Charge asymmetry in top pair production

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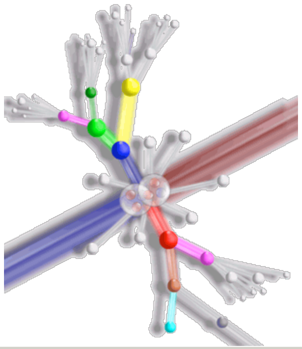
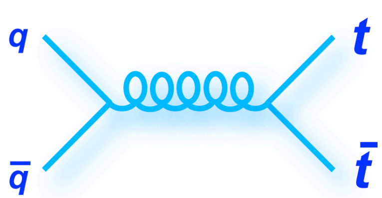


Outlines

- ❑ **Top Production**
- ❑ **Charge Asymmetry at Hadron Colliders**
  - **Tevatron**
  - **LHC**
- ❑ **Tevatron Measurement**
- ❑ **LHC Charge Asymmetry in Lepton+Jets Channel**
- ❑ **Analysis Strategy**
- ❑ **Results**
- ❑ **Summary**

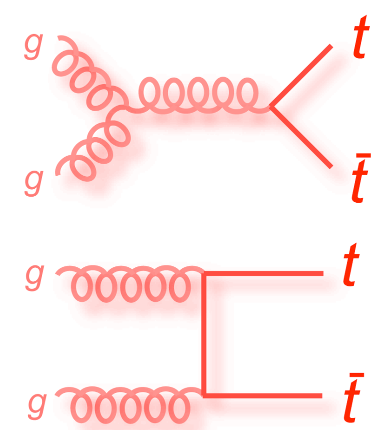
Top Pair Production

- Top quark pair production through strong interactions (dominant process)
- Single top quark Production via electroweak interactions (factor 2-3 smaller than pair production)



quark-antiquark annihilation

gluon fusion



Top pair cross section at NNLO approximation, MSTW2008, m_t =173 GeV

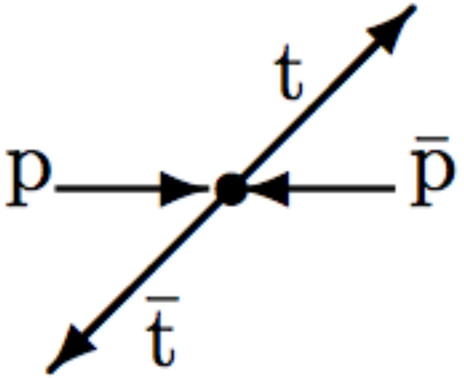
	Tevatron	**LHC8**	**LHC8/TeV**
Production Rate	7.16 pb	245.8 pb	~33
q-qbar contribution	~85%	~20%	~0.2

Phys. Rev. Lett. 110 (2013) 252004, Michal Czakon et al

Asymmetry Definition: Tevatron

Do top quarks follow preferentially the initial quark or antiquark direction?

$$A^i_{\mathrm{FB}} = \frac{N_t(y^i_t > 0) - N_t(y^i_t < 0)}{N_t(y^i_t > 0) + N_t(y^i_t < 0)}$$

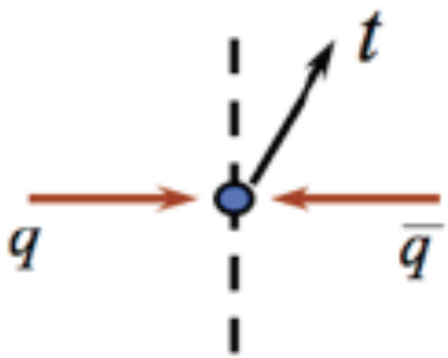


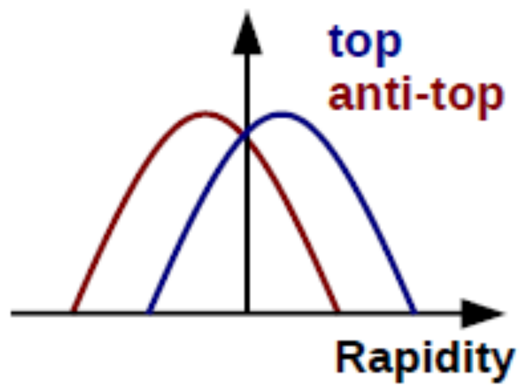
-Within the SM framework at tree level, top-antitop quark pair production at hadron colliders is charge symmetric.

$$\frac{d\sigma^{\mathrm{Born}}_{q\bar{q}}}{d\cos\theta_t} = f_{q\bar{q}}(\cos^2\theta_t); \qquad \frac{d\sigma^{\mathrm{Born}}_{gg}}{d\cos\theta_t} = f_{gg}(\cos^2\theta_t)$$

Charge Asymmetry at Hadron Colliders: Tevatron

-At NLO, QCD predicts an asymmetry for ttbar produced via qqbar initial state, the top quark is predicted to be emitted preferably in the direction of the incoming quark





cms rest frame

~ LAB frame at the Tevatron

$$A^{i}_{\mathrm{FB}} = \frac{N_t(y^i_t > 0) - N_t(y^i_t < 0)}{N_t(y^i_t > 0) + N_t(y^i_t < 0)}$$

