The top forward-backward asymmetry

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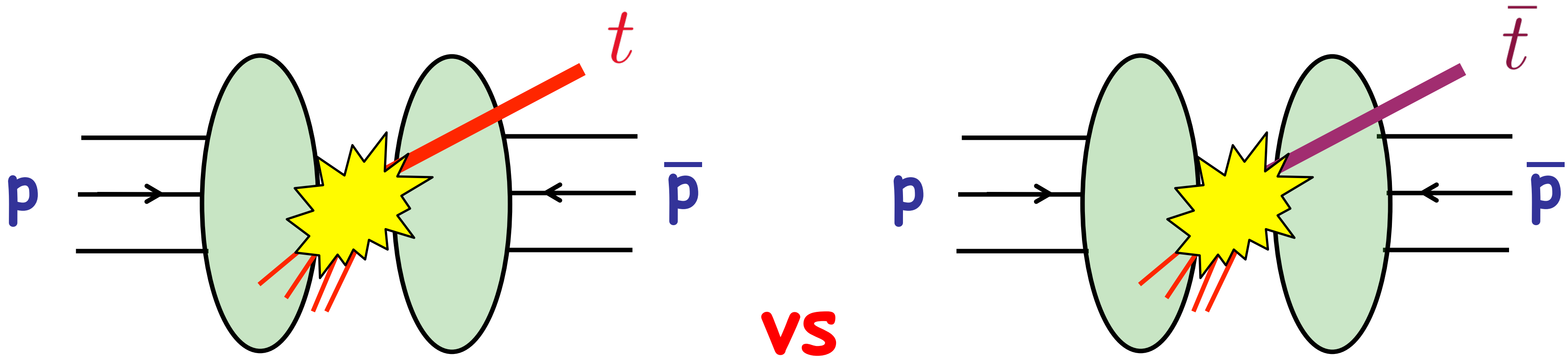
FPCP, Maale Hachamisha, 24.03.2011

Outline:

- Basics of A_{FB}
- Standard Model predictions
- Beyond SM ideas
- Conclusions

Basics of A_{FB}

Charge asymmetry:



Differential in rapidity y :

$$A_{\rm ch}(y) = \frac{N_t(y) - N_{\bar{t}}(y)}{N_t(y) + N_{\bar{t}}(y)}$$

Integrated:

$$A_{\rm ch} = \frac{N_t(y>0) - N_{\bar{t}}(y>0)}{N_t(y>0) + N_{\bar{t}}(y>0)}$$

in $p\bar{p}$:

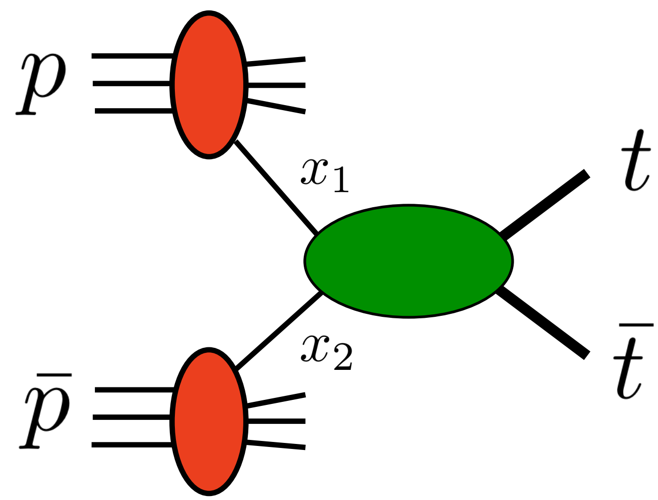
charge asymmetry leads to forward-backward asym.:

$$A_{\mathrm{FB}} = \frac{N_t(y>0) - N_t(y<0)}{N_t(y>0) + N_t(y<0)}$$

$$= A_{\mathrm{ch}}$$

- also: $A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$ $\qquad \Delta y \equiv y_t - y_{\bar{t}}$

Factorization :



$$y = \hat{y} + \frac{1}{2}\log\frac{x_1}{x_2}$$

$$y_t - y_{\bar{t}} = \hat{y}_t - \hat{y}_{\bar{t}}$$

$$A_{\mathrm{ch}} = A_{\mathrm{FB}}$$

$$\propto \int dx_1 dx_2 \left[q_1^p\, \bar{q}_2^{\bar{p}} - \bar{q}_1^p\, q_2^{\bar{p}} \right] \left(\hat{\sigma}_{q\bar{q}\to t}(\hat{y}) - \hat{\sigma}_{q\bar{q}\to\bar{t}}(\hat{y}) \right)$$

$$q\,q - \bar{q}\,\bar{q}$$

- Less dilution for $\Delta y \equiv y_t - y_{\bar{t}}$
- Note, for pp: $A_{\mathrm{FB}} \equiv 0$, but can still define an A_{ch}

Integrated asymmetries:

- D0: not corrected for acceptance or reconstruction

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = \left(8 \pm 4\,(\mathrm{stat})\ \pm 1\,(\mathrm{syst})\right)\%$$

