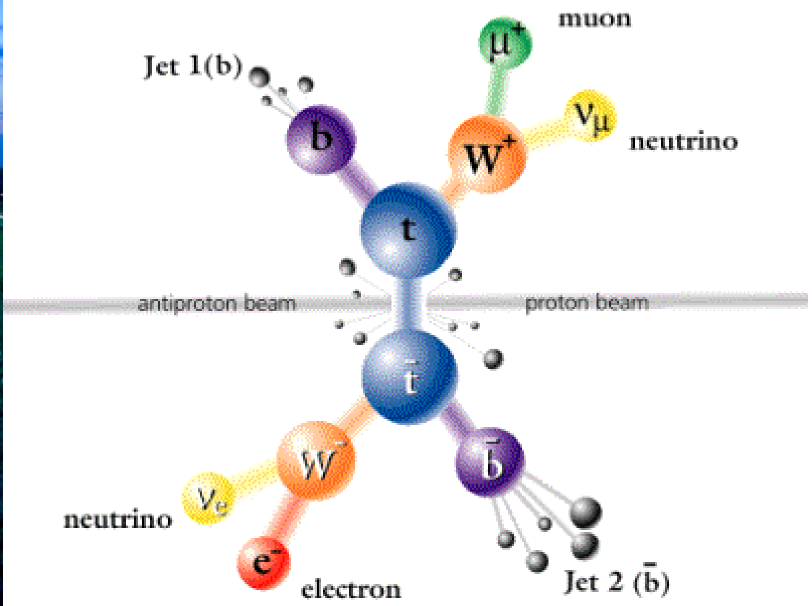
Recent top quark results from DØ

Boris Tuchming – Irfu/Spp CEA Saclay
on behalf of the
DØ collaboration



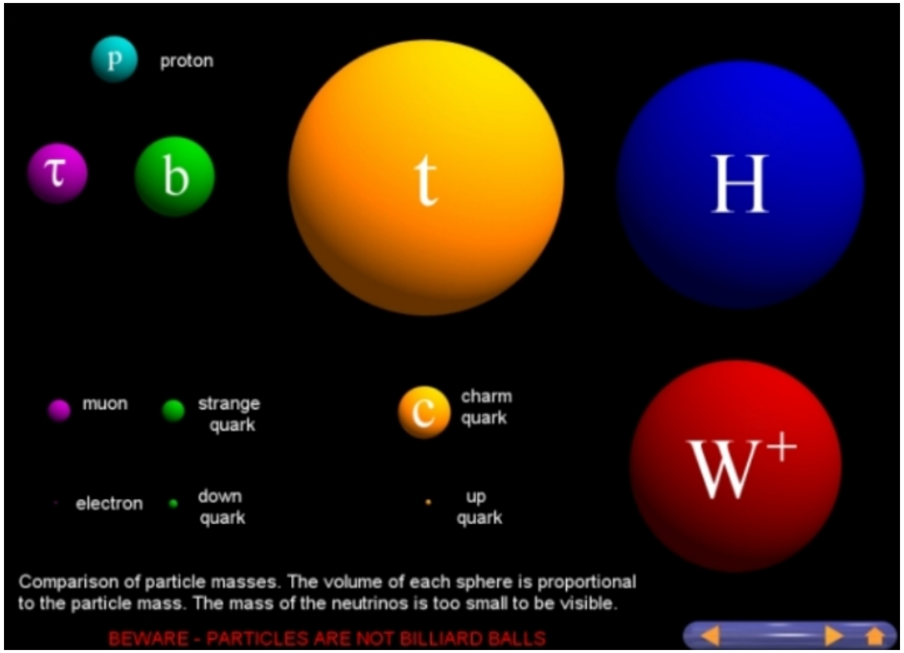
Outline

- Introduction
  - The top quark
  - Tevatron and D0
- Selection of events
  - Signatures
  - Lepton+jets events
  - Dilepton events
- New results
  - Inclusive cross-section
  - Mass
  - A_{FB} and Polarization

Top quark matters as particle of matter

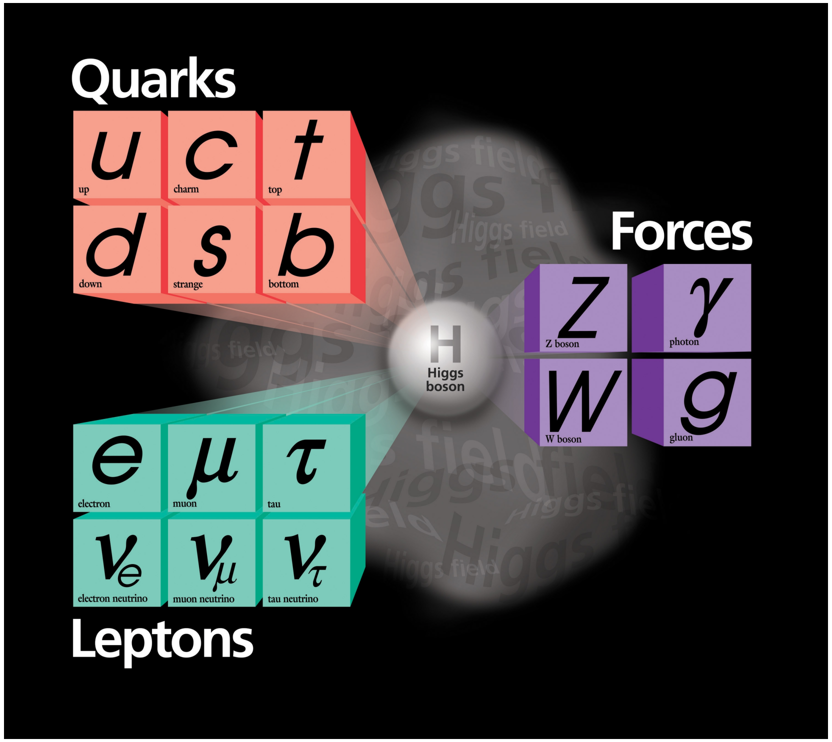
The heaviest known elementary particle

- With m_t~175 GeV, top quark is as heavy as a gold atom



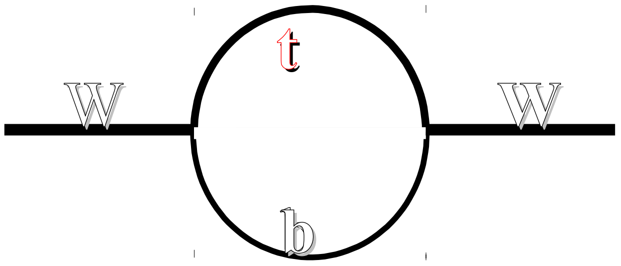
The heaviest known elementary particle

- With m_t~175 GeV, top quark is as heavy as a gold atom
- Large Yukawa couplings to Higgs boson

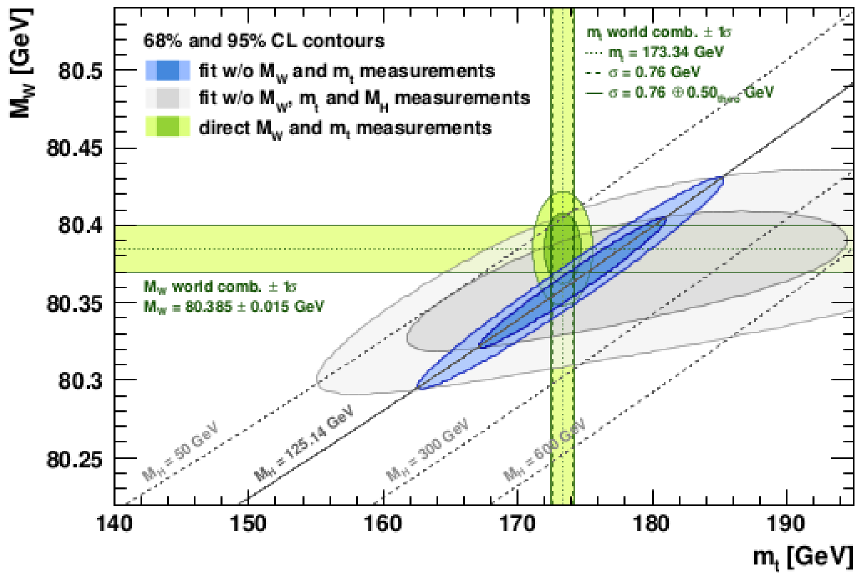


The heaviest known elementary particle

- With m_t~175 GeV, top quark is as heavy as a gold atom



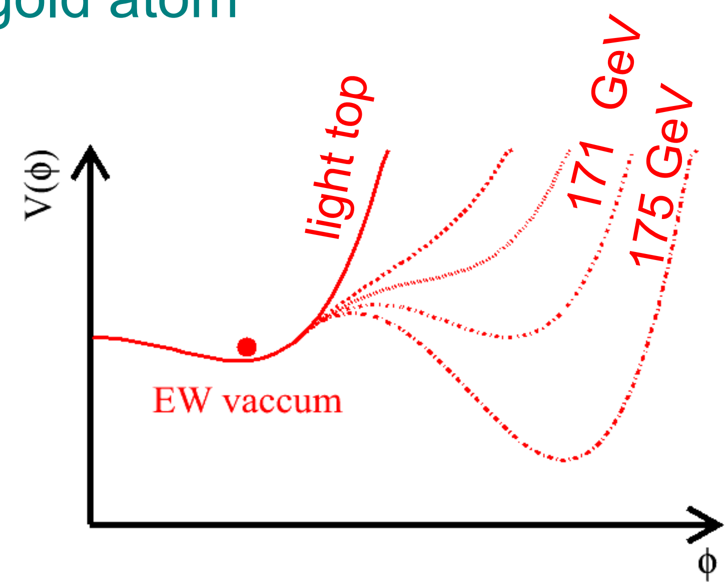
- Large Yukawa couplings to Higgs boson
- Large effects in loop corrections
  - Top mass is key parameter for SM consistency check
  - May play a major role in electroweak symmetry breaking mechanism.
    - Eg in dynamical electroweak symmetry breaking

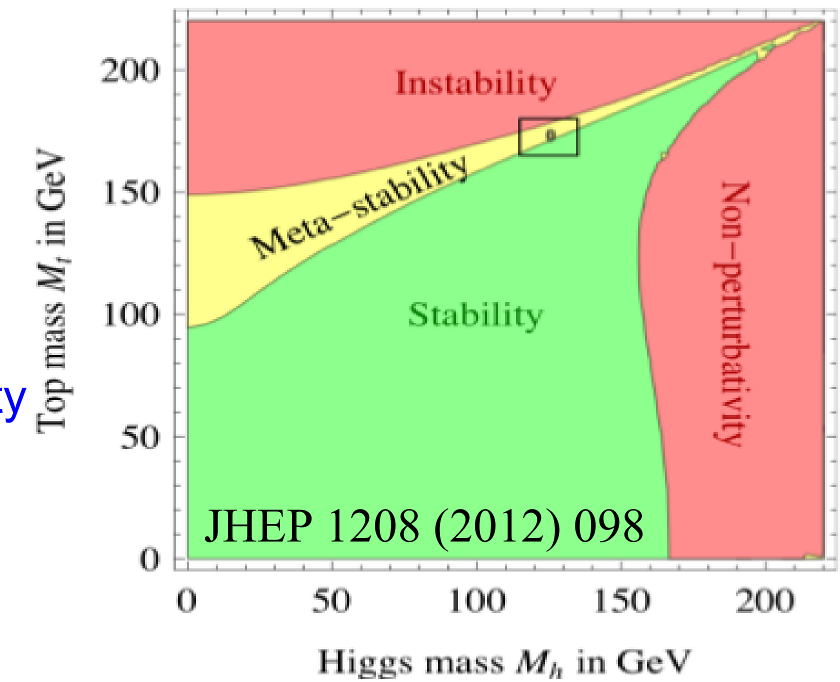


The heaviest known elementary particle

- With m_t~175 GeV, top quark is as heavy as a gold atom

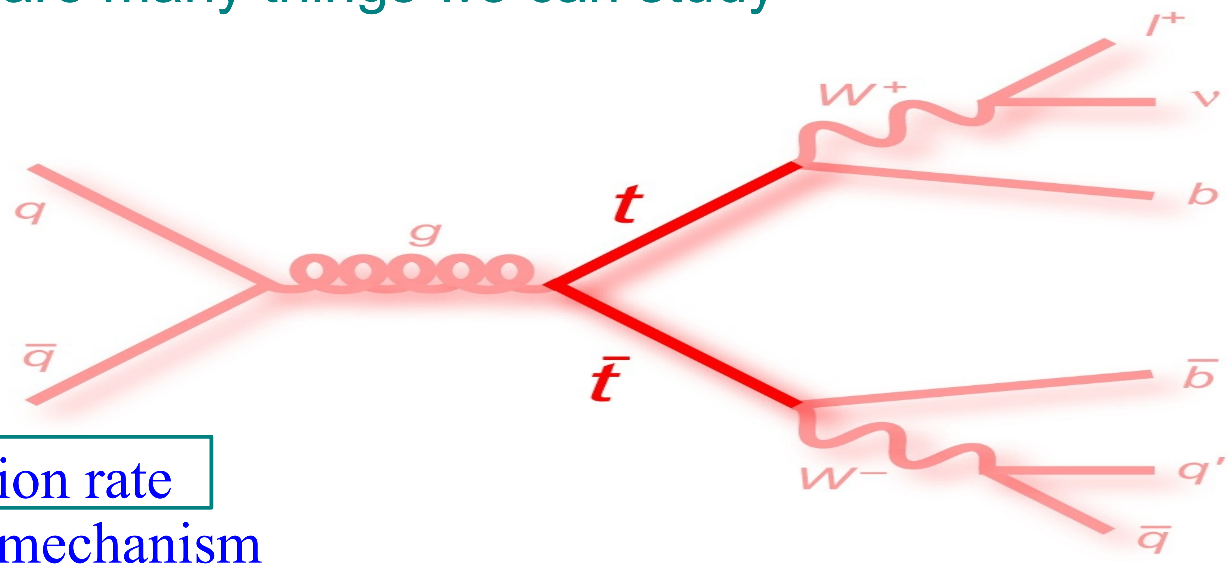
- Large Yukawa couplings to Higgs boson
- Large effects in loop corrections
  - Top mass is key parameter for SM consistency check
  - May play a major role in electroweak symmetry breaking mechanism.
    - Eg in dynamical electroweak symmetry breaking
  - May define the stability of our universe
    - Larger top masses yield EW vacuum instability





Top quark physics

- Large top mass implies
  - Mass is a key parameter of SM
  - May be a proxy to new physics at the TeV scale
  - Decays before hadronization since $m_t \times g^2_W > \Lambda_{QCD}$
    - Access to bare quark properties, e.g. spin
- So there are many things we can study



Production rate
Production mechanism
Production kinematics
Resonant production

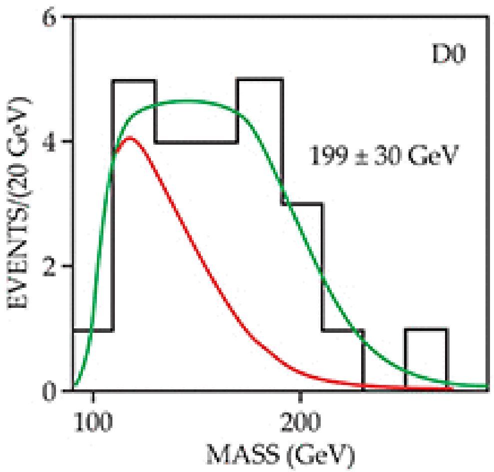
Mass
Width
Liftetime
Spin/Polarization
Charge

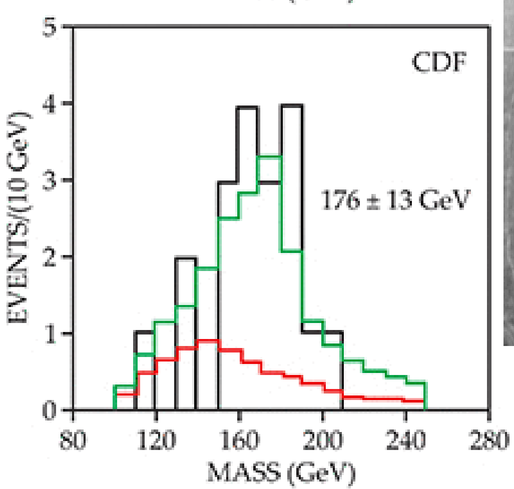
Branching ratio
Rare decay
Non SM decay
Anomalous coupling
V_{tb}

Tevatron and DØ

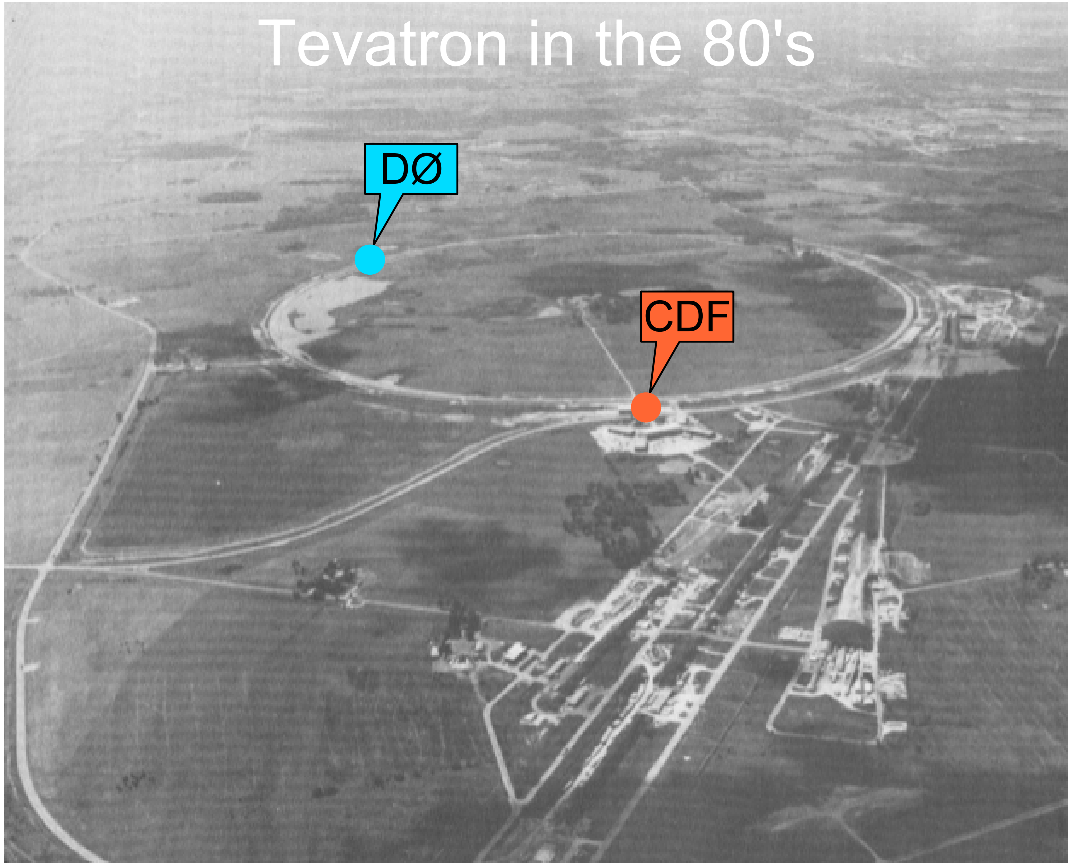
The Tevatron proton-antiproton collider

Birthplace of top quark in 1995
in $p\bar{p}$ collisions
in Run I at 1.8 TeV





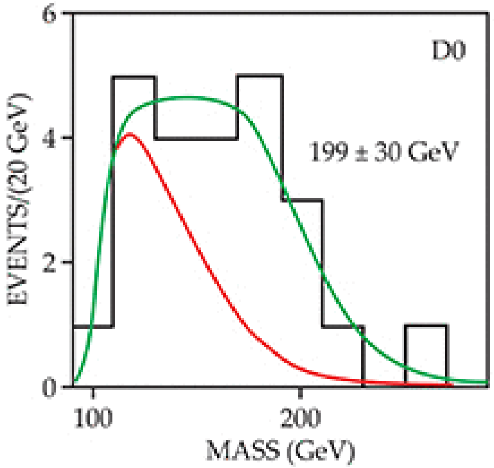
A handful of events

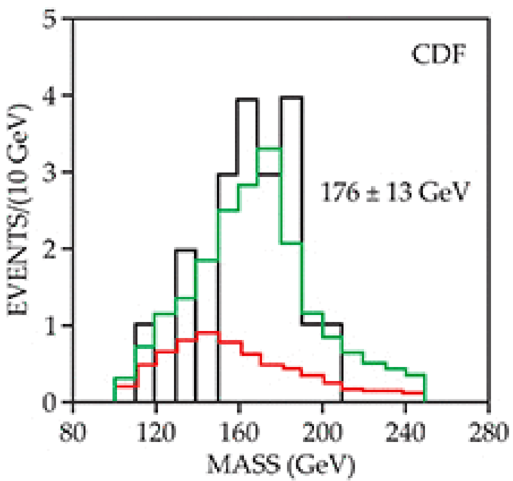


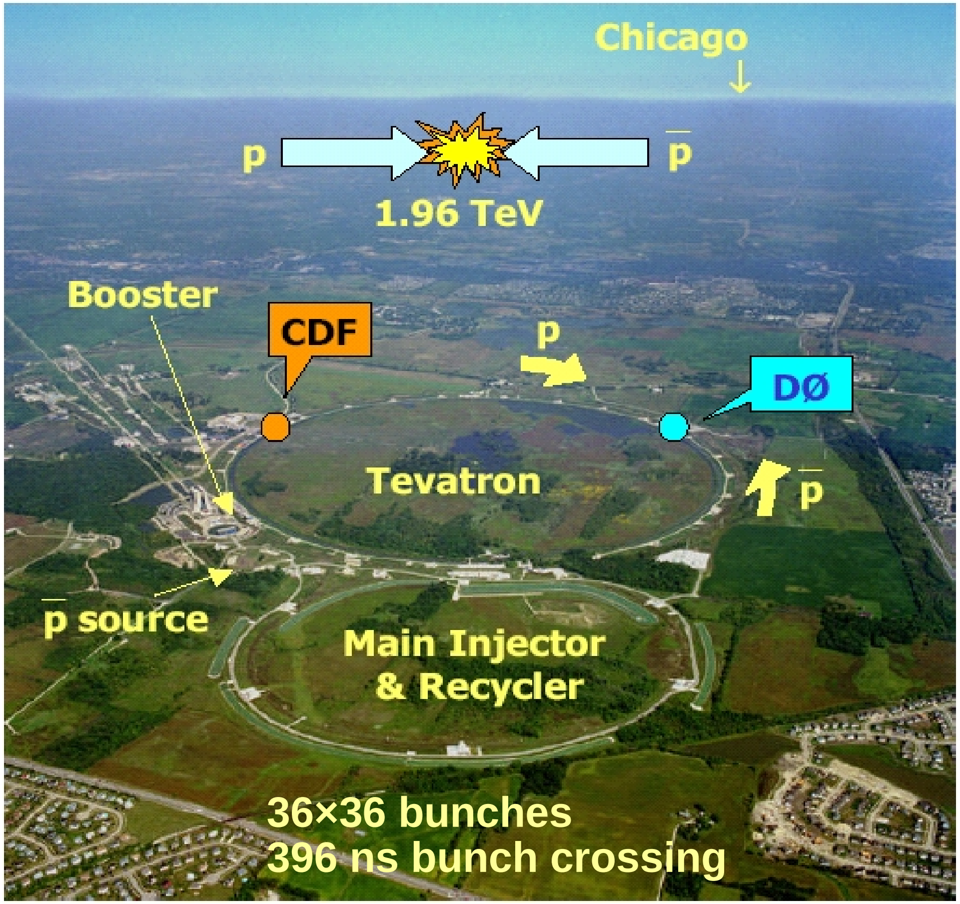
Tevatron Run I: (1993-1996)
~120 pb^{-1} per experiment

The Tevatron proton-antiproton collider

Birthplace of top quark in 1995
in $p\bar{p}$ collisions
in Run I at 1.8 TeV





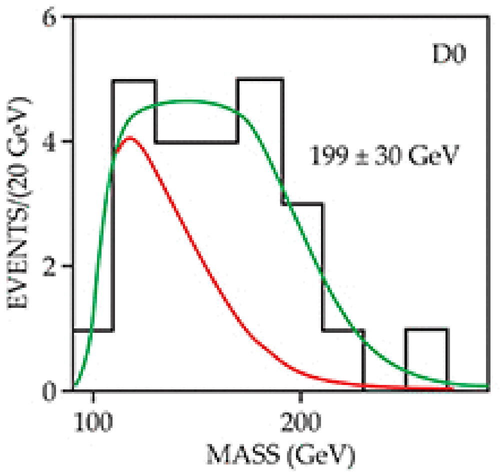


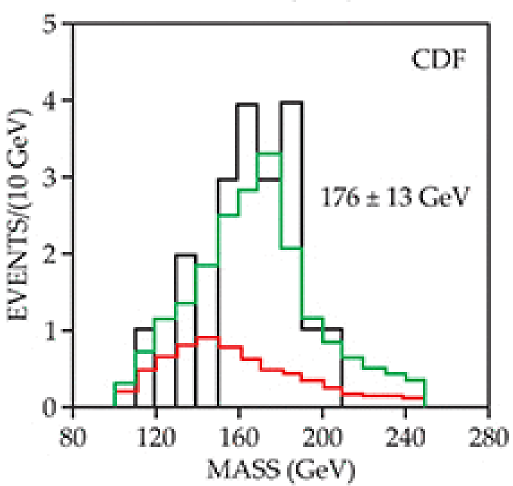
Tevatron Run II: (2001-2011)