Charge Asymmetry at Hadron Colliders: Tevatron

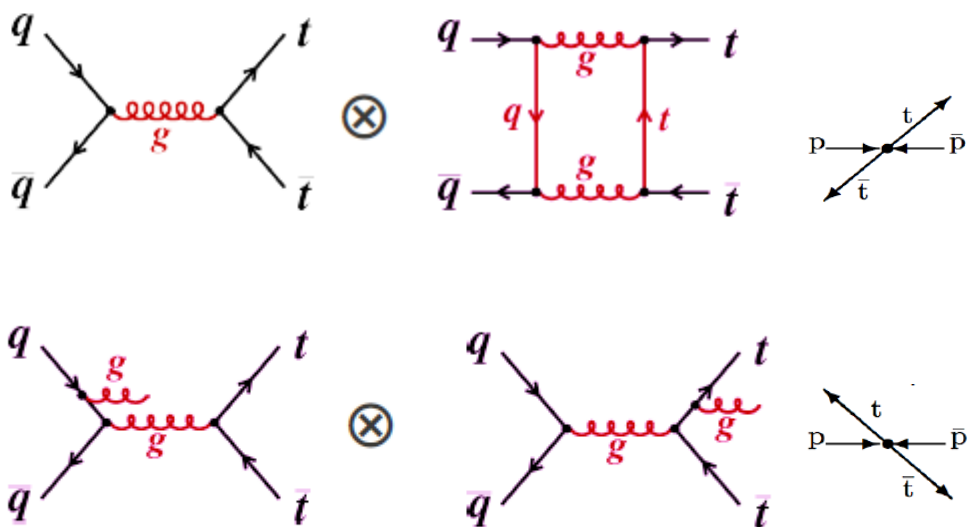
- At O($\alpha^2{}_S$): **top and antitop quarks have** identical angular distributions. A charge asymmetry arises at O($\alpha^3{}_S$)
- Asymmetry in QCD:Interference of C=1 and C=-1 amplitudes are odd under t ↔ tbar → cause asymmetry

Born(α_s^2) and box(α_s^4)

- Coulomb-like repulsion of top and quark and attraction of antitop and quark in QCD
- Interference – α_s^3
- Positive asymmetry
- Final state with no extra partons → small transverse momentum of the tt system

ISR (α_s^3) and FSR(α_s^3)

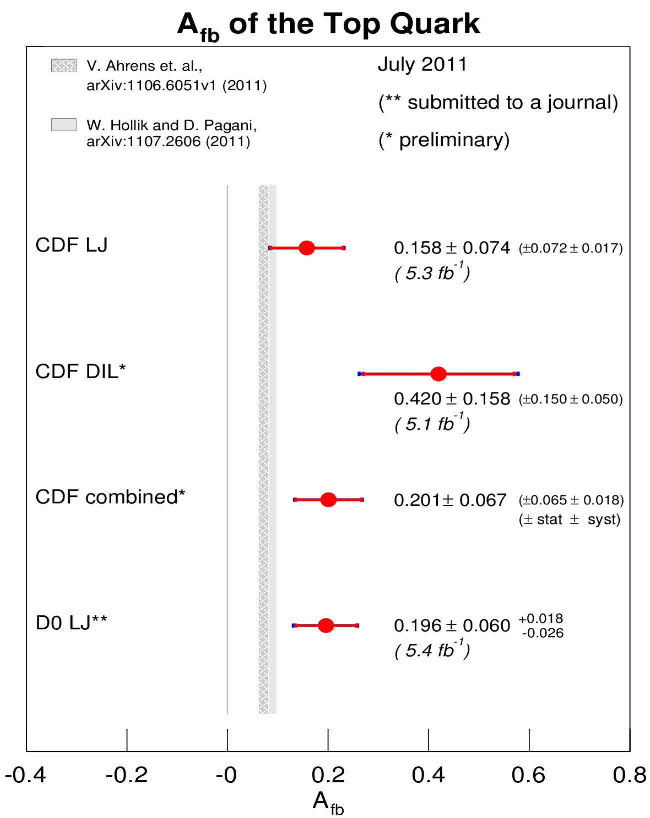
- Interference – α_s^3
- Negative asymmetry
- Final state with extra gluons →large transverse momentum of the tt system
- Possible extra jets



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

Tevatron Measurment

The asymmetry at the parton level as measured in the data, compared to the SM ttbar expectation, as a function of M_{ttbar}



