Measurements of the inclusive cross section and of differential distributions in top quark pair production

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University of Manchester

on behalf of

36th International Conference on High-Energy Physics
Melbourne
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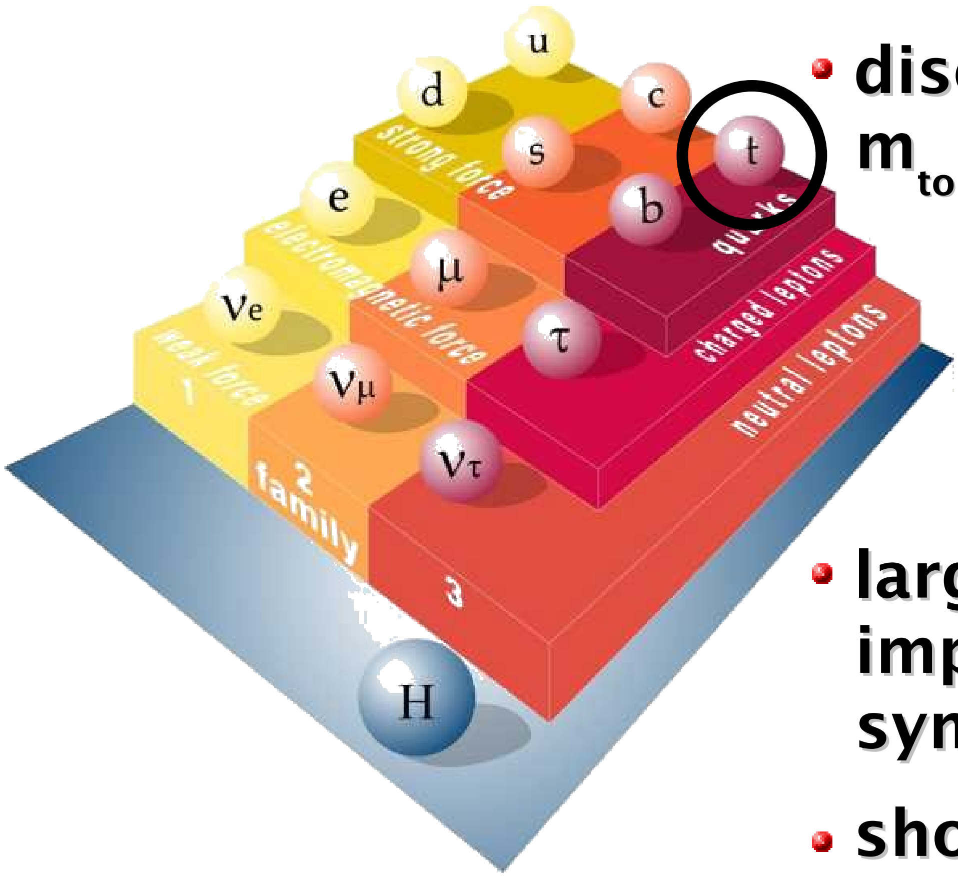
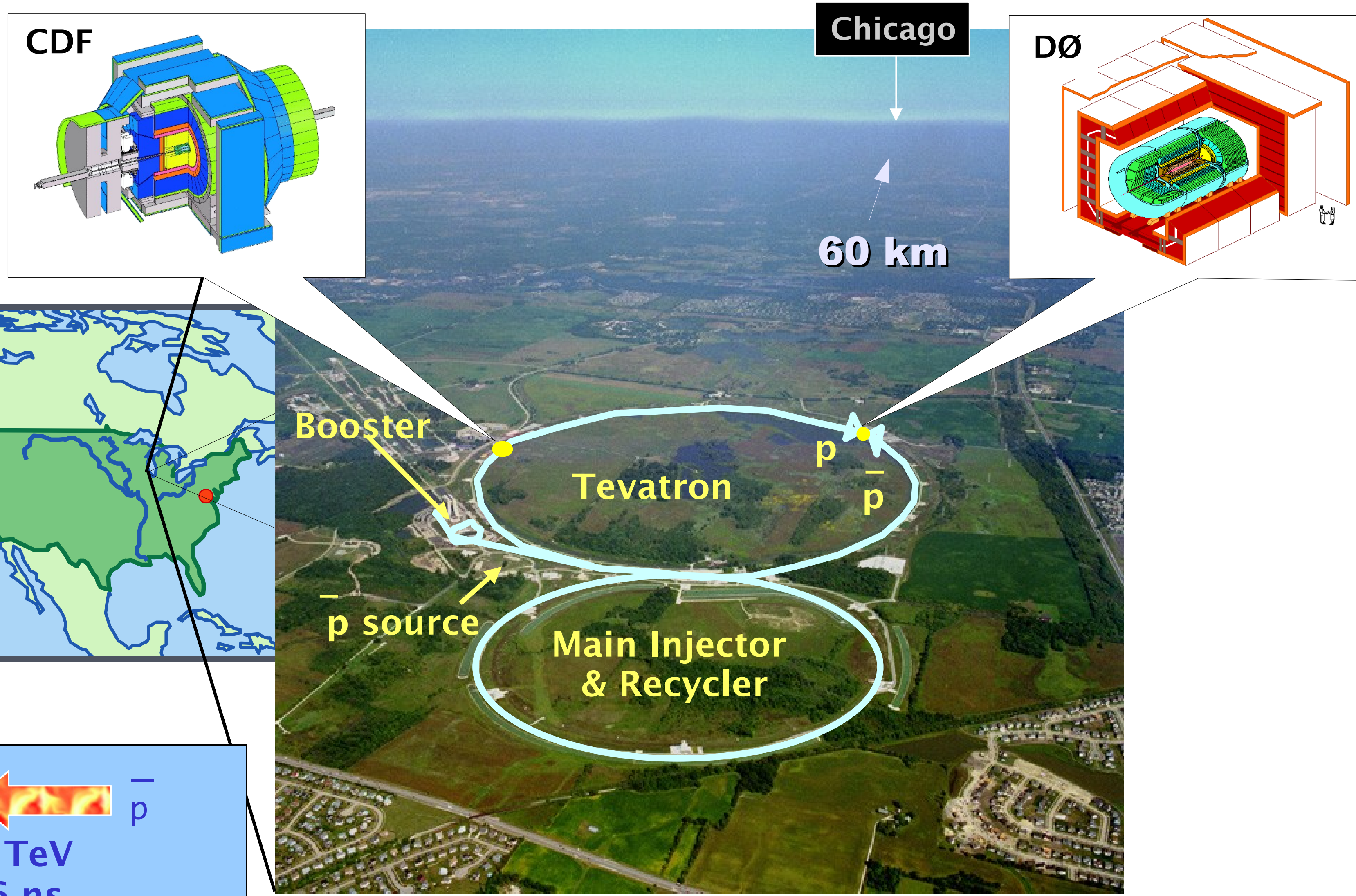
The Top Quark

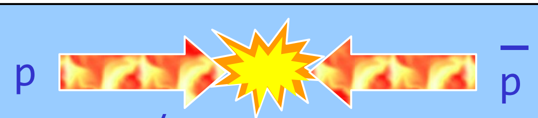


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked"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

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

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





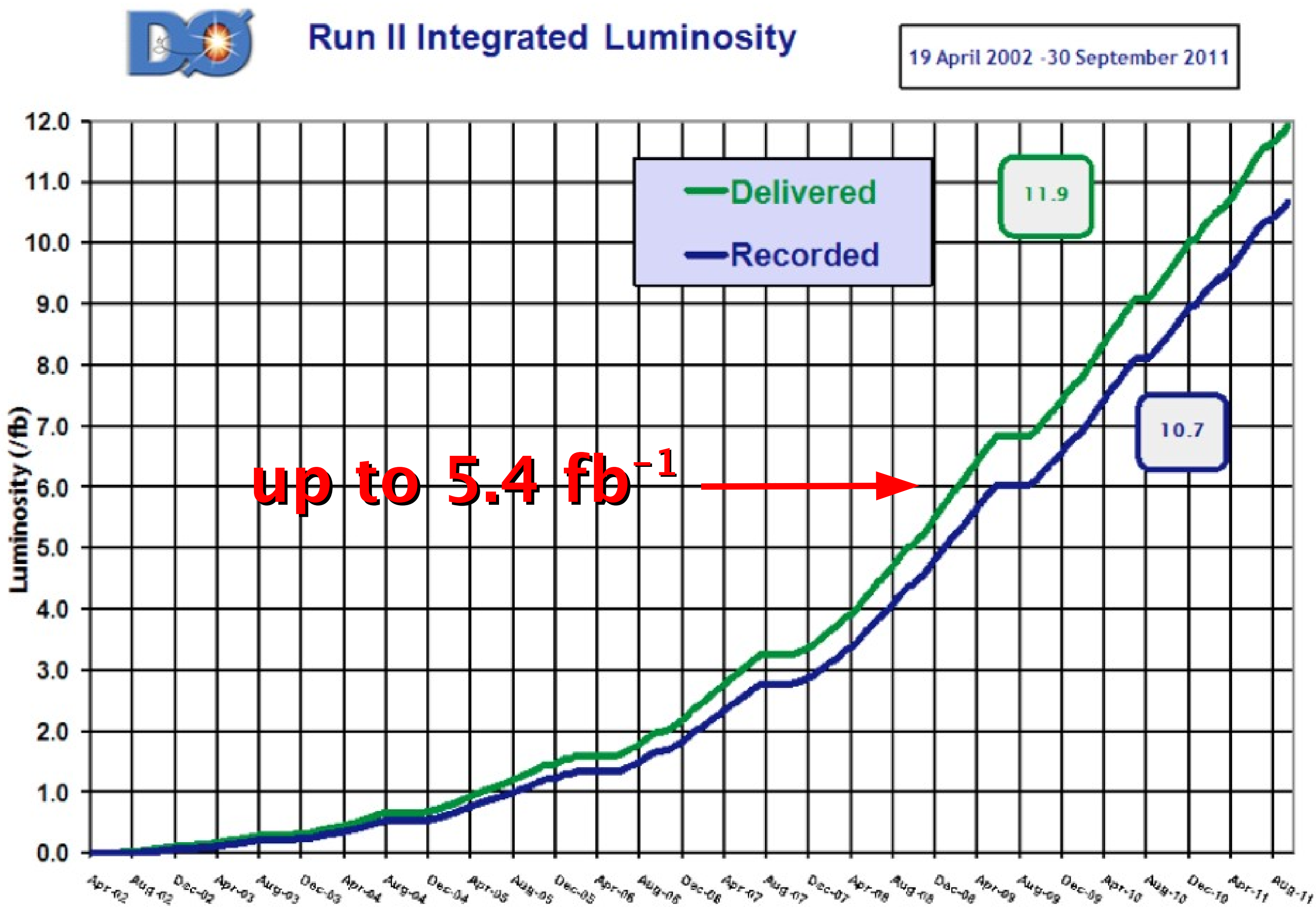
$\sqrt{s}$ =1.96 TeV

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?

Tevatron Integrated Luminosity



Thanks to accelerator and computing divisions!

Outline

Inclusive production cross section

Differential cross section

Top mass

Lorentz invariance violation

Conclusions

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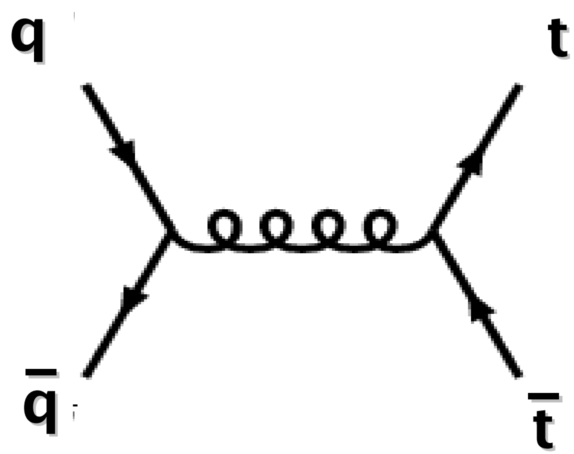
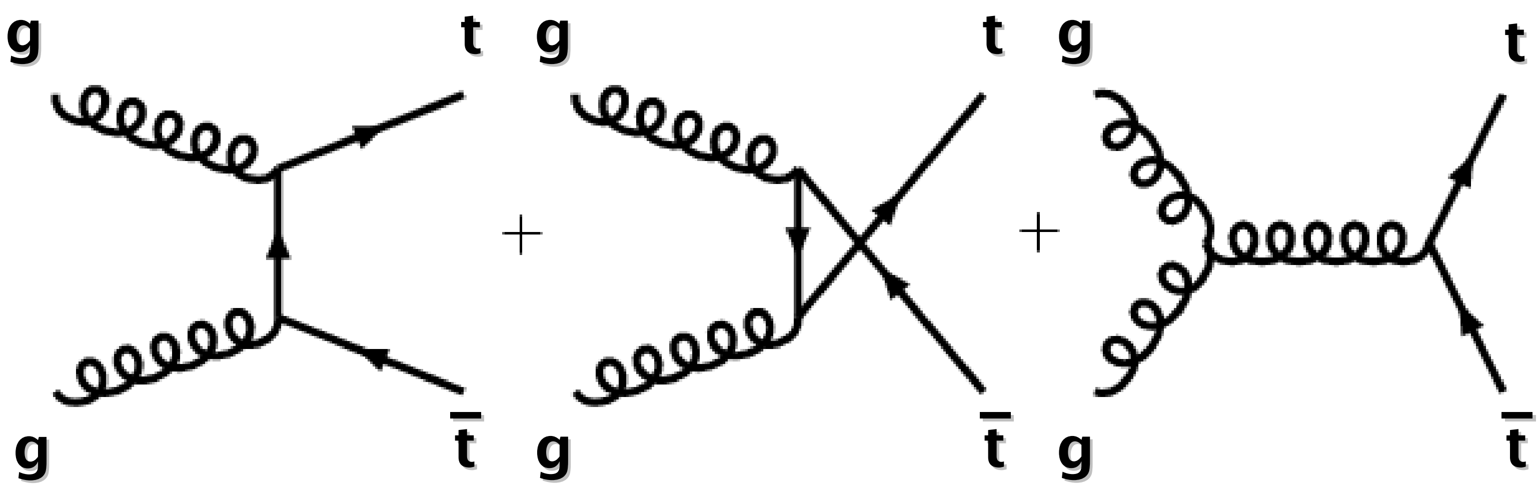
Top Quark Pair Production



85%



15%

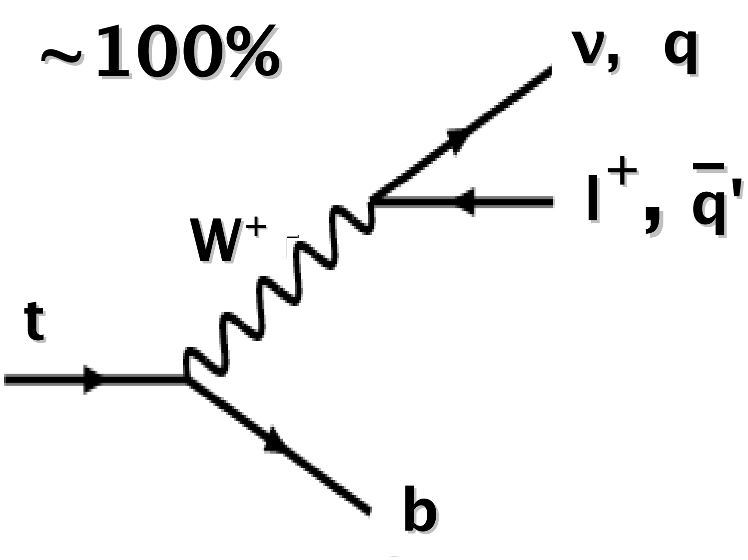
PRD 78, 034003 (2008)

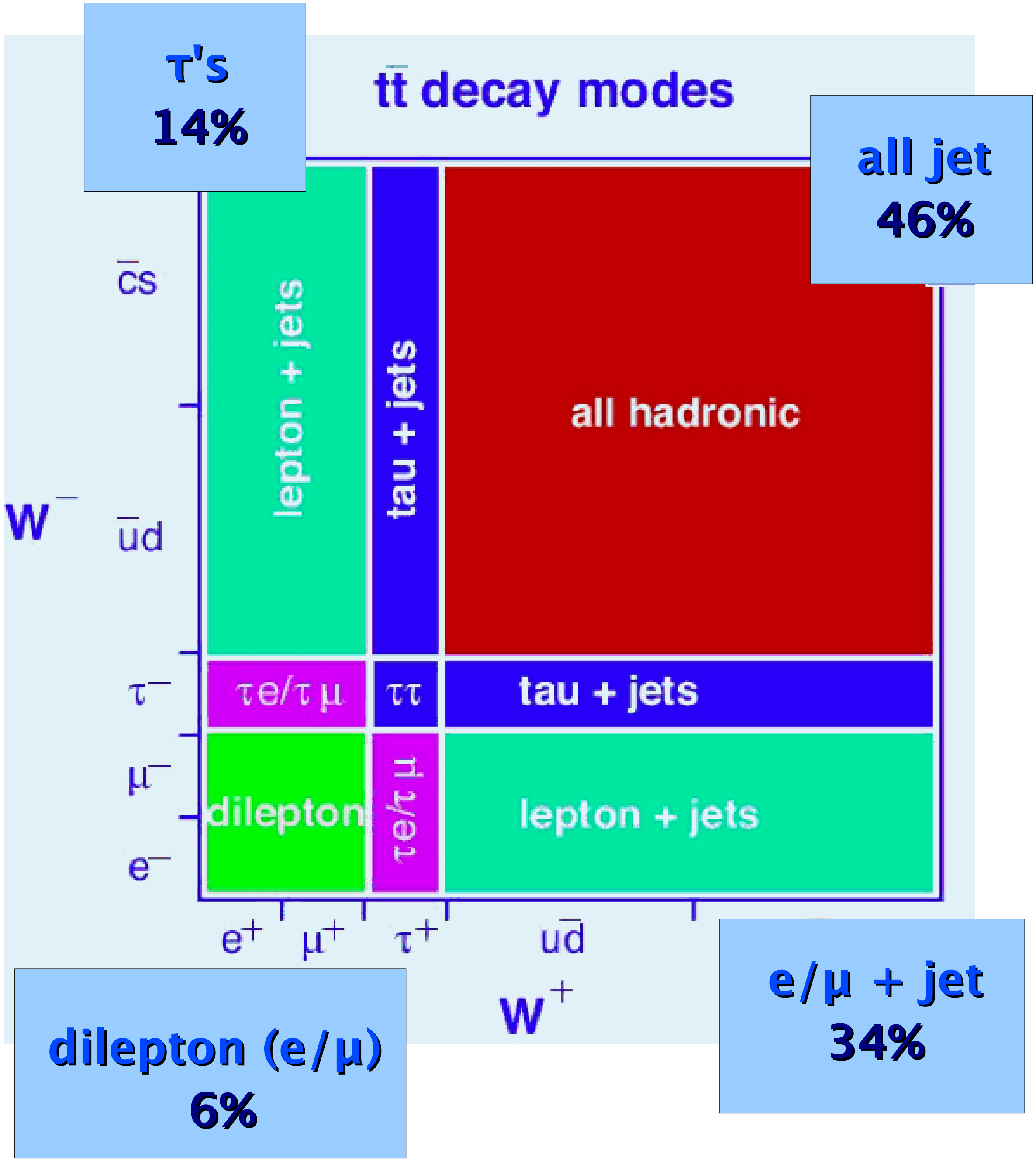
$$\sigma_{t\bar{t}} = 7.46\,^{+0.48}_{-0.67}\text{ pb in NNLO}_{\text{approx}}$$

