# Top Quark Physics at Terascale
# （TeV能区的顶夸克物理）

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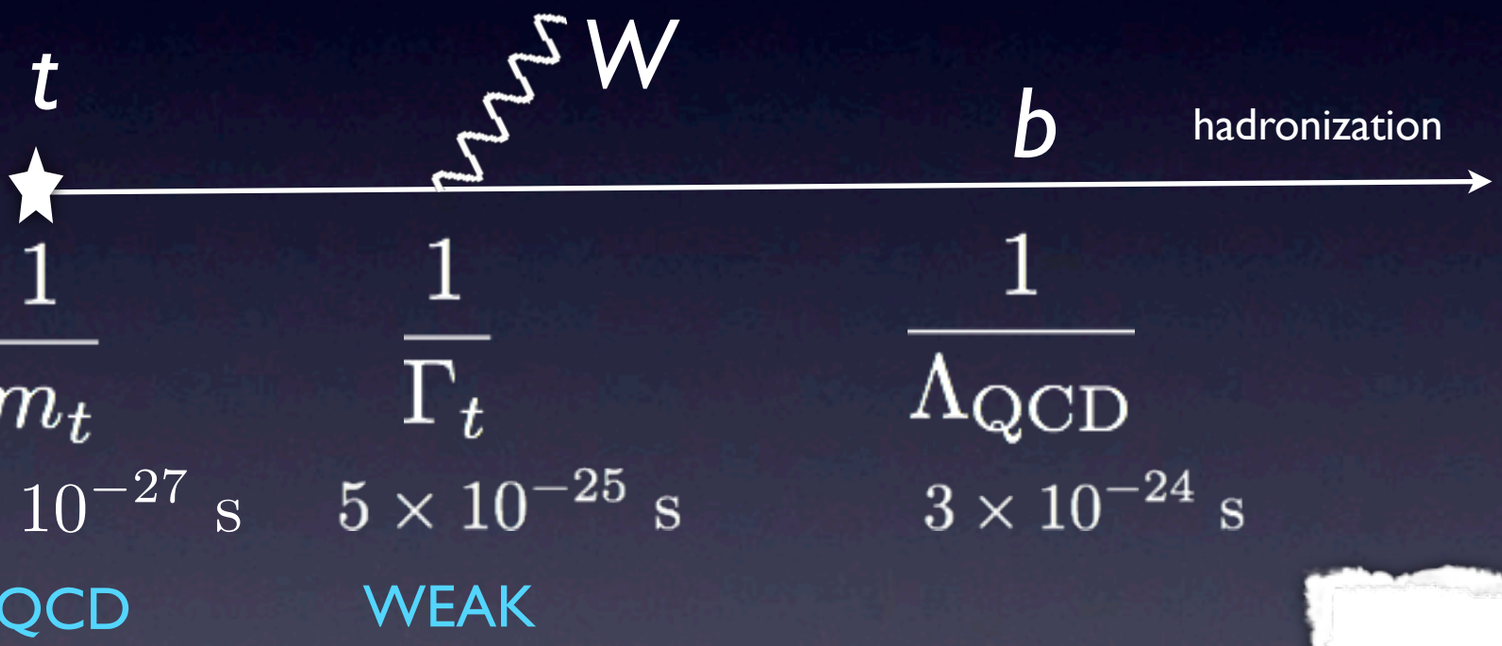
Emphasize on contributions from Chinese community

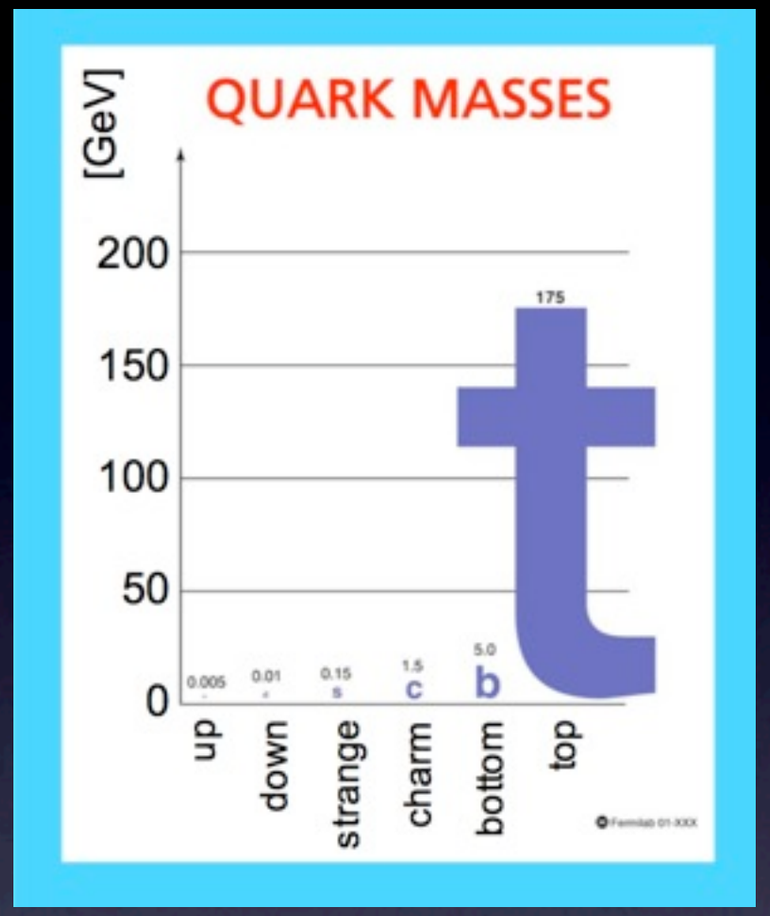
# Top-quark: king of the SM

- Large mass： 173 GeV ( $y_t \sim O(1)$ )

$$m_t \simeq m_W + m_Z \text{ (Coincidence ?)}$$

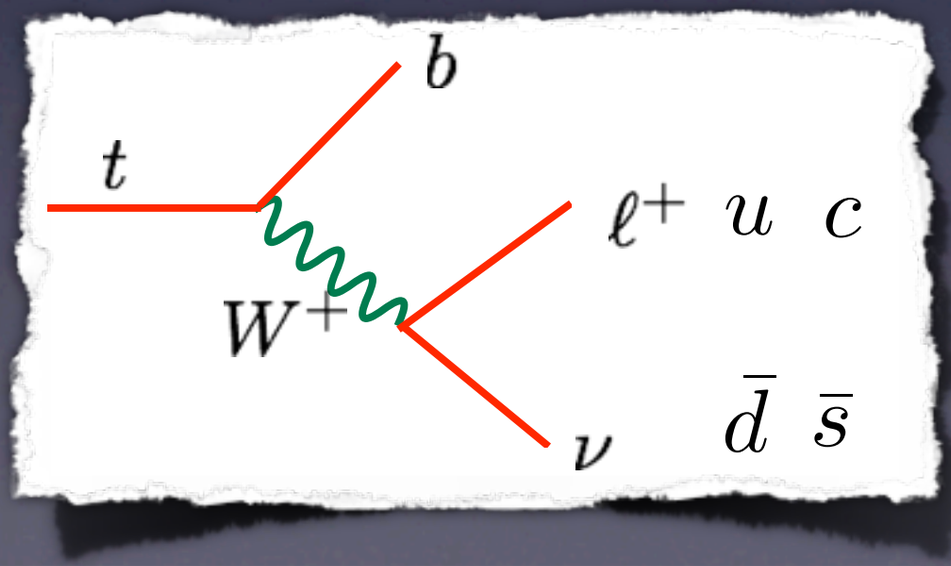
- Short lifetime:




- “bare” quark:

  spin info well kept among its decay products



# Top-quark as a link to new physics

Weakly interacting models

Strongly Interacting models

Extra Dimension

**Theory motivated**

**Data Driven**

top-quark

Effective Operators

$SU(3) \times SU(2) \times U(1)_Y$

Effective Couplings

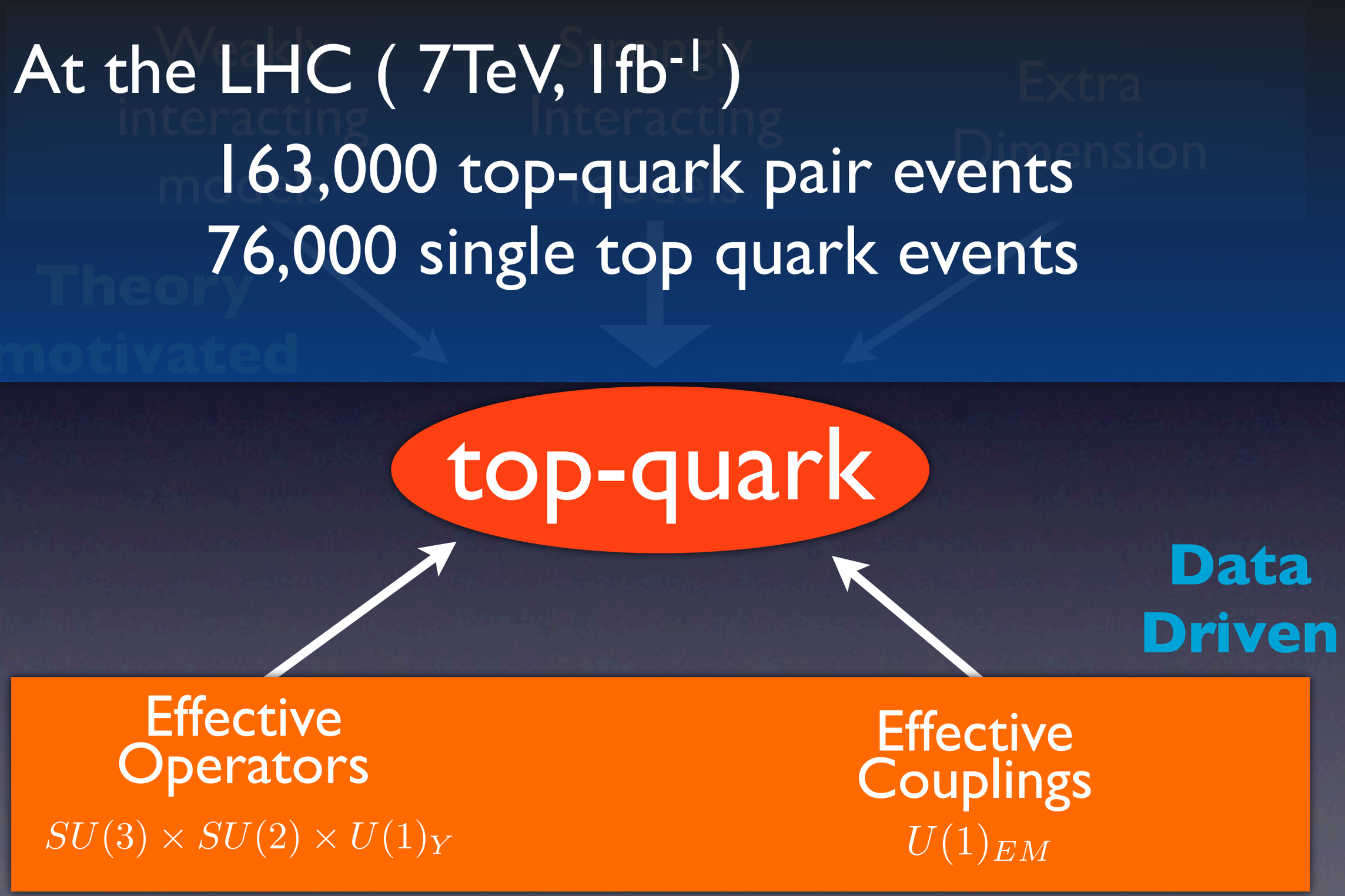
$U(1)_{EM}$

# Top-quark as a link to new physics

At the LHC ( 7TeV, $1 fb^{-1}$ )

163,000 top-quark pair events

76,000 single top quark events



# Top-quark as a probe of new physics

## Extra gauge bosons

Z’ W’ G’

## New heavy quarks

Vector-like Quark

4th Gen

Gluino


## Exotic colored states

## Charged Higgs

## Heavy quark production via pQCD

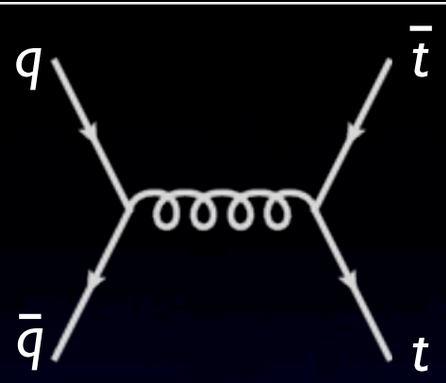
FCNC

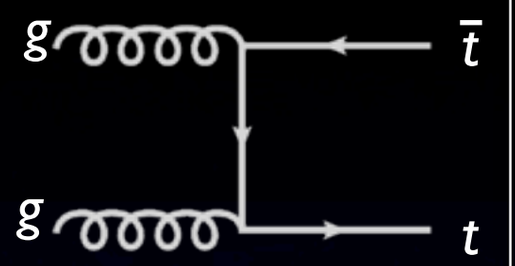
$A_{FB}$

$\not{CP}$

# Top-quark production in the SM

# Top pair production in the SM




| | | |
|---|---|---|
| Tevatron: | **90%** | 10% |
| LHC (7TeV): | 20% | 80% |
| LHC (14TeV): | 10% | **90%** |

NLO + threshold res. (NLL): Moch Uwer, Cacciari et al; Kidonakis, Vogt

NNLL extensions at threshold:
Czakon et al; Beneke et al; Ahrens, *L. L. Yang*, et al

