Top Quark at Hadron Colliders

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Hadron Collider Physics Summer School
Fermilab

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Outline 1st Lecture

Introduction
History of the Top Quark
Top Quark Production
Top Quark Properties
Searches in Top Sector
Conclusions

Summary 1st Lecture

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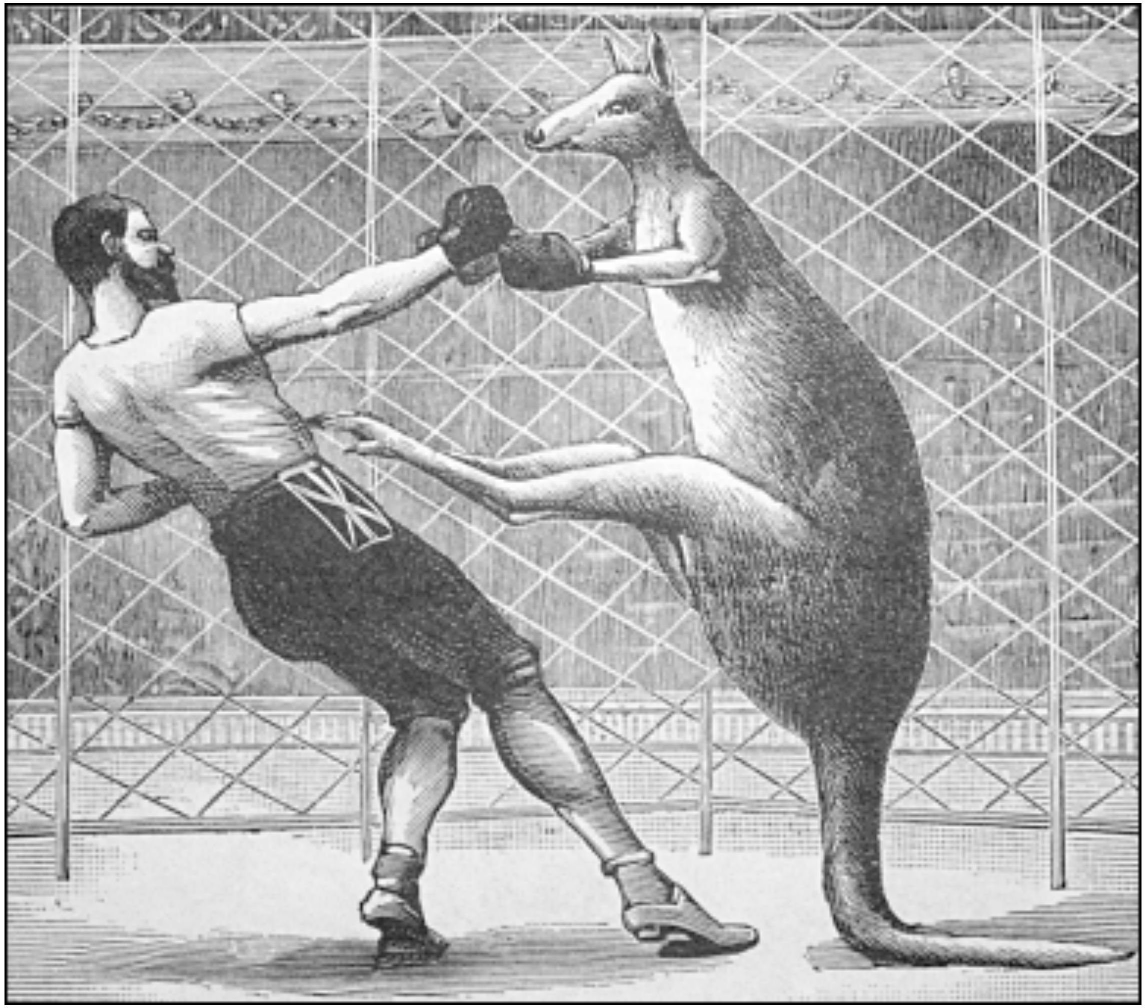
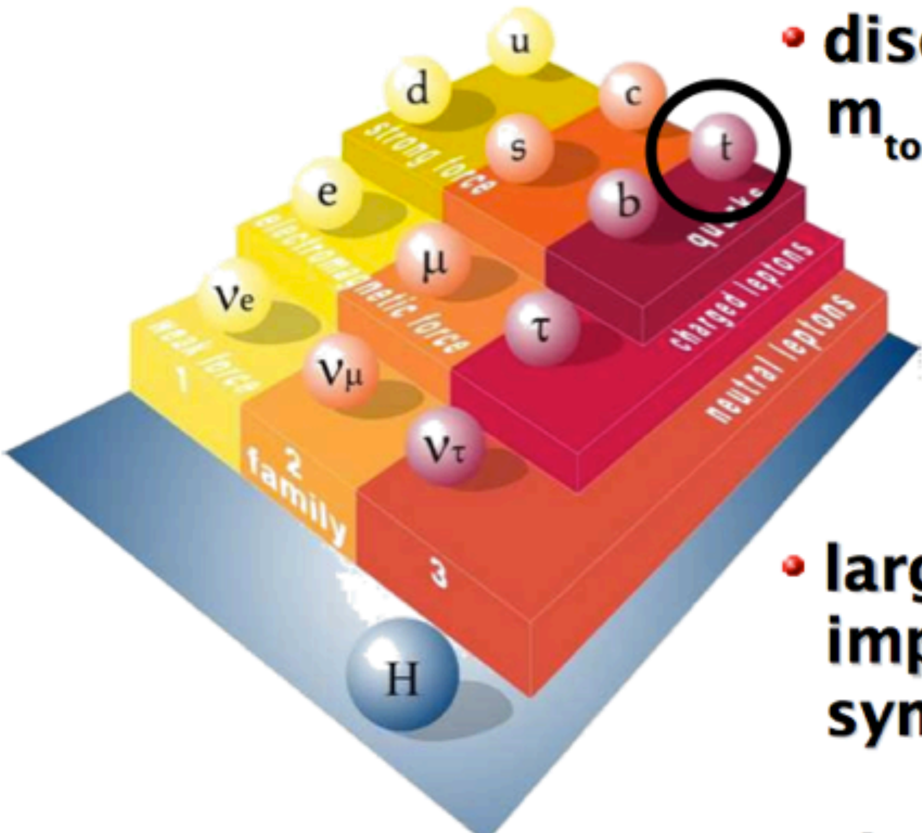
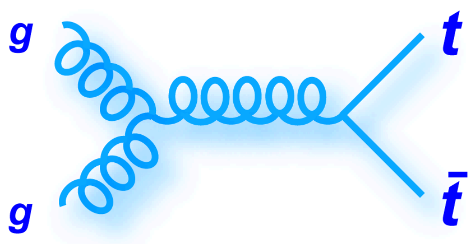


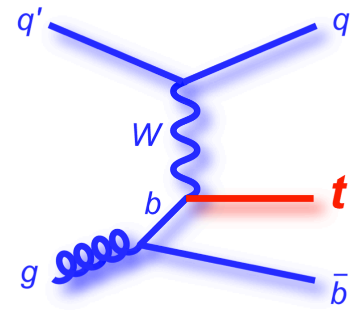
The Top Quark



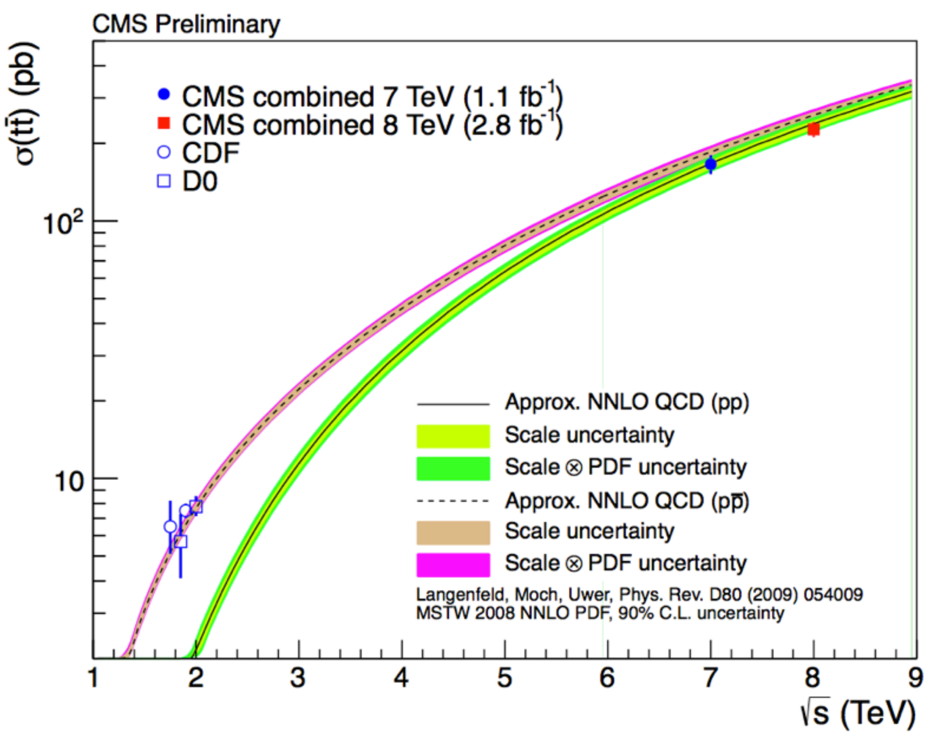
- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\text{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe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

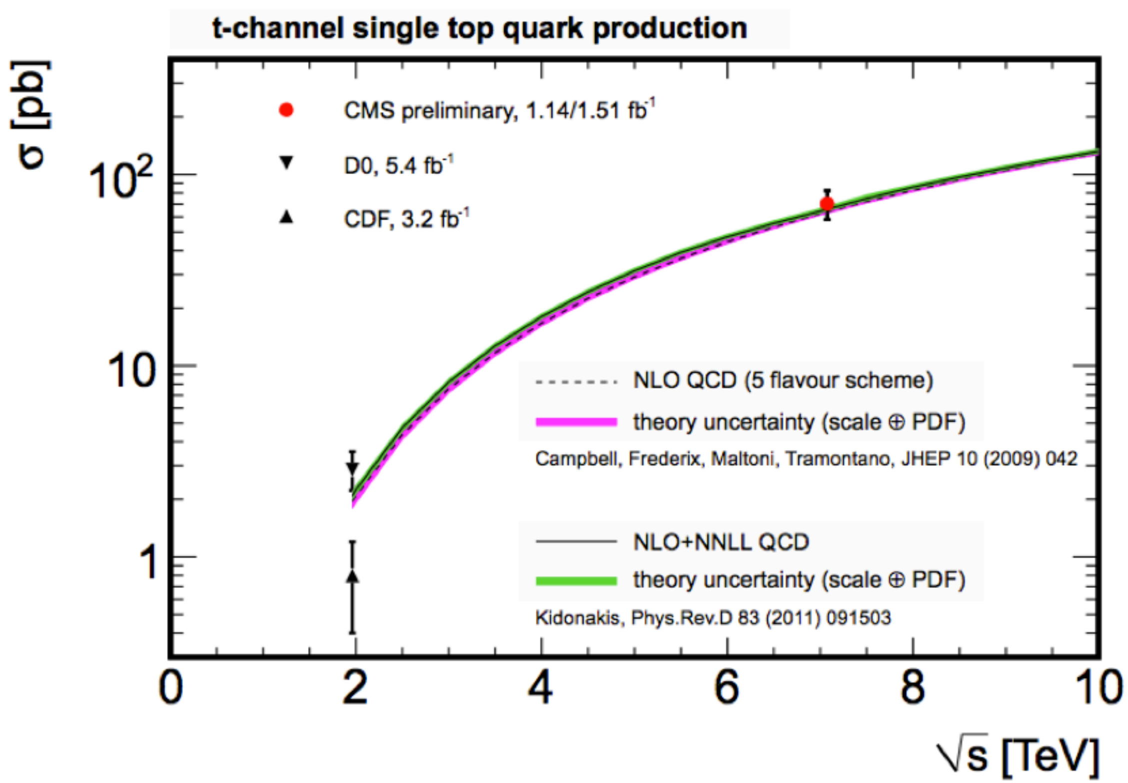
Short Summary 1st Lecture





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

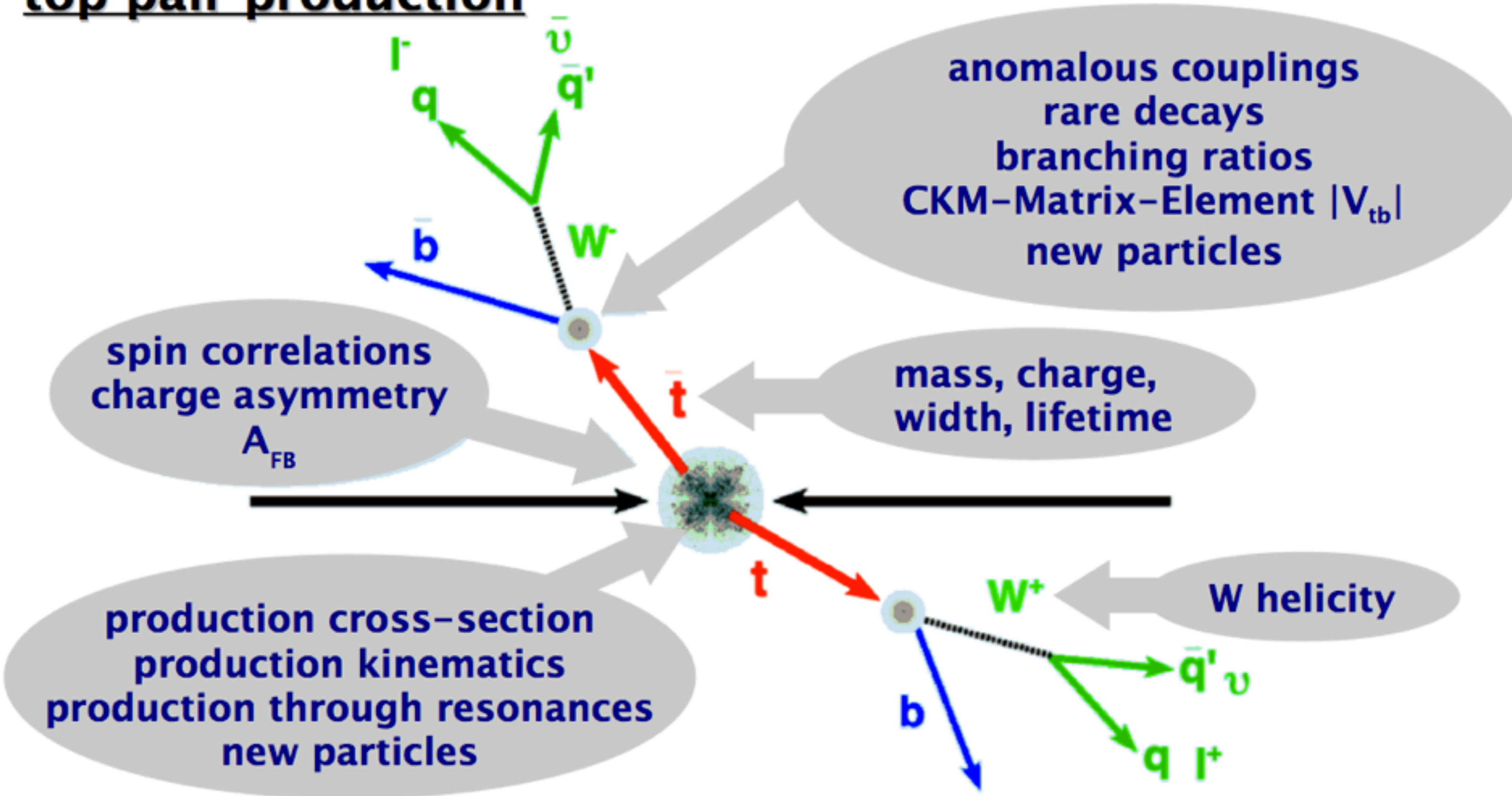




→ good agreement with SM in all channels

Top Quark Analyses

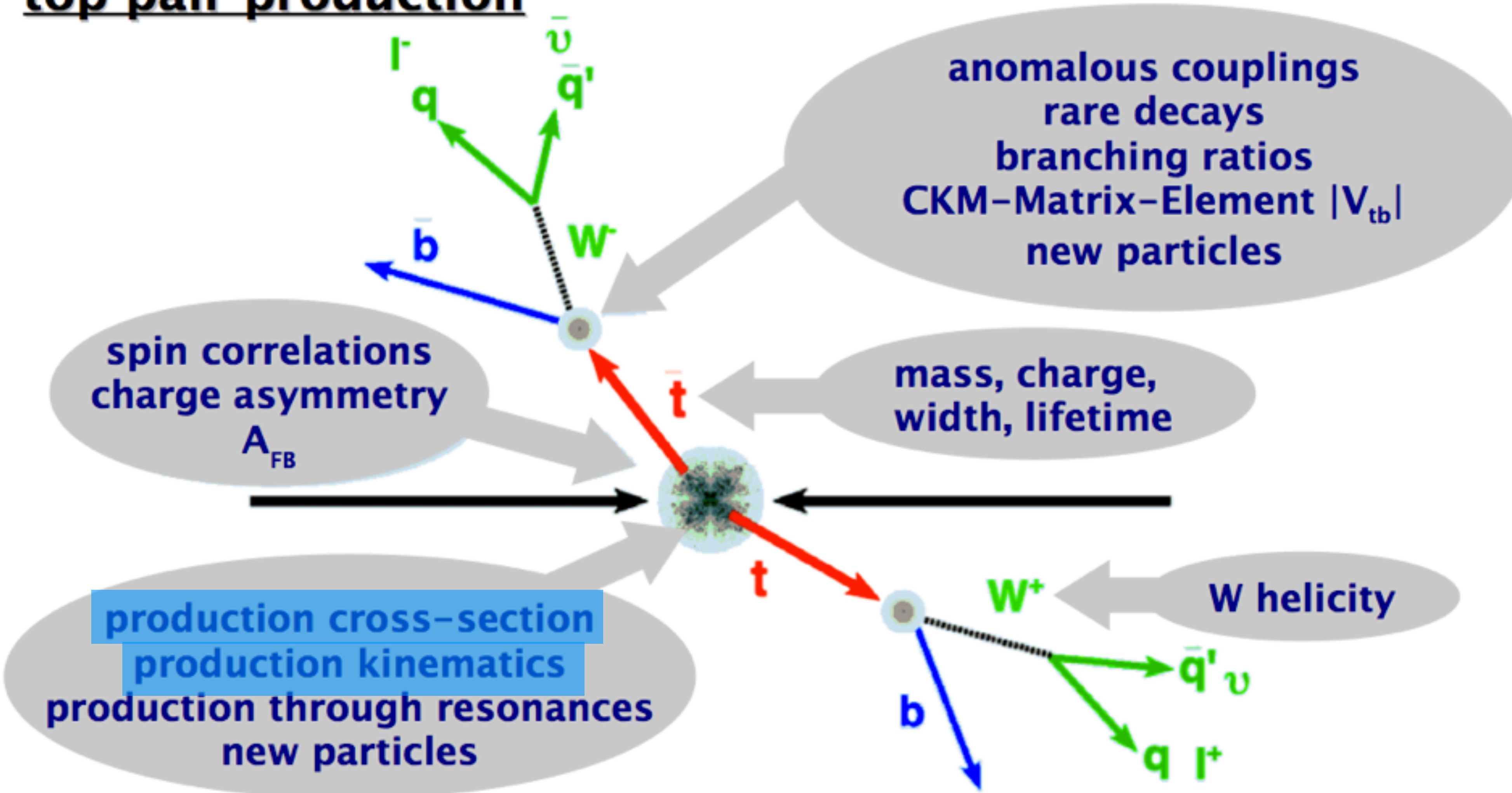
top pair production



single top production production cross section, CKM−Matrix−Element $|V_{tb}|$, anomalous couplings, searches for new particles

Top Quark Analyses: 1st Lecture

top pair production

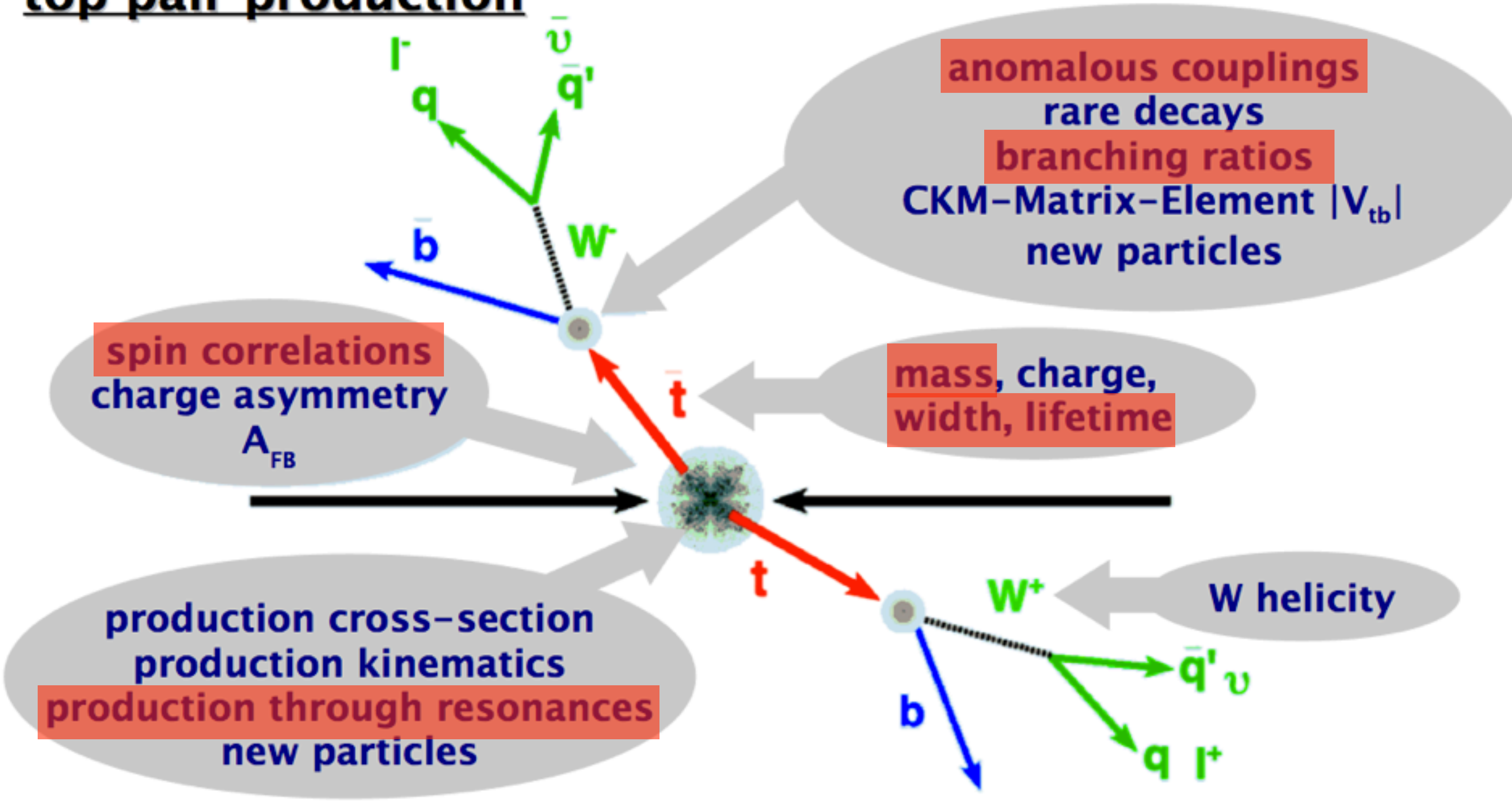


single top production

production cross section, CKM–Matrix–Element $|V_{tb}|$,
anomalous couplings, searches for new particles

Top Quark Analyses: 2nd Lecture

top pair production



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Outline 2nd Lecture

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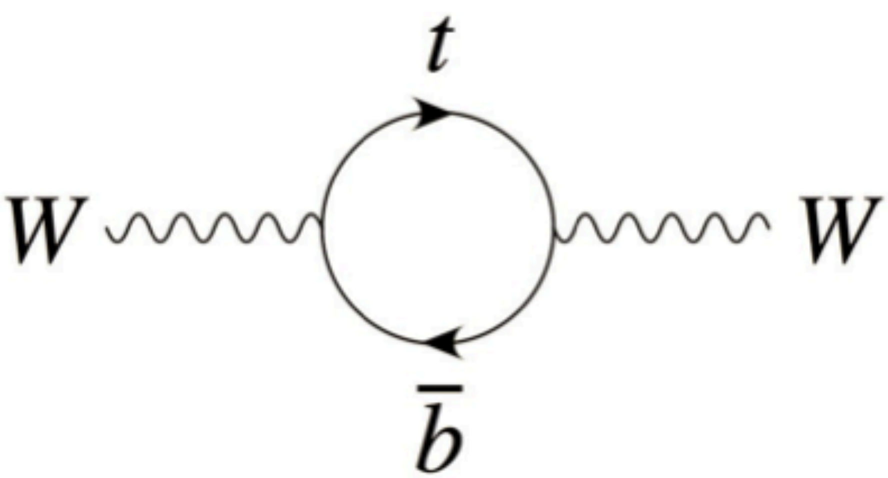
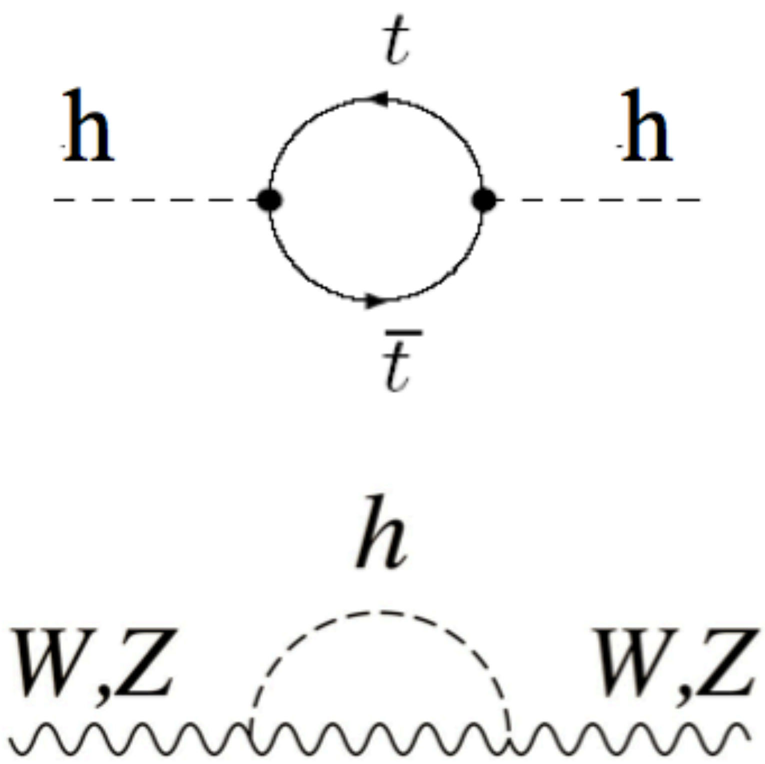
The Top Quark Mass

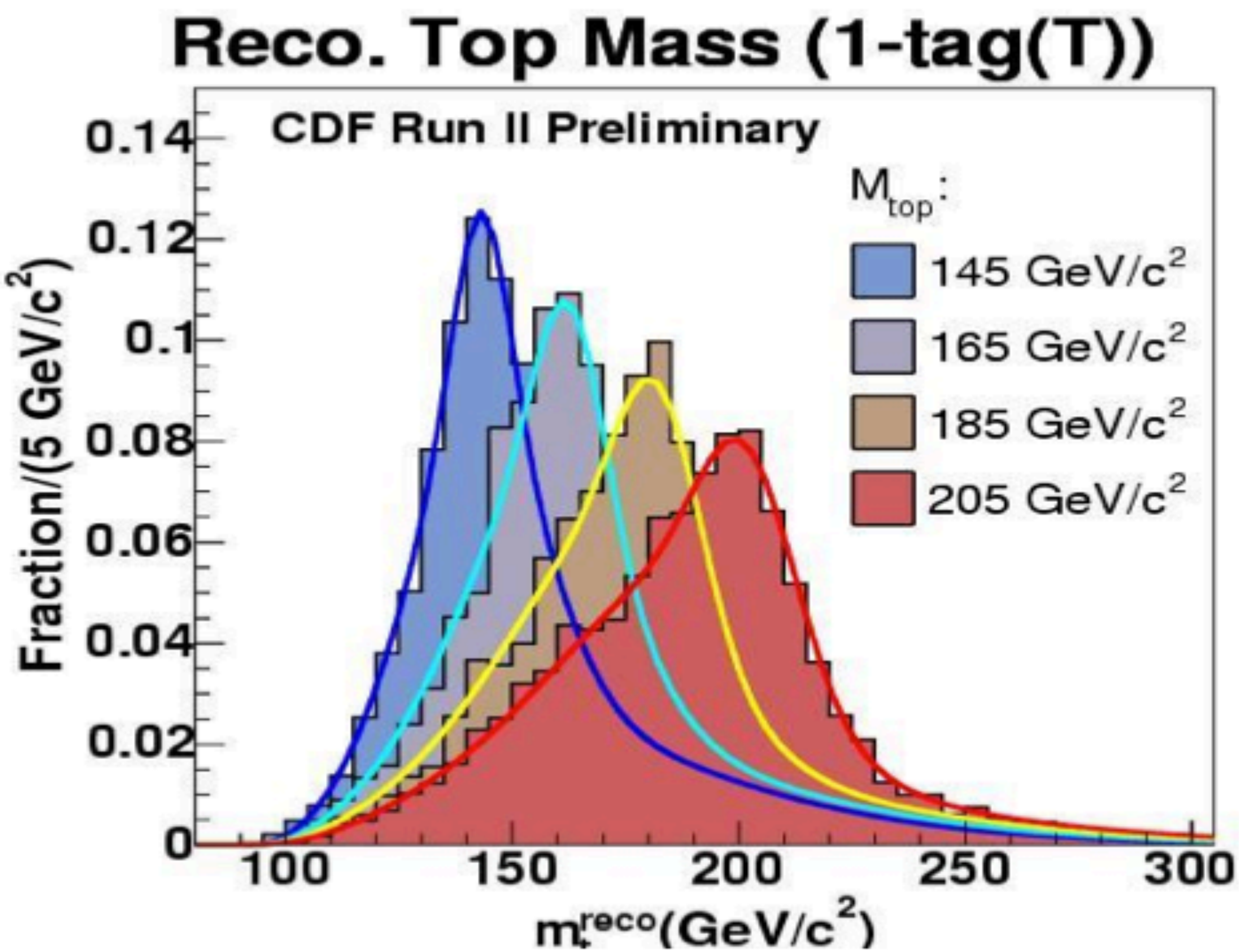
- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with W mass measurement
- prediction on **Higgs mass**





Extraction Techniques: Templates

- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses



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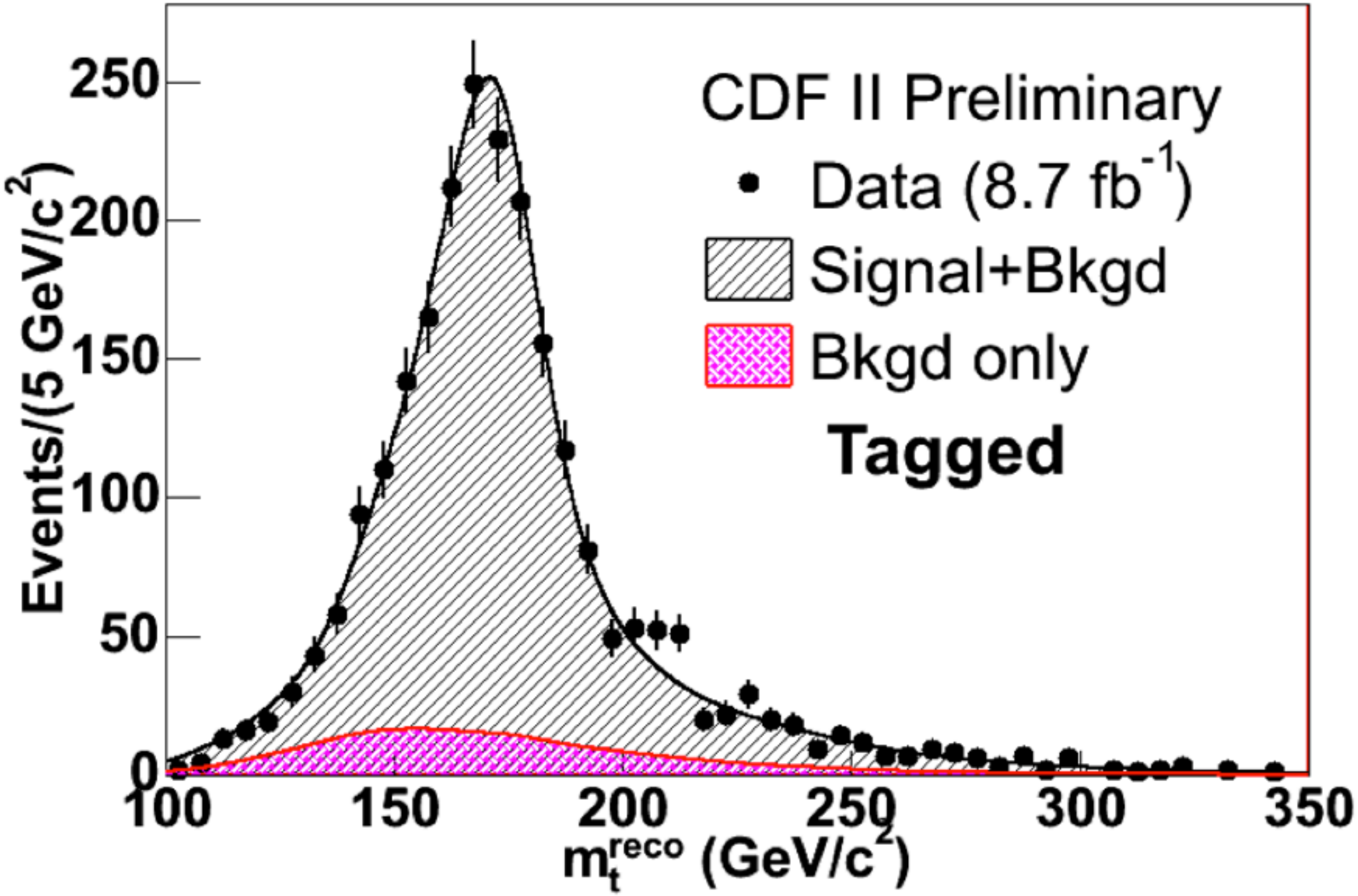
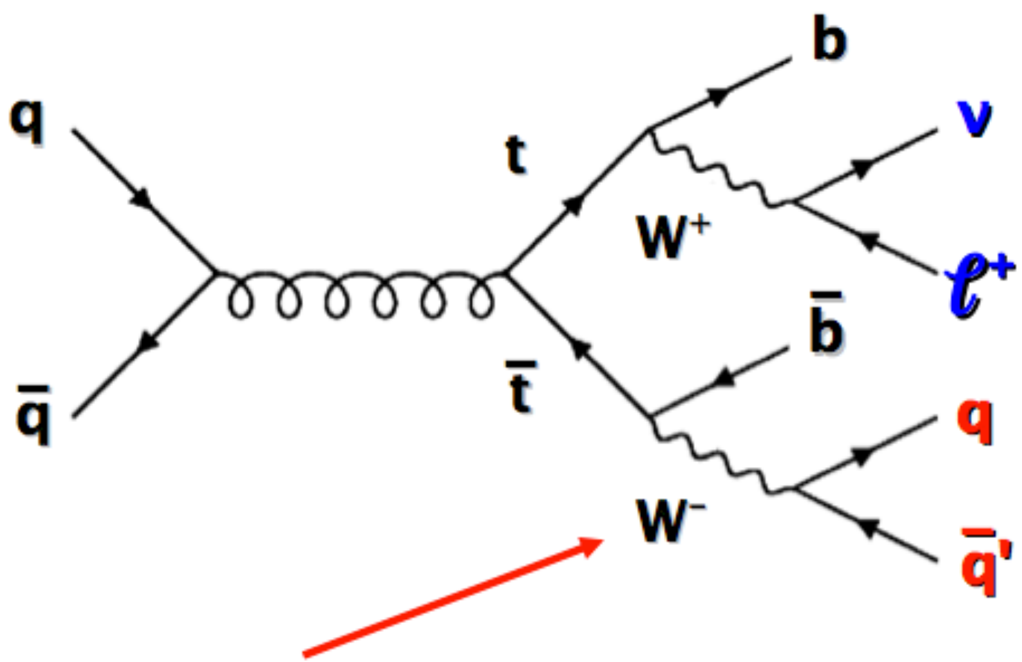


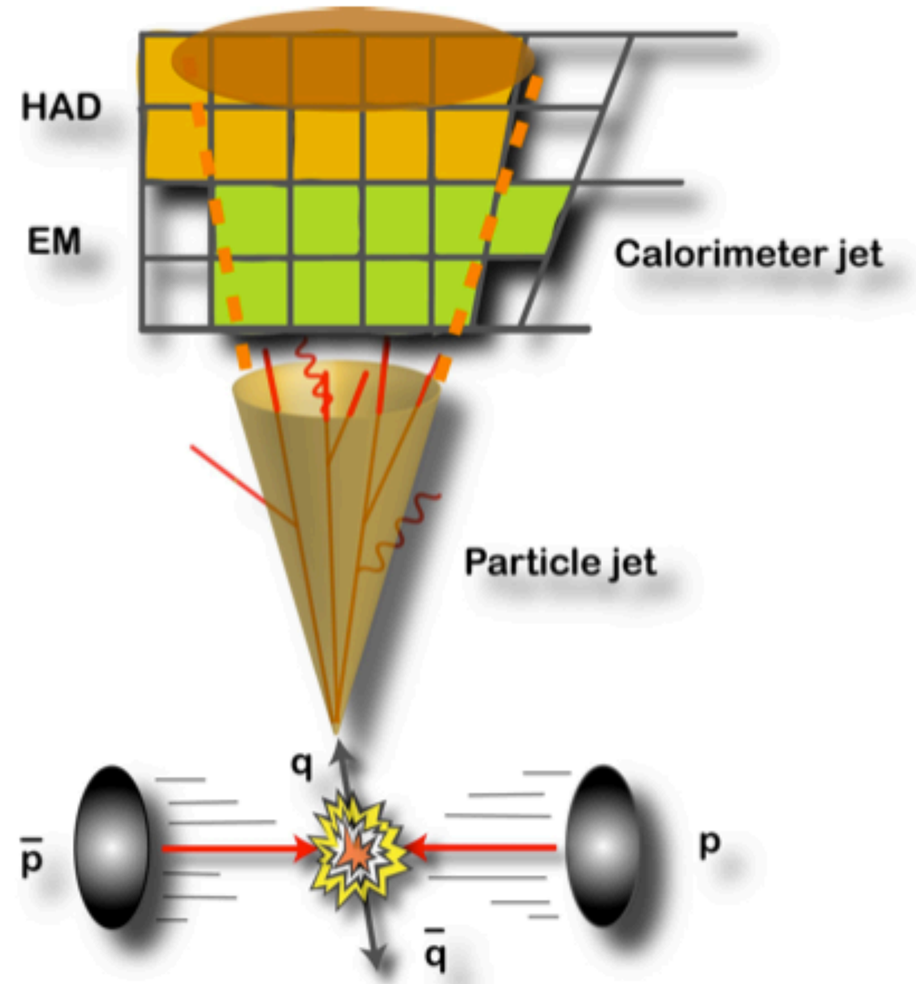
JES calibration



W mass constrains jet energy scale

jet energy scale:

translate jet into parton energy

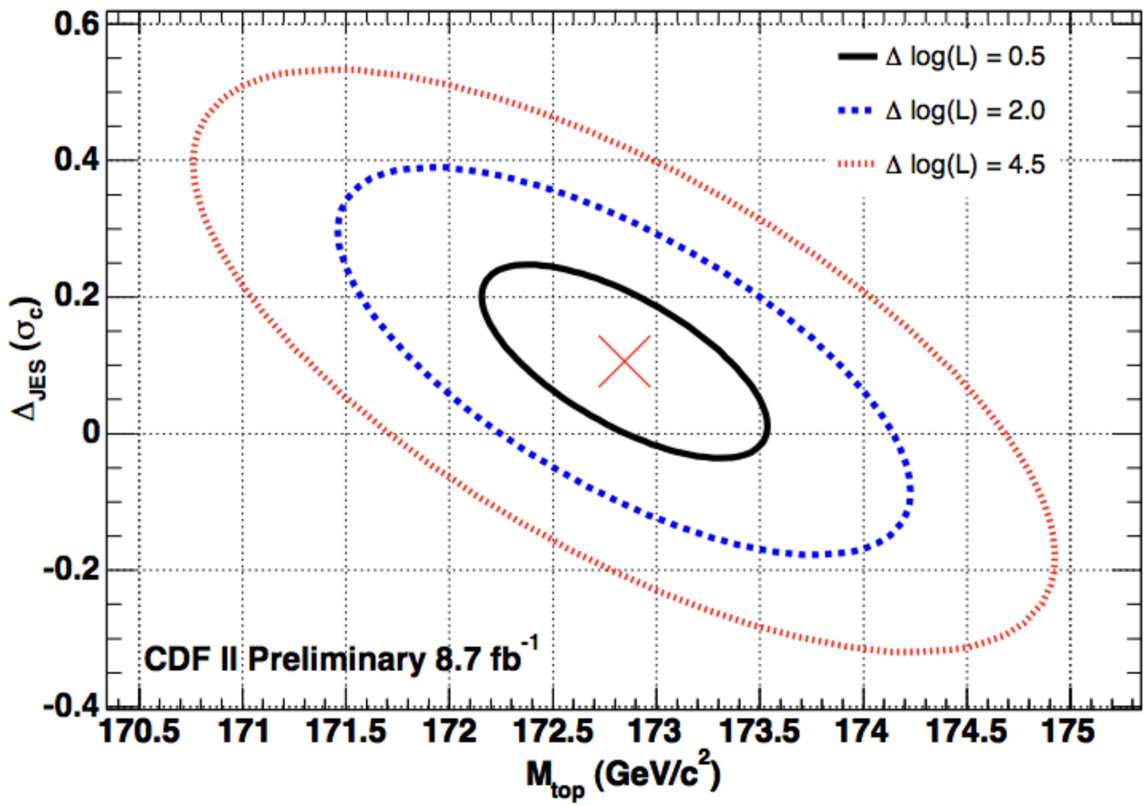


Result in l+jets Channel

maximum Likelihood fit to data:

jet energy scale:

translate jet into parton energy



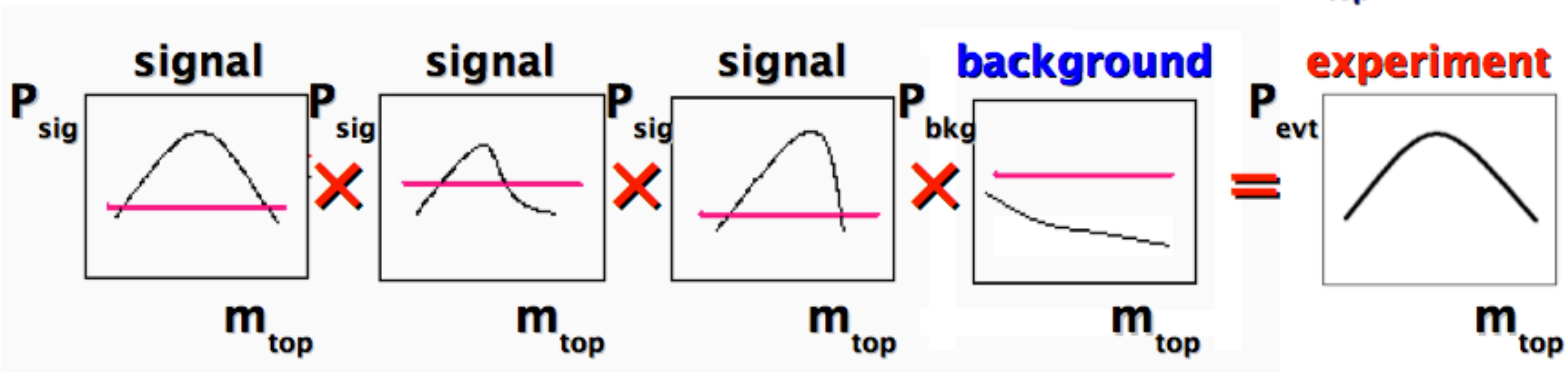
m_{top} = 172.85 ± 0.71 (stat) ± 0.85 (syst) GeV
172.85 ± 1.11 GeV

most precise single measurement

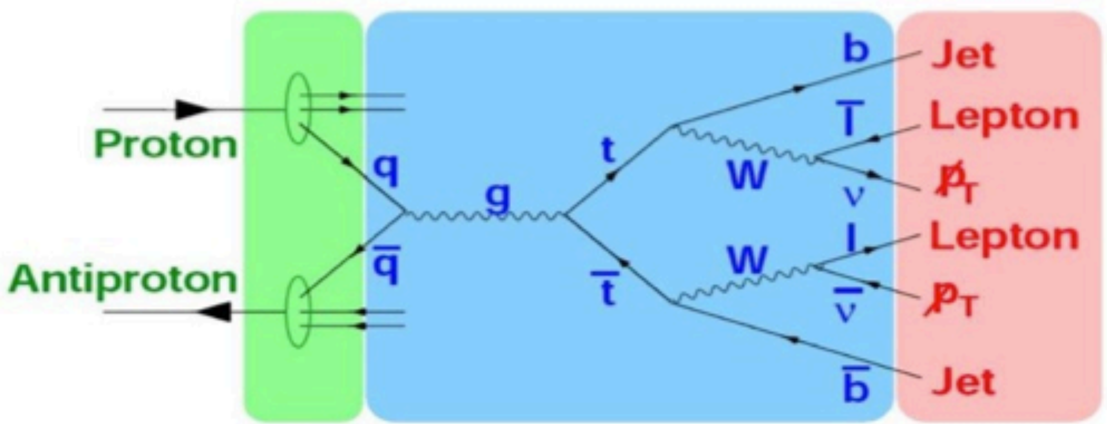
±0.6%

Extraction Techniques: Matrix Element

- probability densities for every event as function of m_{top}



$$P_{sig}(x;m_{top},JES) = Acc(x)\times\frac{1}{\sigma}\int d^n\sigma(y;m_{top})\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x,y;JES)$$



