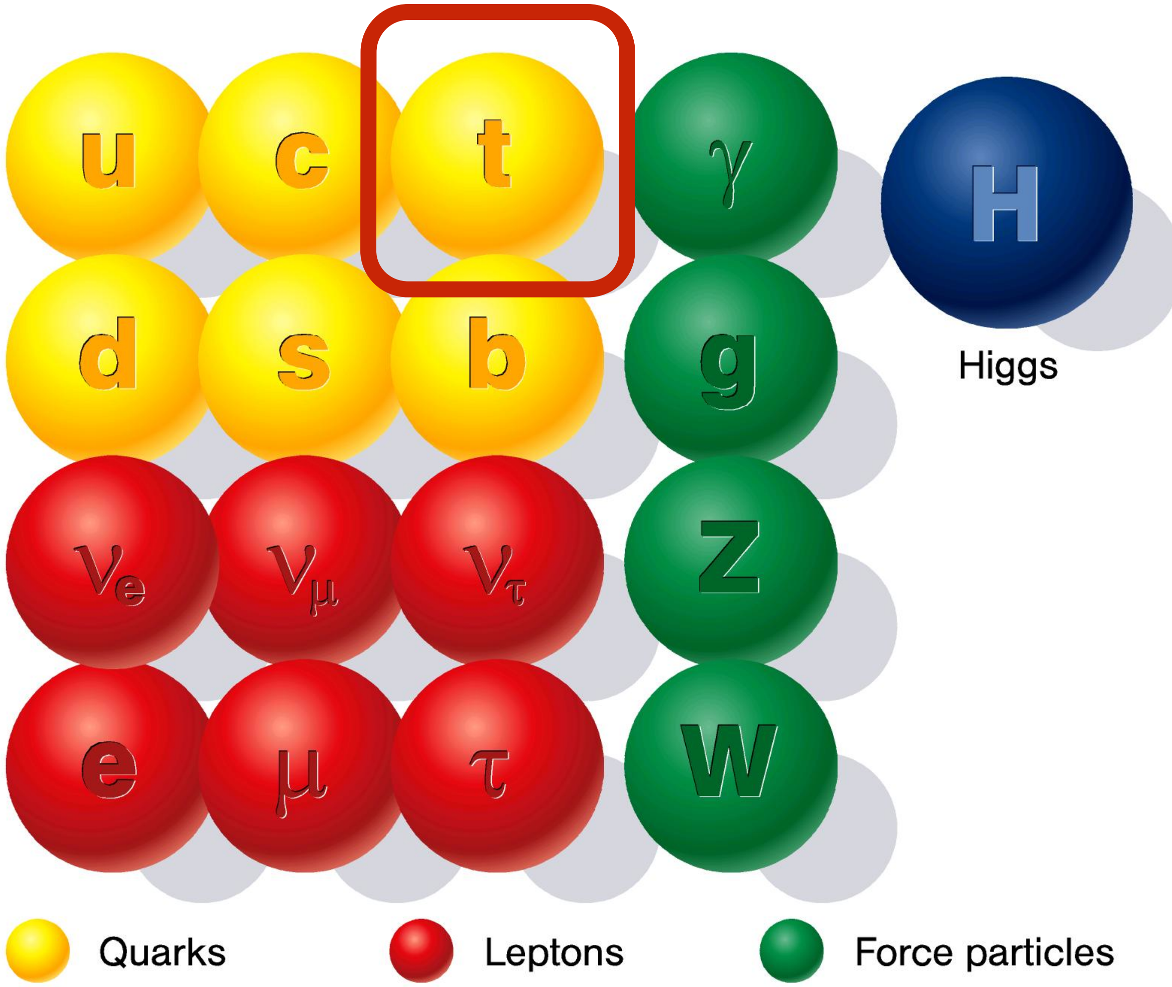
Recent Top Pair Asymmetry Measurements at CMS

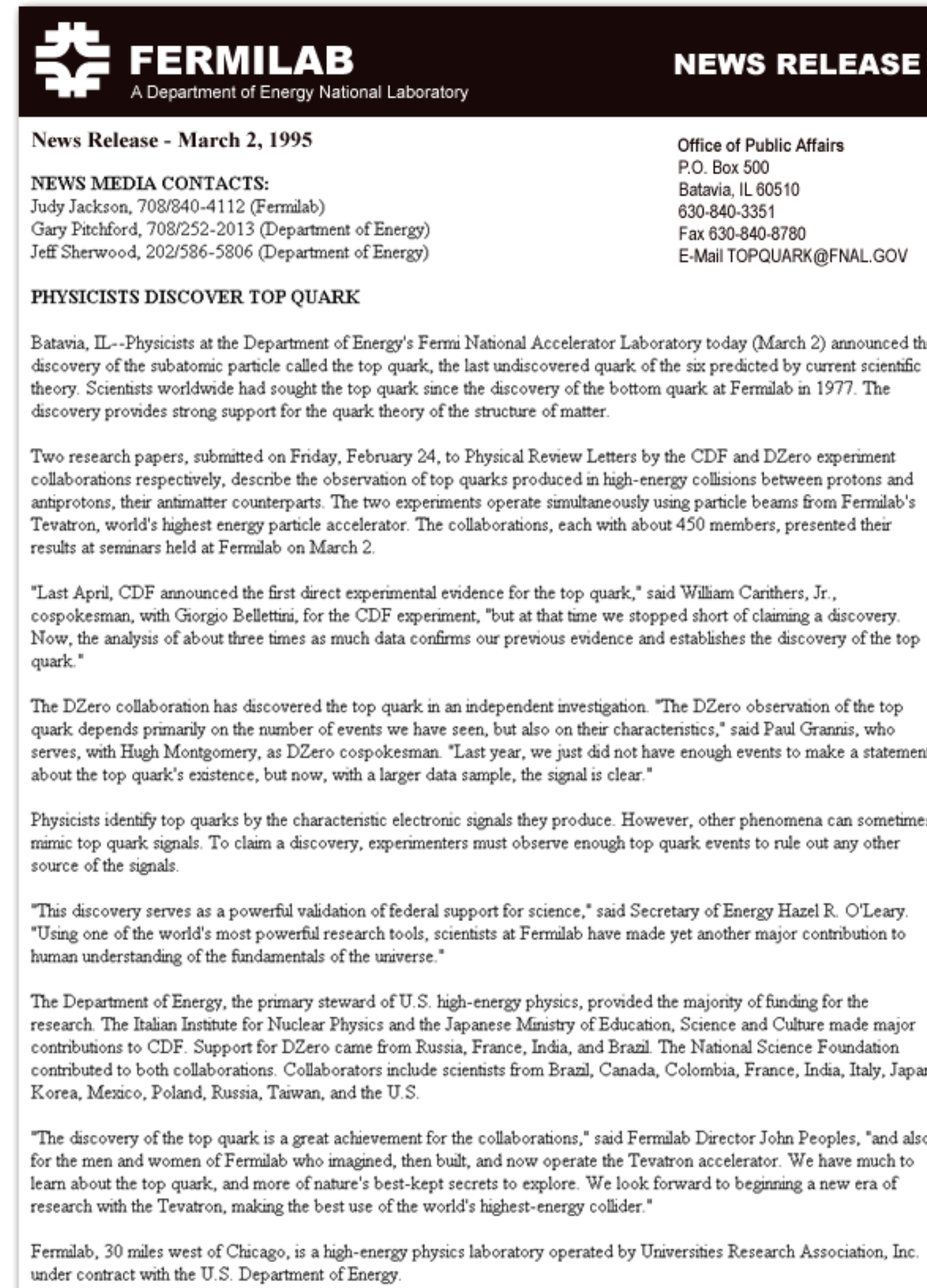
Fermilab Joint Experimental-Theoretical Physics Seminar
14. February 2014

Oliver Gutsche (Fermilab)
for the
CMS collaboration

Top Quark



Discovered by the CDF and D0 collaborations in 1995 at the Tevatron here at Fermilab



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NEWS RELEASE

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PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Two research papers, submitted on Friday, February 24, to Physical Review Letters by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts. The two experiments operate simultaneously using particle beams from Fermilab's Tevatron, world's highest energy particle accelerator. The collaborations, each with about 450 members, presented their results at seminars held at Fermilab on March 2.

"Last April, CDF announced the first direct experimental evidence for the top quark," said William Carithers, Jr., cospokesman, with Giorgio Bellettini, for the CDF experiment, "but at that time we stopped short of claiming a discovery. Now, the analysis of about three times as much data confirms our previous evidence and establishes the discovery of the top quark."

The DZero collaboration has discovered the top quark in an independent investigation. "The DZero observation of the top quark depends primarily on the number of events we have seen, but also on their characteristics," said Paul Grannis, who serves, with Hugh Montgomery, as DZero cospokesman. "Last year, we just did not have enough events to make a statement about the top quark's existence, but now, with a larger data sample, the signal is clear."

Physicists identify top quarks by the characteristic electronic signals they produce. However, other phenomena can sometimes mimic top quark signals. To claim a discovery, experimenters must observe enough top quark events to rule out any other source of the signals.

"This discovery serves as a powerful validation of federal support for science," said Secretary of Energy Hazel R. O'Leary. "Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

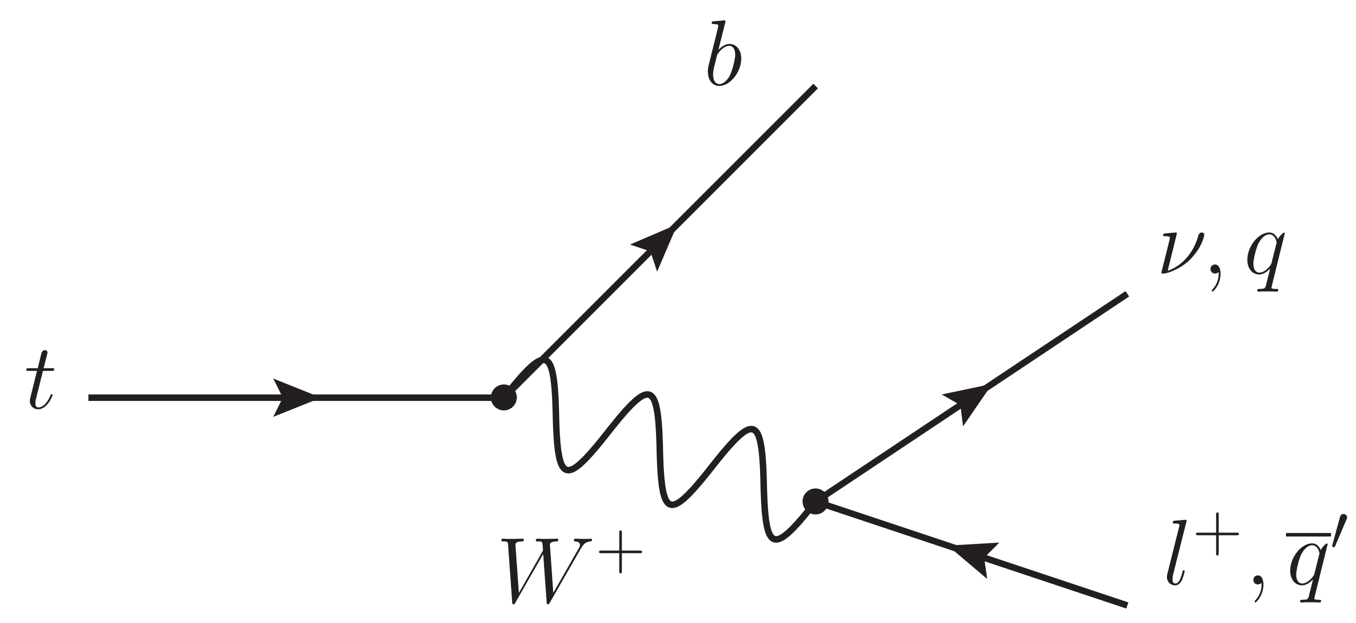
The Department of Energy, the primary steward of U.S. high-energy physics, provided the majority of funding for the research. The Italian Institute for Nuclear Physics and the Japanese Ministry of Education, Science and Culture made major contributions to CDF. Support for DZero came from Russia, France, India, and Brazil. The National Science Foundation contributed to both collaborations. Collaborators include scientists from Brazil, Canada, Colombia, France, India, Italy, Japan, Korea, Mexico, Poland, Russia, Taiwan, and the U.S.

"The discovery of the top quark is a great achievement for the collaborations," said Fermilab Director John Peoples, "and also for the men and women of Fermilab who imagined, then built, and now operate the Tevatron accelerator. We have much to learn about the top quark, and more of nature's best-kept secrets to explore. We look forward to beginning a new era of research with the Tevatron, making the best use of the world's highest-energy collider."

Fermilab, 30 miles west of Chicago, is a high-energy physics laboratory operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

The Top Quark is special

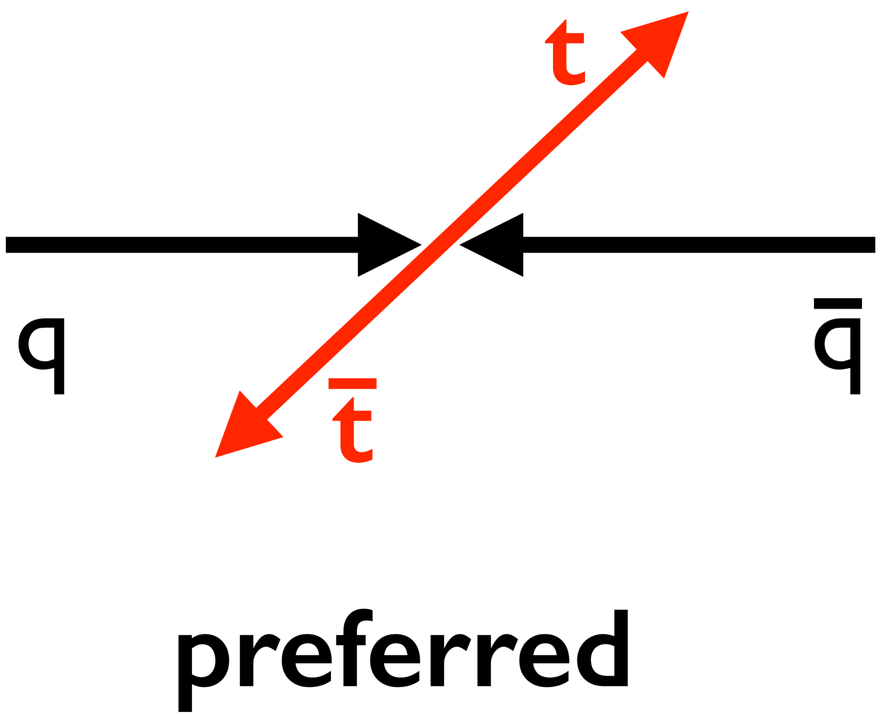
- Very heavy
  - $m_{top} \approx 173$ GeV
- Very short lifetime
  - $\tau \approx 5\text{x}10^{-25}$s
    - Shorter than hadronization timescale
    - Shorter than spin de-correlation timescale (spin effects are passed on to decay products)

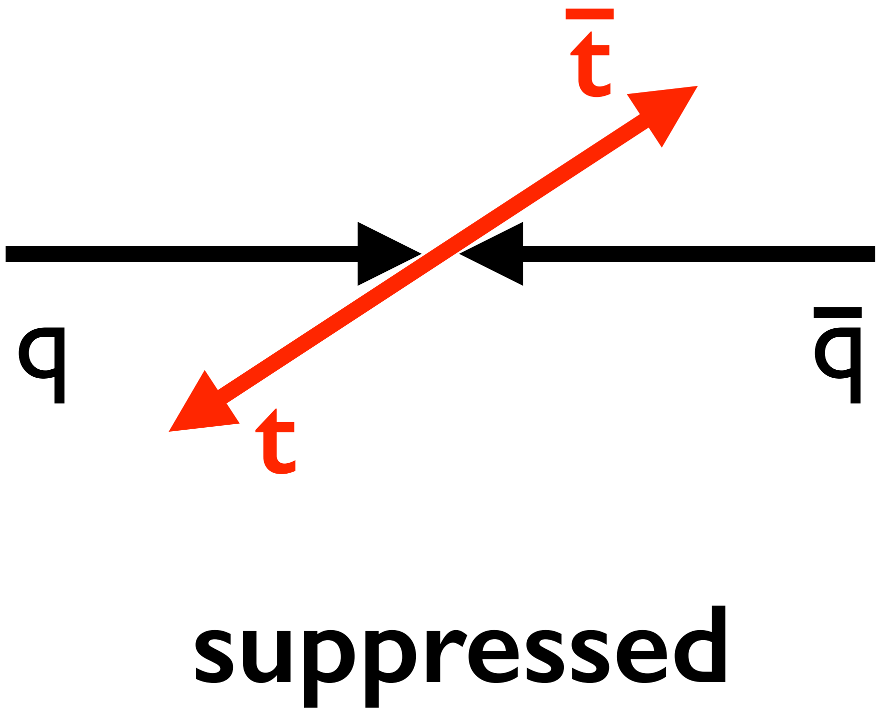


- Laboratory to study top quark properties
- We can measure:
  - Mass, charge, spin
  - Top polarization, spin correlation

Top quark laboratory

- Tests of Standard Model (SM) predictions
  - Very high precision measurements are possible
  - Can be compared to theoretical predictions
- Search for evidence for new physics
  - Top quarks could decay into new particles
  - Top quarks could be produced from decay/exchange of new particles
  - Deviations from the SM could indicate new physics!

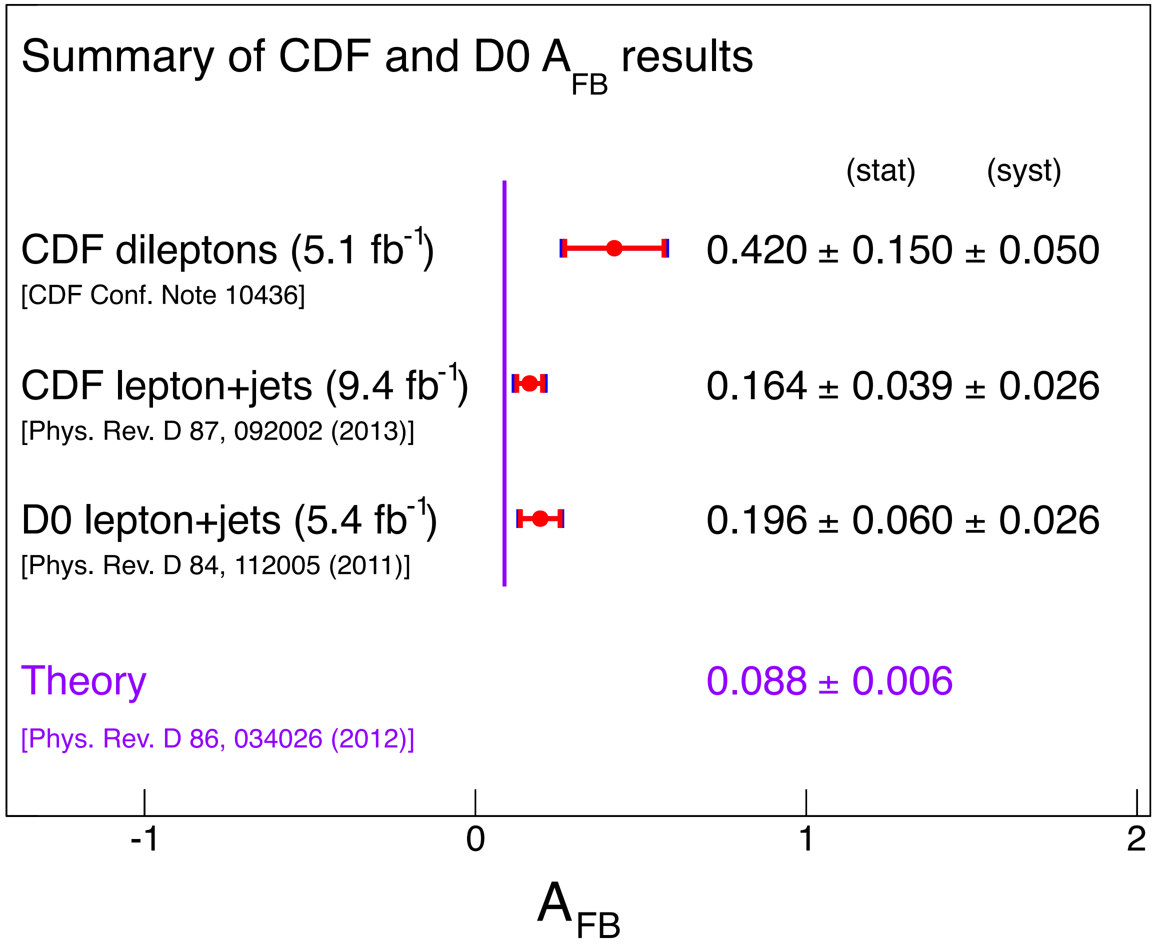




- QCD at NLO predicts a charge asymmetry for top quark pair production in hadron-hadron scattering
  - Top quarks more likely to go into direction of incoming quark
- Important: occurs in **quark-antiquark annihilation**
  - No asymmetries from gluon-gluon fusion

