Top quark pair production cross section and properties of the top quark in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

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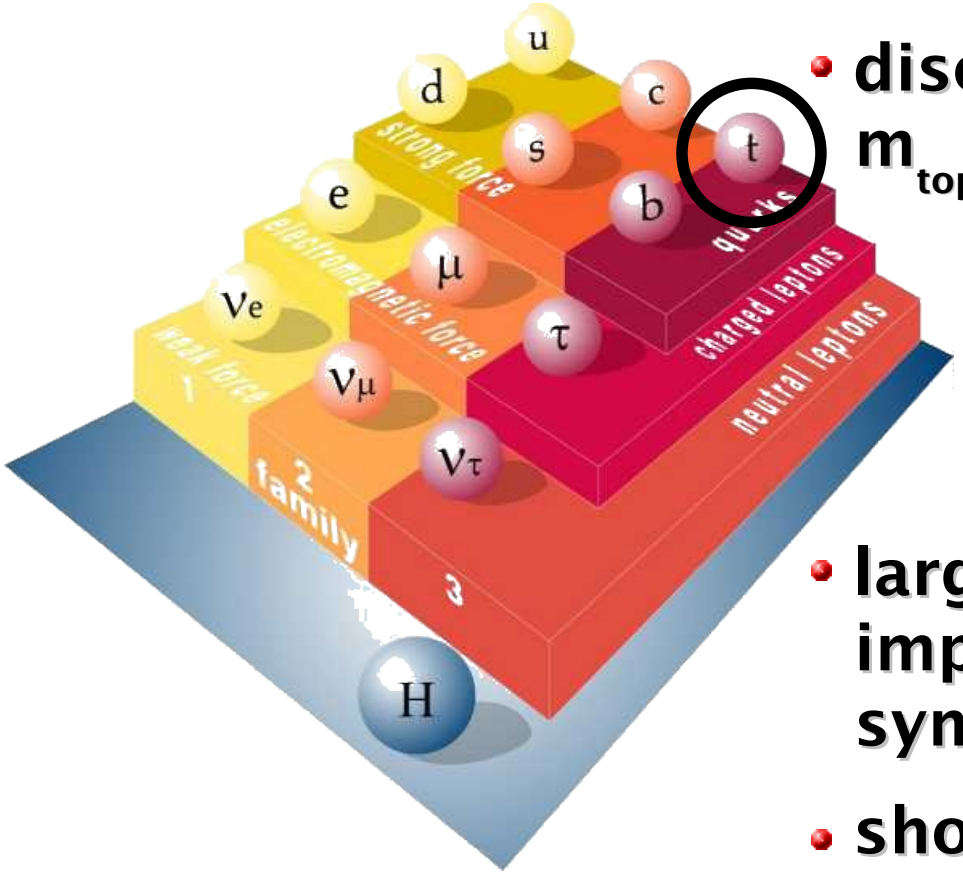
University of Manchester

on behalf of

Europhysics Conference on High-Energy Physics
Grenoble
07/21/2010

The Top Quark



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}s \ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

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

Outline

Top pair production cross section

Top decay couplings

Top mass

Conclusions

Outline

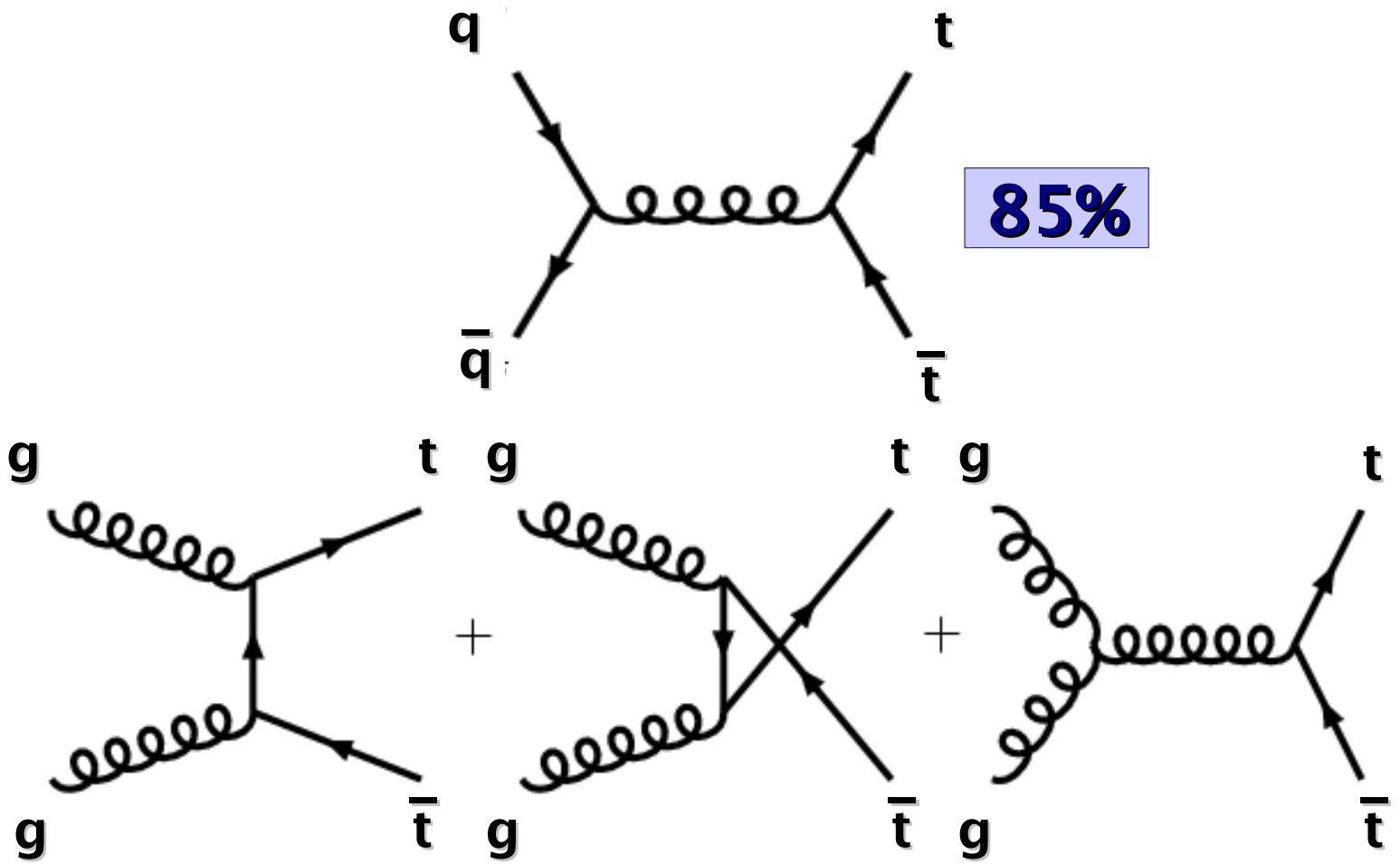
Top pair production cross section

Top decay couplings

Top mass

Conclusions

Top Quark Pair Production

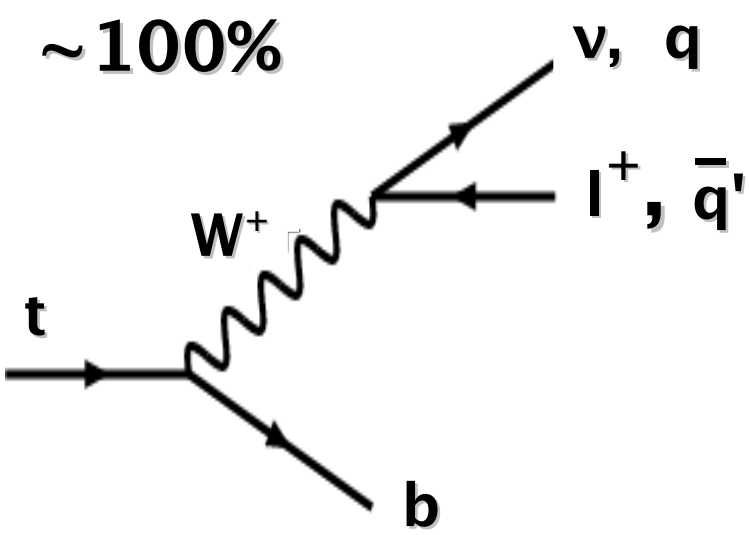


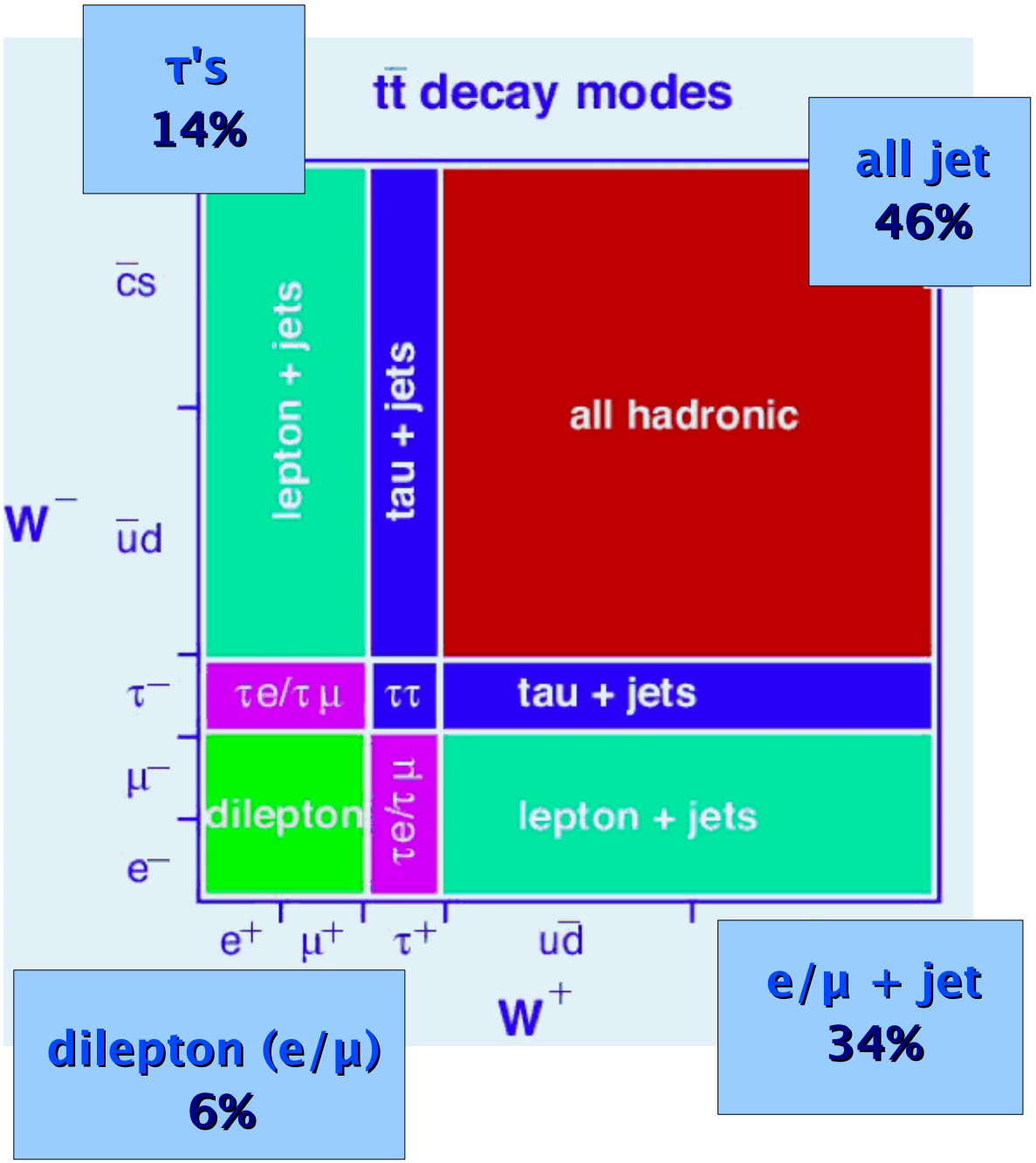
PRD 78, 034003 (2008)

$\sigma_{t\bar{t}} = 7.46^{+0.48}_{-0.67}$ pb in NNLO$_{approx}$
(m_{top} = 172.5 GeV)

Top Pair Signatures

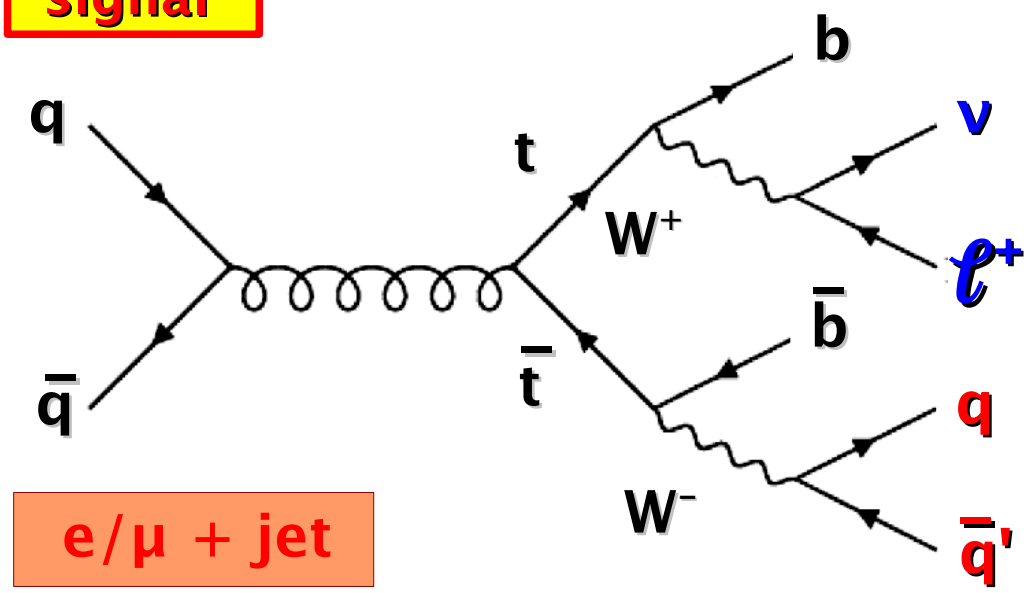
top decay:



