Physics beyond Standard Model & Asymmetries at Hadron Colliders

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Proposals for LHC people

1. New particle search: Color-Octet Vector Boson Zc (140-160 GeV), motivated by A^t_{FB} and di-jet anomalies observed by Tevatron
2. Measure new asymmetry observables in top pair production: A_{OFB} and A_E in order to cross-check Tevatron A_{FB} anomaly
3. Measure A_{OFB} in bottom pair production at Z-pole in order to cross-check A^b_{FB} anomaly at LEP.
4. NLO QCD induced aymmetry for top/bottom can be cross-checked.
5. Discriminating Z' via forward-backward asymmetry measurements

Refs

- **arXiv:1107.5769**
- **arXiv:1104.1917**
- **arXiv:1104.1161**
- **arXiv:1102.1044**
- **arXiv:1101.2507**
- **arXiv:1011.1428**
- **arXiv:1011.0152**
- **arXiv:1008.2685**
- **arXiv:1006.2510**

Contents

1. Why asymmetry and its role to discover BSM and detailed study
2. A^t_{FB} and di-jet anomalies observed by Tevatron and BSM origins
3. New color-octet vector boson Zc?
4. How to cross-check A^t_{FB} at LHC and one-side FB asymmetry
5. Edge Charge Asymmery (A_E) in top study
6. Application 1: Measuring A_{OFB} in bottom pair production in order to cross-check A^b_{FB} anomaly at LEP and/or A^t_{FB} at Tevatron
7. Application: Discriminating Z' via forward-backward asymmetry measurements
8. Conclusions & discussions

Collider Data vs. Physics
--3 steps

- 1 step: Production rate/decay lifetime, determined by strength of interaction (collect data sample)
- 2 step: Energy/momentum to construct resnance, detemined by mass of new particle (discovery)
- 3 step: Angular distribution , determined by nature of couplings and spin of new particle (detail study)

Why forward-backward asymmetry?

- Angular distribution info to study spin, coupling etc
- However data is limited
- History: SLD/LEP, confirm the quantum structure of SM at one-loop level

Theoretical issues with forward-backward asymmetry

- How to define asymmetry observable? (specific asymmetry is most suitable for certain dynamics)
- How to optimize asymmetry to suppress backgrounds? (bump is more insensitive to backgrounds)
- How to extract dynamics info from asymmetry measurements? (compare theoretical prediction and data)

Forward-backward Asymmetry (FBA) of Top Pair Production at Tevatron: Difficult Measurement

- Top quark is the heaviest ever known fermion and is thought to be related to mechanism of electro-weak symmetry breaking and physics beyond the standard model (SM).
- Since it was discovered more than one decade ago, measuring its properties is one of the most active field.
- Most of measured properties such as mass, width, production rate and so on are consistent with SM predictions
- However the CDF and D0 Collaboration have observed possible deviation on forward-backward (FB) asymmetry.

- At top pair frame, FBA is defined as

$$A_{FB} = \frac{\sigma(\Delta Y>0)-\sigma(\Delta Y<0)}{\sigma(\Delta Y>0)+\sigma(\Delta Y<0)},$$

where $\Delta Y \equiv Y_t - Y_{\bar{t}}$ is the difference between rapidity of the top and anti-top quark, which is invariant under $t\bar{t}$ or $p\bar{p}$ rest frame.

CDF & D0 (previous) analysis

$$A_{FB}^{CDF} = 0.158 \pm 0.072 \pm 0.017, \text{with } 5.3 fb^{-1};$$
$$A_{FB}^{D0} = 0.08 \pm 0.04 \pm 0.01, \text{with } 4.3 fb^{-1}.$$

- Consistent with previous measurements
- Corresponding theoretical predictions:

$$5.8 \pm 0.9\% \text{ [1] by MCFM}$$

$$1^{+2}_{-1}\% \quad \text{by MC@NLO}$$

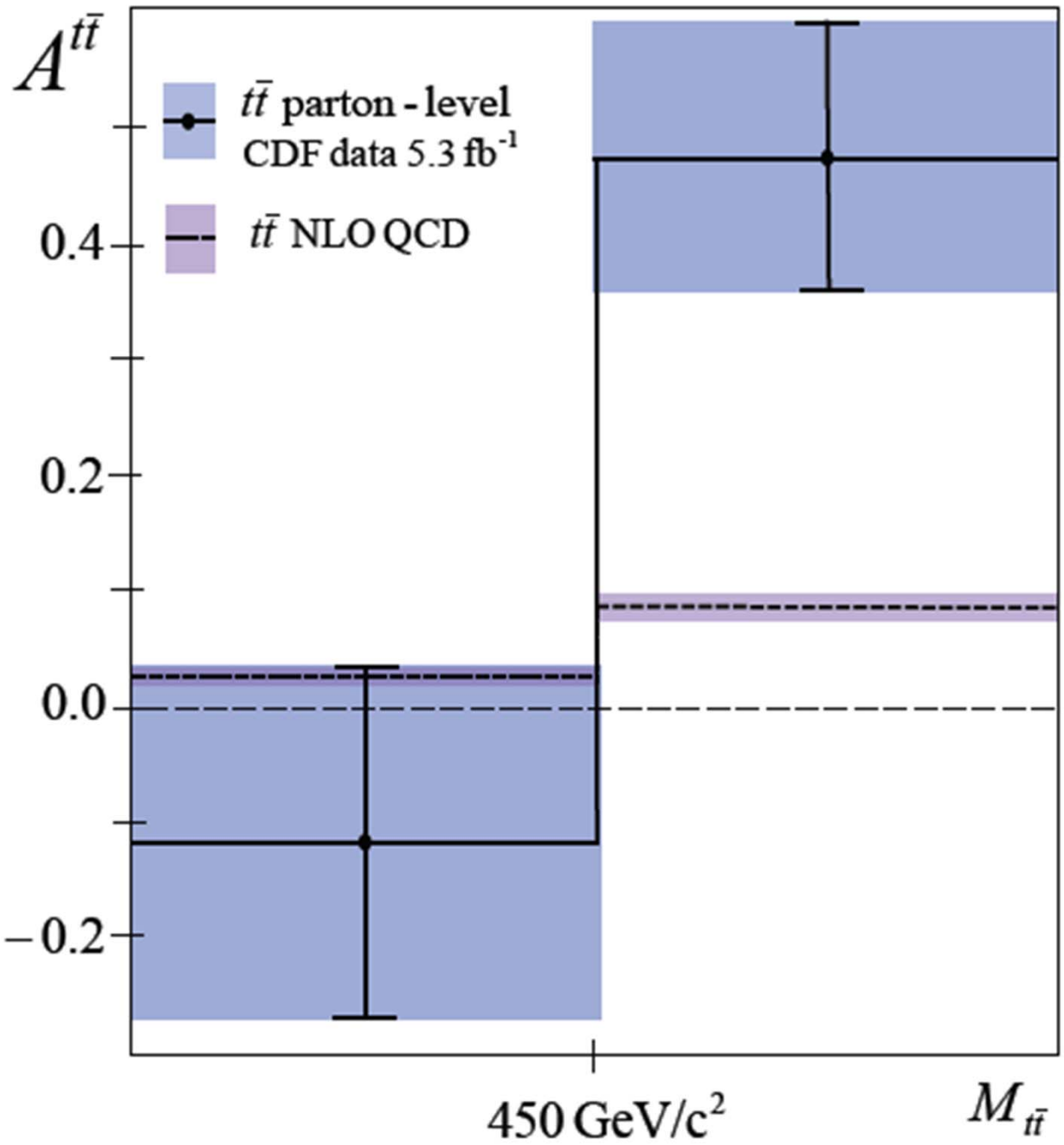

$A^{t\bar{t}}$
$t\bar{t}$ parton - level
CDF data 5.3 fb^{-1}
$t\bar{t}$ NLO QCD
0.4
0.2
0.0
−0.2
450 GeV/c^2
$M_{t\bar{t}}$

TABLE XIII: Asymmetry $A^{t\bar{t}}$ at high and low mass compared to prediction.

selection	$M_{t\bar{t}} < 450$ GeV/c^2	$M_{t\bar{t}} \geq 450$ GeV/c^2
data	-0.016 ± 0.034	0.210 ± 0.049
$t\bar{t}$+bkg (MC@NLO)	$+0.012 \pm 0.006$	0.030 ± 0.007
data signal	$-0.022 \pm 0.039 \pm 0.017$	$0.266 \pm 0.053 \pm 0.032$
$t\bar{t}$ (MC@NLO)	$+0.015 \pm 0.006$	0.043 ± 0.009
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

TABLE II: Naming conventions for data and simulation samples.

sample	level	definition	comparable to
data	data	reco l+jets	
data	signal	data minus bkg	$t\bar{t}$ in data
data	parton	corrected signal	$t\bar{t}$ at creation
MC	$t\bar{t}$+bkg	reco $t\bar{t}$ + bkg	data
MC	$t\bar{t}$	reco $t\bar{t}$ no bkg	data signal
MC	parton	truth level	data parton

CDF, ArXiv: 1101.0034

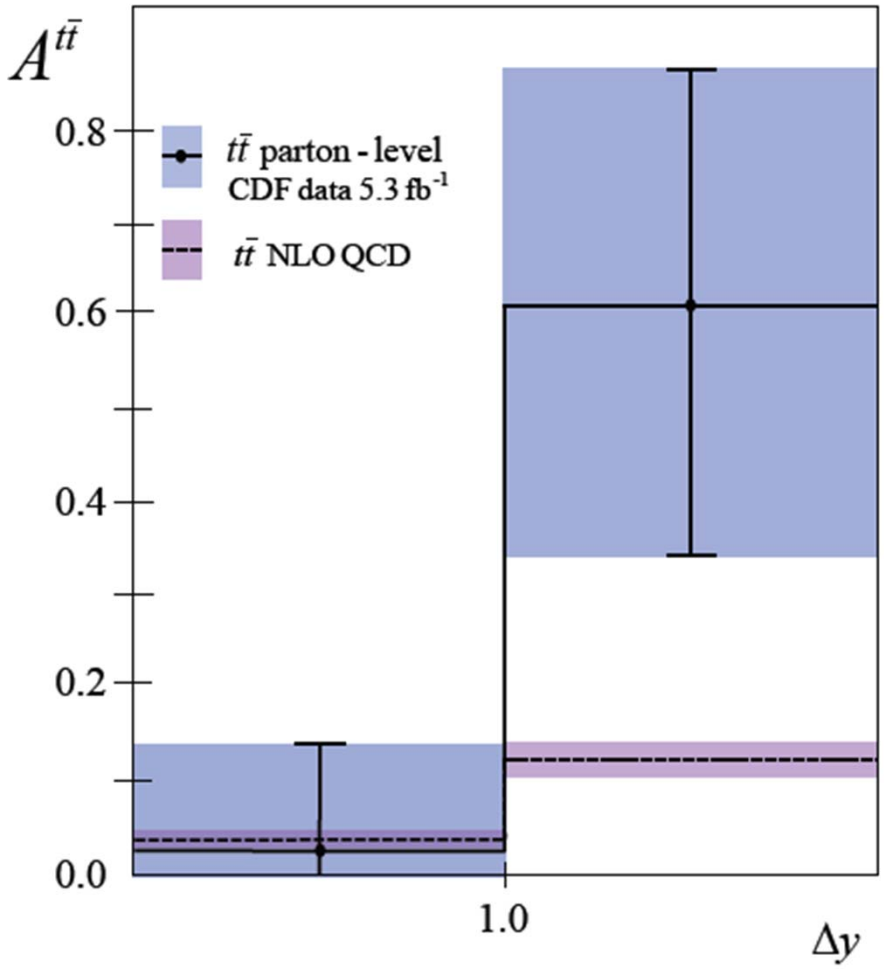
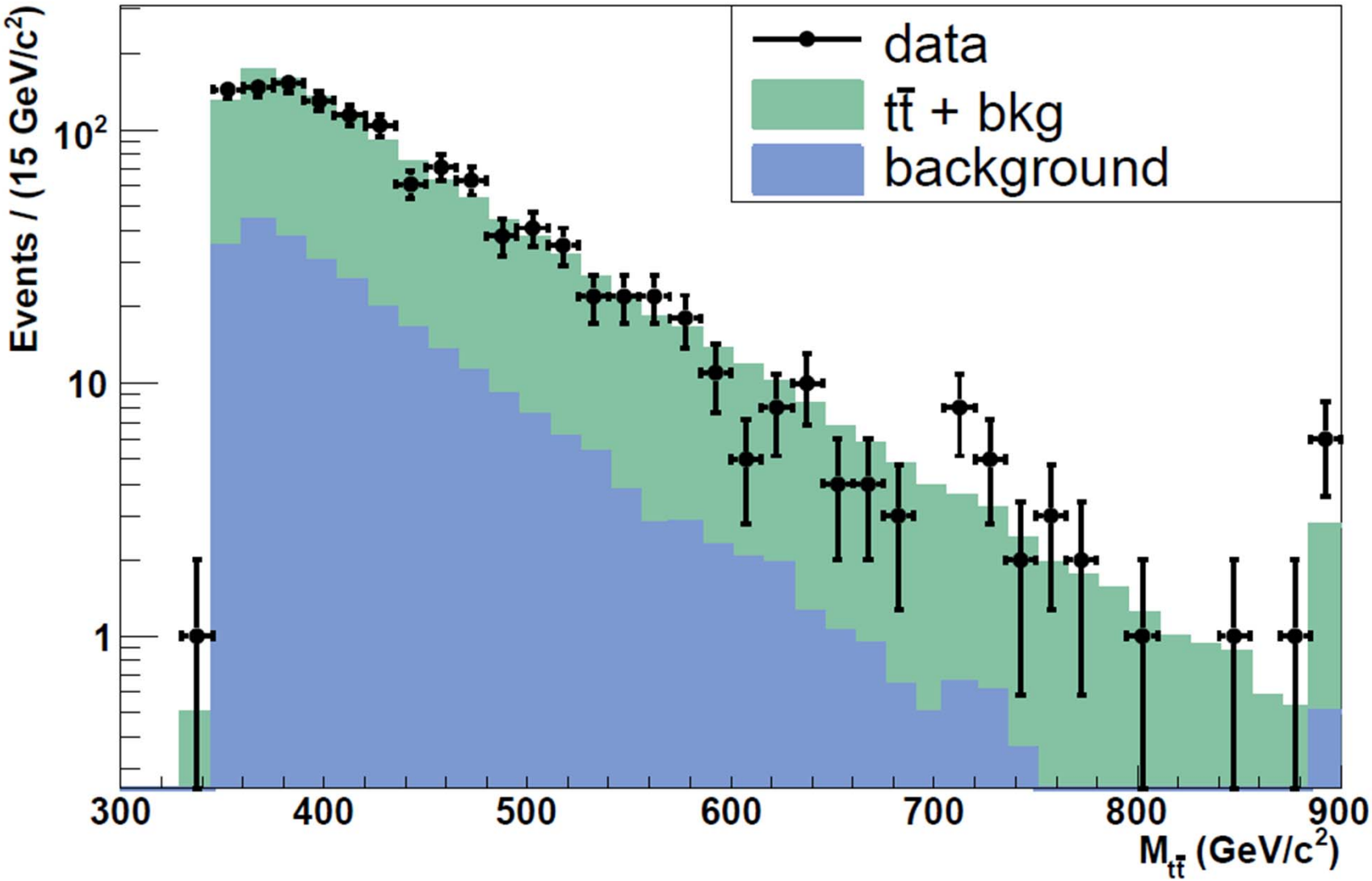

$A^{t\bar{t}}$
0.8
0.6
0.4
0.2
0.0
$t\bar{t}$ parton - level
CDF data 5.3 fb^{-1}
$t\bar{t}$ NLO QCD
1.0
Δy

TABLE VIII: The $t\bar{t}$ frame asymmetry $A^{t\bar{t}}$ at small and large rapidity difference, compared to the SM prediction of MCFM.

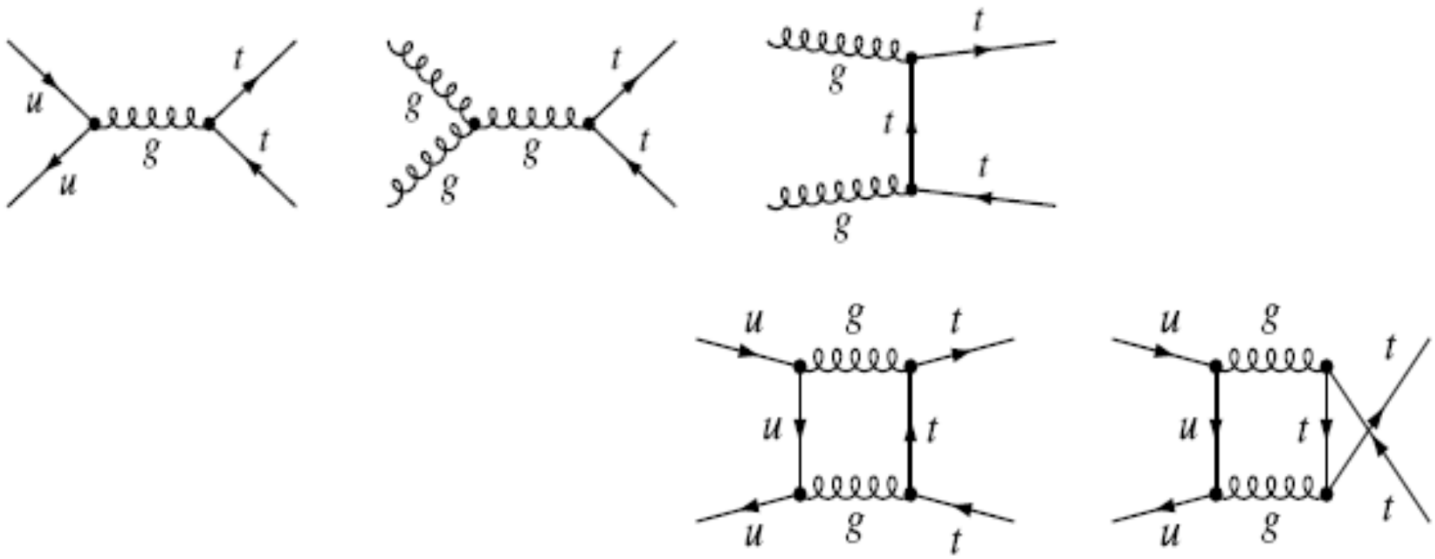
sample	level	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
data	data	0.021 ± 0.031	0.208 ± 0.062
data	parton	$0.026 \pm 0.104 \pm 0.056$	$0.611 \pm 0.210 \pm 0.147$
MCFM	parton	0.039 ± 0.006	0.123 ± 0.018



CDF, ArXiv: 1101.0034

Origin of FBA in QCD (1)

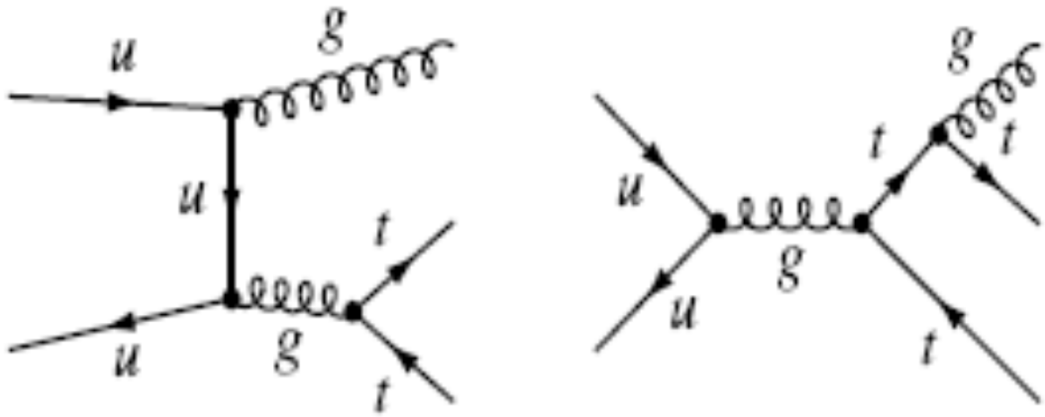
- Interference among tree and virtual diagrams: O(alpha_S^3) effects



J. H. Kuhn and G. Rodrigo, Phys. Rev. Lett. **81**, 49 (1998), 9802268.
J. H. Kuhn and G. Rodrigo, Phys. Rev. **D59**, 054017 (1999), 9807420.

