Karlsruher Institut für Technologie

Measurement of the charge asymmetry in top quark pair production in pp collisions

ICHEP 2012 Melbourne

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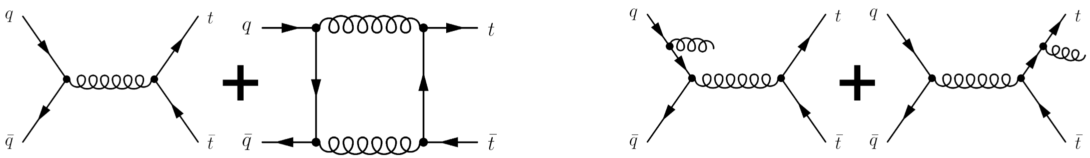
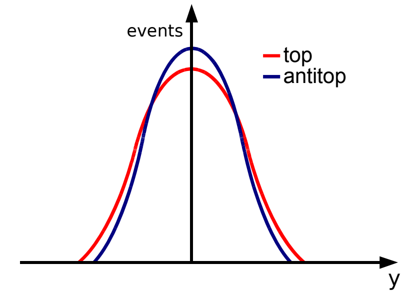
Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie

Preface: Charge asymmetry in $t\bar{t}$ events at LHC

- Higher order effect: interference of diagrams



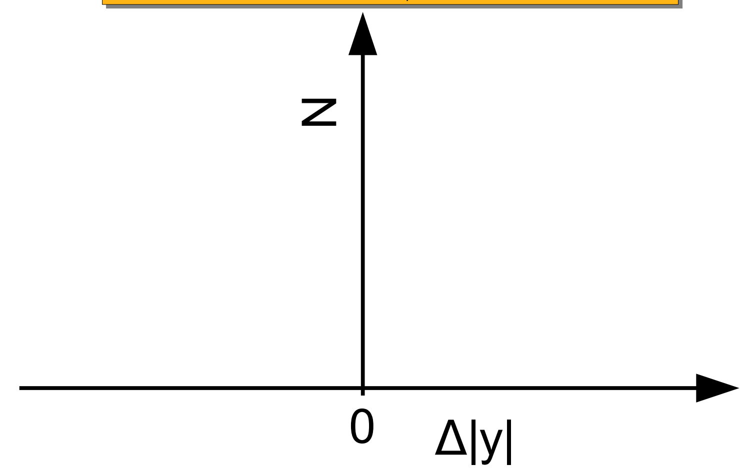


Sensitive variable:

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

Definition of charge asymmetry

$$A_C = \frac{N_+ - N_-}{N_+ + N_-}$$



- Connects directions of top and initial quark and directions of antitop and initial antiquark
- Only in $q\bar{q}$-initial state, not for gg
  - Effect is smaller at LHC compared to Tevatron
- LHC: pp collisions → no FB-asymmetry

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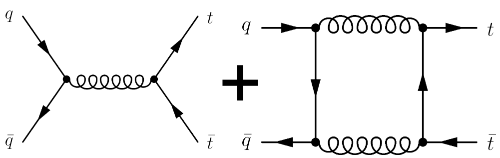

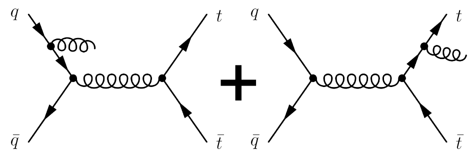

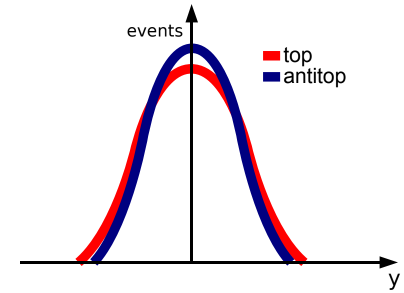

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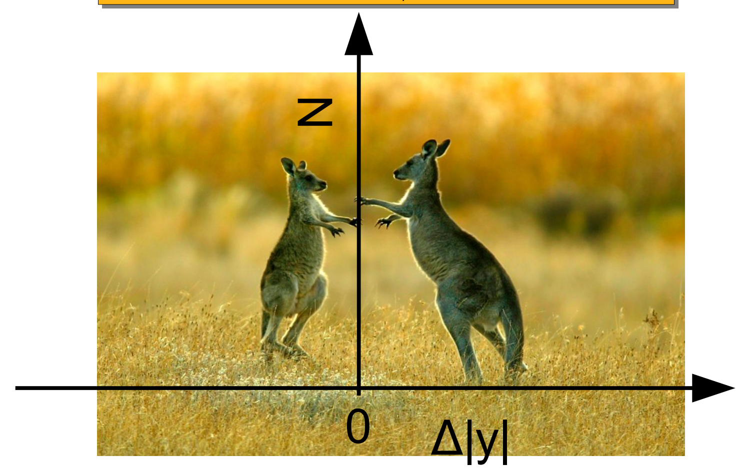
Theory prediction [Kühn, Rodrigo]

$$A_C = +0.0115 \pm 0.0006$$



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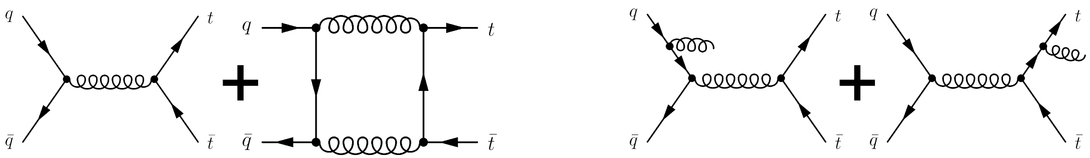

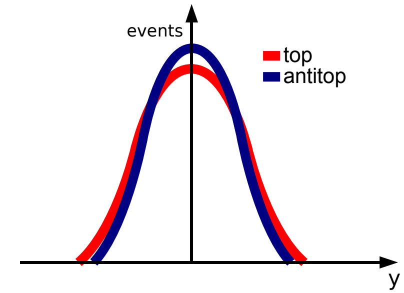

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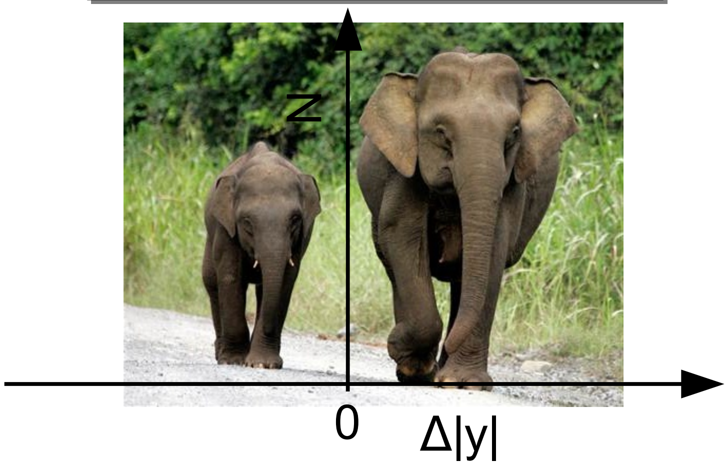
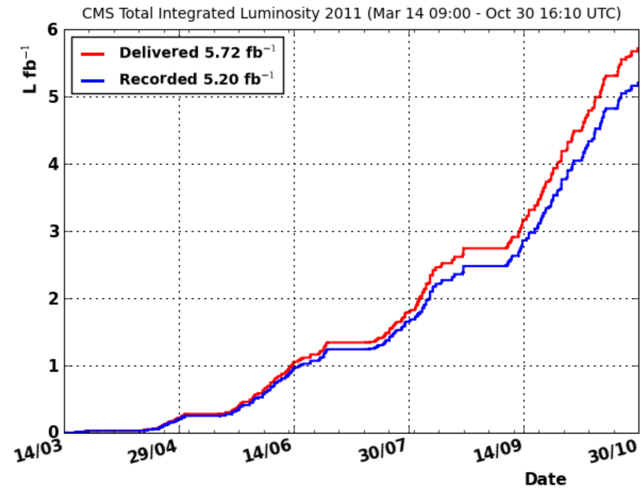