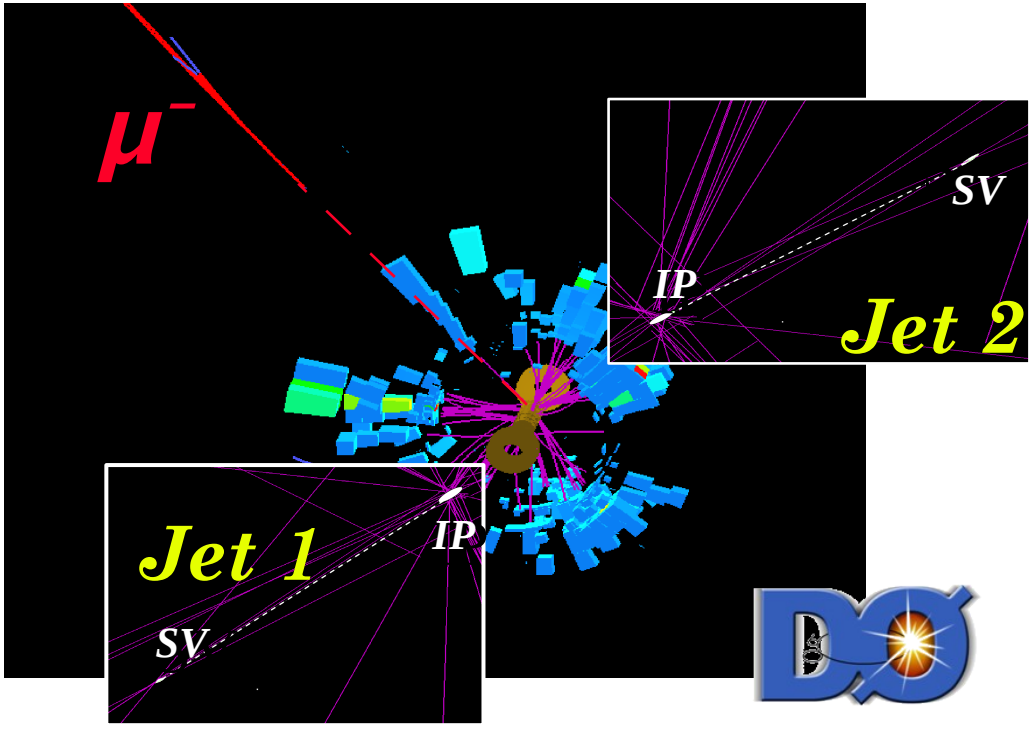


Lepton+jets Signatures

signal



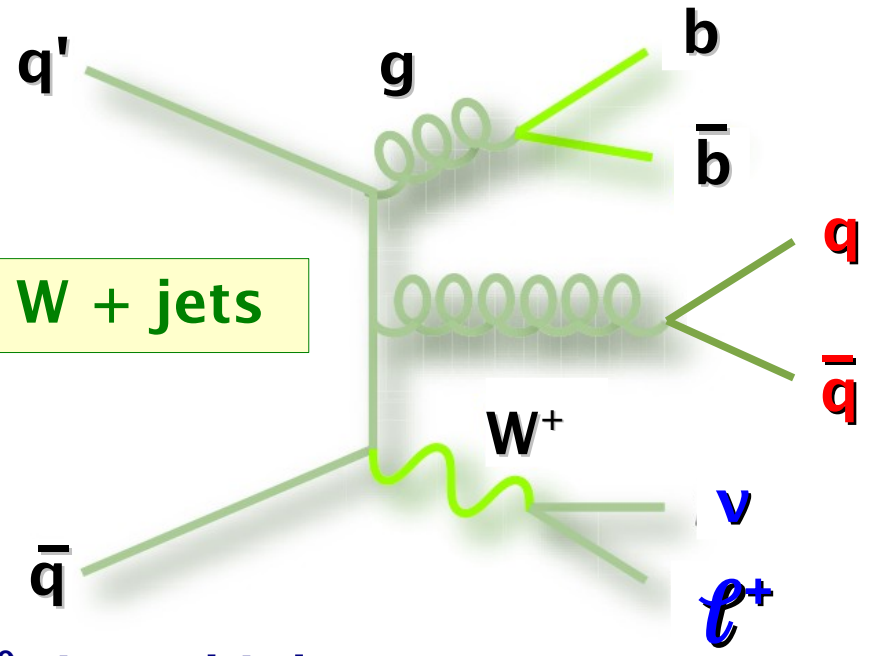
e/μ + jet



background

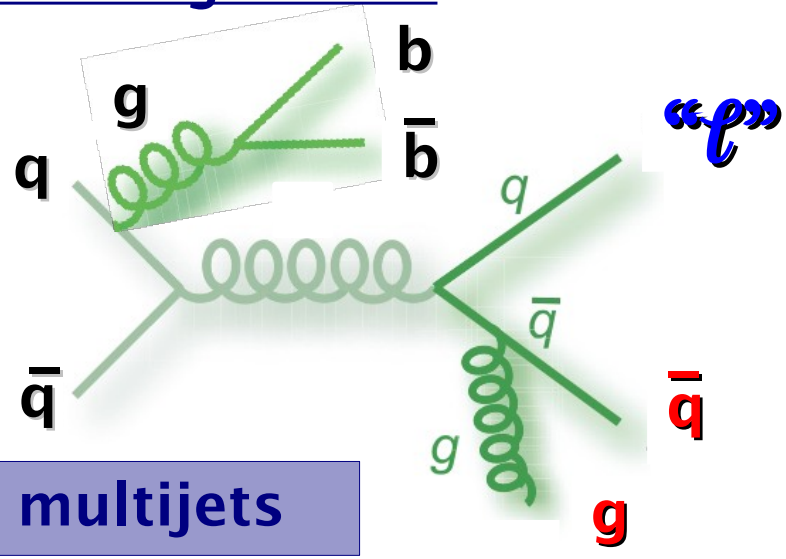
3000 times higher rate

W + jets



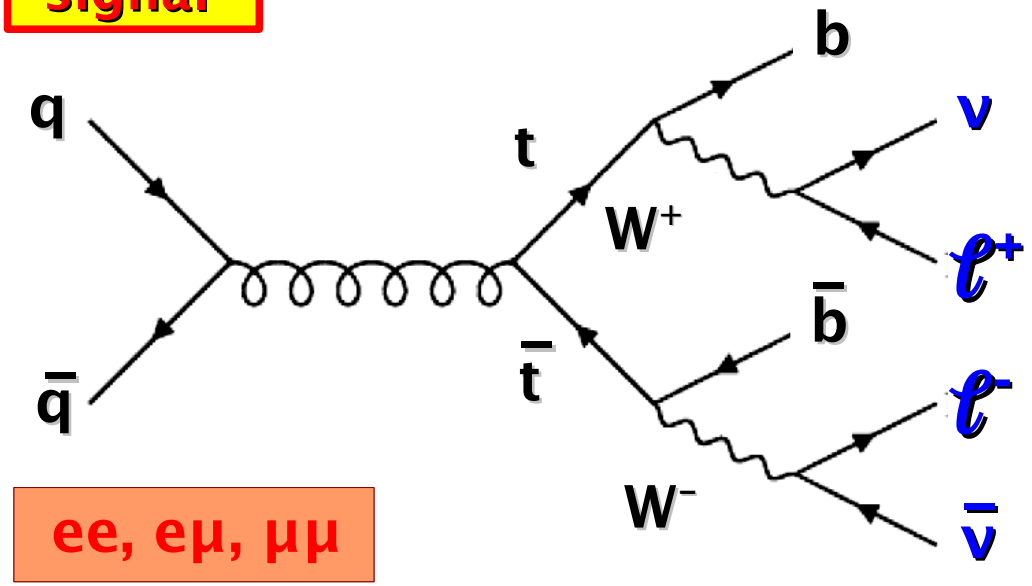
10^{10} times higher rate

multijets

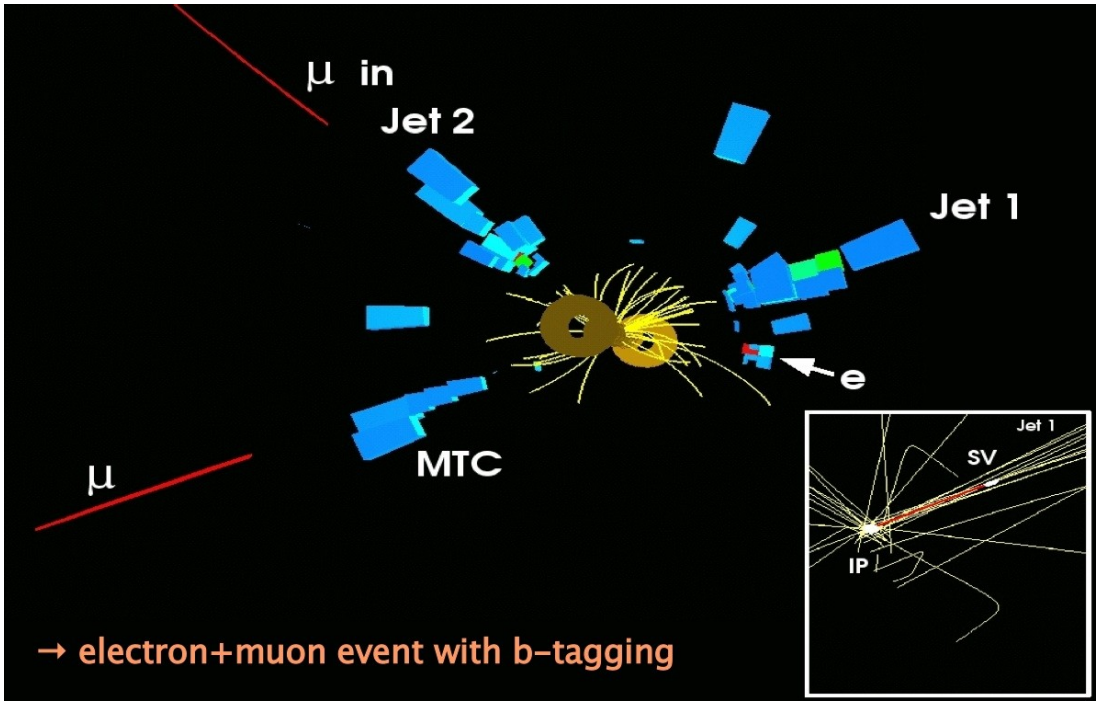


Dilepton Signatures

signal

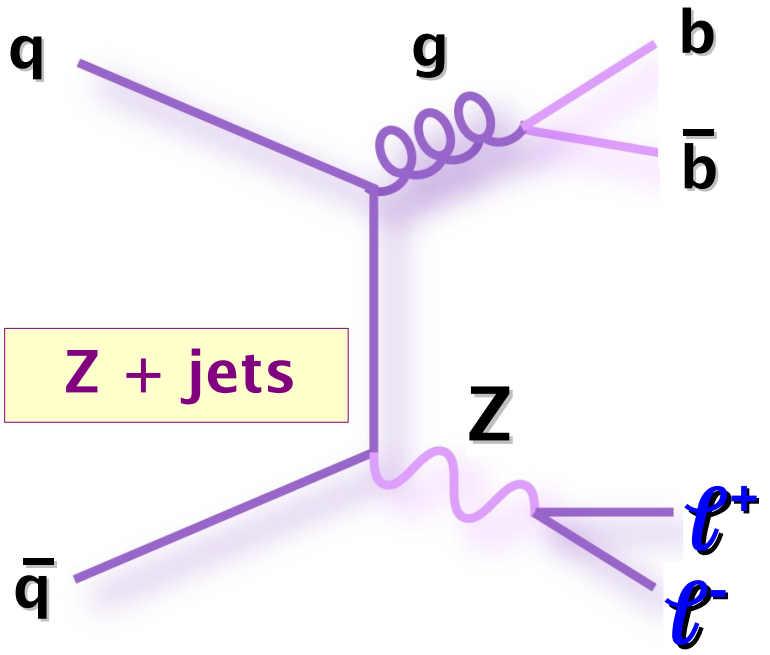


ee, eμ, μμ



background

300 times higher rate



- less statistics
- less background

Top Pair Production Cross Section

- check if production rate is as expected in the SM
- test of the underlying theory: QCD
- powerful search for new physics beyond the SM

Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

5.4 fb^{-1}

Lepton+Jets Topological Cross Section

- **kinematic properties allow separation between signal and background**

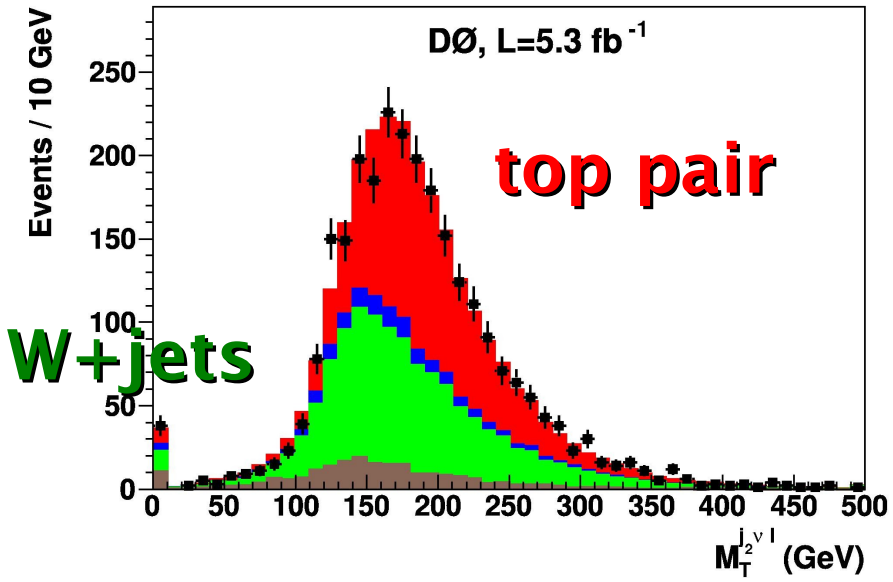
use variables such as:

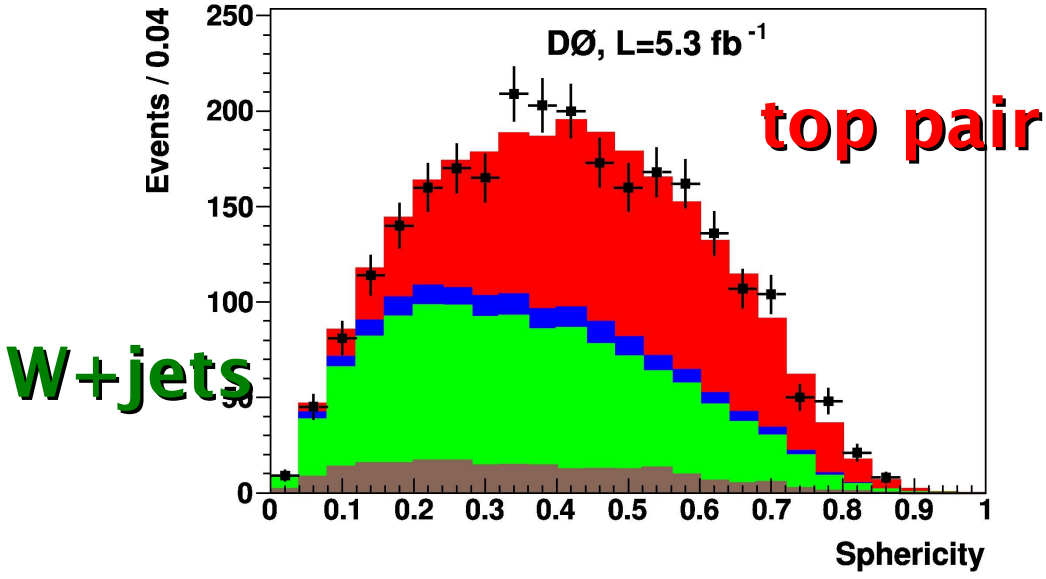
energy-dependent quantities:

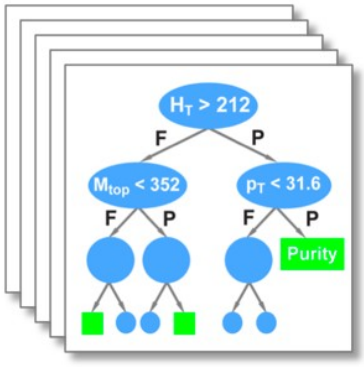
- **e.g. transverse mass of leptonic top**

angular dependent:

- **e.g. sphericity**







Random Forests of Boosted Decision Trees

Lepton+Jets Topological Cross Section

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energy-dependent quantities:

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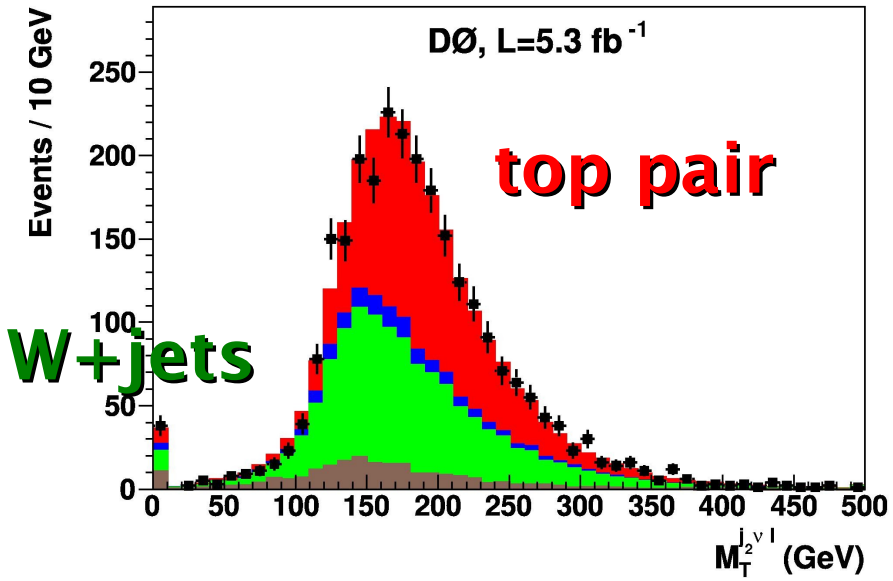
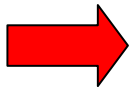
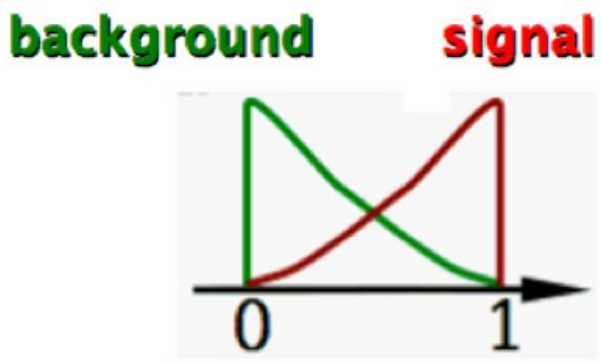
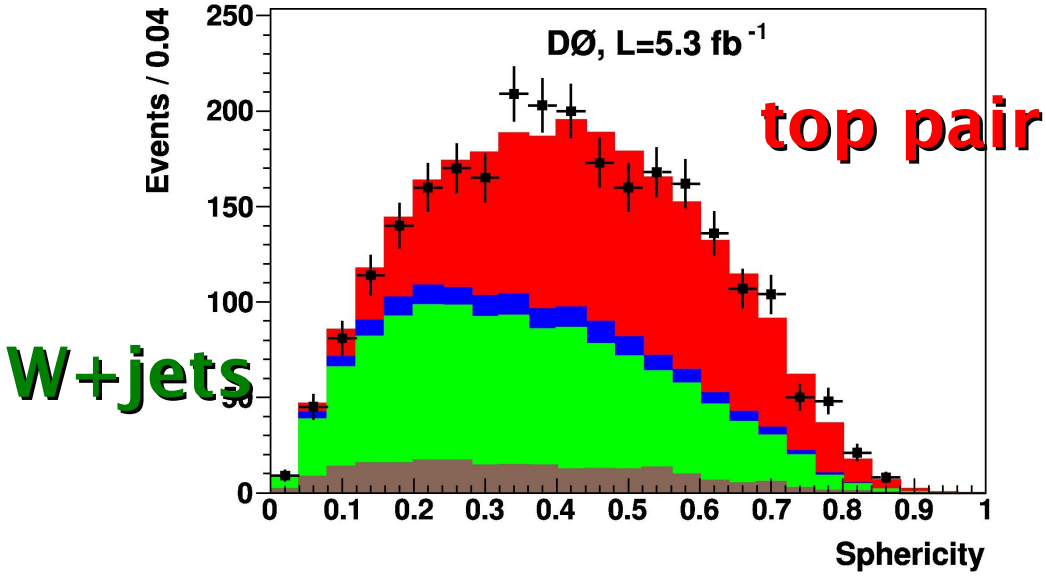




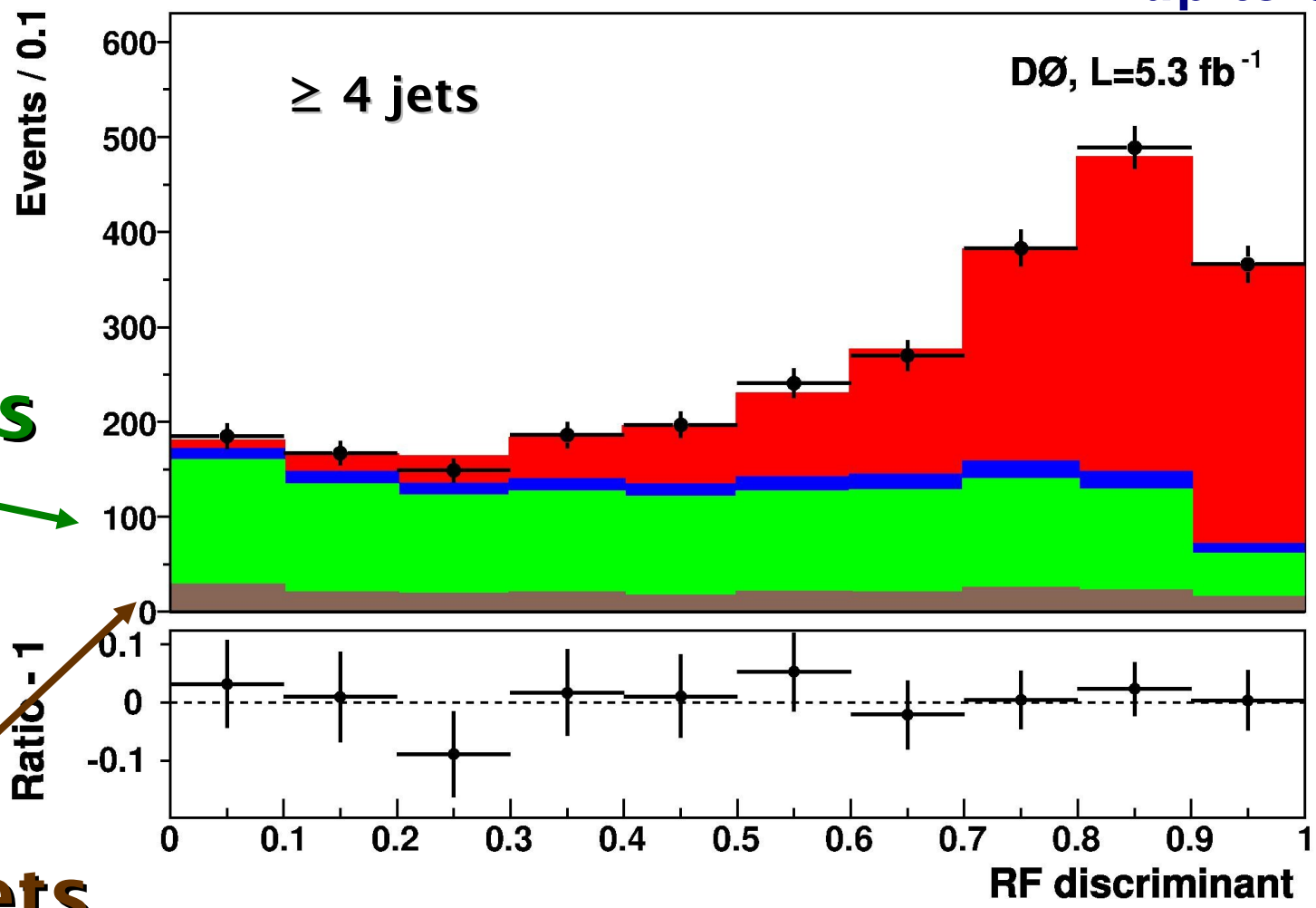
Random Forests of Boosted Decision Trees





Lepton+Jets Topological Cross Section

up to 6 variables



top pair

W+jets

multijets

combine:
2 jets
3 jets
≥4 jets
e and μ

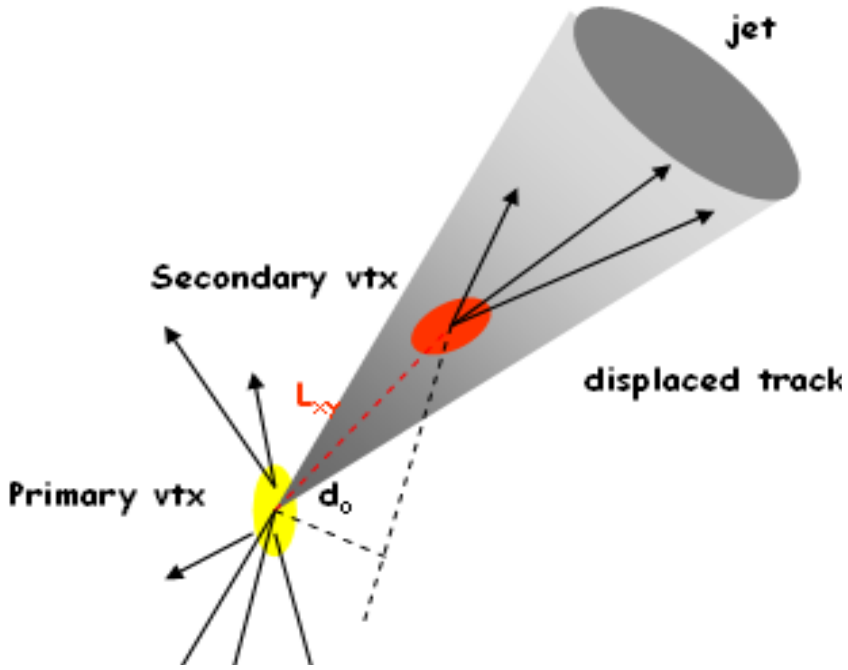
m_{top} = 172.5 GeV

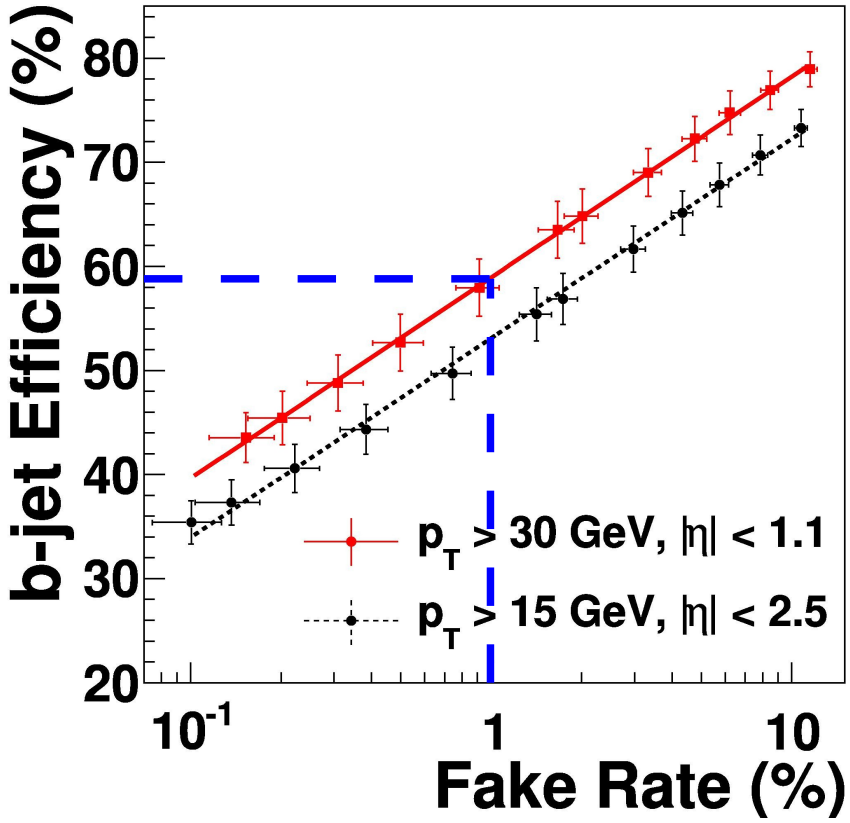
$$\sigma_{t\bar{t}} = 7.68^{+0.71}_{-0.64} \text{ (stat+syst+lumi) pb}$$

b-tagging

- B hadron lifetime $\tau \sim 1$ ps
- B hadrons travel $L_{xy} \sim 3$ mm before decay

