Top Quark Production at the LHC (Single Top and $t\bar{t}$ Cross Sections)

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On behalf of the ATLAS and CMS Collaborations

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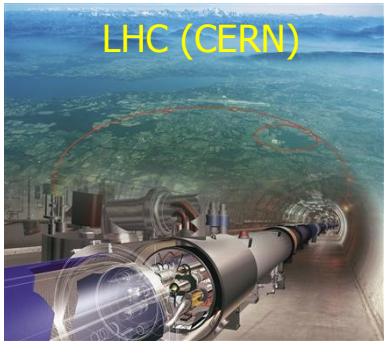
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

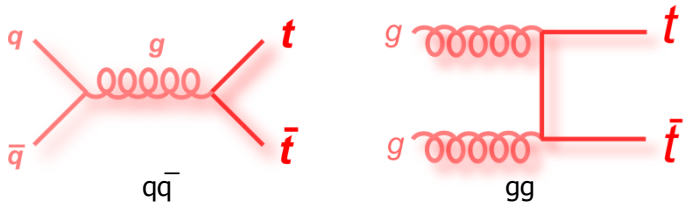
Top Quark – from the Tevatron to the LHC

- Top quark: special particle of the SM and in BSM searches (large mass, decay before hadronis.)
  ⇒ major research topic also at the LHC



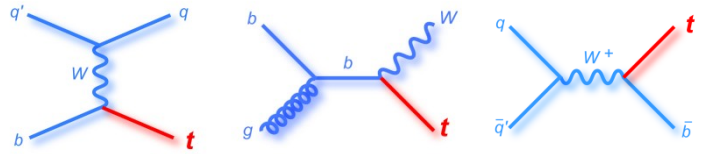
Collider	$p\bar{p}$ (1.96 TeV)	pp (7, 8, 14) TeV
Detectors	CDF, D0 (2x10 fb^{-1})	ATLAS, CMS (2x5 fb^{-1})
Dominant $t\bar{t}$ prd.	$q\bar{q}$	gg
$\sigma_{t\bar{t}}$	7 pb	165 pb
σ_t (t-ch.)	2 pb	65 pb
$t\bar{t}$ pairs	2 x 75,000	2 x 800,000 (~1y)

$t\bar{t}$ production



$q\bar{q}$ gg

single top production



t-channel tW-channel s-channel

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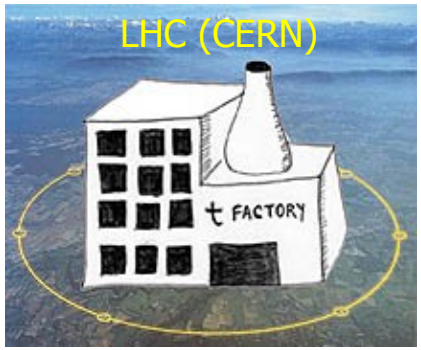

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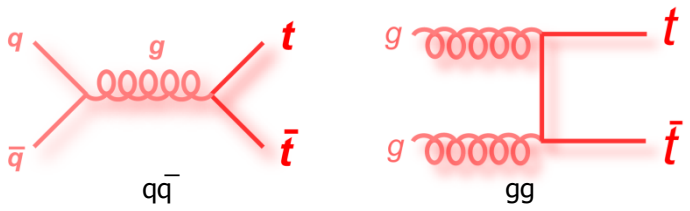

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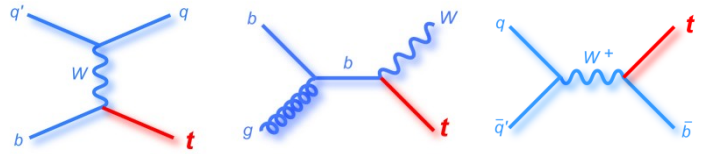
single top production



t-channel tW-channel s-channel

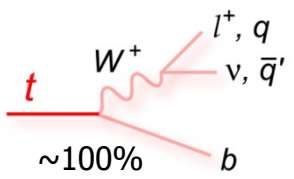
⇒ LHC is a ***Top Factory***

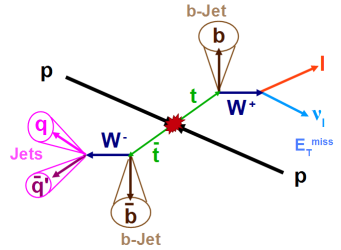
Top Quark Cross Sections at the LHC

- 2010: 40 pb^{-1}
  - *Rediscovery* of the top quark
  - First inclusive cross sections

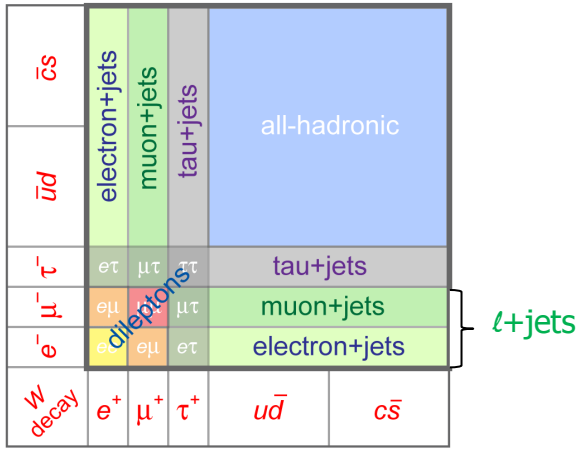
- 2011: 5 fb^{-1} (for some results only part)
  - Precision incl. cross sections
  - Challenging channels
  - Differential cross sections

$\Rightarrow$ Era of precision and properties measurements





Top Pair Decay Channels



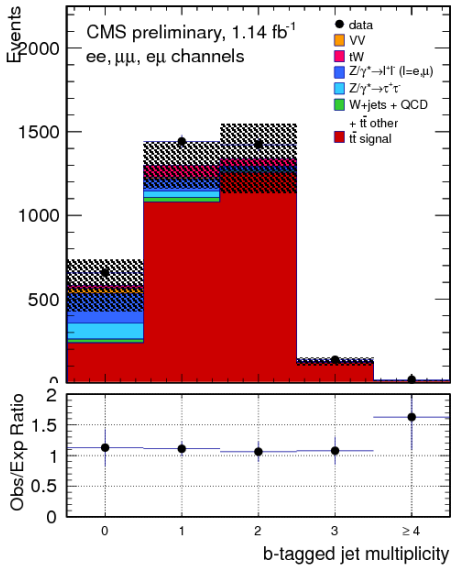
- Almost all physics objects involved:
  isolated leptons (μ, e), τ, jets, b-jets, MET (ν)
  → well-understood/calibrated detector needed
- ATLAS and CMS performing great
  JES few %, b-tag few %, JER ~10%,
  μ/e p_T res. 1-2%, lumi 2-4%