SM expectation (MC@NLO): ~ 1%

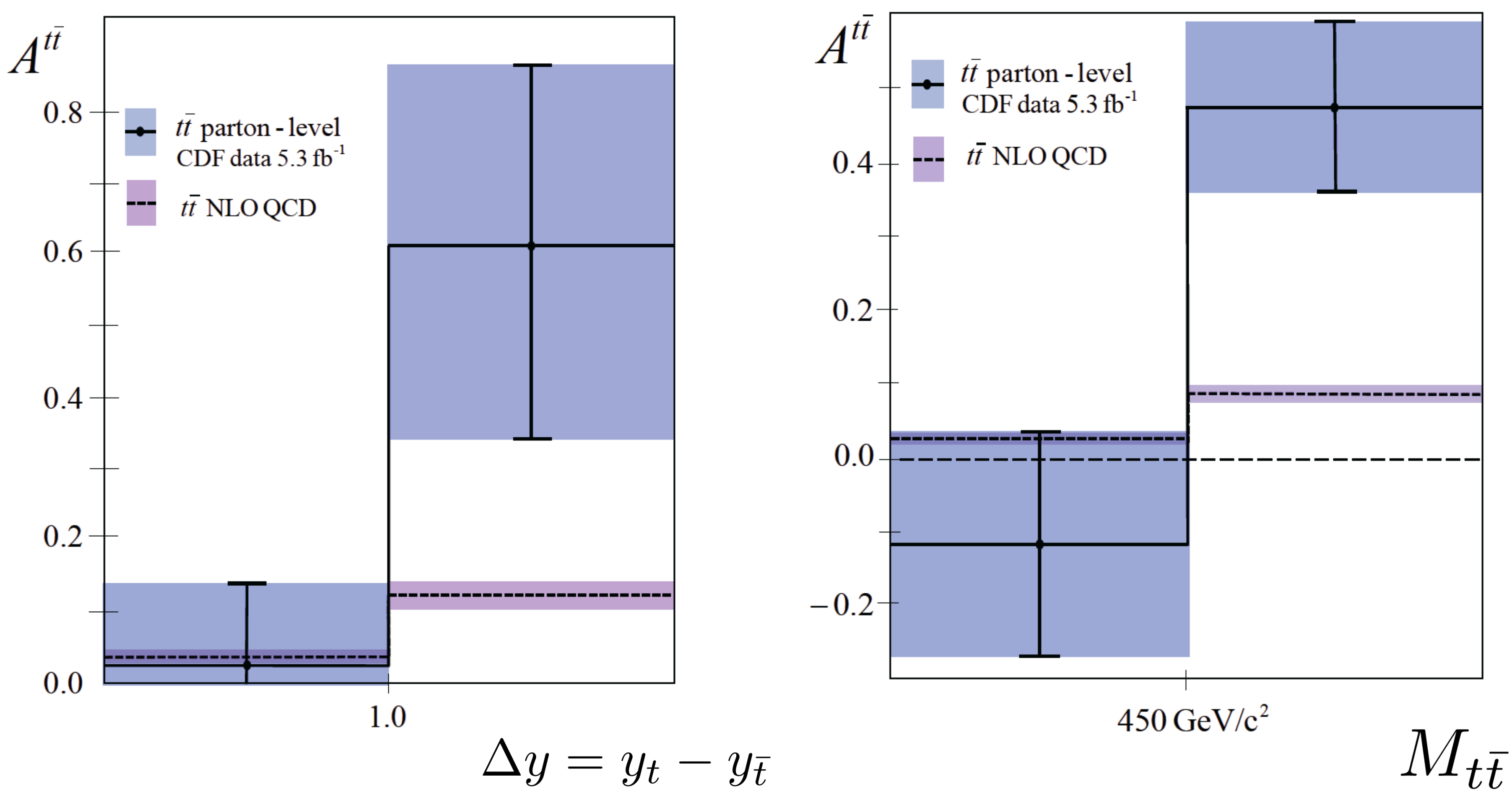
- CDF: fully corrected

$$A_{\mathrm{FB}}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} = \begin{cases} 0.158 \pm 0.075 & \ell + \mathrm{jets} \\ 0.42 \pm 0.15 \pm 0.05 & 2\ell \end{cases}$$

SM expectation: ~ 6%

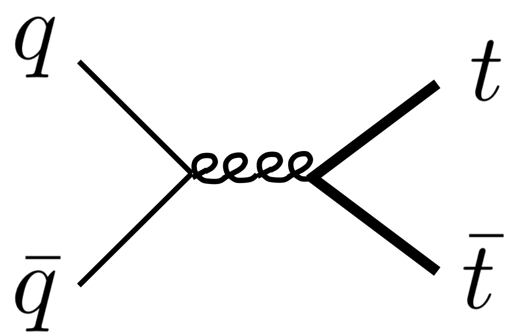
$$A_{\mathrm{FB}} = \frac{N_t(y > 0) - N_t(y < 0)}{N_t(y > 0) + N_t(y < 0)} = 0.150 \pm 0.055$$

SM expectation: ~ 4%


$A^{t\bar{t}}$
0.8
0.6
0.4
0.2
0.0
$t\bar{t}$ parton - level
CDF data 5.3 fb^{-1}
$t\bar{t}$ NLO QCD
1.0
$\Delta y = y_t - y_{\bar{t}}$
$A^{t\bar{t}}$
0.4
0.2
0.0
−0.2
$t\bar{t}$ parton - level
CDF data 5.3 fb^{-1}
$t\bar{t}$ NLO QCD
450 GeV/c^2
$M_{t\bar{t}}$

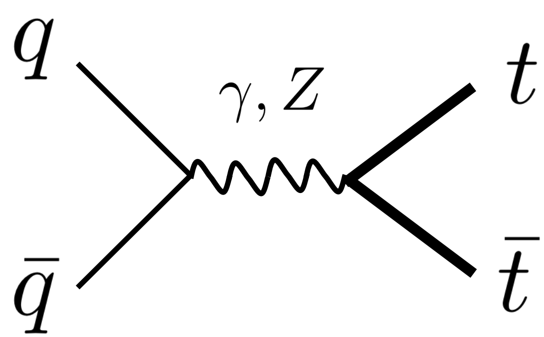
Standard Model predictions

- Tevatron: ~85% of $t\bar{t}$ cross section is from $q\bar{q}$



LO symmetric in $t,\ \bar{t}$: no A_{ch}

- electroweak:

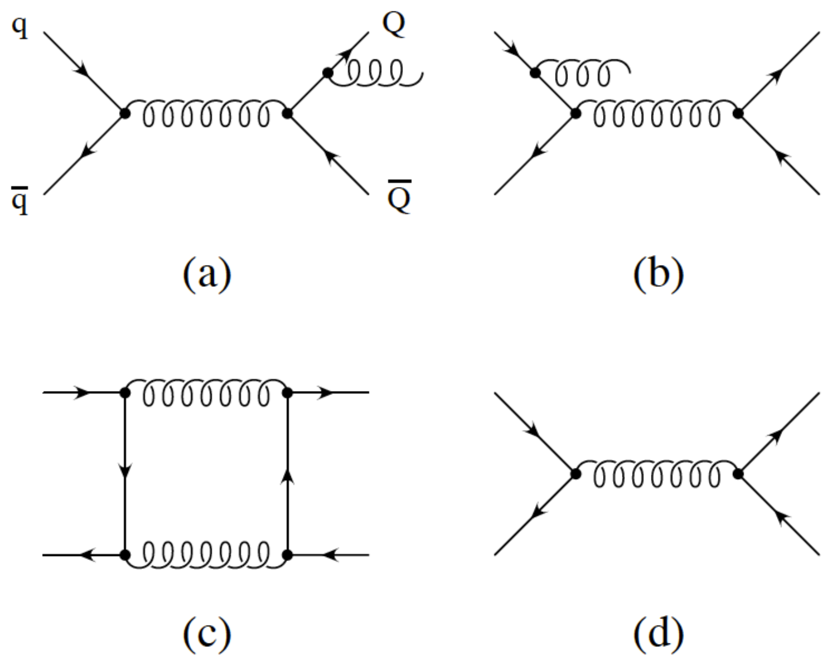


tiny

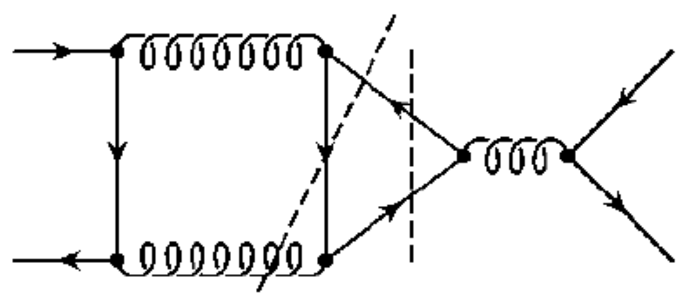
structure is: $A_{\rm FB} \propto (\hat{s} - M_Z^2)\, e_q\, e_t\, g_A^q\, g_A^t\, \cos\theta$

(no interference with QCD $q\bar{q} \to t\bar{t}$)

- however, at $\mathcal{O}(\alpha_s^3)$:



Brown,Sahdev,Mikaelian '79
Halzen,Hoyer,Kim '87
Kühn,Rodrigo '98
QED:
Berends,Gaemers,Gastmans '73
Putzolu '61



- in QCD, effect involves color factor $d_{abc}\, d^{abc}$

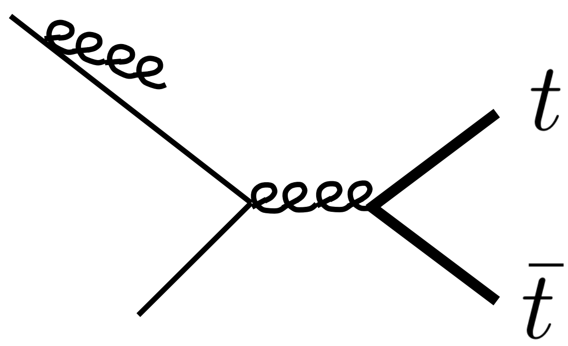
- diagrams are subset of full NLO, and therefore also included there

Beenakker et al.,
Ellis,Dawson,Nason,
MCFM (Campbell,Ellis,et al.)
MC@NLO (Frixione et al.)