Nucl. Instrum. Meth. A 620, 490 (2010)



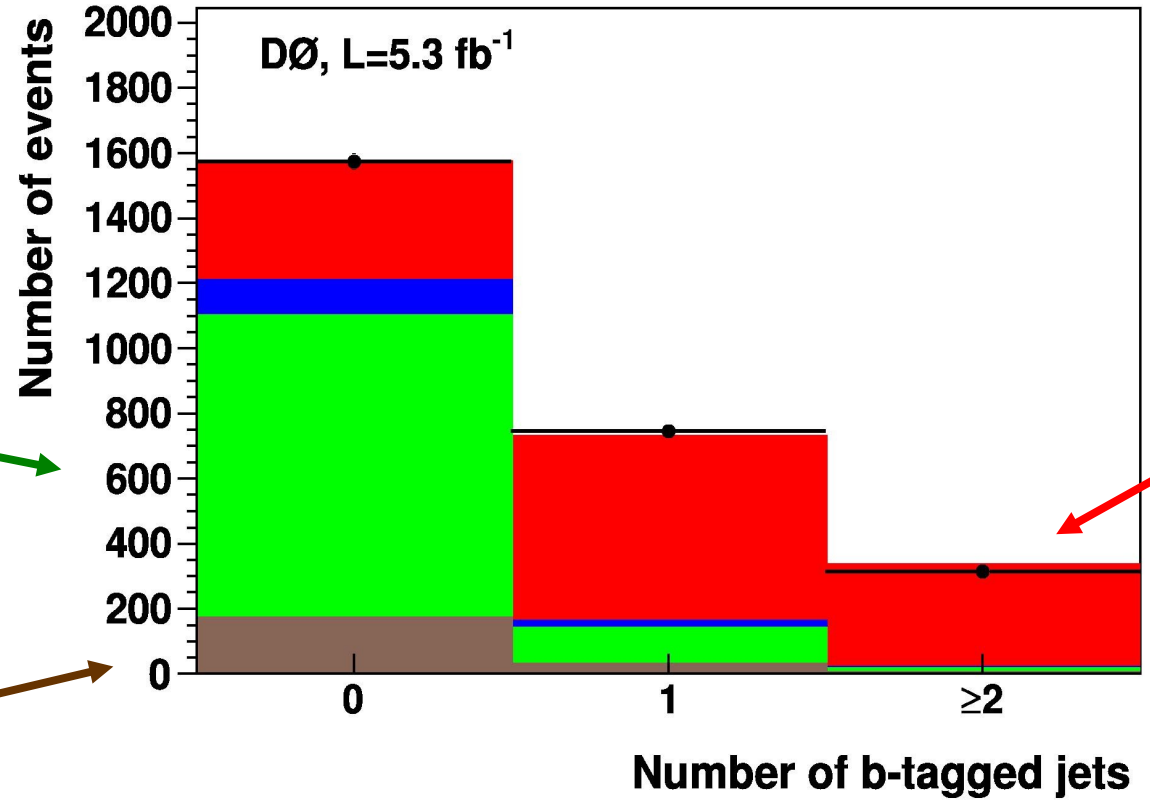


- secondary vertex tagger
- 45% b-jet tagging efficiency (with fake rate of 1%)

- form a 7-variable neural network
- b-jet tagging efficiency 59% (with fake rate of 1%)

Lepton+Jets Cross Section with b-tagging

very powerful tool to reduce the background



W+jets

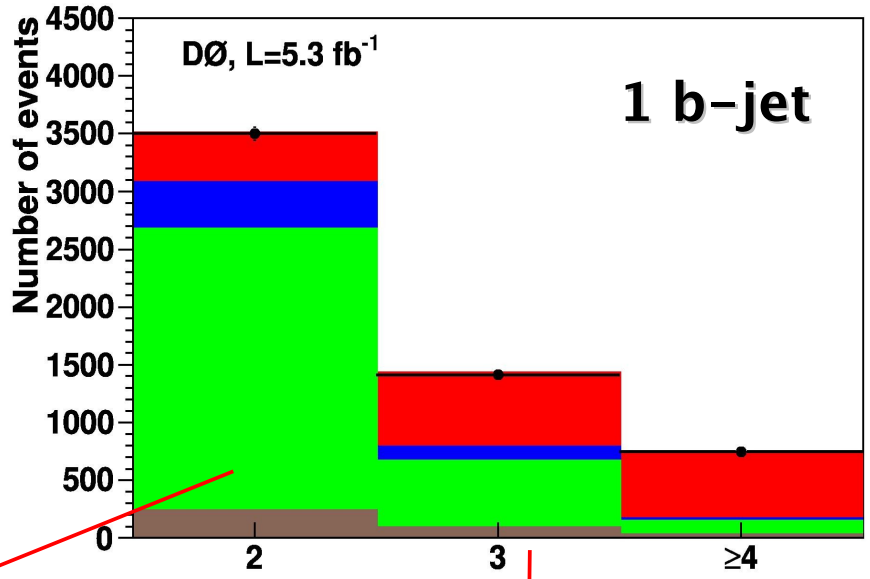
top pair

multijets

$$\sigma_{t\bar{t}} = 8.13^{+1.02}_{-0.90}\ \text{(stat+syst+lumi) pb}$$

m_{top} = 172.5 GeV

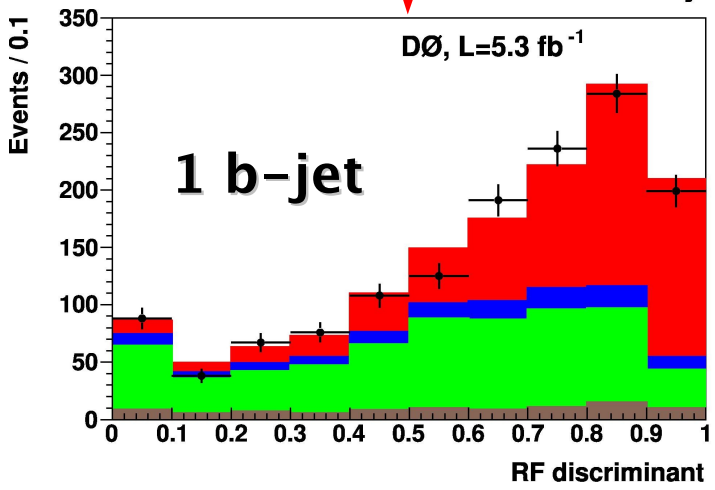
Combined Method



arXiv:1101.0124 [hep-ex]
accepeted In Phys. Rev. D

combine:
2, 3, ≥4 jets
0, 1, ≥2 b-jets
e and μ

W+jets & heavy flavor scale factor f_H



"counting"

Systematically limited:
- **luminosity**
- **JES and JER**
- **b-tagging**

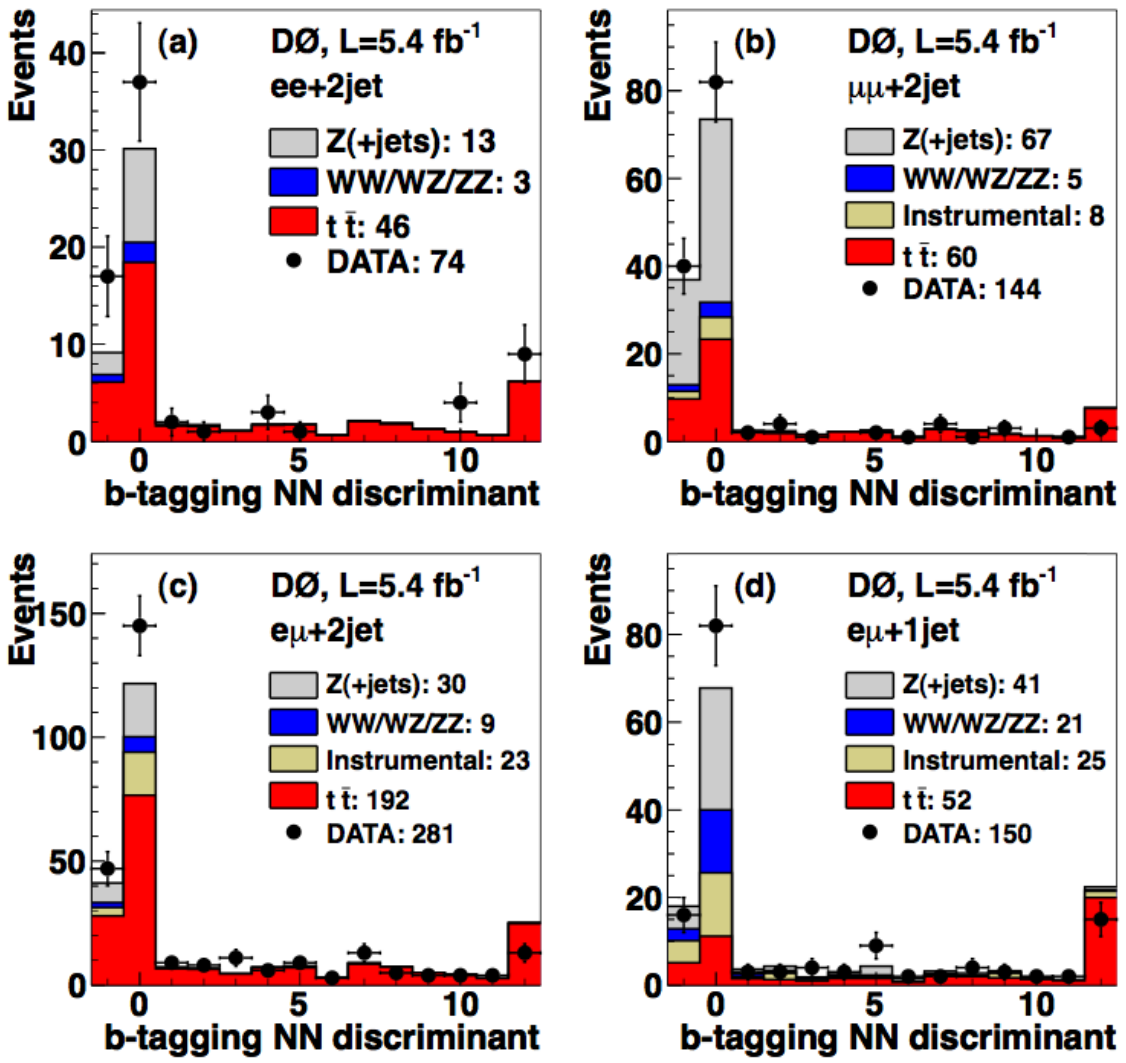
$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\ \text{(stat+syst+lumi) pb}$$

m_{top} = 172.5 GeV

±9%

Dilepton Cross Section with b-tagging

Z+jets



arXiv:1105.5384 [hep-ex]

top pair

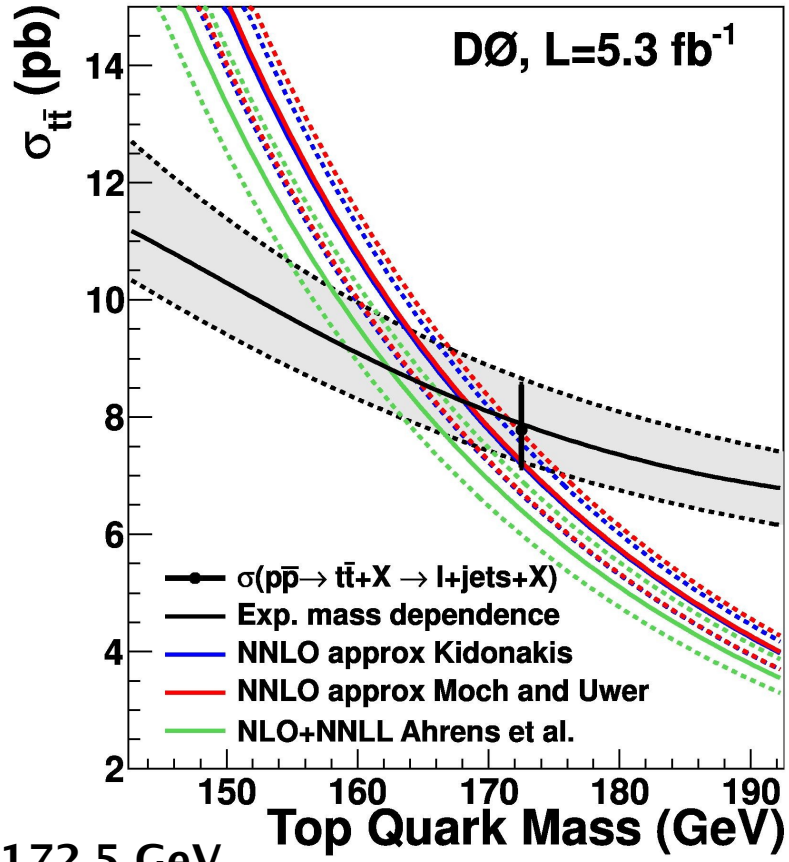
m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79}\ \text{(stat+syst+lumi) pb}$$

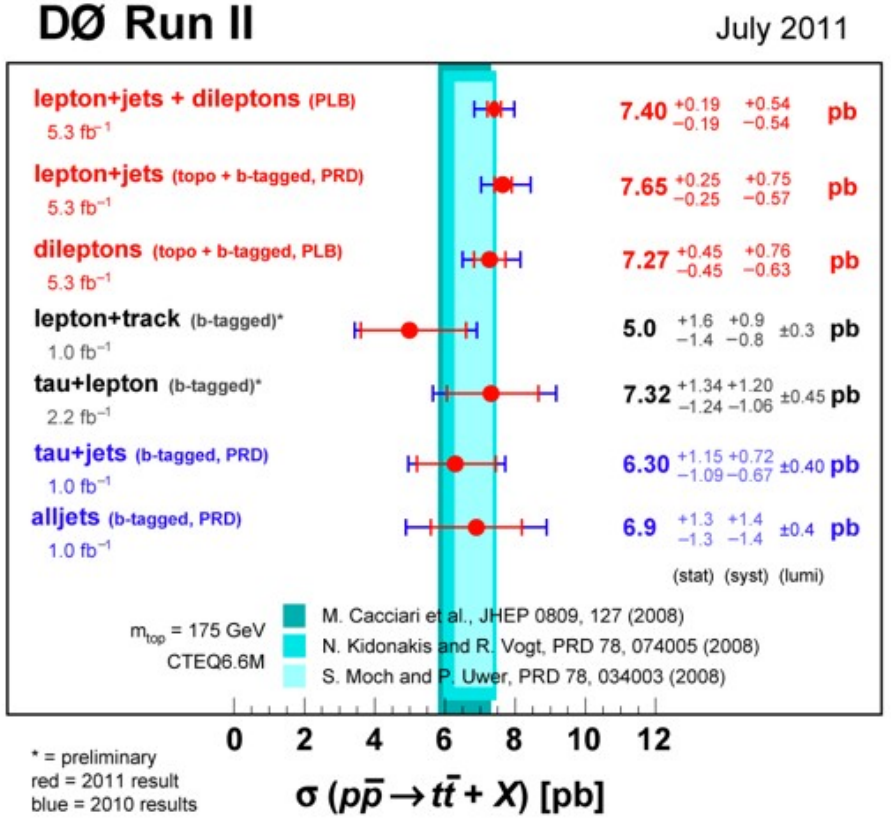
±11%

Top Pair Production Cross Sections

Combination: l+jets and dilepton



m_{top} = 172.5 GeV



all channels measured except for τ_{had} τ_{had}

$$\sigma_{t\bar{t}} = 7.56^{+0.63}_{-0.56}\ (\text{stat+syst+lumi})\ \text{pb}$$

±8%

→ good agreement with higher order QCD calculations

Outline

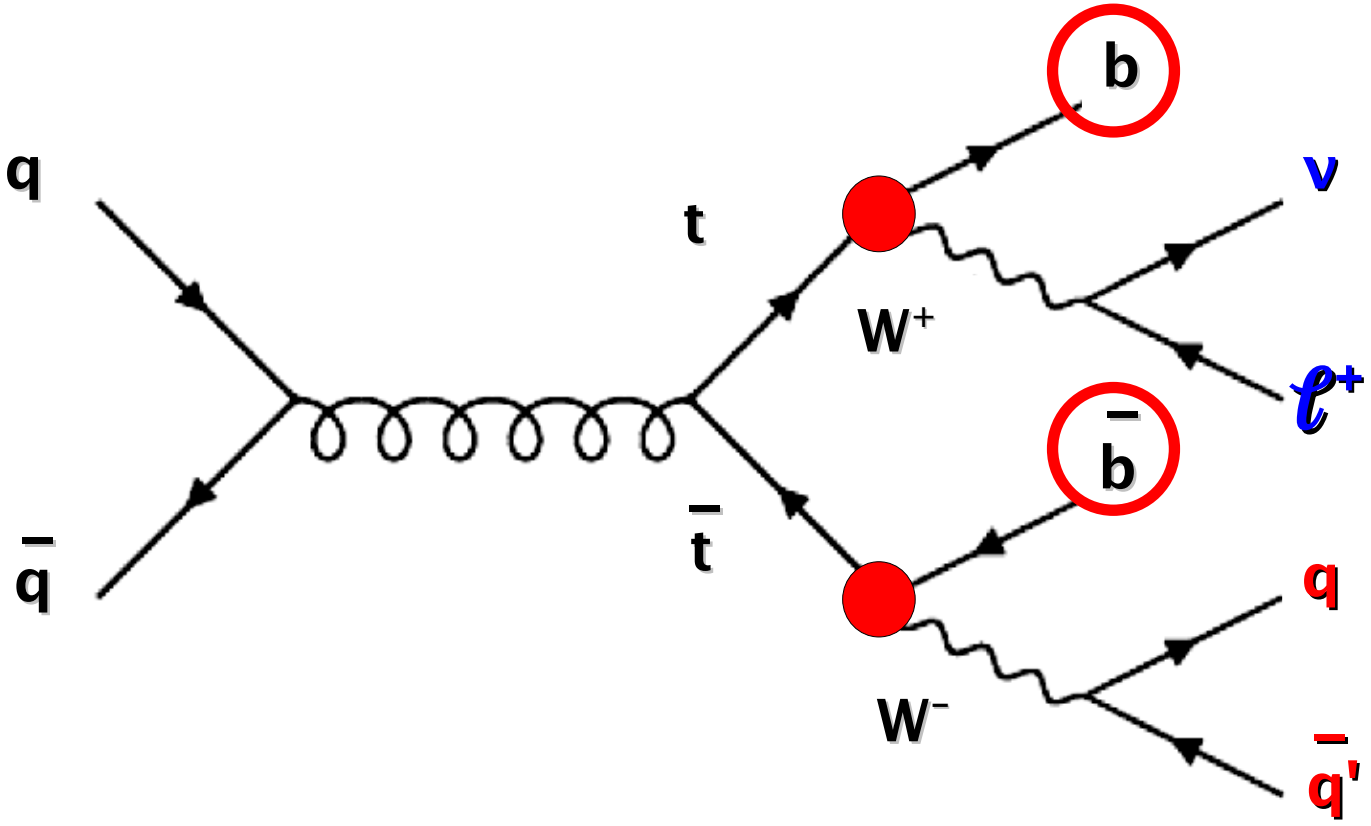
Top pair production cross section

Top decay couplings

Top mass

Conclusions

Searches in Top Decays: b disappearance



Measurement of Branching Fractions

$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

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

Standard Model:

$$R_{SM} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 = 1$$

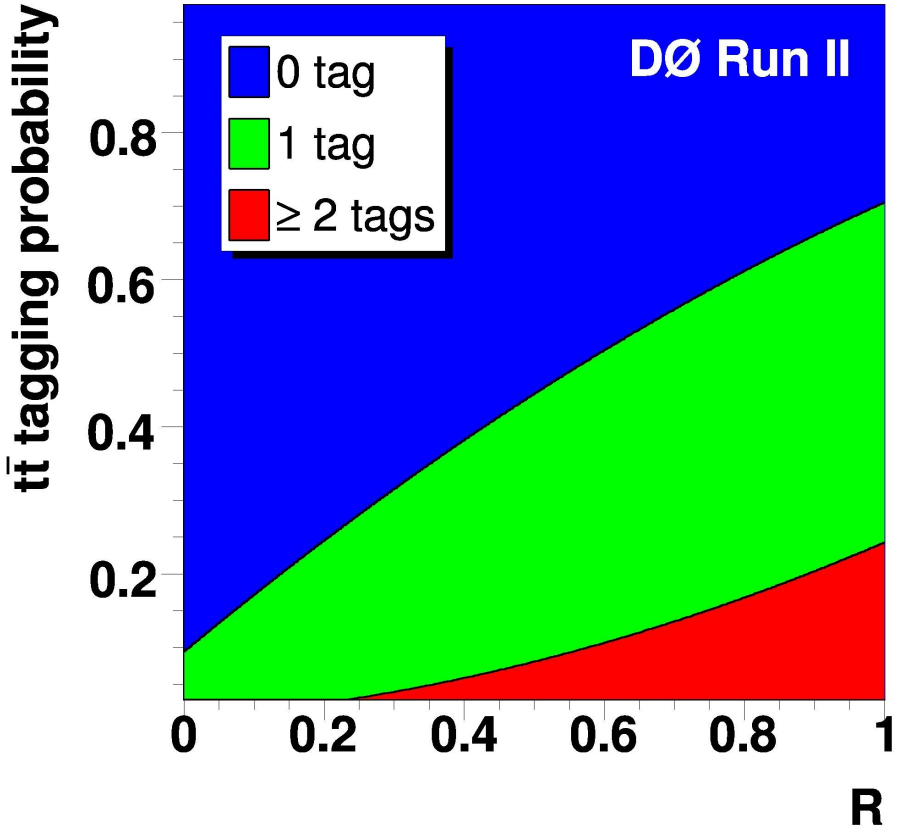
unitarity of CKM matrix

beyond SM:

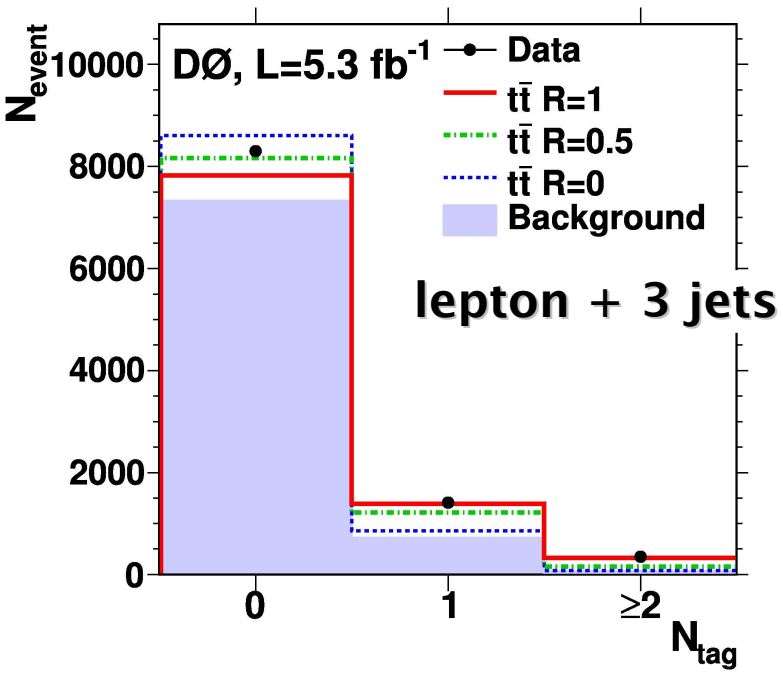
R ≠ 1

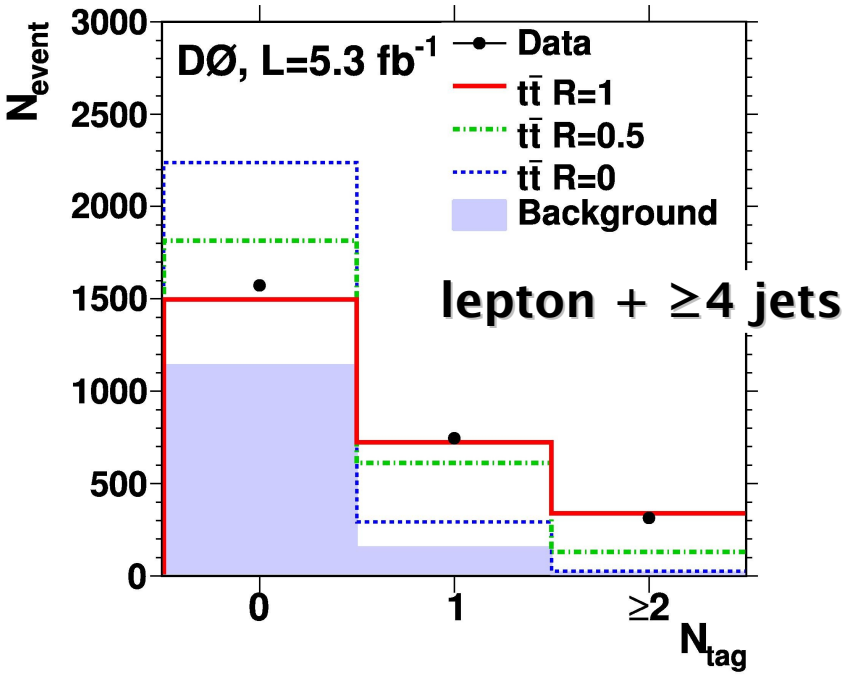
e.g. decay into 4th generation quark: R<1
sensitive to b disappearance

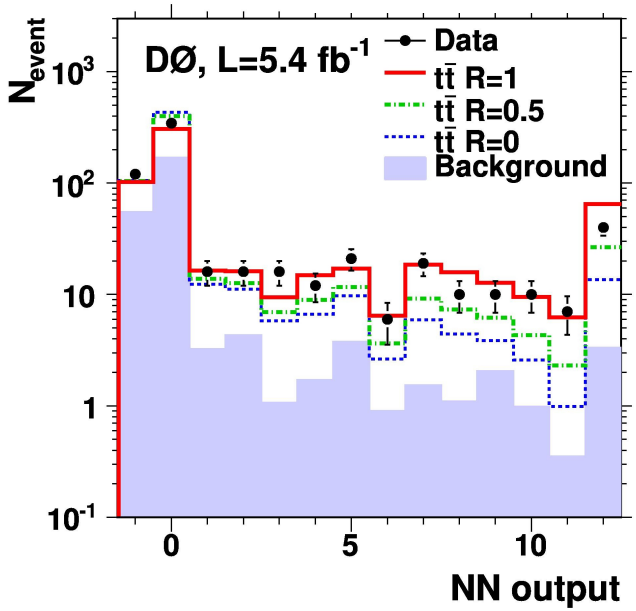
R changes fractions of b-tagged jets:



Measurement of Branching Fractions





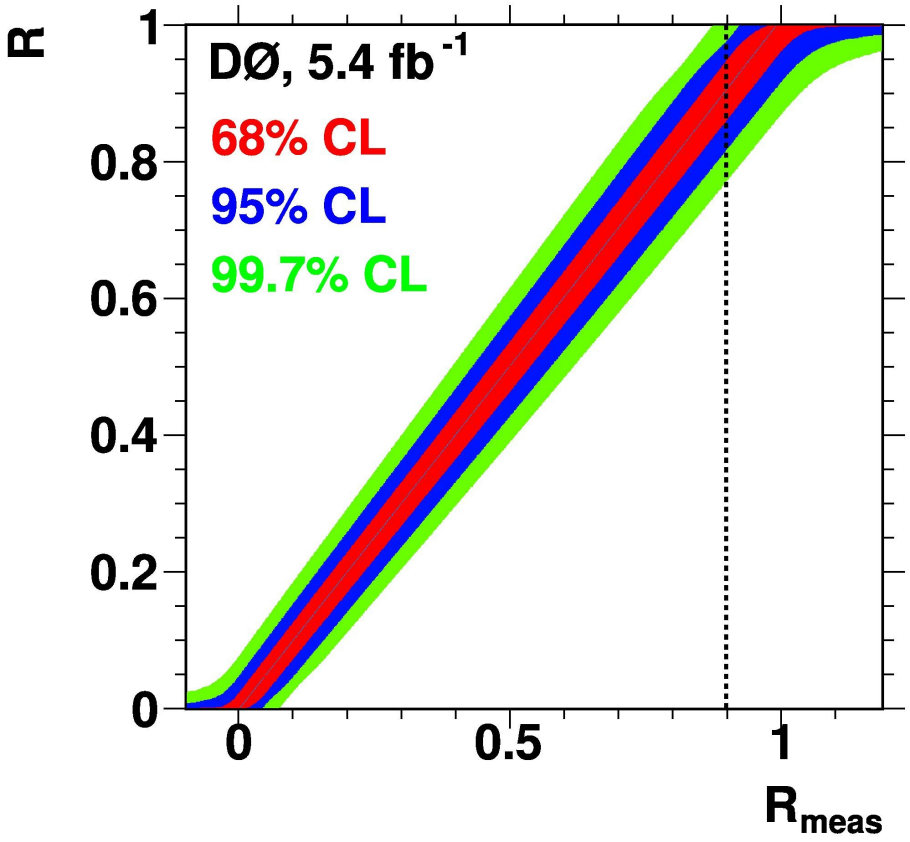


topological information and b-tagging

dilepton

Simultaneous Measurement of σ and R

Maximize total Likelihood function simultaneously for branching ratio R and top pair production cross section



arXiv:1106.5436 [hep-ex]

$R = 0.90 \pm 0.04$ (stat+syst)

using unitarity of CKM matrix:

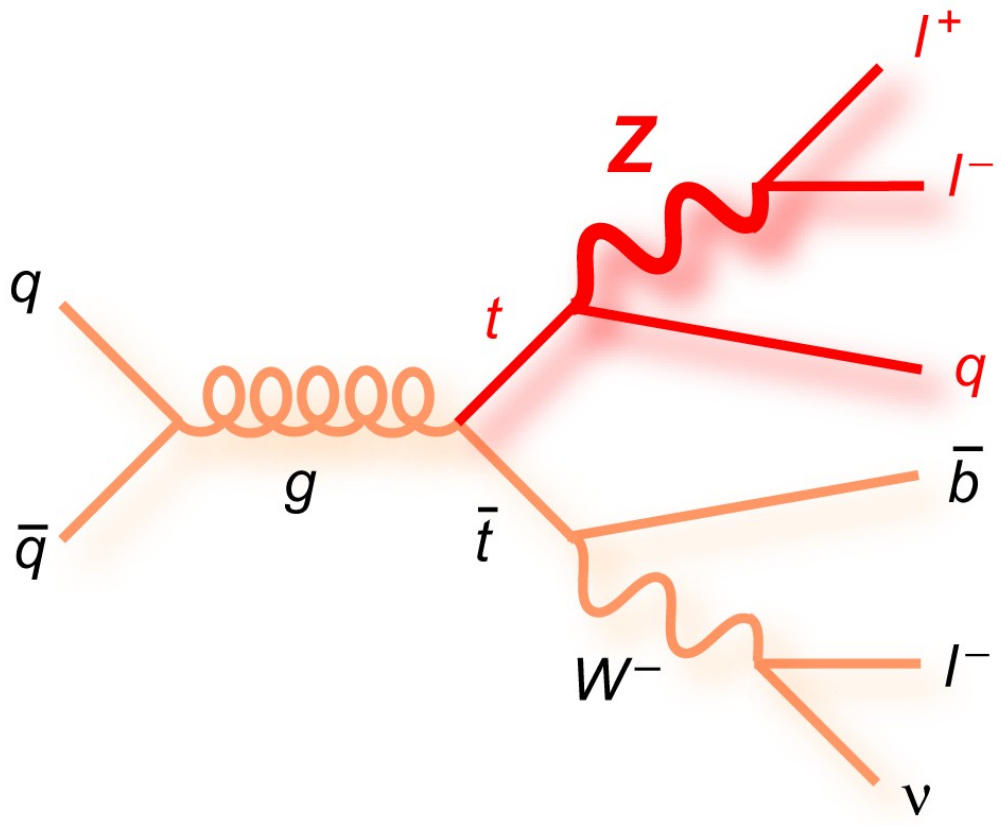
$0.90 < |V_{tb}| < 0.99$ @ 95% C.L.

$\sigma_{t\bar{t}} = 7.74^{+0.67}_{-0.57}$ (stat+syst) pb

⇒ agrees with SM at 1.6% C.L.

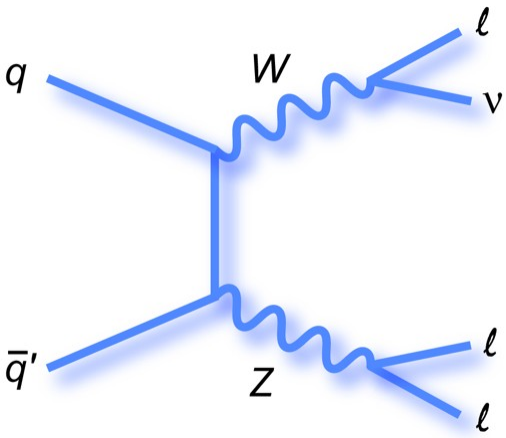
Search for FCNC in Top Quark Decays

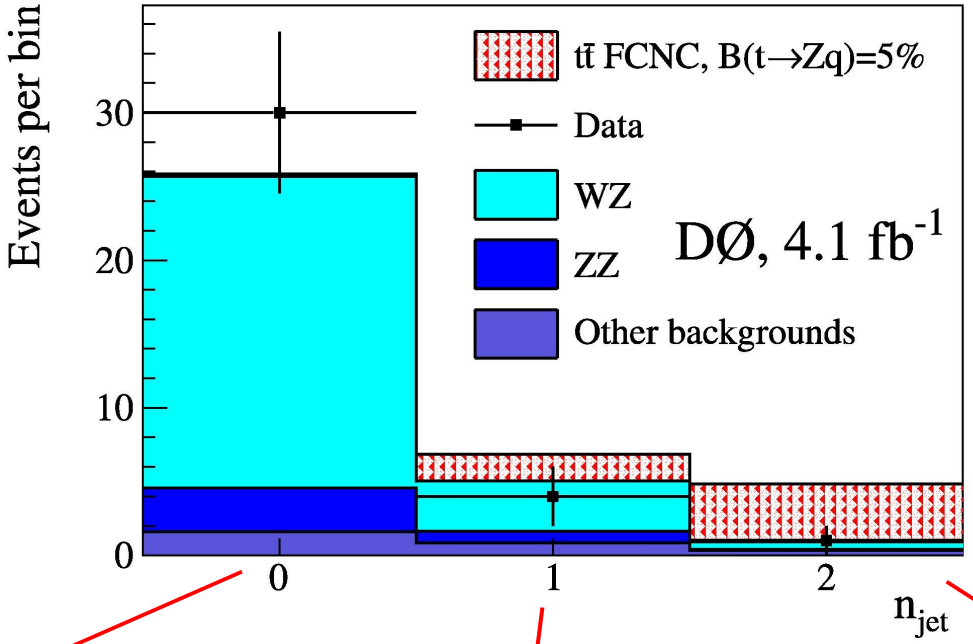
$$\mathcal{L}_{FCNC} = \frac{e}{2\sin\theta_W \cos\theta_W}\,\bar{t}\gamma_\mu(v_Z - a_Z\gamma_5)qZ^\mu + h.c.$$

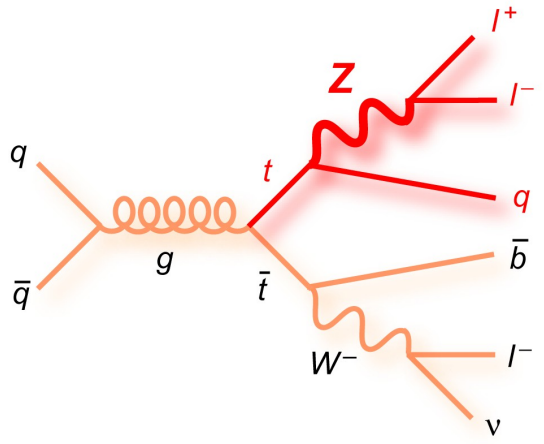


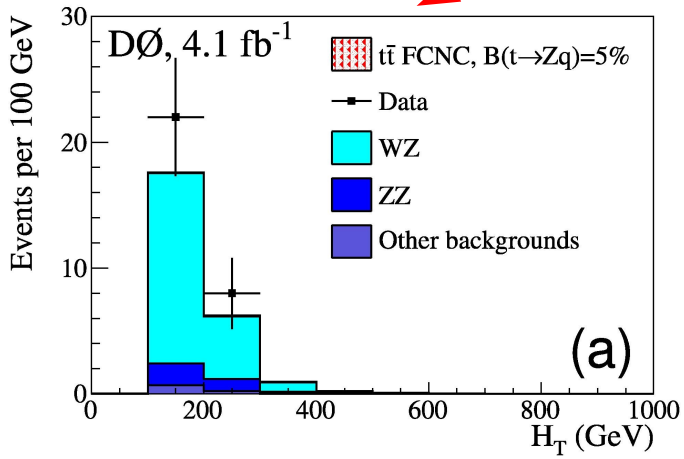
- **select 3 leptons, missing transverse momentum, 2 jets**

