Recent Top Quark Physics Results from CMS

María Aldaya

DESY

for the CMS Collaboration

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Motivation for top quark physics

- The top quark plays a special role in the electroweak sector and in QCD
  - Heaviest elementary particle known to date
  - Decays before hadronizing: unique window on "bare" quark
  - Top and W masses constrain the Higgs mass

➔ A tool for precise SM measurements in the LHC energy regime

- Special role in various beyond SM extensions
  - New physics might preferentially couple/decay to top
  - Non-standard couplings between top and gauge bosons
  - Major source of background for many searches

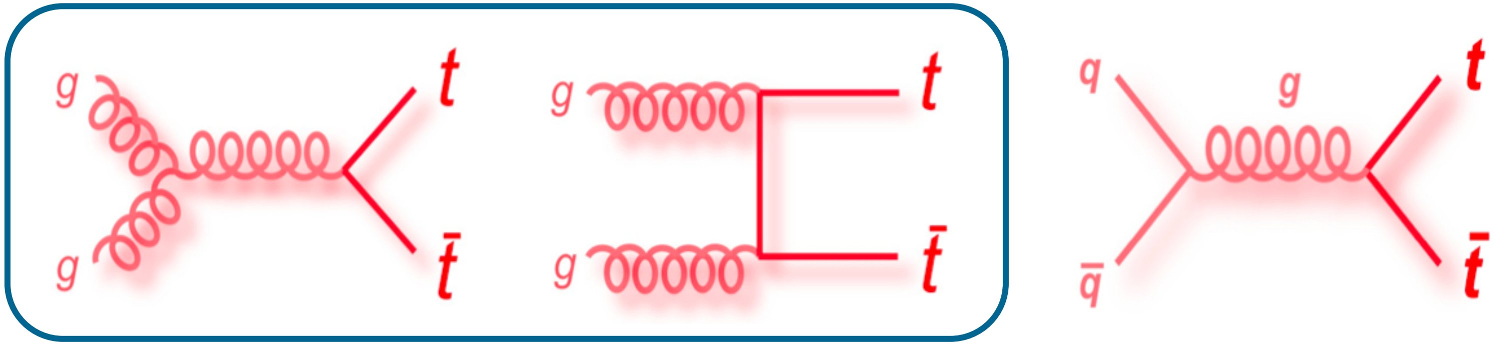
➔ A sensitive probe to New Physics

LHC is a 'top factory': > 600K ttbar events in ~5 fb^{-1} of 2011 data at 7 TeV

- Entering the era of precision measurements: total xsec, differential distributions
- Entering the top properties domain: mass, asymmetries, couplings, spin structure, V_{tb} …

Top quark production …

- Pairwise production of top and antitop via $q\bar{q}$ anihilation or gluon fusion



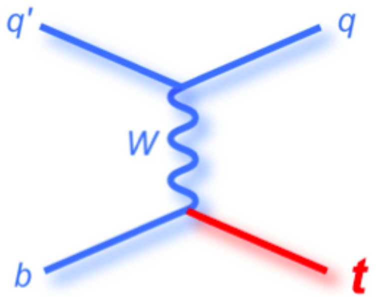
Dominant process at LHC

σ_{tt}(LHC@7TeV) ~ 165 pb, × 20 σ_{tt} (Tevatron)

[approx. NNLO calculation]

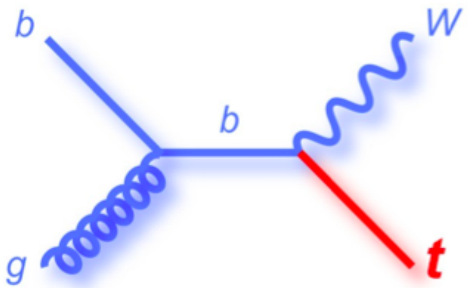
- Production of single top quarks via electroweak force

t-channel



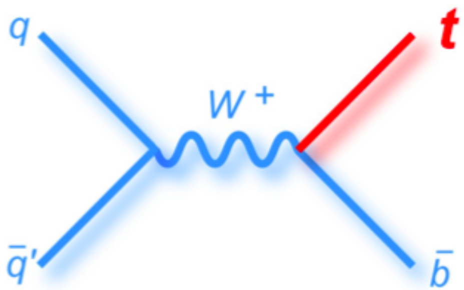
65 ± 3 pb

associated tW production



16 ± 1 pb

s-channel



4.6 ± 0.3 pb

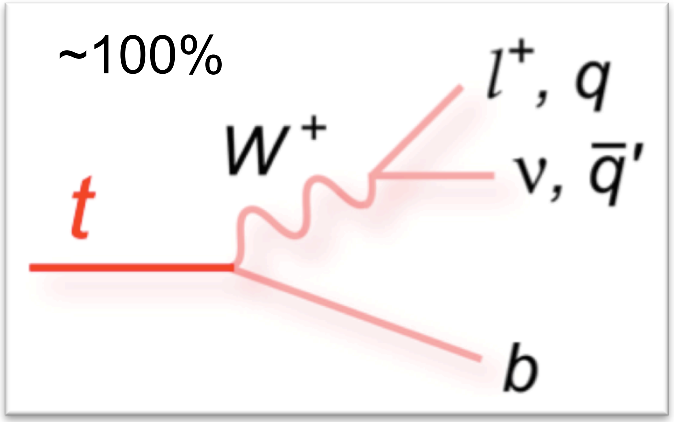
[approx. NNLO calculations for LHC@7TeV]

… and decay

μ/e + jets ~ 34%
1l + 2 b-jets + 2 light-jets +1ν
Good rate, manageable bg
Main background: W+jets

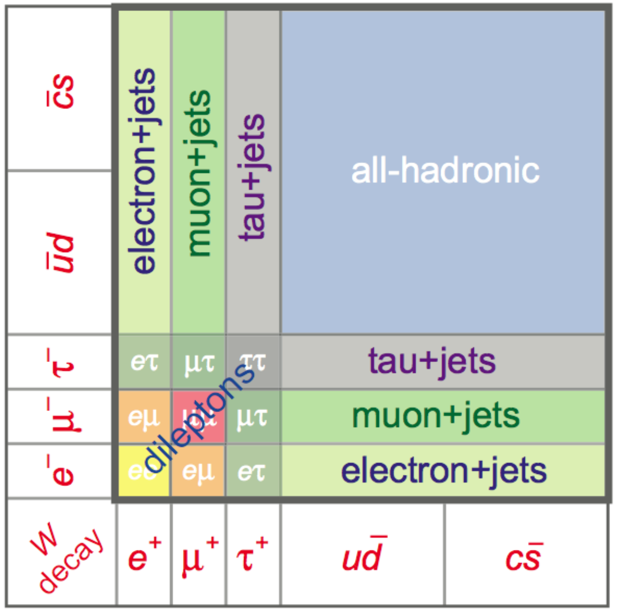
all-hadronic ~ 46%
High rate, huge bg
Main background: QCD

In Standard Model:



W decay modes define top final states

Top Pair Decay Channels



dileptons (μ/e) ~ 6%
2l + 2 b-jets + 2ν
Low rate, low background
Main bkg: Drell-Yan

taus ~ 14%
Low rate, high bg
Main bkg: W+jets, QCD

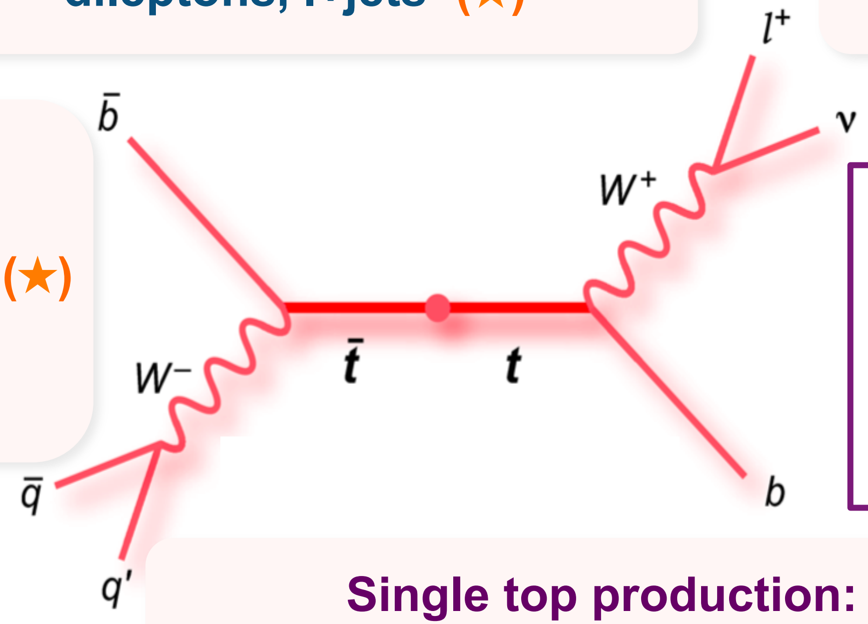
CMS top quark measurements for today

Pair production cross section:
- dileptons, l+jets

Differential top-pair cross sections:
- dileptons, l+jets (★)

Searches:
- top-pair invariant mass (★)

Other properties:
- mass (★)
- charge asymmetry (★)
- W helicity (★)
- charge (★)



Most results shown today from 0.8-4.7 fb^{-1} of data, all taken at $\sqrt{7}$ TeV

(★) = Feb'12 results

Single top production:
- t-channel, associated tW production

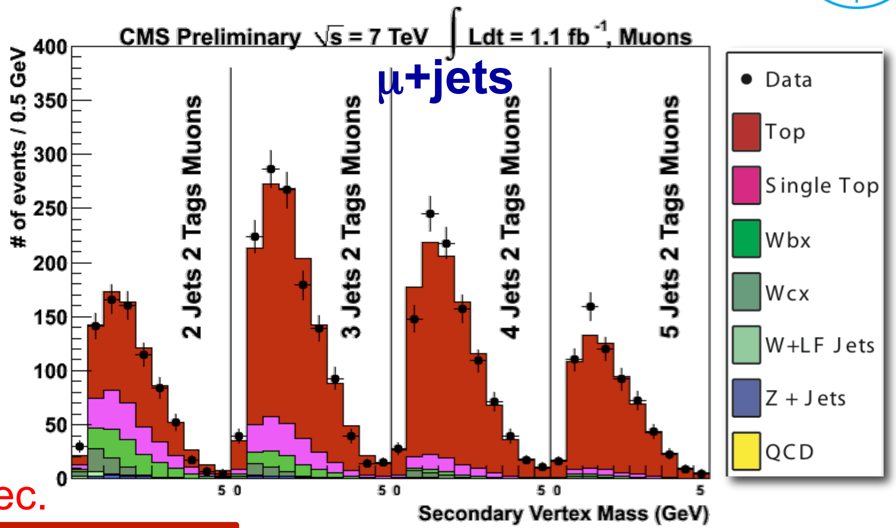
All CMS top quark results are available here:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Top-quark pair
inclusive cross section measurements

Top-pair production cross sections

Lepton+jets channels (0.8-1.1 fb^{-1}):

- 1 isolated high-p_T μ/e, veto on additional leptons, ≥ 4 jets, ≥ 1 b-tagged jet
- Profile likelihood fit to secondary-vertex mass → separates light from heavy flavour
- 9 jet & b-tag multiplicities and 2 lepton flavours
- Combined cross section:



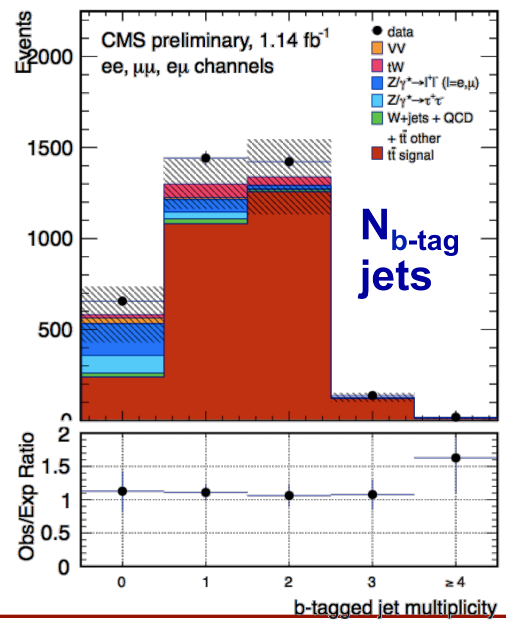
8.7% prec.

$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lum.})\ \text{pb}$$

CMS-PAS TOP-11-003

Dilepton ee, μμ, μe channels (1.1 fb^{-1}): CMS-PAS TOP-11-005

- Cut-and-count method, requiring 2 OS isolated, high-p_T leptons, ≥ 2 jets, ≥ 1 b-tagged jet
- E_T^{miss} for ee, μμ; veto Z-mass region
- Very pure sample after requiring ≥ 1 b-tagged jet
- Combined cross section:



10.8% precision

$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

Summary of 2011 σ($t\bar{t}$) results

CMS-PAS TOP-11-024

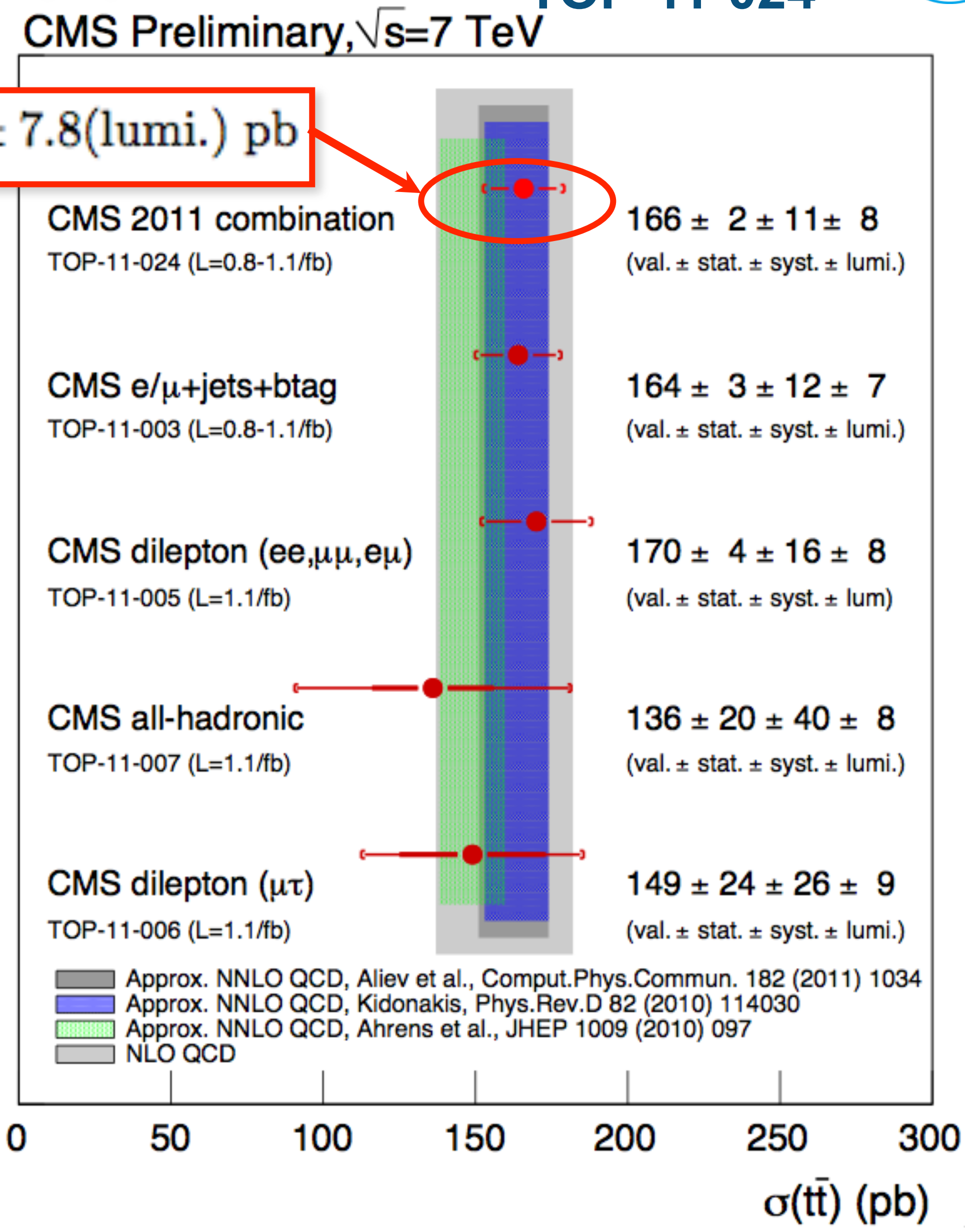
CMS combined 2011:

$$\sigma_{t\bar{t}} = 165.8 \pm 2.2(\text{stat.}) \pm 10.6(\text{syst.}) \pm 7.8(\text{lumi.})\ \text{pb}$$

8% precision

- Measured cross sections in agreement with each other and with approx NNLO predictions
- All measurements are now systematics limited
- Experimental uncertainty close to theory uncertainty

Start to become sensitive to differences between various approximations to NNLO theory !



