Top Quark Physics at the Tevatron

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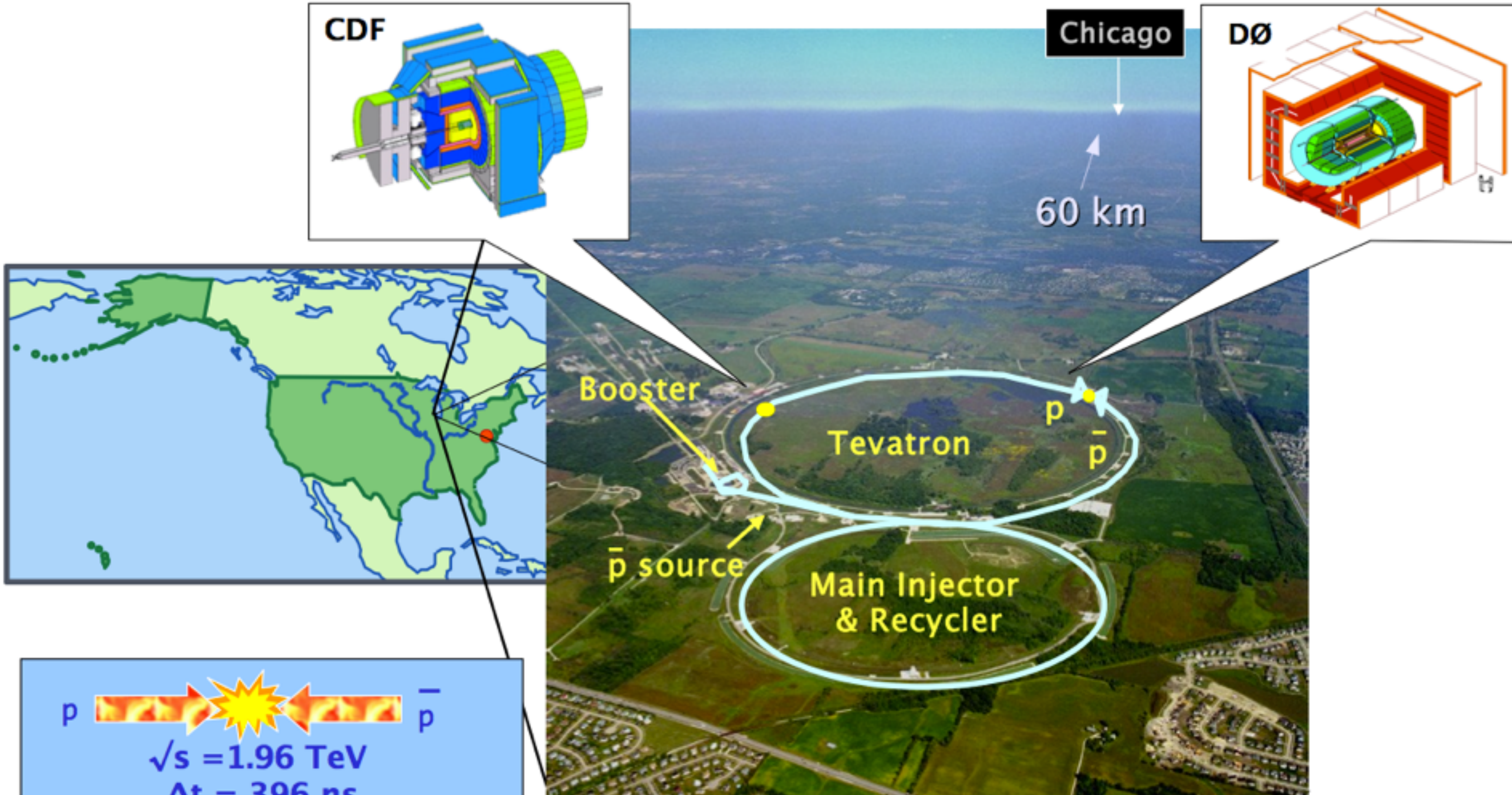
DESY

51st Rencontres de Moriond EW
15 March, 2016

on behalf of

The Tevatron $p\bar{p}$ Collider at Fermilab

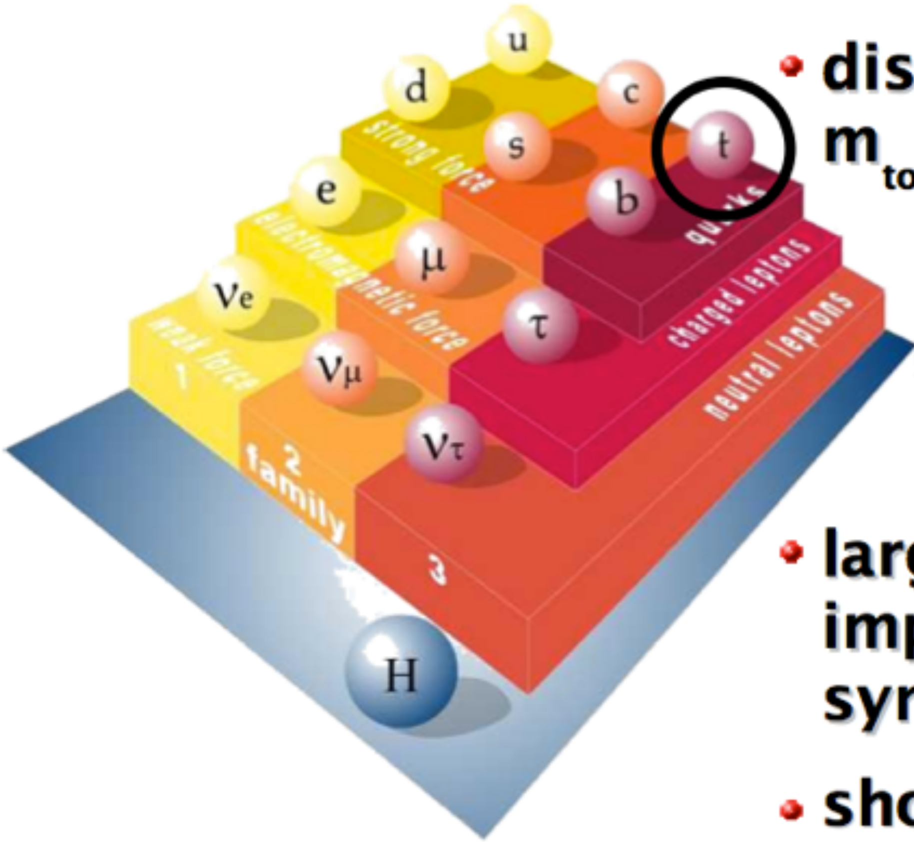


p p̄

$\sqrt{s} = 1.96$ TeV
$\Delta t = 396$ ns

Run I 1987 (92)–95
Run II 2001–11: 100x larger dataset at increased energy

The Top Quark

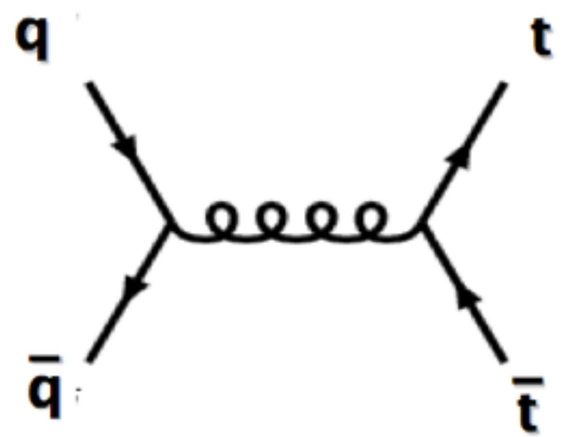


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus

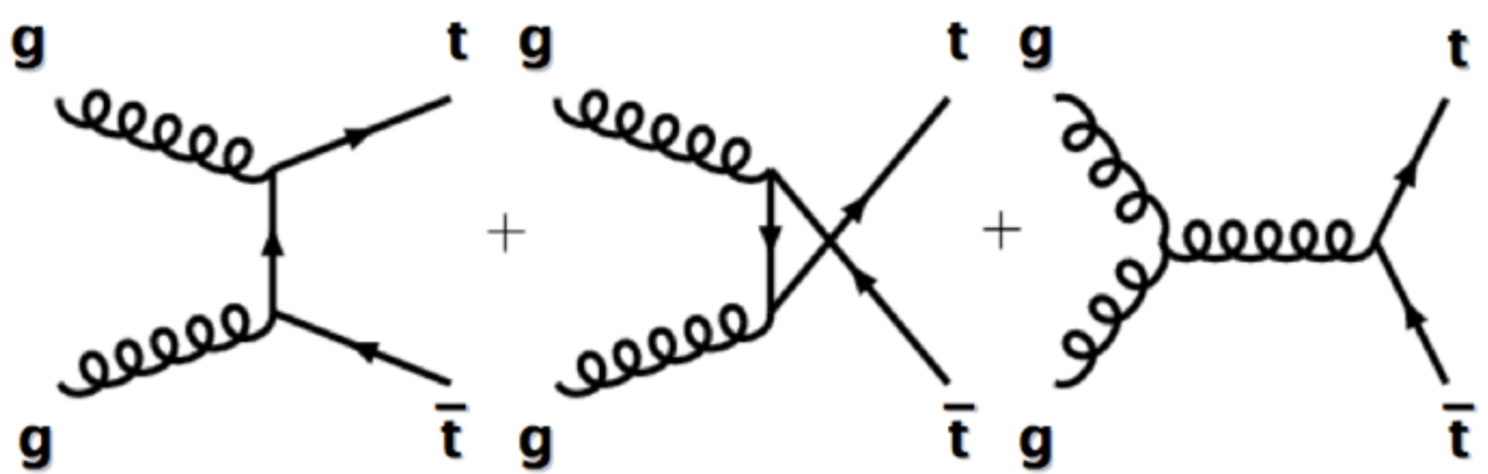
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\mathrm{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting
  → observe “naked” quark

Is the top quark the particle as predicted by the SM?

Top Quark Pair Production



Tevatron
(~85%)



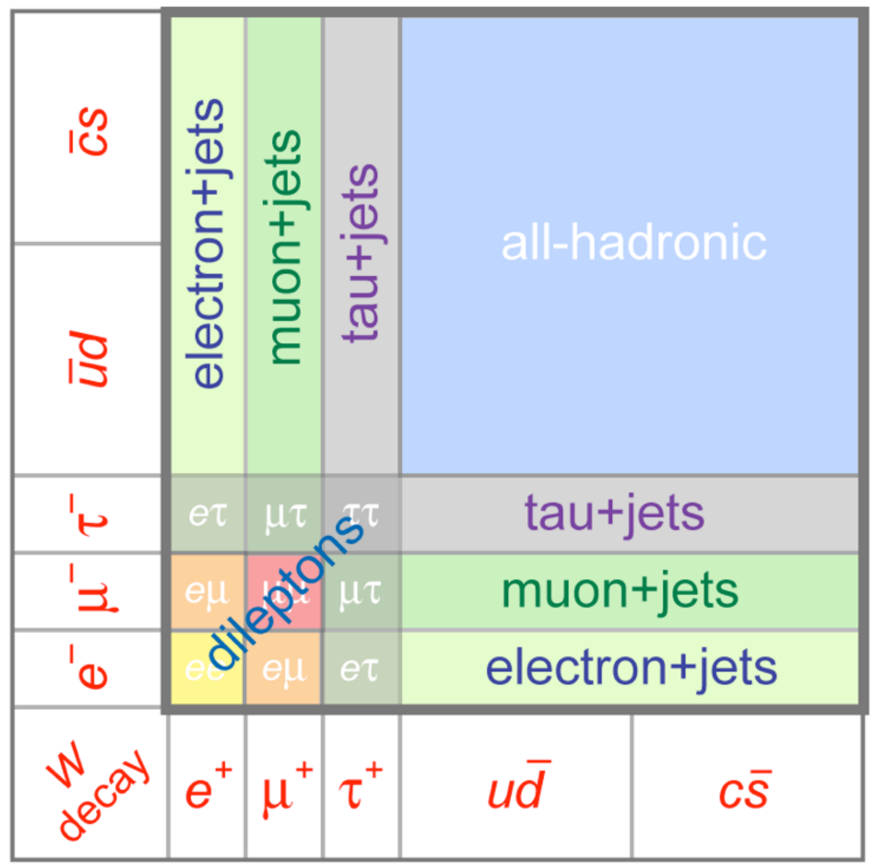
LHC
(~87%)
(8 TeV)

Top Quark Pair Signatures

τ's 14%

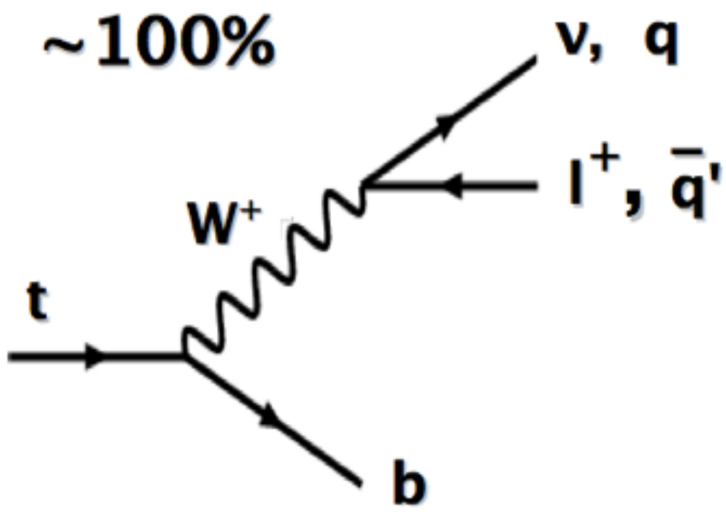
Top Pair Decay Channels

alljets 46%



top decay:

~100%

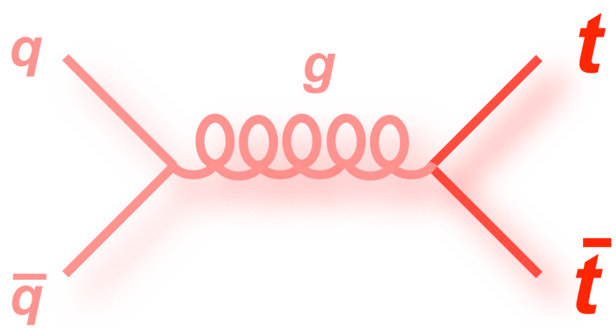


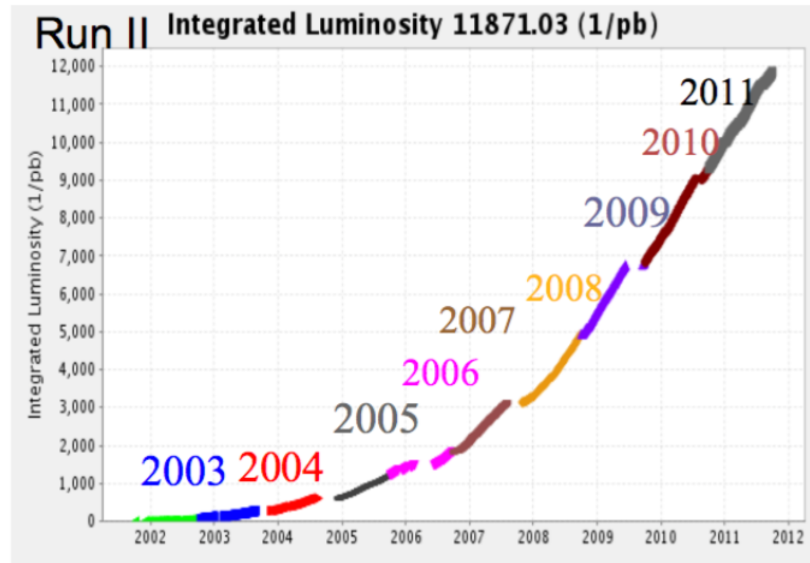
- **high p_T leptons, missing E_T**
- **jets**
- **b-jets**

dilepton (e/μ) 6%

e/μ+jets 34%

$t\bar{t}$ production density matrix





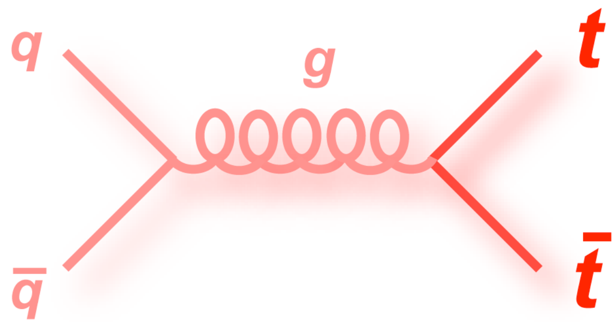
10 fb^{-1}

Top quark properties

- systematic analysis of the top quark pair production mechanism
- high precision measurements
- high sensitivity to new physics
- new and complementary to the LHC

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$



$$q(p_1) + \bar{q}(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

Bernreuther, Heisler, Si, JHEP 1512, 026 (2015)

$t\bar{t}$ production density matrix

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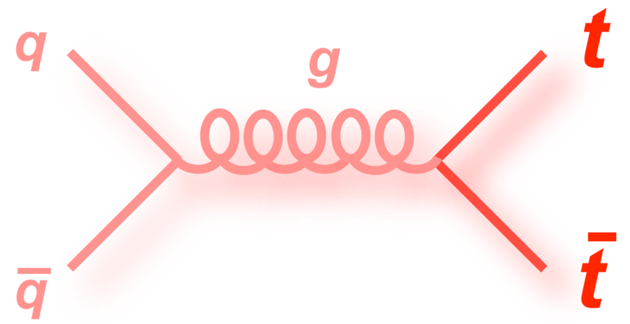

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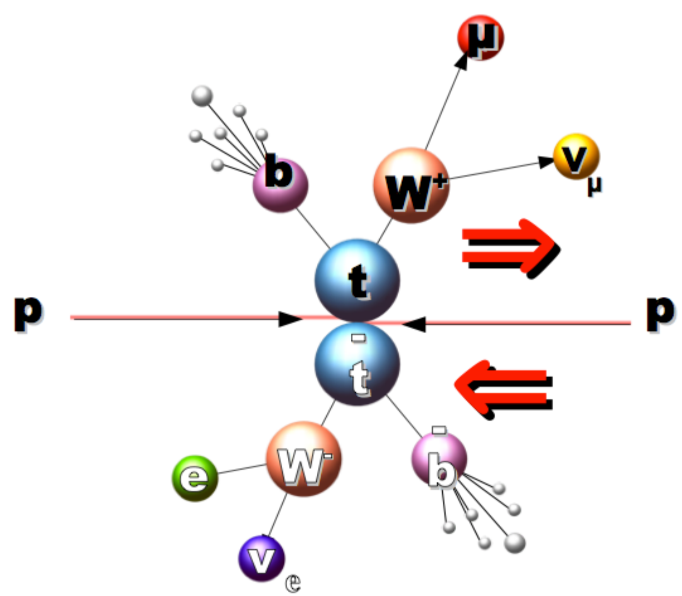
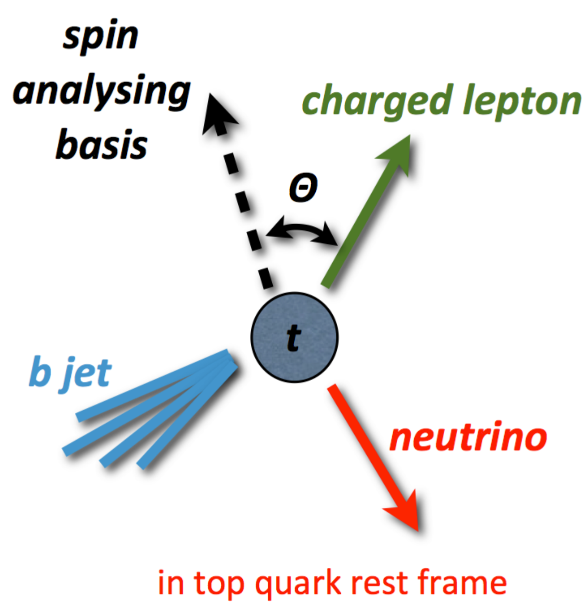




- almost 100% analysis power

- spin information is contained in decay products

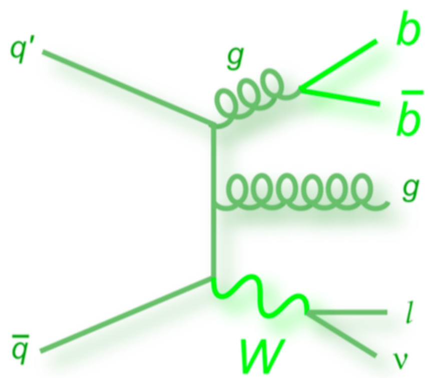
$t\bar{t}$ production density matrix

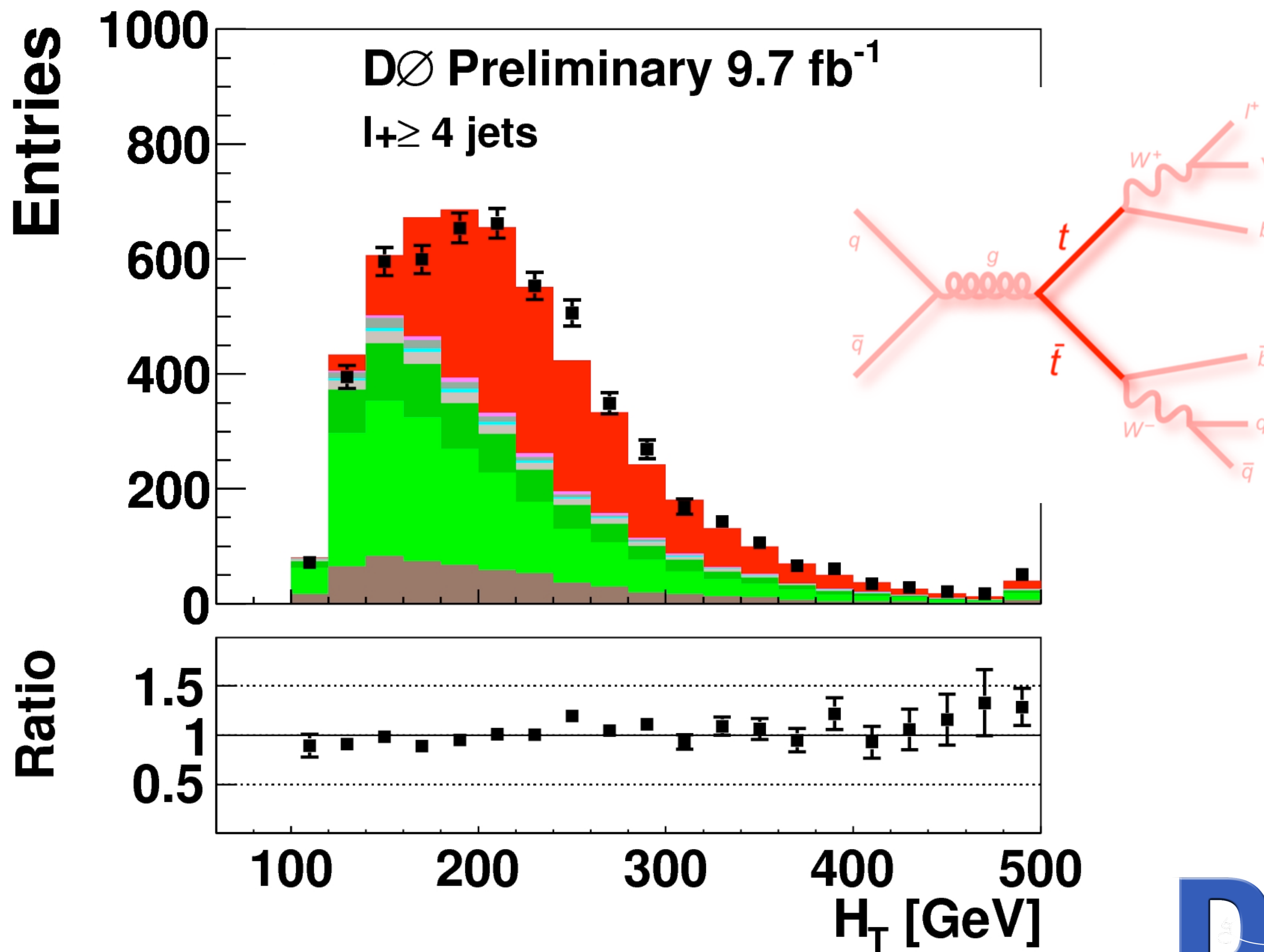
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

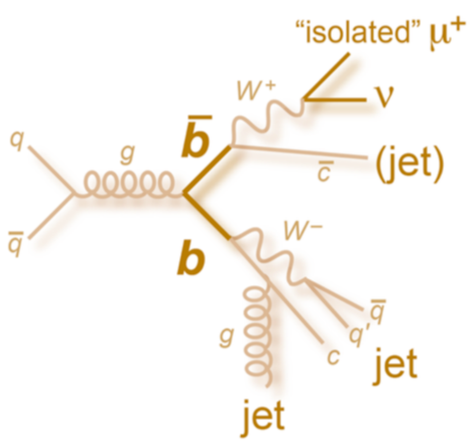
determines cross section and distributions independent of top spin (e.g. p^t_T distribution etc.)