A handful of events

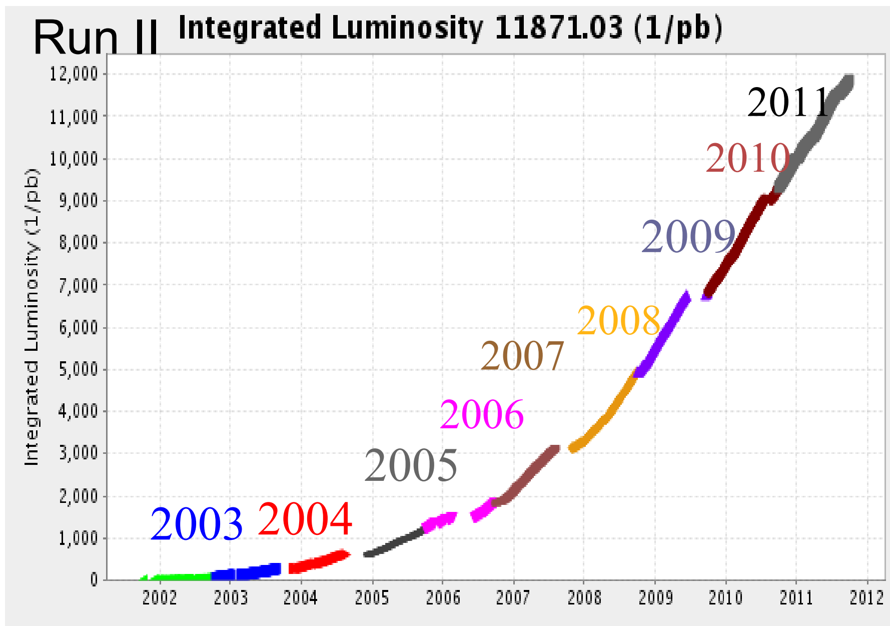
The Tevatron proton-antiproton collider

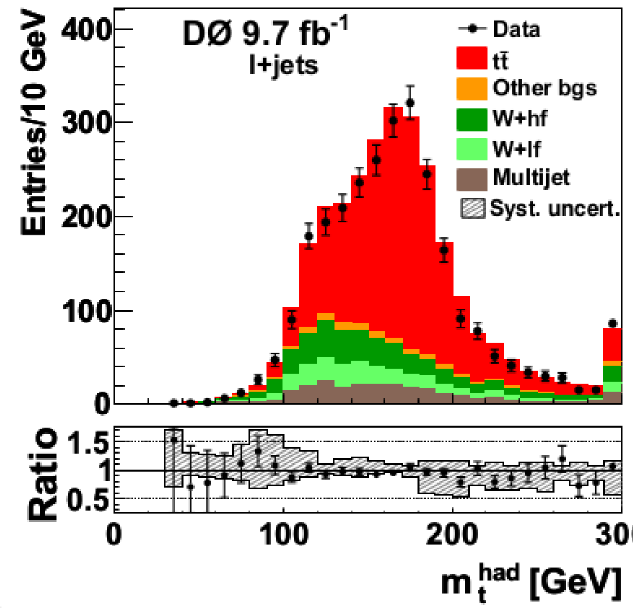
Birthplace of top quark in 1995
in pp collisions
in Run I at 1.8 TeV





A handful of events



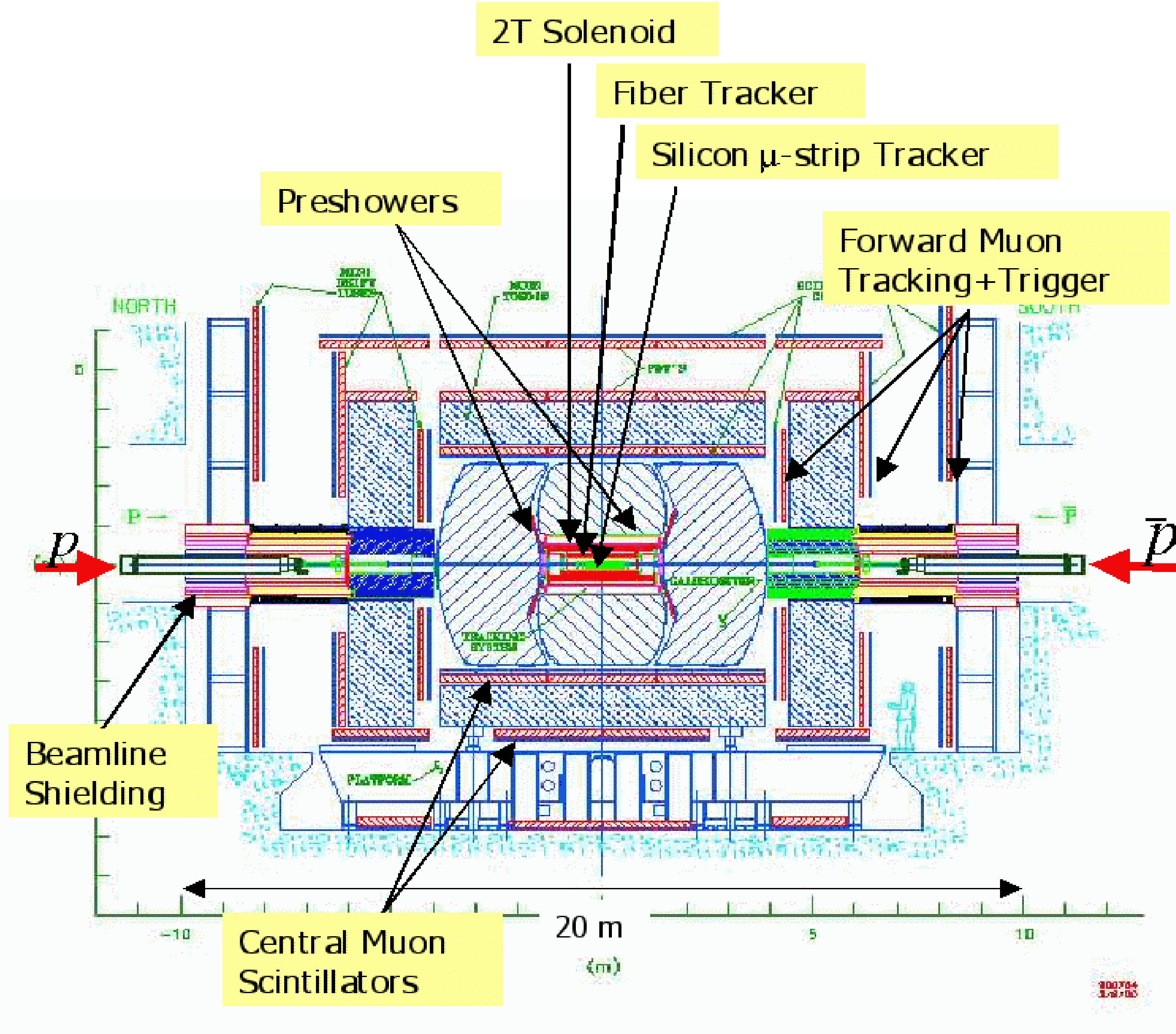


The results of today
rely on the full data set
with thousands of events

Tevatron Run II: (2001-2011)

- A decade of successful running
- Improved in performance over time
- ~12 fb^{-1} delivered per experiment
- ~9.5 fb^{-1} for analysis

D0 detector in Run II



- Tracking and vertexing
  - 2 Tesla Solenoid
  - Silicon (|η| < 3.0, r~10cm)
  - Fiber (|η| < 1.7, r~50 cm)
- Calorimetry
  - LAr/U
  - |η|<4.0
- Muons:
  - Drift chambers/Scintillators
  - |η| <2.0
- Typical coverage
  - Muons |η| < 2
  - Electrons
    - |η|<1.1
    - 1.5<|η|<2.5
  - Jets |η|< 2.5

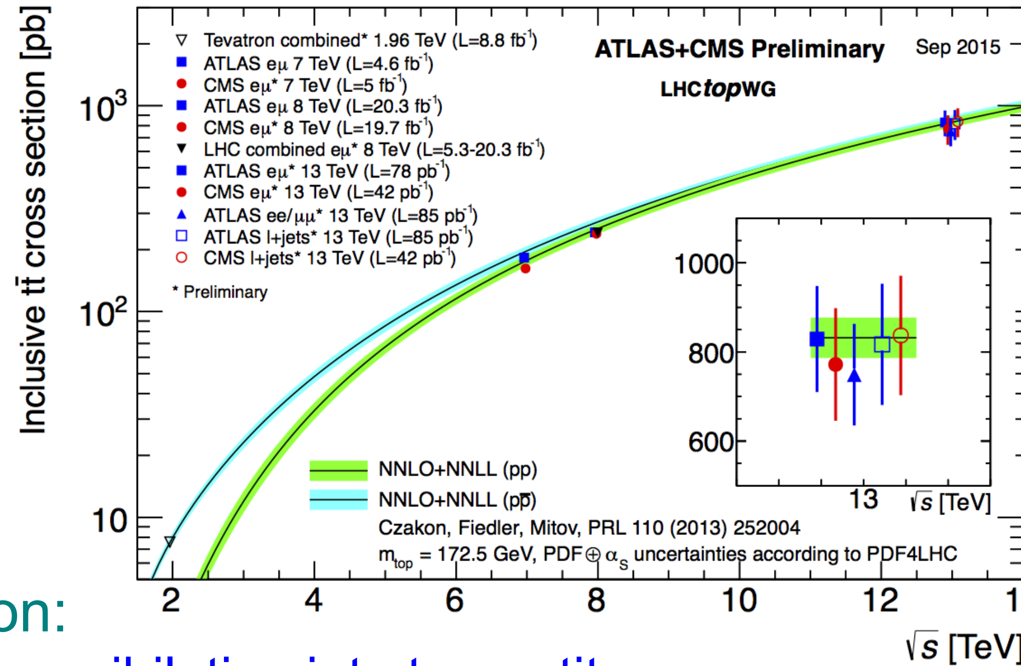
Top quark production and decay

Tevatron matters

Top mostly produced by pairs

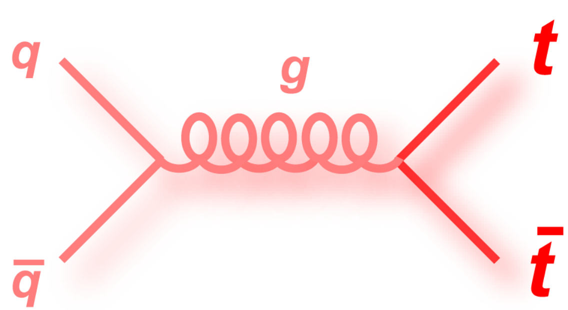
- I won't talk about EW single top production today

Nowadays LHC is by far THE top quark factory

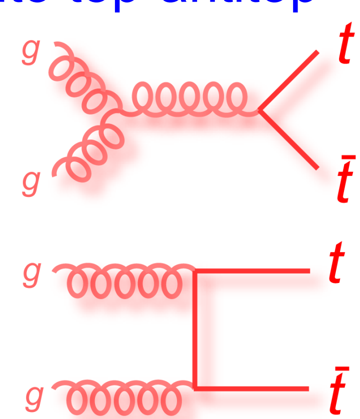


However

- Initial state is different at Tevatron:
  - We are probing quark-antiquark annihilation into top-antitop
  - LHC is probing gluon-gluon fusion



high purity (~85%) $q\bar{q}$ at Tevatron

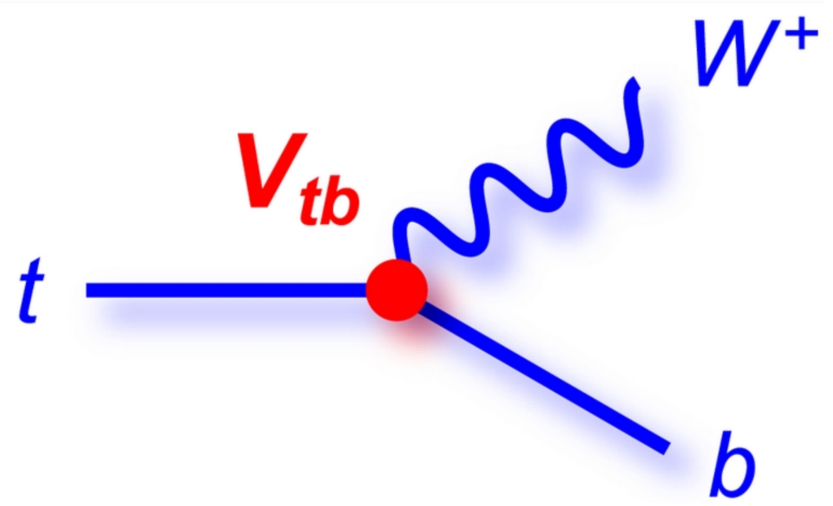


>85% gg at LHC

- We have a well calibrated and understood data set to perform precision measurements

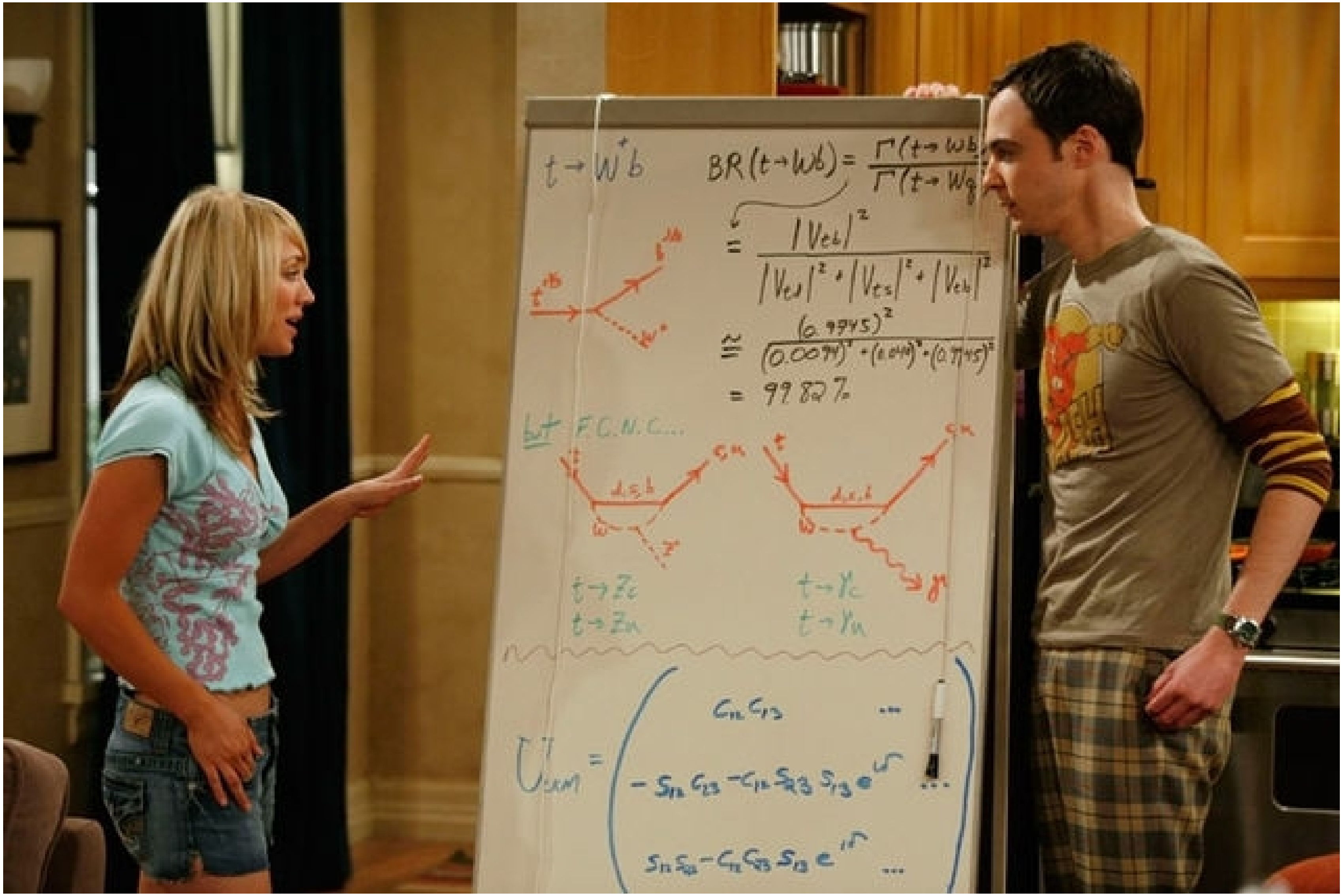
Top pair production signature

- Top decays into Wb (~100%).



Top pair production signature

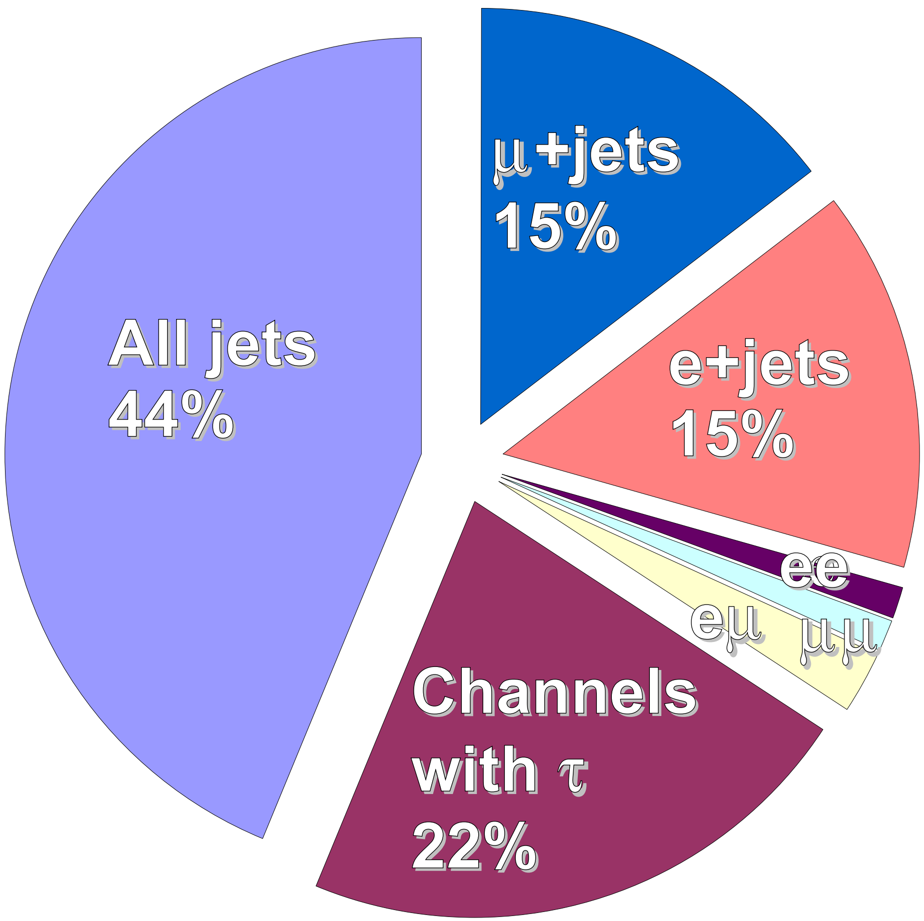
- Top decays into Wb (~100%).



- OK 99.82% to be more precise

Top pair production signature

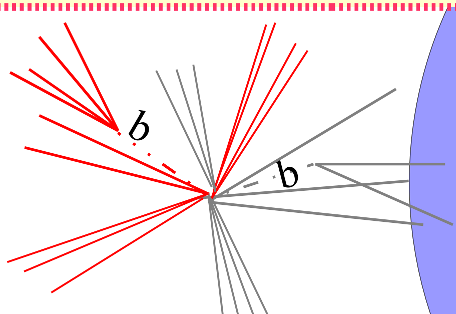
- Top decays into Wb (99.82%). Then W→ eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\ miss}$
  - Tagging of b-quark jets to improve purity

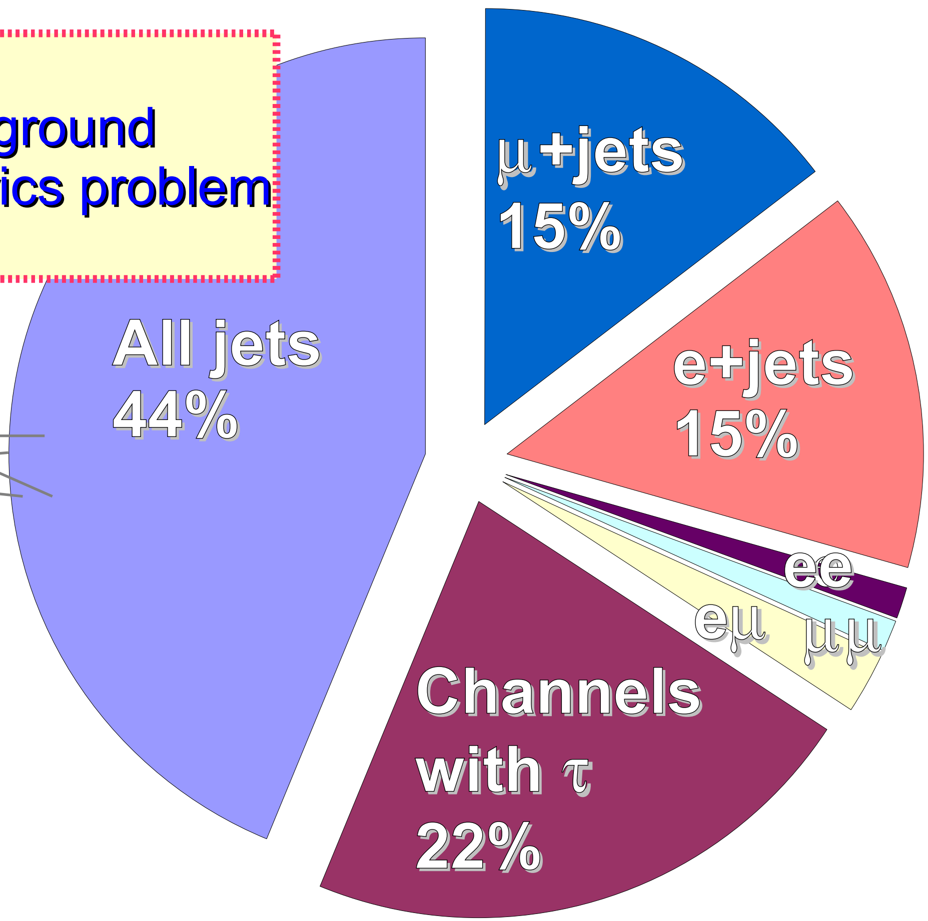


Top pair production signature

- Top decays into Wb (99.82%). Then W$\rightarrow$ eν or $\mu\nu$ or $\tau\nu$ or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\ miss}$
  - Tagging of b-quark jets to improve purity

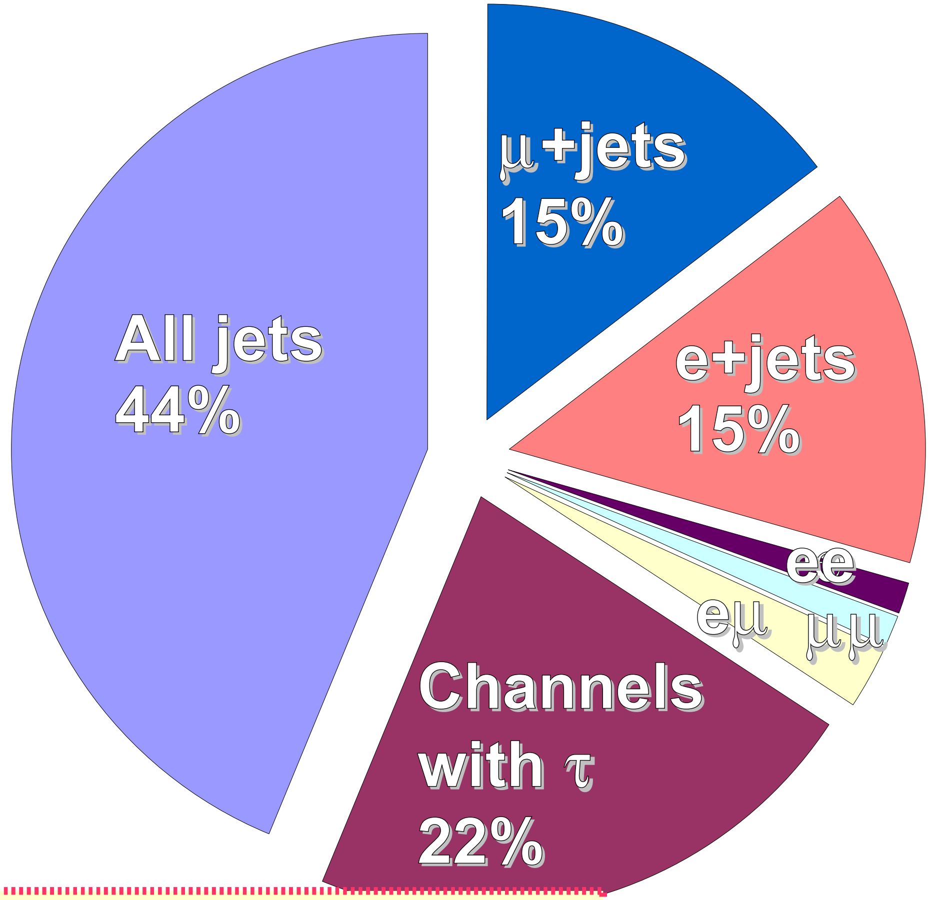
All jets channel
Large QCD background
Huge combinatorics problem
in $t\bar{t}$ reconstrution





