Top-Quark Physics at CMS

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DER FORSCHUNG | DER LEHRE | DER BILDUNG

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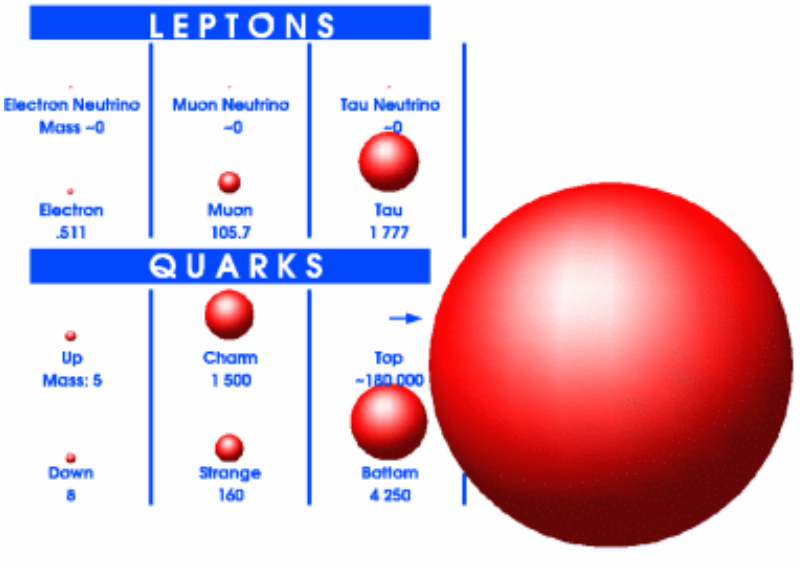
Results Presented in this Talk

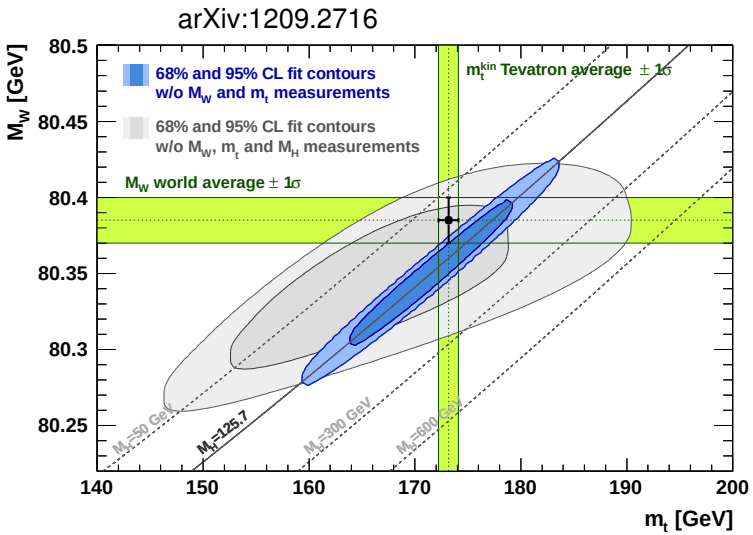
- Inclusive top-pair cross section 
- Differential top-pair cross sections 
- Search for new physics in invariant top-pair mass
- Charge asymmetry
- Top-quark mass 
- Other top-quark properties ($\Delta m(t, \bar{t})$, spin, charge)

Motivation - Why is the Top Quark Special?

Top quark is heaviest particle in SM

- decays before hadronisation
  - direct access to “bare quark”
- allows for precision measurements of SM parameters
  - cross sections, mass, spin, charge
- very sensitive to Higgs
  - test of SM
- vital for BSM searches
  - many theories predict preferred coupling to top quarks
  - often top quarks constitute most important background





slight tension between SM fit and mass measurments but still compatible

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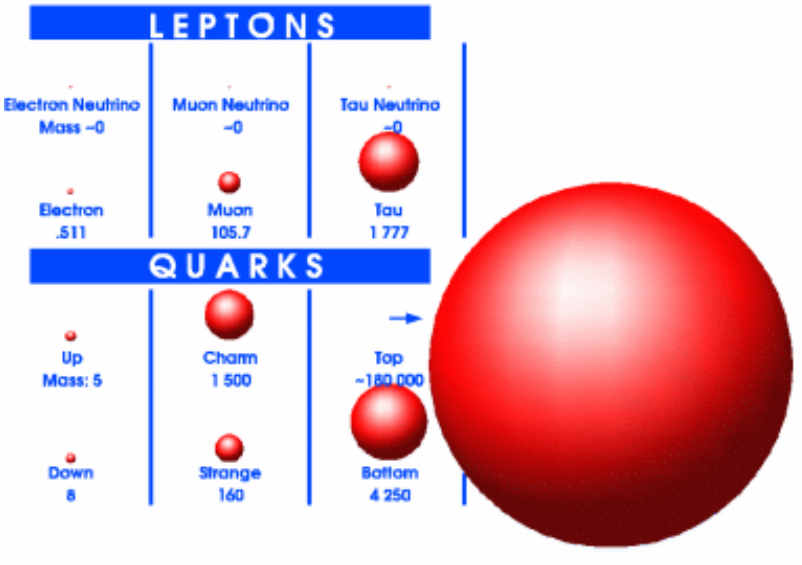
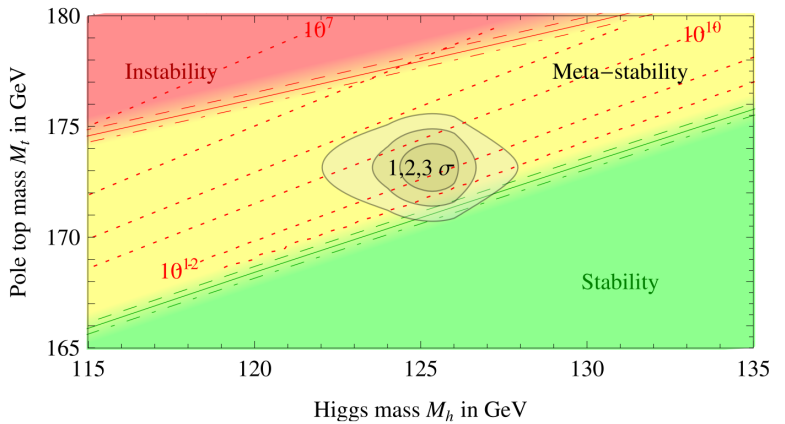