Top-quark pair
differential cross section measurements

$t\bar{t}$ diff. cross sections (1.1 fb^{-1})

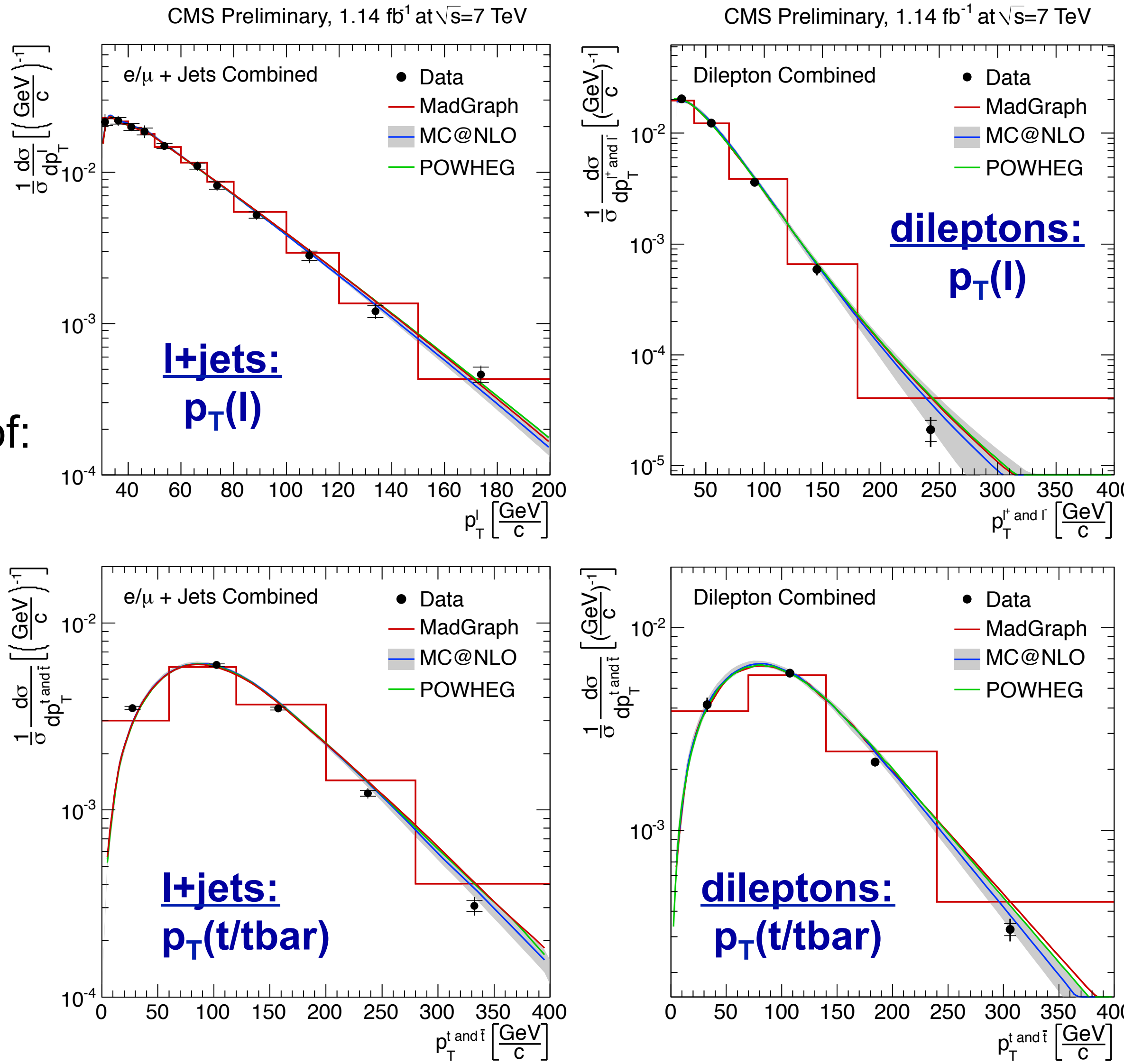
CMS-PAS TOP-11-013

Feb'12

Allows for precise tests of pQCD and constraints on BSM effects

- Measured for the first time at the LHC !
- Measurement in the dilepton & l+jets channels, in "visible" phase space
- Normalized differential cross sections as a function of:
  - p_T(l), η(l), p_T(ll), m(ll)
  - p_T(t/tbar), y(t/tbar)
  - p_T(ttbar), y(ttbar), m(ttbar)
- Comparison to different theory predictions

Good agreement with SM predictions for all variables



$t\bar{t}$ diff. cross sections (1.1 fb^{-1})

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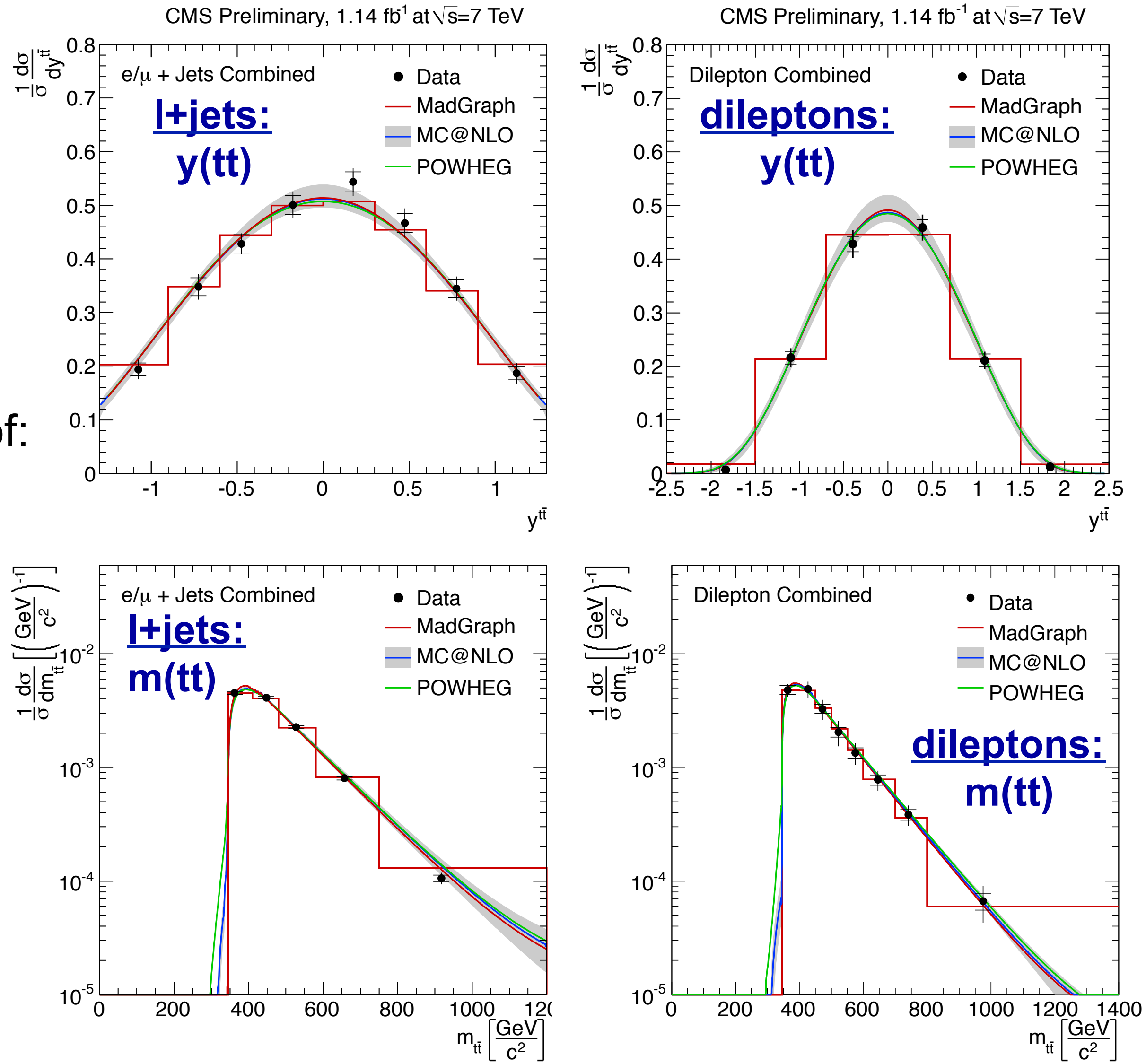


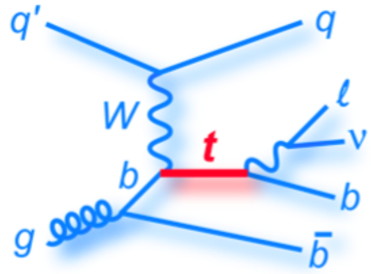
Single top-quark cross section measurements

Single top in t-channel (36 pb^{-1})

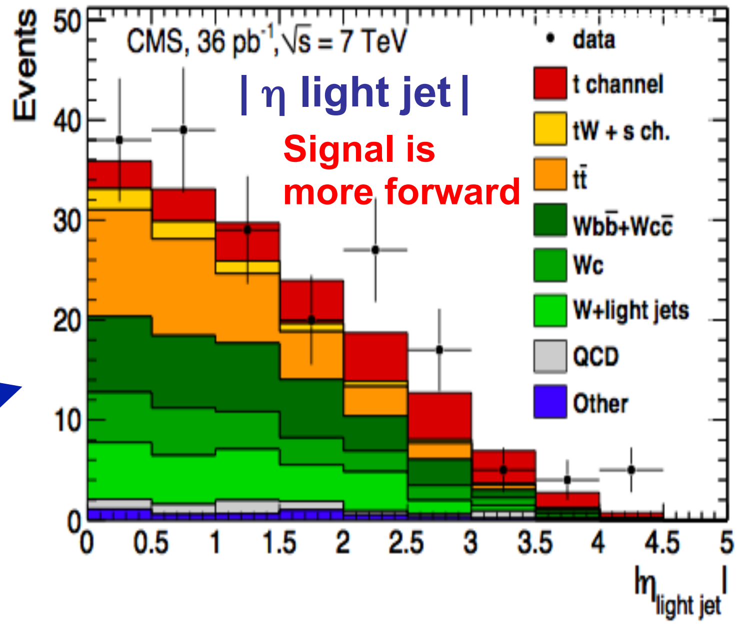
PRL 107 (2011) 091802

Test unitarity of CKM matrix ($\sigma \propto |V_{tb}|^2$)

1 isolated high-p_T μ/e, E_T^{miss}
central b-tagged jet,
forward light jet



- Combination of 2 methods:
  - 2D measurement to angular signal properties
    (robust, minimal model dependence)
  - Likelihood fit to multivariate (BDT) output
    (fully exploits signal topology)



- Both yield a singificance > 3σ
- Cross section:

36% precision

$$83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\ \text{pb}$$

Expected: $\sigma_t = 64.3\ ^{+2.1}_{-0.7}(\text{scale})\ ^{+1.5}_{-1.7}(\text{pdf})$

Main systematics: b-tagging

- V_{tb} extraction at 95% CL
(for V_{ts} , V_{td} << V_{tb}):

$$|V_{tb}| = \sqrt{\frac{\sigma_{\text{exp.}}}{\sigma_{\text{theo.}}}} > 0.62\,(0.68)$$

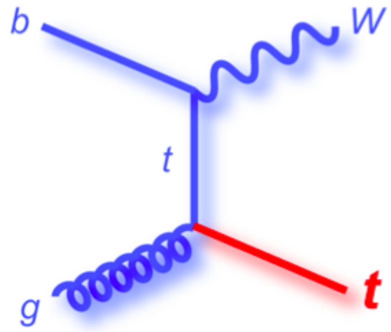
for 2D (BDT) analysis

All measurements consistent with SM predictions

Single top in tW mode (2.1 fb^{-1})

CMS-PAS TOP-11-022

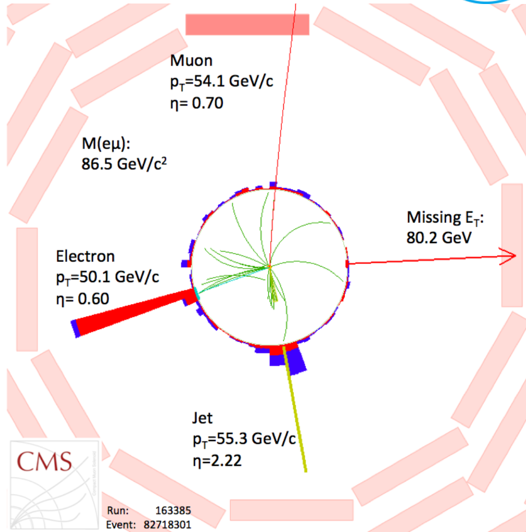
Test unitarity of CKM matrix ($\sigma \propto |V_{tb}|^2$), background for Higgs searches



- Measured for the first time at LHC!

- Good/bad news: looks like ttbar; easy to observe, but much ttbar background

NNLO approx. σ = 15.6 ± 1.3 pb (Tevatron: 0.25 ± 0.03 pb)

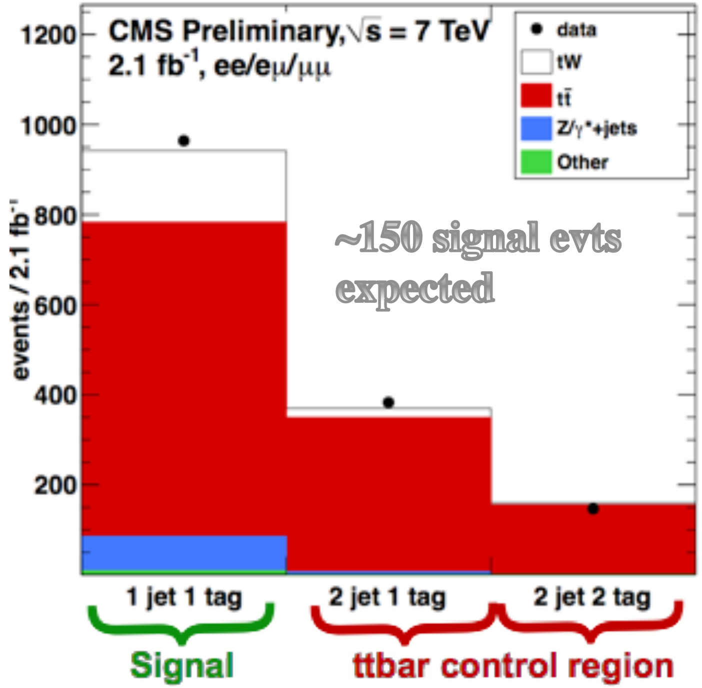


- Cut-and-count method, selecting dilepton events with exclusively 1 b-tagged jet, Z veto, E_T^{miss} for ee, μμ

- Use two ttbar-enriched sidebands to constrain ttbar contribution and b-tagging efficiency (main syst uncert)

- Observed significance: **2.7σ** (1.8σ expected)
- Observed cross section:

$$22^{+9}_{-7}\ (\text{stat} \oplus \text{syst})\ \text{pb}$$



Top-quark properties

Top mass in dileptons (2.3 fb^{-1})

CMS-PAS TOP-11-016

Feb'12

- Typical selection for ee, μμ, μe events:
  - 2 OS high-p_T leptons, ≥2 jets, ≥1 b-tagged jets, Z veto, E_T^{miss}
- Final state reconstruction still under-constrained after imposing p_T conservation, $m_{top} = m_{antitop}$, M_W constraint
- Fully kinematic method to constrain further:

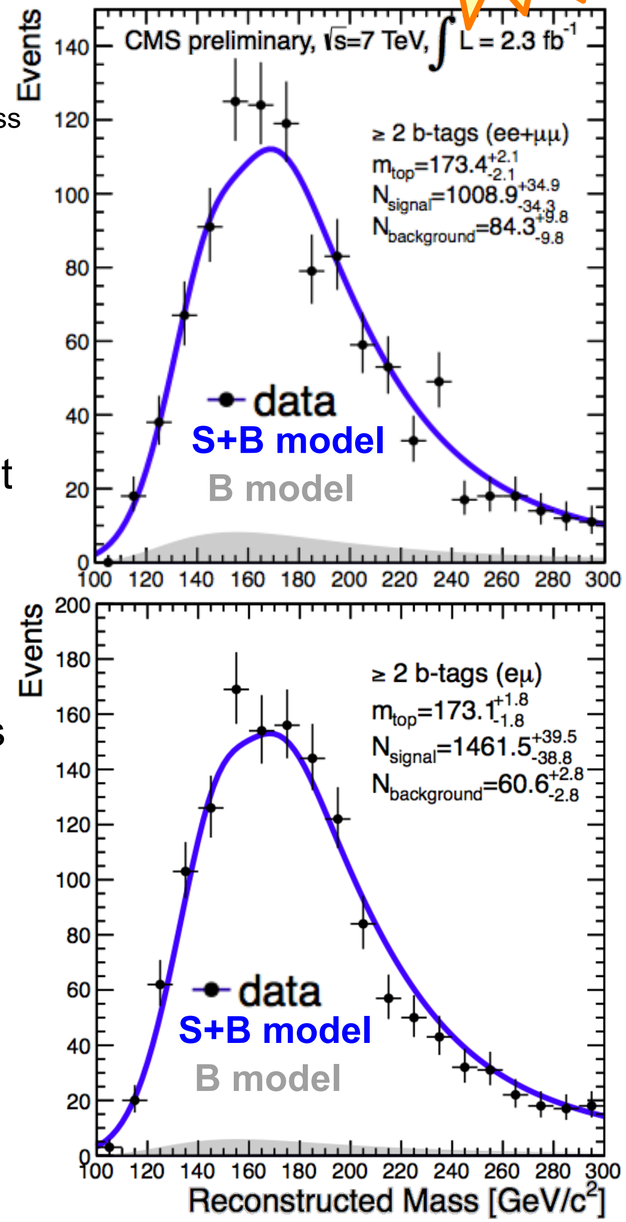
  Use $p_z(tt)$ as additional information, b-tag for l-jet assignment
- Template fits to extract m_t from the mass distributions
- Unbinned maximum likelihood fit to data:
  - Combine same/opposite lepton flavours and 1 or ≥ 2 b-tags

$$m_{top} = 173.3 \pm 1.2(\text{stat.})^{+2.5}_{-2.6}(\text{syst.})\ \text{GeV}/c^2$$