- test of QCD predictions
- search for new physics

Lepton+Jets Channel

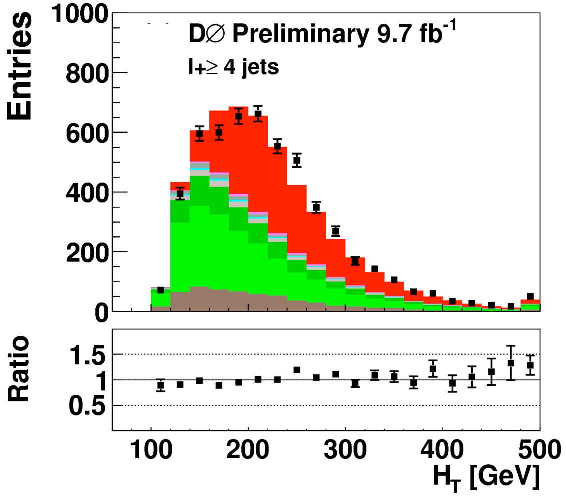




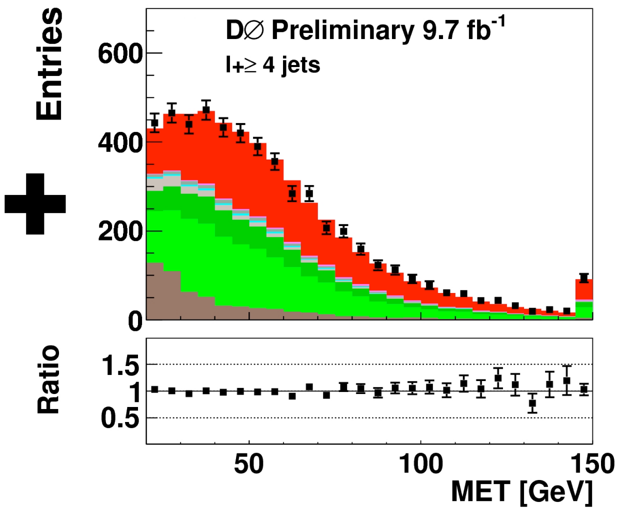


scalar sum of transverse momenta of jets and lepton

Multivariate analysis

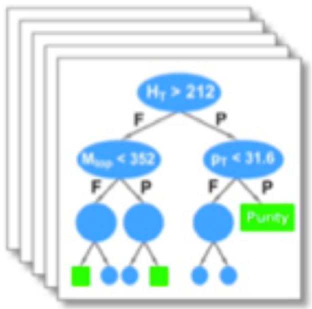


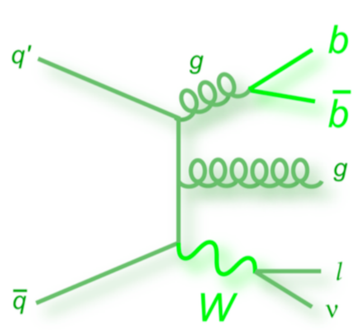
+

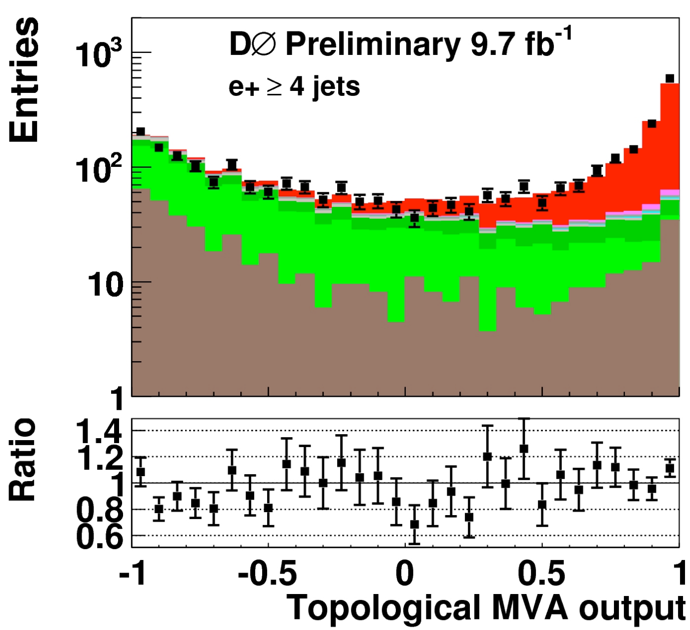


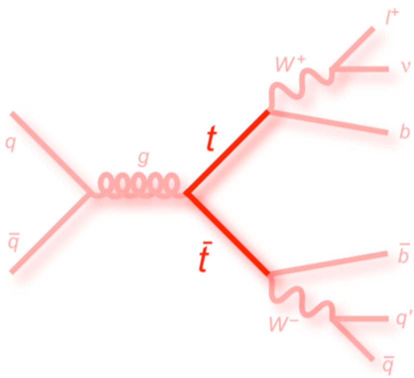
+ ... =

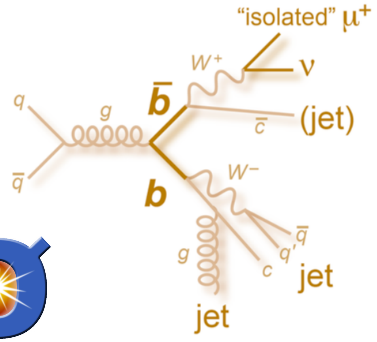
Boosted Decision Trees









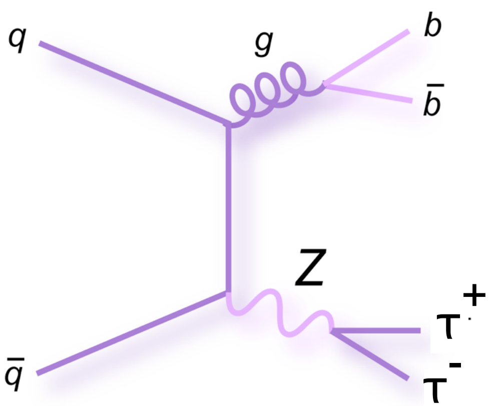


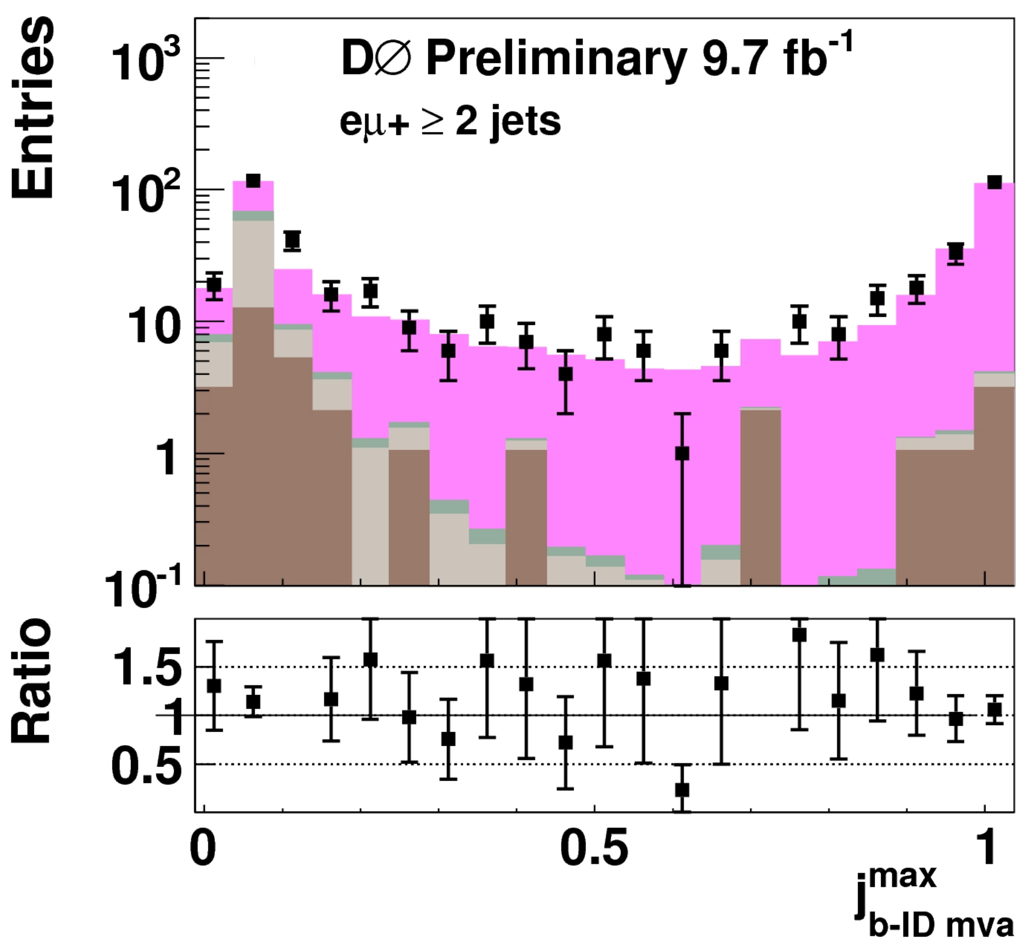
2, 3, ≥4jets

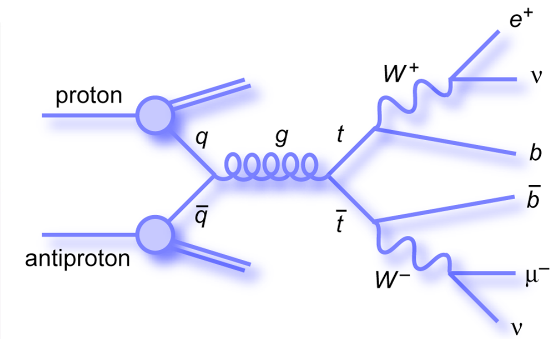
$$\sigma_{t\bar{t}} = 7.63 \pm 0.14\,(\text{stat.}) \;\pm 0.59\,(\text{syst.})\;\text{pb}$$

±7.9%

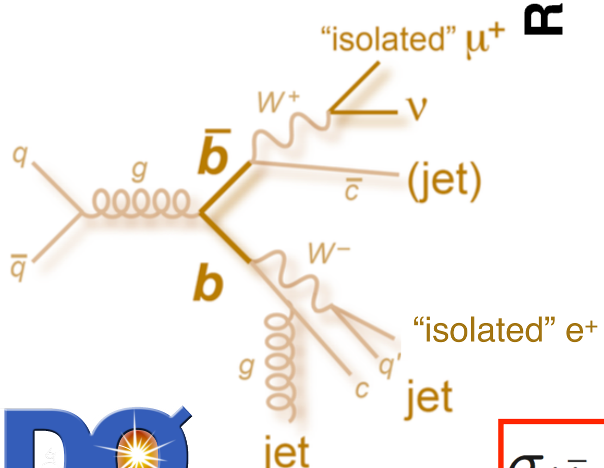
Dilepton Channel

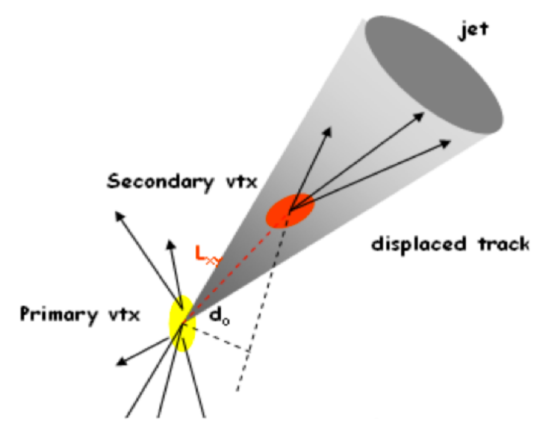






1, ≥2jets

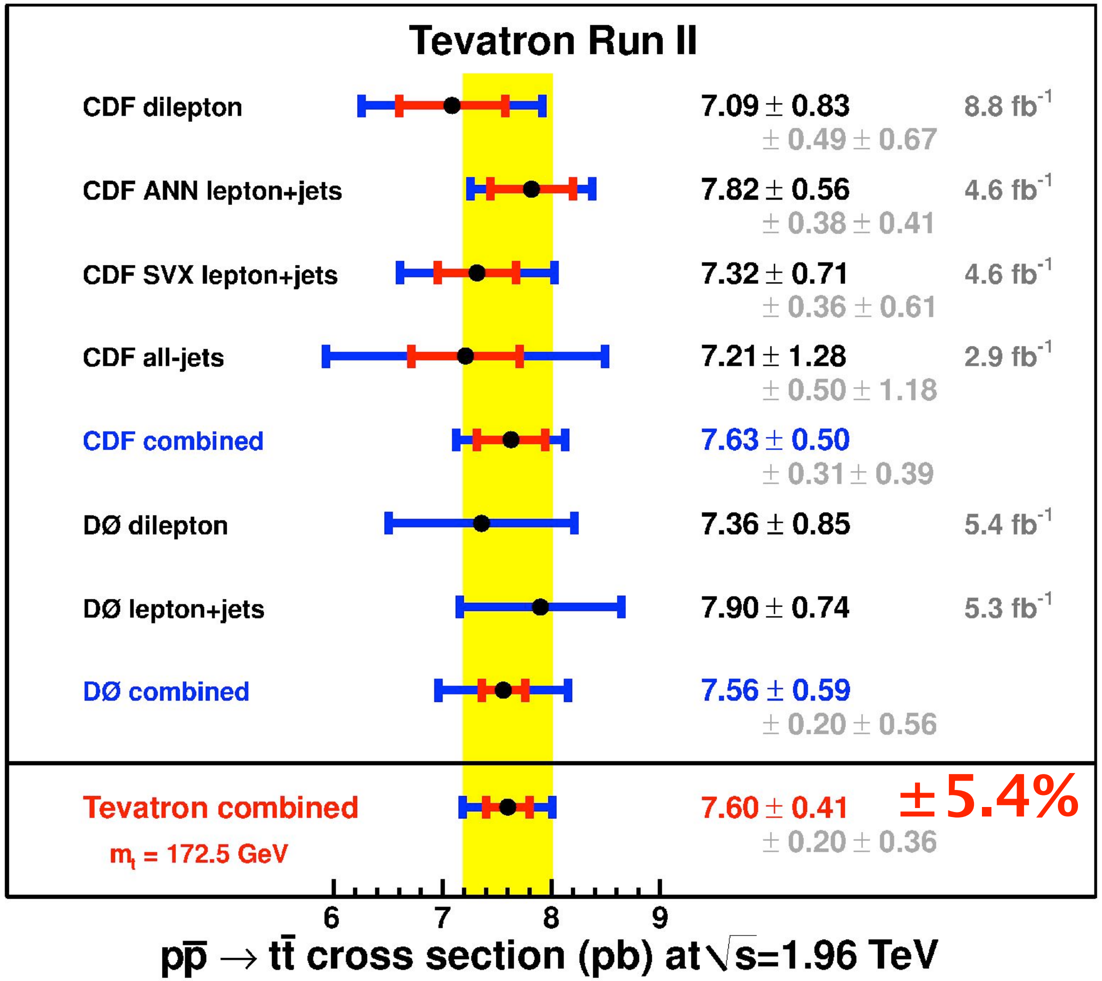




$$\boxed{\sigma_{t\bar{t}} = 7.60 \pm 0.34\,(\text{stat.})\,{}^{+0.60}_{-0.58}\,(\text{syst.})\ \text{pb}}$$

±9.0%

$t\bar{t}$ cross section summary



systematic uncertainties:

- modeling
- b-tagging
- luminosity

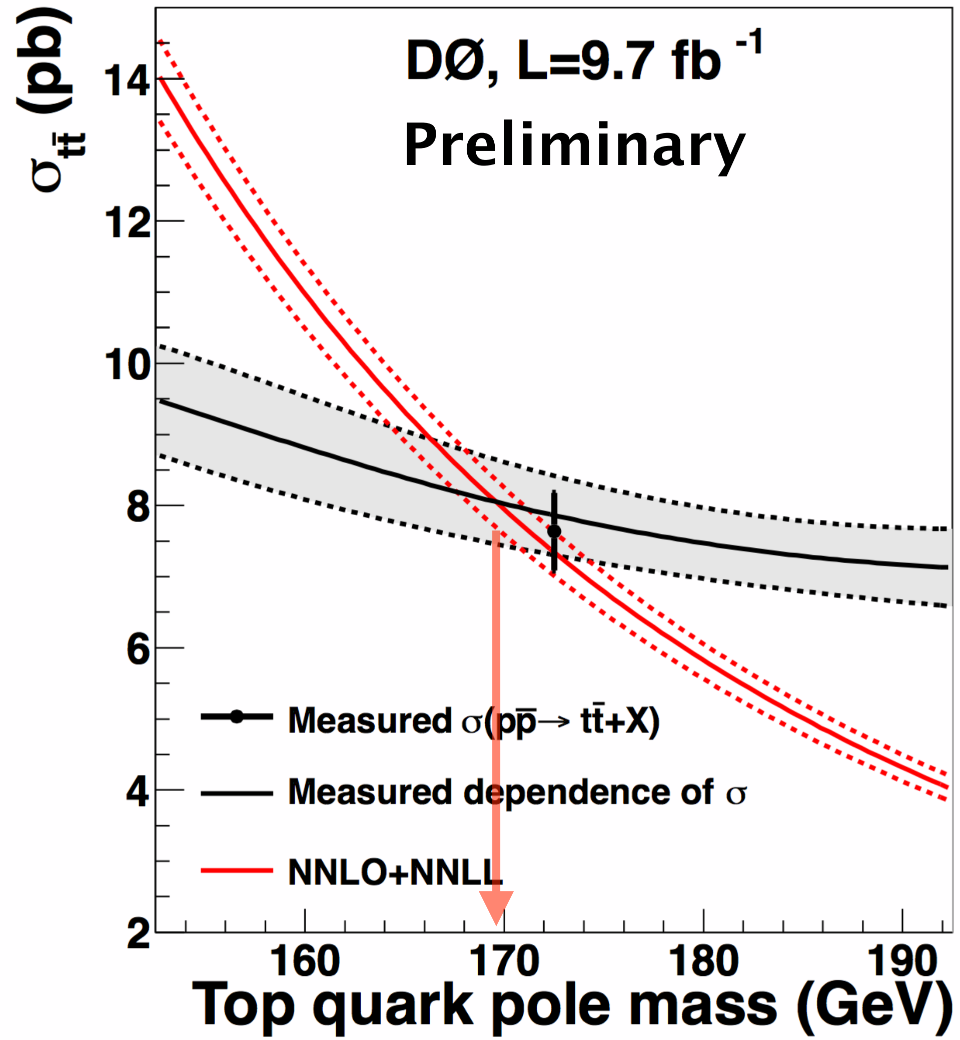
→ in agreement with SM

$$\sigma_{t\bar{t}} = 7.73 \pm 0.13\,(\text{stat.})\ \pm 0.55\,(\text{syst.})\ \text{pb}$$ ±7.3%

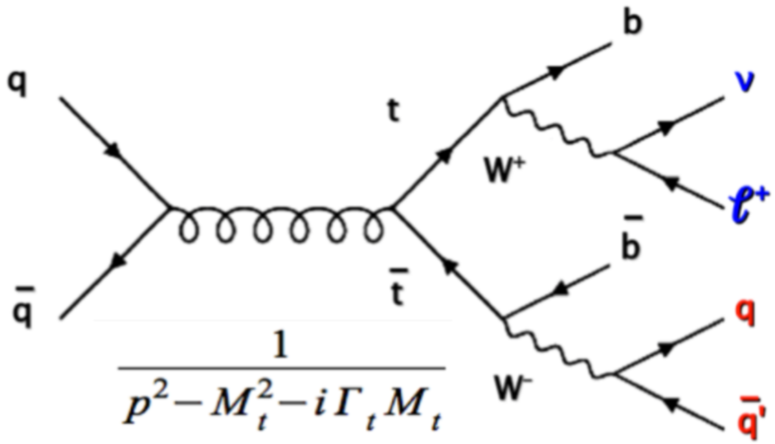
D0 Note 6453-CONF

$$\sigma^{\text{res}}_{\text{tot}} = 7.35^{+0.23}_{-0.27}\,(\text{scale} + \text{pdf})\ \text{pb}$$ NNLO+NNLL

Extraction of top pole mass



quantum field theoretically well defined mass parameter!



→ **in agreement with world average of MC mass of 173.34±0.76 GeV**

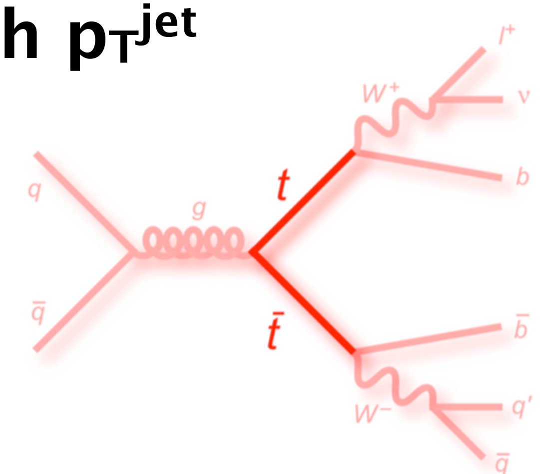
D0 Note 6453-CONF

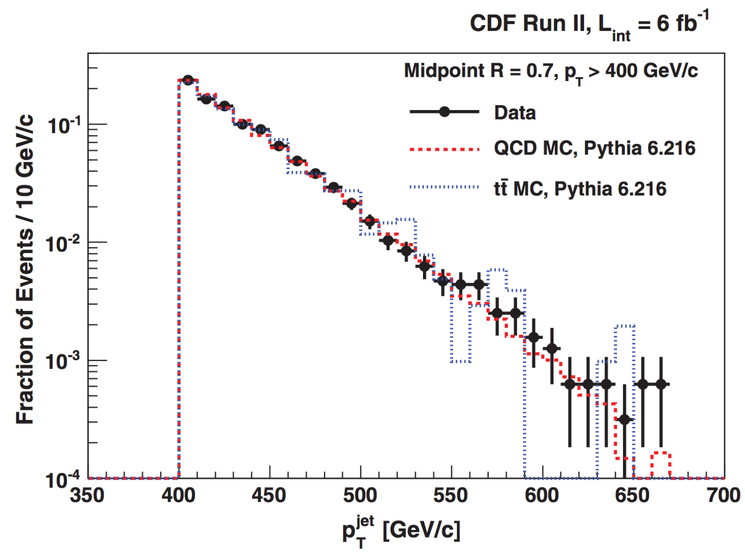
$$\boxed{m_t = 169.5^{+3.3}_{-3.4}\,(\text{tot.})\ \text{GeV}}$$

±1.9%

Searches for new physics

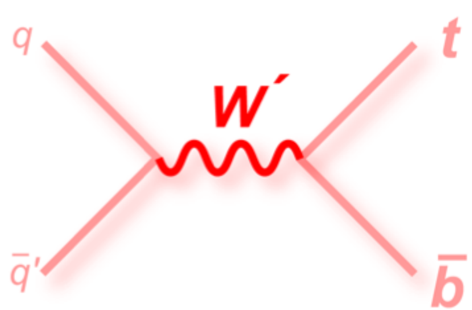
- high p_T^{jet}

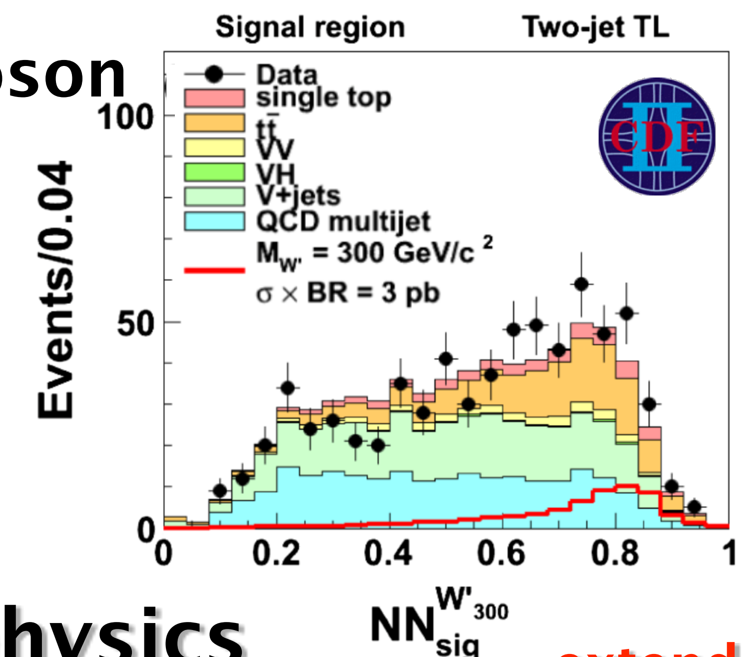




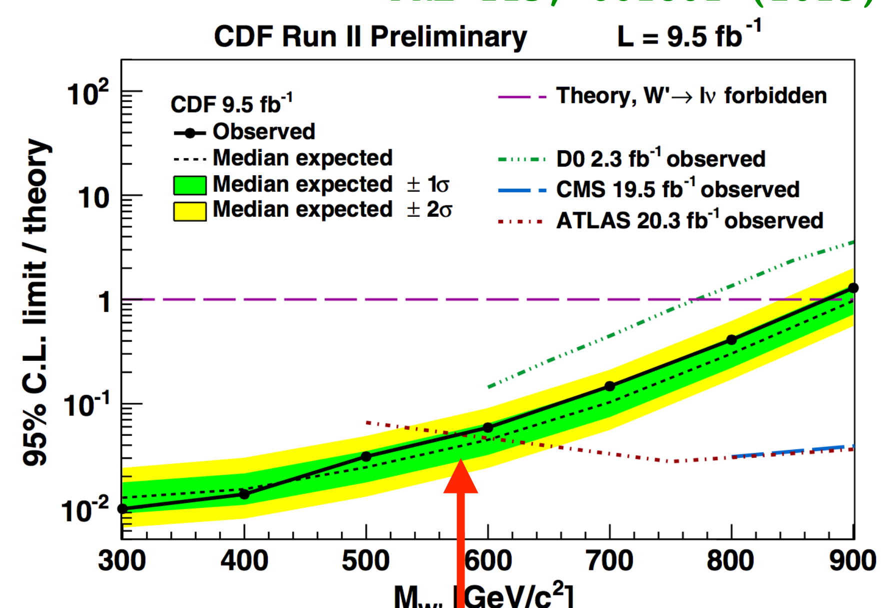
PRD 91, 032006 (2015)

