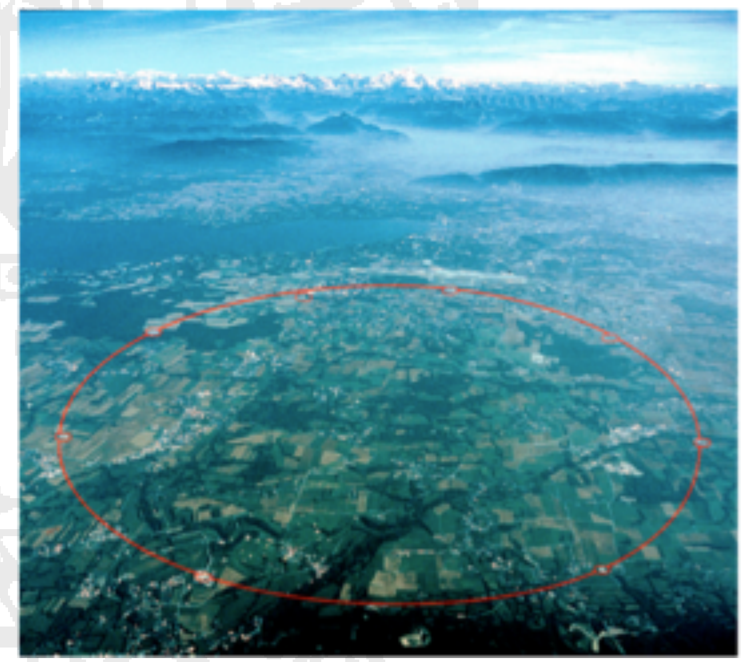
Top topics of top quark physics

from the Tevatron and LHC



FSP 101 ATLAS

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II. Physikalisches Institut, Universität Göttingen

PHYSICS AT THE TERA SCALE
Helmholtz-Alliance

http://top2011.ifae.es/

State of the art in Top physics - theory and experiment

Accelerators and detectors

The top quark

Top quark production
- top quark pairs
- electroweak single top quark

Top quark properties
- mass
- spin correlations
- forward-backward and charge asymmetry

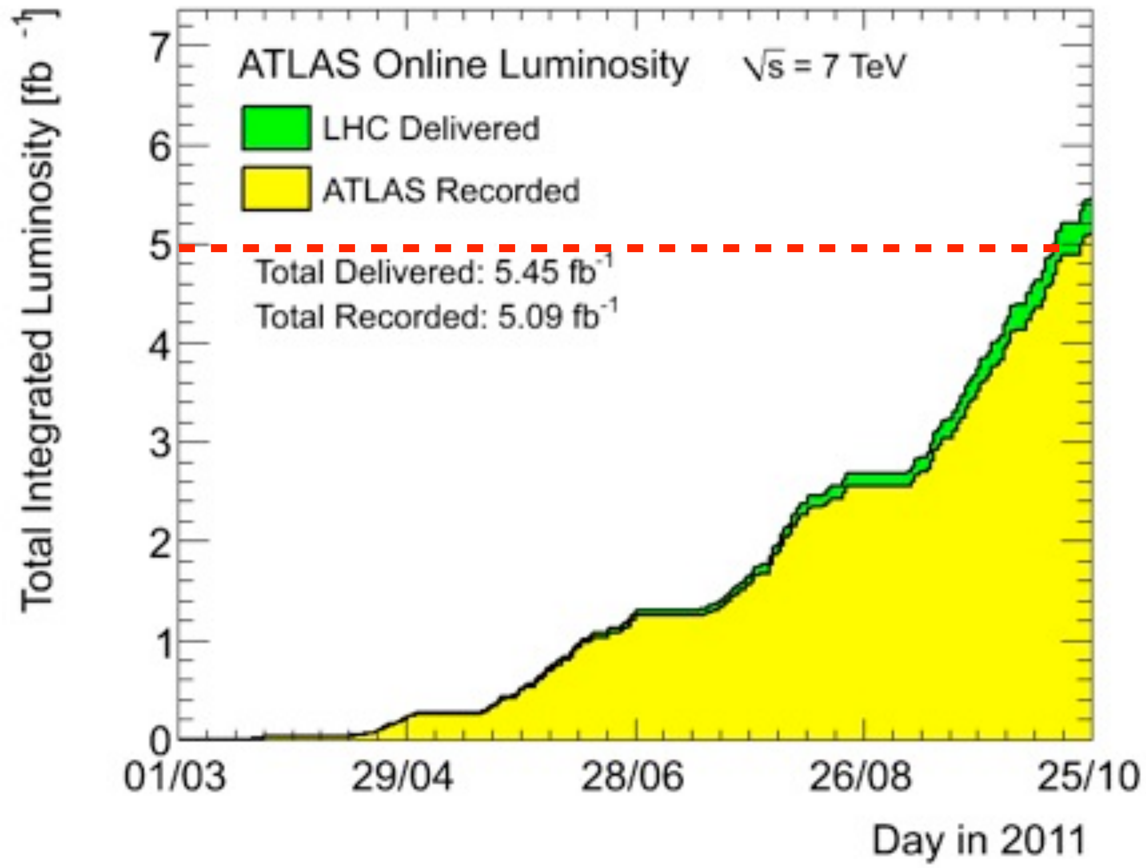
Searches in top quark sector

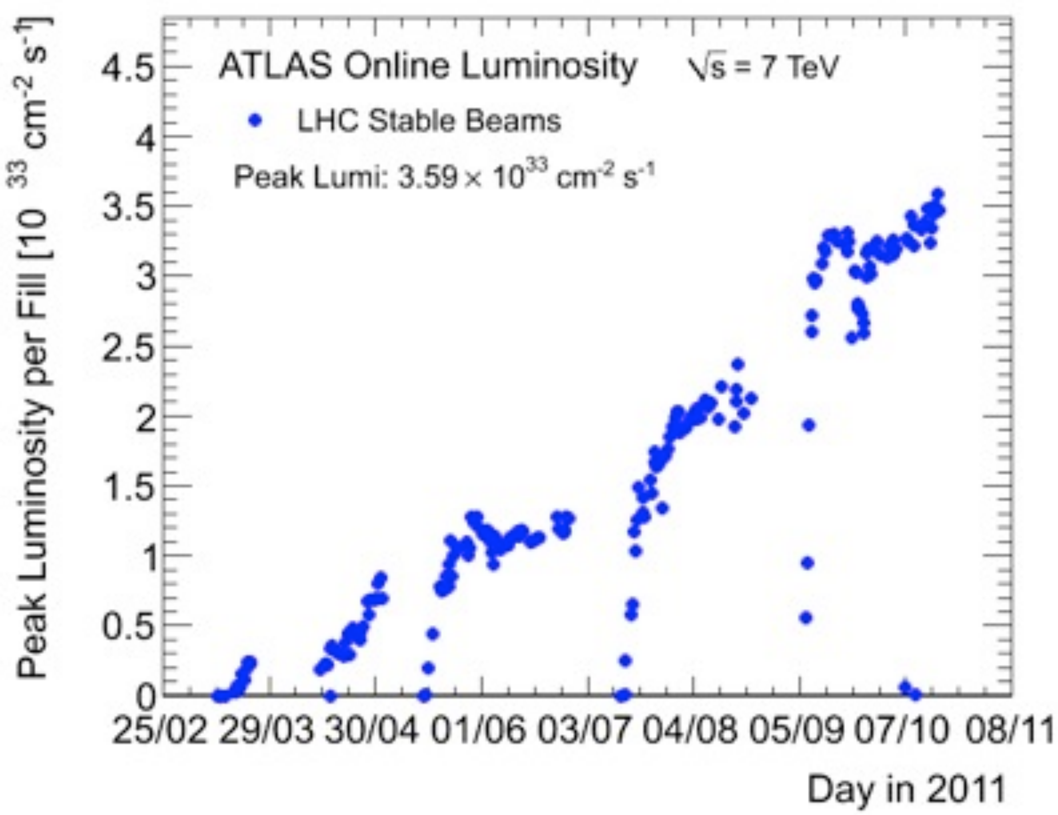
The Fermilab Tevatron

- the birthplace of the top quark
- the highest energy collider in the world ...until December 2009
- $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV
- > 2 fb^{-1}/year, peak luminosity ~$4e^{32}$
- shut down on Sept. 30 2011
- 10.5 fb^{-1} of recorded data per experiment
- current results - up to 6 fb^{-1} of data

The LHC

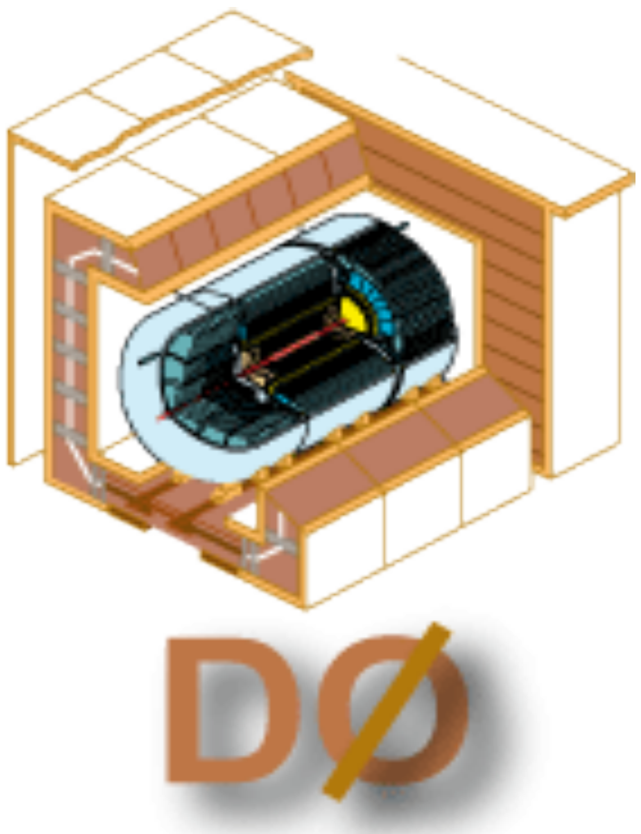
- top quark factory
- the highest energy collider in the world
- pp collisions at $\sqrt{s}$=7 TeV
- >5 fb^{-1} delivered, >5 fb^{-1} recorded
- peak luminosity: $3.6e^{33}$
- results up to 2.1 fb^{-1}
- many more will be published in coming months with the full 2011 data set

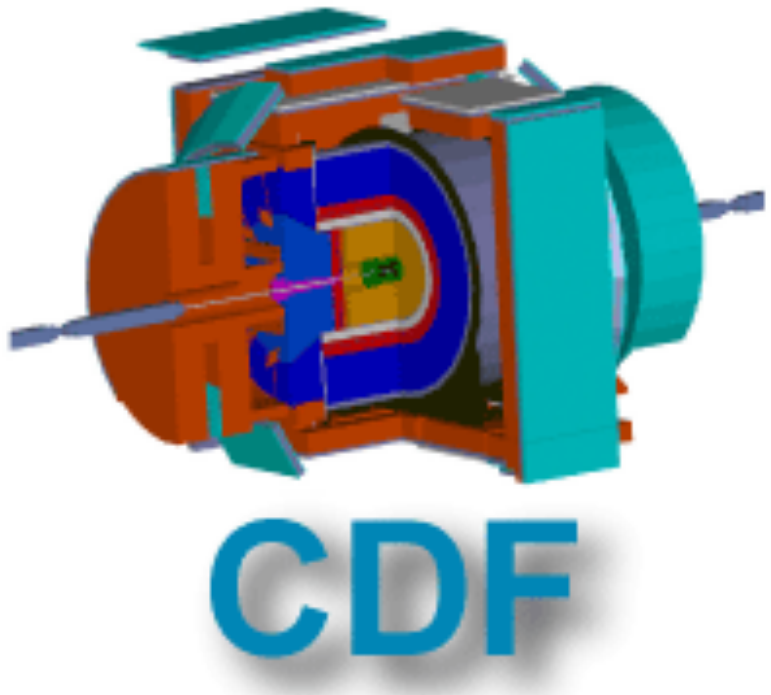




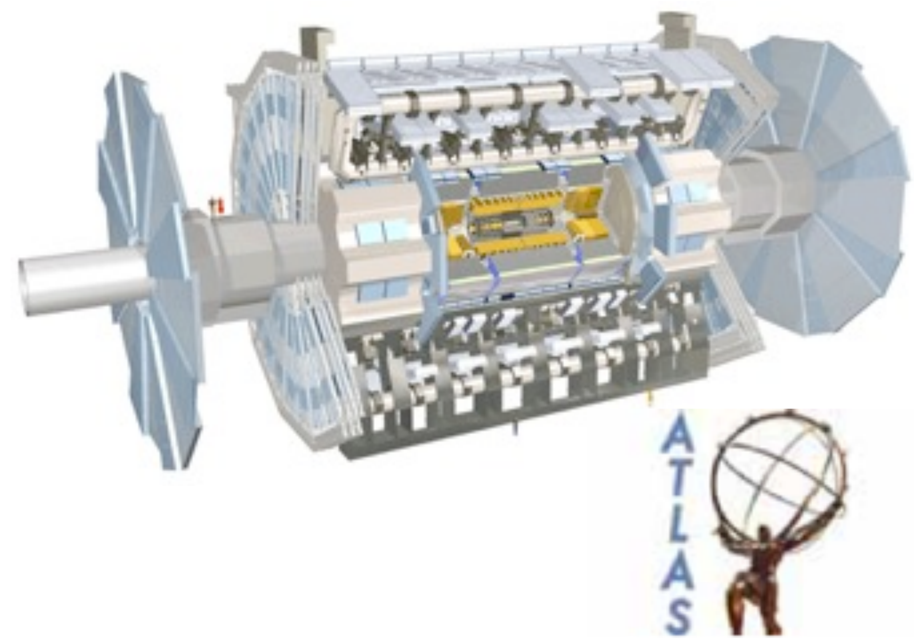
Experiments

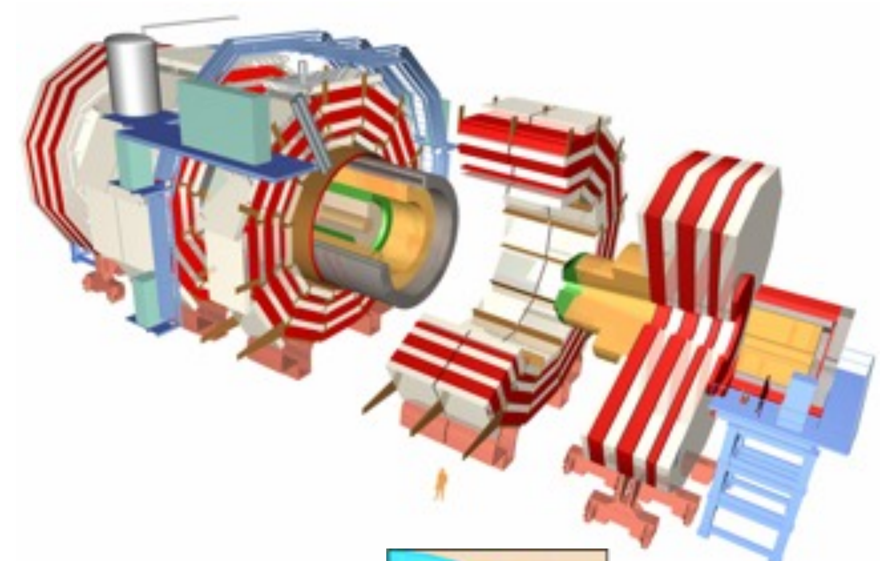
Tevatron





LHC



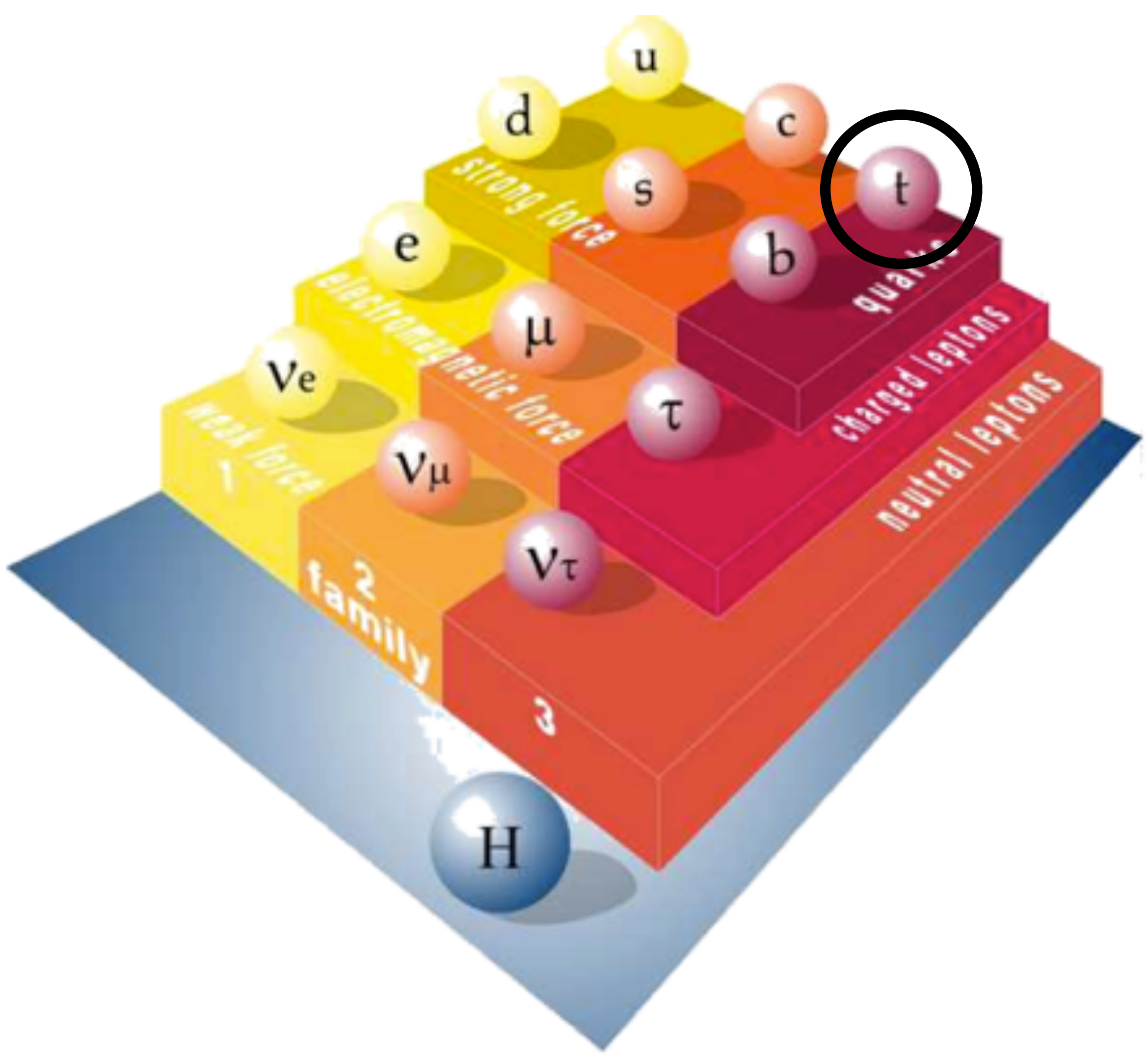


- Multipurpose collider detectors
  - high resolution inner detectors
  - calorimeters
  - outer muon system
  - magnetic field

The 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



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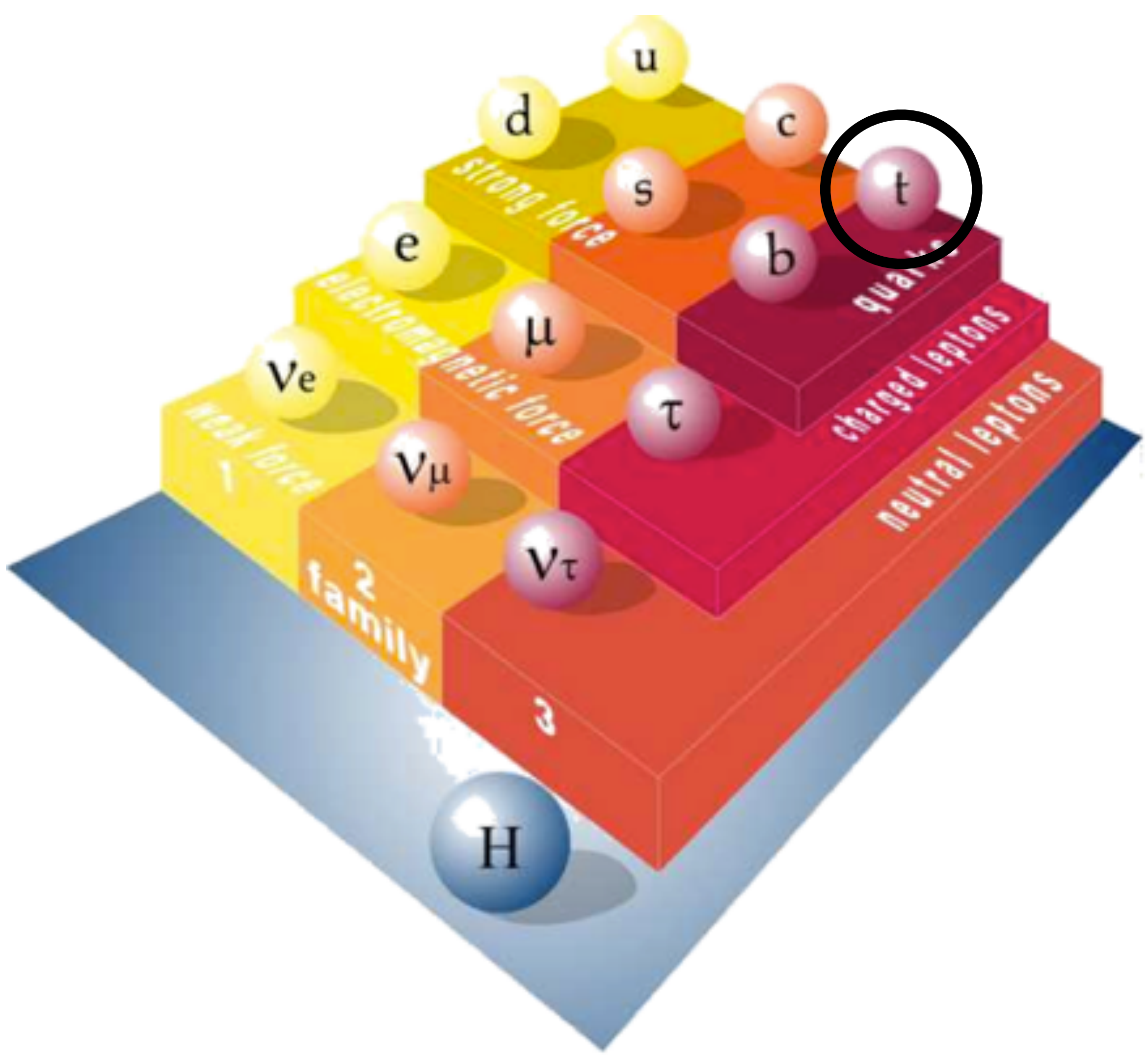
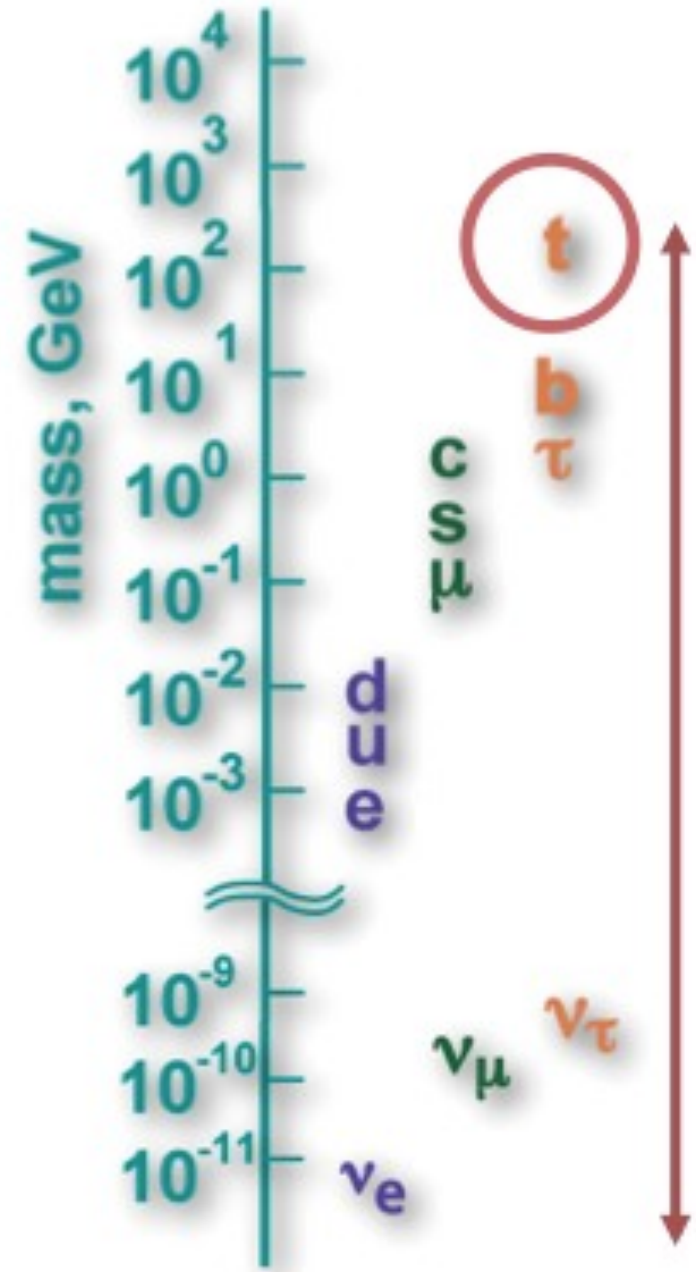


Discovered at Fermilab in 1995



As heavy as the atom of gold

The top quark

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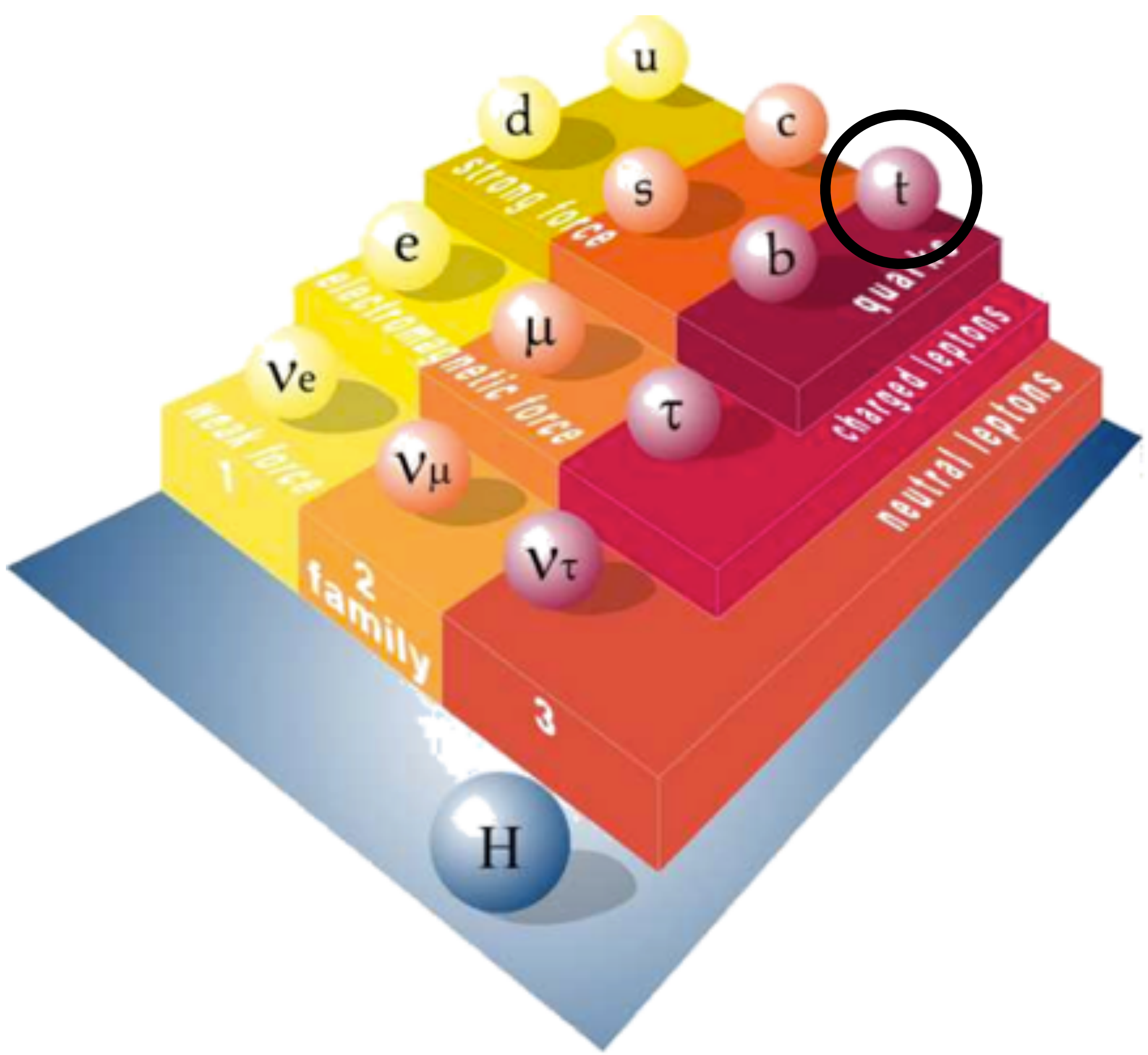


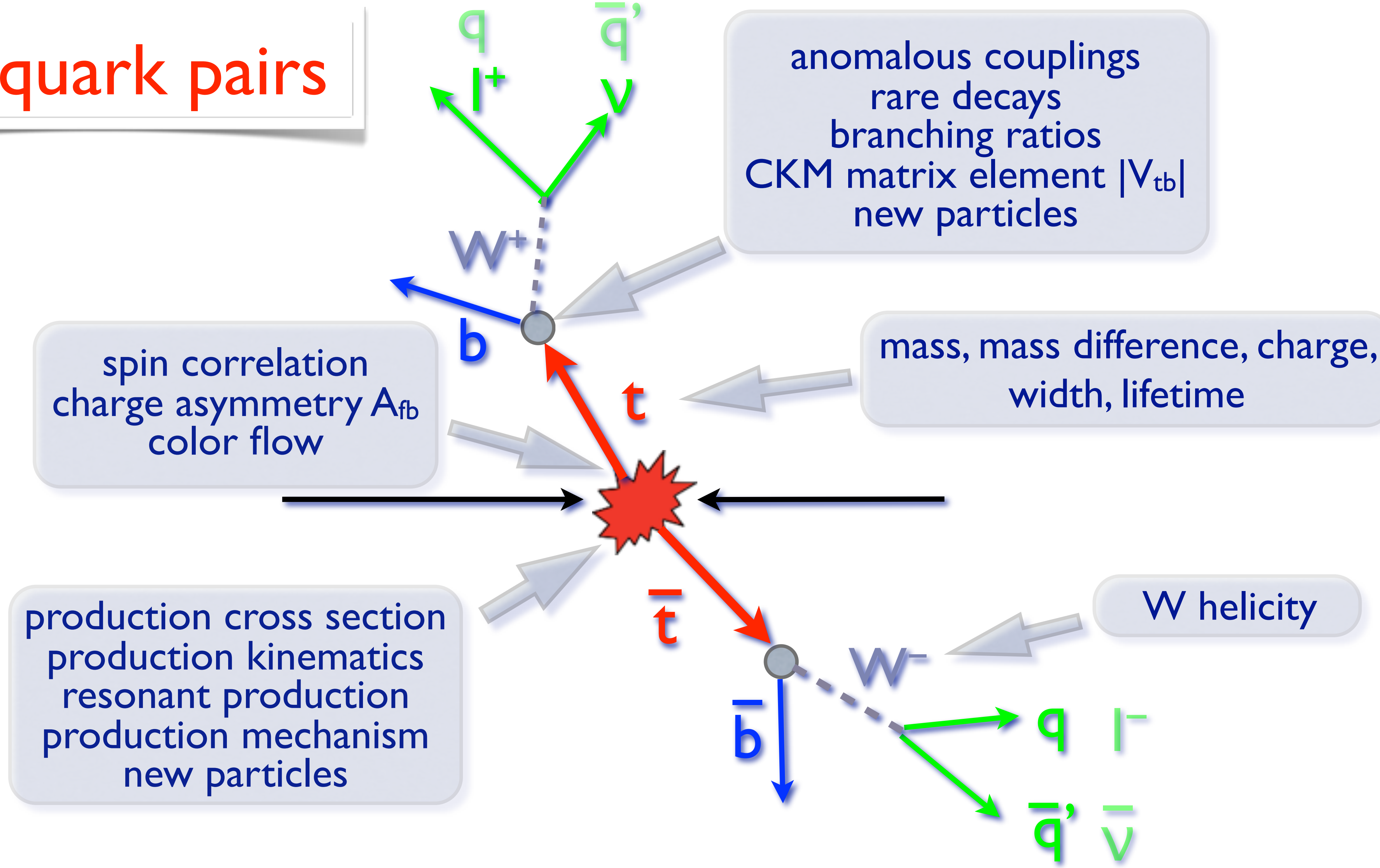
- The heaviest fundamental particle with unique properties
  - Large coupling to Higgs boson (~1)
  - Important role in electroweak symmetry breaking?
  - Short lifetime: decays before fragmenting

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

The most probable place for new physics to show up?

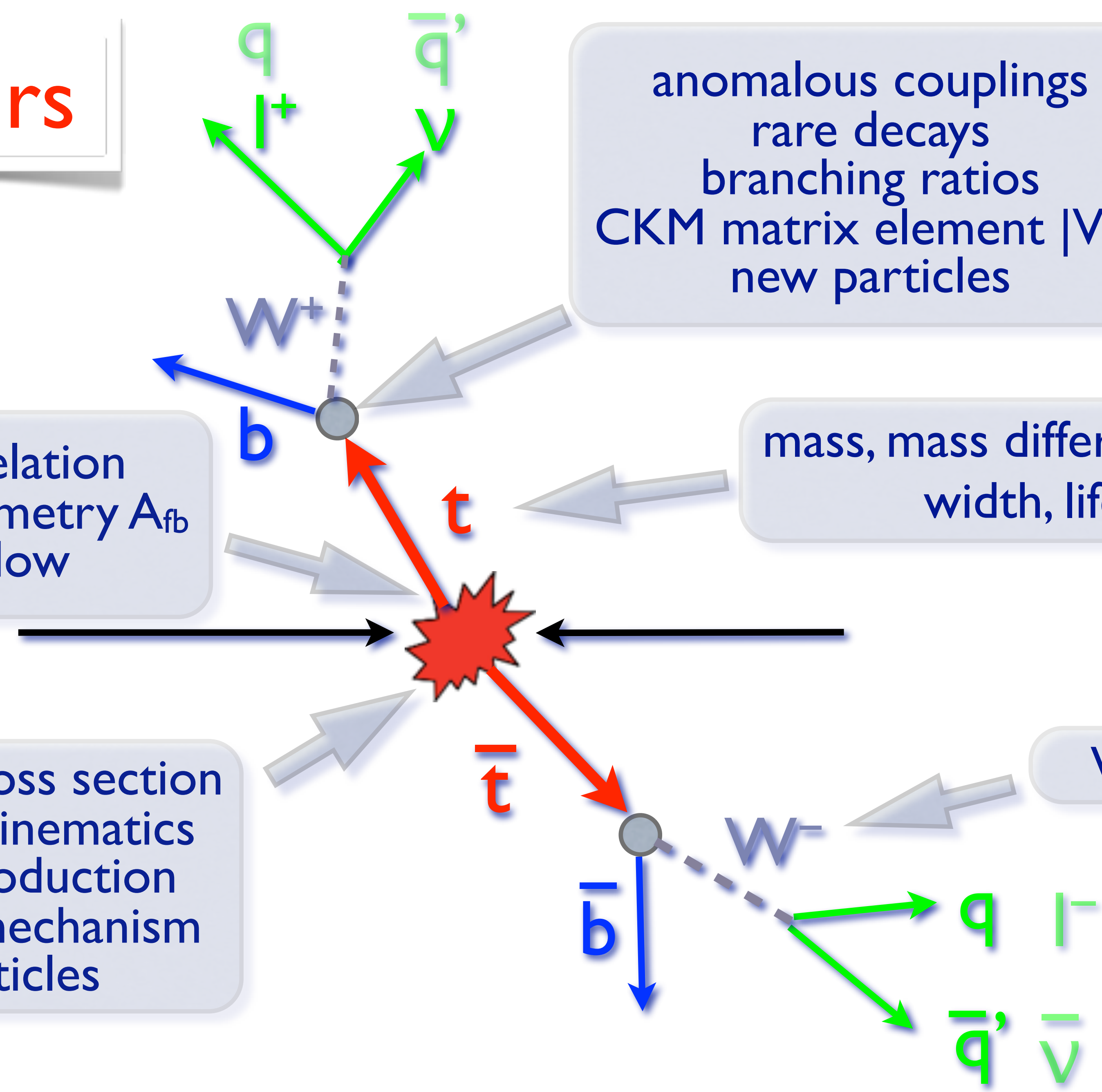
Tevatron contribution

top quark pairs



Tevatron contribution

top quark pairs



anomalous couplings
rare decays
branching ratios
CKM matrix element $|V_{tb}|$
new particles

mass, mass difference, charge, width, lifetime

spin correlation
charge asymmetry A_{fb}
color flow

production cross section
production kinematics
resonant production
production mechanism
new particles

W helicity

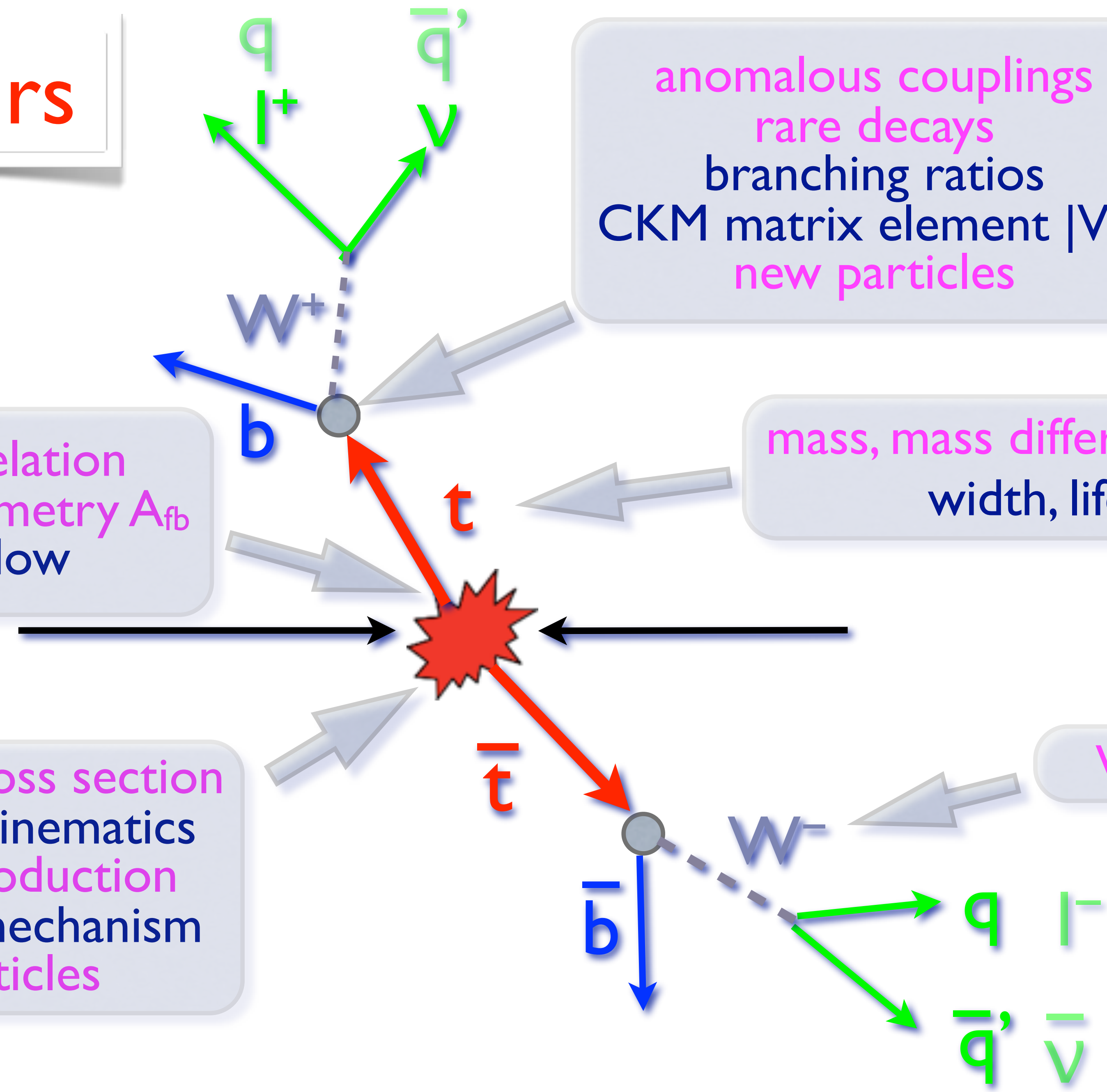
EW top quark production

s- and t-channel production, properties and BSM searches in single top events

LHC is ramping up...

top quark pairs

anomalous couplings
rare decays
branching ratios
CKM matrix element $|V_{tb}|$
new particles



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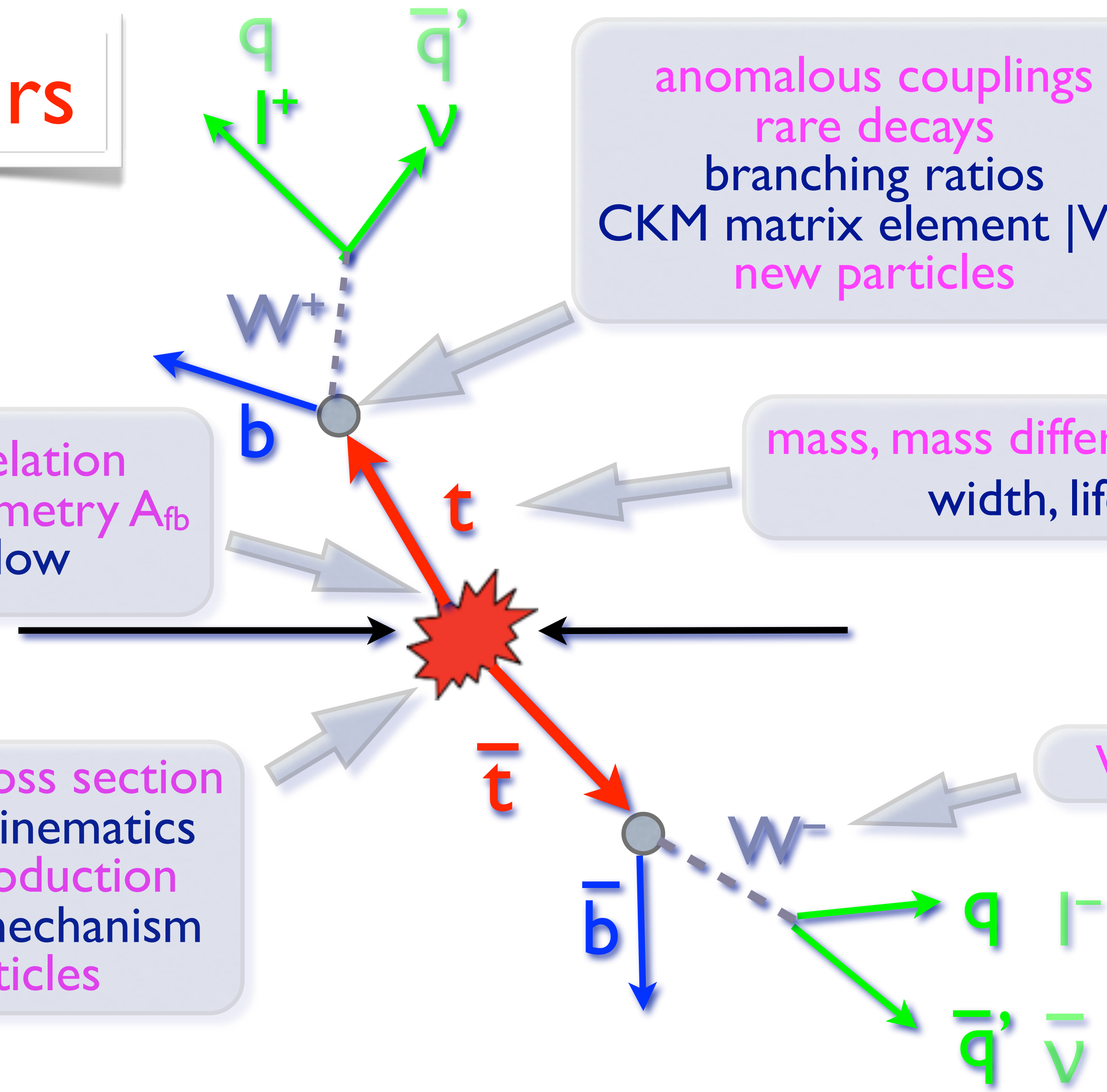

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EW top quark production

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properties and BSM searches
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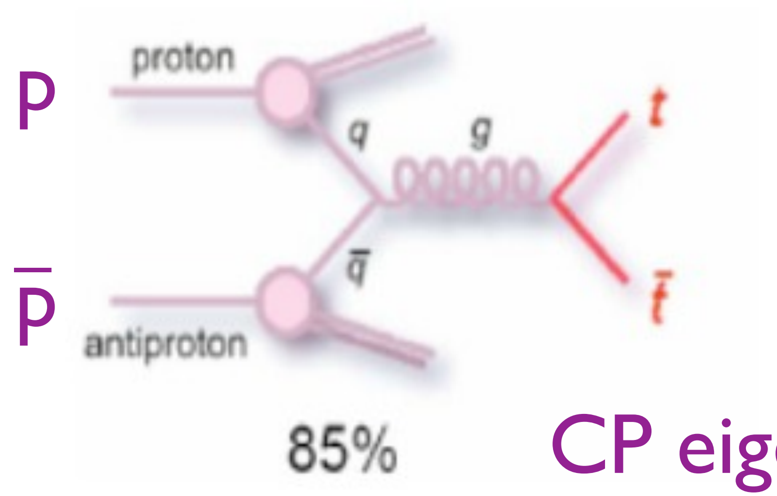
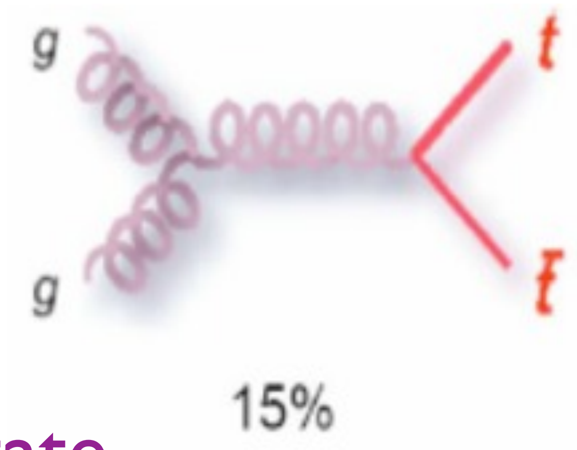
Is it the Standard Model top?