~1.6% precision

- Most precise dilepton mass measurement so far !
- Good agreement with world average $m_t = 173.2 \pm 0.9$ GeV

Dominant systematics: JES



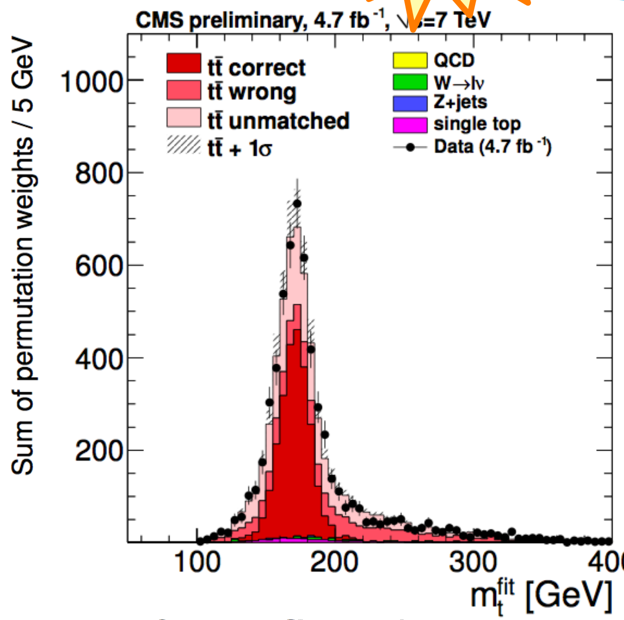
Top mass in μ+jets (4.7 fb^{-1})

CMS-PAS TOP-11-015

Feb'12

Simultaneous measurement of top mass and JES:

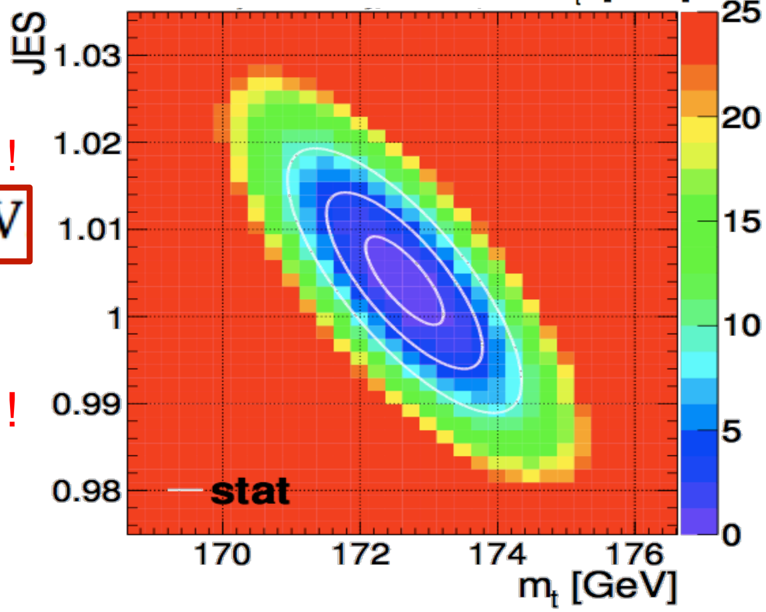
- Select 1 isolated μ, ≥ 4 jets, 2 b-tagged jets
- Reconstruct ttbar system using μ, E_T^{miss} and 4 leading jets, taking into account all possible permutations
- Constrained kinematic fit to reconstructed top mass taking into account b-tag information → m_t^{fit}
- W from reconstructed 2-jet invariant mass → m_W^{reco}
- Event-by-event likelihood as a function of m_t^{fit} and m_W^{reco}, parameterized as a function of m_t and JES factor
- Joint 2D likelihood fit over all events to extract the top mass and JES:



< 1% precision !

$$m_t = 172.6 \pm 0.6\,(\mathrm{stat+JES}) \pm 1.2\,(\mathrm{syst})\ \mathrm{GeV}$$

JES = 1.004 ± 0.013



- Most precise LHC individual mass measurement !
- Consistent with world average

Main systematics: Q^2 scale, b-JES

t-tbar mass difference (1.1 fb^{-1})

CMS-PAS TOP-11-019

Test of CPT invariance: particle and anti-particle must have the same mass

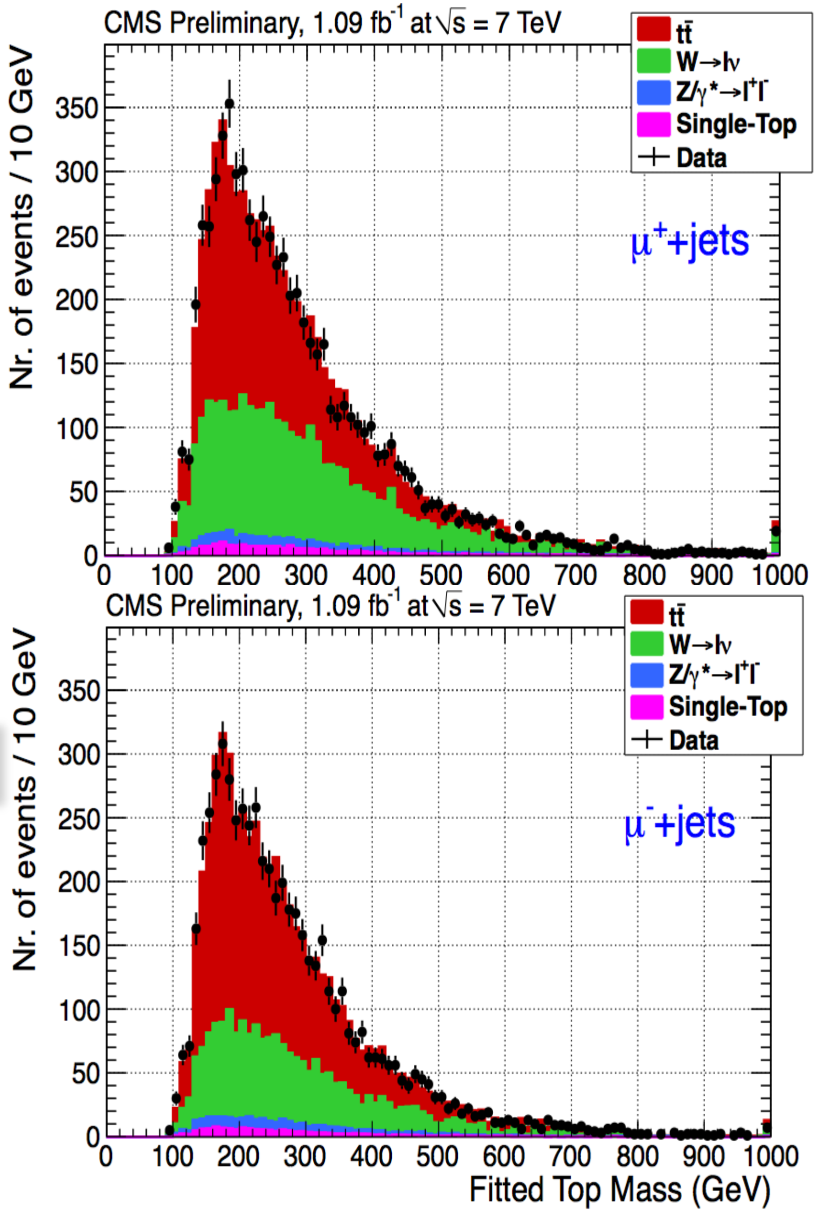
2σ deviation reported by CDF *[PRL 106, 152001 (2011)]*

- Use μ+jets ttbar events (positive/negative μ)
  - 1 isolated high-p_T μ, ≥ 4 jets
- Mass reconstructed from hadronic t, tbar decay
  - Kinematic fit from the jet combination with lowest χ^2
- World's best measurement so far!

$$\Delta m_t^{\text{measured}} = -1.20 \pm 1.21\ (\text{stat}) \pm 0.47\ (\text{syst})\ \text{GeV}$$

- Consistent with SM ($\Delta m = 0$)
- Still statistically limited

JES uncertainty largely cancelled in the mass difference



Top quark mass from $\sigma(t\bar{t})$ (1.1 fb^{-1})

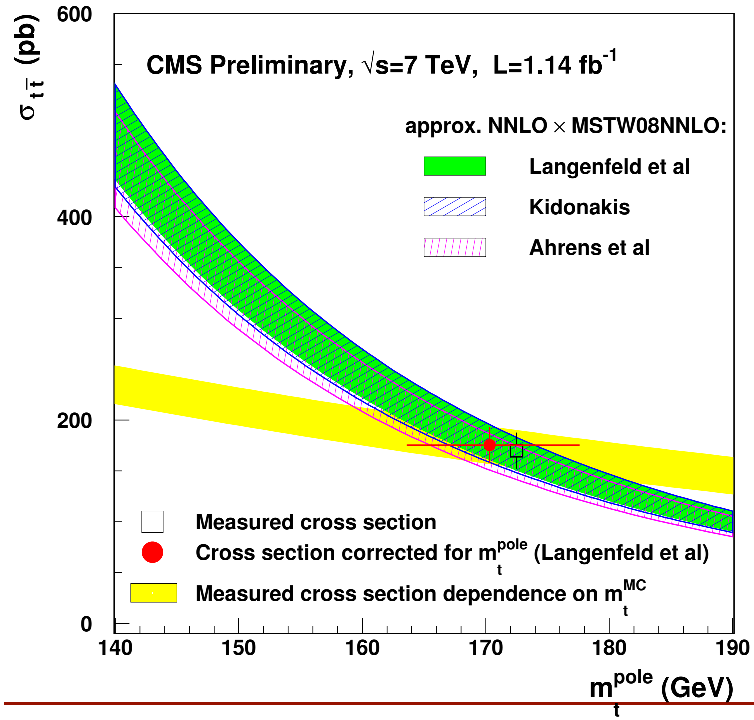
CMS-PAS TOP-11-008

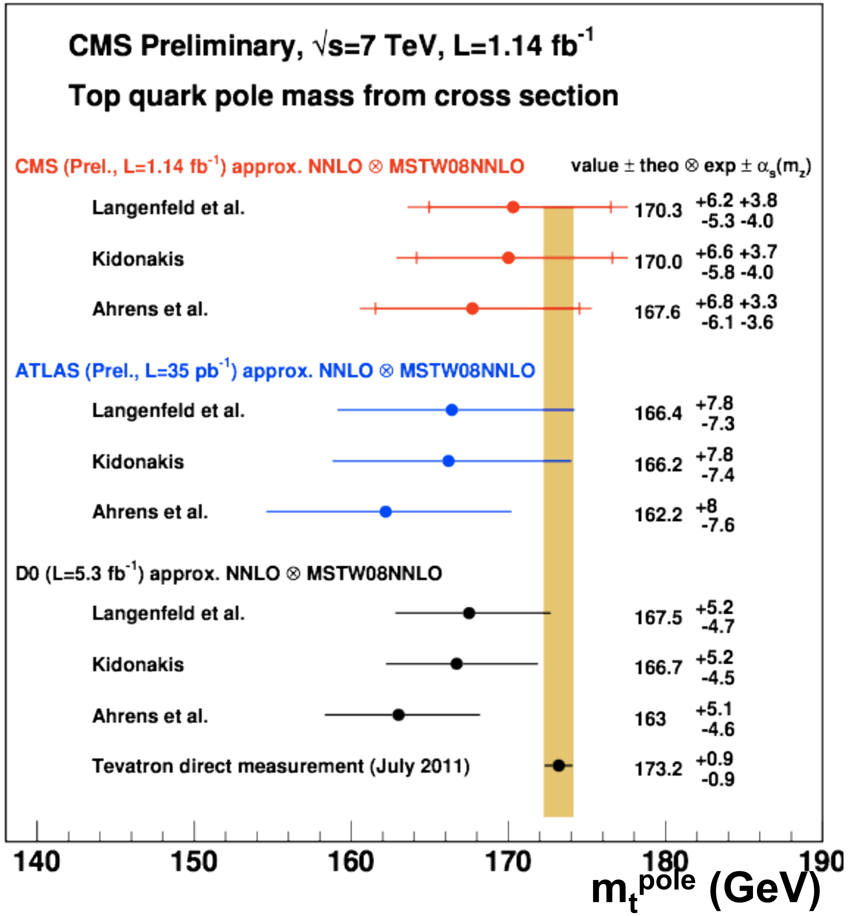
Mass dependence of predicted cross section allows determining m_t from measured σ_{tt}

→ provides top mass value in an exact definition

- Extract top mass, **pole** and **$\overline{\text{MS}}$ mass**, from measured cross section in dileptons

- Most probable mass results from joint likelihood: theory $\otimes$ experiment





Good agreement between different calculations
Results consistent also with other experiments

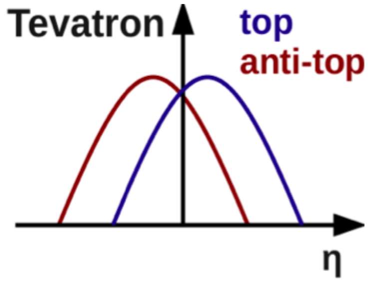
Precision limitations:
- Systematic uncert. of the measurement
- PDF uncert. + α_S uncert. in the PDF

$t\bar{t}$ charge asymmetry (4.7 fb^{-1})

CMS-PAS TOP-11-030

Feb'12

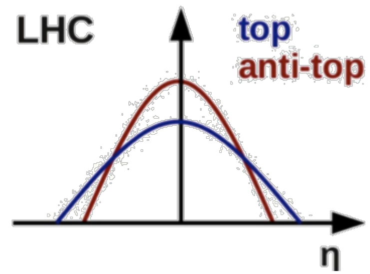
Asymmetries in angular distributions between top and antitop quarks may indicate BSM top production interfering with SM production



- Tevatron (p-pbar): (anti)top quarks preferably emitted in the direction of the incoming (anti)quarks
  - Small qqbar→ttbar NLO effect, not present at LO or in gg→ttbar

→ Forward-backward asymmetry

Reported A_{FB} higher than predicted by SM, especially at high m_{ttbar} *[CDF, Phys.Rev.D:83:112003,2011]*



- LHC (p-p): gg symmetric → SM asymmetries more diluted
  - No valence antiquarks, quarks have higher x on average

→ Asymmetry in "broadness" of (pseudo)rapidity distribution

- Sensitive variable: $\Delta|y| = |y_t| - |y_{tbar}|$
- Charge asymmetry: $$A_C = \frac{N^+ - N^-}{N^+ + N^-}$$

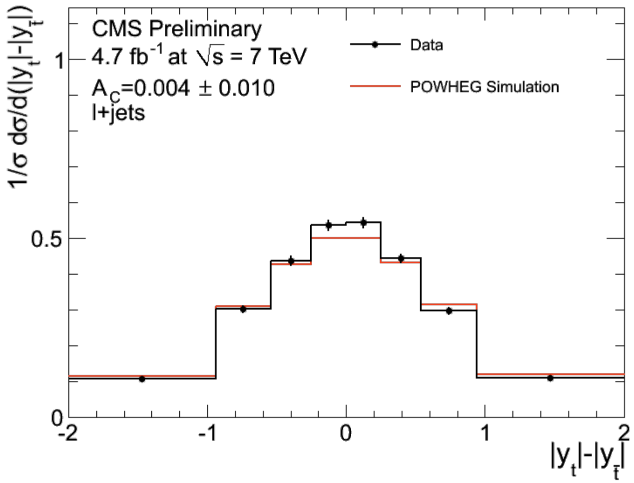
$N^{+(-)}$ = number of events with positive (negative) values of $\Delta|y|$

$t\bar{t}$ charge asymmetry (4.7 fb^{-1})

CMS-PAS TOP-11-030

Feb'12

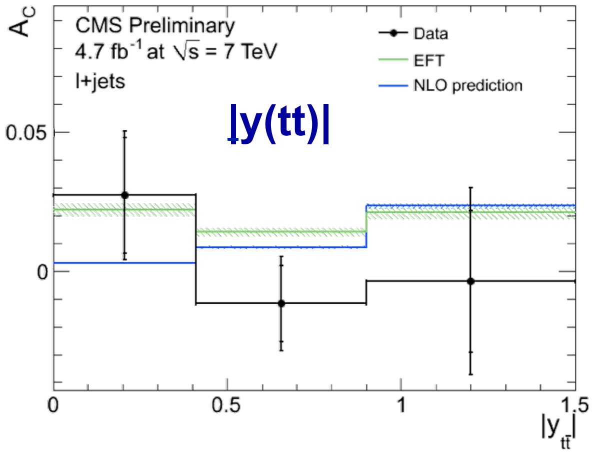
- Inclusive A_C measurement in l+jets:

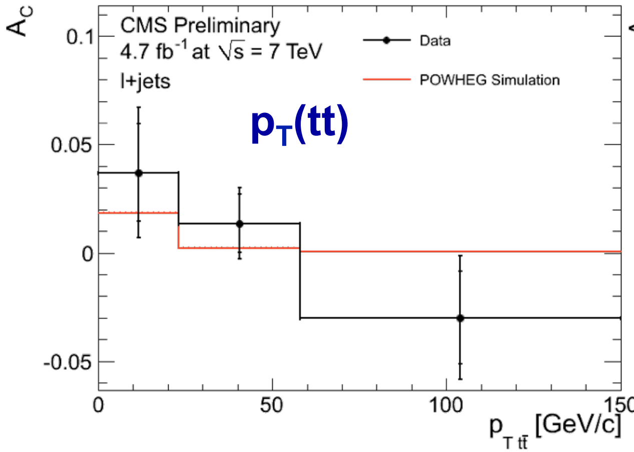


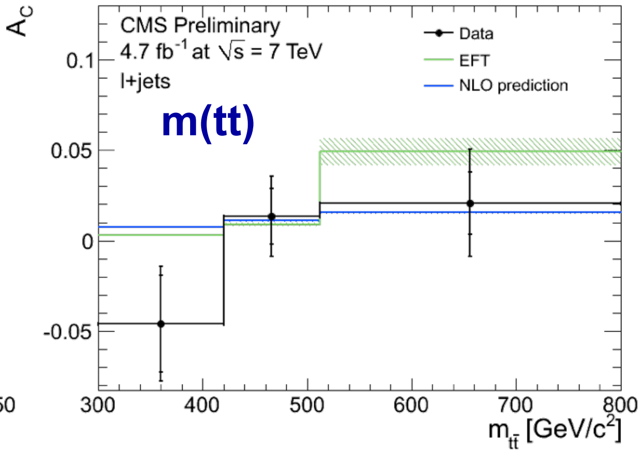
- 1 isolated high-p_T μ/e, veto on additional leptons, ≥ 4 jets, ≥ 1 b-tagged jet
- Kinematic fit to reconstruct ttbar system
- Correct for bg and detector effects

Final corrected	0.004 ± 0.010 (stat.) ± 0.012 (syst.)
Theory prediction (SM)	0.0115 ± 0.0006

- A_C as a function of $|y(tt)|$, $p_T(tt)$, $m(tt)$:







- Compare to different theory predictions

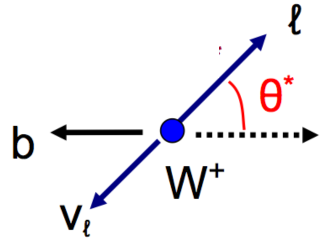
No significant deviation from SM observed so far

W polarization (2.2 fb^{-1})

CMS-PAS TOP-11-020

Feb'12

Anomalous contributions to the tWb vertex change the probabilities of the W helicity states

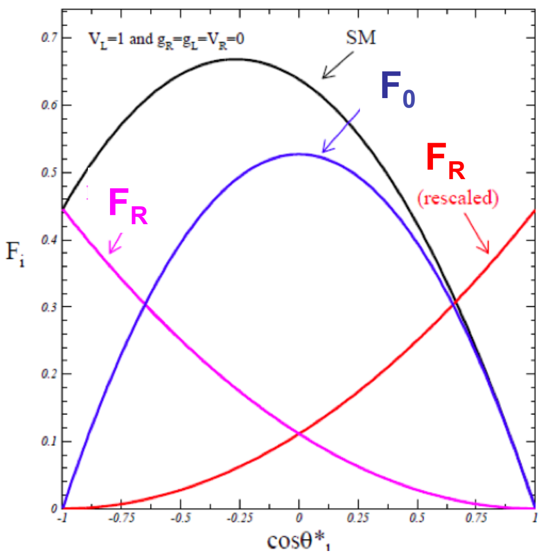


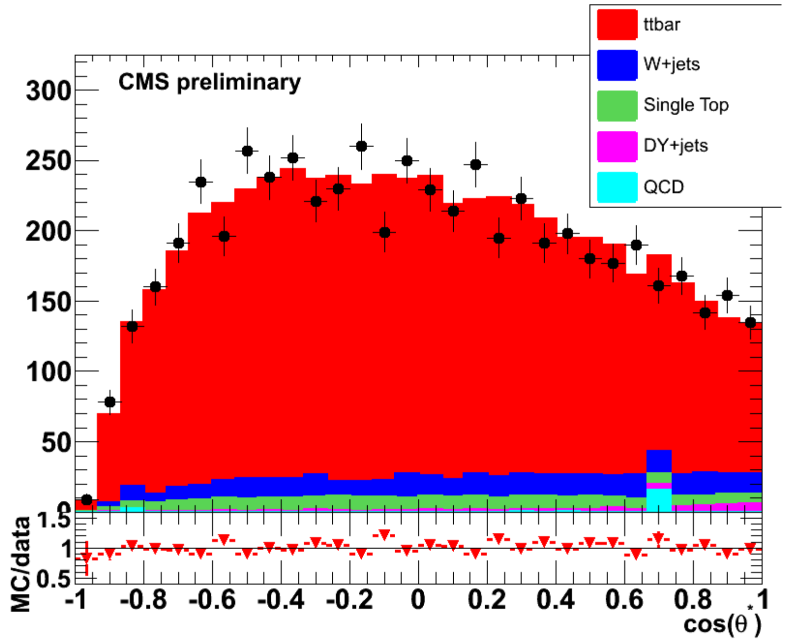
Angle between charged lepton and top direction in W rest frame

- In SM: 3 possible W helicity states:

F_0 (longitudinal) ~ 0.70, F_L (left) ~ 0.30, F_R (right) ~ 0

- Measure sensitive variable, cos(θ*), in **muon+jets** channel:
  - 1 isolated high-p_T μ, ≥ 4 jets, ≥ 1 b-tag
  - Kinematic fit to reconstruct ttbar system





- Helicity fractions extracted from maximum likelihood fit:

$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})$$
$$F_R = 0.040 \pm 0.035\ (\text{stat.}) \pm 0.044(\text{syst.})$$

- Good agreement with SM
- Similar precision as previous measurements (Tevatron, ATLAS)

Top charge in μ+jets (4.7 fb^{-1})

CMS-PAS TOP-11-031

Feb'12

Is the charge of the top quark decay products compatible with 2/3e?

- SM top quark decay: $t^{(2/3)} \rightarrow b^{(-1/3)} + W^{(+1)}, W^{+} \rightarrow \ell^{+} + \nu_{\ell}$
- Possible exotic ("XM") charge: $\tilde{t}^{(-4/3)} \rightarrow b^{(-1/3)} + W^{(-1)}, W^{-} \rightarrow \ell^{-} + \bar{\nu}_{\ell}$

Infer $Q_{b\text{-jet}}$ from soft μ in semileptonic B-hadron decays

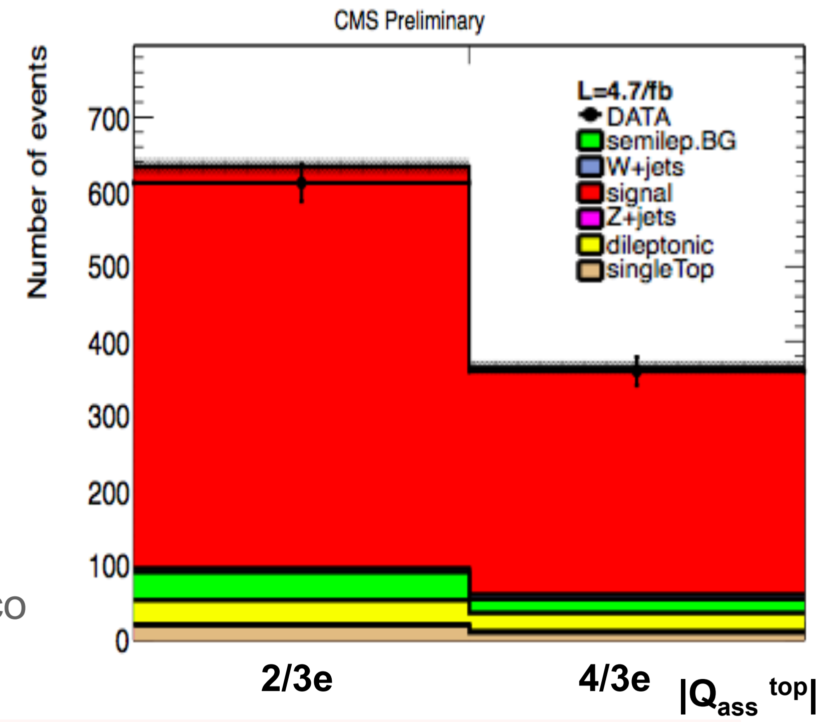
Determine Q_W from W-leptonic decay (Q_μ)

- 1 isolated high-p_T μ, ≥ 4 jets, 2 b-tags, E_T^{miss}
- Assign b-jet to hadronic top using min $|m_{bqq} - m_t|$
- Estimate $Q_t^{lep} = Q_\mu +/- \frac{1}{3}(\text{sign})Q_{b\text{-jet}}^{lep/had}$
- Measure asymmetry from charge counting:

$$A = \frac{N_{SM} - N_{XM}}{N_{SM} + N_{XM}}$$

Parametrized from: probability to reconstruct signal/bg SM events; bg fraction

Complementary prob. of reco SM-like evts and bg fraction



A = 0.96 ± 0.12 (stat.) ± 0.31 (syst.), exotic scenario excluded with high significance

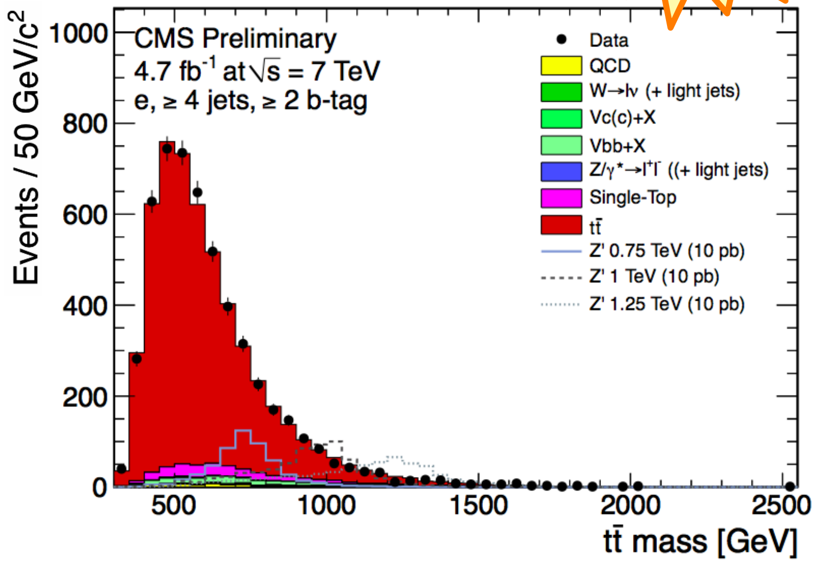
Searches

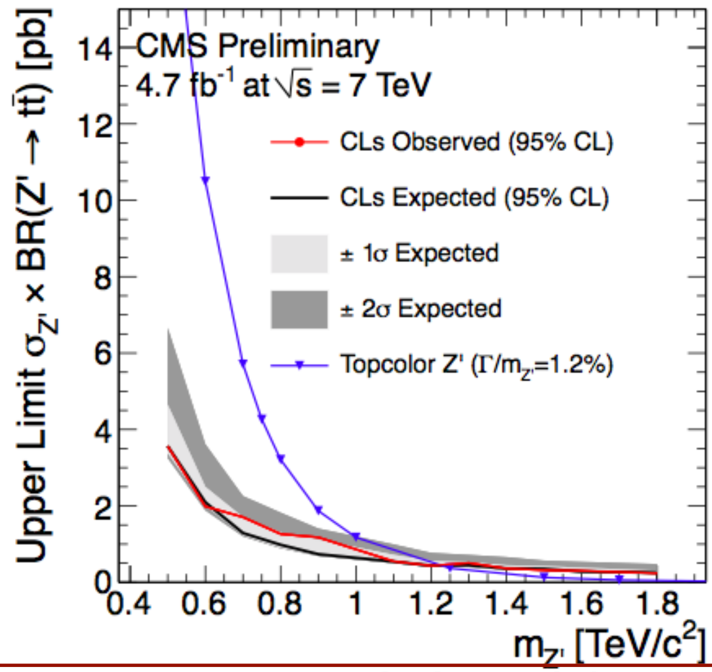
Top-pair invariant mass (4.7 pb^{-1})

CMS-PAS TOP-11-009

Feb'12

- Search for heavy narrow resonances decaying into top pairs with e/μ+jets in the final state
  → can modify the m_{tt} spectrum from SM predictions
- Energetic & isolated e/μ in an energetic hadronic environment with 2 b-jets
- Reconstruct m_{tt} using a kinematic fit
  - Separate in different lepton flavours and jet & b-tag multiplicities (8 categories)
  - For all relevant processes, use data-driven & MC-based templates
- Likelihood template fit to m_{tt}
- No significant signal observed
  - Observed limits exclude narrow Z' -like particle production up to 1.3 TeV (95% C.L.)





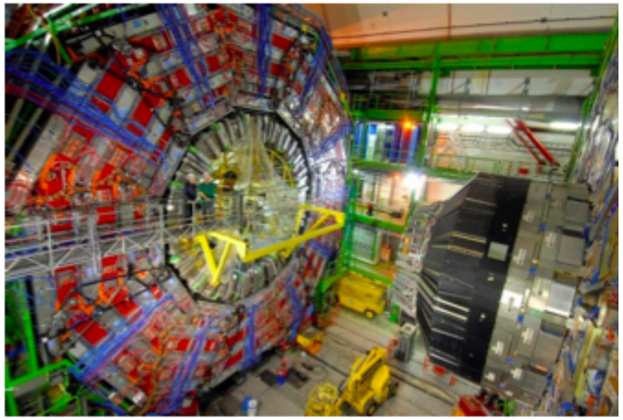
Summary & outlook

- After two years of operation at 7 TeV, the LHC has started to be a real "top factory"
  - Entering the era of precision measurements and top quark properties domain
  - Starting to challenge theory predictions in some areas
- CMS has a huge physics program for top quark physics
  - Cross sections, mass & other properties, searches
- Many results are already competitive with Tevatron in precision
  - Some even exceeded Tevatron!
- So far, good agreement with SM predictions (… unfortunately)
- More results expected soon with up to 5 fb^{-1} of data (full 2011 dataset)
  - Updates of analyses presented here, FCNC in top pairs, $B(t\rightarrow Wb)/B(t\rightarrow Wq)$, searches in m_{tt} in dileptons . . .

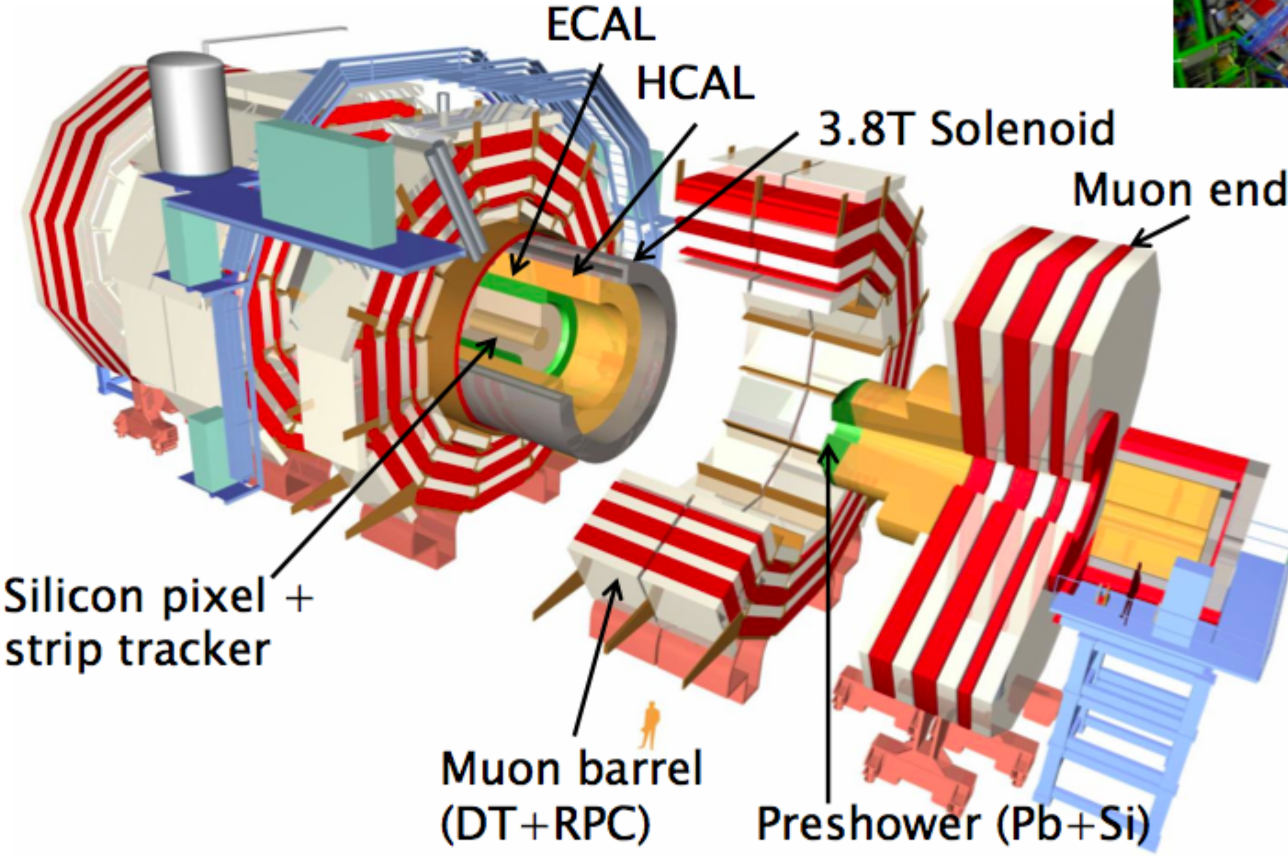
More exciting results to come in 2012, stay tuned !

