Review of Top Quark Production at LHC and Tevatron

HQL 2016

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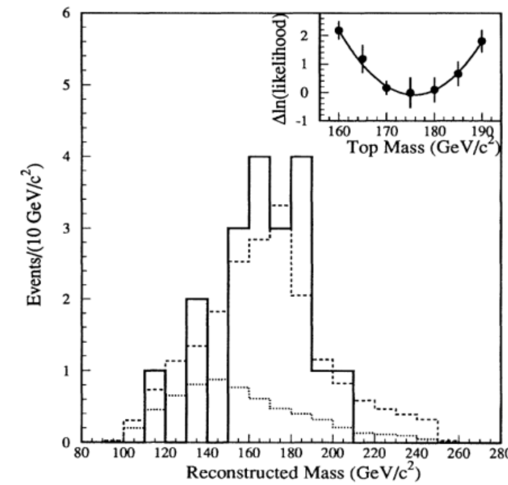
NAGOYA UNIVERSITY

PRL **74** 2626-2631(1995)



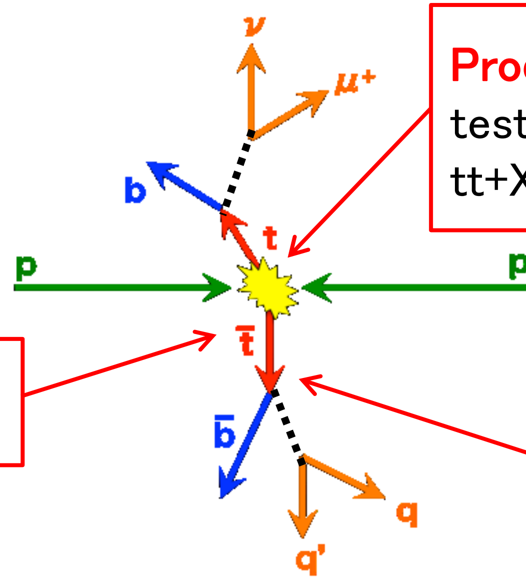
The Top Quark

- Heaviest particle in SM
  $m_{top} \sim$ 173 GeV
- Discovered in 1995 by CDF and D0 at Tevatron
- Strong coupling to Higgs boson
  $Y_t \sim 1$
- Decay within 10^{-25} s before hadronization as "bare−quark"

Play special role in electroweak symmetry breaking

Various interests!

Production
test QCD, test EW, BSM, A_C, tt+X



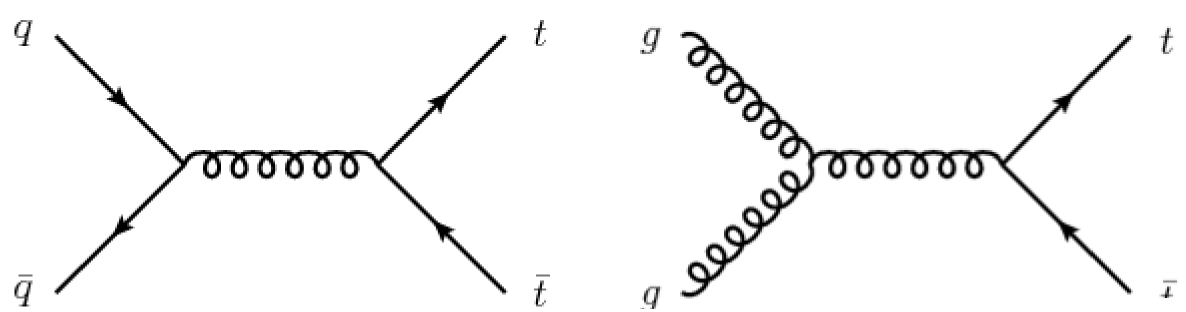
Properties
Mass, Width, Spin, Charge

Decay
test EW, Wtb

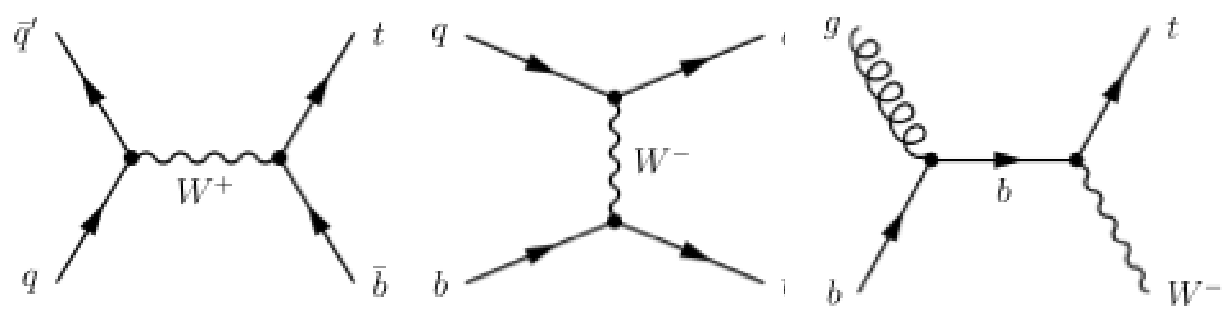
Top quark production

- At Tevatron; 85% of $t\bar{t}$ pairs are produced via quark annihilation
  - **70000 $t\bar{t}$ pairs** produced at Tevatron
- At LHC; 90% of $t\bar{t}$ pairs are produced via gluon fusion
  - **6M $t\bar{t}$ pairs and 3M $t\bar{t}$ pairs** produced in Run1 and Run2

Pair production via QCD

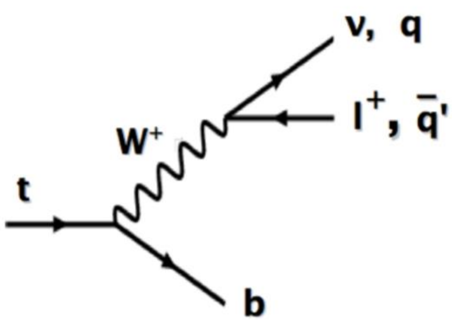


EW single top production

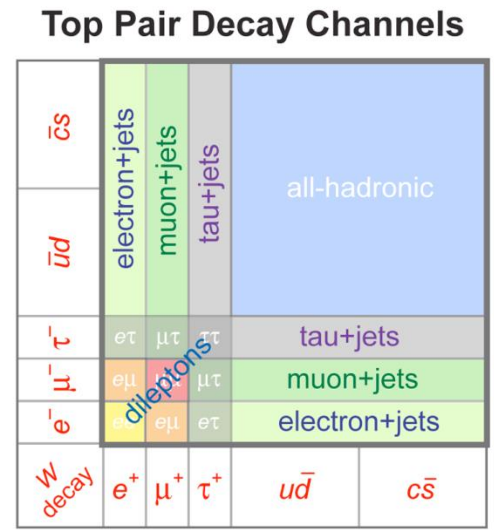


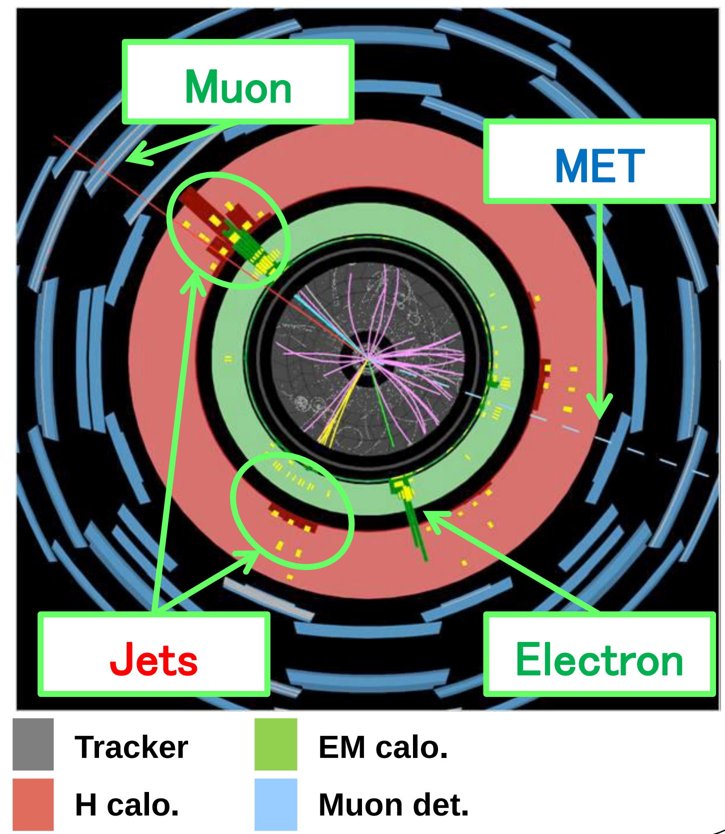
Top Quark Signature

- Top quark decays to W + b (~100%)



- The event signature is characterized by
  - High p_T lepton
  - Jets
  - b-jets
  - Large missing ET





Top quark pair cross-section $\sigma_{t\bar{t}}$

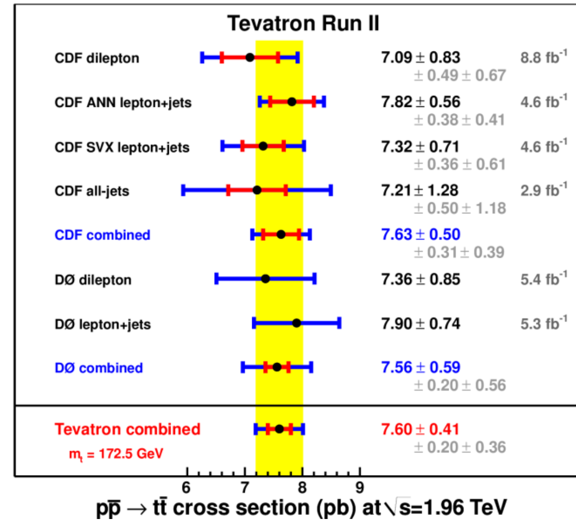
- Good test of pQCD theory
- Unique sensitivity to new physics

√s=1.96TeV

Total cross-section $\sigma_{t\bar{t}}$ at Tevatron

- Tevatron combination:
  - $\sigma_{t\bar{t}} = 7.60 \pm 0.41$ pb

PRD **89**, 072001 (2014)

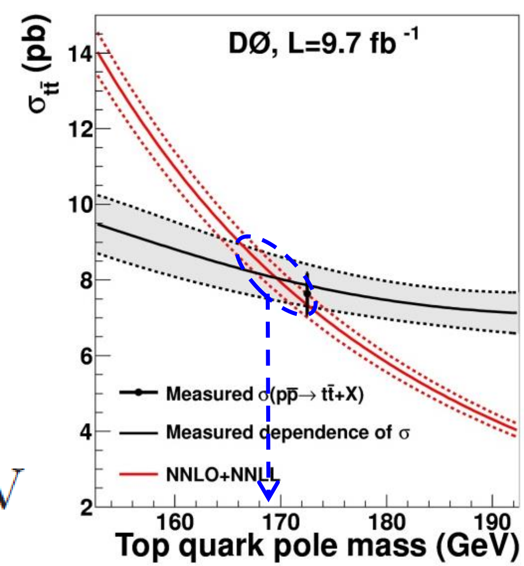


- Recent D0 measurement

D0 Note 6453-CONF (2015)

  - Combine various channels
    - ℓ+jets & di-lepton
  - BDT base analysis

$$\sigma_{t\bar{t}} = 7.73 \pm 0.13\,(\text{stat.}) \pm 0.55\,(\text{syst.})\ \text{pb}$$