Inclusive Cross Sections

Precision Channels

Dilepton
Low rate, low BG (Z+jets) → clean signature

- Event selection based on
  - 2 OS isol. leptons, ≥ 2 jets, MET, optional b-tag
- Signal extraction: „Cut&Count"
  - Z and fake lepton BG from sidebands in data

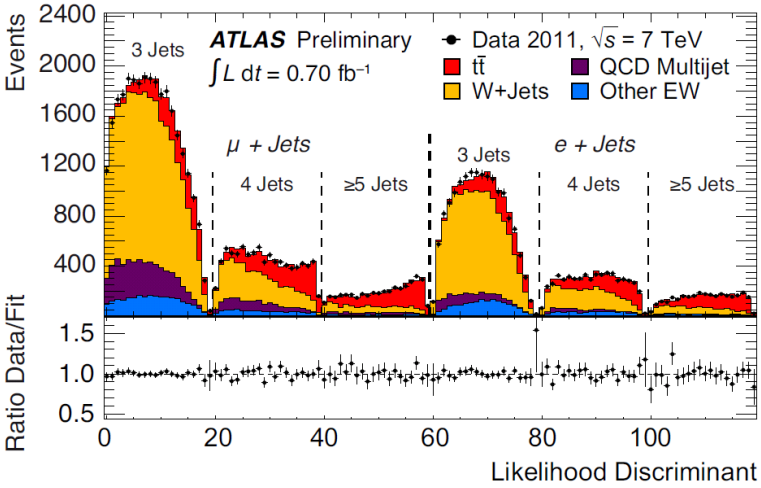


176 ± 5 (stat) +14/-11 (sys) ± 8 (lum) pb (0.7 fb^{-1})
arXiv:1202.4892 9% unc. (sig. model, JES, lumi)

169.9 ± 3.9 (stat) ± 16.3 (sys) ± 7.6 (lum) pb (1.14 fb^{-1})
CMS-PAS-TOP-11-005 11% unc. (b-tag, PU, lep. eff.)

Lepton+Jets
Good rate, manageable BG (W+jets, QCD)

- Event selection based on
  - Single isolated lepton, MET or b-tagging
- Signal extraction with likelihood fit
  - Different jet mult. categories→ in-situ BG det.
  - ATLAS: fit to η(ℓ), lead. jet p_T, aplanarity, H_T
  - CMS: fit to secondary vertex mass (b-kin.)



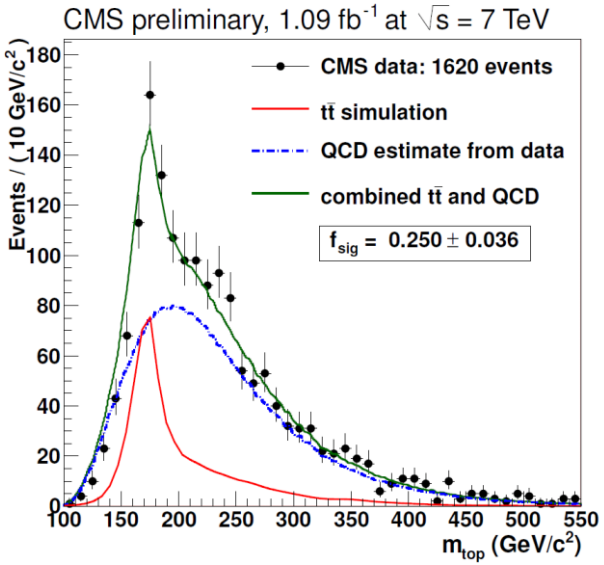
179.0 ± 3.9 (stat) ± 9.0 (sys) ± 6.6 (lum) pb (0.7 fb^{-1})
ATLAS-CONF-2011-121 7% unc. (sig. model, JES, lep. eff.)

164.4 ± 2.8 (stat) ± 11.9 (sys) ±7.4 (lum) pb (0.8-1.1 fb^{-1})
CMS-PAS-TOP-11-003 9% unc. (PDF, JES, lep. eff.)

Challenging Channels

All hadronic
High rate, high BG (multijets)

- Event selection
  - Optimised to reject multijet BG
- Likelihood fit to m_{top}
  - Multijet BG shape from anti-tagged control region

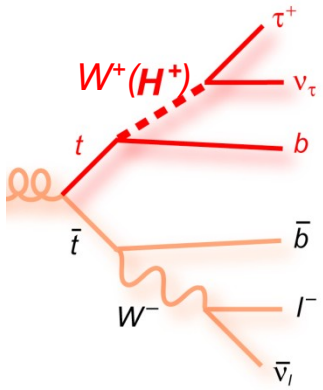


168 ± 12 (stat) +60/-57 (sys) ± 7 (lum) pb (4.7 fb^{-1})
ATLAS-CONF-2012-031 36% unc. (JES, b-tag, ISR/FSR)

135 ± 20 (stat) ± 40 (sys) ± 8 (lum) pb (1.09 fb^{-1})
CMS-PAS-TOP-11-007 33% unc. (b-tag, BG, JES)

Tau (Dilepton and Tau + Jets)
Low to medium rate, high BG (fake taus)

- NEW results (after Moriond)
- Only 3rd generation in decay
  → sensitive to BSM/charged Higgs



- Experimentally challenging
  - Hadronic tau (jet with 1 (3) ch. hadrons)

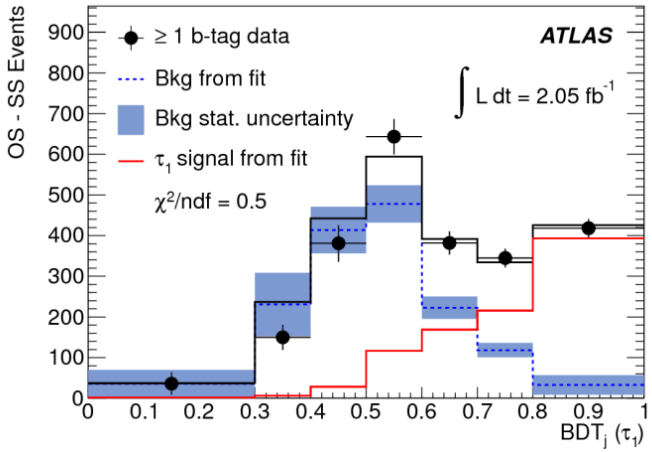
    → large BG due to misid. jets from W+jets, $t\bar{t}$ other channels, QCD multijet