- heavy W' boson





PRL 115, 061801 (2015)



→ no new physics

extending LHC limits

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

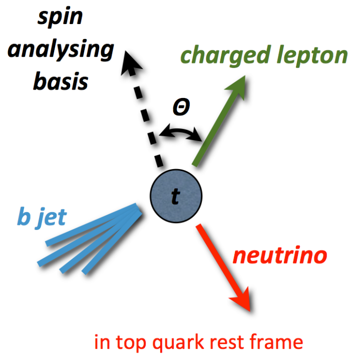
$$\tilde{B}_i^{\pm} = b_1^{\pm} \hat{p}_i + b_2^{\pm} \hat{k}_i + b_3^{\pm} n_i \quad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

longitudinal polarisation

transverse polarisation

$b_1^{\pm}$, $b_2^{\pm} \neq 0$: P-violation (=0 in LO QCD)

$b_3^{\pm} \neq 0$: CP-violation, ($\neq$0 through absorptive parts)



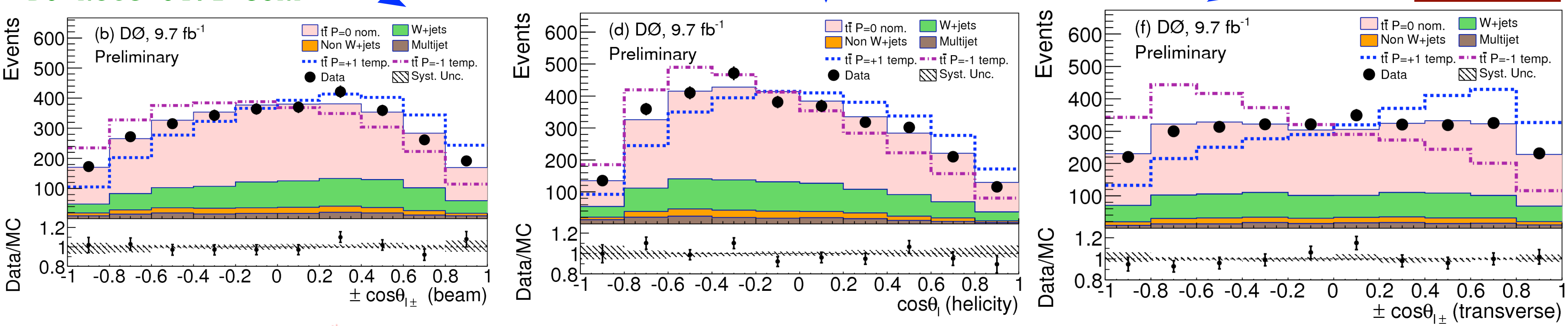
Longitudinal and transverse polarisation

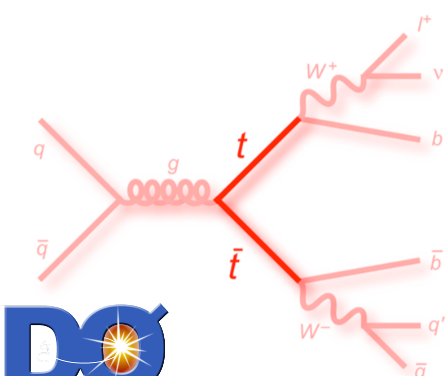
$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

$$\tilde{B}_i^{\pm} = b_1^{\pm} \hat{p}_i + b_2^{\pm} \hat{k}_i + b_3^{\pm} n_i \qquad \mathbf{n} = \hat{\mathbf{p}} \times \hat{\mathbf{k}}$$

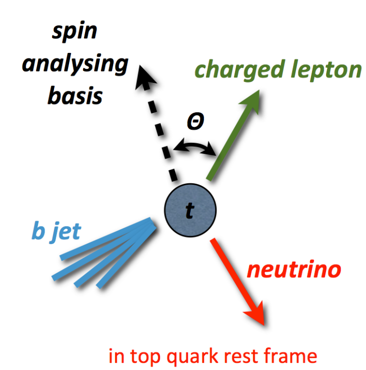
NEW

D0 Note 6471-CONF





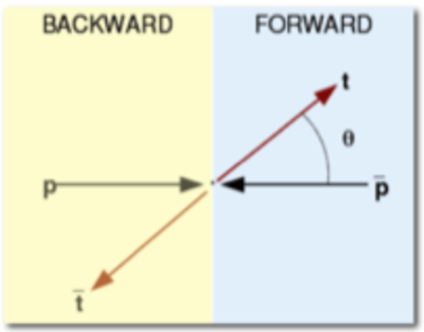
Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$



→ **in agreement with SM**

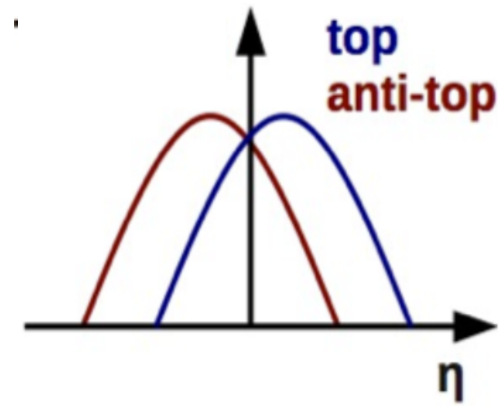
Forward-backward $t\bar{t}$ asymmetry

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

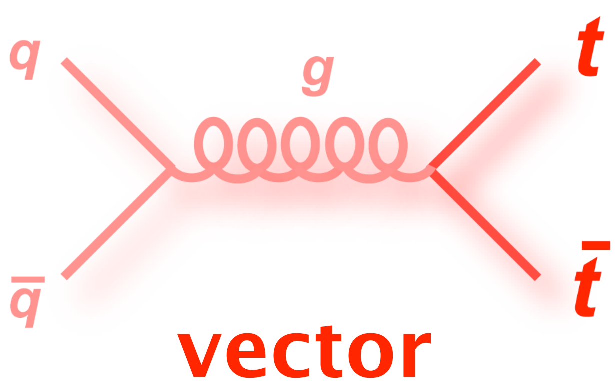


$$\boxed{A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}}$$

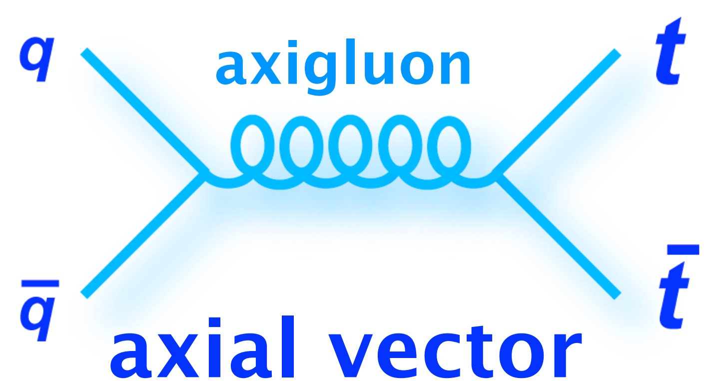
- complementary to LHC



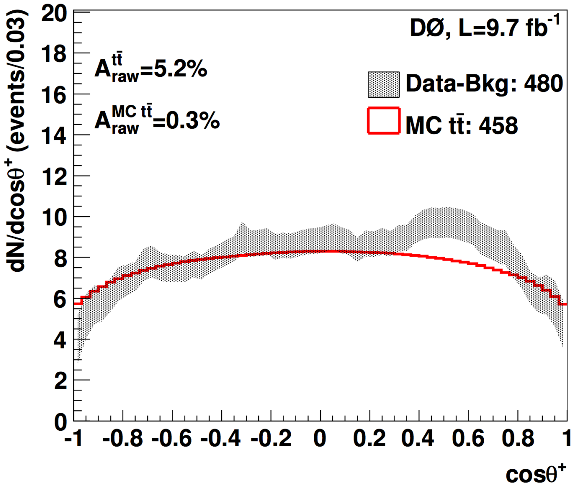
SM



BSM

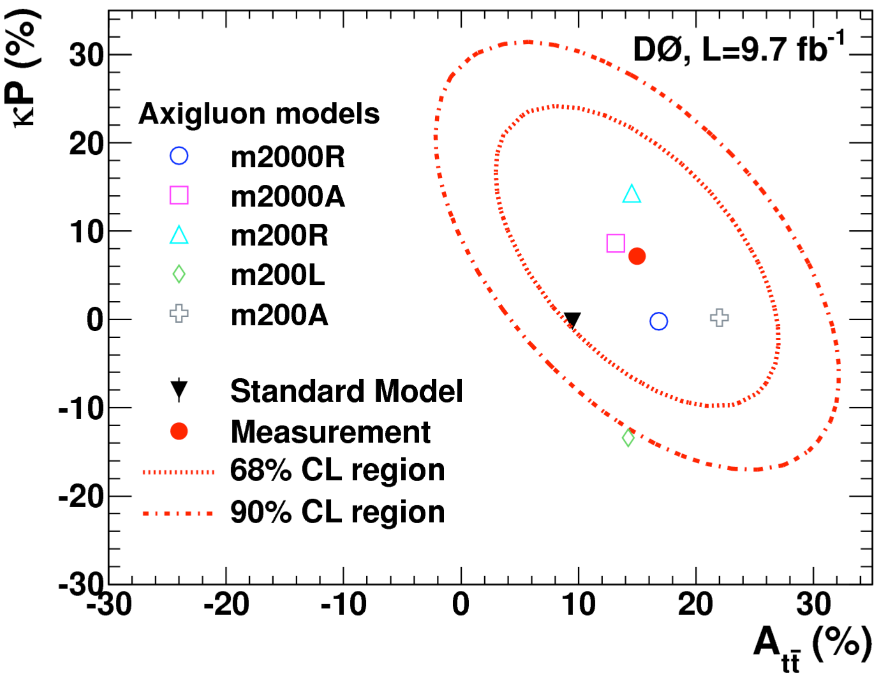


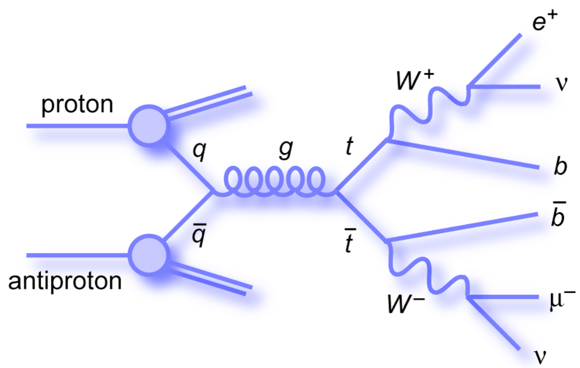
Asymmetry and polarisation



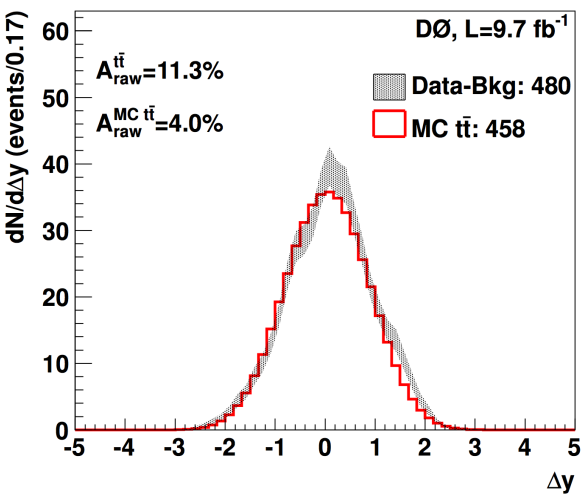
polarisation (helicity)

PRD 92, 052007 (2015)



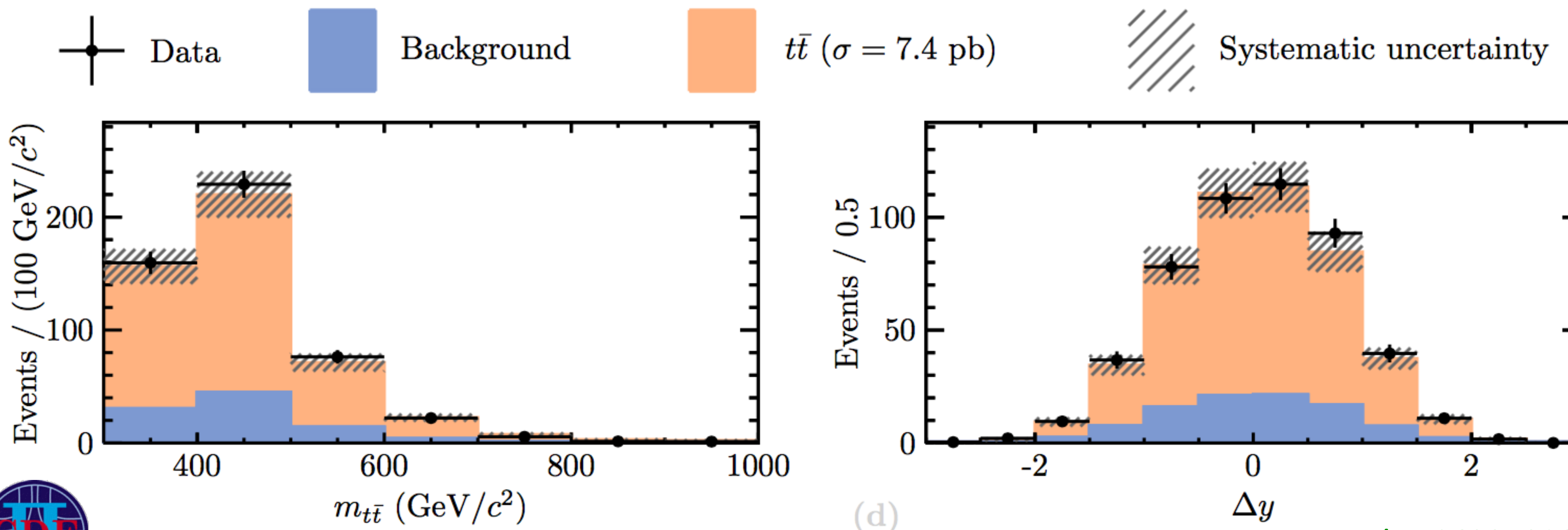


asymmetry

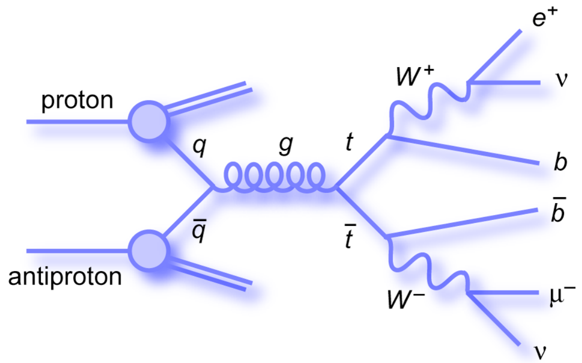


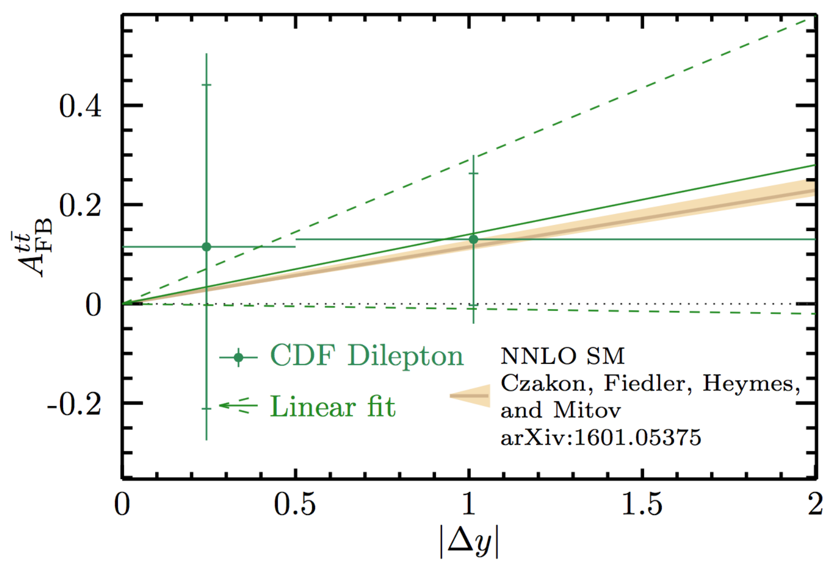
- ME integration method to reconstruct events
- background subtraction and calibration give true parton-level distributions

$t\bar{t}$ FB asymmetry



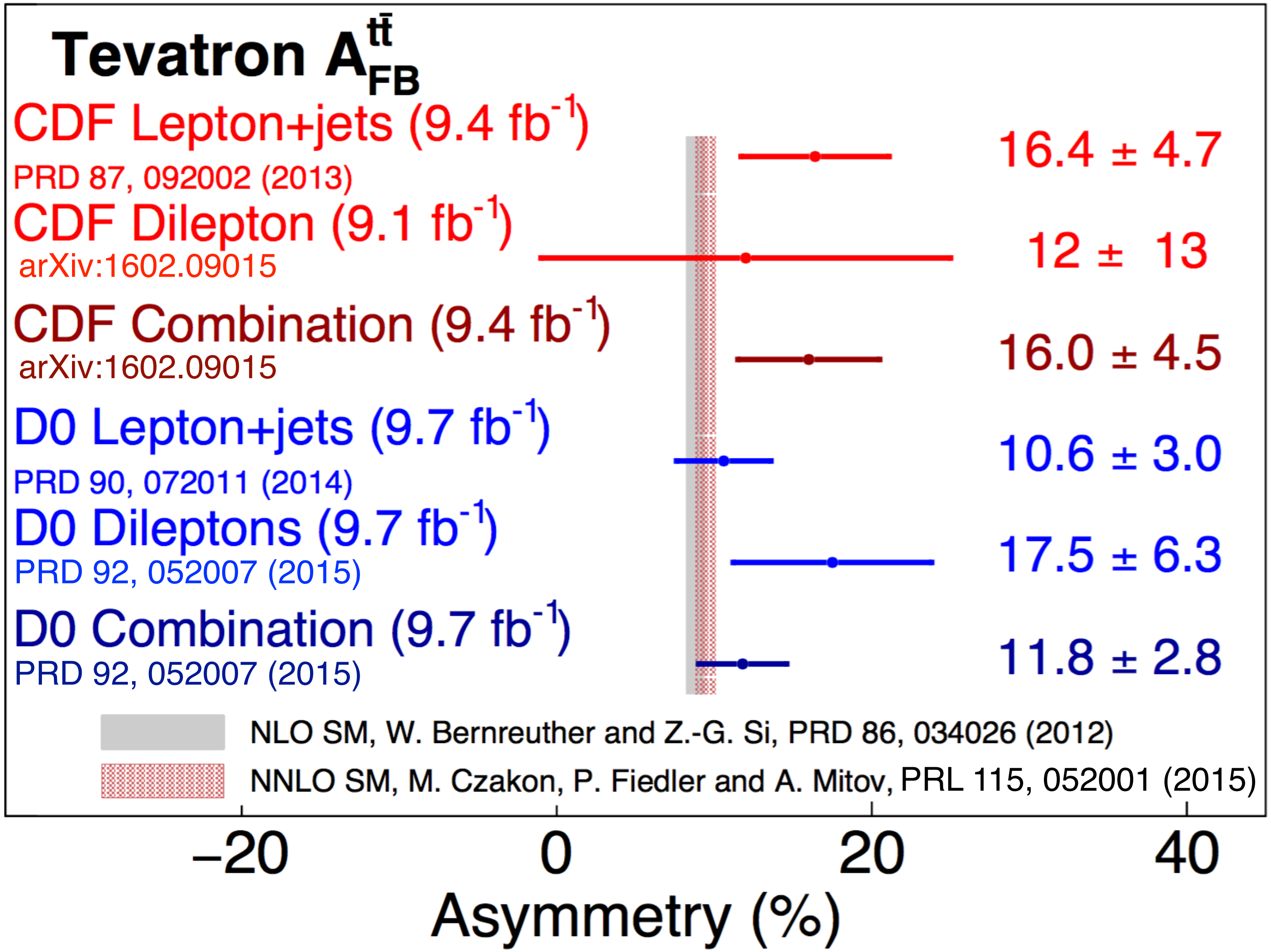
arXiv:1602.09015

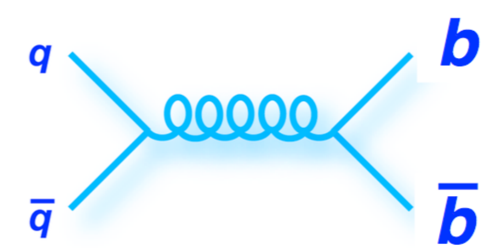




- optimised kinematic top pair reconstruction
- Bayesian procedure to extract parton-level asymmetry

Summary: $t\bar{t}$ FB asymmetry





→ **in agreement with SM**

$A_{FB}^{b\bar{b}}$ in agreement with SM

arXiv:1601.06526

PRD 92, 032006 (2015)

$t\bar{t}$ production density matrix

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

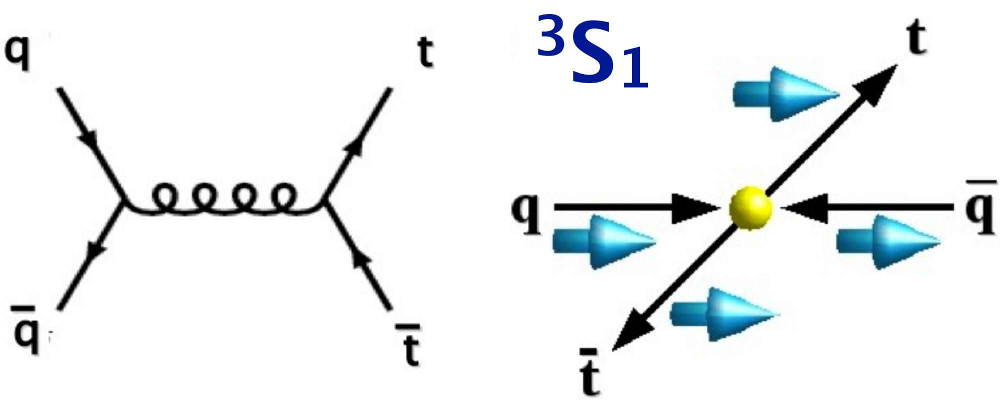
spin correlation

Spin correlation

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$

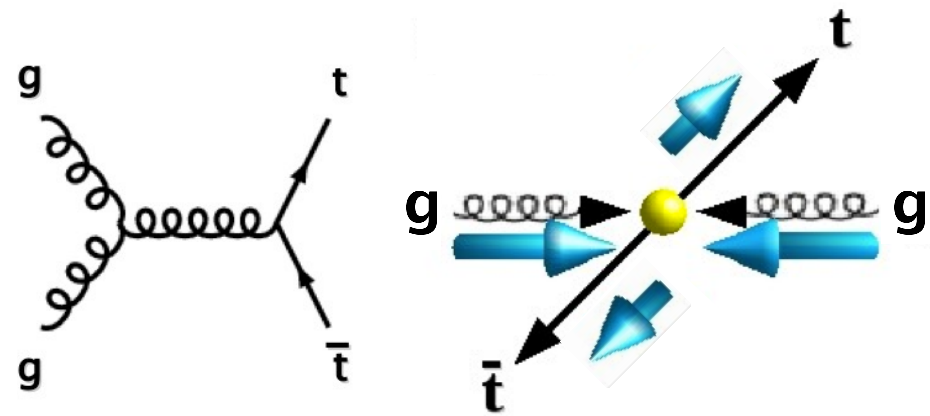
spin correlation

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



Tevatron

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold



LHC

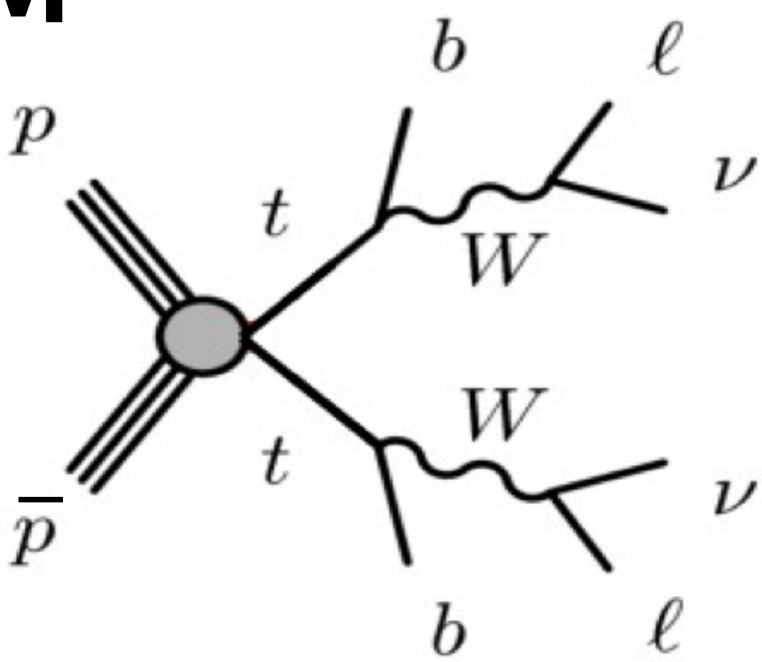
- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold

<u>complementary between Tevatron and LHC</u>

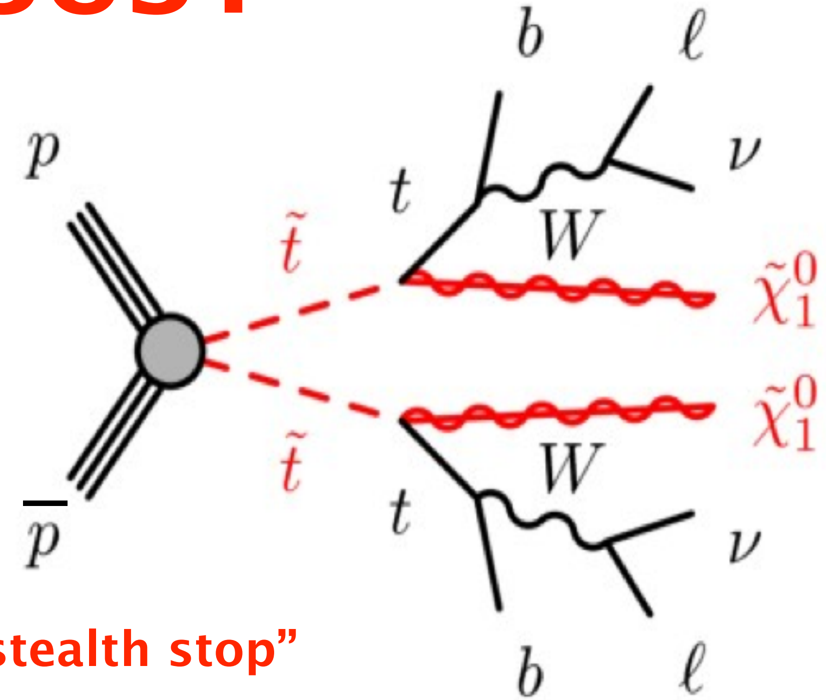
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay

SM



SUSY



“stealth stop”

→ SM spin correlation

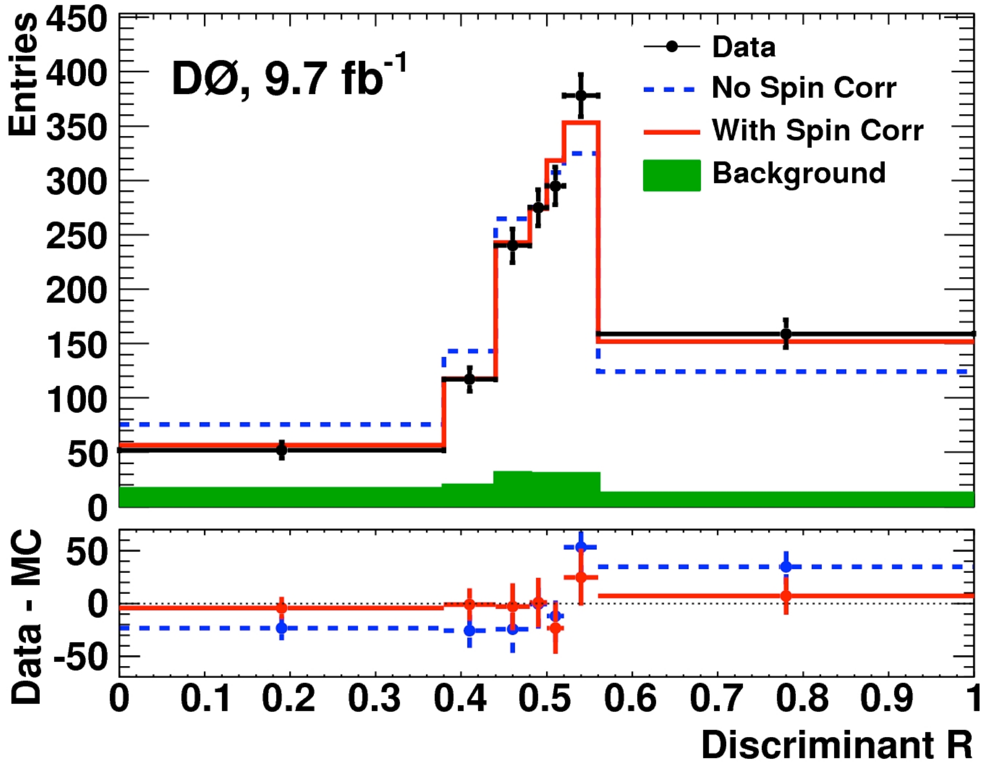
→ no spin correlation

Measurement of Spin Correlation Strength

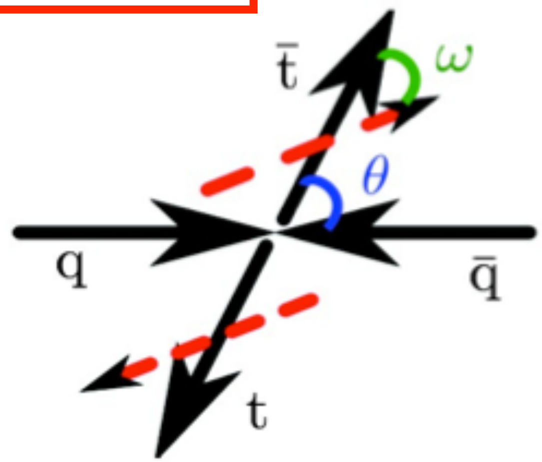
discriminant:
ME technique

$$R = \frac{P_{\rm sgn}(H=c)}{P_{\rm sgn}(H=u) + P_{\rm sgn}(H=c)}$$

combination:
dilepton & l+jets



arXiv:1512.08818



- interpolate between beam and helicity basis
- optimised "off-diagonal" basis

$$O_{\rm off} = 0.89 \pm 0.22 \text{ (stat + syst)}$$

NLO QCD: $O_{\rm off}^{\rm mc@nlo} = 0.766$

→ evidence for spin correlation with 4.2σ

Conclusions

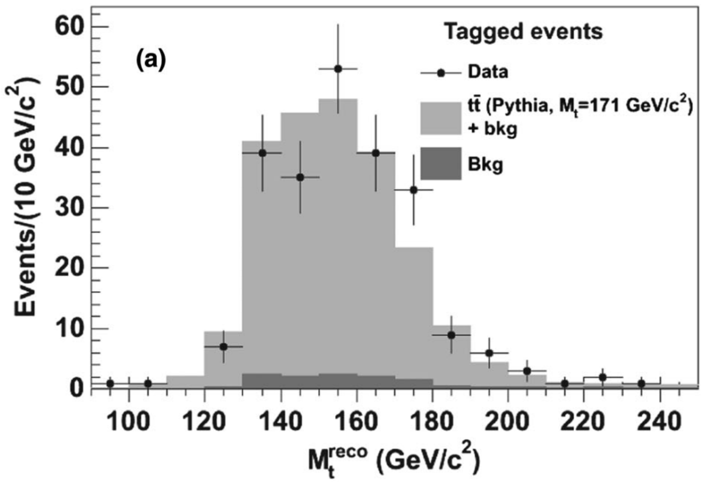
- **Tevatron had very successful top quark analysis program**
  - observation
  - development of analysis techniques
  - high precision measurements
  - searches for new physics
- **legacy results on the full dataset complement LHC**
  - different centre-of-mass energy
  - different initial state $p\bar{p}$
- **Presented a systematic analysis of top quark properties in pair production**

→ **top quark as predicted by SM**

→ **LHC offers new era of high precision and new phenomena discoveries**

Backup

Dilepton top mass at the Tevatron

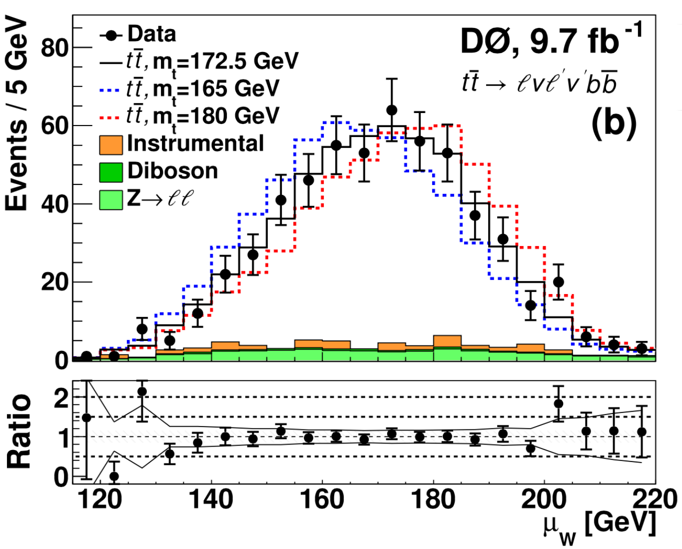


$$M^{\mathrm{hyb}} = w \cdot M_t^{\mathrm{reco}} + (1-w) \cdot M_{\ell b}^{\mathrm{alt}}$$

update

±1.8%

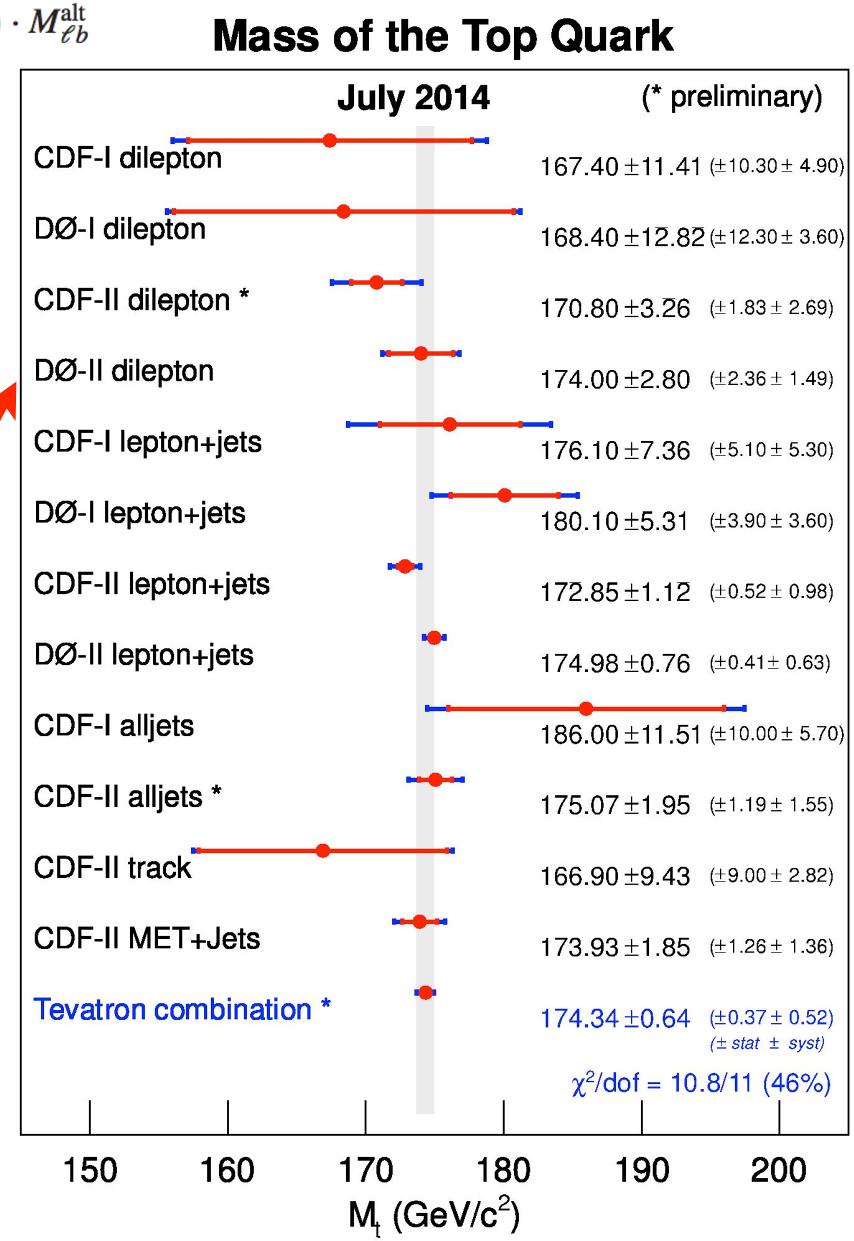
$$\boxed{M_{\mathrm{top}} = 171.5 \pm 1.9\,(\mathrm{stat}) \pm 2.5\,(\mathrm{syst})\ \ \mathrm{GeV}}$$



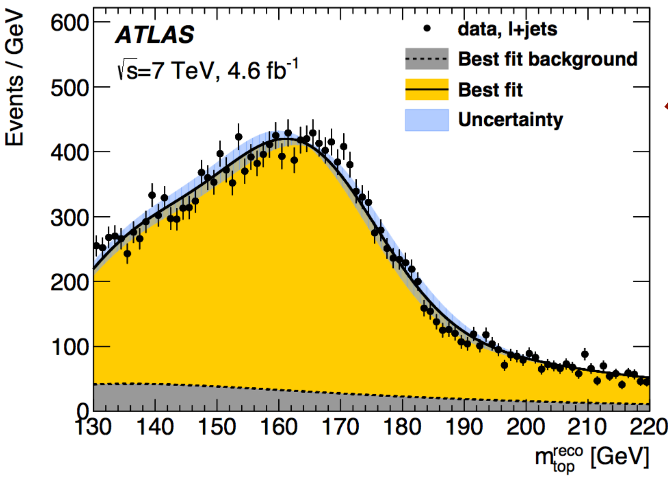
update

±0.9%

$$\boxed{m_t = 173.32 \pm 1.36(\mathrm{stat}) \pm 0.85(\mathrm{syst})\ \ \mathrm{GeV}}$$

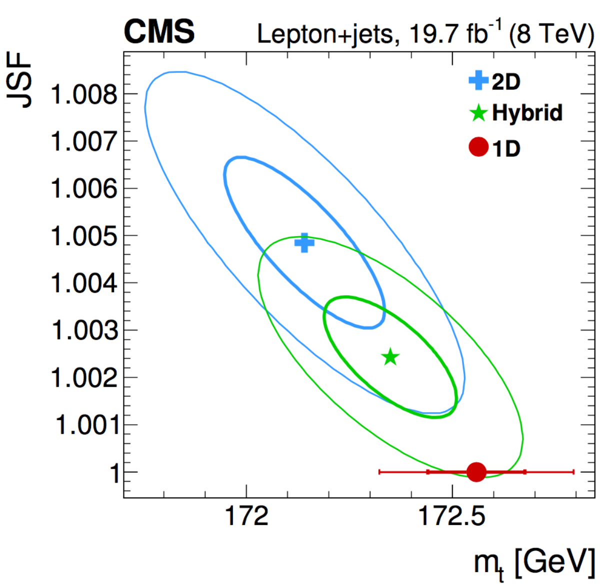


Top mass at the LHC



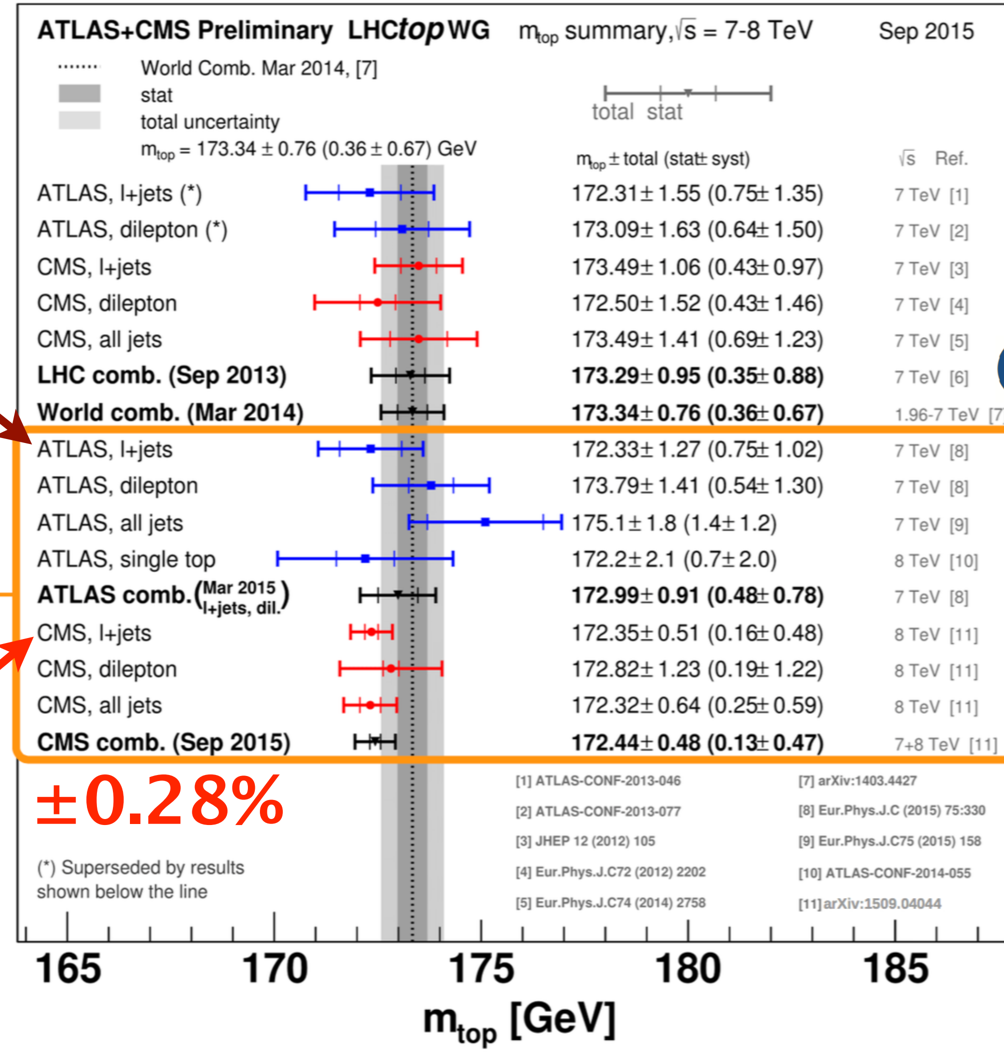
±0.73%

$$m_{\mathrm{top}}^{\ell+\mathrm{jets}} = 172.33 \pm 0.75\,(\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\,(\mathrm{syst})\ \mathrm{GeV}$$



±0.29%

$$m_{\mathrm{t}}^{\mathrm{hyb}} = 172.35 \pm 0.16\,(\mathrm{stat{+}JSF}) \pm 0.48\,(\mathrm{syst})\,\mathrm{GeV}$$



±0.28%

New results waiting for combination!
(in addition to latest results from Tevatron)

→ jet energy scale is crucial

What mass do we measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

m_{top}

- **LO QCD: free parameter**
- **NLO QCD: dependent on the renormalisation scale M**

"Bare" parameters of QCD:

$g_s,\ m_u,\ m_d,\ m_s,\ m_c,\ m_b,\ m_t$

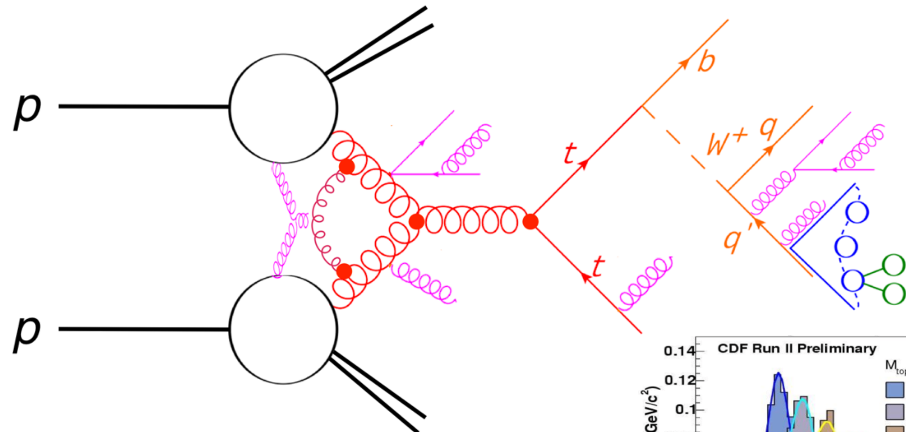
Renormalised parameters of QCD:

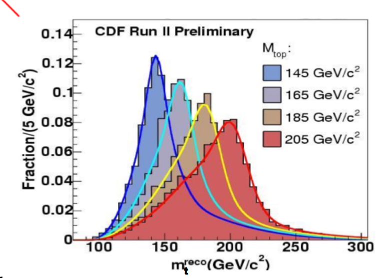
$g_s(M),\ m_u(M),\ m_d(M),\ m_s(M),\ m_c(M),\ m_b(M),\ m_t(M)$

the concept of quark mass is convention-dependent!

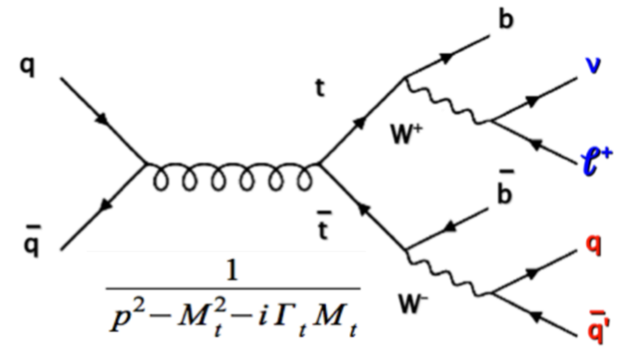
What mass do we need?

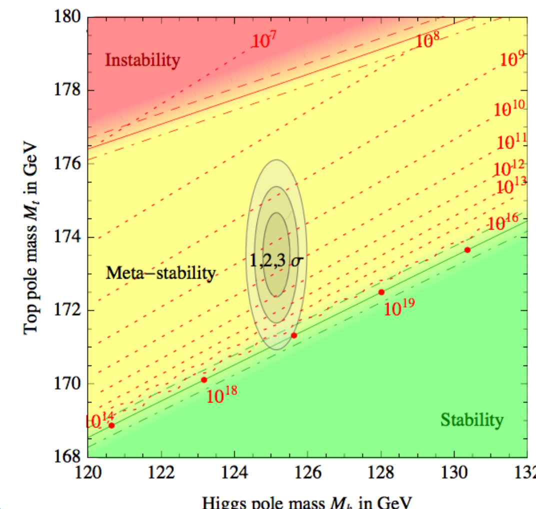
- we measure the MC mass





- we need the pole mass





- we need to calculate:

Scheme-dependent

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{quark}} + \Delta$$

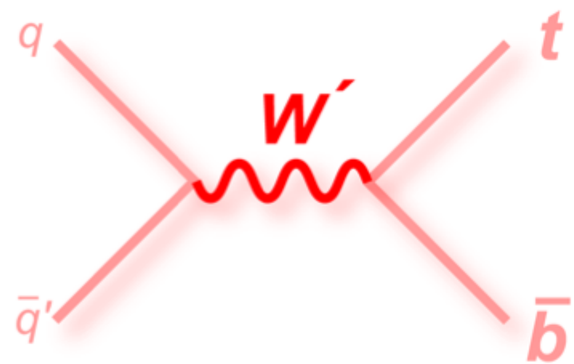
~ O(1 GeV)

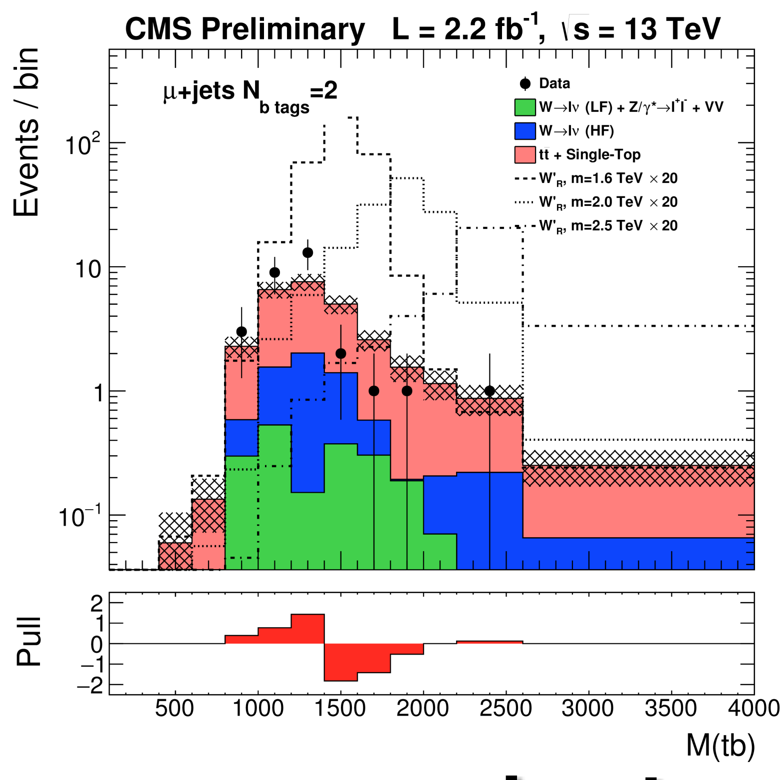
e.g. pole mass

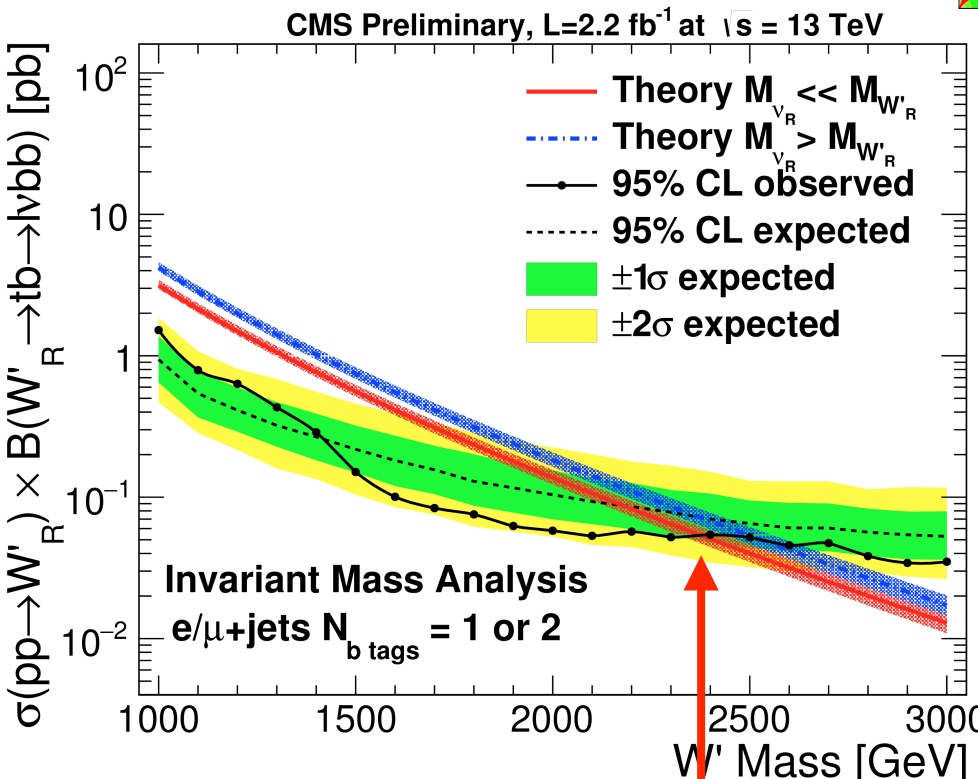
- every MC generator mass can can correspond to a different pole mass

