Top Quark Physics
from the Tevatron to the LHC

Introduction to Terascale Physics 2011
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für Bildung
und Forschung

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Outline

- Introduction
- Top Quark Production
- History of Top Quark Search, Discovery
- Tools for Top Physics at a Hadron Collider
- Measurements of Top Production: Cross Sections, differential CS, Asymmetries, BSM in M(tT)
- Top Properties: Mass
- Top Production: Single Top →Top width and lifetime
- Top decay: W helicity, spin correlations (production and decay)

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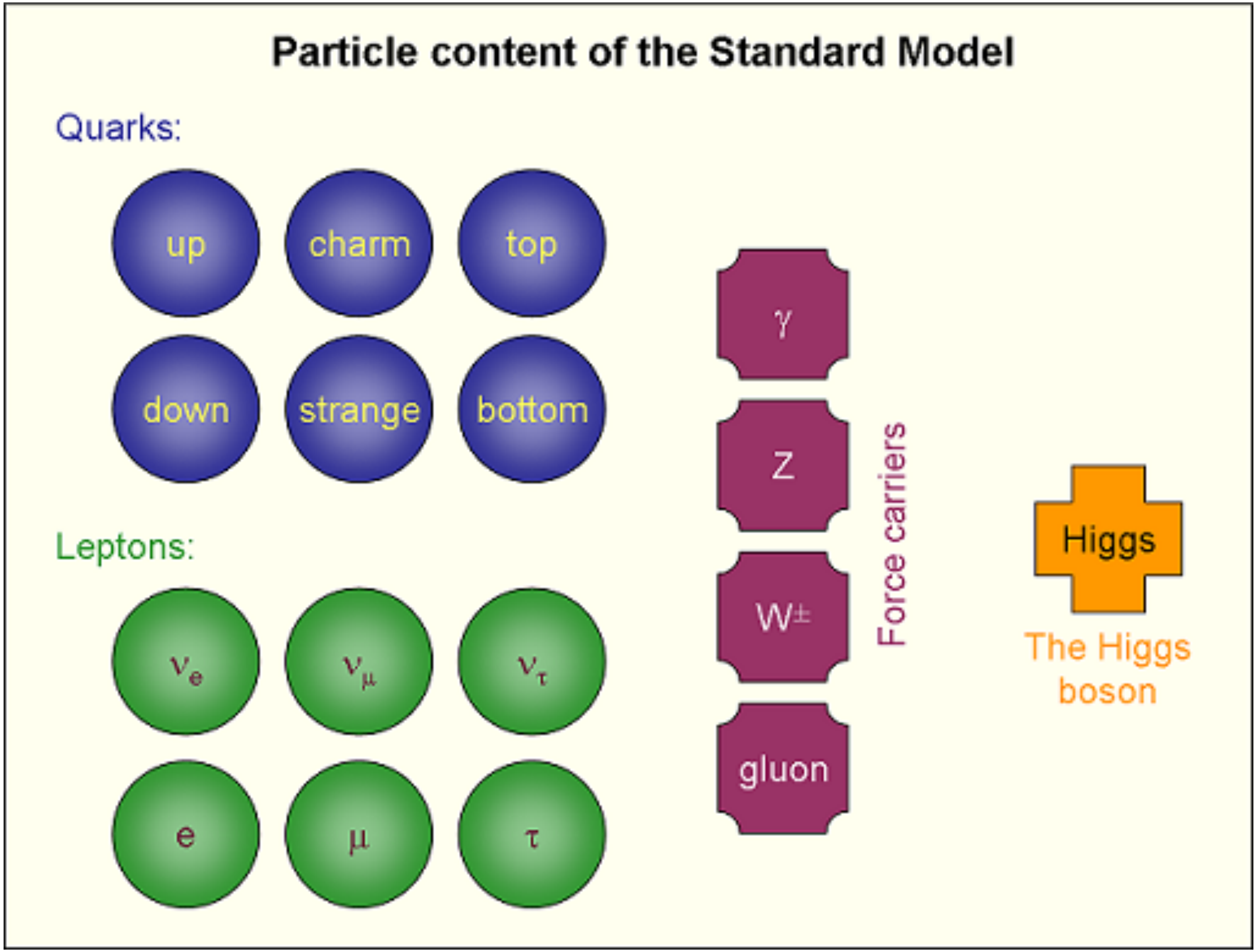
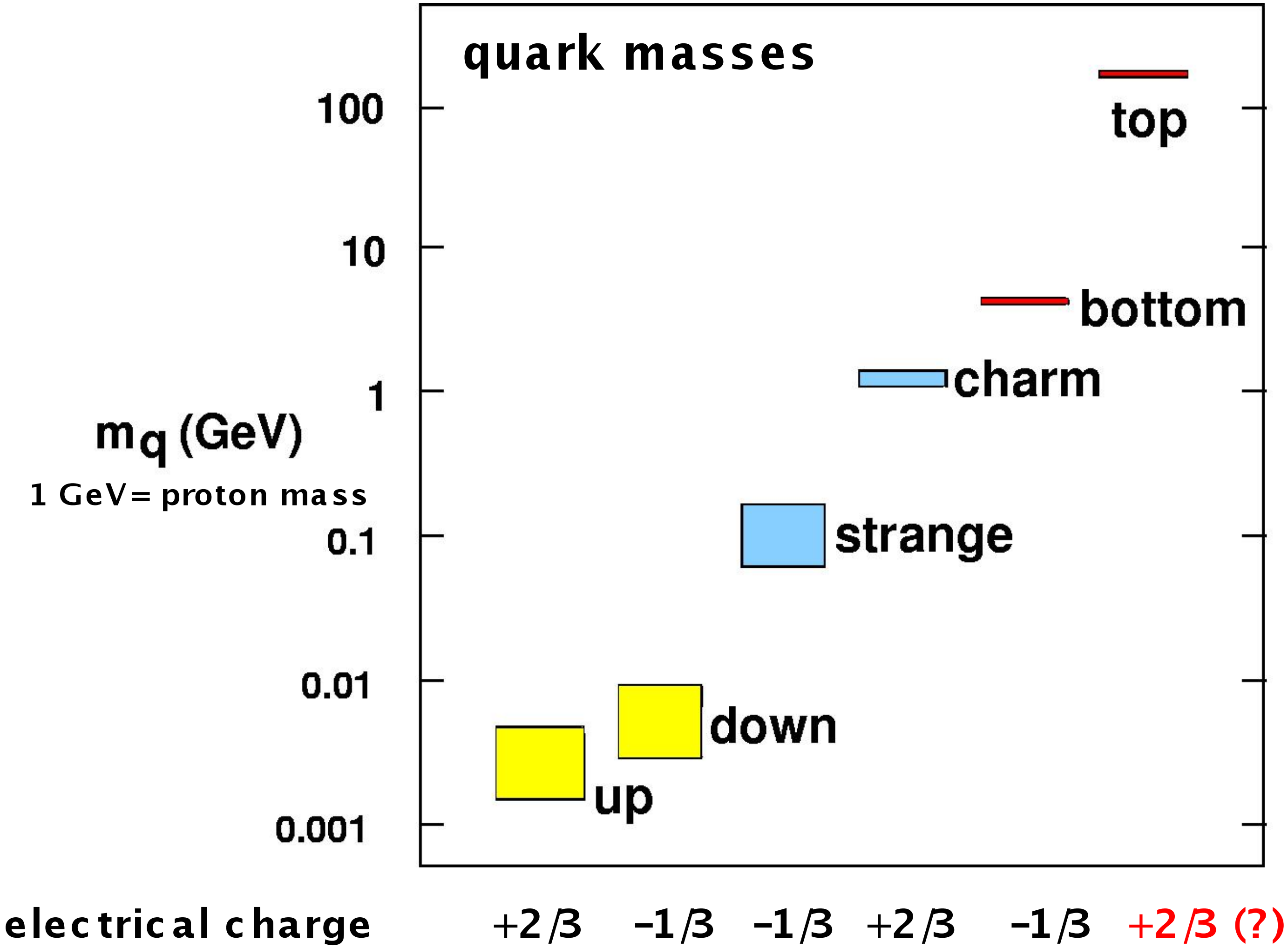
Introduction: The standard model



Quark Properties



Strong mass hierarchy.
Top quark heaviest known particle.Almost as heavy as a gold atom!

Why is the Top Quark so special?

1) Connection to mass:

Standard model described by $SU(3)_{Color} x SU(2)_L x U(1)_Y$ symmetry.
Initially leads to massless particles, in clear contradiction to observation.
One solution: Electroweak symmetry breaking aka Higgs-Mechanism
Introduces new scalar Higgs field with non-zero vacuum expectation value v=246GeV that breaks the SU(2)xU(1) electroweak symmetry.
Electroweak gauge interaction → Weak gauge bosons (W,Z) obtain their masses
Yukawa coupling Y → Lepton and quark masses proportional to Higgs VUV and $Y_{q,l}$
Strong mass hierarchy → Y ranges from 10^{-6}(electron)…10^{-2} (b-quark) up to ~1 for the top quark

$$\boxed{y_t = \sqrt{2}m_t/v \simeq 1}$$

→Top strongly couples to dynamics of electroweak symmetry breaking
Note also: Higgs Boson coupling to Fermions: $g \sim m_f$
→Good laboratory to test mechanism of EWSB. I.e. is it Higgs or something else…

Also: Quantum loop corrections from BSM larger for top quark observables than for lighter particles

New physics can effect tT production in two ways:
1) Production of tT via intermediate particles
2) Decay of top into new particles (for example $t \rightarrow H^+ b$ in models with multiple Higgs doublets)

→Production (1) and decay(2) variables both sensitive to new physics. Look at the complete picture.

Why is the Top Quark so special?

2) Short lifetime (in the end again connected with mass…)

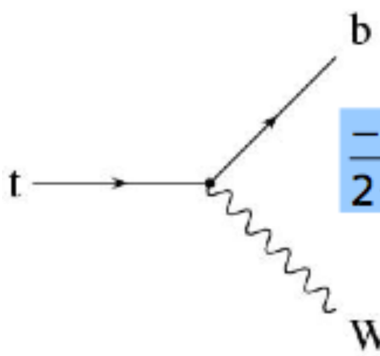
Lifetime τ_{top}~$5\mathrm{x}10^{-25}$s (compare with τ_b~$1.5\mathrm{x}10^{-12}$s)
τ_{top}<< hadronisation timescale (τ_{had}~10^{-23}s)
→Top decays before it hadronizes:
→Spin information preserved in decay products!
→study bare quarks. For example: Quark mass, not meson mass

$m_{top} \gg m_W$ ⇨ real W in top decay

$$\tau_t \sim \frac{1}{|V_{tb}|^2} \cdot \frac{1}{m_t^3} \approx 5 \cdot 10^{-25}\, s$$

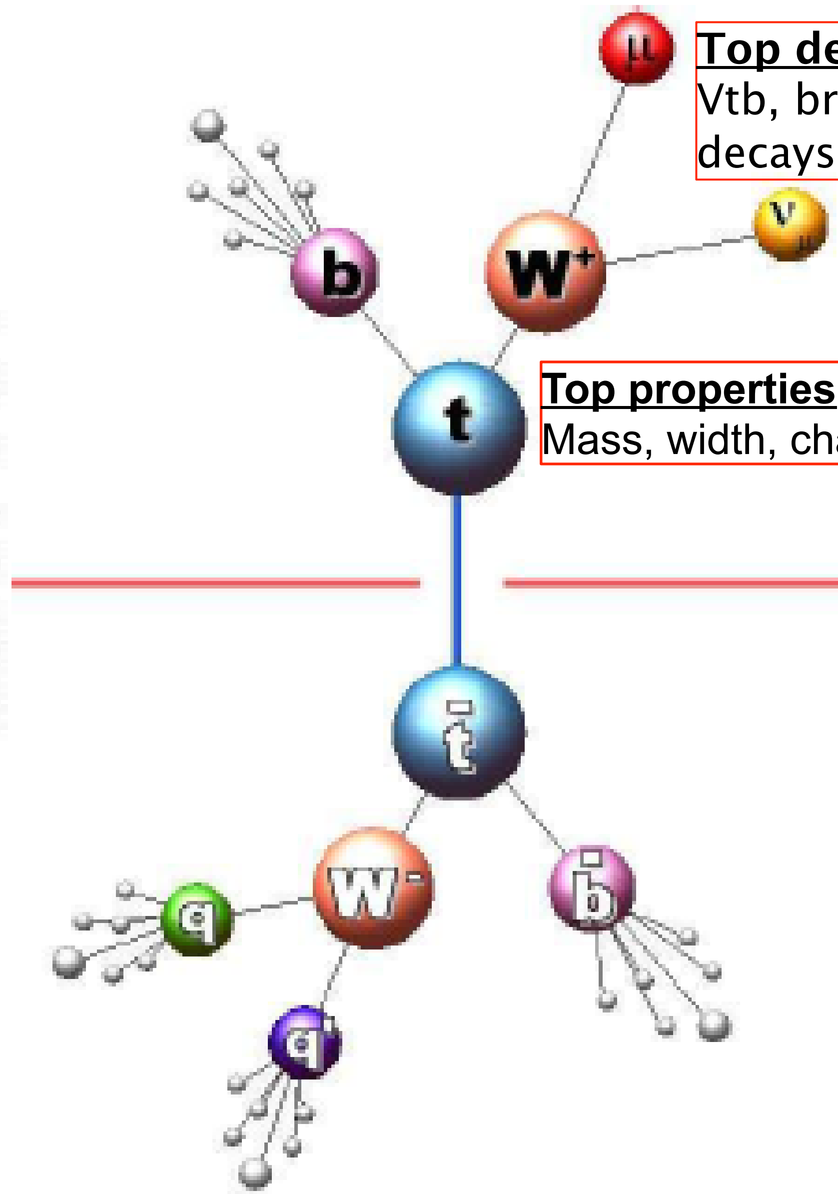
compare to b-quark:

$$\tau_b \sim \frac{1}{a|V_{cb}|^2 + b|V_{ub}|^2} \cdot \frac{1}{m_b^5} \approx 1.5 \cdot 10^{-12}\, s$$



$$\frac{-i\,g}{2\sqrt{2}} \bar{t} \gamma^\mu (1-\gamma^5) V_{tb} b W_\mu$$

Top Quark Physics: Overview



Top decay:
Vtb, branching ratios, rare decays, W helicity

Top properties:
Mass, width, charge, spin,…

Top production:
tT cross section, productions dynamics, spin polarization

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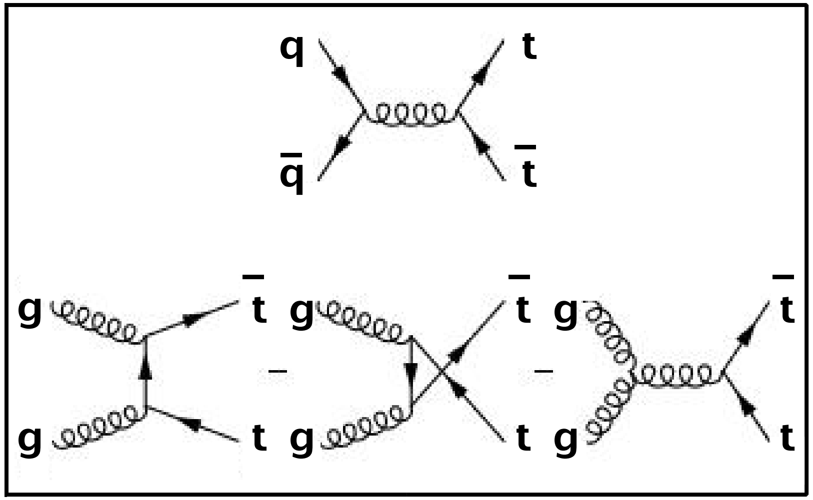
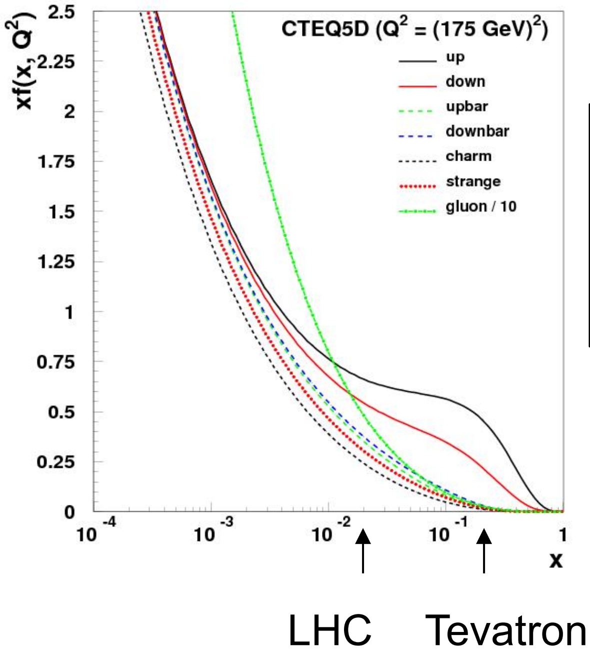
Top Quark Production (tT)