Top quark pair production

Main mechanism: pair production via strong interaction

Tevatron





CP eigenstate

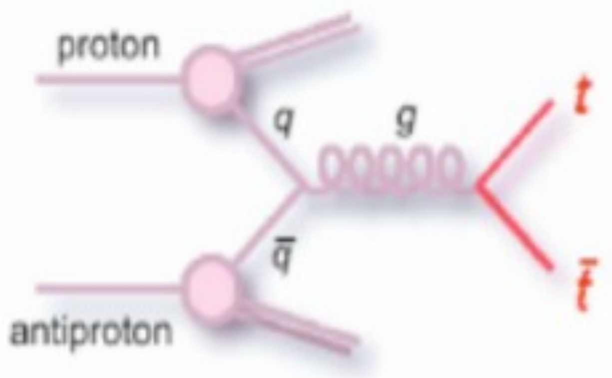
Top quark pair production

Main mechanism: pair production via strong interaction

Tevatron

p

p̄

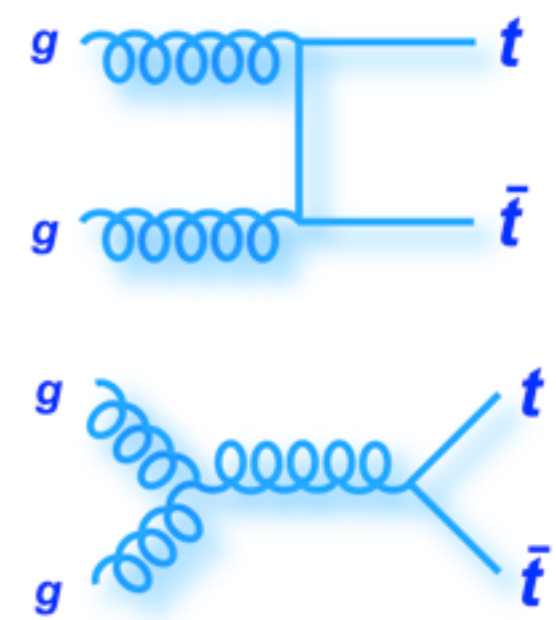


85%

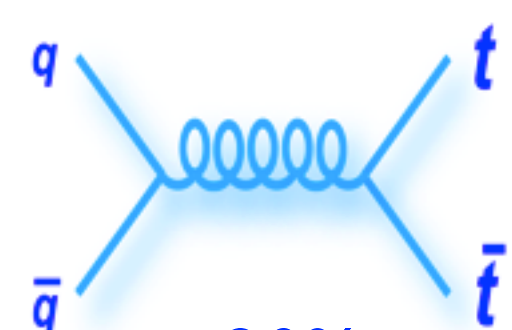
CP eigenstate

15%

LHC



~80%

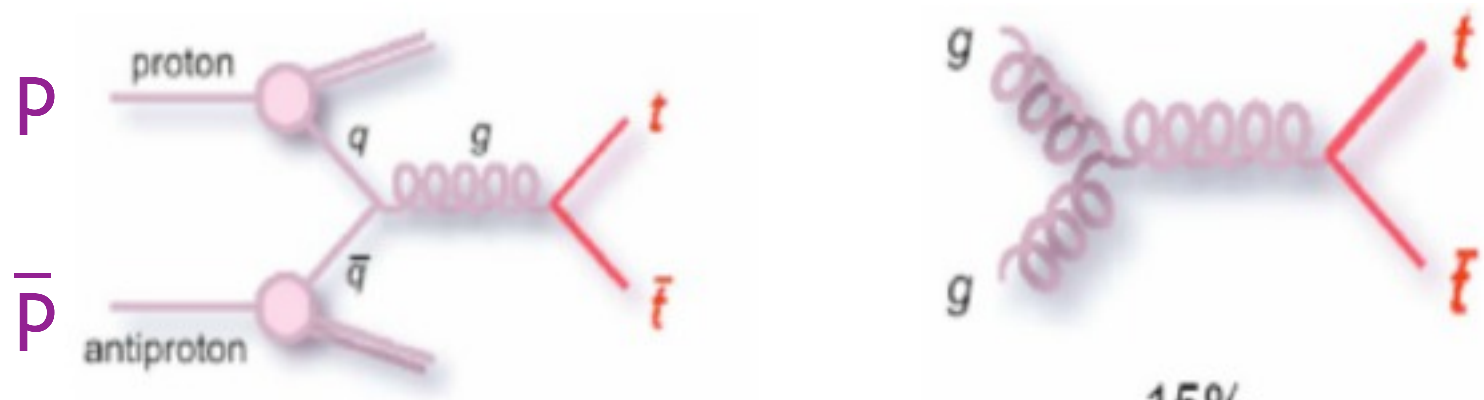


~20%

Top quark pair production

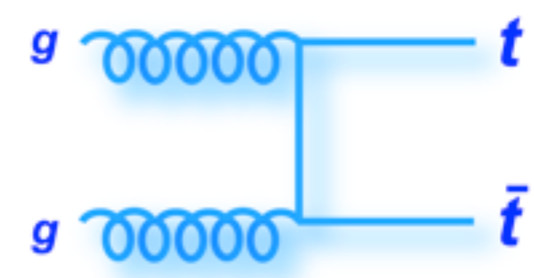
Main mechanism: pair production via strong interaction

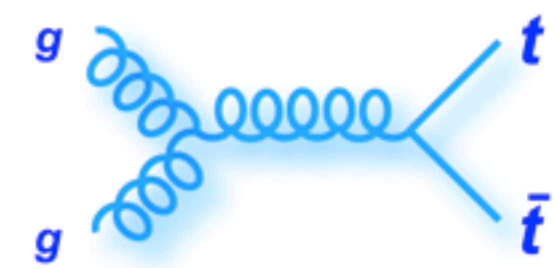
Tevatron



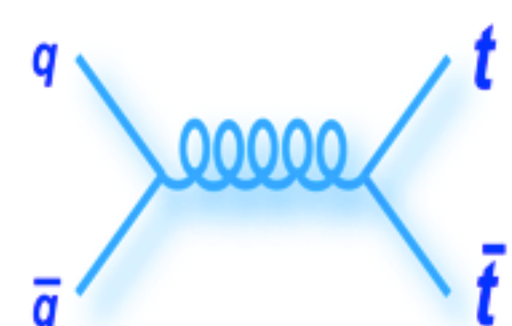
85% CP eigenstate 15%

LHC





~80%



~20%

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

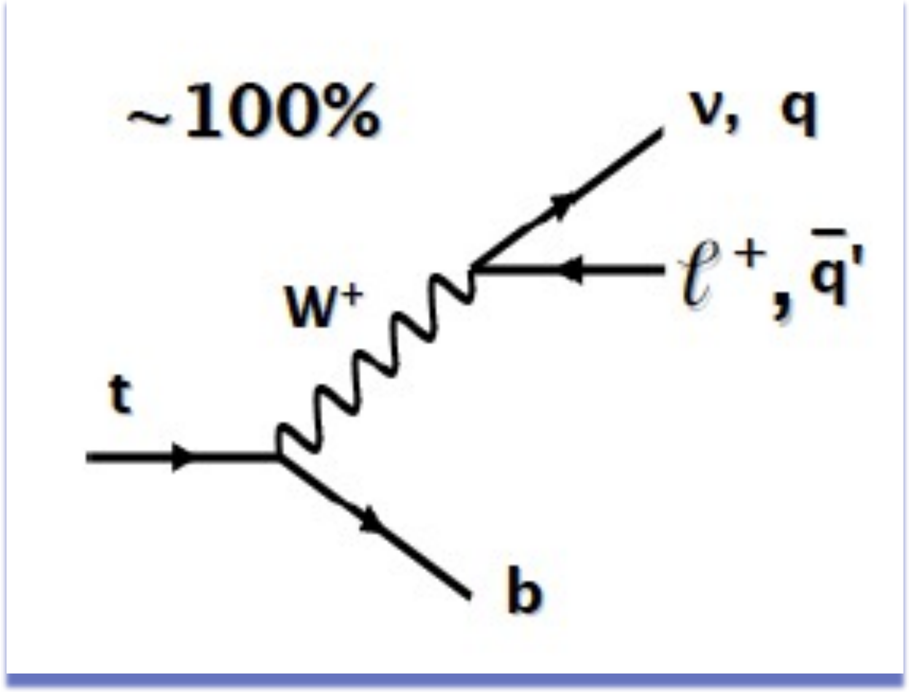
~20 larger than at Tevatron

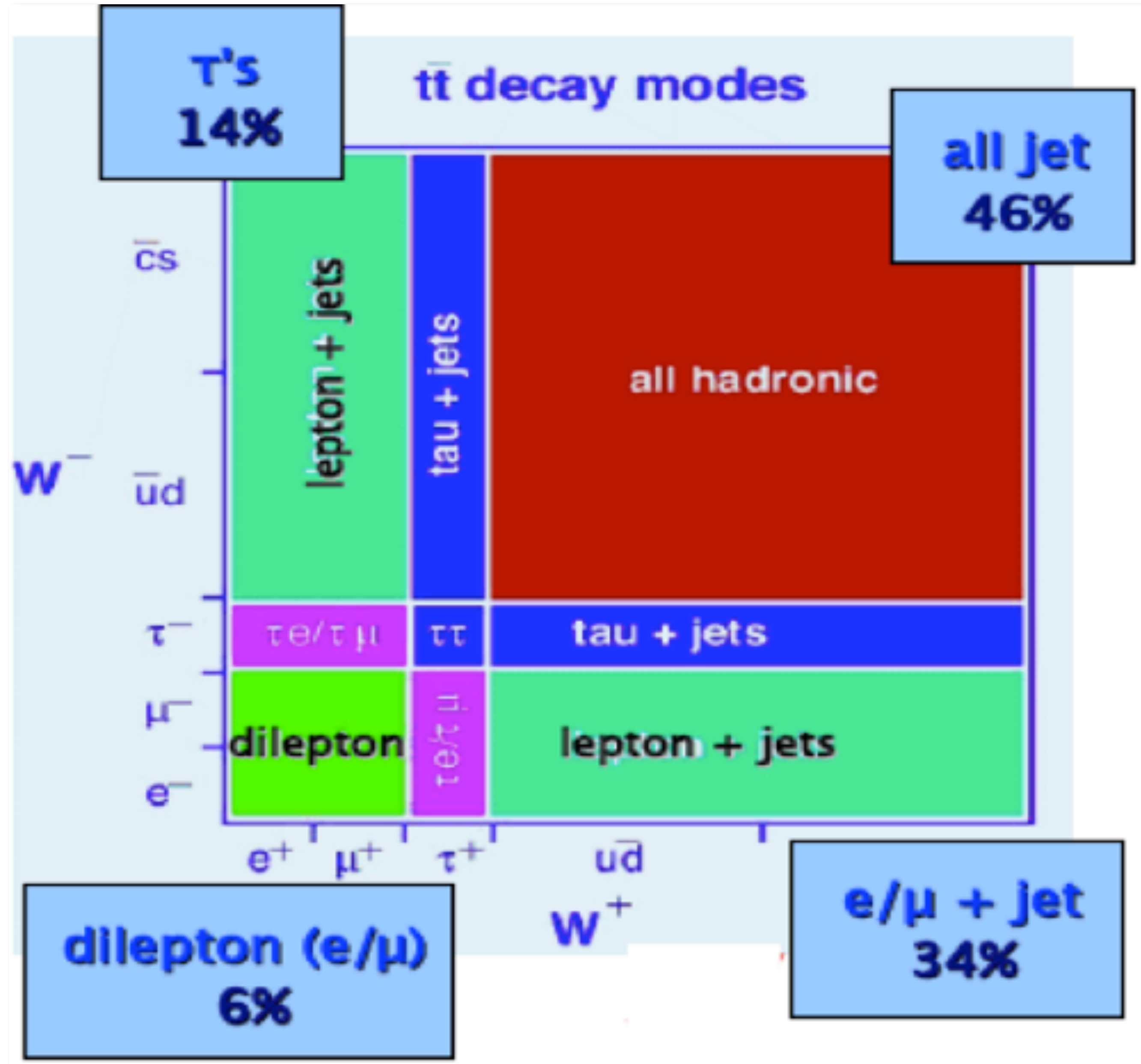
PRD 80, 054009 (2009)

LHC sample @1 fb^{-1} ~20,000 l+jets events
full Tevatron sample ~5,000 l+jets events

Top quark decay

In Standard Model

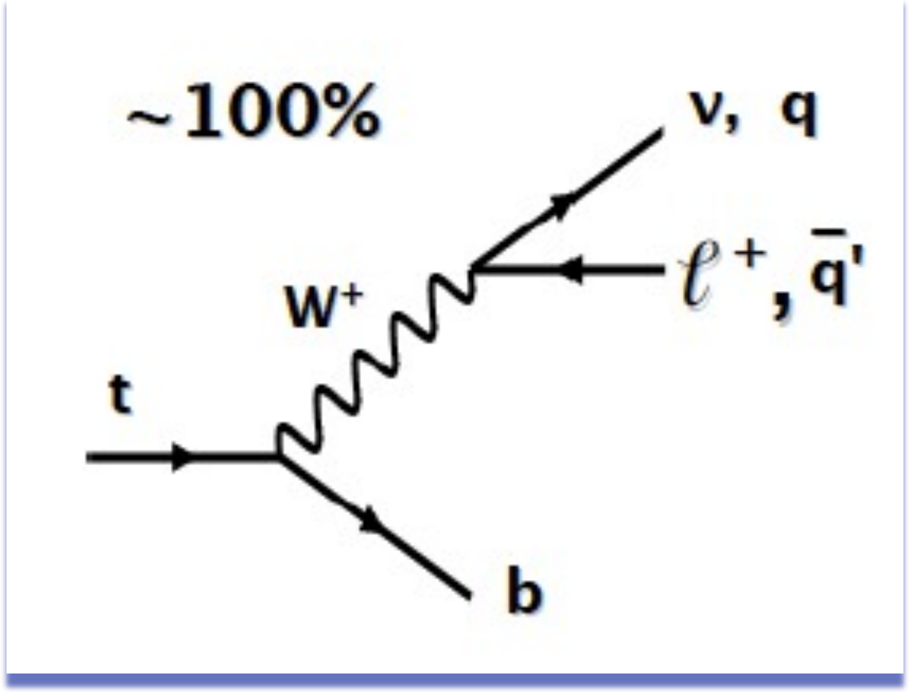


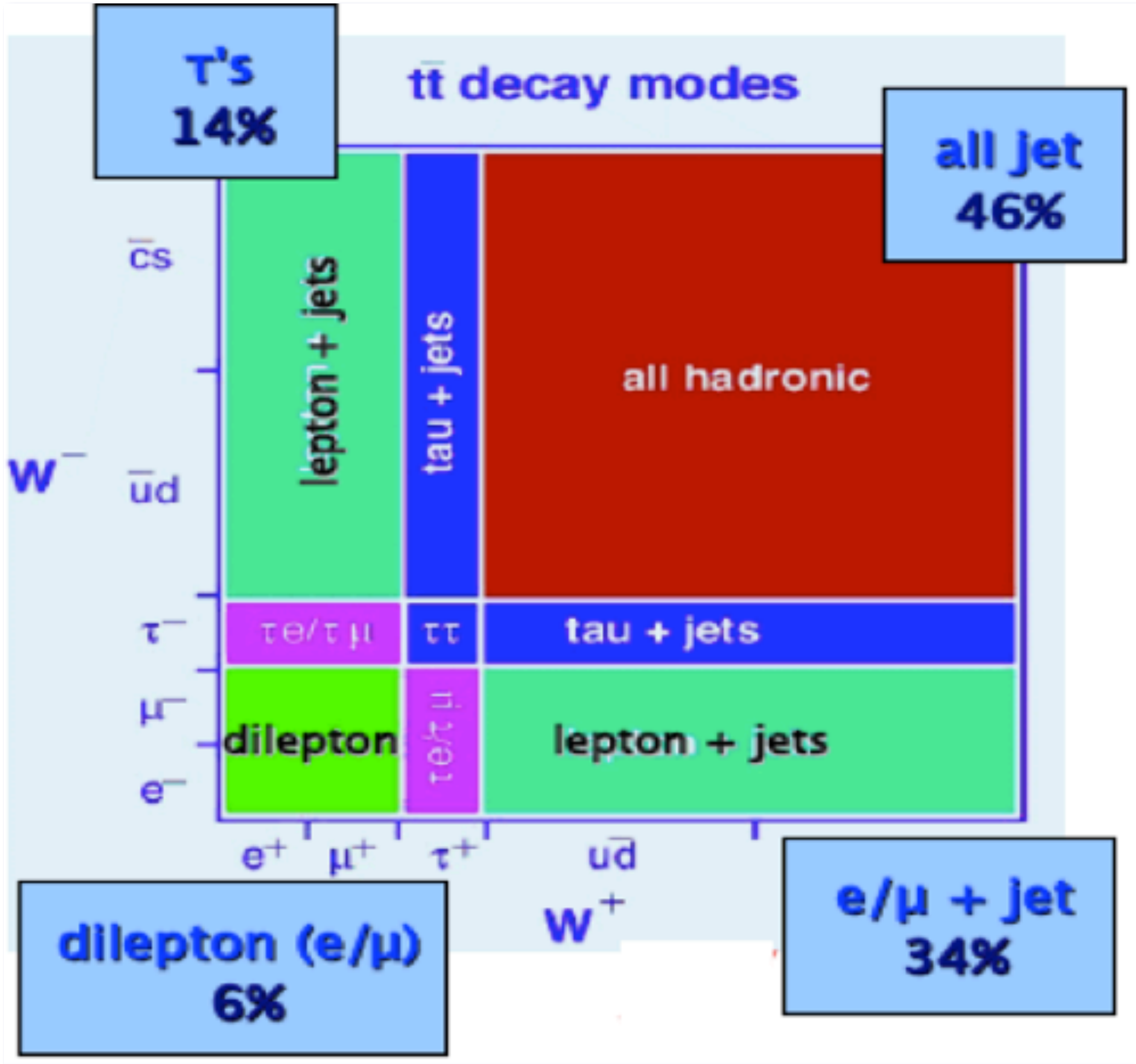


W decay mode defines top pair final state

Top quark decay

In Standard Model



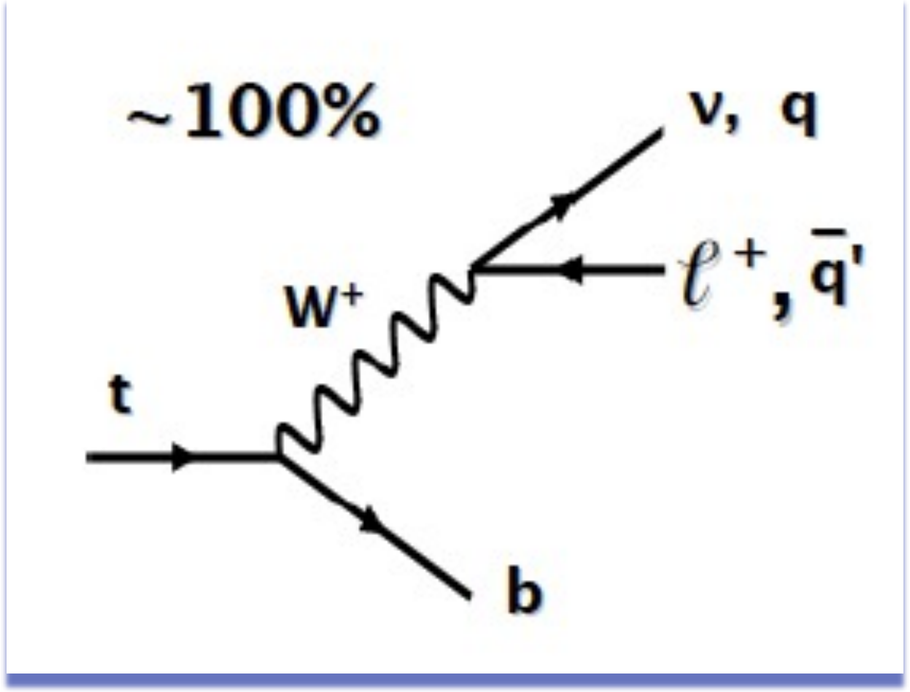


W decay mode defines top pair final state

small rate, small background
main background: Drell-Yan

Top quark decay

In Standard Model



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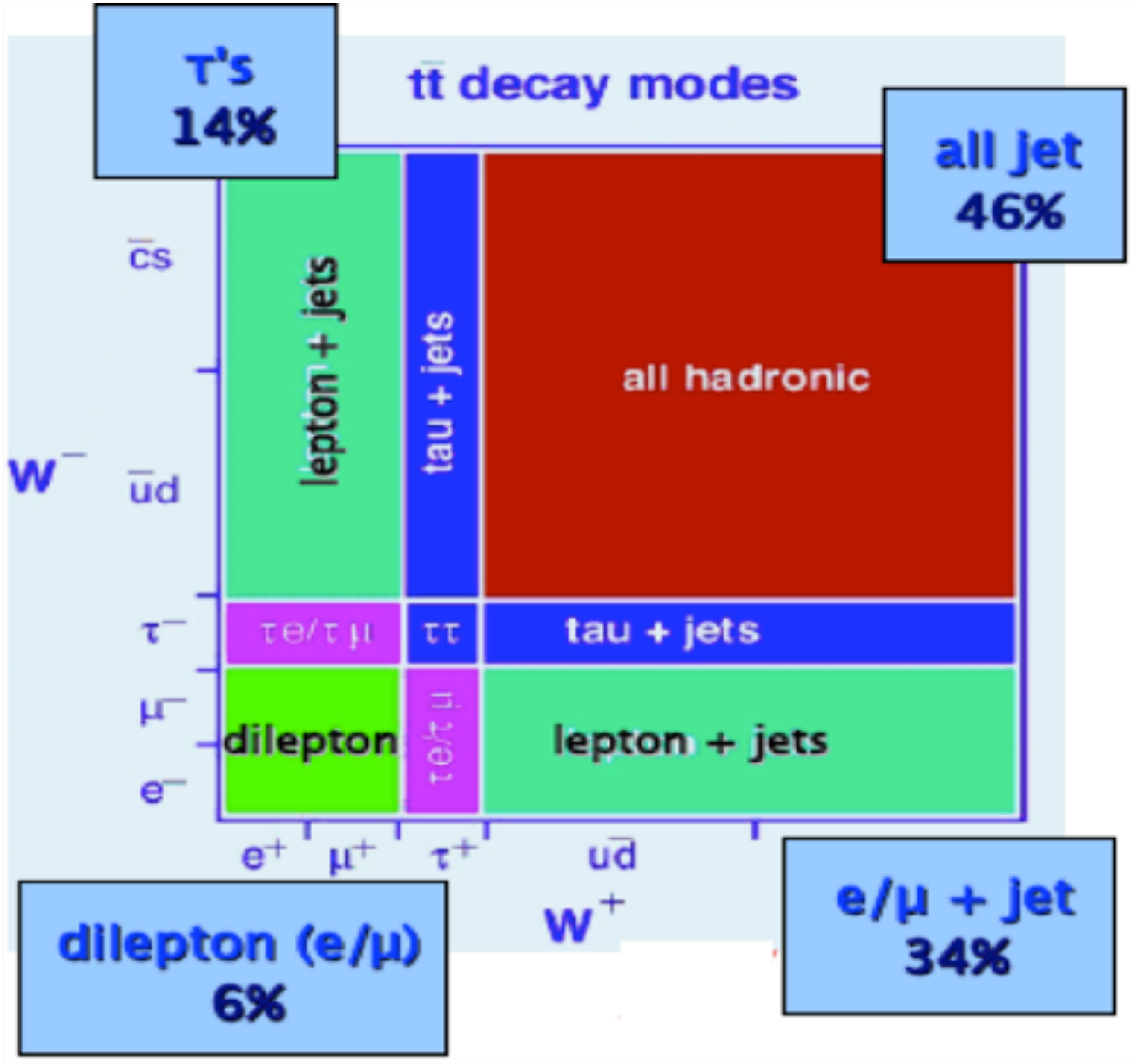
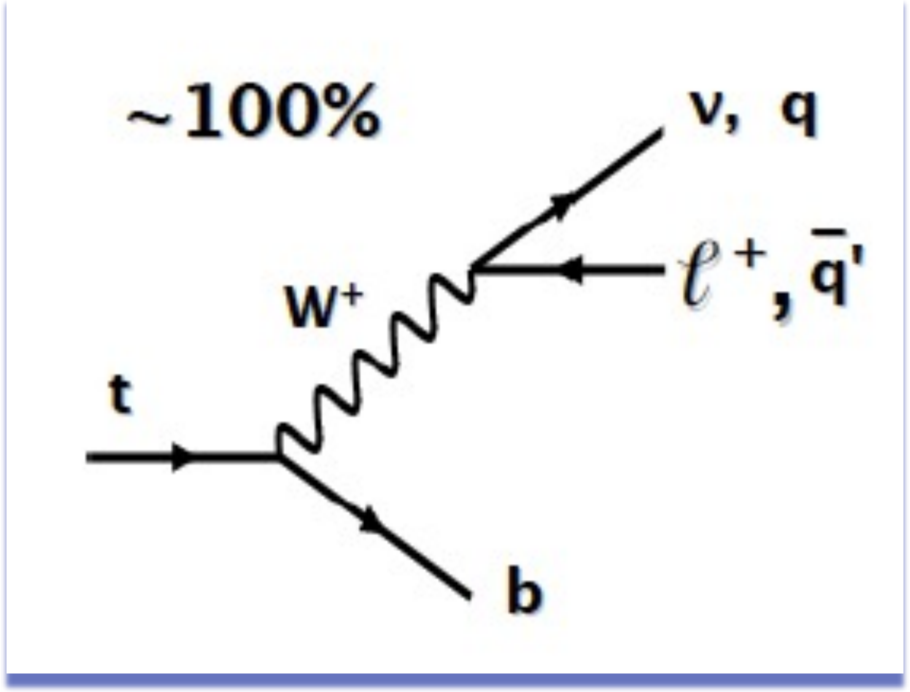


small rate, small background
main background: Drell-Yan

good rate, manageable background
main background: W+jets

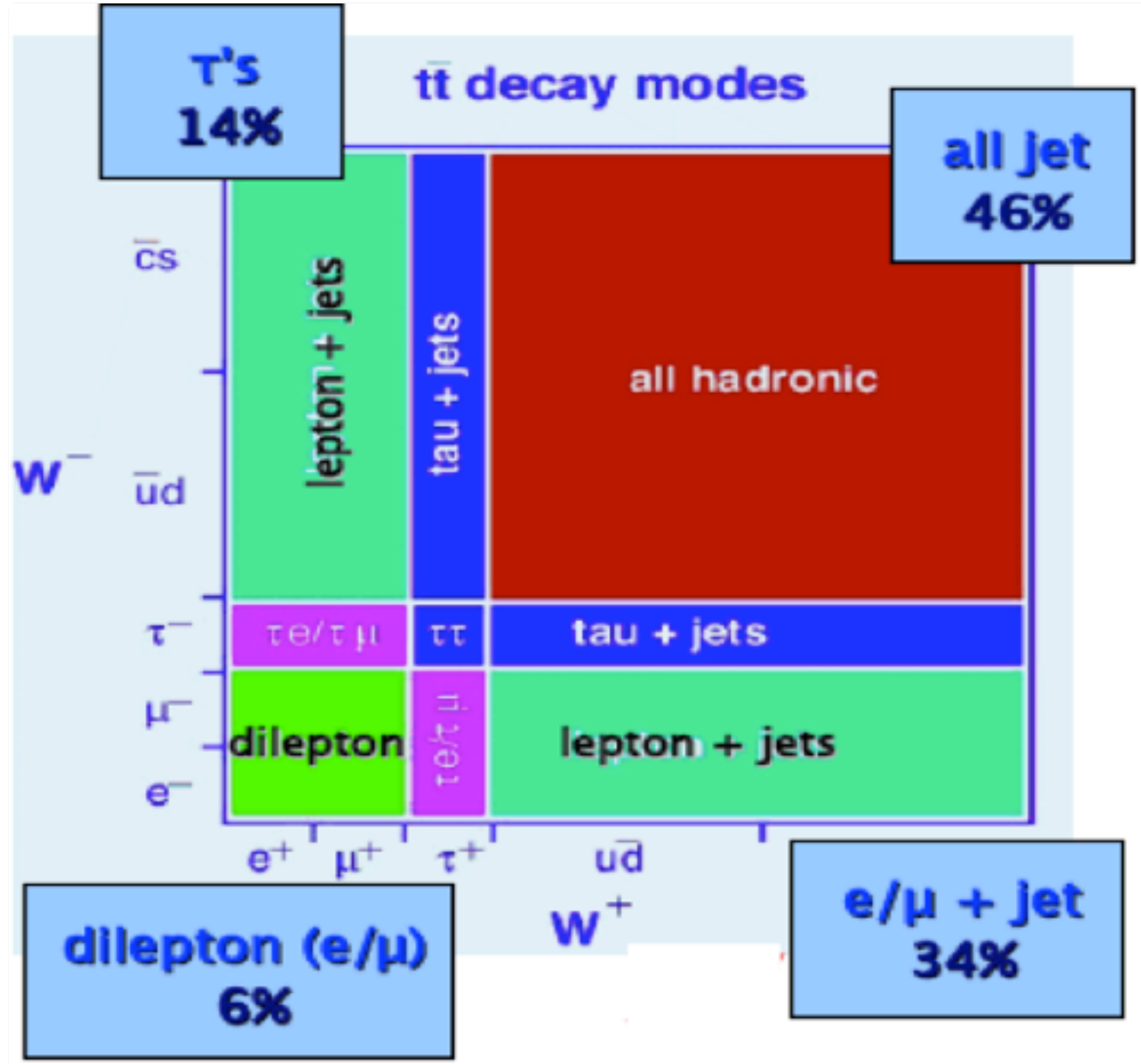
Top quark decay

In Standard Model



W decay mode defines top pair final state

high rate, high background
main background: multijet



small rate, small background
main background: Drell-Yan

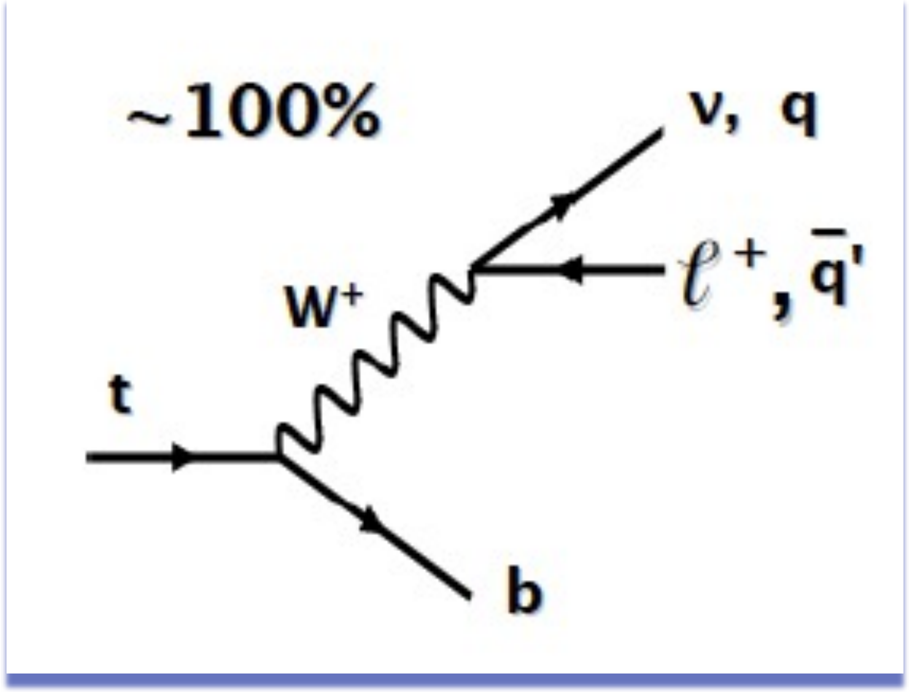
good rate, manageable background
main background: W+jets

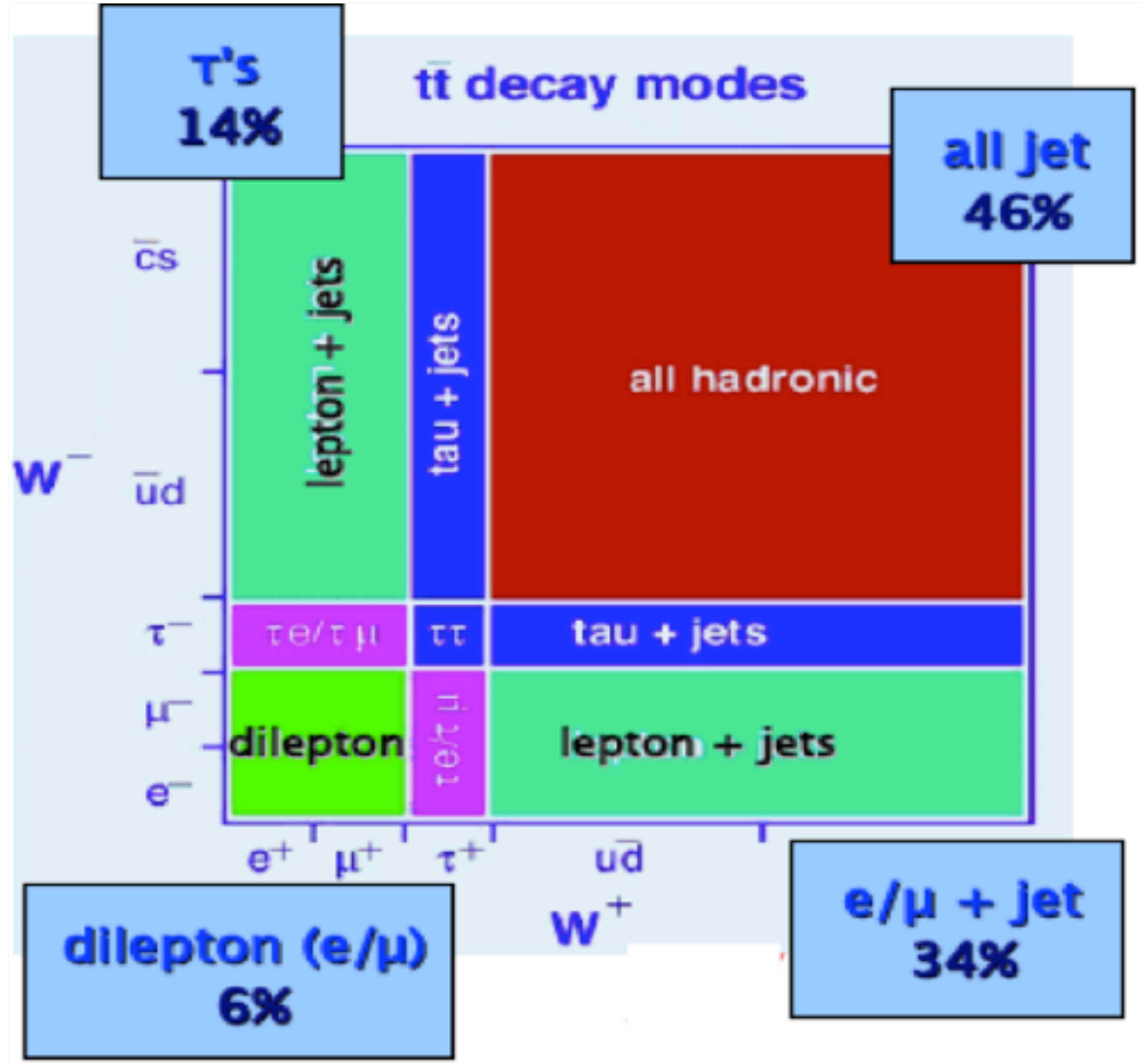
Top quark decay

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

high rate, high background
main background: multijet

In Standard Model





W decay mode defines top pair final state

small rate, small background
main background: Drell-Yan

good rate, manageable background
main background: W+jets

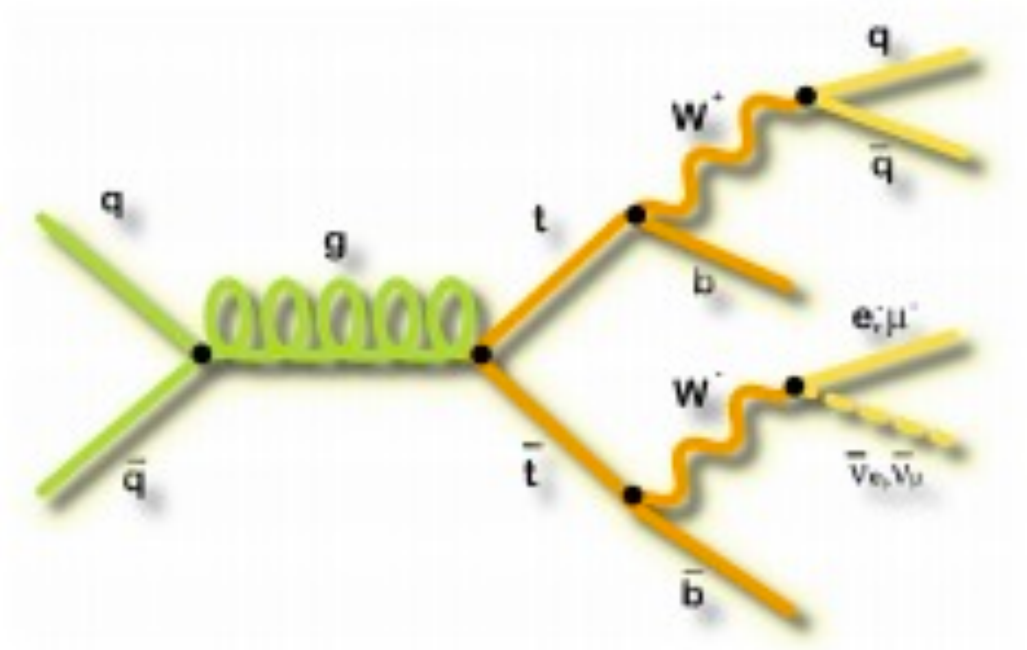
Top quark production

top quark pairs

Top pair cross section

- First step in understanding selected tt sample
- Test of theoretical QCD calculations

lepton+jets channel



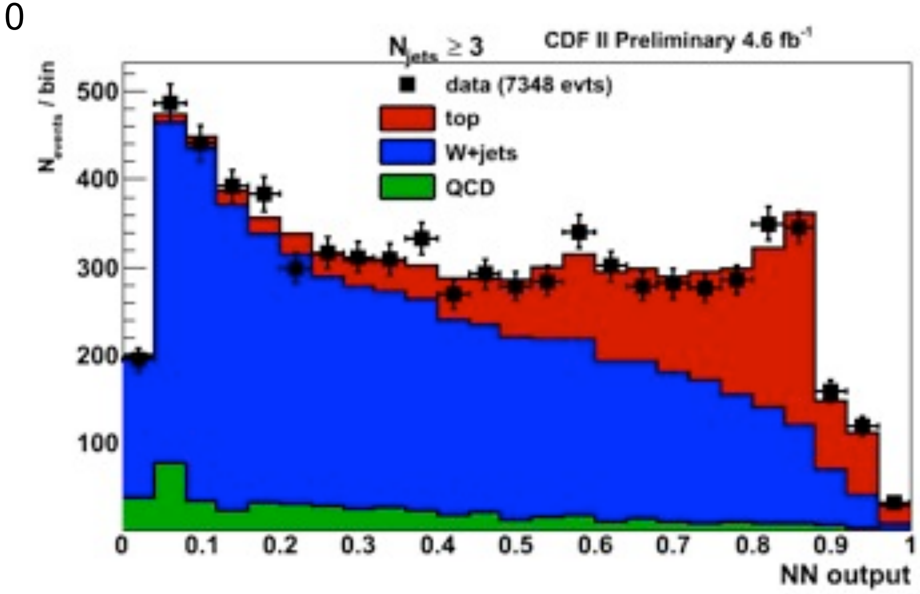
S/B (4 jets)	
topo	1 b-tag
2:3	4:1

- The most precise measurements at the Tevatron
- The most precise results from LHC as well so far
- Methods:
  - kinematic information combined into likelihood discriminant or NN
  - b-jet identification
    - cut on b-tagging algorithm output
    - add continuous b-tagging variable to multivariate discriminant
- Profiling technique: use data to constrain systematic uncertainties