Additional information

The Compact Muon Solenoid detector



- 21m long, 15m in diameter
- 14000 tons



CMS Collaboration:
- *~2500 scientists + engineers*
- *~850 students*
- *173 institutes*
- *40 countries*

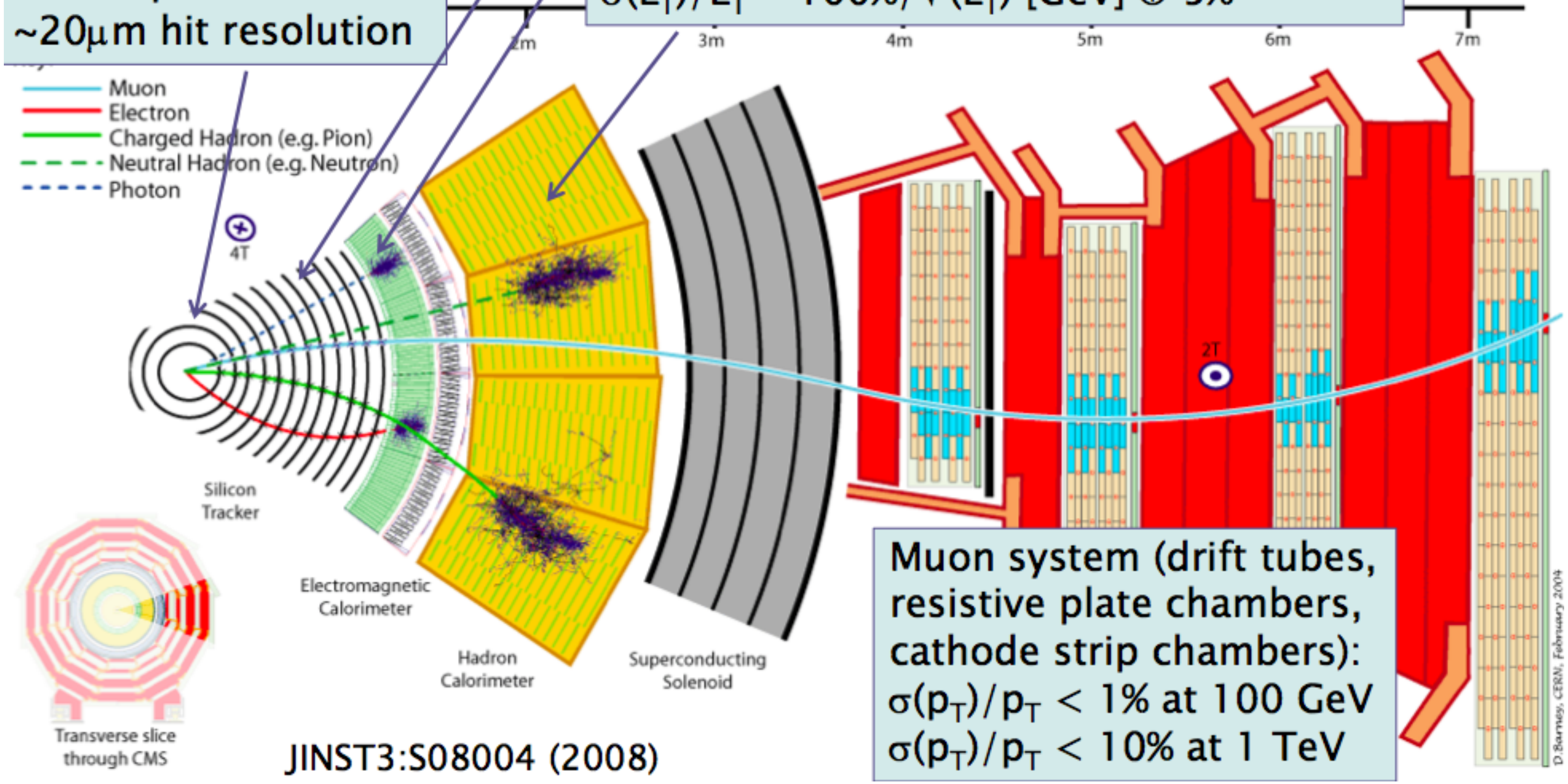
A slice of CMS

EM Calorimeter (lead tungstate crystals):
$\sigma(E)/E \sim 3\%/\sqrt{E}$ [GeV] $\oplus$ 0.3%

Silicon tracker:
$\sigma(p_T)/p_T \sim 15\%$ at 1 TeV

Hadron calorimeter (brass + scintillator):
$\sigma(E_T)/E_T \sim 100\%/\sqrt{E_T}$ [GeV] $\oplus$ 5%

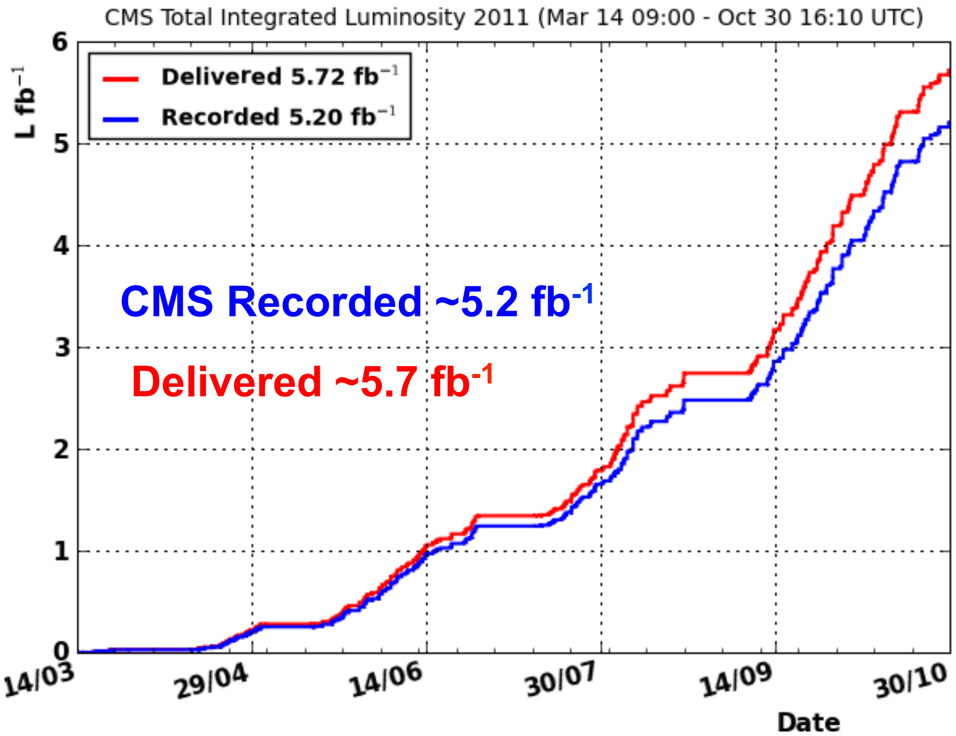
Silicon pixel detector:
~20μm hit resolution



Muon system (drift tubes, resistive plate chambers, cathode strip chambers):
$\sigma(p_T)/p_T < 1\%$ at 100 GeV
$\sigma(p_T)/p_T < 10\%$ at 1 TeV

JINST3:S08004 (2008)

Welcome to the inverse femtobarn era!

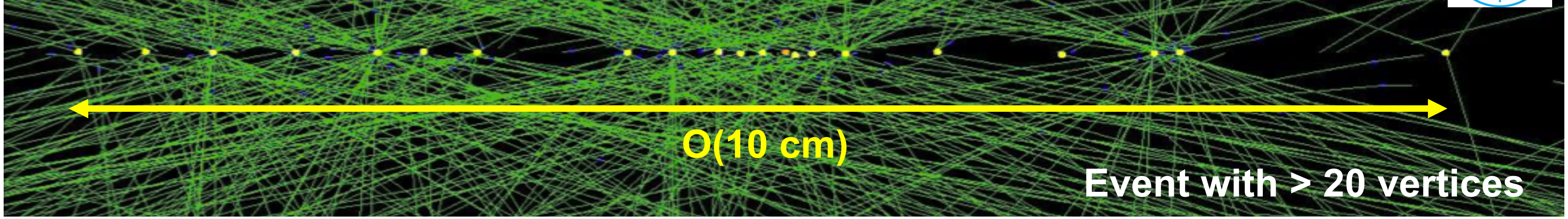


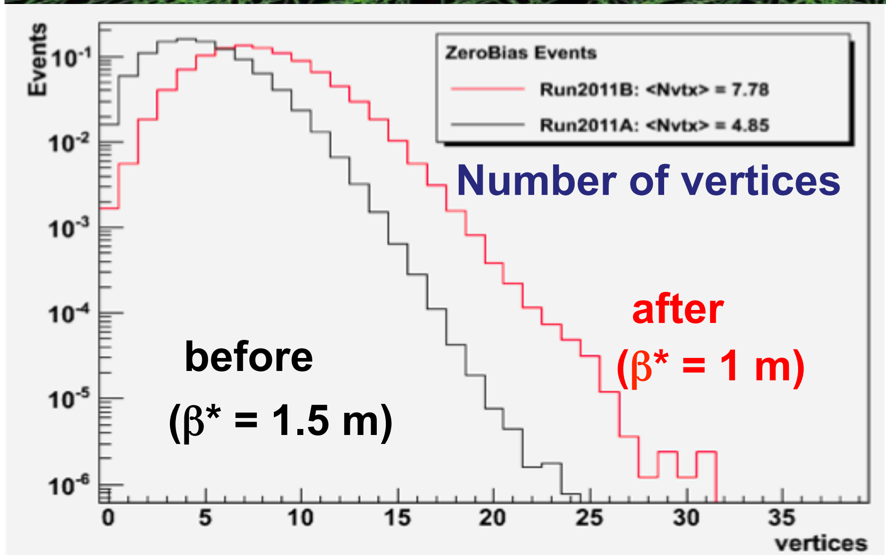
- All subdetector components operation at the level > 98.5%

- Recorded 5.2 fb^{-1} of 5.7 fb^{-1} delivered with > 90% data-taking efficiency
- More than factor of 100 improvement over the 2010 statistics
- Max. inst. $\mathcal{L} \approx 3.54 \times 10^{33}$ cm^{-2}s^{-1}
- Data certification for physics analysis:
  - 85% for all systems perfect
  - 90% for muon analysis (w/o calorimeters)
- Luminosity uncertainty is 3.6%

Excellent performance of the CMS detector in 2011

Challenges of high luminosity



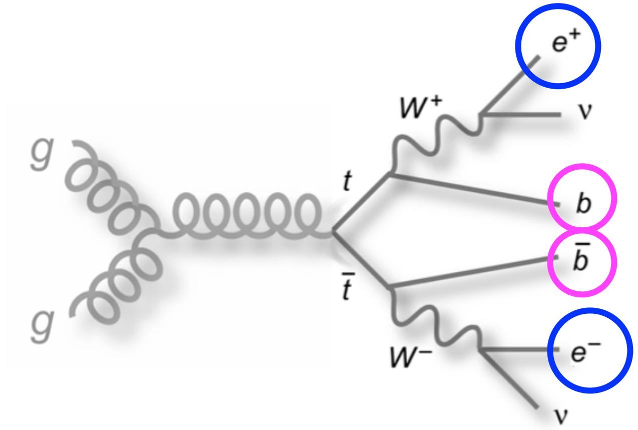


- High multiplicity of interactions in a single collision of two proton bunches (pile-up)
- Number of reconstructed vertices after the August Stop increased by factor 1.5
  - Fills start with ~15 pile-up interactions
  - CMS can deal with this: high granularity → relatively low occupancies

- Good tracker & vertexing performance: able to efficiently reconstruct vertices separated in z by less than 1mm
- Triggers able to cope with this challenging data-taking conditions
- Offline algorithms subtract activity not coming from event primary vertex
  - Protects performance of physics objects like jets, missing energy, and isolated leptons

σ(tt̄) in dileptons (1.14 fb^{-1}) CMS-PAS TOP-11-005

- *Cut-and-count* experiment in the **ee, μμ, μe** channels

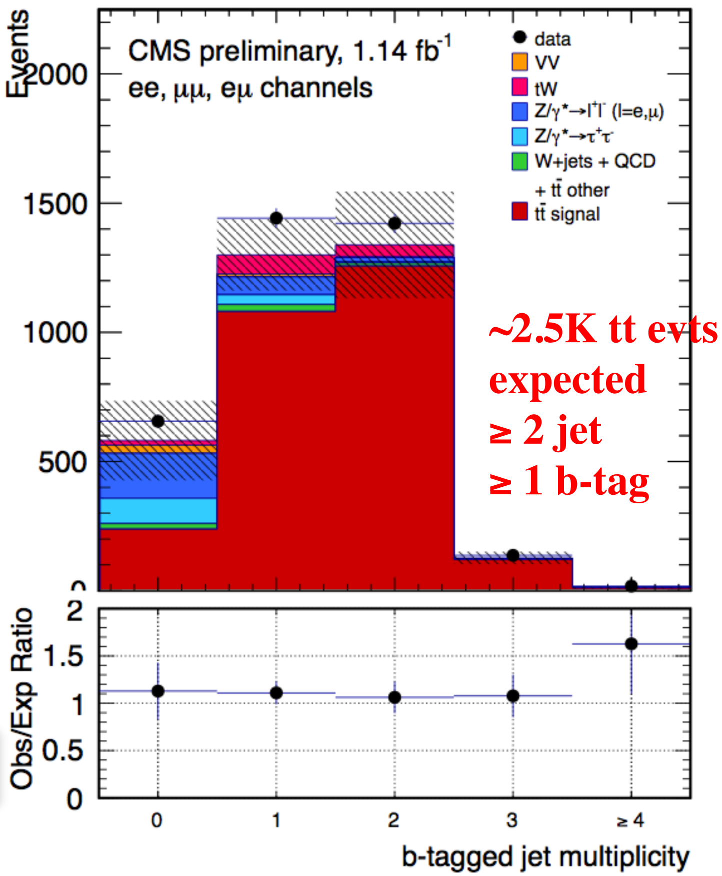


- Require significant E_T^{miss} for **ee, μμ;** Veto Z-mass region
- Very pure sample after requiring ≥ 1 b-tagged jet
- Data-driven estimates for Drell-Yan, W+jets, QCD backgrounds
- Combined cross section:

10.8% precision

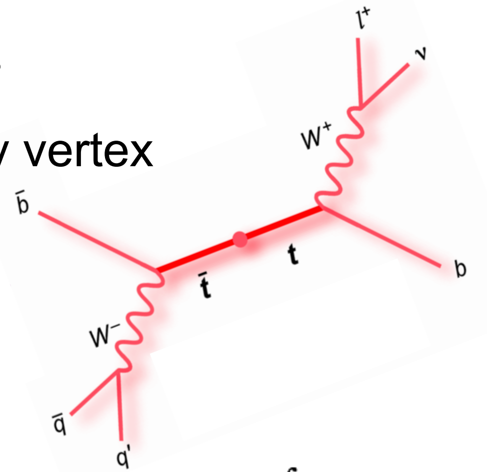
$$\sigma_{t\bar{t}} = 169.9 \pm 3.9\ (\text{stat.}) \pm 16.3\ (\text{syst.}) \pm 7.6\ (\text{lumi.})\text{pb}$$

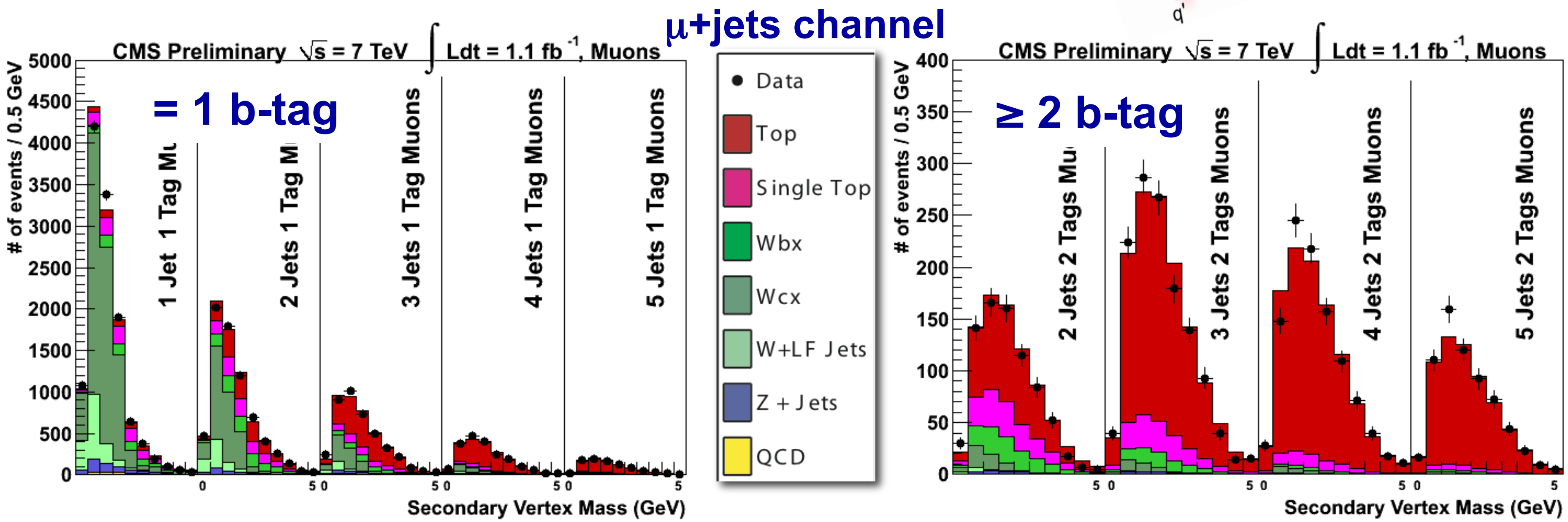
Main systematics from b-tagging, lepton selection, pileup



σ($t\bar{t}$) in l+jets (0.8-1.1 fb^{-1}) CMS-PAS TOP-11-003

- 1 isolated high-p_T μ/e, veto on additional leptons, ≥ 4 jets
- Use only b-tagged events based on displaced secondary vertex
- Profile likelihood fit to secondary-vertex mass
  → separates light from heavy flavour
- 9 different jet & b-tag multiplicities and 2 lepton flavours





- Combined μ+jets & e+jets cross section: 8.7% prec.