Origin of FBA in QCD (2)

- Interference among diagrams: O(alpha_S^3) effects



Theoretical explanations (two ways to get A_FB)

- Higher order effects, not known yet. However unlikely
- T-channel Z’, W’
- S-channel axigluon

Constraints

- Total top pair production rate
- Differential distribution d(sigma)/dM(tt-bar), especially for the high-energy tail
- Di-jets production
- Same-sign top production
- Low-energy measurements
- Etc.

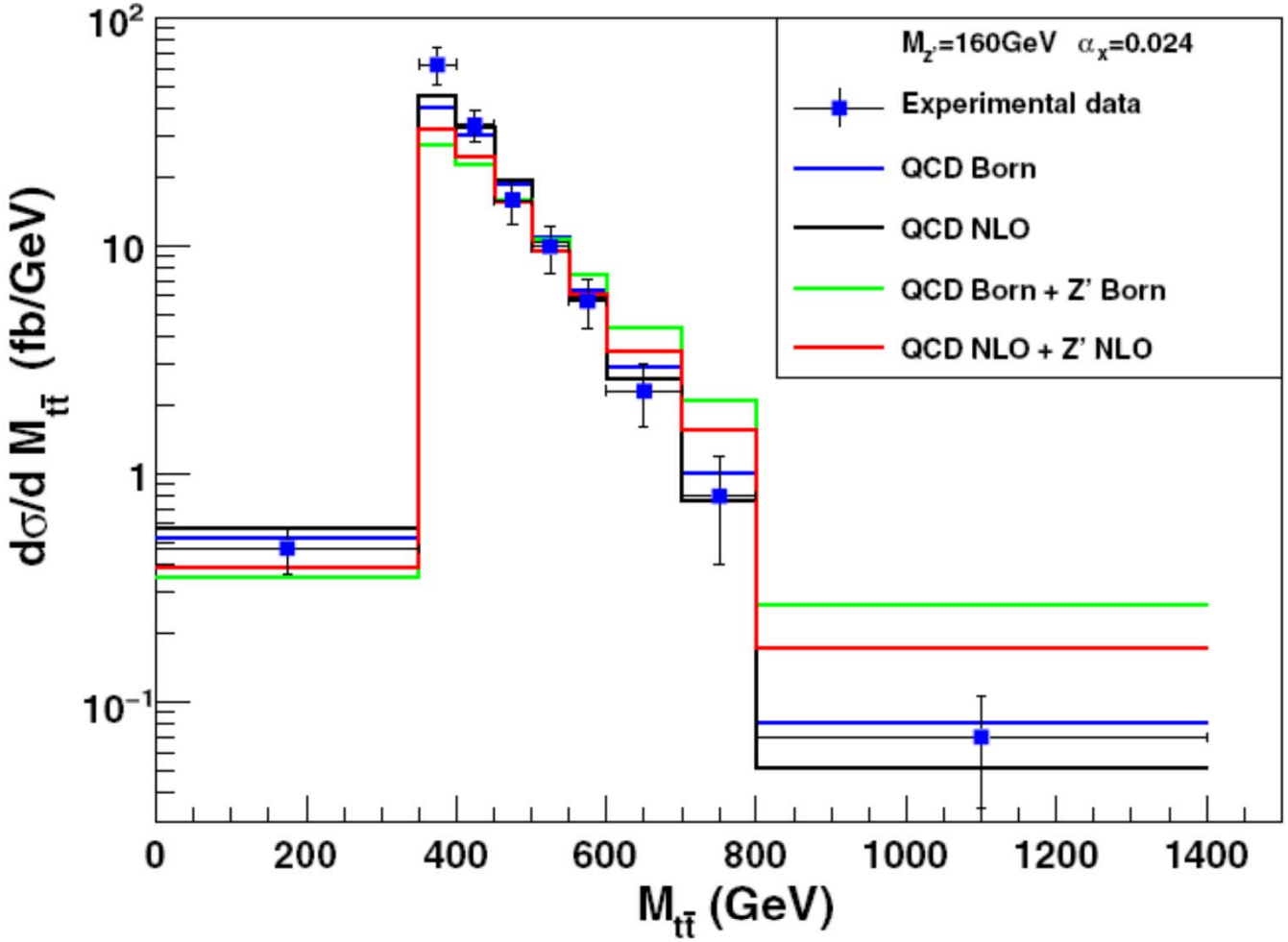
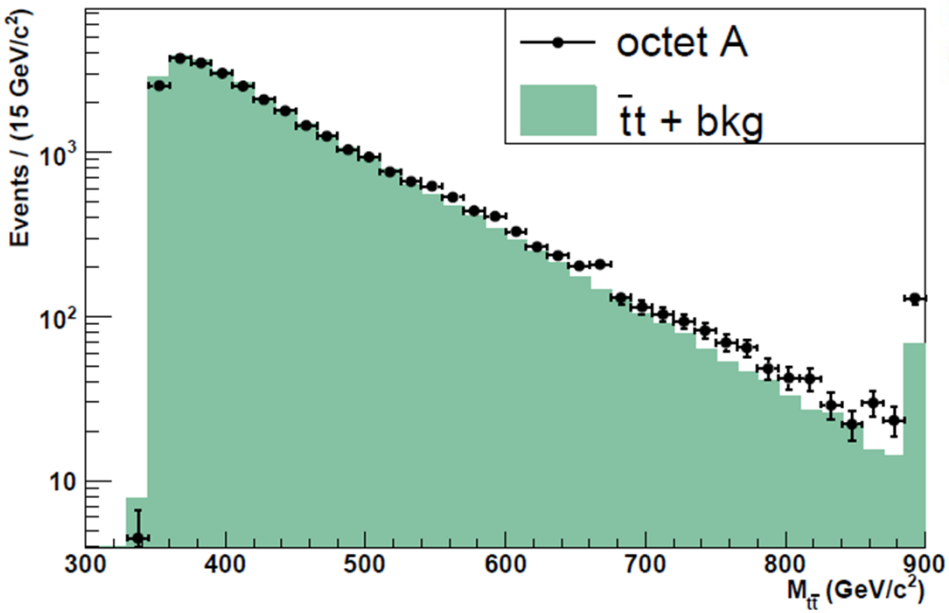


FIG. 6 (color online). Differential cross sections as a function of $M_{t\bar{t}}$ with $\mu_r = \mu_f = m_t$. Here "QCD Born" and "QCD NLO" represent the results in the SM at leading order and next-to-leading order in QCD. "QCD Born + Z' Born" and "QCD NLO + Z' NLO" stand for the predictions in FVZM up to $\mathcal{O}(\alpha_X^2)$ and $\mathcal{O}(\alpha_s^2\alpha_X)$, respectively [cf. Eqs. (2) and (4)].

Why old new physics does not work?

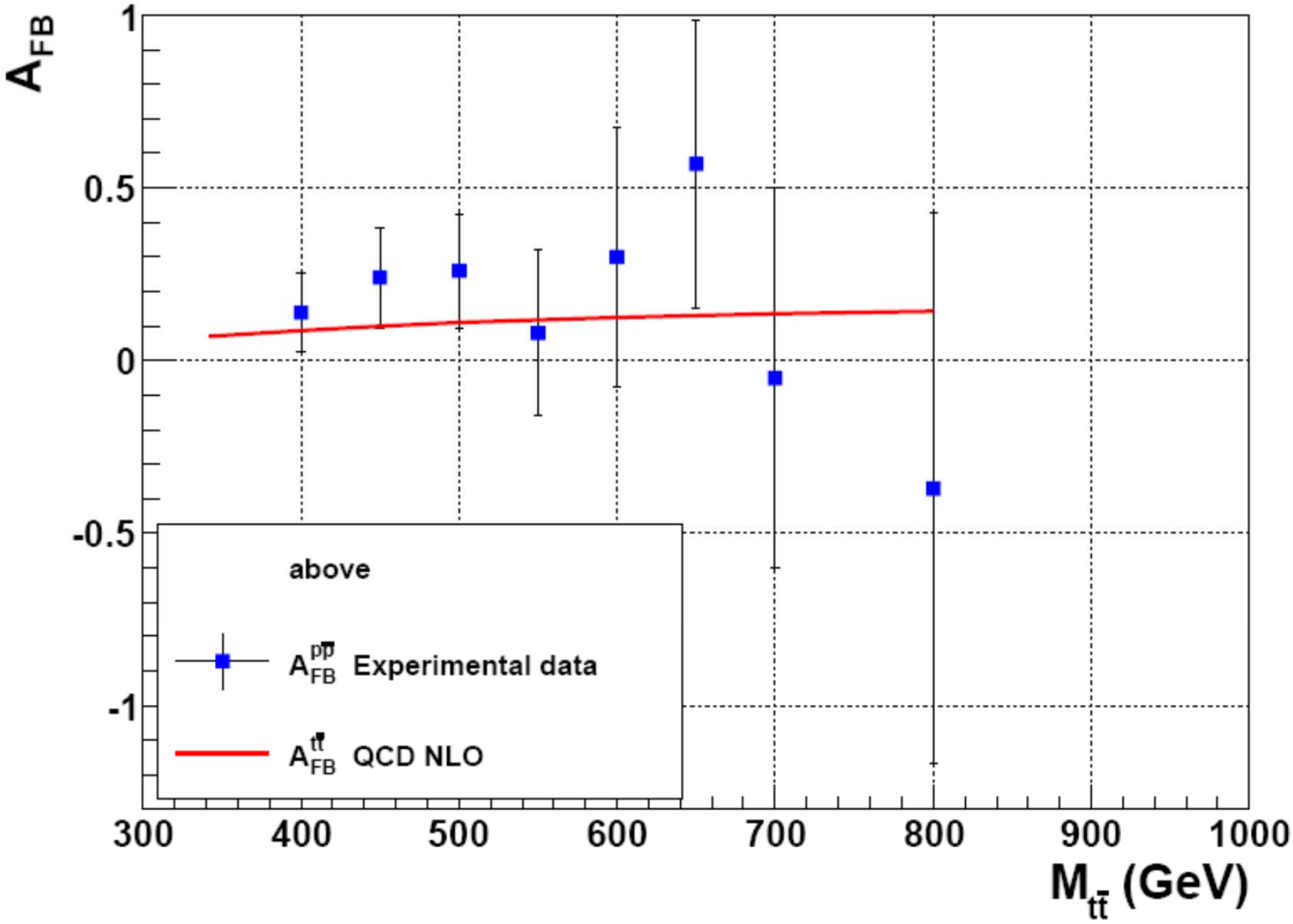
- T-channel new physics: distort shape and large same-sign top production
- S-channel (heavy) axial-gluon, affect distribution at high M ttbar

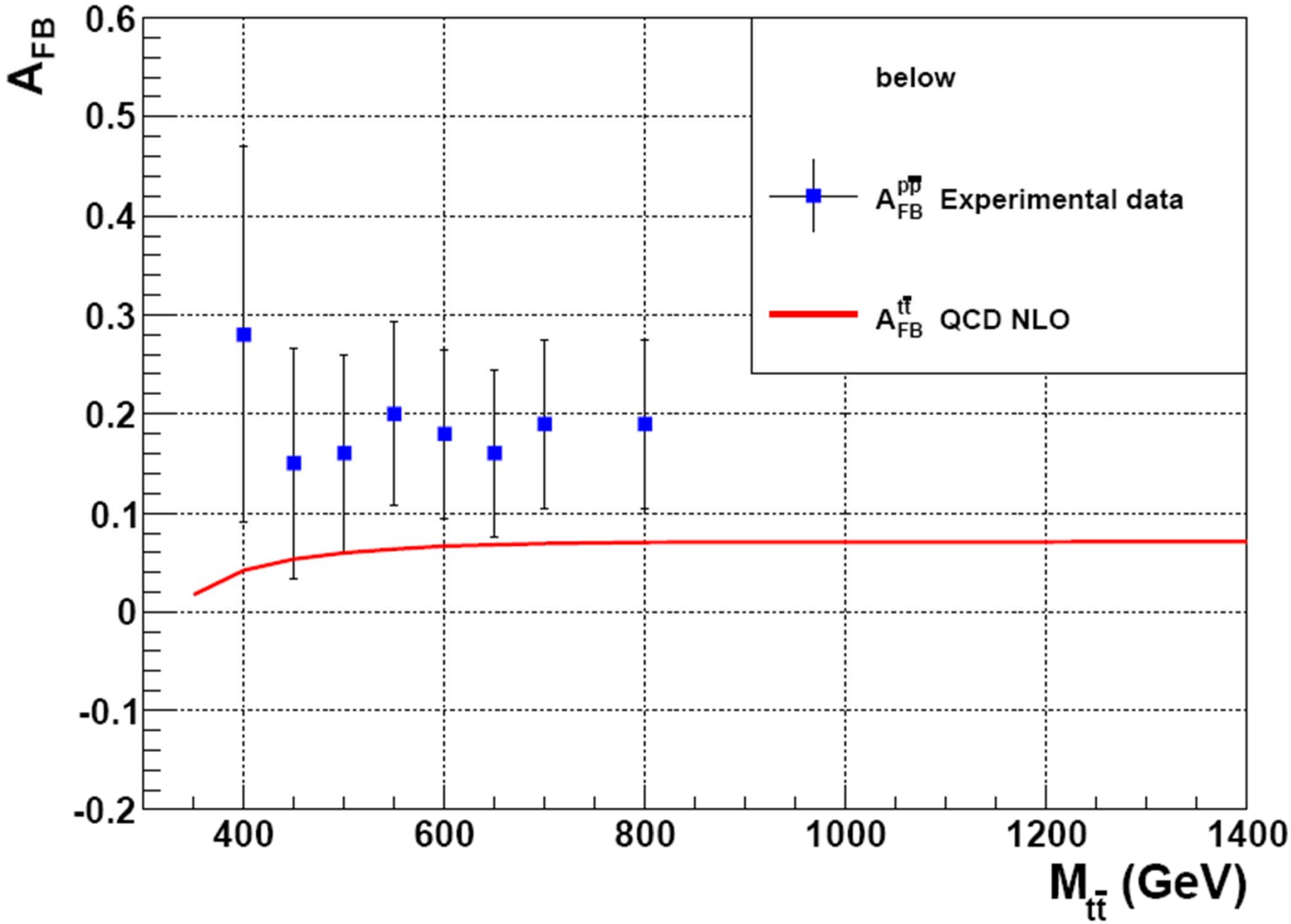


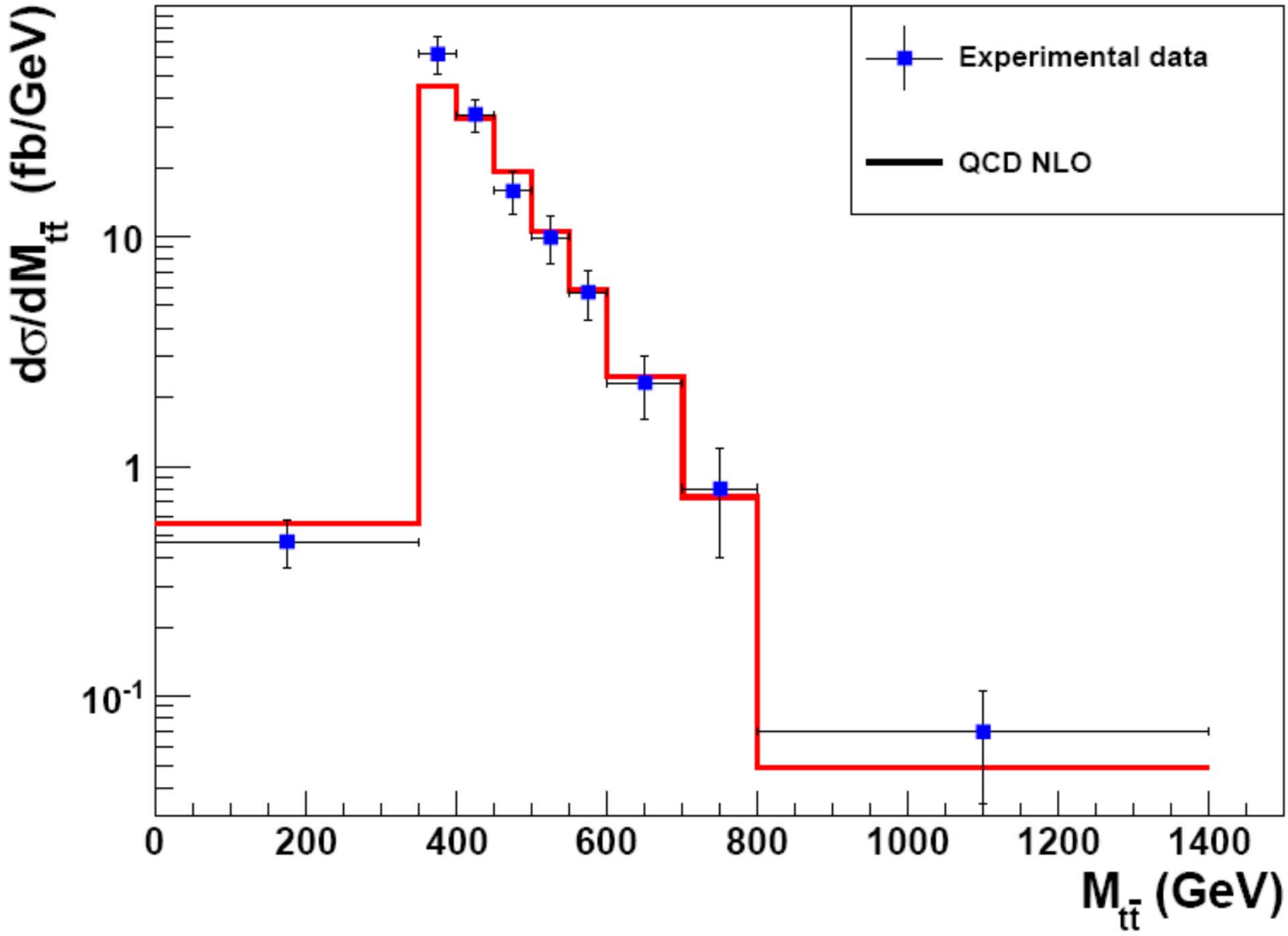
the data [26]. The sample called OctetA, with couplings $g_V = 0$, $g_A(q) = 3/2$, $g_A(t) = -3/2$, and mass $M_G = 2.0$ TeV/c^2, has parton level asymmetries of $A^{p\bar{p}} = 0.110$ and

Totally new idea is indispensable!

