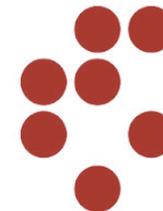


Top Physics Theory

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Slovenia



LHC Days in Split

29 September - 4 October 2014

Diocletian's Palace / Palazzo Milesi

Split, Croatia

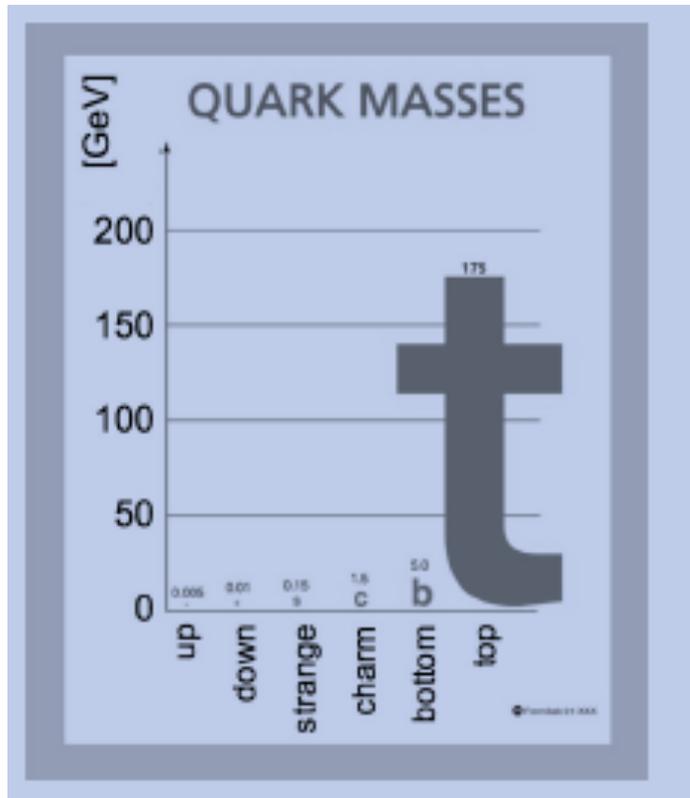


Overview

1. Basic top properties;
2. Top and theory development in LHC era;
3. Top production (SM & NP);
4. Top decays (SM & NP);
5. Summary and outlook.

Top quark ID

The “youngest” quark – after long expectation found at Tevatron in 1995.



$$m_t = (173.21 \pm 0.51 \pm 0.71) \text{ GeV}$$

$$\Gamma = (2.0 \pm 0.5) \text{ GeV}$$

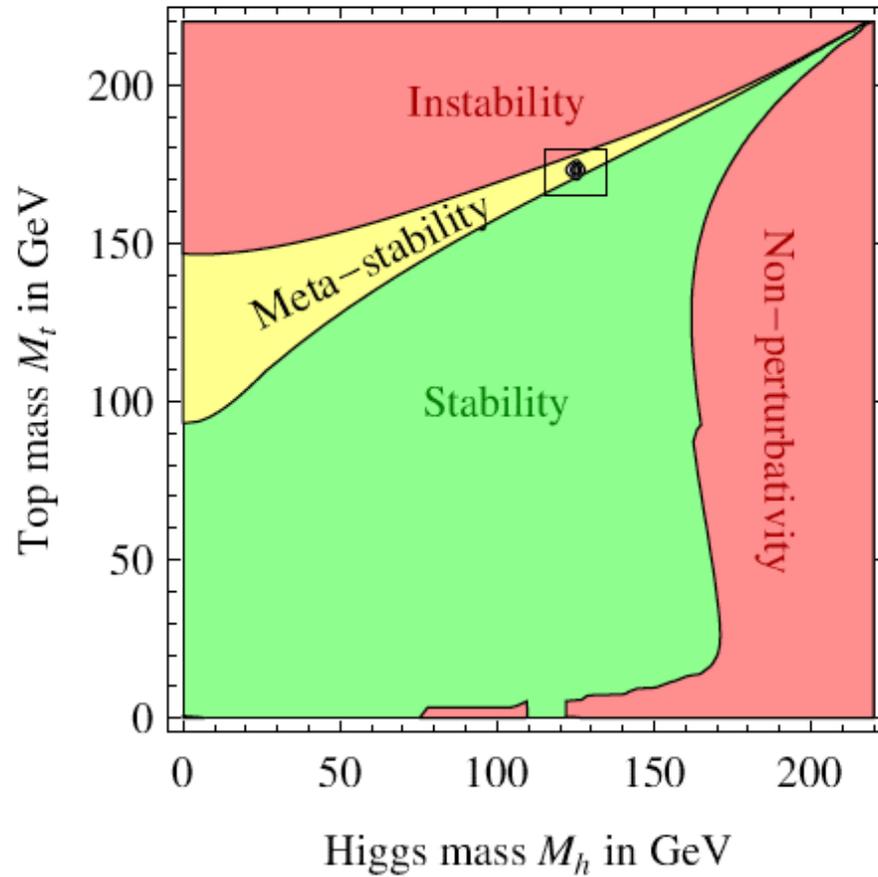
$$Q(t) = 2/3$$

Top decays before hadronizing - “free quark”

$$\alpha_s(m_t) \ll 1 \quad \text{perturbative QCD works!}$$

Electroweak vacuum stability

Why is important to know mass of top and Higgs precisely?



Bezrukov et al, 2012,
Alekhin, et al., 2012,
Butazzo et al., 2012,
(many more)

Degrassi, et al., 2012,
NNLO study of SM Higgs potential

If SM is extrapolated up to Planck scale, then masses of top and Higgs decide on vacuum stability!

Precision on top mass extremely important!

Mixing of top with a vector-like partner

- vector-like quarks are expected to be lightest new degree of freedom addressing EW hierarchy problem;
- vector-like quarks: left and right-handed quark transform the same way under $SU(2)_L$;
- LHC experiments search directly for vector-like quarks and results are not yet conclusive. One should investigate carefully allowed parameter space.



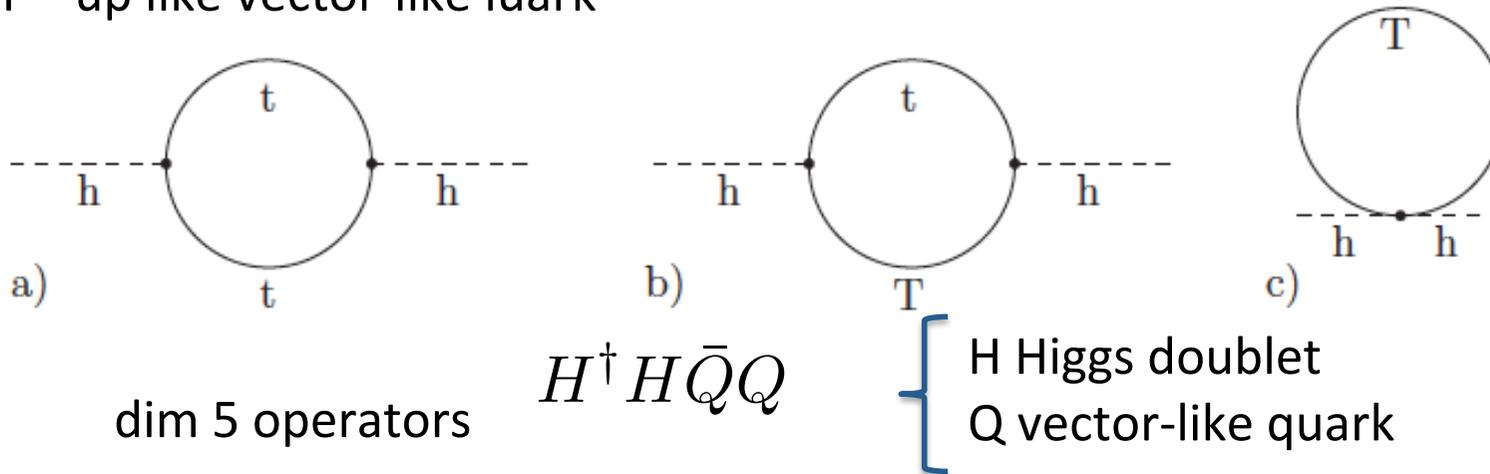
Vector-like quarks appear in many models of New Physics:

composite Higgs models (R. Contino et al, 2006 ...); topcolor models (B. Dobrescu & C. Hill, 1997, 1998, ...); Little Higgs models (N. Arkani-Hamed et al. 2002; M. Perelstein et al. , 2003,...); extra-dimensions (M. Carena et al. 2006,...) E_6 – representation 27, SF, Greljo, Kamenik, Mustac 2013; Dorsner, SF, Mustac, 2014.

Naturalness and vector-like quarks

Vector-like quarks: particle of the same statistics cancel quadratic divergences!

T – up like vector-like quark



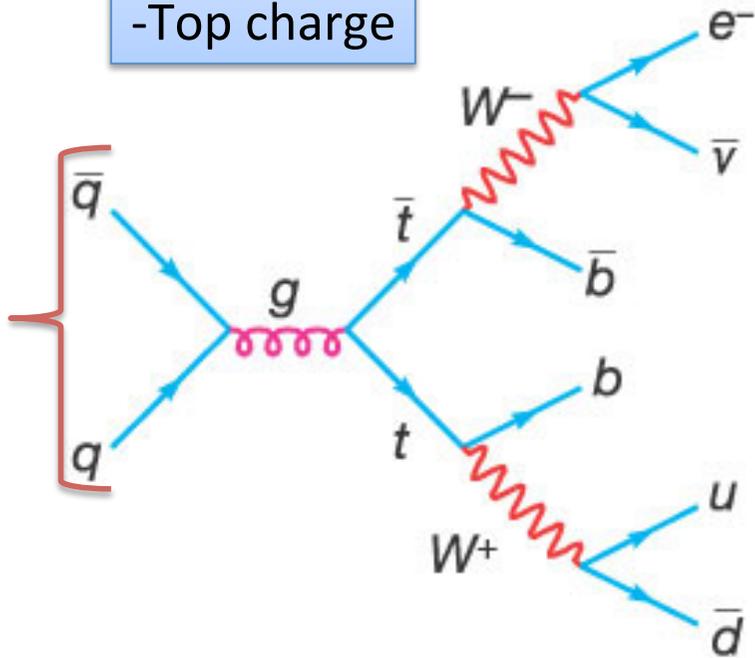
T mixes with the top! Physical top mass arise from Dirac mass term for T and SM Yukawa coupling! T can decay to tH , tZ and bW .