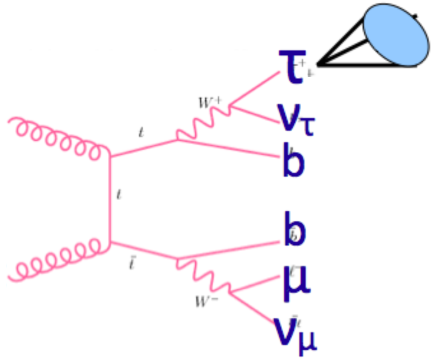
$$\sigma_{t\bar{t}} = 164.4 \pm 2.8(\text{stat.}) \pm 11.9(\text{syst.}) \pm 7.4(\text{lum.})\ \text{pb}$$

Main systematics, determined in situ, due to lepton selection, JES

$\sigma(t\bar{t})$ in $\mu\tau$-channel (1.09 fb^{-1}) CMS-PAS TOP-11-006

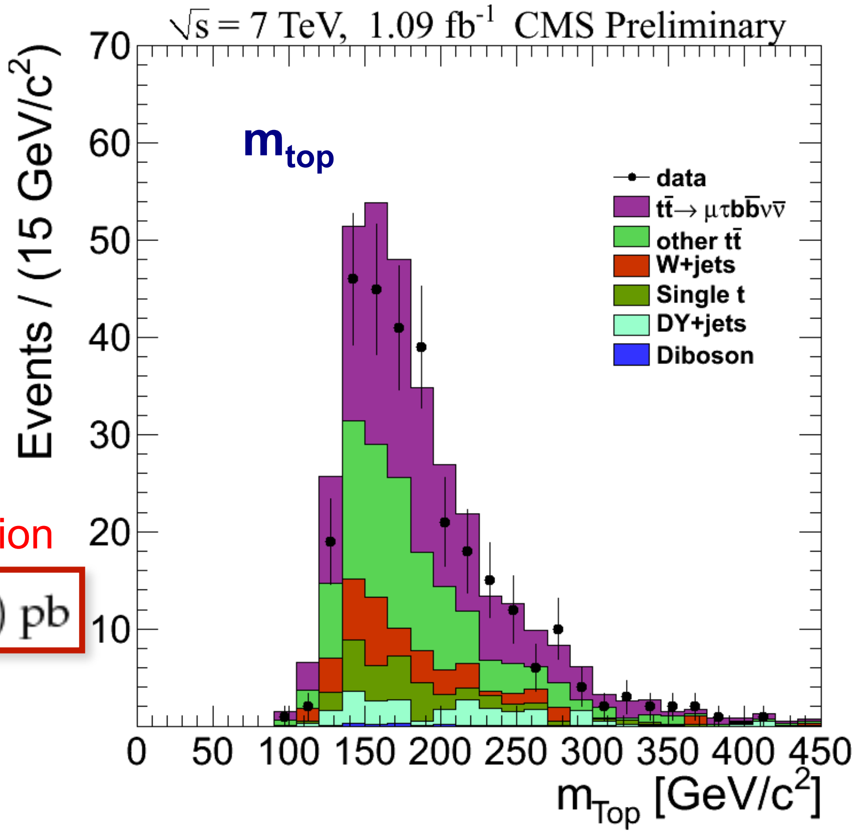
Charged Higgs with $m_H < m_{top}$ could lead to anomalous τ production

- First LHC measurement of ttbar cross section with τ !
- *Cut-and-count* method in the $\tau\mu$ channel
- Selection:
  - 1 isolated, high-p_T μ, veto on additional leptons,
  - ≥ 2 jets, ≥ 1 b-tag, E_T^{miss}
  - 1 τ-jet (opp. muon charge)
- Data-driven estimation of τ-fake background (W+jets and ttbar->l+jets): estimate probability for a jet to fake a had. decaying τ in sideband region and apply to jets in selected evts.



24% precision

$$\sigma_{t\bar{t}}^{\tau-dil} = 148.7 \pm 23.6(\text{stat.}) \pm 26.0(\text{syst.}) \pm 8.9(\text{lumi.})\ \text{pb}$$

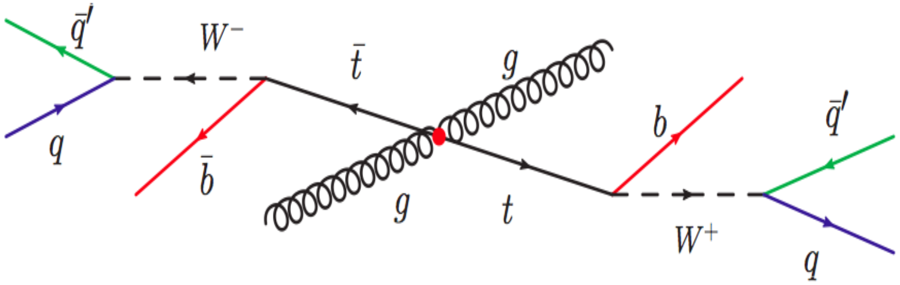


Main systematics from background modelling, tau id, b-tagging

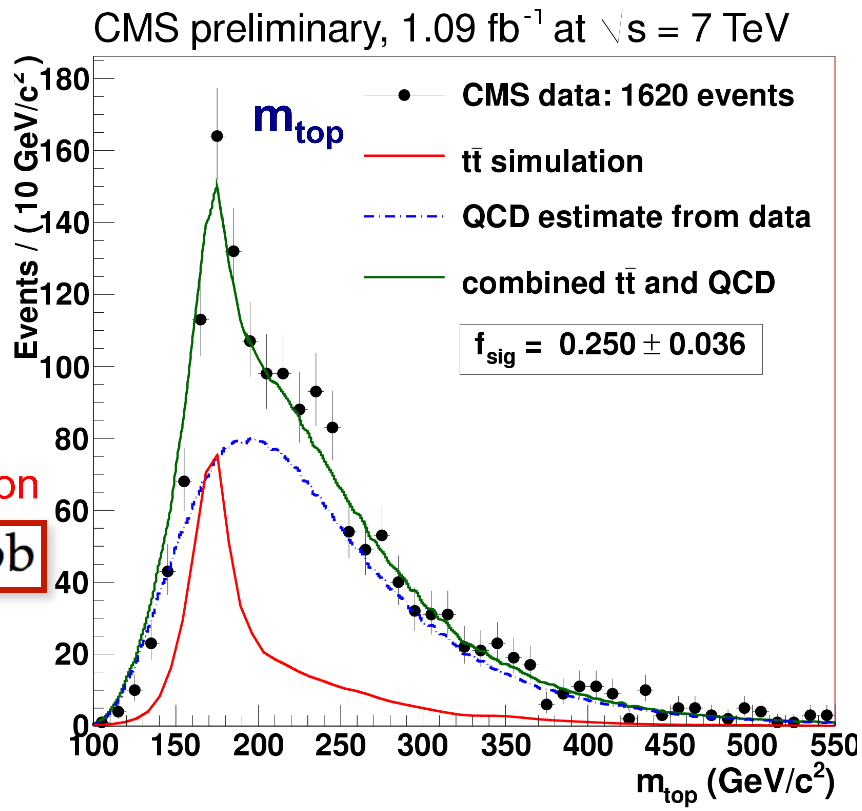
$\sigma(t\bar{t})$ in all hadronic channel (1.09 fb^{-1})

CMS-PAS TOP-11-007

- Large branching ratio (~ 45%), but suffers from large multijet background



- Selection: ≥ 6 high-p_T jets, 2 b-tags
- ttbar reconstruction via kinematic fit
- Cross section from unbinned maximum likelihood fit to reconstructed top mass distribution
- QCD background shape from sideband region in data (zero b-tag)



33% precision

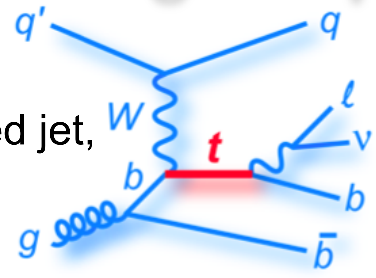
$$\sigma_{t\bar{t}} = 136 \pm 20\,(\text{stat.}) \pm 40\,(\text{sys.}) \pm 8\,(\text{lumi.})\ \text{pb}$$

Main systematics from b-tagging, JES, background

More info: single top in t-channel

- t-channel (dominant):

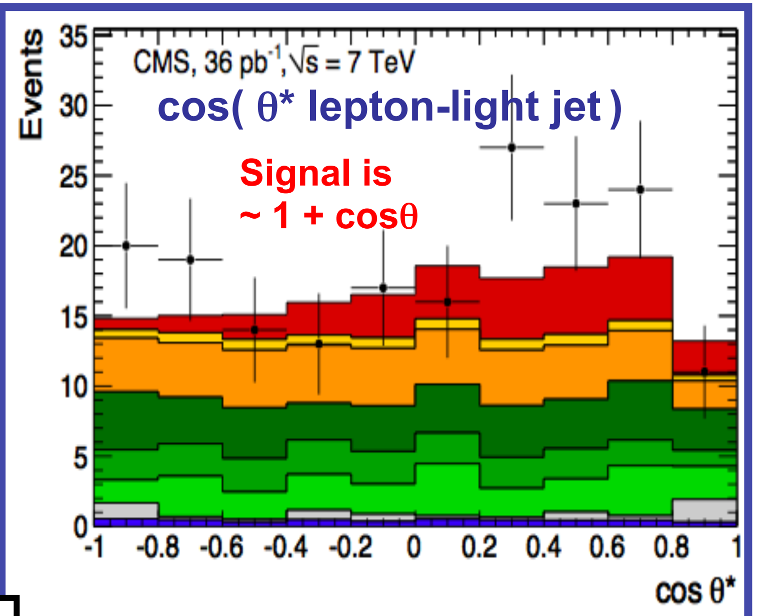
1 isolated high-p_T μ/e, central b-tagged jet, forward light jet, E_T^{miss}

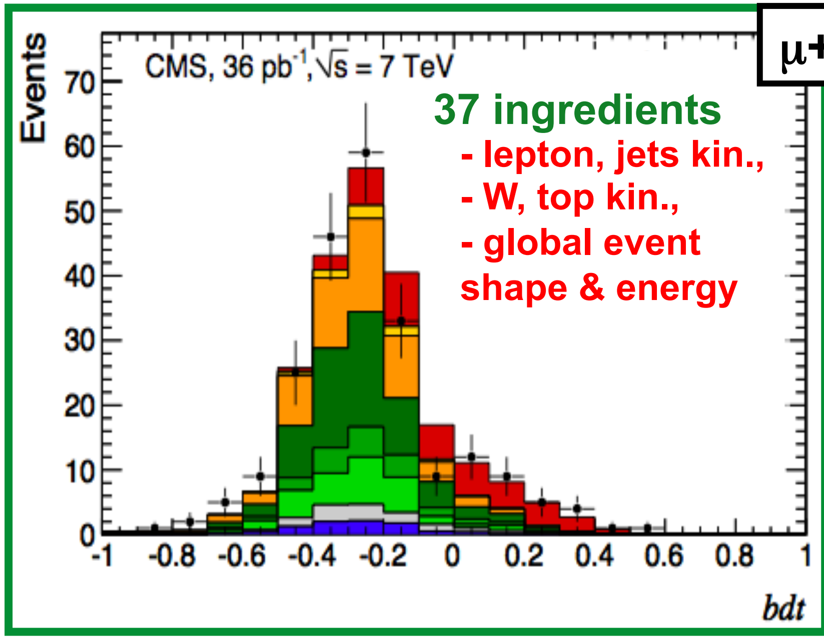


- 2 approaches:
  - 2D likelihood fit to angular signal properties

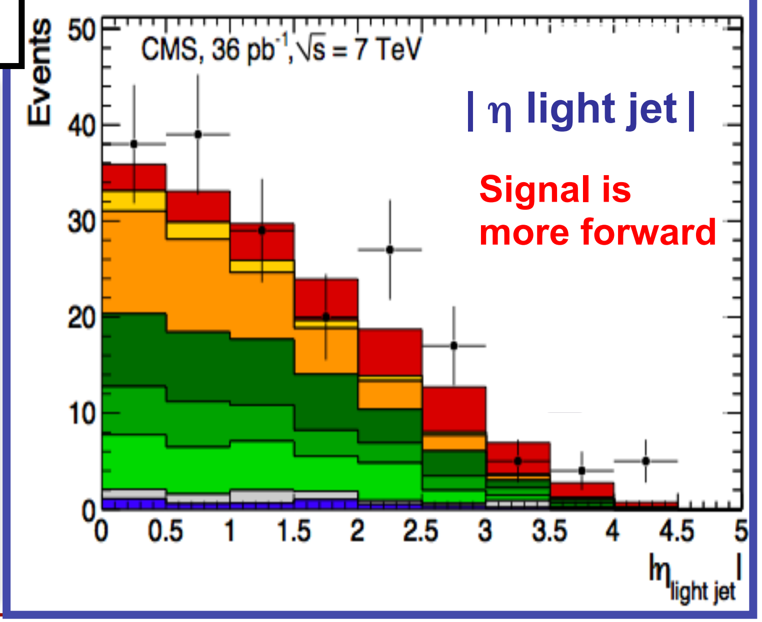
    → Robust, minimal model dependence
  - 1D likelihood fit to multivariate (BDT) output

    → Fully exploits signal topology, maximizes significance





μ+jets & e+jets



More info: single top in t-channel

- All decay channels and analysis methods in agreement within uncertainties
- Significance:
  - 2D analysis: 3.7σ evidence (2.1σ expected)
  - BDT analysis: 3.5σ evidence (2.9σ expected)
- CMS combined cross section:

36% precision

$$83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.)\ \mathrm{pb}$$

Expected: $\sigma_t = 64.3\ ^{+2.1}_{-0.7}(\mathrm{scale})\ ^{+1.5}_{-1.7}(\mathrm{pdf})$

Main systematics:
b-tagging efficiency

- Testing unitarity of CKM matrix: V_{tb} extraction at 95% CL (for V_{ts} , V_{td} << V_{tb})

$$|V_{tb}| = \sqrt{\frac{\sigma_{\mathrm{exp.}}}{\sigma_{\mathrm{theo.}}}} > 0.62\,(0.68)$$ for 2D (BDT) analysis

