statistical uncertainty on shifts very small due to large MC samples

	Standard Selection			Alternative Selection
	Gaussian Fit Δm_t (GeV/c)	Gaussian Ideogram Δm_t (GeV/c)	Full Scan Ideogram Δm_t (GeV/c)	Full Scan Ideogram Δm_t (GeV/c)
Pile-Up ***(30% On-Off)***	1.9	1.4	1.2	1.2
Underlying Event	1.0	0.7	0.5	0.5
Jet Energy Scale ***(2%)***	3.8	1.5	1.3	1.2
Radiation (pQCD)	0.8	0.3	0.2	0.2
Fragmentation	0.4	0.4	0.3	0.3
b-tagging ***(5%)***	2.0	0.5	0.3	0.3
Background	0.4	0.4	0.4	0.4
Parton Density Functions	0.1	0.1	0.1	0.1
Total Systematical uncertainty	4.9	2.3	1.9	1.9
Statistical Uncertainty ($10 fb^{-1}$)	0.32	0.36	0.21	0.31
Total Uncertainty	4.9	2.3	1.9	1.9

only using events where iterative cone, kT and midpoint cone jets coincide

JES systematics

- detail on light and b-JES systematics



Top Quark Mass Measurement

Systematics projected in time

- main uncertainty from b-jet energy scale

	Standard Selection			Alternative Selection
	Gaussian Fit	Gaussian Ideogram	Full Scan Ideogram	Full Scan Ideogram
	Δm_t (GeV/c^2)	Δm_t (GeV/c^2)	Δm_t (GeV/c^2)	Δm_t (GeV/c^2)
Pile-Up ***(5% On-Off)***	0.32	0.23	0.21	0.21
Underlying Event	0.50	0.35	0.25	0.25
Jet Energy Scale ***(1.5%)***	2.90	1.05	0.96	0.90
Radiation (pQCD)	0.80	0.27	0.22	0.20
Fragmentation	0.40	0.40	0.30	0.30
b-tagging ***(2%)***	0.80	0.20	0.18	0.18
Background	0.30	0.25	0.25	0.25
Parton Density Functions	0.12	0.10	0.08	0.10
Total Systematical uncertainty	3.21	1.27	1.13	1.07
Statistical Uncertainty (10fb^{-1})	0.32	0.36	0.21	0.31
Total Uncertainty	3.23	1.32	1.15	1.11

1 GeV uncertainty can be reached with a good detector understanding

(this will be a flagship analysis in early and later LHC days)

Same-Charge Top Pair Visibility

Looking for an excess of SM same charge top pair expectation

- CMS NOTE 2006/065 and Physics TDR Vol.II
- corresponds to search for same-charge signal with same kinematics
- three fully leptonic final states considered: mu+mu, e+mu and e+e
- perform easy selection, using the powerful lepton likelihood:

scaled to 1fb^{-1}	$\mu\mu$	μe and ee	$t\bar{t} \to \tau + X$	Other $t\bar{t}$	$W^{\pm}W^{\mp}$	$Z + jets$	S/N
Before selection	6915.0	20745.0	34606.2	485973.2	189951.7	578033.3	0.0078
Trigger	6114.7	16314.8	17415.6	100137.2	41288.4	266366.7	0.017
Two jets E_T >25 GeV	4398.2	11982.7	13560.9	93858.2	20593.8	66146.7	0.032
b-tag criteria	989.8	2485.4	2289.6	8784.7	133.5	240.0	0.13
Two leptons identified	888.2	30.1	375.8	801.6	1.7	73.3	1.30
Two leptons selected (LR and p_T)	481.5	0.07	48.4	3.01	0.4	53.3	4.7
Efficiency (in %)	6.96	0.0003	0.14	0.0006	0.00022	0.0092	
Opposite-sign	481.3	0	48.3	2.19	0	53.3	
Same-sign	0.2	0.07	0.1	0.82	0.4	0	