Interesting FCNC transitions occur at the tree level
e.g. Atlas searches

Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$	$1 e, \mu \geq 2 b, \geq 4 j$	Yes	14.3	T mass	790 GeV
	Vector-like quark $TT \rightarrow Wb + X$	$1 e, \mu \geq 1 b, \geq 3 j$	Yes	14.3	T mass	670 GeV
	Vector-like quark $TT \rightarrow Zt + X$	$2/\geq 3 e, \mu \geq 2/\geq 1 b$	-	20.3	T mass	735 GeV
	Vector-like quark $BB \rightarrow Zb + X$	$2/\geq 3 e, \mu \geq 2/\geq 1 b$	-	20.3	B mass	755 GeV
	Vector-like quark $BB \rightarrow Wt + X$	$2 e, \mu (SS) \geq 1 b, \geq 1 j$	Yes	14.3	B mass	720 GeV

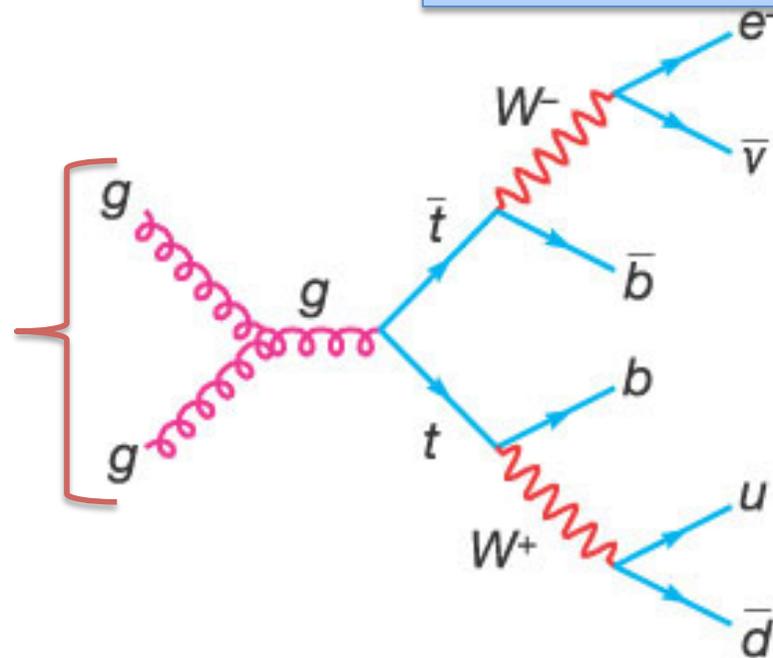
Top production and decay

- Top mass
- Top width
- Top spin
- Top charge



- Production cross-section
- Resonant production
- Top spin polarization
- Forward-backward (charge) asymmetry

- Anomalous couplings
- CP violation
- helicity fractions
- FCNC transitions



- Branching ratios
- $|V_{tb}|$
- Top compositeness

At Tevatron : limited statistics for top
1 pair was produced per day



At LHC: tops are everywhere
1 per second at LHC14

2010:

ATLAS: 37 top candidates
CMS: 10 top candidates

2012

ATLAS: combined channels with integrated luminosity $0.7-1.0 \text{ fb}^{-1}$

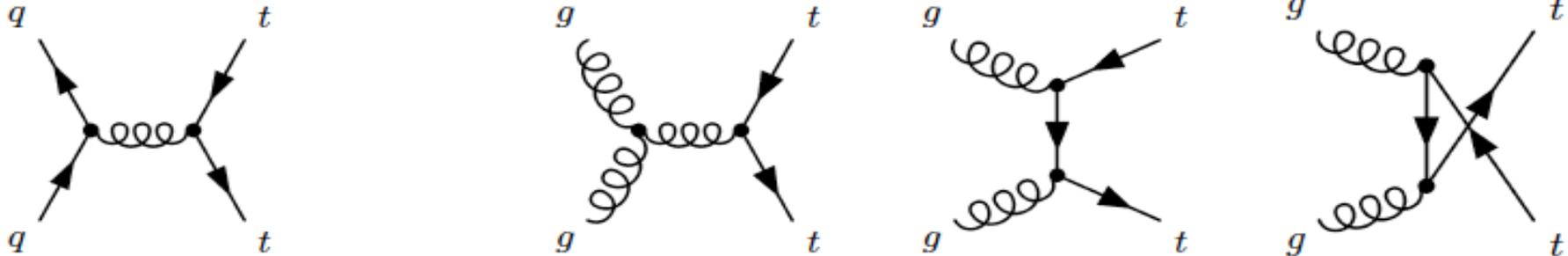
$$\sigma_{t\bar{t}} = 177 \pm 3 \text{ (stat.)} \pm 8 \text{ (syst.)} \pm 7 \text{ (lum.)} \cdot \text{pb}$$

CMS: combined channels with integrated luminosity $0.8-1.1 \text{ fb}^{-1}$

$$\sigma_{t\bar{t}} = 166 \pm 2 \text{ (stat.)} \pm 11 \text{ (syst.)} \pm 08 \text{ (lum.)} \cdot \text{pb}$$

LHC: top factory!

Double top production and QCD



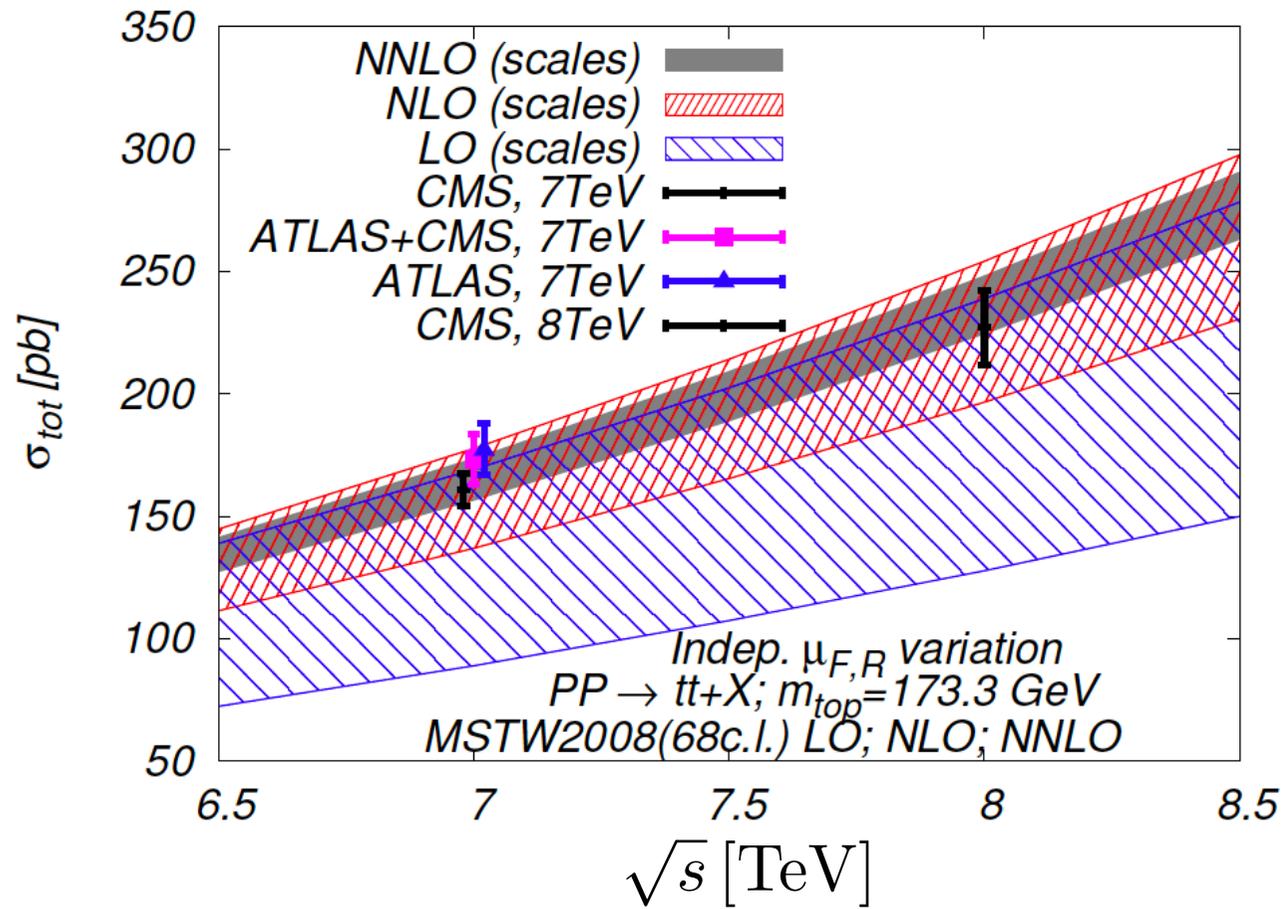
- $q\bar{q}$ production dominant at Tevatron ($\sim 90\%$ of cross section)
- gg production dominant at LHC ($\sim 75\%$ of cross section at 7 TeV)

NLO QCD known for 20 years!

NNLO / NNLL QCD predictions Czakon, Mitov, Fiedler, 2012, 13, 14

$$\sigma^{\text{NNLL}}(8\text{TeV}) = 245.8^{+6.2(2.5\%)}_{-8.4(3.4\%)} (\text{scale})^{+6.2(2.5\%)}_{-6.4(2.6\%)} (\text{PDF})$$

Total inclusive cross section known at NNLO (first calculation for $2 \rightarrow 2$ process)
 [Baernreuther, Fiedler, Mitov, Czakon 13,14]



Uncertainties:

- scales $\sim 3\%$
- pdf (at 68% c.l.) $\sim 2-3\%$
- α_s (parametric) $\sim 1.5\%$
- m_t (parametric) $\sim 3\%$

- NNLO calculation allows full use of impressive precision on experimental cross section;
- Many application possible: m_t , α_s extractions, PDFs,

Contributions of many authors

NLO QCD corrections to $t\bar{t}$ production

Nason, Dawson, Ellis; Beenakker, et al.; Mangano, Nason, Ridolfi

NLO QCD+ NLL Threshold resummation

Bonciani, et al.; Moch, Uwer; Cacciari et al.; Kidonakis, Vogt;
Banfi, Lanenen; Czakon, et al.; Beneke, et al.; ...

Mixed weak-QCD corrections

Beenakker, et al.; Kao, Ladinsky, Yuan; Bernreuther, Fückler, Si;
Kühn, Scharf, Uwer; Moretti, et al.

Mixed QED-QCD corrections

Hollik, et al.

P_T resummation for $t\bar{t}$ production

Huaxing Zhu's Talk

NLO QCD corrections to $t\bar{t} + jet$ production

Dittmaier, Uwer, Weinzierl; Melnikov, Schulze

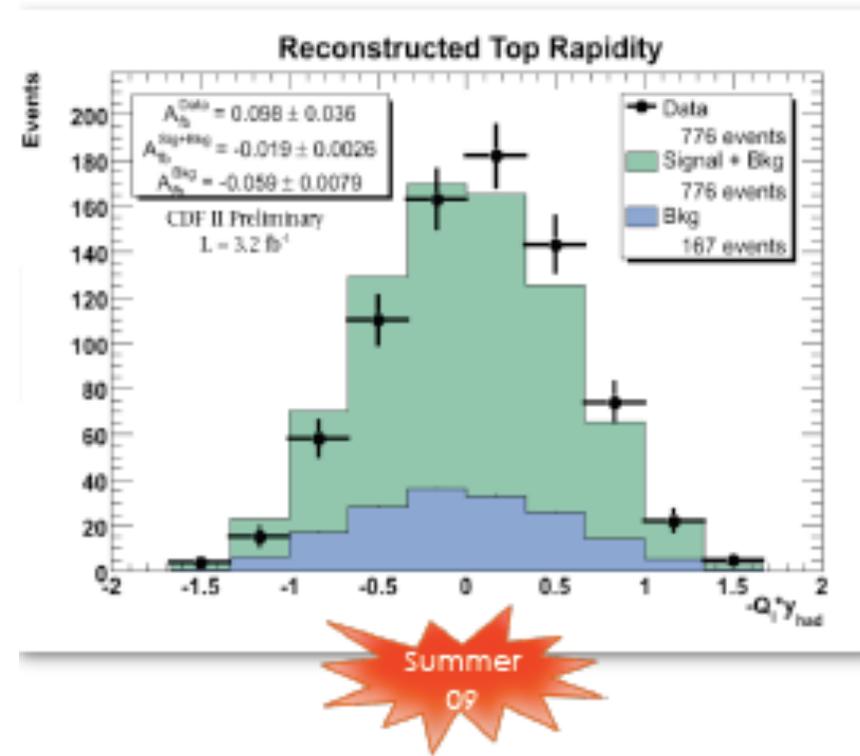
NNLO QCD corrections to hadronic $t\bar{t}$ production

Czakon, Mitov, Moch; Bonciani, et al.