Top pair production signature

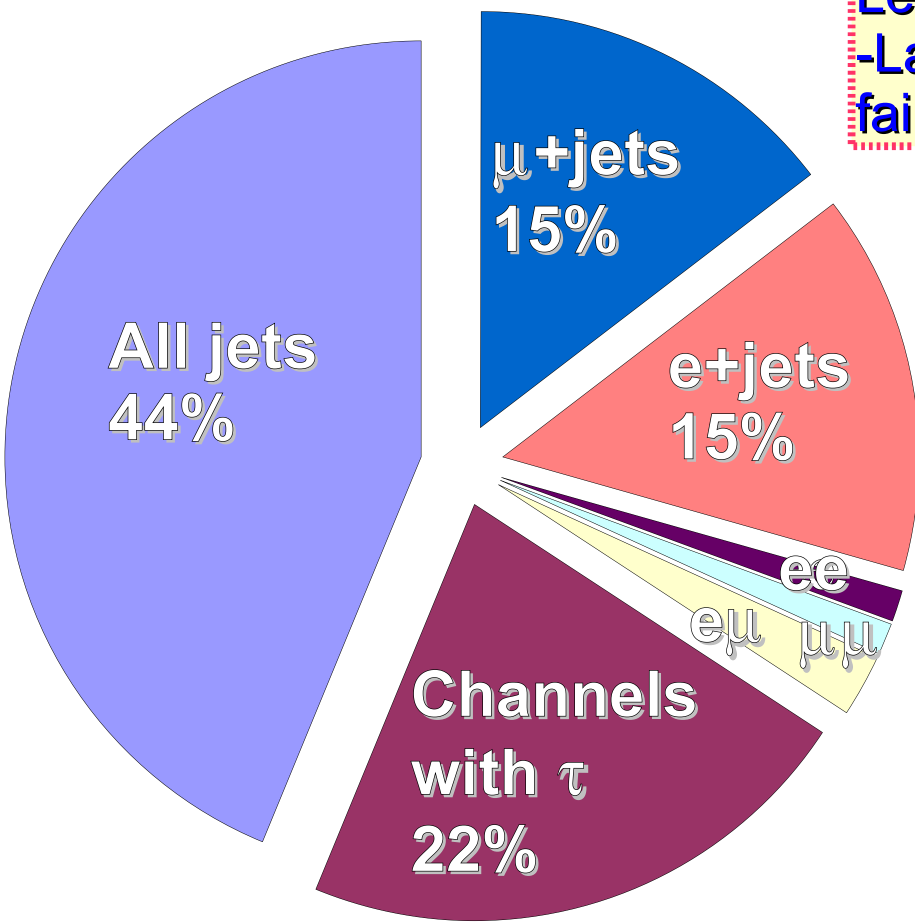
- Top decays into Wb (99.82%). Then W→ eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\ miss}$
  - Tagging of b-quark jets to improve purity



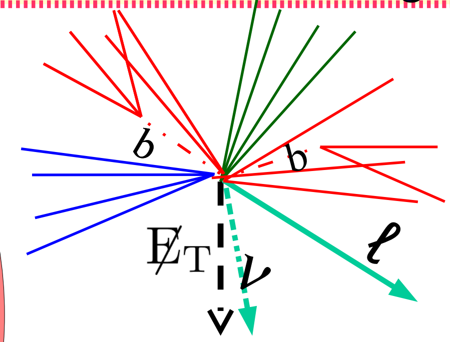
τ are hard to indentify.
Many sub-channels

Top pair production signature

- Top decays into Wb (99.82%). Then W→ eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\,miss}$
  - Tagging of b-quark jets to improve purity

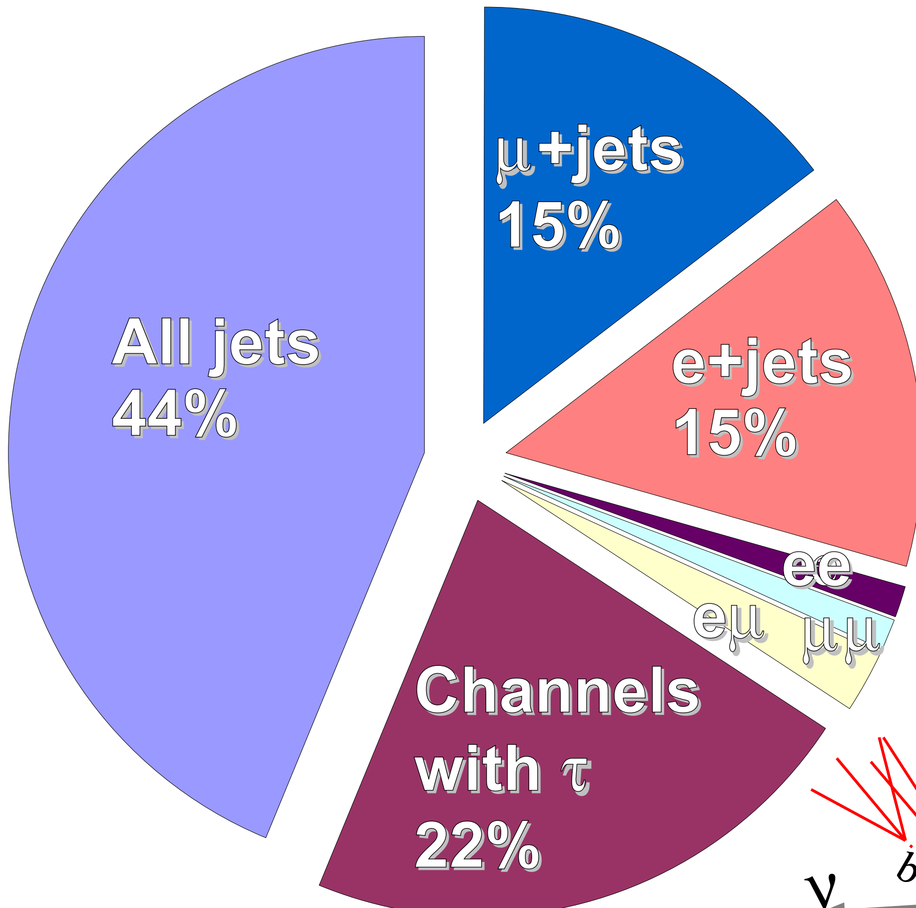


Lepton+jets channels:
-Large yield but
fair amount of background

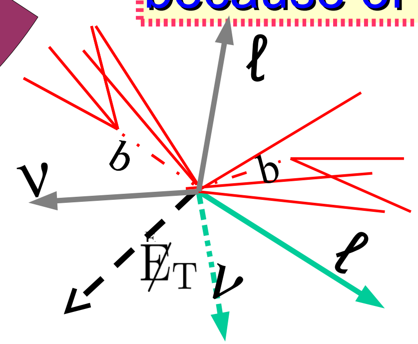


Top pair production signature

- Top decays into Wb (99.82%). Then W→ eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\ miss}$
  - Tagging of b-quark jets to improve purity

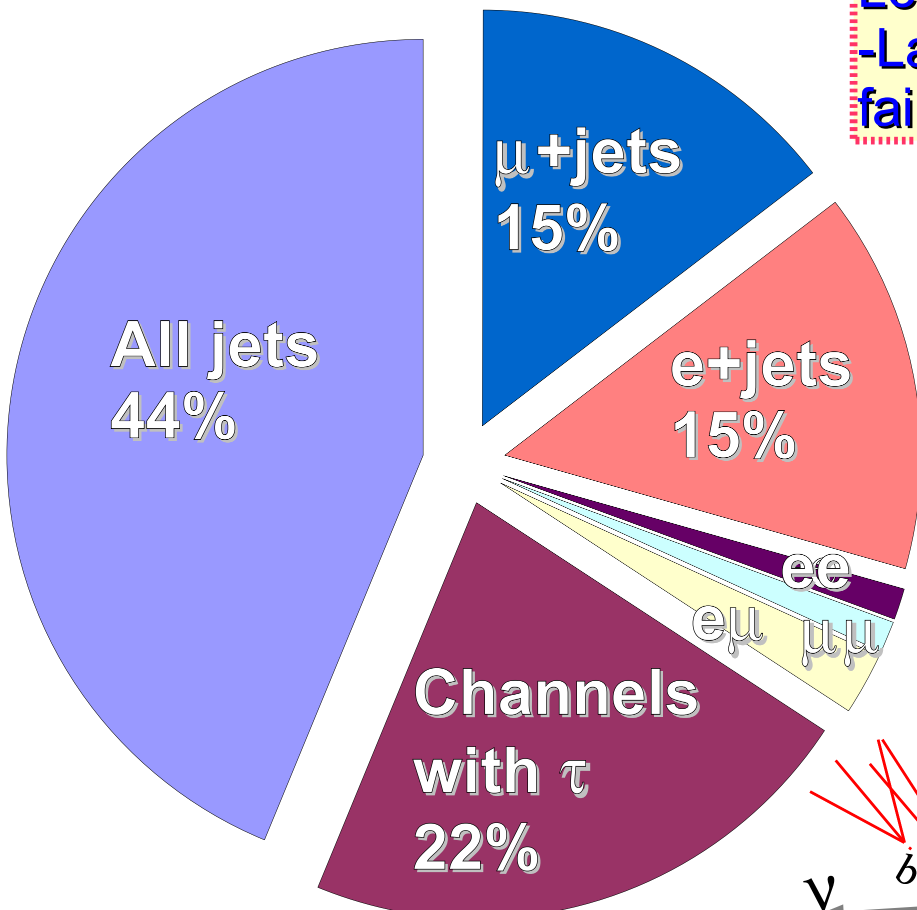


Dileptons channels:
- Pure, but low yield (4.5%).
- Kinematic underconstrained because of 2 neutrinos

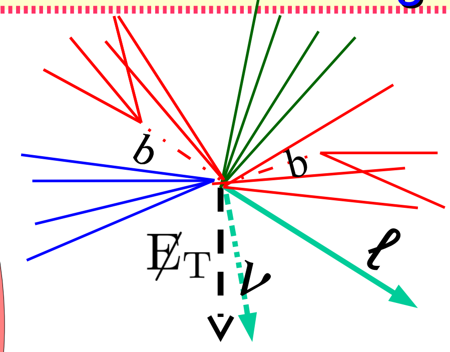


Top pair production signature

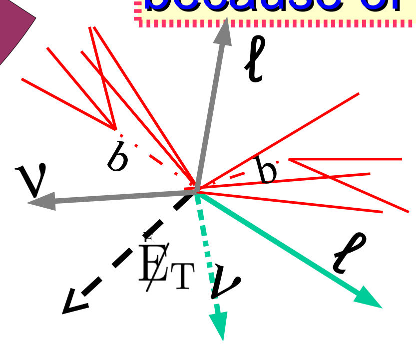
- Top decays into Wb (99.82%). Then W→ eν or μν or τν or jets.
  - Decay products with high momenta, large angular separation
  - Expect to reconstruct energetic objects: e, μ, jets, $E_{T\ miss}$
  - Tagging of b-quark jets to improve purity



Lepton+jets channels:
-Large yield but
fair amount of background

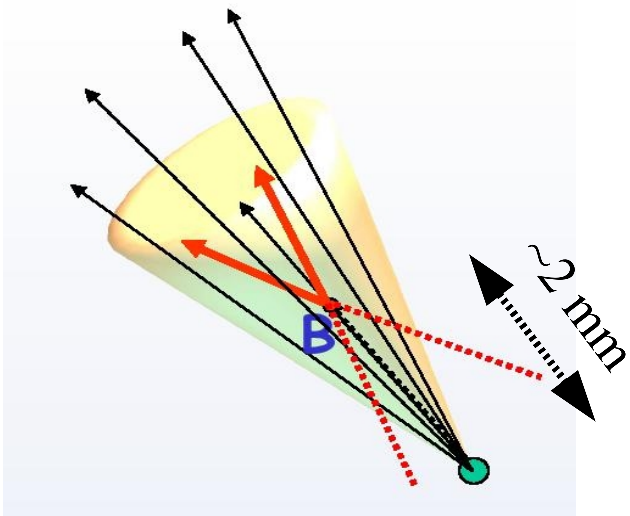


Dileptons channels:
- Pure, but low yield (4.5%).
- Kinematic underconstrained because of 2 neutrinos



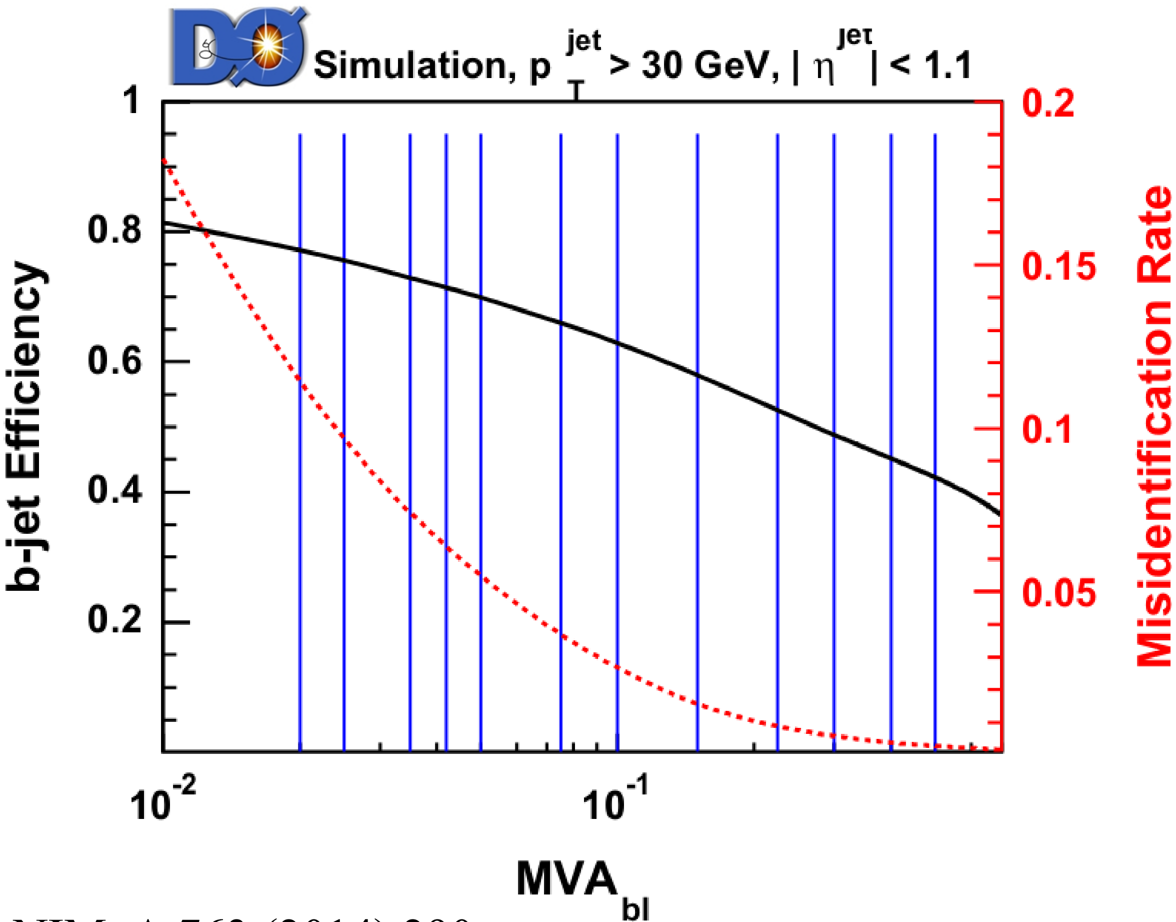
b-jet tagging to increase purity in $t\bar{t}$ pair

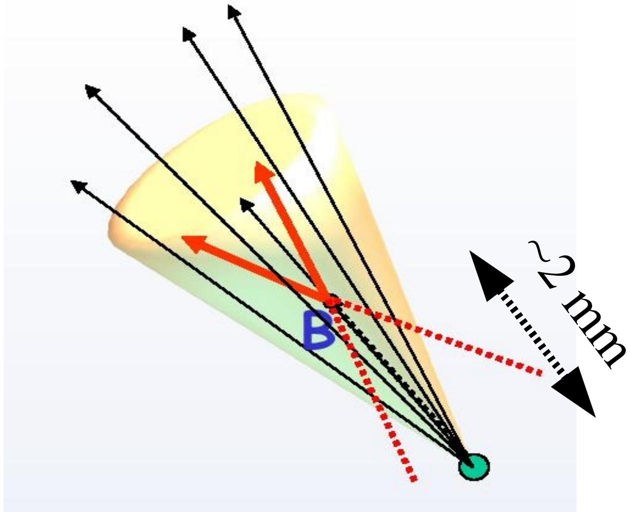
B-hadrons are long lived particles: $c\tau$~0.5 mm.
B-hadrons can decay semi-leptonically: b → $\mu\nu c$



Can make use of:
- High impact parameter of tracks
==> light quark Jet Probability
- Secondary vertex reconstruction (SVX)
- Lepton tag
- b-jet kinematics (large B-hadron mass)
- Combination of above with multivariate techniques

b-jet tagging to increase purity in $t\bar{t}$ pair





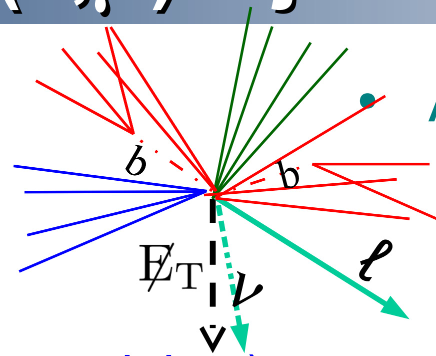
NIM A 763 (2014) 290

MVA Performance ~ ε=60% for 1.5% mis-tag @ P_T=50 GeV

Selection of candidate events

Leptons (e,μ) + jets channels

- Event signature:
  - Central, spherical
  - Hight p_T lepton
  - Large $E_{T\ miss}$
  - 3 or more jets (2 b-quark jets)



- Selection:
  - Single lepton and lepton+jets trigger
  - Isolated lepton p_T>20 GeV
  - $|\eta(\mu)|<2.0$, $|\eta(e)|<1.1$
  - $E_{T\ miss}$> 20 GeV
  - 3 jets p_T>20 GeV
- Further S/B enhancement
  - b-tagging
  - Kinematics
  - Analysis dependent

- Acceptance:
  - 10 – 20%
  - Signal simulated with
    - Alpgen+Pythia
    - MCatNLO + Herwig
- Backgrounds
  - W+jets (Wbbj, Wccj, Wjjj)
    - Determined with MC (Alpgen+Pythia)
    - Large uncertainty on the cross section ~20%: normalized on the DATA
  - Non-W (QCD: fake lepton)
    - Determined from data
  - WW + jets using MC

Leptons (e,μ) + jets channels

- Typical yield

	3 jets	4 jets	3 jets +b-tag	4 jets +b-tag
$t\bar{t}$ signal	~2500	~2400	~2000	~2000
purity in signal	~12%	~40%	~30%	65%
W+jets background	~65%	~45%	~50%	20%

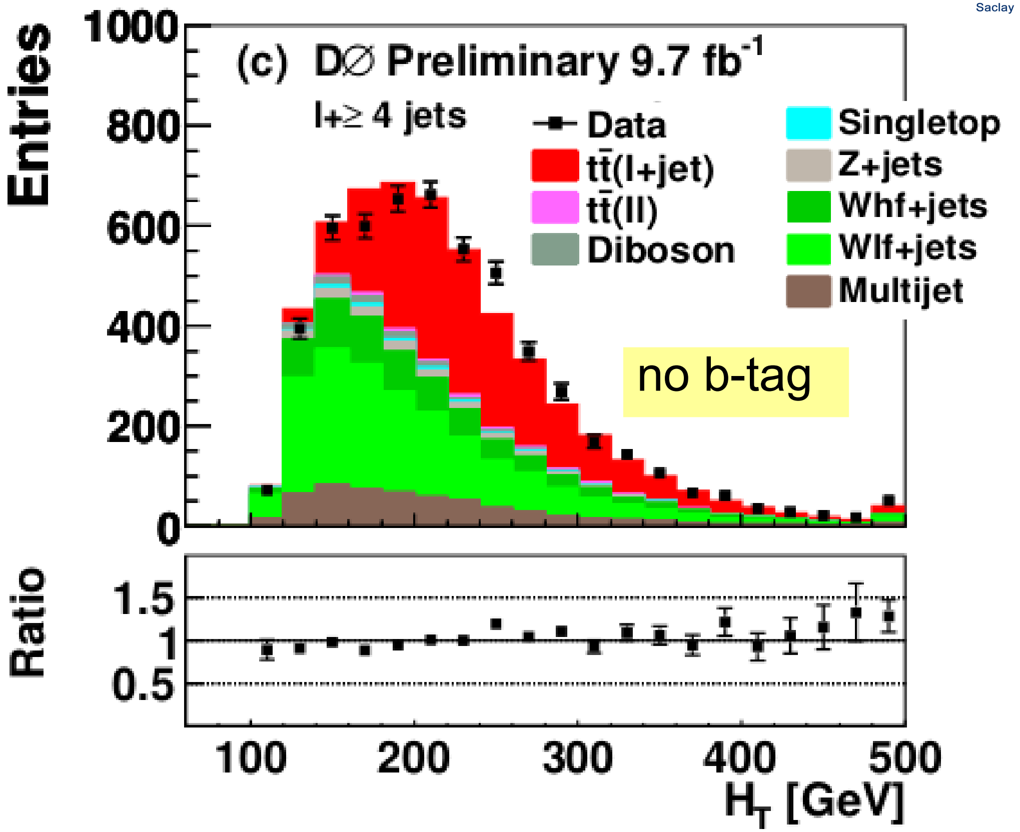
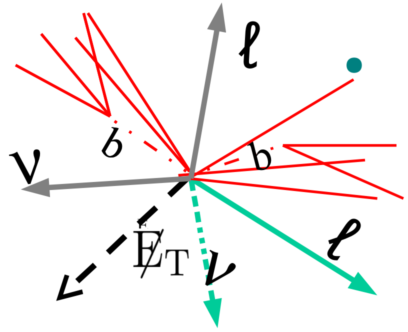


Table from polarization analysis
1 b-tag requirement

	3 jets		≥ 4 jets	
Source	e+jets	μ+jets	e+jets	μ+jets
W+jets	1741 ± 26	1567 ± 15	339 ± 3	295 ± 3
Multijet	494 ± 7	128 ± 3	147 ± 4	49 ± 2
Other Bg	446 ± 5	378 ± 2	87 ± 1	73 ± 1
$t\bar{t}$ signal	1200 ± 25	817 ± 20	1137 ± 24	904 ± 23
Sum	3881 ± 37	2890 ± 25	1710 ± 25	1321 ± 23
Data	3872	2901	1719	1352

Dilepton channels

- Event signature:
  - Central, spherical
  - 2 hight p_T leptons
  - large $E_{T\ miss}$
  - 2 b-quark jets



- Selection:
  - High p_T (di)-lepton trigger
  - Isolated leptons p_T>15 GeV
  - $|\eta(\mu)|<2.0$
  - $|\eta(e)|<1.1$ or $1.5<|\eta(e)|<2.5$
  - $E_{T\ miss}$ > 20 GeV
  - 2 jets p_T>20 GeV
- Further S/B enhancement
  - Topological cuts based on $H_T=\Sigma_i|p_{Ti}|$, $E_{T\ miss}$, $E_{T\ miss}$ significance
  - b-tagging
  - Analysis dependent

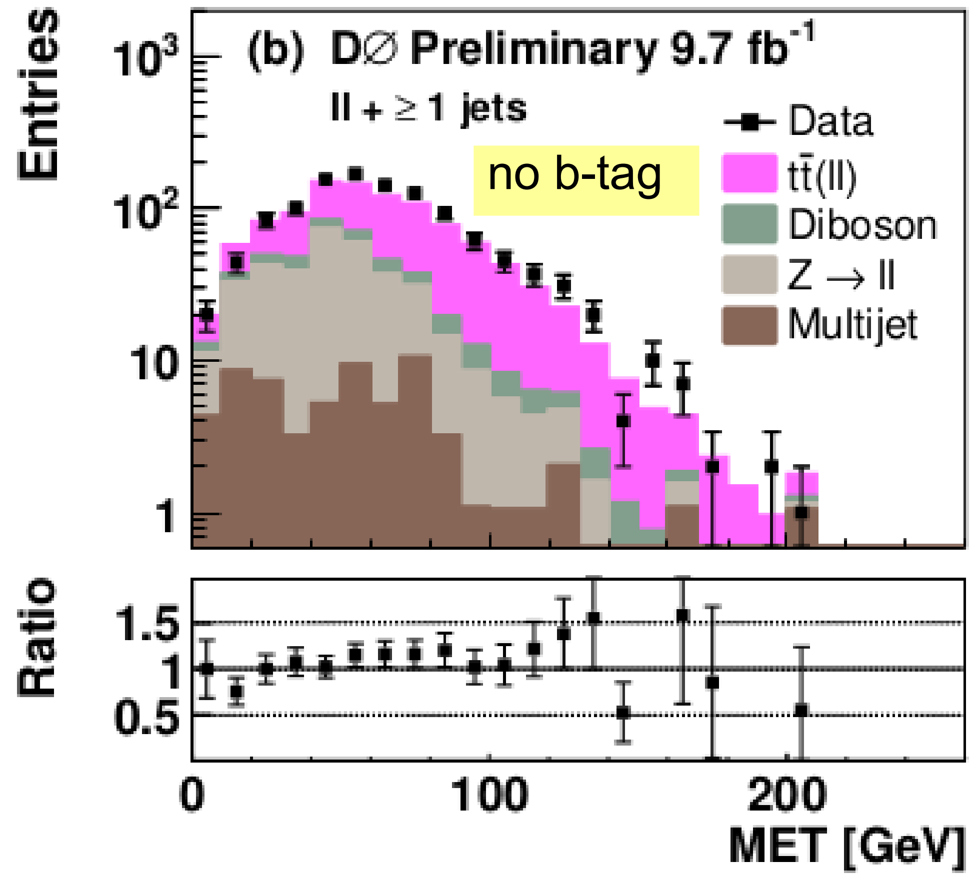
- Acceptance:
  - 10– 15%
  - Signal simulated with
    - Alpgen+Pythia
    - MCatNLO + Herwig