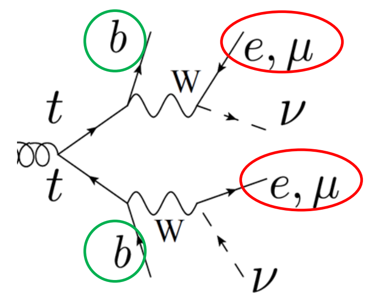


$$m_t = 169.5^{+3.3}_{-3.4}\,(\text{tot.})\ \text{GeV}$$

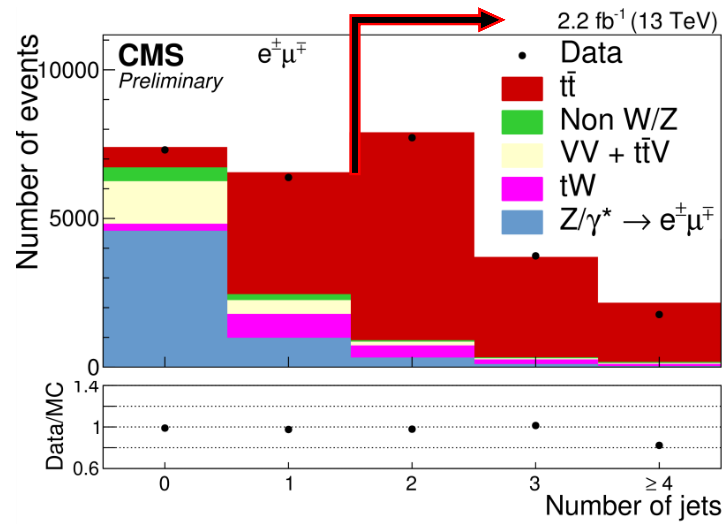
√s=13 TeV

43 pb^{-1}; CMS (PRL 116, 052002 (2016))
2.2 fb^{-1}; CMS-PAS-TOP-16-005

$\sigma_{t\bar{t}}$ in dilepton eμ ①



- Event selections
  - 2 opposite sign (OS) leptons, eμ
  - 2 or more jets (W/O b-tag)
  - $m_{e\mu}$ > 20 GeV (DY&HF veto)
- Use cut & count method
- Systematic
  - trigger/selection 2.6%
  - tt modeling 2.7%
  - luminosity 2.7%
  - JES 2.2
- $\sigma_{t\bar{t}}$ = 793 ± 8 ± 38 ± 21 pb
  (stat) (syst) (lumi)



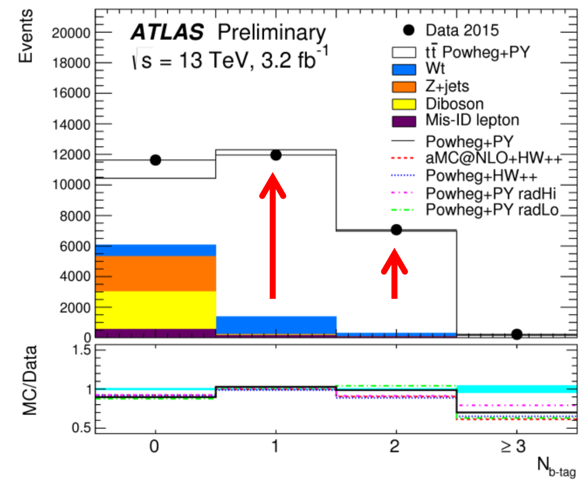
Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	24 ± 9 ± 4
Non-W/Z leptons	109 ± 50 ± 33
Single top quark	463 ± 6 ± 145
VV	15 ± 2 ± 5
$t\bar{t}$V	31 ± 1 ± 10
Total background	642 ± 52 ± 149
$t\bar{t}$ dilepton signal	10199 ± 14 ± 462
Data	10368

$$\sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}} = 832^{+20}_{-29}\,(\mathrm{scale})^{+35}_{-35}\,(\mathrm{PDF}/\alpha_s)\ \mathrm{pb}$$

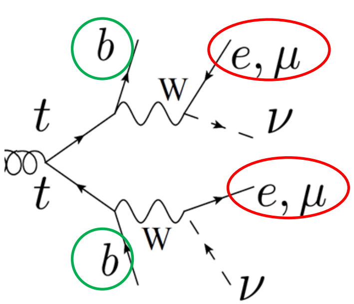
ATLAS (ATLAS-CONF-2016-005)

$\sigma_{t\bar{t}}$ in dilepton eμ ②

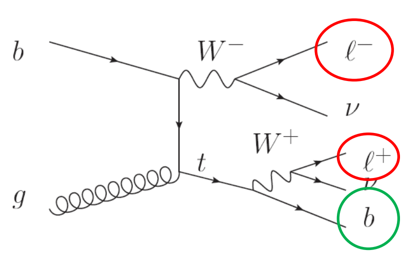
- Event selection
  - 2 OS leptons, **eμ**
  - 1 or 2 b-tagged jets
- Background
  - Wt single top ⇒ same final state
  - Fake lepton estimated in MC with data-driven correction



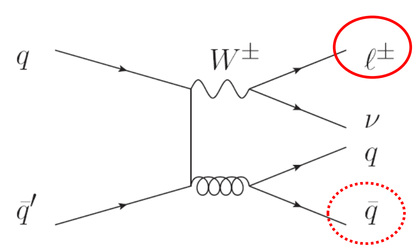
Signal



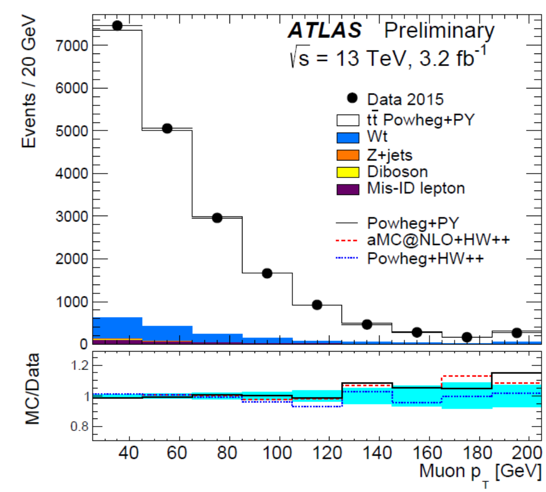
Backgrounds



Wt single top



W+jets (Fake)



√s=13 TeV

ATLAS (ATLAS-CONF-2016-005)

$\sigma_{t\bar{t}}$ in dilepton eμ ③

Event counts	N_1	N_2
Data	11958	7069
Single top	1160 ± 120	224 ± 70
Dibosons	34 ± 12	1 ± 0
$Z(\to \tau\tau \to e\mu)$+jets	37 ± 16	2 ± 1
Misidentified leptons	165 ± 65	116 ± 55
Total background	1390 ± 140	343 ± 89

- Extract $\sigma_{t\bar{t}}$ and ε_b by likelihood fitting
  ε_b; combined probability to select and tag a b-jet from the top decay

Probability to b-tag only one of two b-jets

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\boxed{2\epsilon_b(1 - C_b\epsilon_b)} + N_1^{\mathrm{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu}\boxed{C_b\epsilon_b^{\,2}} + N_2^{\mathrm{bkg}}$$

Probability to b-tag both b-jets

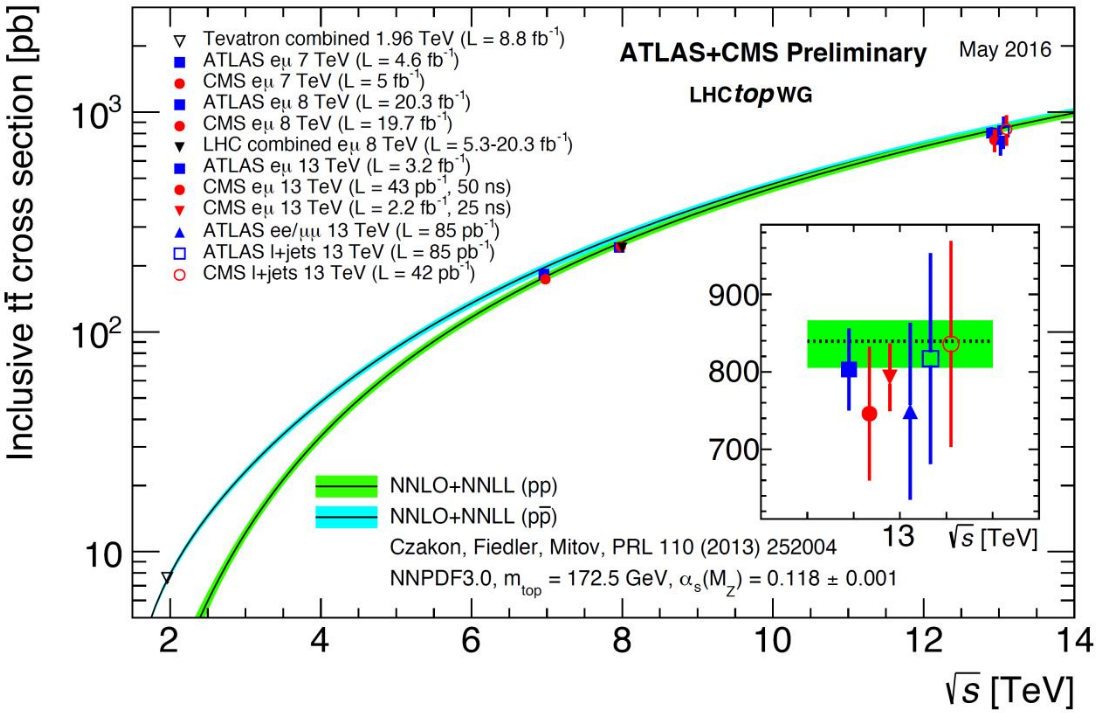
$\varepsilon_{e\mu}$(eμ selection eff.), C_b(tagging correlation), N^{bkg} from MC
N_1,N_2 from measurement
σ_{tt} and ε_b are free

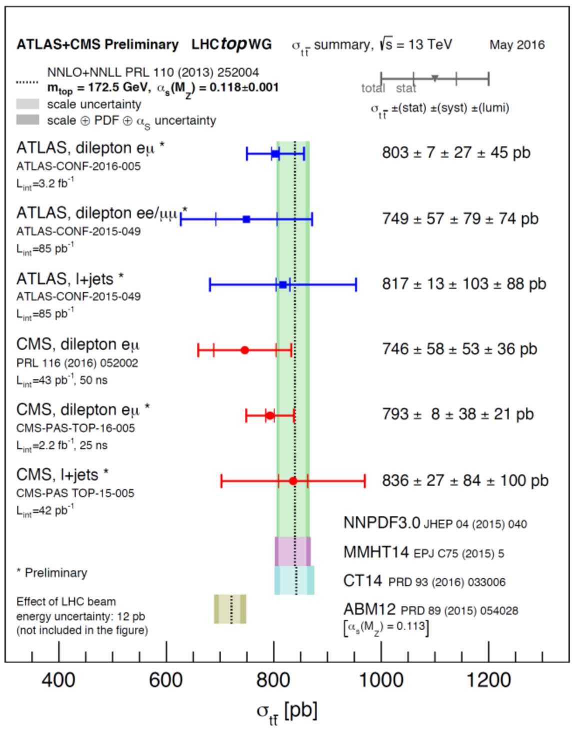
- Advantage; suppress some systematic (ex: b-tag efficiency)
- σ_{tt} = 803±7 (stat)±27 (syst)±45 (lumi) ±12(beam) pb

$$\sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}} = 832^{+20}_{-29}\,(\mathrm{scale})^{+35}_{-35}\,(\mathrm{PDF}/\alpha_s)\ \mathrm{pb}$$