    → fake τ BG always estimated from data

Tau Dilepton

Low rate, high BG (fake taus)

- Event selection based on
  - Like dilepton with 1 μ/e + 1 τ candidate
  - ATLAS: loose τ, CMS: well-id. τ
- Signal extraction
  - ATLAS: fit to BDT discriminant built of 8-10 var. separating real from fake τ (e.g. isol., jet mass)
  - CMS: „Cut&Count"



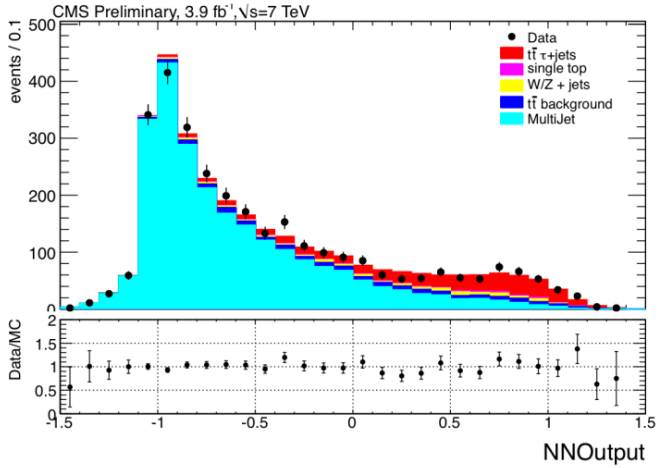
NEW 186 ± 13 (stat) ± 20 (sys) ± 7 (lum) pb (1.08 fb^{-1})
arXiv:1205.2067 13% unc. (b-tag, ISR/FSR, stat.)

CMS NEW 143 ± 14 (stat) ± 22 (sys) ± 3 (lum) pb (2.0-2.2 fb^{-1})
arXiv:1203.6810 18% unc. (fake τ BG, τ ID)

Tau + Jets

Medium rate, high BG (fake taus)

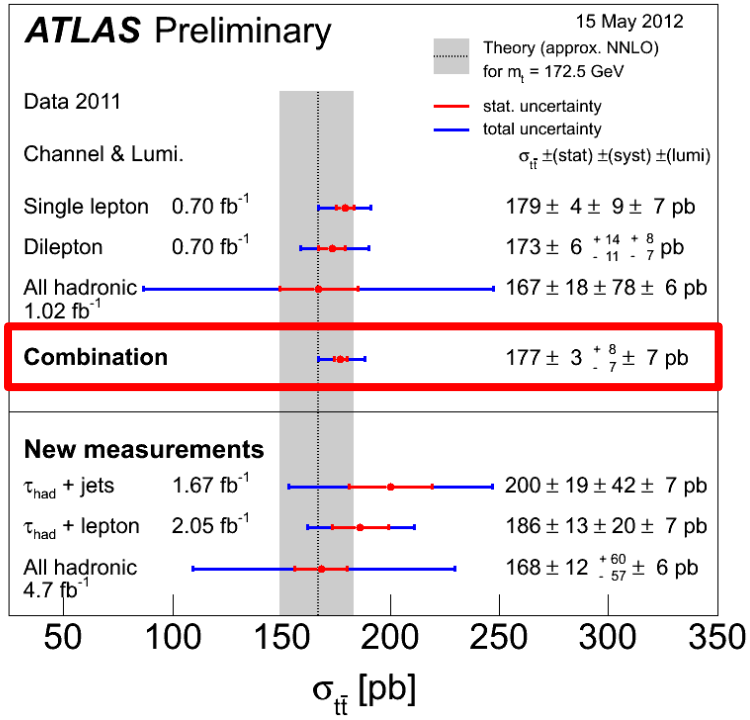
- Event selection based on
  - ATLAS: ≥5 jets, τ cand. from untagged jets
  - CMS: ≥4 jets (w/o τ cand.) + 1 well-id. τ
- Signal extraction
  - ATLAS: fit to ch. track multiplicity of τ cand. (τ 1 or 3 tracks, QCD jets typically more)
  - CMS: fit to NN discriminant built of 7 topol. var. (e.g. MET, ΔΦ(τ, MET), kin. fit χ^2)

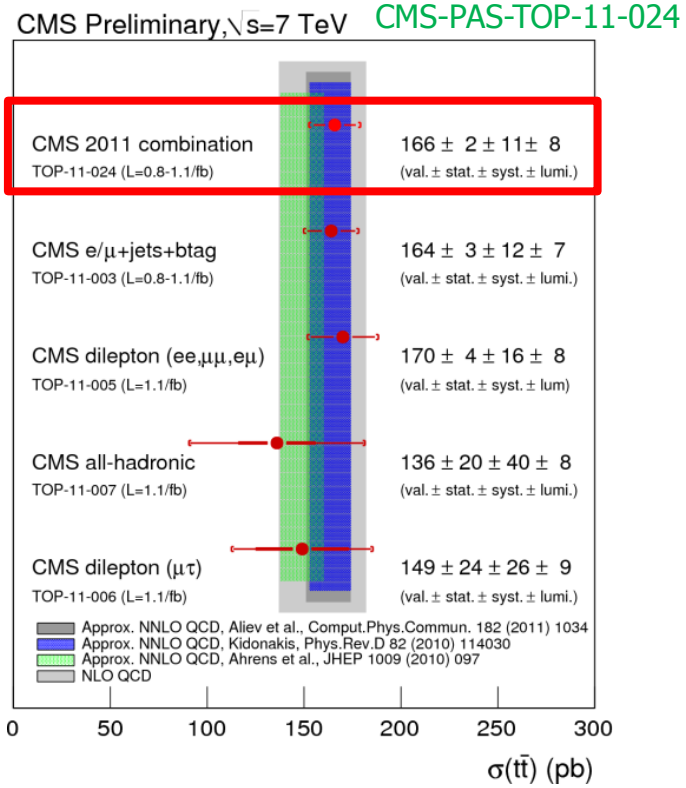


ATLAS 200 ± 19 (stat) ± 43 (sys) pb (1.67 fb^{-1})
ATLAS-CONF-2012-032 24% unc. (ISR/FSR, b-tag)

CMS NEW 156 ± 12 (stat) ± 33 (sys) ± 3 (lum) pb (3.9 fb^{-1})
CMS-PAS-TOP-11-004 23% unc. (JES, τ ID, stat.)