Tevatron: qqbar: 85% gg: 15%
LHC: qqbar: 15% gg: 85%

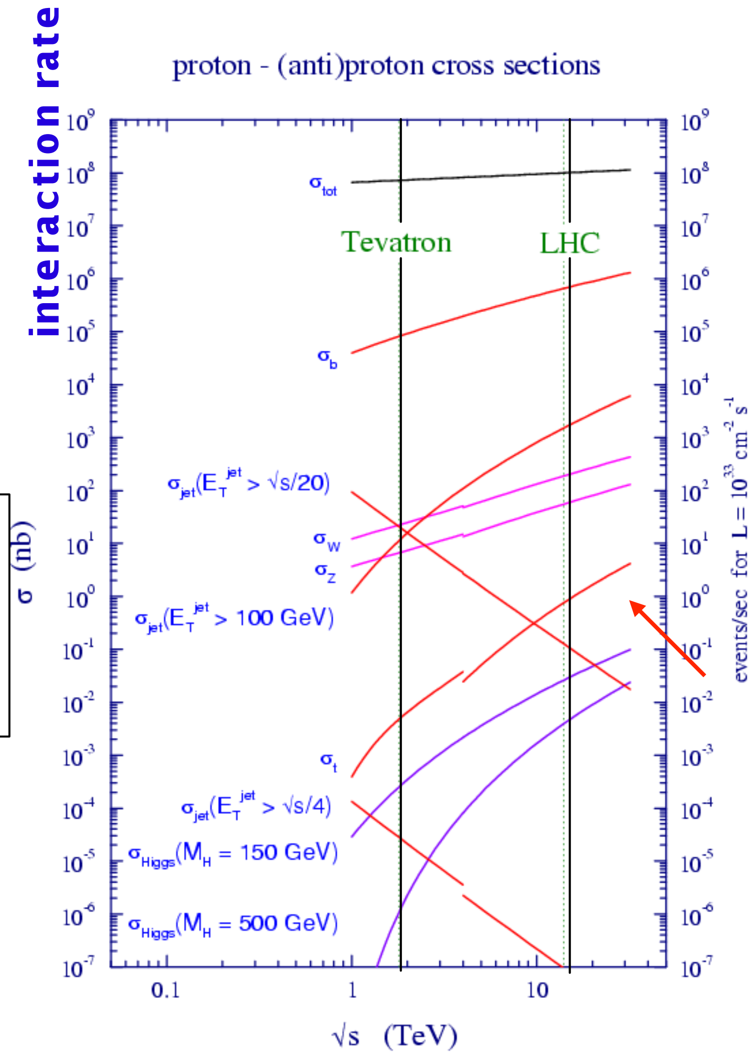




Number of events:

Run I	Run II	LHC
20	800	8x10^6

(Tt sample >=1 btag)



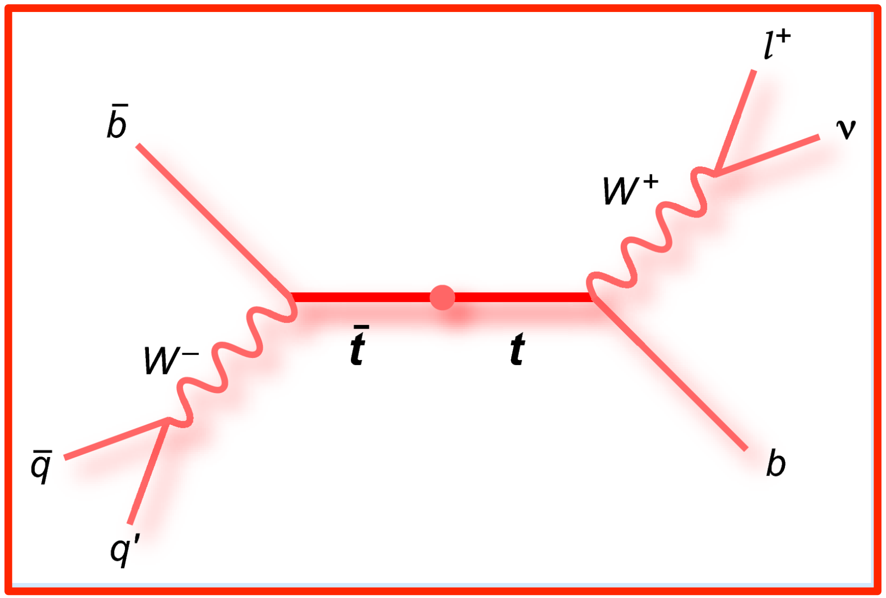
Tt Decay Channels

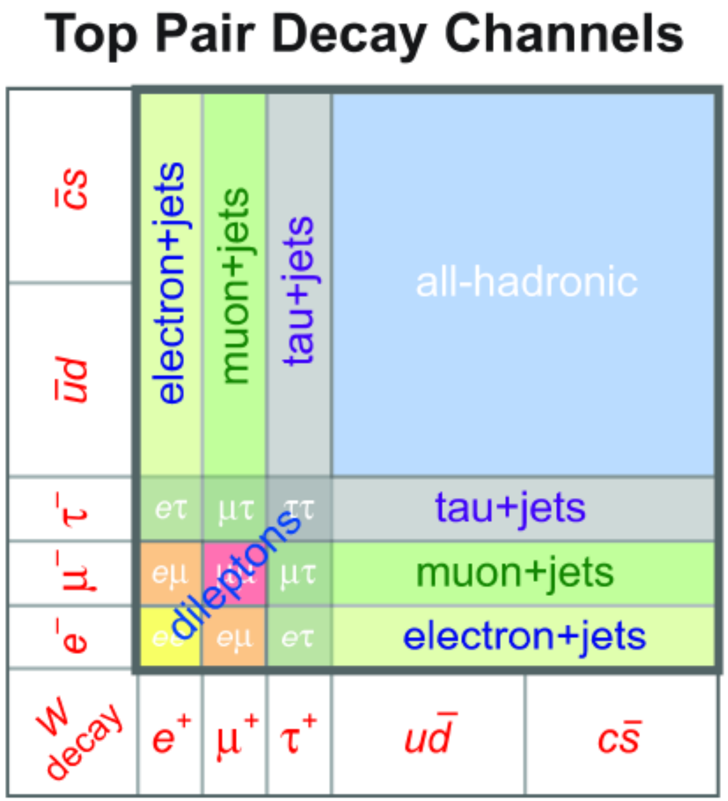
Top quark pairs:

- Top decay ~100% → Wb → **tT** → $b\bar{b}$ + W^+W^-

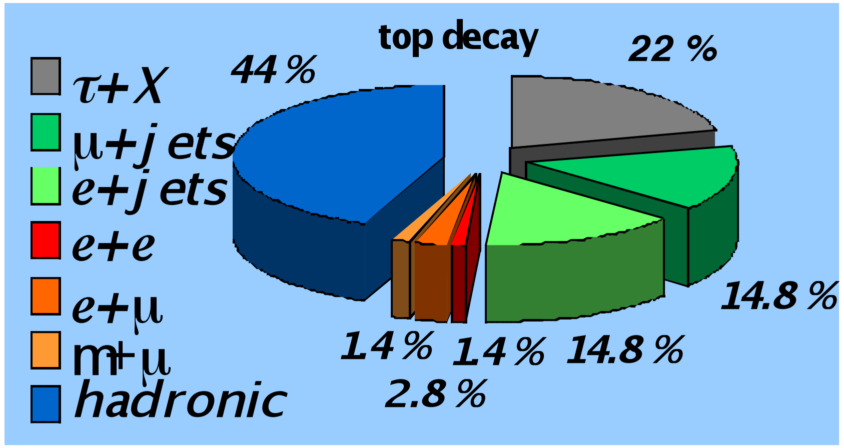
- **decay channels:** (3 leptons, 2 quark families, 3 colour, 2 branches)
  - dileptonic: 3x3 = 9 → 11 %
  - semileptonic: 3x2x3x2 = 36 → 44 %
  - all-hadronic : 2x2x3x3 = 36 → 44 %

  Σ = 81

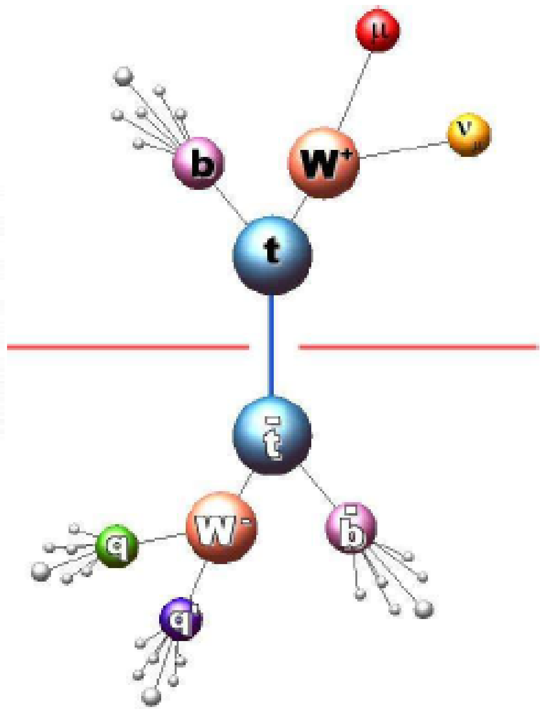




Tt Decay Channels: Experimantal Signatures



- Top decay ~100% →Wb
- Classification of the events and experimental search strategy according to decay of W-bosons



- Dilepton channel (without tau)
  - 5%: 2 charged leptons, 2 jets, 2 ν
- lepton+jets channel (without tau)
  - 30%: 1 charged leptons, 4 jets, 1 ν
- all-jets channel
  - 44%: 6 jets

Note: At least 2 jets are b jets

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History of Particle Discoveries

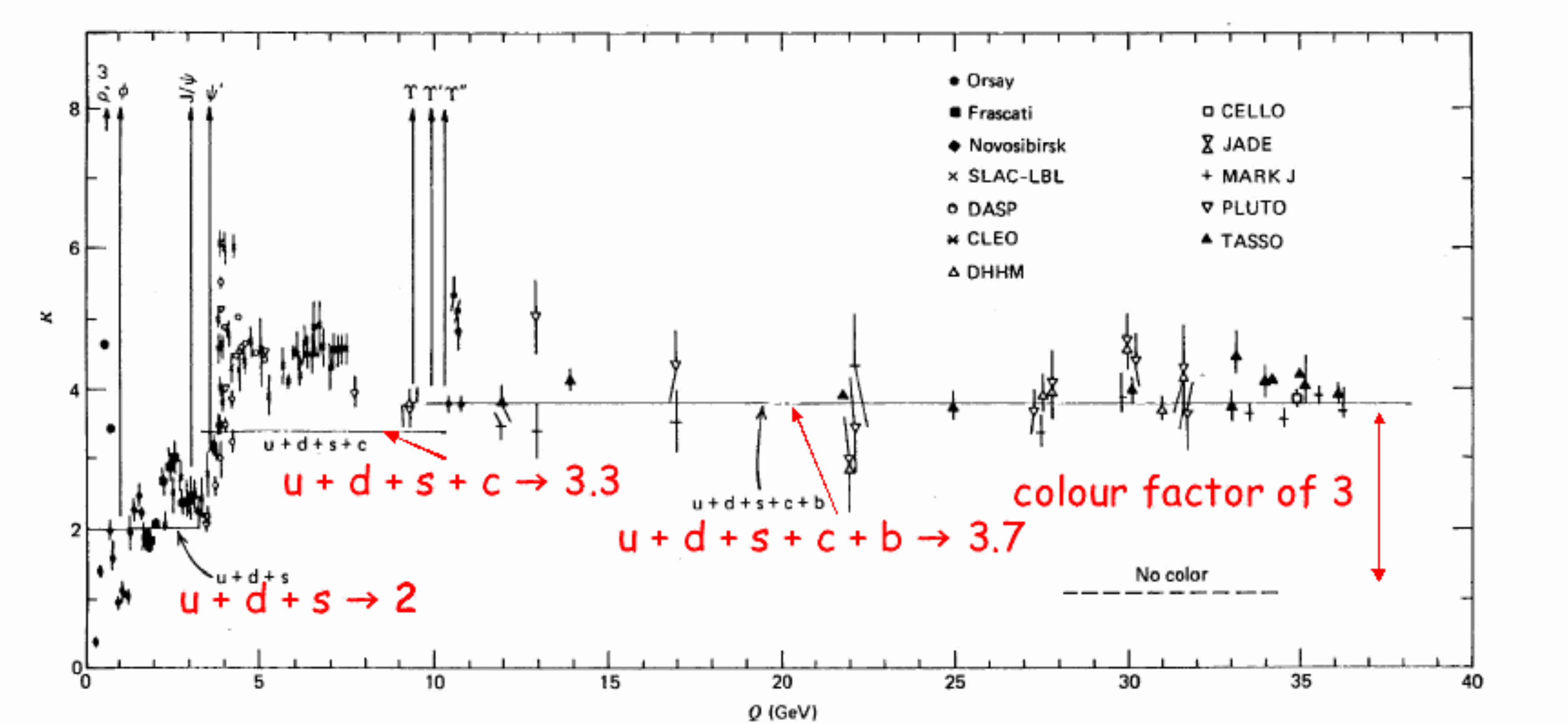
Quarks	Up/Down	1968	SLAC	1990 Nobel Prize
	Strange	1964	BNL	1980 Nobel Prize
	Charm	1974	SLAC/BNL	1976 Nobel Prize
	Bottom	1977	Fermilab	
	Top	1995	Fermilab	
Leptons	Electron	1897	Thomson	1906 Nobel Prize
	E-Neutrino	1956	Reactor	1995 Nobel Prize
	Muon	1937	Cosmic Rays	
	Mu-Neutrino	1962	BNL	1998 Nobel Prize
	Tau	1976	SLAC	1995 Nobel Prize
	Tau-Neutrino	2000	Fermilab	first direct evidence
Exchange Bosons	Photon	1905	Planck/Einstein	1918/1921 Nobel Prize
	Gluon	1979	DESY	1995 EPS Prize
	W/Z	1983	CERN	1984 Nobel Prize

3 generation quark model postulated as early as 1973 by Kobayashi and Maskawa:
Mechanism for CP-violation only possible with 3 generations.
Multi-generation quark model confirmed experimentally soon thereafter: Charm 1974
Third generation tau-lepton (1976) implied third quark generation.

History of Top Quark Search

Reminder (famous plot from your favorite textbook):

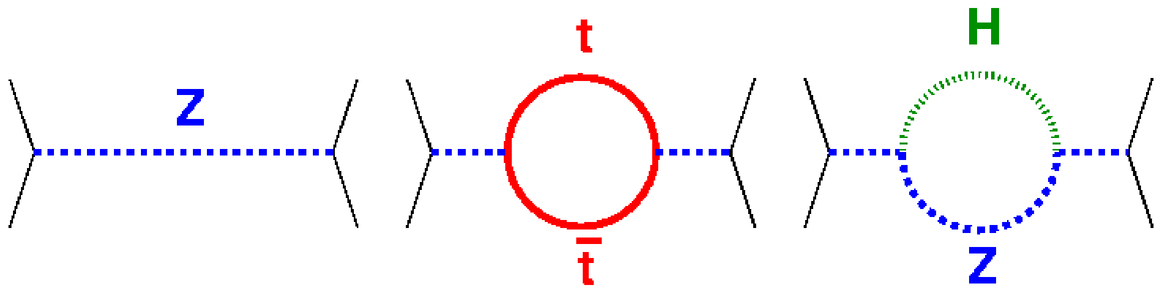
$$R = \frac{\sigma(e^+ + e^- \to hadrons)}{\sigma(e^+ + e^- \to \mu^+ + \mu^-)} = \frac{3\sum(quark\ charge)^2}{1^2}$$



Higher Energy → More hadronic channels open up.