√s=13 TeV

Summary of $\sigma_{t\bar{t}}$ @ LHC13TeV



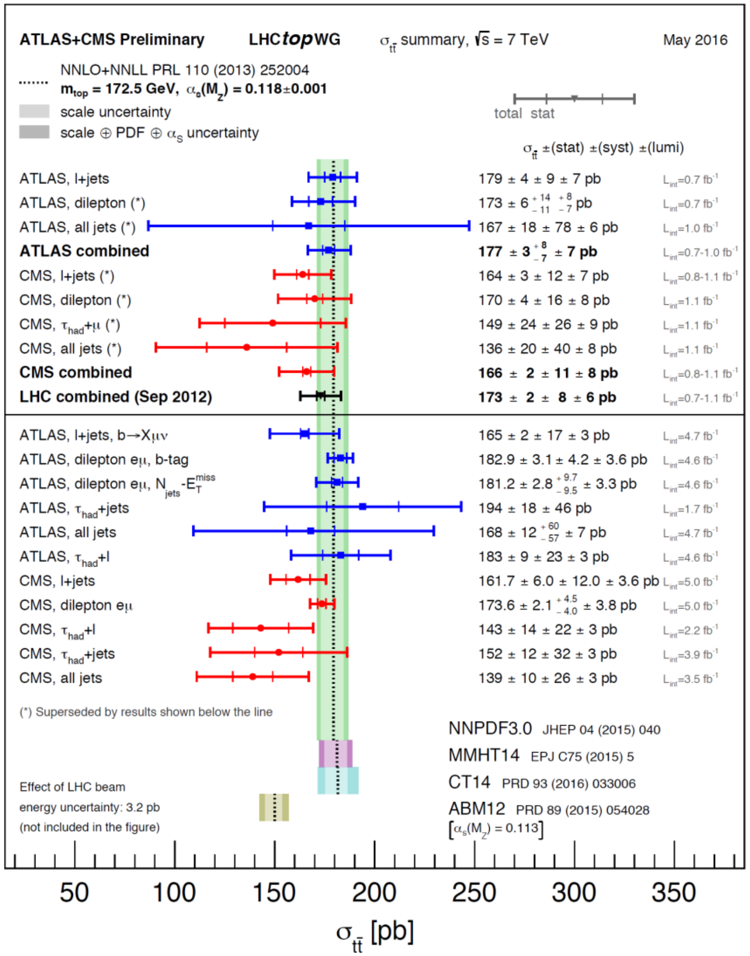


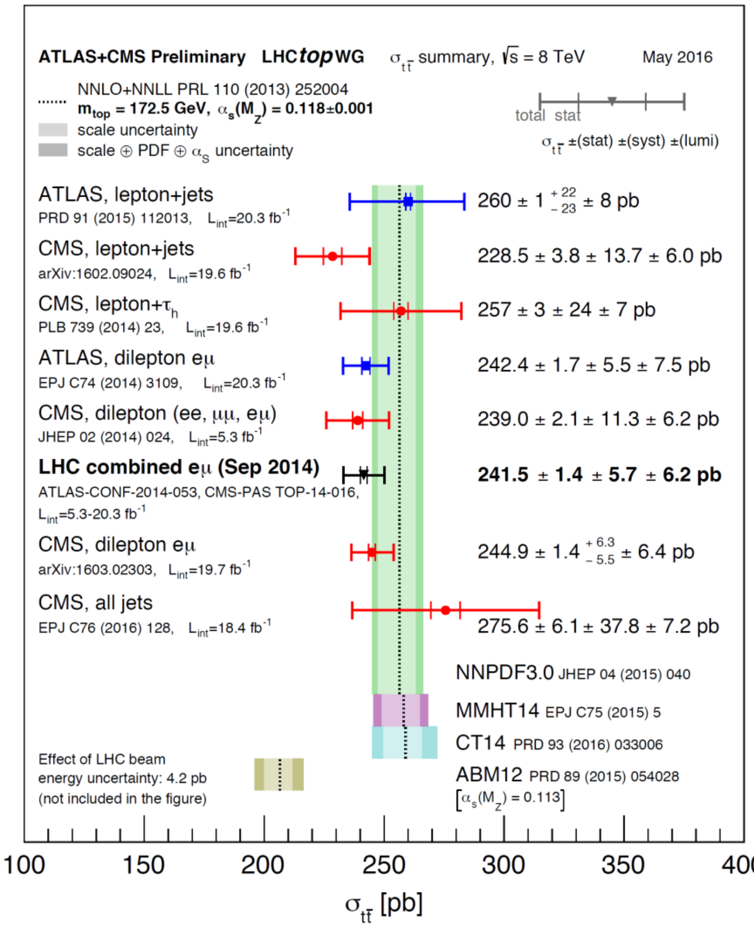
Good agreement with theoretical prediction!

- Precision beyond theoretical prediction
  ⇒ Differential cross-section

$\sqrt{s}$=7,8 TeV

Latest summary of $\sigma_{t\bar{t}}$ at $\sqrt{s}$ = 7 and 8 TeV





Consistent to theoretical prediction!

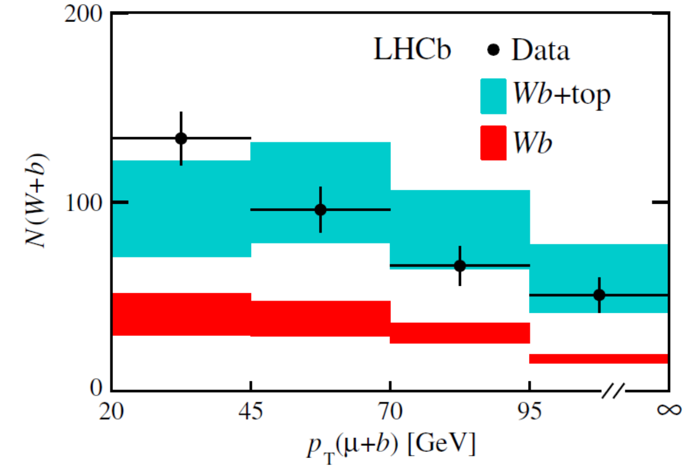
$\sqrt{s}$=7,8 TeV

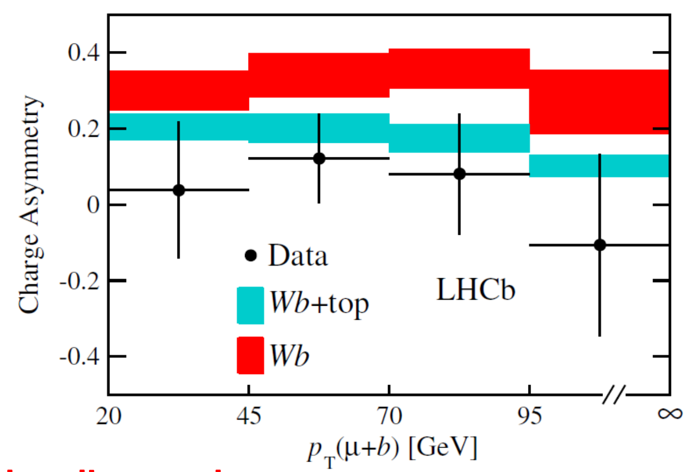
PRL **115**, 112001 (2015)

First observation of top quark production in the forward region

- Top quark production in the forward region
  - Enhance of $t\bar{t}$ via $q\bar{q}$
  - gluon PDF at high momentum
  - $t\bar{t}$ production ~ **75%**
    single top; ~ **25%**

    Inclusive measurement
- Event selection
  - Muon; p_T > 25 GeV, $2.0 < \eta < 4.5$
  - b-jet (anti-k_T, R=0.5)
    p_T = 50 ~ 100 GeV, $2.2 < \eta < 4.2$
  - Isolation; $\Delta R(\mu, j) > 0.5$
  - $p_T(\mu + j) > 20$ GeV





$$\sigma(\text{top})[7\ \text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\ \text{fb},$$

$$\sigma(\text{top})[8\ \text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\ \text{fb}.$$

in agreement with next-to-leading order standard model predictions!

ATLAS-CONF-2015-049

$\sigma_{t\bar{t}}$ / σ_Z measurement

- Measure the ratio $\sigma_{t\bar{t}} / \sigma_{Z\to\ell\ell}$

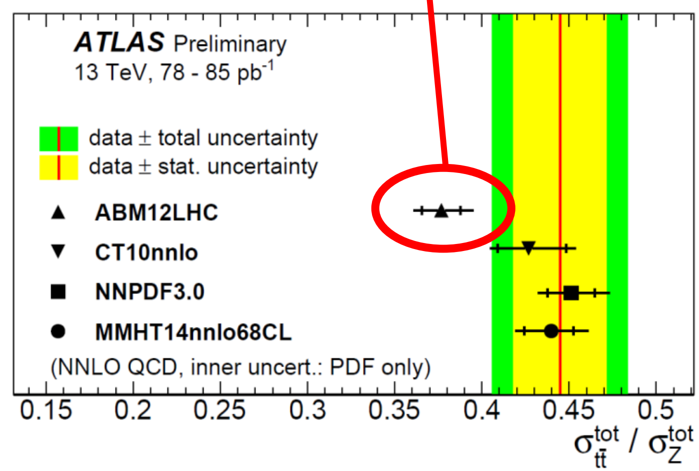
σ_{tt}; eμ final state
σ_Z; 66 GeV $< m_{\ell\ell} <$ 116 GeV

$$R_{t\bar{t}/Z} = \frac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$$

- Sensitive to gluon and sea quark PDF
- Advantage; cancelation of some syst.
  - Integrated luminosity
  - Lepton reconstruction efficiency

$$R_{t\bar{t}/Z} = 0.445 \pm 0.027\ (\text{stat}) \pm 0.028\ (\text{syst})$$

Small tension with ABM12LHC (smaller gg density)



Differential xsec $d\sigma_{t\bar{t}}/dX$

- Differential distribution as a function of top quark kinematics provide more precise SM test
  - ✓ top-pair p_T ⇒ sensitive to I/FSR
  - ✓ top-pair y ⇒ sensitive to PDF
  - ✓ top-pair mass ⇒ sensitive to new physics (large Q^2)
  - ✓ $t\bar{t}$ + jets ⇒ test higher order QCD effect, matching to matrix-element generator and shower model
- Check various distributions thoroughly!

√s=1.96TeV

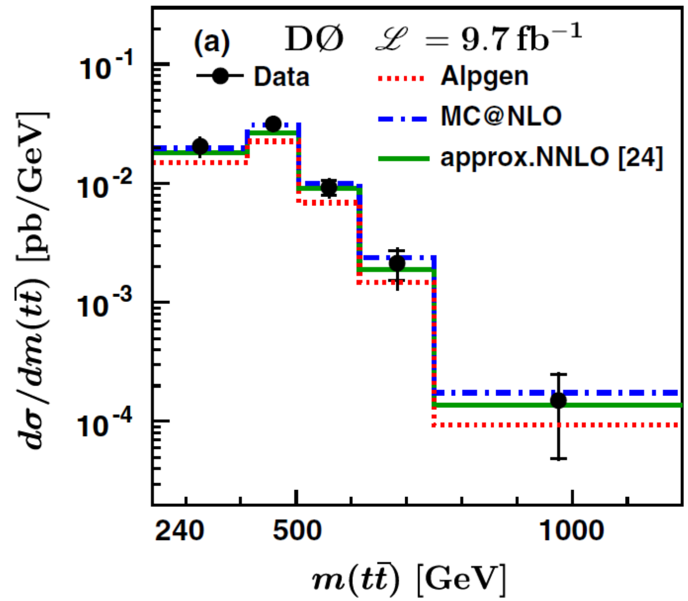
$d\sigma_{t\bar{t}}/dX$ in Tevatron

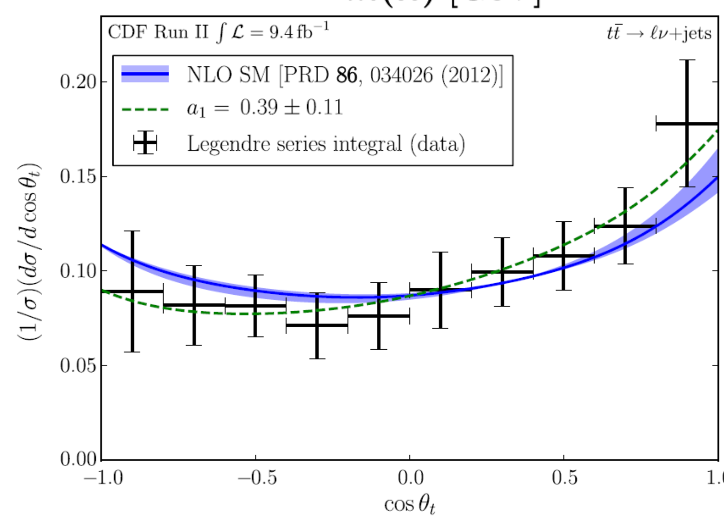
- As a function of m(tt)

  D0, PRD **90**, 092006 (2014)

- As a function of $\cos\theta_t$

  CDF, PRL **111**,182002 (2013)