Inclusive Cross Section Combination





- All final states and decay channels covered (except ττ)
  - Good consistency between channels and experiments
- Combination: 6-8% precision → challenges theory predictions
  - level of approximate NNLO calculation, NLO outperformed
  - consistent with predictions
- Many new results in the last weeks or about to come
  → new combinations coming soon (even more precise)

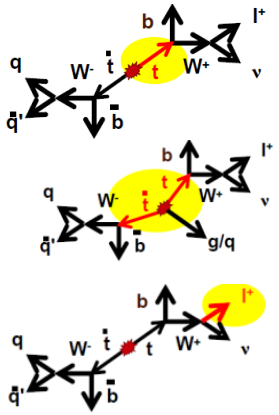
Differential Cross Sections

Differential Cross Sections

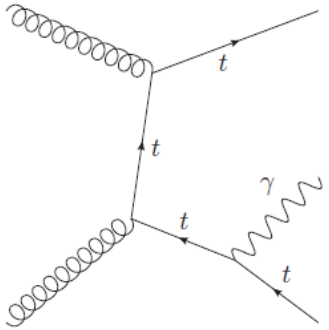
- Differential as a function of kinematical quantities X of

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

  - Top quark — $p_T(t/\bar{t})$, $y(t/\bar{t})$
  - Top quark pair system $t\bar{t}$ — $p_T(t\bar{t})$, $y(t\bar{t})$, $m(t\bar{t})$
  - Top decay products — $p_T(\ell)$, $\eta(\ell)$, $p_T(\ell\,\ell)$, $m(\ell\,\ell)$



- Top Environment: $t\bar{t}$ + other objects
  - $t\bar{t}$ + (no) jets
  - $t\bar{t}$ + photons



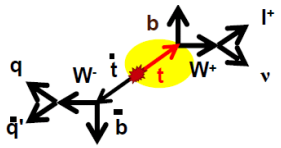
Differential – Top Kinematics

CMS-PAS-TOP-11-013

- Test pQCD, sensitive to BSM and PDF
- Dilepton and ℓ +jets selection
- Event reconstruction (MWT or kin. fit)
- Cross sections

$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

  - Normalised with $\sigma_{t\bar{t}}$
    $\rightarrow$ correlated syst. unc. cancel
  - Visible phase space
  - corrected for detector and hadronisation effects
    $\rightarrow$ parton level



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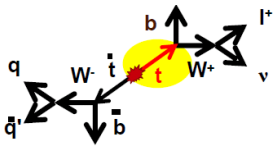
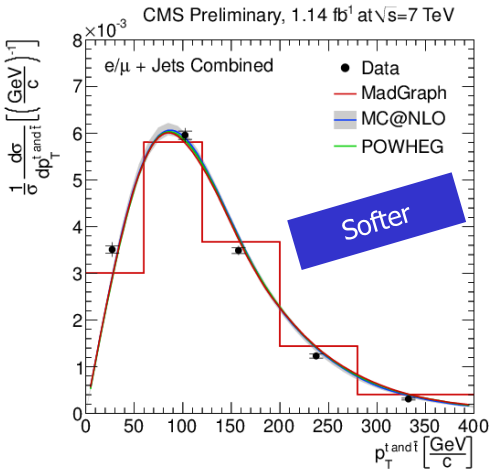
$$\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dX}$$

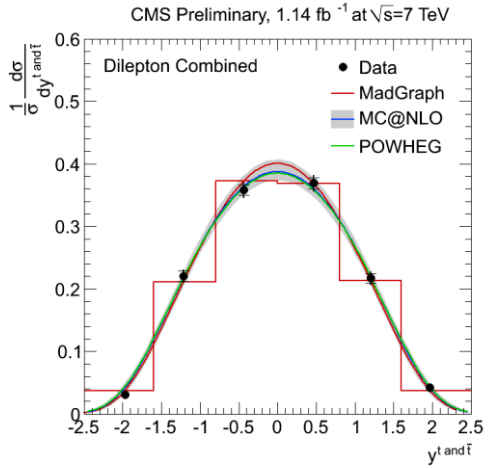


Top p_T, y



Results:

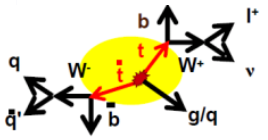
- Comparison to different predictions
  - MadGraph } LO + multileg (MLM)
  - MC@NLO } NLO
  - POWHEG
- Good agreement between
  1) Data and predictions
  2) Different channels
  3) Different model predictions

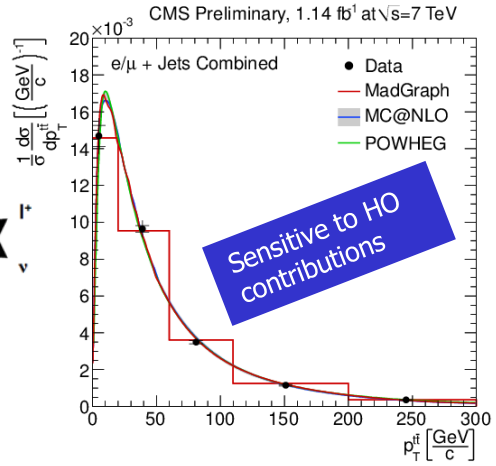


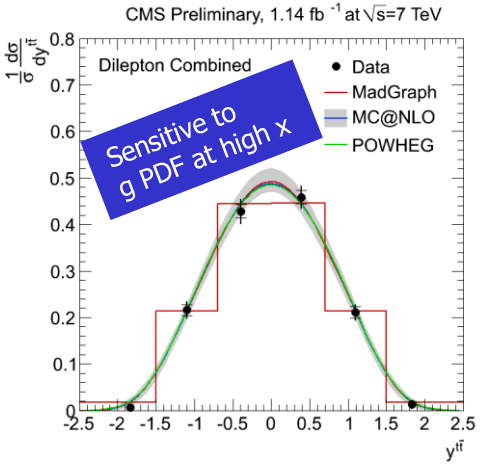
Differential – Top Kinematics

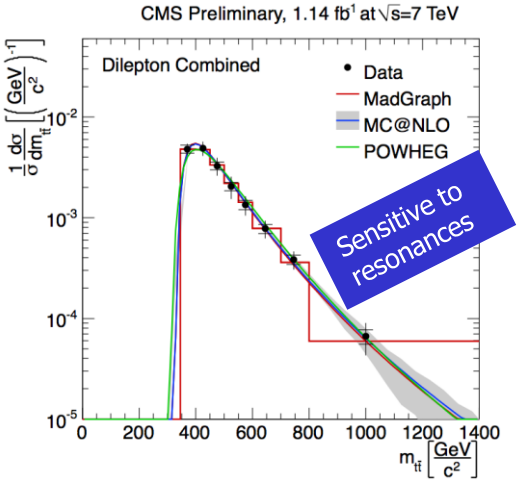
CMS-PAS-TOP-11-013

Top Pair p_T, y, m($t\bar{t}$)