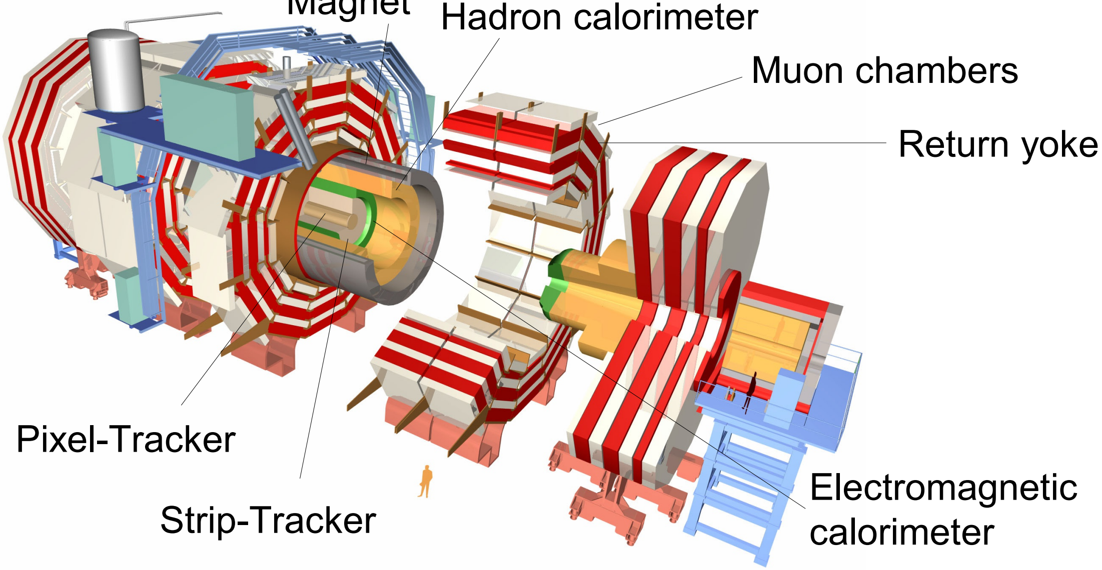
Sensitive to contributions from BSM physics like Axigluons, Z' bosons, axial couplings of the gluon ...

This presentation

- Lepton+jets channel (electron or muon)
- Certified data used for the analysis: **5 fb^{-1}**
- **An inclusive** and **three differential** measurements

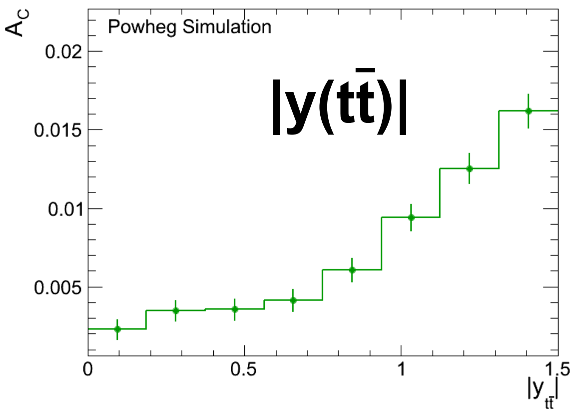
arXiv:1207.0065, submitted to PLB

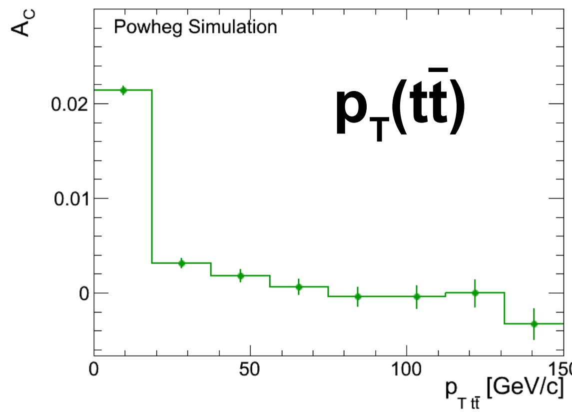


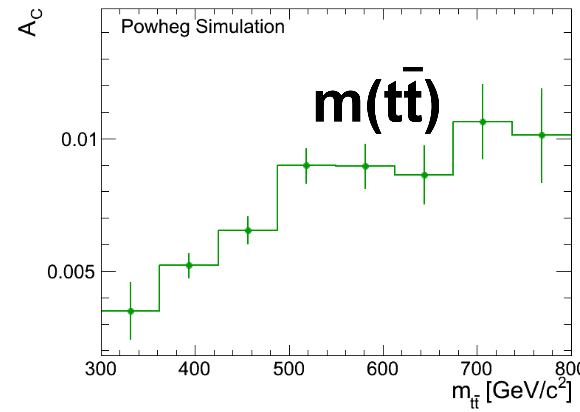


Differential measurements

Measure A_C in bins of 3 kinematic observables







- $q\bar{q}$ contribution increases with $|y(t\bar{t})|$

  → **A_C increases with $|y(t\bar{t})|$**

- Born-box interference leads to positive A_C contribution
- ISR-FSR interference leads to negative A_C contribution
- For larger $p_T(t\bar{t})$, ISR-FSR contribution dominates

  → **A_C decreases with $p_T(t\bar{t})$**

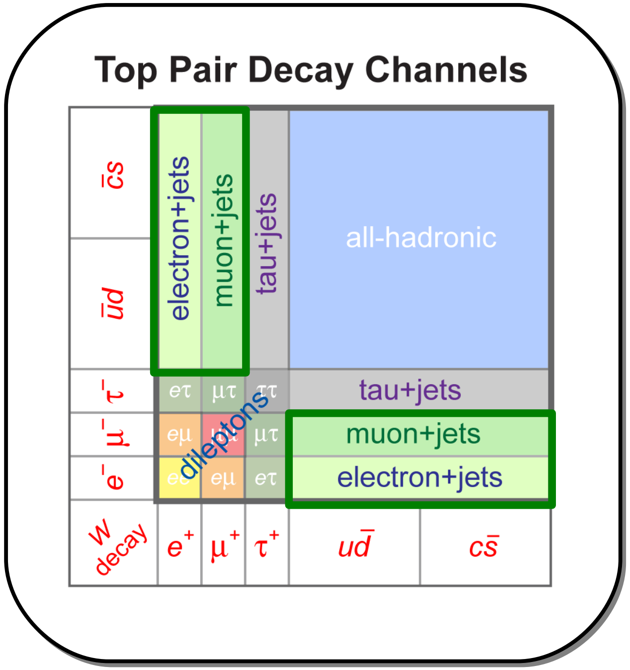
- $q\bar{q}$ contribution increases with $m(t\bar{t})$

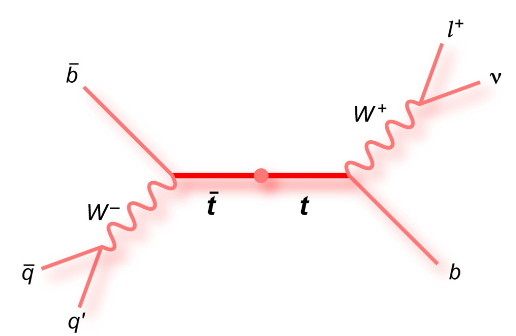
  → **A_C increases with $m(t\bar{t})$**

- Sensitive to heavy particles decaying to $t\bar{t}$: amplitudes could interfere with the SM ones

Lepton+jets event selection

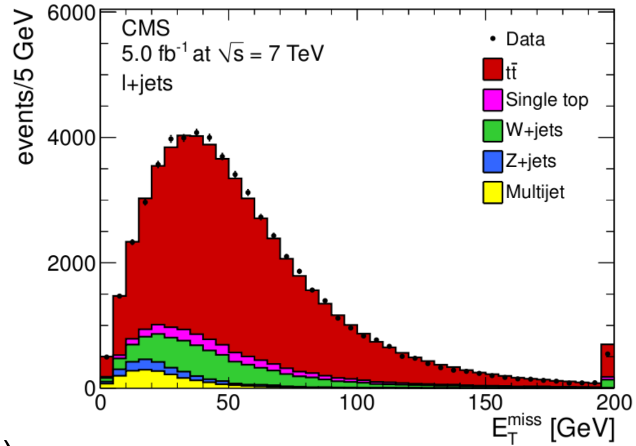
- **Trigger:** Lepton and 3-central-jets cross triggers
- **Lepton cut:** 1 isolated electron or muon
  - Electron: $E_T > 30$ GeV, $|\eta| < 2.5$
  - Muon: $p_T > 20$ GeV, $|\eta| < 2.1$
- **Second lepton veto:** reject events with additional electrons or muons
  - Electron: $E_T > 15$ GeV, $|\eta| < 2.5$
  - Muon: $p_T > 10$ GeV, $|\eta| < 2.5$
- **Conversion rejection** (only electron+jets)
- **Jet cut:** At least 4 jets (PFjets)
  - Jet: $p_T > 30$ GeV, $|\eta| < 2.4$
- **b tag:** at least 1 jet must be tagged