arXiv:1205.6497

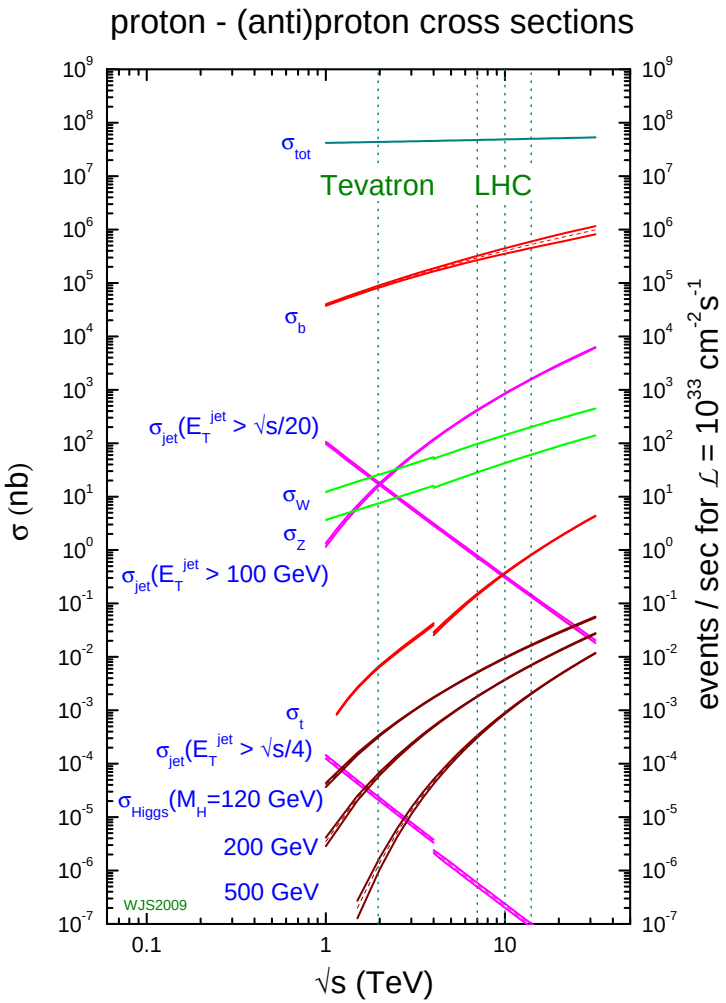


current mass measurements favour meta stable SM vacuum

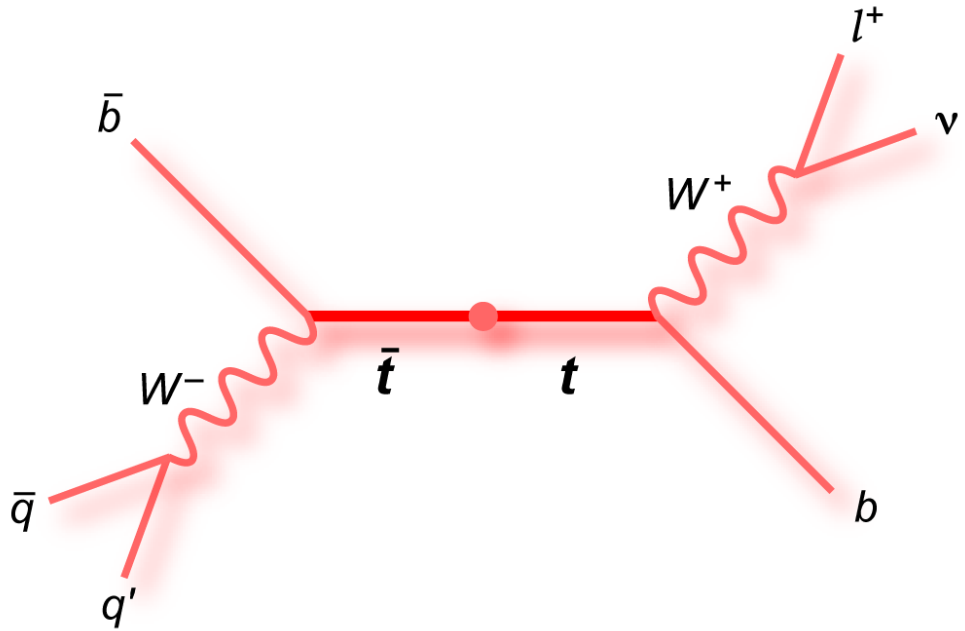
Top Pair Production and Decay

Main production at LHC

- gluon-gluon fusion 80 – 90%



$> 4\,000\,000\ t\bar{t}$ pairs produced

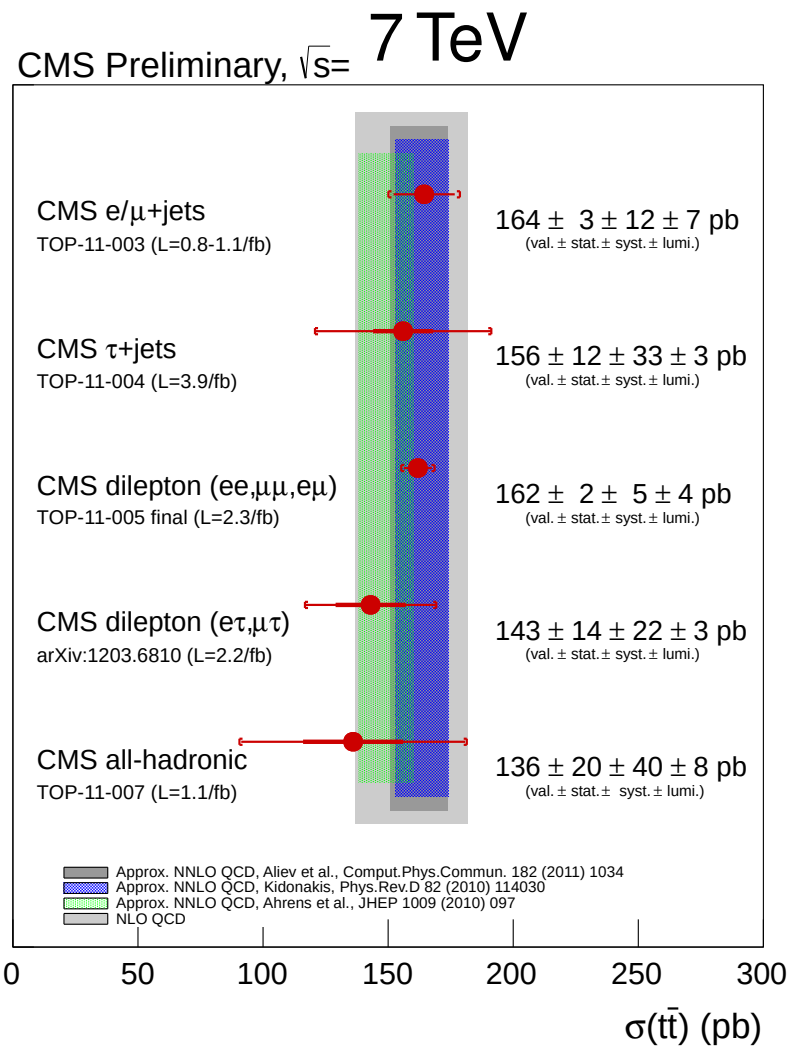


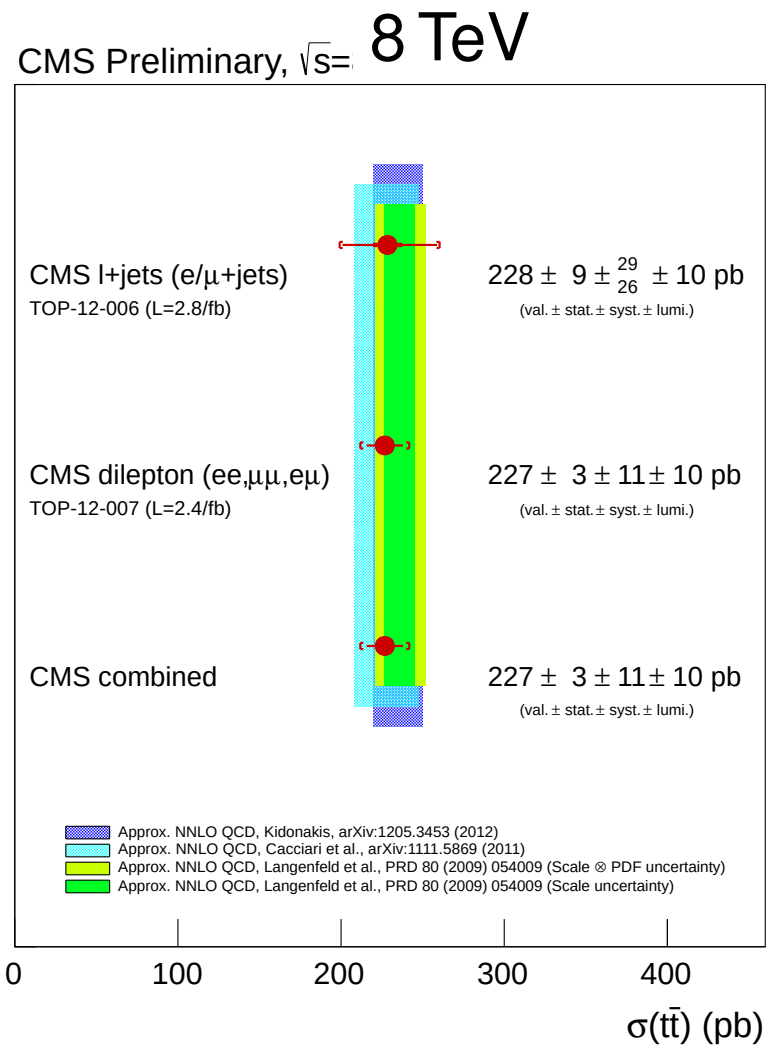
Decay channels specified by W-boson decay

- fullhadronic (BR: $\sim 46\%$)
- semileptonic (BR: $\sim 15\% \times 3$)
- dileptonic (BR: $\sim 1\% \times 9$)