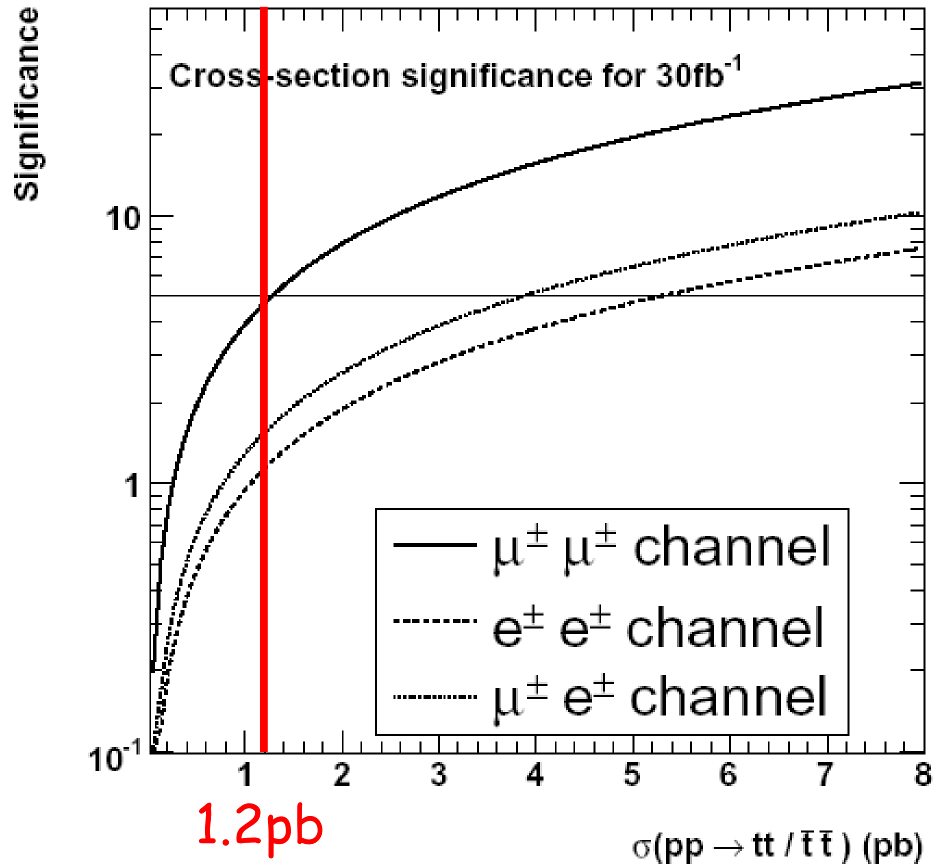
- "wrong" charged leptons can be fakes or charge mis-id'd leptons
- e+e and e+mu final states have many more fakes from electrons

Calculation of the same-sign/opposite sign ratio

$$R = \frac{N_{++,--}}{N_{+-}}$$

- results: $R^{\mu\mu} = 0.0027 \pm 0.0007$
  $R^{ee} = 0.0389 \pm 0.0033$
  $R^{e\mu} = 0.0128 \pm 0.0013$

significance vs. SS tt x-sec.



Discovery reach

- discovery when 5σ deviation from expected value R
- systematics from taus or Z+jets uncertainties negligible
- back-of-the-envelope: no systematics expected from knowledge of charge mis-id

Conclusions

- current Brussels top quark achievements are diverse,
  but all profit from common tools and know-how, technical and physics-wise

- reconstruction topics of top quark events
  lepton identification, optimal jet reconstruction, kinematic fitting
- calibration topics in top quark events
  jet energy scale calibration, b-tag efficiency measurements
- physics topics in top quark events
  top pair cross section, top mass measurement, same sign top visibility

