Tevatron anomalies and LHC cross-checks

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LHCphenOnet

Outline

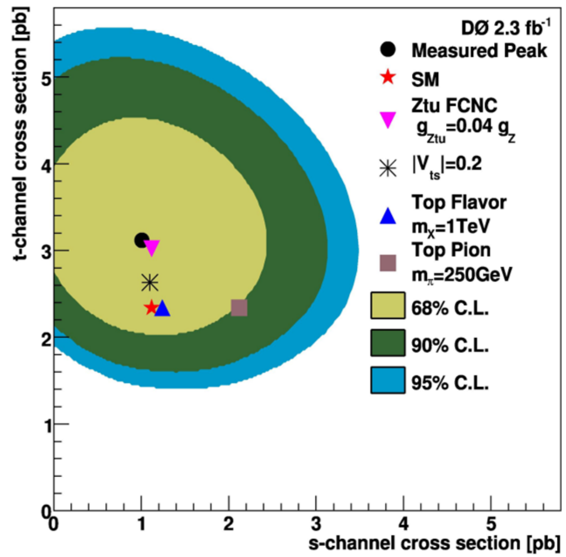
- The top quark charge asymmetry in the SM
- Summary of Tevatron measurements
- BSM explanations
- The charge asymmetry at the LHC

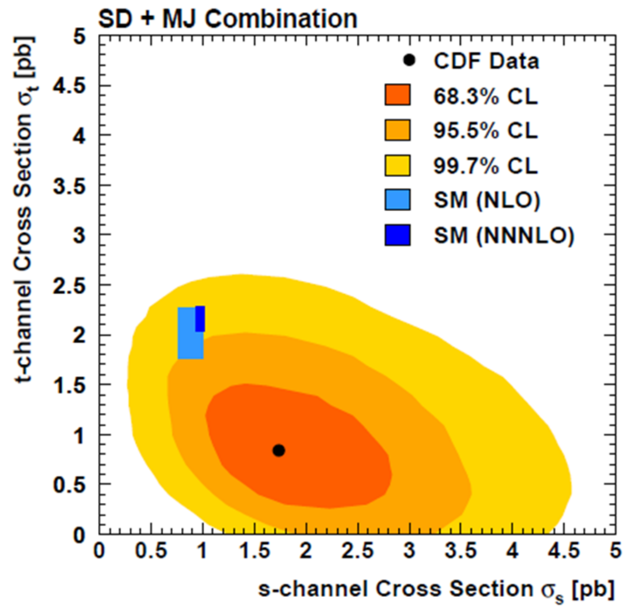
It´s about **charge asymmetry** not
about forward—backward asymmetry

Other Tevatron anomalies

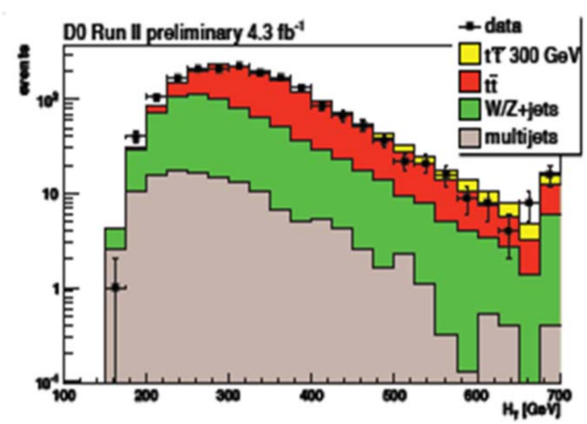
Not covered in this talk [Frederix]

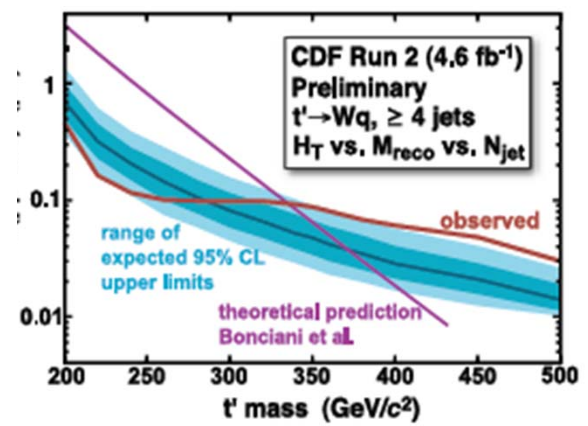
- s- versus t-channel cross-section in **single top** production (only CDF)





- 2σ excess in the tail of the H_T distribution = scalar sum of E_T (D0 and CDF)





The top quark

The top quark is the heaviest known elementary particle: it plays a fundamental role in many extensions of the Standard Model (SM) / alternative mechanisms of EWSB.

Huge statistics from top-antitop quark pair production

Tevatron: σ = 7.6 (5) pb

Integrated luminosity of 10 fb^{-1}: 7×10^4 top quark pairs

LHC @7 TeV: σ = 160 (10) pb

1 fb^{-1} (10 fb^{-1} by the end of 2012 ?): 1.6×10^5 (10^6) top quark pairs

LHC @14 TeV: σ = 940 (80) pb

with 10 fb^{-1}/year: millions of top pairs per year

Production and decay channels are promising probes of new physics.

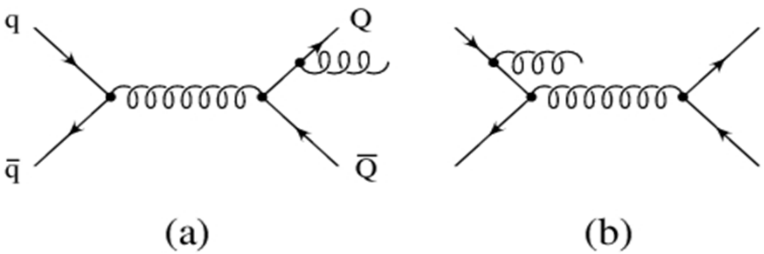
Charge asymmetry in QCD

At $O(\alpha_S^2)$: top and antitop quarks have identical angular distributions

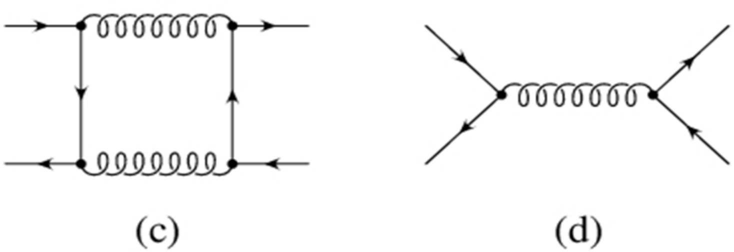
A charge asymmetry arises at $O(\alpha_S^3)$

[Kühn, GR,1998]

Interference of ISR with FSR
LO for ttbar+jet
negative contribution (ttbar+1 jet)



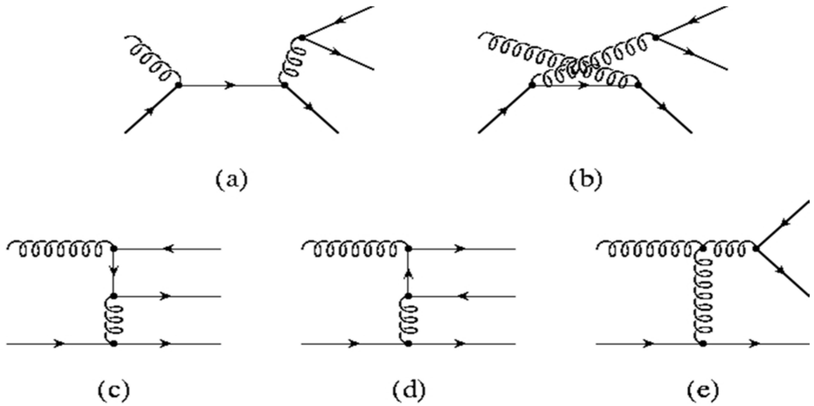
Interference of box diagrams with Born
positive contribution (ttbar+0 jet)



- color factor d_{abc}^2 : **pair in color singlet**
- Loop contribution larger than tree level

top quarks are preferentially emitted in the direction of the incoming quark

Flavor excitation (qg channel) much smaller



A qualitative picture (by J.H.Kühn)