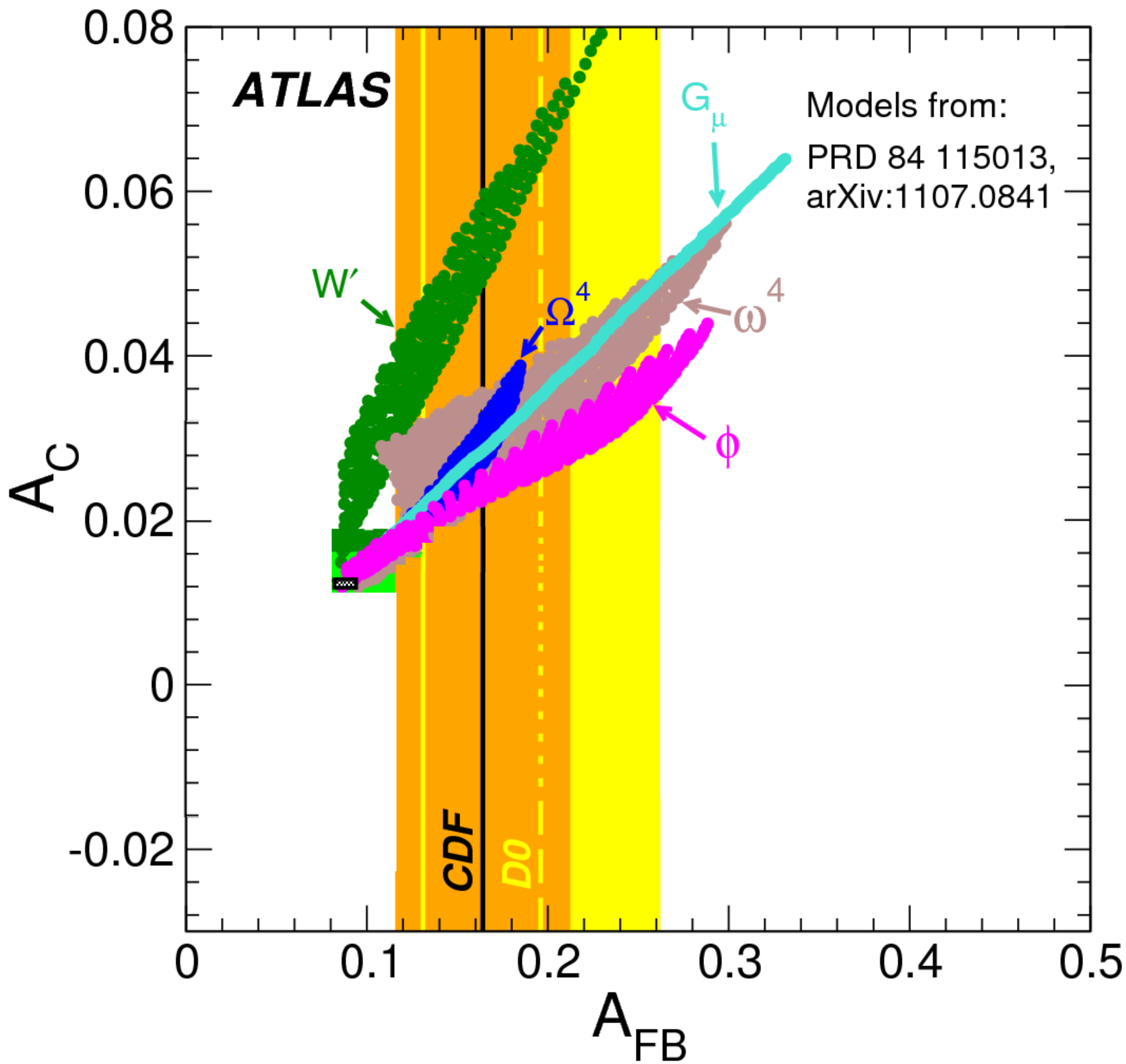
Charge Asymmetry at the Tevatron

- The Top Pair Charge Asymmetry manifests itself at the Tevatron as a **Forward-Backward Asymmetry**
  - Tevatron is a $p\bar{p}$ collider which gives a natural direction
- Measurements from CDF and D0 show a **deviation of ~2σ** from SM predictions
  - Deviations increase with increasing $t\bar{t}$ mass



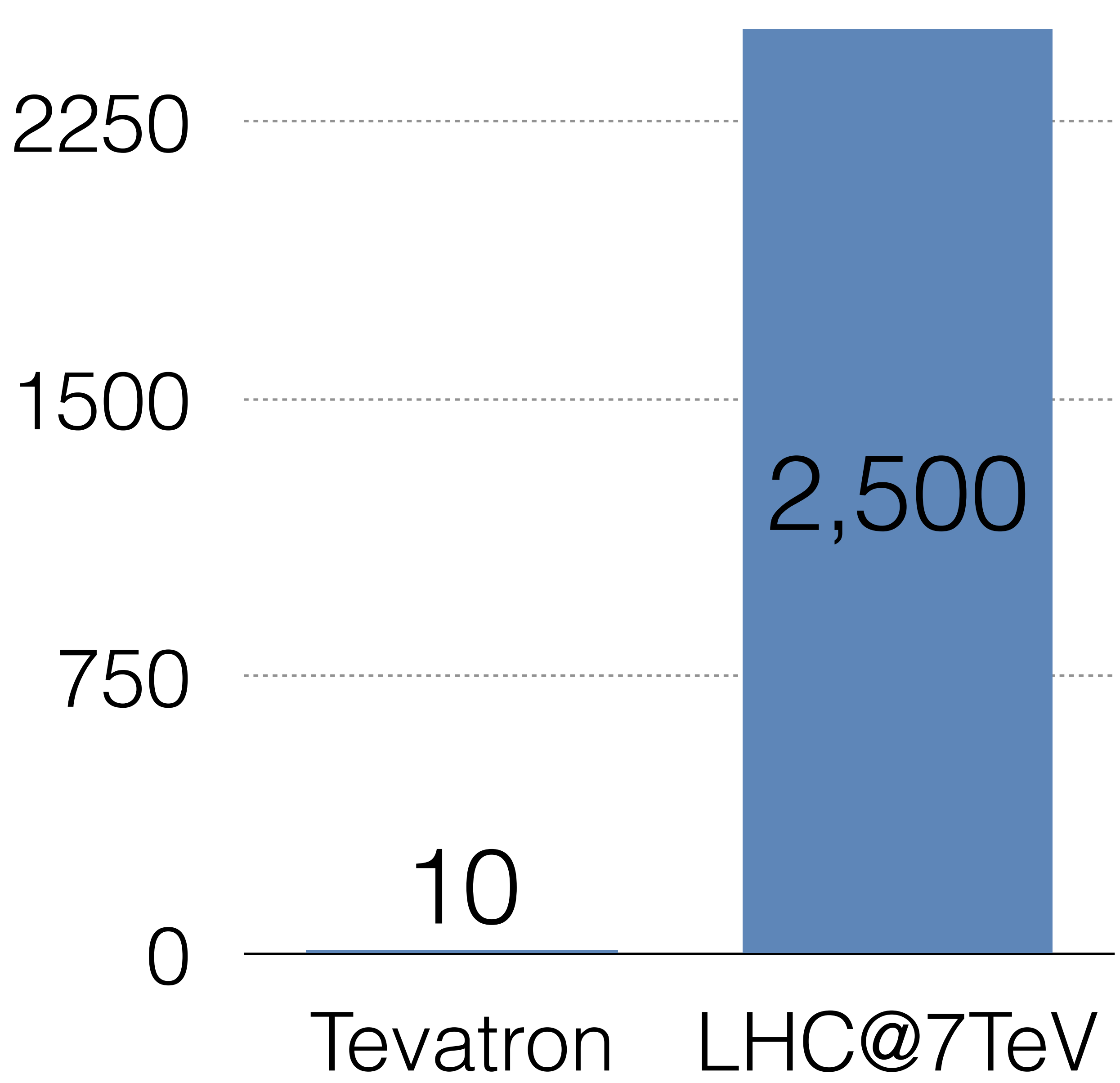
Theory and Charge Asymmetry

- The theory community is very active in proposing explanations for the Charge Asymmetry deviation at the Tevatron
- Question:
  - What can the LHC contribute to shed a light on Charge Asymmetries in top pair production



arXiv:1311.6724

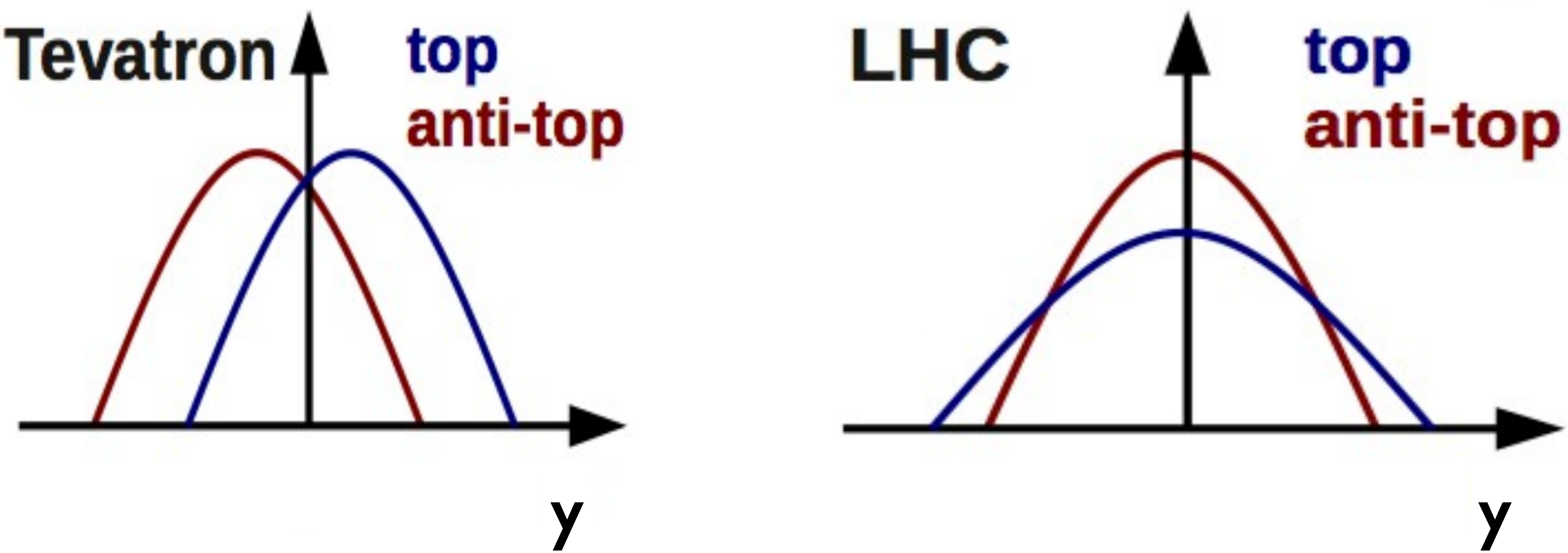
Top Quark Pairs **per hour** at peak inst. luminosity



- Goal is to measure Charge Asymmetries in top quark pairs at the LHC
- The LHC at $\sqrt{s}$ = 7 TeV produces **250 times more top quark pairs** per hour than the Tevatron
- The 2011 CMS data sample contains 850,000 top pairs

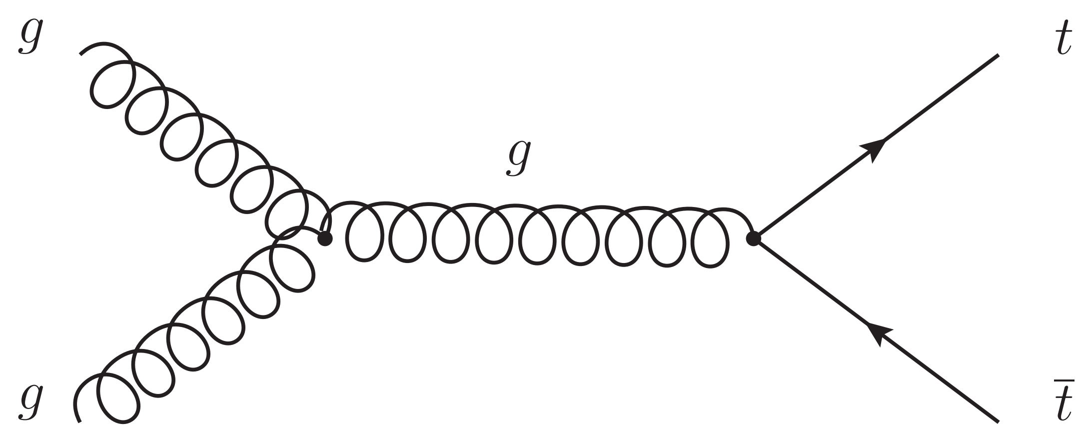
cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb
peak inst. luminosity: Tevatron: ~$4 \times 10^{32} cm^{-2}s^{-1}$, LHC@7TeV: ~$4 \times 10^{33} cm^{-2}s^{-1}$

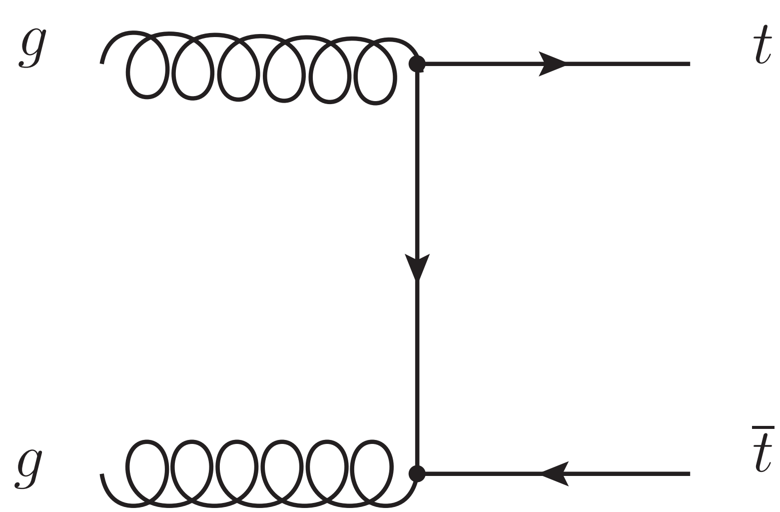
Charge Asymmetry at the LHC

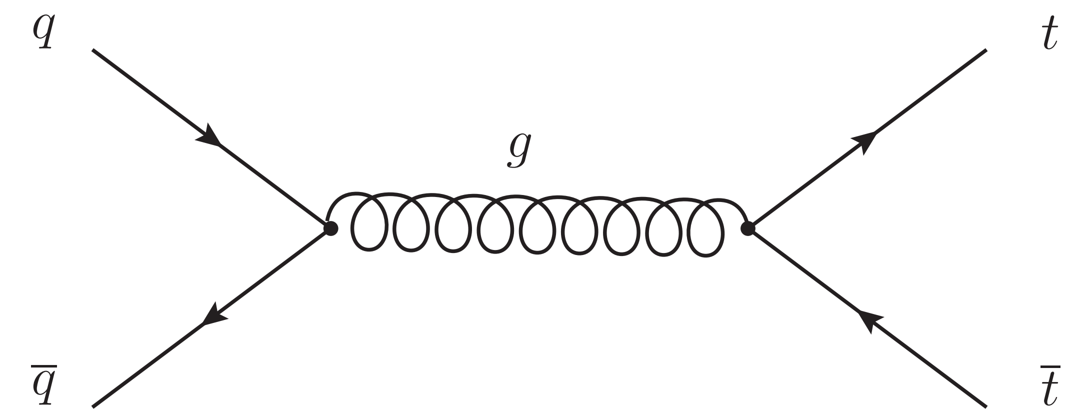


- LHC: pp initial state does not define direction
  - Quark (mainly valence quark) and anti-quark (sea quark) parton distributions inside the protons are not symmetric ➜ Quarks carry more momentum than the anti-quarks
  - **Rapidity distribution of tops broader than of anti-tops**
- LHC: top production is gluon-gluon fusion dominated
  - **Charge Asymmetries are smaller** than at the Tevatron

Top Quark Production







<u>gg fusion:</u>

~85% at the LHC@7TeV

~15% at the Tevatron

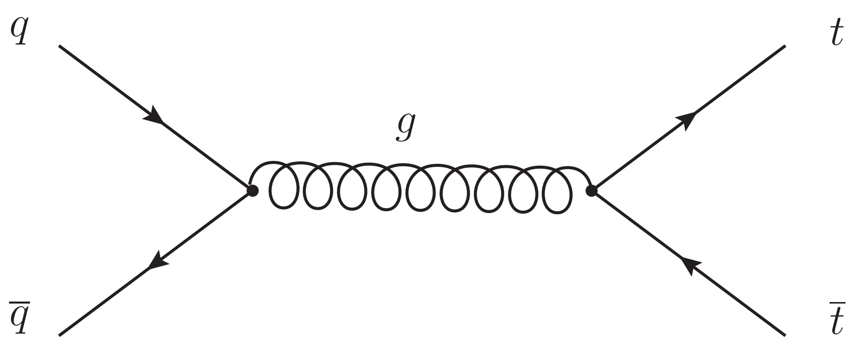
<u>q$\bar{\text{q}}$ annihilation:</u>

~15% at the LHC@7TeV

~85% at the Tevatron

Charge Asymmetry and the Standard Model

Born + Box Interference
Positive Contribution to A_{FB}



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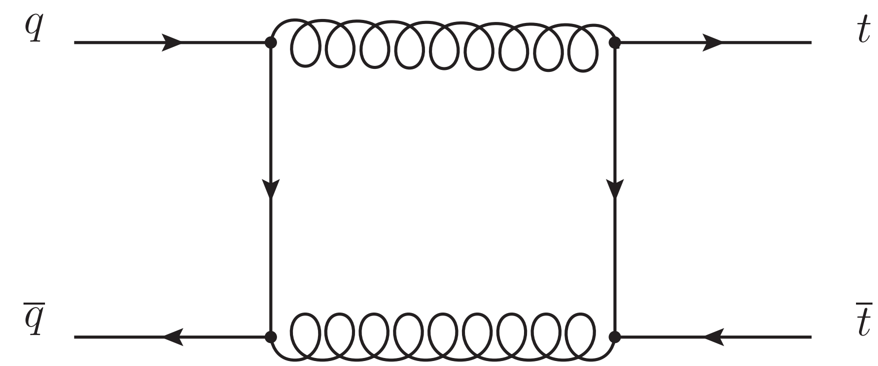
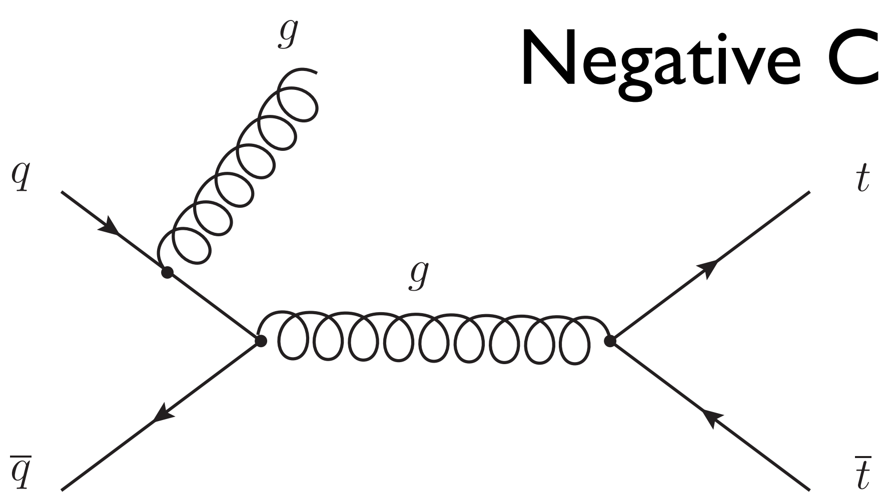