Analysis techniques depend on channel

Inclusive $t\bar{t}$ Cross Section $\sigma_{t\bar{t}}$

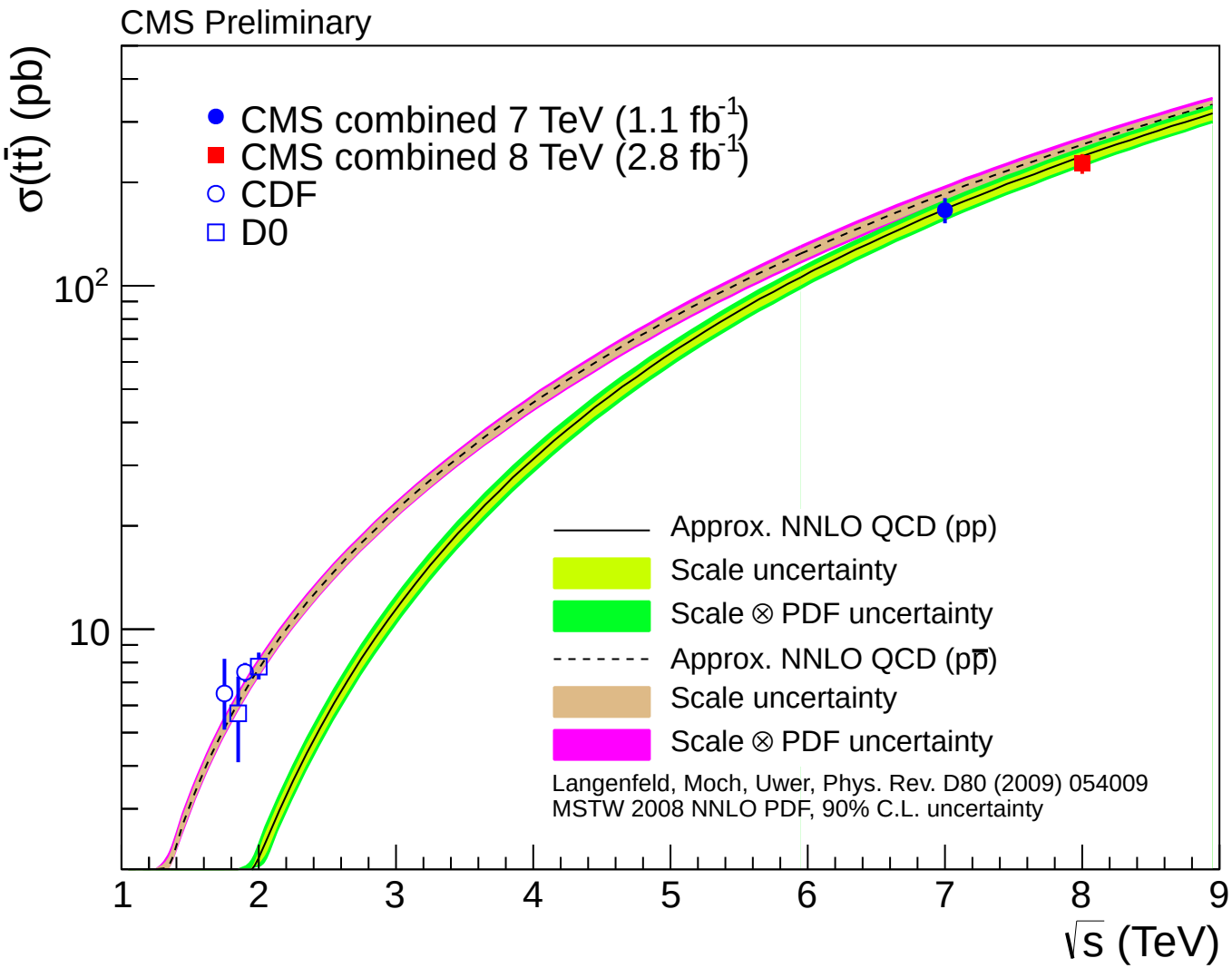




CMS measured $\sigma_{t\bar{t}}$ at 2 different centre-of-mass energies (7 TeV and 8 TeV)

- uncertainties partially smaller than for approx. NNLO calculations ($\mathcal{O}(5\%)$)
- ▶ all channels in good agreement with SM prediction

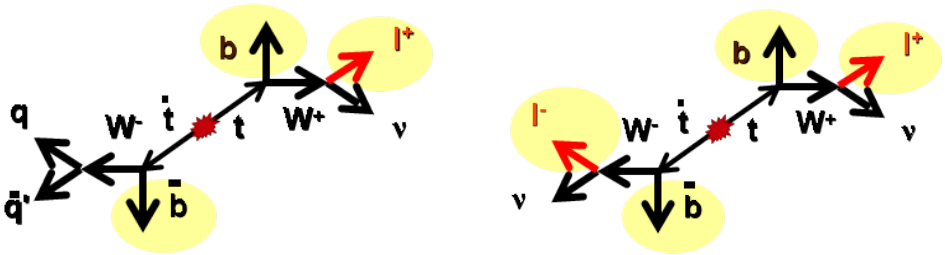
Test of QCD at Different Energy Scales



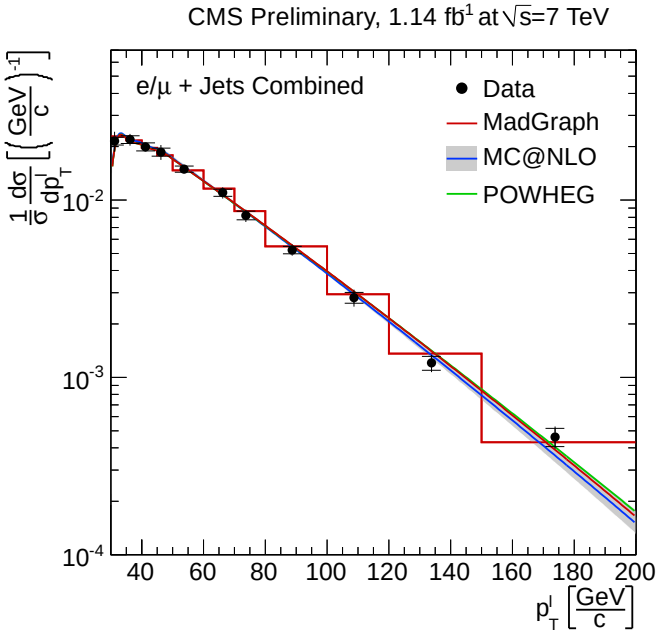
Remarkable agreement with SM QCD predictions over wide energy range

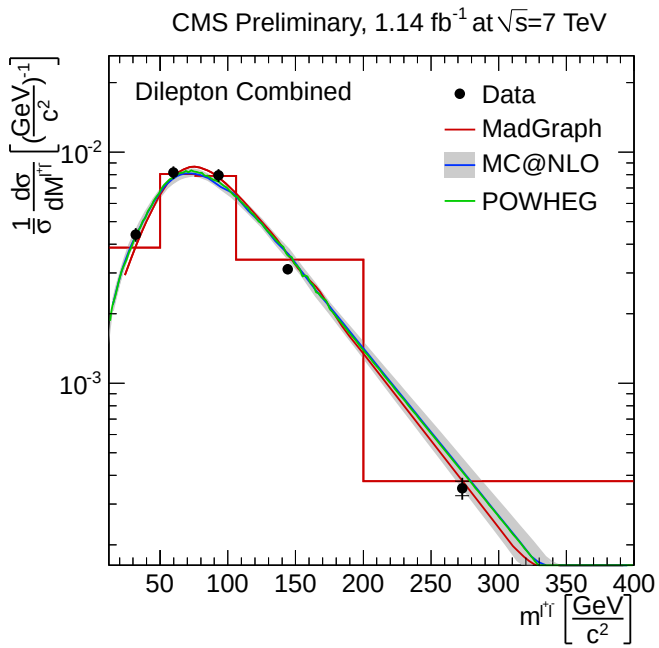
Differential $t\bar{t}$ Cross Sections (CMS-TOP-11-013)

Measure kinematics of final-state particles



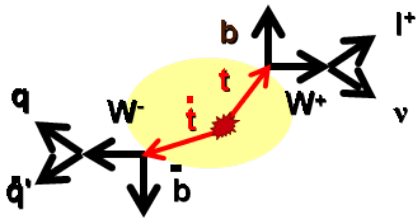
- easy to reconstruct
- no full event reconstruction needed
  - no association of particles to t or $\bar{t}$
  - no recontruction of unmeasured neutrinos
- correct for detector effects only
  - model independent
- variables:
  - p_T and η of leptons and b jets
    - ★ test of the event generators
  - invariant dilepton mass
    - ★ important background for searches
  - p_T of dilepton system
    - ★ sensitive to spin correlation