Search for W' production

13 TeV





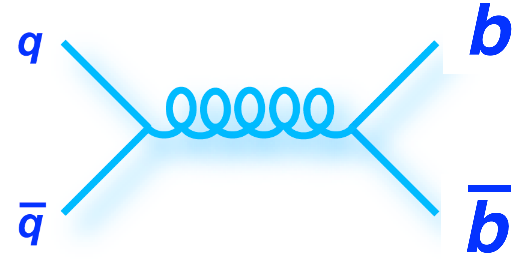


2.38 TeV

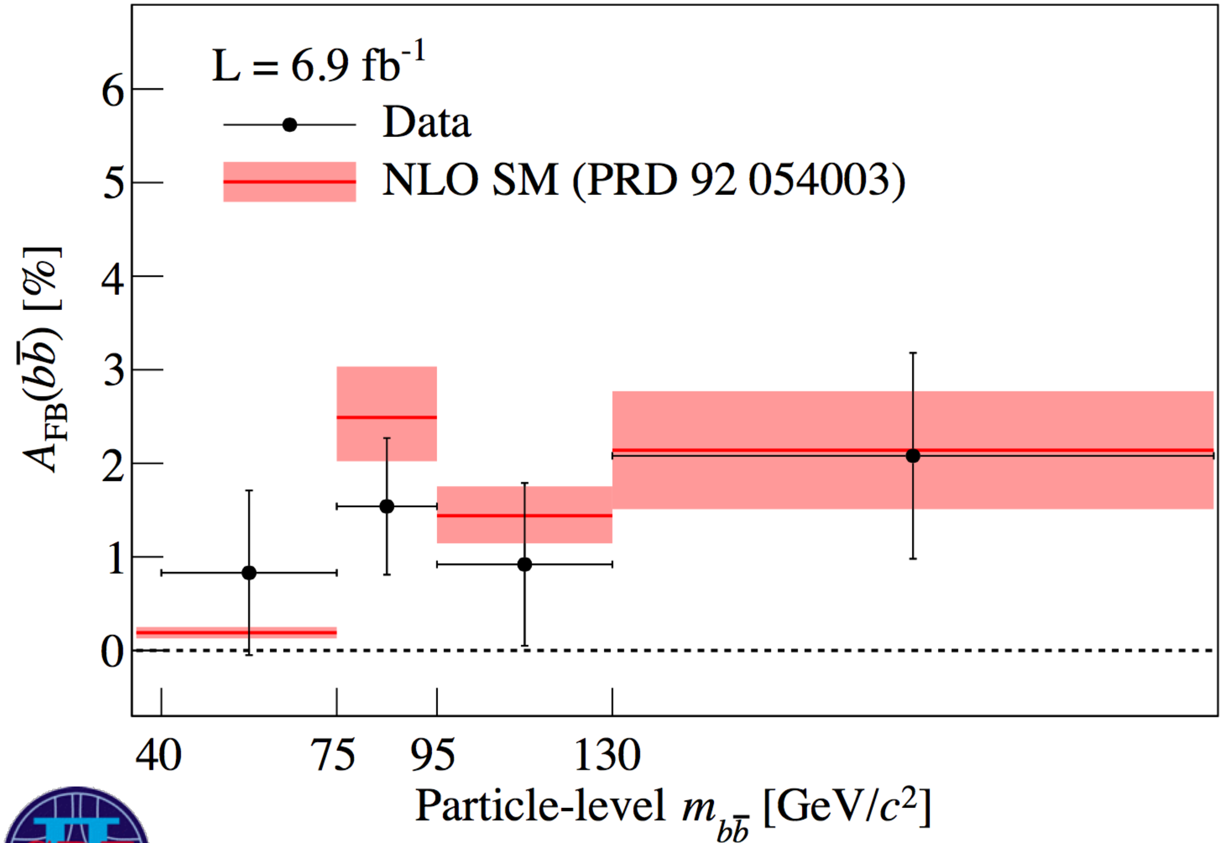
→ **no new physics**

FB asymmetry of $b\bar{b}$ production

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



arXiv:1601.06526



→ **in agreement with SM**

FB asymmetry of b$\bar{\text{b}}$ production

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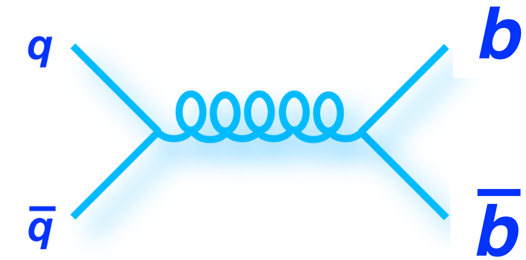
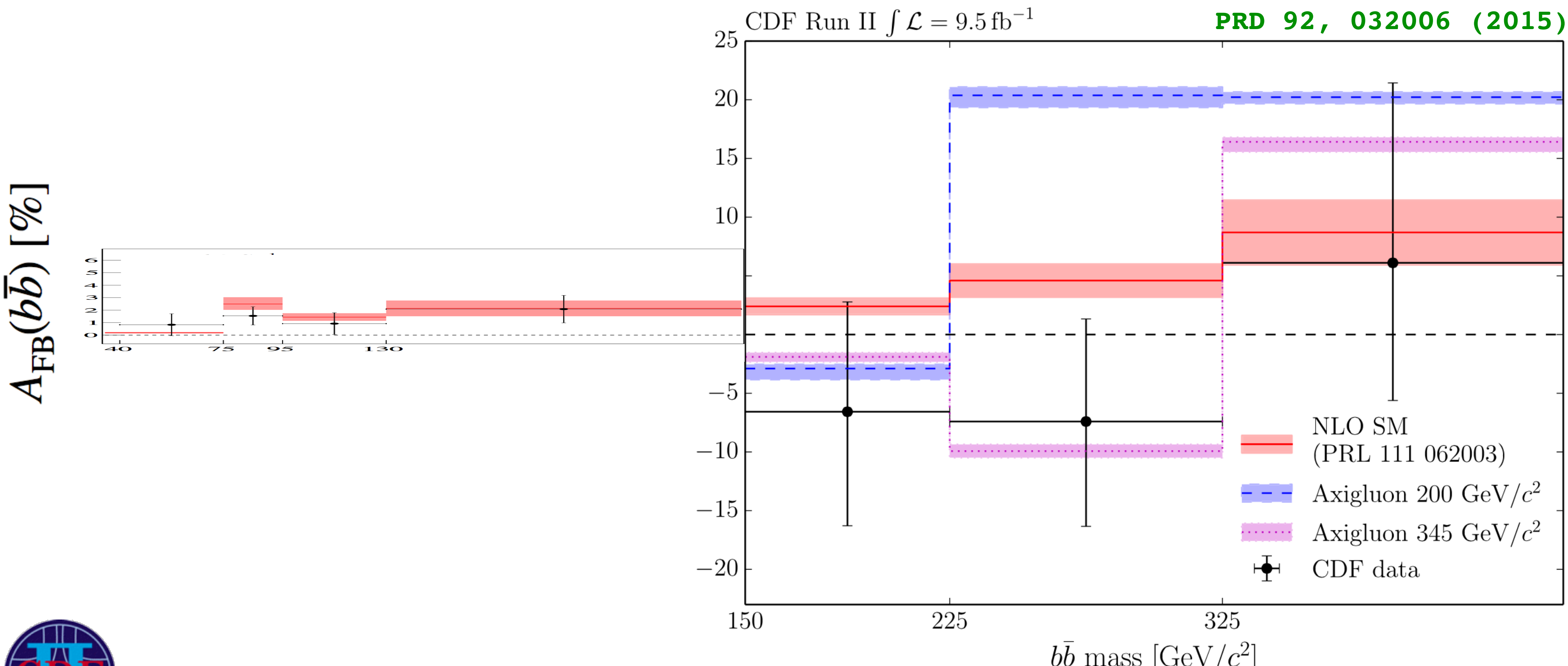


PRD 92, 032006 (2015)



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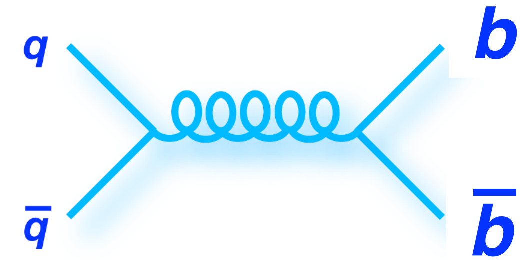
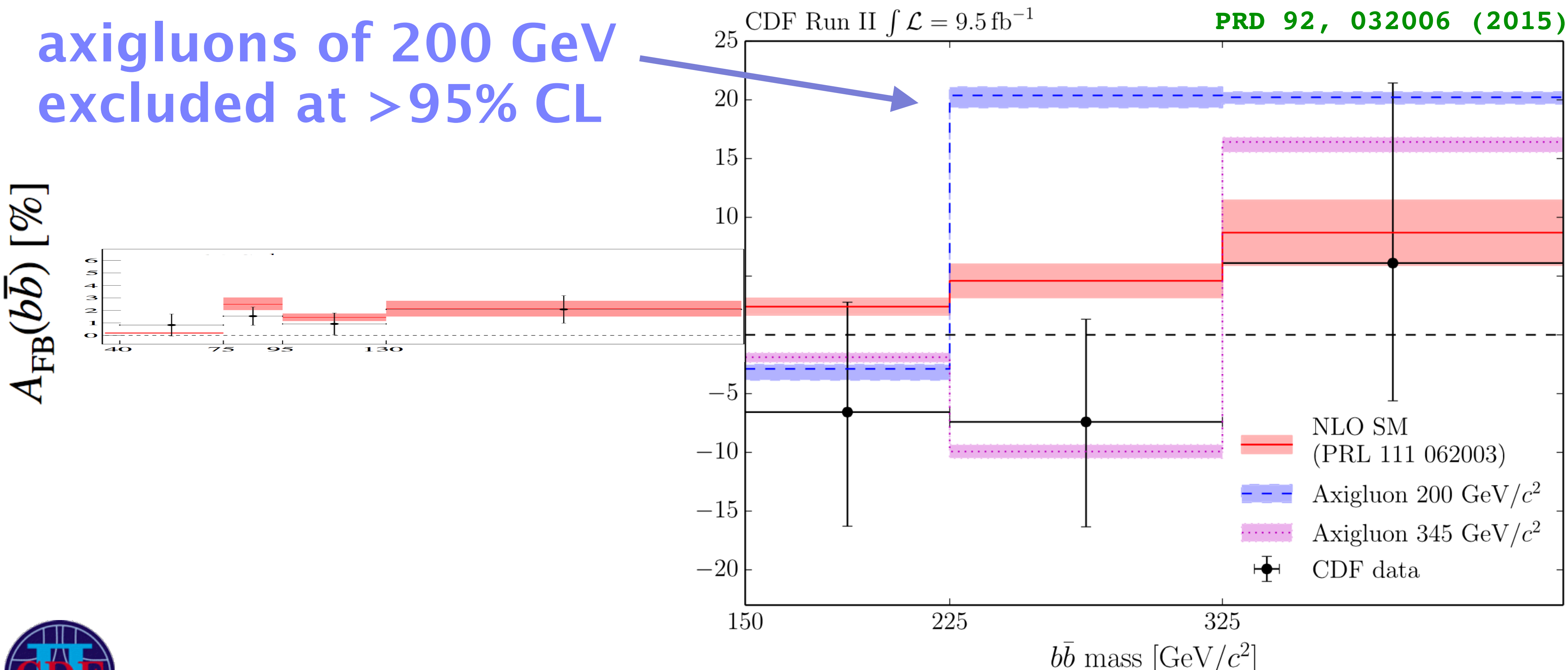


axigluons of 200 GeV excluded at >95% CL



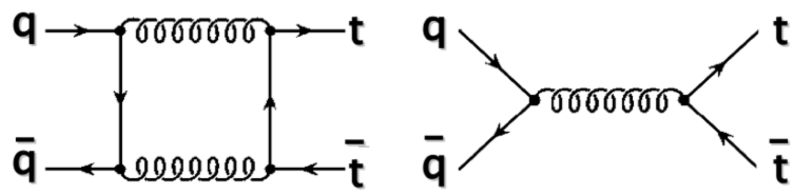
→ **in agreement with SM**

Charge Asymmetry

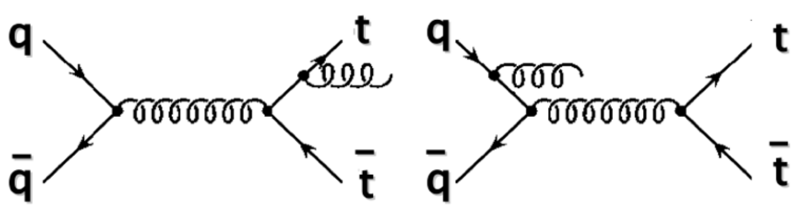
- asymmetry in $O(\alpha_s^3)$

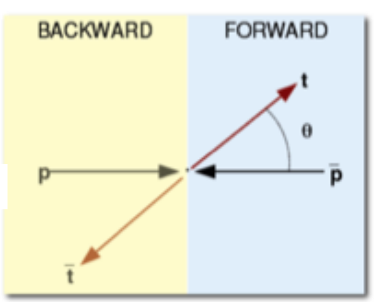
NLO QCD

interference between:



interference between:





$$A_{fb} = \frac{F - B}{F + B}$$

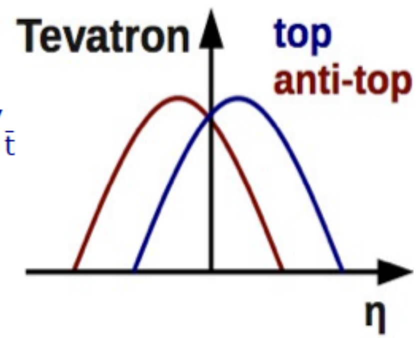
"NLO is LO for asymmetry"

- **complementary to the LHC**

Tevatron

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

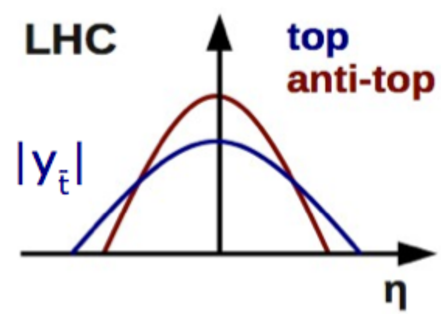
$\Delta y = y_t - y_{\bar{t}}$



LHC

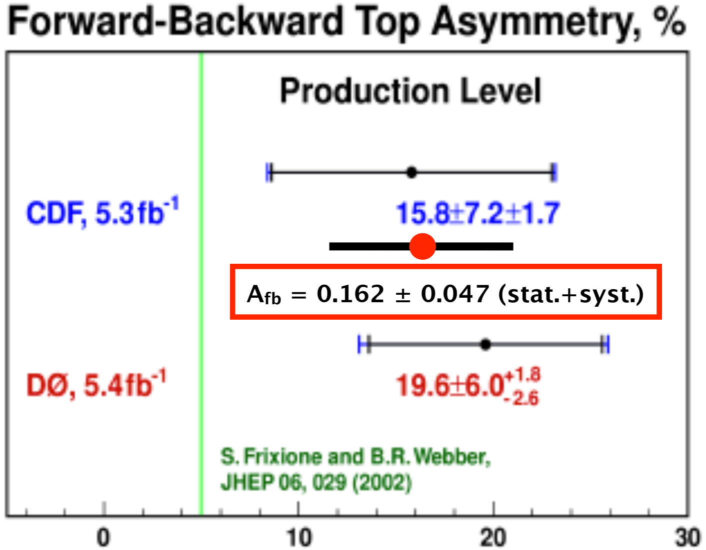
$$\boxed{A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}}$$

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



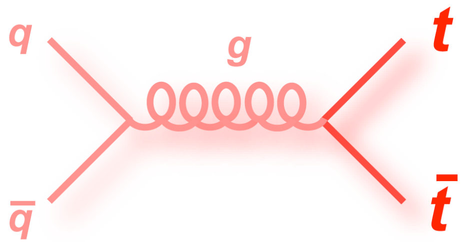
Forward Backward and Leptonic Asymmetry

- measured asymmetries in l+jets (arXiv:1107.4995) and dilepton (arXiv:1207.0364) channel
  - unfolded A_{FB} = 19.6% in l+jets agrees within 2.4 SD with MC@NLO prediction of 5.0%
  - combined lepton based asymmetry from l+jets and dilepton:
    $$\boxed{A_{FB}^{l} = (11.8 \pm 3.2)\ \%}$$
    agrees within 2.2 SD with prediction of 4.7%



- however:
  - all results dominated by statistical uncertainty
  - ongoing work for improved predictions
- many models predict very different values for A_{FB} and A_{FB}^{l}
  → new results with full data set (~9 fb^{-1}) in l+jets and dilepton in preparation

$t\bar{t}$ production density matrix



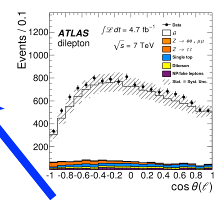
$$q(p_1) + \bar{q}(p_2) \to t(k_1, s_1) + \bar{t}(k_2, s_2)$$

determines cross section and distributions independent of top spin (e.g. p^t_T distribution etc.)

$$|M|^2 \propto A + \mathbf{B}^+ \cdot \mathbf{s}_1 + \mathbf{B}^- \cdot \mathbf{s}_2 + C_{ij} s_{1i} s_{2j}$$ **(LO)**

$b_1^\pm$, $b_2^\pm \neq 0$: P–violation (=0 in LO QCD)

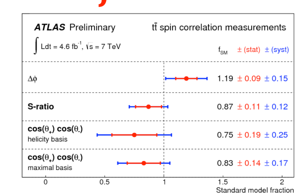
arXiv:1307.6511 [hep-ex]



$b_3^\pm \neq 0$: only in NLO QCD, "T"–odd (absorptive parts)

ATLAS-CONF-2013-101

c_1, c_2, c_3, c_4: C–even, P–even $\neq 0$ in LO QCD



$$\tilde{B}_i^\pm = b_1^\pm \hat{p}_i + b_2^\pm \hat{k}_i + b_3^\pm n_i\,,$$

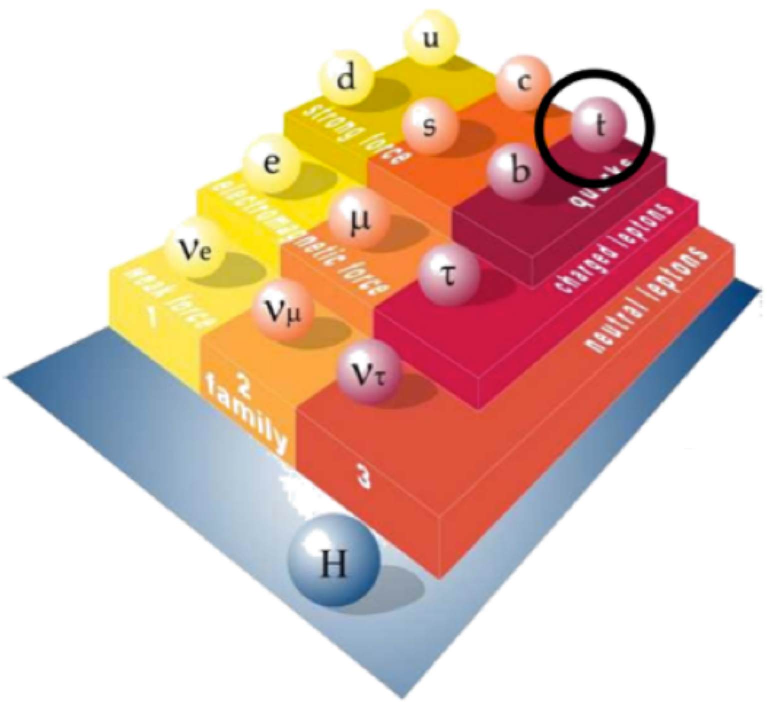
$$\tilde{C}_{ij} = c_1 \delta_{ij} + c_2 \hat{p}_i \hat{p}_j + c_3 \hat{k}_i \hat{k}_j$$

$$+ c_4(\hat{p}_i \hat{k}_j + \hat{k}_i \hat{p}_j) + c_5 \epsilon^{ijl} \hat{p}_l + c_6 \epsilon^{ijl} \hat{k}_l$$

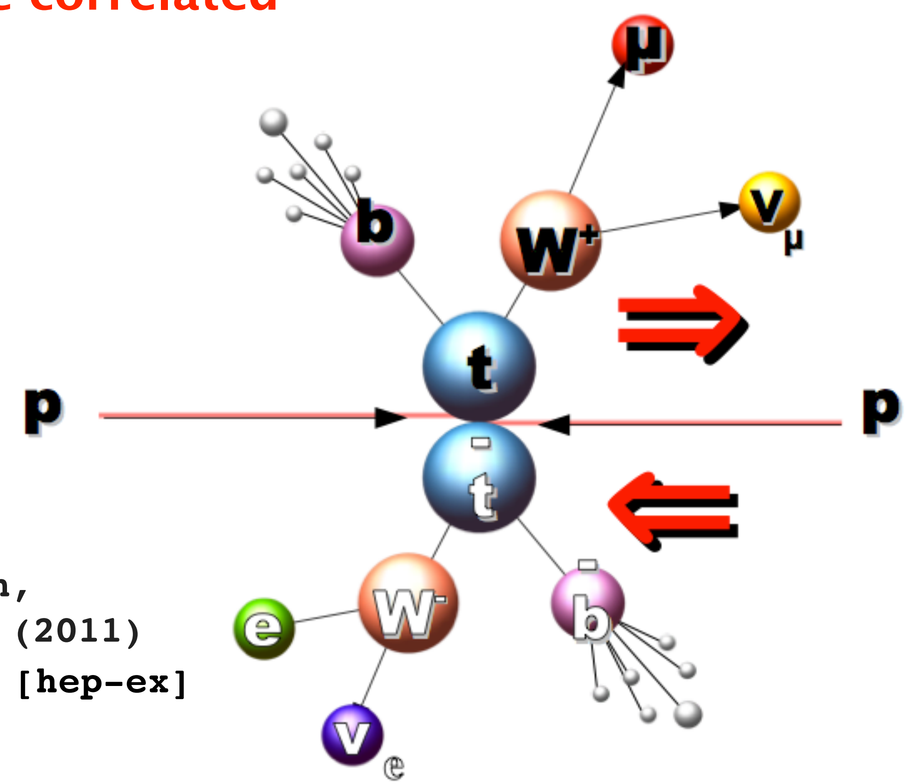
c_5, c_6: P–odd, CP–odd $\neq 0$ only in BSM

→ **systematic analysis of top quark properties**

Top Pair Spin Correlation



- top quark: discovered in 1995 by CDF&DØ
- does the top quark have spin 1/2?
- top quark pair production: top quarks are not polarised, but spin of top and anti-top quarks are correlated



- top quarks have short lifetime:

$$\boxed{\tau_t = (3.3^{+0.9}_{-0.6}) \times 10^{-25}\ \mathrm{s}}$$

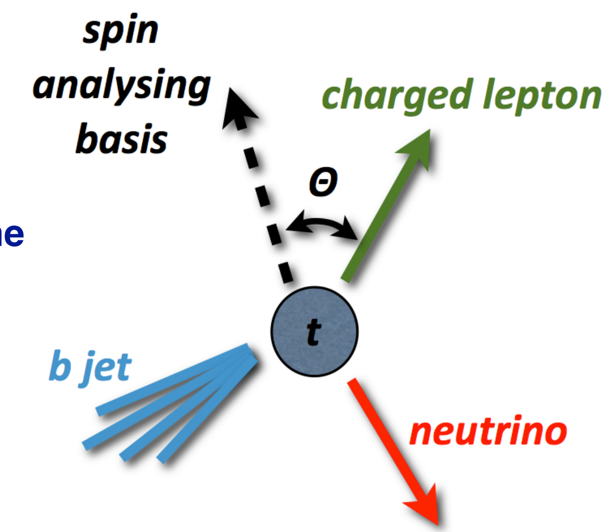
DØ Collaboration,
PRL 106, 022001 (2011)
arXiv:1201.4156 [hep-ex]

- decay before spins can flip
- spin information is contained in decay product
- measure $t\bar{t}$ spin correlation: consistent with SM prediction for a spin 1/2 particle?