QED: $e^+ e^- \rightarrow \mu^+ \mu^-$

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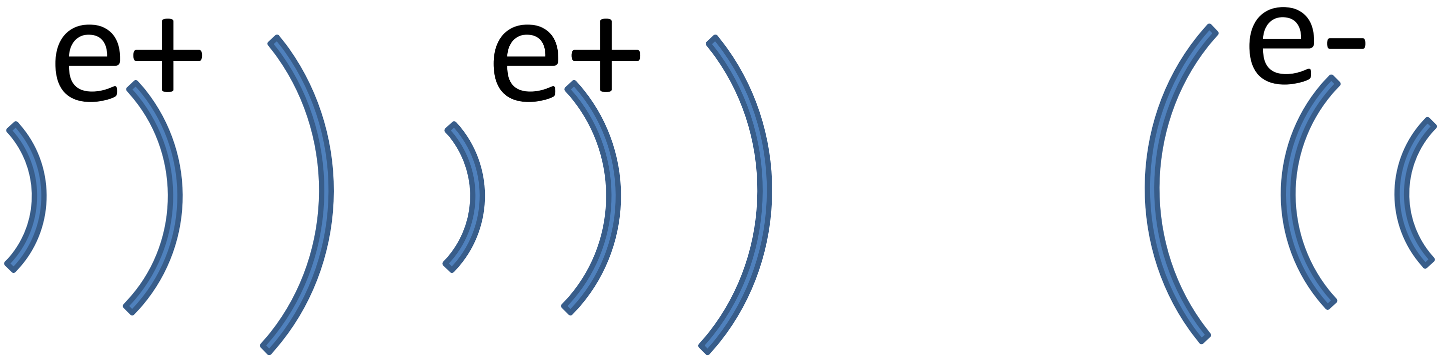

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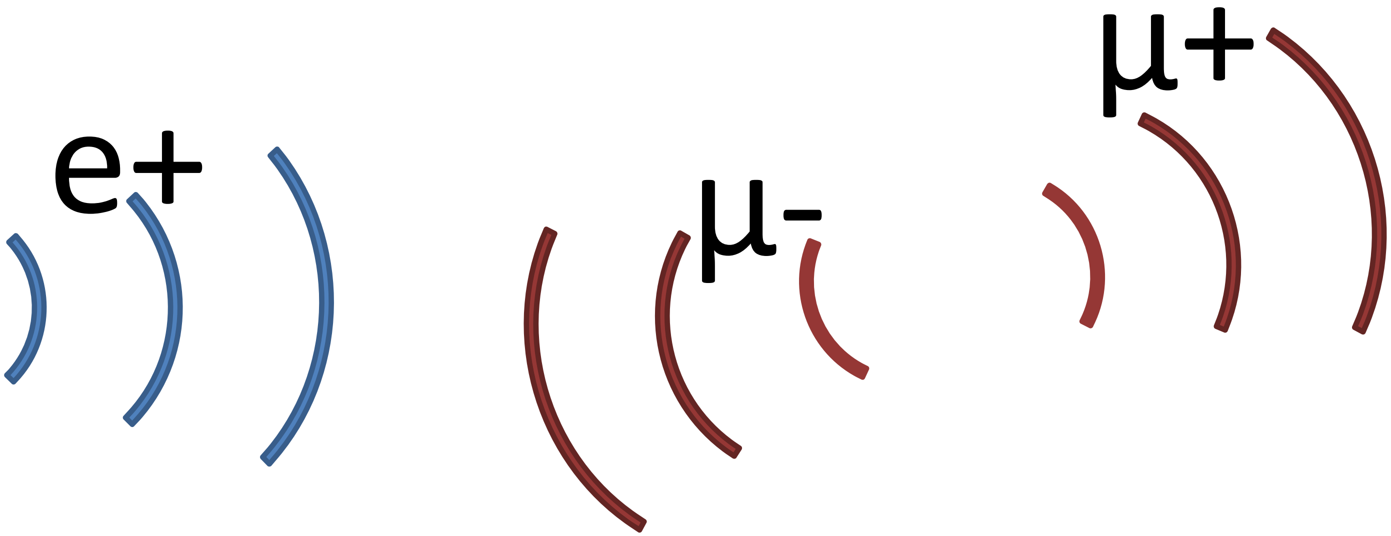
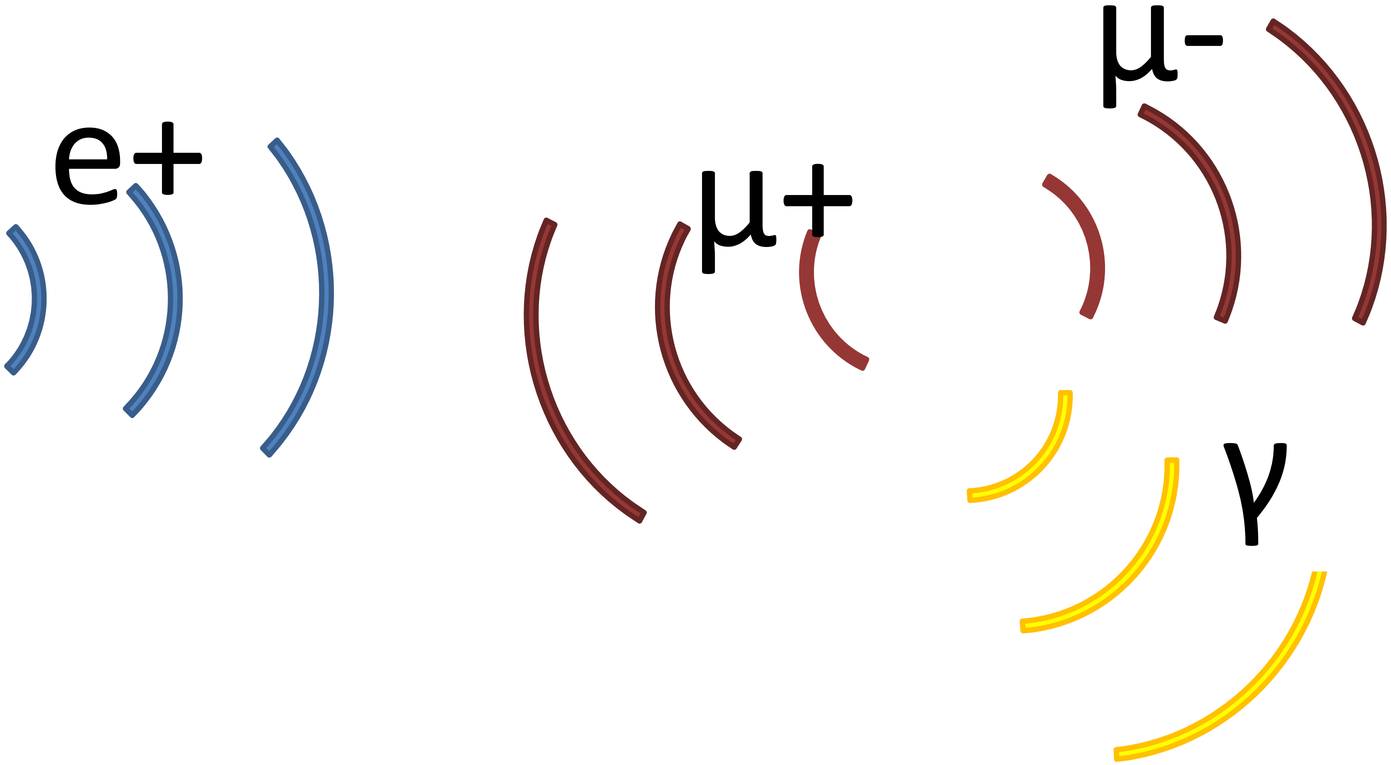


▶ The system is **less perturbed** if **the outgoing positive electric charge field** flows in the direction of **the incoming positive electric charge field**

A qualitative picture (by J.H.Kühn)

QED: $e^+ e^- \rightarrow \mu^+\mu^-$



▶ **$\mu^+\mu^-\gamma$** final state, emission of **extra radiation** requires to **decelerate** the electric charges: negative charge asymmetry