ISR/FSR Interference
Negative Contribution to A_{FB}



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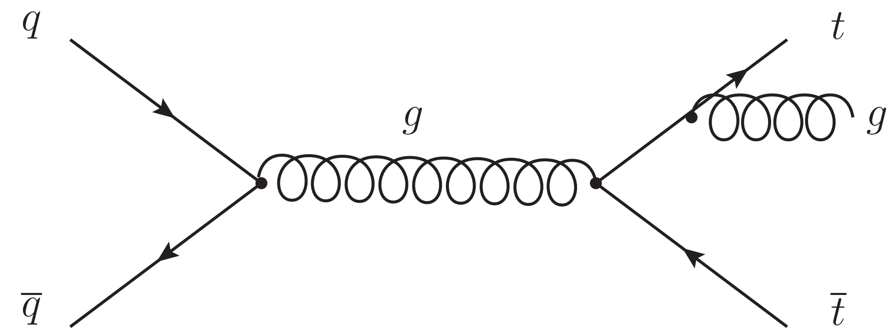
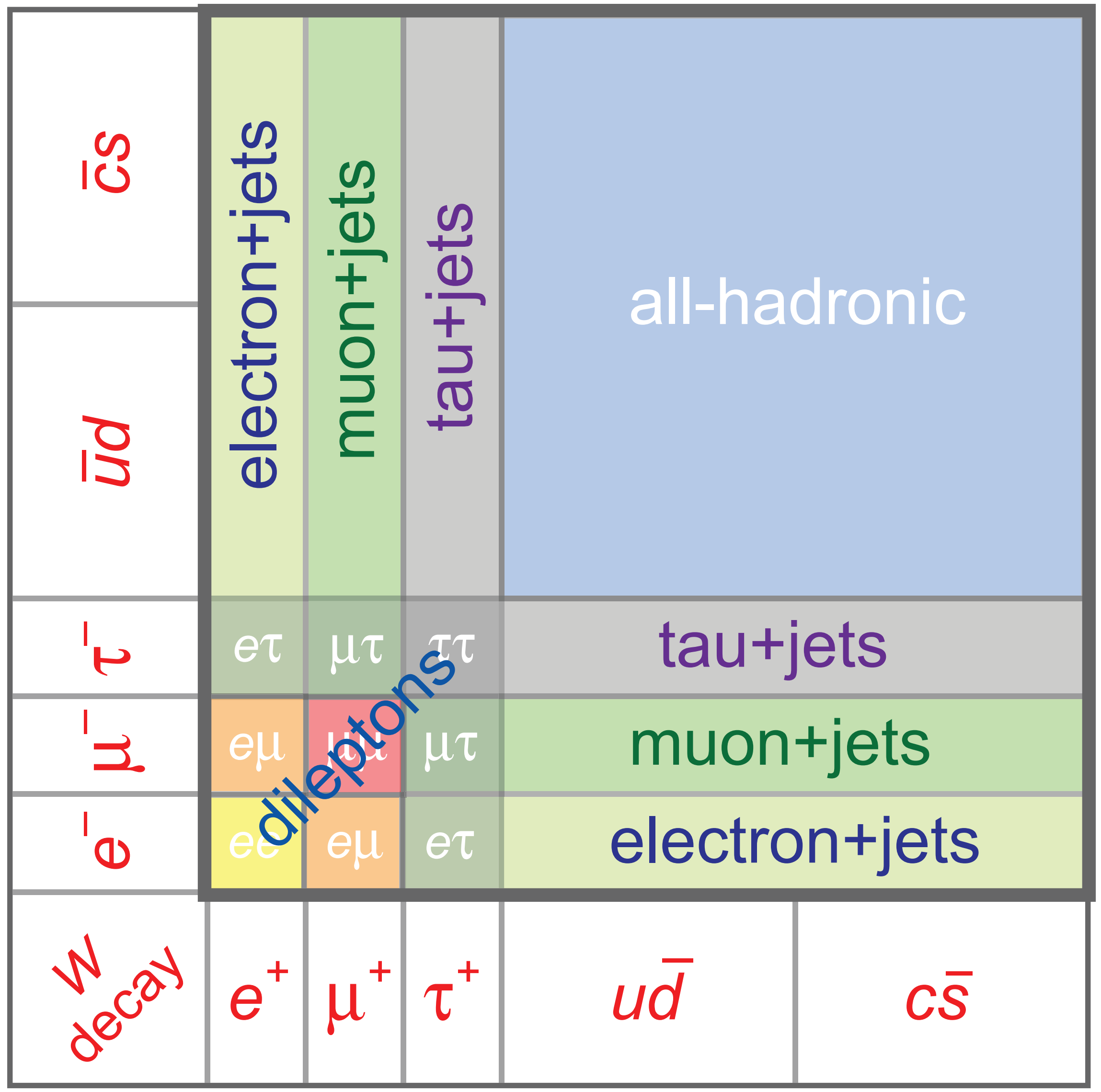


- The SM predicts a non-zero Charge Asymmetry at NLO
  - Tevatron: ~8%
  - LHC@7TeV: ~1%
- Calculations by Bernreuther and Si: Phys. Rev. D 86, 034026 (2012)

Top Quark Decay Channels



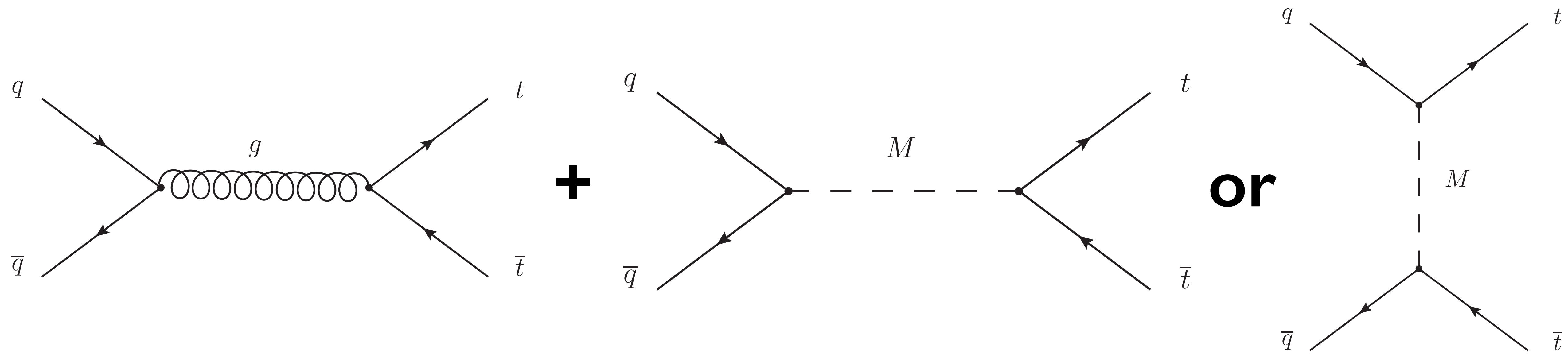
all-hadronic
46%
largest branching ratio but largest backgrounds

dilepton (l=e,μ)
6%
small branching ratio but small backgrounds

lepton+jets (l=e,μ)
34%
Large branching ratio and manageable backgrounds

- Leptonic decay channels include taus decaying leptonically

Charge Asymmetry and New Physics

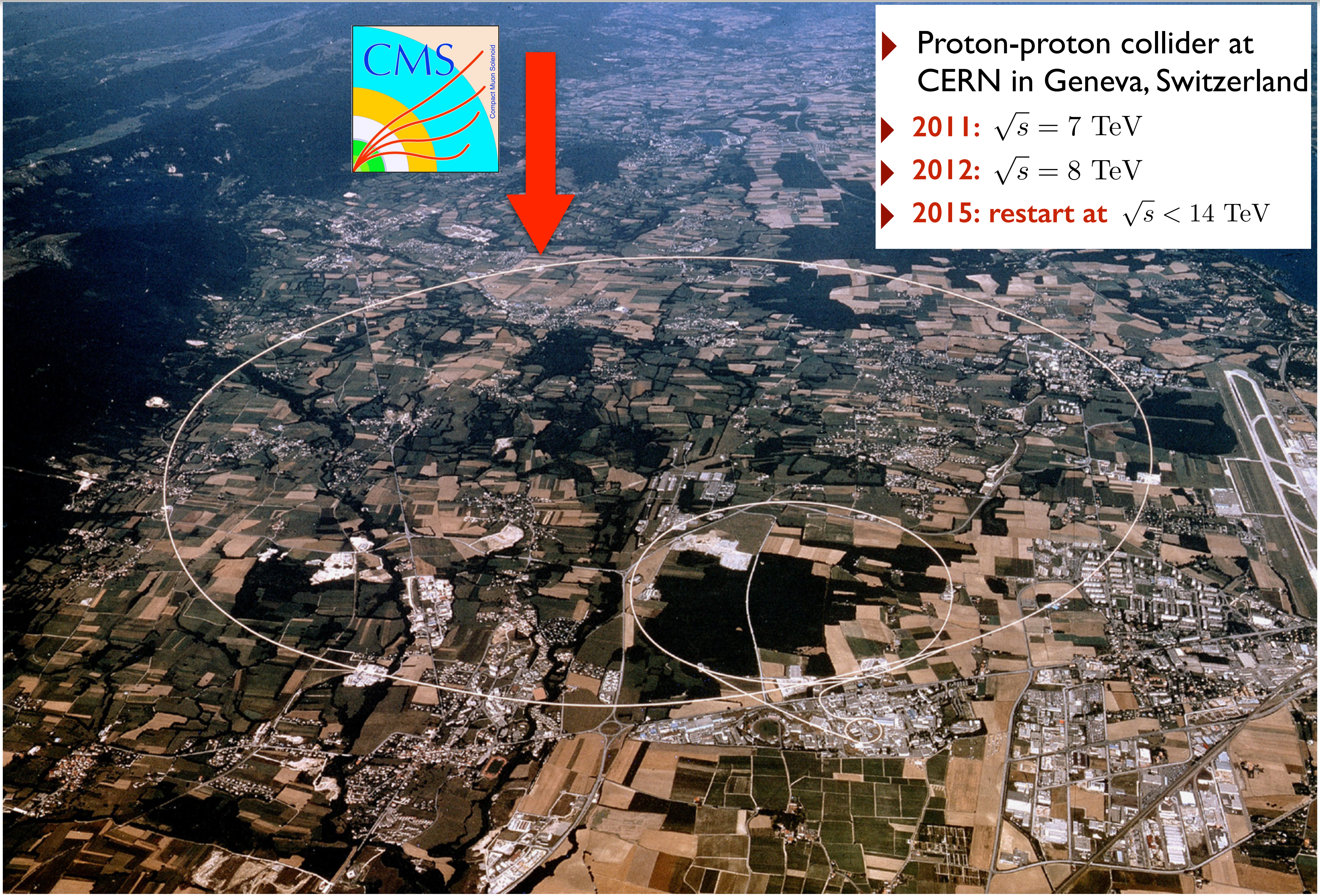


- Could new physics be responsible to increase the Charge Asymmetry?
  - There are many theoretical models that include **new particles** whose interactions generate non-SM Charge Asymmetries
  - For new particles inaccessible by direct production: Charge Asymmetries arising from interference between SM and new physics amplitudes can give sensitivity
- Examples:
  - s-channel mediator (e.g. axigluon):
    - parity violating axial coupling
  - t-channel flavor changing mediator (e.g. W', Z'):
    - dominant flavor-off-diagonal coupling

Phys. Rev. D 84, 074034 (2011)

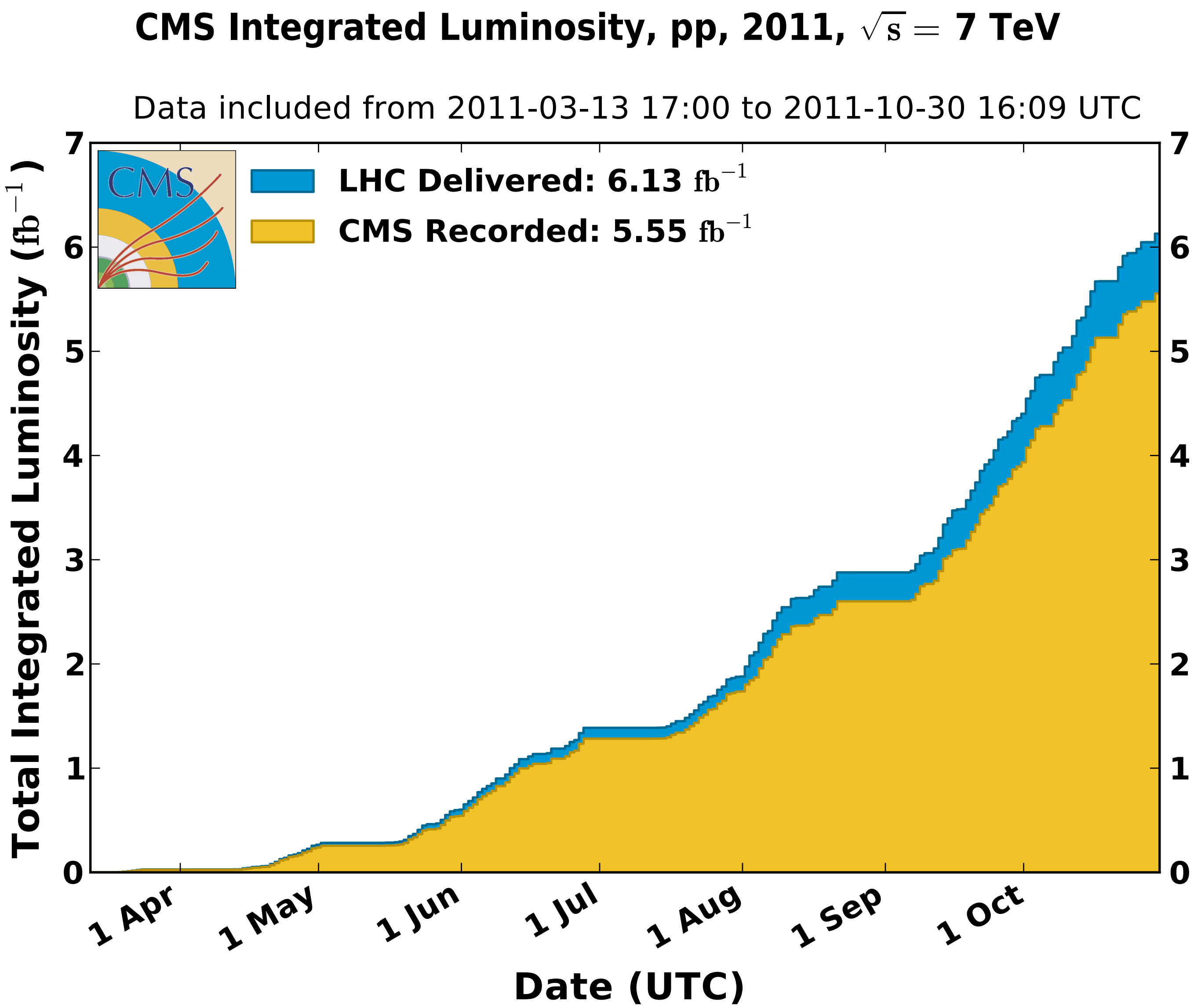
First measurement of Charge Asymmetry at CMS in dileptonic $t\bar{t}$ events

LHC

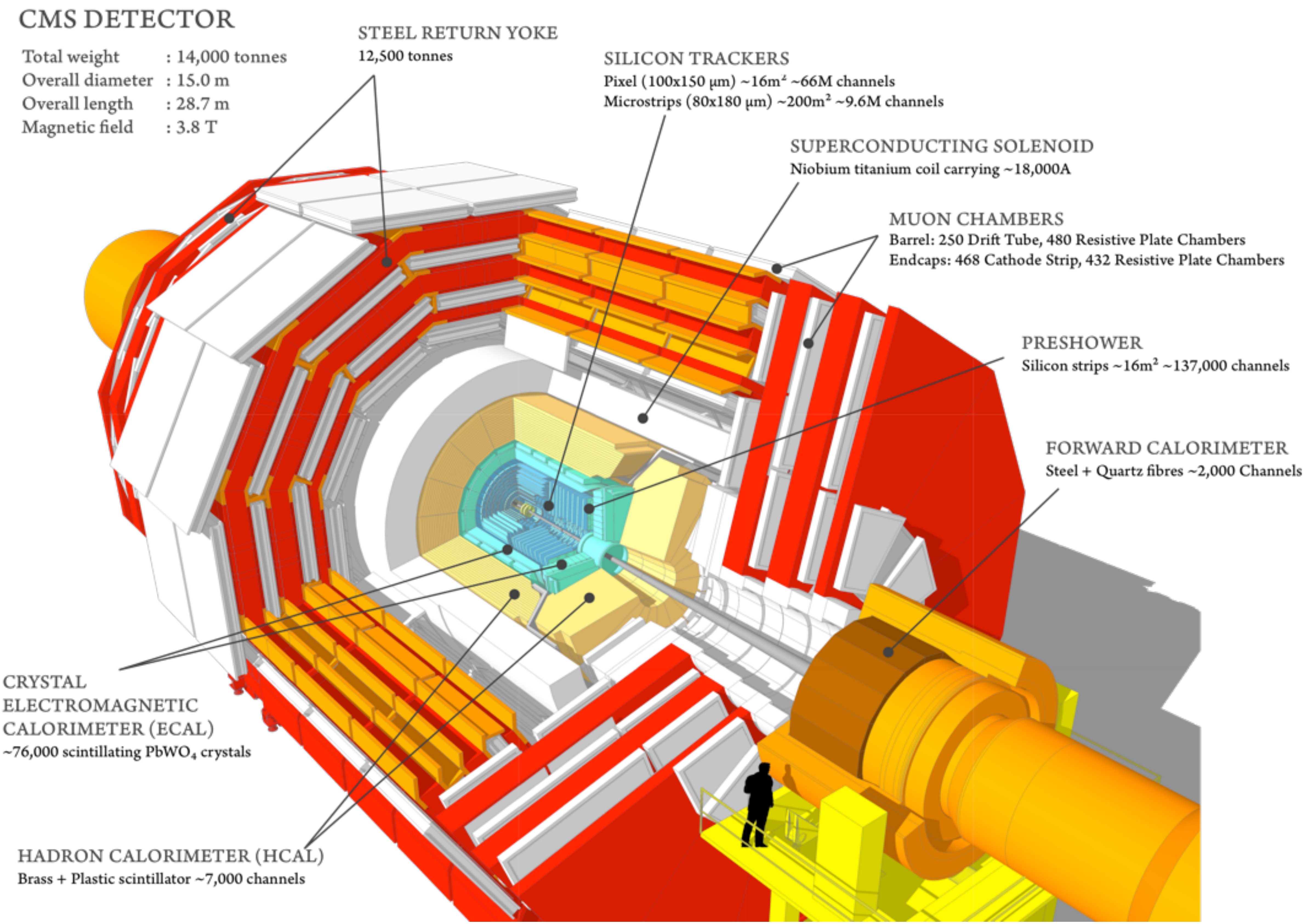


- Proton-proton collider at CERN in Geneva, Switzerland
- **2011:** $\sqrt{s} = 7\ \mathrm{TeV}$
- **2012:** $\sqrt{s} = 8\ \mathrm{TeV}$
- **2015: restart at** $\sqrt{s} < 14\ \mathrm{TeV}$

LHC@7TeV performance in 2011



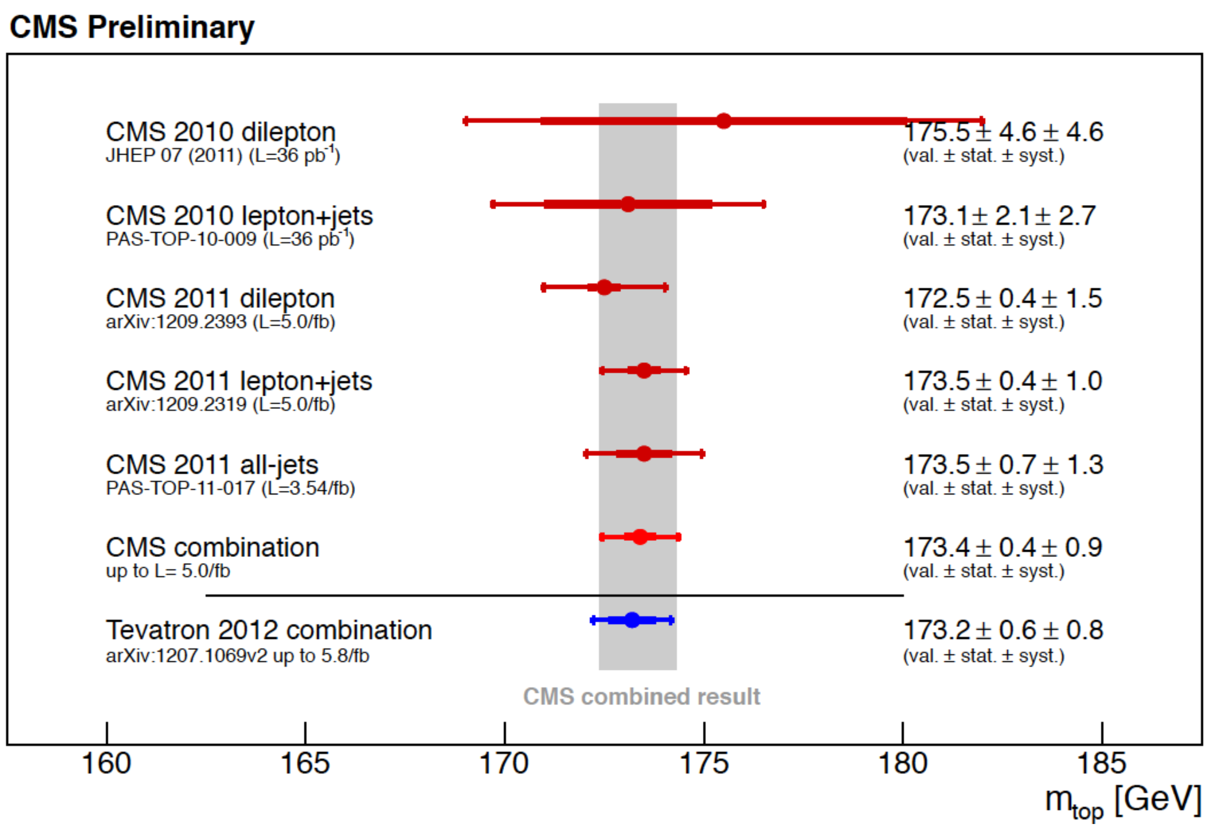
- Very good performance of the LHC accelerator resulting in over 6 fb^{-1} delivered luminosity for CMS
  - Peak instantaneous luminosity was 4×10^{33} $cm^{-2}s^{-1}$
- In the end, 5 fb^{-1} were usable for physics analysis



CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

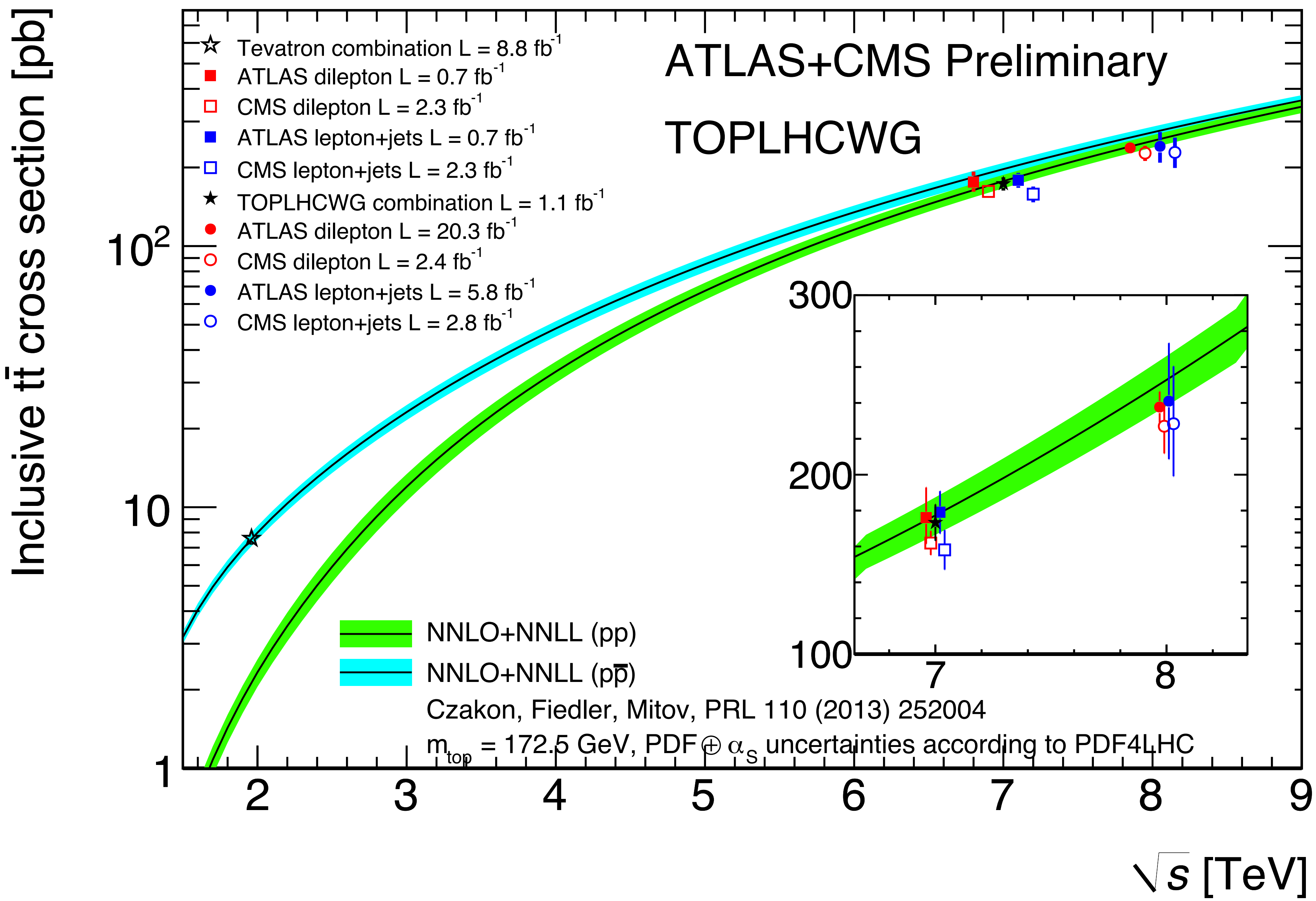
Top mass measurements at CMS

- Can we measure the top mass at CMS to the same precision as the Tevatron?



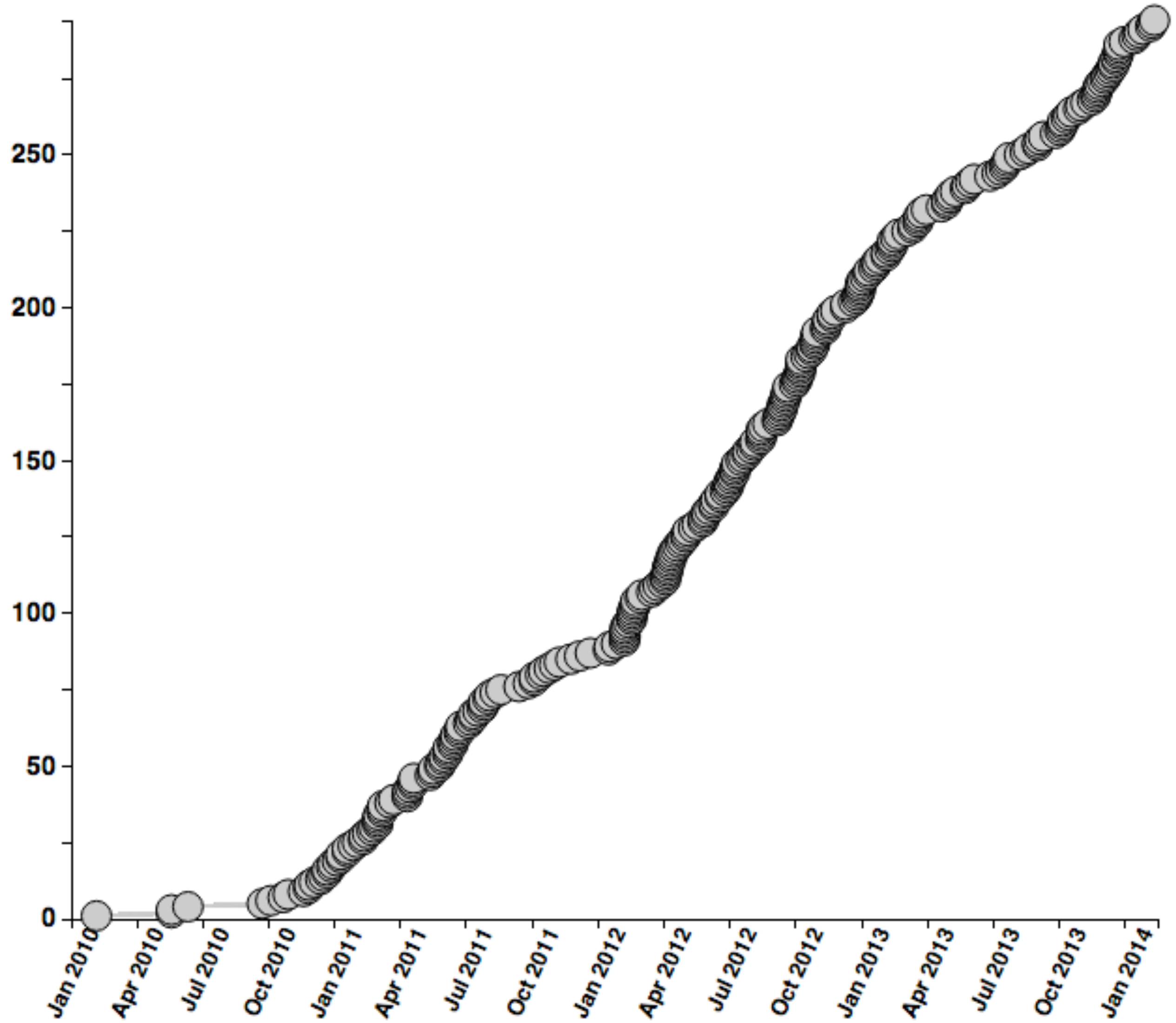
- Latest Tevatron combination (8.7 fb^{-1}): 173.20 ± 0.87 GeV
  - arXiv:1305.3929
- Latest CMS combination (20 fb^{-1}) : 173.49 ± 0.98 GeV
  - CMS-PAS-TOP-13-002
- Latest Atlas/CMS combination (4.9 fb^{-1}): 173.29 ± 0.95 GeV
  - CMS-PAS-TOP-13-005

- Can we measure the top cross section precisely at CMS?

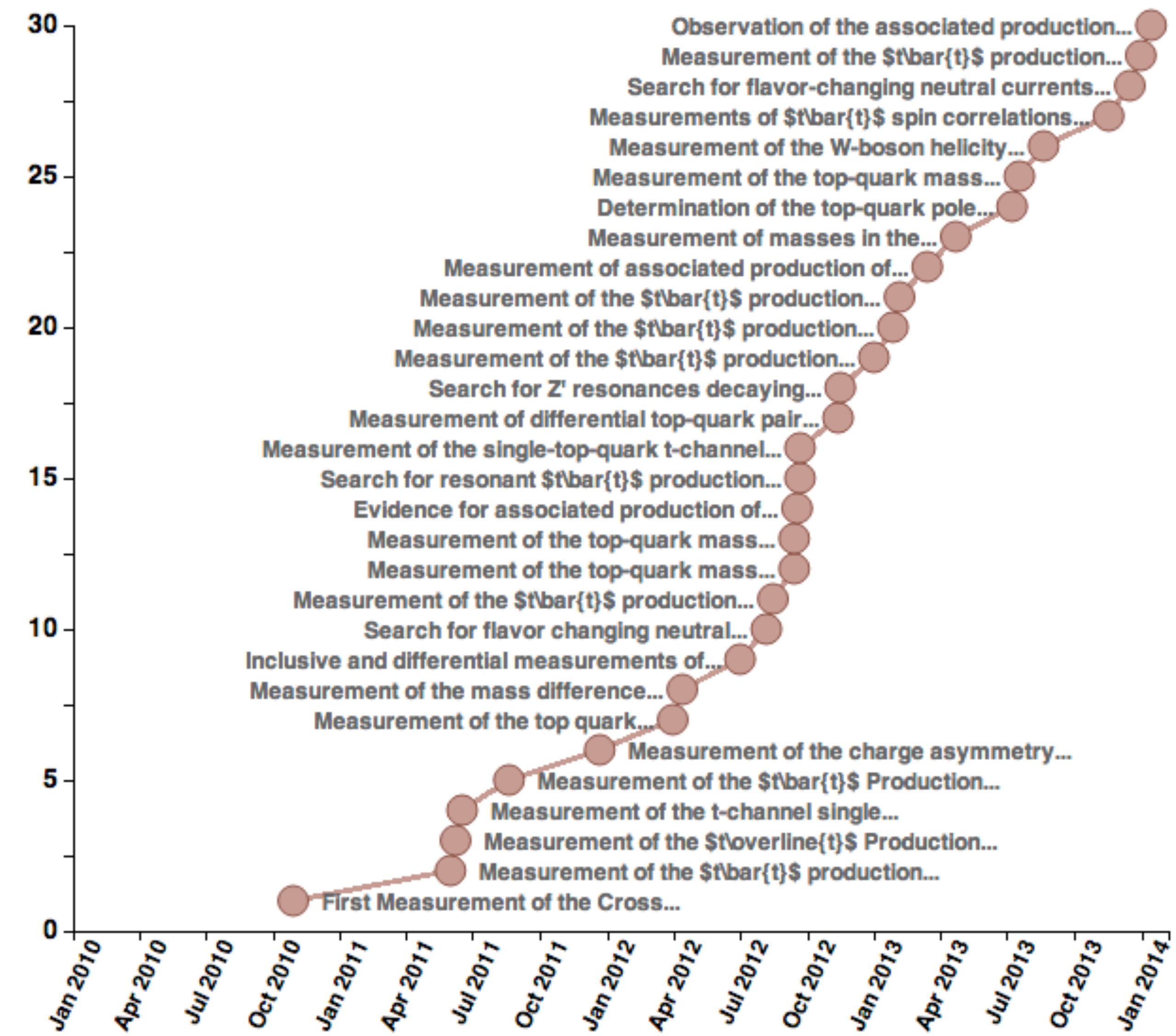


Top physics at CMS

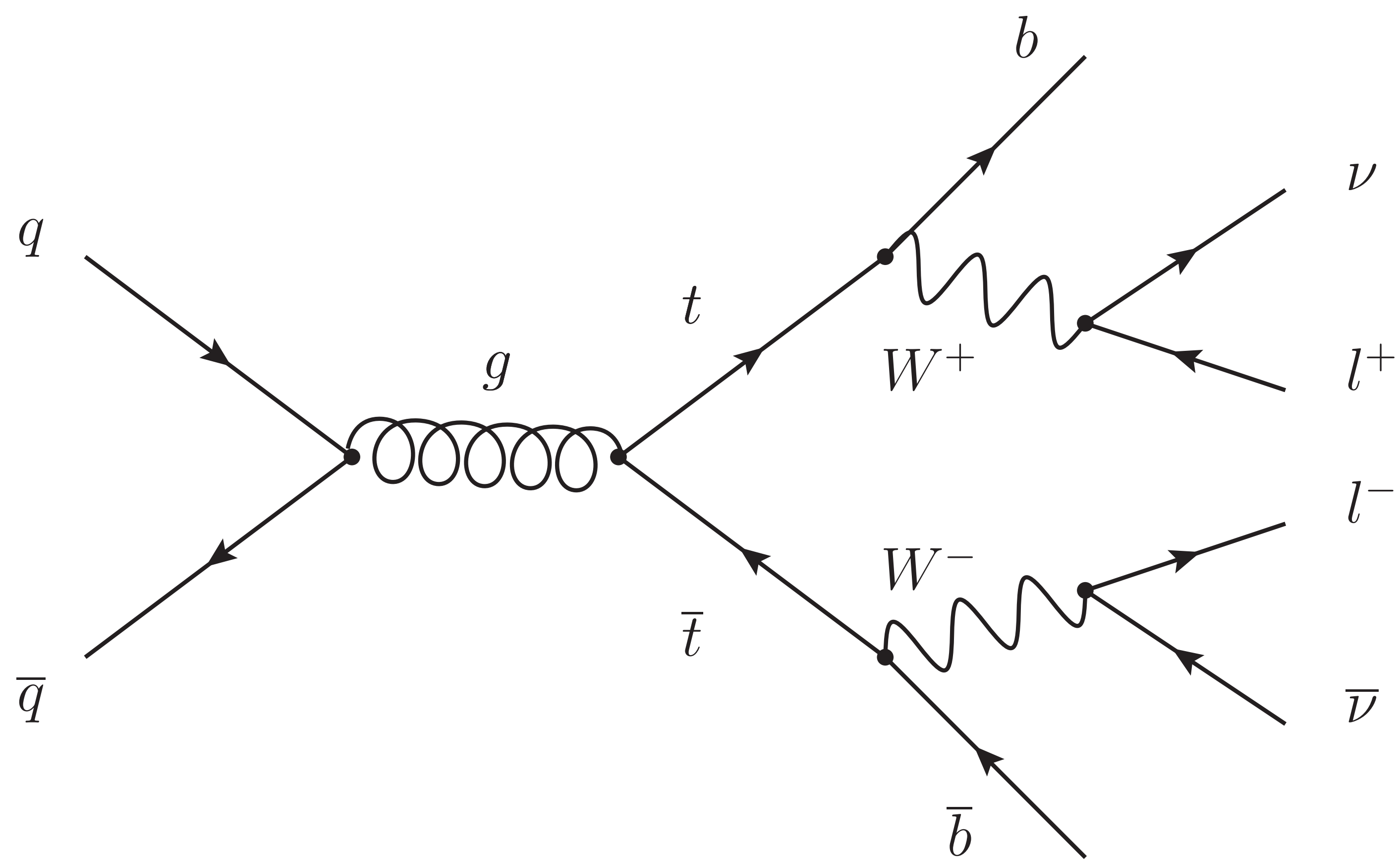
293 CMS publications



30 CMS top publications



- CMS published 293 papers since 2010, of which 30 were top physics publications
  - More than 10% of all CMS publications are top physics publications
  - All CMS top results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

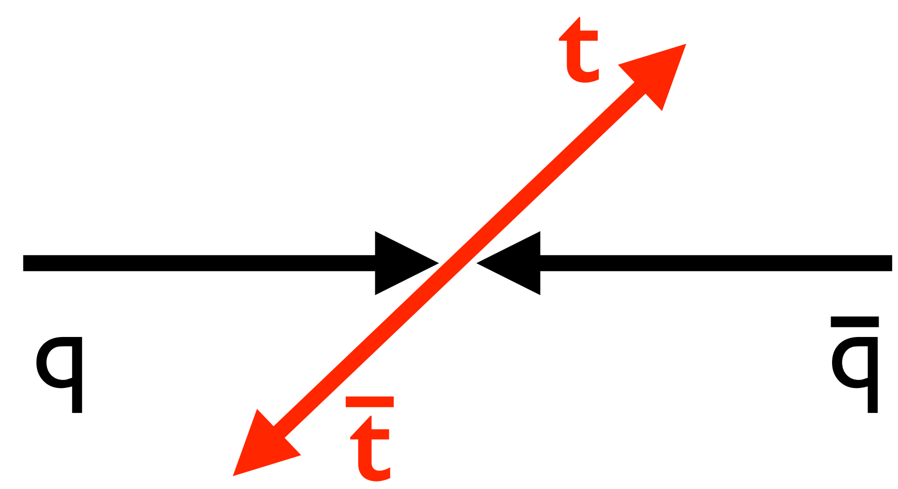


- Strategy
  - Select $t\bar{t}$ events optimizing signal to background
  - Reconstruct the $t\bar{t}$ system kinematics using analytical approach
  - Unfold to the parton level

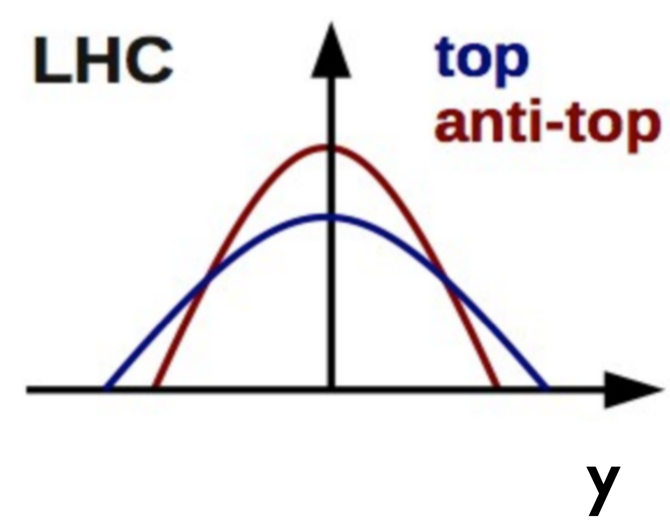
- Presented are the results using the 7 TeV dataset from 2011

Top Charge Asymmetry

- For a positive **Top Charge Asymmetry:**
  - Top quark more likely to be produced in the direction of the incoming quark in the $t\bar{t}$ rest frame
  - Resulting in a broader rapidity distribution of top quarks than of top antiquarks in the laboratory frame.