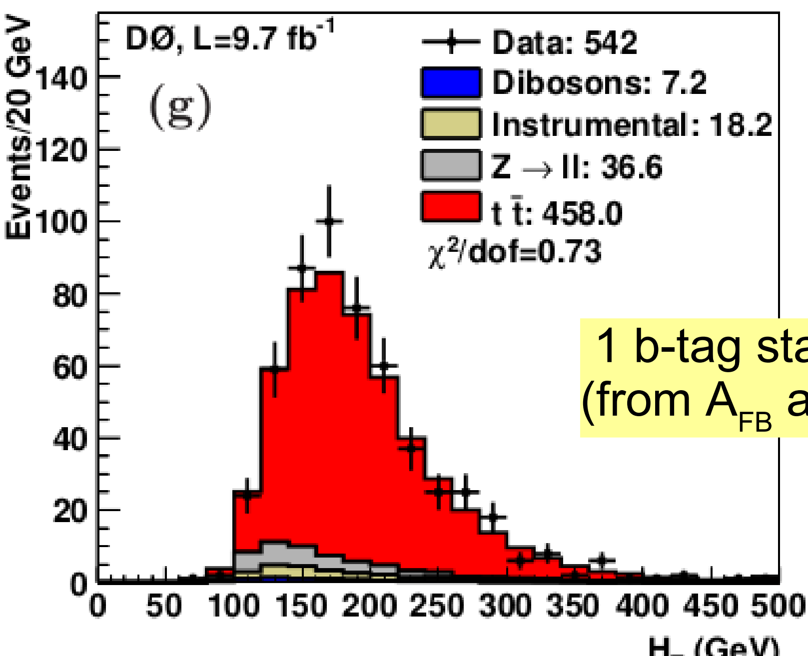
- Backgrounds:
  - $Z \rightarrow \mu\mu$, ee, $\tau\tau$ + jets
    - using MC
  - WW, WZ + jets
    - using MC
  - W+jets, QCD (fake lepton)
    - Determined from data

Dilepton channels

- Typical yield

	ℓℓ+2 jets eμ+1 jet	ℓℓ+2 jets +1 b-tag
$t\bar{t}$ signal	~600	~460
purity in signal	~55%	~88%
Z+jets background	~28%	~7%





1 b-tag stage (from A_{FB} analysis)

	$Z\to\ell\ell$	Dibosons	Instrumental	$t\bar{t}\to\ell\ell jj$	Total expected	Data
$\mu\mu$	$10.65^{+0.5}_{-0.5}$	$1.7^{+0.1}_{-0.1}$	$0.0^{+0.0}_{-0.0}$	$79.3^{+0.6}_{-0.6}$	$91.7^{+0.7}_{-0.7}$	92
$e\mu$	$13.03^{+0.5}_{-0.5}$	$3.7^{+0.2}_{-0.2}$	$16.4^{+0.7}_{-0.7}$	$283.1^{+1.0}_{-1.0}$	$316.2^{+1.3}_{-1.3}$	346
ee	$12.92^{+0.4}_{-0.4}$	$1.9^{+0.1}_{-0.1}$	$1.8^{+0.08}_{-0.08}$	$95.5^{+0.6}_{-0.6}$	$112.1^{+0.8}_{-0.8}$	104

Measurement of production cross-section

Strategy to measure cross-section

- Simplest method: “cut and count” $\sigma = \frac{N_{\rm sig} - N_{bkg}}{\mathcal{L} \times \mathcal{A}}$
- Disadvantages:
  - Issue when background suffers from large uncertainty.
    - Need to be constrained by (same) data
  - Mix together regions of phase space pure v.s. less pure in signal
- Our method:
  - Separate into different channels using lepton flavor, jet multiplicity
    - Different S/B, different background composition
  - Use shape of continuous discriminants which separate signal from background

Cross-section extracted from a likelihood fit with profiling

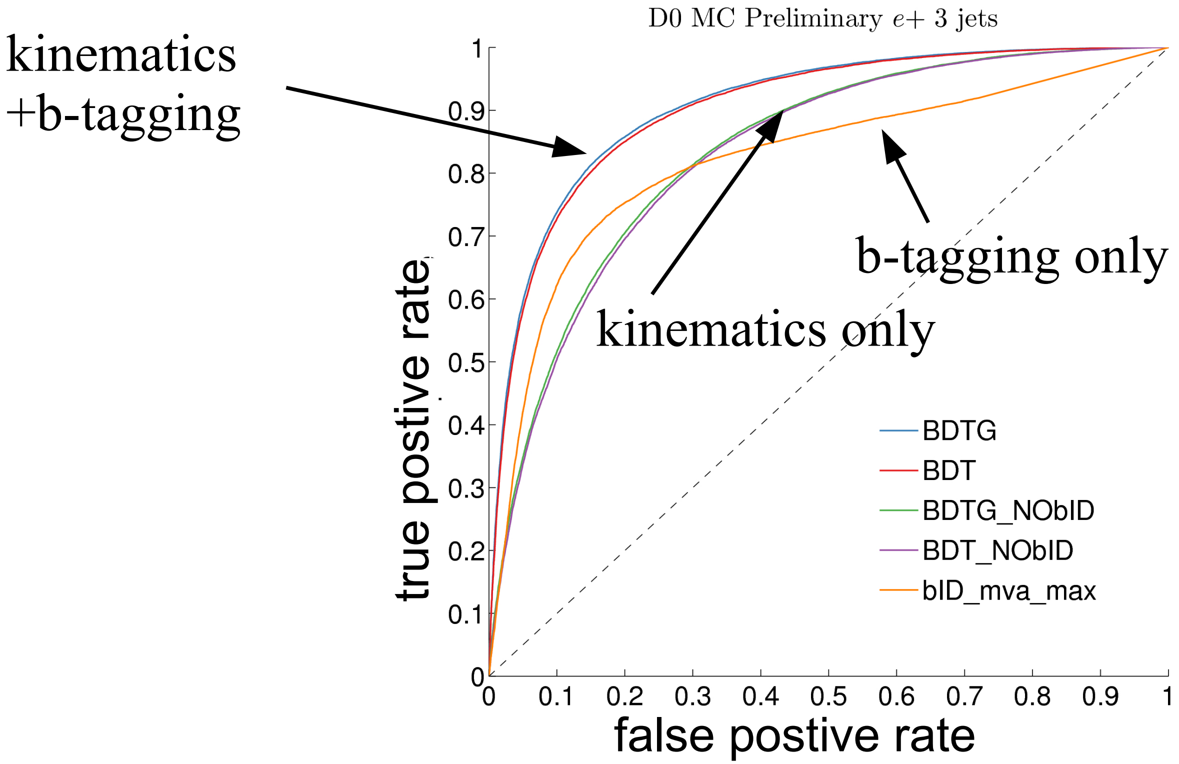
- Systematics treated as nuisance parameters
- Perform simultaneous fit of signal and nuisance parameters
  - Backgrounds with large uncertainties (W+jets) are constrained by data
- Reduces impact of systematic uncertainties thanks to correlation across channels.

$$\mathcal{L}(\vec{s}, \vec{b} | \vec{n}, \vec{\theta}) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{\rm bins}} \mu_{ij}^{n_{ij}} \frac{e^{-\mu_{ij}}}{n_{ij}!} \times \prod_{k=1}^{n_{\rm sys}} e^{-\theta_k^2/2}$$

$$\mu_{ij} = s_{ij}(\vec{\theta}) + b_{ij}(\vec{\theta})$$

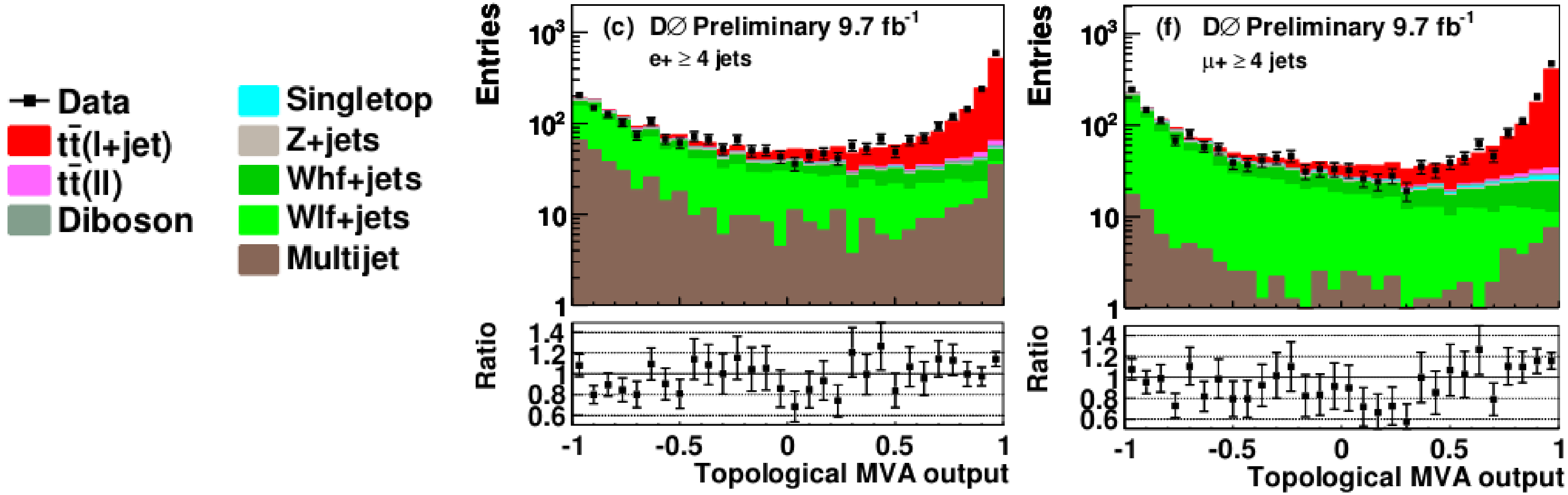
Lepton+jets mutivariate analysis

- Large background
- Use multivariate analysis to discriminate signal against background
  - Train separately MVA according to jet multiplicity and lepton flavor
  - Try to reduce dependence of acceptance as a function of top mass hypothesis
  - Use ~ 30 variables, well modeled by MC
    H_T, aplanarity, sphericity, M_T(jets), lepton p_T, b-tagging ..
  - Mix kinematics information and b-tagging
  - Use "gradient boosted" decision tree.

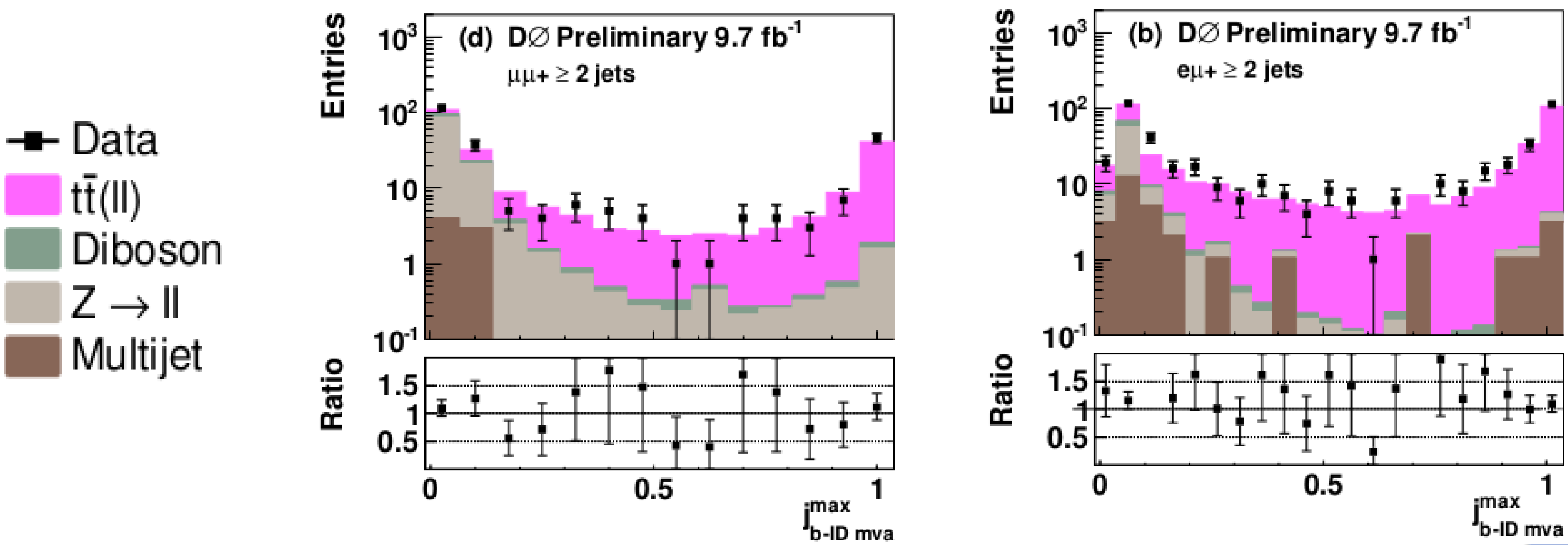


Signal vs background separation

- ℓ+jets: use MVA mixing kinematics and b-tagging



- Dilepton: use b-tag discriminant



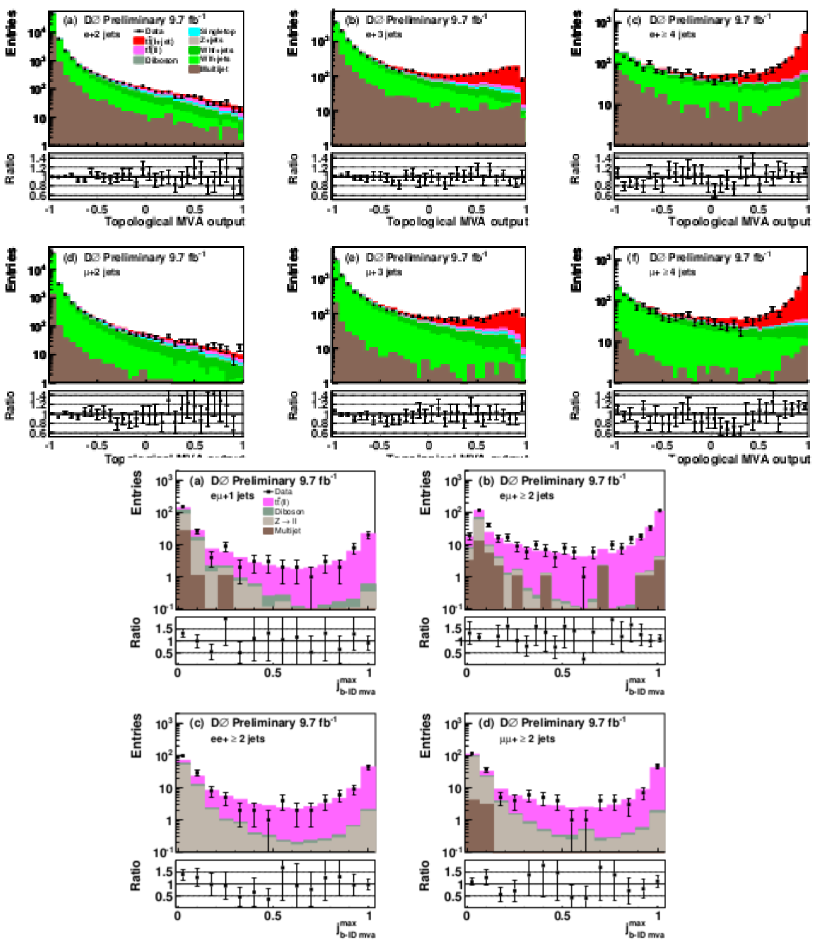
Inclusive cross-section

Simultaneous fit of dilepton and lepton+jets channels

$\sigma(t\bar{t})$= 7.73 ± 0.13 (stat) ± 0.55 (syst) pb
(for m_t = 172.5 GeV)

$\delta\sigma/\sigma = 7.3\%$

D0-Conf-6453



Source of uncertainty	Uncertainties δ_{combined}, pb
Modeling of signal	
Alternative signal model	±0.09
Hadronization	±0.25
Color reconnection	±0.11
ISR/FSR variation	±0.06
PDF	±0.08
Modeling of detector	
Jet modeling & identification	±0.06
b-jet modeling & identification	±0.16
Lepton modeling & identification	±0.02
Trigger efficiency	±0.01
Luminosity	±0.20
Sample Composition	
MC cross sections & branching ratios	±0.03
Z/W p_T reweighting	±0.16
Multijet contribution	±0.09
W+jets heavy flavor scale factor	±0.15
W+jets light parton scale factor	±0.05
MC statistics	±0.01
Total systematic uncertainty	±0.55

Inclusive cross-section

Simultaneous fit of dilepton and lepton+jets channels

$\sigma(t\bar{t})$= 7.73 ± 0.13 (stat) ± 0.55 (syst) pb
(for m_t = 172.5 GeV)

$\delta\sigma/\sigma = 7.3\%$

D0-Conf-6453

- Dominant uncertainties
  - Signal model (hadronization)
  - Luminosity
- Sensitivity limited by systematics
  - Not a large improvement relative to 5.3 fb^{-1} result (7.56±0.59 pb)
- Result in good agreement with theory:
  - σ_{th}=7.35 ± 0.25 pb assuming m_t=172.5 GeV

Baernreuther, Czakon & Mitov
PRL 109, 132001 (2012)

Source of uncertainty	Uncertainties δ_{combined}, pb
Modeling of signal	
Alternative signal model	±0.09
Hadronization	±0.25
Color reconnection	±0.11
ISR/FSR variation	±0.06
PDF	±0.08
Modeling of detector	
Jet modeling & identification	±0.06
b-jet modeling & identification	±0.16
Lepton modeling & identification	±0.02
Trigger efficiency	±0.01
Luminosity	±0.20
Sample Composition	
MC cross sections & branching ratios	±0.03
Z/W p_T reweighting	±0.16
Multijet contribution	±0.09
W+jets heavy flavor scale factor	±0.15
W+jets light parton scale factor	±0.05
MC statistics	±0.01
Total systematic uncertainty	±0.55

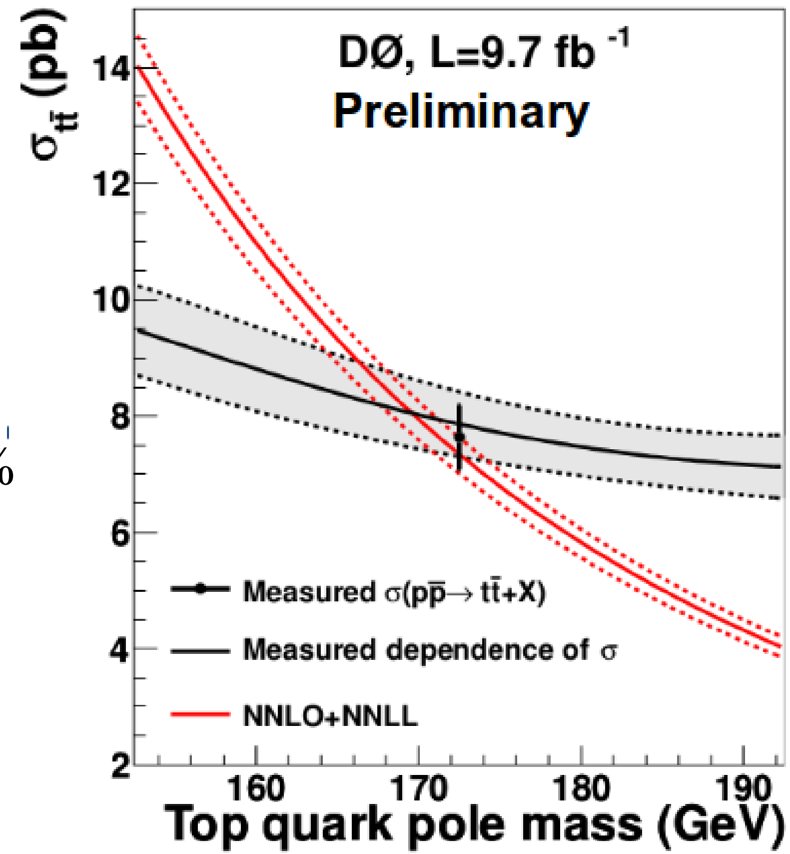
Top mass from cross-section

- Exploit dependence as a function of top mass
  - Measure cross-section for different top mass hypotheses
    - Dependence due to variation of acceptance
  - The theoretical prediction depends on the top "pole mass"
    - Use NNLO+NNLL pQCD calculation top++
- Construct a Bayesian posterior probability of the top mass
  - Flat prior on top mass
- Extract top mass
  - Advantage: well defined "pole mass", as opposed to "MC mass" obtained in direct measurement

m_t = 169.4±1.2 (theo) ±3.5 (exp) GeV
m_t = 169.4 ± 3.7 GeV

$\delta m_t/m_t = 2.2\%$

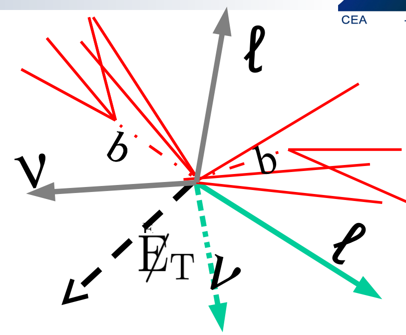
D0-Conf-6453



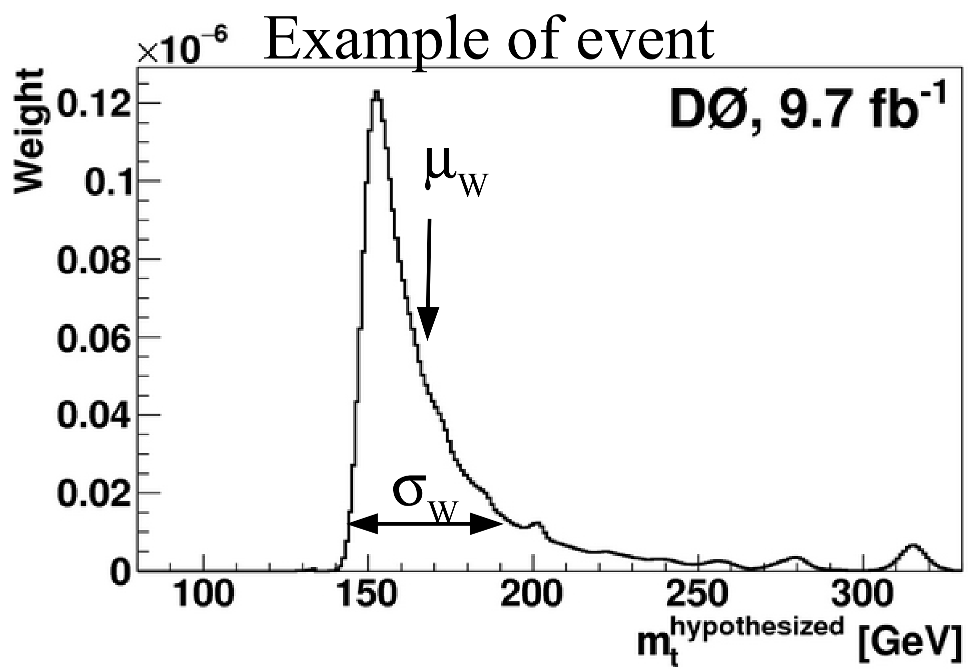
- Improvement over the 5.3 fb^{-1} result $167.5^{+5.2}_{-4.7}$ GeV (PLB 703, 422 (2011)) due to reduced dependence of measurement vs mass