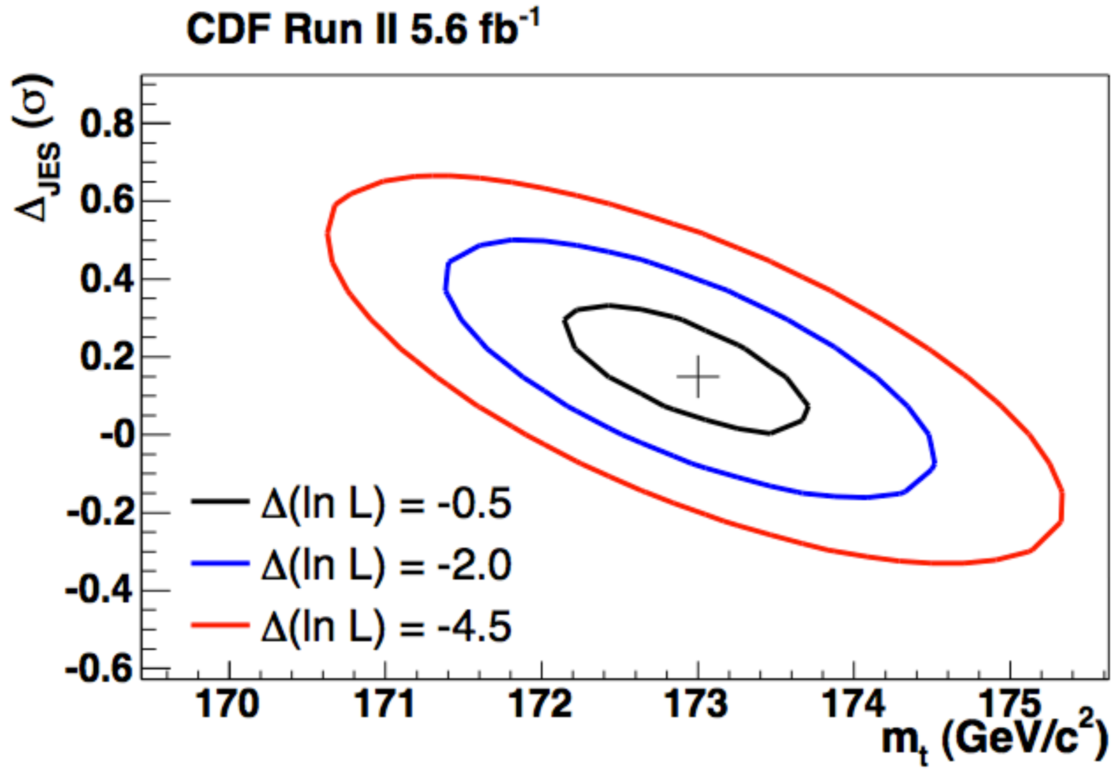
PDF's LO-Matrix element transfer functions (probability to measure x when y was produced)

Result in l+jets Channel

maximum Likelihood fit to data:

jet energy scale:

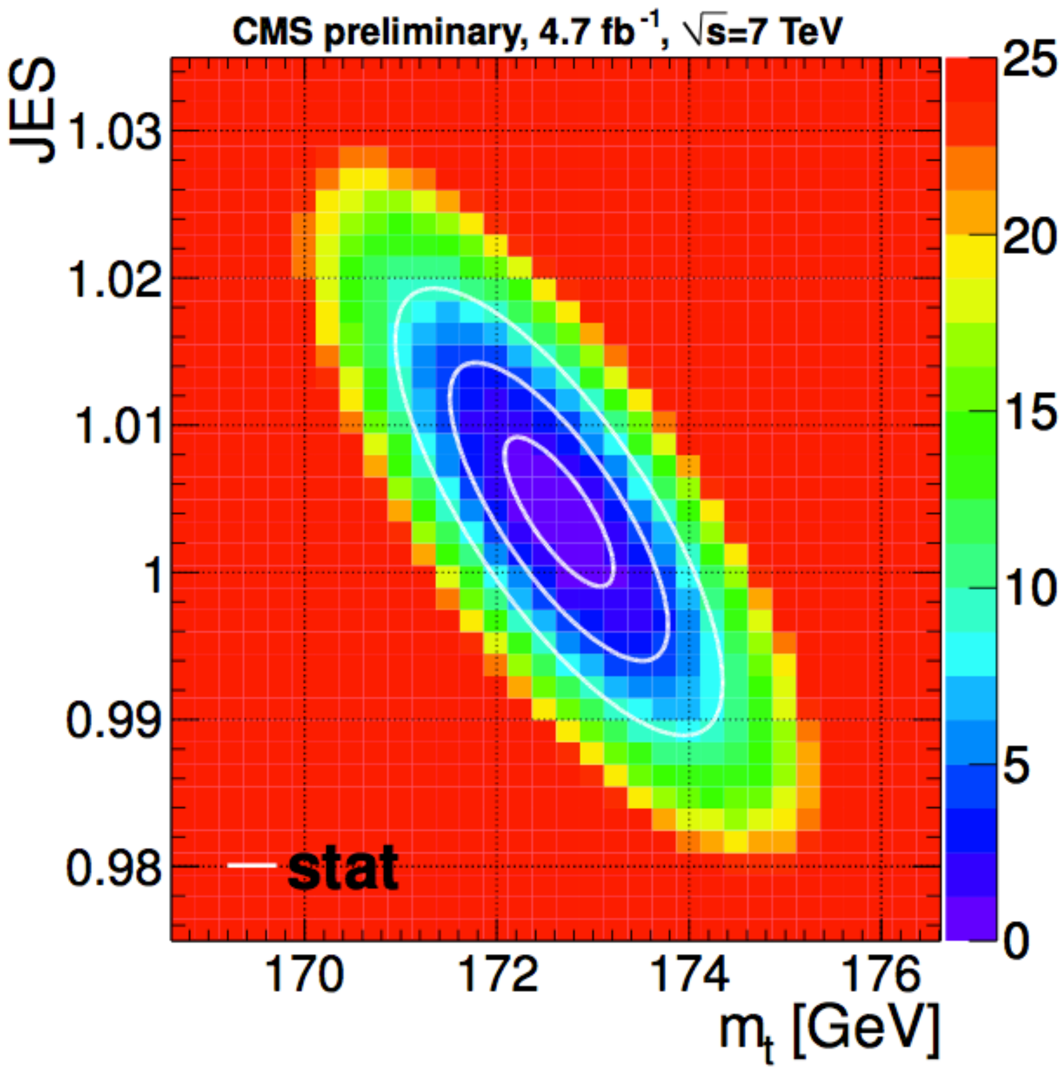
translate jet into parton energy



m_{top} = 173.0 ± 0.7 (stat) ± 0.6 (JES) ± 0.9 (syst) GeV
= 173.0 ± 1.2 GeV

±0.7%

Result in l+jets Channel

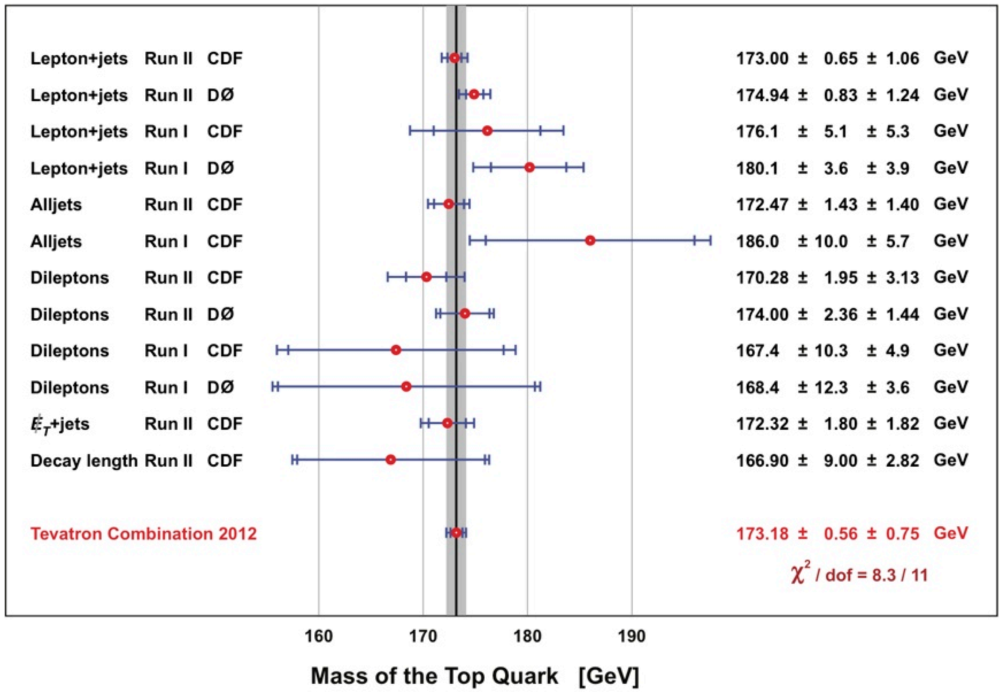


ideogram method

m_{top} = 172.6 ± 0.7 (stat+JES) ± 1.2 (syst) GeV **±0.8%**

Top Mass Combinations

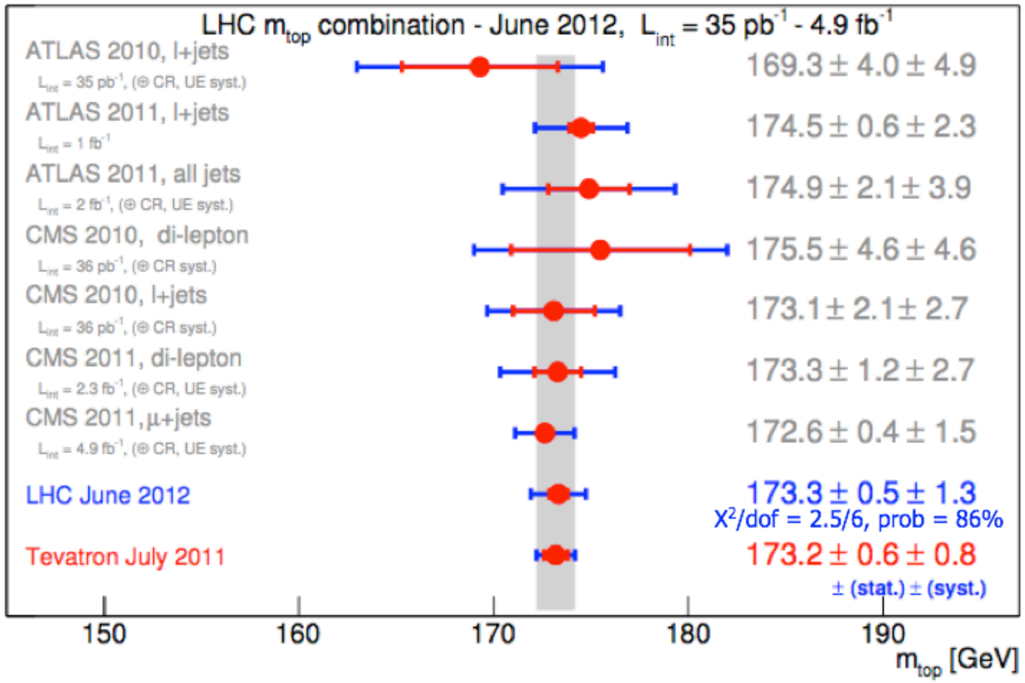
Tevatron



$$m_t^{comb} = 173.18 \pm 0.56\,(\text{stat}) \pm 0.75\,(\text{syst})\ \text{GeV}$$
$$= 173.18 \pm 0.94\ \text{GeV}$$

±0.5%

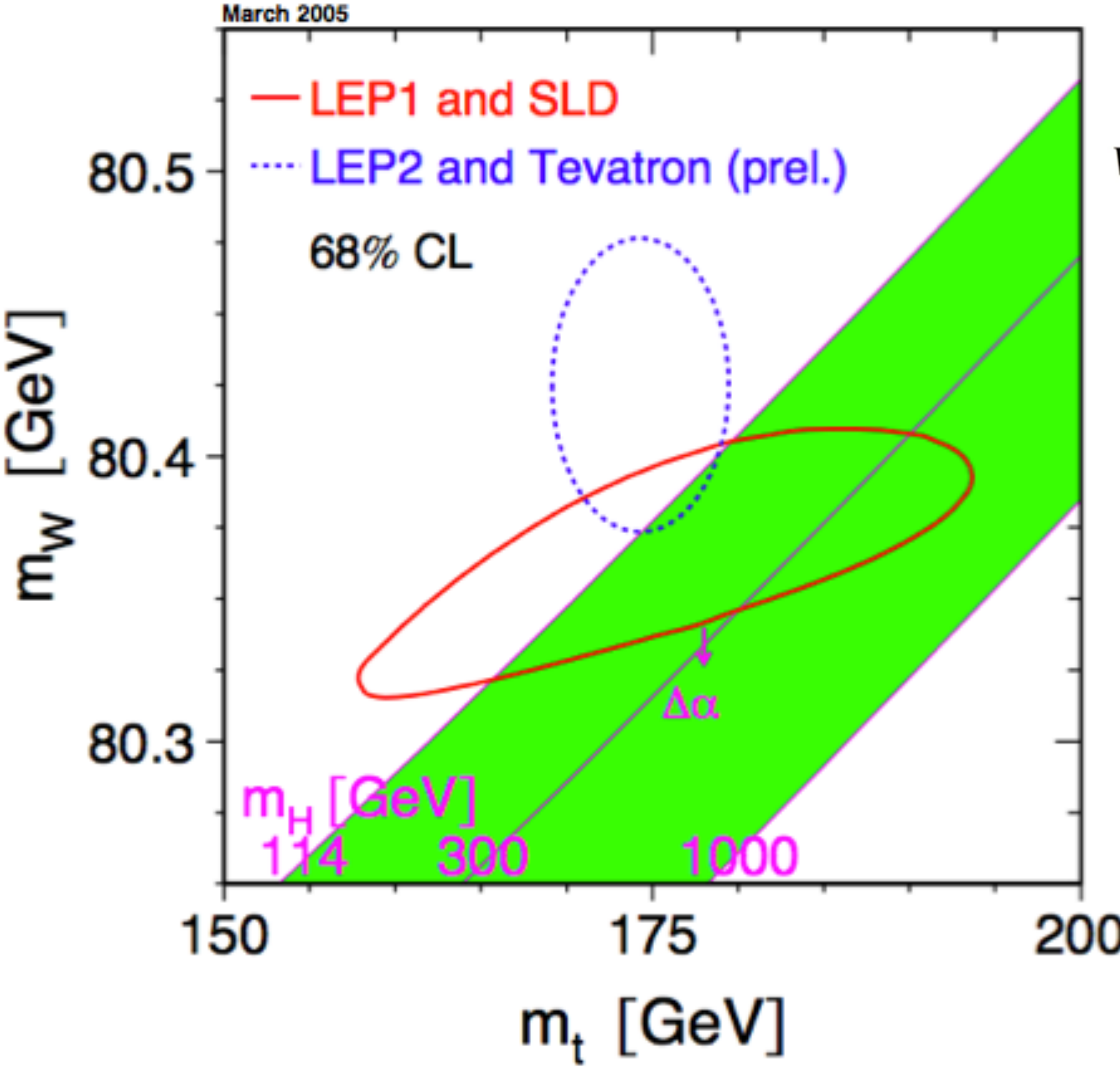
LHC

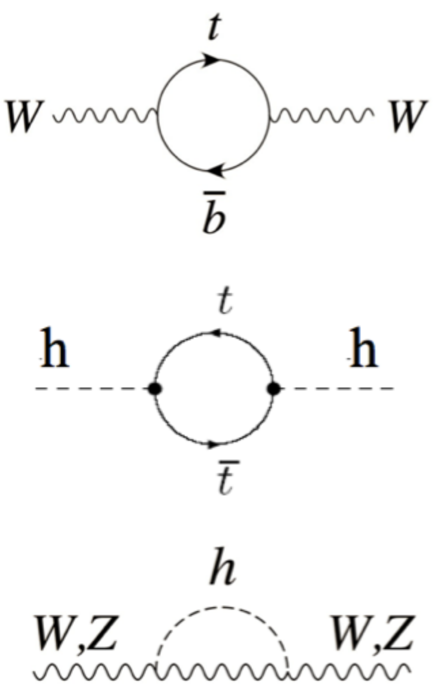


$$m_{top} = 173.3 \pm 0.5\ (\text{stat}) \pm 1.3\ (\text{syst})\ \ \text{GeV}$$

±0.8%

History m_{top} vs. M_W





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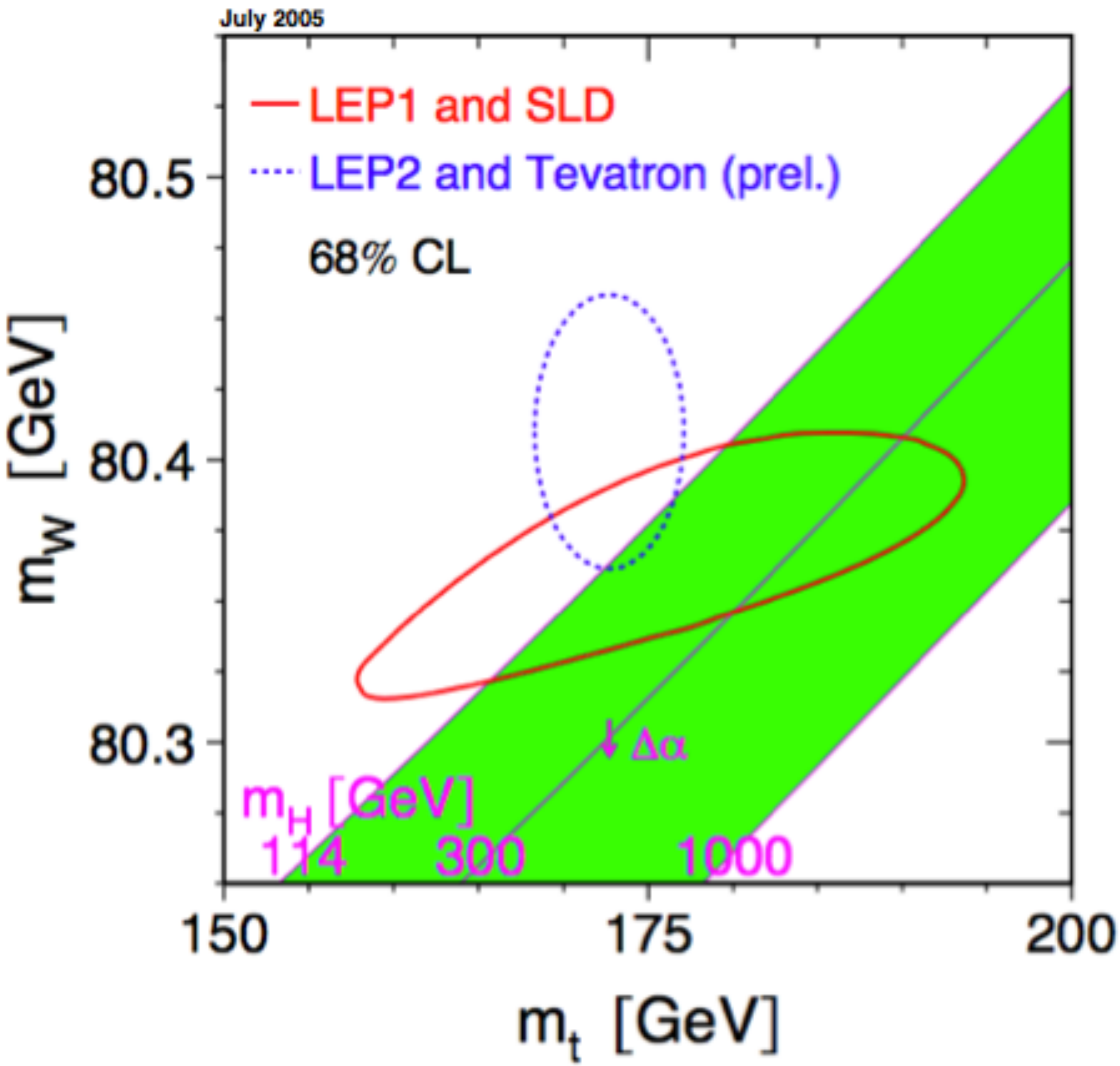

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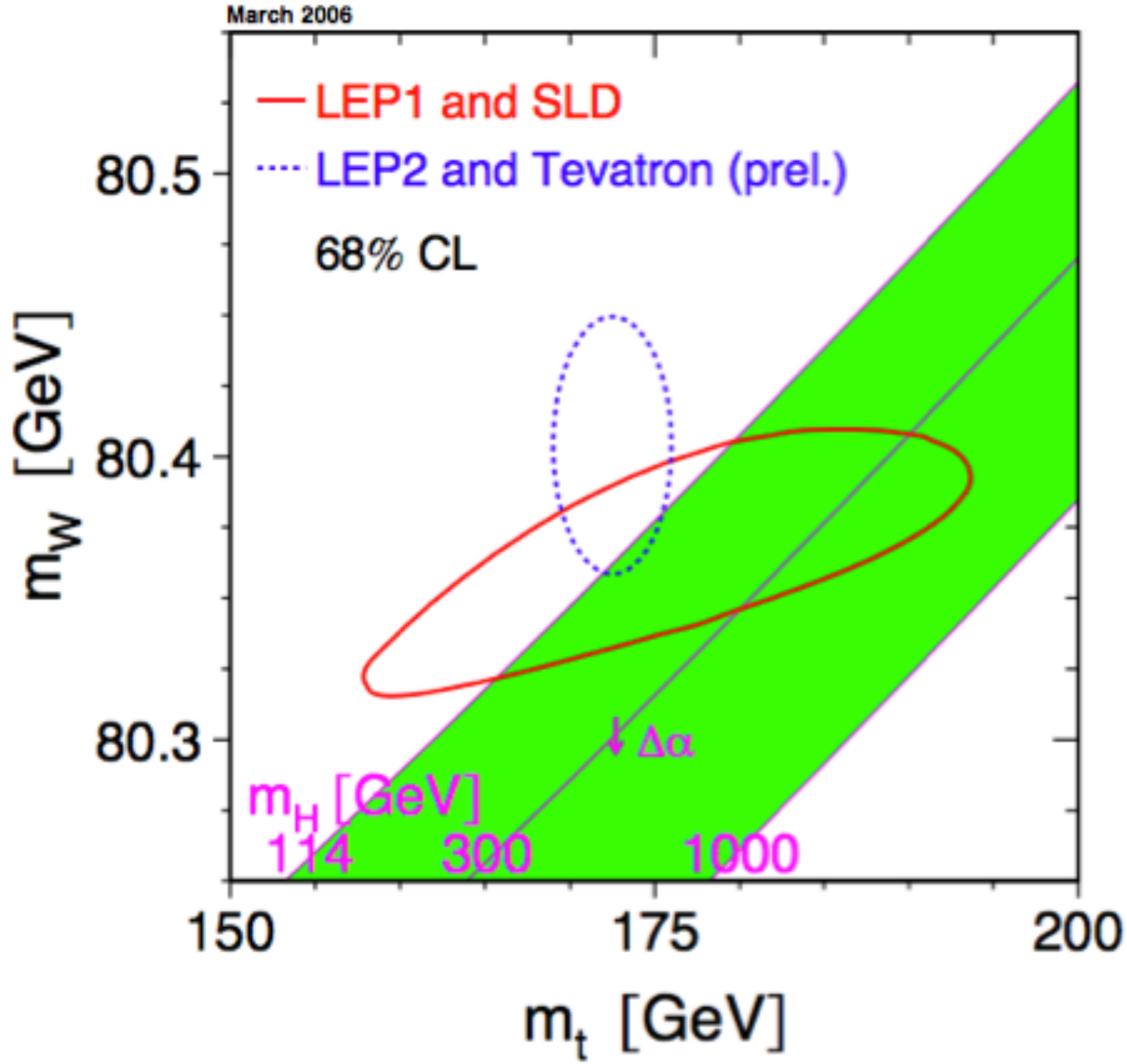

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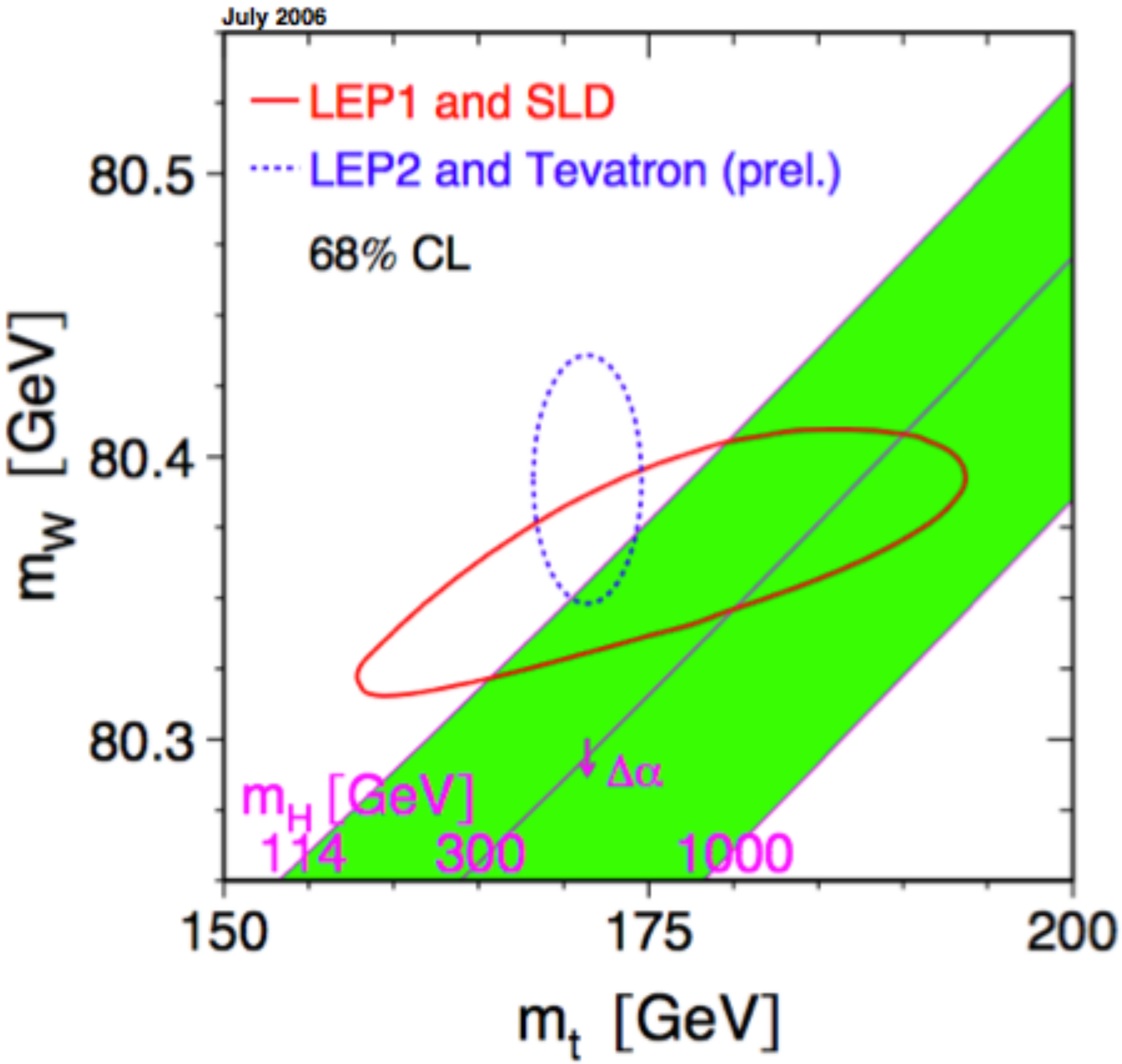

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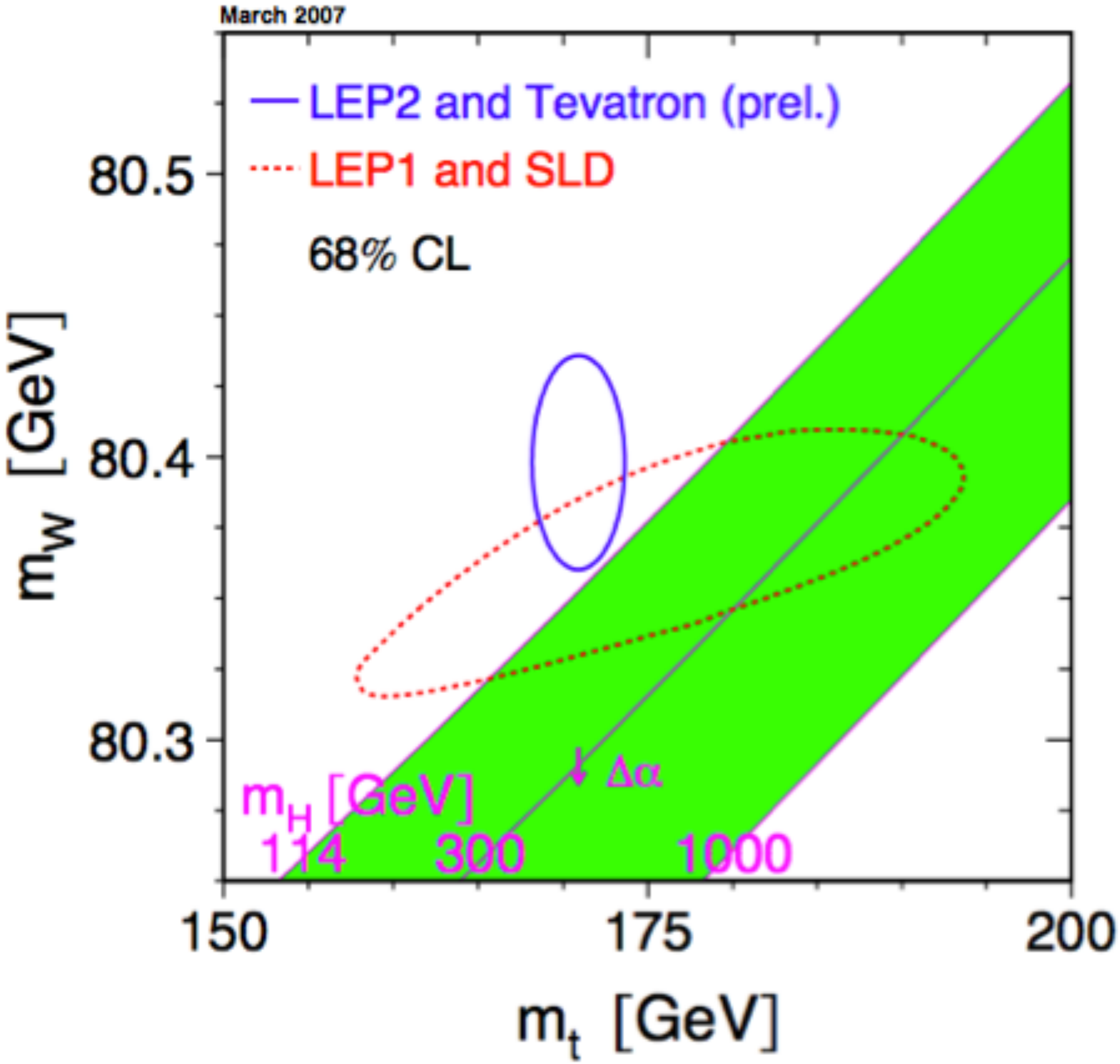

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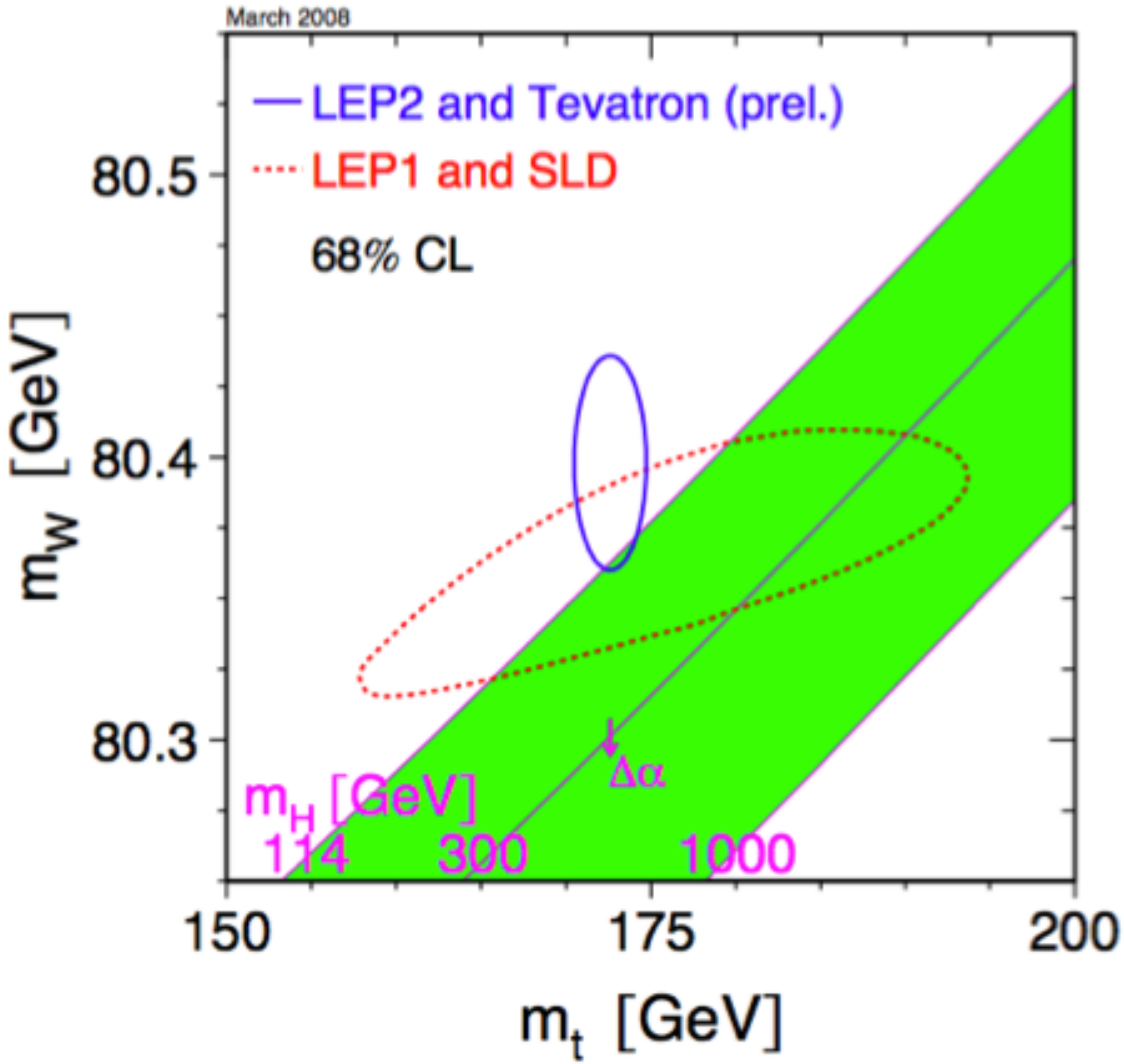

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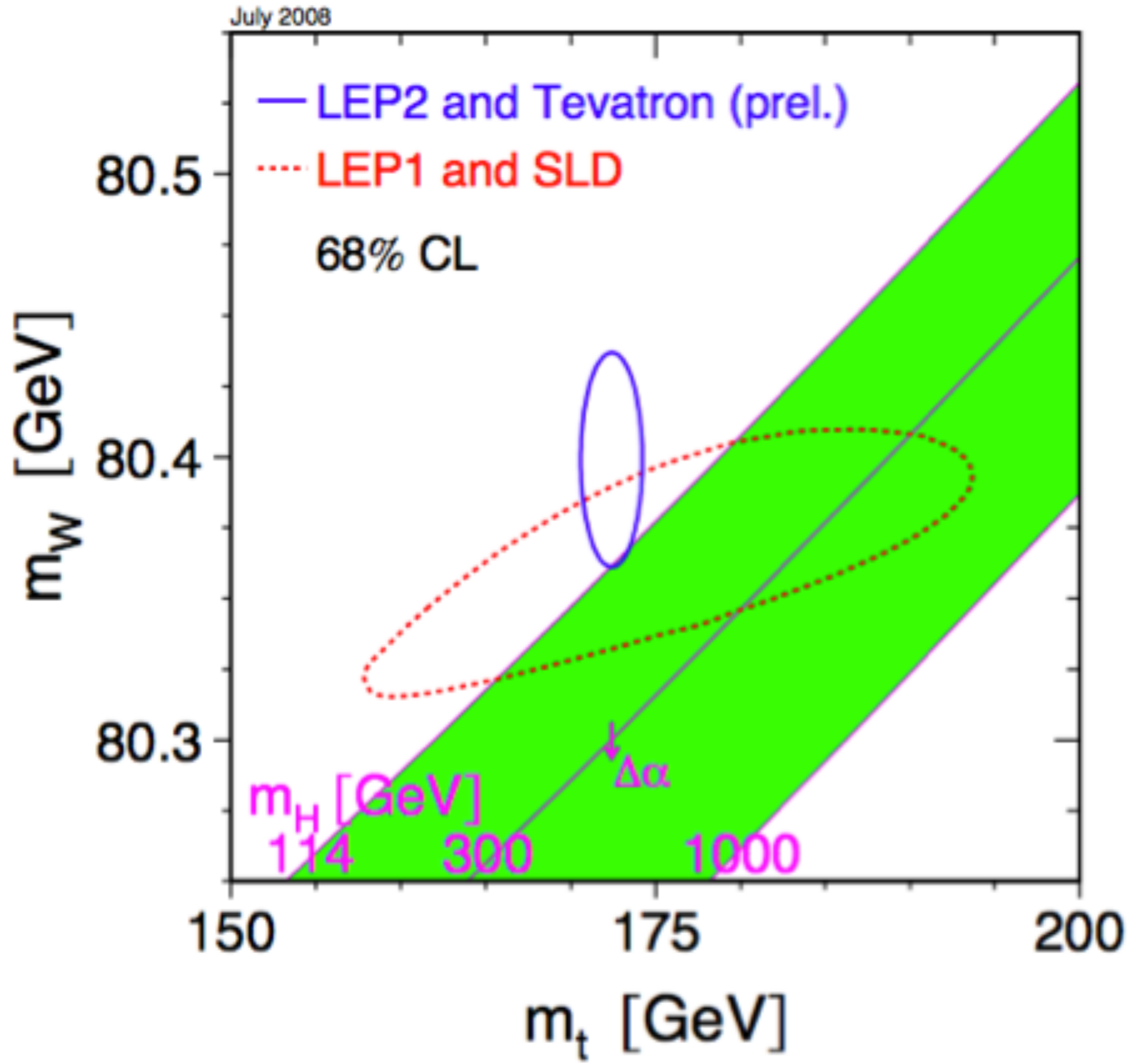