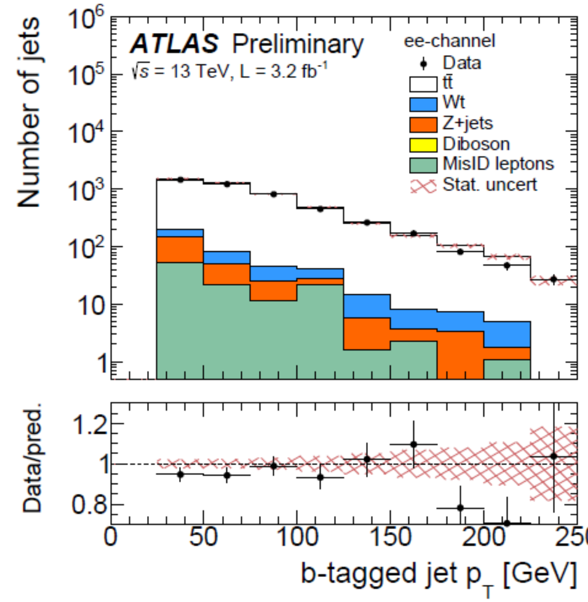
- No evidence for new physics
- Deviations in $\cos\theta_t$
  ⇒ possible source of the forward–backward asymmetry

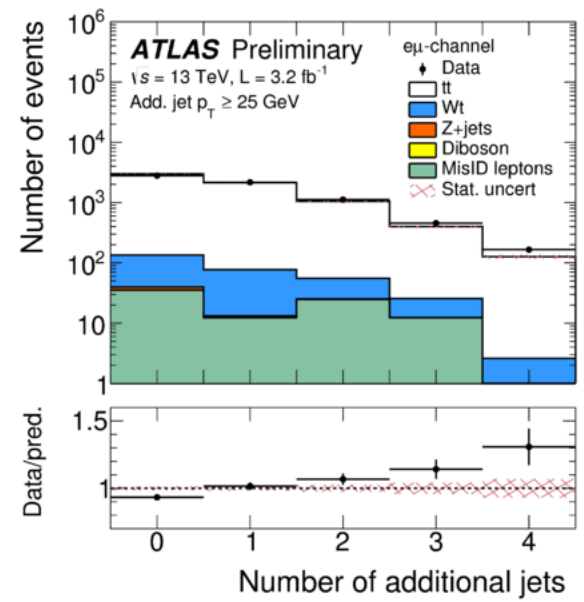
√s=13 TeV

ATLAS-CONF-2015-065

$t\bar{t}$ + jets ①

- Event selections
  - Two OS leptons (ee, eμ, μμ)
  - DY veto ; $M_{\ell\ell} > 40$ GeV
  - Z veto ; 81 GeV $< M_{\ell\ell} <$ 101 GeV
  - At least two b-jets
  - Categorize by additional jet p_T (25GeV, 40GeV, 60GeV, 80GeV)
- Backgrounds
  - $Z \rightarrow \ell\ell$ + b-jets
  - Fake lepton
  - Wt and others
- Unfold to particle level "fiducial space"
  - Correct detector resolution
  - Advantage to large extrapolation to parton level



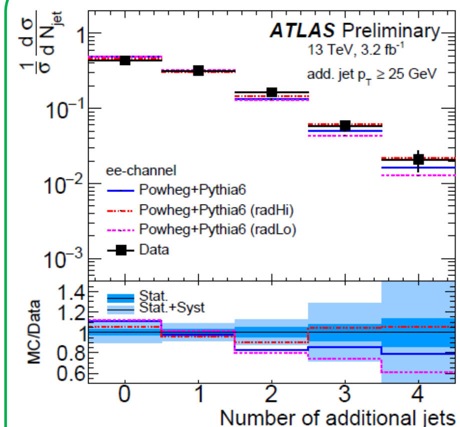


(ATLAS-CONF-2015-065)

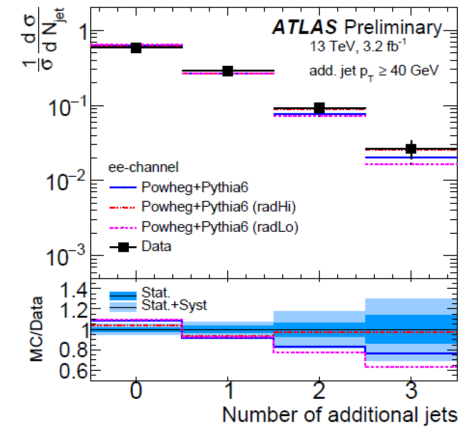
$t\bar{t}$ + jets ②

- Comparison with different radiation scale and model
- Powheg+Pythia6 predicts slightly less jets than observed, but trend is within the current uncertainties

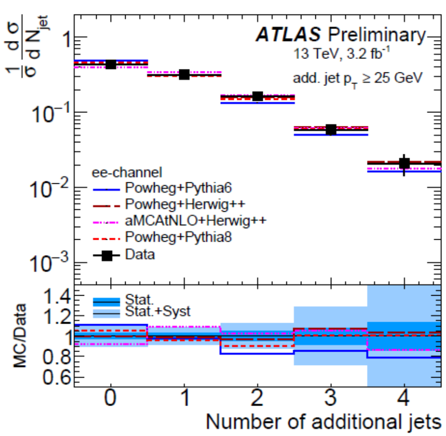
different radiation scale



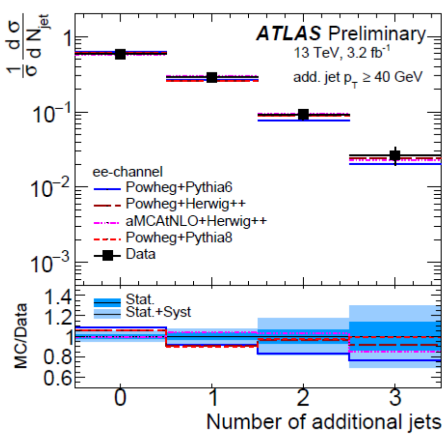
p_T > 25GeV



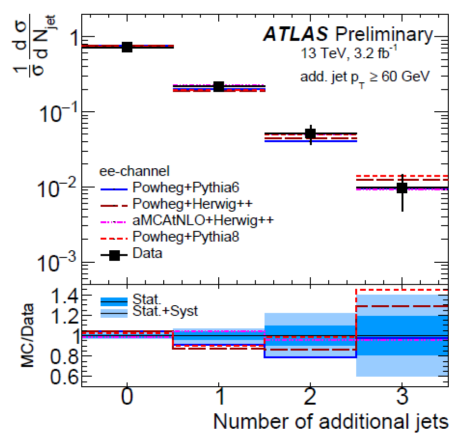
p_T > 40GeV



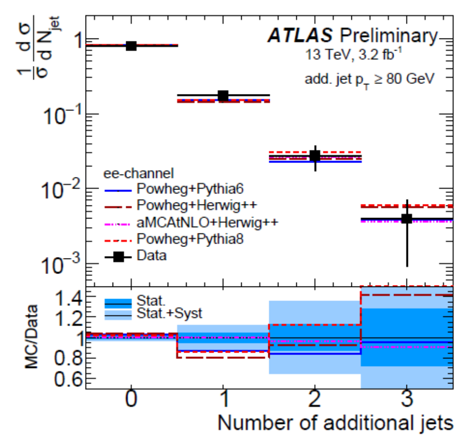
p_T > 25GeV



p_T > 40GeV



p_T > 60GeV

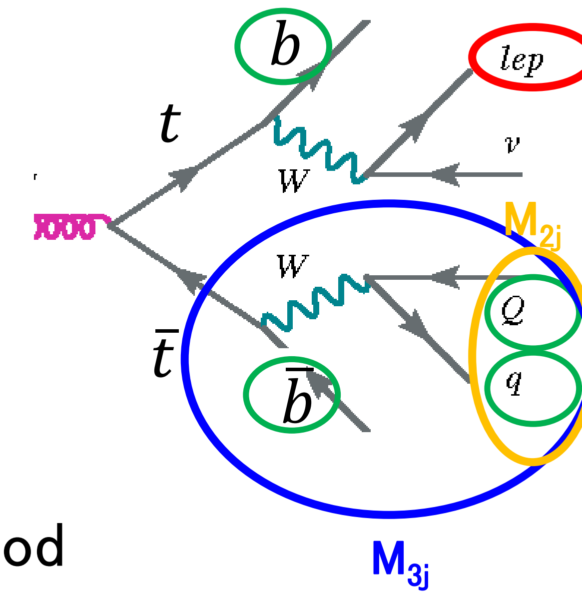


p_T > 80GeV

different model

CMS-PAS-TOP-16-008

$d\sigma_{t\bar{t}}/dX$ in lepton + jets ①



- Event selection
  - **1 lepton**, $p_T > 30$ GeV & $|\eta| < 2.1$
  - **4 or more jets**, $p_T > 25$ GeV & $|\eta| < 2.4$ at least 1 b-tagged
- Top quark reconstruction
  - Best jets permutation chosen from likelihood ← taking into account the **M_{3j}** and **M_{2j}**
  - Neutrino momentum by constrain m_t and m_W
- Backgrounds subtraction from MC
- Unfold to parton and particle level

√s=13 TeV

CMS–PAS–TOP–16–008

$d\sigma_{t\bar{t}}/dX$ in lepton + jets ②

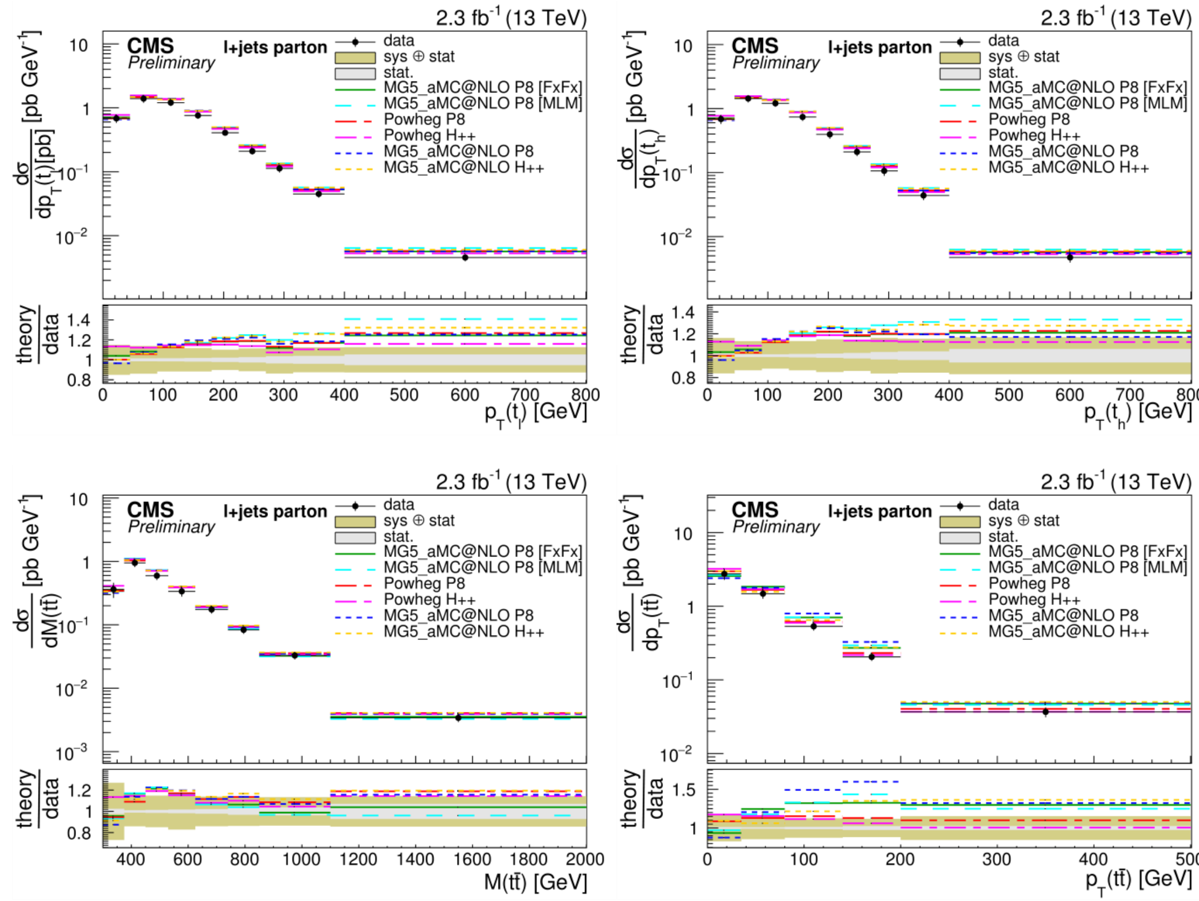
- Generally,
  MC models describe data well

- Slight model difference in top pair p_T distribution

  Powheg looks better?