Data again

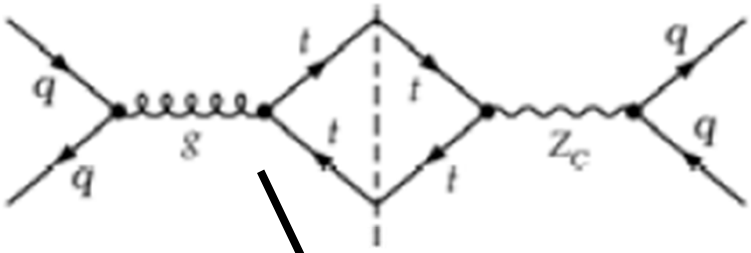

A_{FB}
1
0.5
0
-0.5
-1
300
400
500
600
700
800
900
1000
$M_{t\bar{t}}$ (GeV)
above
$A_{FB}^{p\bar{p}}$ Experimental data
$A_{FB}^{t\bar{t}}$ QCD NLO

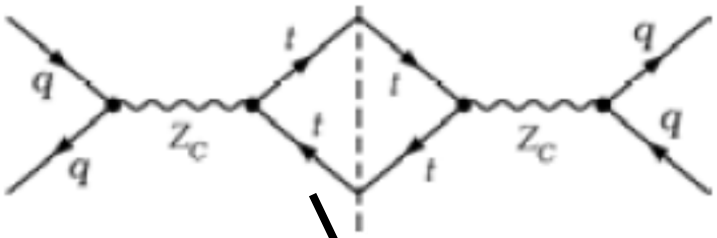

below
$A_{FB}^{p\bar{p}}$ Experimental data
$A_{FB}^{t\bar{t}}$ QCD NLO
A_{FB}
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
400
600
800
1000
1200
1400
$M_{t\bar{t}}$ (GeV)


Experimental data
QCD NLO
dσ/dM$_{t\bar{t}}$ (fb/GeV)
10
1
10^{-1}
0
200
400
600
800
1000
1200
1400
M$_{t\bar{t}}$ (GeV)

Phenomenological model with Color-Octet Vector Boson (Zc)

- Color-octet to get interference with QCD contribution, which indues the measured A_fb
- Light, without conflict with top-pair total and differential cross sections
- Coupling with light quark g_q is less than that of top quark g_t, evading di-jet measurements





$$\sum_{Color,Spin} |M|^2 = \frac{C_A C_F}{2}\{4g_s^4(1+c^2+4m^2)$$

$$+\boxed{\frac{8g_s^2\hat{s}(\hat{s}-M_G^2)}{(\hat{s}-M_G^2)^2+M_G^2\Gamma_G^2}[g_V^q g_V^t(1+c^2+4m^2)+2g_A^q g_A^t c]}+\frac{4\hat{s}^2}{(\hat{s}-M_G^2)^2+M_G^2\Gamma_G^2}\times$$

$$[((g_V^q)^2+(g_A^q)^2)\times((g_V^t)^2(1+c^2+4m^2)+(g_A^t)^2(1+c^2-4m^2))+8g_V^q g_A^q g_V^t g_A^t c]\}, \tag{2}$$

where $m = m_t/\sqrt{\hat{s}}$, $\beta = \sqrt{1-4m^2}$,$c = \beta\cos\theta$ and $g_V^{q(t)}/g_A^{q(t)}$ are vector- and axial-vector couplings among light quarks (top) and Z_c. Here the terms at rhs represent QCD am-

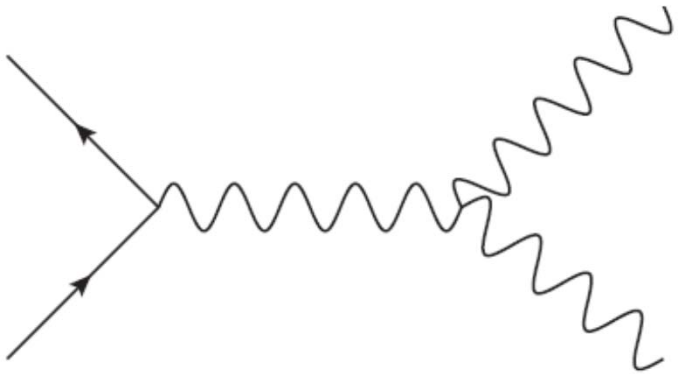
Why axial-vector coupling?

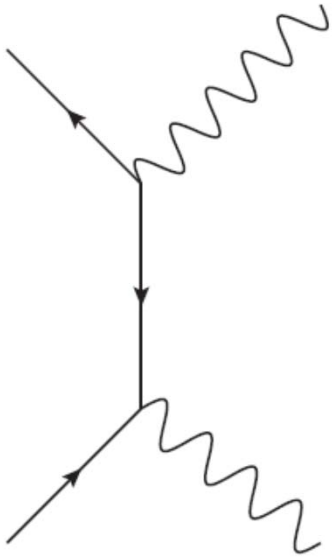
stood as following. If taking the more generic coupling of Z_C as $(g_V\gamma^\mu + g_A\gamma^\mu\gamma^5)$ in the beginning, we find that g_V has to be much smaller than g_A in order to account for $\delta\sigma$ and $\delta\sigma_A$ simultaneously. The underlying reason is very simple. The g_V contributes to the cross section which is independent on β, while g_A contributes to asymmetric cross section which is proportional to β (cf. Eq. 3). For $M_{t\bar{t}}$ in 350-400 GeV, β is small, therefor g_V has to be much smaller than g_A in order not to contribute much more cross section than that of asymmetric one. It is the observed $\delta\sigma$ and $\delta\sigma_A$ that fix the coupling g_V much less than g_A.

Di-jet+e/mu+Et-missing

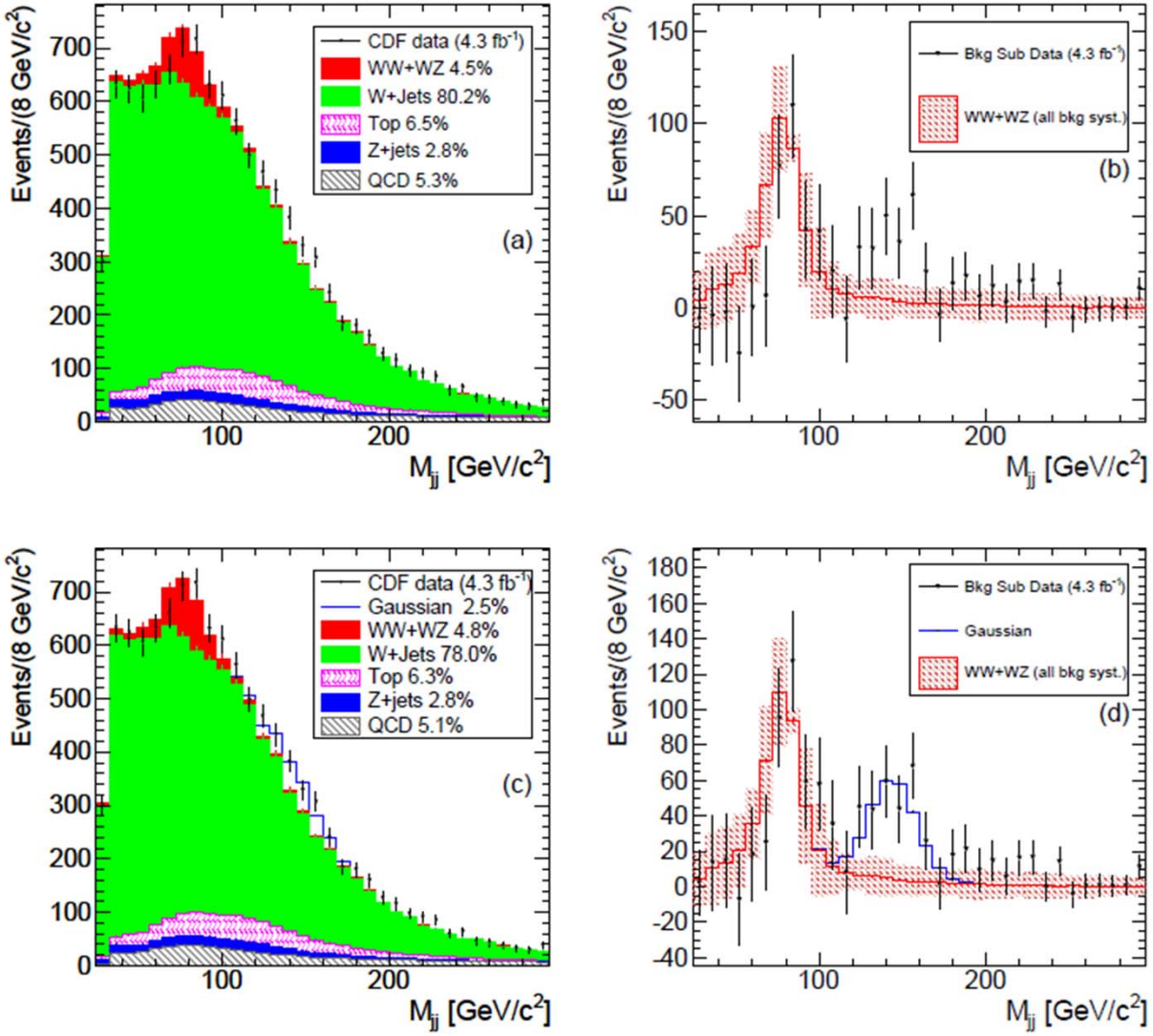
CDF, PRL106,171801(2011), aXiv: 1104:0699

- PP-bar ->W W +WZ
- W-> e/mu+Et-missing, W/Z->jj
- 4.3/fb (2011)





Bump?


Events/(8 GeV/c²)
CDF data (4.3 fb⁻¹)
WW+WZ 4.5%
W+Jets 80.2%
Top 6.5%
Z+jets 2.8%
QCD 5.3%
(a)
M_jj [GeV/c²]
Bkg Sub Data (4.3 fb⁻¹)
WW+WZ (all bkg syst.)
(b)
CDF data (4.3 fb⁻¹)
Gaussian 2.5%
WW+WZ 4.8%
W+Jets 78.0%
Top 6.3%
Z+jets 2.8%
QCD 5.1%
(c)
Bkg Sub Data (4.3 fb⁻¹)
Gaussian
WW+WZ (all bkg syst.)
(d)

Kenneth Lane

“I haven‘t been sleeping very well for the past six months.”

---<New Scientists>

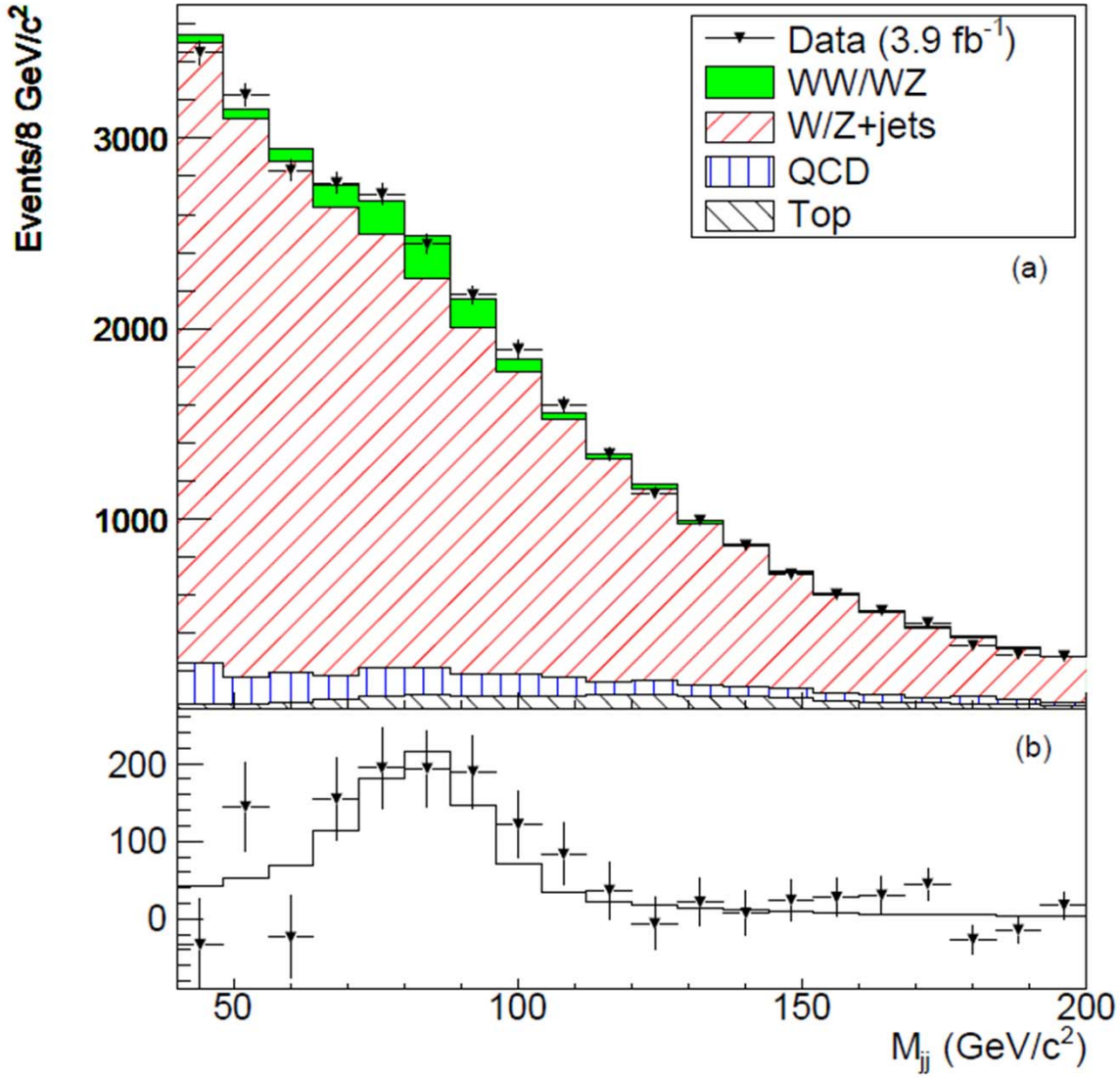
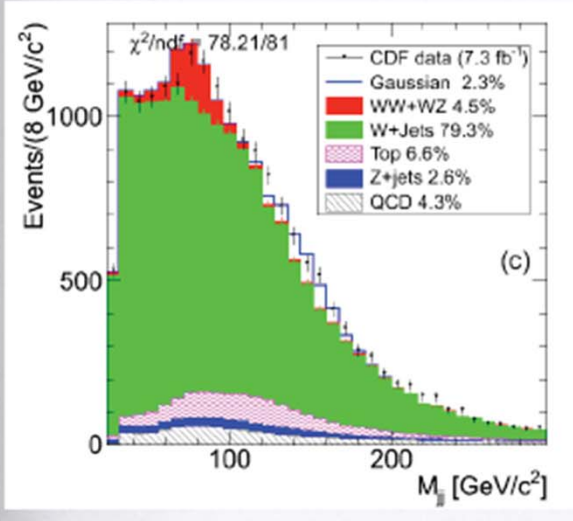
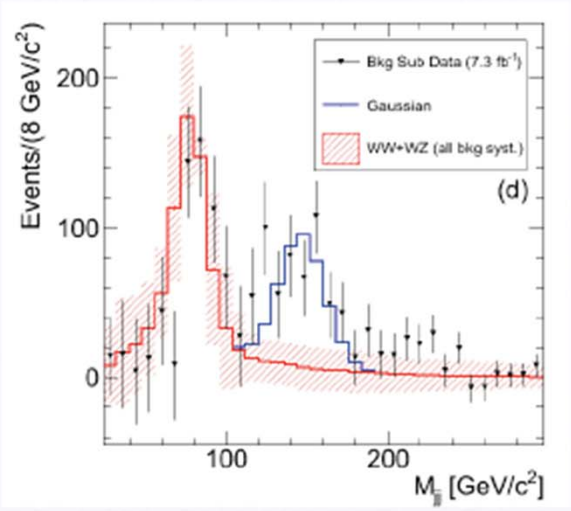


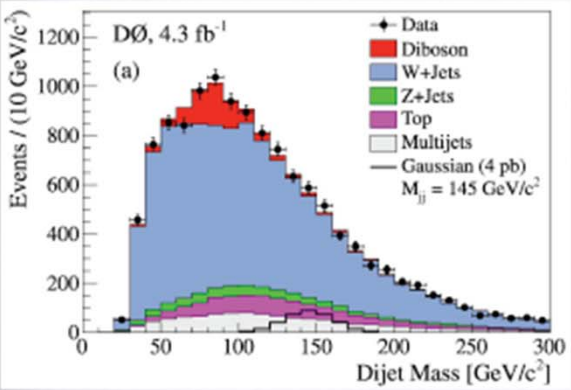
FIG. 1: Dijet invariant mass distribution of reconstructed $W/Z \rightarrow jj$ candidates compared to the fitted signal and background components (a), and for the corresponding background subtracted distribution (b).