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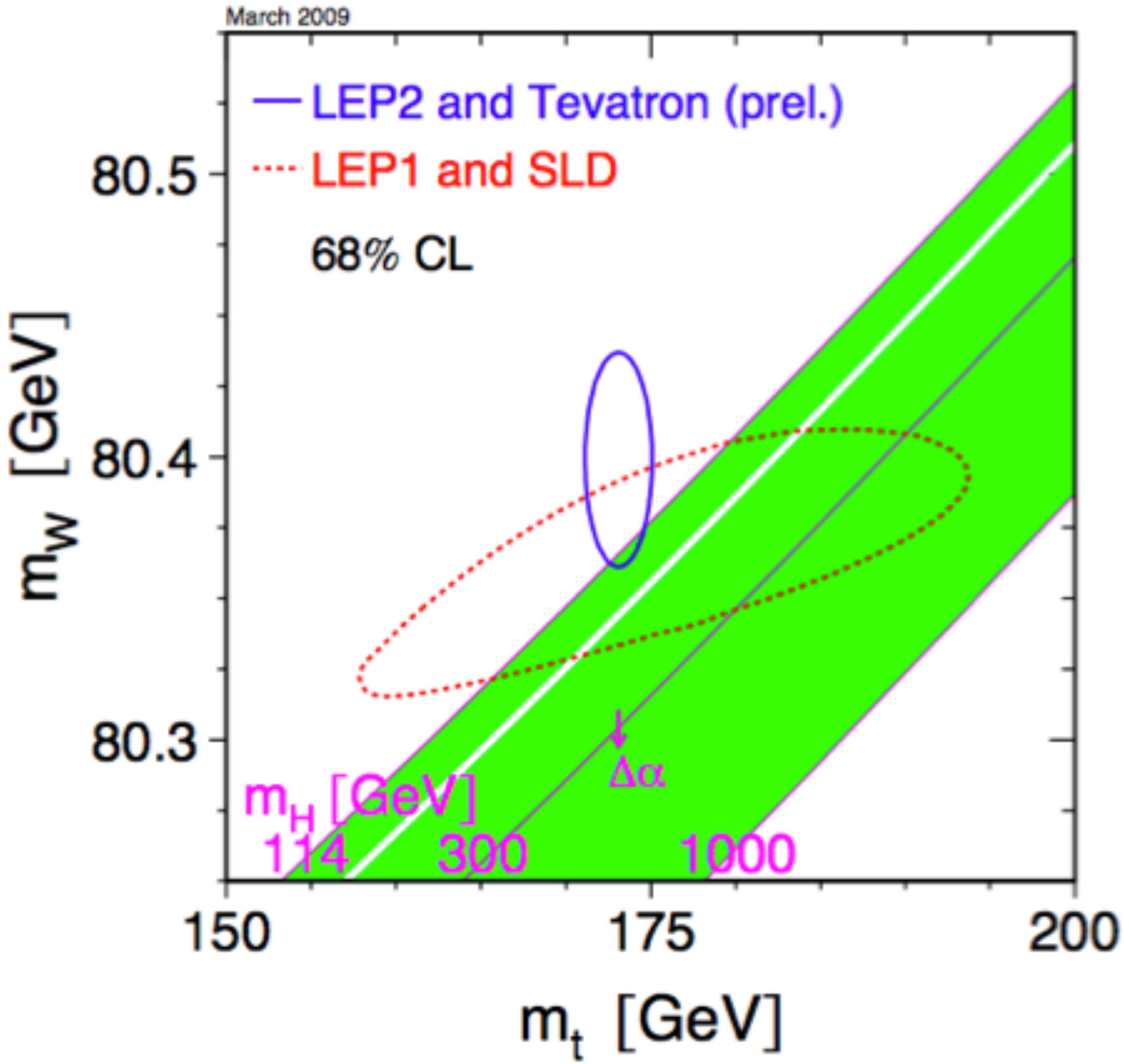

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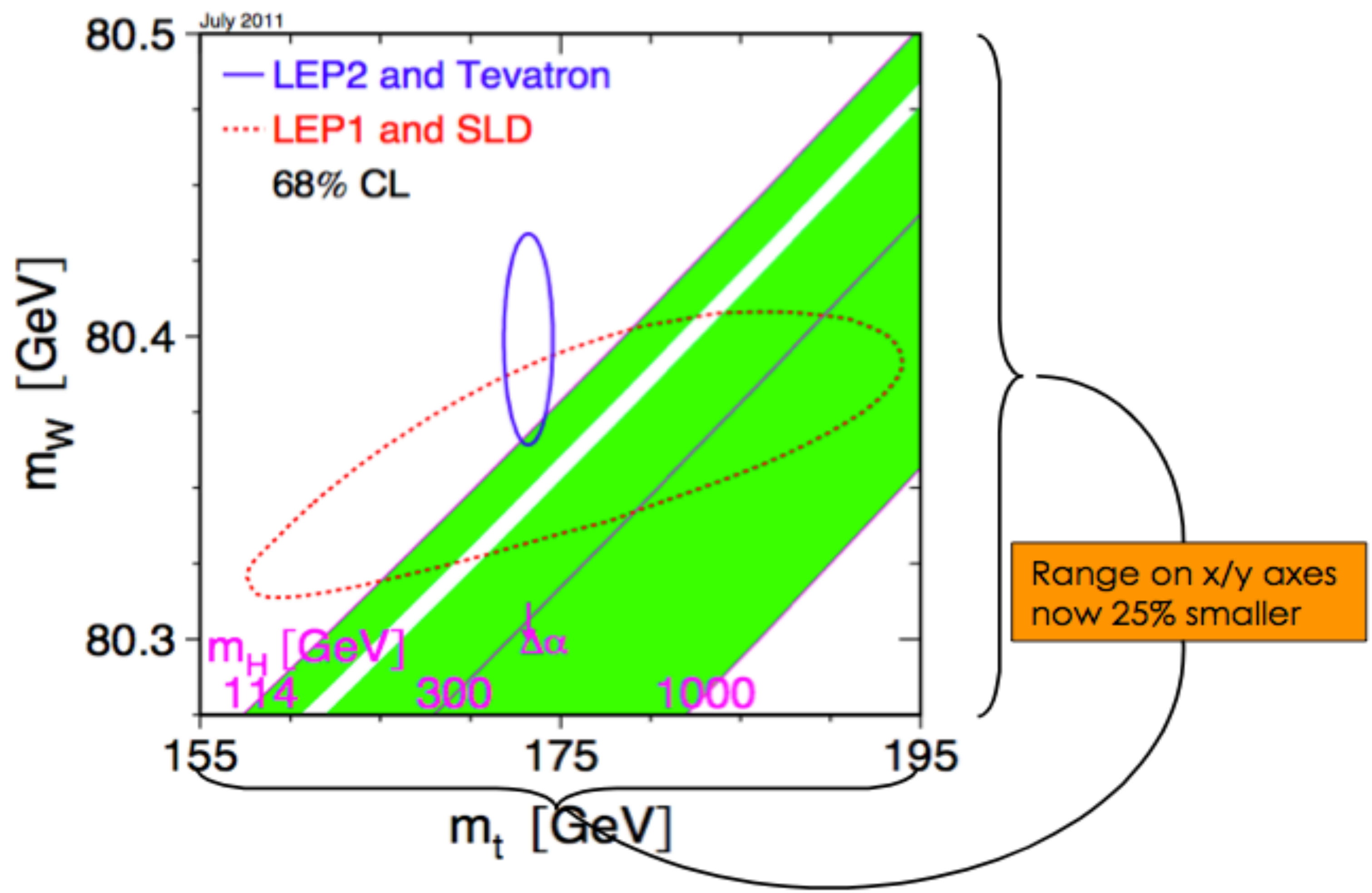

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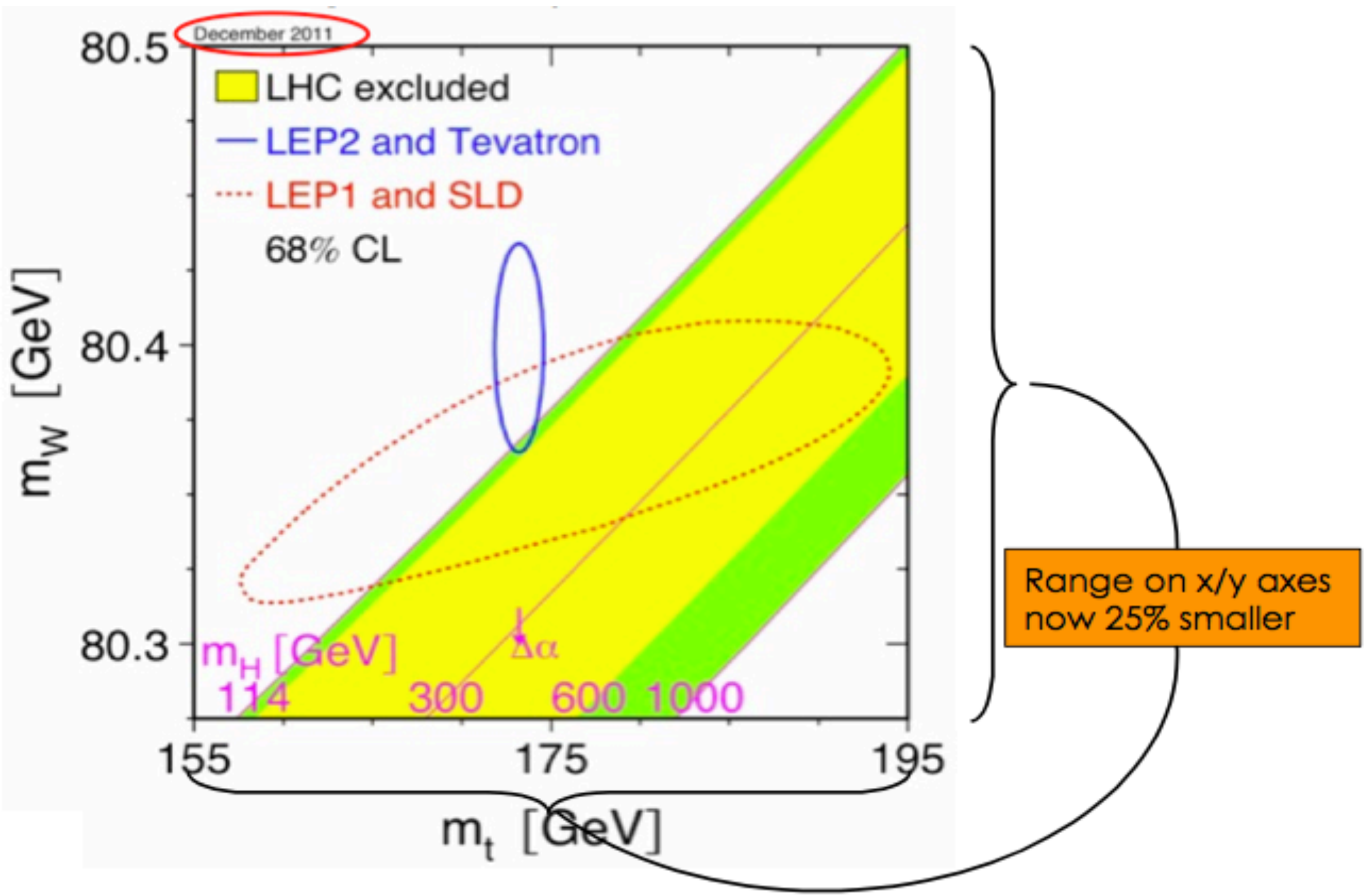

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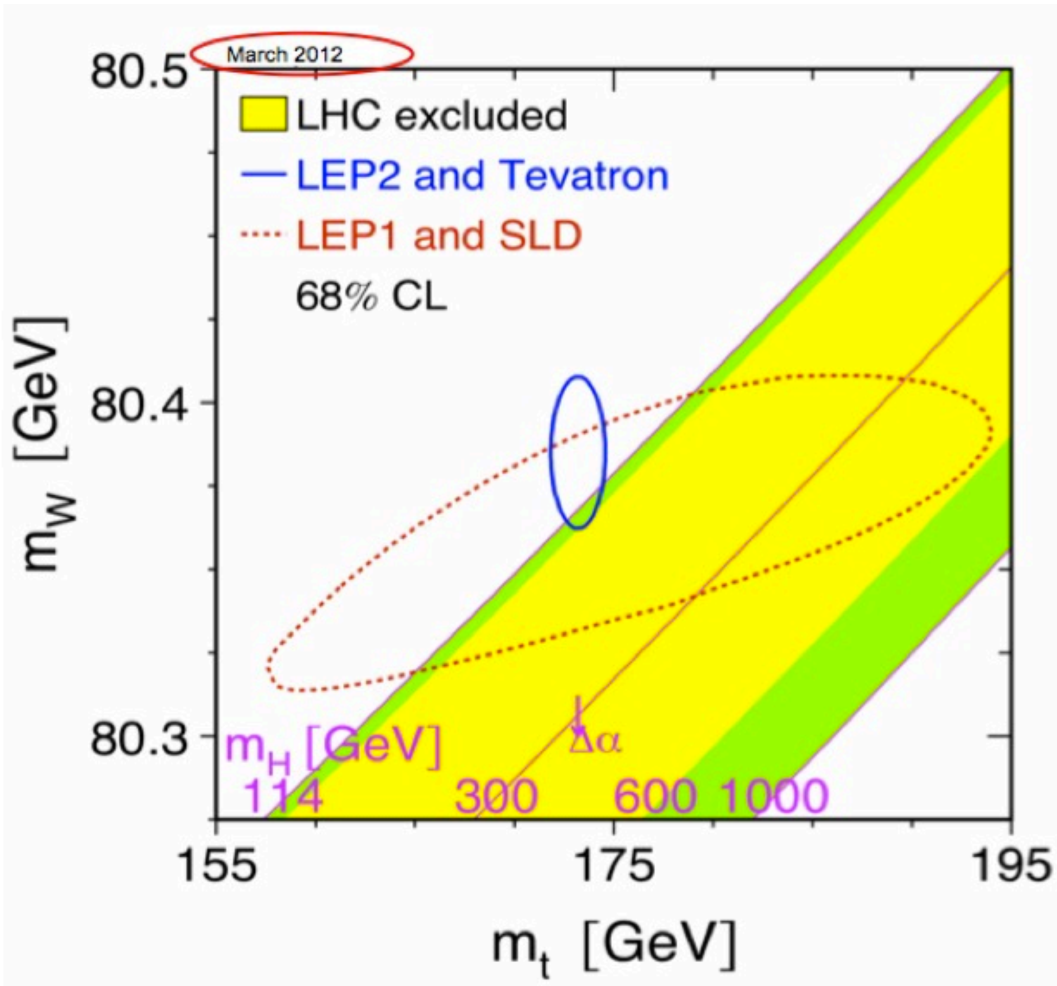

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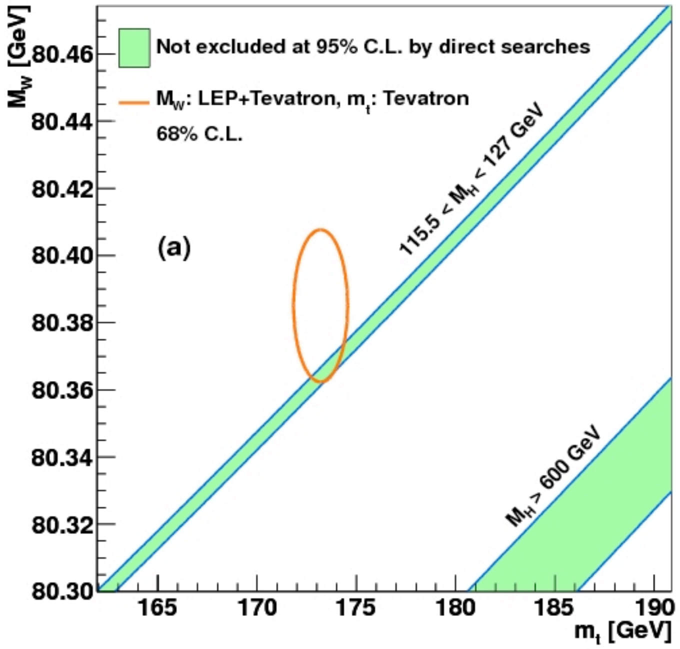
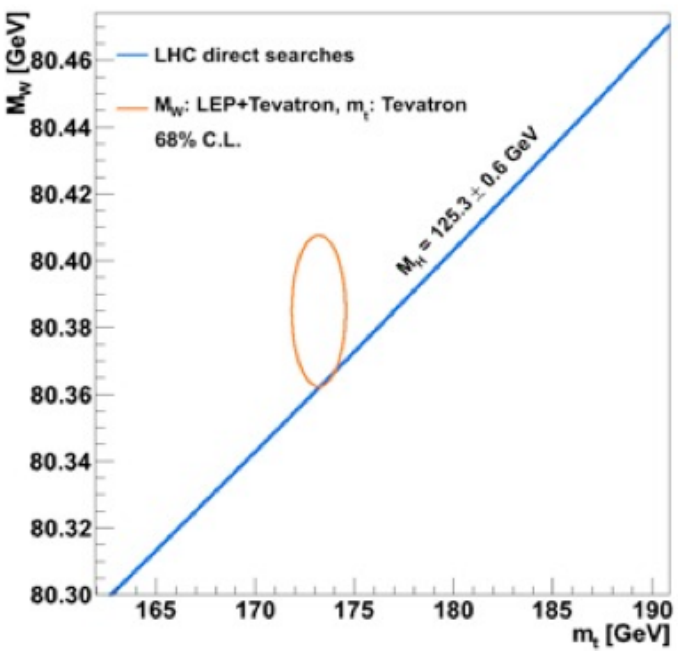


History m_{top} vs. M_W

July 2012

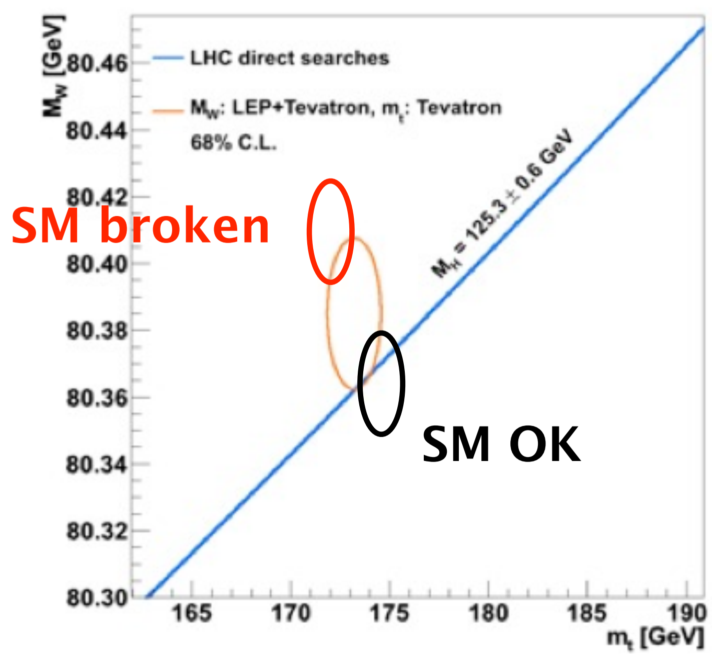


→ Standard Model is self-consistent

History m_{top} vs. M_W

future:
$\Delta(m_W)$=15 MeV
$\Delta(m_t)$=1 GeV

July 2012



improved W mass measurement is critical

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!

Different Top Mass Definitions

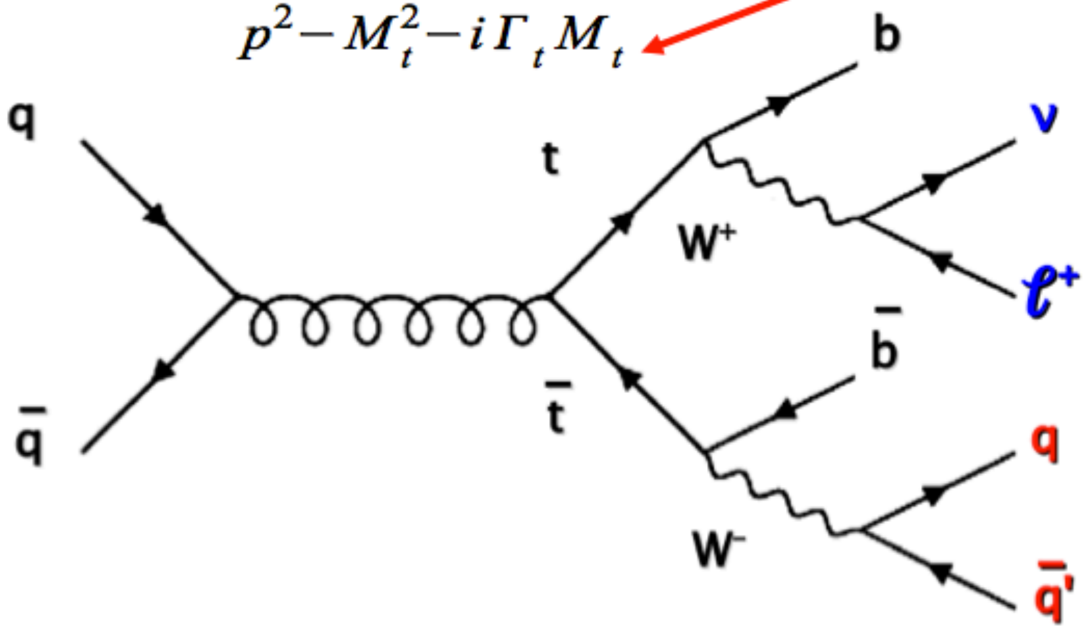
hep-ph/0001002

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

$\overline{\text{MS}}$ scheme

pole mass

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



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

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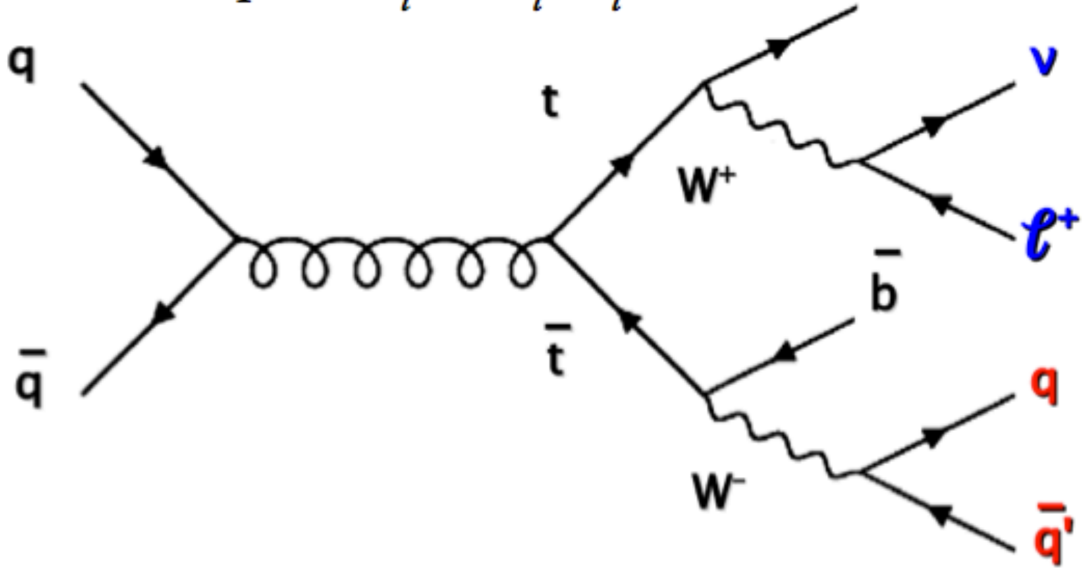
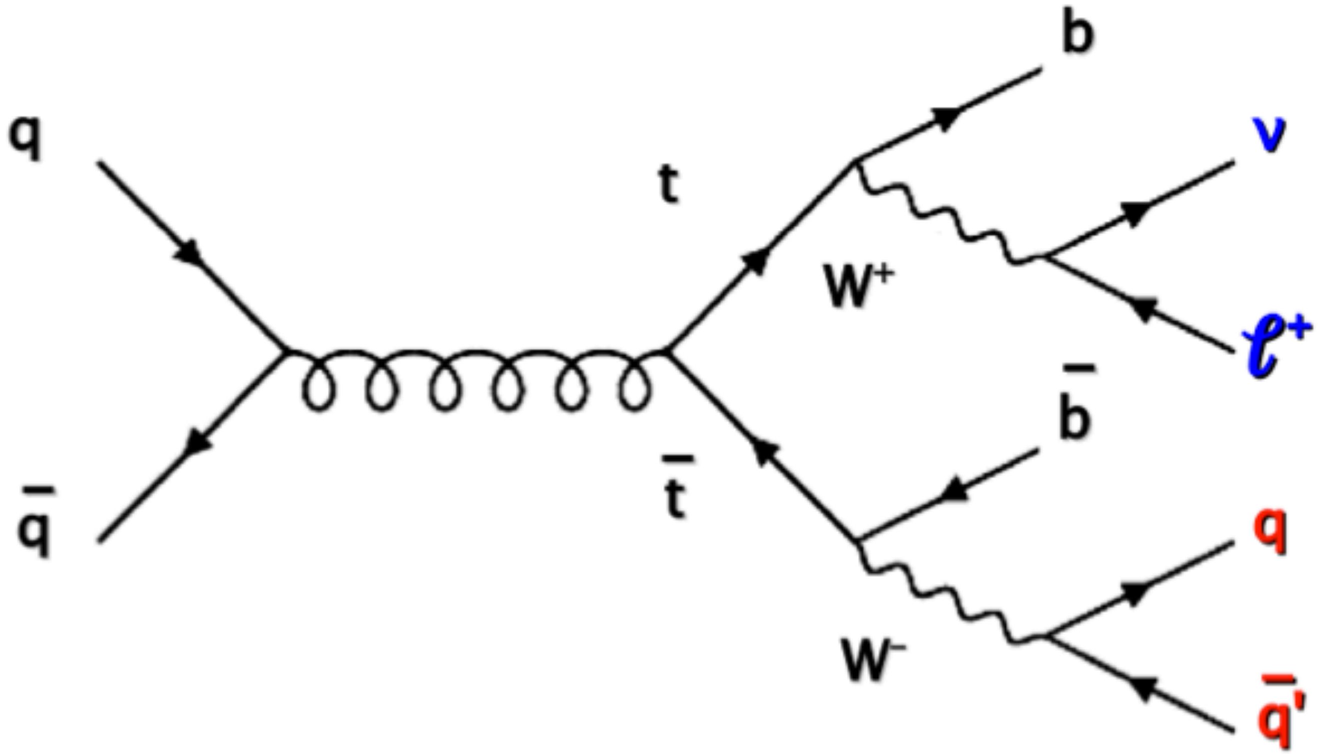


→ difference between $\overline{\mathrm{MS}}$ and pole mass is ≈10 GeV…

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

Which Top Mass Does a LO MC Contain?

- matrix element in LO QCD



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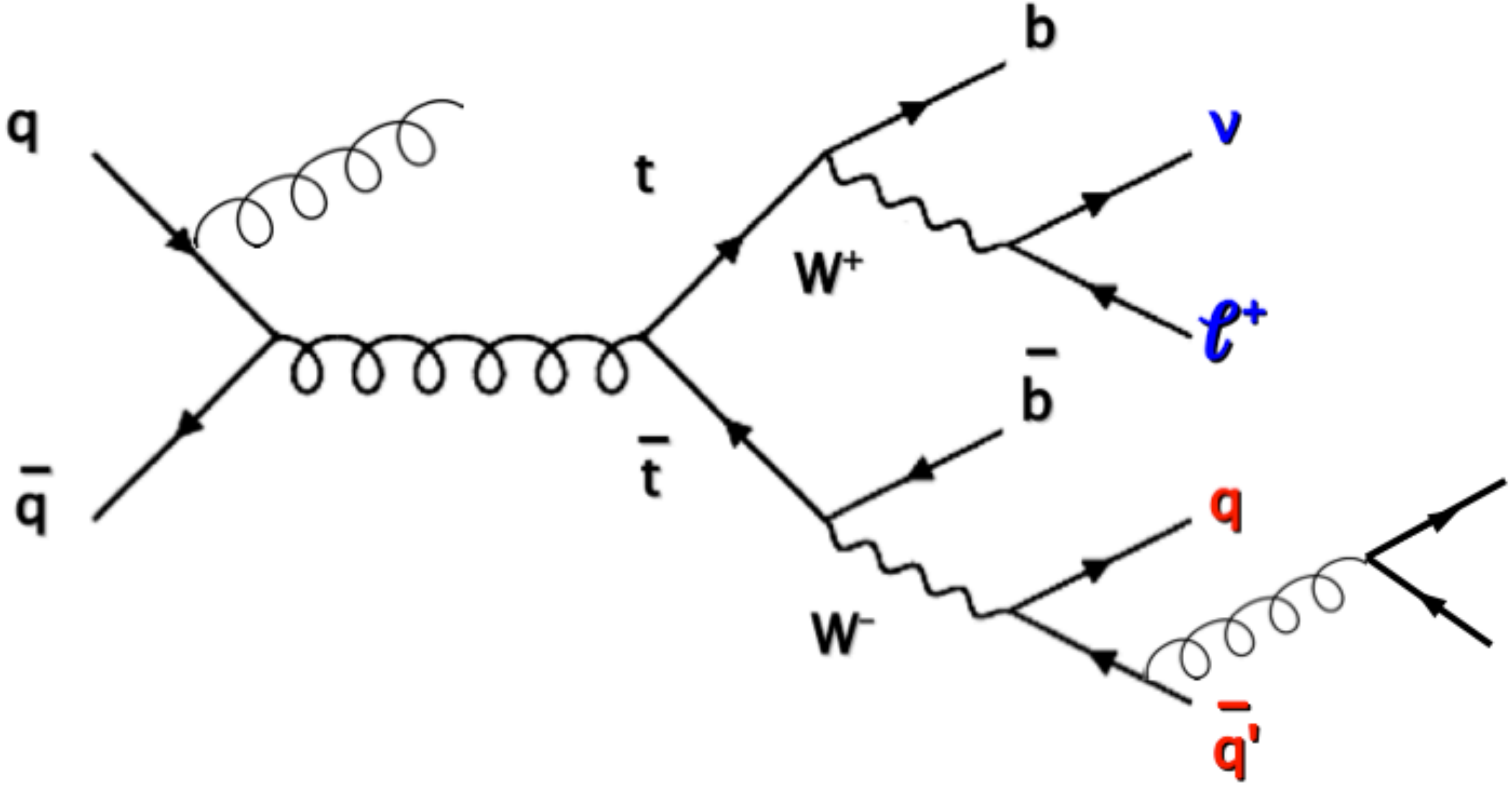

- parton showers simulate higher orders,

Which Top Mass Does a LO MC Contain?

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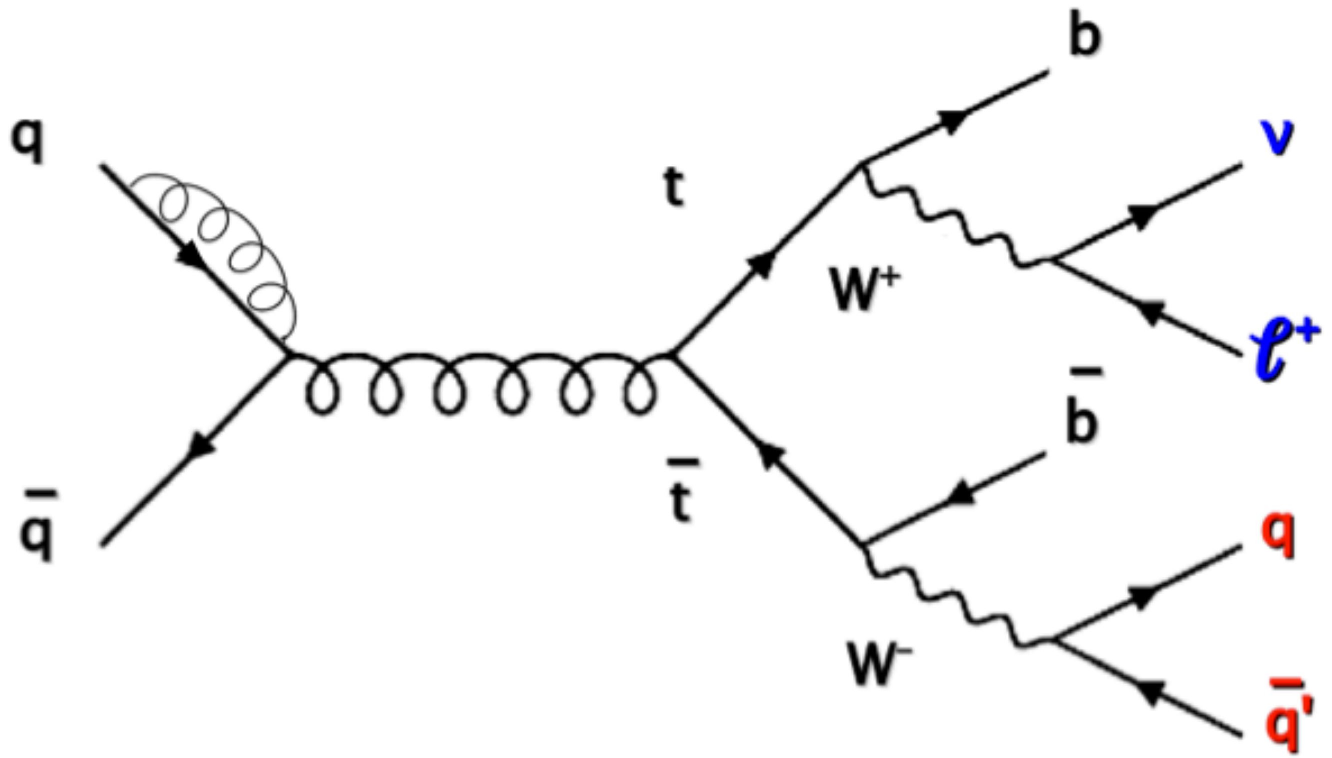

- parton showers simulate higher orders, i.e. not only radiating additional gluons!

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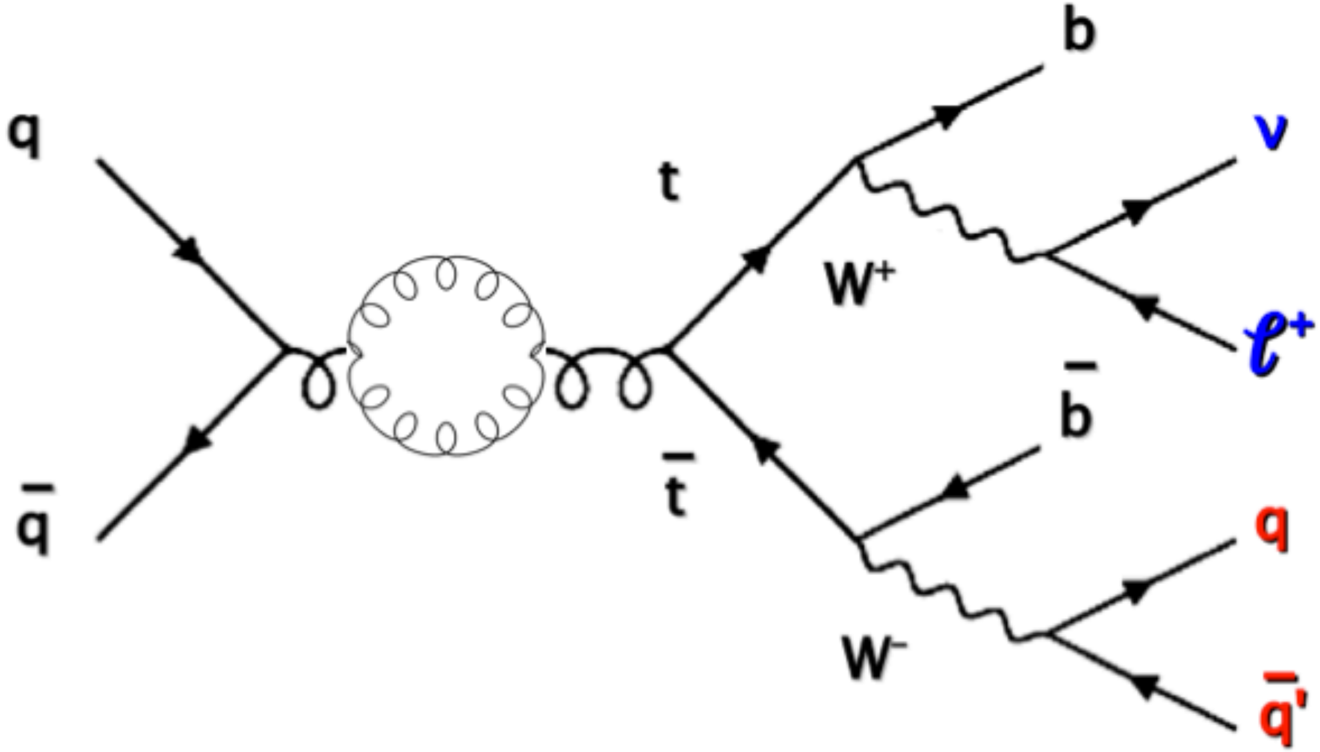

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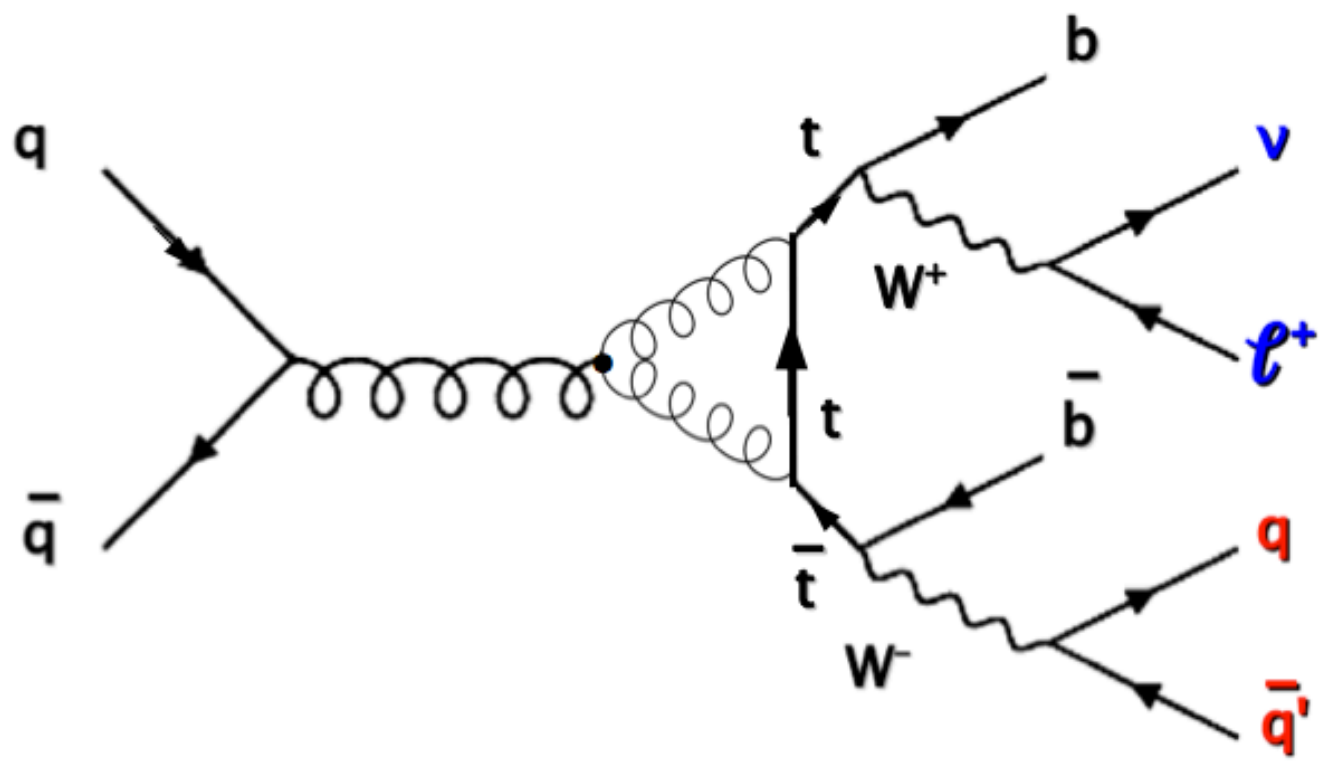

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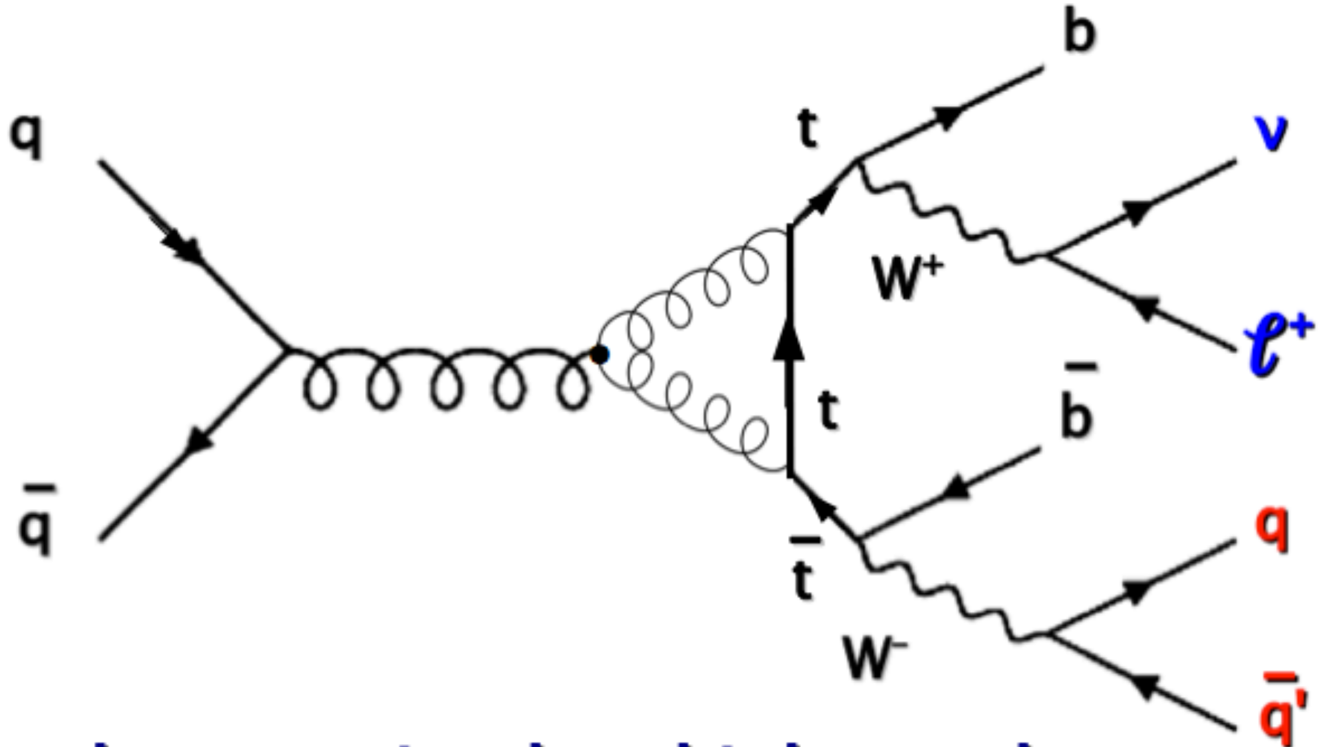
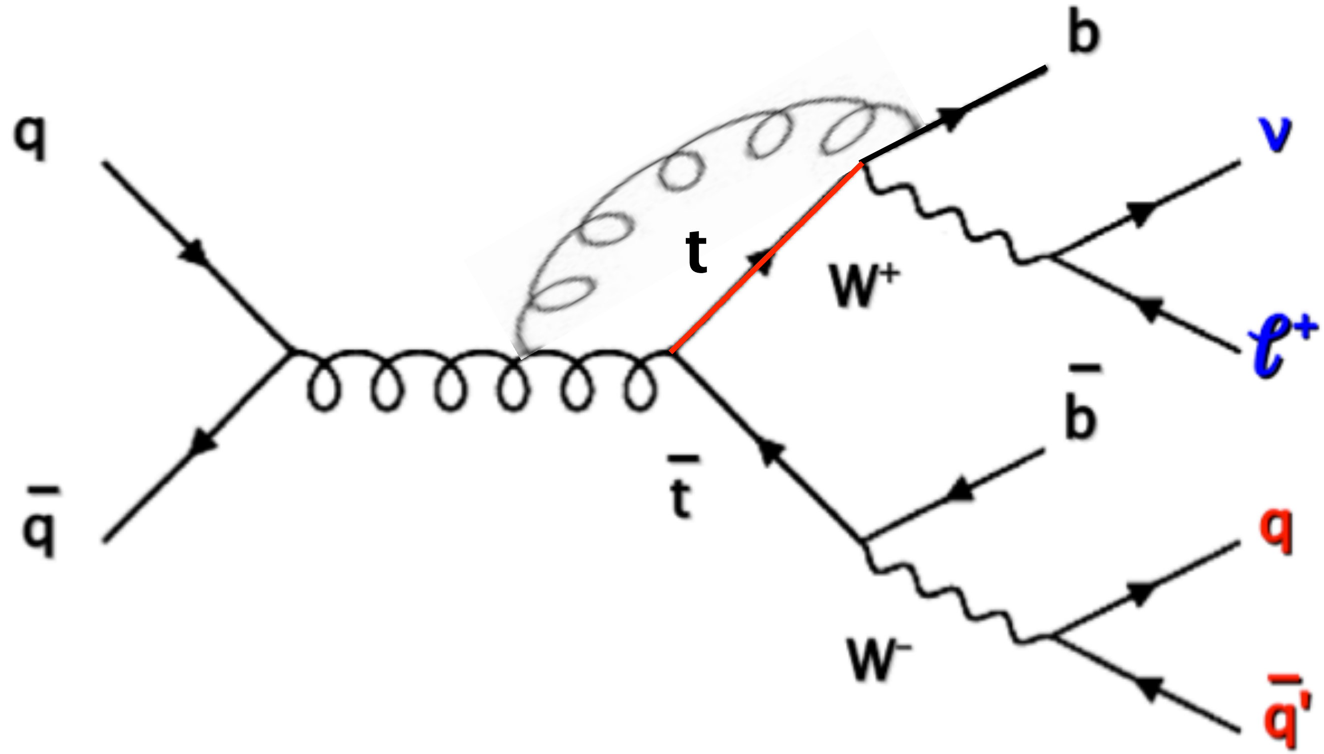


- parton showers simulate higher orders, i.e. not only radiating additional gluons!