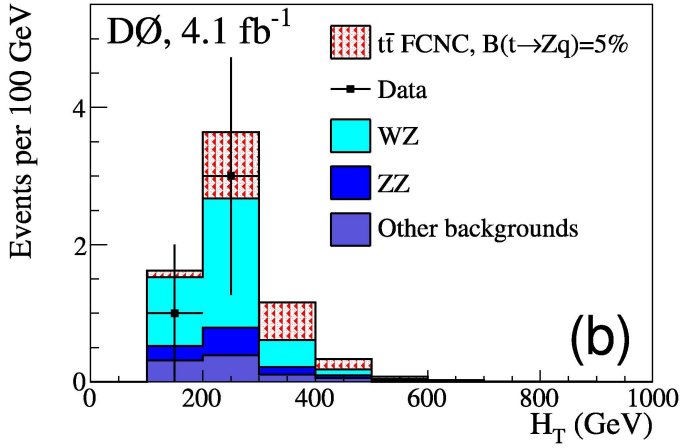
Search for FCNC in Top Quark Decays

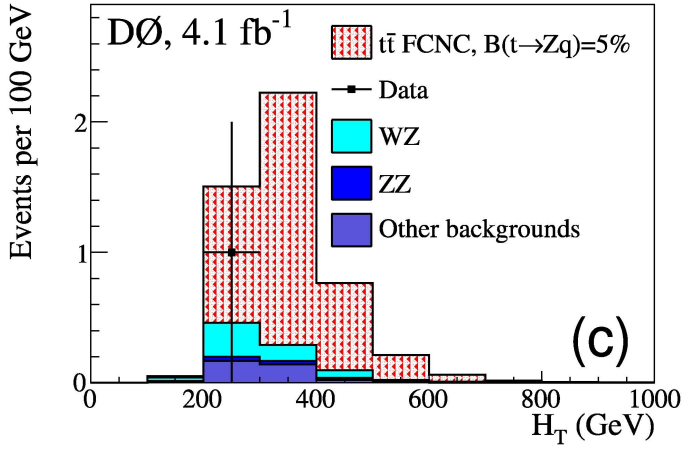










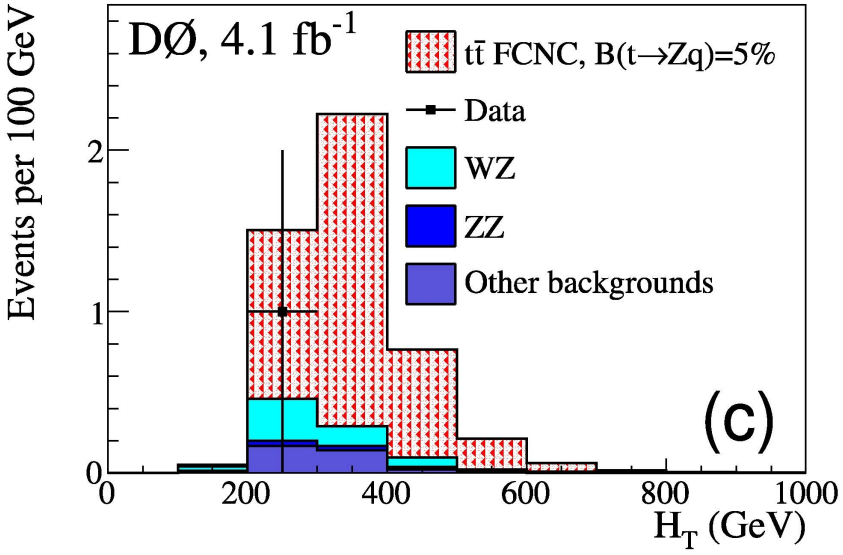


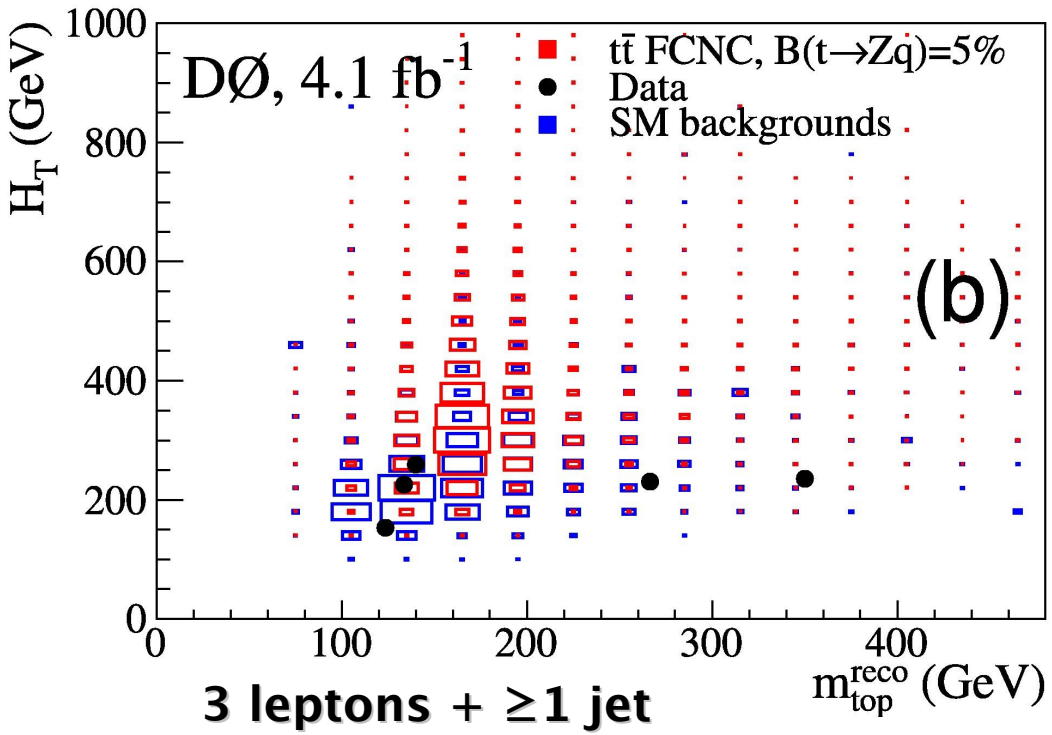
3 leptons + 0 jets

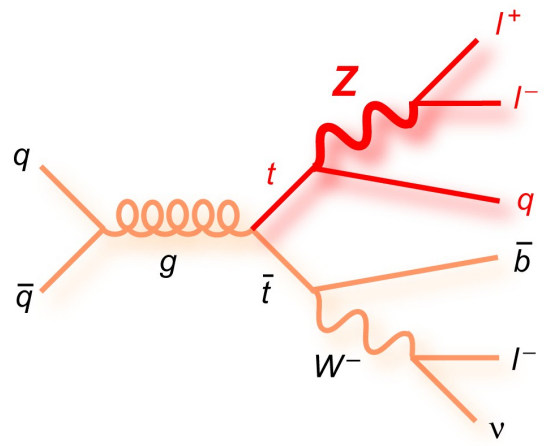
3 leptons + 1 jet

3 leptons + ≥2 jets

Search for FCNC in Top Quark Decays

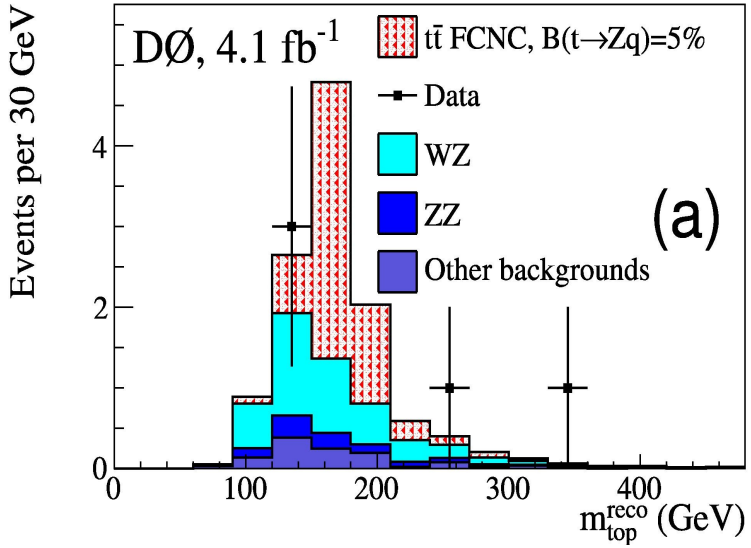






m_{top}^{reco}

3 leptons + ≥1 jet

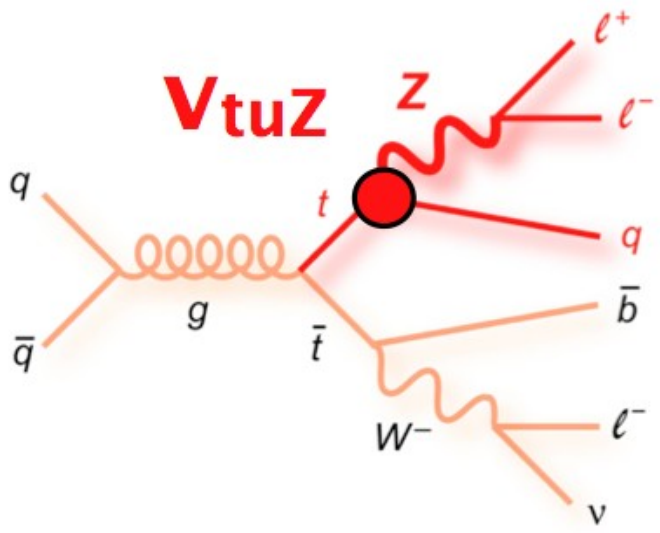


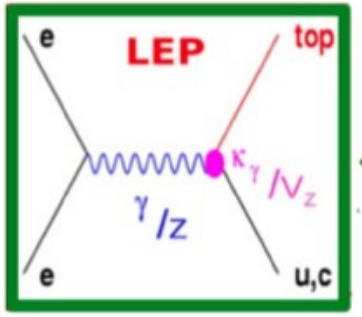
Phys. Lett. B701, 313 (2011)

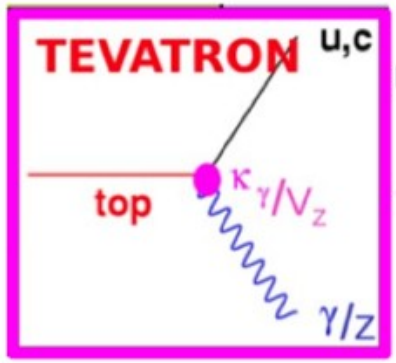
95% C.L.

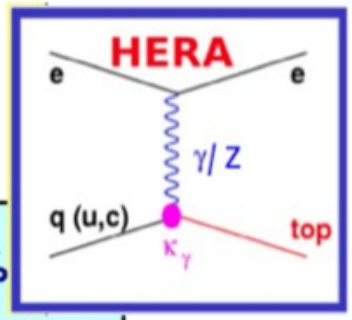
B(t→Zq) < 3.2% (3.8% expected)

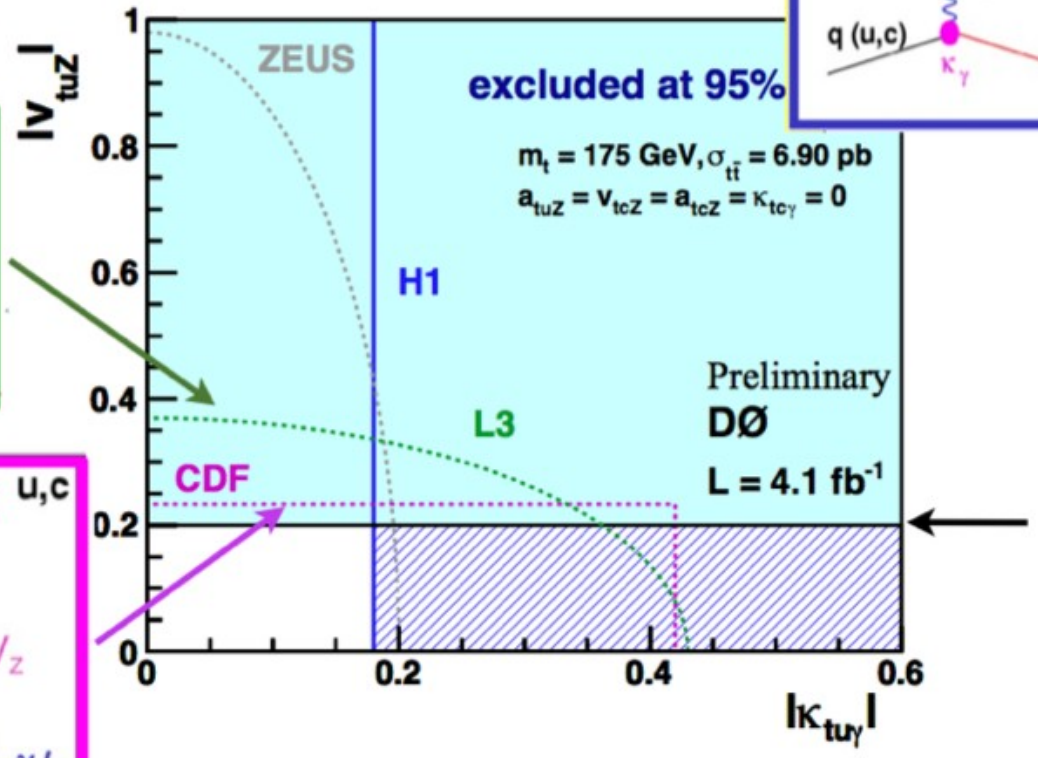
Excluded Regions by Colliders











world's best limit

Outline

Top pair production cross section

Top decay couplings

Top mass

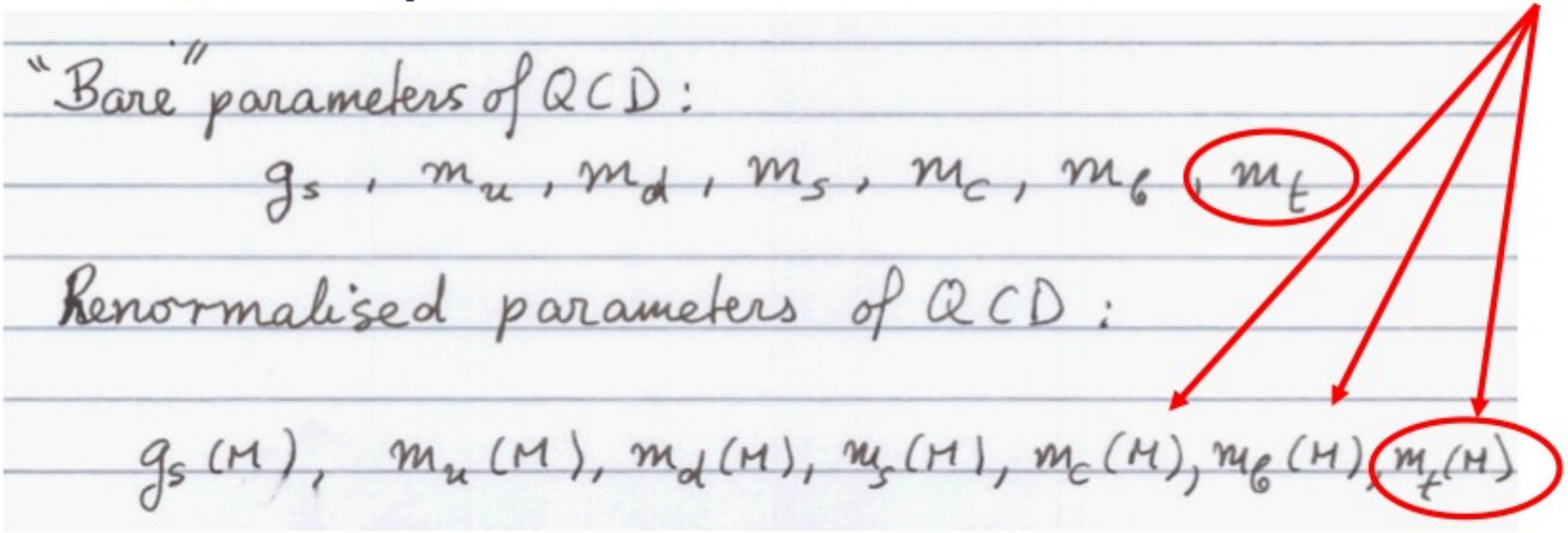
Conclusions

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**

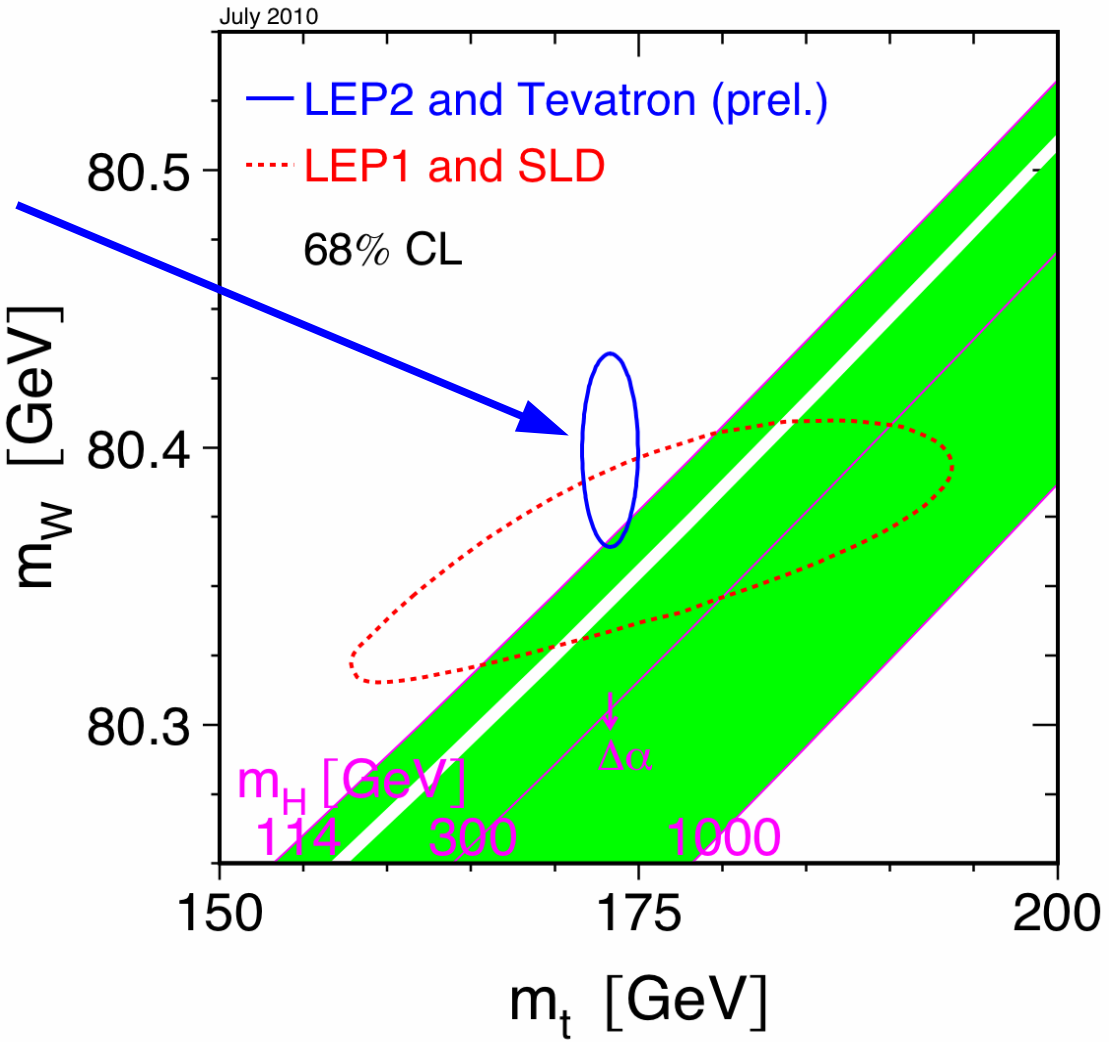


the concept of quark mass is convention-dependent!

Important to know...

- measurement reconstructing decay products: depends on MC mass details
- how does MC mass relate to pole mass or running mass scheme?

pole mass



- can we measure pole or MS mass in direct and well-defined way?

Important to know...

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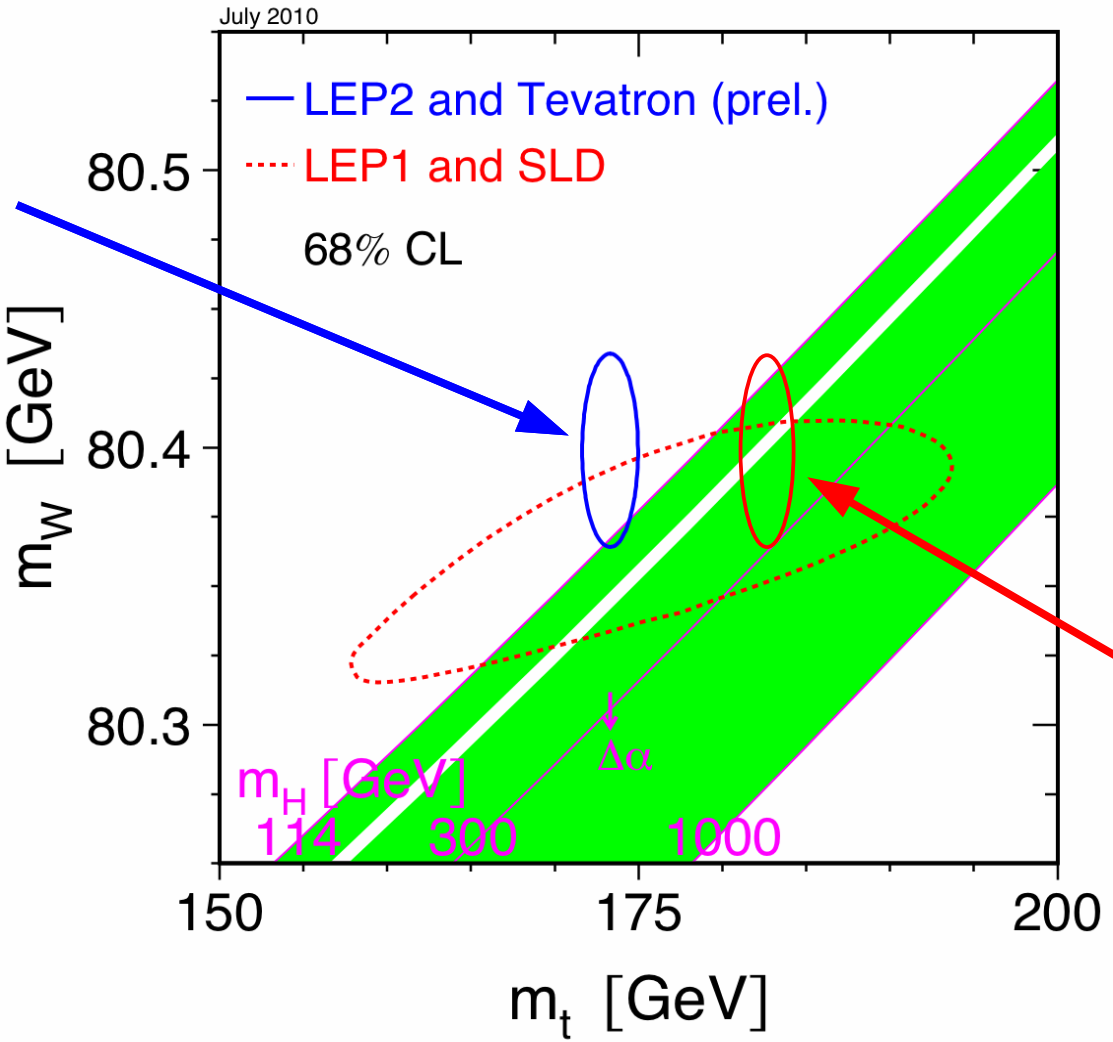


world average interpreted as $\overline{\text{MS}}$ mass

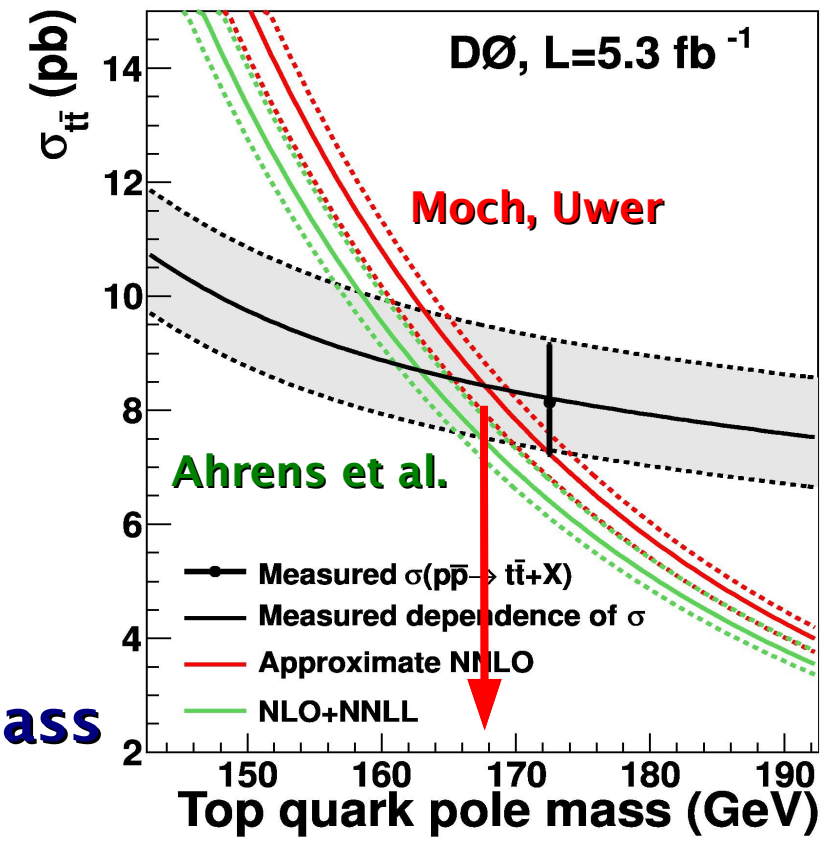
~10 GeV (3-loop)

- can we measure pole or $\overline{\text{MS}}$ mass in direct and well-defined way?