Forward – backward anomaly in $t\bar{t}$ production at Tevatron

In summer 2009 Tevatron published anomalous behavior in top –anti-top production:

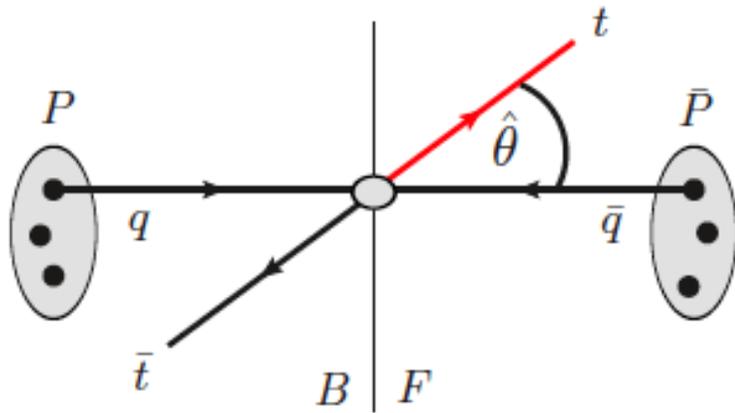
CDF



$$A_{FB}(t\bar{t}) = 0.193 \pm 0.065 \text{ (stat.)} \pm 0.024 \text{ (syst.)}$$

D0

$$A_{FB}(t\bar{t}) = 0.12 \pm 0.08 \text{ (stat.)} \pm 0.015 \text{ (syst.)}\%$$



$$A_{\text{FB}}^t = \frac{N_t(F) - N_t(B)}{N_t(F) + N_t(B)}$$

rapidity $y = \frac{1}{2} \log \frac{E + p_z}{E - p_z}$

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

Forward-backward asymmetry

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

for

$$p\bar{p} \rightarrow t\bar{t}X$$

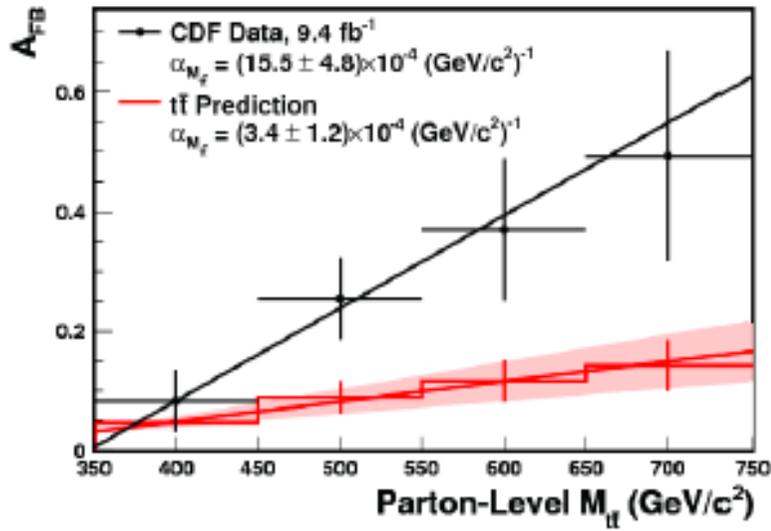
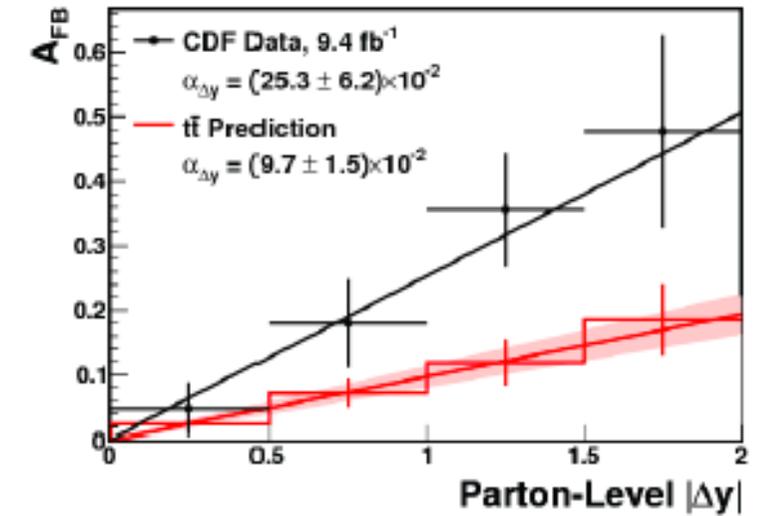
in the $t\bar{t}$ rest frame

This is equivalent to A_{FB} in $q\bar{q} \rightarrow t\bar{t}$ process, instead of y , $\cos \theta$

$$A_{\text{FB}} = \frac{N(\cos \theta > 0) - N(\cos \theta < 0)}{N(\cos \theta > 0) + N(\cos \theta < 0)}$$

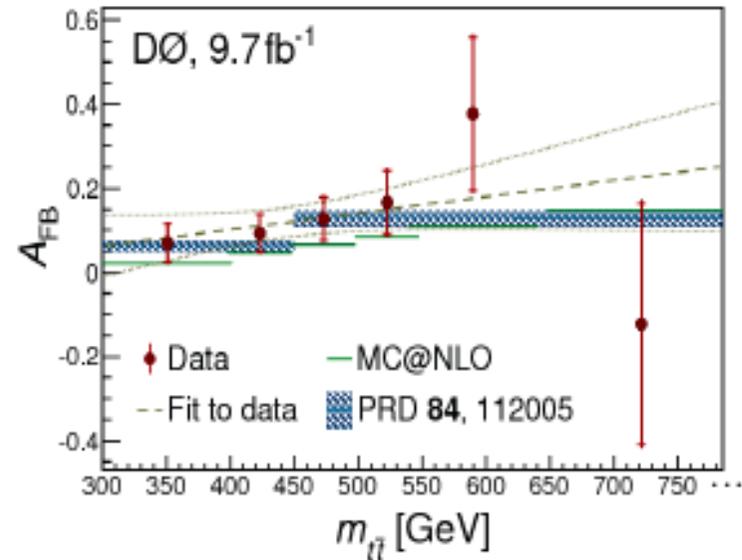
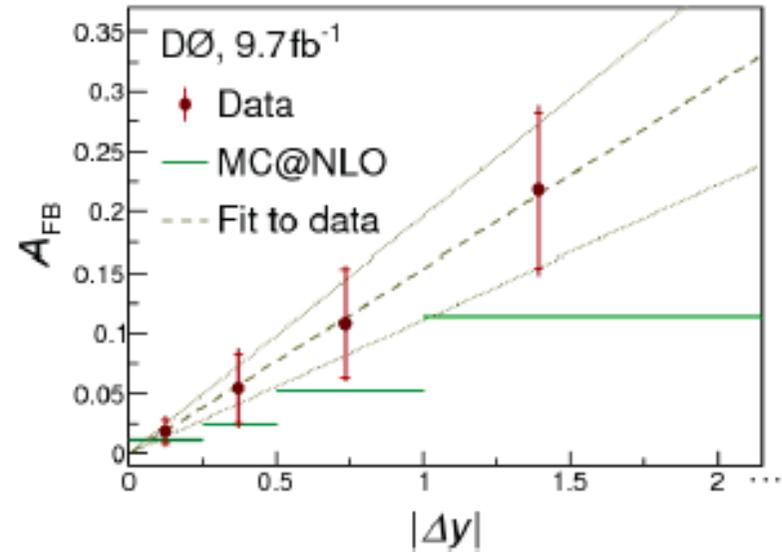
CDF Inclusive asymmetry (2012)

$A_{FB} = 0.164(47)$ 1.6σ

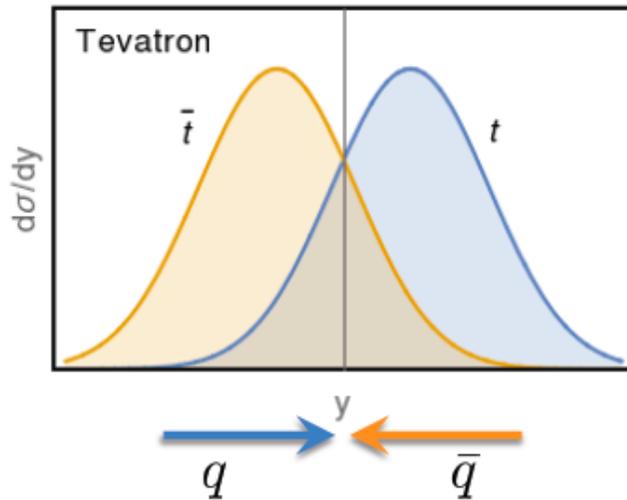


D0 Inclusive asymmetry (2014)

$A_{FB} = 0.106(30)$ 0.6σ

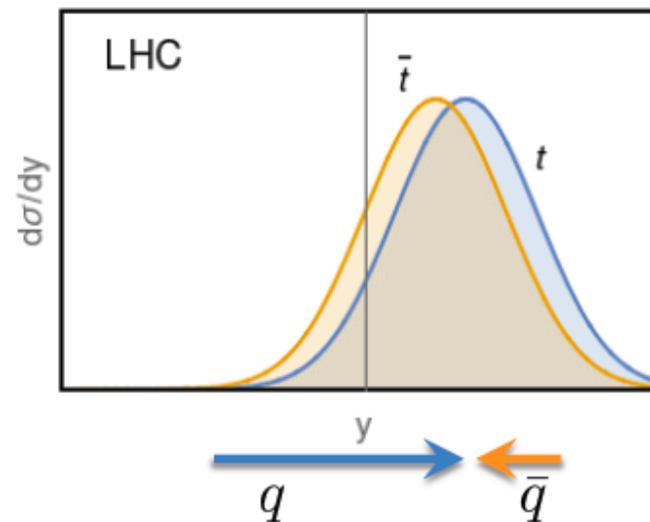
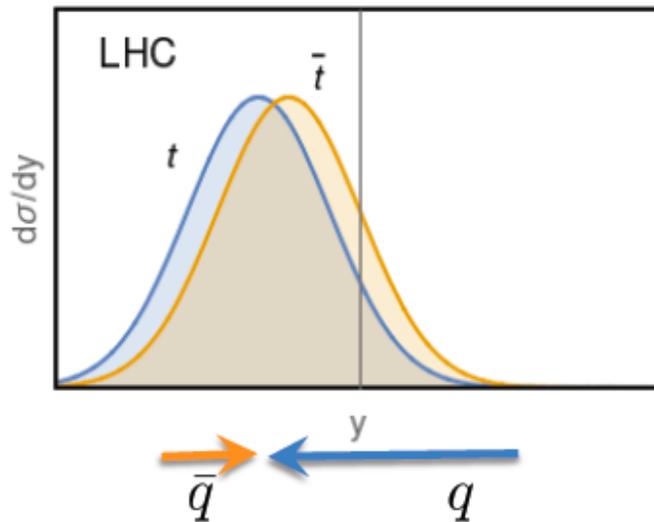


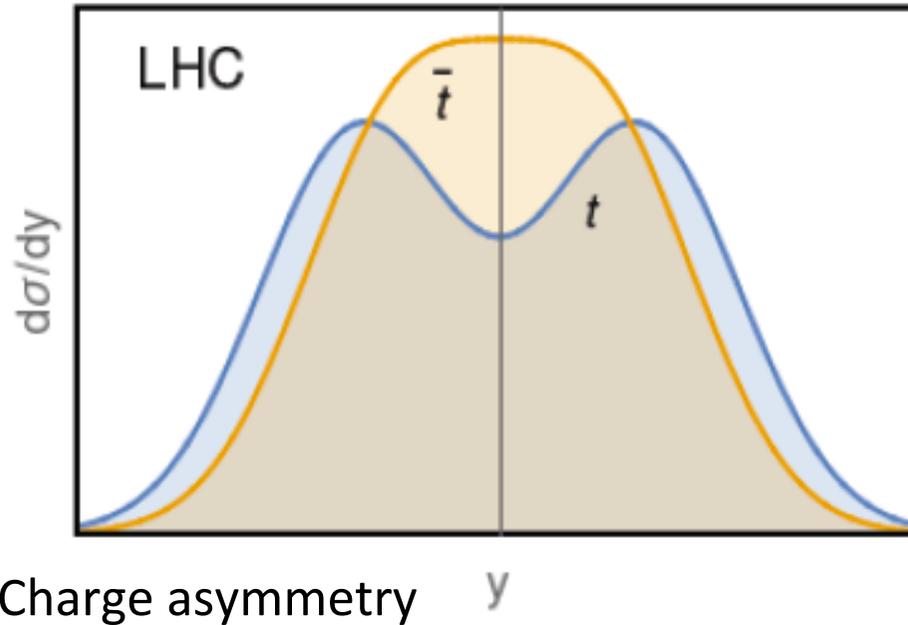
From Tevatron to LHC



At Tevatron: valence quarks and valence anti-quarks of similar momentum collide;