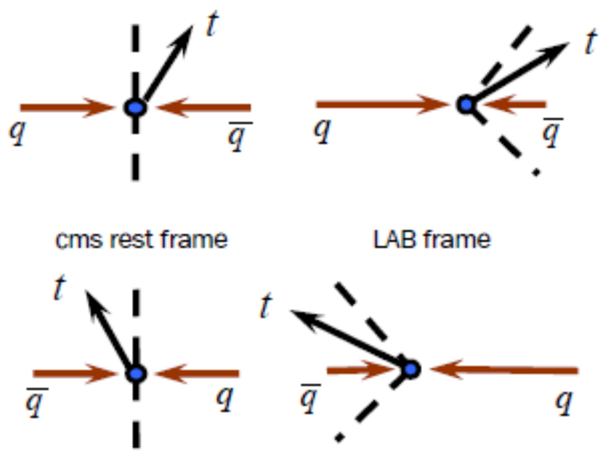
CDF:arXiv:1211.1003

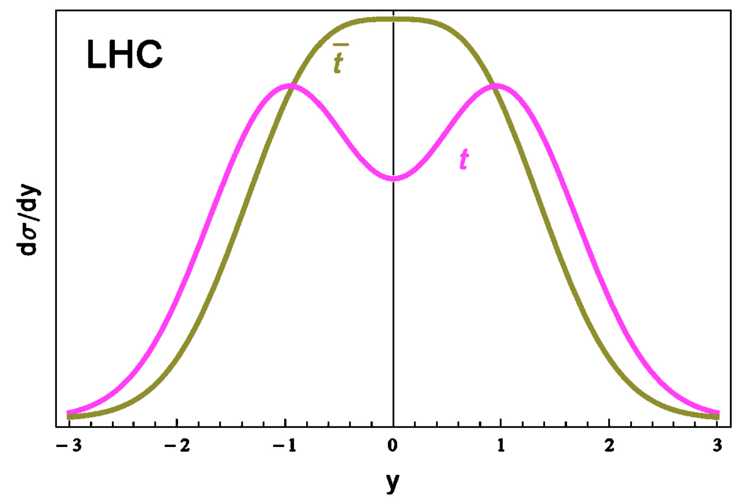
Parton level $M_{t\bar{t}}$ (GeV/c^2)	Data A_{FB} ± stat ± syst	SM $t\bar{t}$ A_{FB}
< 450	0.084 ± 0.046 ± 0.030	0.047 ± 0.014
450 - 550	0.255 ± 0.062 ± 0.034	0.090 ± 0.027
550 - 650	0.370 ± 0.084 ± 0.087	0.117 ± 0.035
≥ 650	0.493 ± 0.158 ± 0.110	0.143 ± 0.043
< 450	0.084 ± 0.046 ± 0.030	0.047 ± 0.014
≥ 450	0.295 ± 0.058 ± 0.033	0.100 ± 0.030

- Tevatron measures a larger inclusive A_{FB} than predicted by SM (Discrepancy to SM prediction remains at $2-3\sigma$ level)
- CDF measures large asymmetry for M_{tt}>450GeV
- Sign of new Physics?

Charge asymmetry at pp-collider: LHC

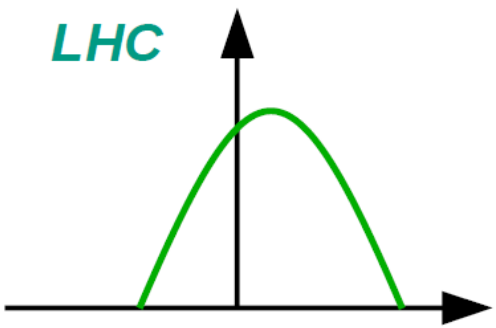
Since valence quarks carry on average more momentum than sea antiquarks, production of top quarks with larger rapidities will be preferred in the SM, and antitop quarks will be produced more frequently at smaller rapidities.





Instead of looking at two rapidity distributions separately, a sensitive combined variable used at the LHC:

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



The Analysis Strategy

The charge asymmetry occurs only in quark-antiquark initial states. Since at the LHC the quarks in the initial state are mainly valence quarks while the antiquarks are always sea quarks, the larger average momentum fraction of quarks leads to an excess of top quarks produced in the forward directions.

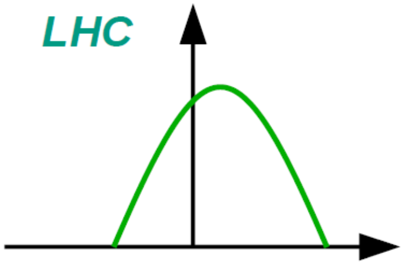
The difference of the absolute values of the rapidities of top quark and antiquark is a suitable observable to measure the ttbar charge asymmetry:

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

The difference between the number of events with positive and negative values in the sensitive variable is defined as the A_C

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

SM prediction: A_C **= 0.01**



Charge Asymmetry

-In addition to measure the inclusive asymmetry, it is of particular importance to measure the differential asymmetry as a function of variables that are suited to enhance the charge asymmetry in certain kinematic regions.

-The charge asymmetry is expected to depend on the invariant mass of the ttbar system ($\mathbf{m}_{tt}$).

-The contribution of the qqbar initial state processes is enhanced for larger values of $\mathbf{m}_{tt}$.

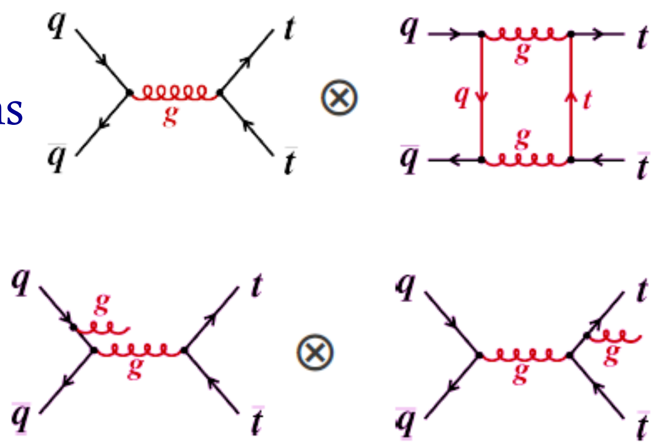
-This observable is also sensitive to new physics contributions; potential new heavy particles could be exchanged between initial quarks and antiquarks and contribute to the tt production.

-The amplitudes associated with these new contributions would interfere with those of the SM processes, leading to an effect on the ttbar charge asymmetry, which increases as a function of the invariant mass of the ttbar system.

Charge Asymmetry

The transverse momentum of the top pair in the laboratory frame, $\mathbf{p_T}$(ttbar), is sensitive to the ratio of the positive and negative contributions to the overall asymmetry.

