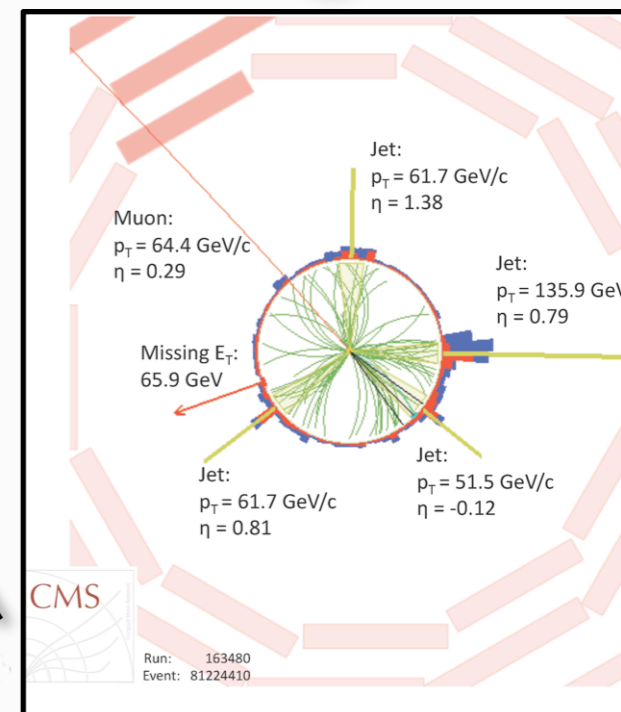
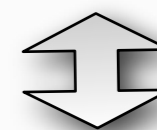
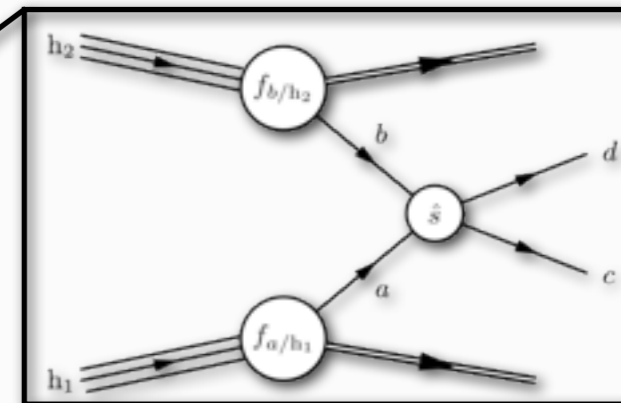
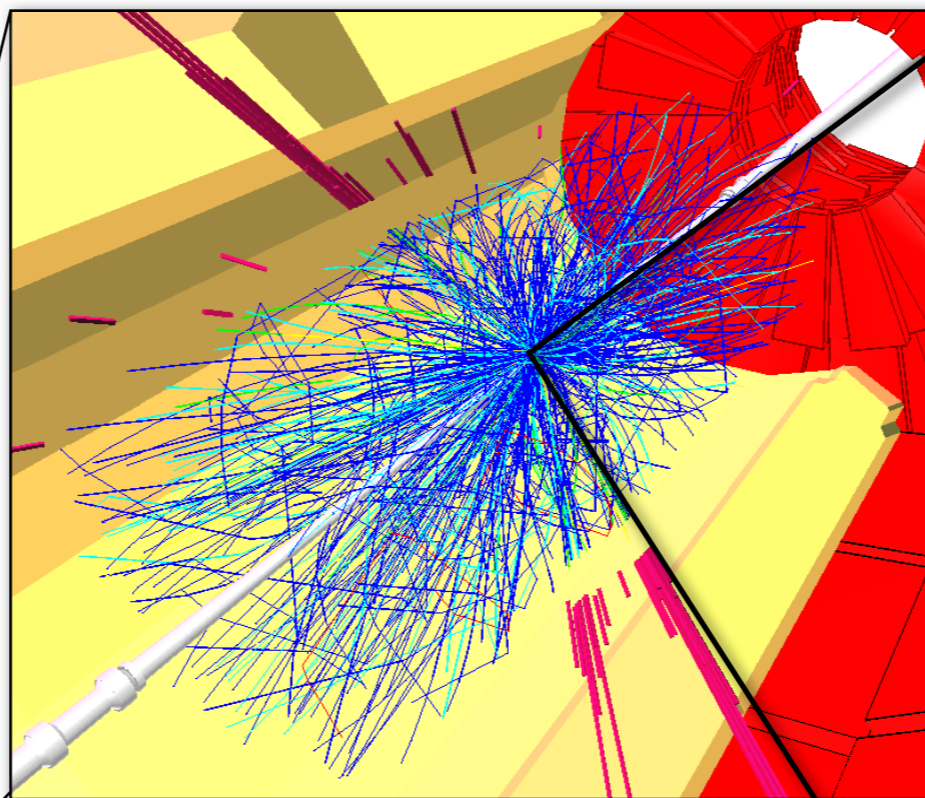


