Physics Program

of the experiments at

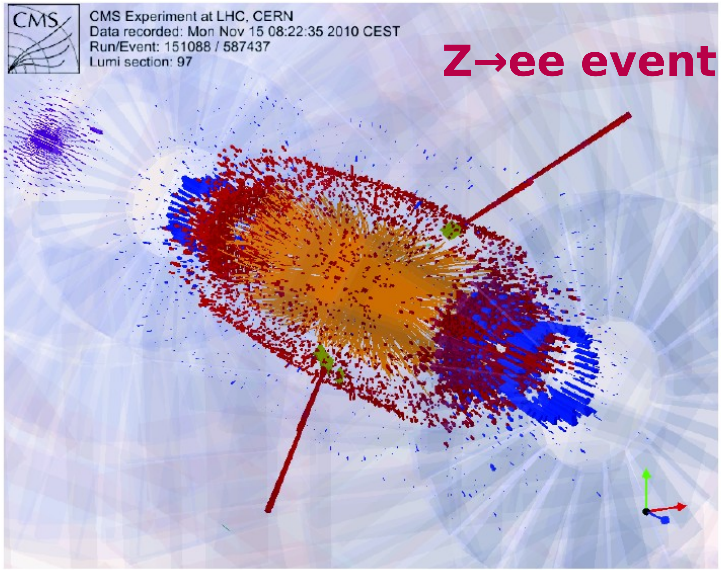
Large Hadron Collider

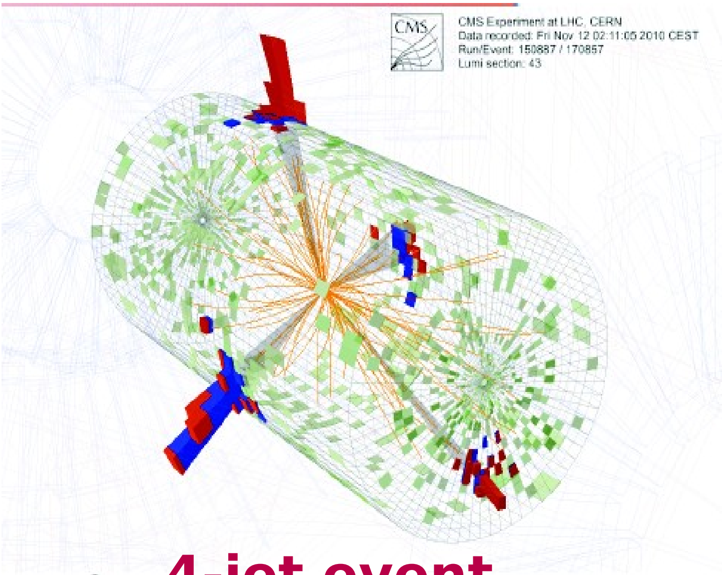
Lecture 7

Physics with top quarks

Latest news!!!

- Very successful commissioning of heavy ion set-up followed by very quick step up in the intensity
- After 6 days maximum number of colliding bunches reached (121 x 121 bunches)
- Up to 1.75 μb^{-1} reached last morning
- LHCC open presentation by all experiments **TODAY!!**



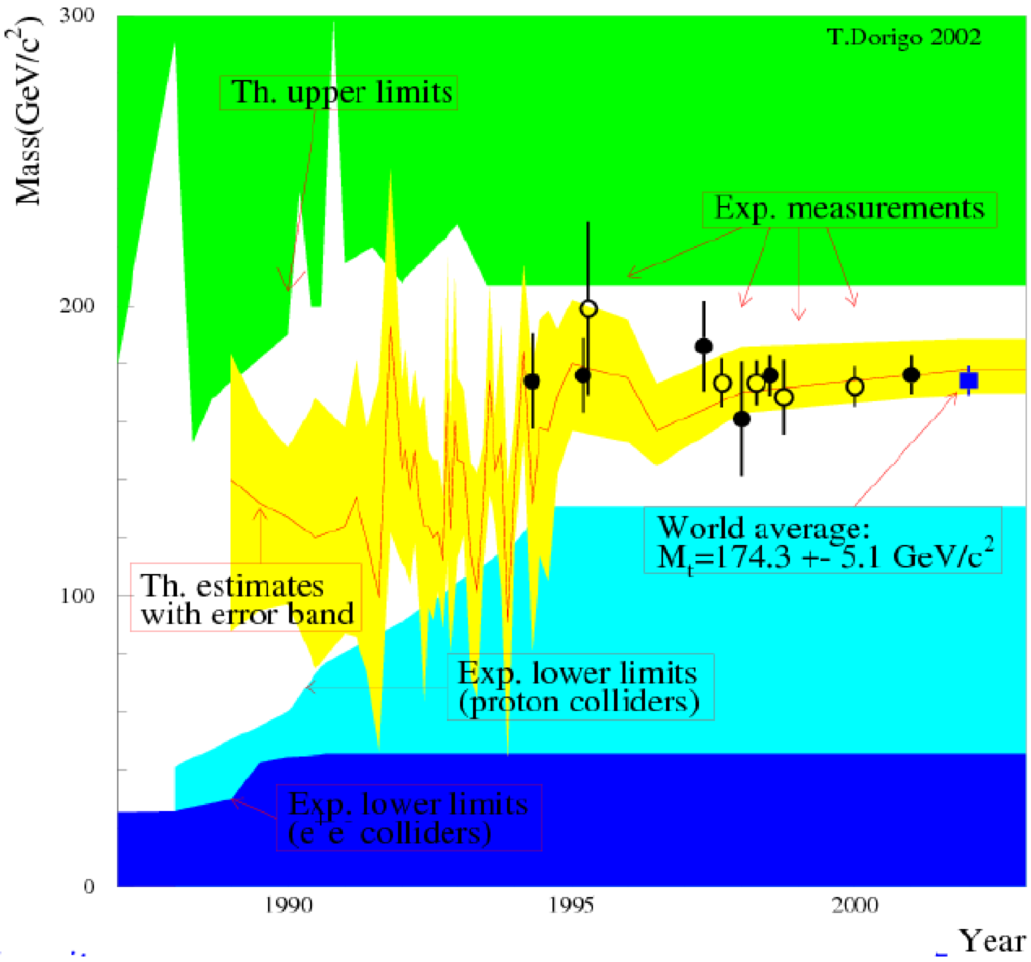


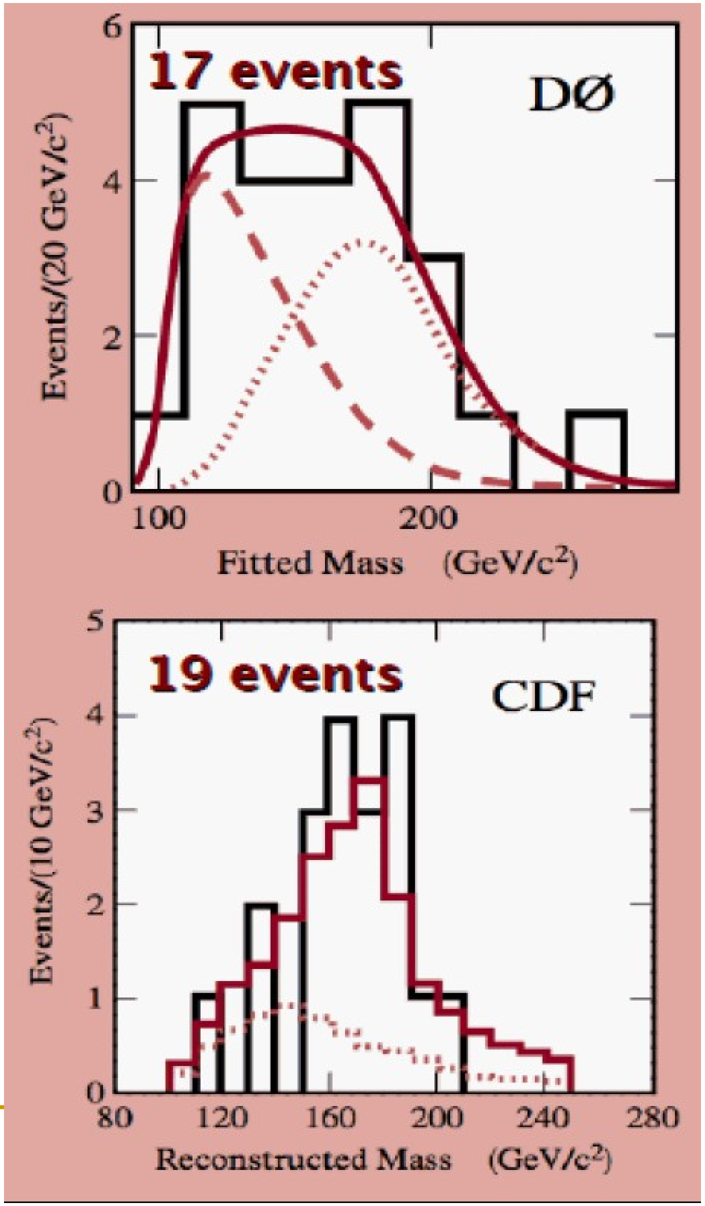
4-jet event

A brief history of the top quark

- **1971:** three quark generations first hypothesized by Kobayashi and Masakawa
- **1977:** Isospin partner needed for anomaly cancellations after b-quark discovery
- **1983:** PETRA determines I^3_b with A_{fb} measurements
- **1984:** UA1 "discovery" (mt = 40+- 10 GeV with 12 events observed and 3.5 expected, then retracted
- **1987:** B mixing measurements imply a large top mas.
- **1992:** LEP determines I^3_b = -1/2
- **1988-1993:** increasing lower limits on top mass by CDF and D0
- **1994:** first evidence by CDF, m_t=174+-12 GeV
- **1995: Observation of top pairs by CDF & D0**
- **2008:** Observation of single top by CDF and D0

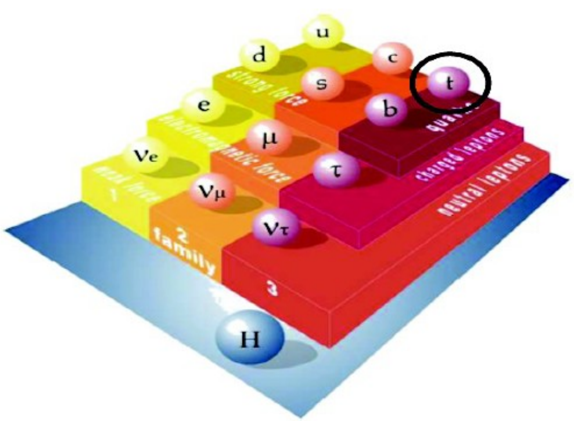
A brief history of top quark

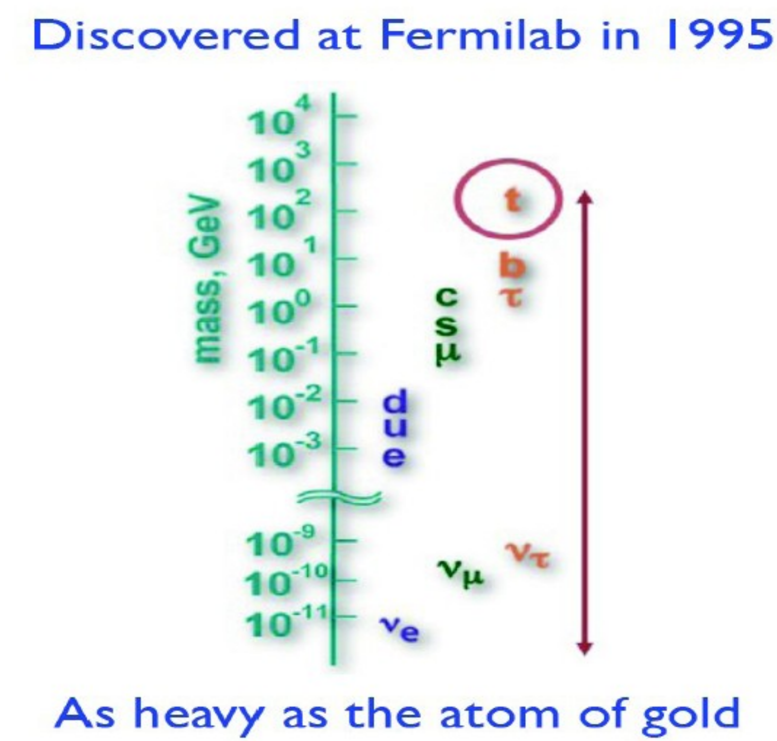




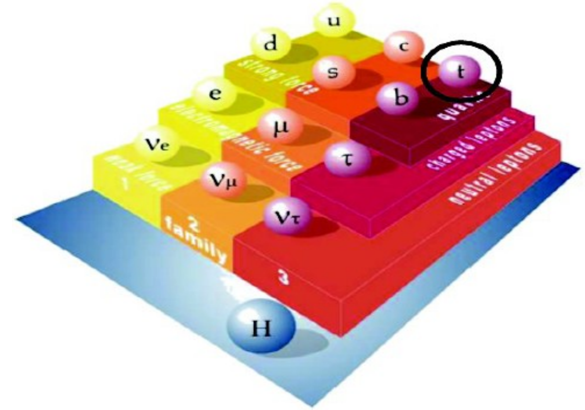
The top quark

- Needed in theory as isospin partner of b-quark
- Properties well defined by the Standard Model
- Unknown – top quark mass





The top quark



- The heaviest fundamental particle with unique properties
  - Large coupling to Higgs boson (~1)
  - Important role in electroweak symmetry breaking?
  - Short lifetime: decays before fragmenting

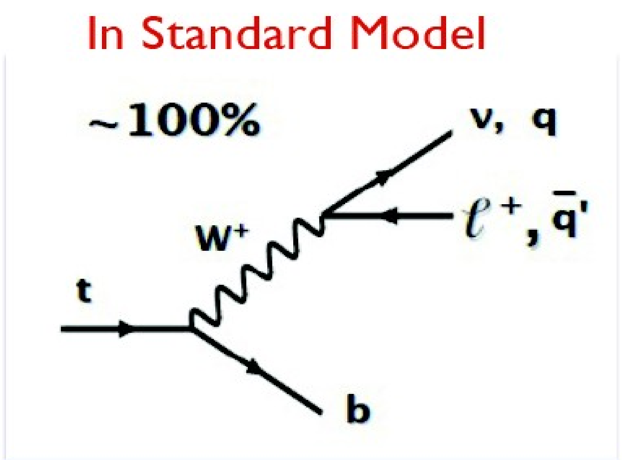
$$\tau \approx 5 \times 10^{-25} s << \Lambda_{QCD}^{-1}$$

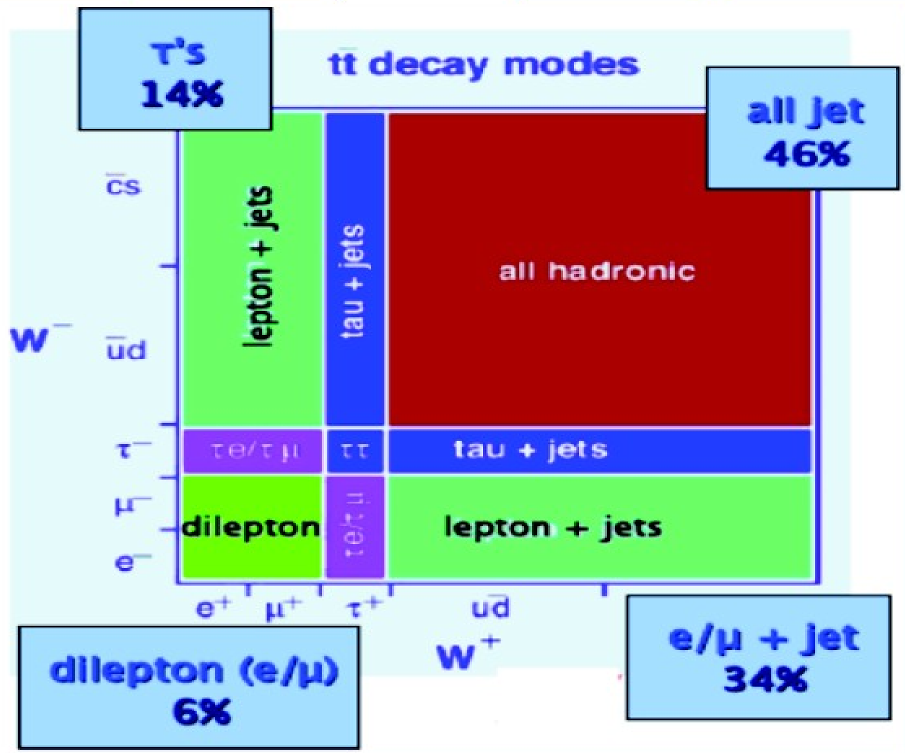
The most probable place for new physics to show up?