Inclusive asymmetry at Tevatron

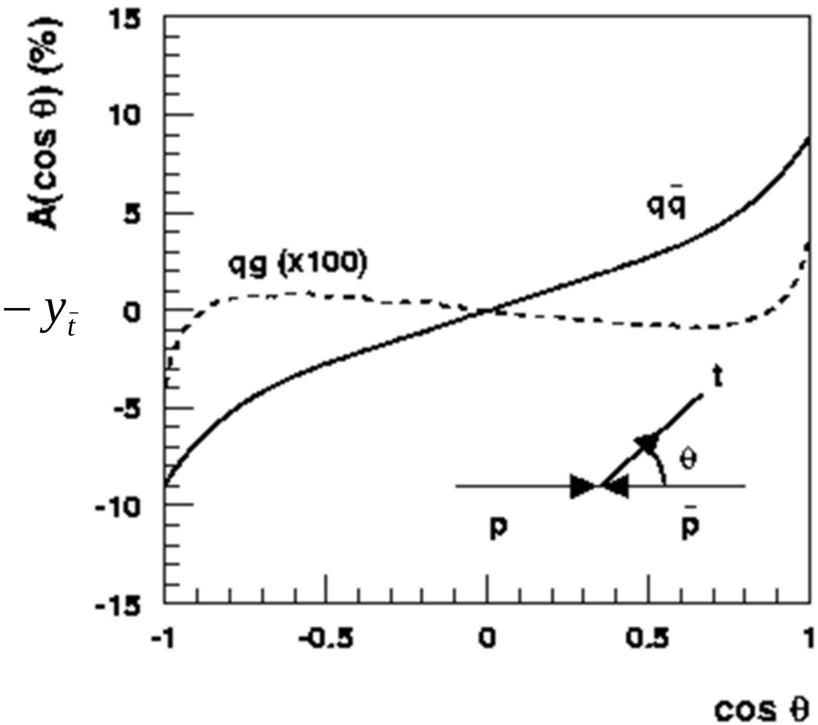
Charge conjugation symmetry* ($N_{\bar{t}}(y) = N_t(-y)$)

forward-backward

[Kühn, GR,1998; Antuñano, Kühn, GR, 2008]

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

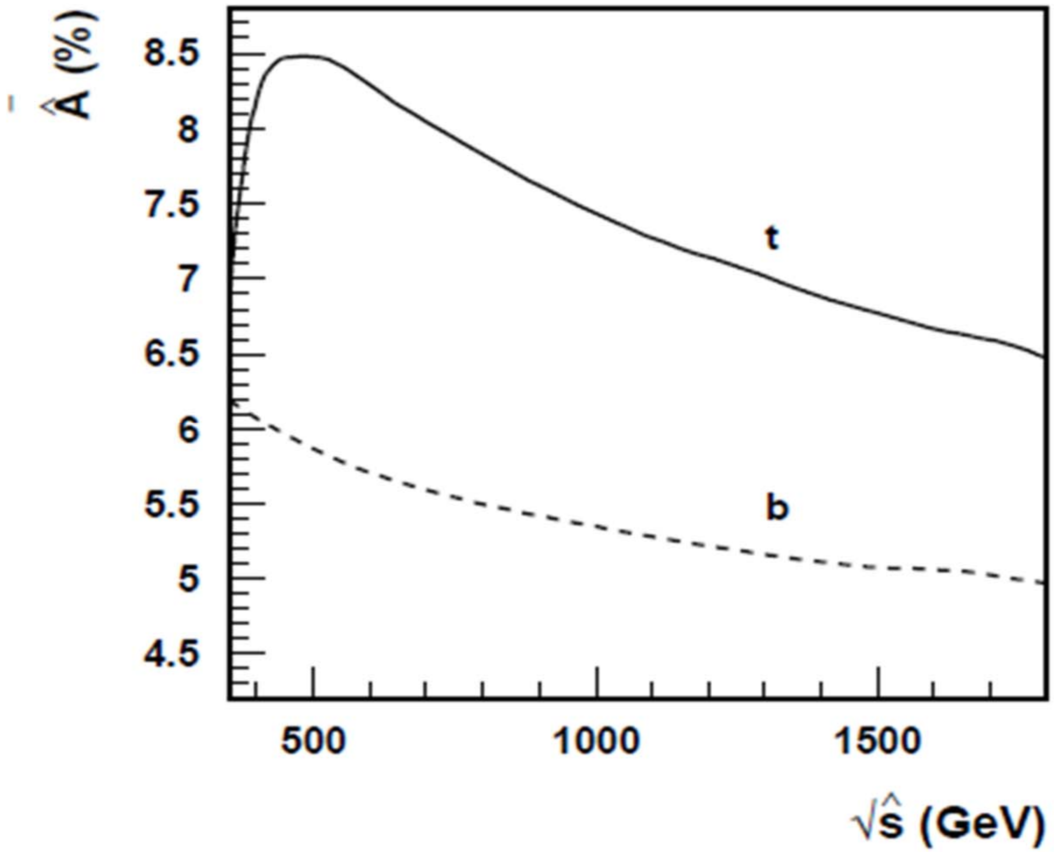
$$A^{t\bar{t}} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)} = 0.078(9) \quad \Delta y = y_t - y_{\bar{t}}$$



- mixed QCD-EW interference: factor 1.09 included [Hollik, Pagani, claim 1.19]
- stable to NLL threshold resummations (one per mille) [Almeida,Sterman,Vogelsang]
- NNLL threshold resummations [Ahrens,Ferroglia,Neubert,Pecjak,Yang] Not expanding the asymmetry in α_S : the asymmetry decreases by 20% at NLO (K factor), but only by 5% at NLO+NNLL

* CP violation arising from electric or chromoelectric dipole moments do not contribute to the asymmetry

Partonic asymmetry and dependence on M_{ttbar}



[Kühn, GR,1998]

- The asymmetry increases with M_{ttbar} because gluon fusion get supressed.
- Same effect for **bottom production**, but much more supressed by gluon fusion: inclusive asymmetry almost vanishes

  A=4.3%-5.1% for M_{bbar}>300 GeV |cos θ|<0.9

Very challenging experimentally.

Asymmetry measurements at Tevatron

D0 [Conf. Note 6062, PRL101(2008)202001] **uncorrected**

ttbar rest frame

A_{FB}^{ttbar} = 0.12 ± 0.08 (stat) ± 0.01 (syst) 0.9 fb^{-1}
A_{FB}^{ttbar} = 0.08 ± 0.04 (stat) ± 0.01 (syst) 4.3 fb^{-1}

CDF [Conf. Note 10436, 10185 and 9724, PRL101(2008)202001]

ppbar rest frame

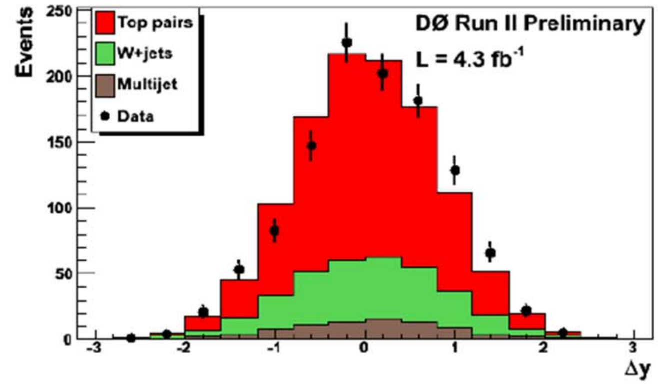
A_{FB}^{ppbar} = 0.17 ± 0.07 (stat) ± 0.04 (syst) 1.9 fb^{-1}
A_{FB}^{ppbar} = 0.193 ± 0.065 (stat) ± 0.024 (syst) 3.2 fb^{-1}
A_{FB}^{ppbar} = 0.150 ± 0.050 (stat) ± 0.024 (syst) 5.3 fb^{-1}

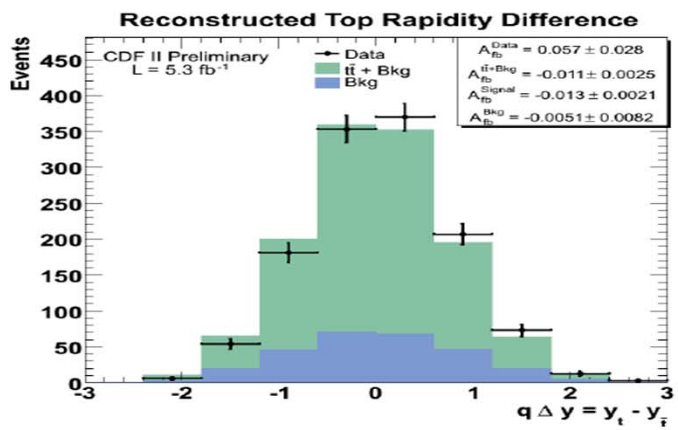
ttbar rest frame

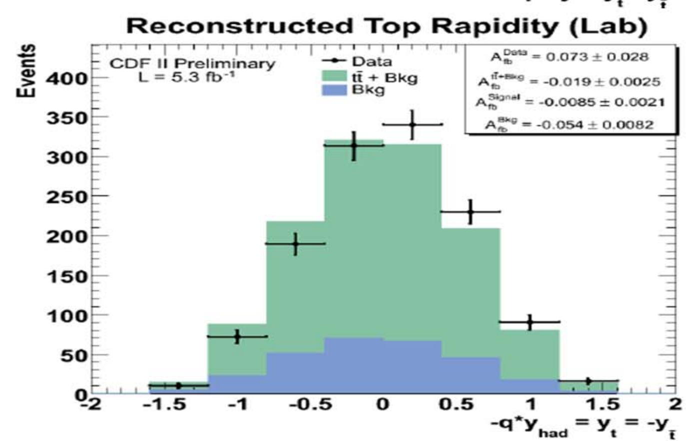
A_{FB}^{ttbar} = 0.24 ± 0.13 (stat) ± 0.04 (syst) 1.9 fb^{-1}
A_{FB}^{ttbar} = 0.158 ± 0.072 (stat) ± 0.017 (syst) 5.3 fb^{-1}

ttbar rest frame (dilepton channel)

A_{FB}^{ttbar} = 0.42 ± 0.15 (stat) ± 0.05 (syst) 5.1 fb^{-1}







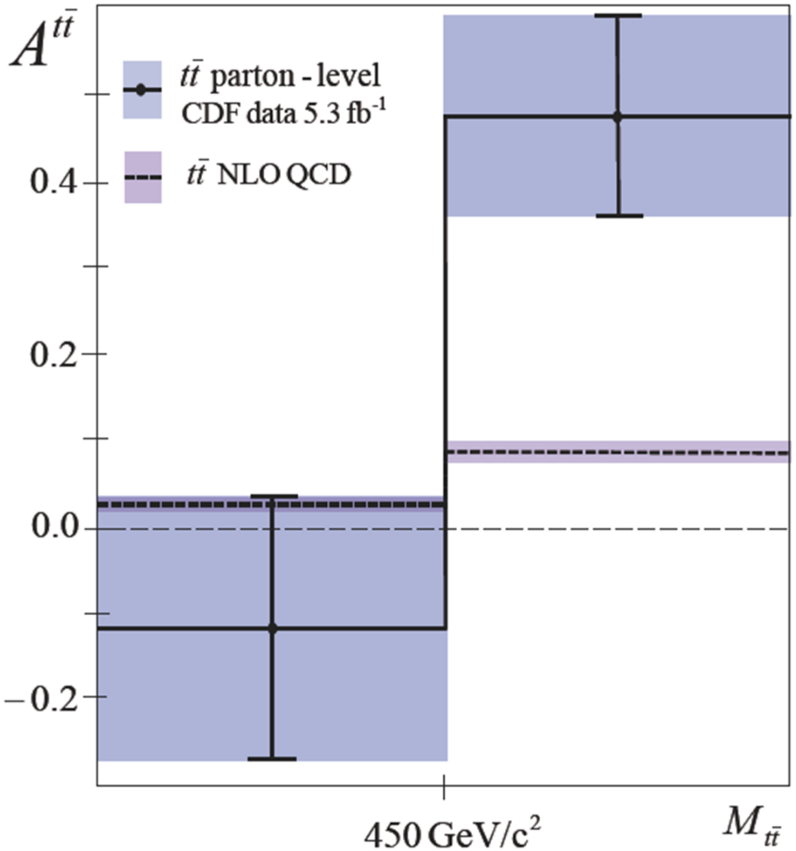
About 3σ above zero
room for positive BSM within 2σ

Invariant mass dependent charge asymmetry

CDF [arXiv:1101.0034] ttbar rest frame 5.3 fb^{-1}

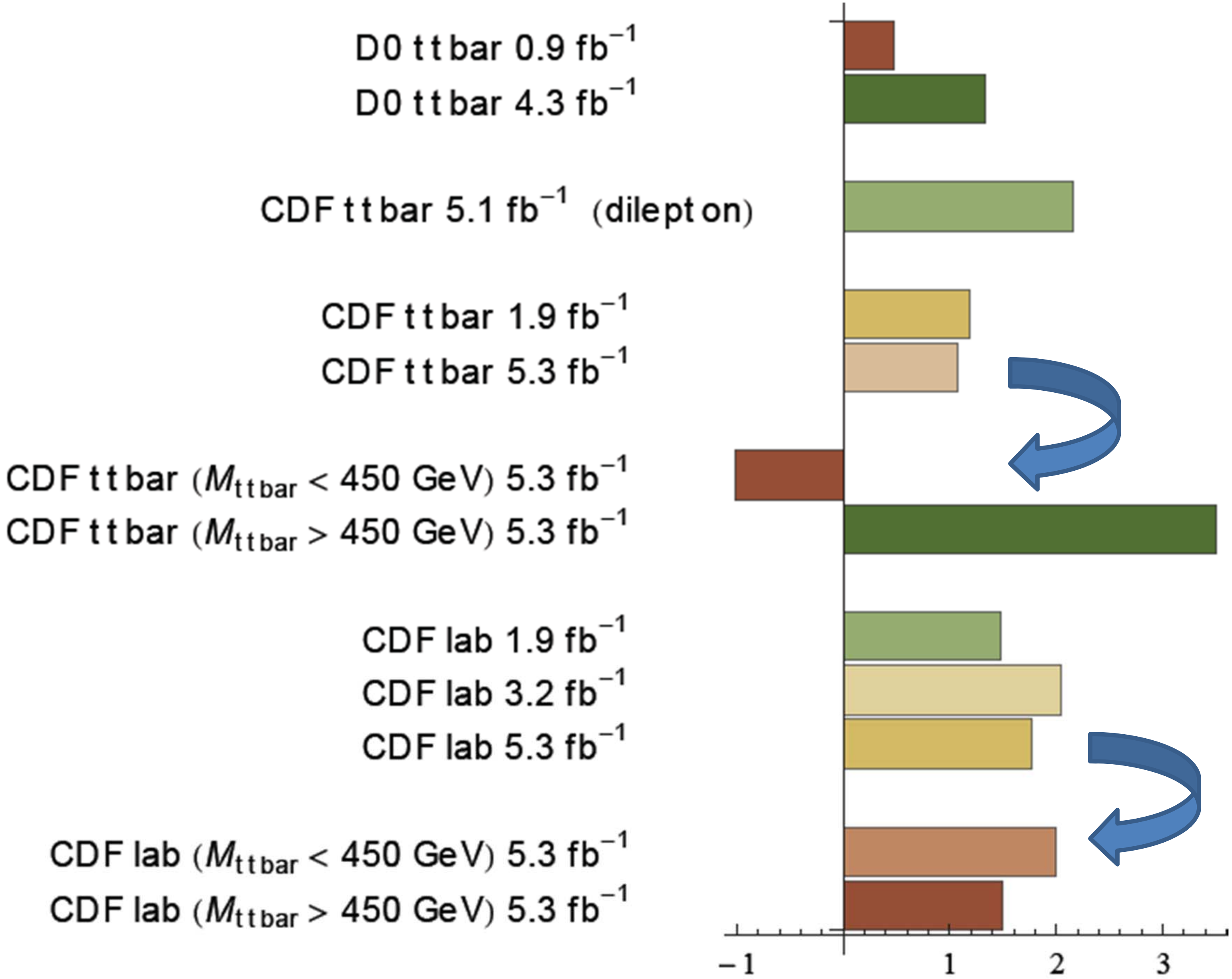
A_{FB}^{ttbar} (M_{ttbar}<450GeV) = -0.116 ± 0.146 (stat) ± 0.047 (syst)

A_{FB}^{ttbar} (M_{ttbar}>450GeV) = 0.475 ± 0.101 (stat) ± 0.049 (syst)



- below 450 GeV: negative asymmetry but still compatible with the SM within 1σ
- above 450 GeV: positive asymmetry, disagrees with the SM at 3.4σ
- The deviation from the SM in the lab frame is not as significant !!!

Tevatron summary



Which model BSM

Color octet gauge bosons

- **$SU(3)_L$ x $SU(3)_R \rightarrow SU(3)_C$** [Pati , Salam, Hall, Nelson, Frampton, Glashow, 1975-1987]
  chiral color models: **axigluon / colorons**

- Kaluza-Klein excitations of the gluon in warped extra dimensions [Randall, Sundrum, Dicus, McMullen, Nandi, Djoadi, Moreau, Richard]

$$\mathcal{L} = g_S T^a \bar{q}_i \gamma^\mu \left(g_V{}^{q_i} + g_A{}^{q_i} \gamma_5 \right) G_\mu' q_i$$

- Charge asymmetry for colorons (g_A=0) and KK gluons ($g_A \approx 0$ for light quarks) suppressed at LO

Color octet gauge bosons: s-channel

Color-octet resonances might produce a charge asymmetry through the interference with the LO SM amplitude

$$\mathcal{L} = g_S T^a \bar{q}_i \gamma^\mu \left(g_V{}^{q_i} + g_A{}^{q_i} \gamma_5 \right) G_\mu{}' q_i$$

But this asymmetry is negative because it is proportional to

$$(s_{hat} - m_G)\, g_A{}^q\, g_A{}^t$$

A positive asymmetry can be generated if

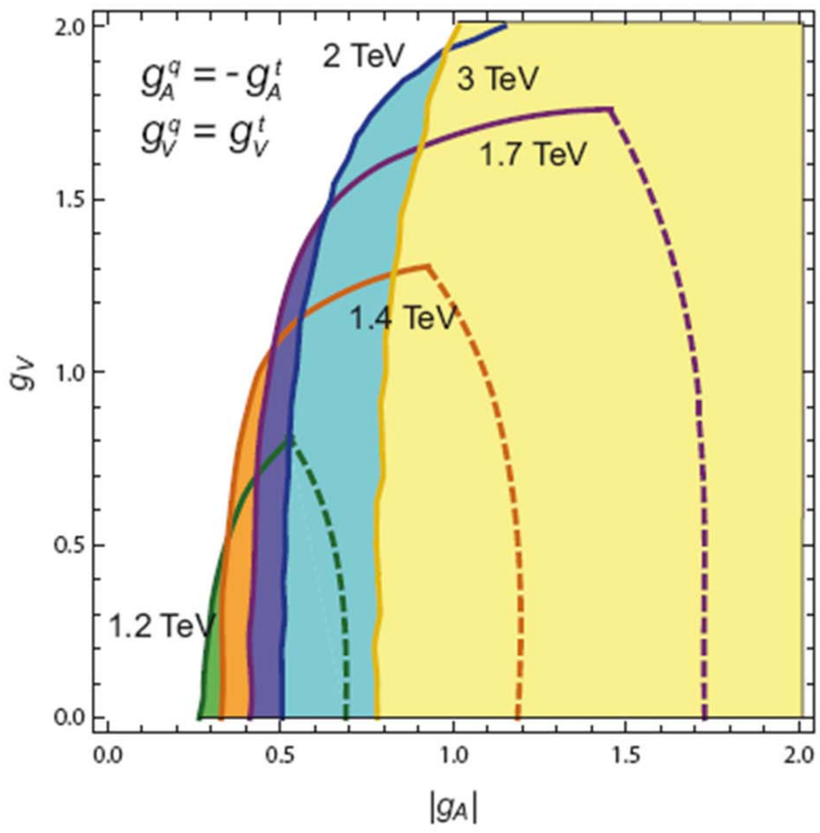
1) very light axigluon: but would be visible in M_{ttbar} : new decay channels to enlarge the width [Marques Tavares, Schmalz / Barcelo, Carmona, Masip, Santiago]

2) vector-axial couplings of opposite sign: **sign($g_A{}^q$)= - sign($g_A{}^t$)**
[Ferrario, GR / Frampton,Shu,Wang / Bauer, Goertz, Haisch, Pfoh, Westhoff / Bai, Hewett, Kaplan, Rizzo / Zerwekh / Hewet, Shelton, Spannowsky, Tait, Takeuchi / Haisch, Westhoff / Agular-Saavedra, Perez-Victoria, …]

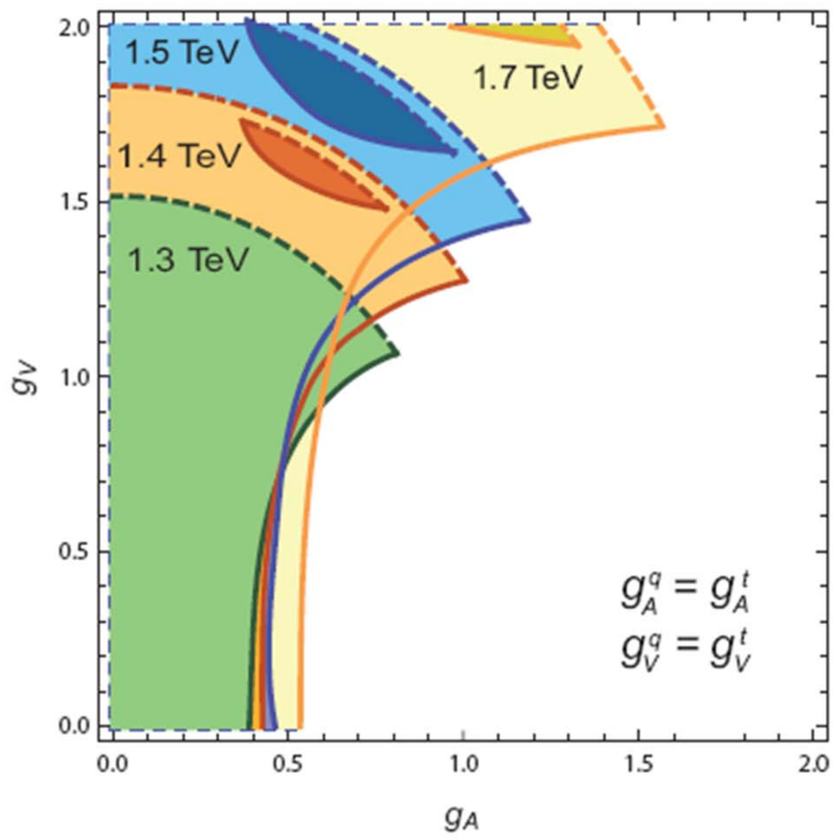
3) squared of the BSM amplitude dominates, which is proportional to $g_V{}^q\, g_V{}^t\, g_A{}^q\, g_A{}^t$: large vector couplings [Ferrario, GR]

Color octet gauge bosons

- Combining limits on the charge asymmetry (solid lines) and the invariant mass distribution (dashed)



Flavor non-universal axigluon: $g_A^q = - g_A^t$



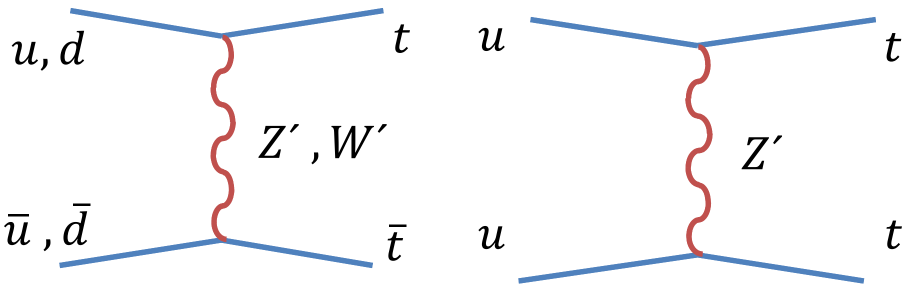
Flavor universal axigluon: $g_A^q = g_A^t$

Z’ and W’: t-channel

- Grand Unified Theories (GUT) based on larger gauge groups, e.g., E6 and SO(10), or left-right symmetric models often introduce additional gauge bosons, such as W′ and Z′, which decay to f fbar´ and f fbar, respectively.

- KK excitations of the W and Z in models of extra dimensions

Z’ and W’: t-channel



- Because of color algebra a Z' or W' in the s-channel do not interfere with the LO QCD amplitude

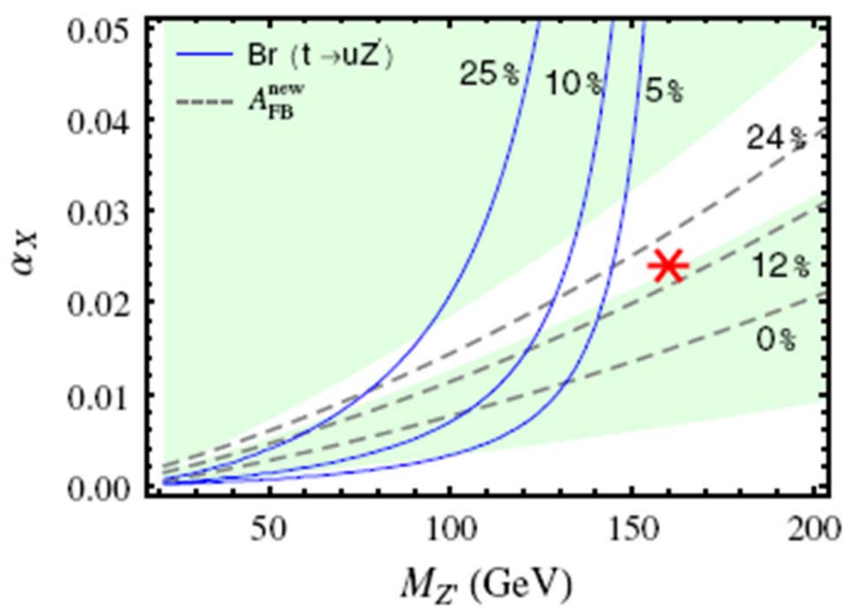
A sizeable charge asymmetry requires **large flavour violating couplings** with the extra weak vector bosons in the t-channel (mostly) [Jung,Murayama,Pierce,Wells]

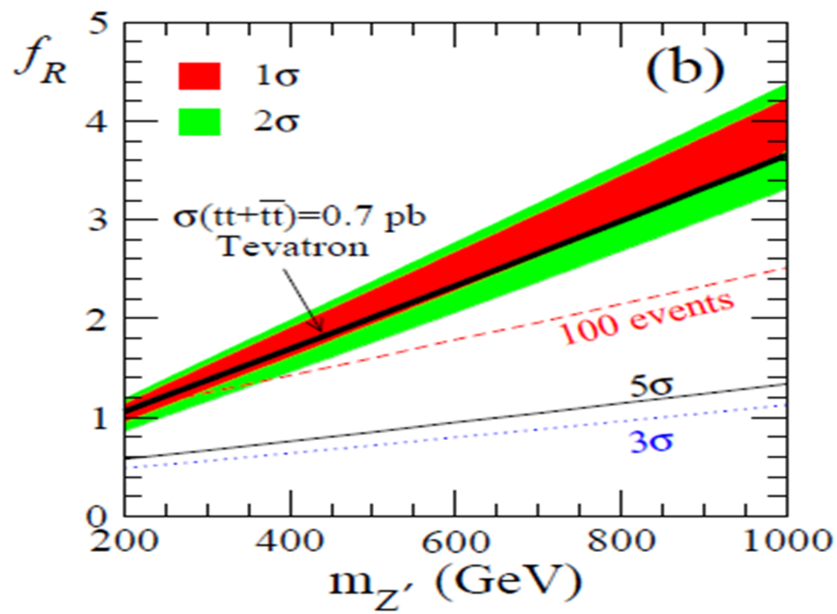
- **like sign $tt + \bar{t}\bar{t}$**, very constrained at Tevatron, and CMS

Z' and W': t-channel

[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng,Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta]

- Only an small region of the parameter space can accommodate the data, large amount of fine tuning





- Requires relatively light Z´ and/or W´: O(200-700 GeV)

Colored scalars

- The E6 GUT model predicts the presence of a diquark (colored scalars) which decays to qq or qbar qbar.

- colored scalars (singlet, triplet, sextet and octet) in SU(5) GUT

$$5_H = H_1 + T = (\mathbf{1},\mathbf{2},1/2)+(\mathbf{3},\mathbf{1},-1/3)$$

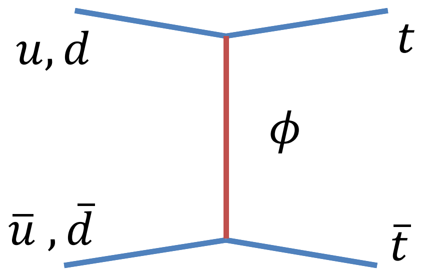
$$24_H = \Sigma_i = (\mathbf{8},\mathbf{1},0)+(\mathbf{1},\mathbf{3},0)+(\mathbf{3},\mathbf{2},-5/6)+(\mathbf{3bar},\mathbf{2},5/6)+(\mathbf{1},\mathbf{1},0)$$

$$45_H = (\mathbf{8},\mathbf{2},1/2) +(\mathbf{6bar},\mathbf{1},-1/3)+(\mathbf{3},\mathbf{3},-1/3)+(\mathbf{3bar},\mathbf{2},-7/6)$$

$$+(\mathbf{3},\mathbf{1},-1/3)+(\mathbf{3bar},\mathbf{1},4/3)+(\mathbf{1},\mathbf{2},1/2)$$

- MSSM: squarks (triplet) and sleptons (singlet)

Colored scalars: t-channel



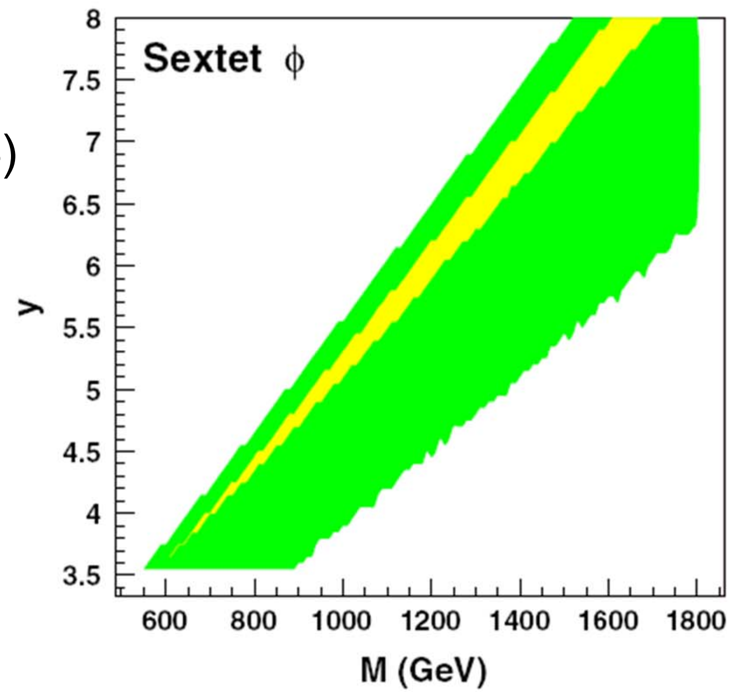
[Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz]

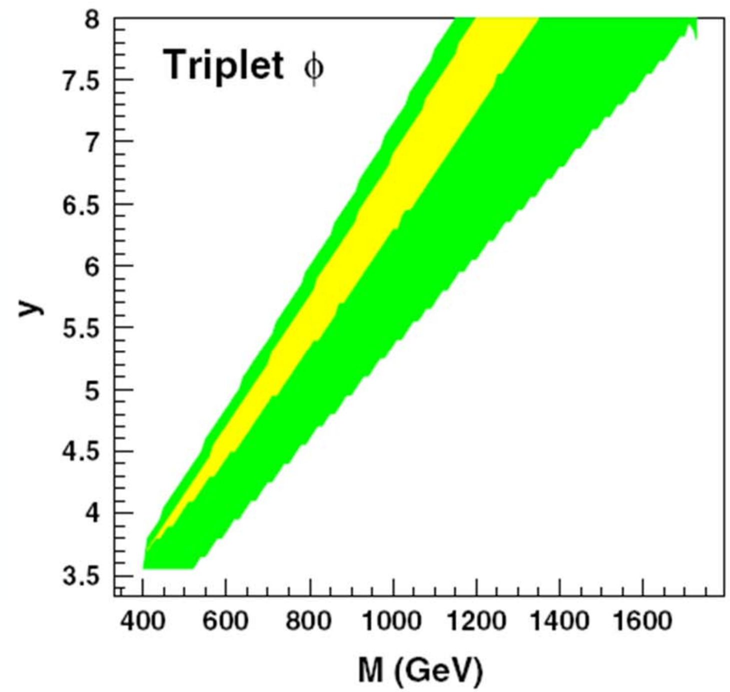
- Requires large flavour violating couplings
- Potential uu→ tt (same sign dileptons)

$$L = \phi^a \bar{t} T^a (g_S + g_P \gamma_5) u \qquad y = \sqrt{g_S^2 + g_P^2}$$

[Shu,Tait,Wang]

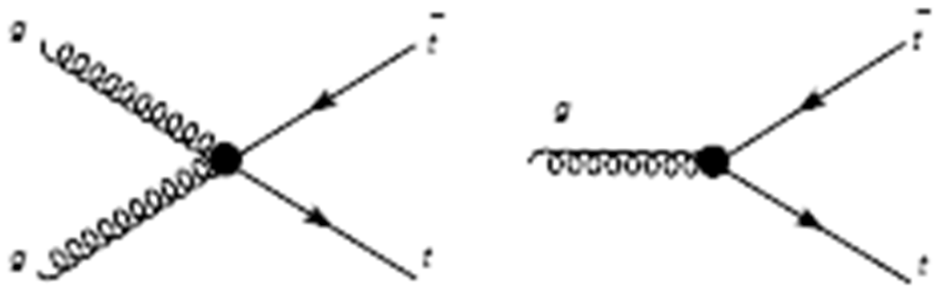
- Triplet (**3**bar,**1**,4/3)
- Sextet (**6**,**1**,4/3)



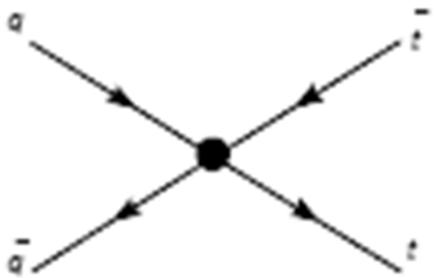


EFT

[Degrande, Gerard, Grojean, Maltoni, Servant/ Bauer, Goertz, Haisch, Pfoh, Westhoff/ Zhang, Willenbrock/ Aguilar-Saavedra, Perez-Victoria / Gabrieli, Raidal / Blum, Delaunay, Gedalia, Hochberg, Lee, Nir, Perez, Soreq]

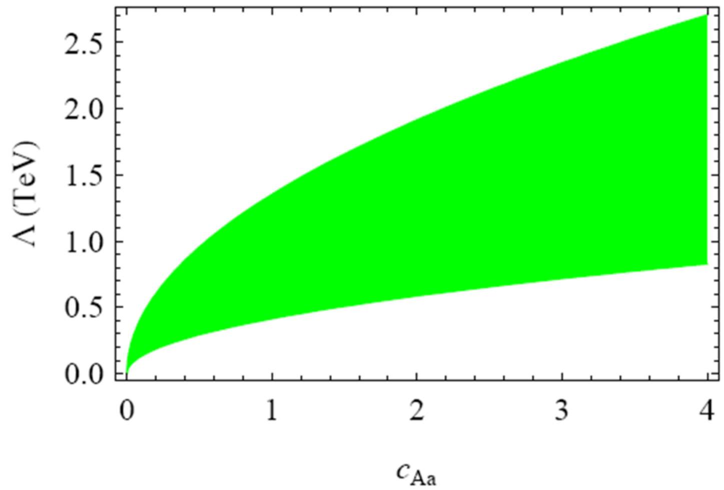


Chromomagnetic operator $O_{hg} = (H\bar{Q})\sigma^{\mu\nu}T^{A}t\, G^{A}_{\mu\nu}$

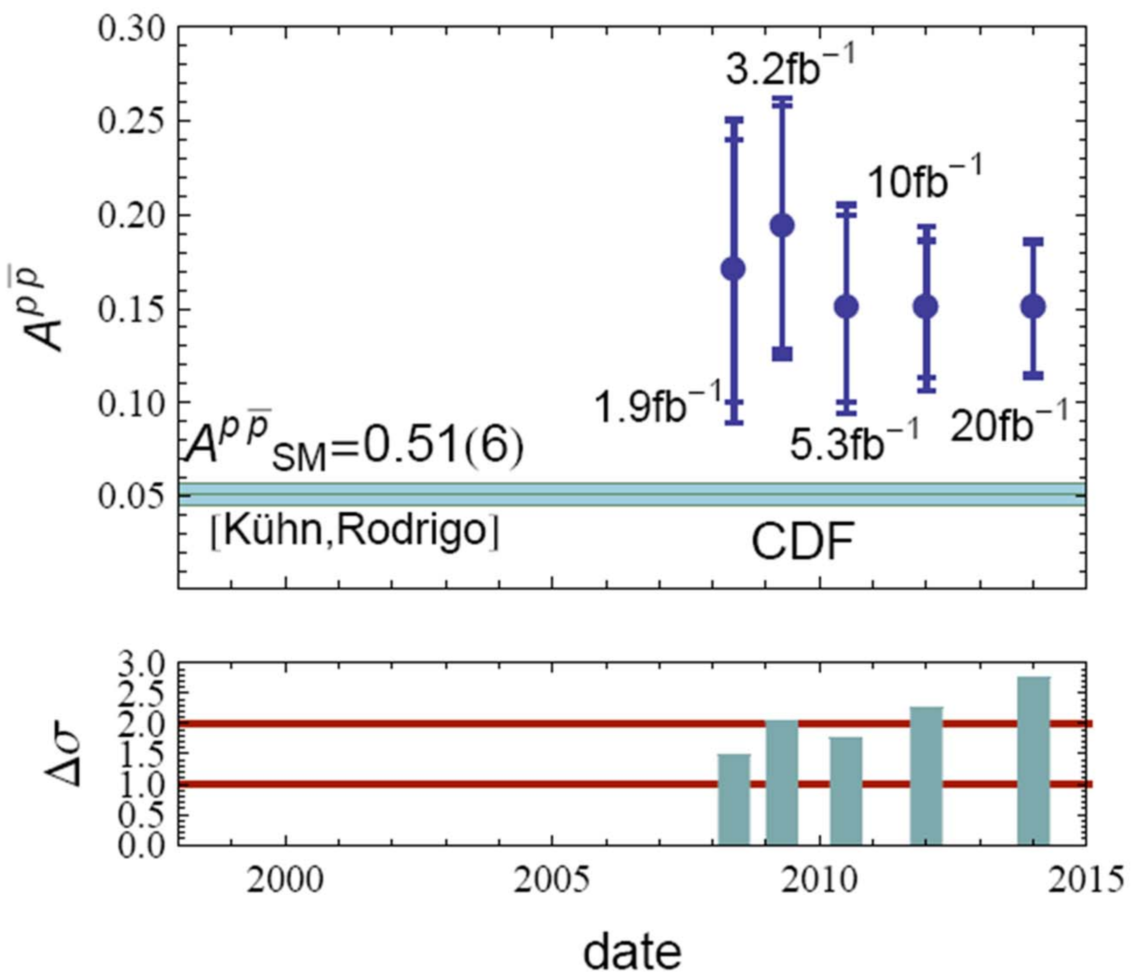


Four-fermion operators

- New physics scale Λ in the TeV or even sub-TeV region



Prospects for future evolution



- Scaling the statistical error in the **large invariant mass region**: 4-5 σ assuming same central value
- see talks by CDF/DO on Saturday (top and EW session)
- 20 fb^{-1}: combining CDF and D0

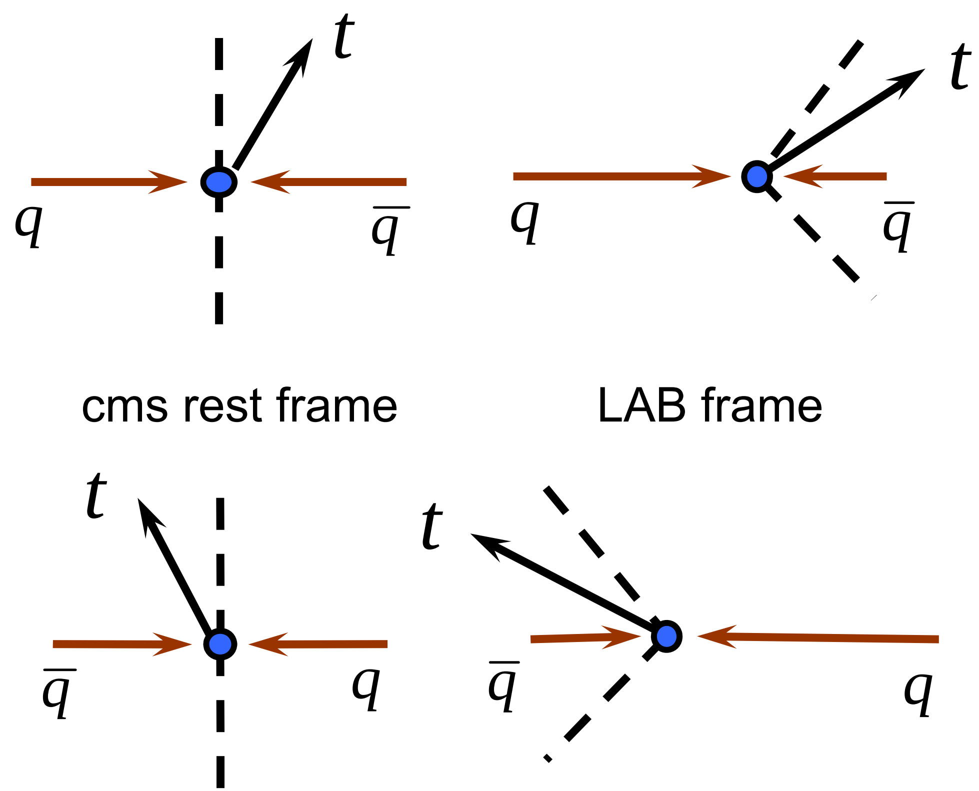
@ the LHC

Charge asymmetry at LHC

LHC is symmetric ➡ no forward-backward

But suppose that there is a charge asymmetry at parton level (QCD predicts that tops are preferentially emitted in the direction of incoming quark, BSM asymmetry can be positive or negative)