Rainer Wallny
ETH Zürich



XXVIe Rencontres
de Physique de la
Vallée d'Aoste La Thuile 28 Feb.2013

- $t\bar{t}$ pair production
- $t\bar{t}$ charge asymmetry
- single top production

The Top Quark is special

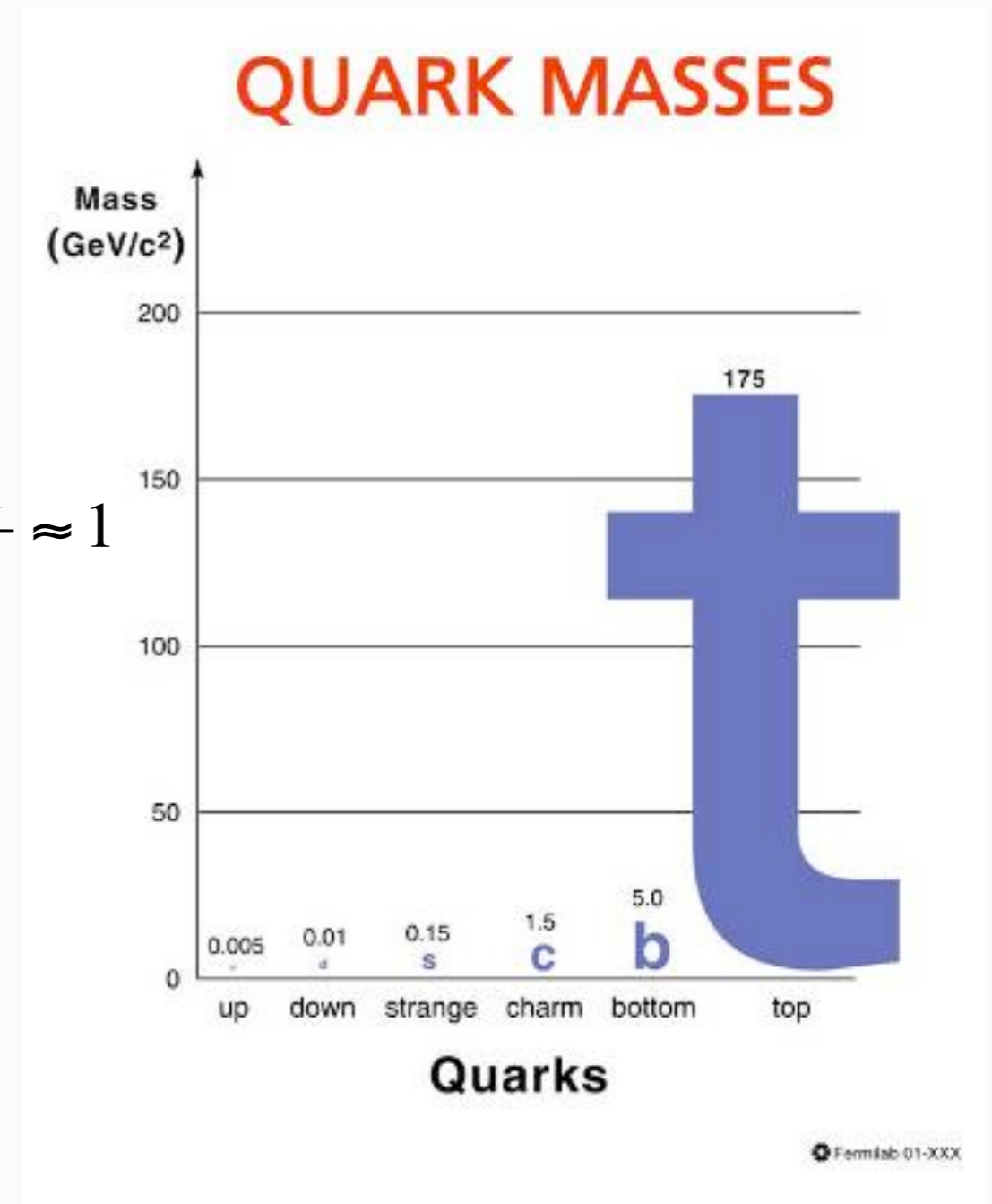
- Top quark is unusually massive

