Physics from the Top

Scott Willenbrock
U. of Illinois at Urbana-Champaign

Chris Quigg Symposium

December 15, 2009

with thanks to

Aran Garcia-Bellido (D0)

Veronica Sorin (CDF)

Tom Schwarz (CDF)

Fall 1984

Fermi National Accelerator Laboratory

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LBL-16875
DOE/ER/01545-345
February, 1984

Supercollider Physics

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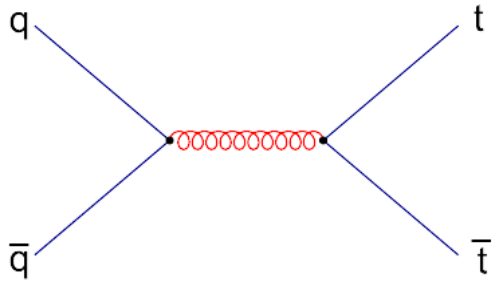
Single top

Top pair production

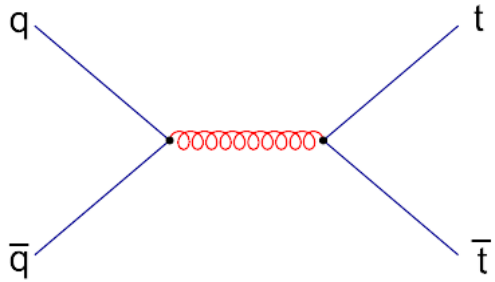
Tevatron



7.3 pb

Top pair production

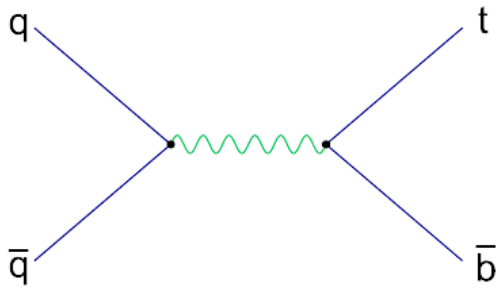
Tevatron



7.3 pb

Single top production

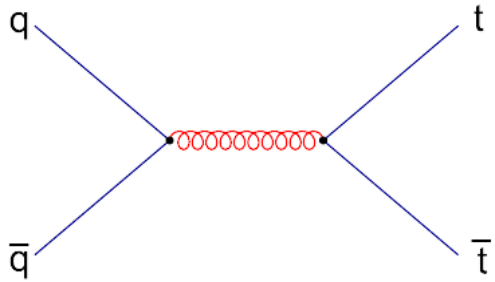
s-channel single top



0.9 pb

Top pair production

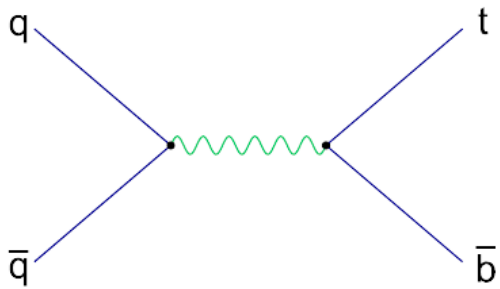
Tevatron



7.3 pb

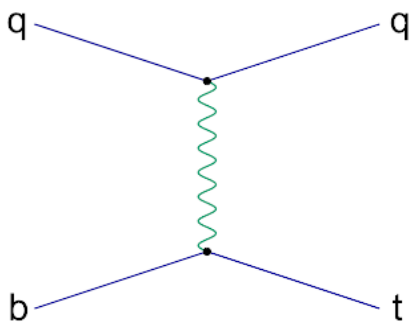
Single top production

s-channel single top



0.9 pb

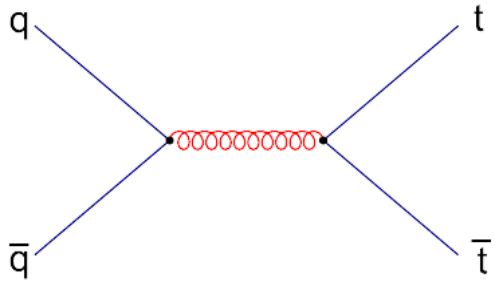
t-channel single top



2.0 pb

Top pair production

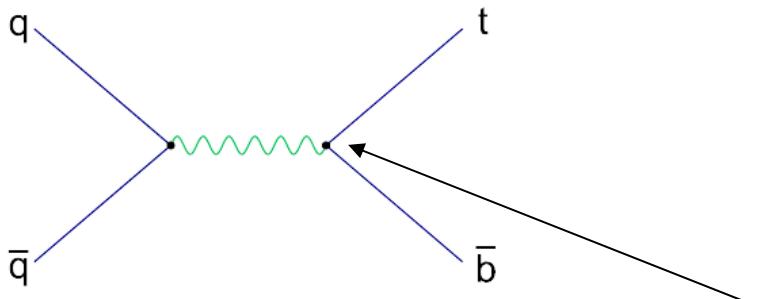
Tevatron



7.3 pb

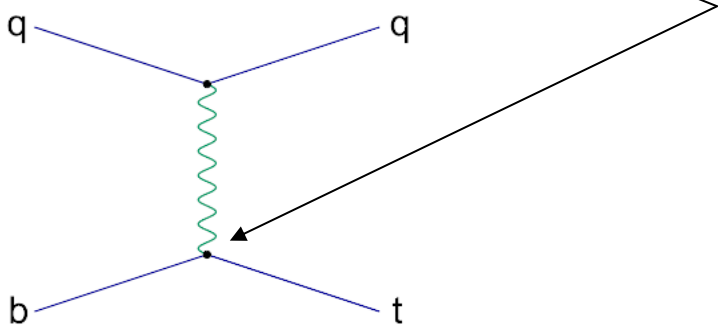
Single top production

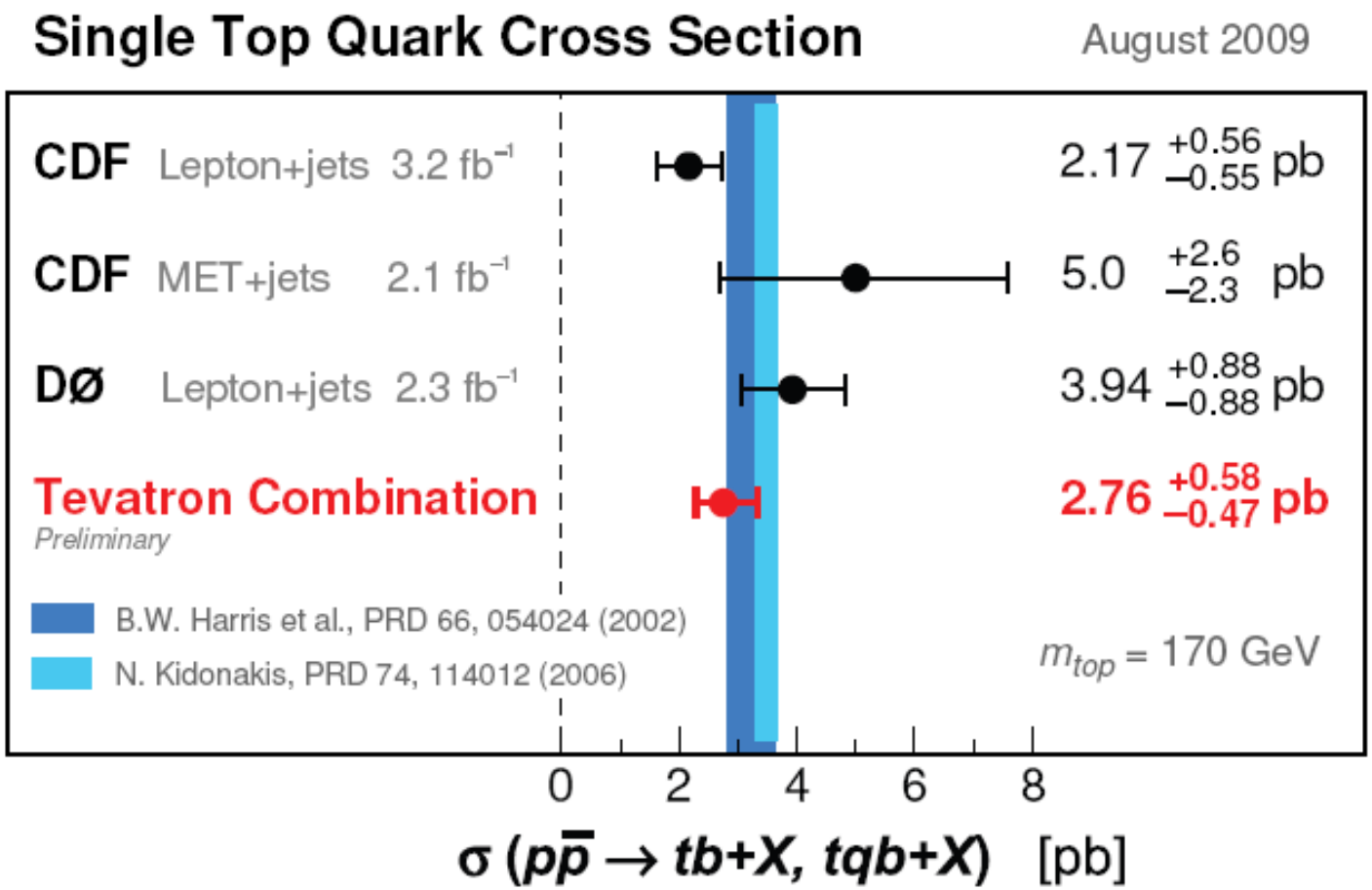
s-channel single top

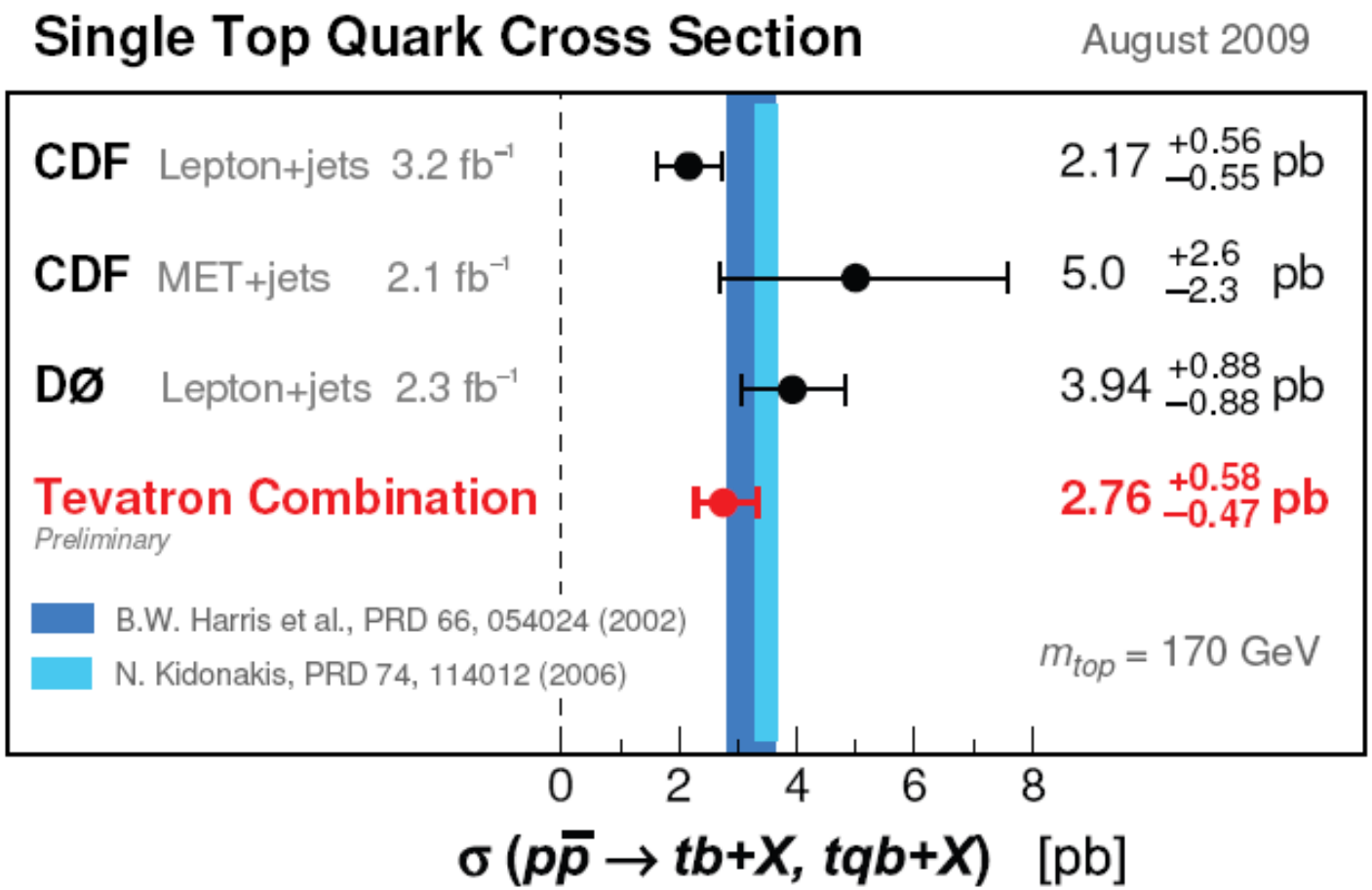


V_{tb}

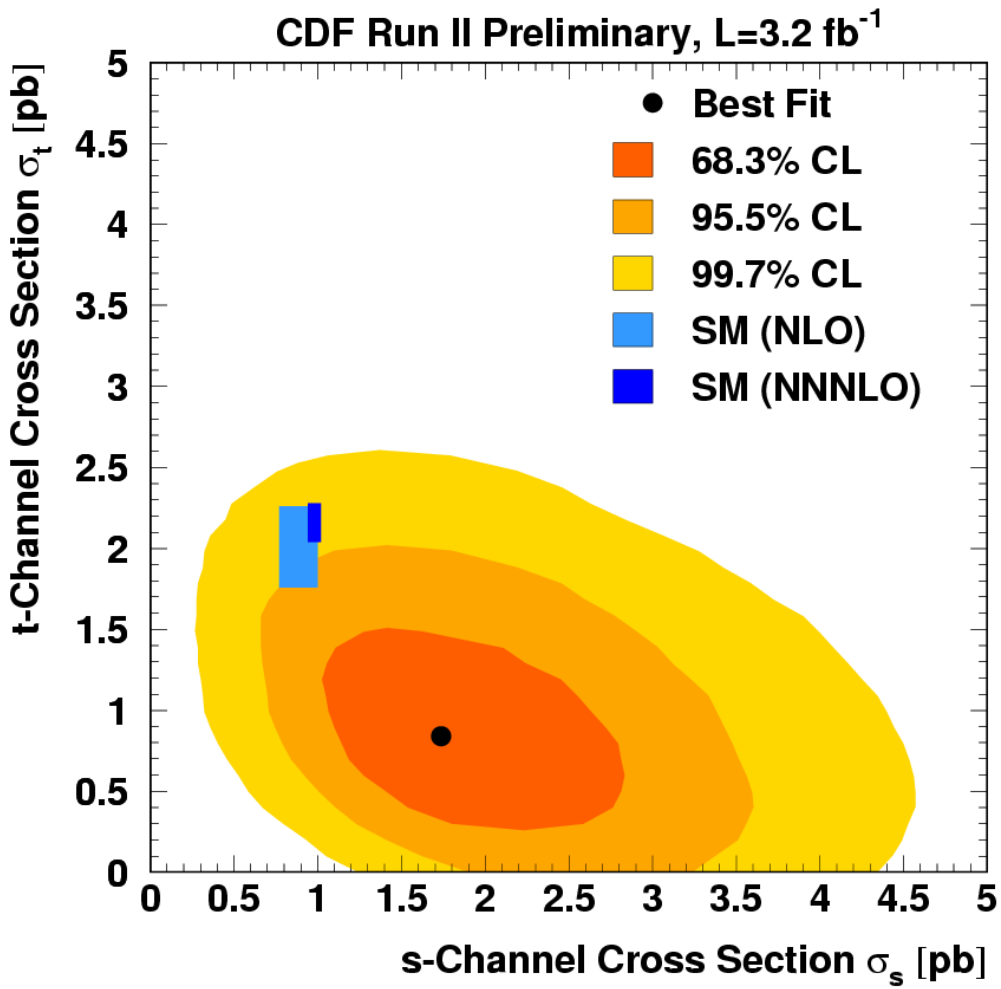
t-channel single top

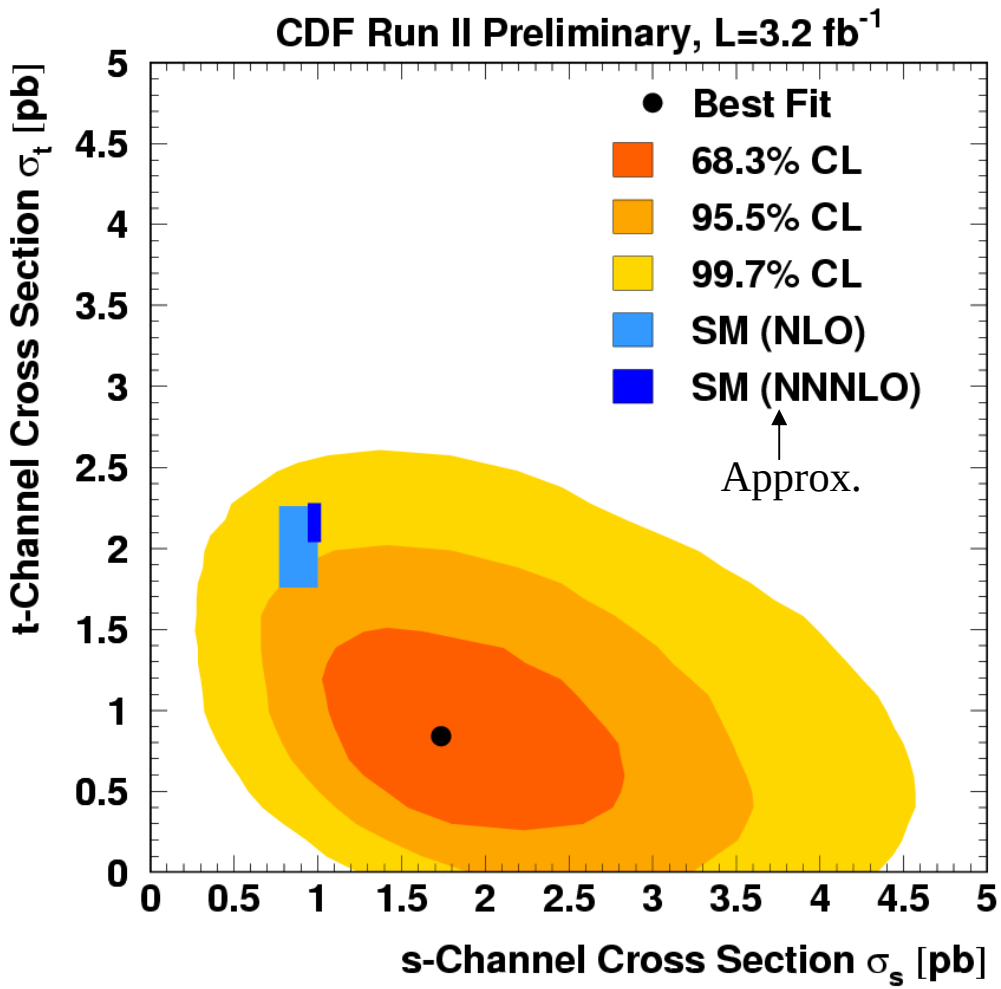


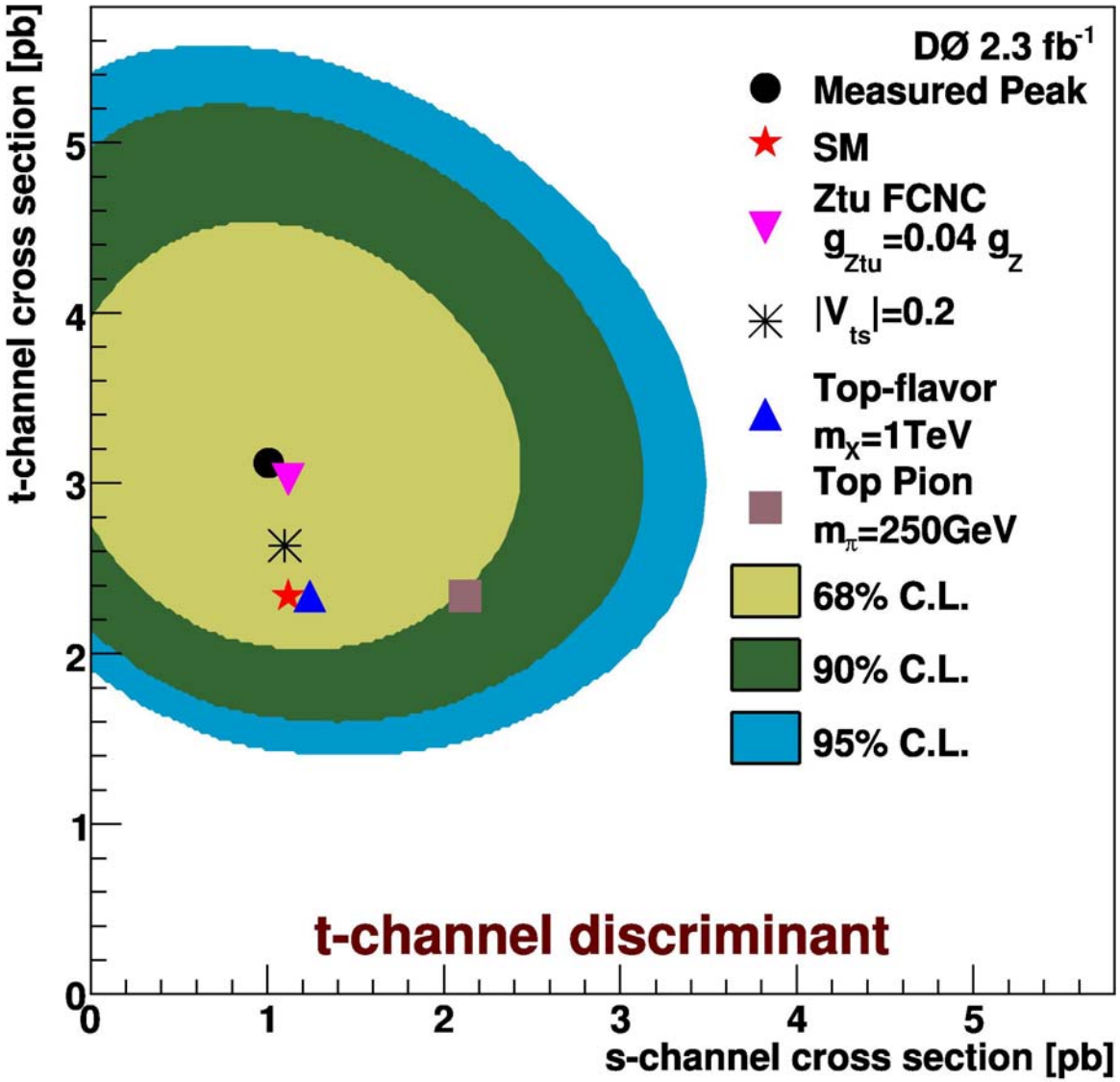

Single Top Quark Cross Section
August 2009
CDF Lepton+jets 3.2 fb⁻¹
2.17 +0.56 −0.55 pb
CDF MET+jets 2.1 fb⁻¹
5.0 +2.6 −2.3 pb
DØ Lepton+jets 2.3 fb⁻¹
3.94 +0.88 −0.88 pb
Tevatron Combination
Preliminary
2.76 +0.58 −0.47 pb
B.W. Harris et al., PRD 66, 054024 (2002)
N. Kidonakis, PRD 74, 114012 (2006)
m_top = 170 GeV
0
2
4
6
8
σ (pp̄ → tb+X, tqb+X) [pb]

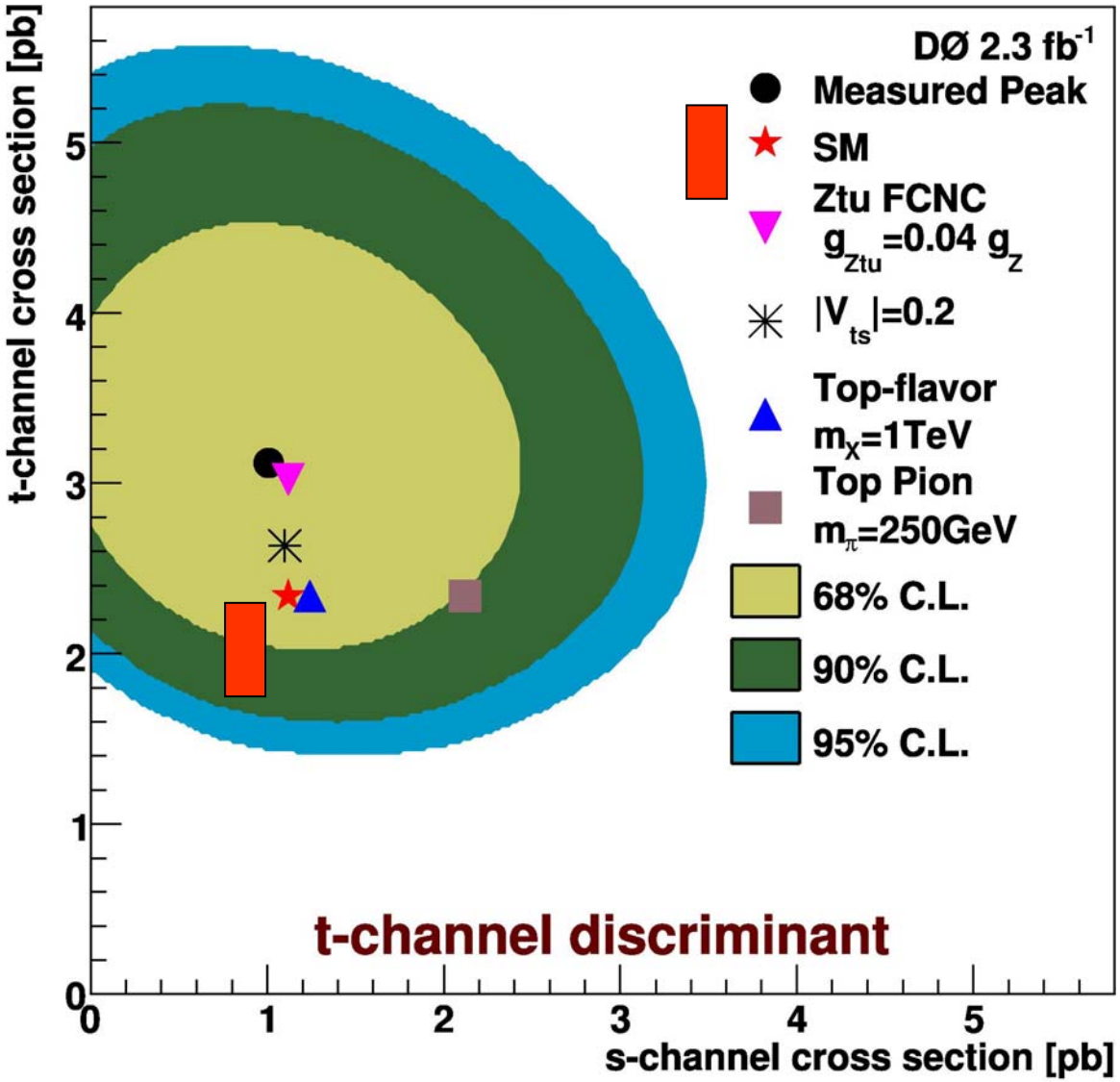


$$V_{tb} = 0.88 \pm 0.07 \quad \text{CDF+D0}$$


CDF Run II Preliminary, L=3.2 fb^{-1}
Best Fit
68.3% CL
95.5% CL
99.7% CL
SM (NLO)
SM (NNNLO)
t-Channel Cross Section σ_t [pb]
s-Channel Cross Section σ_s [pb]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

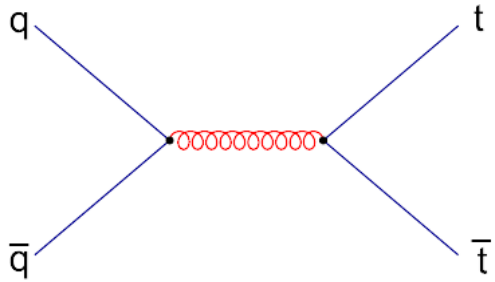

CDF Run II Preliminary, L=3.2 fb^{-1}
Best Fit
68.3% CL
95.5% CL
99.7% CL
SM (NLO)
SM (NNNLO)
Approx.
t-Channel Cross Section σ_t [pb]
s-Channel Cross Section σ_s [pb]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


DØ 2.3 fb-1
Measured Peak
SM
Ztu FCNC
gZtu=0.04 gZ
|Vts|=0.2
Top-flavor
mX=1TeV
Top Pion
mπ=250GeV
68% C.L.
90% C.L.
95% C.L.
t-channel discriminant
t-channel cross section [pb]
s-channel cross section [pb]
0
1
2
3
4
5


DØ 2.3 fb-1
Measured Peak
SM
Ztu FCNC
gZtu=0.04 gZ
|Vts|=0.2
Top-flavor
mX=1TeV
Top Pion
mπ=250GeV
68% C.L.
90% C.L.
95% C.L.
t-channel discriminant
t-channel cross section [pb]
s-channel cross section [pb]
0
1
2
3
4
5

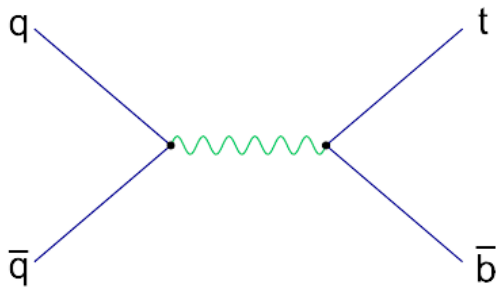
Top pair production

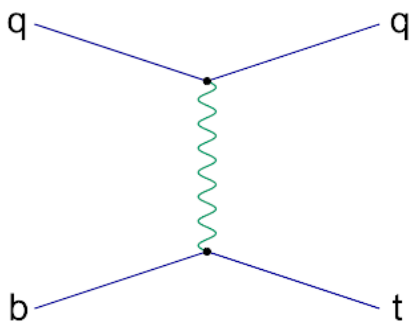
	Tevatron	LHC
	7.3 pb	900 pb



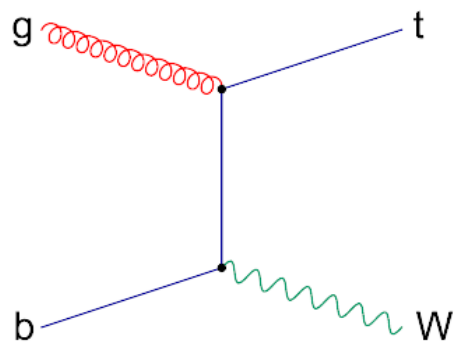
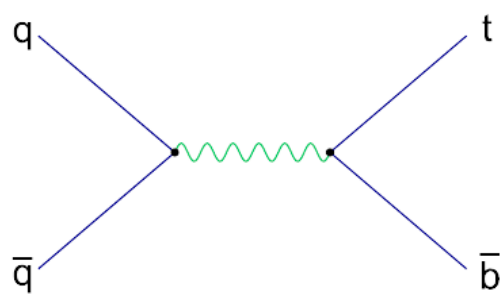
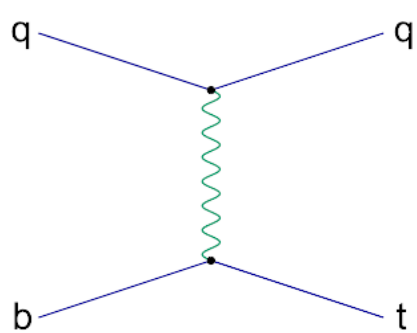
Single top production

	Tevatron	LHC
s-channel single top	0.9 pb	10.6 pb
t-channel single top	2.0 pb	240 pb

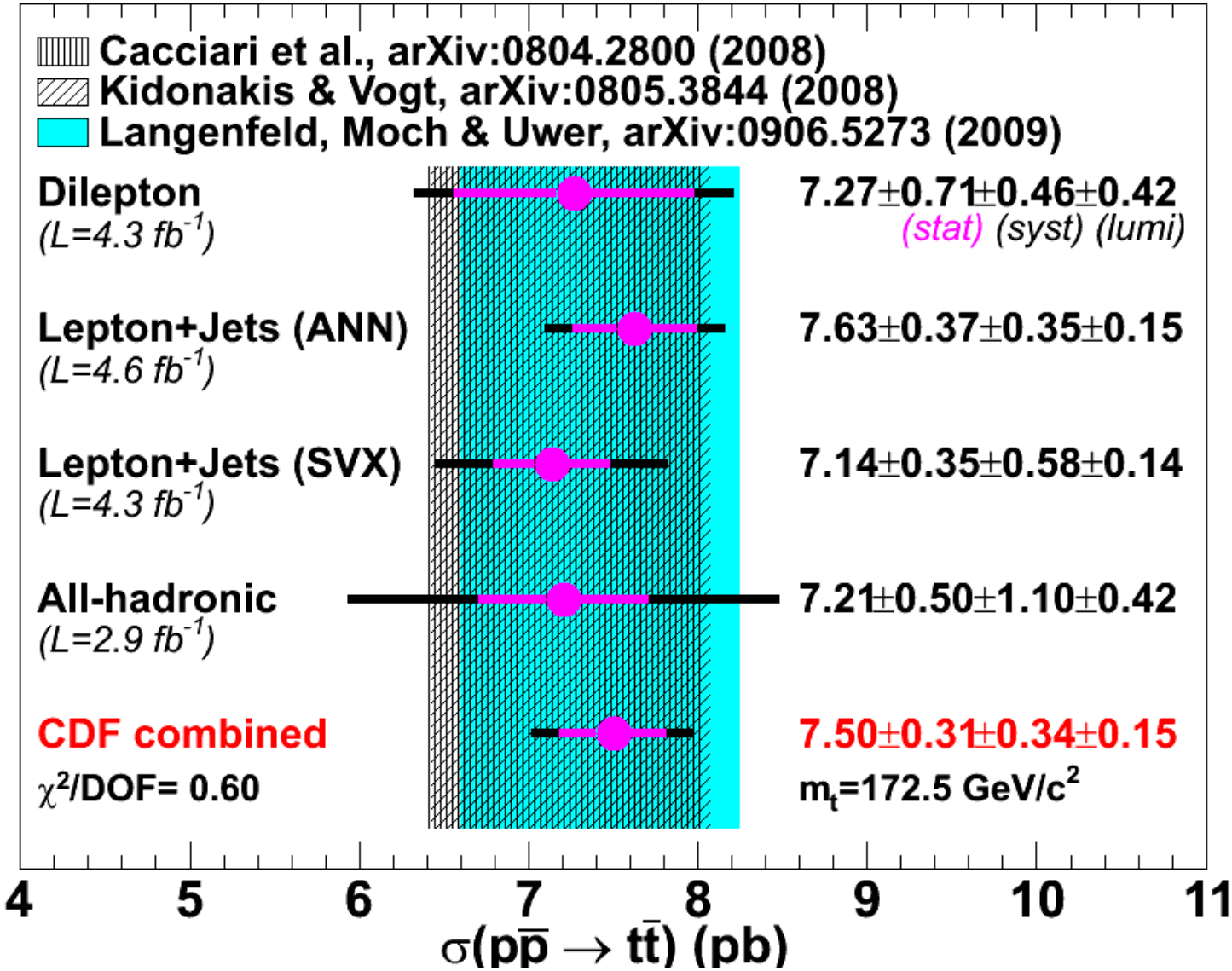


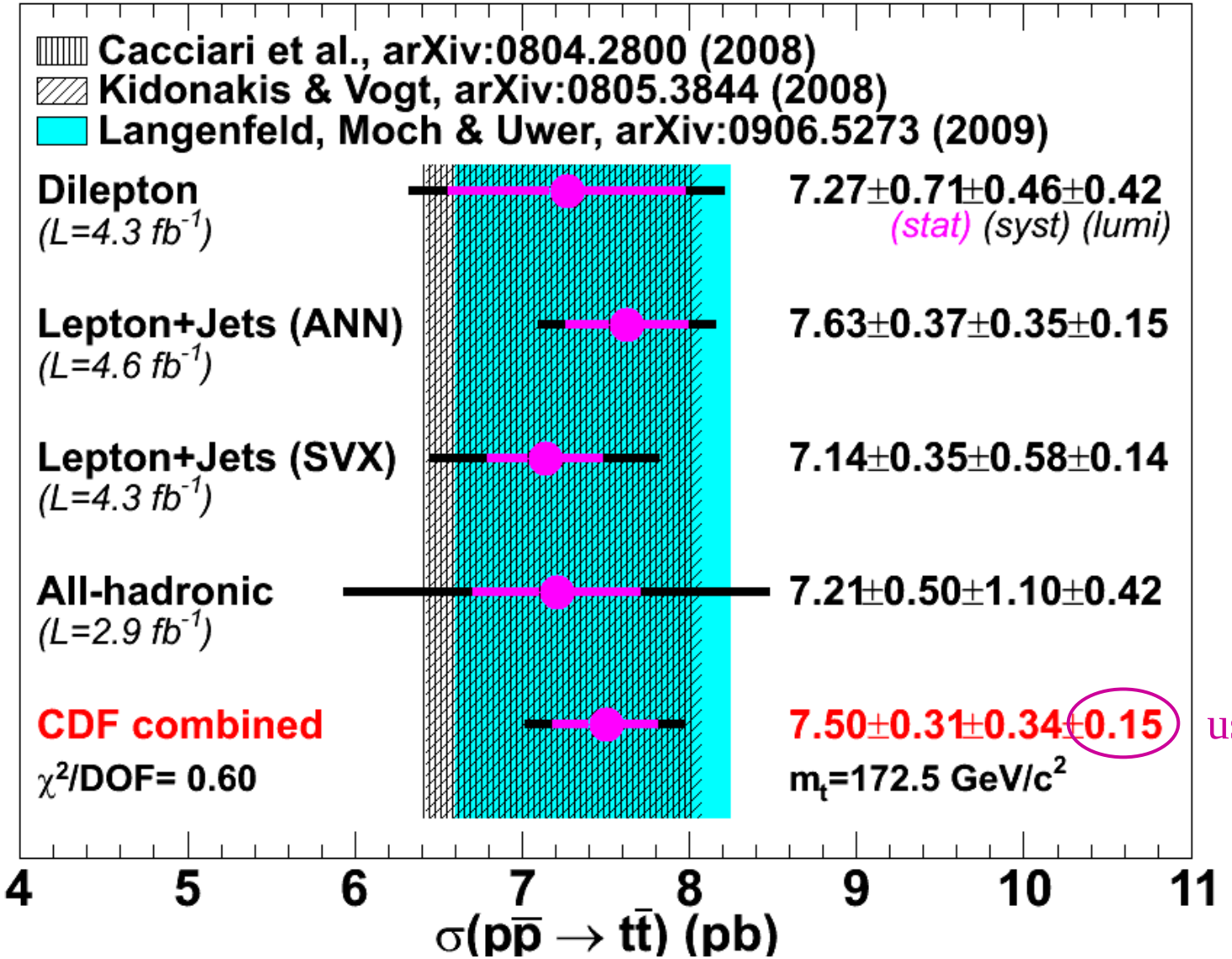


Single top production

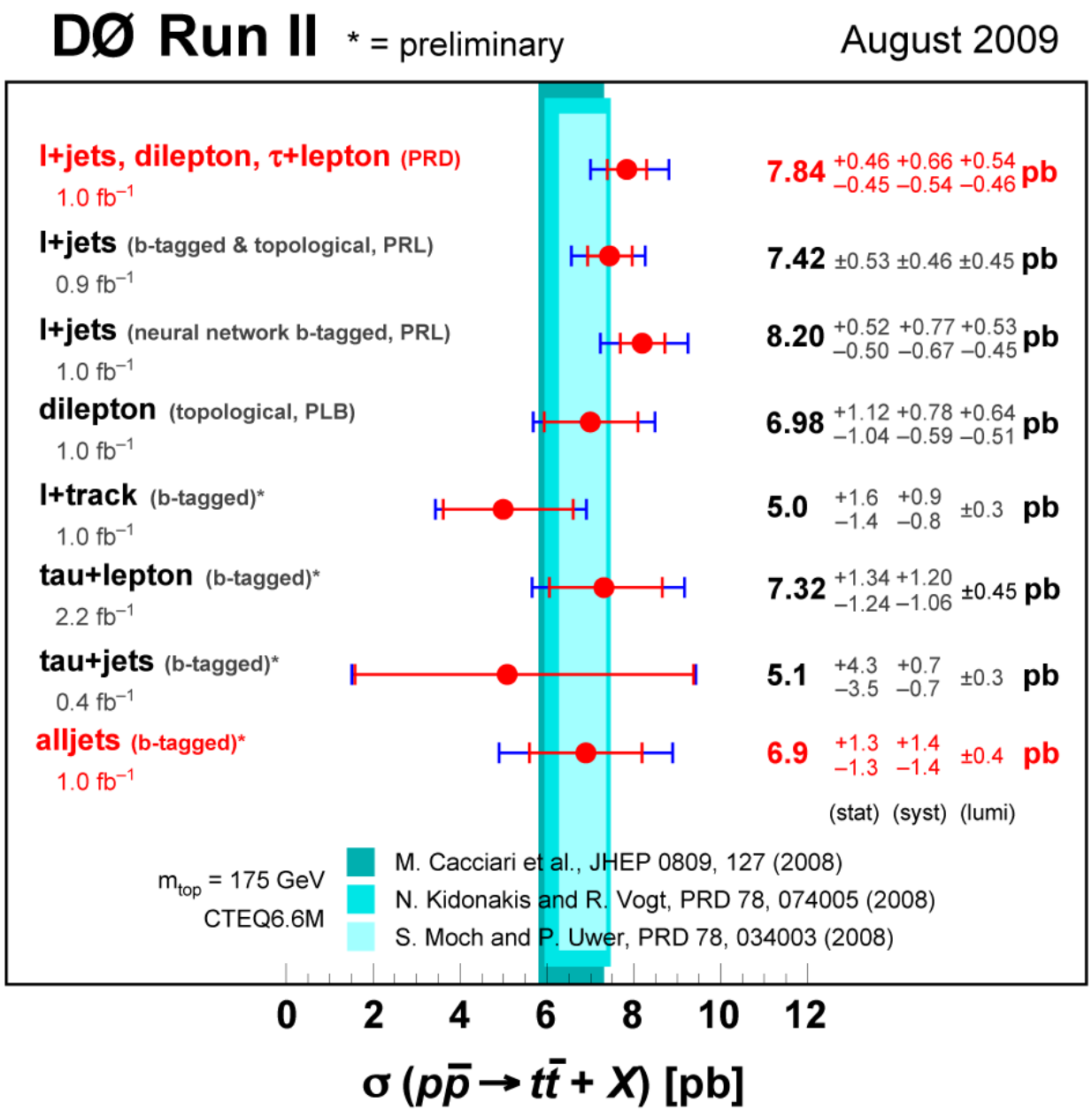
		Tevatron	LHC
Wt associated		0.15 pb	70 pb
s-channel single top		0.9 pb	10.6 pb
t-channel single top		2.0 pb	240 pb

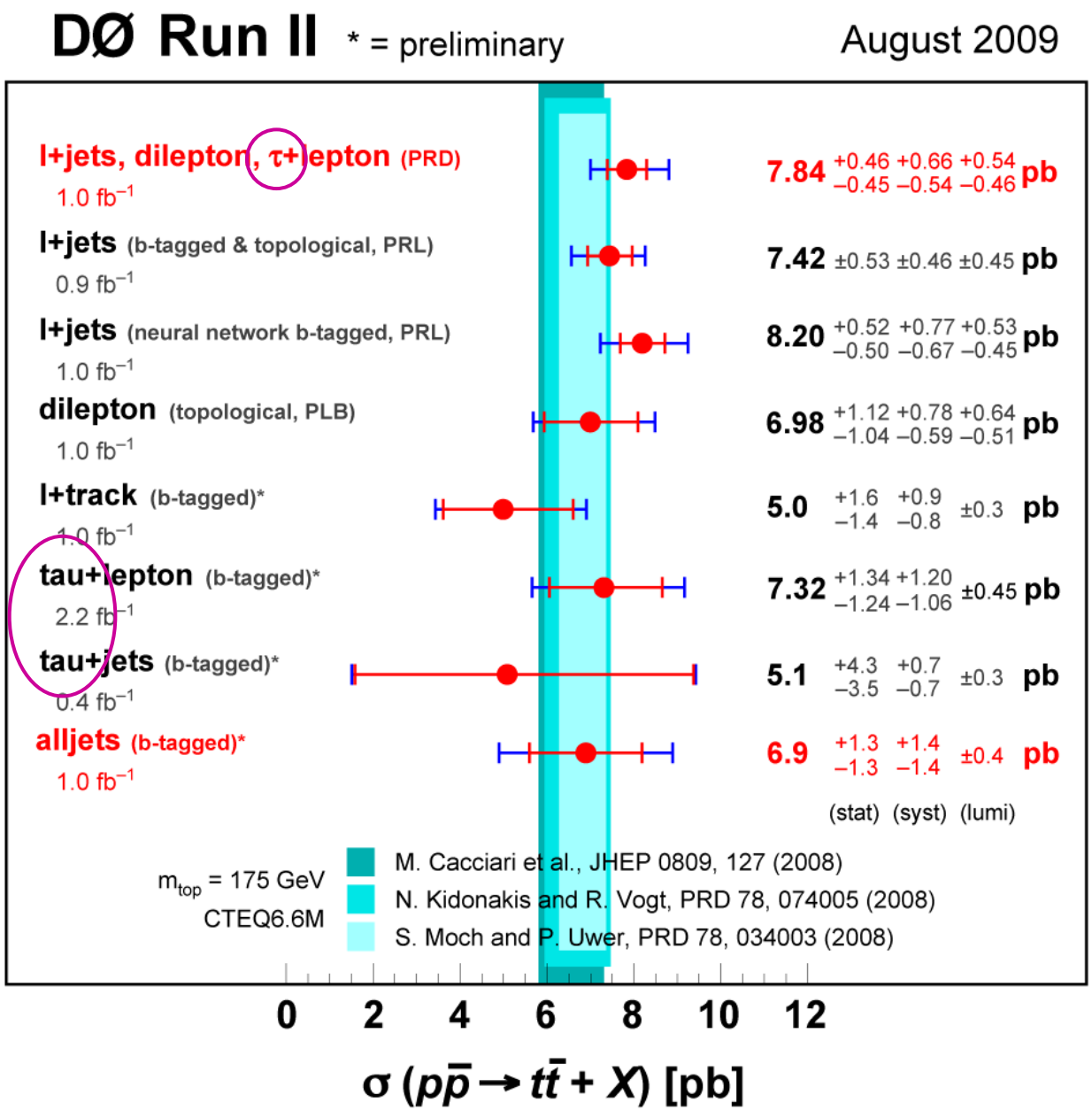
$t\bar{t}$ cross section


Cacciari et al., arXiv:0804.2800 (2008)
Kidonakis & Vogt, arXiv:0805.3844 (2008)
Langenfeld, Moch & Uwer, arXiv:0906.5273 (2009)
Dilepton
(L=4.3 fb-1)
7.27±0.71±0.46±0.42
(stat) (syst) (lumi)
Lepton+Jets (ANN)
(L=4.6 fb-1)
7.63±0.37±0.35±0.15
Lepton+Jets (SVX)
(L=4.3 fb-1)
7.14±0.35±0.58±0.14
All-hadronic
(L=2.9 fb-1)
7.21±0.50±1.10±0.42
CDF combined
7.50±0.31±0.34±0.15
χ2/DOF= 0.60
mt=172.5 GeV/c2
4
5
6
7
8
9
10
11
σ(pp̄ → tt̄) (pb)

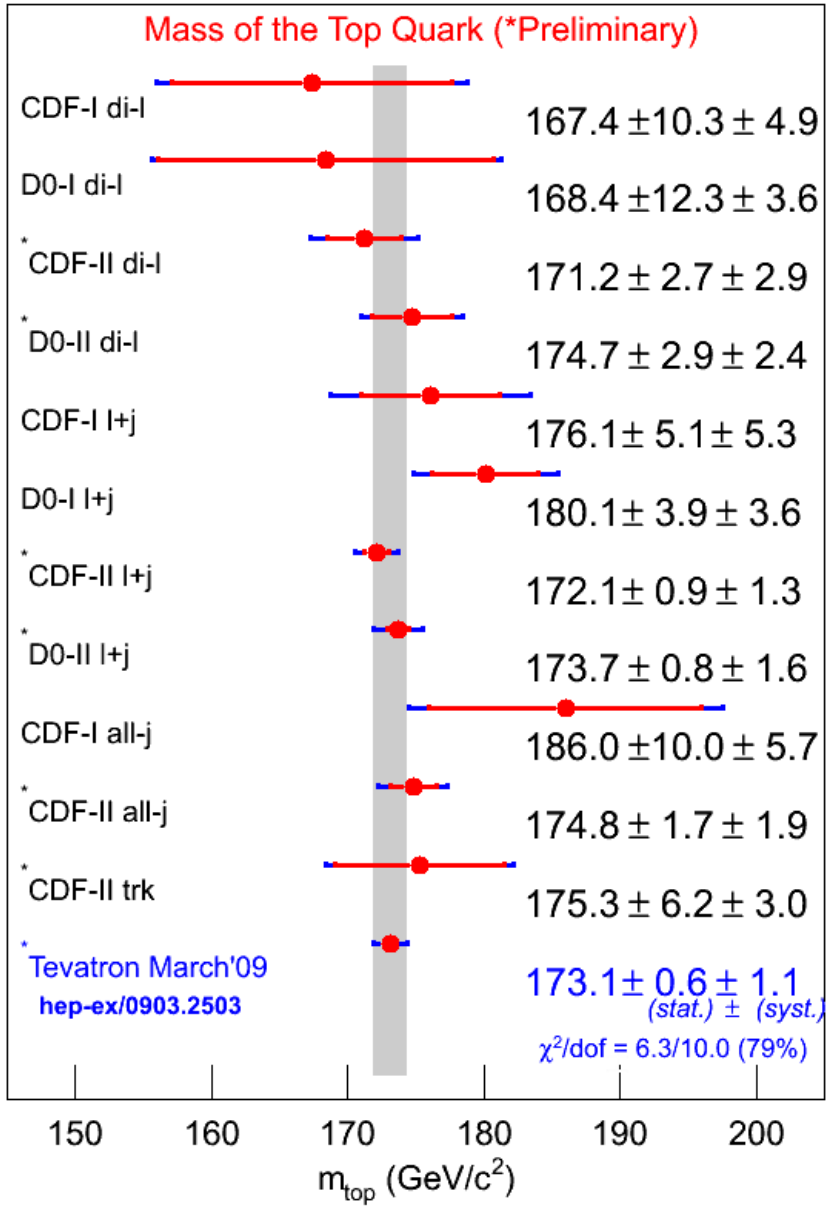


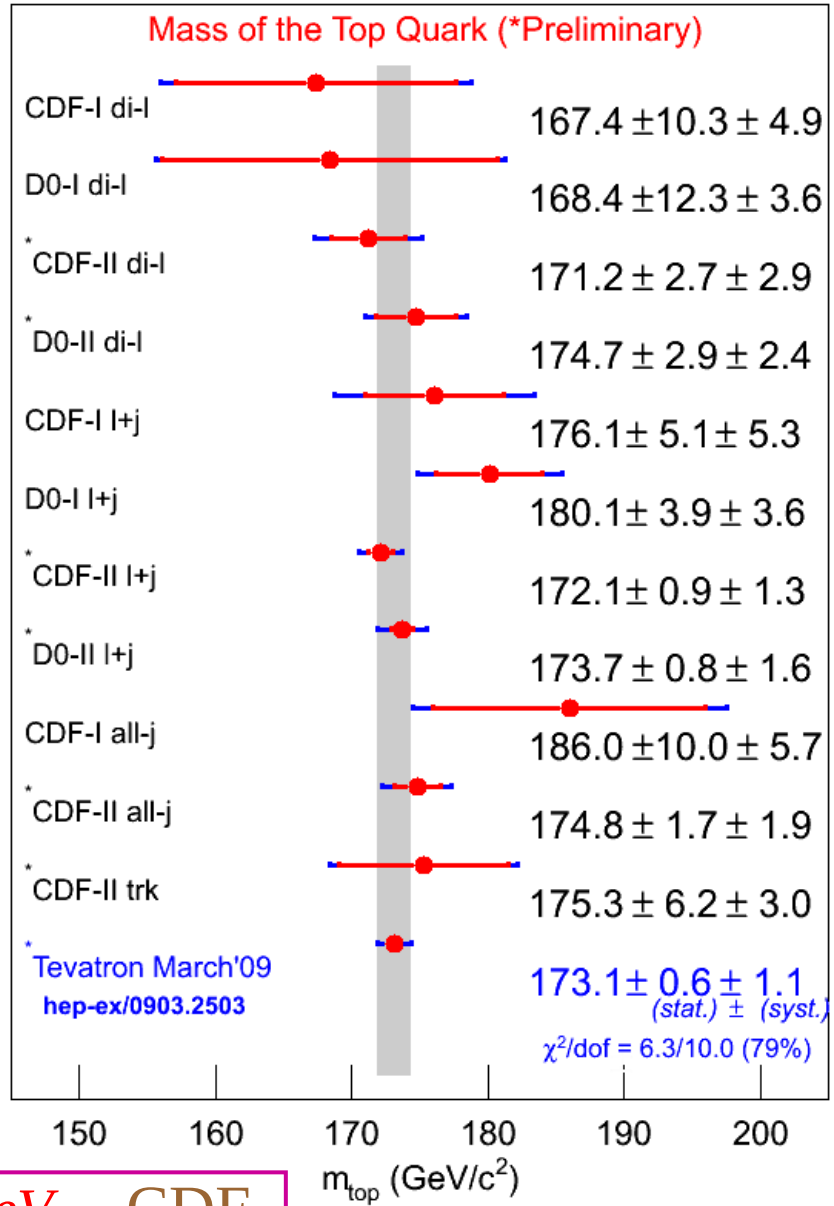
using $\sigma(Z)$


DØ Run II
* = preliminary
August 2009
l+jets, dilepton, τ+lepton (PRD)
1.0 fb⁻¹
7.84 +0.46 +0.66 +0.54 −0.45 −0.54 −0.46 pb
l+jets (b-tagged & topological, PRL)
0.9 fb⁻¹
7.42 ±0.53 ±0.46 ±0.45 pb
l+jets (neural network b-tagged, PRL)
1.0 fb⁻¹
8.20 +0.52 +0.77 +0.53 −0.50 −0.67 −0.45 pb
dilepton (topological, PLB)
1.0 fb⁻¹
6.98 +1.12 +0.78 +0.64 −1.04 −0.59 −0.51 pb
l+track (b-tagged)*
1.0 fb⁻¹
5.0 +1.6 +0.9 −1.4 −0.8 ±0.3 pb
tau+lepton (b-tagged)*
2.2 fb⁻¹
7.32 +1.34 +1.20 −1.24 −1.06 ±0.45 pb
tau+jets (b-tagged)*
0.4 fb⁻¹
5.1 +4.3 +0.7 −3.5 −0.7 ±0.3 pb
alljets (b-tagged)*
1.0 fb⁻¹
6.9 +1.3 +1.4 −1.3 −1.4 ±0.4 pb
(stat) (syst) (lumi)
m_top = 175 GeV
CTEQ6.6M
M. Cacciari et al., JHEP 0809, 127 (2008)
N. Kidonakis and R. Vogt, PRD 78, 074005 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)
0 2 4 6 8 10 12
σ (pp̄ → tt̄ + X) [pb]

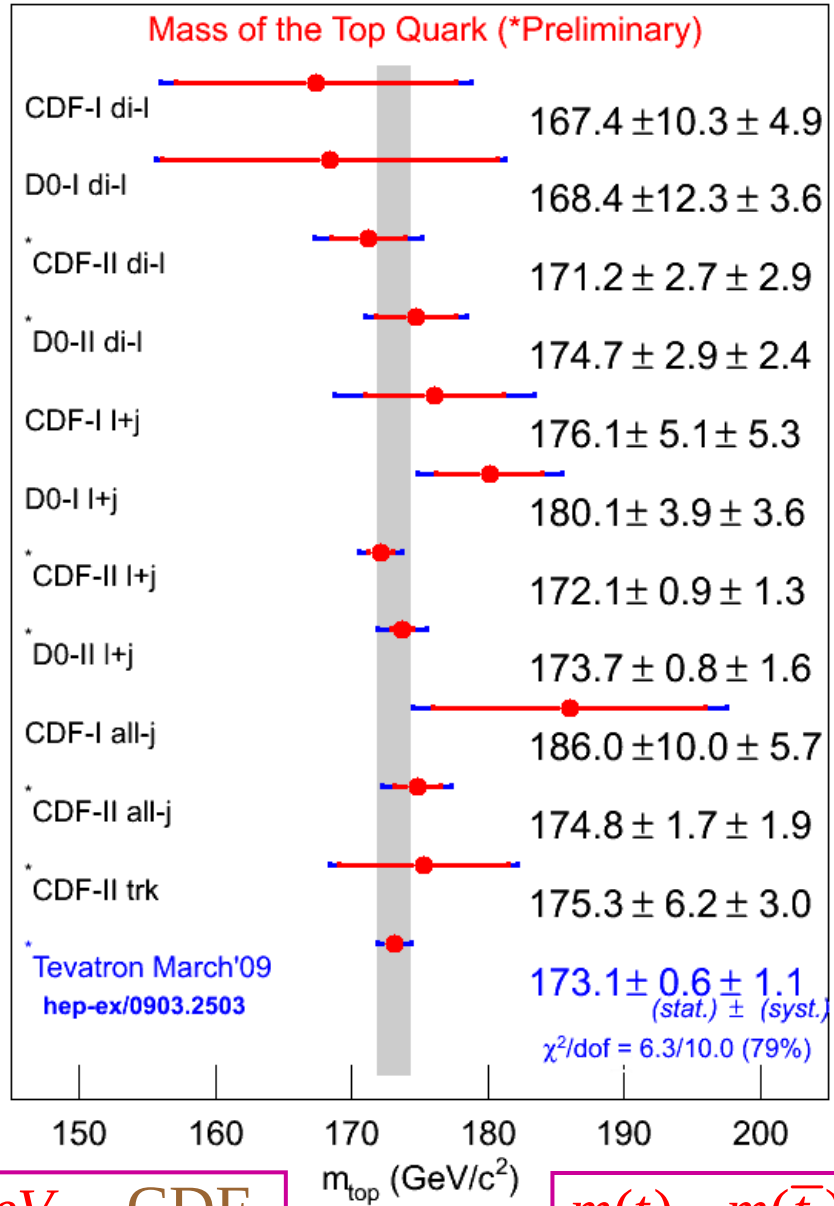

DØ Run II
* = preliminary
August 2009
l+jets, dilepton, τ+lepton (PRD)
1.0 fb⁻¹
7.84 +0.46 +0.66 +0.54 −0.45 −0.54 −0.46 pb
l+jets (b-tagged & topological, PRL)
0.9 fb⁻¹
7.42 ±0.53 ±0.46 ±0.45 pb
l+jets (neural network b-tagged, PRL)
1.0 fb⁻¹
8.20 +0.52 +0.77 +0.53 −0.50 −0.67 −0.45 pb
dilepton (topological, PLB)
1.0 fb⁻¹
6.98 +1.12 +0.78 +0.64 −1.04 −0.59 −0.51 pb
l+track (b-tagged)*
1.0 fb⁻¹
5.0 +1.6 +0.9 −1.4 −0.8 ±0.3 pb
tau+lepton (b-tagged)*
2.2 fb⁻¹
7.32 +1.34 +1.20 −1.24 −1.06 ±0.45 pb
tau+jets (b-tagged)*
0.4 fb⁻¹
5.1 +4.3 +0.7 −3.5 −0.7 ±0.3 pb
alljets (b-tagged)*
1.0 fb⁻¹
6.9 +1.3 +1.4 −1.3 −1.4 ±0.4 pb
(stat) (syst) (lumi)
m_top = 175 GeV
CTEQ6.6M
M. Cacciari et al., JHEP 0809, 127 (2008)
N. Kidonakis and R. Vogt, PRD 78, 074005 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)
0 2 4 6 8 10 12
σ (pp̄ → tt̄ + X) [pb]

Top mass


Mass of the Top Quark (*Preliminary)
CDF-I di-l
167.4 ±10.3 ± 4.9
D0-I di-l
168.4 ±12.3 ± 3.6
*CDF-II di-l
171.2 ± 2.7 ± 2.9
*D0-II di-l
174.7 ± 2.9 ± 2.4
CDF-I l+j
176.1± 5.1± 5.3
D0-I l+j
180.1± 3.9 ± 3.6
*CDF-II l+j
172.1± 0.9 ± 1.3
*D0-II l+j
173.7 ± 0.8 ± 1.6
CDF-I all-j
186.0 ±10.0 ± 5.7
*CDF-II all-j
174.8 ± 1.7 ± 1.9
*CDF-II trk
175.3 ± 6.2 ± 3.0
*Tevatron March'09
hep-ex/0903.2503
173.1± 0.6 ± 1.1
(stat.) ± (syst.)
χ²/dof = 6.3/10.0 (79%)
150
160
170
180
190
200
m_top (GeV/c²)

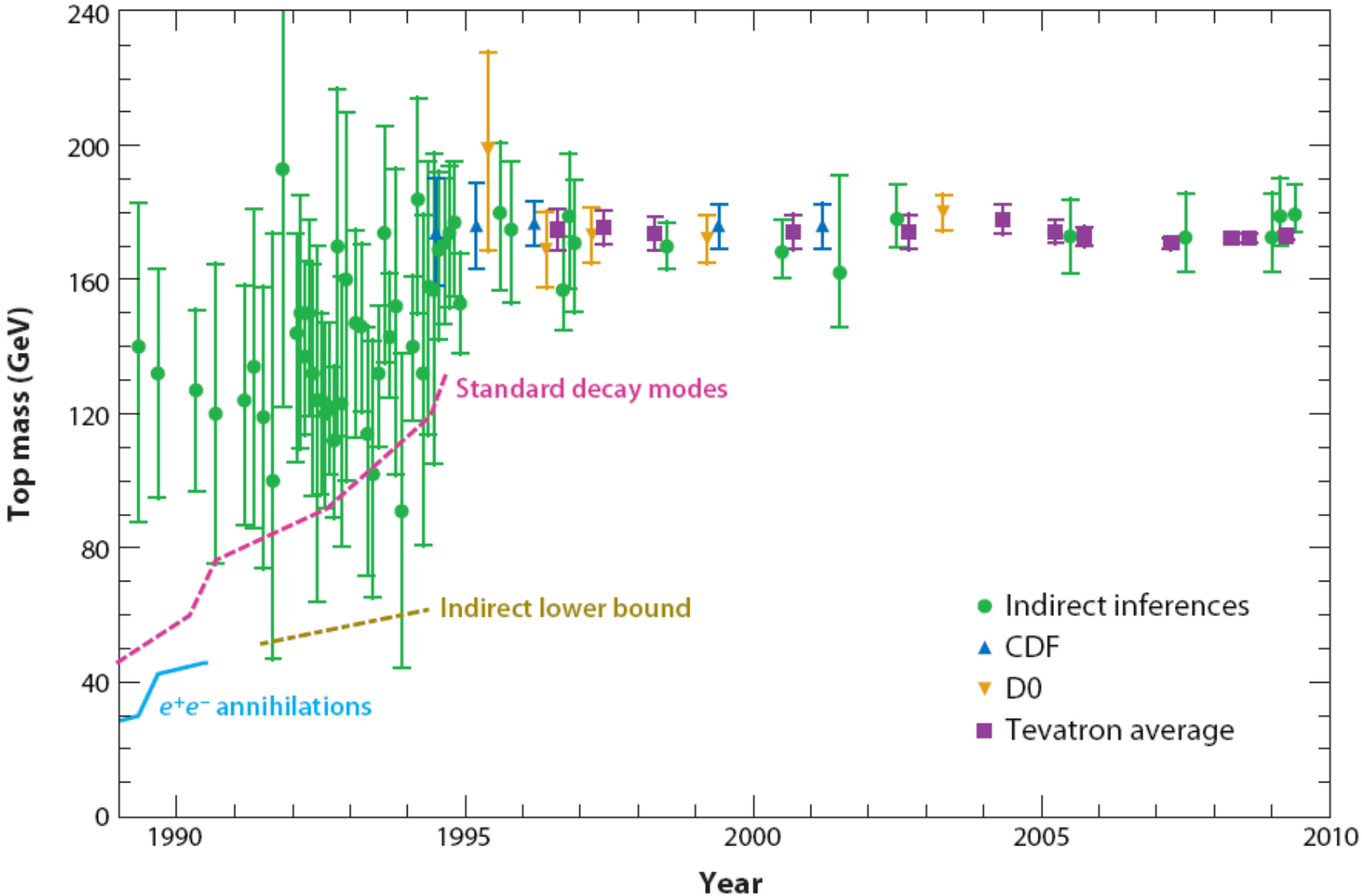


$m(t) = 172.6 \pm 1.6 GeV$ CDF

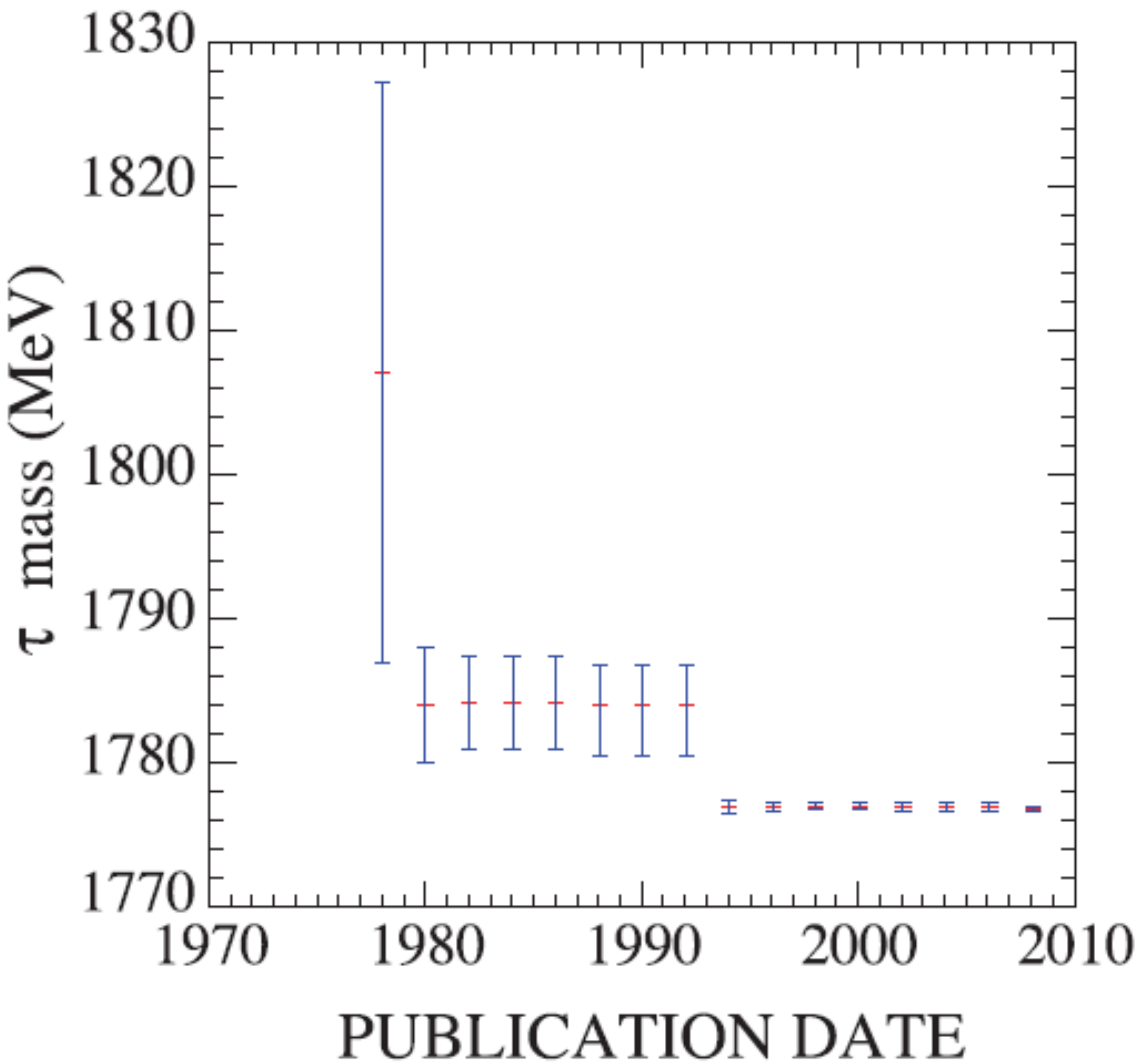


$m(t) = 172.6 \pm 1.6 GeV$ CDF

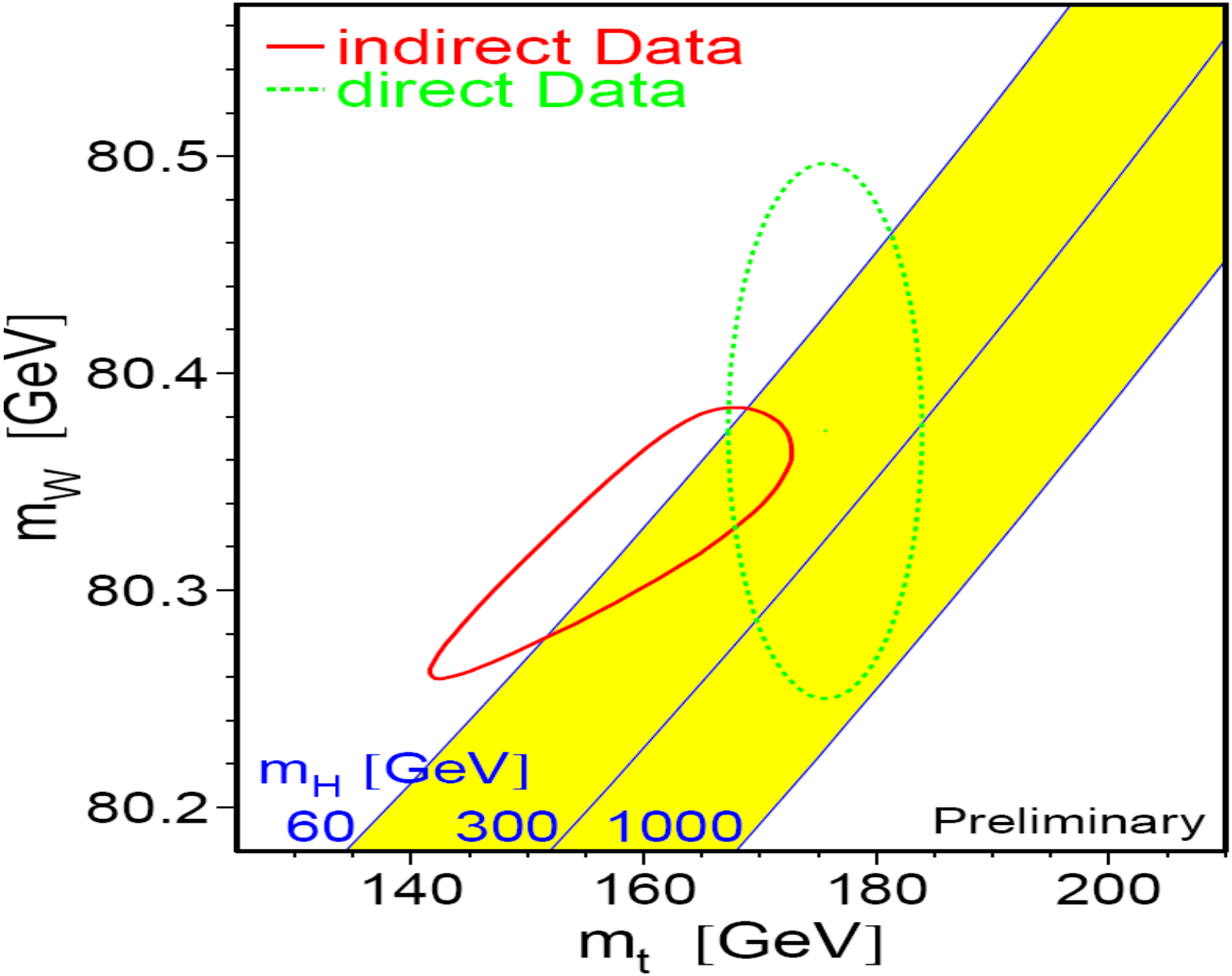
$m(t) - m(\bar{t}) = 3.8 \pm 3.7 GeV$ D0


Top mass (GeV)
240
200
160
120
80
40
0
1990
1995
2000
2005
2010
Year
Standard decay modes
Indirect lower bound
e^+e^- annihilations
Indirect inferences
CDF
D0
Tevatron average

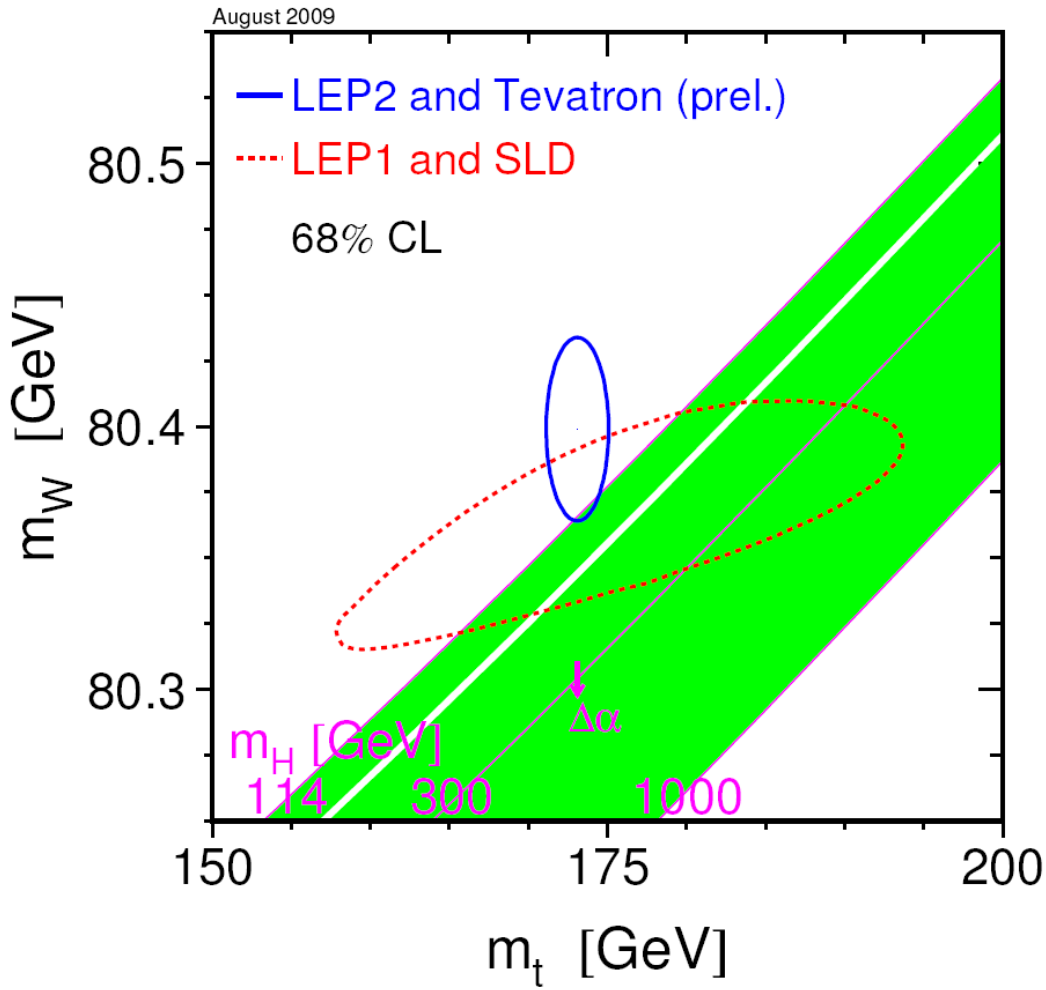
Quigg



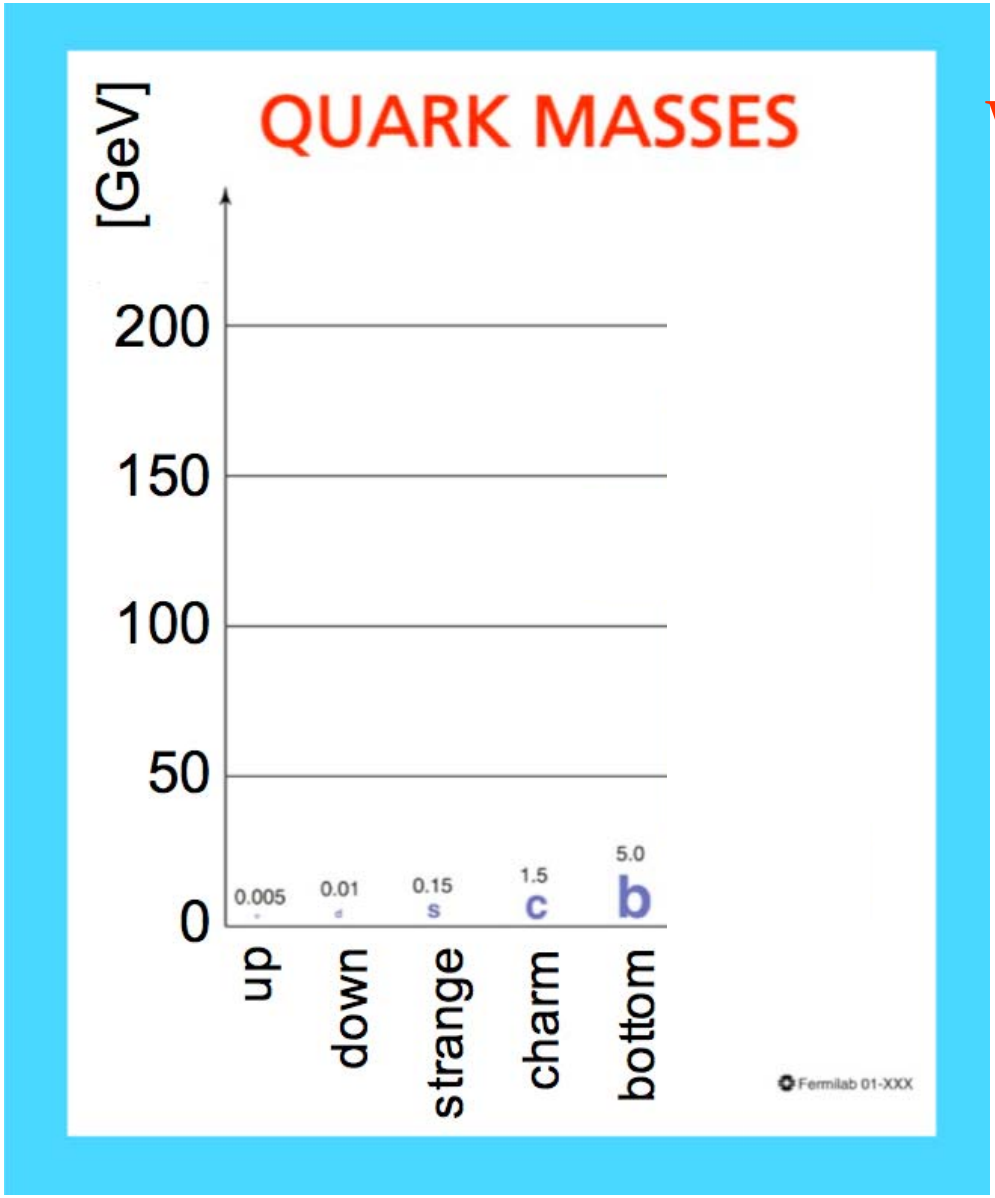
Particle Data Group



LEPEWWG
1997



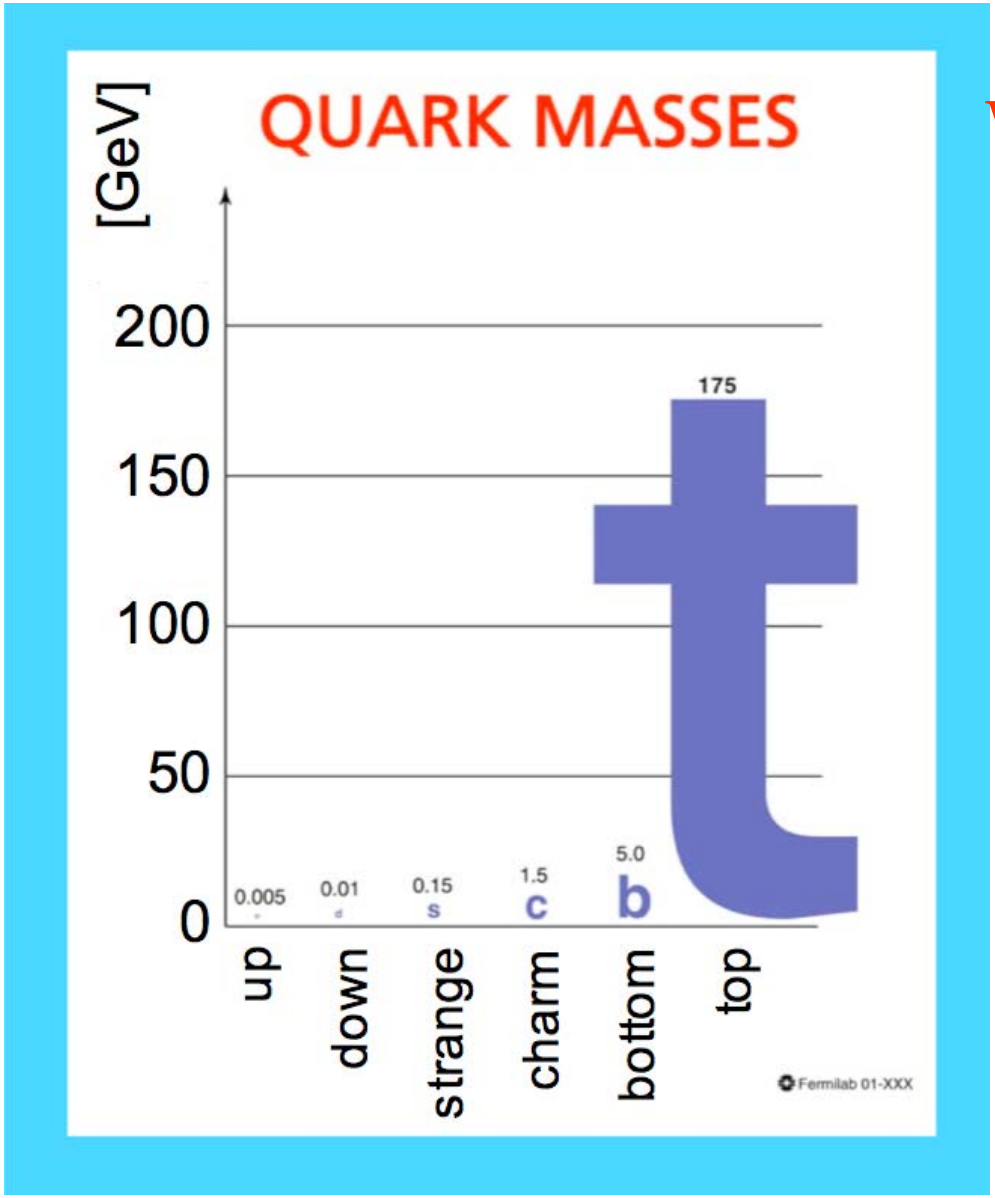
LEPEWWG 2009



WEAK BOSON MASSES

80 W

91 Z



WEAK BOSON MASSES

80 W

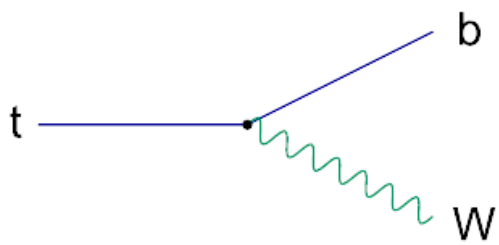
91 Z

The future of Top

The future of Top

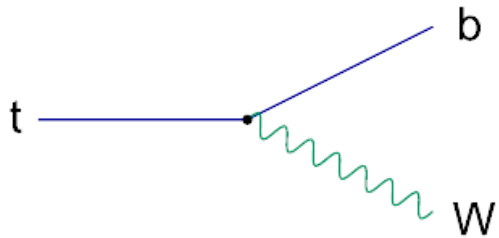
"The future is now"

Spin

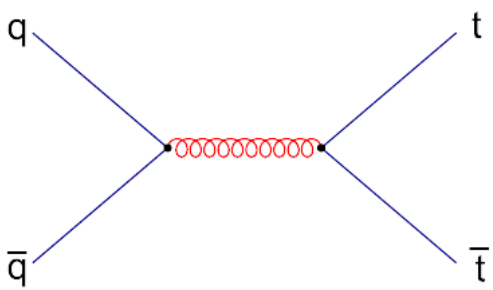


CDF	D0	SM
$F_0 = 0.62 \pm 0.11$	$F_0 = 0.49 \pm 0.14$	$F_0 = 0.7$
$F_+ = -0.04 \pm 0.05$	$F_+ = 0.11 \pm 0.08$	$F_+ = 0$

Spin

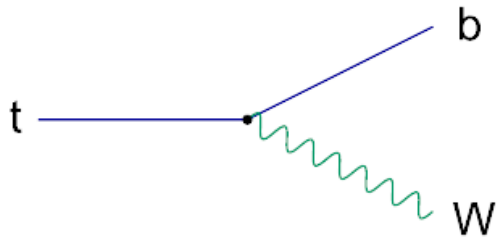


CDF	D0	SM
$F_0 = 0.62 \pm 0.11$	$F_0 = 0.49 \pm 0.14$	$F_0 = 0.7$
$F_+ = -0.04 \pm 0.05$	$F_+ = 0.11 \pm 0.08$	$F_+ = 0$

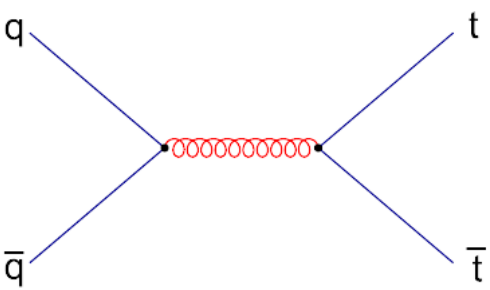


$C = -0.17^{+0.64}_{-0.53}$	D0	$C = 0.78$	SM
$\kappa = 0.32^{+0.55}_{-0.78}$	CDF	$\kappa = 0.8$	SM

Spin

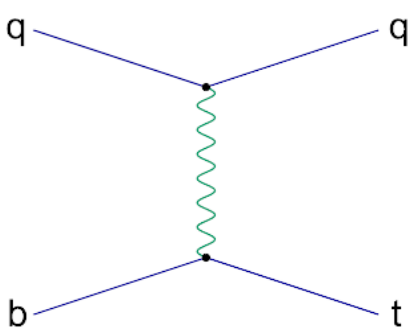


CDF	D0	SM
$F_0 = 0.62 \pm 0.11$	$F_0 = 0.49 \pm 0.14$	$F_0 = 0.7$
$F_+ = -0.04 \pm 0.05$	$F_+ = 0.11 \pm 0.08$	$F_+ = 0$



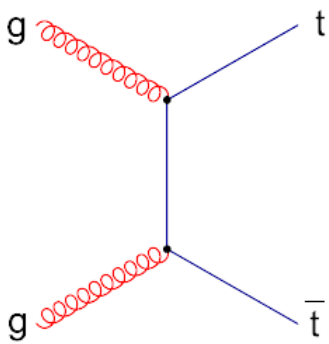
$C = -0.17^{+0.64}_{-0.53}$ D0 $C = 0.78$ SM

$\kappa = 0.32^{+0.55}_{-0.78}$ CDF $\kappa = 0.8$ SM



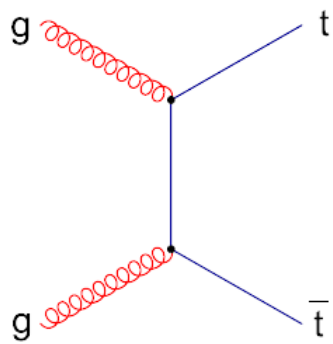
$P = -1^{+1.5}_{-0}$ CDF $P = -1$ SM

Dynamics

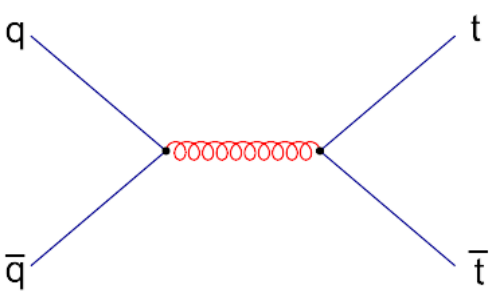


$\sigma(gg \to t\bar{t}) / \sigma(p\bar{p} \to t\bar{t}) = 0.07^{+0.15}_{-0.07}$ CDF 0.15 SM

Dynamics



$$\sigma(gg \to t\bar{t}) / \sigma(p\bar{p} \to t\bar{t}) = 0.07^{+0.15}_{-0.07}$$ CDF 0.15 SM

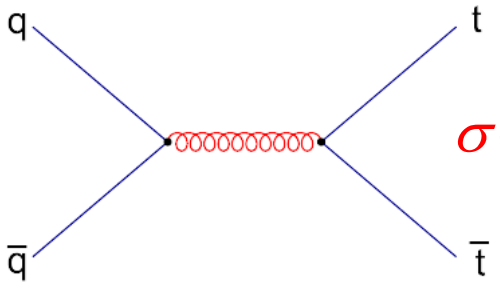


$$A_{FB} = 0.193 \pm 0.065 \pm 0.024$$ CDF

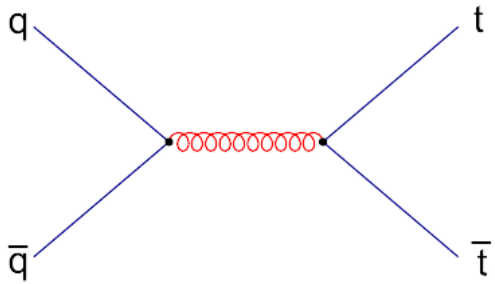
$$A_{FB} = 0.12 \pm 0.08 \pm 0.01$$ D0

0.05 SM

Dynamics

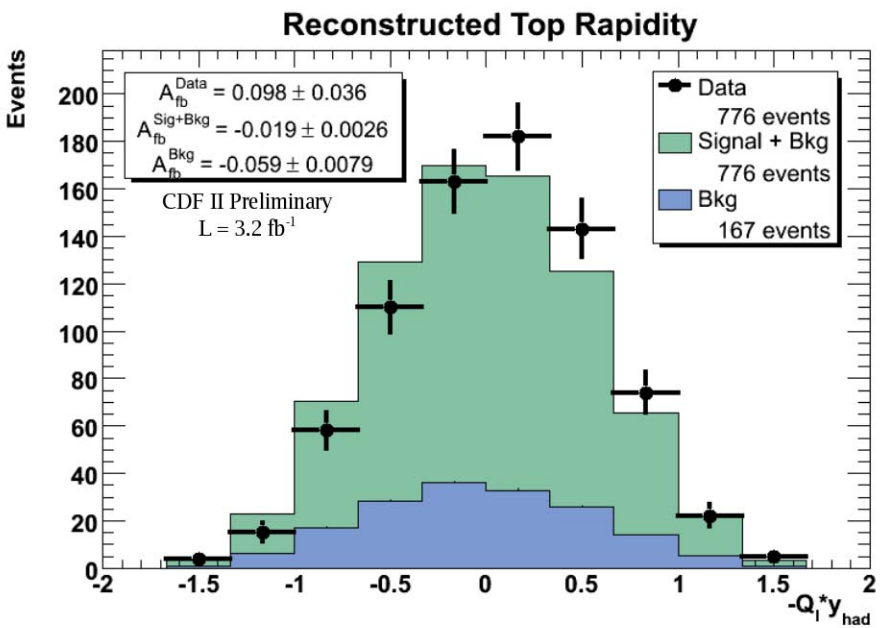


$$\sigma(gg \to t\bar{t}) / \sigma(p\bar{p} \to t\bar{t}) = 0.07^{+0.15}_{-0.07}$$ CDF 0.15 SM

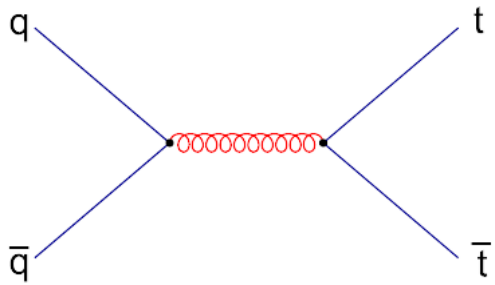


$$A_{FB} = 0.193 \pm 0.065 \pm 0.024$$ CDF

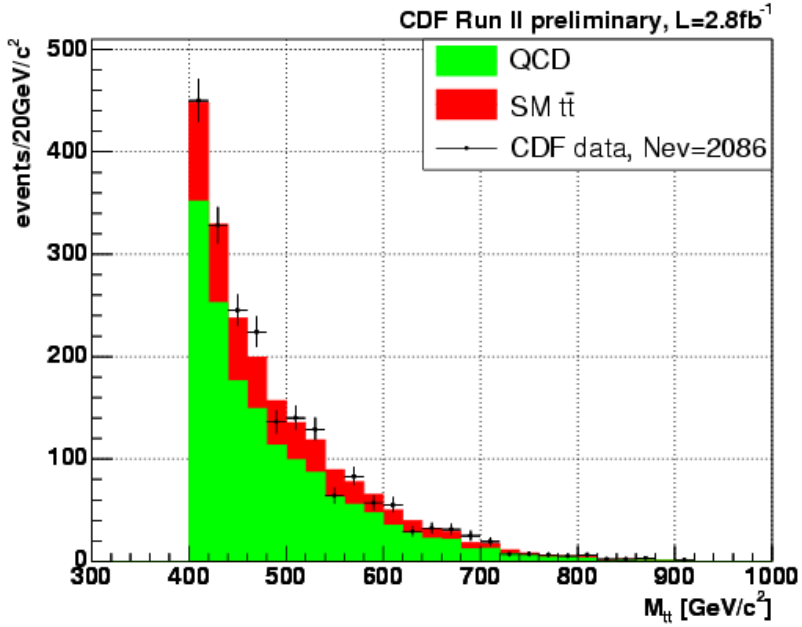
0.05 SM



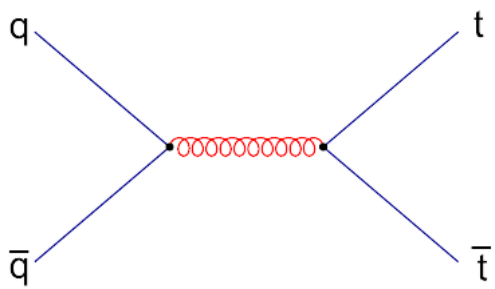
Searches



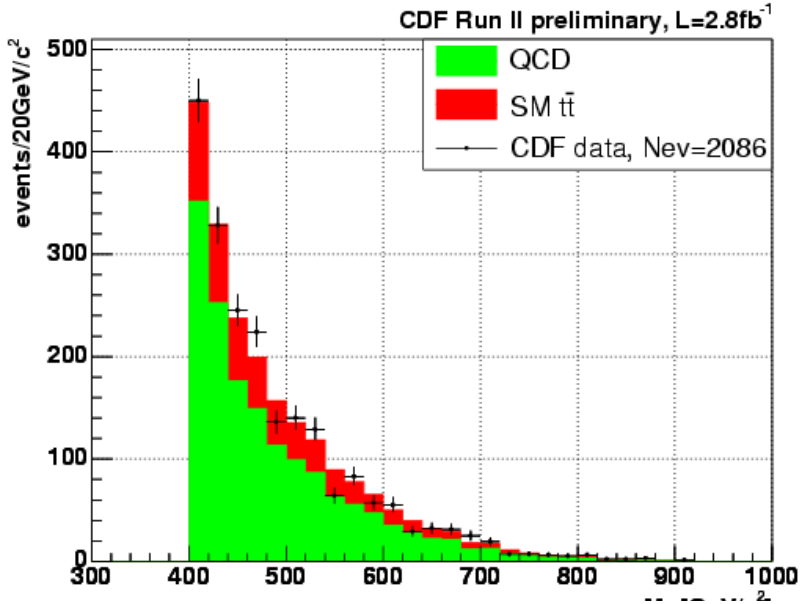
$$M_{Z'} > 805 GeV$$

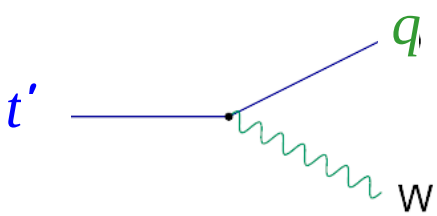


Searches

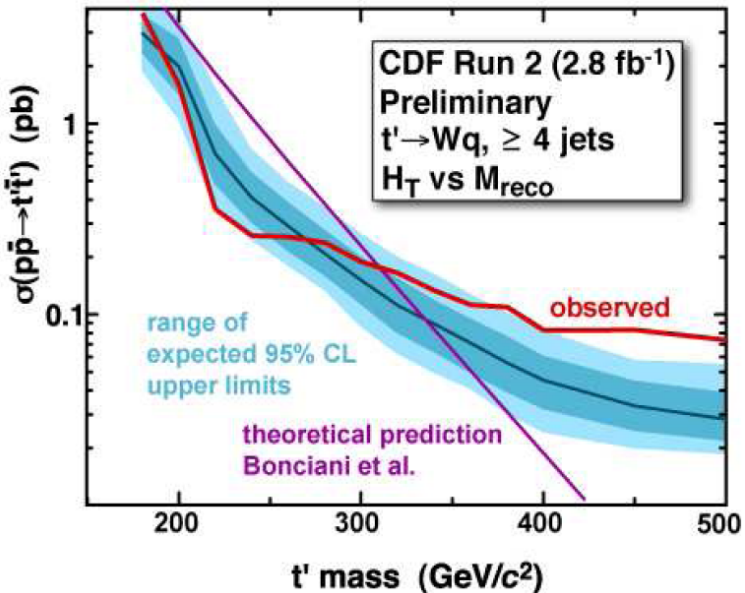


$M_{Z'} > 805 GeV$



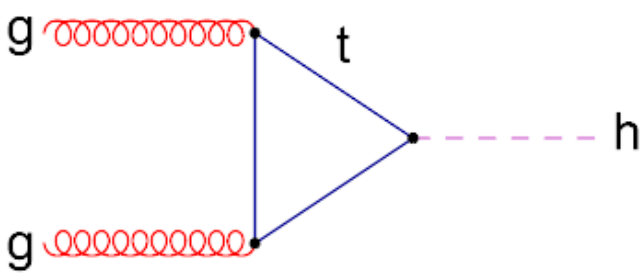


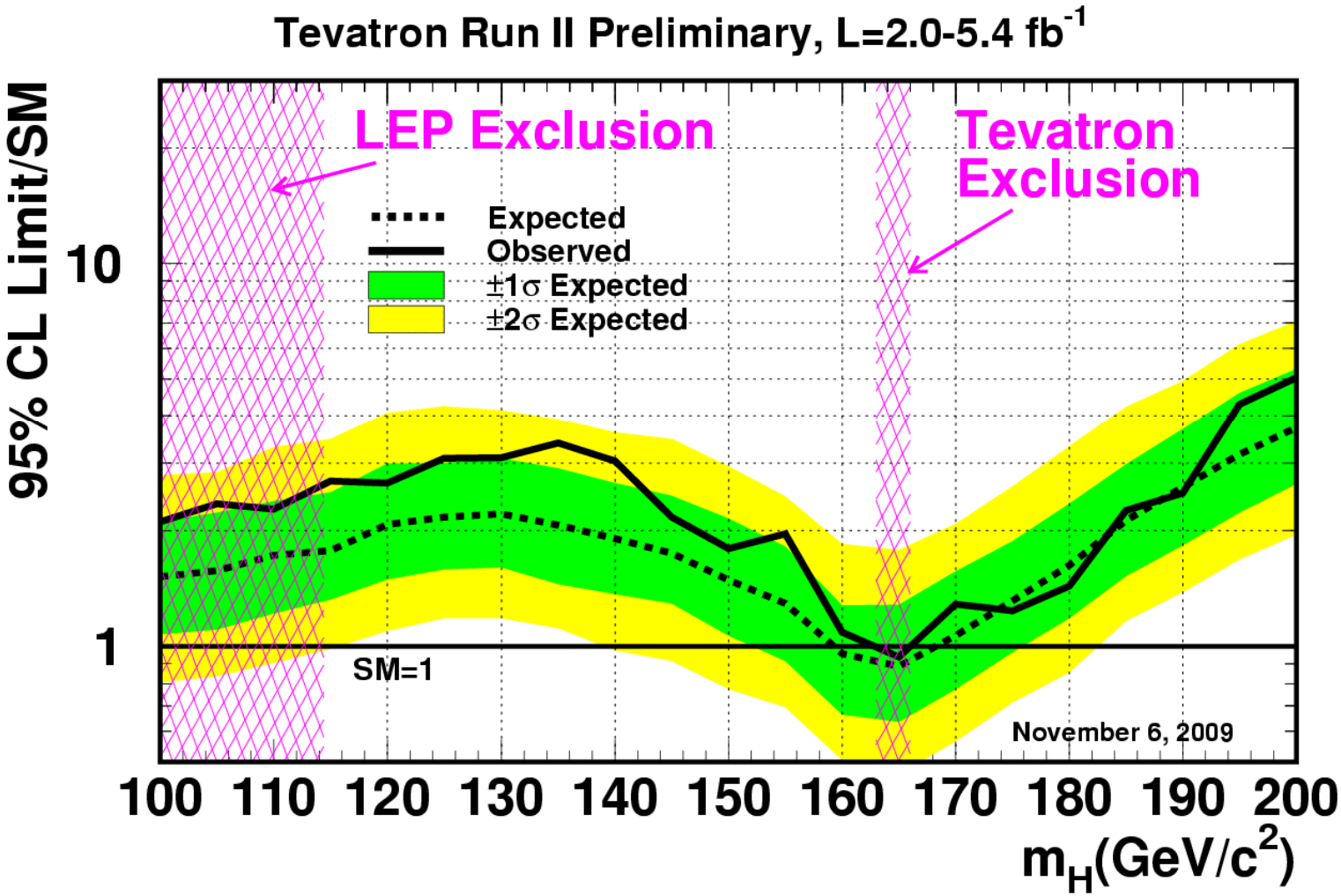
$m_{t'} > 311 GeV$

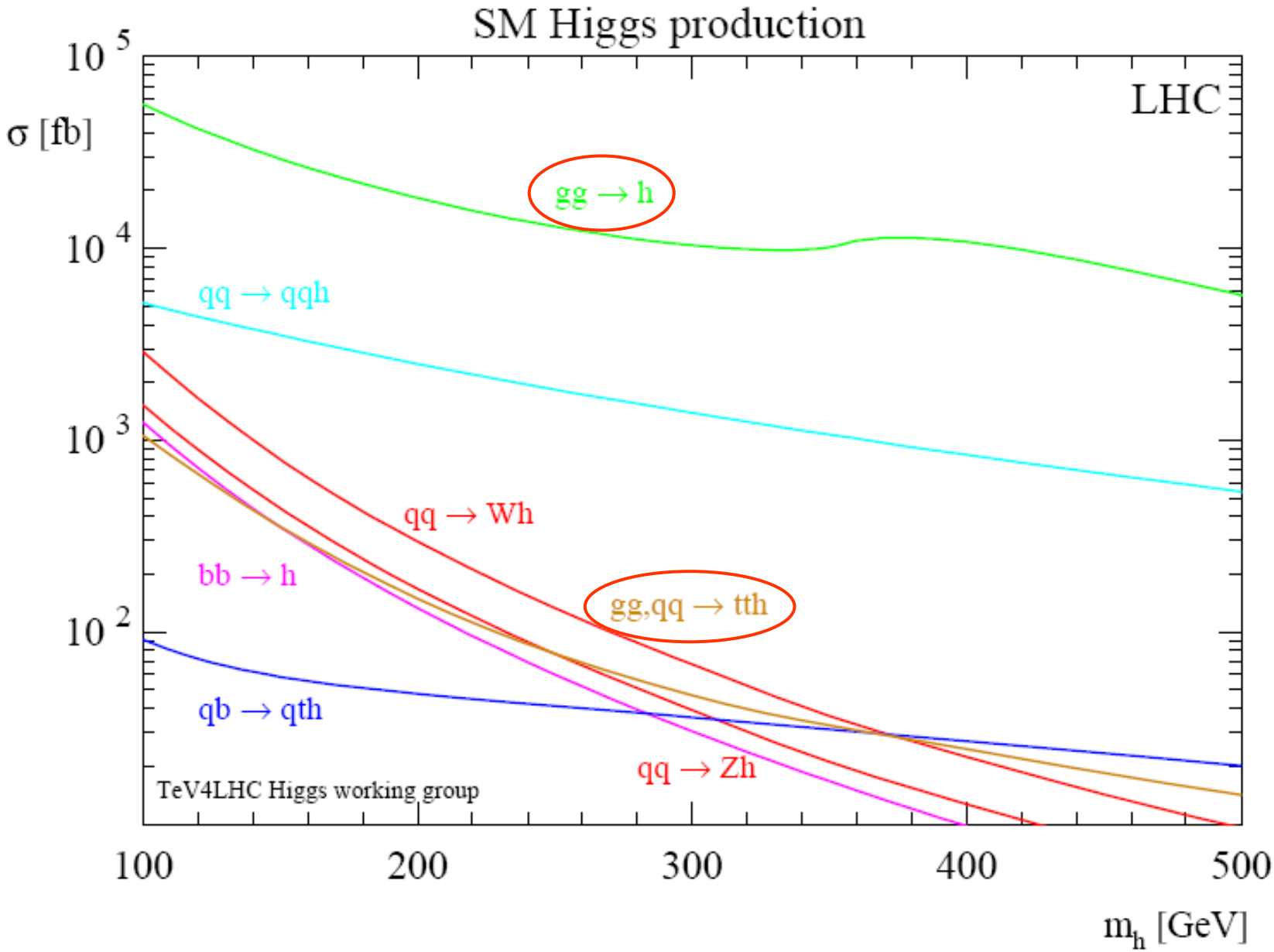


Physics from the Top

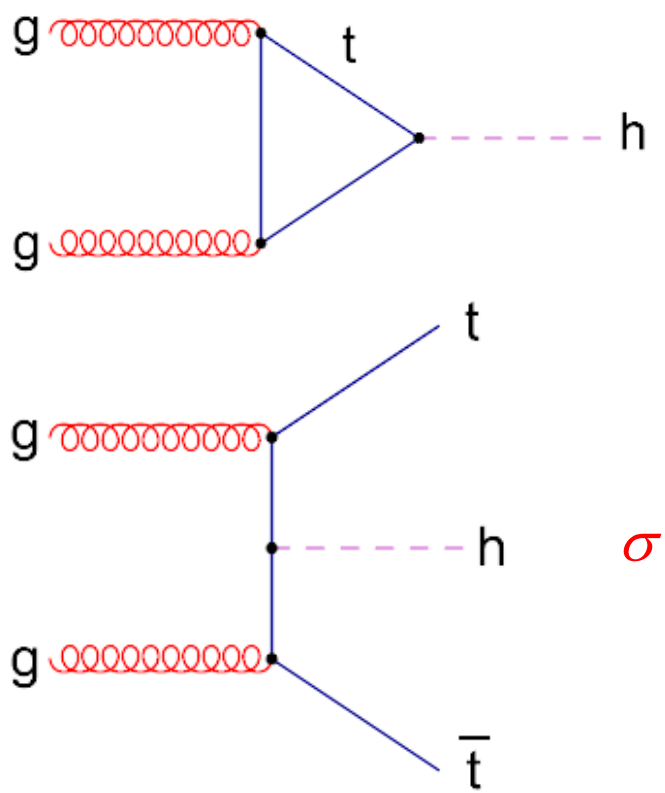
Higgs production




Tevatron Run II Preliminary, L=2.0-5.4 fb^{-1}
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
November 6, 2009
95% CL Limit/SM
10
1
100 110 120 130 140 150 160 170 180 190 200
m_H(GeV/c^2)


SM Higgs production
LHC
σ [fb]
10 5
10 4
10 3
10 2
gg → h
qq → qqh
qq → Wh
bb → h
gg,qq → tth
qb → qth
qq → Zh
TeV4LHC Higgs working group
100
200
300
400
500
m_h [GeV]

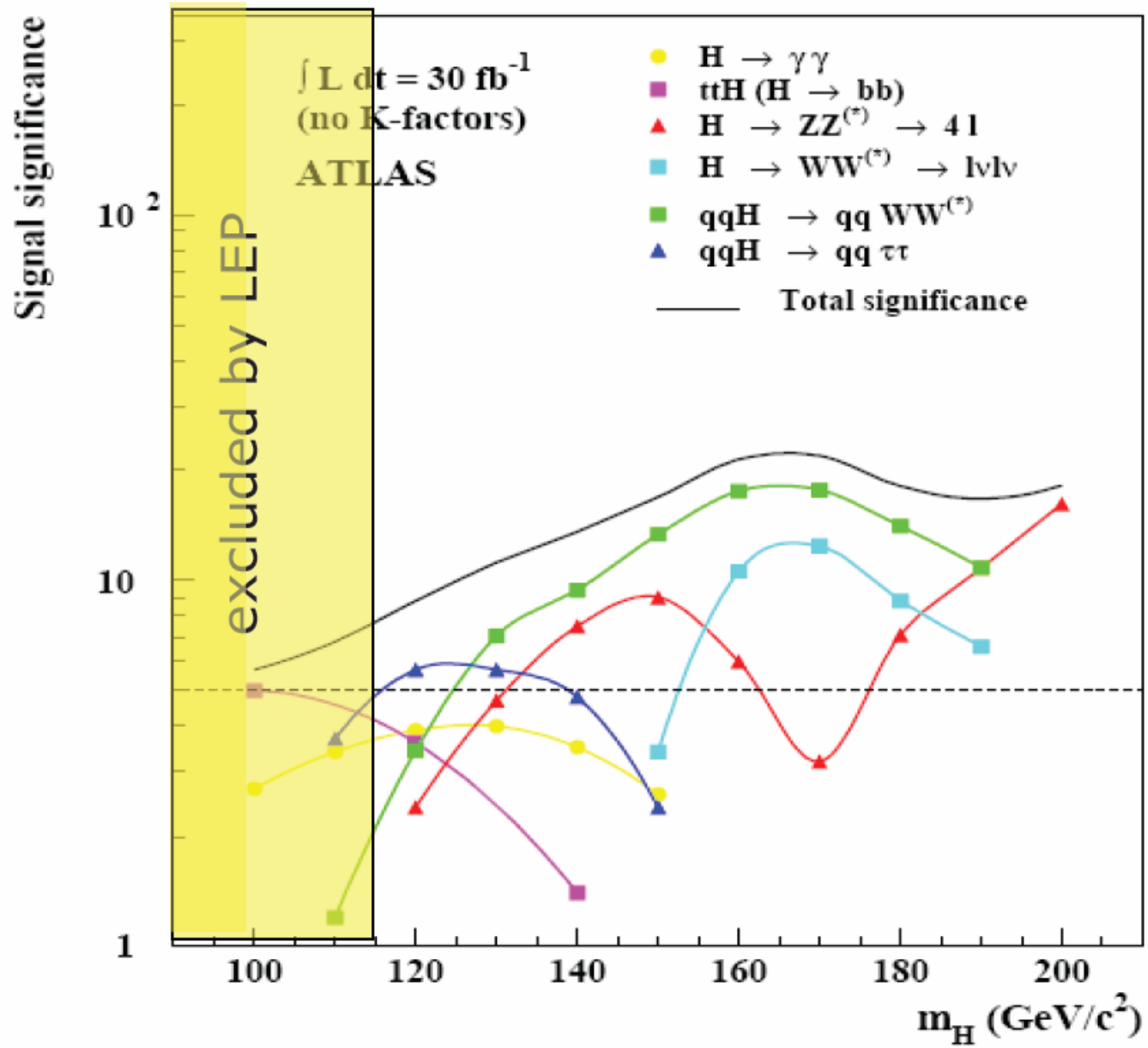
Higgs production

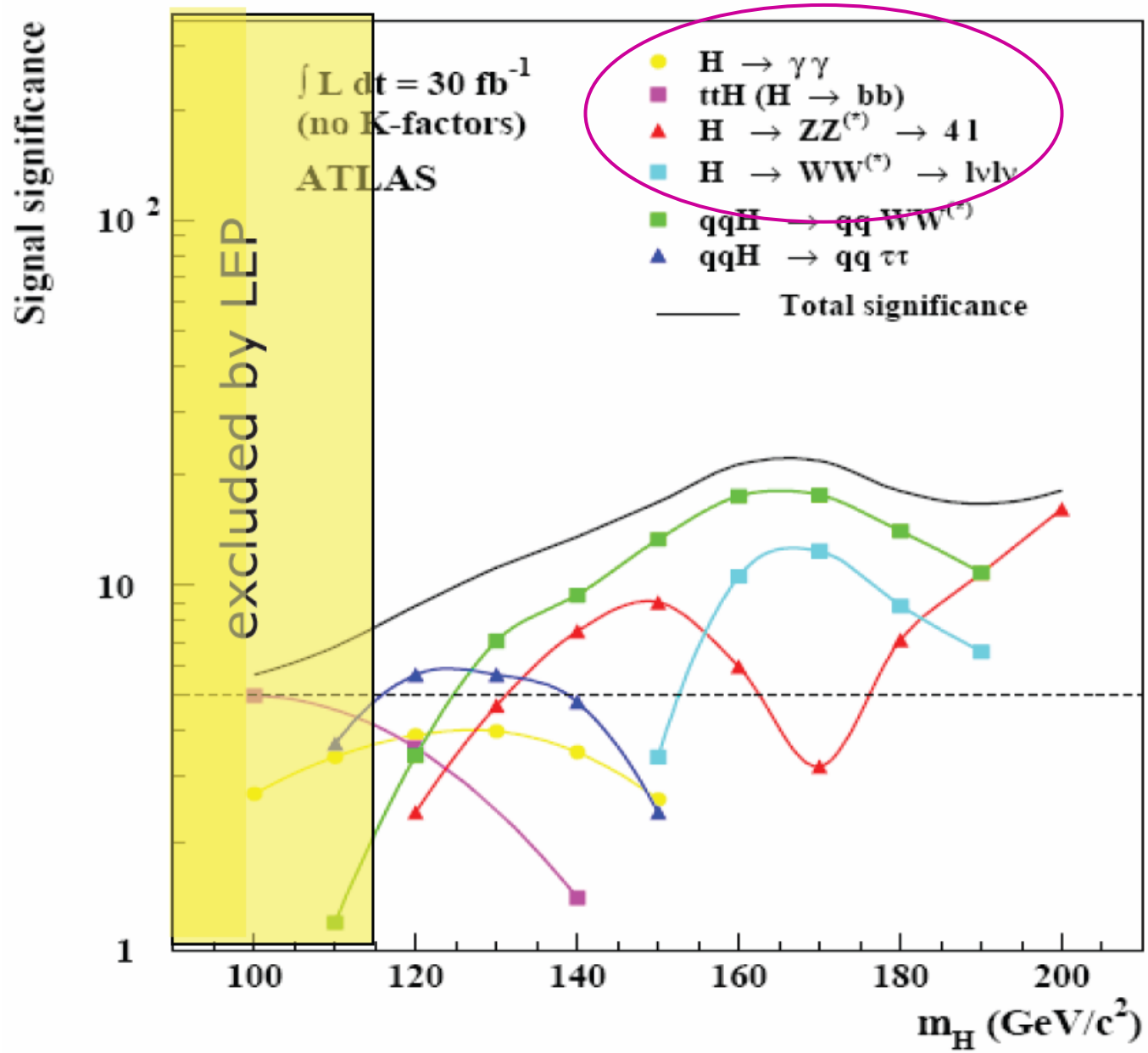


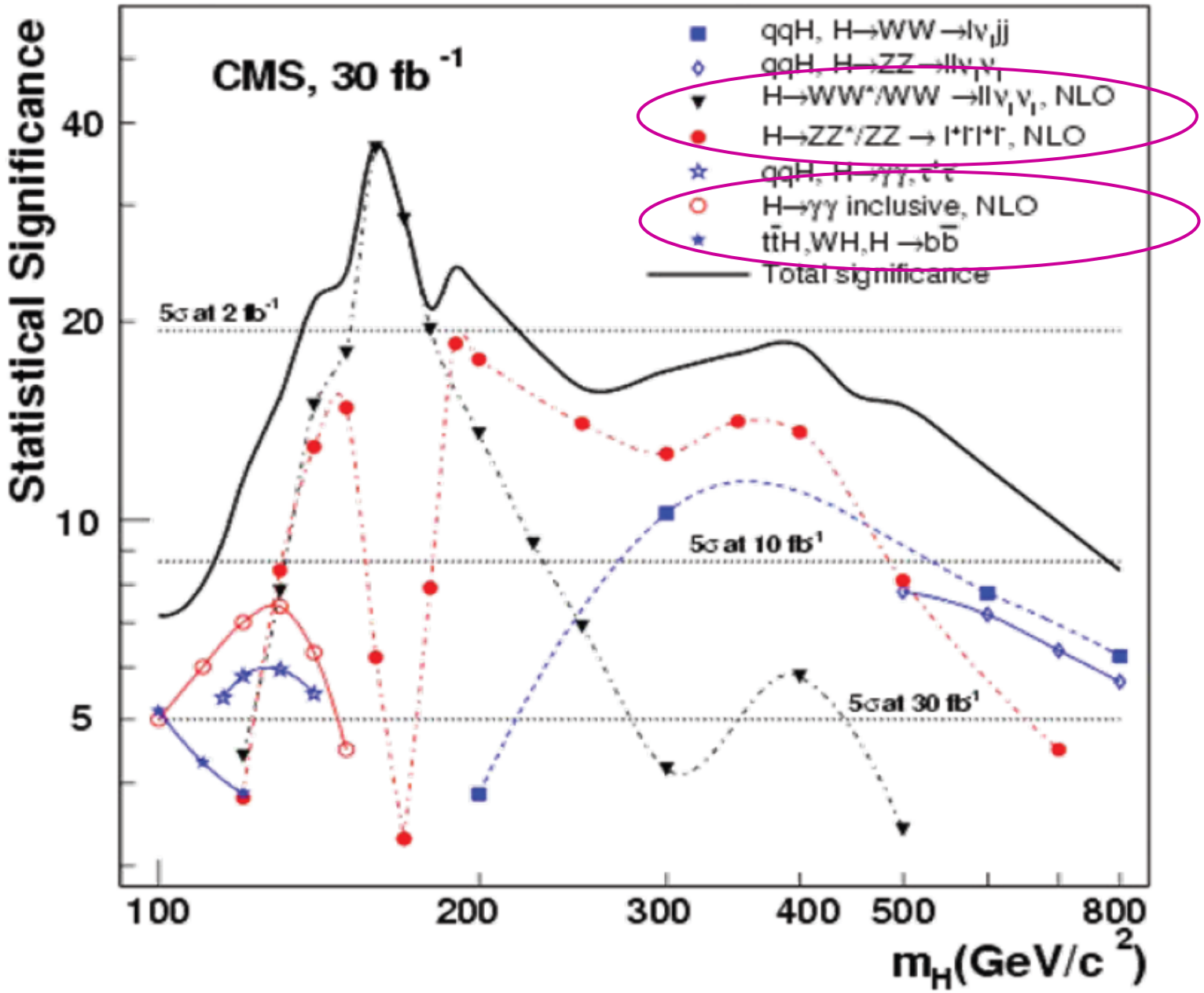
$$\sigma(p\bar{p} \to t\bar{t}h) < 64 \times SM$$

$$(m_h = 115 GeV)$$

D0


Signal significance
∫ L dt = 30 fb-1
(no K-factors)
ATLAS
excluded by LEP
H → γγ
ttH (H → bb)
H → ZZ(*) → 4 l
H → WW(*) → lνlν
qqH → qq WW(*)
qqH → qq ττ
Total significance
10 2
10
1
100
120
140
160
180
200
mH (GeV/c2)


Signal significance
$\int L\,dt = 30\ fb^{-1}$
(no K-factors)
ATLAS
excluded by LEP
$H \to \gamma\gamma$
$ttH\ (H \to bb)$
$H \to ZZ^{(*)} \to 4l$
$H \to WW^{(*)} \to l\nu l\nu$
$qqH \to qq\ WW^{(*)}$
$qqH \to qq\ \tau\tau$
Total significance
10^2
10
1
100
120
140
160
180
200
m_H (GeV/c^2)


CMS, 30 fb -1
qqH, H→WW→lνjj
qqH, H→ZZ→llνlνl
H→WW*/WW →llνlνl, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ, τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
Statistical Significance
40
20
10
5
100
200
300
400
500
800
mH(GeV/c 2)

Conclusion

Top is now a teenager

Back-up Slides

$V_{tb} = 0.91 \pm 0.11$ (exp) ± 0.07 (theory)

95% CL upper limit on BR: $90 < H^+ < 150$ GeV

$BR(t \to Zq) < 3.7\%$ at 95% CL

$F_0 = 0.62 \pm 0.11$ & $F_+ = -0.04 \pm 0.05$

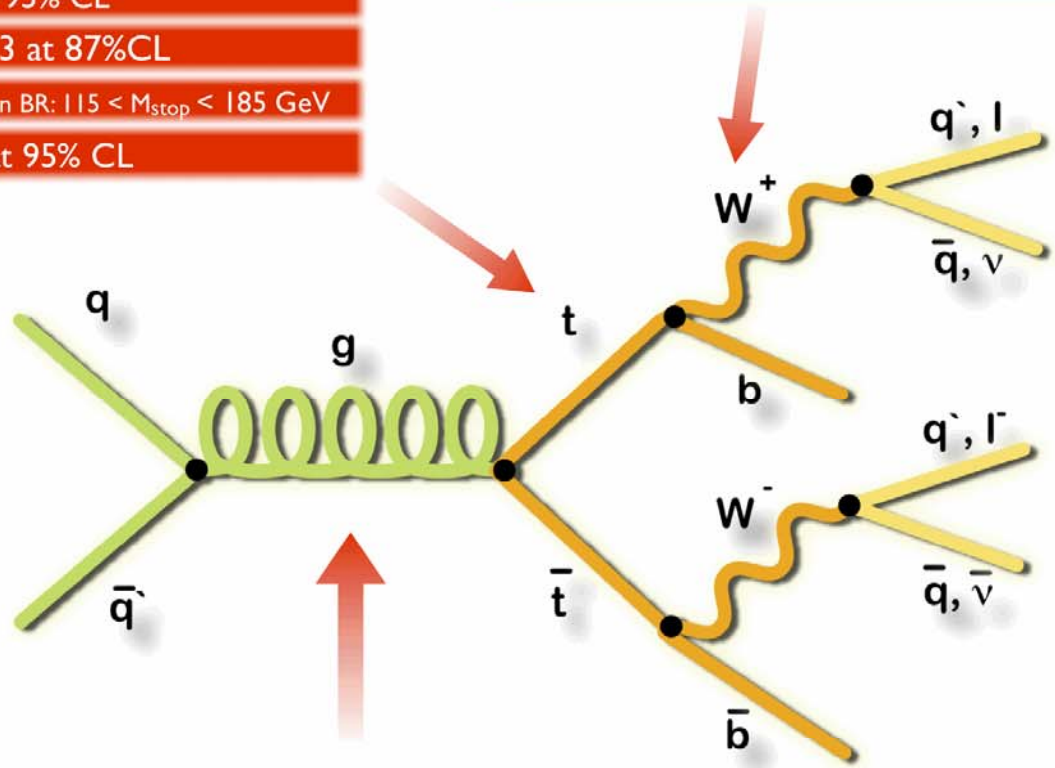
$M_t = 172.6 \pm 0.9_{stat} \pm 1.2_{sys}$ GeV/c^2

$\Gamma_t < 13.1$ GeV at 95% CL

Exclude q = -4/3 at 87%CL

95% CL upper limit on BR: $115 < M_{stop} < 185$ GeV

$M_{t'} < 311$ GeV at 95% CL



$\sigma_{l+jets} = 7.5 \pm 0.4_{stat} \pm 0.4_{sys} \pm 0.1_{z\text{-}theory}$ pb

$\sigma_{ll} = 6.6 \pm 0.7_{stat} \pm 0.4_{sys} \pm 0.4_{lumi}$ pb

$\sigma_{all\text{-}jets} = 7.2 \pm 0.5_{stat} \pm 1.1_{sys} \pm 0.4_{lumi}$ pb

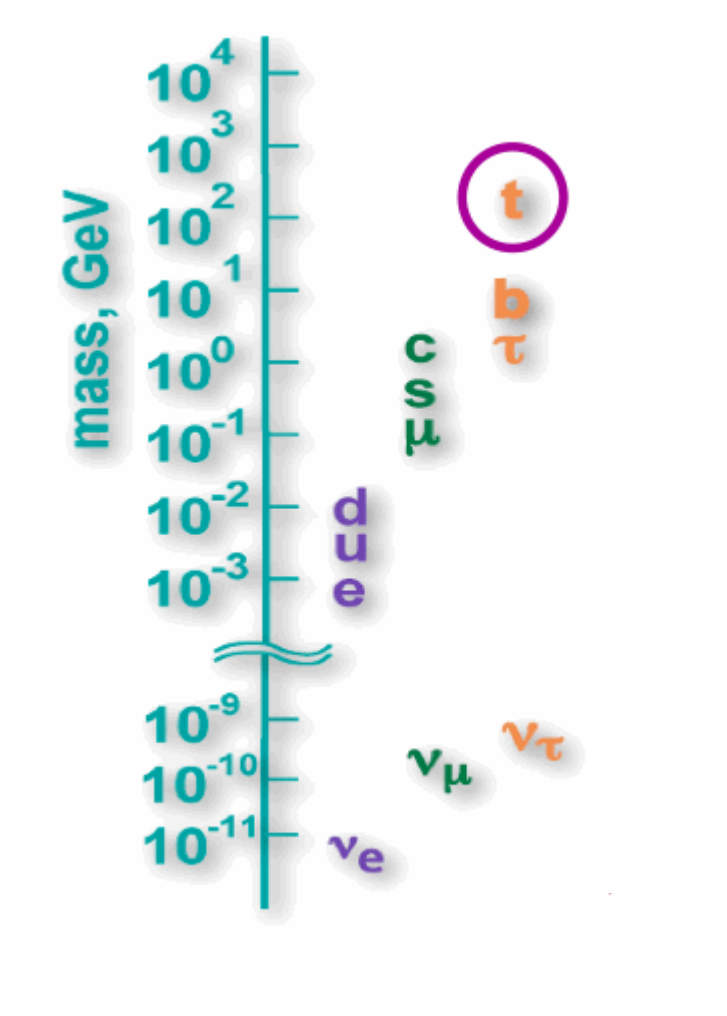
$\sigma_{tt+j} = 1.6 \pm 0.2_{stat} \pm 0.5_{sys}$ pb

$F_{gg} = 0.07^{+0.15}_{-0.07}$ (stat+sys)

$A_{fb}^{lab} = 0.19 \pm 0.07_{stat} \pm 0.02_{sys}$

$M_{Z'} < 805$ GeV at 95% CL

Spin Correlations $\kappa = 0.3^{+0.6}_{-0.8}$


mass, GeV
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-9}
10^{-10}
10^{-11}
t
b
τ
c
s
μ
d
u
e
ν_τ
ν_μ
ν_e