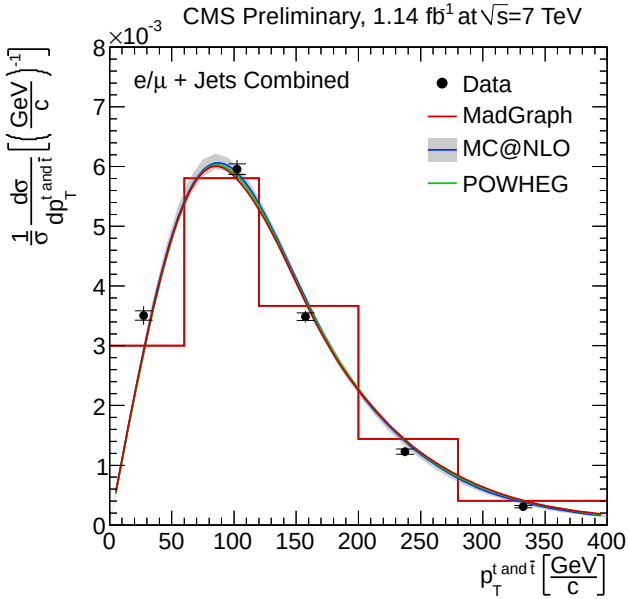


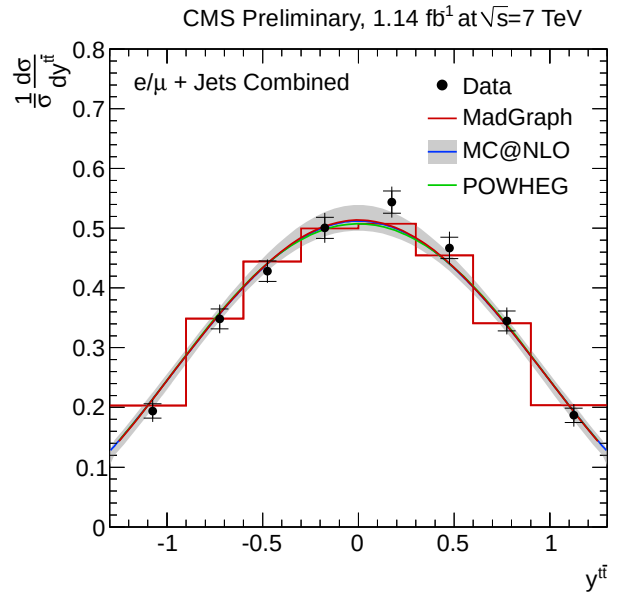
Differential $t\bar{t}$ Cross Sections (CMS-TOP-11-013)

Measure kinematics of top quarks and $t\bar{t}$ system



- full kinematic event reconstruction
  - assign each particle to its mother
  - reconstruct neutrinos
- unfolding to parton level
  - correct for detector & hadronization effects
- variables:
  - p_T and y of top quarks
    - ★ p_T measured softer than predicted by MC
    - ★ sensitive to difference (NLO ↔ NNLO)
  - p_T and y of $t\bar{t}$ system
    - ★ $p_T^{t\bar{t}}$ is sensitive to radiation (ISR/FSR)
    - ★ $y^{t\bar{t}}$ is possible input to PDF fits
  - invariant $t\bar{t}$ mass
    - ★ search for resonances

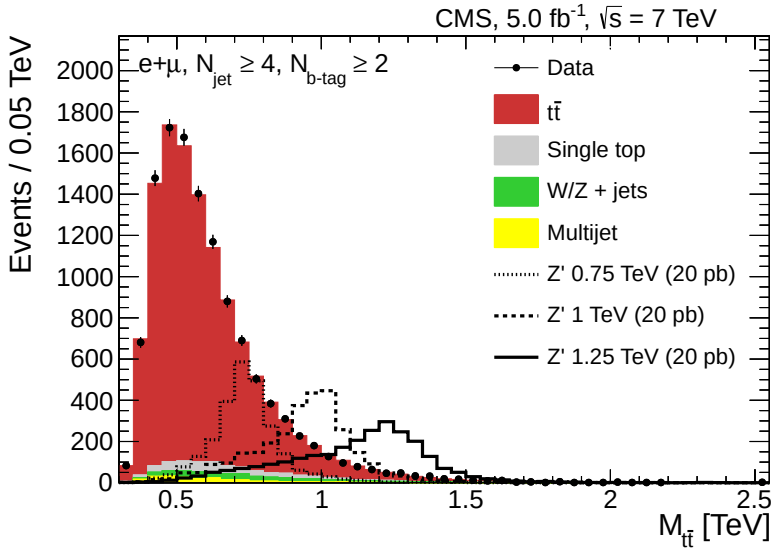


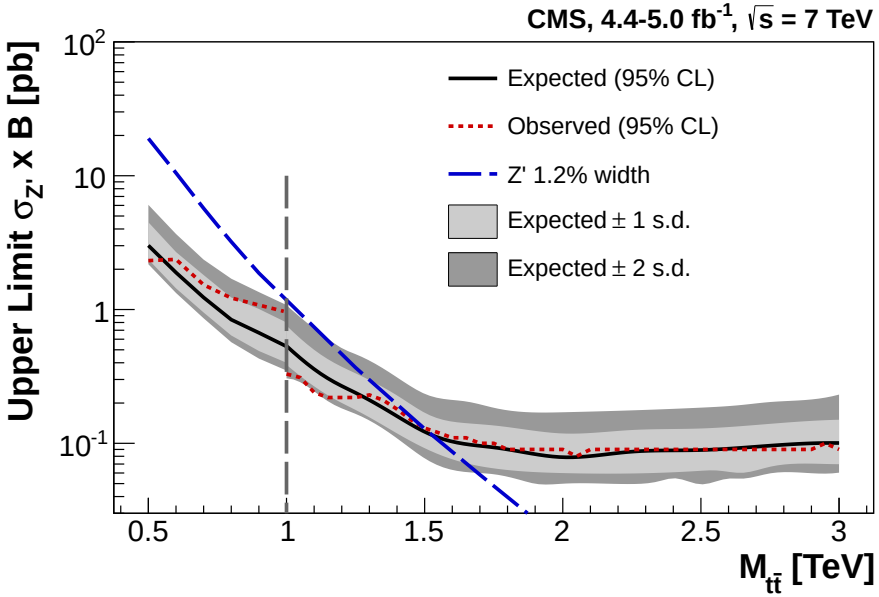


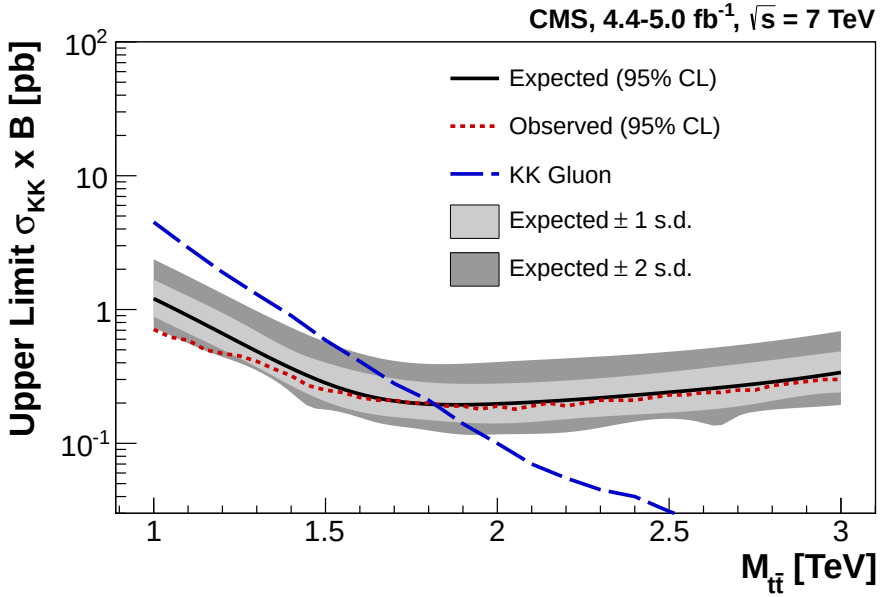
Invariant Top-Pair Mass $m_{t\bar{t}}$ (arXiv:1209.4397)

Most obvious distribution for searches

- heavy particles decay into $t\bar{t}$ pair
  - resonances in $m_{t\bar{t}}$ spectrum
    - peak at the mass of the particle
- model independent
- measurement in agreement with SM
  - limits for different models (95% CL)
    - Z'(1.2% width): 1.49 TeV
    - KK gluon: 1.82 TeV





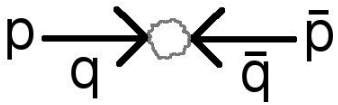


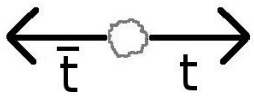
Charge Asymmetry - Principles

- $t\bar{t}$ production by gluon-gluon fusion is symmetric
- Asymmetry only arises from quark-antiquark annihilation

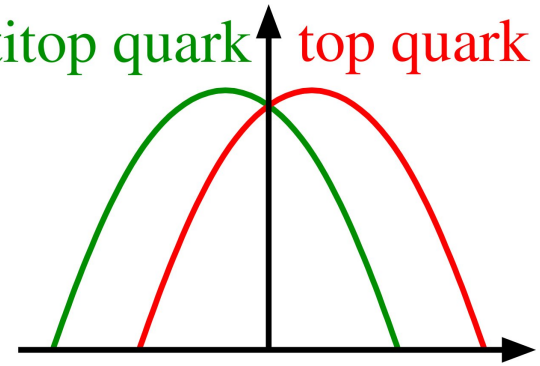
Tevatron:

- proton-antiproton collider





favoured direction for $t/\bar{t}$



forward-backward asymmetry in angular distribution of top quarks

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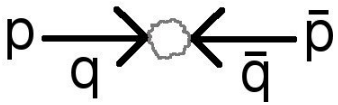

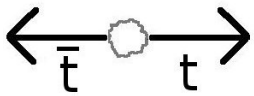

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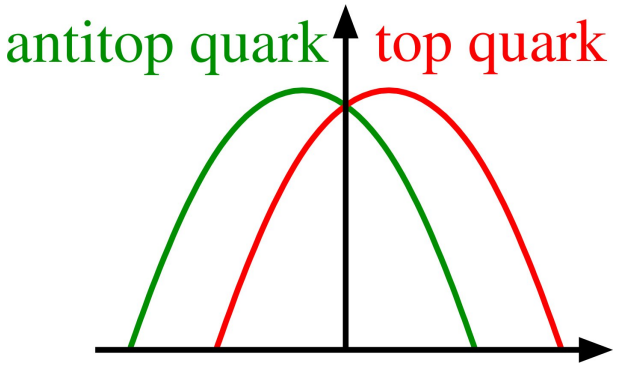
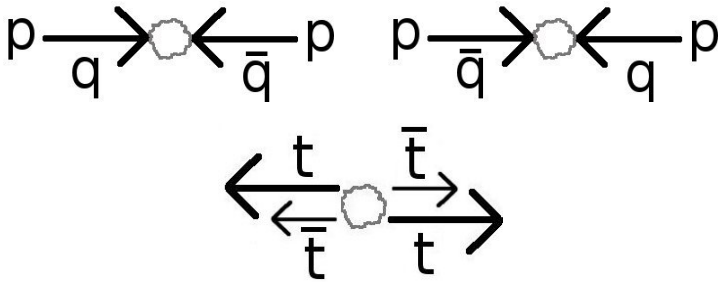


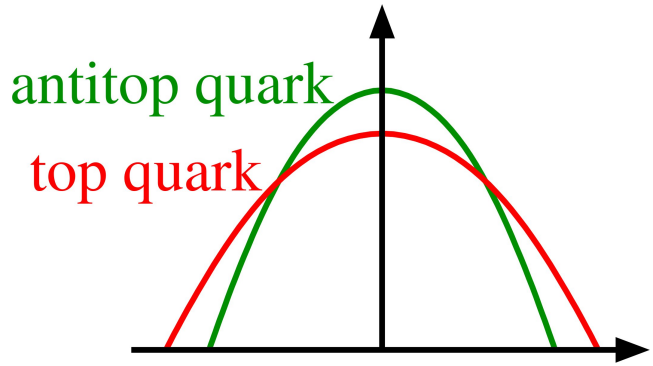
forward-backward asymmetry in angular distribution of top quarks

LHC:

- proton-proton collider



momentum in proton direction:
$p_Z(t) > p_Z(\bar{t})$

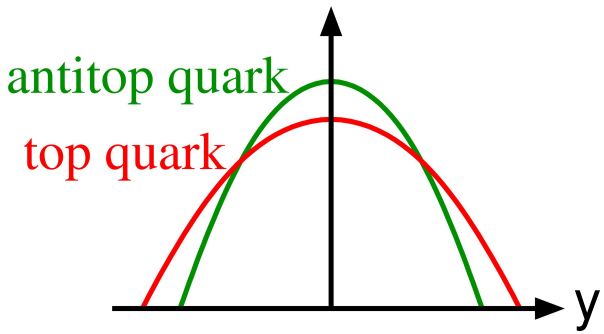


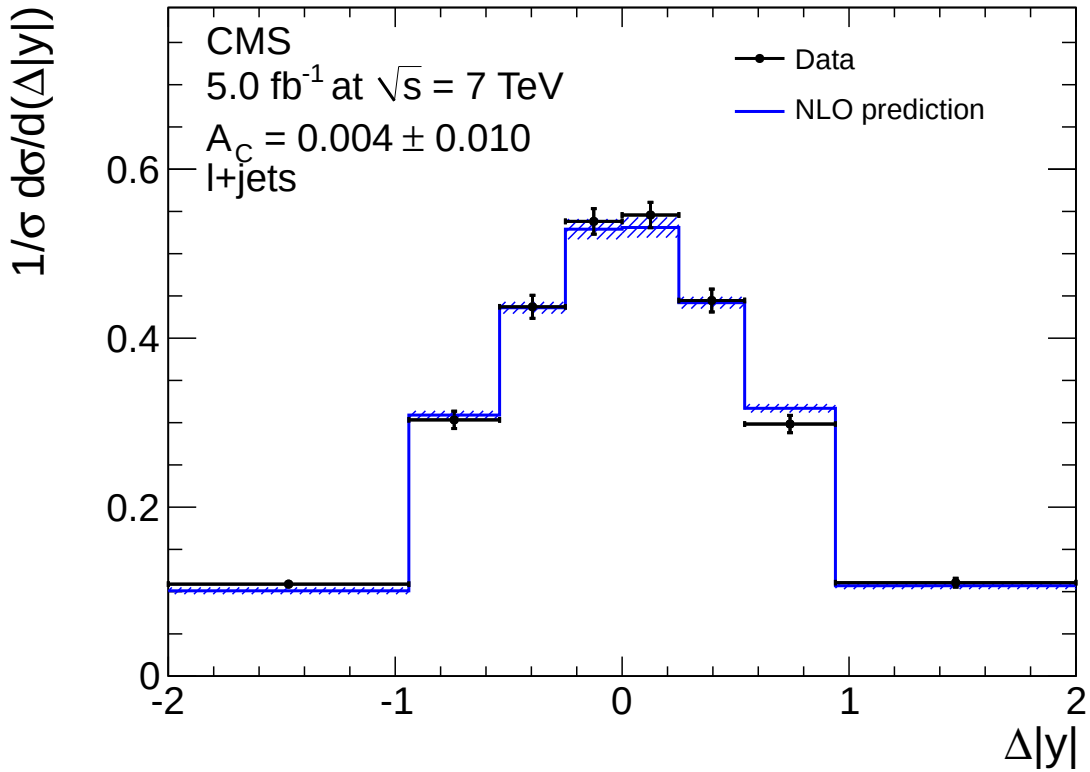
central-decentral asymmetry in angular distribution of top quarks

Charge Asymmetry - Measurement

Define sensitive variable: $\Delta|y| = |y_t| - |y_{\bar{t}}|$

- SM predicts asymmetry in this variable
  - $A_C^{SM} = 0.0115 \pm 0.0006$
- CMS measured (arXiv:1207.0065)
  - $A_C = 0.004 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$
    - ★ compatible with SM prediction





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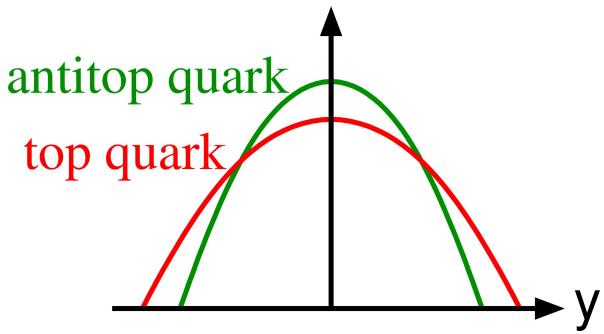
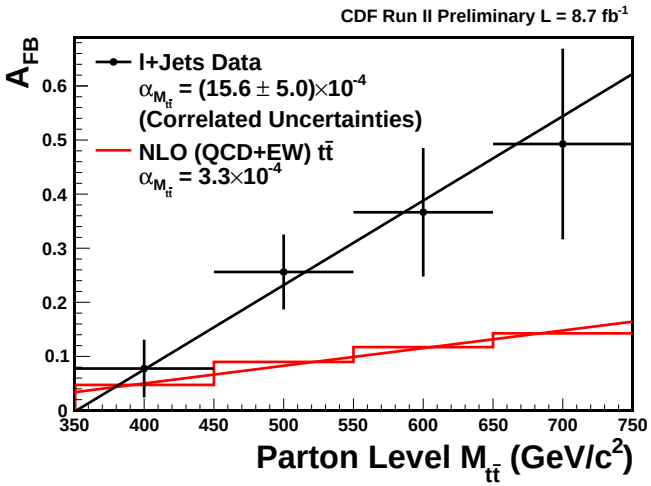
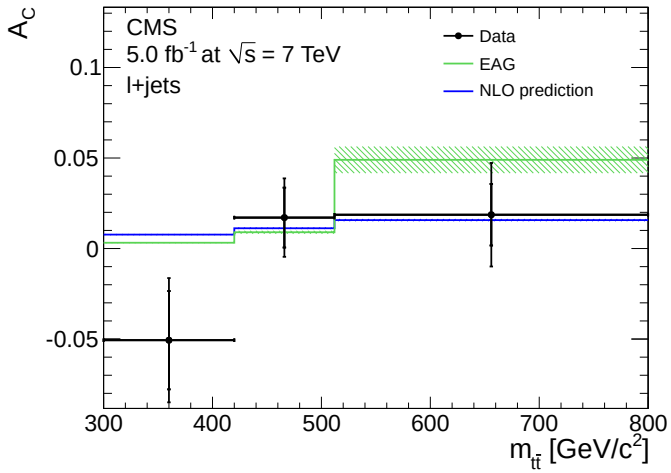