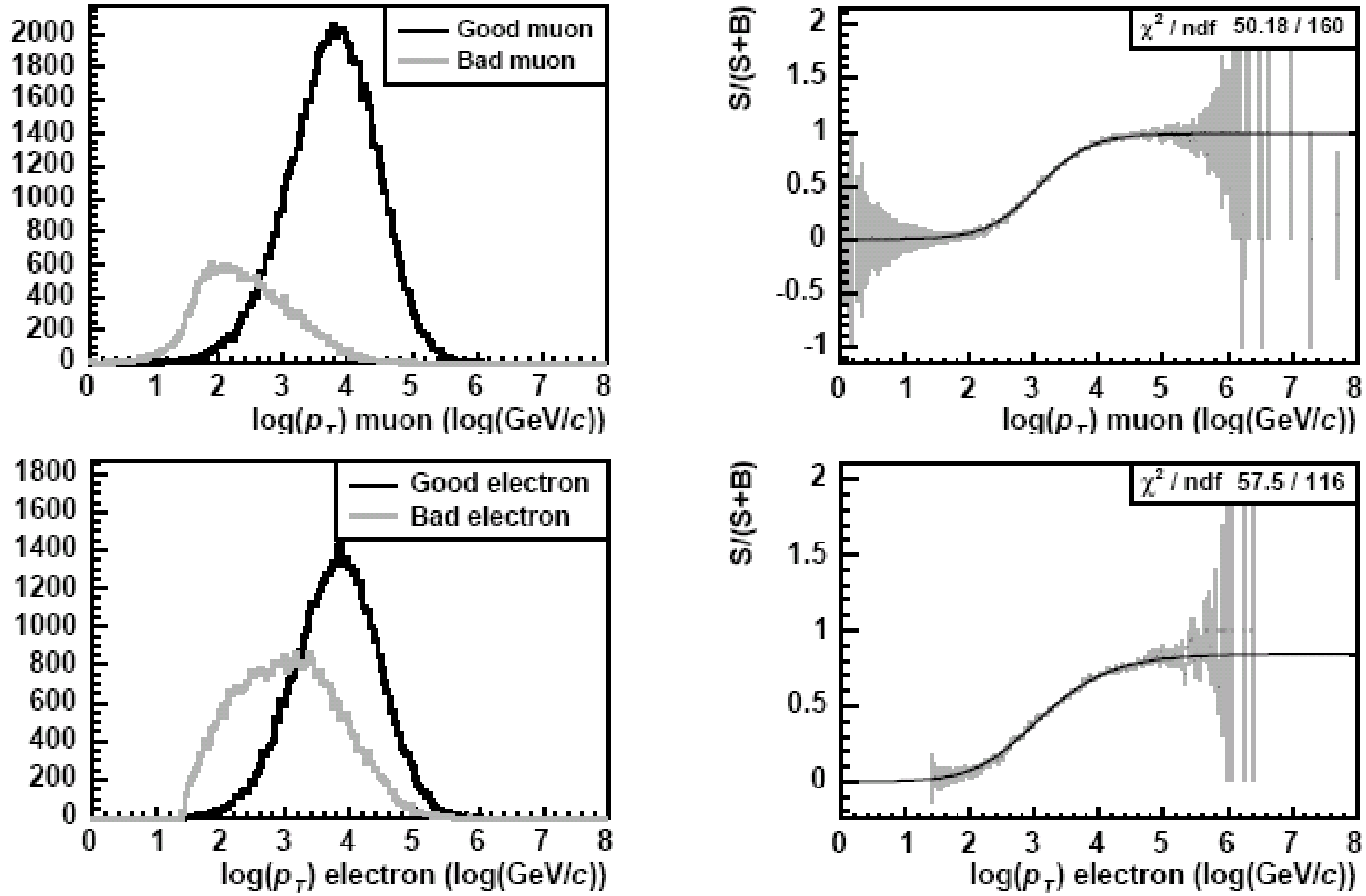
- all results published in CMS Notes and Physics TDR Vol. I & II

Thank you!