The interference between the Born and the box diagrams leads to a positive contribution, while the interference between initial state and final state radiation (ISR and FSR) results in a negative contribution.



The presence of additional hard radiation implies on average a higher transverse momentum of the ttbar system.

Consequently in events with large values of $\mathbf{p_T}$(ttbar) the negative contribution from the ISR-FSR interference is enhanced. SM expects to observe a decrease with increasing the transverse momentum of the ttbar system.

The Analysis Strategy

The analysis steps:

✧ ttbar events selection in the channels of e+jets/ μ +jets.

✧ The estimation of backgrounds.

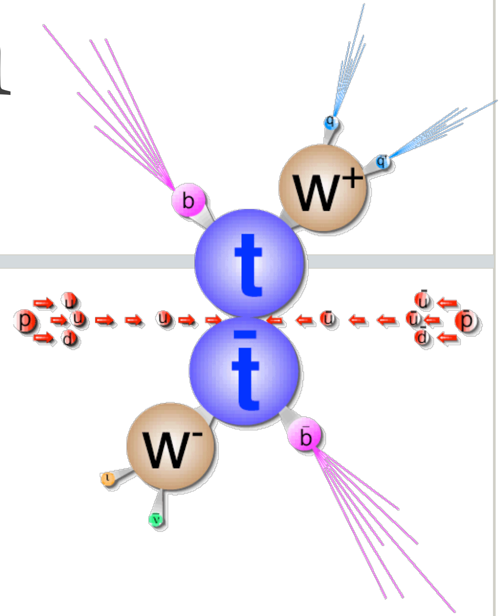
✧ The reconstruction of momentum of the top and anti-top quarks.

✧ To be able to compare with predictions of theory, the measured distribution of the sensitive variable must be corrected for selection efficiency and non-perfect reconstruction …

✧ Based on the corrected distributions, the inclusive and differential asymmetries are measured.

✧ The systematic uncertainties need to be included.

Event Selection



Event signature:

- One isolated energetic electron or muon
- Four jets, two of them are b-jets
- Missing transverse energy

Selection cuts:

- Trigger: single lepton trigger

- Exactly one isolated muon (electron): p_T>26 GeV (E_T>30 GeV), $|\eta|<2.1$ ($|\eta|<2.5$)
  - Events containing additional more loosely electrons or muons are discarded.

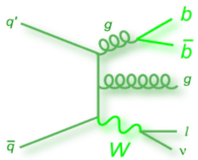
- At least 4 jets reconstructed with anti-kT algorithm with p_T>30 GeV and $|\eta|<2.5$ ($\Delta R=0.5$)

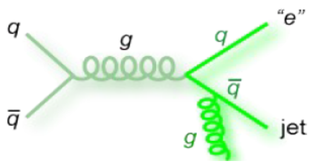
- At least one b-tagged jet should be present in the event. The btagging algorithm is the Combined Secondary Vertex. It makes use of the formation of secondary vertices, together with track-based lifetime information.

CMS PAS TOP-12-033

Backgrounds Estimation

The backgrounds to **ttbar** signal in the single lepton channel are



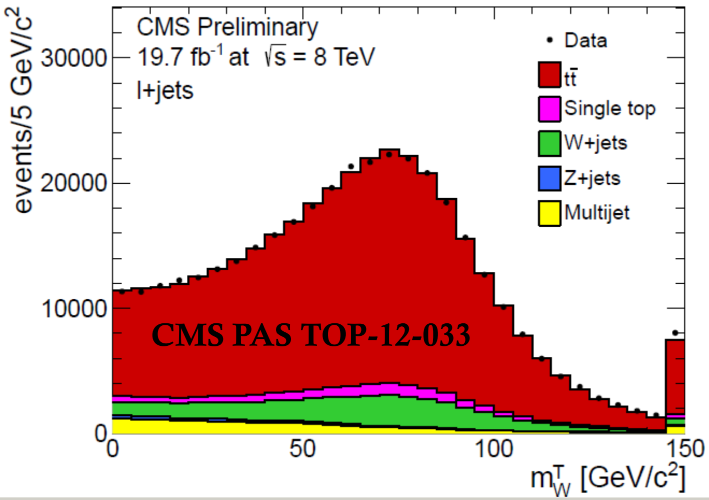


- **W(→ l)+jets**
- **single top**
- **Z+jets**
- **Multi-jet QCD** with fake leptons, arising from heavy flavor decays or jets faking lepton signatures
- **Di-boson (WW/ZZ/WZ)**

Background contributions are estimated in electron and muon separately by means of binned maximum-likelihood fits to the two discriminating distributions. Simultaneous likelihood fits to:

-m_{TW}, for $m_{TW} < 50$ GeV (The m_{TW} distribution discriminates between events with and without real W bosons)

- M3 for $m_{TW} > 50$ GeV



QCD multi-jet rate is several orders of magnitude larger than that of any other process, this specific background can be modelled directly from data

-The QCD template is used from data with less-well isolated leptons

Event Yield

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Results for the numbers of events for background and ttbar contributions from fits to data, along with their statistical uncertainties.

process	electron+jets	muon+jets	total
single top (t + tW)	6804 ± 690	8395 ± 868	15199 ± 1109
W+jets	20344 ± 1557	18401 ± 1450	38745 ± 2128
Z+jets	1761 ± 805	1771 ± 632	3532 ± 1024
multijet	11053 ± 1517	5491 ± 678	16544 ± 1662
total BG	39963 ± 2419	34057 ± 1928	74020 ± 3093
$t\bar{t}$	136886 ± 1486	164239 ± 1483	301124 ± 2099
observed data	176835	198290	375125

The analysis corresponds to an integrated luminosity of 19.7/fb.
Around 30K top pair candidates have been selected with a high purity.