- Needs a method to **reconstruct the top pair** and a **clean $t\bar{t}$ event sample**



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

$$\Delta|y_t| = |y_t| - |y_{\bar{t}}| \qquad y = \frac{1}{2}\ln\frac{E + p_z}{E - P_z}$$

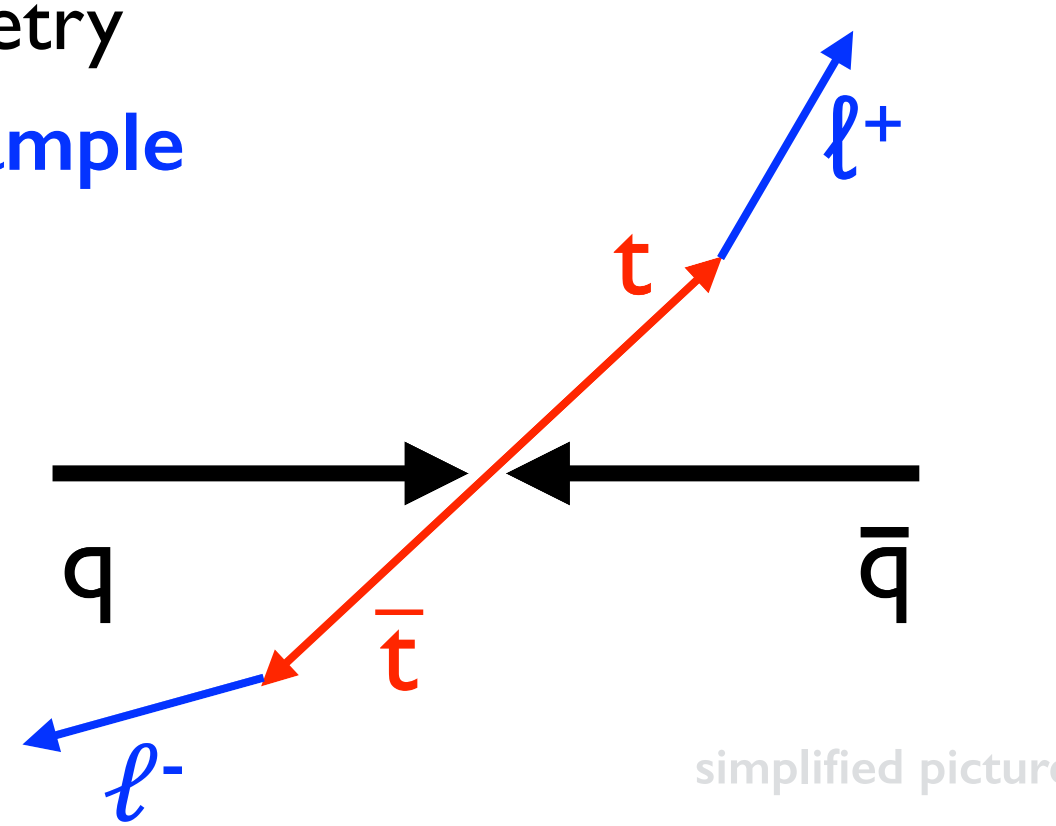
NLO prediction at parton level at LHC@7TeV:
(1.23 ± 0.05) %

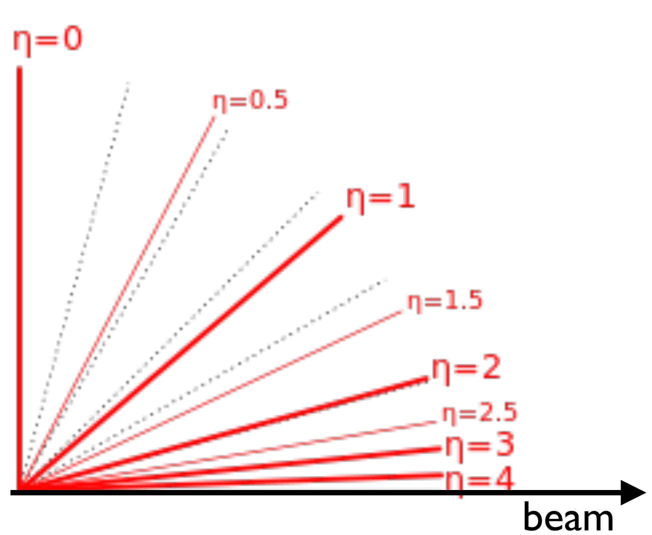
Lepton Charge Asymmetry:

- We can measure a Charge Asymmetry using both reconstructed leptons
- No tt reconstruction needed
- Diluted, smaller than Top Charge Asymmetry
- **Pure leptonic**, needs a **clean $t\bar{t}$ event sample**

$$A_C^{\mathrm{lep}} = \frac{N(\Delta|\eta_\ell| > 0) - N(\Delta|\eta_\ell| < 0)}{N(\Delta|\eta_\ell| > 0) + N(\Delta|\eta_\ell| < 0)}$$

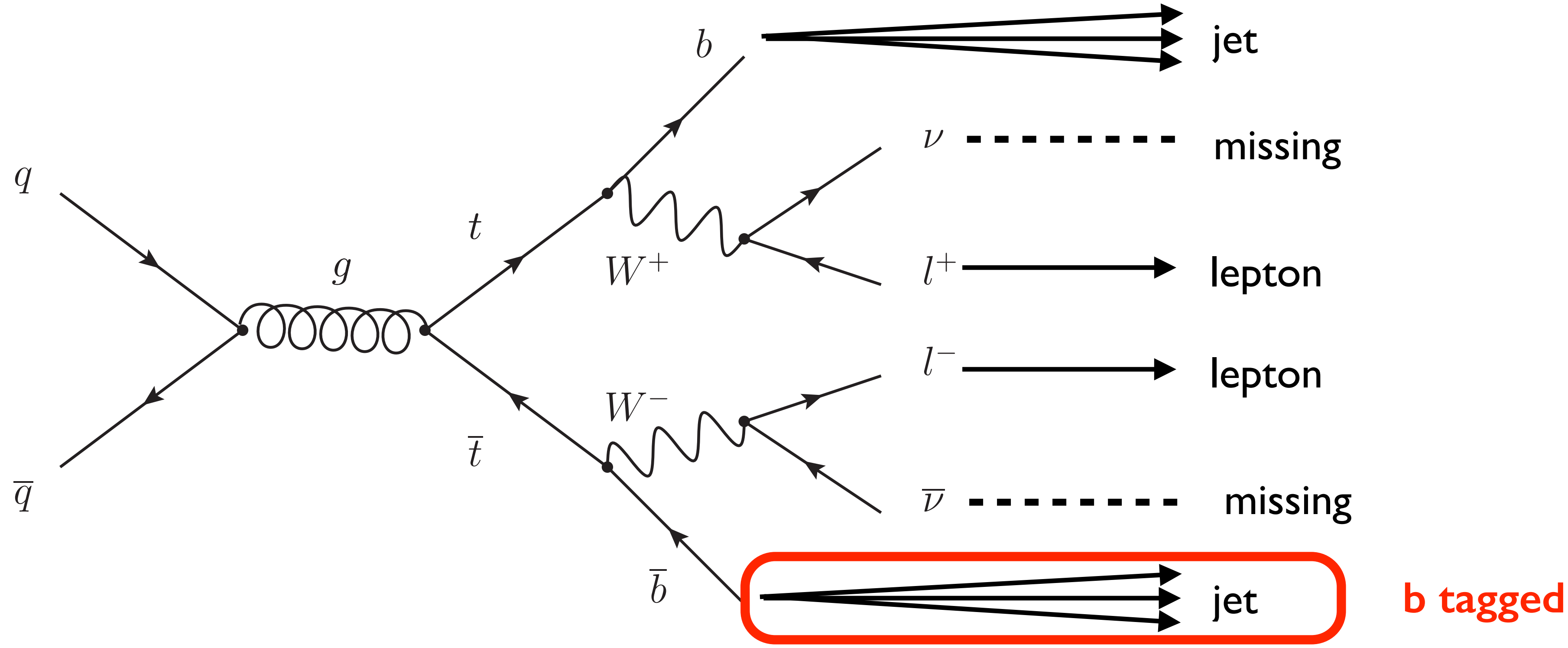
$$\Delta|\eta_\ell| = |\eta_{\ell^+}| - |\eta_{\ell^-}| \qquad \eta = -\frac{1}{2}\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





NLO prediction at parton level at LHC@7TeV:
(0.70 ± 0.03) %

Dilepton $t\bar{t}$ selection



- Selection is designed to **reject events other than $t\bar{t}$**
  - Backgrounds: W+jets, Drell-Yan (DY), Diboson (WW, WZ, ZZ), Single top

- Dilepton triggers: dimuon, dielectron or electron-muon
- **2 opposite-charged isolated leptons, ≥2 jets with ≥1b tag**
- **missing transverse energy (MET) > 40 GeV** (ee and μμ channels only)

- Event selection is 92% pure

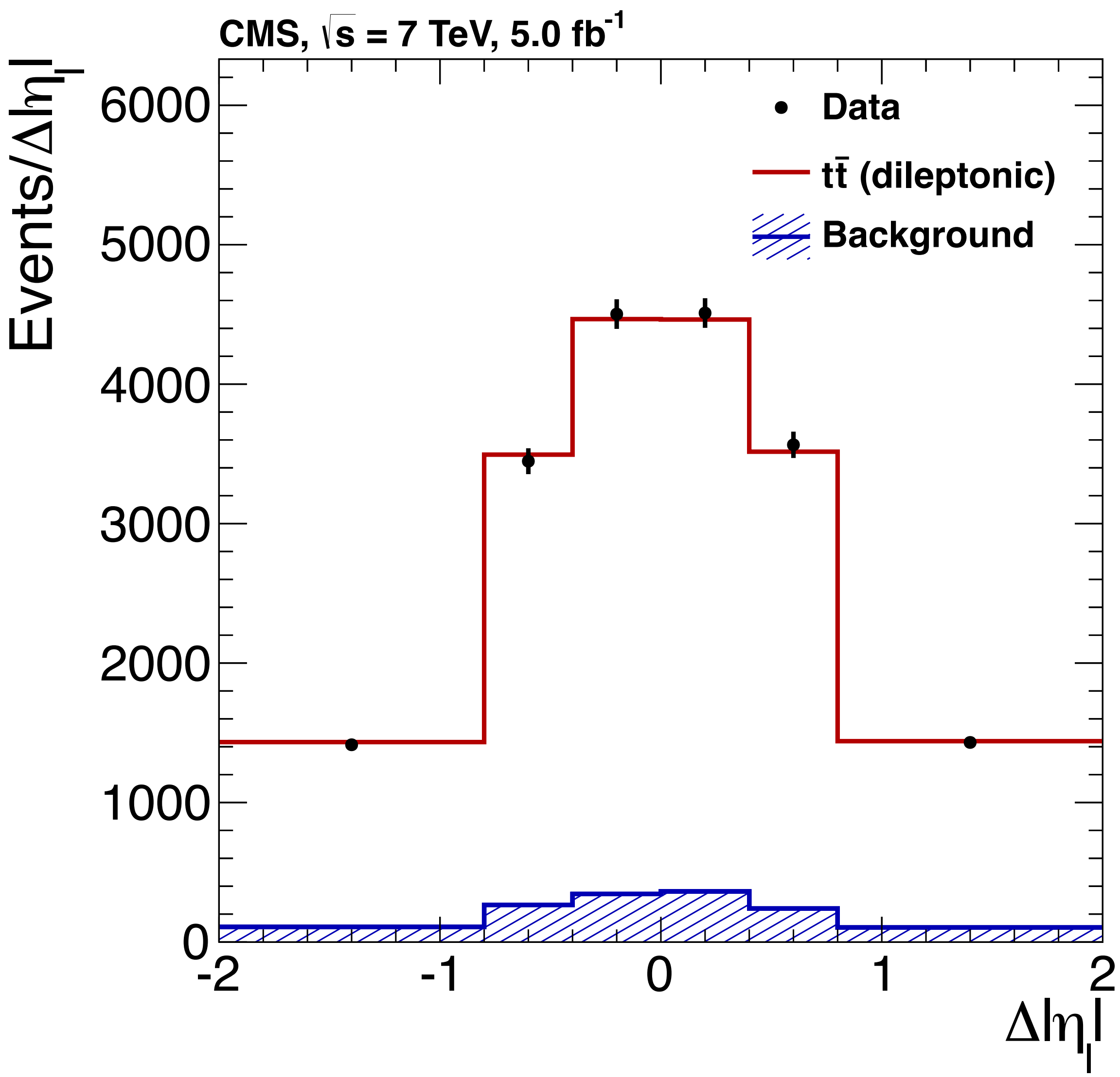
Pure $t\bar{t}$ event sample: backgrounds

event yields for 5 fb^{-1}, statistical errors

Sample	ee	$\mu\mu$	eμ	All
$t\bar{t}$ (non-dileptonic)	38.3 ± 1.6	4.02 ± 0.45	91.7 ± 2.4	134.0 ± 2.9
W + jets	< 2.0	4.7 ± 3.3	11.1 ± 5.1	15.8 ± 6.1
Drell–Yan	30.2 ± 4.4	29.6 ± 4.1	35.0 ± 4.5	94.8 ± 7.5
Diboson	8.27 ± 0.44	10.20 ± 0.47	27.90 ± 0.81	46.4 ± 1.0
Single top-quark	72.5 ± 2.1	86.8 ± 2.2	289.4 ± 4.2	448.7 ± 5.2
Total (background)	149.3 ± 5.5	135.3 ± 5.8	455.1 ± 8.4	740 ± 11
Data	1631	1964	6229	9824

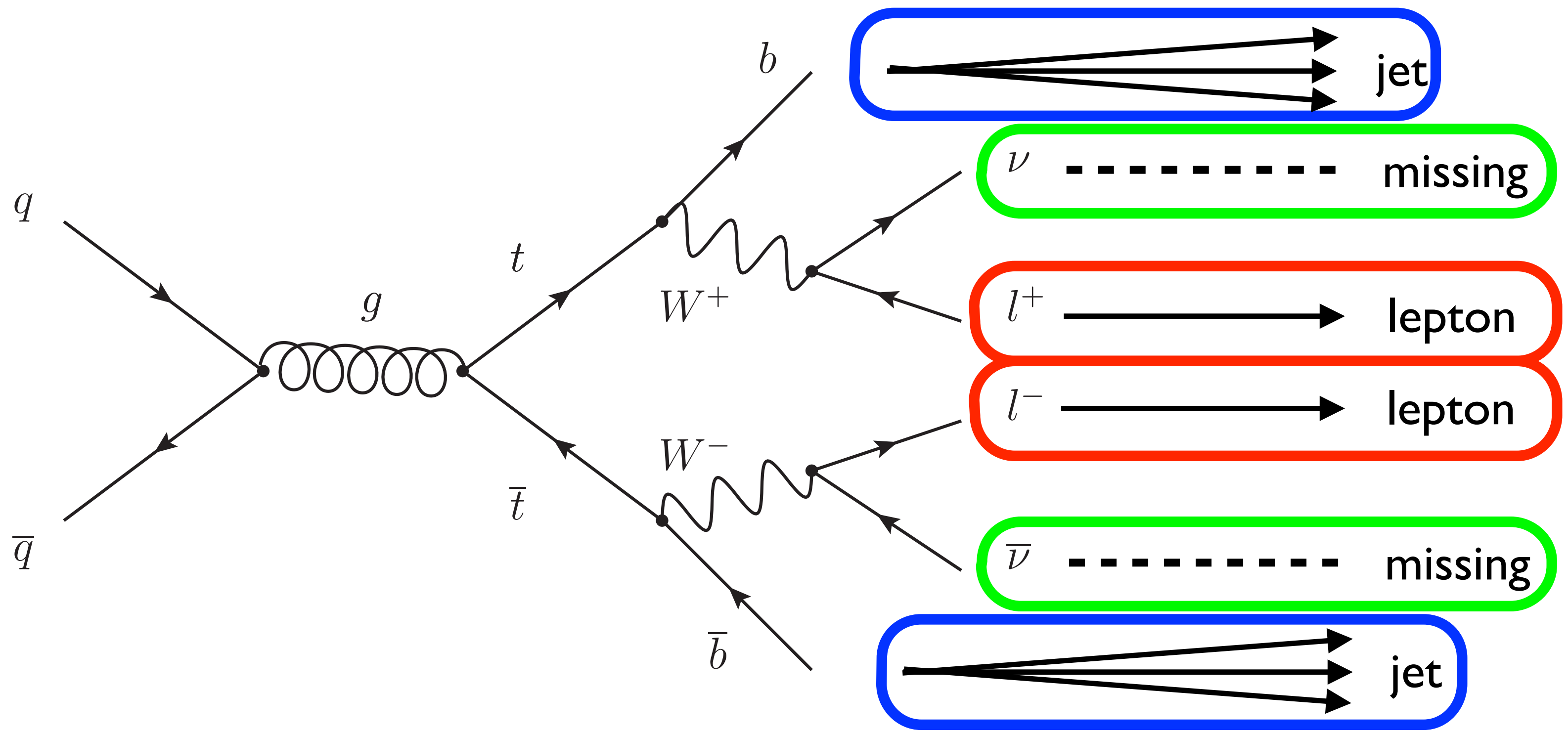
- Backgrounds normalized to NLO and NNLO calculations
  - Cross-checks for DY and fake lepton components using data-driven methods
    - Reasonable agreement, data-driven methods used to assign an appropriate background normalization systematic

Data vs. Simulation

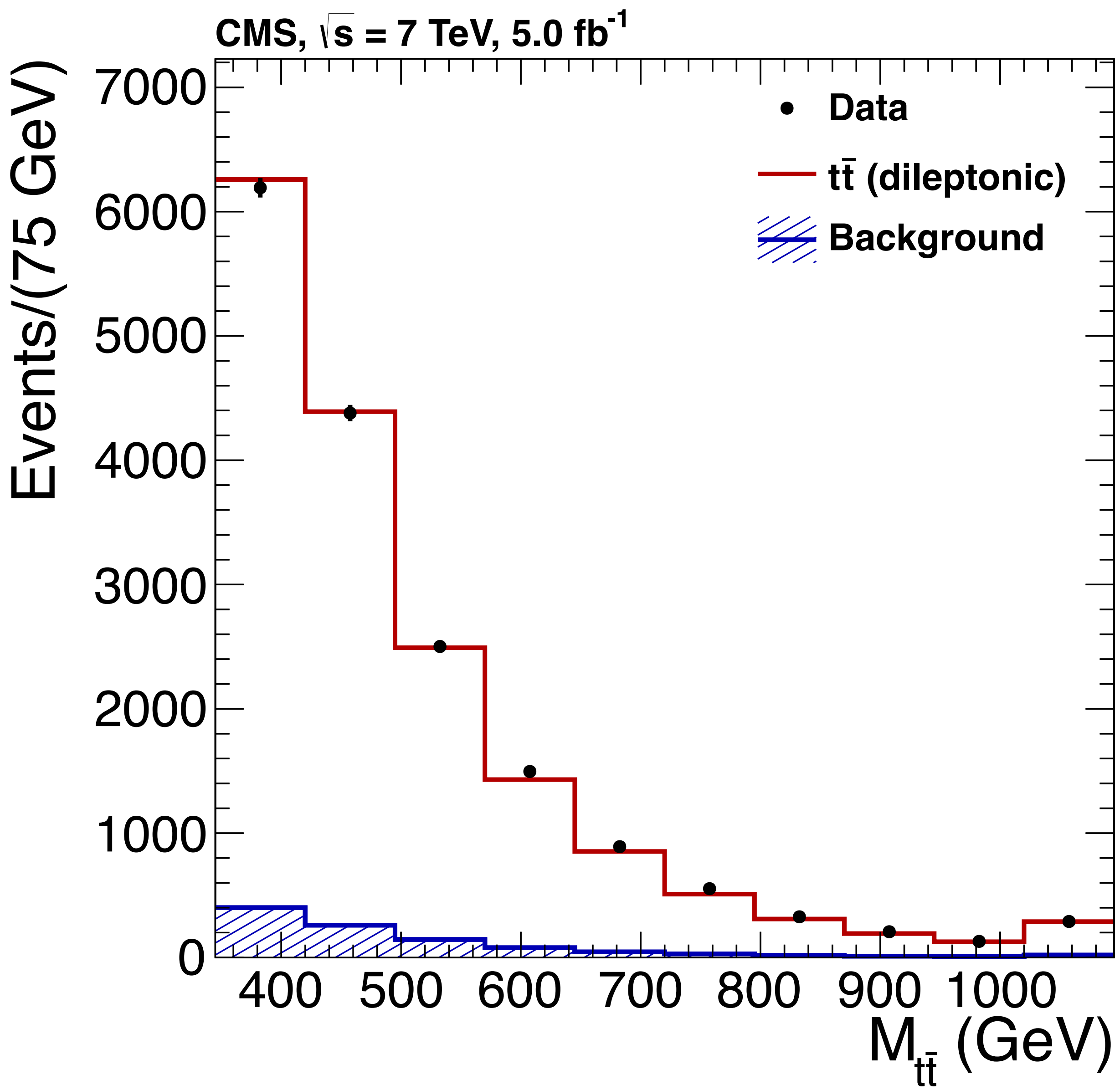


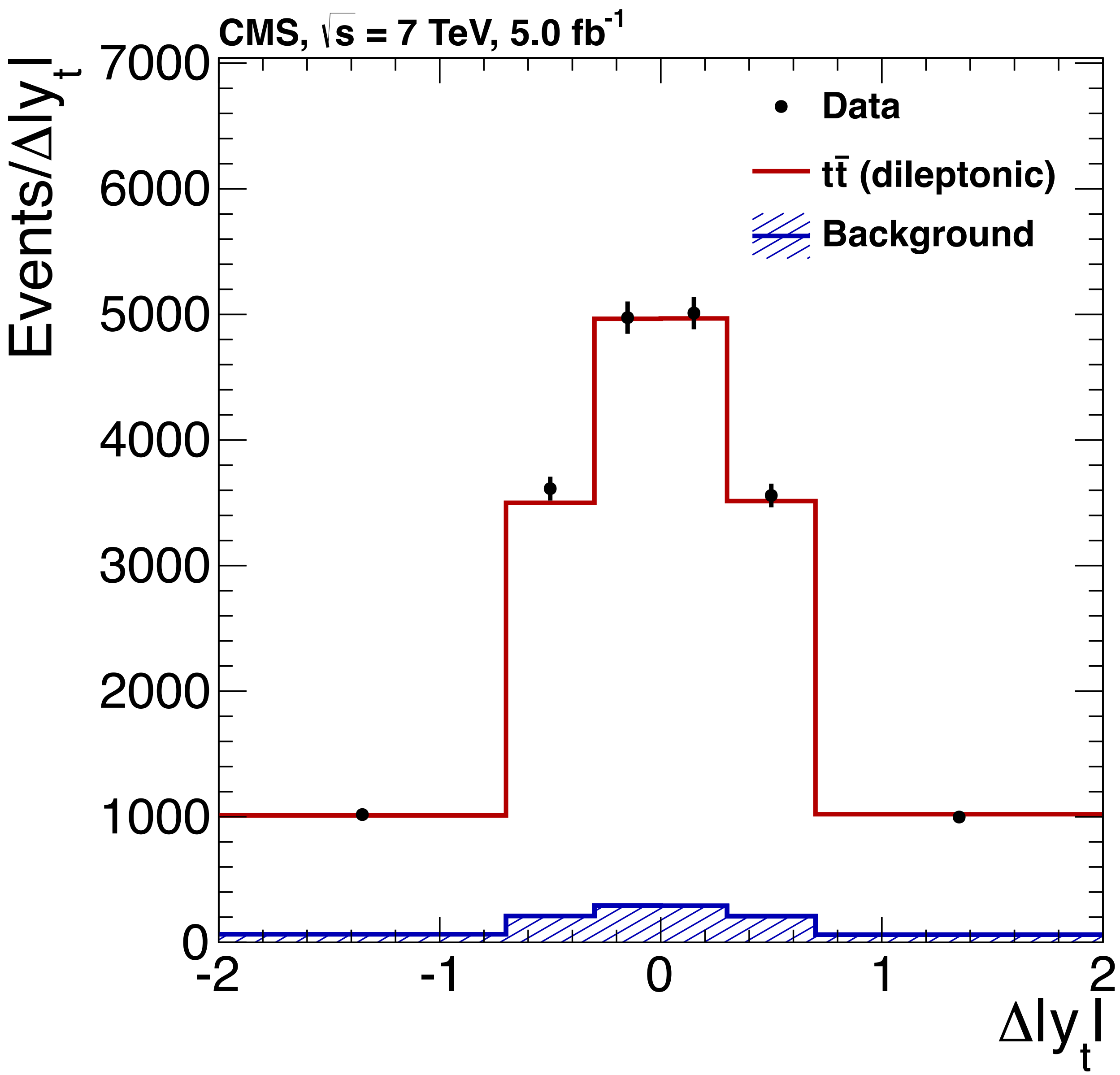
purely leptonic

- Signal simulation normalized so that total MC yield matches the data
- Event selection dominated by dileptonic $t\bar{t}$ events (> 92%)
- The data shape is well described by the signal plus background simulation



- Following the Tevatron, an analytical method is used to reconstruct the top and anti-top quark momenta
  - Analytical Matrix Weighting Technique (AMWT)
    - Input: 2 highest-pt reconstructed jets, 2 leptons and missing transverse energy, fix top quark mass at 172.5 GeV and W mass at 80.4 GeV





- The data shape is well described by the signal plus background simulation.