BACKUP
SLIDES

Transverse momentum

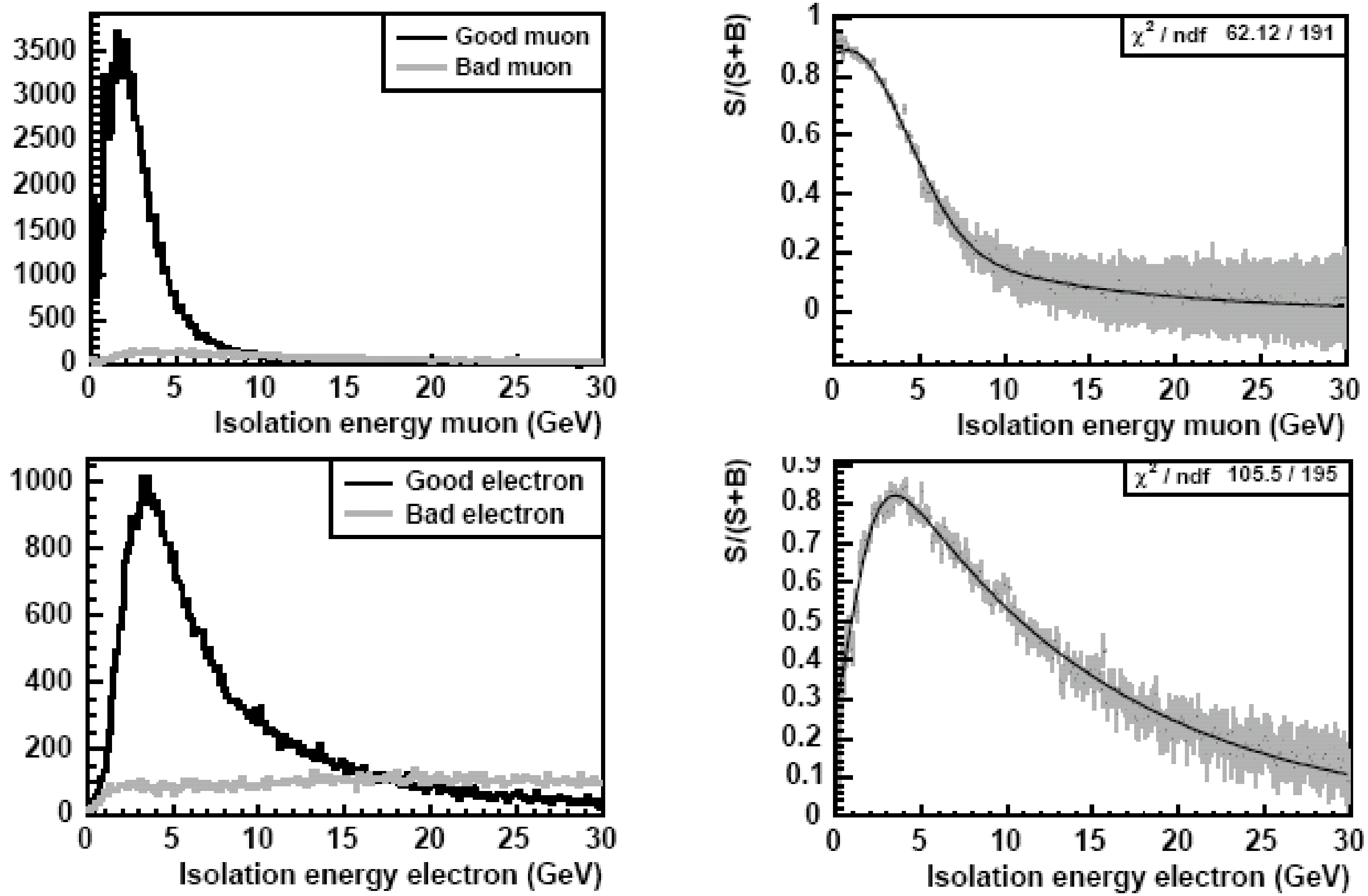
- logarithm of the transverse momentum of the lepton