Partial results at NNLL QCD: Czakon; Bonciani et al

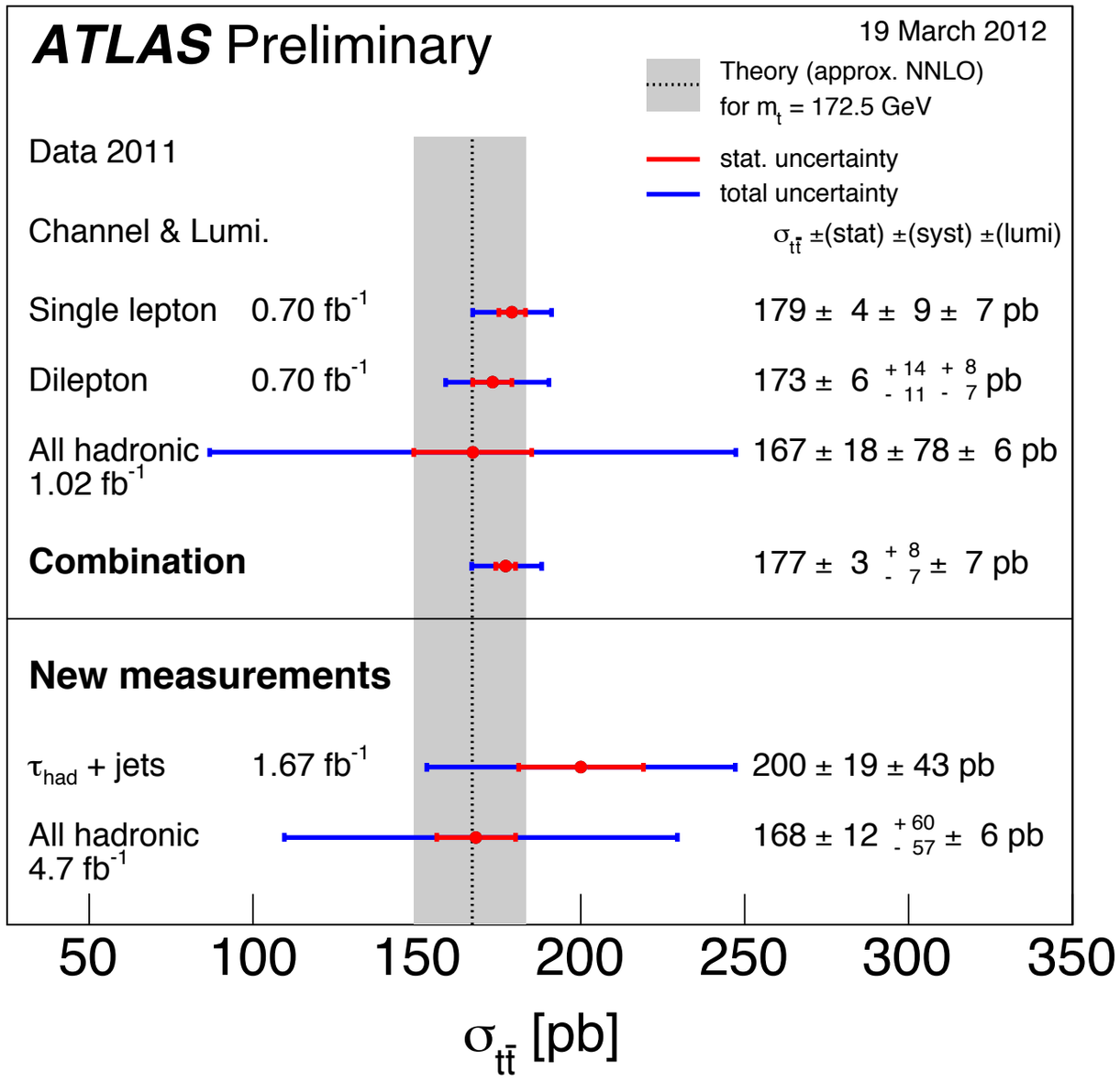
ttbar + jet at NLO: Dittmaier et al; Melikov, Schulze

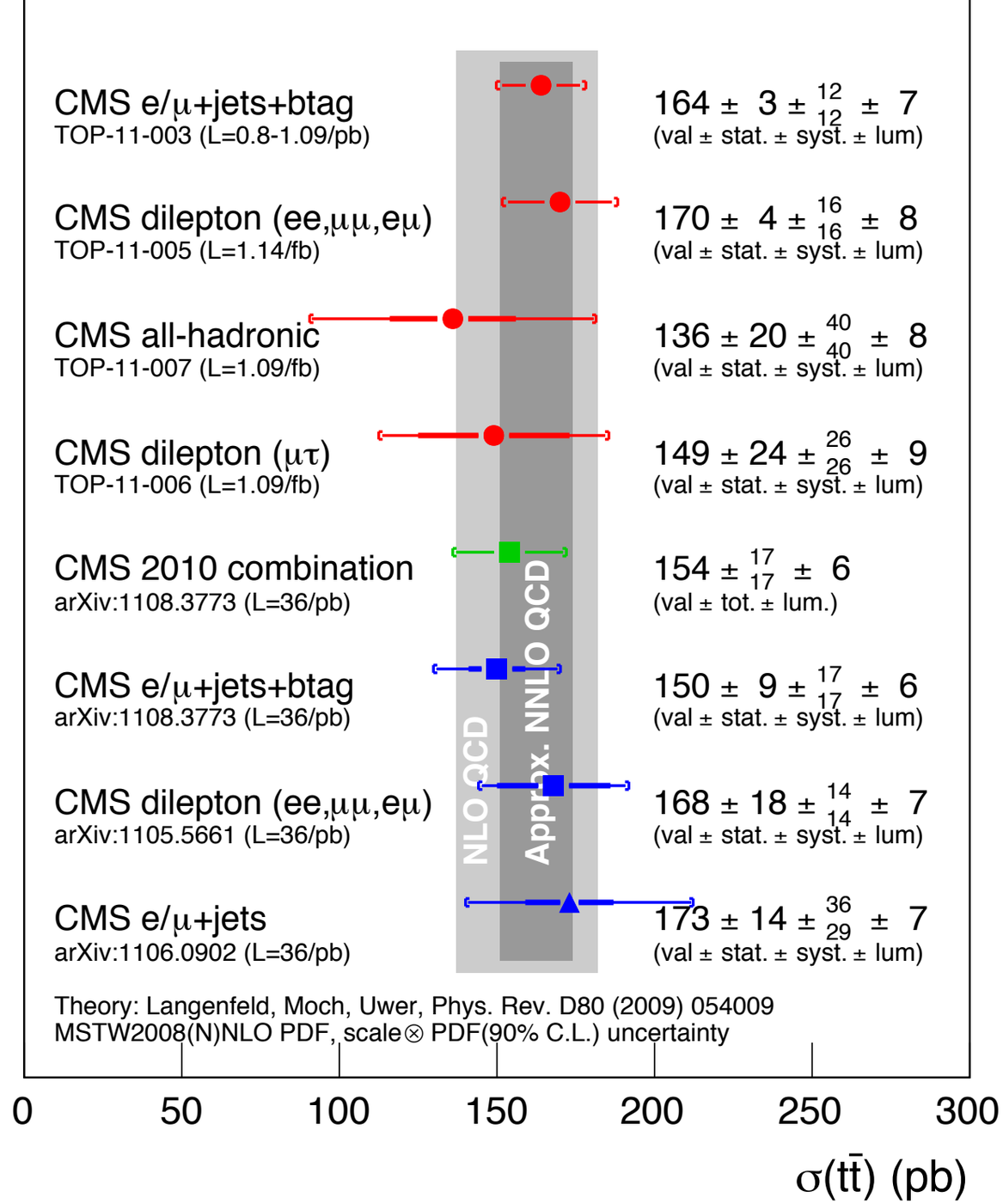
ttbar + bb: Bredenstein et al, Bevilacqua et al

ttbar + jet with top decay at NLO: Melnikov, Schulze;
with weak interference corr. Bernreuther, *Zong-Guo Si*

ttbar spin correlations: Mahlon, Parke; Bernreuther, *Zong-Guo Si*

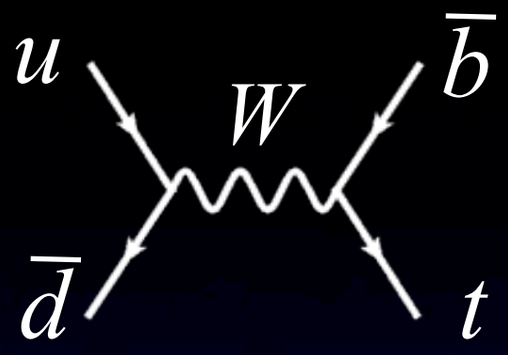
# Top pair production cross section



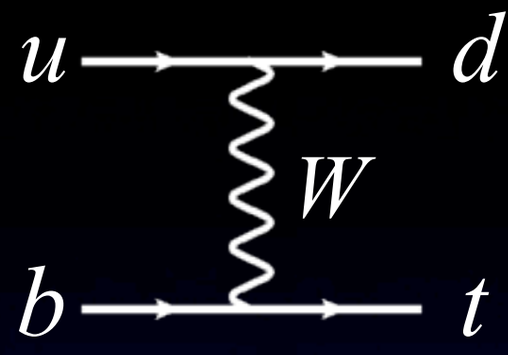

Exp uncertainties ~10-20%

# Single top production in the SM



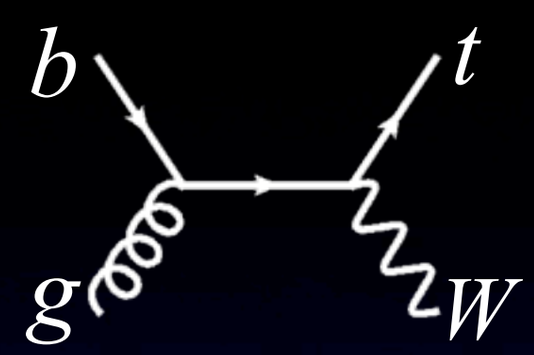

s-channel

$Q_W^2 > 0$



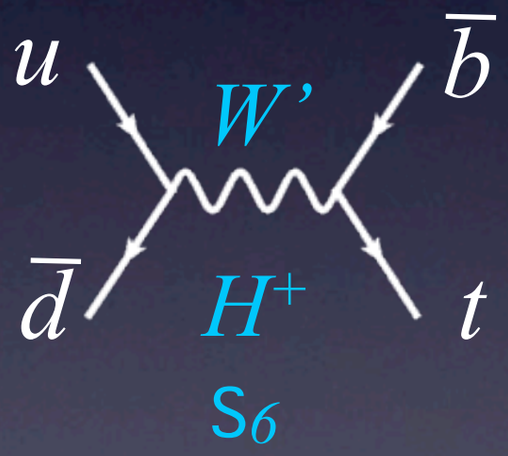

*t*-channel

$Q_W^2 < 0$

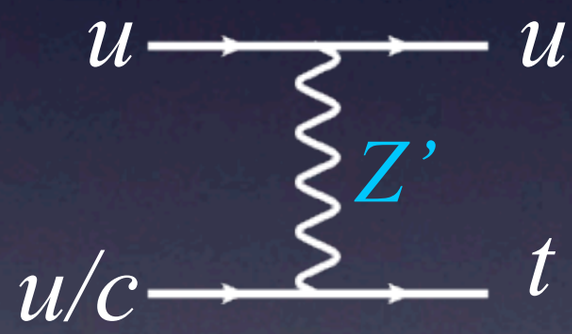



*t*W

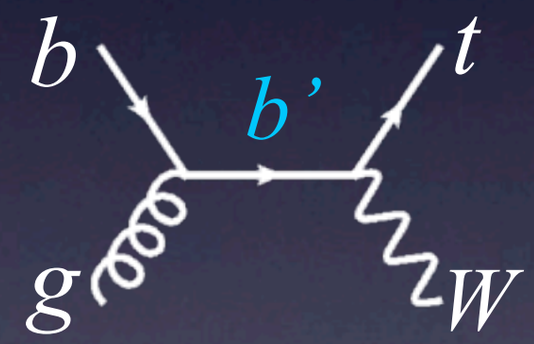
$Q_W^2 = m_W^2$




New resonance

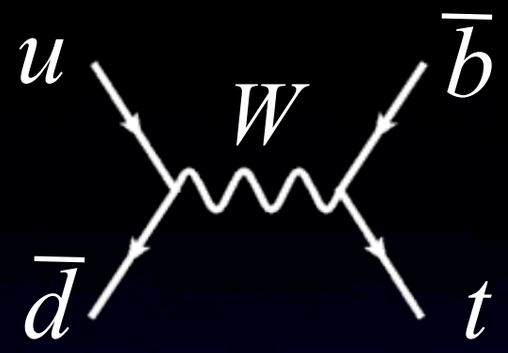



FCNC

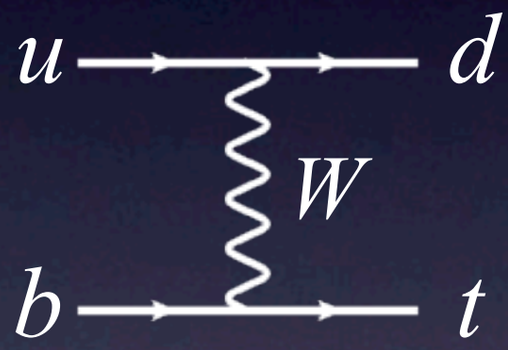



Excited quark

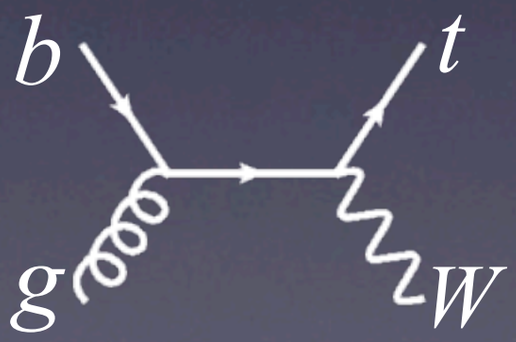
# Single top production at the NLO




s-channel

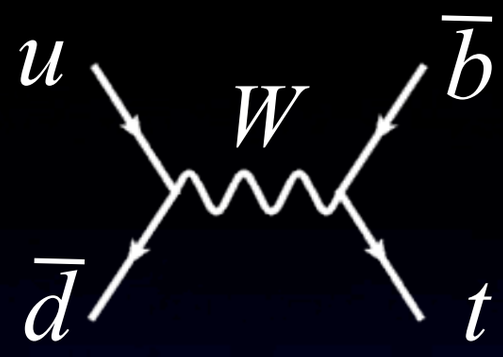



*t*-channel




*t*W

# Single top production at the NLO

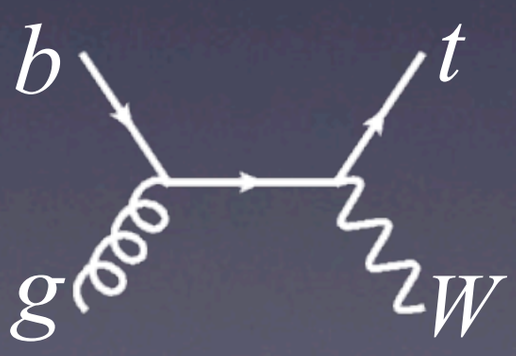



s-channel

Harris, et al, PRD66 (2002) 054024
Qing-Hong Cao, C.-P. Yuan, PRD71 (2005) 054002
Campbell, et al, PRD70 (2004) 094012
Zhu, C. S. Li, Wang, Zhang, JHEP 1102 (2011) 099
Heim, Qing-Hong Cao, et al, PRD81 (2010) 034005


t-channel

Harris, et al, PRD66 (2002) 054024
Campbell, et al, PRD70 (2004) 094012
Qing-Hong Cao, et al, PRD72 (2005)094027
Frixione, et al, JHEP 0807 (2008) 029
Campbell, et al, PRL102 (2009) 182003
Wang, C. S. Li, Zhu, Zhang, 1010.4509
Reinhdard, Yuan, Mueller, Qing-Hong Cao, PRD83 (2011) 034019



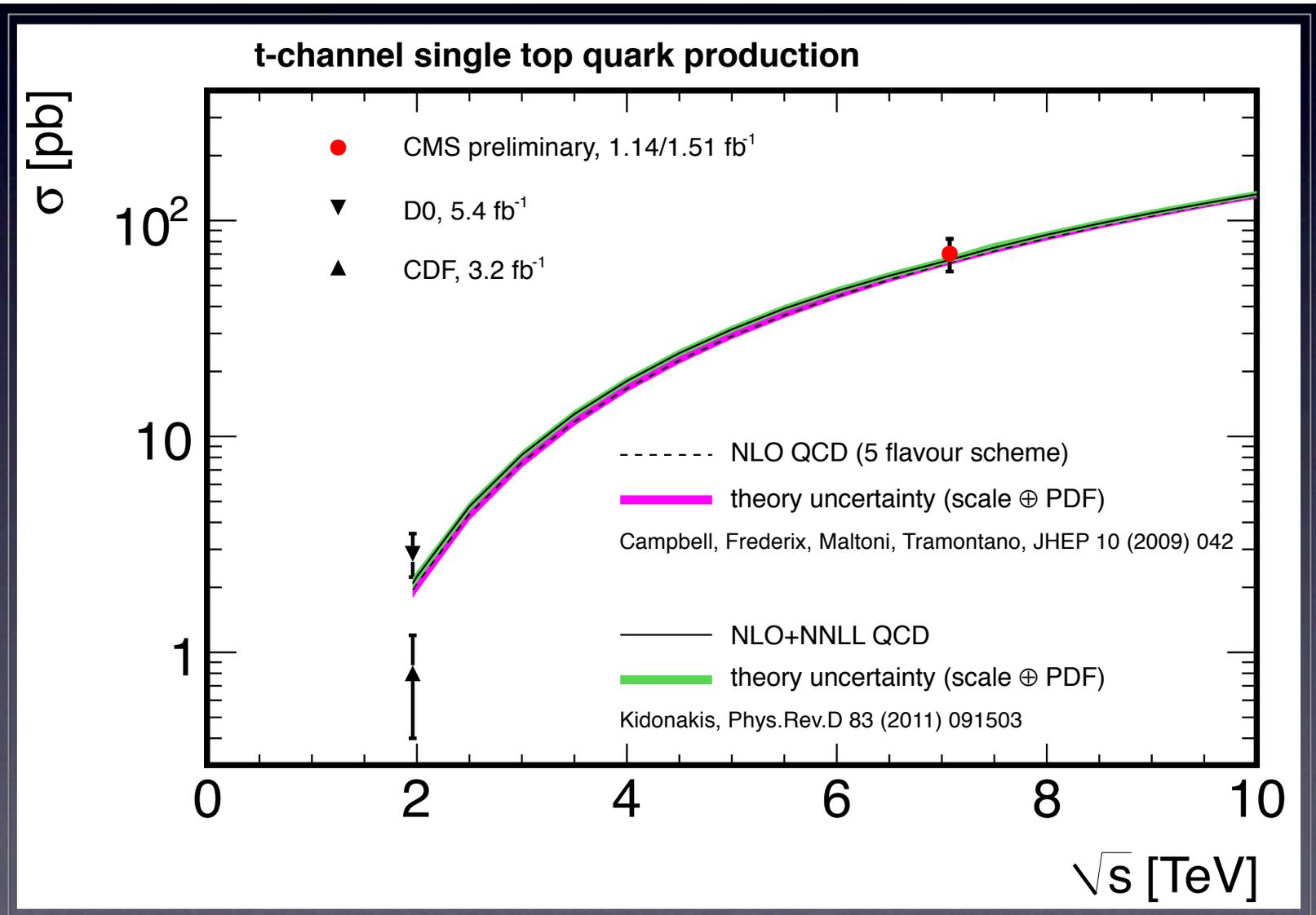

tW

Shou-Hua Zhu, PLB524 (2002) 283
Qing-Hong Cao, 0801.0539

# Single top measurements at LHC

$$\sigma_{t-\mathrm{ch.}} = 70.2 \pm 5.2(\mathrm{stat.}) \pm 10.4(\mathrm{syst.}) \pm 3.4(\mathrm{lumi.})\ \mathrm{pb}$$

$$|V_{\mathrm{tb}}| = \sqrt{\frac{\sigma_{t-\mathrm{ch.}}}{\sigma^{\mathrm{th}}_{t-\mathrm{ch.}}}} = 1.04 \pm 0.09\,(\mathrm{exp.}) \pm 0.02\,(\mathrm{th.})$$

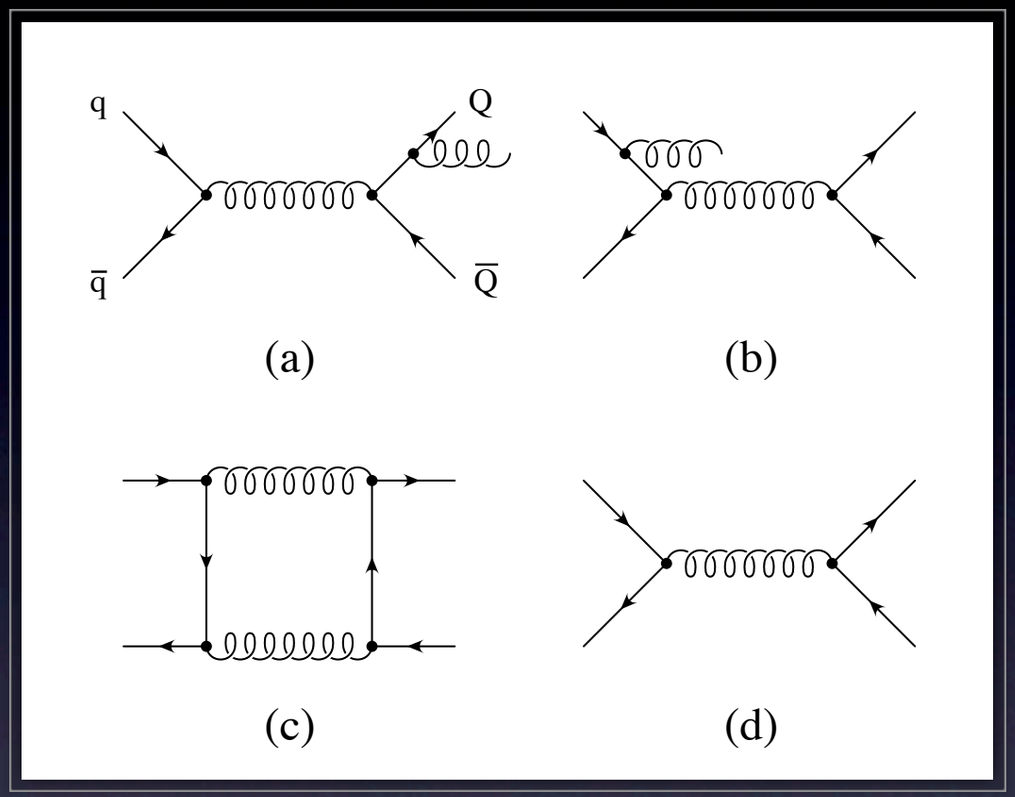


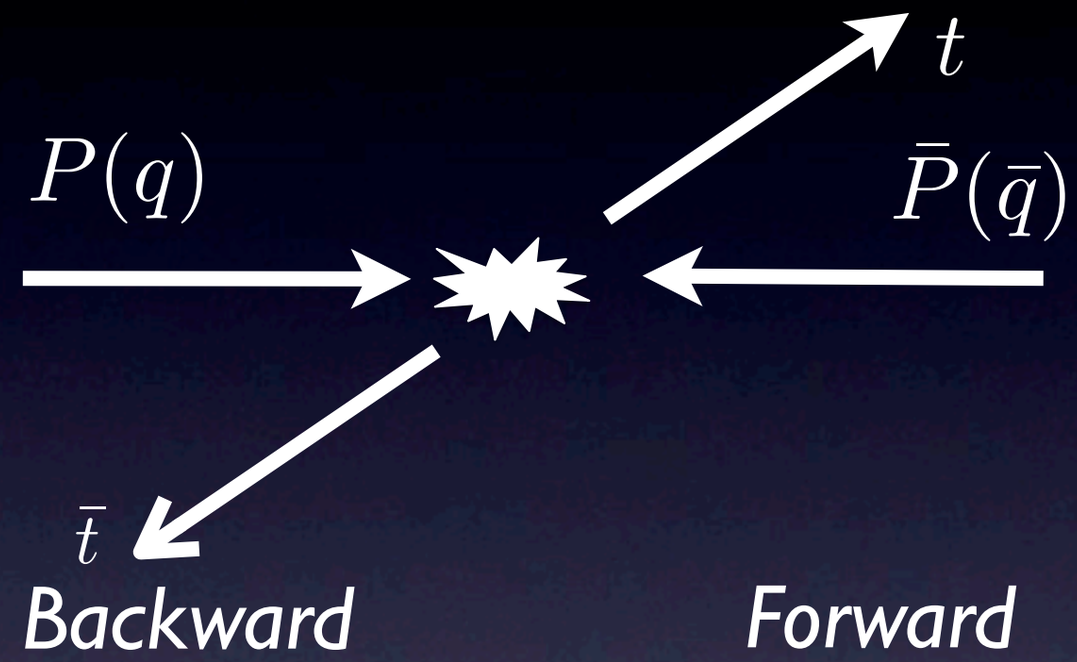

LHC is powerful

# Top-quark Forward-Backward Asymmetries

# Top-quark F-B asymmetry in the SM

- A charge asymmetry arises at NLO



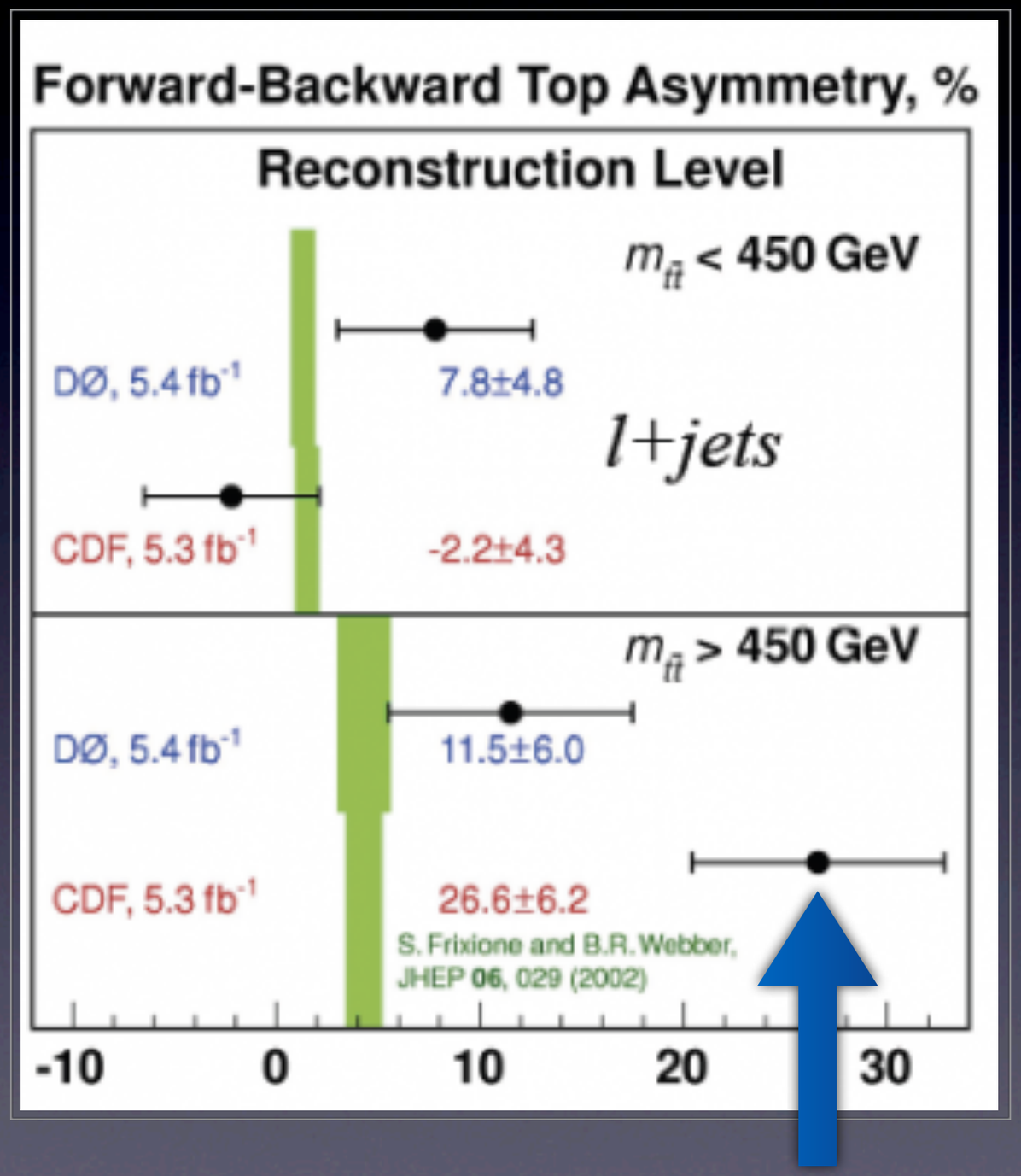




Top quarks are produced along the direction of the incoming quark

$$A^{p\bar{p}} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)} = 0.051(6)$$

$$A^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$

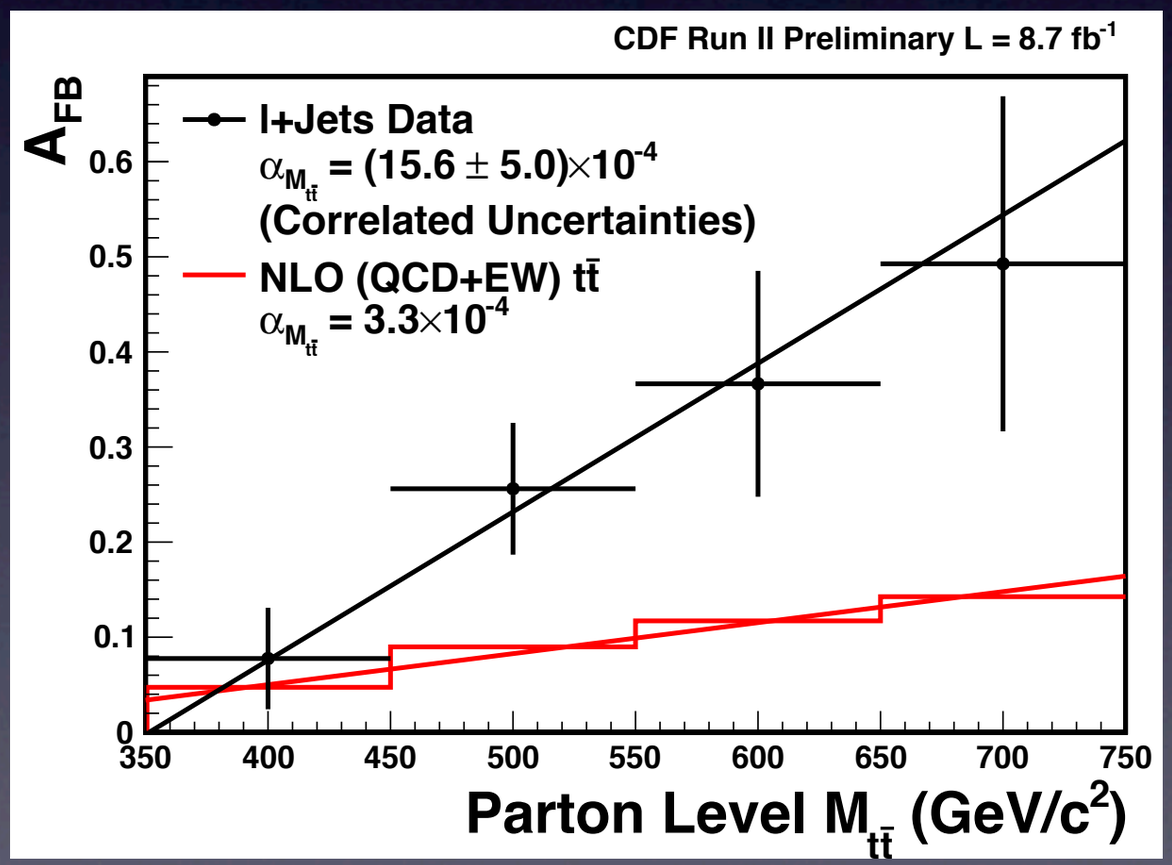
# Top-quark $A_{FB}$ at the Tevatron




## CDF new data (8.7fb$^{-1}$):

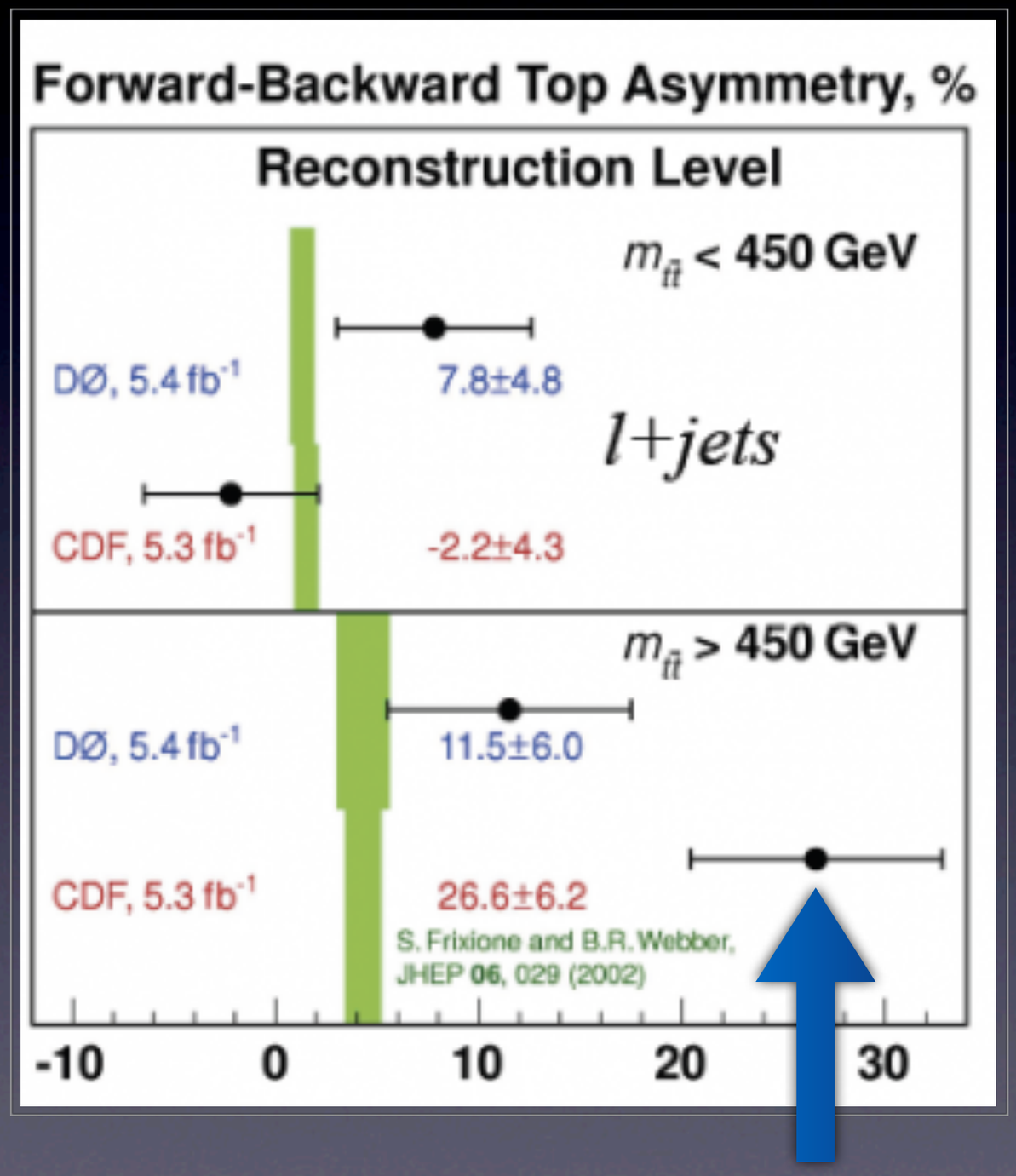
$$A_{FB}^{\text{inclusive}} = 0.162 \pm 0.041 \pm 0.022$$

$$A_{FB}^{\text{NLO+EW}} = 0.066$$




1101.0034 (cited > 240)

# Top-quark $A_{FB}$ at the Tevatron

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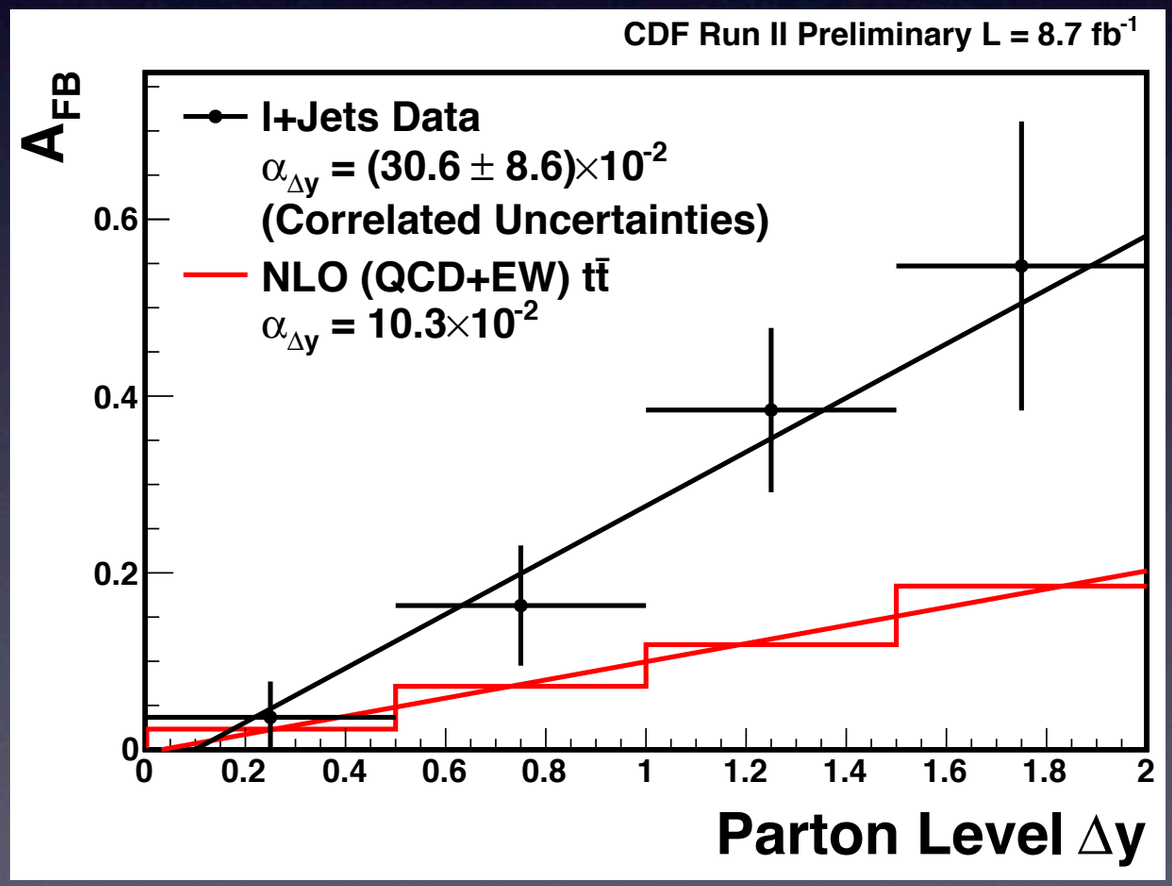
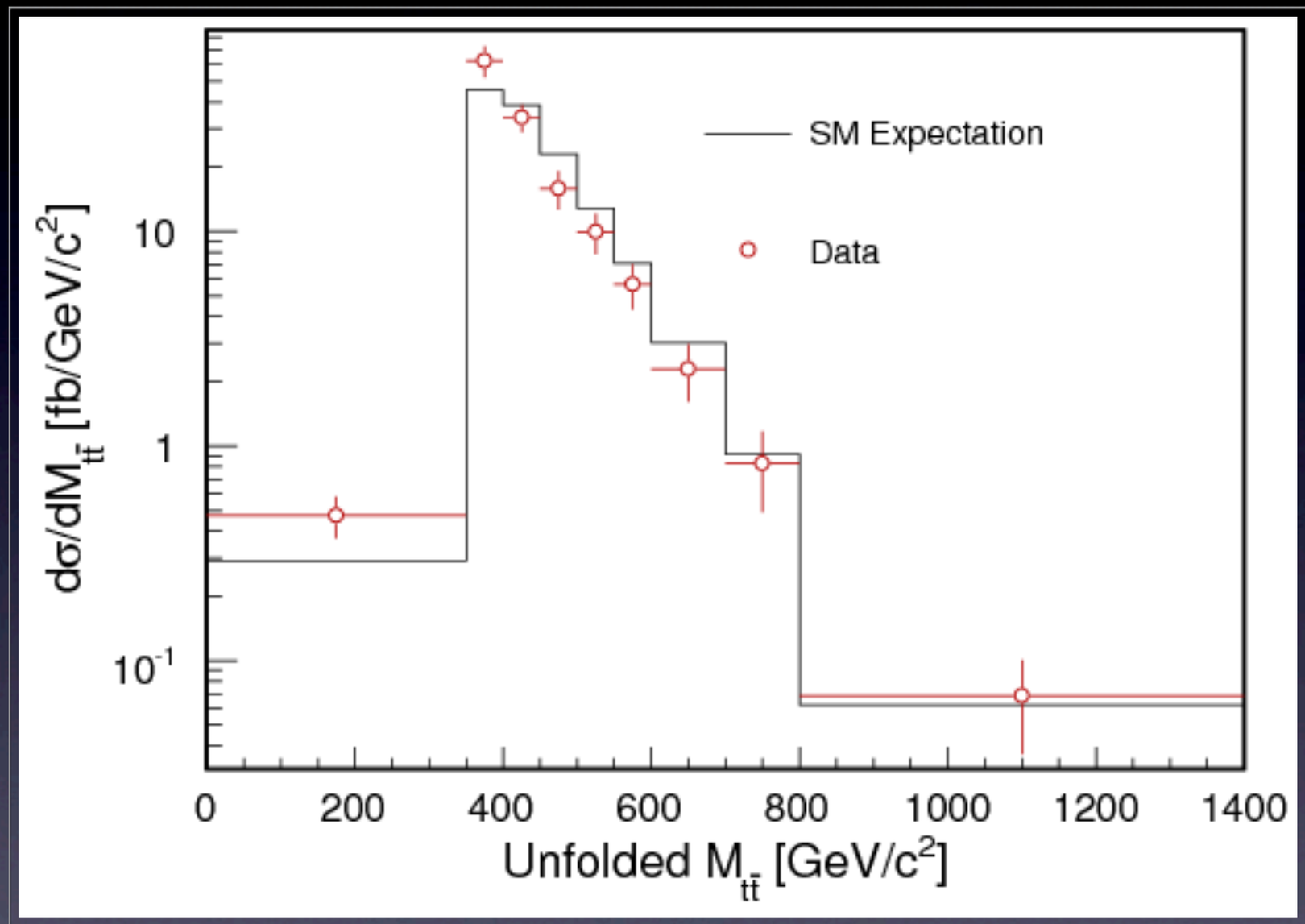



1101.0034 (cited > 240)

# Top-quark $A_{FB}$ and NP models

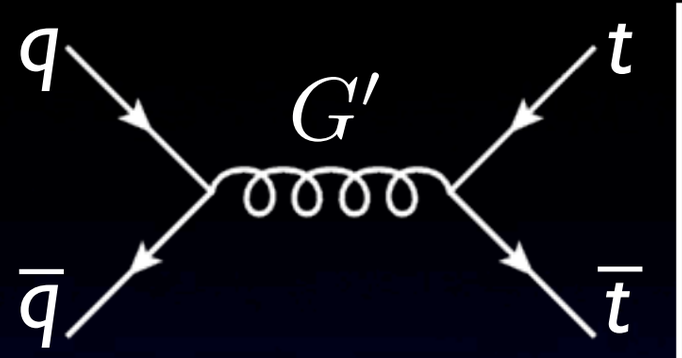
CDF, Phys.Rev.Lett. 102 (2009) 222003




It provides upper bounds on NP resonance.
The large bin (800GeV-1400GeV) is
the most sensitive to a heavy resonance

# Top-quark $A_{FB}$ and NP models

## *s-channel*




Frampton, Shu, Wang, 0911.2955

Qing-Hong Cao, McKeen, et al, 1003.3461

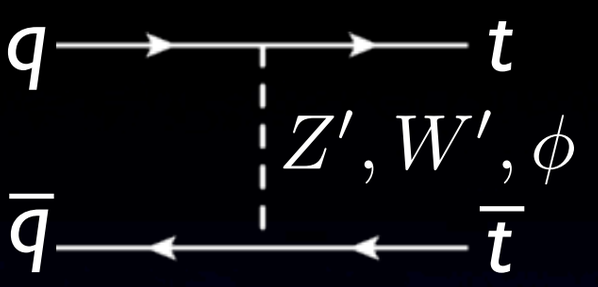
Wang, Wang, Xiao, Xu, Zhu, 1104.1917

Wang, Wang, Xiao, Zhu, 1107.5769

Bai, et al, 1101.5203

Zhu, C. S. Li, Shao, Wang, Yuan, 1201.0672

## *t-channel* (Flavor changing)




Cheung, Keung, Yuan, 0908.2589

Shu, Tait, Wang, 0911.3237

Cao, Heng, Wu, Yang, 0912.1447

Qing-Hong Cao, McKeen, et al, 1003.3461

Cheung, Yuan, 1101.1445

Cao, Wang, Wu, Yang, 1101.4456


Shu, Wang, Zhu, 1104.0083

Chen, Law, Li, 1104.1497

Cui, Han, Schwartz, 1106.3086

Liu, Tang, Wu, 1108.5012

Cao, Hikasa, Wang, Wu, Yang, 1109.6543

Yan, Wang, Shao, Li, 1110.6684

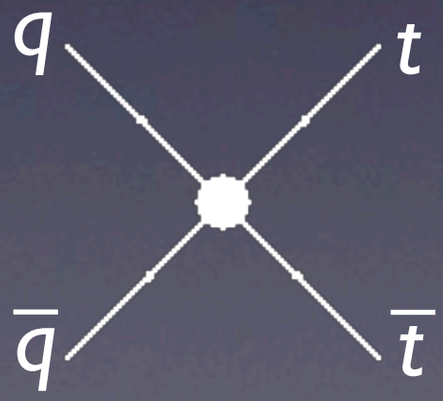
Wang, Wu, Yang, 1111.4771

Han, Liu, Wu, Yang, 1203.2321

Duffty, Sullivan, Zhang, 1203.4489


## *Effective theory*

(7 operators)

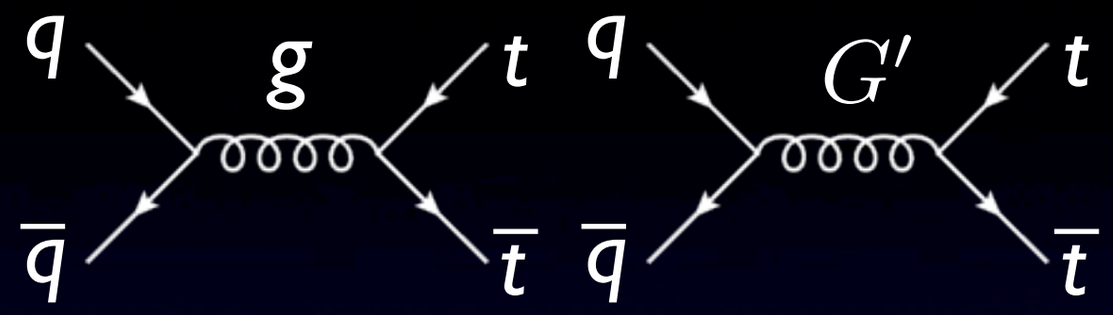



Qing-Hong Cao, McKeen, et al, 1003.3461

Shao, C. S. Li, Wang, Gao, Zhang, Zhu, 1107.4012

# S-channel: axigluon

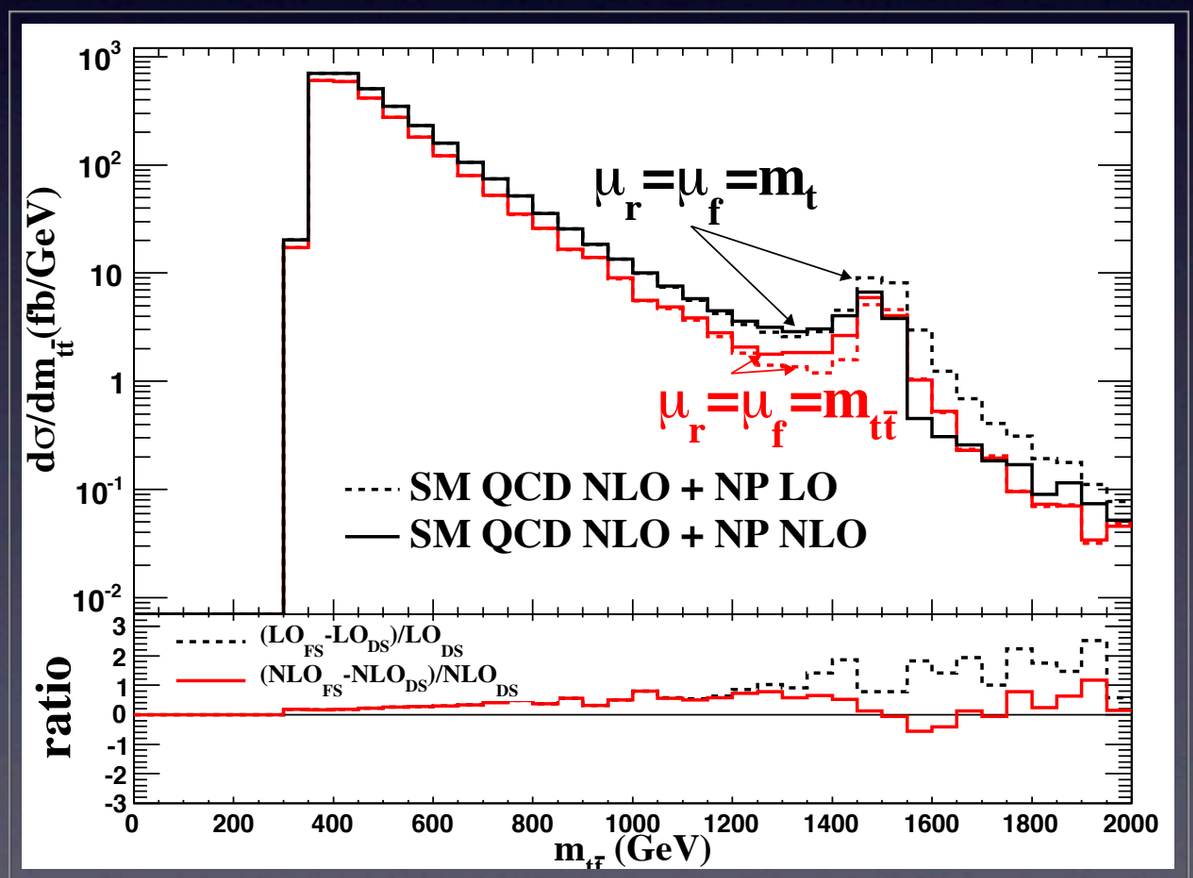
- Axigluon
  - additional gauge group
- KK-Gluon
  - new space-time structure




Dijet constraints requires *SMALL* couplings to light flavor quarks.

Large $A_{FB}$ demands *LARGE* couplings to top quarks.

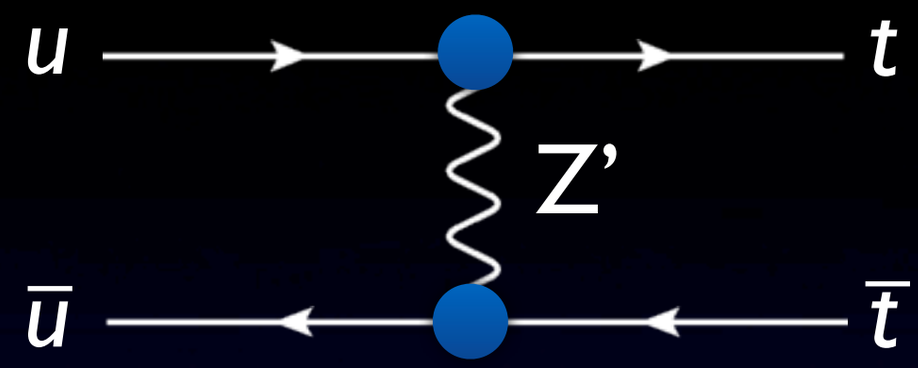
Boosted top "jet" (jet substructure)




Zhu, C. S. Li, Shao, Wang, Yuan, 1201.0672
(NLO QCD corrections)

# Minimal FCNC Z' is disfavored

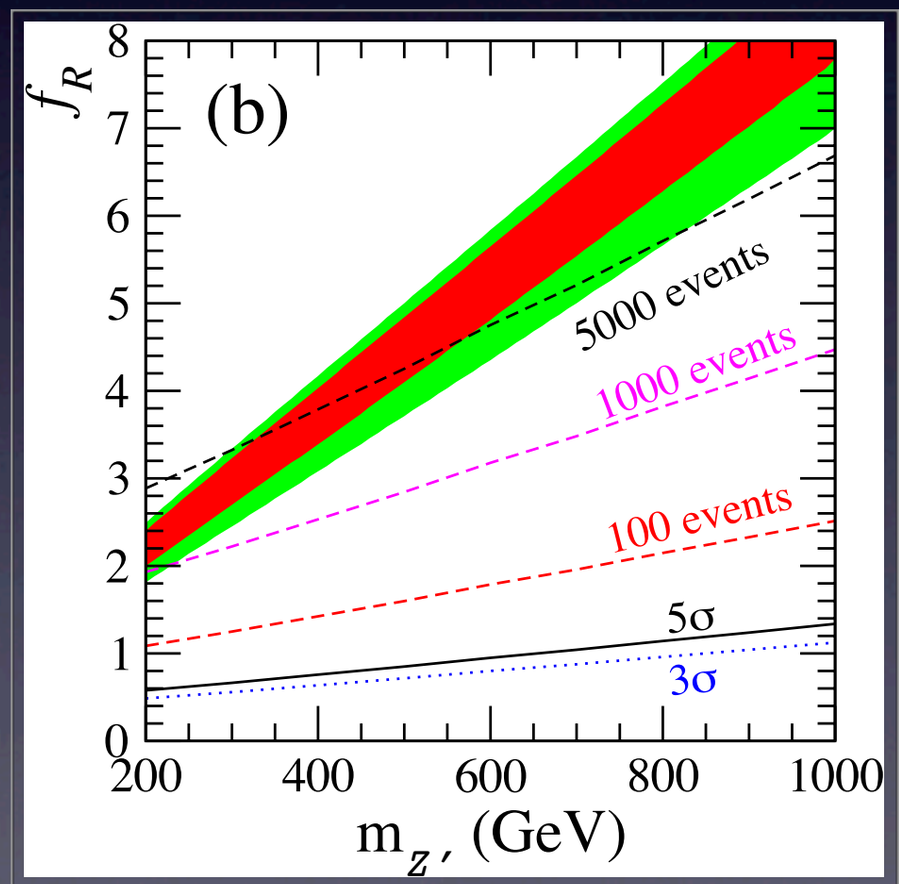
$$\mathcal{L} = g\bar{u}\gamma^{\mu}(f_L P_L + f_R P_R)tZ'_{\mu} + h.c.$$




Left-handed coupling is highly constrained by $B_d$ - $\overline{B}_d$ mixing.

$A_{FB}$ prefers a LARGE $f_R$.

Berger, *Qing-Hong Cao*, Chen, C. S. Li, Zhang,
PRL 106 (2011) 201801,




Other studies on same-sign top pair :

J. Cao et al, hep-ph/0703308, hep-ph/0409334
J. Cao, Wang, Wu, Yang, 1101.4456

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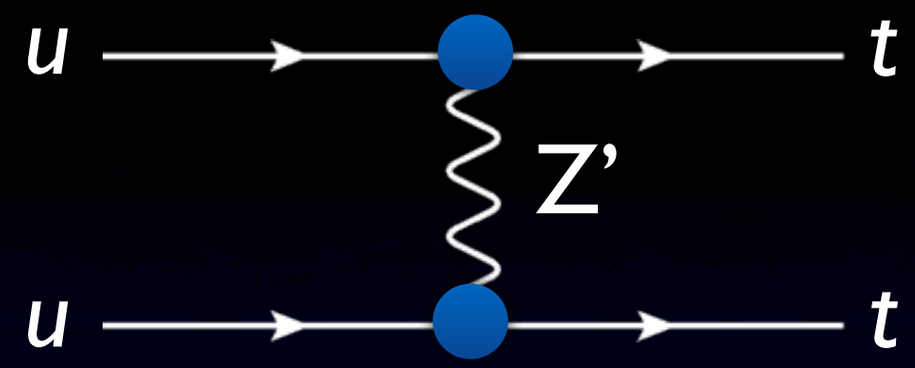


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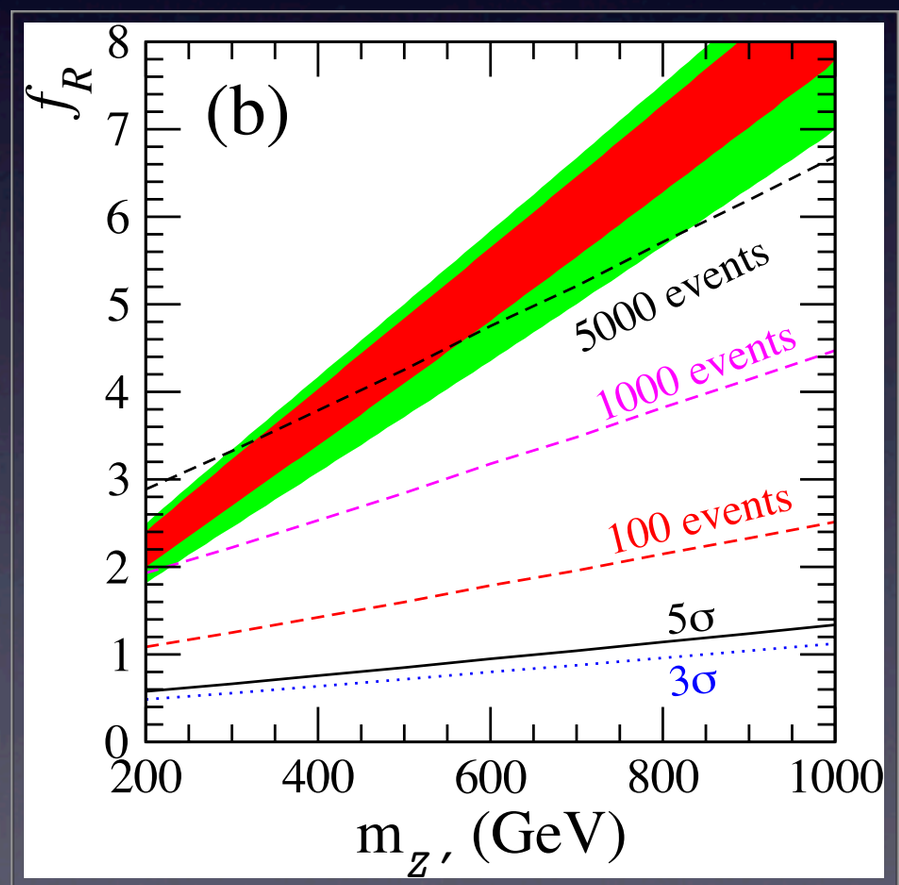


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J. Cao, Wang, Wu, Yang, 1101.4456

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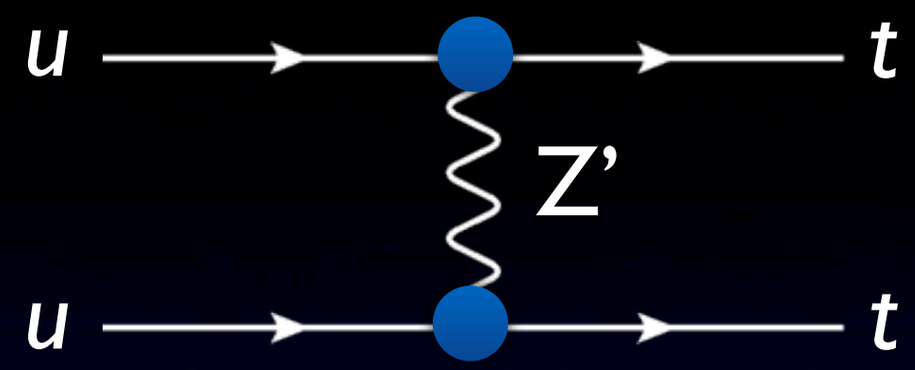


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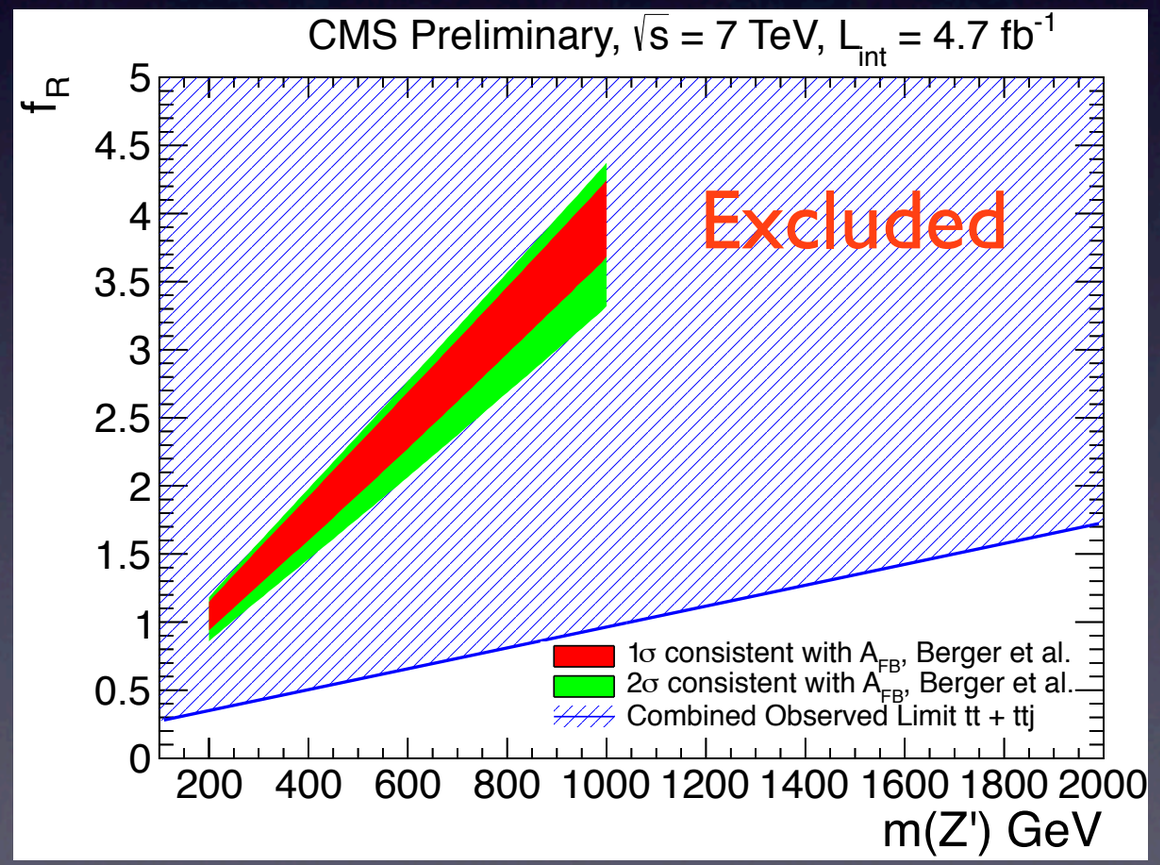
PRL 106 (2011) 201801,



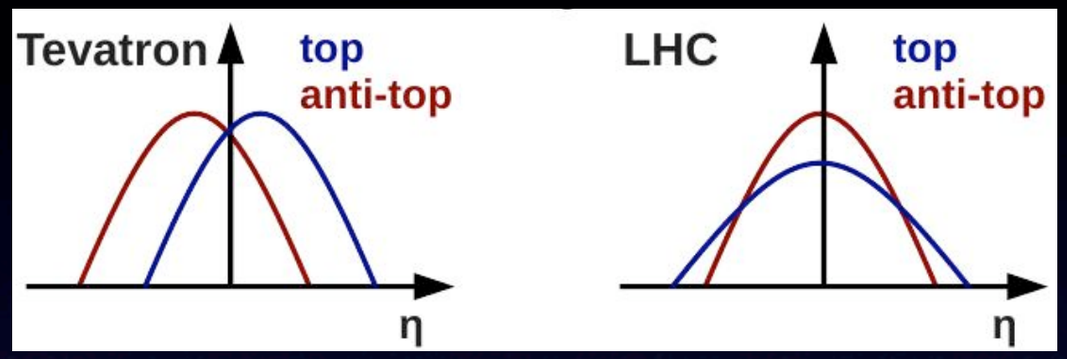

Other studies on same-sign top pair :

J. Cao et al, hep-ph/0703308, hep-ph/0409334
J. Cao, Wang, Wu, Yang, 1101.4456

# Top-quark $A_{FB}$ at the LHC

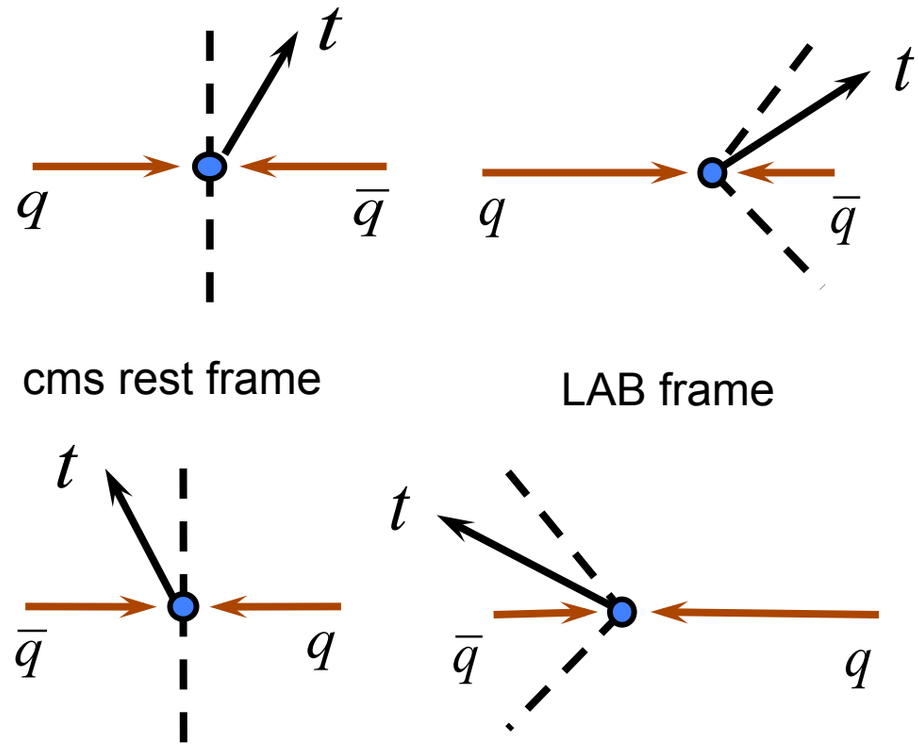
- $A_C$ definition

*LHC is symmetric (no F or B)*




$$\Delta y^{\rm Tev} = y_t - y_{\bar t} \qquad \Delta y^{\rm LHC} = |y_t| - |y_{\bar t}|$$

Quarks carry more momenta than antiquarks




$$A_C^{t\bar t} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

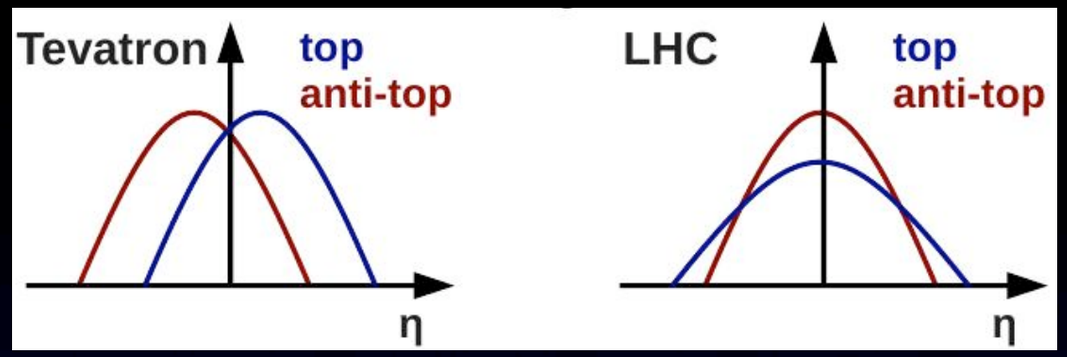
- One side asymmetry You-Kai Wang, Bo Xiao, Shou-Hua Zhu, 1008.2685

$$A_{\rm OFB} = \frac{\sigma(\Delta Y>0)-\sigma(\Delta Y<0)}{\sigma(\Delta Y>0)+\sigma(\Delta Y<0)}\Big| P^z_{t\bar t} > P^z_{\rm cut}, M_{t\bar t} > M_{\rm cut}$$

# Top-quark $A_{FB}$ at the LHC

- $A_C$ definition

$$A_C^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$




$$\Delta y^{\rm Tev} = y_t - y_{\bar{t}} \quad \Delta y^{\rm LHC} = |y_t| - |y_{\bar{t}}|$$

- One side asymmetry

You-Kai Wang, Bo Xiao, Shou-Hua Zhu, 1008.2685

$$A_{\rm OFB} = \frac{\sigma(\Delta Y>0)-\sigma(\Delta Y<0)}{\sigma(\Delta Y>0)+\sigma(\Delta Y<0)}\Big|_{P^z_{t\bar{t}}>P^z_{\rm cut}, M_{t\bar{t}}>M_{\rm cut}}$$

- Difficulty: gg fusion is dominant and symmetric

$$A_C \sim \frac{\sigma_{q\bar{q}}}{\sigma_{q\bar{q}} + \sigma_{gg}} \times A_{FB}^t \times \epsilon$$

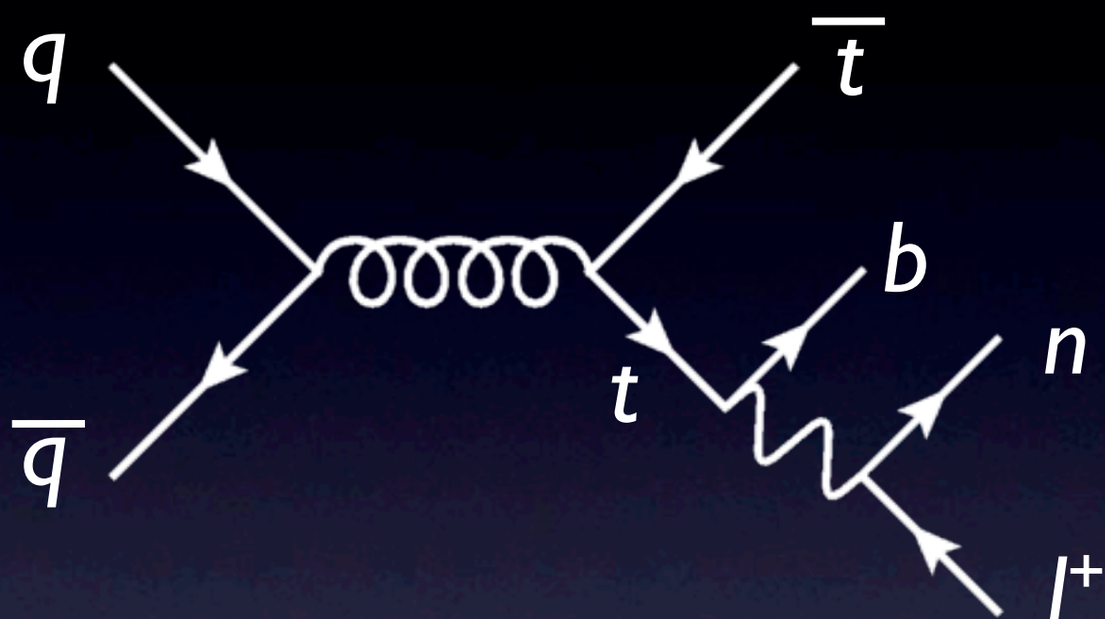
$$\sim 20\% \times 5\% \times 50\% \sim 0.005$$

Separate *qq* and *gg* initial state

It is hard to measure in hadron collision.

# $A_{FB}^{\ell}$ versus $A_{FB}^{t}$

- Charged lepton is maximally correlated with top-spin.




Bernreuther, Zong-Guo Si, NPB837 (2010) 90

SM: $A_{FB}^{t} = 0.051 \pm 0.001$

$A_{FB}^{\ell} = 0.021 \pm 0.001$

$$\left.\frac{A_{FB}^{\ell}}{A_{FB}^{t}}\right|_{\rm SM} \sim \frac{1}{2}$$

D0: $A_{FB}^{t} = 0.196 \pm 0.065$

$A_{FB}^{\ell} = 0.152 \pm 0.040$

$$\left.\frac{A_{FB}^{\ell}}{A_{FB}^{t}}\right|_{\rm D0} \sim \frac{3}{4}$$

CDF: ($8.7 fb^{-1}$) $A_{FB}^{t} = 0.085 \pm 0.025$

$A_{FB}^{\ell} = 0.066 \pm 0.025$

(Before unfolding)

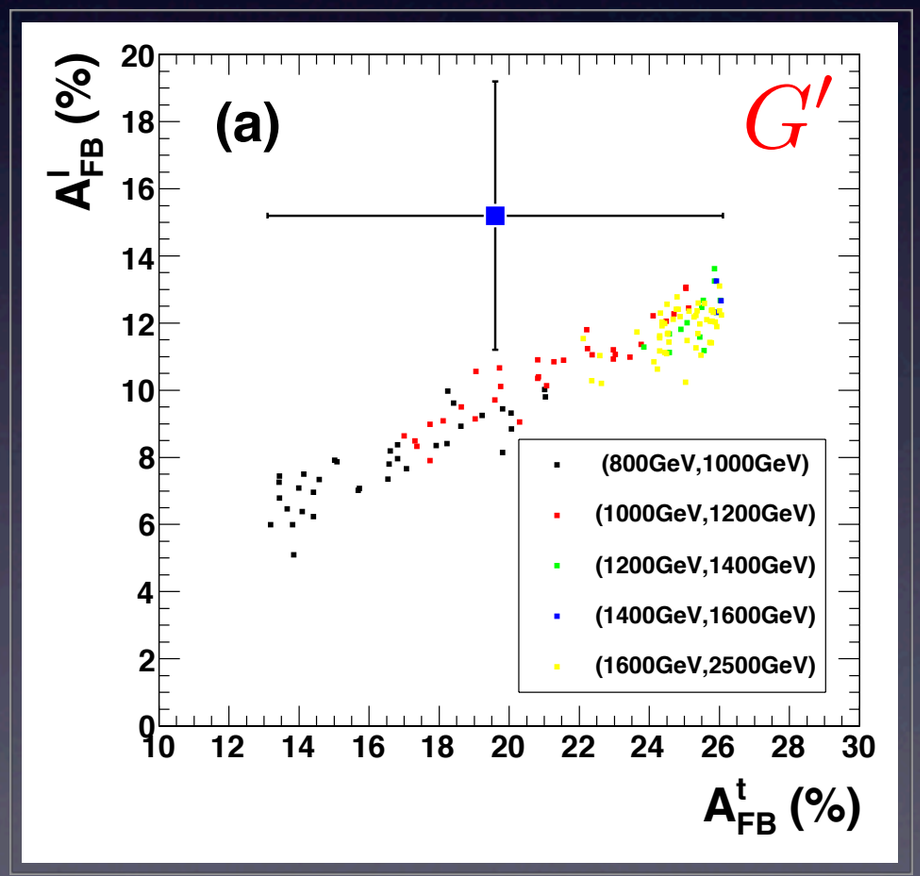
$$\left.\frac{A_{FB}^{\ell}}{A_{FB}^{t}}\right|_{\rm inc} \sim \frac{3}{4} \qquad \left.\frac{A_{FB}^{\ell}}{A_{FB}^{t}}\right|_{>450} \sim \frac{3}{5}$$

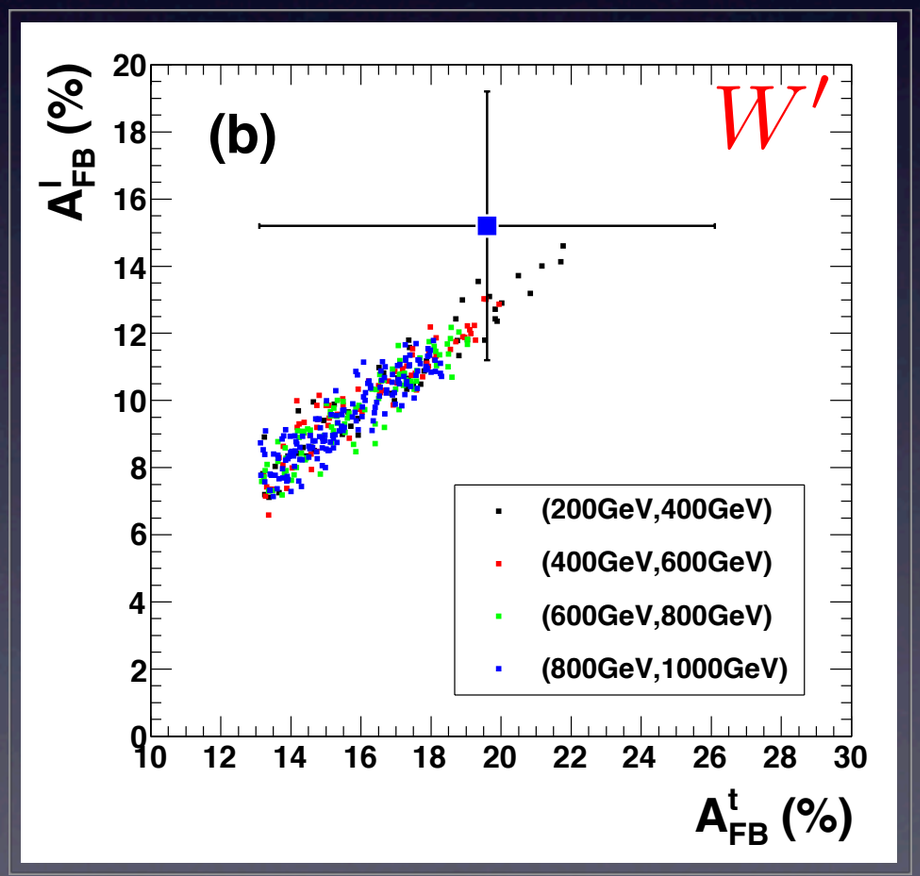
# $A_{FB}^{\ell}$ versus $A_{FB}^{t}$

Berger, *Qing-Hong Cao*, Chen, Yu, Zhang, PRL 108 (2012) 072002

- $A_{FB}^{t}$ and $A_{FB}^{\ell}$ is connected by the top-quark and charged lepton spin correlation.

$$A_{FB}^{\ell} \approx \rho_{t_L} A_{FB}^{t_L} \times \left(2\mathcal{R}_F^{t_L} - 1\right) + \rho_{t_R} A_{FB}^{t_R} \times \left(2\mathcal{R}_F^{t_R} - 1\right)$$



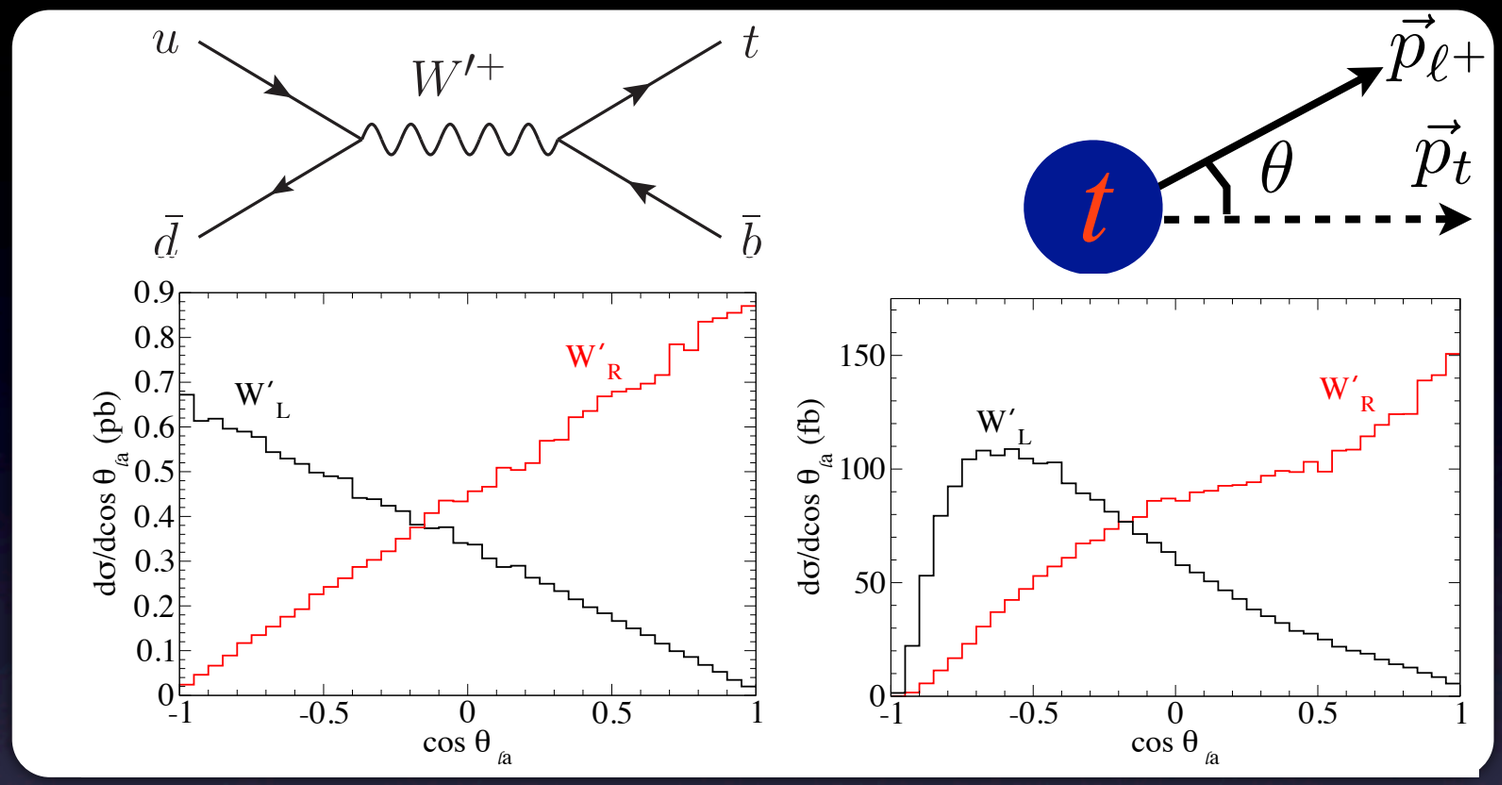

$$A_{FB}^{\ell} \simeq 0.47 \times A_{FB}^{t} + 0.25\%$$

$$A_{FB}^{\ell} \simeq 0.75 \times A_{FB}^{t} - 2.1\%$$

# Search for heavy resonances ($t\bar{t}$, $tt$, $tb$, $t\bar{t}$+$VV$, direct-$t$)

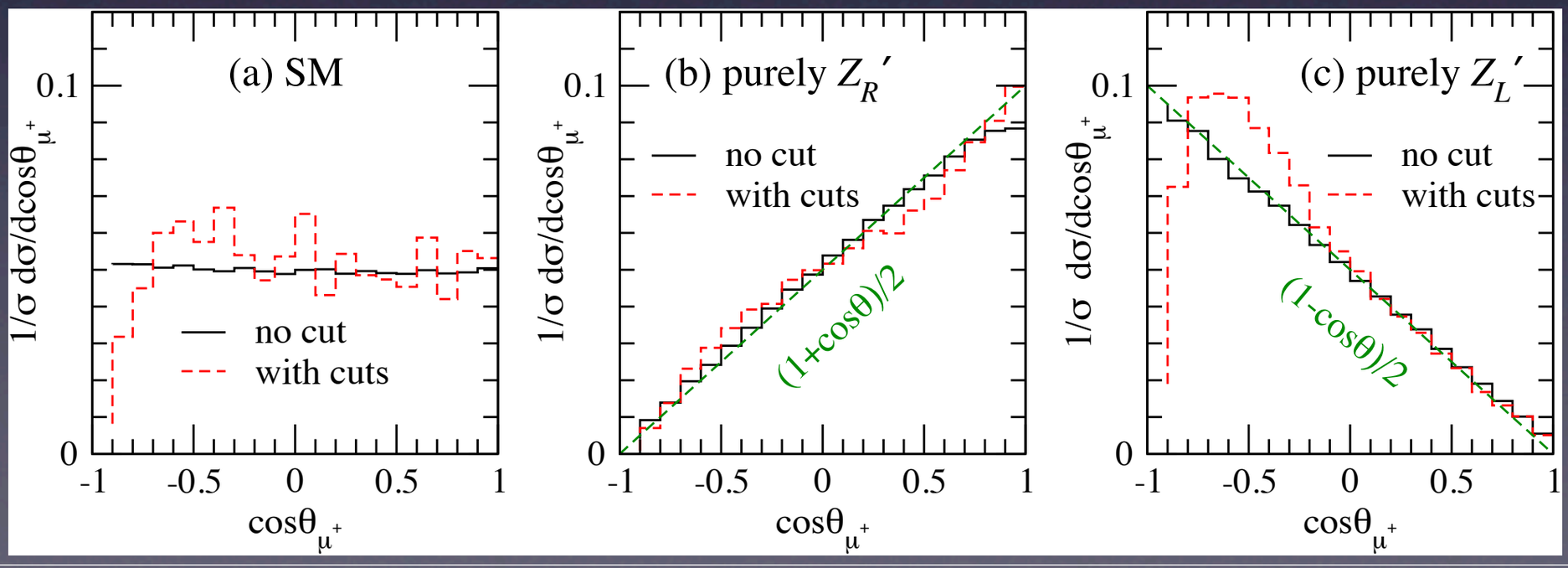
# Measuring W'-t-b and Z'-t-t couplings

★ Top polarization can probe the handness of W'-t-b coupling.




Gopalakrishna, Han, Lewis, Si, Zhou, PRD82 (2010) 115020

★ Top polarization can probe the handness of Z'-t-t coupling.

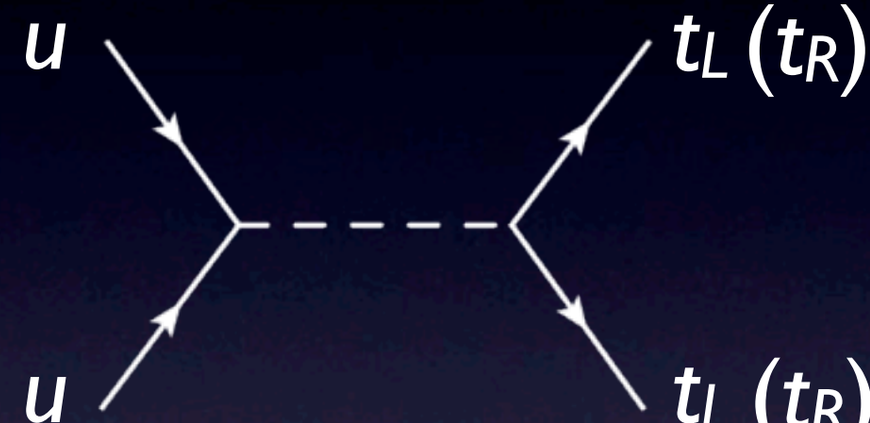



Berger, Qing-Hong Cao, Chen, Zhang, PRD83 (2011) 114026

# Exotic color scalars

- Same-sign top-quark pair

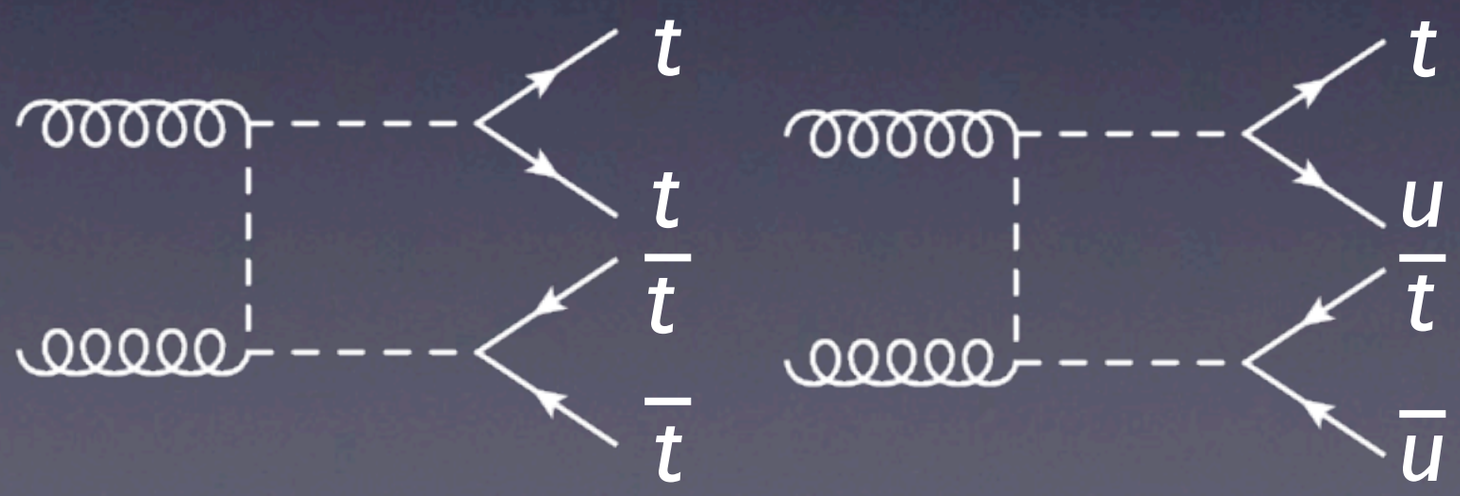
Mohapatra, Okada, Hai-Bo Yu, 0709.1486
Berger, *Qing-Hong Cao*, Chen, Shaughnessy, Zhang, PRL 105 (2010) 181802




$$3 \otimes 3 = 6 \oplus \bar{3}$$

- Four top-quarks or two top-quarks plus jets

Chen, Klemm, Rentala, Wang, 0811.2105



# Motivation for heavy quark

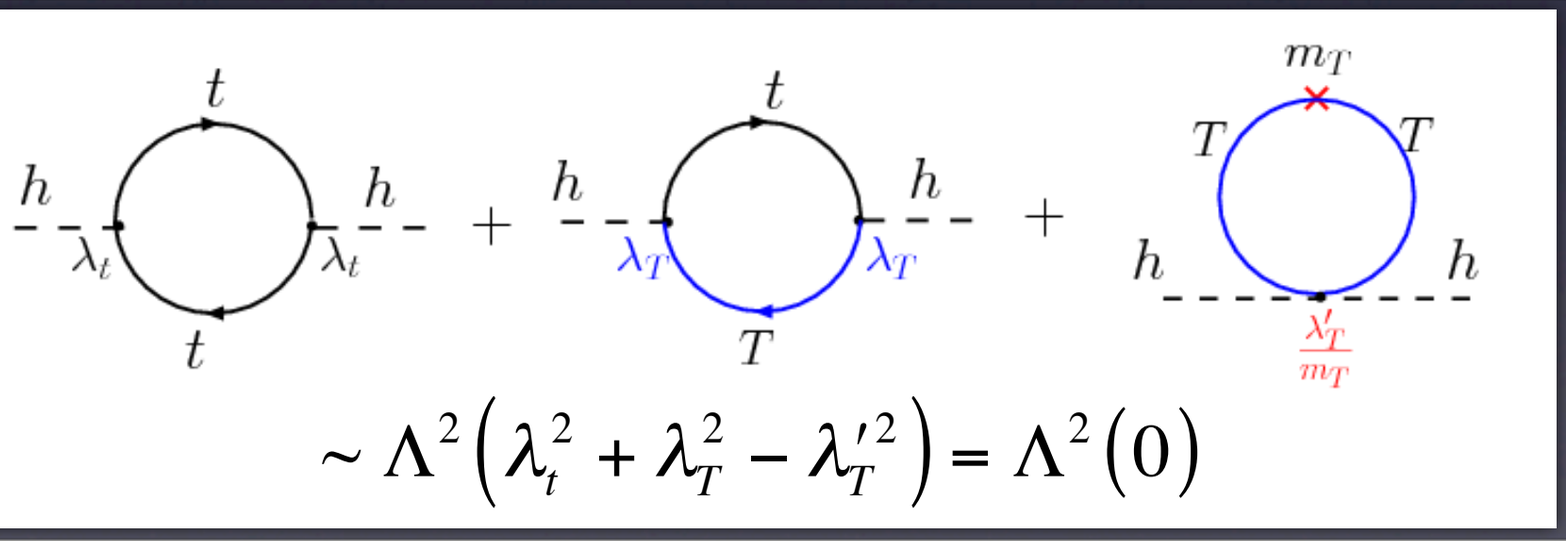
- Natural NP models always have non-trial couplings between tops and new physics:

  *Higgsless, Little Higgs, RS, SUSY, TC, ...*

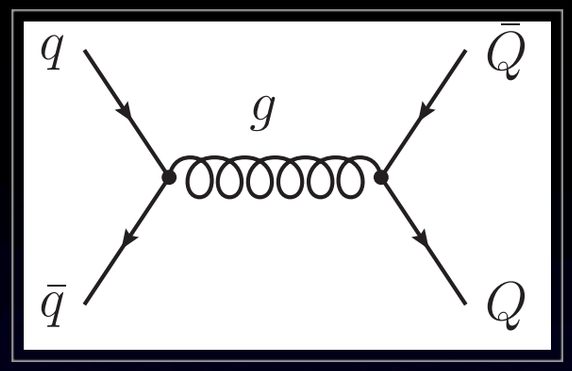
- New heavy quark loops stabilize EWSB

...

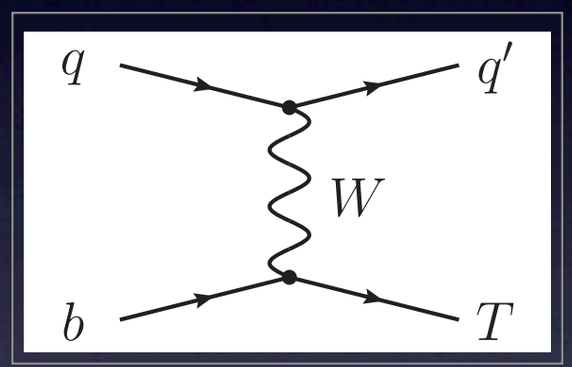
## The Little Higgs Models



# Heavy quark production and decay




- Pair production via QCD
  - Major discovery channel for small $M_Q$
  - Sensitive to decay BRs, but not the couplings




- Single production via EW
  - Determine the weak coupling strength of heavy quark
  - Probe the mixing of SM quarks and heavy quarks
  - Depend on quark flavors

- Heavy quark decay
  - through Yukawa mixing with SM quarks
  - via CKM mixing

eg.

$$T' \to W^+ b,\ Zt,\ ht$$

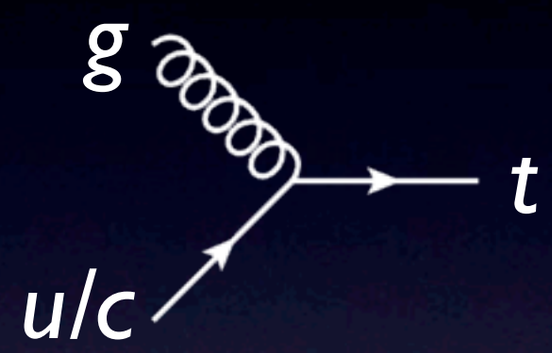
# Direct top-quark production

- Anomalous g-q-t FCNC coupling

$$\mathcal{L} = g_s \sum_{q=u,c} \frac{\kappa_{tqg}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c.$$

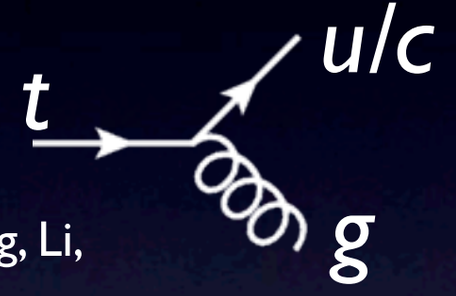
★ NLO $K_F$ ~1.3-1.5
★ promising at the LHC

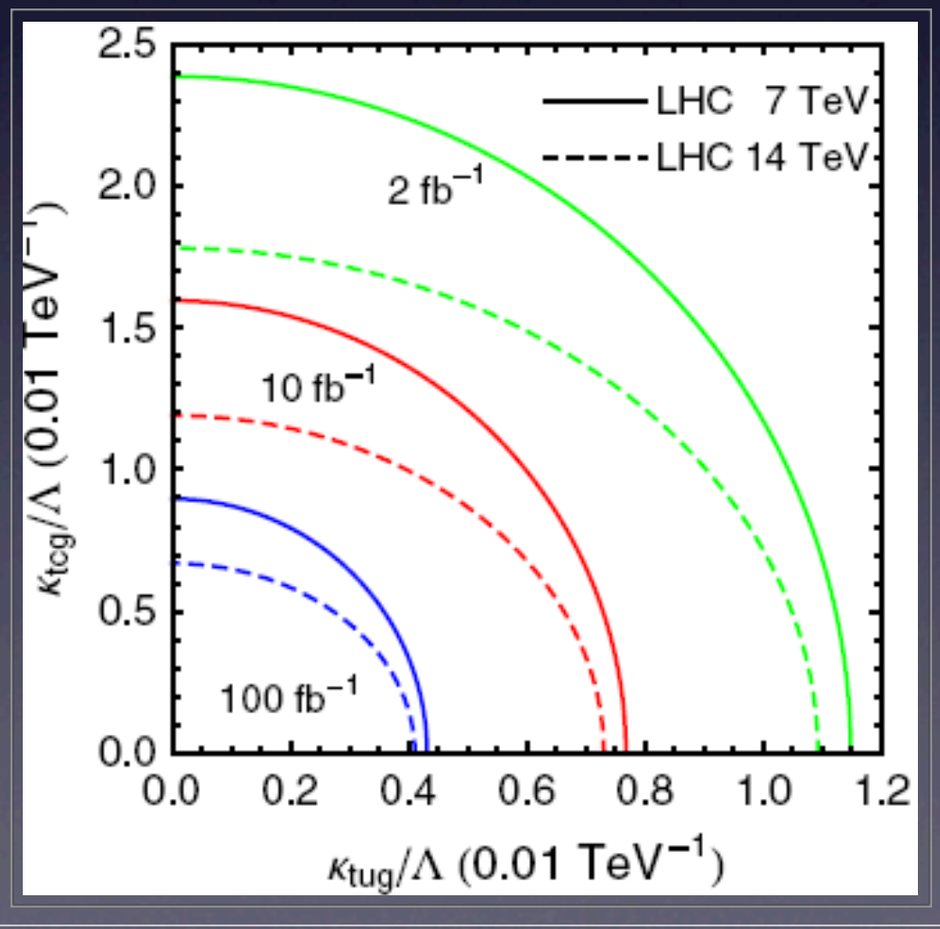
Gao, C. S. Li, Yang, Zhang,
PRL 107 (2011) 092002

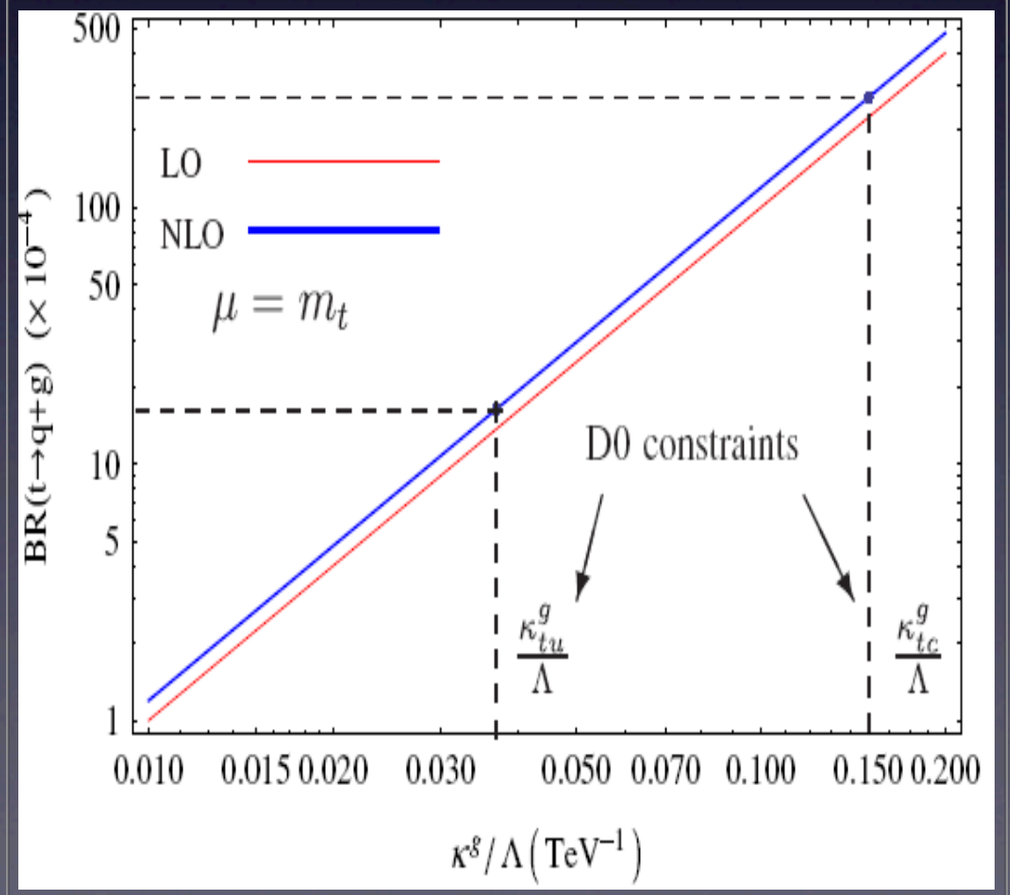



★ NLO $K_F$ ~1.2

Zhang, C. S. Li, Gao, Zhang, Li,
PRL 102 (2009) 072001



# More ...

- CP violation in single-top production

  and top-quark pair productions

- Top-quark effective theory
  - *Wtb* coupling (*W* Helicity)
  - Top-quark chromo-dipole, etc.
- Top-quark spin correlations
- Top-quark rare decay
- Top-quark Yukawa couplings
- ...

# Summary

## Questions

What is the Higgs boson mass?

Do we understand heavy flavor production in QCD?

Are there more than three fermion generations?

Are there new massive particles?

Does top quark have the expected couplings?

## Measurements

- Top quark mass
- Top quark pair production cross section
- Charge asymmetry of top pair
- $m_{t\bar{t}}$ distribution
- Single top production
- Search for t-prime quark
- Searches for $H^+ \to t\bar{b}$ or $t \to H^+\bar{b}$
- Constraints on Wtb coupling
- W boson helicity
- Search for FCNC top interaction


# SUSY国际会议

(plenary speaker)

Kingman Cheung, Keith Dienes, Yuanning Gao, Rohoni Godbole, Hong-Jian He, Gondon Kane, Rocky Kolb, Shih-Chang Lee, Kirill Melnikov, Takeo Moroi, Hitoshi Murayama, Pran Nath, Sanjay Padhi, Pavel Fileviez Perez, Adrian Perieanu, Pascal Pralavorio, Fernando Quevedo, Nathan Seiberg, Guido Tonelli, Michael Turner, Henry Tye, Liantao Wang, Yi-Fang Wang, Yueliang Wu, Zhi-Zhong Xing, C.-P. Yuan, Dieter Zeppenfeld

# Pre-SUSY暑期学校

- Standard Model (Jens Erler)
- SUSY theories (X. Tata)
- SUSY phenomenology (Mihoko Nojiri)
- Higgs physics
- BSM (C. Chacko)
- Monte Carlo tools (Johan Alwall)
- Collider phenomenology (Michael Spannowsky)
- Dark matter (Jason Kumar)

感谢兄弟院校的大力支持！

# Thank You!