Polarisation power

$$\boxed{\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i}=\frac{1}{2}(1+\alpha_i\cos\theta_i)}$$

in $t\bar{t}$ ZMF frame



in top quark rest frame

dilepton channel promises largest sensitivity

Brandenburg, Si, Uwer,
Phys. Lett. B539, 235 (2002)

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
α_i (LO)	-0.41	0.41	1	1	-0.31
α_i (NLO)	-0.39	0.39	0.998	0.93	-0.31

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

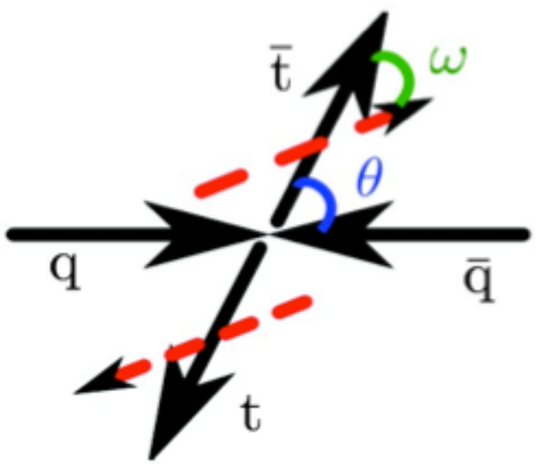
$$\text{where } C=A\,\alpha_1\alpha_2$$

linear extraction:

A=C

Spin correlation strength

Tevatron



- interpolate between beam and helicity basis
- optimised “off-diagonal” basis

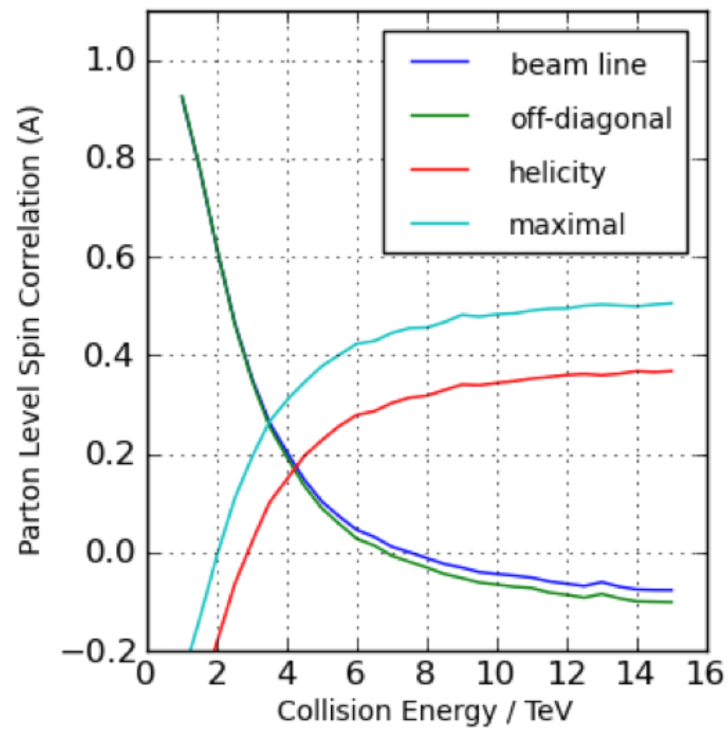
$$\boxed{\tan\omega = \sqrt{(1-\beta^2)}\tan\theta}$$

NLO QCD: A= 0.78

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

LHC

HERWIG++



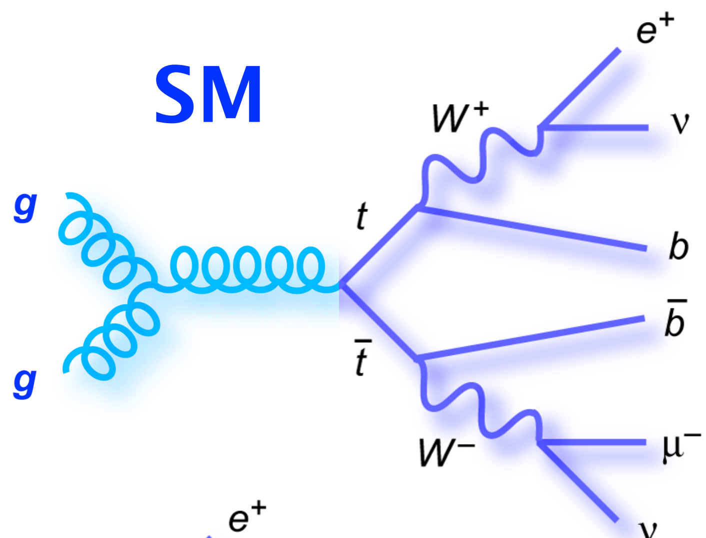
- there is no “optimal” basis for gg fusion on an event-by-event basis
- maximal basis

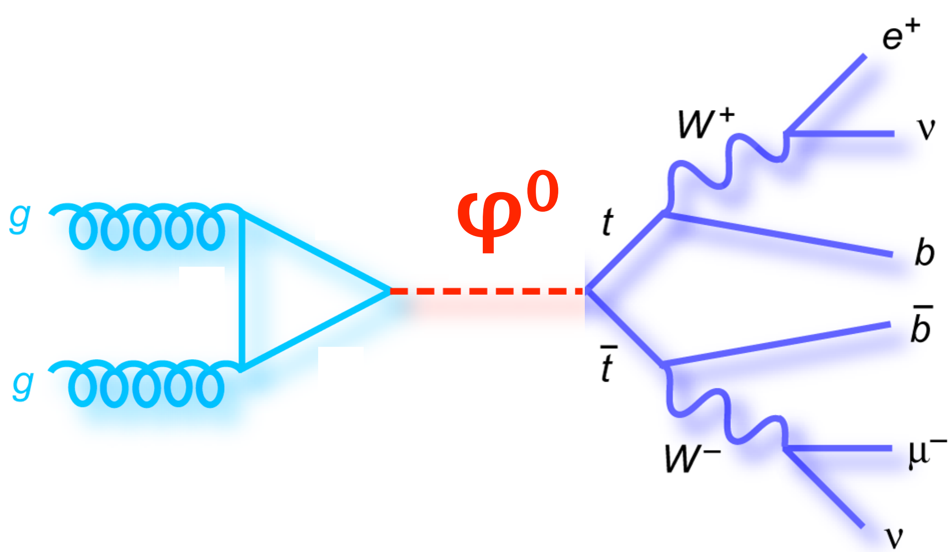
NLO QCD: A = 0.44

Uwer, Phys. Lett., B609:271–276, 2005

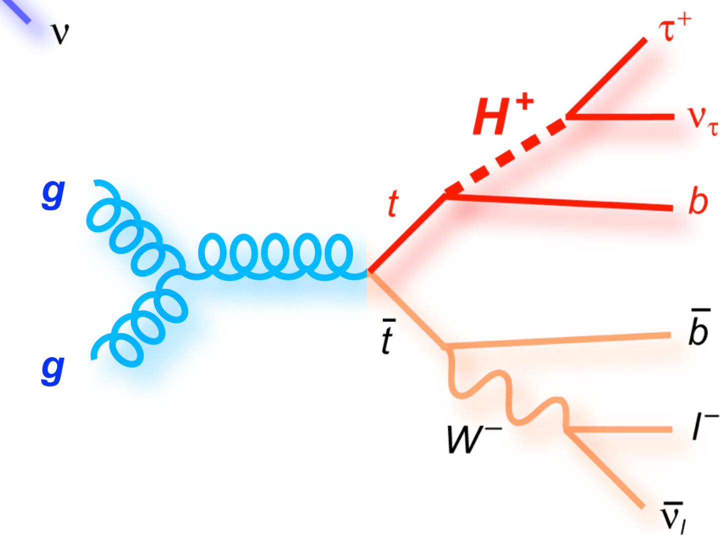
New physics impact on spin correlations

- important test of SM and sensitive search for physics beyond
- analyse the whole chain of top pair production and top decay





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



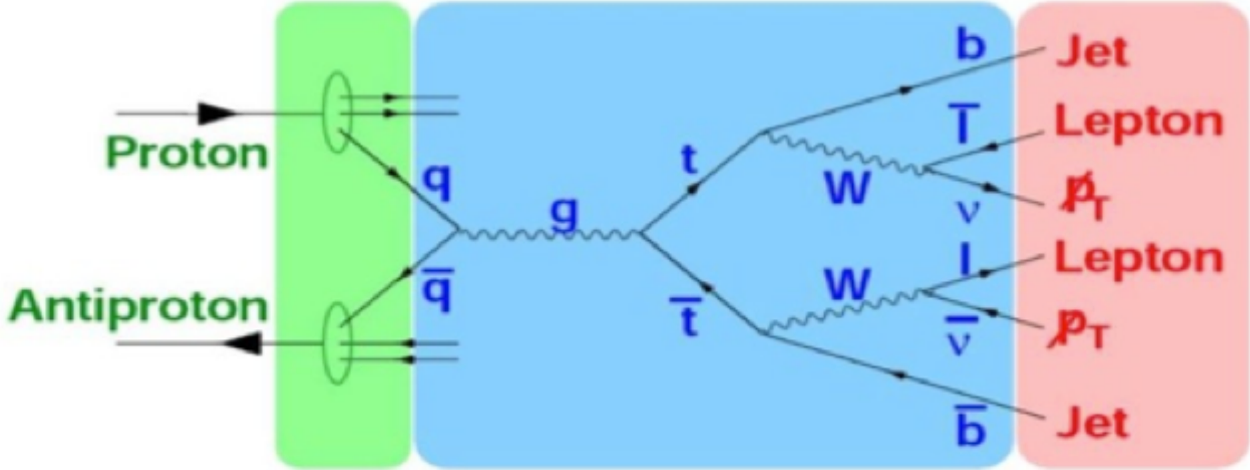
charged Higgs, b’, ...

Matrix Element Method

$$P_{\mathrm{sgn}}(x; m_t, H) = \frac{1}{\sigma_{\mathrm{obs}}(m_t)} \int \boxed{f_{\mathrm{PDF}}(\epsilon_1)\; f_{\mathrm{PDF}}(\epsilon_2)} \mathrm{d}\epsilon_1 \mathrm{d}\epsilon_2$$

$$\cdot \boxed{\frac{(2\pi)^4 \left|\mathcal{M}(y, m_t, H)\right|^2}{\epsilon_1 \epsilon_2 s}} \boxed{W(x,y)}\, \mathrm{d}\Phi_6$$

H=correlated
or
H=uncorrelated
spins



PDF's **LO-Matrix element** **transfer functions (probability to measure x when y was produced)**

Matrix Element

G. Mahlon and S. J. Parke,
Phys. Rev. D 53, 4886 (1995)
Phys. Lett. B 411, 173(1997)

H=uncorrelated

$$\sum |\mathscr{M}|^2 = \boxed{\frac{g_s^4}{9} F\overline{F} \ \left(2 - \beta^2 s_{qt}^2\right) /2}$$

kinematics of top
and anti-top decay

β: velocity of top in $t\bar{t}$ rest frame
s_{qt}: sine between initial quark and top

Matrix Element

β: velocity of top in $t\bar{t}$ rest frame
s_{qt}: sine between initial quark and top
c_{qt}: cosine between initial quark and top

G. Mahlon and S. J. Parke,
Phys. Rev. D 53, 4886 (1995)
Phys. Lett. B 411, 173(1997)

$$\sum |\mathscr{M}|^2 = \frac{g_s^4}{9} F\overline{F} \left[\left(2 - \beta^2 s_{qt}^2\right) - \Delta \right]$$

H=correlated

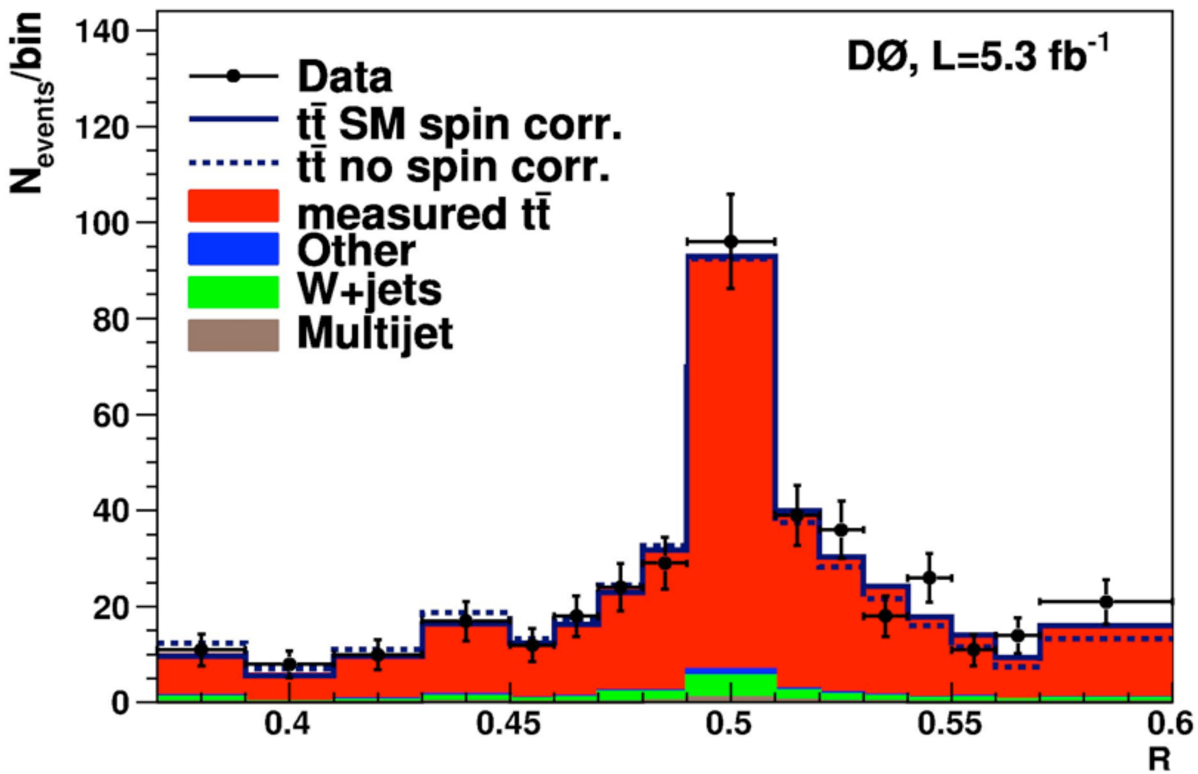
kinematics of top
and anti-top decay

$$\Delta = \frac{(1 - c_{\bar{\ell}q} c_{\ell\bar{q}}) - \beta(c_{\ell\bar{t}} + c_{\bar{\ell}t}) + \beta c_{qt}(c_{\bar{\ell}q} + c_{\ell\bar{q}}) + \frac{1}{2}\beta^2 s_{qt}^2 (1 - c_{\bar{\ell}\ell})}{\gamma^2 (1 - \beta c_{\bar{\ell}t})(1 - \beta c_{\ell\bar{t}})}$$

First Evidence for Spin Correlation

MEs: per event ↔ spin correlation: ensemble of events

discriminant
$$R = \frac{P_{\text{sgn}}(H=c)}{P_{\text{sgn}}(H=u)+P_{\text{sgn}}(H=c)}$$



combination:
dilepton & l+jets

Phys. Rev. Lett. 107, 032001 (2011)

Phys. Rev. Lett. 108, 032004 (2012)

$$f_{\text{meas}} = 0.85 \pm 0.29(\text{stat}+\text{syst})$$

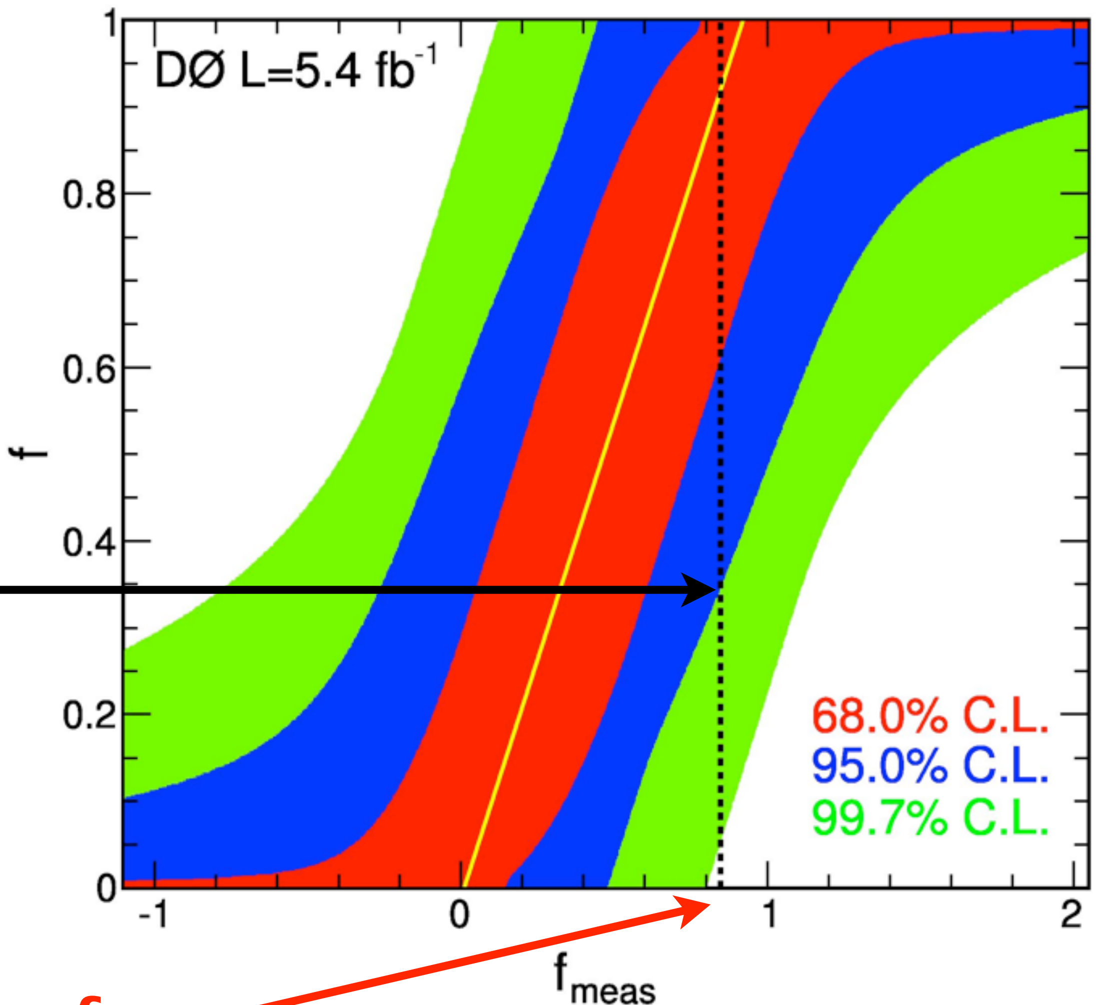
correlation strength:

$$C = 0.66 \pm 0.23\,(\text{stat+syst})$$

NLO QCD: $C = 0.777^{+0.027}_{-0.042}$

→ first evidence for spin correlation with 3.1σ

Exclusion Limits



f > 0.344
at 95% CL

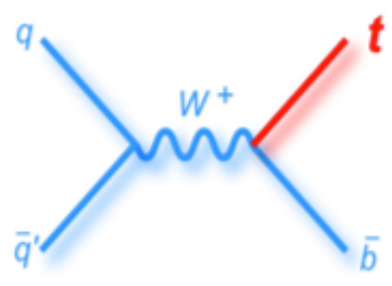
first exclusion of hypothesis H=uncorrelated (f=0) with >99.7% CL: 3.1σ

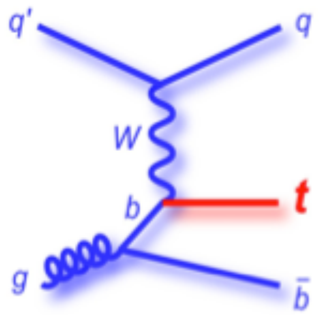
$\sigma_{t\bar{t}}$ in agreement with SM

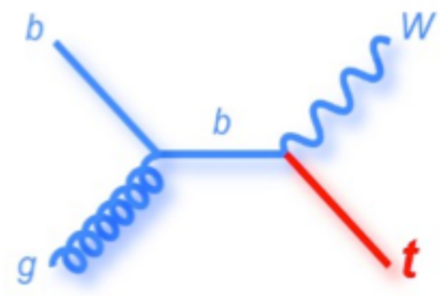
Single Top Quark Production

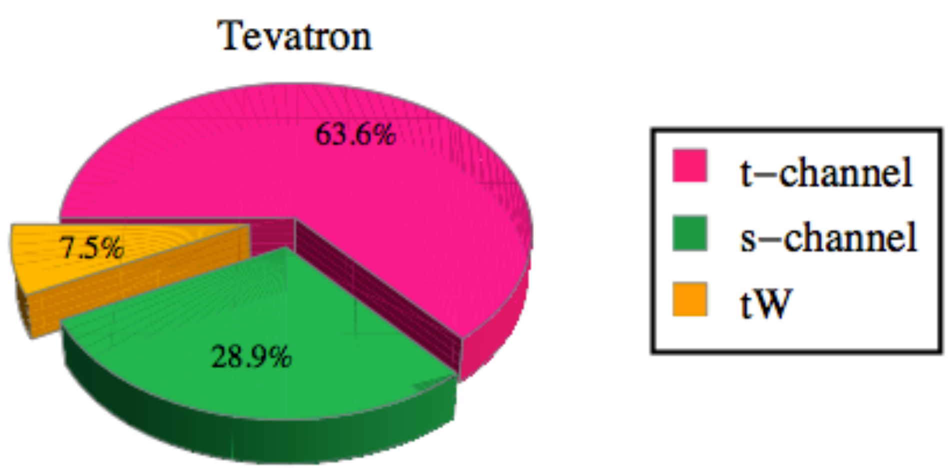
direct measurement of $|V_{tb}|$

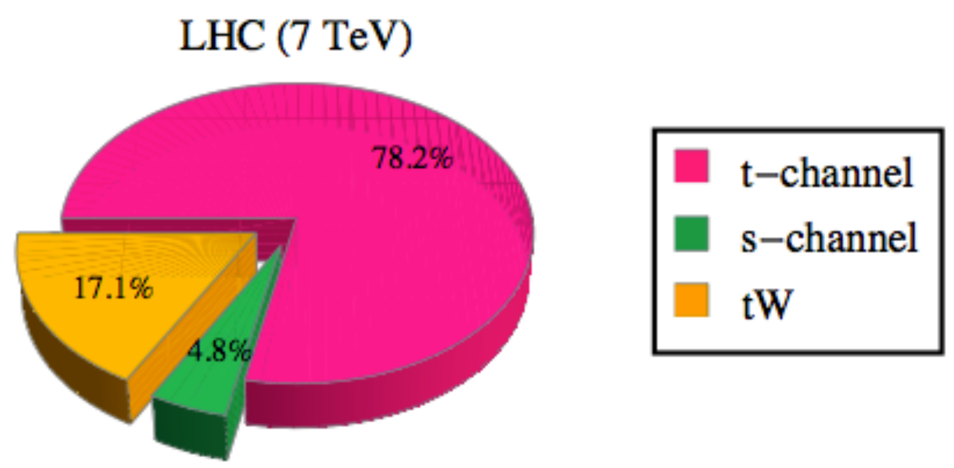
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \color{red}{V_{tb}} \end{pmatrix}$$







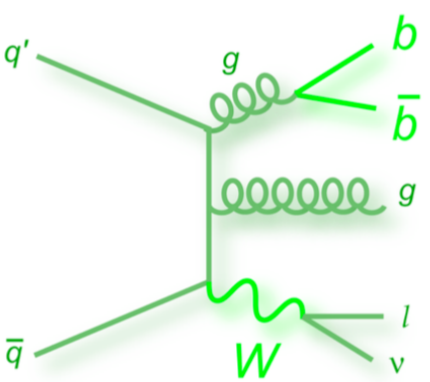


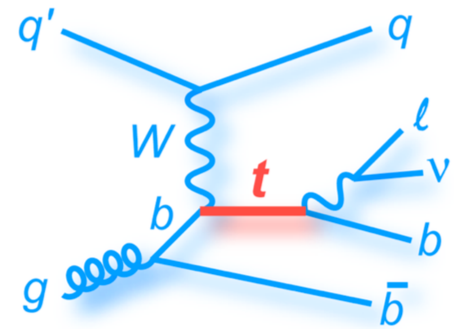


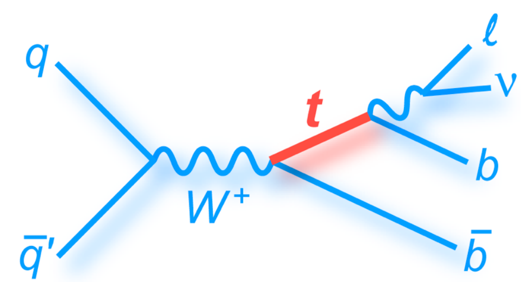
⇒ **important to measure all channels separately to search for new physics**

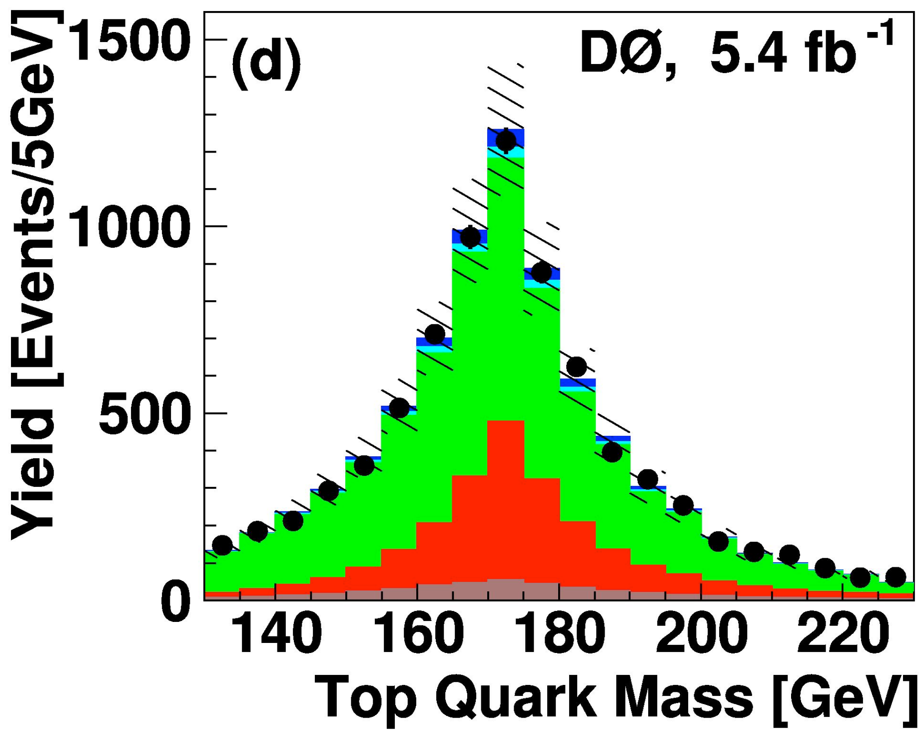
BUT: do not separate Wt in higher orders – an unphysical question!