Background estimation

- Binned likelihood fit with 2 variables:
  - MET < 40 GeV: **MET**
  - MET > 40 GeV: **M3**
- Electron+jets and muon+jets channels are fitted separately

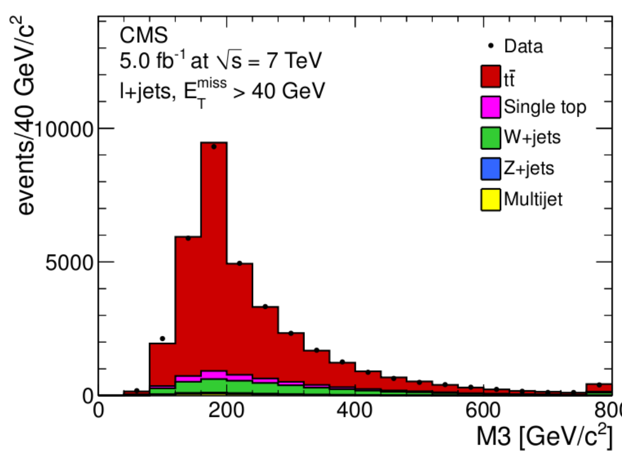


(M3: invariant mass of the combination of three jets yielding the largest p_T)

Simulation is normalized to the fit results

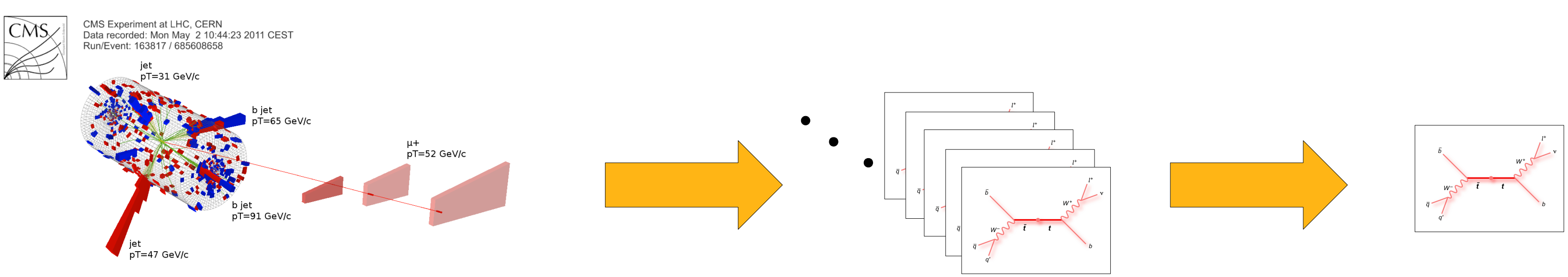
Process	Electron+jets	Muon+jets	Total
Single top (t + tW)	1113 ± 338	1418 ± 505	2532 ± 608
W^++jets	1818 ± 227	1807 ± 290	3625 ± 369
W^-+jets	1454 ± 224	1320 ± 275	2773 ± 355
Z+jets	535 ± 153	600 ± 170	1135 ± 229
Multijet	1142 ± 227	863 ± 209	2005 ± 308
Total BG	6062 ± 540	6008 ± 698	12070 ± 882
$t\bar{t}$	18634 ± 390	26976 ± 468	45610 ± 609
Observed data	24705	32992	57697

BG-contribution to selected dataset: **~20%**



Reconstruction of the $t\bar{t}$ pair

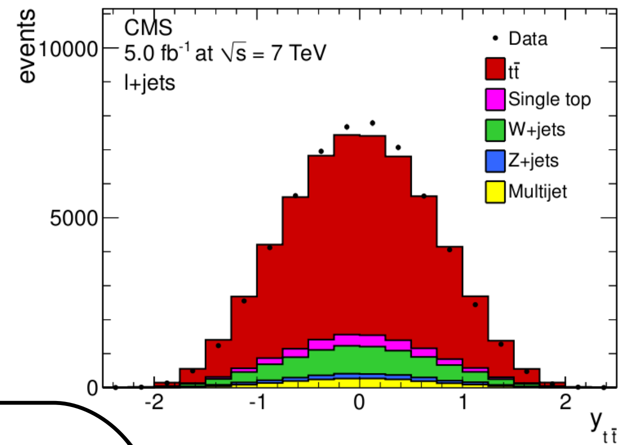
- Reconstruct the fourmomenta of top and antitop from the measured lepton, jets, MET
- W_{lep} is reconstructed from the lepton and MET
  - z-component of the neutrino vector from W-boson mass constraint
- Consider all possible jet – quark assignments
- Leads to <u>several hypotheses</u> per event
- Select **1 hypothesis** per event, based on a likelihood method using:
  - Masses of the reconstructed top quarks and W_{had}
  - b-tagger output for the jets assigned to b-quarks and light quarks
  - In **72%** of all events $\Delta|y|$ is reconstructed with the **correct sign**

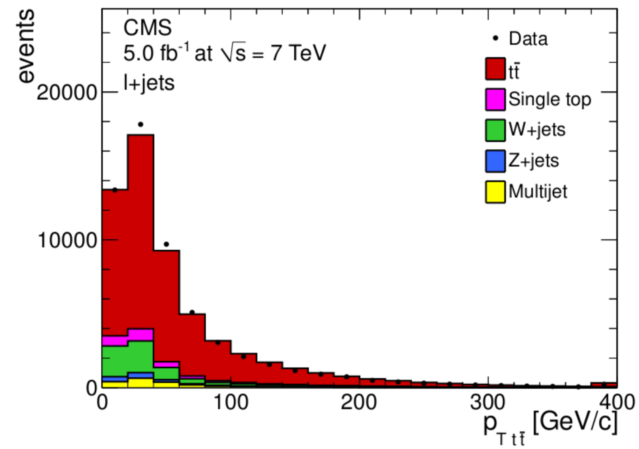


Variables after reconstruction

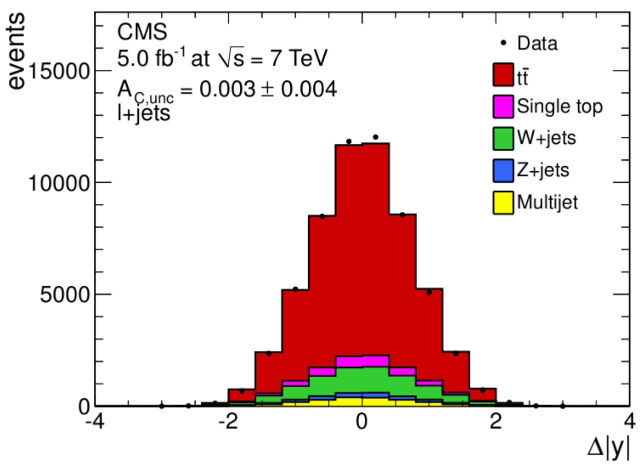
Simulation is normalized to the BG-fit-results