Lepton Identification Variables

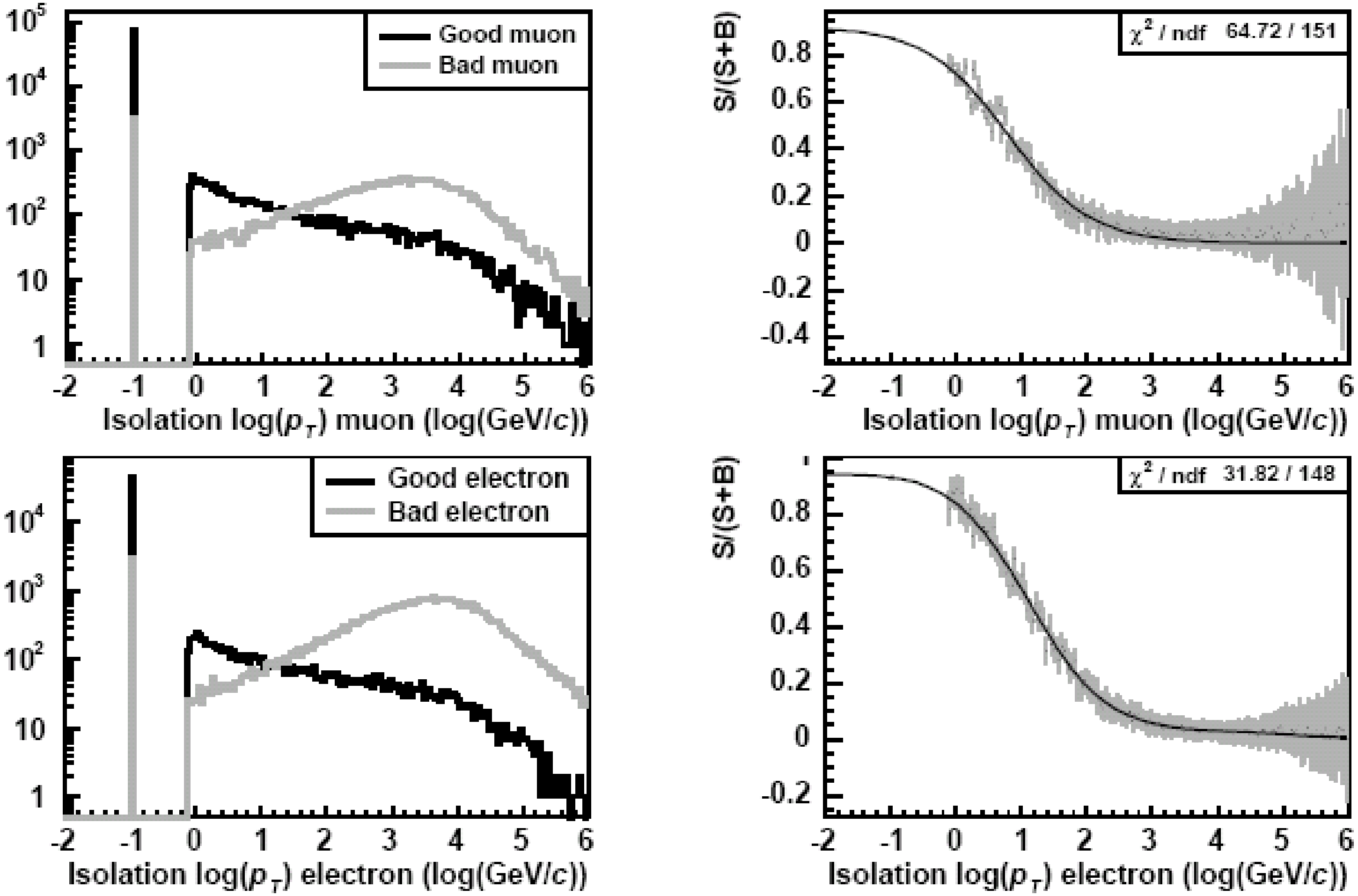
Isolation energy

- energy deposited in ECAL+HCAL in a half cone $\Delta R=0.3$ around the impact point of the lepton on the calorimeter surface
- the half cone taken at ϕ-side where more neutrals from a jet are expected