⇒ VERY DIFFICULT TO SAY...

- arguments that it should be close to pole mass

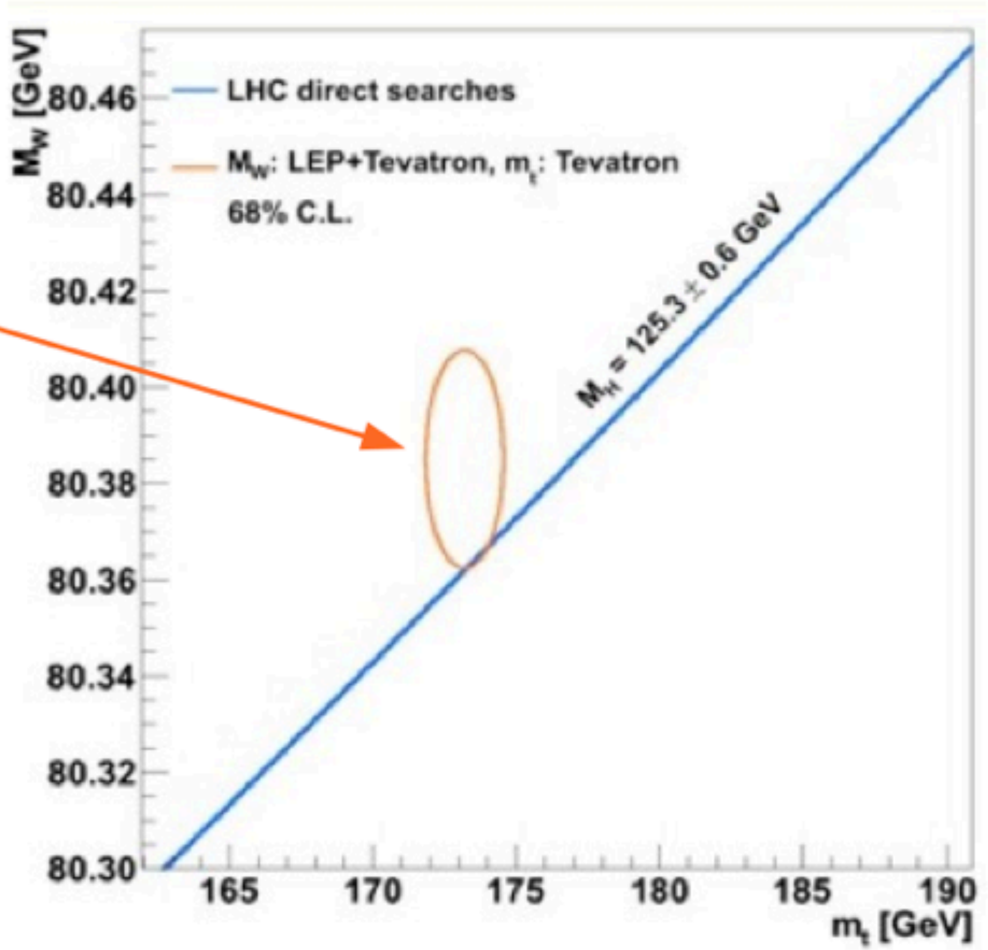
Do NLO MCs Contain Mass information?



- only if they have contributions like this, since top quark propagator needs to be renormalized
- current Powheg, MC@NLO calculate top quarks on-shell
- might be available soon (but only for dilepton final states...)

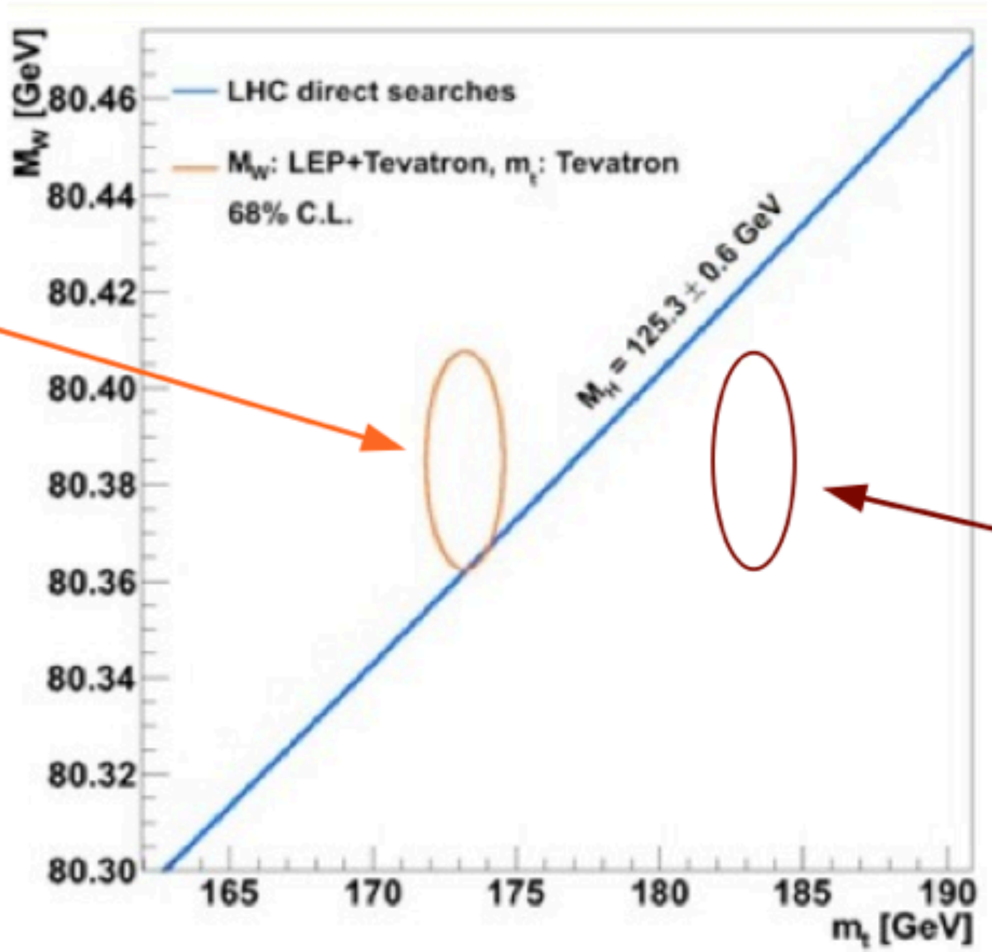
Important to Know...

pole mass



Important to Know...

pole mass

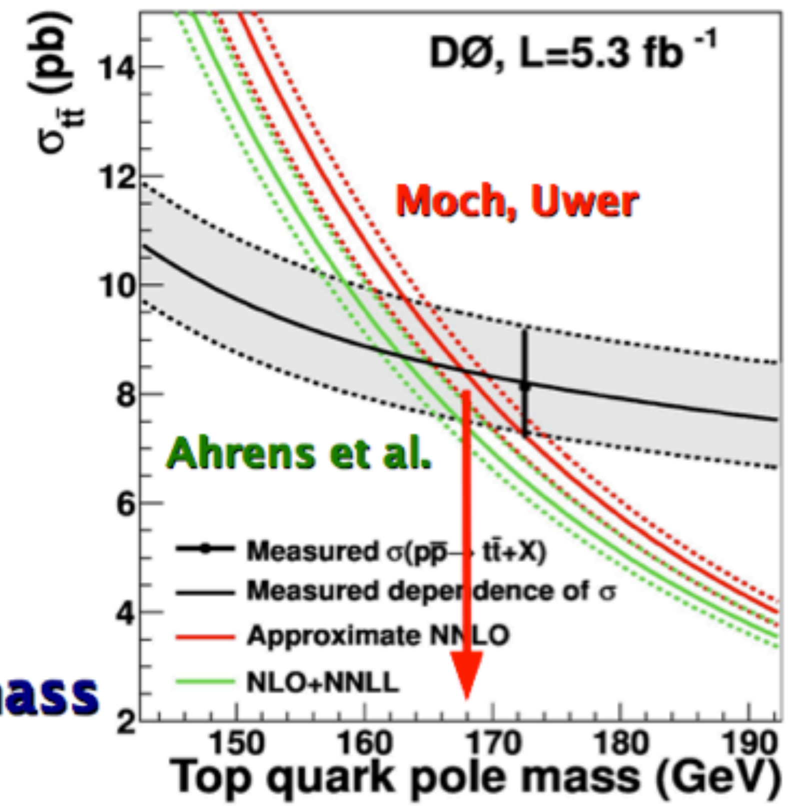


world average interpreted as $\overline{\text{MS}}$ mass

~10 GeV (3-loop)

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

Top Quark Pole Mass



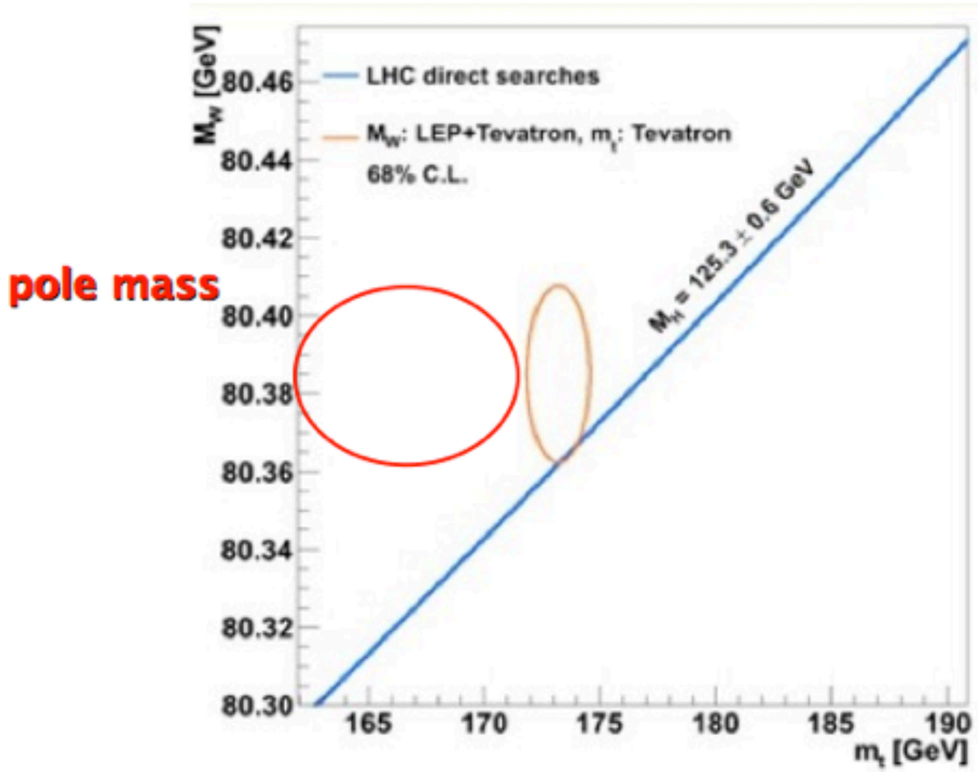
MC mass = pole mass

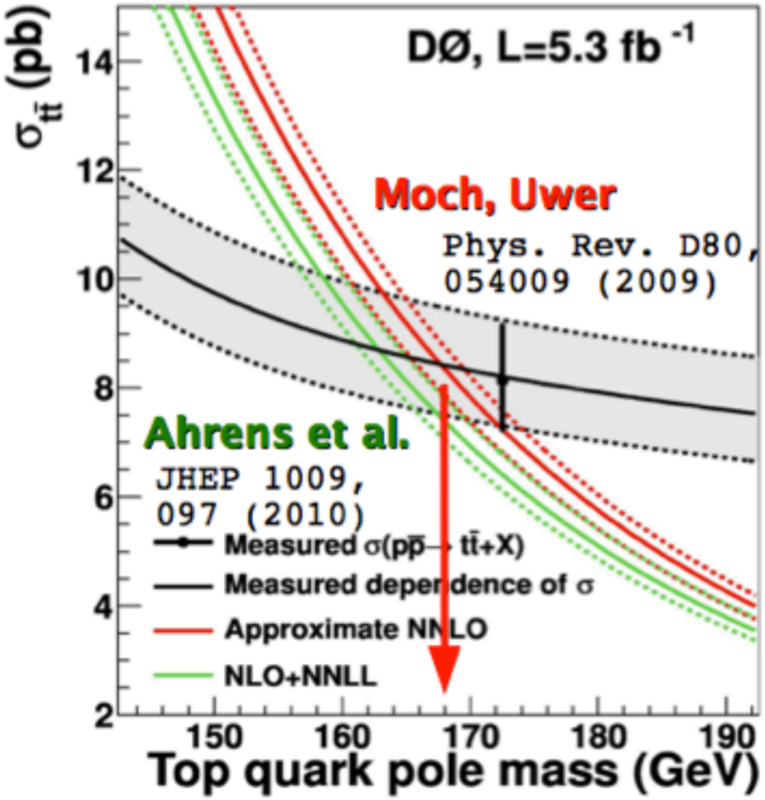
- **use b-tagged cross section since less dependent on mass**
- **difference due to MC mass interpretation is included into systematics**

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

±2.9%

Top Quark Pole Mass





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- difference due to MC mass interpretation is included into systematics

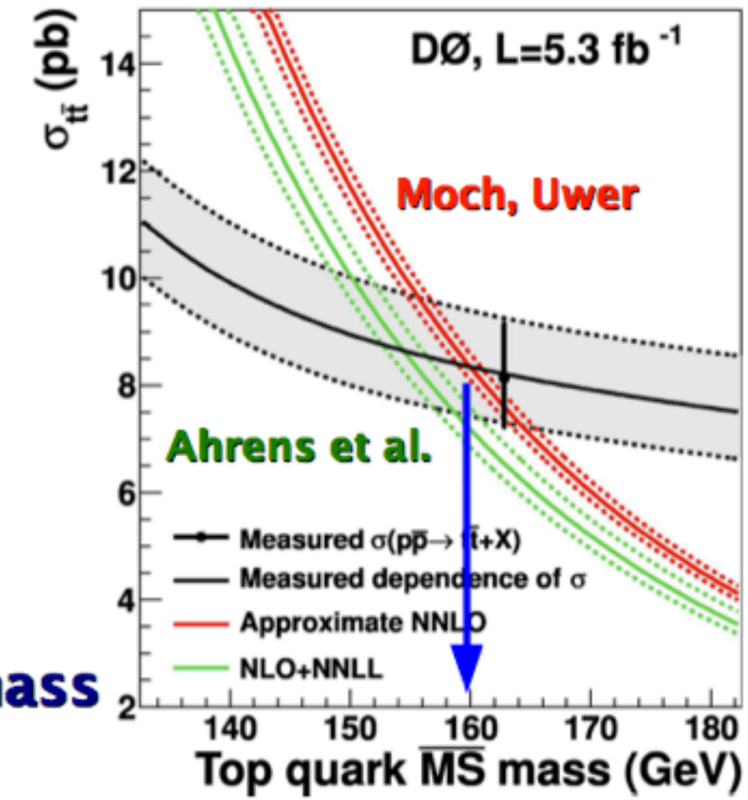
$$m_t^{pole} = 166.7^{+5.2}_{-4.5}\ \text{GeV}$$

±2.9%

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

Top Quark Pole Mass

better convergence of higher order resummation



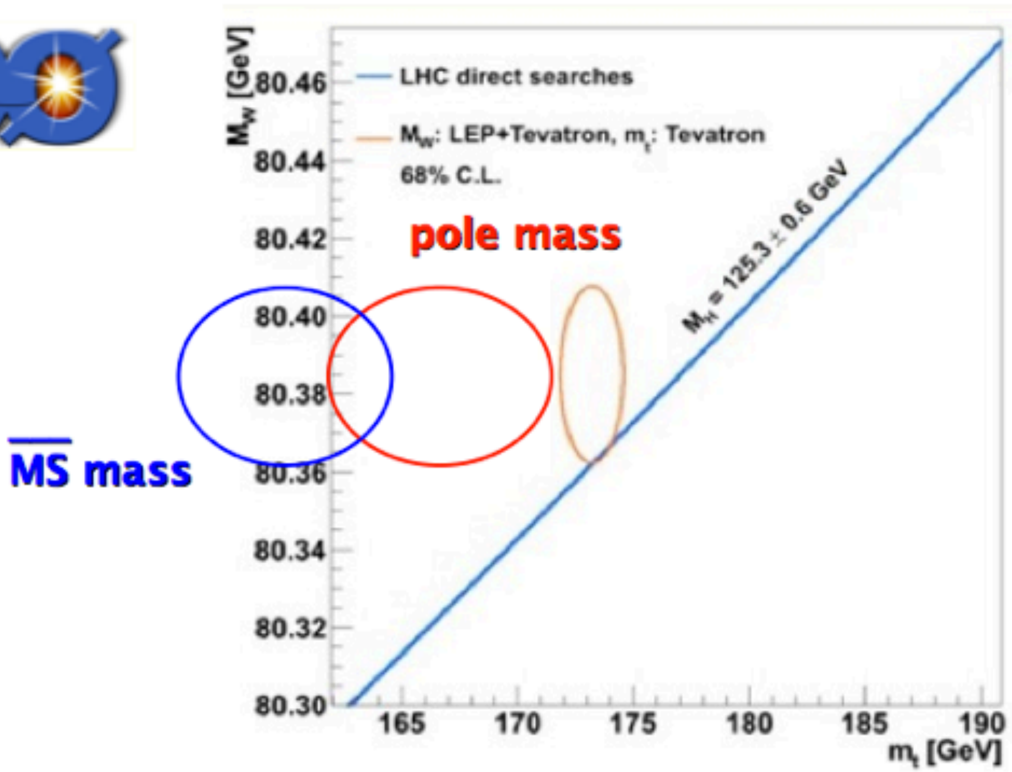
MC mass = pole mass

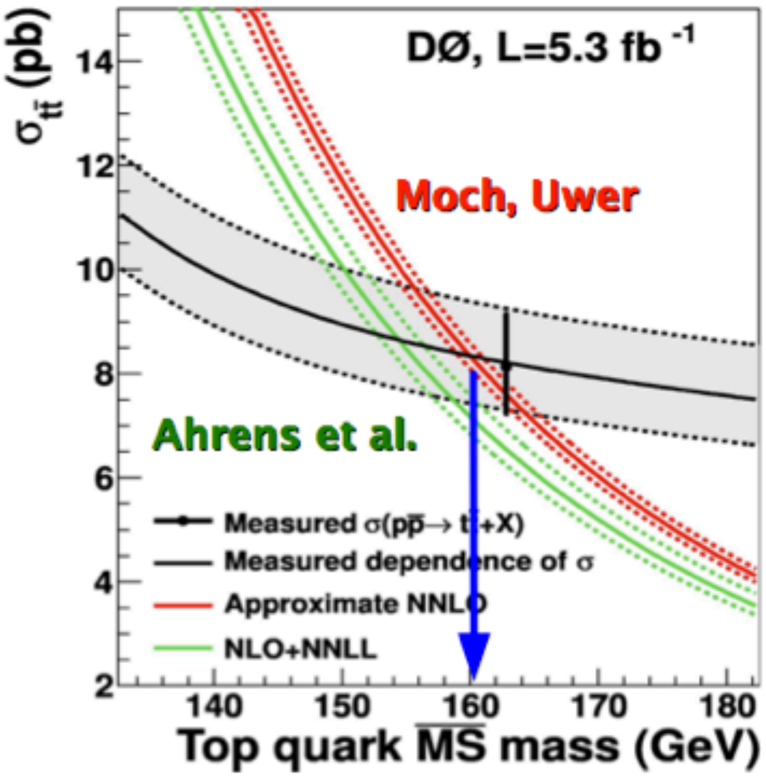
- first extraction of $\overline{MS}$ mass taking selection efficiency into account

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

±2.8%

Top Quark Pole Mass





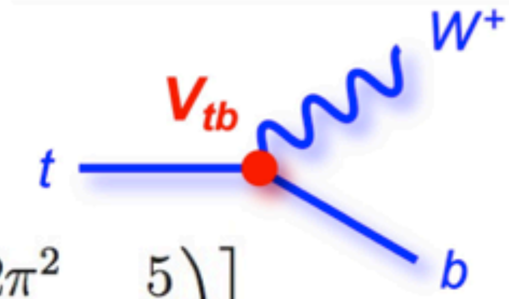
- first extraction of $\overline{MS}$ mass taking selection efficiency into account

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

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

Top Quark Decay Width

$$\Gamma_t^0 = \frac{G_F m_t^3}{8\pi\sqrt{2}}$$

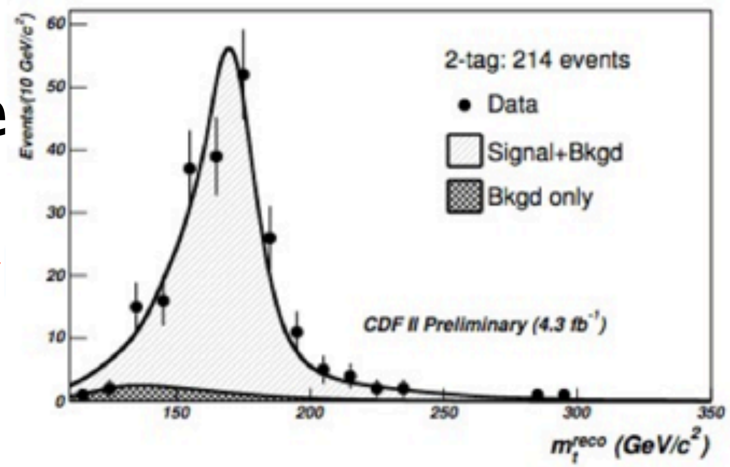


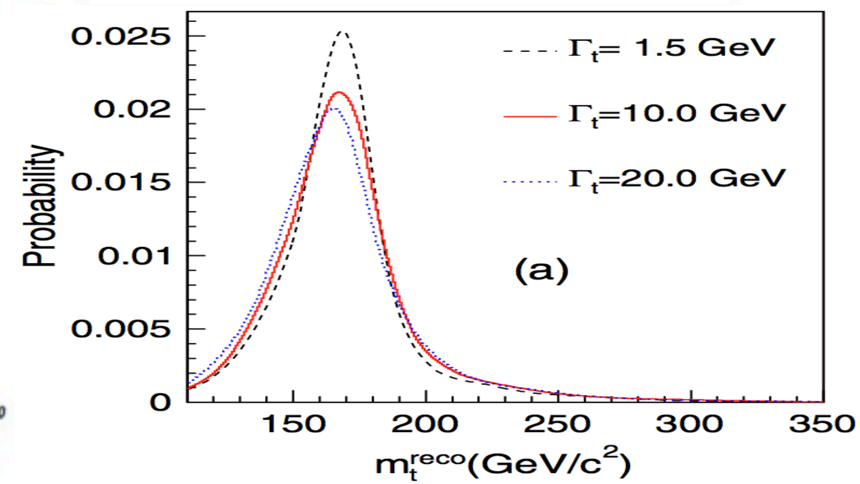
NLO: $$\Gamma_t = \Gamma_t^0 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

$$\Gamma_t = 1.26 \text{ GeV for } m_t = 170 \text{ GeV}$$

2-dim template fit Γ_t vs. JES:

$\Gamma_t < 7.6$ GeV





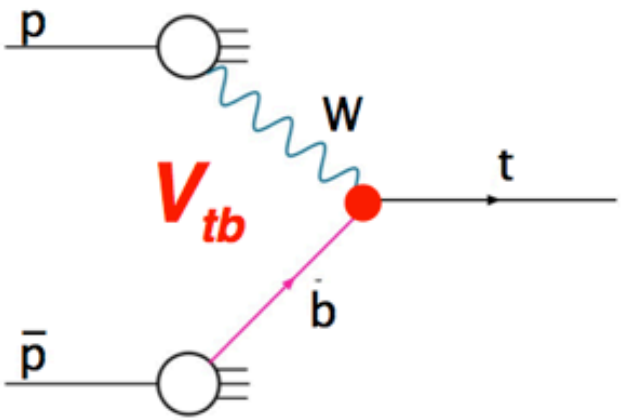
$\Longrightarrow$ **model independent but not really sensitve**

Top Quark Decay Width

- **indirect determination (direct extraction not sensitive enough)**

t-channel cross section:

σ(t-channel) = 2.26 ± 0.12 pb
approximate NNLO, m_t = 172.5 GeV



Top Quark Decay Width

- indirect determination (direct extraction not sensitive enough)

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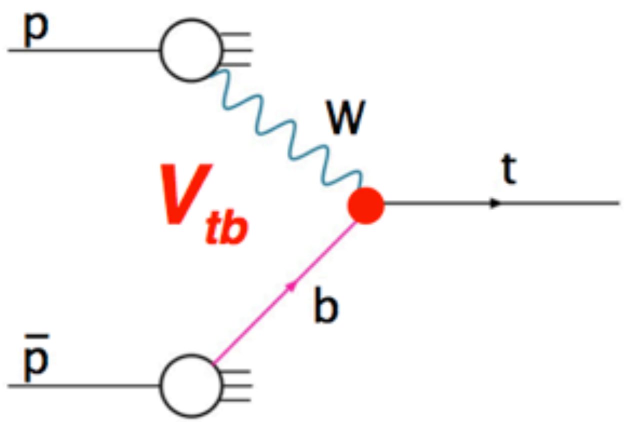
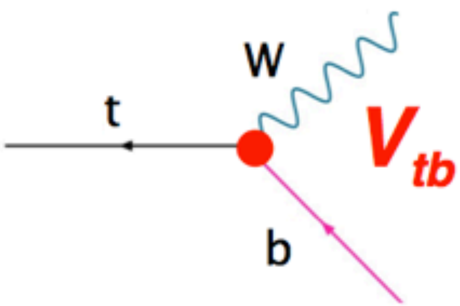


partial decay width:

$\Gamma(t \to Wb)$ = 1.33 GeV
NLO, m_t = 172.5 GeV



Top Quark Decay Width

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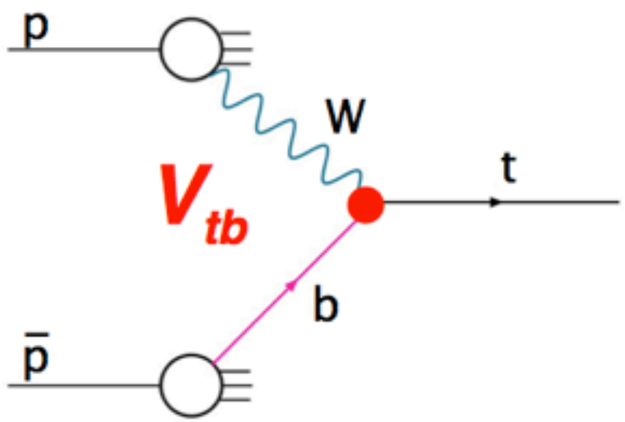
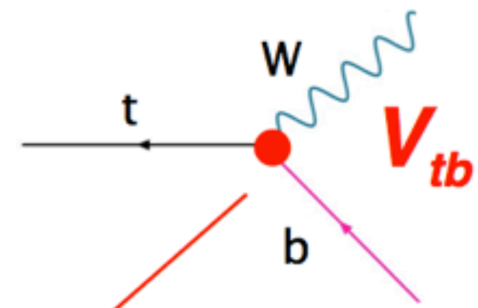


partial decay width:

Γ(t→Wb) = 1.33 GeV
NLO, m_t = 172.5 GeV



$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}$$

← $t\bar{t}$ production

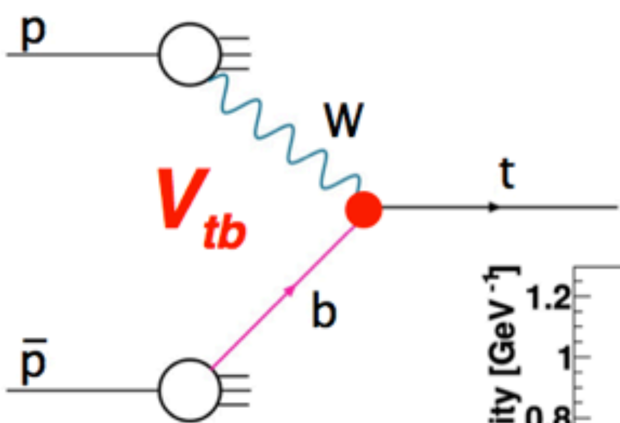
- combine both measurements
- assume that coupling in top production and decay is the same

Top Quark Decay Width

t-channel cross section:

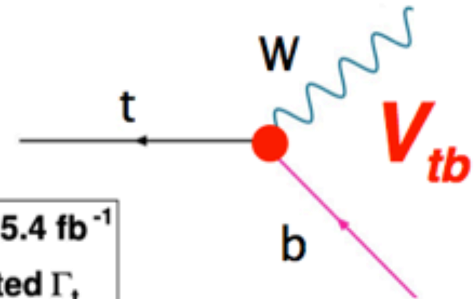
$$\sigma(p\bar{p} \to tqb + X) \; = \; 2.90 \pm 0.59 \;\; \text{pb}$$

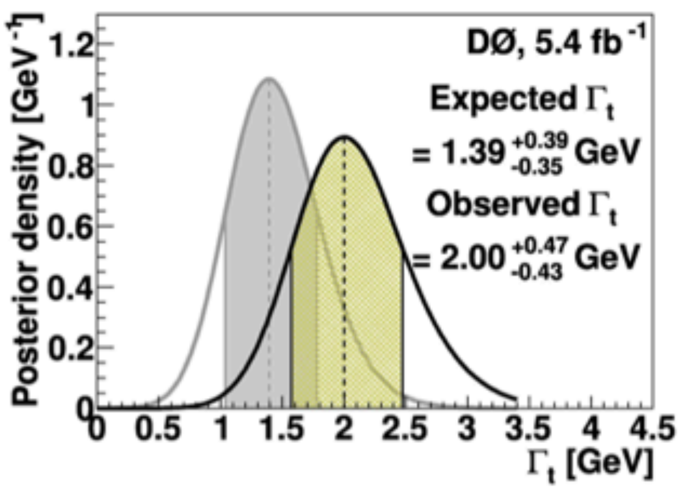
m_t =172.5 GeV



partial decay width:

R= 0.90±0.04 (stat+syst)





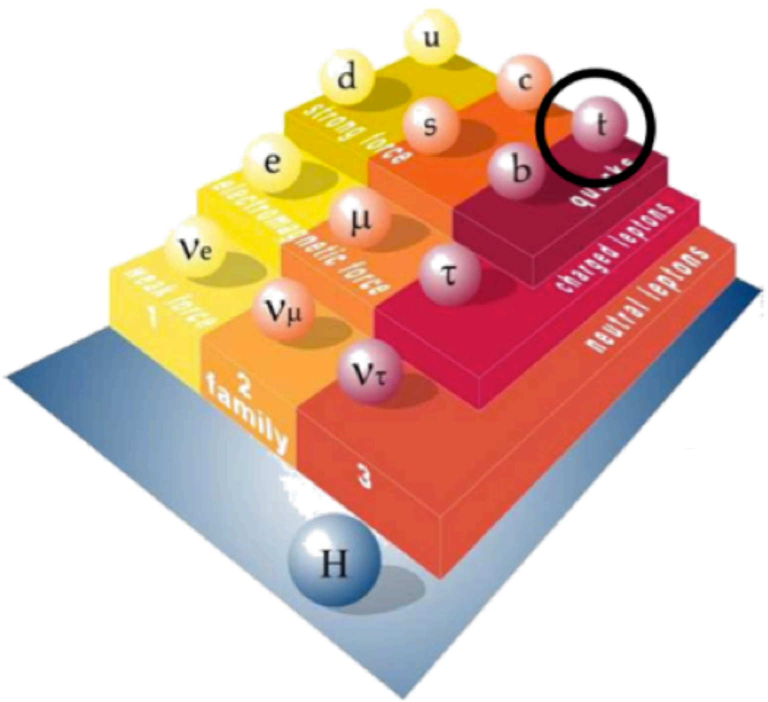
Phys. Rev. D84 012008 (2011)

$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

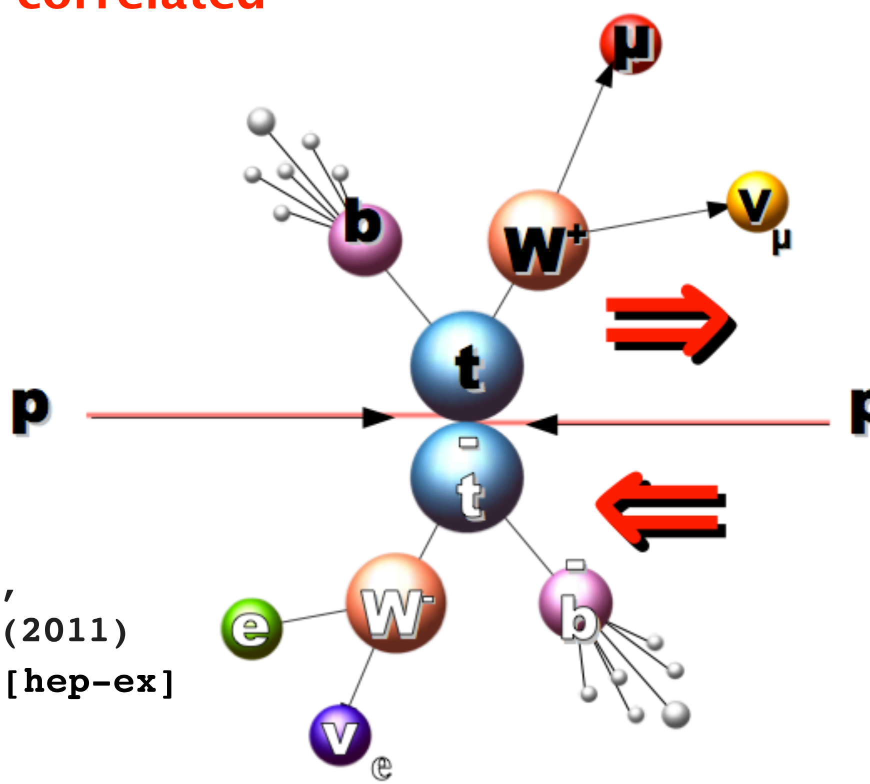
$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s}$$

$\Longrightarrow$ **most precise determination**

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:

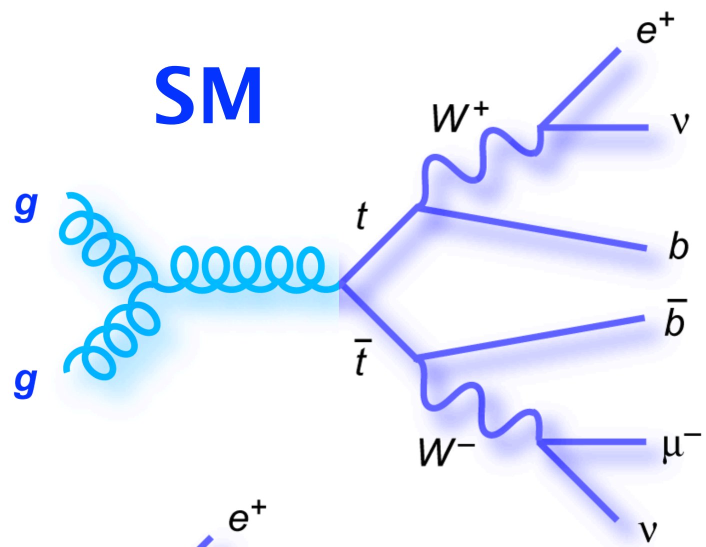
$$\tau_t = (3.3^{+0.9}_{-0.6}) \times 10^{-25}\ \mathrm{s}$$

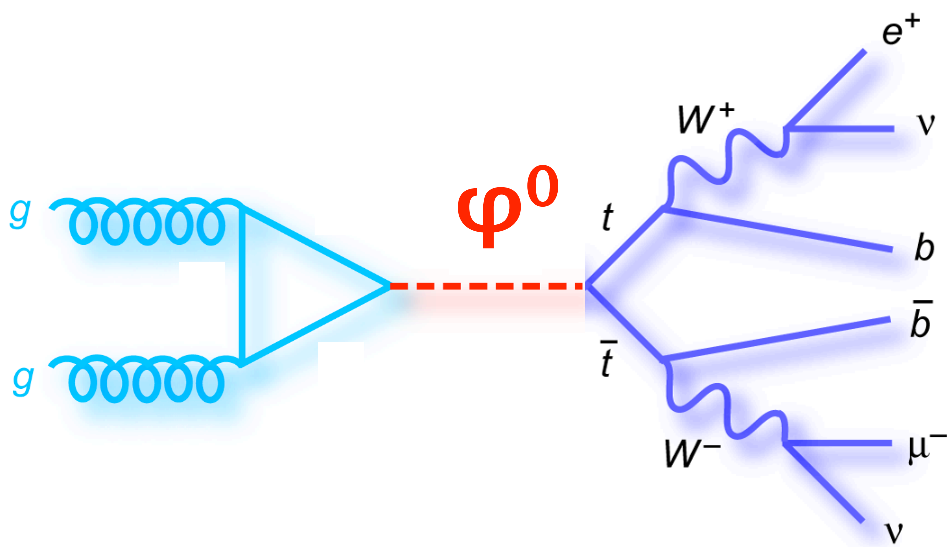
DØ Collaboration,
PRL 106, 022001 (2011)
arXiv:1201.4156 [hep-ex]

- 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?

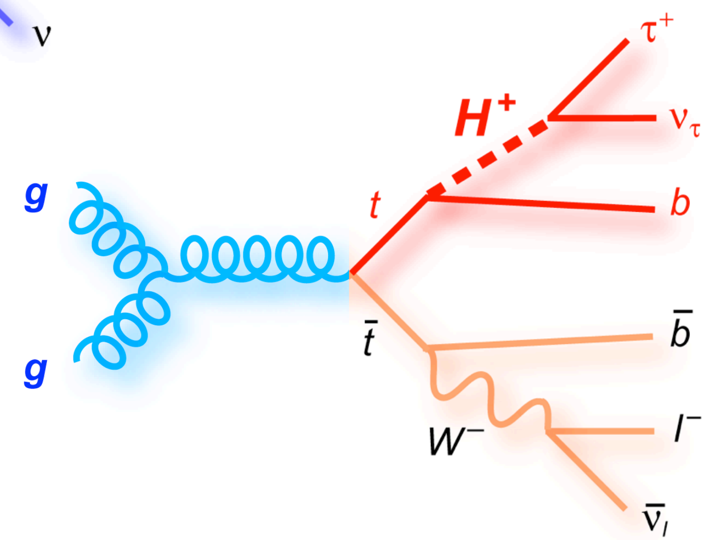
New physics impact on spin correlations

- 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', ...