Direct measurement of the mass in dilepton events

Method to measure top mass in dilepton events

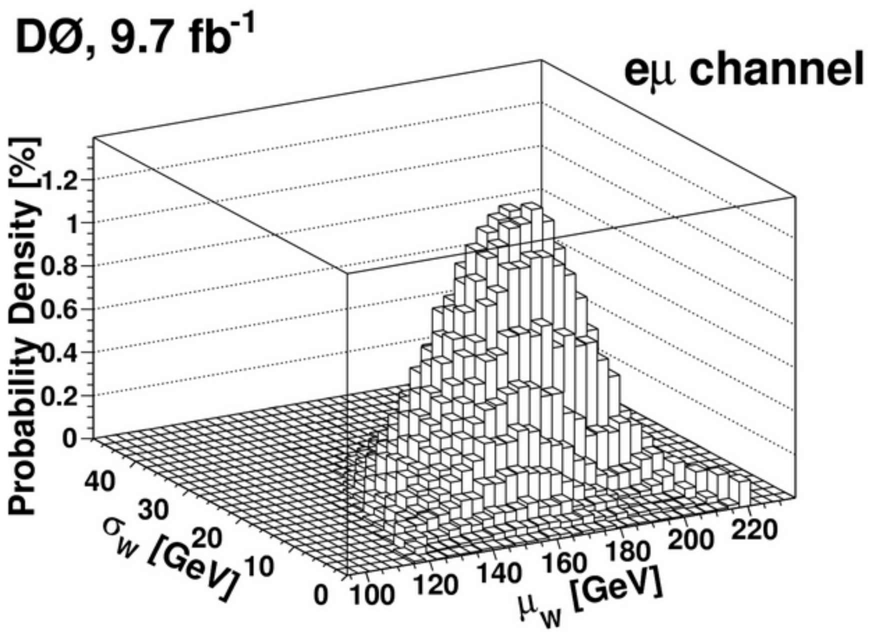


- Kinematic underconstrained because of two neutrinos
- Extract sensitive information with "neutrino weighting method"
- For each event
  - Fix a top mass hypothesis $m_t^{hypothesized}$
  - Assume a given pseudorapidity for the neutrinos (use a Gaussian prior)
  - Solve kinematics and compute likelihood measuring agreement between calculated and observed $E_{T\ miss}$
  - Integrate over neutrino directions
  - → Obtain a likelihood (or weight) as a function of $m_t^{hypothesized}$
- Extract 2 observables per event
  - Mean and RMS (μ_W, σ_W) of weight distribution



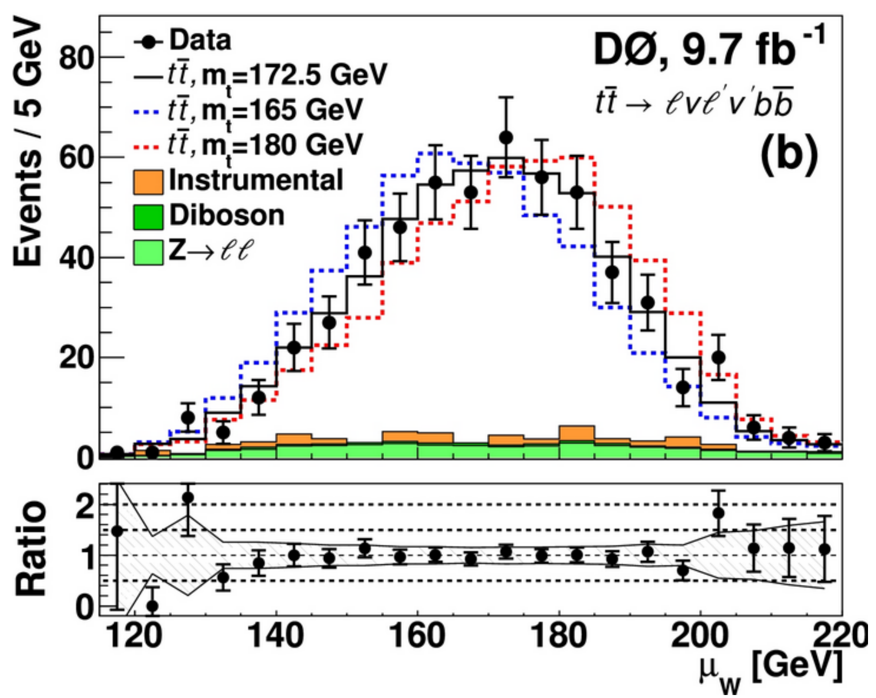
Templates for mass measurement

- Mass extracted from a fit to the data using 2D templates of the observables (μ_W,σ_W)
  - Templates produced at masses from 150 to 200 GeV



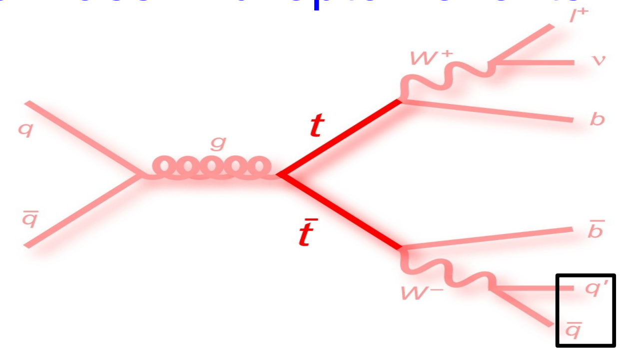
2D signal template @ m_t=172.5 GeV

μ_w template for different m_t



Optimization of systematic uncertainties

- A dominant uncertainty due to the scale of the jet energies: JES
  - JES calibrated in γ+jet events has ~ 2% uncertainty
  - A 2% shift on JES yields ~1% shift on the top mass in dilepton events



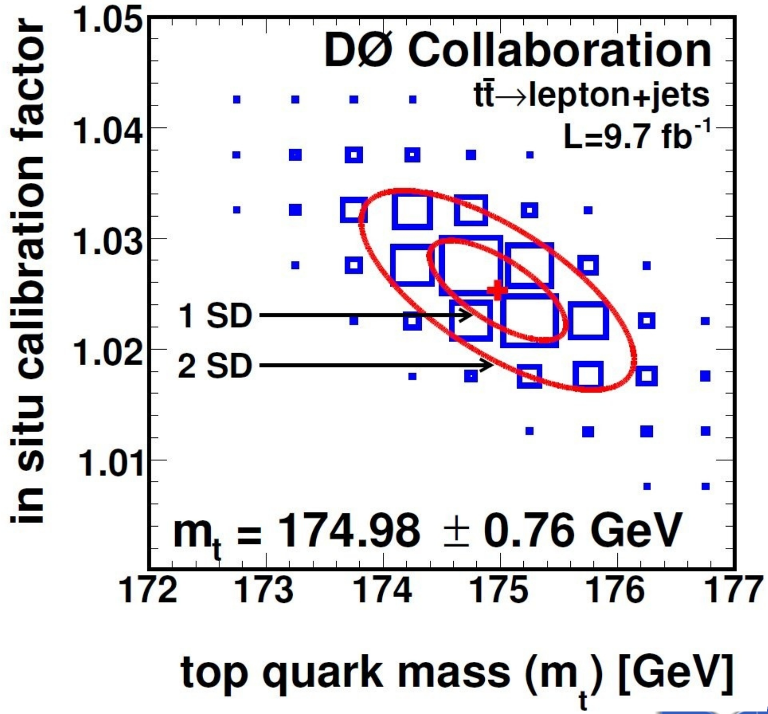
M ~ 80 GeV

- Simultaneous measurement of top mass and JES scale factor kJES and in ℓ+jets channel
  - JES constrained in-situ using dijet mass from W → qq' decay

m_t= 174.98 ± 0.76 GeV
kJES= 1.025 ± 0.005

$\delta m_t/m_t = 0.43\%$

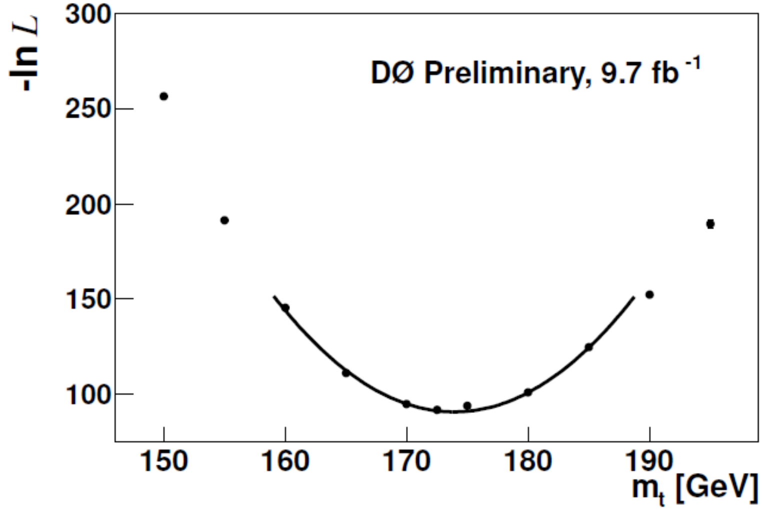
PRL 113, 032002 (2014)
PRD 91, 112003 (2015)



- kJES factor propagated to the dilepton channel
- Reduce by ~ 4 the JES uncertainty

D0 dilepton top mass measurement

- Maximum likelihood fit of 2D templates
- Use JES calibration from D0 ℓ+jets measurement



m_t = 173.32 ± 1.32 (stat) ± 0.85 (syst) GeV

arXiv:1508.03322
submitted to Phys. Lett. B

$\delta m_t/m_t = 0.9\%$

- Dominant uncertainties
  - JES (stat) uncertainty from ℓ+jets measurement
  - Residual JES
  - Higher order effects
- Smallest systematic uncertainty in dilepton measurements (including LHC)

Source	σ_{m_t} [GeV]
Jet energy calibration	
Absolute scale	∓ 0.47
Flavor dependence	∓ 0.27
Residual scale	$^{+0.36}_{-0.35}$
b quark fragmentation	$+0.10$
Object reconstruction	
Trigger	-0.06
Electron p_T resolution	± 0.01
Muon p_T resolution	∓ 0.03
Electron energy scale	± 0.01
Muon p_T scale	± 0.01
Jet resolution	∓ 0.12
Jet identification	$+0.03$
b tagging	∓ 0.19
Signal modeling	
Higher-order effects	-0.33
ISR/FSR	± 0.15
$p_T(t\bar{t})$	-0.07
Hadronization	-0.11
Color reconnection	-0.22
Multiple $p\bar{p}$ interactions	-0.06
PDF uncertainty	± 0.08
Background modeling	
Signal fraction	± 0.01
Heavy-flavor scale factor	± 0.04
Method	
Template statistics	± 0.18
Calibration	± 0.07
Total systematic uncertainty	± 0.85

Tevatron masses

- Latest Tevatron combination, July 2014

m_t = 174.34 ± 0.64 GeV

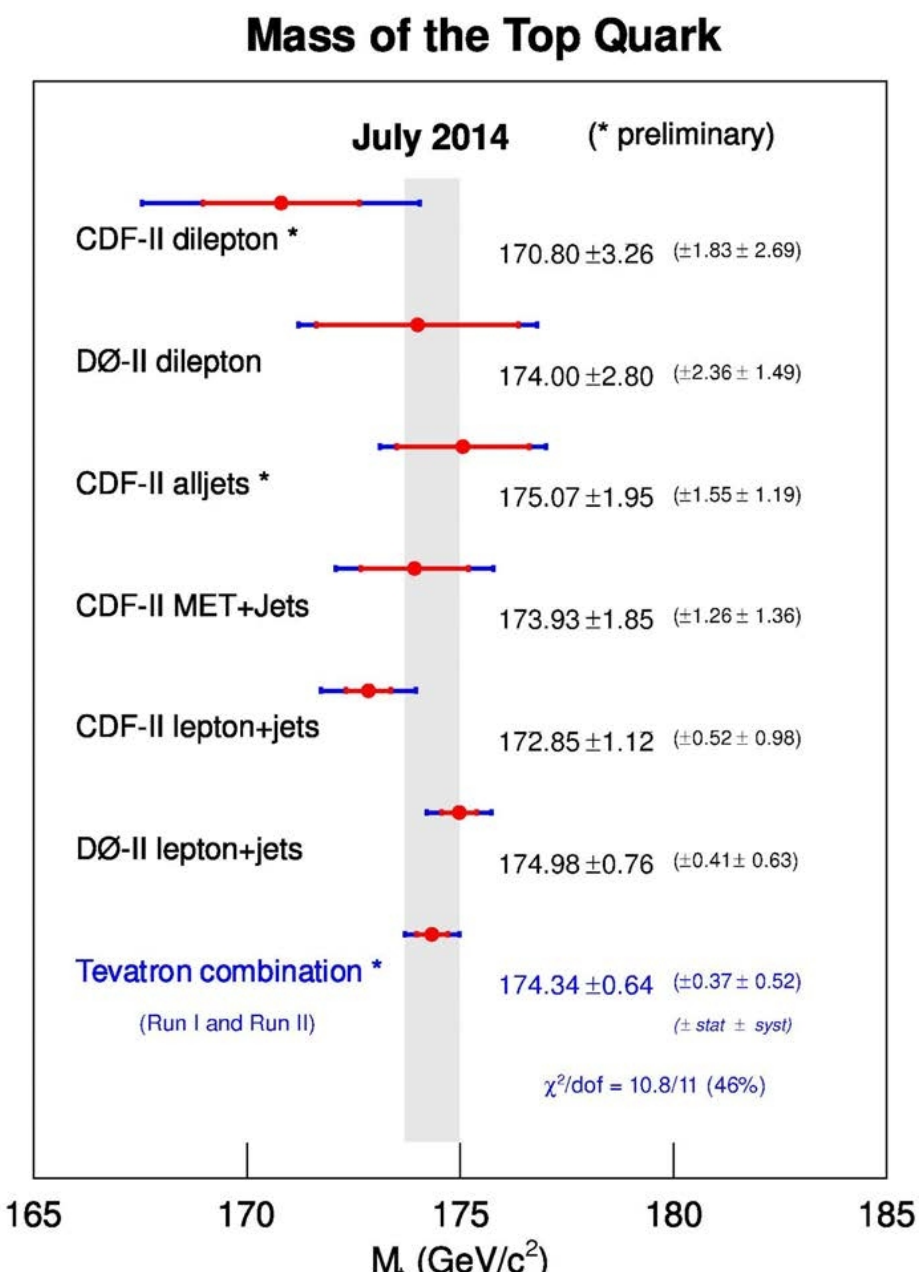
$\delta m_t/m_t = 0.37\%$

- New D0 dilepton measurement to be included

m_t = 173.32 ± 1.32 (stat) ± 0.85 (syst) GeV

$\delta m_t/m_t = 0.9\%$

  - Large improvement over D0 5.4 fb^{-1} dilepton result: 174.0 ± 2.4 ± 1.5 GeV
  - Systematic uncertainties reduced due to JES calibration
  - Also improved statistical uncertainty due to optimization of neutrino weighting method

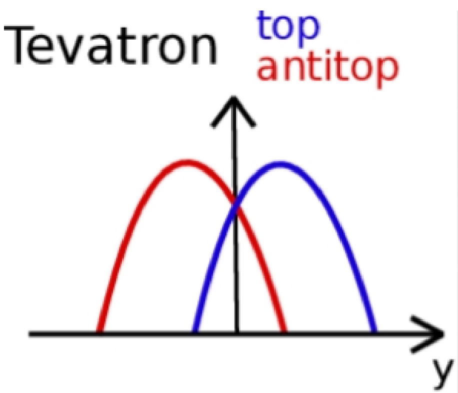


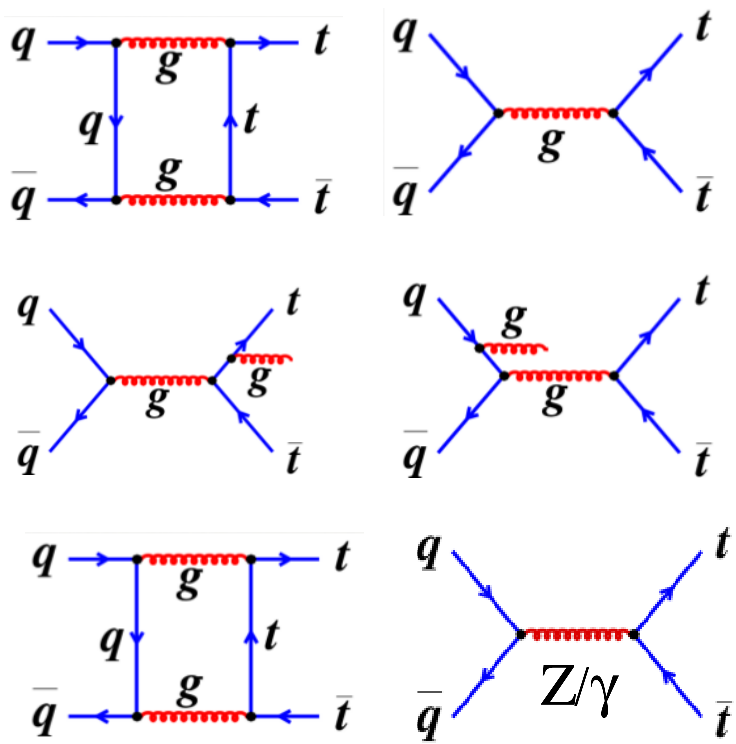
arXiv:1407.2682

Forward-backward asymmetry and polarization

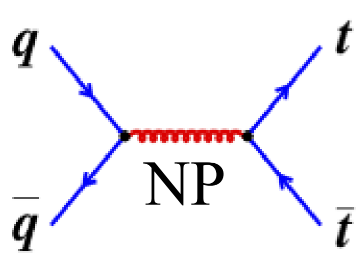
Forward-backward asymmetry (A_{FB})

- QCD + EW theory predicts positive asymmetry in $t\bar{t}$ production: top quark tend to go in the same direction as incoming proton at Tevatron





- Main positive contribution due to interference between born and box diagrams
- Negative contribution in ISR/FSR interferences
- Also non negligible impact of interferences between QCD box and electroweak diagrams



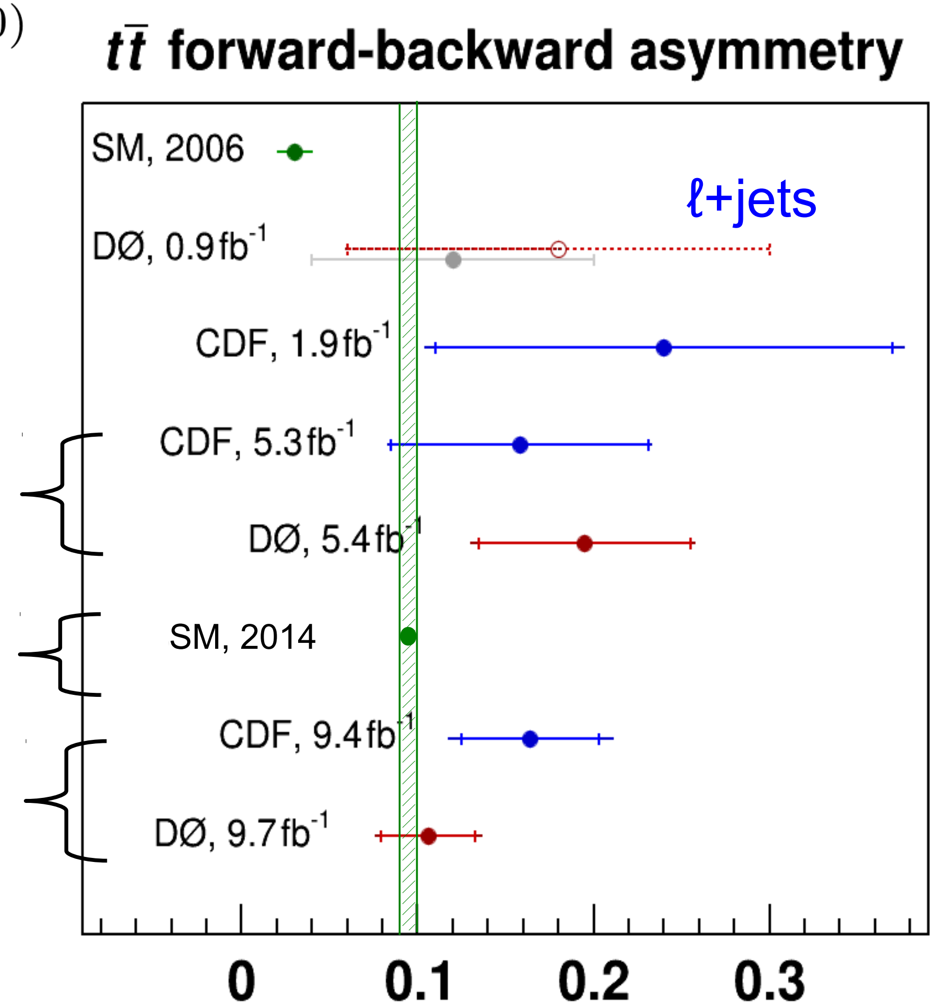
- New Physics could affect quantitatively the asymmetry
  - Eg axigluon models

A_{FB} History

- Observable: $A_{FB} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$

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

- A lot of excitement in the past years:
  - Tevatron ℓ+jets analyses were showing departure from SM expectations
- Nowadays:
  - SM expectations evaluated to be higher: ~9.5±0.5% (arXiv:1411.3007)
  - More data, more refined analysis: latest experimental results are lower than before

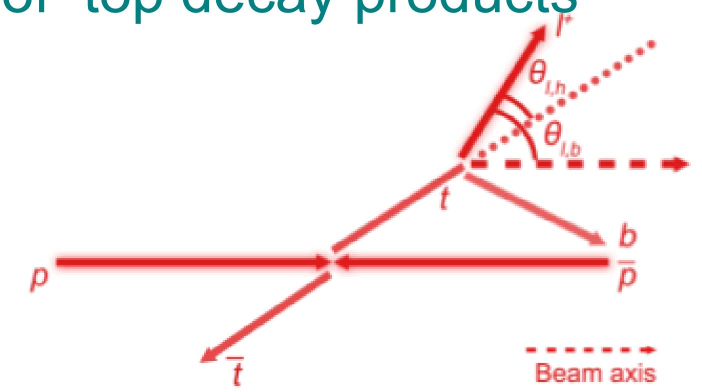


- In this talk: A_{FB} in dilepton channel
  - First publication in dilepton channel
  - Complete the set of Tevatron measurements
  - Difficulty: reconstruct the $t\bar{t}$ kinematics given 2 escaping neutrinos

Top polarization

- Polarization affects angular distributions of top decay products
- Simplest decay product to study: lepton

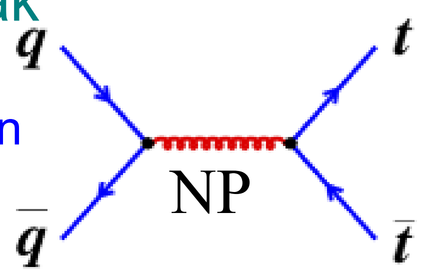
$$\frac{d\sigma}{d\cos\theta^{\pm}} = \frac{1}{2}\left(1 + \kappa P_n^{\pm} \cos\theta^{\pm}\right)$$



  - Beam basis: use proton beam boosted in $t\bar{t}$ rest frame as quantization axis
  - Helicity basis: use $t\bar{t}$ axis in $t\bar{t}$ rest frame
  - Transverse: use cross product (beam x top) in $t\bar{t}$ rest frame
  - Lepton direction measured in parent top rest frame

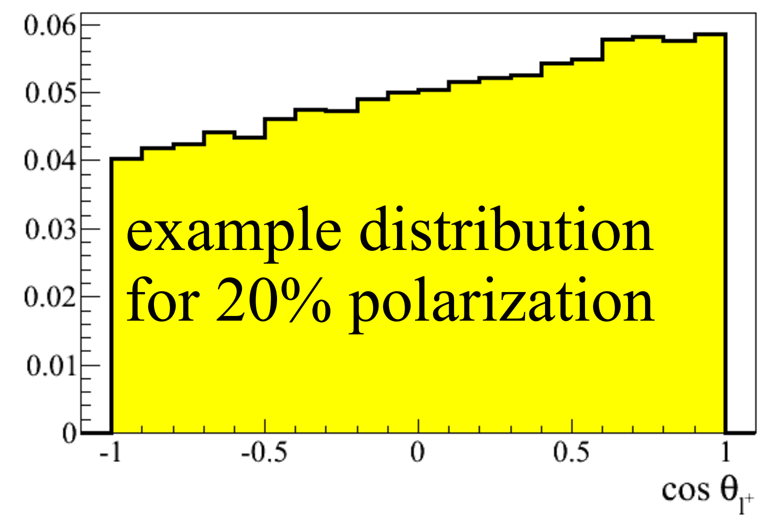
κ= spin analyzing power of lepton ~0.99 as predicted by QCD

- Within SM, top quarks are expected to have a very weak polarization (in all basis)<1%.
  - Need a parity violating effect to yield longitudinal polarization
    - eg : Axigluon models with right-handed couplings
    - Contribution from SM Z boson negligible
  - Small QCD -induced transverse polarization <1%



A_{FB} and polarization in beam basis

- Polarization is slope of cos(ℓ⁺) distribution
  - This is also 2 x asymmetry of that distribution
- Polarization in beam basis is ~2x asymmetry of y(ℓ⁺)-y(t) distribution
- So one has 3 asymmetries
  - for $y(t)-y(\bar{t})$ → A_{FB}
  - for y(ℓ⁺)-y(t) → polarization of top
  - for $y(\ell^-)-y(\bar{t})$ → polarization of antitop
- Acceptance and reconstruction effects create correlations between the three measured asymmetries.