Top Quark Pole Mass

arXiv:1104.2887 [hep-ex]

Theoretical prediction	m_t^{pole} (GeV)	Δm_t^{pole} (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO [12]	$164.8^{+5.7}_{-5.4}$	-3.0
NLO+NLL [13]	$166.5^{+5.5}_{-4.8}$	-2.7
NLO+NNLL [14]	$163.0^{+5.1}_{-4.6}$	-3.3
Approximate NNLO [15]	$167.5^{+5.2}_{-4.7}$	-2.7
Approximate NNLO [16]	$166.7^{+5.2}_{-4.5}$	-2.8



MC mass = pole mass

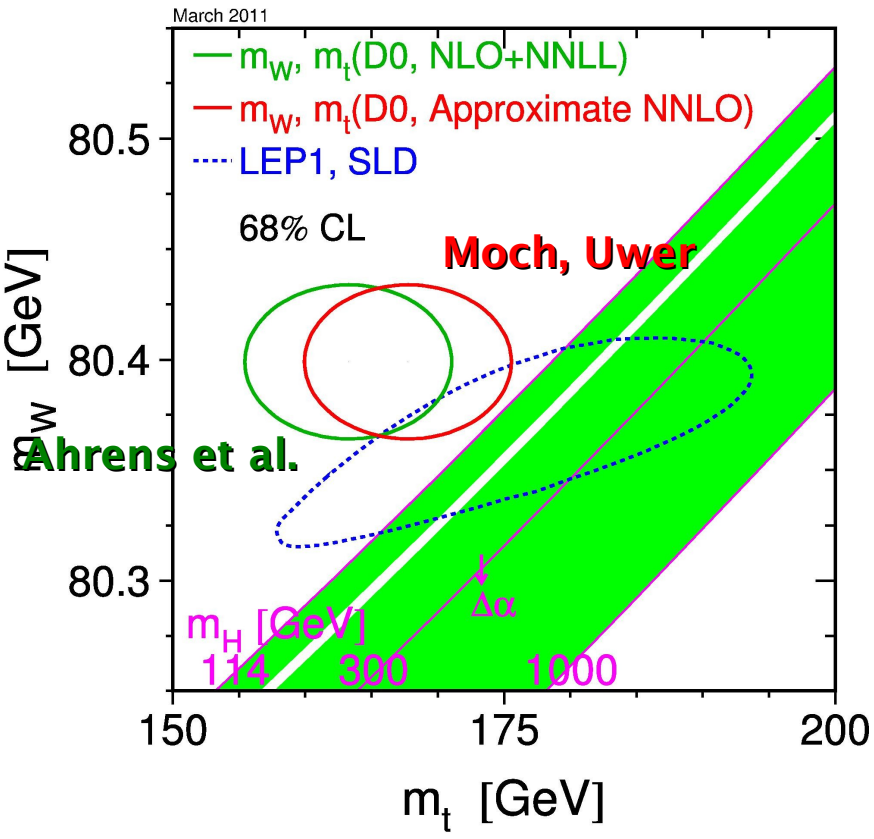
- use b-tagged cross section since less dependent on mass
- difference due to MC mass interpretation is included into systematics

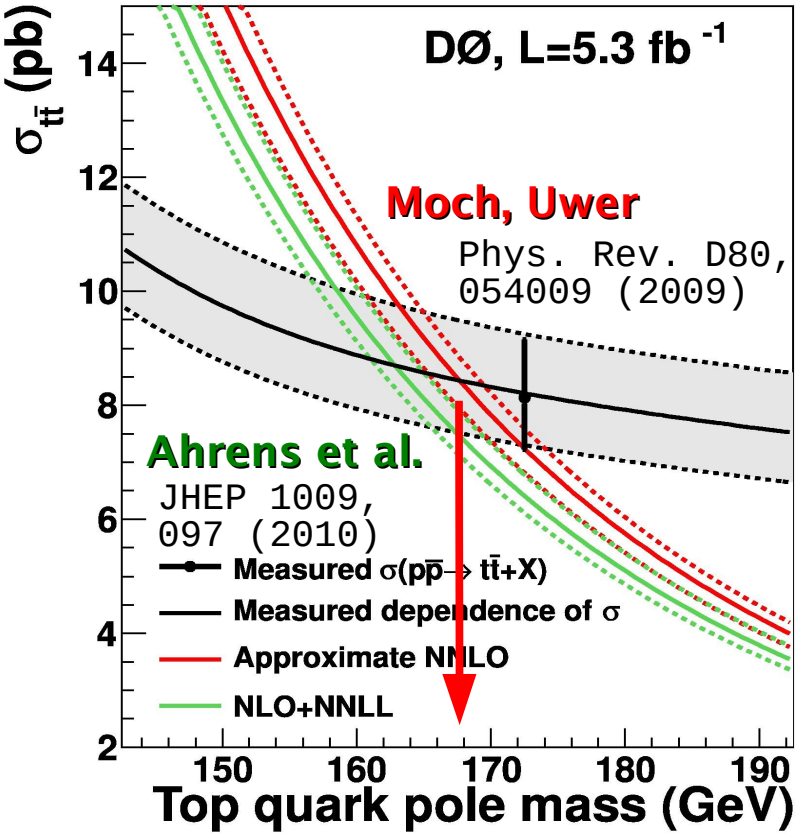
$$m_t^{\text{pole}} = 166.7^{+5.2}_{-4.5}\ \text{GeV}$$

±2.9%

- 1σ consistent with Tevatron average: m_t = 173.3 ± 1.1 GeV

Top Quark Pole Mass





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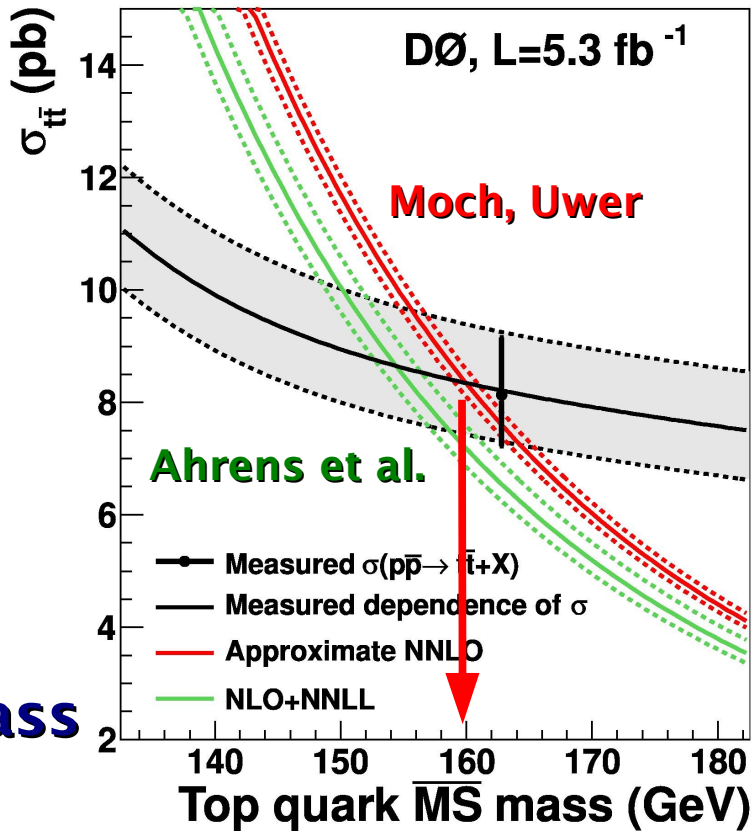
Top Quark $\overline{\text{MS}}$ Mass

better convergence of higher order resummation

Theoretical prediction	$m_t^{\overline{\text{MS}}}$ (GeV)	$\Delta m_t^{\overline{\text{MS}}}$ (GeV)
MC mass assumption	$m_t^{\text{MC}} = m_t^{\text{pole}}$	$m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$
NLO+NNLL [14]	$154.5^{+5.0}_{-4.3}$	-2.9
Approximate NNLO [15]	$160.0^{+4.8}_{-4.3}$	-2.6

arXiv:1104.2887 [hep-ex]



MC mass = pole mass

- **first extraction of $\overline{\text{MS}}$ mass taking selection efficiency into account**

$$m_t^{\overline{\text{MS}}} = 160.0^{+4.8}_{-4.3}\ \text{GeV} \qquad \pm 2.8\%$$

- **2σ consistent with Tevatron average: m_t = 173.3 ± 1.1 GeV**
- **Tevatron average is more consistent with a pole mass!**

Outline

Top pair production cross section

Top decay couplings

Top mass

Conclusions

Conclusions

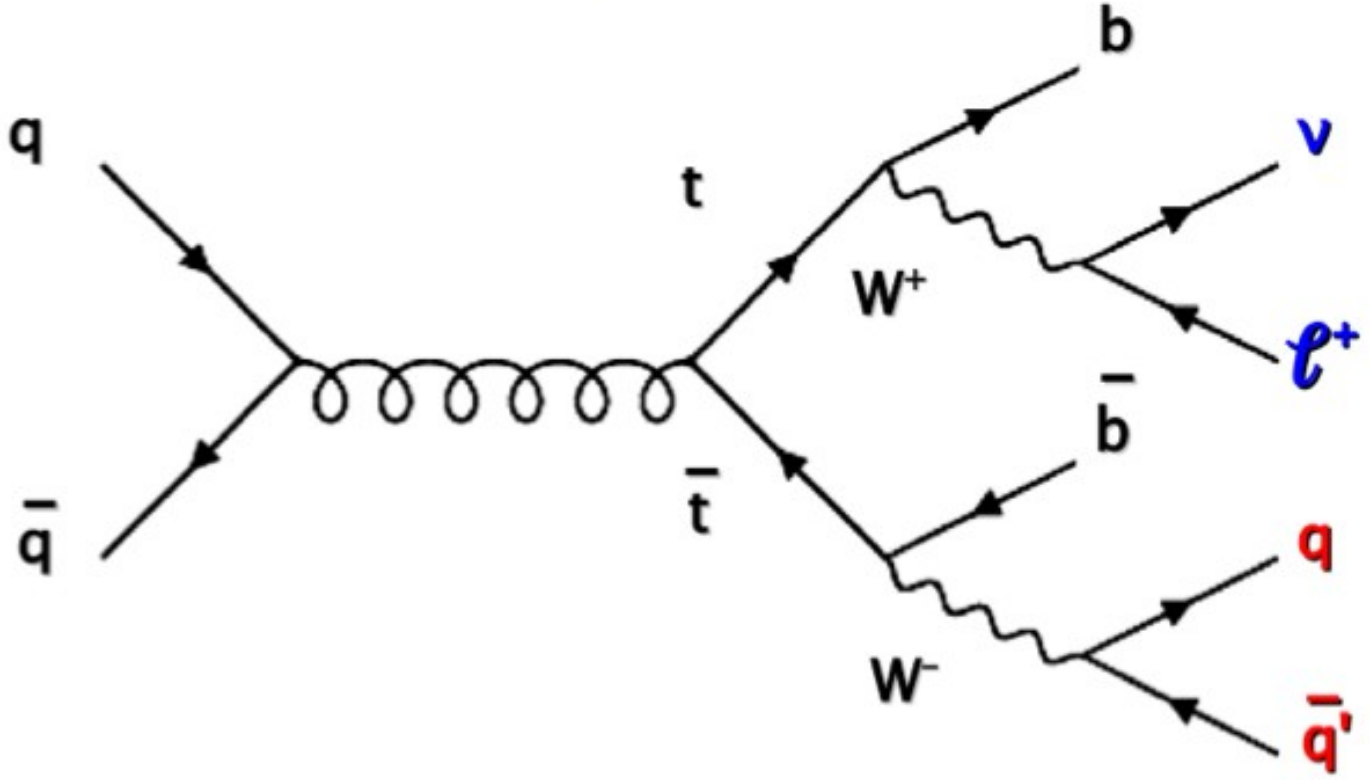
Highlights of top pair production physics:

- top pair production
  8% precision, many channels analyses, differential cross section, good agreement with NLO QCD predictions
- precision measurements (see talk by G. Petrillo)
  e.g. top mass
- top properties and searches (see also A. Grohsjean)
  high precision/sensitivity, some measured for first time
- excellent prospects for top quark physics at the Tevatron and the LHC

Backup

Which top mass does a LO MC contain?

- **matrix element in LO QCD**



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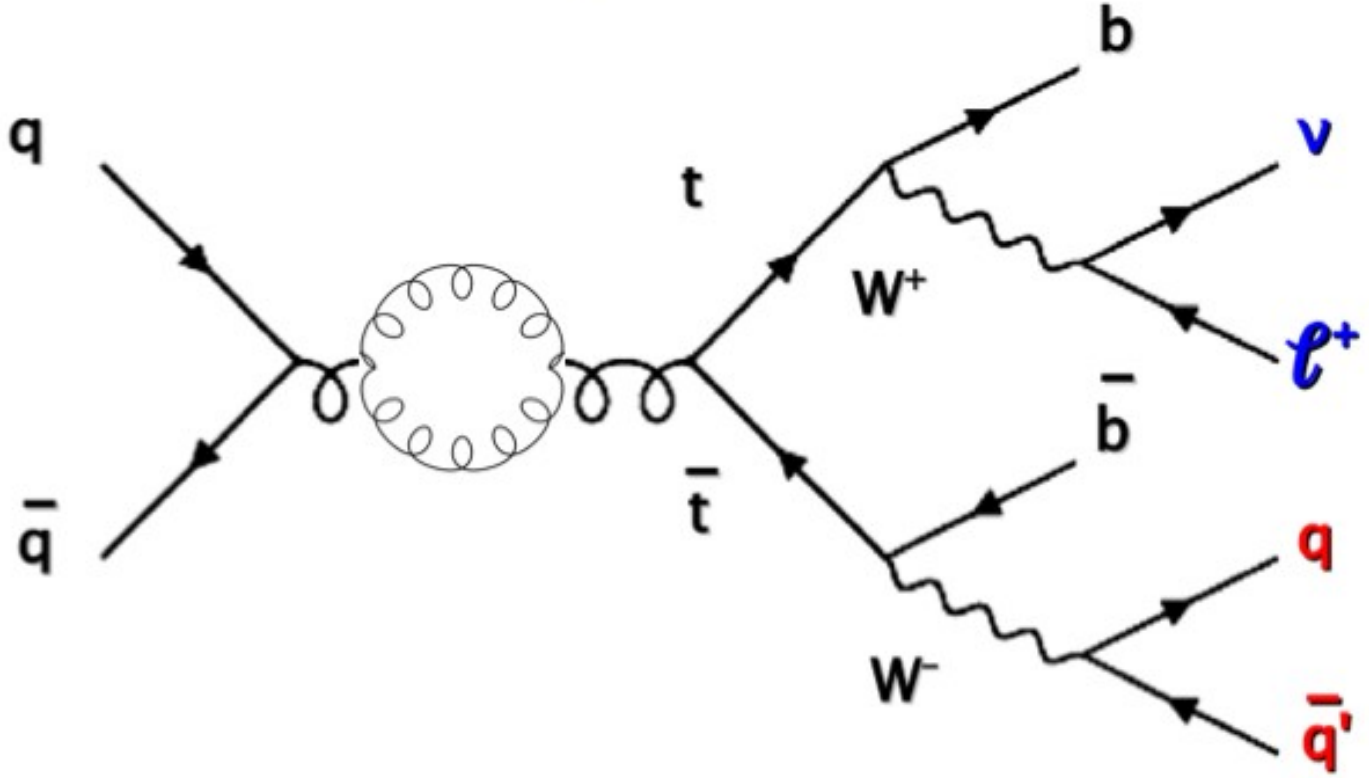
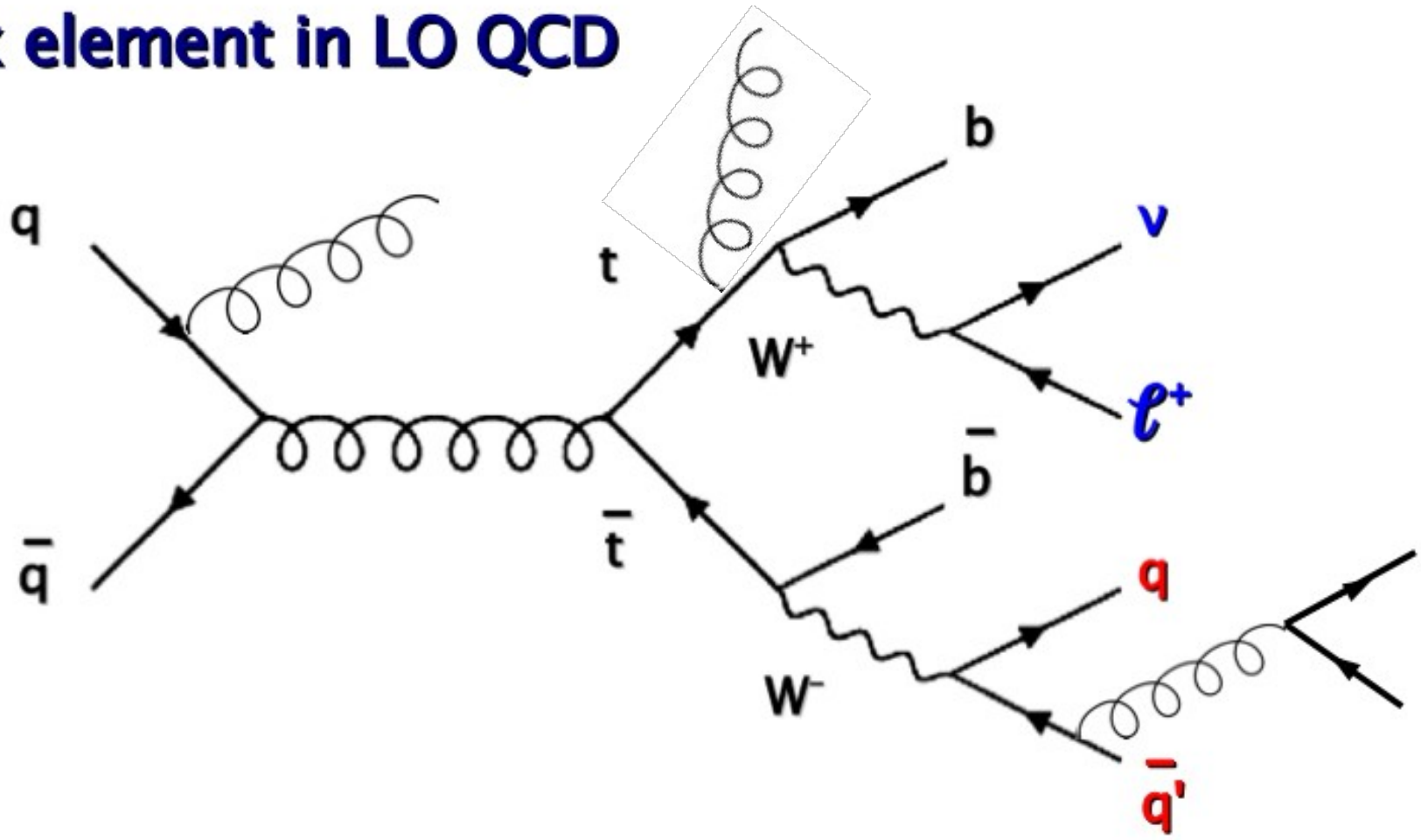


- parton showers simulate higher orders,
  i.e. not only radiating additional gluons!

Which top mass does a LO MC contain?

- matrix element in LO QCD



- parton showers simulate higher orders,

Which top mass does a LO MC contain?