Measure separately for events with different invariant mass $m_{t\bar{t}}$:

CDF



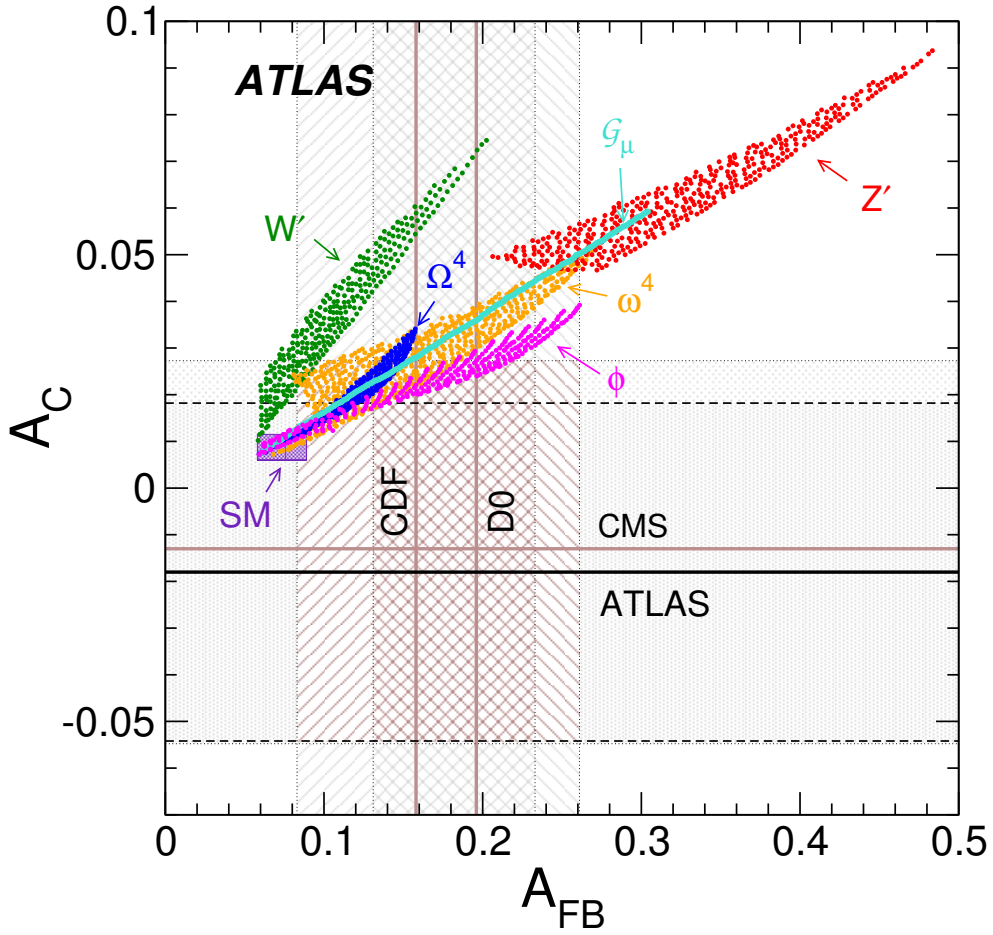


CMS

- CDF (at Tevatron) measures deviation from SM (CDF Note 10807)
- no significant deviation at CMS (arXiv:1207.0065)

Charge Asymmetry Combination (arXiv:1203.4211v2)

LHC charge asymmetry A_C and Tevatron forward-backward asymmetry A_{FB}

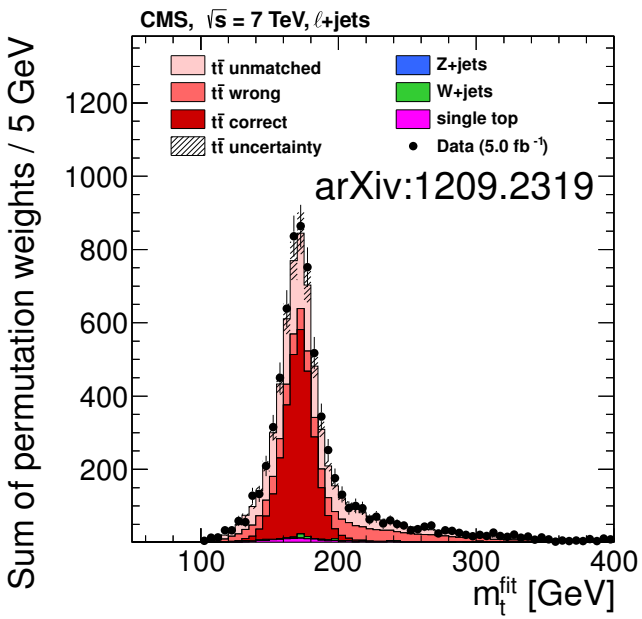


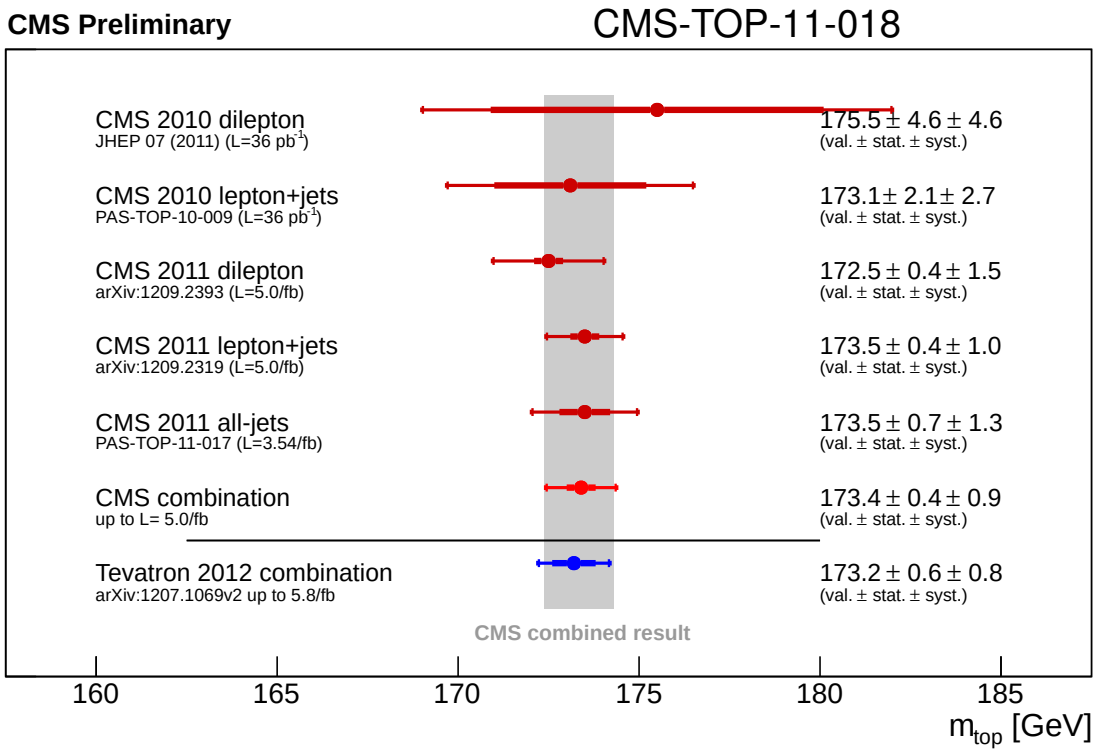
- several BSM models disfavoured/constrained by the CMS measurement (figure shows old inclusive CMS result (1.1 fb^{-1}))