Top pair cross section

PRL 105:012001,2010

- both methods: NN and b-tagging and their combination
- Take ratio to Z cross section
- Trade luminosity uncertainty for Z theory uncertainty



4.6 fb^{-1}

7% relative precision, 8.8% with luminosity uncertainty

$$\sigma_{t\bar{t}} = 7.63 \pm 0.37(\text{stat}) \pm 0.35(\text{syst}) \pm 0.15\ (\text{theory})\ \text{pb}$$

...to be compared to Tevatron goal of 10%

Top pair cross section

PRL 105:012001,2010

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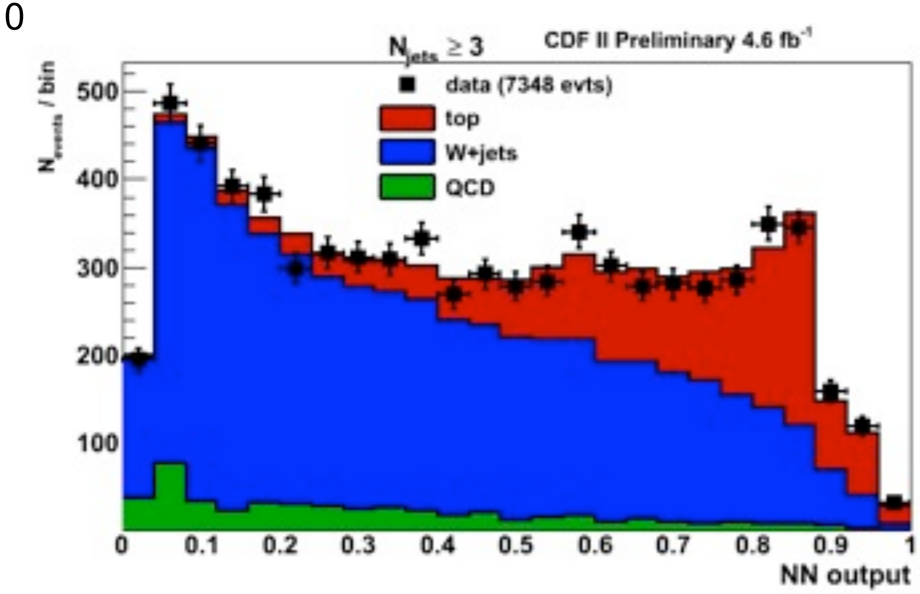

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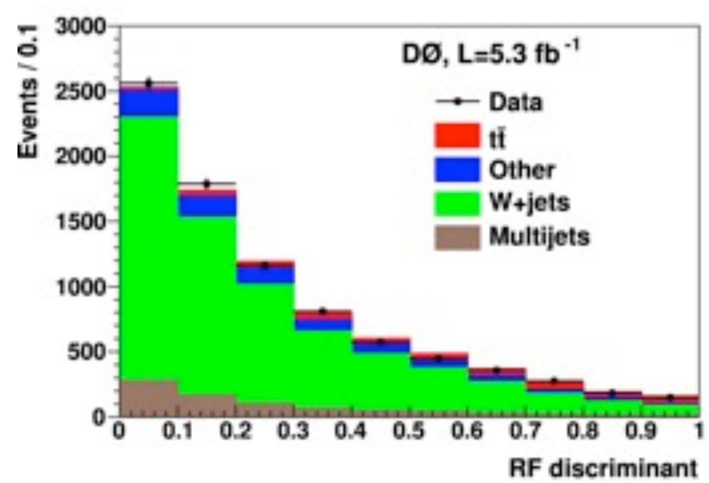
$\sigma_{t\bar{t}} = 7.63 \pm 0.37(\text{stat}) \pm 0.35(\text{syst}) \pm 0.15\ (\text{theory})$ pb

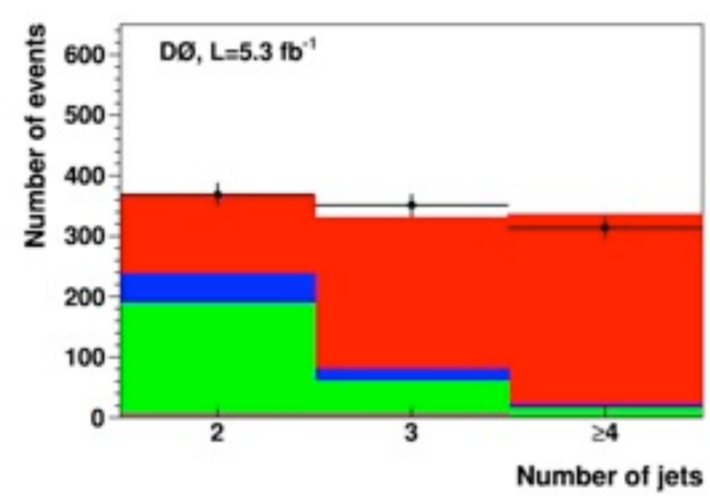
...to be compared to Tevatron goal of 10%

- combined method
  - BDT for background dominated samples: nj=2, 3 0 b-tag, nj=3 1 b-tag
  - b-tag counting for nj≥4, nj=3 2 b-tags
- nuisance parameters for systematics
- largest uncertainty from luminosity



PRD,84:012008,2011

$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\ \text{pb}$$



9-10% relative precision

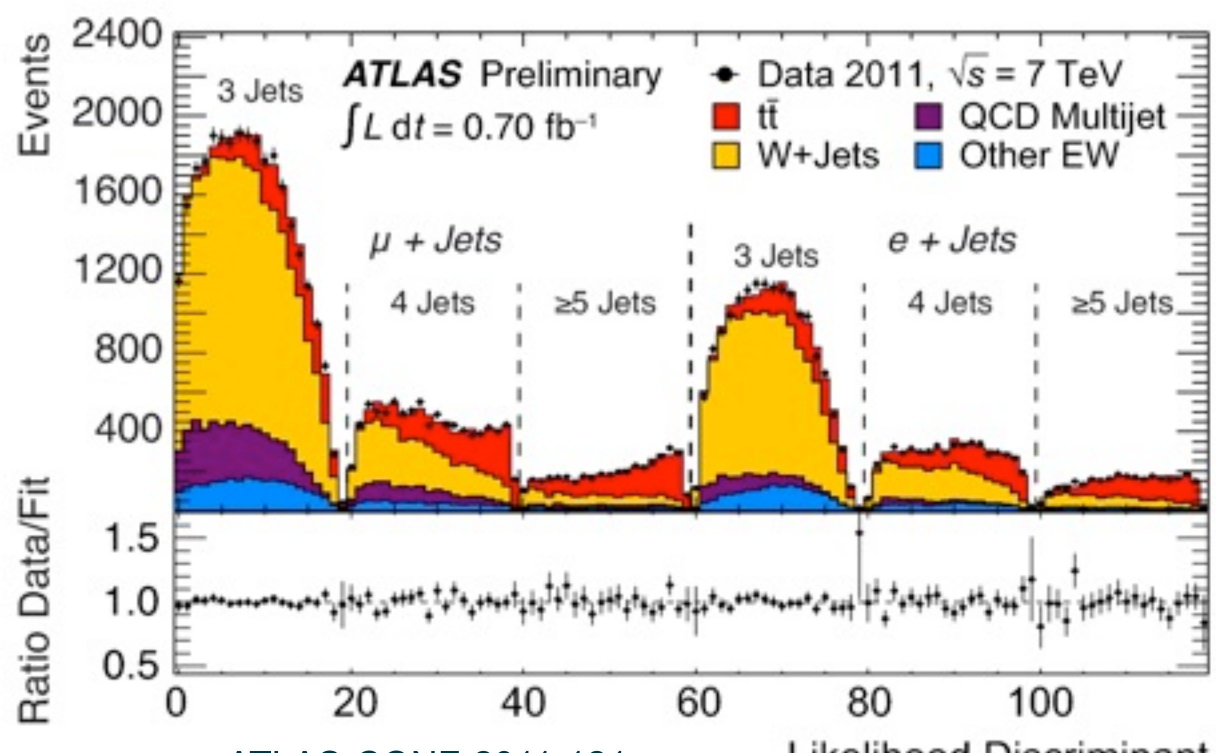
Top pair cross section

- multivariate discriminant
- no b-tagging information
  - allows to avoid additional systematic uncertainties
- systematics included via nuisance parameters

0.7 fb^{-1}

Total uncertainty ~6.6%

179 ± 3.9(stat)± 9.0(syst) ± 6.6 (lumi) pb



ATLAS-CONF-2011-121

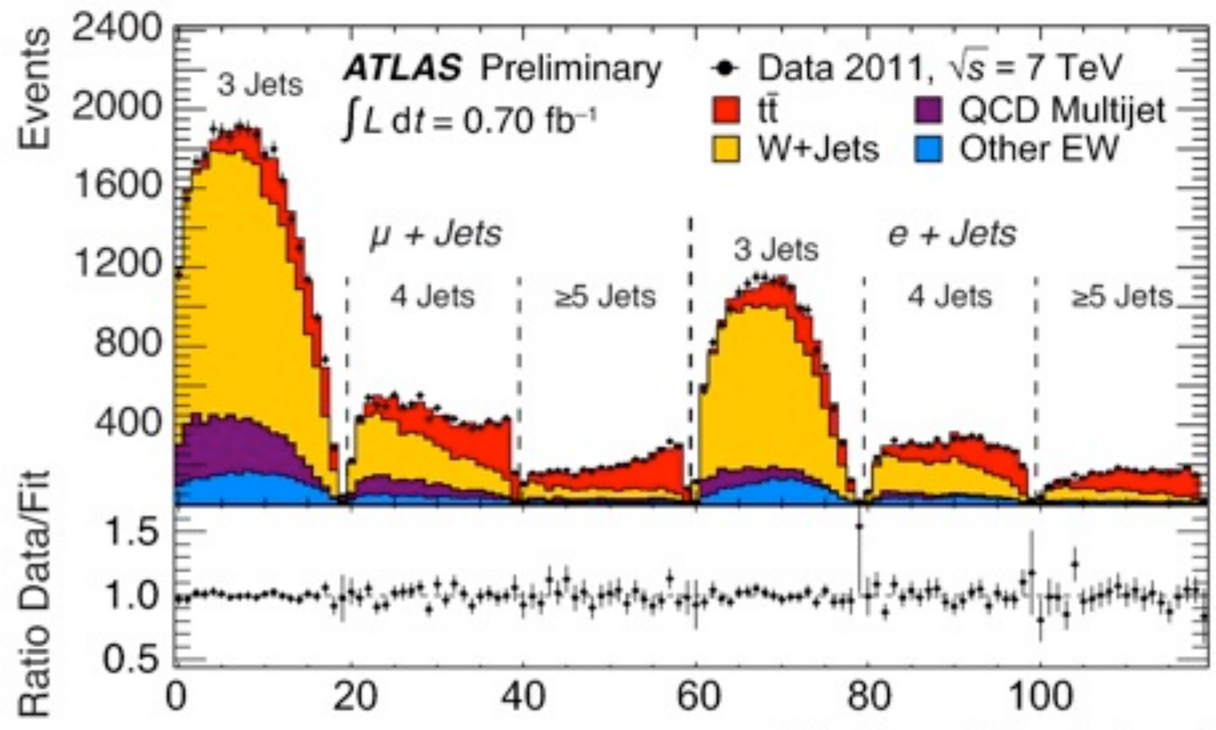
Top pair cross section

- multivariate discriminant
- no b-tagging information
  - allows to avoid additional systematic uncertainties
- systematics included via nuisance parameters

0.7 fb^{-1}

Total uncertainty ~6.6%

179 ± 3.9(stat)± 9.0(syst) ± 6.6 (lumi) pb



ATLAS-CONF-2011-121

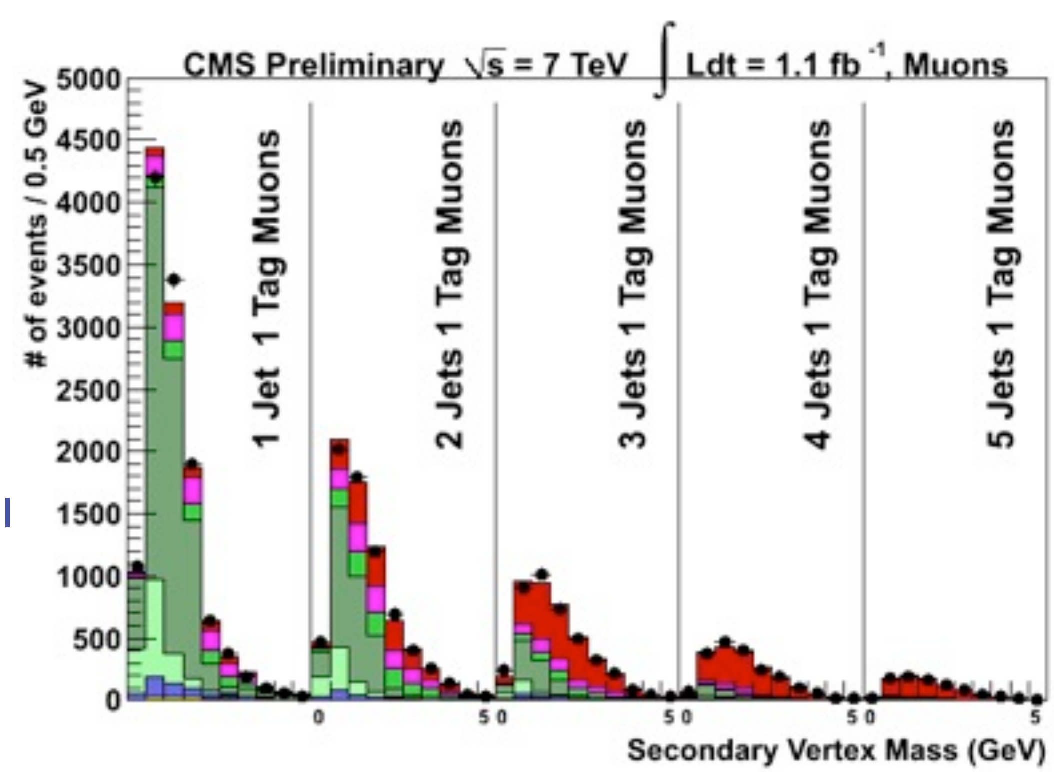
- fit to secondary vertex mass distribution
  - use events with 1, 2, 3, 4, ≥5 jets
  - split in 1 and ≥2 tags
- systematics included via nuisance parameters

CMS-PAS-TOP-11-003

0.8-1.1 fb^{-1}

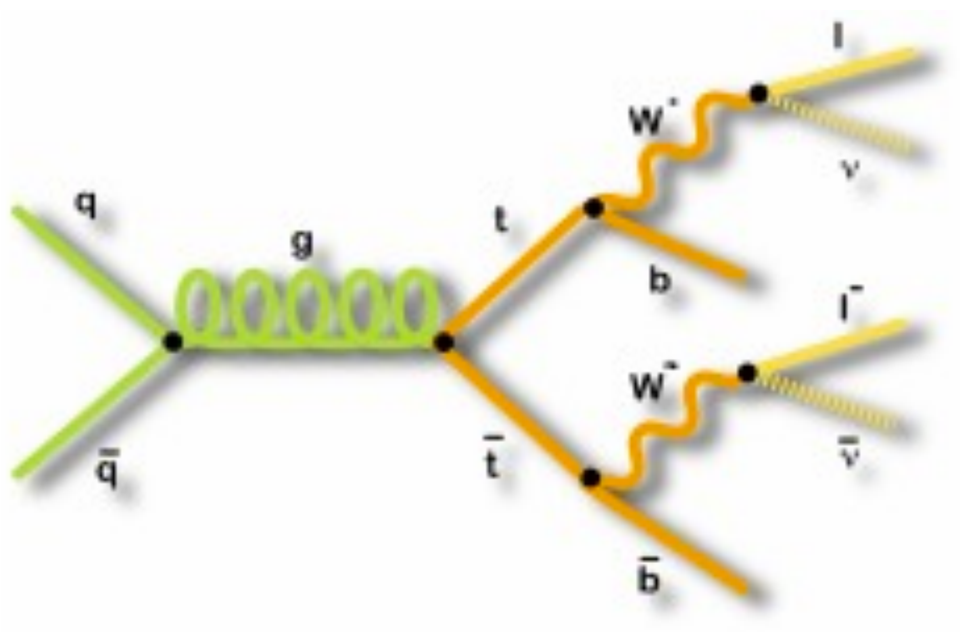
$\sigma_{t\bar{t}}$ = 164 ± 2.8(stat)± 11.9(syst) ± 7.4 (lumi) pb

Total uncertainty ~8.7%



Top pair cross section

dilepton channel

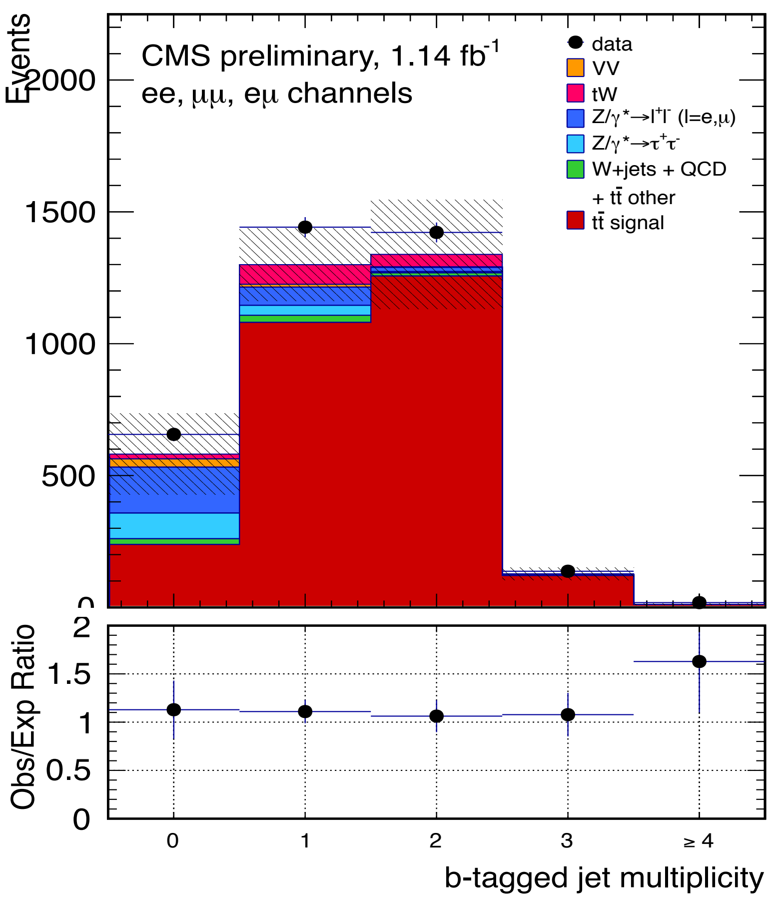


S/B	
topo	1 b-tag
3:1	15:1

- Statistically limited at the Tevatron for very long time
- Systematically limited at LHC with the current data set
- Low backgrounds motivate the methods
- Methods:
  - mainly cut and count w/o b-tagging
  - recently with b-jet identification
    - cut on b-tagging algorithm output
    - add continuous b-tagging variable to multivariate discriminant
- Profiling technique to constrain systematic uncertainties

Top pair cross section

- ~2,500 dilepton events after b-tagging
  - MET>30 GeV in ee, μμ channels
- cut and count
- systematics dominated by b-tagging and pileup



1.1 fb^{-1}

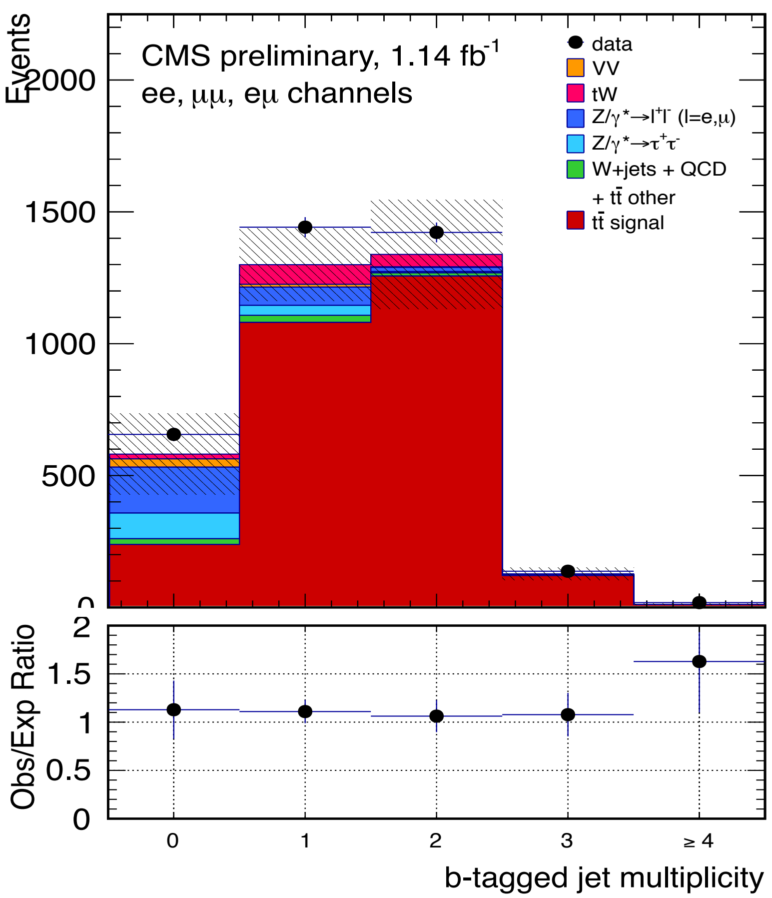
CMS-PAS-TOP-11-005

$$\sigma_{t\bar{t}} = 164 \pm 3.9(\text{stat}) \pm 16.3(\text{syst}) \pm 7.6\ (\text{lumi})\ \text{pb}$$

Total uncertainty ~11.2%

Top pair cross section

- ~2,500 dilepton events after b-tagging
  - MET>30 GeV in ee, μμ channels
- cut and count
- systematics dominated by b-tagging and pileup



1.1 fb^{-1}

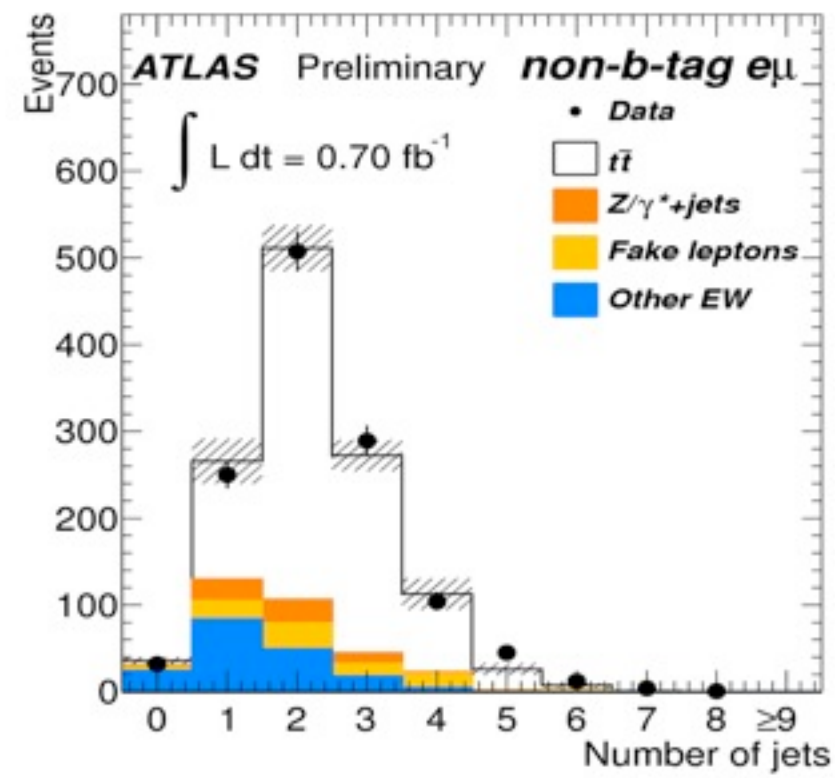
CMS-PAS-TOP-11-005

$$\sigma_{t\bar{t}} = 164 \pm 3.9(\text{stat}) \pm 16.3(\text{syst}) \pm 7.6\ (\text{lumi})\ \text{pb}$$

Total uncertainty ~11.2%

- ~1,100 dilepton events after b-tagging
  - MET>60 GeV in ee, μμ channels
  - HT>130 GeV in eμ channel
- cut and count with and w/o tagging
- systematics dominated JES and luminosity

0.7 fb^{-1}



ATLAS-CONF-2011-100

$$\sigma_{t\bar{t}} = 177 \pm 6\ (\text{stat})\ ^{+17}_{-14}(\text{syst}) \pm 8\ (\text{lumi})\ \text{pb}$$

Total uncertainty ~11%

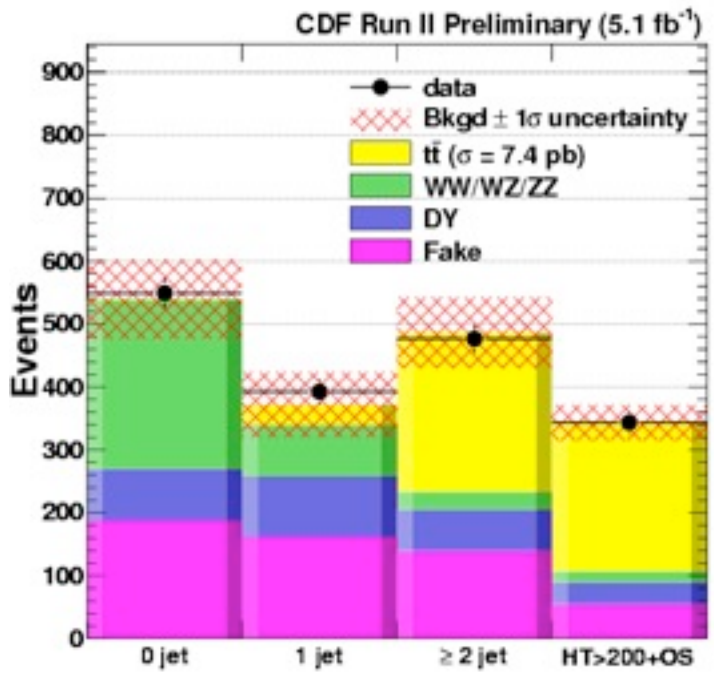
Top pair cross section

- 240 dilepton events
- cut and count with and w/o b-tagging

$$\sigma_{t\bar{t}} = 7.40 \pm 0.58(\text{stat}) \pm 0.63(\text{syst}) \pm 0.45\ (\text{lumi})\ \text{pb}$$
$$\sigma_{t\bar{t}} = 7.25 \pm 0.66(\text{stat}) \pm 0.47(\text{syst}) \pm 0.44\ (\text{lumi})\ \text{pb}$$

13% relative precision, with luminosity uncertainty

PRL 105:012001,2010



5.1 fb^{-1}

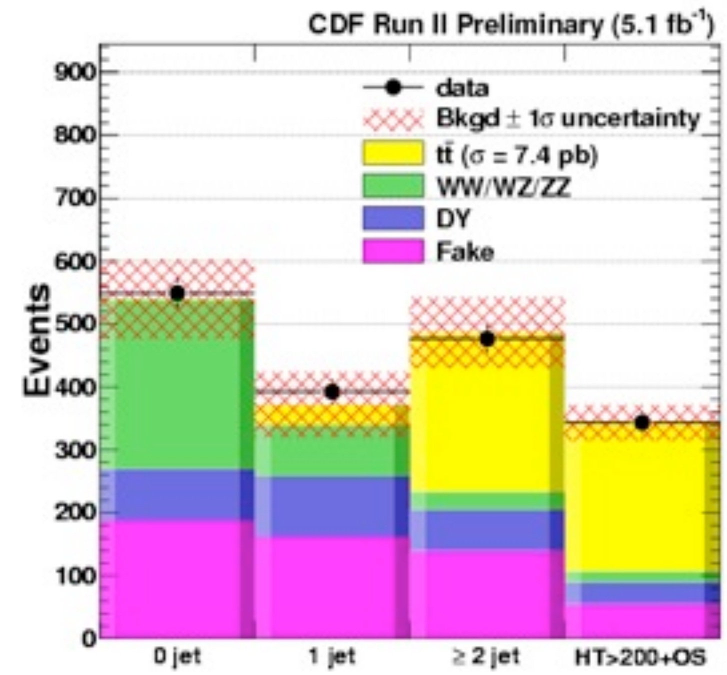
Top pair cross section

PRL 105:012001,2010

- 240 dilepton events
- cut and count with and w/o b-tagging

$$\sigma_{t\bar{t}} = 7.40 \pm 0.58(\text{stat}) \pm 0.63(\text{syst}) \pm 0.45\ (\text{lumi})\ \text{pb}$$
$$\sigma_{t\bar{t}} = 7.25 \pm 0.66(\text{stat}) \pm 0.47(\text{syst}) \pm 0.44\ (\text{lumi})\ \text{pb}$$

13% relative precision, with luminosity uncertainty



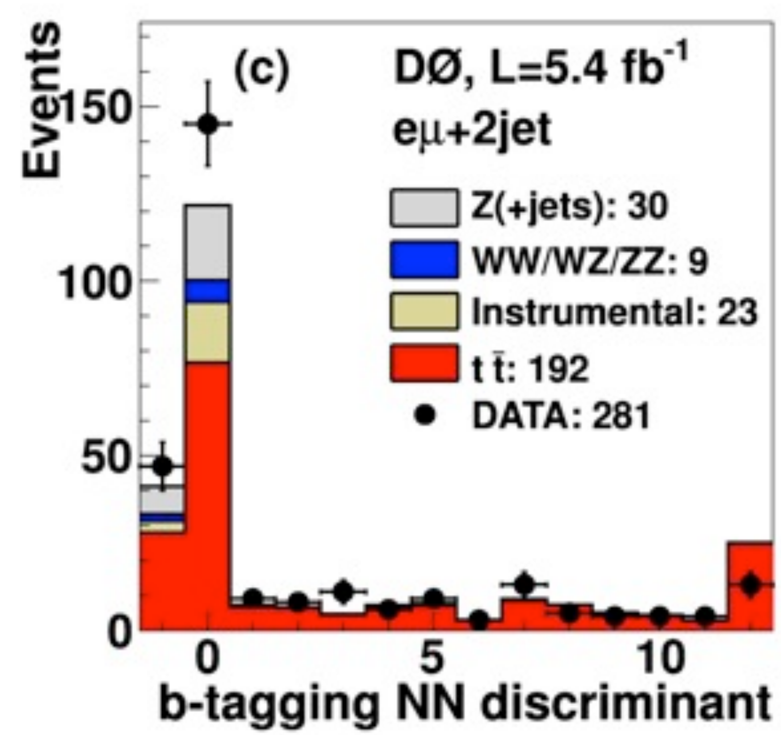
5.1 fb^{-1}

- 350 dilepton events
  - fit to b-tagg NN discriminant distribution
  - the smallest output value among 2 leading jets
- nuisance parameters for systematics
- largest uncertainties: statistical and luminosity

PLB,704, 403,2011

$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}$$

12% relative precision

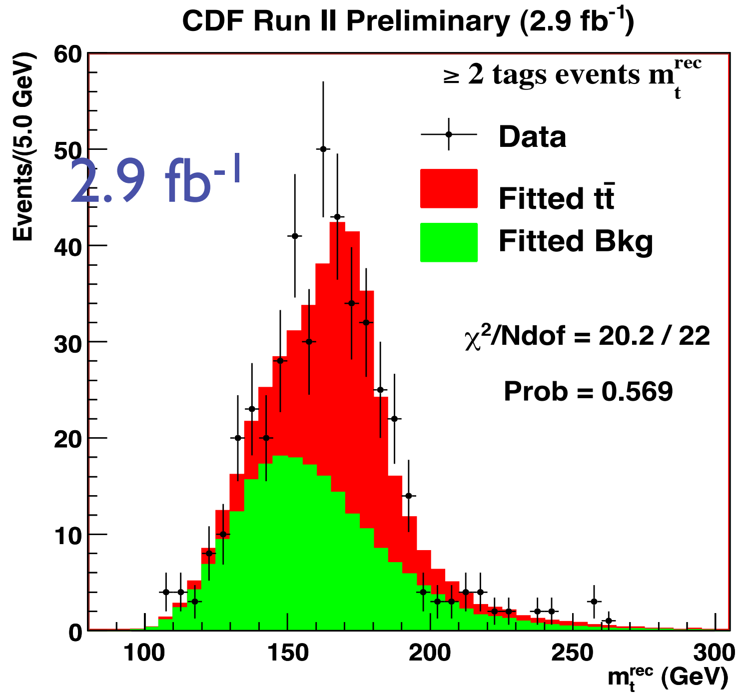


Top pair cross section

all-hadronic channel

- NN selection to suppress large QCD background
- simultaneous measurement with the mass
- 2D JES vs mass template fit
- single and double tagged events

~850 top events



$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\text{stat}) \pm 1.1(\text{syst}) \pm 0.4\ (\text{lumi})\ \text{pb}$$

Total uncertainty ~18%
reduced at the measured m_t

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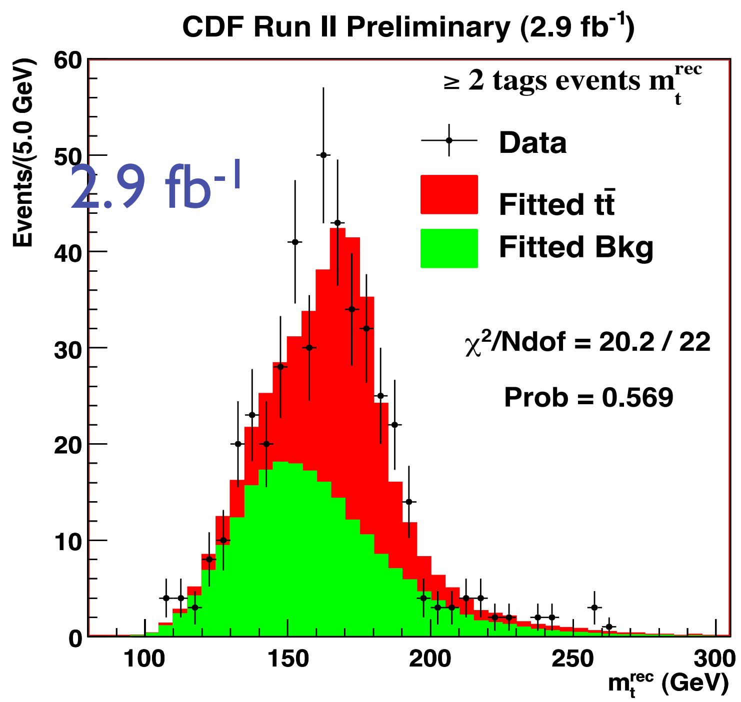
Top pair cross section

all-hadronic channel

- NN selection to suppress large QCD background
- simultaneous measurement with the mass
- 2D JES vs mass template fit
- single and double tagged events

~850 top events

2.9 fb^{-1}

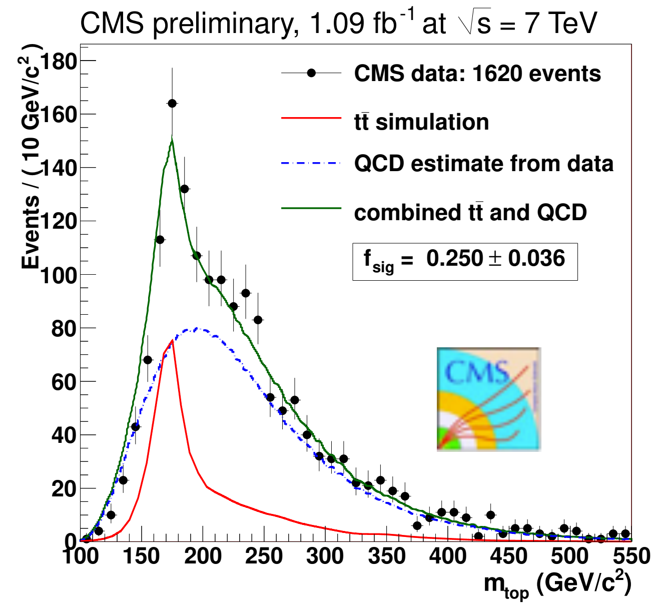


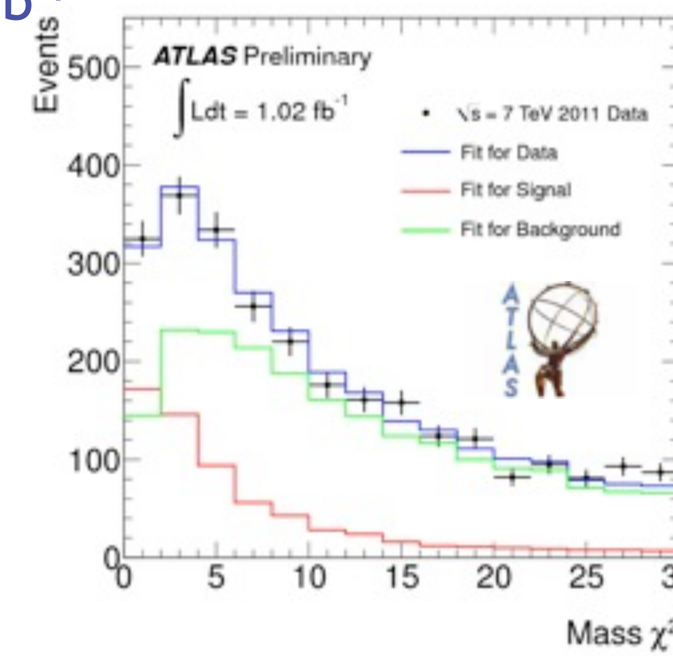
$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\text{stat}) \pm 1.1(\text{syst}) \pm 0.4\ (\text{lumi})\ \text{pb}$$

Total uncertainty ~18%
reduced at the measured m_t

- Similar idea: use distributions sensitive to m_t

1 fb^{-1}





Total uncertainty ~33%

Total uncertainty ~48%

$$\sigma_{t\bar{t}} = 136 \pm 20(\text{stat}) \pm 40(\text{syst}) \pm 8\ (\text{lumi})\ \text{pb}$$
$$\sigma_{t\bar{t}} = 176 \pm 18(\text{stat}) \pm 78(\text{syst}) \pm 6\ (\text{lumi})\ \text{pb}$$

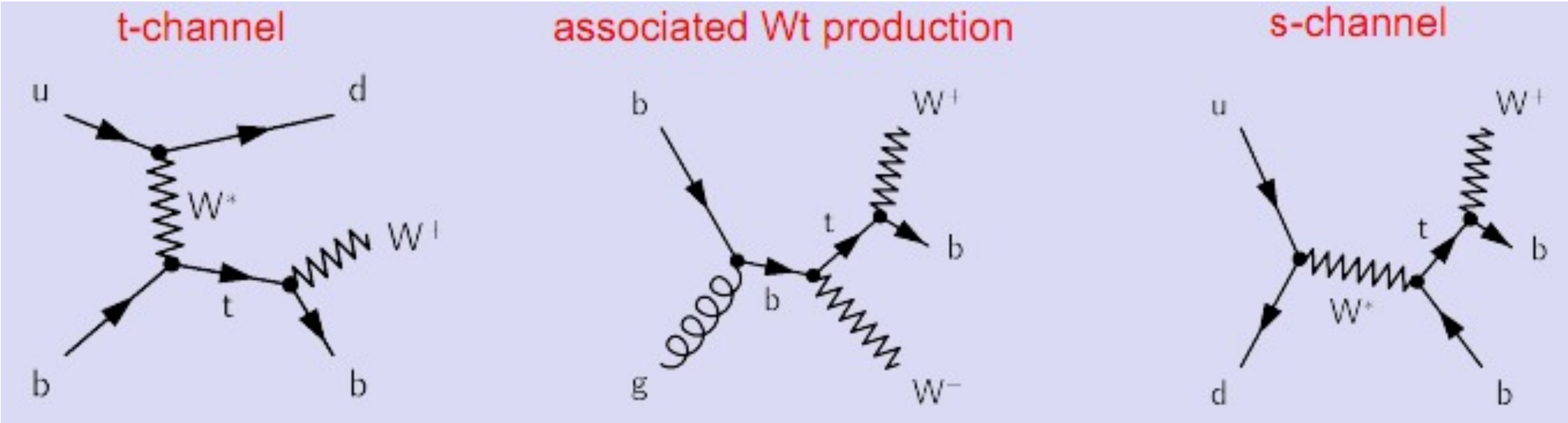
- systematics dominated by b-tagging and background model (from data) and JES, ISR/FSR (Atlas)