At LHC no forward-backward, but charge asymmetry, valence quarks collide with sea anti-quarks, which carries less momentum





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

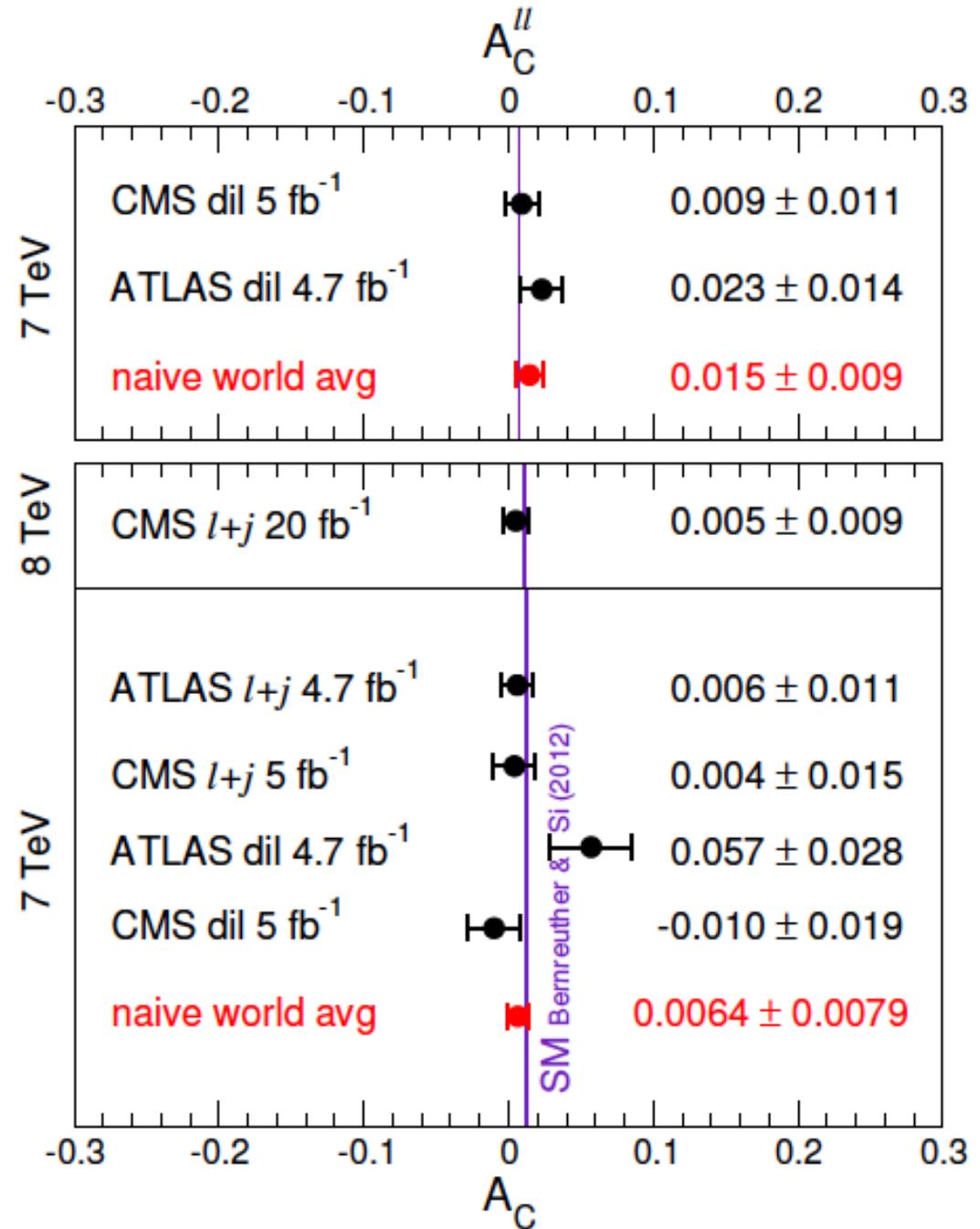
$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

At Tevatron $A_{FB} = A_C$
(if there is no CP violating couplings)

At LHC $A_{FB} = 0$; $A_C(\text{total}) = 0$

$pp \rightarrow t\bar{t}$ symmetric
However, more tops than anti-tops
in the forward direction!

At LHC gg dominates over q q production: it causes that the charge asymmetry is diluted.



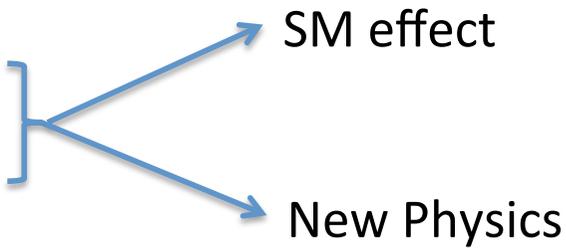
A_{FB} in SM appears at $\mathcal{O}(\alpha_s^3)$



QCD diagrams that generate asymmetry (Khun&Rodrigo '98)

- charge asymmetry starts at NLO (Khun&Rodrigo'98);
- for $t \bar{t} + \text{jets}$ starts already at LO;
- EW effect $\sim 25\%$ effect Holik, Pagani '11, Bernreuther, Si'12..

A_{FB} Tevatron anomaly can be explained as



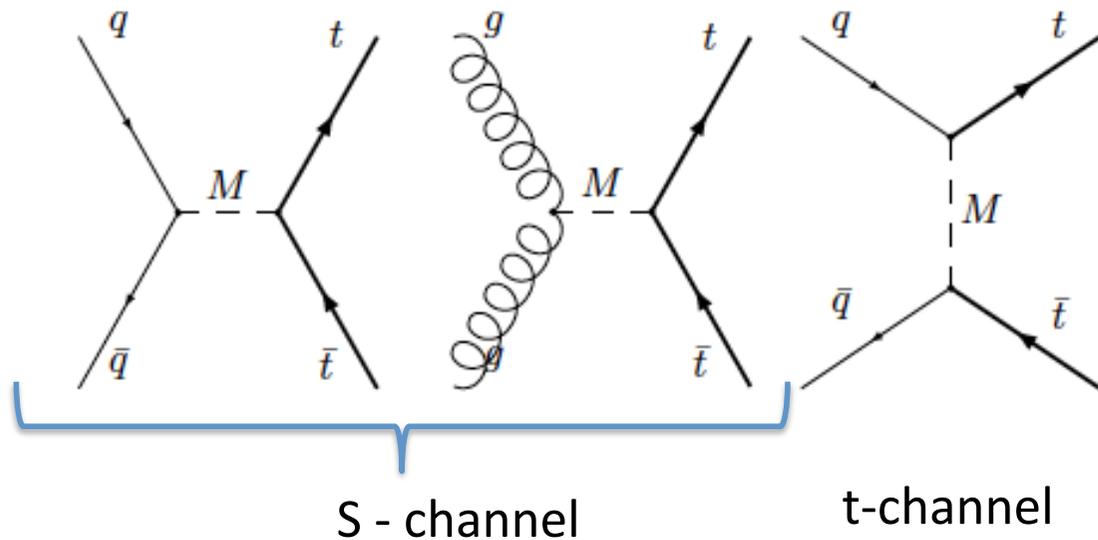
SM effect

New Physics

NP can be treated by:

- effective Lagrangian;
- real resonances;

NP can interfere with the SM (linear effect) or without interference – quadratic effect.



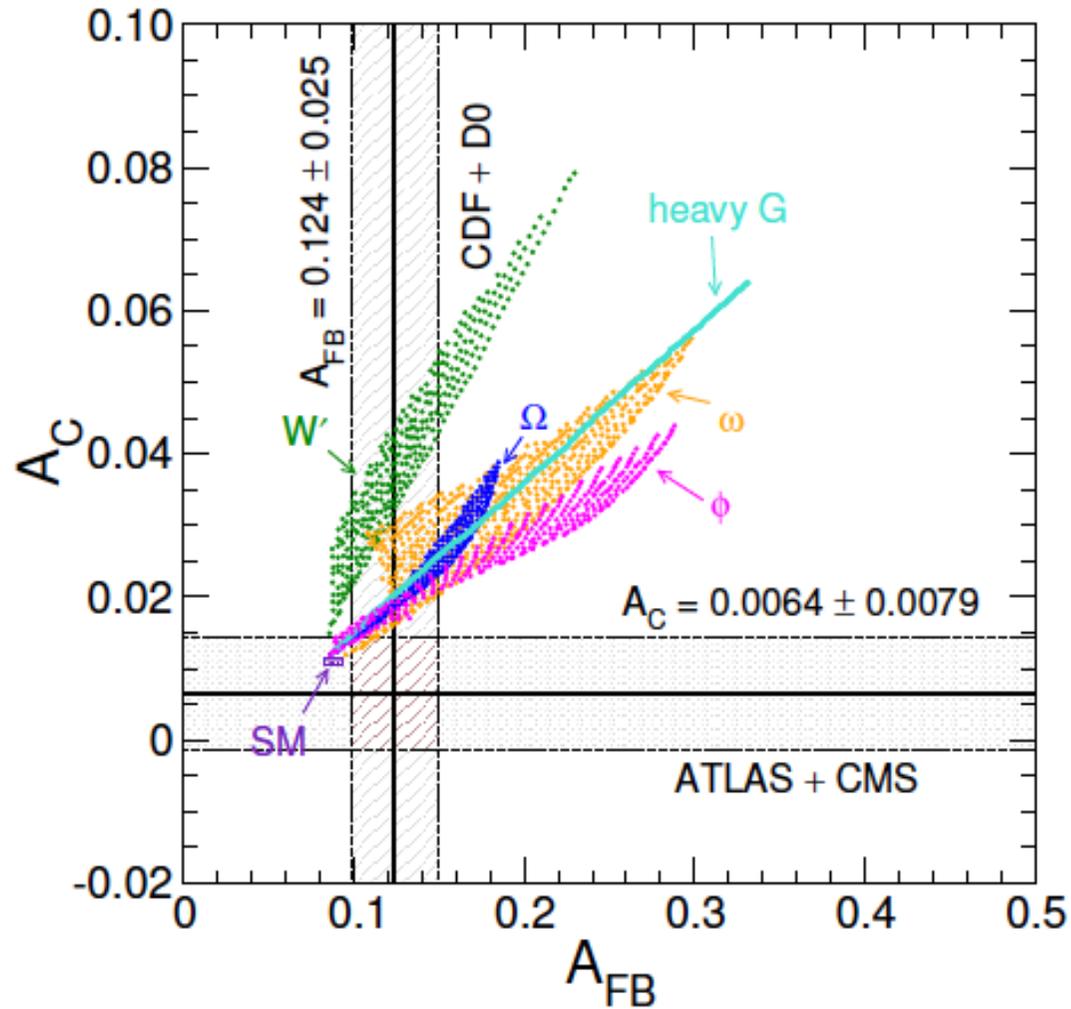
- axigluon → s-channel
- color triplet → u-channel
- color sextet
- doublet
- W'
- Z' → t-channel