Unfolding

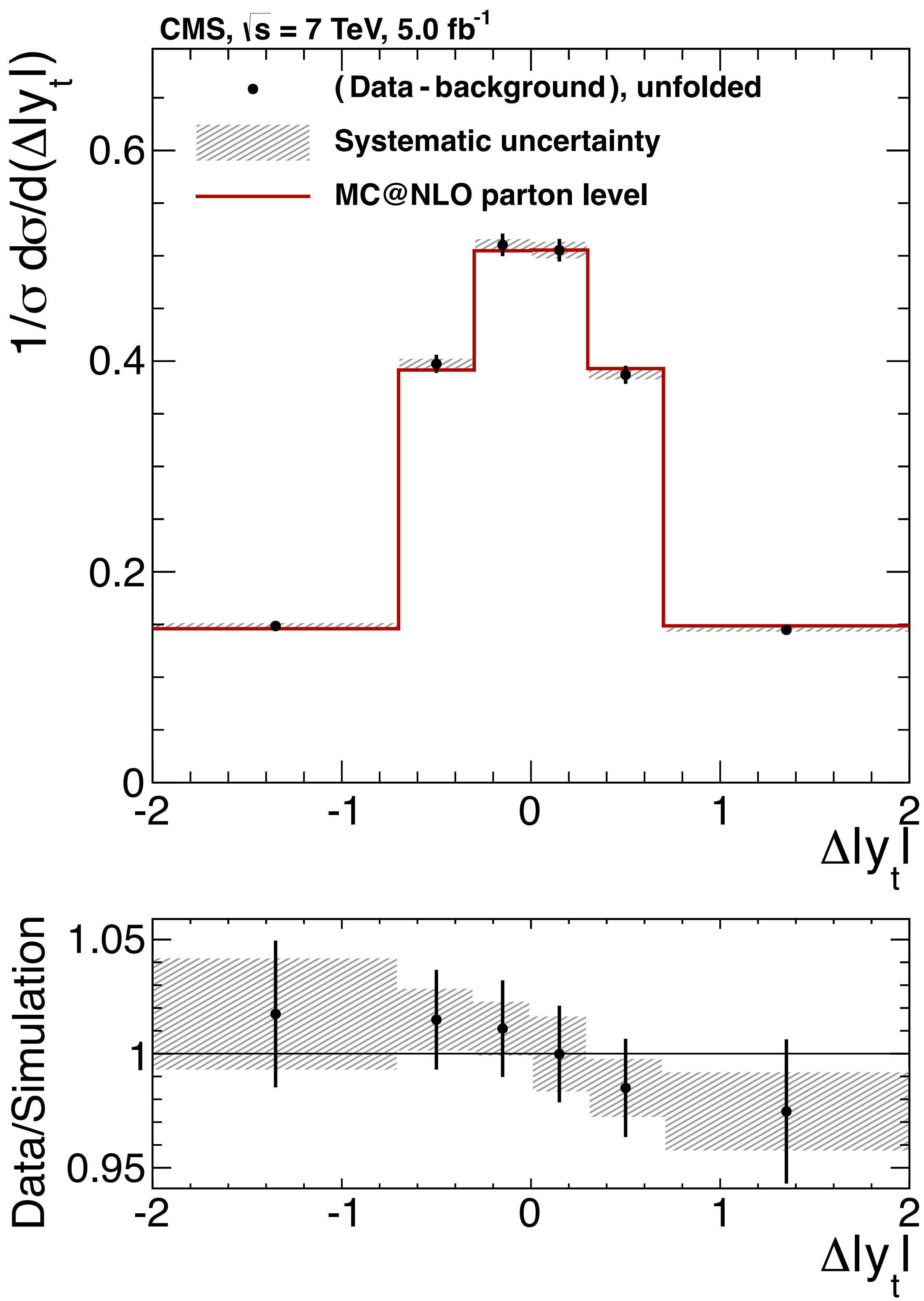
- Goal is to compare measurement (reconstructed quantities) to theoretical predictions (parton-level quantities)
  - Two possibilities:
    - Run theoretical predictions through detector simulation
    - Unfold measurement to parton level ➜ chosen here to allow for direct comparison to future predictions
- Prescription:
  - Start from background subtracted distributions
  - Apply correction technique to account for acceptance and resolution effects
  - End with parton level distributions
- The regularized Singular Value Decomposition (SVD) unfolding technique is used (Nucl.Instrum.Meth.A372:469-481,1996)

Systematics for Charge Asymmetries

	Top Charge Asymmetry	Lepton Charge Asymmetry
Asymmetry variable	**A_C**	**A^{lep}_C**
	Experimental uncertainties	
Jet energy scale	**0.003**	**0.001**
Lepton energy Scale	<0.001	<0.001
Background	0.001	0.001
Jet energy resolution	<0.001	<0.001
Pileup	<0.001	0.001
Scale factor for b tagging	<0.001	<0.001
Lepton selection	<0.001	<0.001
	$t\bar{t}$ modeling uncertainties	
Fact. and renorm. scales	**0.004**	**0.005**
Top-quark mass	0.001	0.001
Parton distribution functions	<0.001	<0.001
τ-lepton decay	<0.001	<0.001
Unfolding	**0.006**	**0.001**
Top-quark p_T reweighting	0.001	<0.001
Total Systematic Uncertainty	**0.008**	**0.006**
NLO prediction	0.0123 ± 0.0005	0.0070 ± 0.0003

- Largest experimental systematics:
  - Jet Energy Scale (JES):
    - Affects the ttbar kinematics solution from AMWT as well as the event selection
    - It is estimated by varying the JES within their uncertainties, and propagating this to the MET
- Largest modeling systematics:
  - Factorization and renormalisation scales:
    - Varied up and down by a factor 2
- Unfolding systematics:
  - Based on linearity tests

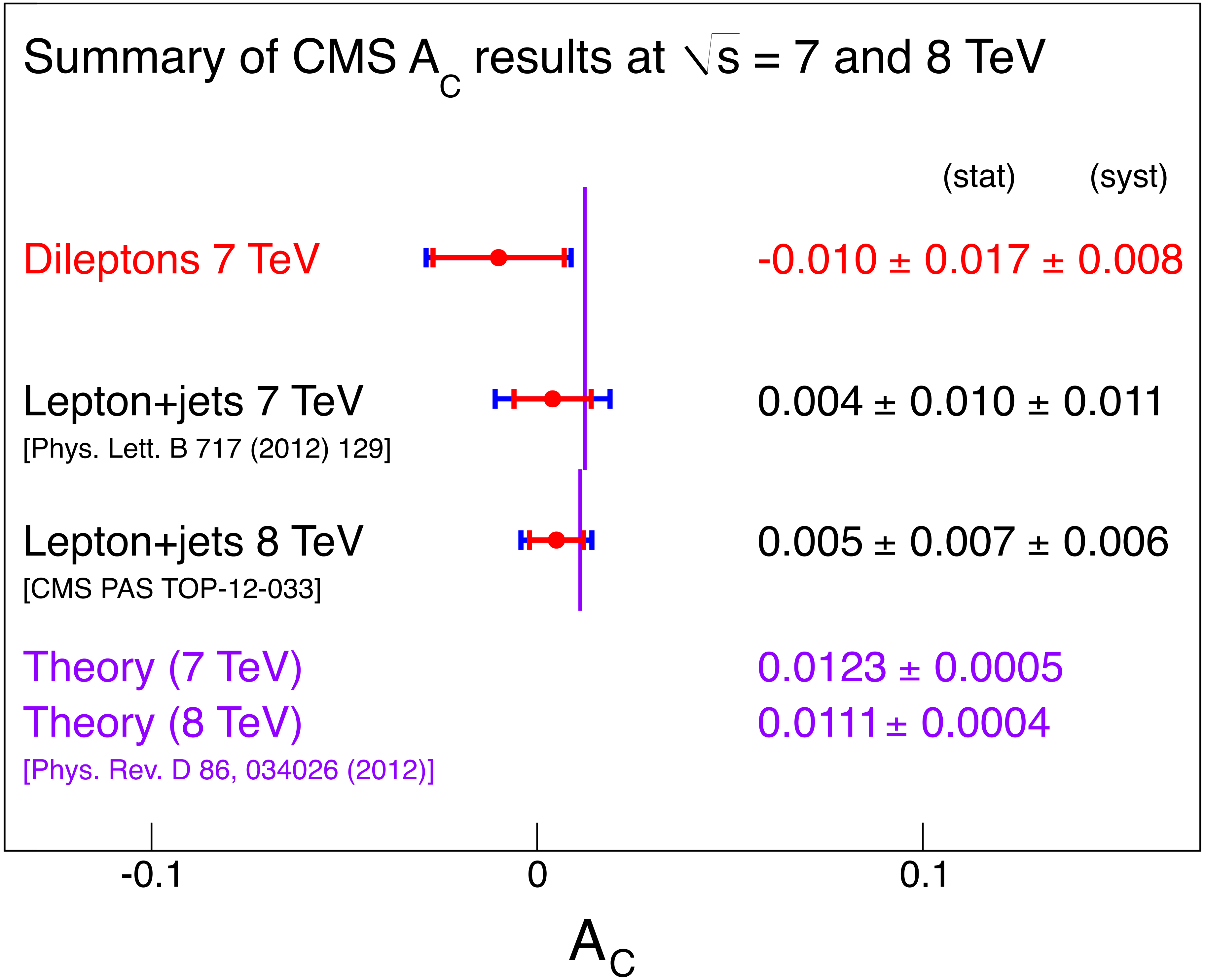
Results: Top Charge Asymmetry



	Top Charge Asymmetry
NLO theory	(1.23 ± 0.05) %
Data (unfolded)	**(-1.0 ± 1.7 ± 0.8) %**
	stat. syst.

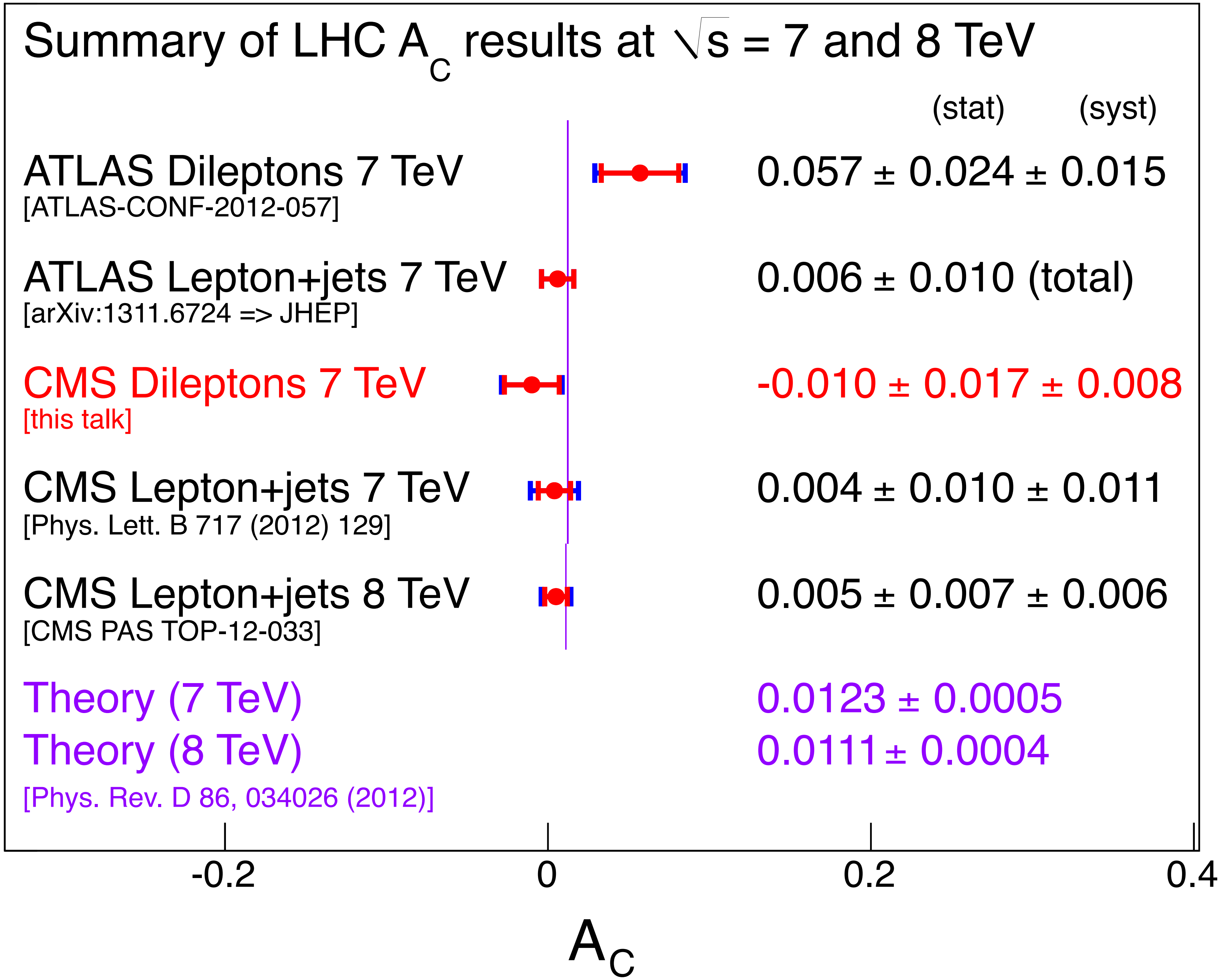
- Measured and unfolded Top Charge Asymmetry compatible with theoretical prediction from the SM and is statistically limited

CMS Top Charge Asymmetry overview



Measurements in different final states and at different center-of-mass energies give consistent picture: compatible with the predictions of the Standard Model

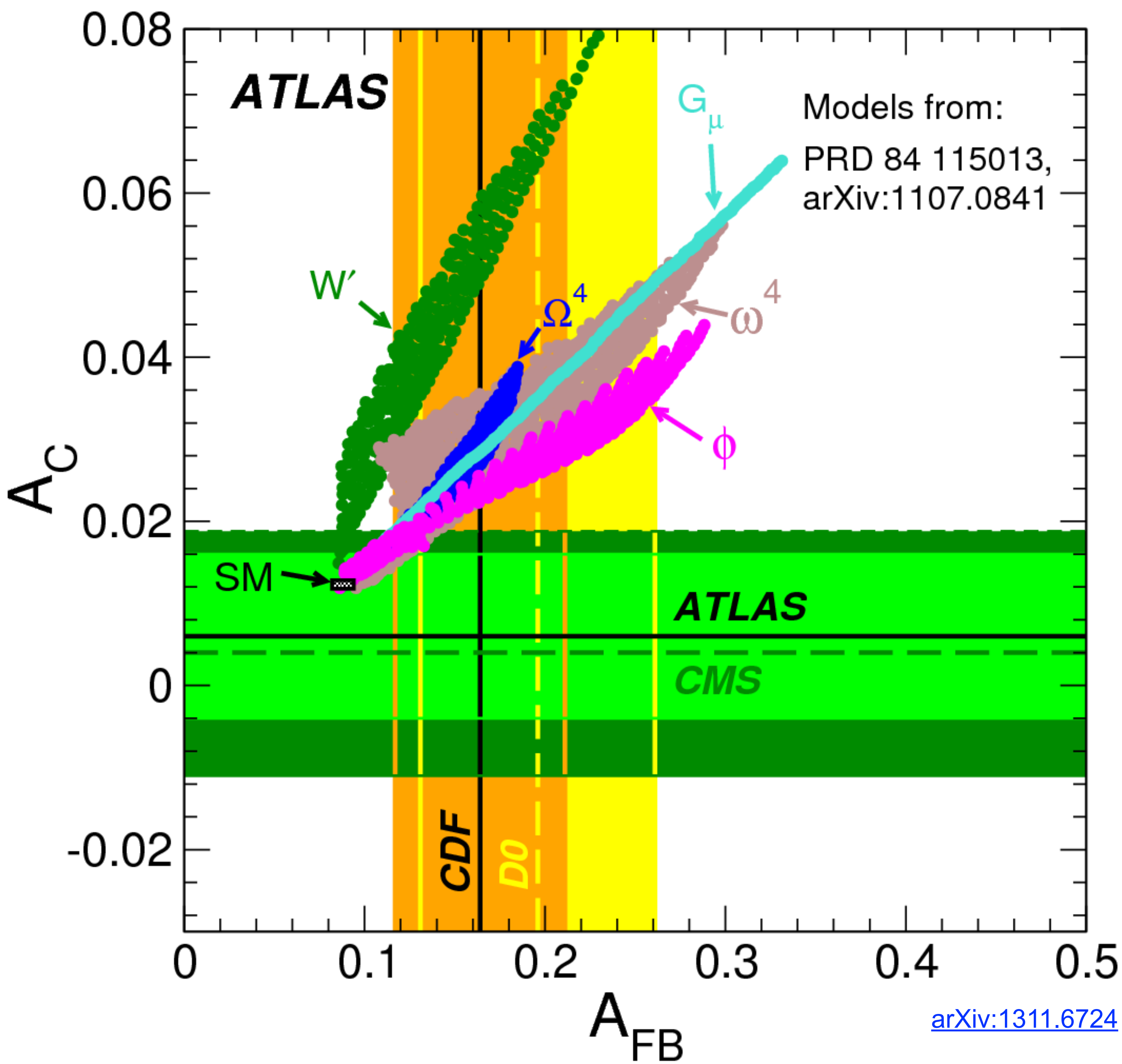
CMS Top Charge Asymmetry overview



Consistent picture also for Atlas and CMS results

Comparing Tevatron and LHC

- There is no direct relation between A_{FB} at the Tevatron and A_C at the LHC
  - $p\bar{p}$ vs pp and 3 times higher center-of-mass energy
  - All comparisons are model-dependent
- Plot shows A_C vs A_{FB} parameter space
  - Areas favored by experiment are shaded
  - Allowed areas in different theories marked by dots
  - All results: l+jets $t\bar{t}$ event selection