- First measurements in μτ channel
- Important for new physics searches

Top quark production

electroweak single top quark

Electroweak top production



Cross sections at LHC, $\sqrt{s}$=7 TeV, m_t=173 GeV

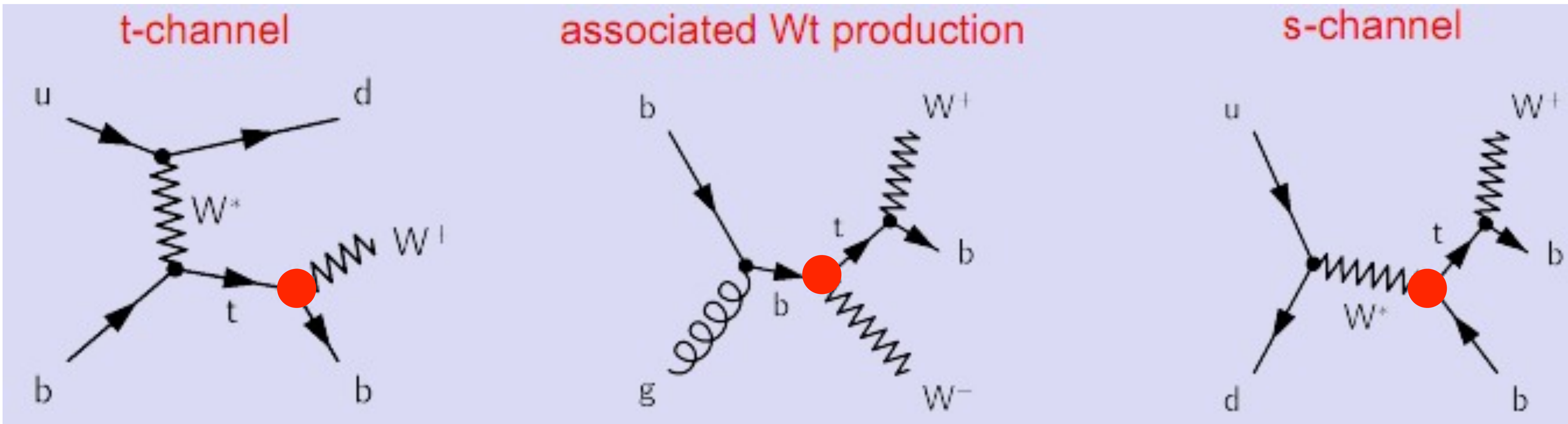
62.4±2.6 pb	15.6±1.3 pb	4.6±0.2 pb

Cross sections at Tevatron, $\sqrt{s}$=1.96 TeV, m_t=173 GeV

2.1±0.1 pb	0.25±0.03 pb	1.05±0.05 pb

N. Kidonakis, arXiv 1103.2792, 1005.4451, 1001.5034 $NNLO_{approx}$

Electroweak top production



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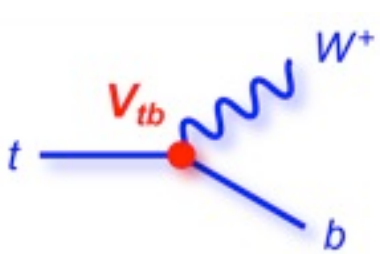
$\sigma \sim |V_{tb}|^2$

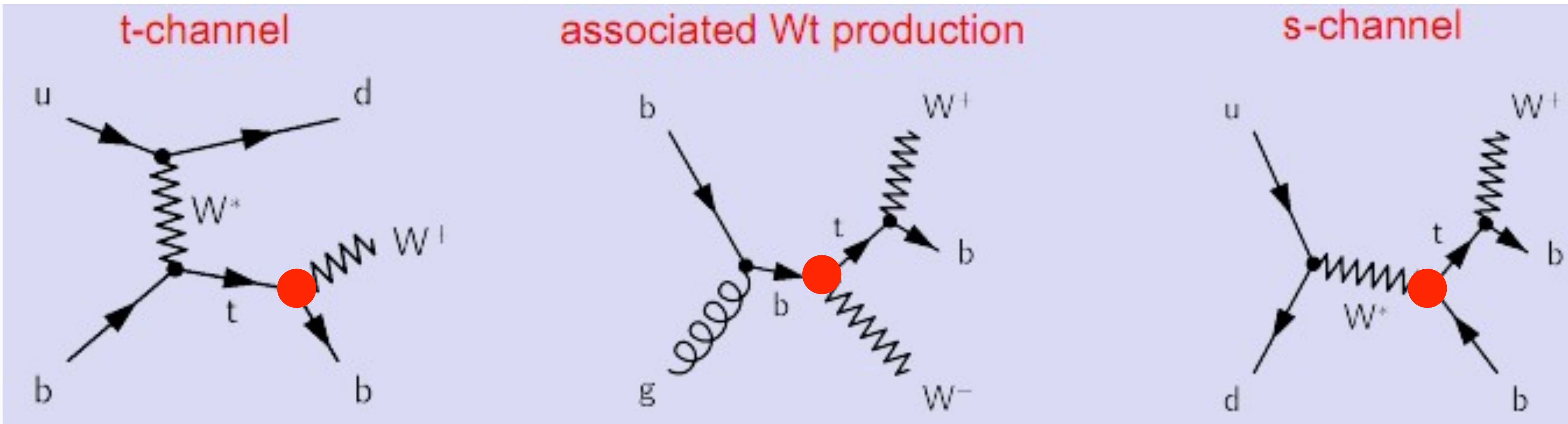


$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$

Test unitarity of CKM matrix

4^{th} generation

Electroweak top production



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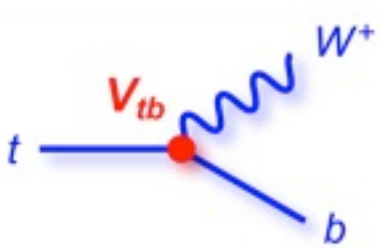
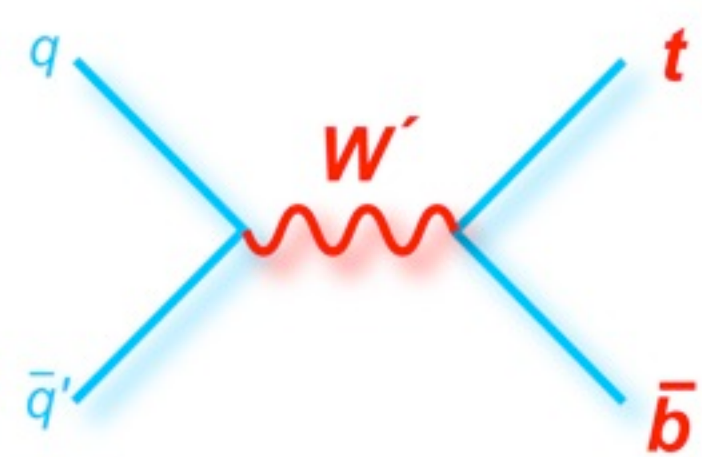


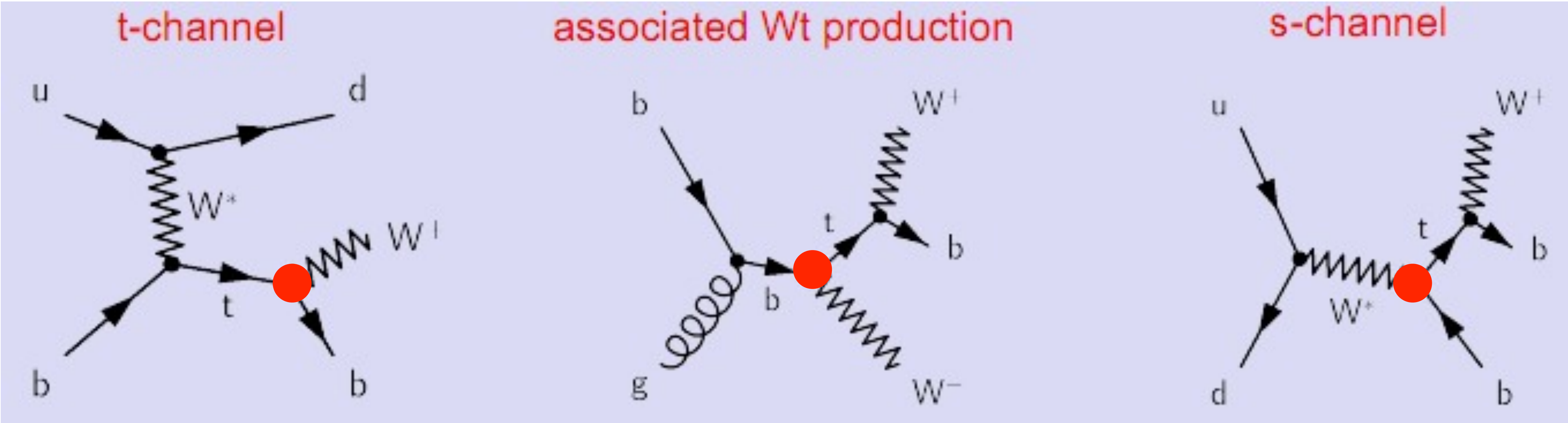
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Test unitarity of CKM matrix
4th generation



Sensitive to new physics

Electroweak top production



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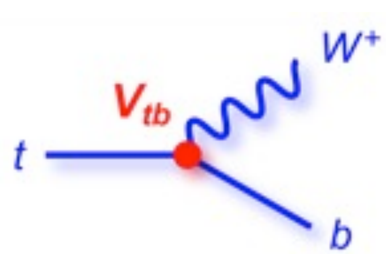
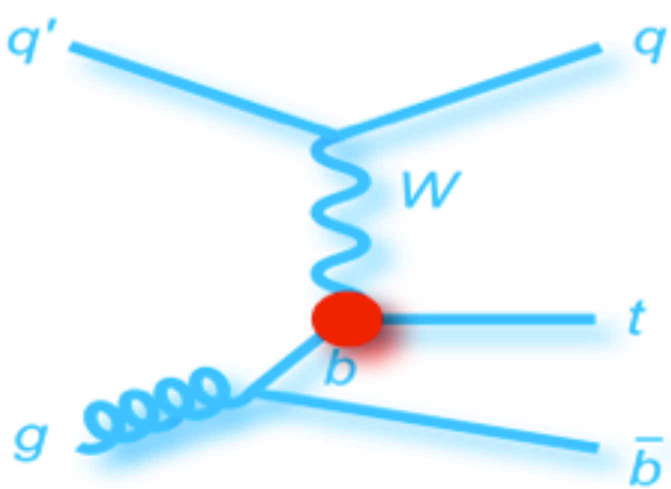
$\sigma \sim |V_{tb}|^2$



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

Test unitarity of CKM matrix

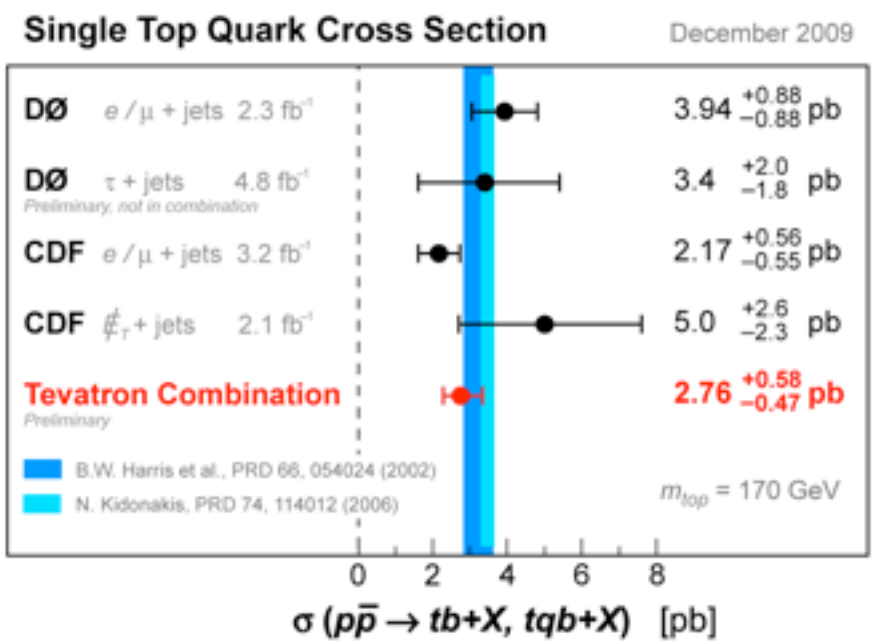
4th generation



Sensitive to new physics

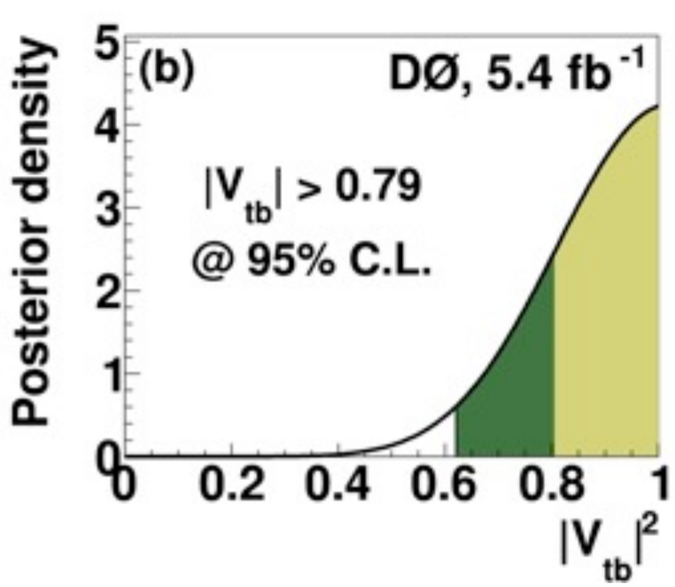
- Long road towards observation at the Tevatron
- s+t channels assuming SM ratio

arXiv:0908.2171v1 [hep-ex]



Direct measurement of $|V_{tb}|$

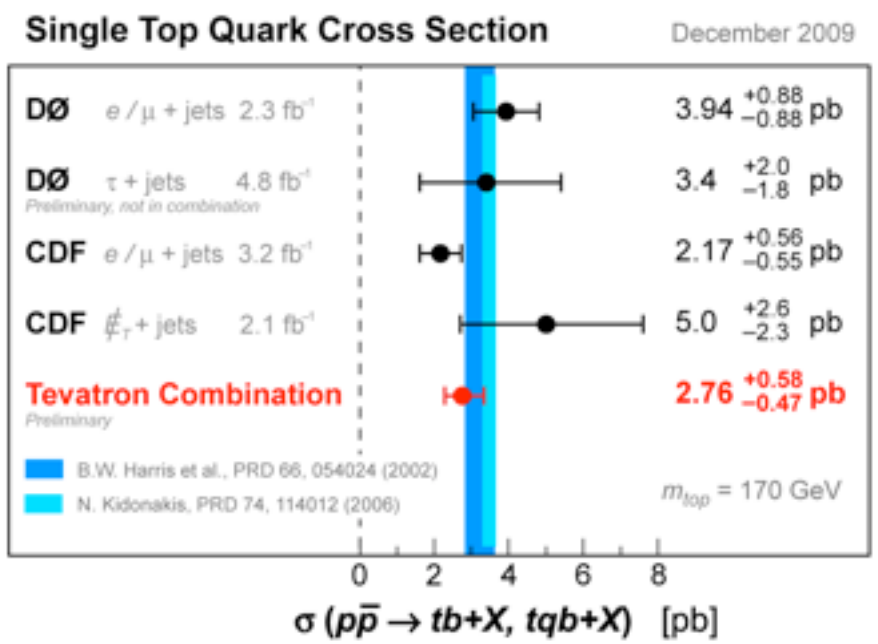
$|V_{tb}|>0.77$ @95% CL



Wednesday, October 26, 2011

Single top at Tevatron

- Long road towards observation at the Tevatron
- s+t channels assuming SM ratio



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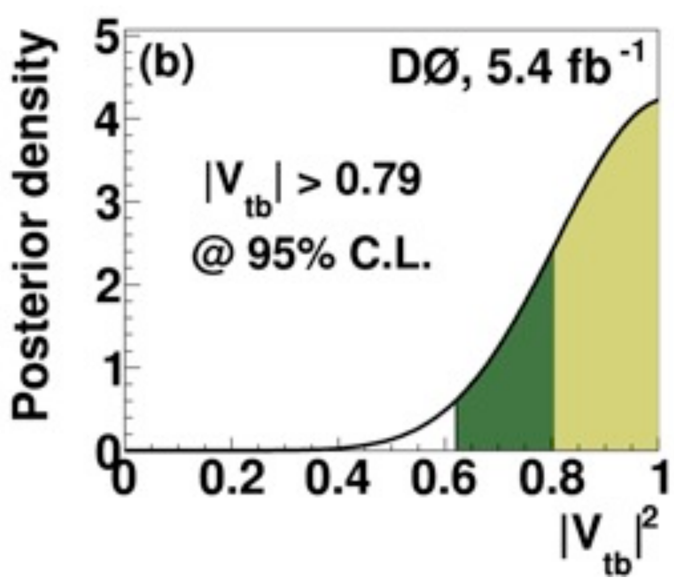
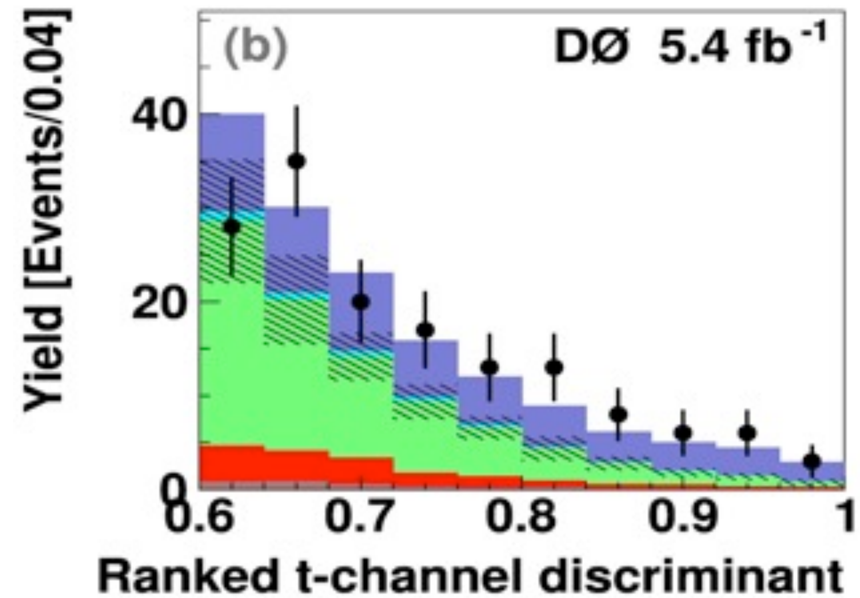
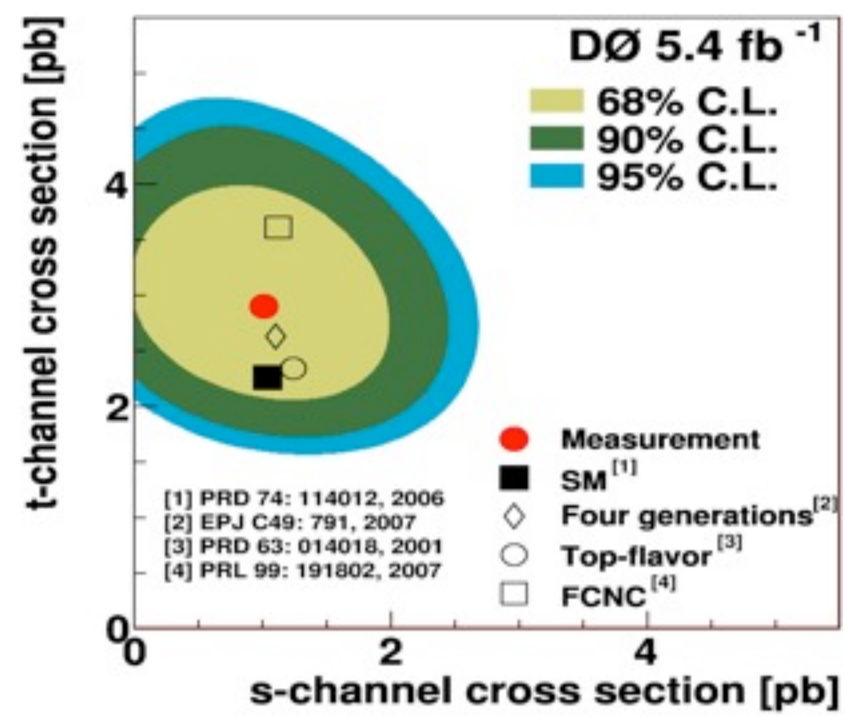


- Independent s- and t-channel
  - 5.5σ observation of t-channel



σ(t-ch) = 2.90 ± 0.59 pb

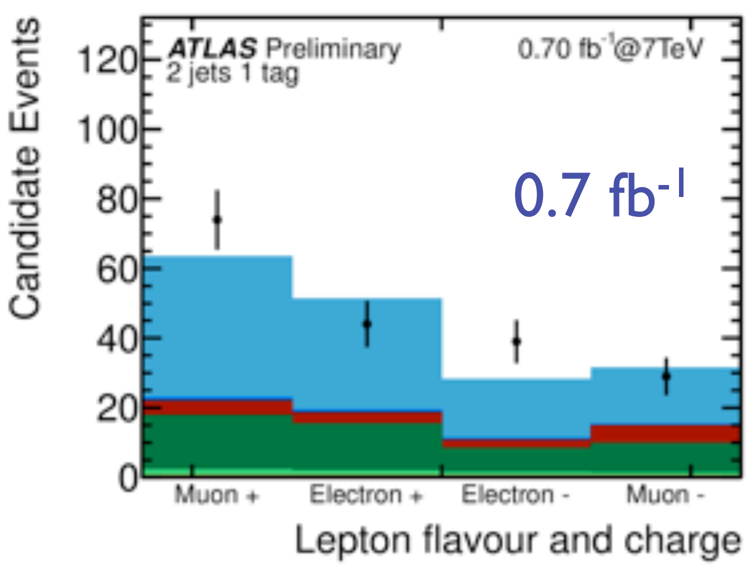


Single top at LHC

- t-channel signal established at LHC
- methods
  - cut and count, NN discriminant
- systematically dominated already

$$\sigma_{t\text{-ch}} = 90 \pm 9 \text{ (stat) } {}^{+31}_{-20} \text{ (syst) pb}$$

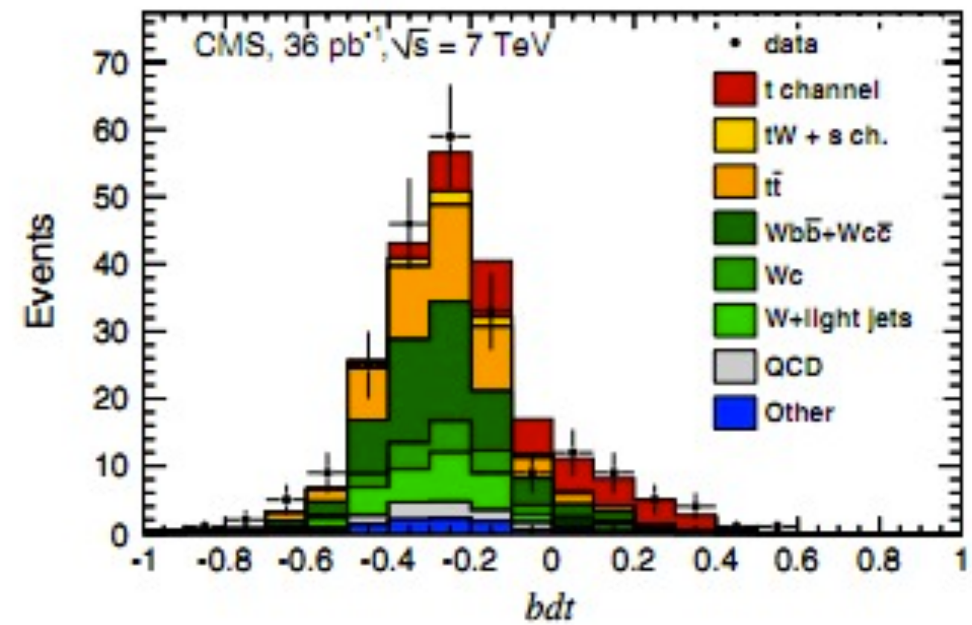
expected (observed) significance
5.4 (7.6) σ



- limit on s-channel production

$$\sigma_s < 26.5\text{pb}$$

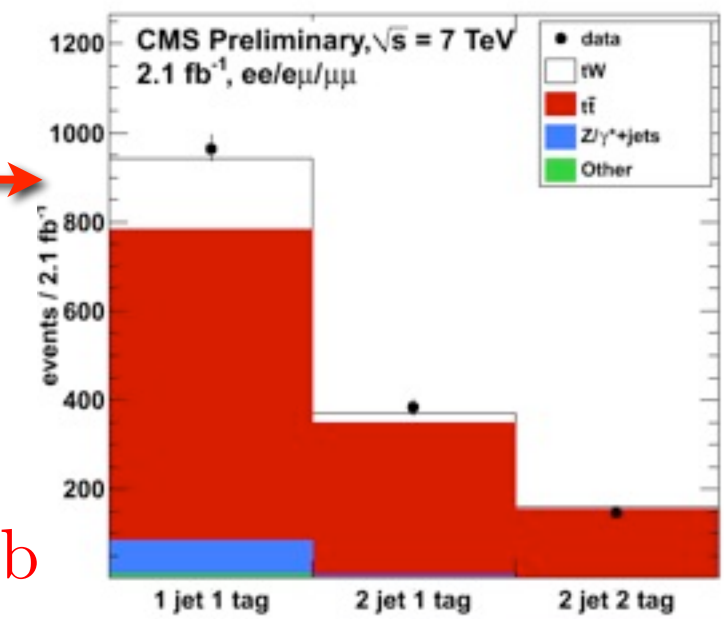
- evidence for t-channel production



expected (observed) 2.9 (3.5) σ

- Wt-channel production
- dilepton final state
- cut & count

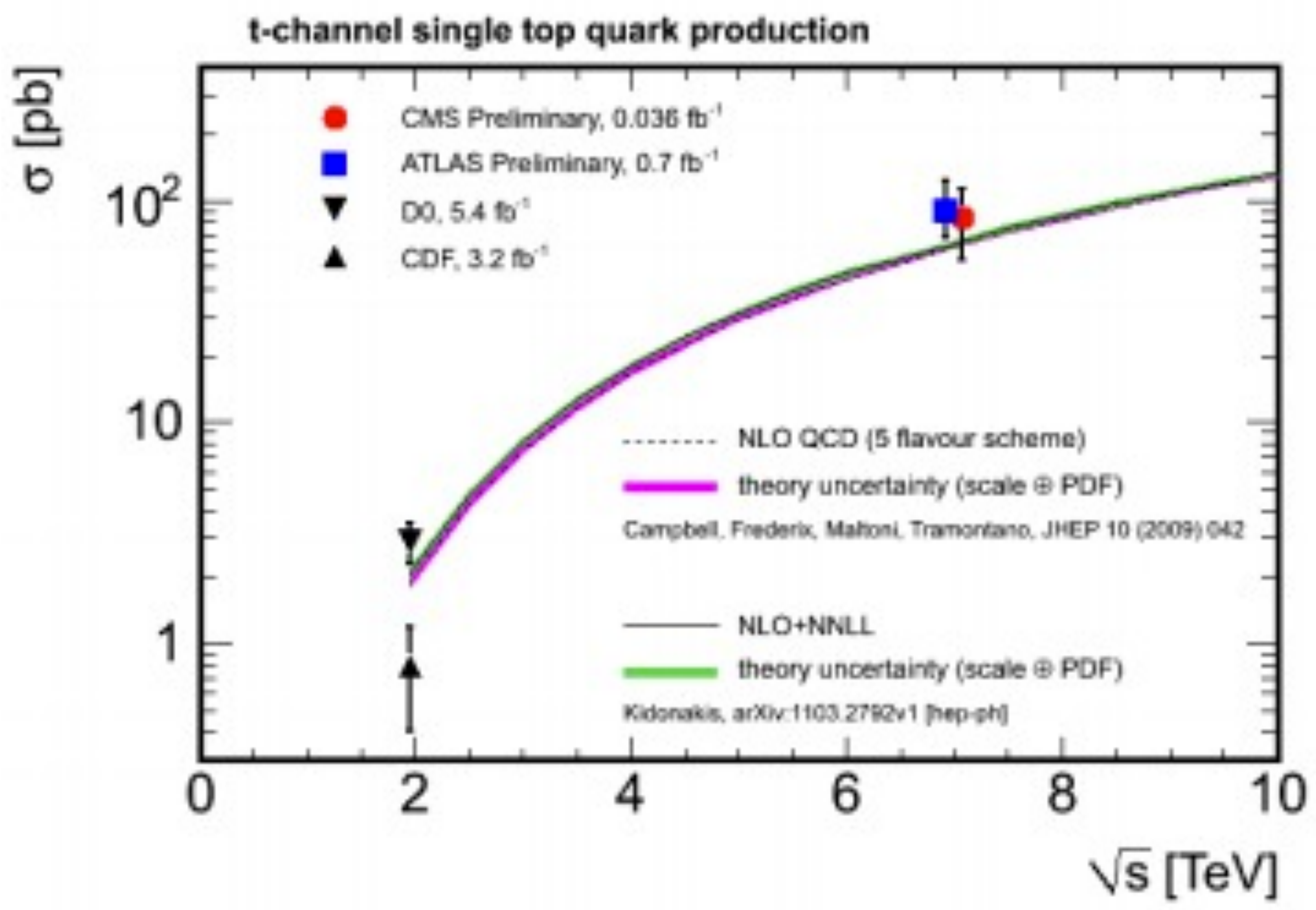
~150 signal events →



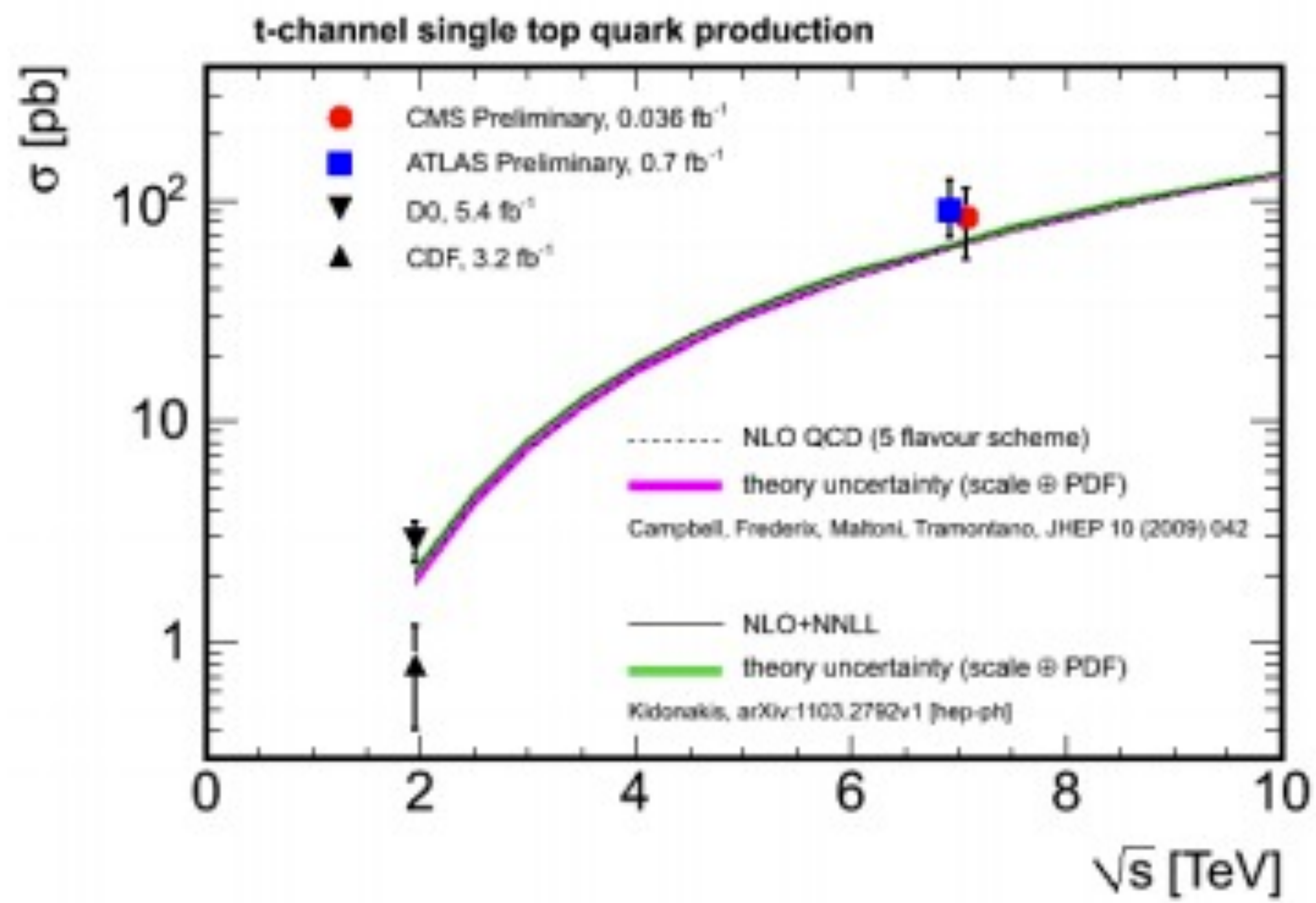
expected (observed)
1.8 (2.7) σ

$$\sigma_{Wt} = 22^{+9}_{-7}(\text{total})\text{pb}$$

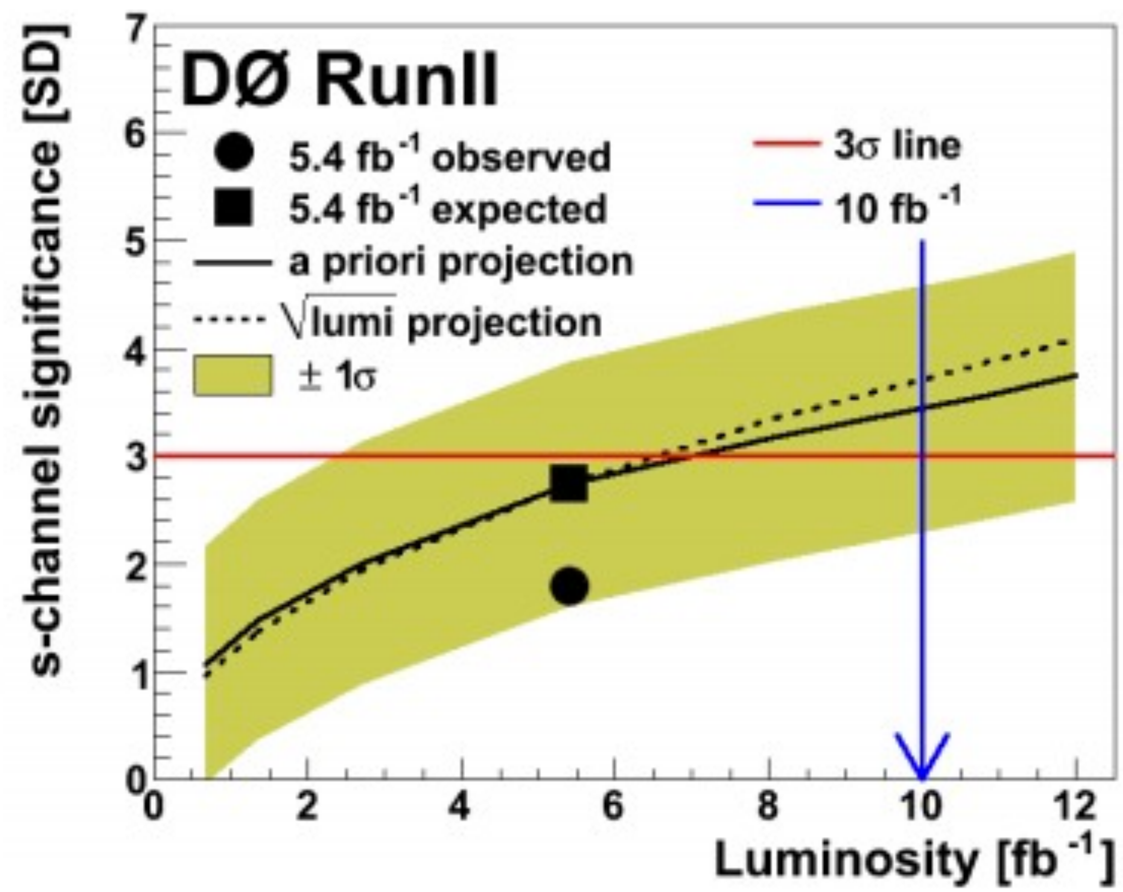
Single top summary and prospects



Single top summary and prospects



- s-channel is very challenging at LHC
- can be one of the Tevatron legacy measurements
- observation is unlikely but evidence is realistic



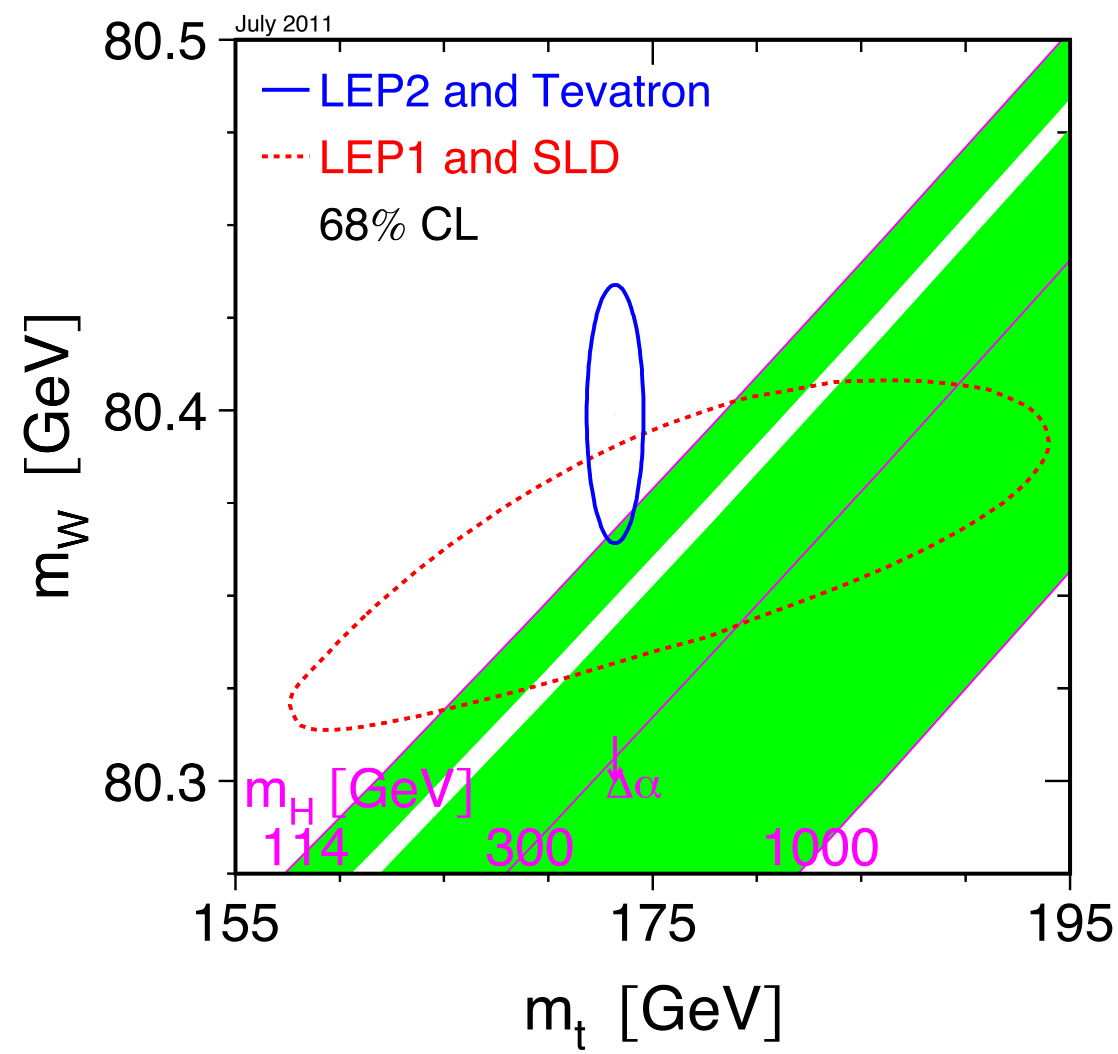
Top quark properties
mass

Top quark mass

- Together with W mass constrains SM Higgs mass
- Provides guideline for SM Higgs searches
- Constraint on Higgs mass can point to physics beyond the SM
- Precise knowledge of top quark mass is essential