Existing NP scenarios:

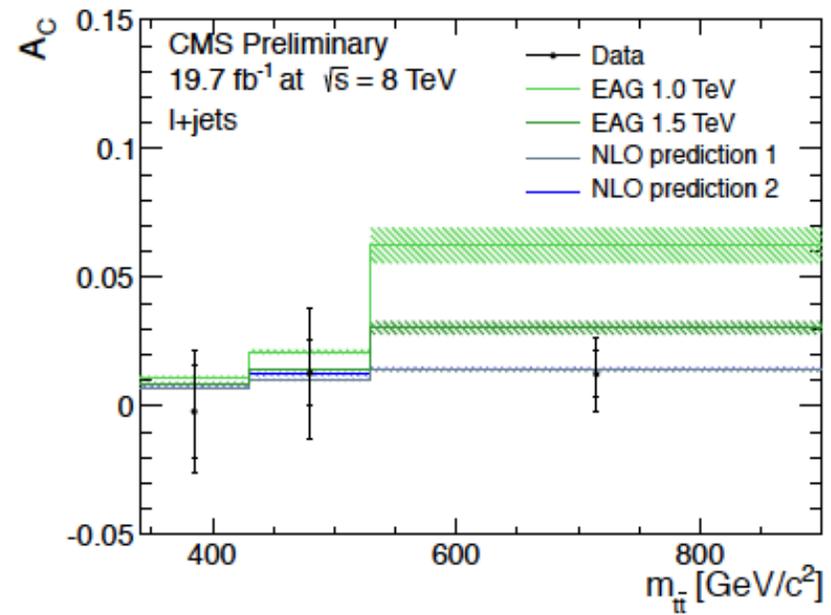
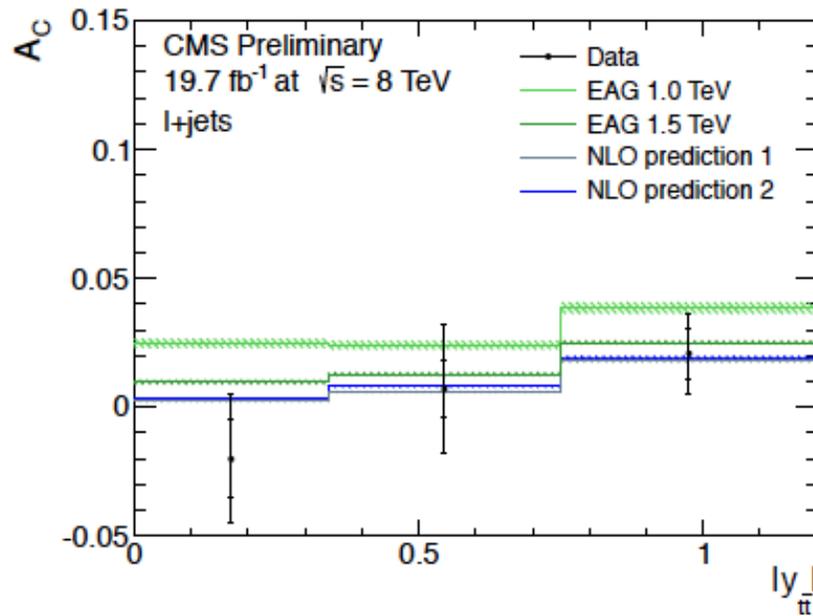
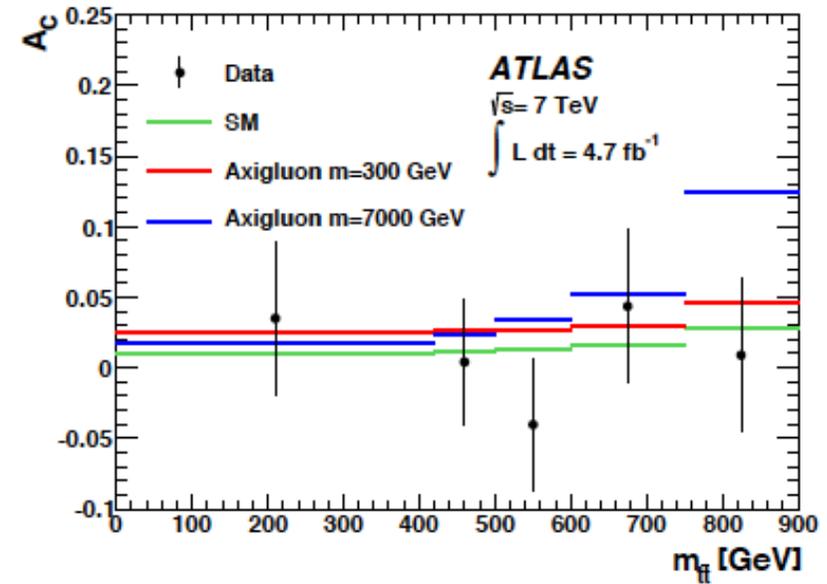
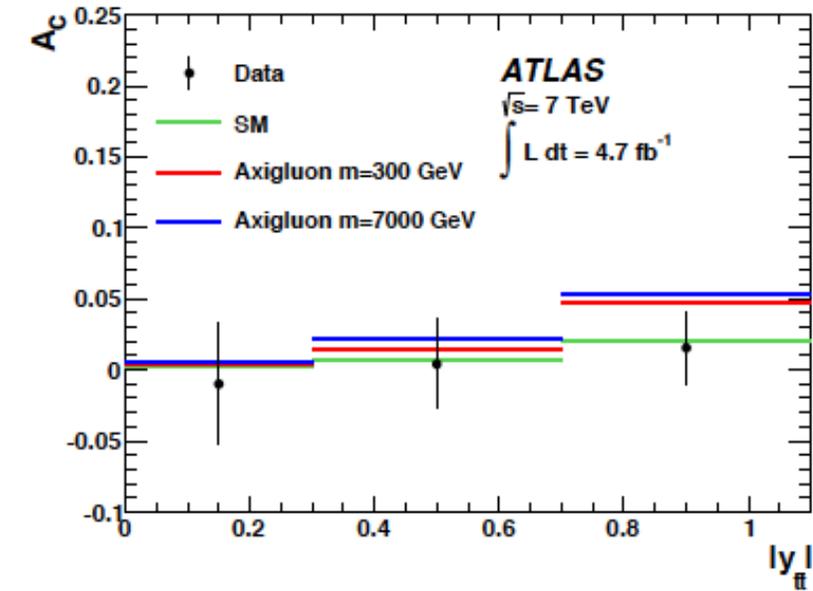
For a recent review see Aguilar-Saavedra & Perez-Victoria 2014

Model selection:

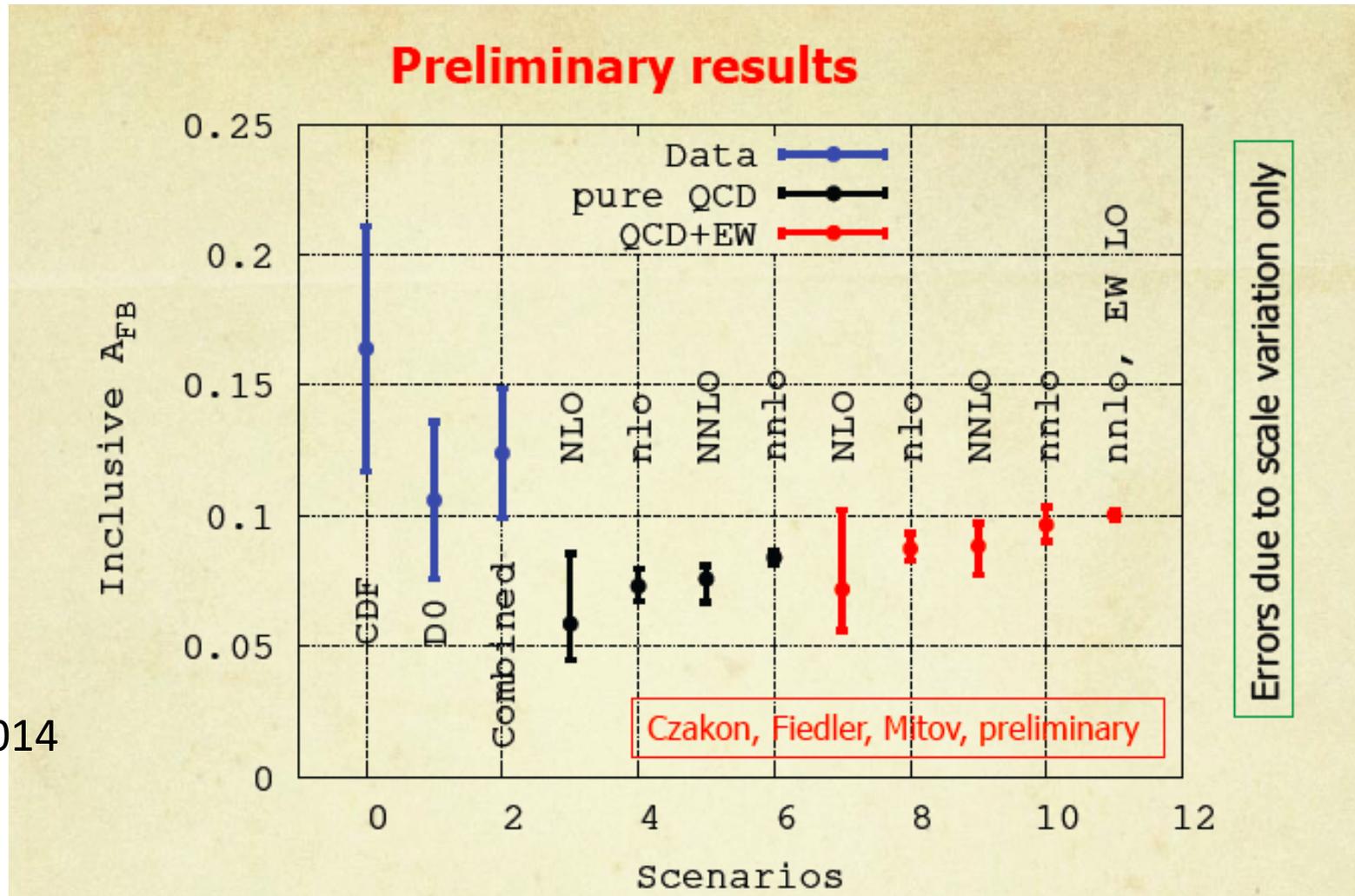
<p>Colour:</p> $3 \otimes \bar{3} = 8 \oplus 1$ $3 \otimes 3 = 6 \oplus \bar{3}$ <p>Isospin:</p> $2 \otimes 2 = 3 \oplus 1$ $2 \otimes 1 = 2$ $1 \otimes 1 = 1$ <p>Hypercharge:</p> $\sum Y = 0$	<p>axigluon</p>	<table border="0" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2" style="text-align: center;">Vectors</th> <th colspan="2" style="text-align: center;">Scalars</th> <th></th> </tr> <tr> <th style="text-align: left;">Label</th> <th style="text-align: left;">Rep.</th> <th style="text-align: left;">Label</th> <th style="text-align: left;">Rep.</th> <th></th> </tr> </thead> <tbody> <tr> <td style="vertical-align: middle;">Z'</td> <td style="border: 1px solid black; padding: 2px;">B_μ</td> <td style="border: 1px solid black; padding: 2px;">$(1, 1)_0$</td> <td style="border: 1px solid black; padding: 2px;">ϕ</td> <td style="border: 1px solid black; padding: 2px;">$(1, 2)_{-\frac{1}{2}}$</td> <td rowspan="2" style="vertical-align: middle; padding-left: 10px;">isodoublet</td> </tr> <tr> <td></td> <td style="padding: 2px;">W_μ</td> <td style="padding: 2px;">$(1, 3)_0$</td> <td style="padding: 2px;">Φ</td> <td style="padding: 2px;">$(8, 2)_{-\frac{1}{2}}$</td> </tr> <tr> <td style="vertical-align: middle;">W'</td> <td style="border: 1px solid black; padding: 2px;">B_μ^1</td> <td style="border: 1px solid black; padding: 2px;">$(1, 1)_1$</td> <td style="padding: 2px;">ω^1</td> <td style="padding: 2px;">$(3, 1)_{-\frac{1}{3}}$</td> <td></td> </tr> <tr> <td></td> <td style="border: 1px solid black; padding: 2px;">G_μ</td> <td style="border: 1px solid black; padding: 2px;">$(8, 1)_0$</td> <td style="padding: 2px;">Ω^1</td> <td style="padding: 2px;">$(\bar{6}, 1)_{-\frac{1}{3}}$</td> <td></td> </tr> <tr> <td></td> <td style="padding: 2px;">H_μ</td> <td style="padding: 2px;">$(8, 3)_0$</td> <td style="border: 1px solid black; padding: 2px;">ω^4</td> <td style="border: 1px solid black; padding: 2px;">$(3, 1)_{-\frac{4}{3}}$</td> <td style="vertical-align: middle; padding-left: 10px;">colour triplet</td> </tr> <tr> <td></td> <td style="padding: 2px;">G_μ^1</td> <td style="padding: 2px;">$(8, 1)_1$</td> <td style="border: 1px solid black; padding: 2px;">Ω^4</td> <td style="border: 1px solid black; padding: 2px;">$(\bar{6}, 1)_{-\frac{4}{3}}$</td> <td style="vertical-align: middle; padding-left: 10px;">colour sextet</td> </tr> <tr> <td></td> <td style="padding: 2px;">Q_μ^1</td> <td style="padding: 2px;">$(3, 2)_{\frac{1}{6}}$</td> <td style="padding: 2px;">σ</td> <td style="padding: 2px;">$(3, 3)_{-\frac{1}{3}}$</td> <td></td> </tr> <tr> <td></td> <td style="padding: 2px;">Q_μ^5</td> <td style="padding: 2px;">$(3, 2)_{-\frac{5}{6}}$</td> <td style="padding: 2px;">Σ</td> <td style="padding: 2px;">$(\bar{6}, 3)_{-\frac{1}{3}}$</td> <td></td> </tr> <tr> <td></td> <td style="padding: 2px;">Y_μ^1</td> <td style="padding: 2px;">$(\bar{6}, 2)_{\frac{1}{6}}$</td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td style="padding: 2px;">Y_μ^5</td> <td style="padding: 2px;">$(\bar{6}, 2)_{-\frac{5}{6}}$</td> <td></td> <td></td> <td></td> </tr> </tbody> </table>	Vectors		Scalars			Label	Rep.	Label	Rep.		Z'	B_μ	$(1, 1)_0$	ϕ	$(1, 2)_{-\frac{1}{2}}$	isodoublet		W_μ	$(1, 3)_0$	Φ	$(8, 2)_{-\frac{1}{2}}$	W'	B_μ^1	$(1, 1)_1$	ω^1	$(3, 1)_{-\frac{1}{3}}$			G_μ	$(8, 1)_0$	Ω^1	$(\bar{6}, 1)_{-\frac{1}{3}}$			H_μ	$(8, 3)_0$	ω^4	$(3, 1)_{-\frac{4}{3}}$	colour triplet		G_μ^1	$(8, 1)_1$	Ω^4	$(\bar{6}, 1)_{-\frac{4}{3}}$	colour sextet		Q_μ^1	$(3, 2)_{\frac{1}{6}}$	σ	$(3, 3)_{-\frac{1}{3}}$			Q_μ^5	$(3, 2)_{-\frac{5}{6}}$	Σ	$(\bar{6}, 3)_{-\frac{1}{3}}$			Y_μ^1	$(\bar{6}, 2)_{\frac{1}{6}}$					Y_μ^5	$(\bar{6}, 2)_{-\frac{5}{6}}$			
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Model parameters have to be constrained by all other top observables, cross sections, as well as all flavor physics (see e.g. Dorsner, SF, Kamenik & Kosnik 2011,2012,13... Gresham et al, 2012, 2013 (many more))