arXiv:1311.6724

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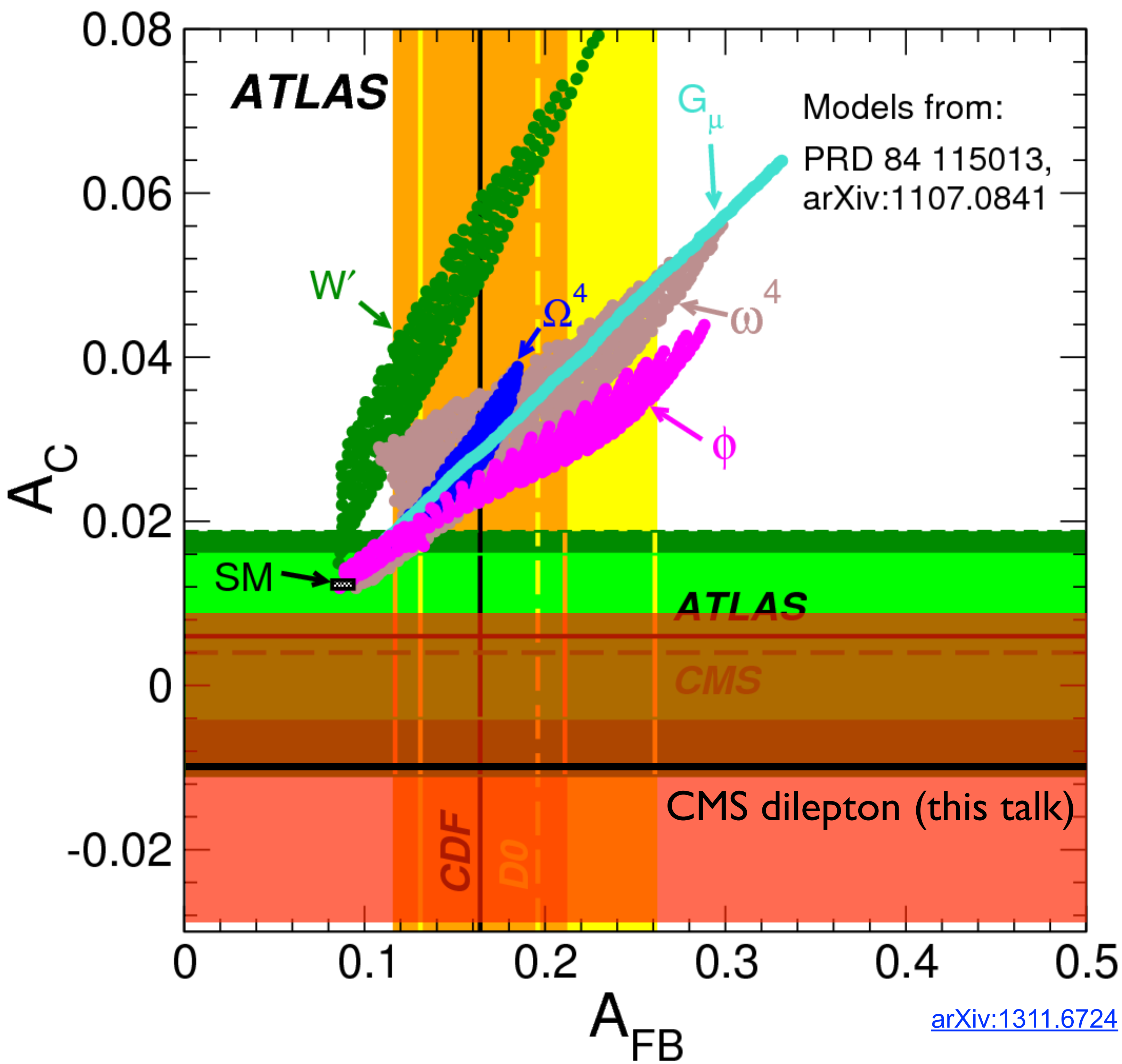
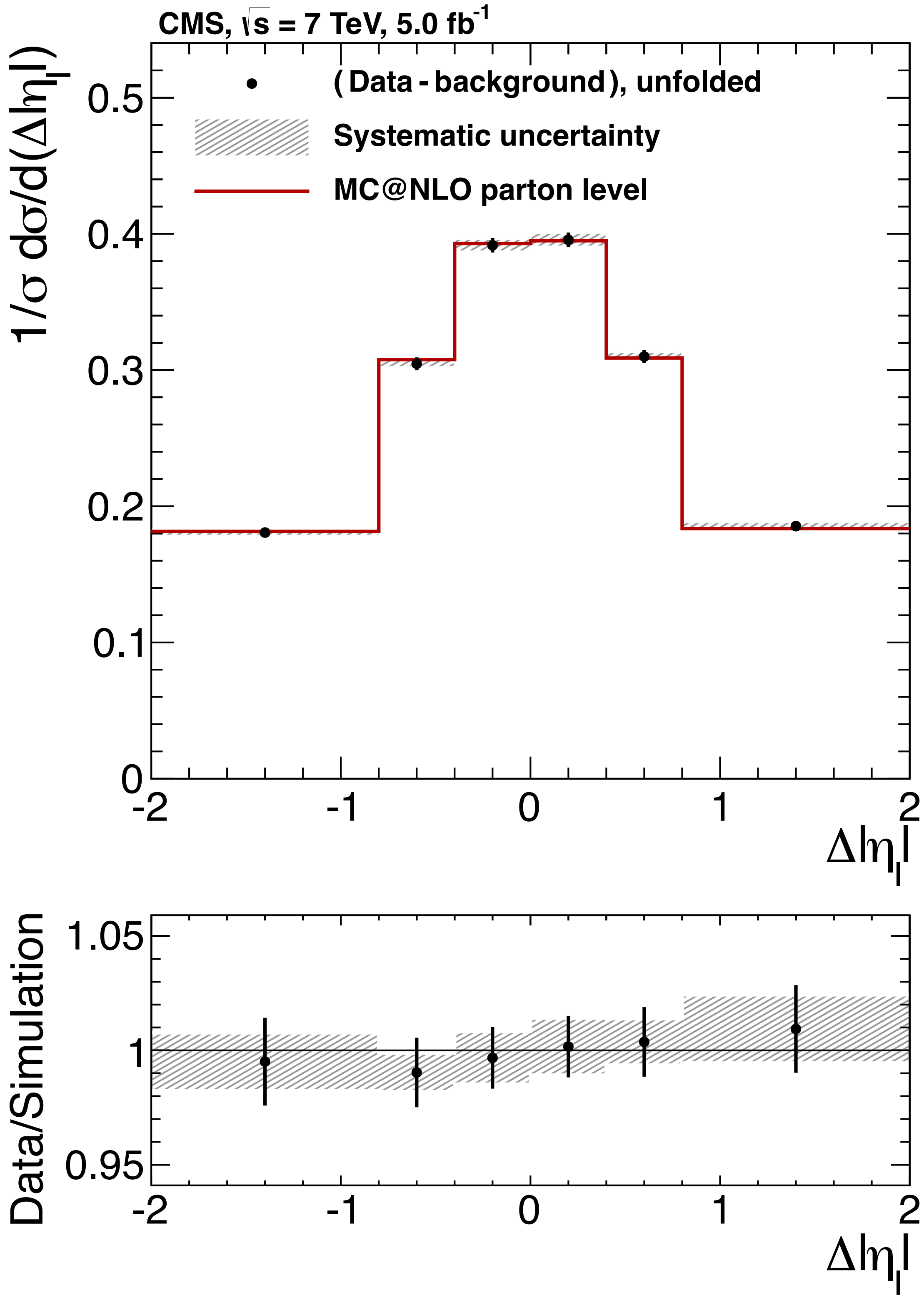
  - Allowed areas in different theories marked by dots
  - **Now including results from this talk**



arXiv:1311.6724

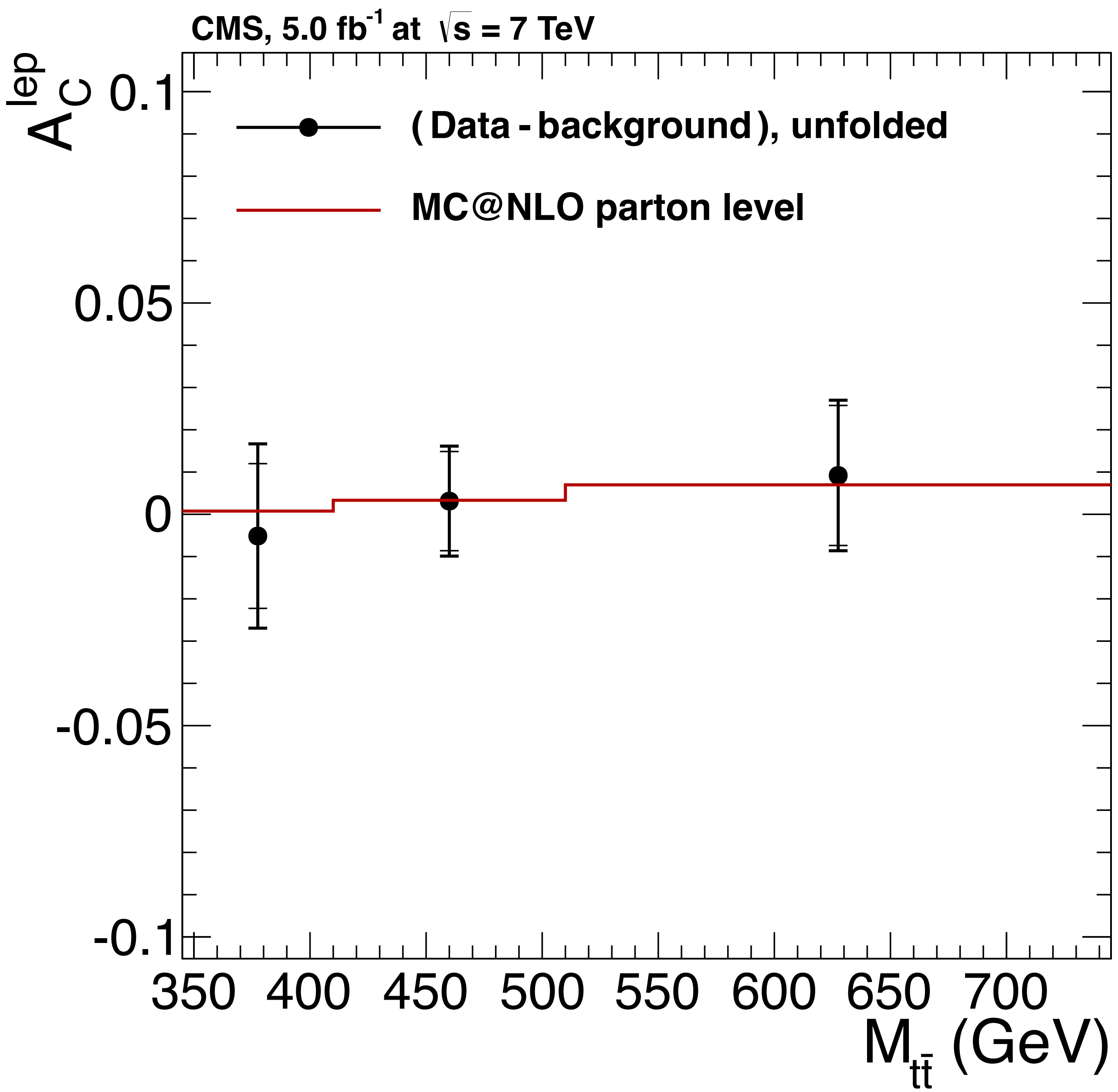


	Lepton Charge Asymmetry
NLO theory	(0.7 ± 0.03) %
Data (unfolded)	**(0.9 ± 1.0 ± 0.6) %**

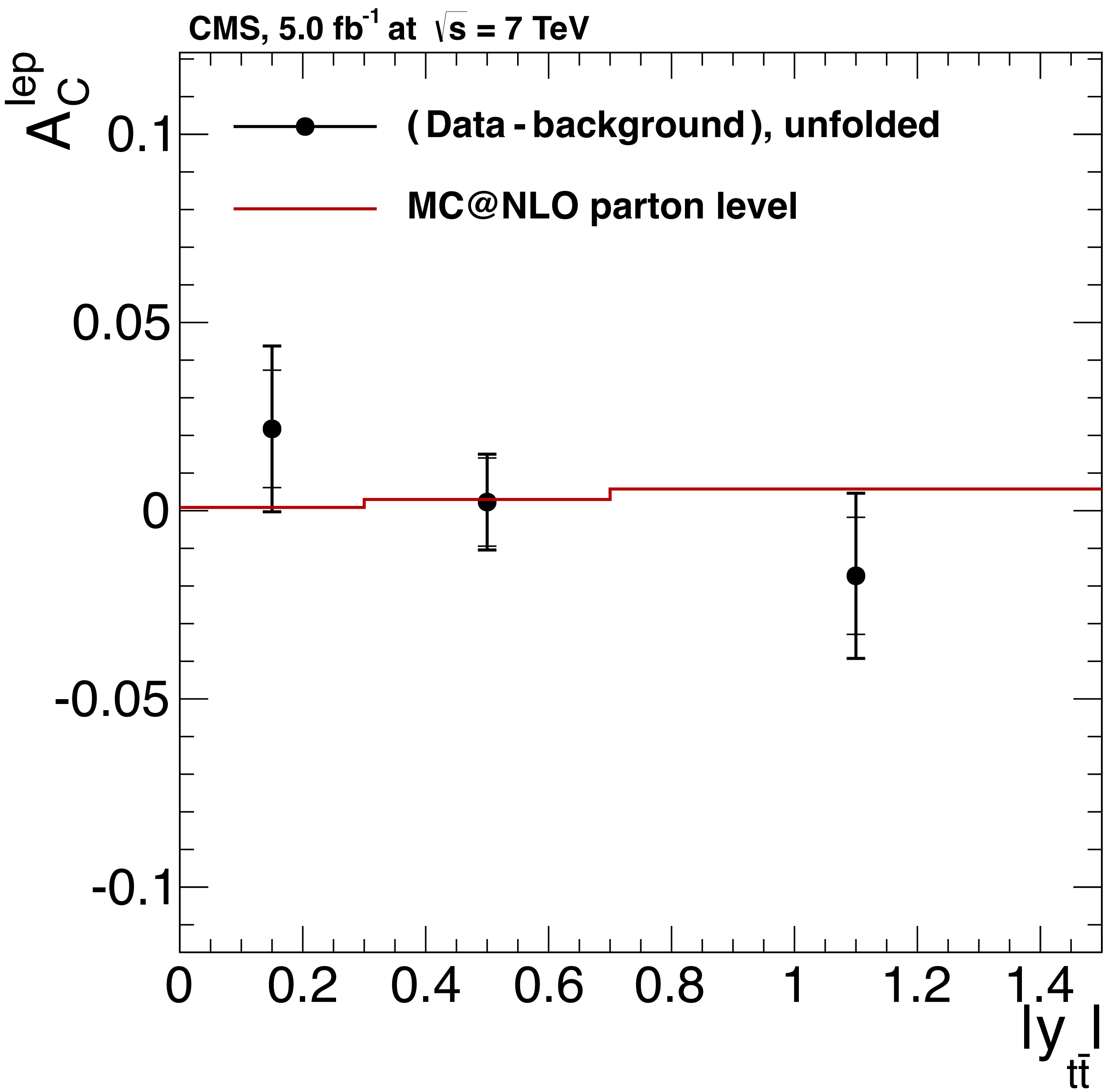
stat. syst.

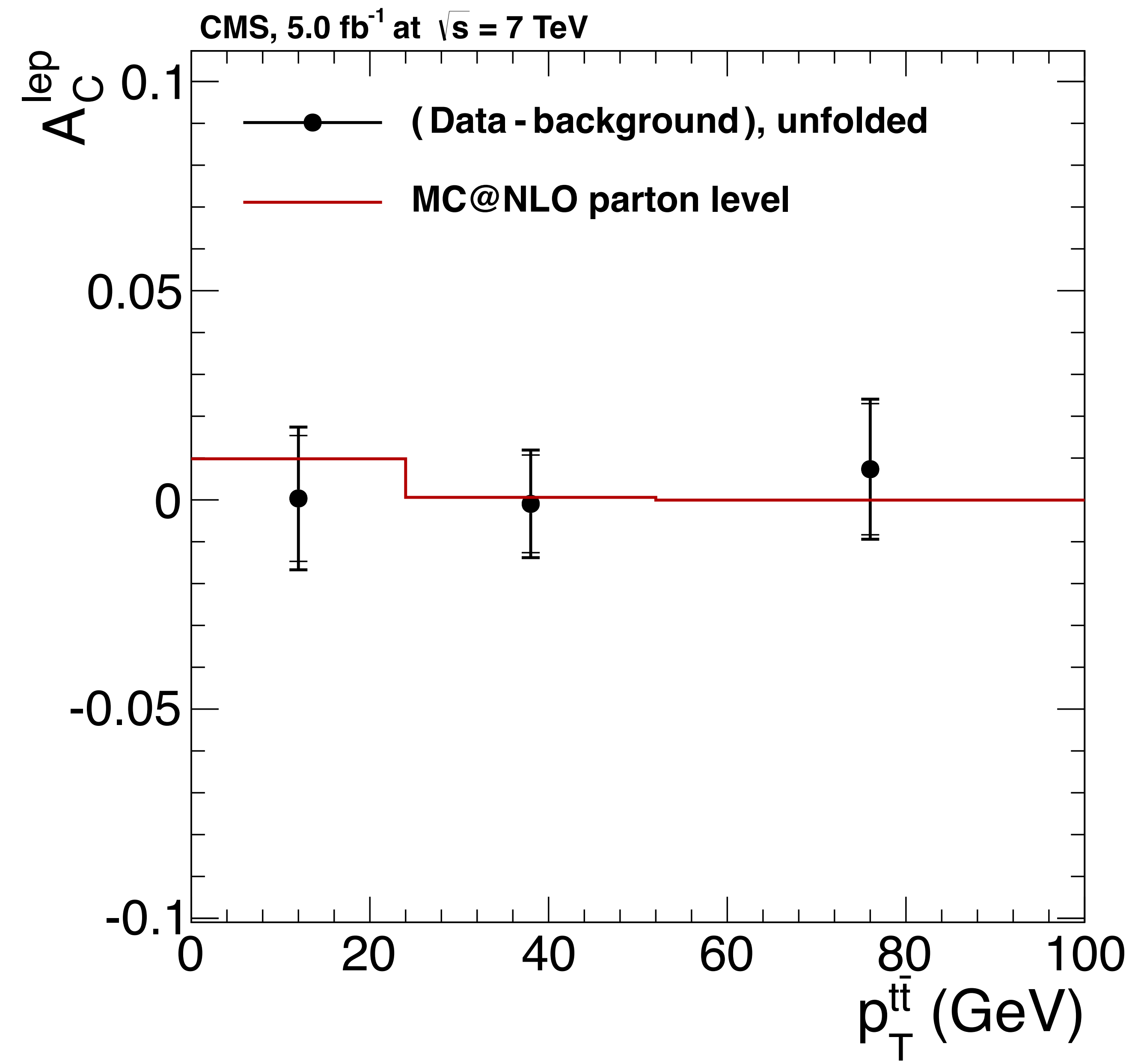
- Measured and unfolded Lepton Charge Asymmetry compatible with theoretical prediction from the SM and is statistically limited

Differential Lepton Charge Asymmetries



- Calculate Lepton Charge Asymmetry differentially
  - Investigate increased deviation at the Tevatron at higher mass of the $t\bar{t}$ system
- Differential in:
  - $M_{t\bar{t}}$: enhanced sensitivity to new physics
  - $y_{t\bar{t}}$: probes relative contribution from qq/gg
  - $p_T^{t\bar{t}}$: sensitive to the ratio of the positive and negative SM contributions to the overall asymmetry
- All bins are compatible with parton level NLO generator predictions

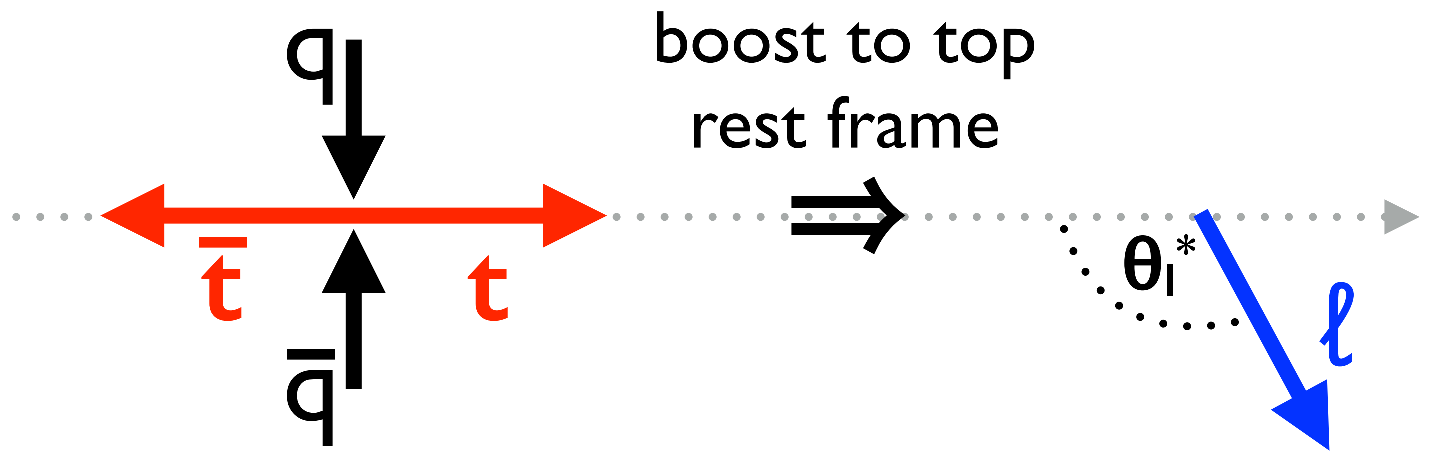




- All bins are compatible with parton level NLO generator predictions

Top polarization and spin correlation measurements using asymmetry variables

Top Polarization Asymmetry



tt center-of-mass (CM) frame

simplified picture

decay probability of lepton from top quark

$$(1 \pm \cos\theta^*_\ell)/2$$

- Top polarization can be measured by the angular distribution of the lepton in the parents top's rest frame

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*_\ell} = (1 + P\cos\theta^*_\ell)/2$$