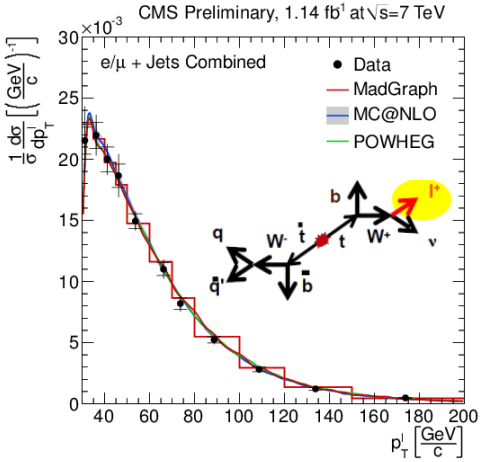


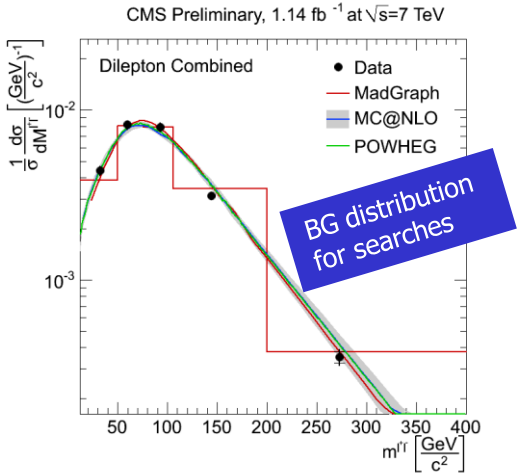






Lepton p_T, m($\ell\ell$)





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$t\bar{t}$ + Jets

- Test of pQCD, potential of constraining ISR/FSR

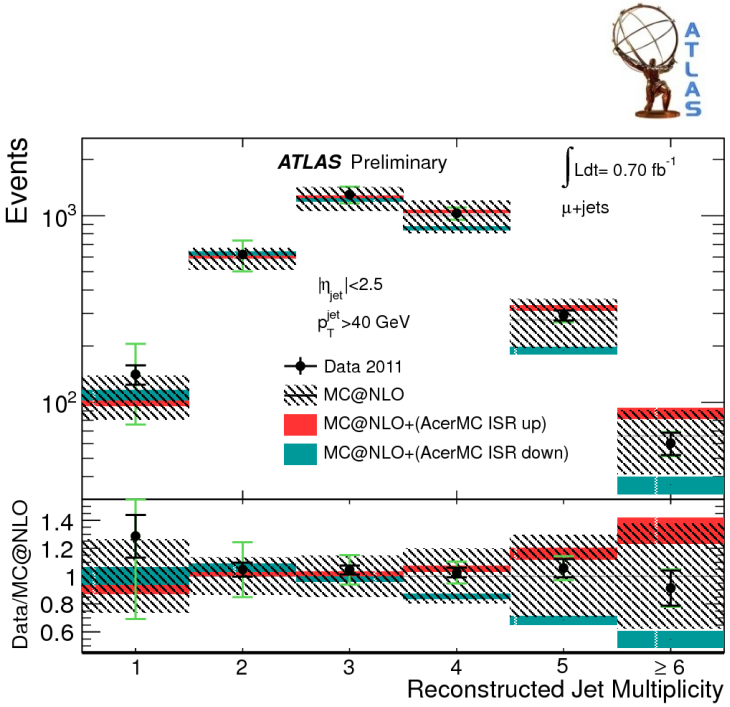
- Different ways to measure jet activity in $t\bar{t}$ events:

1. $p_T(t\bar{t})$ = p_T(additional jets) See previous slides

2. Jet multiplicity ATLAS-CONF-2011-142

   Results at reconstruction level after BG subtraction:
   - Consistent with MC@NLO
   - No distinction between different ISR tunes possible at current precision

3. Veto additional jets See next slides



$t\bar{t}$ + (no) Jets

NEW

arXiv:1203.5015

Jet veto to quantify jet activity

$$f(Q_0) = \frac{\sigma(Q_0)}{\sigma}$$

$\sigma(Q_0)$: $\sigma_{t\bar{t}}$ with no jet

σ: total $\sigma_{t\bar{t}}$

$f(Q_0)$ = „gap" fraction of evts. with NO jet above $p_T = Q_0$
= 1 - fraction of evts. WITH a jet

- Many systematics cancel in ratio
- Dilepton channel
- Corrected for detector effects → hadron level