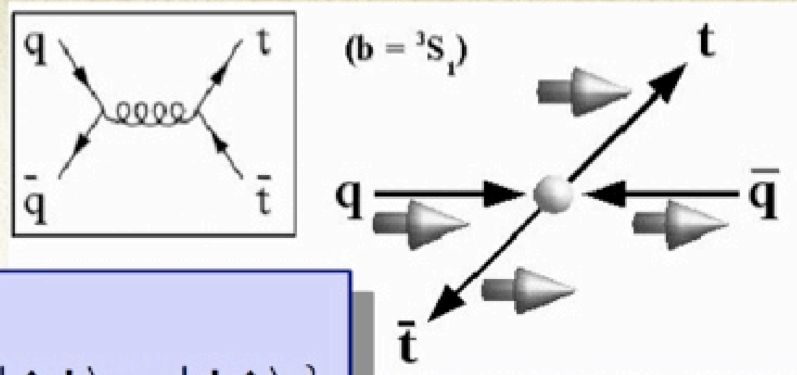
Spin correlation strength

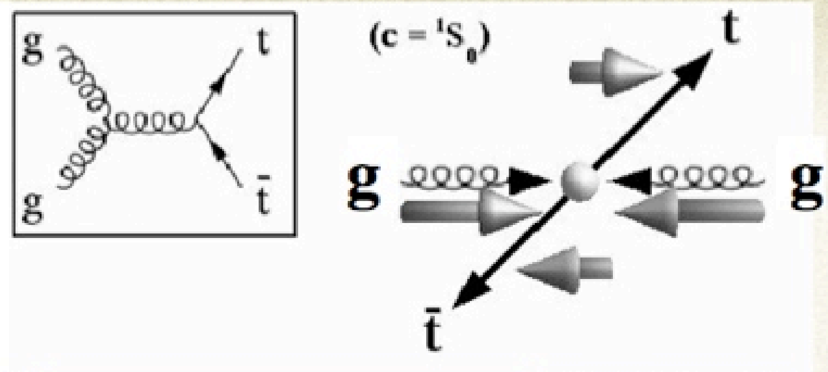
$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

Spin correlation helicity basis

near threshold:

Comics: Habilitation, Arnulf Quadt





$|\uparrow\uparrow\rangle$
$1/\sqrt{2}\,\{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\}$
$|\downarrow\downarrow\rangle$

$C \approx 1/3 - 2/3$
$= -33\%$

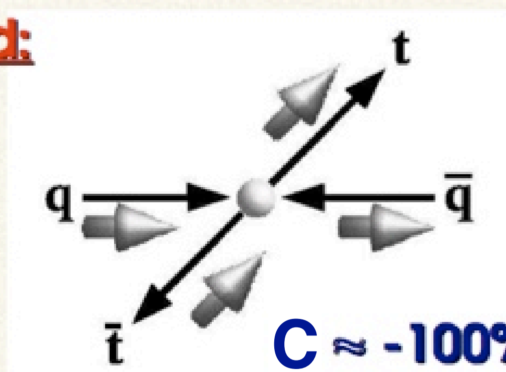
$1/\sqrt{2}\,\{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\}$

$C \approx +100\%$

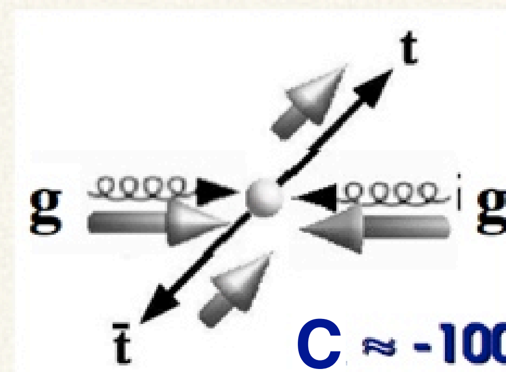
Arens, Sehgal, Phys. Lett. B302, 501 (1993)
Stelzer, Willenbrock, Phys.Lett. B374, 169 (1996)

far above threshold:

(helicity conservation
of the strong
and weak interactions)



$C \approx -100\%$



$C \approx -100\%$

Tevatron: (LO)

- **helicity: $C = -47\%$**

$$C = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

LHC: (LO)

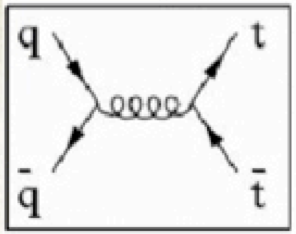
- **helicity: $C = 32\%$**

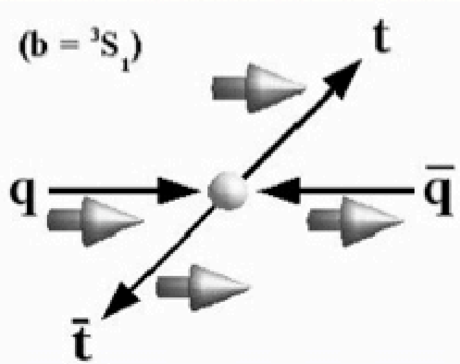
hep-ph/0403035

Spin correlation beam basis

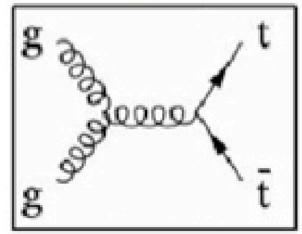
near threshold:

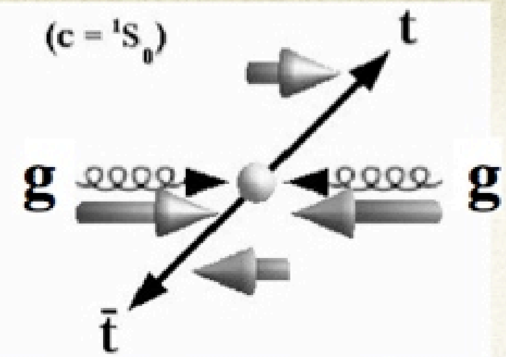
Comics: Habilitation, Arnulf Quadt





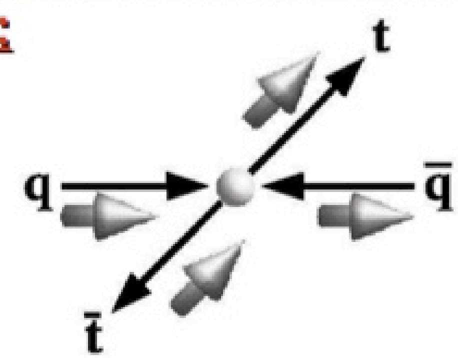
C ≈ 100%



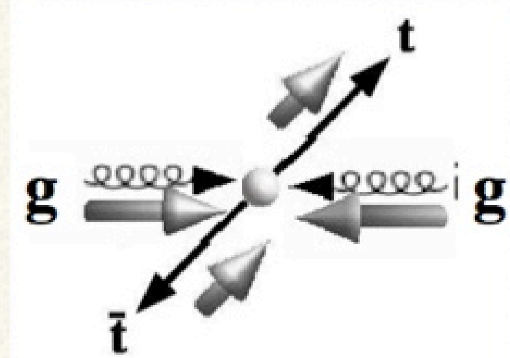


C ≈ -75%

far above threshold:



C ≈ 0%



C ≈ 0%

$$C = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}}$$

hep-ph/0403035

Tevatron: (LO)

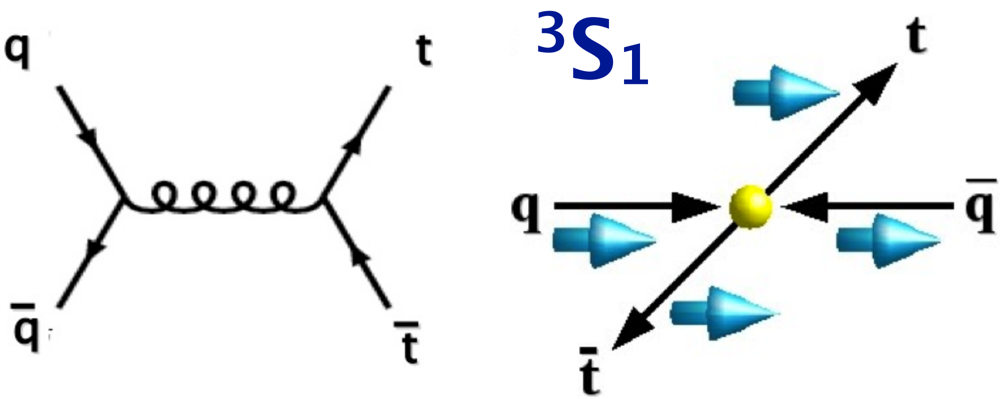
- beam: C = 93%
- off-diagonal: C = 94%

LHC: (LO)

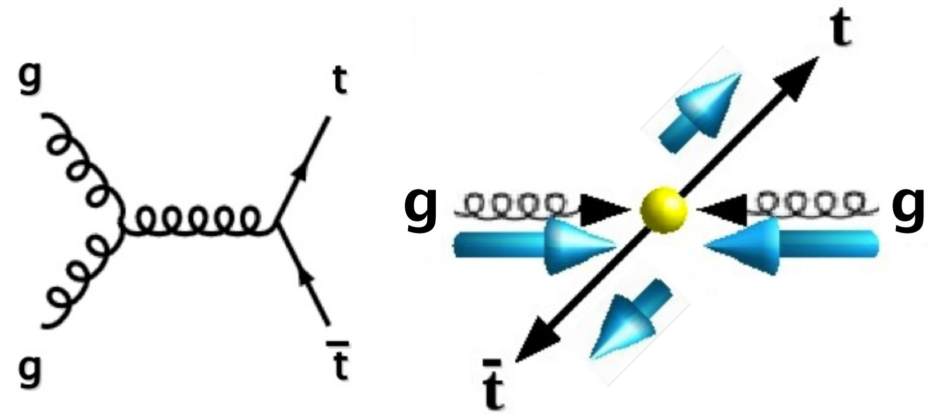
- beam: C = -0.5%
- off-diagonal: C = -2.7%

Spin correlation strength

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



Tevatron



LHC

- dominated by $q\bar{q}$ annihilation
- $t\bar{t}$ pairs close to the threshold
- beam axis as spin quantisation axis
  NLO QCD: A = 0.78

- dominated by gg fusion
- $t\bar{t}$ pairs far off the threshold
- helicity basis as spin quantisation axis
  NLO QCD: A = 0.32

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

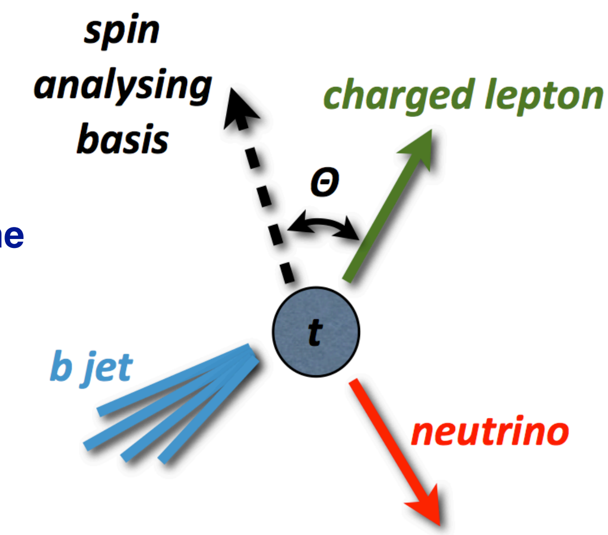
- optimised “off-diagonal” basis
- maximal basis

complementary between Tevatron and LHC

Polarisation power

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

in $t\bar{t}$ ZMF frame



dilepton channel promises largest sensitivity

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

in top quark rest frame

	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

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

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

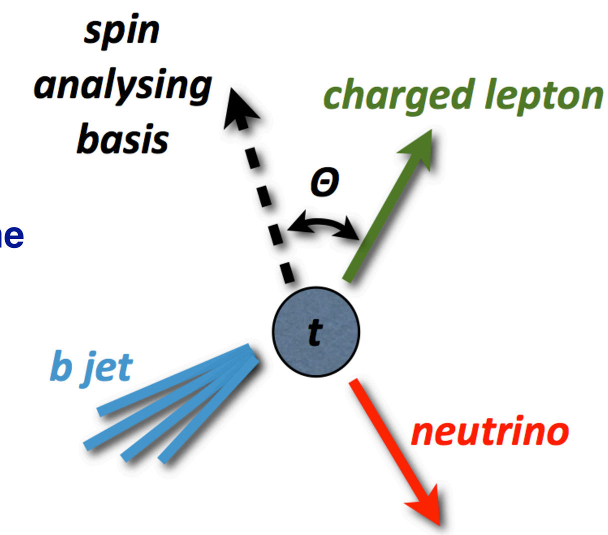
linear extraction:

A=C

Polarisation power

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

in $t\bar{t}$ ZMF frame



in top quark rest frame

dilepton channel: explore simultaneously

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

	b-quark	W^+	l^+	$\bar{d}$-quark or $\bar{s}$-quark	u-quark or c-quark
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$$\text{where } C=A\,\alpha_1\alpha_2$$

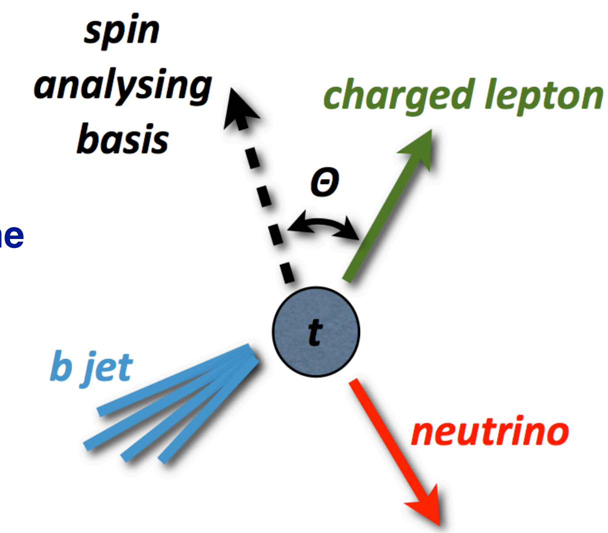
linear extraction:

A=C

Polarisation power

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

in $t\bar{t}$ ZMF frame



in top quark rest frame

use lowest energy quark in l+jets channel

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

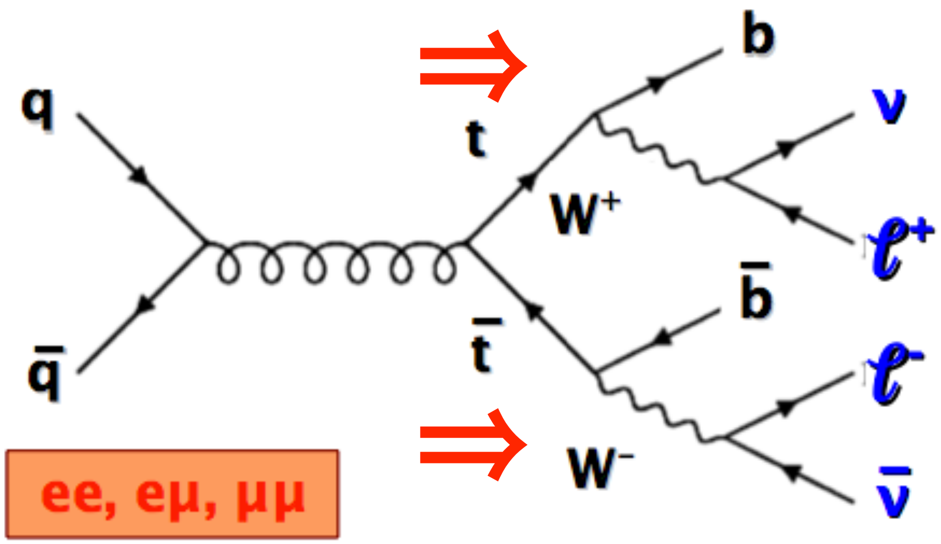
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

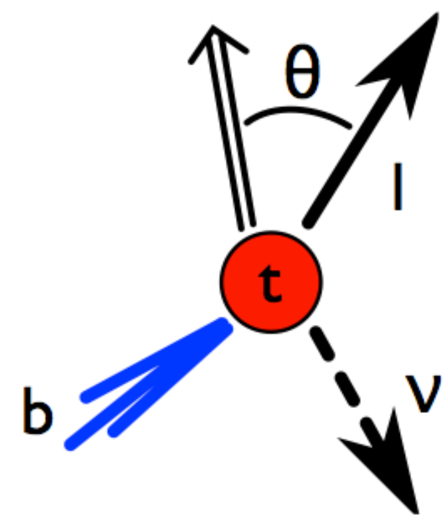
$$\text{where } C=A\alpha_1\alpha_2$$

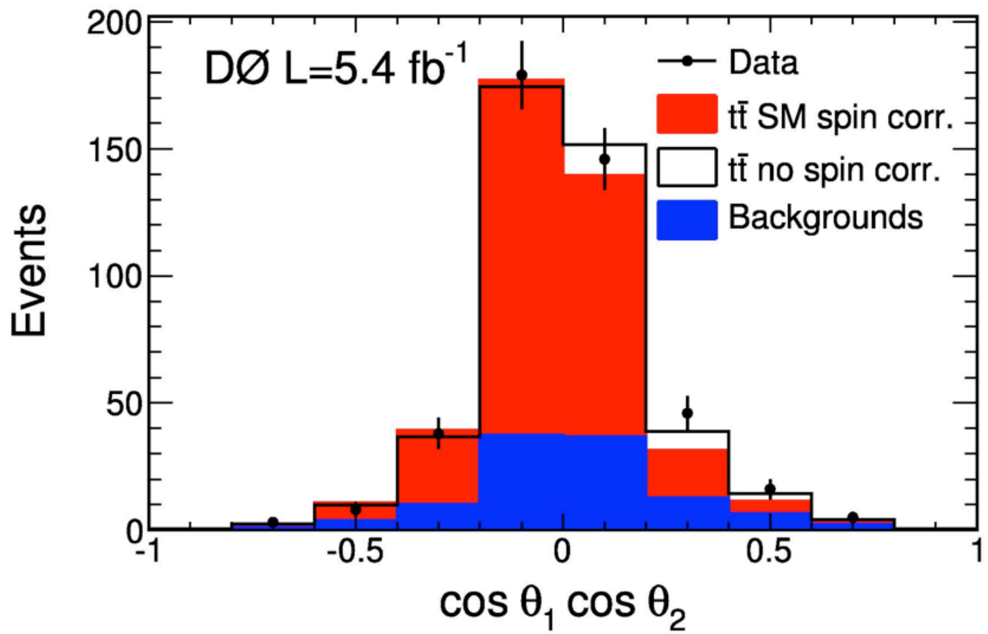
linear extraction:

A=C

Template Method







Phys. Lett. B 702, 16 (2011)

correlation strength:

$$C = 0.10^{+0.45}_{-0.45}\ (\mathrm{stat{+}syst})$$

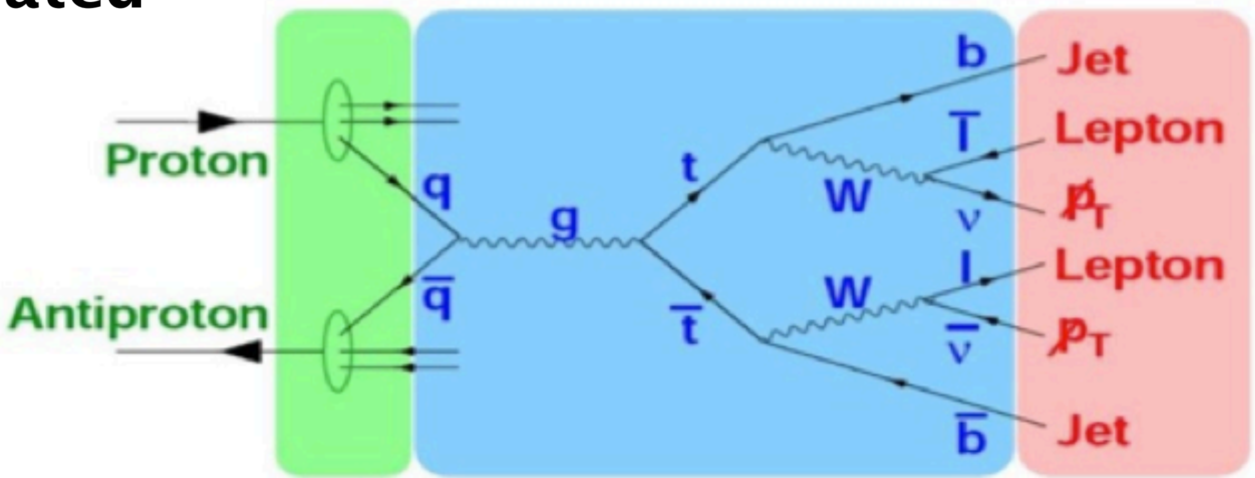
NLO QCD: $C = 0.777^{+0.027}_{-0.042}$

agreement within 2 sd

Matrix Element Method

$$P_{\text{sgn}}(x; m_t, H) = \frac{1}{\sigma_{\text{obs}}(m_t)} \int f_{\text{PDF}}(\epsilon_1)\; f_{\text{PDF}}(\epsilon_2) d\epsilon_1 d\epsilon_2 \cdot \frac{(2\pi)^4 \left|\mathcal{M}(y, m_t, H)\right|^2}{\epsilon_1 \epsilon_2 s} W(x, y)\, d\Phi_6$$

H=correlated
or
H=uncorrelated
spins



PDF's LO-Matrix element

transfer functions (probability to measure x when y was produced)

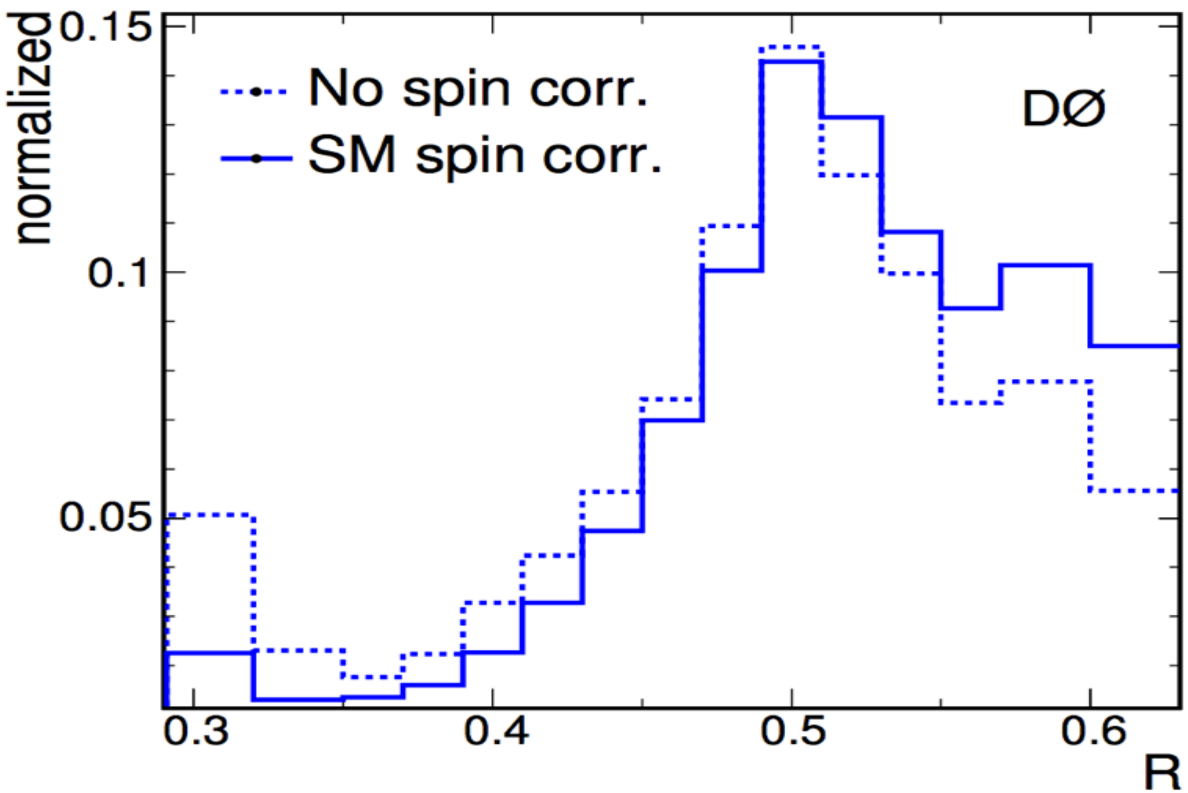
Transformation into Templates

MEs: per event ↔ spin correlation: ensemble of events

discriminant

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

K. Melnikov, M. Schulze arXiv:1103.2122 (hep-ph)



MC@NLO on parton level dilepton

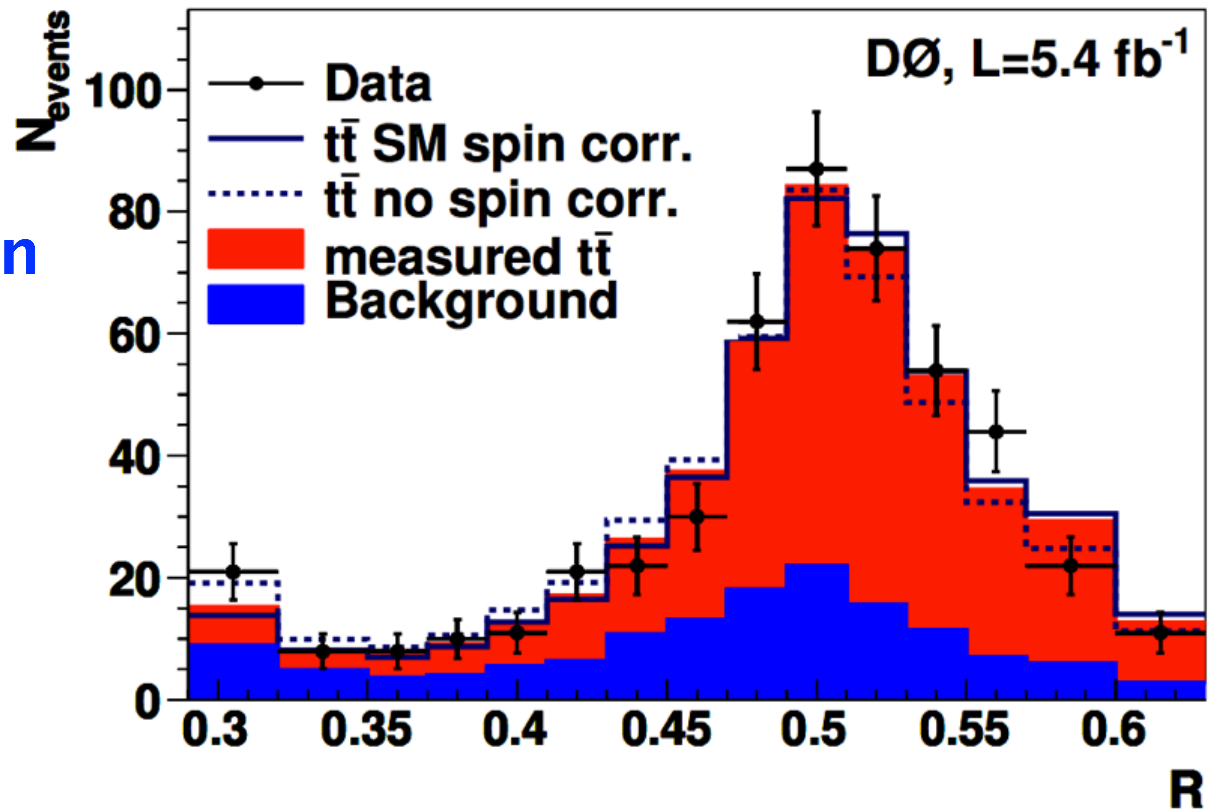
Transformation into Templates

MEs: per event ↔ spin correlation: ensemble of events

discriminant

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

dilepton



biggest loss: undetected neutrinos

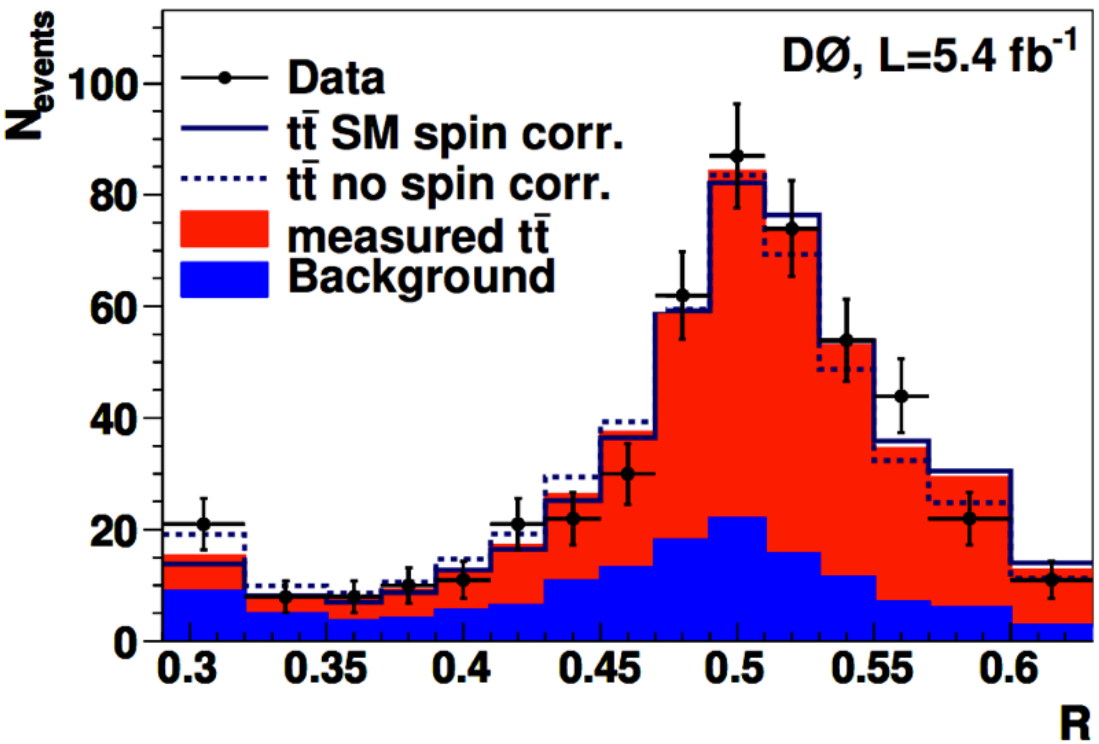
Transformation into Templates

MEs: per event ↔ spin correlation: ensemble of events

discriminant

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

dilepton



measure by template fit to data assuming 2 hypotheses:

- SM correlation: N_{SM} events
- no correlation: N_0 event
- any mixing fraction of N_{SM} or N_0

$$f^{SM} = N_{SM} \,/\, (N_{SM} + N_0)$$

$$C^{SM} = C^{SM}_{theory} \cdot f^{SM}$$

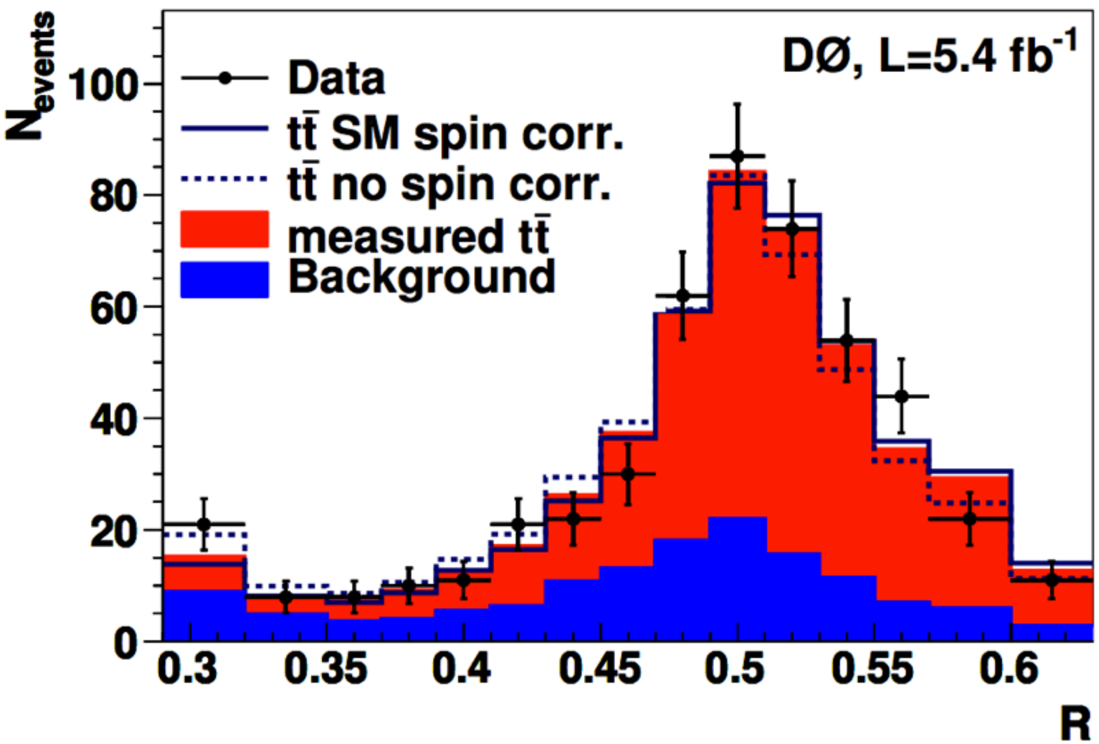
Transformation into Templates

MEs: per event ↔ spin correlation: ensemble of events

discriminant

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

dilepton



combination:
dilepton & l+jets

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

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

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

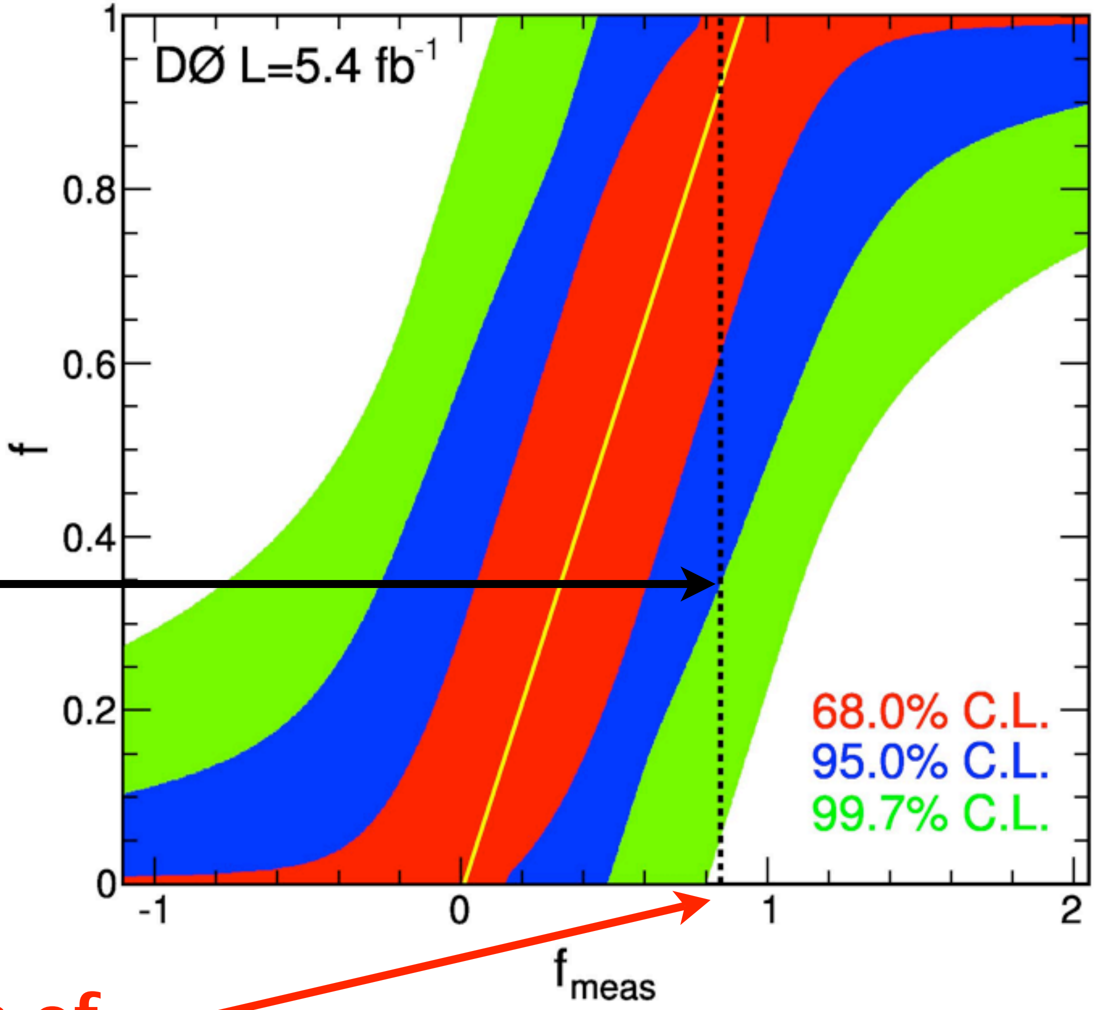
correlation strength:

$C = 0.66 \pm 0.23$ (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

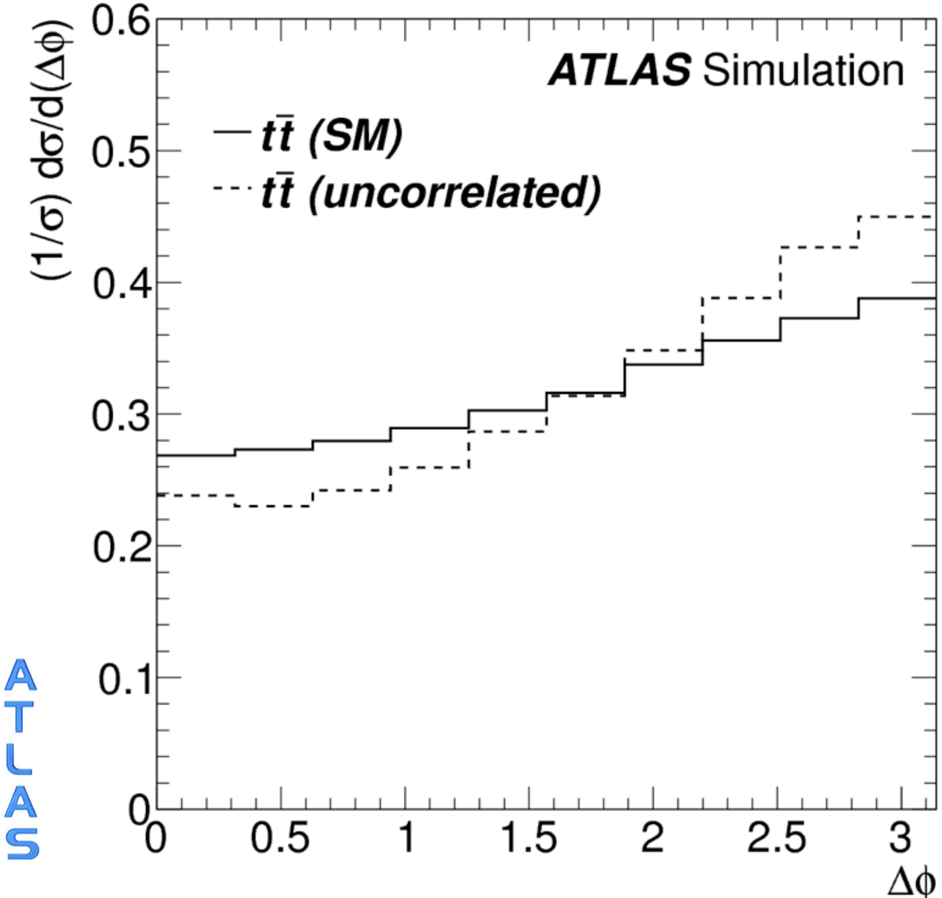
first exclusion of hypothesis H=uncorrelated (f=0) with >99.7% CL: 3.1σ

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

Spin Correlation at the LHC

- first measurement of spin correlation between top and anti-top quark in dilepton final states at the LHC
- azimuthal angle between charged leptons in laboratory frame: sensitive and simple!

Mahlon, Parke, PRD D81, 074024 (2010)



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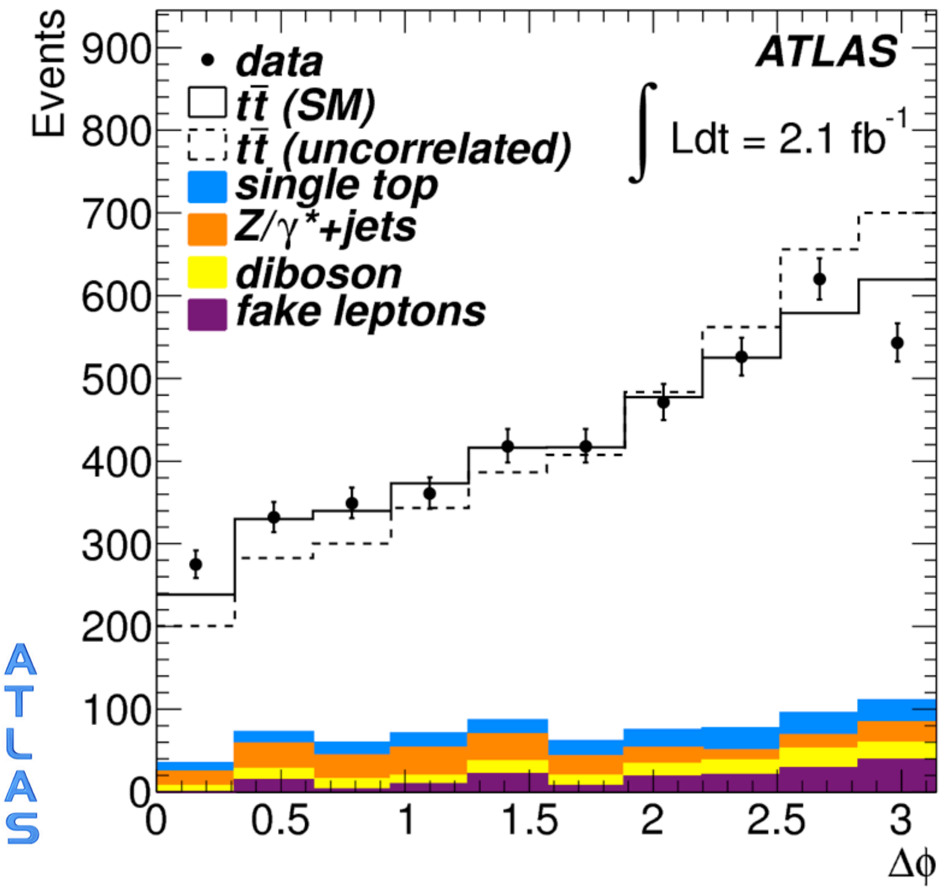
Phys. Rev. Lett. 108, 212001 (2012)



Spin Correlation at the LHC

- first measurement of spin correlation between top and anti-top quark in dilepton final states at the LHC
- azimuthal angle between charged leptons in laboratory frame: sensitive and simple!