Top quark decays

small rate, high background
backgrounds: multijet, W+jets

high rate, high background
main background: multijet





W decay mode defines top pair final state

small rate, small background
main background: Drell-Yan

good rate, manageable background
main background: W+jets

Top quark properties

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

t

$I(J^P) = 0(\frac{1}{2}^+)$

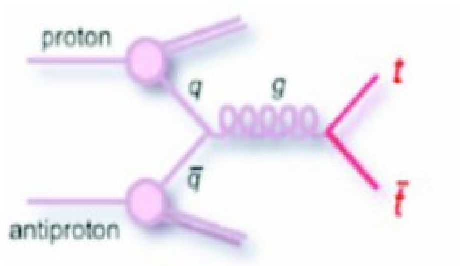
Charge $= \frac{2}{3}\,e$ Top $= +1$

Mass $m = 174.2 \pm 3.3$ GeV [b] (direct observation of top events)
Mass $m = 172.3^{+10.2}_{-7.6}$ GeV (Standard Model electroweak fit)

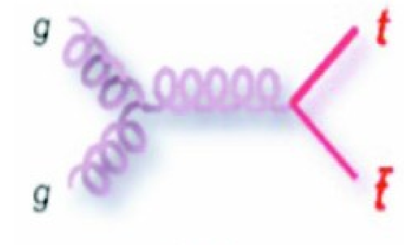
t DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$W\,q\,(q = b, s, d)$				–
$W\,b$				–
$\ell\,\nu_\ell$ anything	[c,d]	(9.4 ± 2.4) %		–
$\tau\,\nu_\tau\,b$				–
$\gamma\,q\,(q=u,c)$	[e]	$< 5.9 \times 10^{-3}$	95%	–
$\Delta T = 1$ weak neutral current ($T1$) modes				
$Z\,q\,(q=u,c)$	$T1$ [f]	< 13.7 %	95%	–

Top quark pair production

Tevatron



85%



15%

NNLO$_{approx}$ for m_t = 172.5 GeV, CTEQ 6.6 PDF

$\sqrt{s}$ (TeV)	2	7	14
$\sigma_{t\bar{t}}$ (pb)	7.46	160.8	886.3

~9% uncertainty

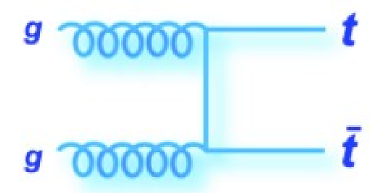
PRD 80, 054009 (2009)

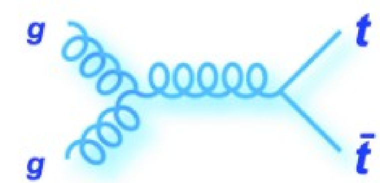
~20 larger than at Tevatron

250 pb^{-1} LHC sample ~ 5 fb^{-1} Tevatron sample

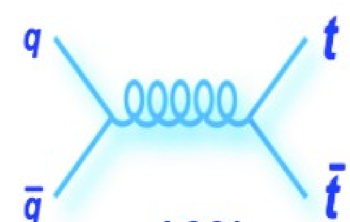
assuming similar efficiency

LHC



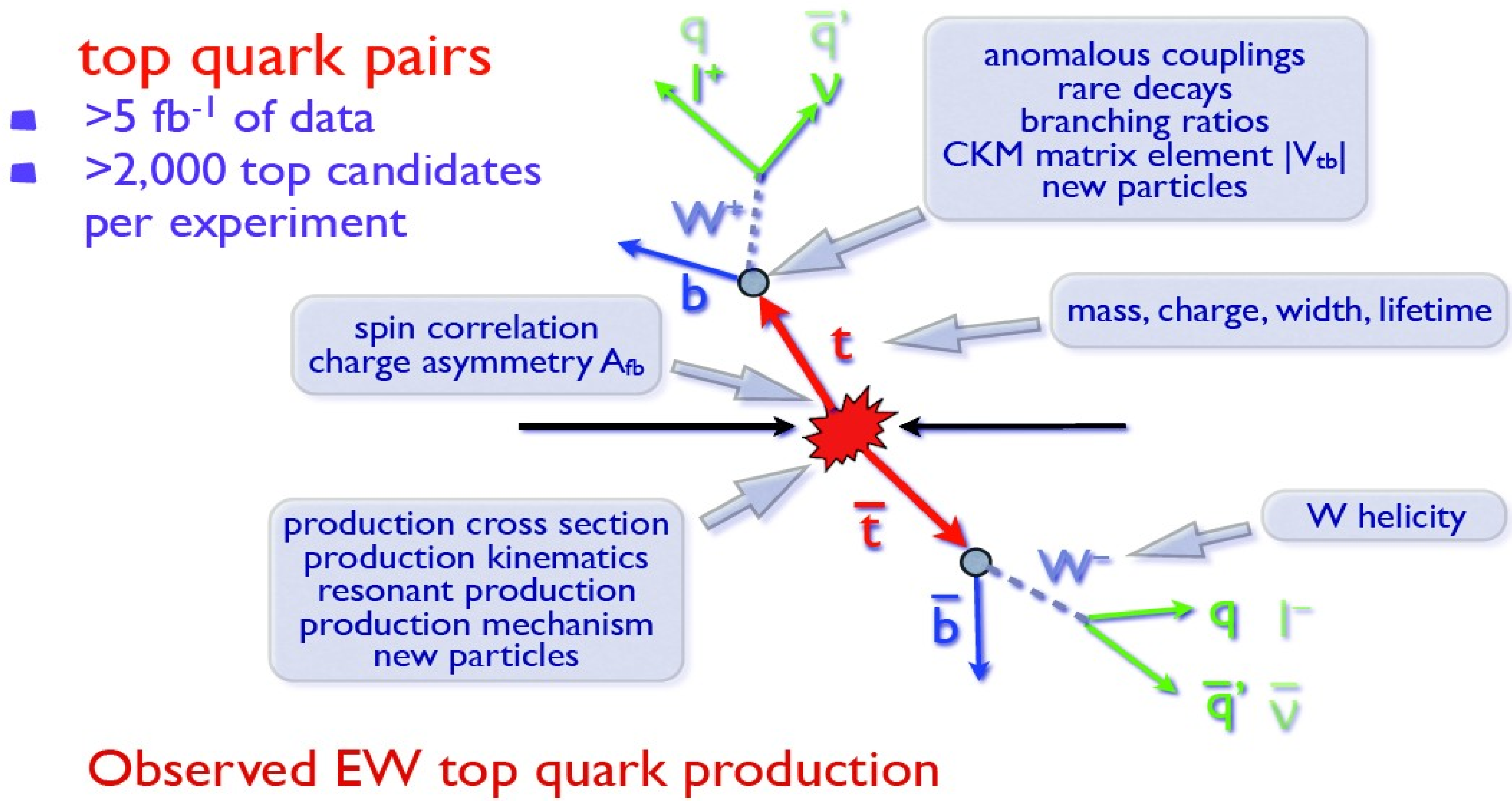


~90%



~10%

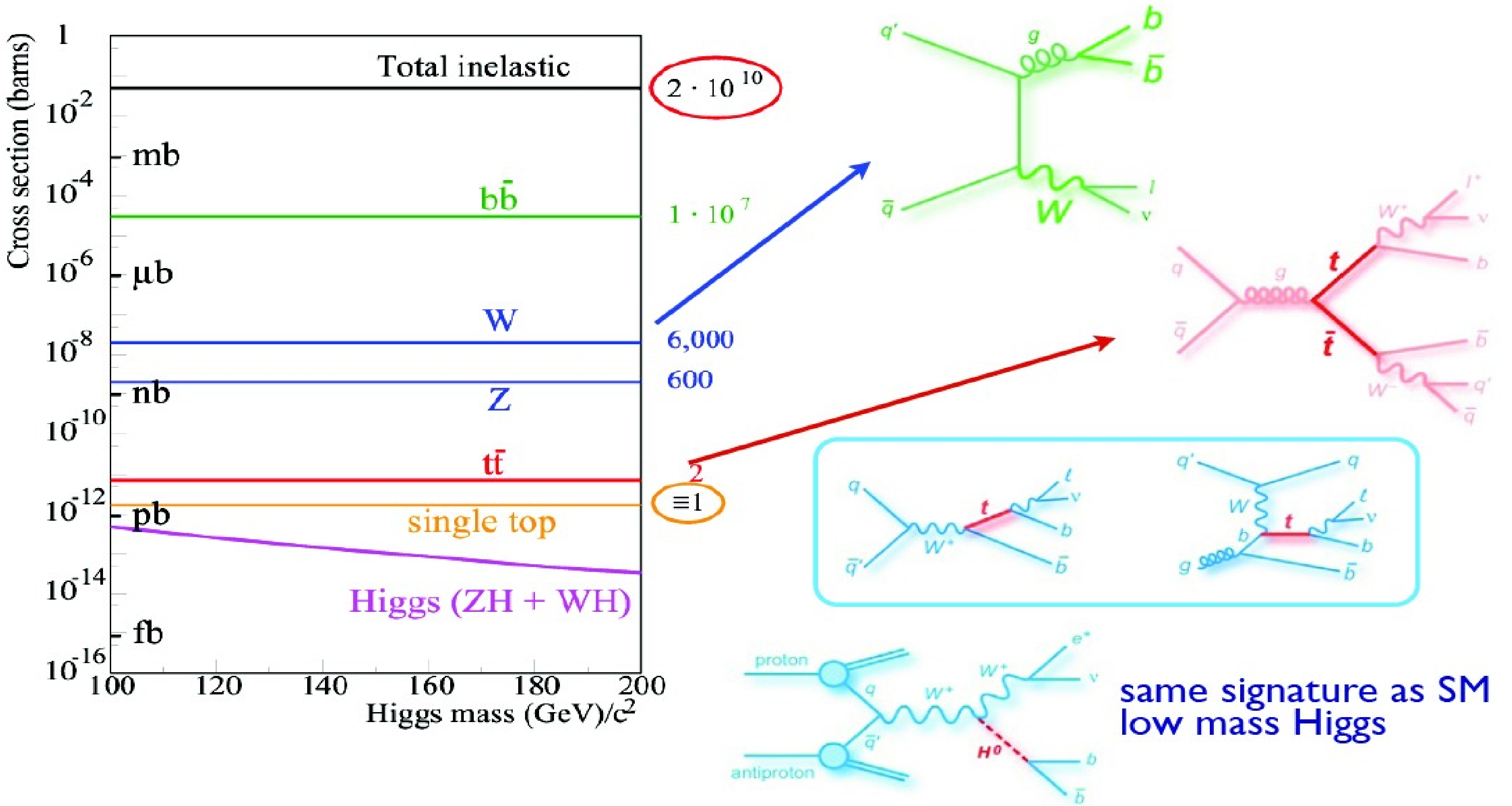
Top quark pairs at Tevatron



Top quark properties

Property	Run II Measurement	SM prediction	Luminosity (fb^{-1})
m_t	CDF: 172.6 ± 0.9(stat) ± 1.2(syst) GeV D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV		4.3 3.6
σ_{ttbar} (@m_t=172.5 GeV) σ_{ttbar} (@m_t=170 GeV)	CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb D0: 7.84 $^{+0.46}_{-0.45}$ (stat) $^{+0.66}_{-0.54}$ (syst) $^{+0.54}_{-0.46}$ (lumi) pb	7.4 ± 0.6 pb 8.06 +0.6 pb	4.5 1
$\sigma_{singletop}$ (@m_t=170 GeV)	Tevatron: 2.76 $^{+0.58}_{-0.47}$ (stat+syst)	2.86±0.8 pb	3.2-2.3
$\vert V_{tb} \vert$	Tevatron: 0.91 ± 0.08 (stat+syst)	1	3.2-2.3
σ(gg->ttbar)/σ(qq->ttbar)	D0: 0.07+0.15-0.07(stat+sys)	0.18	1
m_t - m_{tbar}	D0: 3.8 ± 3.7 GeV	0	1
σ(tt→ll)/σ(tt→l+jets)	D0: 0.86 $^{+0.19}_{-0.17}$ (stat+syst)	1	1
σ(tt→ τ l)/σ(tt→ll + l+jets)	D0: 0.97 $^{+0.32}_{-0.29}$ (stat+syst)	1	1
$\sigma_{ttbar+jets}$ (@m_t=172.5 GeV)	CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst)	1.79+0.16 -0.31 pb	4.1
cTtop	CDF: 52.5 μm @ 95%C.L.	10^{-10} μm	0.3
T top	CDF: <13.1 GeV @ 95%C.L.	1.5 GeV	1
BR(t->Wb)/BR(t->Wq)	CDF: >0.61 @ 95% C.L. D0: 0.97 $^{+0.09}_{-0.08}$ (stat+syst)	1	0.2 0.9
F_0	CDF: 0.62 ± 0.11 D0: 0.490 ±0.106 (stat) ±0.085 (syst)	0.7	2 2.7
F_+	CDF: -0.04 ± 0.05 D0: 0.110 ±0.059 (stat) ±0.052 (syst)	0.0	2 2.7
Charge	CDF: - 4/3 excluded with 87% C.L. D0: 4e/3 excluded at 92% C.L.	2/3	1.5 0.37
Spin correlations	CDF: κ = 0.32 + 0.55 - 0.78, -0.46 < K < 0.87 @ 68%C.L. D0: κ =−0.17 $^{+0.65}_{-0.53}$ (stat + syst)	0.78 $^{+0.027}_{-0.022}$	2.8 4.2
Charge asymmetry	CDF: 0.19 ± 0.07(stat) ± 0.02(syst) % D0: 12 ± 8 (stat) ± 1 (syst) %	0.05 +- 0.015	3.2 0.9