$t\bar{t}$ + (no) Jets

NEW

arXiv:1203.5015

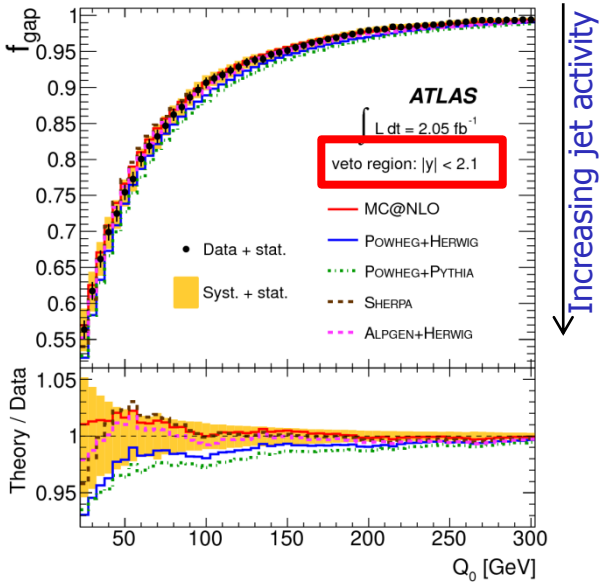
$$f(Q_0) = \frac{\sigma(Q_0)}{\sigma}$$

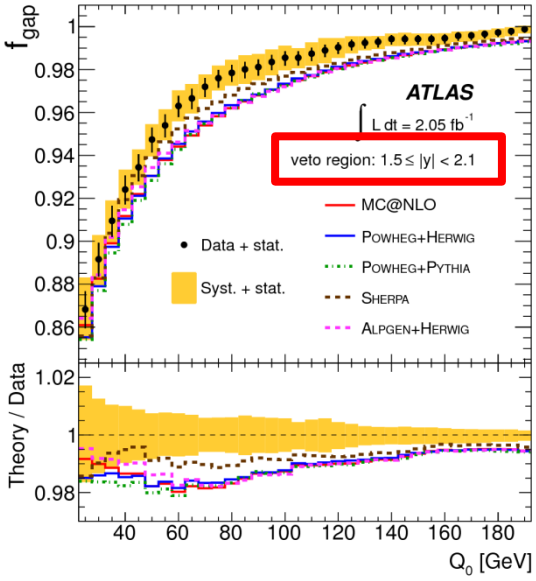
$\sigma(Q_0)$ ← $\sigma_{t\bar{t}}$ with no jet

σ ← total $\sigma_{t\bar{t}}$

Results:

- Compared to different NLO and LO+multileg generators
- For different central rapidity regions up to y=2.1
- Full y region: agreement; precision ≈ spread of models
- Slight discrepancies in y sub-regions





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- Compared to different NLO and LO+multileg generators
- For different central rapidity regions up to y=2.1
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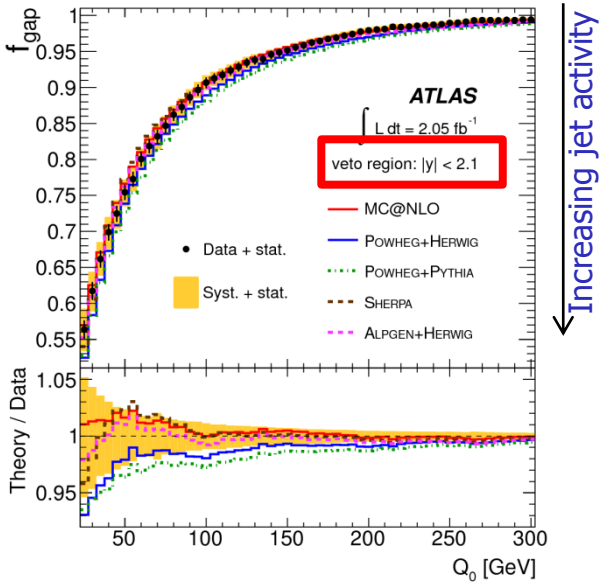
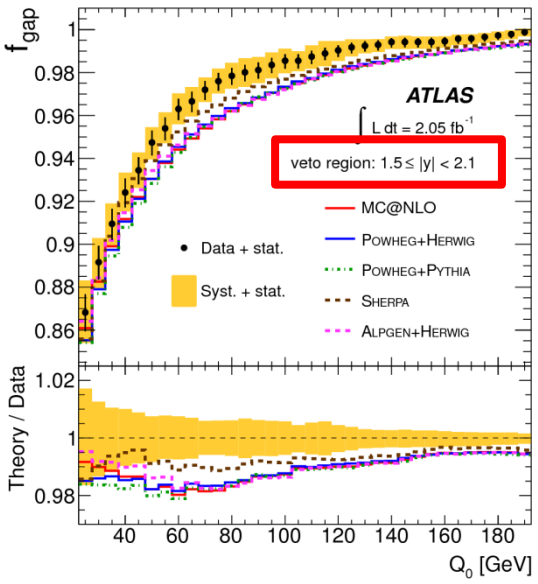
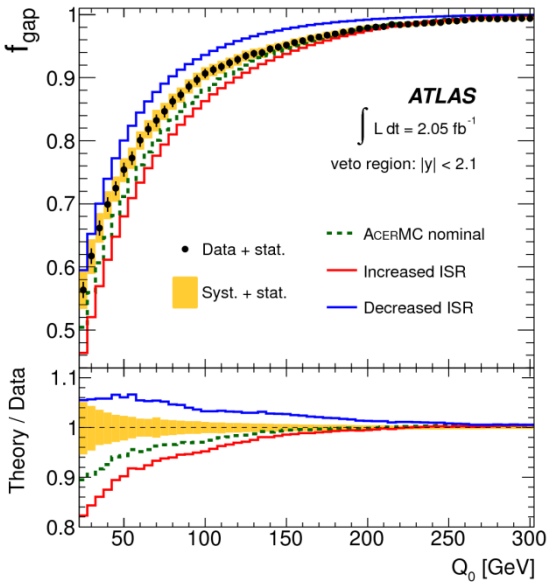
- Compared to AcerMC with different ISR tunes
  → precision can constrain ISR models!







$t\bar{t} + \gamma$

ATLAS-CONF-2011-153

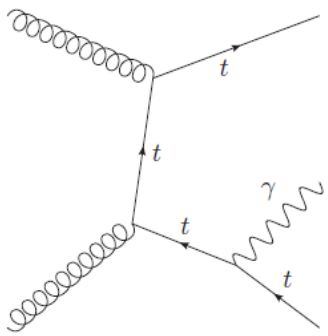
- Probing QED coupling of top quark
- Result:

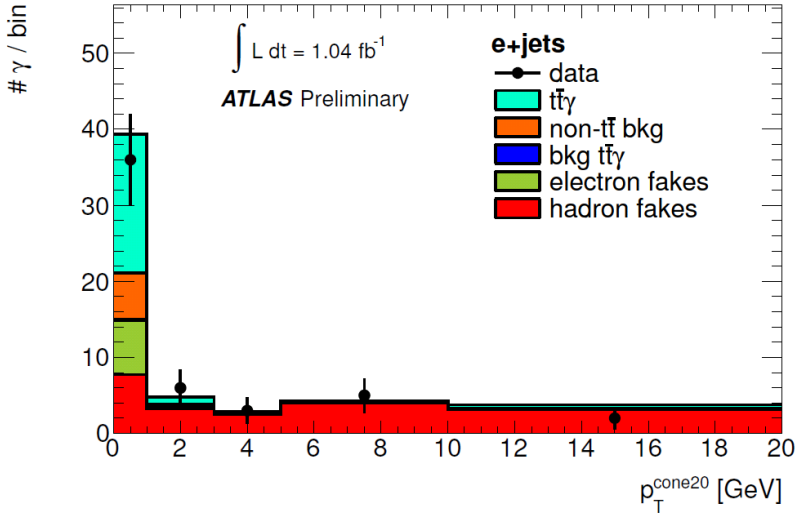
$$\sigma_{t\bar{t}\gamma} \times \mathrm{Br} = 2.0 \pm 0.5\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.}) \pm 0.08\,(\mathrm{lumi.})\ \mathrm{pb}$$