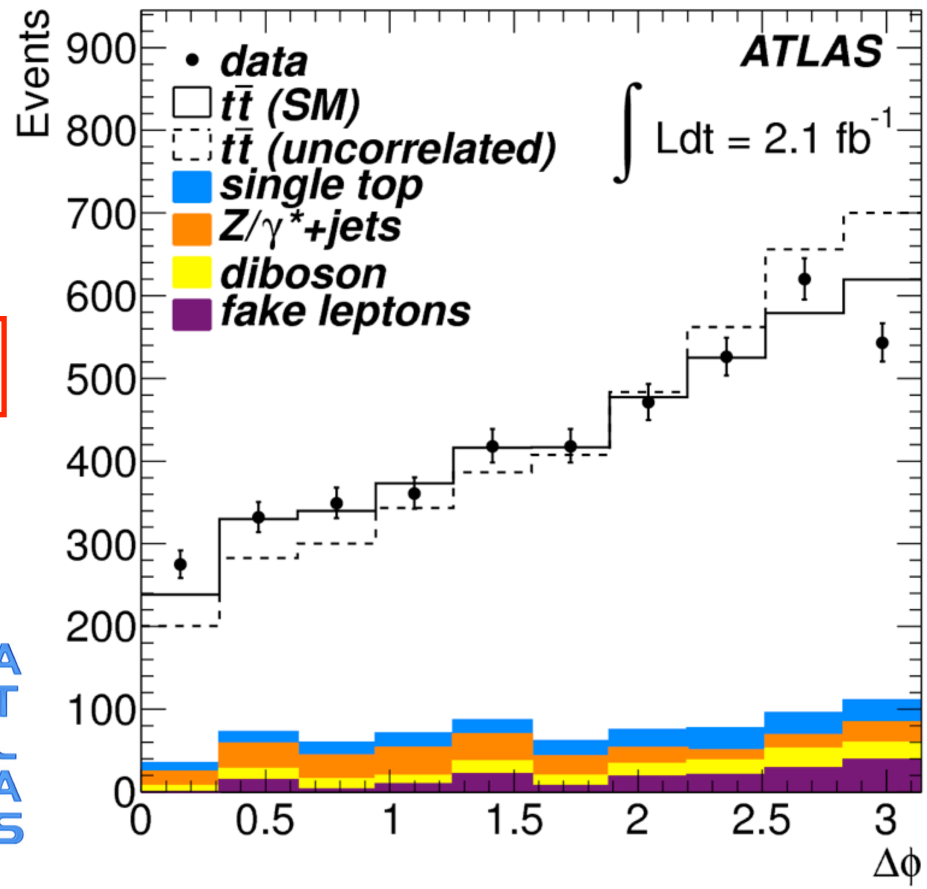
Phys. Rev. Lett. 108, 212001 (2012)

$$f^{SM} = 1.30 \pm 0.14\,(\mathrm{stat})\,^{+0.27}_{-0.22}\,(\mathrm{syst})$$

(=1 in SM)

$$C_{helicity} = 0.40\,^{+0.09}_{-0.08}$$

(=0.32 in NLO QCD)



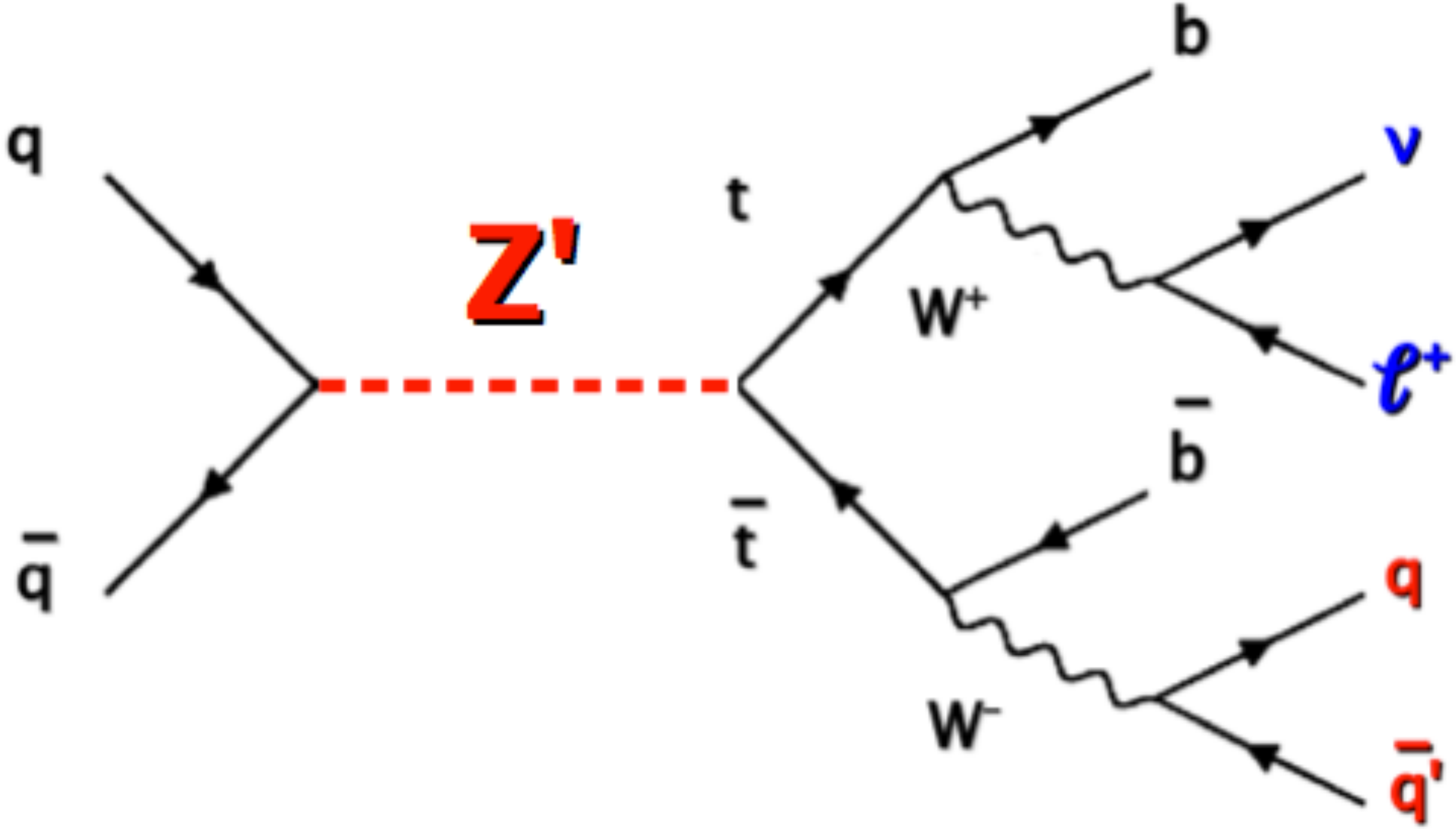
→ first observation of spin correlation with 5.1σ

→ correlation agrees with SM spin 1/2 hypothesis

Outline

Introduction
History of the Top Quark
Top Quark Production
Top Quark Properties
Searches in Top Sector
Conclusions

Searches in Top Production

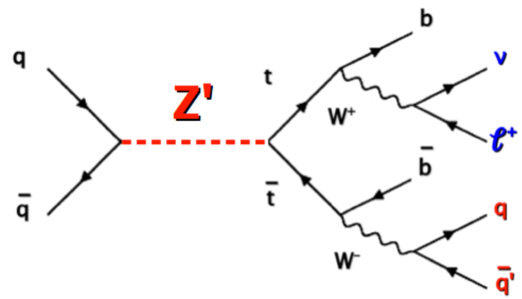


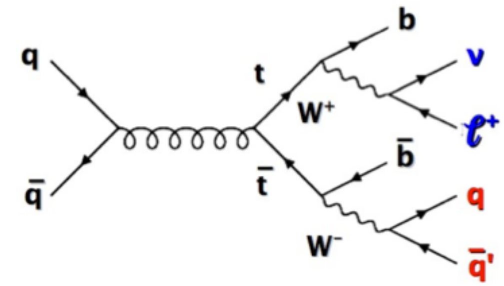
(see BSM lecture by L.-T. Wang)

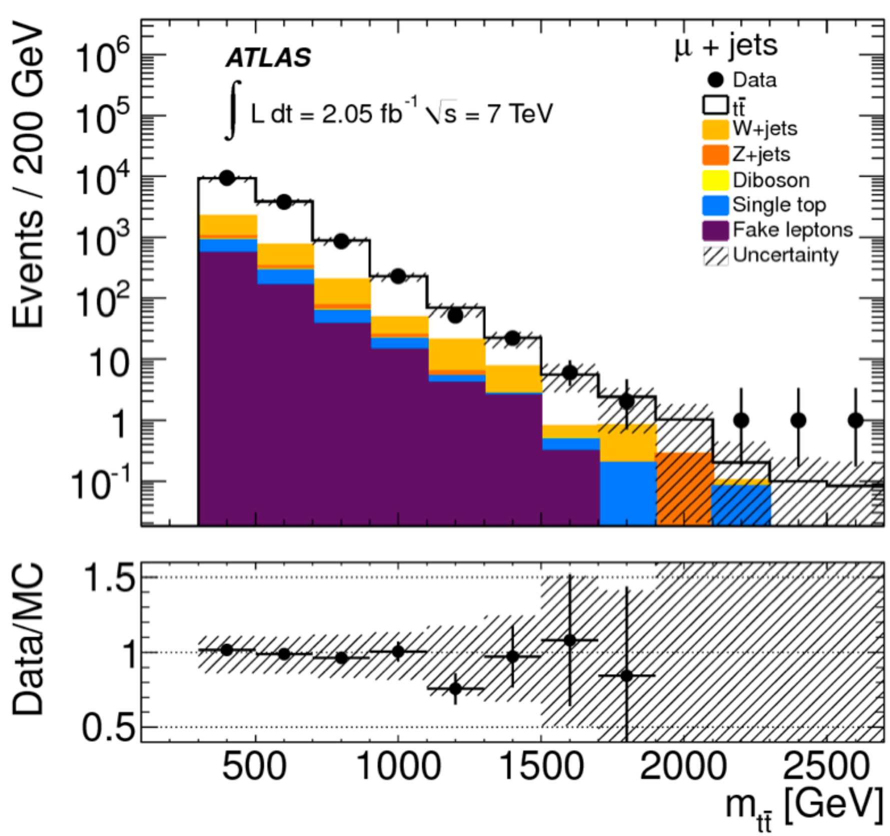
Searches for New ttbar Resonances

search for Z', axigluons, ... :

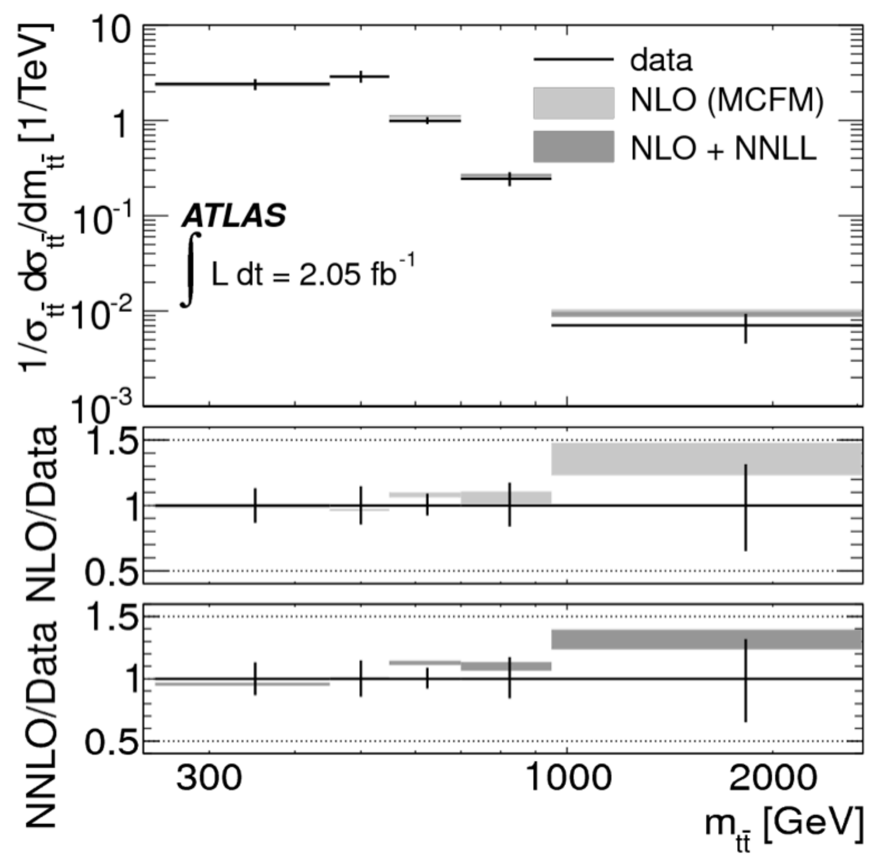
experimental signature is bump in $m_{t\bar{t}}$ distribution





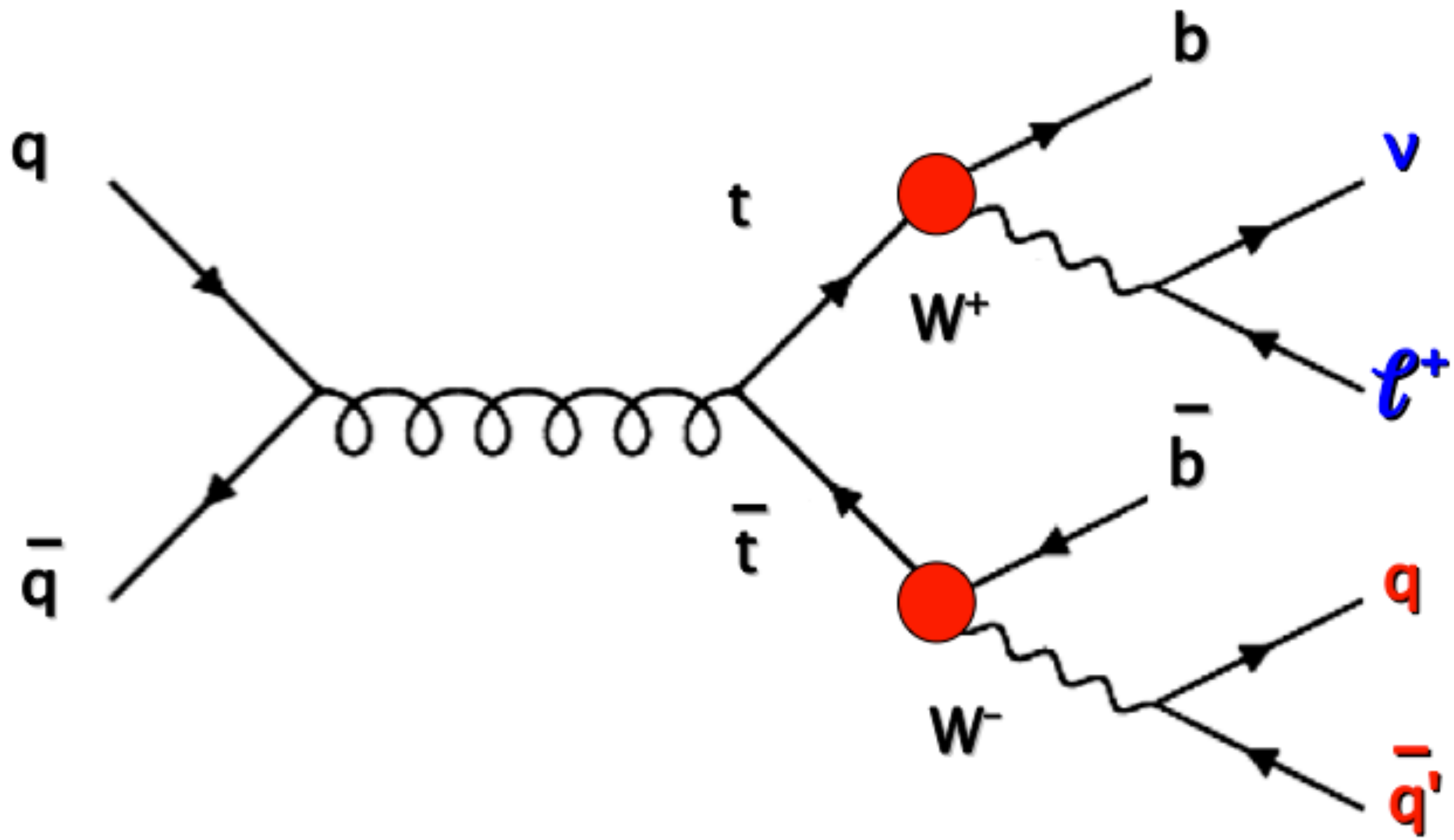


unfold

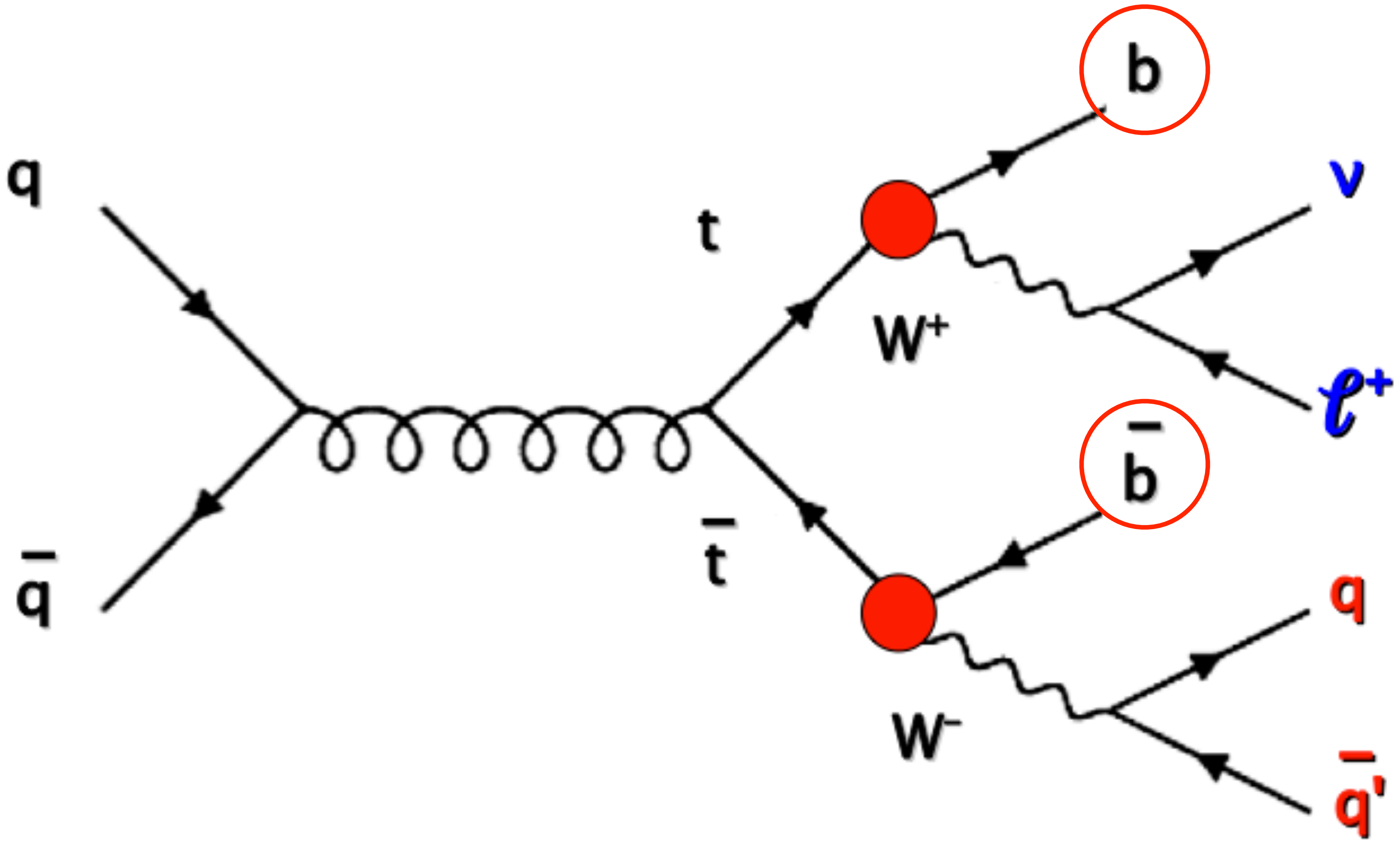


→ no hint for new physics

Searches in Top Decays



Searches in Top Decays: b Disappearance



Measurement of Branching Fractions

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

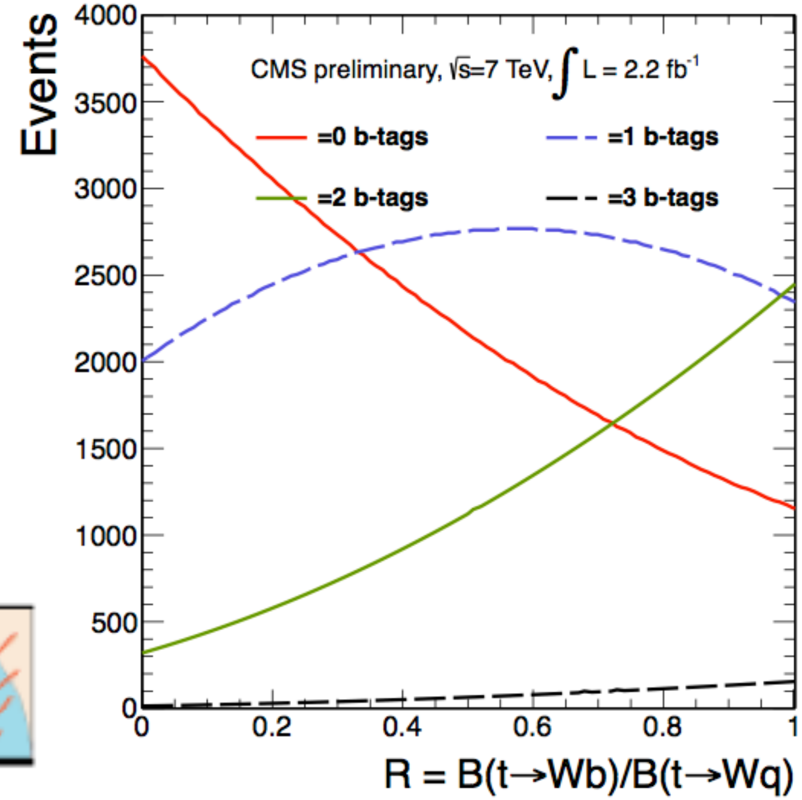
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

R changes fractions of b-tagged jets:



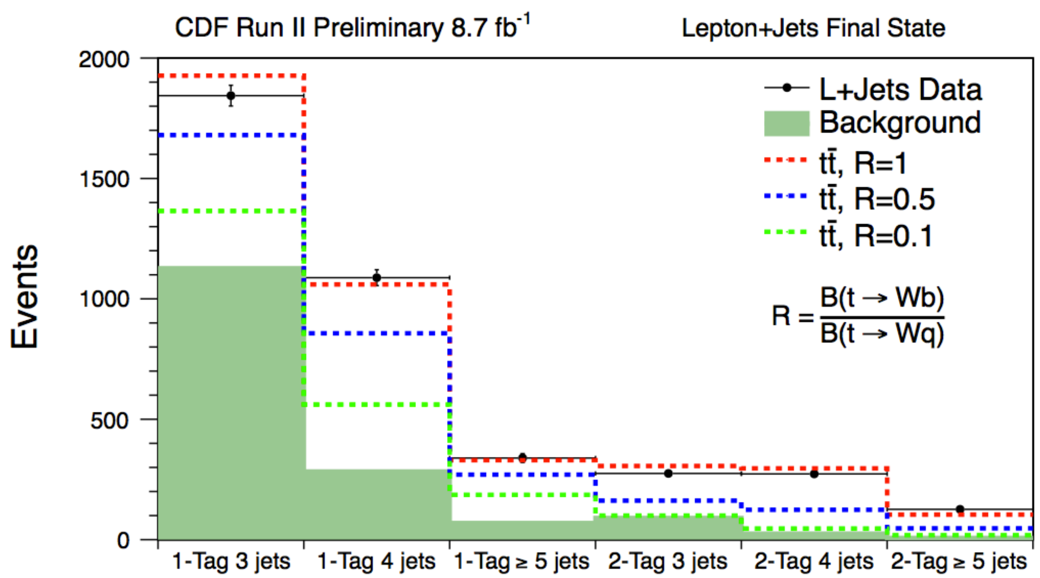
beyond SM:

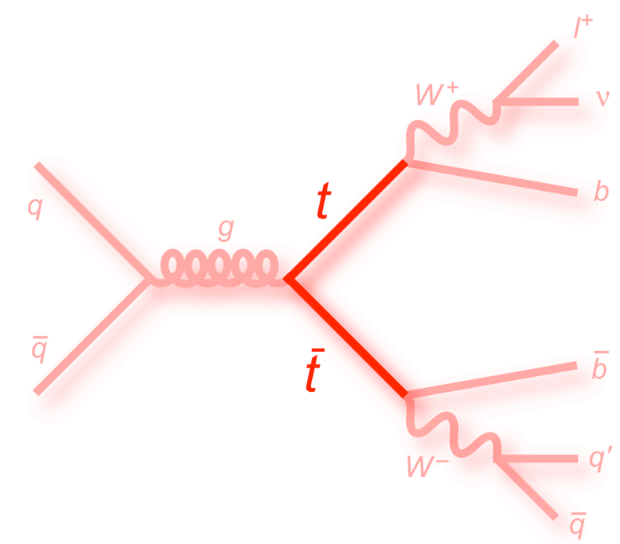
$$R \neq 1$$

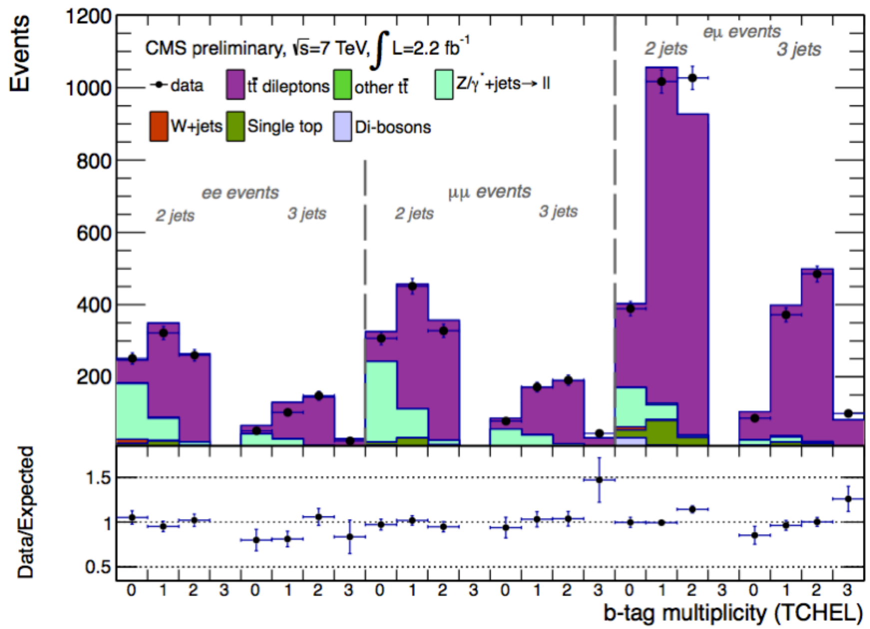
e.g. decay into 4th generation quark: R<1

sensitive to b disappearance

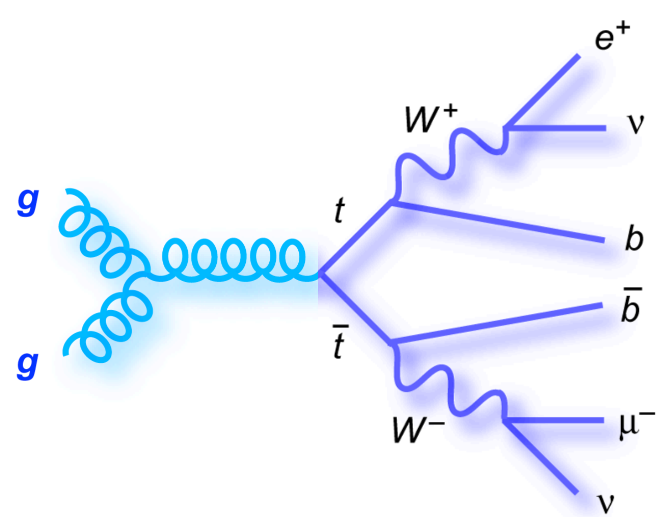
Measurement of branching fractions





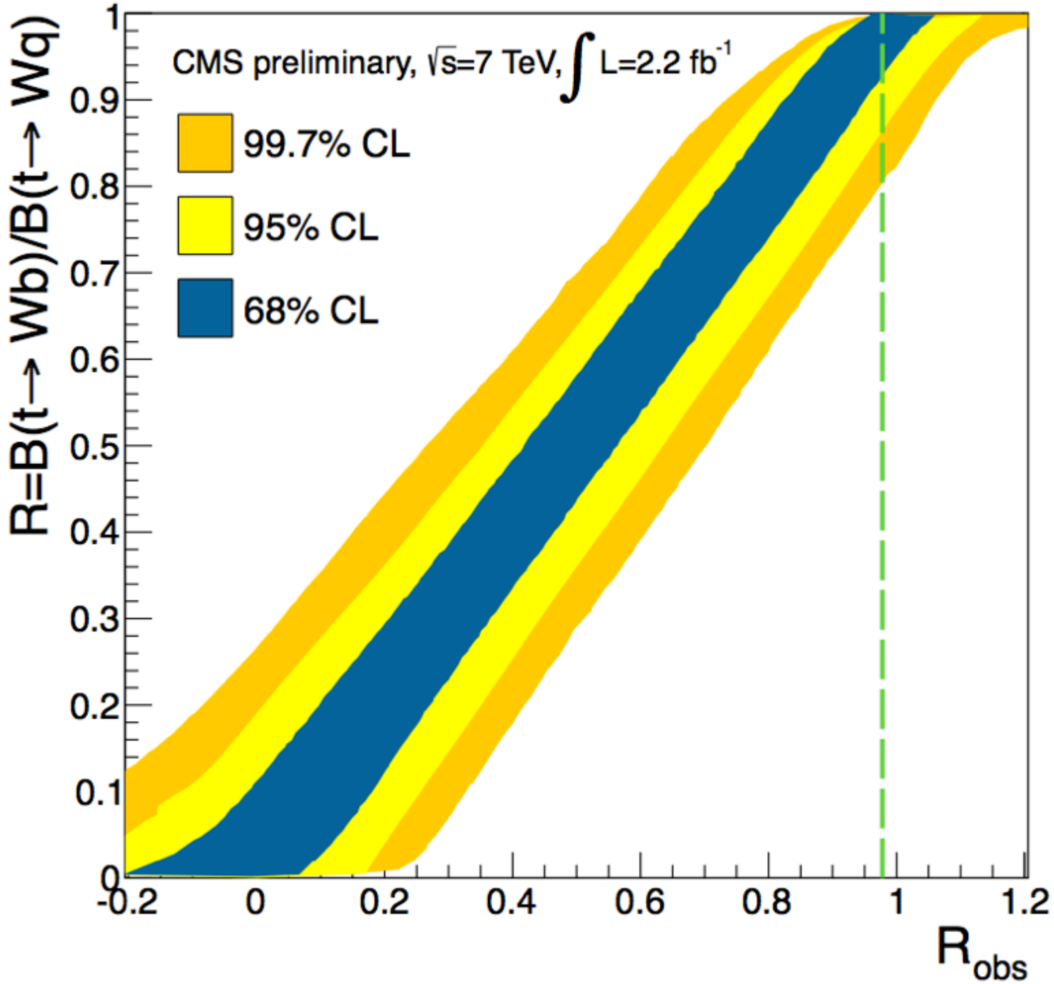


R=1



Measurement of branching fractions

maximum likelihood fit to data

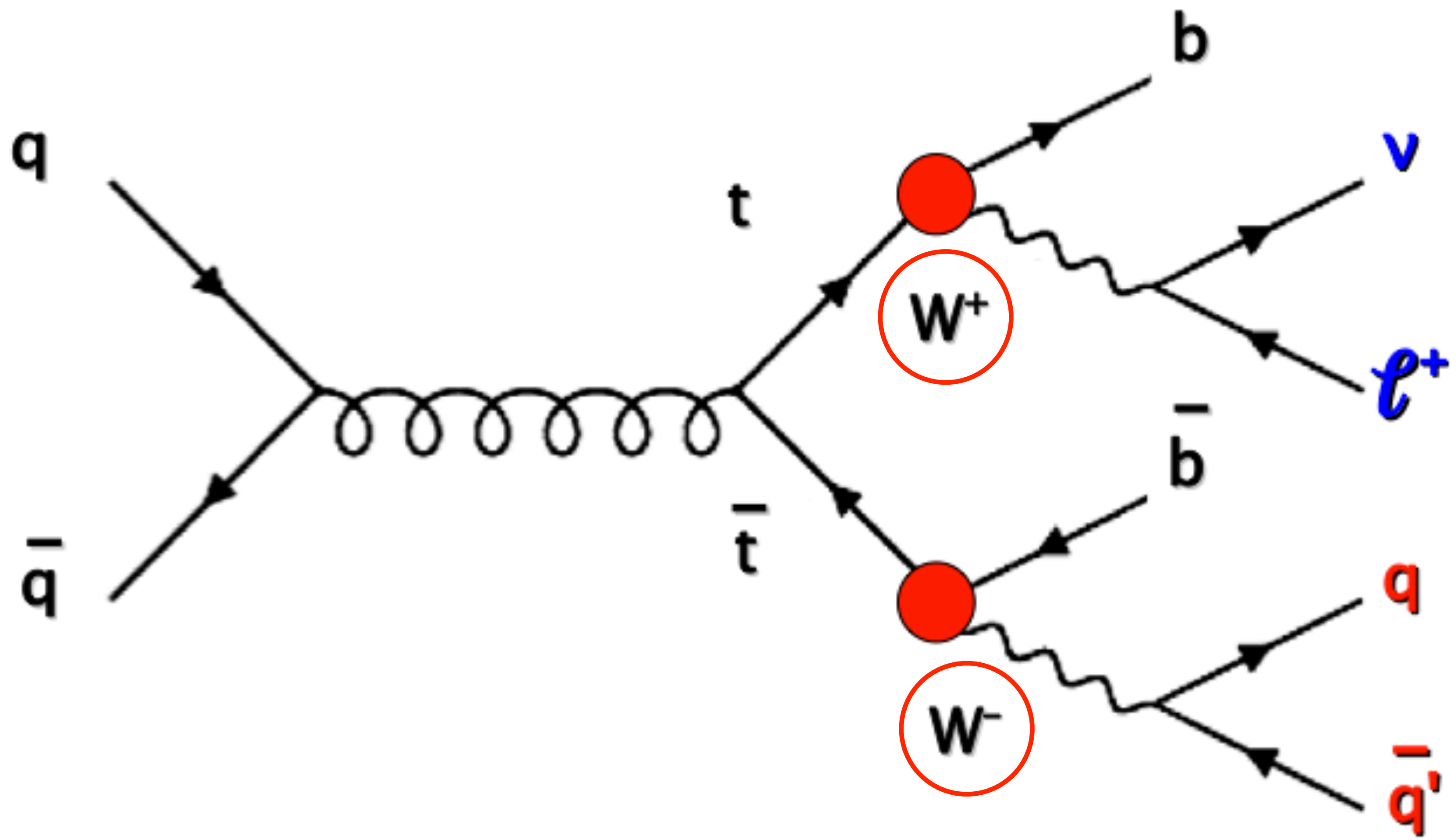


$$R = 0.98 \pm 0.04$$

good agreement with SM prediction: R=1

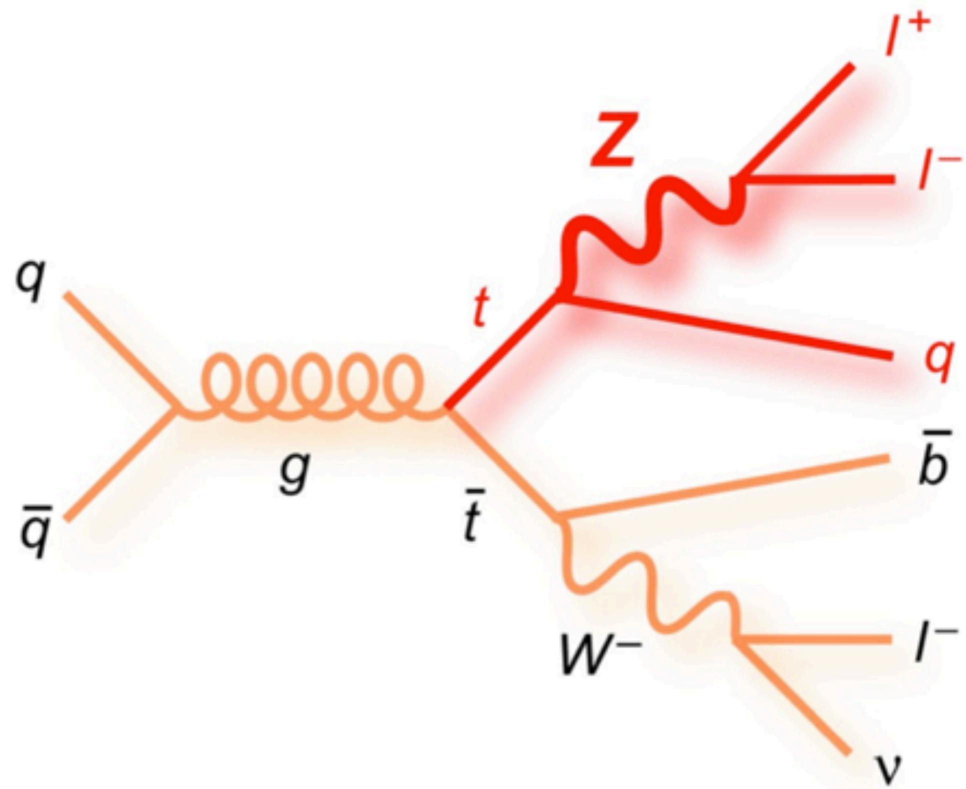
→ most precise measurement

Searches in Top Decays: W Disappearance



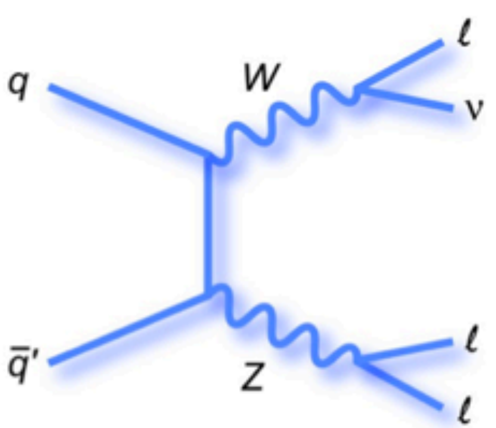
Search for FCNC in Top Quark Decays

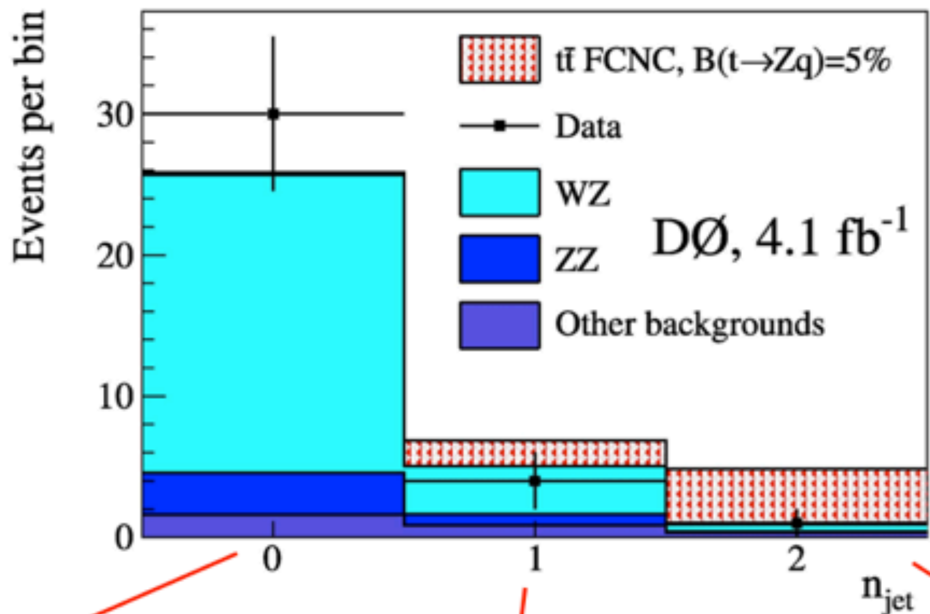
$$\mathcal{L}_{FCNC} = \frac{e}{2\sin\theta_W \cos\theta_W}\,\bar{t}\gamma_\mu(v_Z - a_Z\gamma_5)qZ^\mu + h.c.$$

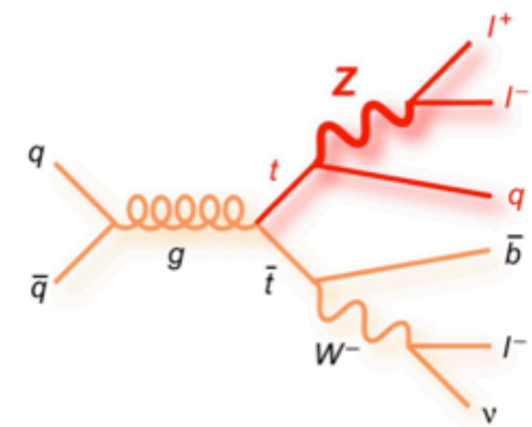


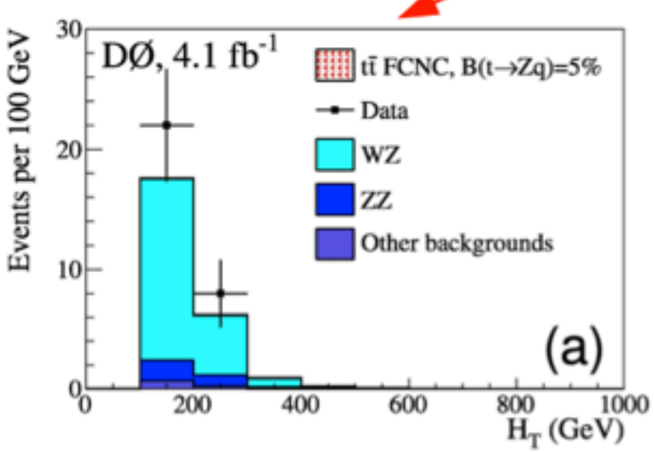
- **select 3 leptons, missing transverse momentum, 2 jets**

Search for FCNC in Top Quark Decays

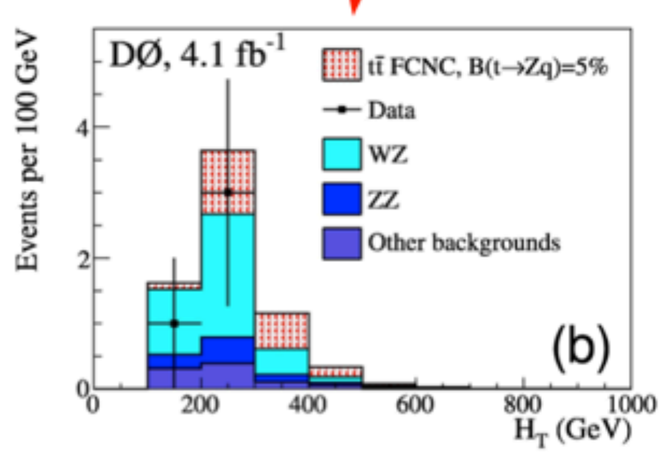




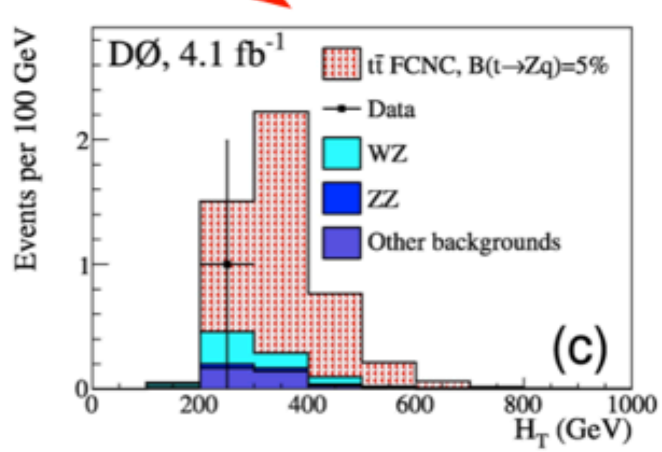




3 leptons + 0 jets

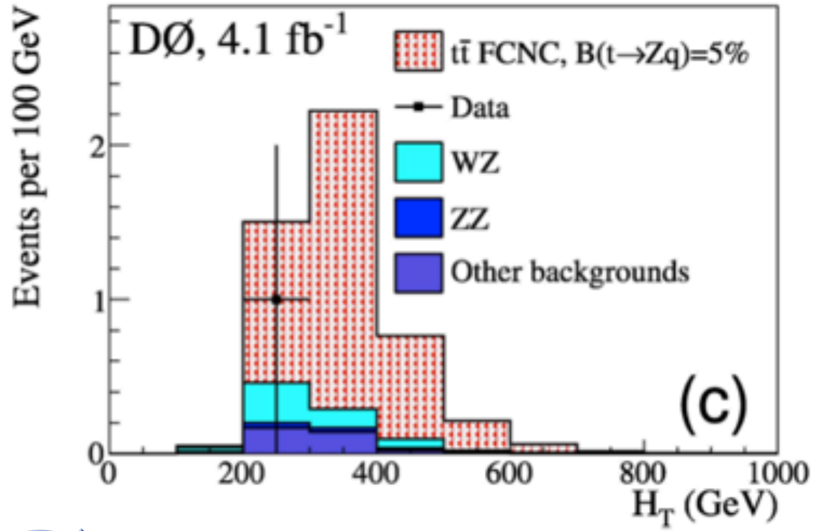


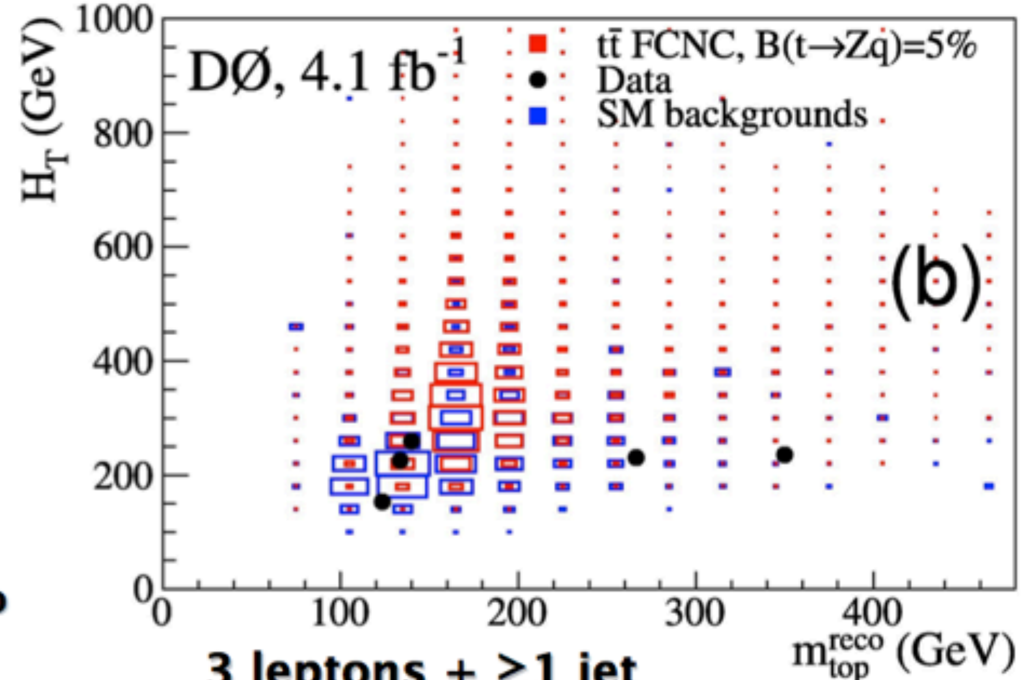
3 leptons + 1 jet



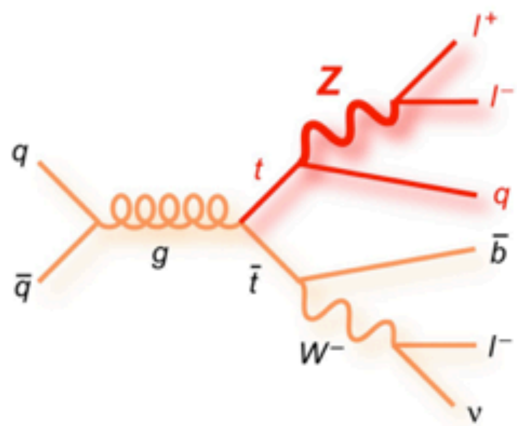
3 leptons + ≥2 jets

Search for FCNC in Top Quark Decays

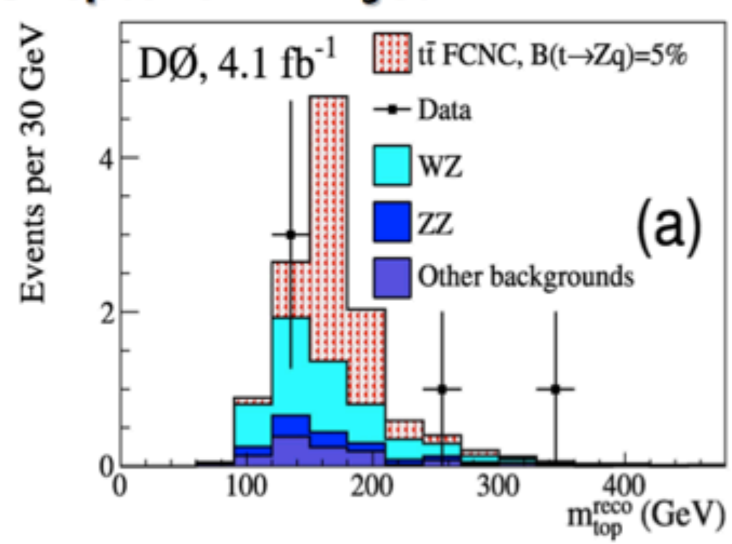




3 leptons + ≥1 jet



m_{top}^{reco}

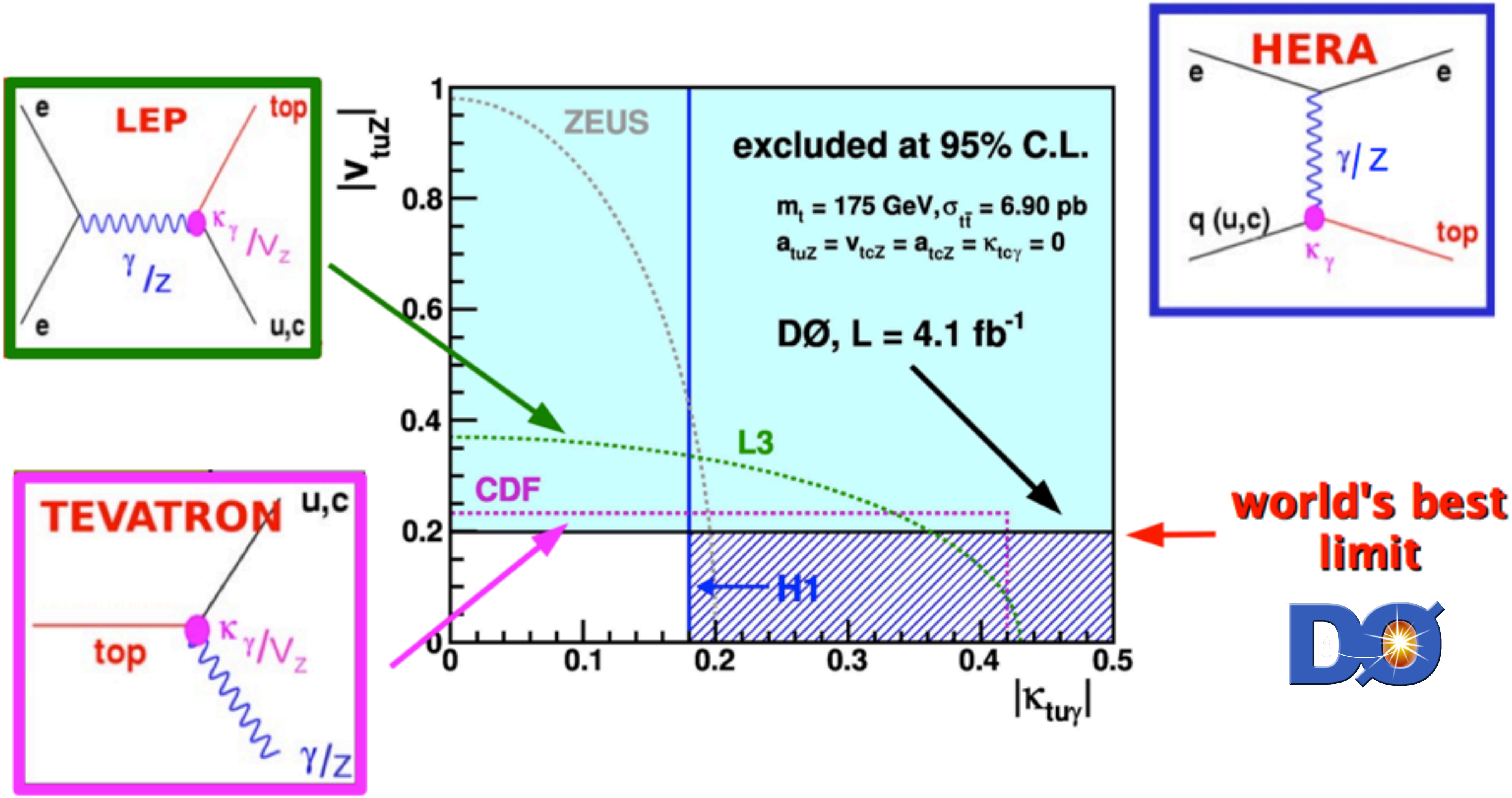


Phys. Lett. B701, 313 (2011)

95% C.L.

B(t→Zq) < 3.2% (3.8% expected)

Search for FCNC in Top Quark Decays



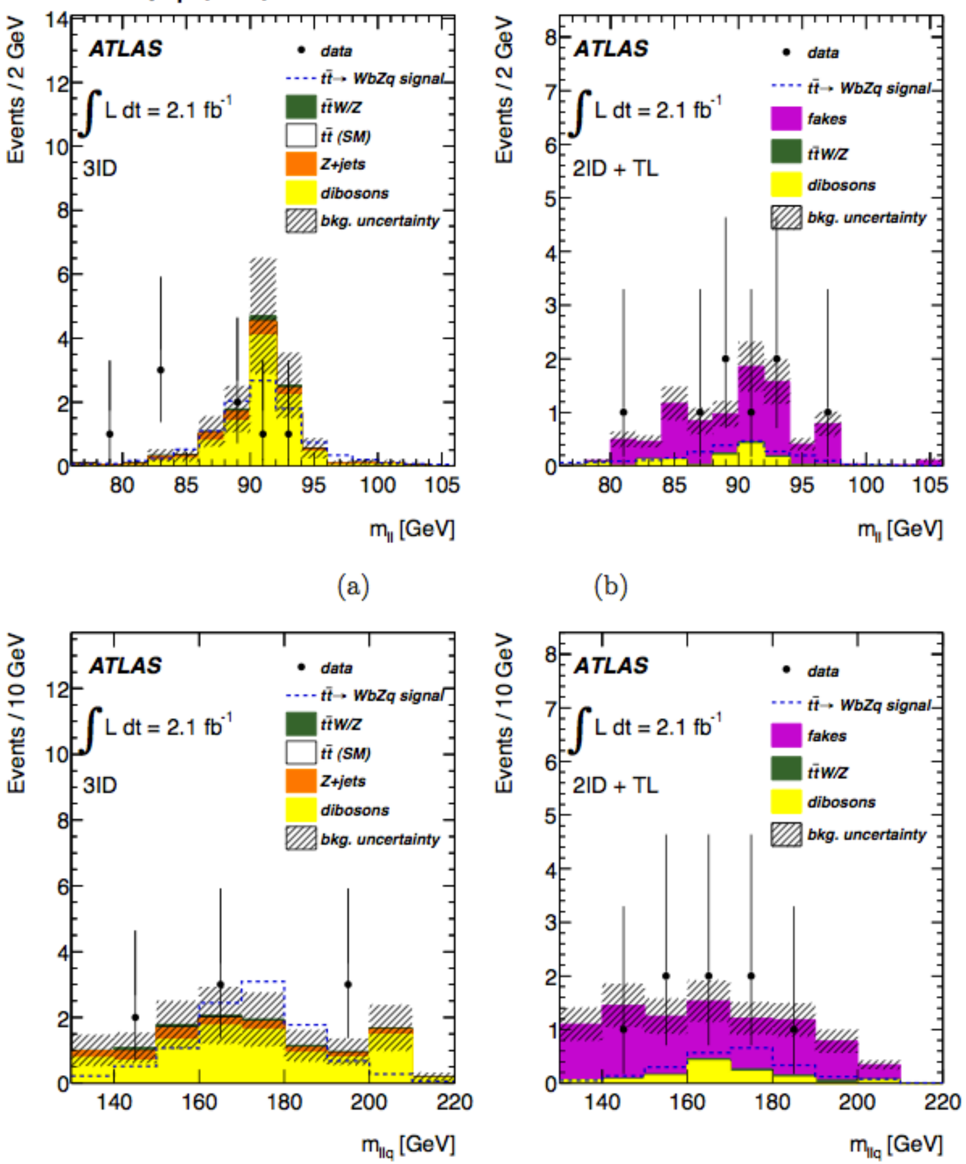
Search for FCNC in Top Quark Decays

3 ID selection

- p_T (1st)>25 GeV

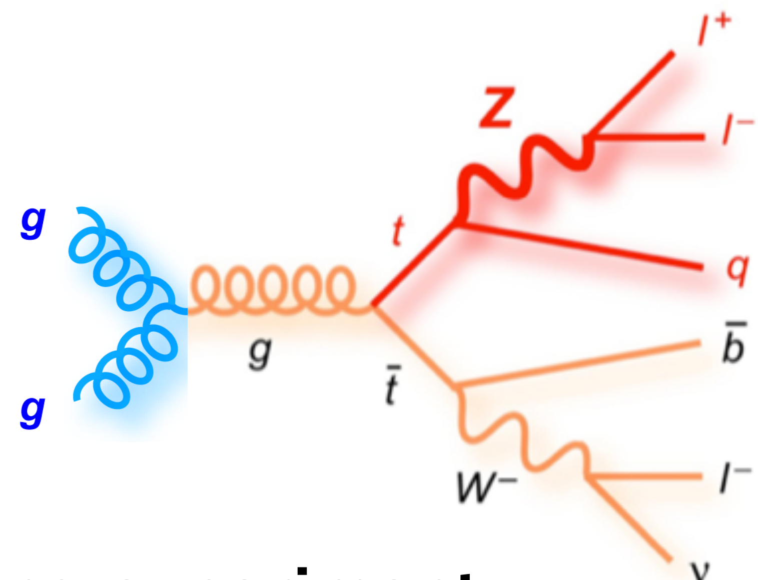
2ID+TL selection

- 2ID + 'track lepton', p_T (TL)>25GeV



$t\bar{t} \rightarrow qZ\ bW \rightarrow qll\ bl\nu$

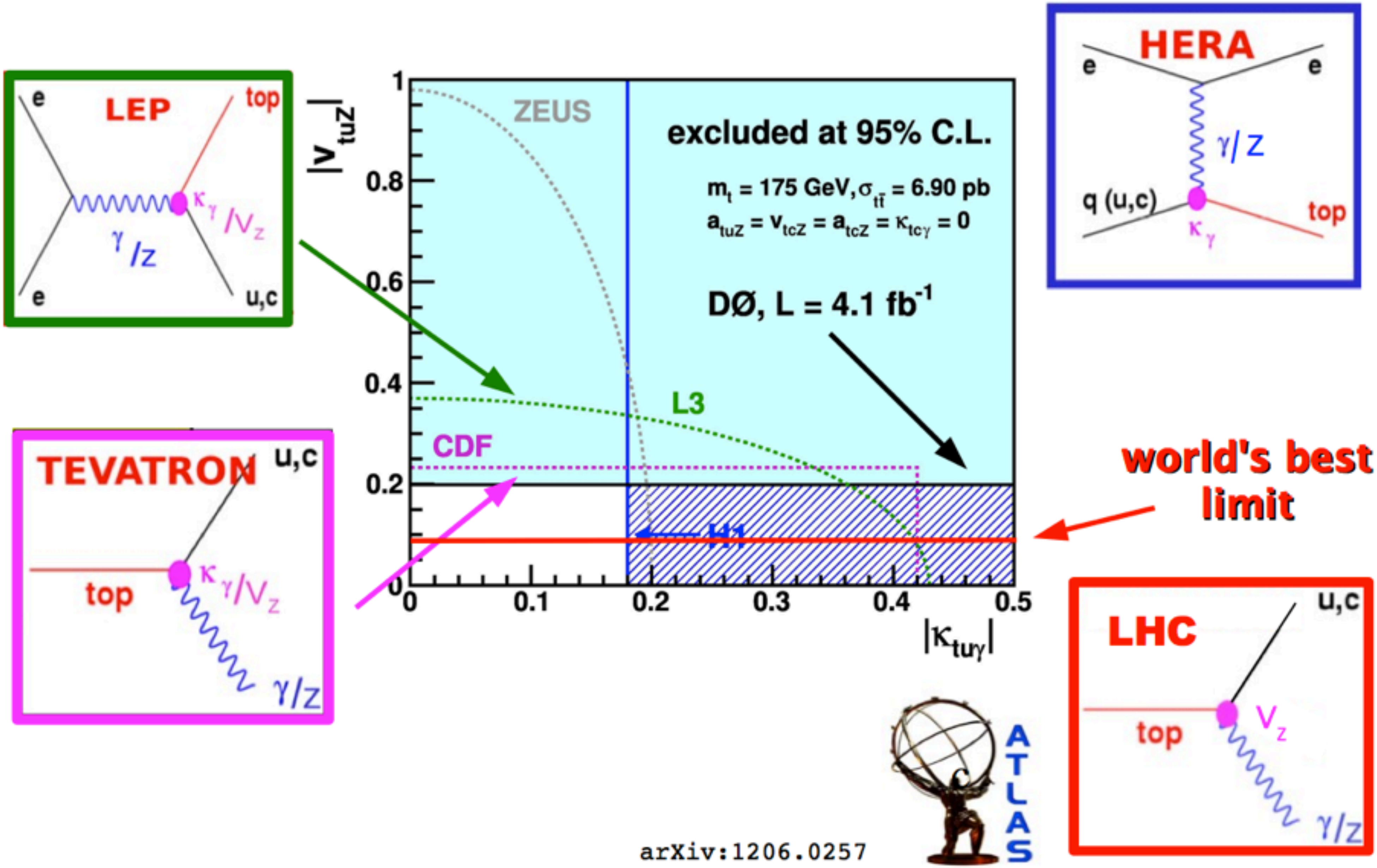
- 3 leptons (p_T > 20 GeV)
- 2 same flavour $|m(l^+l^-) - m(Z)| < 15$ GeV
- $E_T^{miss} > 20$ GeV, >= 2 jets (p_T>25 GeV)



counting experiment:

B(t→Zq)<0.73%
(0.93% expected)

Search for FCNC in Top Quark Decays



Outline

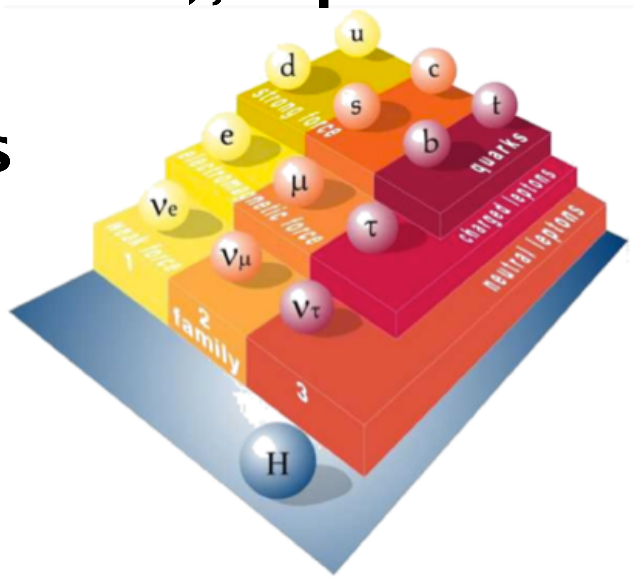
Introduction
History of the Top Quark
Top Quark Production
Top Quark Properties
Searches in Top Sector
Conclusions

Summary

- **we are in the middle of the precision top physics era**
  - top pair cross section (4% LHC)
  - V_{tb} (8% Tevatron)
  - top mass (0.5% Tevatron, 0.8% LHC)
  - differential cross sections
- new processes: t-channel single top (observation), Wt (evidence), ttZ (evidence), ttγ (close to evidence - charge!)
- new properties: spin correlations (observation), top polarisation, color flow, jet veto, ...
- many stringent searches for new physics

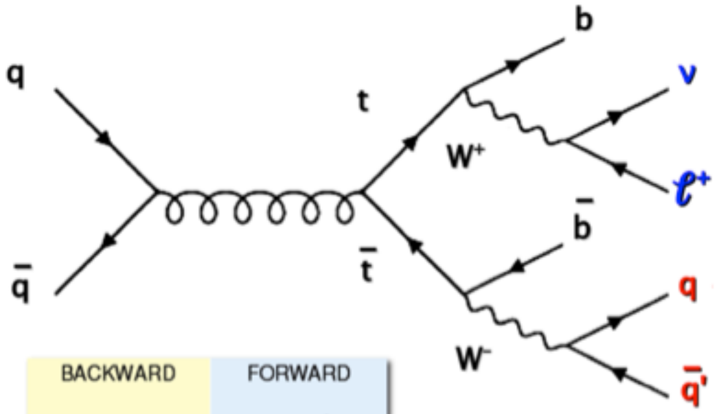
→ good agreement with SM

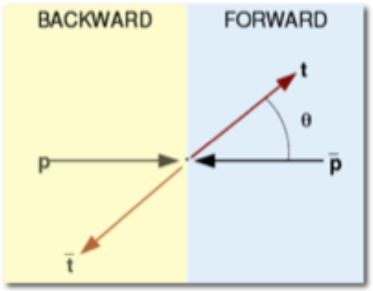
→ tremendous success of the whole field



Backup

Forward Backward Charge Asymmetry

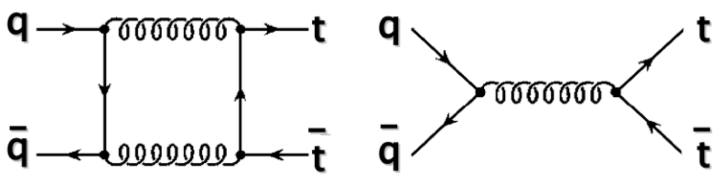




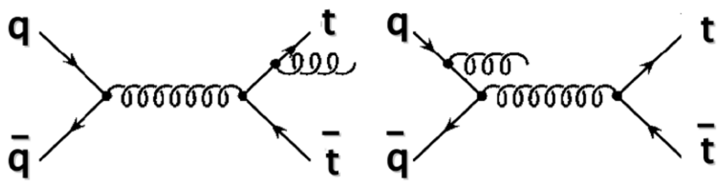
$$A_{fb} = \frac{F - B}{F + B}$$

- asymmetry in $O(\alpha_s^3)$ **NLO QCD**

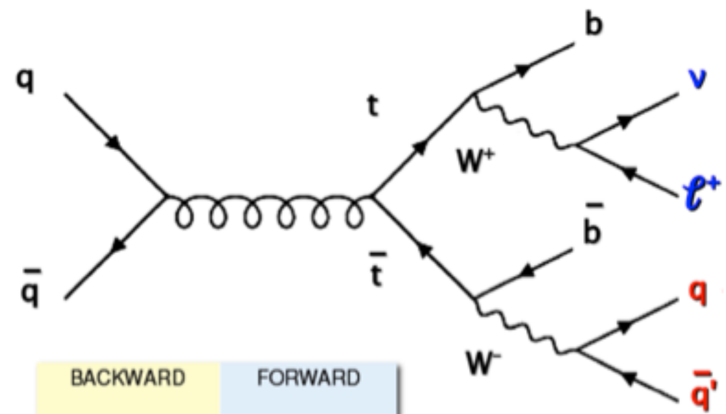
interference between:

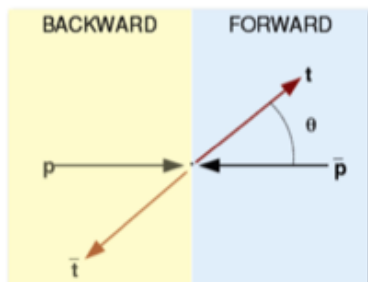


interference between:

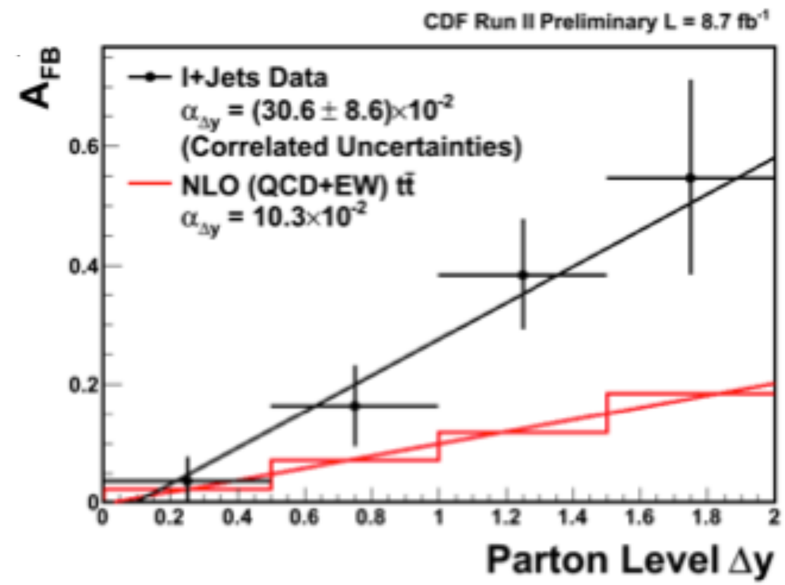


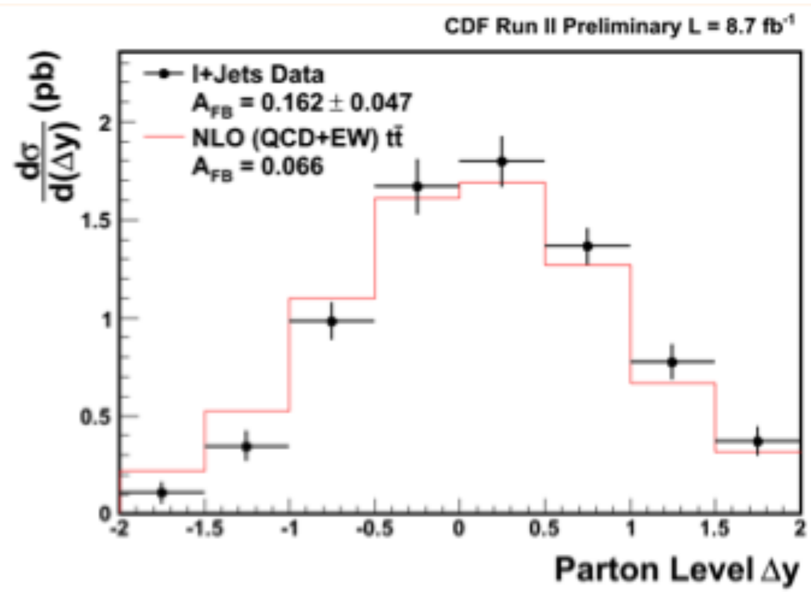
Forward Backward Charge Asymmetry

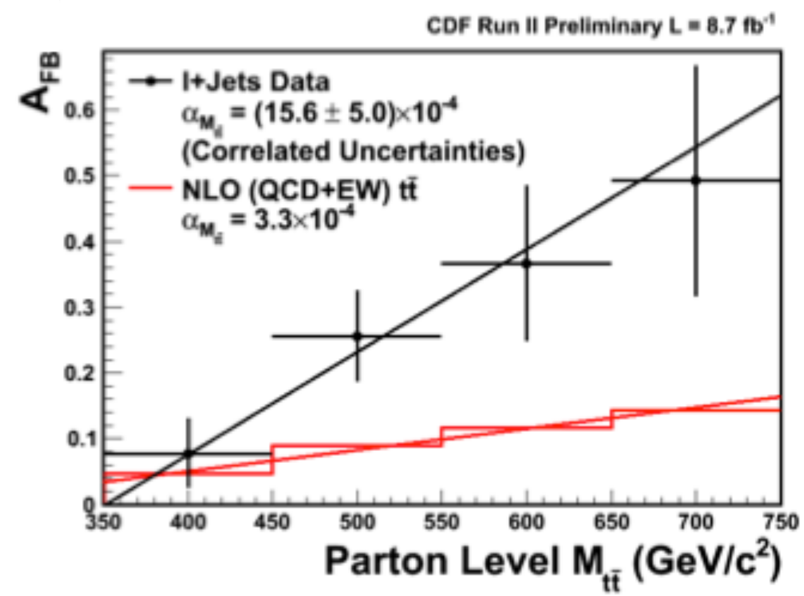




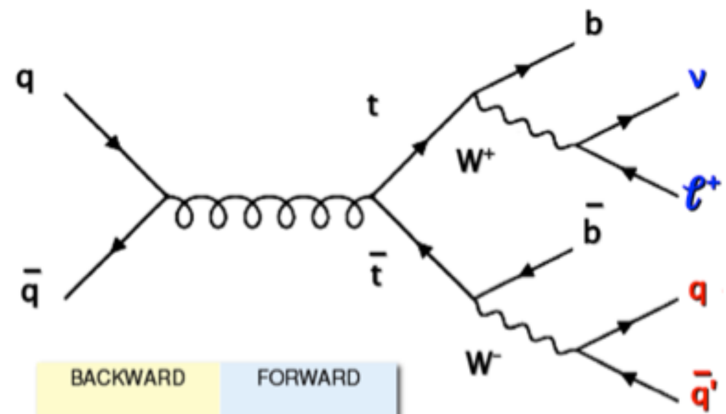
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)}$$

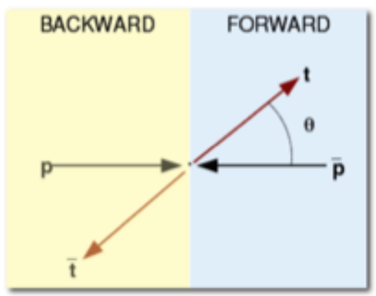






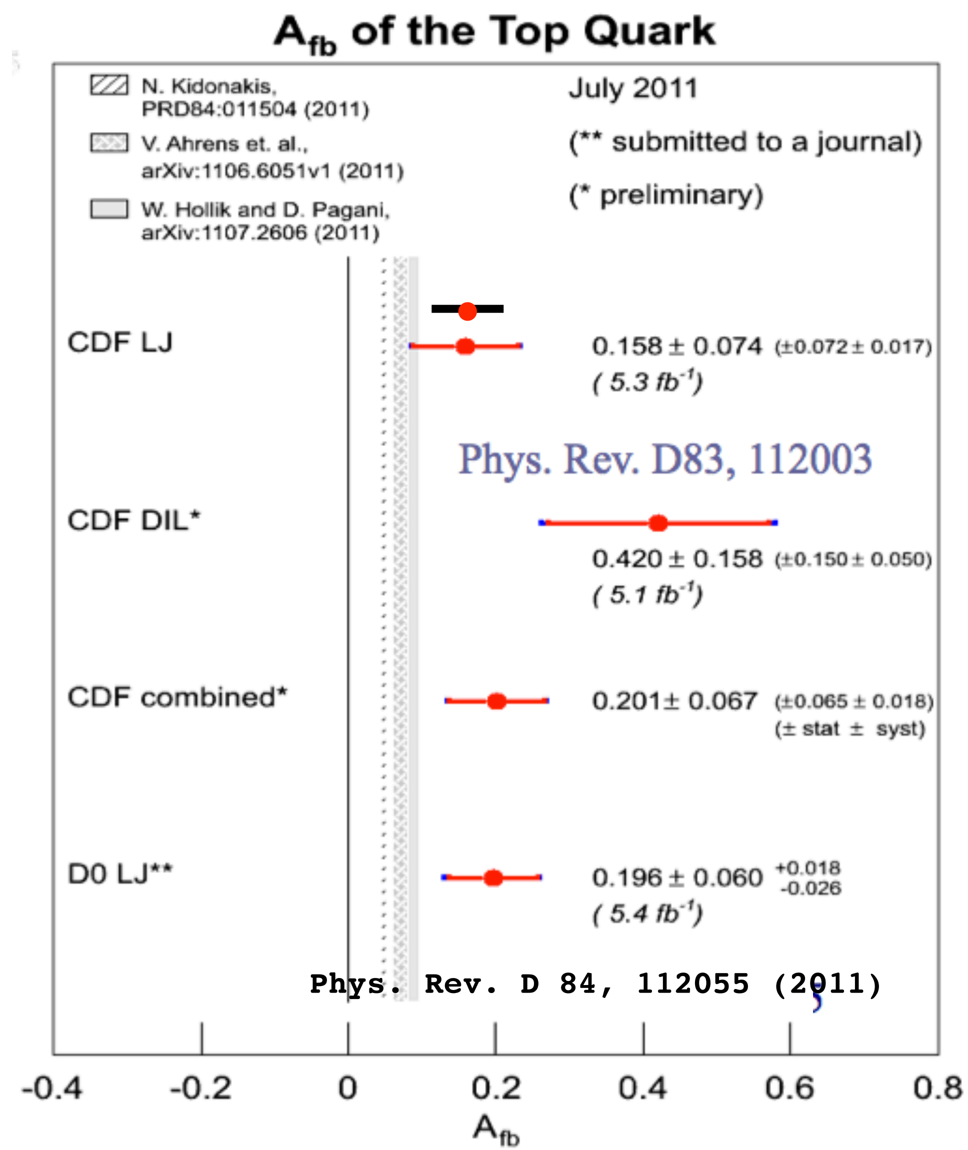
Forward Backward Charge Asymmetry



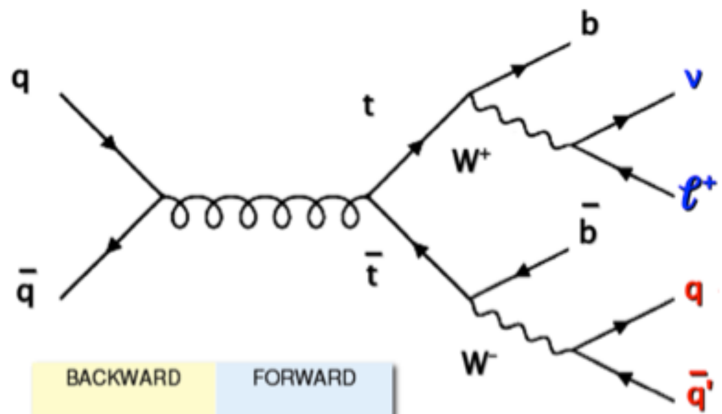


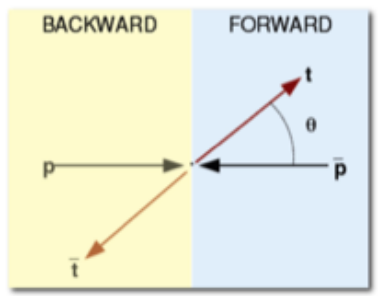
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

A_{fb} = 0.162 ± 0.047 (stat.+syst.)

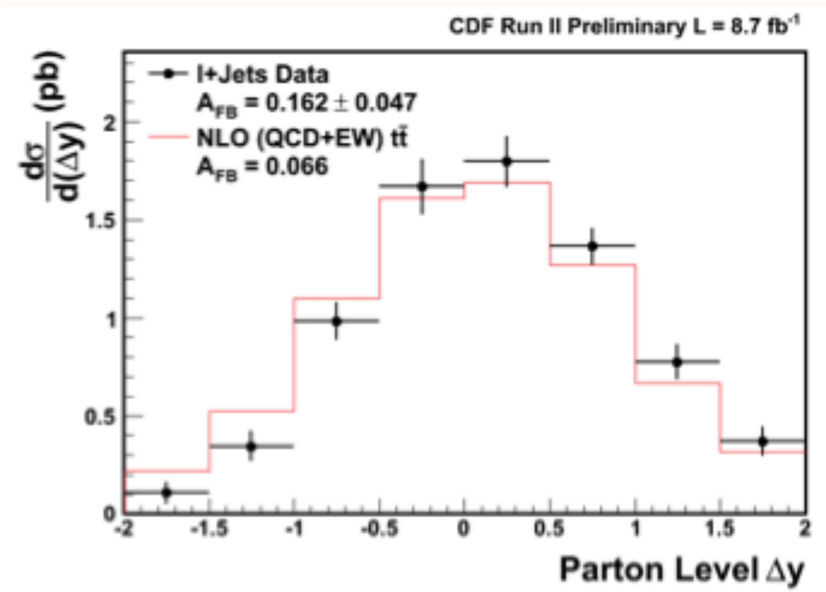


Forward Backward Charge Asymmetry





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

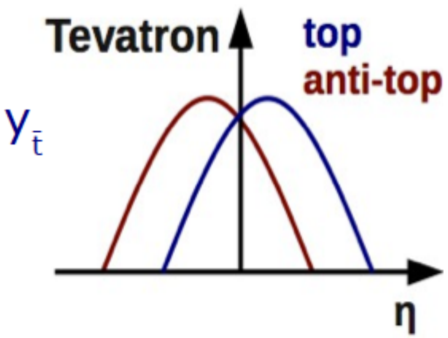


- complementary to the LHC

Tevatron

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

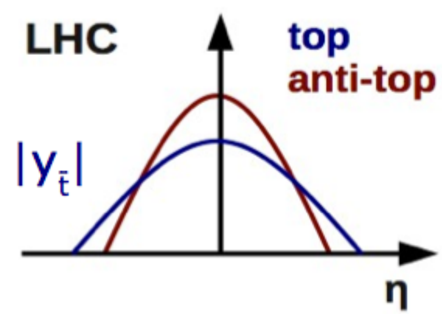
$\Delta y = y_t - y_{\bar{t}}$



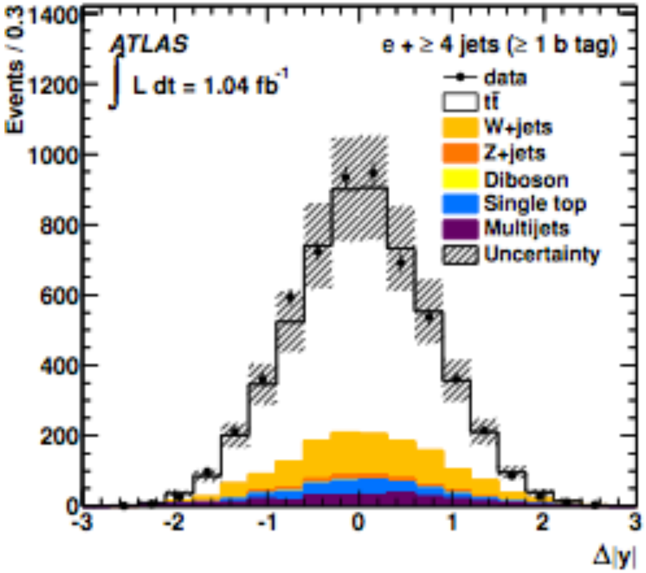
LHC

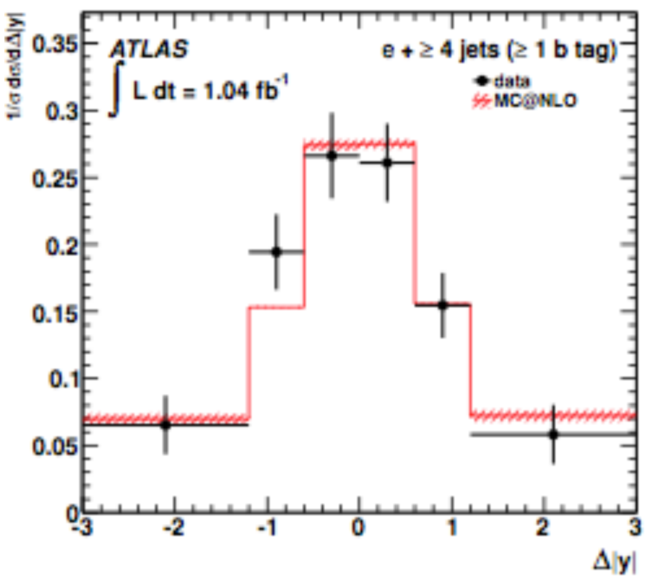
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

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



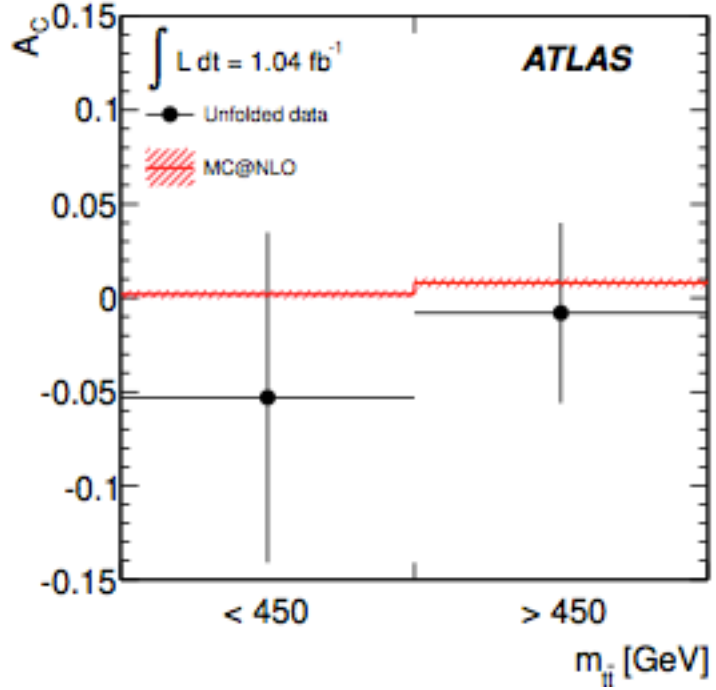
Charge Asymmetry: LHC





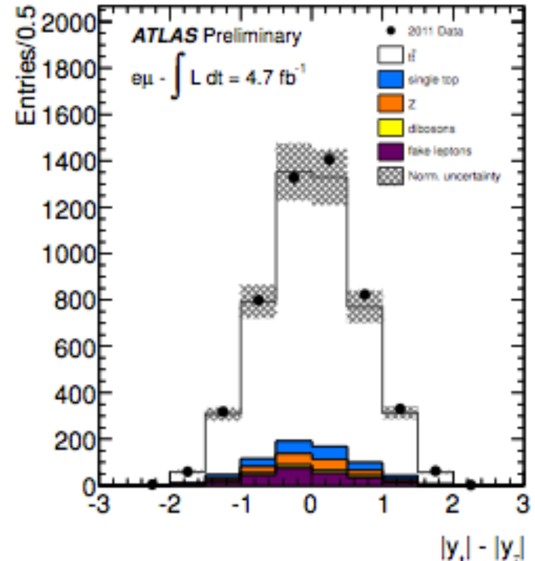
Ac (l+jets) = −1.8 ± 3.6%

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



Ac (combined) = 2.9 ± 2.8%

MC@NLO:
Ac = 0.6 ± 0.2%



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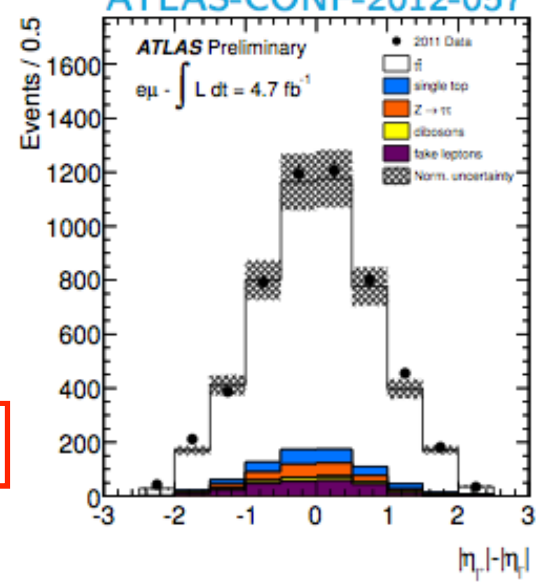
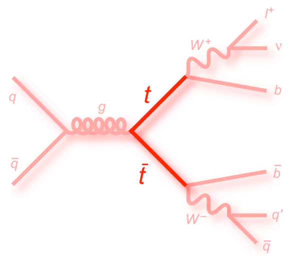
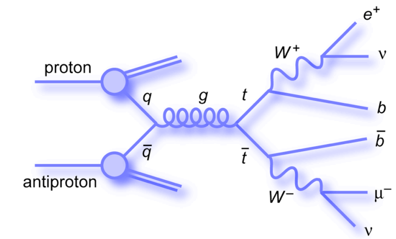