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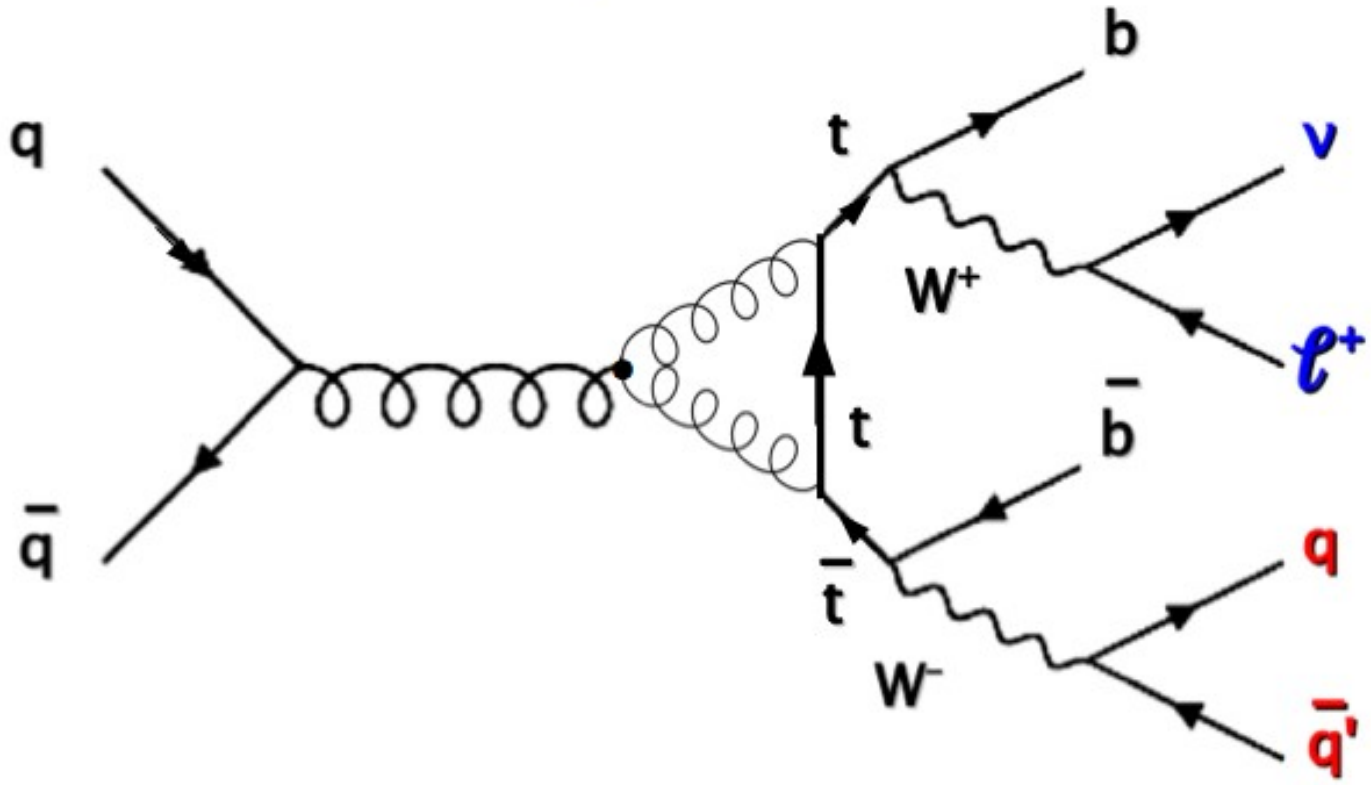

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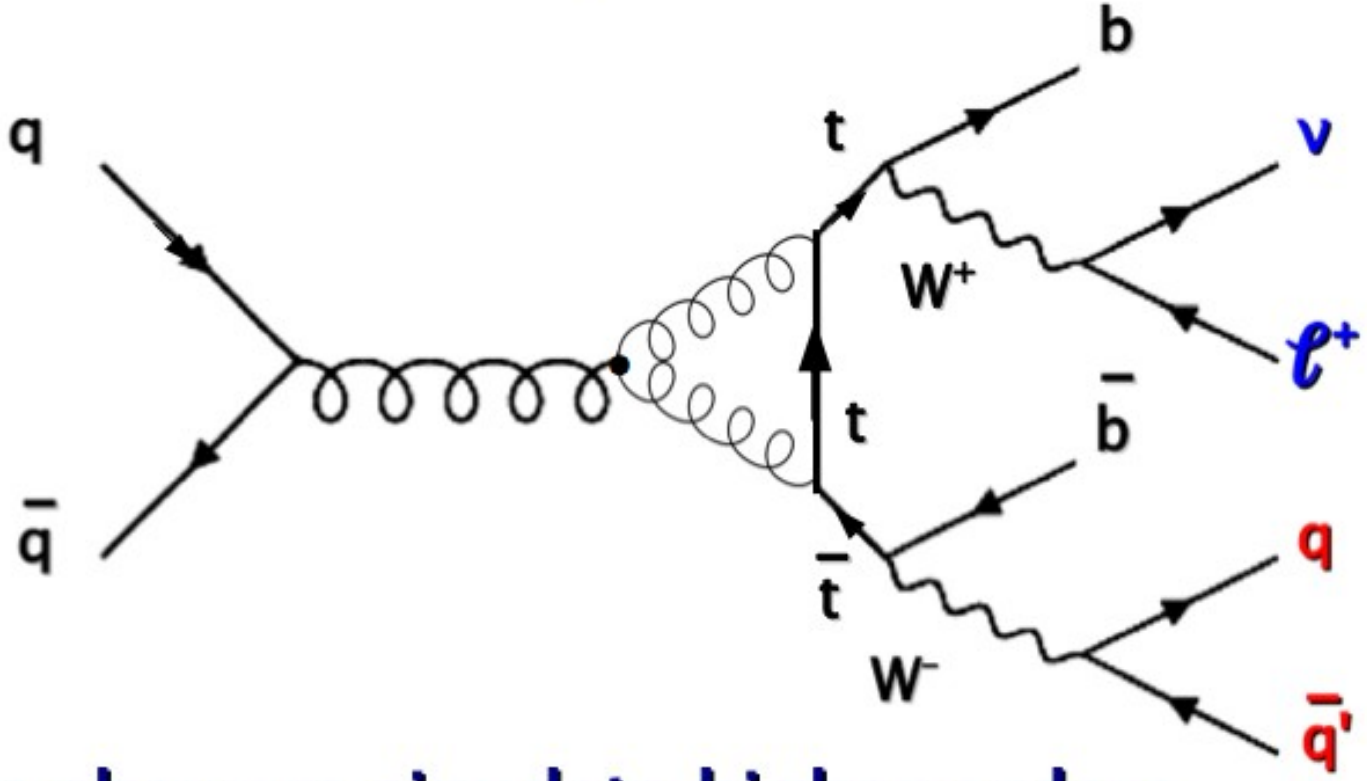
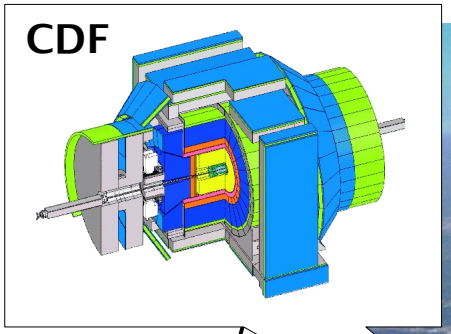


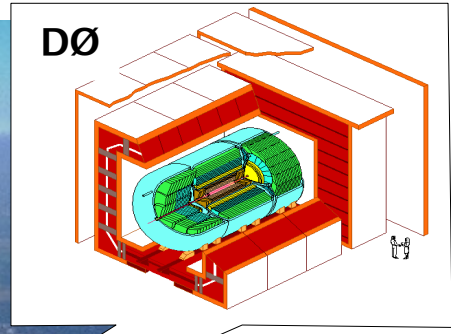
- parton showers simulate higher orders,
  i.e. not only radiating additional gluons! (LL)

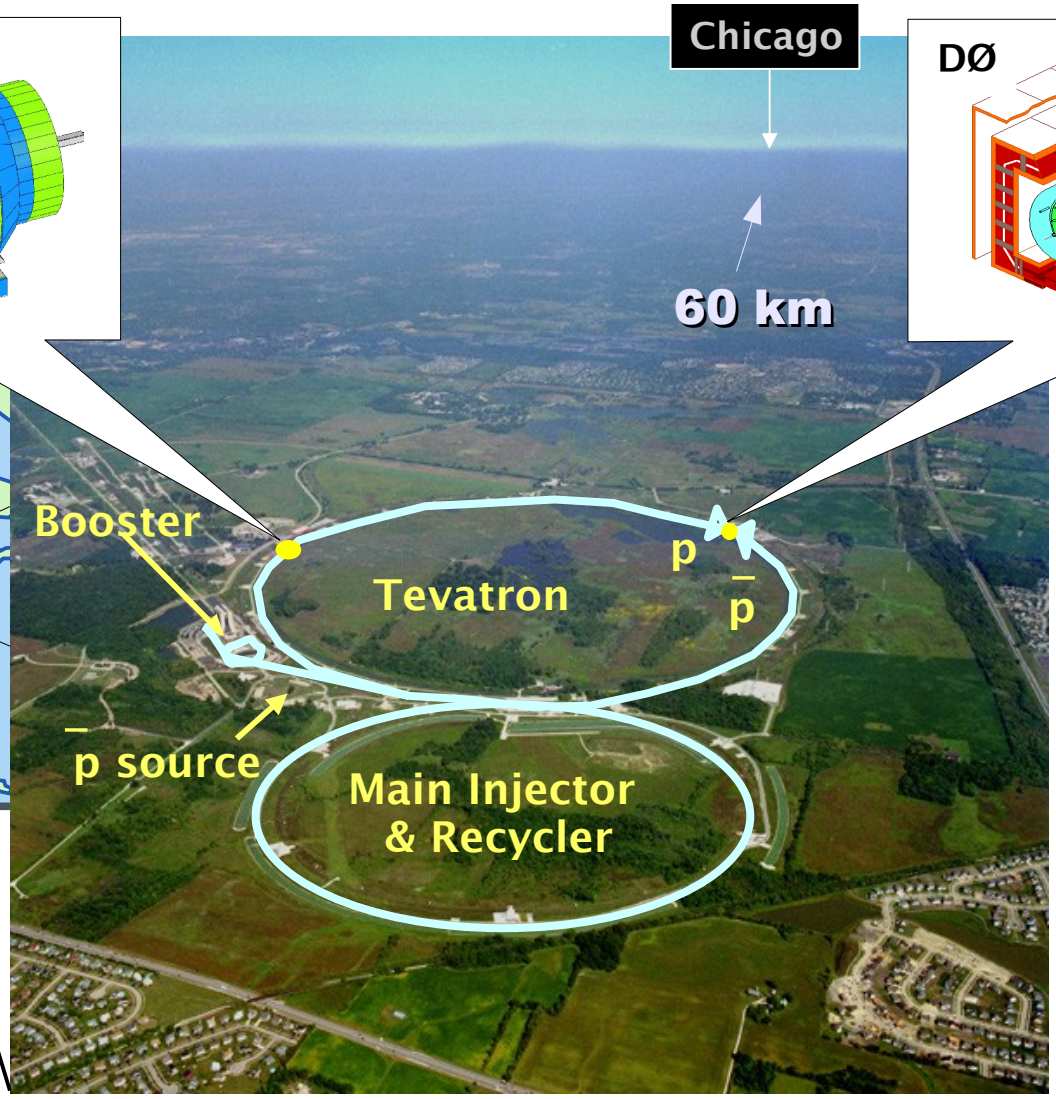
  ⇒ very hard to answer...

- arguments that it should be close to pole mass

The Tevatron at FERMILAB: $p\bar{p}$ Collisions







$\sqrt{s}$ = 1.96 TeV

Δt = 396 ns

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

Is the top quark the particle as predicted by the Standard Model?

Combined Method

Source	$\sigma_{t\bar{t}}$ [pb]	Offset [pb]	$+\sigma$ [pb]	$-\sigma$ [pb]
Statistical only	7.58		+0.24	−0.24
Muon identification		−0.04	+0.05	−0.05
Electron identification		+0.14	+0.12	−0.12
Triggers		-0.09	+0.09	−0.11
Background normalization		+0.00	+0.07	−0.06
Signal modeling		−0.06	+0.23	−0.21
b-tagging		−0.14	+0.12	−0.12
Monte Carlo statistics		−0.01	+0.06	−0.06
Fake background		−0.01	+0.06	−0.04
f_H		−0.00	+0.02	−0.02
Jet energy scale		−0.03	+0.00	−0.00
Jet reconstruction and identification		+0.18	+0.18	−0.17
Luminosity		+0.12	+0.51	−0.44
Template statistics		+0.00	+0.03	−0.03
Other		+0.01	+0.14	−0.13
Total systematics			+0.65	−0.58
Fit result	7.78		+0.77	−0.64

$m_{top} = 172.5$ GeV

$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\ \text{(stat+syst+lumi) pb}$$

±9%

Different Top Mass Definitions

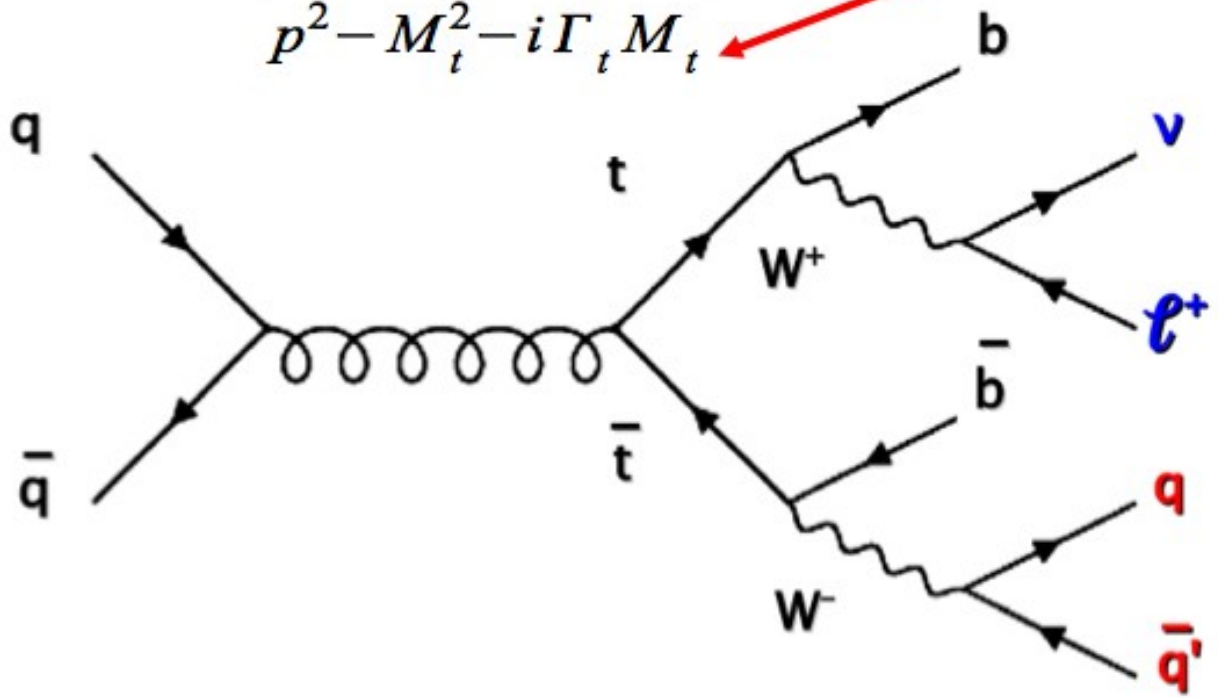
hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\rm MS}}(m_t) = \frac{M_t}{1+\frac{4}{3\pi}\alpha_s(M_t)}$$

pole mass

$\overline{\rm MS}$ scheme

$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$

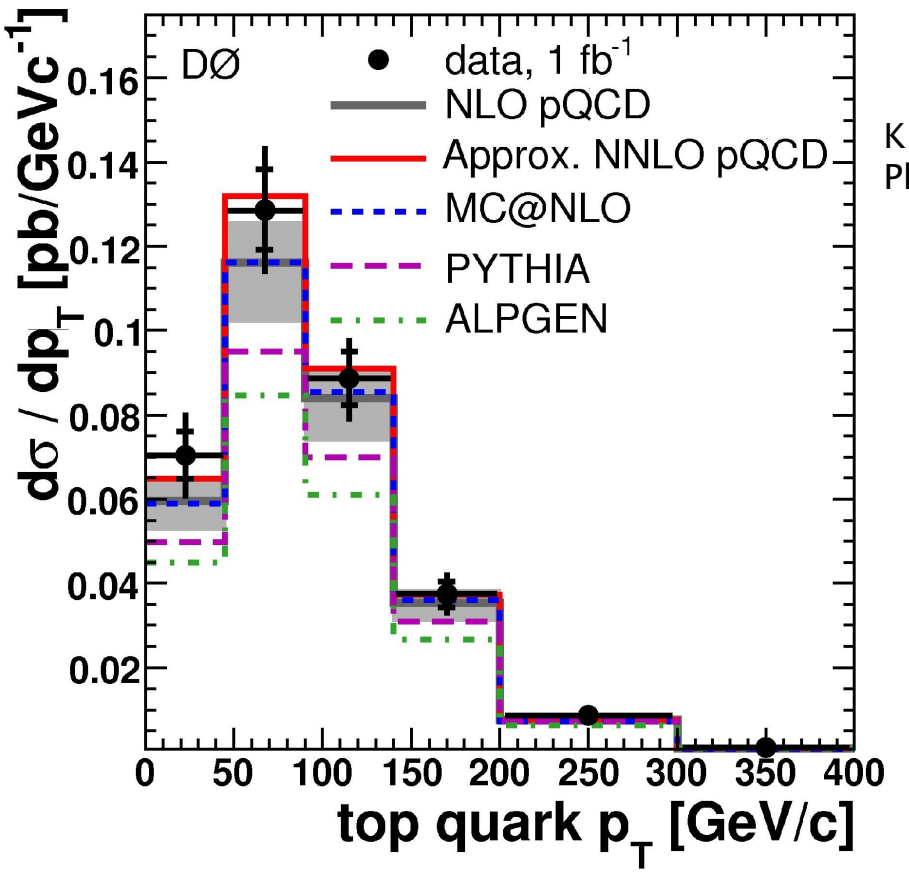


⇒ difference between $\overline{\rm MS}$ and pole mass is ≈10GeV...

Differential Cross Section

- important test of NLO QCD
- unfolding of distributions

arXiv:1001.1900 [hep-ex]



Kidonakis, Vogt,
Phys. Rev. D78, 074005 (2008)

- need NLO QCD to describe normalisation correctly

Differential Cross Section

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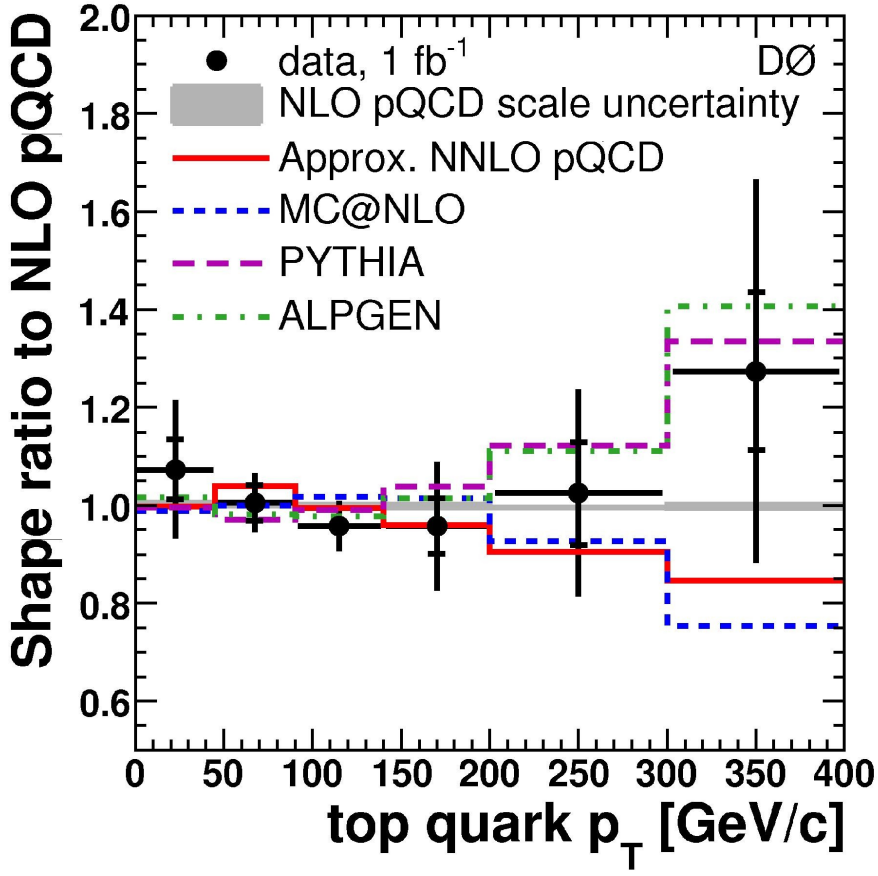

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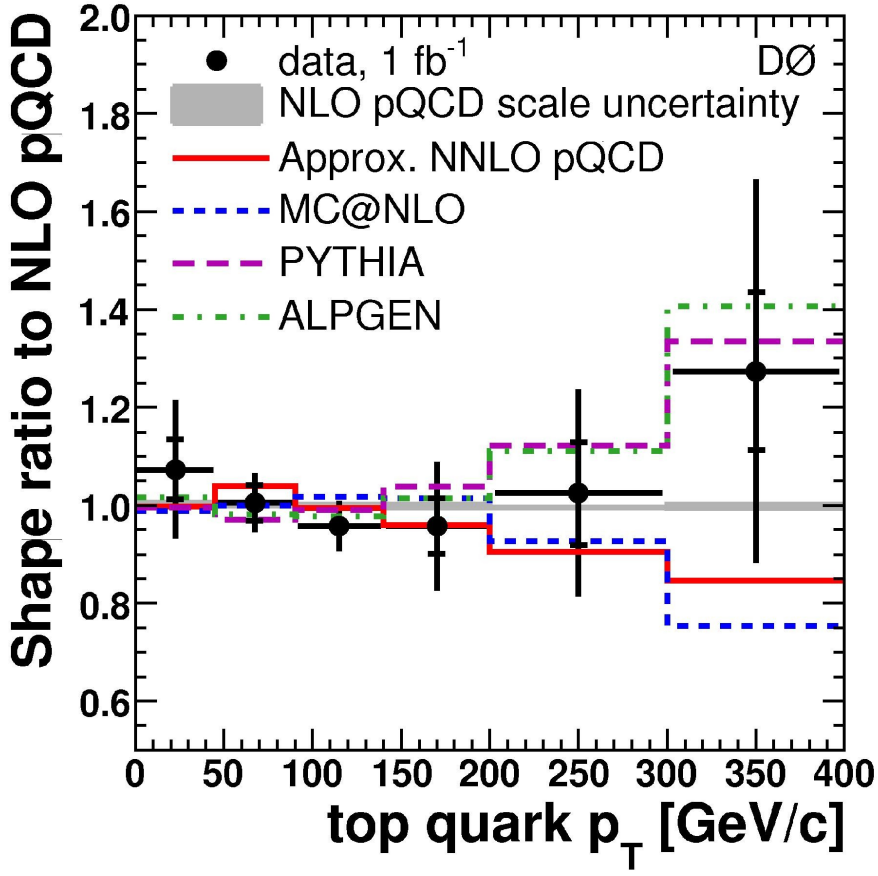

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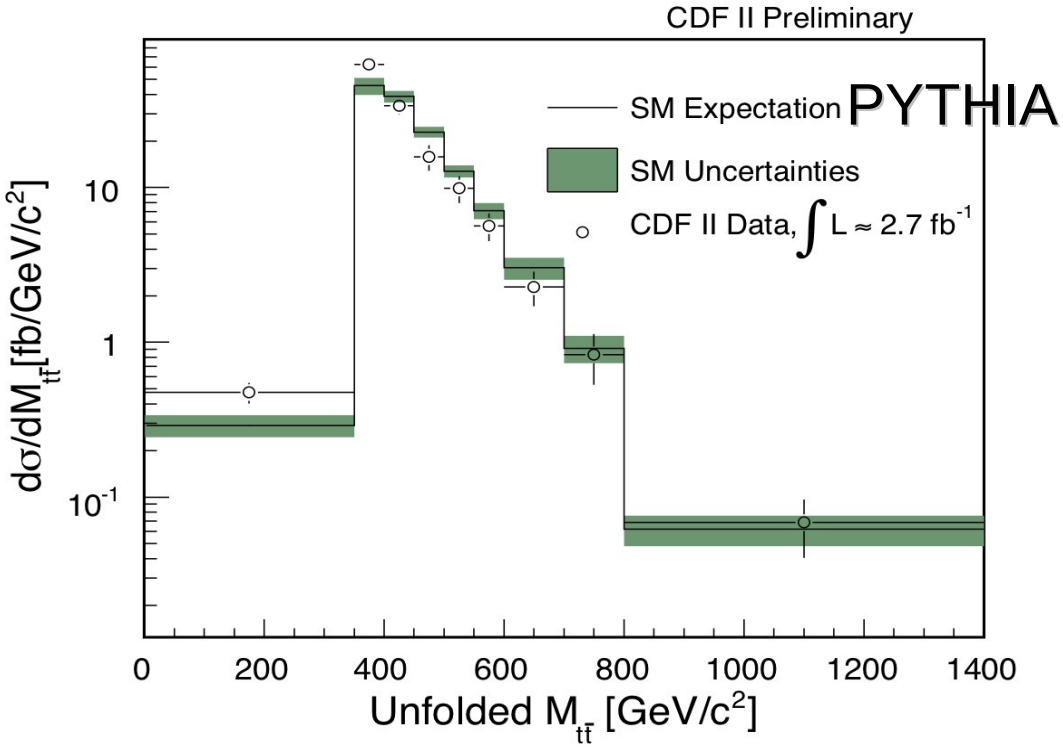
PRL 102, 222003 (2009)



- no deviation from the SM

Differential Cross Section

- important test of NLO QCD
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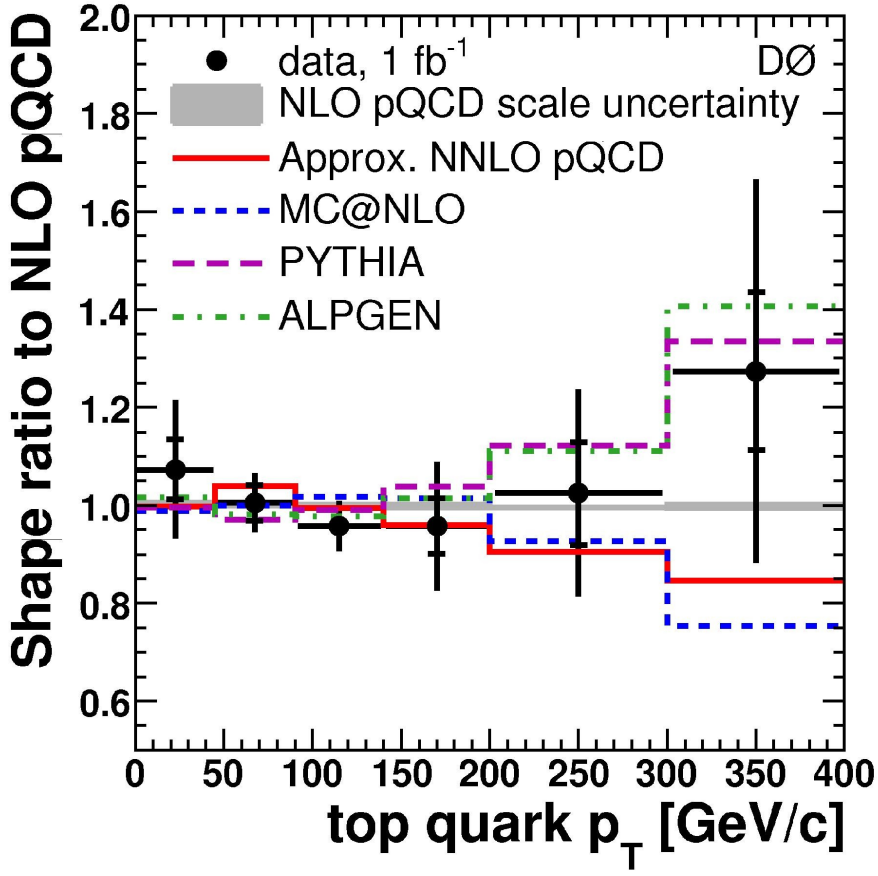
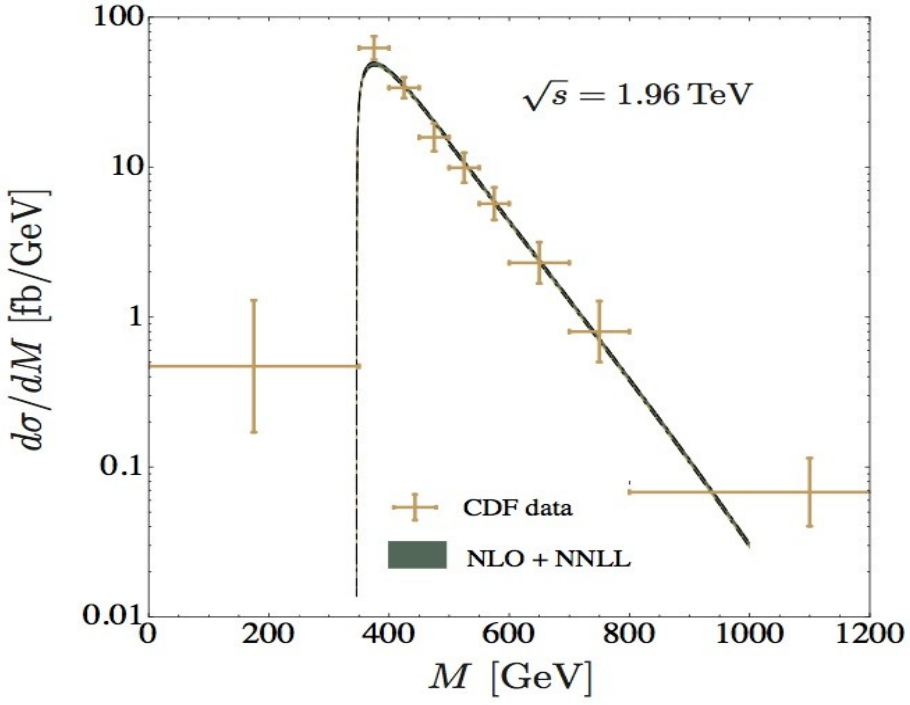
arXiv:1001.1900 [hep-ex]



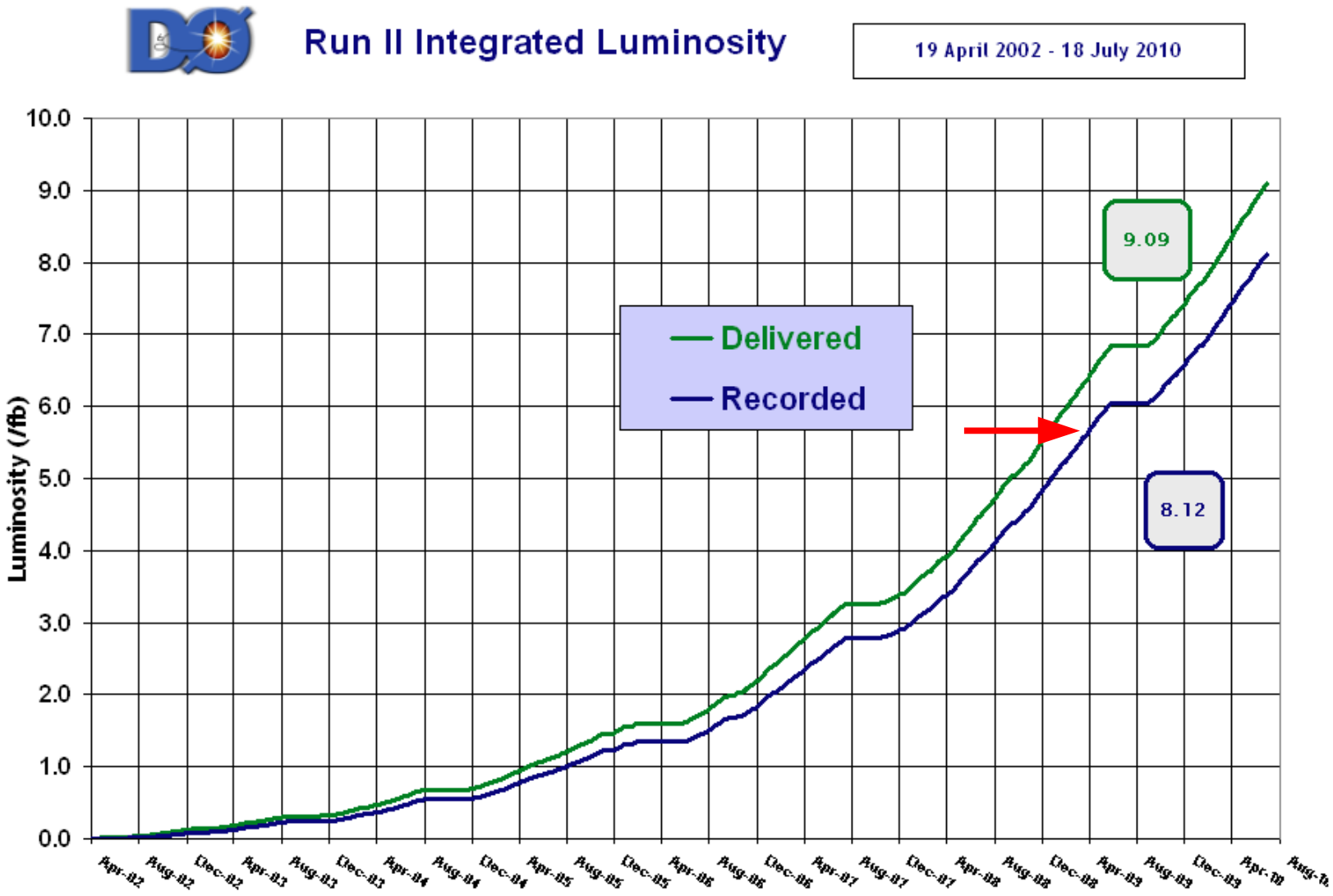
- need NLO QCD to describe normalisation correctly

Ahrens, Ferrogia, Neubert, Pecjak, Yang
arXiv:1006.4682 [hep-ph]

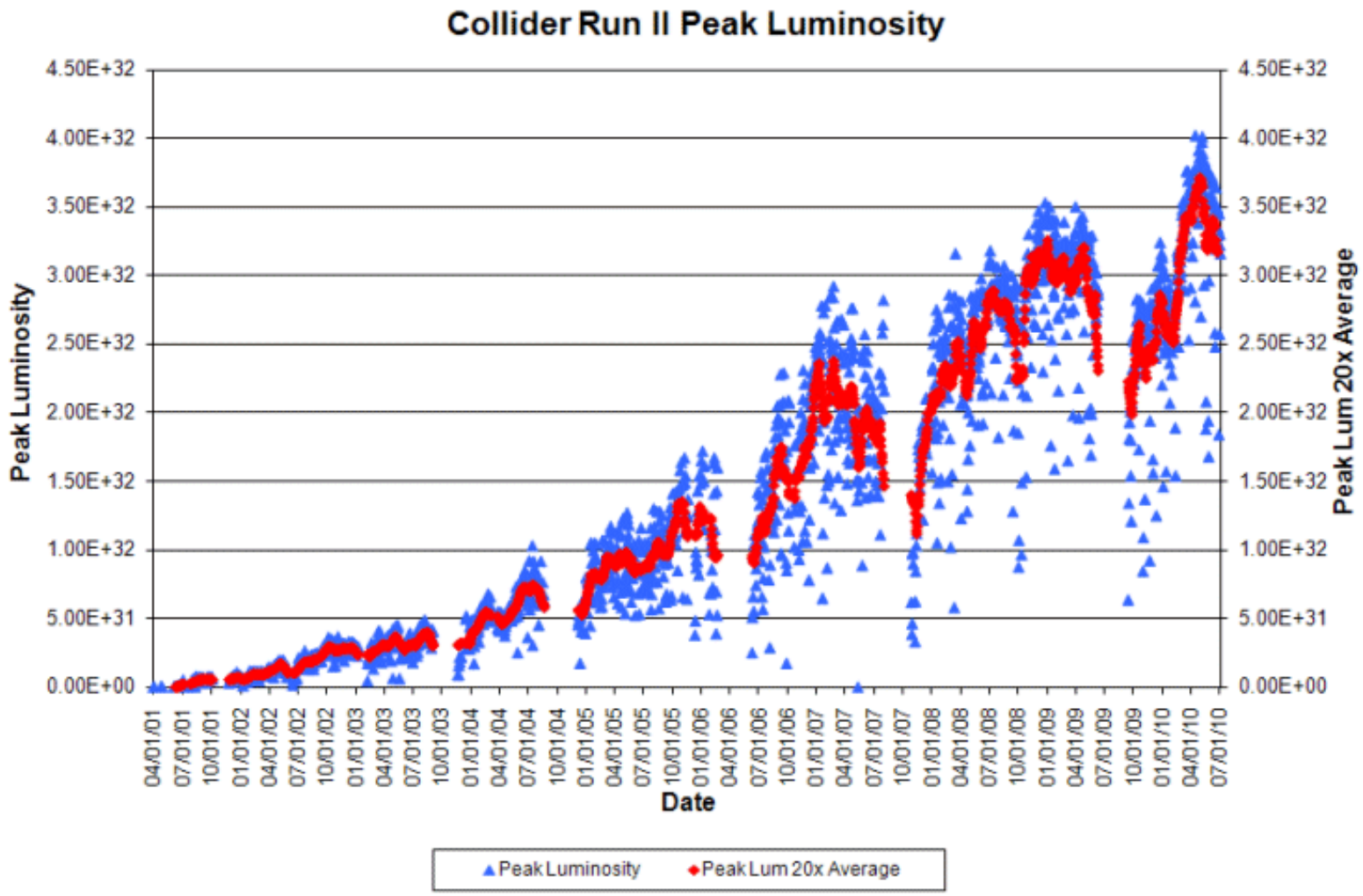


- no deviation from the SM
- NLO+NNLL: improvement

Tevatron Integrated Luminosity

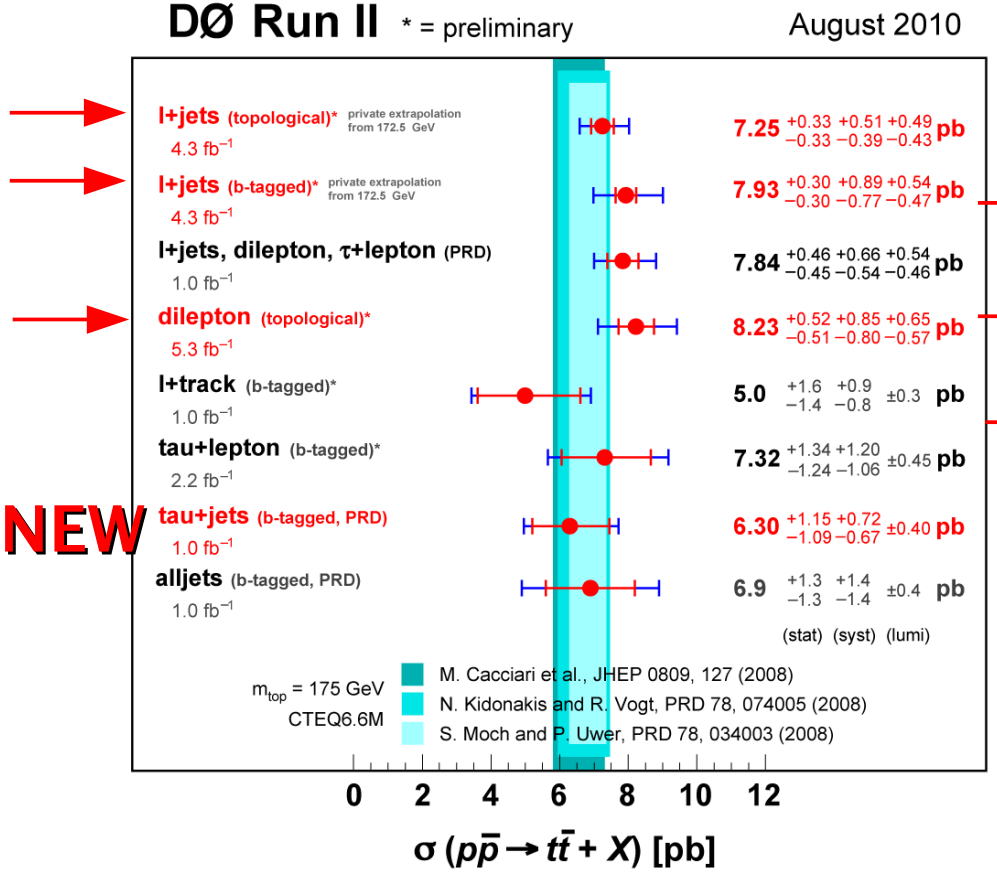


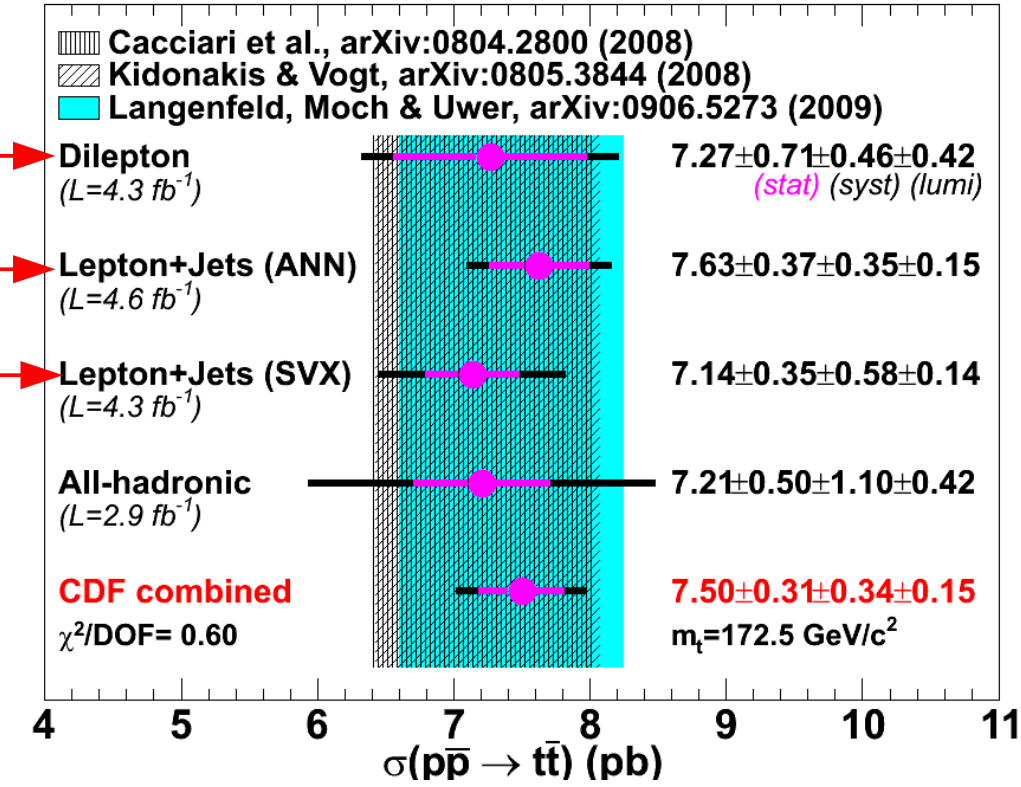
Tevatron Instantaneous Luminosity



- peak luminosity of $4.0 \cdot 10^{32}$ cm^{-2} s^{-1}
- took many years to achieve this!

Top Pair Production Cross Sections





NEW MET+2, 3, ≥ 4 jets (orthogonal)

all channels measured except for τ_{had} τ_{had}

combination: ±6% !

⇒ **good agreement with SM in all channels**