(extrapolated to $p_T(\gamma)$>8 GeV in dilepton and ℓ +jets channel)

→ 2.7σ (expected 3.0 ±0.9)

→ consistent with SM (2.1 ±0.4 pb)



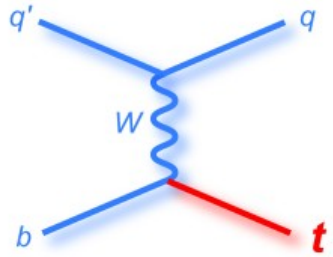


Single Top Cross Sections

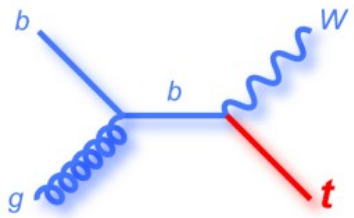
Single Top

- Electroweak charged current production of top quarks
- Directly sensitive to CKM matrix element: $\sigma_t \sim |V_{tb}|^2$

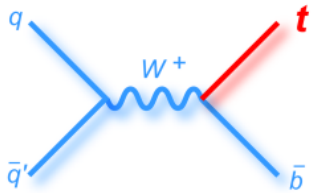
- NEW results (after Moriond)



t-channel
65 pb

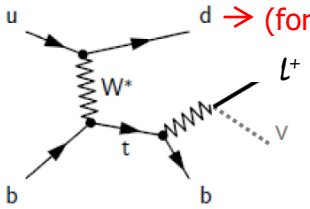


tW-channel
15.7 pb



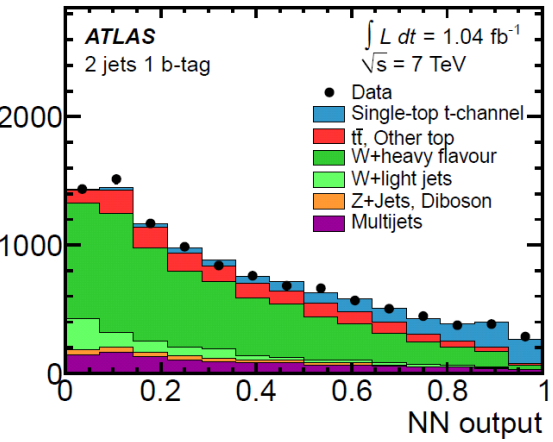
s-channel
4.6 pb [Kidonakis]

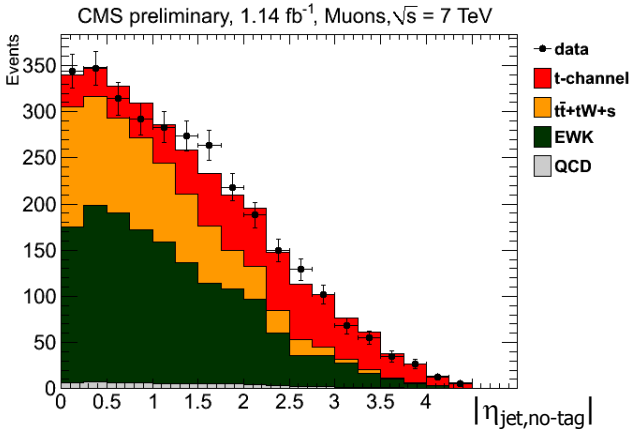
Single Top t-channel



→ (forward) light recoil jet (jet,no-tag)

- Event selection: lepton channel
  - 2 (or 3) jets $|\eta|<4.5$ (5), 1 b-tag+1 no-tag
  - CMS: $130 < m_{\ell\nu b} < 220$ GeV (reco. top mass)
- Signal extraction
  - QCD and W+jets BG from sidebands in data
  - ATLAS: fit to NN discriminant built of 12-18 topol. var. (e.g. $m_{\ell\nu b}$, $|\eta_{jet,no\text{-}tag}|$, $E_{T,\,jet,no\text{-}tag}$)
  - CMS: fit to $|\eta_{jet,no\text{-}tag}|$



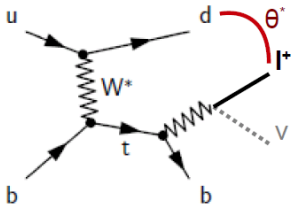


NEW

83 ± 4 (stat) +20/-19 (sys) pb (1.04 fb^{-1})
arXiv:1205.3130 24% unc. (ISR/FSR , b-tag)

70.2 ± 5.2 (stat) ± 10.4 (sys) ± 3.4 (lum) pb (1.1-1.5 fb^{-1})
CMS-PAS-TOP-11-021 17% unc. (JES, stat., BG)

Single Top t-channel



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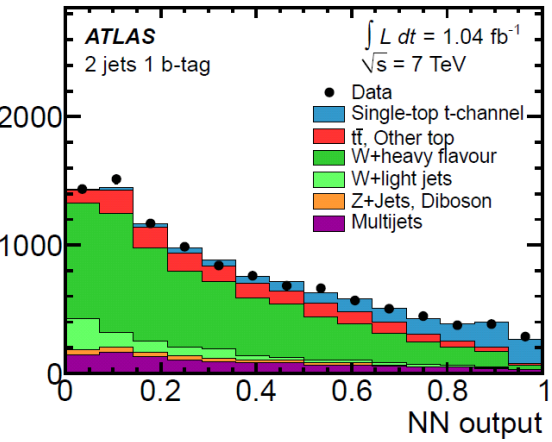