Recent development in QCD: NNLO QCD + EW for A_{FB}



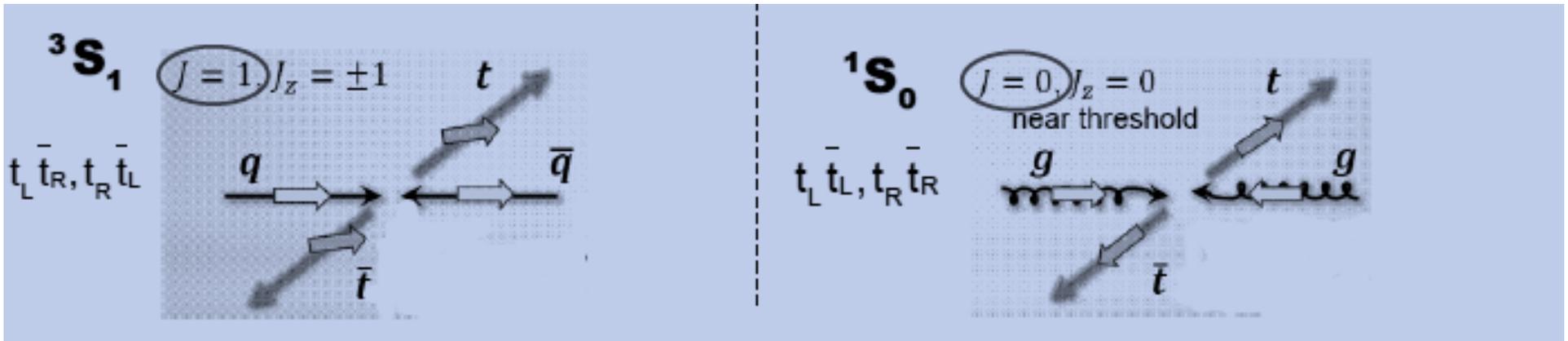
Presented by
Mitov@CKM2014

SM: $A_{FB} \sim 10\%$

Top quark polarization and $t\bar{t}$ spin correlations

NP seems to be very squeezed in $t\bar{t}$ production.

spin correlations or top polarizations \longrightarrow additional inside on NP effects



From angular distribution of the decay products one can measure top polarization effects!

Bernreuther et al., 2001

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_f d\cos\theta_{\bar{f}}} = \frac{1}{4} (1 + B_t \cos\theta_f + B_{\bar{t}} \cos\theta_{\bar{f}} - C \cos\theta_f \cos\theta_{\bar{f}})$$

B_t } top, ani-top
 $B_{\bar{t}}$ } polarizations

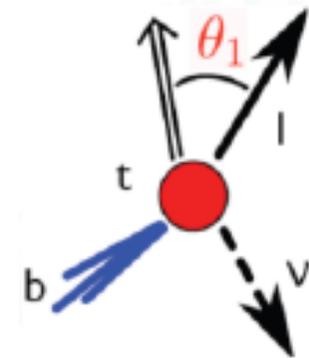
$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

top, anti-top spin correlation

$$C \rightarrow C\kappa_f\kappa_{\bar{f}}, \quad B_{t(\bar{t})} \rightarrow B_{t(\bar{t})}\kappa_{f(\bar{f})}$$

κ_t “spin analyzing power”, Jazabek, 1994

i	l^+ , \bar{d} , \bar{s}	ν_l , u , c	b	W^+	$j_<$
κ	1	-0,31	-0,41	0,41	0,51



In the top (anti-top) rest frame

Spin observables:

$$\mathcal{O}_1 = \mathbf{S}_t \cdot \mathbf{S}_{\bar{t}}$$

$$\mathcal{O}_2 = \mathbf{S}_t \cdot \hat{\mathbf{a}}, \quad \mathcal{O}_2 = \mathbf{S}_{\bar{t}} \cdot \hat{\mathbf{b}}$$

$$\mathcal{O}_3 = 4(\mathbf{S}_t \cdot \hat{\mathbf{a}})(\mathbf{S}_{\bar{t}} \cdot \hat{\mathbf{b}})$$

quantization axes

$$\hat{\mathbf{a}} = -\hat{\mathbf{b}} = \hat{\mathbf{k}}_1, \quad \text{helicity basis}$$

$$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{p}}, \quad \text{beamline basis}$$

$$\hat{\mathbf{a}} = \hat{\mathbf{b}} = \hat{\mathbf{d}}_X, \quad \text{off-diagonal} \\ \text{(specific for each} \\ \text{model X)}$$

$$\langle \mathcal{O}_2 \rangle = B_t$$

$$\langle \mathcal{O}_3 \rangle = C$$

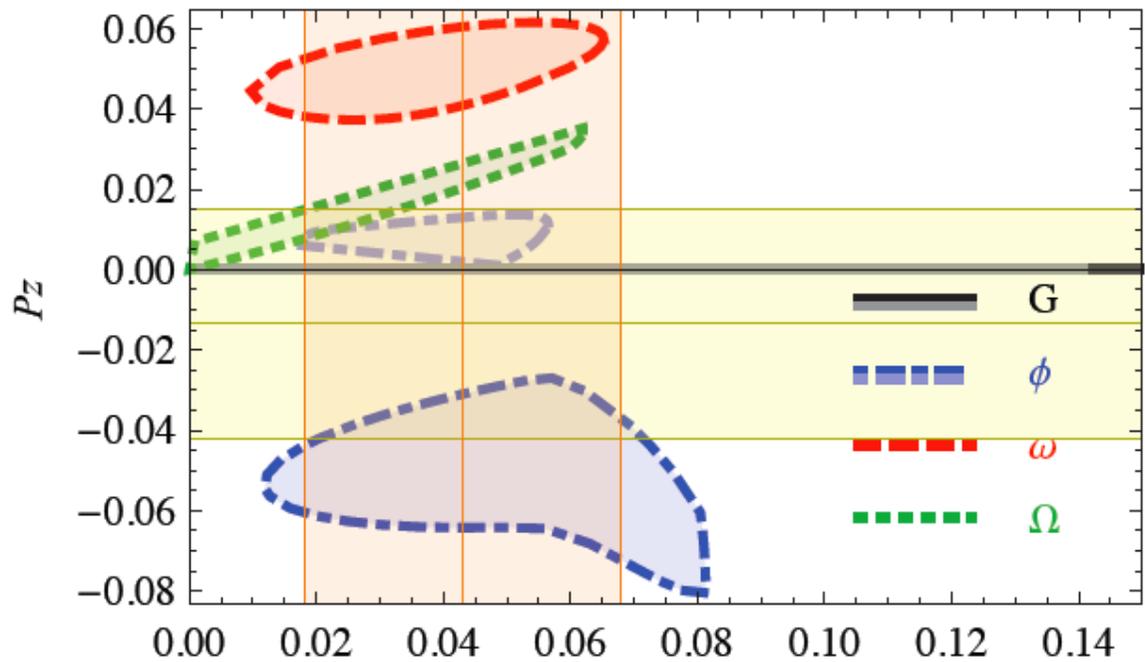
Opening angle distribution

$$\frac{d\sigma}{d\cos\phi_{1+1-}} = \frac{\sigma}{2} (1 - \kappa_t D \cos\phi_{1+1-}) \quad \text{e.g. in dilepton channel}$$