Top Mass Measurement

Most precise measurement to date:

- 2D-ideogram method
  - full event reconstruction
  - 2D fit of mass and jet-energy scale (JES)
    - ★ reduces uncertainty

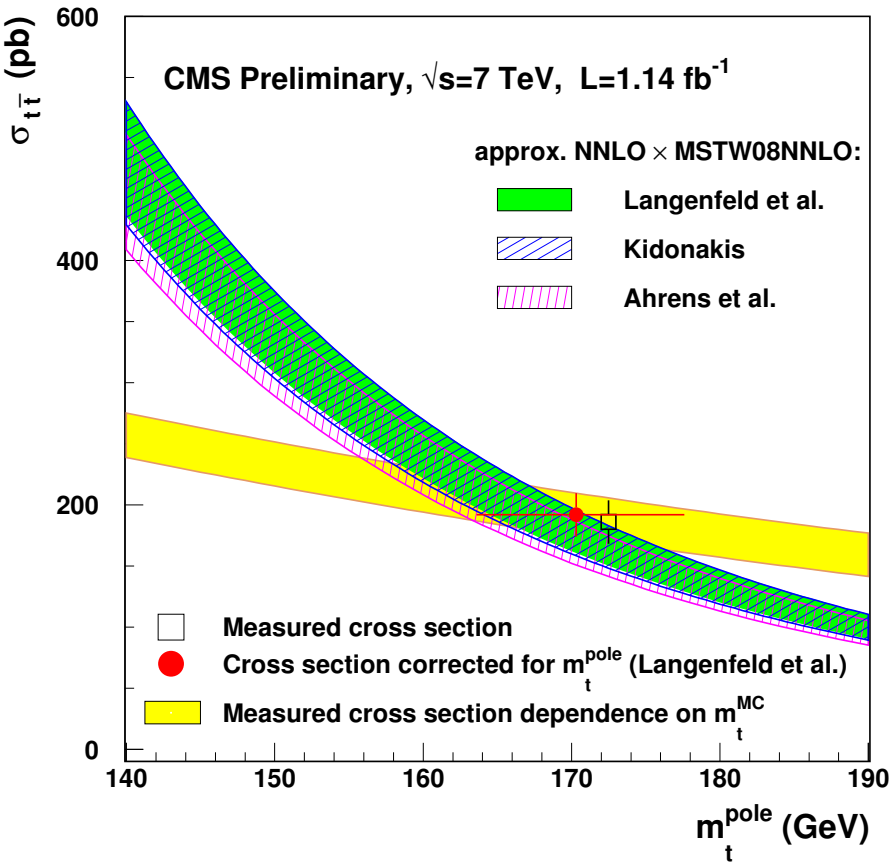


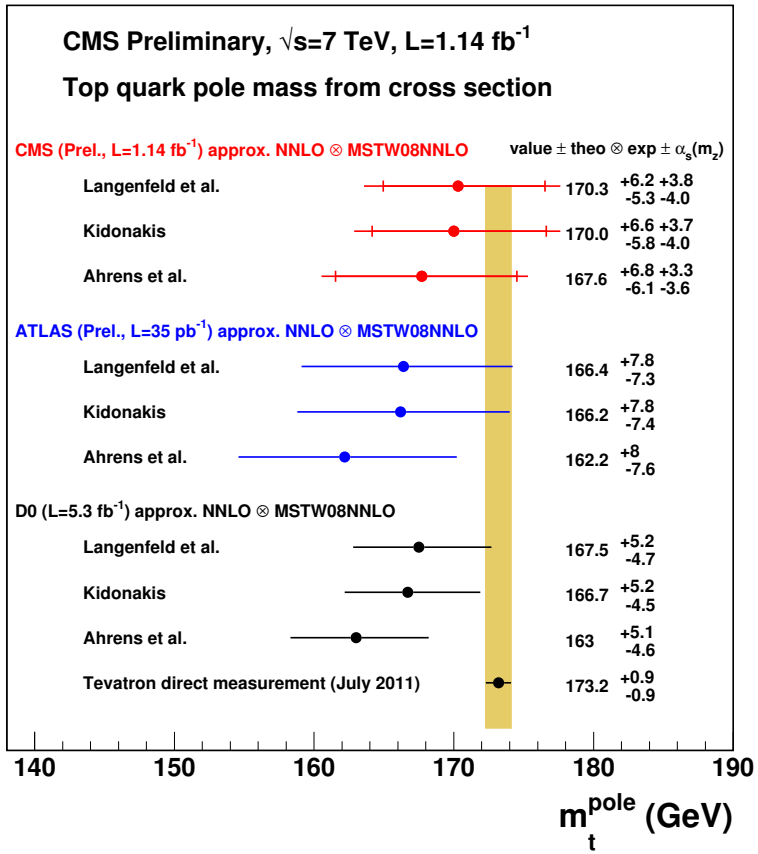


CMS combination:

- 173.4±1.0 (stat.+syst.) GeV
  - already reached Tevatron precision
- But which mass are we measuring?
  - some kind of MC mass
  - but it is close to the pole mass

Pole Mass from Cross Section Measurement



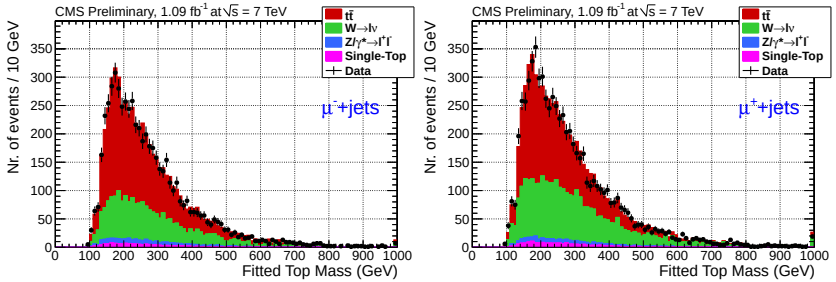


- Measurement compatible with direct measurement
  - nearly 10 times larger uncertainty

Is it the SM Top Quark? (Mass Difference, Spin Correlation, Charge)

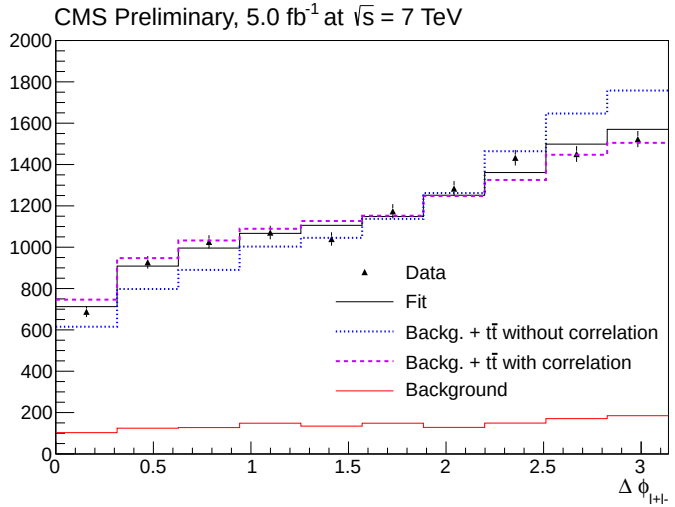
Mass Difference

- measure m_t separately for $\mu^{\pm} + jets$
- $\Delta m_t = -1.20 \pm 1.21(\text{stat}) \pm 0.47(\text{syst})$ GeV
- $m_t = 0$ indicates "no CPT violation"



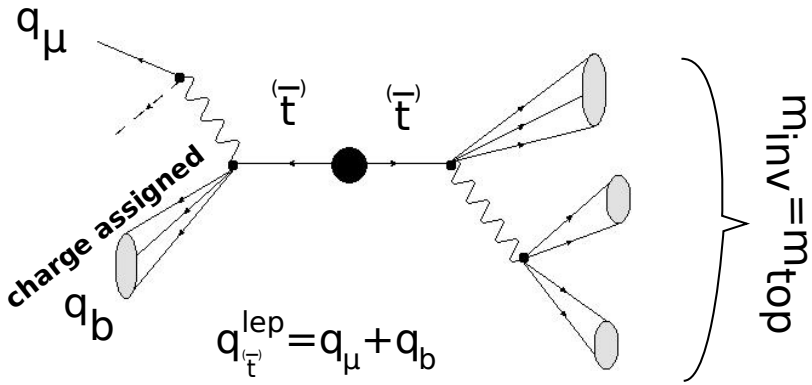
Spin Correlation

- $\Delta\phi$ of leptons in helicity basis
- $A^{hel}_{meas} = 0.24 \pm 0.02(stat.) \pm 0.08(sys.)$
- compatible with SM ($A^{hel}_{SM} = 0.31$)