→Still large error to conclude

Parton level



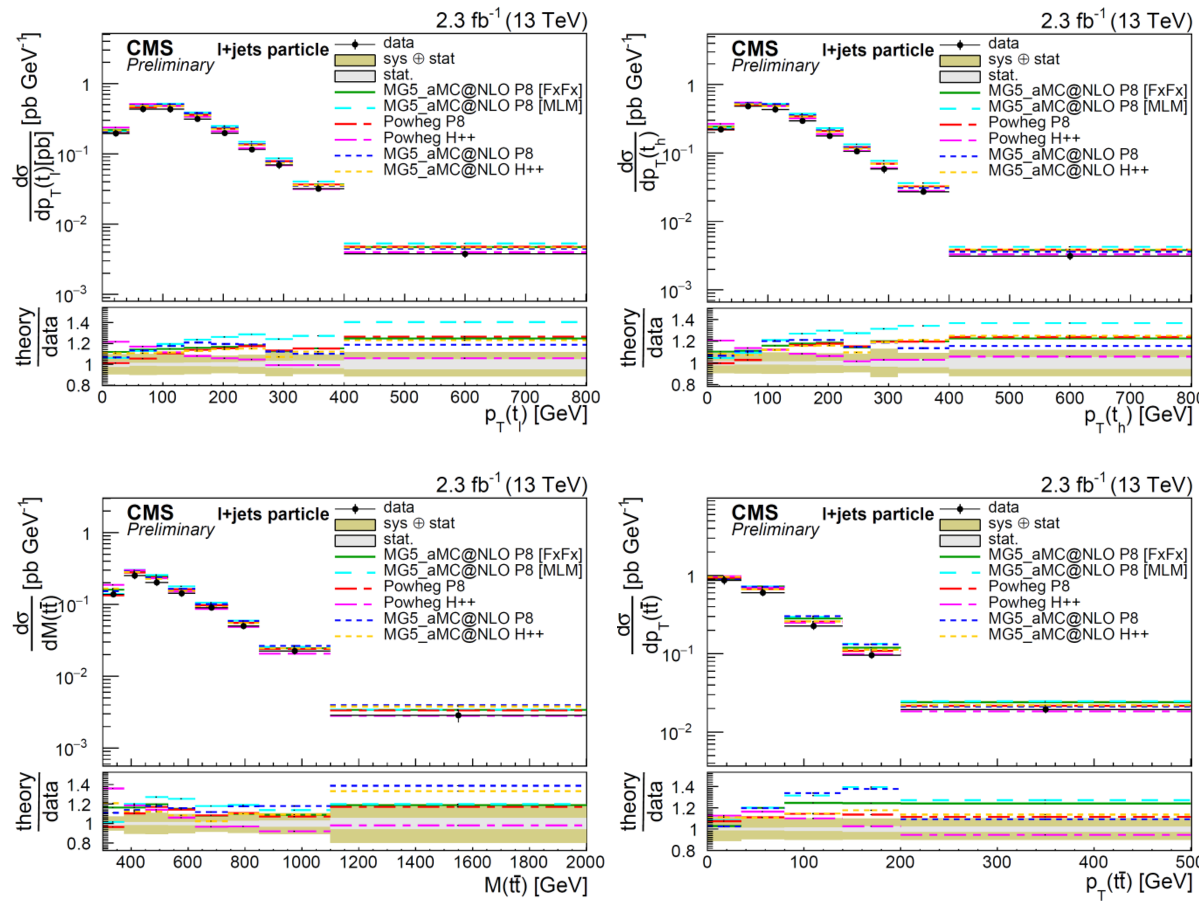
√s=13 TeV

CMS−PAS−TOP−16−008

$d\sigma_{t\bar{t}}/dX$ in lepton + jets ③

- Generally, MC models describe data well
- Slight model difference in top pair p_T distribution

Particle level

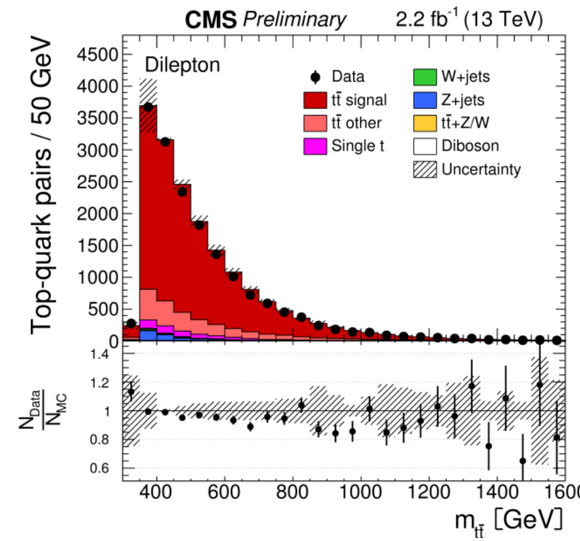


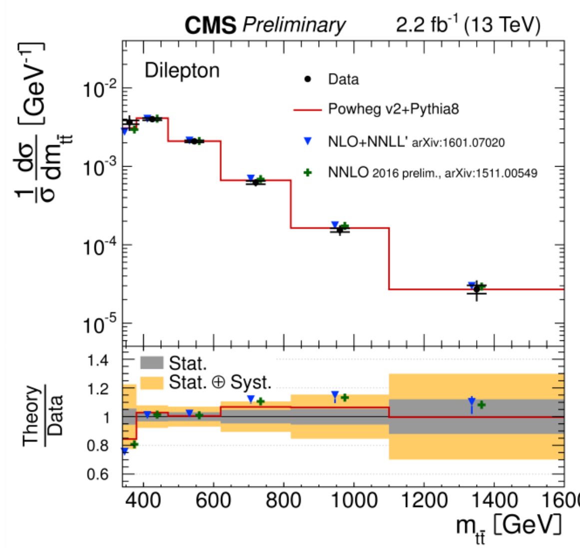
source	particle [%]	parton [%]
statistical uncertainty	1–5	1–5
b tagging	2–3	2–3
jet energy scale	5–7	6–8
jet energy resolution	< 1	< 1
lepton selection	3	3
E_T^{miss} (non jet)	< 1	< 1
pileup	< 1	< 1
background	1–3	1–3
PDF	< 1	< 1
fact./ren. scale	< 1	< 1
NLO generator	1–6	1–10
parton shower scale	1–5	2–9
POWHEG + PYTHIA8 vs. HERWIG++	< 3	1–12

CMS−PAS−TOP−16−011

$d\sigma_{t\bar{t}}/dX$ in dilepton ①

- Differential cross−section as a function of kinematics of top quark and top−pair and jet multiplicity
- Broadly in agreement with the predictions
- Uncertainty is dominated by signal modeling
  - NLO generator, PS



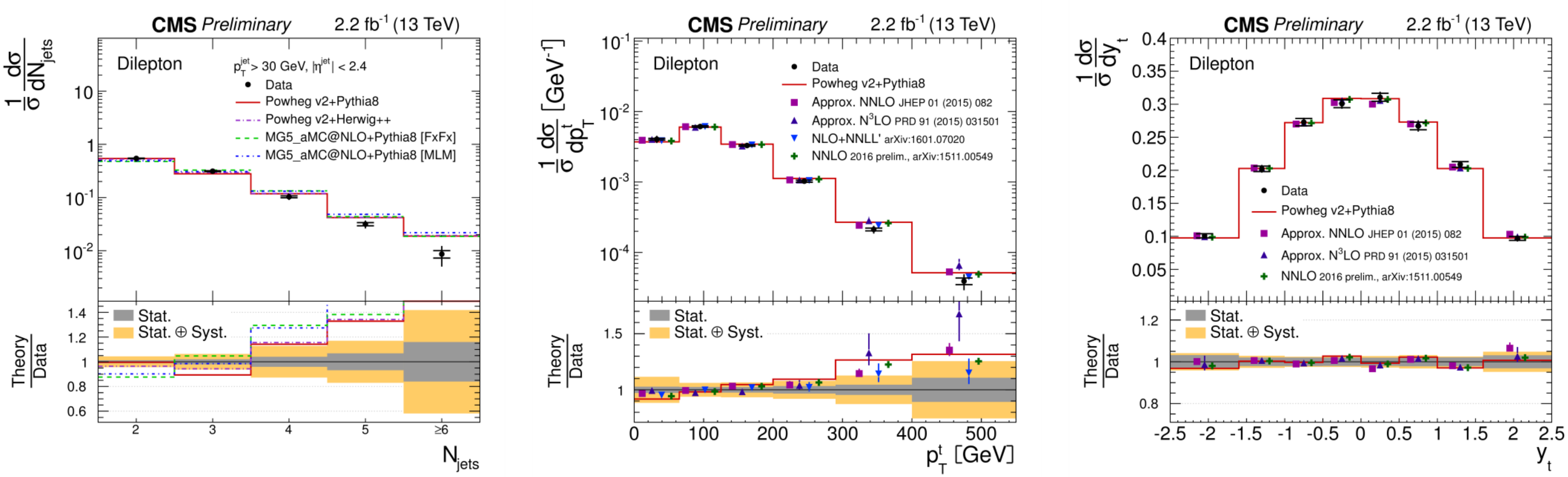


$\sqrt{s}$=13 TeV

CMS-PAS-TOP-16-011

$d\sigma_{t\bar{t}}/dX$ in dilepton ②

- Observe discrepancies in large jet activity
  MC harder than data ⇒ need further tune
- Top p_T and rapidity better described at NLO+NNLL

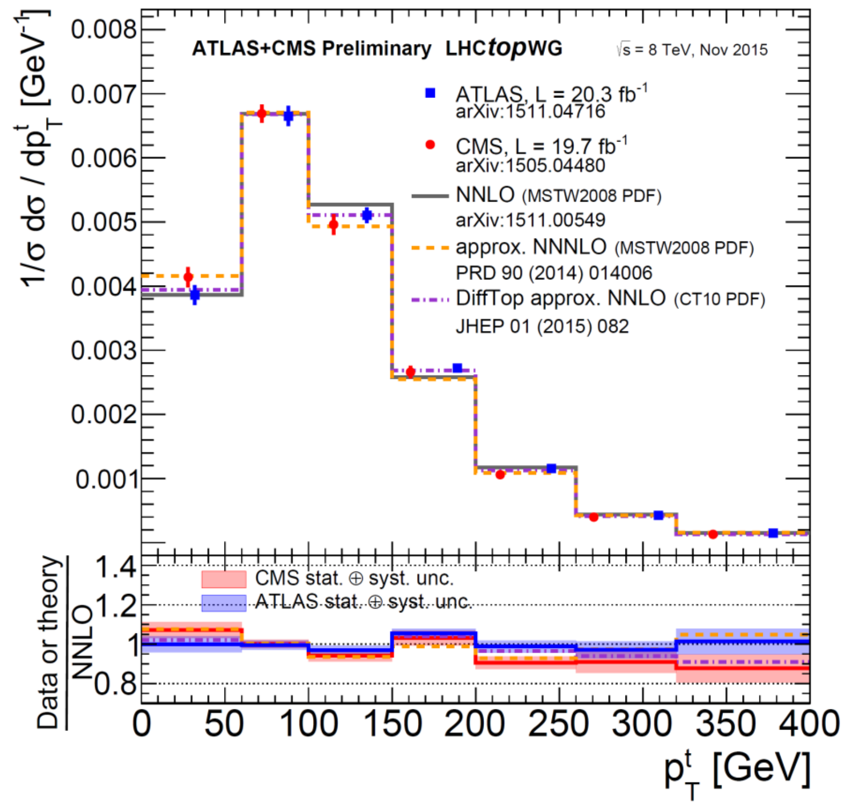


√s=8 TeV

ATLAS arXiv:1511.04716
CMS arXiv:1505.04480

$d\sigma_{t\bar{t}}/dX$ results at 8 TeV

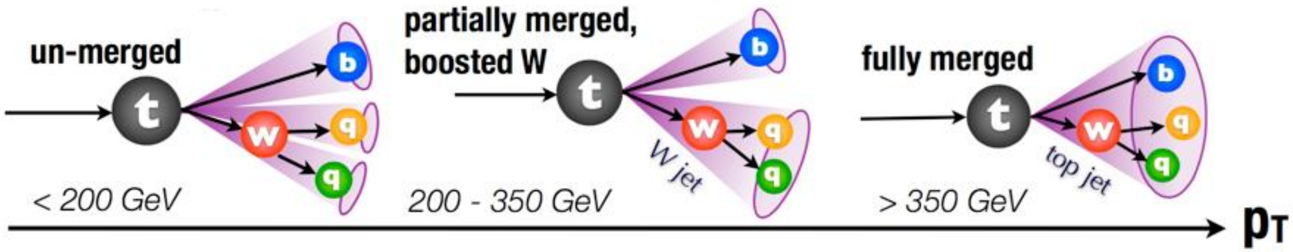
- Higher order theories show nicely agreement for the top p_T
- not so well described by Powheg+Pythia
  ⇒ same trend seen in new 13 TeV CMS results