- however, for *asymmetric* part, they are LO

- as a result, loops are UV-finite

- diagrams also collinear-finite:



would be $\sim \; P_{qq} \times \sigma_{q\bar{q}\to t\bar{t}}$

- single IR divergence that cancels between real & virtual

Kühn,Rodrigo

$$\frac{d\sigma_A^{q\bar{q},virt+soft}}{d\cos\hat{\theta}} = \frac{\alpha_s^3}{2\hat{s}} \frac{d_{abc}^2}{16N_C^2} \beta \Big\{ B(c) - B(-c) + (1+c^2+4m^2) \times \left[4\log\left(\frac{1-c}{1+c}\right)\log(2w) + D(c) - D(-c) \right] \Big\}$$

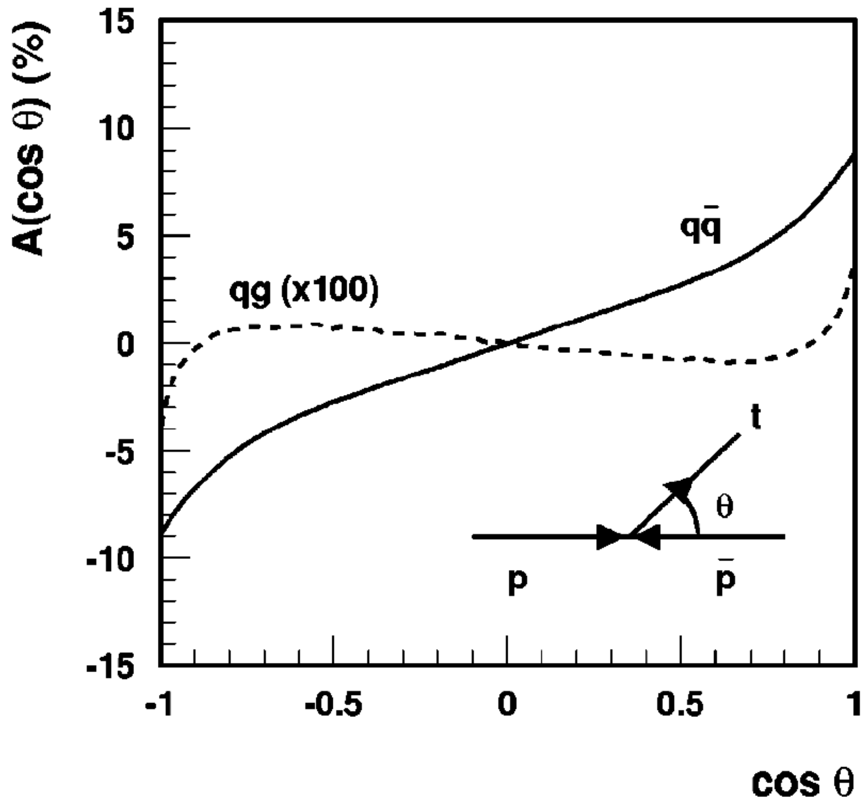
$$\beta = \sqrt{1-4m^2}, \quad c = \beta\cos\hat{\theta}, \quad w = E_{cut}^g/\sqrt{\hat{s}}$$

- $\log(E^g_{cut})$ cancels against 2->3 contributions

- nominally, 2->3 < 0
  soft+virt > 0, and larger

$$\Big\} \Rightarrow A_{\rm ch} > 0$$

Kühn,Rodrigo



Integrated Δy asymmetry ~ 6%

Stability of this prediction ?

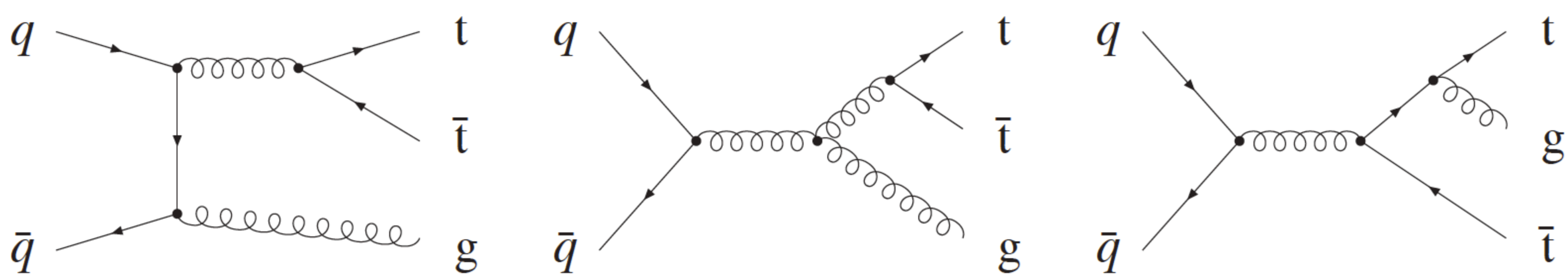
Why (might need to) worry:

- only LO
- NLO gives ~30% correction to $t\bar{t}$ cross section, significant scale uncertainty
- NLO for *charge-asymmetric* part not available (would be part of NNLO for full cross sec.)
- recent findings for asymmetry in $t\bar{t} + \mathrm{jet}$

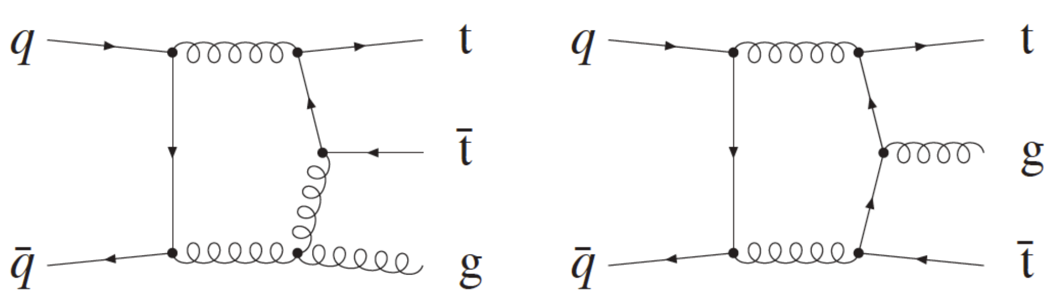
- NLO computation of $t\bar{t} + \mathrm{jet}$ production