- Decays before it hadronizes

- Yukawa coupling to Higgs field suspiciously close to unity $y_t = \frac{\sqrt{2}m_t}{v} \approx 1$

- Large impact on radiative corrections of SM observables

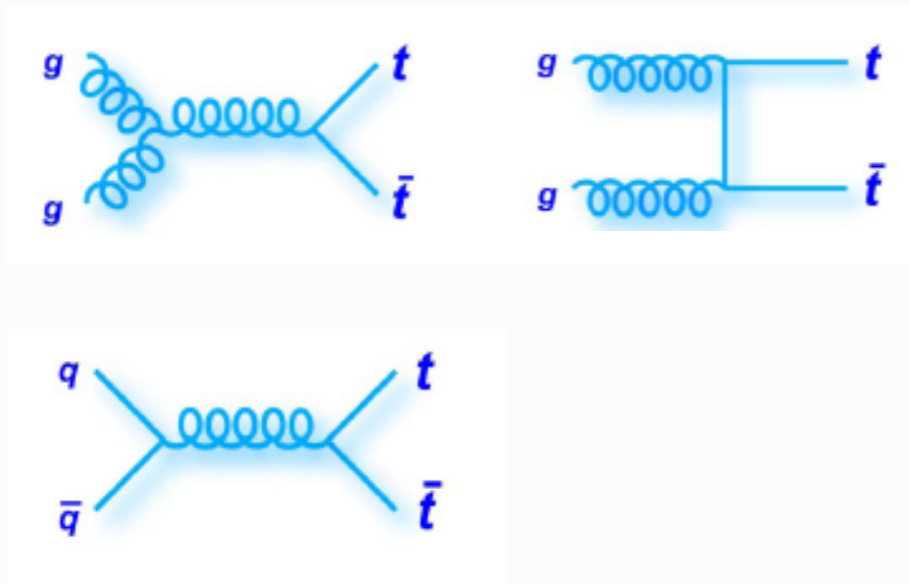
- New physics may preferentially couple/decay to top quarks