A challenge at Tevatron

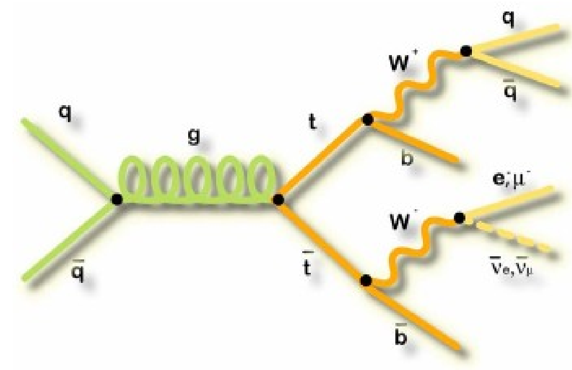


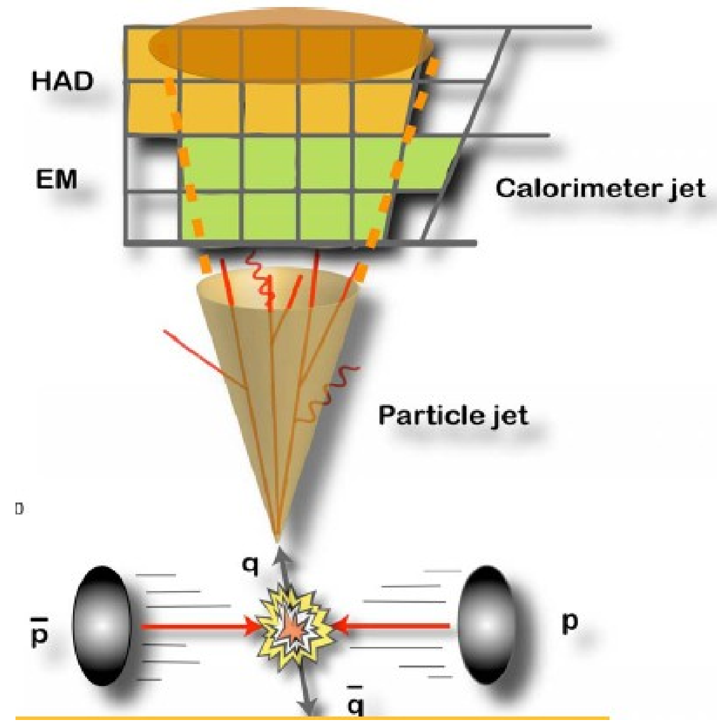
same signature as SM low mass Higgs

- Multivariate techniques to extract signal

Experimental challenges

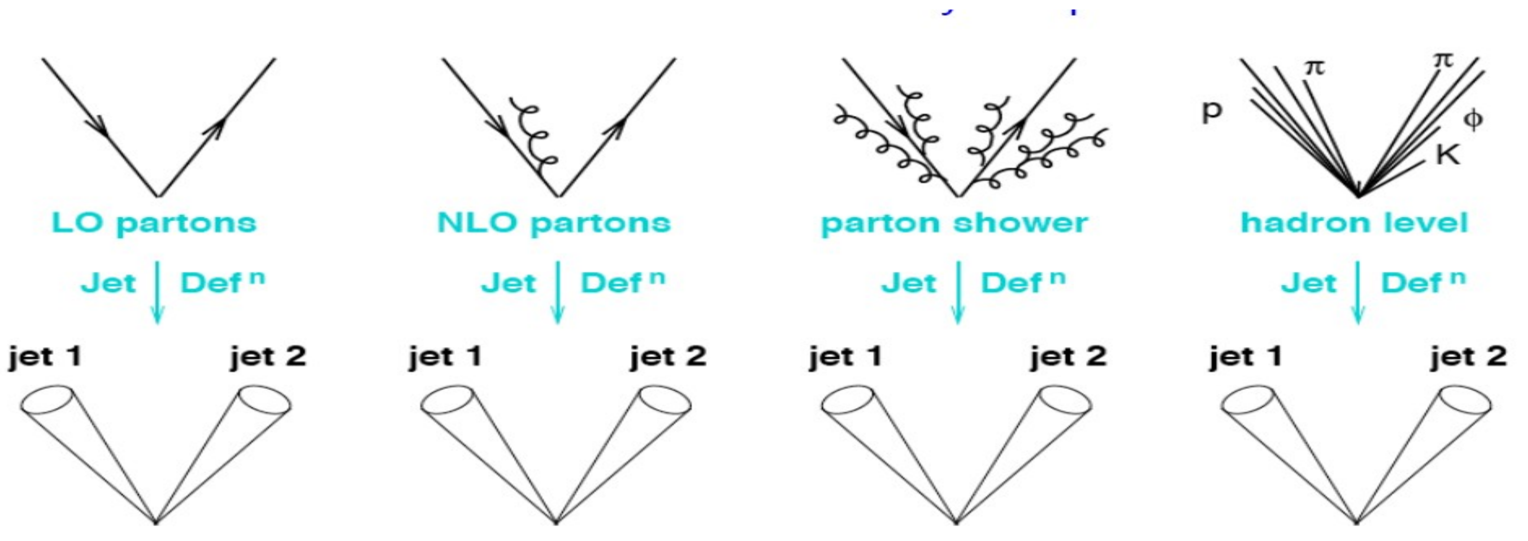
- Only jets can be measured
- Clear mapping between reconstructed objects and partons
- Jet energy scale calibration to particle level
  - dominant uncertainty
- In-situ calibration using hadronic W mass





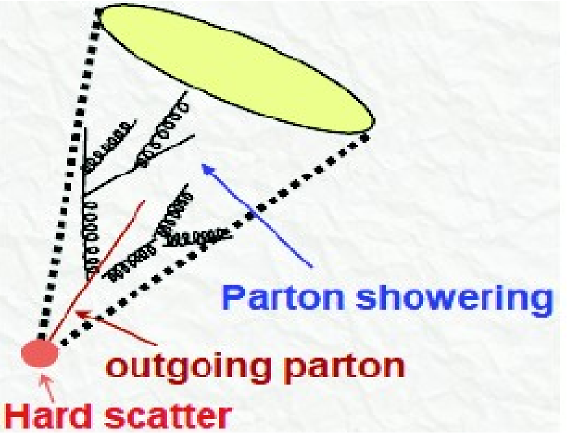
Finding top quarks: jet algorithms

- Projection to jets should be resilient to QCD effects
- The algorithm should behave in similar manner (as much as possible) at the parton, particle and detector levels



(Legacy) cone algorithms

- The cone algorithm is (was) most often used in hadron-hadron colliders
  - Perhaps most intuitive
  - Draw a cone radius R in $\eta-\phi$ space
  - Non-trivial where we start the cone:
    - use seeds to build towers
    - combine seed towers with other towers within a radius R
    - re-calculate jet centroid using new list of towers.... inside cone
    - lather, rinse, iterate until a stable solution is found



$$R_{\text{cone}} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

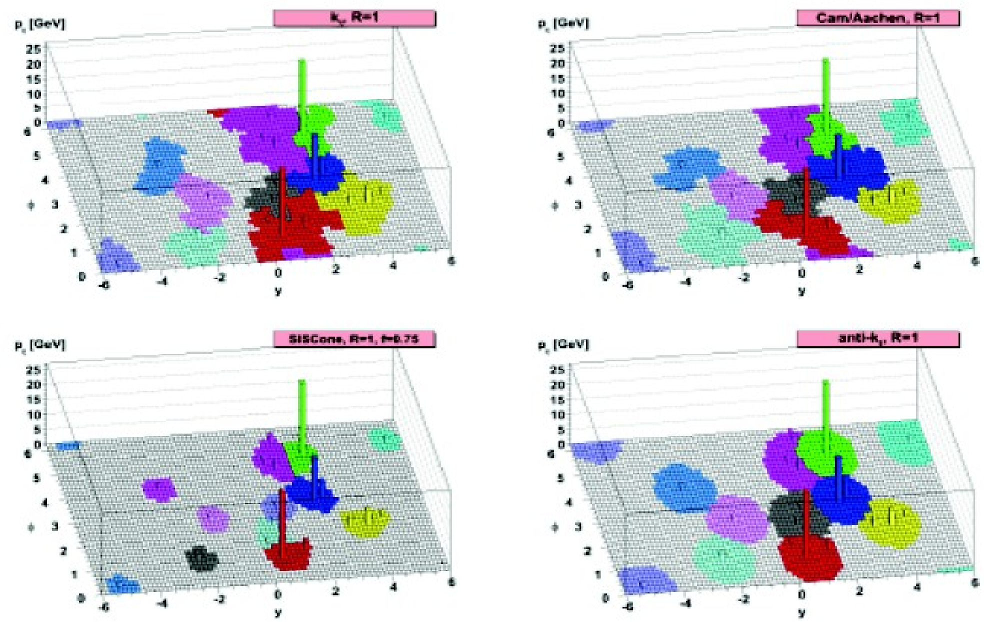
- You may end up with overlapping cones; split-and-merge procedure

K_T recombination algorithms

- Infra-red and collinear safe
  - Resultant jets stable under these effects
- Two general classes
  - Cone algorithms around seeds
    - Require split-merge if overlapping cones
  - Clustering algorithms
    - May give irregular shapes with complicated background corrections
- Anti-k_t is a clustering algorithm
  - p=1 for k_t clustering, p=0 for Cambridge/Aachen, p=-1 for anti-k_t
  - Cluster smallest distance and recompute

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2} \qquad \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

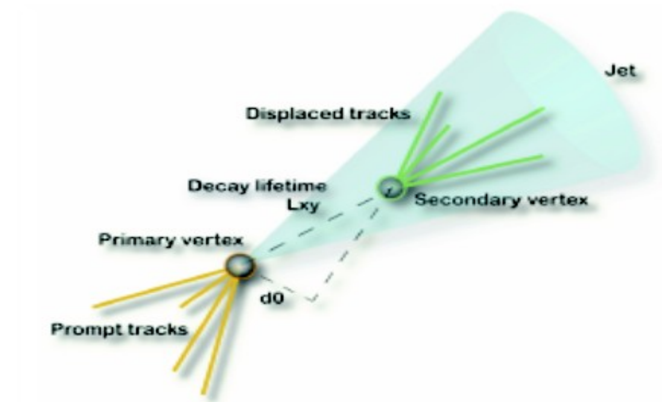
$$d_{iB} = k_{ti}^{2p}$$

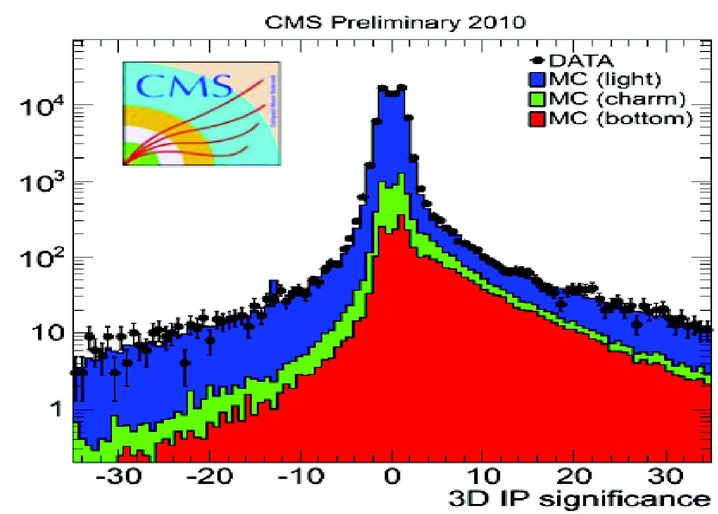


arXiv:0802.1189v2

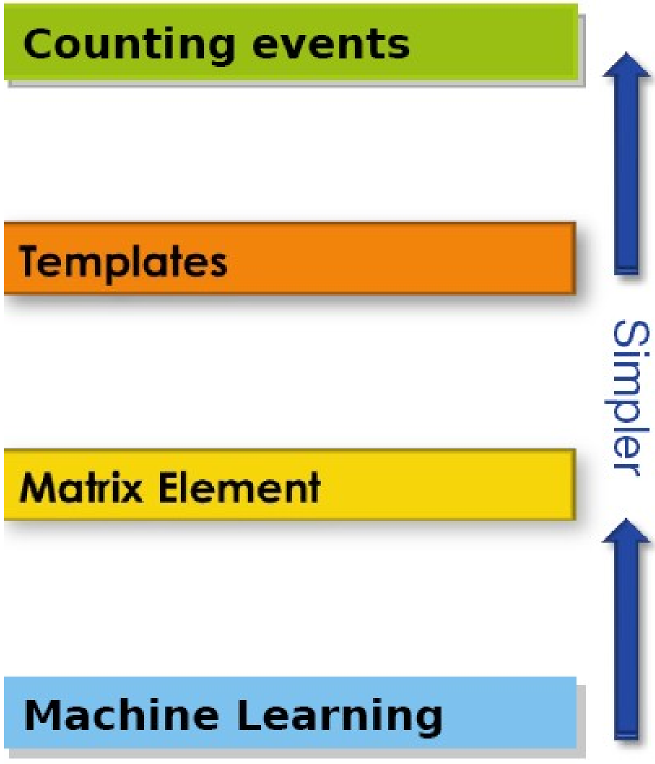
Finding top quarks: b-tagging

- Powerful tool to suppress backgrounds
- Utilizes
  - Long live time of B-hadrons
  - Semileptonic B decays





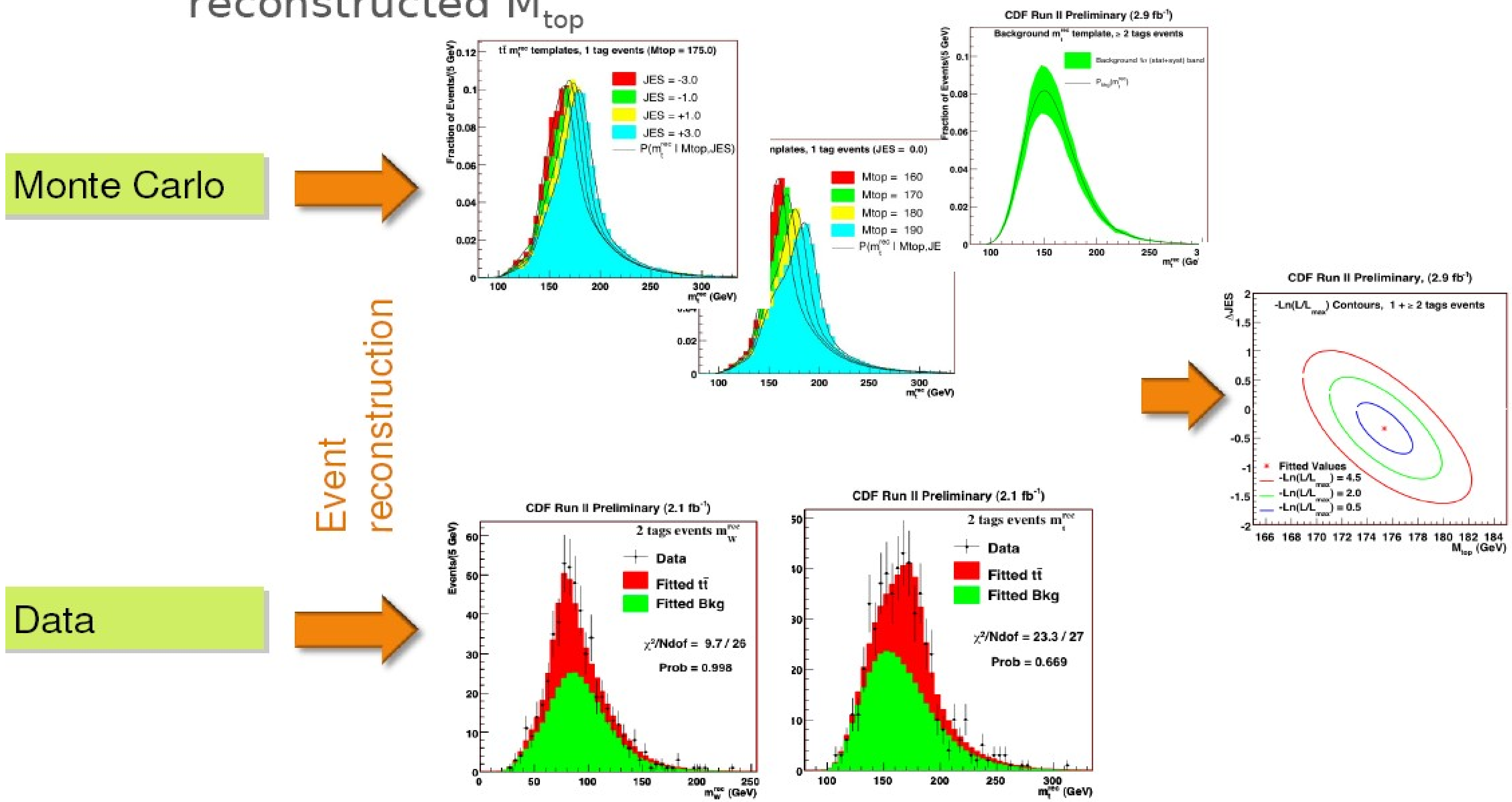
General methods



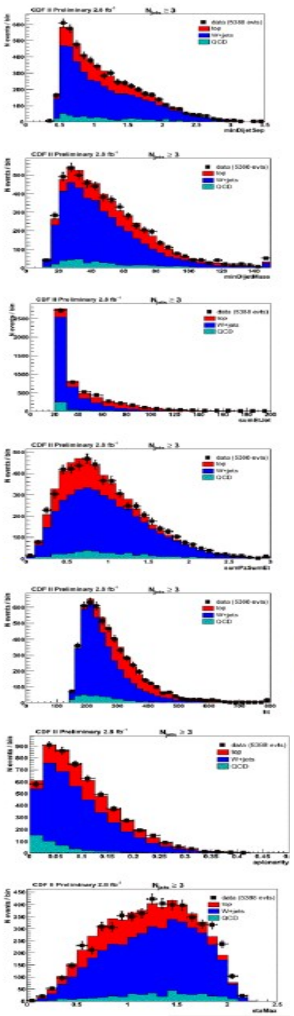
- More sophisticated methods are used as the experimental challenge increases
  - Small S/B, signal, background kinematically similar, higher precision
- Simple vs multivariate techniques
  - A simple kinematic variable can be calculated by theorists while NN distribution cannot
  - Multivariate technique exploit correlations between variables
    - Need to understand if the Monte Carlo models correlations correctly