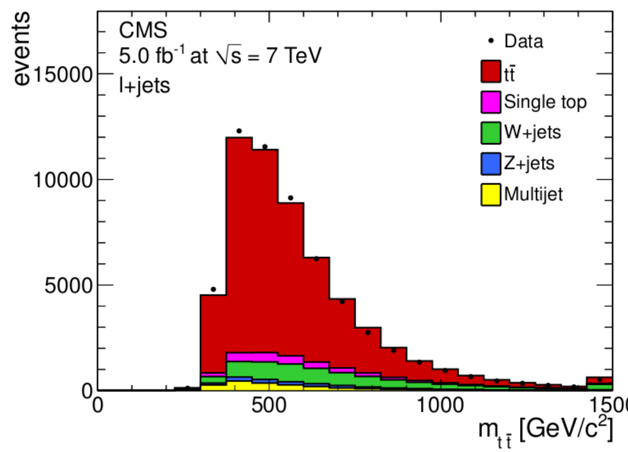
Kinematic variables





Sensitive variable





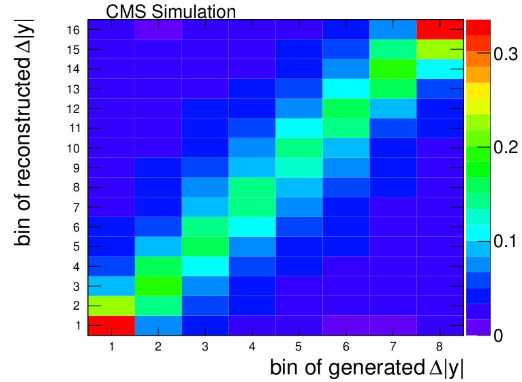
Unfolding

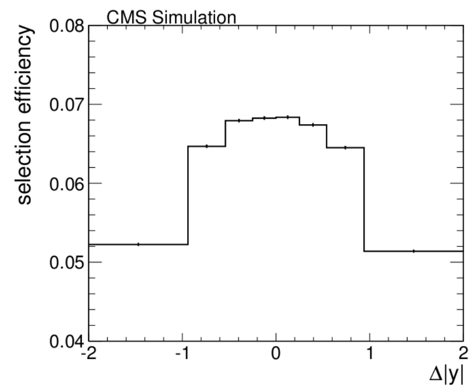
Reconstructed distributions are diluted and have to be corrected.

- BG contribution is subtracted (taking uncertainties and correlations into account)
- Migration effects from the reconstruction
- $\Delta|y|$- and V- dependent selection efficiency ($V = |y(t\bar{t})|$, $p_T(t\bar{t})$, $m(t\bar{t})$)

Smearing matrix

Measured spectrum $\vec{w} = S \cdot \vec{x}$ True spectrum





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Smearing matrix

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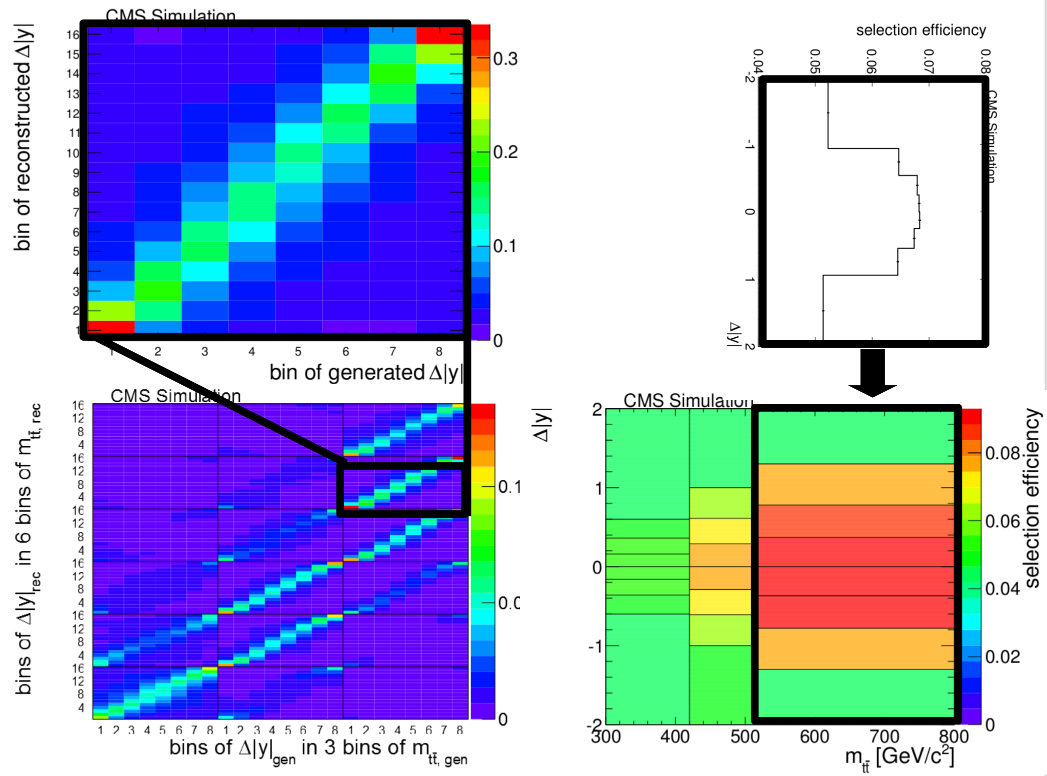
2 dimensional unfolding for the differential measurements



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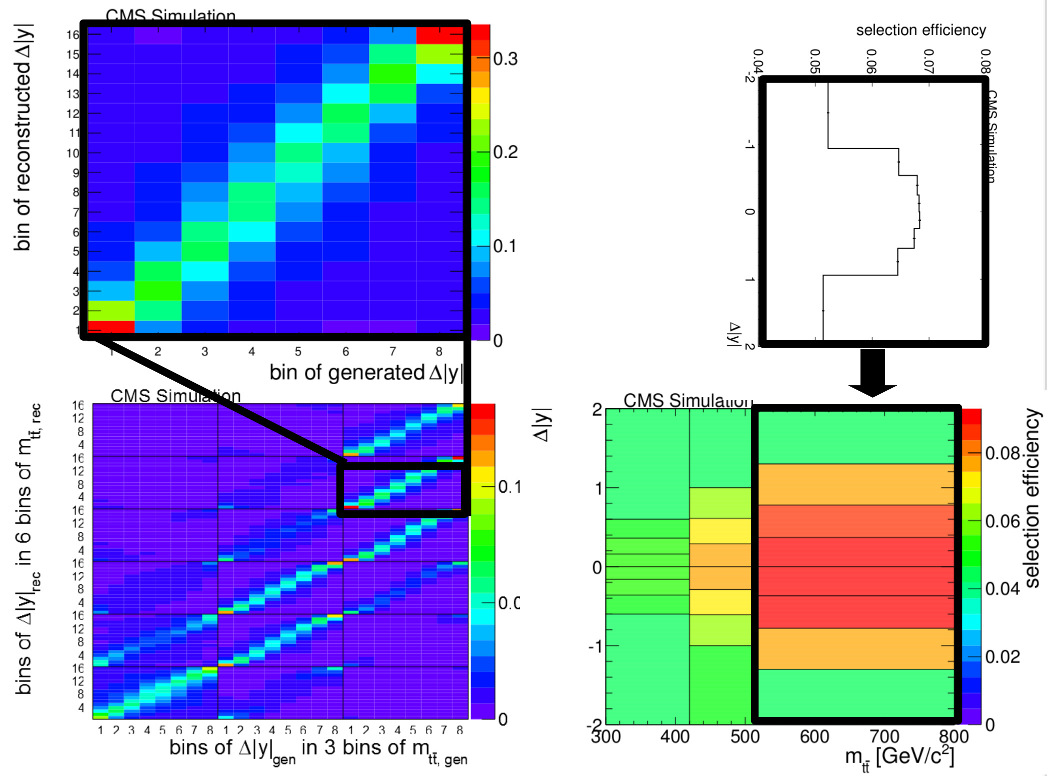
Smearing matrix