Reconstruction of ttbar System

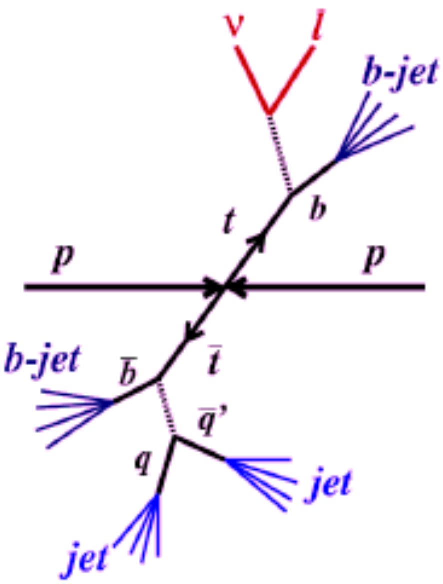
In order to measure charge asymmetry, need to reconstruct the full event kinematics to compute Δy

- Known objects: jets, charged lepton, $E_{T,miss}$

- Ambiguities in assignment of jets and lepton to top quark *(there are 24 hypotheses for four-jet event)*

- The hypothesis is selected which describes the ttbar topology best by
  – applying the constraints on W-boson and top masses
  – exploiting b-tag discriminator of jets

- The charge of electron or muon defines the charge of the leptonically decaying top. The hadronically decaying top quark is assumed to have opposite charge



Corrections and Unfolding

To be able to compare the resulting asymmetry with theory predictions, the reconstructed distributions have to be corrected for several effects to be able to compare the generator level. The measured distributions are corrected for:

-Background contributions
-Reconstruction effects
-Selection efficiencies

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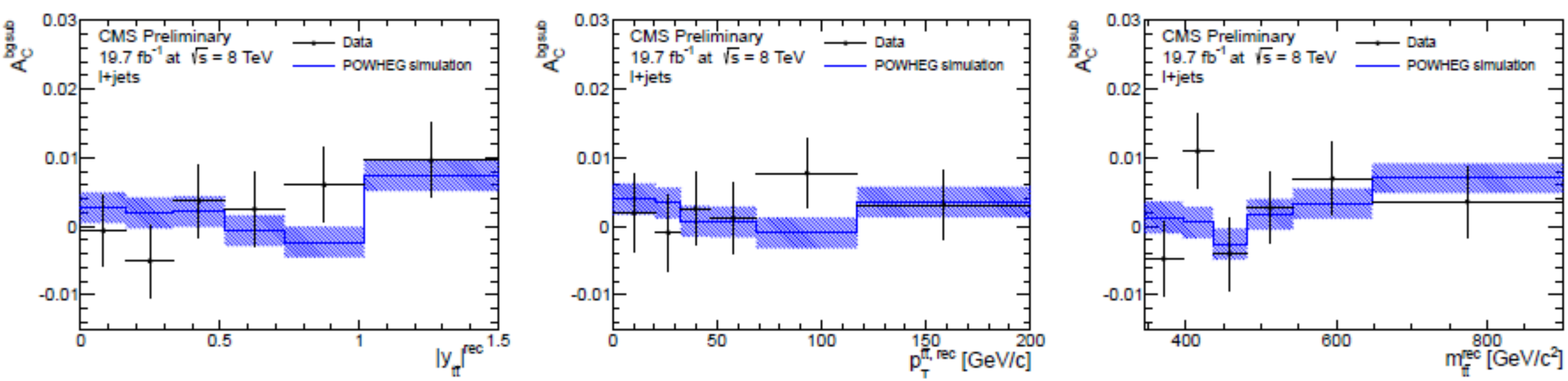
The distributions of background processes are normalized to the estimated rates and subtracted from the data. Background-subtracted asymmetries:



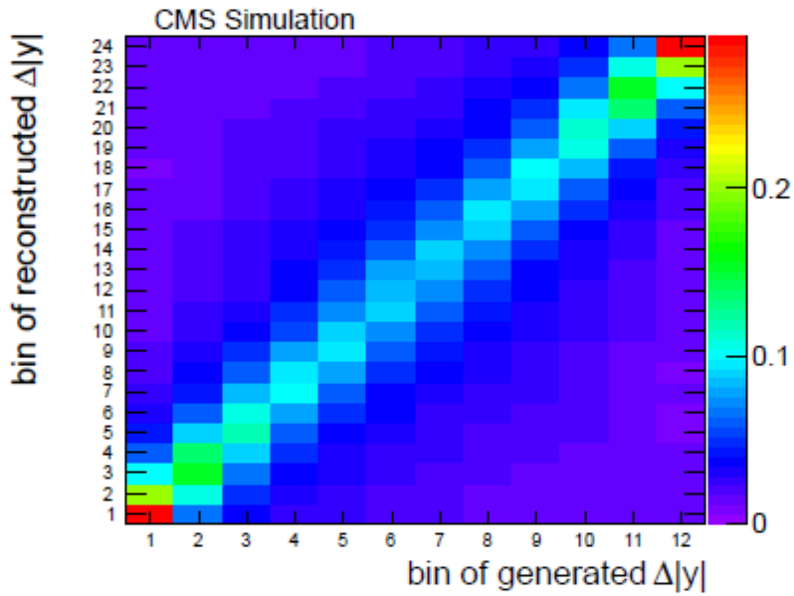
Unfolding

➢The remaining background-free distributions are translated from the reconstruction level to the particle level after event selection, and from there to the particle level before event selection.