Dittmaier,Uwer,Weinzierl '07
Melnikov,Schulze '10

LO:

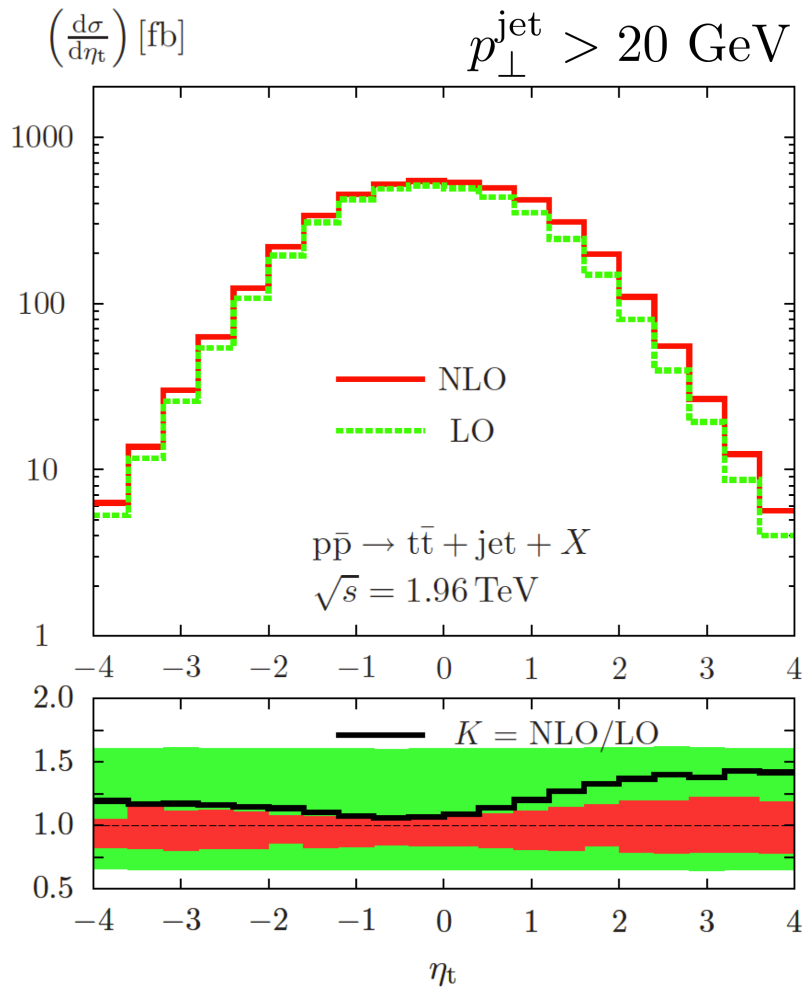


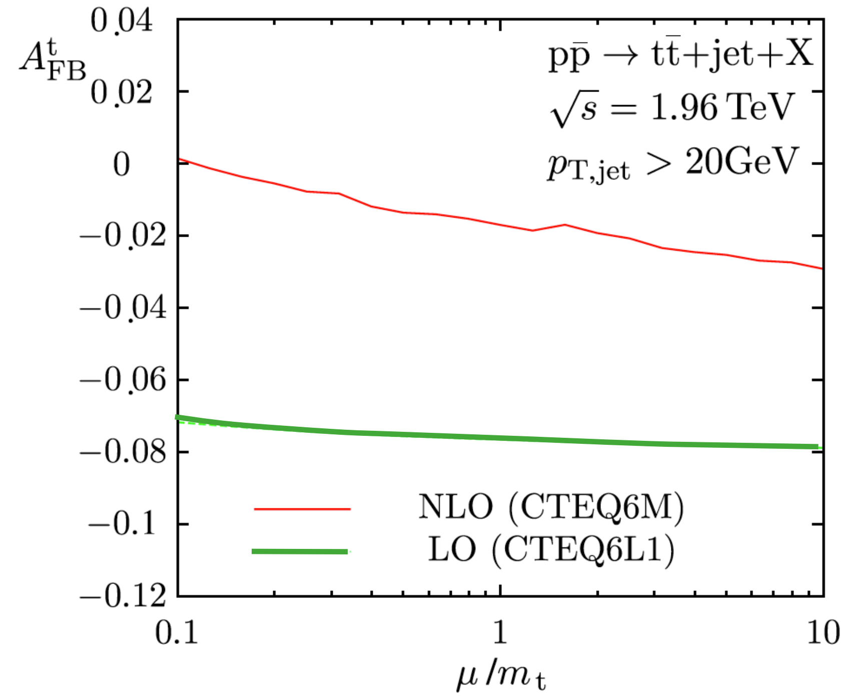
NLO:



+ real

- true NLO – also for *charge-asymmetric piece !*





Note, $A_{\text{FB}} < 0$

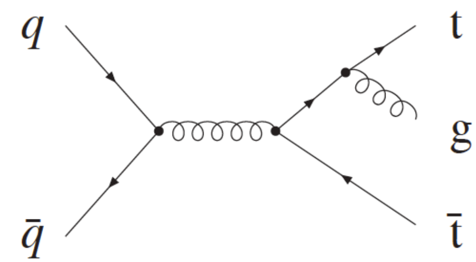
Dittmaier,Uwer,Weinzierl

Why so different ?

Melnikov,Schulze

- $t\bar{t} + \text{jet}$ is different observable

- LO: Only real-emission diagrams



Recall, $\sim \alpha_s^3 \log(E^g_{\text{cut}}) \sim \alpha_s^3 \log(p_\perp^{\text{jet}}) < 0$

- denominator of A_{FB}: $\sim \alpha_s \log^2(p_\perp^{\text{jet}})\, \sigma_{q\bar{q}\to t\bar{t}}$

soft+coll. LO incl.

- NLO for *asymmetric* part: double-logs arise

$$\alpha_s \log^2(p_\perp^{\text{jet}})\, A_{\text{FB}}^{\text{incl.}}\, \sigma_{q\bar{q}\to t\bar{t}} \sim \alpha_s^4 \log^2(p_\perp^{\text{jet}}) > 0$$

- therefore:

$$A_{\mathrm{FB}}^{t\bar{t}+\mathrm{jet}} \sim \frac{-C\,\alpha_s^3\,\log(p_\perp^{\mathrm{jet}}) + \alpha_s\log^2(p_\perp^{\mathrm{jet}})\,A_{\mathrm{FB}}^{\mathrm{incl.}}\,\sigma_{q\bar{q}\to t\bar{t}}}{\sigma_{t\bar{t}+\mathrm{jet}}}$$

- beyond that no reason for "new effects"

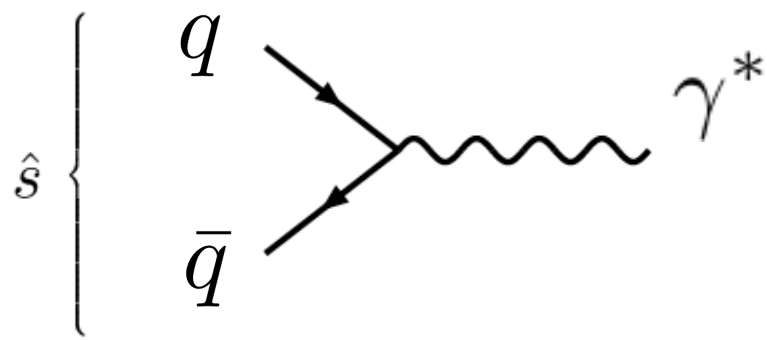
- *inclusive* observables: $\log(E_{\mathrm{cut}}^g)$ cancel order-by-order:
  expect much more stability

Still: how stable is inclusive asymmetry?