$(m_{top} = 172.5\text{ GeV})$

Top Pair Signatures

top decay:





Lepton+Jets Topological Cross Section

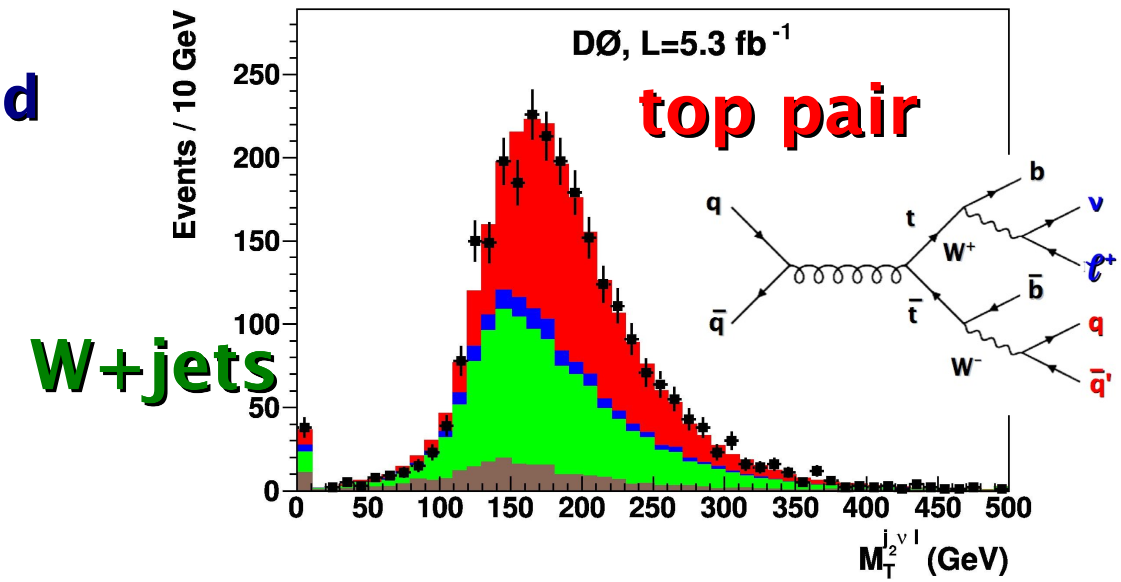
powerful test of QCD and search for new physics

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

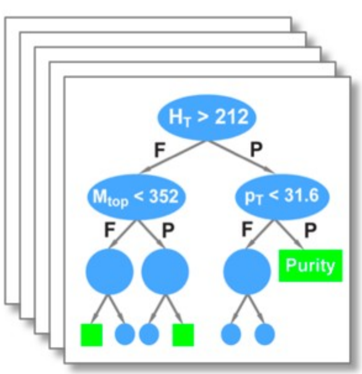
use variables such as:

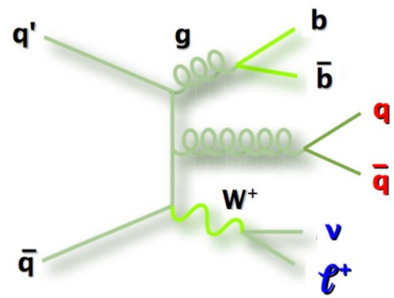
energy-dependent quantities:
- **e.g. transverse mass of leptonic top**

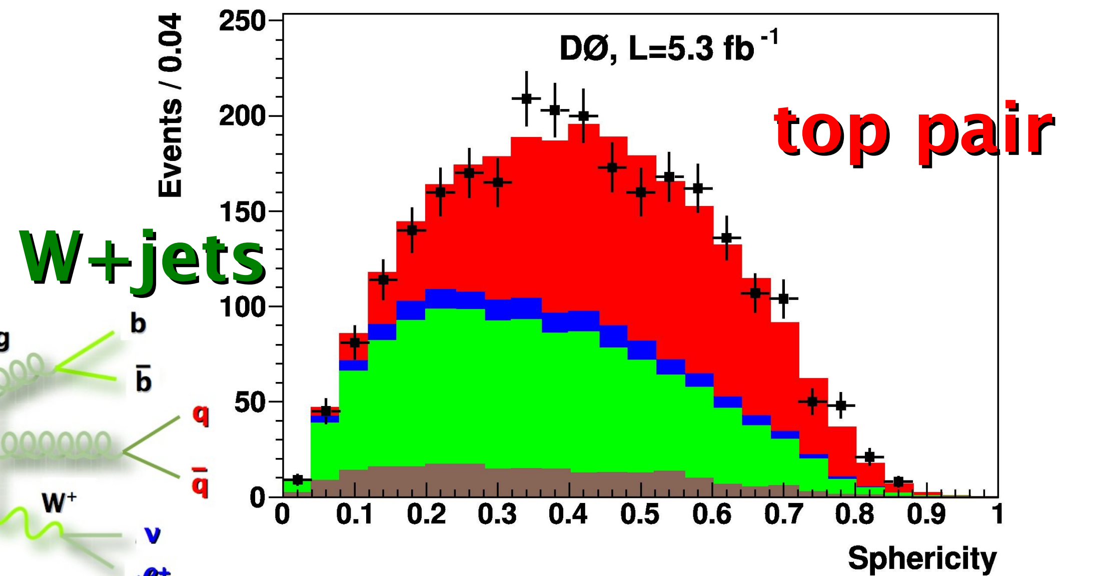
angular dependent:
- **e.g. sphericity**



→ **Random Forests of Boosted Decision Trees**







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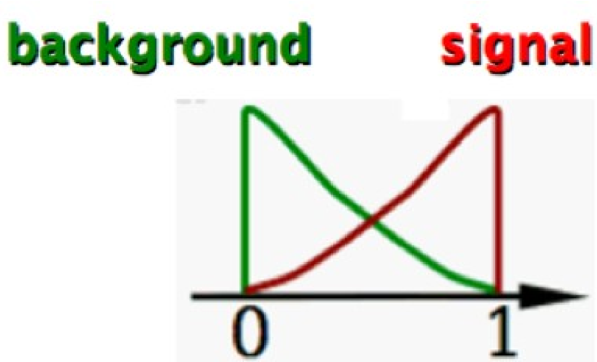
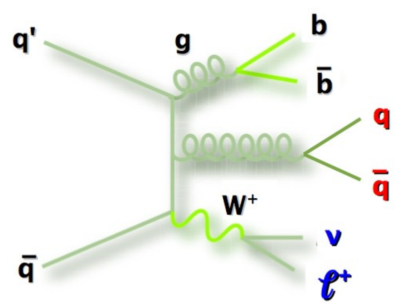
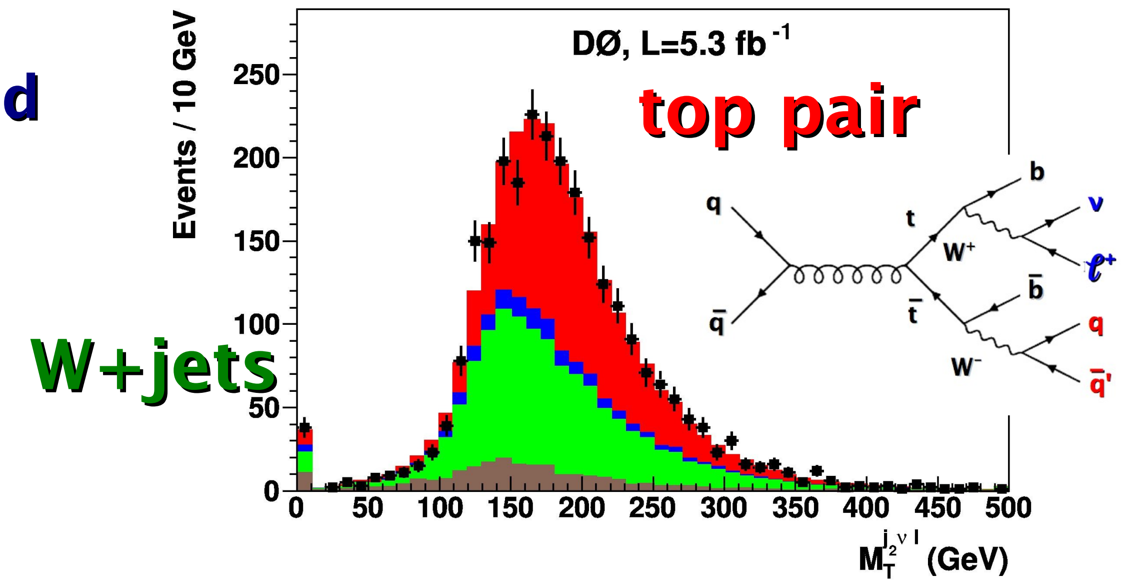
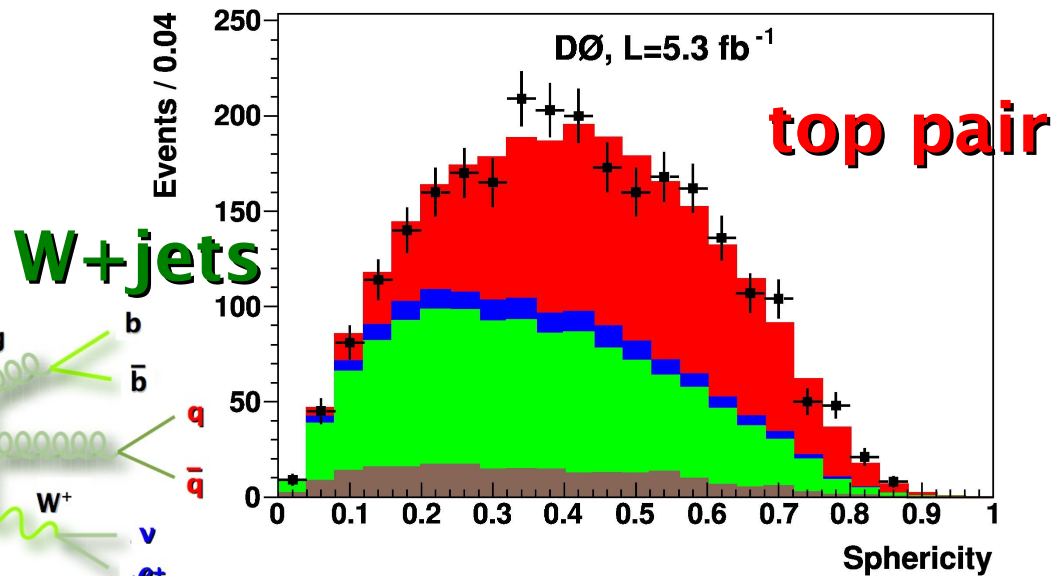


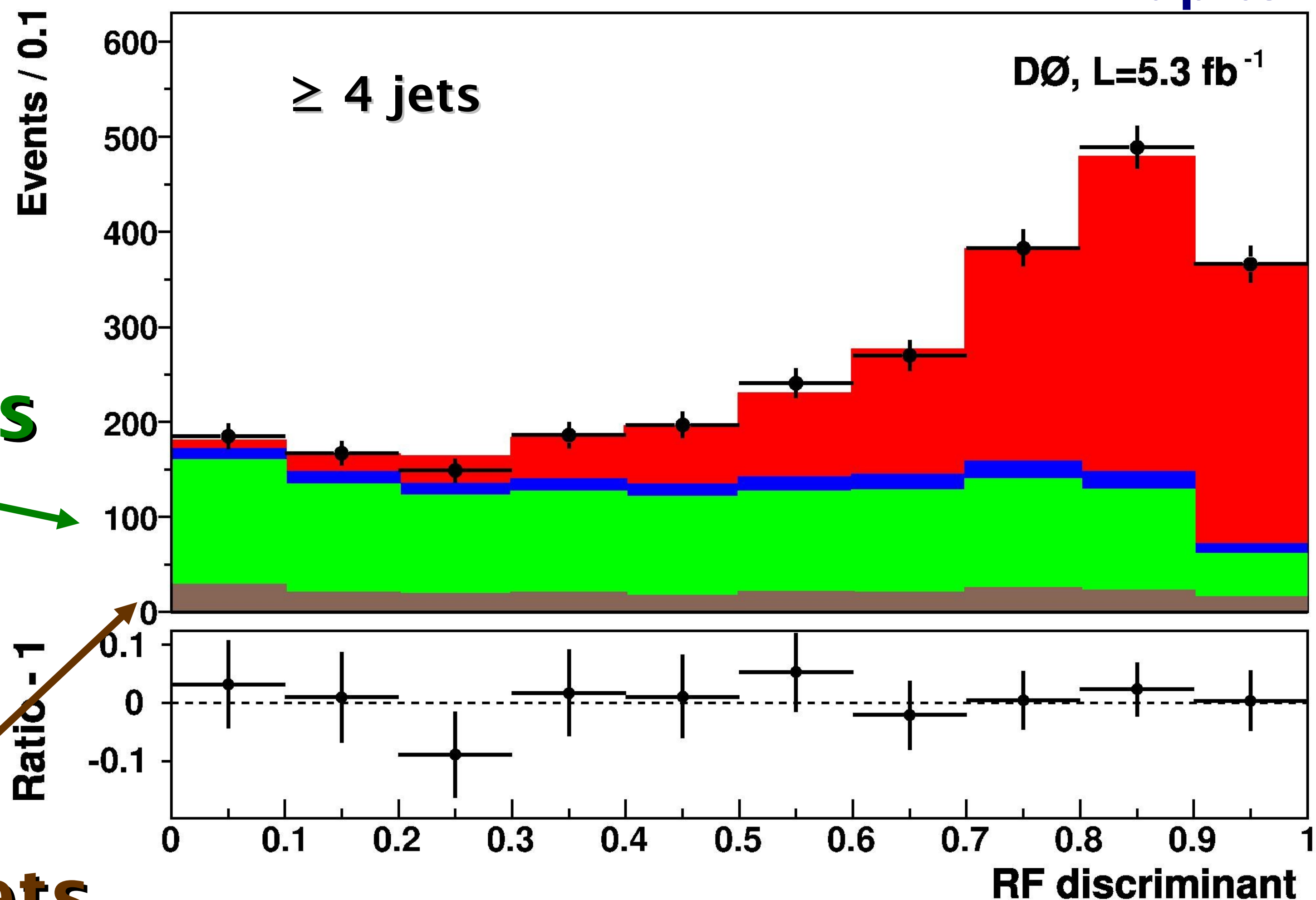






Lepton+Jets Topological Cross Section

up to 6 variables



top pair

W+jets

multijets

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

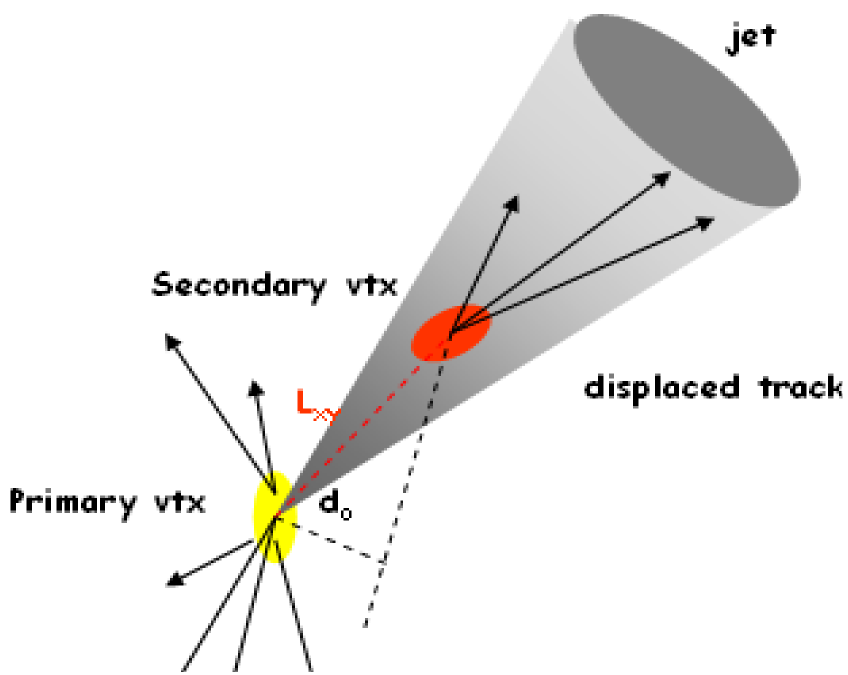
m_{top} = 172.5 GeV

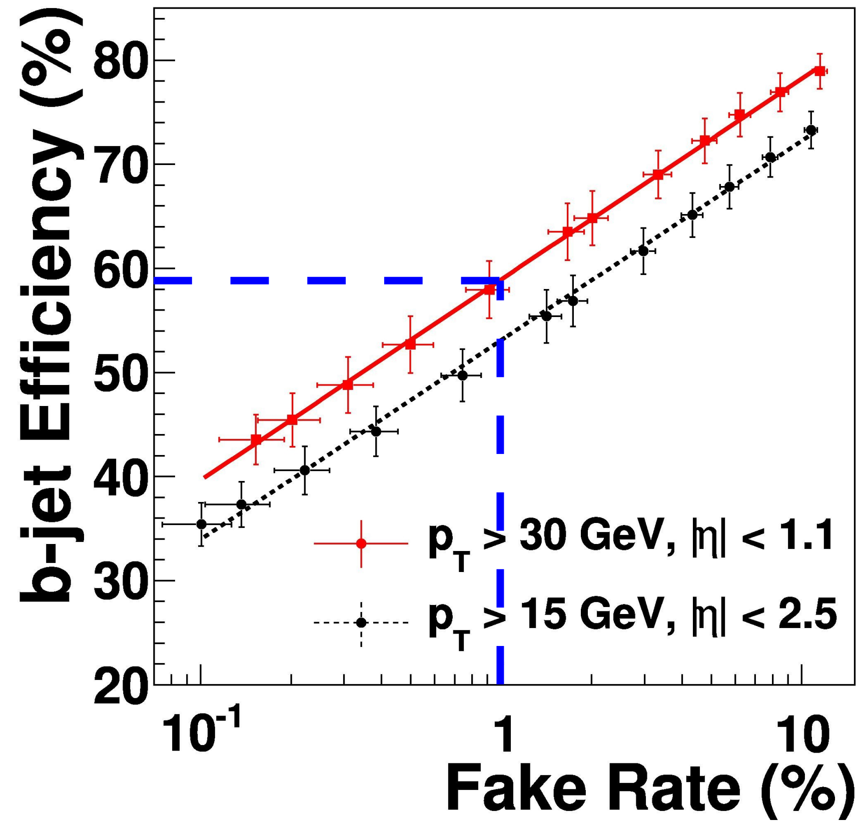
$$\sigma_{t\bar{t}} = 7.68^{+0.71}_{-0.64} \text{ (stat+syst+lumi) pb}$$

b–tagging

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

- B hadron lifetime τ ~ 1 ps
- B hadrons travel L_{xy} ~ 3 mm before decay





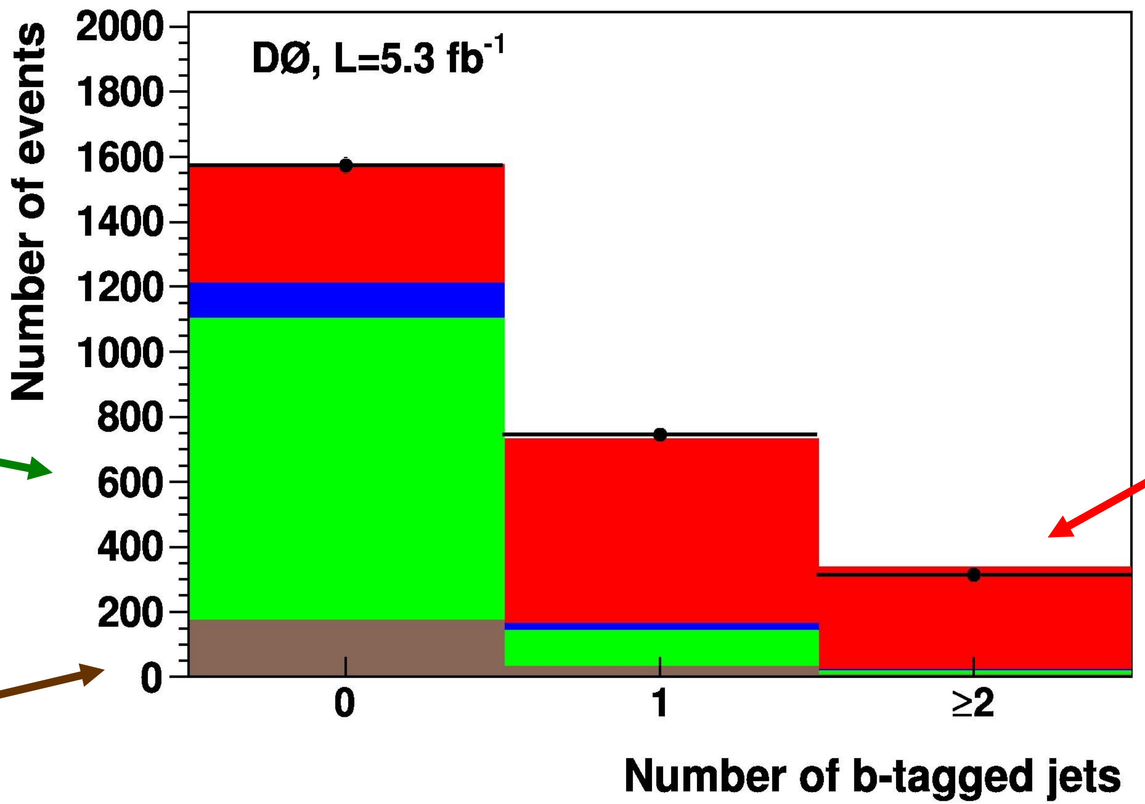
- secondary vertex tagger
- 45% b–jet tagging efficiency (with fake rate of 1%)