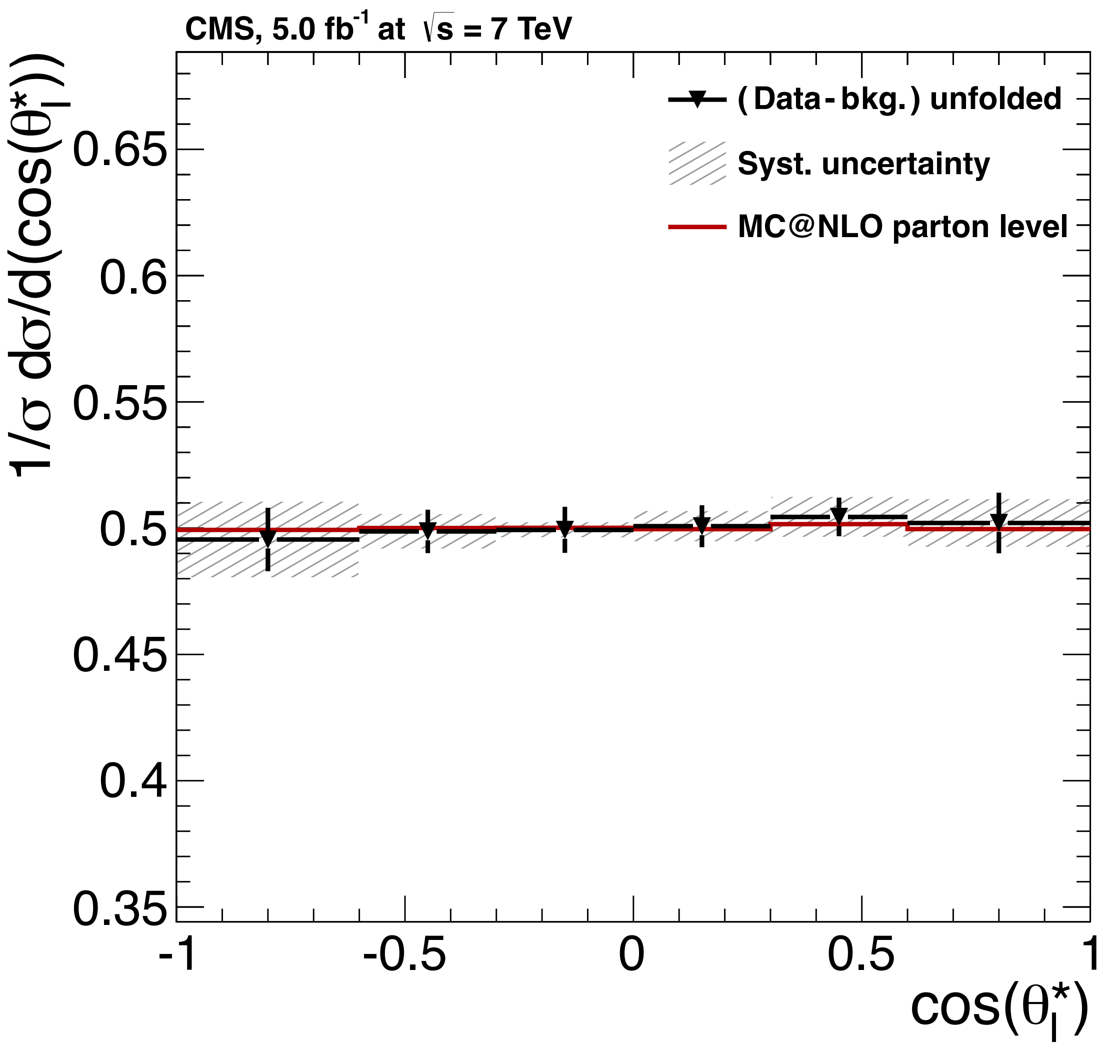
- Constructing an asymmetry sensitive to the polarization of the top quark:

$$P = 2A_P \qquad A_P = \frac{N(\cos(\theta^\star_\ell) > 0) - N(\cos(\theta^\star_\ell) < 0)}{N(\cos(\theta^\star_\ell) > 0) + N(\cos(\theta^\star_\ell) < 0)}$$

- $\cos\theta^*_\ell$ is measured in the helicity basis:
  - Angles relative to the parent top's momentum in its rest frame
  - No distinction between positively and negatively charged leptons, two measurements per event

MC@NLO at parton level:
(0.0 ± 0.1) %

Top Polarization Asymmetry



	Top Polarization Asymmetry
MC@NLO (parton level)	(0.0 ± 0.1) %
Data (unfolded)	**(0.5 ± 1.3 ± 1.4 ± 0.8) %**

stat. syst. pt reweighting.

- The measured and unfolded Top Polarization is compatible with parton level NLO predictions

Top Spin Correlation Asymmetries

- Direct Top Spin Correlation Asymmetry
  - Using the same measurement of $\cos\theta^{*}_{\ell}$ but distinguishing positive and negative lepton charge to measure the correlation

$$A_{c_1c_2} = \frac{N(c_1 \cdot c_2 > 0) - N(c_1 \cdot c_2 < 0)}{N(c_1 \cdot c_2 > 0) + N(c_1 \cdot c_2 < 0)}$$

$$c_1 = \cos(\theta^{\star}_{\ell+}) \qquad c_2 = \cos(\theta^{\star}_{\ell-})$$

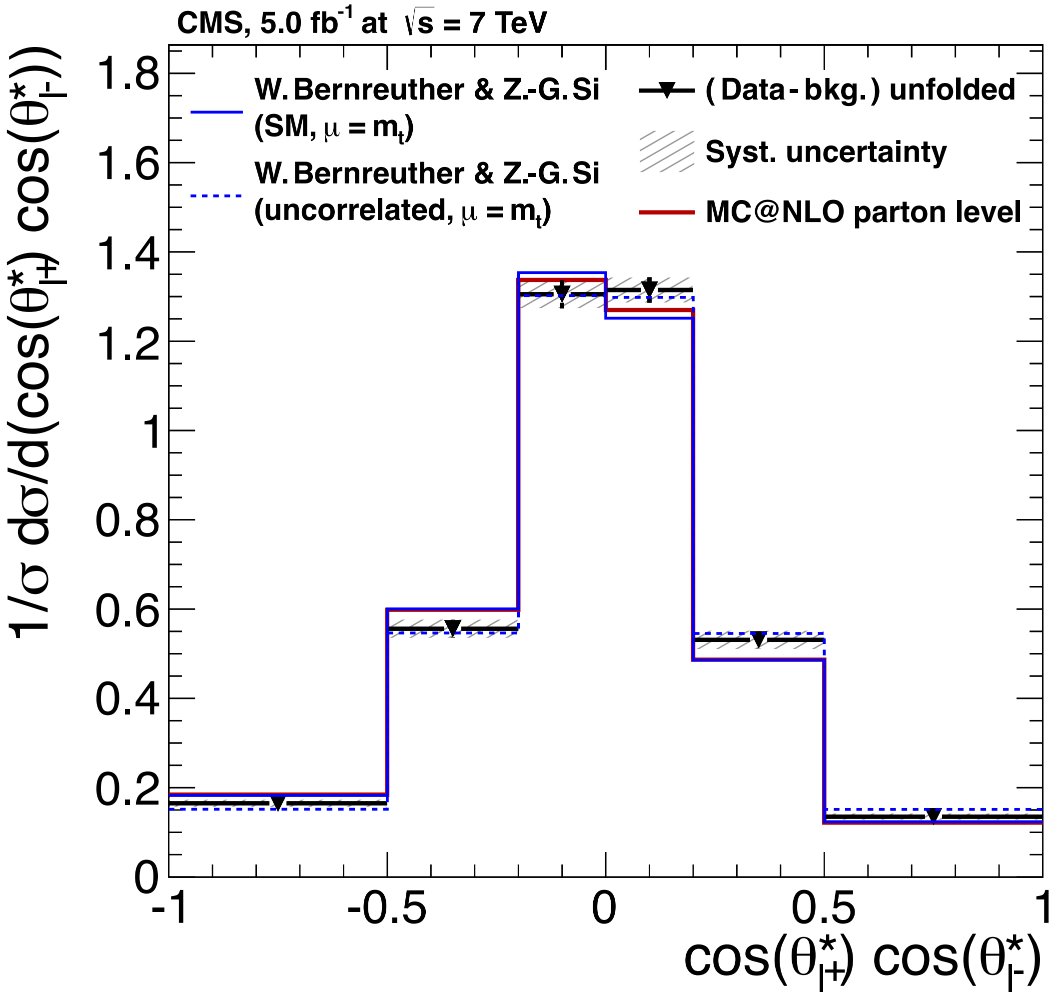
NLO prediction at parton level:
(-7.8 ± 0.6) %

- Indirect Top Spin Correlation Asymmetry
  - Correlation between the top spins results in a correlation in the lepton directions when the top decays

$$A_{\Delta\phi} = \frac{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) - N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}{N(\Delta\phi_{\ell^+\ell^-} > \pi/2) + N(\Delta\phi_{\ell^+\ell^-} < \pi/2)}$$

NLO prediction at parton level:
($11.5^{+1.4}_{-1.6}$) %

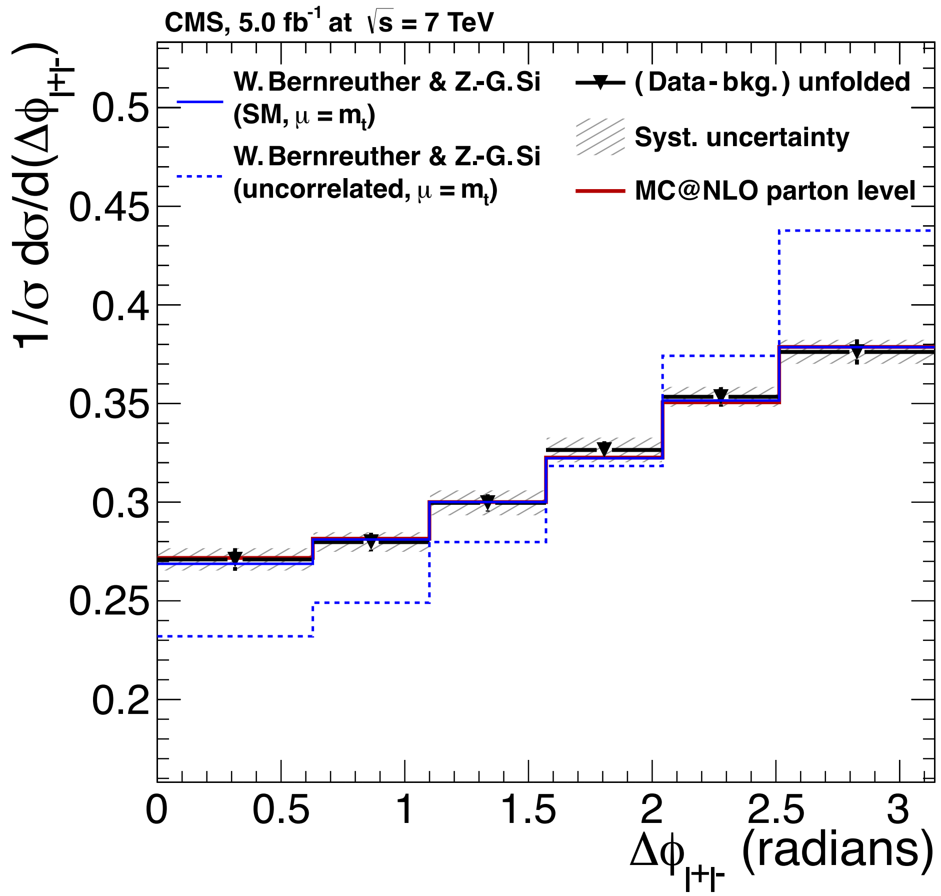
Direct Top Spin Correlation Asymmetry



	Direct Top Spin Correlation Asymmetry
NLO (SM, correlated)	(-7.8 ± 0.1) %
Data (unfolded)	**(-2.1 ± 2.3 ± 2.5 ± 1.0) %**
	stat. syst. pt reweighting.

- The measured and unfolded asymmetry is compatible with parton level NLO predictions

Indirect Top Spin Correlation Asymmetry



	Direct Top Spin Correlation Asymmetry
NLO (uncorrelated)	($21.0\ ^{+1.3}_{-0.8}$) %
NLO (SM, correlated)	($11.5\ ^{+1.4}_{-1.6}$) %
Data (unfolded)	**(11.3 ± 1.0 ± 0.6 ± 1.2) %** stat. syst. pt reweighting.

- The measured and unfolded asymmetry is compatible with parton level NLO predictions
- The purely leptonic asymmetry $A_{\Delta\phi}$ strongly favors $t\bar{t}$ spin correlations and disfavors the uncorrelated case

Summary and Outlook

- Presented Top Asymmetry measurements in the dilepton final state
  - Charge Asymmetries are compatible with SM predictions

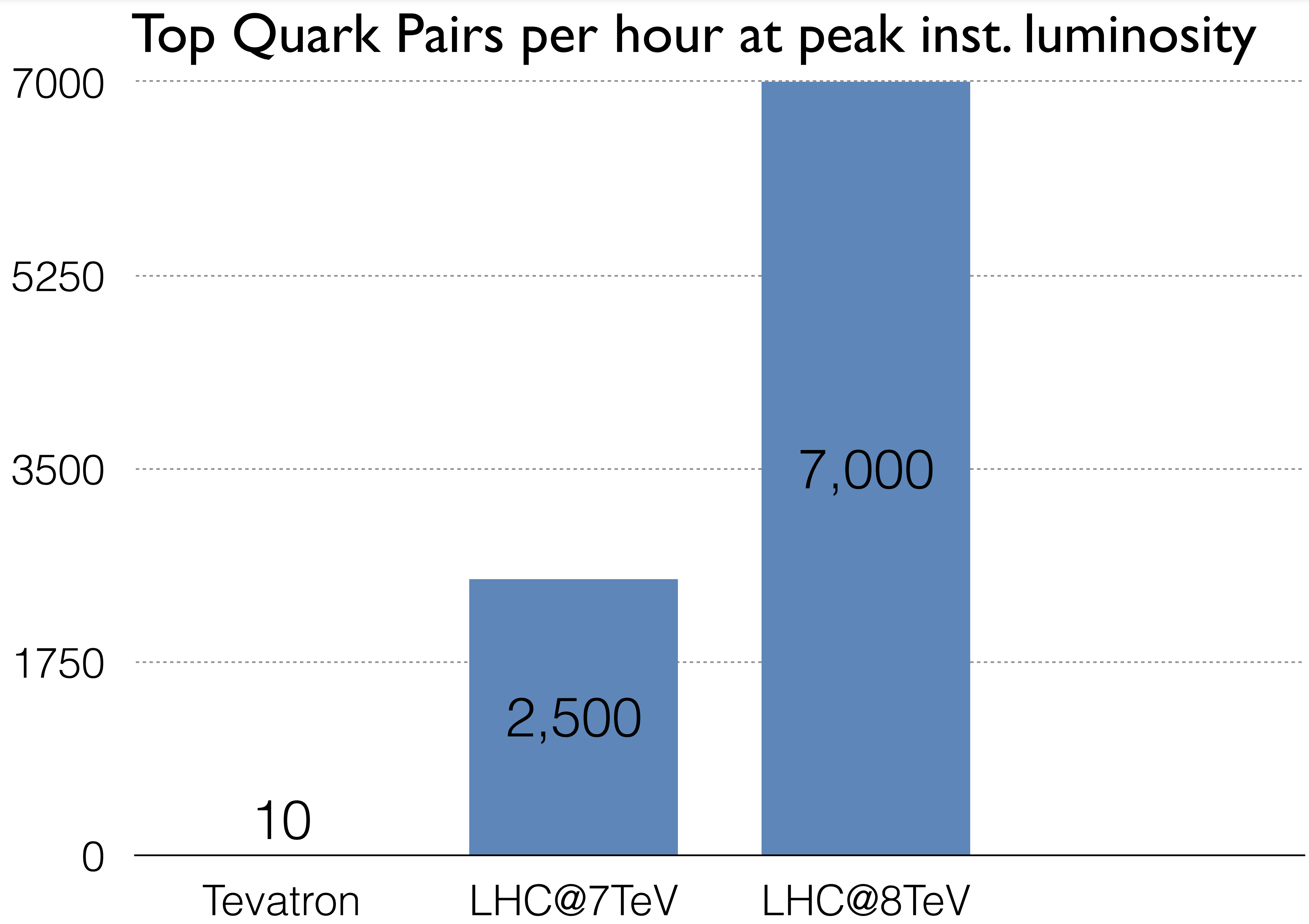
	Top Charge Asymmetry
NLO theory	(1.23 ± 0.05) %
Data (unfolded)	**(-1.0 ± 1.7 ± 0.8) %** (stat. syst.)

  - The Top Polarization Asymmetry does not show deviations from SM
  - While the direct Top Spin Correlation Asymmetry does not have sensitivity using the 2011 dataset, the indirect asymmetry strongly favors $t\bar{t}$ spin correlations and disfavors the uncorrelated case

- The presented results are published in the following papers:
  - arXiv:1311.3924 (submitted to PRL) and arXiv:1402.3803 (submitted to JHEP)
  - and all CMS top results can be found here:
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

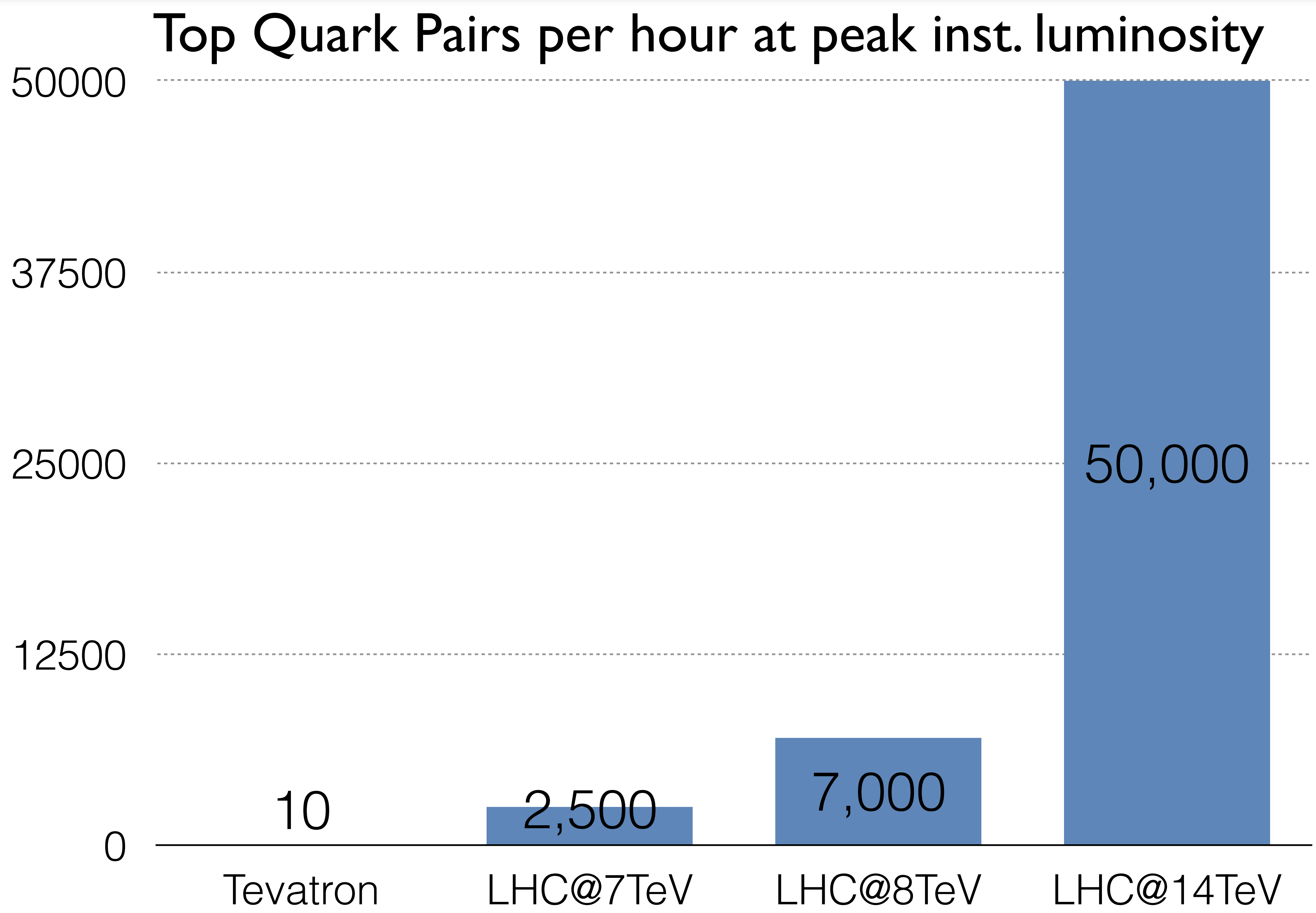
- Plan is to repeat the measurements using the increased statistics at $\sqrt{s}$ = 8 TeV and also in the new running period.

Outlook



cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb, LHC@8TeV ~246pb
peak inst. luminosity: Tevatron: ~4x$10^{32}$$cm^{-2}s^{-1}$, LHC@7TeV: ~4x$10^{33}$$cm^{-2}s^{-1}$, LHC@8TeV: ~8x$10^{33}$$cm^{-2}s^{-1}$

Outlook



cross sections from arXiv:1303.6254: Tevatron ~7pb, LHC@7TeV ~172pb, LHC@8TeV ~246pb, LHC@14TeV ~954pb
peak inst. luminosity: Tevatron: ~$4x10^{32}cm^{-2}s^{-1}$, LHC@7TeV: ~$4x10^{33}cm^{-2}s^{-1}$, LHC@8TeV: ~$8x10^{33}cm^{-2}s^{-1}$, LHC@14TeV: ~$1.5x10^{34}cm^{-2}s^{-1}$ (estimate for 2015)