But: Top not found this way…

Steinbrück

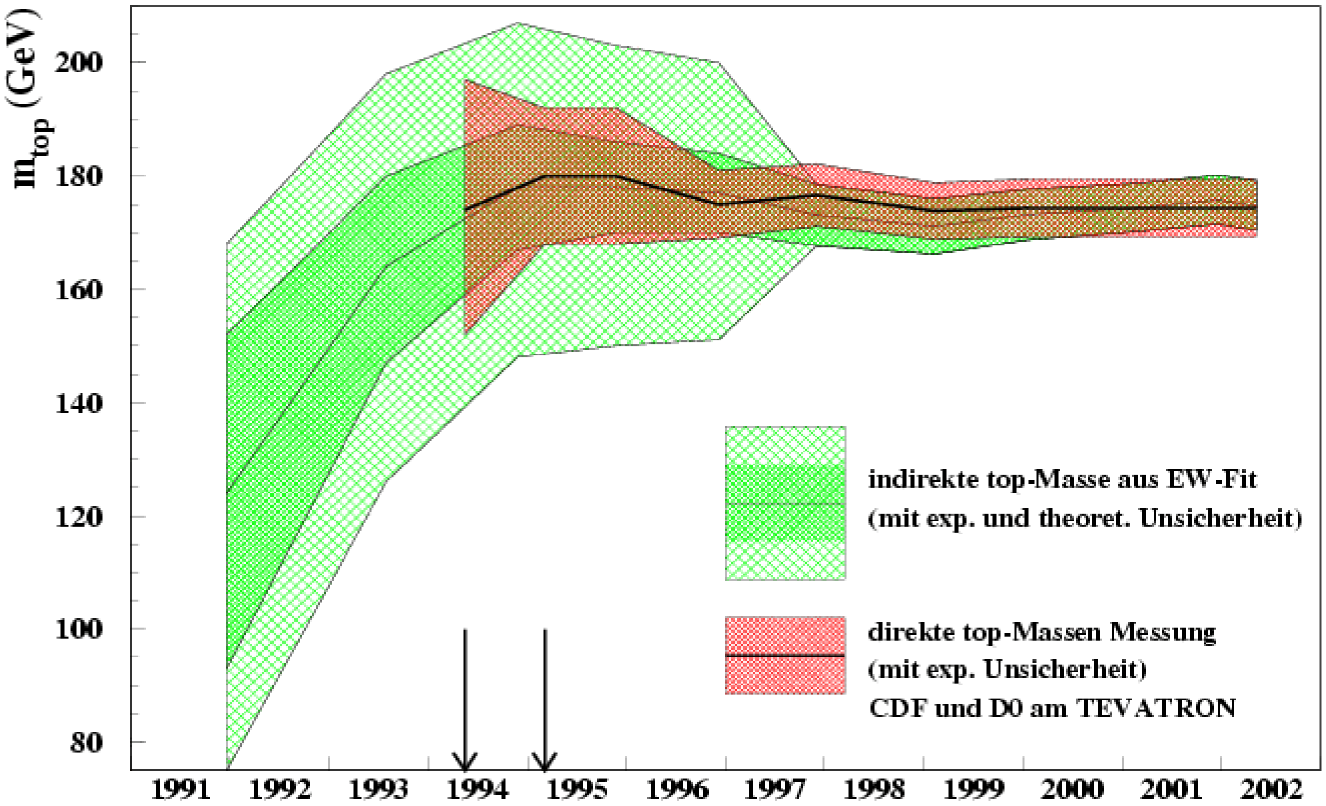


$$M_Z^2 = M_Z^{2\ \text{0.order}} / (1 - \Delta)$$

$$\Delta \approx \ldots\ m_t^2 \ldots + \ldots\ \ln m_h\ \ldots$$

Z and W mass are altered by higher order loop corrections,
i.e. virtual Tt pairs, etc.

Can we get some indirect hints?



Precision EW measurements (like the one of the Z boson mass) can therefore be used to constrain/ predict the mass of the top quark!

Success: Measured value after direct discovery at FNAL right on!

Finally: Top Discovery in 1995!

Table 1.2. History of the search for the top quark at e^+e^- and at hadron colliders. The quoted uncertainties for the top quark mass from the 1995 discovery publications are statistical and systematic uncertainties, respectively.

Year	Collider	Particles	References	Limit on m_t
1979-84	PETRA (DESY)	e^+e^-	[50]-[63]	> 23.3 GeV/c^2
1987-90	TRISTAN (KEK)	e^+e^-	[64]-[68]	> 30.2 GeV/c^2
1989-90	SLC (SLAC), LEP (CERN)	e^+e^-	[69]-[72]	> 45.8 GeV/c^2
1984	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[75]	> 45.0 GeV/c^2
1990	Sp$\bar{p}$S (CERN)	$p\bar{p}$	[76, 77]	> 69 GeV/c^2
1991	TEVATRON (FNAL)	$p\bar{p}$	[78]-[80]	> 77 GeV/c^2
1992	TEVATRON (FNAL)	$p\bar{p}$	[81, 82]	> 91 GeV/c^2
1994	TEVATRON (FNAL)	$p\bar{p}$	[84, 85]	> 131 GeV/c^2
1995	TEVATRON (FNAL)	$p\bar{p}$	[42]	$= 174 \pm 10^{+13}_{-12}$ GeV/c^2
			[43]	$= 199^{+19}_{-21} \pm 22$ GeV/c^2

Finally: Top Discovery in 1995!

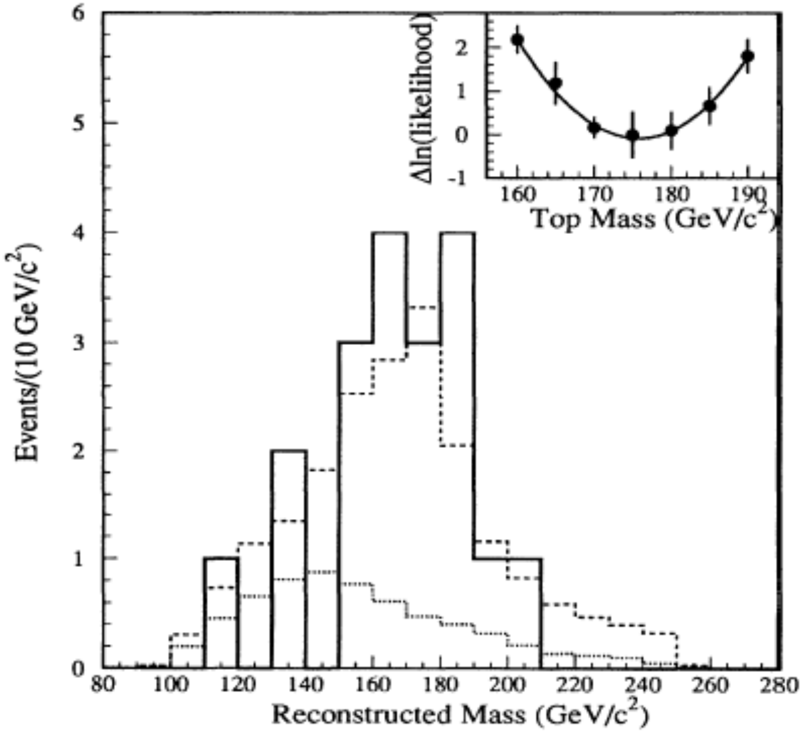
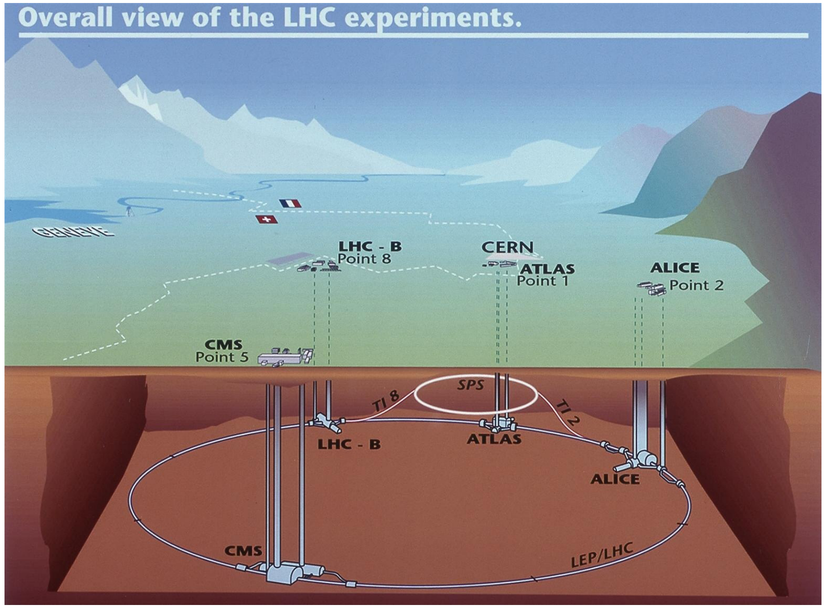


FIG. 3. Reconstructed mass distribution for the b-tagged $W+\geq$4-jet events (solid). Also shown are the background shape (dotted) and the sum of background plus $t\bar{t}$ Monte Carlo simulations for $M_{\rm top} = 175$ GeV$/c^2$ (dashed), with the background constrained to the calculated value, $6.9^{+2.5}_{-1.9}$ events. The inset shows the likelihood fit used to determine the top mass.

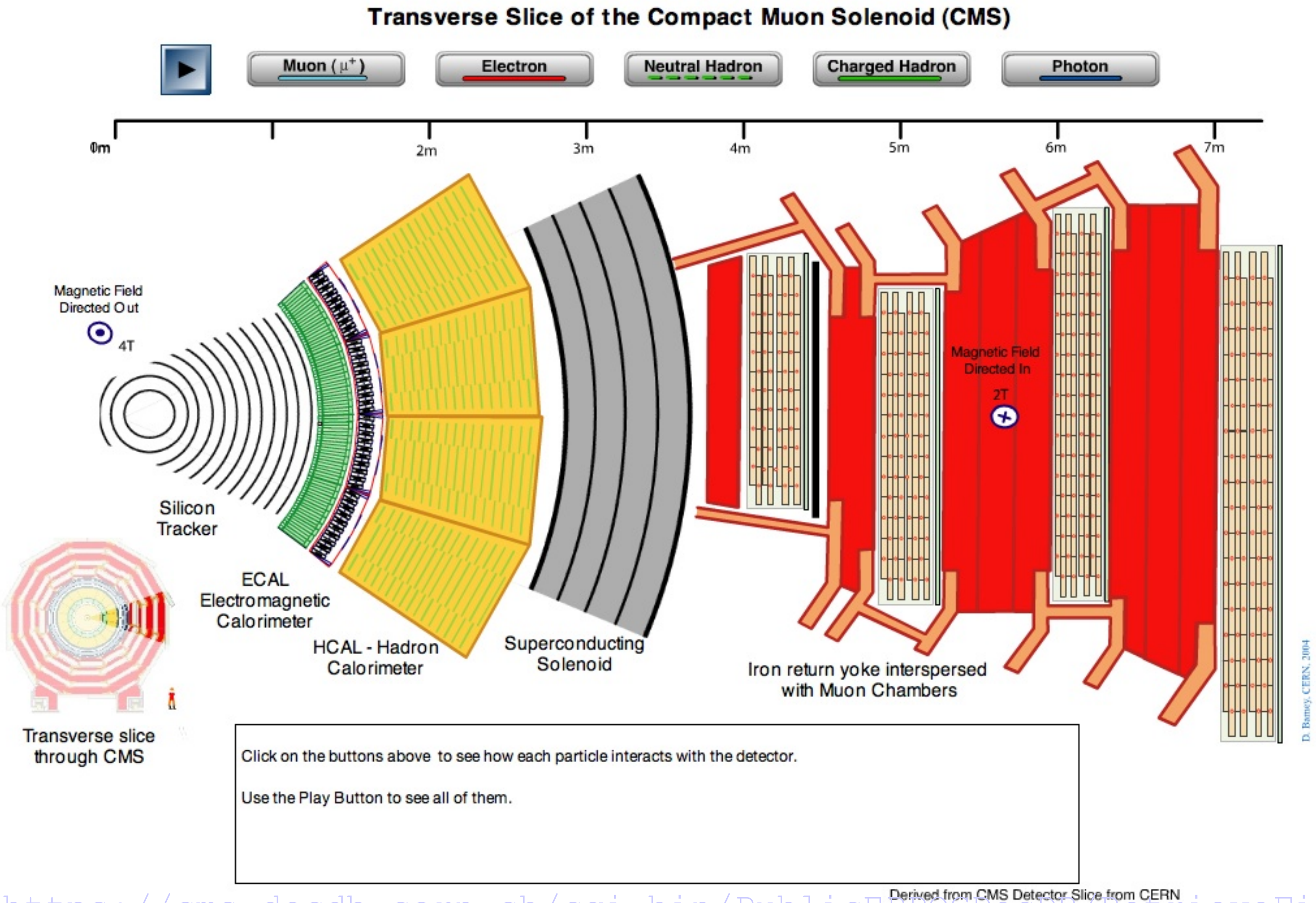
Simultaneously discovered at CDF and D0.

Top Factories: Tevatron →LHC



location	:	Fermilab, USA	CERN, Geneve, Switzerland
start	:	1987	2008 (restart 2010)
collider type	:	proton – anti-proton	proton – proton
experiments (**top**)	:	**CDF, D0**	**ATLAS, CMS**, ALICE, LHC-B
√s	:	1.8 GeV→ 1.96 GeV	14 TeV (7 TeV for 2010)
L (instantaneous)	:	$10^{30} \rightarrow 3\text{x}10^{32}$ $cm^{-2}s^{-1}$	10^{34} ($4\text{x}10^{32}$ for 2010) $cm^{-2}s^{-1}$
L (integrated)	:	≈ 10,000 pb^{-1}	≈ 300/3000 fb^{-1}
σ(tt) expected	:	≈ 7 pb	≈ 850 pb (7 TeV: 160 pb)
tT events / 50 pb^{-1}	:	≈ 350	≈ 42,500 (8,000)

The Experiments: Example CMS



https://cms-docdb.cern.ch/cgi-bin/PublicEPPOGDocDB/RetrieveFile?docid=97&version=1&filename=CMS_Slice_elab.swf

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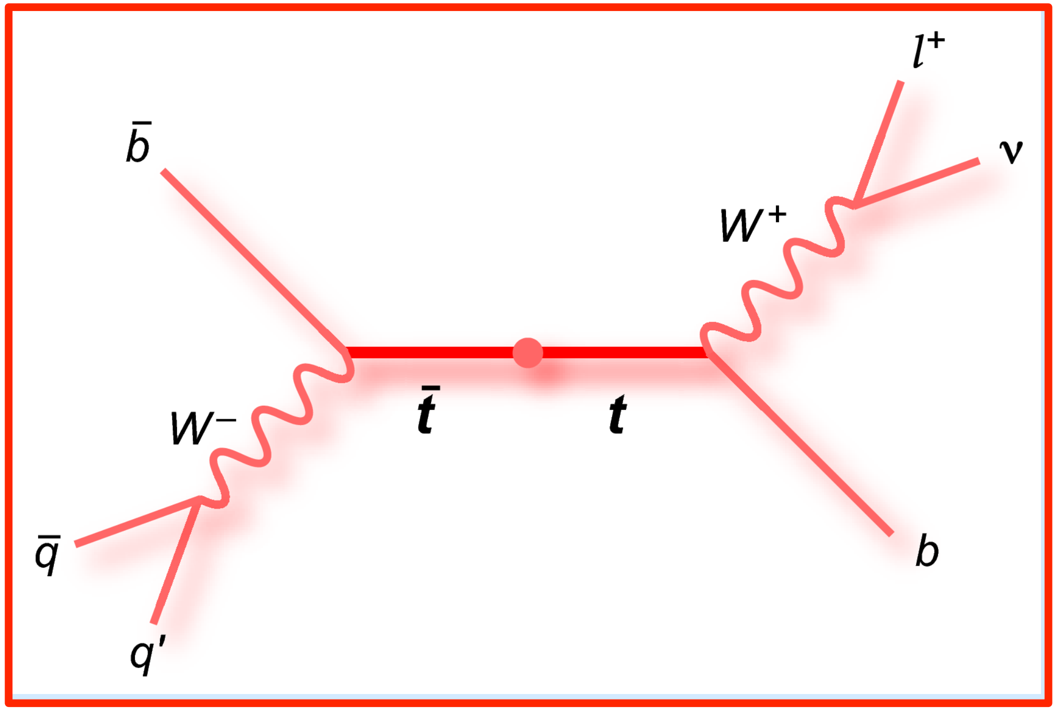
Top Event Reconstruction: The Ingredients



A Tt event contains:

• 2 b-quark jets (but: not always detectable)

And:

• either 2 charged leptons and large missing ET (neutrinos!)

• or 1 charged lepton, large missing ET and 2 more jets

• or 4 more jets

Complex signatures

• All detector components used to identify electrons, muons, taus, jets, b-jets, MET

• In turn: Top events can be used in understanding the detector. Especially interesting @LHC: Large Tt-data samples, high purity samples possible

Tools: b tagging

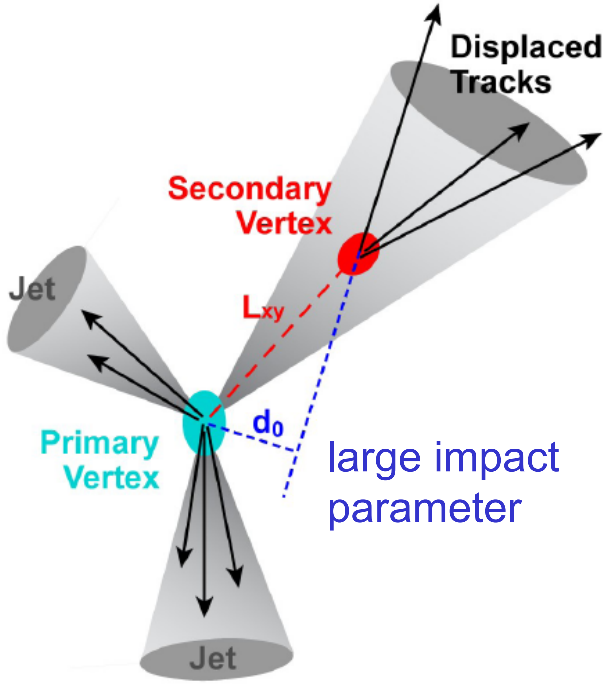
- B tagging algorithms attempt to identify (tag) jets produced by b-quarks

- Identifying b-quarks is crucial for analyses of top quarks, Higgs, SUSY,…

Separate b-jets from light (u,d,s,g) jets using specific b-hadron properties:

-large lifetime ~1.5 ps (→$c\tau$~450μm) →large decay length: 20 GeV b-hadron decays after ~2 mm
→search for tracks or vertices displaced w.r.t. primary vertex

- large mass ~5 GeV
→search for leptons, from semileptonic B decays, with large transverse momentum w.r.t. jet axis



b tagging: Impact Parameter

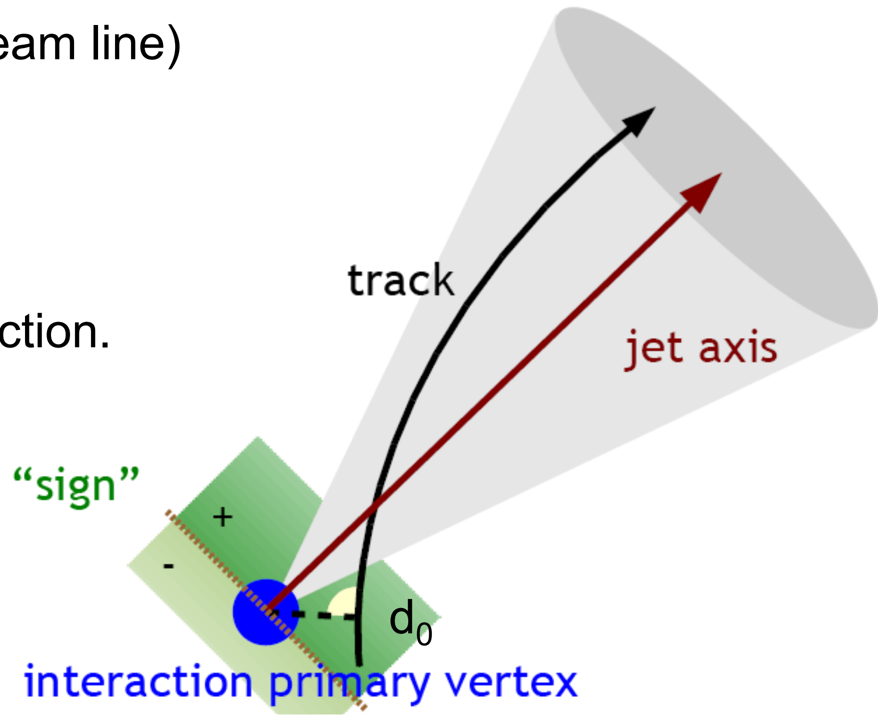
-Large B hadron lifetime → large impact parameter,d_0, of B decay products
-Impact parameter: Distance of track and primary vertex (PV) at closest approach

→Search for tracks displaced w.r.t. primary vertex

-Can use either 2D (transverse plane to beam line)
or 3D impact parameter

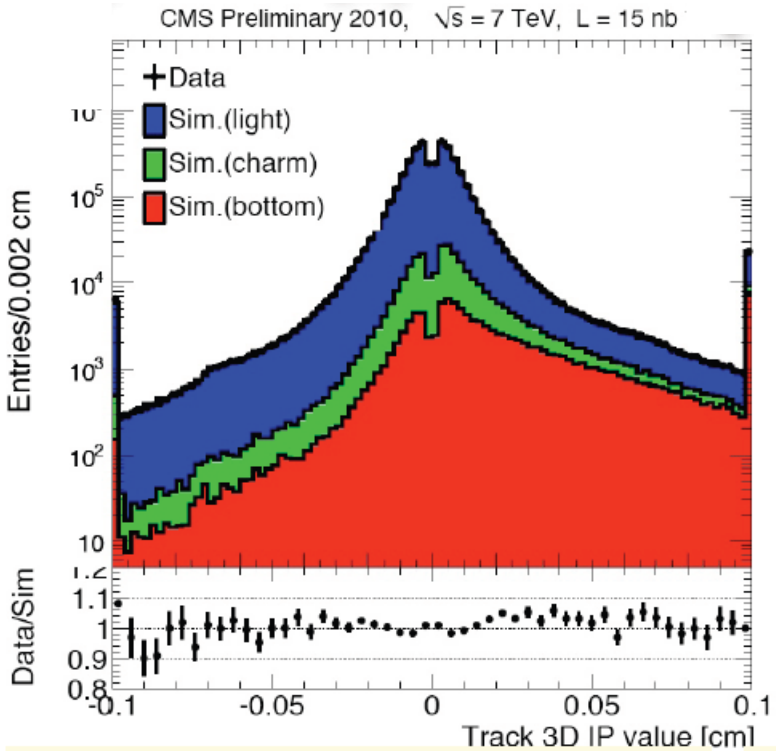
- Use "sign" of the impact parameter
  -positive if track intersection with jet axis is downstream the PV along jet direction.
  -negative: Used to measure IP-resolution

- Impact parameter significance, $d_0/\sigma d_0$, used as discriminant between signal (true b-jets) and background (fake b-jets)

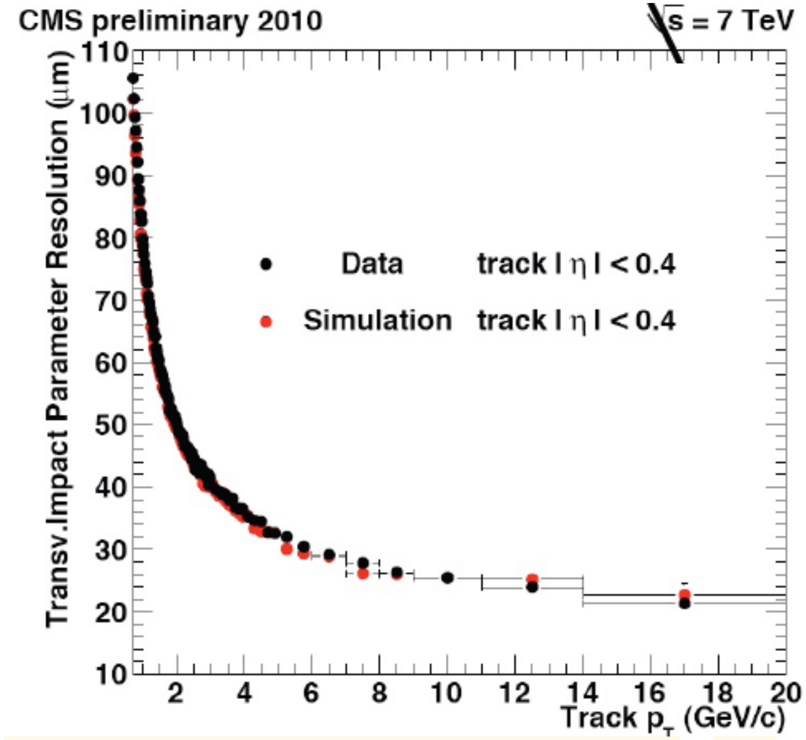


Btagging: Impact Parameter

3D-Impact parameter



IP-resolution (here: 2D)



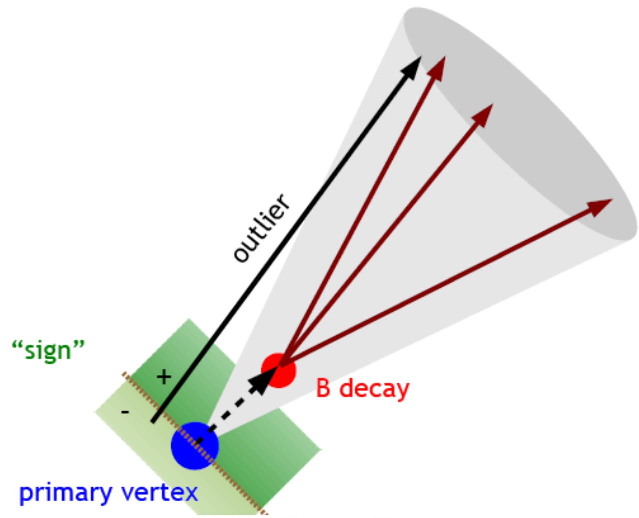
Several methods to exploit tracks with large impact parameters

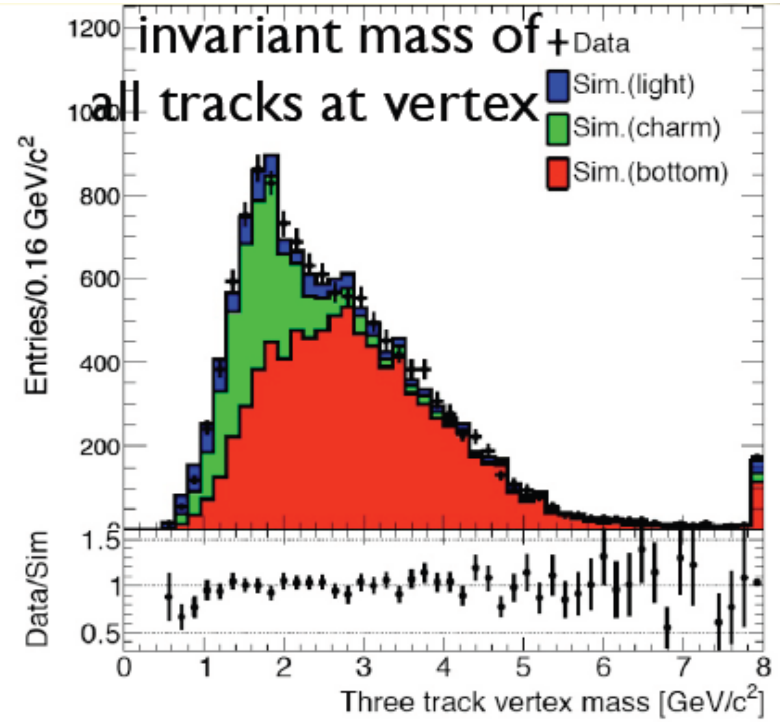
- Track counting: Count tracks with IP(significance) above some threshold
- Track Probability: Calculate probability that track comes from primary vertex. Combine for all tracks in a jet to get overall probability: Use as discriminant

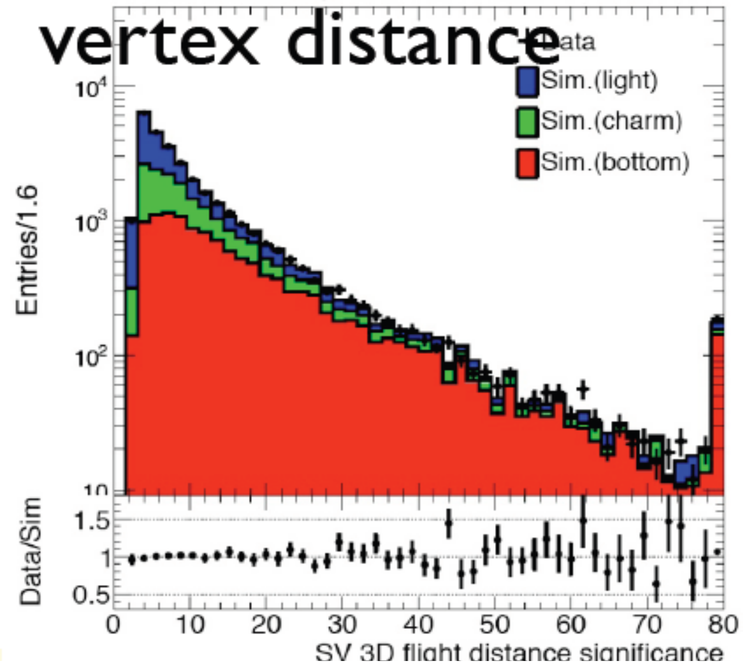
Secondary Vertex btagging

- Large B hadron lifetime → decay vertex (secondary vertex) significantly displaced w.r.t. primary vertex
- Determine 2D or 3D decay distance

Secondary vertex tagging:
- Search for secondary vertex using all tracks in jet
- Use decay distance significance d/σ_d as discriminant
- Also: vertex mass, impact parameter, often combined



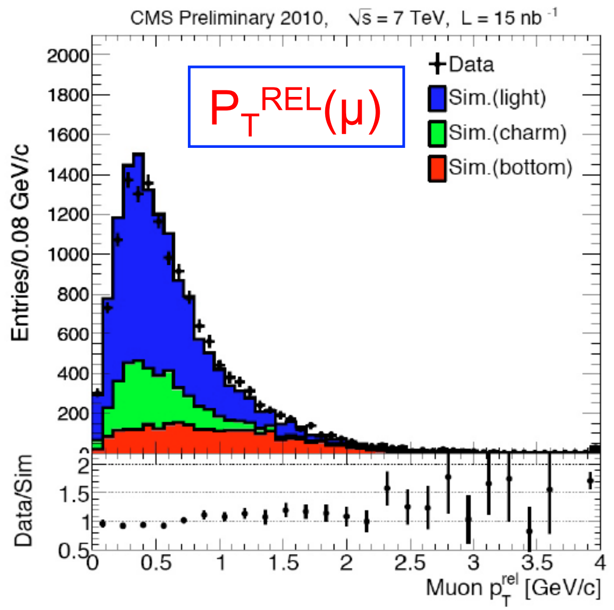


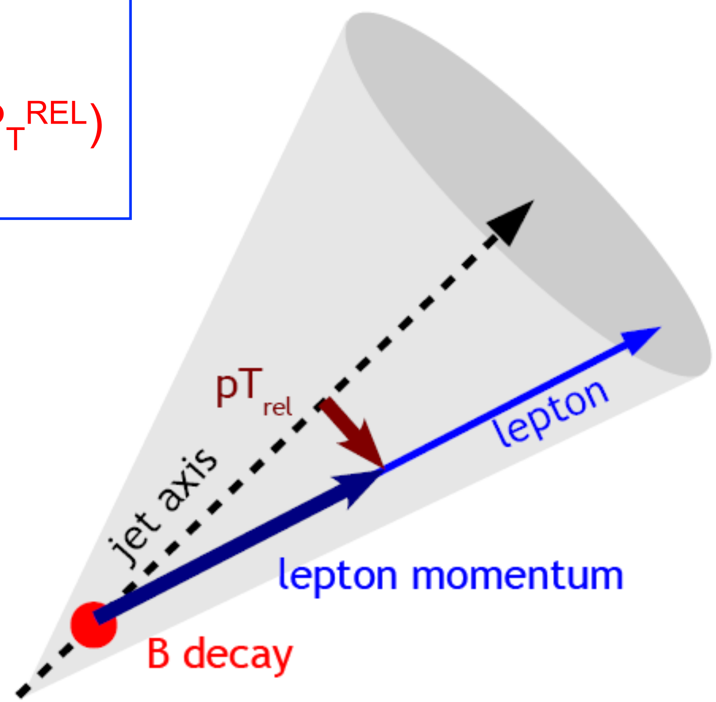


Soft Lepton Tagging

- Exploit large semileptonic branching fraction of B decays (Br(b → lepton) ≈ 10%) along with the large b-hadron mass (~5 GeV)

- Leptons from b decays are characterized by:
    - large impact parameter w.r.t. PV
    - large transverse momentum w.r.t. jet axis (P_T^{REL})
    - large angular distance w.r.t. jet axis





-Often variables from the different methods described here are combined using multi variate techniques

Tools: Kinematic Fits

Idea:

Exploit the full event to fully reconstruct tT kinematics

→Improve resolution of momenta of reconstructed particles

Difficulties:

-jet-parton matching.

For example l+jets: 4!/2=12 jet-parton assignments considered in a 4 jet event. Reduces to 6 if 1 jet is b-tagged, 2 if both jets are btagged: Another strong reason for btagging!

Wrong combinations: Combinatorial background.

Using highest chisq typically yields right combination in 65-85%, depending on details of the selection and the channel. Most difficult: all-jets channel

-Unknown longitudinal momentum of neutrino, inability to distinguish two neutrinos

Example (lepton+jets channel@Tevatron):

$$\chi^2 = \sum_{i=l,jets} \frac{\left(p_T^{i,fit} - p_T^{i,meas}\right)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{\left(p_j^{uc,fit} - p_j^{uc,meas}\right)^2}{\sigma_{j,uc}^2} + \frac{\left(m_{l\nu} - m_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{jj} - m_W\right)^2}{\Gamma_W^2} + \frac{\left(m_{bl\nu} - m_t\right)^2}{\Gamma_t^2} \frac{\left(m_{bjj} - m_t\right)^2}{\Gamma_t^2}$$

leptons, jets — unclustered Energy — W mass — top mass

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Top Cross Section

Cross section measurements are conceptually simple*:

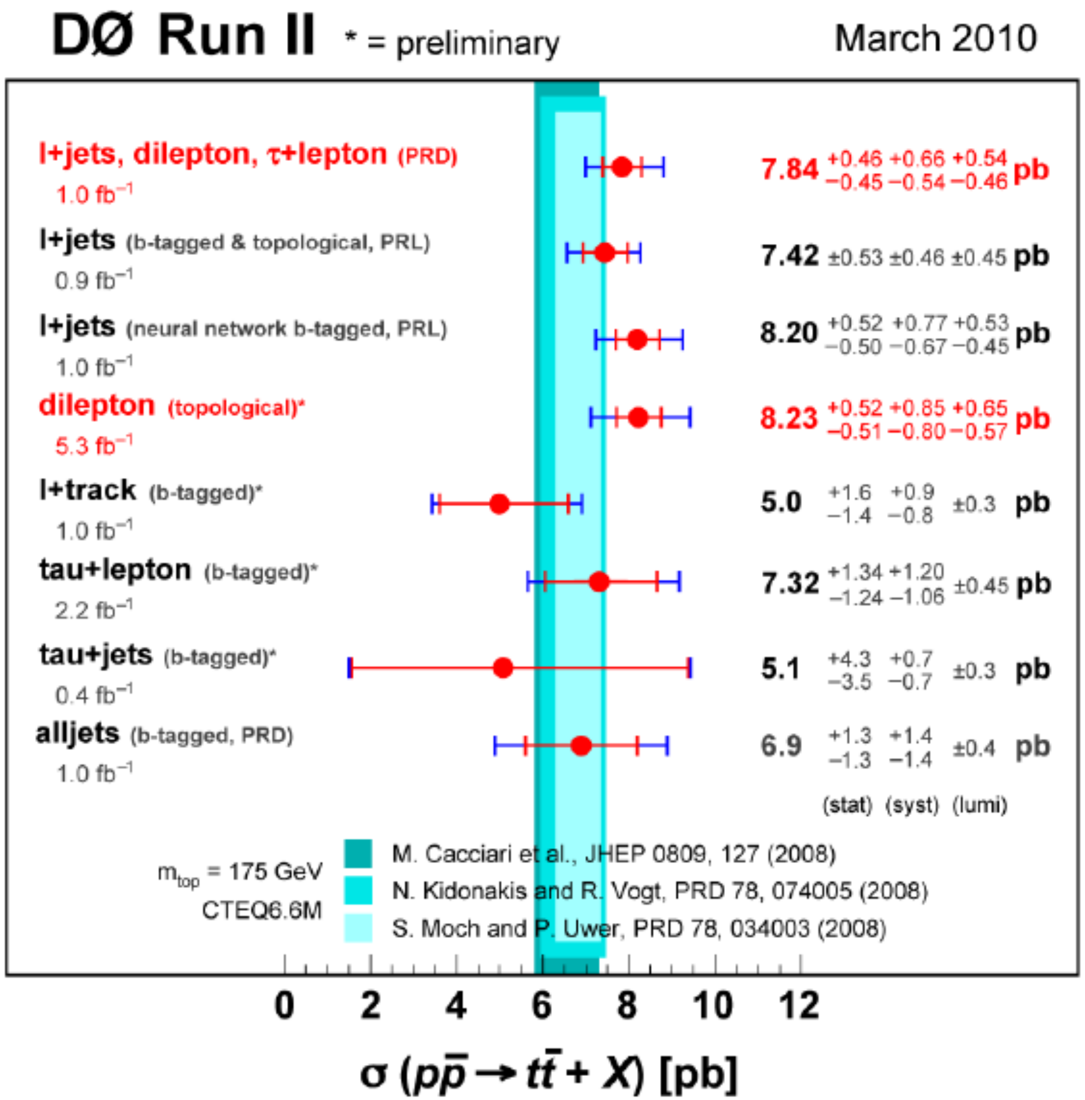
Data driven methods or from Monte Carlo

$$\sigma = \frac{N_{meas} - N_{bkg}}{L \cdot A \cdot \varepsilon}$$

Monte Carlo

Data/Monte Carlo

* The devil is in the details!



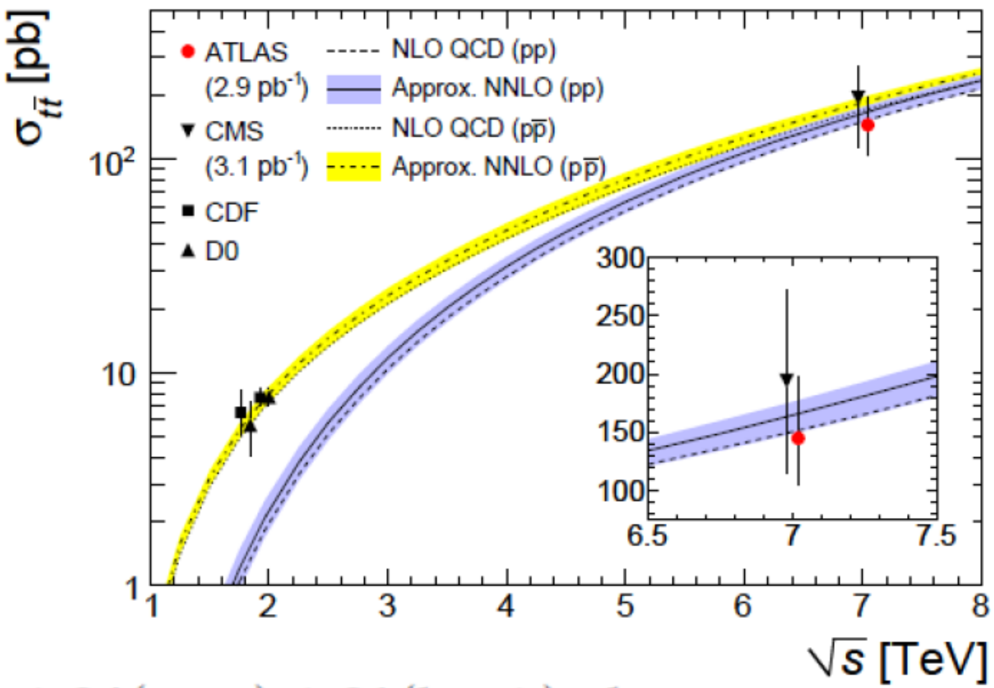
Many channels. Different methods

Top Cross Section Tevatron→LHC

First Top publication at the LHC based on ~3 pb^{-1}

CMS: 11 dilepton events

ATLAS: 9 dilepton + 37 semileptonic events

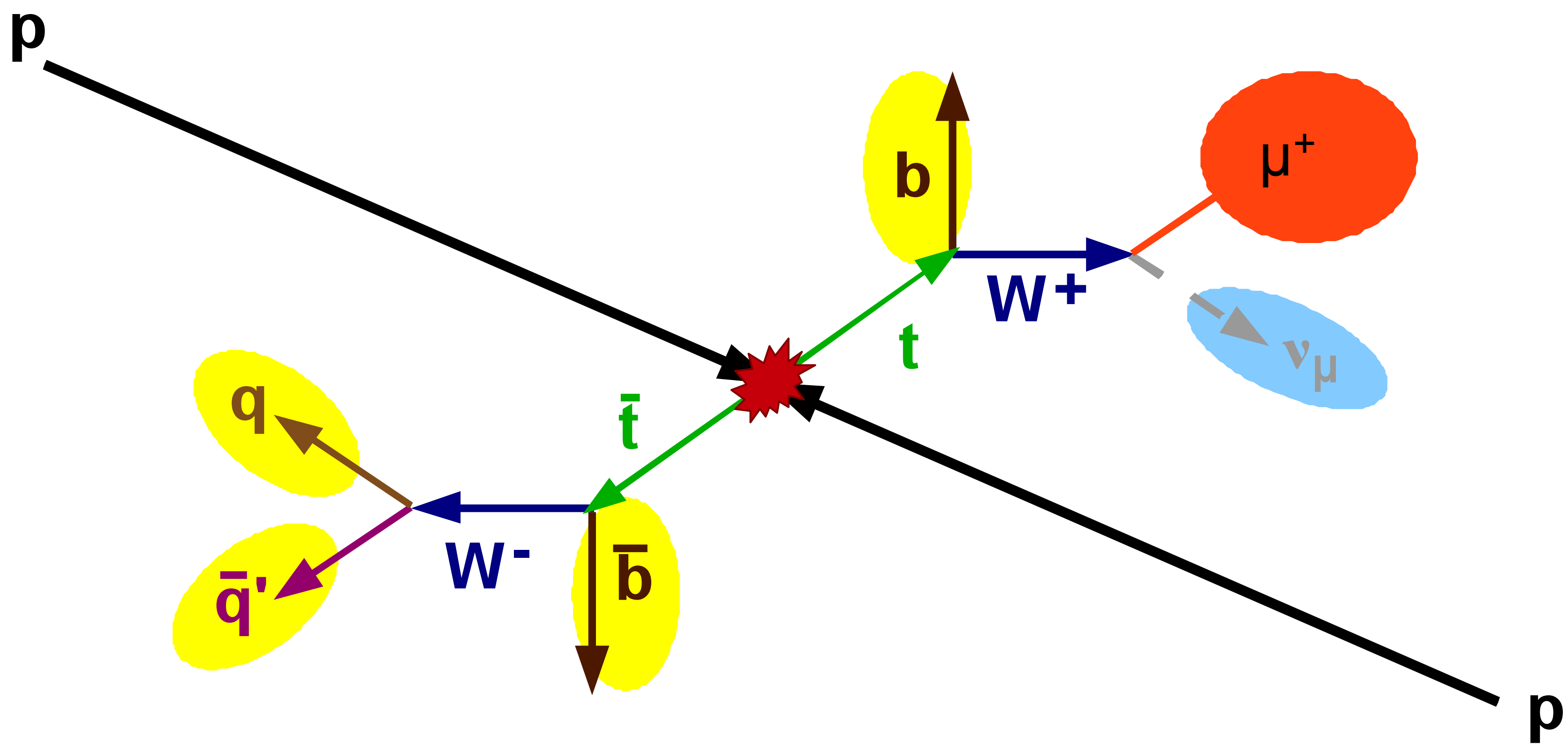


CMS $\sigma(pp \to t\bar{t}) = 194 \pm 72(\text{stat.}) \pm 24(\text{syst.}) \pm 21(\text{lumi.})$ pb.

ATLAS

	Cross-section [pb]	Signal significance [σ]
Single lepton channels	$142 \pm 34 \,^{+50}_{-31}$	4.0
Dilepton channels	$151 \,^{+78}_{-62} \,^{+37}_{-24}$	2.8
All channels	$145 \pm 31 \,^{+42}_{-27}$	4.8

Tt→ μ+jets event

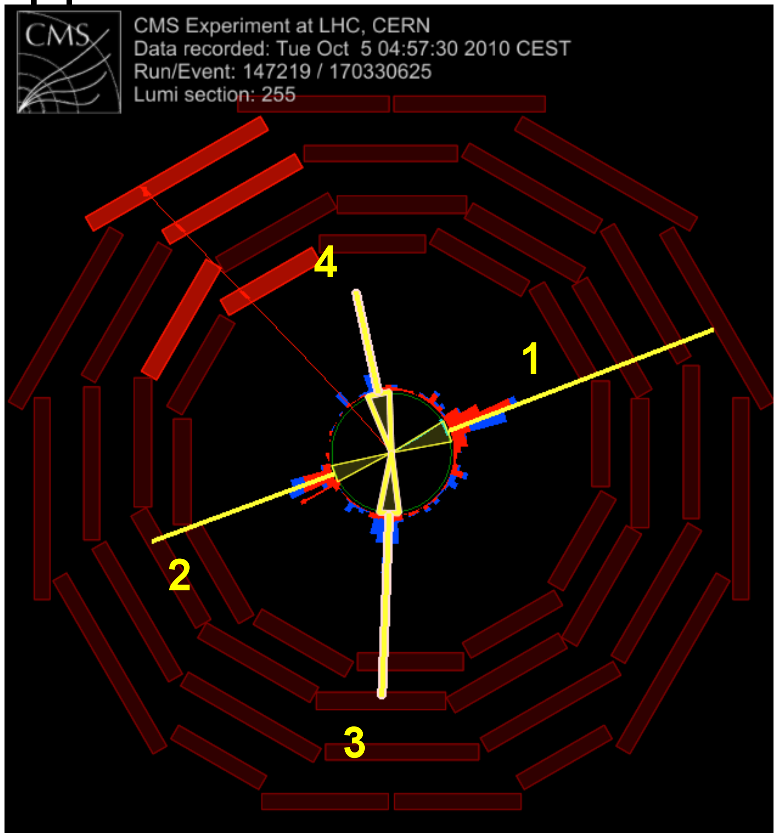


1 isolated Muon + 4 jets + missing E_T

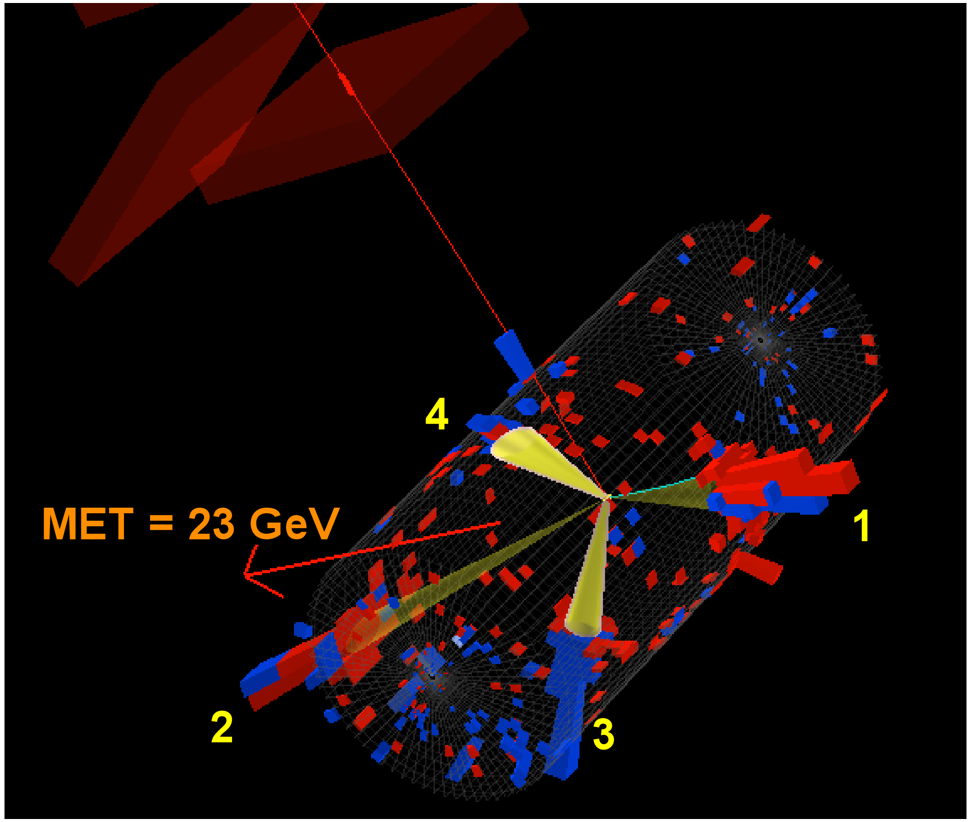
(2 b-jets)

Candidate μ+jets event (CMS)

r-φ plane:



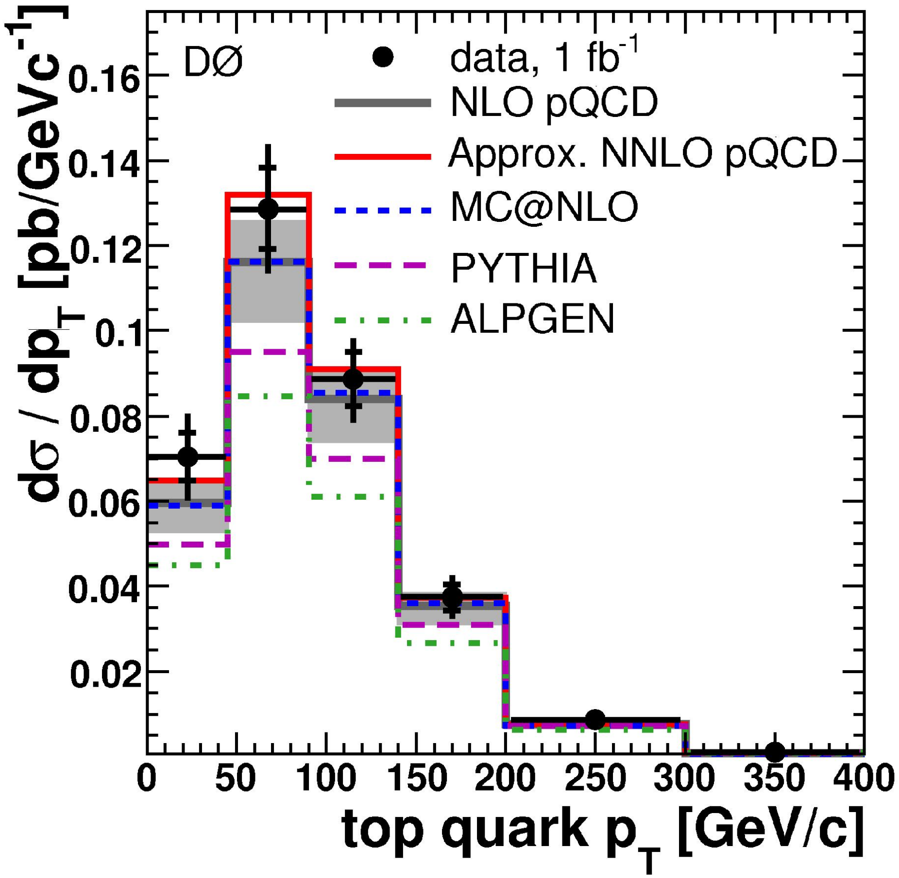
3D view:



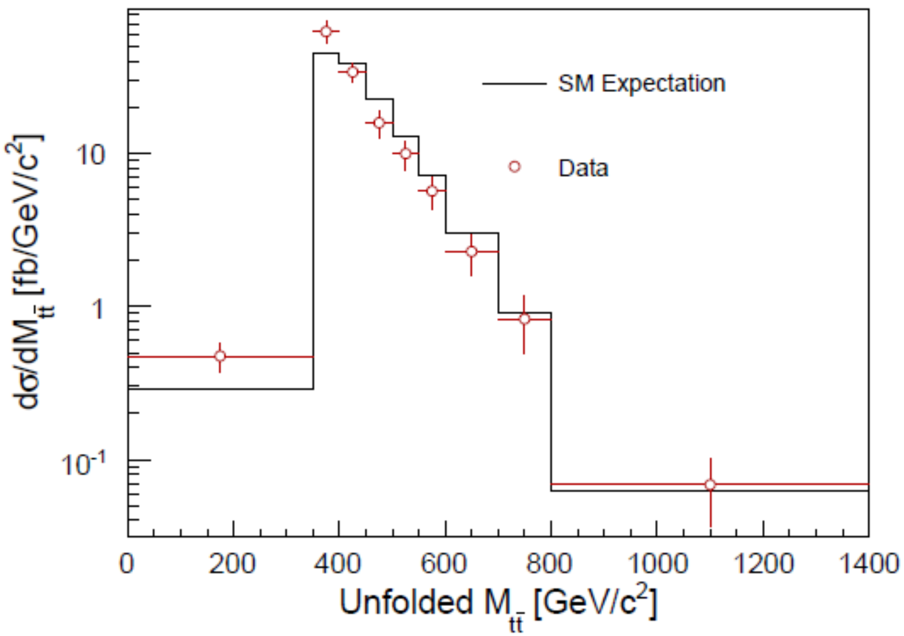
		p_t [GeV]	$\|\eta\|$	
muon:		61	-0.12	
jets:	**1**	152	-0.05	
	2	106	1.37	
	3	100	-1.61	**b tagged!**
	4	57	1.79	**b tagged!**

Differential Cross Sections

Differential tT cross sections in top quark pT and tT mass: Test of SM top production, sensitive to physics beyond SM.



CDF 2.7 fb-1

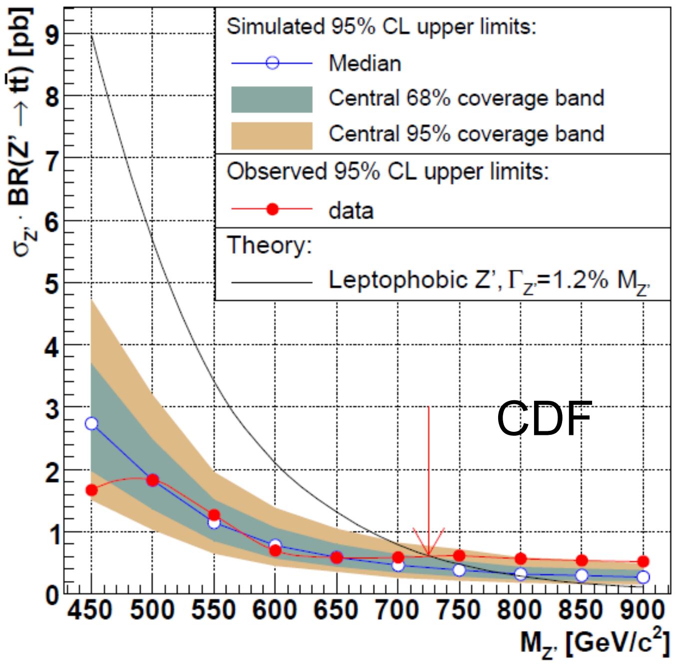


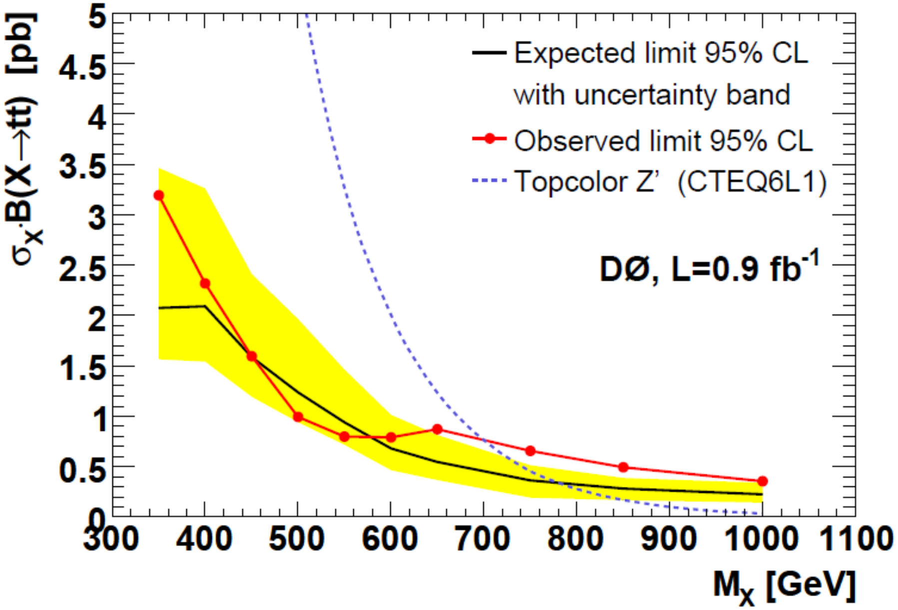
Consistent with standard model.

No sign for heavy particle decaying into tT.

Top and BSM in M(tT)

- Search for heavy resonances decaying into tT pairs.
- Predicted by many SM-extensions
- Resonances with small natural width would yield enormous peaks in tT mass distribution





Forward-backward Asymmetry

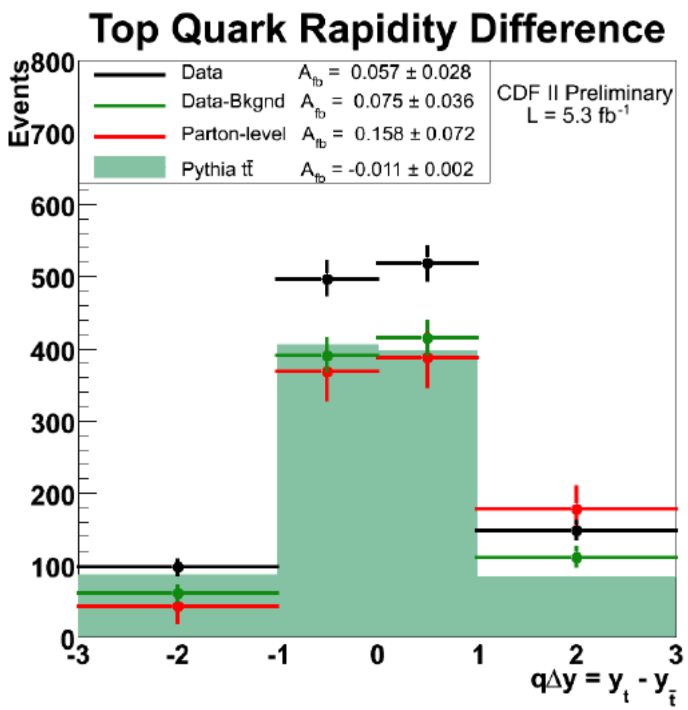
The forward-backward asymmetry in tT events is defined as

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

$$\Delta y = y_t - y_{\bar{t}}$$

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

Sensitive to new physics



Use semileptonic channel: Charge of the lepton used to separate top from anti-top

SM prediction (NLO QCD): 0.058 ± 0.009 (in the tT rest frame)

CDF measurement (2010, 5.3 fb^{-1}): 0.158 ± 0.072(stat) ± 0.017(syst) →
Compatible within large errors

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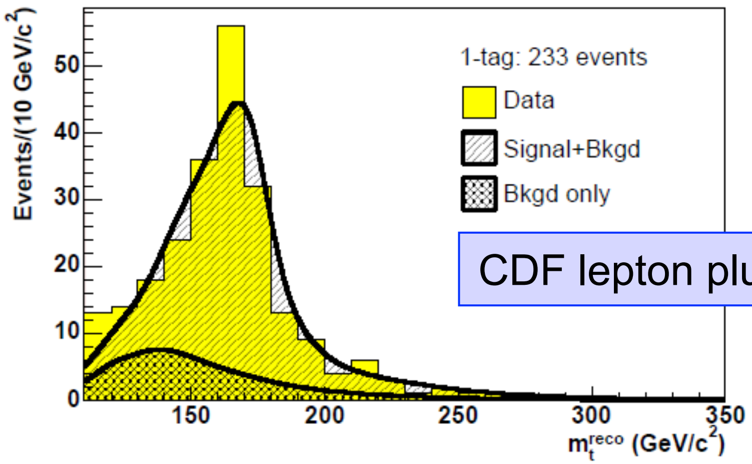
Methods to Extract the Top Mass

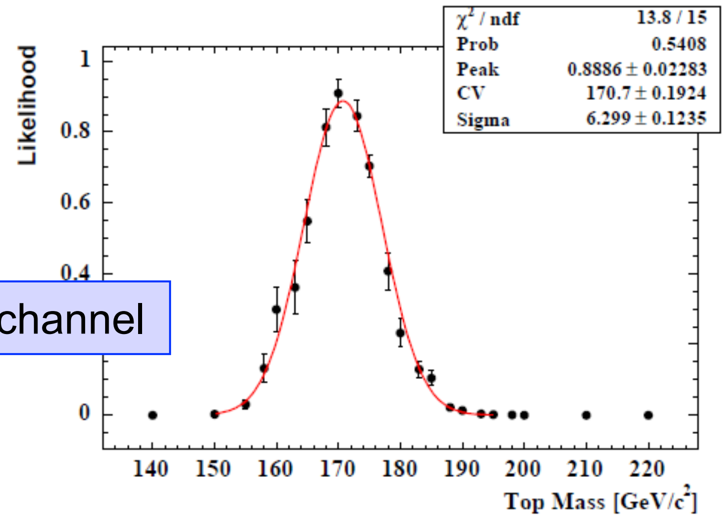
1. Select top-like events
2. Further reduce backgrounds to obtain clean sample
3. Reconstruct final state
4. Use sophisticated technique to extract top mass

Simplest method: Template fit

- Reconstruct m_T for each event
- Build templates in reconstructed m_T using Monte Carlo generated with different m_T
- Extract m_T using a maximum likelihood fit to the data



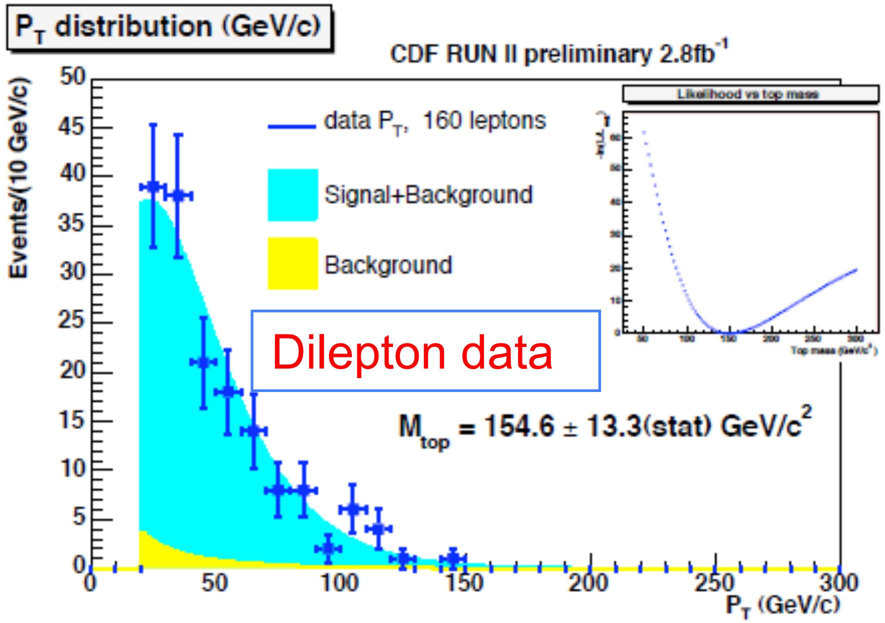
CDF lepton plus jets channel



Methods to extract the top mass

Any variable that‘s correlated with the top mass can in principle be used.

New measurement: Using lepton pT in the l+jets and dilepton channels (CDF).

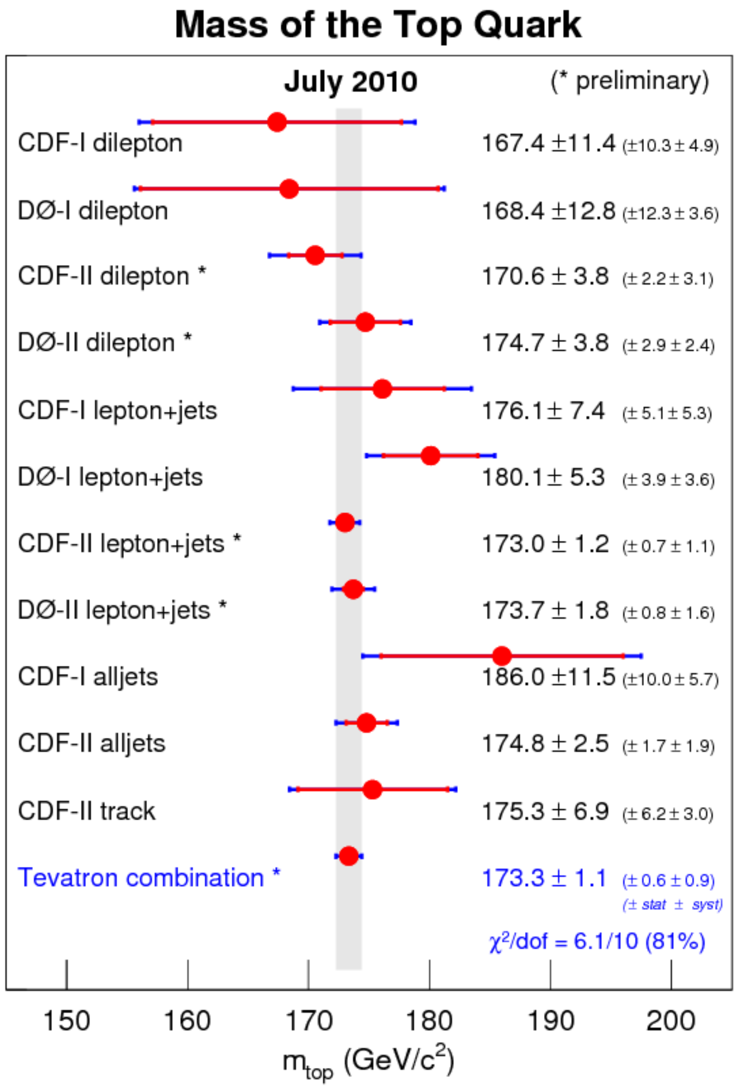


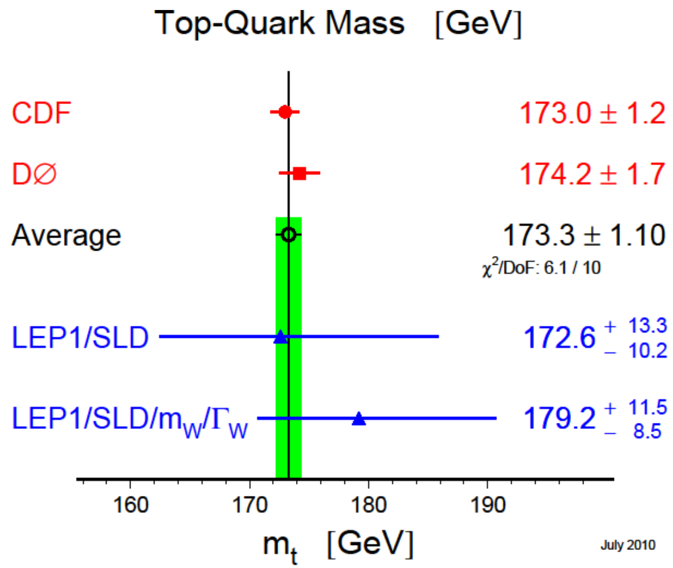
	δMass (GeV)				
source of systematic	e+jets	μ+jets	l+jets	DIL	combination
Global P_T scale	0.2	0.1	0.1	0.1	0.1
Local P_T scale	0.6	1.5	1.1	0.7	1.0
MC statistics	0.4	0.4	0.4	0.3	0.2
Generator	0.7	2.2	1.2	1.5	1.0
IFSR	1.5	0.7	0.8	1.3	0.7
PDF	0.6	0.6	0.6	0.7	0.6
Background shape*	3.6	0.0	1.8	0.4	1.4
Background constrain	0.0	0.0	0.0	0.3	0.1
JES	0.0	0.0	0.0	0.4	0.1
Multiple Interactions	0.1	0.1	0.1	0.2	0.1
Q^2	0.7	0.8	0.5	0.0	0.4
Bias from the fit	0.0	0.0	0.0	0.3	0.1
Total	4.1	3.0	2.7	2.3	2.3

$$m_t = 176.9 \pm 8.0(stat) \pm 2.7(syst)\ GeV$$

- Statistics dominated
- Systematics independent of Jet Energy scale!

Top Mass Measurement at the Tevatron





Combining all channels and different methods gives final precision.

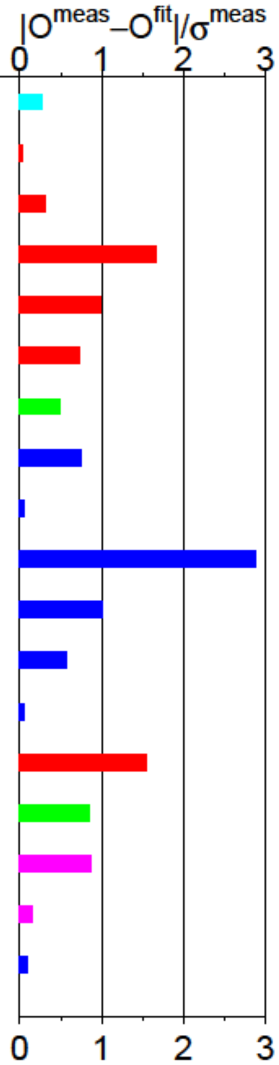
Advantages of combination:

- Full use of sample statistics
- cross checks
- Different systematic uncertainties

Mass of top quark has best relative precision of all quark masses!

The Complete Picture…

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

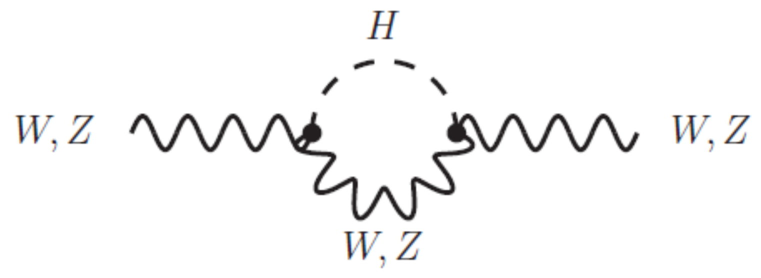


July 2010

- Famous Pull plot of electroweak precision measurements.
- It all fits together beautifully!
- No measurement inconsistent with global electroweak fit

Steinbrück

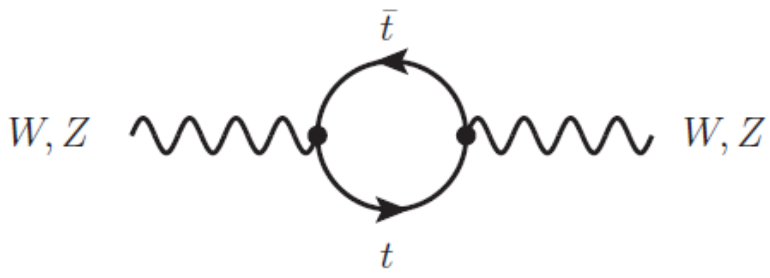
What does the Top mass Measurement tell us?



$$\sim g' \ln(m_H/m_W)$$

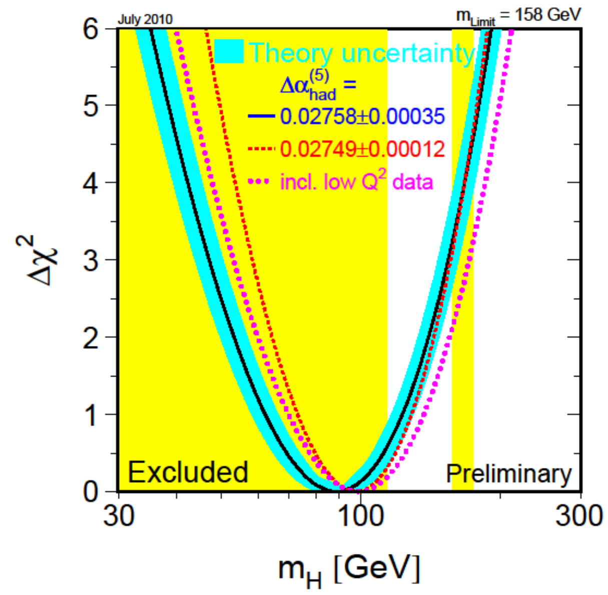
Loop corrections to W/Z propagators.

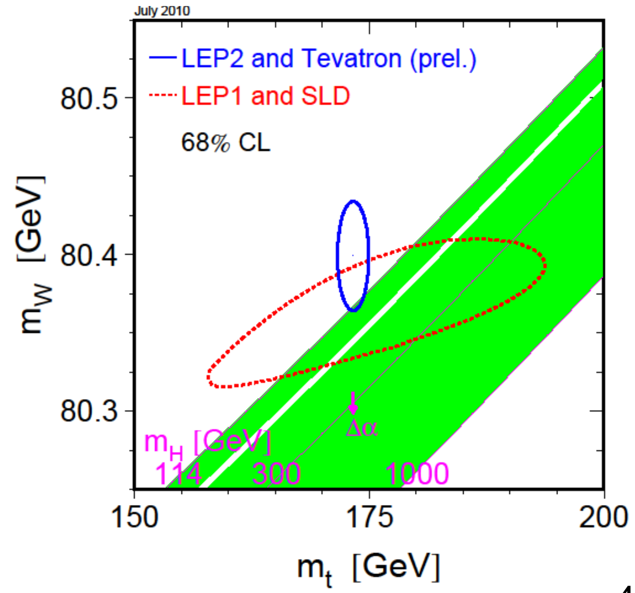
Depend on logarithmic on m_H and quadratic on m_t.



$$\sim G_F m_t^2$$

Precision EW data prefers light Higgs boson.





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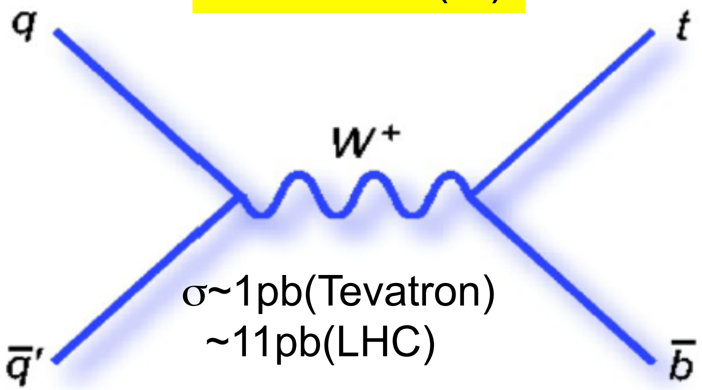
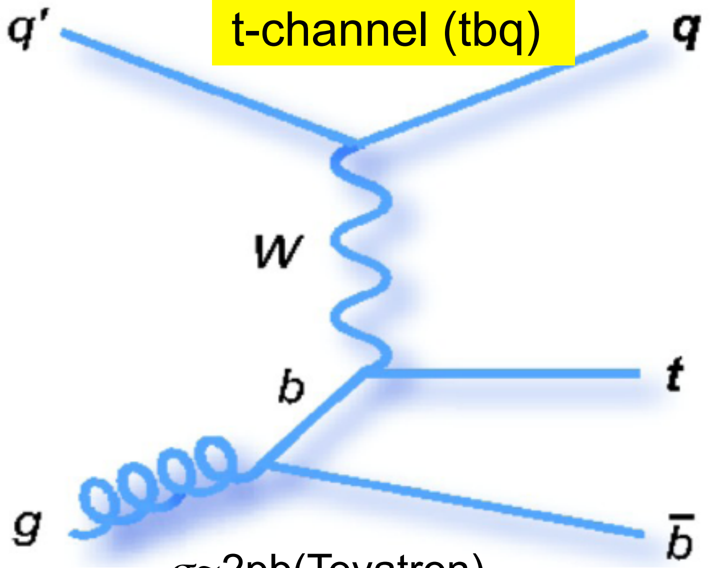
Electroweak Single Top Production

s-channel (tb)



σ~1pb(Tevatron)
~11pb(LHC)

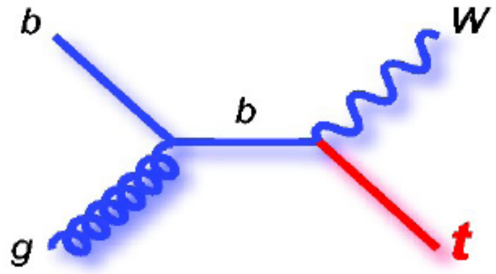
t-channel (tbq)

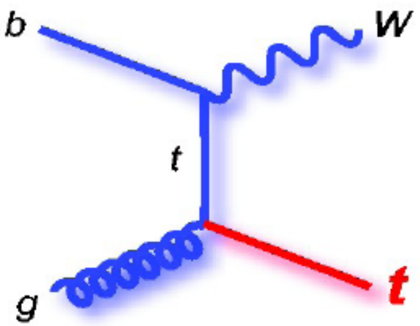


σ~2pb(Tevatron)
~235pb(LHC)

tW-production

σ~0.25pb(Tevatron)
~95pb(LHC)





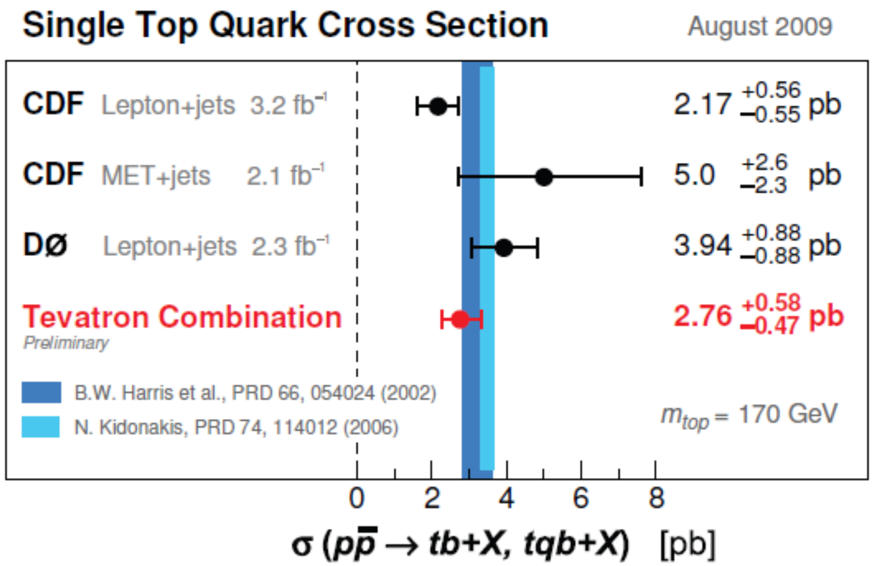
Single Top: Motivation

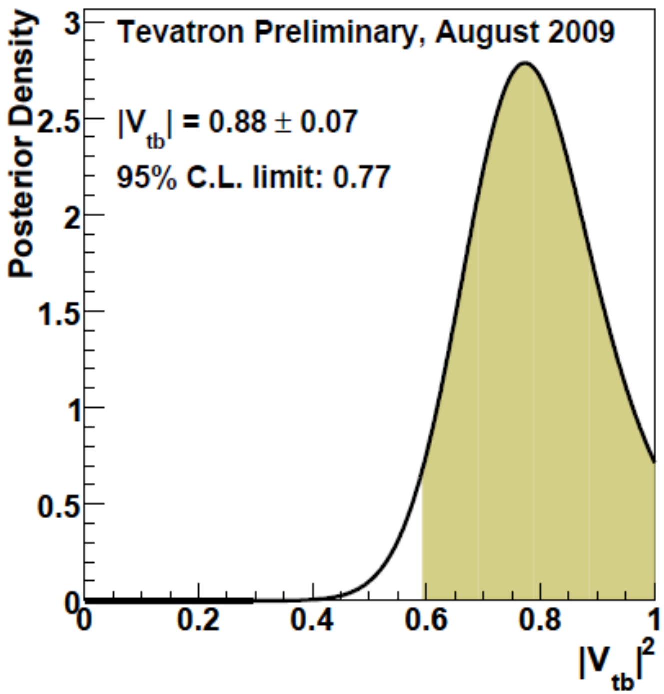
- Direct measurement of V_{tb}: $\sigma \sim |V_{tb}|^2$ V_{tb} (PDG): $0.999152 ^{+0.000030}_{-0.000045} \approx 1$
- SM process!
- Sensitivity to new physics:
  - s-channel: Resonances like W‘, charged Higgs boson, Kaluza-Klein excited W_{KK} …
  - t-channel: flavor changing neutral currents (t - Z/γ/g - c/u couplings), fourth generation quarks
- Measurement of top properties
  - Top partial decay width and lifetime
  - CP violation: Compare t and T rates
- Signature similar to WH associated production

Single Top@Tevatron

Cross section not that much smaller than for tT, but much more difficult to distinguish from background.

Very sophisticated analysis, i.e. boosted decision trees





Can be used to measure $|V_{tb}|$

Top Width

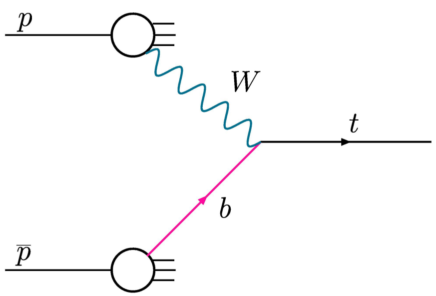
SM: Total top quark width dominated by partial width $\Gamma(t \to Wb)$

$$\Gamma(t \to Wb) \;=\; \frac{G_F m_t^3}{8\pi\sqrt{2}}\,|V_{tb}|^2 \left(1-\frac{M_W^2}{m_t^2}\right)^2 \left(1+2\frac{M_W^2}{m_t^2}\right) \times \left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]$$

Leading to $\Gamma(t \to Wb) = 1.26\,GeV$ BSM: additional channels, i.e. 4th generation b'→tW

would enhance the total width.

- The width of an unstable particle can be measured by analyzing its mass/transverse mass spectrum (example: direct W width measurement)
- However: Experimental precision for transverse top mass spectrum not good enough, only leads to upper limit
- Indirect measurement via cross section of t-channel single top production

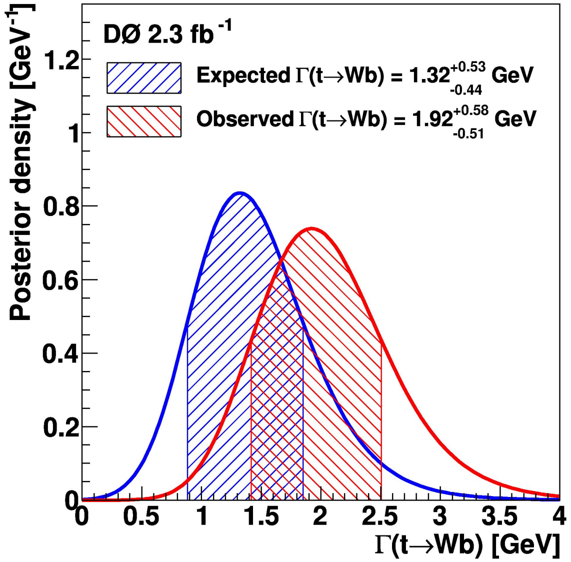


$$\Gamma(t \to Wb) = \sigma(t\text{–channel})\,\frac{\Gamma(t \to Wb)_{\text{SM}}}{\sigma(t\text{–channel})_{\text{SM}}}$$

- Using the measurement B(t→bW) one can determine the total width:

$$\Gamma_t = \frac{\sigma(t\text{–channel})\;\Gamma(t \to Wb)_{\text{SM}}}{\mathcal{B}(t \to Wb)\;\sigma(t\text{–channel})_{\text{SM}}}$$

Top width



Most probable value:

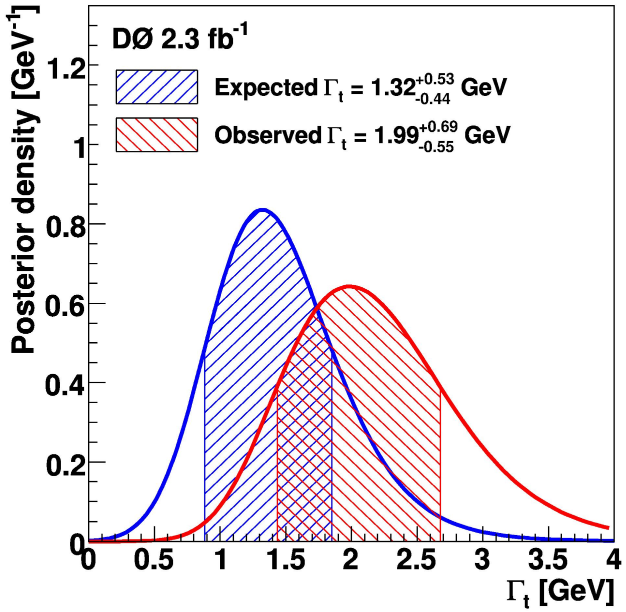
$$\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51}\ GeV$$

Can either be used to set a lower limit on the total width or, using the previous measurement of

$$\mathcal{B}(t \to Wb) = 0.962^{+0.068}_{-0.066}(\text{stat})\ ^{+0.064}_{-0.052}(\text{syst})$$

to determine the total width to $\Gamma(t) = 1.99^{+0.69}_{-0.55}\ GeV$ which can also be expressed as

$$\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}\ \text{s}$$



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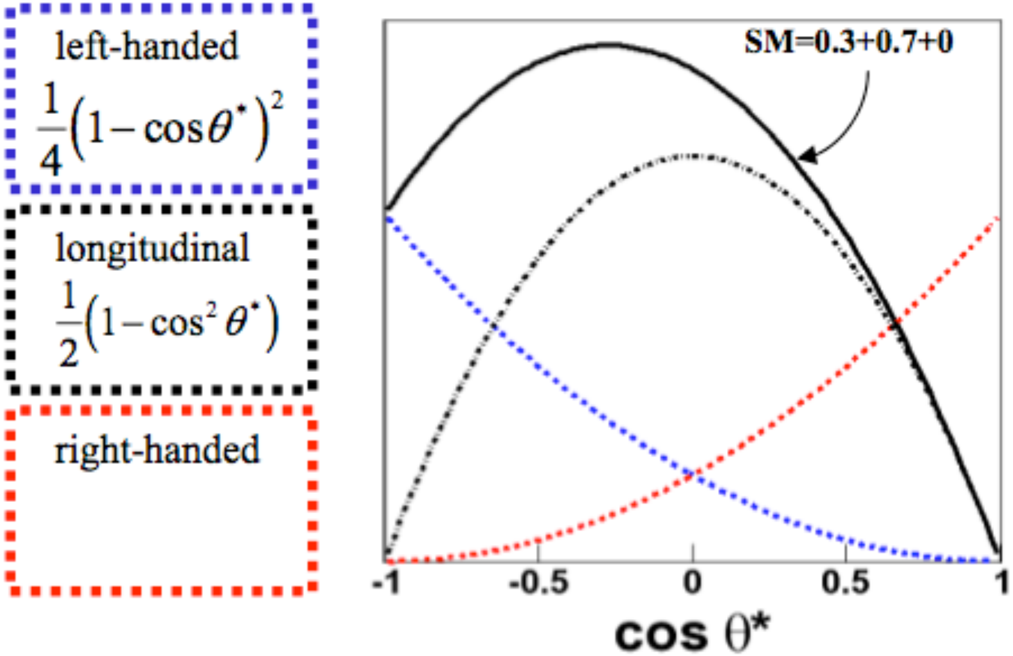
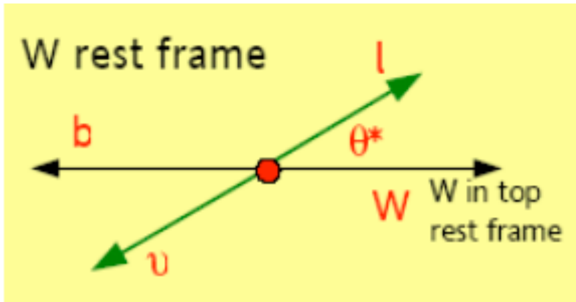
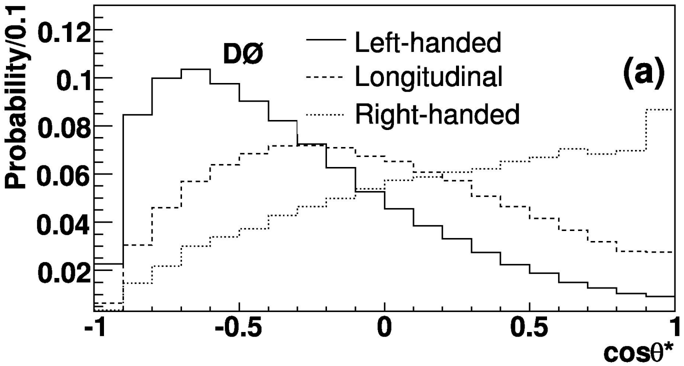
W helicity

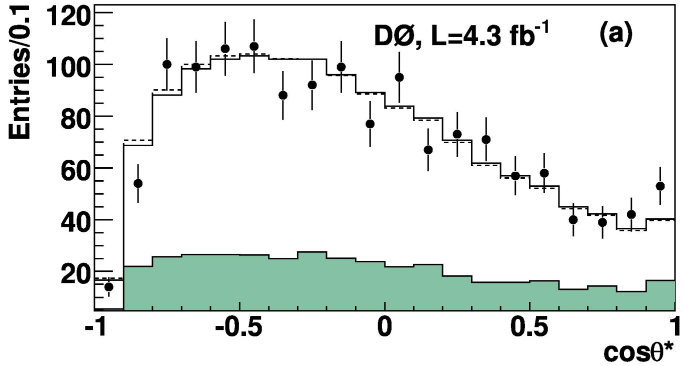
- Measurement of the fraction of longitudinally polarized (f0) and right-handed polarized (f+) W bosons from top quark decay
- SM prediction: 70% longitudinal W's at tWb vertex
- BSM can alter this
- Measurement via angular distributions (lepton angle in W rest frame):



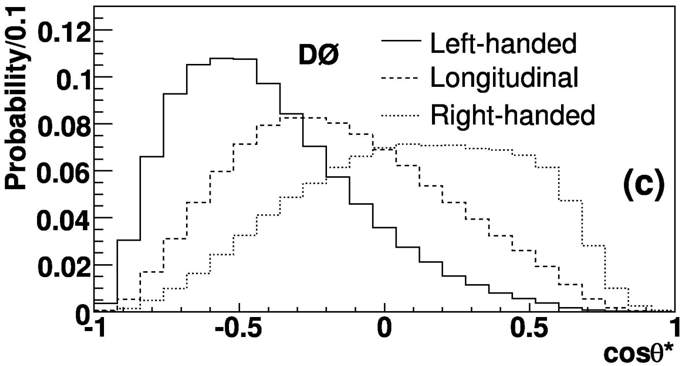


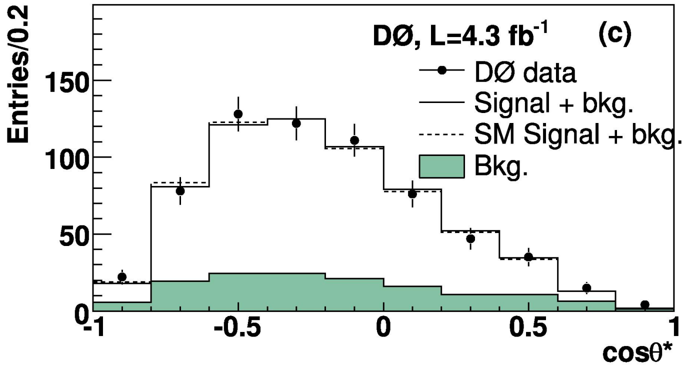
W helicity





lepton in l +jets





dilepton events

Combined result for 5.4 fb-1:	f0 = 0.669 ±0.078 (stat) ±0.065 (syst)
	f+ = 0.023 ±0.041 (stat) ±0.034 (syst)

Spin correlations

- The spins of the t and T at production are correlated.
- τ_{top} < hadronization time scale and spin flip timescale → correlation preserved and affect the angular decay products
- The angular correlations are strongest for the charged leptons from the W decay or the down type quarks, the two dimensional distribution in the respective angles are:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}\left(1 - C\cos\theta_1 d\cos\theta_2\right)$$

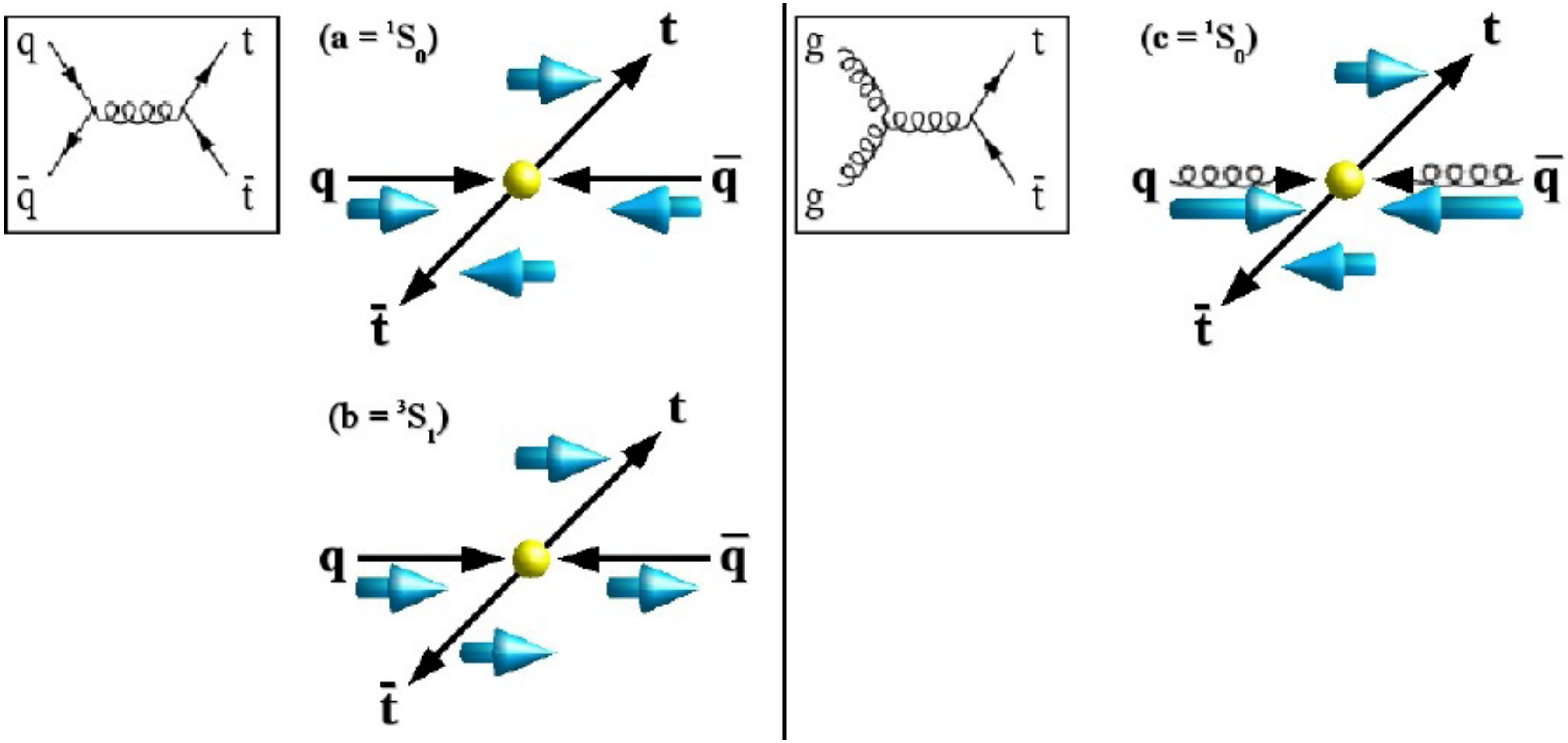
C is the spin-correlation coefficient, $C = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)+N(\uparrow\downarrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\uparrow\downarrow)}$ depending on:

- quantization axis used (i.e. beam axis or helicity basis)
- fraction of tT pairs produced at threshold
- m_{tT}
- fraction produced by gg-fusion

→Different spin correlation coefficient at LHC compared to Tevatron

Finding spin correlation would confirm top as spin ½ particle and the decay before hadronisation. Spin correlation can be altered by certain BSM models

Spin correlations

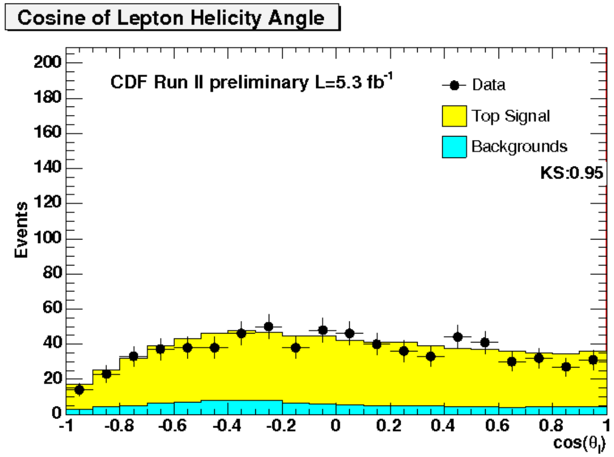


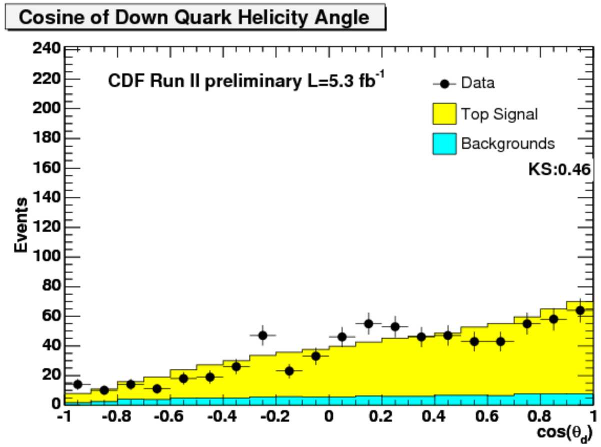
qq: Opposite helicity production (b) dominates

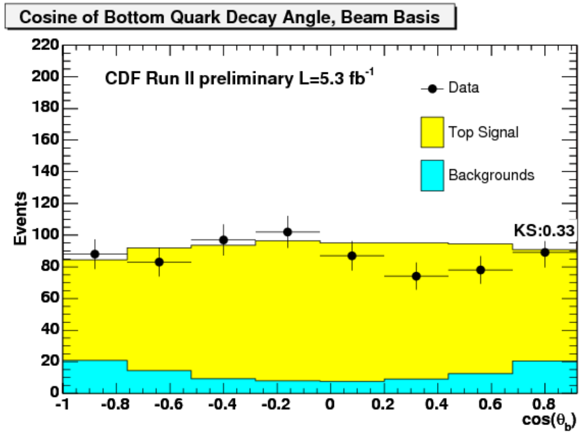
gg: Equal helicity production (c) dominates

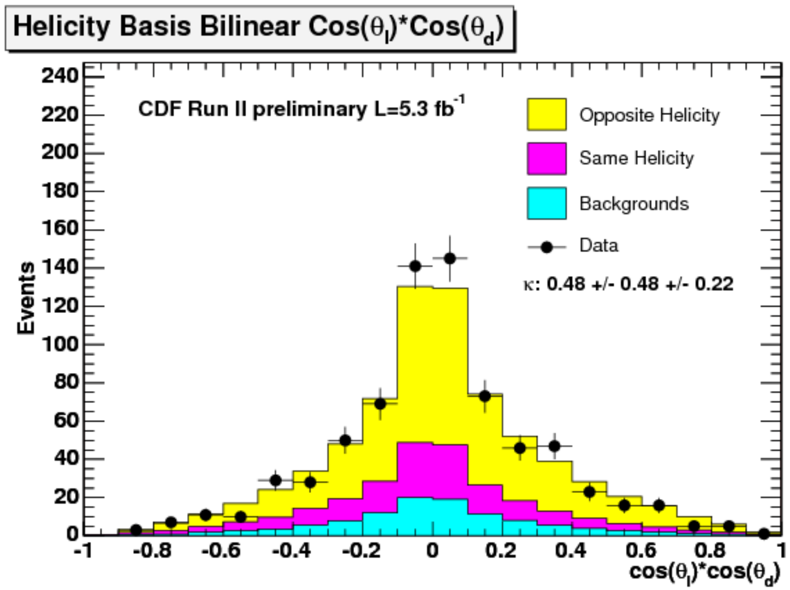
Spin correlations: Analysis

- helicity angles









C = 0.48 ± 0.48 stat ± 0.22 syst (SM: C=0.4)

Opposite helicity fraction:

f_{ohel} = 0.74 ± 0.24 (stat) ± 0.11 (syst)

Conclusions

- The top quark is special:
  - Short lifetime→decay before hadronisation→study bare quarks
  - Large mass→ Introcate link to electroweak symmetry breaking
    → link to physics beyond the standard model
- Predicted for a long time, discovered late @the Fermilab Tevatron
- Since the discovery, based on a few events, top quark physics has evolved into precision physics with a large number of measurements
  - Production: Tt cross section, differential CS, Tt asymmetries, single top,...
  - Decay: W helicity, spin corellations, ...
  - Properties: Mass, widths, lifetime, charge,...
- Much more to come at LHC, which will produce loads of tT pairs