Templates/likelihood example

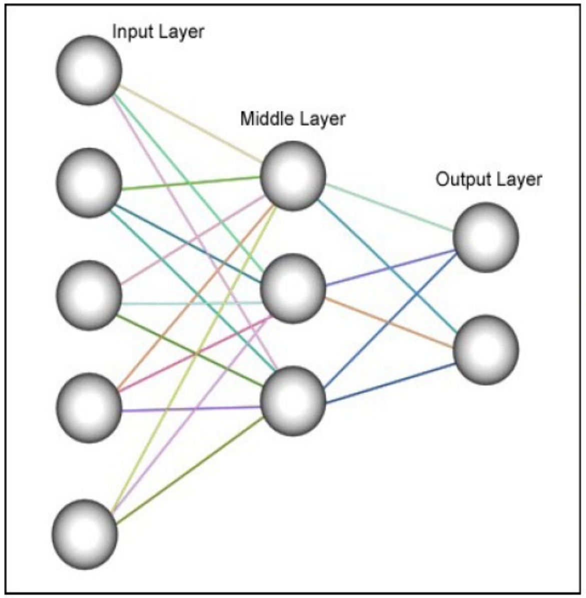
- Top quark mass measurement all-jets: 2D templates M_{jj} and reconstructed M_{top}



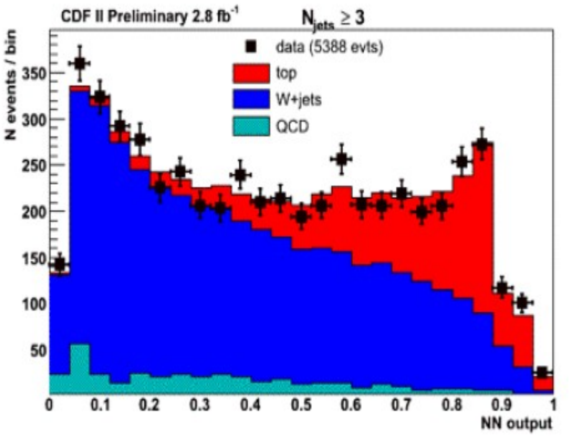
Neural networks



- Uses correlations between inputs in order to decide if event looks signal like or background like
  - Trained on Monte carlo kinematic distributions
  - Thoroughly validated in actual data

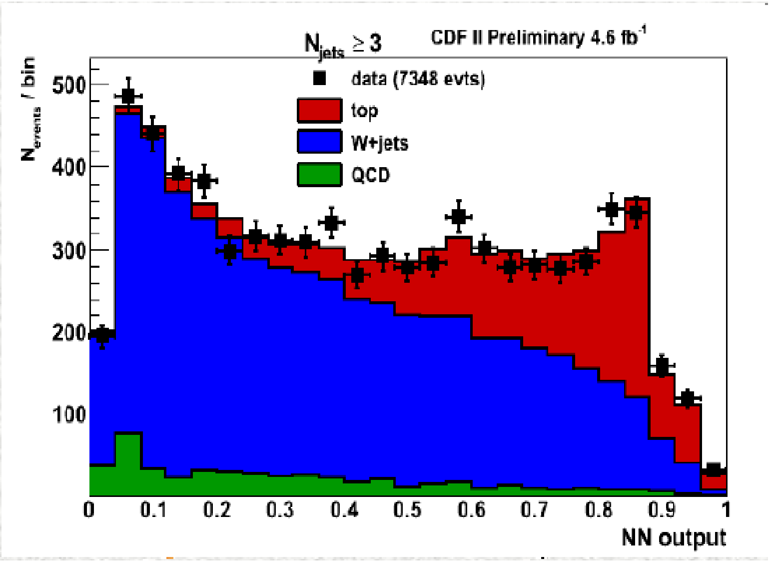


Many NN packages available



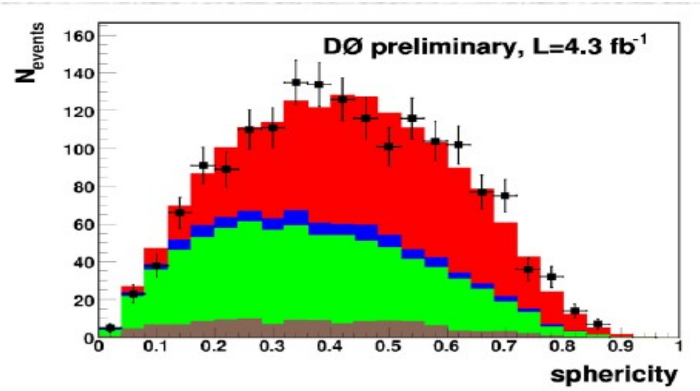
Cross-section measurement

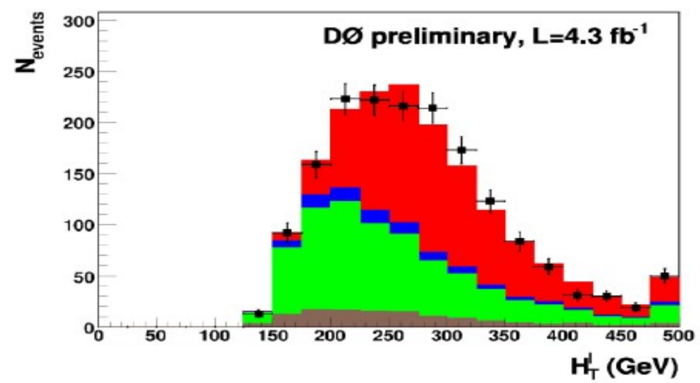
- The most precise result come from CDF when they normalise cross-section to the yield of Z bosons in the same dataset – this gets rid of most of the 5.6% luminosity uncertaintity.
- Data selection is loose, no b-tagging
- QCD and W+jets backgrounds are derived by a fit to the missing Et distribution.
- Result systematic dominated by jet energy scale and to modeling (2.5-3%), 2% from Z theory, 1% from Q^2 scale in W+jets



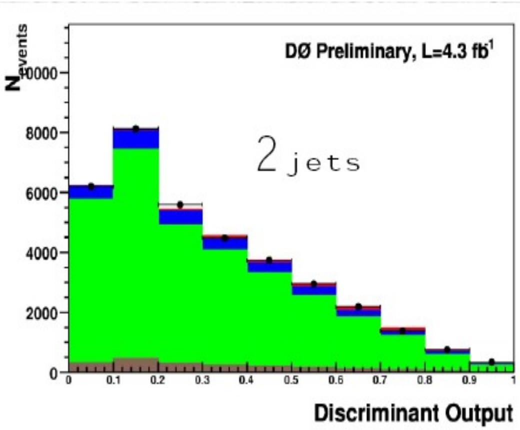
Top pair cross-section measurement from D0

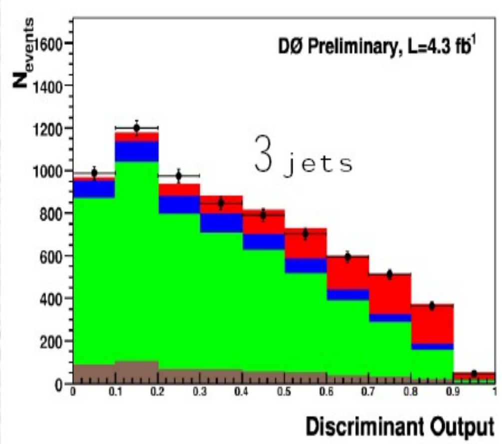
Result: $\sigma_{tt} = 7.70^{+0.79}_{-0.70}$ pb

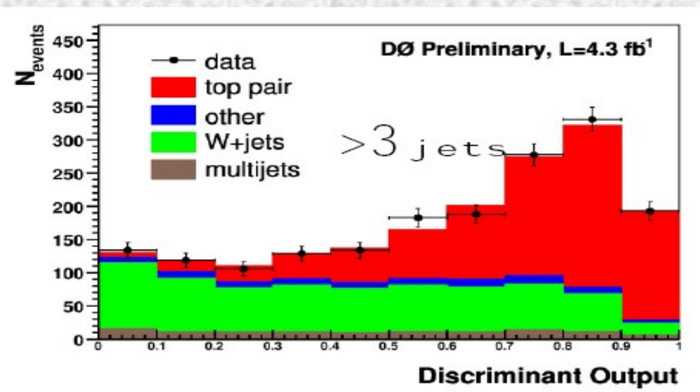




- Single lepton channel
- Using kinematics, no b-tagging
- Boosted decision trees (BDT), 6 classes of events

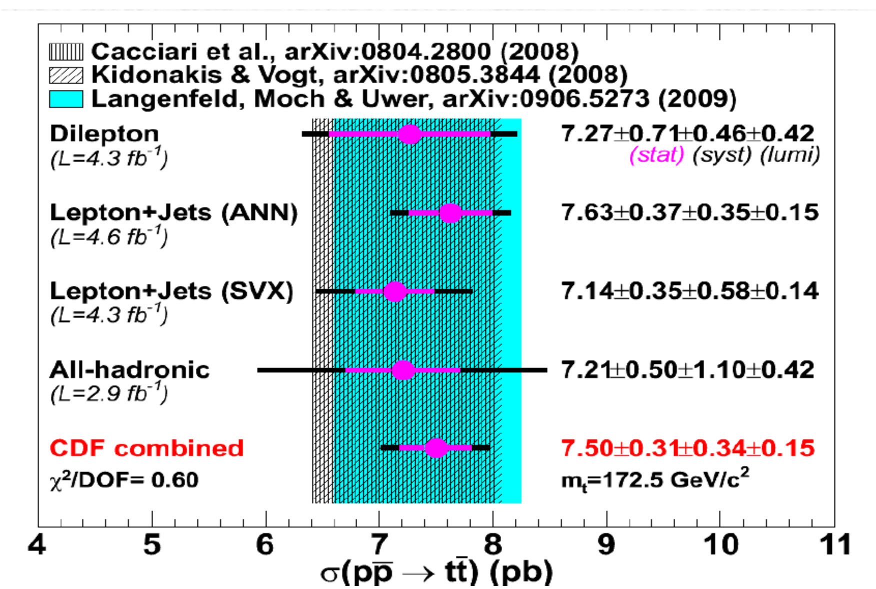


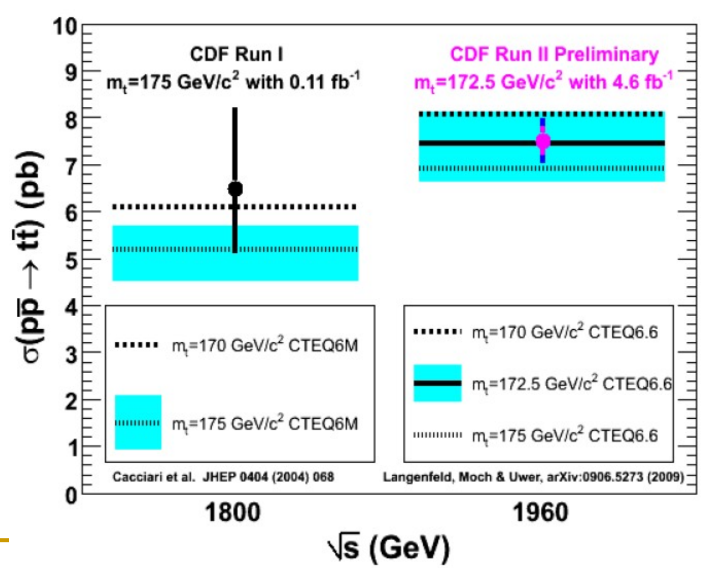




Cross-section measurement

- It is now "less hot" subject at Tevatron
  - Still very precise check on perturbative QCD NLO calculations; new production mechanisms, new decay modes. **Exp. precision better than theoretical predictions**
  - Interest nowdays driven by top being background to other searches (eg. SUSY, 4-th gen, Higgs,...)



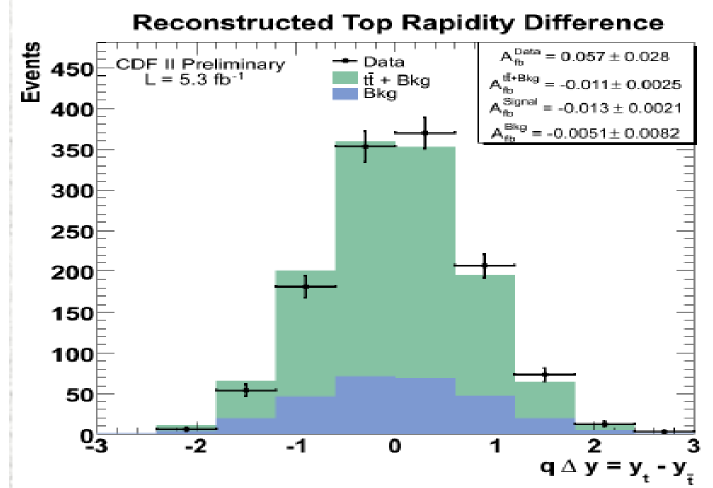


Forward-backward asymmetry in top-pair production

- A recent “hot topic”: do t^+ get produced preferentially in proton direction?
- AT LO QCD the answer is no, at NLO few percent asymmetry is predicted in SM.
  - Larger asymmetries could be the effect of Z'→ tt in production
  - Smaller asymmetries could indicate New Physics

Asymmetry, defined in the tt frame as

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}$$



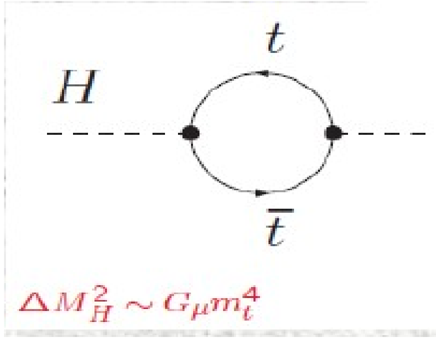
Both D0 and CDF measure a non-zero asymmetry. No easy combination (CDF unsmears data, D0 smears MC&NLO theory).