$\Delta r_t \sim m_t^2$ $\quad \Delta r_{Higgs} \sim \ln(m_H^2)$

m_{top} = 173.2 ± 0.9 GeV



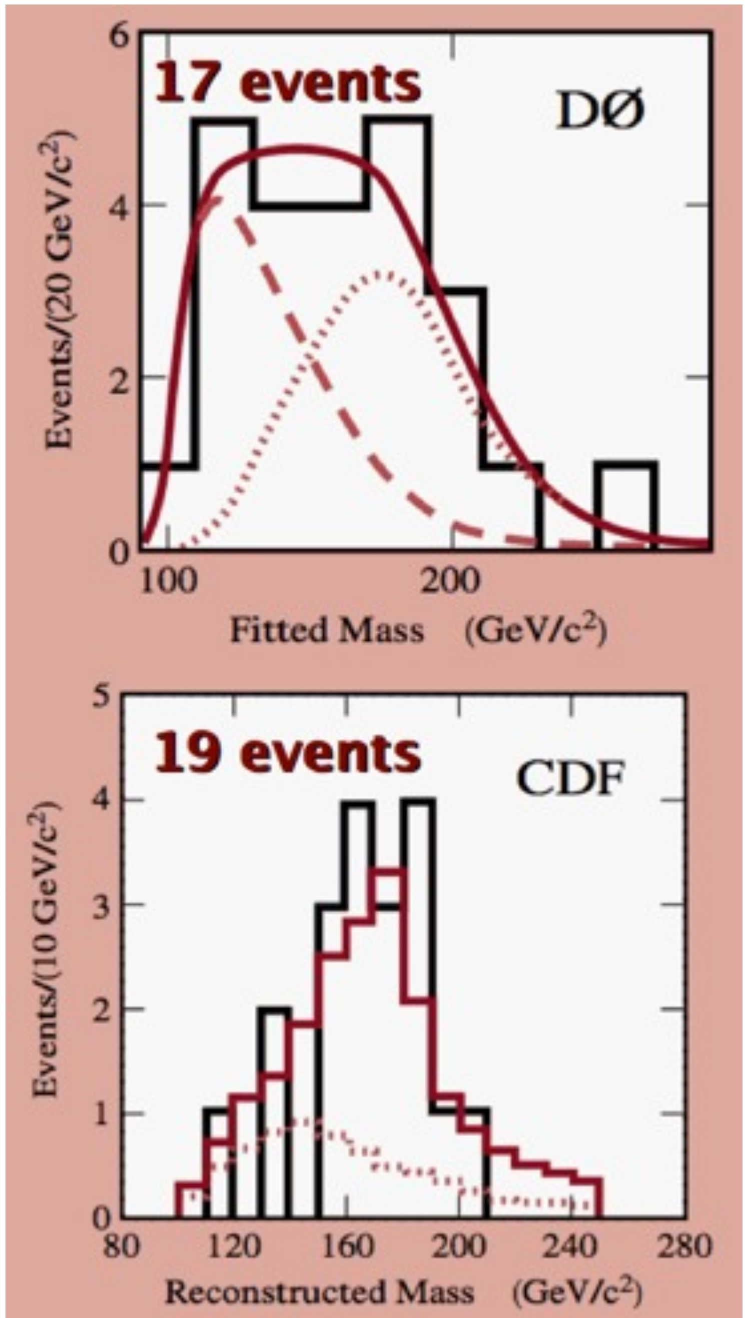
1 GeV change of m_{top} leads to ~10 GeV change of m_{Higgs}

The most precisely known top quark property

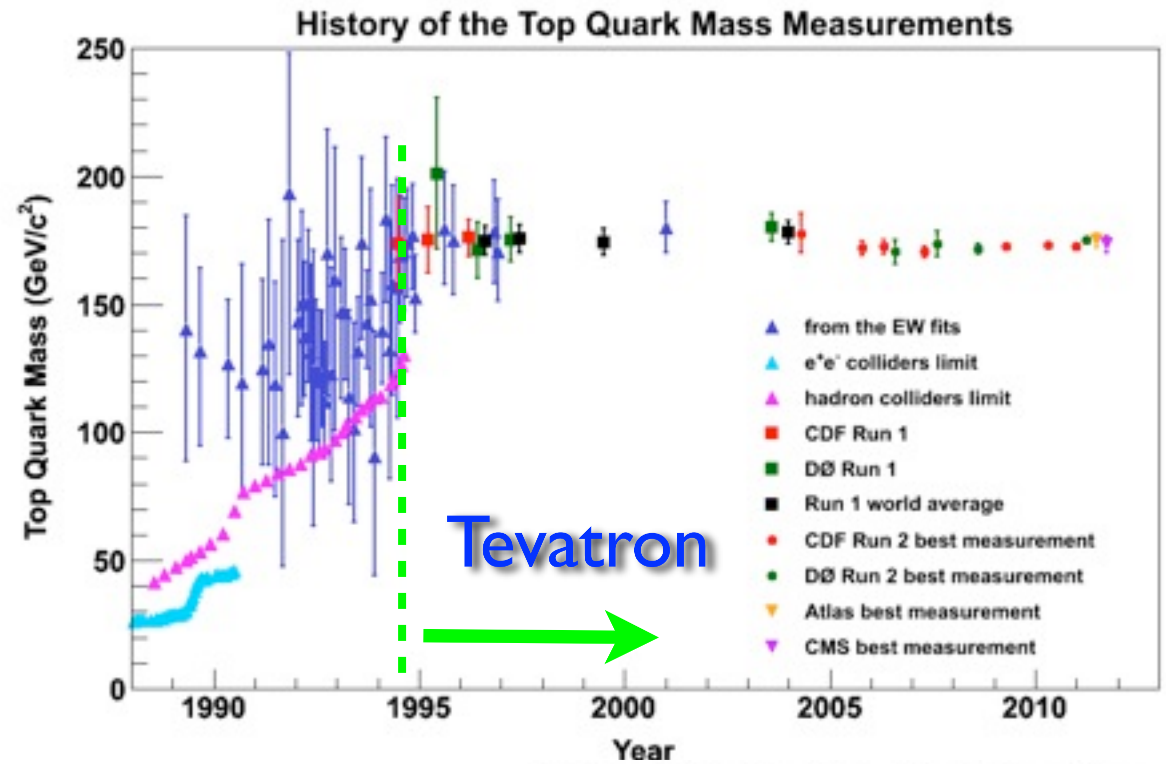
Top mass history

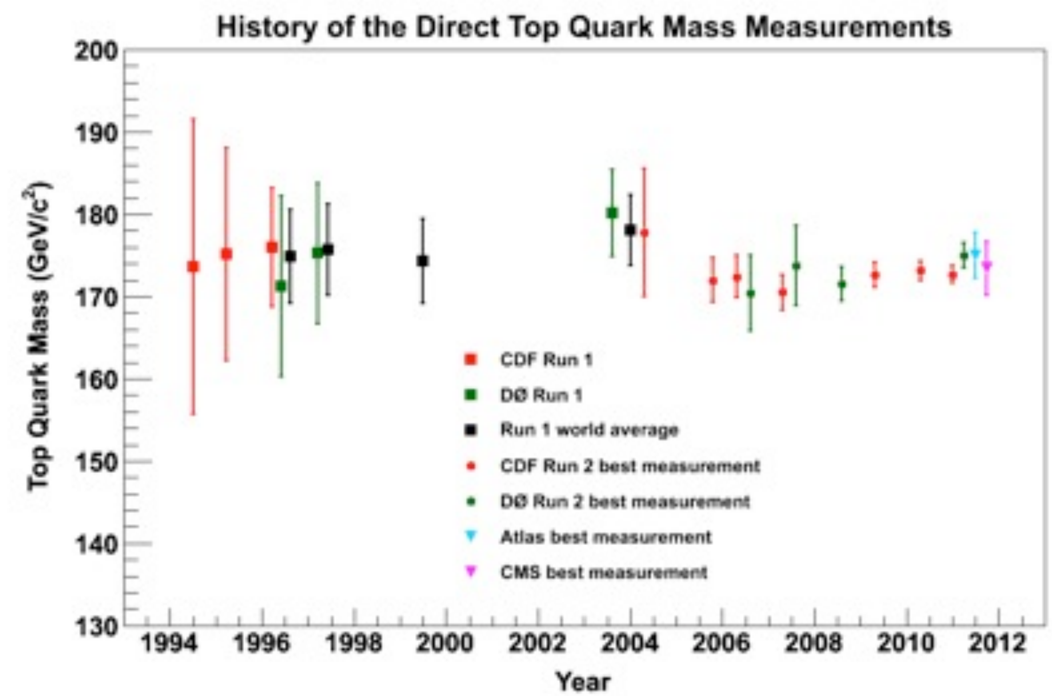
First measurements from the top discovery papers

$199^{+19}_{-21}(\text{stat}) \pm 22(\text{syst})$



$176 \pm 8(\text{stat}) \pm 10(\text{syst})$



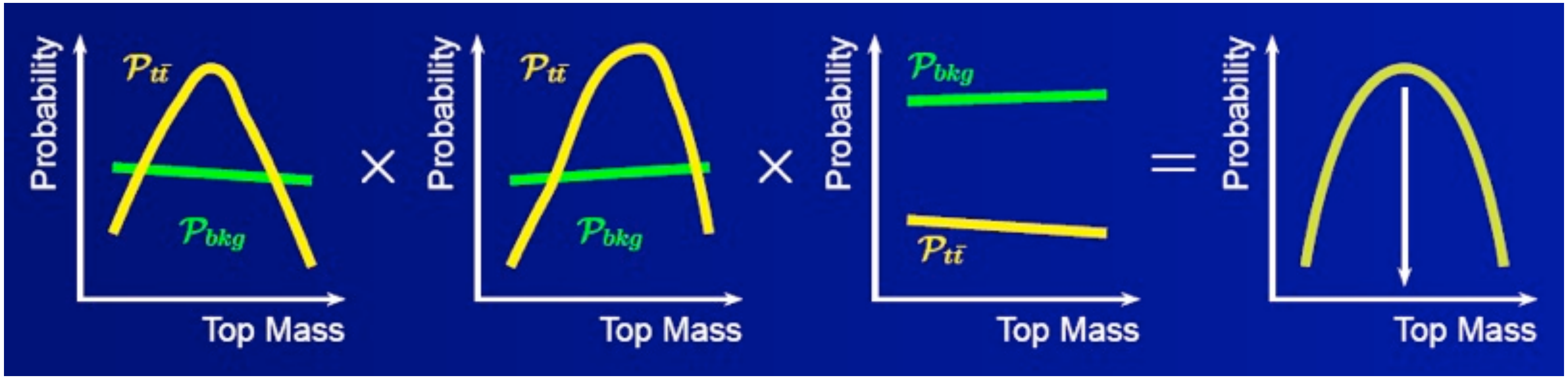


Breakthrough ideas:

- matrix element method
- in-situ JES calibration using hadronic W decay

Matrix element method

- General and widely used technique at Tevatron (top mass, W helicity, single top search, top resonance search)
- First introduced for top quark mass measurement by D0
- Calculate per event probability density for signal and background as a function of m_t using 4-vectors of reconstructed objects $P_{event}(x; m_t, \mathrm{JES}) = f_t P_{t\bar{t}}(x; m_t, \mathrm{JES}) + (1 - f_t) P_{bkg}(x; \mathrm{JES})$
- Probabilities are calculated using differential cross sections of the processes under study: $\sim|M|^2$
- Map reconstructed objects to parton level using Transfer Functions
- Multiply probabilities to extract the most likely mass

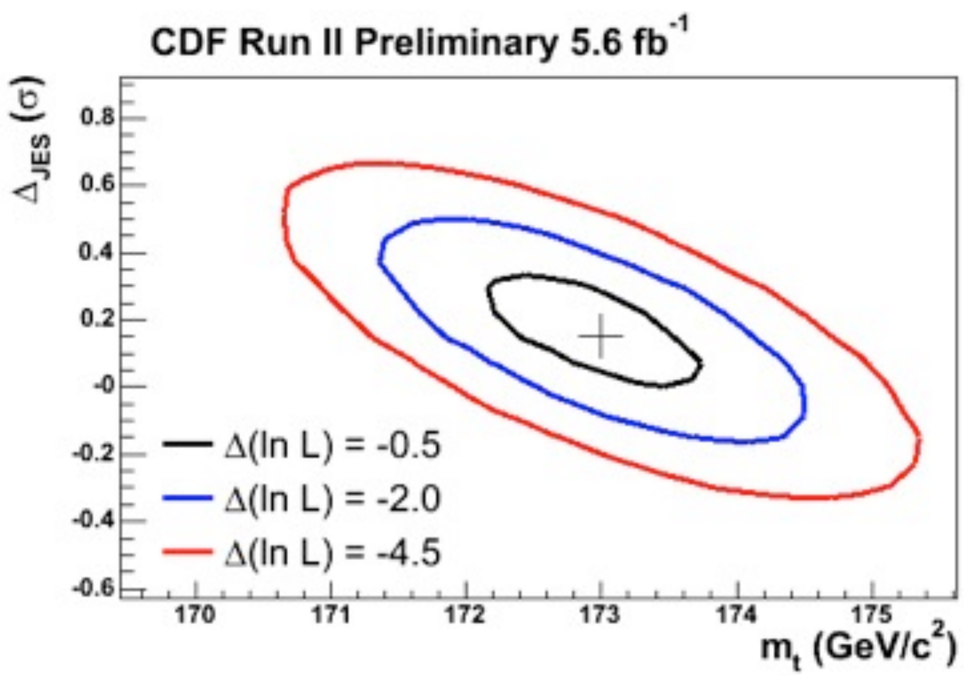


Powerful but computationally very expensive method due to multidimensional integration

ME results: l+jets

- The most precise measurement
  - ME includes $gg \to t\bar{t}$ and $q\bar{q} \to t\bar{t}$ as well as spin correlations
  - Angular TFs in addition to momentum TFs - 19 integrations
  - TFs derived for light and b-jets in several eta regions
  - no explicit evaluation of background probability

PRL 105:0252001,2010



$\Delta_{JES} = 0.15 \pm 0.18\ \sigma$ **$\Delta m_t / m_t \sim 0.7\%$**

$m_t = 173.0 \pm 0.9$ (stat+JES) ± 0.9 (syst) GeV

ME results: l+jets

The most precise measurement

- ME includes $gg \rightarrow t\bar{t}$ and $q\bar{q} \rightarrow t\bar{t}$ as well as spin correlations
- Angular TFs in addition to momentum TFs - 19 integrations
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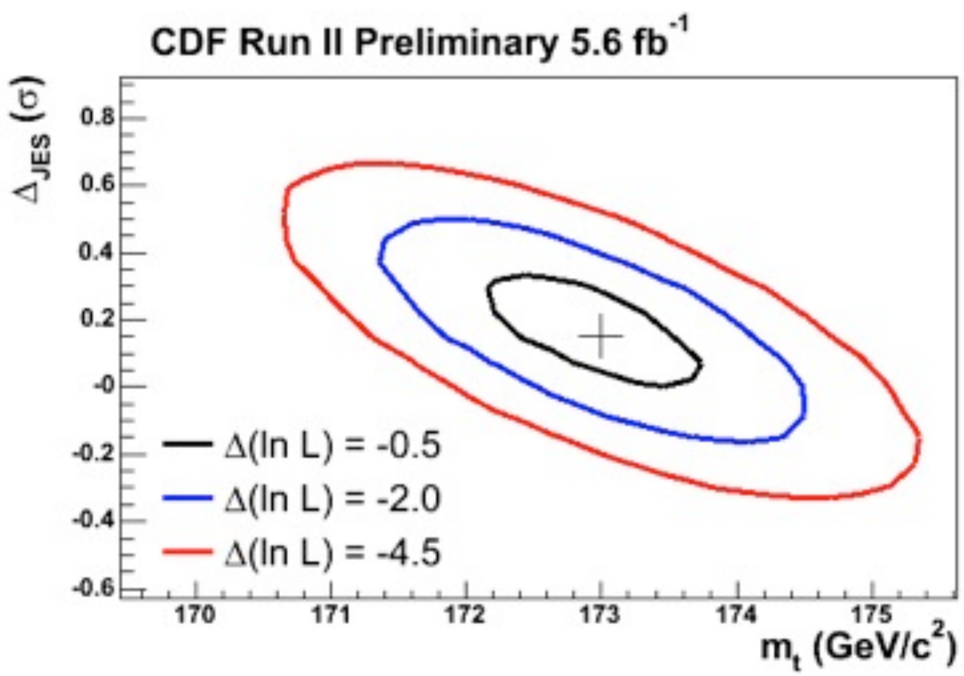


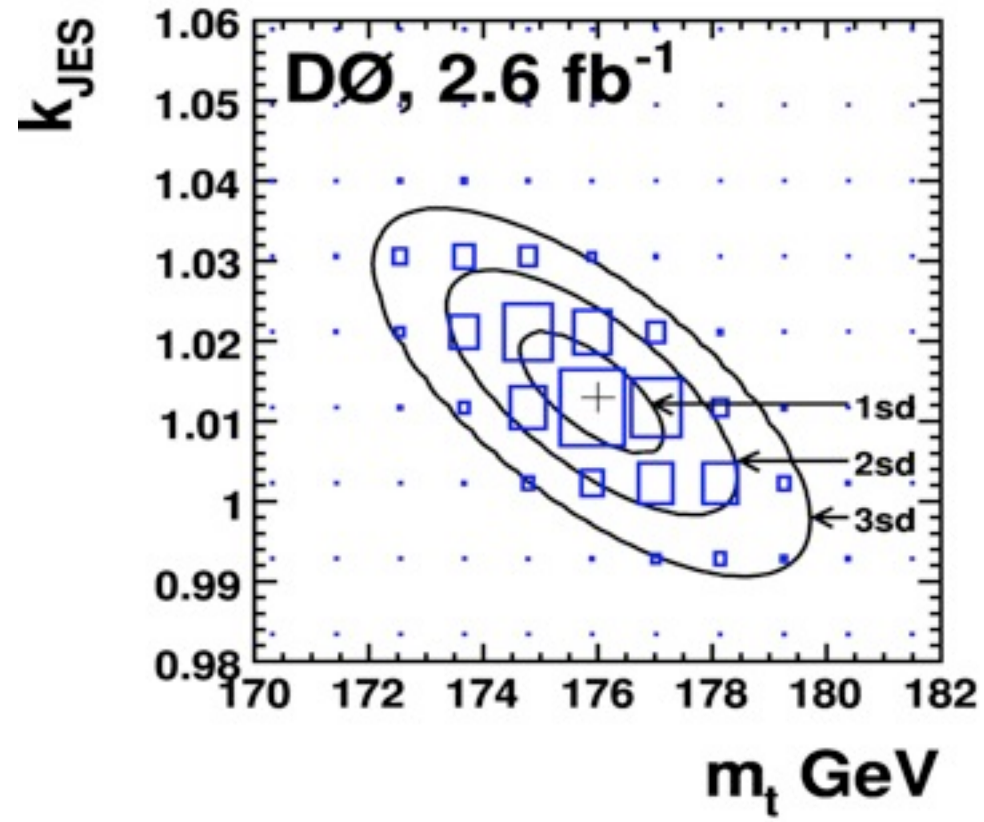
$\Delta_{JES} = 0.15 \pm 0.18\ \sigma$ $\Delta m_t / m_t \sim 0.7\%$

$m_t = 173.0 \pm 0.9\ \text{(stat+JES)} \pm 0.9\ \text{(syst) GeV}$

ME in D0

- only $q\bar{q} \rightarrow t\bar{t}$
- separate ME for background
- no angular TFs - 10 integrations

Phys.Rev.D84:032004,2011



$k_{JES} = 1.013 \pm 0.008\ \sigma$

$\Delta m_t / m_t \sim 0.85\%$ 3.6 fb^{-1}

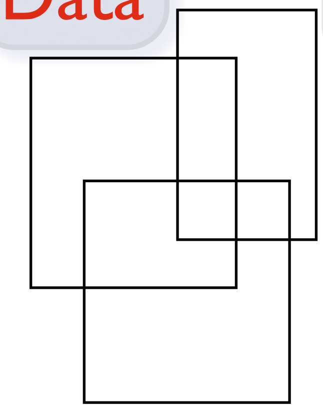
$m_t = 174.94 \pm 0.83\text{(stat)} \pm 0.78\text{(JES)} \pm 0.96\text{(syst) GeV}$

Template method

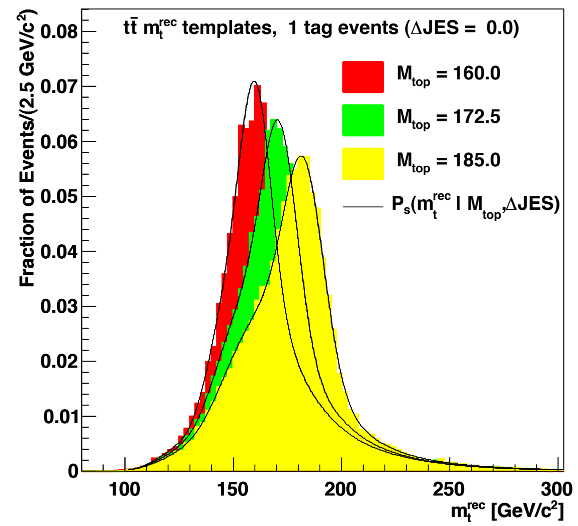
Data

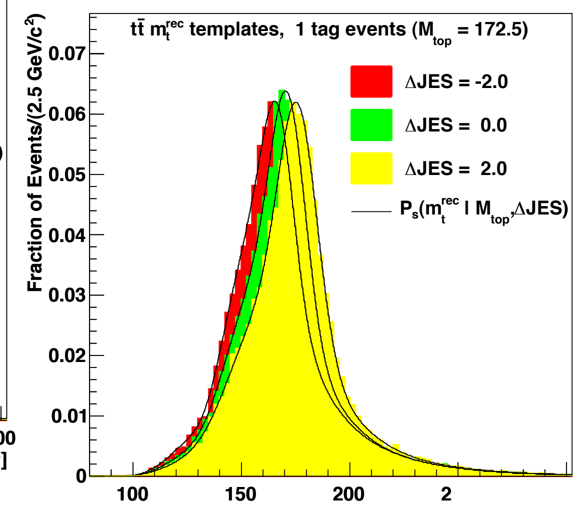
Bg

tt MC



Kinematic fit

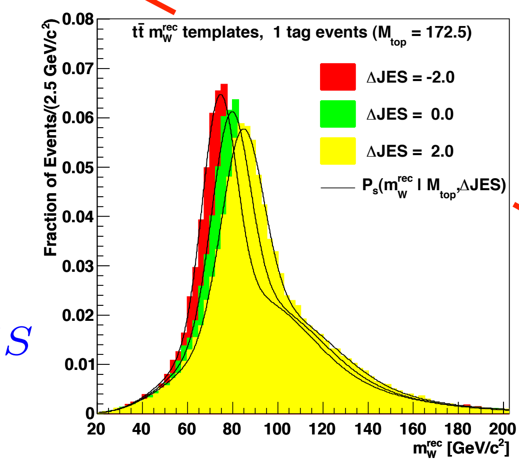




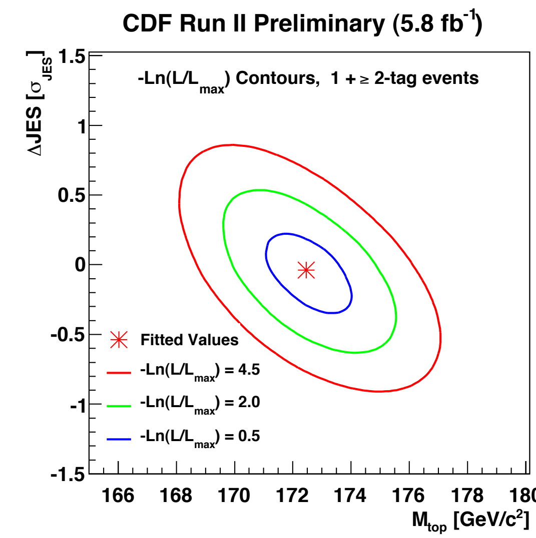
reconstructed top mass from χ^2 fit

reconstructed W mass from χ^2 fit

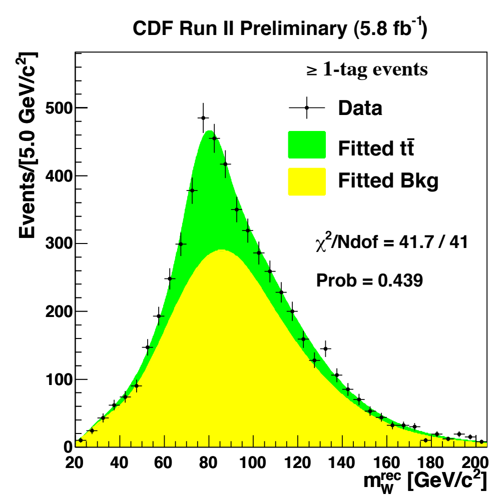
$$JES = 1 + \Delta_{JES} \cdot \sigma_{JES}$$

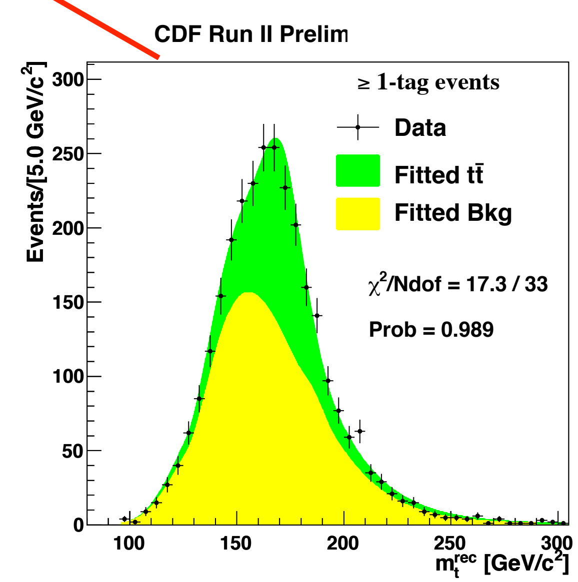


Likelihood fit



- choose one or more observables sensitive to true m_t
- generate MC based templates at different m_t (and ΔJES) values
- determine most likely top mass by comparing data to templates
- heavily relies on MC



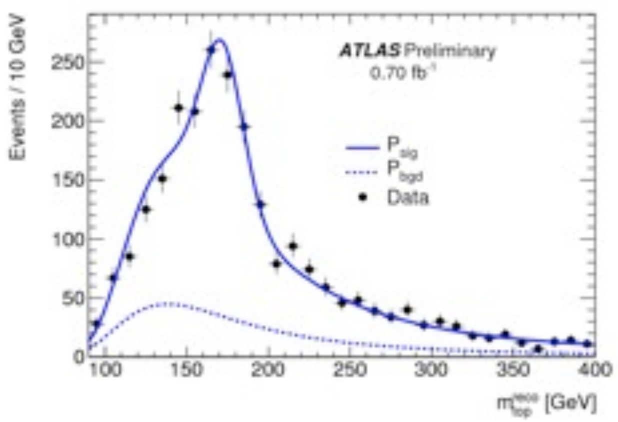


result

Mass at LHC: lepton+jets

templates method

2D fit to reconstructed hadronic top mass and JES



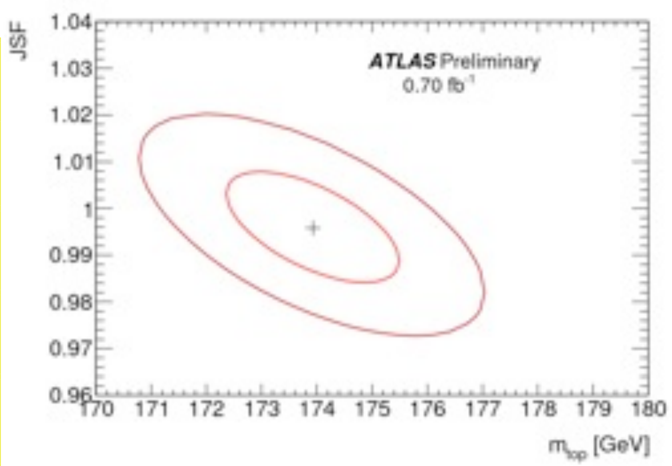
0.7 fb^{-1}

at least 1 b-tag

4720 reconstructed top events

muon+jets:

JES (stat)	0.7
JES (res)	0.8
bJES	1.7
ISR/FSR	0.7
CR	0.9
signal model	1.2



μ+jets:

m_t = 175.9 ± 1.0 (stat) ± 2.7 (syst) GeV

e+jets:

m_t = 173.9 ± 1.2 (stat) ± 3.1 (syst) GeV

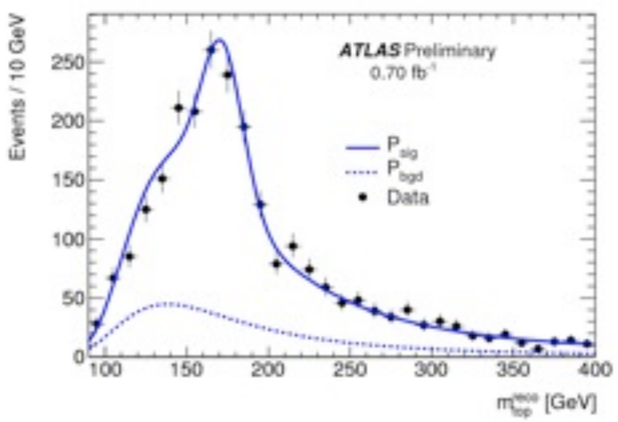
combined 2010/2011 (ATLAS-CONF-2011-120)

m_t = 175.9 ± 0.9 (stat) ± 2.7 (syst) GeV

Mass at LHC: lepton+jets

templates method

2D fit to reconstructed hadronic top mass and JES



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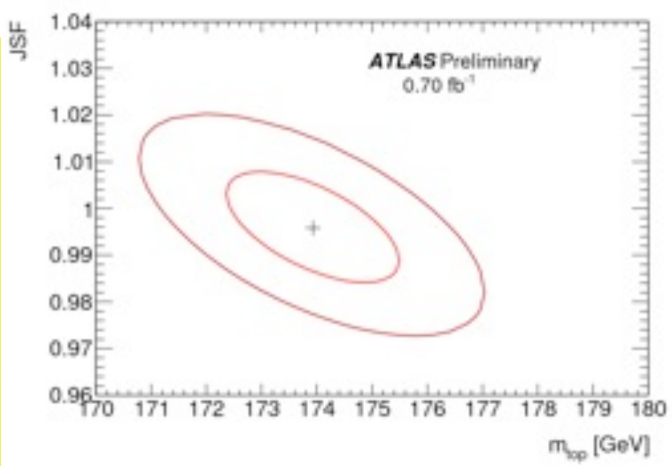


μ+jets:

m_t = 175.9 ± 1.0 (stat) ± 2.7 (syst) GeV

e+jets:

m_t = 173.9 ± 1.2 (stat) ± 3.1 (syst) GeV

combined 2010/2011 (ATLAS-CONF-2011-120)

m_t = 175.9 ± 0.9 (stat) ± 2.7 (syst) GeV

ideogram technique

- ~380 top events
- Simplified version of D0 analysis - JES is not included in the fit
  - Take advantage of already small JES uncertainties
- Scaling stat uncertainty to 0.7 fb^{-1} luminosity: 0.5 GeV

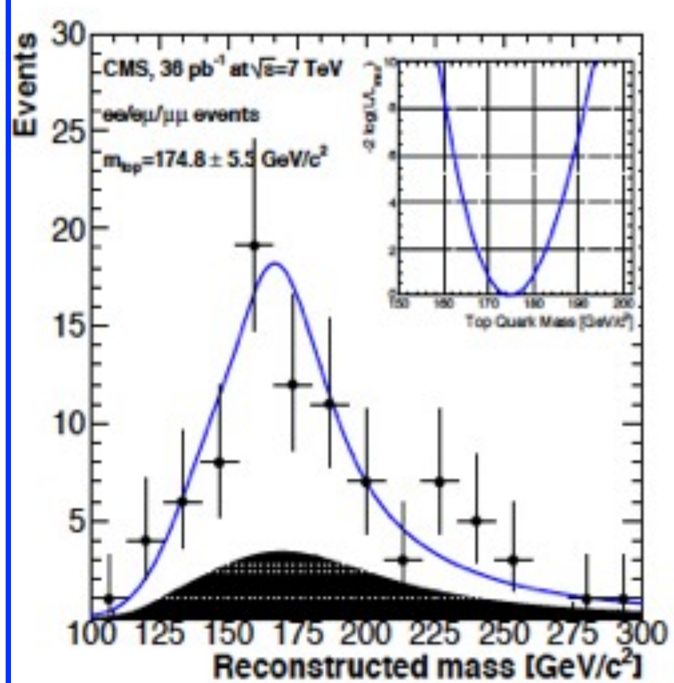
Source	Ideogram analysis δm_t (GeV)
JES (overall data/MC)	+2.4-2.1
JER (10% effect)	0.07
MET (10% effect)	0.4
Factorization scale	1.1
ME-PS matching threshold	0.4
ISR/FSR	0.2
Underlying event	0.2
Pile-up effect	0.1
PDF	0.1
Background	0.5
B-tagging	0.05
Fit calibration statistics	0.1
Total systematic uncertainty	+2.8- 2.5

m_t = 173.1 ± 2.1(stat) ± 2.5(syst) GeV

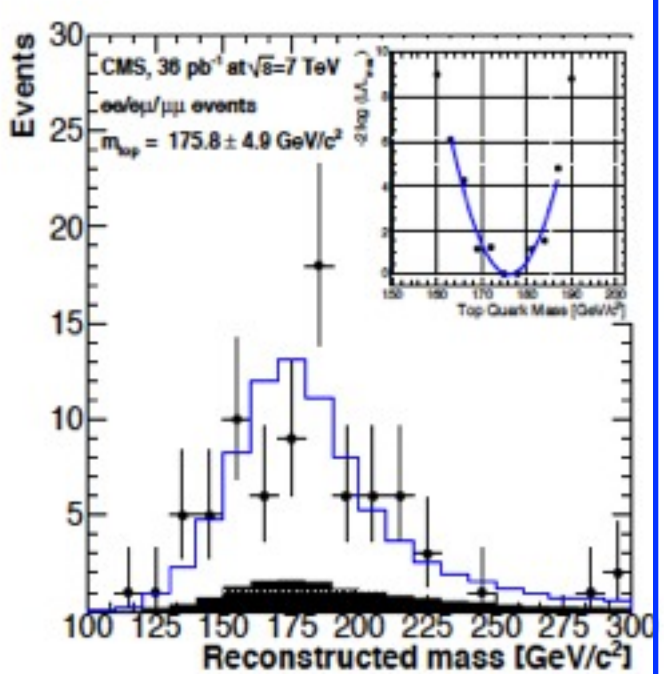
Dilepton channel

- Template technique
- 36 pb^{-1} ~90 top events
- MWT and KINb top reconstruction methods
- 57% statistical correlation

KINb



AMWT

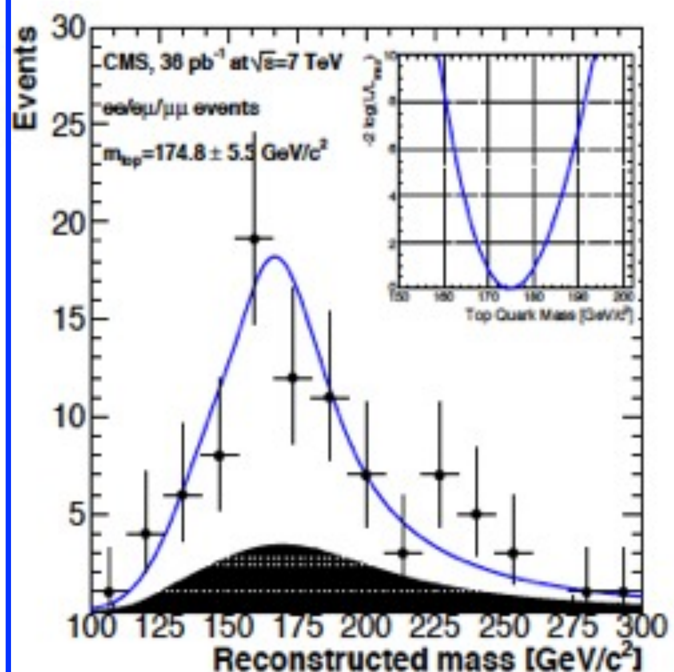


combined: m_t = 175.5 ± 4.6 (stat) ± 4.6 (syst) GeV

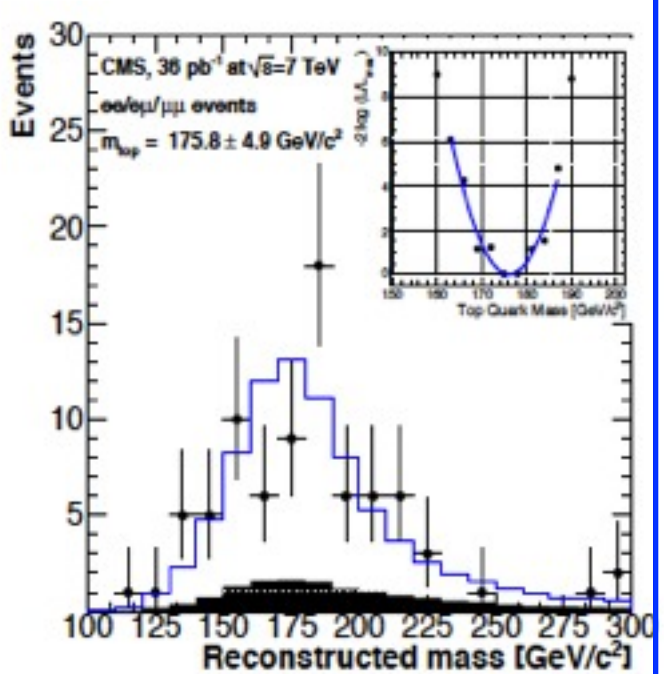
Dilepton channel

- Template technique
- 36 pb^{-1} ~90 top events
- MWT and KINb top reconstruction methods
- 57% statistical correlation

KINb



AMWT



combined: m_t = 175.5 ± 4.6 (stat) ± 4.6 (syst) GeV

- Matrix element technique
- 5.4 fb^{-1}, ~360 top events
- ME for background - Z+2jets
- TFs for jet energies and muon $1/p_T$
- $6+n_\mu$ integrations

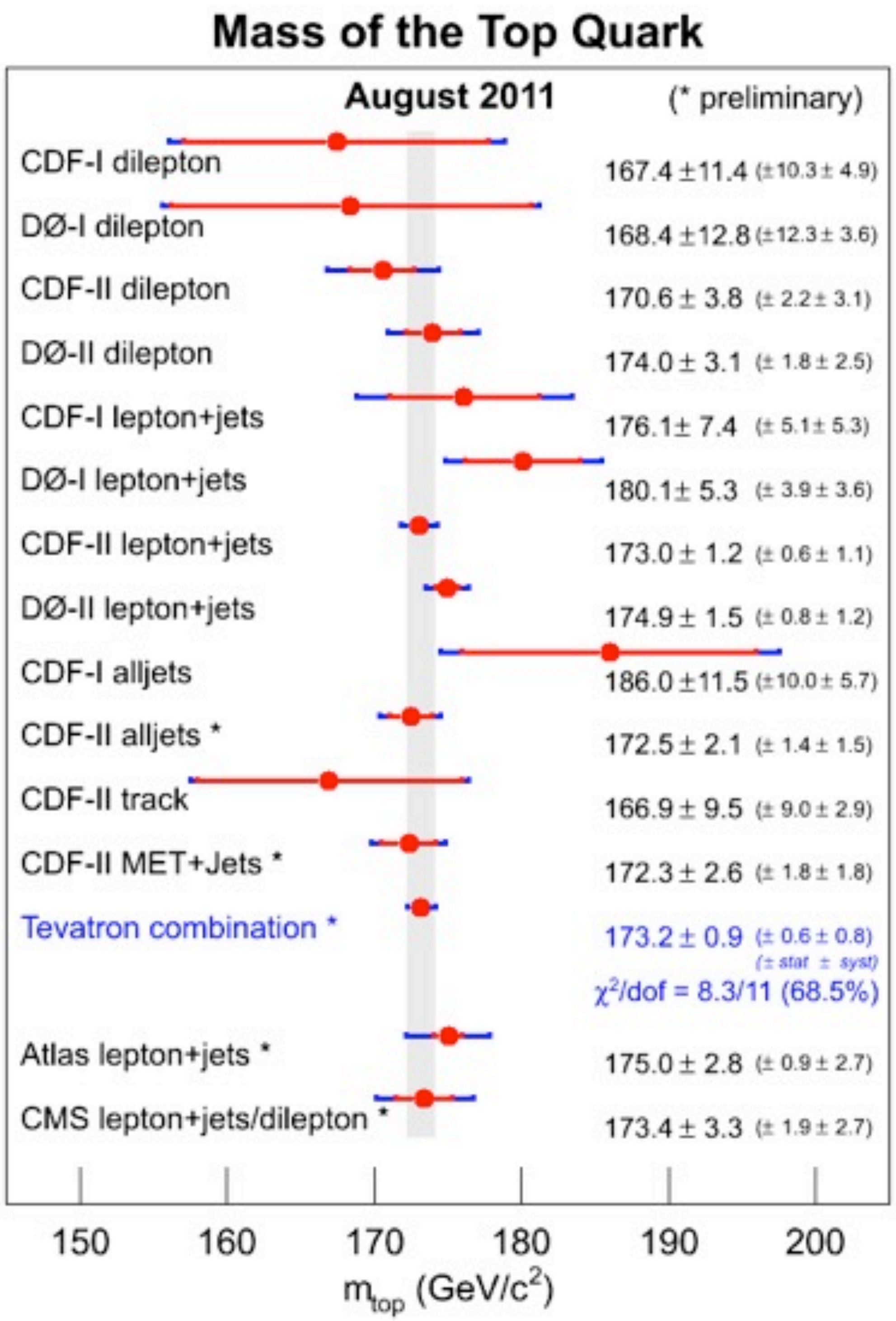
Source	Uncertainty (GeV)
Detector modeling:	
b/light jet response	±1.6
JES	±1.5
Jet resolution	±0.3
Muon resolution	±0.2
Electron p_T scale	±0.4
Muon p_T scale	±0.2
ISR/FSR	±0.2
Signal modeling:	
Higher order and hadronization	±0.7
Color reconnection	±0.1
b-quark modeling	±0.4
PDF uncertainty	±0.1
Method:	
MC calibration	±0.1
Signal fraction	±0.5
Total	±2.4

2.2 GeV

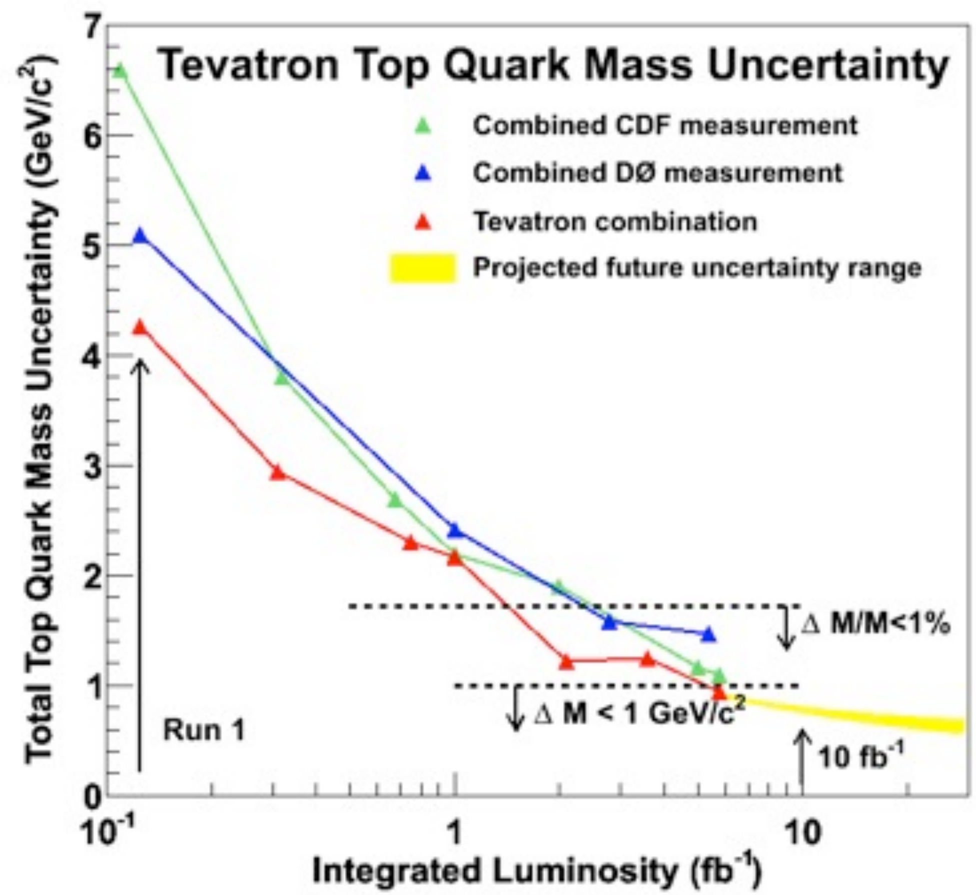
m_t = 174.0 ± 1.8 (stat) ± 2.4 (syst) GeV

