Physics of Top

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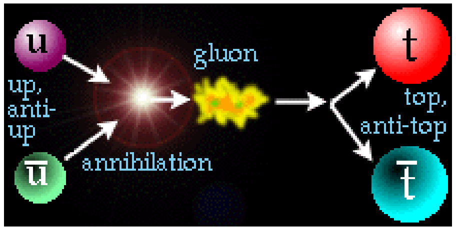
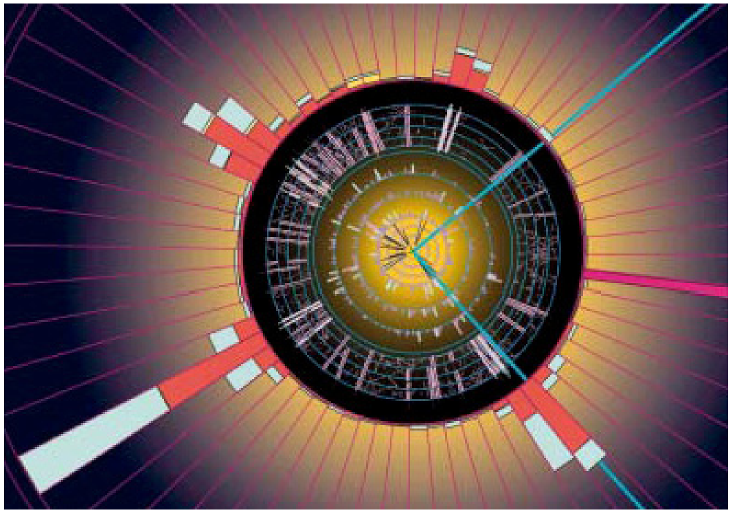
July 2, 2007
@ Chong Qing University

- Mass of Top Quark
- Single-Top Production
- General Analysis of Single-Top Production and Top Decay
- Top & Electroweak Symmetry Breaking
- Discriminate Models of Electroweak Symmetry Breaking
- Conclusion

March 2, 1995





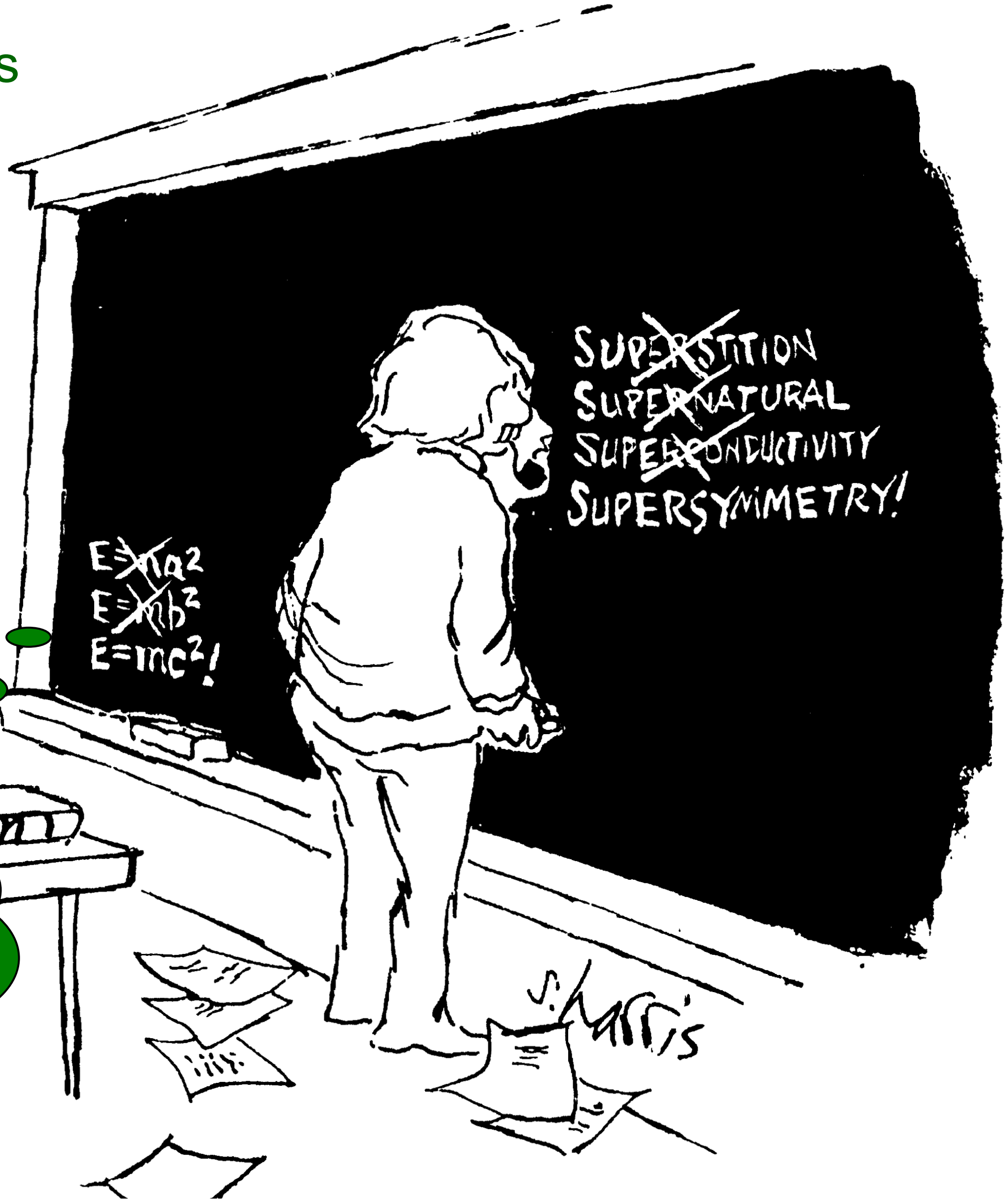
We had champaign
at the MSU High Energy physics
conference room to celebrate the
discovery of the Top Quark at FNAL
Tevatron by CDF & D0 groups.

Recently,

$$m_t = 170.9 \pm 1.8 \text{ GeV}$$

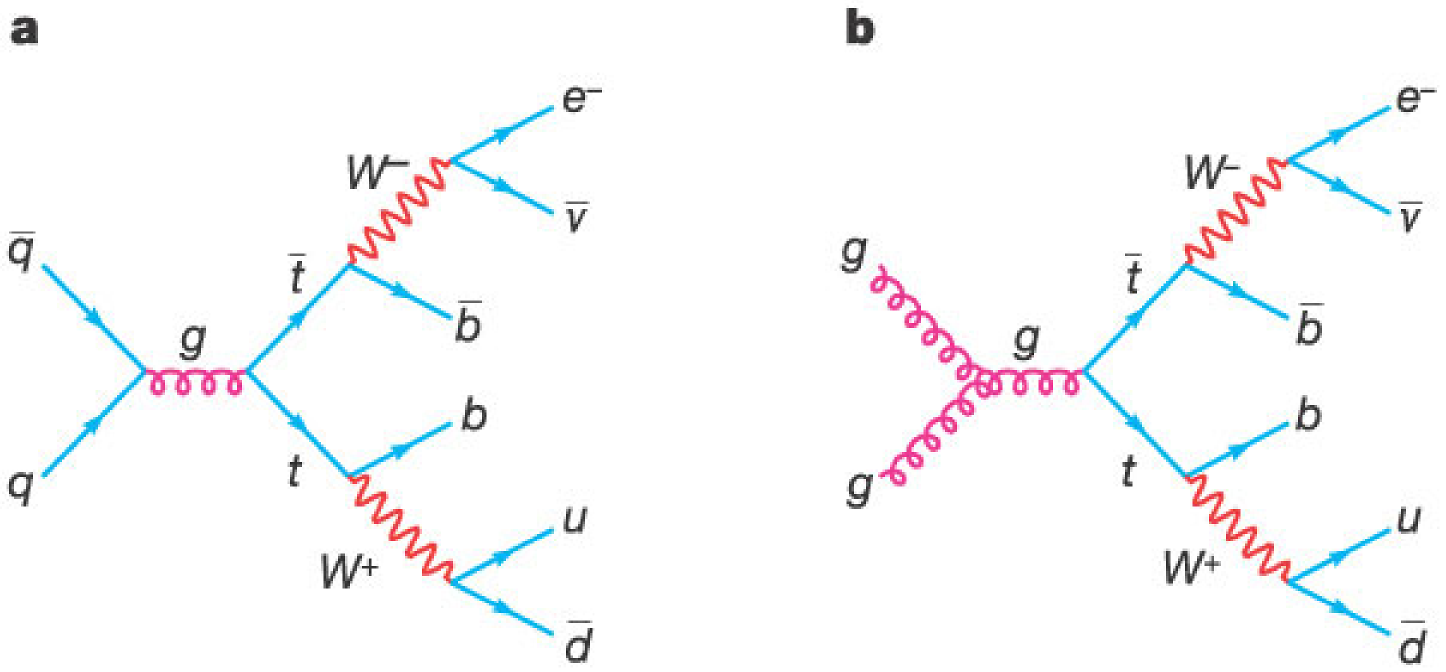
Lessons we learned from the History on the discovery of Top Quark

- Only Experimental Data has the final say about Mother Nature.
- The interaction between Experimentalists and Theorists is essential for the advance of science.



Theorists should not give up any probable idea.

$t\bar{t}$ Pair Production



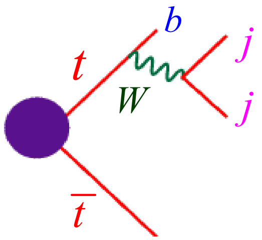
Challenge in measuring m_t from *bjj* invariant mass:

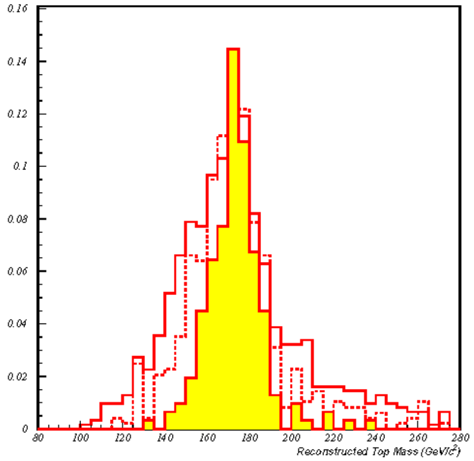
- Jet energy resolution
  (under-lying hadronic activity,…)

- not much better than 2-3 GeV in δm_t, i.e. $\delta m_t > \Gamma_t$

Need better measurement of m_t

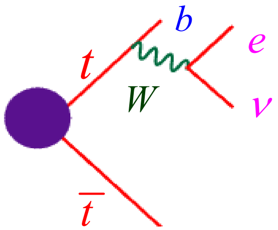
- From the invariant mass of ($b\,j\,j$)

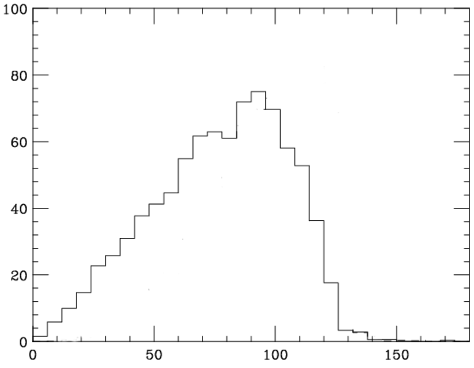




m_{bjj}

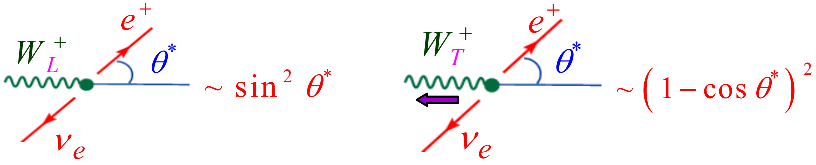
- From the invariant mass of ($b\,e$)





m_{be}

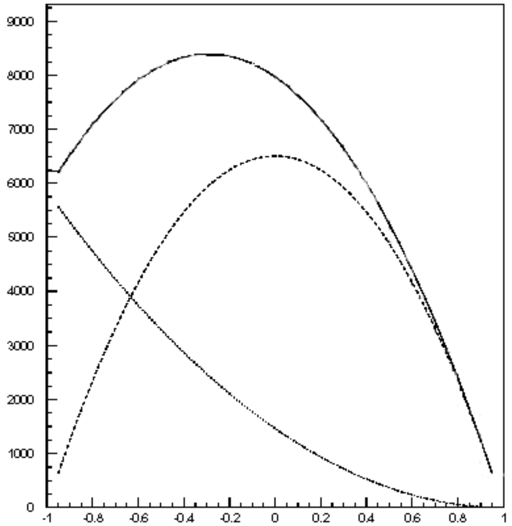
- From the polarization of W



$$F(\cos\theta^*) \sim (1-f_{\rm Long})\left(\frac{1-\cos\theta^*}{2}\right)^2 + f_{\rm Long}\left(\frac{\sin\theta^*}{\sqrt{2}}\right)^2$$

$$f_{\rm long} = \frac{\Gamma\left(t\to bW_L\right)}{\Gamma\left(t\to bW_L\right)+\Gamma\left(t\to bW_T\right)} = \frac{m_t^2}{2\,m_W^2+m_t^2}$$

$$\cos\theta^* = \frac{2m_{be}^2}{m_t^2-m_W^2}-1$$



$\cos\theta^*$

Improve m_t measurement at ILC

- Top production at threshold

  ➔ From σ_{tt}, p_t^{peak} and A_{FB}

  δm_t (theory) ~ 100 MeV

- Top production at continuum

  ➔ From direct reconstruction

  δm_t (theory) ~ 500 MeV

Note: AT ILC, $\delta m_t < \Gamma_t$.

Impact of a Precise m_t Measurement

Experimental

	Today	TeV/LHC	ILC	GigaZ
$\delta\, sin^2\theta_{eff}$(x$10^5$)	16	14-20	-	1.3
δM_W [MeV]	34	15	10	7

Intrinsic theoretical:

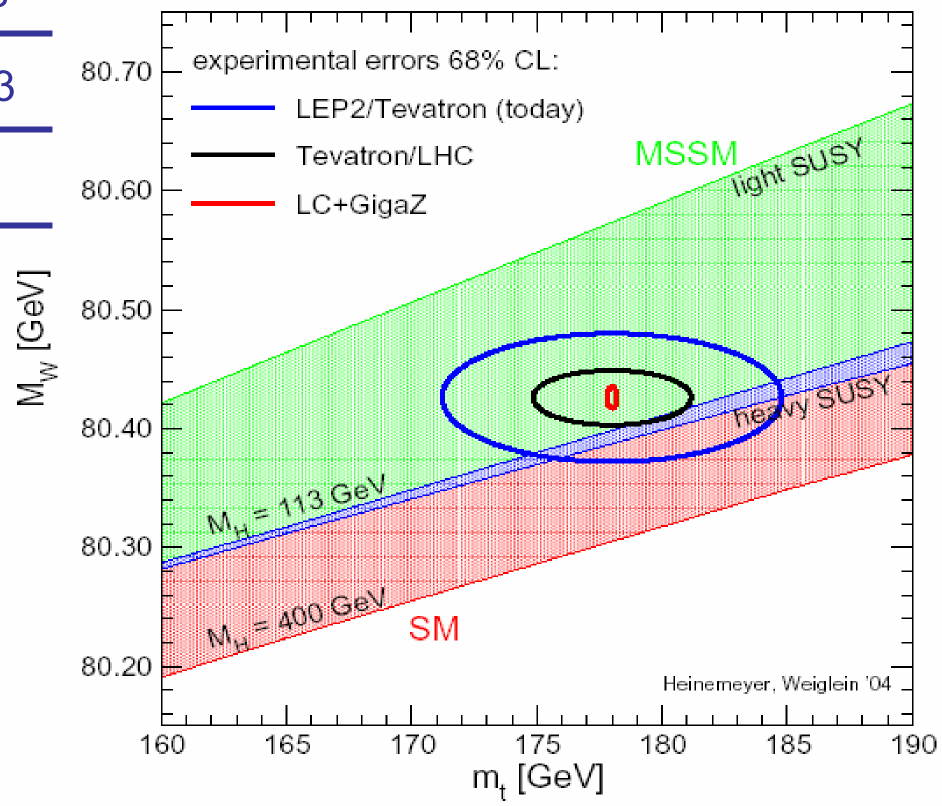
$\delta M_W =$ 4 MeV, $\delta\, sin^2\theta_{eff} = 4.9\times10^{-5}$

Parametric theoretical:

$\delta m_t = 4.3$ GeV $\Rightarrow \delta M_W = 26$ MeV,
$\delta sin^2\theta_{eff} = 14\times10^{-5}$

Tevatron Run-2 :
LHC: $\delta m_t = 1.5$ GeV $\Rightarrow \delta M_W =$ 9 MeV,
$\delta\, sin^2\theta_{eff} = 4.5\times10^{-5}$

ILC: $\delta m_t = 0.1$ GeV $\Rightarrow \delta M_W =$ 1 MeV,
$\delta\, sin^2\theta_{eff} = 0.3\times10^{-5}$



At Run 2, $\delta m_t \sim$ 2-3 GeV $\Rightarrow$ no longer the dominant error

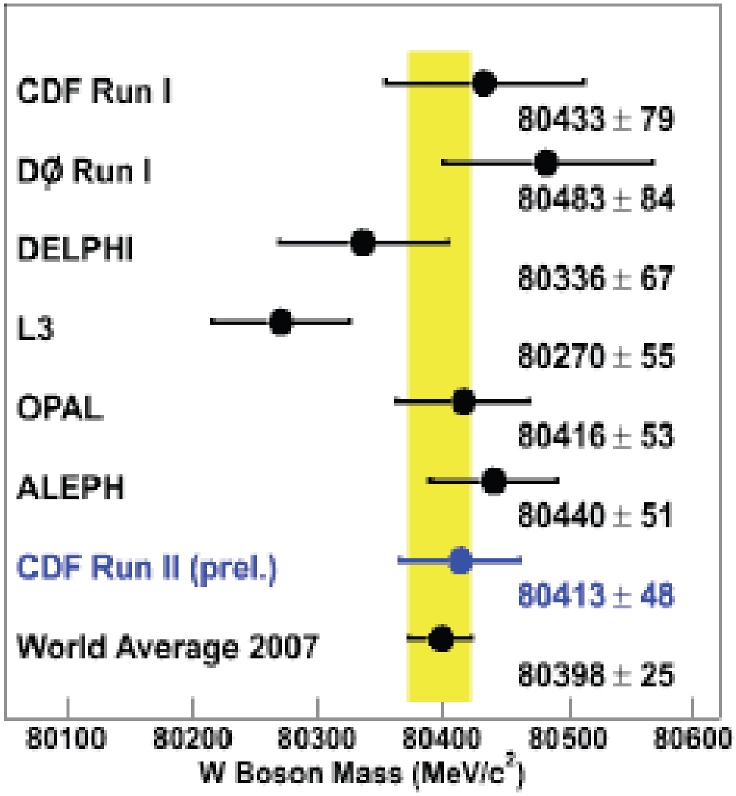
Result of *W* Boson and Top Mass Measurements at Tevatron, by 2007

W Mass

- Combining all six mass fits yields:

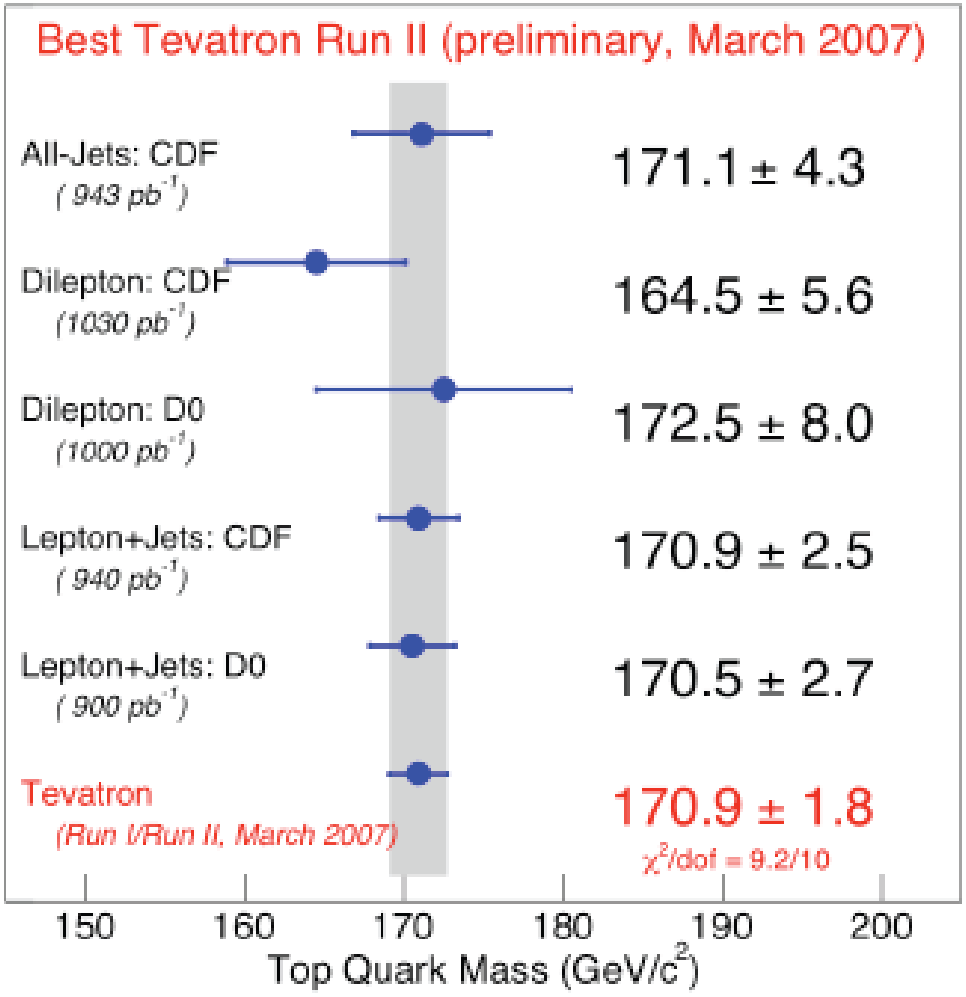
M_W=80413±48 MeV (stat+syst), P(χ^2)=44%

- New CDF result is the world's most precise single measurement



- World average increases: 80392 to 80398 MeV
- Uncertainty reduced ~15% (29 to 25 MeV)

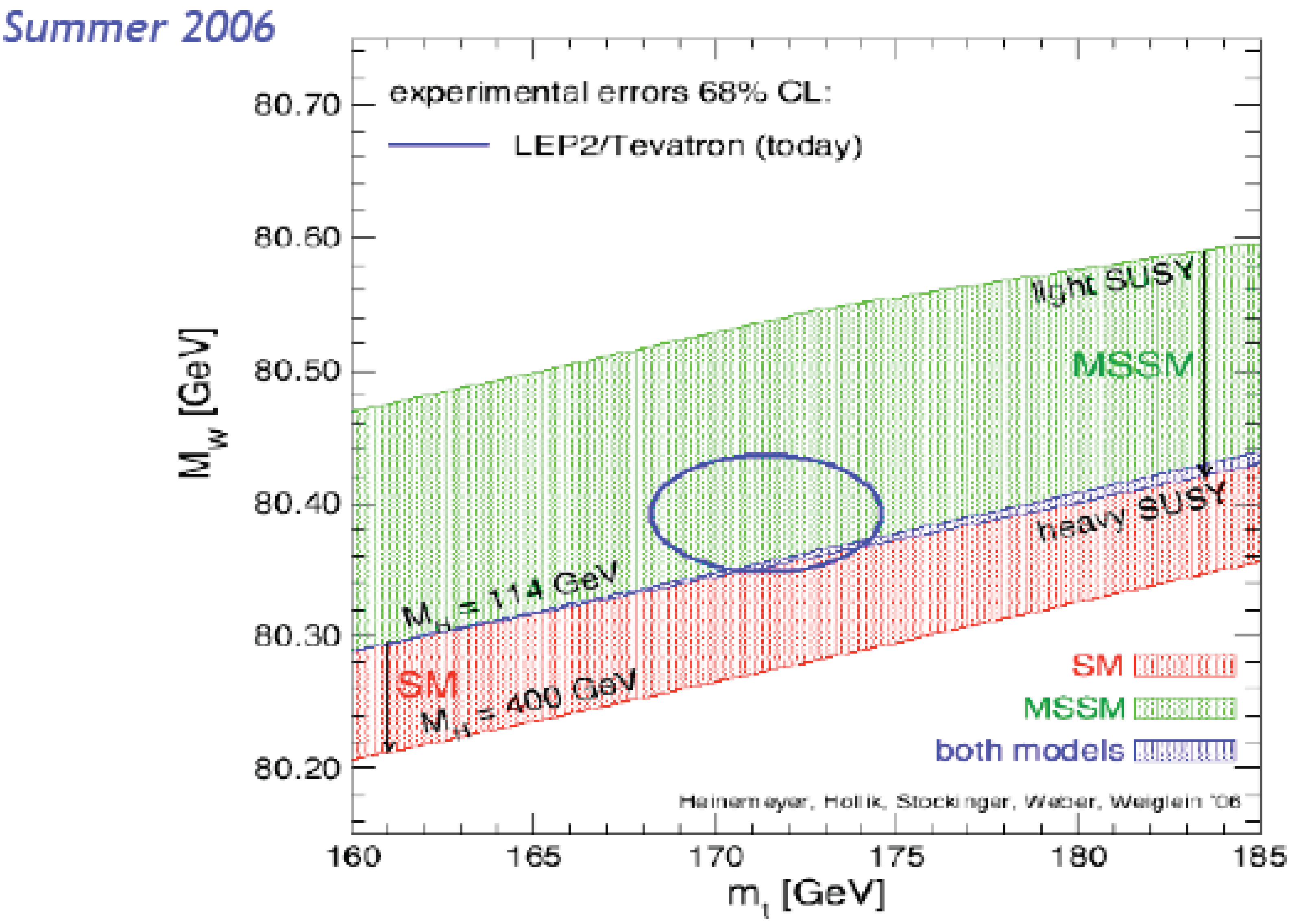
Top Mass



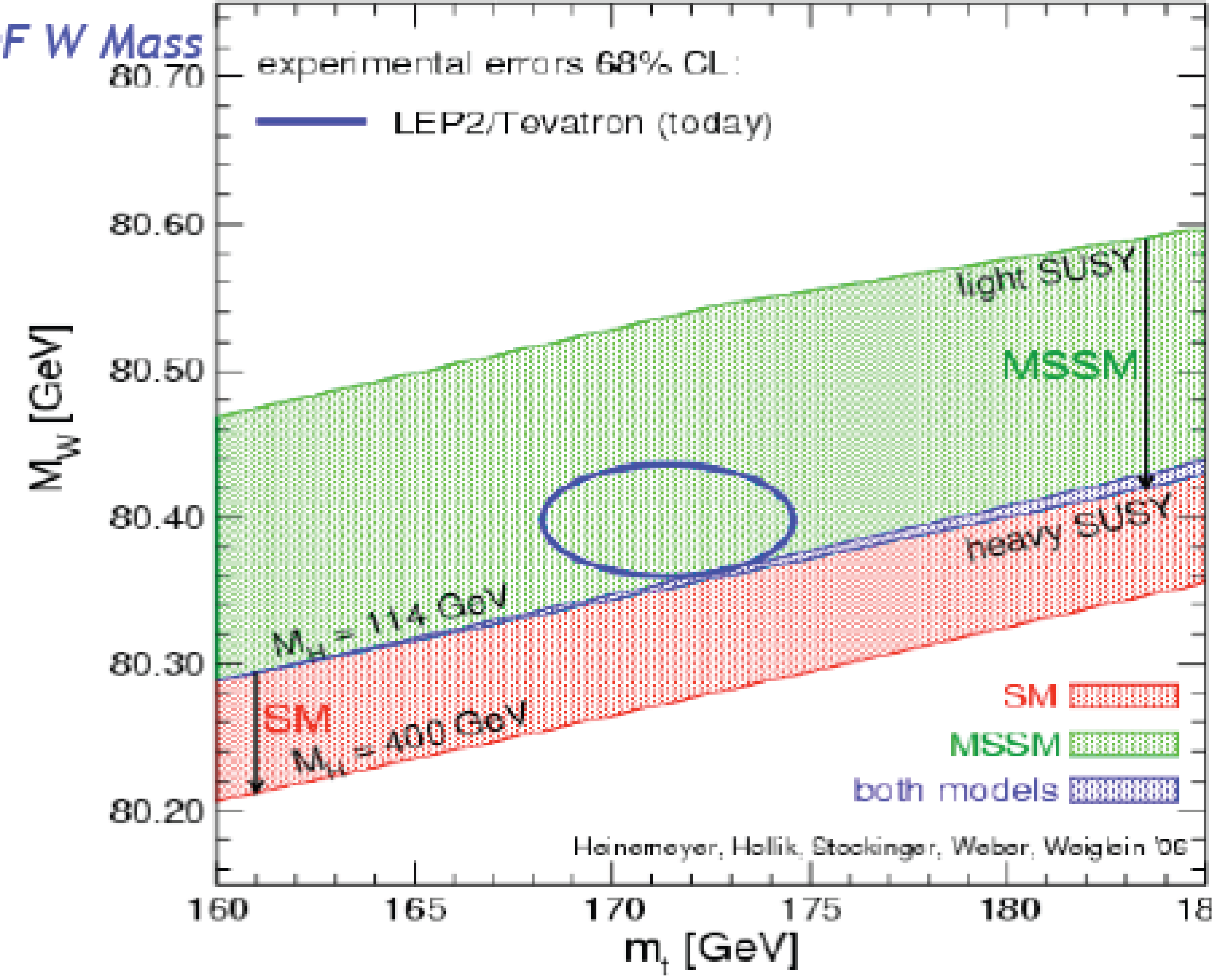
New Tevatron average (3 weeks ago): Top mass now measured to 1.8 GeV

http://tevewwg.fnal.gov/top

Summer 2006


Summer 2006
experimental errors 68% CL:
LEP2/Tevatron (today)
light SUSY
MSSM
heavy SUSY
M_h = 114 GeV
SM
M_H = 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Stockinger, Weber, Weiglein '06
80.20
80.30
80.40
80.50
80.60
80.70
M_W [GeV]
160
165
170
175
180
185
m_t [GeV]

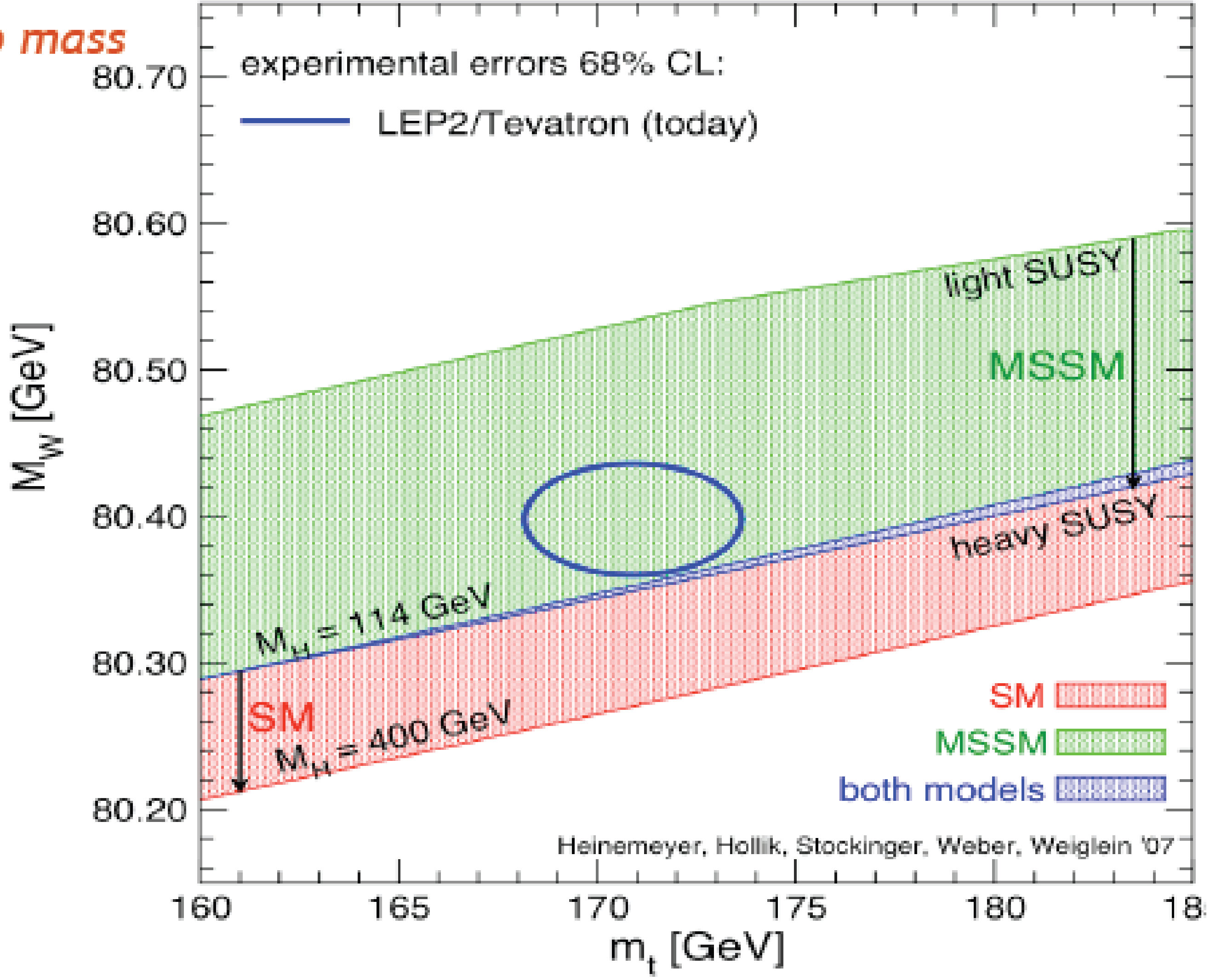
Winter 2007



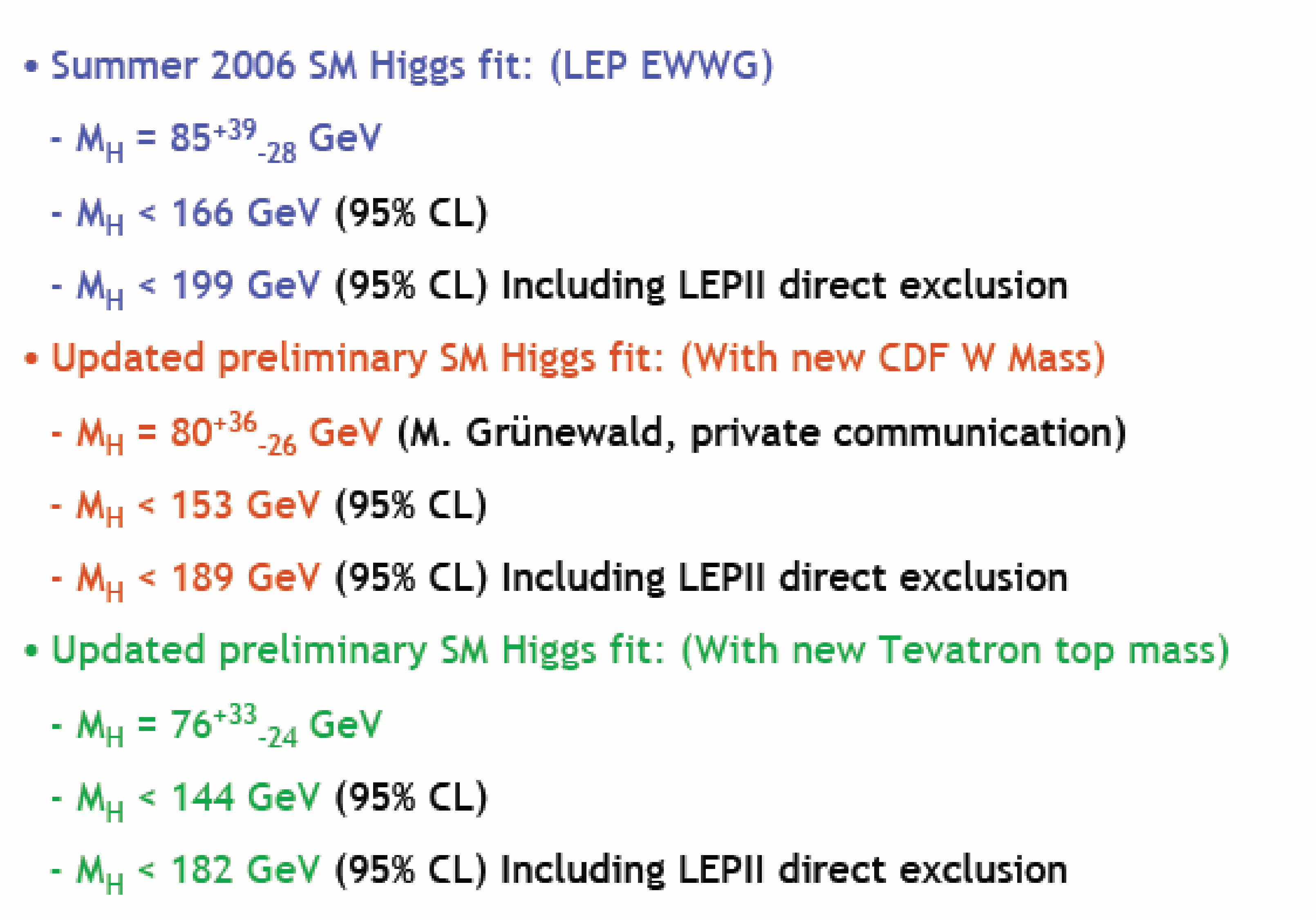
Winter 2007
New CDF W Mass

March 2007

March 2007
New top mass

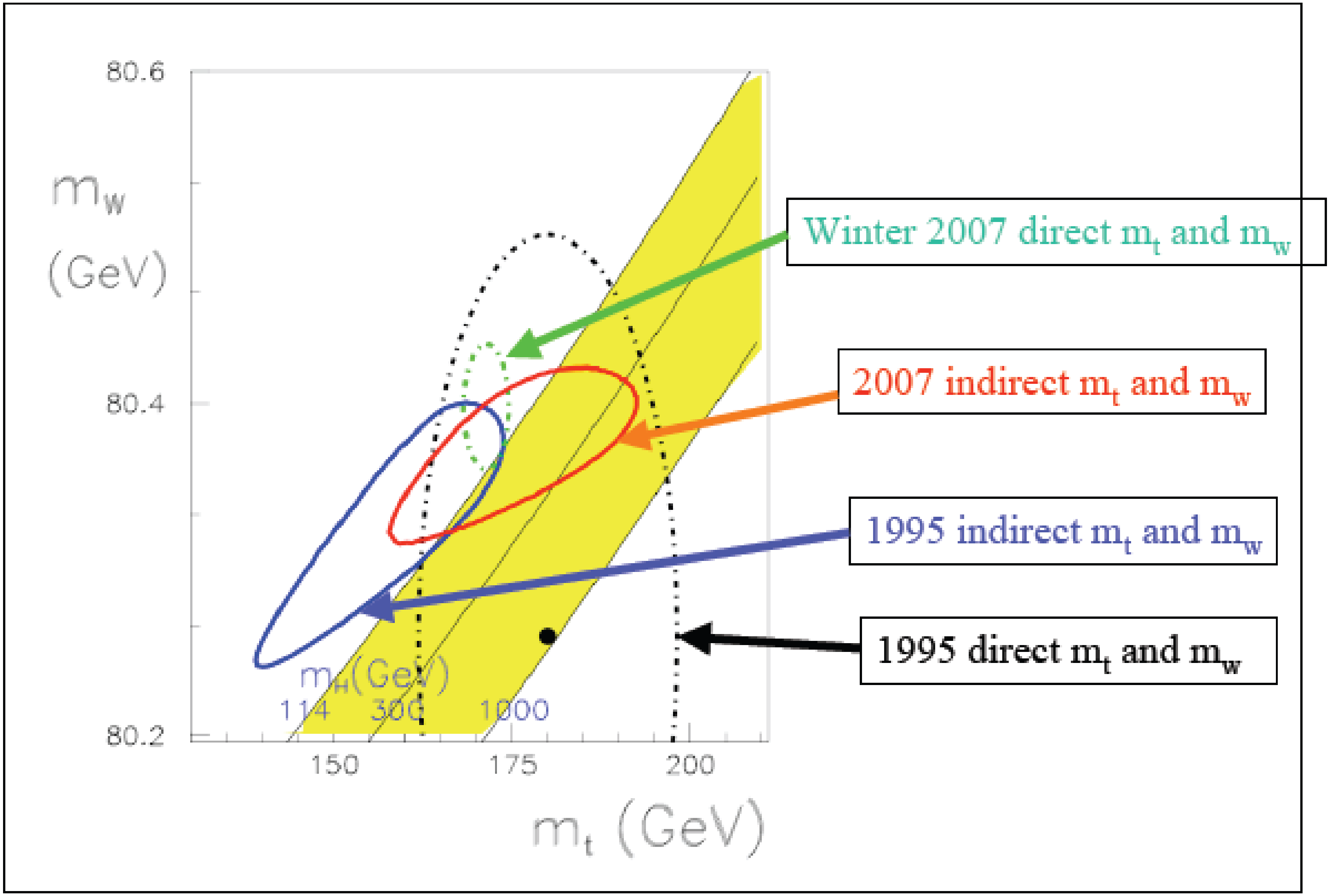


Standard Model M_H



- Summer 2006 SM Higgs fit: (LEP EWWG)
  - $M_H = 85^{+39}_{-28}$ GeV
  - $M_H < 166$ GeV (95% CL)
  - $M_H < 199$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new CDF W Mass)
  - $M_H = 80^{+36}_{-26}$ GeV (M. Grünewald, private communication)
  - $M_H < 153$ GeV (95% CL)
  - $M_H < 189$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new Tevatron top mass)
  - $M_H = 76^{+33}_{-24}$ GeV
  - $M_H < 144$ GeV (95% CL)
  - $M_H < 182$ GeV (95% CL) Including LEPII direct exclusion

Progress since 1995



Winter 2007 direct m_t and m_W

2007 indirect m_t and m_W

1995 indirect m_t and m_W

1995 direct m_t and m_W

Top quark Decay $\left(m_t > m_W\right)$

- If the *SU(2)* structure $\begin{pmatrix} t \\ b \end{pmatrix}_L$ of the Standard Model holds,

  then $t \rightarrow bW^+$ always occurs at tree level in any model.

  ⇒ $\mathrm{Br}\left(t \rightarrow bW\right) \sim 1$

- For a Standard Model *t* , the decay width $t \rightarrow bW^+$

$$\Gamma_t \sim 1.6\ \mathrm{GeV}\left(\frac{m_t}{180}\right)^3$$

Lifetime

$$\tau_{\mathrm{decay}} = \frac{1}{\Gamma_t} \sim 4.4\times 10^{-25}\left(\frac{m_t}{180}\right)^3\ \mathrm{sec}$$

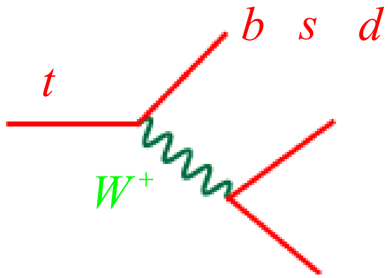
⇒ *t* decays before it feels non-perturbative strong interaction.

$$\left(\frac{1}{\Lambda_{\mathrm{QCD}}} \sim \frac{1}{0.2\ \mathrm{GeV}} \sim 3.3\times 10^{-24}\ \mathrm{sec}\right)$$

Studying Property of Bare quark, e.g., Spin of Top

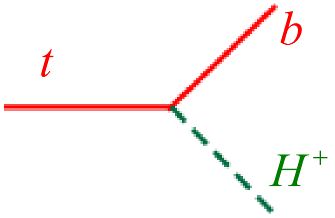
Decay Branching Ratio of Top quark

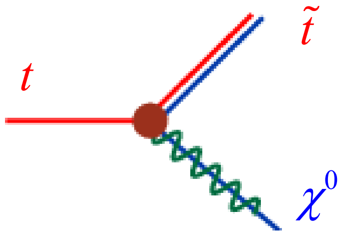
- In the SM:

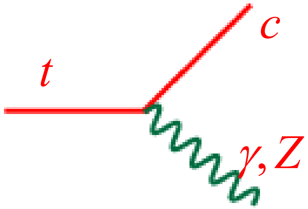


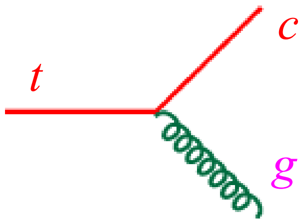
$$\underbrace{\begin{matrix}\nu_e & \nu_\mu \\ e^+ & \mu^+\end{matrix}}_{\left(\begin{matrix}\text{most useful}\\ \text{leptonic mode}\\ \text{Br} = \frac{2}{9}\end{matrix}\right)} \qquad \begin{matrix}\nu_\tau \\ \tau^+\end{matrix} \qquad \underbrace{\begin{matrix}u & u & u & c & c & c \\ d & d & d & s & s & s\end{matrix}}_{\left(\begin{matrix}\text{jj mode}\\ \text{Br} = \frac{2}{3}\end{matrix}\right)}$$

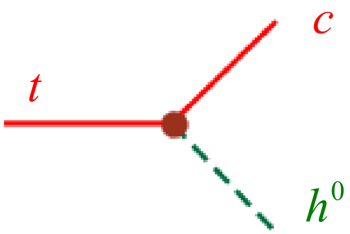
- New Physics:











Measuring Br($t \rightarrow bW$)

At tree level:

$$\frac{\mathrm{BR}(t \rightarrow Wb)}{\mathrm{BR}(t \rightarrow Wq)} = \frac{\left|V_{tb}\right|^2}{\left|V_{td}\right|^2 + \left|V_{ts}\right|^2 + \left|V_{tb}\right|^2}$$

$$V_{tb} >> V_{ts}, V_{td}$$

It does not offer a chance to measure the *magnitude* of the *W*-*t*-*b* coupling

Also,

the total decay width of top (Γ_t) cannot be accurately measured from the *bjj* invariant mass distribution.

What if … ?

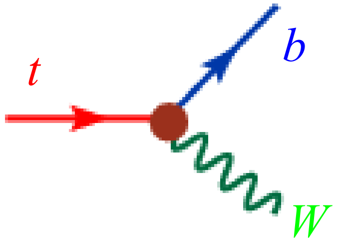
It is however possible that new physics

might not change the $\mathrm{Br}(t \to bW)$,

$\Big($ e.g. no additional new light fields with mass less than m_t $\Big)$

but will strongly modify the width of $\Gamma(t \to bW)$,

due to the interaction



is strongly modified.

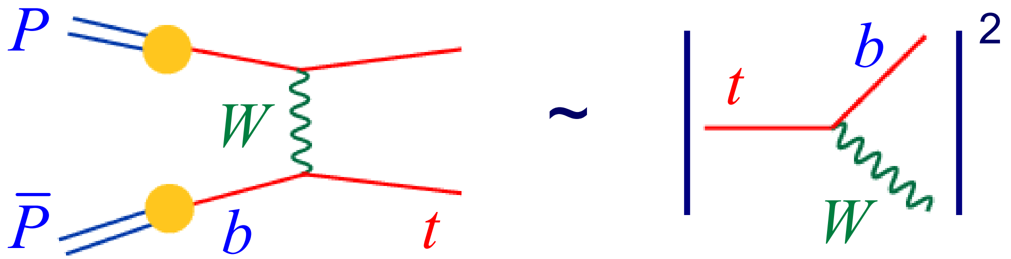
Hence, the lifetime of top quark is different from SM's prediction.

⇨ Need to study the interaction of $t - b - W$.

$P\bar{P} \to t\,X$ and $P\bar{P} \to \bar{t}\,X$

(single top production)

Since



⇒ Measuring σ_t

assume SM → CKM element V_{tb}

in general → $\Gamma\left(t \to bW\right)$

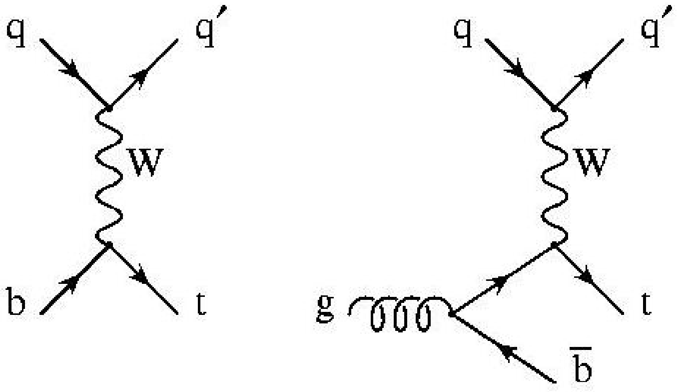
Combine with $\mathrm{Br}\left(t \to bW\right)$

⇒ $$\Gamma_{\text{tot}} = \frac{\Gamma\left(t \to bW\right)}{\mathrm{Br}\left(t \to bW\right)}$$ ⇒ Lifetime of Top

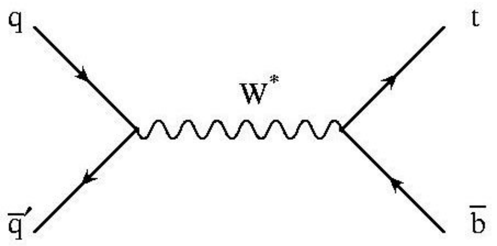
$$\tau_{\text{top}} = \frac{1}{\Gamma_{\text{tot}}}$$

Single-top Productions

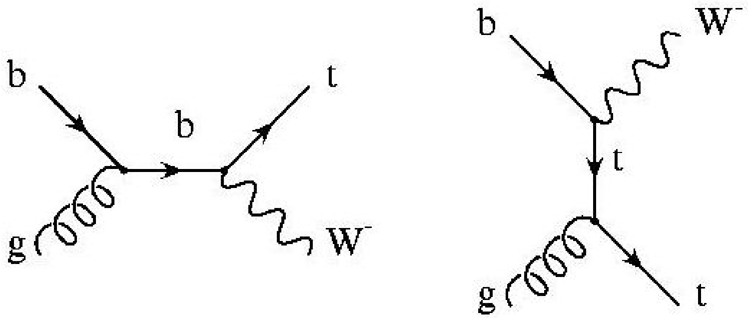
- t-channel



- s-channel



- W t



New Physics Ideas

(related to single-top production)

- New Resonances:

$$W', H^+, \pi^+, \ldots$$

- FCNC:

$$tcZ, tuZ, tcg, tc\gamma, \ldots$$

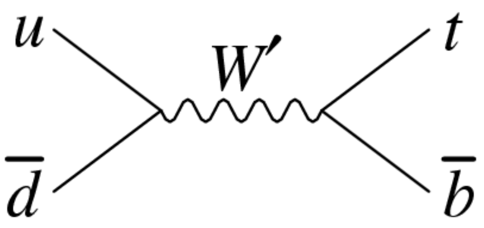
- FCC:

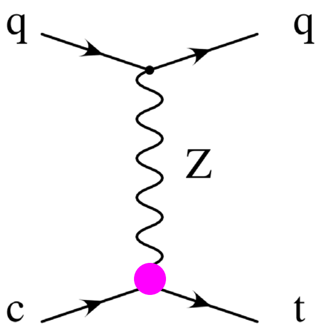
$$tsW^+, tdW^+, cbH^+, \ldots$$

s- Versus *t*-channels

- s-channel Mode
  - Smaller rate
  - Extra b quark final state
  - $\sigma_s \alpha |V_{tb}|^2$ in SM
- Sensitive to resonances
  - Possibility of on-shell production.
  - Need final state b tag to discriminate from background: no FCNCs.

- t-channel Mode
  - Dominant rate
  - Forward jet in final state
  - $\sigma_t \alpha |V_{tb}|^2$ in SM
- Sensitive to FCNCs
  - New production modes.
  - t-channel exchange of heavy states always suppressed.





All Together

- The **s-channel** mode is sensitive to charged **resonances**.
- The **t-channel** mode is more sensitive to **FCNCs** and new interactions.
- The **t W** mode is a more direct measure of top's coupling to W and a down-type quark (down, strange, bottom).

➡ From a theoretical point of view,

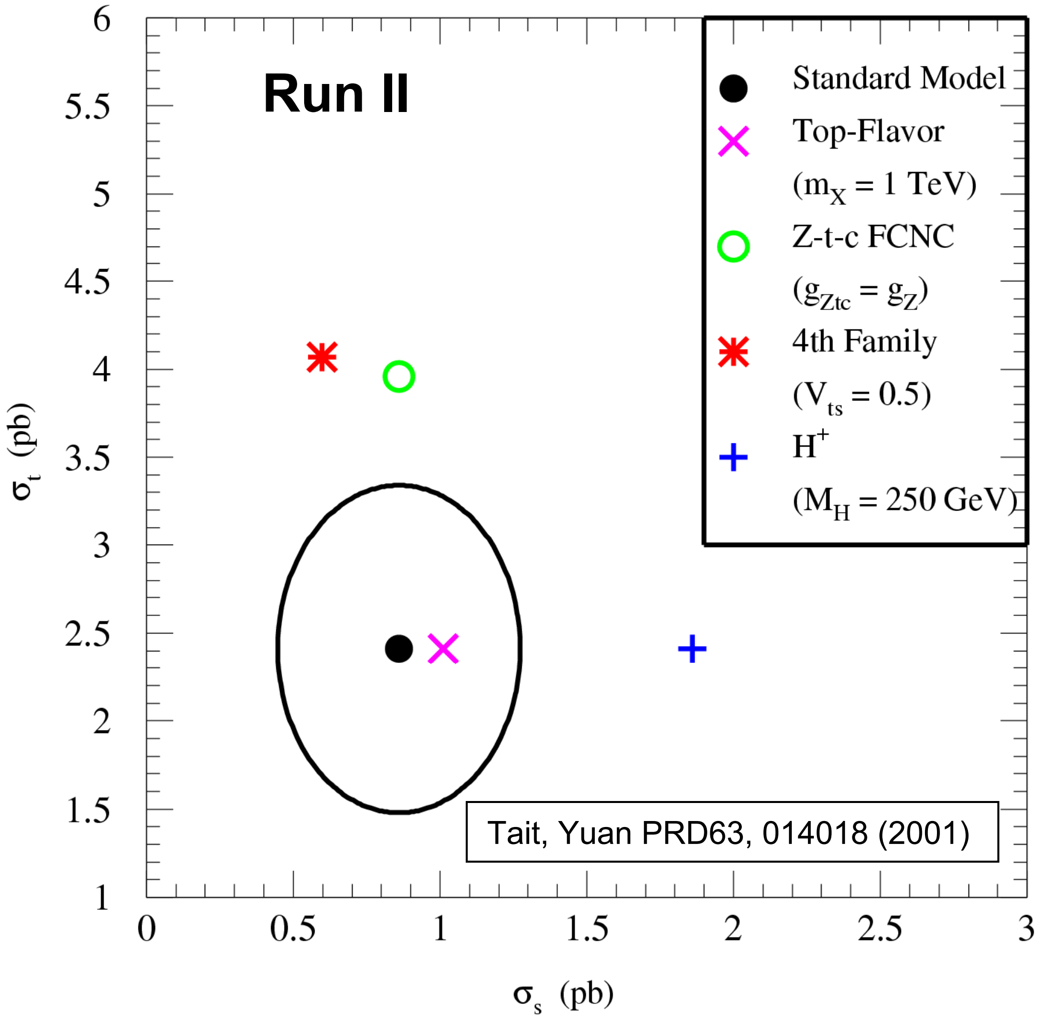
they are sensitive to different New Physics.

From an experimental point of view,

they have different signatures and

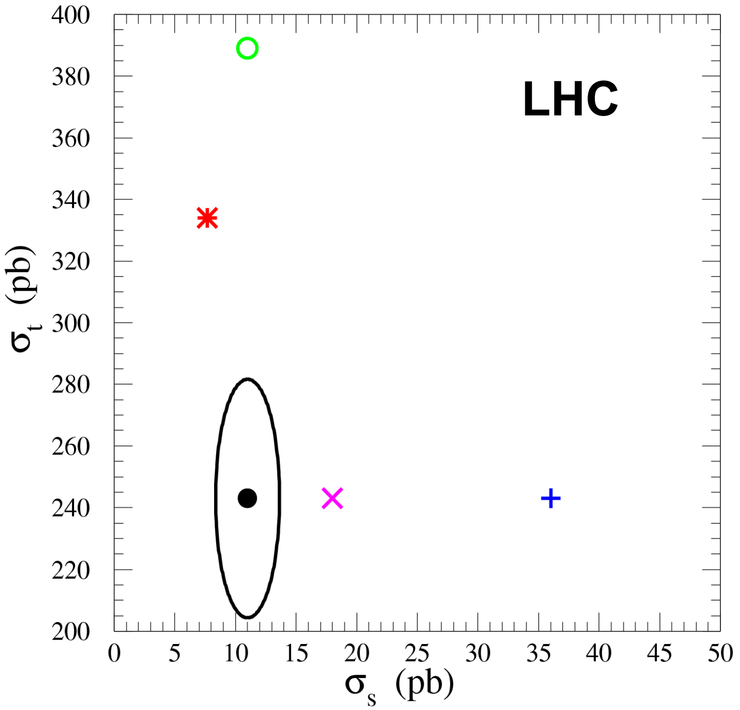
different systematic errors.

σ_s-σ_t Plane



Tait, Yuan PRD63, 014018 (2001)

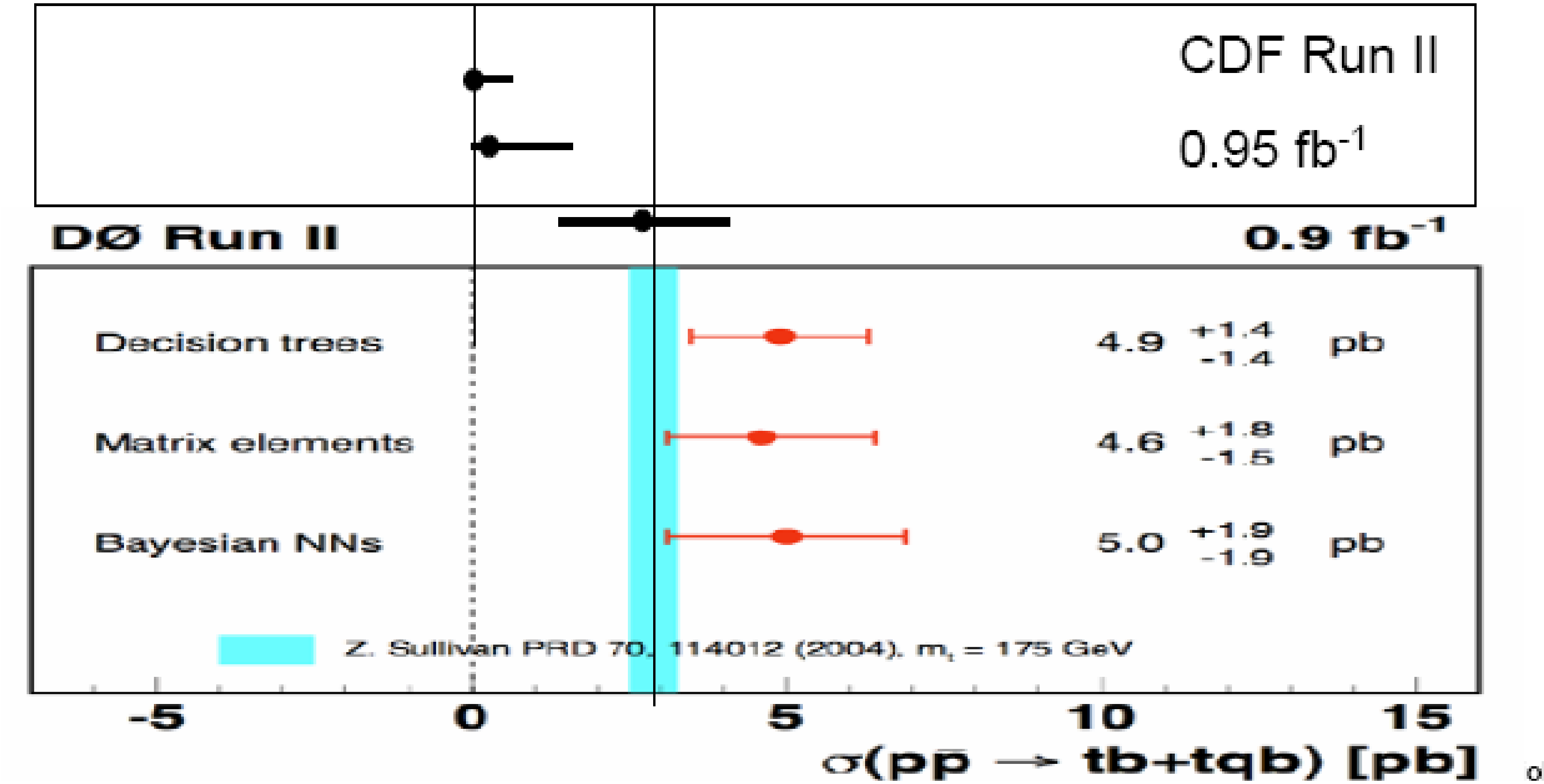
Theory + statistical (2/100 fb^{-1})
3σ deviation curves



Recent Results of CDF and D0

- For completeness, D0 latest
  - Expected sensitivities:
    - 1.3, 1.8, 2.1σ
  - Observe fluctuation high:
    - 2.4, 2.9, 3.4 σ

- CDF
  - Expected sensitivities:
    - 2.0, 2.5, 2.6σ
  - Observe fluctuation low:
    - 0, 2.3, 0 σ



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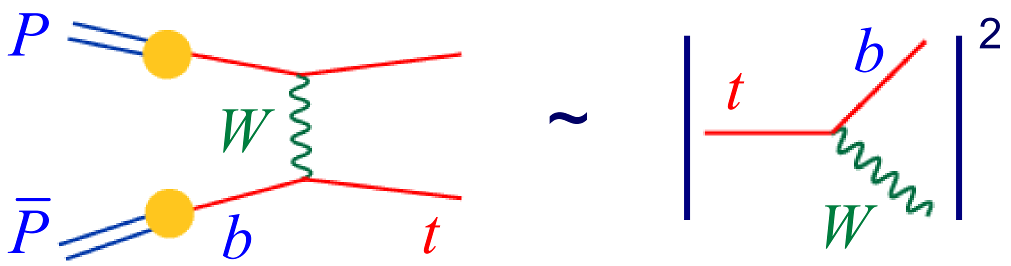
March 9, 2009

- Single-top quark events were discovered at the FNAL Tevatron Run-2.
- The first direct measurement of *t-b-W* coupling
- Testing the weak interaction of top quark

$P\bar{P} \to t\, X$ and $P\bar{P} \to \bar{t}\, X$

(single top production)

Since



The asymmetry in the production rate

$$A_t^{\mathrm{CPX}} = \frac{\sigma(p\bar{p} \to t) - \sigma(p\bar{p} \to \bar{t})}{\sigma(p\bar{p} \to t) + \sigma(p\bar{p} \to \bar{t})}$$

can be used to measure CP-violation.

$$\mathrm{C}: \; P \leftrightarrow \bar{P}$$
$$\mathrm{P}: \; \vec{x} \leftrightarrow -\vec{x}$$

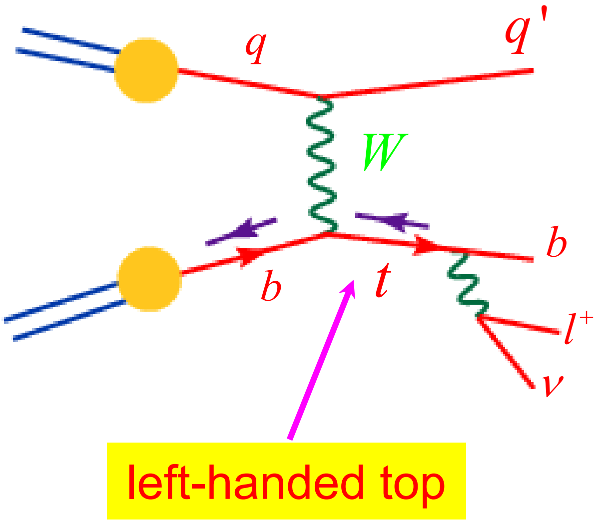
This observable is unique for $p\bar{p}$ collider.
(Tevatron)

For 2 fb^{-1}, $\delta A_t^{\mathrm{CPX}} \sim 20\%$

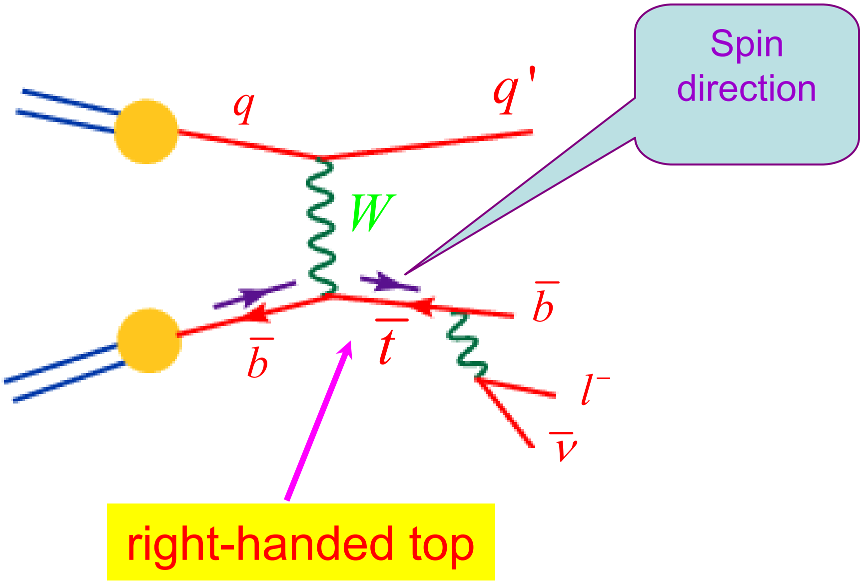
A SM t ($\bar{t}$) is purely

left-handed (right-handed) polarized

in the single-top process.



left-handed top



Spin direction

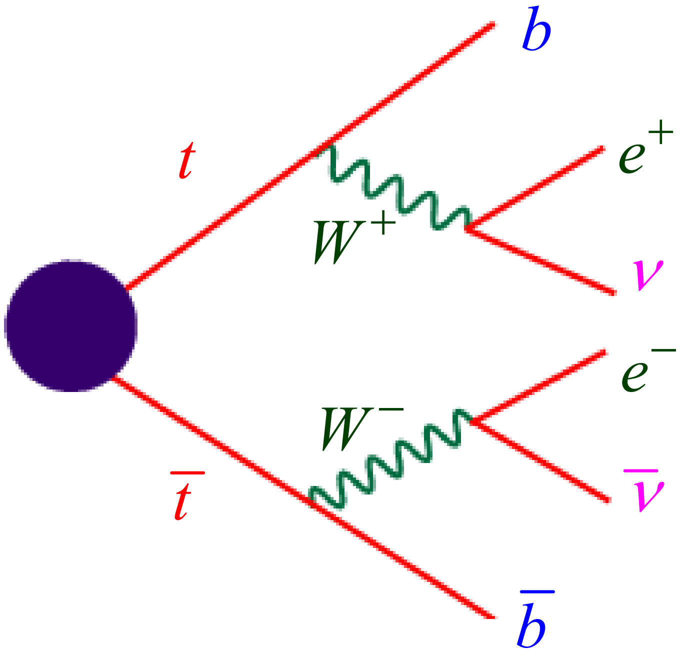
right-handed top

Measuring both

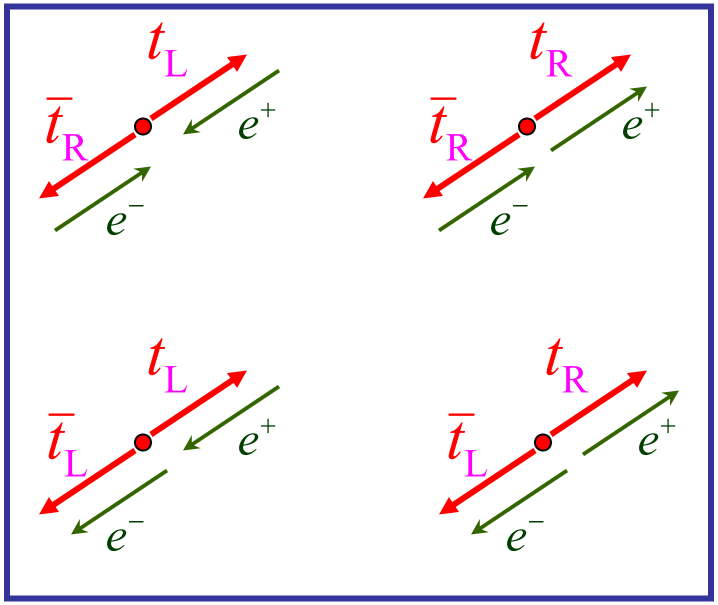
$$\left\langle \vec{\sigma}_t \bullet \vec{p}_b \times \vec{p}_{l^+} \right\rangle \text{ and } \left\langle \vec{\sigma}_{\bar{t}} \bullet \vec{p}_{\bar{b}} \times \vec{p}_{l^-} \right\rangle$$

⇨ Probe CP-violation at the LHC

Spin correlation in $t\bar{t}$ events



In the $t\bar{t}$ center-of-mass frame



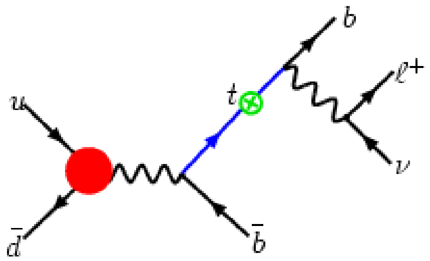
If $\sigma(t_L\bar{t}_L) \neq \sigma(t_R\bar{t}_R)$, then CP is violated.

s- and *t*-channel single top production and decay at NLO QCD

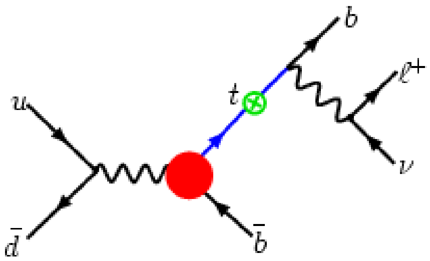
Phenomenology at Run-2 of Tevatron

Categorizing Single-top processes at NLO QCD

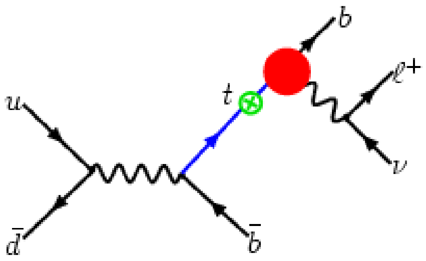
- We separate the single-top processes into smaller gauge invariant sets to organize our calculations.



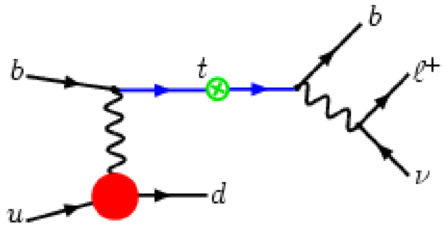
INIT



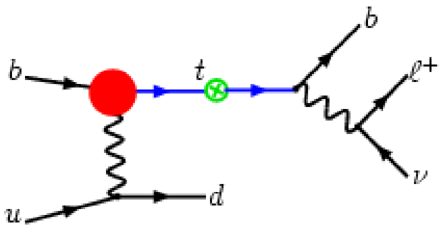
FINAL



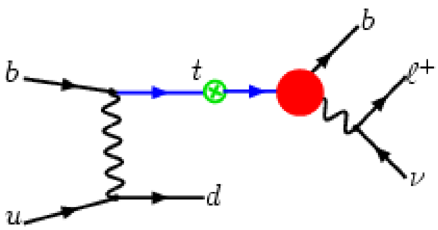
SDEC



LIGHT



HEAVY



TDEC

● includes soft + virtual and real emission corrections.

- Keeping track on each individual contribution is useful to compare event generators with exact NLO predictions.

Acceptance study

	s-channel				*t*-channel			
	σ [fb]		Accept. (%)		σ [fb]		Accept. (%)	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO
(a)	22.7	32.3	73	64	65.6	64.0	66	61
(b)	19.0	21.7	61	46	56.8	48.1	57	46
(c)	14.7	21.4	47	45	31.1	34.0	31	32

Kinematics cuts:

$p_T^\ell \geq 15$ GeV

$|\eta_\ell| \leq \eta_\ell^{max}$

$\not{E}_T \geq 15$ GeV,

$E_T^j \geq 15$ GeV

$|\eta_j| \leq \eta_j^{max}$

$\Delta R_{\ell j} \geq R_{\rm cut}$

$\Delta R_{jj} \geq R_{\rm cut}$

(a) loose cuts: $\eta_\ell^{\rm max} = 2.5, \eta_j^{\rm max} = 3.0,$ and $R_{cut} = 0.5$

(b) loose cuts: $\eta_\ell^{\rm max} = 2.5, \eta_j^{\rm max} = 3.0,$ and $R_{cut} = 1.0$

(c) tight cuts: $\eta_\ell^{\rm max} = 1.0, \eta_j^{\rm max} = 2.0,$ and $R_{cut} = 0.5$

The acceptances are sensitive to kinematics cuts:

- Large $R_{\rm cut}$ reduces acceptances significantly because of $\Delta R_{\ell j}$.
- With tight cuts, LO and NLO acceptances are almost same.
- With loose cuts, LO and NLO acceptances are quite different.

➡ $NLO \neq LO \times K_{\rm FAC}$

➡ Maximizing the acceptance.

Top quark reconstruction

- To study the kinematics and spin correlations, top quark needs to be reconstructed.

$$t = W^+ + b$$

Tasks: (1) W boson reconstruction (determining p_z^ν)

$$M_W^2 = (p_e + p_\nu)^2 \longrightarrow p_{z1}^\nu \ , \ p_{z2}^\nu$$

(2) Identifying b-jet (In the case of two b-jets in the final state, b -jet needs to be separated from $\bar{b}$ -jet.)

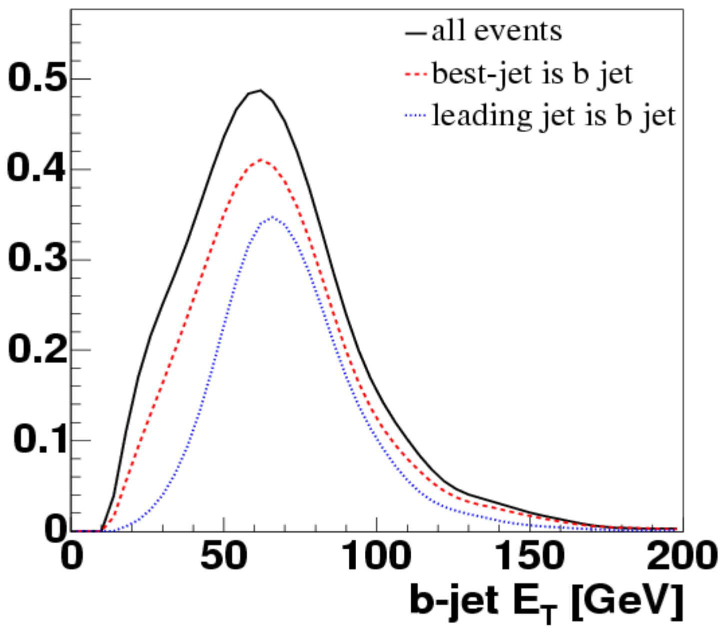
- Two algorithms (determining p_z^ν based on the scenario of b identification)

	best-jet algorithm	leading b-tagged jet algorithm
b	using top mass constrain to pick up correct b-jet from top quark decay	using leading b-tagged jet to pick up correct b-jet from top quark decay
p_z^ν	smaller $\lvert p_z^\nu \rvert$	using top mass constrain to pick up correct p_z^ν
Eff.	~70%	LO: 92% NLO: 84%

b identification efficiency:

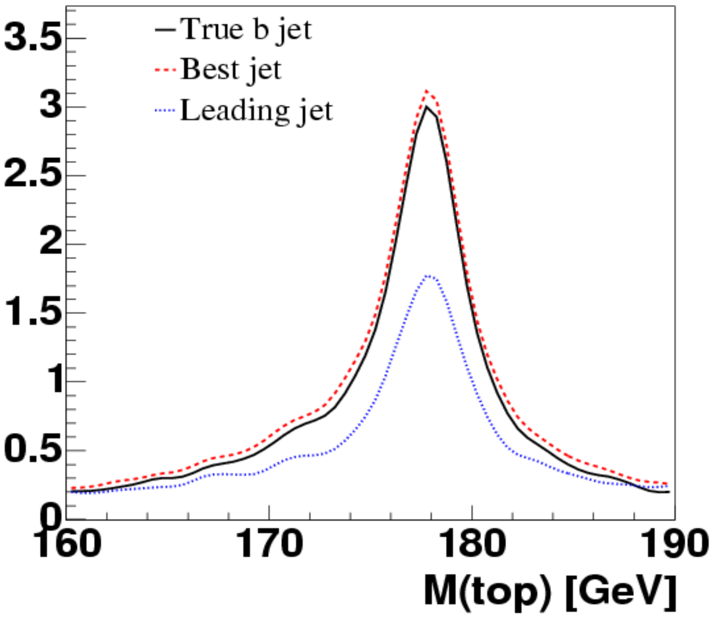
s-channel (two b-jets in final state)

- Fraction of picking up correct b
- Reconstructed top quark mass



Best-jet algorithm: 80%

Leading-jet algorithm: 55%

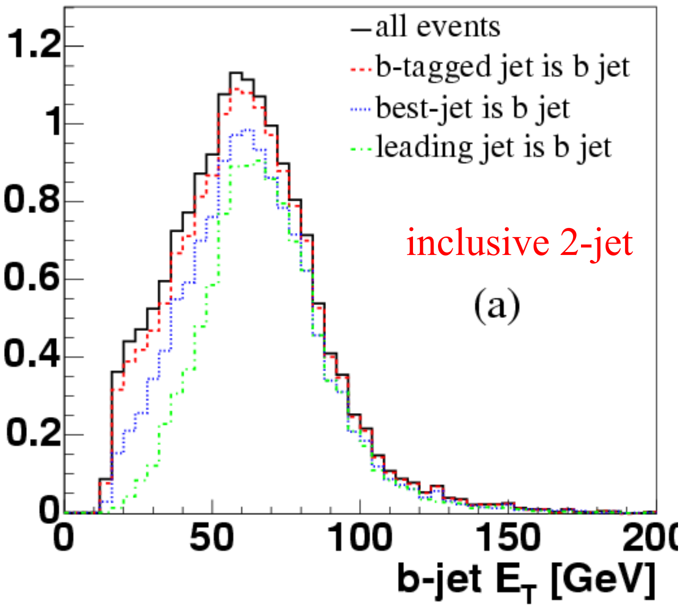


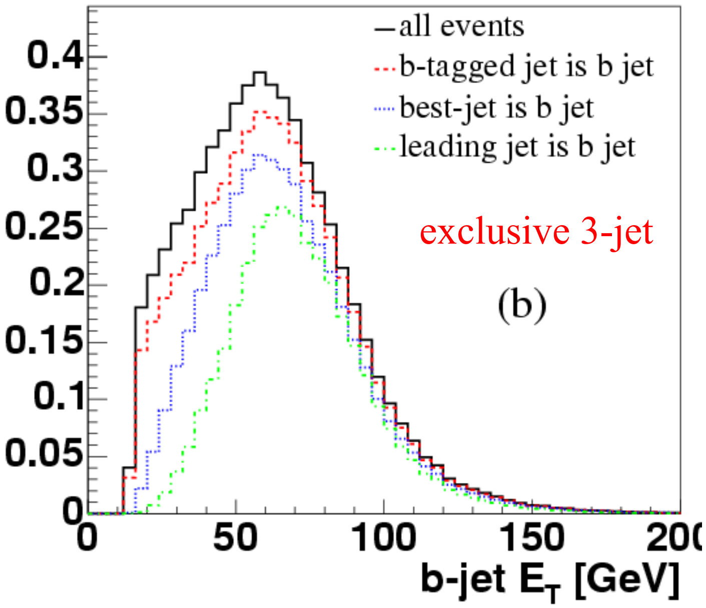
More evident

The best-jet algorithm shows a higher efficiency than the leading-jet algorithm.

b identification efficiency:

t-channel (one or two b-jets in final state)





- Leading *b*-tagged jet corresponds to the *b* quark from top decay most of the time

Leading b-tagged jet

inclusive 2-jet event: 95%

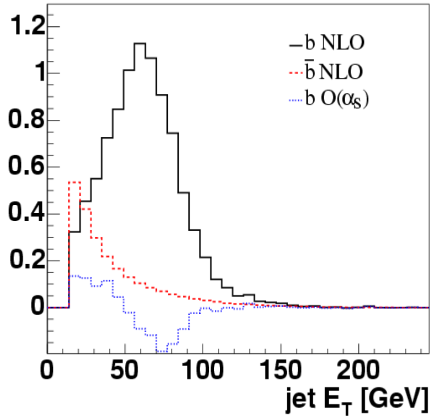
exclusive 3-jet event: 90%

Best-jet

inclusive 2-jet event: 80%

exclusive 3-jet event: 72%

works well due to the kinematical differences between b and $\bar{b}$



Top quark polarization (*t*-channel) : spin bases

- Helicity basis:

  tq(j)-frame

  z: along the top quark direction of motion in the c.m. frame of system

  tq-frame

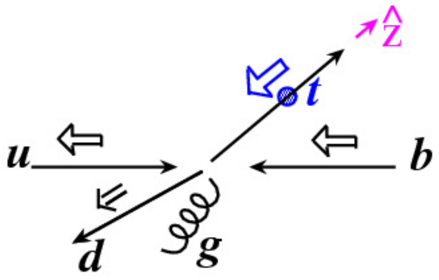
  z: along the top quark direction of motion in the c.m. frame of top quark and the spectator

- Beamline basis:

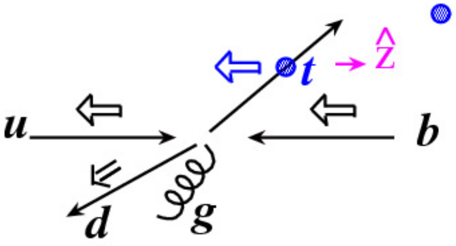
  z: along the incoming proton direction

- Spectator basis:

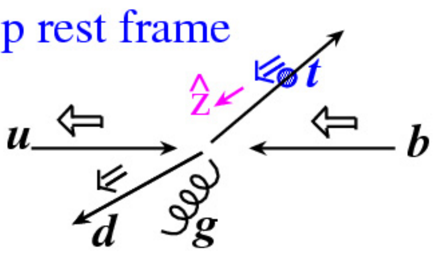
  z: along the spectator direction of motion



Helicity basis



Beamline basis



Spectator basis

Degree and fraction of top quark polarization

- Among top quark decay products, charged lepton is maximally correlated with top quark spin.

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(t \to b e \ell \nu)}{\mathrm{d}\cos\theta} = \frac{1}{2}(1 + \mathcal{D}\cos\theta)$$

degree of polarization: $\mathcal{D} = \dfrac{N_- - N_+}{N_- + N_+}$

fraction of polarization: $\mathcal{F}_\mp = \dfrac{1 \pm \mathcal{D}}{2}$

		$\mathcal{D}$		$\mathcal{F}$	
		LO	NLO	LO	NLO
Helicity $tq(j)$	Parton level	0.96	0.74	0.98	0.87
	Recon. event	0.84	0.73	0.92	0.86
Helicity tq	Parton level	0.96	0.94	0.98	0.97
	Recon. event	0.84	0.75	0.92	0.88
Spectator	Parton level	-0.96	-0.94	0.98	0.98
	Recon. event	-0.85	-0.77	0.93	0.89
Beamline	Parton level	-0.34	-0.38	0.67	0.69
	Recon. event	-0.30	-0.32	0.65	0.66

At the parton level,
tq-frame have larger d.o.p.
than tq(j)-frame.

After event reconstruction,
tq-frame and tq(j)-frame
have almost the same d.o.p.

Helicity basis (tq-frame)
give almost the same d.o.p.
as the spectator basis.

☞ Beamline basis gives the worst degree of polarization of top quark.

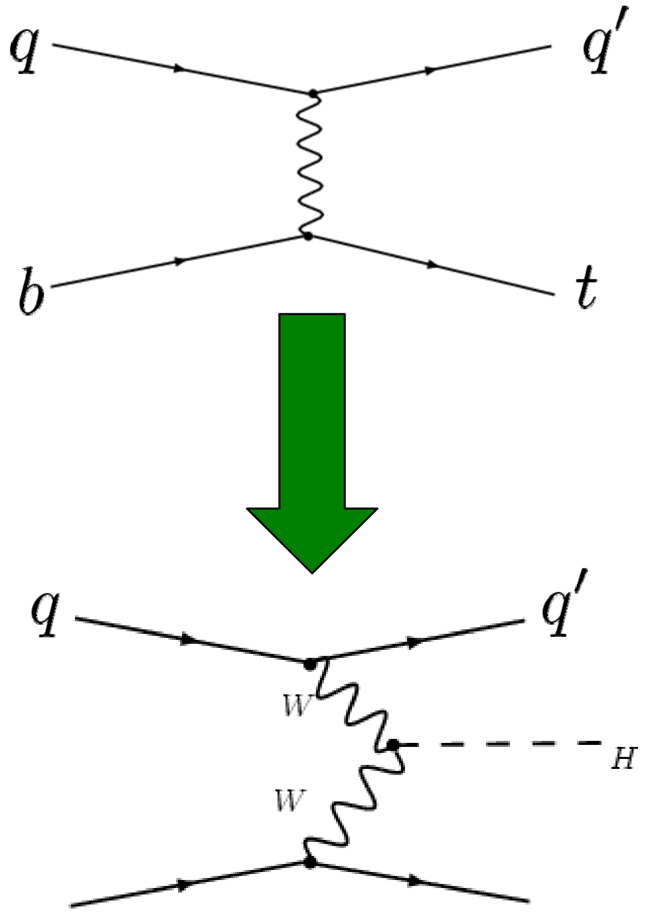
☞ High order QCD corrections blur the spin correlation effect.

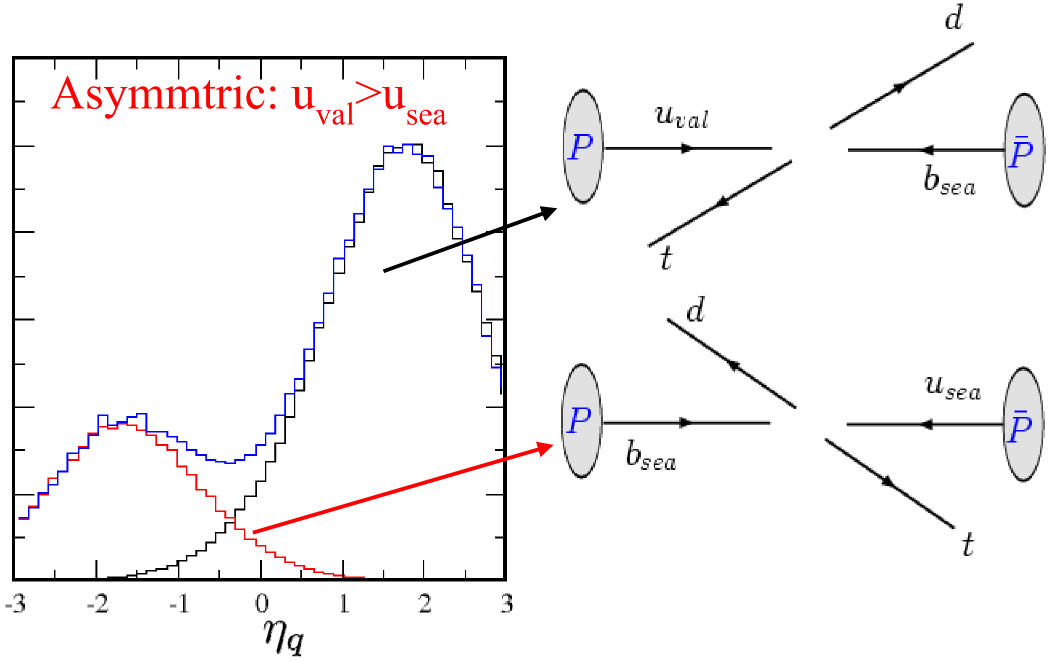
Connection to Higgs boson search at LHC: light forward jet

Asymmetric rapidity distribution of the spectator jet

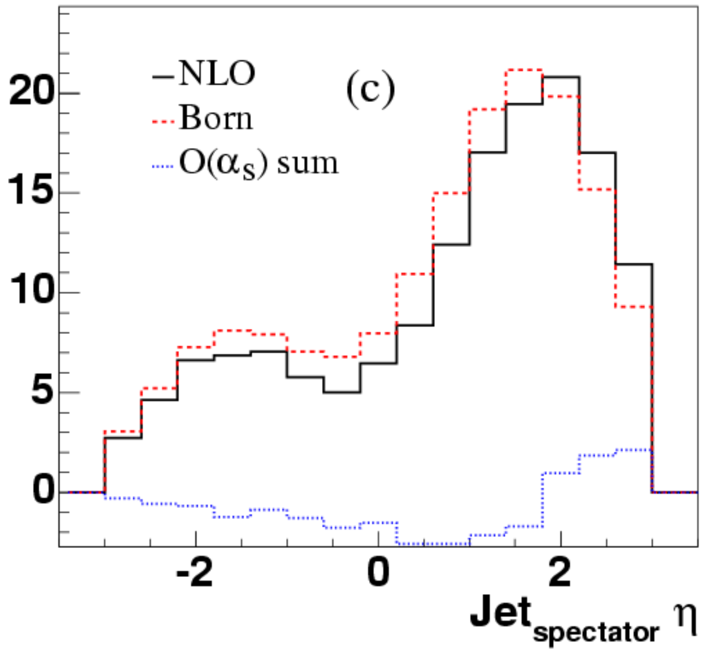
(Unique signature at Tevatron)

⟹ Its kinematics needs to be well studied.





Rapidity distribution of the spectator jet at NLO

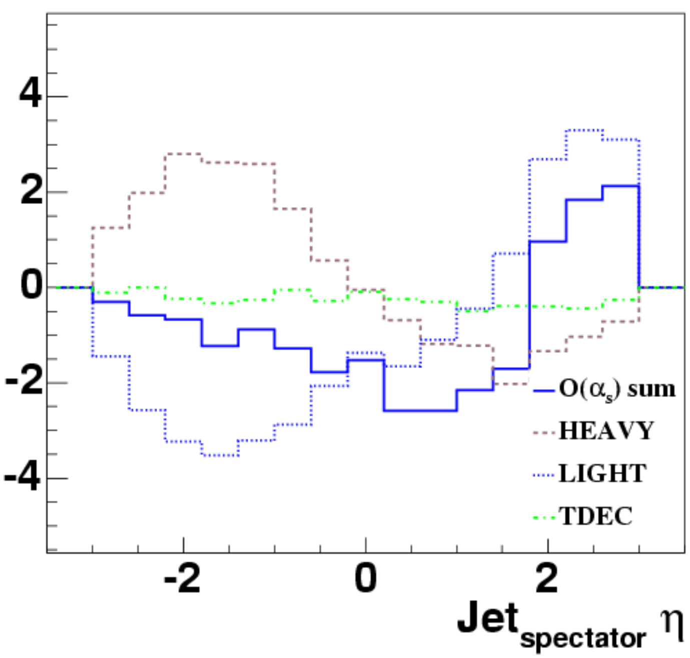


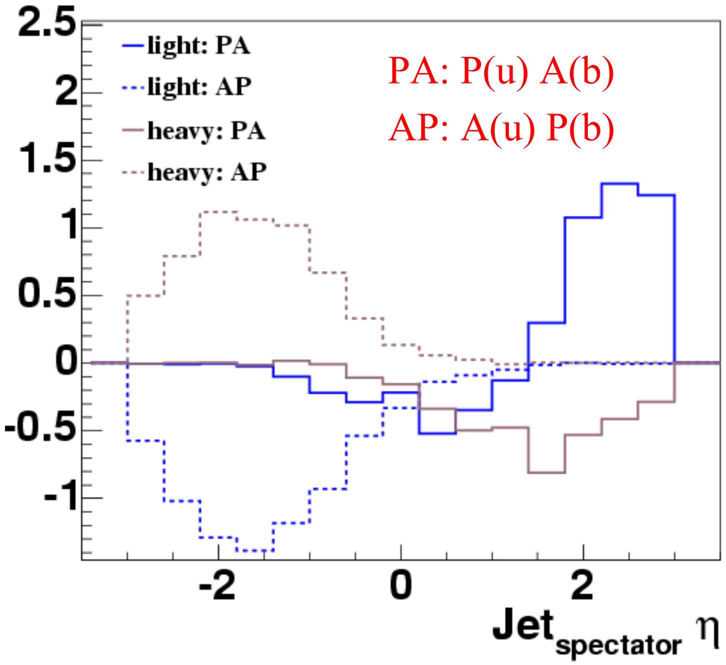
- The $O(\alpha_S)$ corrections shift the spectator jet to more forward direction due to additional gluon radiation.

➡ imposing harder cut on spectator jet's rapidity to suppress backgrounds

- The shift is small because the $O(\alpha_S)$ corrections are small.

Why so?





- LIGHT and HEAVY corrections have almost opposite behavior.
- LIGHT shifts the spectator jet to the forward direction while HEAVY shifts it to the central region.
- TDEC contribution does NOT change the distribution.

General Analysis of single-top production and *W*-helicity in top decay

❶ General Formulation of t-b-W couplings

❷ What have we known from indirect measurements?

❸ How to perform direct measurements at Tevatron & LHC?

❹ Distinguish different models of EWSB

General Formulation of t-b-W couplings

(not necessary to be on-shell)

- New physics effects can be summarized in effective Lagrangian:

$$\begin{aligned}\mathcal{L} = & \frac{g}{\sqrt{2}} W_\mu^- \bar{b}\gamma^\mu (f_1^L P_L + f_1^R P_R) t \\ & - \frac{g}{\sqrt{2} m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t \\ & + \frac{g}{\sqrt{2} m_W} \bar{b} (f_3^L P_L + f_3^R P_R) \partial_\mu t W^{-\mu} \\ & + \frac{g}{\sqrt{2} m_W} \bar{b} (f_4^L P_L + f_4^R P_R) t \partial_\mu W^{-\mu} + h.c.\end{aligned}$$

$\Longrightarrow$ 8 different form factors

General Formulation of *t-b-W* couplings

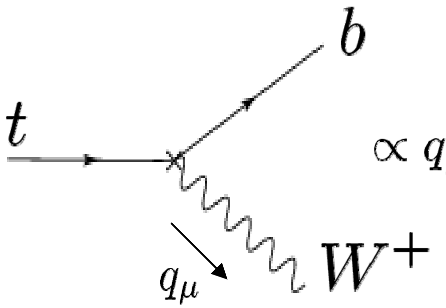
(for on-shell t and b)

- Gordon Identity ⟹ reduce from 8 to 6 form factors

$$\mathcal{L} \supset \gamma_\mu, \sigma_{\mu\nu} q^\nu, q_\mu$$

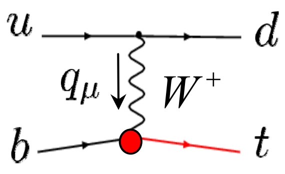
q_μ term: not contribute for either on-shell or off-shell W boson.

☞ on-shell W boson in top decay

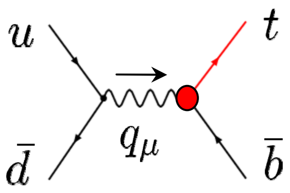


$\propto q_\mu \epsilon^\mu = 0$

☞ off-shell W boson in single top production



$q_\mu \propto (p_u - p_d)_\mu \sim 0$



$q_\mu \propto (p_u + p_d)_\mu \sim 0$

⟹ reduce from 6 to 4 form factors

General Formulation of *t-b-W* couplings

- The general t-b-W effective Lagrangian (dim-4 and dim-5 couplings)

$$\mathcal{L}_{tbW} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu (f_1^L P_L + f_1^R P_R) t$$

$$- \frac{g}{\sqrt{2} m_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

☞ In the SM,

$$f_1^L = 1,\ f_1^R = f_2^L = f_2^R = 0.$$

☞ The couplings may be sensitive to new physics.

Propose a most general analysis

Choose independent experimental observables
to study the constraints of effective *w-t-b* couplings.

- ☞ Four independent variables in the effective Lagrangian

$$\left.\begin{array}{l} f_1^L \\ f_1^R \\ f_2^L \\ f_2^R \end{array}\right\} \begin{array}{l}\text{four}\\ \text{form}\\ \text{factors}\end{array}$$

- ☞ Four experimental observables

$$\left.\begin{array}{l} f_0 \\ f_- \end{array}\right\} \text{top decay} \qquad (f_0 + f_- + f_+ = 1)$$

$$\left.\begin{array}{l} \sigma_t \\ \sigma_s \end{array}\right\} \text{Single top production}$$

How to perform direct measurements at Tevatron and LHC?

- Measurement of W Helicity fractions in top decay

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = f_0 \frac{3}{4}\sin^2\theta + f_- \frac{3}{8}(1-\cos\theta)^2 + f_+ \frac{3}{8}(1+\cos\theta)^2$$

- Theoretical prediction:

LO:

$$f_0 = \frac{\Gamma_0}{\Gamma_t} = \frac{a_t^2}{a_t^2+2} = 0.71$$

$$f_- = \frac{\Gamma_-}{\Gamma_t} = \frac{2}{a_t^2+2} = 0.29$$

$$f_+ = \frac{\Gamma_+}{\Gamma_t} = 0$$

$$a_t = \frac{m_t}{m_W} = \frac{178.0}{80.4}$$

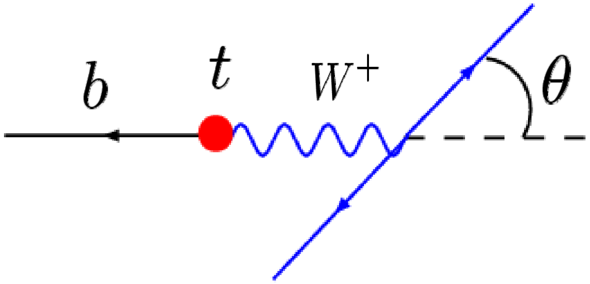
Beyond LO:

$$f_0 = 0.701$$

$$f_- = 0.297$$

$$f_+ = 0.002$$

$$O(\alpha_s^2), EW, m_b, \Gamma_W$$



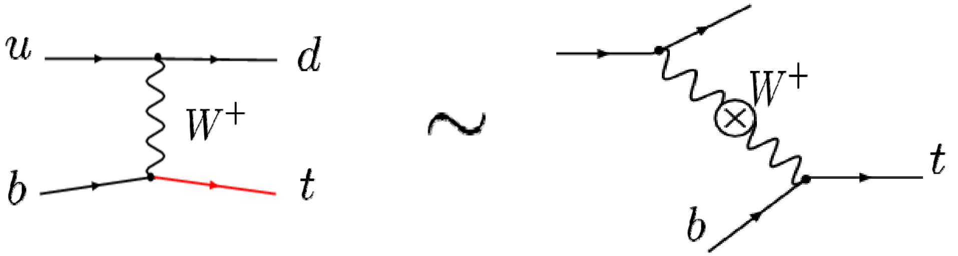
General analysis

How to combine f_0 and f_- (or f_+) measurements with the single top cross section measurements?

- Can σ_t be expressed as

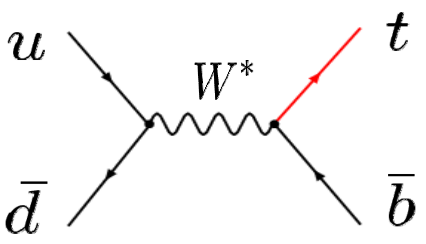
small

$$\sigma_t \sim (\cdots) f_0 + (\cdots) f_- + (\cdots) f_+ + (\cdots)$$

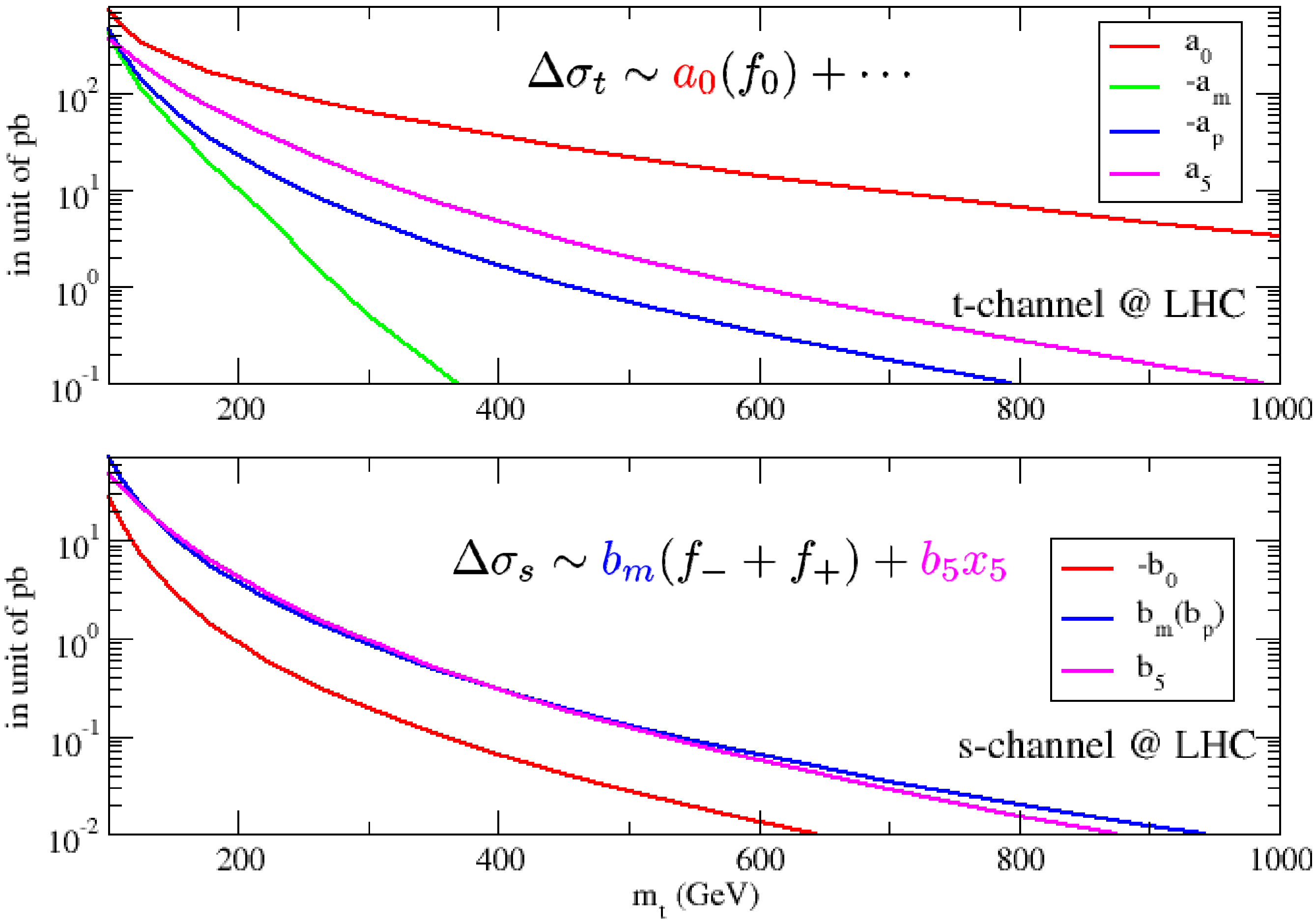


- Can σ_s be expressed as

$$\sigma_s \sim (\cdots) f_0 + (\cdots) f_- + (\cdots) f_+ + (\cdots)$$



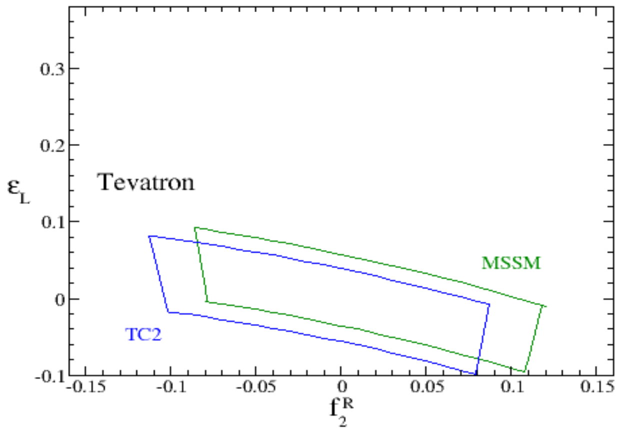
Coefficients v.s. top quark mass (or t' in new physics models)

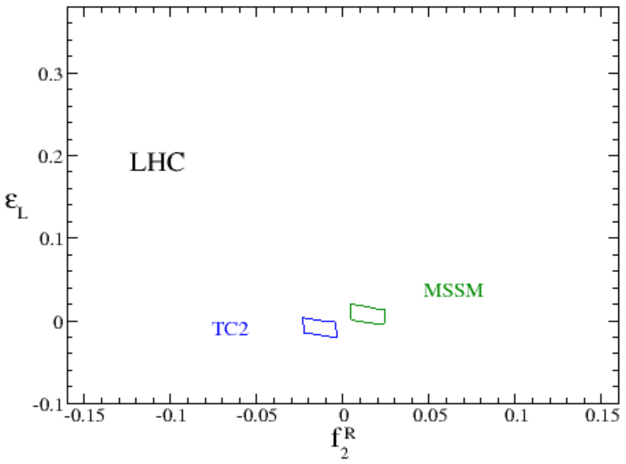


Distinguish different model of EWSB

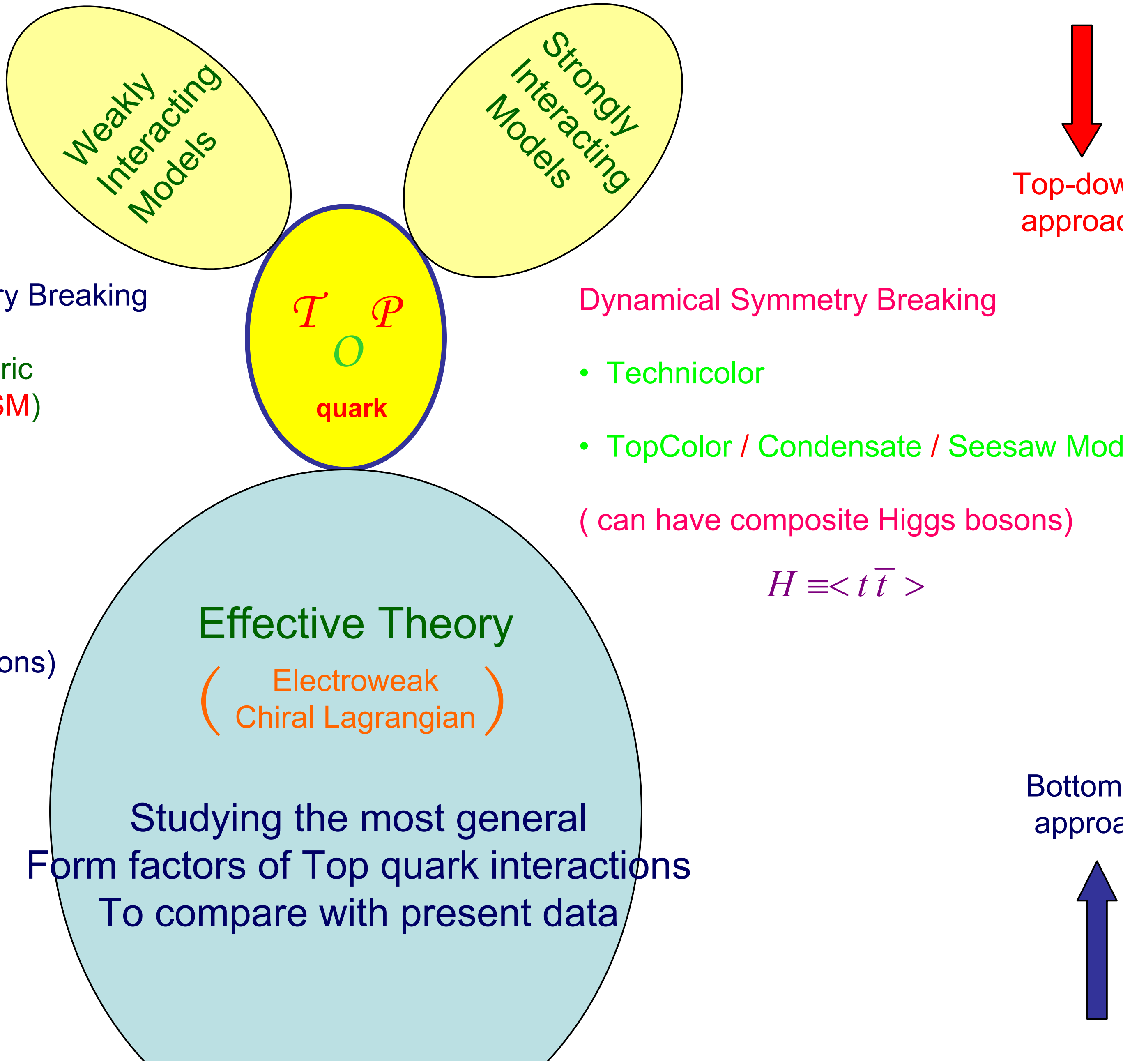
(assume $f_1^R \sim f_2^L \sim 0$ for small b_R contribution)

	MSSM	TC2
ε_L	0.01	-0.01
f_2^R	0.005	-0.005
$\Delta f_0 / f_0^{SM}$	-0.5%	0.5%
$\Delta f_- / f_-^{SM}$	1.2%	-1.2%
Tevatron $\Delta\sigma_t / \sigma_t^{SM}$	2.1%	-2.0%
Tevatron $\Delta\sigma_s / \sigma_s^{SM}$	3.2%	-3.1%
LHC $\Delta\sigma_t / \sigma_t^{SM}$	2.2%	-2.1%
LHC $\Delta\sigma_s / \sigma_s^{SM}$	3.4%	-3.3%
$\Delta\Gamma_t / \Gamma_t^{SM}$	3.5%	-3.4%





Top and Electroweak Symmetry Breaking (in 4-dim)



Weakly Interacting Models

Strongly Interacting Models

T O P

quark

Top-down approach

Spontaneously Symmetry Breaking

- Minimal Supersymmetric Standard Model (MSSM) with Radiative EWSB and soft SUSY-breaking
- Little Higgs Model

(Elementary Higgs bosons)

$h, H, H^{\pm}, A$

Dynamical Symmetry Breaking

- Technicolor
- TopColor / Condensate / Seesaw Models

(can have composite Higgs bosons)

$H \equiv < t\bar{t} >$

Effective Theory

(Electroweak Chiral Lagrangian)

Studying the most general
Form factors of Top quark interactions
To compare with present data

Bottom-up approach

Why New Physics in Top-Higgs System?

SM works perfectly at scale O(100)GeV. But,

How does Electroweak Symmetry Break (EWSB)?
Why are Fermion Masses so different?

Hint: Fermi-Scale ($v = 2^{-\frac{1}{4}} G_F^{-\frac{1}{2}}$) versus M_t and $M_{W,Z}$

$$M_t \approx \frac{v}{\sqrt{2}} \approx M_W + M_Z$$ ⇒ Common origin?

Why? 2 possible solutions:

- DEWSB: TopColor / Condensate / Seesaw Models
- SUSY: MSSM with Radiative EWSB and

  Soft SUSY-breaking [& Horizontal $U(1)_H$]

New features:

Bottom: *t*-partner + Small m_b + Large-Y_b
Charm: Large $c_R - t_R$ flavor-mixing
Stop-Scharm: Large $\tilde{t} - \tilde{c}$ flavor-mixing
$\phi^{\pm}$: ϕ^0-partner and Large $c - b - \phi^{\pm}$ coupling
ϕ^0: Large $c - t - \phi^0$ coupling

⇒ Collider signature!

Soft SUSY Breaking and $\tilde{t}-\tilde{c}$ Mixings

- MSSM Squark Mass-terms and Trilinear A-terms:

$$\tilde{M}^2_{\tilde{u}} = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^{2\dagger}_{LR} & M^2_{RR} \end{pmatrix} \qquad M^2_{LR} = A_u \frac{v\sin\beta}{\sqrt{2}} - M_u \mu \cot\beta$$

Where $A'_u = A\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & x \\ 0 & y & 1 \end{pmatrix}$ in 3 - $\tilde{q}$ families

If *x* = 0, then $\tilde{c}_L$ decouples
y = 0, then $\tilde{c}_R$ decouples

If (*x*,*y*) ~ *O*(1), then
large flavor mixing in $\tilde{t}-\tilde{c}$ sector

- For ($\tilde{c}_L, \tilde{c}_R, \tilde{t}_L, \tilde{t}_R$)

$$M_{\tilde{u}} = \begin{pmatrix} \tilde{m}_0^2 & 0 & 0 & A_x \\ 0 & \tilde{m}_0^2 & A_y & 0 \\ 0 & A_y & \tilde{m}_0^2 & -X_t \\ A_x & 0 & -X_t & \tilde{m}_0^2 \end{pmatrix}$$

$$A_x = x\frac{Av\sin\beta}{\sqrt{2}}$$

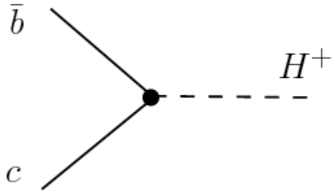
$$A_y = y\frac{Av\sin\beta}{\sqrt{2}}$$

$$X_t = -\frac{Av\sin\beta}{\sqrt{2}} + \mu m_t \cot\beta$$

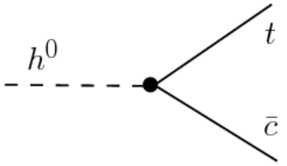
with $m_{\tilde{t}_1} < m_{\tilde{c}_1} < m_{\tilde{c}_2} < m_{\tilde{t}_2}$

Soft SUSY Breaking and $\tilde{t}-\tilde{c}$ Mixings

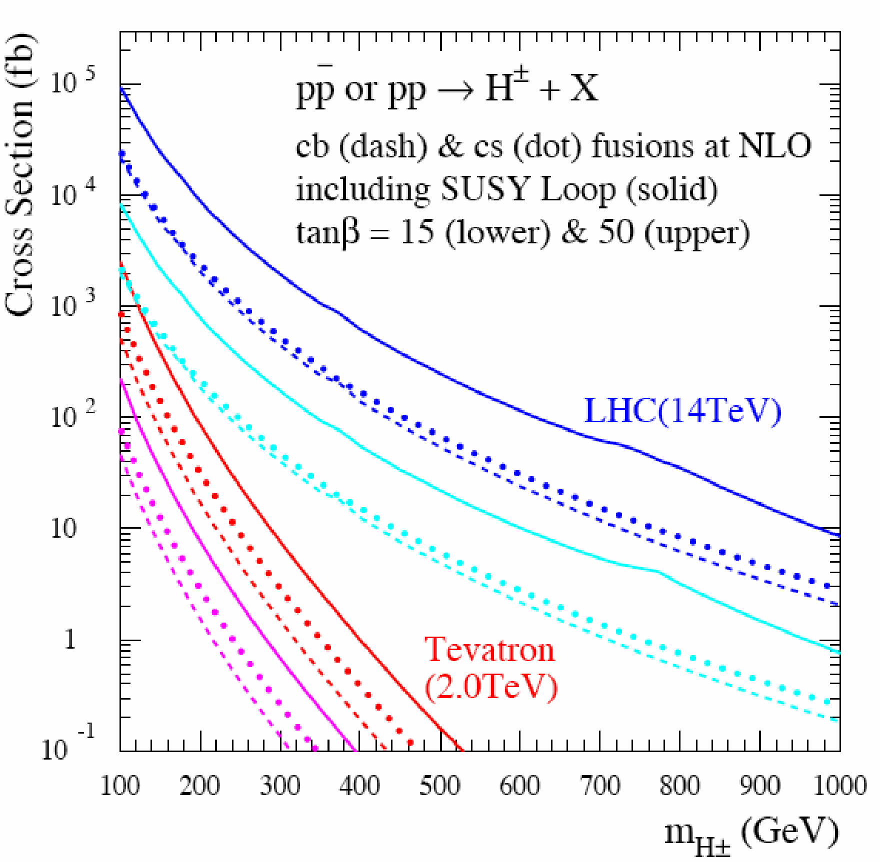
- Large $\tilde{t}-\tilde{c}$ mixing can enhance



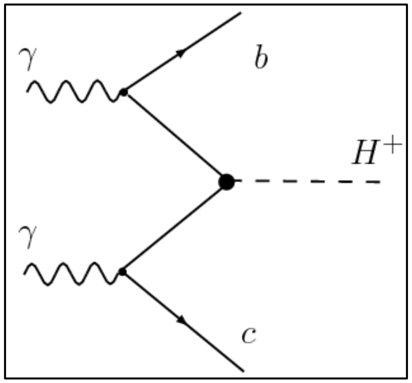
production and



decay via radiative corrections



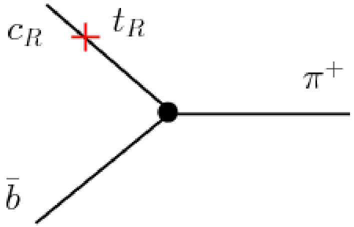
Br($t \to ch^0$) can range from 10^{-5} to 10^{-3}, and is sensitive to $\tilde{t}_1$ mass and squark mixing



can test the chirality of b-c-h^+ coupling

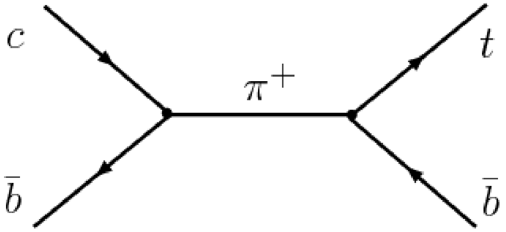
Charged Resonances in TopColor and Topflavor

- In TopColor model,



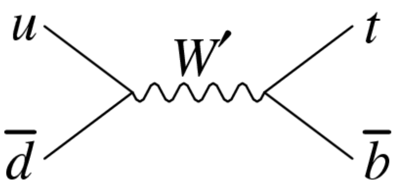
large t_R-c_R mixing enhances production

⇒ $p\overset{(-)}{p} \to \pi^+ \to t\bar{b}$



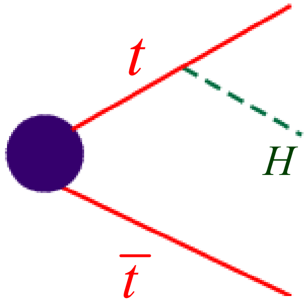
- In Topflavor model, $W' \to t\bar{b}$

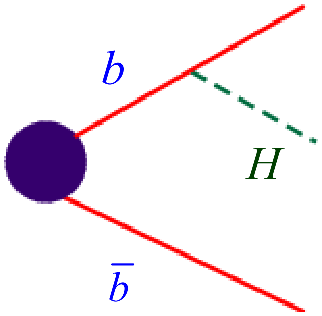
⇒ $p\overset{(-)}{p} \to W' \to t\bar{b}$



Discriminating Models of Electroweak Symmetry Breaking

Testing the interaction of Top, Bottom and Higgs Boson





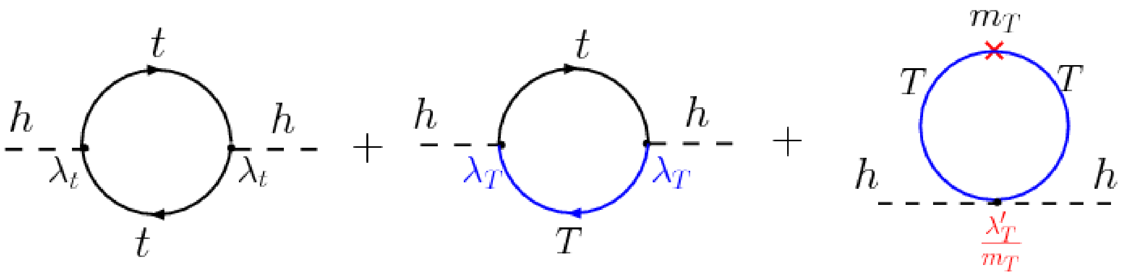
SM: $y_t^{\mathrm{SM}} = \frac{m_t}{\sqrt{2}v} = 1$ $y_b^{\mathrm{SM}} = \frac{m_b}{\sqrt{2}v} = \frac{1}{40}$

MSSM: $(\tan\beta = 40)$ $y_t = y_t^{\mathrm{SM}} \cdot \cot\beta = \frac{1}{40}$ $y_b = y_b^{\mathrm{SM}} \cdot \tan\beta = 1$

TopColor: $H \equiv < t\bar{t} >$ $y_t = 1$ $y_b = 1$

Little Higgs Models

- Cancellation of Λ^2 in top sector:



$$\sim \Lambda^2\left(\lambda_t^2+\lambda_T^2-\lambda_T'\right)=\Lambda^2\left(0\right)$$

⇒ (approximate) global symmetry relates *T* with *t* (Little Higgs mechanism)

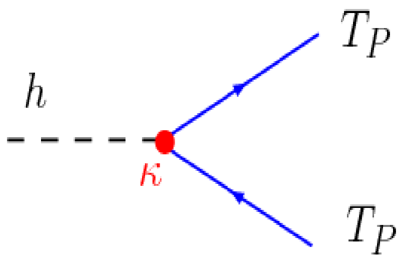
- To ensure ρ=1 at tree level, T-parity was introduced.

SM particles (*t*) ⟷ T-partners (T_P)

a) Lightest T-odd particle A_H' , dark matter candidate

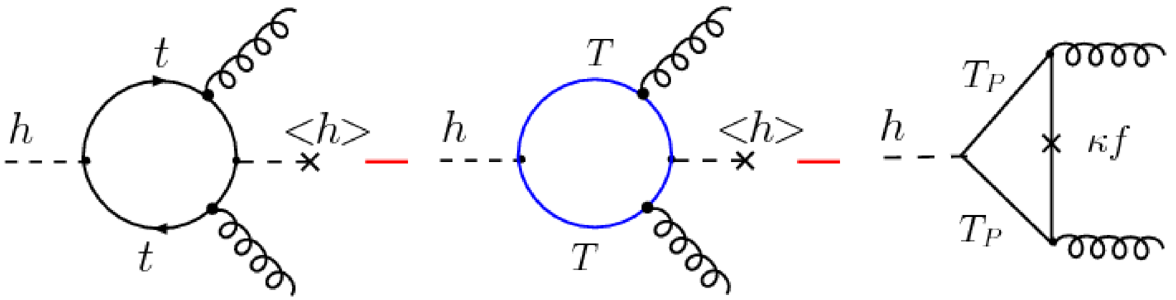
b) Need mass term for T_P

Induce new Higgs coupling
(non-decoupling effects!!!)



Little Higgs Models

- σ(*gg*→*h*)



⇨ Large suppression in σ(*gg*→*h*)

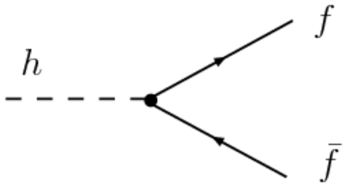
$$v = \langle h \rangle = 246\,\mathrm{GeV}$$

$$f \simeq \frac{\Lambda}{4\pi}$$

$$\frac{\sigma(gg\to h)_{LH}-\sigma(gg\to h)_{SM}}{\sigma(gg\to h)_{SM}} = \begin{cases} -\frac{3}{2}\frac{v^2}{f^2} & \text{(from T)} \\ -\frac{3}{2}\frac{v^2}{f^2} & \text{(from } T_p\text{)} \end{cases}$$

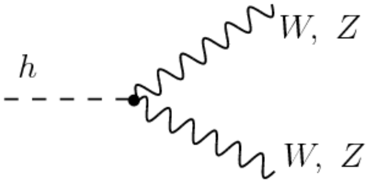
$$\simeq \begin{cases} -37\% \text{ for } f = 700 \text{ GeV}, \\ -18\% \text{ for } f = 1000 \text{ GeV}. \end{cases}$$

- Higgs couplings



$$\sim\left(1-\frac{3}{4}\frac{v^2}{f^2}\right)$$

for $f \neq t,\ b$



$$\sim\left(1-\frac{1}{4}\frac{v^2}{f^2}\right)$$

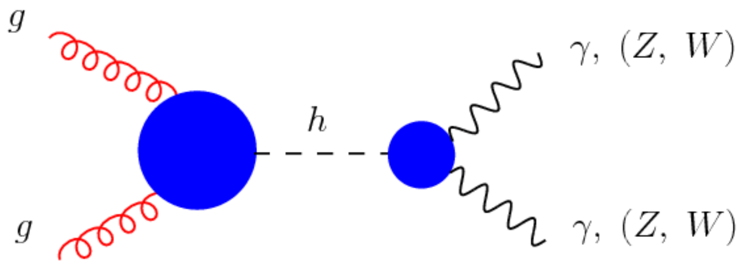
⇨ $\Gamma^h_{tot}(LH) < \Gamma^h_{tot}(SM)$

Little Higgs Models

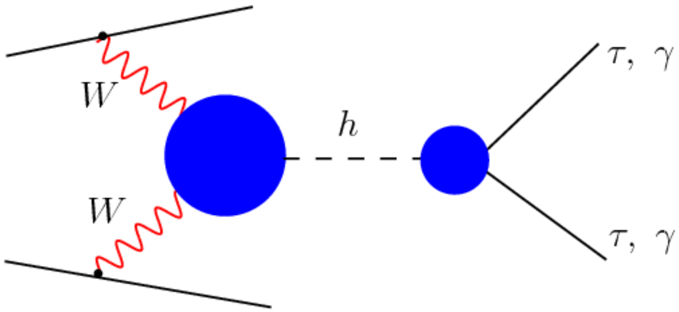
- For m_h ~ 120 GeV, Case-B,

$\mathrm{Br}(h\to\gamma\gamma)_{LH}$ up by ~ 30%

$\mathrm{Br}(h\to bb)_{LH}$ about the same

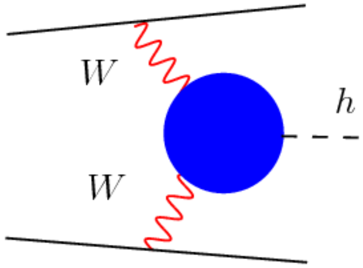


down by
~ 14%
for f = 700 GeV



up by
~ 22%
for f = 700 GeV

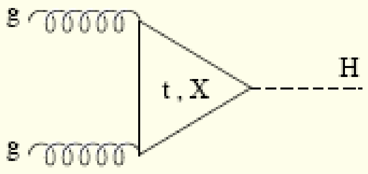
could dramatically modify Higgs discovery potential at LHC for m_h ~ 100 GeV



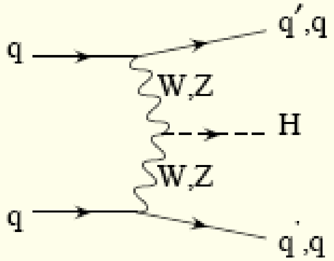
becomes dominant discovery channel

SM Higgs Production Channels

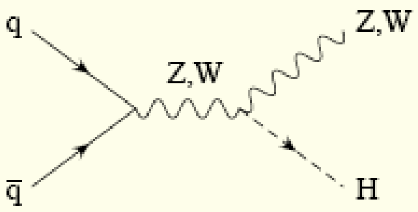
$gg \rightarrow H$



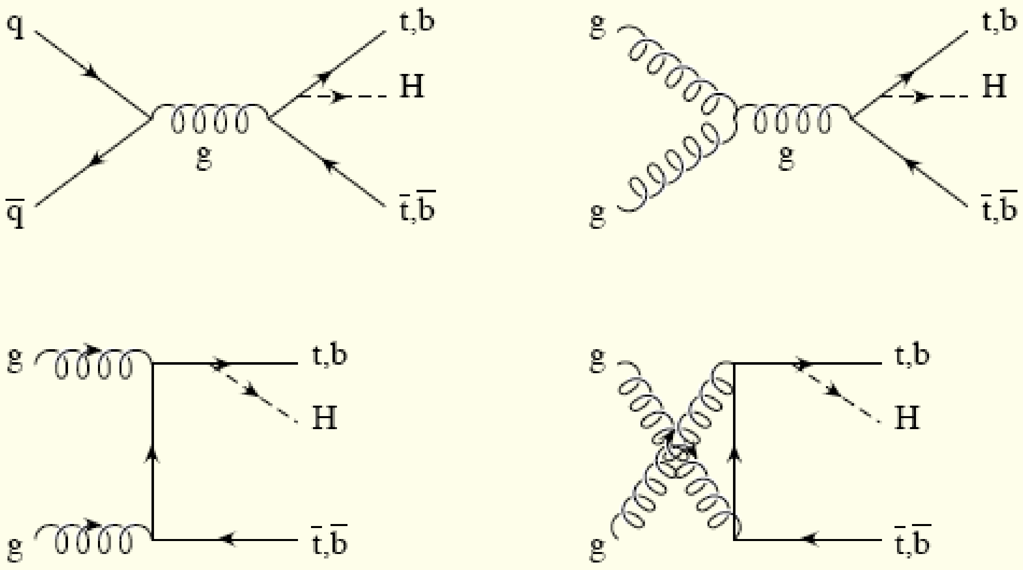
$qq \rightarrow qqH$



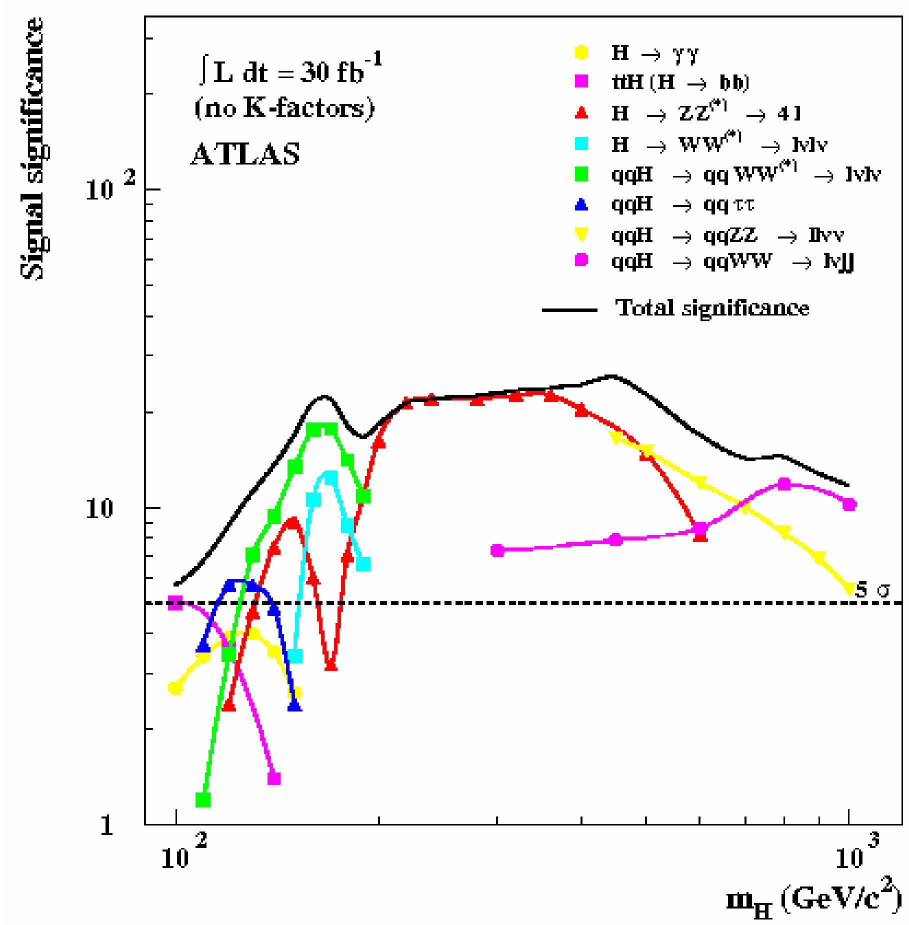
$qq \rightarrow WH, ZH$

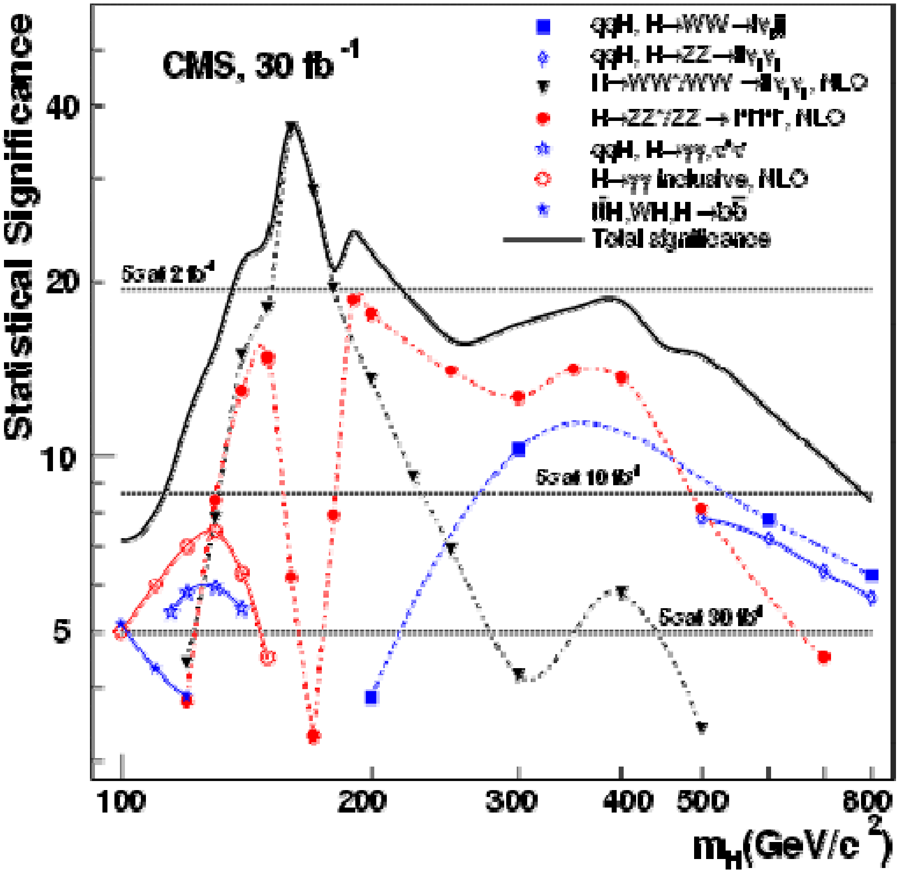


$q\bar{q}, gg \rightarrow t\bar{t}H, b\bar{b}H$



SM Higgs Discovery Potential





What if all gluon-gluon fusion processes are down by a factor of 2?

If Higgs boson exists

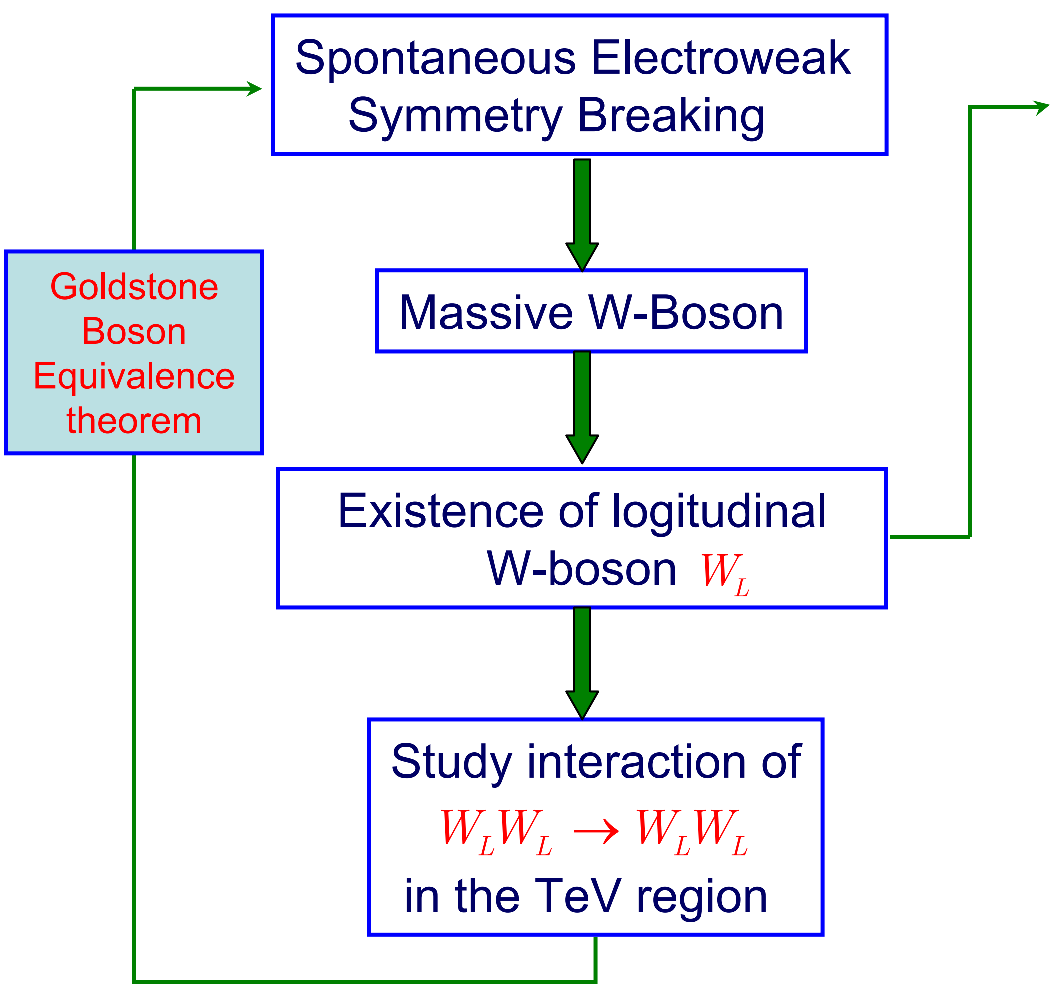
Discovering the Higgs boson and studying its interaction is essential to probe the electroweak symmetry breaking and the flavor symmetry breaking

Otherwise,

Studying interaction among longitudinal W and Z bosons in the TeV region and interaction of longitudinal W (Z) boson and heavy fermions (top and bottom)

What motivated my 1990 single-top paper

(with $m_t = 180\ \text{GeV}$)



Spontaneous Electroweak Symmetry Breaking

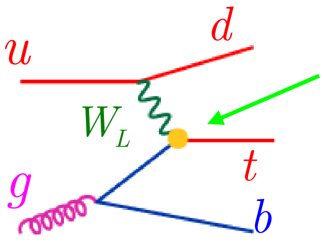
Massive W-Boson

Existence of logitudinal W-boson W_L

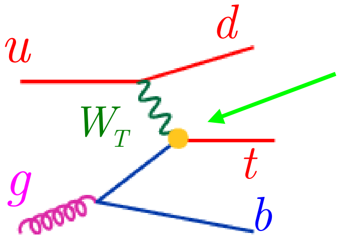
Study interaction of $W_L W_L \to W_L W_L$ in the TeV region

Goldstone Boson Equivalence theorem

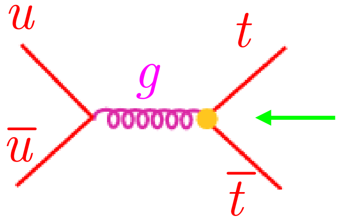
W_L can also interact strongly with top quark if $m_t \simeq \frac{v}{\sqrt{2}} \approx 175\ \text{GeV}$



$g^2{}_{\text{eff}} \simeq \left(\frac{\sqrt{2}m_t}{v}\right)^2 \simeq 1$



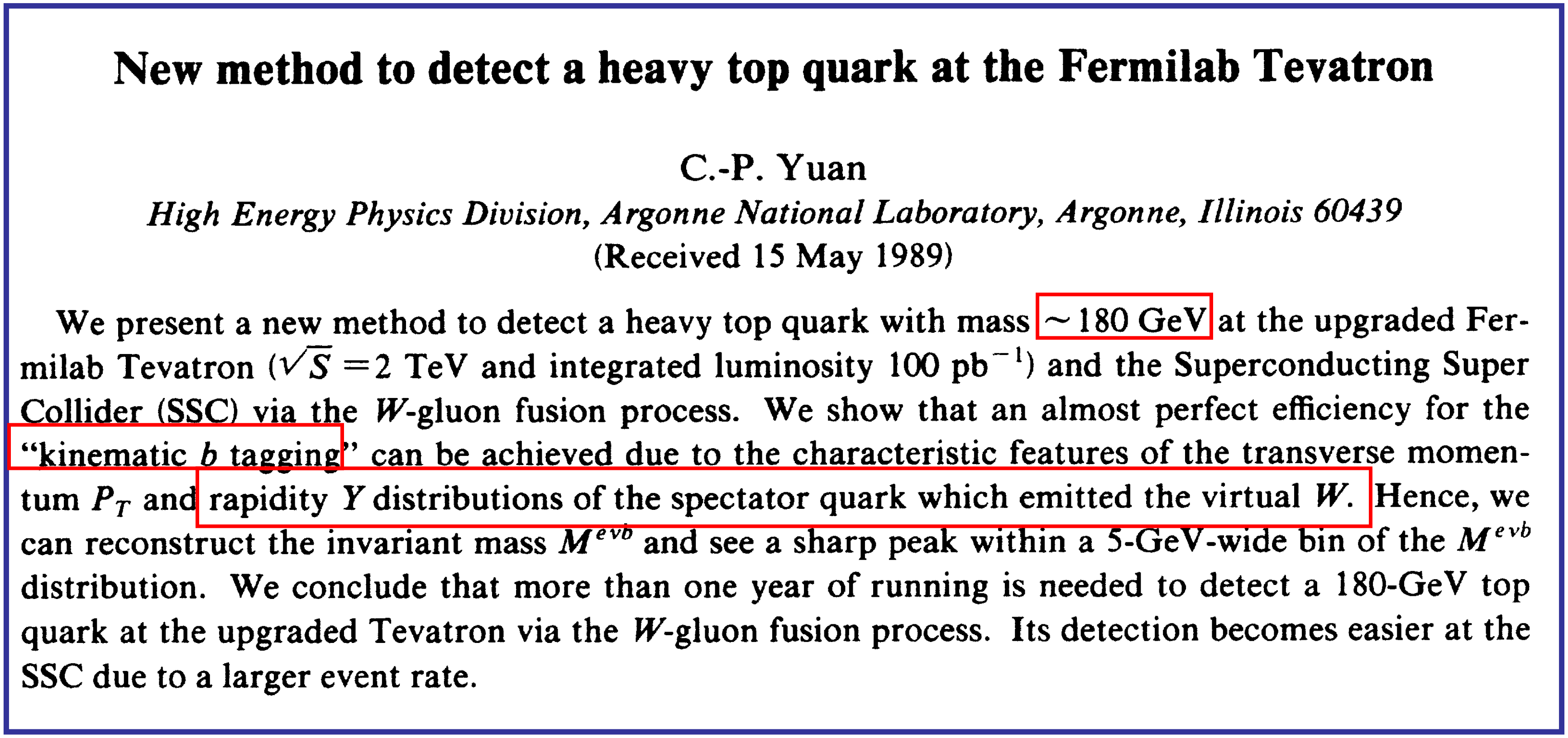
$g^2{}_{\text{weak}} \simeq \frac{1}{2.5}$



$(g_S)^2 \simeq 1$

What motivated my 1990 single-top paper

(with $m_t = 180\ \mathrm{GeV}$)



New method to detect a heavy top quark at the Fermilab Tevatron

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(Received 15 May 1989)

We present a new method to detect a heavy top quark with mass ~ 180 GeV at the upgraded Fermilab Tevatron ($\sqrt{S} = 2$ TeV and integrated luminosity 100 pb^{-1}) and the Superconducting Super Collider (SSC) via the W-gluon fusion process. We show that an almost perfect efficiency for the "kinematic b tagging" can be achieved due to the characteristic features of the transverse momentum P_T and rapidity Y distributions of the spectator quark which emitted the virtual W. Hence, we can reconstruct the invariant mass $M^{e\nu b}$ and see a sharp peak within a 5-GeV-wide bin of the $M^{e\nu b}$ distribution. We conclude that more than one year of running is needed to detect a 180-GeV top quark at the upgraded Tevatron via the W-gluon fusion process. Its detection becomes easier at the SSC due to a larger event rate.

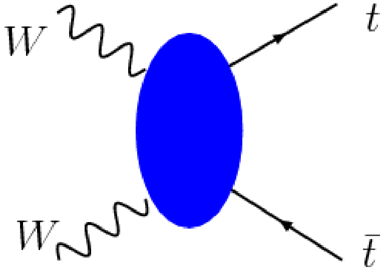
The first paper in the literature to discuss the unique kinematics of the forward jet in the t-channel single-top event.

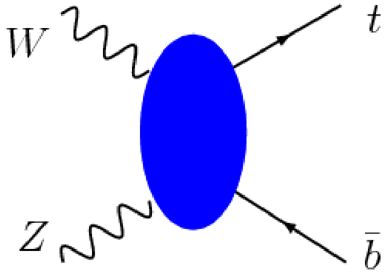
Higgsless Model

(Extra-dimension Models)

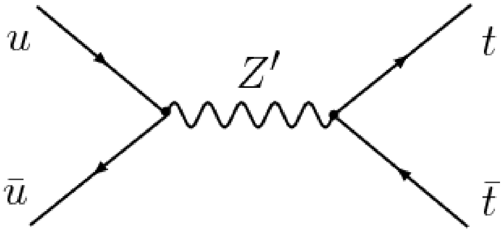
- No elementary or composite Higgs boson to regulate unitarity violation in the TeV region for

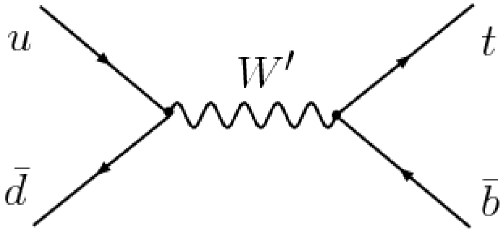
  W W, ZZ → W W, Z Z and W Z → W Z
- Need to study W W, Z Z → t t , W Z → t b scatterings in the TeV region





- Look for W’ and Z’, to delay unitarity breakdown





Summary

We need experimental Data
to advance our knowledge.

Tevatron

↓

LHC

↓

LC

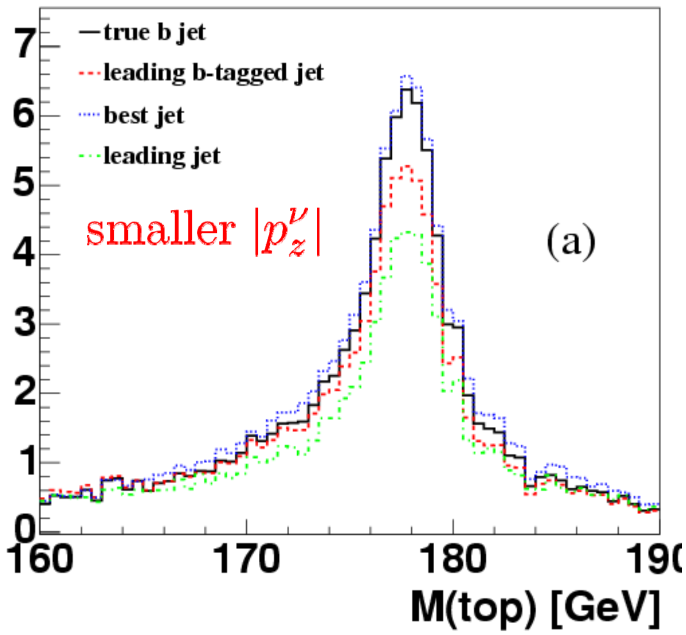
↓

VLHC

Supplementary Slides

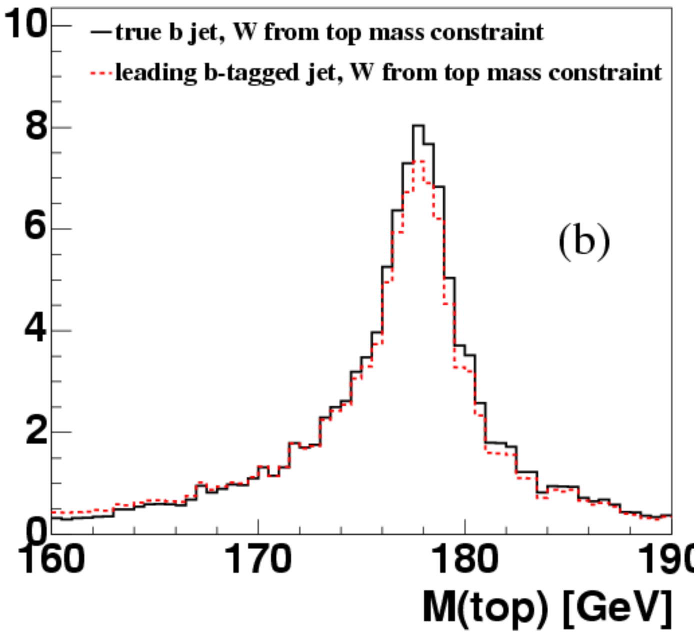
Smaller p_Z^ν vs. Top quark mass constrained p_Z^ν :

(t-channel)



Leading jet :	worst
Leading *b*-tagged jet:	good
Best jet:	best

Best jet algorithm can pick up wrong jets to get correct top quark mass.



The overall height of the mass peak is higher than in the left figure indicating this method reconstruct *W* boson and *b*-jet correctly more often.

General Formulation of *t-b-W* couplings

- Top quark couplings to gauge bosons in the non-linear chiral Lagrangian framework (SU(2)×U(1) invariant)

$$\begin{aligned}\mathcal{L} = {} & \bar{b}\gamma^{\mu}(\kappa_{1L}^{\dagger}P_L + \kappa_{2R}^{\dagger}P_R)t\Sigma_{\mu}^{-} + \partial_{\nu}\Sigma_{\mu}^{-}\bar{b}\sigma^{\mu\nu}(\kappa_{3L}^{\dagger}P_L + \kappa_{4R}^{\dagger}P_R)t \\ & +\bar{b}(\kappa_{5L}^{\dagger}P_L + \kappa_{6R}^{\dagger}P_R)\partial_{\mu}t\Sigma^{-\mu} + \bar{b}(\kappa_{7L}^{\dagger}P_L + \kappa_{8R}^{\dagger}P_R)t\partial_{\mu}\Sigma^{-\mu} + h.c.\end{aligned}$$

Here, κ_L, and κ_R are two arbitrary complex parameters,

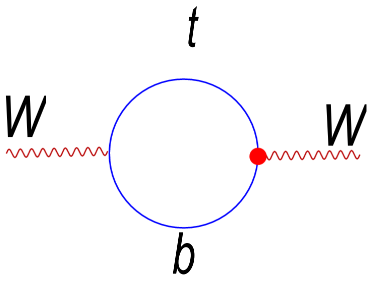
$$\Sigma_{\mu}^{\pm} = \frac{1}{\sqrt{2}}(\Sigma_{\mu}^{1} \mp i\Sigma_{\mu}^{2}), \qquad \Sigma_{\mu}^{a} = -\frac{i}{2}Tr(\tau^{a}\Sigma^{\dagger}D_{\mu}\Sigma),$$

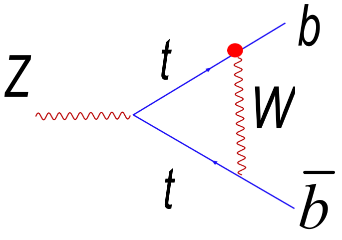
$$\begin{pmatrix} t \\ b \end{pmatrix}_L \equiv \Sigma F_L = \Sigma\begin{pmatrix} f_1 \\ f_2 \end{pmatrix}_L, \qquad \begin{array}{l} t_R = f_{1R} \\ b_R = f_{2R} \end{array}.$$

- In the unitary gauge,

$$\Sigma_{\mu}^{\pm} \rightarrow -\frac{1}{2}gW_{\mu}^{\pm},\ t_L \rightarrow f_{1L},\ t_R \rightarrow f_{2R},\ \text{etc.}$$

What do we know from indirect measurements?

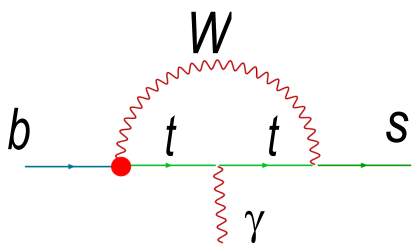


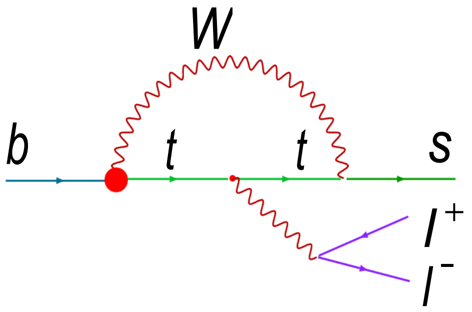


Indirect limits on dim-4 and dim-5 couplings

coupling	LEP	$b \to s\gamma$	$b \to sl^+l^-$
$\varepsilon_L \equiv f_1^L - 1$	0.02	0.3	0.5
f_2^R	0.1	-	0.4
f_1^R	-	0.002	-
f_2^L	-	0.005	-

● one coupling at a time.



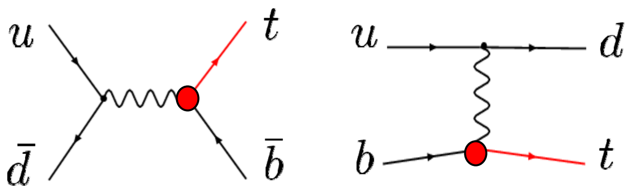


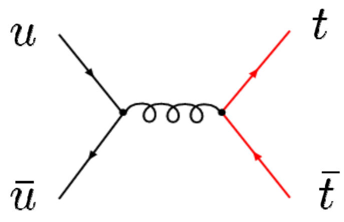
☞ May cancel with other contributions (originated from other light fields)

☞ Assume no other new physics effect

What do we know from direct measurements?

coupling	Tevatron	LHC
ε_L	10^{-1}	10^{-2}
f_2^R	0.3	0.003
f_1^R	0.7	0.08
f_2^L	0.3	0.05





$$A_{FB} = \frac{\Gamma_F - \Gamma_B}{\Gamma_F + \Gamma_B}$$

● one coupling at a time.

Tevatron: $(2\,fb^{-1}) \times (6\,pb) \sim 10^4$ tt events

LHC: $(100\,fb^{-1}) \times (8 \times 10^2\,pb) \sim 10^8$ tt events

How to perform direct measurements at Tevatron and LHC?

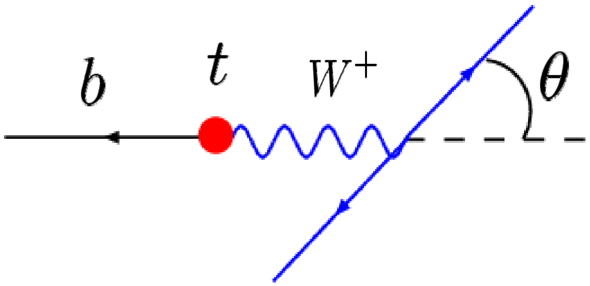
- Measurement of W helicity fractions in top decay

$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\cos\theta} = f_0 \frac{3}{4}\sin^2\theta + f_- \frac{3}{8}(1-\cos\theta)^2 + f_+ \frac{3}{8}(1+\cos\theta)^2$$

- Experimental measurements: (from $t\bar{t}$ pairs @ Tevatron)

D0: $f_0 = 0.56 \pm 0.32$, $f_- < 0.24$

hep-ex/0404040



CDF: $f_0 = 0.91 \pm 0.38$, $f_- < 0.18$

hep-ex/0411070

$\Longrightarrow$ Expected @ $2\ \mathrm{fb}^{-1}$: $\frac{\Delta f_0}{f_0} \sim 10\%,\ f_+ < 0.05$

Four observables in terms of four independent variables

$$f_0 = \frac{a_t^2\left(1+x_0\right)}{a_t^2\left(1+x_0\right)+2\left(1+x_m+x_p\right)}$$

$$f_- = \frac{2\left(1+x_m\right)}{a_t^2\left(1+x_0\right)+2\left(1+x_m+x_p\right)}$$

$$f_+ = \frac{2x_p}{a_t^2\left(1+x_0\right)+2\left(1+x_m+x_p\right)}$$

$$\left(f_0+f_-+f_+=1\right)$$

$$x_0 = \left(f_1^L + f_2^R/a_t^2\right)^2 + \left(f_1^R + f_2^L/a_t^2\right)^2 - 1$$

$$x_m = \left(f_1^L + f_2^R a_t^2\right)^2 - 1$$

$$x_p = \left(f_1^R + f_2^L a_t^2\right)^2 - 1$$

$$x_5 = a_t^2\left(\left(f_2^R\right)^2 + \left(f_2^L\right)^2\right)$$

$$a_t = m_t/m_W$$

only depend on $f_2^{L,R}$,
not $f_1^{L,R}$.

$$\Delta\sigma \equiv \sigma - \sigma_{SM}$$

$$\Delta\sigma_t = a_0x_0 + a_mx_m + a_px_p + a_5x_5$$
$$\sim(\cdots)f_0 + (\cdots)f_- + (\cdots)f_+ + a_5x_5$$

$$\Delta\sigma_s = b_0x_0 + b_mx_m + b_px_p + b_5x_5$$
$$\sim(\cdots)f_0 + (\cdots)f_- + (\cdots)f_+ + a_5x_5$$

t-channel	a_0	a_m	a_p	a_5
Tevatron	0.896	-0.069	-0.153	0.247
LHC (t)	165.2	-19.1	-34.2	62.5

s-channel	b_0	b_m	b_p	b_5
Tevatron	-0.081	0.352	0.352	0.230
LHC (t)	-1.41	5.67	5.67	6.34

CTEQ6L1

Distinguish different model of EWSB

An illustration with two couplings (to simplify discussion)

- Assume b_R couplings are small (for $m_b \sim 0$) $\Longrightarrow f_1^R = f_2^R \sim 0 \Longrightarrow f_+ \sim 0$

$$f_- = \frac{2\left(1+\varepsilon_L + a_t f_2^R\right)^2}{a_t^2\left(1+\varepsilon_L + f_2^R / a_t\right)^2 + 2\left(1+\varepsilon_L + a_t f_2^R\right)^2}$$

If $f_2^R \to 0$, then

$$f_- = \frac{2}{a_t^2 + 2} = f_-^{SM}$$

- The sign of Δf_- depends on models $\quad f_2^R \lessgtr 0 \Leftrightarrow \Delta f_- \lessgtr 0$

☞ MSSM $\quad \varepsilon_L = 0.01, \quad f_2^R = 0.005 \qquad f_0 \searrow \qquad f_- \nearrow$

ε_L can be either positive or negative.
SUSY-QCD and SUSY-EW corrections have opposite contributions.

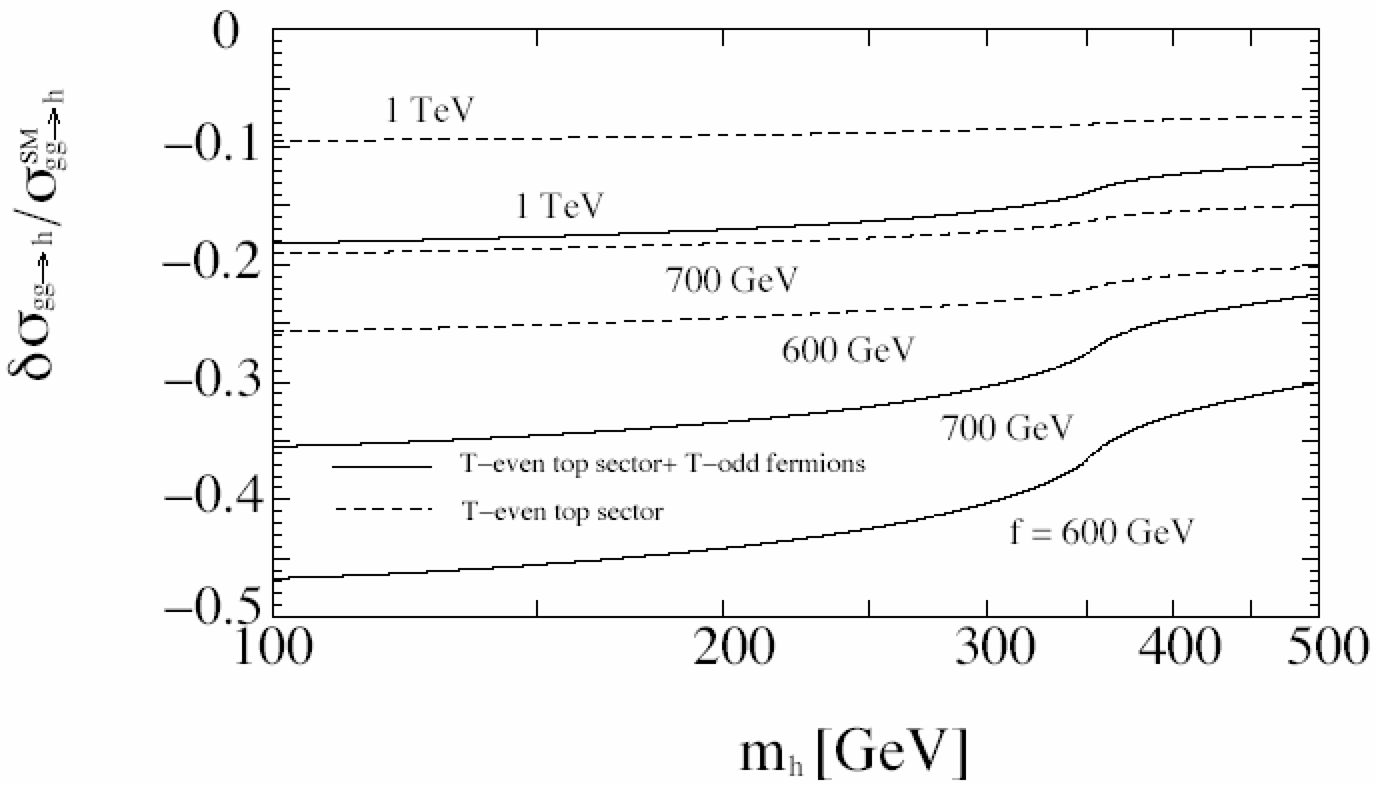
☞ TC2 $\quad \varepsilon_L = -0.01, \quad f_2^R = -0.005 \qquad f_0 \nearrow \qquad f_- \searrow$

typically, $\varepsilon_L<0$

Little Higgs Models

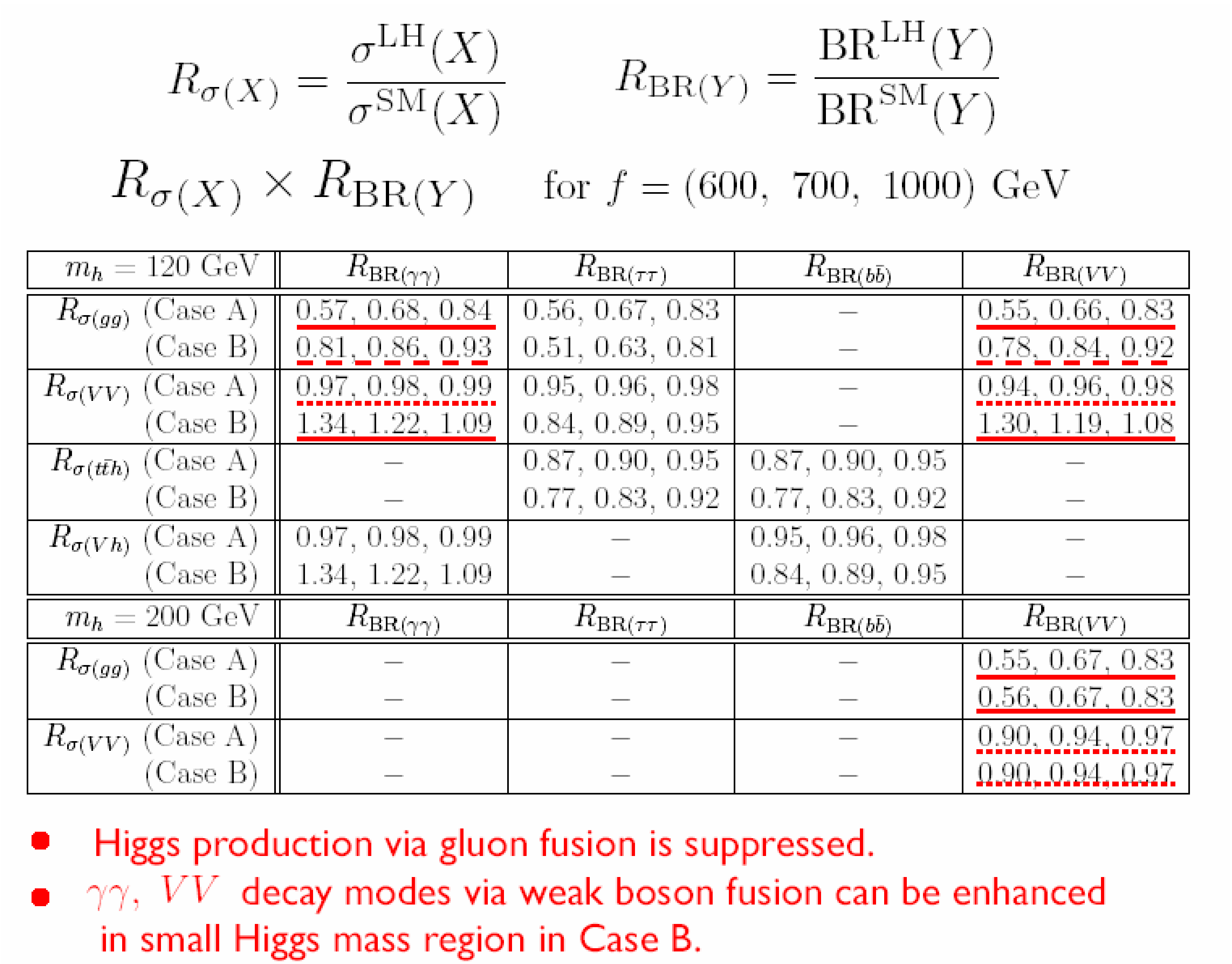
Correction to Higgs production cross section via gluon fusion process

$$\frac{\delta\sigma_{gg\to h}}{\sigma^{\mathrm{SM}}_{gg\to h}} \quad (\text{where } \delta\sigma_{gg\to h} = \sigma^{\mathrm{LH}}_{gg\to h} - \sigma^{\mathrm{SM}}_{gg\to h})$$



The production cross section can be significantly suppressed

Little Higgs Models



$$R_{\sigma(X)} = \frac{\sigma^{\rm LH}(X)}{\sigma^{\rm SM}(X)} \qquad R_{{\rm BR}(Y)} = \frac{{\rm BR}^{\rm LH}(Y)}{{\rm BR}^{\rm SM}(Y)}$$

$$R_{\sigma(X)} \times R_{{\rm BR}(Y)} \qquad \text{for } f = (600,\ 700,\ 1000)\ \text{GeV}$$

$m_h = 120$ GeV		$R_{{\rm BR}(\gamma\gamma)}$	$R_{{\rm BR}(\tau\tau)}$	$R_{{\rm BR}(b\bar{b})}$	$R_{{\rm BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	0.57, 0.68, 0.84	0.56, 0.67, 0.83	–	0.55, 0.66, 0.83
	(Case B)	0.81, 0.86, 0.93	0.51, 0.63, 0.81	–	0.78, 0.84, 0.92
$R_{\sigma(VV)}$	(Case A)	0.97, 0.98, 0.99	0.95, 0.96, 0.98	–	0.94, 0.96, 0.98
	(Case B)	1.34, 1.22, 1.09	0.84, 0.89, 0.95	–	1.30, 1.19, 1.08
$R_{\sigma(t\bar{t}h)}$	(Case A)	–	0.87, 0.90, 0.95	0.87, 0.90, 0.95	–
	(Case B)	–	0.77, 0.83, 0.92	0.77, 0.83, 0.92	–
$R_{\sigma(Vh)}$	(Case A)	0.97, 0.98, 0.99	–	0.95, 0.96, 0.98	–
	(Case B)	1.34, 1.22, 1.09	–	0.84, 0.89, 0.95	–
$m_h = 200$ GeV		$R_{{\rm BR}(\gamma\gamma)}$	$R_{{\rm BR}(\tau\tau)}$	$R_{{\rm BR}(b\bar{b})}$	$R_{{\rm BR}(VV)}$
$R_{\sigma(gg)}$	(Case A)	–	–	–	0.55, 0.67, 0.83
	(Case B)	–	–	–	0.56, 0.67, 0.83
$R_{\sigma(VV)}$	(Case A)	–	–	–	0.90, 0.94, 0.97
	(Case B)	–	–	–	0.90, 0.94, 0.97

- Higgs production via gluon fusion is suppressed.
- $\gamma\gamma,\ VV$ decay modes via weak boson fusion can be enhanced in small Higgs mass region in Case B.