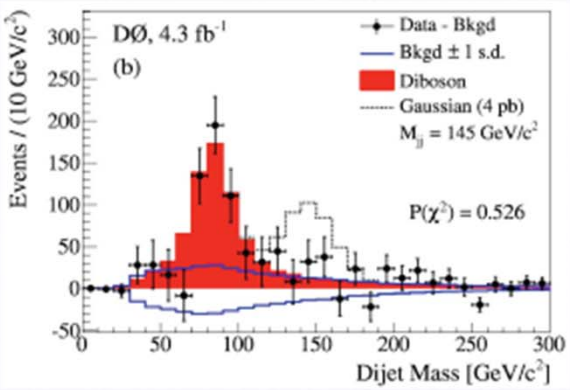
Dijet Resonance in W+jets





Updated to 7.3 fb^{-1}, the significance of the bump is 4.76



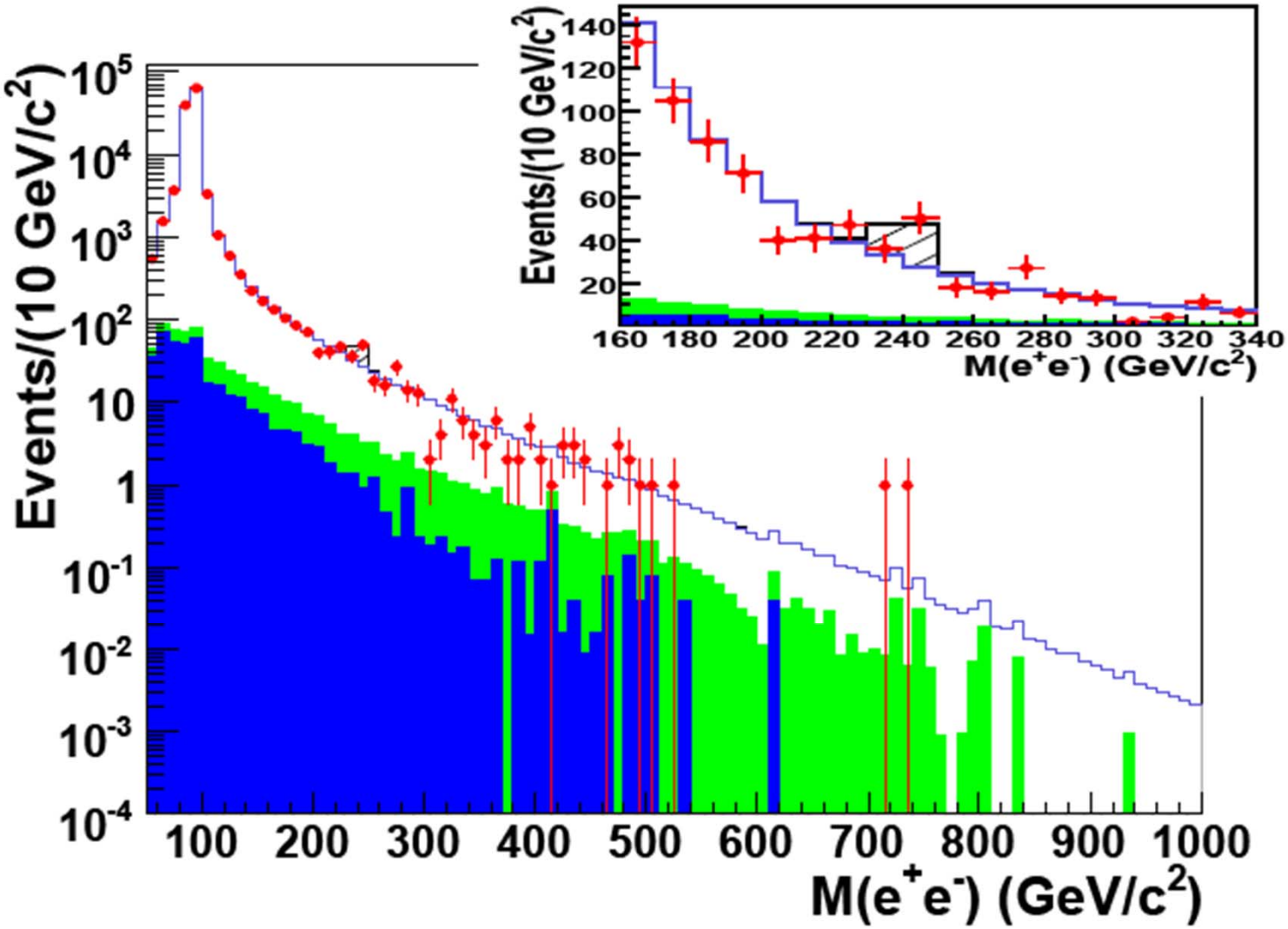


DØ's result doesn't favor such a resonance.

Task forces are commanded between CDF and DØ, and internally in these collaborations.

Origin of di-jet

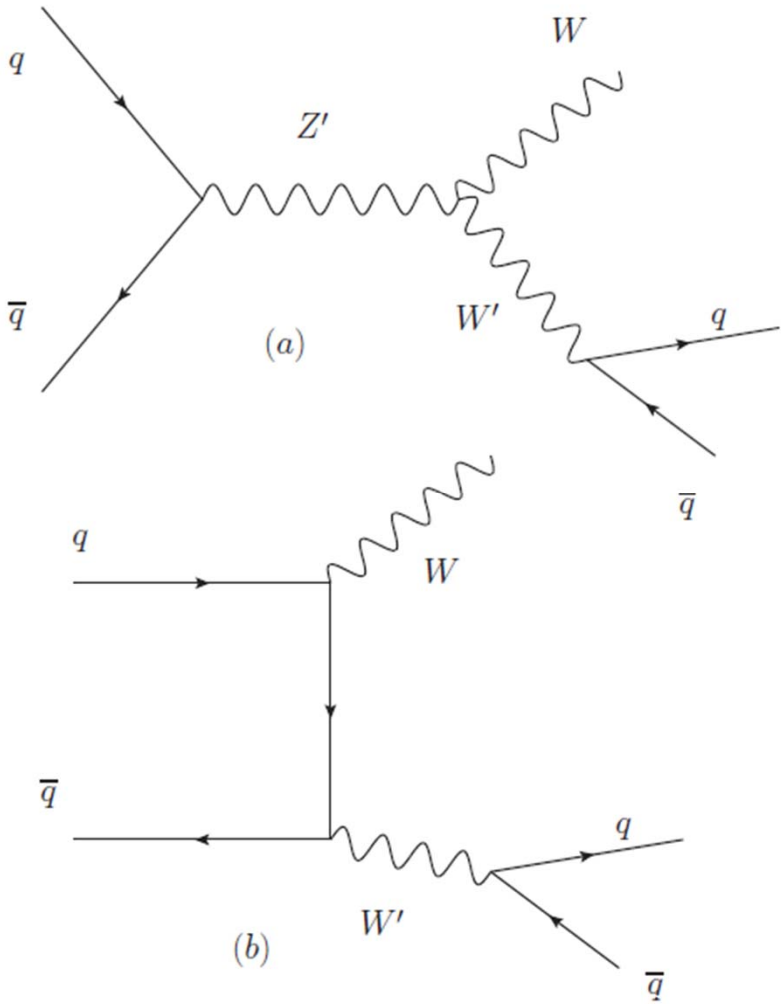
- “Fluctuations obviously”
- “Unclean subtraction of single top events”
- BSM, new particle should be lepton-phobia, due to the experimental constraints
- Color-octet Zc, not couple with lepton naturally



CDF 2.5/fb, arXiv: 0810.2059

O(100 GeV) Deci-weak Z' & W'?

arXiv:1104.1161



As shown in Ref. [6], the cross section for e^+e^- bump production is

$$\sigma(p\bar{p} \to Z')Br(Z' \to e^+e^-) \simeq 42\ fb \tag{2}$$

with $m_{Z'} = 240GeV$. Based on the subtraction figure in [9], the extra contribution can be read roughly

$$\sigma(p\bar{p} \to Z')Br(Z' \to WW')Br(W' \to jj) \sim \mathcal{O}(1\ pb) \tag{3}$$

with $m_{W'} = 120 - 160GeV$. In order to fill the gap between e^+e^- and di-jet productions, we require

$$\frac{Br(Z' \to WW')Br(W' \to jj)}{Br(Z' \to e^+e^-)} \gg 1. \tag{4}$$

In principle, we don't know yet the structure and coupling strength of SM fermions with W'/Z', as well as $W - Z' - W'$. From Eq. 4, it is natural to require that couplings of Z' and leptons are less than those with quarks and gauge bosons. In fact the couplings among leptons and extra gauge bosons are severely constrained due to the precise measurements by LEP and other experiments. Therefore we focus on the couplings among quarks and extra gauge bosons. For simplicity, we choose the coupling structure the same as that of SM, but with an additional suppression factor $\kappa_{Z'f\bar{f}}$, $\kappa_{W'q\bar{q}}$ and $\kappa_{W-Z'-W'}$ respectively.

In order to account for the CDF data, we simulate the di-jet invariant distribution arising from WW/WZ as well as $W'W$ production with $m_{Z'} = 240$ GeV and $m_{W'} = 150$ GeV respectively. For the latter case there are two Feynman diagrams at tree level as depicted in Fig. 1.

We choose the benchmark parameter set as $\kappa_{Z'f\bar{f}} = 0.07$, $\kappa_{W'q\bar{q}} = 0.3$ and $\kappa_{W-Z'-W'} = 0.1$, which do not contradict with other measurements [6, 10, 11]. The di-jet invariant

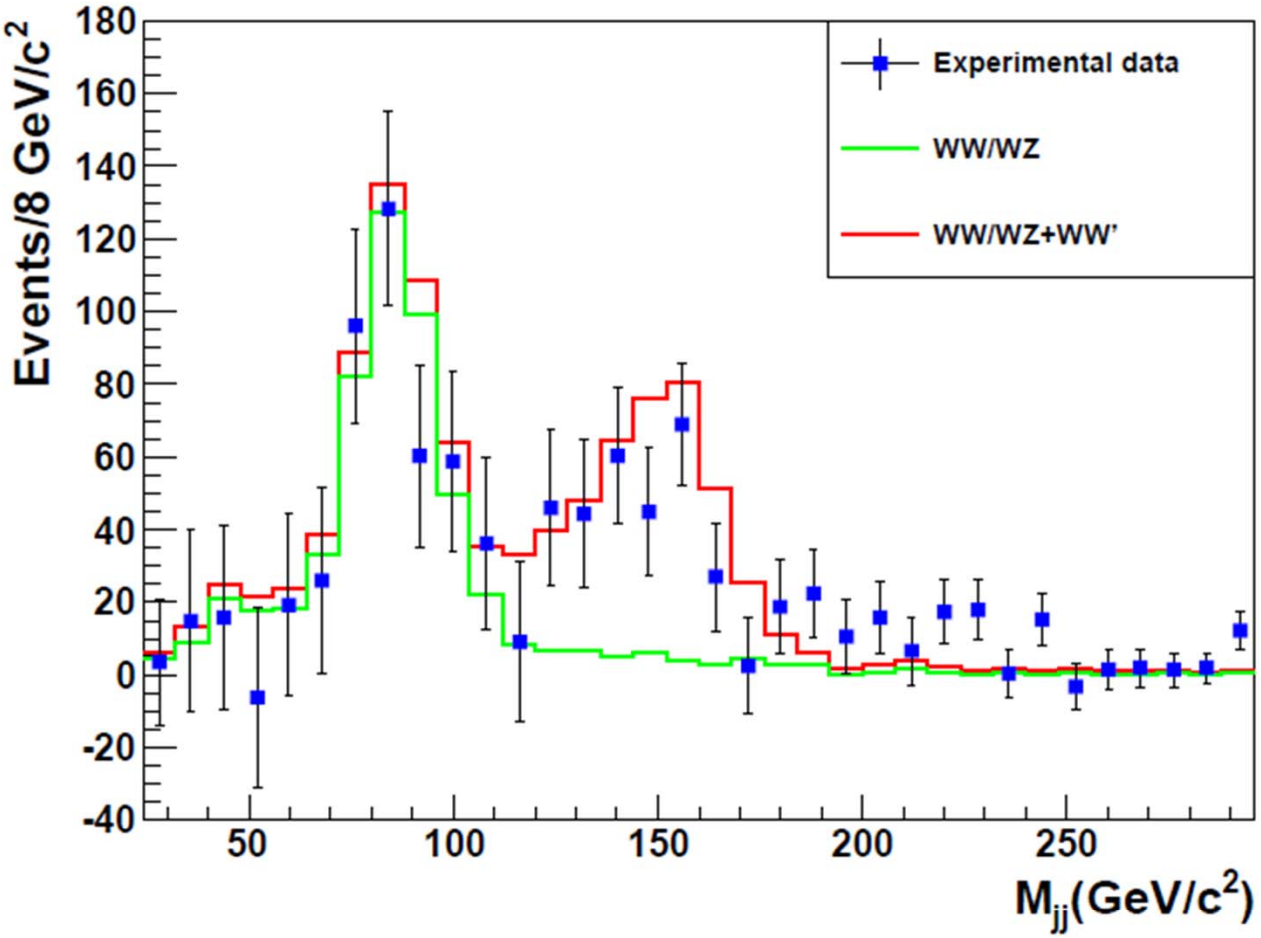


FIG. 2: Di-jet invariant mass distribution at Tevatron with integrated luminosity $\mathscr{L} = 4.3\ fb^{-1}$. Data is taken from Ref. [9].

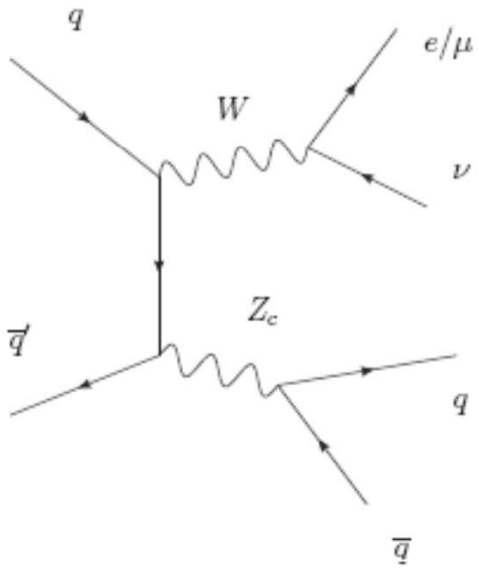
Color Octet Axial-Vector Zc

arXiv:1104.1917

$$p\overline{p} \to q\overline{q}' \to W(\to e/\mu + \nu) + Z_c(\to q\overline{q}),$$

The interaction Lagrangian of Z_c and quarks can be written as

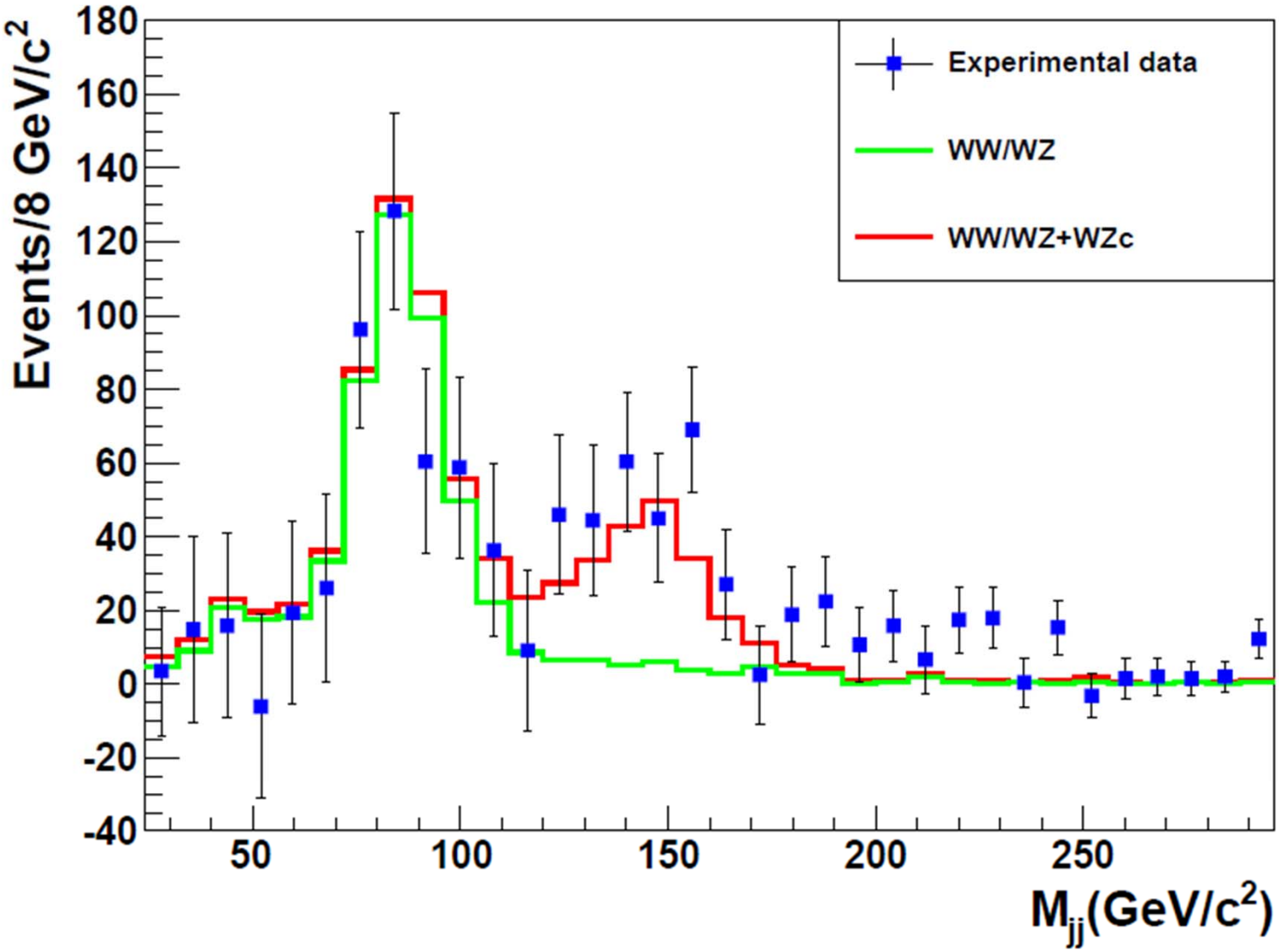
$$\mathscr{L} = i\overline{q}\left(g_V + g_A\gamma_5\right)\gamma_\mu T^a q Z_c^{\mu,a} + h.c.$$



Q:Why light Zc viable?
A: Due to QCD backgrounds

1. Jet is usually not measured so well as that of charged leptons and the di-jet mass peak can be buried by large mass resolution if the Z_c contribution is less than the huge QCD backgrounds. As the consequence, the Tevatron constraints on new particle less than 200 GeV are quite weak [9]. The UA2 experiment can only effectively constrain such light particle with the coupling strength larger than $\mathscr{O}(g_s)$. The required parameter to account for the new bump is only $0.2g_s$, as shown below, which is permitted by direct searches of past experiments.

2. The shapes and magnitudes of P_T^j and m_{jj} after including the Z_c contributions are not distorted severely, especially at high energy region (much larger than m_{Z_c}). As such the quark composite scale limit is *not* applicable to Z_c.