Measured spectrum $\vec{w} = S \cdot \vec{x}$ True spectrum

- Solve equation with matrix inversion
- Regularization to stabilize the result



Cross Checks

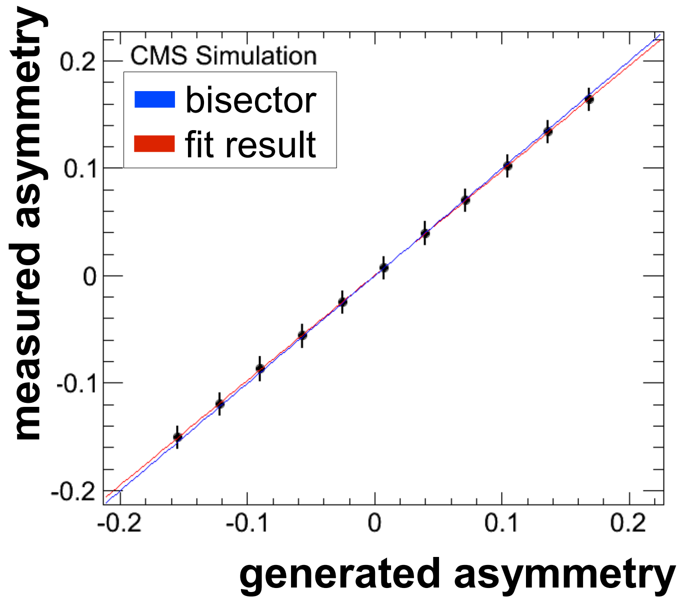
- Unfolding method is checked for stability using pseudo experiments
- Samples are re-weighted to artificially generate different asymmetries

$$w = k \cdot \Delta |y| + 1$$

- For inclusive measurement as well as for single bins of the differential measurements
- To test the model-independence of the unfolding procedure:
  - Produced asymmetries depending on the kinematic variables V

$$w = k(V) \cdot \Delta |y| + 1$$

Linearity check for the inclusive measurement



Systematic uncertainties

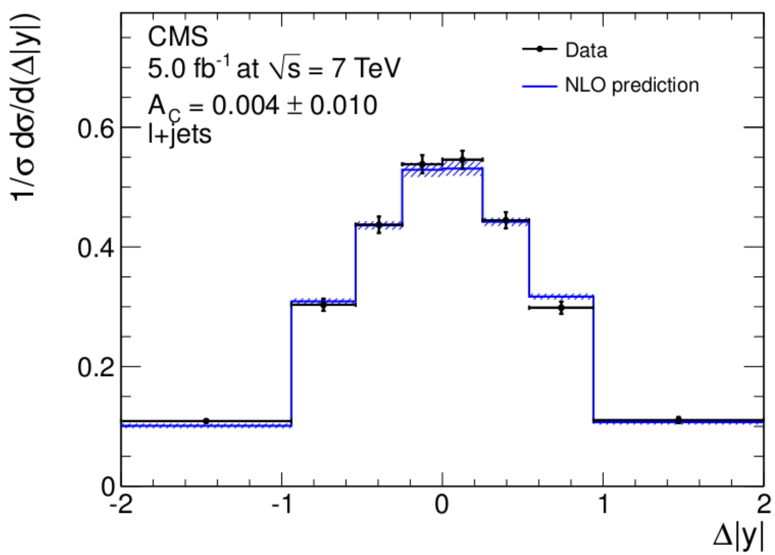
- **Repeat** the **BG estimation** with shifted fit-templates
- **Repeat** the **measurement** using shifted templates for BG-subtraction and unfolding

Systematic uncertainties of the inclusive measurement

Systematic uncertainty	Shift (±) in inclusive A_C
JES	0.003
JER	0.002
Lepton ID/sel. efficiency	0.006
Generator	0.001
Hadronization	0.001
Q^2 scale	0.002
PDF	0.002
Pileup	< 0.001
W+jets	0.004
Multijet	0.001
Migration matrix	0.002
Model dependence	0.007
Total	0.011

- Largest contributions in **differential measurements**:
  - JES, Lepton ID, Model dependence
  - Generator, Hadronization (only for $m(t\bar{t})$ and $p_T(t\bar{t})$)

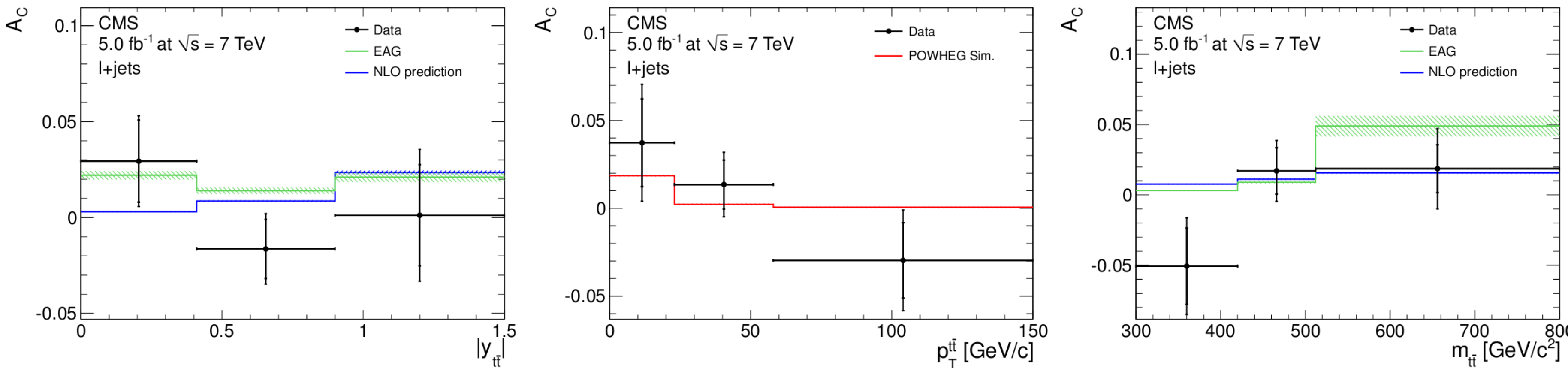
Result (inclusive measurement)



Measured asymmetry is small:
consistent with null-asymmetry
as well as with the **SM prediction**

Uncorrected	0.003 ± 0.004 (stat.)
BG-subtracted	0.002 ± 0.005 (stat.) ± 0.003 (syst.)
Final corrected	0.004 ± 0.010 (stat.) ± 0.011 (syst.)
Theoretical prediction (SM) [Kühn, Rodrigo, arXiv:1109.6830]	0.0115 ± 0.0006

Results (differential measurements)



- Measured asymmetries are compared to
  - **SM prediction at NLO** [1]
  - **SM simulation at NLO** (POWHEG)
  - **BSM prediction** with an effective axial-vector coupling of the gluon at the one-loop level (EAG) [2]
    - Can explain the strong dependence of A_{FB} on $m(t\bar{t})$ as seen by CDF
- Within the (large) uncertainties: **no significant deviations from the SM predictions**

[1] Kühn, Rodrigo - arXiv:1109.6830 [2] Gabrielli, Racioppi, Raidal - PRD 85 (2012) 074021, arXiv:1112.5885; arXiv:1203.1488

Conclusion

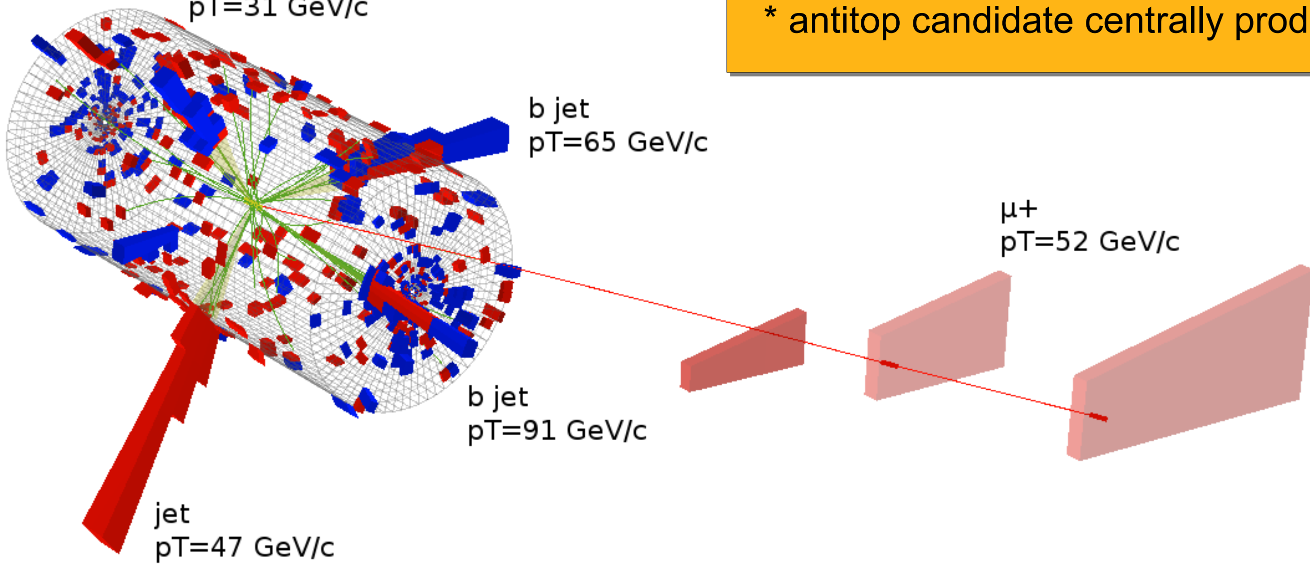
- CMS has measured the $t\bar{t}$ charge asymmetry in the l+jets channel using the entire 7 TeV dataset
- A_C has been measured inclusively and differentially
- The measured charge asymmetries are comparable with null-asymmetry as well as with SM predictions