- 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



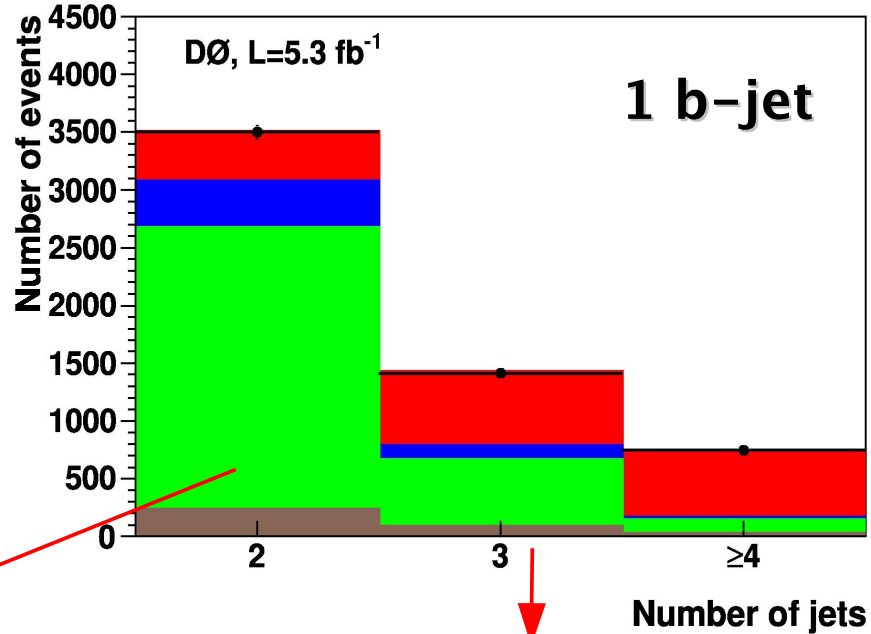
top pair

multijets

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

m_{top} = 172.5 GeV

Combined Method

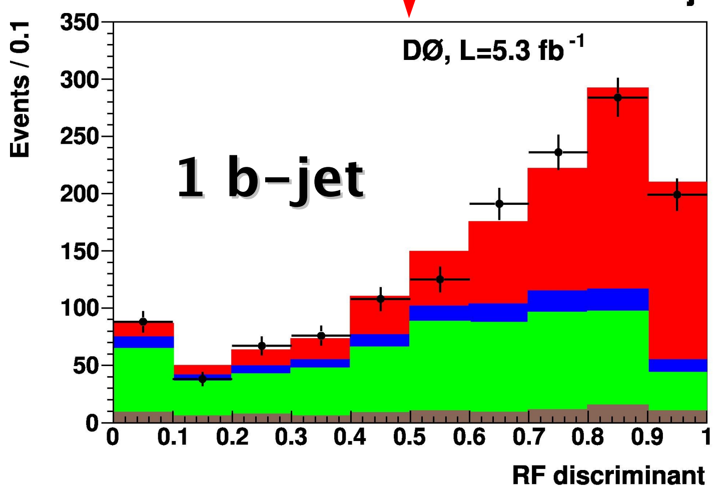


Phys. Rev. D 84, 012008 (2011)

binned maximum likelihood fit (systematics included as nuisance parameters)

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

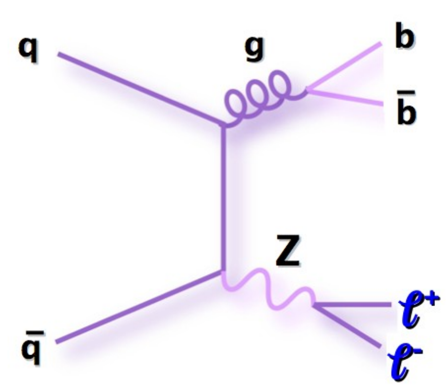
$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64} \text{ (stat+syst+lumi) pb}$$

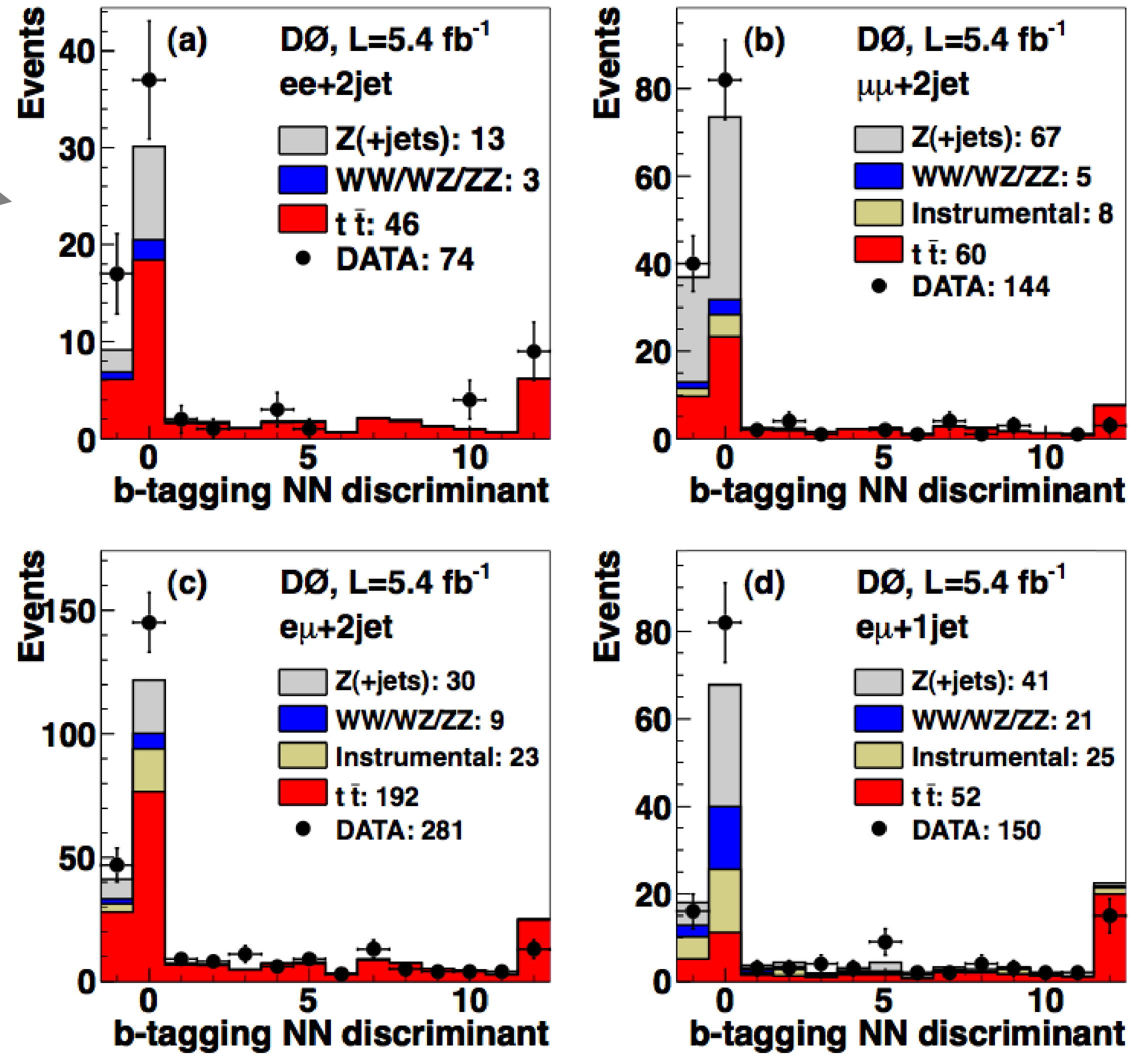
m_{top} = 172.5 GeV

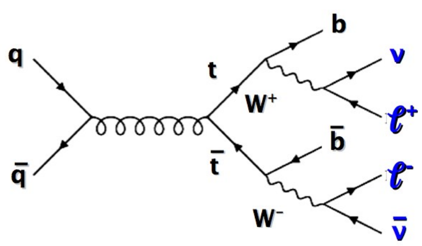
±9%

Dilepton Cross Section with b-tagging

Z+jets







top pair

Phys. Lett. B 704, 403 (2011)

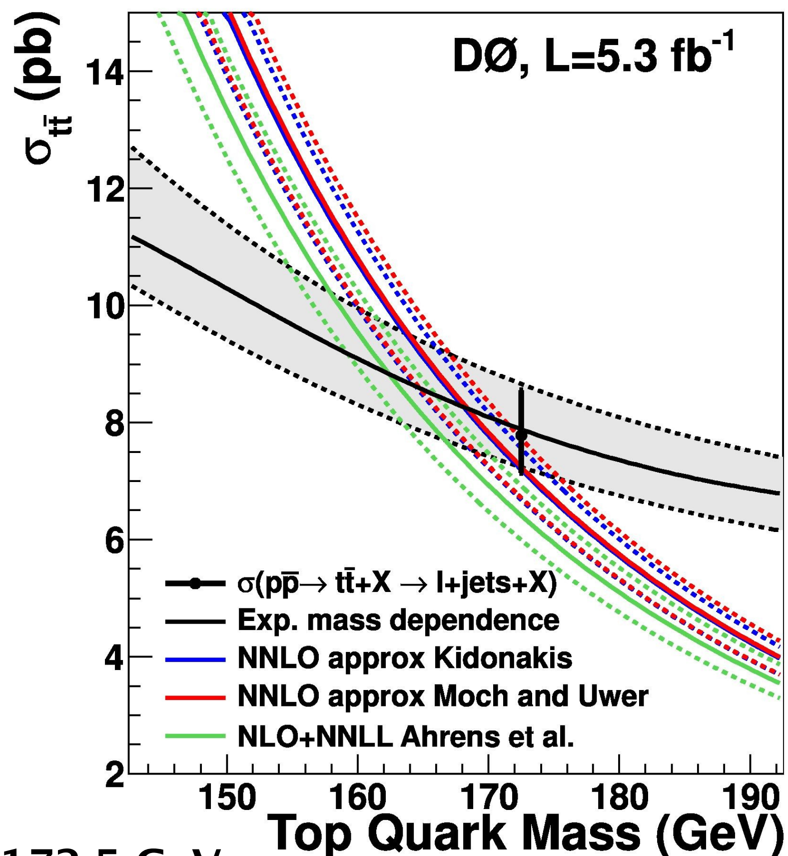
$m_{top} = 172.5$ GeV

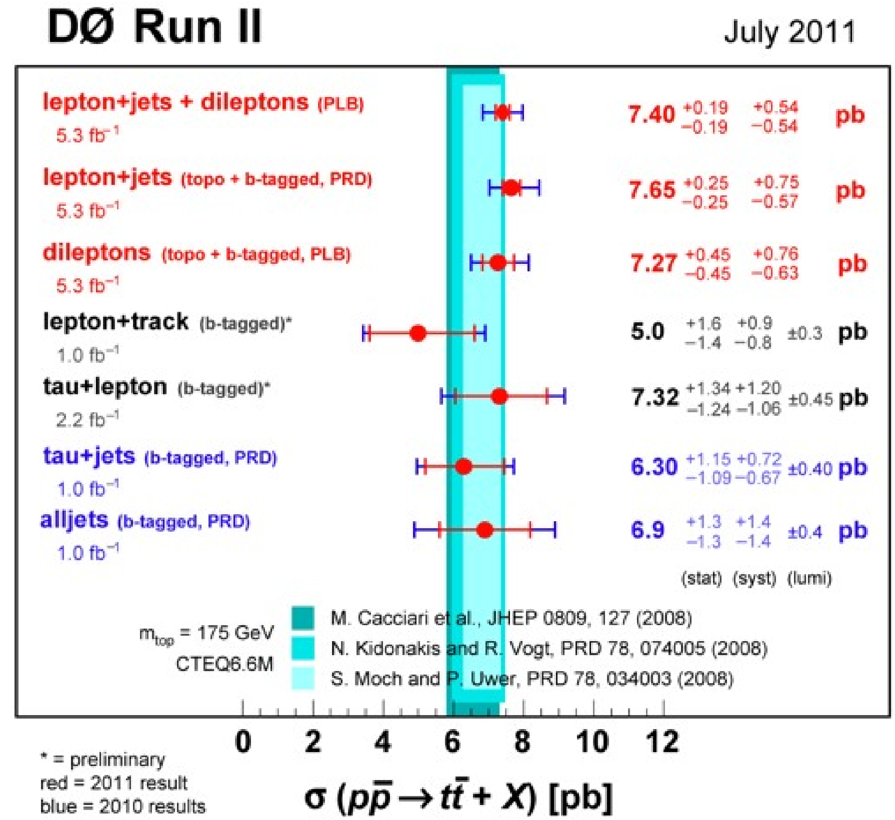
$$\sigma_{t\bar{t}} = 7.36^{+0.90}_{-0.79} \text{ (stat+syst+lumi) pb}$$

±11%

Top Pair Production Cross Sections

Combination: l+jets and dilepton





all channels measured except for $\tau_{had}\ \tau_{had}$

$m_{top} = 172.5$ GeV

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

±8%

→ **good agreement with higher order QCD calculations**

Outline

Inclusive production cross section

Differential cross section

Top mass

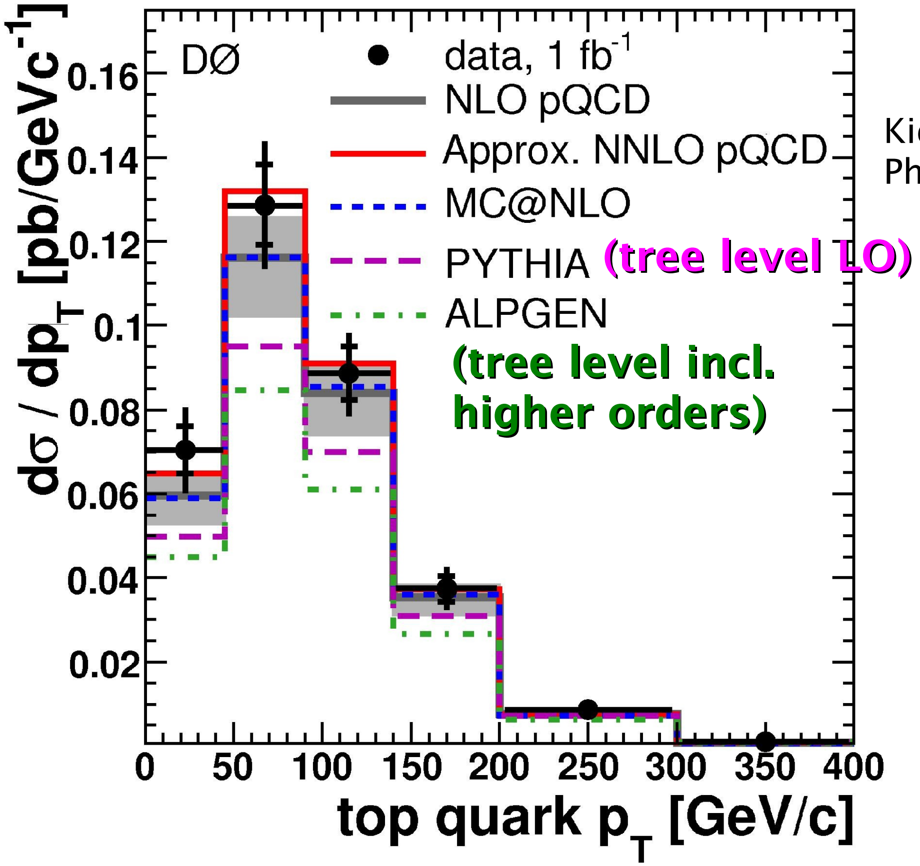
Lorentz invariance violation

Conclusions

Differential Cross Section

- **important test of NLO QCD**
- **unfolding of distributions**

Phys. Lett. B 693, 515 (2010)



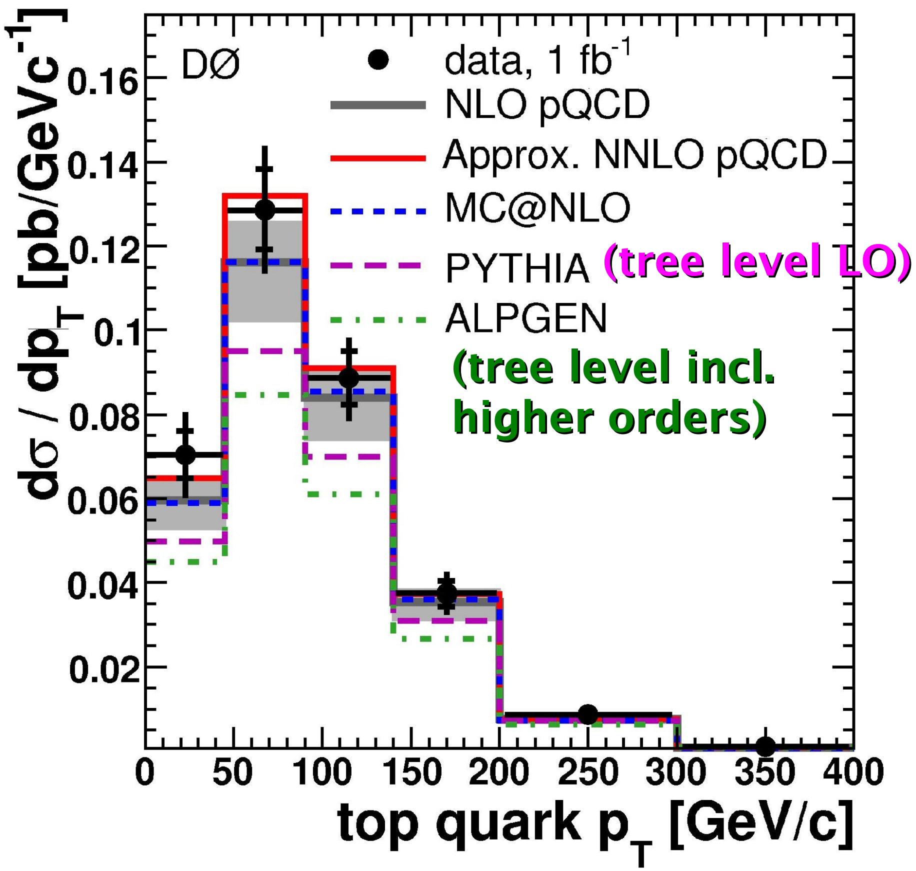
Kidonakis, Vogt,
Phys. Rev. D78, 074005 (2008)