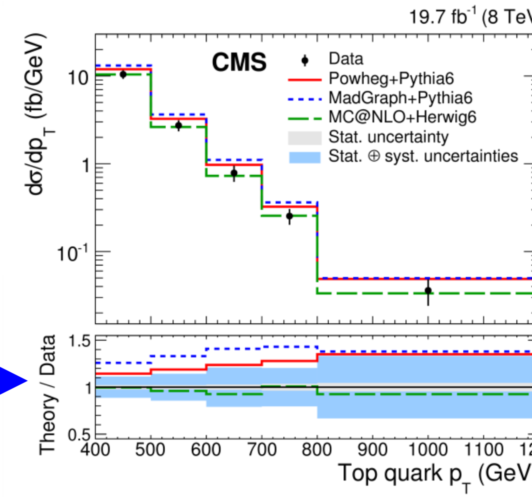
√s=8 TeV

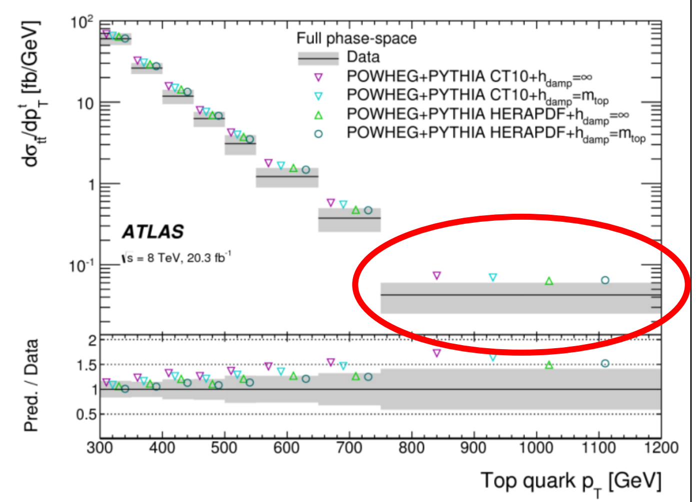
ATLAS arXiv:1511.04716
CMS arXiv:1605.00116

$d\sigma_{t\bar{t}}/dX$ in "boosted" regime



- Decay objects merged in higher $p_{T,t}$ or m_{tt}
- Events are selected using Fat jet topology
  - Clustered within large cone radius (R=1.0 for ATLAS, 0.8 for CMS)
- Large uncertainty on fat jet energy scale
- Good agreement with MC@NLO+HW
- Higher xsec in PWG+PY at higher top p_T





Single top production

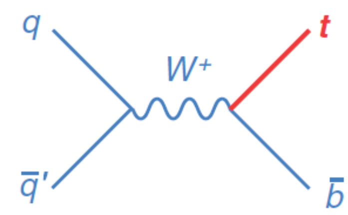
- Direct measurement of $|V_{tb}|$
- Sensitive to BSM (ex W')
- Large background in many searches of Higgs or SUSY

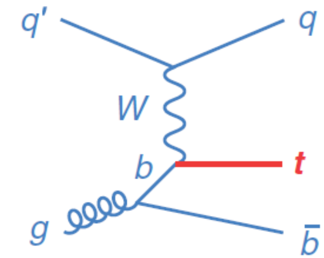
$\sqrt{s}$=1.96 TeV

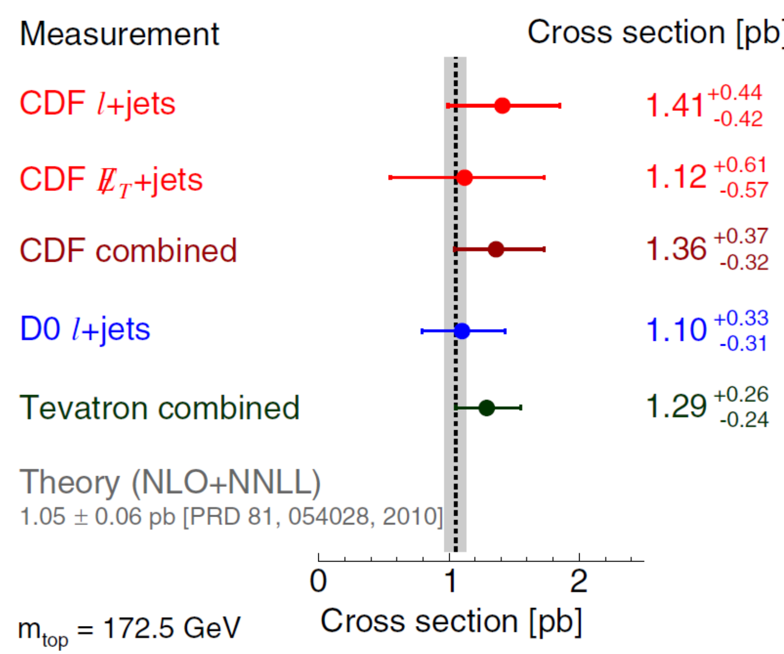
PRL **112**, 231803 (2014)

Observation of s–ch single top production

- Combination of the CDF and D0 measurements
- $\sigma_s = 1.29^{+0.26}_{-0.24}$ [pb]
  $\Rightarrow$ Significance of **6.3 σ**
- Common event selection
  - **High p_T lepton**
  - **MET**
  - **Jets with one or two b–jets**







PLB, **756,** 228–246(2016)

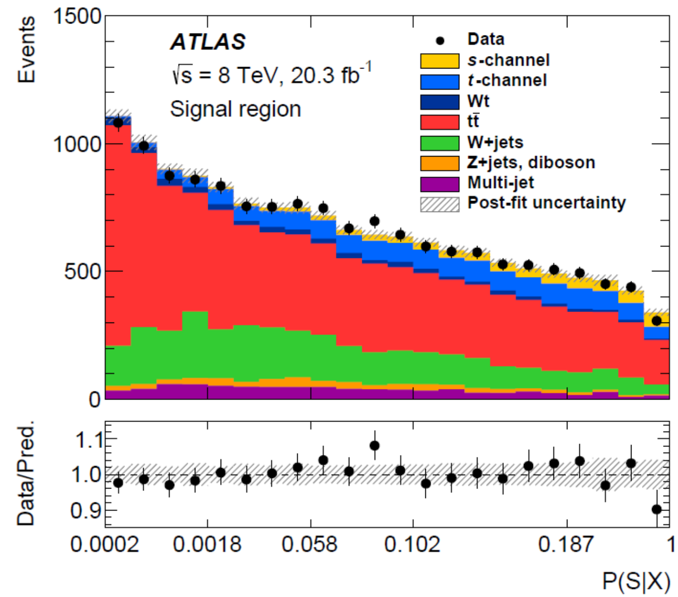
Evidence for s–ch single top quark

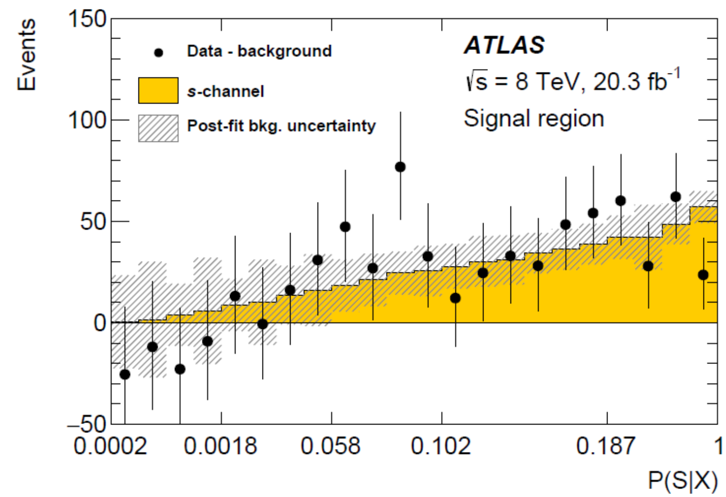
- Event selections
  - Muon or Electron
  - exactly 2 b–jets
  - $E_T^{miss} > 50$ GeV
  - $m_T(W) > 30$ GeV

$$m_T(W) = \sqrt{2p_T(\ell)E_T^{\mathrm{miss}}\left(1 - \cos\Delta\phi\left(\ell, E_T^{\mathrm{miss}}\right)\right)}$$

- Using discriminant based on the **matrix element method**
- $\sigma_s = 4.8 \pm 0.8\ ^{+1.6}_{-1.3}$ pb (stat) (syst)

significance 3.2σ!

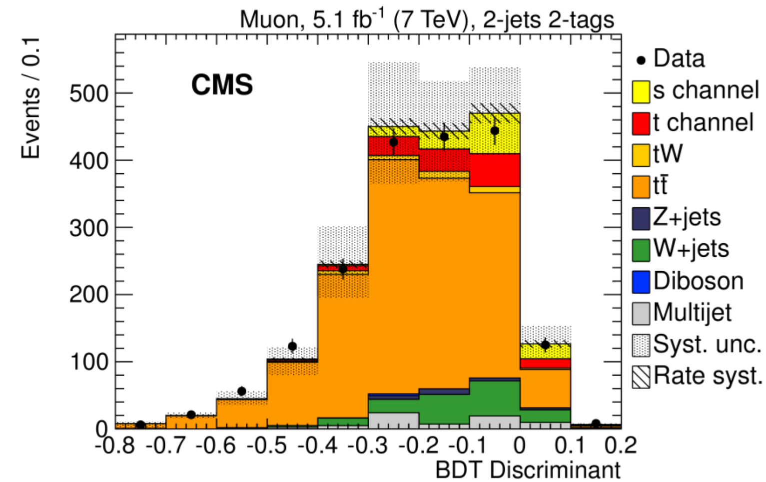


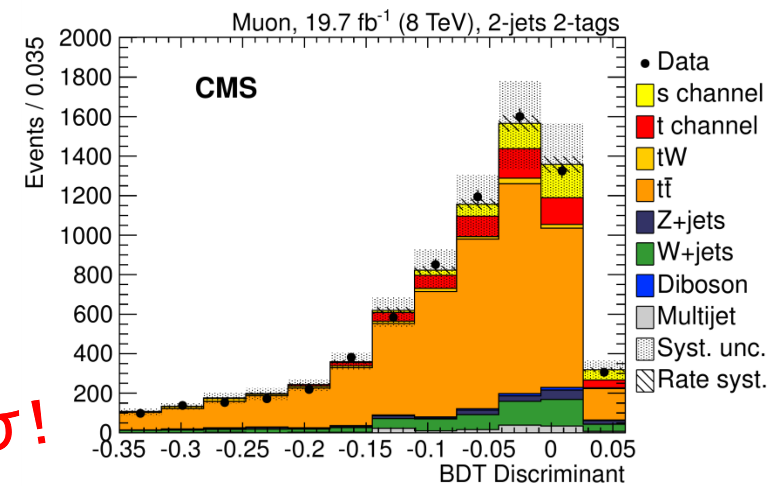


arXiv:1603.02555

Search for s–ch single top quark

- Event categorized by N–jets and M b–tag
- Simultaneous fit for BDT based MVA discriminant
  - Constrains W+jets and tt BKG





7TeV muon channel

$$\sigma_s = 7.1 \pm 8.1\,(\mathrm{stat} + \mathrm{syst})\,\mathrm{pb},$$

8TeV combined

$$\sigma_s = 13.4 \pm 7.3\,(\mathrm{stat} + \mathrm{syst})\,\mathrm{pb},$$

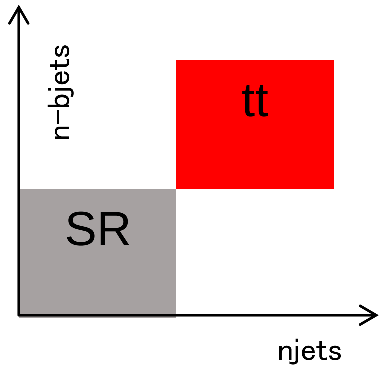
significance 2.5 σ !