Thank you

Backup

$t\bar{t}$ candidate event

CMS Experiment at LHC, CERN
Data recorded: Mon May 2 10:44:23 2011 CEST
Run/Event: 163817 / 685608658



Top quark pair candidate event
* high probability to be $t\bar{t}$ event
* 2 b-tagged jets
* top candidate in forward direction
* antitop candidate centrally produced

Backup: Triggers

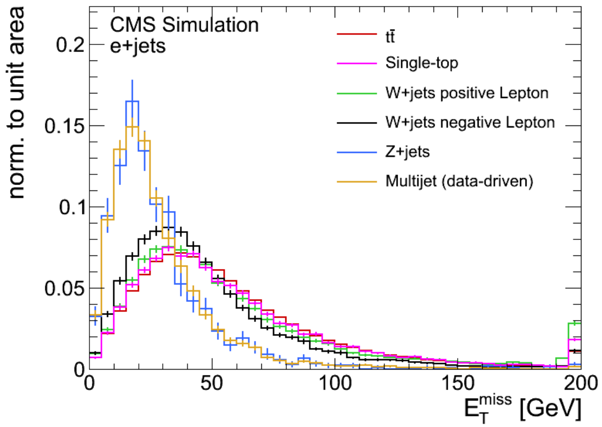
- HLT_Ele25_CaloIdVT_TrkIdT_CentralTriJet30 (160404 – 163869)
- HLT_Ele25_CaloIdVT_TrkIdT_TriCentralJet30 (163870 – 165969)
- HLT_Ele25_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_TriCentralJet30 (165970 – 178380)
- HLT_Ele25_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_TriCentralPFJet30 (178420 – 180252)

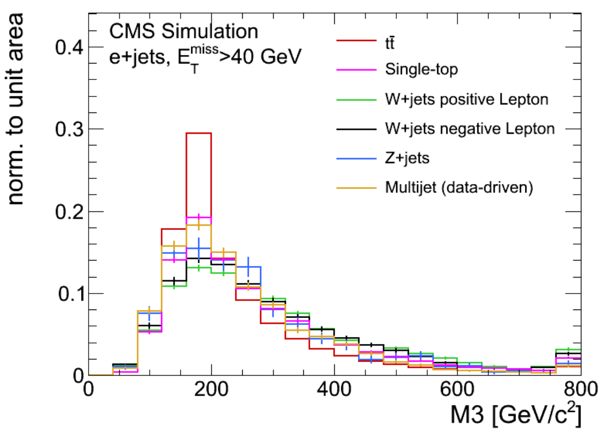
- HLT_Mu17_TriCentralJet30 (160404 – 165969)
- HLT_IsoMu17_TriCentralJet30 (165970 – 173198)
- HLT_IsoMu17_eta2p1_TriCentralJet30 (173236 – 178380)
- HLT_IsoMu17_eta2p1_TriCentralPFJet30 (178420 – 180252)

Backup: More details on BG estimation

For illustration purpose: fit-templates for e+jets channel

- Binned Likelihood-fit
- Fit **MET** in the range **MET<40 GeV**
- Fit **M3** in events with **MET>40 GeV**
- Fit **electron+jets** and **muon+jets separately**
- MC-Templates, except for QCD:
  - Data-driven QCD template, from events with non-isolated charged leptons
- Constrain single top and Z+jets to the theory prediction using Gauss constraints (width: 30%)





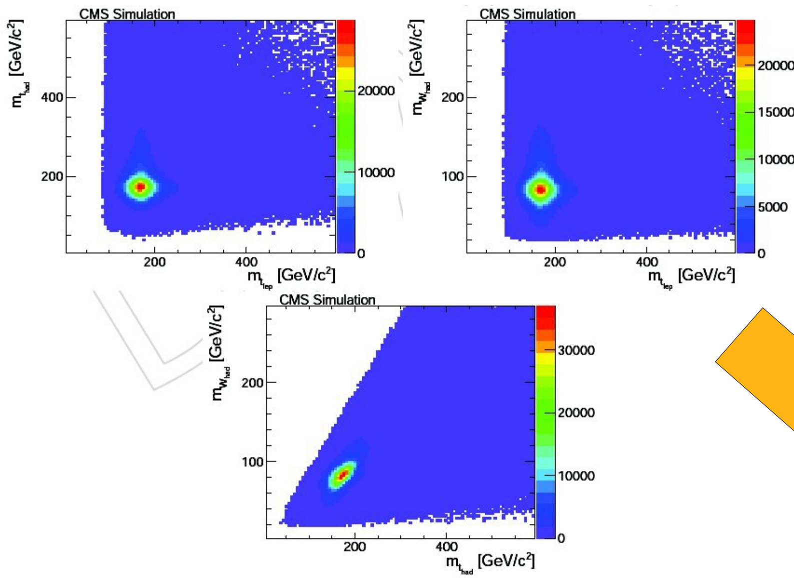
M3: Invariant mass of the three jets with the highest vectorially summed pT

Backup: Reconstruction details (1)

- Select **1 hypothesis** per event, based on a likelihood method using:
  - Masses of the reconstructed top quarks and W_{had}
  - b-tagger output for the jets assigned to b-quarks and light quarks
- Calculate the probability for each hypothesis to be the **best possible assignment**
  - Best possible: Defined on MC as the hypothesis where...
    - reconstructed and generated top quarks
    - reconstructed and generated W bosons

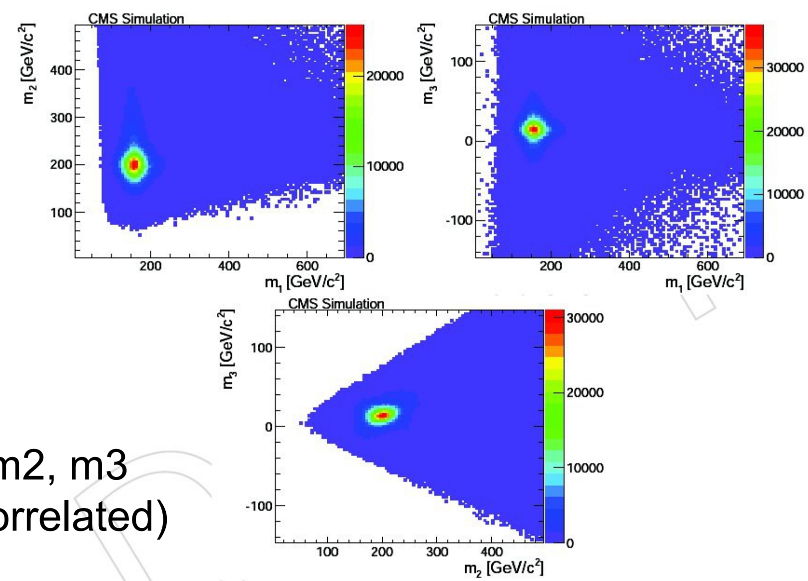
    ...are closest to each other in η-ϕ space
- Performance test on MC:
  - In **72%** of all events $\Delta|y|$ is reconstructed with the **correct sign**

Backup: Reconstruction details (2)



Masses of the 2 top quarks and the hadronically decaying W boson

$$\begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix} = \begin{pmatrix} 1.00 & -0.06 & 0.00 \\ 0.05 & 0.94 & 0.35 \\ -0.02 & -0.35 & 0.94 \end{pmatrix} \begin{pmatrix} m_{t,\mathrm{lep}} \\ m_{t,\mathrm{had}} \\ m_{W,\mathrm{had}} \end{pmatrix}$$



m1, m2, m3 (uncorrelated)

Backup: Reconstruction details (3)