Almeida,Sterman,WV
Ahrens, Neubert et al.

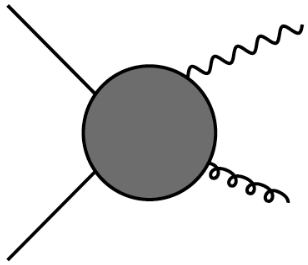
- investigate higher orders of perturbation theory
- for simplicity, consider Drell-Yan first:

LO :



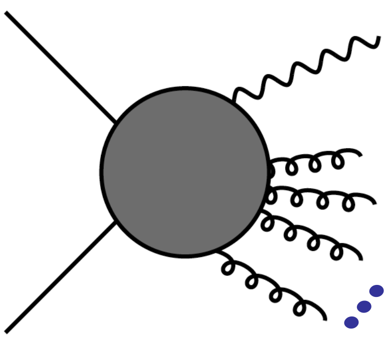
$$z \equiv \frac{M_{\ell\ell}^2}{\hat{s}} = 1 \qquad\qquad \frac{d\sigma_{q\bar{q}}^{\mathrm{LO}}}{dM_{\ell\ell}} \sim \delta(1-z)$$

- NLO correction:



$$z \longrightarrow 1: \qquad \frac{d\sigma_{q\bar{q}}^{\mathrm{NLO}}}{dM_{\ell\ell}} \sim \alpha_s \left(\frac{\log(1-z)}{1-z}\right)_+ + \ldots$$

- higher orders:



$$\frac{d\sigma_{q\bar{q}}^{\mathrm{N^kLO}}}{dM_{\ell\ell}} \sim \alpha_s^k \left(\frac{\log^{2k-1}(1-z)}{1-z}\right)_+ + \ldots$$

"threshold logarithms"

- $z \rightarrow 1:$ soft / collinear gluons

Large logs resummed to all orders

Sterman; Catani, Trentadue

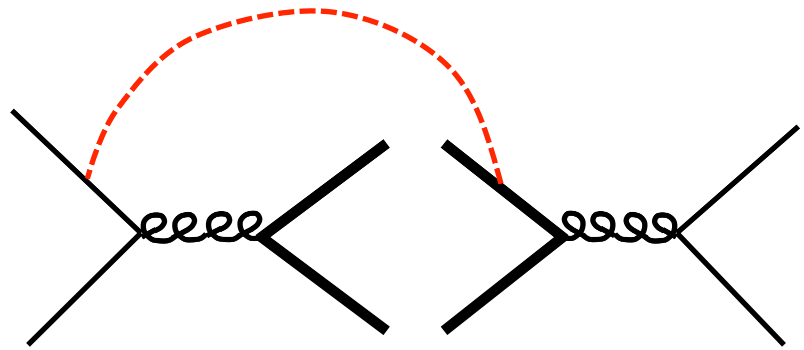
- factorization of matrix elements
- and of phase space when integral transform is taken

$$\hat{\sigma}_{q\bar{q}} \propto \exp\left[2\int_0^1 dy\, \frac{y^N - 1}{1-y} \int_{\mu_F^2}^{Q^2(1-y)^2} \frac{dk_\perp^2}{k_\perp^2} A_q\left(\alpha_s(k_\perp^2)\right) + \ldots \right]$$

$$A_q(\alpha_s) = C_F \left\{ \frac{\alpha_s}{\pi} + \left(\frac{\alpha_s}{\pi}\right)^2 \left[\frac{C_A}{2}\left(\frac{67}{18} - \zeta(2)\right) - \frac{5}{9} T_R n_f \right] \right\}$$

- contains all leading logs
- does not depend on scattering angle

Application to heavy flavor production:



Kidonakis,Sterman
Mitov,Sterman
Beneke et al.
Ahrens et al.

- leads to 2x2 matrix problem

$$\sigma^{\rm res}_{q\bar{q}}(N,\theta) \;\propto\; \underbrace{\Delta_q(N)\,\Delta_{\bar{q}}(N)}_{\text{like Drell-Yan}}\;{\rm Tr}\left[H_{q\bar{q}}(\theta)\;\underbrace{{\rm e}^{-\int_{M_{t\bar{t}}}^{M_{t\bar{t}}/N}\frac{d\mu}{\mu}\,\boldsymbol{\Gamma}^\dagger(\alpha_s,\theta)}\;S_{q\bar{q}}\;{\rm e}^{\int_{M_{t\bar{t}}}^{M_{t\bar{t}}/N}\frac{d\mu}{\mu}\,\boldsymbol{\Gamma}(\alpha_s,\theta)}}_{\text{this part depends on scattering angle !}}\right]$$

(next-to-leading log)

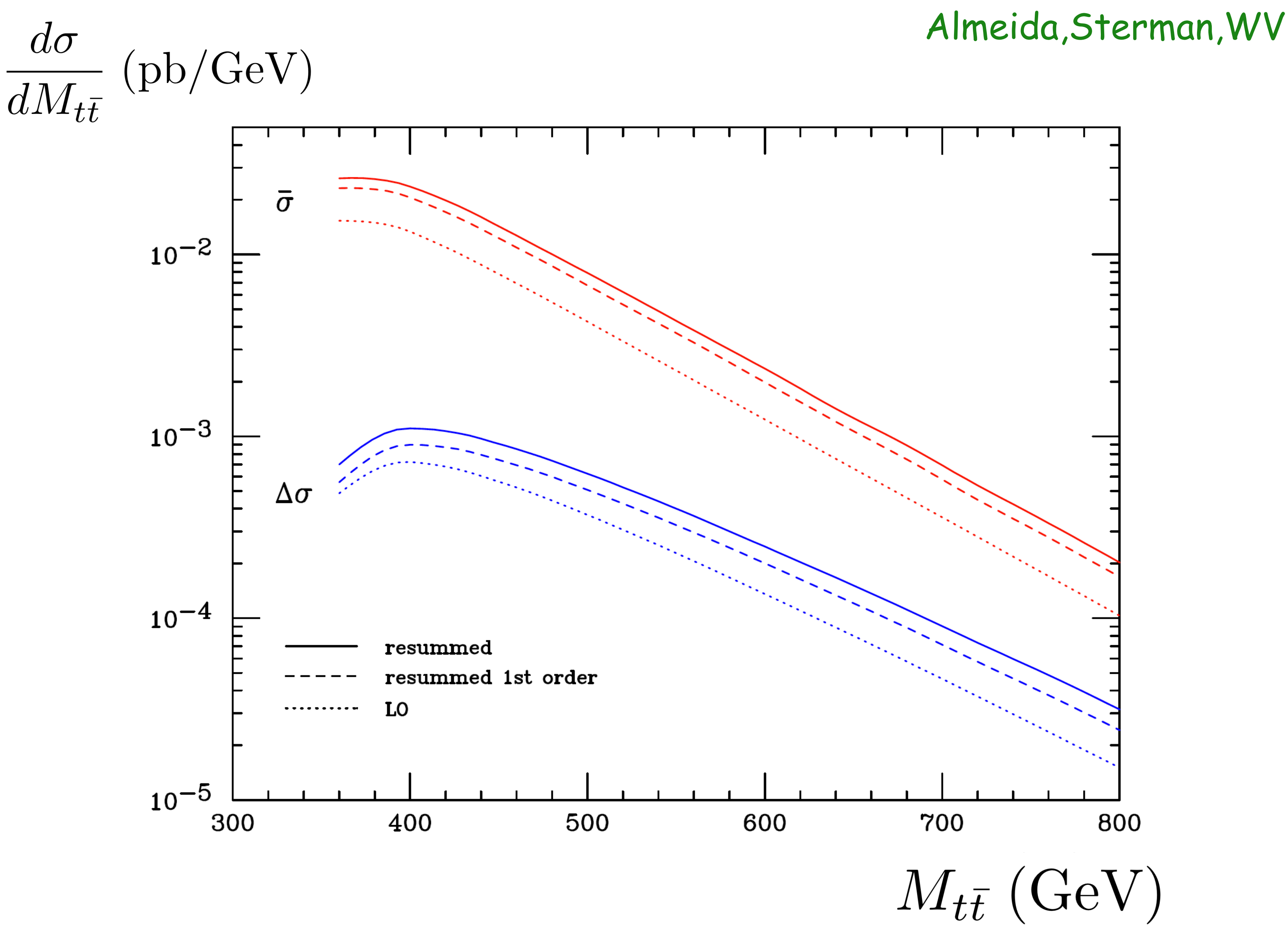
To good approximation:

Almeida,Sterman,WV

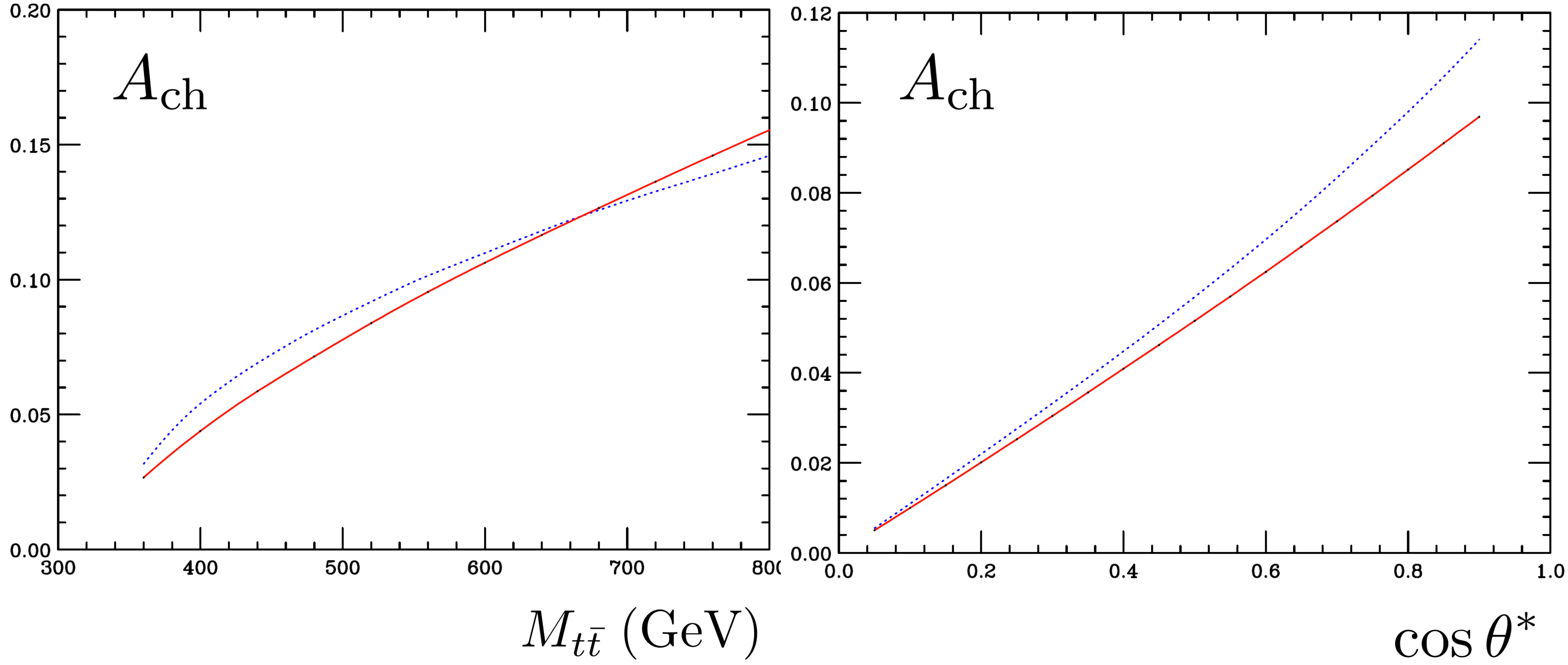
$$\hat{\sigma}^{(\mathrm{res})}_{q\bar{q}}(N,\theta) = \hat{\sigma}^{(\mathrm{Born})}_{q\bar{q}}(\theta)\ (\Delta_q(N))^2 \left\{1 + \frac{\beta\cos\theta(8C_F - 3C_A)\ln(1-2\lambda)}{\pi b_0}\right\} \mathrm{e}^{-\frac{C_A}{2\pi b_0}\ln(1-2\lambda)}$$

$$\lambda = \alpha_s b_0 \log(N)$$

- leading-log part cancels in A_{FB}



Almeida,Sterman,WV
$\frac{d\sigma}{dM_{t\bar{t}}}$ (pb/GeV)
$\bar{\sigma}$
$\Delta\sigma$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
300
400
500
600
700
800
resummed
resummed 1st order
LO
$M_{t\bar{t}}$ (GeV)



- general trend is like CDF data, but less pronounced
- stability of results confirmed to NNLL for integrated asymmetry

Ahrens,Ferroglia,Neubert, Pecjak,Yang

Ideas beyond the SM

A lot of activity…

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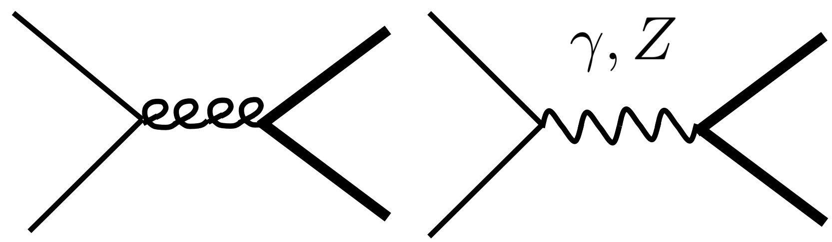
[7] C. Degrande, J.-M. Gerard, C. Grojean, F. Maltoni, and G. Servant, (2010), arXiv:1010.6304 [hep-ph]; J. Aguilar-Saavedra and M. Perez-Victoria, (2011), arXiv:1103.2765 [hep-ph].