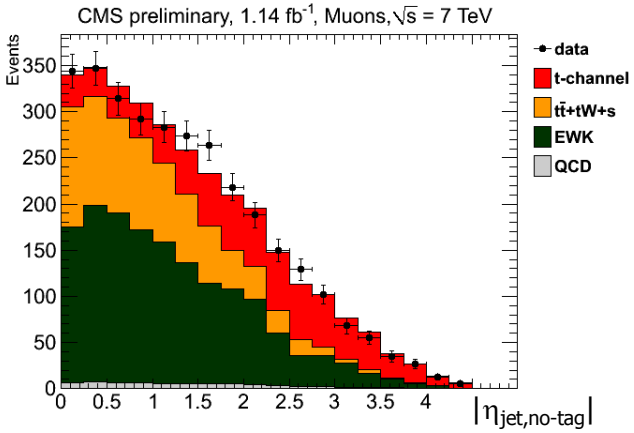

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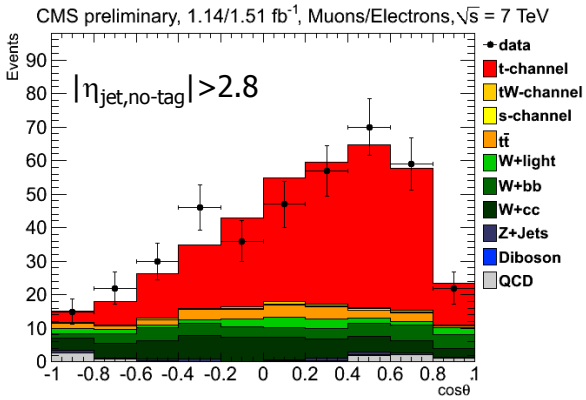
70.2 ± 5.2 (stat) ± 10.4 (sys) ± 3.4 (lum) pb (1.1-1.5 fb^{-1})
CMS-PAS-TOP-11-021 17% unc. (JES, stat., BG)

- Derived properties
  - cos θ* between ℓ and recoil jet in t rest frame
    → probes V-A nature of couplings



- CKM element from $|V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma^{th}_{t-ch.}}}$

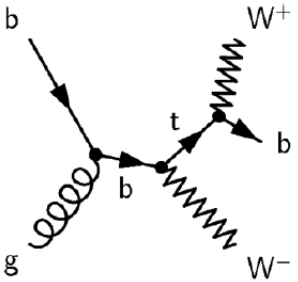
$|V_{tb}| = 1.13$ +0.14/-0.13

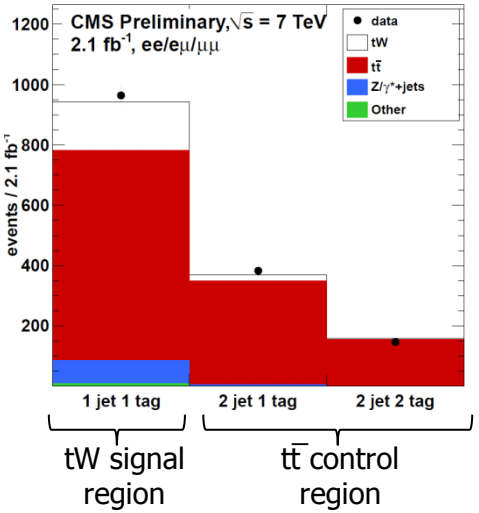
$|V_{tb}| = 1.04 \pm 0.09$

Single Top tW and s-channel

tW-channel

- Similar to $t\bar{t}$
  (one b less at LO, some NLO diagrams identical)
- Dilepton event selection
  - tW signal region: 1jet
  - $t\bar{t}$ control region: 2 jets
    → $t\bar{t}$ BG constrained from control region in data

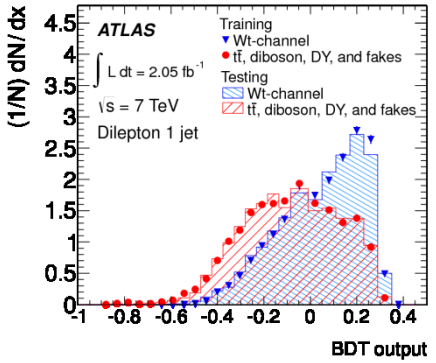




NEW

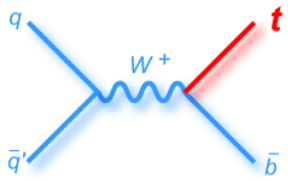
16.8 ± 2.9 (stat) ± 4.9 (sys) pb (2.05 fb^{-1})
arXiv:1205.5764 3.3σ (3.4 σ exp.)

22 +9/-7 (stat+sys) pb (2.1 fb^{-1})
CMS-PAS-TOP-11-022 2.7σ (1.8 ± 0.9 σ exp.)



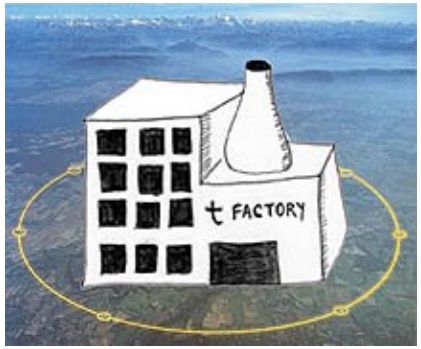
s-channel

- Very low cross section (2 pb)
- First limit: < 26.5 pb (20.5 expected), 95% CL (0.7 fb^{-1})
  ATLAS-CONF-2011-118



Conclusions

- Top factory LHC is running and producing wealth of results

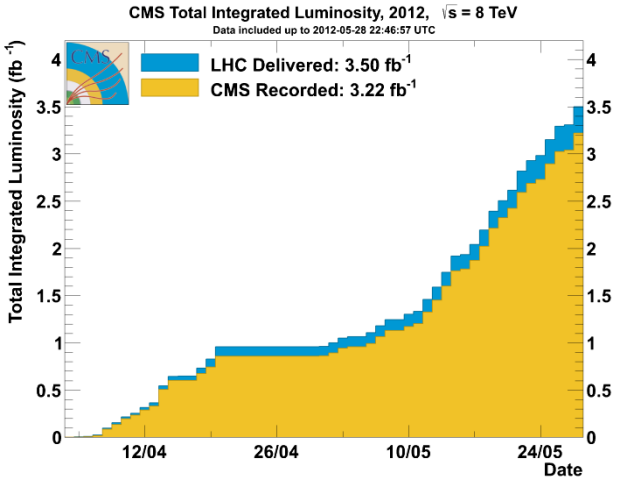


- Era of top physics
  - → precision inclusive cross sections (~6%)
  - → complete picture of all final states
  - → differential measurements

  } exploit all information

  - → challenges theory
  - → so far good agreement with SM

- Outlook
  - 2011 7 TeV data analysis continues → more results to come
  - 2012 8 TeV run
    → even higher cross section (x 1.5) and S/B
    → more lumi. → more differential/environmental measurements



- More information

ATLAS: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
CMS: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP