Is The Top Quark Asymmetry Just Standard-Model Physics?

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Outline

- Top quark production at Tevatron and LHC
- Standard Model predictions
- Monte Carlo event generation
- Tevatron data
- QCD asymmetry as a coherence effect
- LHC data and prospects
- Conclusions

Top Production at Tevatron

- $p\bar{p}$ at 1.96 TeV
- CDF & D0
- ~9 fb^{-1}/expt
- $\sigma_{t\bar{t}}$~8 pb

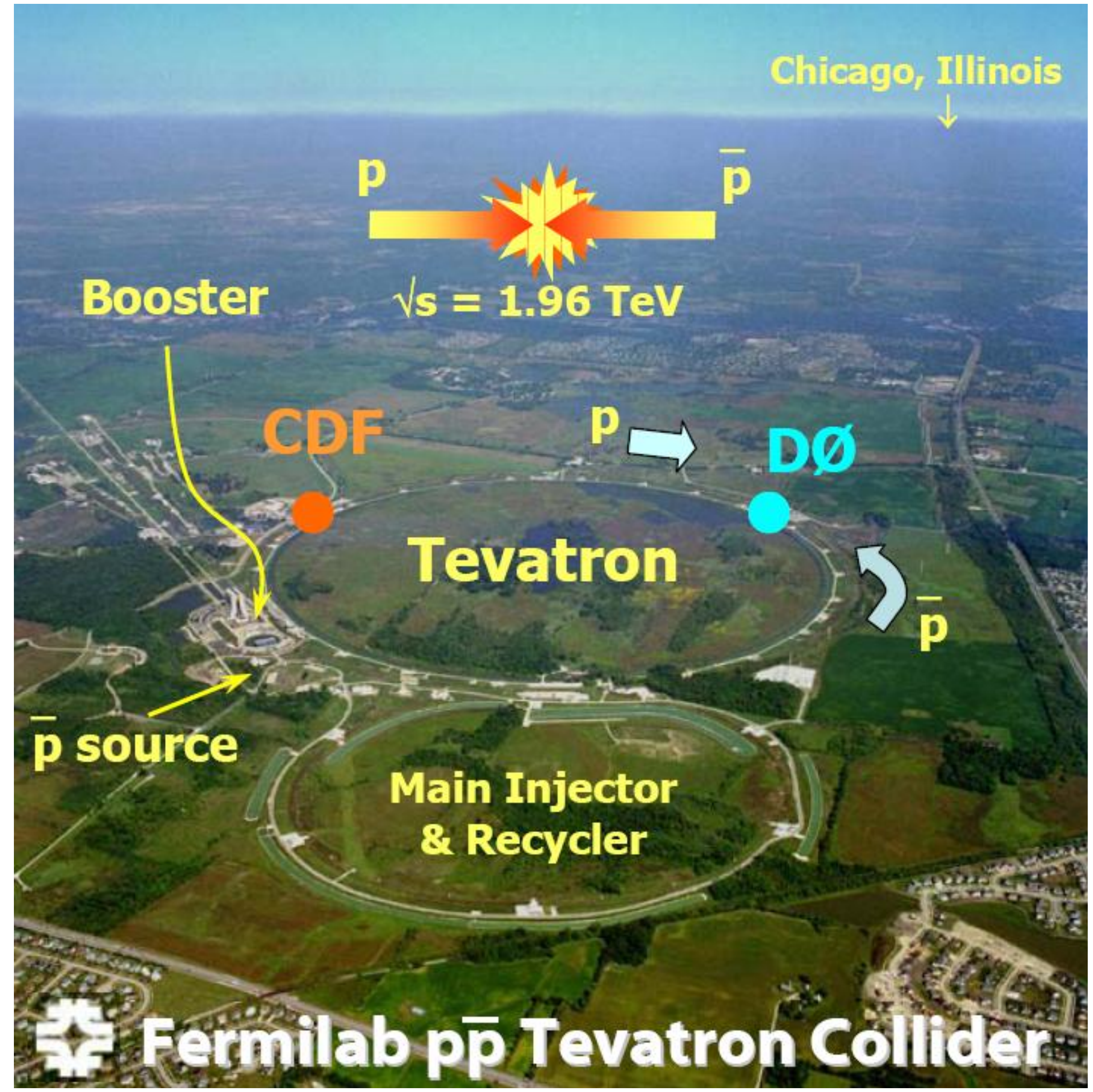
➡ ~70,000 $t\bar{t}$

$$t \to Wb$$

$$W \to e\nu_e, \mu\nu_\mu \to l + \not{E}$$

$$(W \to \tau\nu_\tau)$$

$$W \to u\bar{d}, c\bar{s} \to jj$$



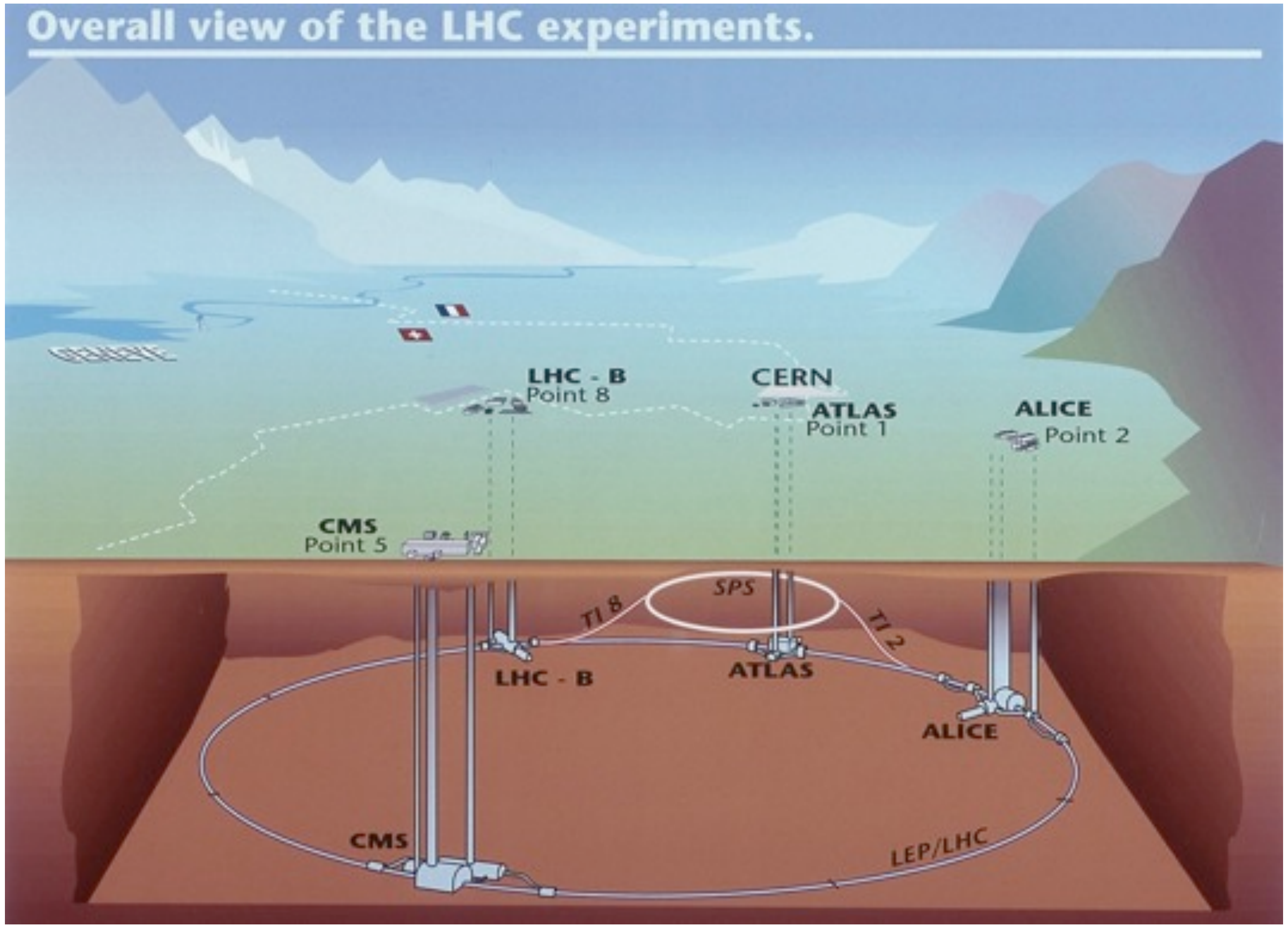
➡ $t\bar{t} \to b\bar{b}l\bar{l} + \not{E}\,(5\%),\ t\bar{t} \to b\bar{b}ljj + \not{E}\,(30\%)$

Top Production at LHC

- pp at 7,8 TeV
- ATLAS & CMS
- ~6 fb^{-1}/expt
- $\sigma_{t\bar{t}}$ ~160 pb

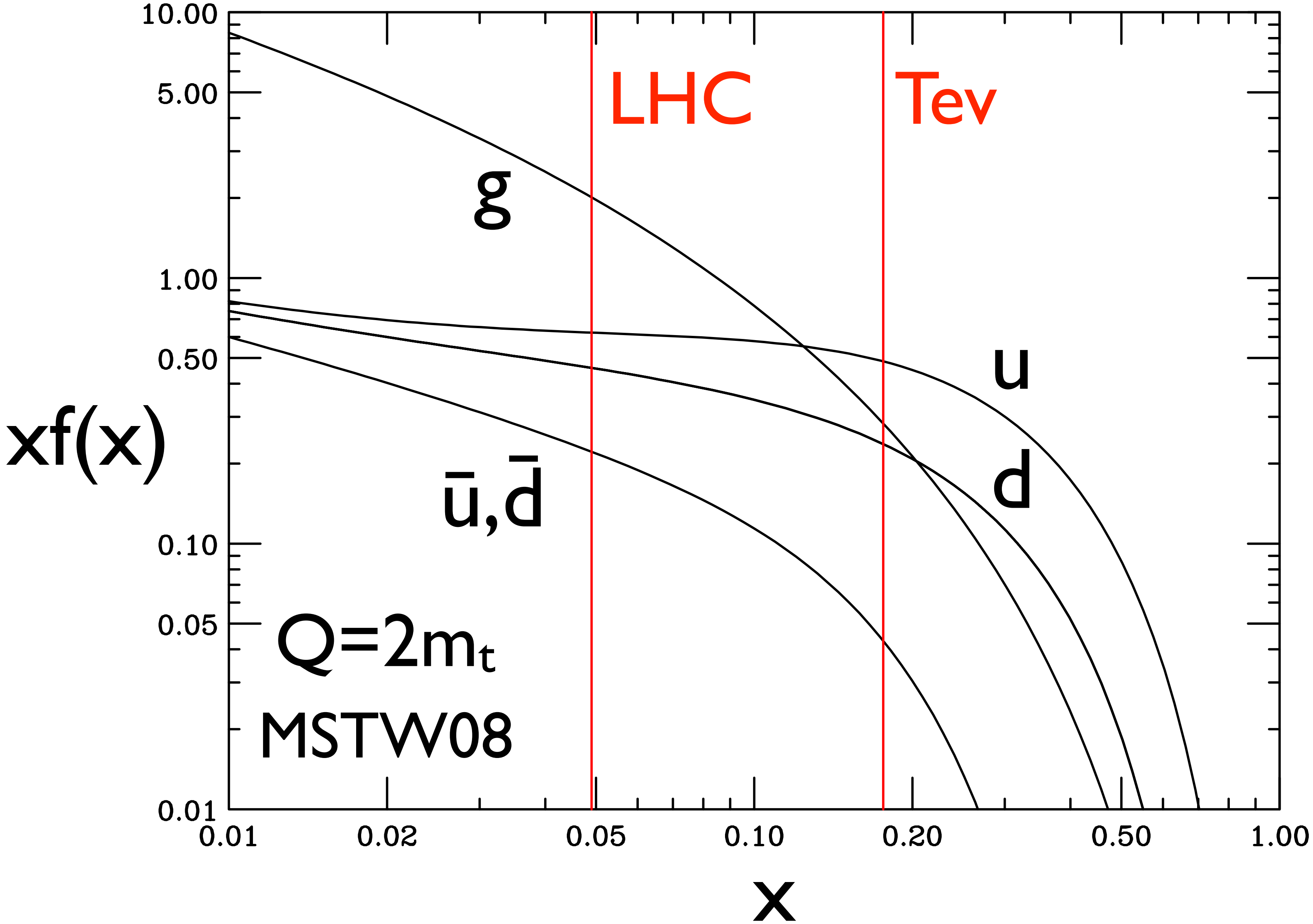
→ ~10^6 $t\bar{t}$

- Expect ~20 fb^{-1} this run (2012)



But dominated by gg rather than $q\bar{q}$ collisions

Parton distributions



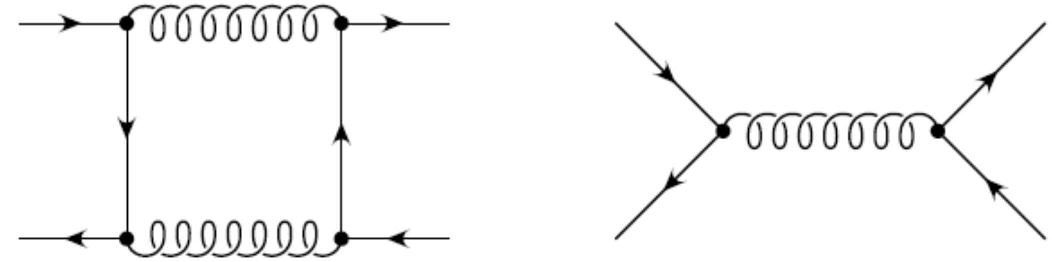
- $u\bar{u}\to t\bar{t}$ dominates at Tevatron, $gg\to t\bar{t}$ at LHC

Standard Model Prediction

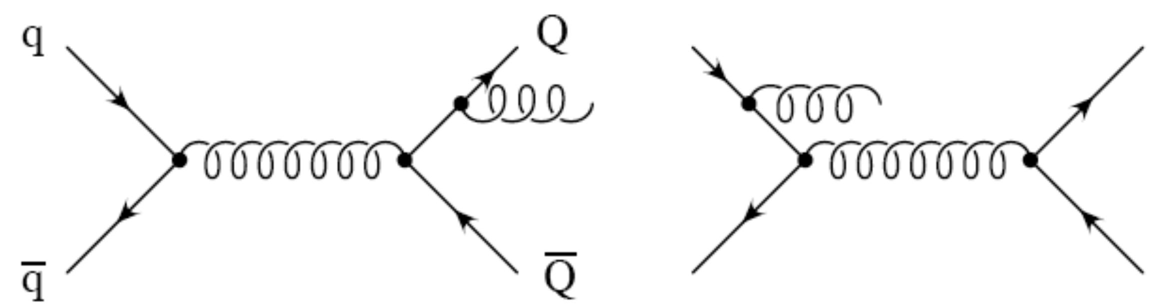
- Only $q\bar{q}$ asymmetric
- NLO effect ~5% at parton level
- t prefers q direction

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right)$$

➡ Expect $y_t > y_{\bar{t}}$



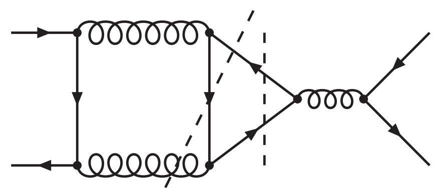
$A_{\rm FB} > 0$ dominant (low $p_T^{t\bar{t}}$)

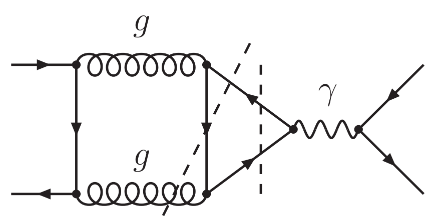
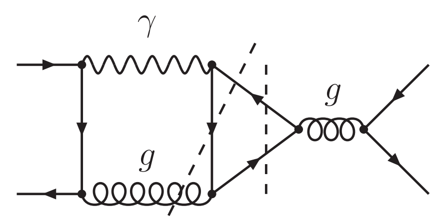
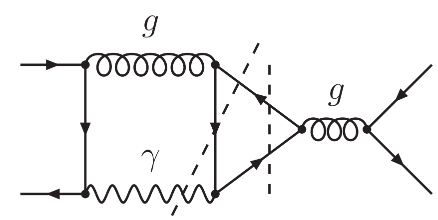


$A_{\rm FB} < 0$ if extra jet or high $p_T^{t\bar{t}}$

$$\Delta y = y_t - y_{\bar{t}} \quad \Rightarrow \quad A_{\rm FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} > 0$$

QED/EW Contributions

$$\Delta\sigma_{\mathrm{FB}}^{\mathrm{QCD}} \sim$$ 

$$\Delta\sigma_{\mathrm{FB}}^{\mathrm{QED}} \sim$$   

$$= f_q^{\mathrm{QED}} \times \Delta\sigma_{\mathrm{FB}}^{\mathrm{QCD}} \qquad f_q^{\mathrm{QED}} = 3\,\frac{\alpha_{\mathrm{QED}}\,Q_t\,Q_q}{\frac{\alpha_S}{2}\left(\frac{d_{abc}^2}{4}\right)^2} = \frac{\alpha_{\mathrm{QED}}}{\alpha_S}\,\frac{36}{5}\,Q_t\,Q_q$$

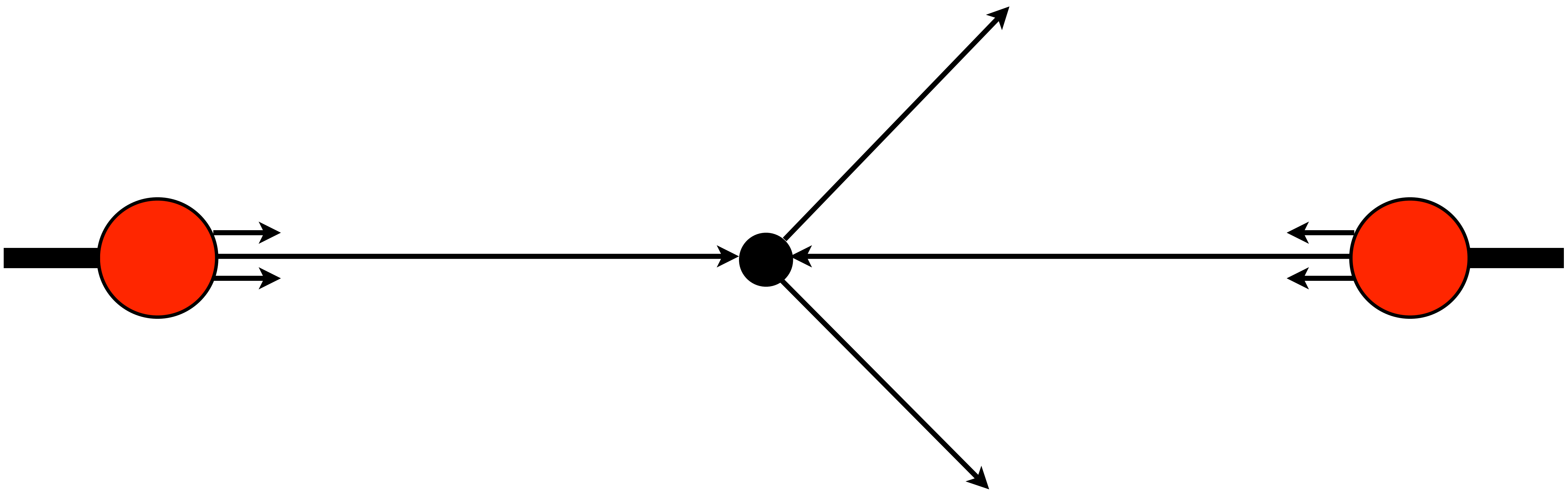
$$f_{\mathrm{Tevatron}}^{\mathrm{QED}} = \frac{4f_u^{\mathrm{QED}} + f_d^{\mathrm{QED}}}{5} = \frac{\alpha_{\mathrm{QED}}}{\alpha_S}\,\frac{56}{25} \approx 0.18$$

Kuhn & Rodrigo, JHEP01(2012)063

+5% from Z^0 contributions → 23% increase

Bernreuther & Si, arXiv:1205.6580

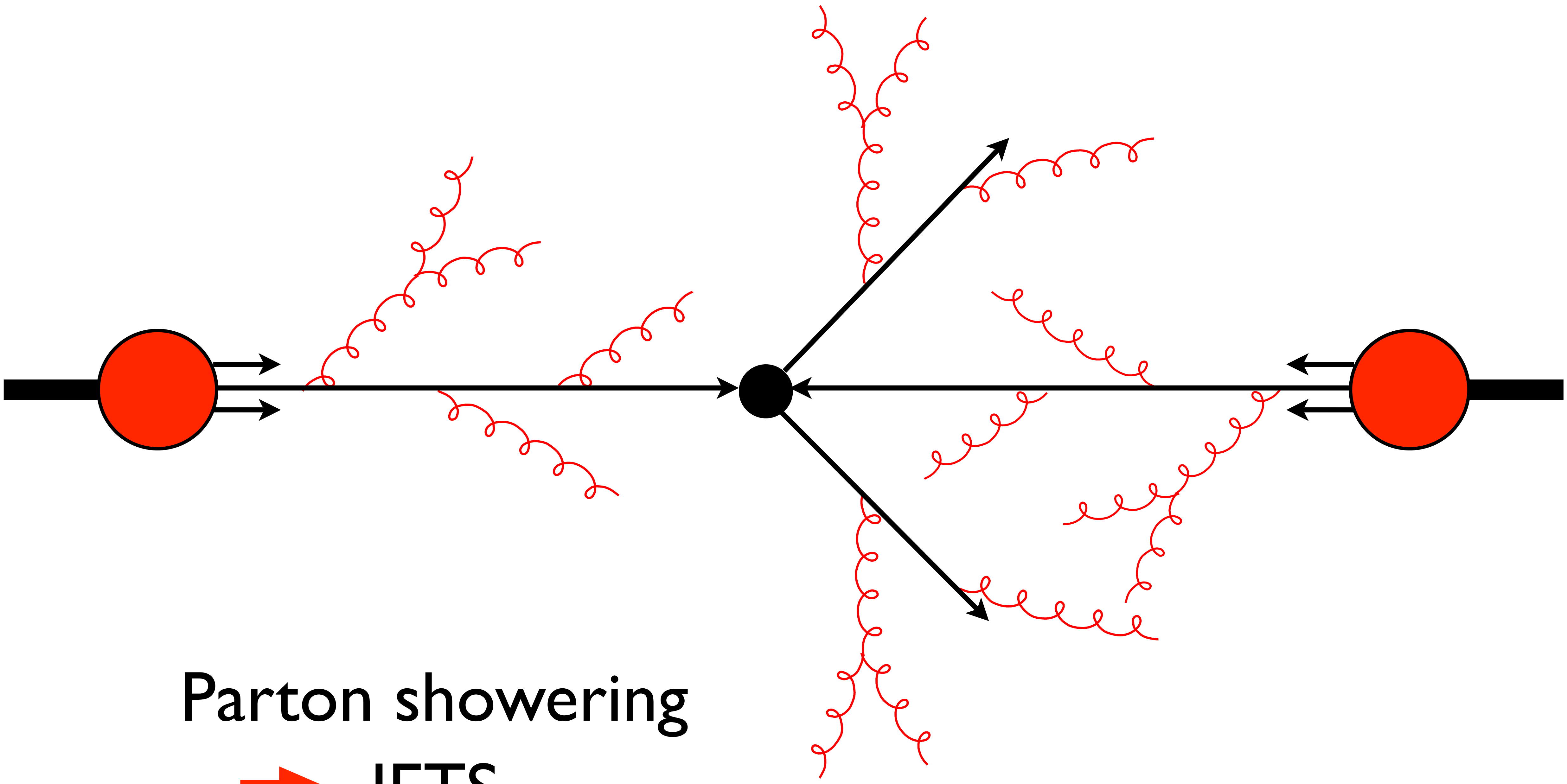
Monte Carlo Event Generation



Hard subprocess

e.g. $u\bar{u} \to t\bar{t}$

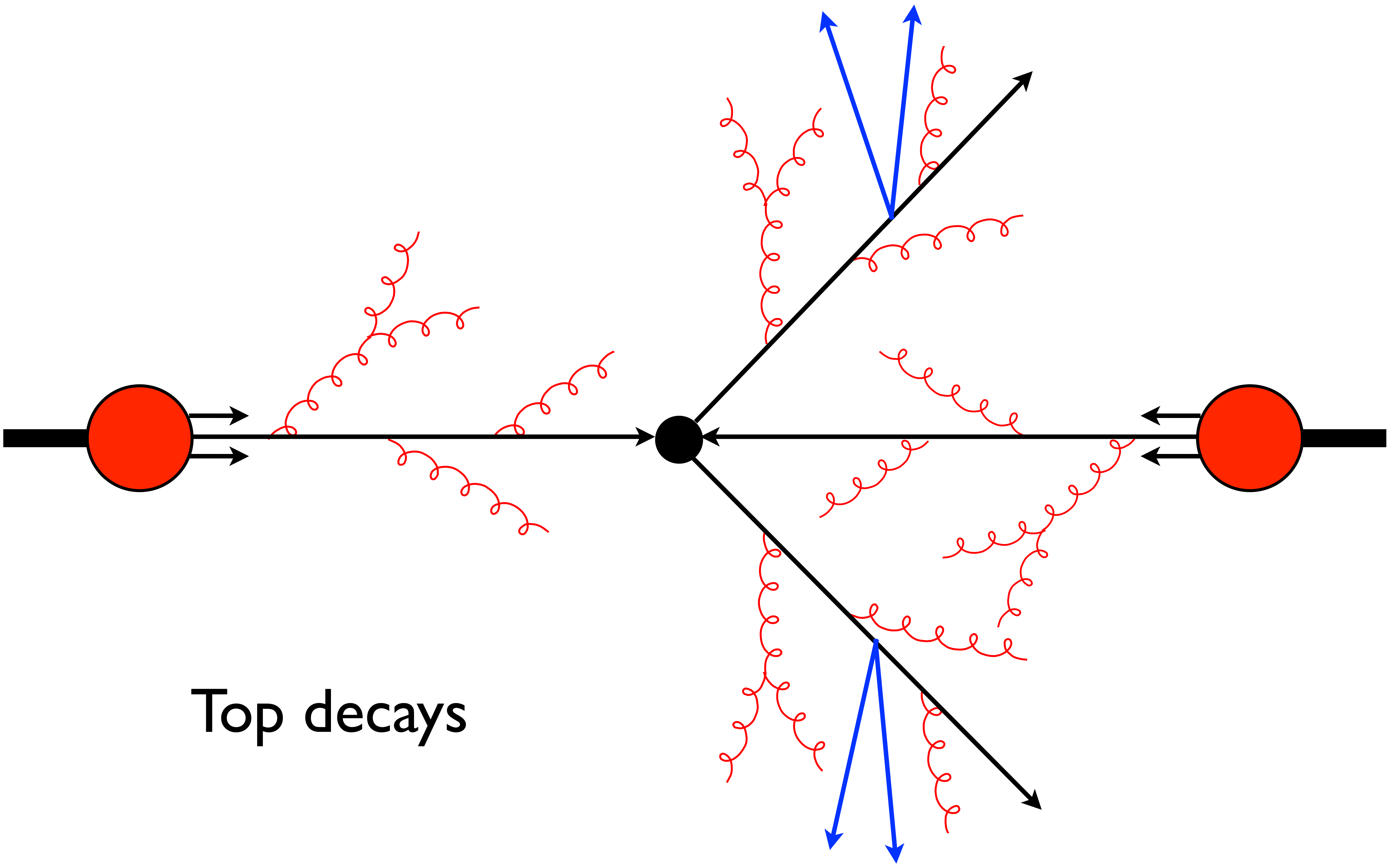
Monte Carlo Event Generation



Parton showering

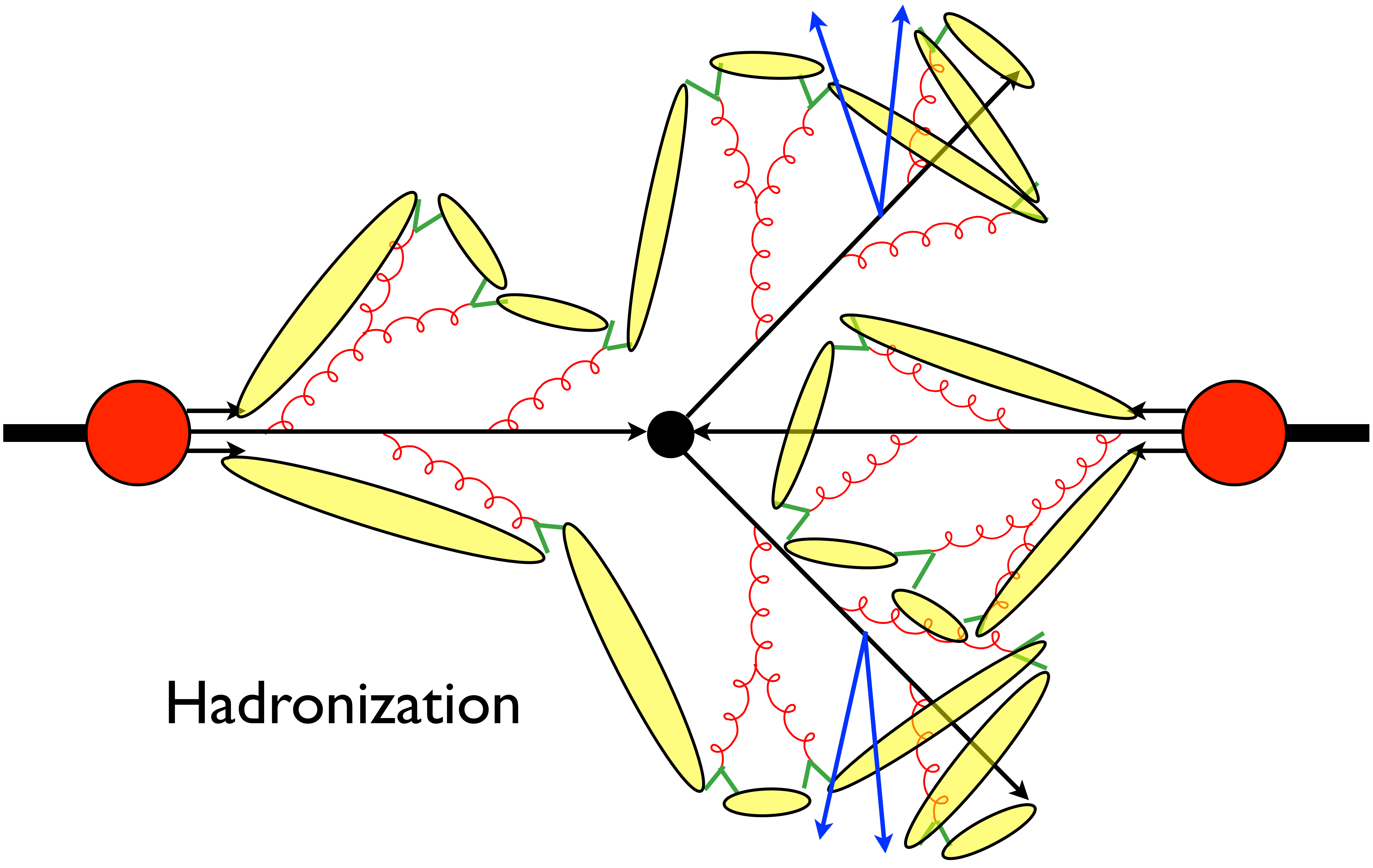
→ JETS

Monte Carlo Event Generation

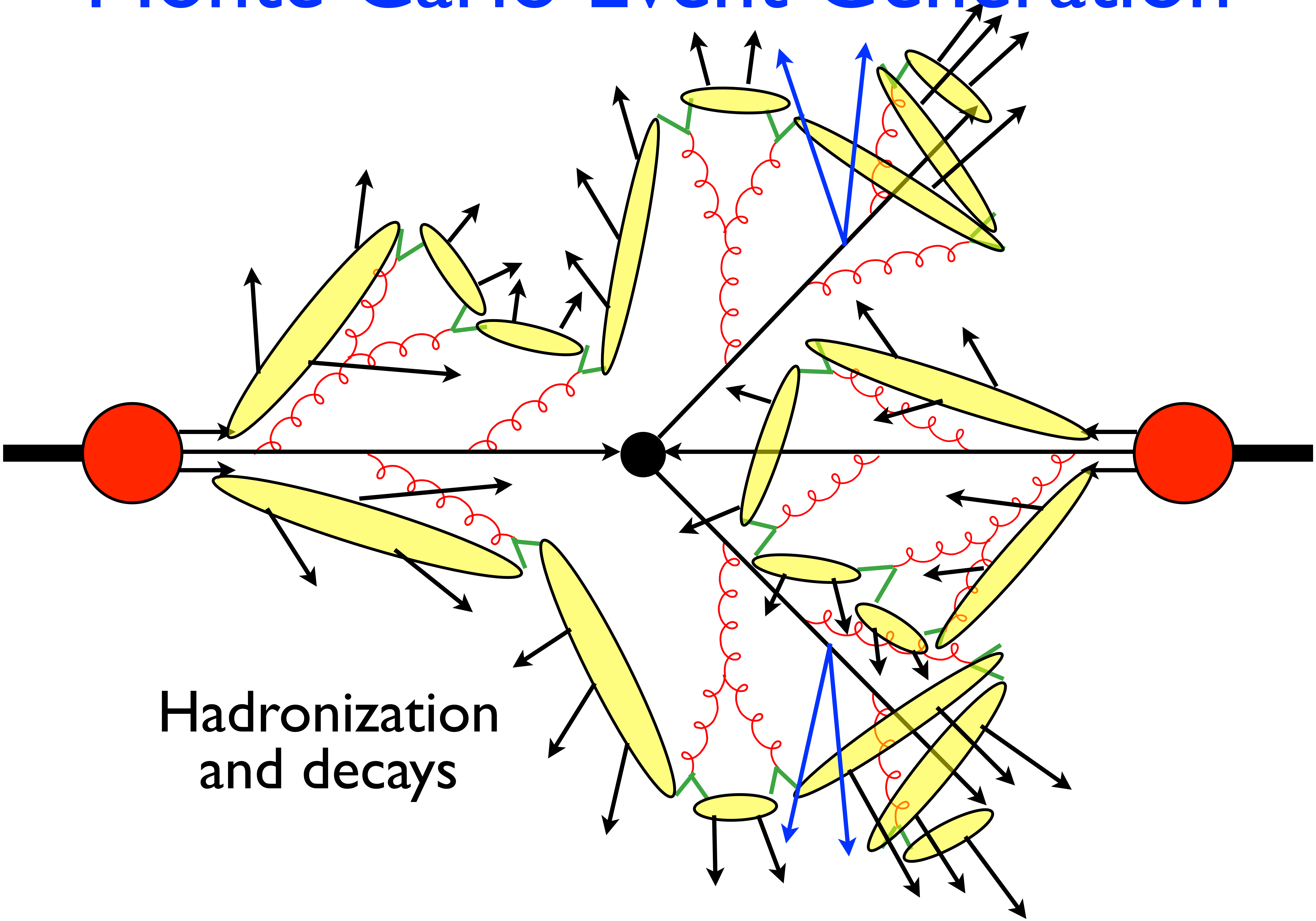


Top decays

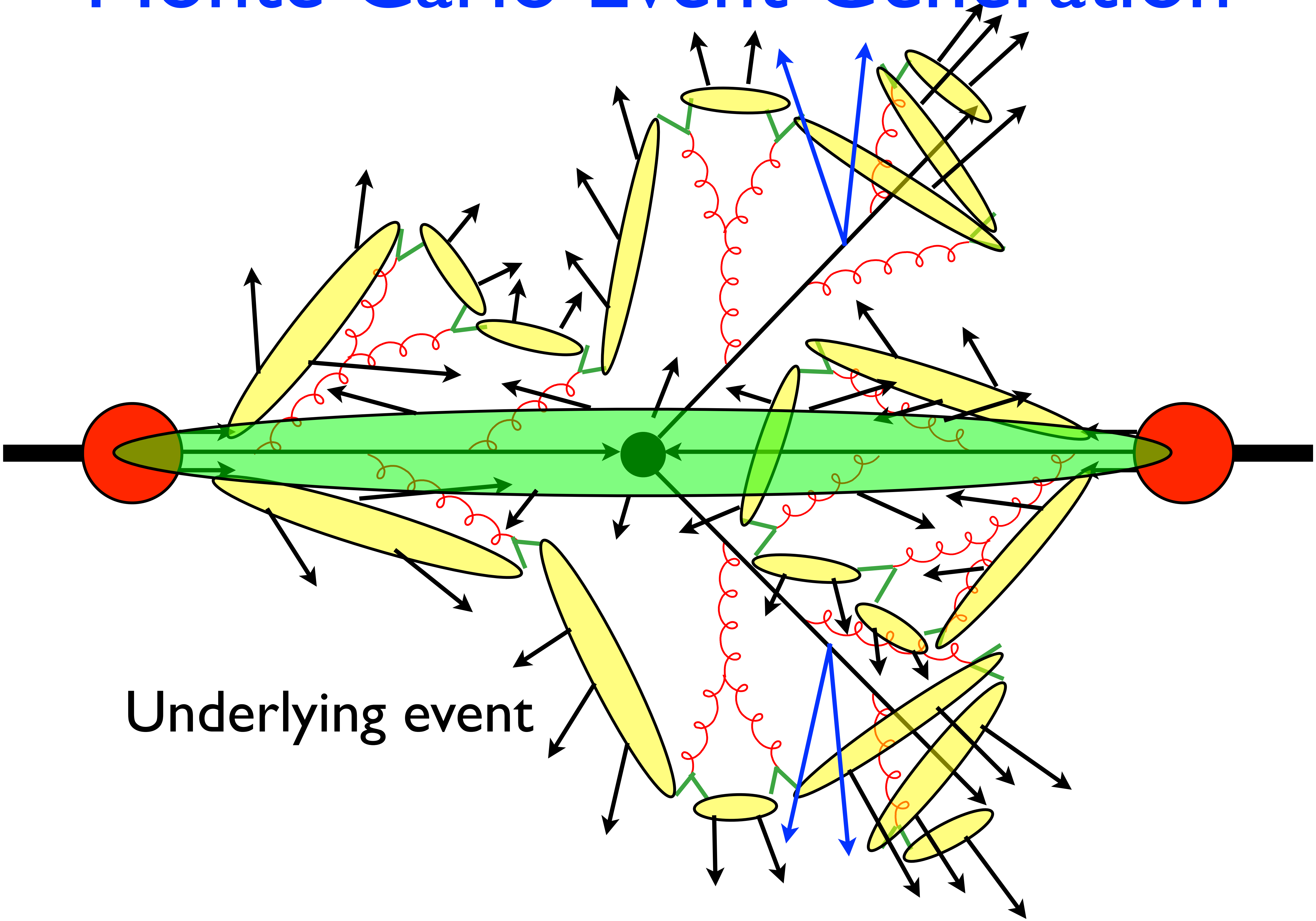
Monte Carlo Event Generation



Monte Carlo Event Generation

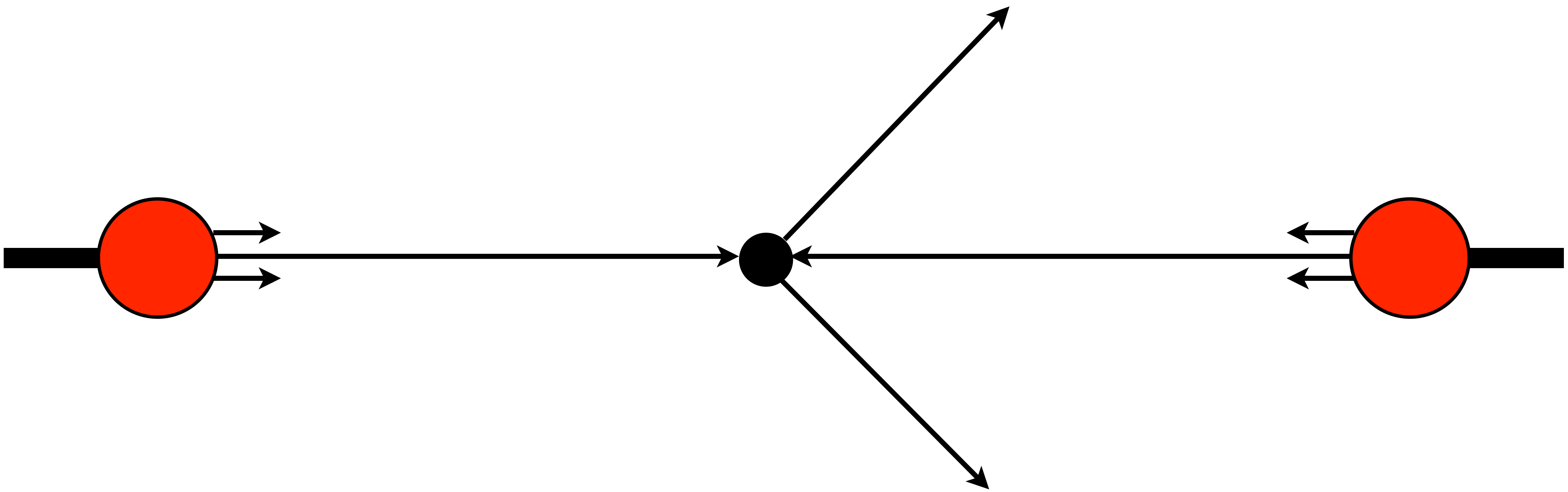


Monte Carlo Event Generation



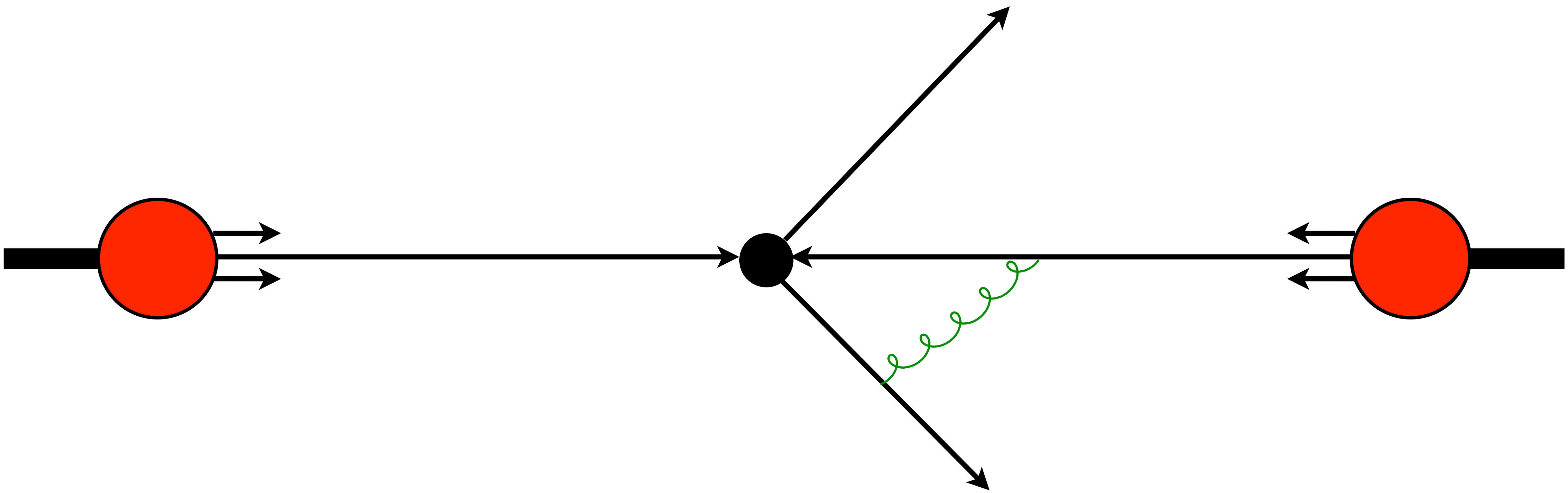
Underlying event

Including Next-to-Leading Order



Hard subprocess

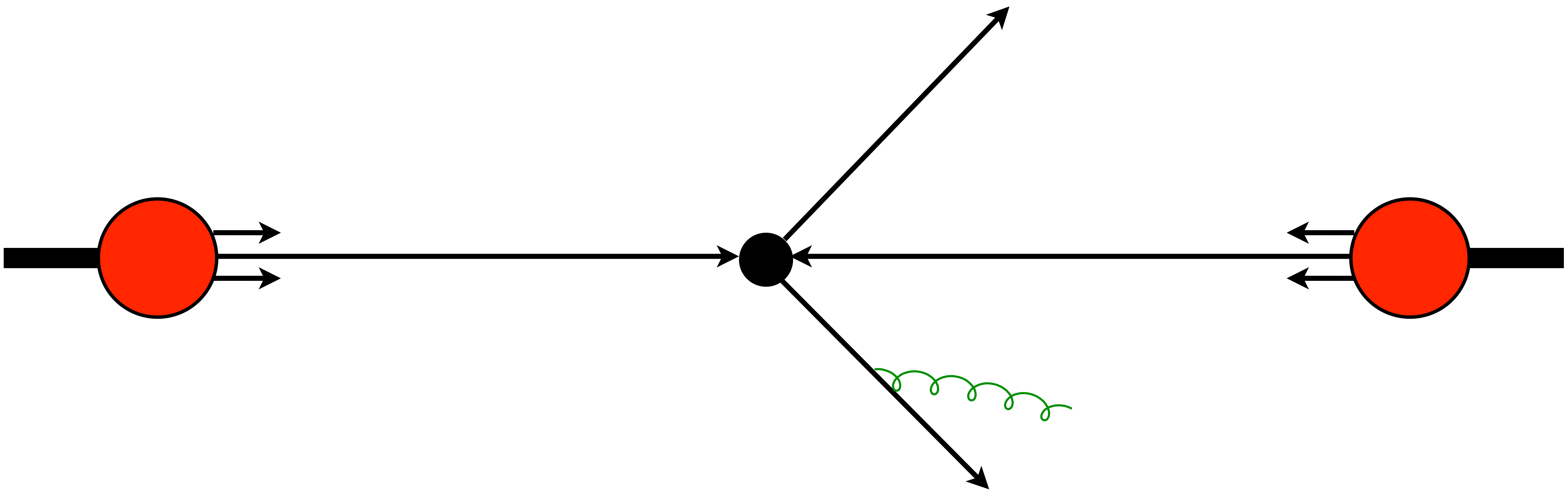
Including Next-to-Leading Order



NLO Hard subprocess

(loop correction)

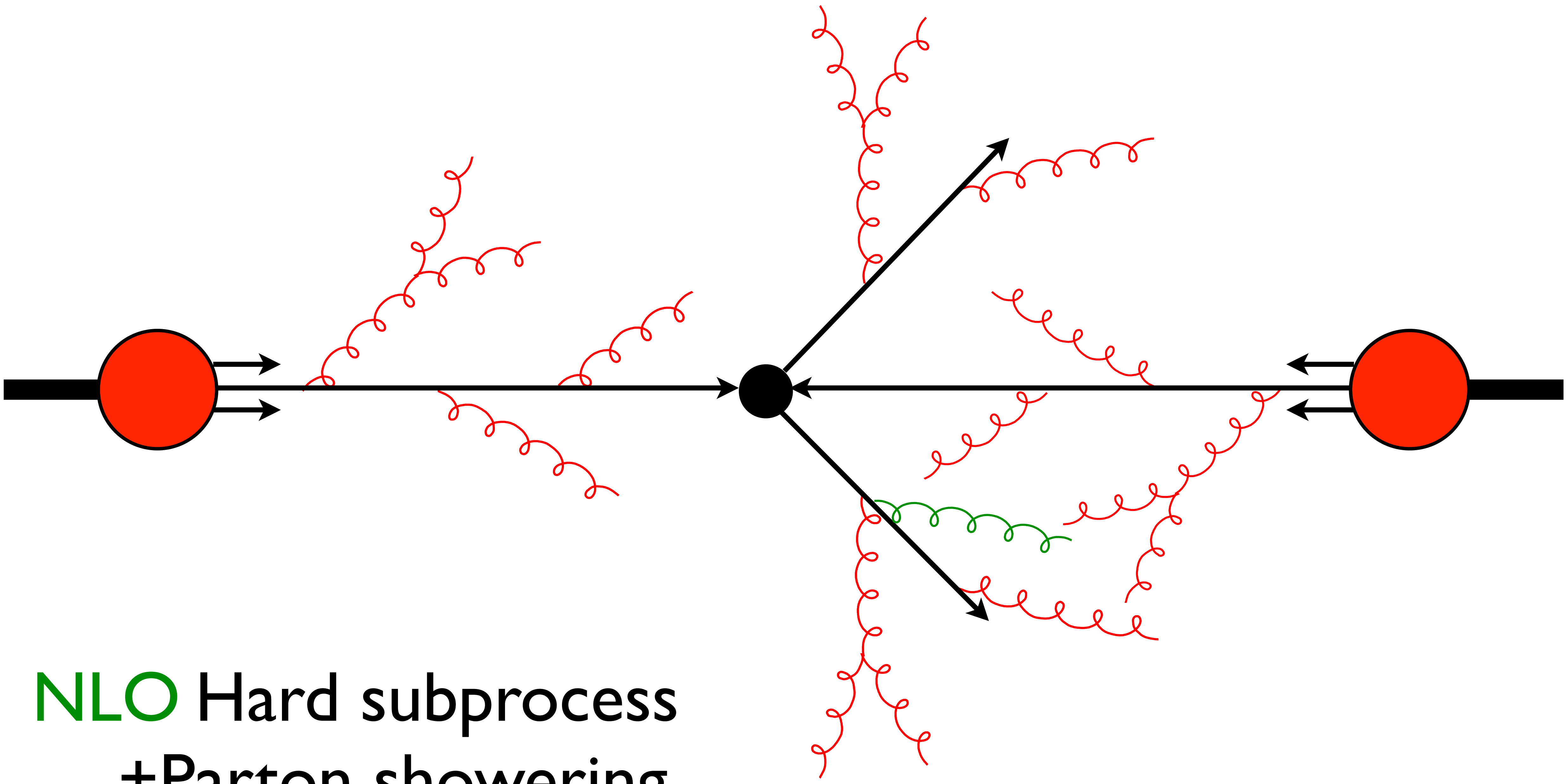
Including Next-to-Leading Order



NLO Hard subprocess

(real emission)

Monte Carlo Event Generation



NLO Hard subprocess

+Parton showering

= Double counting?? ➡ need matching prescription

MC@NLO matching

finite virtual

divergent

$$
\begin{aligned}
d\sigma_{\rm NLO} &= \left[B(\Phi_B) + V(\Phi_B) - \int \sum_i C_i(\Phi_B,\Phi_R)\, d\Phi_R\right] d\Phi_B + R(\Phi_B,\Phi_R)\, d\Phi_B\, d\Phi_R \\
&\equiv \left[B + V - \int C\, d\Phi_R\right] d\Phi_B + R\, d\Phi_B\, d\Phi_R \\
d\sigma_{\rm MC} &= B(\Phi_B)\ d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\ \Delta_{\rm MC}(k_T(\Phi_B,\Phi_R))\ d\Phi_R\right] \\
&\equiv B\, d\Phi_B\ [\Delta_{\rm MC}(0) + (R_{\rm MC}/B)\ \Delta_{\rm MC}(k_T)\ d\Phi_R]
\end{aligned}
$$

Sudakov factor = P(no emission above p_T)

$$\Delta_{\rm MC}(p_T) = \exp\left[-\int d\Phi_R \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\ \theta(k_T(\Phi_B,\Phi_R) - p_T)\right]$$

$$
\boxed{
\begin{aligned}
d\sigma_{\rm MC@NLO} \ = \ &\left[B + V + \int (R_{\rm MC} - C)\ d\Phi_R\right] d\Phi_B\ [\Delta_{\rm MC}(0) + (R_{\rm MC}/B)\ \Delta_{\rm MC}(k_T)\ d\Phi_R] \\
&+ (R - R_{\rm MC})\ \Delta_{\rm MC}(k_T)\ d\Phi_B\, d\Phi_R
\end{aligned}
}
$$

finite $\gtrless 0$

MC starting from one emission

MC starting from no emission

- Expanding gives NLO result

S Frixione & BW, JHEP 06(2002)029

POWHEG matching

$$d\sigma_{\rm MC} = B(\Phi_B)\, d\Phi_B \left[\Delta_{\rm MC}(0) + \frac{R_{\rm MC}(\Phi_B,\Phi_R)}{B(\Phi_B)}\Delta_{\rm MC}(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]$$

$$\boxed{d\sigma_{\rm PH} = \overline{B}(\Phi_B)\, d\Phi_B \left[\Delta_R(0) + \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\Delta_R(k_T(\Phi_B,\Phi_R))\, d\Phi_R\right]}$$

$$\overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int\left[R(\Phi_B,\Phi_R) - \sum_i C_i(\Phi_B,\Phi_R)\right] d\Phi_R$$

$$\Delta_R(p_T) = \exp\left[-\int d\Phi_R \frac{R(\Phi_B,\Phi_R)}{B(\Phi_B)}\theta(k_T(\Phi_B,\Phi_R) - p_T)\right]$$

Use exact R in Sudakov factor for hardest emission

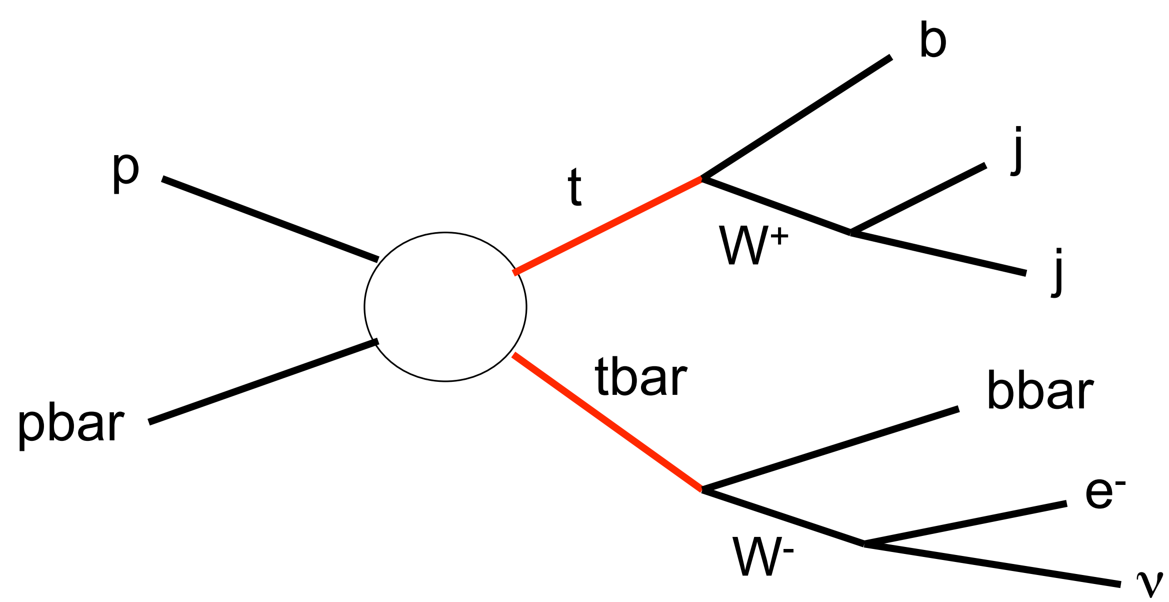
- NLO with (almost) no negative weights

arbitrary NNLO

- High p_T always enhanced by $K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S)$

P Nason, JHEP 11(2004)040

Lepton+jets mode

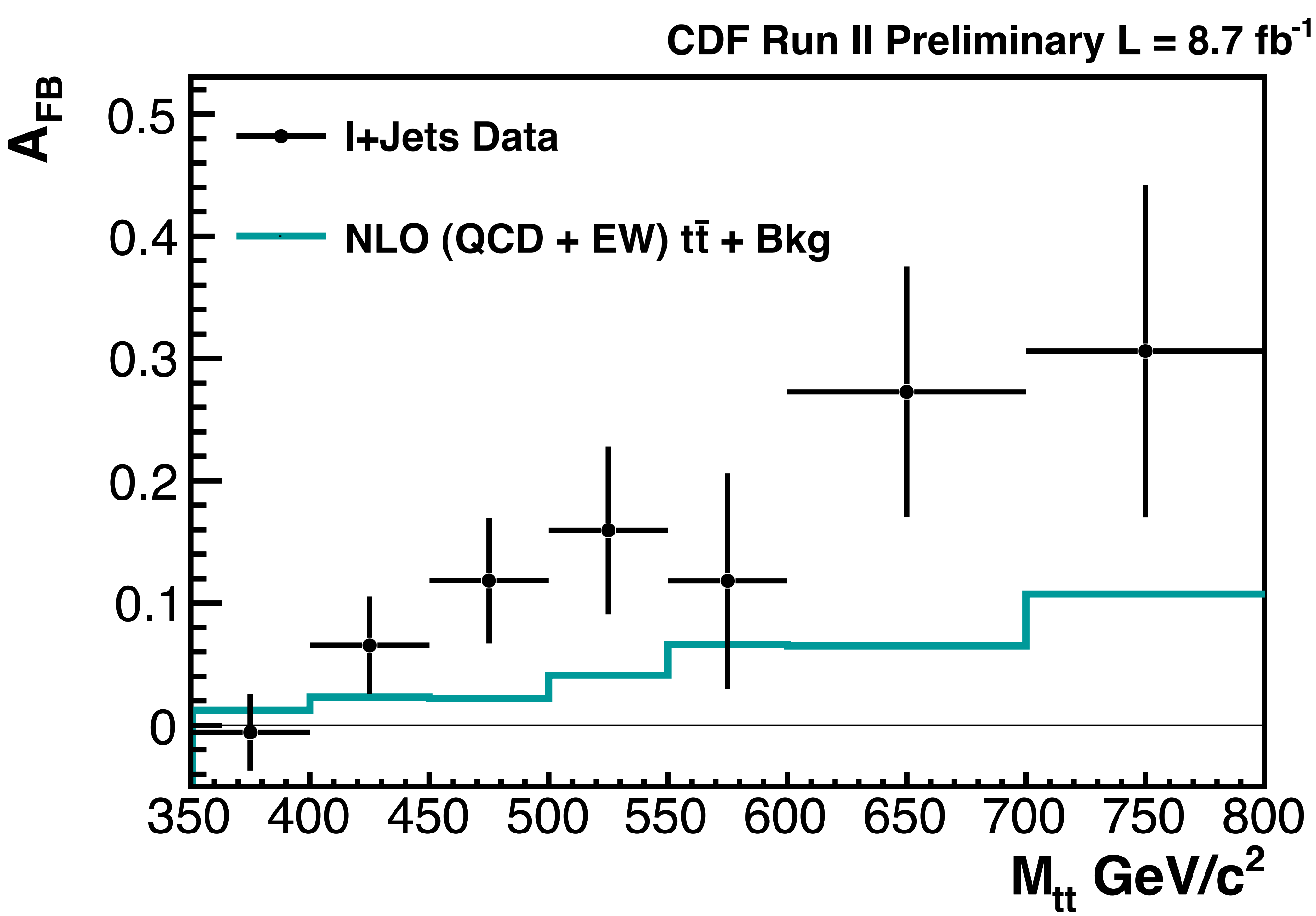


- CDF: 2498 events
- Acceptance/selection cuts reduce asymmetry
  - Lepton and at least 4 jets (inc. 1 b-jet) with $p_T > 20\,\mathrm{GeV/c}\,,\quad |\eta| < 2 \;\; (|\eta|_b < 1)$
  - Missing $E_T \geq 20\,\mathrm{GeV}$
- Simulate SM with MC@NLO or POWHEG

CDF Results

CDF Note 10807

- CDF report a large effect, increasing with $t\bar{t}$ invariant mass
- SM predicts a smaller NLO effect
- MC@NLO and POWHEG in good agreement
- CDF claim P_{NLO}=0.0065

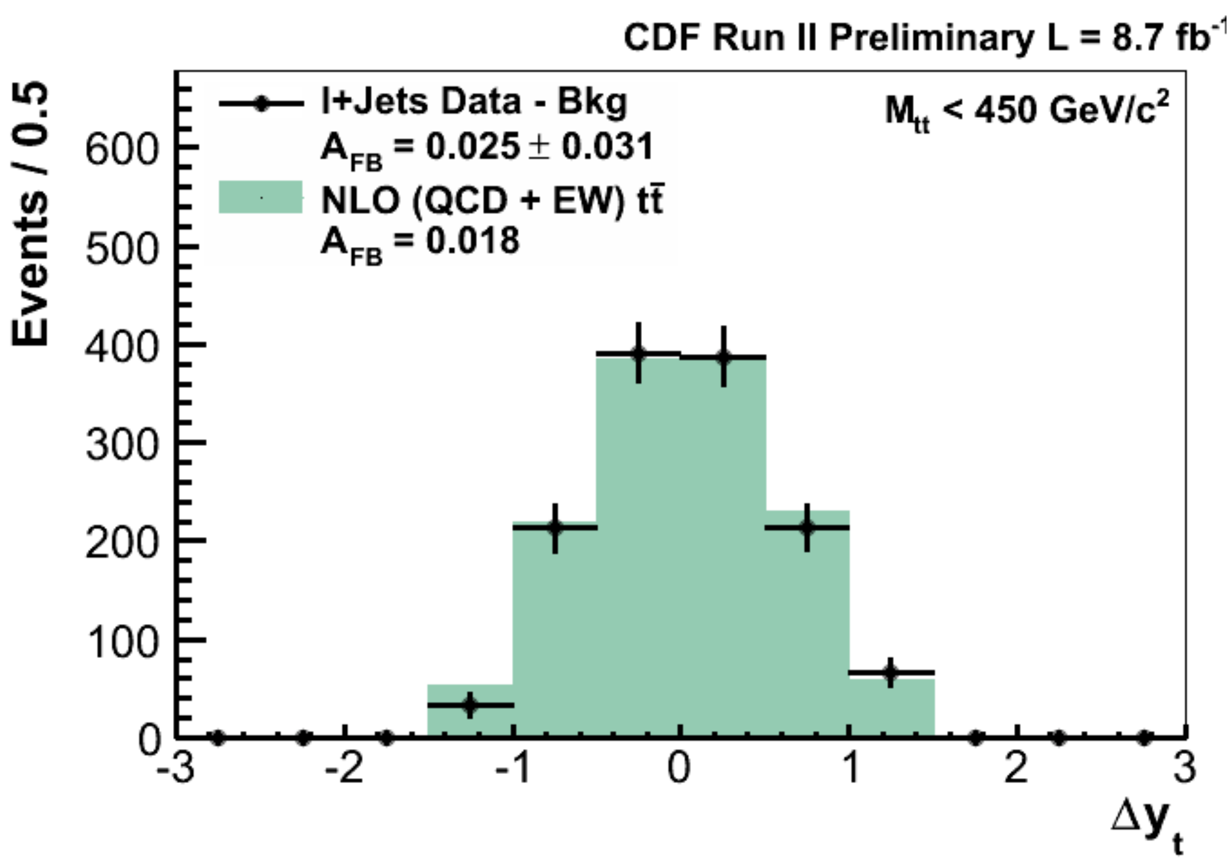


$$\Delta y \equiv y_t - y_{\bar{t}}$$

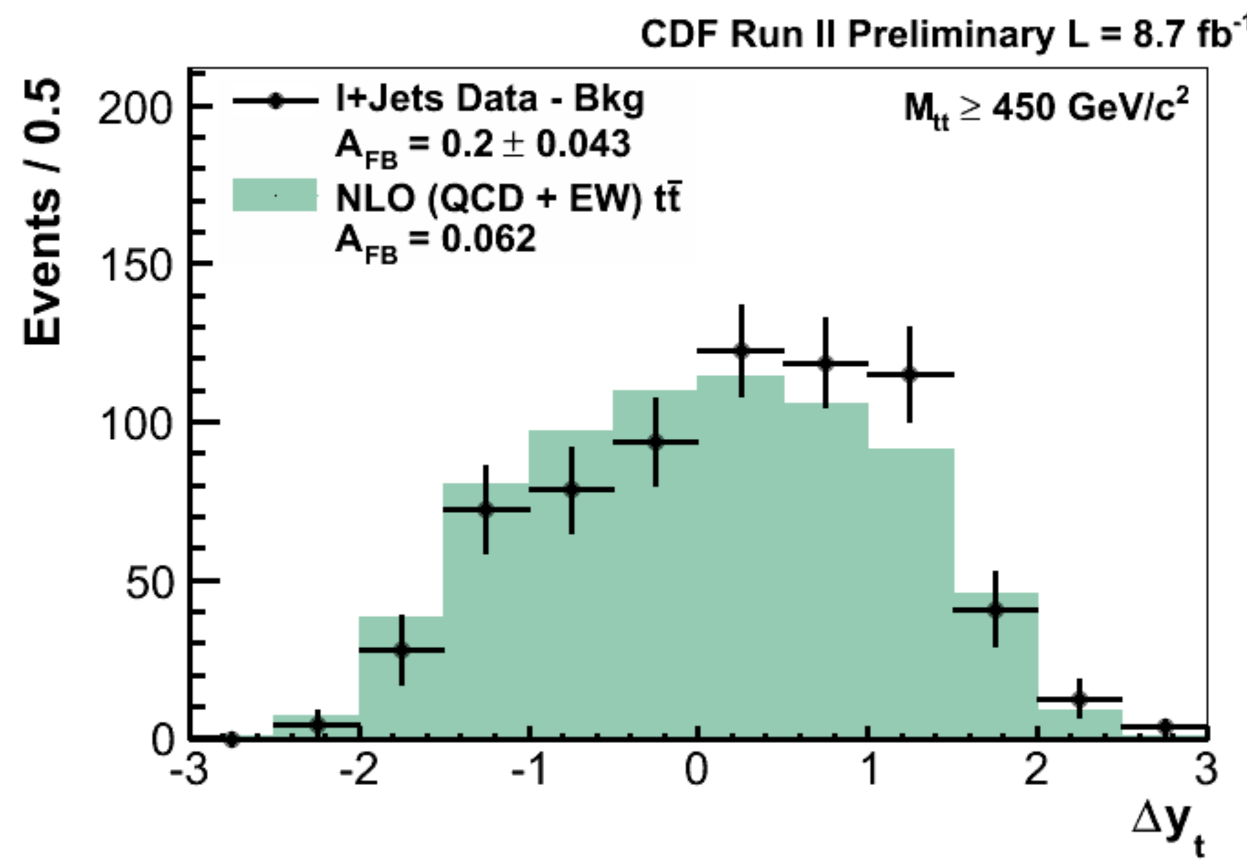
$$A_{\mathrm{FB}} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

CDF data: low vs high mass

M_{tt} < 450 GeV/c^2

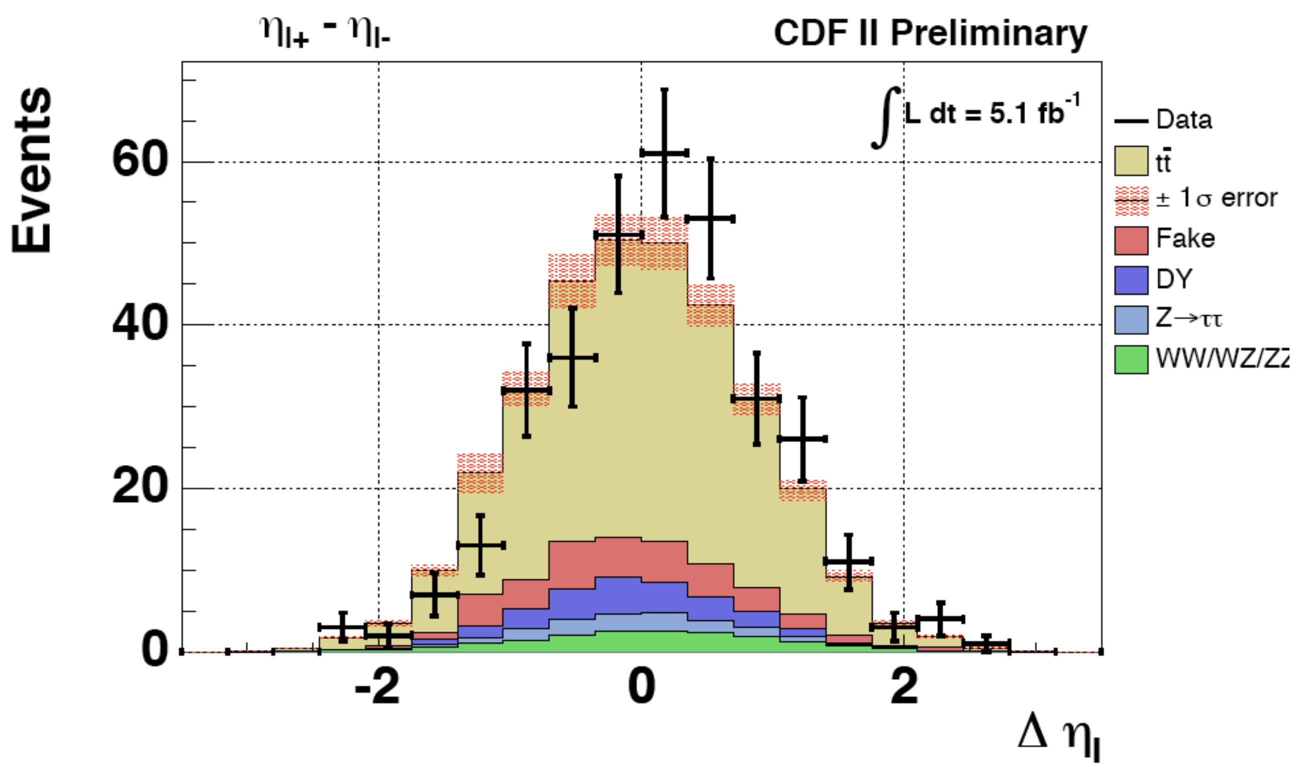


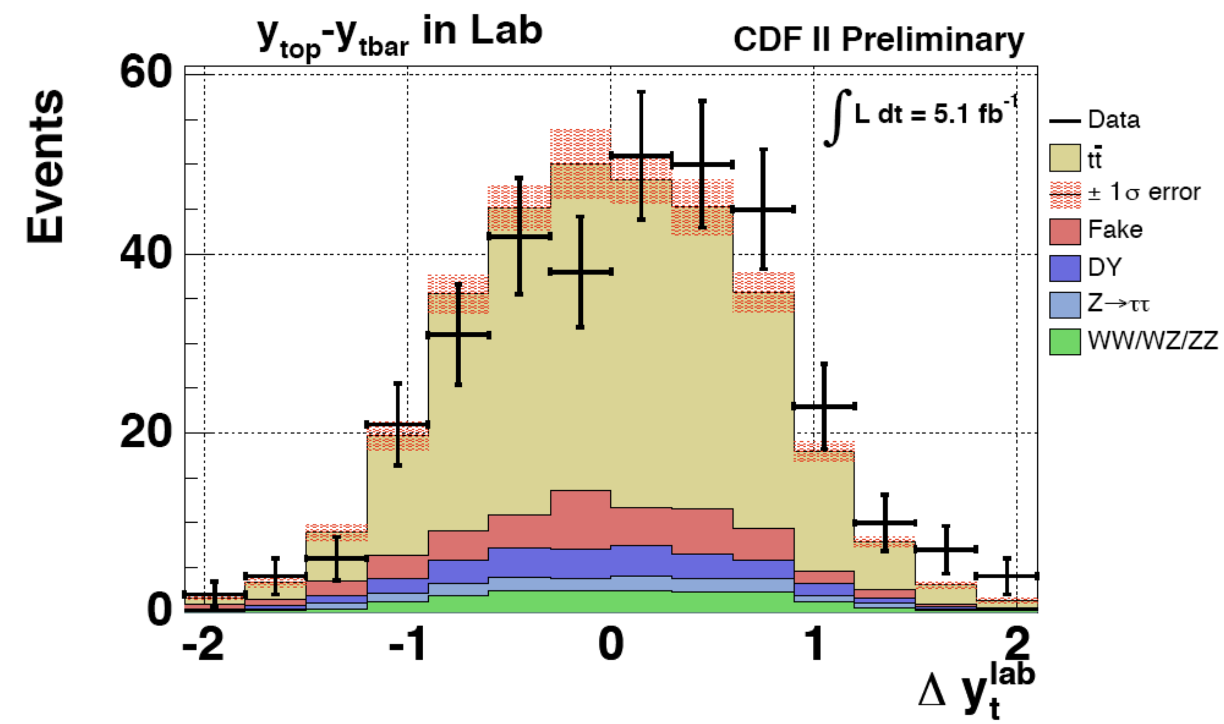
M_{tt} > 450 GeV/c^2



- No significant asymmetry below $M_{t\bar{t}} = 450$ GeV

Dilepton decay mode





$$A_{obs}^{\Delta\eta_l} = 0.138 \pm 0.054$$

$$A_{pred}^{\Delta\eta_l} = -0.022 \pm 0.022$$

$$A_{obs}^{\Delta y_t} = 0.138 \pm 0.054$$

$$A_{pred}^{\Delta\eta_l} = -0.015 \pm 0.023$$

- Consistent with lepton+jets mode
- Results from 8.7 fb^{-1} coming soon

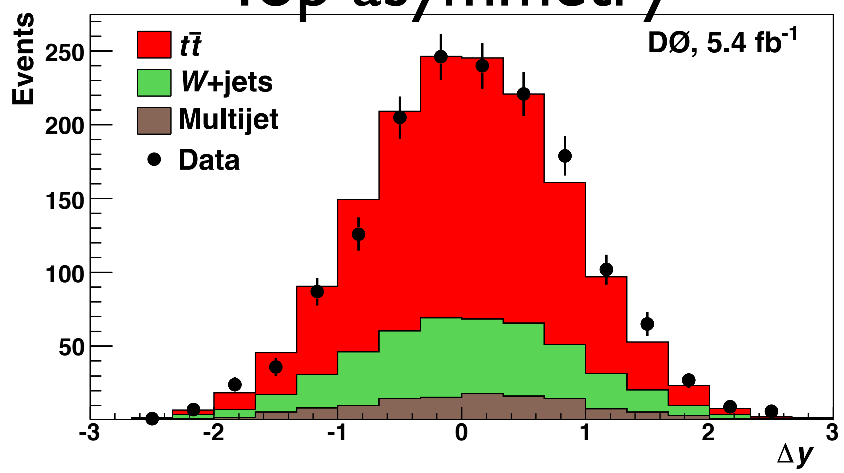
D0 Results

arXiv:1107.4995

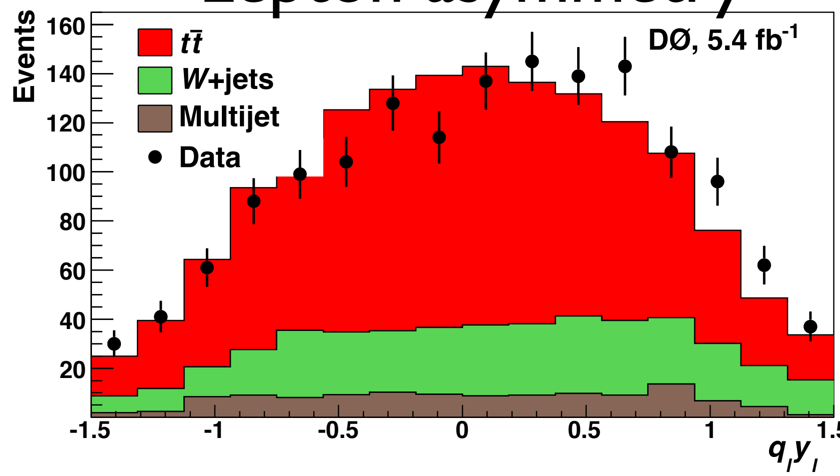
	$l+\geq4$ jets	$l+4$ jets	$l+\geq5$ jets
$A_{\mathrm{FB}}(\%)$	9.2±3.7	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	3.9±0.8	-2.9±1.1

	$l+\geq4$ jets	$l+4$ jets	$l+\geq5$ jets
A^l_{FB} (%)	14.2± 3.8	15.9± 4.3	7.0± 8.0
MC@NLO A^l_{FB} (%)	0.8± 0.6	2.1± 0.6	-3.8± 1.2

Top asymmetry



Lepton asymmetry



- Disagreement with SM = 3.4 s.d.
- CDF $M_{t\bar{t}}$ dependence not confirmed (?)

$t\bar{t}$ A_{FB} at Tevatron

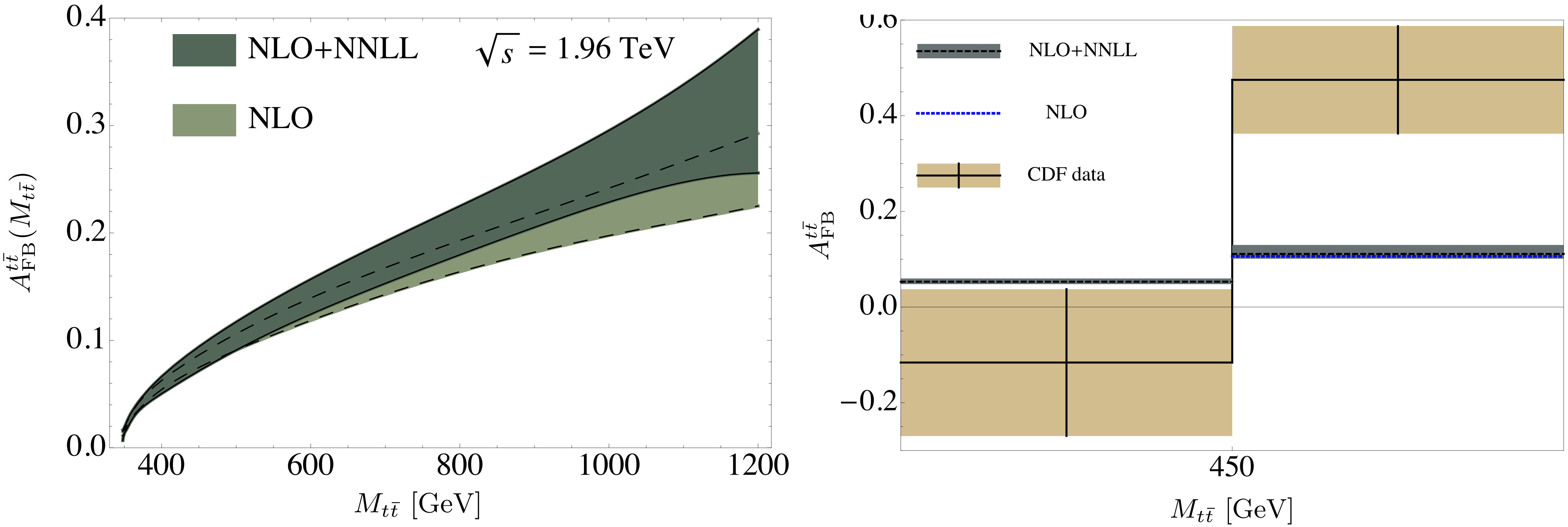
Selection	NLO (QCD+EW)	CDF, 5.3 fb^{-1}	D0, 5.4 fb^{-1}	CDF, 8.7 fb-1
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
M_{tt} < 450 GeV/c^2	4.7	−11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
M_{tt} ≥ 450 GeV/c^2	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7
|Δy| < 1.0	4.3	2.6 ± 11.8	6.1 ± 4.1 (Bkg. Subtracted)	8.8 ± 4.7
|Δy| ≥ 1.0	13.9	61.1 ± 25.6	21.3 ± 9.7 (Bkg. Subtracted)	43.3 ± 10.9

- CDF/D0 disagreement?

D. Mietlicki, Moriond, 2012

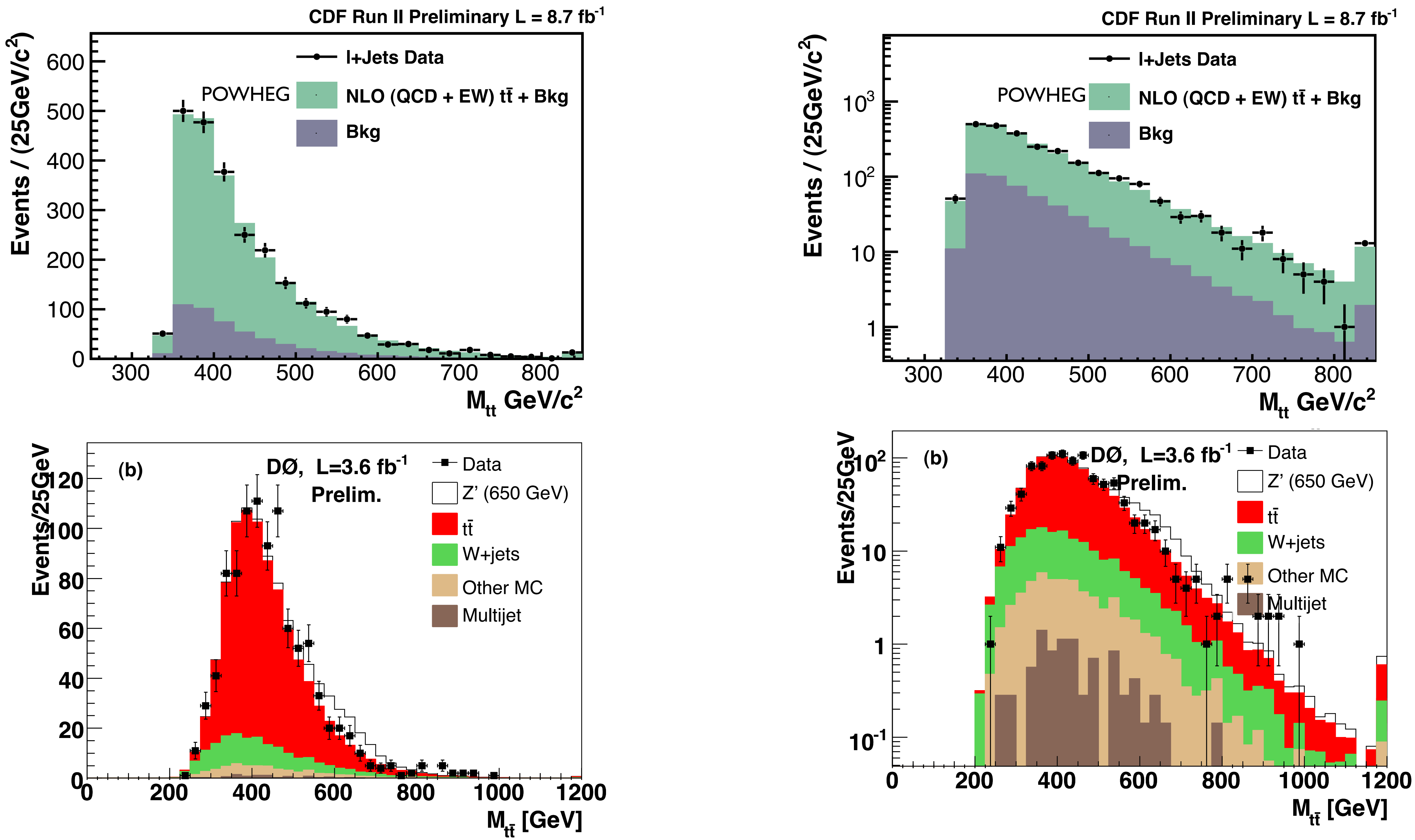
NLO+NNLL Prediction

Ahrens, Ferroglia, Neubert, Pecjak, Yang, PRD84(2011)074004



- Stable w.r.t. soft gluon resummation
- Could still be hard HO effects

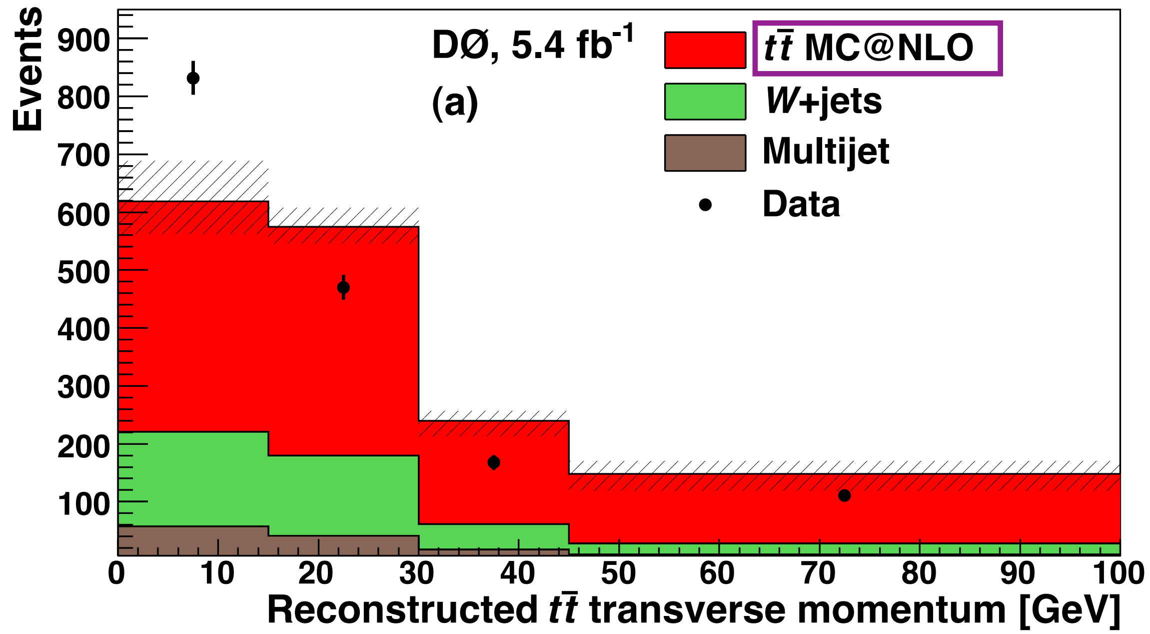
$t\bar{t}$ inv. mass at Tevatron

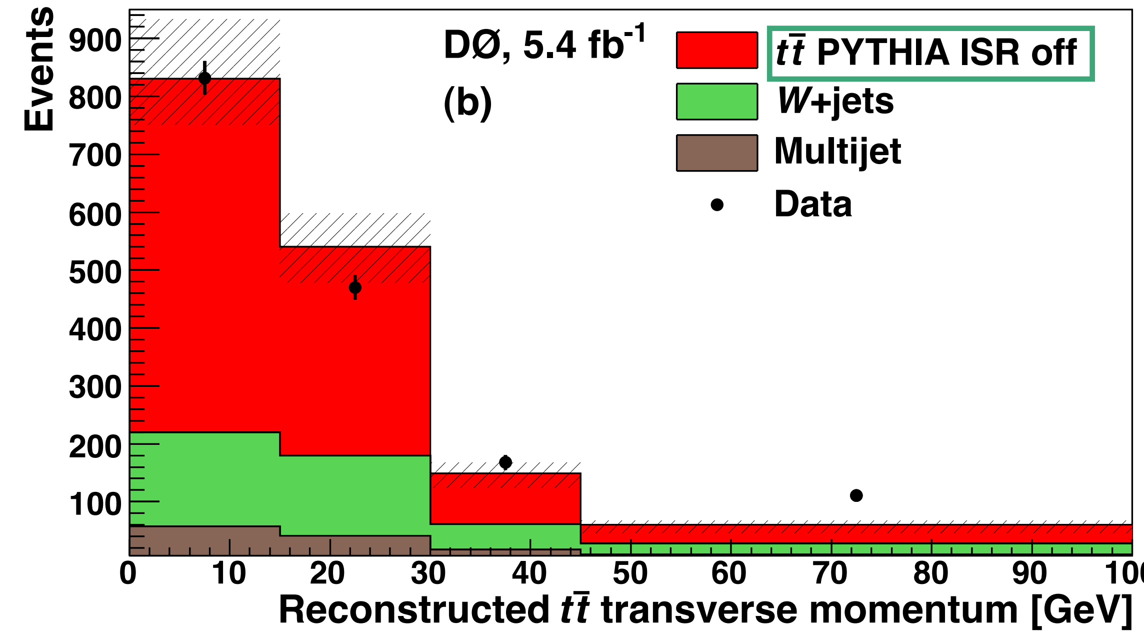


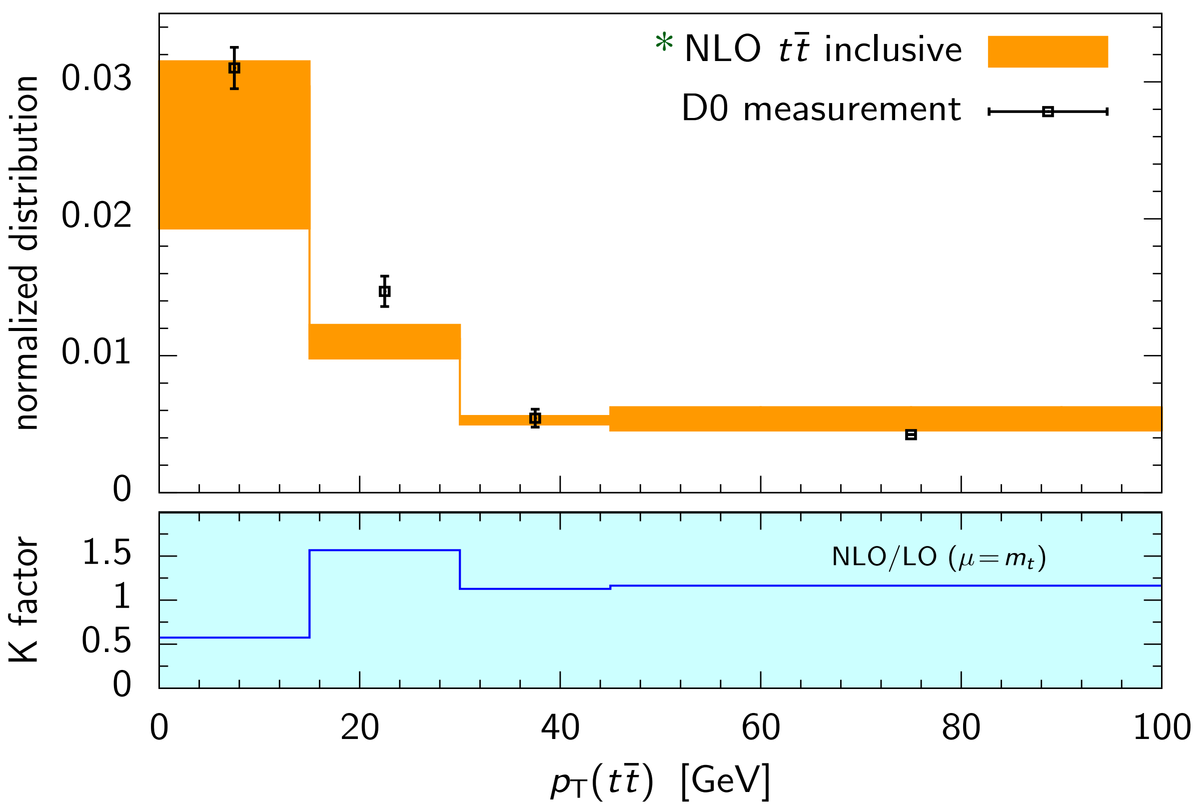
- CDF/D0 in agreement with SM

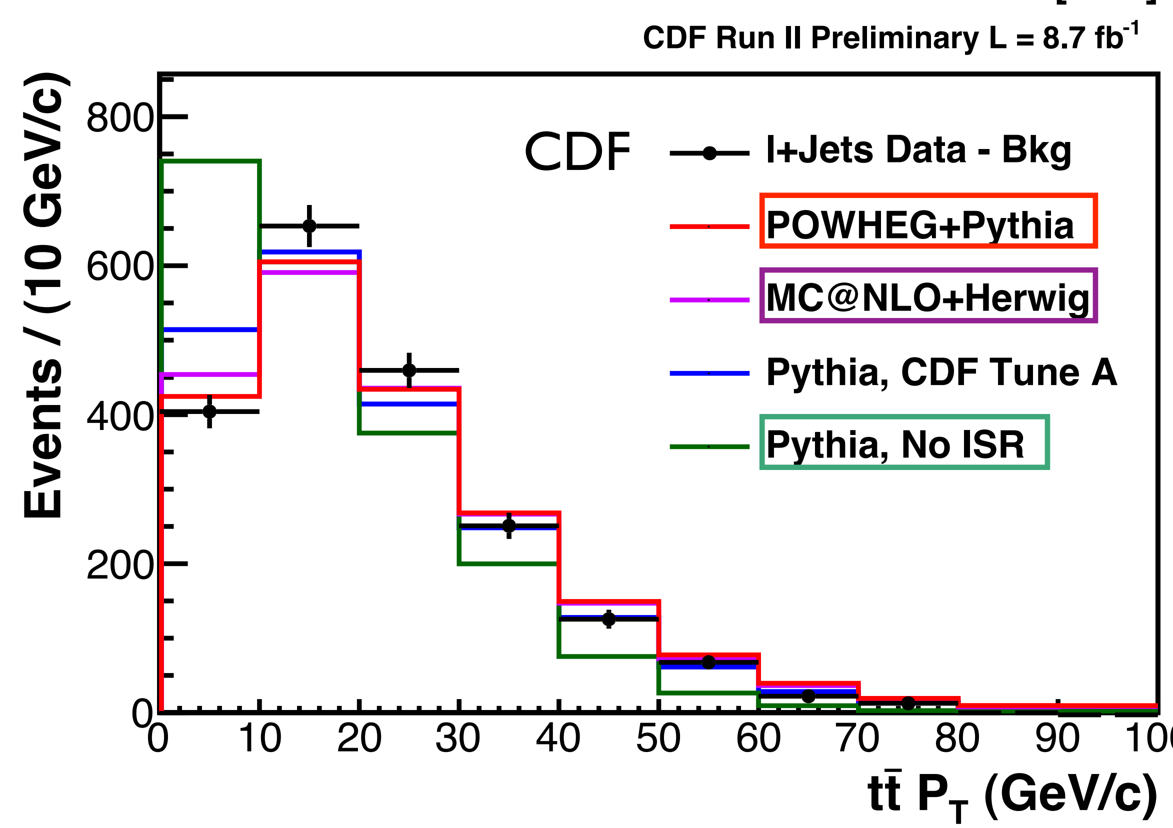
$t\bar{t}$ p_T at Tevatron

D0, Phys Rev D84 (2011) 112005





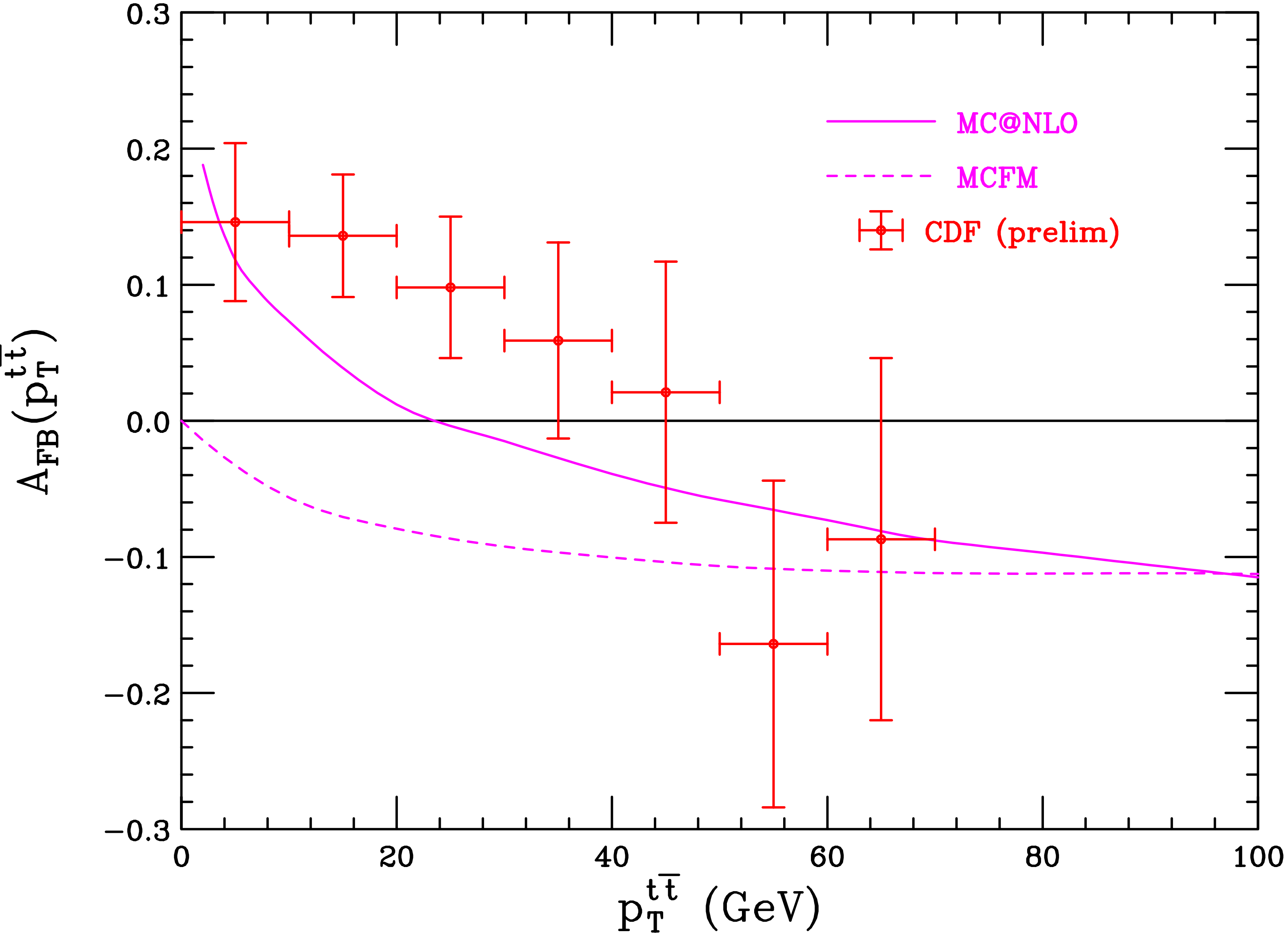




* Melnikov, Scharf, Schulze, PRD85(2012)034025

- CDF/D0 disagreement

$t\bar{t}$ p_T dependence of asymmetry



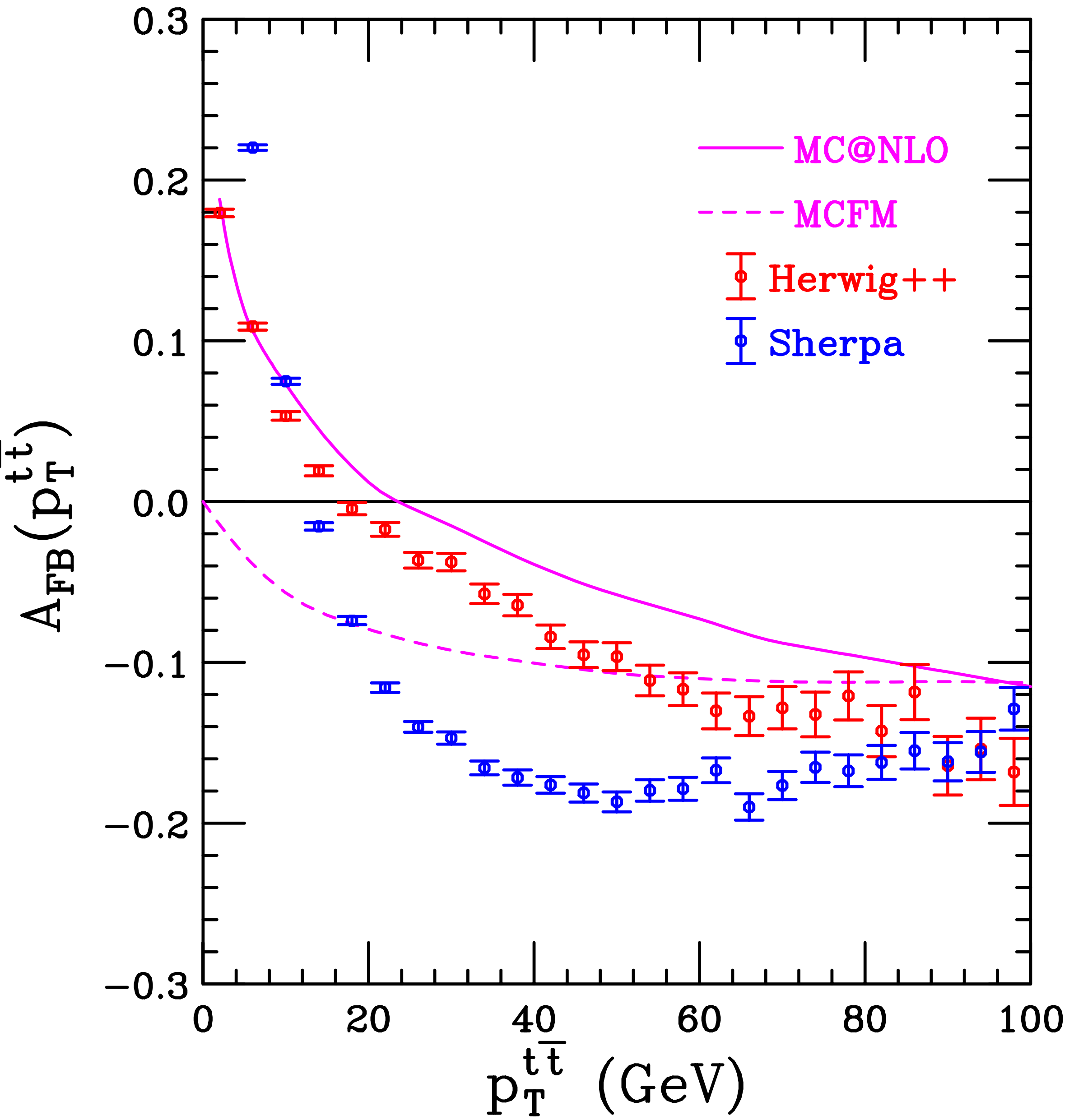
- Pure NLO (MCFM) has delta-function at $p_T = 0$
- CDF data disagree with MC@NLO
- Asymmetry should change sign at ~25 GeV

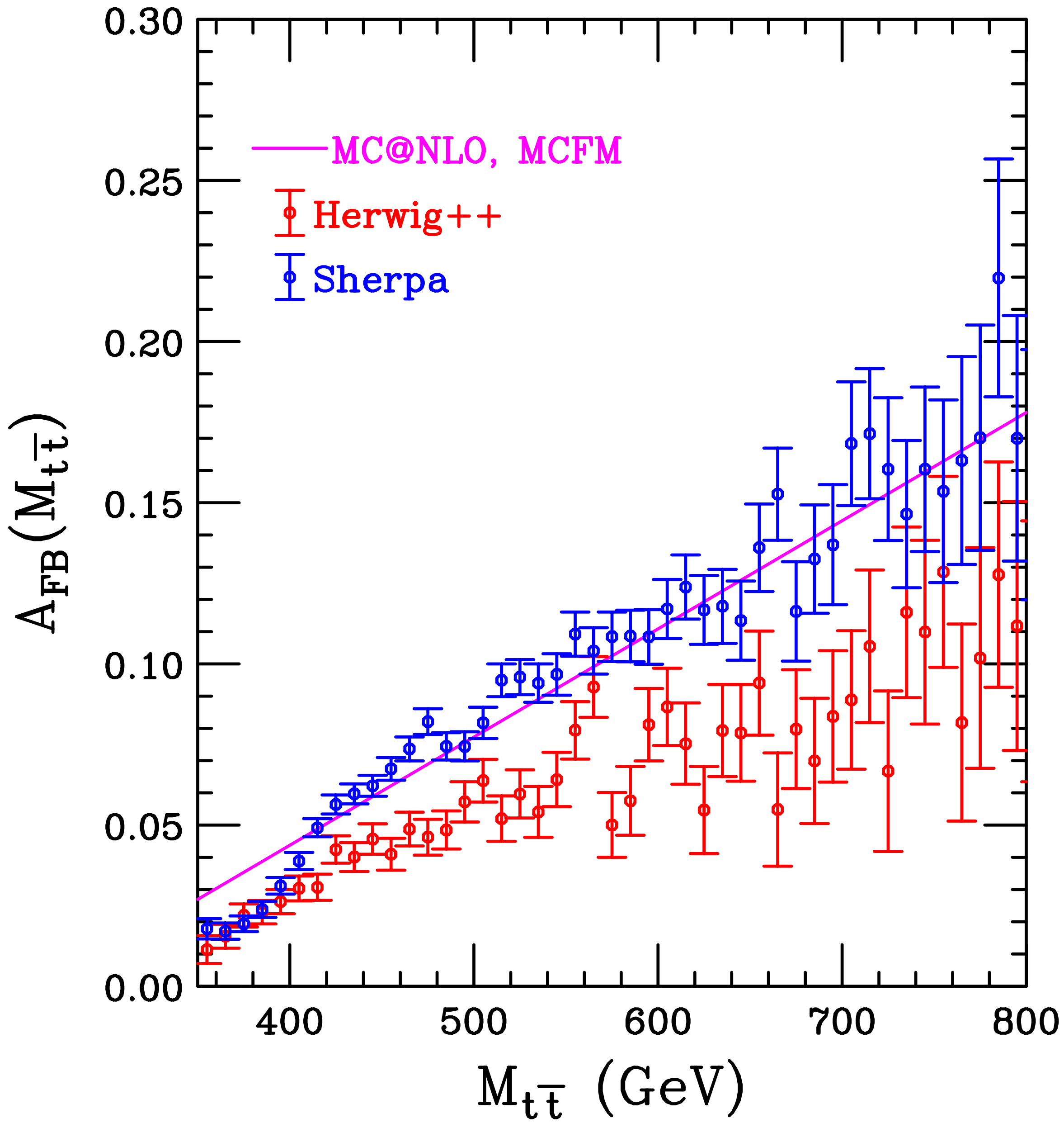
A_{FB} in LO Monte Carlos

- Leading-order Monte Carlo = Born process + parton showers
- Born process has no asymmetry
- Hence LO MC has no asymmetry?

Skands, Winter, BW, arXiv:0512:1466

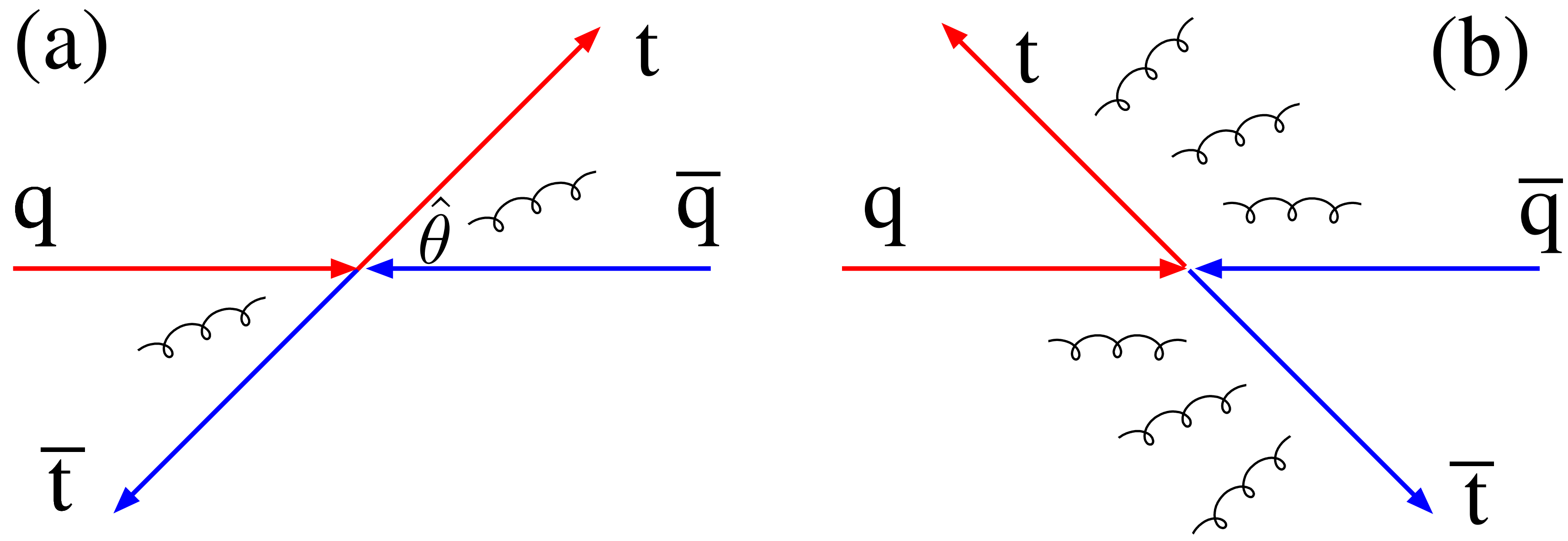
Wrong!





- LO MCs with coherent showering do!

What's going on?



- QCD radiation controlled by colour flow
- Backward top → more radiation
- More radiation → bigger recoils

→ bigger $p_T(t\bar{t})$

Soft gluon limit

$$\frac{d^2\hat{\sigma}_A/dp_T\,d\cos\hat{\theta}}{2\,d\hat{\sigma}_B/d\cos\hat{\theta}} = \frac{\alpha_S}{2\pi}\frac{16}{p_T}\frac{(N^2-4)}{2N}\log\left(\frac{1-\beta\cos\hat{\theta}}{1+\beta\cos\hat{\theta}}\right) \qquad (0<\cos\hat{\theta}<1)$$

$$\beta = \sqrt{1-\frac{4m_t^2}{\hat{s}}}\,, \quad \frac{1-\beta\cos\hat{\theta}}{1+\beta\cos\hat{\theta}} = \frac{p_q\cdot p_t}{p_q\cdot p_{\bar{t}}}$$

- Negative asymmetry (for $p_T>0$)
- Dipole shower gives $\frac{\alpha_S}{2\pi}\frac{16}{p_T}C_F\log\left(\frac{p_q\cdot p_t}{p_q\cdot p_{\bar{t}}}\right)$, i.e. N^2-1 in place of N^2-4

⇒ 60% overestimate

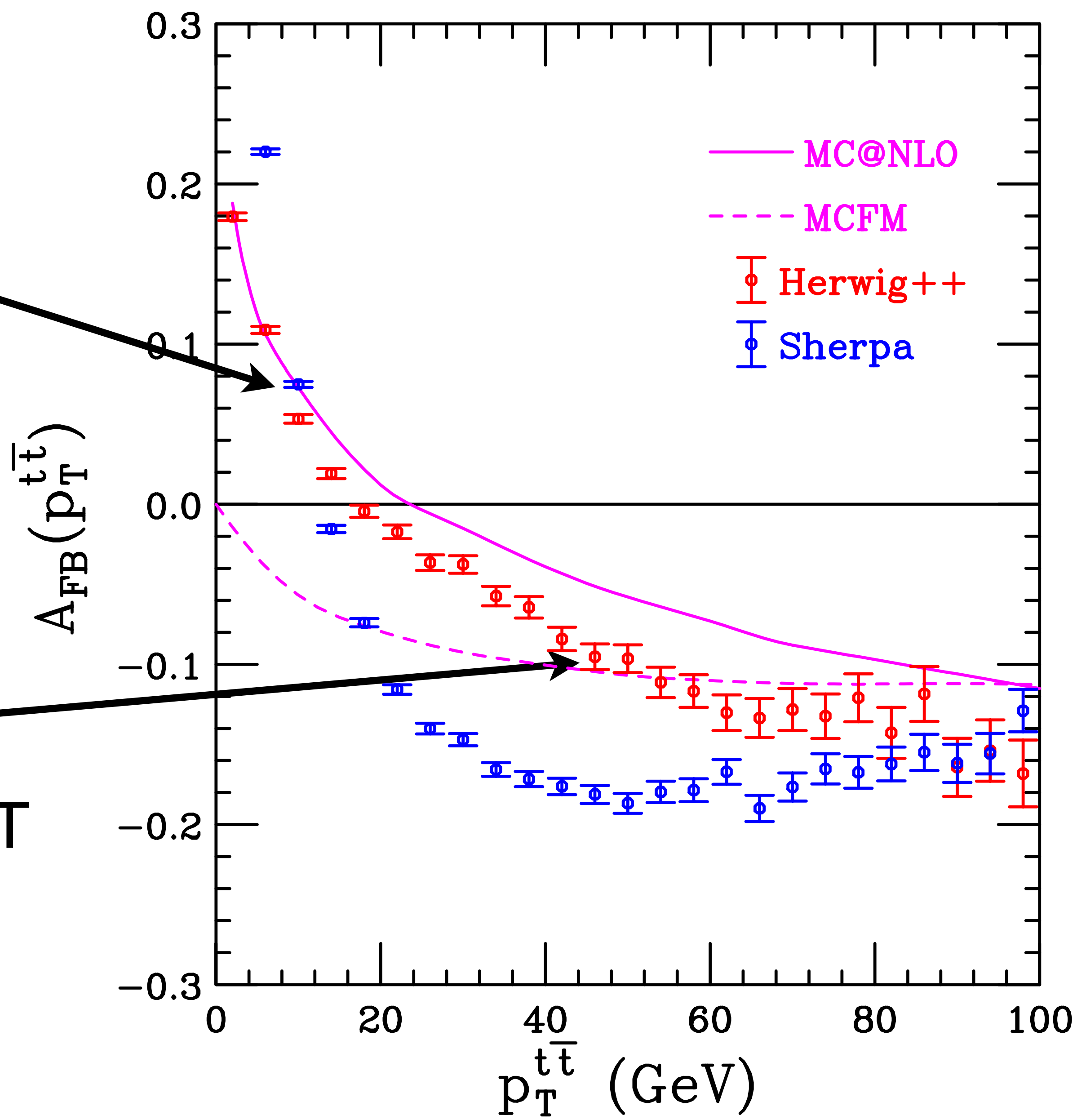
A_{FB} vs $p_T(t\bar{t})$

Forward tops left at low p_T

➡ $A_{FB}>0$

Backward tops moved to high p_T

➡ $A_{FB}<0$



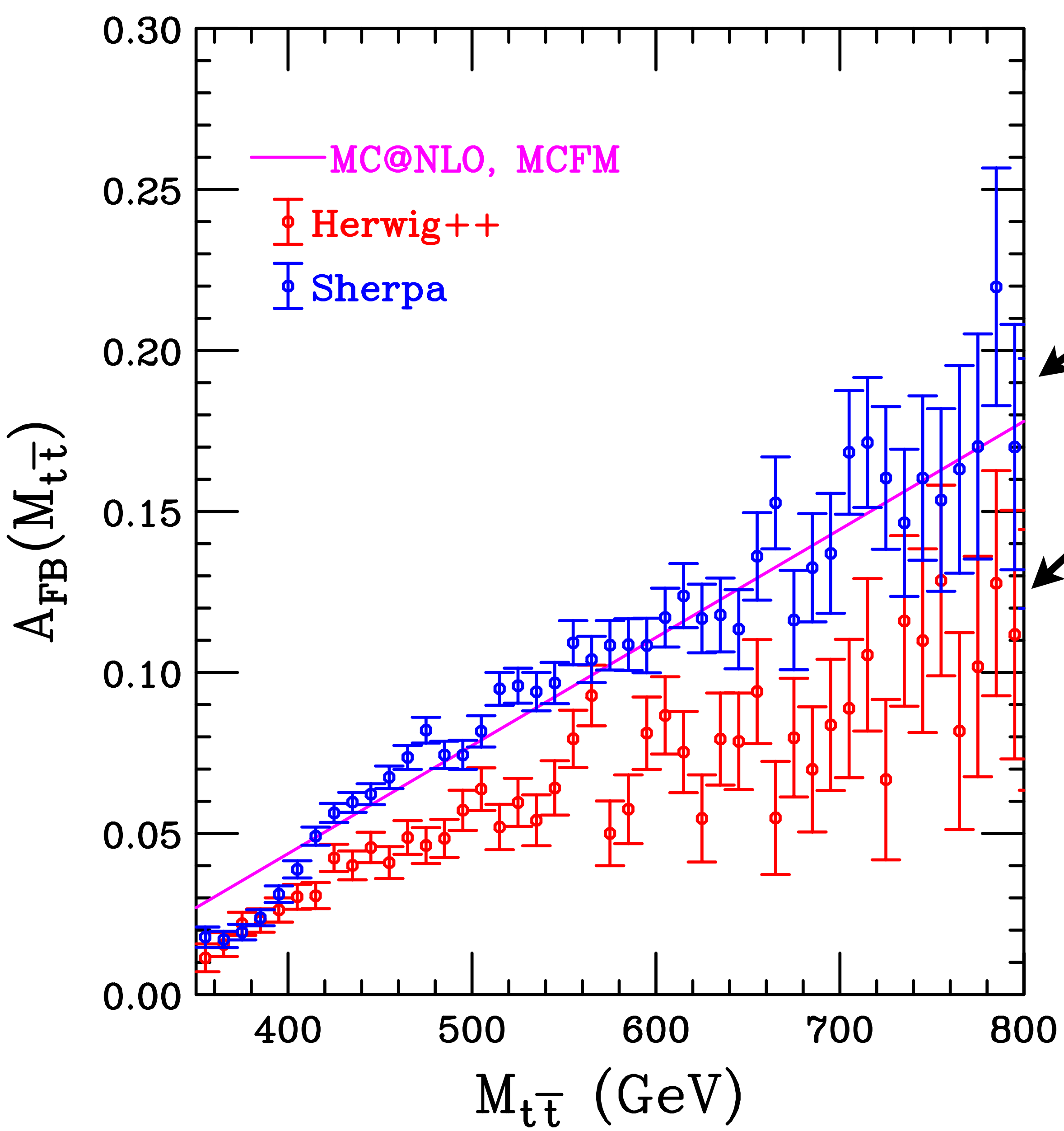
Inclusive A_{FB} vs $m(t\bar{t})$

- Less radiation from forward tops
- Sudakov factor is larger: $\Delta_+ > \Delta_-$
- Migration from F to B is smaller: $P_{+-} < P_{-+}$

$$\Delta\sigma_{+-} = \int d\sigma^{\rm LO}\big|_{\Delta y>0} \left[\Delta_+ + (1-\Delta_+)(P_{++} - P_{+-})\right] - \int d\sigma^{\rm LO}\big|_{\Delta y<0} \left[\Delta_- + (1-\Delta_-)(P_{--} - P_{-+})\right]$$

$$\boxed{= -2\int d\sigma^{\rm LO}\big|_{\Delta y>0} (1-\Delta_+)P_{+-} + 2\int d\sigma^{\rm LO}\big|_{\Delta y<0} (1-\Delta_-)P_{-+} \quad > 0}$$

Inclusive A_{FB} vs $m(t\bar{t})$



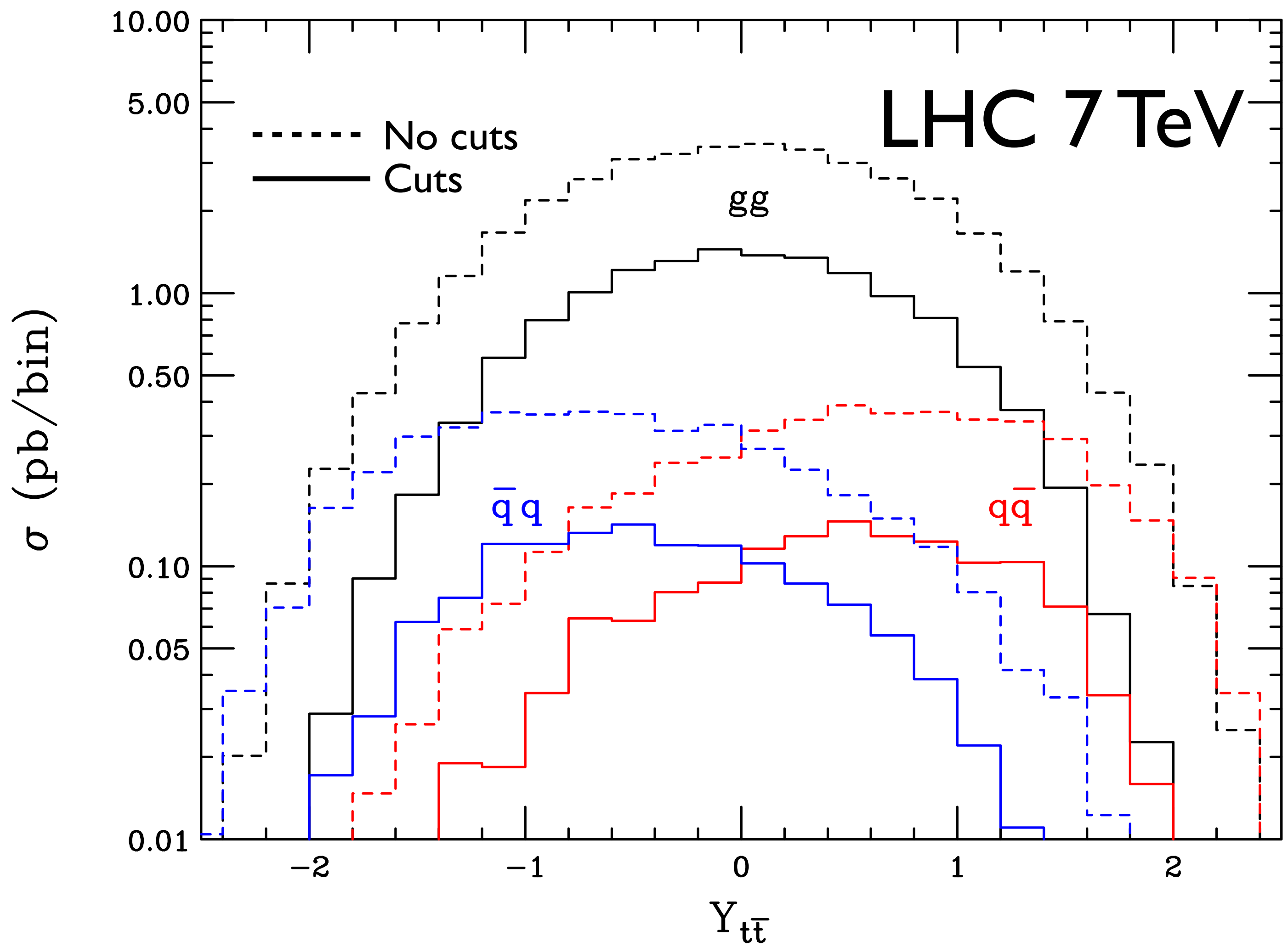
Sherpa coherent dipole shower

Herwig++ coherent parton shower

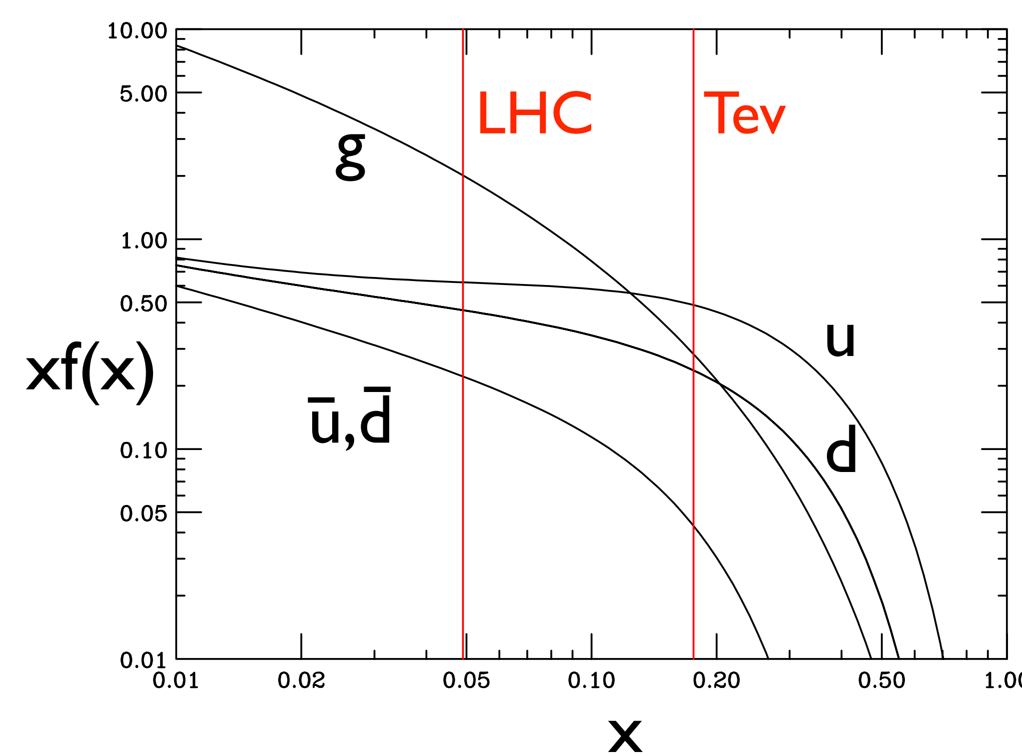
- QCD loop effects reproduced (approximately) by Sudakov factors in coherent showering
- Shows importance of higher order recoil effects (not yet computed exactly)

Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- SM effect is small

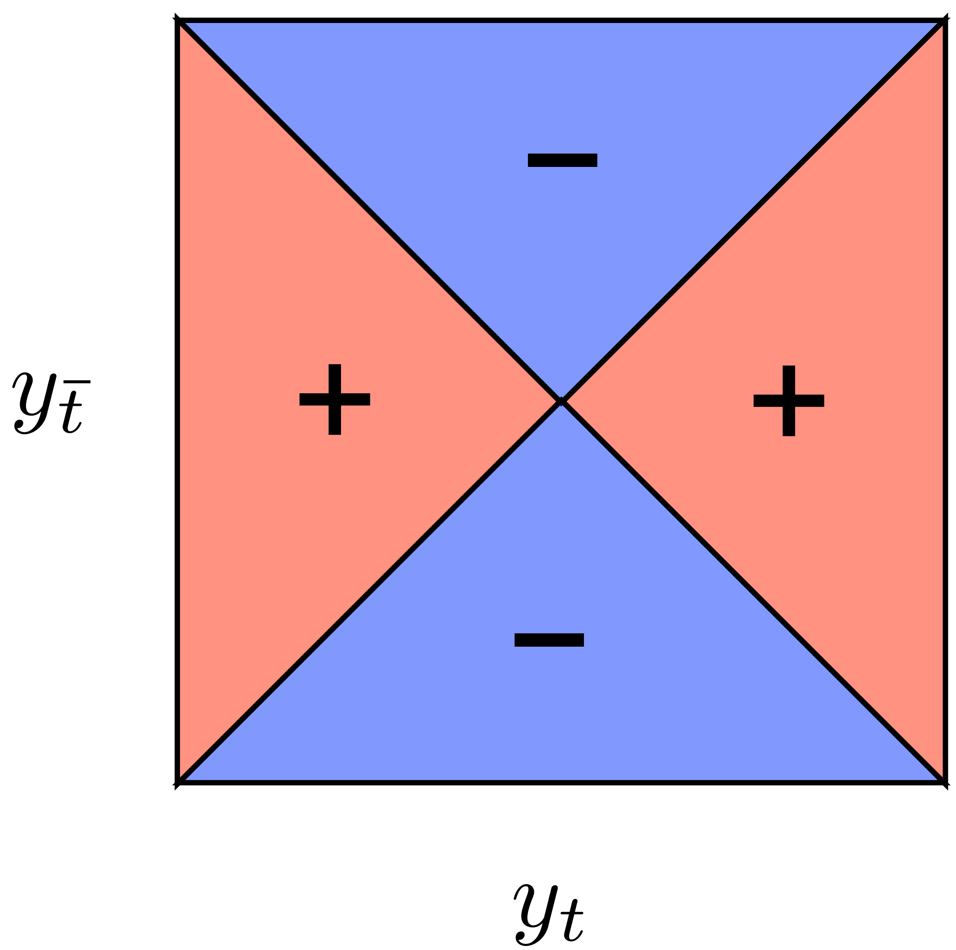


$$\Delta y = y_t - y_{\bar{t}}\ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$



Top quark asymmetry at LHC

- LHC is a pp collider ➡ no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Rapidity correlation should be as shown below
- Top rapidity distribution should be wider



$$\Delta y = y_t - y_{\bar{t}}\ , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}})$$

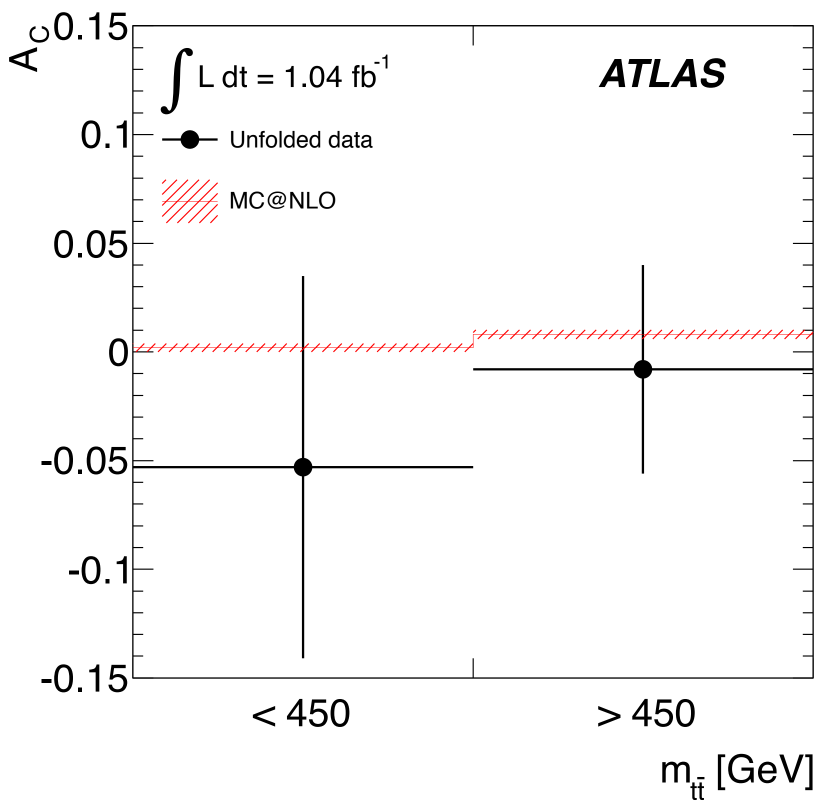
$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

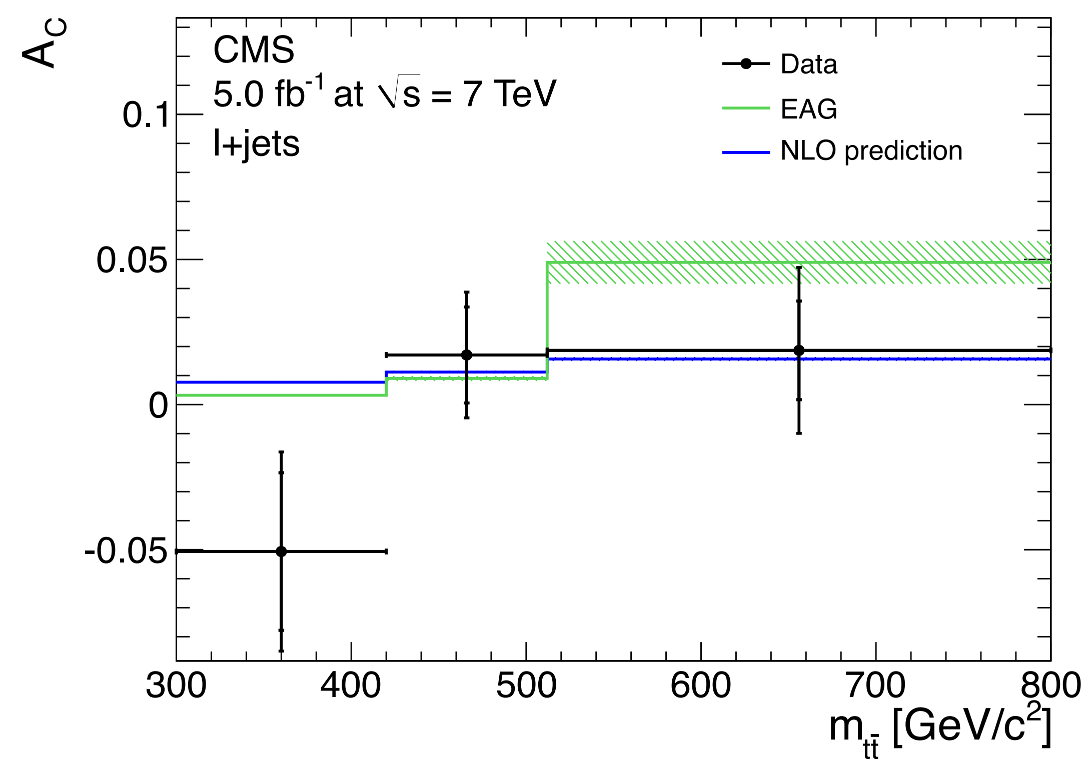
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

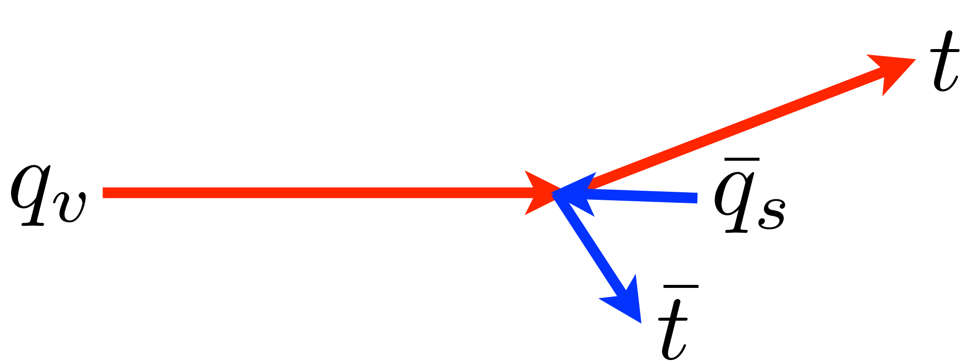
$$\Delta|y| \equiv |y_t| - |y_{\bar{t}}| > 0 \iff \Delta y \cdot Y_{t\bar{t}} > 0$$

$t\bar{t}$ A_C at LHC

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \qquad \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$$



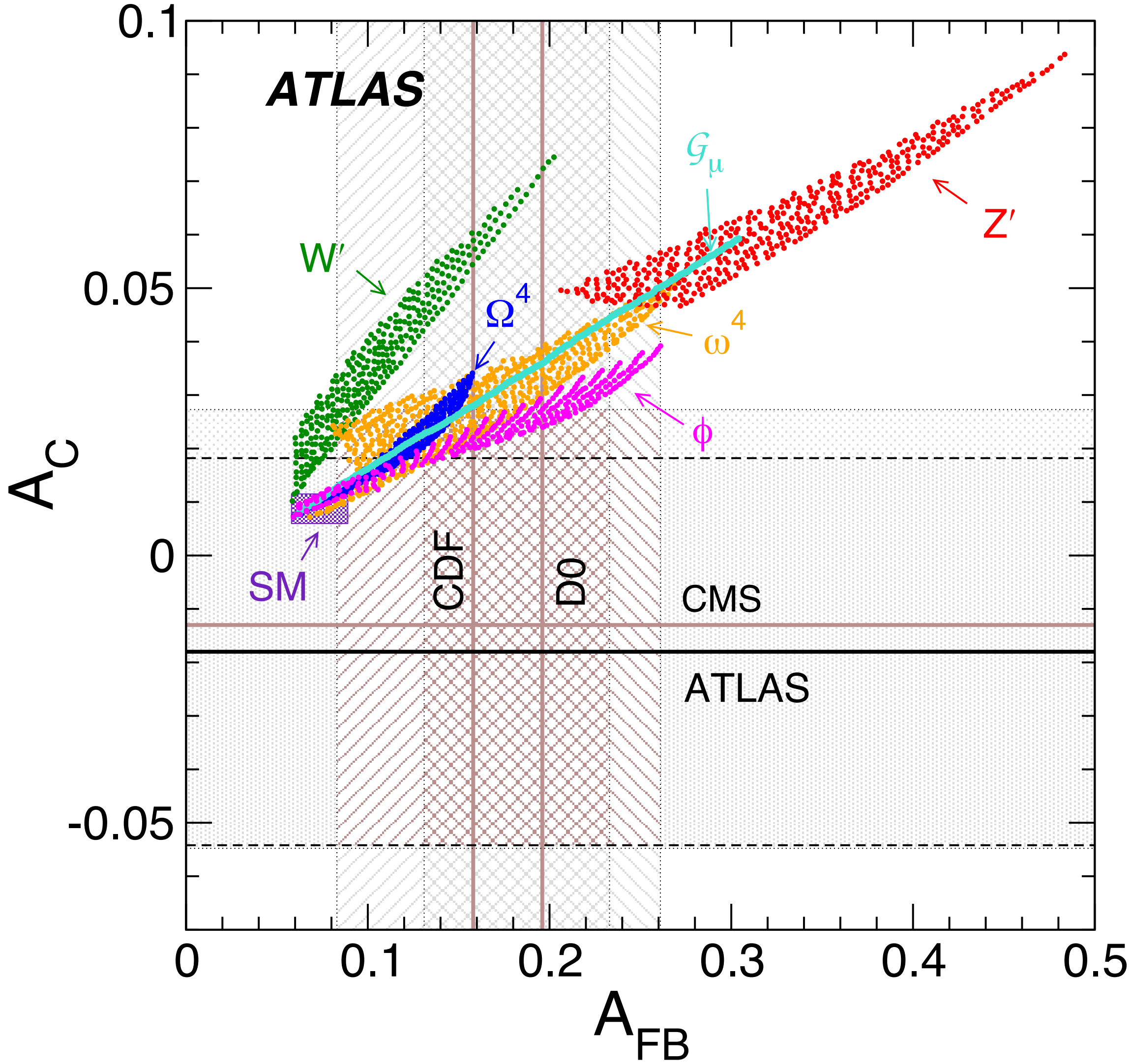




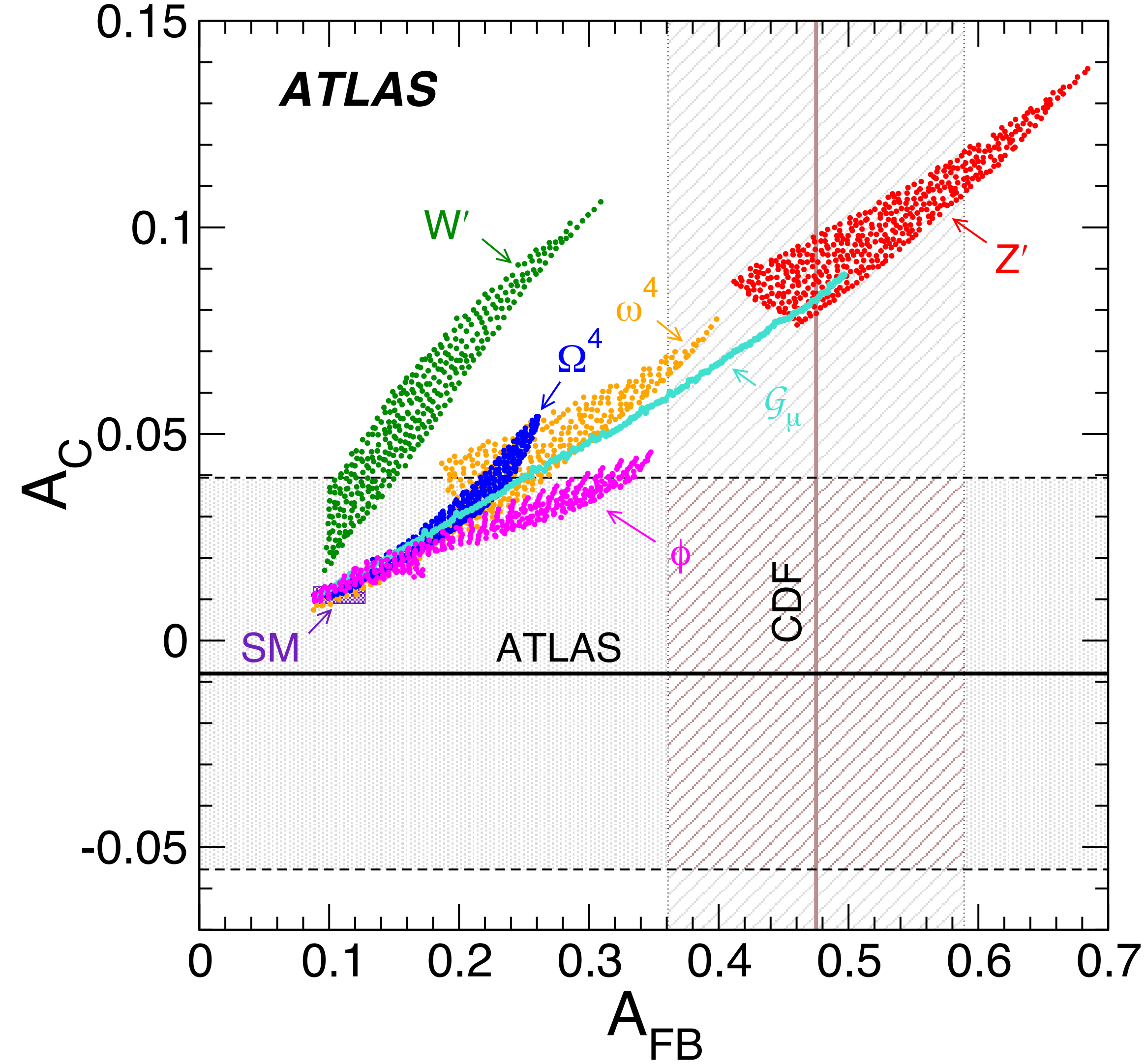
- Much smaller than A_{FB}
- Good SM agreement (so far)
- EAG = effective axigluon, fits CDF

Comparisons with BSM Models

All M_{tt}



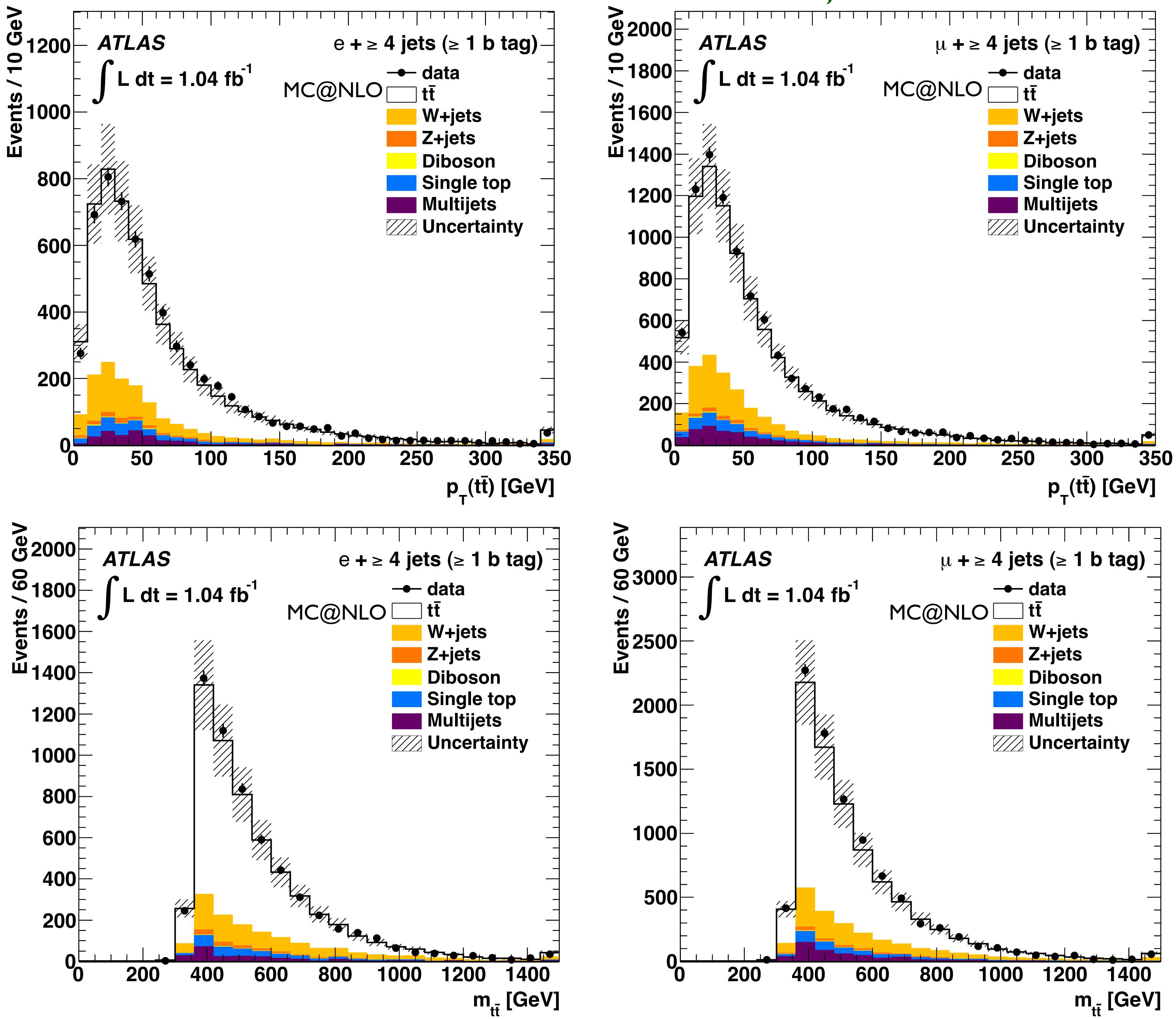
M_{tt}>450 GeV



- Not clear that any model is much better than SM

$t\bar{t}$ p_T & m_{tt} at LHC

ATLAS, arXiv:1203.5015



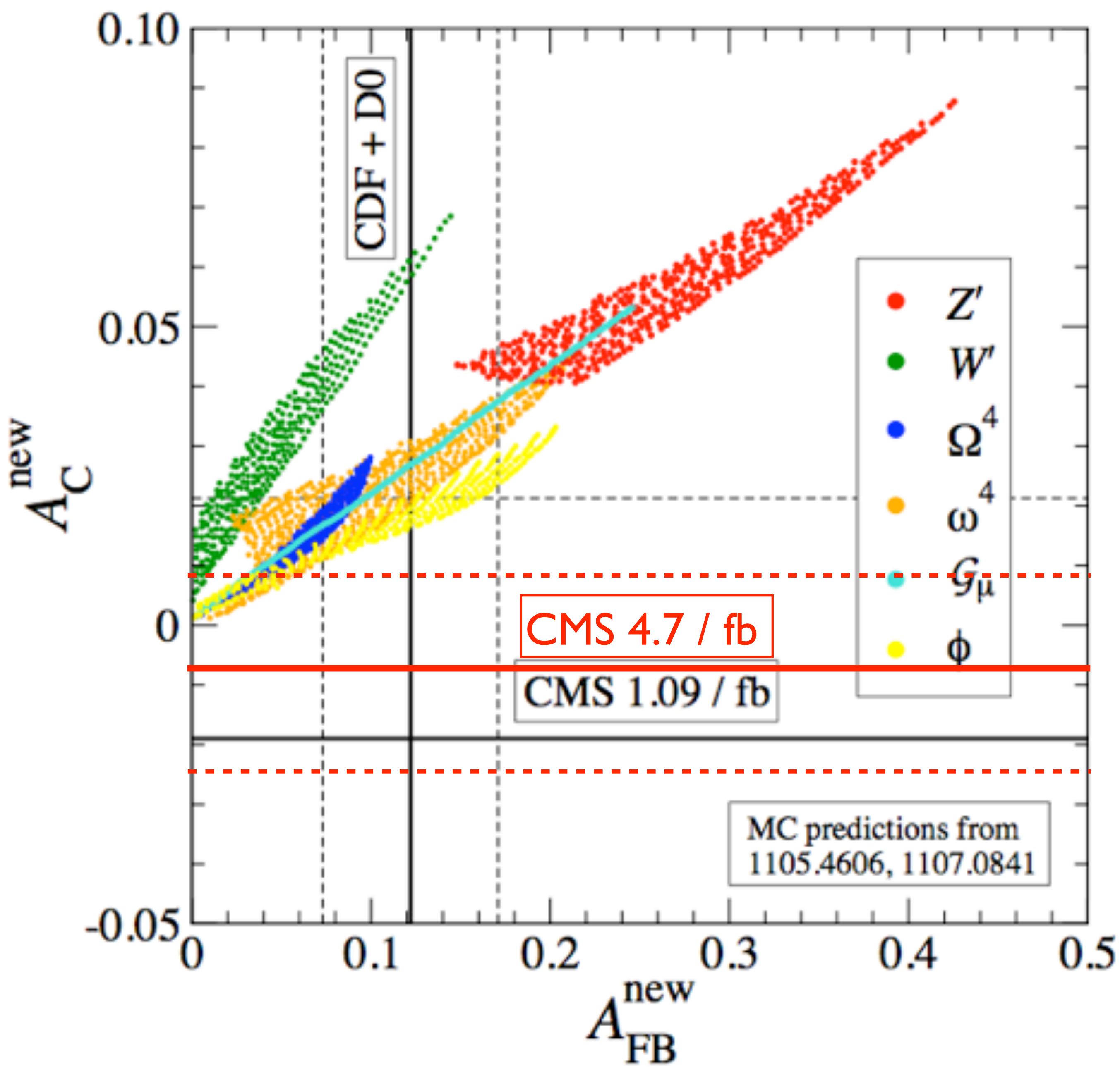
- Good agreement with MC@NLO

Conclusions

- Asymmetry larger than NLO SM seen by CDF in several independent data sets
- D0 also see this but no mass dependence
- D0 top pair p_T also inconsistent with SM
- HO SM prediction not yet clear (recoils)
- Asymmetry at CDF (not SM) level could be seen at LHC in this run
- So far no sign of BSM at LHC

Backup

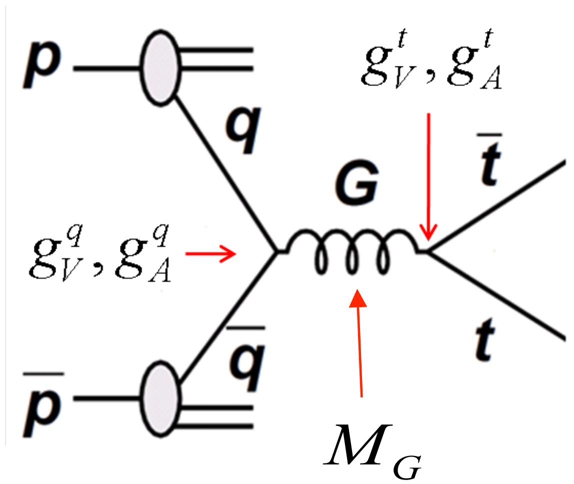
A_C vs A_{FB} in various models



- NB: A^{new} is deviation from SM (so SM is 0,0)

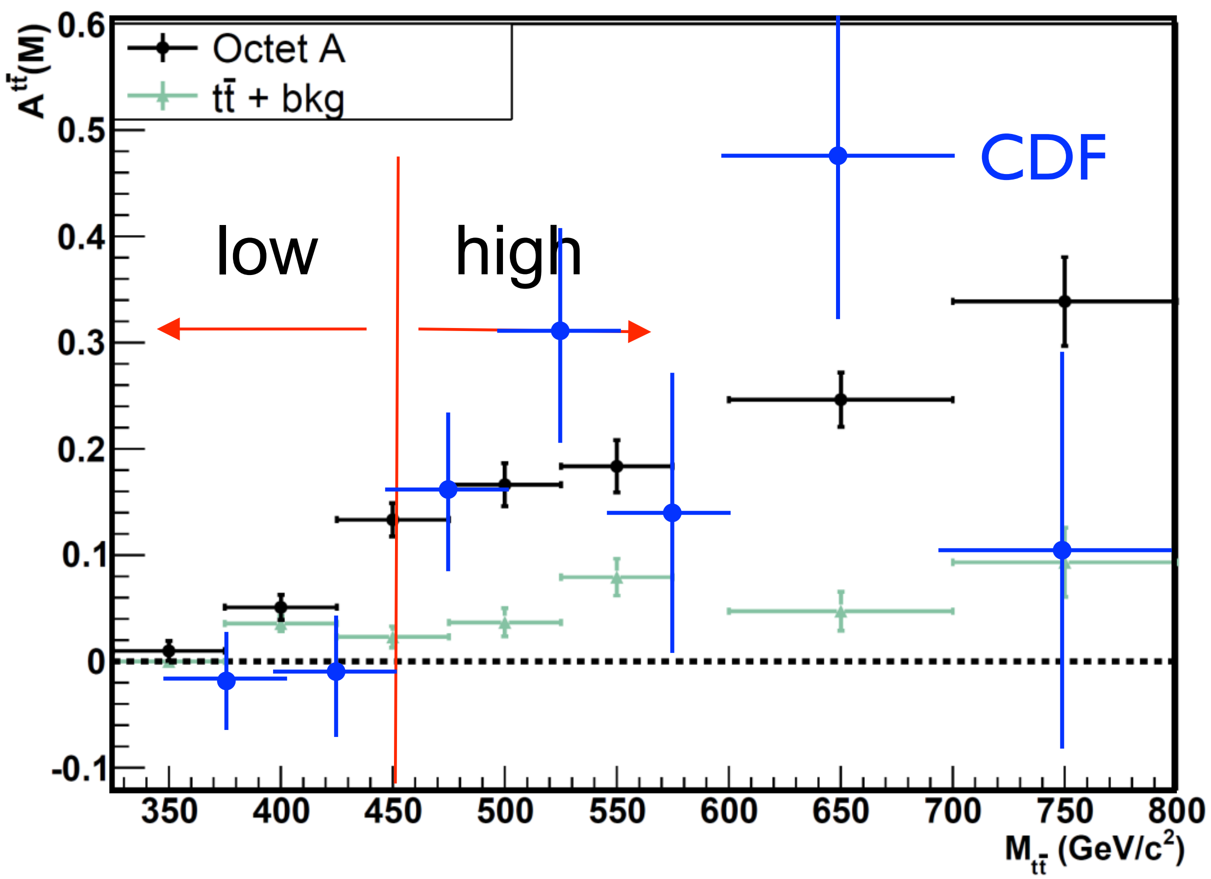
Adapted from J Aguilar-Saavedra, arXiv:1202:2382

"Axigluon" model



Ferrario & Rodrigo, PRD80(09) 051701

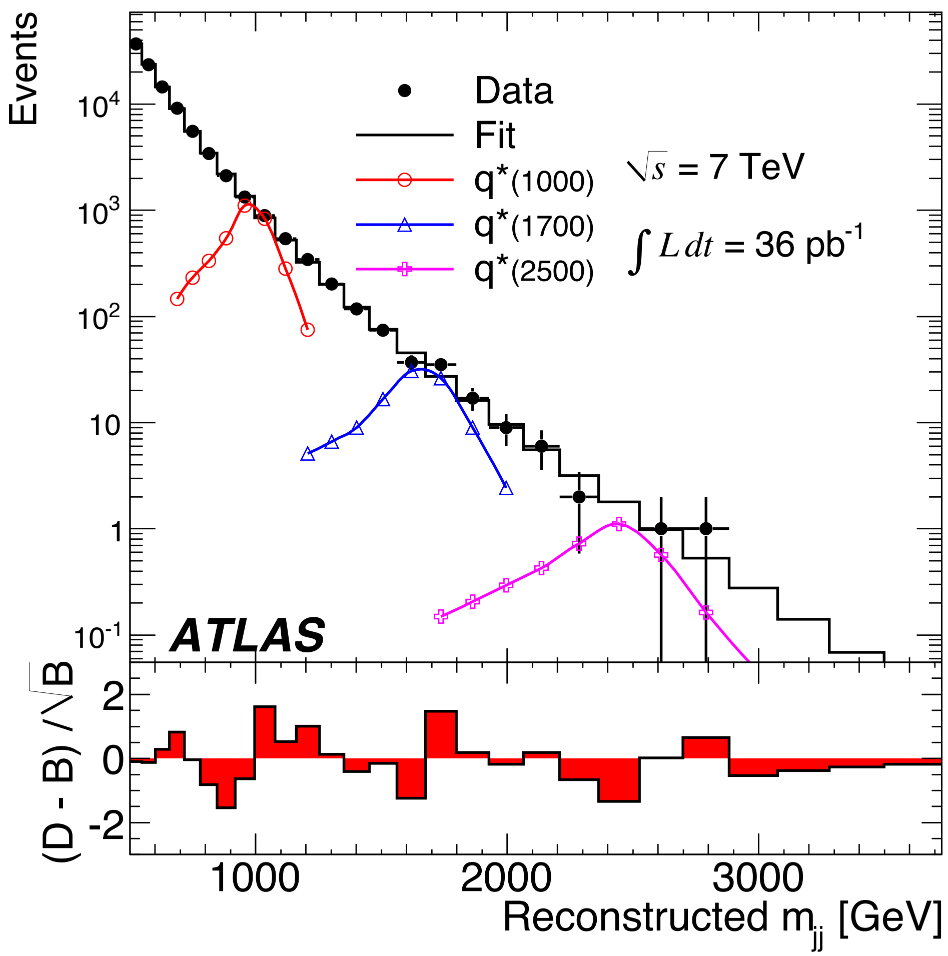
- sample "Octet A"
  - $g_V = 0$, $|g_A = 3|$
  - $g^q{}_A = - g^t{}_A$
  - $M_G = 2.0$ TeV
  - xsec ratio: $\sigma/\sigma_{sm} = 1.02$
  - M_{tt} spectrum ~ compares to Pythia
  - Model: Parton $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
  - Data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$

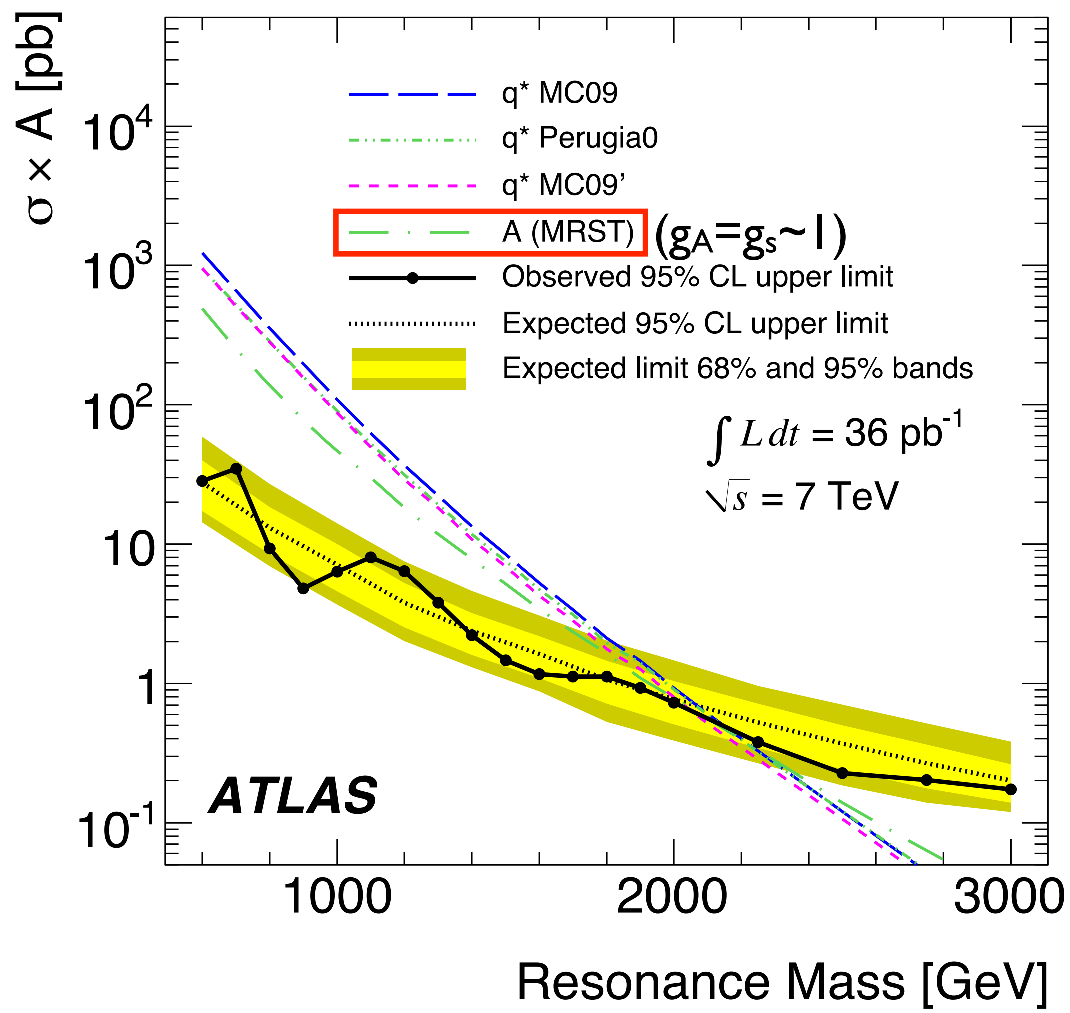


- Can fit CDF $A^{t\bar{t}}$ data
- $M_{t\bar{t}}$ spectrum will differ

Axigluon search in dijets

ATLAS, arXiv:1103.3864

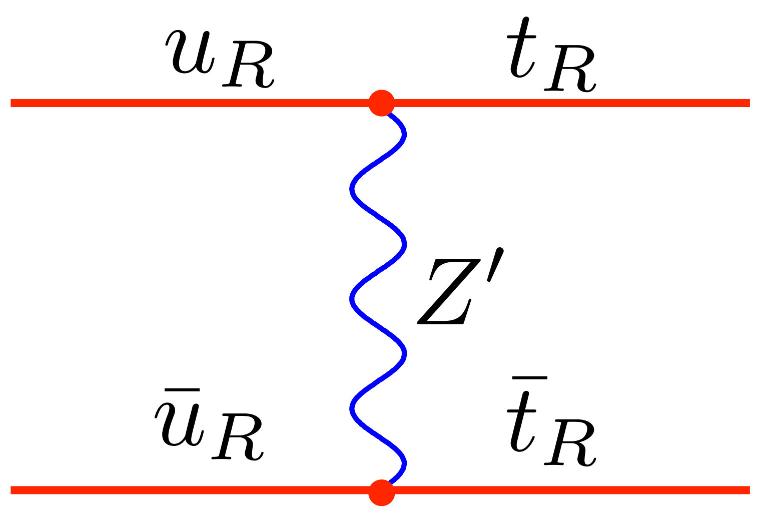




- Resonance bump would be similar to q^*
- Exclude $0.6 < M_G < 2.1$ TeV

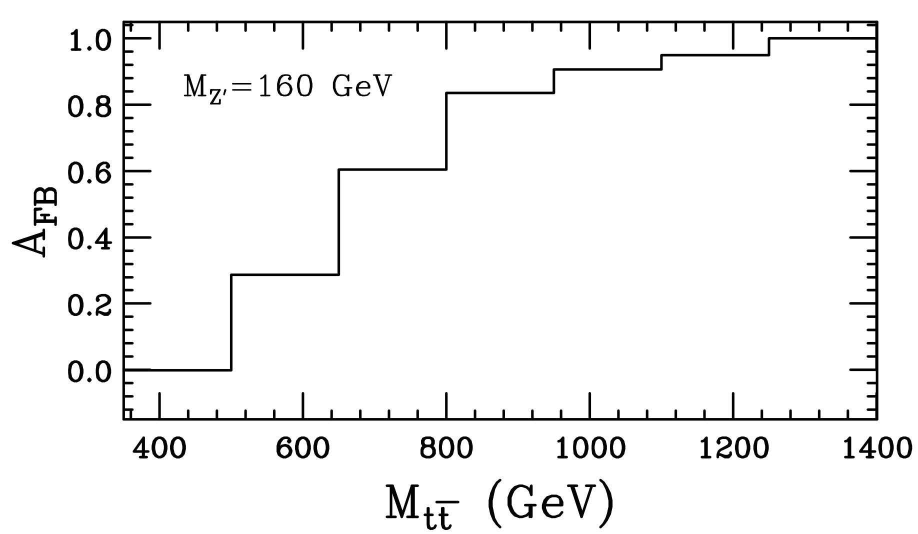
Z' exchange models

Jung, Murayama, Pierce, Wells, PRD81(2010)015004

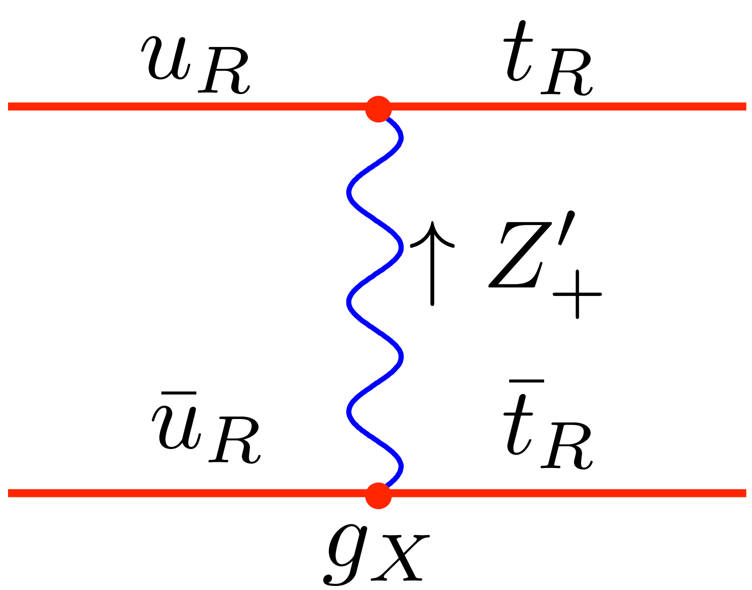


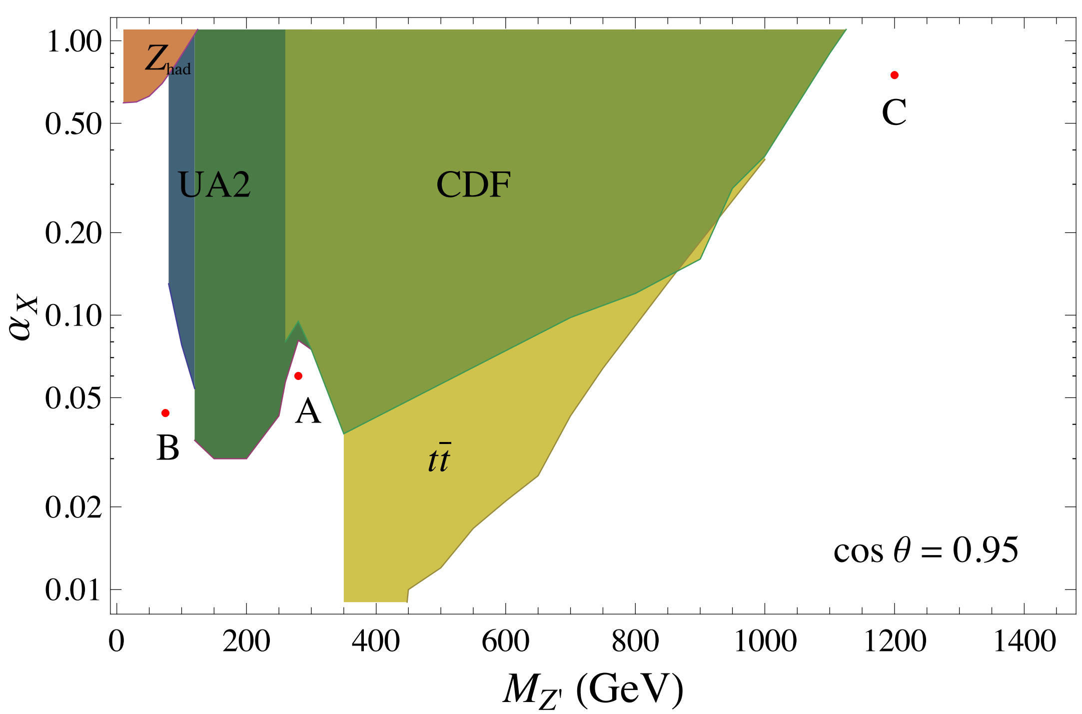
- Rutherford scattering → asymmetry
- Interferes with QCD $u\bar{u} \to g^* \to t\bar{t}$
- RH coupling avoids FCNC constraints
- Data favour light Z' mass, below top
- BUT...
  - Also get $uu \to tt$
  - and $u\bar{u} \to Z'Z' \to t^*\bar{u}t^*\bar{u}$

→ need mixing so $Z' \to u\bar{u}$



Nonabelian Z' model



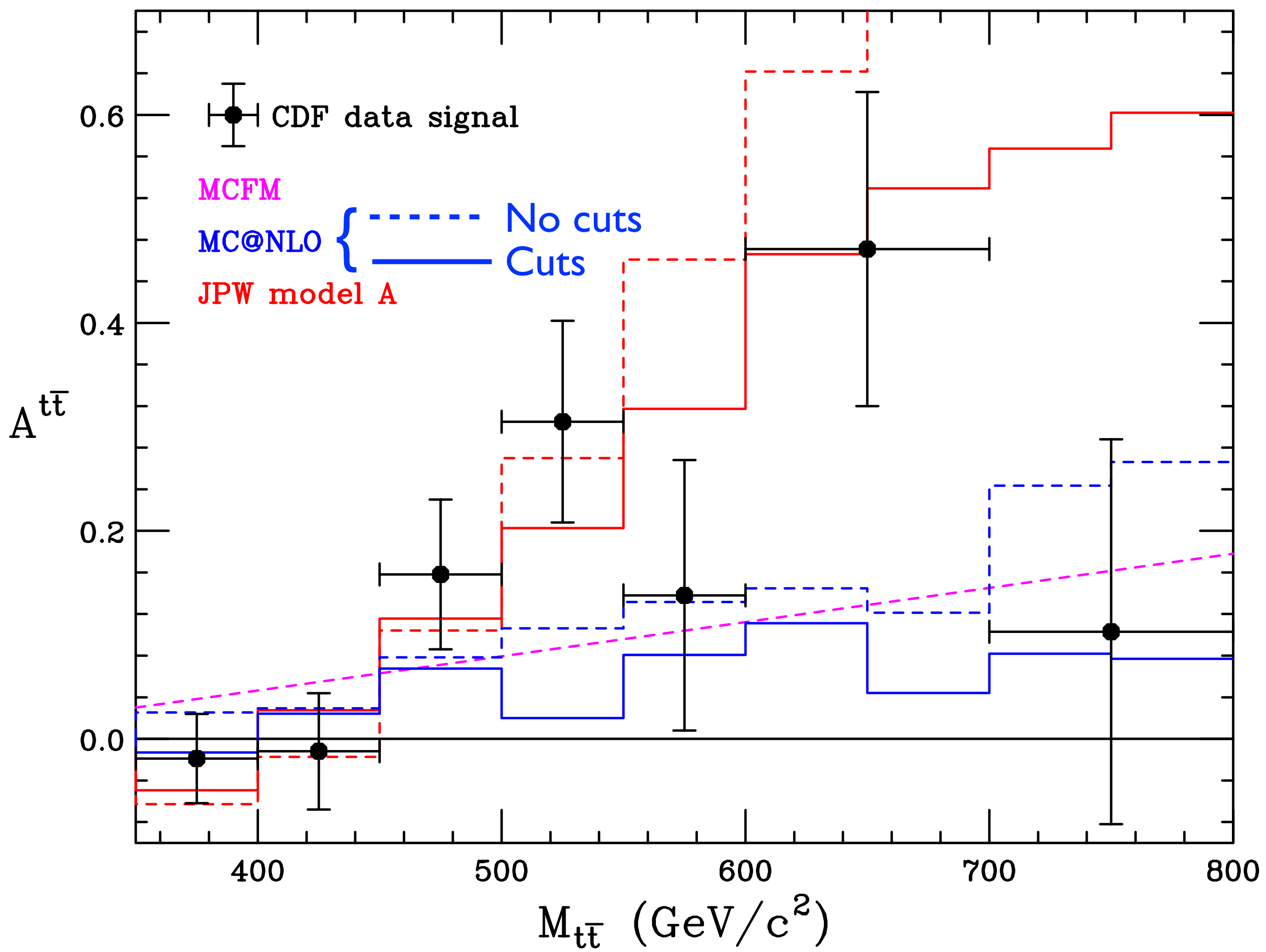


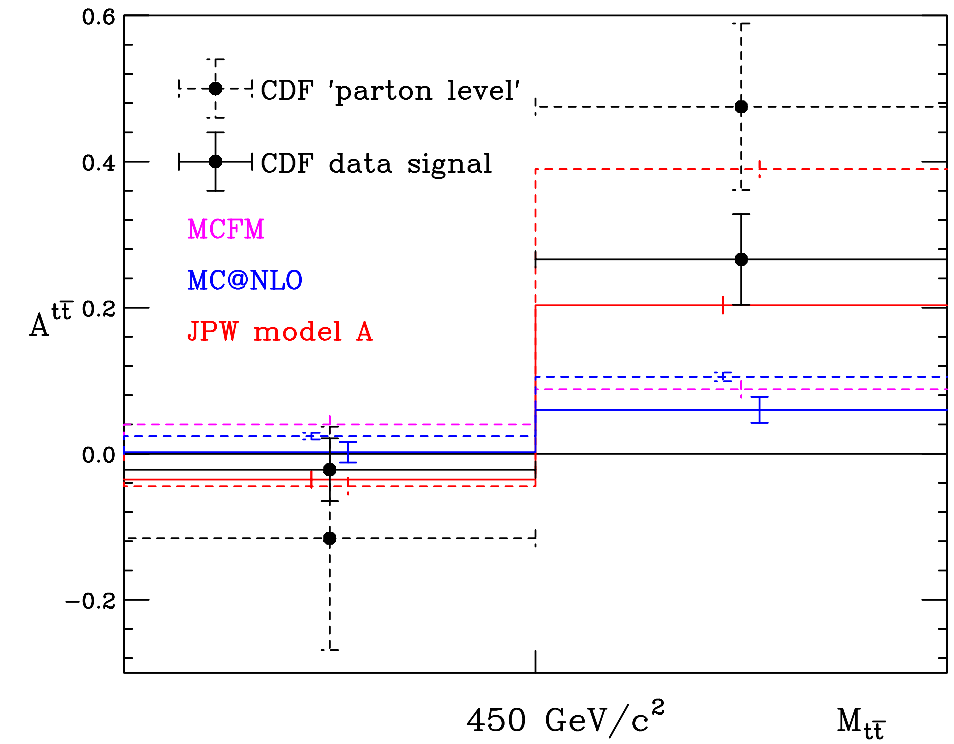
Jung, Pierce, Wells, arXiv:1103.4835

- SU(2)x doublet $\begin{pmatrix} t_R \\ u_R \end{pmatrix}$
- Gauge triplet $Z'_\pm, Z'_0$ (they call W', Z')
- Don't get $uu \to tt$ (when unbroken)
- Flavour mixing reduces $Z'_0 \to u\bar{u}$
- Data favour $m_t < m_{Z'} < 2m_t$ (point A)

Z' model asymmetry

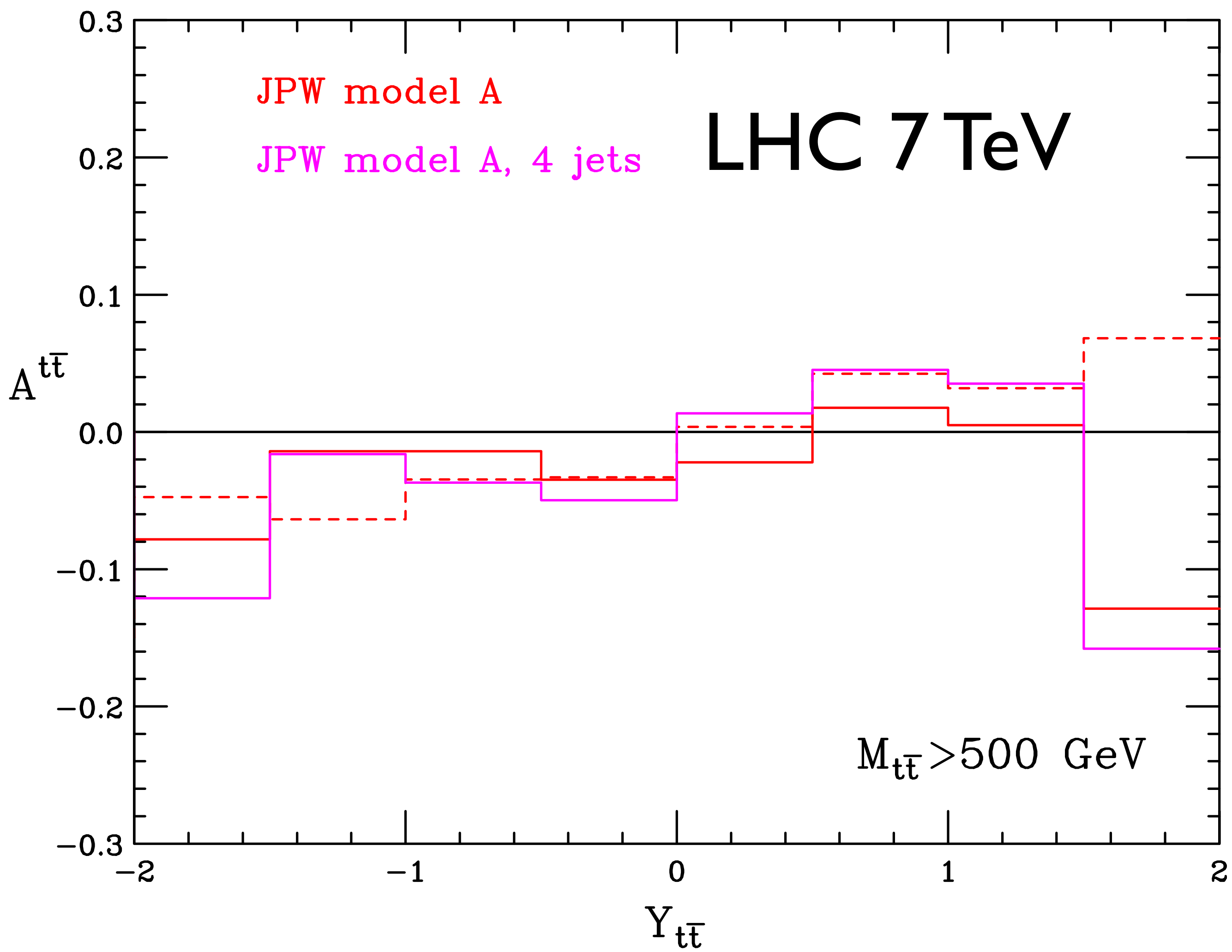
- Jung-Pierce-Wells nonabelain model (point A) can fit data:

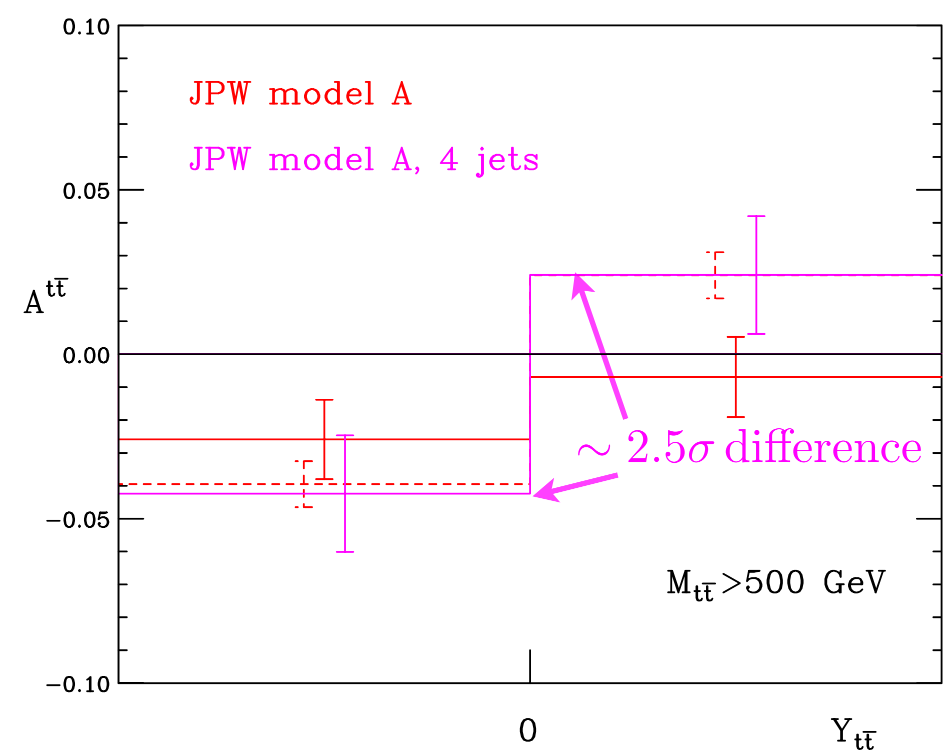




CDF asymmetry at LHC?

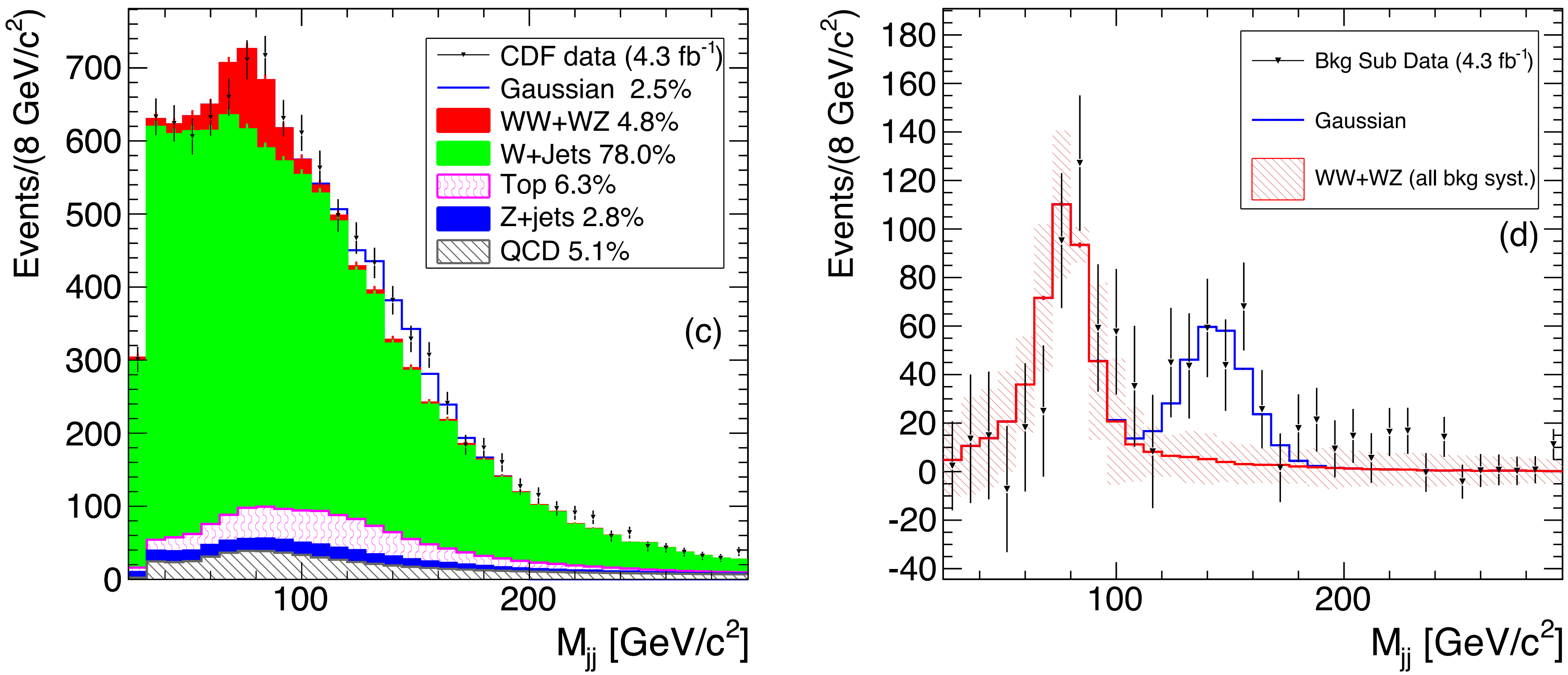
- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ (q vs $\bar{q}$)
- Jung-Pierce-Wells model (point A) → smaller effect ($u\bar{u}$ only)



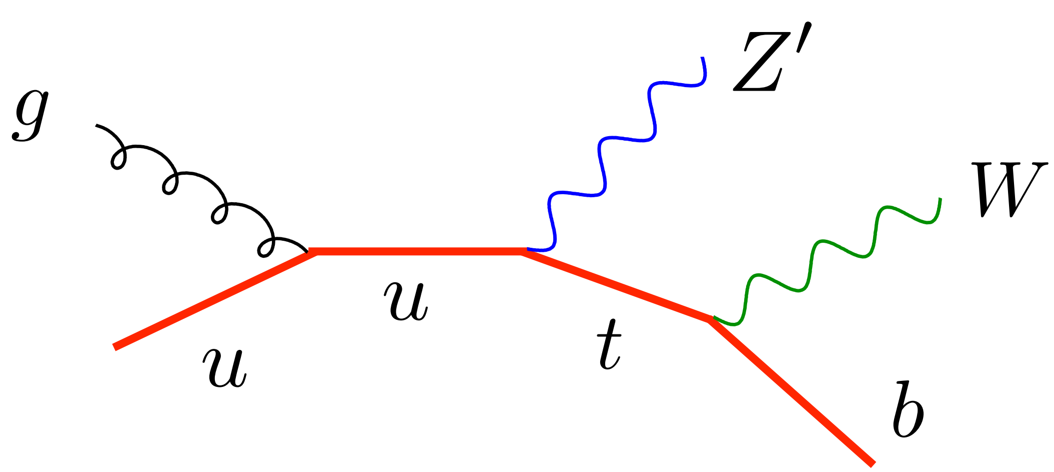


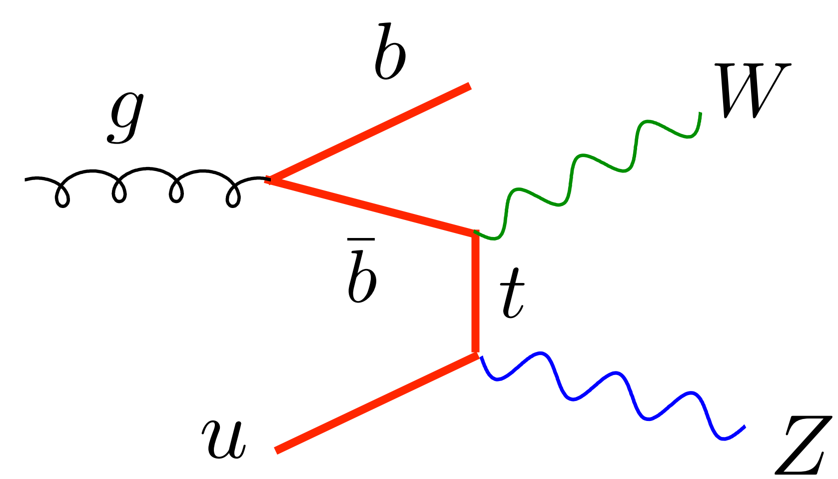
CDF Wjj anomaly

CDF, arXiv:1104.0699



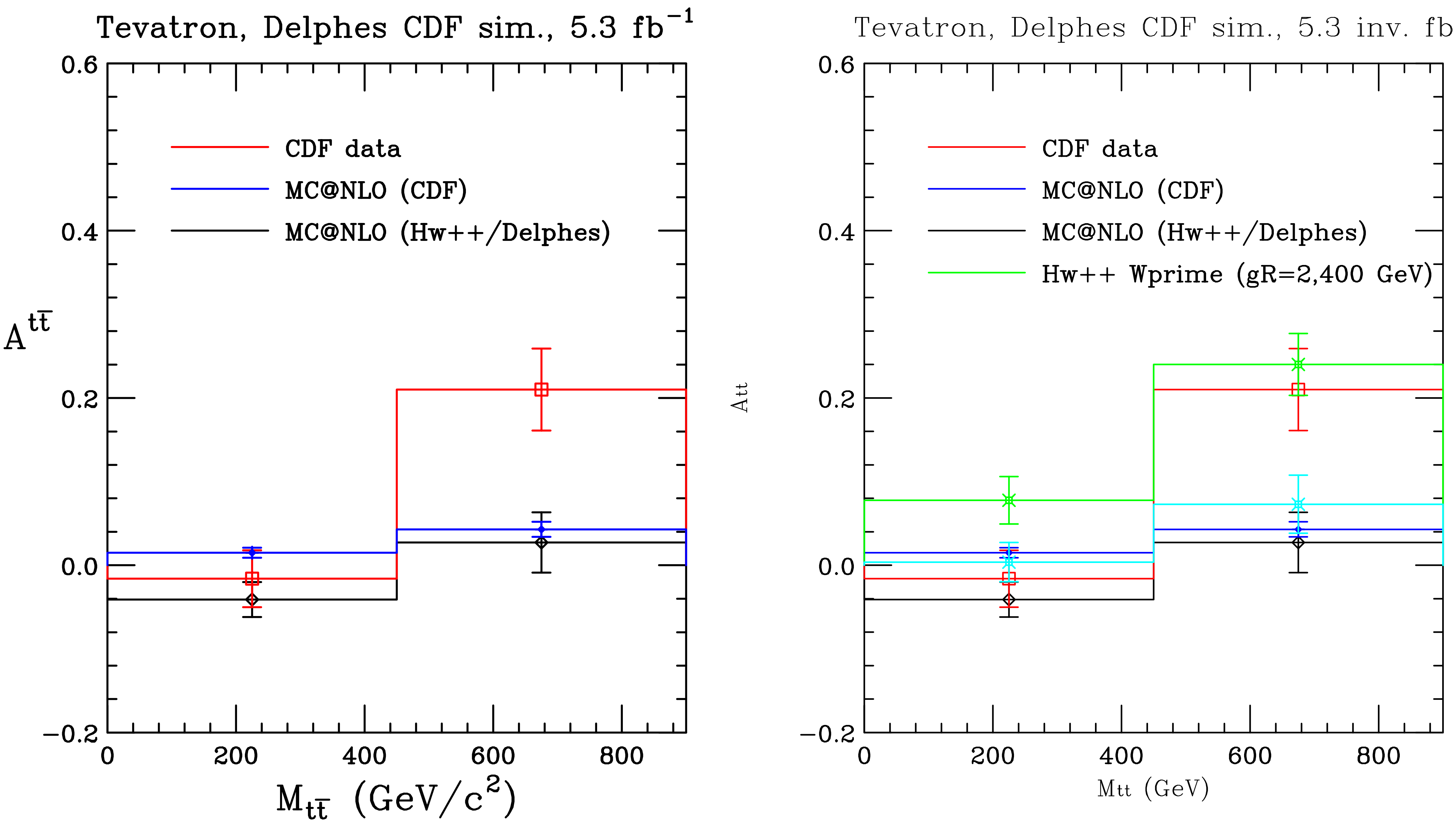
- No anomaly in γjj ➔ flavour-changing Z'?





W' model

A Papaefstathiou, in prep.



- Includes simulation of CDF detector