(from Krohn et al.)

Main idea: exotic tree-level contributions

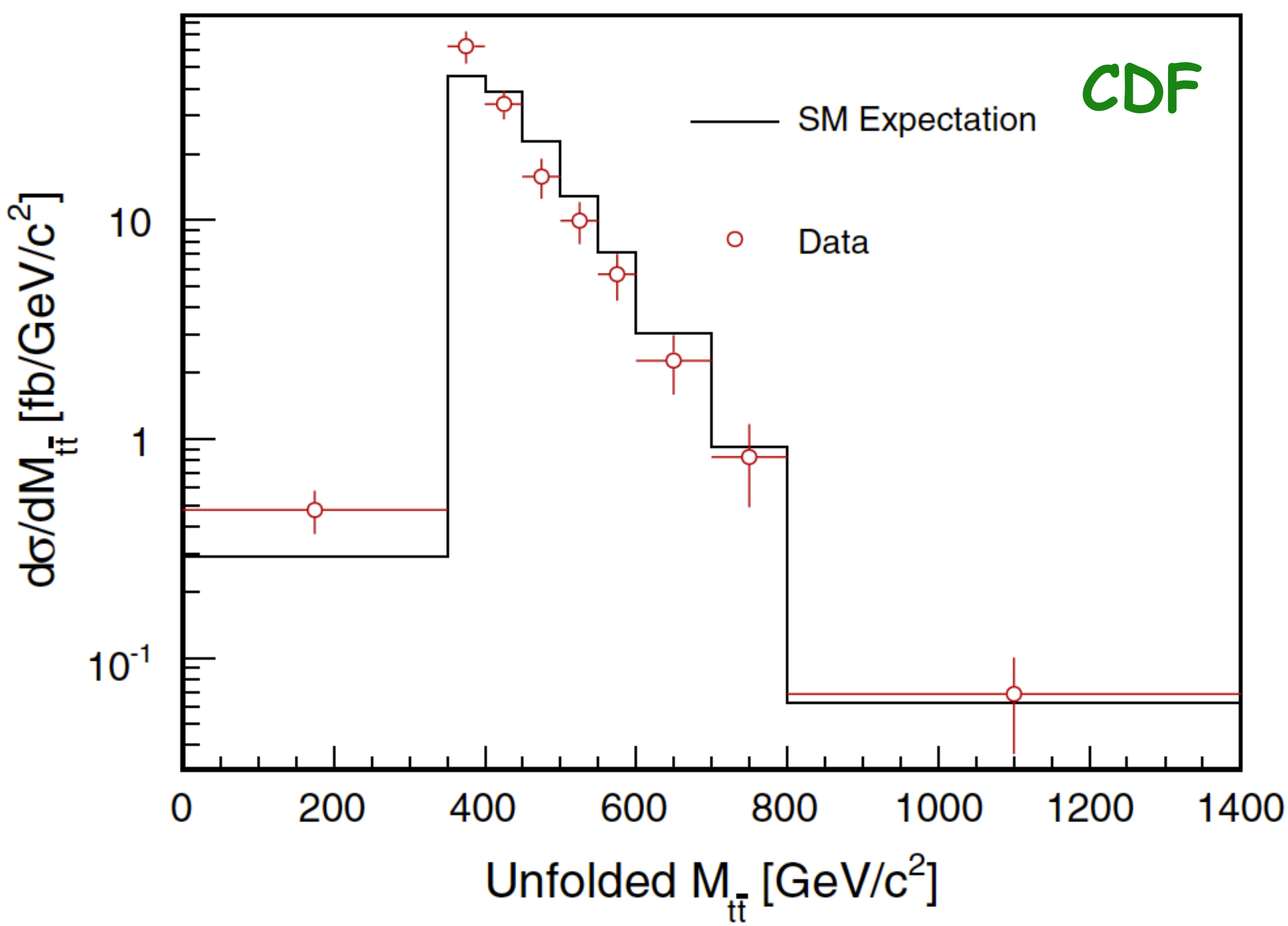
Reviews, see: Cao,McKeen,Rosner,Shaughnessy,Wagner
Rodrigo,Ferrario; Shu,Wang,Zhu;
Gresham,Kim,Zurek

- recall, no interference of



- without interference, hard to get large A_{FB} without generating large (unwanted) contributions to

$$\sigma_{t\bar{t}}\ ,\quad d\sigma/dM_{t\bar{t}}$$



also total cross section

Cacciari et al.; Moch,Uwer;
Kidonakis,Vogt; Ahrens et al.

Two main avenues:

Heavy color-octet gauge bosons

- occur in several models, such as chiral color ("axigluon") extra dim.

  Pati,Salam; Frampton,Glashow; Hill et al.; Agashe, Perez, et al. Choudhury et al.; Bai et al.

- model-independent analysis:

  Rodrigo,Ferrario

$$\mathcal{L} = g_S\, t^a\, \bar{q}_i (g_V^{q_i} + g_A^{q_i}\,\gamma_5)\, \gamma^\mu\, G_\mu^a\, q_i$$

flavor-non-universal: $g_{V,A}^t \neq g_{V,A}^q$

$$\frac{d\hat\sigma^{q\bar q\to t\bar t}}{d\cos\theta^*} = \alpha_s^2 \frac{\pi\sqrt{1-4m^2}}{9\hat s} \times$$

$$\times\Bigg[(1+4m^2+c^2)\left(1 - \frac{2g_V^q g_V^t \hat s(M_{G'}^2-\hat s)}{(\hat s - M_{G'}^2)^2 + M_{G'}^2\Gamma_G^2} + \frac{g_V^{t\,2}(g_V^{q\,2}+g_A^{q\,2})\hat s^2}{(\hat s - M_{G'}^2)^2 + M_{G'}^2\Gamma_G^2}\right)$$

$$+ (1-4m^2+c^2)\, g_A^{t\,2}(g_V^{q\,2}+g_A^{q\,2})\frac{\hat s^2}{(\hat s - M_{G'}^2)^2 + M_{G'}^2\Gamma_G^2}$$