Isolation p_T

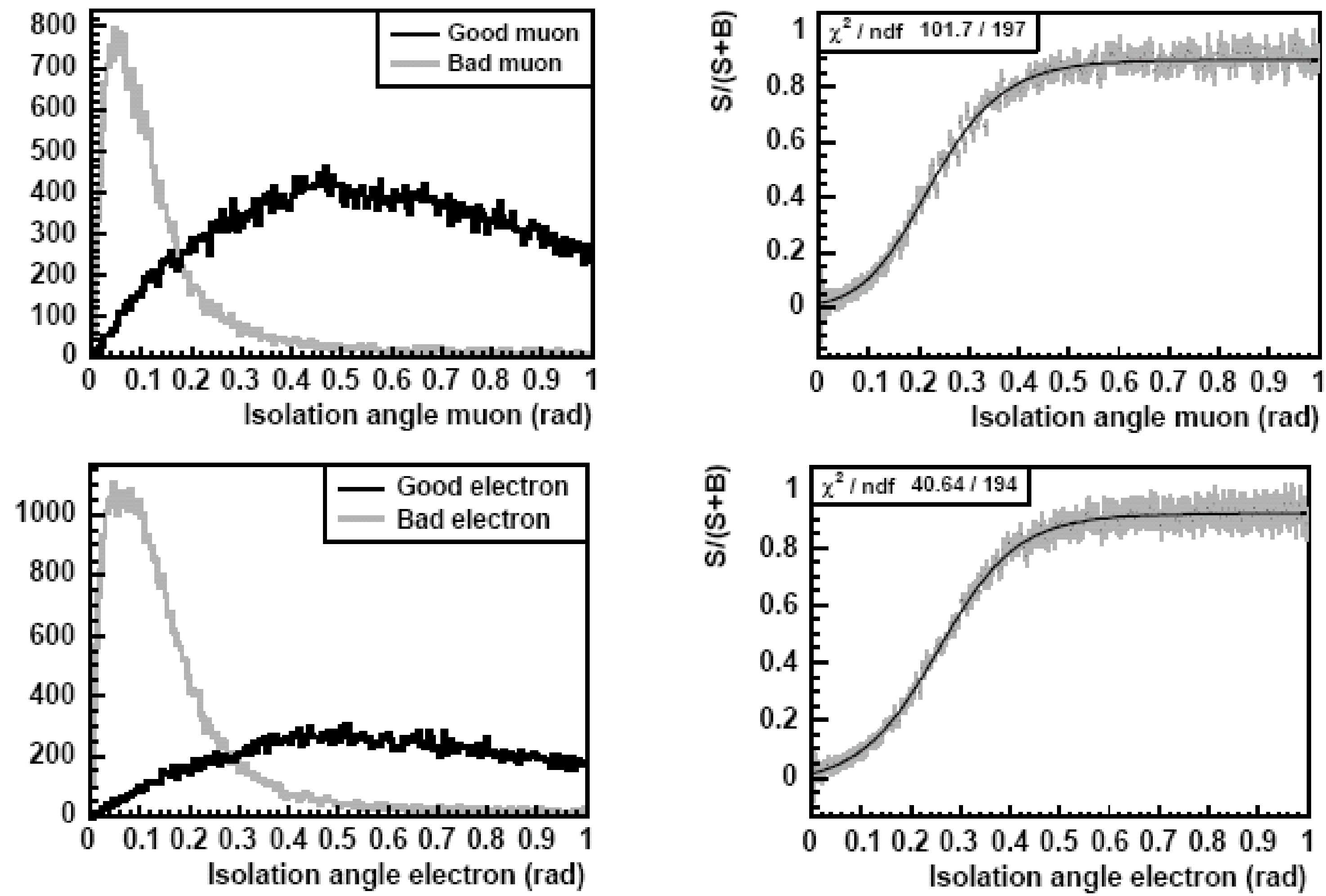
- logarithm of the sum of the p_T of the tracks in a cone $\Delta R = 0.3$ around the lepton, excluding the lepton track (-1 if no tracks)
- tracks are required to be associated to the primary vertex