➢The corrected distributions are then independent from the detector environment and analysis specifications.

➢This is done using a so called "smearing matrix" that translates the true spectrum into the measured spectrum. The smearing matrix includes reconstruction and selection effects. Both the migration matrix and the selection efficiency are determined from simulation.

Migration matrix between the generated and the reconstructed values in Δy



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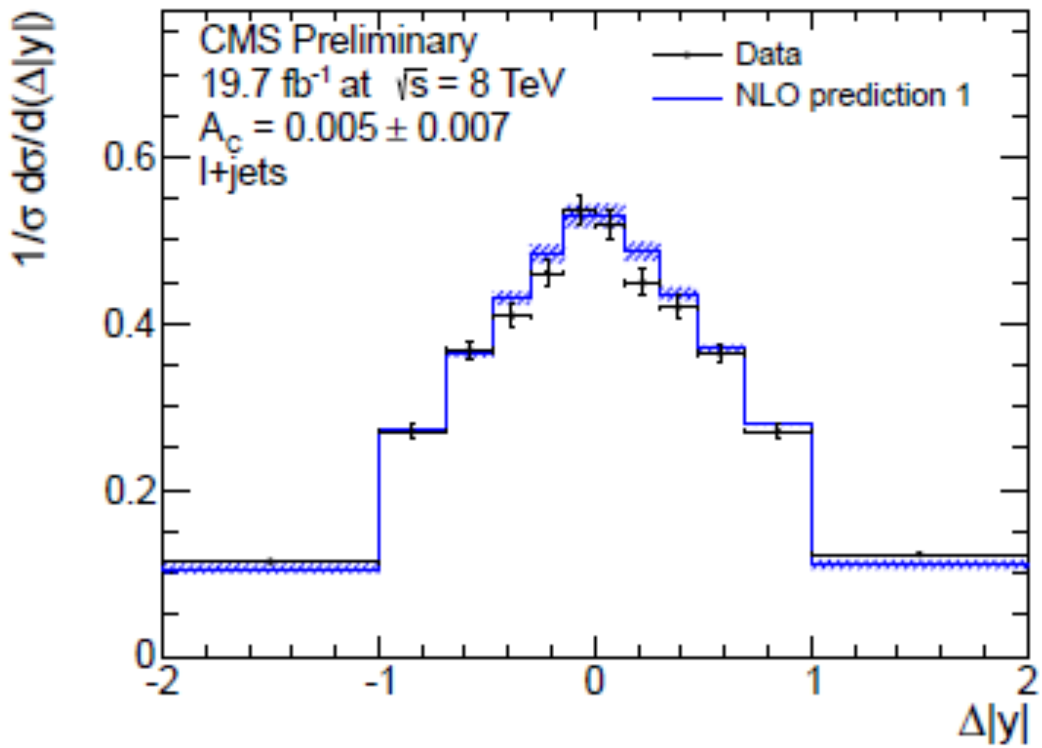
Unfolded distributions

Unfolded inclusive Δy distribution



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The measured inclusive charge asymmetry: 0.005 ± 0.007 (stat.)

Systematics

The measured charge asymmetry A_C can be affected by several sources of systematic uncertainty.

Systematic uncertainty	shift in inclusive A_C	range of shifts in differential A_C
JES	0.001	0.001 – 0.005
JER	0.001	0.001 – 0.005
Pileup	0.001	0.000 – 0.003
b tagging	0.000	0.001 – 0.003
Lepton ID/sel. efficiency	0.002	0.001 – 0.003
Generator	0.003	0.001 – 0.015
Hadronization	0.000	0.000 – 0.016
p_T weighting	0.001	0.000 – 0.003
Q^2 scale	0.003	0.000 – 0.009
W+jets	0.002	0.001 – 0.007
Multijet	0.001	0.002 – 0.009
PDF	0.001	0.001 – 0.003
Unfolding	0.002	0.001 – 0.004
Total	0.006	0.007 – 0.022

Results

The measured inclusive asymmetry at the different stages of the analysis and the corresponding theory prediction from the SM:

Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)
Theory prediction [Kühn, Rodrigo]	0.0102 ± 0.0005
Theory prediction [Bernreuther, Zi]	0.0111 ± 0.0004

Inclusive charge asymmetry at the LHC is consistent with SM predictions

As it can be seen the measurement is statistically limited.

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Differential Charge Asymmetries