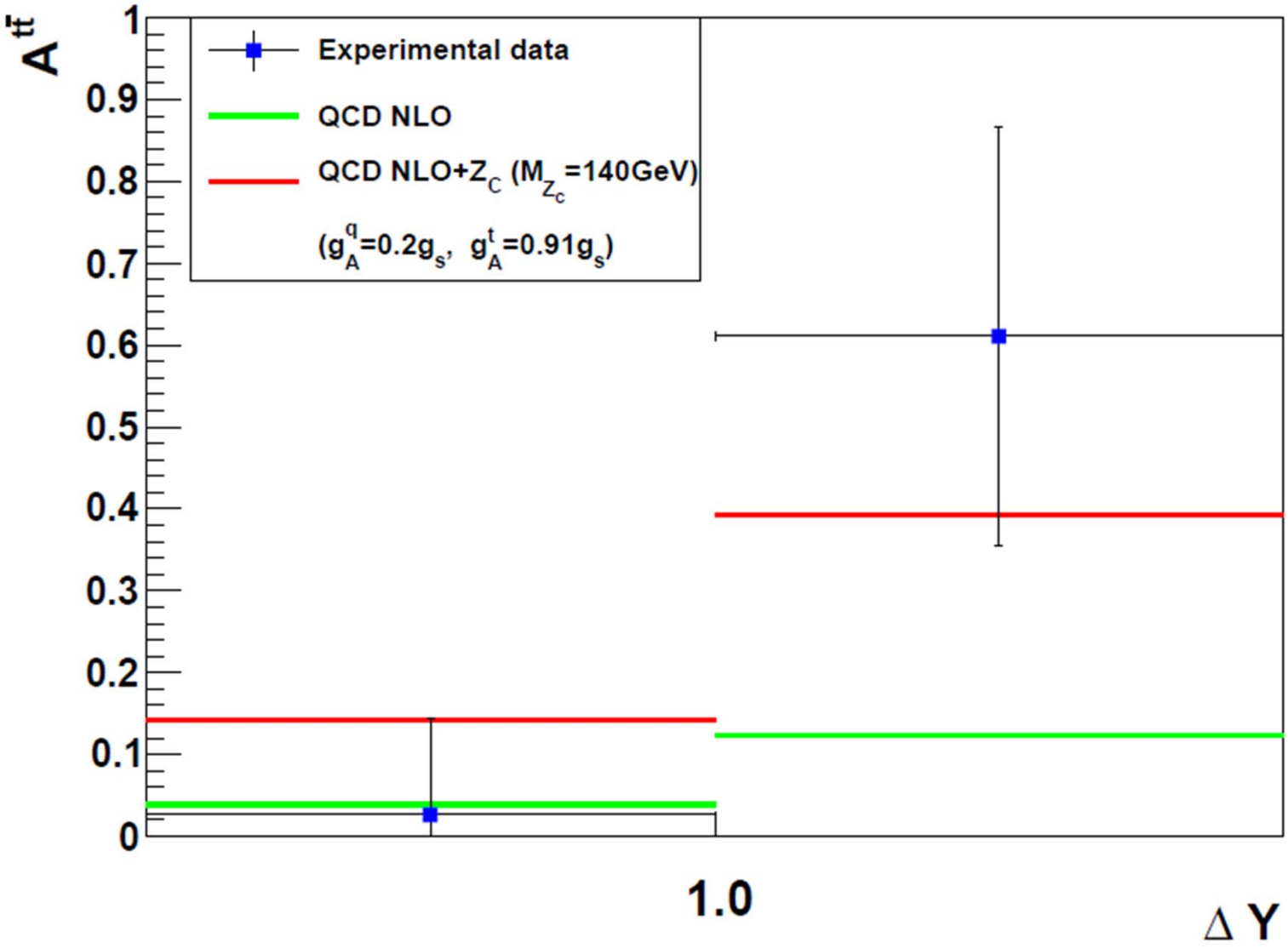
$g_V = 0$ and $g_A = 0.2\ g_s$:

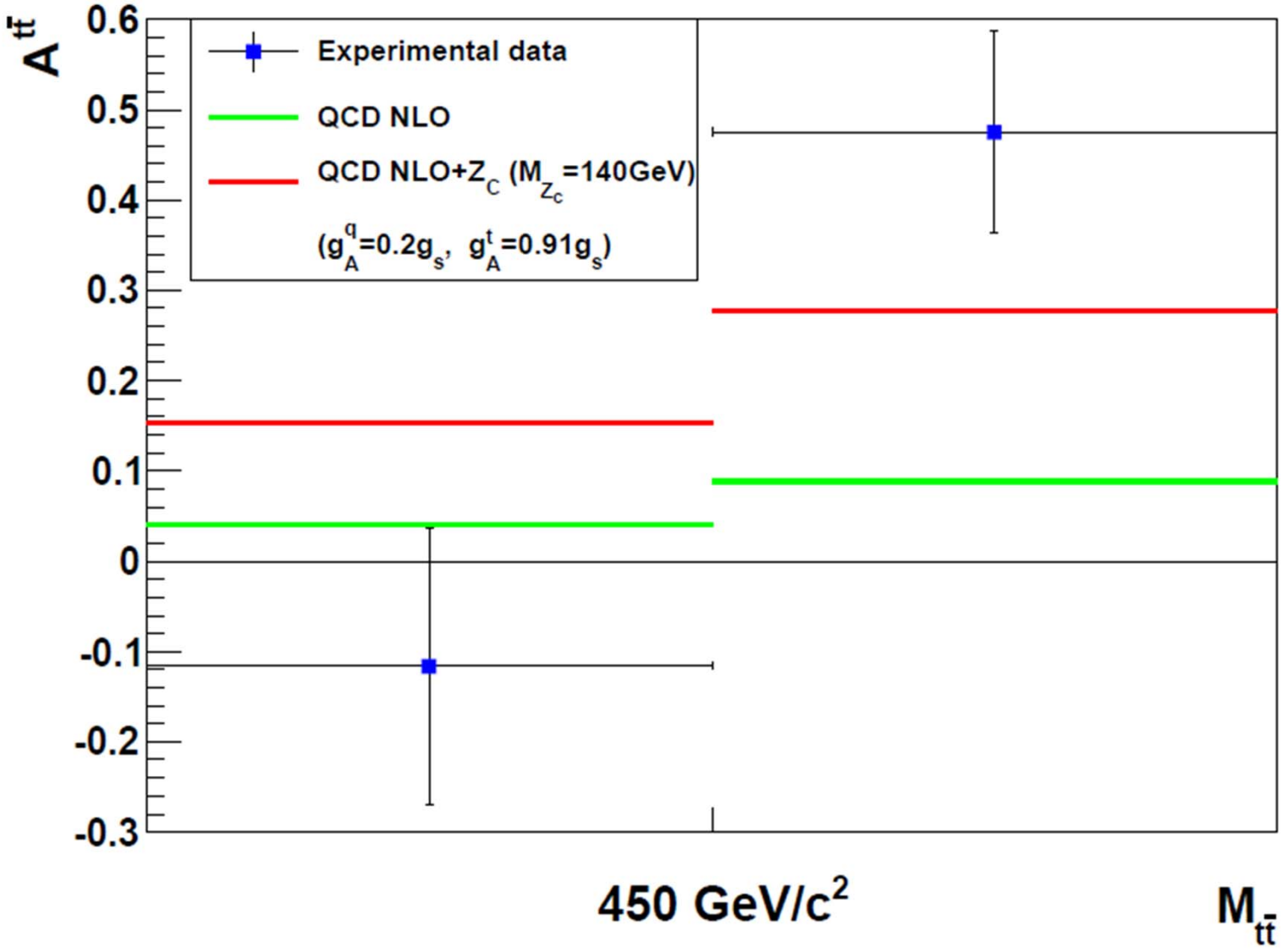
at Tevatron. Since the choice of $g_V = 0$ affects $d\sigma/dM_{t\bar{t}}$ insignificantly, we don't show the numerical results here. Instead we will focus on the A^t_{FB} as functions of Δy and $M_{t\bar{t}}$.

The numerical investigation indicated that if we choose $g^t_A = g^q_A$, we can't obtain the observed A^t_{FB}. Instead if we choose

$$g^t_A/g^q_A = 4.5,$$

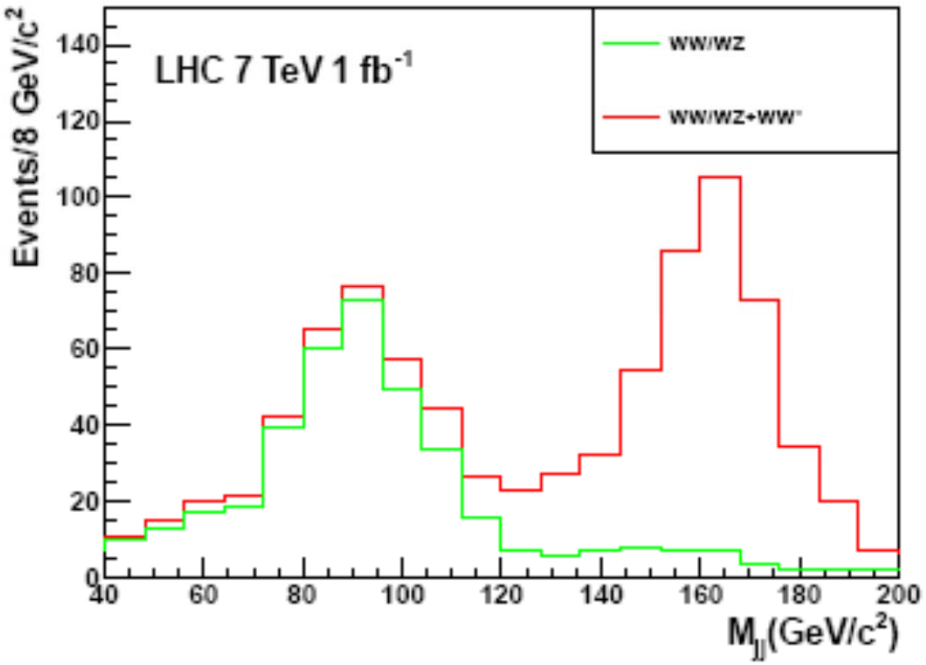
$A^t_{FB} \simeq 20\%$. For comparison the experimental measurement is $A^t_{FB} \simeq 15.8\% \pm 7.5\%$. In


$A^{t\bar{t}}$
Experimental data
QCD NLO
QCD NLO+Z_C (M_{Z_c}=140GeV)
(g_A^q=0.2g_s, g_A^t=0.91g_s)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.0
Δ Y


$A^{t\bar{t}}$
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Experimental data
QCD NLO
QCD NLO+Z_C (M_{Z_c}=140GeV)
(g_A^q=0.2g_s, g_A^t=0.91g_s)
450 GeV/c^2
$M_{t\bar{t}}$

Zc at LHC

- W(->l nu)jj + gamma jj signal
- Zc Zc -> 4j
- PP->t tbar asymmetry measurement
- etc



Pause

- Extra Color-Octet Vector Boson Zc works well, though not perfect for current top forward-backward asymmetry measurement (with large uncertainty)!
- Properties of Z_c: (1) light (120-160 GeV); (2) axial-vector coupling with quarks, g_t > g_q (same sign)
- Implication (1): top condensate? If true, associated partners? Underlying dynamics?
- Implication (2): related with EWSB?

LHC: Top Factory

- How to examine the same higher-order effects?
- Necessary measurement before claim of new physics beyond the SM
- However, LHC is proton-proton collider: no preferred direction

A way out: Central FBA

$$A_C = \frac{\sigma_t(|Y| \leq Y_C) - \sigma_{\bar{t}}(|Y| \leq Y_C)}{\sigma_t(|Y| \leq Y_C) + \sigma_{\bar{t}}(|Y| \leq Y_C)}.$$

A_C is defined as the ratio between the difference and the sum of the events of top and anti-top quark in a central region $|Y| < Y_C$ in the laboratory

J. H. Kuhn and G. Rodrigo, Phys. Rev. Lett. **81**, 49 (1998), 9802268.

J. H. Kuhn and G. Rodrigo, Phys. Rev. **D59**, 054017 (1999), 9807420.

O. Antunano, J. H. Kuhn, and G. Rodrigo, Phys. Rev. **D77**, 014003 (2008), 0709.1652.

G. Rodrigo, PoS **RADCOR2007**, 010 (2007), 0803.2992.

P. Ferrario and G. Rodrigo, Phys. Rev. **D78**, 094018 (2008), 0809.3354.

P. Ferrario and G. Rodrigo, (2010), 1006.5593.

Disadvantage of Central FBA

The obvious disadvantage of this definition is that at the LHC, such asymmetry is quite small. The reason is that most of the tt-bar events via gg fusion lies in central region, but they are symmetric.

One-side FBA (1)

- Find the preferred direction!
- Requirements: Examine the same QCD effects!
- LHC does not have the preferred directions in the laboratory rest frame. However except the symmetric gluons, the incoming partons do have preferred direction. Usually the valence quark momentum is larger than that of the sea quark.

One-side FBA (2)

- For example, in u ubar -> t tbar (take u quark's direction as the positive z direction), momentum of u is most probably larger than that of u-bar. Approximately, this will induce the z direction tt-bar total momentum in lab frame Pz > 0.

One-side FBA (3)

- So even in pp rest frame, u ubar -> t tbar can contribute an asymmetric t tbar distribution.
- However, this asymmetry is totally canceled with the opposite direction ubar u -> t tbar events.
- If we observe only one-side t tbar events, i.e. Pz > 0, such asymmetry will be kept.

One-side FBA (4): Definition

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

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

or

$$A_{OFB} = \frac{F_- + B_-}{F_+ + B_+} \equiv \frac{\sigma^A}{\sigma} \qquad (5)$$

with

$$F_\pm = (\sigma(\Delta Y > 0) \pm \sigma(\Delta Y < 0))|_{P^z_{t\bar{t}}>P^z_{cut},M_{t\bar{t}}>M_{cut}} \qquad (6)$$

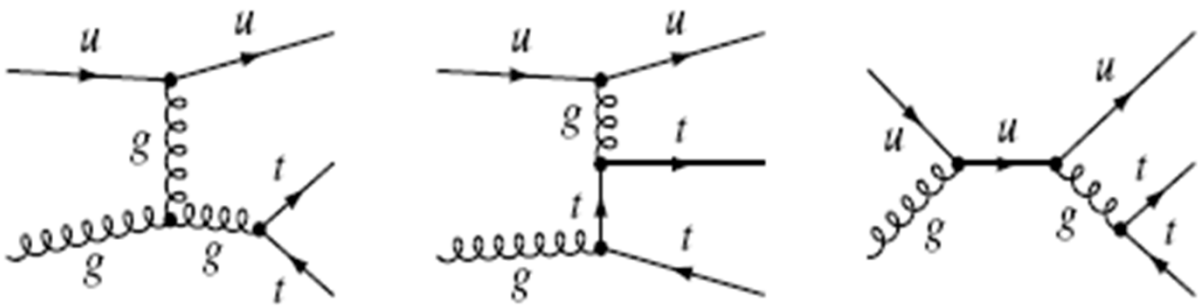
$$B_\pm = (\sigma(\Delta Y < 0) \pm \sigma(\Delta Y > 0))|_{P^z_{t\bar{t}}<-P^z_{cut},M_{t\bar{t}}>M_{cut}}$$

Any comments?

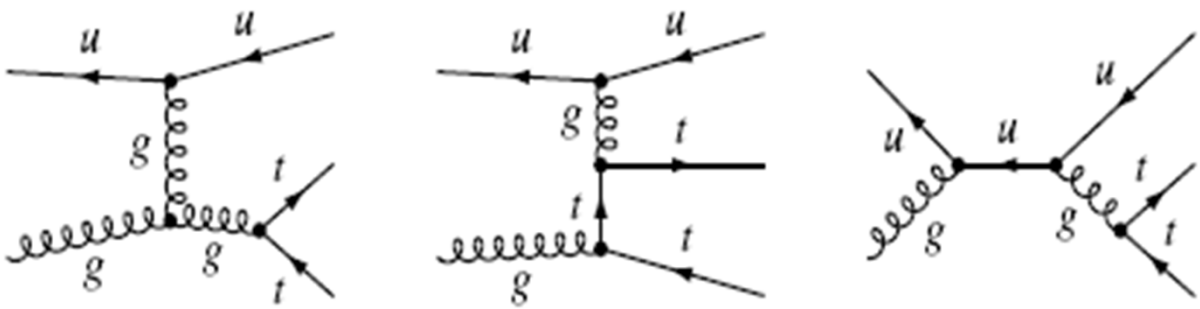
- One may argue that determination of the momentum in beam line direction may has problem, especially when one neutrino is missing when using the associated charged lepton to trigger the top/anti-top event.
- This issue can be solved by requiring invariant mass of the neutrino and charged lepton just equal to that of the W boson. So z direction top pair momentum is still a measurable quantity

G. Strycker *et al.*, CDFnote **9724** (2009).

Extra diagrams at LHC

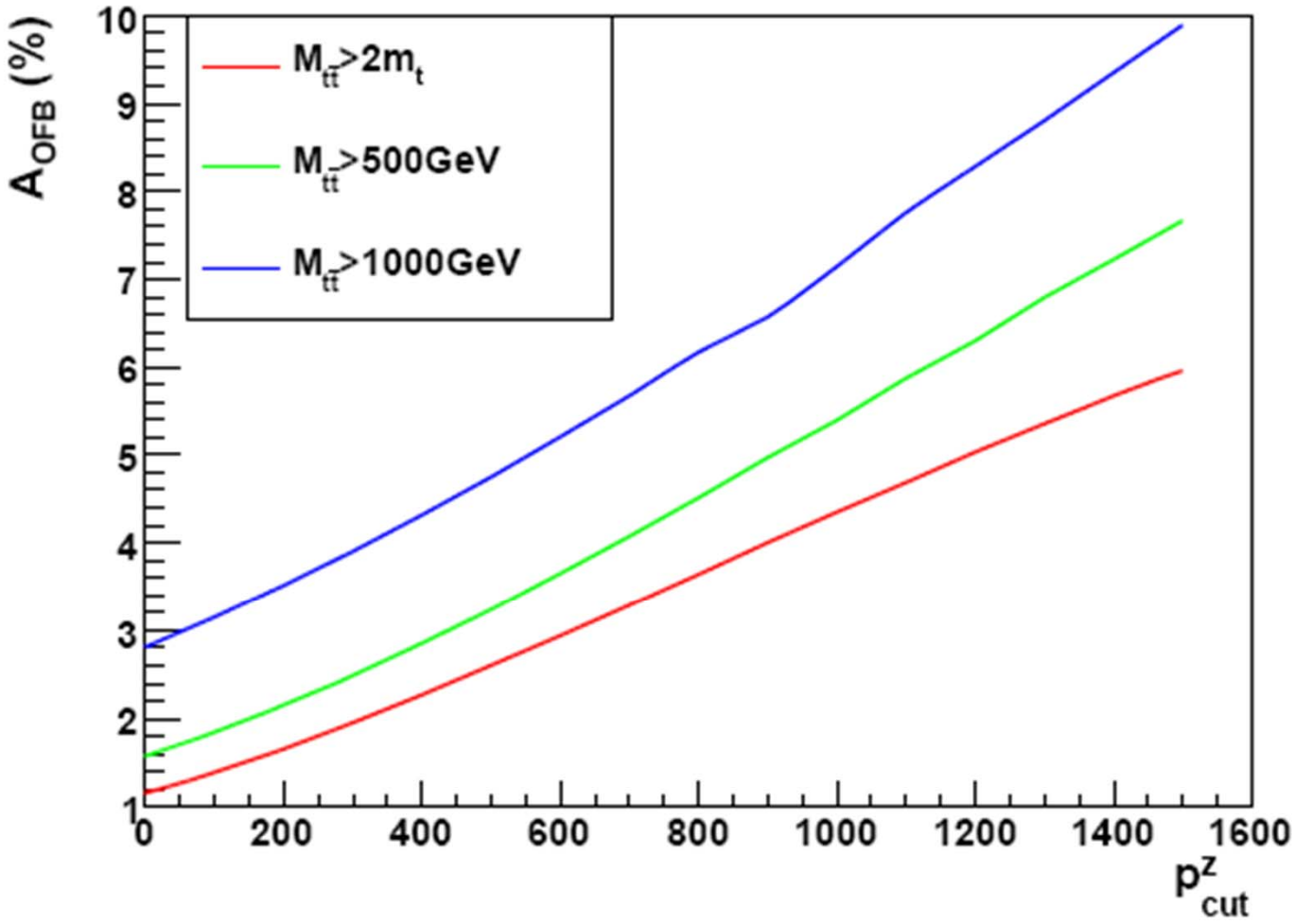


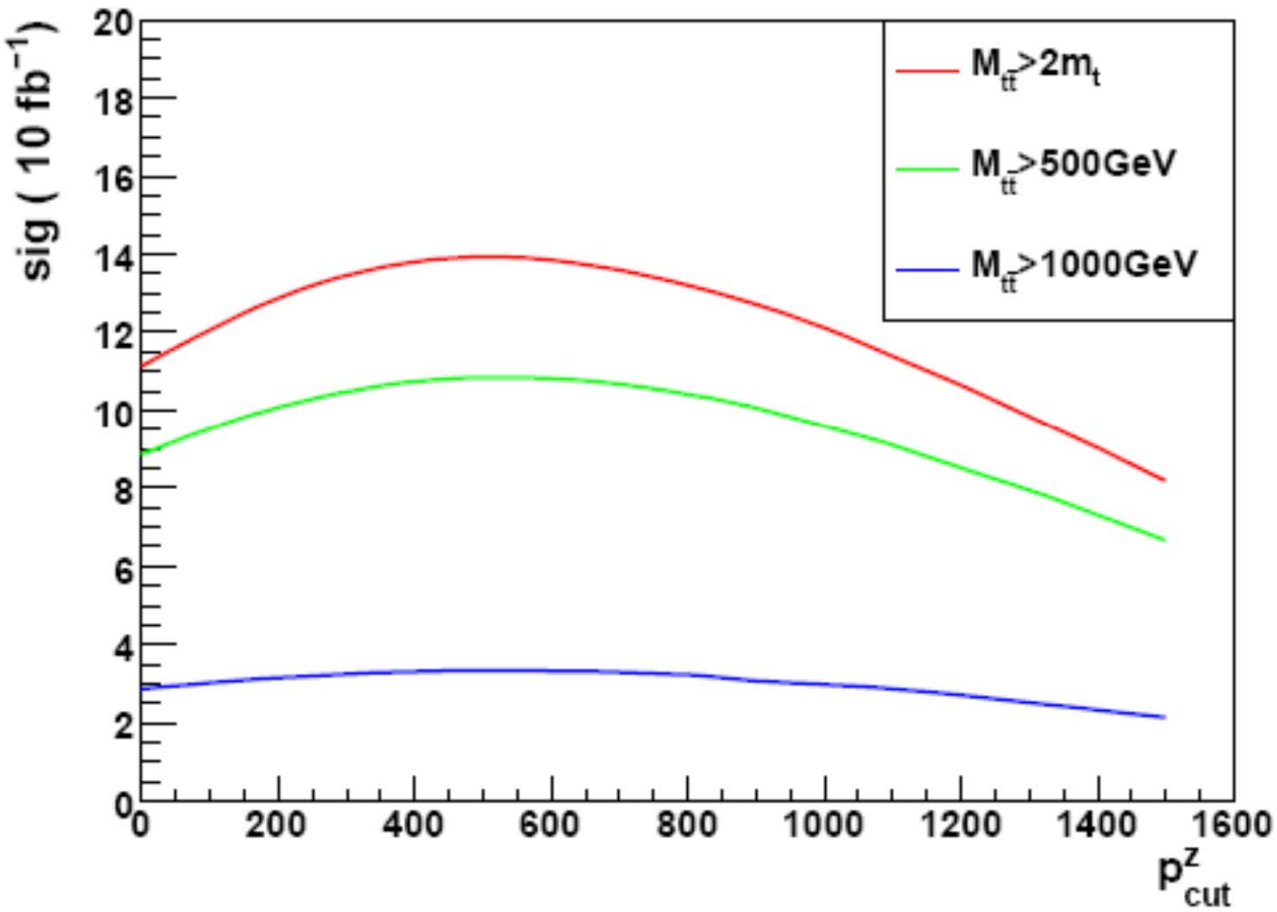
(a)



(b)

Numerical results at 7TeV LHC

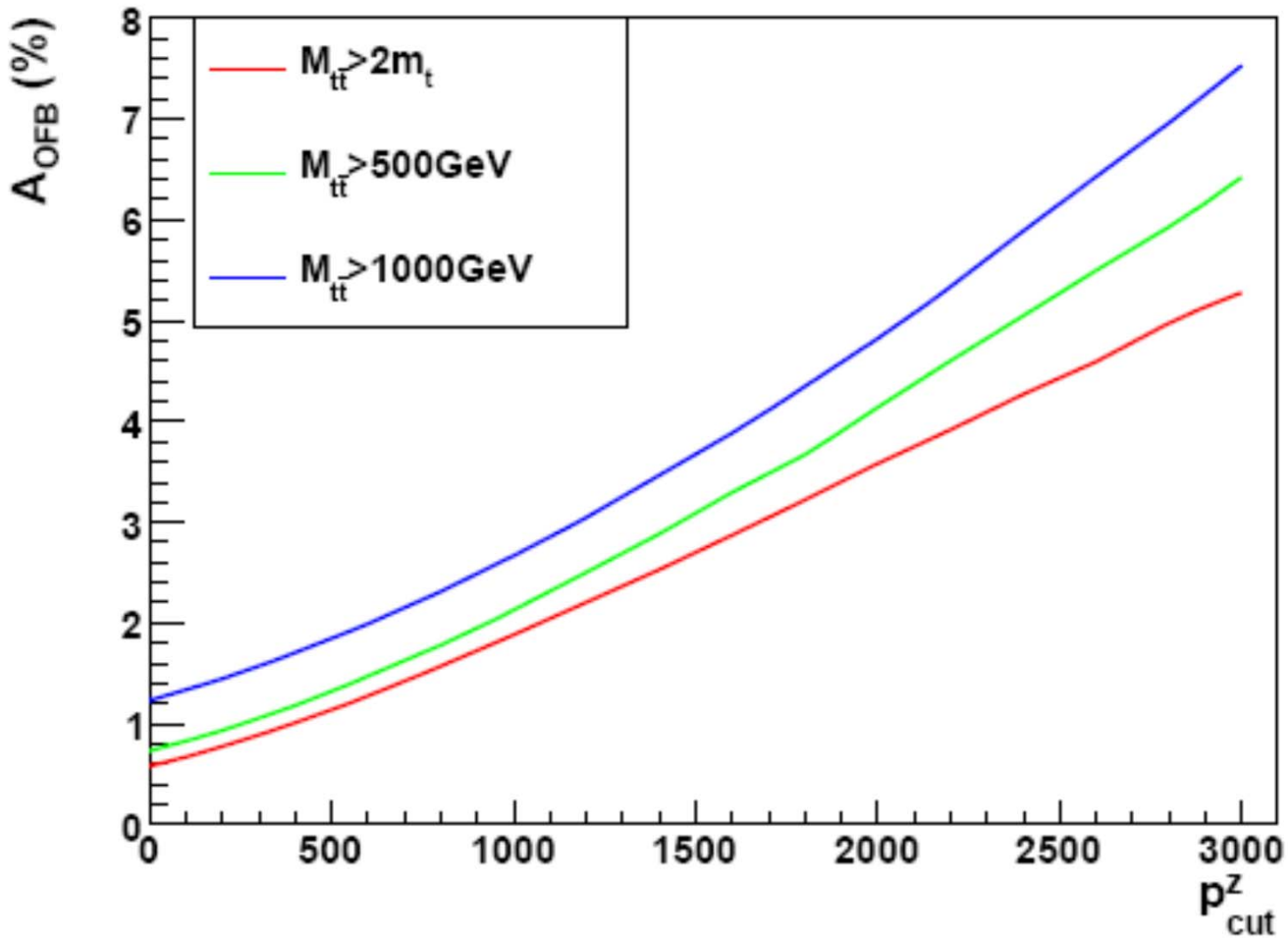


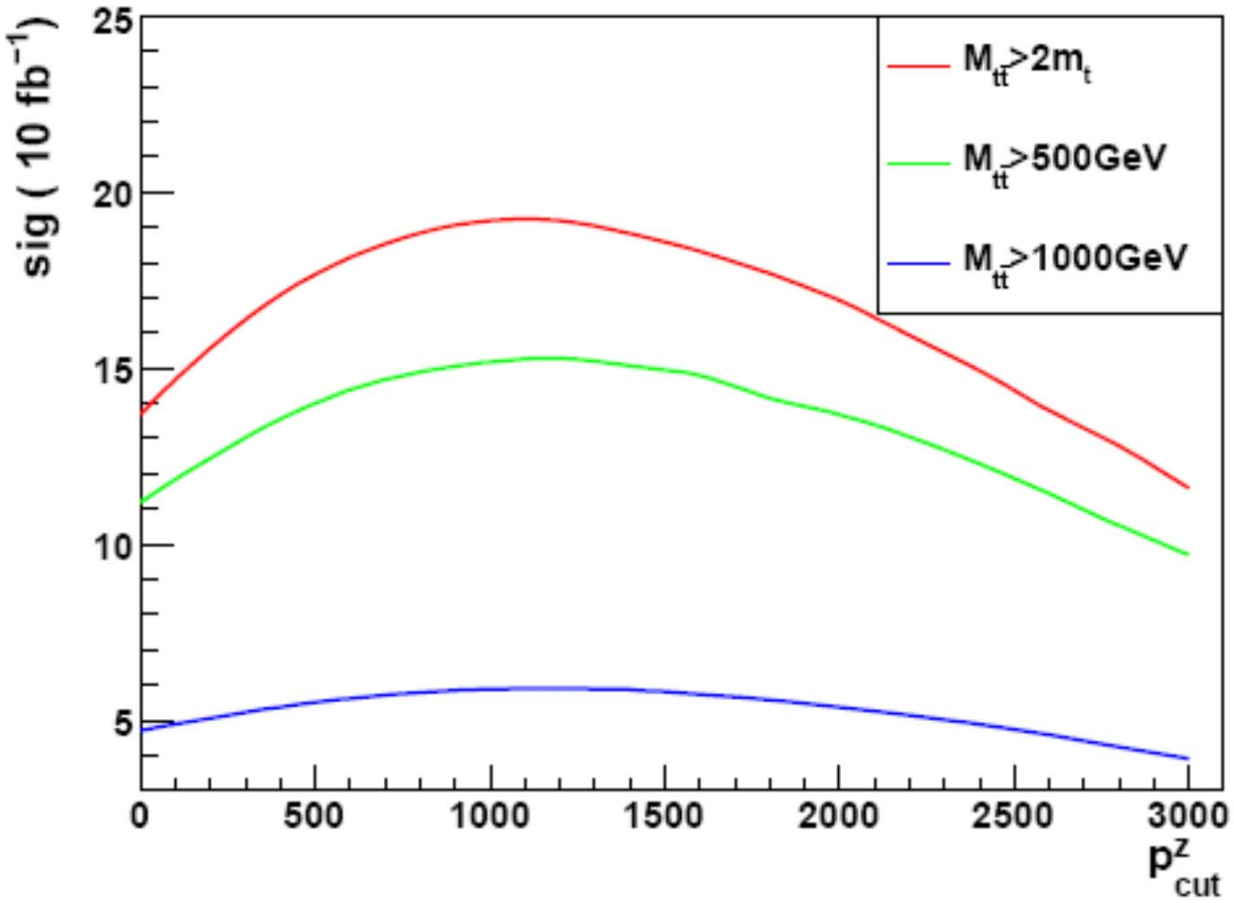


$$sig = \sqrt{\mathscr{L}}\sigma^A / \sqrt{\sigma}$$

With luminosity 10 fb-1

Numerical results at 14TeV LHC




sig (10 fb^{-1})
25
20
15
10
5
0
500
1000
1500
2000
2500
3000
p^z_{cut}
M_{tt}>2m_t
M_{tt}>500GeV
M_{tt}>1000GeV

Pause

- Soft gluon resummation/higher-order effects can account for FBA at Tevatron? Unlikely!
- New Physics? Too early to conclude! LHC can answer this question!
- Angular distribution is essential to study the nature of top couplings
- One-side FBA at LHC is proposed. Excellent observable to study SM effects and BSM.
- Once preferred direction can be defined, we can further investigate the anomaly of FBA of bottom quark at LEP, for example (next topic).

Edge Charge Asymmetry for Top Pair Production Study

Single or pair?

From the experience of using A_{OFB} and other forward backward asymmetries for top pair production we gradually realized that the varies kinds of top quark forward backward asymmetry can be classified into two categories.

- One category needs **top pair information**, i.e. it needs to know which top and anti-top are pair produced and it also needs to know the momentums of both the top and anti-top. $A_{FB}^{t\bar{t}}$ at Tevatran and A_{RFB} and A_{OFB} at LHC belong to this category.
- The other category needs only **single top information**, i.e. it doesn't need to know which top and anti-top are pair produced and even one of the momentums of the top pair is discarded is permitted. $A_{FB}^{p\bar{p}}$ at Tevatran and A_C at LHC belong to this category.

Semi-leptonical mode for top pair production

The favored detecting channel of top pair production is $t\bar{t} \to bb\,2jl\nu$,

where one of the top/antitop momentum cannot be well reconstructed due to the missing neutrino. So, for the top quark forward backward asymmetry, there is a trade-off between the two categories. The first category has better momentum reconstruction than the second one, while the second category usually has larger asymmetry significance than the first one.

So, even the A_{OFB} we defined has larger asymmetry significance than

the A_C, it has larger momentum uncertainties though.

Supress the symmetric gg contributions

Can we define a new kind of LHC forward backward asymmetry which avoids the top pair momentum reconstruction difficulties like the A_C and at the same time has larger asymmetry significance than the A_C?

The answer is yes.

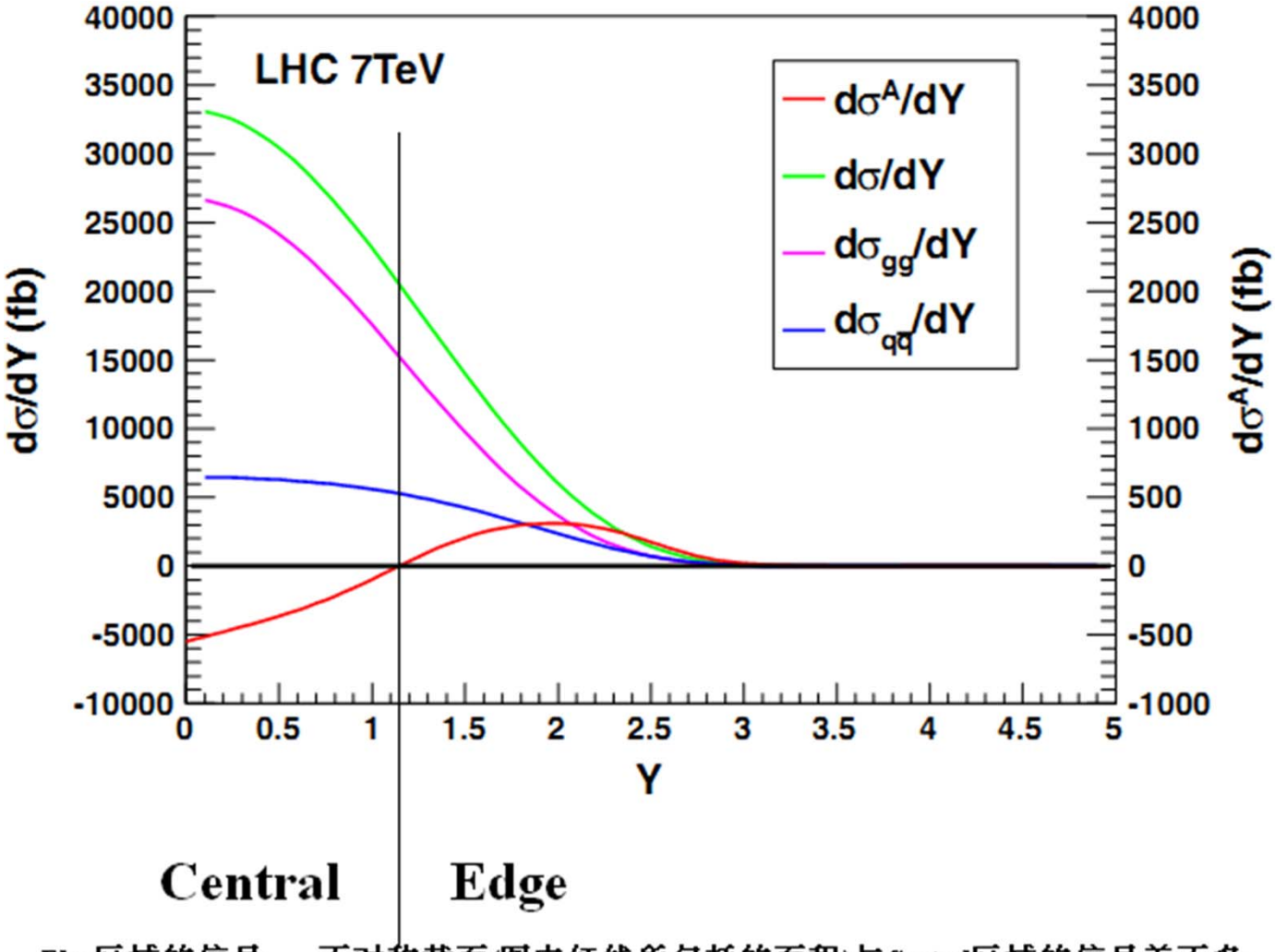
The reason for the asymmetry significance of A_C to be small is that the $gg \to t\bar{t}$ symmetric events distributed mainly in the central region, which forms a large background to the A_C. If we take the edge region events instead to define the charge asymmetry, the $gg \to t\bar{t}$ symmetric background can be significantly reduced, and the asymmetry significance can hopefully be larger.

Edge Charge Asymmetry

The new kind of LHC forward backward asymmetry we defined is the edge charge asymmetry

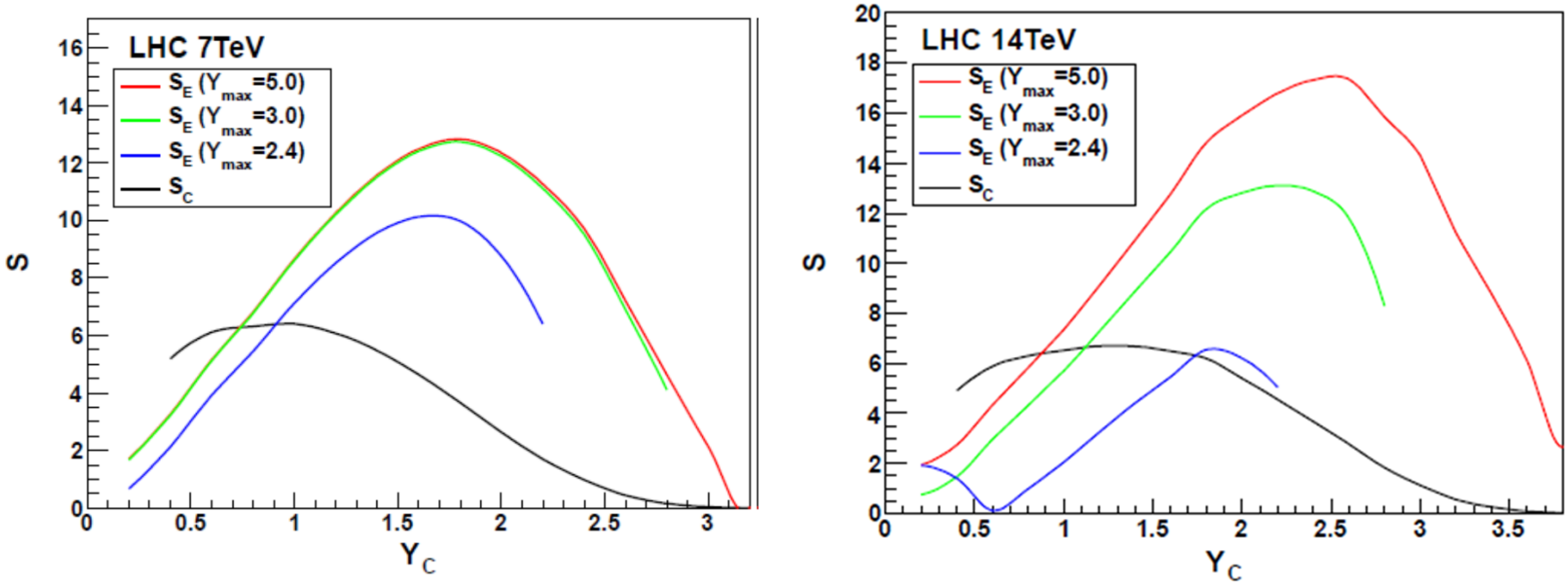
$$A_{\mathrm{E}}(Y_{\mathrm{C}}) = \frac{\sigma_f(Y_{\mathrm{C}} < |Y_f|) - \sigma_{\bar{f}}(Y_{\mathrm{C}} < |Y_{\bar{f}}|)}{\sigma_f(Y_{\mathrm{C}} < |Y_f|) + \sigma_{\bar{f}}(Y_{\mathrm{C}} < |Y_{\bar{f}}|)}$$

which is similar to the central charge asymmetry but take the complementary edge rapidity region instead.



Edge区域的信号——不对称截面(图中红线所包括的面积)与Central区域的信号差不多；
但是Edge区域的背景——截面(图中绿线所包括的面积)远小于Cetnral区域的背景。

ECA in SM



The maximal asymmetry significance of A_E is Larger than that of A_C

Pause

- Edge charge asymmetry is excellent observable for top pair production study
- Advantages: Signal keeps the same, but suppress gg fusion contributions, and significance higher
- Disadvantages: Boosted tops

Applications of the LHC forward backward asymmetry

Remarks on forward-backward asymmetry

- Applicable to any dynamics
- How to optimize asymmetry to suppress backgrounds?
- How to extract dynamics info from asymmetry measurements? (compare theoretical prediction and data)

Origin of FBA

Now there are four kinds of LHC F-B asymmetry at our hands. Before going on to the application of the LHC F-B asymmetry, we would like to sum briefly the regions where the LHC F-B asymmetry can apply:

1. the higher order effects of the vector-like gauge interactions

   For example, the F-B asymmetries rising from the QED or QCD higer order effects.

2. the interference effects between t-channel Feynman diagram and s-channel Feynman diagram

   For example, the F-B asymmetry of $e^+e^- \to e^+e^-$, the F-B asymmetry rising from the interference of a flavor changing Z' mediated t-channel Feynman diagram and the SM s-channel Feynman diagram.

3. the chiral coupling effects

   For example, the F-B asymmetry rising from the diagram which contains a Z or an axigluon or a Z'.

Charged leptons as final states

A_{OFB} is defined as

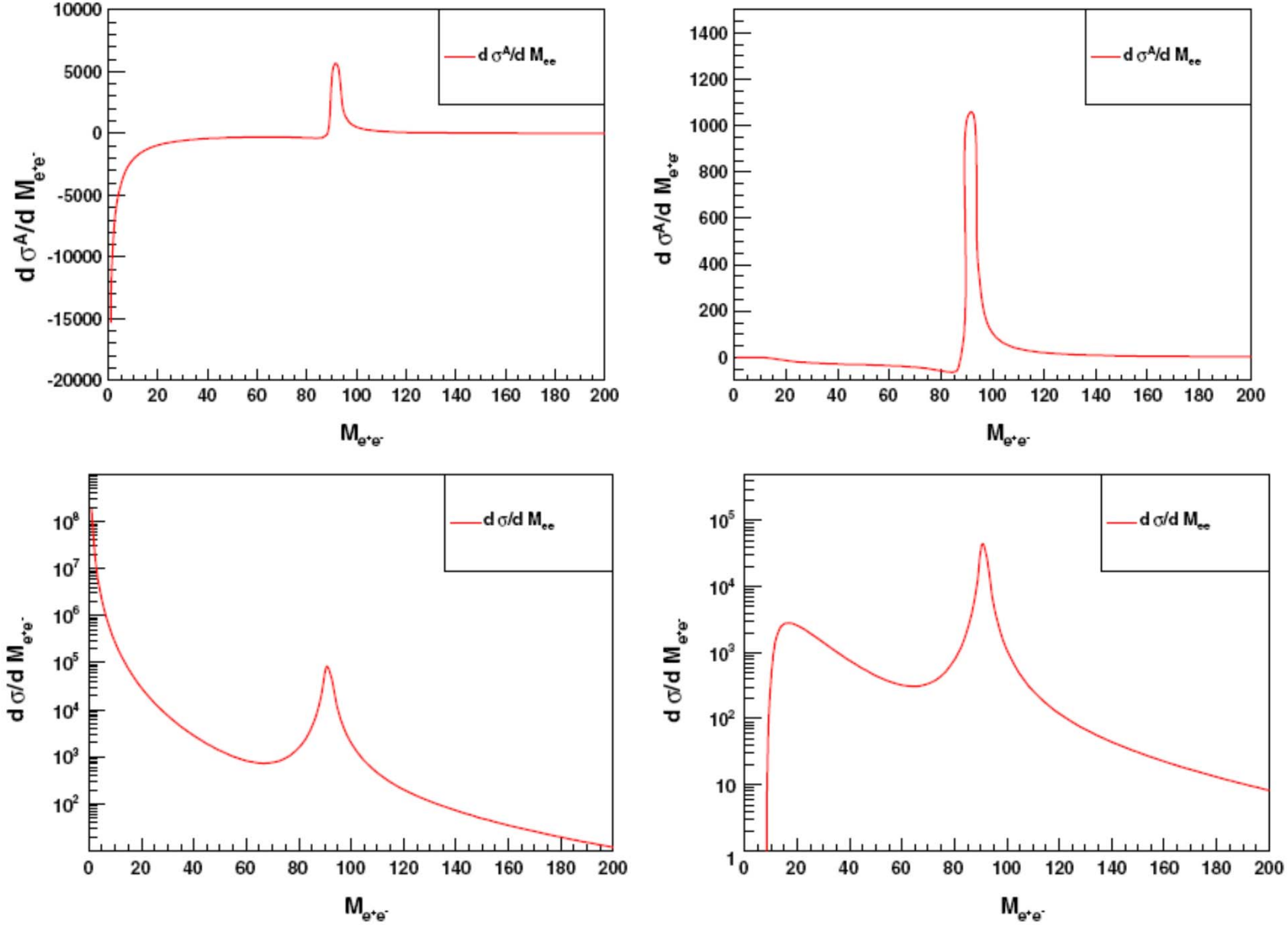
$$A_{\mathrm{OFB}} = \frac{F_- + B_-}{F_+ + B_+} \equiv \frac{\sigma^A}{\sigma}, \tag{4}$$

with

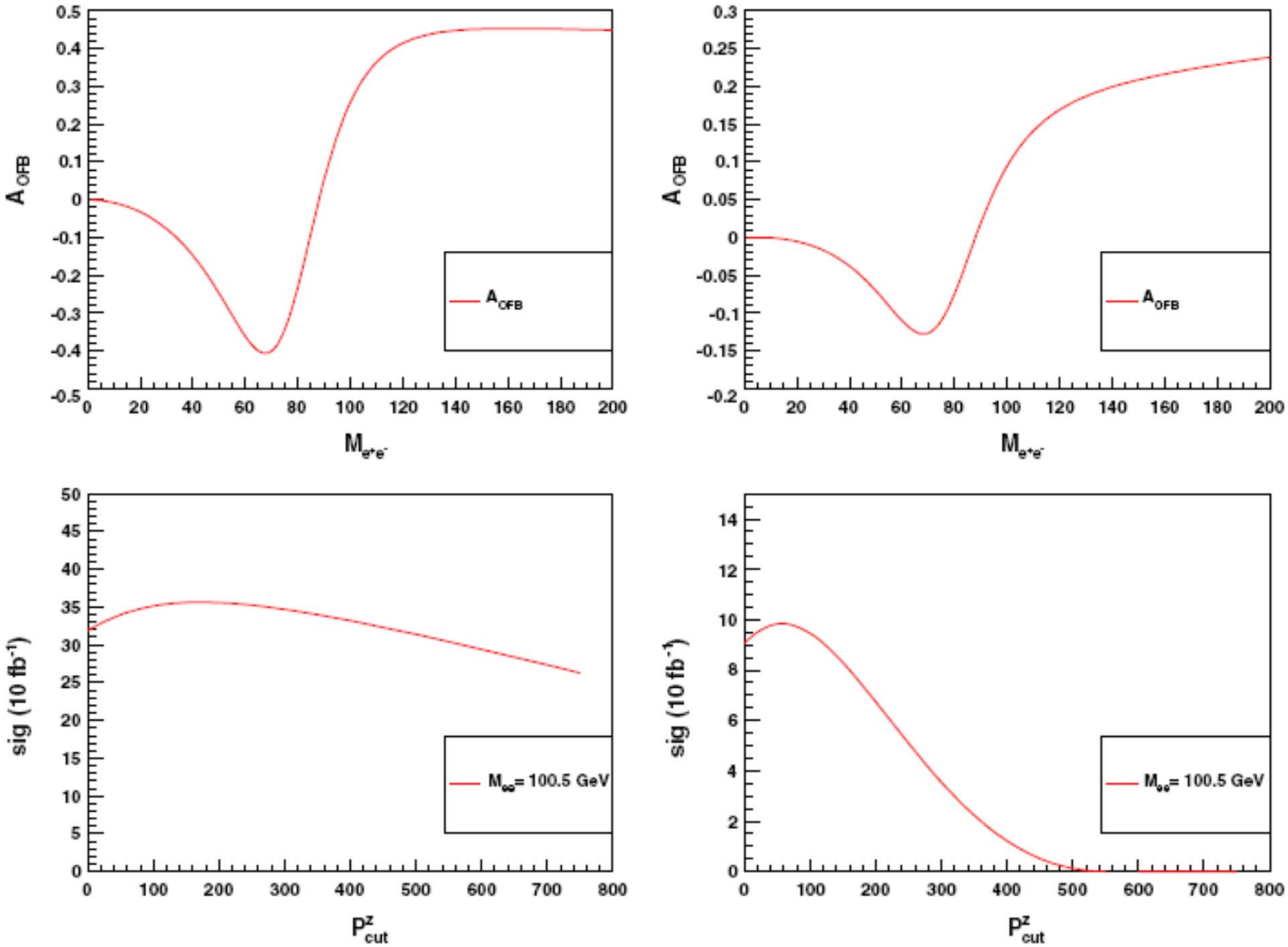
$$F_\pm = (\sigma(\Delta Y > 0) \pm \sigma(\Delta Y < 0))|_{P^z_{f^+f^-} > P^z_{\mathrm{cut}}, M_{f^+f^-} > M_{\mathrm{cut}}}, \tag{5}$$

$$B_\pm = (\sigma(\Delta Y < 0) \pm \sigma(\Delta Y > 0))|_{P^z_{f^+f^-} < -P^z_{\mathrm{cut}}, M_{f^+f^-} > M_{\mathrm{cut}}}, \tag{6}$$

where $P^z_{f^+f^-}$ is the final particle pair's z-direction momentum and $M_{f^+f^-}$ is the invariant mass of the final particle pair.



$\sqrt{s} = 7$ TeV. The left plots have no η cut, and the right plots have a $|\eta| < 2.4$ cut. Optimal $P^z_{\rm cut}$ are determined by the sig plots. The left upper three plots have $P^z_{\rm cut} = 150$ GeV and the right upper three plots have $P^z_{\rm cut} = 50$ GeV.


A_OFB
M_e+e-
A_OFB
A_OFB
M_e+e-
A_OFB
sig (10 fb^-1)
P^z_cut
M_ee= 100.5 GeV
sig (10 fb^-1)
P^z_cut
M_ee= 100.5 GeV

Bottom quark pair as final states

- FBA has two origins: (1) via s-channel Z exchange (2) Higher-order QCD effects, same as top pair production
- Z contribution is negligible other than Z-pole. Cross-check of LEP measurement 2.9 sigma deviation at LHC
- QCD-induced FBA for bottom quark can be compared with top case.

One word for LHCb

Note that the definition in Eq. (4) is based on the CMS or ATLAS detector at the LHC. For the LHCb, one can take the real "one-side" definition, namely,

$$A_{\mathrm{OFB}} = \frac{F_-}{F_+}. \tag{11}$$

In this case b-tagging requirements should also be adjusted accordingly. The obvious difference is that there will be a lower bound on η, e.g., $2.0 < \eta < 5.5$ [40]. As most of the $b\bar{b}$ events are boosted in the z direction, LHCb has the unique advantage to collect more bottom events to reach a higher precision measurement of forward-backward asymmetry.

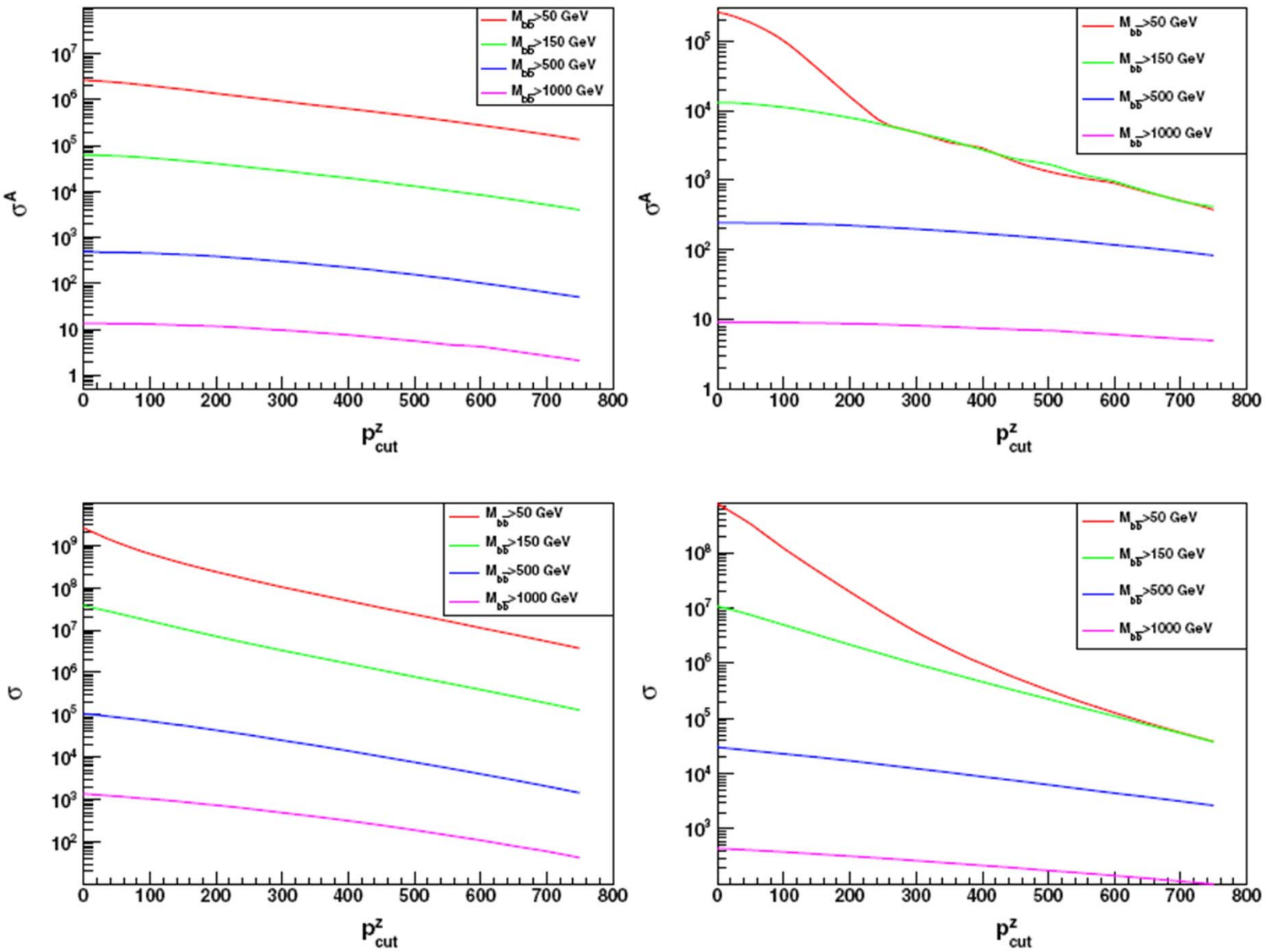
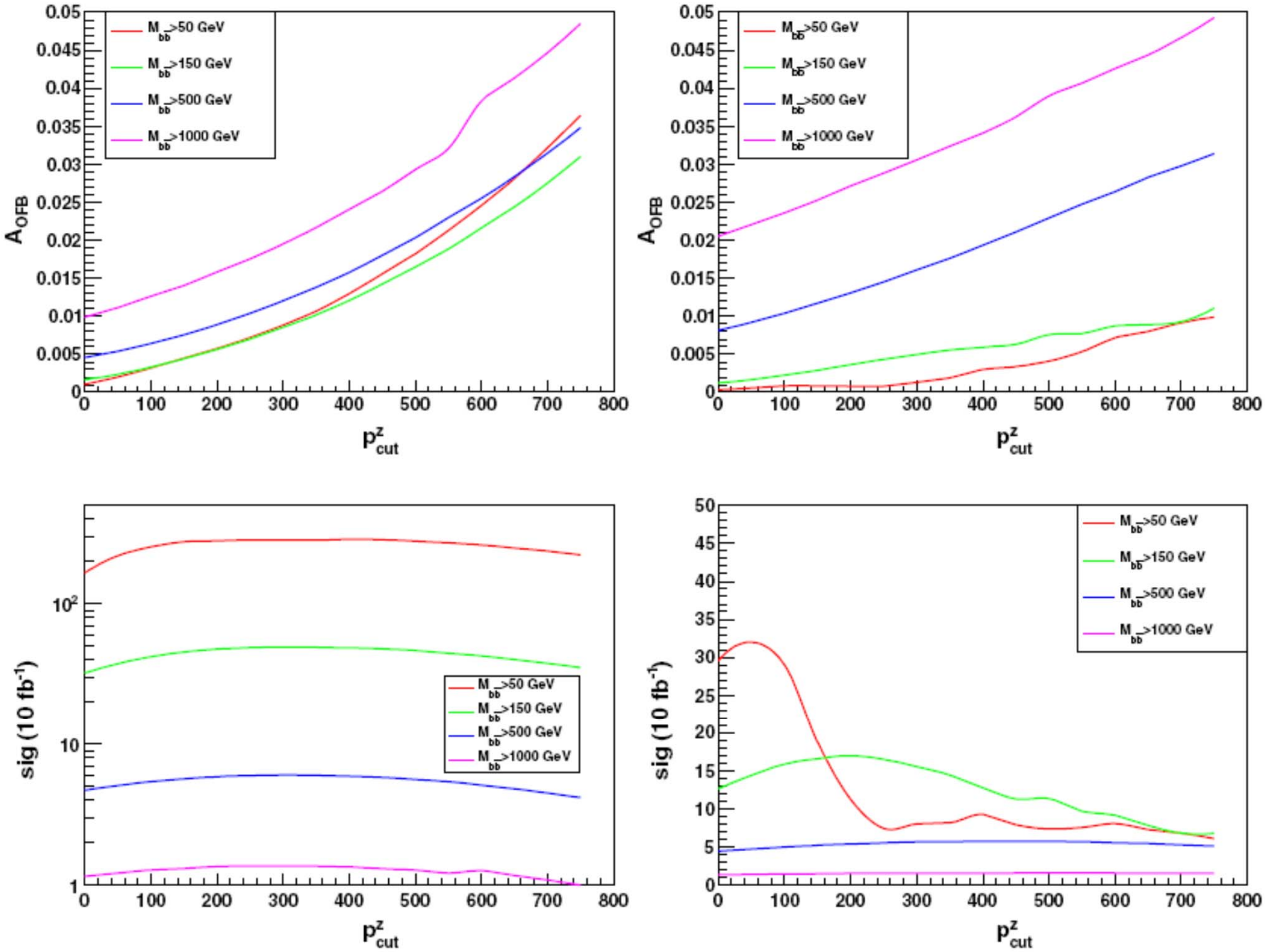


FIG. 3 (color online). σ^A, σ, A_{OFB}, and sig as a function of $P^z_{b\bar{b}}$ for $\sqrt{s} = 7$ TeV. For the right (left) column plots b-jet cuts are (not) applied.


A_{OFB}
p^z_{cut}
M_{bb}>50 GeV
M_{bb}>150 GeV
M_{bb}>500 GeV
M_{bb}>1000 GeV
sig (10 fb^{-1})

OFBA at Z-pole

$$F_{\pm} = (\sigma(\Delta Y > 0) \pm \sigma(\Delta Y < 0))|_{P^z_{b\bar{b}} > P^z_{\rm cut}, m_Z - \delta E/2 < M_{b\bar{b}} < m_Z + \delta E/2},$$

$$B_{\pm} = (\sigma(\Delta Y < 0) \pm \sigma(\Delta Y > 0))|_{P^z_{b\bar{b}} < -P^z_{\rm cut}, m_Z - \delta E/2 < M_{b\bar{b}} < m_Z + \delta E/2},$$

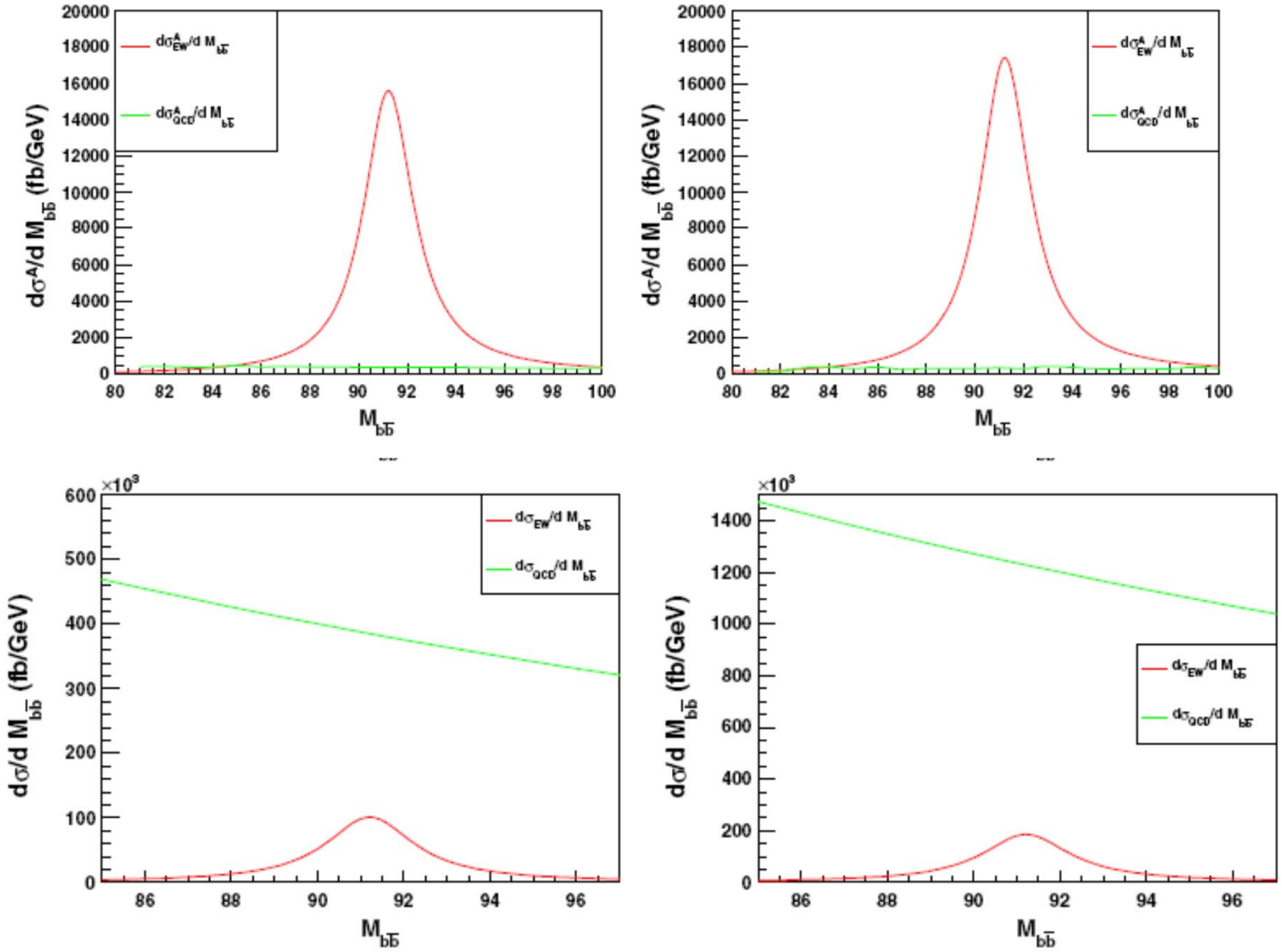
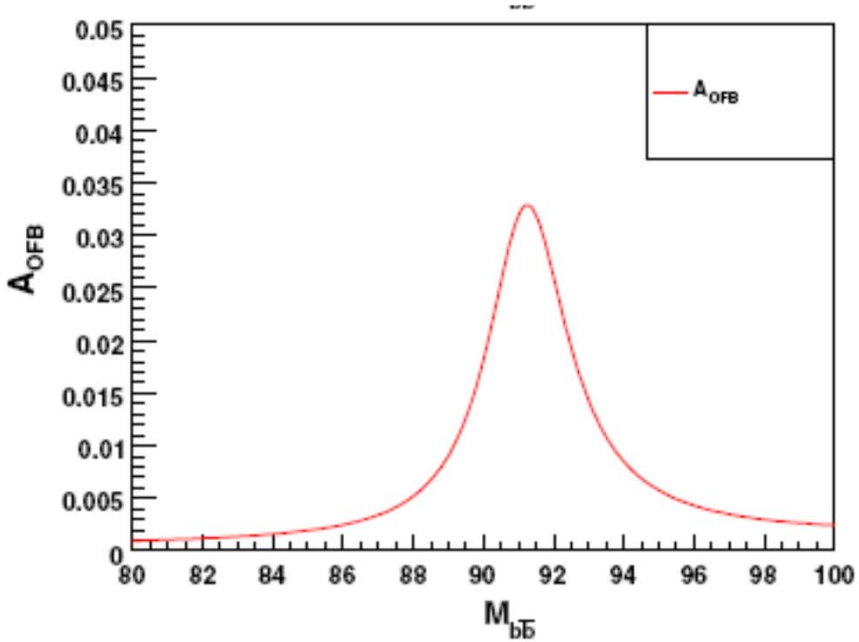
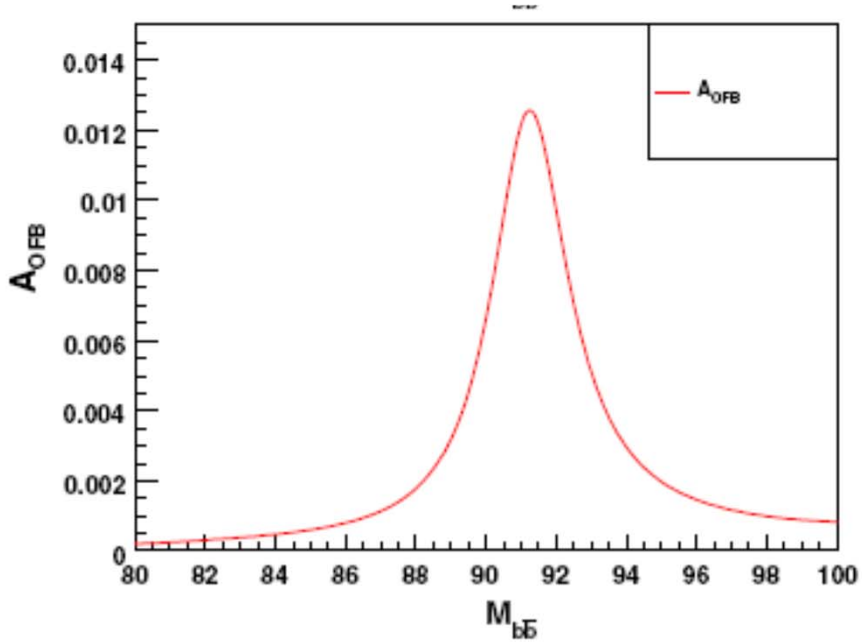


FIG. 7 (color online). Differential distributions of σ^A, σ, and $A_{\rm OFB}$ with $\sqrt{s} = 7$ TeV (left column) and $\sqrt{s} = 14$ TeV (right column). Here the b-jet cut is applied. $P^z_{b\bar{b}} = 150$ GeV. Here $A_{\rm OFB}$ contains the contributions from both EW and QCD.


0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
80
82
84
86
88
90
92
94
96
98
100
A_{OFB}
$M_{b\bar{b}}$
A_{OFB}


0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
80
82
84
86
88
90
92
94
96
98
100
A_{OFB}
$M_{b\bar{b}}$
A_{OFB}

Can we reach LEP precision?

as $\sigma(A^b_{\mathrm{EWOFB}}) = \sqrt{4N^F_{\mathrm{EW}}N^B_{\mathrm{EW}}/(N^F_{\mathrm{EW}} + N^B_{\mathrm{EW}})^3}$, where $N^F_{\mathrm{EW}}/N^B_{\mathrm{EW}}$ are EW induced forward/backward events. For a comparable precision, it can be required that the statistical fluctuation of A^b_{EWOFB} at the LHC should be of the same order $\mathcal{O}(0.001)$ as that of A^b_{FB} at the LEP. By taking the relative data in Fig. 7 into $\sigma(A^b_{\mathrm{EWOFB}})$, the effective luminosity is calculated to be $\epsilon\mathcal{L} = 9.8\ \mathrm{fb}^{-1}$ for 7 TeV and $\epsilon\mathcal{L} = 5.0\ \mathrm{fb}^{-1}$ for 14 TeV. Here ϵ is the b quark selecting efficiency.

Early LHC physics Z’: How to dicriminate different models

Application of LHC F-B asymmetry to Z' identification

The way of using LHC F-B asymmetry to identify Z' has been studied for many years and by many authors. The type of LHC F-B asymmetry they use is the A_{RFB}.

Based on these existing works, we enrich the types of LHC F-B asymmetry used and do the optimizing choice of the varies kinds of LHC F-B asymmetry and get the optimized cut for each kind of LHC F-B asymmetry, and also calculate the NLO QCD contribution to the LHC F-B asymmetry which is missing in the existing works.

Two benchmark models

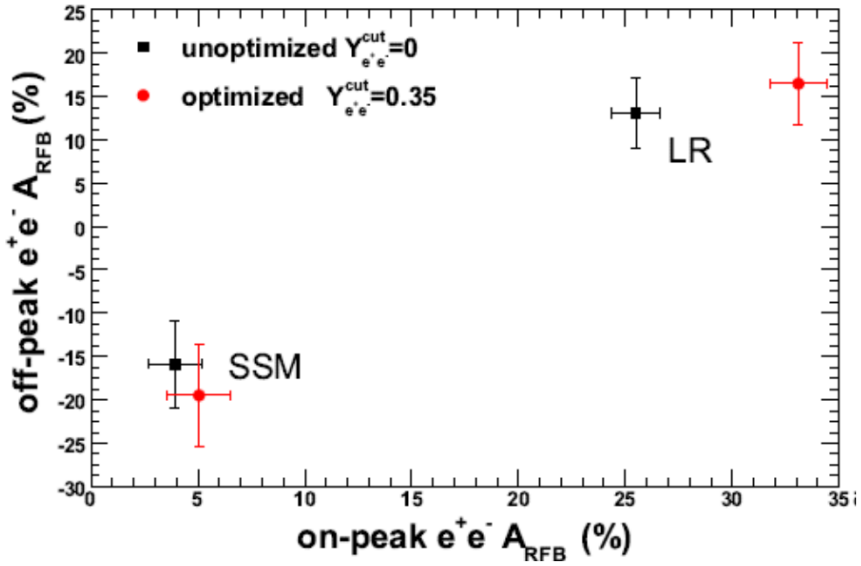
Left-Right model Z'
symmetry group $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$

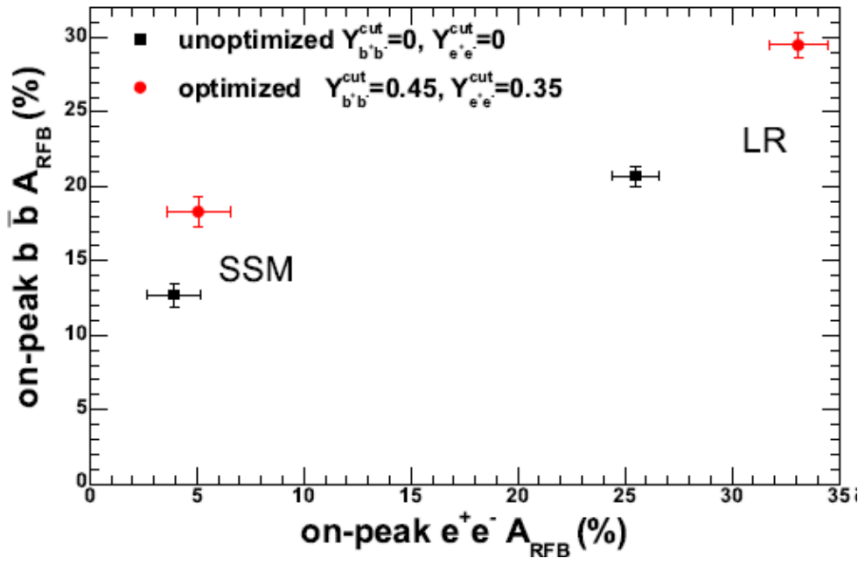
$$g_{Z'} J^{\mu}_{Z'} Z'_{\mu} = \frac{e}{c_W} \sum_f \bar{\psi}_f \gamma^{\mu} [\frac{1-\gamma^5}{2} g_L^{fZ'} + \frac{1+\gamma^5}{2} g_R^{fZ'}] \psi_f Z'_{\mu}.$$

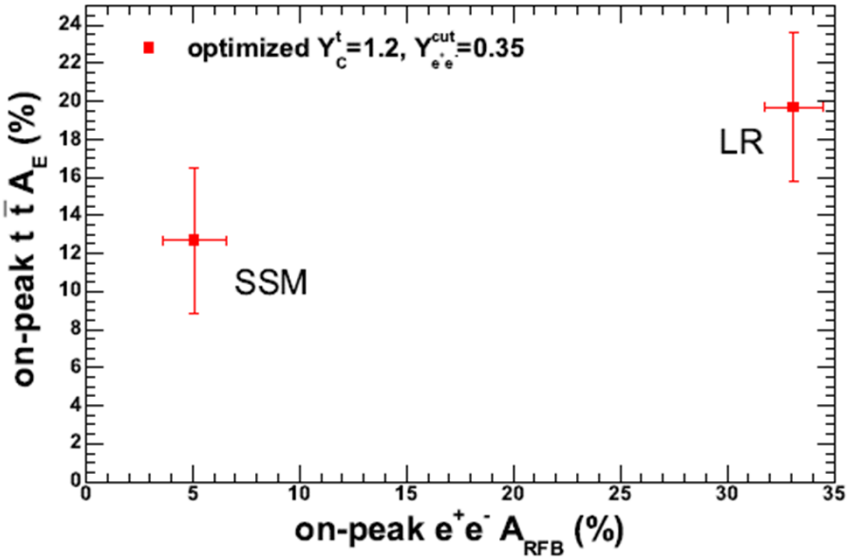
Sequential Standard Model Z'

$$g_{Z'} J^{\mu}_{Z'} Z'_{\mu} = -\frac{g}{2c_W} \sum_f \bar{\psi}_f \gamma_{\mu} (g_V^f - g_A^f \gamma_5) \psi_f Z'_{\mu}.$$

Application of LHC F-B asymmetry to Z' identification







Pause

- Aymmetry can be utilized to investigate SM and/or BSM
- For specific dynamics: Choice of observable, and optimal conditions
- Higher-order QCD effects for bottom and top can be cross-checked at LHC.
- LEP bottom FBA can be cross-checked at LHC
- Z’ models can be excellently distingushed.

Discussions

- (Forward-backward) asymmetry is useful observable based on angular distribution in order to determine coupling structure and/or discover BSM
- Tevatron measurements may find anomaly for FBA and/or di-jet measurements. LHC will cross-check Tevatron observations
- LHC is not just discovery machine. Asymmetry will be extremely important for machine to do precise measurement.

Thanks!