- A_{FB} measurements depend on actual polarization
  - First measurement of A_{FB} in dilepton channel was suffering from a large model dependence mostly due to polarization (D0 6445-CONF)
  - ~ ΔA_{FB}~ 5% for 20% polarization
  - Note that effects are weaker in ℓ+jets channels
- We now perform simultaneous measurement of A_{FB} and polarization

Kinematic reconstruction in dilepton events

CEA - Saclay

- Use same kind of Matrix Element integration as for D0 mass in ℓ+jets channel

$$L_z = \frac{1}{\mathcal{A}\cdot\sigma_{tot}} \sum_{flavors} \int_{x,q_1,q_2,p_T^{t\bar{t}},\phi^{t\bar{t}}} W(x,z) W(p_T^{t\bar{t}}) f_{PDF}(q_1) f_{PDF}(q_2) d^6\sigma_{hs}(x) dp_T^{t\bar{t}} d\phi^{t\bar{t}} dq_1 dq_2$$

$d^6\sigma(x)$ differential cross-section

$f_{PDF}(q_i)$: parton density function

$W(p_T)$: pdf for ttbar transverse momentum

W(x,z) transfer functions to relate reconstructed quantities z to true 4-vectors x

Kinematic reconstruction in dilepton events

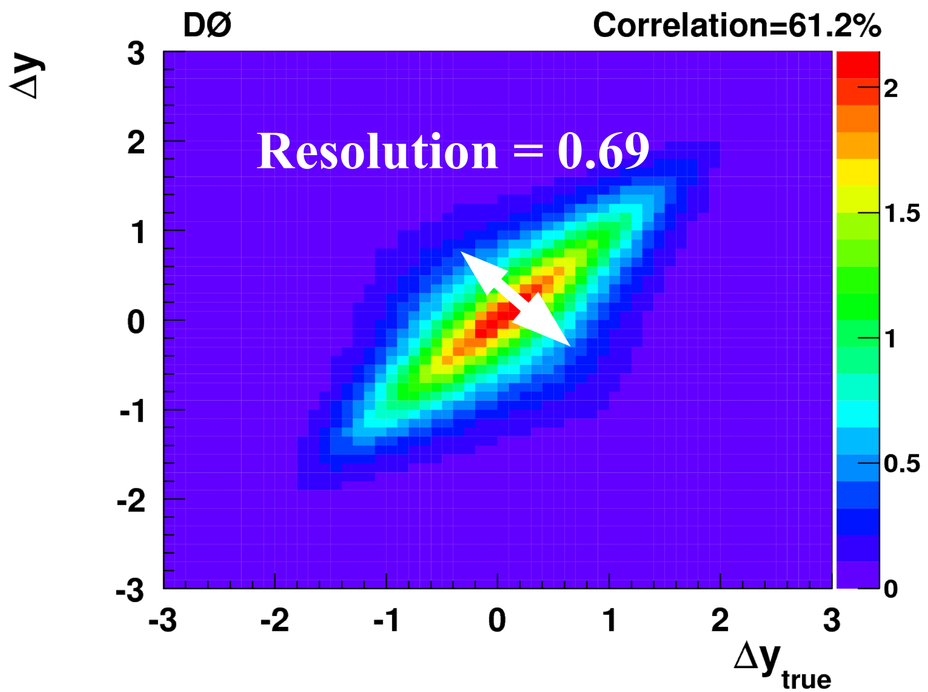
- Use same kind of Matrix Element integration as for D0 mass in ℓ+jets channel

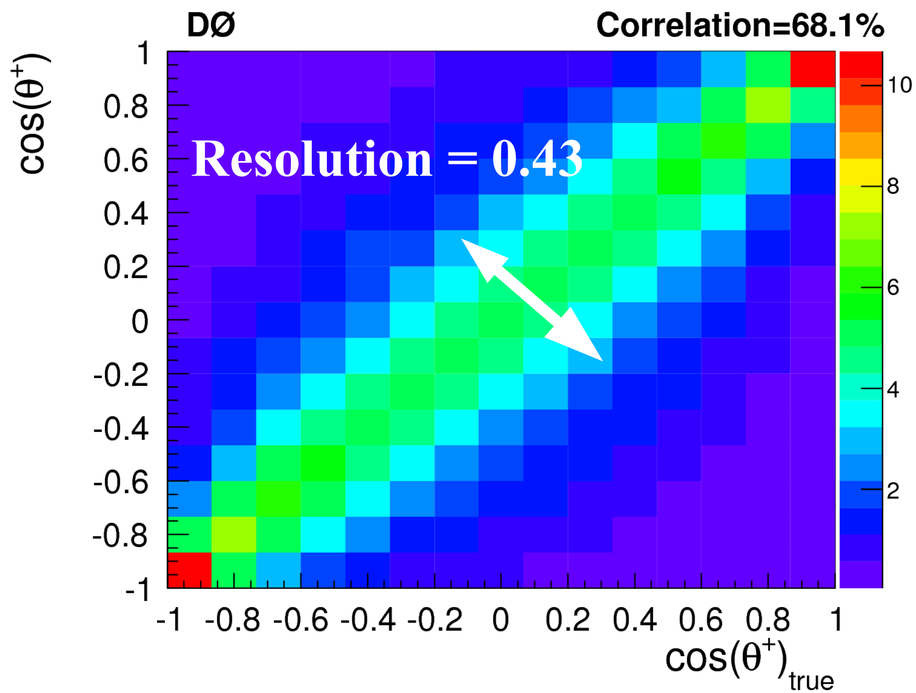
But: Insert a δ function for any parton-level kinematic variable K (eg K=$\Delta y_{t\bar{t}}$)

$$L_z(K) = \frac{1}{\mathcal{A}\cdot\sigma_{tot}} \sum_{flavors} \int_{x,q_1,q_2,p_T^{t\bar{t}},\phi^{t\bar{t}}} \delta\left(K(x)-K\right) W(x,z) W(p_T^{t\bar{t}}) f_{PDF}(q_1) f_{PDF}(q_2) d^6\sigma_{hs}(x) dp_T^{t\bar{t}} d\phi^{t\bar{t}} dq_1 dq_2$$

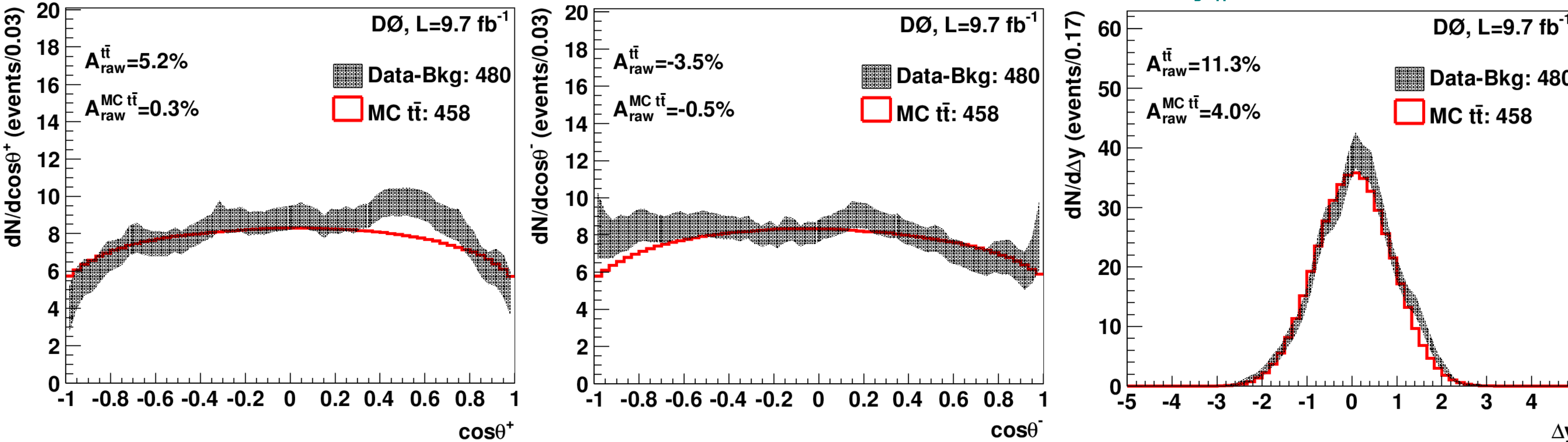
We obtain a likelihood function of K for each given event

- With this method: obtain likelihood functions for $\Delta y_{t\bar{t}}$, cos θ+, cos θ-





- Accumulate likelihood= Reconstruct distribution of $\Delta y_{t\bar{t}}$, cos θ+, cos θ-



$$\kappa P_{\rm beam} = A^{\ell^+}_{\rm beam} - A^{\ell^-}_{\rm beam}.$$

$$A^{\ell^\pm}_{beam} = \frac{N(\cos\theta^\pm > 0) - N(\cos\theta^\pm < 0)}{N(\cos\theta^\pm > 0) + N(\cos\theta^\pm < 0)}$$

$$A_{FB} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$

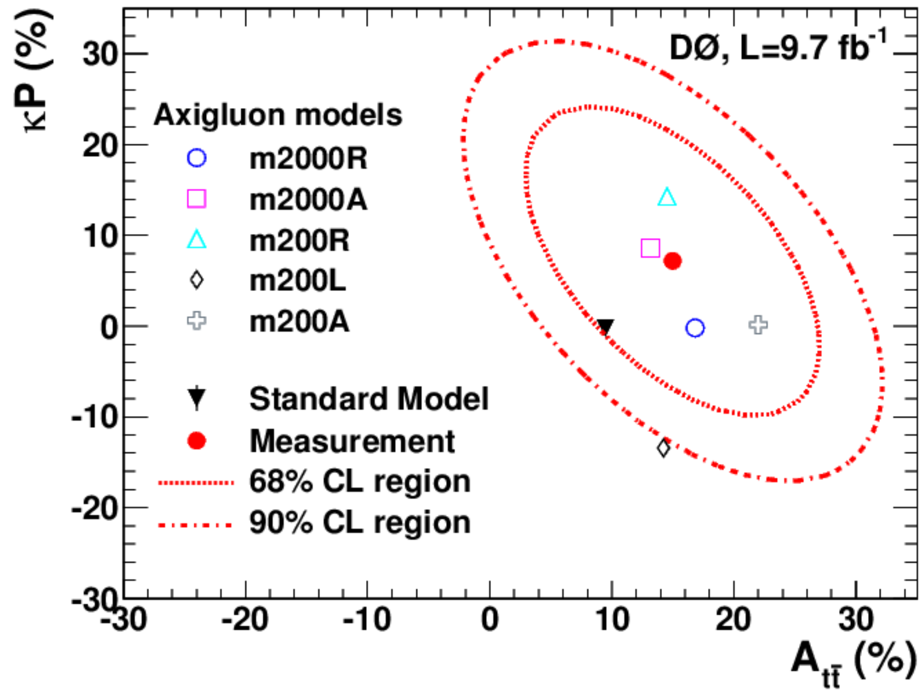
- Measurement from background subtracted data
  - Extraction of raw polarization (beam basis): 8.7±5.3 (stat)%
  - Extraction of raw A_{FB}: 11.3 ± 3.4 (stat)%
- Raw measurements need to be corrected for detector (resolution & acceptance) effects

2D measurement of A_{FB} and polarization

- Correct raw measurements for reconstruction and acceptance effects
  - Use 2x2 calibration matrix
  - Obtained from reweighted $t\bar{t}$ MC
  - Closure tests with BSM models

$$\begin{pmatrix} A^{t\bar{t}}_{\rm raw} \\ \kappa P_{\rm raw} \end{pmatrix} = C \cdot \begin{pmatrix} A^{t\bar{t}} \\ \kappa P \end{pmatrix} + O$$

- Corrected results
  - A_{FB} = 15.0 ± 6.4 (stat) ± 4.9 (syst) %
  - κP = 7.2 ±10.5 (stat) ± 4.2 (syst) %
  - Correlation (A_{FB},κP)= -56%



- Main uncertainties:
  - Statistics
  - Hadronization
  - Model dependence=response to different BSM benchmarks

1D Results

- Polarization measurement as a test of SM:
  - Constrain A_{FB} to SM prediction of 9.5±0.5%
  - Ignore BSM response uncertainty

    κP = 11.3 ± 9.1 (stat) ± 1.9 (syst) %

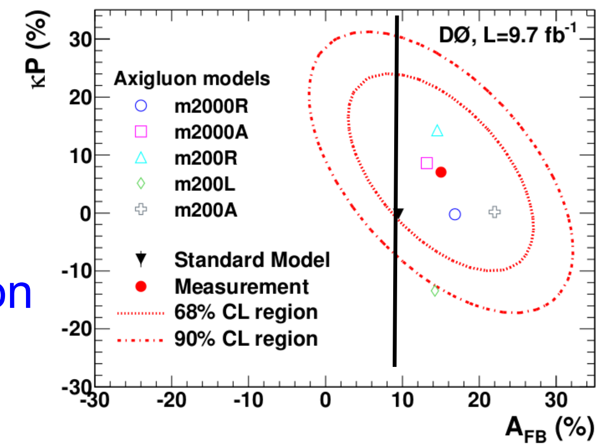
  - First measurement of polarization (beam basis) at Tevatron

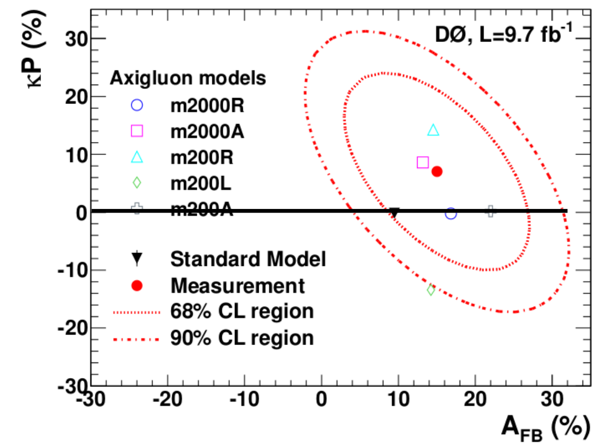
- A_{FB} measurement as a test of SM
  - constraining κP to SM value of -0.19%,
  - Ignore BSM response uncertainty

    A_{FB} = 17.5 ± 5.6 (stat) ± 3.1 (syst) %

- Combination of A_{FB} from dilepton and ℓ+jets
  - D0 ℓ+jets A_{FB} = 10.6 ± 2.9 (stat)±1.1(syst)%
    - Different dominant sources of systematic uncertainties.
    - Also big statistical uncertainties
    - Correlation with dilepton <10%
  - BLUE weight 83% for ℓ+jets, 17% for dilepton

    A_{FB} = 11.8 ± 2.6 (stat) ± 1.2 (syst) %

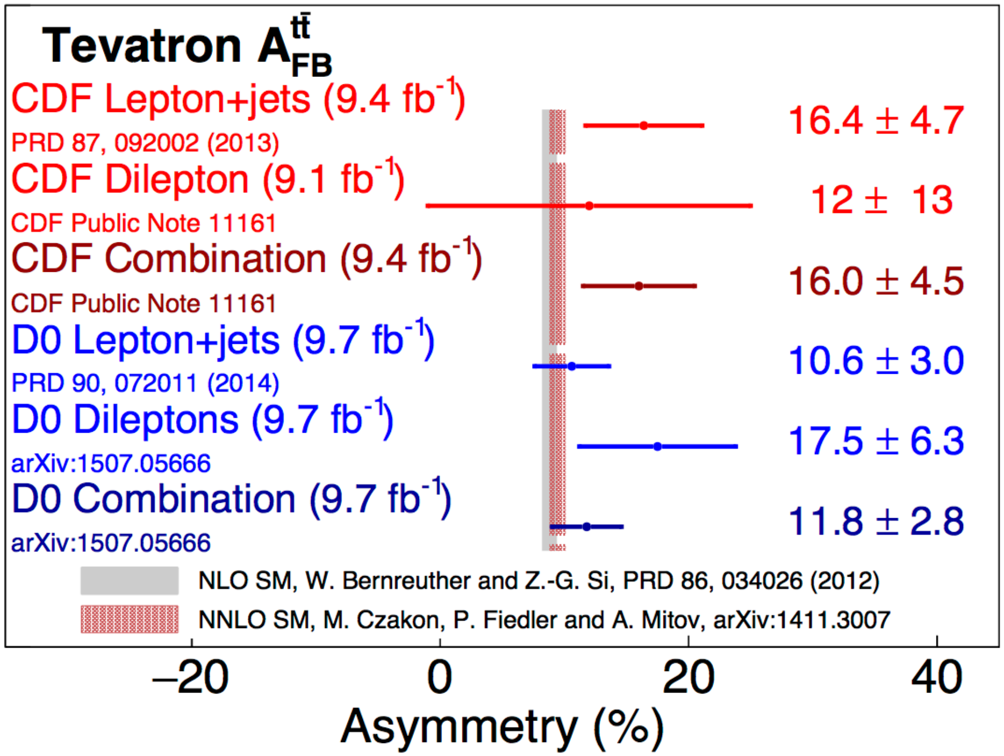


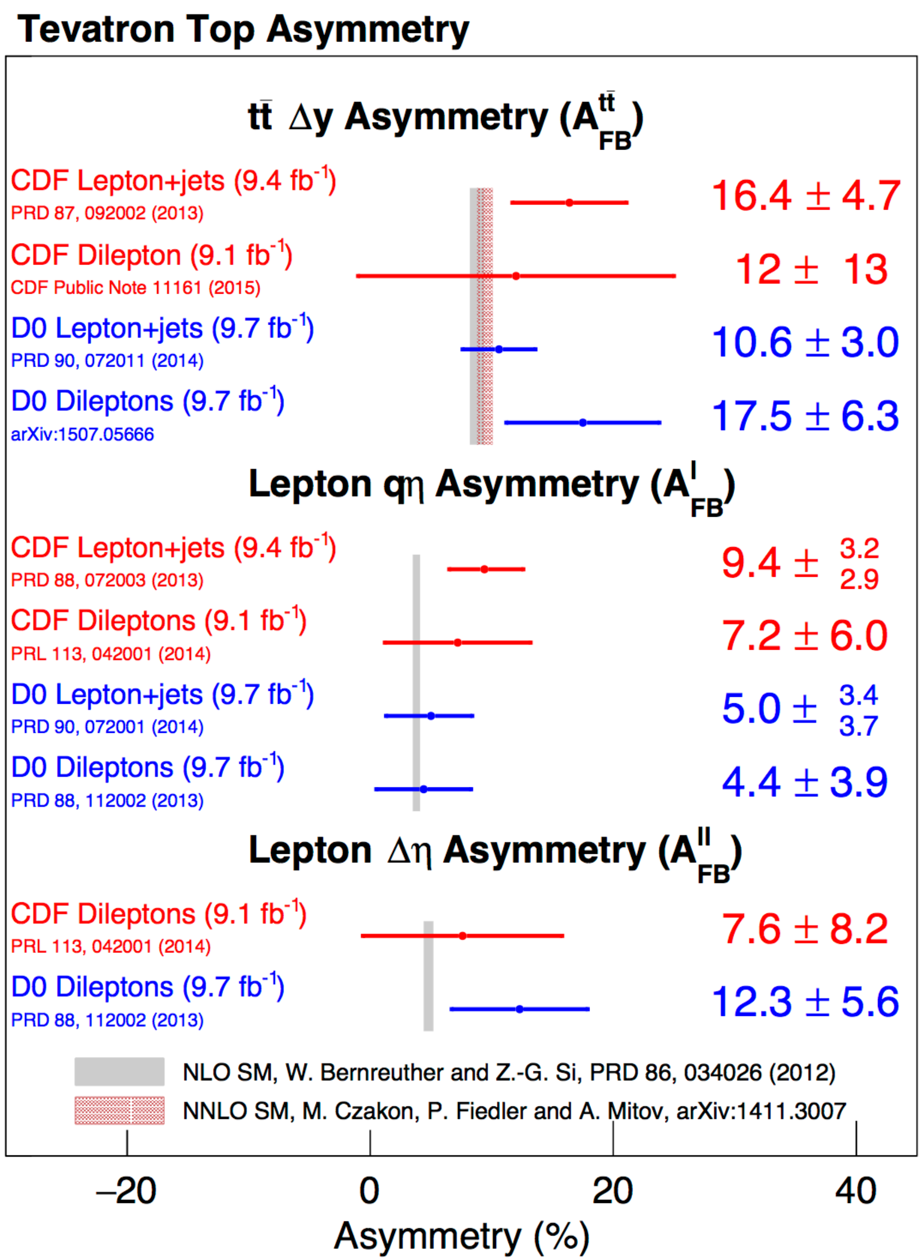


arXiv:1507.05666
Phys. Rev. D 92, 052007 (2015)

Tevatron forward-backward asymmetries

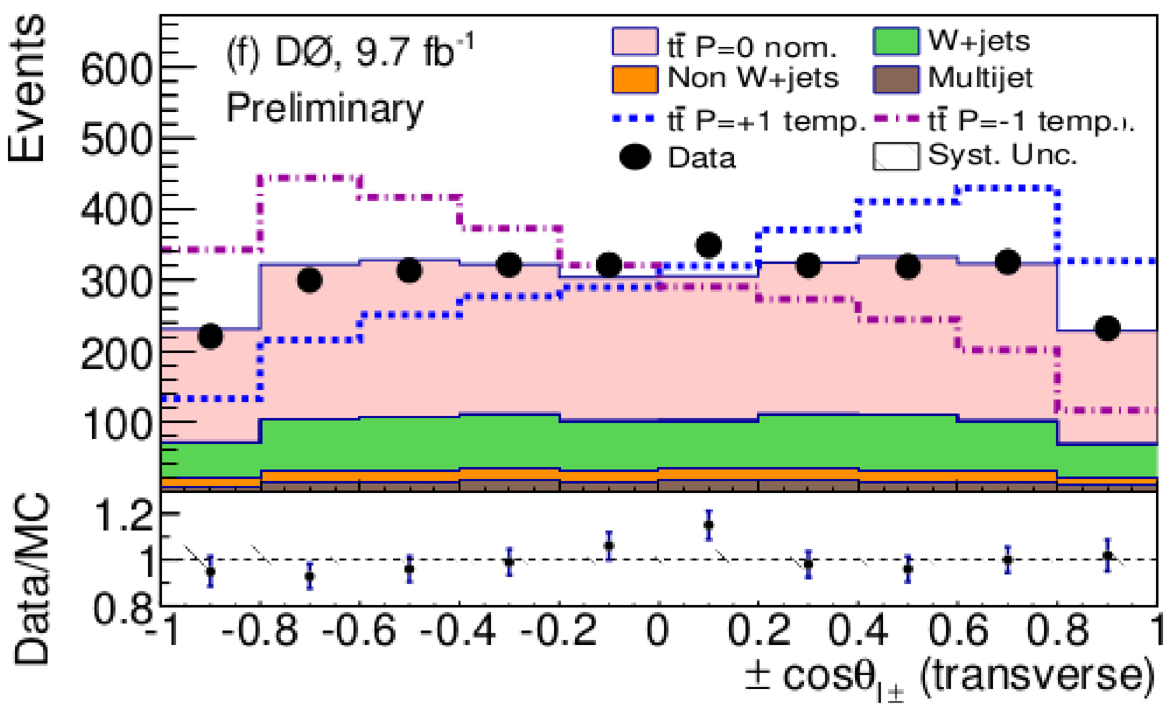
- This new measurement complete the set of measurements performed at Tevatron
- Results consistent with SM
- Working on combining D0+CDF





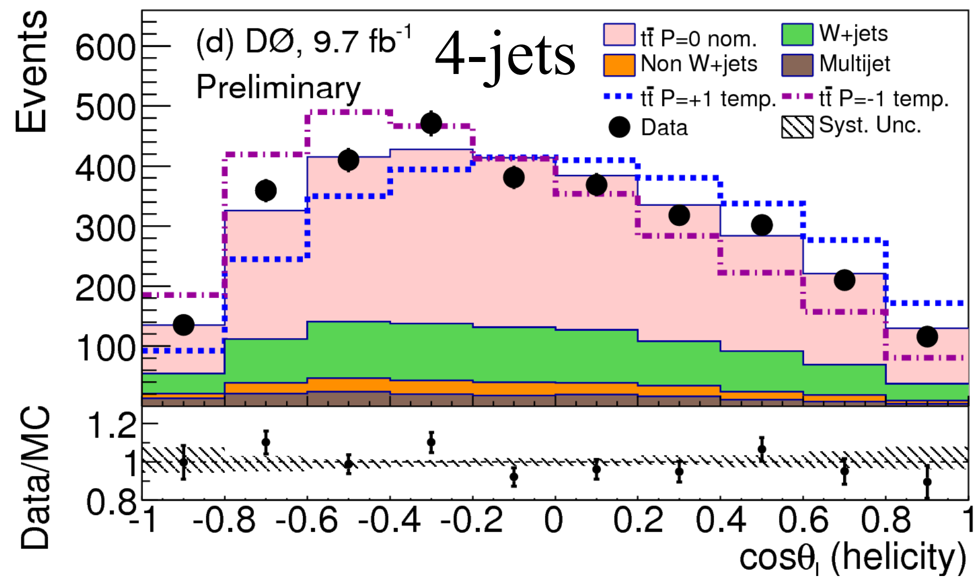
Polarization measurements in ℓ+jets channel

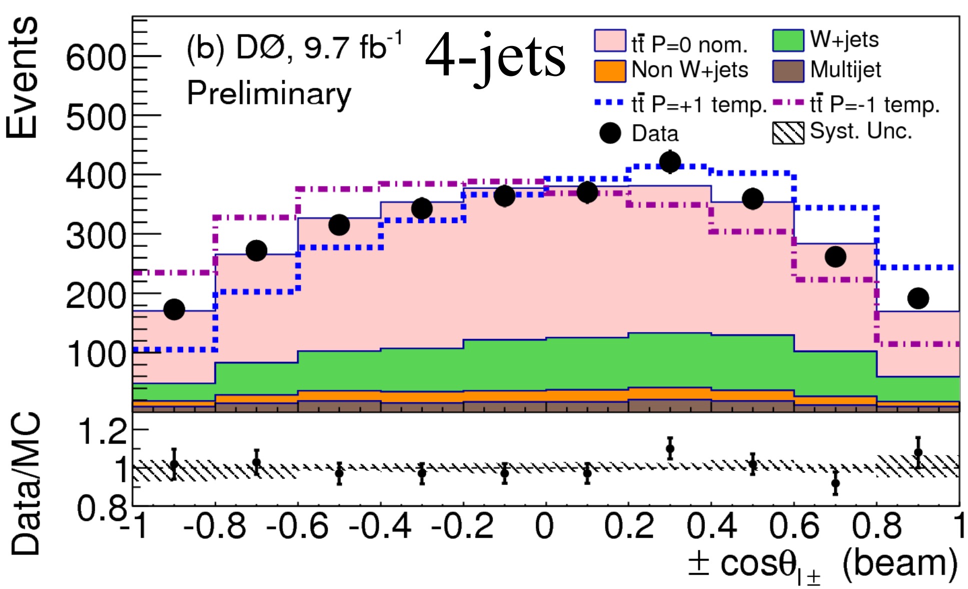
- Enhance signal with b-tagging requirements
- Use multivariate likelihood to determine signal vs background composition
- Reconstruct full $t\bar{t}$ event with kinematic fitter
  - Same kinematic fitter as for ℓ+jets A_{FB} measurement (PRD 90, 072011 (2014))
  - Also reconstruct events with 3jets +1lost jet (Demina et. al NIMA A 788,128, (2015))
- Obtain lepton angular distribution in different bases
- Create MC templates for 100% and -100% polarization