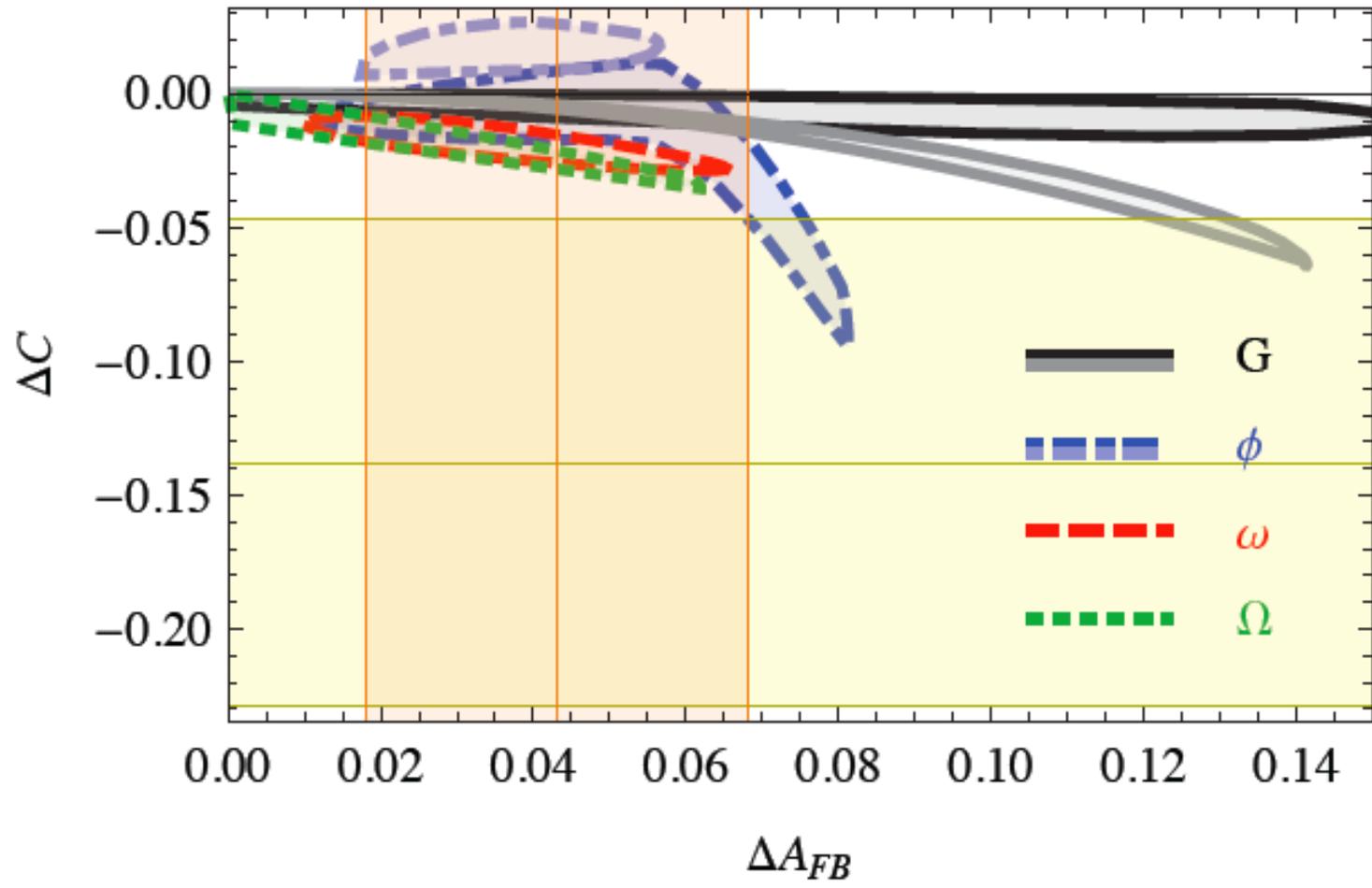
$$\langle \mathcal{O}_1 \rangle = D$$

$$pp, p\bar{p} \rightarrow t\bar{t}X \rightarrow l^+ l'^- X$$

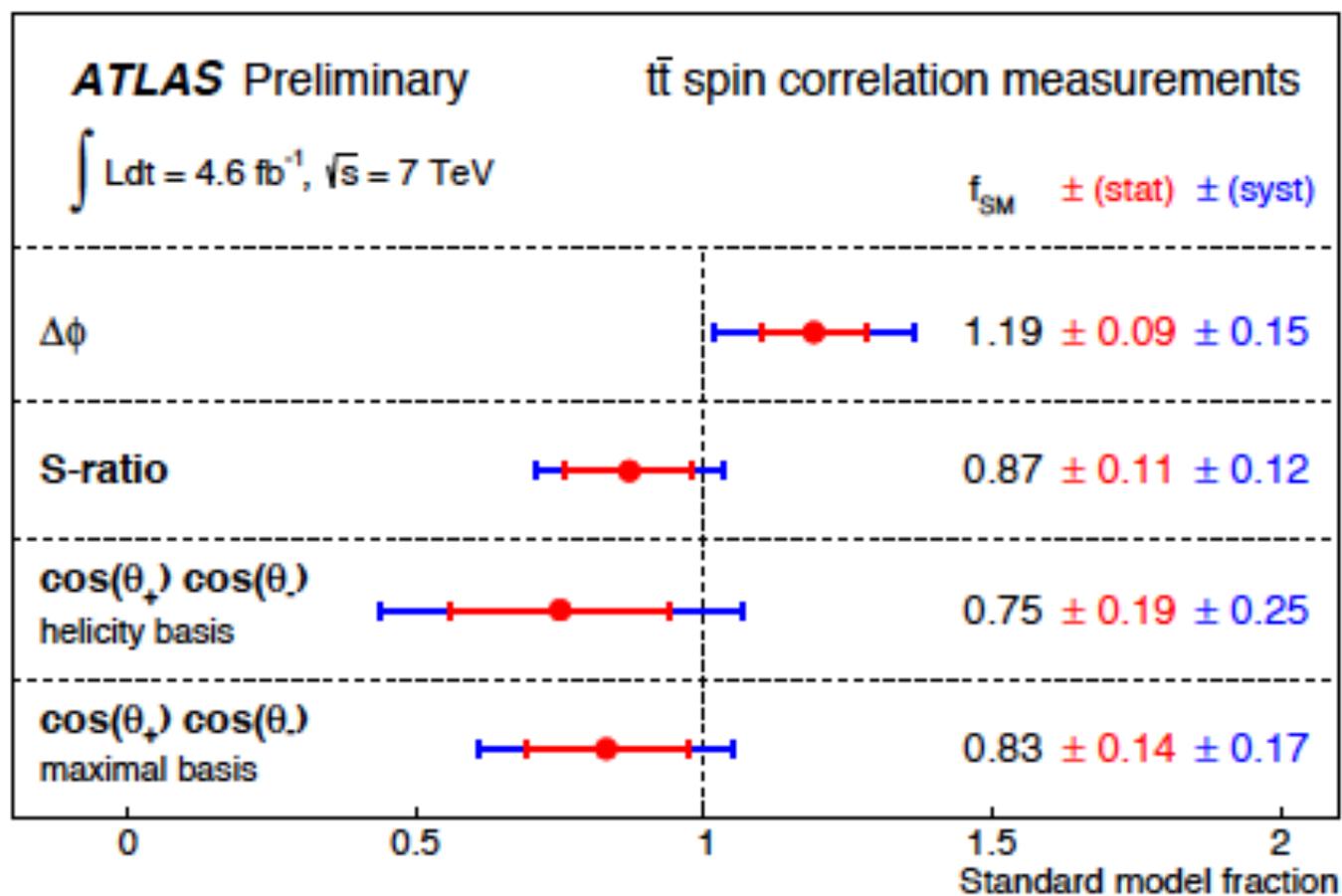
Collider	basis	measurement	SM prediction
Tevatron	beamline	$C = 0.58 \pm 0.20$	$0.791^{+0.013}_{-0.014}$
LHC7	helicity	$P = -0.014 \pm 0.029$	0
LHC7	helicity	$C = 0.17 \pm 0.09$	0.310 ± 0.006



SF, Kamaenik & Melic,
2012;
Aguilar-Saavedra &
Perez-Victoria 2014



SF, Kamaenik & Melic,
2012;
Aguilar-Saavedra &
Peres Victoria 2014



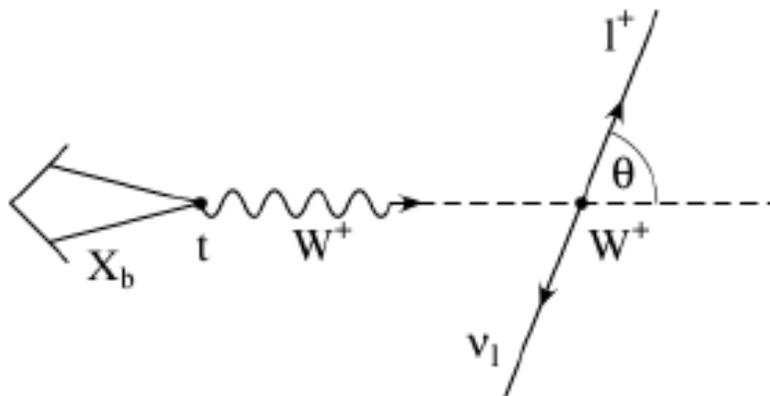
Dominant decay mode: $t \rightarrow bW$

$t \rightarrow qW$
 important CKM matrix elements V_{td}, V_{ts}, V_{tb}

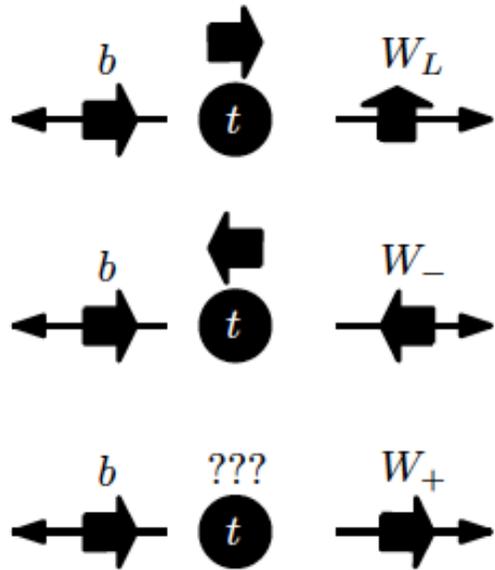
}

$\Gamma = (2.0 \pm 0.5) \text{ GeV}$

$$\Gamma_{t \rightarrow bW} = \Gamma_L + \Gamma_- + \Gamma_+, \quad \mathcal{F}_i = \Gamma_i / \Gamma$$



$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta} = \frac{3}{8} (1 + \cos \theta)^2 \mathcal{F}_+ + \frac{3}{8} (1 - \cos \theta)^2 \mathcal{F}_- + \frac{3}{4} \sin^2 \theta \mathcal{F}_L$$



W helicities

$$\mathcal{F}_L^{\text{SM}} = 0.687(5), \quad \mathcal{F}_+^{\text{SM}} = 0.0017(1)$$

Czarnecki et al, 2005

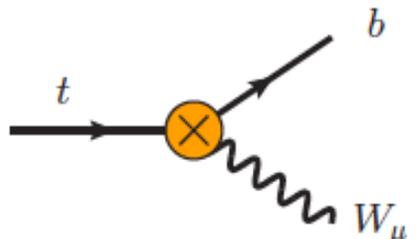
\mathcal{F}_+

is highly suppressed in SM,
Non-zero value comes from QCD & EW
corrections $m_b \neq 0$

This might indicate presence of new physics!

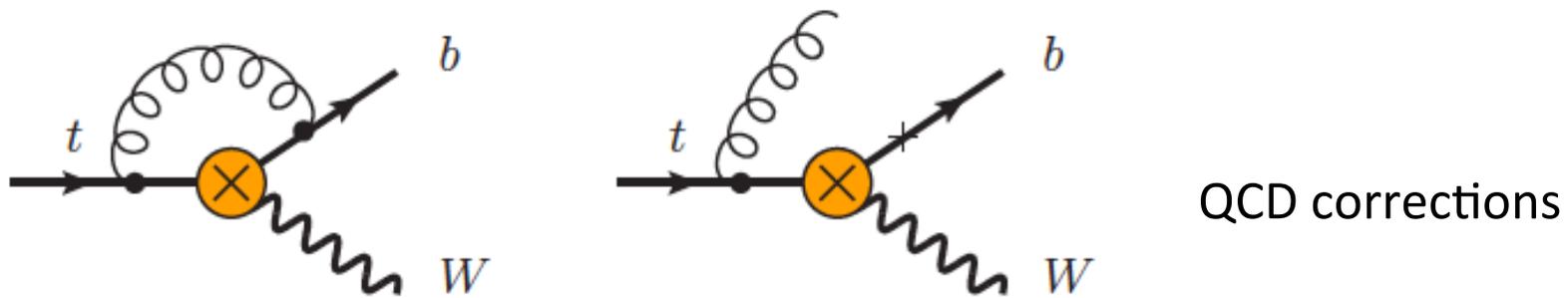
	CMS [CMS PAS TOP-13-008]	ATLAS [JHEP 1206 (2012) 088]
F_0	$0.659 \pm 0.015(\text{stat}) \pm 0.023(\text{syst})$	$0.67 \pm 0.03(\text{stat}) \pm 0.06(\text{syst})$
F_L	$0.350 \pm 0.010(\text{stat}) \pm 0.024(\text{syst})$	$0.32 \pm 0.02(\text{stat}) \pm 0.03(\text{syst})$
F_R	$-0.009 \pm 0.006(\text{stat}) \pm 0.020(\text{syst})$	$0.01 \pm 0.01(\text{stat}) \pm 0.04(\text{syst})$

\mathcal{F}_i at NLO in QCD



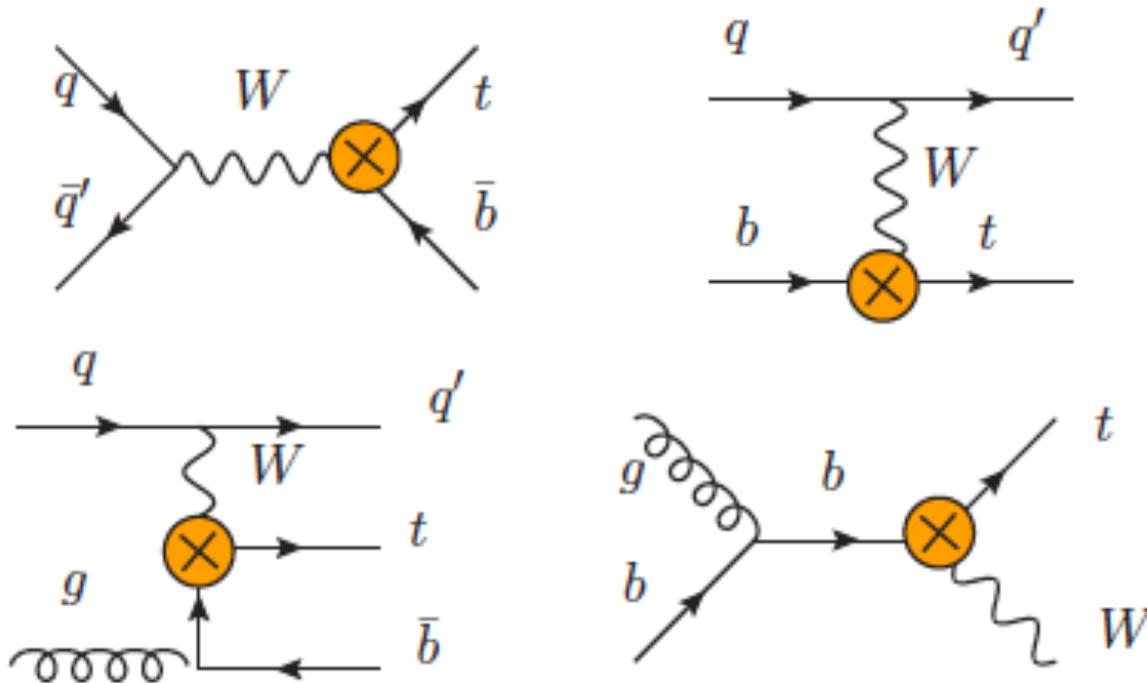
$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) t W_\mu^- + \text{H.c.}$$

Most general parameterization of TW b vertex (Drobnak, SF, Kamenik, 2010,11,12)



- QCD corrections are important (similarly as in SM);
- Anomalous couplings cannot increase \mathcal{F}_+ to 1%;
(B physics constraints: $b \rightarrow s\gamma$, $B^0 - \bar{B}^0$)

Single top production: the same anomalous couplings appear!



Aguilar-Saavedra et al., 2012
 Drobnak, SF & Kamenik, 2012
 Bernardo et al., 2014
 Fabrechiesi et al., 2014

$$F_0 = 0.659 \pm 0.015 \text{ (stat)} \pm 0.023 \text{ (syst)}$$

$$F_L = 0.350 \pm 0.010 \text{ (stat)} \pm 0.024 \text{ (syst)}$$

CMS, 2013

LHC	g_R	g_L	V_R
Allowed Regions (Re)	[-0.15 , 0.01]	[-0.09 , 0.06]	[-0.13 , 0.18]

only real values in the fit

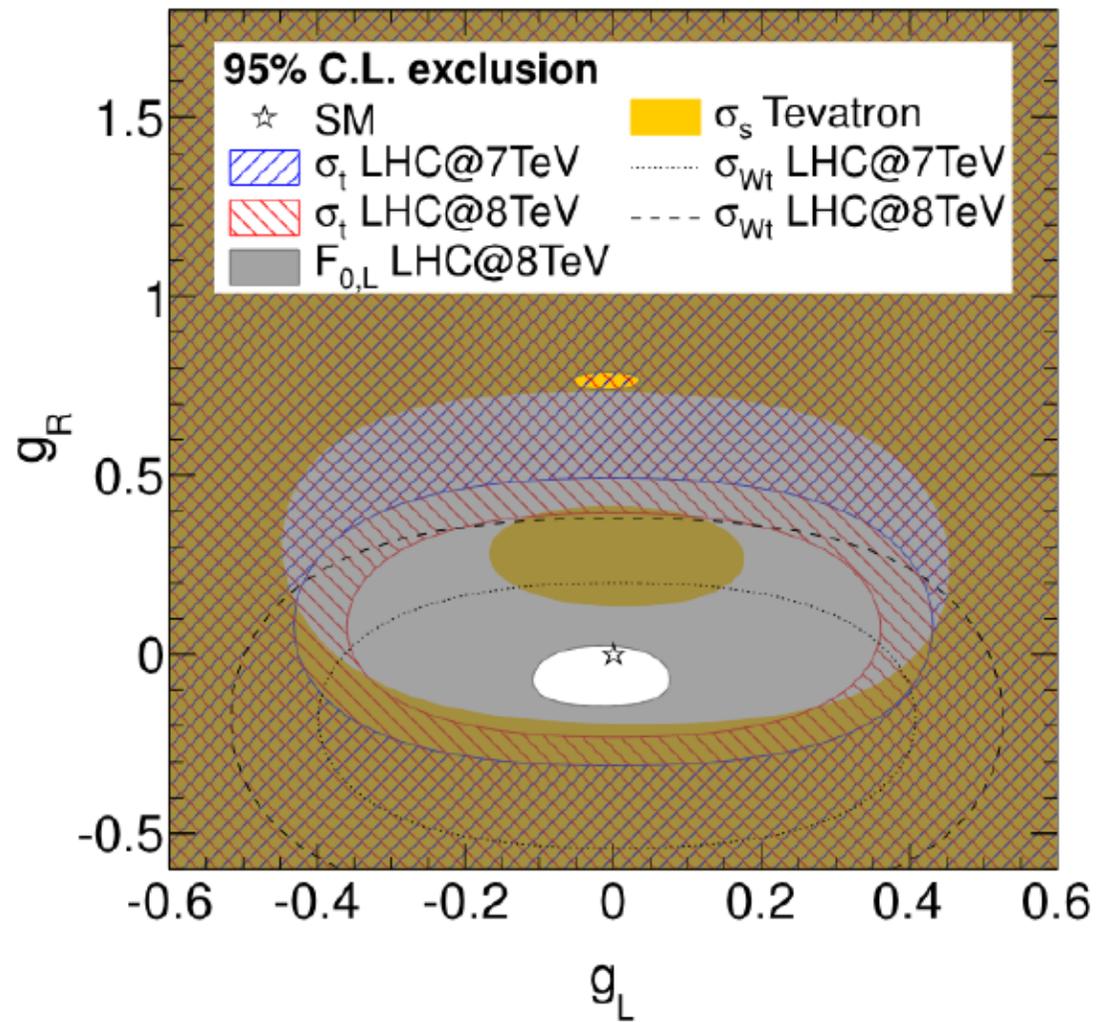
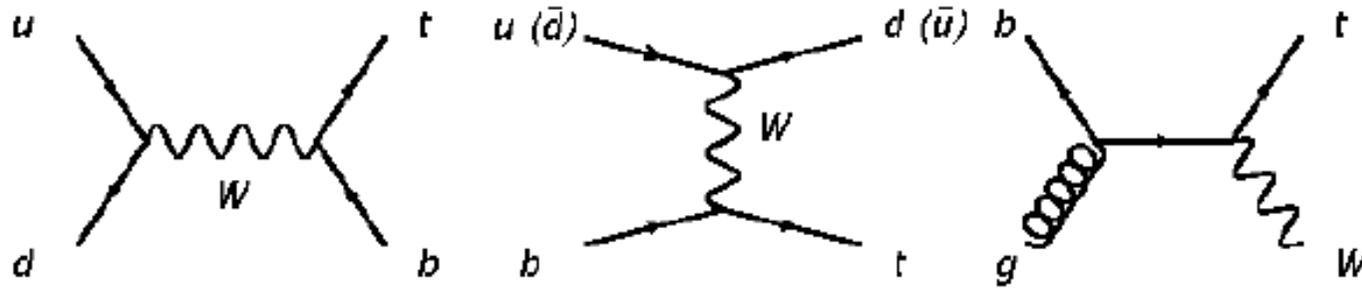
LHC	g_R	g_L	V_R
Allowed Regions (Re)	[-0.16 , 0.13]	[-0.11 , 0.08]	[-0.15 , 0.21]
Allowed Regions (Im)	[-0.34 , 0.34]	[-0.09 , 0.09]	[-0.18 , 0.18]

real and Imaginary couplings in the fit

LHC+Tevatron	g_R	g_L	V_R
Allowed Regions (Re)	[-0.13 , 0.11]	[-0.10 , 0.07]	[-0.15 , 0.20]
Allowed Regions (Im)	[-0.31 , 0.31]	[-0.09 , 0.09]	[-0.17 , 0.17]

LHC	g_R	g_L	V_R
Allowed Regions (Im)	[-0.29 , 0.29]	[-0.08 , 0.08]	[-0.16 , 0.16]
LHC+Tevatron	g_R	g_L	V_R
Allowed Regions (Im)	[-0.27 , 0.27]	[-0.07 , 0.07]	[-0.15 , 0.15]

only imaginary couplings



Summary

- double top production: success story of LHC and QCD (known σ at NNLO order);
- A_{FB} Tevatron anomaly seems to be only SM effect!
- top (anti-top) polarization and spin correlations give more insight in SM + NP effects;

- Top dominant decay mode $t \rightarrow Wb$ carefully investigated within SM and assuming deviation from SM using helicity formalism;
- LHC results on helicity functions confronted with single top production.

Outlook

Top properties would be known very precisely in the next LHC run:

- Important to know if we live in an unstable world!
- Naturalness – can we understand more?

More studies on associate top – Higgs production top-Z etc., bounds on exotics (vector-like quarks could be potentially very important!

Very exciting era in the next LHC run!