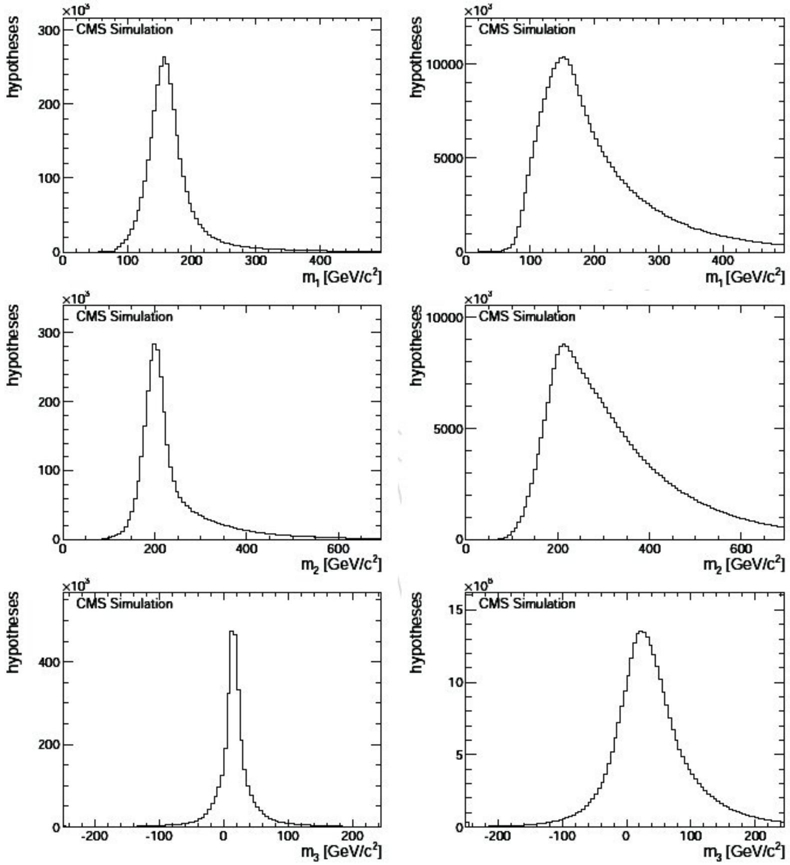


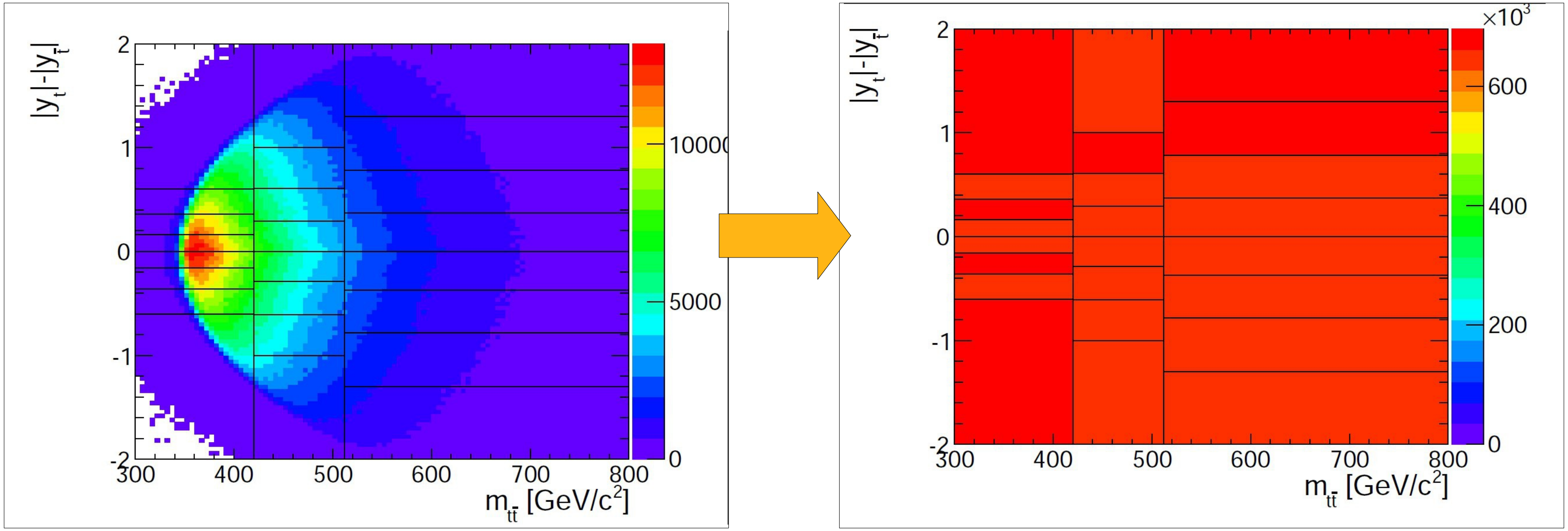
Figure 8: Decorrelated masses m_1, m_2, m_3 for the best possible hypotheses (left) and for all hypotheses (right).

We choose the hypothesis with the largest ψ value

$$\psi = L_1(m_1)L_2(m_2)L_3(m_3)P_b(x_{b,\mathrm{lep}})P_b(x_{b,\mathrm{had}})(1 - P_b(x_{q1}))(1 - P_b(x_{q2}))$$

Backup: Binning

For illustration: True Δ|y| vs true $m_{t\bar{t}}$



In order to stabilize the unfolding procedure, the binning has to fulfill:

- Reconstructed spectrum should be flat (similar statistics in each bin)
- Unfolded spectrum should be flat

Optimized binning for **reconstructed** and **unfolded (true)** spectra **independently**

Backup: Unfolding details (1)

- **Regularized unfolding** through a **generalized matrix inversion** method
- TUnfold package

Covariance matrix of the measured spectrum

  - Least-square problem:

$$F_{\mathrm{LS}}(\vec{x}) = (S\vec{x} - \vec{w})^{\mathrm{T}} V_w^{-1} (S\vec{x} - \vec{w})$$

  - Solution:

$$\vec{x}_{\mathrm{LS}} = S^{\#}\vec{w} \text{ with } S^{\#} = (S^{\mathrm{T}} V_w^{-1} S)^{-1} S^{\mathrm{T}} V_w^{-1}$$

Generalized inverse matrix

    - In general: unstable, huge fluctuations
  - Regularization:

$$F(\vec{x},\kappa) = F_{\mathrm{LS}}(\vec{x}) + \tau ||L(\vec{x} - \vec{x_{\mathrm{bias}}})||^2 + \kappa(N_{\mathrm{obs}} - \sum_{i=1}^{n} (S\vec{x})_i)^2$$

Regularization term

Proportional to **2^{nd} derivatives of x - x_{bias}**

Normalization term

    - Bias distribution: from default MC sample → Curvature of difference between unfolded and default MC distribution is used for regularization
  - For τ we choose the value that minimizes the global correlation between the data points of the unfolded spectrum (Minimum of Global Correlation Method)

Backup: Unfolding details (2)

Background subtraction

In a first step the predicted background is subtracted from the reconstructed data distributions. For this we use the fitted numbers of events and their uncertainties for the various background processes given in table 2. For all background processes but the QCD multijet BG we use the templates derived from the MC samples listed in table 1. The QCD template is derived directly from data by inverting some of the event selection cuts, as described earlier. To take not only the statistical uncertainties on the fit results but also the correlation between the fit parameters into account, we transform the background templates $\vec{b}_i$ (where i represents the different BG processes) into orthogonal templates $\vec{b}'_j$ with uncorrelated uncertainties. For this purpose the covariance matrix of the background estimation fit V_b is used:

$$\vec{b}'_j = \sum_{i=1}^{N} \vec{b}_i (\vec{v}_j)_i^2 \,, \tag{11}$$

where $\vec{v}_{j_i}$ is the i^{th} element of the eigenvector $\vec{v}_j$ of the covariance matrix. The properly normalized orthogonal background templates are then subtracted from the data, assuming Gaussian uncertainties on the background rates as well as on statistical fluctuations in the background templates.