CDF: A_{lab}=0.150±0.050±0.024 (NLO QCD predicts A_{lab}=0.038±0.006)

D0 (4.3/fb): simultaneously fit sample composition and A_{fb}; measure A_{fb} = 8±4±1% (MC@NLO predicts A_{fb}=1±2% for SM top pairs)

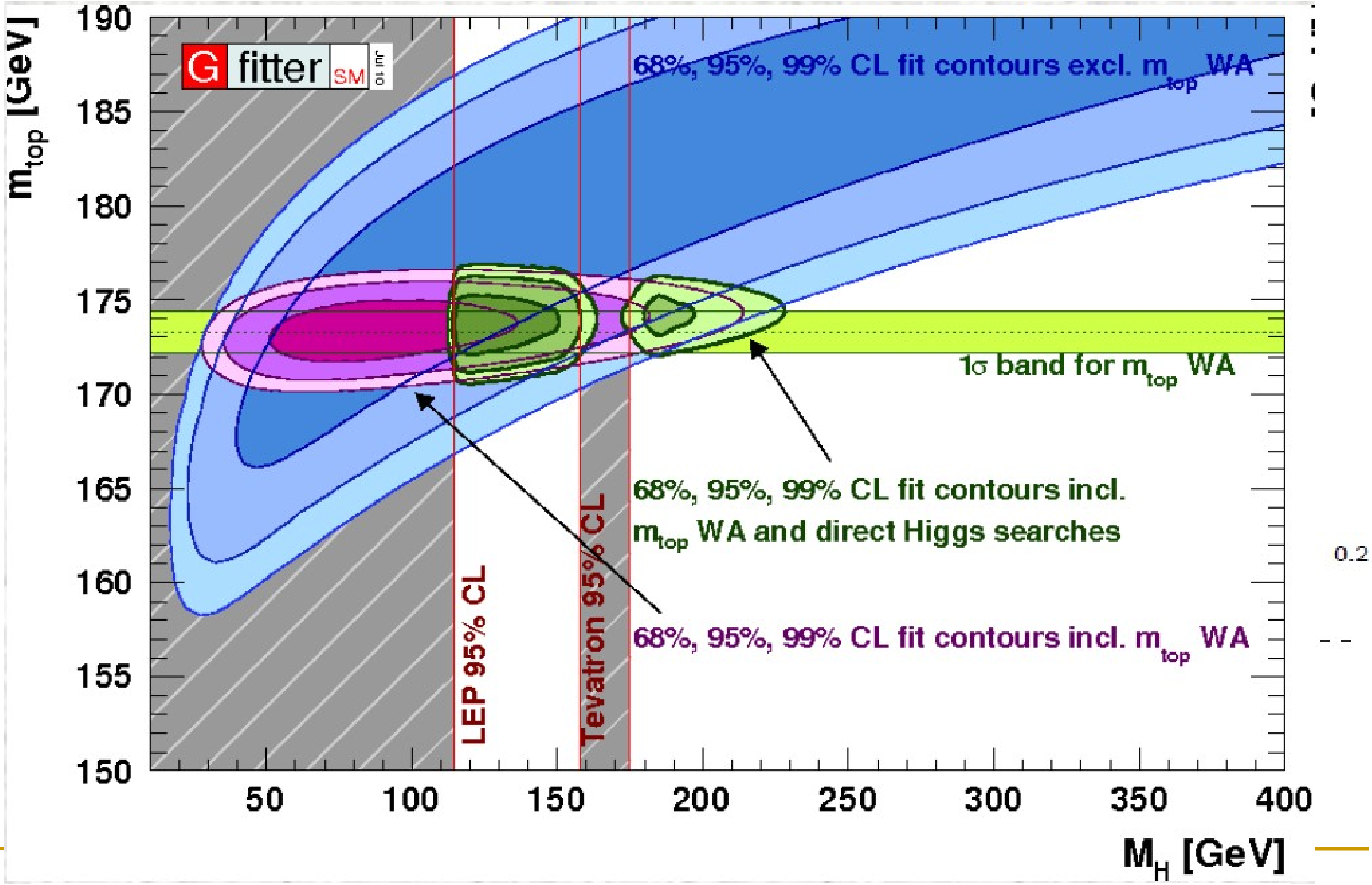
Top mass

$$M_t = 173.32 \pm 0.56(\text{stat}) \pm 0.89(\text{syst})\ \text{GeV}$$



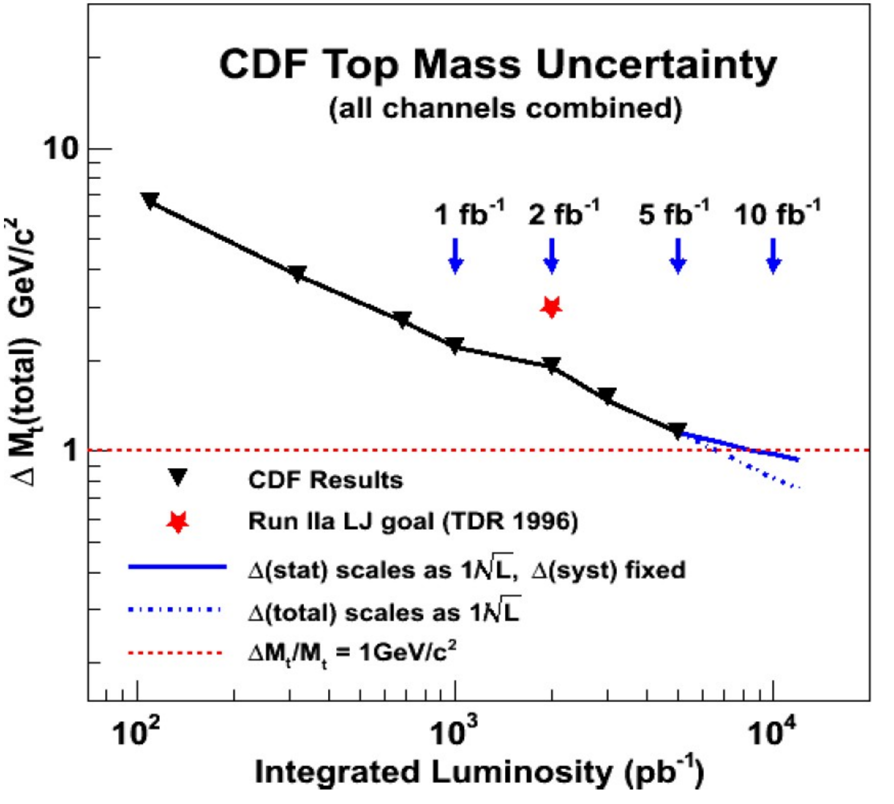
- Top is the quark whose mass is best known: $\mathcal{O}$(0.67%) and decreasing.
- Do we need to know this mass better?
  - From SM perspective the answer is NO, not for constraining the mass of the Higgs boson
  - Precision on the other SM parameters still significantly driven by δm_t
  - As far as EW parameters, both in the SM and in the MSSM a sub-GeV m_t knowledge makes a big difference.
  - In SUSY (and almost any other BSM model) m_H is free, and tightly connected to m_t via loops:
    - δm_t=1GeV ↔ δm_H= 1 GeV

Top mass


G fitter SM
Jul 10
68%, 95%, 99% CL fit contours excl. m_{top} WA
1σ band for m_{top} WA
68%, 95%, 99% CL fit contours incl.
m_{top} WA and direct Higgs searches
68%, 95%, 99% CL fit contours incl. m_{top} WA
LEP 95% CL
Tevatron 95% CL
m_{top} [GeV]
M_H [GeV]
190
185
180
175
170
165
160
155
150
50
100
150
200
250
300
350
400
0.2

Future precision on the top mass

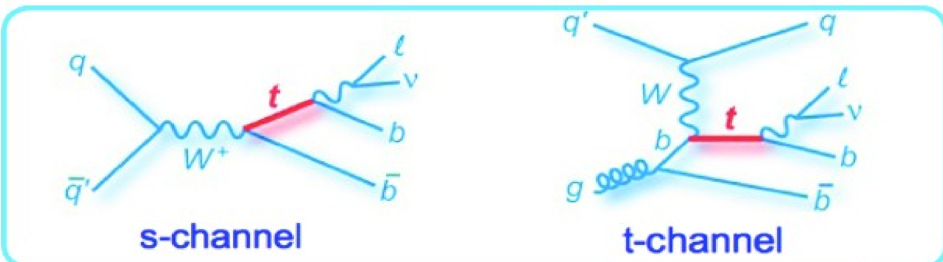
- Tevatron:
  - CDF alone will reach precision below 1 GeV
  - With D0 combination, likely get to 600 MeV
- A true legacy, will be hard to surpass at LHC



Electroweak top production

- Predicted 10 years before top discovery
- Observed 14 years after top discovery

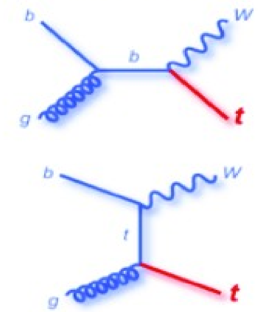
S.Willenbrock, D. Dicus, Phys. Rev. D34, 155 (1986); S Cortese and R Petronzio, PLB 253, 494 (1991)



σ=1.04±0.04 pb σ=2.26±0.12 pb

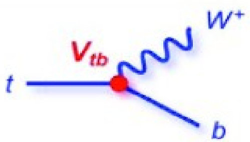
NNNLO$_{approx}$, m_{top}=172.5 GeV

Wt channel

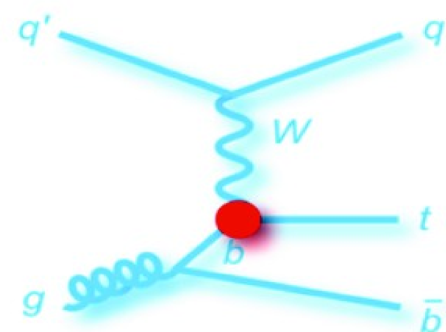


Small at Tevatron, important at LHC

$\sigma \sim |V_{tb}|^2$



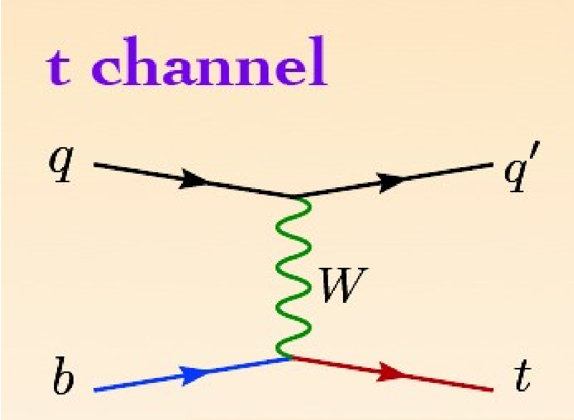
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



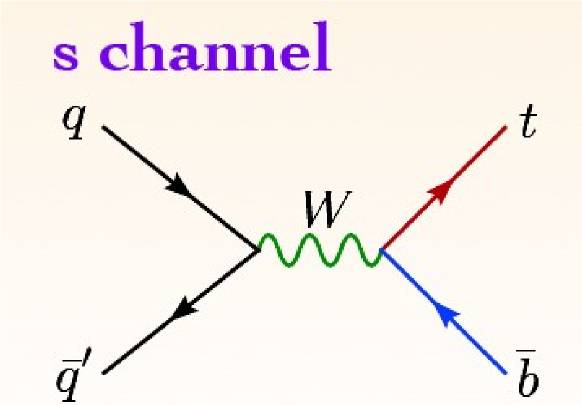
in t-channel

Single top production

- Contrary to top pair production, single tops are not produced via strong force, but by the weak force.
- There are three distinct (interferences are color suppressed) production mechanisms named after virtuality of the W boson
  - t- channel
    - relative t-channel enhancement at LHC
    - also enhancement from b-quark
  - s- channel
    - just like “Drell-Yan process”
    - relative enhancement at Tevatron
    - more sensitive to quark PDF's
  - W-associated single-top production



Cross section	
Tevatron	2.0 pb
LHC 14 TeV	240 pb



Cross section	
Tevatron	0.86 pb
LHC 14 TeV	10 pb

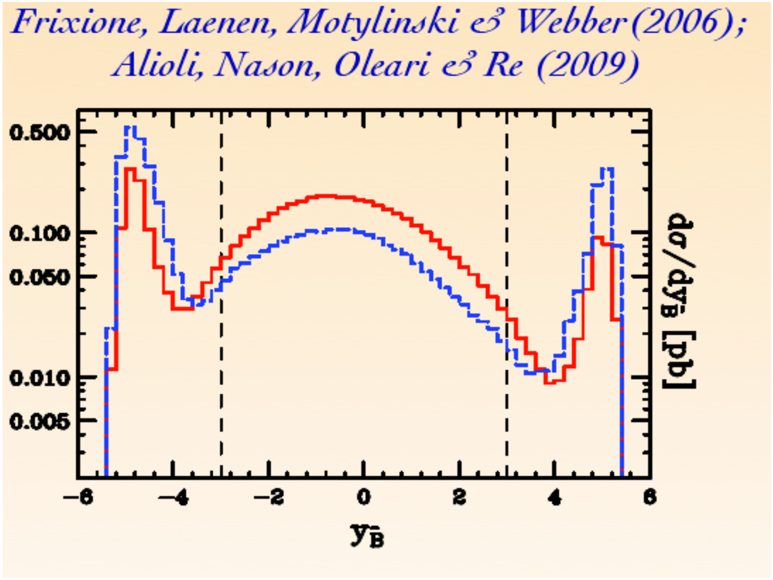
t-channel process

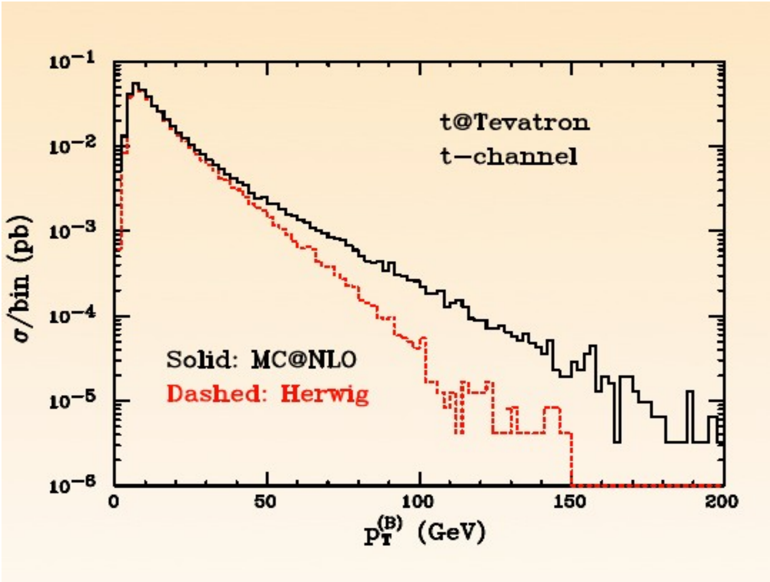
- For the t-channel process situation is complicated due to the initial state b-quark
- The LO+parton shower greatly underestimate importance of the spectator b-quark

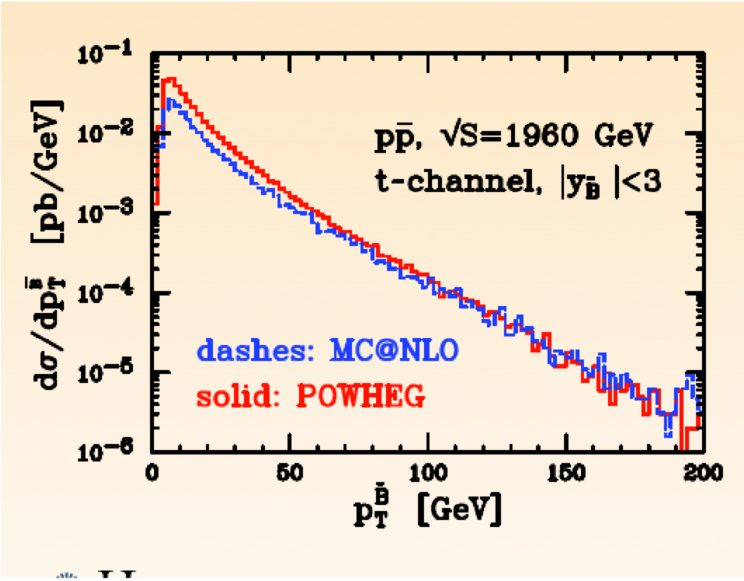
- With NLO calculations, spectator b-quark spectrum is described only at first non-zero order (thus, in fact, LO)

t-channel process

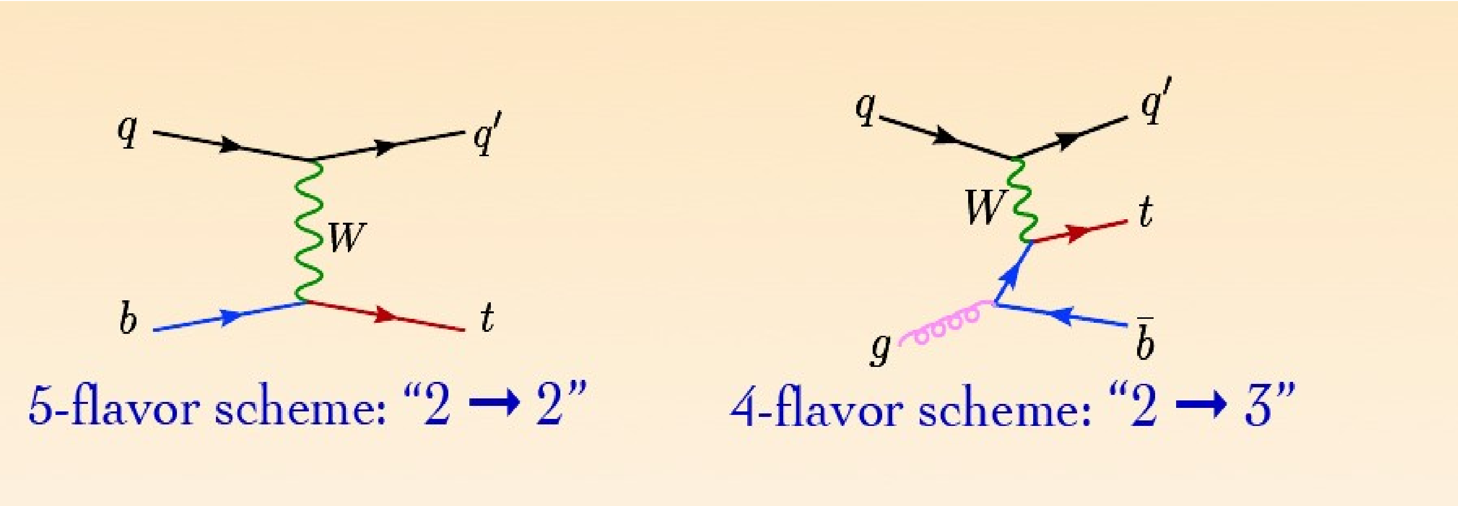
- McatNLO and POWHEG
  - Sizeable differences in shape and normalisation for spectator b-quark
  - b-quark massless, low p_T range not well described







The two schemes

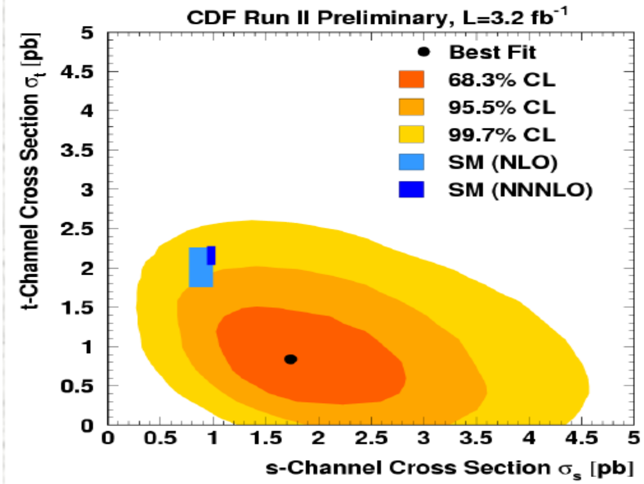


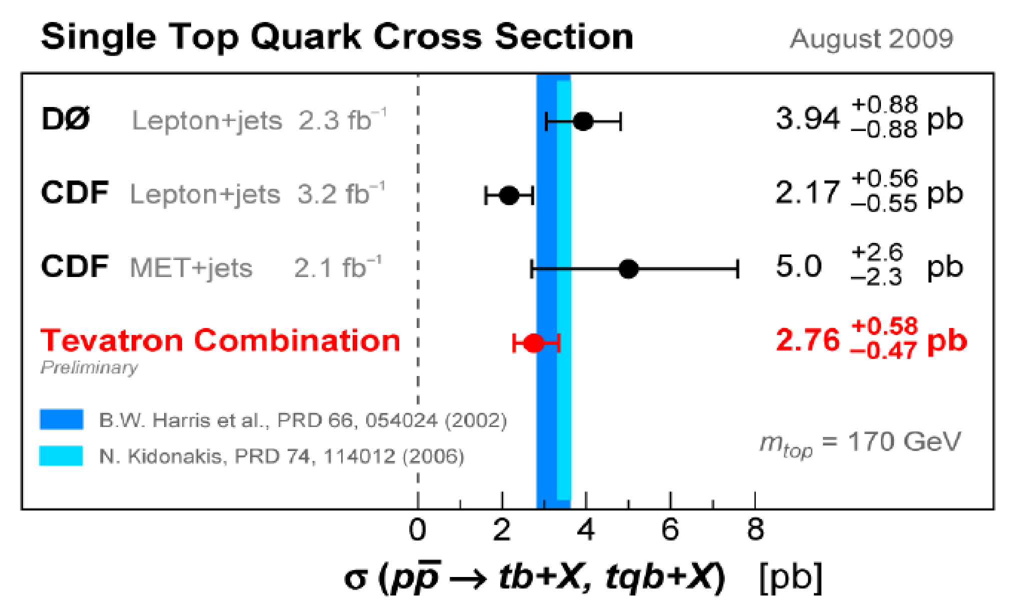
- At all orders both description should agree; otherwise differ by:
  - evolution of logarithms in PDF's: they are resumed
  - available phase-space
  - approximation by large logarithm

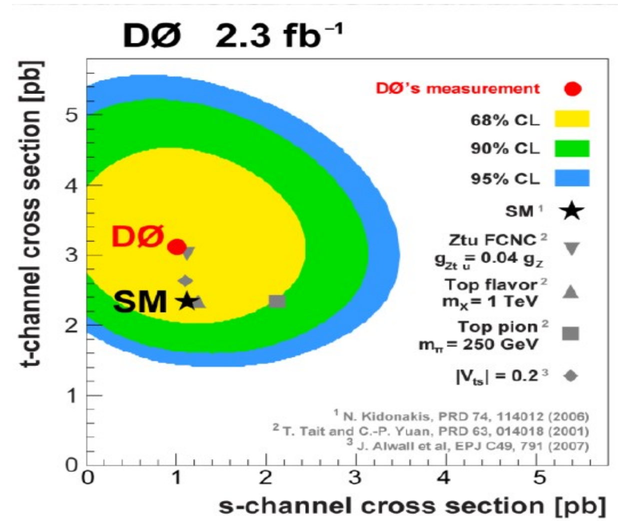
Single top cross-section

- The resulting cross-section in good agreement with SM predictions
- Separate measurements in

  s- and t-channel also extracted
- From the same data $|V_{tb}| = 0.88 \pm 0.07$







Comparison of methods

- Boosted decision tree (BDT) is also a multivariate technique with a different learning algorithm
- Likelihood function is a template analysis which uses many variables
- Among multivariate analyses there is no clear winner

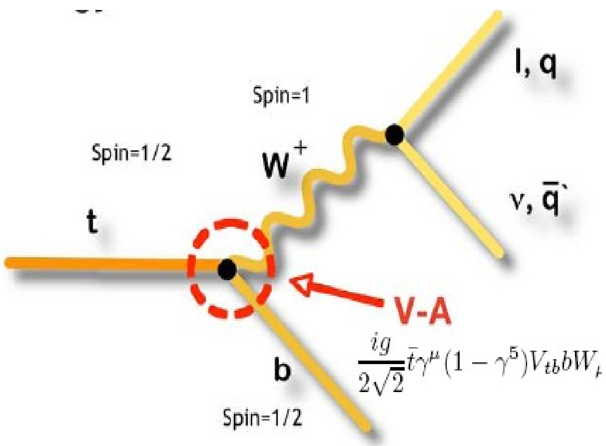
DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance Expected	Significance Measured
Boosted Decision Trees	$3.74^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70^{+1.18}_{-0.93}$ pb	4.1 σ	5.4 σ
Matrix Elements	$4.30^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ
Combination	3.94 ± 0.88 pb	4.5 σ	5.0 σ

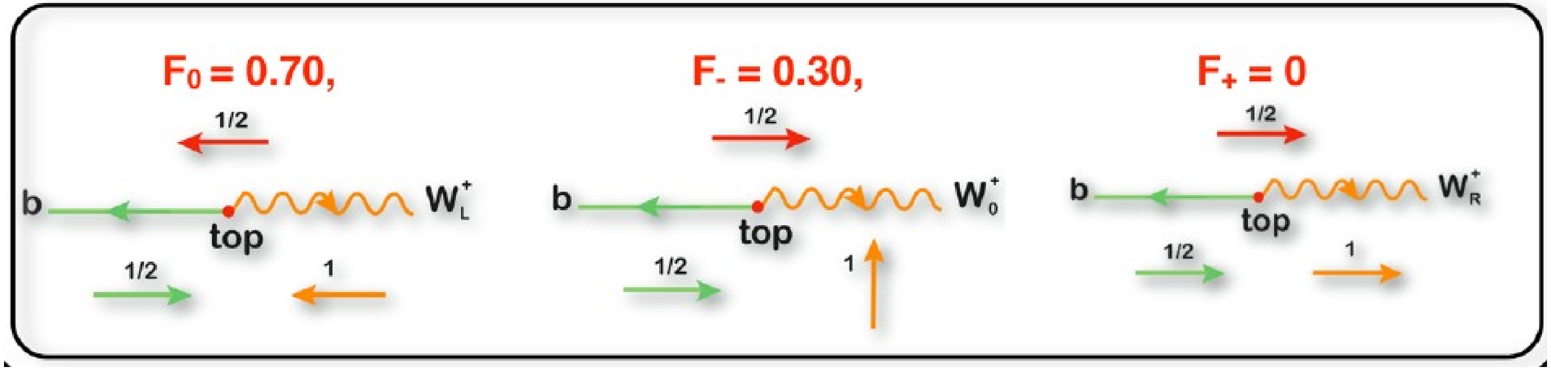
CDF 3.2 fb^{-1} Single Top Results

Analysis	Cross Section (pb)	Significance (Std. Dev.)	Sensitivity (Std. Dev.)
LF	$1.6^{+0.8}_{-0.7}$	2.4	4.0
ME	$2.5^{+0.7}_{-0.6}$	4.3	4.9
NN	$1.8^{+0.6}_{-0.6}$	3.5	5.2
BDT	$2.1^{+0.7}_{-0.6}$	3.5	5.2
LFS	$1.5^{+0.9}_{-0.8}$	2.0	1.1
SD	$2.1^{+0.6}_{-0.5}$	4.8	> 5.9
MJ	$4.9^{+2.5}_{-2.2}$	2.1	1.4
Combined	$2.3^{+0.6}_{-0.5}$	5.0	> 5.9

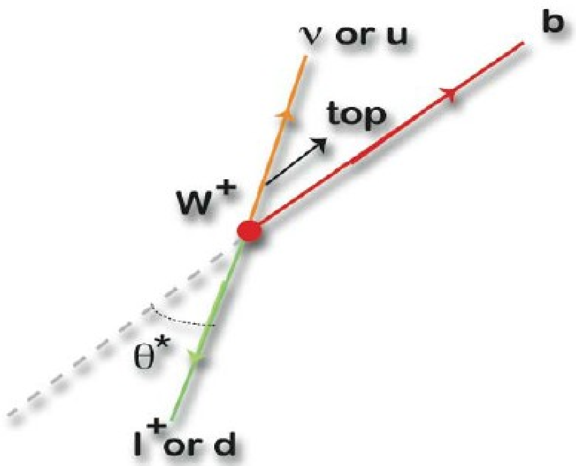
Top couplings

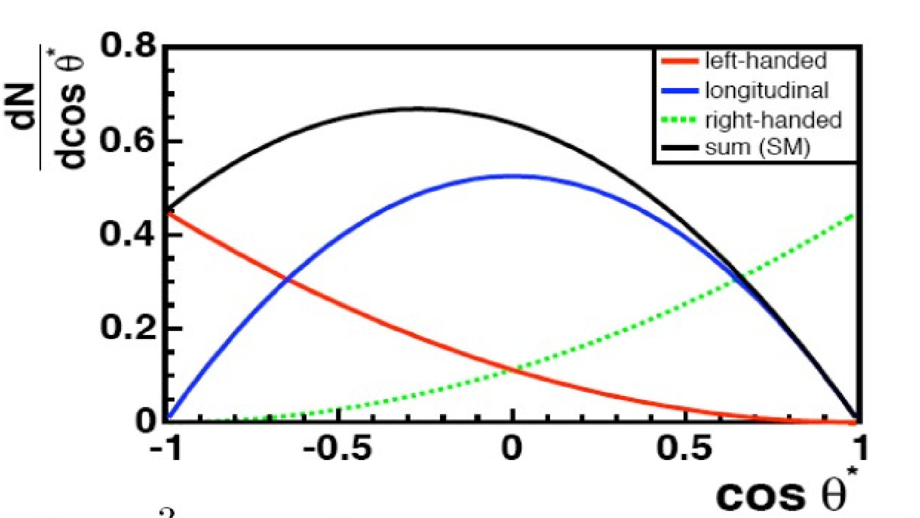
- Important to directly measure top couplings
- The V-A character of the decay determines the W boson helicity fractions





Extracting top couplings





$$w(cos\theta^*) = f_+ \frac{3}{8}(1 - cos\theta^*)^2 + f_0 \frac{3}{4}(1 - cos^2\theta^*) + (1 - f_0 - f_+)(1 + cos\theta^*)^2$$

$$P_{t\bar{t}}(x; f_0) = \frac{1}{\sigma_{t\bar{t}}(m_t)} \int d\rho dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{perm,\nu} |M_{t\bar{t}}(f_0)|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{jet}(x,y)$$

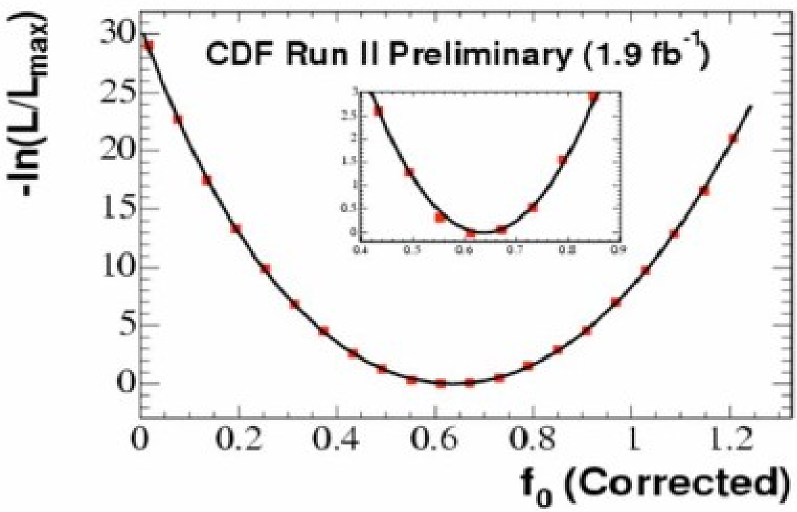
- Same technique as top mass but parametrizing the matrix element as a function of f_0 assuming $f_+=0$

Measurement of f_0

- Using 1.9 fb^{-1} and assuming $f_+=0$ for $m_t=175$ GeV/c^2 we measure

$$f_0 = 0.637 \pm 0.084(stat) \pm 0.069(sys)$$

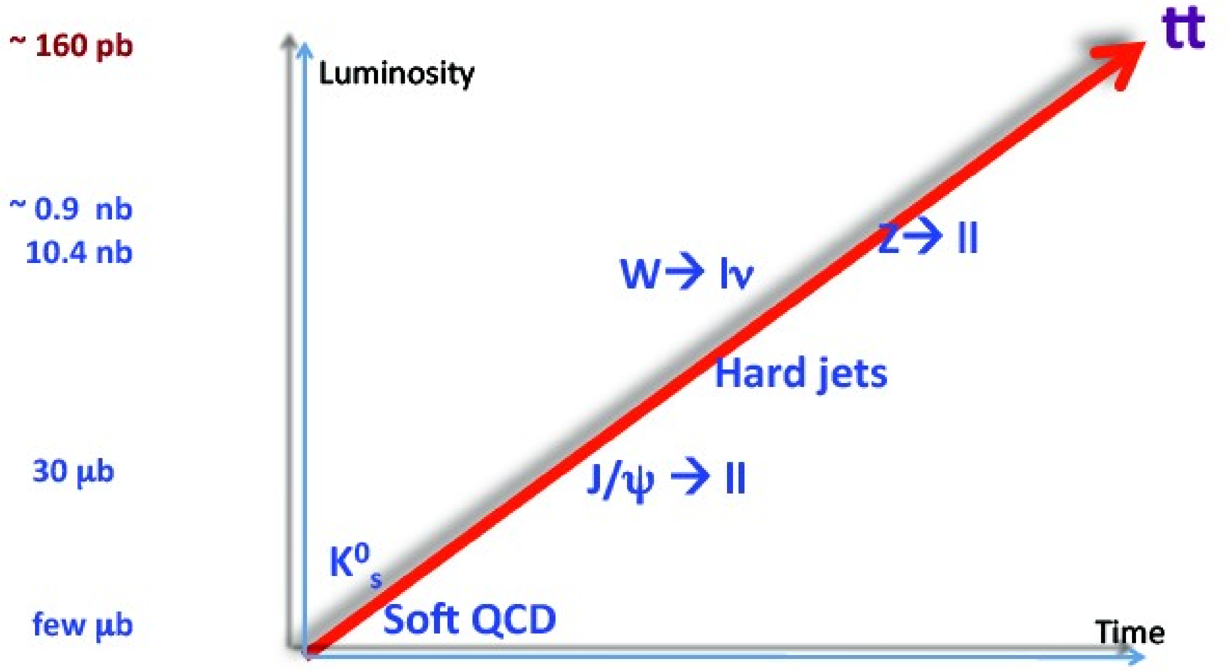
- Consistent with standard model expectations



Next: perform analysis in 2D f_0 and f_+ (model independent)

Systematic uncertainties (GeV/c^2)	
JES	0.019
Initial state radiation	0.026
Final state radiation	0.020
Generator	0.050
Background	0.009
PDFs	0.023
b-tagging	0.002
Method	0.012
Total	0.069

LHC: the road to the top and beyond

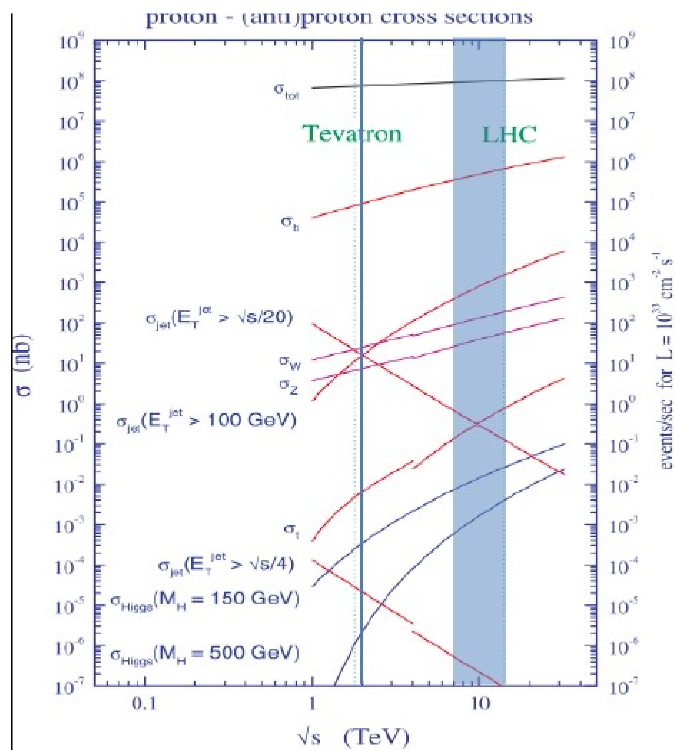


Top production at LHC

- The LHC is a top factory
  - **Tevatron :** ≈ 85% quark-antiquark annihilation

  - **LHC :** ≈ 85% gluon fusion

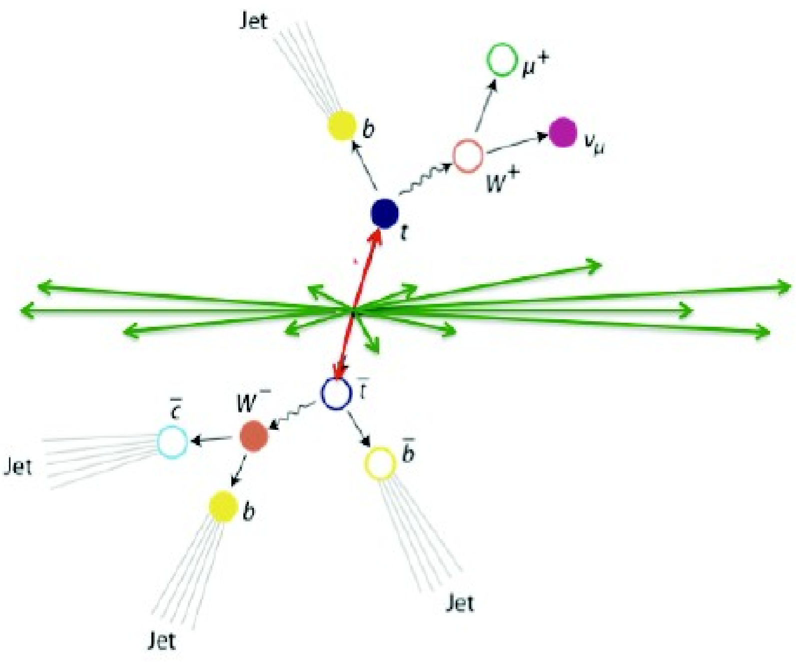
  - σ_{tt} LHC (7 TeV) ~ 20 σ_{tt} Tevatron
- We expect 1fb-1 by the end of 2011
  - We might have double the statistics available at the Tevatron



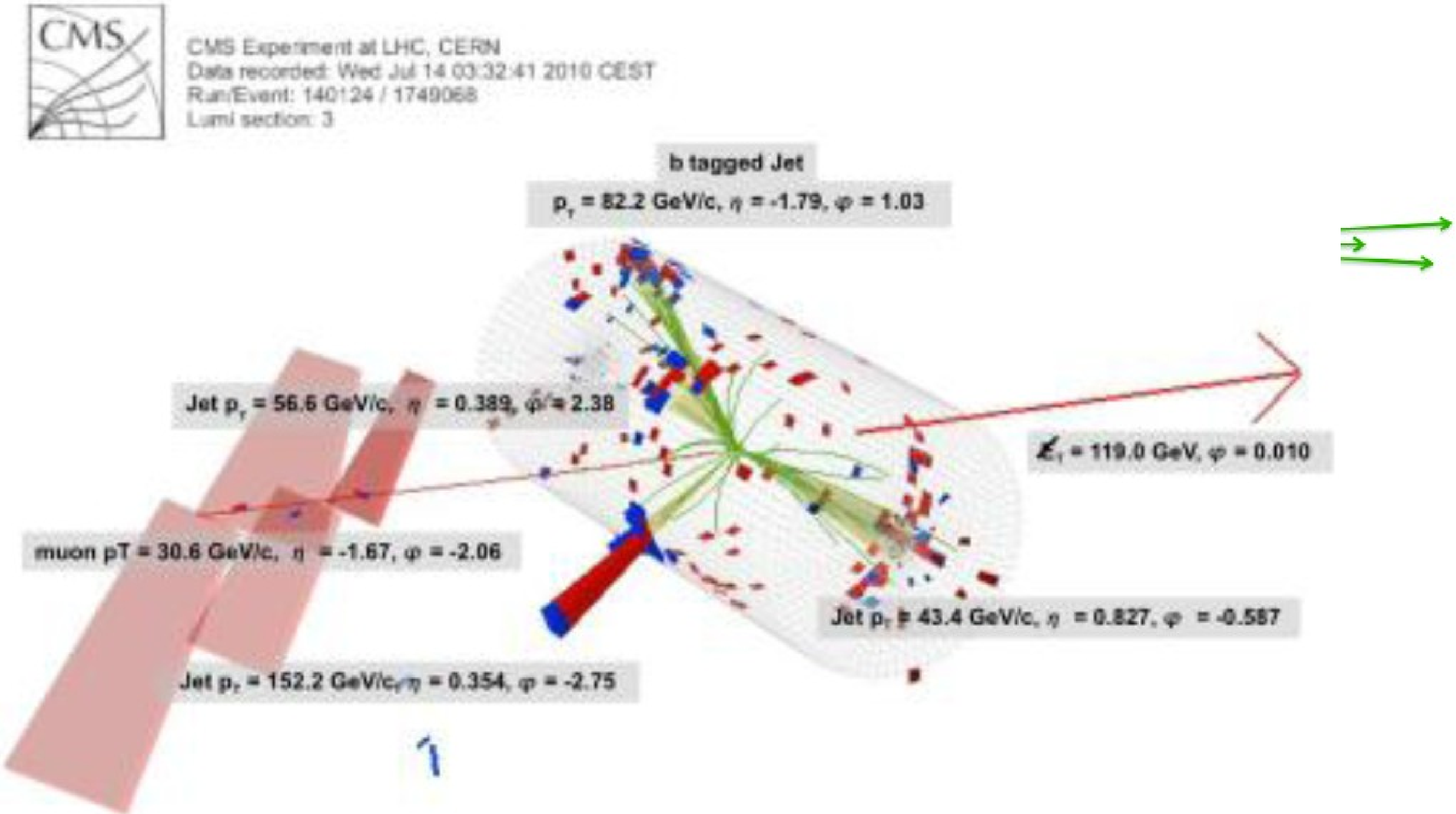
Steps towards: rediscovery

- Detector performance
  - Jets
  - Electrons, muons
  - MET
  - B-tagging

- Soft physics
  - Pile-up
  - Underlying event



CMS candidate event

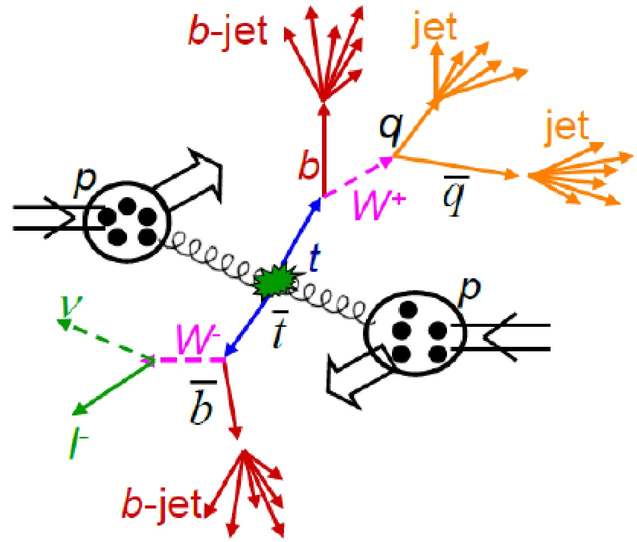
- 

CMS analysis: lepton-hadron

- Triggering on single leptons:
  - μ+X(p_T>9GeV/c), e+X(E_T>15GeV)
- Exactly one prompt, isolated, good quality lepton:

$$\text{Rel.isol.} = \frac{\sum_{R<0.3} p_T^{\text{track}} + \sum_{R<0.3} p_T^{\text{ECAL}} + \sum_{R<0.3} p_T^{\text{HCAL}}}{p_T(\text{lepton})}$$

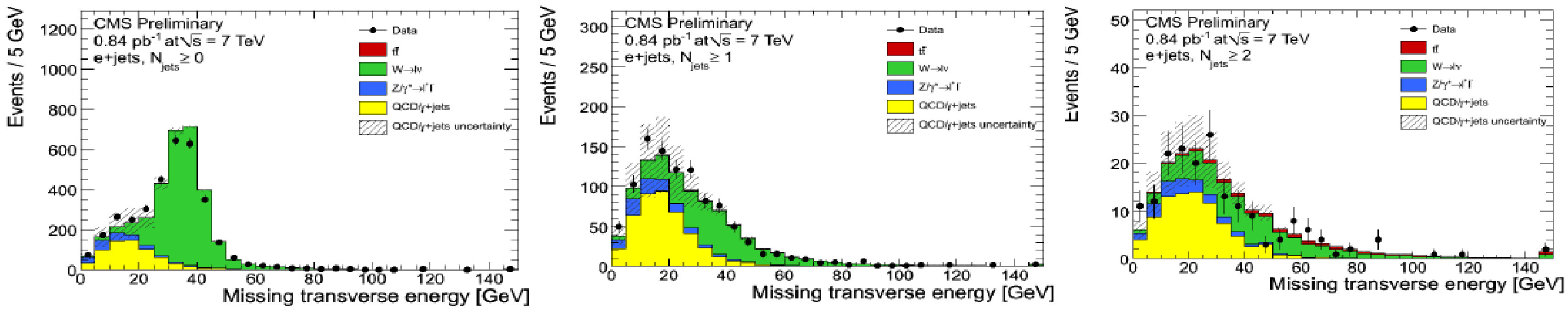
  - Muons: p_T>20 GeV/c, |η|<2.1
    - Rel.isol.<0.05
  - Electrons: p_T>30 GeV/c, |η|<2.4
    - Rel.isol.<0.1, conversion veto
- Missing transverse energy not used in event selection (yet)



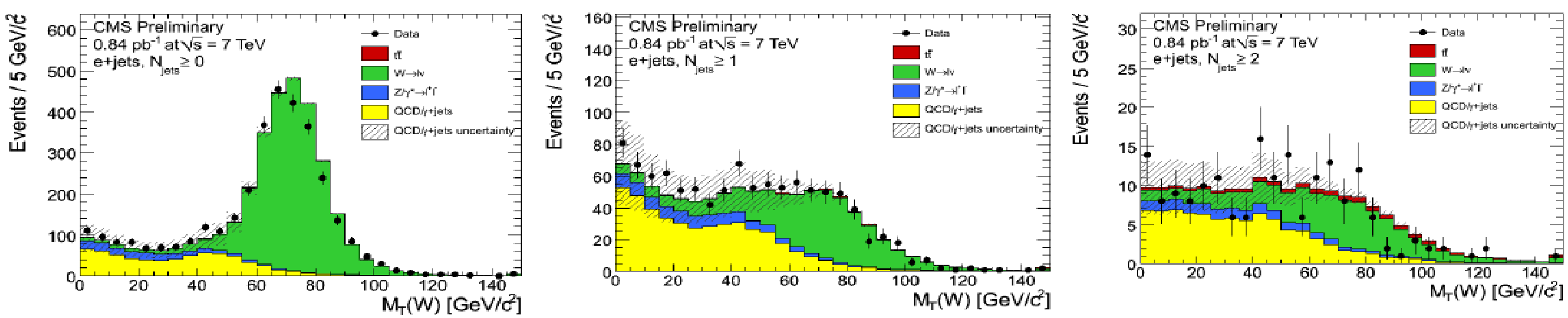
- Jet reconstruction:
  - Anti-K_T algorithm (R=0.5)
  - p_T>30 GeV/c, |η|<2.4
  - Expected four jets, two from b quarks

Top quark: CMS analysis

- Missing transverse energy (crucial variable for top measurement):



- W transverse mass (calculated from electron + missing E_T):



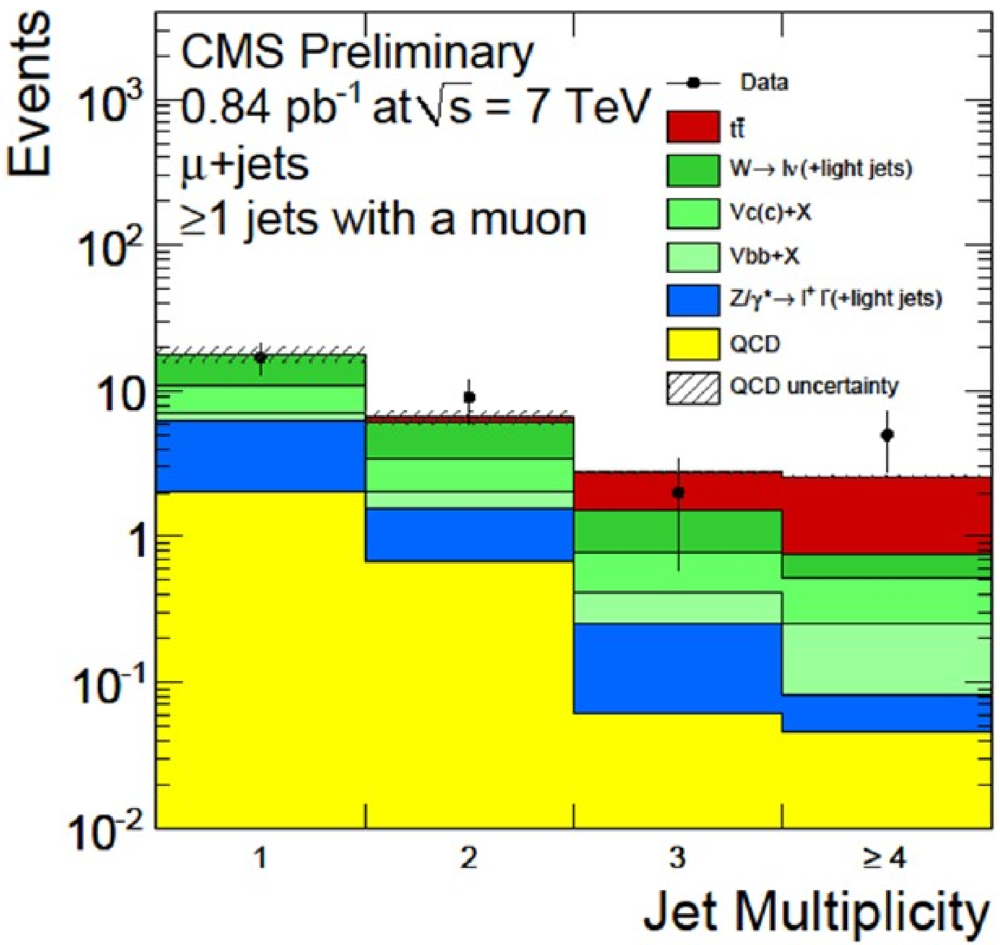
Njets≥0 Njets≥1 Njets≥2

12

Top quark: CMS analysis

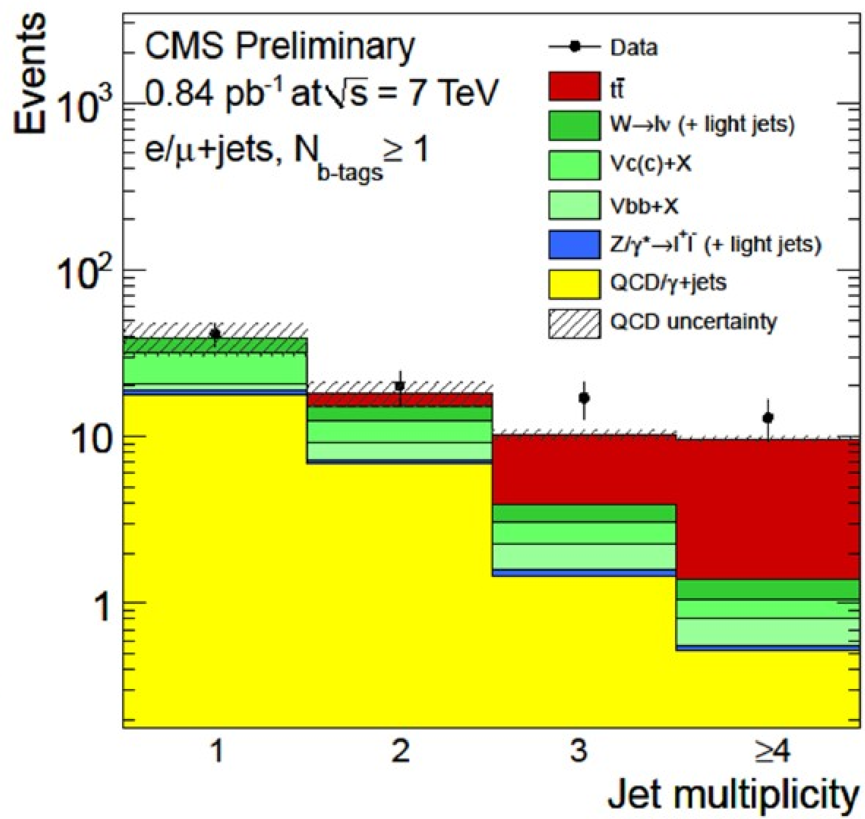
- "Muon-in-jet" tagging:
  - Requiring a jet with a (soft, no isolated) muon within ΔR<0.4
  - Sensitive to semi-leptonic decays of the b quarks

- Observed 7 events with
  - Consistent with expected top signal plus ~2.5 background events



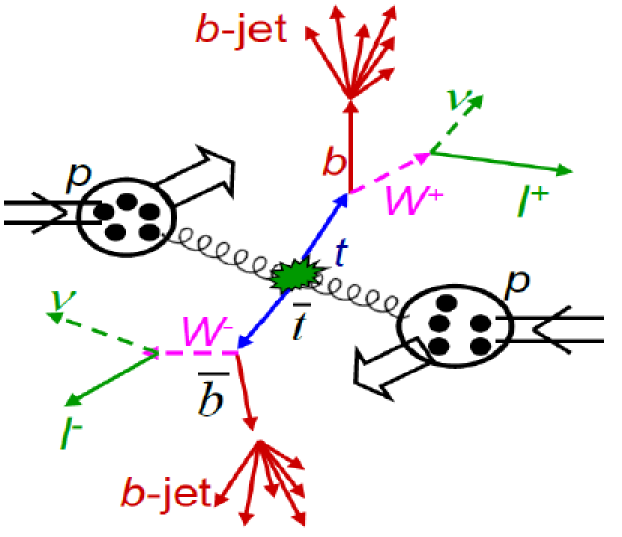
Combination of lepton flavours

- Combining muon+jets and electron+jets channels
- Secondary vertex tagger
  - Fake rate: ~1%
- Signal region $N_{jets} \geq 3$:
  - Observed 30 events
  - Predicted for background: 5.3
  - Expected from top signal: 15



CMS analysis: lepton-lepton

- Same trigger as for lepton+jets events
  - μ+X(p_T>9GeV/c), e+X(E_T>15GeV)
- Two prompt, isolated, opposite charged leptons (ee, μμ, eμ):
  - p_T>20 GeV/c, |η|<2.5
  - Rel. isolation < 0.15
- Z boson veto
  - $|M_{ll}-M_Z|$>15 GeV/c^2
- Missing E_T>30 GeV
  - Missing E_T>20 GeV for eμ events
  - Calorimeter + tracking information



- Jet reconstruction:
  - Using calorimeter + tracking
  - Anti-K_T algorithm (R=0.5)
  - p_T>30 GeV/c, |η|<2.5
  - Expected two b-jets

CMS: cross-section

- Top pair production in pp collisions at √s = 7 TeV:

$$\sigma^{t\bar{t}} = \frac{S_{\text{obs}}}{SF \cdot \mathcal{L} \cdot A}$$

- S_{obs} = number of observed event after background subtraction
- SF = scale factor correcting for differences beween data and MC
- A = expected signal acceptance (1.6%)
- $\mathcal{L}$ = integrated luminosity (3.1 pb^{-1})

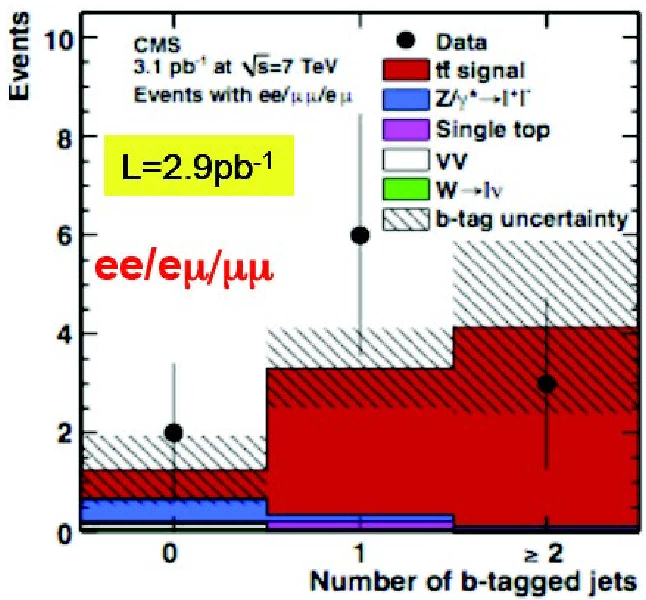
Source	Systematic uncertainty
Lepton selection	4.4%
Energy scale	3.7%
ISR/FSR	1%
Decay model	2%
Branching ratio	1.7%
Backgrounds	15%
Luminosity	11%

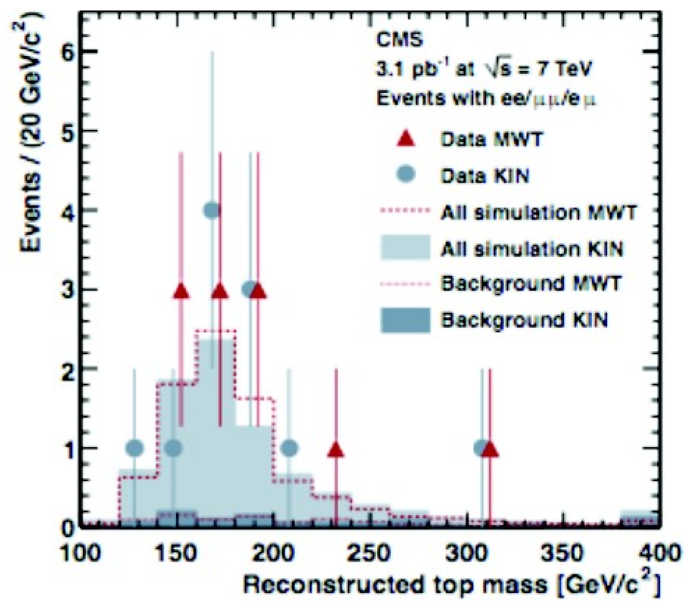
$$\sigma^{t\bar{t}}_{\text{data}} = 194 \pm 72(stat) \pm 24(syst) \pm 21(lum)\ \text{pb}$$

CMS: Published results

Full selection applied: Z-Veto, |M(ll)-M(Z)|>15 GeV
MET >30 (20) GeV in ee,μμ, (eμ); N(jets)≥2

$\sigma(pp \rightarrow t\bar{t})$ = 194 ± 72(stat.) ± 24(syst.) ± 21(lumi.) pb



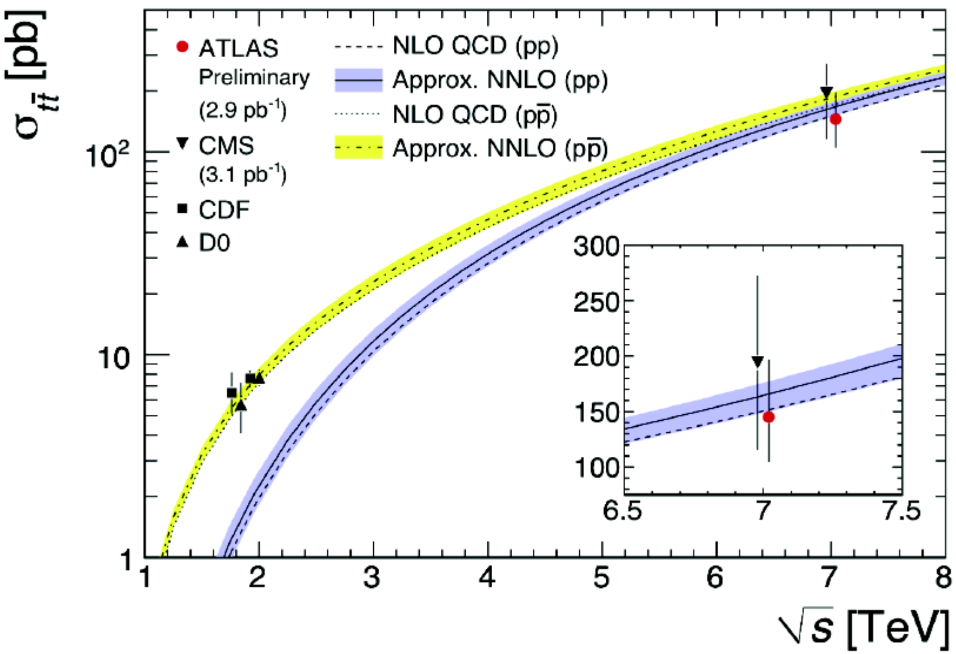


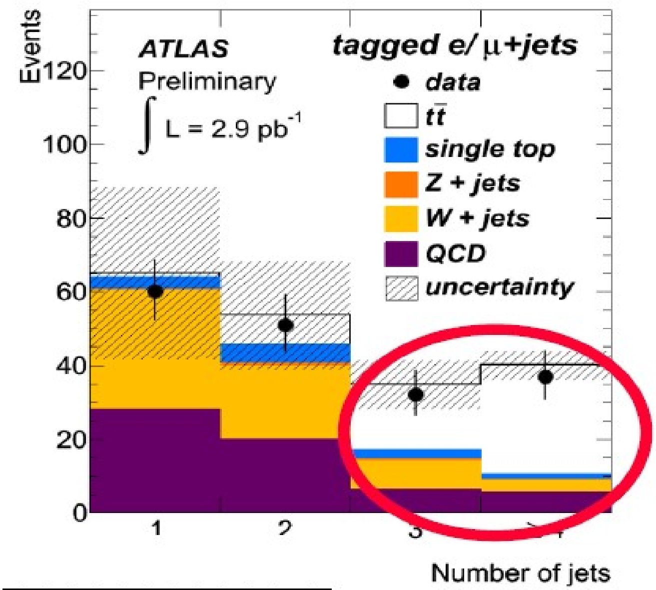
Accepted by PL-B arXiv:1010.5994

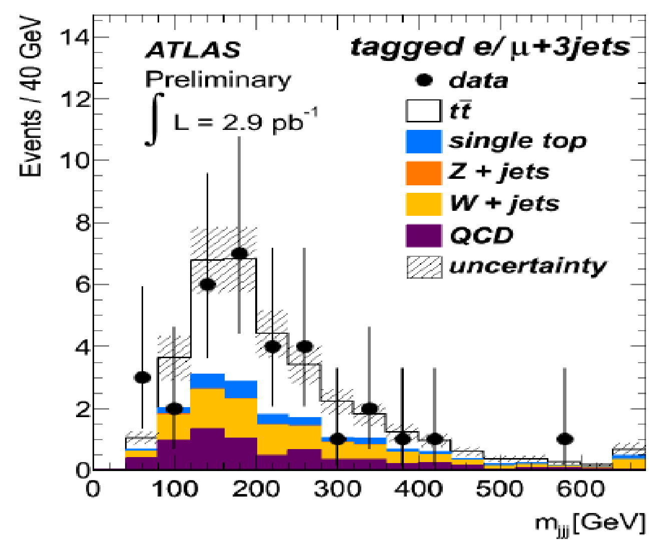
November 17, 2010 LHCC open meeting 33

ATLAS: public results

Combining all channels, $\sigma_{t\bar{t}} = 145 \pm 31^{+42}_{-27}$ pb
Significance of ~4.8σ w.r.t. background only hypothesis.







Next topics

- 24.11 – Hot topics: new exclusion limits
- 1.12 – dibosons and anomalous couplings
- 8.12, 15.12 – Higgs (SM)
- 5.01 - Searches: new exclusion limits
- 12.01 - Higgs (MSSM)
- 19.01, 26.01 - SUSY