Lepton Identification Variables

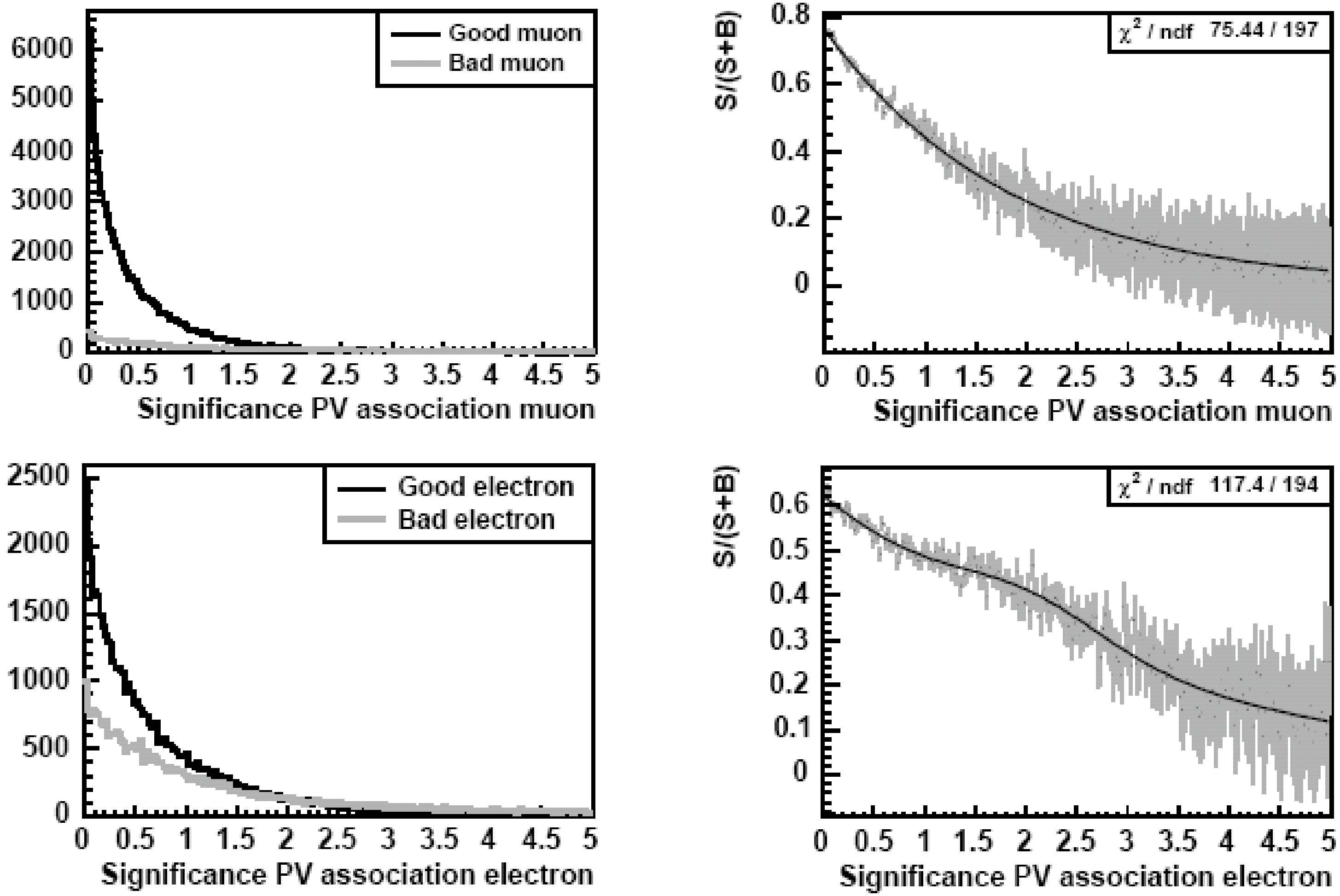
Isolation angle

- minimal angle in euclidian space between the lepton and a jet
- jets are clustered excluding a small cone around the lepton



Primary vertex significance

- significance of the z-distance between the reconstructed primary vertex and the point of closest approach of the lepton to this vertex



Reconstruction quality

- likelihood ratio discriminator to suppress fake electrons from jets (ElectronLikelihood in ORCA, see e-gamma webpage)