Top Physics at Hadron Colliders

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Outline

Talk also available from `http://cern.ch/cammin/ismd2005.pdf`

Tevatron

- Motivation
- The Tevatron
- Top-pair properties
- $t\bar{t}$ production
- Top-Quark mass
- Single top
- Other topics

LHC

- The LHC
- Top mass
- Spin correlations
- Single top
- FCNC
- $t\bar{t}$ as background

Motivation

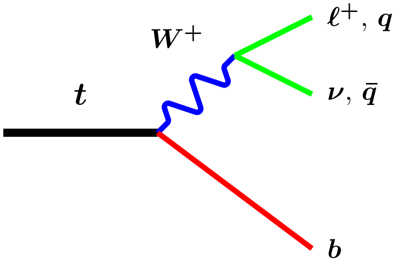
Why top physics?

- Large mass $\sim$ 175 GeV
  heaviest known fundamental particle
- m_t in the order of EWSB
- Lifetime $5 \cdot 10^{-25} s$ shorter than hadronization time
  "free quark"
- BR(t $\rightarrow$ Wb) $\approx$ 100% (in Standard Model)
- Top-Higgs Yukawa coupling ~ 1
- background for many discovery channels

What to study

- production cross section
- production kinematics
- resonances
- spin
- charge
- width
- mass
- W helicity
- CP violation
- anomalous couplings
- $|V_{tb}|$
- branching ratios
- rare/non-SM decays

Characteristics of top decays and top-quark pairs



t $\rightarrow$ Wb $\sim$ 100%

Reconstruction involves electrons, muons, jets, b-jets, $\not{E}_T$

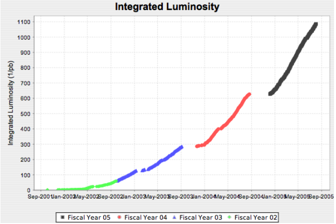
- all had: large BR, large BG
- ℓ+jets: BR & BG manageable
- dilepton: low BR & BG

The Tevatron

Run I phase: 1992–1996
Run II phase: 2001–
$p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

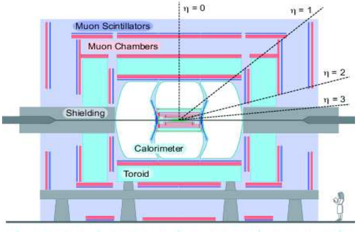
DØ and CDF multi purpose detectors

- Tracking in magnetic field.
- Silicon tracker
- Calorimeters
- Muon chambers

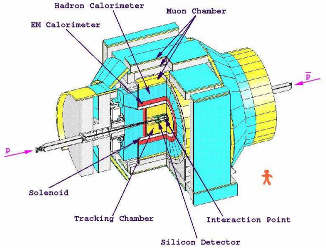


More than 1 fb^{-1} delivered!
Current analyses use up to $\sim$400 pb^{-1}.

DØ



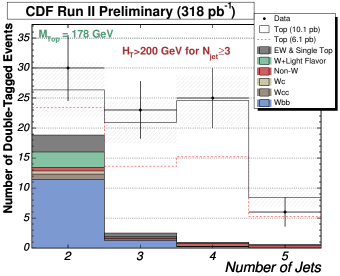
CDF



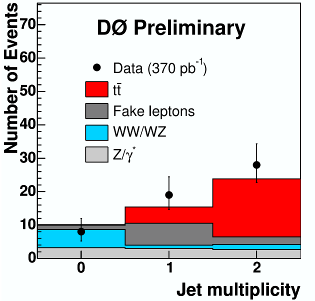
Tevatron: Top-pair production cross section

- main production mode at Tevatron
- Theory prediction $\sigma_{t\bar{t}} \approx 7$ pb (Cacciari et al., JHEP 0404:068,2004)
- final states: ℓ+jets, dilepton, full hadronic
- topological or b-tagged analyses
- main backgrounds (in ℓ+jets): W+jets, QCD multijet
- $\sigma_{t\bar{t}} = (N_{obs} - N_{bkg}) / \left(\varepsilon \cdot A \cdot \int \mathcal{L} dt \right)$

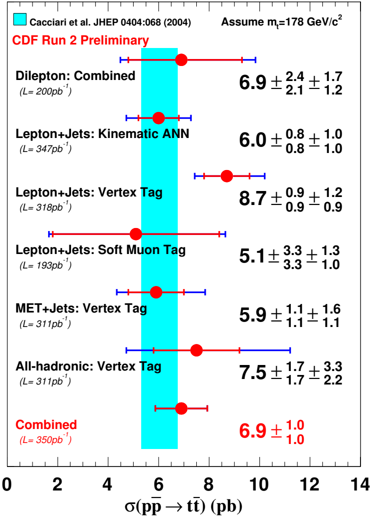
CDF, ℓ+jets, double-tag



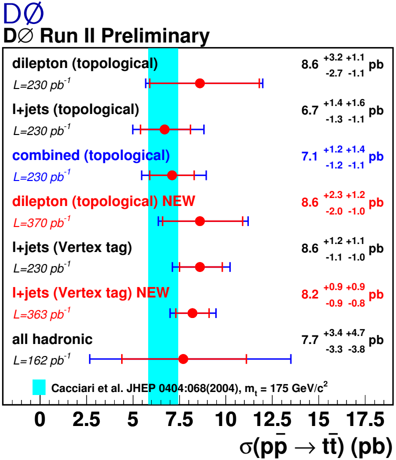
DØ, di-lepton



CDF

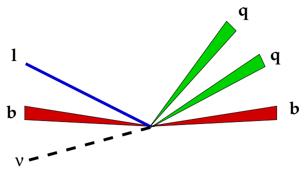

Cacciari et al. JHEP 0404:068 (2004)
Assume m_t=178 GeV/c^2
CDF Run 2 Preliminary
Dilepton: Combined
(L= 200pb^-1)
6.9 ± 2.4/2.1 ± 1.7/1.2
Lepton+Jets: Kinematic ANN
(L= 347pb^-1)
6.0 ± 0.8/0.8 ± 1.0/1.0
Lepton+Jets: Vertex Tag
(L= 318pb^-1)
8.7 ± 0.9/0.9 ± 1.2/0.9
Lepton+Jets: Soft Muon Tag
(L= 193pb^-1)
5.1 ± 3.3/3.3 ± 1.3/1.0
MET+Jets: Vertex Tag
(L= 311pb^-1)
5.9 ± 1.1/1.1 ± 1.6/1.1
All-hadronic: Vertex Tag
(L= 311pb^-1)
7.5 ± 1.7/1.7 ± 3.3/2.2
Combined
(L= 350pb^-1)
6.9 ± 1.0/1.0
0 2 4 6 8 10 12 14
σ(pp̄ → tt̄) (pb)

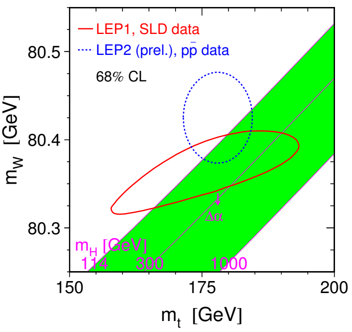
DØ


DØ Run II Preliminary
dilepton (topological)
L=230 pb^-1
8.6 +3.2 +1.1 -2.7 -1.1 pb
l+jets (topological)
L=230 pb^-1
6.7 +1.4 +1.6 -1.3 -1.1 pb
combined (topological)
L=230 pb^-1
7.1 +1.2 +1.4 -1.2 -1.1 pb
dilepton (topological) NEW
L=370 pb^-1
8.6 +2.3 +1.2 -2.0 -1.0 pb
l+jets (Vertex tag)
L=230 pb^-1
8.6 +1.2 +1.1 -1.1 -1.0 pb
l+jets (Vertex tag) NEW
L=363 pb^-1
8.2 +0.9 +0.9 -0.9 -0.8 pb
all hadronic
L=162 pb^-1
7.7 +3.4 +4.7 -3.3 -3.8 pb
Cacciari et al. JHEP 0404:068(2004), m_t = 175 GeV/c^2
0 2.5 5 7.5 10 12.5 15 17.5
σ(pp̄ → tt̄) (pb)

- top mass is of fundamental interest
- small Δm_t helps to constrain predictions for Higgs mass
- advanced analysis techniques needed (matrix element, ideogram, templates, dynamic likelihood, neutrino weighting)
- channels: ℓ+jets, dilepton with and without b-tagging

  (b-tag suppresses bkg. + reduces combinatorics)
- limited by syst. uncertainties; jet energy scale being dominant



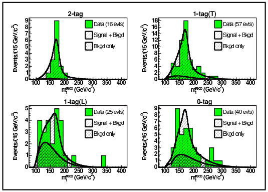


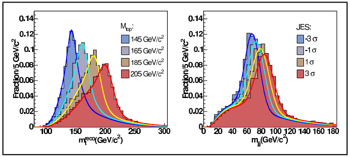
CDF: Template method

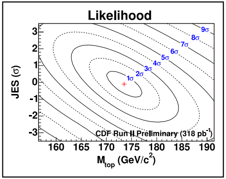
χ^2 minimization to reconstruct m_t:

$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{\left(\hat{p}_T^i - p_T^i\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(\hat{p}_j^{UE} - p_j^{UE}\right)^2}{\sigma_j^2}$$
$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{\ell\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t^{reco})^2}{\Gamma_t^2} + \frac{(m_{b\ell\nu} - m_t^{reco})^2}{\Gamma_t^2}$$

- b-tagging reduces combinatorics
- 4 subsamples: 2, 1(L), 1(T), 0 tags
- In-situ JES calibration from m_W constraint
- template fits m_t^{reco} and m_{jj} from Herwig







$\mathcal{L}_{\text{sample}} = \mathcal{L}_{\text{shape}}^{m_t^{reco}} \times \mathcal{L}_{\text{shape}}^{m_{jj}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}}$

total LH: $\mathcal{L} = \mathcal{L}_{\text{2tag}} \times \mathcal{L}_{\text{1tag(T)}} \times \mathcal{L}_{\text{1tag(L)}} \times \mathcal{L}_{\text{0tag}}$

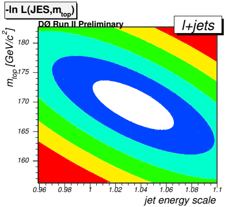
$$m_t = (173.5^{+2.7}_{-2.6}(\text{stat.}) \pm 2.5(\text{JES}) \pm 3.0(\text{syst.}))\ \text{GeV}$$

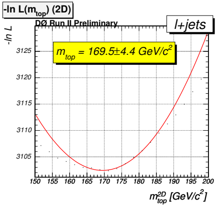
$(\mathcal{L} = 318\ \text{pb}^{-1})$

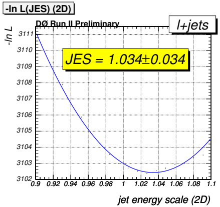
DØ Matrix element method

- makes maximal use of information in event by calculating probability for event to be signal or background from the ME
  - $P(x; M_{top}) = \frac{1}{\sigma} \int d^n\sigma(y; M_{top}) dq_1 dq_2 f(q_1) f(q_2) W(x, y)$
  - LO matrix element differential cross section
  - f(q) probability distribution of initial parton having momentum q
  - probability of parton level variable y to be measured as variable x
- Input: 4-vectors of final-state particles, acceptance, resolution of detector
- maximize a likelihood L as a function of m_{top}
- In-situ JES calibration
- $P_{\mathrm{evt}}(x; m_t, JES) =$
  $f_{\mathrm{top}} \cdot P_{\mathrm{sgn}}(x; m_t, JES) + (1 - f_{\mathrm{top}}) \cdot P_{\mathrm{bkg}}(x; JES)$
- exactly 4 jets, no b-tagging
- 150 candidates, $f_{\mathrm{top}} = 0.364$

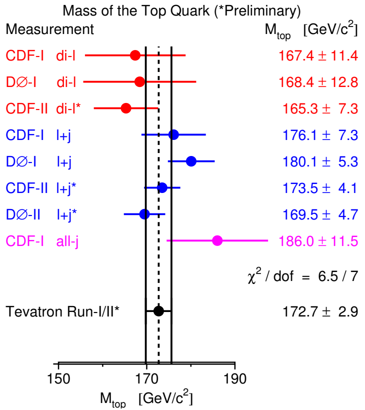
preliminary result:
$m_t = (169.5 \pm 4.4(\mathrm{stat.+JES})^{+1.7}_{-1.6}(\mathrm{syst.}))$ GeV (320 pb^{-1})



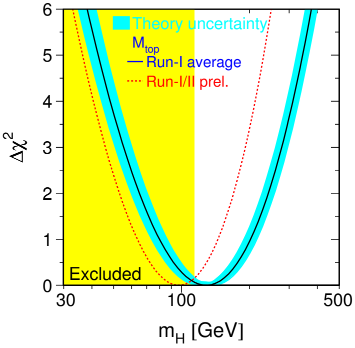




Tevatron: Combined result



Electroweak fits



Preliminary world average:

$m_t = (172.7 \pm 1.7[\text{stat.}] \pm 2.4[\text{syst.}])$ GeV

Combination weights (%)

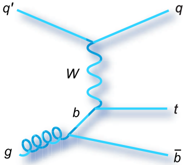
Run-I published		Run-II preliminary		
CDF	DØ	CDF		DØ
all-j, ℓ+j, di-ℓ	ℓ+j, di-ℓ	ℓ+j	di-ℓ	ℓ+j
1.9	20.9	36.0	8.0	33.3

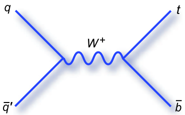
$m_H = 91^{+45}_{-32}$ GeV

$m_H < 186$ GeV (95% CL)

(direct LEP-2 limit not included)

Tevatron: Search for single top





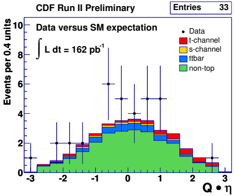
- NLO prediction:

  $\sigma_{\text{t-channel}} = 1.98 \pm 0.25$ pb,

  $\sigma_{\text{s-channel}} = 0.88 \pm 0.11$ pb
- high p_T lepton, missing E_T, 2 jets

CDF: 162 pb^{-1}

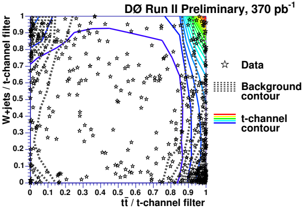
Templates



s+t	$<$ 17.8 pb @ 95% C.L.
t	$<$ 10.1 pb
s	$<$ 13.6 pb

DØ: 370 pb^{-1}

Likelihood discriminant



t	$<$ 5.0 pb @ 95% C.L.
s	$<$ 6.4 pb

$R = BR(t \to Wb)/BR(t \to Wq)$

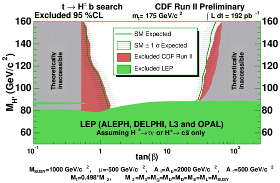
CDF $R = 1.12^{+0.27}_{-0.23}$(stat + syst) (162 pb^{-1})

DØ $R = 1.03^{+0.19}_{-0.17}$(stat + syst) (230 pb^{-1})

Turn it into limits:
CDF: $R > 0.61$ @95% *CL*
DØ: $R > 0.64$ @95% *CL*

Charged Higgs

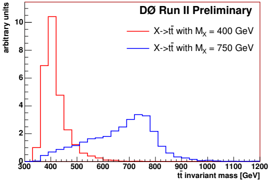
- in MSSM: $t \to H + b$ competes with $t \to Wb$
- $BR(t \to Hb) < 0.7$ @ 95% CL for $80\ GeV < m_H < 150\ GeV$



- Anomalous gtt couplings: no deviation from SM
- Top charge: 2/3 or −4/3? → soon to come

Resonances $X \to t\bar{t}$

- Search for narrow-width heavy resonance
- ℓ+jets final state
- use lifetime tag to identify b-jets
- based on 370 pb^{-1} of integrated luminosity
- backgrounds: non-resonant SM $t\bar{t}$, W+jets, multijet with fake lepton
- $M_{Z'} < 680$ GeV, $\Gamma_{Z'} = 0.012 M_Z$ excluded in technicolor models @ 95% CL



W helicity

CDF $f_+ < 0.18$ at 95% CL (Run I)

CDF $f_0 = 0.25^{+0.35}_{-0.21}$ (194, 162 pb^{-1})

DØ $f_+ < 0.25$ at 95% CL (230, 370 pb^{-1})

Top mass systematics

Jet energy scale is by far the dominant systematic in most top results.

(and will be so at LHC!)

Example:

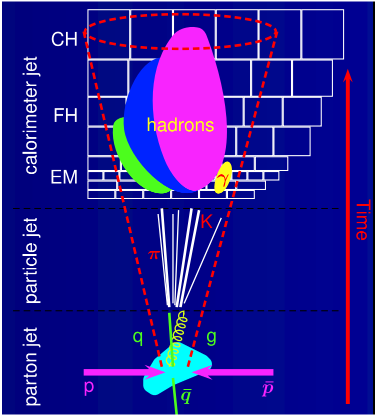
$\Delta m_t^{\text{Tevatron}}(\text{all}) = 2.4$ GeV

$\Delta m_t^{\text{Tevatron}}(\text{JES}) = 2.0$ GeV

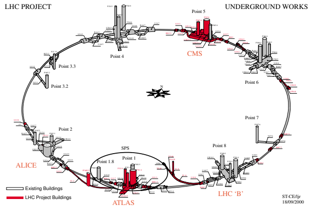
In DØ:

$$E_{corr} = \frac{E_{meas} - \text{Offset}}{\text{Response} \times \text{Showering}}$$

using zero + minimum bias events
γ+jets, Z+jets, dijet events
(Z$\rightarrow$ b$\bar{\text{b}}$ in the future(?))



The Large Hadron Collider



- pp collision at $\sqrt{s} = 14$ TeV
- initial low lumi: $\mathcal{L} \lesssim 10^{33}$ cm^{-2}s^{-1}
  - $\lesssim 2$ minimum bias
  - 10 fb^{-1}/ year
- design high lumi $\mathcal{L} \lesssim 10^{34}$ cm^{-2}s^{-1}
  - ≈ 20 minimum bias
  - 100 fb^{-1}/ year

Atlas pit webcam

CMS construction webcam

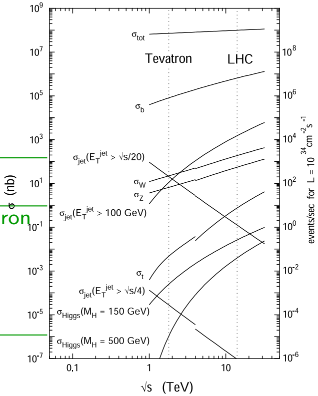
Top physics at the LHC

Production mechanism:

90% $gg \rightarrow t\bar{t}$
10% $qq \rightarrow t\bar{t}$

- top-quark factory
- calibrate detector
- precision measurements
- test for new physcis
- major background to new physcis

Process	N/s	N/yr	total collected before LHC start
$W \rightarrow \ell\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \rightarrow ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	1	10^7	10^4 Tevatron
$b\bar{b}$	10^6	10^{12-13}	10^9 Belle/BaBar (?)
H(130)	0.02	10^5	?



Top mass @ LHC

- Large production rate ($\sim$ 8M $t\bar{t}$ pairs/yr) $\rightarrow$ small stat. error on m_t
  10 fb^{-1} $\rightarrow$
  Δm_t(stat.) $\approx$ 0.07 GeV.
- golden channel: lepton + jets
- b-tagging is crucial
  reduces physics and combinatorial bkg.
- In-situ jet energy calibration from m_W constraint

Typical selection:

- isolated lepton $p_T > 20$ GeV
- $\not{E}_T > 20$ GeV
- 4 jets with $p_T > 40$ GeV
- at least 1 b-tagged jet
- typical selection efficiency: 5–10%
- Main bkg. from W/Z+jets, WW/ZZ,WZ $< 2\%$

hadronic side:

- pair of non-tagged jets with m_{jj} closest to m_W $|m_{jj} - m_W| < 20$ GeV
- assign b-jet to reconstructed W_{had}
-

	1b-tag	2b-tags
purity (%)	65	69
eff (%)	2.5	1.2

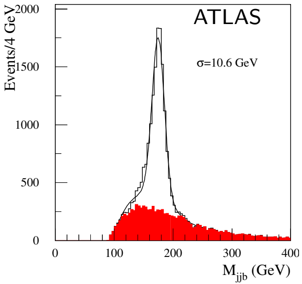
- external JES calibration 5–10%
- ΔJES=1% $\rightarrow \Delta m_t = 1.6$ GeV
- light and b-JES from Z+jets → 1%, but biases m_W → need in-situ calibration from m_W

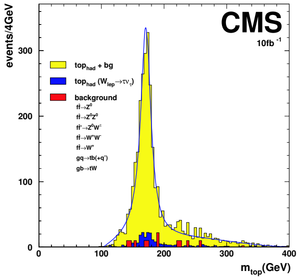
→ $\Delta m_t < 2$ GeV (syst+stat)
FSR: 1 GeV, b-JES $0.7 \times \xi$%

Kinematic fit

- reconstruct whole event
- kinematic fit to $t\bar{t}$ hypothesis

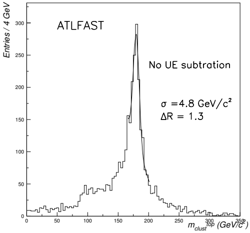
→ $\Delta m_t \sim 1$ GeV



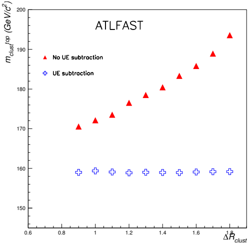


Other approaches: High p_T $t\bar{t}$ events

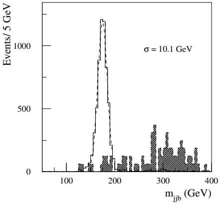
- ℓ+jets channel
- $p_T > 200$ GeV
- "two-hemisphere" topology
- jets from t → jjb overlay
  → reconstruct cells in large cone, not individual jets



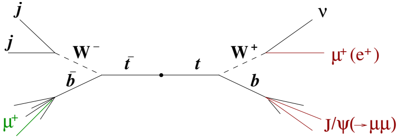
Underlying event subtraction



Also possible in all-jets channel:

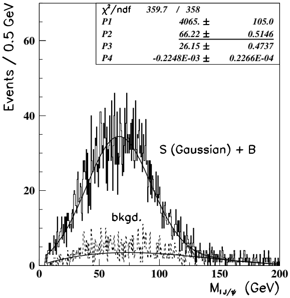


CMS

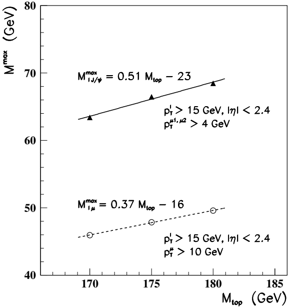


- very clean signature
- BR $\sim 5.3 \times 10^{-5}$ (needs high lumi)
- $\sim$ 1000 evts/yr

$M_{\ell J/\Psi}$



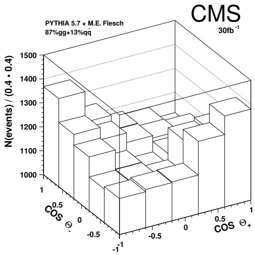
Correlation M^{max} / m_t



syst. uncertainty on $m_t \lesssim 1$ GeV

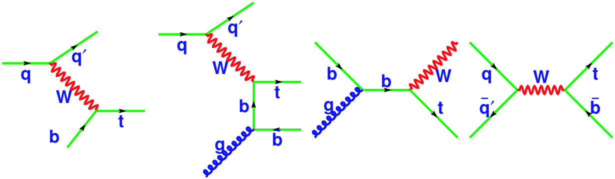
Spin correlations

- spin information in $t\bar{t}$ events not diluted due to hadronization
- test SM properties of top quark; probe presence of non-SM interactions
- $\mathcal{A} = \dfrac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$
- SM prediction: $\mathcal{A}(gg) = 0.431$, $\mathcal{A}(qQ) = -0.469$
  $\rightarrow \mathcal{A}(\mathrm{LHC}) = 0.311$
- Use dilepton final state
  observables: θ^+, θ^-: angle between lepton and top in $t\bar{t}$ rest frame



- fit double differential
  $$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\,d\cos\theta^*_{\ell-}} = \frac{1}{4}\left(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-}\right)$$
- CMS result for 30 fb^{-1}:
  $\Delta\mathcal{A}$(stat)=0.035, $\Delta\mathcal{A}$(syst)=0.028

Single top



Wg fusion: 244 pb^{-1} Wt: 60 pb^{-1} W^*: 10 pb^{-1}

- Precise determination of W-t-b vertex and coupling strength
- Main backgrounds (xsec in pb)

	σ	$\sigma \times BR(W \rightarrow \ell\nu)$
$t\bar{t}$	833	246
Wbb	300	67
Wjj	$19 \cdot 10^3$	$4 \cdot 10^3$

$\int \mathcal{L}dt = 30\ \text{fb}^{-1}$

Process	S	B	S/B
Wg fusion	27k	8.5k	3.1
Wt	6.8k	30k	0.22
W^*	1.1k	2.4k	0.46

Measurement of V_{tb}

Process	ΔV_{tb}(stat.)	ΔV_{tb}(theory)
Wg fusion	0.4%	6%
Wt	1.4%	6%
W^*	2.7%	5%

Critical: fake lepton rate, b-ID and fake rate, reconstruction of low energy jets, reconstruction of forward jets

More top topics

FCNC top decays...

$t \rightarrow qZ, \quad t \rightarrow q\gamma, \quad t \rightarrow qg$

...strongly suppressed in SM

($BR_{t \rightarrow qX}$ [X=Z,γ,g] $< 10^{-10}$)

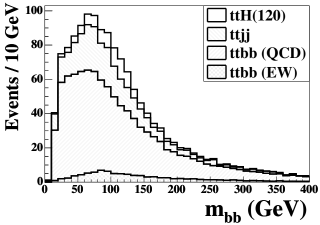
BRs can be strongly enhanced in models like SUSY, multi-Higgs doublets, exotic quarks

ATLAS sensitive to branching ratios 10^{-3}–10^{-4} (with 100 fb^{-1})

Top as background

$t\bar{t}$ major background to many new physics processes ($t\bar{t}H^0$, ...)

Example: $t\bar{t}H^0$, $H^0 \rightarrow b\bar{b}$



- $\sigma_{t\bar{t}} + X \approx 1000 \times \sigma(t\bar{t}H^0(120))$
- need precise knowledge of rate and shape of $t\bar{t}$ +X background
- should be obtained from the data
- requires excellent b-tagging performance

Conclusions

Tevatron

- a variety of analysis techniques applied to get the best out of the data (multivariate techniques, b-tagging, matrix element calculations, ...)
- results not limited by statistics any more (JES largest uncertainty)
- latest combination: $m_t = (172.7 \pm 1.7[\text{stat.}] \pm 2.4[\text{syst.}])$ GeV

LHC

- ... will produce a plethora of top quarks ($\sim 8M/yr$ at low luminosity)
- expect precise results after only one year of data taking
  ... once the detectors are understood...
- measurements will be limited by systematics
- precise tests of the SM, search for new physics with top events
- $t\bar{t}$ background for discoveries
  ($\rightarrow$ rates and shapes need to be studies in data)