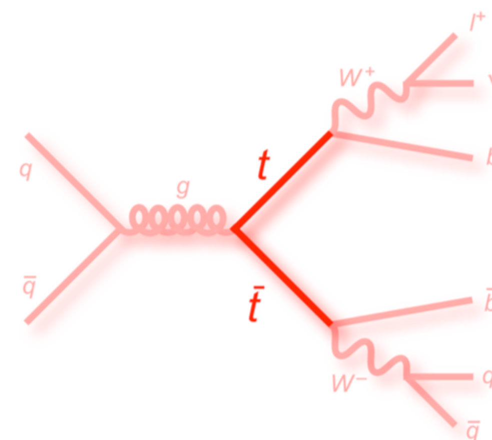
Recontructed Top Mass

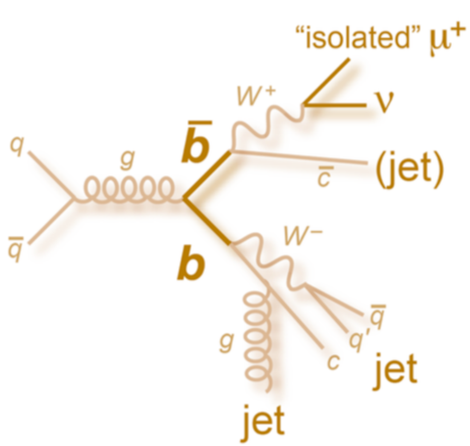








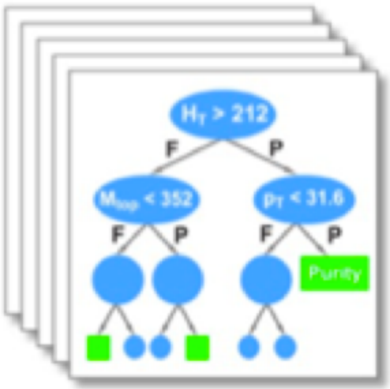




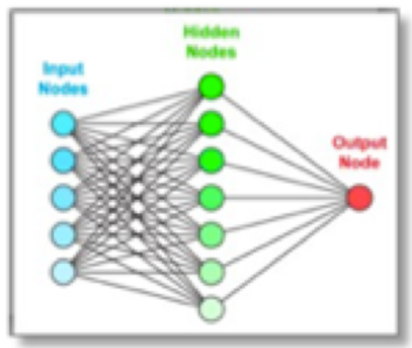
- ➞ signal and background look similar
- ➞ errors larger than signal contribution

Multivariate Analyses

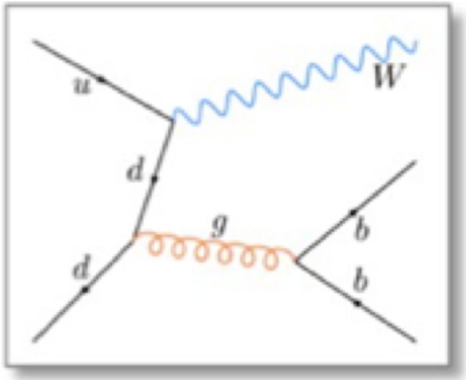
Boosted Decision Trees



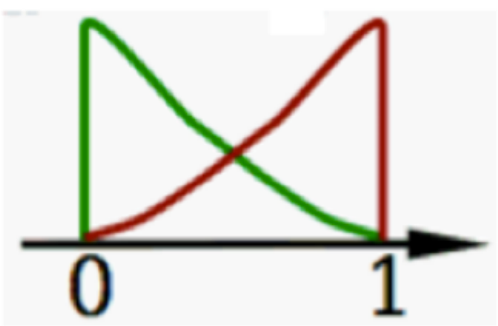
Neural Networks



Matrix Elements



background **signal**



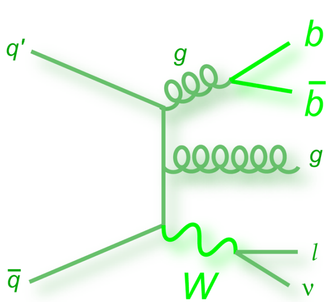
→ **s+t channel observed by CDF and D0 in 2009**

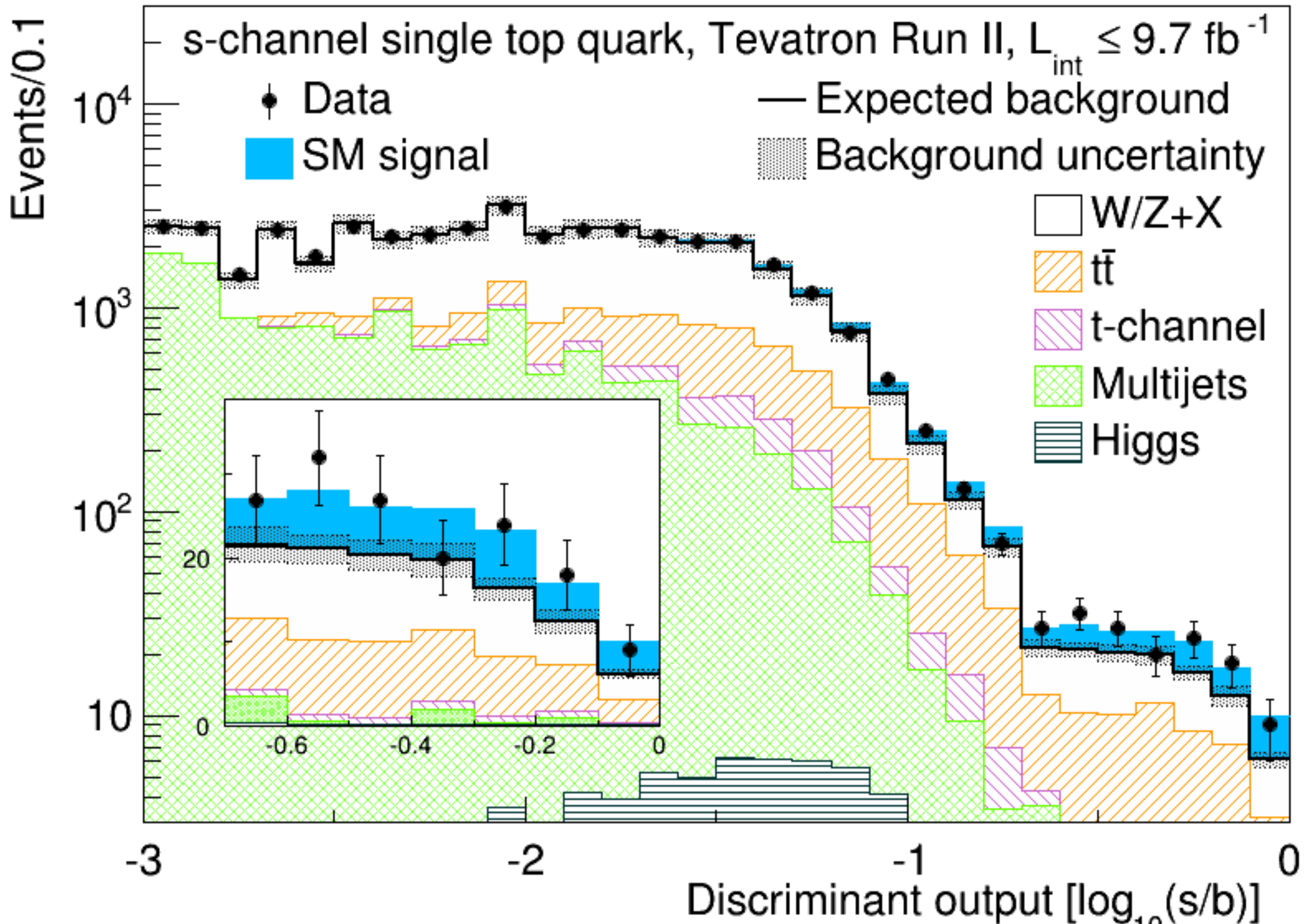
→ **important step to establish MVA techniques**

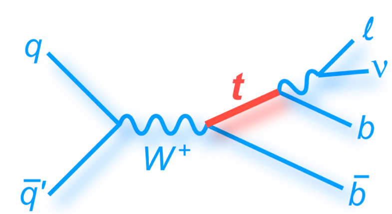
s-channel Production

Phys. Rev. Lett. 112, 231803 (2014)

- Tevatron: combine individual discriminants including all correlations

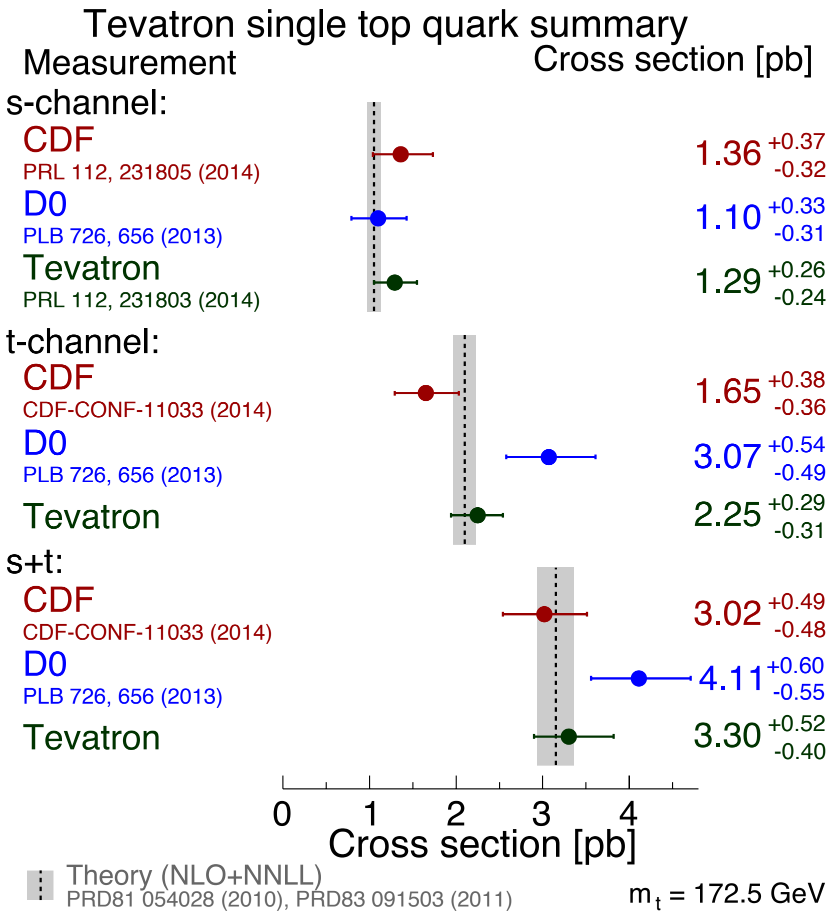


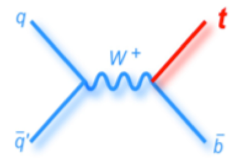




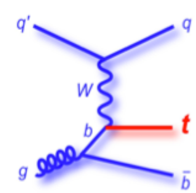
→ observation: 6.3 s.d.

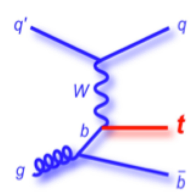
Single channel cross sections

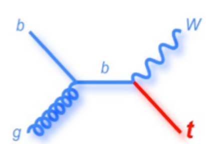




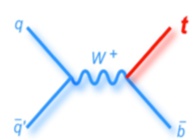
→ observation







→ observation



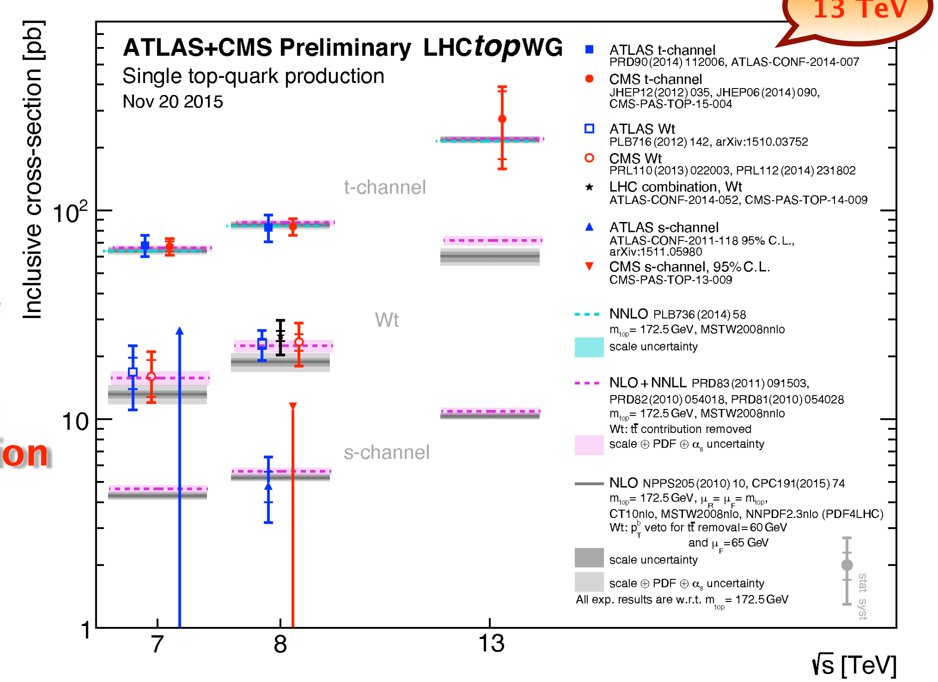
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{tb}| = 0.998 \pm 0.041$ ±4.1%

$|V_{tb}| > 0.92$ @ 95%CL

→ no hint for anomalous contribution

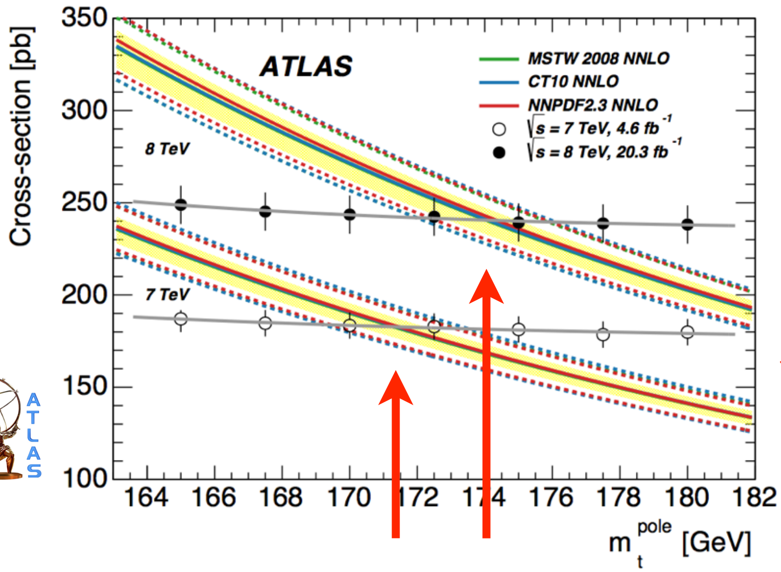
13 TeV



this is the final word from the Tevatron!

→ all production modes observed!

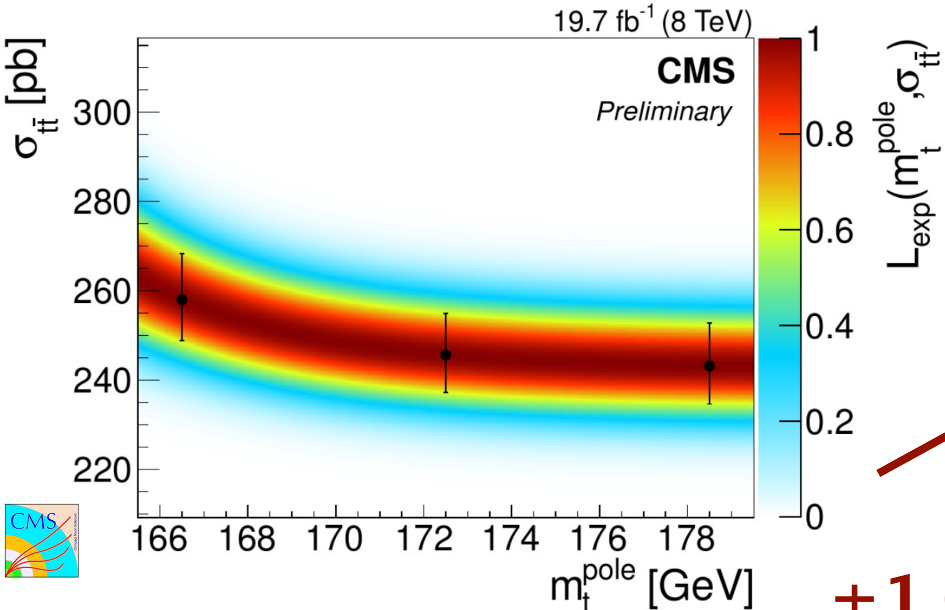
Top Quark Pole Mass

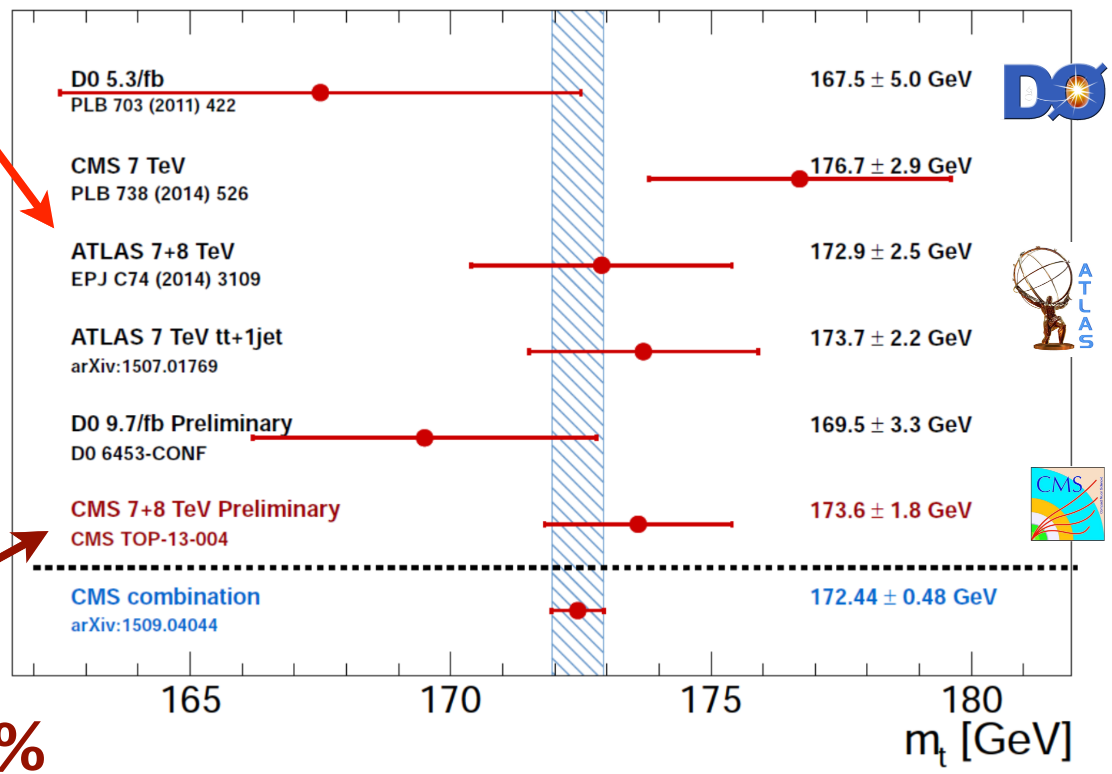


$$m_t^{\mathrm{pole}} = 172.9^{+2.5}_{-2.6}\,\mathrm{GeV}\ (\sqrt{s} = 7/8\,\mathrm{TeV})$$

→ pole mass unambiguously!