So far, all results consistent with SM predictions

More info: single top in t-channel

Event yield summary

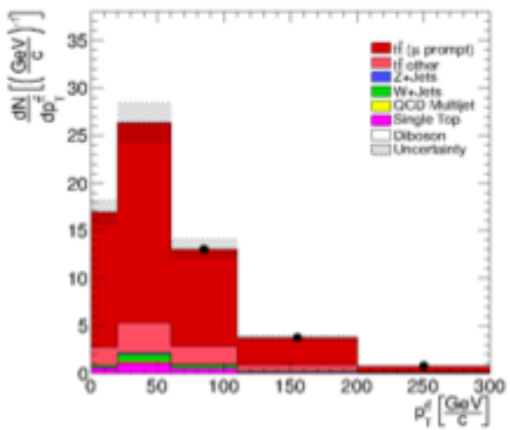
Process	2D, μ channel	2D, e channel	BDT, μ channel	BDT, e channel
single top, t channel	17.6 ± 0.7 (†)	11.2 ± 0.4 (†)	17.6 ± 0.7 (†)	10.7 ± 0.5 (†)
single top, s channel	0.9 ± 0.3	0.6 ± 0.2	1.4 ± 0.5	1.0 ± 0.3
single top, tW	3.1 ± 0.9	2.4 ± 0.7	3.8 ± 1.1	< 0.1
WW	0.29 ± 0.09	0.23 ± 0.07	0.32 ± 0.10	0.23 ± 0.07
WZ	0.24 ± 0.07	0.17 ± 0.05	0.33 ± 0.10	1.5 ± 0.4
ZZ	0.018 ± 0.005	0.011 ± 0.003	0.020 ± 0.006	< 0.1
$W+$ light partons	18.2 ± 5.5	11.6 ± 2.3	8.4 ± 4.2	7.0 ± 3.5
$Z + X$	1.7 ± 0.5	1.6 ± 0.3	0.7 ± 0.2	0.05 ± 0.03
QCD	0.6 ± 0.3	$2.6^{+3.4}_{-2.6}$	4.9 ± 2.5	5.3 ± 5.3
$VQ\bar{Q}$	20.4 ± 10.2	14.1 ± 7.1	17.6 ± 8.8	11.7 ± 5.8
Wc	$12.9^{+12.9}_{-6.5}$	$9.4^{+9.4}_{-4.7}$	$9.2^{+9.2}_{-4.6}$	$5.9^{+5.9}_{-2.9}$
$t\bar{t}$	20.3 ± 3.6	15.6 ± 2.8	34.9 ± 4.9	22.9 ± 3.2
Total background	78.6 ± 15.2	58.4 ± 11.0	82.4 ± 13.1	55.9 ± 10.2
Signal + background	96.2 ± 15.3	69.6 ± 11.0	100.0 ± 13.2	66.6 ± 10.2
Data	112	72	139	82

More info: single top in t-channel

Systematics combined mu/e (given in %)

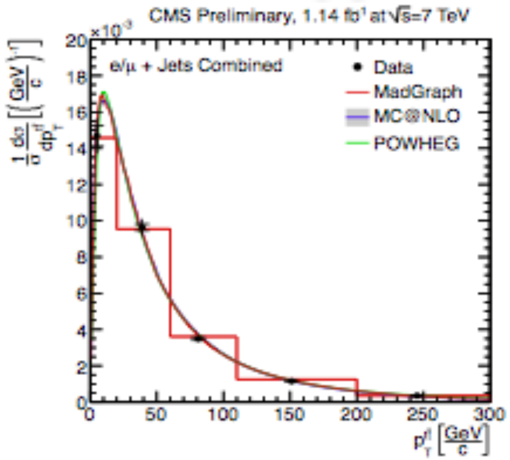
uncertainty	correlation	impact on 2D −	2D +	BDT −	BDT +
statistical only	60	52		39	
shared shape/rate uncertainties:					
ISR/FSR for $t\bar{t}$	100	−1.0	+1.5	< 0.2	< 0.2
Q^2 for $t\bar{t}$	100	+3.5	−3.5	+0.3	−0.4
Q^2 for V+jets	100	+5.7	−12.0	+2.6	−4.5
Jet energy scale	100	−8.8	+3.6	−5.1	+1.2
b tagging efficiency	100	−19.6	+19.8	−15.2	+14.6
MET (uncl. energy)	100	−5.7	+3.7	−3.9	−0.5
shared rate-only uncertainties:					
$t\bar{t}$ (±14%)	100	+2.0	−1.9	+0.5	−0.6
single top s (±30%)	100	−0.4	+0.5	−0.4	+0.4
single top tW (±30%)	100	+1.1	−1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ (±50%)	100	−3.0	+2.9	+1.7	−1.9
Wc ($^{+100\%}_{-50\%}$)	100	−3.0	+6.1	−2.4	+4.4
Z+jets (±30%)	100	−0.6	+0.7	+0.4	−0.2
electron QCD (BDT: ±100%, 2D: $^{+130\%}_{-100\%}$)	50	+2.9	−3.7	−1.7	+1.7
muon QCD (BDT: ±50%, 2D: ±50%)	50	< 0.2	< 0.2	−2.1	+2.1
signal model	100	−5.0	+5.0	−4.0	+4.0
BDT-only uncertainties:					
electron efficiency (±5%)	0	—	—	−1.4	+1.4
muon efficiency (±5%)	0	—	—	−3.6	+3.5
V+jets (±50%)	0	—	—	−1.5	< 0.2
2D-only uncertainties:					
muon W+light (±30%)	0	−1.4	+1.4	—	—
electron W+light (±20%)	0	−0.6	+0.7	—	—
W+light model uncertainties	0	−5.4	+5.4	—	—

More info: differential cross sections (I)



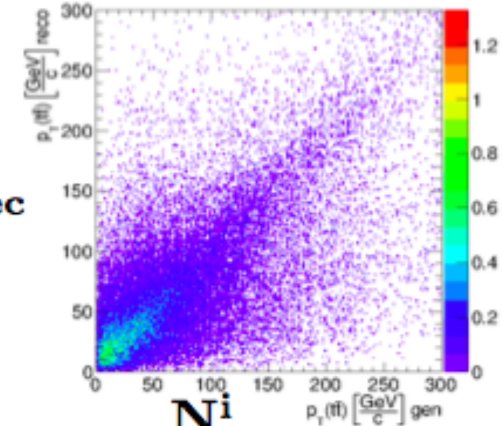
$$\frac{1}{\sigma}\frac{d\sigma^i}{dX} = \frac{1}{\sigma}\frac{N^i_{Data} - N^i_{BG}}{\Delta^i_X\ \epsilon^i\ \mathcal{L}_{int}}$$

→



$$\epsilon^i = \frac{N^i_{rec}}{N^i_{gen}}$$

N^i_{rec}



N^i_{gen}

- Normalised to unity
- Restricted to visible phase space
  - quarks $p_T > 30$, $|\eta| < 2.4$
  - lepton $p_T > 30$, $|\eta| < 2.1$ (l+jets)
    lepton $p_T > 20$, $|\eta| < 2.4$ (dilepton)
- Corrected back to parton level (MC)
- Corrected for detector effects
  - Bin-by-bin corrections
    purity, stability limited to $\geq 50\%$
  - SVD unfolding for $d\sigma/dM_{t\bar{t}}$ in the dilepton channel only

More info: differential cross sections (II)

Systematics: typical values per bin

Source	Method	l+jets (in %)	dilepton (in %)
Background	vary with 30–50%	0.5	3.0
Trigger & lepton eff.	p_T, η dependent	0.5	2
Jet Energy Scale	p_T, η dependent	0.5	1.0
Jet Energy Resolution	p_T, η dependent	1.0	<1.0
Pile-up	vary $\pm$0.6 PU evts	<1.0	<1.0
b-tagging	p_T, η dependent	1–4	1.7
Kinematic reconstruction	p_T, η dependent	–	1–4
Q^2, matching scale	vary factor 0.5–2	3.5	1.2
Hadronisation	Pythia vs Herwig	2–4	2–10
Top Quark Mass	172.5 ± 0.9	0.5	0.5
PDF	PDF4LHC	0.5	0.5

More info: top mass in dileptons (I)

Fully Kinematic Method (KINb)

- Top quark reconstruction:
  - Solve equations of tt system many times per event
  - Scan kinematic phase space: vary p_T(jet), E_T^{miss} & p_z(tt) independently according to resolution
  - Accept solutions with lowest m(tt) if $|m_{top} - m_{antitop}| < 3$ GeV
  - Choose the l-jet combination with largest number of solutions
  - m_{KIN} = outcome of gaussian fit around most probable value (± 50 GeV)

- Top mass determination:
  - Unbinned likelihood fit to m_{KIN}
  - Free parameters: m_{top}, $N_{sig,}$ N_{bg}
  - Background templates from simulation (shapes fixed); signal template (gaussian + landau) from fit to simulated signal sample

More info: top mass in dileptons (II)

Event yields

Table 1: Number of expected events for the different background contributions are compared with data, after the selection requirements and after KINb reconstruction. The events with valid KINb solutions which have 1 or at least 2 b-tagged jets are shown in the leftmost columns. The uncertainty reflects the uncertainty in the luminosity (3.6%), theoretical cross sections, jet energy scale and resolution, contamination from pile-up, trigger and selection efficiencies and the limited statistics in the MC samples.

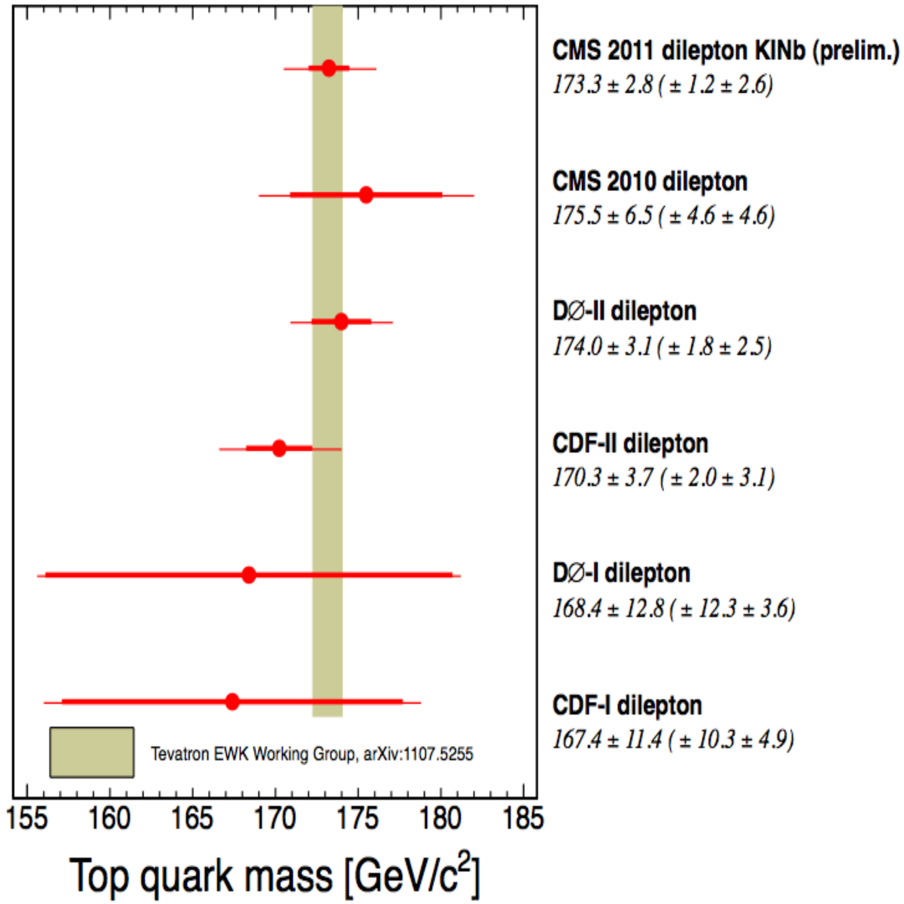
Process	Pre-selection	KINb	=1 b-tag	$\geq$ 2 b-tags
Di-bosons	73 ± 14	55 ± 10	18 ± 4	4 ± 1
Single top	247 ± 92	182 ± 68	88 ± 33	76 ± 29
W+jets	22 ± 10	16 ± 8	8 ± 6	-
$Z/\gamma^* \to \ell\ell$	1091 ± 97	756 ± 71	238 ± 29	47 ± 11
other $t\bar{t}$	32 ± 4	28 ± 3	11 ± 2	14 ± 2
$t\bar{t}$ dileptons	5057 ± 463	4209 ± 385	1379 ± 127	2623 ± 240
total expected	6522 ± 482	5246 ± 398	1742 ± 134	2765 ± 242
data	6358	5047	1692	2620

More info: top mass in dileptons (III)

Systematics

Source	Δm_{top} (GeV/c^2)
JES	$^{+1.90}_{-2.00}$
flavor-JES	$^{+1.08}_{-1.13}$
JER	$\pm$ 0.30
LES	$^{+0.12}_{-0.18}$
Unclustered E_T^{miss}	$\pm$ 0.43
Fit calibration	$\pm$ 0.40
DY normalization	$\pm$ 0.40
Factorization scale	$\pm$ 0.41
Jet parton matching scale	$\pm$ 0.65
Pile-up	$\pm$ 0.19
b-tagging uncertainty	$\pm$ 0.30
mis-tagging uncertainty	$\pm$ 0.43
MC generator	$\pm$ 0.14
PDF uncertainty	$\pm$ 0.39
Total	$^{+2.52}_{-2.63}$

Comparison to CMS and Tevatron



More info: top mass in μ+jets (I)

Ideogram method:

- Probability for single permutation

$$P\left(m_{t,i}^{fit}, m_{W,i}^{reco} | m_t, \mathrm{JES}\right) = \sum_j f_j P_j\left(m_{t,i}^{fit} | m_t, \mathrm{JES}\right) \cdot P_j\left(m_{W,i}^{reco} | m_t, \mathrm{JES}\right),$$

$j \in \{cp, wp, un\}$, f_j, P_j from simulation

- Likelihood for event with n permutations

$$\mathcal{L}\left(\mathrm{event} | m_t, \mathrm{JES}\right) = \sum_{i=0}^{n} P_{\mathrm{fit}}(i)\, P\left(m_{t,i}^{fit}, m_{W,i}^{reco} | m_t, \mathrm{JES}\right),$$

- Every event is assigned a weight $w_{event} = \sum_i P_{\mathrm{fit}}(i)$, sum of event weights normalized to number of events
- Most likely m_t and JES given data sample (Maximum Likelihood)

$$\mathcal{L}\left(m_t, \mathrm{JES} | \mathrm{sample}\right) \sim \prod_{\mathrm{events}} \mathcal{L}\left(\mathrm{event} | m_t, \mathrm{JES}\right)^{w_{event}}$$

More info: top mass in μ+jets (II)