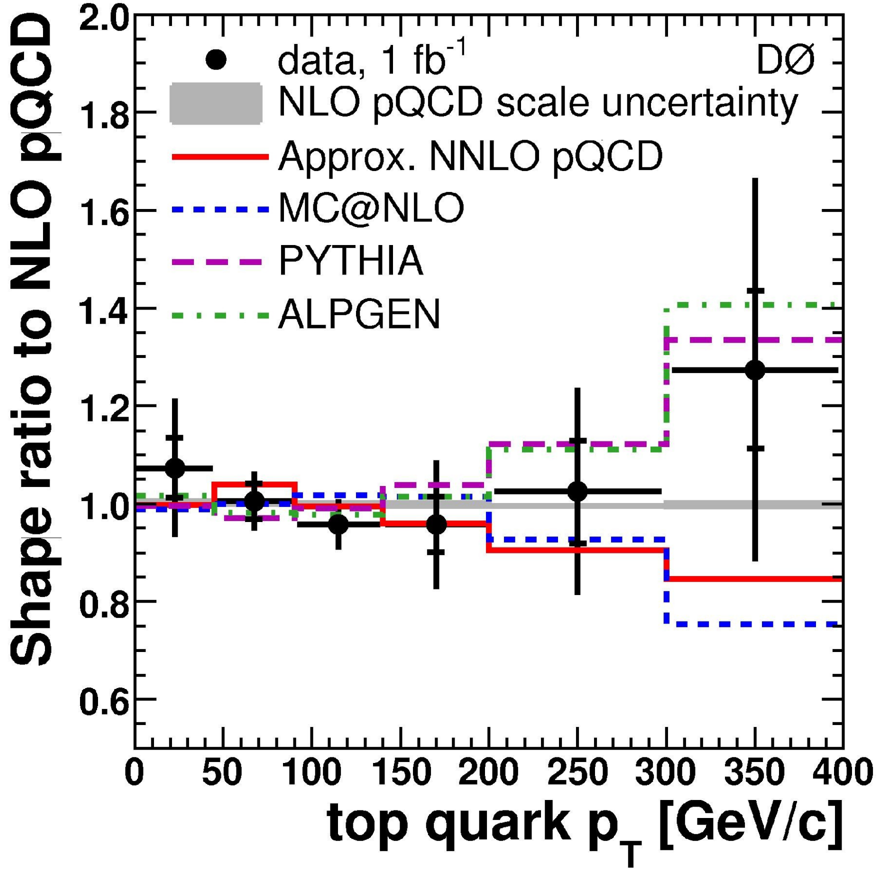
- **need NLO QCD to describe normalisation correctly**

Differential Cross Section

- important test of NLO QCD
- unfolding of distributions

Phys. Lett. B 693, 515 (2010)





- need NLO QCD to describe normalisation correctly
- shape described well by PYTHIA and ALPGEN

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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:

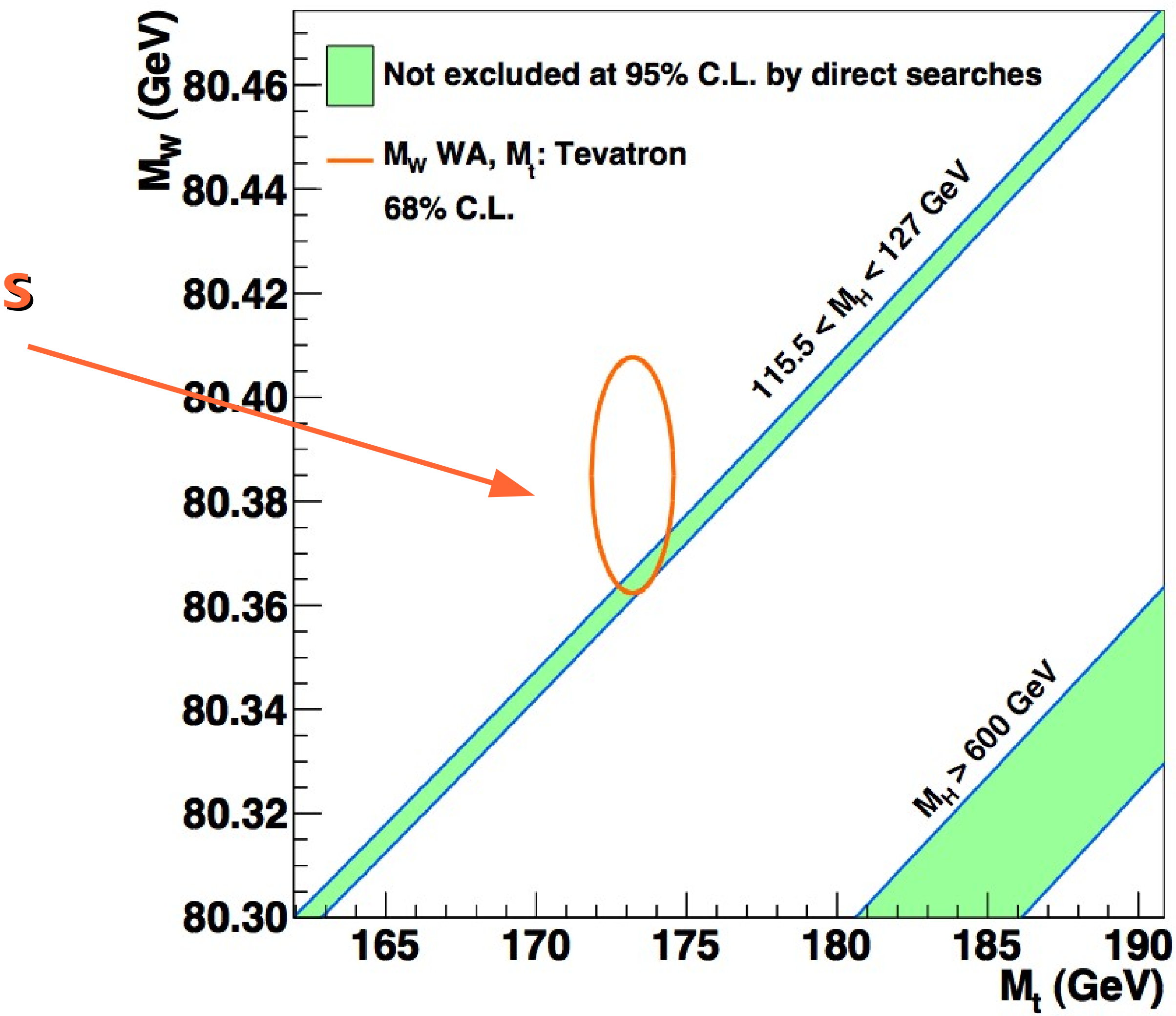
$g_s(M), m_u(M), m_d(M), m_s(M), m_c(M), m_b(M), m_t(M)$

the concept of quark mass is convention–dependent!

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 $\overline{\text{MS}}$ mass in direct and well-defined way?**

Important to know...

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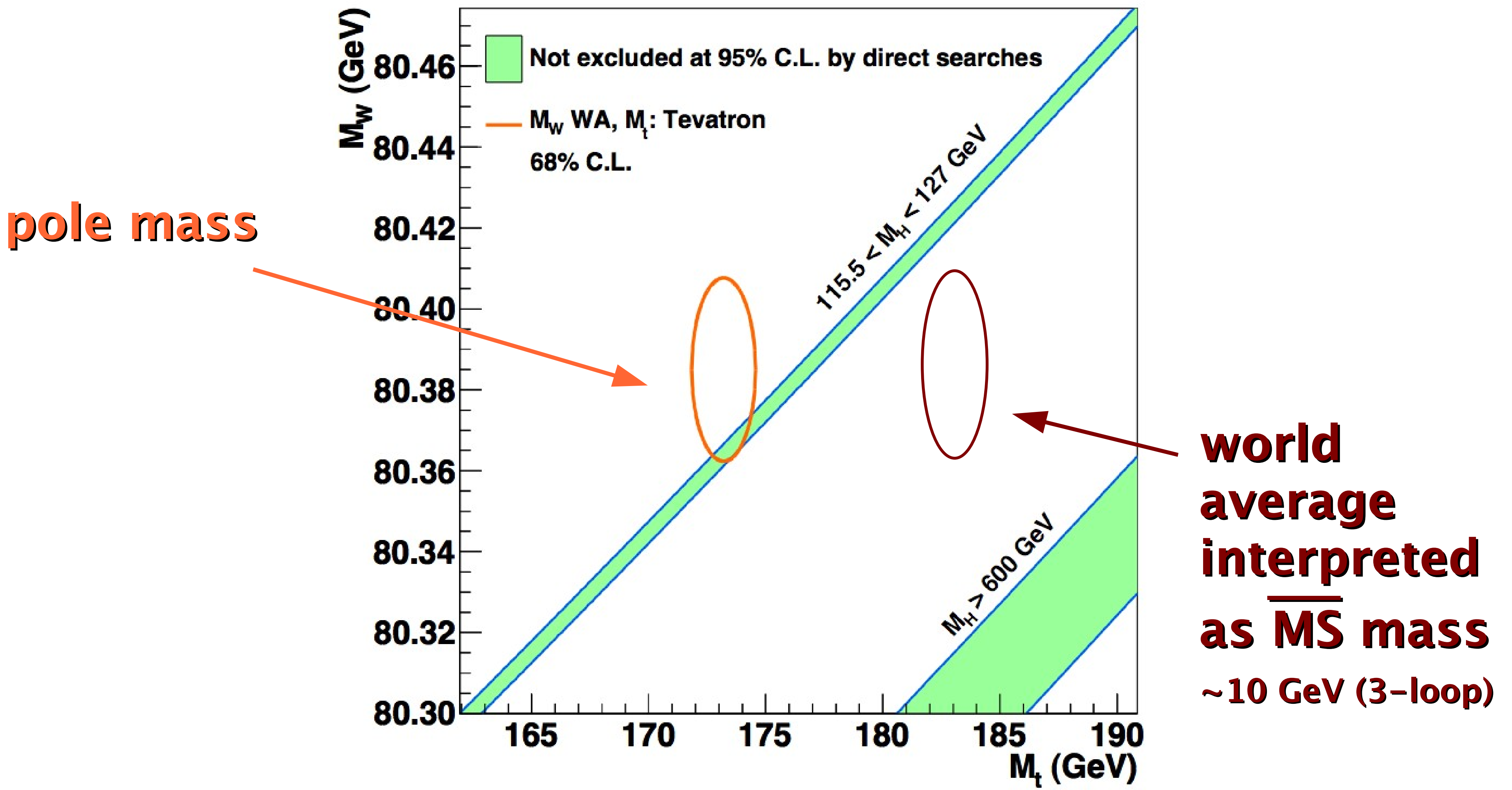
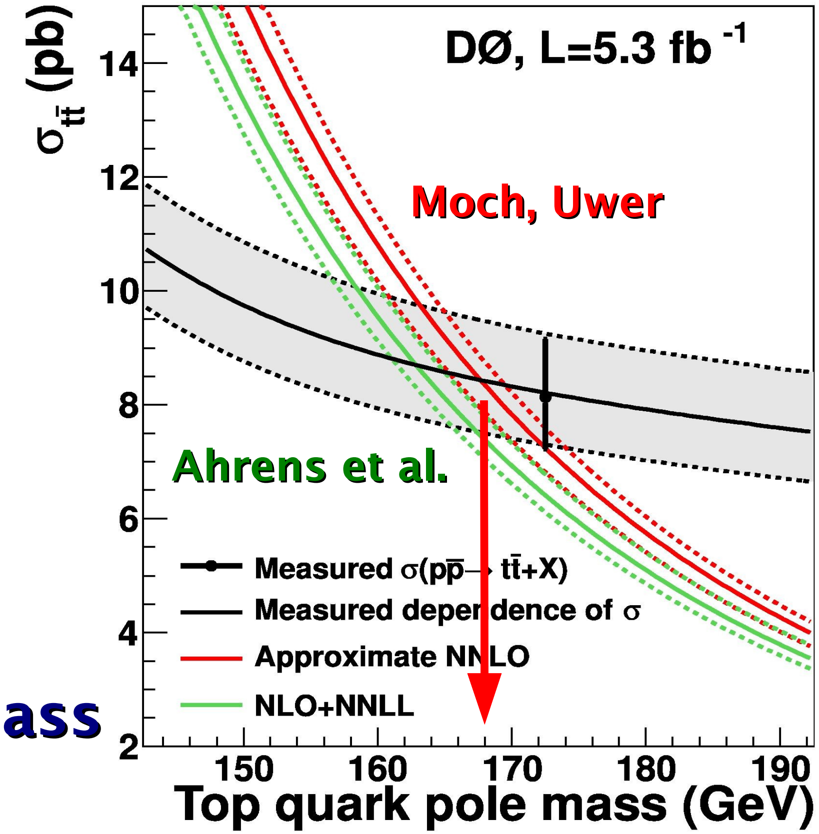


- can we measure pole or $\overline{\text{MS}}$ mass in direct and well-defined way?

Top Quark Pole Mass



MC mass = pole mass

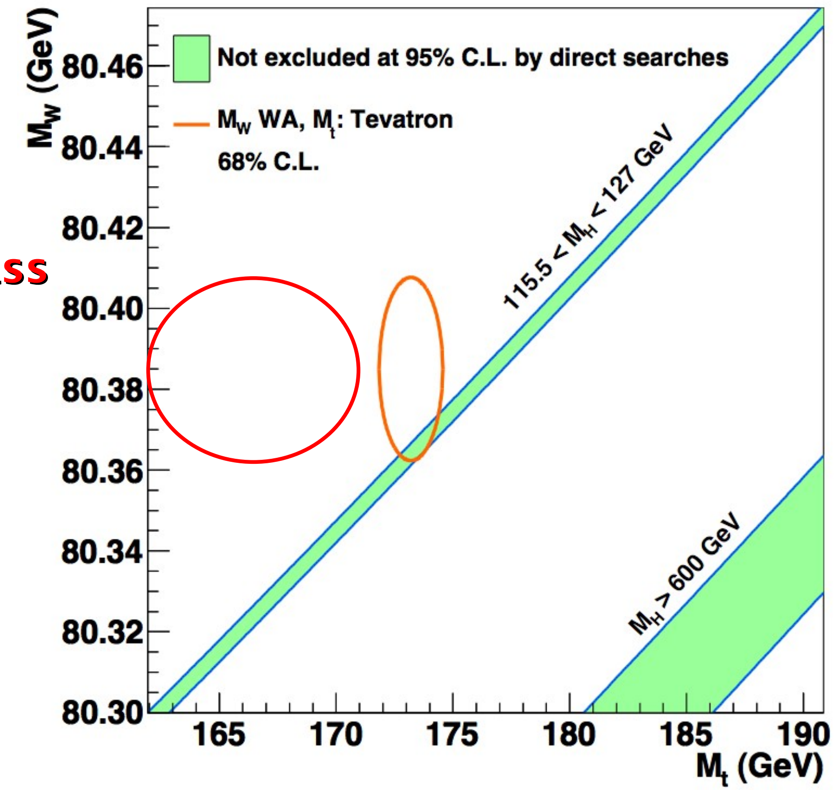
- **use b-tagged cross section since less dependent on mass**
- **difference due to MC mass interpretation is included into systematics**

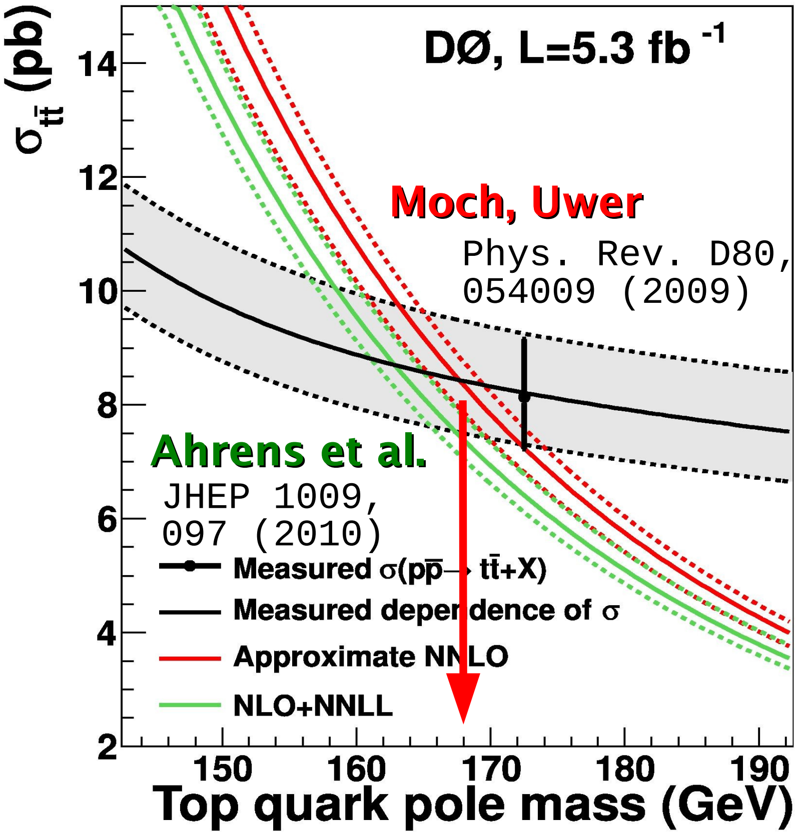
$$m_t^{pole} = 166.7^{+5.2}_{-4.5}\ \mathrm{GeV}$$

±2.9%

Top Quark Pole Mass

pole mass





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- **difference due to MC mass interpretation is included into systematics**

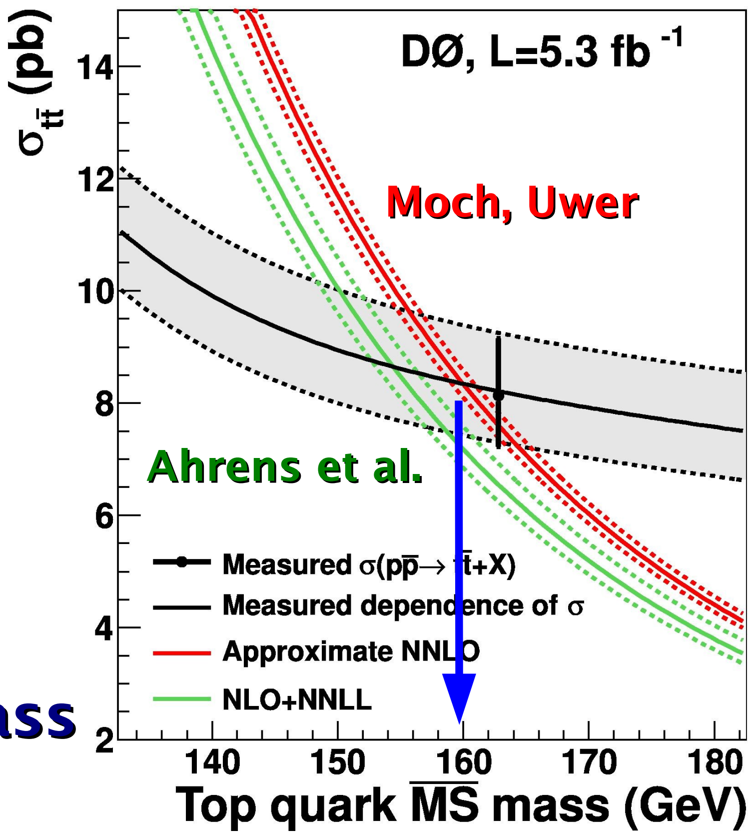
$$m_t^{pole} = 166.7^{+5.2}_{-4.5}\ \text{GeV}$$

±2.9%

- **1σ consistent with Tevatron average: $m_t = 173.3 \pm 1.1$ GeV**

Top Quark $\overline{MS}$ Mass

better convergence of higher order resummation



MC mass = pole mass

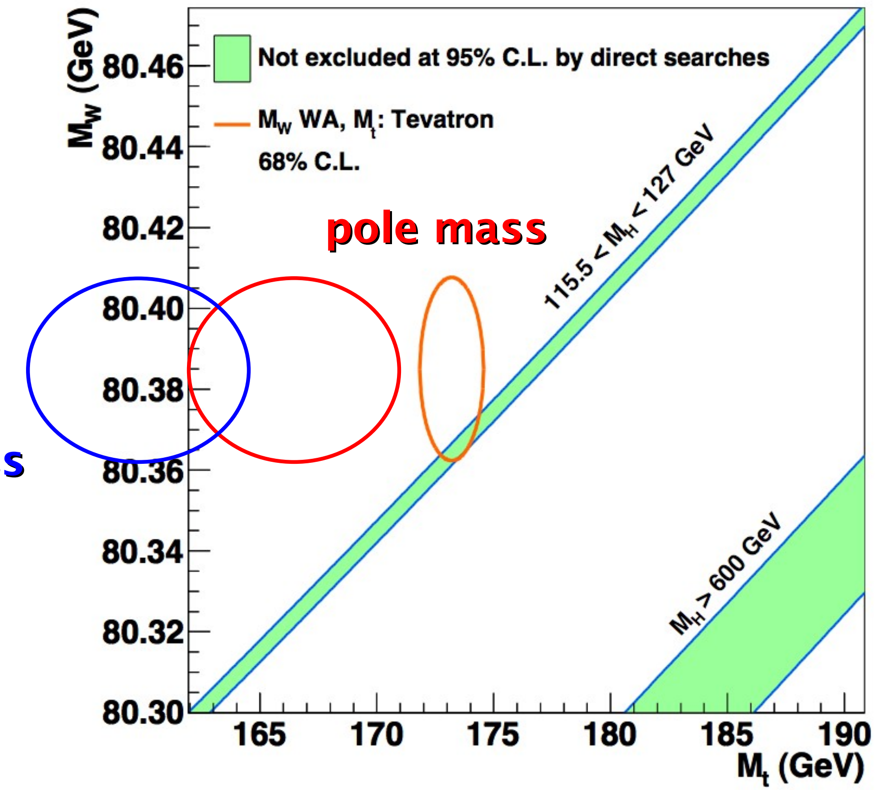
- **first extraction of $\overline{MS}$ mass taking selection efficiency into account**

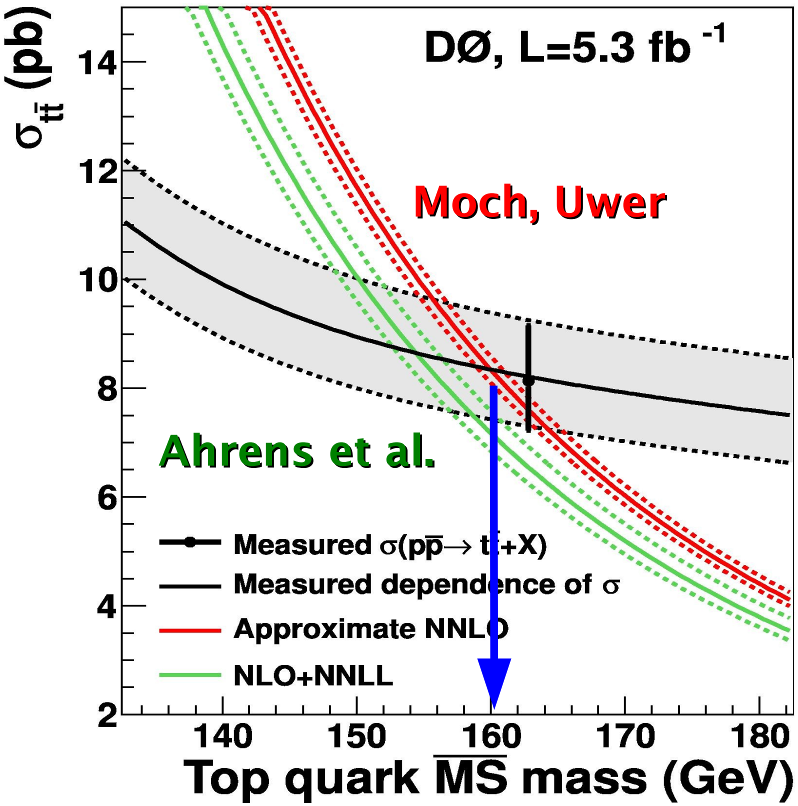
$$m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.3}\ \text{GeV}$$

±2.8%

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

$\overline{\text{MS}}$ mass





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

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

±2.8%

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

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Top mass

Lorentz invariance violation

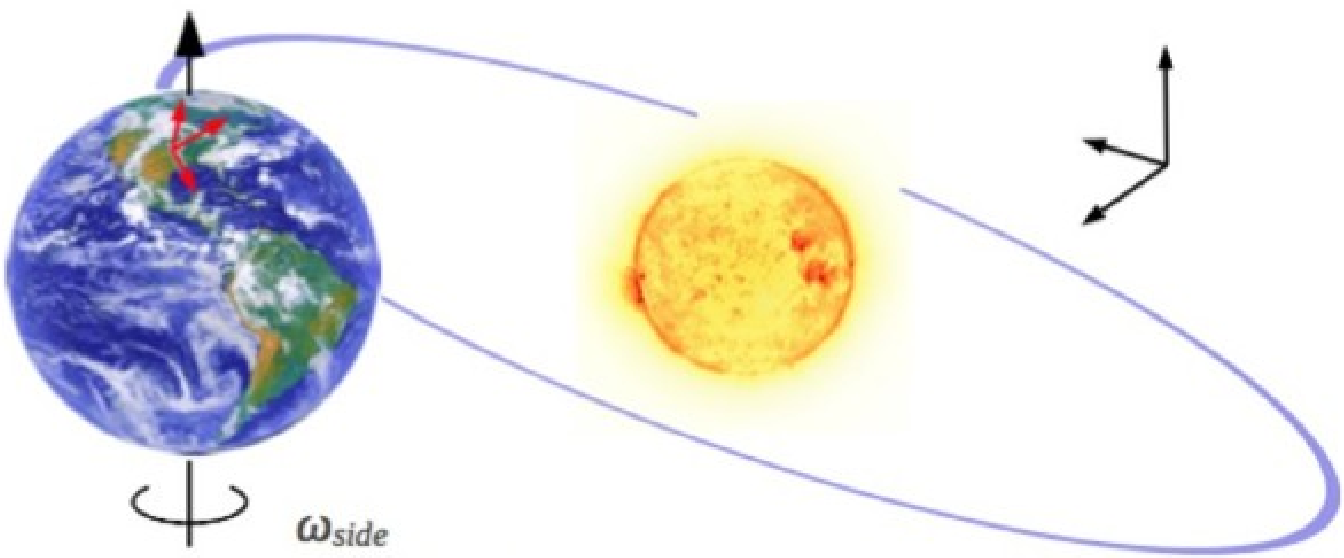
Conclusions

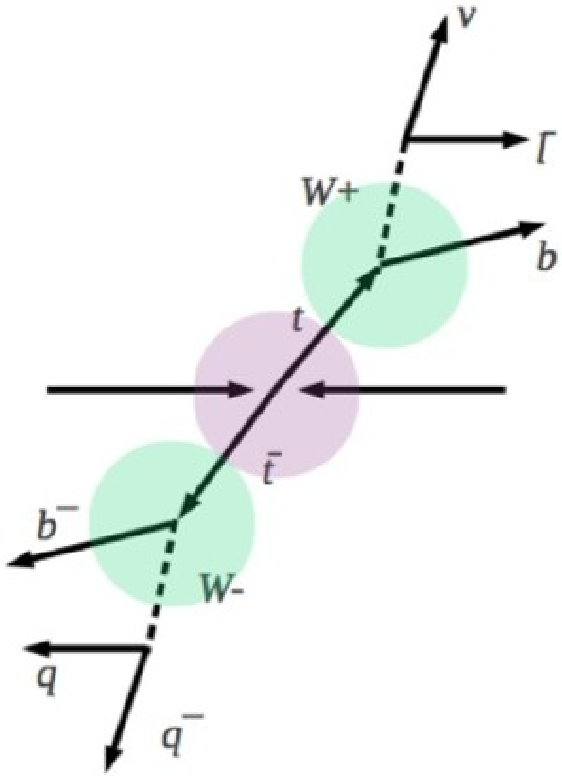
Search for Lorentz invariance violation

General Lorentz invariance violating terms added to SM Lagrangian:

$$|M|^2 = \overbrace{P F \bar{F}}^{\text{Standard Model}} + (c_R + c_L)_{\mu\nu} \overbrace{(\delta P_p + \delta P_\nu)^{\mu\nu} F \bar{F}}^{\text{Production Corrections}} + (c_L)_{\mu\nu} \overbrace{(P (\delta F)^{\mu\nu} \bar{F} + P F (\delta \bar{F})^{\mu\nu})}^{\text{Decay Corrections}}$$

symmetric traceless matrices:
strength of Lorentz invariance violation





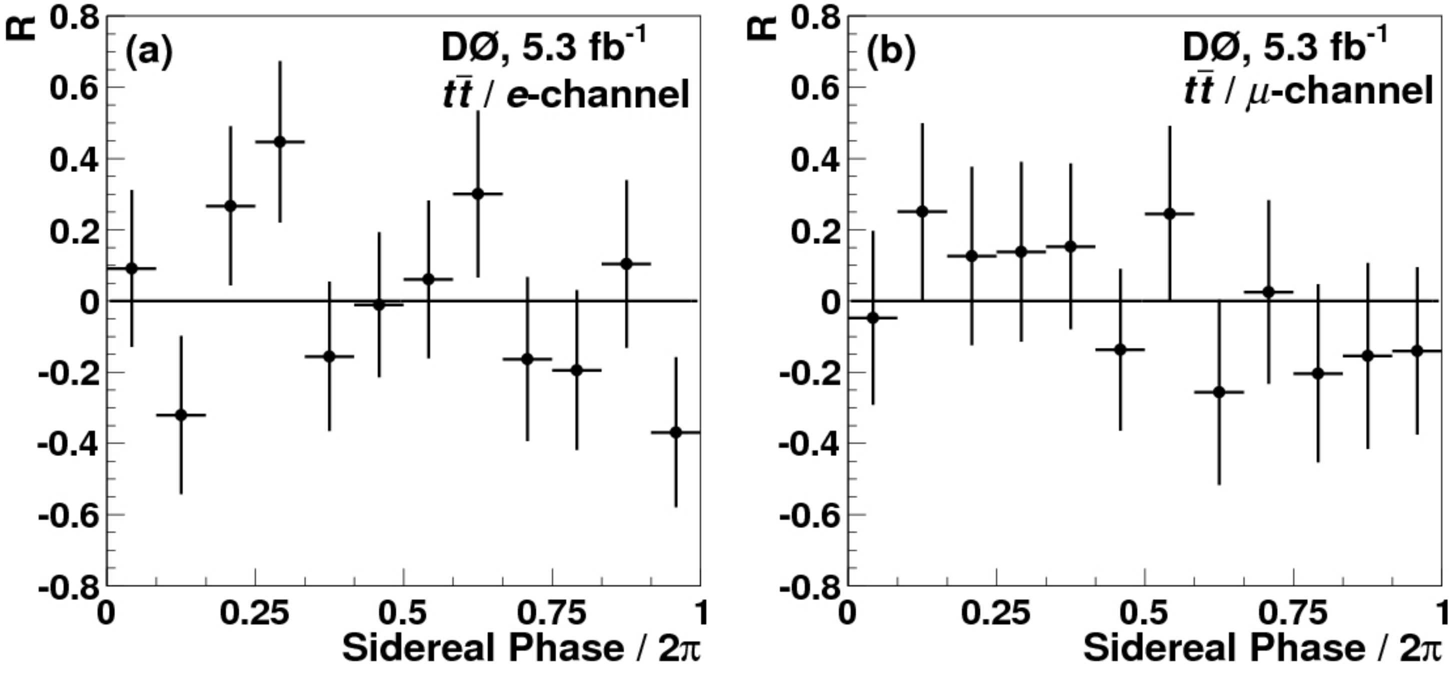
$$c_{L(R)}^{\text{Apparatus}} = \hat{R}(\omega_{side} t)_{(\text{Sun} \to \text{Apparatus})} c_{L(R)}^{\text{Sun}}$$

Search for Lorentz invariance violation

$$N_i \approx N_{\mathrm{tot}} \frac{\mathcal{L}_i}{\mathcal{L}_{\mathrm{int}}} \left[1 + f_{\mathrm{S}} f_{SME}(\phi_i)\right]$$

- $\mathcal{L}_i$ is the integrated luminosity over appropriate bin of sidereal phase ϕ_i
- f_S is the fraction of signal ($t\bar{t}$) events

$$R_i \equiv \frac{1}{f_{\mathrm{S}}} \left(\frac{N_i / N_{\mathrm{S+B}}}{\mathcal{L}_i / \mathcal{L}_{\mathrm{int}}} - 1 \right)$$



→ **no indication of time dependence of $t\bar{t}$ cross section**

→ **first constraints on LIV in free quark sector $(c_L)_{XX}$, $(c_L)_{XY}$, ... , $(c_R)_{XX}$, ...**

Conclusions

Highlights of top pair production physics:

- **top pair production cross section**

  8% precision, many channels analyzed, good agreement with NLO QCD predictions, no new physics observed

- **differential cross section is investigated**

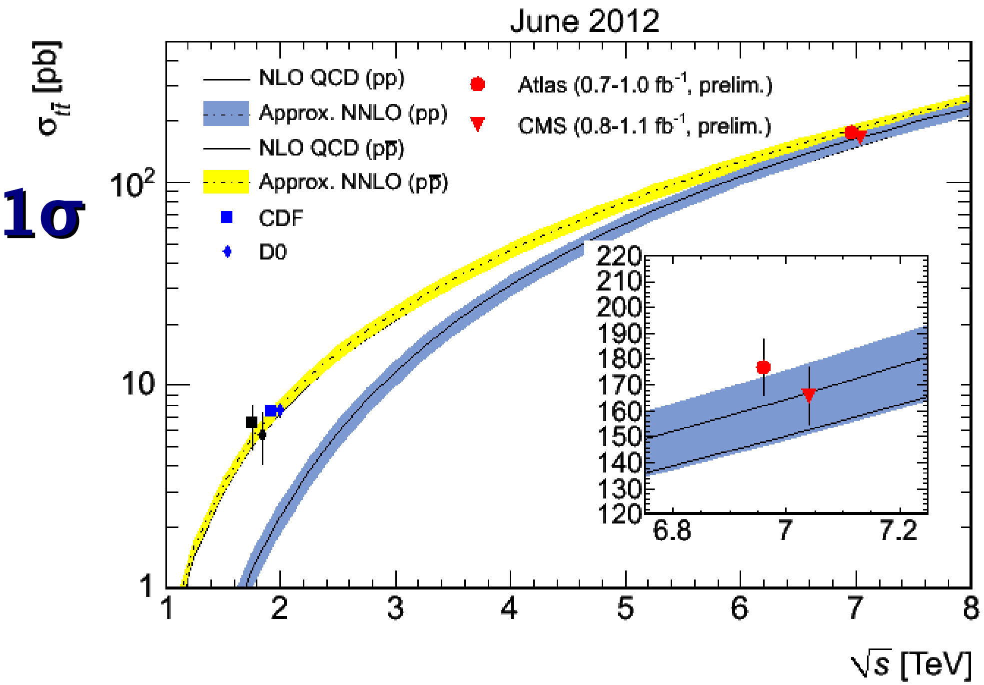
  e.g. top quark transverse momentum, powerful QCD tests

- **pole and $\overline{\text{MS}}$ mass**

  pole mass agrees with Tevatron combination within 1σ

- **top quark production as expected in SM**

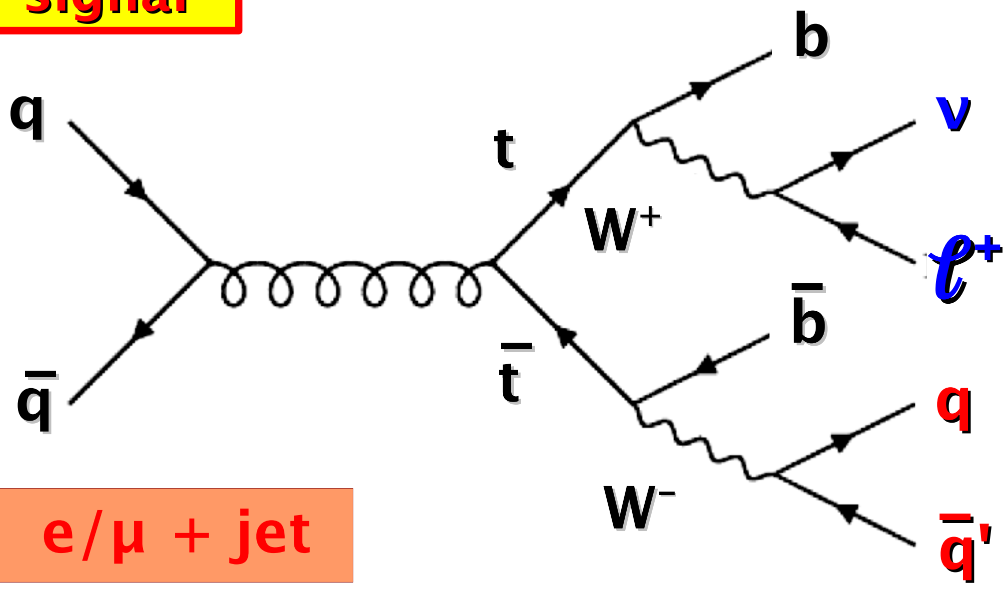
  new tests using NNLO+NNLL calculations: 3% uncertainty



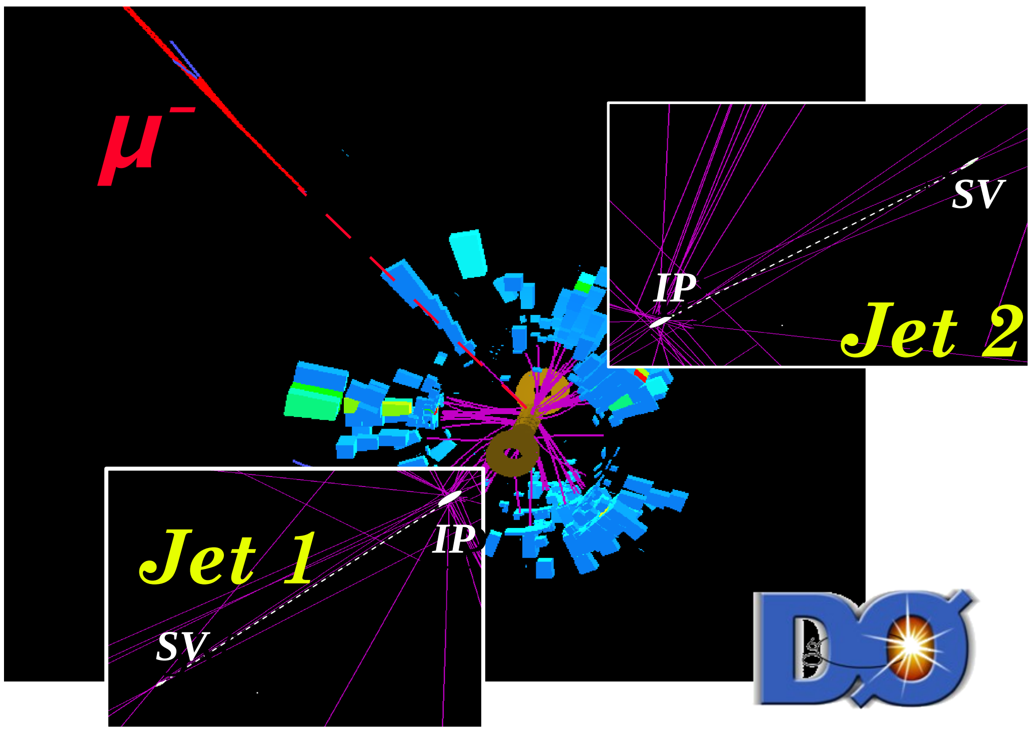
Backup

Lepton+jets Signatures

signal



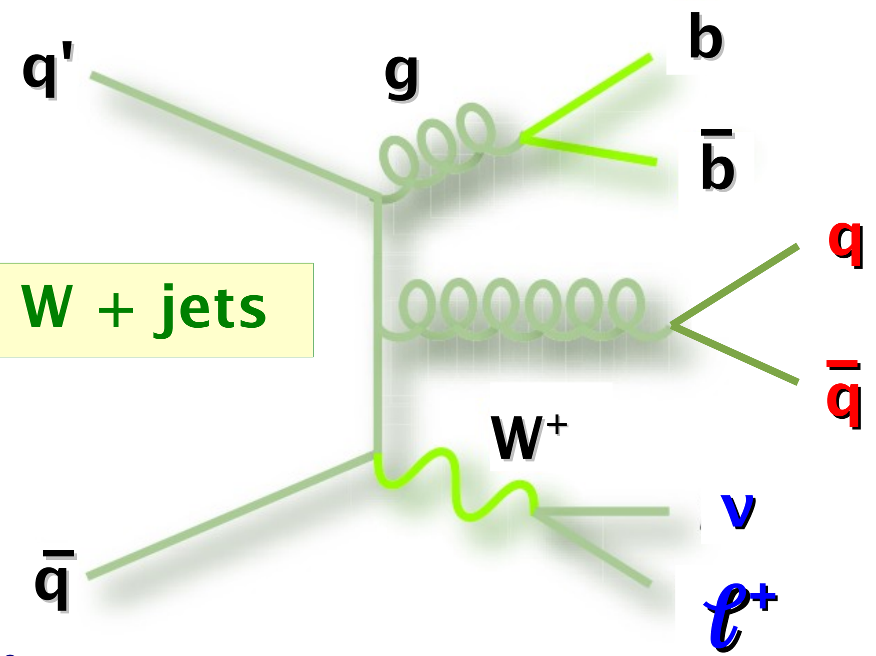
e/μ + jet



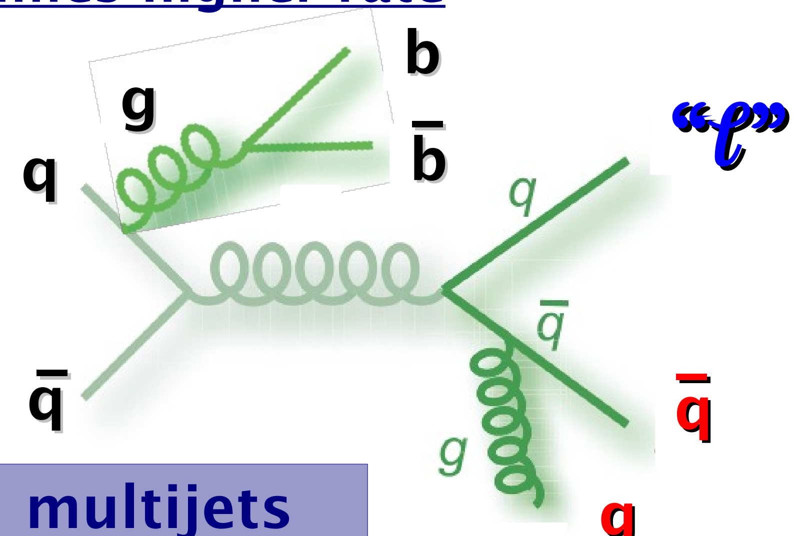
background

3000 times higher rate

W + jets



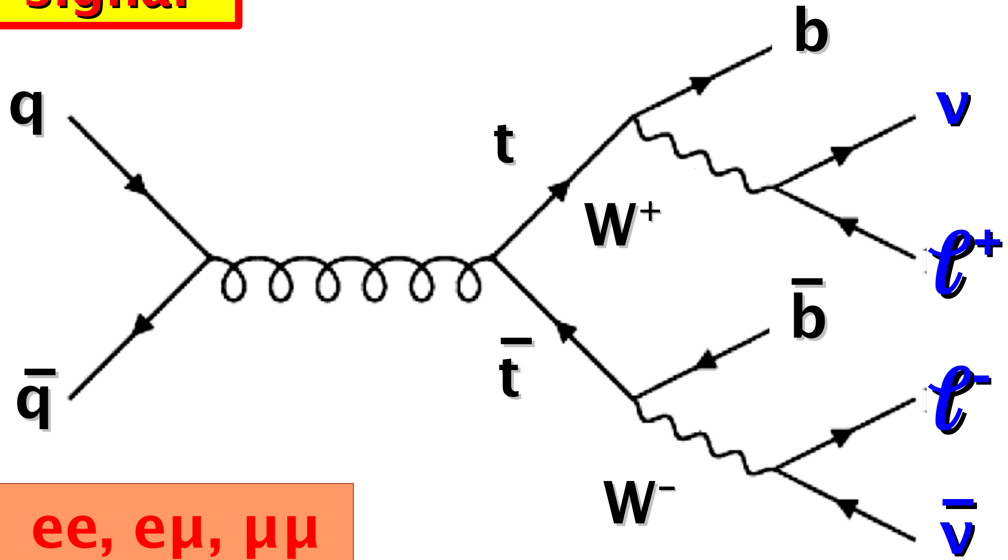
10^{10} times higher rate



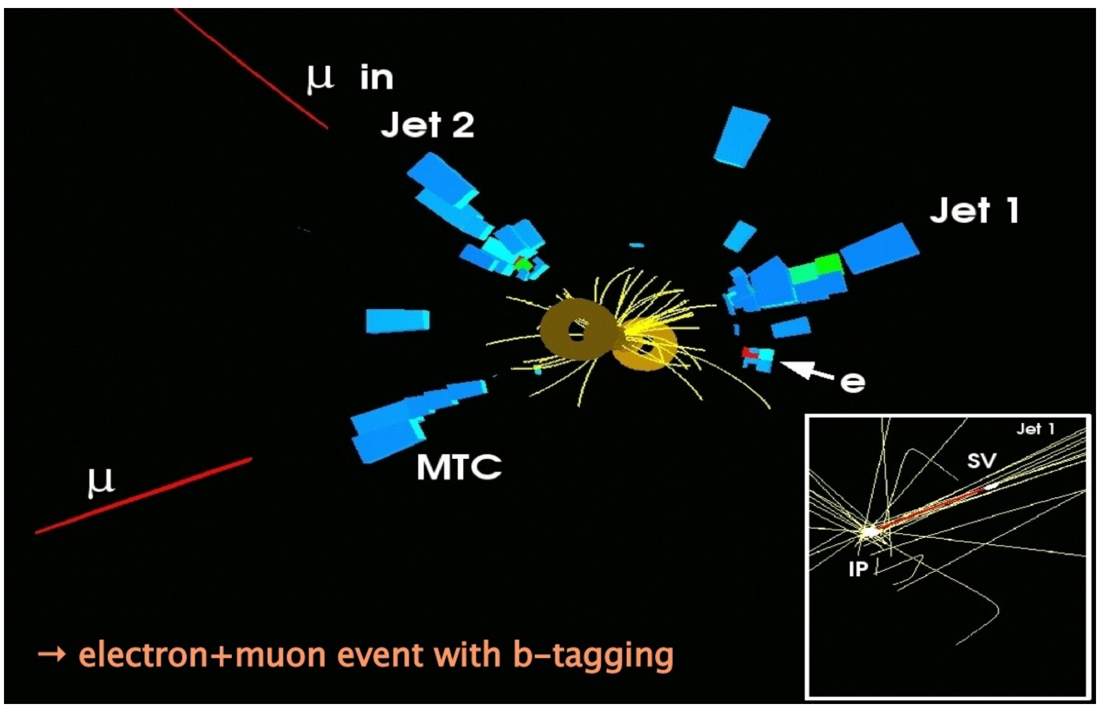
multijets

Dilepton Signatures

signal

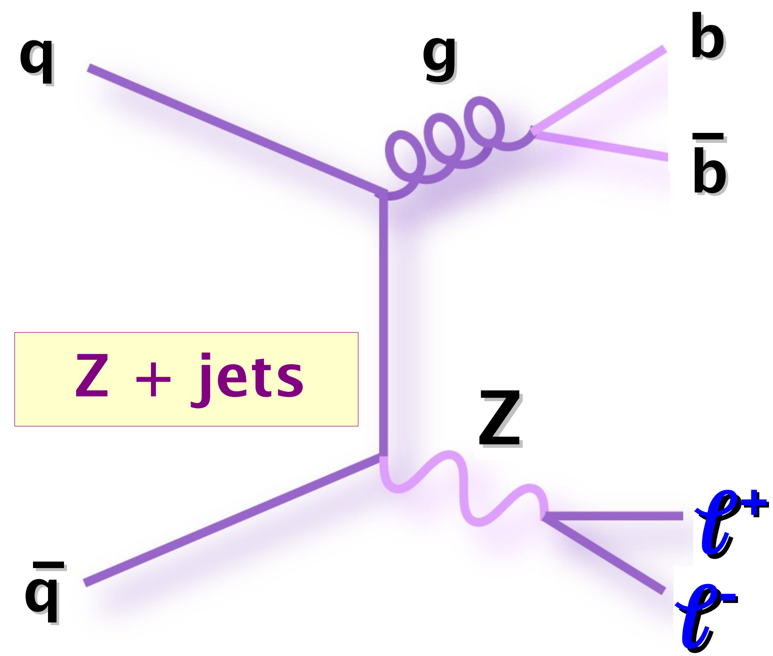


ee, eμ, μμ



background

300 times higher rate



- less statistics
- less background

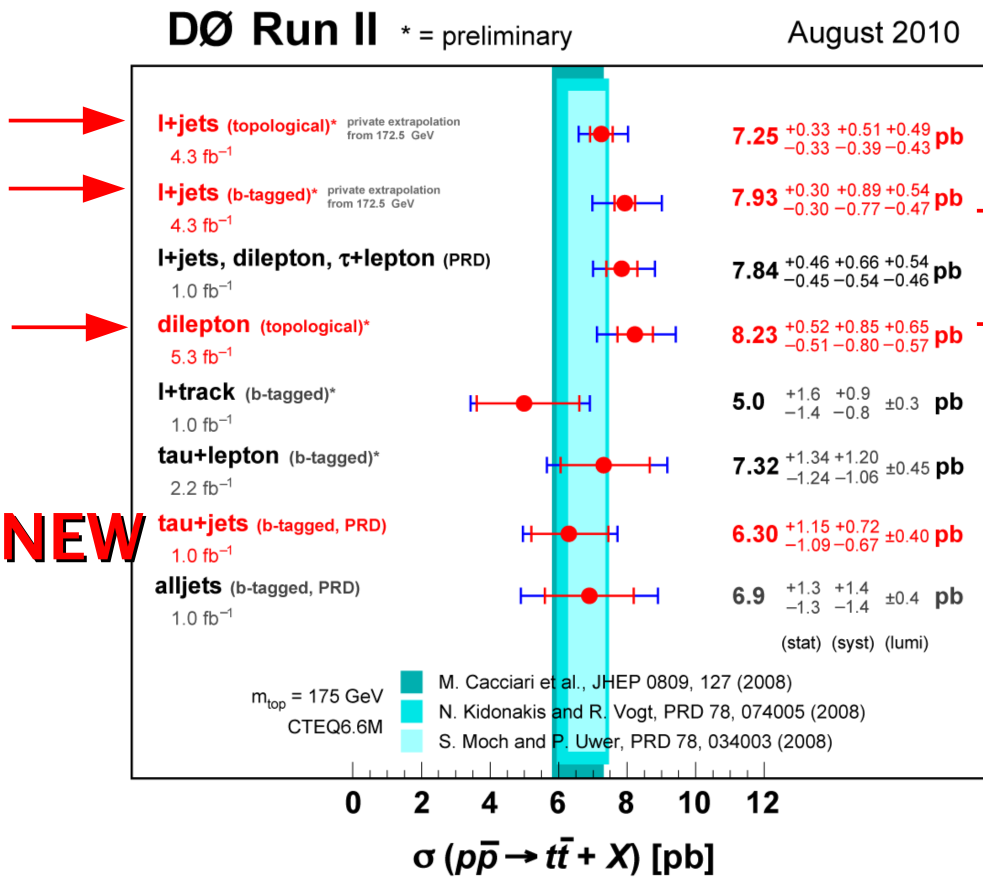
Top Pair Production Cross Section

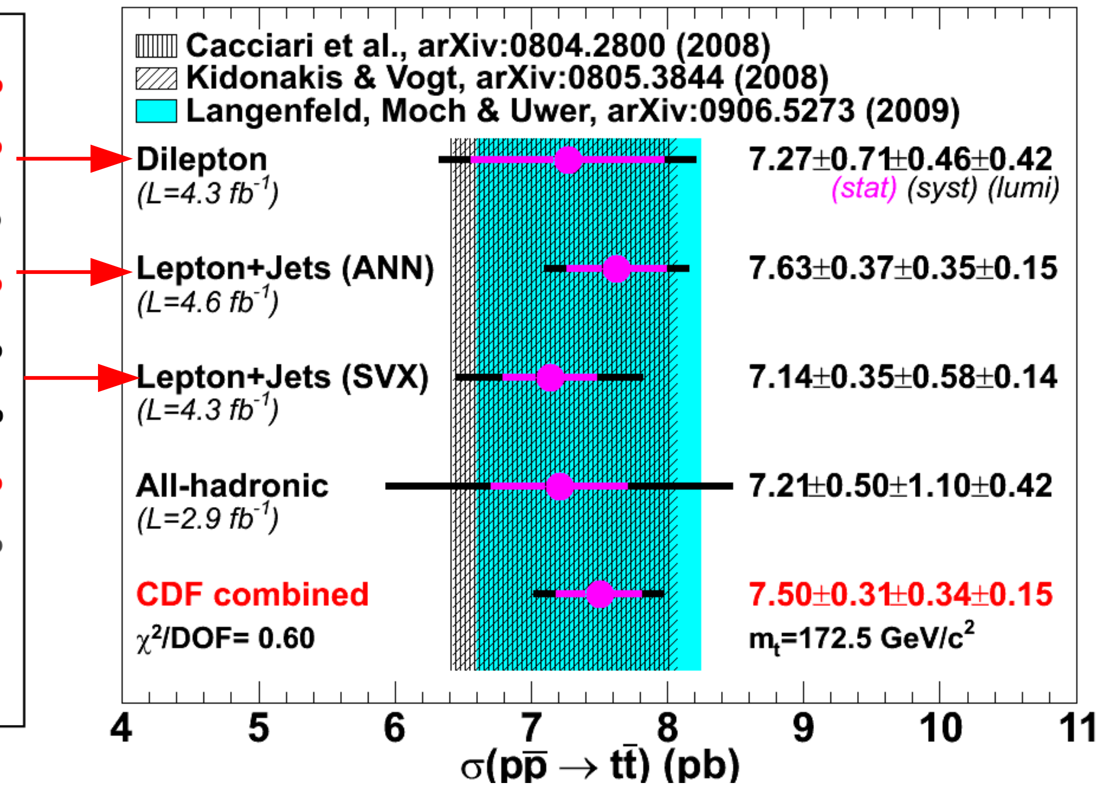
- check if production rate is as expected in the SM
- test of the underlying theory: QCD
- powerful search for new physics beyond the SM

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

$5.4\ fb^{-1}$

Top Pair Production Cross Sections





NEW MET+2, 3, ≥ 4 jets (orthogonal)

all channels measured except for $\tau_{had}\ \tau_{had}$

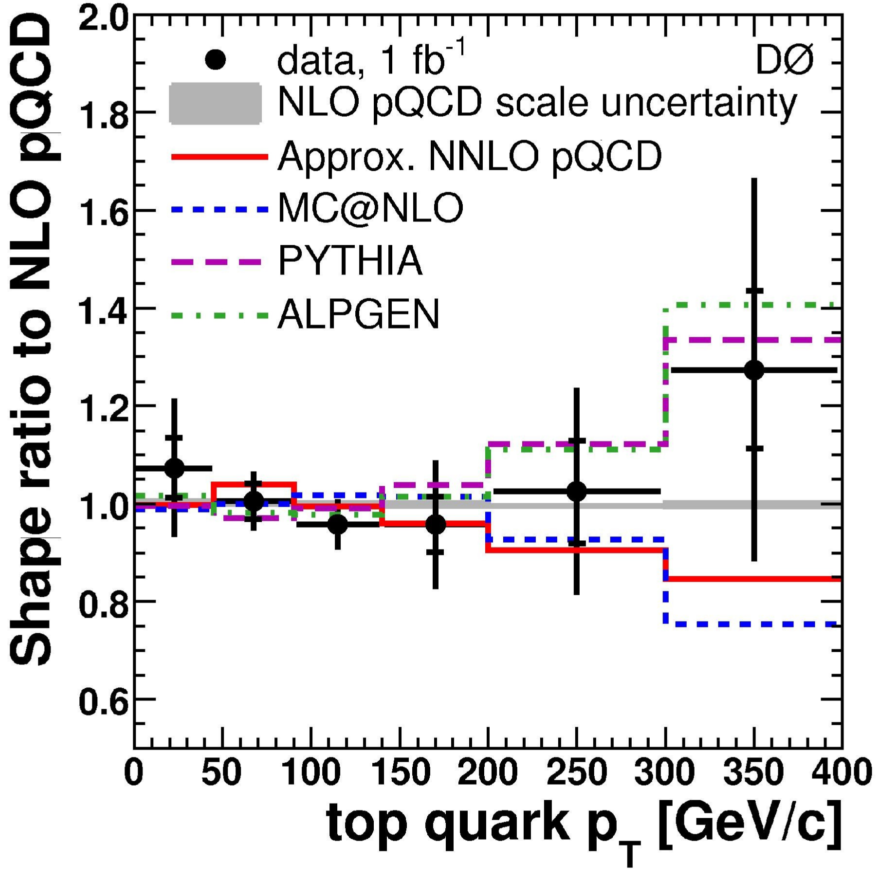
combination: ±6% !

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

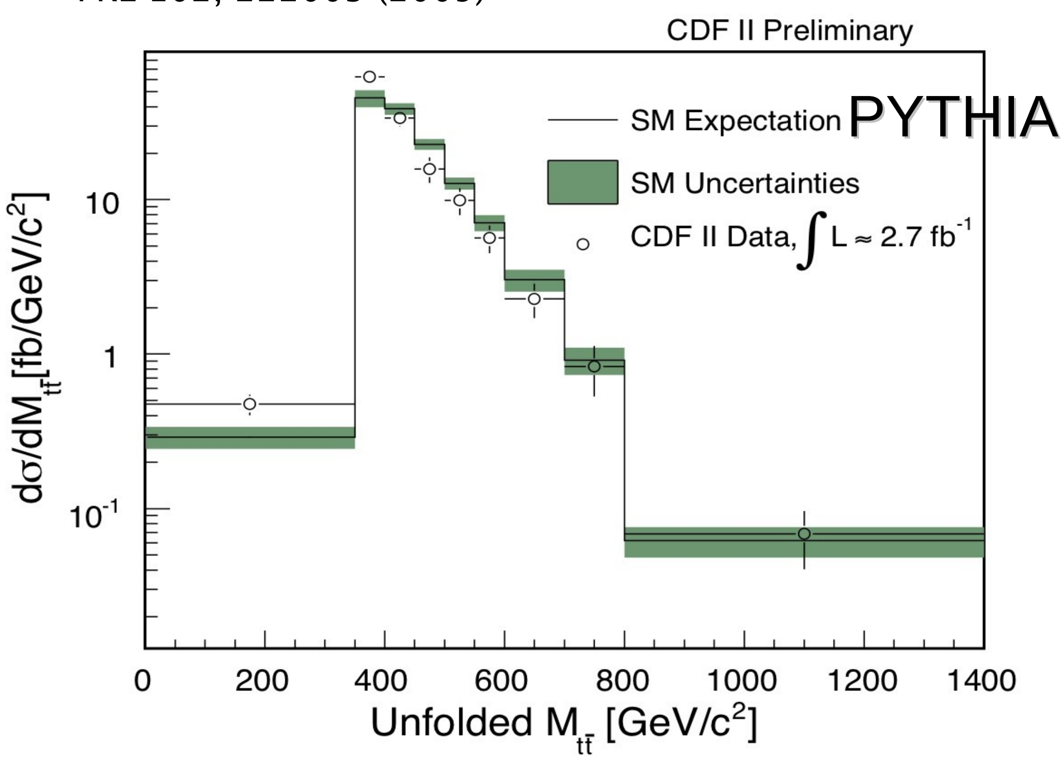
Differential Cross Section

- important test of NLO QCD
- unfolding of distributions

arXiv:1001.1900 [hep-ex]



PRL 102, 222003 (2009)



- need NLO QCD to describe normalisation correctly
- no deviation from the SM

Differential Cross Section

- **important test of NLO QCD**
- **unfolding of distributions**

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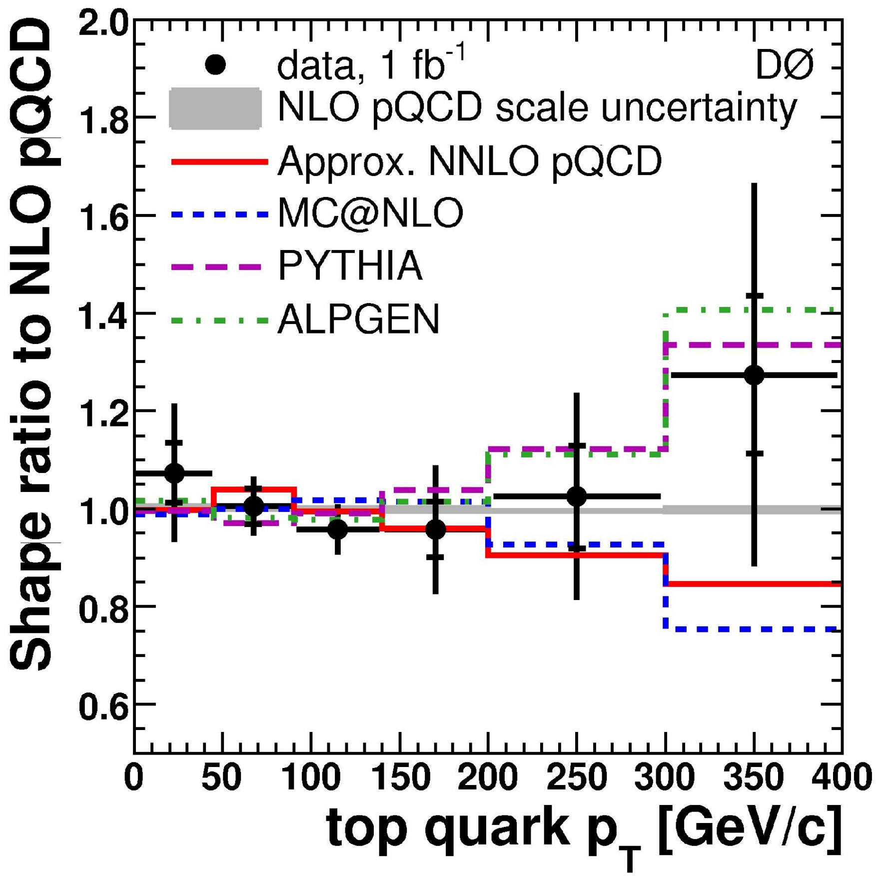
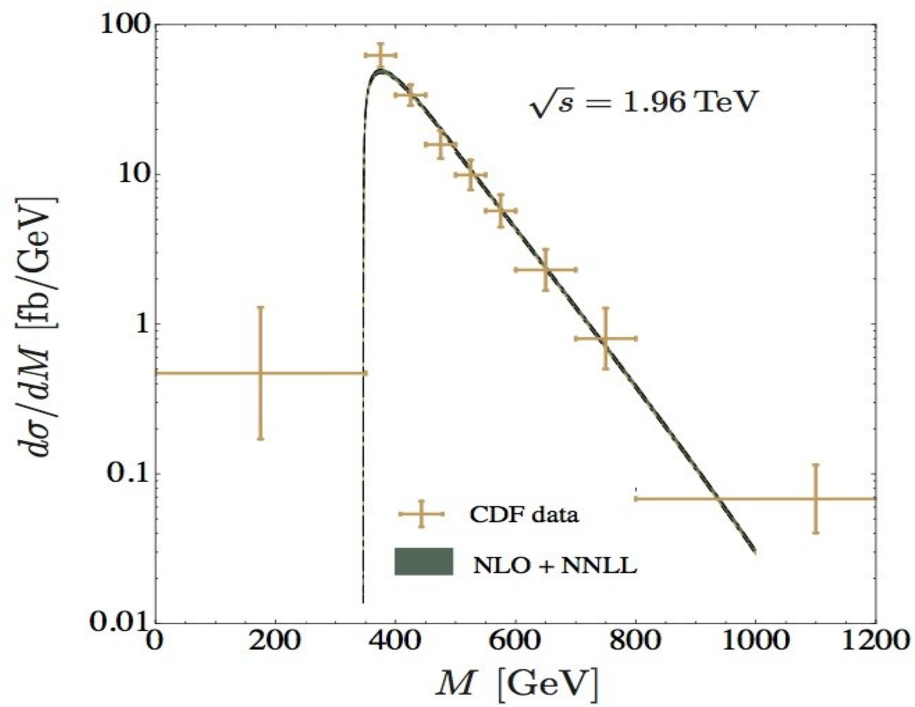


Ahrens, Ferrogia, Neubert, Pecjak, Yang
arXiv:1006.4682 [hep-ph]

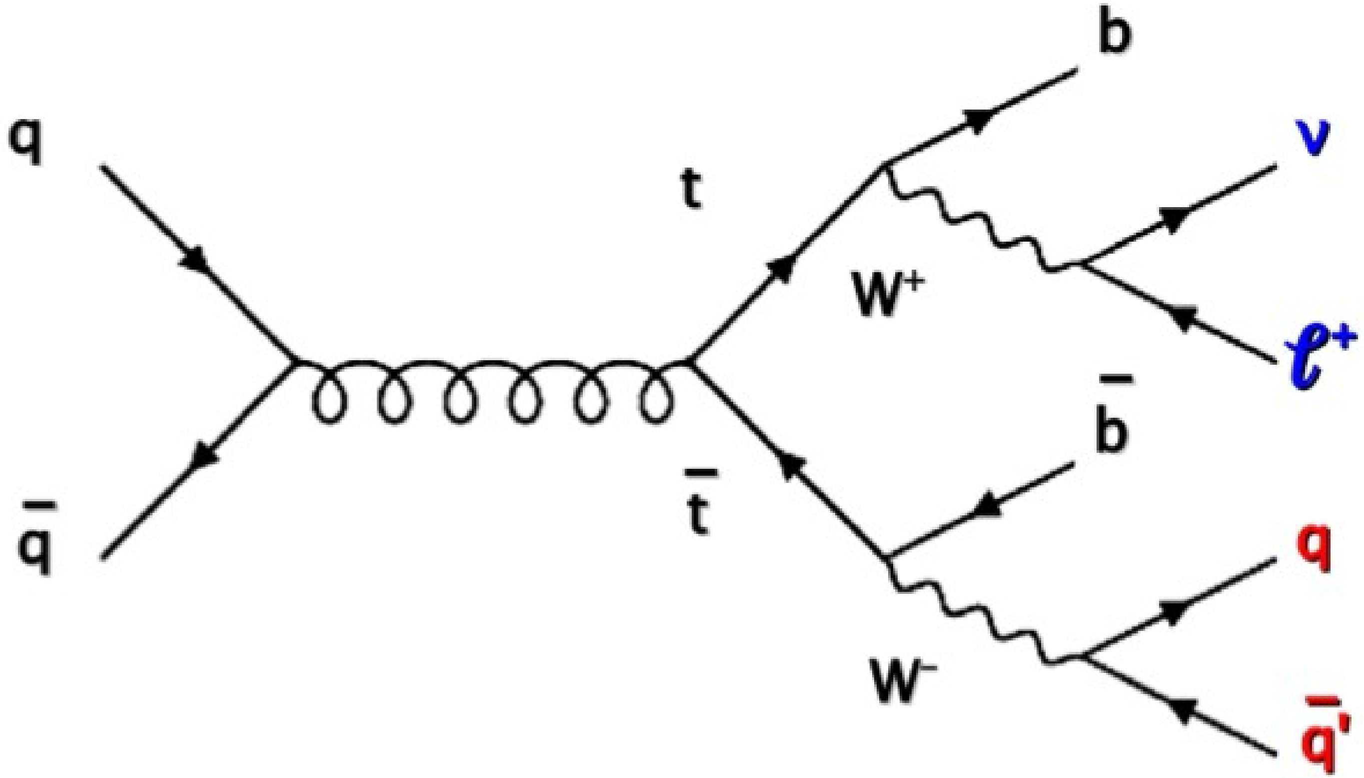


- **need NLO QCD to describe normalisation correctly**

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

Which top mass does a LO MC contain?

- matrix element in LO QCD



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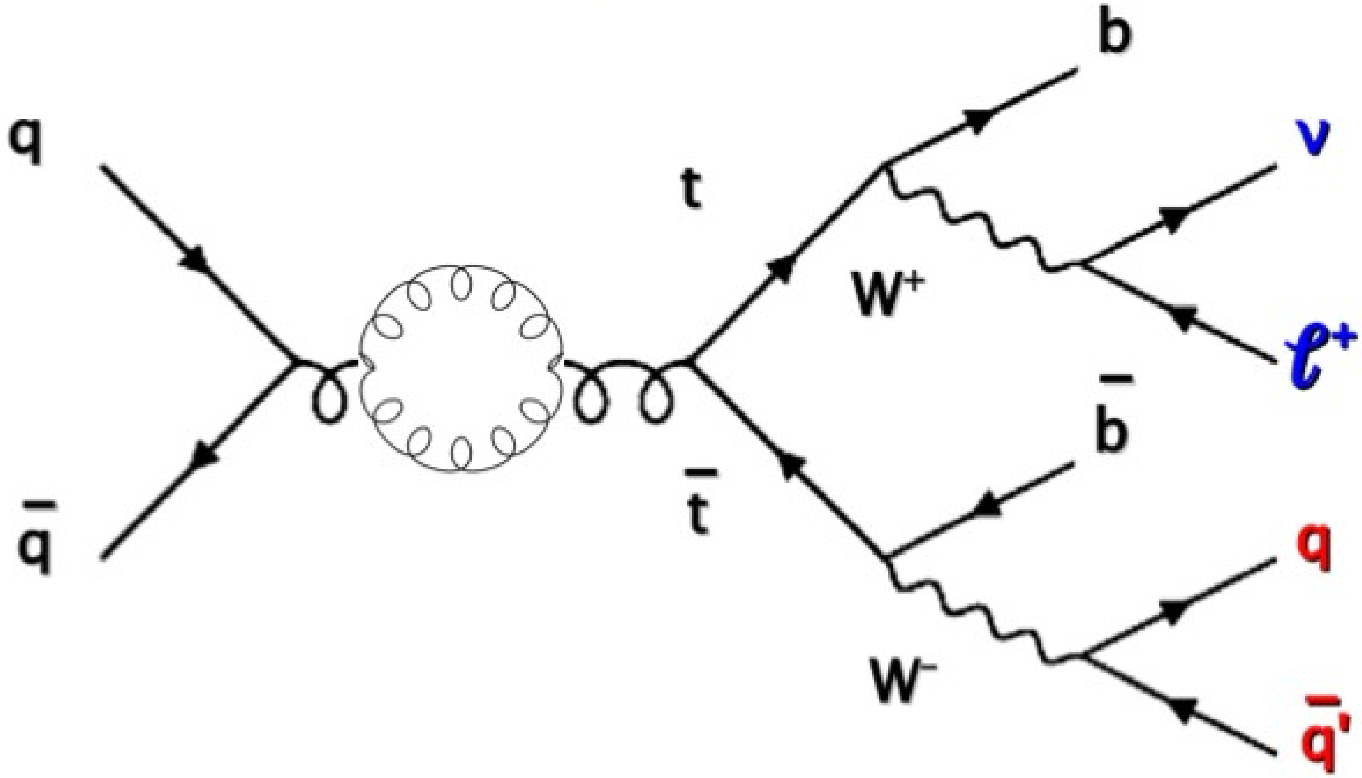

- parton showers simulate higher orders, i.e. not only radiating additional gluons!

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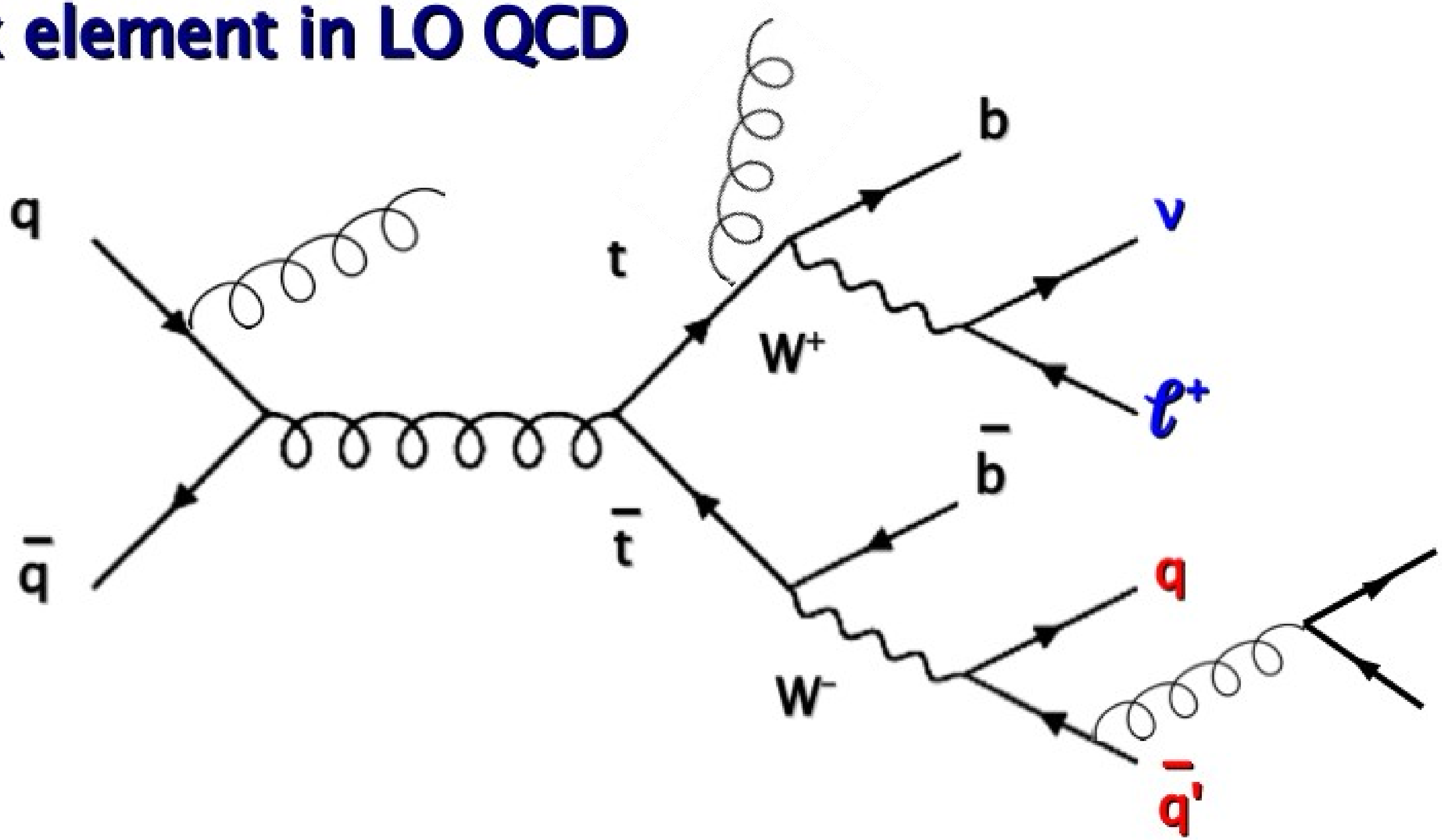