CMS measures the charge asymmetry differentially in M_{tt} and $P_{tt,T}$

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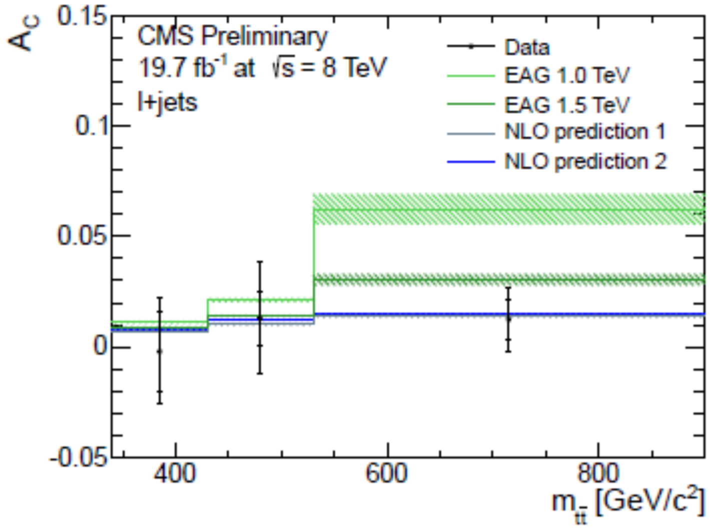
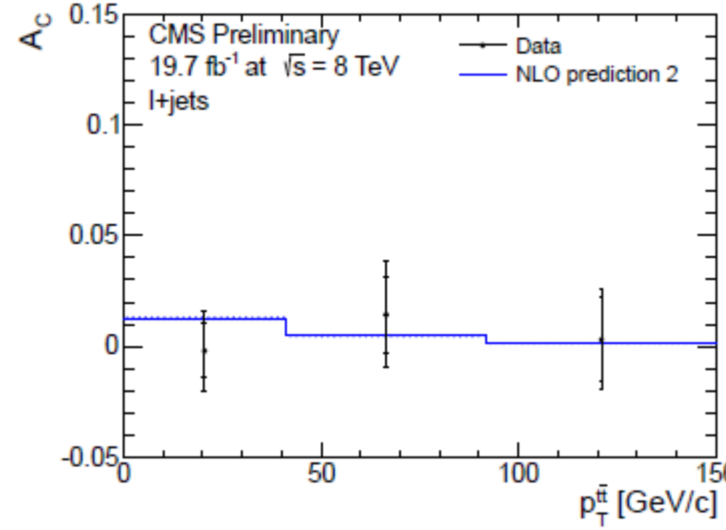
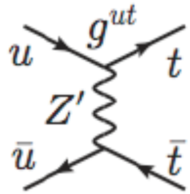




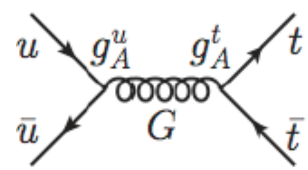
The inner error bars on the differential asymmetry values indicate the statistical uncertainties while the outer error bars represent the statistical and systematic uncertainties. There is bin-by-bin agreement between SM predictions and measurement.

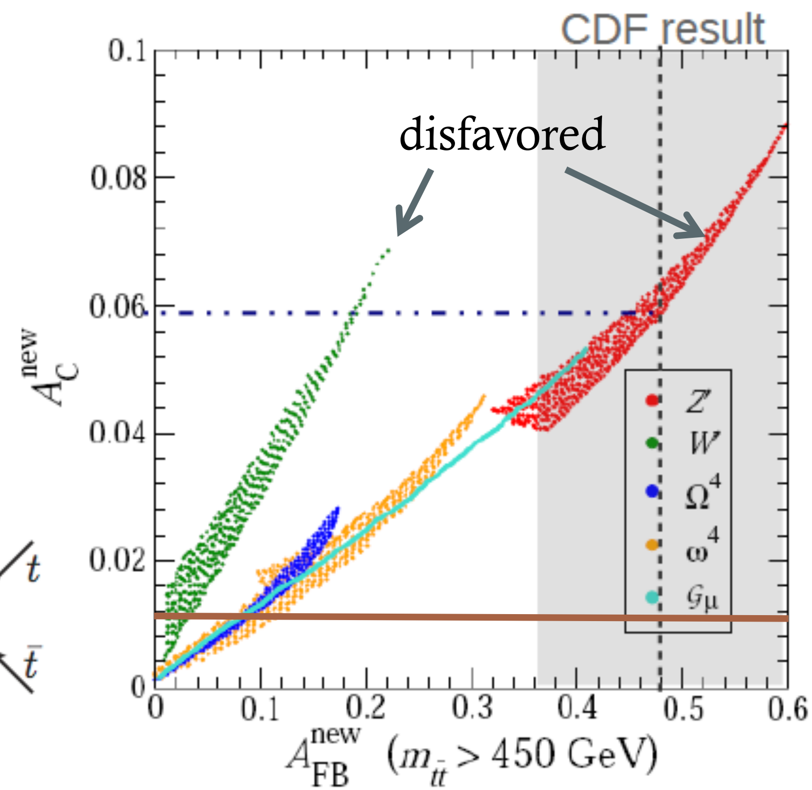
Asymmetries and new Physics Models

- W': W' boson with right-handed couplings exchanged in t-channel in ddbar→ttbar
- Z': Flavor violating Z' exchanged in t-channel in uubar→ttbar and with right-handed Z'tu couplings



- G_μ: Axigluon, color octet vector with axial couplings,
  massive gluon field





We should look for a model which give the cross sections and charge asymmetry consistent with SM while enhances the FB! It is difficult!