The most precise measurement

Top mass summary and prospects



m_t =173.18 ± 0.56 (stat) ±0.76 (syst) GeV
= 173.2 ± 0.9 GeV ±0.54%



- Each Tevatron experiment will achieve uncertainty of 0.9 -1.0 GeV with 10 fb^{-1}
- Tevatron combination: ~0.7 - 0.8 GeV
- Expect significant improvement of LHC results
  - simultaneous mass and JES measurement
  - more sophisticated techniques
  - CMS-ATLAS combination

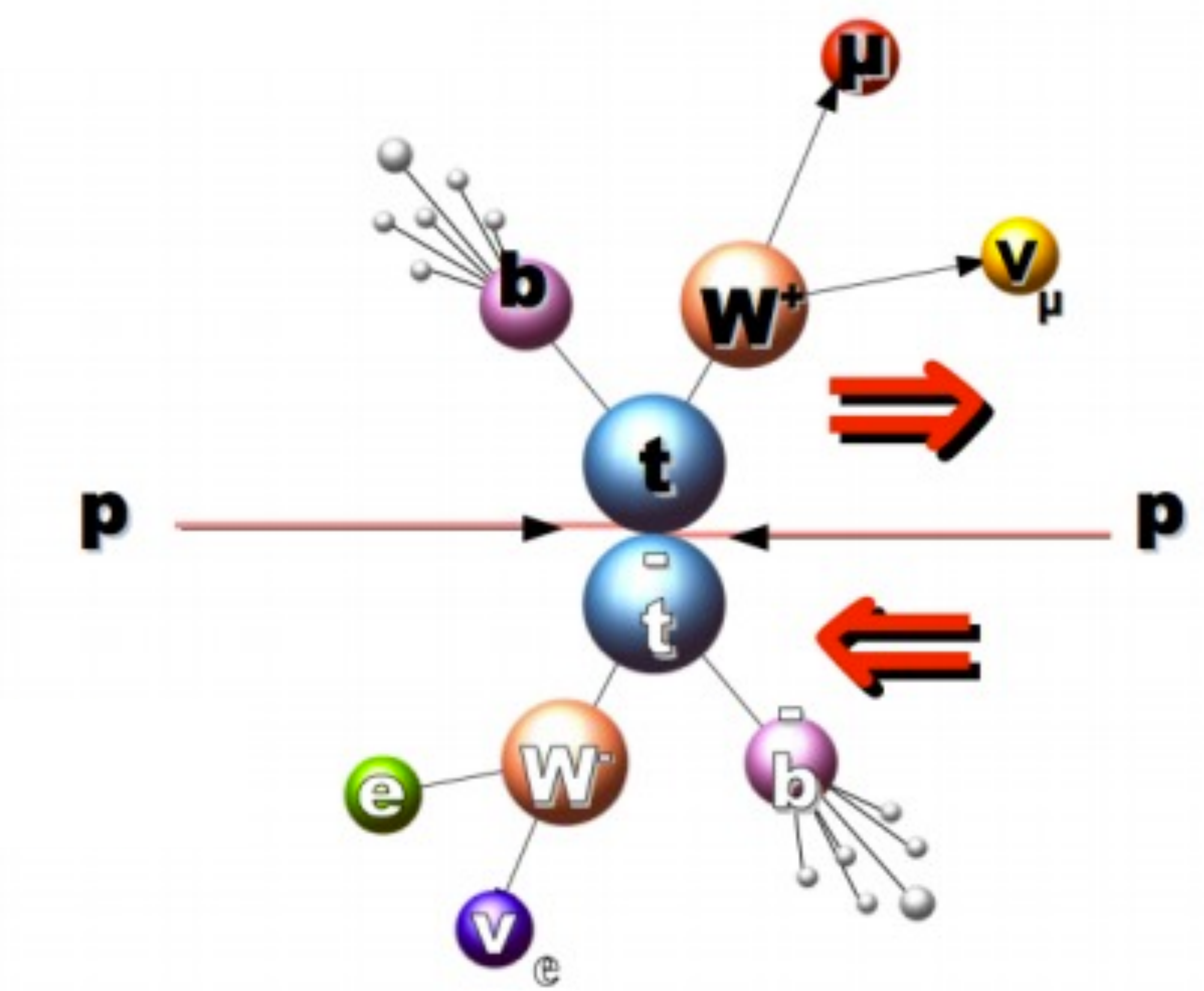
Top quark properties

spin correlations

Spin correlations

- short lifetime
- decay before the spin can flip
- flight directions of top decay products carry information about top polarization at production

- top pairs: top quarks are not polarized but spin of top and anti-top are correlated

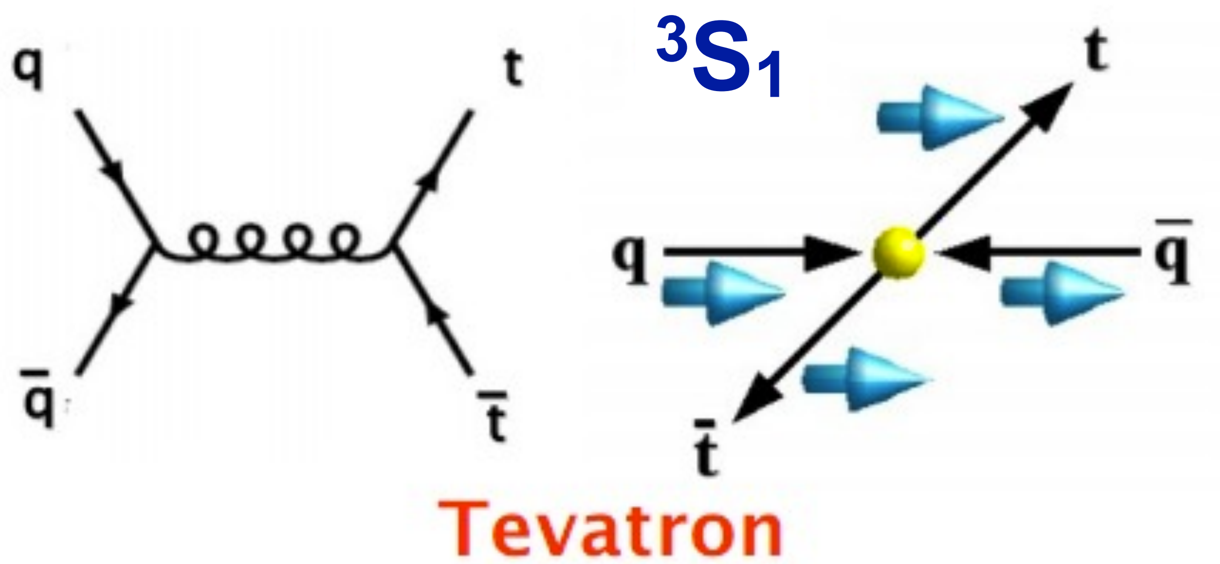


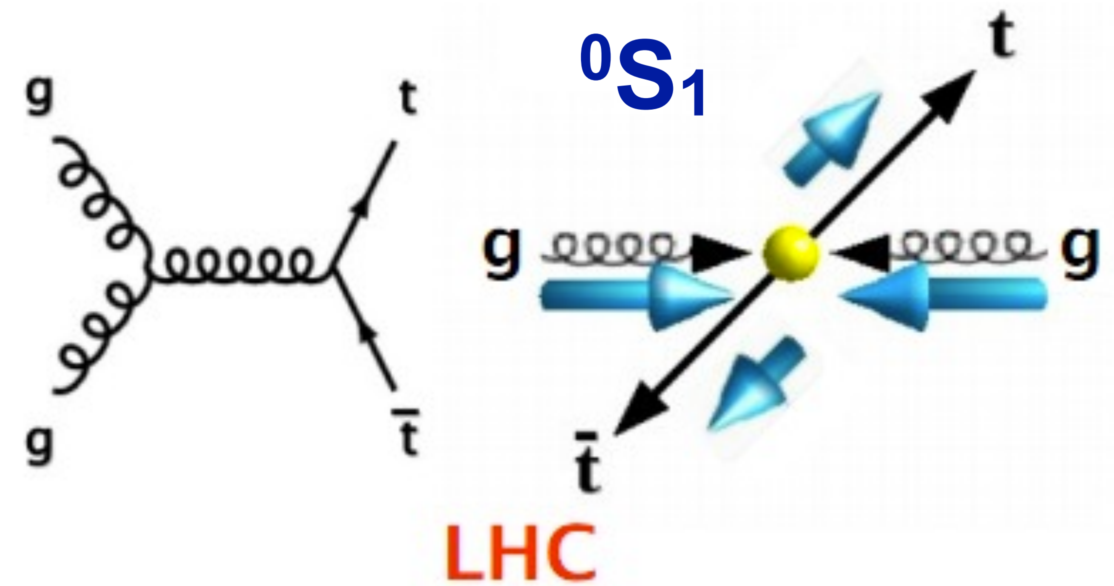
$t\bar{t}$ spin correlation: is it consistent with SM prediction for a spin 1/2 particle?

Spin correlation strength

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

Strength depends on spin quantization axis





- dominated by $q\bar{q}$ annihilation
- pair production close to threshold
- beam axis as spin quantization axis NLO QCD:A=0.78

- dominated by gg
- pair production far off the threshold
- helicity basis as spin quantization axis NLO QCD:A=0.32

Bernreuther, Brandenburg, Si, Uwer, Nucl. Phys. B690, 81 (2004)

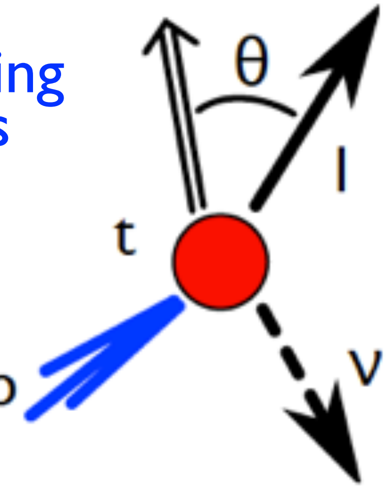
Tevatron and LHC are complimentary!

Spin correlations: template method

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

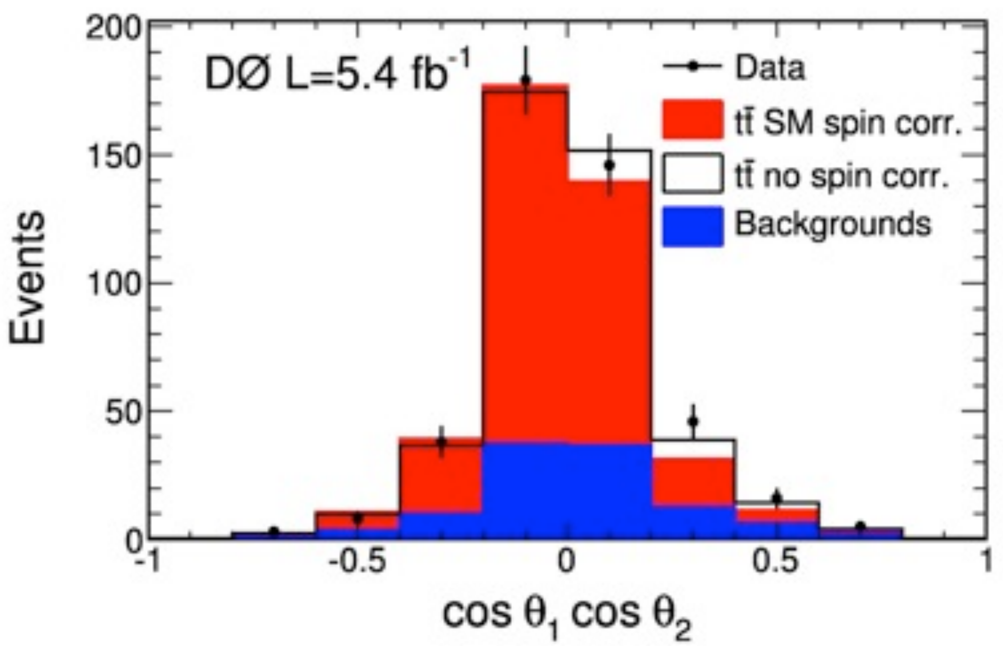
$$\text{where } C = A\alpha_1\alpha_2$$

spin analyzing basis



A - correlation strength at production
α_1=1 (charged lepton), α_2=−0.41(b-quark)

Dilepton channel

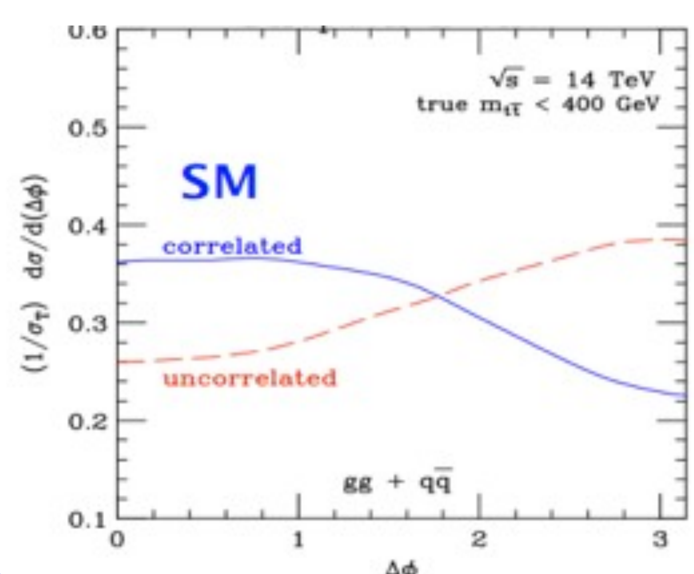


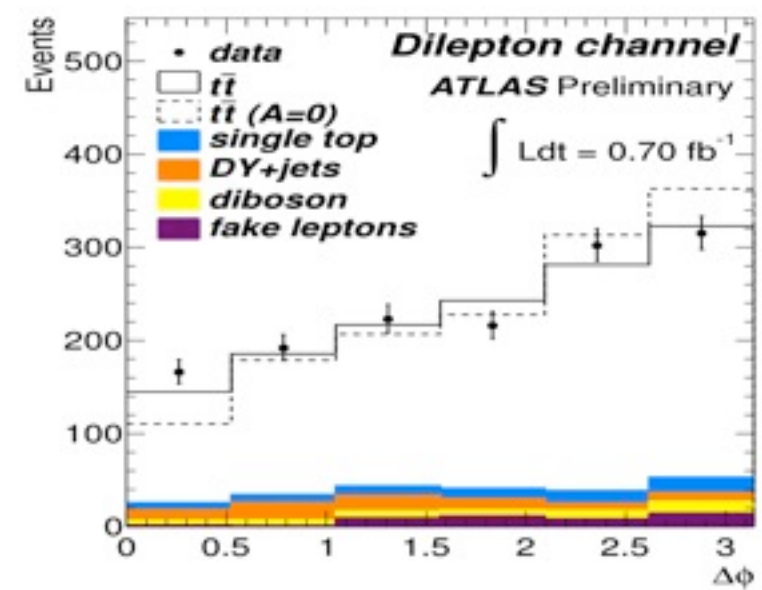
template method with dilepton event reconstruction

A = 0.10 ± 0.45 (stat+sys)

- avoid complicated event reconstruction
- use azimutal angle between charged leptons in lab frame

Mahlon, Parke, PRD D81, 074024 (2010)





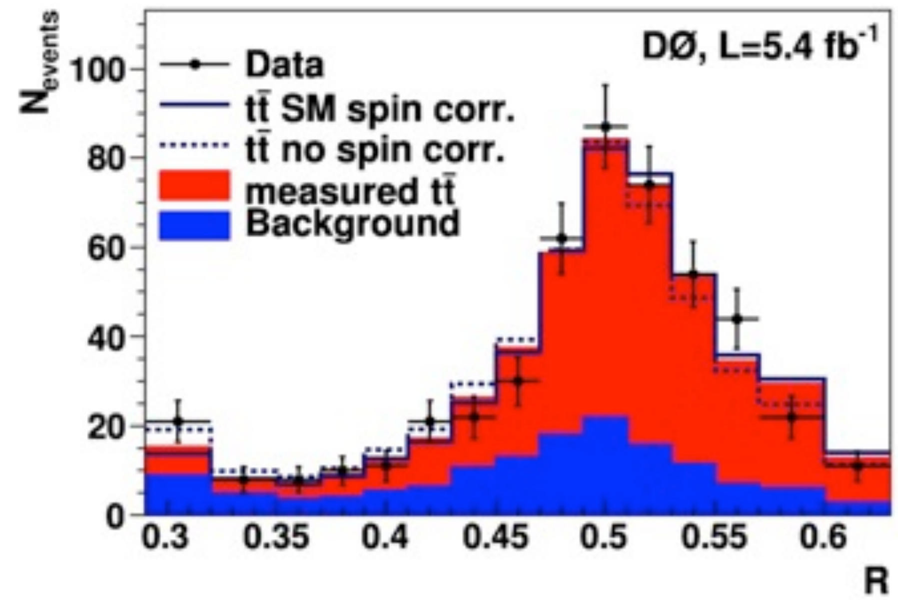
$$f_{SM} = 1.06^{+0.46}_{-0.34}$$

Spin correlations: ME method

- spin correlation is defined only for a set of particles
- ME provides per event probability
- construct a discriminating variable

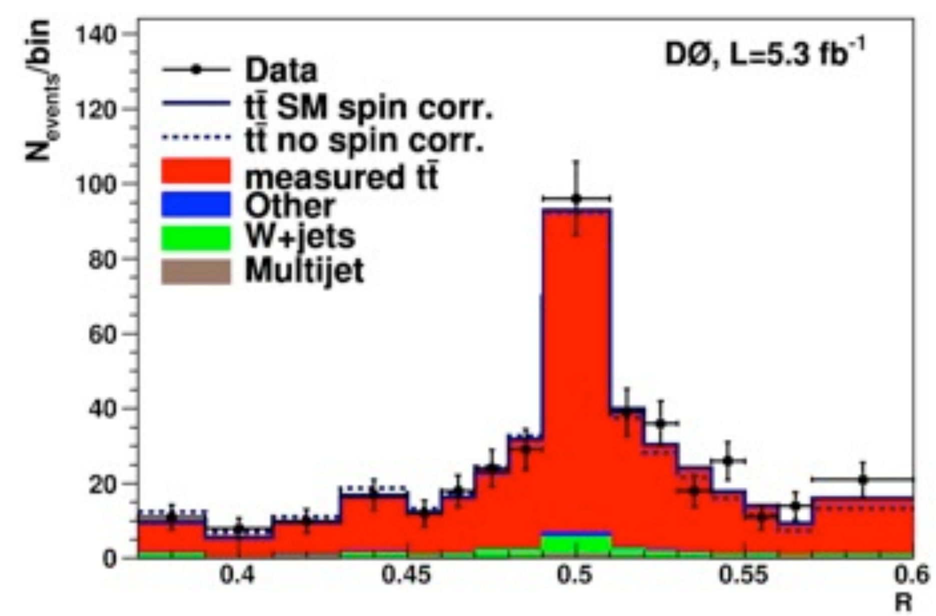
$$R(x) = \frac{P_{t\bar{t}}(x, H=1)}{P_{t\bar{t}}(x, H=0) + P_{t\bar{t}}(x, H=1)}$$

- build templates in R
- extract fraction of events with SM spin correlation
- >30% improvement of sensitivity



dilepton channel

A = 0.57 ± 0.31 (stat+sys)



l+jets channel ≥2 b-tags

A = 0.89 ± 0.33 (stat+sys)

Combination

f_{meas} = 0.85 ± 0.29 (stat+syst)

f(0)<0.05 @ 99.7% CL

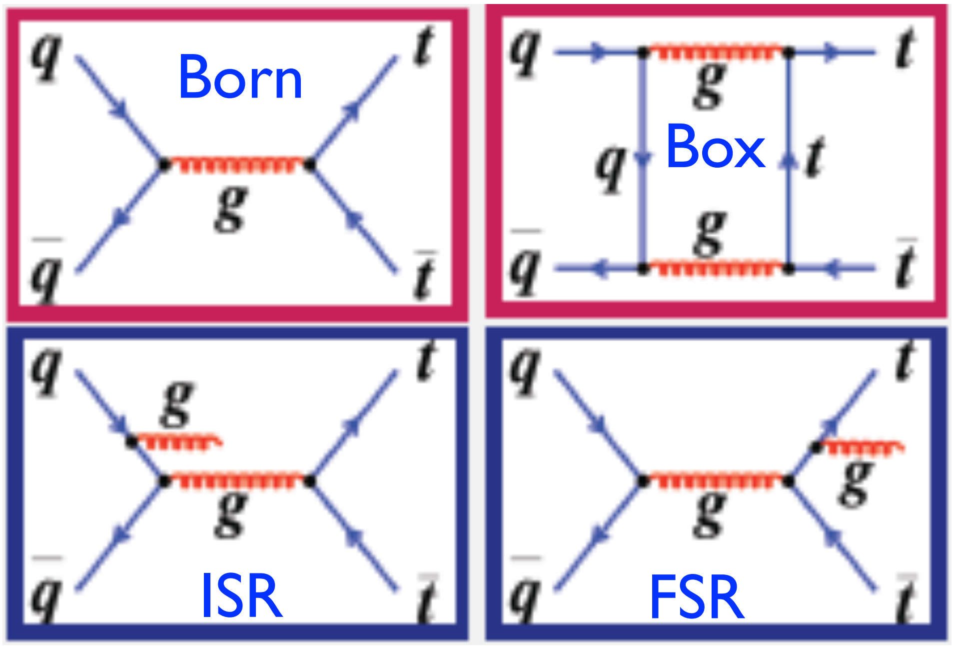
First evidence for presence of correlations @ 3.1σ

Top quark properties

forward-backward and charge asymmetry

Forward-backward asymmetry

- NLO: asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state
  - top quarks are emitted preferably in the direction of incoming quark, anti-tops - in the direction of incoming anti-quark
  - in SM predicted asymmetry is small
  - exchange of new particles (Z‘ or axigluon) could modify it



NLO: A_{fb} ~ 5%
with EW A_{fb}
increased by 9%

Forward-backward asymmetry

- NLO: asymmetry for $t\bar{t}$ produced via $q\bar{q}$ initial state
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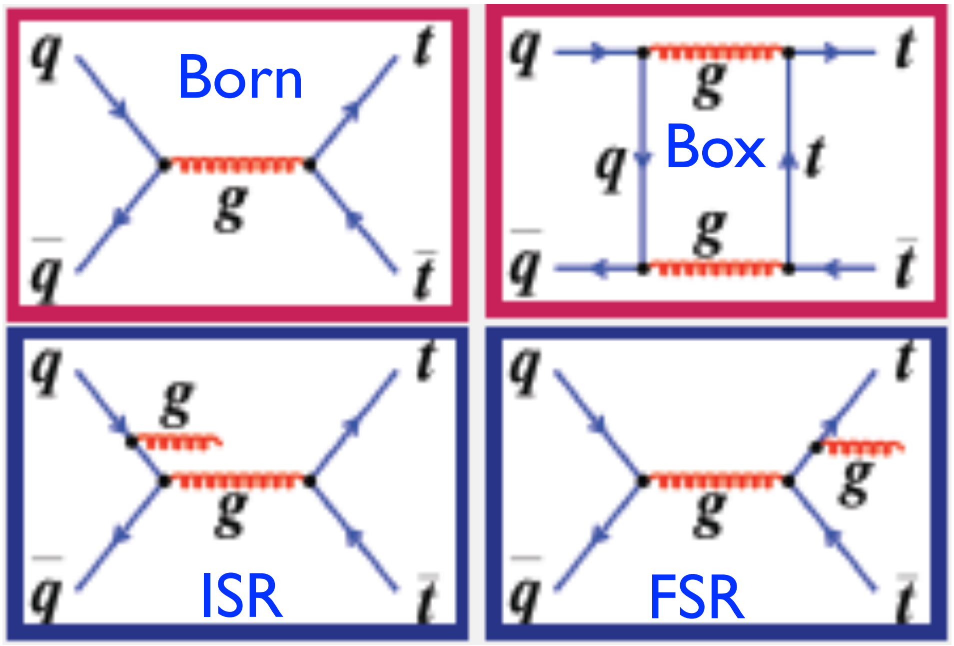

NLO: A_{fb} ~ 5%
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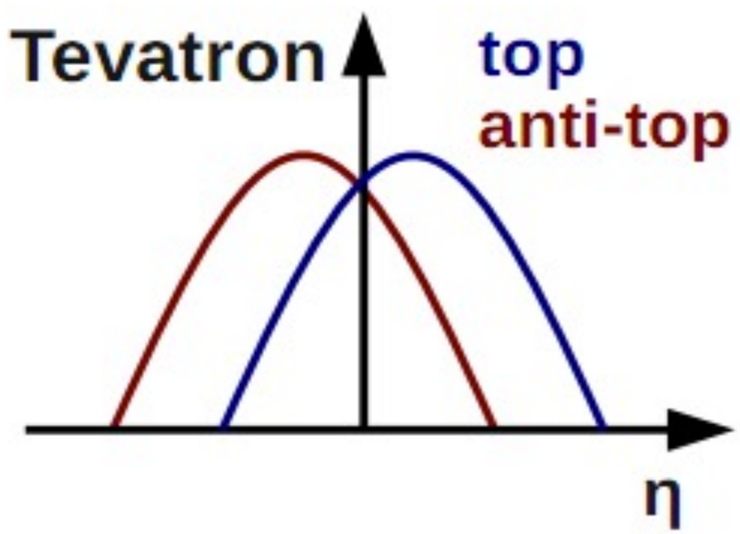
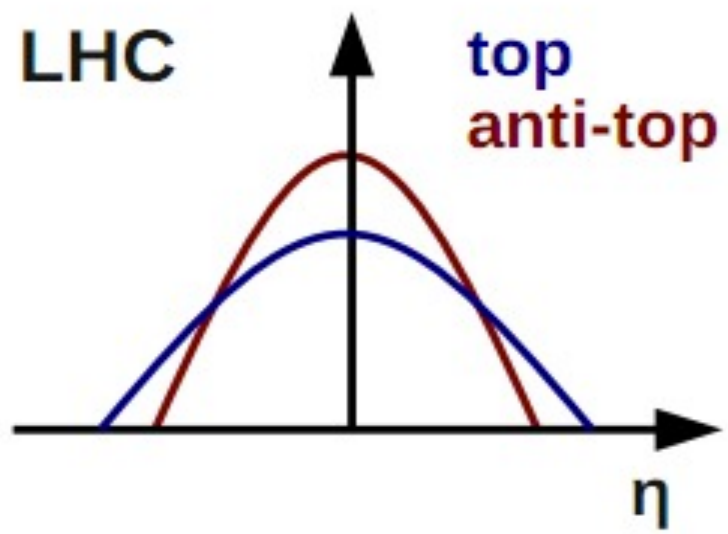


forward-backward asymmetry
= charge asymmetry



central-forward asymmetry

proton PDF: larger momenta of quarks than anti-quarks

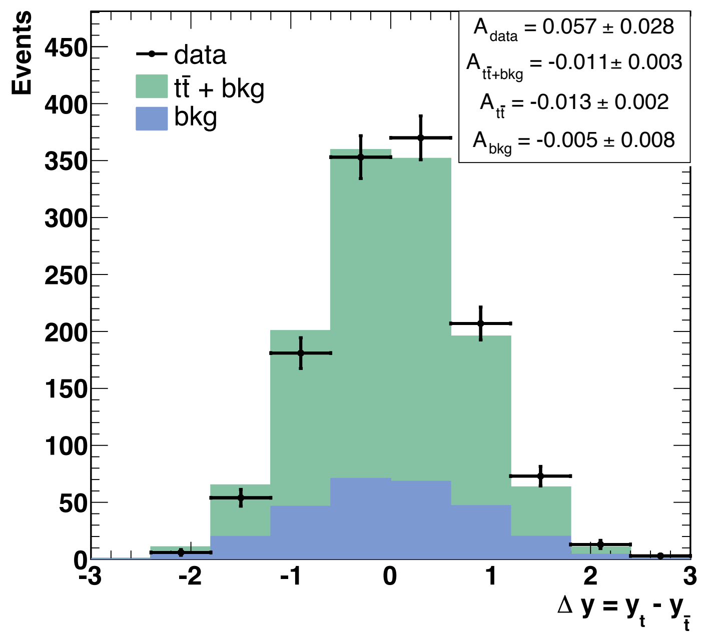
much smaller effect at LHC due to small $q\bar{q}$ fraction

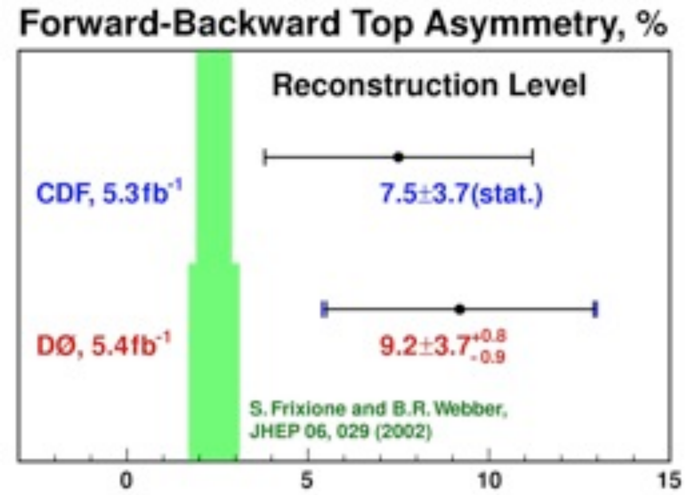
Charge asymmetry at Tevatron

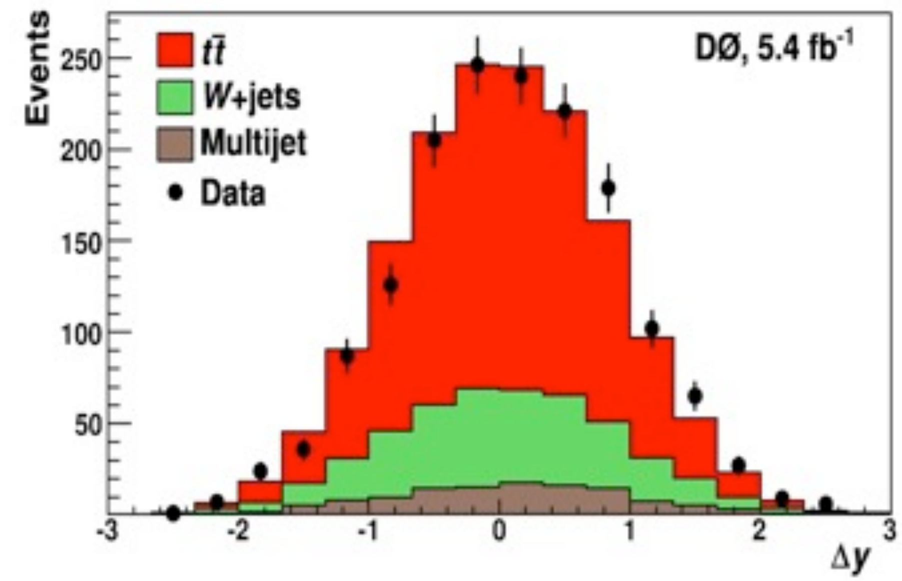
lepton+jets channel

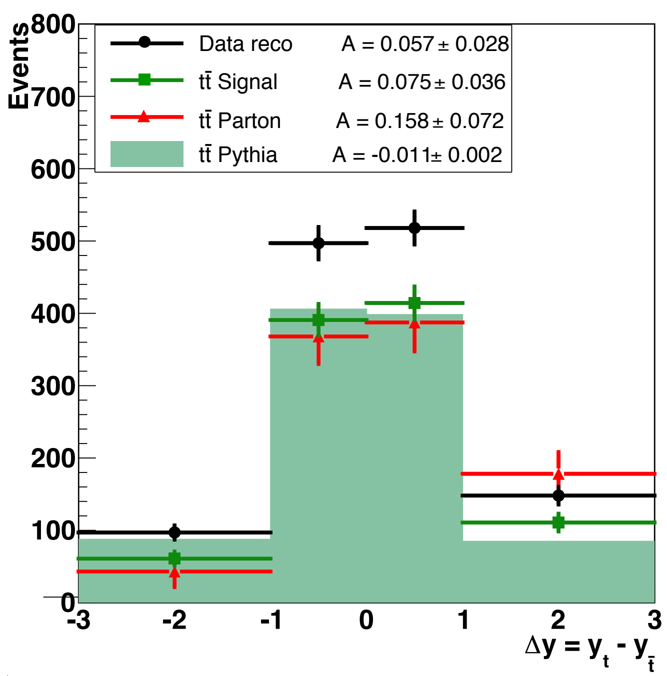
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

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

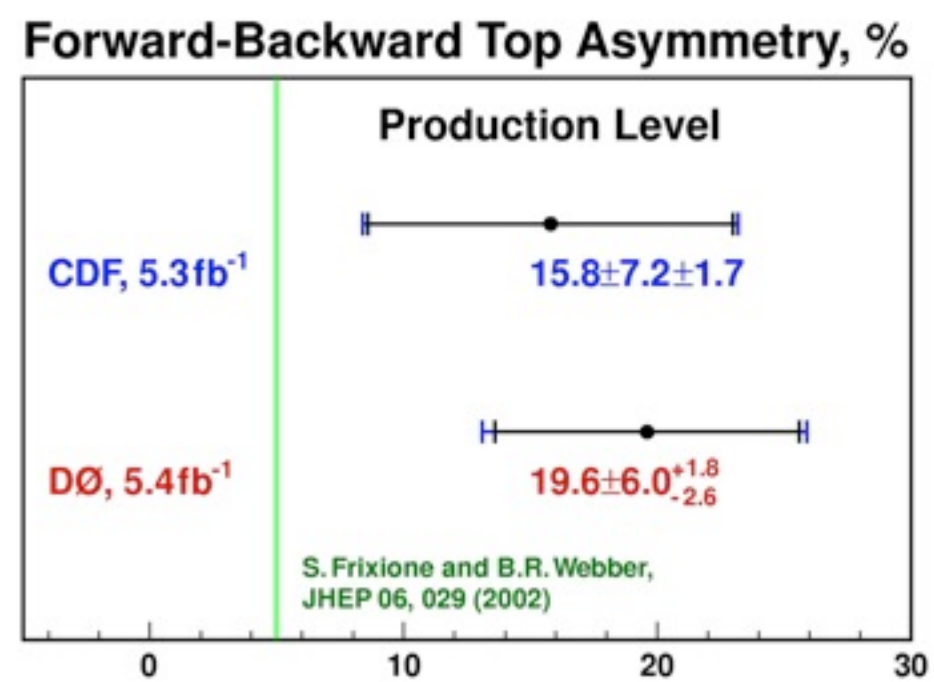






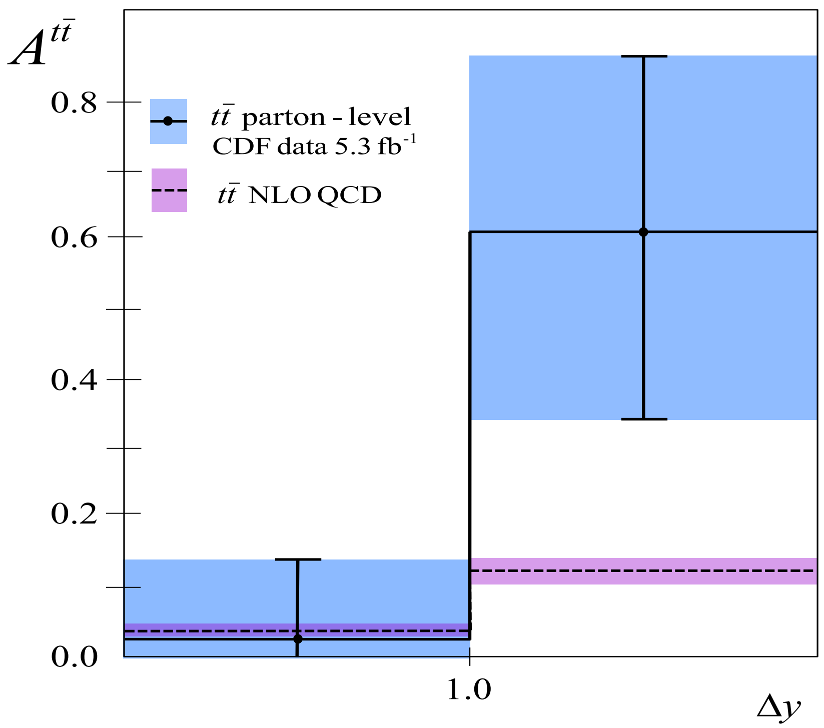


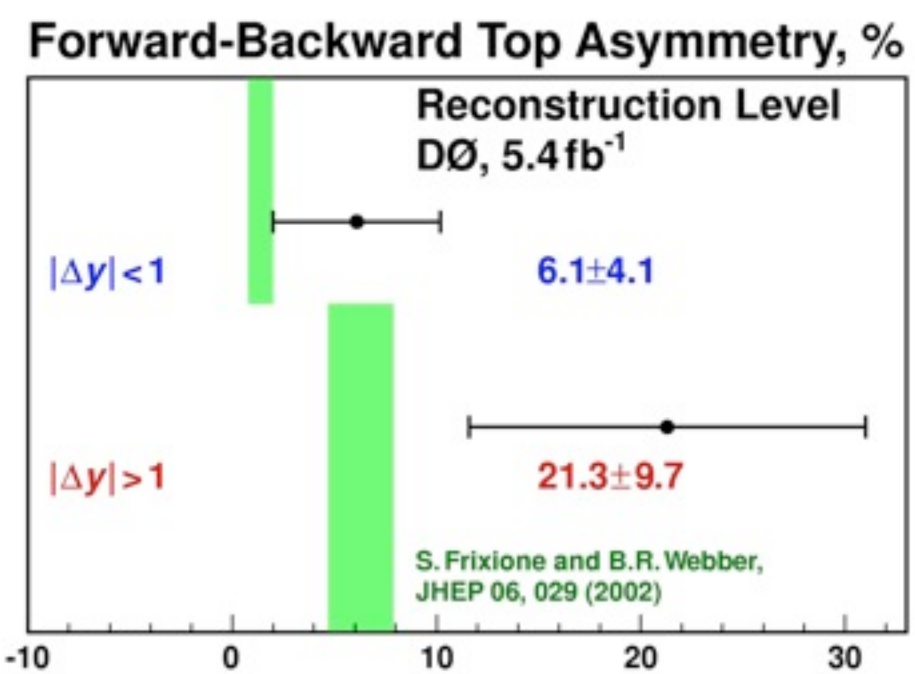
subtract background and correct for detector acceptance and resolution



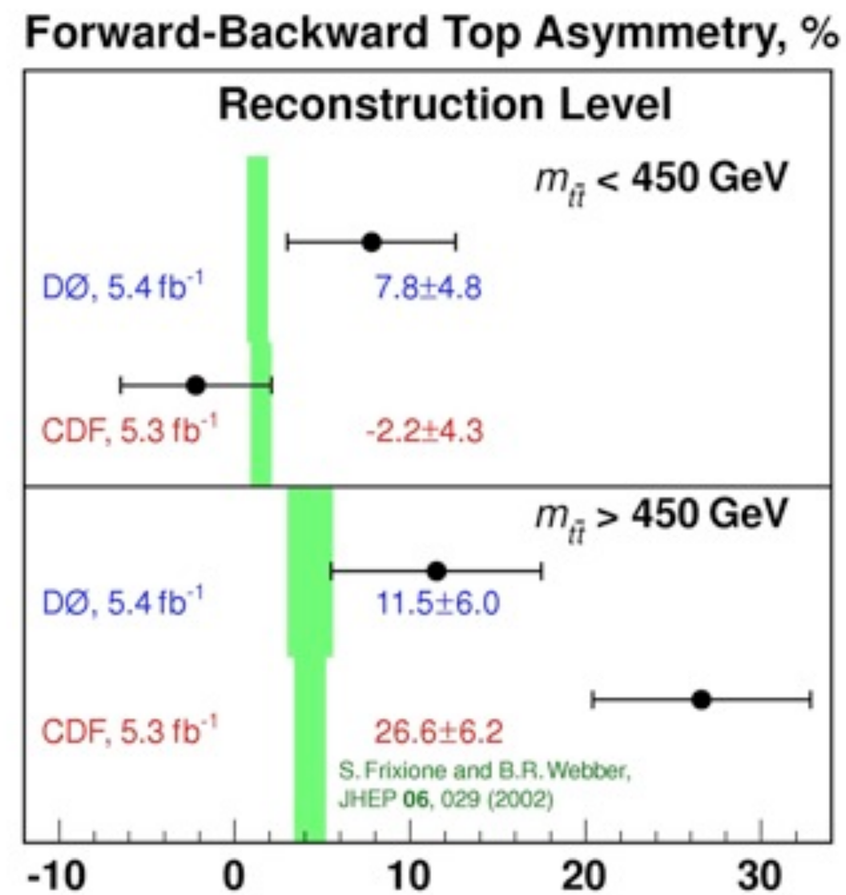
Charge asymmetry: kinematic dependence

- split into low and high Δy





- Explore $M_{t\bar{t}}$ dependence of asymmetry
- Cut is optimized based on sensitivity to color-octet model