√s=13 TeV

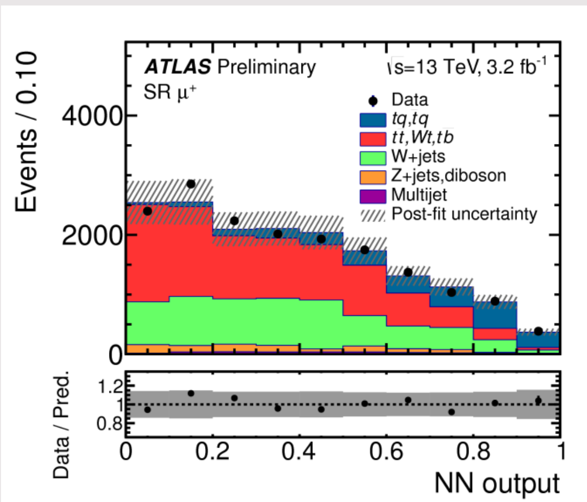
ATLAS−CONF−2015−079

t−ch single top ①

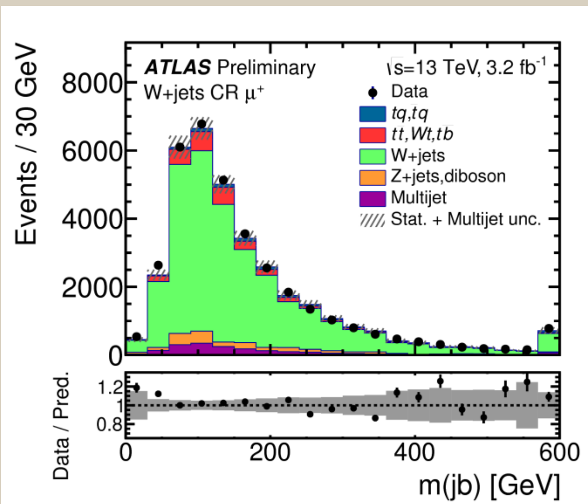
- Event selections
  - **1 muon**
  - 2 jets with **1 b−jet**
  - E_T^{miss} > **30 GeV**
  - $m_T(W)$ > 50 GeV
- Checked backgrounds in each CR region
  - tt; 3 jets with 2 b−jets
  - W+jets; Only pass weaken b−tag requirement



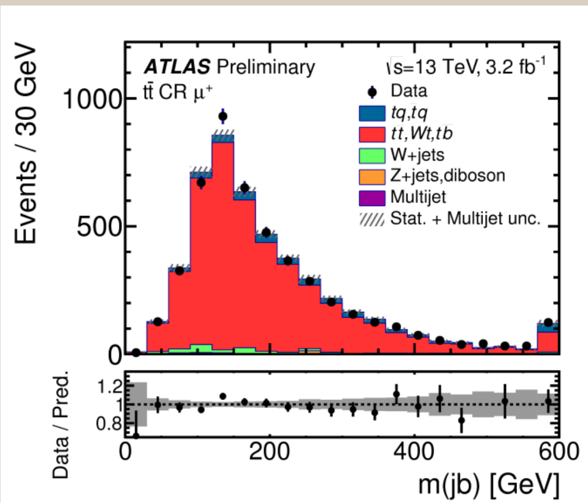
Signal region



W+jets control region



tt control region

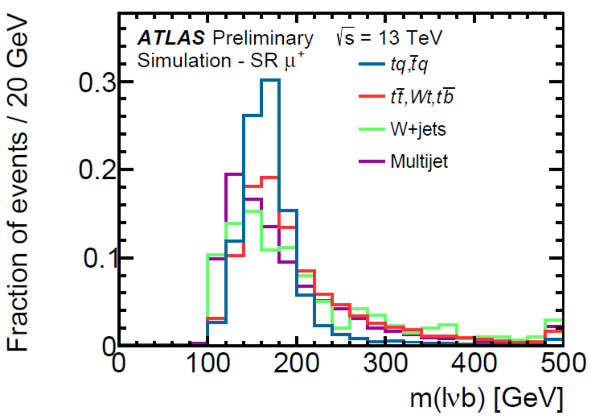


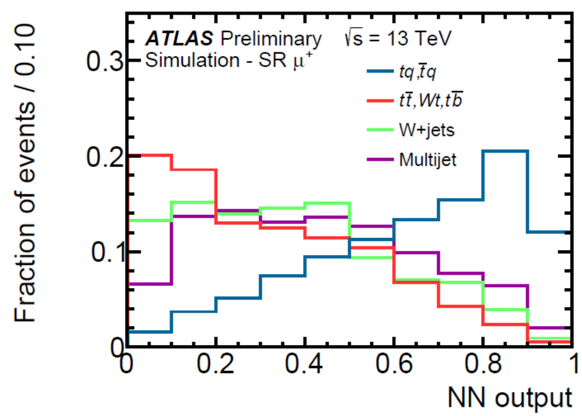
√s=13 TeV

ATLAS−CONF−2015−079

t−ch single top ②

- MVA with Neural Network





Variable	Corr. loss
$m(\ell\nu b)$	31.8 %
$m(jb)$	29.0 %
$m_{\mathrm{T}}(W)$	23.1 %
$\lvert\eta(j)\rvert$	15.8 %
$m(\ell b)$	8.5 %
$\cos\Theta(\ell,j)_{\ell\nu b\ \mathrm{r.f.}}$	6.6 %
$\Delta R(\ell\nu b,j)$	7.4 %
$\eta(W)$	6.8 %
$\Delta p_{\mathrm{T}}(\ell\nu b,j)$	5.5 %
$\Delta R(\ell,j)$	2.1 %

$$\sigma_{tq} = 130.3 \pm 5.8(stat) \pm 16.5(syst) \pm 7.7(lumi)\ [\mathrm{pb}]$$

$$\sigma_{\bar{t}q} = 90.2 \pm 5.3(stat) \pm 18.4(syst) \pm 5.3(lumi)\ [\mathrm{pb}]$$

$$\sigma_{tq,\mathrm{NLO}} = 136.0^{+5.4}_{-4.6}\ [\mathrm{pb}]$$

$$\sigma_{\bar{t}q,\mathrm{NLO}} = 81.0^{+4.1}_{-3.6}\ [\mathrm{pb}]$$

Direct measurement of V_{tb}

(assuming Vtb>>Vts,Vtd, left chiral coupling)

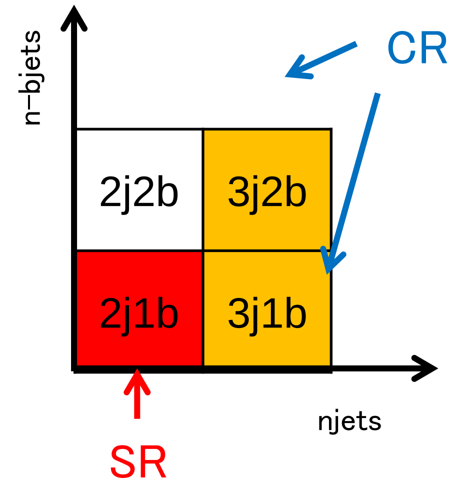
$$\left|f_{LV}V_{tb}\right| = 0.98 \pm 0.08$$

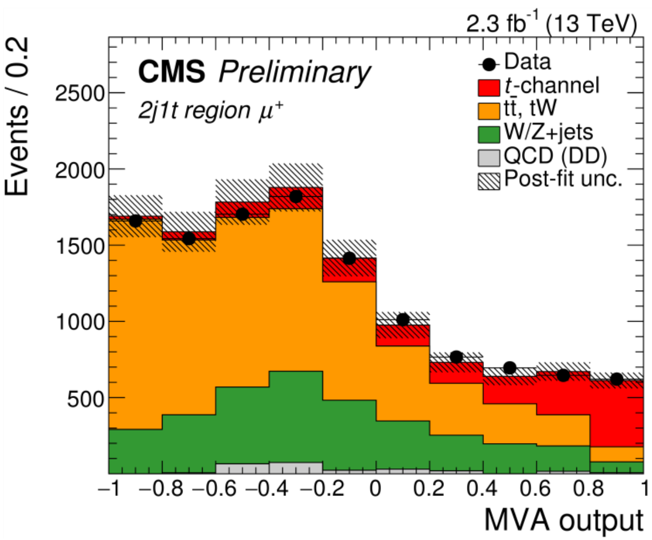
√s=13 TeV

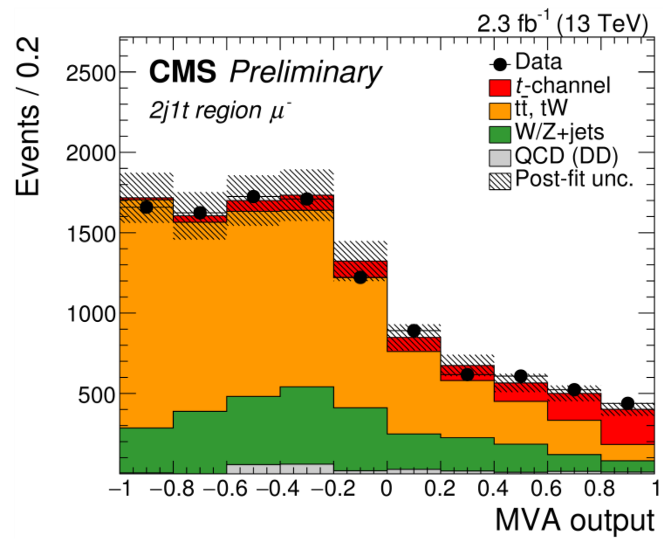
CMS−PAS−TOP−16−003

t−ch single top ③

- Event categorized by N−jets and M b−tag
- Simultaneous fit of NN based MVA output
  - To constrains tt backgrounds







$$\sigma_{t\text{-ch.},t} = 141.5 \pm 6.7\,(\text{stat.}) \pm 9.4\,(\text{exp.})\,^{+19.3}_{-19.6}\,(\text{theo.}) \pm 3.8\,(\text{lumi.})\,\text{pb} = 141.5\,^{+22.8}_{-23.0}\,\text{pb},$$

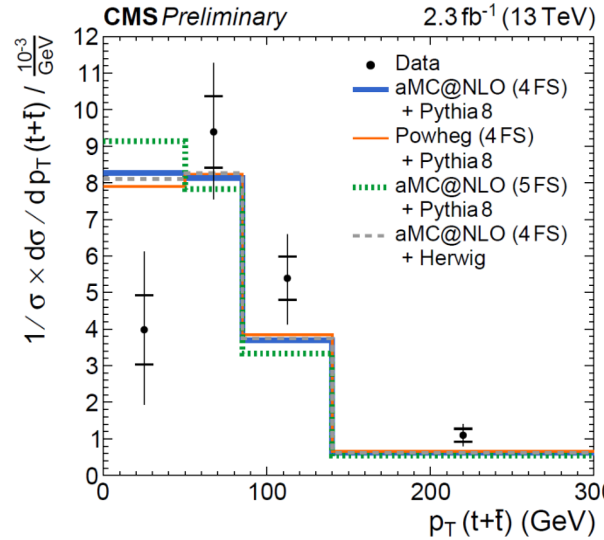
$$\sigma_{t\text{-ch.},\bar{t}} = 81.0 \pm 6.2\,(\text{stat.}) \pm 8.1\,(\text{exp.})\,^{+10.9}_{-10.9}\,(\text{theo.}) \pm 2.2\,(\text{lumi.})\,\text{pb} = 81.0\,^{+15.1}_{-15.1}\,\text{pb}.$$