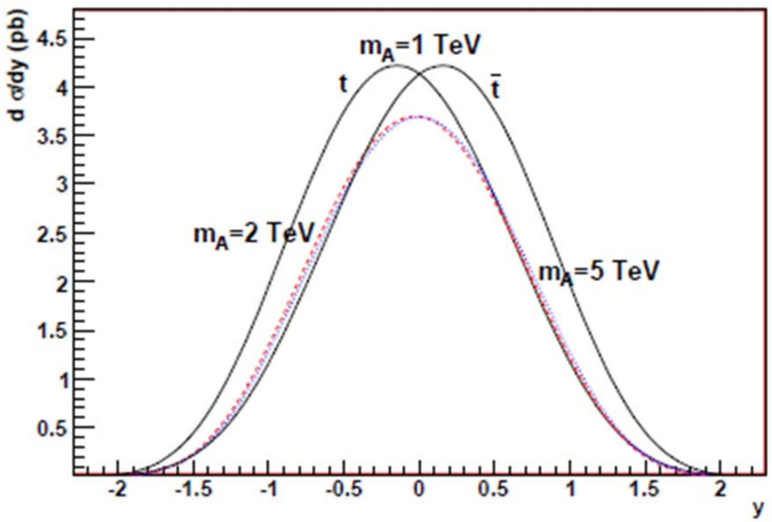
quarks carry more momenta than antiquarks



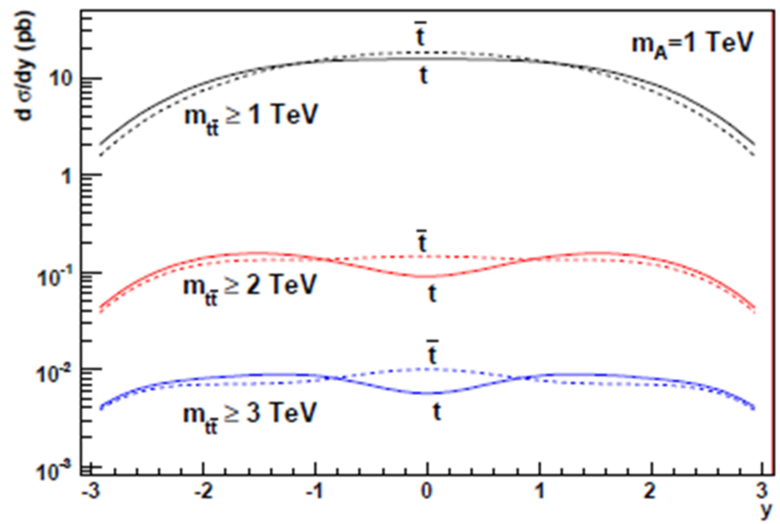
- Excess of tops (or antitops) in the forward and backward regions
- Top cross section is gg dominated, which is symmetric; but gg can be suppressed by selecting pairs with large invariant mass

From Tevatron to LHC

Tevatron



LHC



$$A_C = \frac{N_t(|y|<y_C) - N_{\bar{t}}(|y|<y_C)}{N_t(|y|<y_C) + N_{\bar{t}}(|y|<y_C)}$$

central charge asymmetry

$$A_{\bar{C}} = \frac{N_t(|y|>y_C) - N_{\bar{t}}(|y|>y_C)}{N_t(|y|>y_C) + N_{\bar{t}}(|y|>y_C)}$$

anti-central charge asymmetry
[Edge charge asymmetry,
Forward charge asymmetry]

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

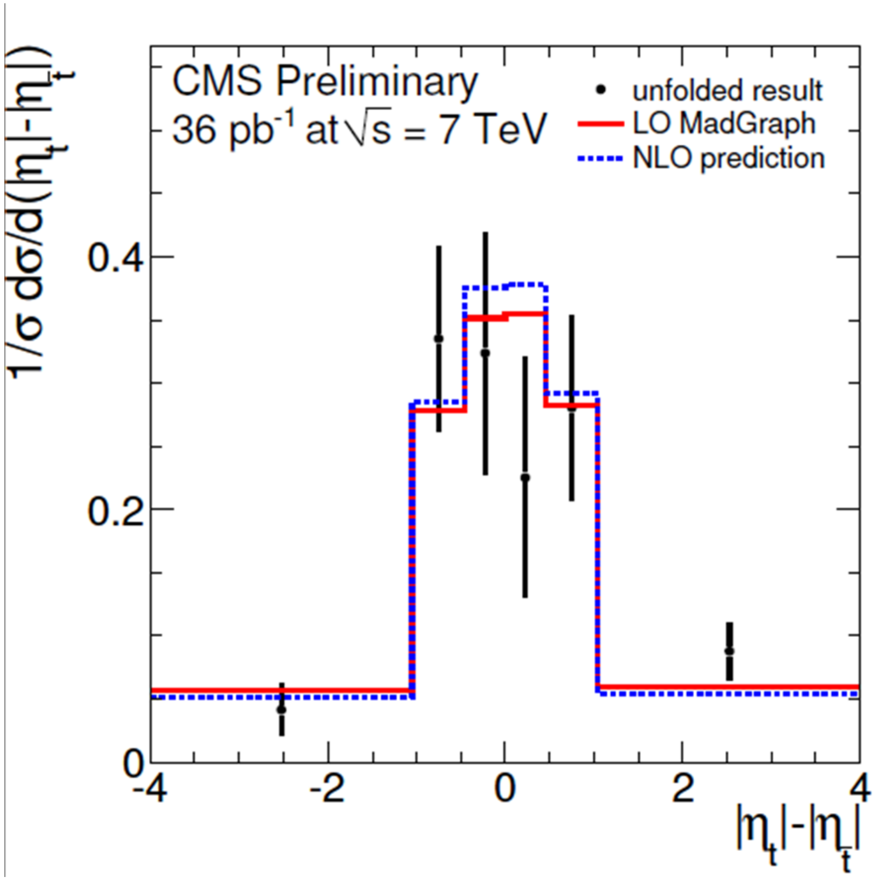
$\Delta = |\eta_t| - |\eta_{\bar{t}}|$ or $\Delta = |y_t| - |y_{\bar{t}}|$

First measurement at the LHC (CMS)

CMS PAS TOP-10-010 presented at Moriond 2011

A_η = 0.060 ± 0.134 (stat) ± 0.026 (syst) **36 pb^{-1}**

A_η^{SM} = 0.0130 (11)



- The charge asymmetry is defined in the variable

$$\Delta = |\eta_t| - |\eta_{\bar{t}}|$$

- scaling the statistical error

1 fb^{-1} : 2.5%, better than Tevatron
10 fb^{-1} : 8 per mille
100 fb^{-1} : 3 per mille

See talks by CMS / ATLAS

Some predictions BSM

Benchmark models compatible with Tevatron measurements

LHC (7 TeV)	A_n	A_n (M_{ttbar}>450 GeV)
SM	0.0130 (11)	0.0138 (13)
OctetU: flavour universal (g_V=2,g_A=0.8,m_G=1.6TeV)	0.0277 (24)	0.0404 (12)
OctetA: non-universal (g_A^q=-g_A^t=3/2,m_G=2TeV)	0.0294 (12)	0.0392 (11)
OctetB: non-universal (g_A^q=-g_A^t=3/2,mG=1.8TeV)	0.0334 (12)	0.0373 (11)

The asymmetry though the decay products

[Godbole, Rao, Rindani,Singh / Jung, Ko, Lee/ Choudhury, Godbole, Rindani, Saha/ Cao, Wu, Yang / Melnikov, Schulze / Bernreuther, Si/ Krohn, Liu, Shelton, Wang / Bai, Han/ Baumgart, Tweedie]

- Direction of the lepton (antilepton) correlated with the direction of the top quark (antitop quark), particularly for very boosted tops: asymmetry partially washed out

- The top quark decays before hadronizing: polarizations (angular distribution of the lepton wrt the parent top) and spin correlations will be altered by BSM

Conclusions

- Tevatron has reported systematically a **positive 1-2 σ deviation from the SM,** in the measurement of the top quark charge asymmetry (forward--backward), with 3.4 σ in the ttbar rest frame M_{ttbar} >450 GeV

- Early to claim new physics, but, together with $d\sigma/dM_{ttbar}$, dijet cross-section, same sign like tops, B-physics, allows to set/revisit constrains BSM in the top quark sector

- Tevatron results are statistically dominated, but measurements at the LHC will become soon statistically "unlimited"

- Stay tuned with CDF/D0 and CMS/ATLAS presentations …