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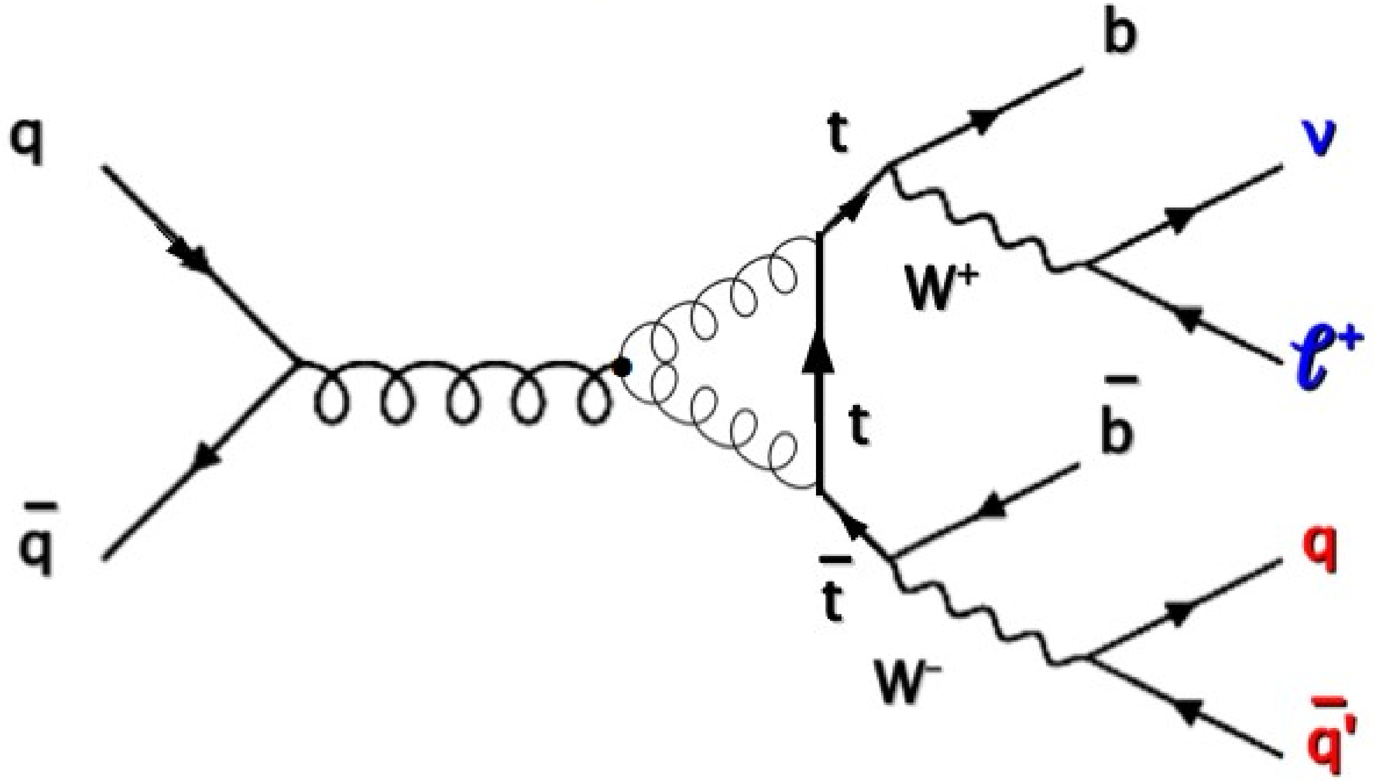

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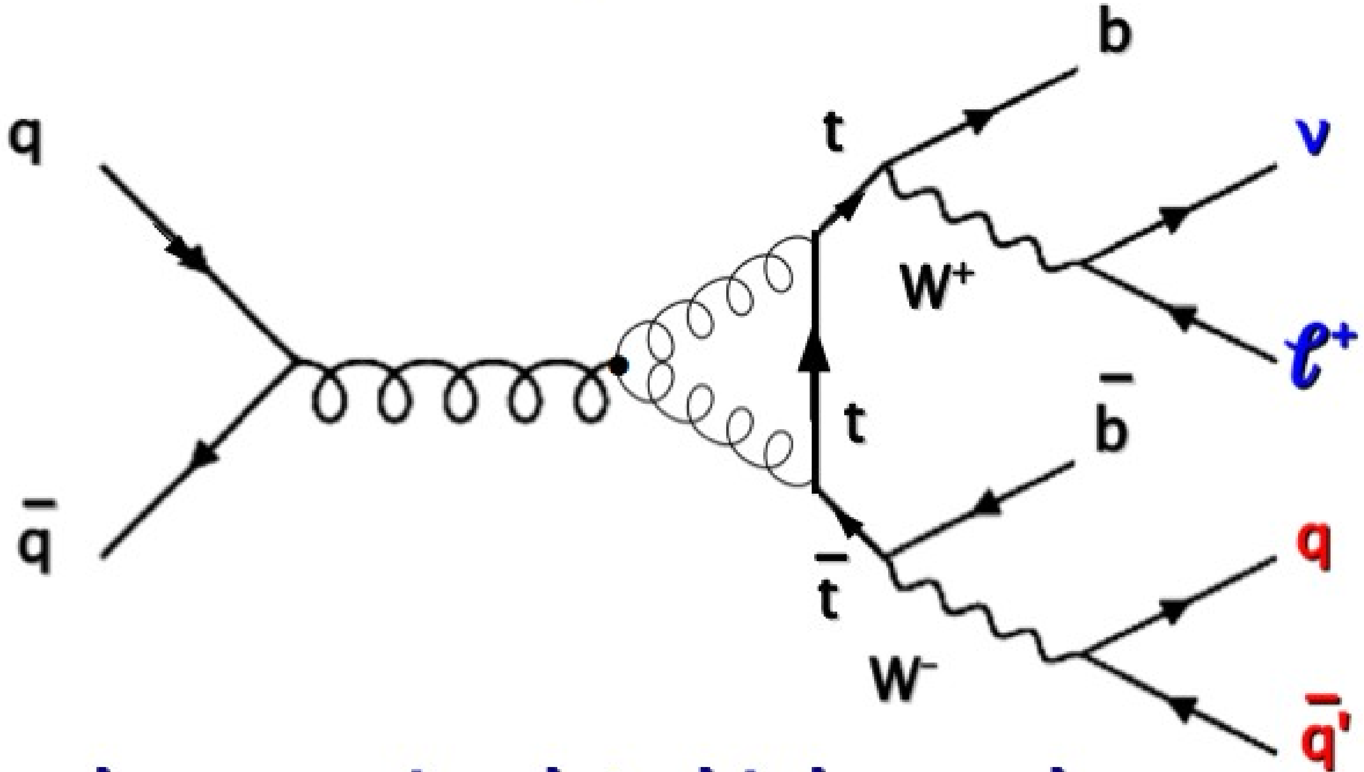


- parton showers simulate higher orders,
  i.e. not only radiating additional gluons! (LL)

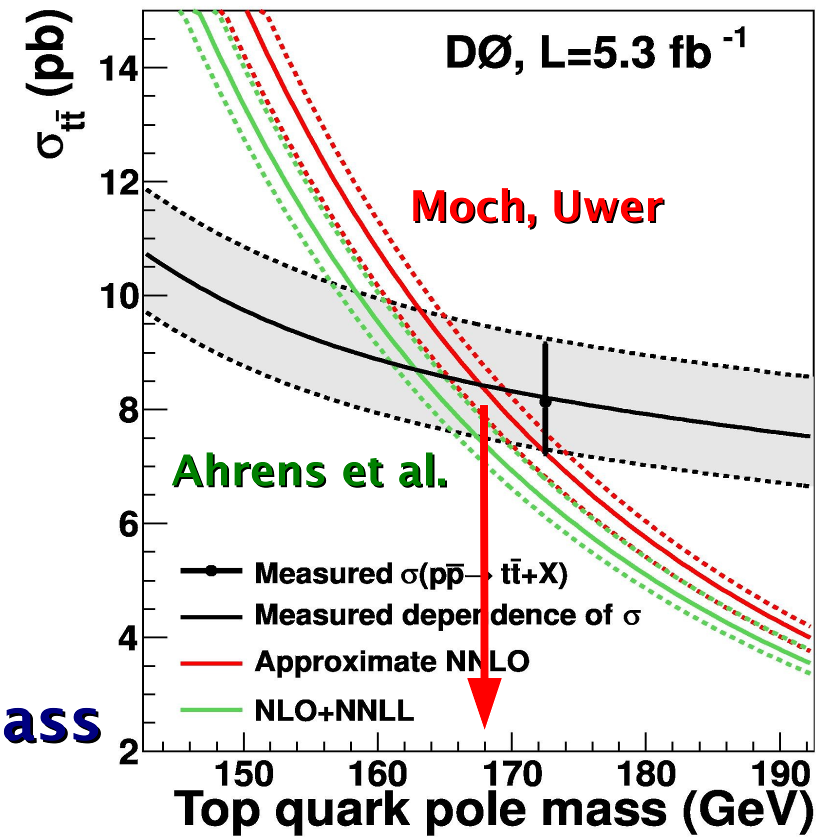
  ⇒ very hard to answer...

- arguments that it should be close to pole mass

Top Quark Pole Mass

arXiv:1104.2887 [hep-ex]

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 [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**

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

±2.9%

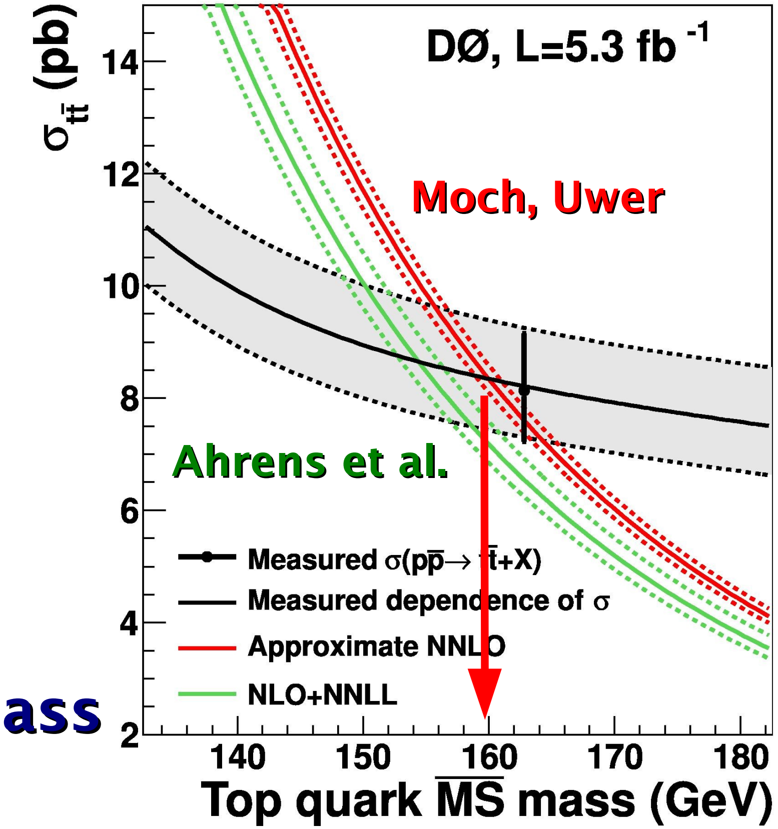
- **1σ consistent with Tevatron average: m_t = 173.3 ± 1.1 GeV**

Top Quark $\overline{MS}$ Mass

better convergence of higher order resummation

Theoretical prediction	$m_t^{\overline{MS}}$ (GeV)	$\Delta m_t^{\overline{MS}}$ (GeV)
MC mass assumption	$m_t^{MC} = m_t^{pole}$	$m_t^{MC} = m_t^{\overline{MS}}$
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 $\overline{MS}$ mass taking selection efficiency into account**

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

±2.8%

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

Different Top Mass Definitions

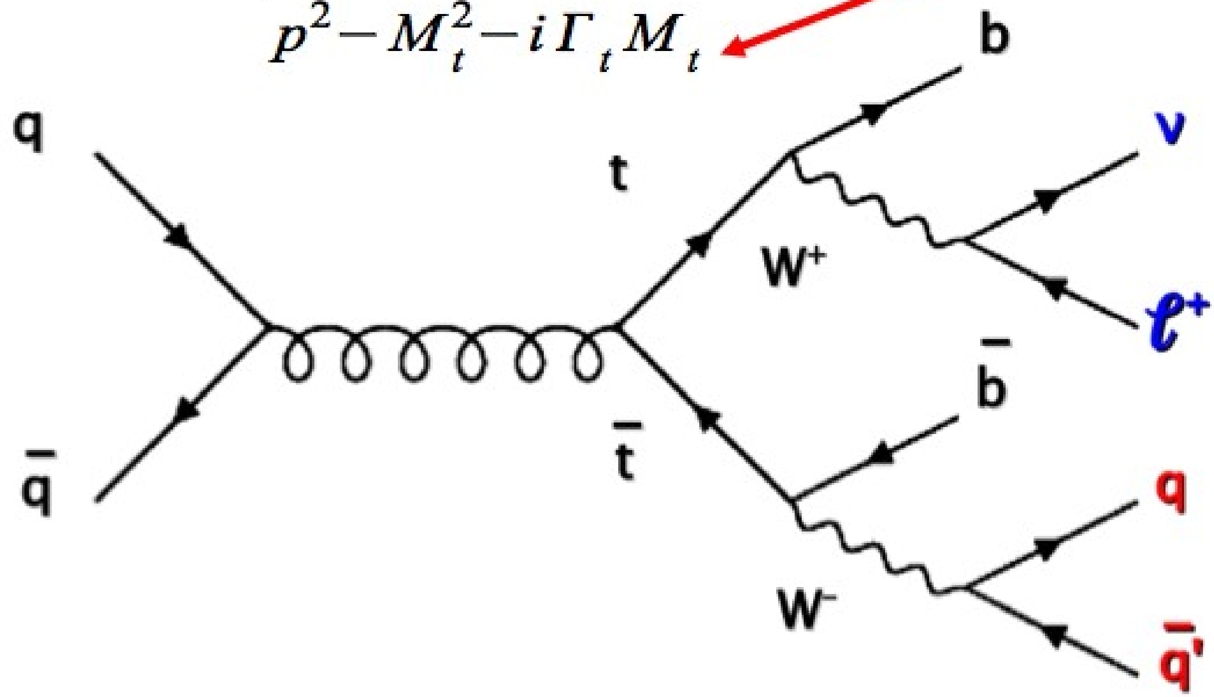
hep-ph/0001002

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

pole mass

$\overline{\rm MS}$ scheme

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



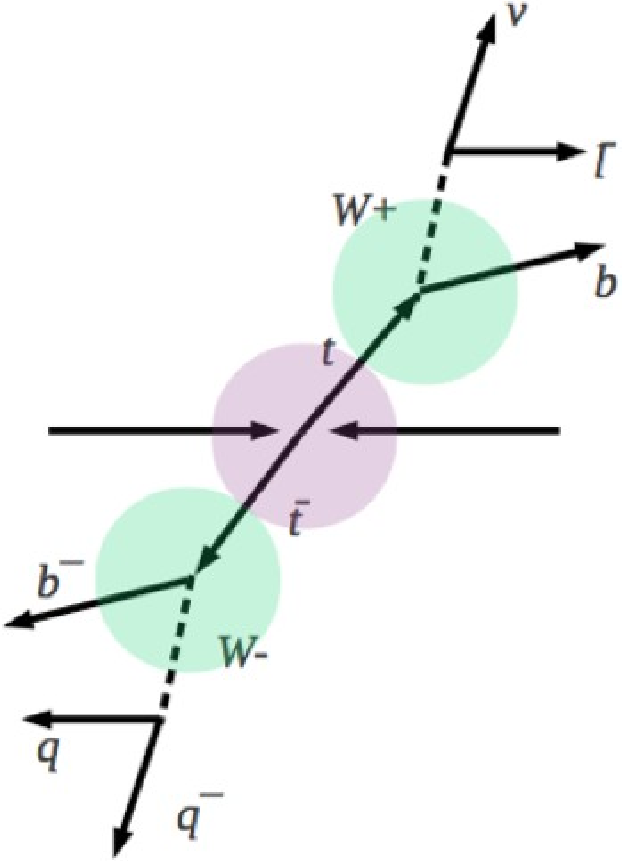
⇒ difference between $\overline{\rm MS}$ and pole mass is ≈10GeV...

Search for Lorentz invariance violation

- General Lorentz-violating terms added to SM Lagrangian
  - Effective field theory treatment for LV
  - Not constrained to be the same for all particle species

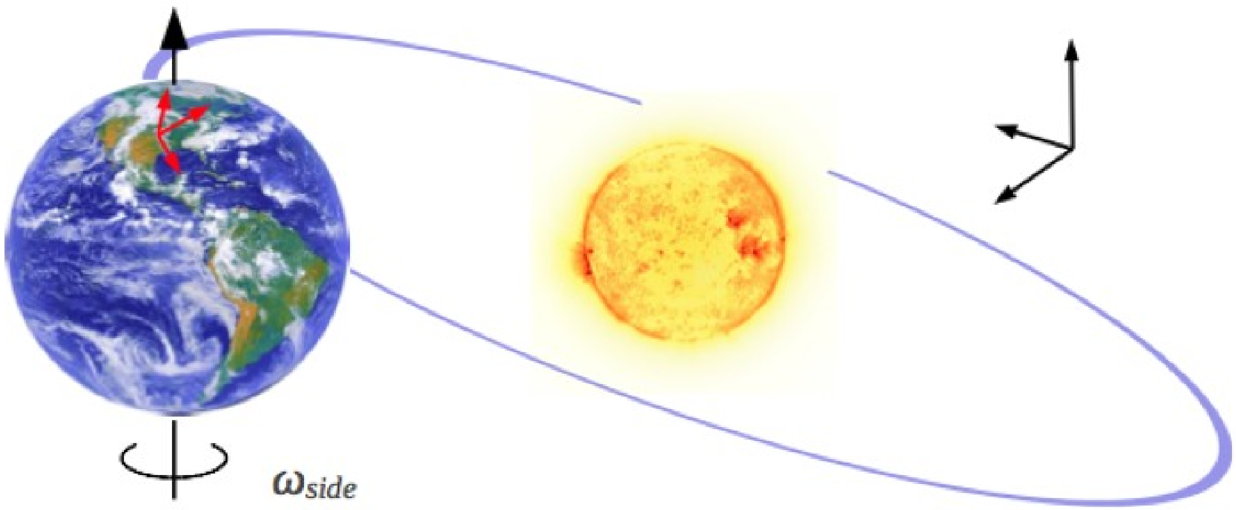
$$|M|^2 = \overbrace{P F \bar{F}}^{\text{Standard Model}} + (c_R + c_L)_{\mu\nu} \overbrace{(\delta P_p + \delta P_\nu)^{\mu\nu} F \bar{F}}^{\text{Production Corrections}} + (c_L)_{\mu\nu} \overbrace{(P(\delta F)^{\mu\nu} \bar{F} + P F (\delta \bar{F})^{\mu\nu})}^{\text{Decay Corrections}}$$

  - c_R and c_L are symmetric, traceless matrices containing coefficients which parametrize the strength of Lorentz violation in the top quark sector
  - Set limits on elements of c_R and c_L, as well as linear combinations $c = c_L + c_R$ and $d = c_L - c_R$.
  - Top sector only accessible to high-energy particle colliders
    - Tight limits already set on LV other particle sectors



Search for Lorentz invariance violation

- GOAL: Estimate components of c_R and c_L matrices



$$c_{L(R)}^{\text{Apparatus}} = \hat{R}\left(\omega_{side} t\right)_{(\text{Sun} \rightarrow \text{Apparatus})} c_{L(R)}^{\text{Sun}}$$

SM extension

- D-Zero events projected onto different components of SME matrices c_R and c_L
  - Varies with sidereal frequency as detector rotates with Earth
  - Unique signature!
  - Time-dependent event rate.