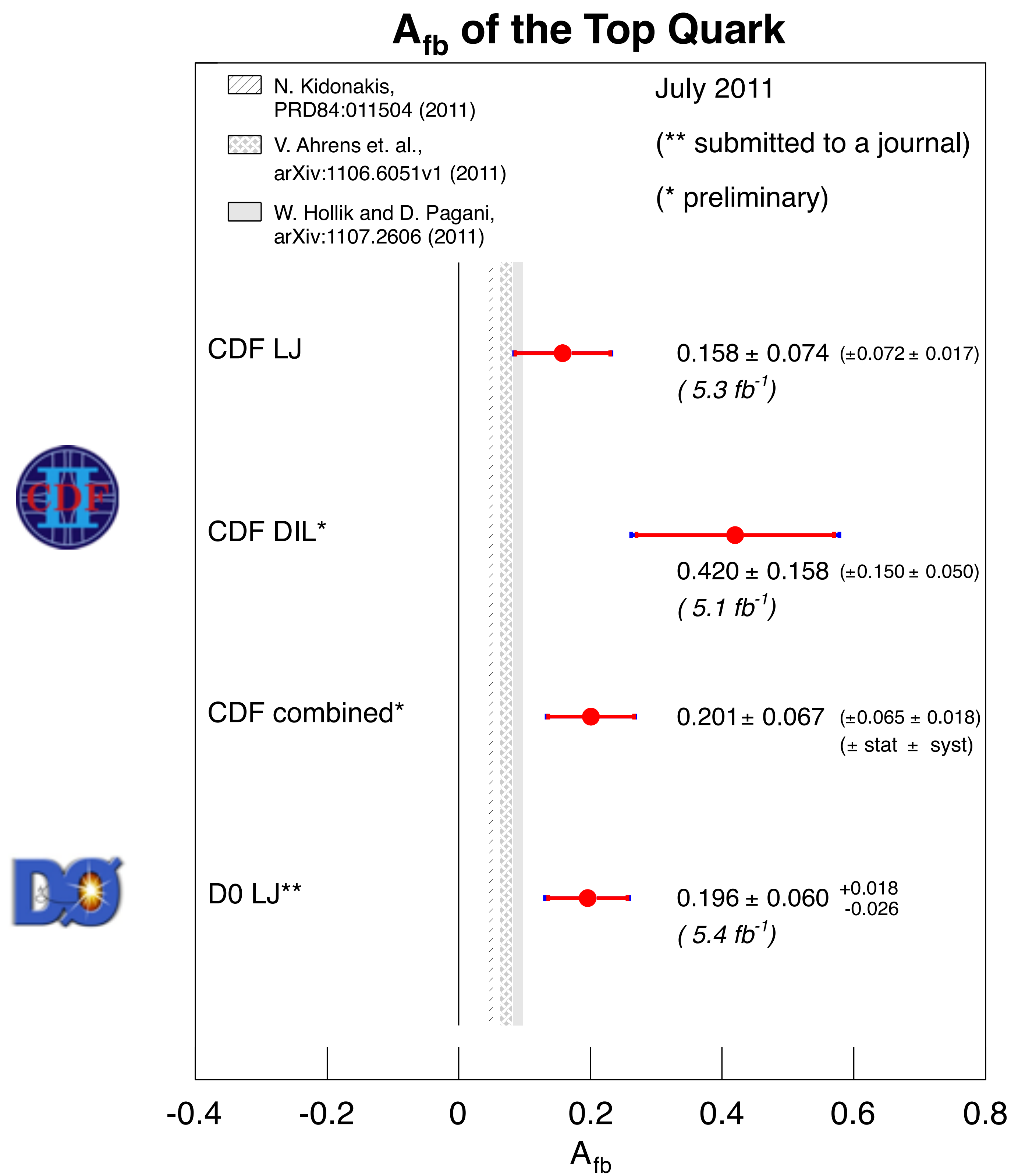


$$A^{t\bar{t}}(M_{t\bar{t}} < 450\text{GeV}) = -0.116 \pm 0.153$$

$$A^{t\bar{t}}(M_{t\bar{t}} \geq 450\text{GeV}) = 0.475 \pm 0.114$$

3.4σ from SM prediction

Charge asymmetry at Tevatron: summary



Charge asymmetry at LHC

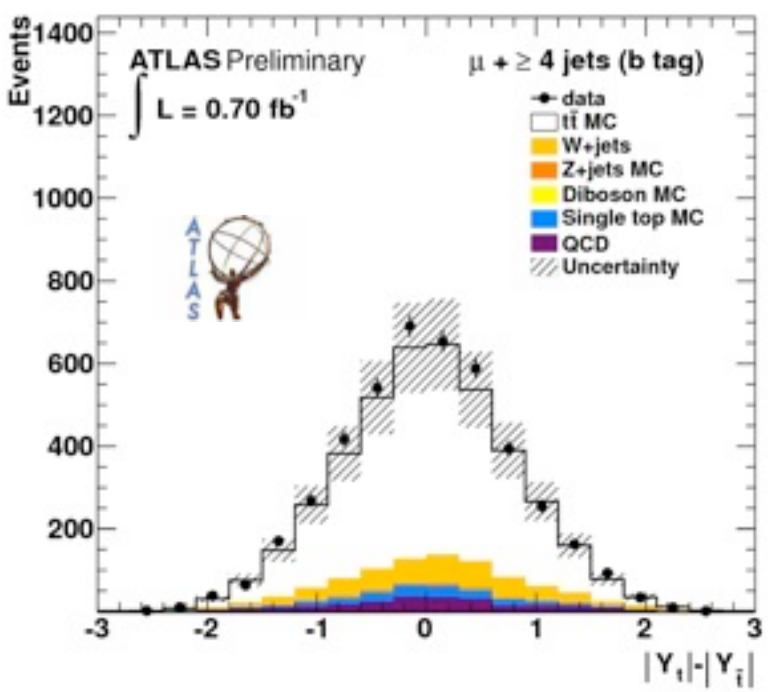
$$A_C = \frac{N(\Delta > 0) - N(\Delta < 0)}{N(\Delta > 0) + N(\Delta < 0)}$$

in $t\bar{t}$ rest frame

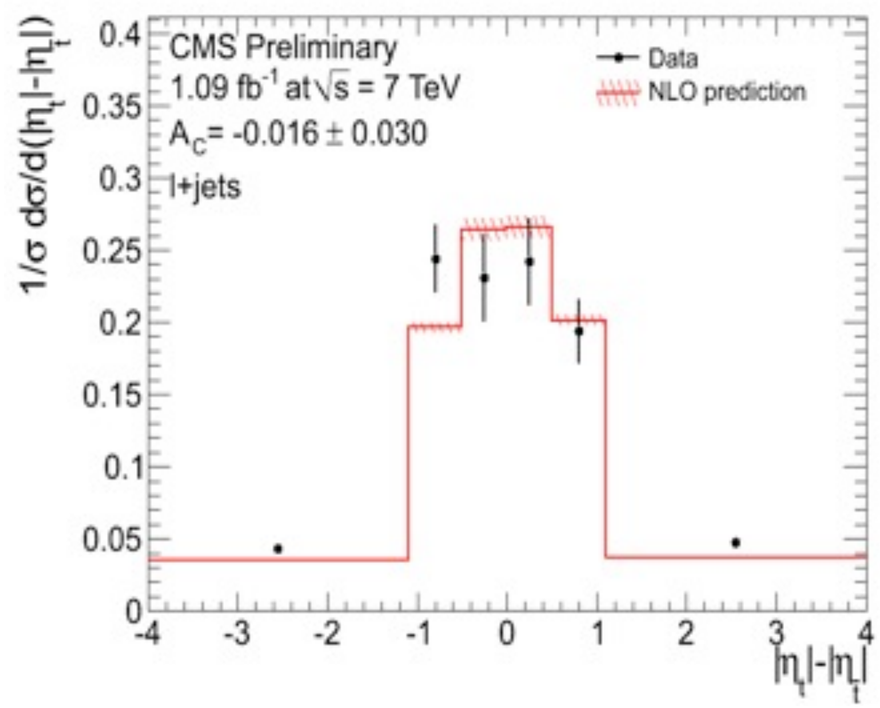
$$\Delta^\eta = |\eta_t| - |\eta_{\bar{t}}| \,,\ \Delta^{y^2} = (y_t - y_{\bar{t}})(y_t + y_{\bar{t}})$$

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

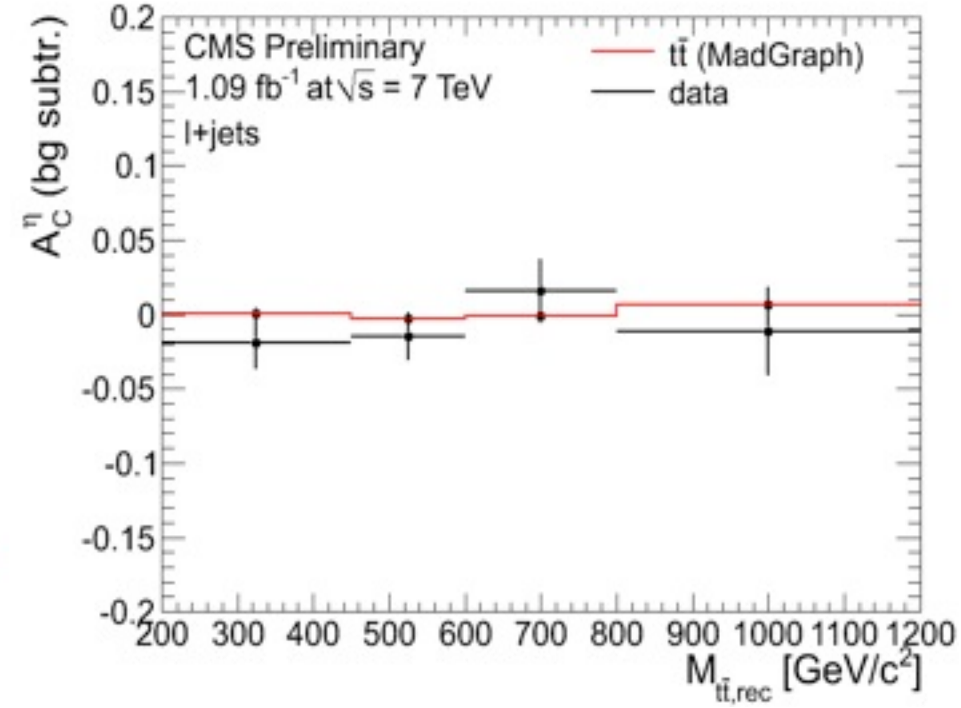
0.7 fb^{-1}



unfolded



1.1 fb^{-1} raw

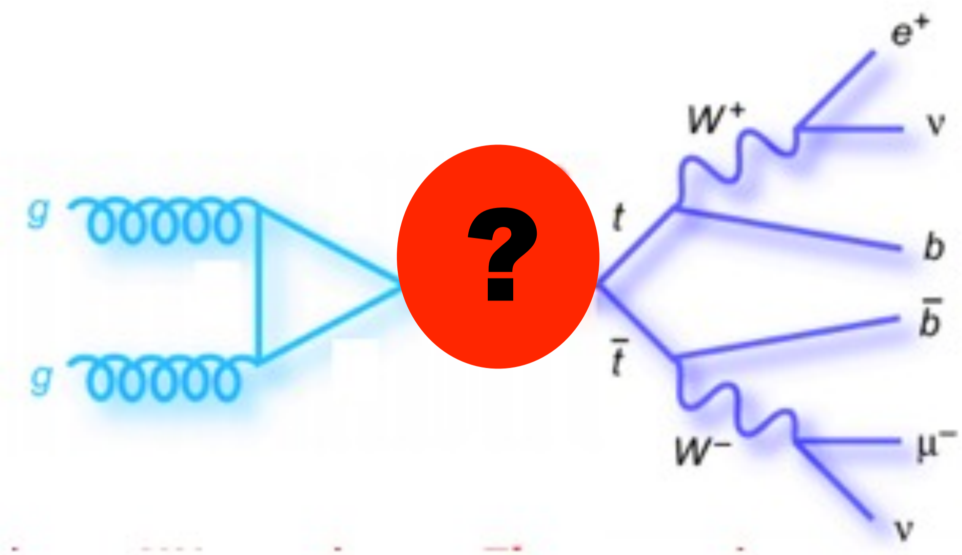


	unfolded data	SM prediction
Altas: A_C^y (0.7 fb^{-1})	-0.024 ± 0.016 (stat) ± 0.023 (syst)	0.006 (MC@NLO)
CMS: A_C^η (1.1 fb^{-1})	-0.016 ± 0.030 (stat)$^{+0.010}_{-0.019}$ (syst)	0.0130

no deviation from SM prediction observed within large uncertainties

Searches in top quark sector

Resonant top pair production



- Searches are ramping fast at LHC
- Cross sections for the production of heavy particles are strongly enhanced with respect to SM due higher centre-of-mass energy
- Experimentally - study $M_{t\bar{t}}$ spectrum
- Complication: strong boost of top quarks from the decay of heavy particles (m>1 TeV)
  - standard reconstruction does not work

Tevatron

most results for topcolor leptophobic narrow Z' →

heavy gluon G →

Spin	color	parity $(1, \gamma_5)$	some examples/Ref.
0	0	(1,0)	SM/MSSM/2HDM, Ref. [51, 52, 53]
0	0	(0,1)	MSSM/2HDM, Ref. [52, 53]
0	8	(1,0)	Ref. [54, 55]
0	8	(0,1)	Ref. [54, 55]
1	0	(SM,SM)	Z'
1	0	(1,0)	vector
1	0	(0,1)	axial vector
1	0	(1,1)	vector-left
1	0	(1,-1)	vector-right
1	8	(1,0)	coloron/KK gluon, Ref. [56, 57, 58]
1	8	(0,1)	axigluon, Ref. [57]
2	0	–	graviton "continuum", Ref. [17]
2	0	–	graviton resonances, Ref. [18]

LHC

Harris, Hill, Parke, arXiv:hep-ph/9911288

← benchmark to compare with Tevatron

← Randall-Sundrum KK gluon representative for all colored wide resonances

Lillie, Randall, Wang, arXiv:hep-ph/0701156

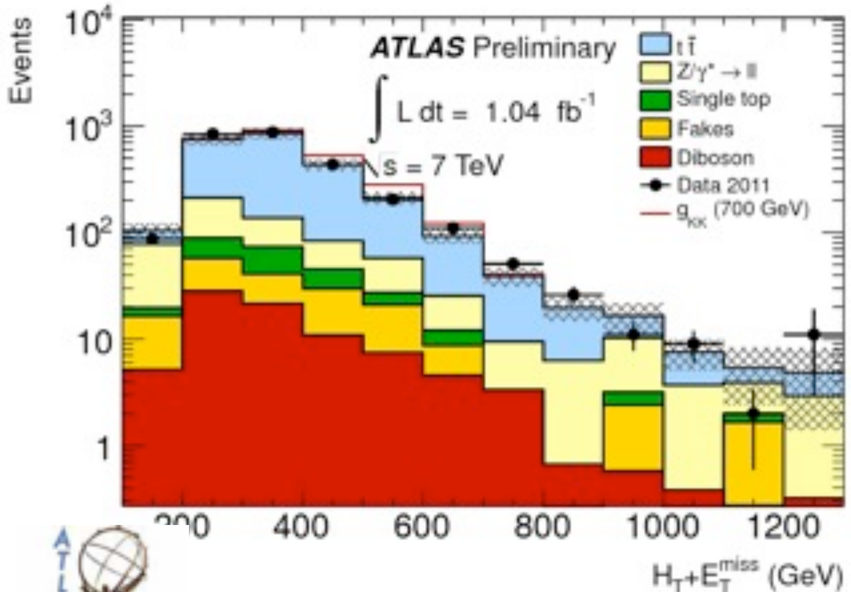
NEW: quantum black holes not a resonance but increases the number of events at high mass

Maede, Randall, arXiv:0708.3017v1 [hep-ph]

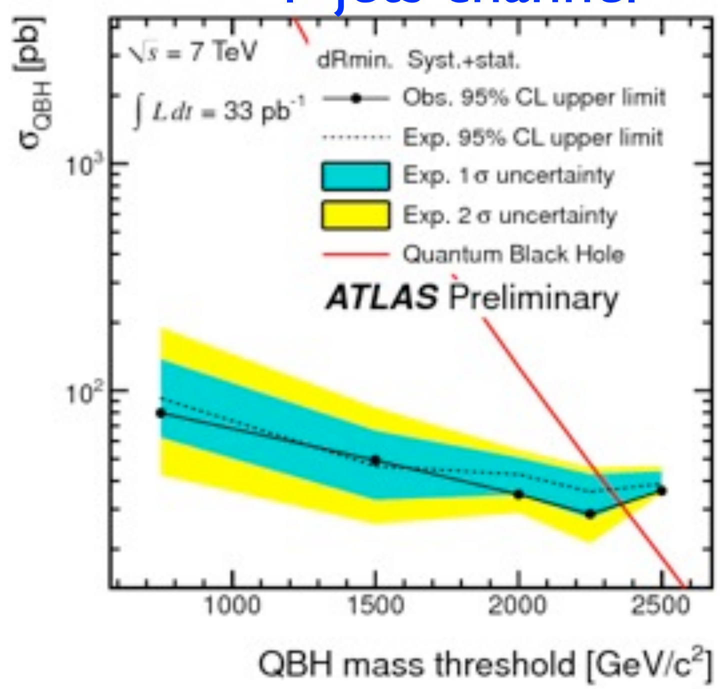
Resolved topology

- standard selection as for cross section

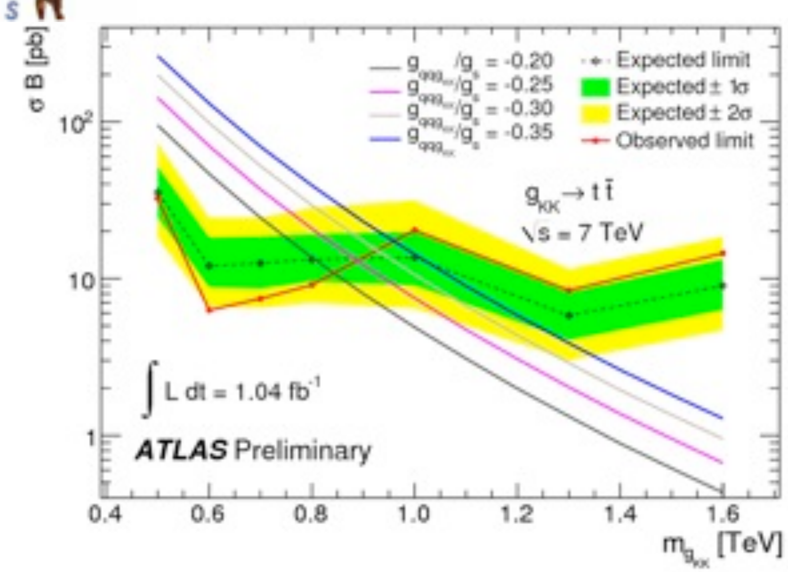
dilepton channel

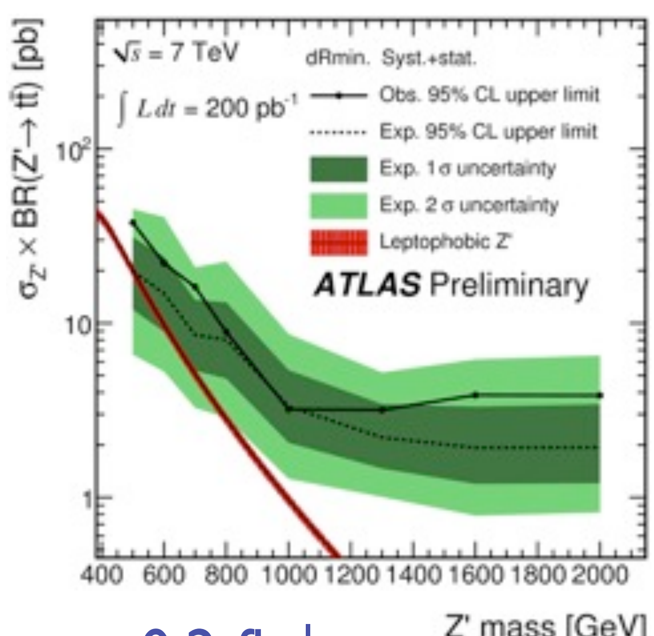


l+jets channel



95% CL exclusion of QBH mass threshold < 2.35 TeV





95% CL exclusion of KK gluon mass < 840 GeV

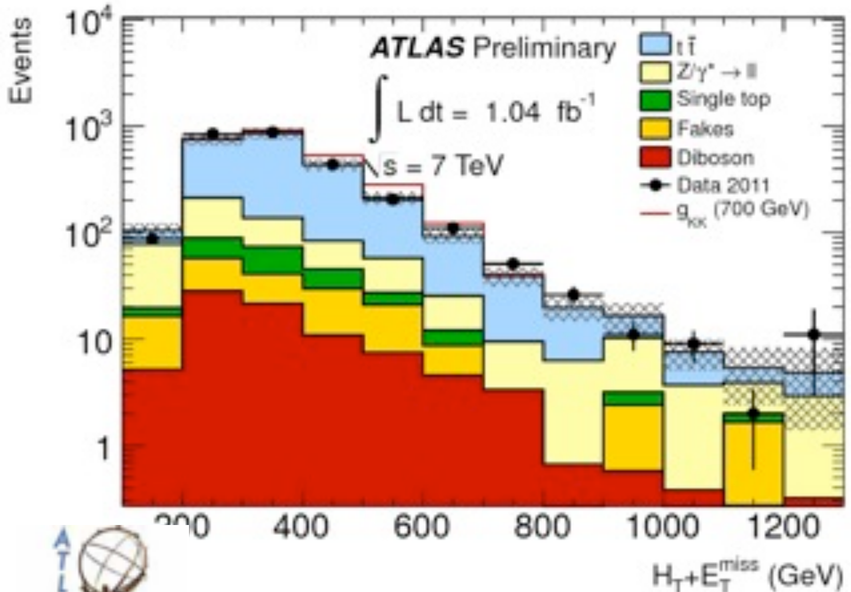
0.2 fb^{-1}

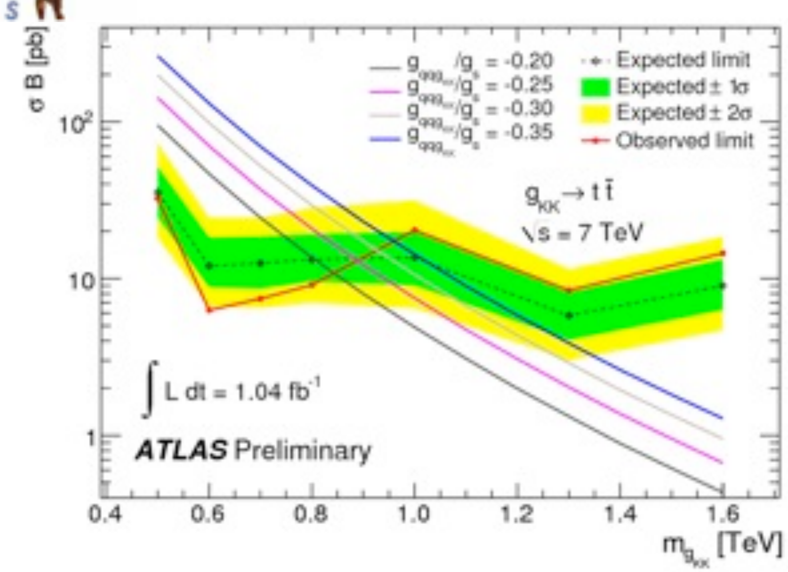
no exclusion of Z' with 1.2% width

Resolved topology

- standard selection as for cross section

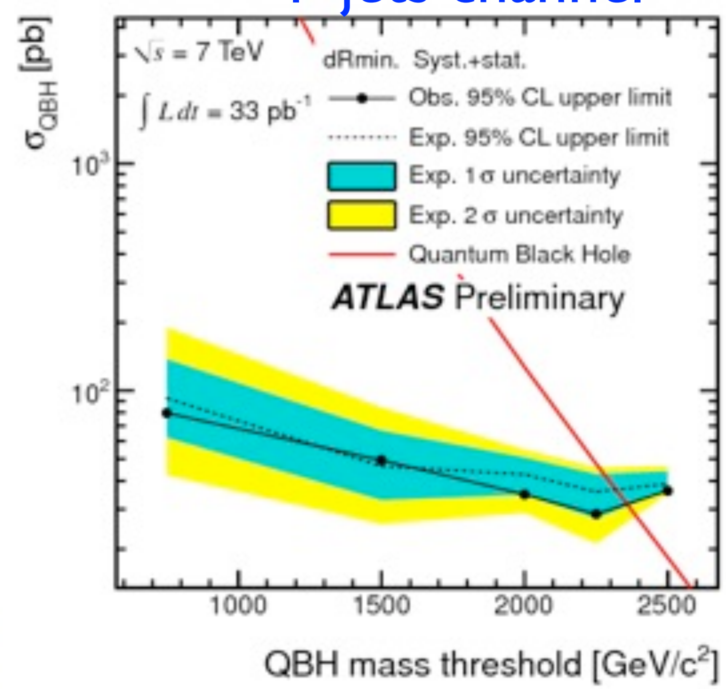
dilepton channel



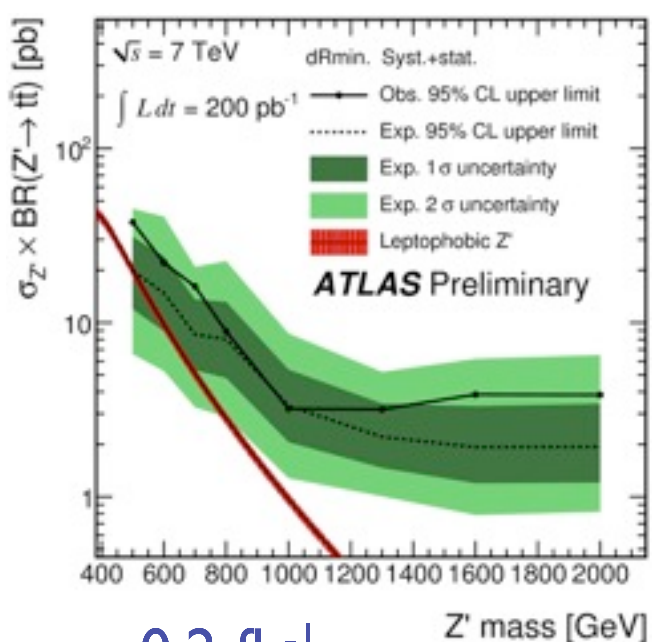


95% CL exclusion of KK gluon mass < 840 GeV

l+jets channel



95% CL exclusion of QBH mass threshold < 2.35 TeV



$0.2\ fb^{-1}$

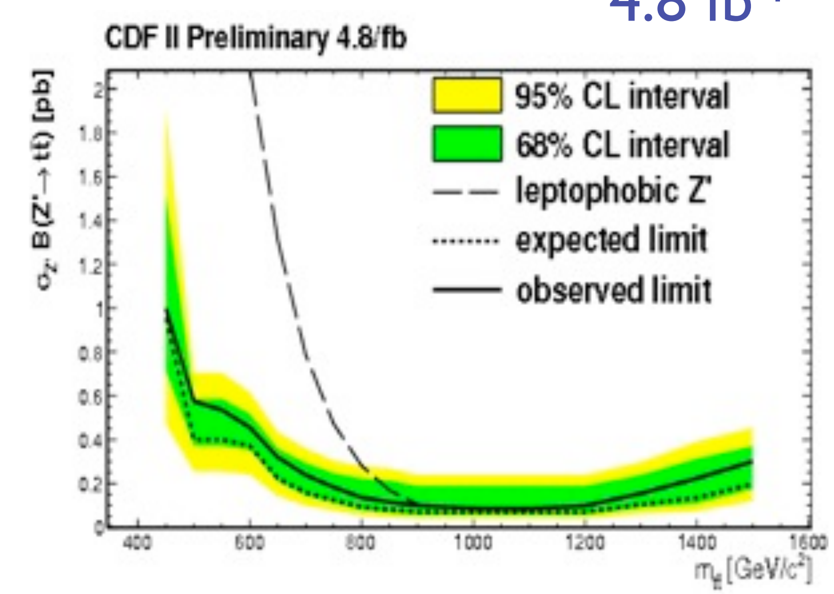
no exclusion of Z' with 1.2% width

Matrix element technique

- for each event apply $t\bar{t}$ hypothesis
- construct likelihood
- determine how likely it is to fluctuate to data for each mass point

l+jets channel

$4.8\ fb^{-1}$



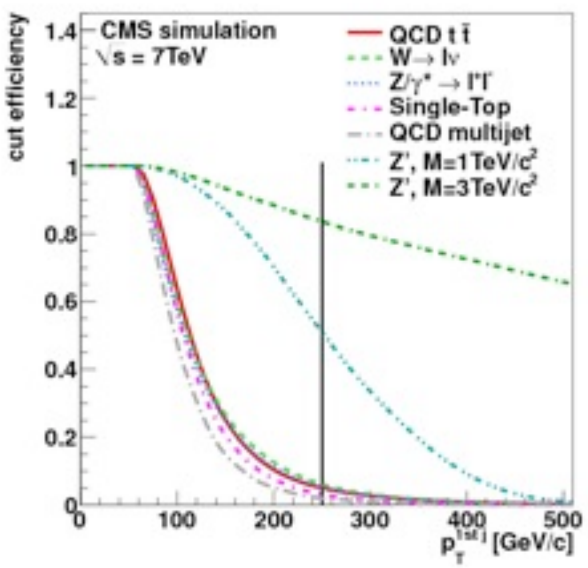
still the best limit: exclusion 95% CL of Z' (1.2% width) with mass < 900 GeV

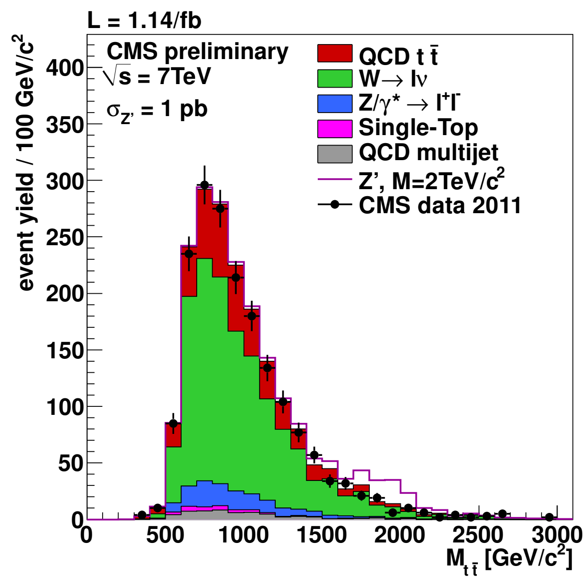
Boosted topology

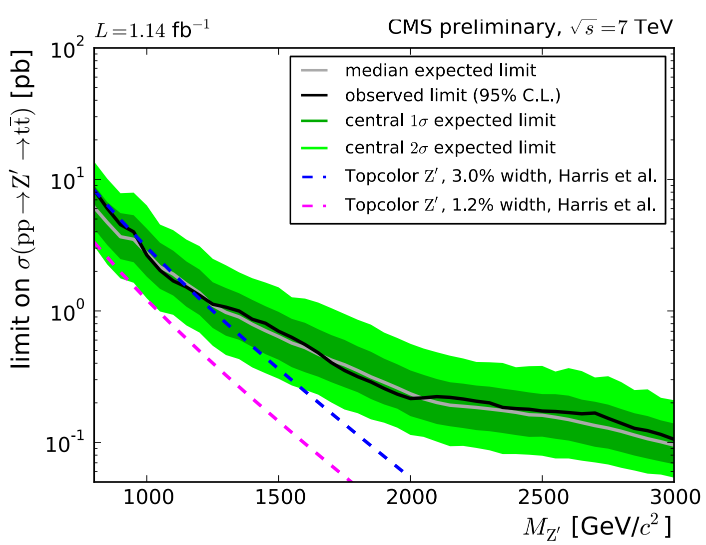
Cuts in μ+jets channel:

- at least 2 jets with pT>50 GeV, leading jet pT>250 GeV
- HT_{lep}>150 GeV

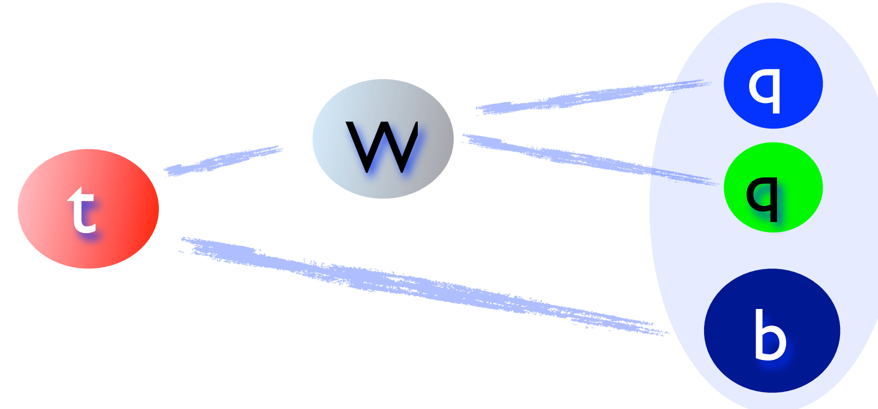
1.1 fb^{-1}







Z' (3% width) excluded in mass ranges 805-935 and 960-1060 GeV



All top quark decay products are contained in one jet

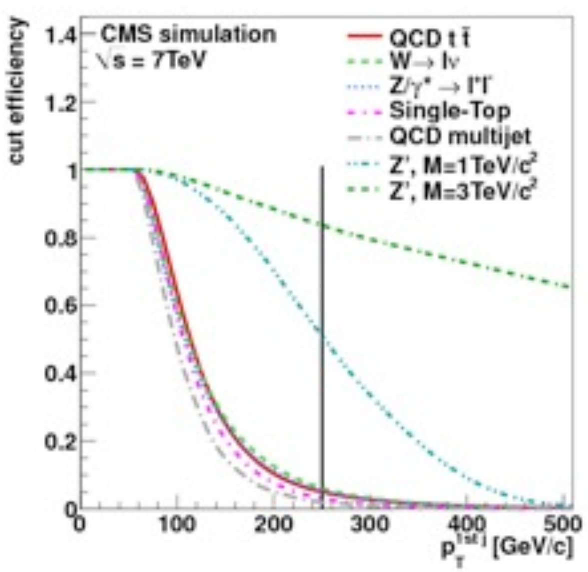
Wednesday, October 26, 2011

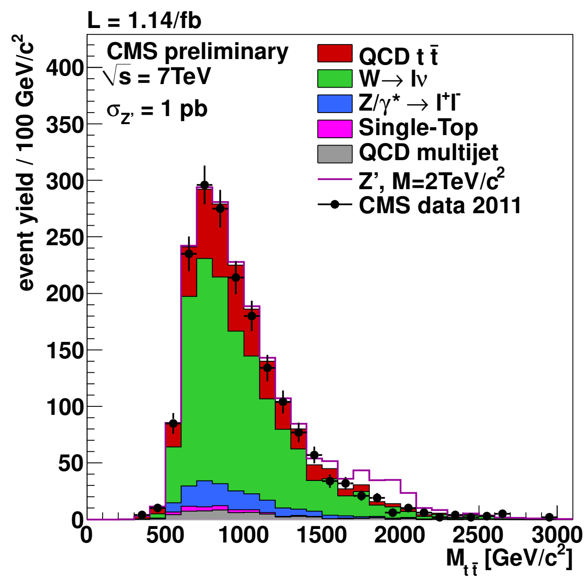
Boosted topology

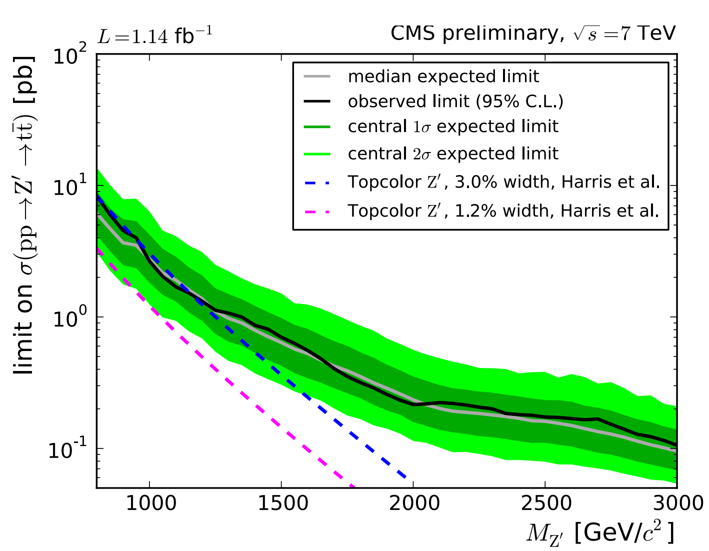
Cuts in μ+jets channel:

- at least 2 jets with pT>50 GeV, leading jet pT>250 GeV
- HT_{lep}>150 GeV

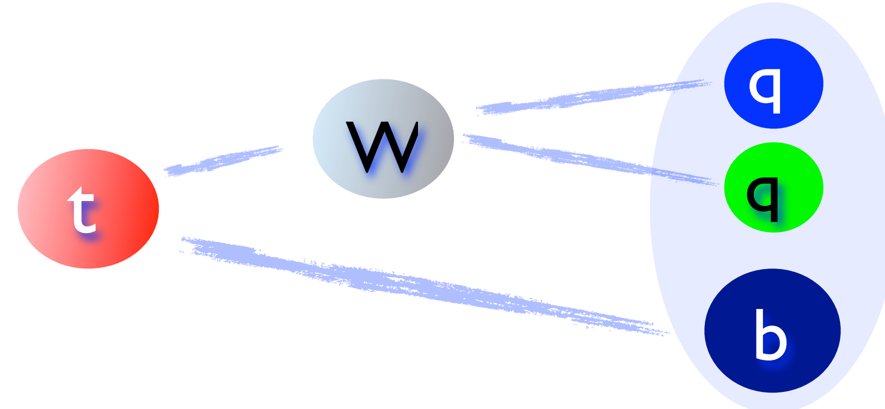
1.1 fb^{-1}





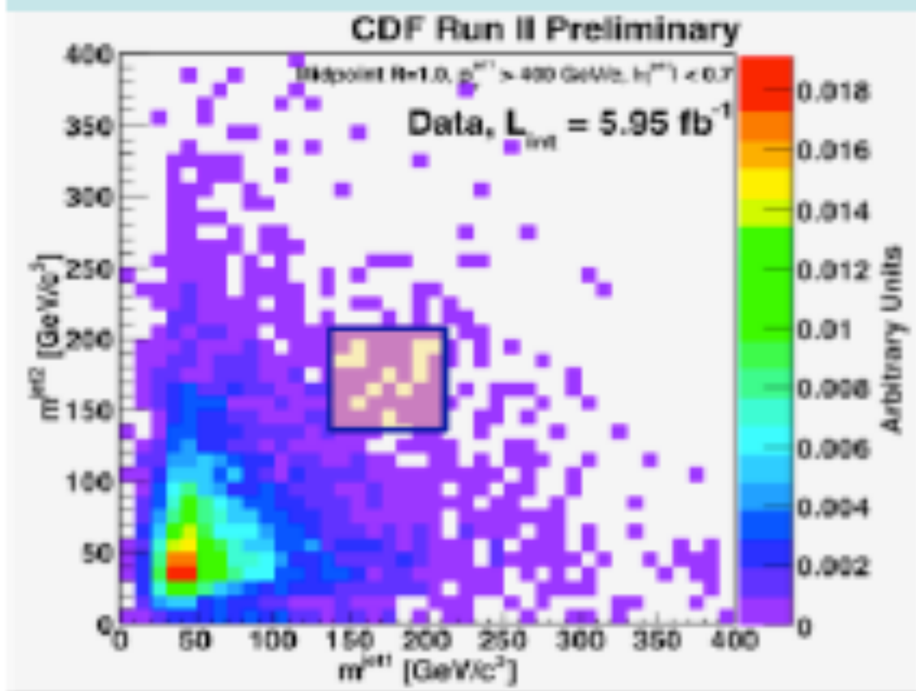


Z' (3% width) excluded in mass ranges 805-935 and 960-1060 GeV



All top quark decay products are contained in one jet

all-hadronic decays:
two tops with mass ~175



(jet1 mass vs jet2 mass)

6 fb^{-1}

$\sigma_{t\bar{t}}$ < 54 fb for top quark p_T>400 GeV

Other searches: summary

LHC

search	decay
charged Higgs	Atlas: $H^+ \rightarrow$ cs, τυ
	CMS: $H^+ \rightarrow$ τυ
FCNC	Atlas: t → qZ, qg → t
	CMS:T → tZ
	Atlas, CMS: same sign top pairs
anomalous coupling	Atlas: from W helicity fractions
exotic quarks	Atlas,CMS: b' → tW
	CMS: t' → bW
	Atlas t' → qW
exotic top partners	Atlas: t' → tA
✔ top charge	Atlas: -4/3 charge excluded at 5 σ

Tevatron

search	decay
✔ ttγ	CDF: 3σ evidence
FCNC	D0: t → qZ
anomalous coupling	D0: from single top
exotic quarks	CDF: b' → tW
	CDF, D0 t' → qW
associated Higgs	CDF: ttH limit
✔ top charge	CDF: -4/3 charge excluded at 99% CL

Summary of top properties measurements

Property		Measurement	SM Prediction	Luminosity (fb^{-1})
$\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb	$7.46^{+0.48}_{-0.67}$ pb	up to 4.6
		D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb		5.6
	$pp \to t\bar{t}$	Atlas: $179.0 \pm 9.8(\text{stat}+\text{syst}) \pm 6.6(\text{lumi})$ pb	$164.6^{+11.4}_{-15.7}$ pb	0.7
		CMS: $164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lumi})$ pb		0.8-1.1
σ_{tbq} (for $M_t = 172.5$ GeV)	$p\bar{p} \to t\bar{t}$	CDF: 0.8 ± 0.4 pb ($M_t = 175$ GeV)	2.26 ± 0.12 pb	3.2
		D0: 2.90 ± 0.59 pb		5.4
	$pp \to t\bar{t}$	Atlas: 90^{+32}_{-22} pb	$64.6^{+3.3}_{-2.6}$ pb	0.7
		CMS: $83.6 \pm 29.8(\text{stat}+\text{syst}) \pm 3.3(\text{lumi})$ pb		0.035
σ_{tb} (for $M_t = 172.5$ GeV)	$p\bar{p} \to tb$	CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV)	1.04 ± 0.04 pb	3.2
		D0: $0.68^{+0.38}_{-0.35}$ pb		5.4
	$pp \to tb$	Atlas: < 26.5 pb		0.7
σ_{Wt} (for $M_t = 172.5$ GeV)	$pp \to Wt$	Atlas: < 39.1 pb	15.7 ± 1.4 pb	0.7
$\lvert V_{tb}\rvert$		CDF: $\lvert V_{tb}\rvert = 0.91 \pm 0.11(\text{stat}+\text{sys}) \pm 0.07(\text{theory})$	1	3.2
		D0: $\lvert V_{tb}\rvert = 1.02^{+0.10}_{-0.11}$		5.4
$R = B(t \to Wb)/B(t \to Wq)$		CDF: > 0.61 @ 95% CL	1	0.2
		D0: 0.90 ± 0.04		5.4
$\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$	$p\bar{p} \to t\bar{t}$	CDF: $0.07^{+0.15}_{-0.07}$	0.18	1
M_t		Tev: 173.2 ± 0.9 GeV	-	up to 5.8
		Atlas: 175.9 ± 2.8 GeV	-	0.7
		CMS: 173.4 ± 3.3 GeV	-	0.036
$M_t - M_{\bar{t}}$		CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV	0	5.6
		D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV		3.6
		CMS: $-1.2 \pm 1.2(\text{stat}) \pm 0.5(\text{syst})$ GeV		1.1
W helicity fraction		Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$	0.7	up to 5.4
		Atlas: $f_0 = 0.75 \pm 0.08(\text{stat}+\text{syst})$	0.7	0.7
Charge		CDF: -4/3 excluded @ 95% CL	2/3	5.6
		D0: 4/3 excluded @ 92% CL		0.37
Γ_t		CDF: < 7.6 GeV @ 95% CL	1.26 GeV	4.3
		D0: $1.99^{+0.69}_{-0.55}$ GeV		up to 2.3
spin correlation	$p\bar{p} \to t\bar{t}$, beam	CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$	$0.777^{+0.027}_{-0.042}$	5.3
		D0: $0.66 \pm 0.23(\text{stat}+\text{sys})$		5.4
	$pp \to t\bar{t}$, helicity	Atlas: $0.34^{+0.15}_{-0.11}$	0.32	0.7
Charge asymmetry	$p\bar{p} \to t\bar{t}$	CDF: 0.158 ± 0.074	0.06	5.3
		D0: 0.196 ± 0.065		5.4
	$pp \to t\bar{t}$	Atlas: $A_C^y = -0.024 \pm 0.016(\text{stat}) \pm 0.023(\text{syst})$	0.006	0.7
		CMS: $A_C^\eta = -0.016 \pm 0.030(\text{stat})^{+0.010}_{-0.019}(\text{syst})$	0.013	1.1

Conclusions

- Taking baton from the Tevatron - LHC proved to be a top quark factory
  - strong and steady flow of top properties measurements and searches in top sector
    - many cross section measurements are more precise that at Tevatron
    - searches have better sensitivity
- Legacy measurements from Tevatron with full data set are yet to come
- So far top quark looks very Standard Model like
  - is FB asymmetry at Tevatron a hint of physics BSM ?
  - 5σ observation with full data set seems possible

Instead of outlook...