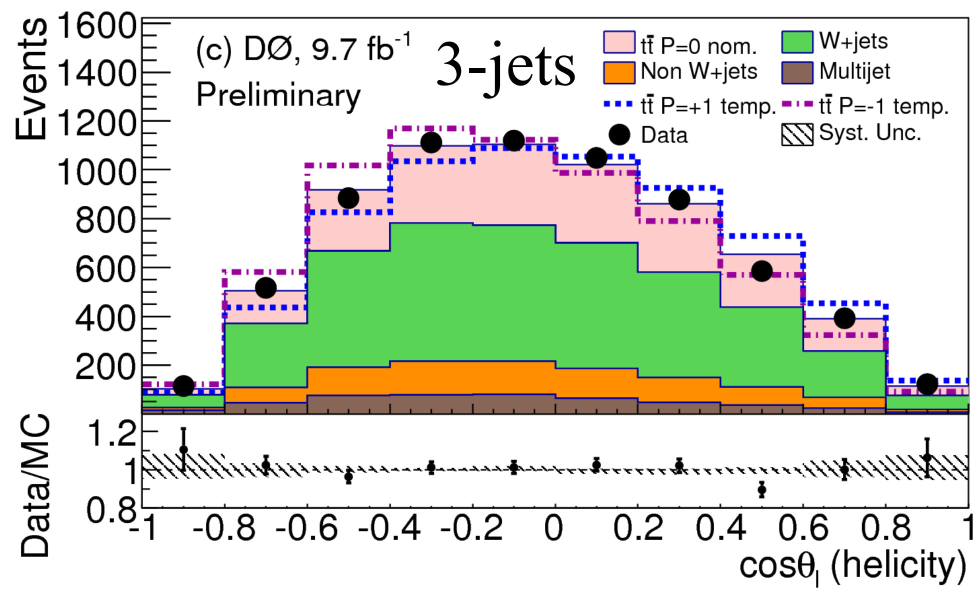


Polarization measurements in ℓ+jets channel

- Fit data with fraction f^{+} ($1-f^{+}$) of template of 100% (-100%) polarization
  - Polarization= $2f^{+} - 1$
  - W+jets background model tuned on data control sample
  - Separate templates according to lepton flavor x jet multiplicity







Polarization measurements in ℓ+jets channel

- Dominant uncertainties:
  - Statistics
  - Jet energy scale
  - b-tagging
  - PDF

- Results in agreement with SM expectations

Beam	P_b = + 7.0 ± 5.5 %	(SM: -0.2%)
Helicity	P_h = −10.2± 6.0 %	(SM:-0.4%)
Transverse	P_t = + 4.0 ± 3.4 %	(SM:+1.1%)

D0-Conf-6471

- First measurement of transverse polarization at hadron collider

Source	Beam	Helicity	Transverse
Signal and background modeling:			
Alternate signal	±0.009	±0.014	±0.003
Initial/final state radiation	±0.008	±0.003	±0.003
Color reconnection	±0.003	±0.007	±0.003
Multijet background	±0.001	±0.008	±0.002
Background normalization	±0.004	±0.003	±0.002
b-jet fragmentation	±0.001	±0.001	±0.000
PDF uncertainty	±0.013	±0.011	±0.003
Top quark mass	±0.002	±0.005	±0.003
Instantaneous luminosity	±0.000	±0.002	±0.002
Detector modeling:			
Residual jet energy scale	±0.009	±0.022	±0.003
Flavor-dependent jets response	±0.009	±0.008	±0.007
b-tagging	±0.009	±0.014	±0.005
Trigger efficiency	±0.002	±0.005	±0.001
Lepton momentum scale	±0.002	±0.008	±0.001
$t\bar{t}$ transverse momentum	±0.005	±0.001	±0.002
Jet energy resolution	±0.003	±0.005	±0.005
Jet identification efficiency	±0.001	±0.004	±0.003
Lepton identification	±0.006	±0.016	±0.002
Vertex confirmation	±0.004	±0.002	±0.004
Method:			
W+jets calibration	±0.002	±0.003	±0.001
Sample composition	±0.012	±0.007	±0.004
MC template statistics	±0.001	±0.001	±0.001
$A_{\rm FB}$ uncertainty	±0.005	±0.000	±0.000
Total systematic uncertainty	±0.030	±0.041	±0.015
Total statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.060	±0.034

Summary

- Twenty years after discovery, Tevatron data provides valuable insight into top quark physics.
  - Precise measurements
  - Complementarity with LHC using the $p\bar{p}$ initial state
- Latest D0 measurements to complete the picture
  - Inclusive cross-section
  - Extraction of pole mass from cross section
  - Mass with reduced uncertainties in dilepton events
  - Forward-backward asymmetry
  - Polarization in different bases
- Latest measurements are in agreement with Standard Model
- In particular:
  - New mass measurements favor lighter top quark mass, i.e., favor stability of our universe
- Still more top-quark results expected soon from D0
  - Spin correlation
  - Mass with dilepton events and matrix element method, Mass from all-jets events
  - Mass from differential cross-section
  - Combination with CDF for mass and A_{FB}
  - Combination with LHC for mass

D0 top web page: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Support slides

A_{FB} dilepton uncertainties

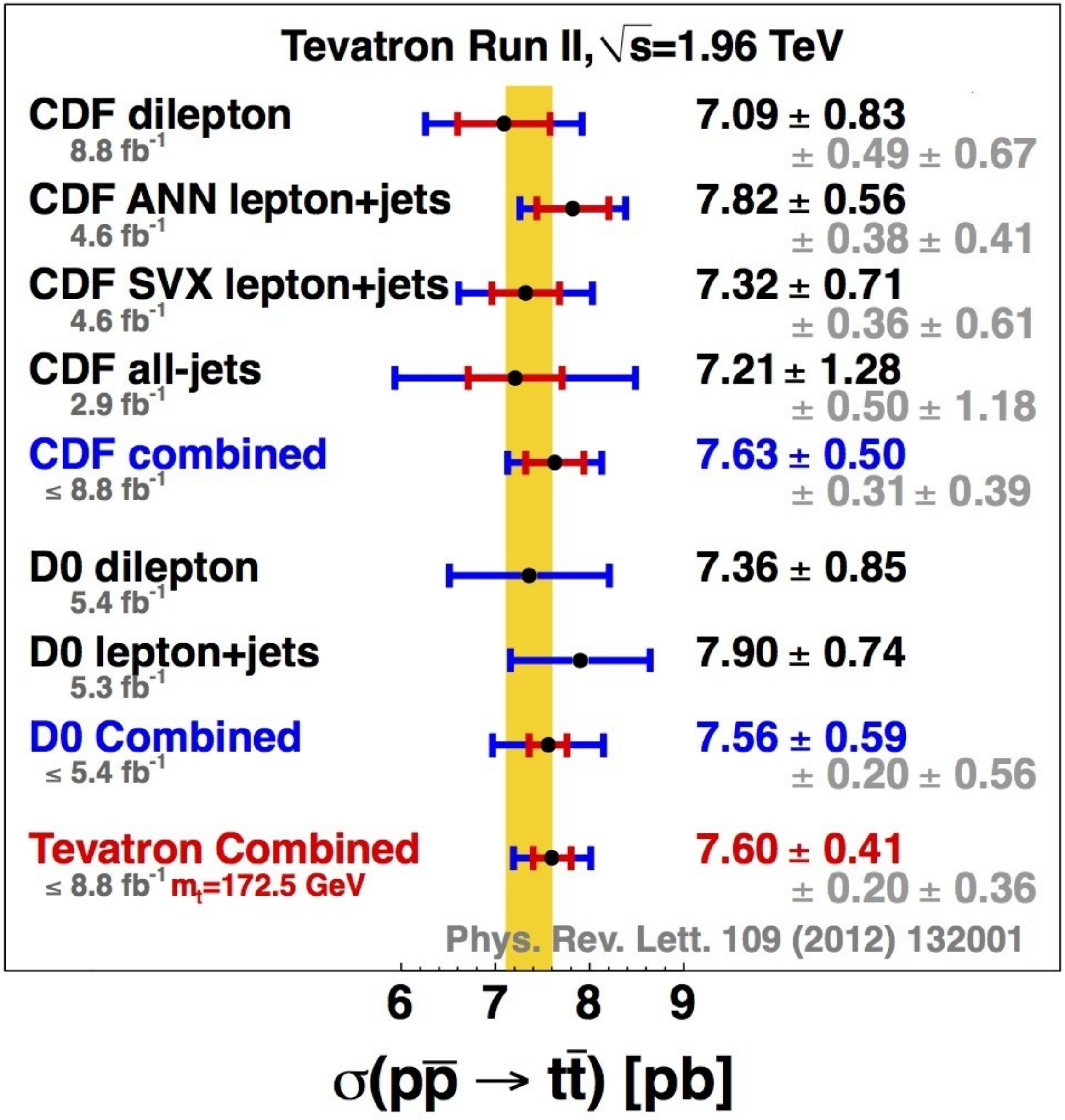
Main contributors:

- Hadronization
- Model dependence
- Statistics

Source of uncertainty	Uncertainty on A^{tt} (%)	Uncertainty on κP (%)	Correlation (%
Detector modeling			
Jet energy scale	0.13	0.50	−100
Jet energy resolution	0.03	0.06	100
Flavor-dependent jet response	0.02	0.06	−100
b tagging	0.14	0.43	− 94
Signal modeling			
ISR/FSR	0.16	0.41	−100
Forward/backward ISR	0.10	0.07	−100
Hadronization and showering	3.28	1.94	−100
Higher order correction	0.02	0.71	−100
PDF	0.12	0.30	− 98
Top quark mass	0.03	0.21	−100
Background model			
Instrumental background shape	0.16	0.53	100
Instrumental background normalization	0.29	0.01	100
Background normalization	0.44	0.18	100
Calibration			
$\Delta y_{t\bar{t}}$ model	1.28	0.11	100
MC statistics	0.60	0.61	− 39
Model dependence			
Maximum $A^{t\bar{t}}$ variation	2.91	2.35	−100
Maximum κP variation	1.49	2.58	−100
Statistical uncertainty	6.40	10.53	− 50
Total systematic without model dependence	3.62	2.40	− 74
Total systematic	4.88	4.24	− 83
Total	8.05	11.35	− 56

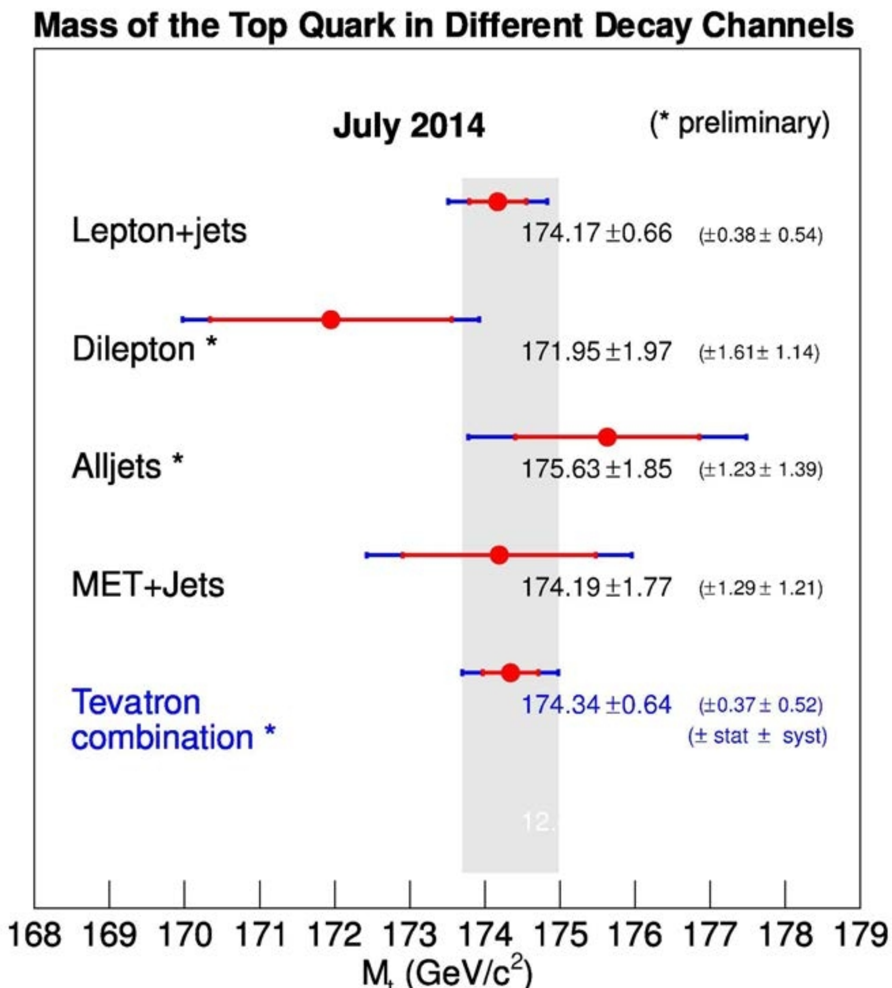
Tevatron cross-sections

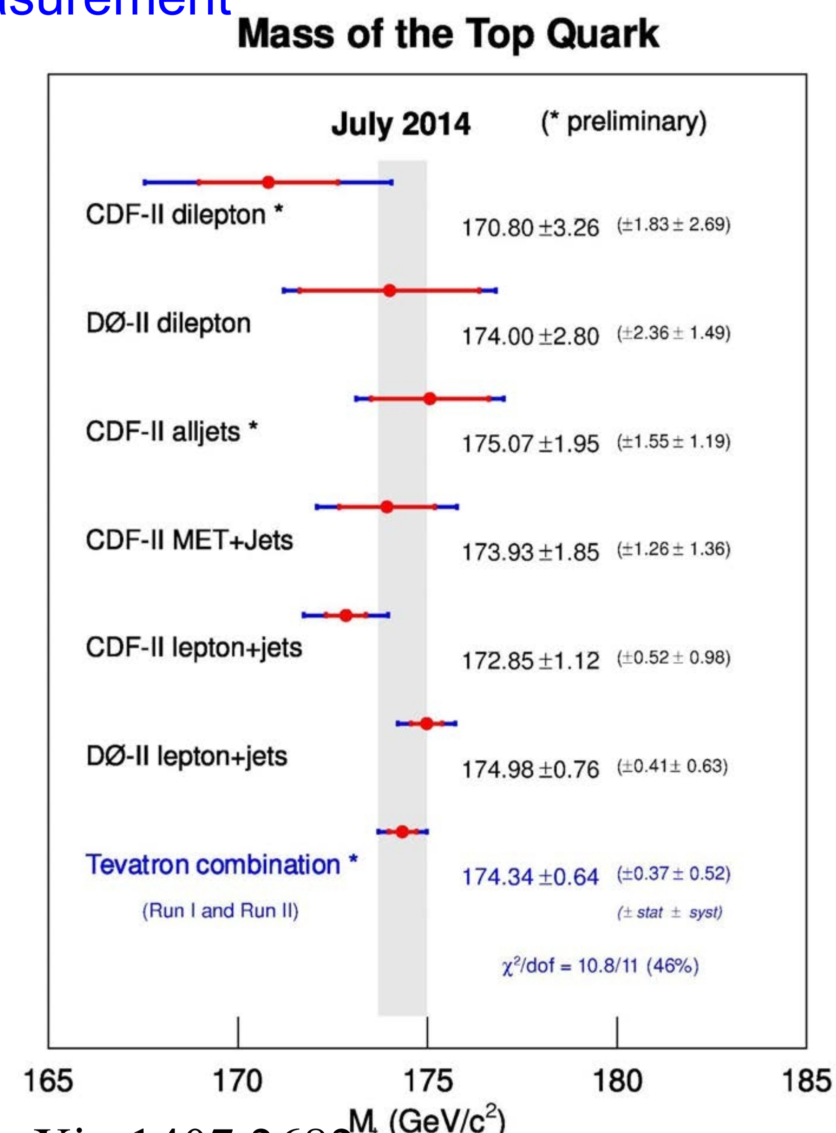
- Summary of measurements (not including this new one)



Tevatron mass combination

- Latest Tevatron combination on July 2014
  - Does not include recent updates from CDF dilepton, all-jets channels
  - Does not include new D0 dilepton measurement



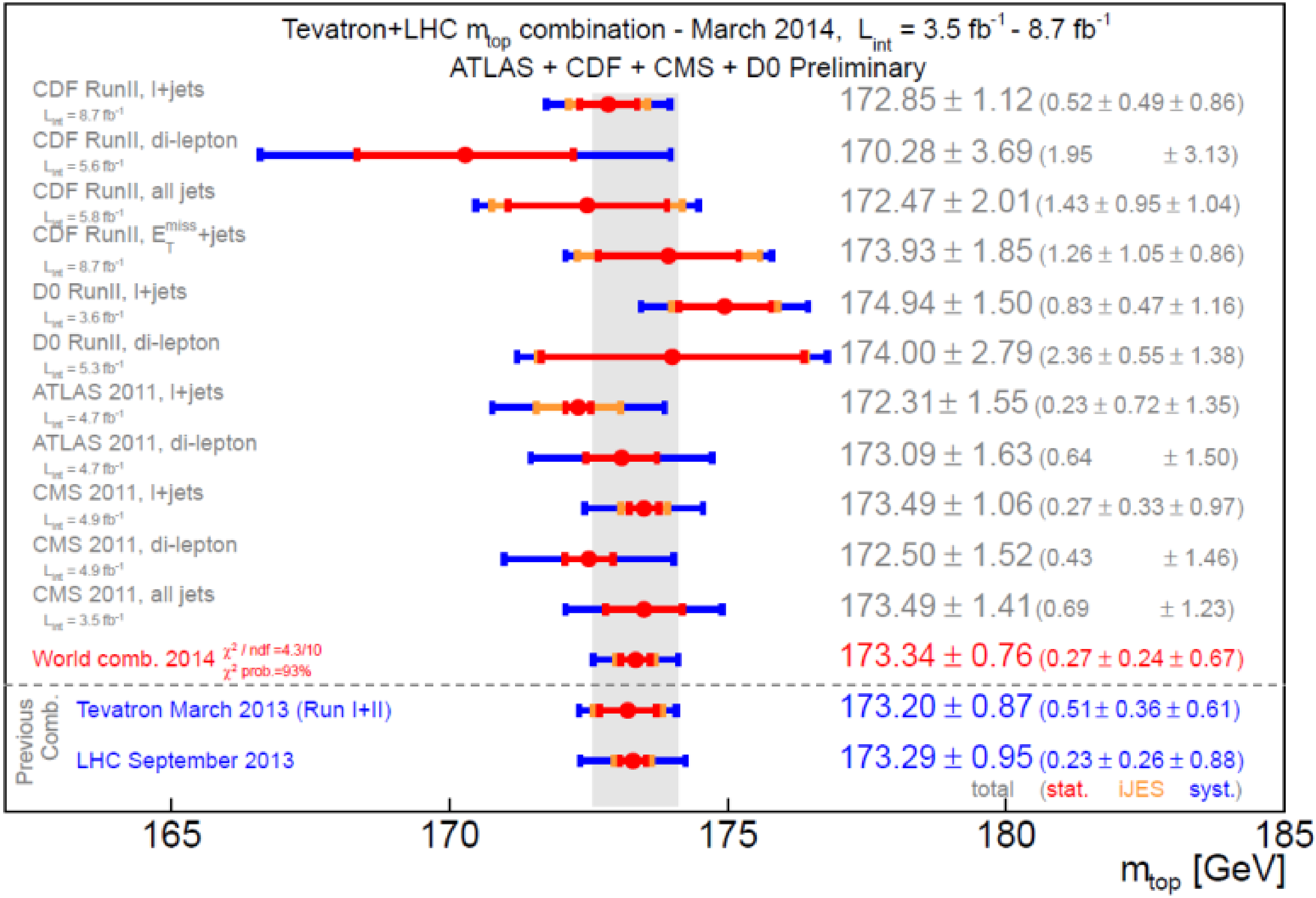


mt = 174.34 ± 0.37 (stat.) ± 0.52 (syst) GeV

m_t = 174.34 ± 0.64 GeV $\delta m_t/m_t = 0.37\%$

arXiv:1407.2682

World combination March 2014



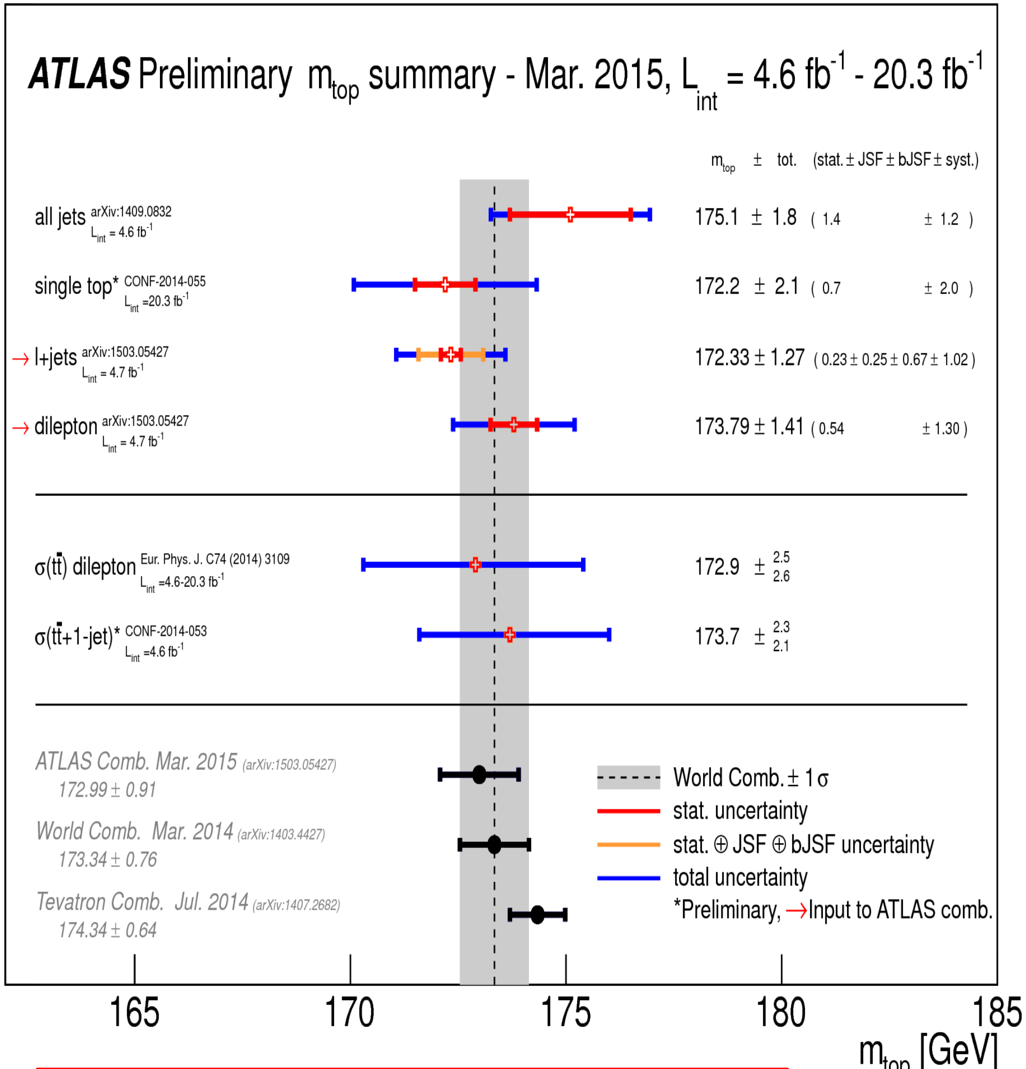
m_t = 173.34 ± 0.76 (total) GeV

arXiv:1403.4427

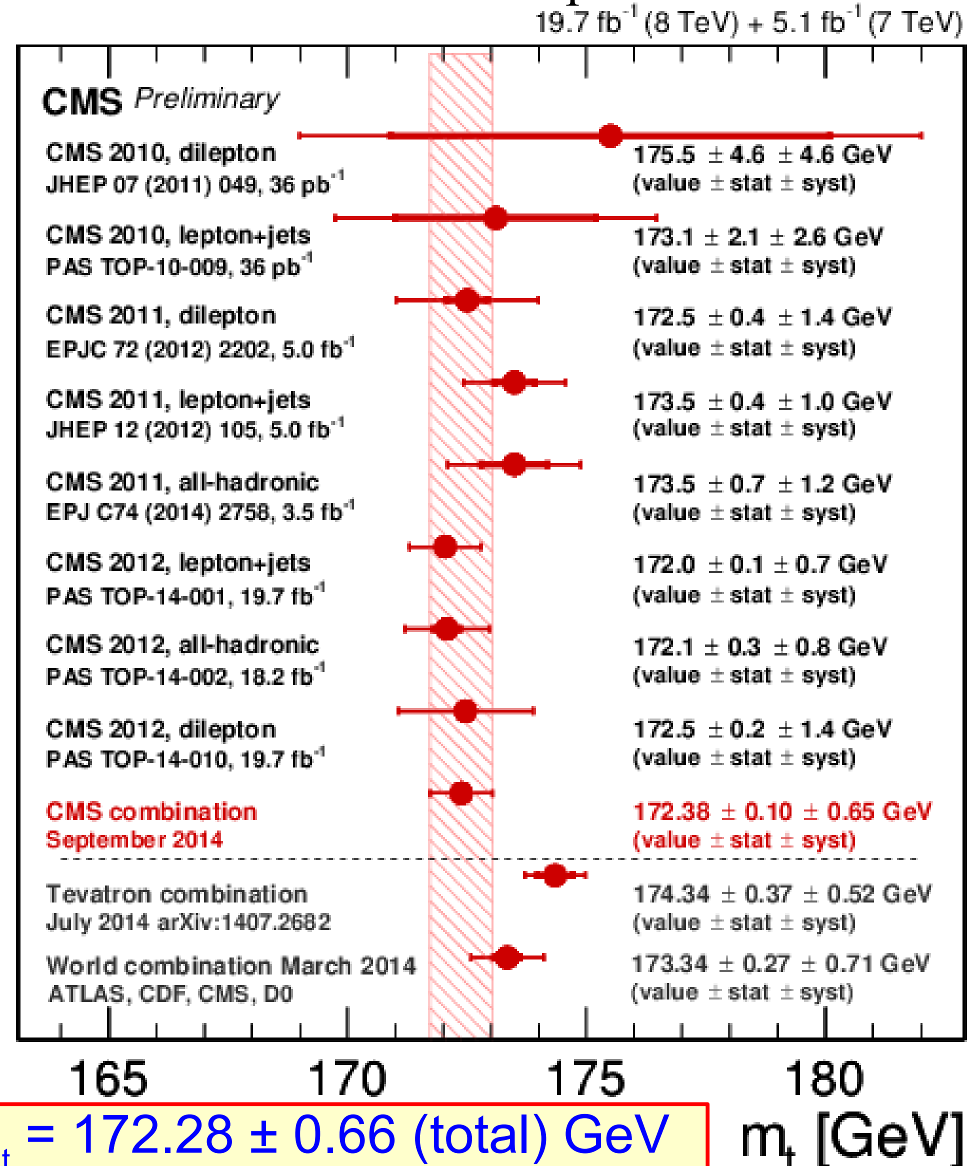
$\delta m_t / m_t = 0.43\%$

LHC (direct) measurements

March 2015



September 2014



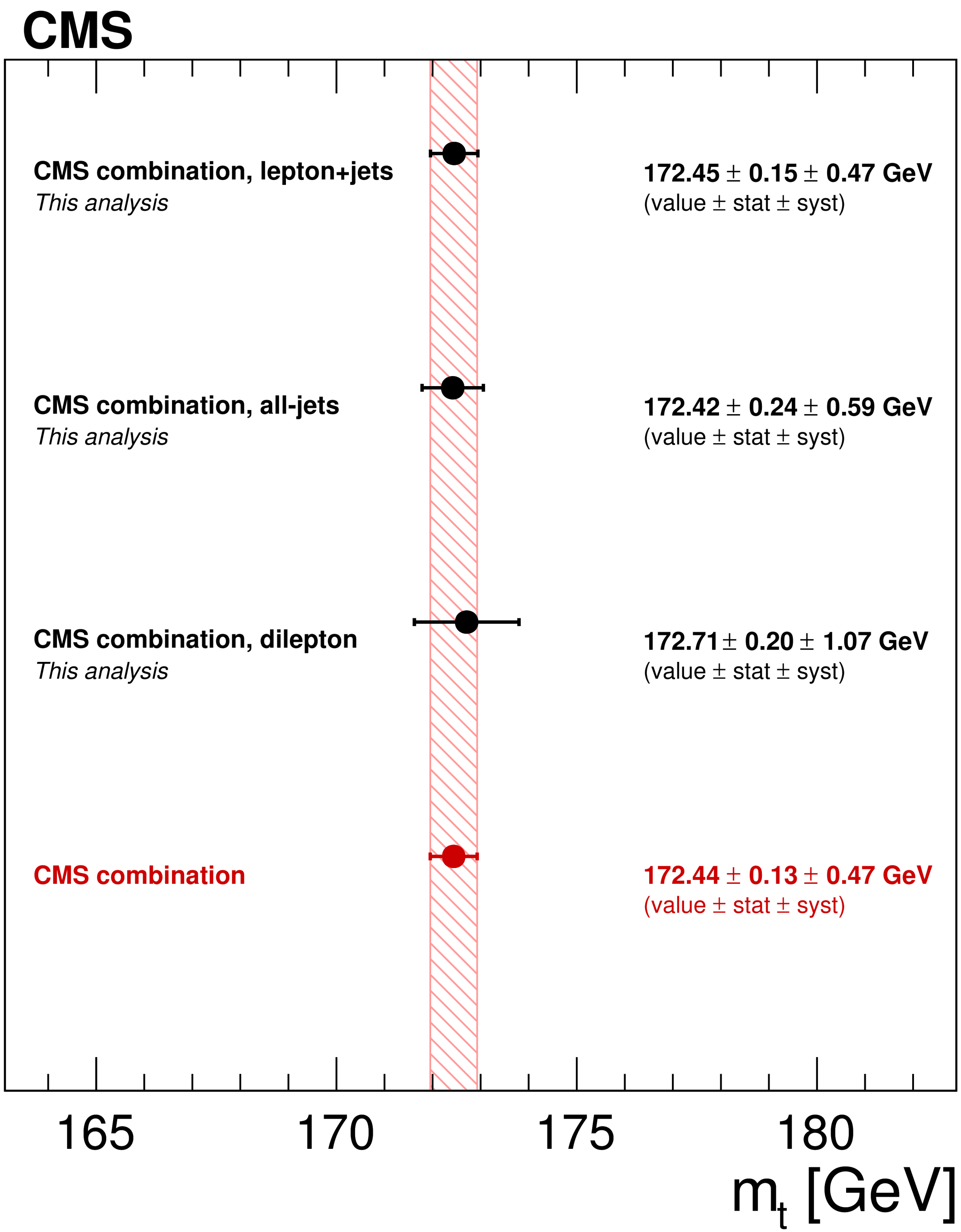
$m_t = 172.99 \pm 0.91$ (total) GeV

$\delta m_t/m_t = 0.53\%$

$m_t = 172.28 \pm 0.66$ (total) GeV

$\delta m_t/m_t = 0.38\%$

Latest CMS mass results



CDF measurements in 2014

Combination with BLUE method

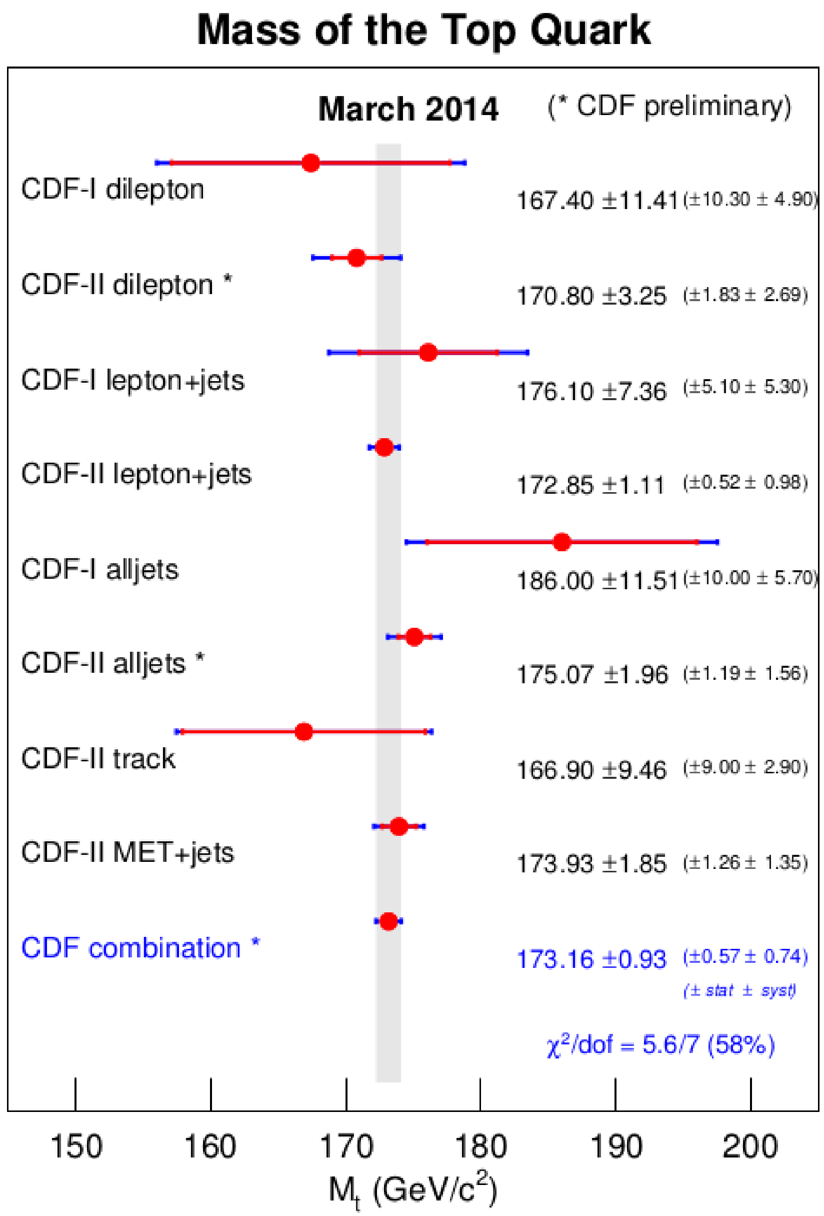
Recent update to be included

- Dilepton RunII

  170.80±3.25 → 171.5±3.14
- Alljets
  - unchanged

m_t=173.16 ± 0.57 (stat.) ± 0.74 (syst) GeV

m_t=173.16 ± 0.93 (total) GeV



CDF Conf. Note 11080

$\delta m_t/m_t = 0.54\%$

2D calibration

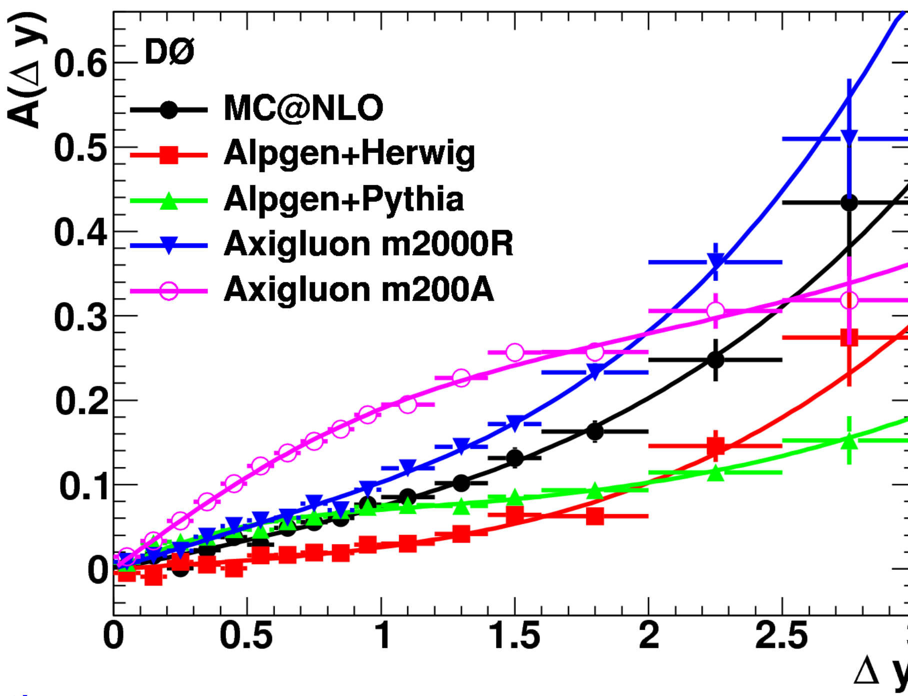
Determine relation between raw measurements and true (A_{FB},Polar).

- Reweight MC@NLO $t\bar{t}$ MC
- Reweight lepton angle (in beam basis) distribution

$$w(\cos\theta^+, cos\theta^-) = \frac{1 + \text{Polar}^{wanted} \cdot (\cos\theta^+ - \cos\theta^-) - \text{SpinCorr} \cdot \cos\theta^+ \cdot \cos\theta^-}{1 + \text{Polar}^{original} \cdot (\cos\theta^+ - \cos\theta^-) - \text{SpinCorr} \cdot \cos\theta^+ \cdot \cos\theta^-}$$

- Reweight Δy with a dedicated function
  - Fit differential asymmetry $A(\Delta y)$ with the function $\beta.(\tanh(\Delta y/\alpha) + (\Delta y/\gamma)^3$
  - Use this functional form to reweight MC@NLO events and obtain pseudo samples of different A_{FB}

$$w(\Delta y) = \frac{1 + \frac{A_{FB}^{test}}{A_{FB}^{MC}} \times \beta \times \left(\tanh(\frac{\Delta y}{\alpha}) + (\frac{\Delta y}{\gamma})^3\right)}{1 + \beta \times \left(\tanh(\frac{\Delta y}{\alpha}) + (\frac{\Delta y}{\gamma})^3\right)}$$



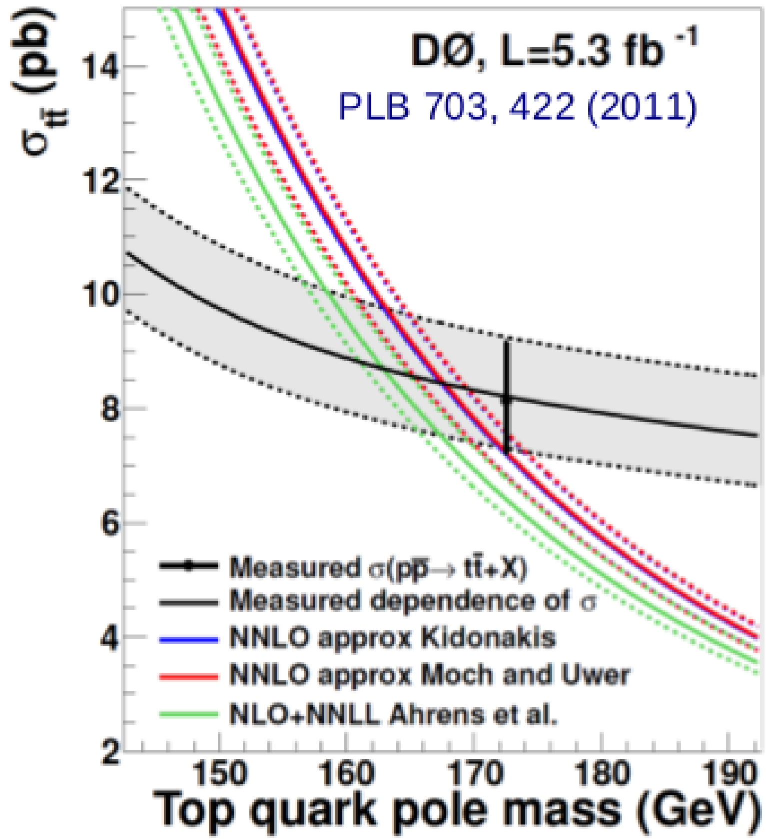
  - This reweighting preserves the shape of the differential asymmetry, but enhance its magnitude

Alternative methods

- Mass is convention dependent:

Depends on the renormalization scheme

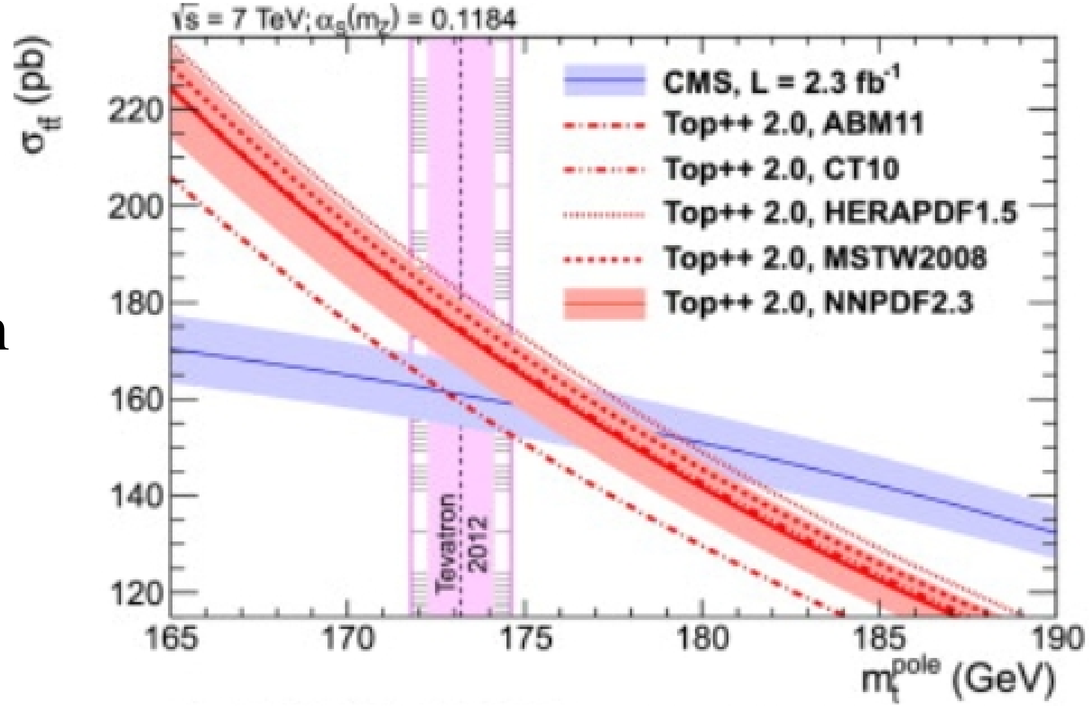
- Direct mass measurement is close to the pole mass
- Derive m_t^{pole} from intersection of measured $\sigma_{t\bar{t}}$ and theoretical predictions:



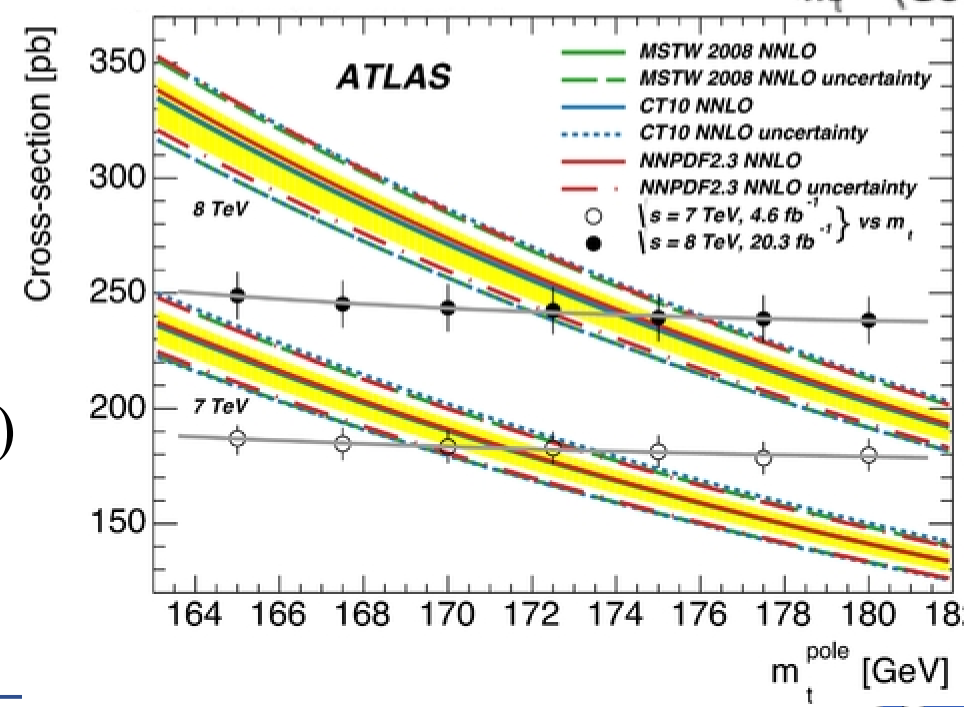
Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{MC} = m_t^{pole}$	$m_t^{MC} = m_t^{\overline{MS}}$
NLO [11]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [12]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [13]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [14]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [15]	$166.7^{+5.2}_{-4.5}$	-2.8

→ m_t = 167.5 + 5.4 – 4.7 GeV

Top mass from cross-section at LHC



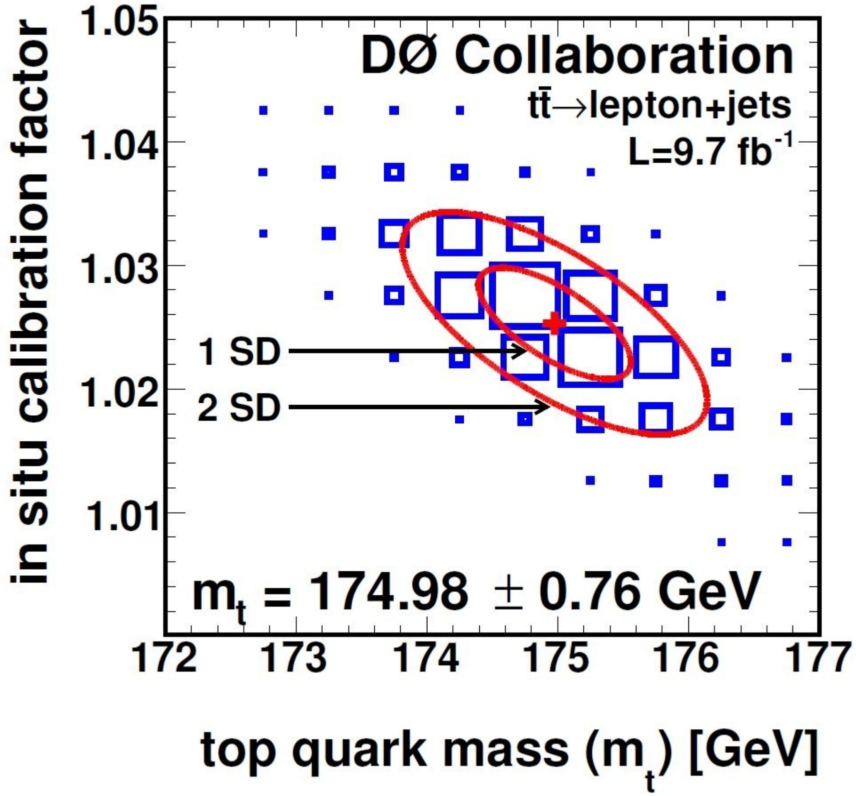
CMS: 176.7 ± 3.0 GeV (7 TeV)
PLB 728 (2014) 496 + corrigendum



ATLAS = 172.9 ± 2.6 GeV (7 & 8 Tev)
EPJC74 (2014) 3109

D0 ℓ+jets mass with matrix element method

2D-likelihood fit to extract top mass



Source of uncertainty	Effect on m_t (GeV)
Signal and background modeling:	
Higher-order corrections	$+0.15$
Initial/final state radiation	∓0.06
Transverse momentum of the $t\bar{t}$ system	-0.07
Hadronization and underlying event	$+0.26$
Color reconnection	$+0.10$
Multiple $p\bar{p}$ interactions	-0.06
Heavy-flavor scale factor	∓0.06
Modeling of b-quark jet	$+0.09$
Parton distribution functions	±0.11
Detector modeling:	
Residual jet energy scale	±0.21
Flavor-dependent response to jets	∓0.16
Tagging of b jets	∓0.10
Trigger	±0.01
Lepton momentum scale	±0.01
Jet energy resolution	±0.07
Jet identification efficiency	-0.01
Method:	
Modeling of multijet events	$+0.04$
Signal fraction	±0.08
MC calibration	±0.07
Total systematic uncertainty	±0.49
Statistical uncertainty	±0.58
Total uncertainty	±0.76

PRL 113, 032002 (2014)
PRD 91, 112003 (2015)

Main systematics from residual JES, hadronization and underlying event

m_t = 174.98 ± 0.58 (stat+JES) ± 0.49 (syst) GeV
m_t = 174.98 ± 0.76 (total) GeV

$\delta m_t/m_t = 0.43\%$

Comparable uncertainty to Tevatron+LHC 2014 combination

- Observable: $A_{FB} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$ $\Delta y = y_t - y_{\bar{t}}$
  - Directly related to the $t\bar{t}$ production asymmetry
- Other observables: lepton based asymmetries

$$A_{\rm FB}^{\ell\ell} = \frac{N(\Delta\eta>0)-N(\Delta\eta<0)}{N(\Delta\eta>0)+N(\Delta\eta<0)} \qquad \Delta\eta = \eta_{\ell+} - \eta_{\ell-}$$

$$A_{\rm FB}^{\ell} = \frac{N_\ell(q\times\eta>0)-N_\ell(q\times\eta<0)}{N_\ell(q\times\eta>0)+N_\ell(q\times\eta<0)}$$

  - Can be affected by effects at the top or W decay vertices