±1.4%

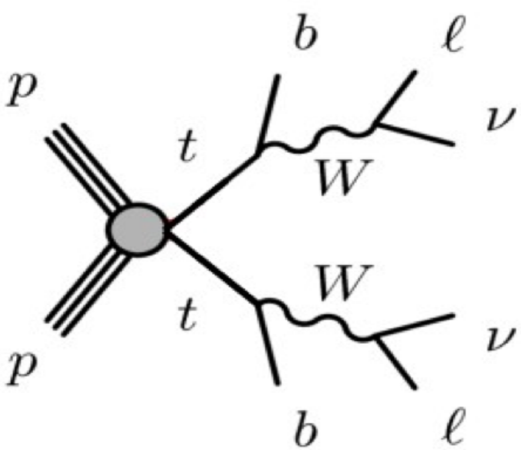


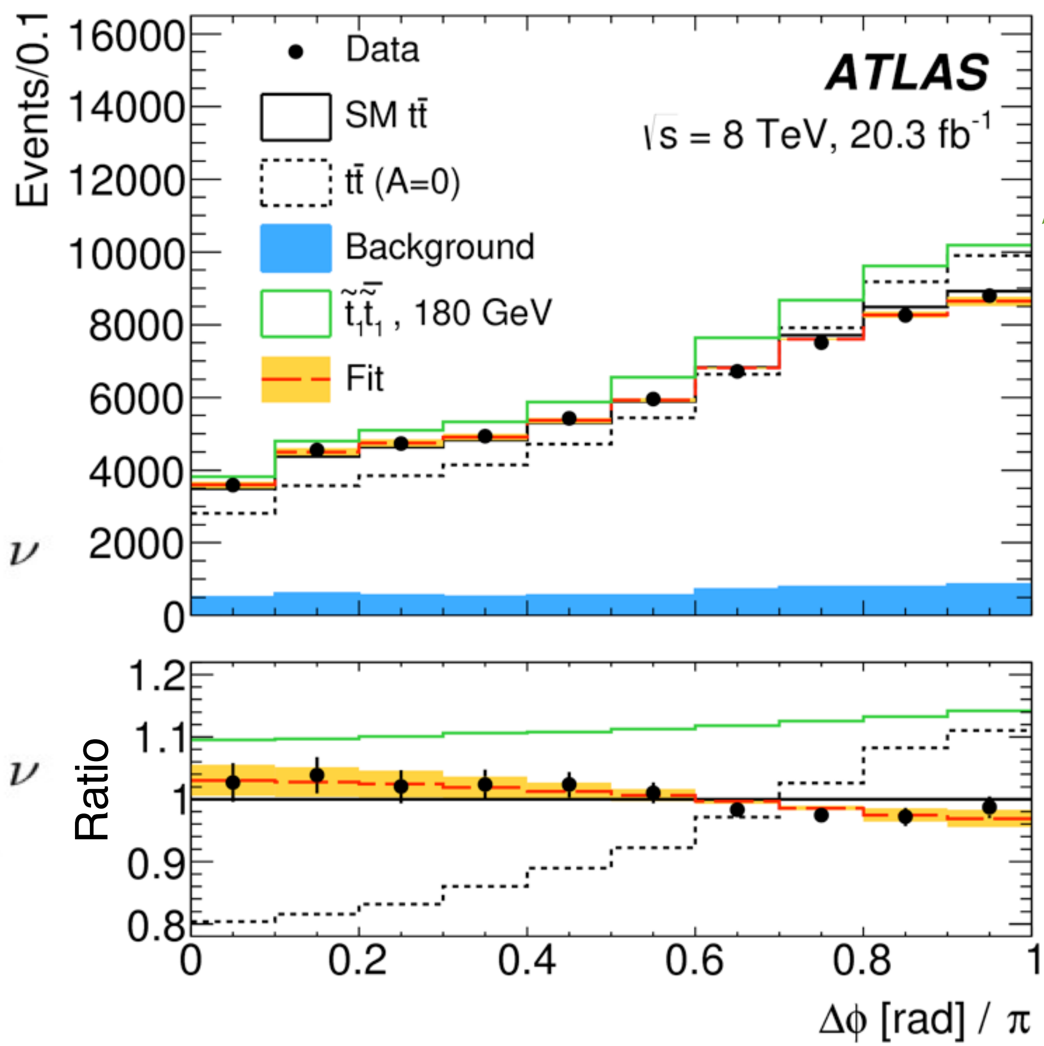


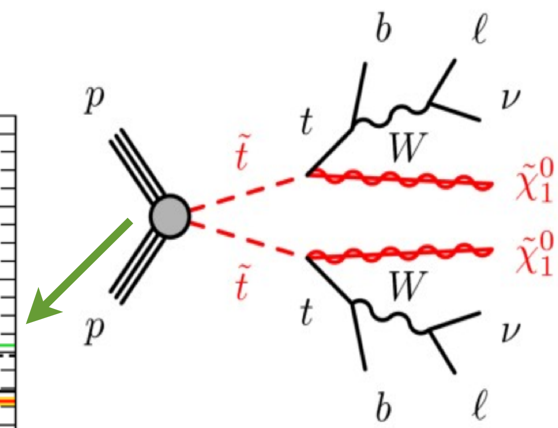
±1.0%

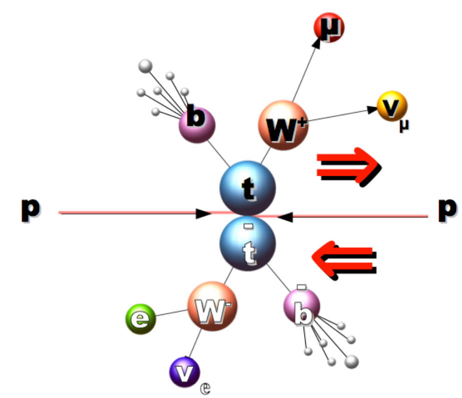
M_t^{pole}=173.6 ± 1.8 GeV

Spin correlations for “Stealth” Stop



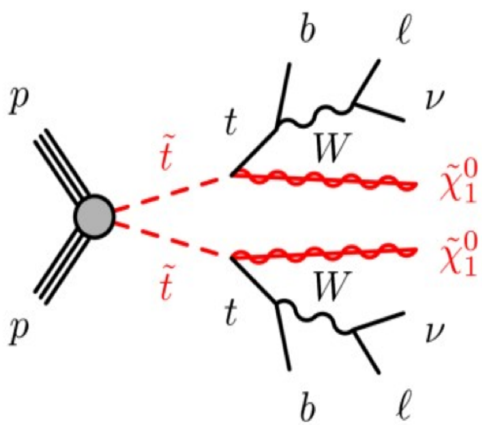


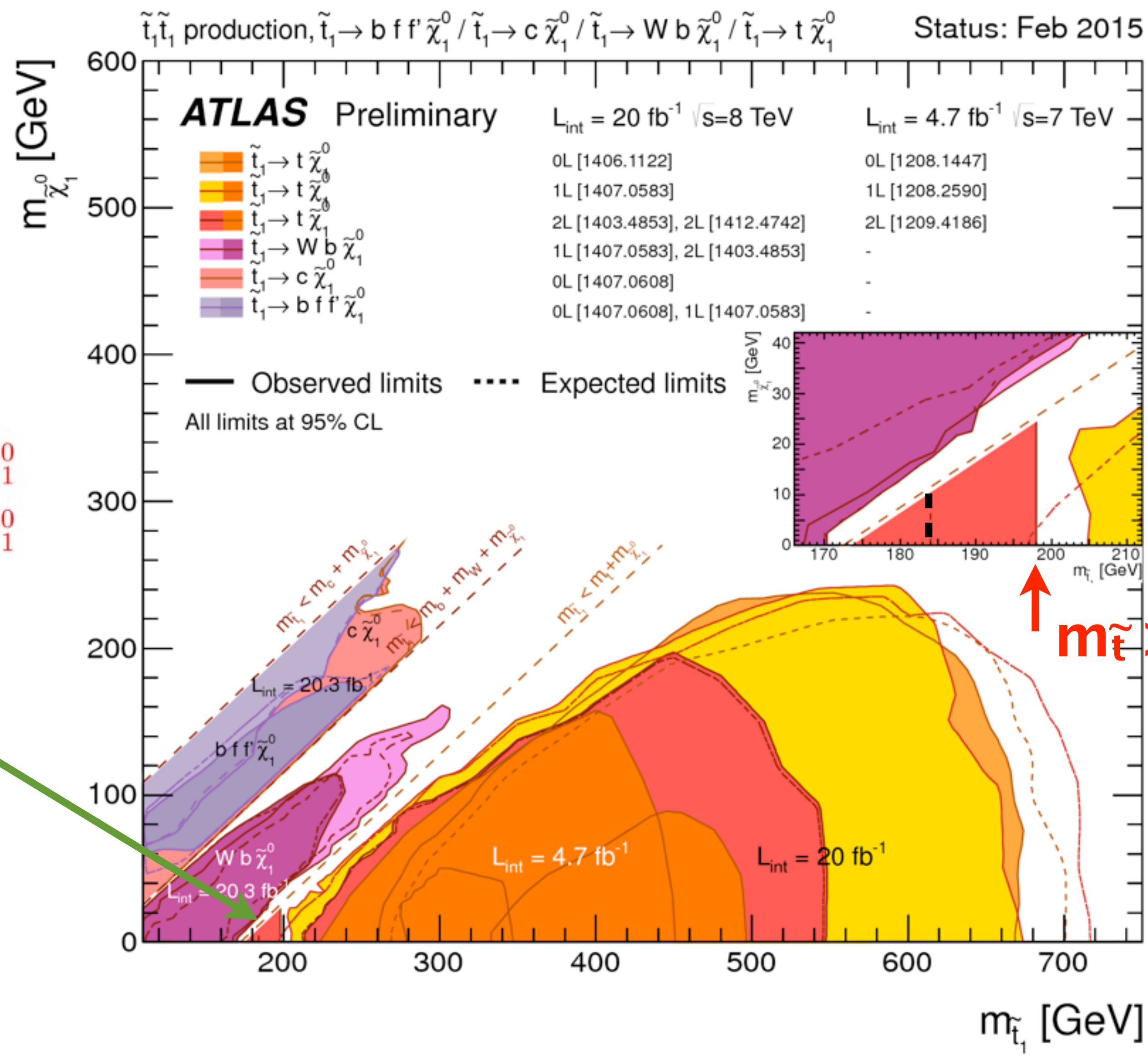




→ **no hint of stop quarks**

Stop searches





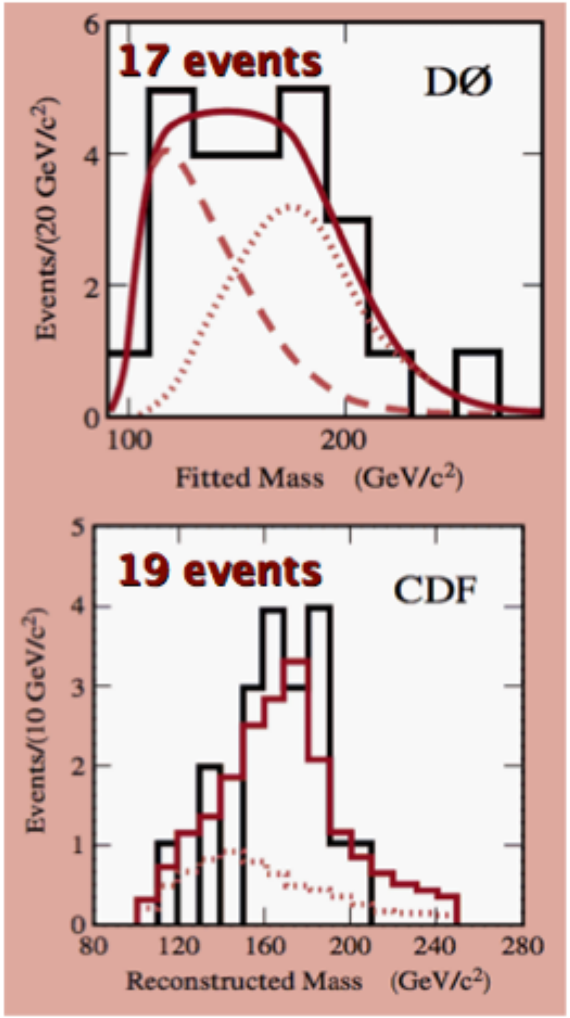
$m_{\tilde{t}} > 198$ GeV

→ **using a “standard candle” for complementary exclusion**

The Top Quark

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



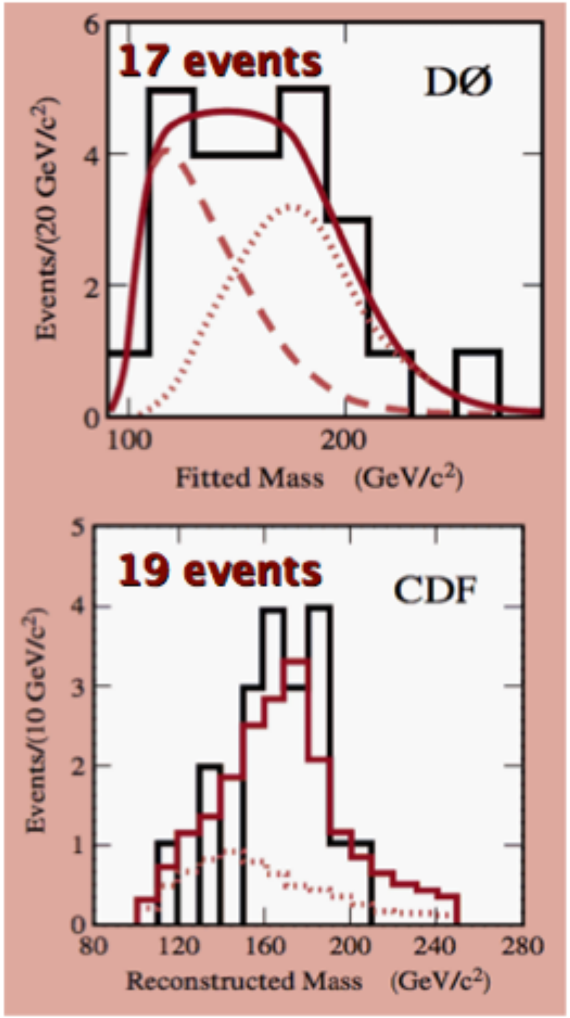
1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab

The Top Quark

discovery

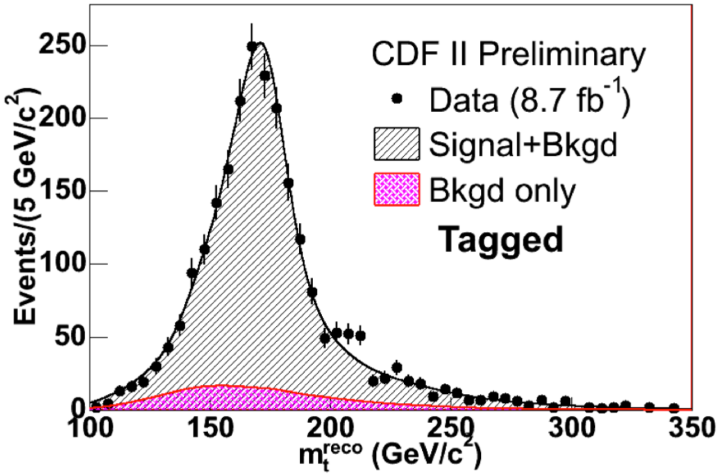
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

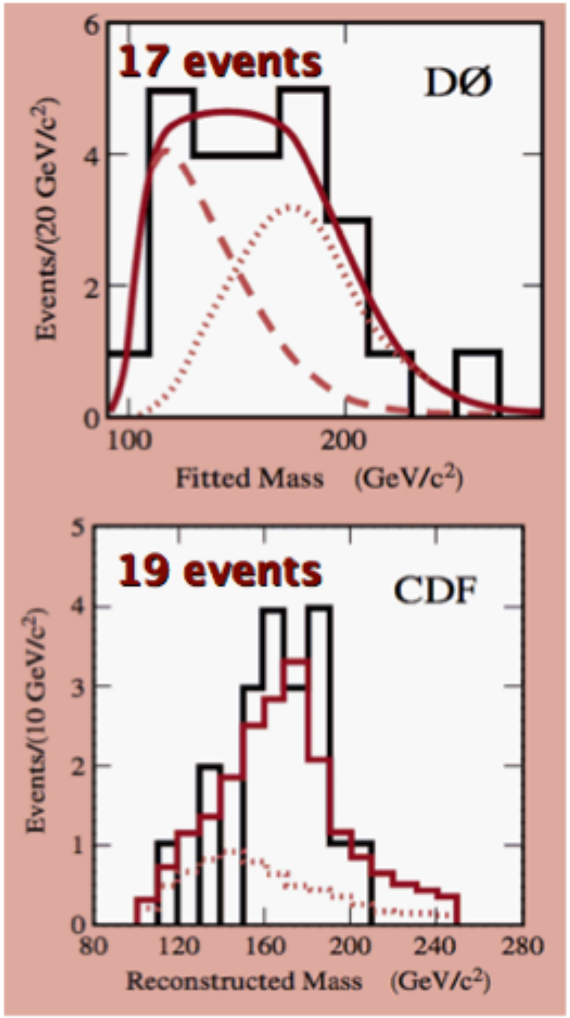
1000s of events



The Top Quark

discovery

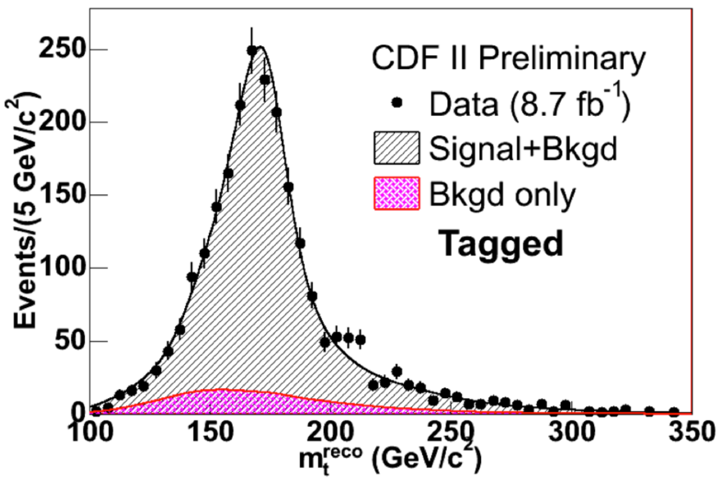
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



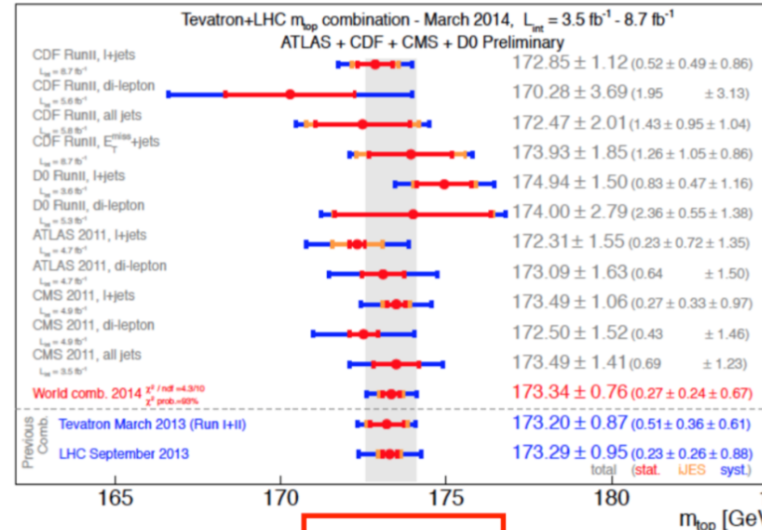
1995, CDF and DØ experiments, Fermilab

today

1000s of events



precision

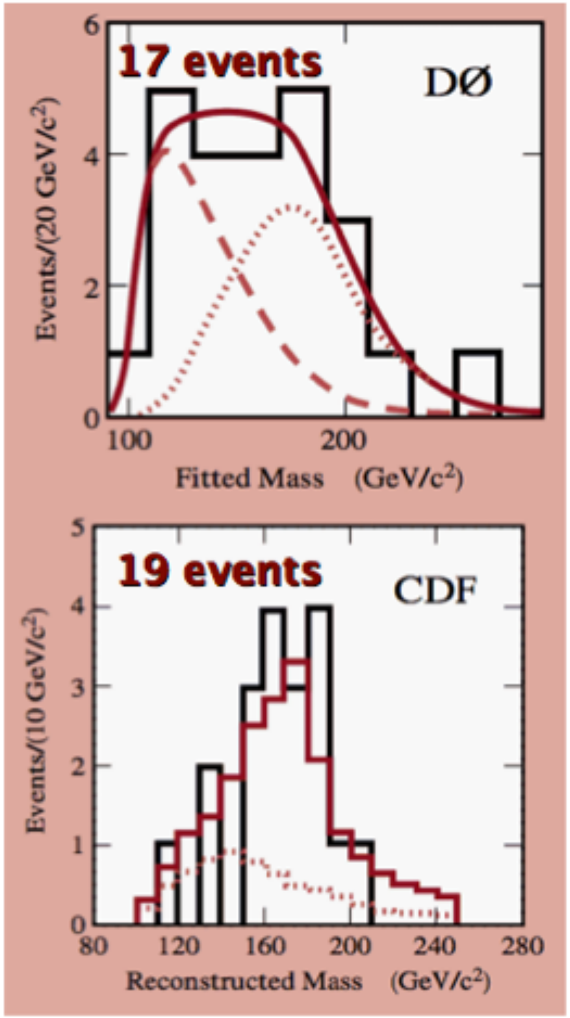


±0.44%

The Top Quark

discovery

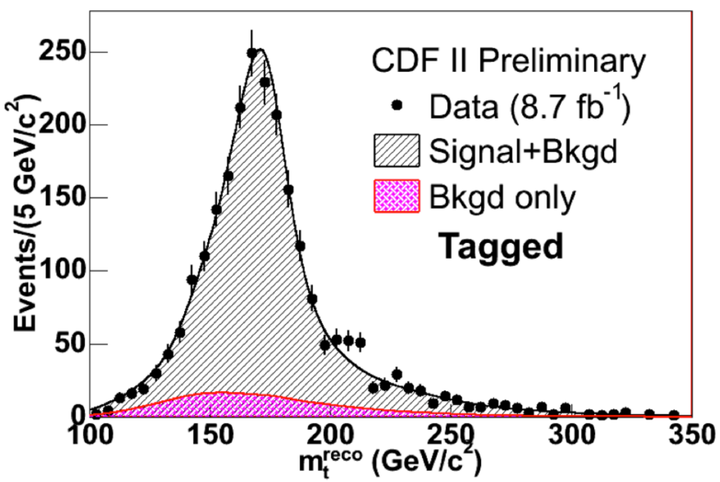
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



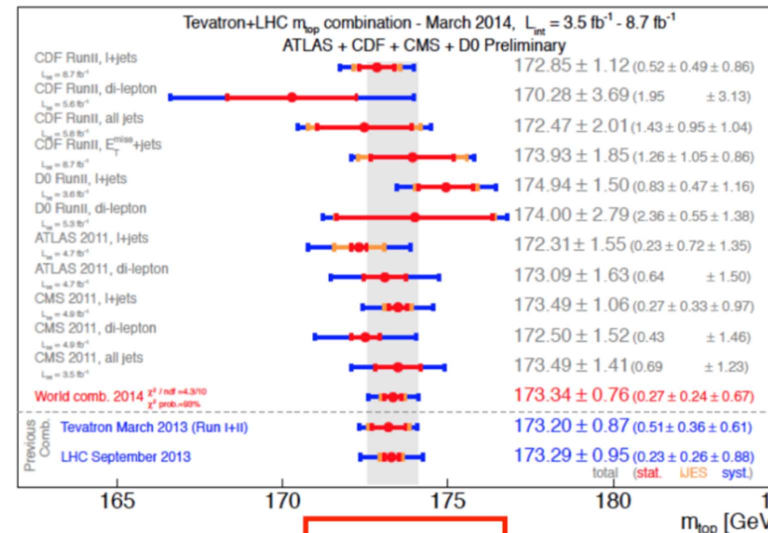
1995, CDF and DØ experiments, Fermilab

today

1000s of events



precision



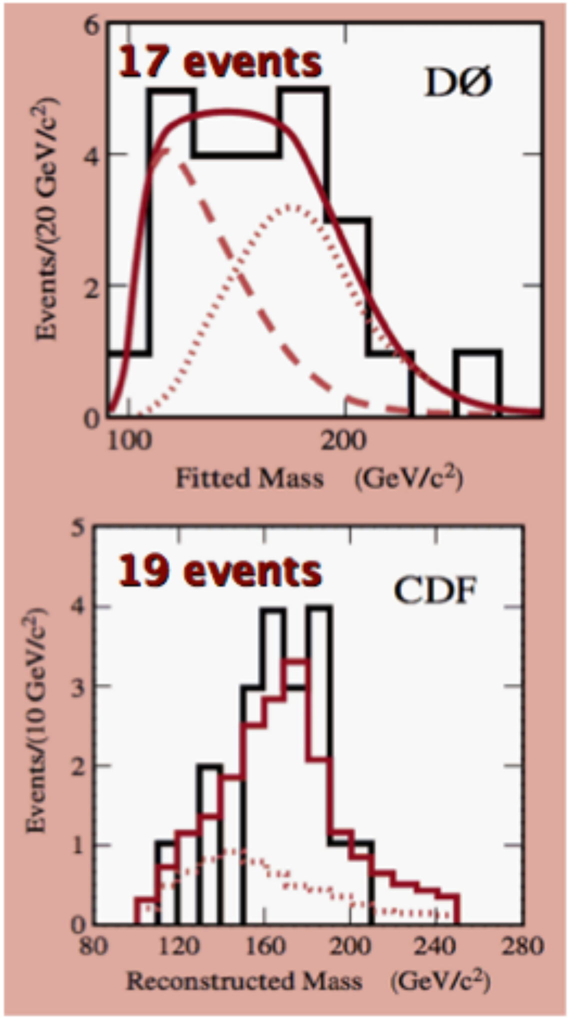
±0.44%

searches

The Top Quark

discovery

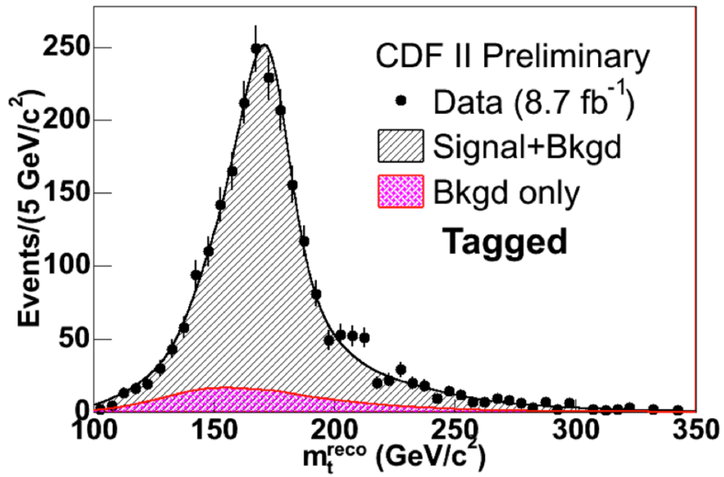
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



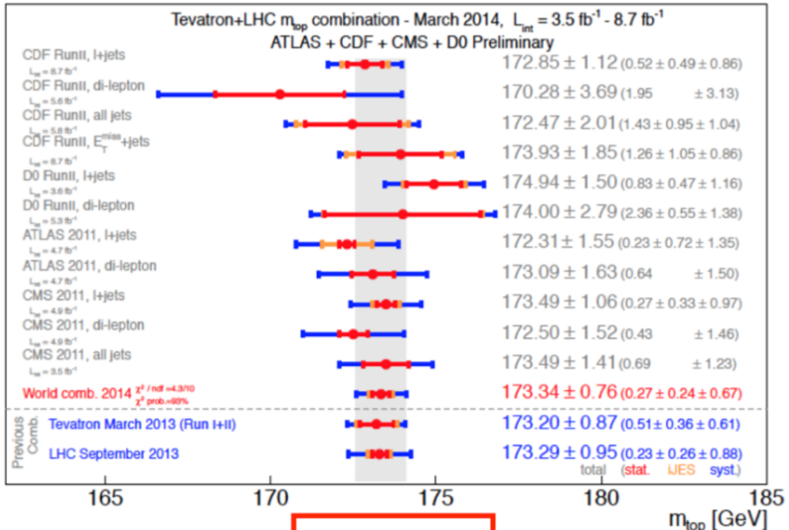
1995, CDF and DØ experiments, Fermilab

today

1000s of events



precision



±0.44%

searches

- **high precision measurements**
- **sensitivity to new phenomena**
- **complementary to LHC**

June 3rd, 2015: First Collisions @ 13 TeV