P. Grannis on the Top (1994, New York Times):

"This monster, compared with all the other quarks, is like a big cowbird's egg in a nest of little sparrow eggs. It's so peculiar it must hold clues to some important new physics."

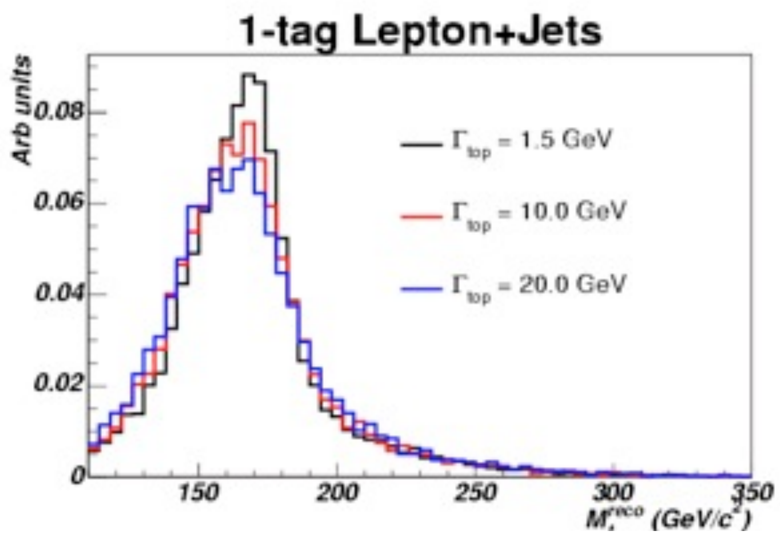
Backup

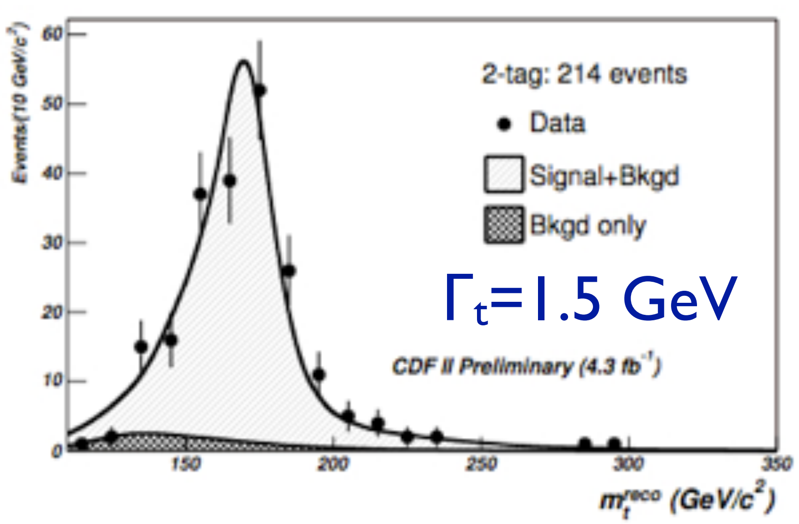
Top quark width

SM: Γ_t~1.5 GeV at NLO for m_t=172.5 GeV

Additional decay modes: $t \rightarrow H^+b$, $t \rightarrow dW^+$, $t \rightarrow sW^+$?

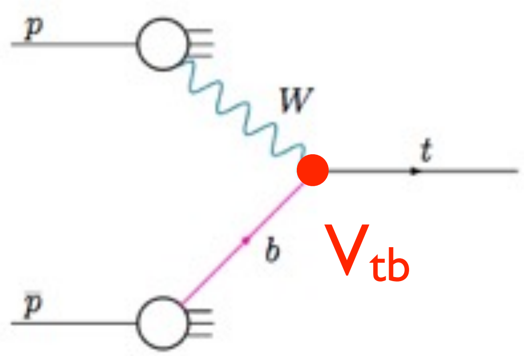
- Direct measurement: build templates in Γ_t
- reconstruct m_{reco} and m_W





Γ_t < 7.5 GeV at 95% C.L.

- Indirect measurement
- use single top t-channel cross section
- combine with measured branching ratio
- assumption: coupling in top production and decay is the same



$$\Gamma(t \rightarrow bW) = \sigma(t-ch)\frac{\Gamma(t \rightarrow bW)_{SM}}{\sigma(t-ch)_{SM}}$$

$$\Gamma_t = \frac{\Gamma(t \rightarrow bW)}{\mathcal{B}(t \rightarrow bW)}$$ ←

Phys. Rev. Lett. 100, 192003 (2008)

$$\Gamma_t = (1.99^{+0.69}_{-0.55})GeV, \ \tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}s$$

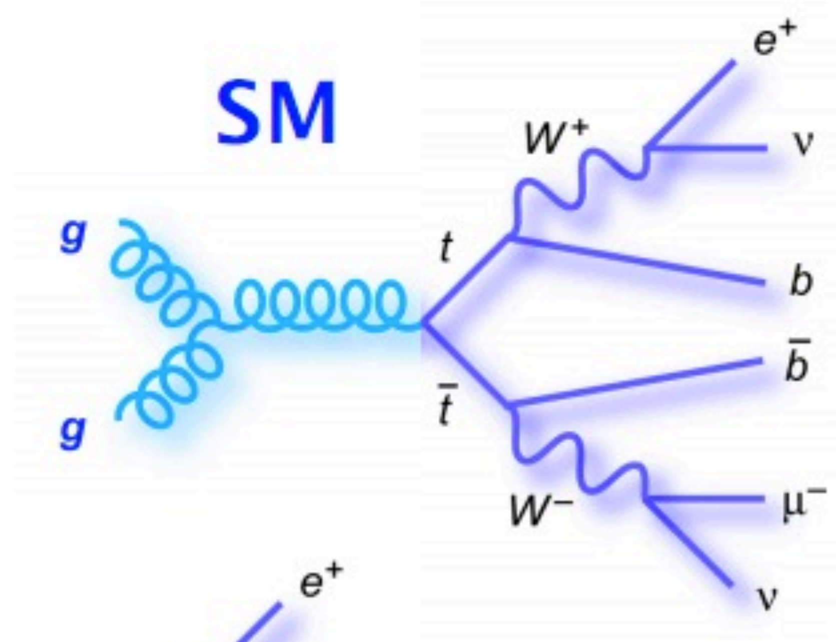
4th generation b' quark with $m_{b'} > m_t - m_W$

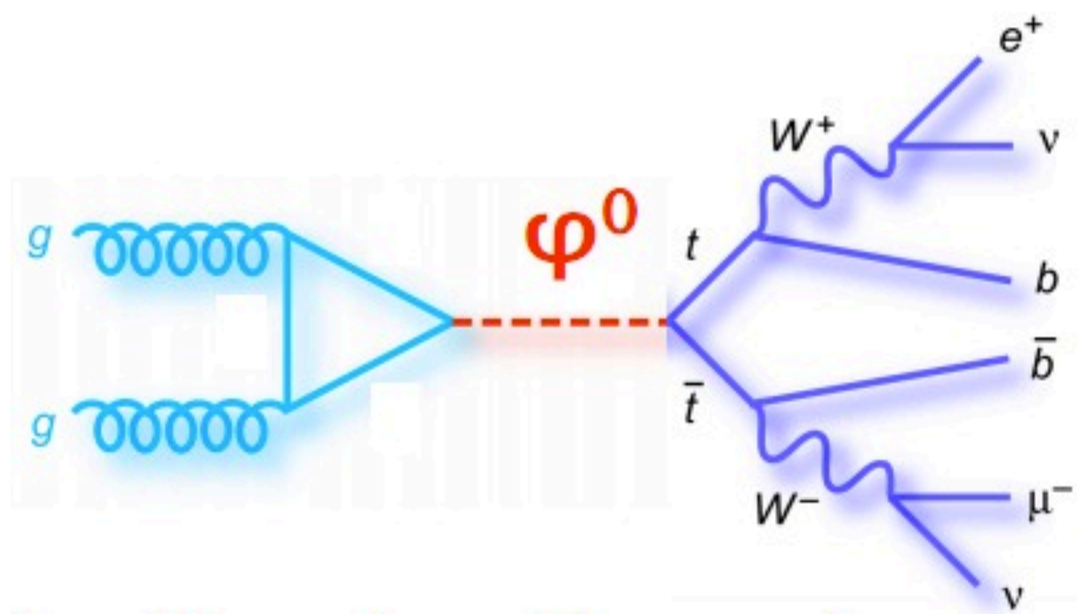
4x4 unitary new CKM matrix

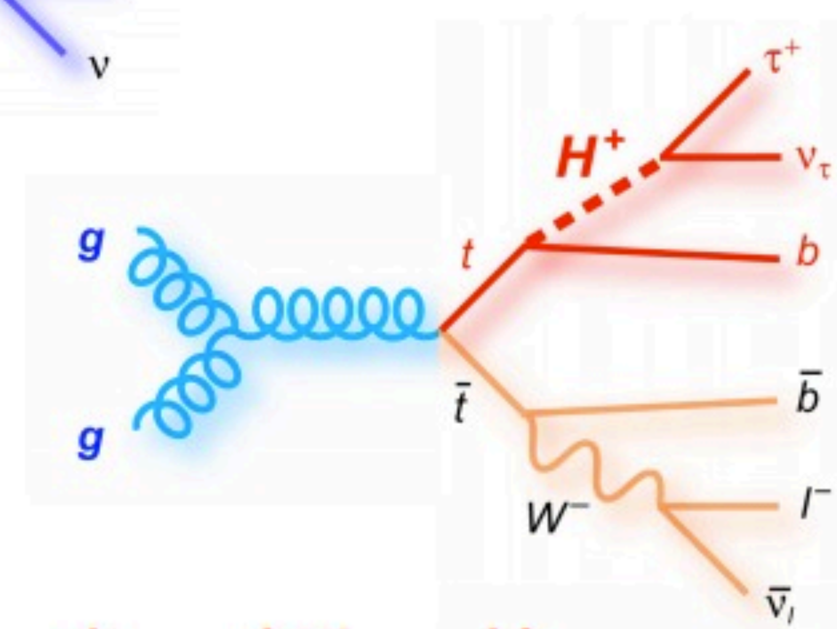
$|V_{tb}|^2+|V_{tb'}|^2=1$, small $|V_{ts}|$, $|V_{td}|$

$$|V_{tb'}| < 0.63 \text{ at } 95\% \text{ C.L.}$$

New physics in production and decay



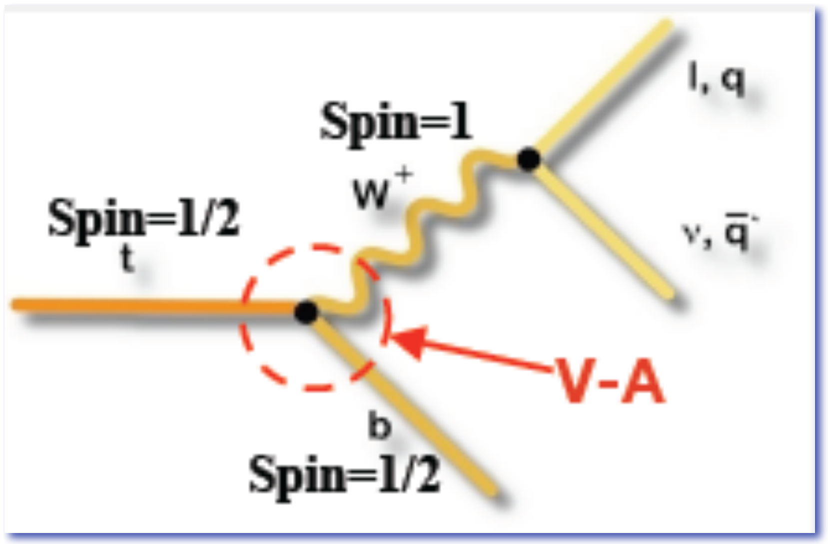


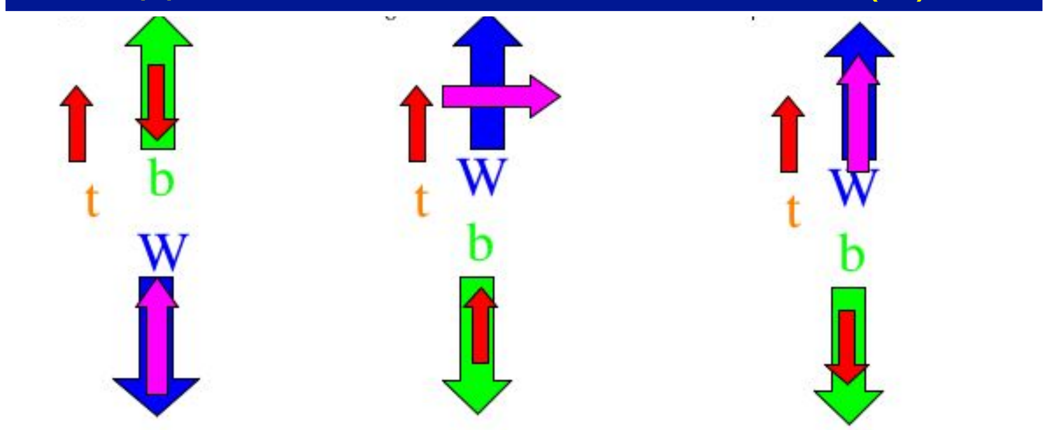


Higgs, KK gravitons, Z', stop pairs, ...

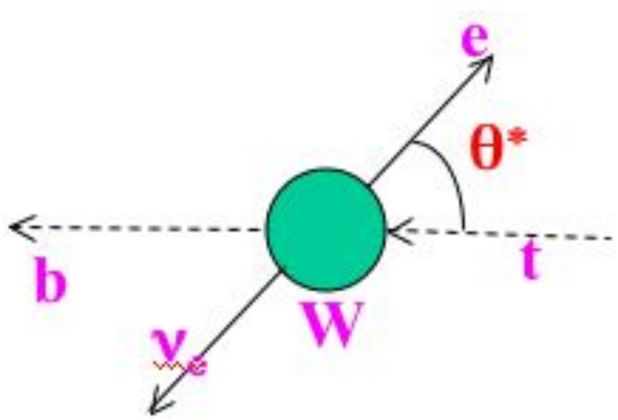
charged Higgs, b'

W helicity

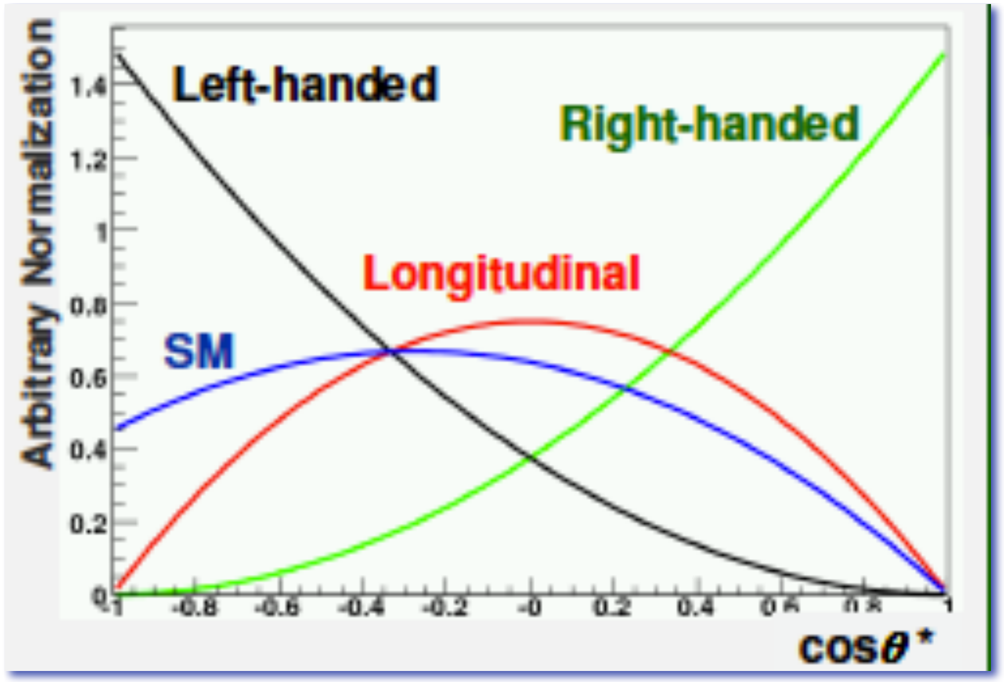




Lorentz structure of Wtb vertex predicts: 0.3 0.7 0



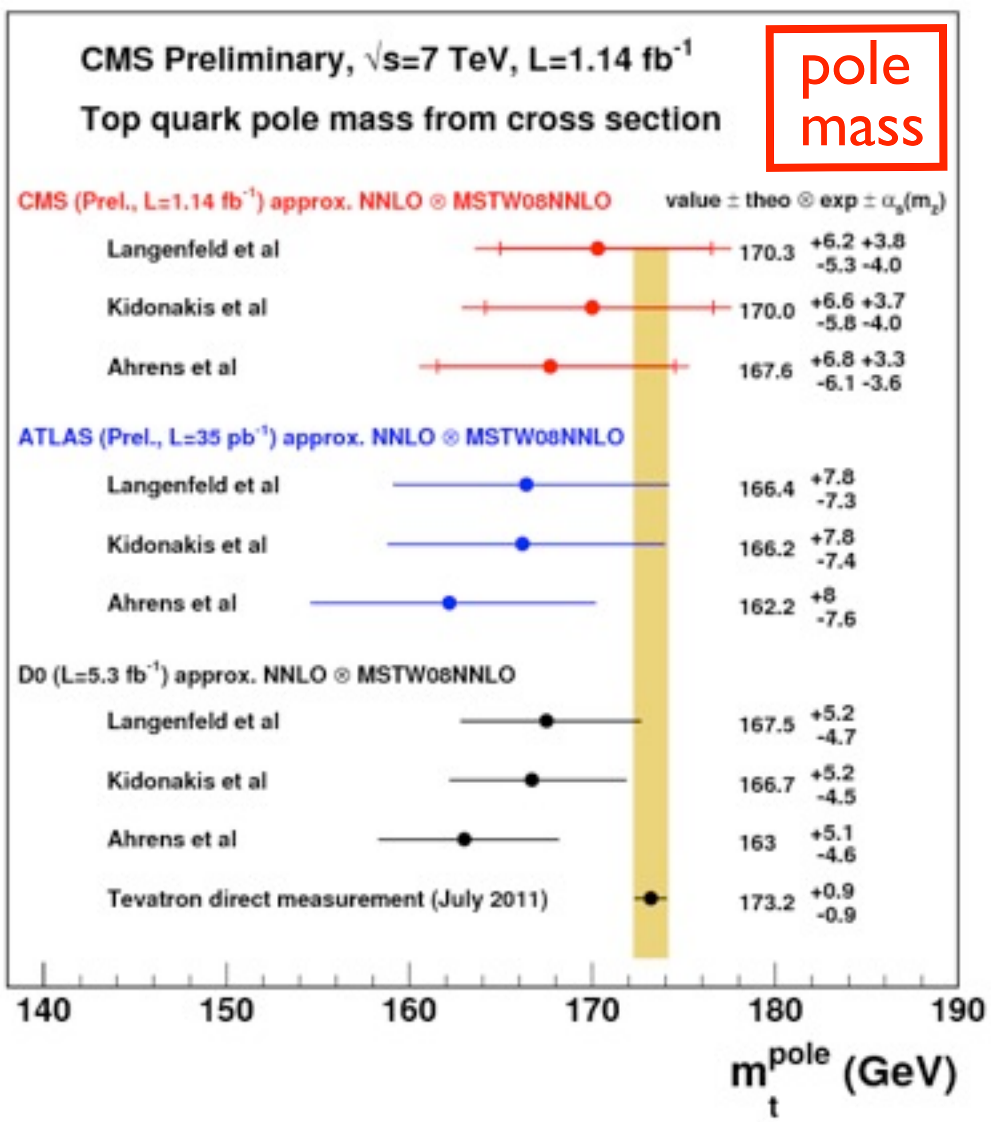
Measure angle between the momenta of d-type fermion and top quark in W rest frame

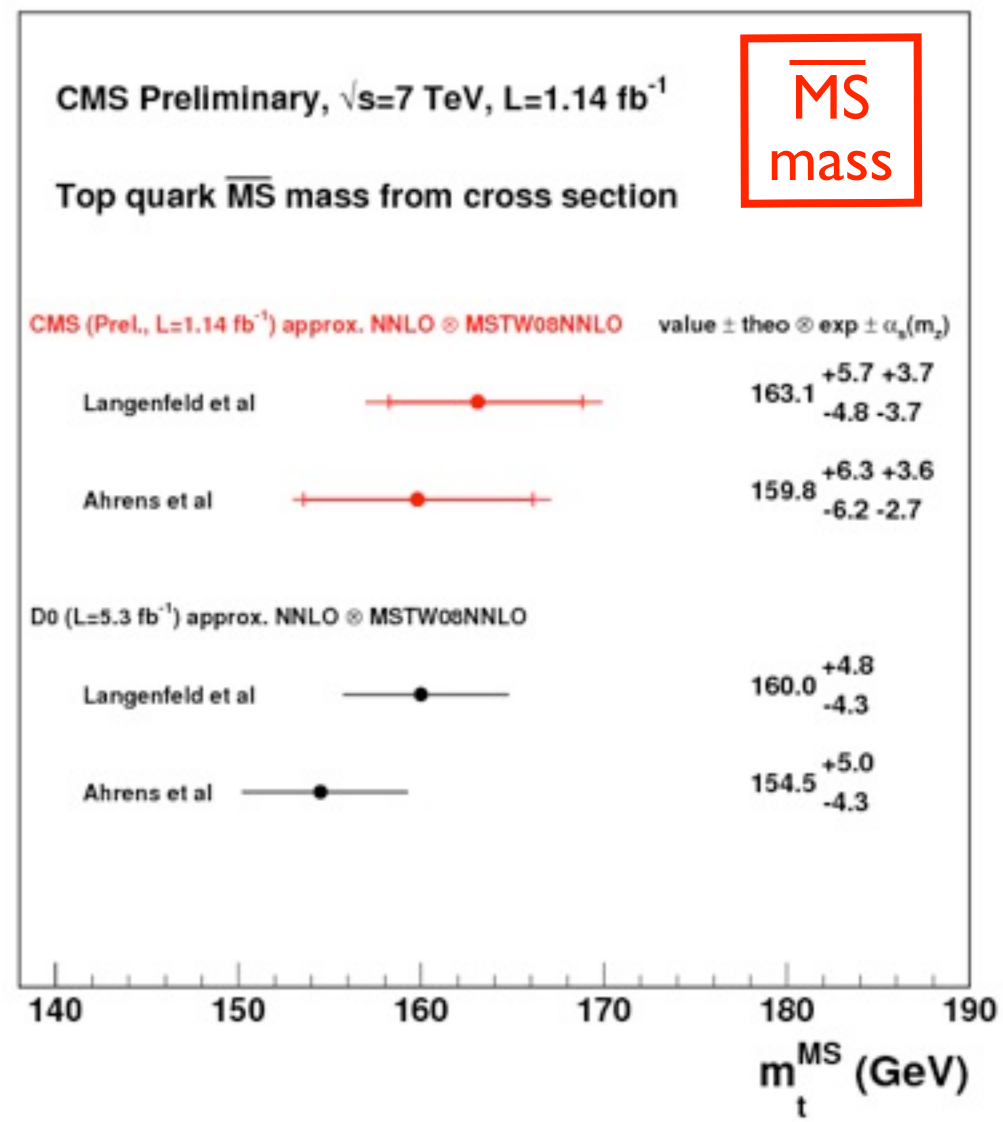


Other possible variables: lepton p_T and M_{lb}^2
Lower sensitivity than $\cos\vartheta^*$

Mass extraction from cross

- First performed by D0 for the pole mass
- Routinely extracted from the cross section (D0, ATLAS, CMS)
- The most precise cross section measurement does not guarantee the smallest uncertainty on m_t
  - minimum dependence on m_t is required - counting experiment?
- Dedicated optimization is needed to achieve good precision

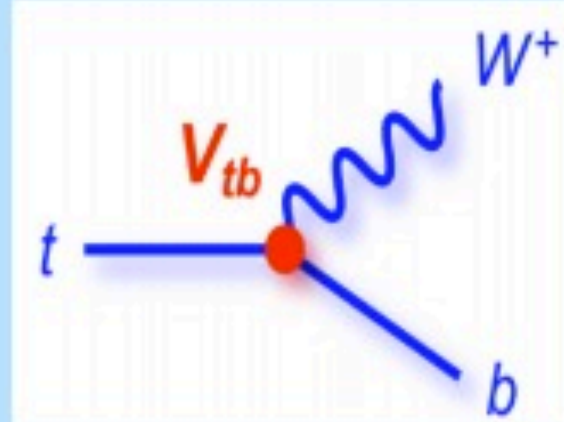




CKM matrix element V_{tb}

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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



- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- General form of the Wtb vertex

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

- Measurement assumes SM production mechanisms
  - Pure V–A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)
    - f_1^L : strength of the left-handed Wtb coupling, is allowed to be anomalous
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
- Does not assume 3 generations or unitarity of the CKM matrix

Ideogram method

- Like in ME method likelihood is constructed for each event
- Use a constrained kinematic fit to extract the mass information: fitted mass m_i, estimated uncertainty σ_i^2, and goodness of fit χ^2

probability that a solution has the correct jet-parton assignment

wrong jet-parton assignment

$$P_{t\bar{t}}(x_{\mathrm{mass}}|m_t) = \sum_{i}^{24} w_i \left(f_{cp} \cdot \int_{m_{min}}^{m_{max}} dm' \, G(m'|m_i,\sigma_i) \, BW(m'|m_t,\Gamma_t) + (1-f_{cp}) \, WP(m_i|m_t) \right)$$

- w_i: weight of each permutation based on b-tagging information and fit χ^2
- $G(m'|m_i,\sigma_i)$: Gaussian mass resolution function
- $BW(m'|m_t,\Gamma_t)$: top quark Breit-Wigner lineshape
- $WP(m_i|m_t)$: PD for wrong permutations from MC

- Method first applied to the W mass at LEP
- Aim: achieve similar statistical uncertainties as the ME method but without the burden of huge computational requirements
- Used by D0 (l+jets), CDF (all hadronic) and CMS (l+jets)

Probability calculation

$$d\sigma = \frac{(2\pi)^4|\mathcal{M}|^2}{4\sqrt{(q_1 \cdot q_2) - m_1 \cdot m_2}} d\Phi_6$$

Normalization
acceptance & efficiency

Differential cross section based on LO ME

$$P_{t\bar{t}}(x; m_t, JES) = \frac{1}{\sigma(m_t)} \int d^n\sigma(y, m_t)\, dq_1 dq_2 f(q_1) f(q_2)\, W(x, y, JES)$$

Probability to observe a set of kinematic variables x for a given mass and JES

Initial state
Probability distribution that a parton will have a momentum q

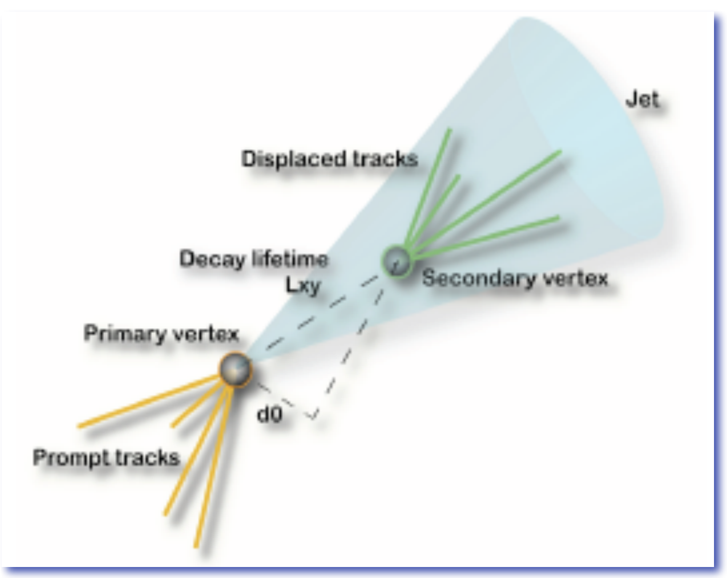
Transfer function
Probability to measure x when parton-level y was produced

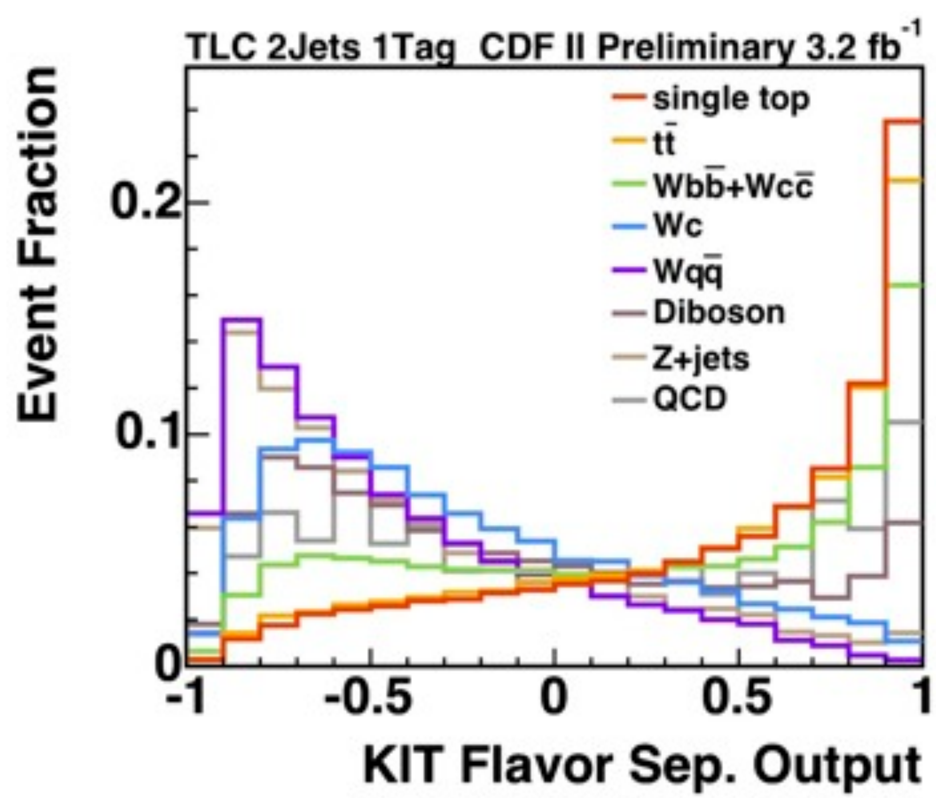
Integrate over unknown q_1, q_2, y

- Utilizes more precise statistical model of the process than template methods by using full event information
  - achieves better statistical precision
- Multidimentional integration is very CPU intensive

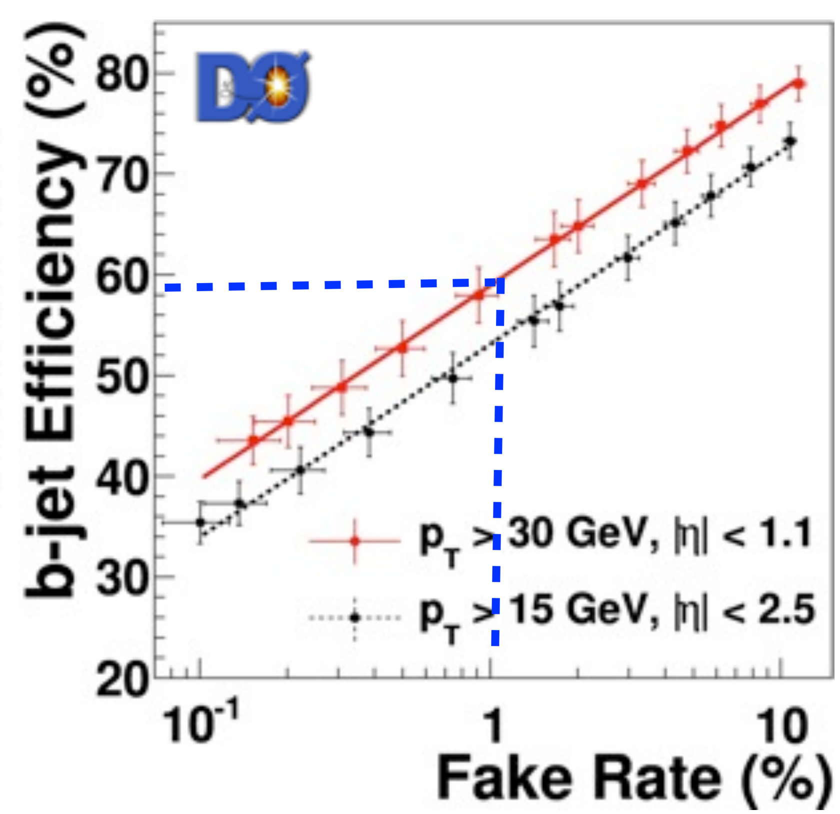
Finding top quarks: b-tagging

- Powerful tool to suppress backgrounds to top
- Utilizes
  - long live time of B-hadrons
  - semileptonic B decays
- CDF: Neural network heavy flavor separator applied after SVX tagger
  - separates b from charm and light
  - 25 input variables
- D0: Neural Network tagger
  - combines track and secondary vertex properties - 7 variables





NIM, A620, 400 (2010)



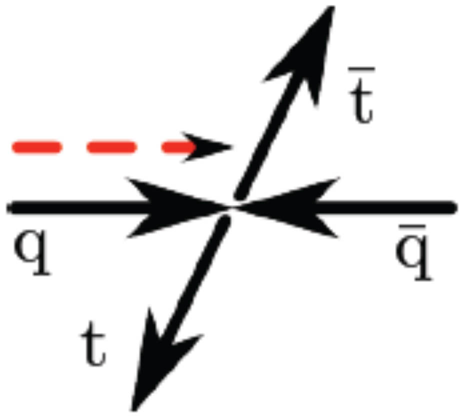
Tevatron experience: b-tagging usually improves the sensitivity

Tevatron combination

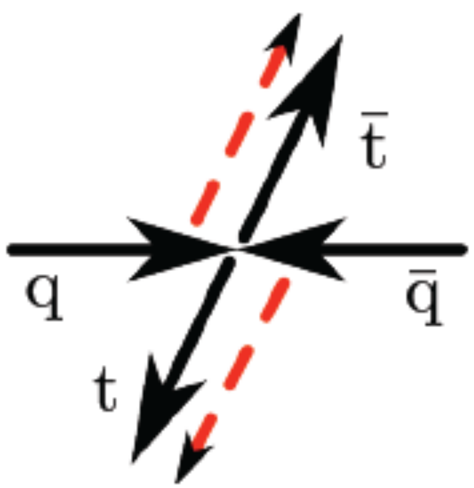
Summer 2011

Systematic source	δm_{top} (GeV)
method calibration	0.09
signal model	0.51
JES statistical	0.39
Residual jet energy scale	0.25
b-jet energy scale	0.15
Lepton p_T	0.10
Multiple hadron interactions	0.08
Detector model	0.10
Background MC	0.14
Background data	0.12
Total	**0.75**

Spin correlations: axis

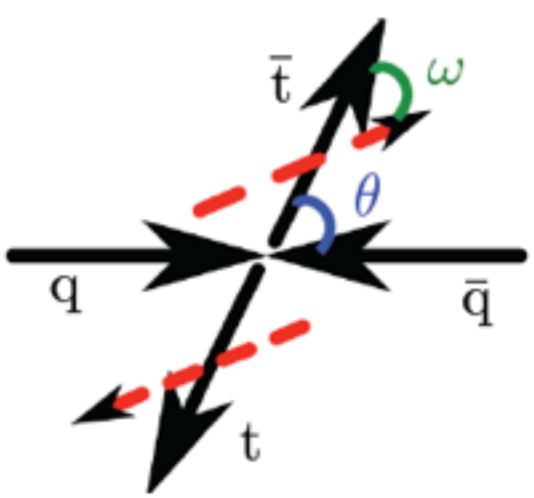


beamline: A = 0.777 at NLO
best for production at threshold



helicity: A = -0.352 at NLO
use direction of (anti)top quark in $t\bar{t}$ rest frame to quantize the spin

Helicity angle: angle between decay product momentum in top rest frame and top quark momentum in $t\bar{t}$ rest frame



$$\tan\omega = \sqrt{1-\beta^2}\tan\theta$$

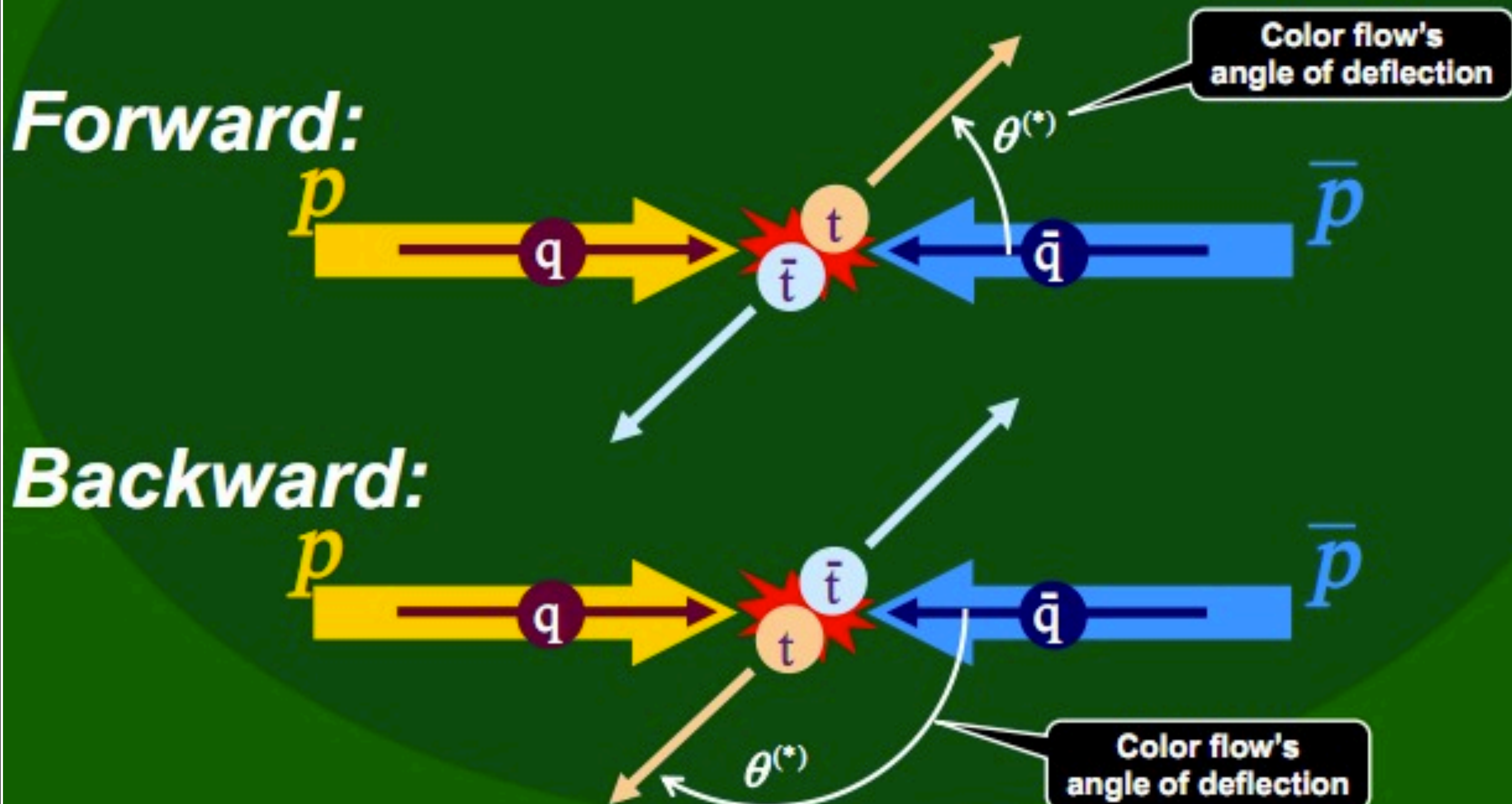
off-diagonal: A = 0.782 at MCNLO
good for pairs above threshold

Bernreuther, Brandenburger, Si and Uwer et al., Nucl. Phys. B 690, 81 (2004)

SM motivations

It's not about the incoming protons

It's about the incoming quarks and their QCD charges



Wednesday, October 26, 2011