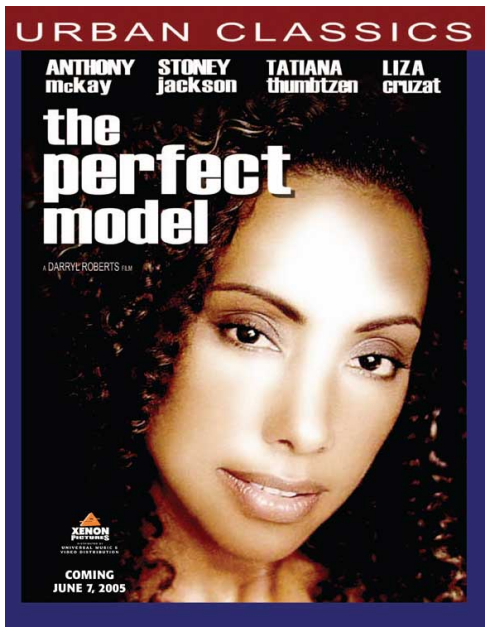
Charge

- association of muon to b or $\bar{b}$
- $A_{meas} = 0.97 \pm 0.12(stat.) \pm 0.31(sys.)$
- $A_{meas} = 1 \quad => \quad q_t = 2/3e$ (SM)
- $A_{meas} = -1 \quad => \quad q_t = -4/3e$



Conclusion

- Top Quark Physics is a valuable tool for
  - validating simulations
  - probing the SM
  - performing beyond SM searches
- With $\mathcal{O}(10^6)$ $t\bar{t}$ pairs clearly entered era of precision measurements
  - $t\bar{t}$ cross section uncertainty: $< 5\%$
  - top-quark mass uncertainty: ≈ 1 GeV
  - all CMS measurements in top sector compatible with SM so far
    - ⋆ no sign for BSM physics in searches
  - from top perspective, SM looks like perfect model



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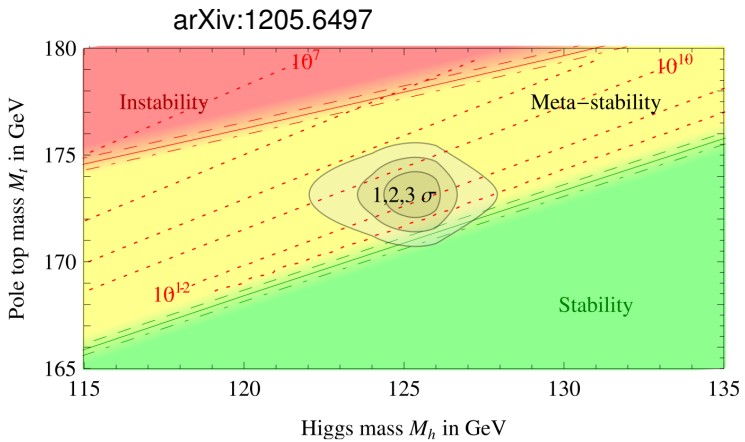
  - all CMS measurements in top sector compatible with SM so far
    - ★ no sign for BSM physics in searches
  - from top perspective, SM looks like perfect model
- Still at the beginning of 8 TeV analyses
  - precision will be improved further
  - reach of the searches will increase
- Let's see what the future brings!
  - hopefully we live in a stable universe

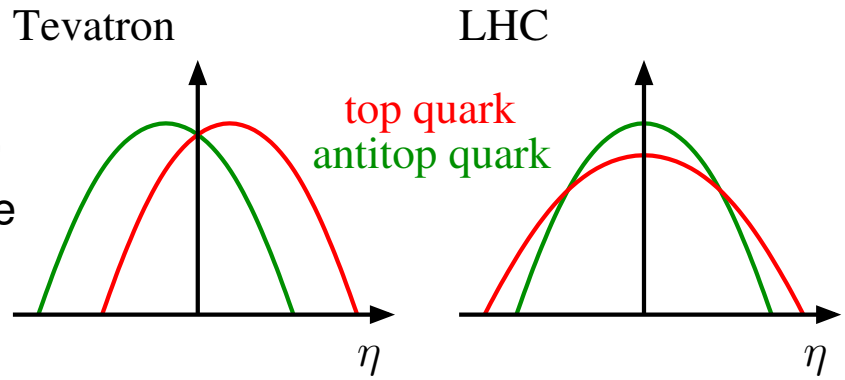


Backup

Charge Asymmetry A_C (arXiv:1207.0065)

Origin of asymmetry:

- gg fusion symmetric
- asymmetry from $q\bar{q}$ annihilation
  - interference at NLO (born-box, ISR-FSR)
    - ★ available NLO calculations effectively are LO asymmetry calculations

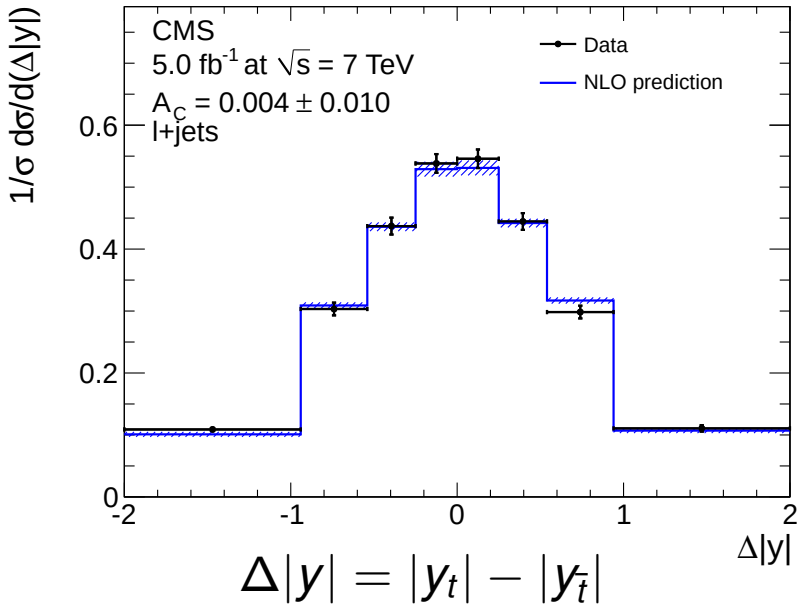


Appearance of asymmetry:

- Tevatron: proton-**anti**proton collider
  - large $q\bar{q}$ contribution
  - forward-backward asymmetry
- LHC: proton-proton collider
  - small $q\bar{q}$ contribution
  - top quarks have broader distribution
  - asymmetry $A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$

Measurement of asymmetry at CMS:

- $A_C = 0.004 \pm 0.010(\text{stat}) \pm 0.011(\text{syst})$
  - compatible with SM prediction
    - ★ $A_C^{SM} = 0.0115 \pm 0.0006$

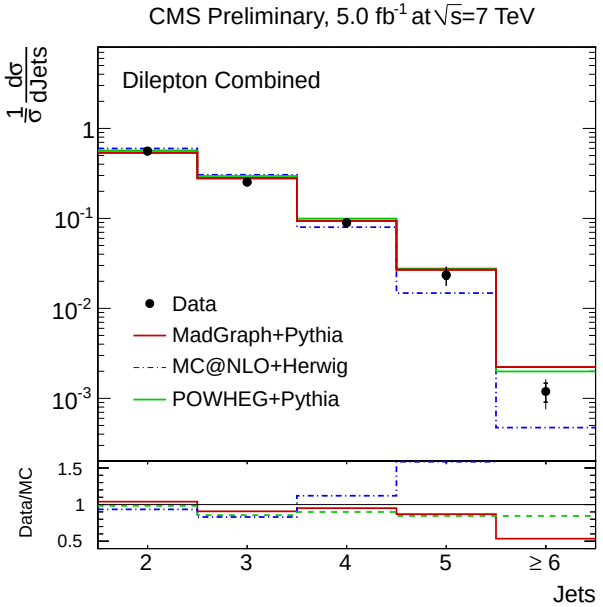


$\Delta|y| = |y_t| - |y_{\bar{t}}|$

Measurements of $t\bar{t}$ + *jets* (CMS-TOP-12-023)

Measure additional number of jets in $t\bar{t}$ events

- test of parton shower model
  - MadGraph+Pythia and POWHEG+Pythia
    - ★ both do quit well in describing data
  - MC@NLO+Herwig
    - ★ underpredicts jet multiplicity
- jets created by Herwig are presumably too soft



Vary Q^2 and matching scale in MadGraph

- test of event generator tuning
  - increasing the scales
    - ★ slightly improves agreement with data
- scales could be too small (not significant)