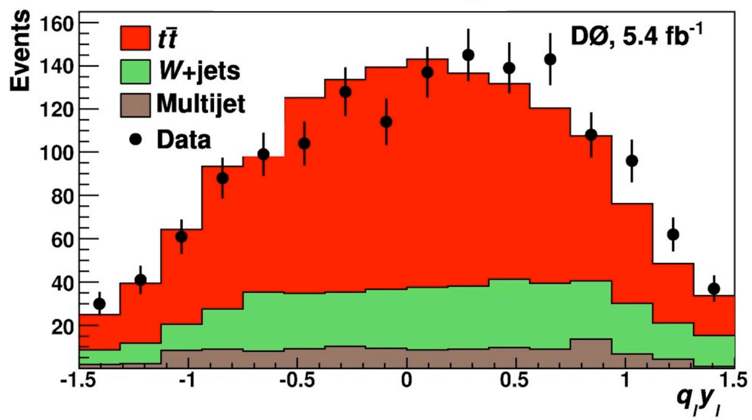
Ac (dilepton) = 5.7 ± 2.8%

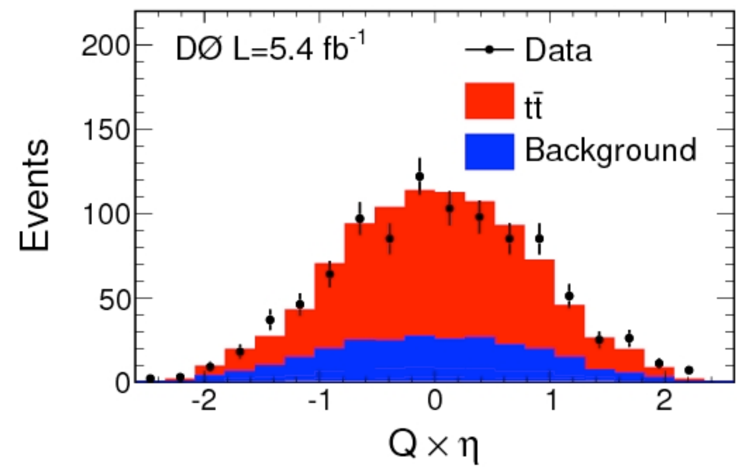
Leptonic Asymmetry

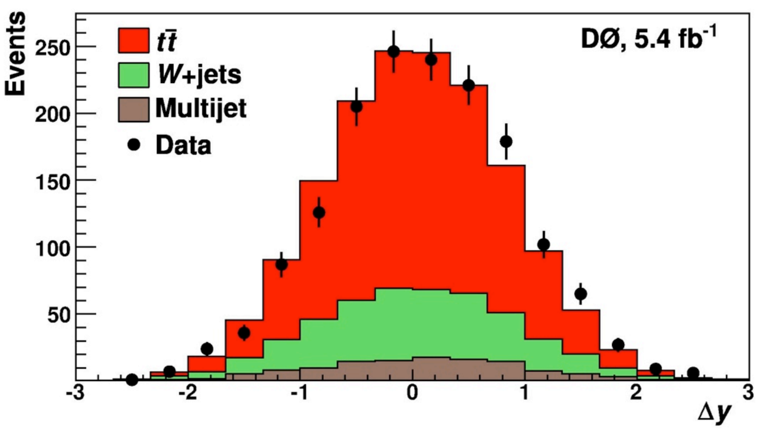


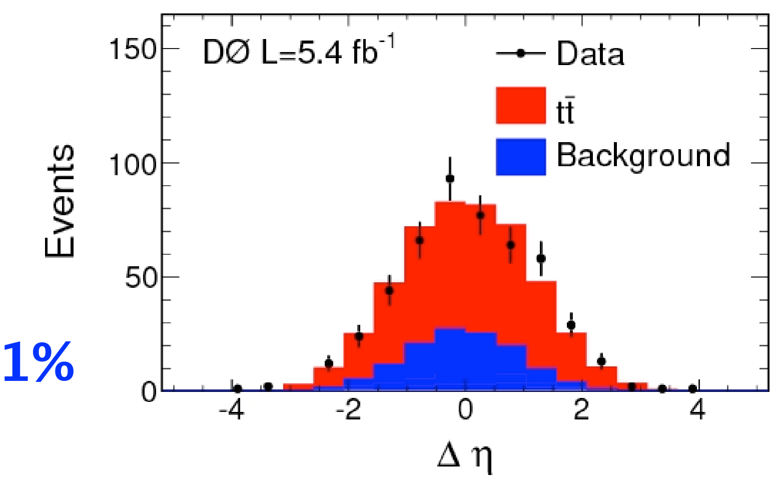
$$A_{FB}^{l} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$











MC@NLO:
$A^{\ell}_{FB} = 2.1 \pm 0.1\%$

QCD+EWK:
$A^{\ell}_{FB} = 4.7 \pm 0.1\%$

$A^{\ell}_{FB} = 15.2 \pm 4.0\%$

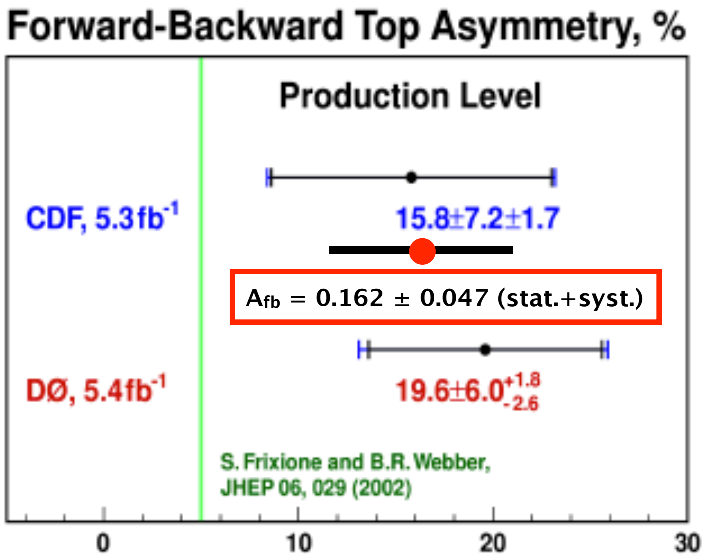
$A^{\ell}_{FB} = 5.8 \pm 5.3\%$

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:

    $$A_{FB}^{l} = (11.8 \pm 3.2)\ \%$$

    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

Measurement of Branching Fractions

with Y. Peters

Standard Model:

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

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

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

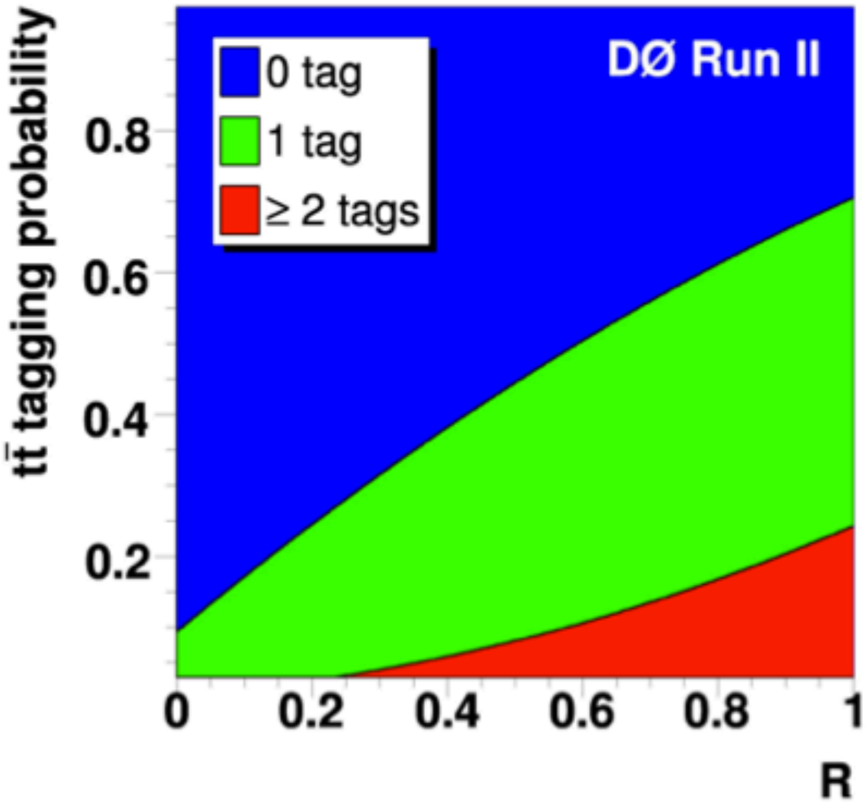
unitarity of CKM matrix

beyond SM:

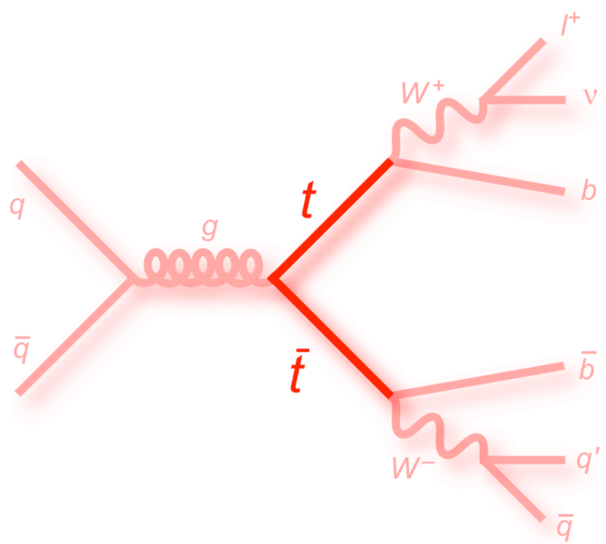
$$R \neq 1$$

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

R changes fractions of b-tagged jets:

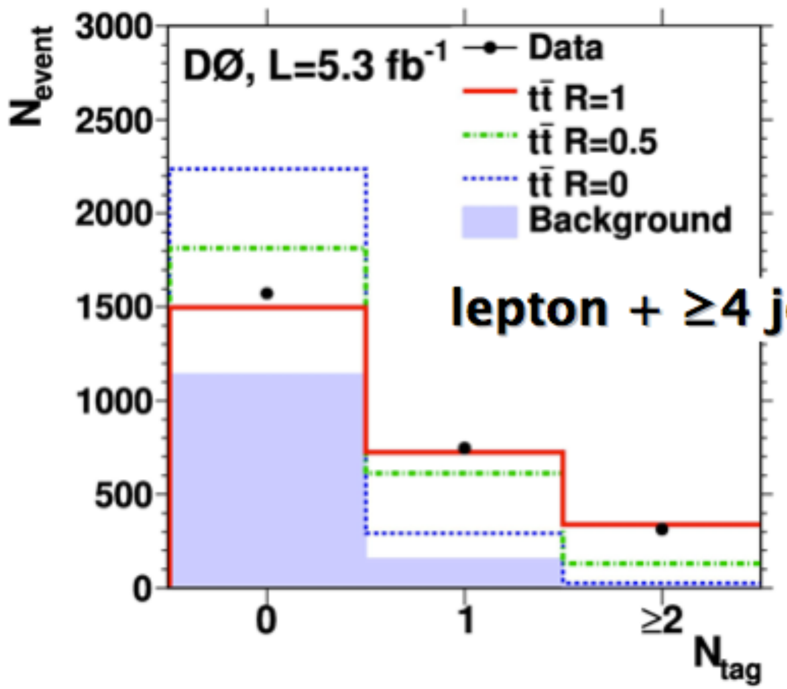


Measurement of branching fractions



combined l+jets and dilepton

R= 0.90±0.04 (stat+syst)



lepton + ≥4 jets

using unitarity of CKM matrix:

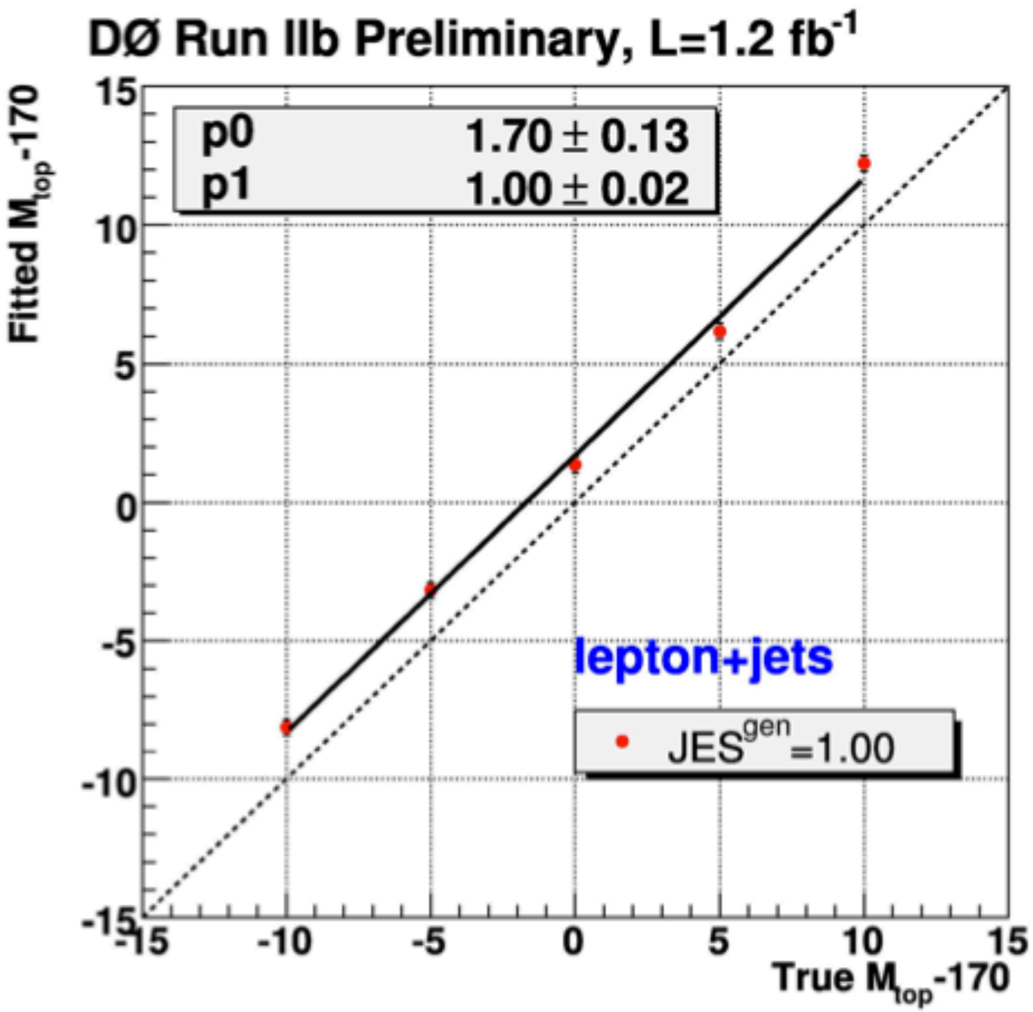
$0.90 < |V_{tb}| < 0.99$ @ 95% C.L.

→ most precise measurement

Phys. Rev. Lett. 107, 121802 (2011)

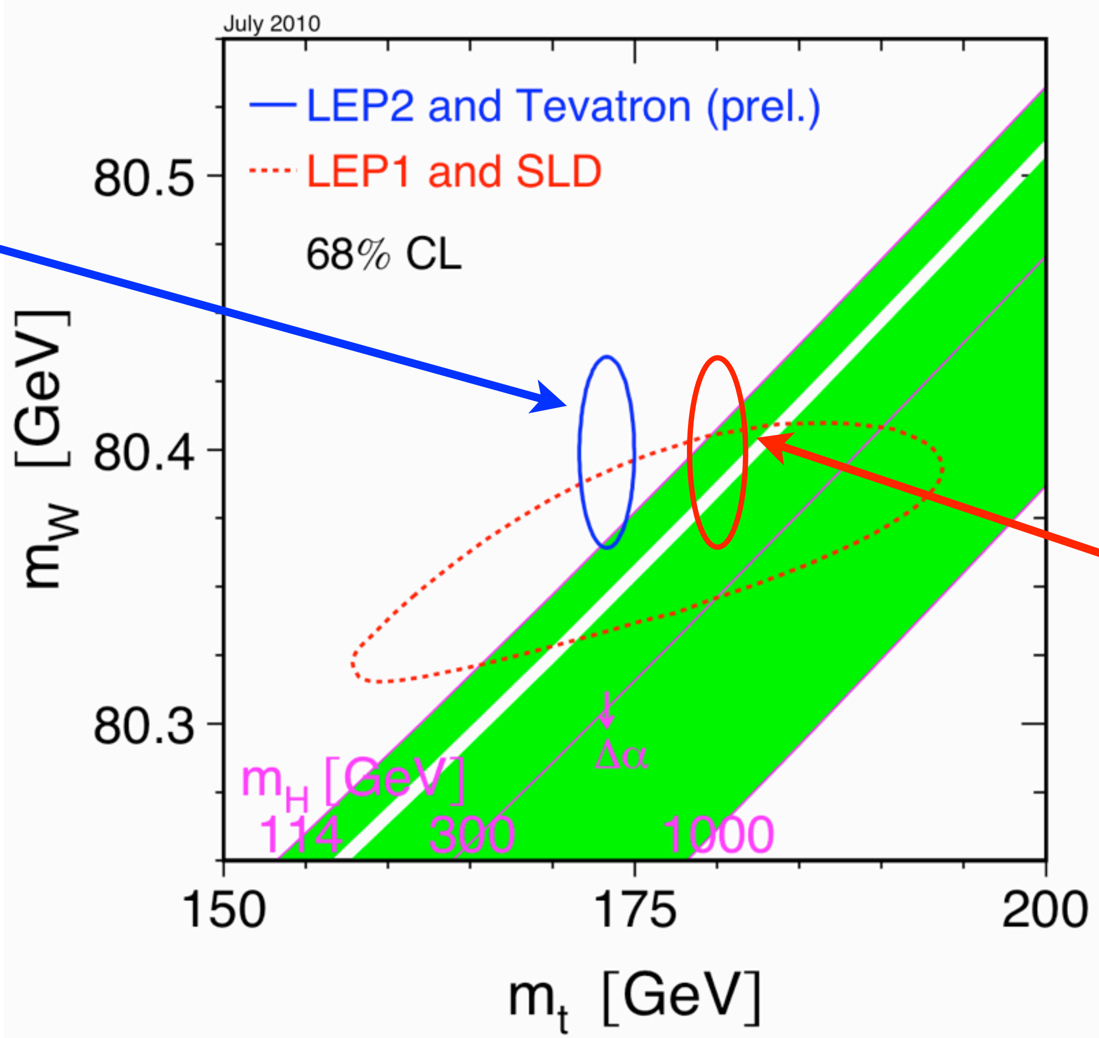
Calibration of the Method

- pseudo experiments: compare measured mass with generated
- correct for differences: calibration curve



Important to Know...

pole mass



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

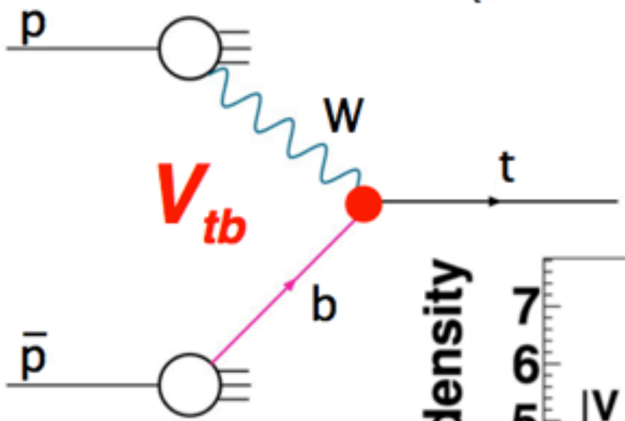
together with understanding of systematics one of the most challenging questions in the future!

Top Quark Decay Width

t-channel cross section:

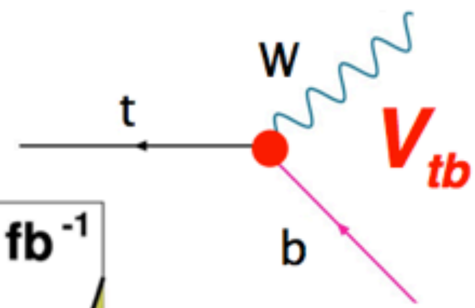
$$\sigma(p\bar{p} \to tqb + X) \ = \ 2.90 \pm 0.59 \ \text{pb}$$

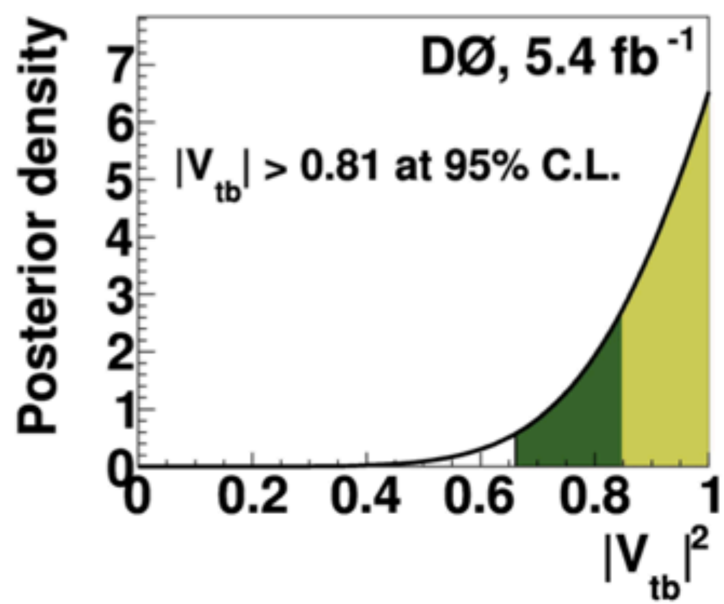
m_t =172.5 GeV



partial decay width:

R= 0.90±0.04 (stat+syst)





$$|V_{tb}| > 0.81 \text{ at the 95\% C.L.}$$

Top Quark Decay Width

t-channel cross section:

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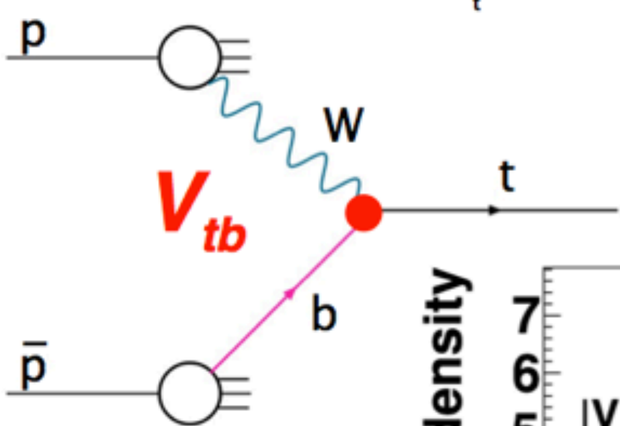

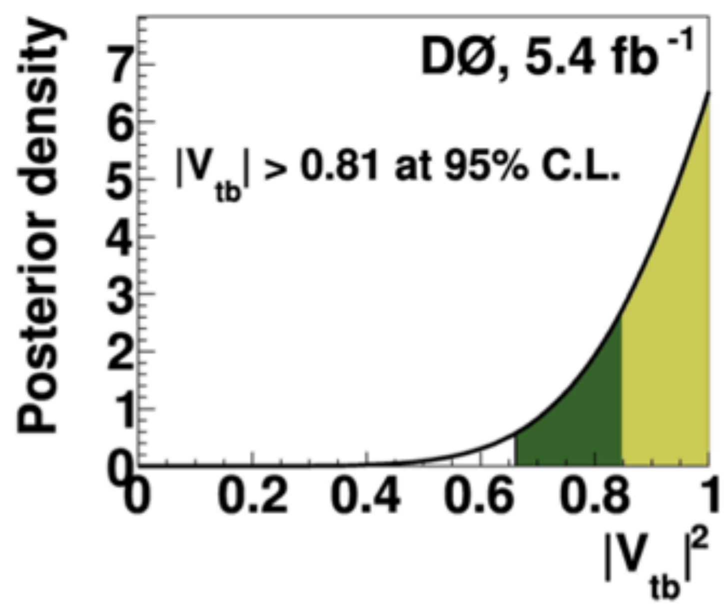

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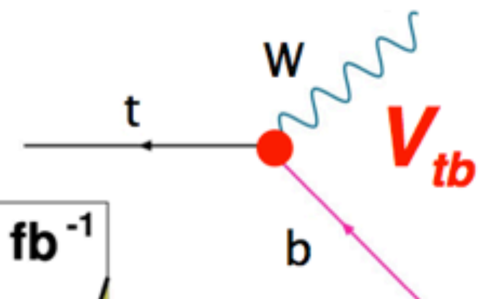
R= 0.90±0.04 (stat+syst)



4th generation b' quark:

$$m_{b'} \; > m_t - m_W$$

$$|V_{td}|, |V_{ts}| \; \ll \;\; 1$$

$$|V_{tb'}|^2 \; = \; 1 - |V_{tb}|^2$$

$$|V_{tb}| > 0.81 \text{ at the } 95\% \text{ C.L.}$$

$$|V_{tb'}| < 0.59 \text{ at } 95\% \text{ C.L.}$$

Measurement in dilepton channel

- reconstruct event by maximizing kinematic likelihood and picking most likely b-quark jet combination

$$\mathcal{L}\left(\vec{p}_{\nu}, \vec{p}_{\bar{\nu}}, E_b^{\rm guess}, E_{\bar{b}}^{\rm guess}\right) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$

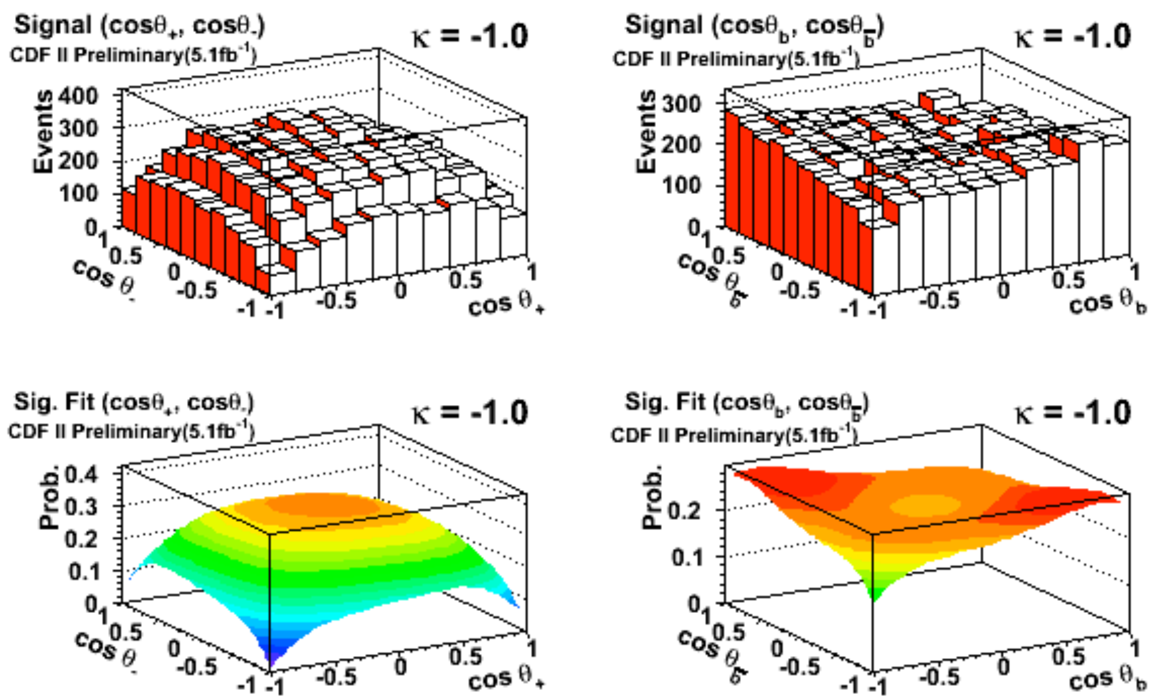
MC priors

$$\frac{1}{\sigma_b}\exp\left[-\frac{1}{2}\left\{\frac{E_b^{\rm meas}-E_b^{\rm guess}}{\sigma_b}\right\}^2\right] \times \frac{1}{\sigma_{\bar{b}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\bar{b}}^{\rm meas}-E_{\bar{b}}^{\rm guess}}{\sigma_{\bar{b}}}\right\}^2\right] \times$$

$$\frac{1}{\sigma_x^{\rm MET}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\rm meas}-\not{E}_x^{\rm guess}}{\sigma_x^{\rm MET}}\right\}^2\right] \times \frac{1}{\sigma_y^{\rm MET}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\rm meas}-\not{E}_y^{\rm guess}}{\sigma_y^{\rm MET}}\right\}^2\right]$$

b-jet resolution

"neutrino resolution"



Measurement in dilepton channel

- **reconstruct event by maximizing kinematic likelihood and picking most likely b-quark jet combination**

$$\mathcal{L}\left(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b^{\text{guess}}, E_{\bar{b}}^{\text{guess}}\right) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$

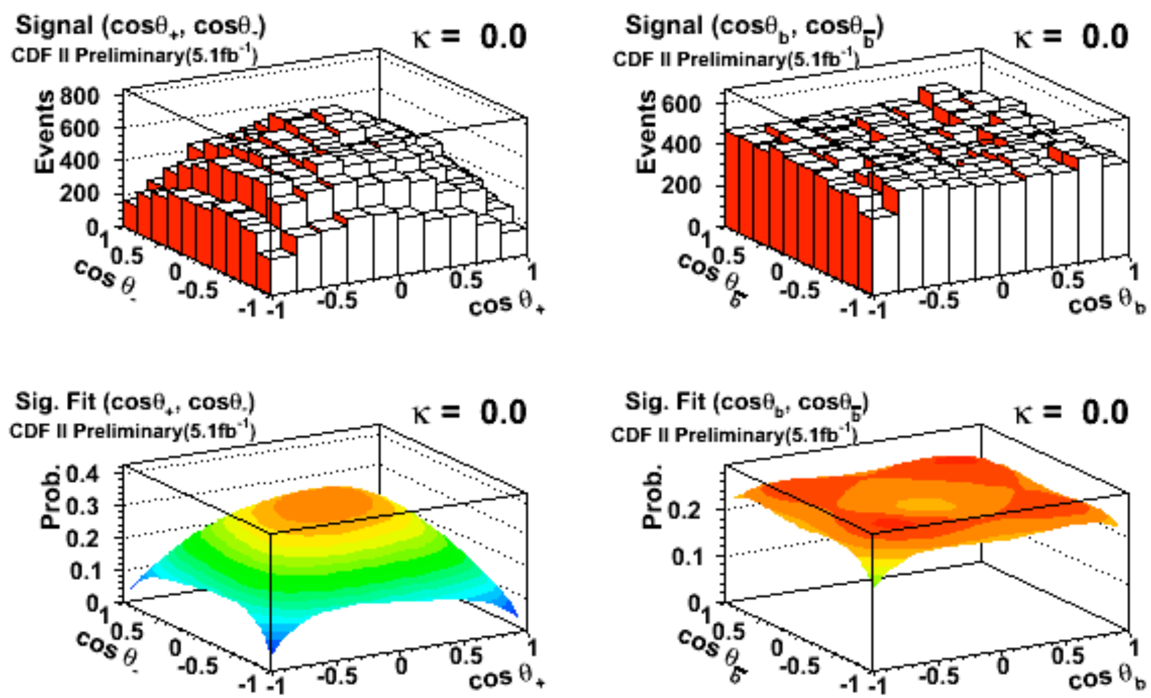
← **MC priors**

$$\frac{1}{\sigma_b}\exp\left[-\frac{1}{2}\left\{\frac{E_b^{\text{meas}} - E_b^{\text{guess}}}{\sigma_b}\right\}^2\right] \times \frac{1}{\sigma_{\bar{b}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\bar{b}}^{\text{meas}} - E_{\bar{b}}^{\text{guess}}}{\sigma_{\bar{b}}}\right\}^2\right] \times$$

$$\frac{1}{\sigma_x^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}} - \not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}} - \not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right]$$

b-jet resolution →

"neutrino resolution" ↙



Measurement in dilepton channel

- reconstruct event by maximizing kinematic likelihood and picking most likely b-quark jet combination

$$\mathcal{L}\left(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b^{\text{guess}}, E_{\bar{b}}^{\text{guess}}\right) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$

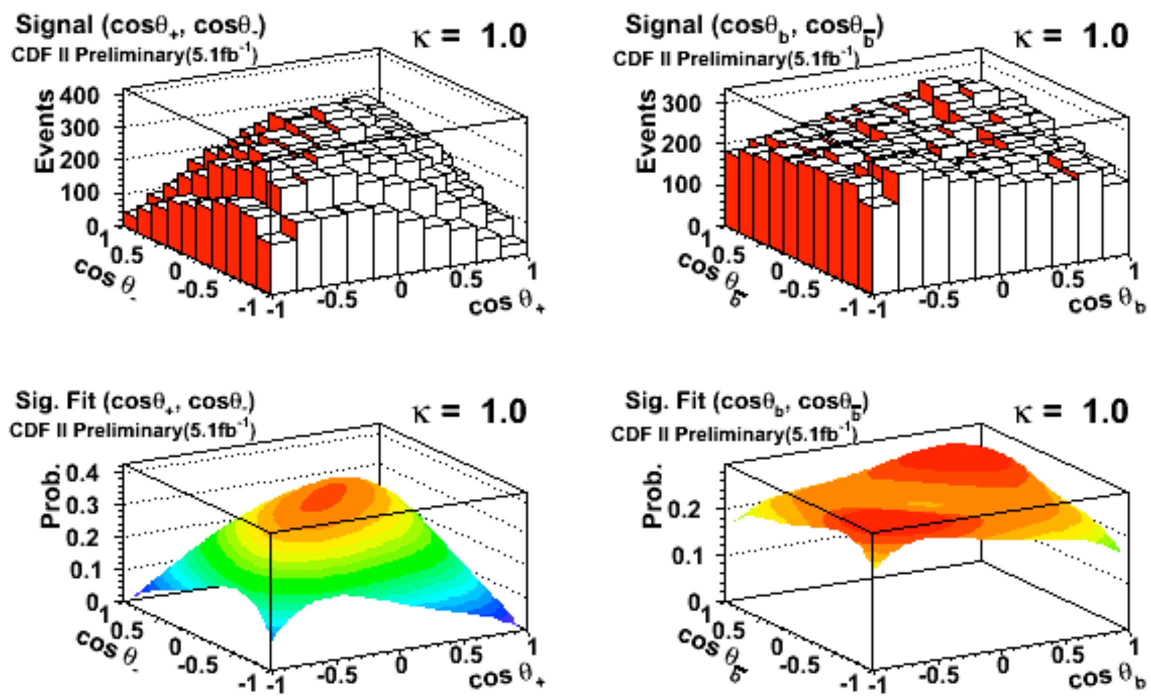
$$\frac{1}{\sigma_b}\exp\left[-\frac{1}{2}\left\{\frac{E_b^{\text{meas}} - E_b^{\text{guess}}}{\sigma_b}\right\}^2\right] \times \frac{1}{\sigma_{\bar{b}}}\exp\left[-\frac{1}{2}\left\{\frac{E_{\bar{b}}^{\text{meas}} - E_{\bar{b}}^{\text{guess}}}{\sigma_{\bar{b}}}\right\}^2\right] \times$$

$$\frac{1}{\sigma_x^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}} - \not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\text{MET}}}\exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}} - \not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right]$$

← **MC priors**

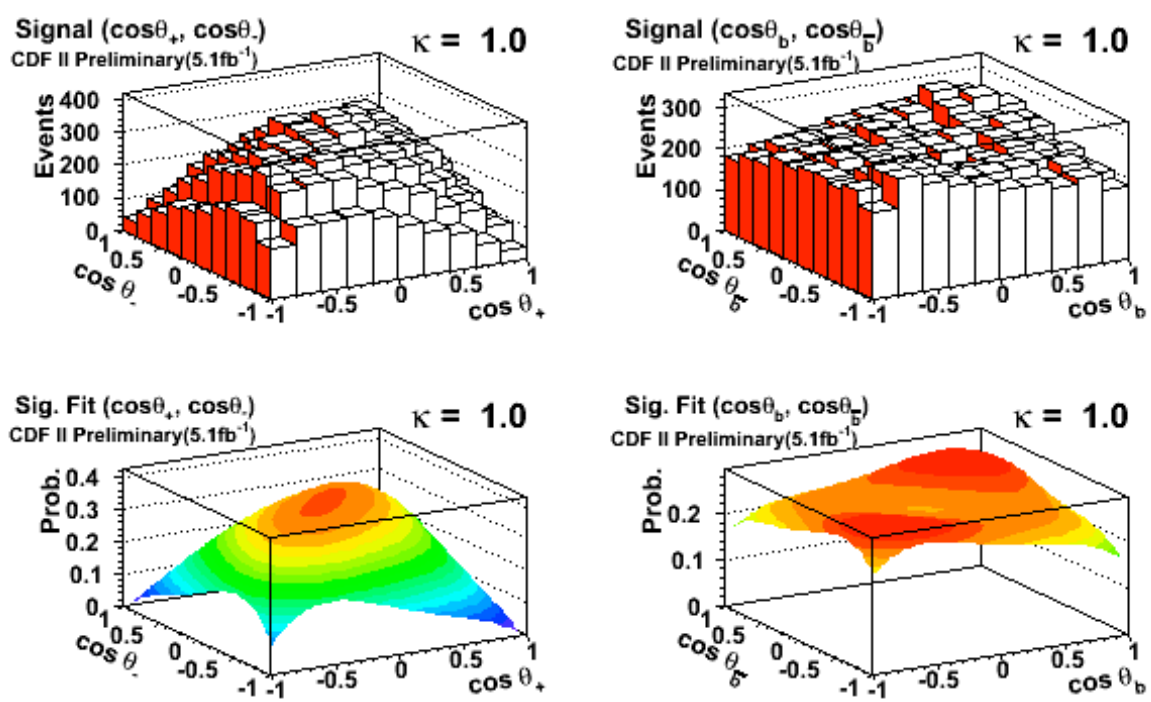
b-jet resolution

"neutrino resolution"



Measurement in dilepton channel

- reconstruct event by maximizing kinematic likelihood and picking most likely b-quark jet combination
- fit both 2d templates simultaneously with binned maximum likelihood method

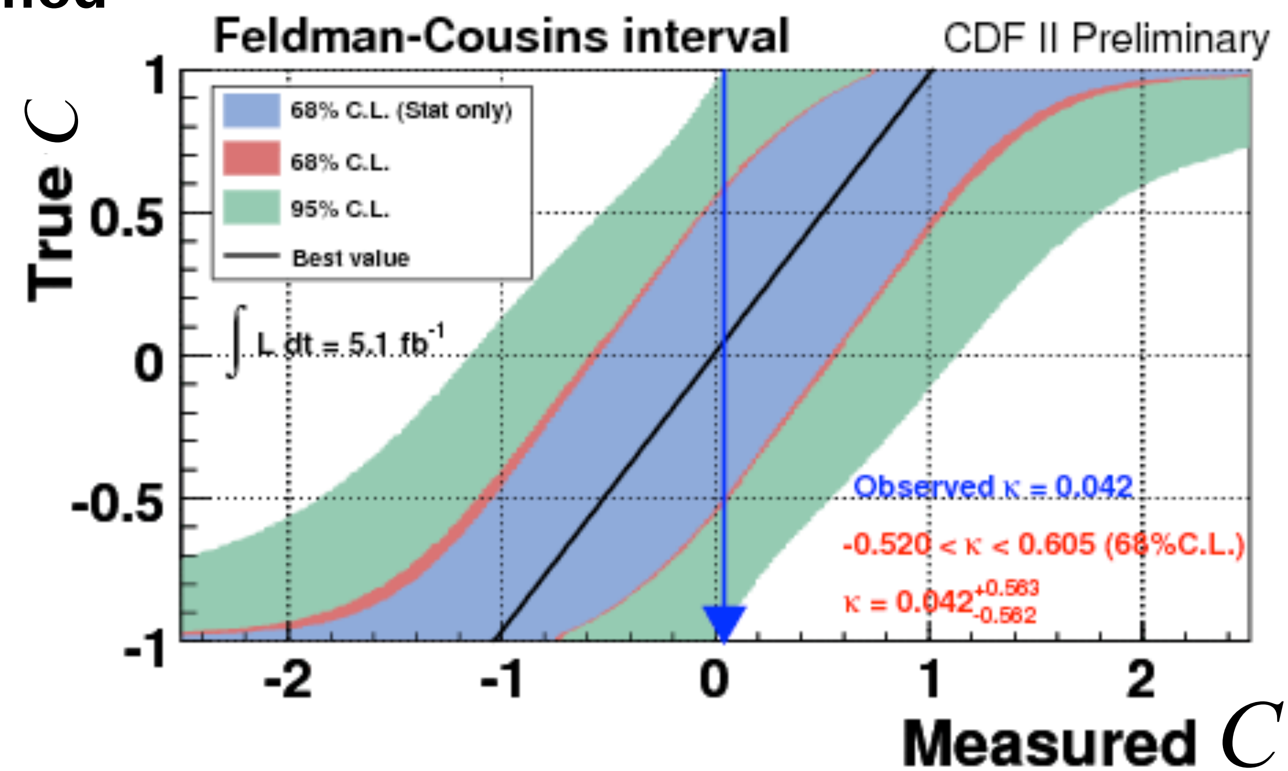


Measurement in dilepton channel

- reconstruct event by maximizing kinematic likelihood and picking most likely b-quark jet combination
- fit both 2d templates simultaneously with binned maximum likelihood method

5.1 fb^{-1}

CDF, Conf. Note 10719



$-0.520 < C < 0.605$ (68%C.L.)

$$C = 0.042^{+0.563}_{-0.562}$$