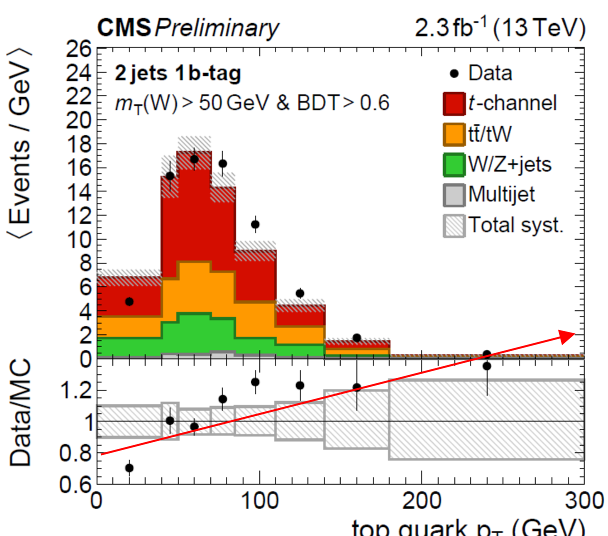
√s=13 TeV

CMS-PAS-TOP-16-004

Differential t–ch single top

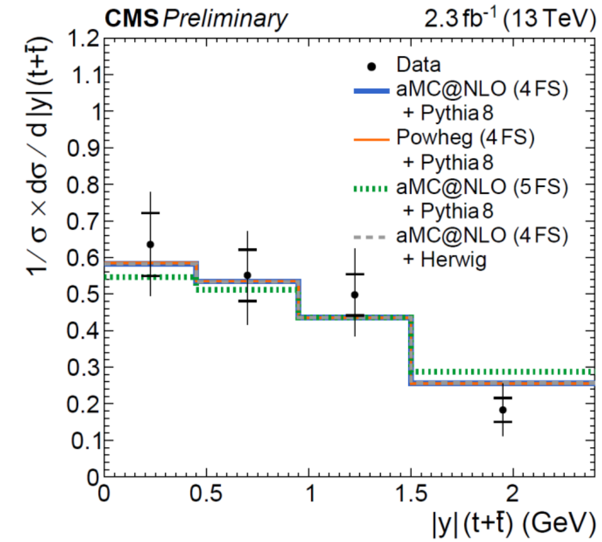
- As a function of the $p_{T,t}$ and $|y_t|$
- No significant deviation form theoretical predictions within the experimental uncertainties





Analysis detail

- ✓ Event categorized by N–jets and M b–tag
- ✓ BDT based MVA discriminant
- ✓ Data/MC checked in signal enriched region
- ✓ Unfold to parton level



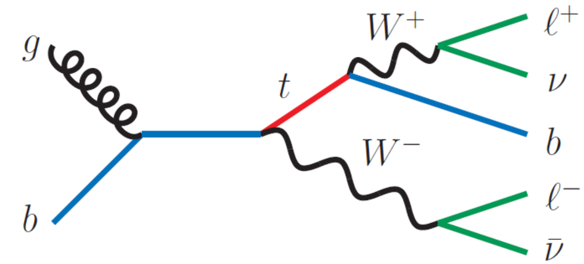
Signal enriched region; slightly harder?

√s=8 TeV

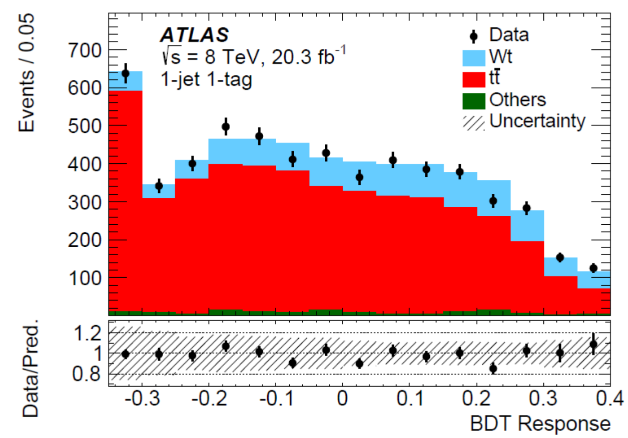
JHEP **01,** 064, 2016

Wt single top production

- Events containing two leptons and one central b-jet are selected
- Event categorized by N jets and M b-tag
  - to fit & to validate BKG
- Events are classified base on BDT



Signal enriched region



Result

$$23.0 \pm 1.3\,(\text{stat.})^{+3.2}_{-3.5}\,(\text{syst.}) \pm 1.1\,(\text{lumi.})\,\text{pb}\,,$$

Fiducial cross-section

$$0.85 \pm 0.01\,(\text{stat.})^{+0.06}_{-0.07}\,(\text{syst.}) \pm 0.03\,(\text{lumi.})\,\text{pb}\,.$$

Consistent to theoretical prediction!

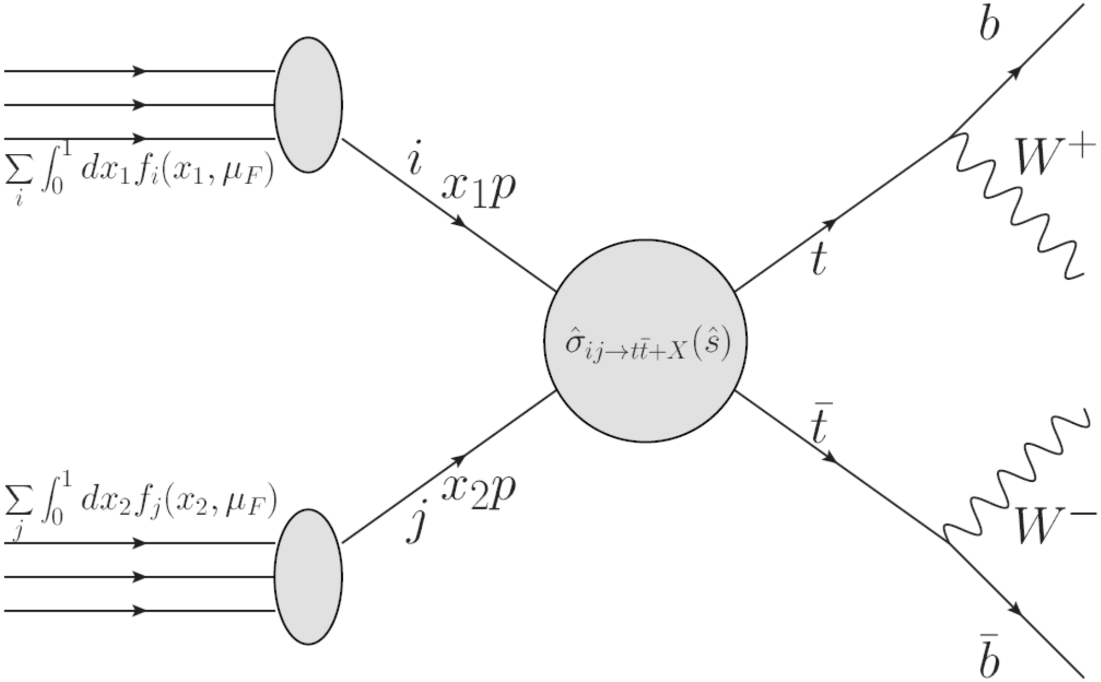
Summary

- Many top quark production measurements in Tevatron and LHC
  - With different energy ($\sqrt{s}$ = 1.96, 7, 8, 13 TeV)
  - With different initial state ($p\bar{p}$, pp)
- Latest top production results agree with SM predictions
  - Top quark pair production cross-section
    - ✓ Good agreement in various energies and regions
    - ✓ Very precise measurement
  - Differential top quark pair production cross-section
    - ✓ MC models reproduce shape well
    - ✓ Potential further tuning
  - Single top production cross-section
    - Good agreement with theoretical predictions

Thanks !

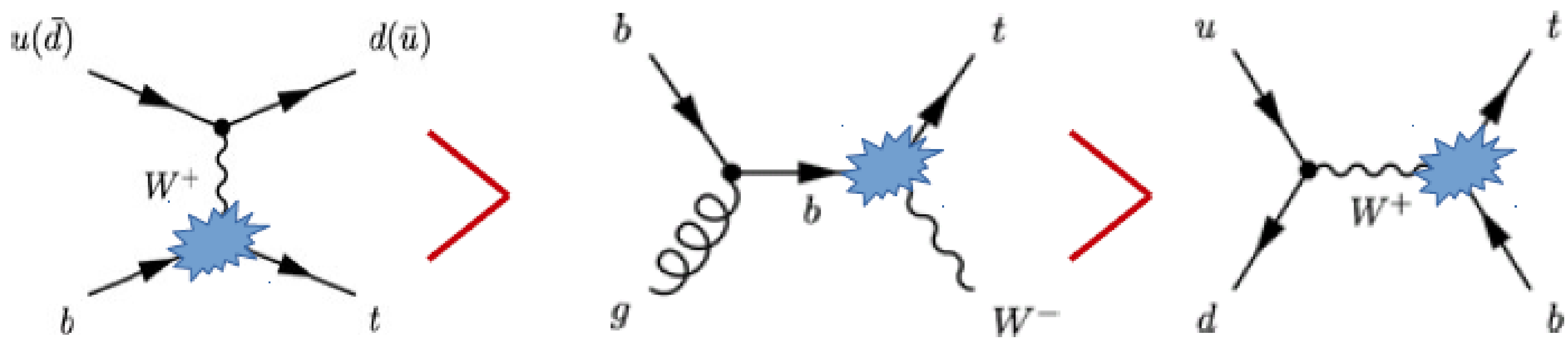
Top quark pair cross-section $\sigma_{t\bar{t}}$

$$\sigma_{p\bar{p}\to t\bar{t}} = \sum_{i,j=g,q,\bar{q}} \int_0^1 f_i(x_1)\, \mathrm{d}x_1 \int_0^1 f_j(x_2)\, \mathrm{d}x_2 \ \times \hat{\sigma}_{ij\to t\bar{t}}\,(\alpha_s),$$



top cross-sections

	CMS energy	R_{qq}	R_{gg}	$\sigma_{t\bar{t}}^{\mathrm{NNLO+NNLL}}$ [pb]	scale unc.	PDF unc.
LHC	7	15	85	172	3%	3%
	8	12	88	245.8	3%	2.5%
	14	10	90	953.6	3%	2%
Tevatron	1.96	90	10	7.165	2%	2%



t-channel　　tW　　*s*-channel

σ_t @ LHC13TeV　217 pb　72 pb　10 pb

Matrix Element Method

- The ME method directly uses theoretical calculations to compute a per-event signal probability
- The method was introduced to Top quark measurement in Tevatron (~90's)

$$P(x|\text{process}_i) = \frac{1}{\sigma_i}\frac{d\sigma_i}{dx}$$

This probabilities are estimated for each process

phase space

differential cross-section of h.s.

parton level cut

$$\frac{d\sigma}{dx} = \underbrace{\boxed{\sum_j}}_{\text{configuration}} \boxed{\int dy} \left[\underbrace{f_{1,j}(q_1,Q^2)\, f_{2,j}(q_2,Q^2)}_{\text{PDF}} \boxed{\frac{d\sigma_{hs,j}}{dy}} \underbrace{W_j(x,y)}_{\text{Transfer function}} \Theta_{\text{parton}}(y) \right]$$

$$d\sigma_{hs,j} = \frac{(2\pi)^4}{4\sqrt{(q_1\cdot q_2)^2 - m_1^2 m_2^2}}|\mathcal{M}|^2 d\Phi$$