Climbing to the *Top:*
Physics towards the LHC

Michele Gallinaro
LIP, Lisbon
Feb 8, 2007

Past, present, and future

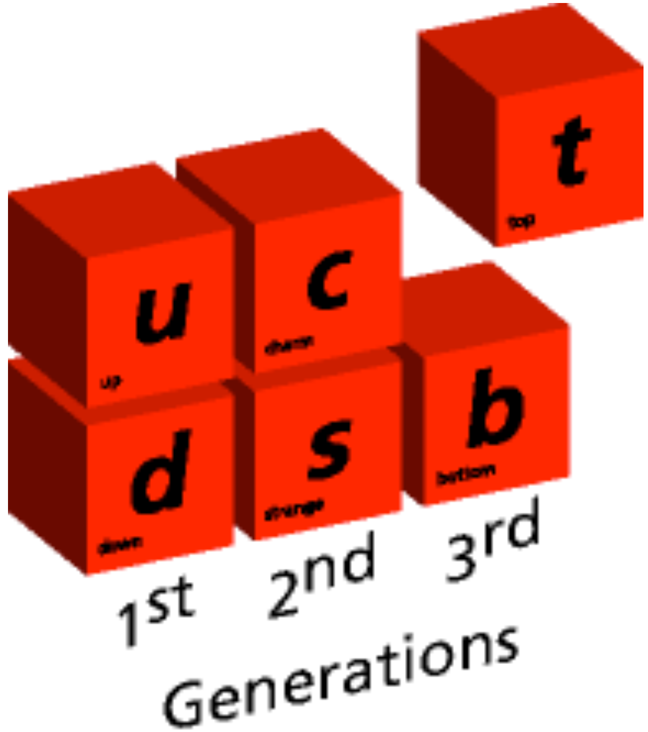
- (Pre)Discovery
- Is it top? Was it top?
- Current measurements
- Top quark at the LHC

Standard Model

1964: quark model proposed to explain the structure of particles

1967: electroweak unification with W, Z and H (Glashow, Weinberg, Salam)

model evolved to include a 3rd generation



took ~30 years to complete picture, but last quark finally discovered at Fermilab in 1994

Top searches in e^+e^- collisions

PETRA could reach ~20 GeV (late ‘70s)

- search for narrow toponium resonance
- look for increase in R =(# of hadron events)/(# of $\mu\mu$ events)
- negative results: M_{top}>23 GeV

TRISTAN built to study top quark (early ‘80s)

- energy ~50-64 GeV
- similar search techniques
- M_{top}>30 GeV

SLC/LEP ~90 GeV (late ‘80s)

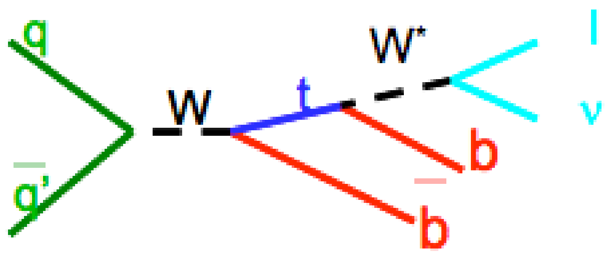
- look for $Z \rightarrow$ttbar
- M_{top}>45 GeV

Top searches at hadron colliders

CERN Sp$\bar{p}$S built to observe W,Z ($\sqrt{s}$=540 GeV)

– access to much higher masses
– large background and difficult event reconstruction

1984: UA1 ($W \rightarrow t\bar{b} \rightarrow l\nu b\bar{b}$)



– isolated high-P_T lepton
– 2 or 3 jets
– observe 5 events
– background: 0.2 events
– consistent with M_{top}~40 GeV, but stopped short of claiming discovery

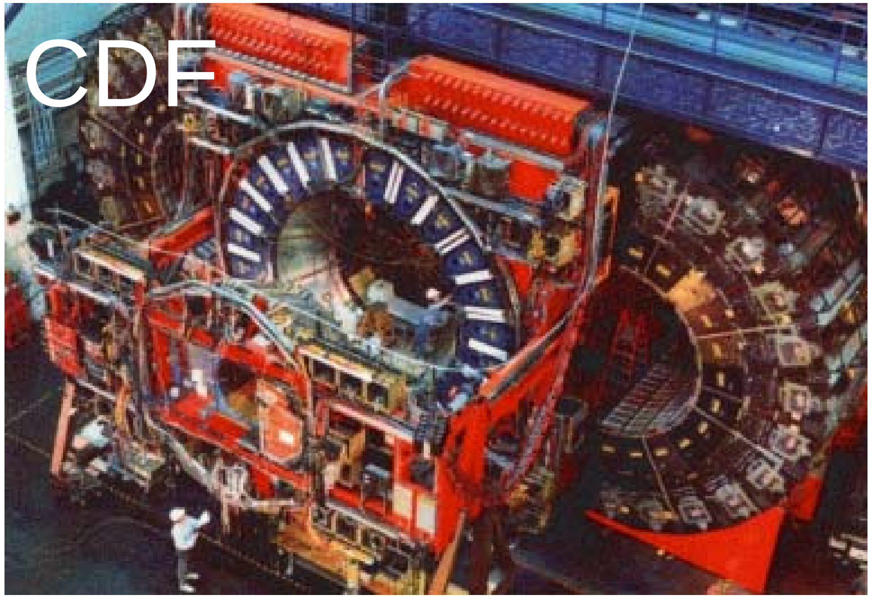
1988: UA1/UA2

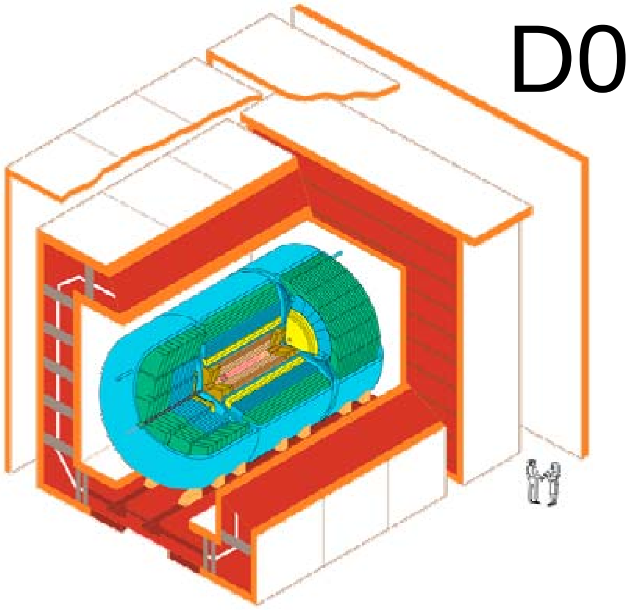
– larger data sample (600 nb^{-1})
– conclusion: M_{top}>44 GeV (later M_{top}>75 GeV)

Fermilab joins the hunt

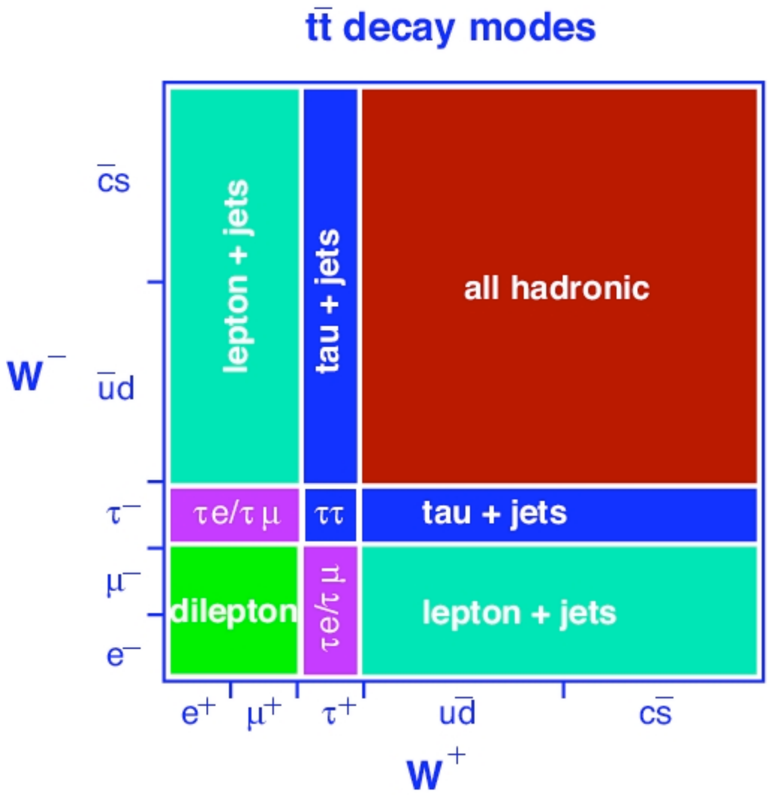
Pair production dominates at Fermilab
Change of strategy: $M_{top} > M_W + M_b$

CDF: silicon vertex detector added to magnetic spectrometer
D0: excellent calorimetry, large muon coverage

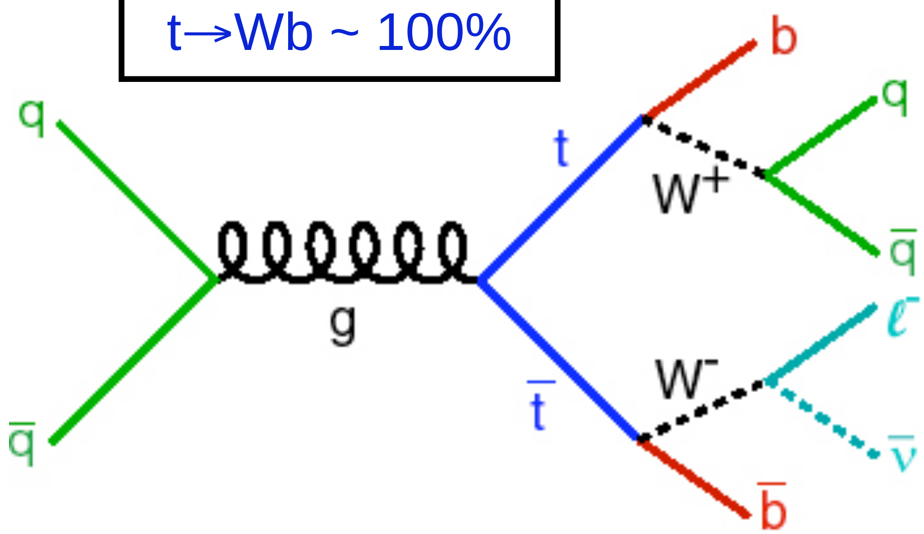




How does top decay?



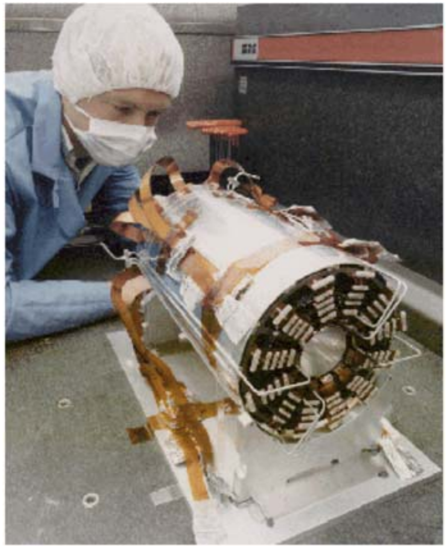
Standard Model:
$t \to Wb \sim 100\%$



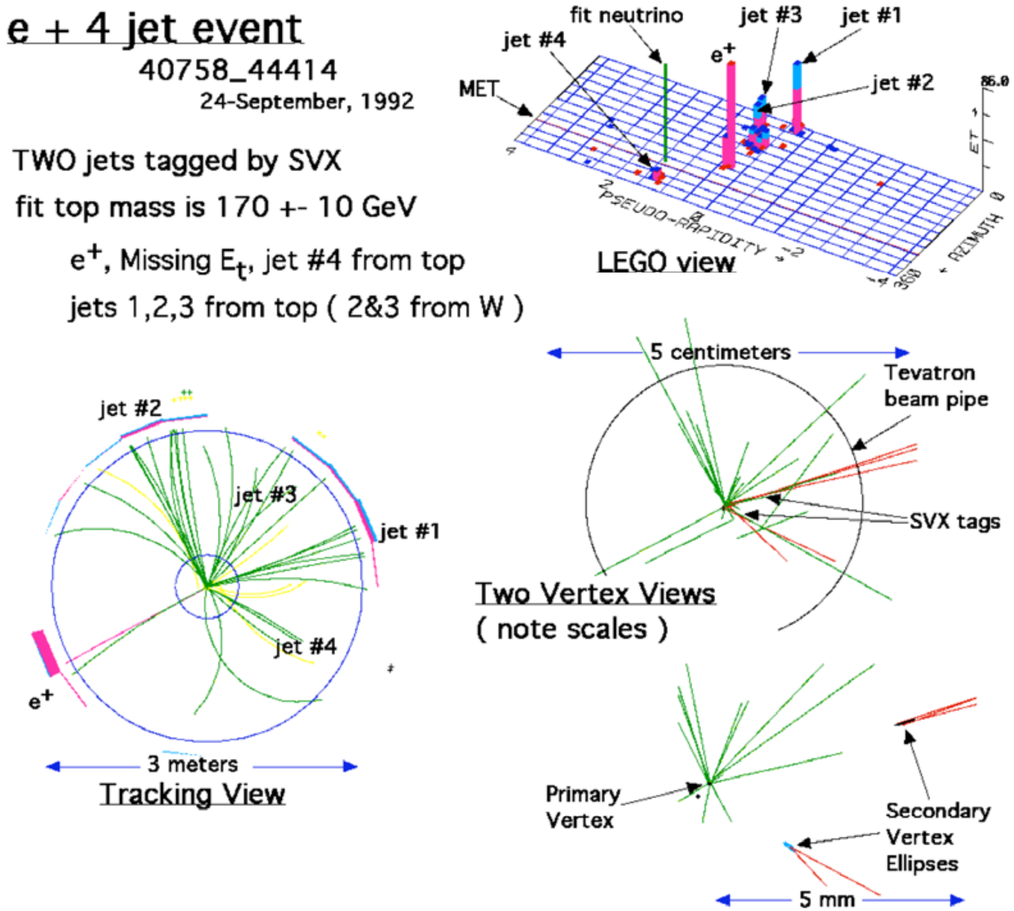
$tt \to l\nu l\nu bb$	di-lepton	5%	$e+\mu$
$tt \to l\nu qqbb$	lepton+jets	30%	$e+\mu$
$tt \to qqqqbb$	all hadronic	44%	

Detecting the top quark

- Strategy
  - dilepton: +2 jets
  - single lepton: b-tagging



CDF vertex detector
(40 μm impact parameter resolution)
powerful discriminant against background

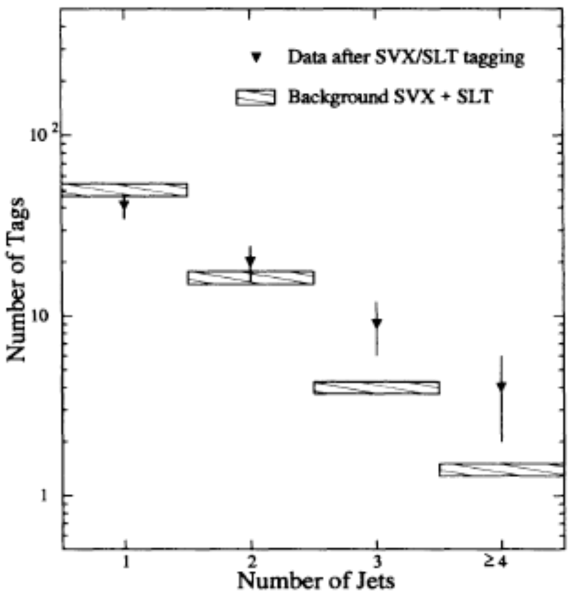


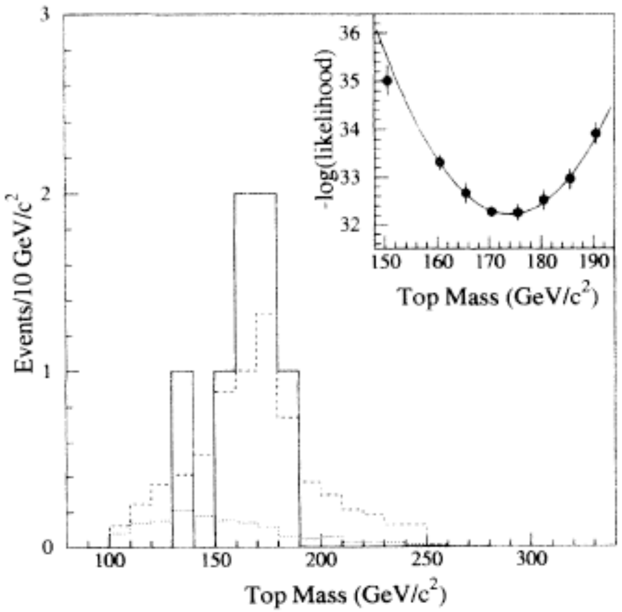
First evidence (1994)

VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.





First measurements

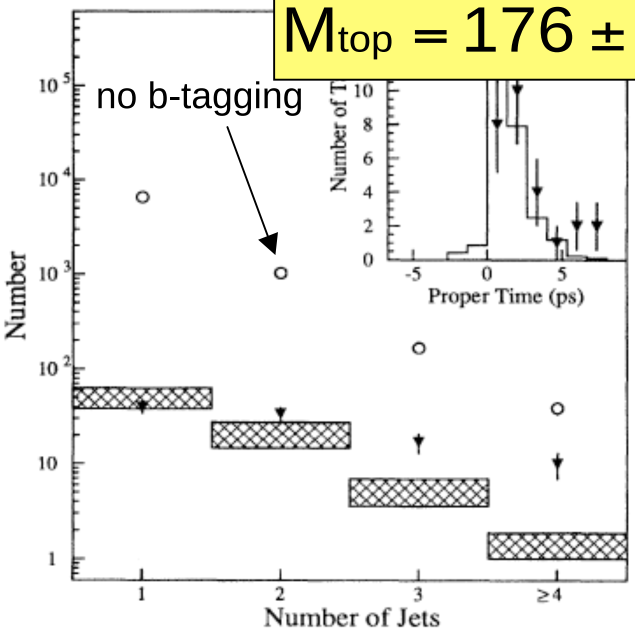
VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

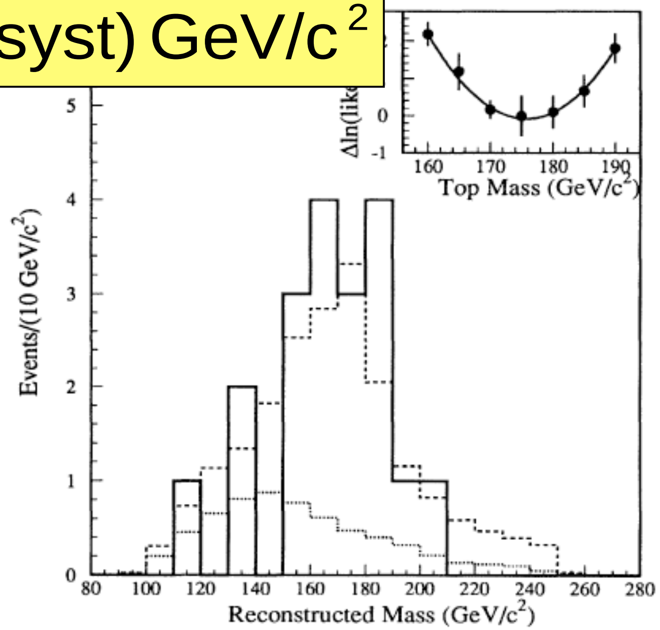
Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a ... ark mass to be 176 ± 8(stat) ± ...

$$\sigma_{tt} = 6.8^{+3.6}_{-2.4}\ \text{pb}$$

$$M_{top} = 176 \pm 8(\text{stat}) \pm 10(\text{syst})\ \text{GeV}/c^2$$



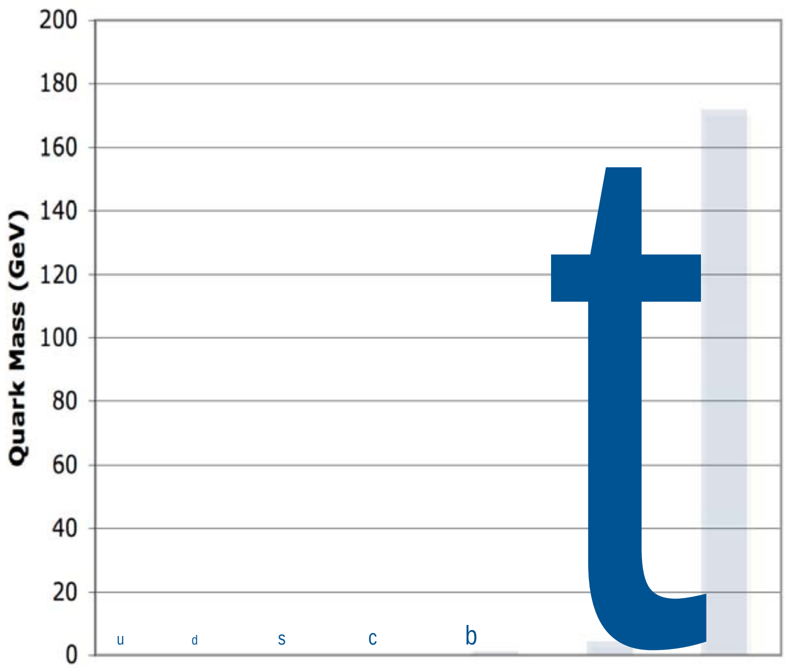


Why is top important ?

special: top is the heaviest fermion

- ✓ top-Higgs Yukawa coupling~1
- ✓ Higgs mass
- ✓ for M_{top}=175 GeV:
  Γ~1.4 GeV >> Λ_{QCD}
  ⇨no hadronization
- ✓ connection to EWSB?

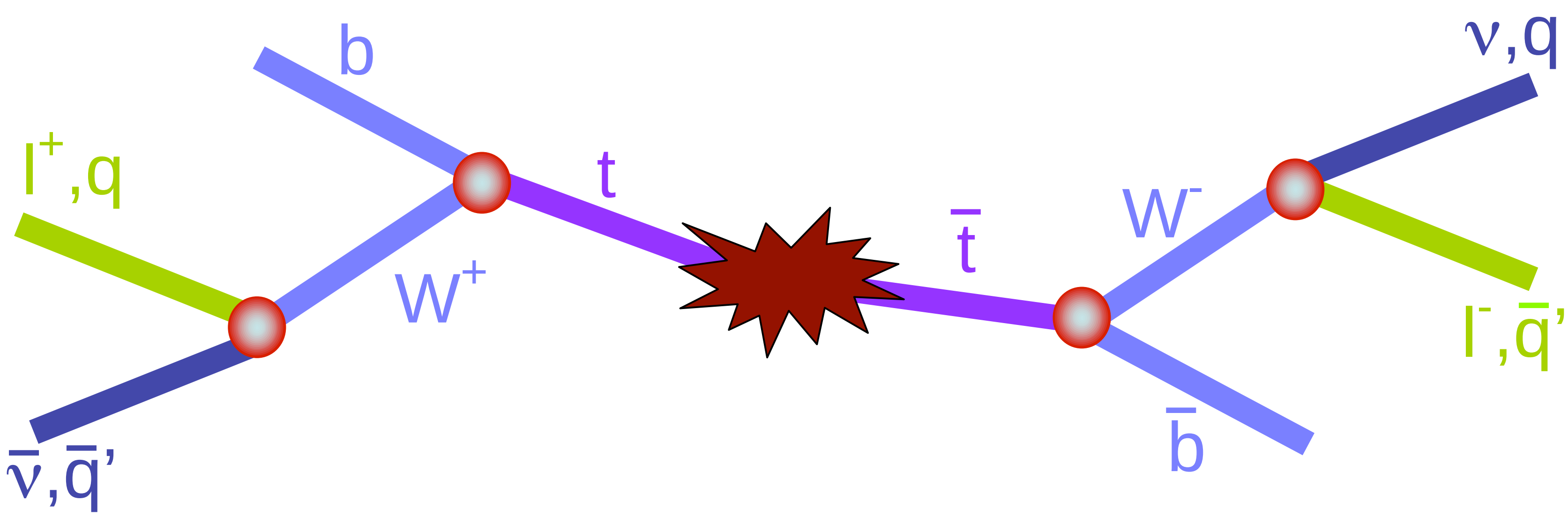
quark masses



study of top quark properties

⇨precision measurements may provide insight into physics beyond the SM

If it is really top…



PRODUCTION
Cross section
Resonances X→tt
Fourth generation t'
Spin-correlations
New physics (SUSY)
Flavour physics (FCNC)
...

PROPERTIES
Mass
Kinematics
Charge
Lifetime and width
W helicity
Spin
...

DECAY
Branching ratios
Charged Higgs (non-SM)
Anomalous couplings
Rare decays
CKM matrix elements
Calibration sample @LHC
...

Top quark samples @ TeV

In 1/fb of integrated luminosity:

7000 tt events produced

trigger+BR ↓

200 dilepton
1000 lepton+jets
2000 all-hadronic

event selection ↓

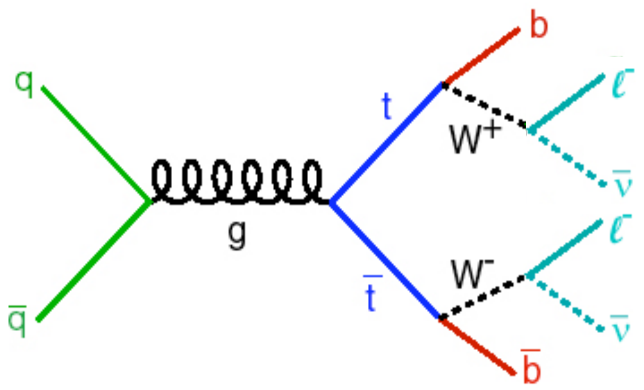
50 dilepton, S/B~2:1
200 lepton+jets, S/B~3:1
300 all-hadronic, S/B~1:5

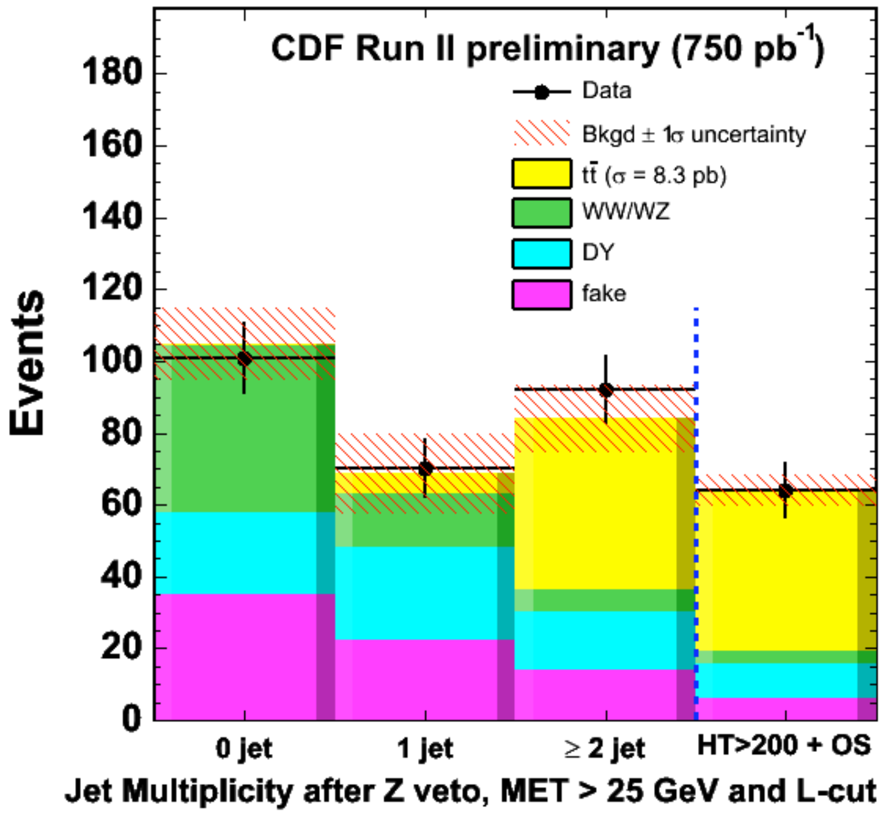
Cross section measurement

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

- ✓ testing non-SM top production mechanisms
- ✓ top sample may contain an admixture of exotic processes

Dilepton channel

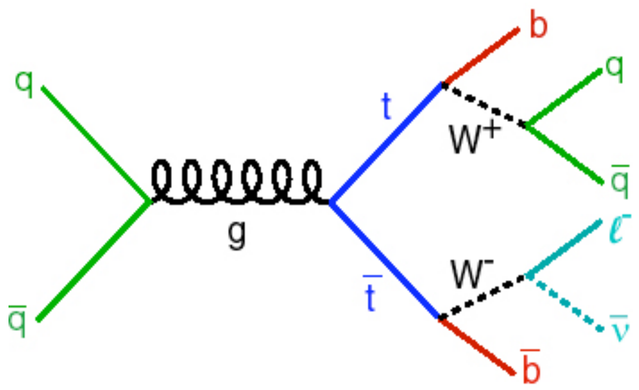




Branching Ratio (BR) ~5%
background: small

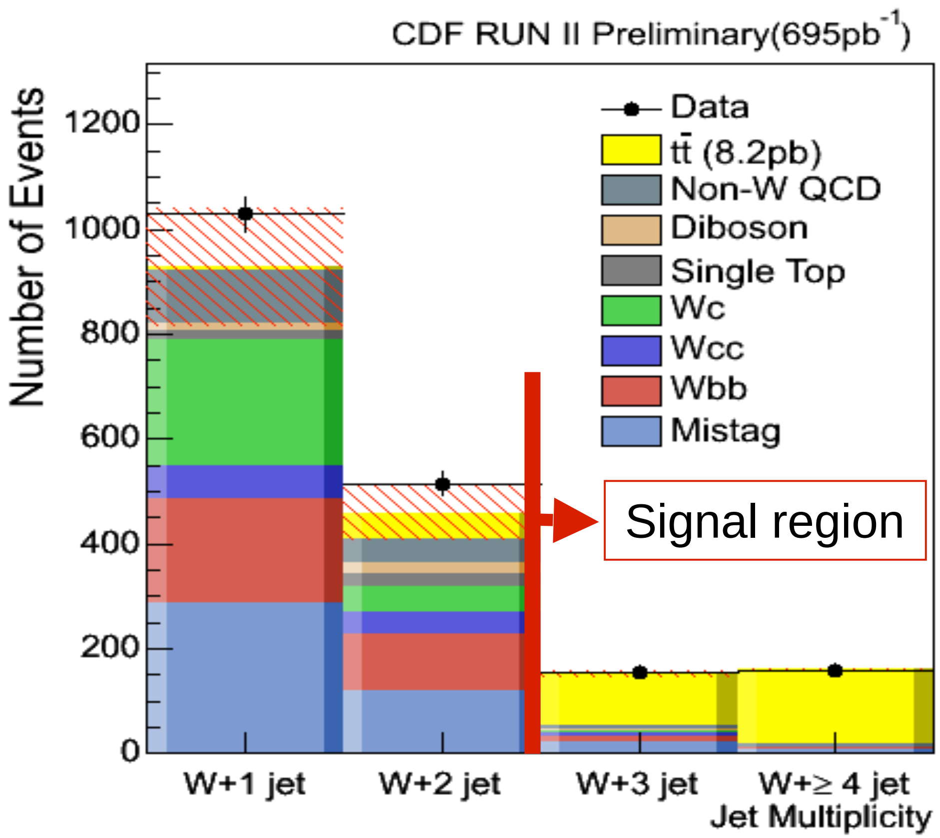
- ➢two leptons + ≥2 jets + $\not{E}_T$
- ➢more kinematical variables

Lepton + jets

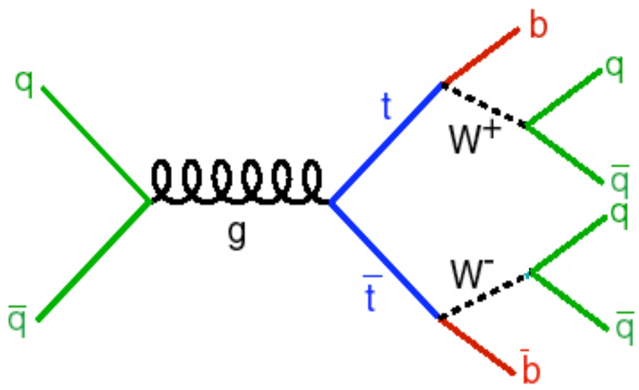


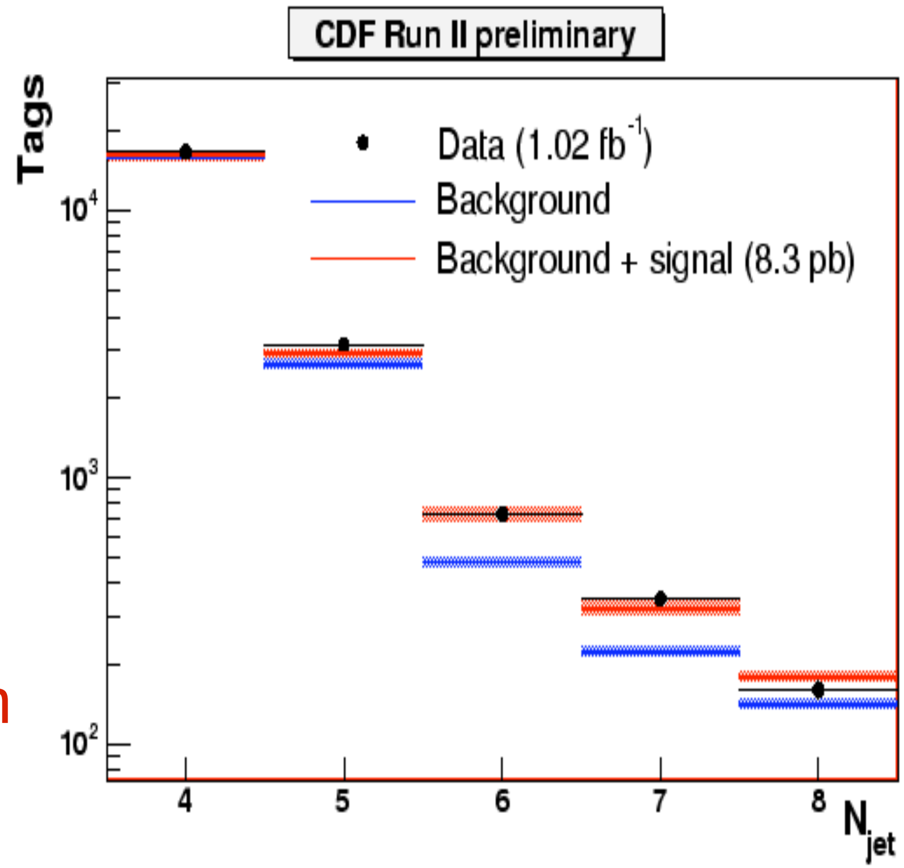
BR ~30%
background: moderate

- ➢one lepton + ≥3 jets + $\not{E}_T$
- ➢may require b-tag



All hadronic



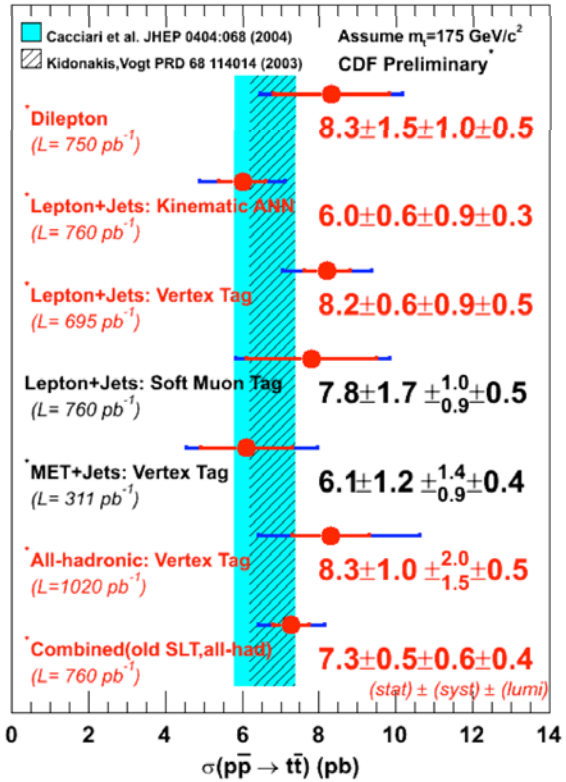


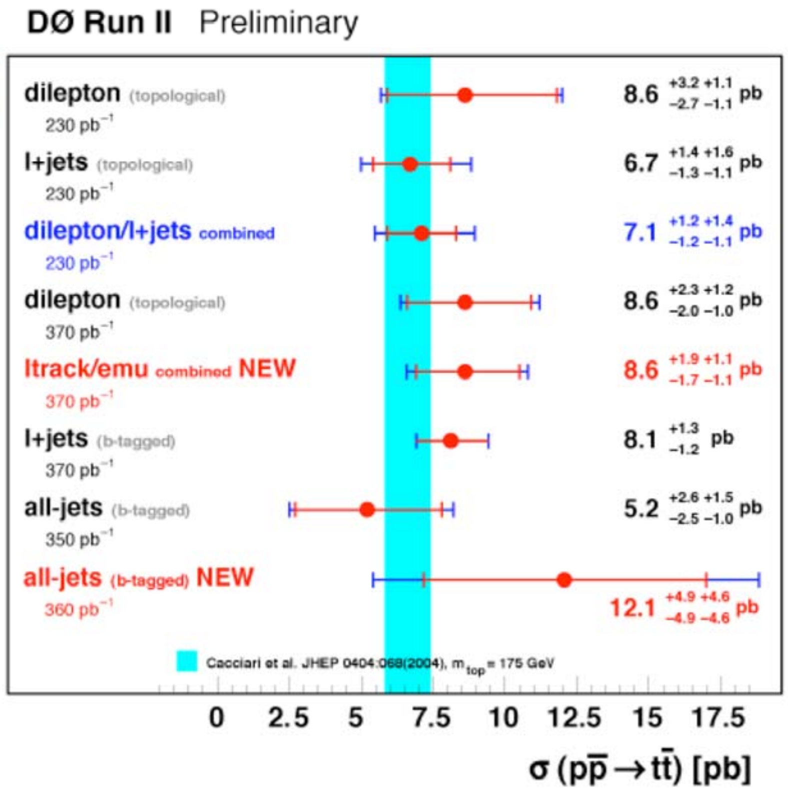
BR ~44%

background: large

- ≥6 jets + kinematical selection
- optimize S/√B
- requires b-tag

Cross section summary

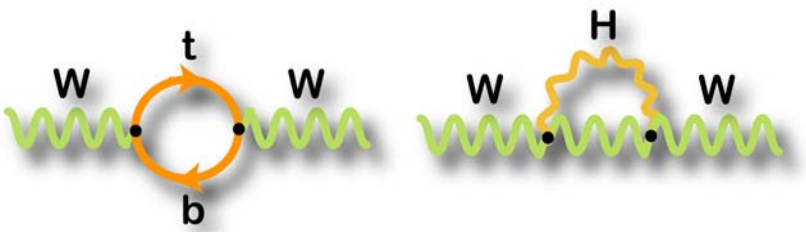




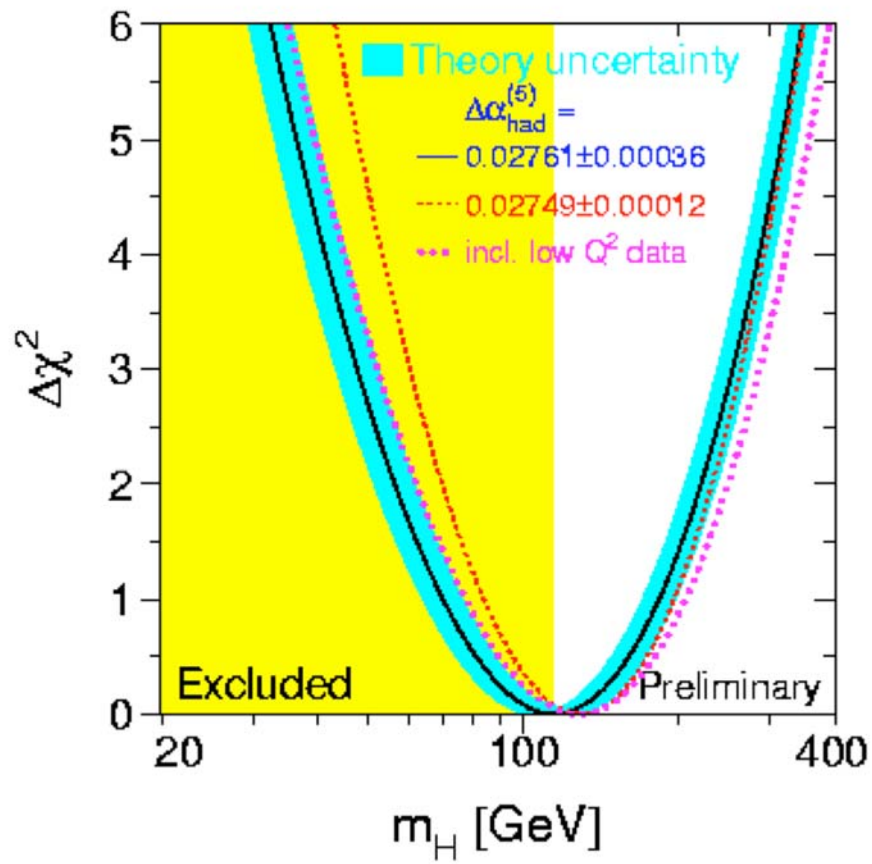
- Different channels and techniques are in agreement

Top quark mass

- top quark mass is a fundamental parameter of the SM
- top and W mass measurements constrain the Higgs mass



- top is the only fermion with a mass of the order of EWSB scale



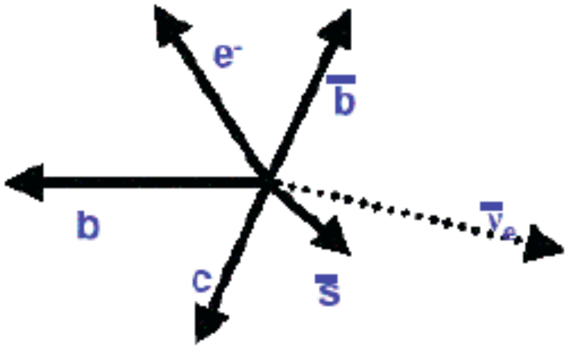
Measuring the top mass

Challenging:

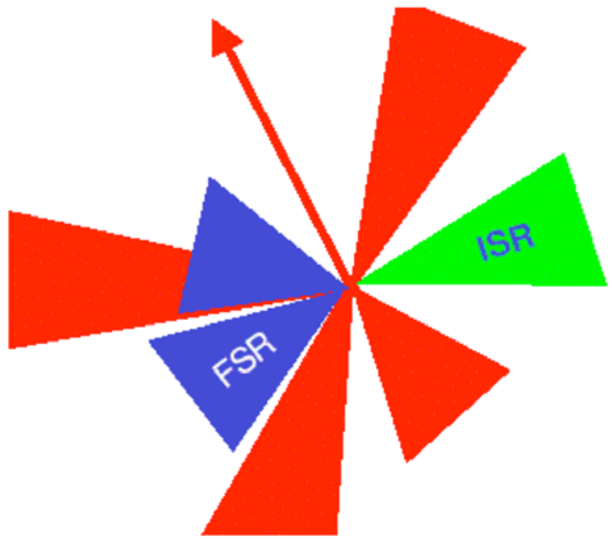
➢ **Lepton+jets**
- undetected neutrino
  - P_x and P_y from E_T conservation
  - 2 solutions for P_z from $M_W = M_{l\nu}$
- leading 4-jet combinatorics
  - 12 possible jet-parton assignments
  - 6 with 1 b-tag
  - 2 with 2 b-tags
- ISR + FSR

➢ **Dileptons**
- less statistics
- two undetected neutrinos
- less combinatorics: 2 jets

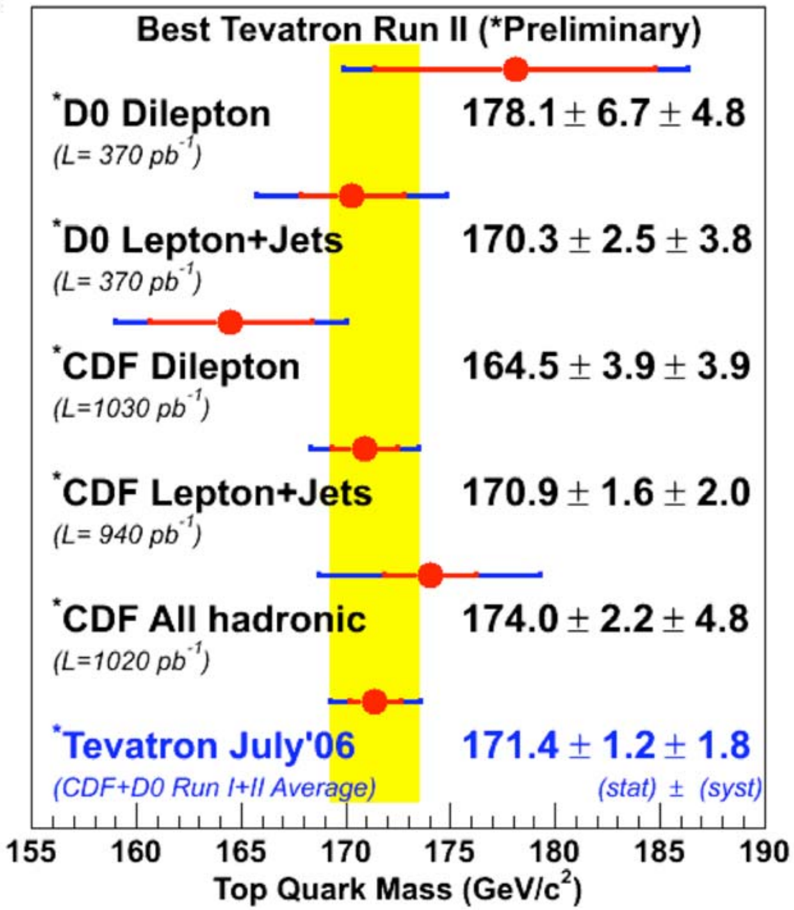
LO final state:



experiment sees:



Top mass measurement



- several reconstruction methods used to measure the top mass
- all channels:
  - ✓dilepton+2 jets
  - ✓lepton+4 jets
  - ✓6 jets
- largest systematic uncertainty due to jet energy measurement

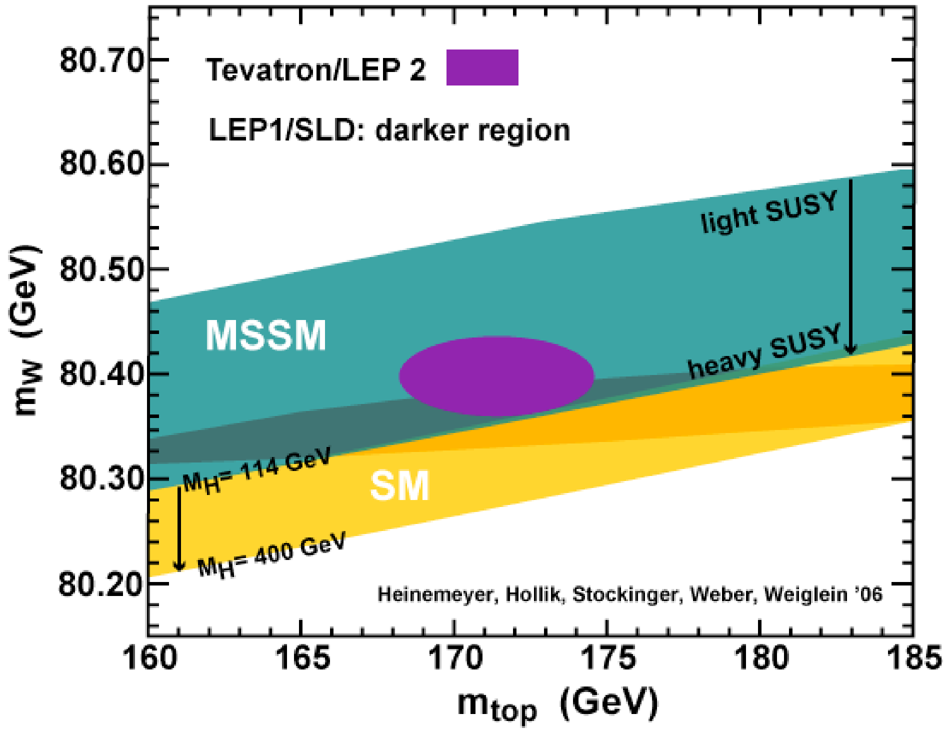
Tevatron measurement

$m_{top} = 171.4 \pm 2.1\ GeV/c^2$ (1.2%)

Global EWK fit:

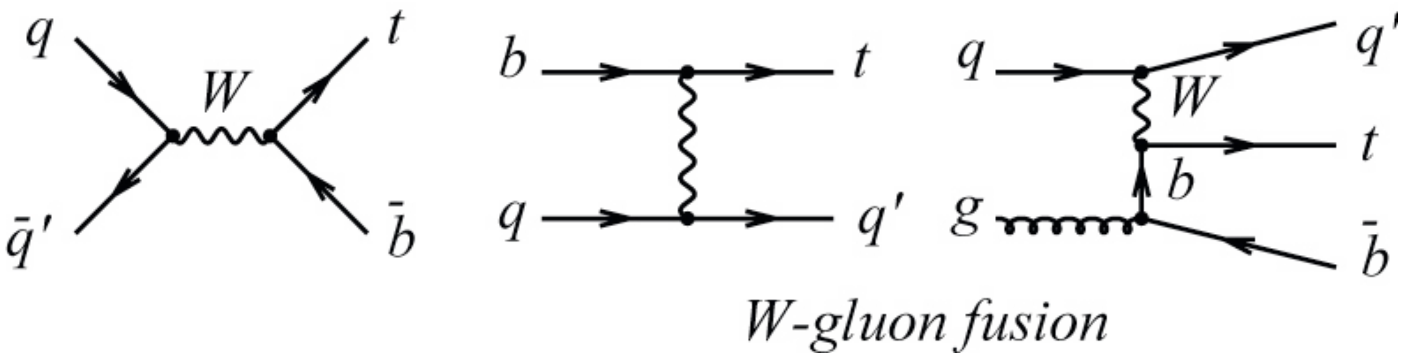
- $M_H = 85^{+39}_{-28}\ GeV/c^2$, or $M_H < 166 GeV/c^2$
- direct search (LEP): $M_H > 114\ GeV/c^2$

⇨ fit suggests SM Higgs is light

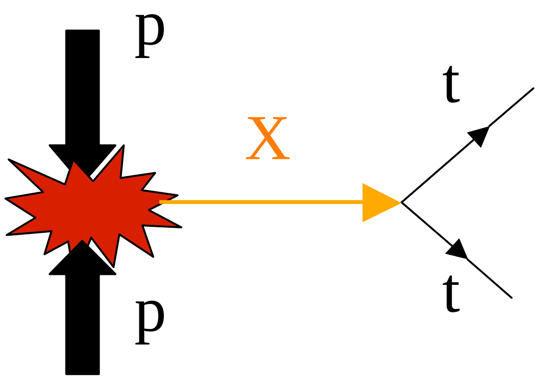


How else is top produced?

Standard Model Tevatron Single Top Production



$$\sigma(\bar{p}p \rightarrow t + X \ @ \ M_{top} = 175 GeV) \approx 3 \text{ pb}$$



Resonance Production?

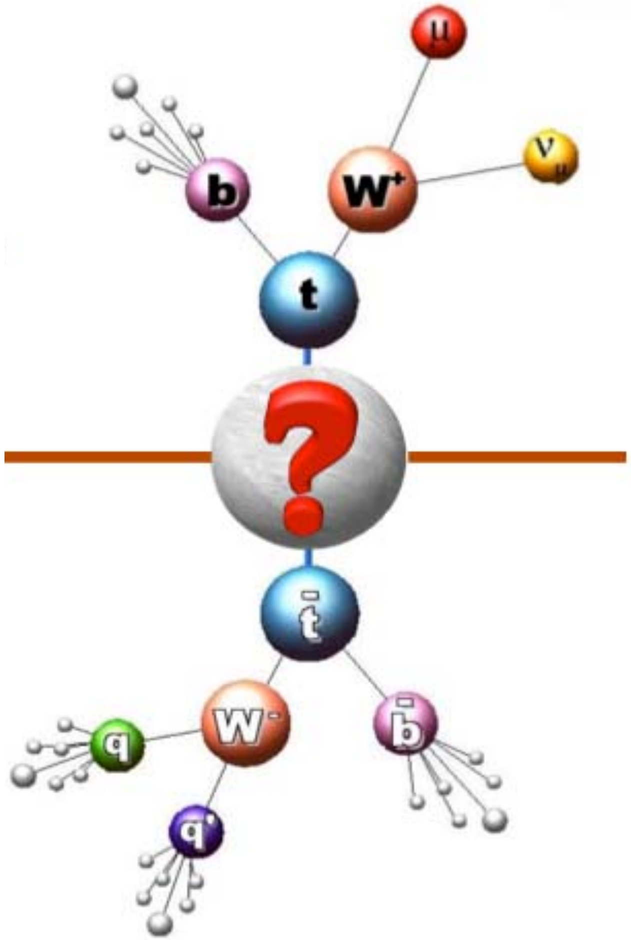
Top Color-Assisted Technicolor

OR

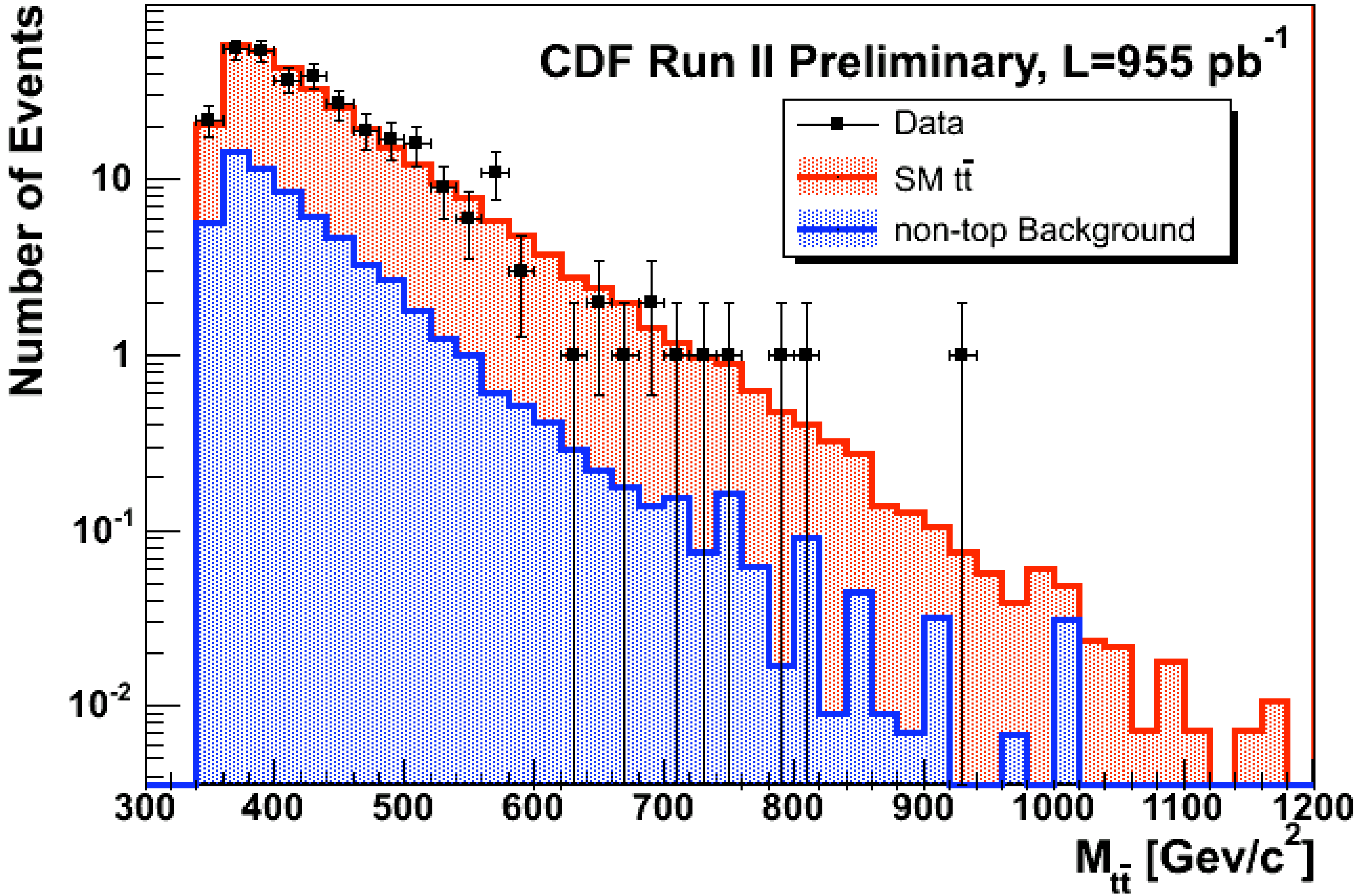
?????

Do top quarks resonate?

- No resonance expected in SM
- Why is Top so heavy?
  - new physics?
  - is third generation ‘special’?
  - couples predominantly to third generation quarks
- Top is relatively unknown experimentally
- Experimental check
  - search for a bump in the invariant mass spectrum

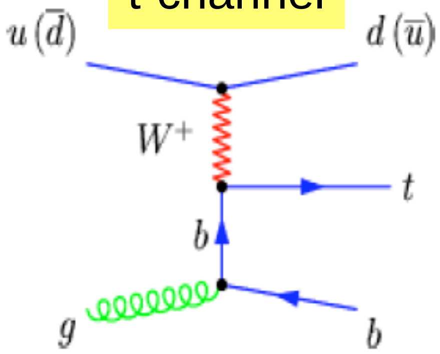


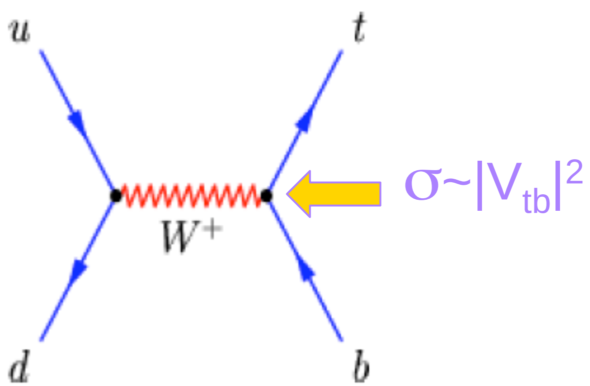
Any hint in the current data?



Single top

t-channel





s-channel

Dominant channels at the Tevatron:

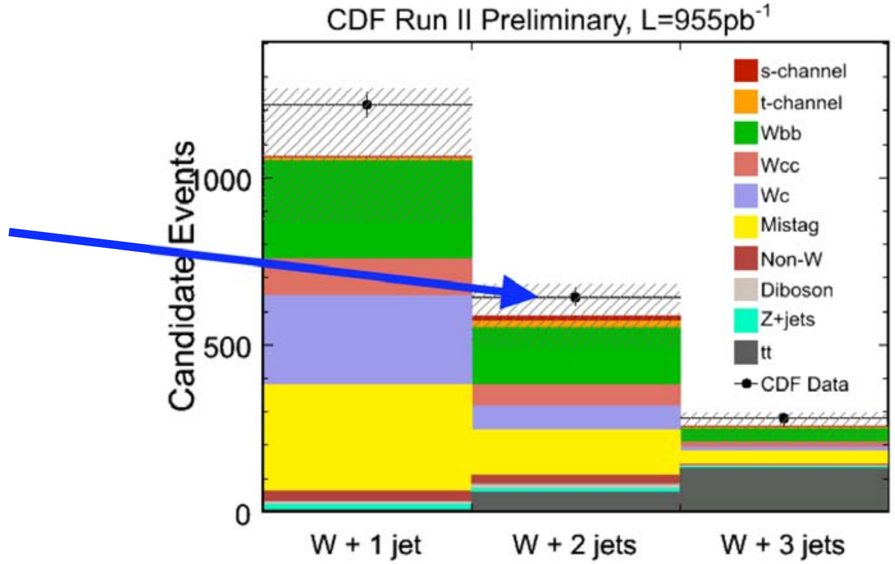
- t-channel:
  - 1.98 pb @1.96TeV
  - hard b-jet, soft b-jet (usually invisible)
- s-channel:
  - 0.88 pb @1.96 TeV
  - two hard-b-jets, W decay products

Why search for single top?

- direct measure of $|V_{tb}|$
- sensitive to non-SM phenomena (W', FCNC)

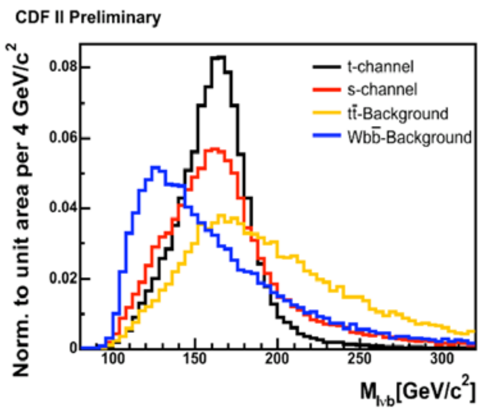
Search for single top

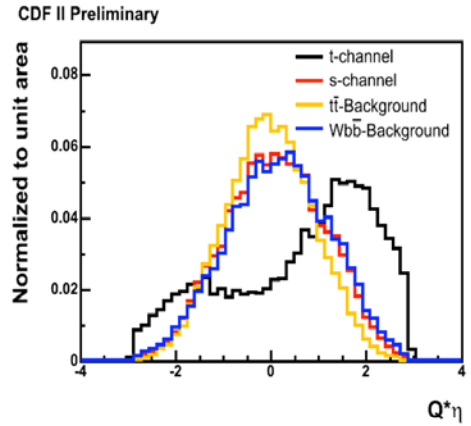
Single top bin swamped in background uncertainty
⇨ counting experiment impossible



Need multivariate techniques:

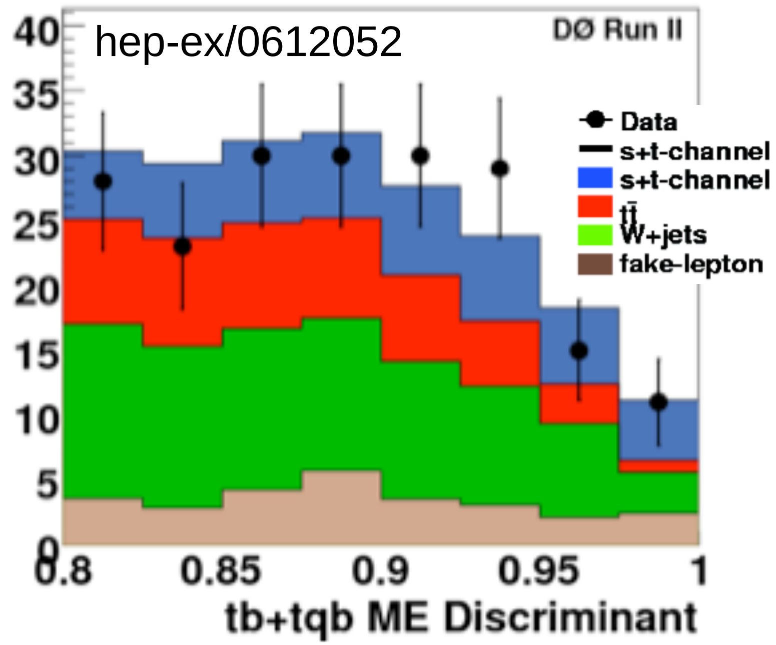
1. Likelihood
2. Matrix element
3. Neural network





Single top results

- Very large background
- Excess over background expectation

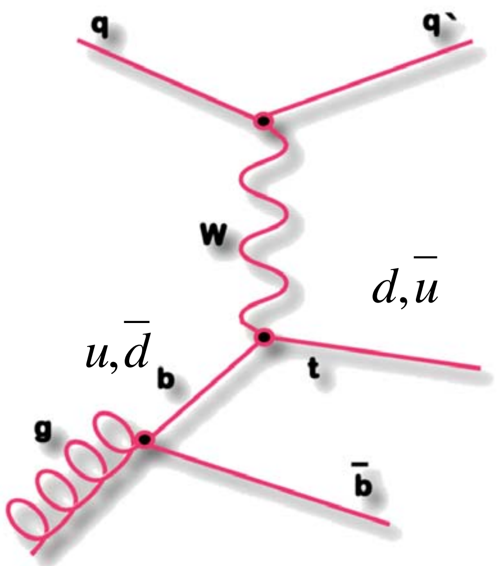


- s+t cross section: 4.9 ± 1.4 pb
- 3.4 σ significance
- first direct measurement:

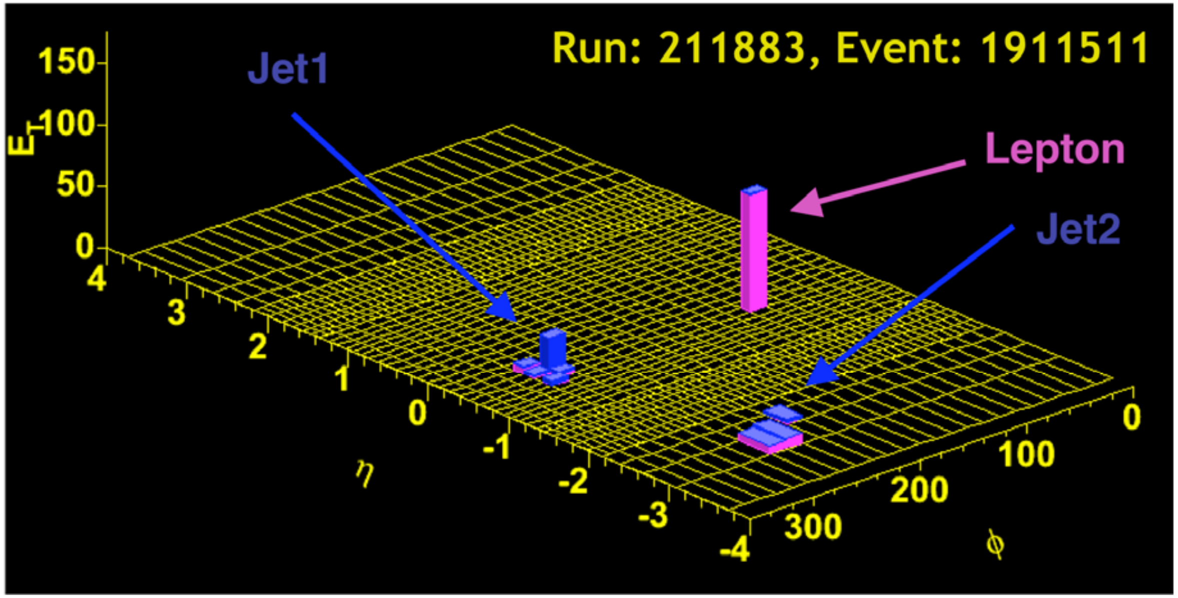
  $0.68 \leq |V_{tb}| \leq 1.00$ @ 95% CL

First evidence for single top events

Single Top Candidate Event



Central Electron Candidate
Charge: -1, Eta=-0.72
MET=41.85, MetPhi=-0.83
Jet1: Et=46.7 Eta=-0.61 (b-tagged)
Jet2: Et=16.6 Eta=-2.91



Is it really top?

- is the top quark we observe really the SM top?
- top properties may provide hint for New Physics
  - production: new resonances
  - decay:
    - $t \rightarrow Wb$?
    - $W \rightarrow b$? or $W \rightarrow q$?
    - W or H?
    - is it a V-A weak decay?

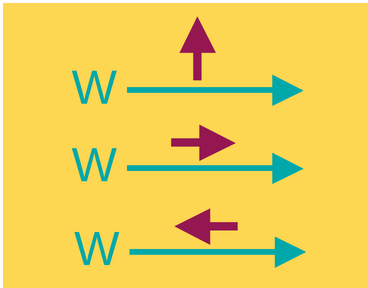
⇨ Still little known on top quark

W helicity in top decays

- Top decays before hadronization:
  spin information directly passed to its decay products (Wb)

- helicity of the ***W*** boson:
  - examines nature of **tbW** vertex
  - provides a stringent test of SM

- helicity of W can be:

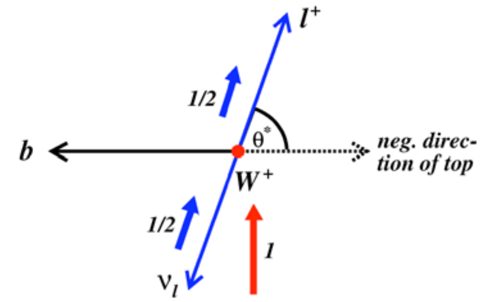


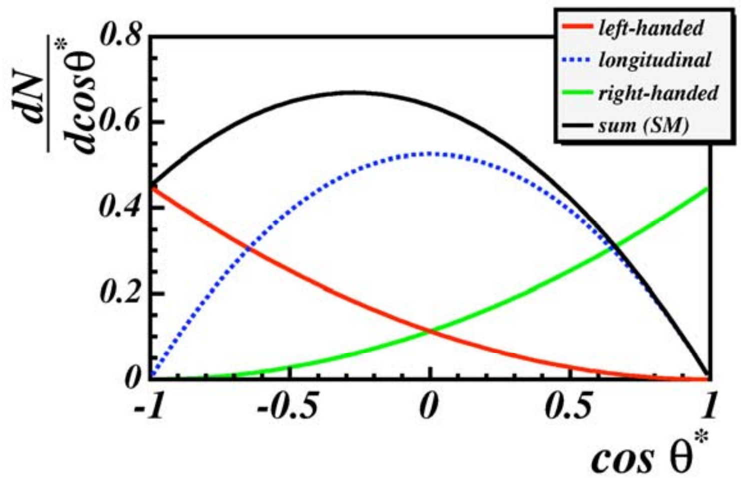
longitudinal (F_0)
left-handed (F_{V-A})
right-handed (F_{V+A})

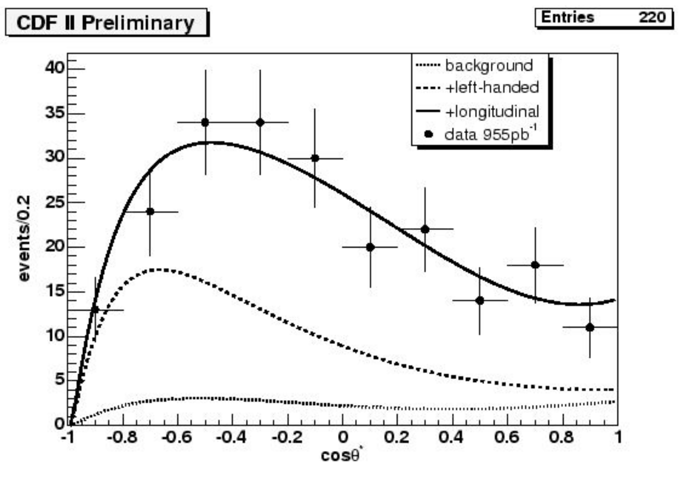
- SM predicts V-A: $\mathbf{F_0=0.70,\ F_{V-A}=0.30,\ F_{V+A}=0}$
  (if V+A ⇨ F_0=0.70, F_{V-A}=0, F_{V+A}=0.30)

W helicity in top decays (cont)

- Can be measured using variables sensitive to angular distributions of W decays (lepton p_T, cos θ*, M_{lb}^2)





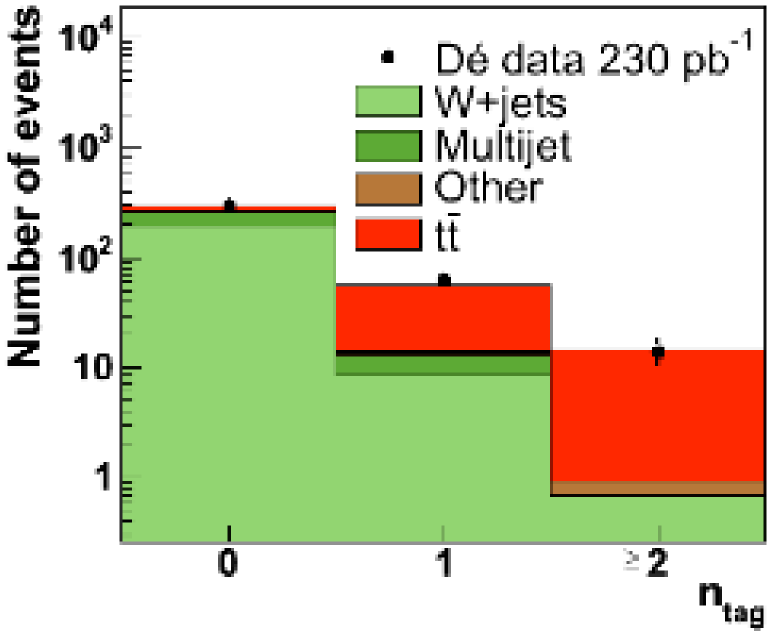


F_0 = 0.74 ± 0.25 ± 0.06
F_+ = -0.06 ± 0.10 ± 0.03
F_+ < 0.11 @ 95% CL

(hep-ex/0612011)

Is BR(t→Wb)~100% ?

- In the SM, $R = \frac{BR(t\to Wb)}{BR(t\to Wq)} \approx |V_{tb}|^2$ (q=b,s,d) 0.9980<R<0.9984
- measure R by comparing the number of ttbar events with 0, 1 and 2 b-tags
- $R \approx O(10^{-1})$ ⇨evidence for New Physics (e.g. 4th generation hep/ph-0607115)



$R = 1.03^{+0.17}_{-0.15}(stat)^{+0.09}_{-0.07}(syst)$

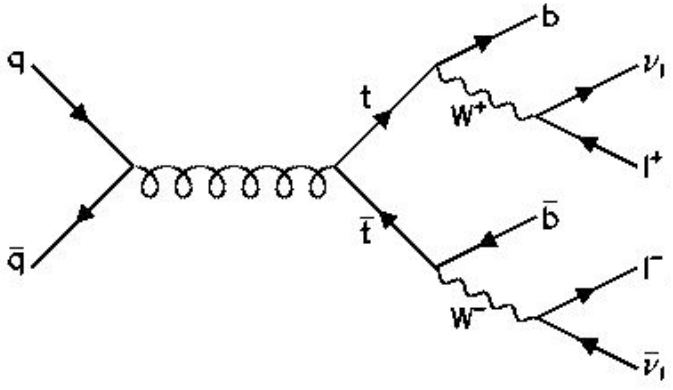
$|V_{tb}|>0.71$ @95% CL (lepton+jets)

$|V_{tb}|>0.68$ @95% CL (single top)

(hep/ex-0612052)

Not yet sensitive to SM

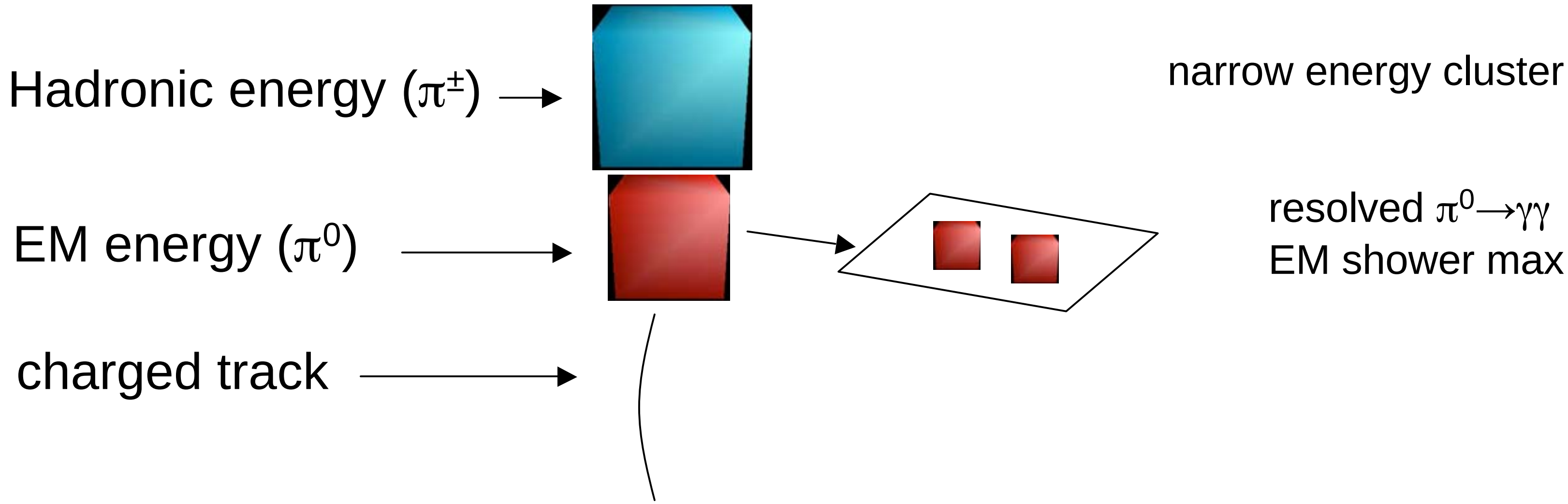
Taus in top decays

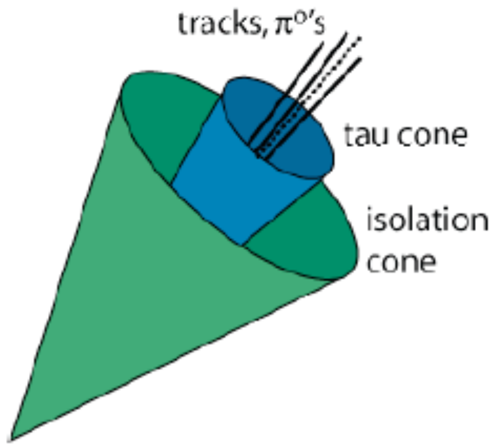


Channel	Signature	BR
Dilepton(e/μ)	*ee*,μμ,*e*μ + 2*b*-jets	4/81
Single lepton	*e*,μ + jets + 2*b*-jets	24/81
All-hadronic	jets + 2*b*-jets	36/81
Tau dilepton	*e*τ, μτ +2 *b*-jets	4/81
Tau+jets	τ + jets + 2*b*-jets	12/81

- should have same rate as *e*μ dilepton channel
- probe to New Physics processes
- challenging (lower p_T than *e* or μ due to ν's)

Tau identification





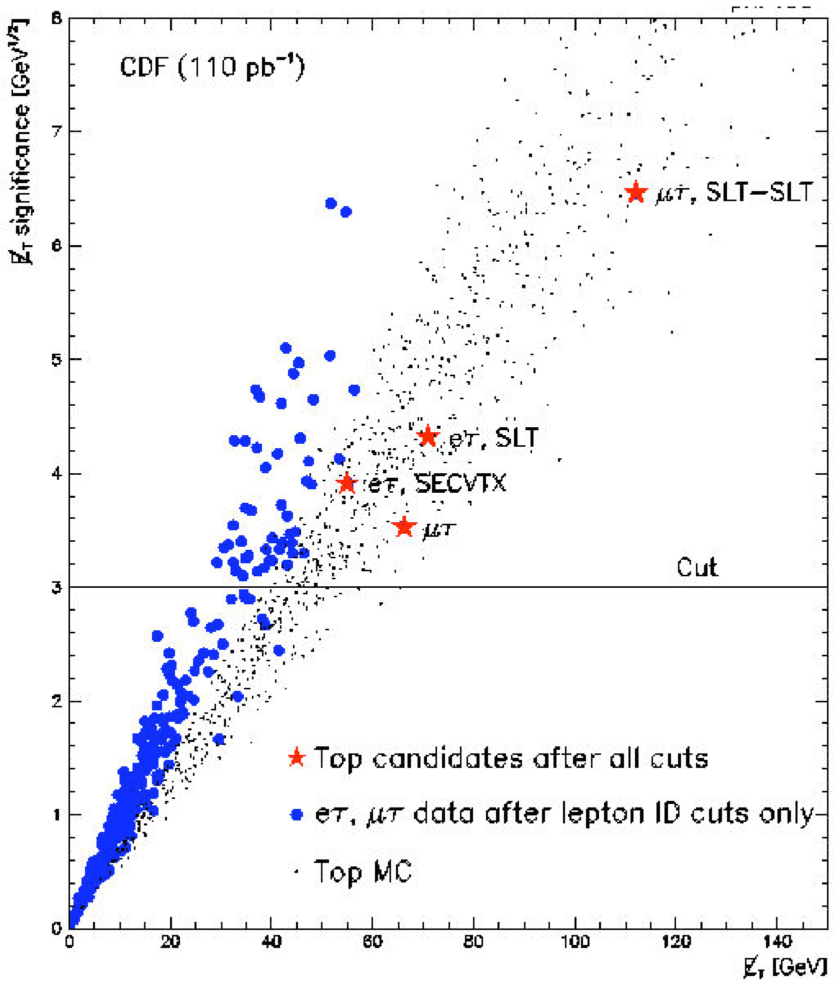
Cone-based algorithm: reconstruct hadronic tau decays from $\pi^{\pm}$ and π^0

Requires track isolation to discriminate against jets

Tau dileptons in data

- 4 candidates found in 110pb^{-1}
  - ⇨3 events are b-tagged
- impact parameter of tau tracks
  - ⇨2 tau tracks have d/σ >0

Selection	Track-based	Calorimeter-based	Combined
tau fakes	0.25 +/- 0.02	0.78 +/- 0.04	1.0 +/- 0.1
Z/gamma->tau tau	0.89 +/- 0.28	1.48 +/- 0.38	1.8 +/- 0.5
WW, WZ	0.14 +/- 0.08	0.24 +/- 0.10	0.3 +/- 0.1
Total Background	**1.28 +/- 0.29**	**2.50 +/- 0.43**	**3.1 +/- 0.5**
Expected from ttbar	0.70 +/- 0.30	1.10 +/- 0.40	0.9 +/- 0.1
Observed events	4	4	4
Observed events with b-tags	3	3	3
Total acceptance	(0.085 +/- 0.016)%	(0.134 +/- 0.023)%	(0.172 +/- 0.014)%



Charged MSSM Higgs production

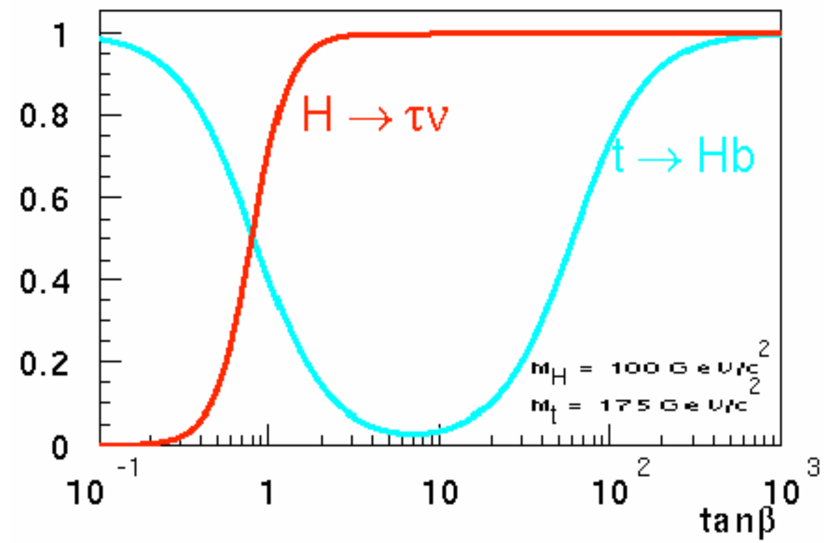
Does top always decay to W^+b?

If top decays: $t \rightarrow H^+b$ $(m_H < m_t - m_b)$

- BR($t \rightarrow H^+b$) could be large
- $H^+ \rightarrow \tau^+\nu_\tau$ enhanced if $\tan\beta$ large

⇨**observe more taus**

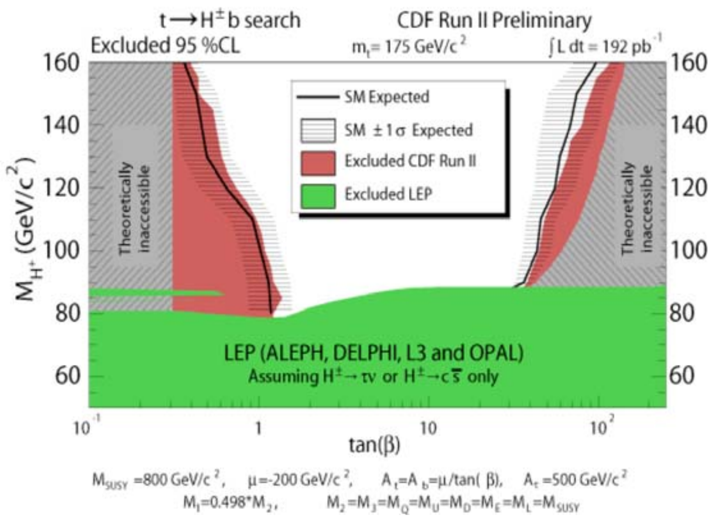
($\tan\beta$: ratio of vacuum expectation values)

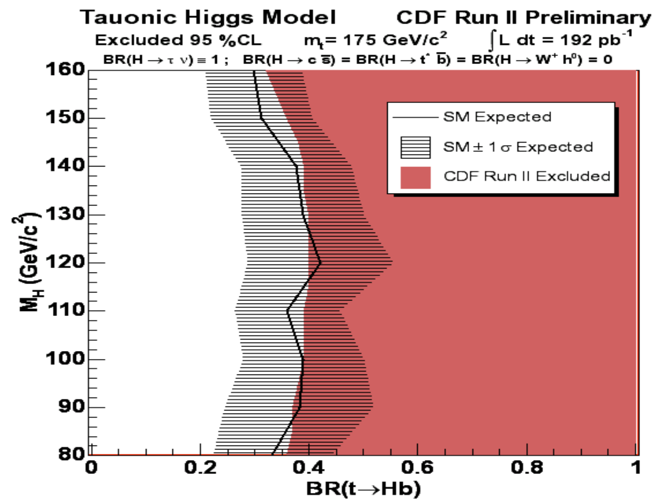


Search for H±: Results

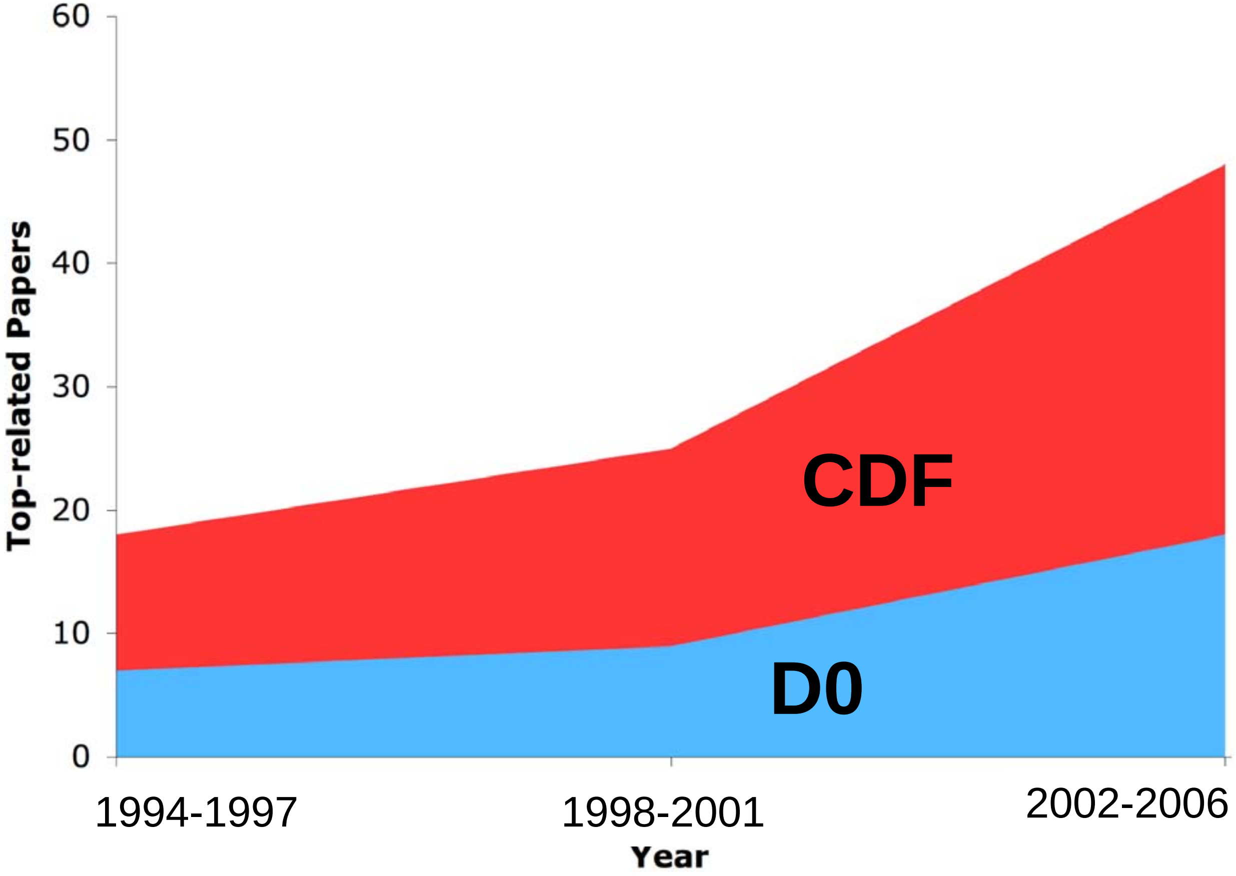
Final state	Background	SM exp.	data
2l+jets	2.7 ± 0.7	11	13
l+jets(1b)	20.3 ± 2.5	54	49
l+jets (≥2b)	0.9 ± 0.2	10	8
l+τ_h+jets	1.3 ± 0.2	2	2

⇨data agree with SM expectations

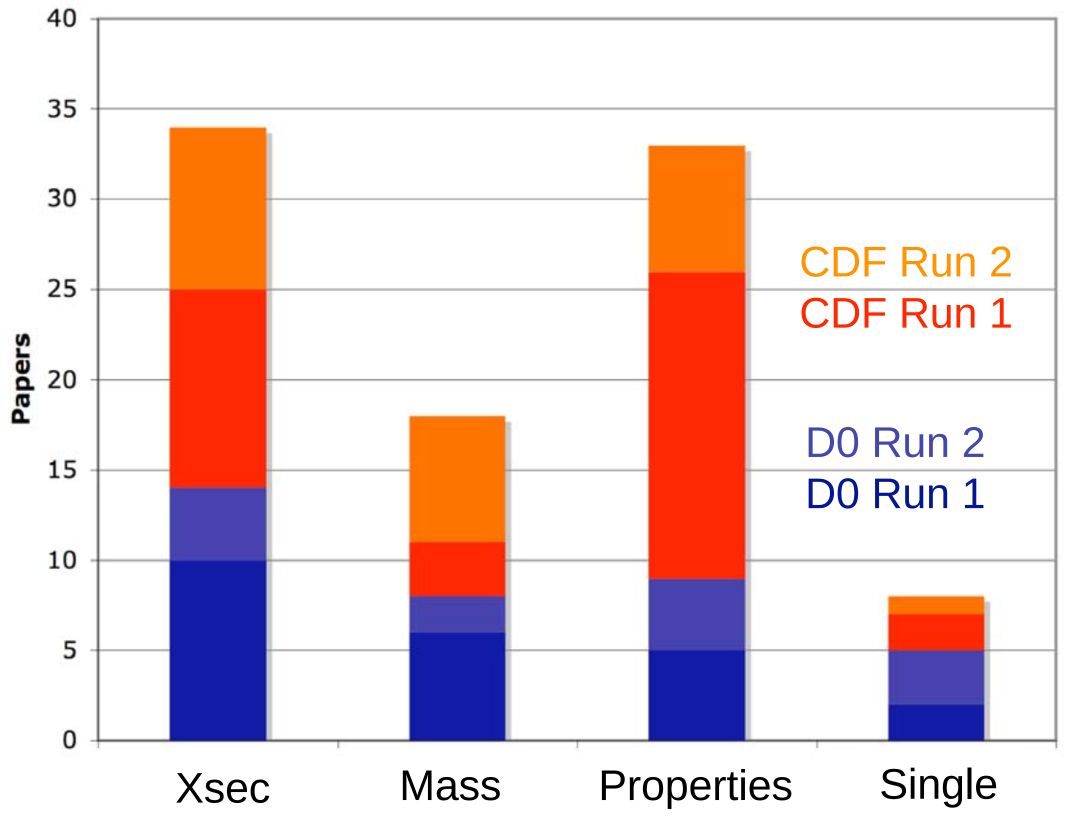




Top-related publications

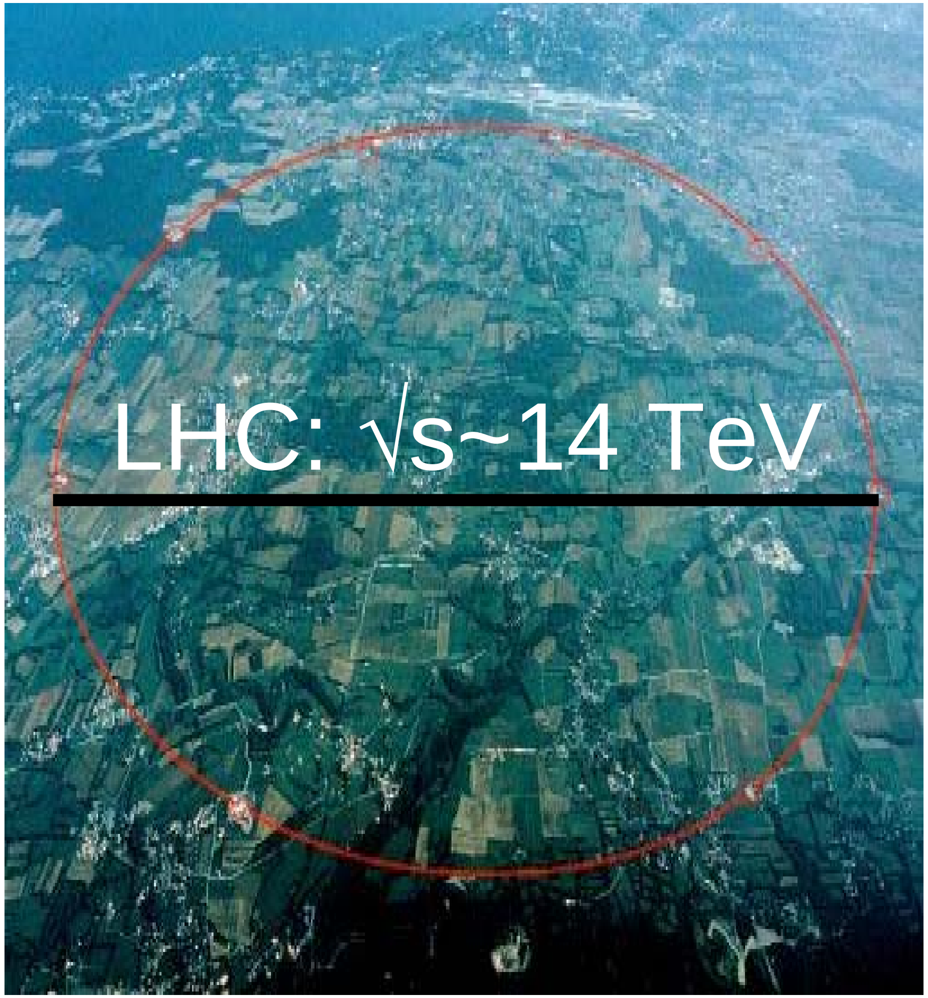


By subject

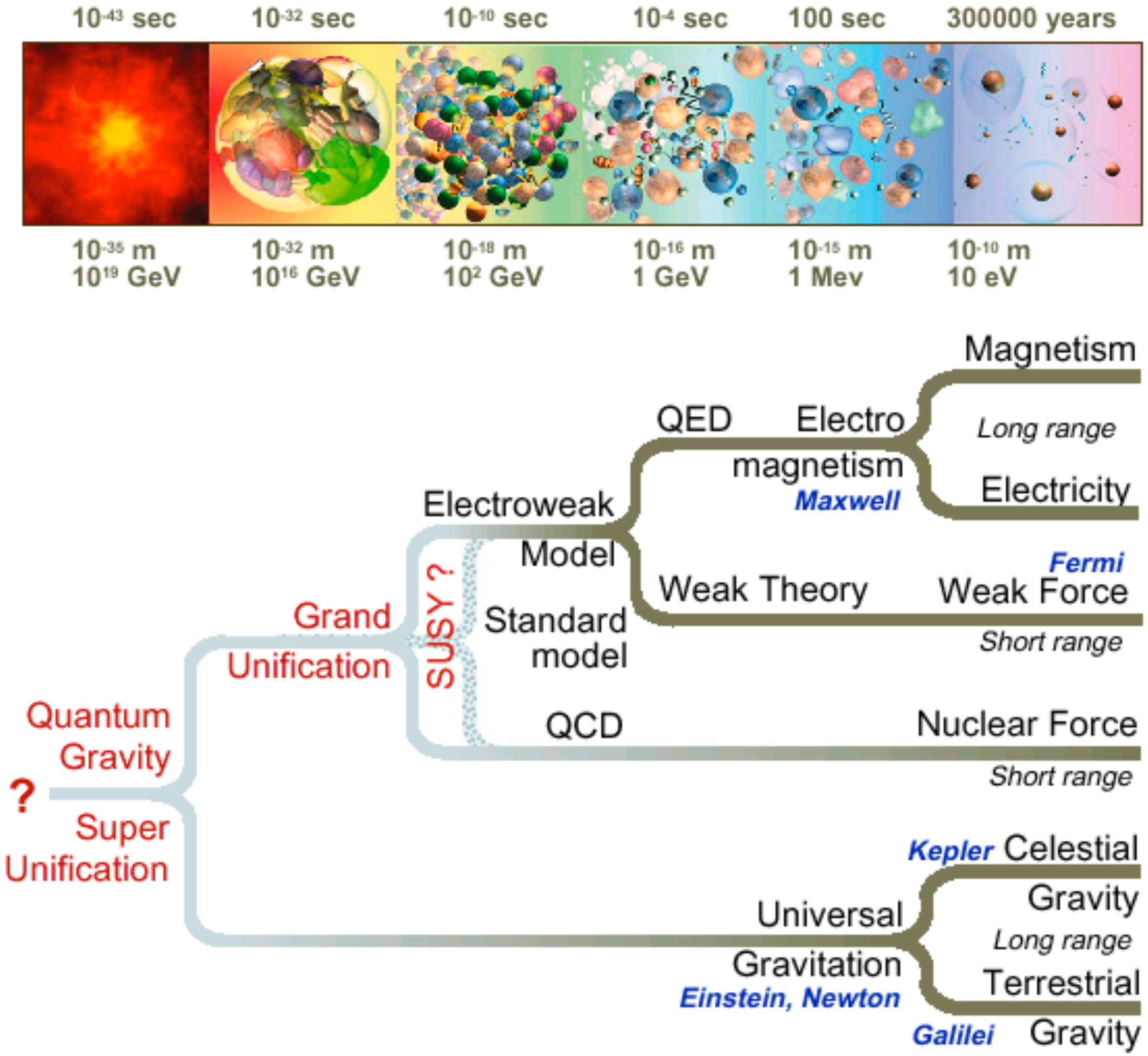


40
35
30
25
20
15
10
5
0
Papers
CDF Run 2
CDF Run 1
D0 Run 2
D0 Run 1
Xsec
Mass
Properties
Single

New energy frontier



A smaller scale



Tev2LHC

- **Tevatron Run II:**

  Integrated luminosity ~ $1fb^{-1}$

  Peak luminosity ~ $2.7x10^{32}$ cm^{-2} sec^{-1}

  Current high energy frontier for new physics searches

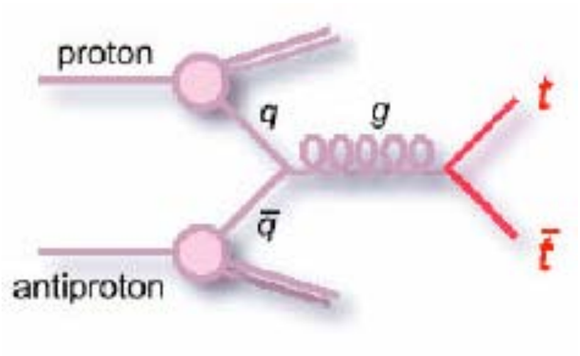
- **The LHC:**

  CM energy: > x7, integrated luminosity > x100

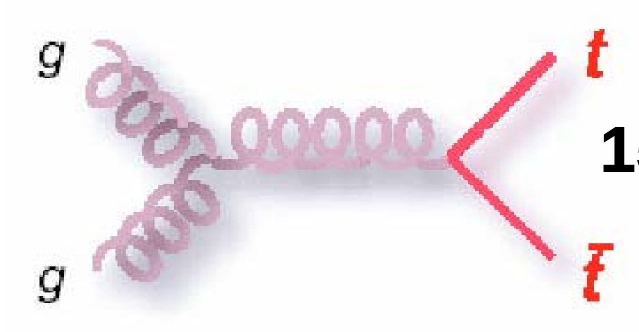
⇨**New physics discovery expected**

…however, it will be challenging!

Top quark production



85%



15%

	Run 1	Run 2	LHC
	ppbar	ppbar	pp
E_{CM}	1.8 TeV	1.96TeV	14 TeV
qq	90%	85%	5%
gg	10%	15%	95%
σ_{tt}	5.0 pb	6.7 pb	830 pb

- σ $(tt)_{LHC}$~100 x $\sigma(tt)_{TEV}$
- at LHC, fraction of qq vs gg is inverted
- top mostly produced in pairs
- typical S/B 0.5 at TeV, 2.5 at LHC

LHC startup @ 900 GeV in 2007

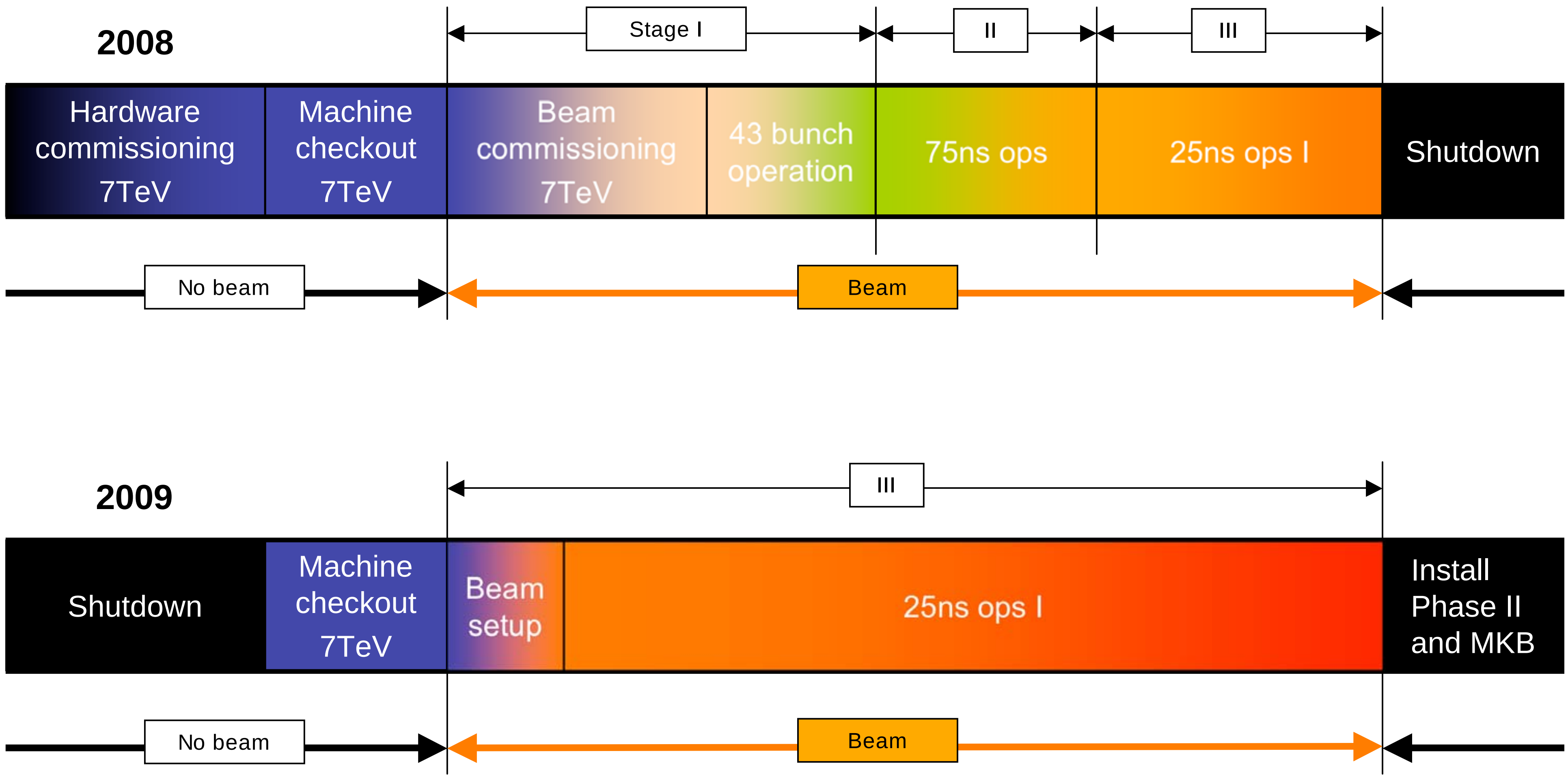
			Reasonable	Maximum
k_b	43	43	156	156
i_b (10^{10})	2	4	4	10
β^* (m)	11	11	11	11
intensity per beam	$8.6\ 10^{11}$	$1.7\ 10^{12}$	$6.2\ 10^{12}$	$1.6\ 10^{13}$
beam energy (MJ)	.06	.12	.45	1.1
Luminosity $(cm^{-2}s^{-1})$	$2\ 10^{28}$	$7.2\ 10^{28}$	$2.6\ 10^{29}$	$1.6\ 10^{30}$
event rate [1] (kHz)	0.4	2.8	10.3	64
W rate [2] (per 24h)	0.5	3	11	70
Z rate [3] (per 24h)	0.05	0.3	1.1	7

several days →

1. Assuming 450GeV inelastic cross section 40 mb
2. Assuming 450GeV cross section $W \rightarrow l\nu$ 1 nb
3. Assuming 450GeV cross section $Z \rightarrow ll$ 100 pb

From Cern/Accelerator Division

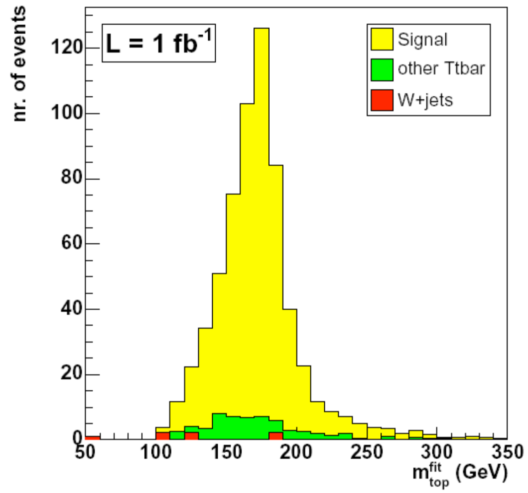
Collisions at 14 TeV



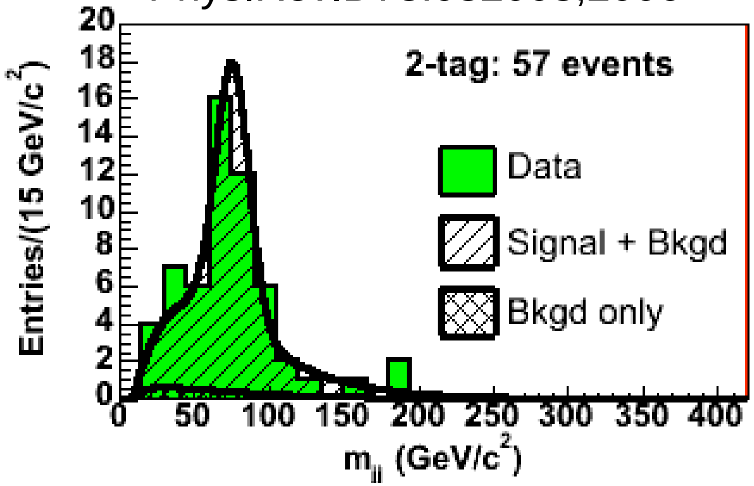
From Cern/Accelerator Division

Top quarks at the LHC

- $\sqrt{s}$=900 GeV in 2007, 14 TeV in 2008
- 0.1-1.0 fb^{-1} expected in 2008
- LHC is a top factory
  - 10 tt pairs/day @TeV ⇔ 1 tt pair/sec @LHC
  - approx. 830k ttbar events/fb
- yield in 1/fb (after selection):
  - dilepton (e/μ): ~5k events
  - lepton+jets: ~35k events
- energy scale calibration (W→jj)



Phys.Rev.D73:032003,2006



Di-lepton channel

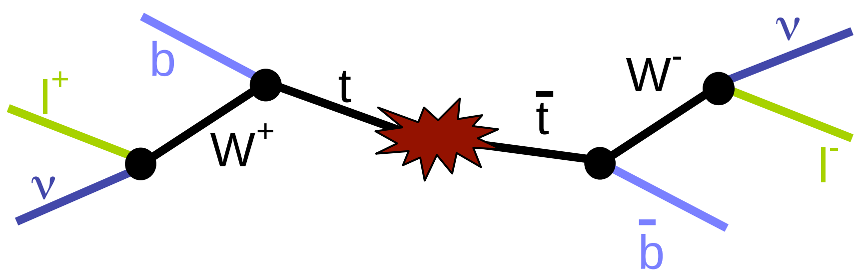
- Measure BR in top decays:

$$R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$$

SM: R = 0.9980 to 0.9984 @ 95% CL

$R=1.03\,^{+0.17}_{-0.15}(stat)\,^{+0.09}_{-0.07}(syst)$ (hep-ex/0607115)

- Complementary to lepton+jets
- Advantages:
  - less combinatorial ambiguity
  - less background
- Disadvantages:
  - lower statistics



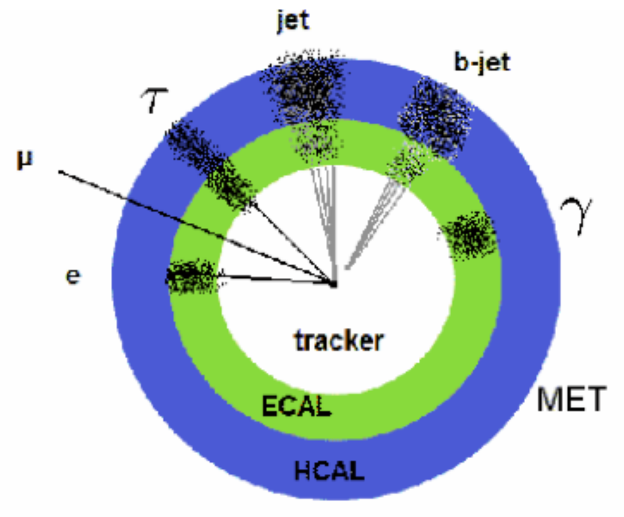
Presented at Top working group: Feb 2007
Collaboration with A. Giammanco & D. Kcira (Louvain)

Di-lepton channel (cont)

- Selection:
  - 2 leptons+ ≥2 jets + MET
  - no b-tagging in preselection
  - 4% uncertainty achieved on b-tagging efficiency
- S/B = 5197/957 ~5 with 1/fb (CMS 2006/013)
- Plan:
  - reproduce/improve efficiencies
  - study background:
    - W/Z+jets, single top, gluon splitting, etc.
  - simultaneous extraction of R and ε(b)
    - 2 unknowns with 2 observables: N(2tag)/N(1tag) and N(1tag)/N(0tag)

Tau dileptons

- Measure: $R = \frac{BR(tt \rightarrow l\tau)}{BR(tt \rightarrow ll)}$ (l=e,μ)



- Advantages:
  - increase statistics
  - cross-check to other BRs
- Disadvantages:
  - small statistics/larger background
  - soft tau p_T due to neutrinos

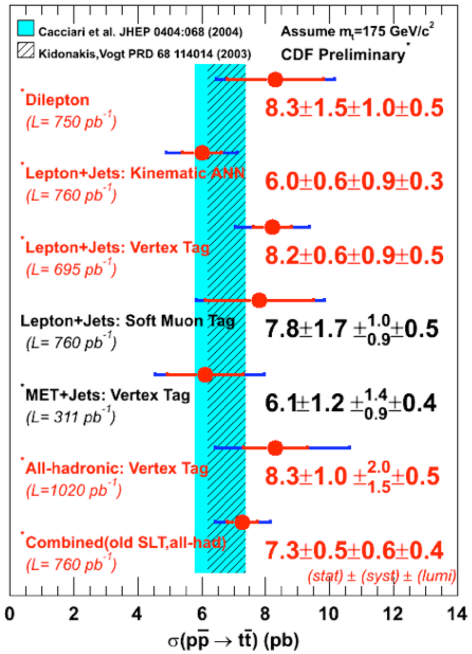
⇨ test lepton universality
⇨ probe non-standard physics ($t \rightarrow Hb$, …)

Tau dileptons (cont)

- Selection:
  - e/μ + ≥ 2 jets + MET + tau
  - no b-tagging in preselection
- Expected event yield in 1/fb:
  - S/B = 750(290)/1370(36) ~ 0.5 (8.0)
    (after b-tagging in parenthesis)
    from CMS 2006/077
- Background to SUSY/Higgs searches

In 10/fb:
$\Delta\sigma_{tt,\tau\text{-dil}}/\sigma_{tt,\,\tau\text{-dil}}$=16% (sys) ±1.3%(stat) ± 3%(lum)

tau dileptons PRL79(1997)3585



Conclusions

- top is a relatively unknown particle
- some current measurements are still statistically limited

- LHC is a top factory
- use top quarks to re-establish SM
- precision measurements can provide hint to New Physics