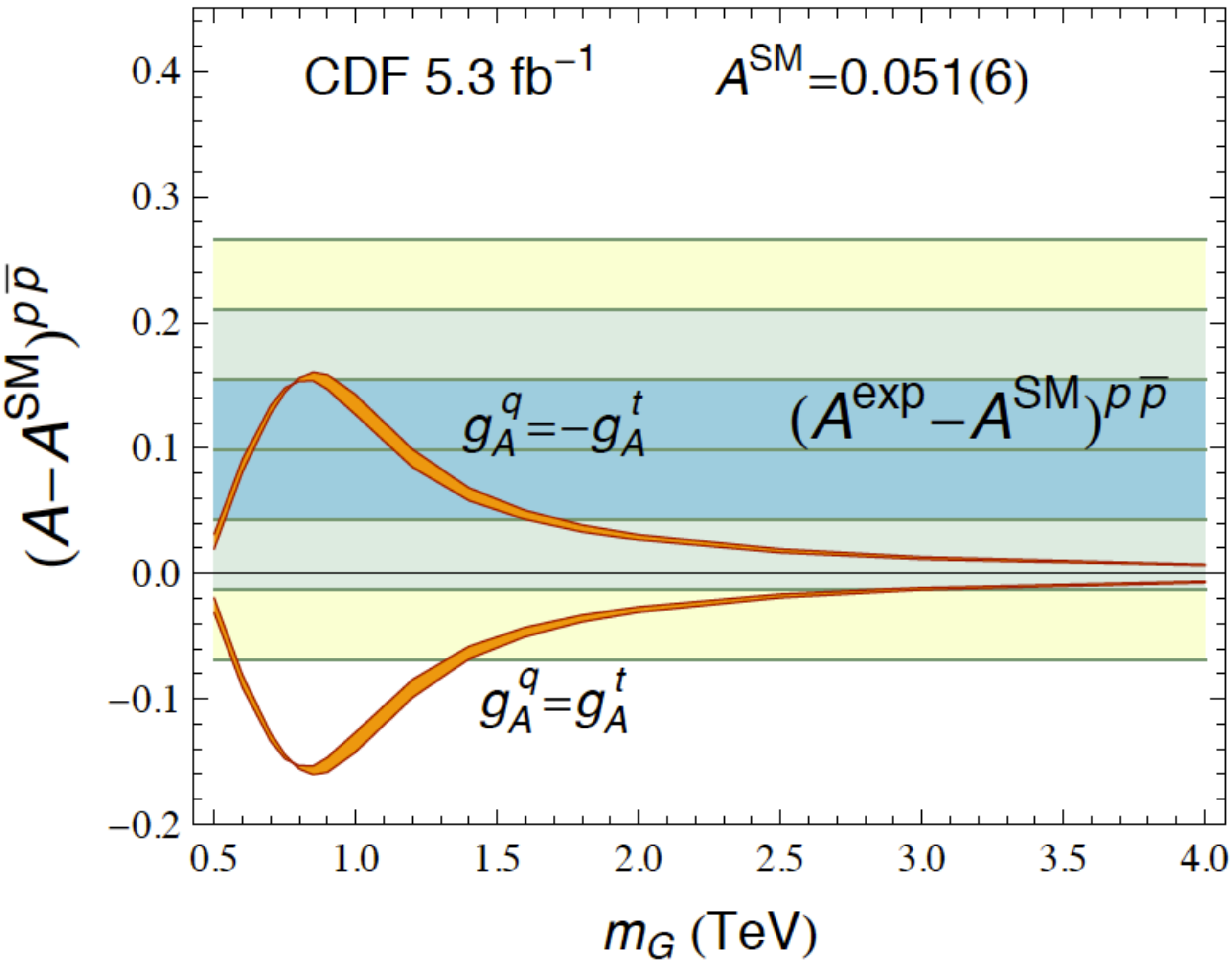
$$-4g_A^q g_A^t c\left(\frac{\hat s(M_{G'}^2-\hat s)}{(\hat s - M_{G'}^2)^2 + M_{G'}^2\Gamma_G^2} - 2g_V^q g_V^t \frac{\hat s^2}{(\hat s - M_{G'}^2)^2 + M_{G'}^2\Gamma_G^2}\right)\Bigg]$$

$$c = \beta\cos\theta^*$$

- interference contributes to positive A_{FB} if $g_A^t\, g_A^q < 0$
- if flavor-universal $g_{V,A}^t = g_{V,A}^q$ interference can't do it
- Need $|\dots|^2$ and large vector couplings.

Beware of: $d\sigma/dM_{t\bar t}$

LHC dijets



Rodrigo,Ferrario

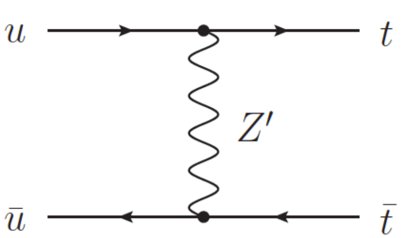
$$g_V^t = g_V^q = 0$$

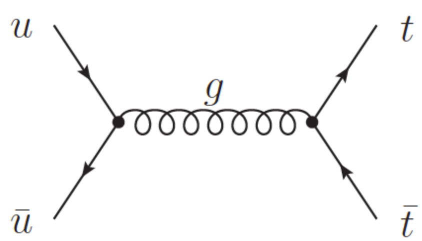
Extra weak gauge bosons

Berger et al.; Fox et al.
Aguilar-Saavedra,Perez-Victoria
Jung,Murayama,Pierce,Wells

$$\mathcal{L} = \frac{1}{\sqrt{2}}\bar{t}\gamma^\mu(g_L P_L + g_R P_R)uZ'_\mu + \frac{1}{\sqrt{2}}\bar{d}\gamma^\mu(\tilde{g_L} P_L + \tilde{g_R} P_R)tW'_\mu$$

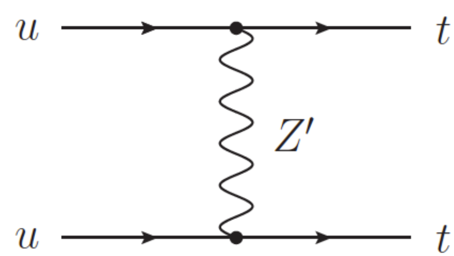
- large flavor-violating couplings
- t-channel avoids large features in $d\sigma/dM_{t\bar{t}}$
- ...and is efficient in generating A_{FB}





$$\mathcal{A}_{int} = \frac{2g_s^2}{9}\frac{(g_L^2+g_R^2)}{\hat{s}\hat{t}_{Z'}}\left[2\hat{u}_t^2 + 2\hat{s}m_t^2 + \ \ldots\right]$$

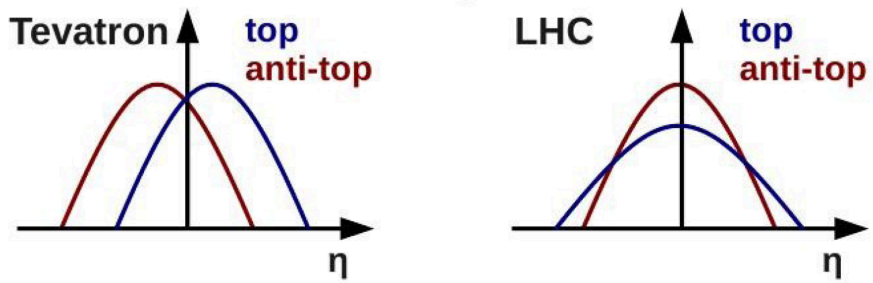
- predicts *same-sign* tt pairs. Constraints from Tevatron, copious at LHC.



- in some models, helps with CDF Wjj anomaly

Conclusions:

- tantalizing situation – but, too soon for conclusions
- if data persist, QCD unlikely to explain observed A_{FB}
- LHC should provide answers:



$$A_C(y_C) = \frac{\sigma_t(|y| \leq y_C) - \sigma_{\bar{t}}(|y| \leq y_C)}{\sigma_t(|y| \leq y_C) + \sigma_{\bar{t}}(|y| \leq y_C)}$$

Antunano, Kühn, Rodrigo

- Tosi's talk: $A_{\mathrm{ch}}(|\eta_t| - |\eta_{\bar{t}}|) = 0.060 \pm 0.134 \pm 0.026$

  QCD: ~1% (Rodrigo)

- plus: like-sign tops, dijets, …