Calibration of JES and mass fits

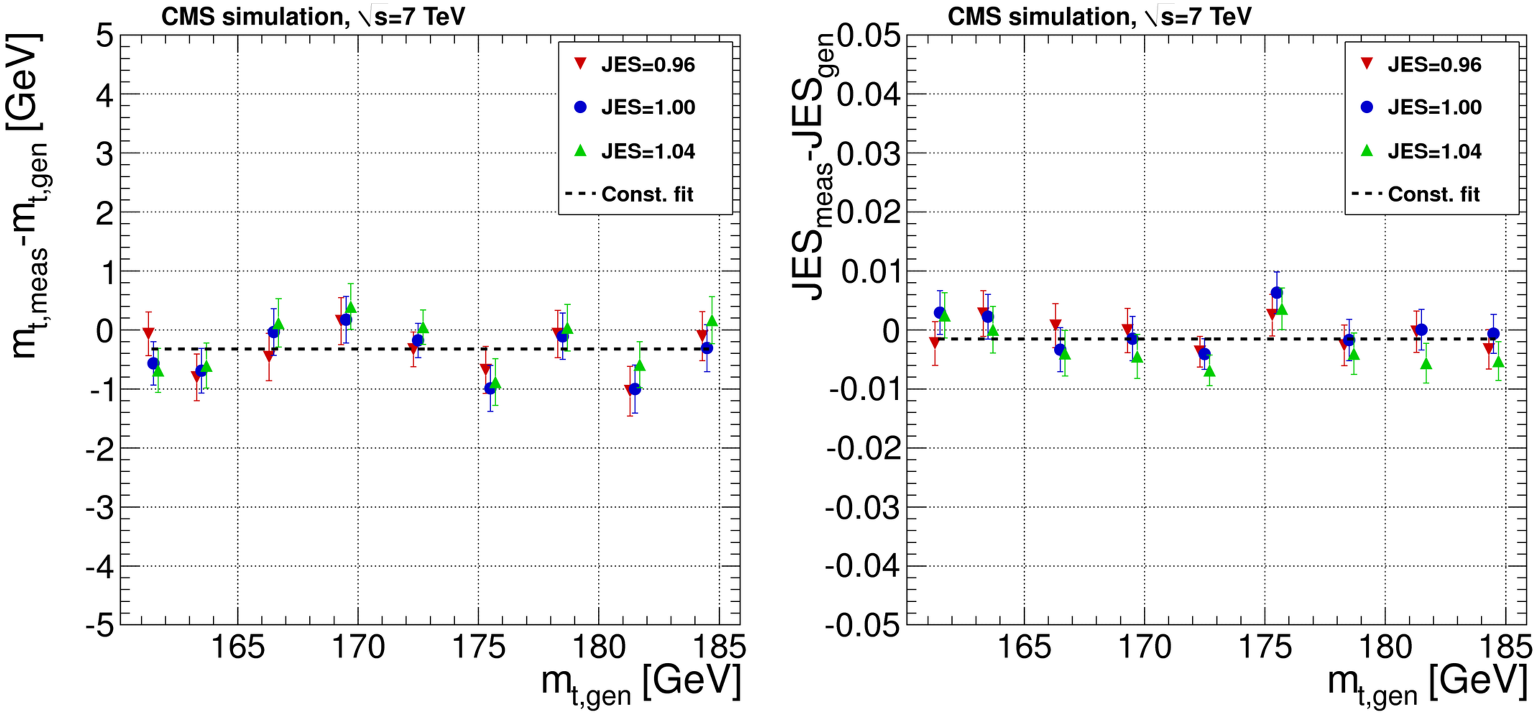


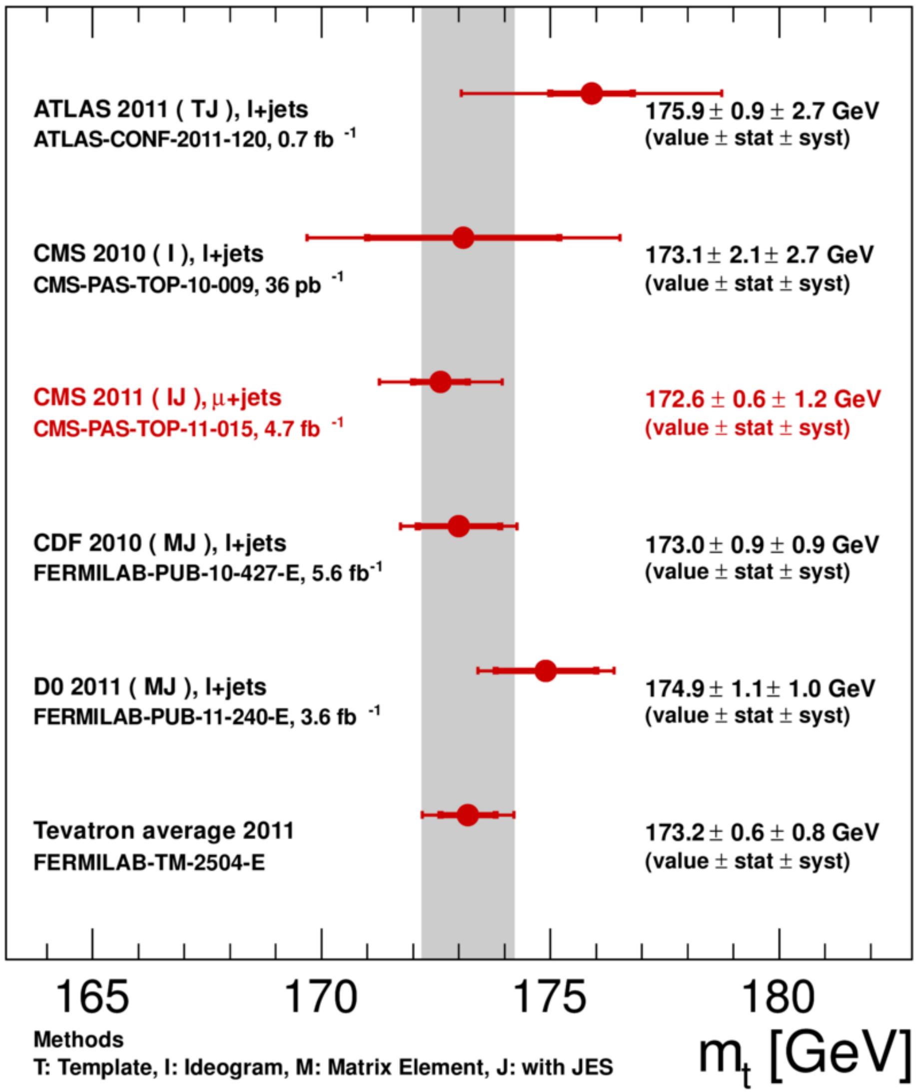
Figure 5: Difference (a) between the measured top mass $m_{t,\mathrm{meas}}$ and the generated top mass $m_{t,\mathrm{gen}}$ and (b) between the measured JES and the generated JES before calibration for different generated top masses and three different JES. The ideogram method is able to measure the mass and JES input values with a small bias even before calibration.

More info: top mass in μ+jets (III)

Systematics

	δ_{m_t} (GeV)	δ_{JES}
Calibration	0.15	0.001
b-tagging	0.17	0.002
b-JES	0.66	0.000
p_T- and η-dependent JES	0.23	0.003
Jet energy resolution	0.21	0.003
Missing transverse energy	0.08	0.001
Factorization scale	0.76	0.007
ME-PS matching threshold	0.25	0.007
Non-$t\bar{t}$ background	0.09	0.001
Pile-up	0.38	0.005
PDF	0.05	0.001
Total	1.18	0.012

Comparison to other experiments



More info: t-tbar mass difference

Systematics

- Correlated sources between t and tbar (partially) cancel (e.g., global JES)
- Many systematic model uncertainties can be neglected (e.g., ISR/FSR, hadronization)
- Dominant contributions: JES/JER, b(bar)-tagging

Source of systematic effect	Uncertainty on Δm_t (GeV)
Jet Energy Scale	0.16
Jet Energy Resolution	0.18
b vs $\bar{b}$ Jet Response	0.10
Signal fraction	0.03
Background composition	0.13
Pileup	0.1
b-tagging efficiency	0.08
b vs $\bar{b}$ tagging efficiency	0.17
Fit calibration statistics	0.3
Parton distribution functions	0.05
Total	0.47

More info: top mass from cross section (I)

Some top quark mass definitions:

The on-shell or pole mass: $\sqrt{p^2} = m - \frac{i}{2}\Gamma$

- Based on the concept of quarks being free particles
- Long range effects: irreducible ambiguity of $\Lambda_{\mathrm{QCD}} \approx 0.2$ GeV
- Top quark decay: color connection of the hadronizing b quark to the rest of the event (e.g. a proton remnant)

The $\overline{\mathrm{MS}}$ mass (modified "minimal subtraction" scheme):

- Short-distance mass calculated perturbatively, divergences removed using renormalization
- In principle would allow for arbitrary accuracy
- Preferred by theory community; used by Particle Data Group for all quarks - except top

$m_t^{\mathrm{pole}} / m_t^{\overline{\mathrm{MS}}} \approx 1.06$

Monte Carlo masses:

- Typically identified with the pole mass, but not necessarily the same!

More info: top mass from cross section (II)

Some basic facts about theory parameters

…and their determination.

- Parameters are only defined in a specific model i.e. SM
- In general: Parameters ≠ Observables
- Precise values depend on specific scheme used to define them
- Determination through comparison: theory ← → experiment

Top-quarks appear not as asymptotic states,
(no free quarks due to confinement)

⬇

Top-quark mass is "just" a parameter like α_s

→ renormalisation scheme dependent,
only indirect determination possible

Peter Uwer | Top-quark mass | 3rd Linear Collider Forum, DESY HH, 7-9.2.2012 | page 6

More info: top mass from cross section (III)

- Pole and MS mass related → re-parameterization of pole-mass cross-section function $\sigma(m_t)$

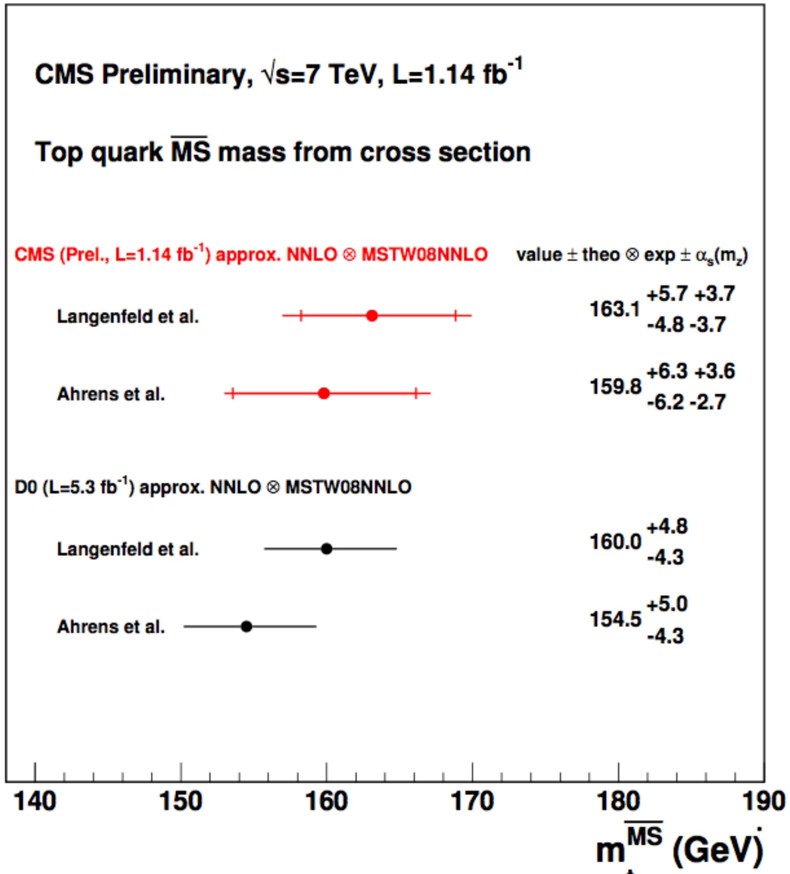
$$m_t^{\overline{\mathrm{MS}}} = m_t^{\mathrm{pole}} / \left(1 + \frac{4}{3}\frac{\alpha_S(m_t^{\overline{\mathrm{MS}}})}{\pi} + 8.2364\left(\frac{\alpha_S(m_t^{\overline{\mathrm{MS}}})}{\pi}\right)^2 + 73.638\left(\frac{\alpha_S(m_t^{\overline{\mathrm{MS}}})}{\pi}\right)^3\right)$$

Pole and MS masses for different PDFs

Approx. NNLO × MSTW08NNLO	m_t^{pole} / GeV	$m_t^{\overline{\mathrm{MS}}}$ / GeV
Langenfeld et al. [7]	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis [8]	$170.0^{+7.6}_{-7.1}$	–
Ahrens et al. [9]	$167.6^{+7.6}_{-7.1}$	$159.8^{+7.3}_{-6.8}$

Approx. NNLO × HERAPDF15NNLO	m_t^{pole} / GeV	$m_t^{\overline{\mathrm{MS}}}$ / GeV
Langenfeld et al. [7]	$171.7^{+6.8}_{-6.0}$	$164.3^{+6.5}_{-5.7}$
Ahrens et al. [9]	$169.1^{+6.7}_{-5.9}$	$161.0^{+6.8}_{-6.1}$

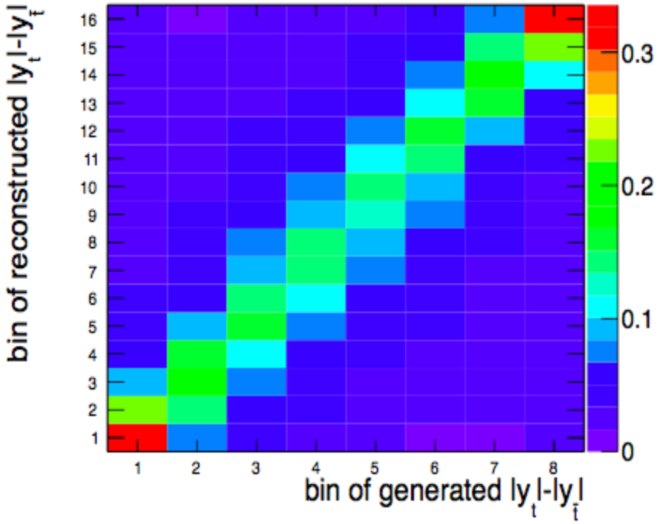
MS mass results

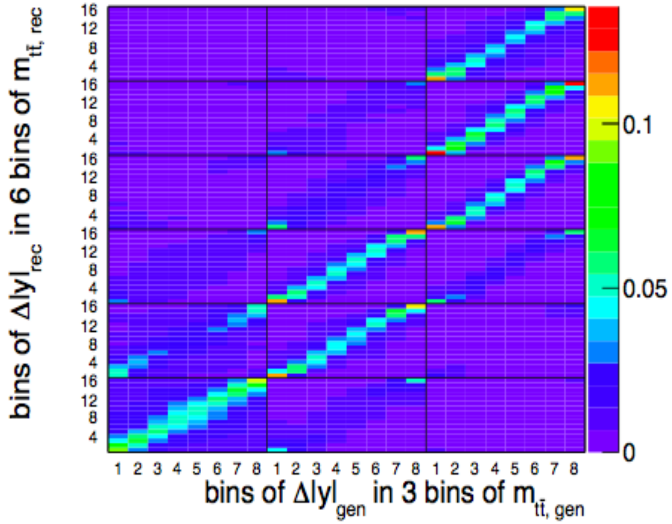


More info: charge asymmetry (I)

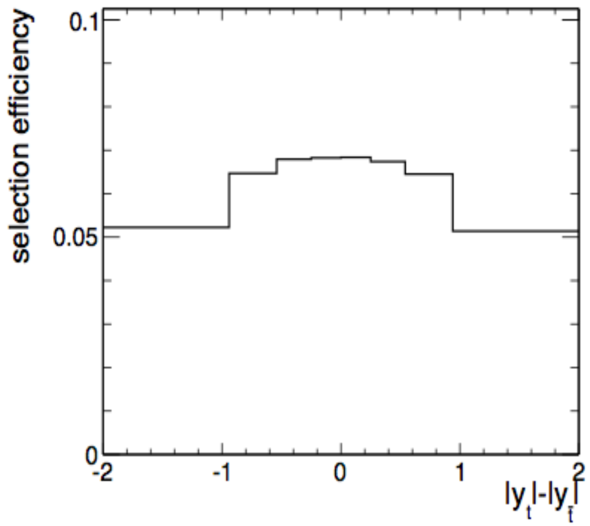
Unfolding: correct the measurement from bg contribution and smearing & selection effects

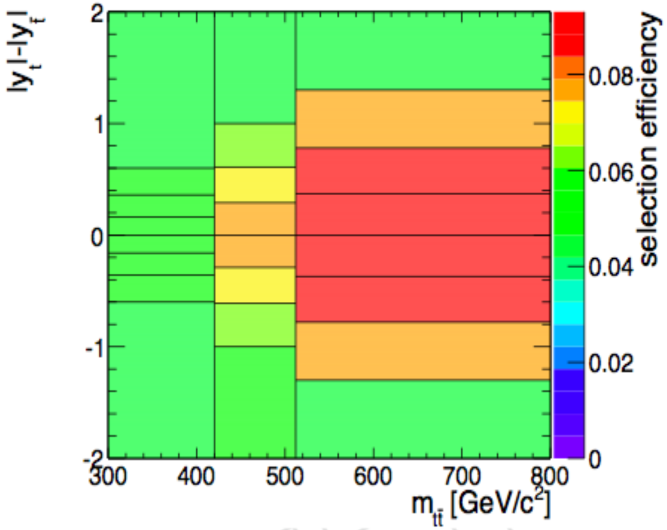
Migration matrices





Selection efficiencies





More info: charge asymmetry (II)

Systematics

Systematic uncertainty	inclusive A_C
JES	0.002
JER	0.002
Pileup	0.001
Generator	0.001
Migration matrix	0.002
Unfolding	0.008
W+jets	0.004
Multijet	0.001
b tagging	0.000
Lepton ID/sel. efficiency	0.006
Q^2 scale	0.002
Hadronization	0.001
PDF	0.002
Total	0.012

More info: W helicity fractions

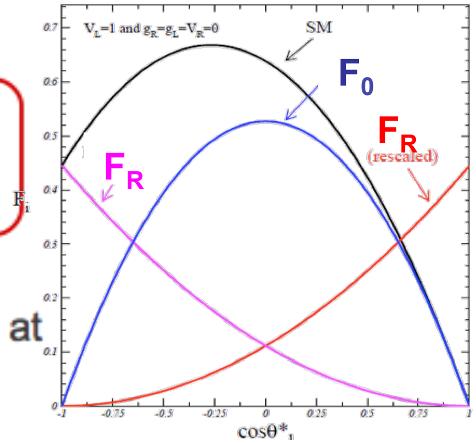
- Measurement is **affected by two aspects**:
  - Distortions due to detector effects: resolution, acceptance, ...
  - Generalizing the generator level polarization to any scenario

- Weighting procedure is used:

$$\rho(\cos\theta^*_{rec}) = \int R(\cos\theta^*_{rec}, \cos\theta^*_{gen}) \frac{\rho(\cos\theta^*_{gen})}{\rho^{SM}(\cos\theta^*_{gen})} \rho^{SM}(\cos\theta^*_{gen})\, d\cos\theta^*_{gen}$$

Detector response matrix taking into account reconstruction/acceptance effects on the generated events

SM prediction used at generator level ▶



- The fractions F_0, F_L and F_R are extracted using a binned likelihod fit to cos θ*

$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!} \exp\left(-N_{MC}(i;\vec{F})\right)$$

$$\begin{aligned} N_{MC}(i,\vec{F}) &= N_{BKG}(i) + N_{t\bar{t}}(i;\vec{F}) \\ N_{t\bar{t}}(i;\vec{F}) &= \mathcal{F}_{t\bar{t}} \left[\sum_{t\bar{t}\ \text{events, bin}\ i} W(\cos\theta^*_{gen};\vec{F}) \right] \end{aligned}$$

Can fit F_0, $F_L + \mathcal{F}_{t\bar{t}}$ (3D), $F_0 + \mathcal{F}_{t\bar{t}}$ (2D) or $\mathcal{F}_{t\bar{t}}$ alone (1D)