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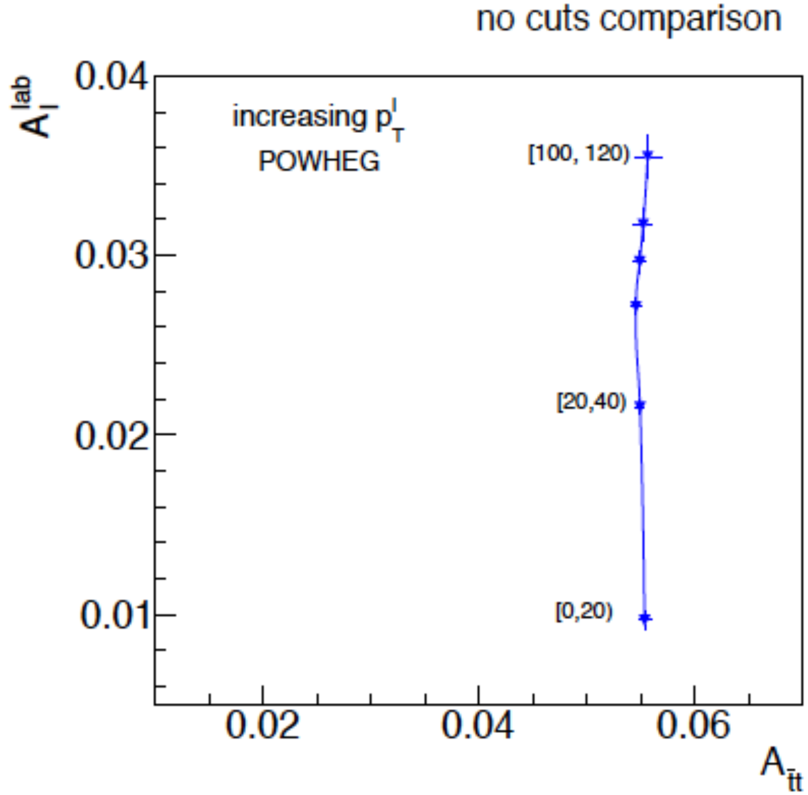
More Detailed Phenomenological Studies: Lepton Asymmetry

FB for leptons from ttbar decay leptonic asymmetry can be defined. smaller than $A_{\mathbf{FB}}$, but should be more precisely measurable



$$A_l\left(p_T^l\right) = \frac{N_{Y_l>0}\left(p_T^l\right) - N_{Y_l<0}\left(p_T^l\right)}{N_{Y_l>0}\left(p_T^l\right) + N_{Y_l<0}\left(p_T^l\right)},$$

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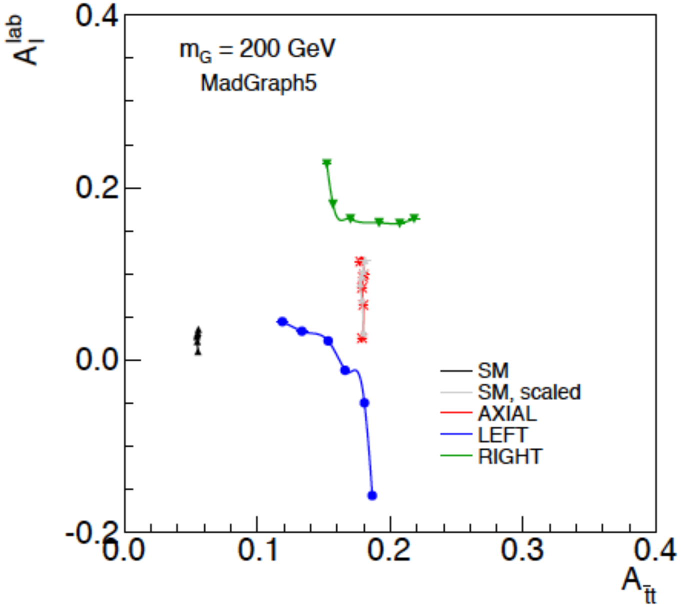
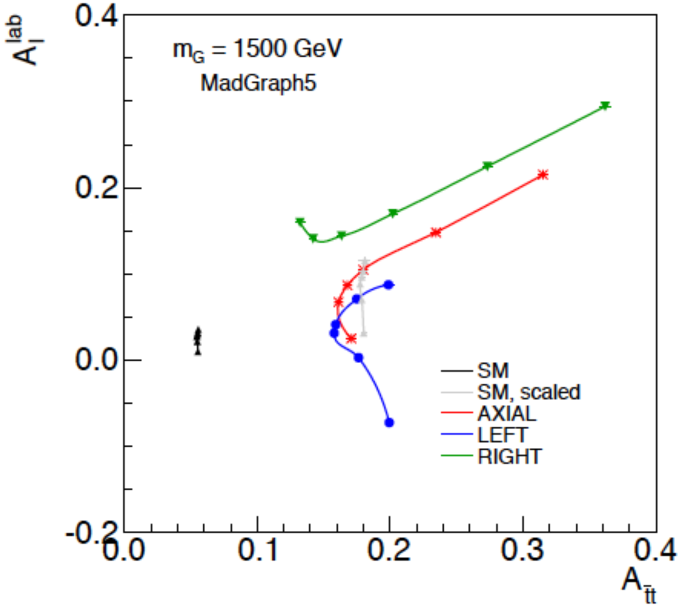
Lepton Asymmetry





It has been shown that the leptonic asymmetry is robust against:
-Variation of Q-scale
-Hadronization
-Reconstruction and Cuts

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Adam Falkowski, Michelangelo L. Mangano, Adam Martin, Gilad Perez, Jan Winter

Summary

- The measured charge asymmetry at LHC is consistent with SM prediction of ~1%.

- Study of Ac in differential distributions might show hints for new physics in top quark pair production. The differential distributions are in well agreement with the SM predictions with large statistical uncertainties.

- Asymmetry measurements larger than theory prediction at Tevatron → hint for new physics?

- There are several models to explain the observed excess by Tevatron experiments and there is a class of BSM models consistent with the LHC and Tevatron data.

Thanks to the CMS Collaboration for providing the results.

Thanks for your attention!