Backup: Unfolding details (3)

In order to solve $\vec{w} = S\vec{x}$, this equation is formulated as a least-square (LS) problem. The solution vector $\vec{x}$ can be found by minimizing:

$$F_{\mathrm{LS}}(\vec{x}) = (S\vec{x} - \vec{w})^{\mathrm{T}} V_w^{-1} (S\vec{x} - \vec{w}) \,, \qquad (12)$$

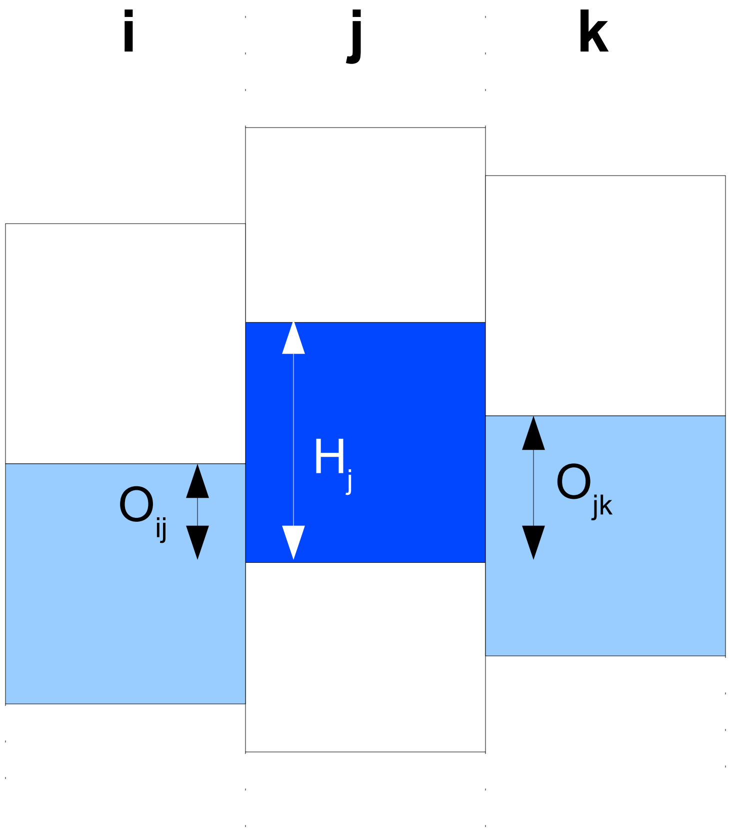
where V_w is the covariance matrix of the measured distribution $\vec{w}$. Introducing a generalized inverse matrix $S^{\#}$, the solution $\vec{x}_{\mathrm{LS}}$ is then given by:

$$\vec{x}_{\mathrm{LS}} = S^{\#}\vec{w} \text{ with } S^{\#} = (S^{\mathrm{T}} V_w^{-1} S)^{-1} S^{\mathrm{T}} V_w^{-1} \,. \qquad (13)$$

In general, this solution is unstable and shows huge fluctuations for small changes in $\vec{w}$. This is not a numerical problem but is inherited from the properties of the matrix S. Usually, the singular values of S are of different orders of magnitude. The generalized inversion of S will therefore be dominated by the smallest singular values which belong to highly fluctuating eigenmodes of $\vec{w}$. Consequently, the solution $\vec{x}$ will be dominated by small and insignificant fluctuations of $\vec{w}$. The details of the singular value analysis can be found in [48]. A modification of the χ^2 function F_{LS} is introduced to regularize the problem and to avoid unphysical fluctuations [49, 50]:

$$F(\vec{x}, \kappa) = F_{\mathrm{LS}}(\vec{x}) + \tau ||L(\vec{x} - \vec{x_{\mathrm{bias}}})||^2 + \kappa (N_{\mathrm{obs}} - \sum_{i=a}^{n} (S\vec{x}_i))^2 \,. \qquad (14)$$

Backup: Unfolding details (4)



The coefficients of L are weighted with

$$w=\frac{O_{ij}\cdot O_{jk}}{H_j^2}$$

to account for the non-100% overlap of the bins in the kinematic variable (due to the special binning)

The sum over all weights for a given central bin j is 1:

$$\sum_{i,k} w_{ijk}=1$$

Backup: Effective axial-coupling

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Effective axial-vector coupling of gluon as an explanation to the top quark asyn

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Implications of the effective axial-vector coupling of gluon on top-quark charge asymmetry at the LHC

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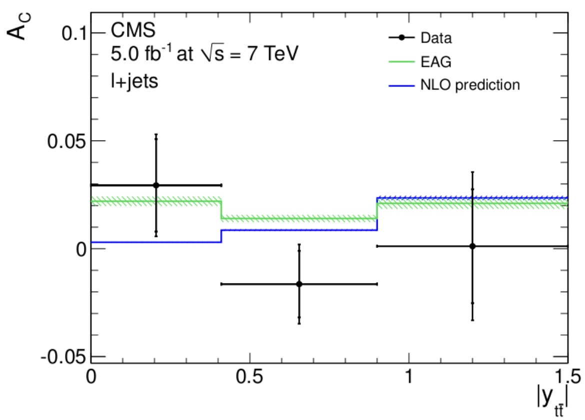
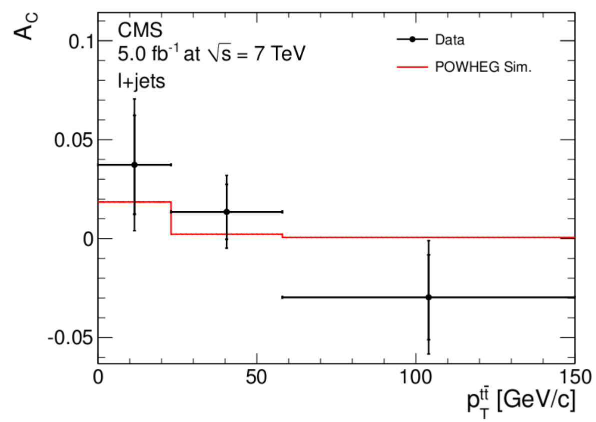
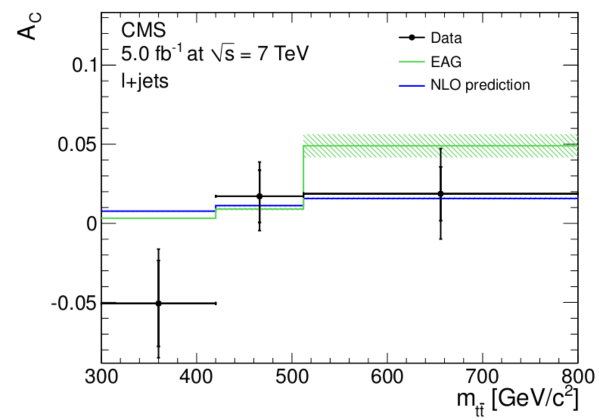
(arXiv:1112.5885)

Our proposal consists in adding an **anomalous effective axial-coupling to the gluon with quarks** that is induced at one loop level. We treated this vertex in the **approximation of the effective theory**. Color gauge invariance requires that such a coupling must vanish with vanishing external momenta, namely $g_A(q^2) \sim q^2/\Lambda^2$, where Λ is the **scale of new physics** assumed to be larger than any other scale in the set up. In this framework the observed Tevatron $t\bar{t}$ anomaly can be explained in a consistent way with a universal anomalous gluon coupling with Λ of order of TeV. **Because of the q^2 behavior** of the effective coupling, this scenario is testable at the LHC.

Backup: Differential results







Kinematic variable	A_C in bin 1	A_C in bin 2	A_C in bin 3
$\|y_{t\bar{t}}\|$	$0.029 \pm 0.021 \pm 0.010$	$-0.016 \pm 0.015 \pm 0.010$	$0.001 \pm 0.026 \pm 0.022$
$\|y_{t\bar{t}}\|$(SM pred.)	0.0030 ± 0.0002	0.0086 ± 0.0004	0.0235 ± 0.0010
$p_T^{t\bar{t}}$	$0.037 \pm 0.025 \pm 0.022$	$0.014 \pm 0.014 \pm 0.012$	$-0.030 \pm 0.021 \pm 0.019$
$p_T^{t\bar{t}}$ (simulation)	0.0185 ± 0.0004	0.0022 ± 0.0004	0.0006 ± 0.0004
$m_{t\bar{t}}$	$-0.051 \pm 0.027 \pm 0.021$	$0.017 \pm 0.017 \pm 0.014$	$0.019 \pm 0.017 \pm 0.023$
$m_{t\bar{t}}$ (SM pred.)	0.0077 ± 0.0003	0.0112 ± 0.0004	0.0157 ± 0.0006

[Kühn, Rodrigo, arXiv:1109.6830]