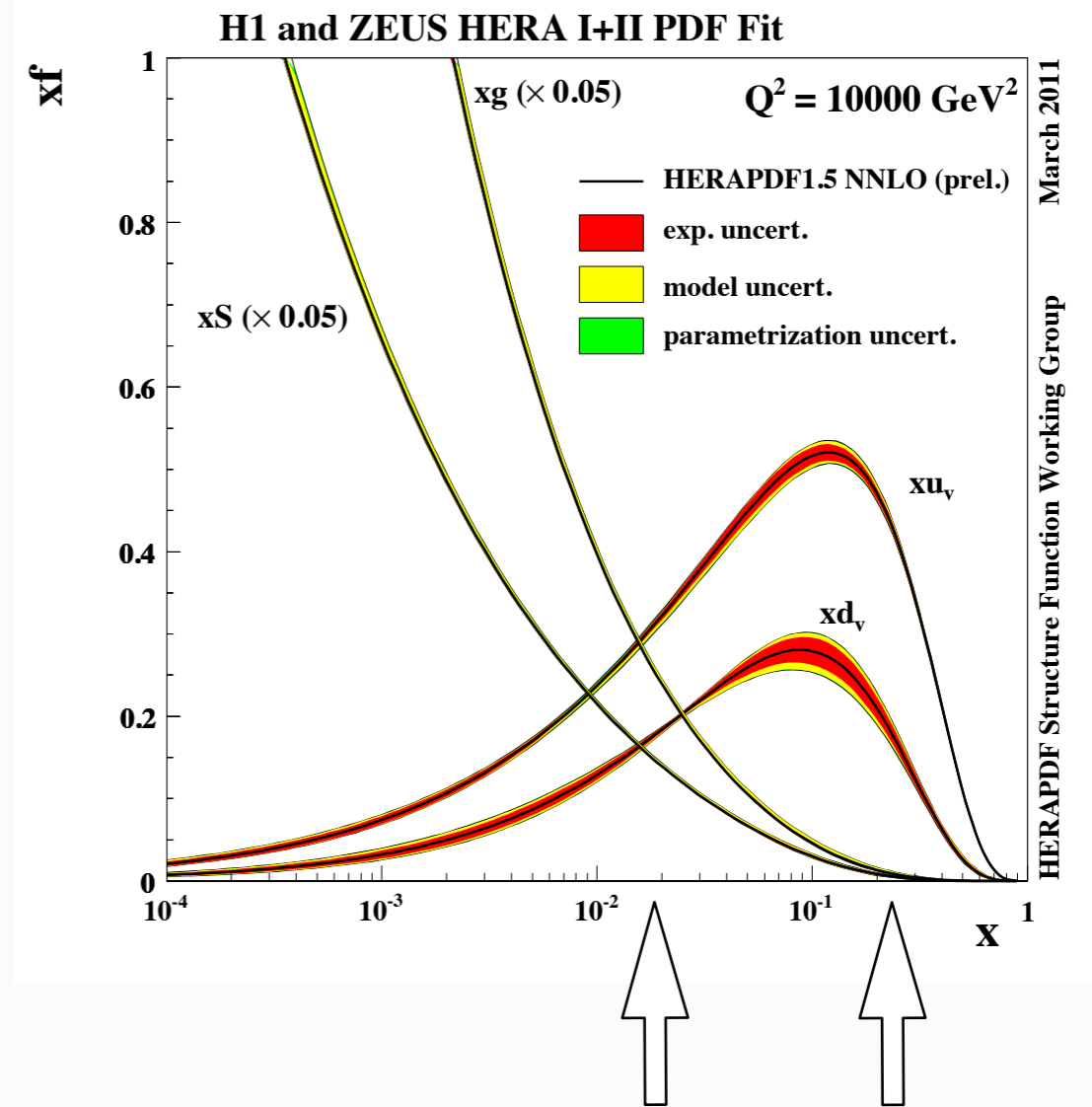
Is it the Standard Model top quark ?

Top Quark Pair Production Cross Section

- $t\bar{t}$ production dominated by gluon fusion at the LHC (~ 90%)



- State of the art theory approx. NNLO
 - uncertainties down to ~5%
 - missing calculations ($gg \rightarrow t\bar{t}$) forthcoming

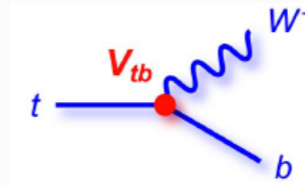


$\sigma_{t\bar{t}}$ [pb]	Tevatron	LHC (7 TeV)	LHC (8 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$158.1^{+19.5+6.8}_{-21.2-6.2}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$
NNLO	$7.00^{+0.21+0.29}_{-0.31-0.25}$	$160.9^{+11.1+7.2}_{-11.5-6.7}$	$229.8^{+16.5+9.7}_{-16.7-9.0}$
NNLL	$7.15^{+0.21+0.30}_{-0.20-0.25}$	$162.4^{+6.7+7.3}_{-6.9-6.8}$	$231.8^{+9.6+9.8}_{-9.9-9.1}$

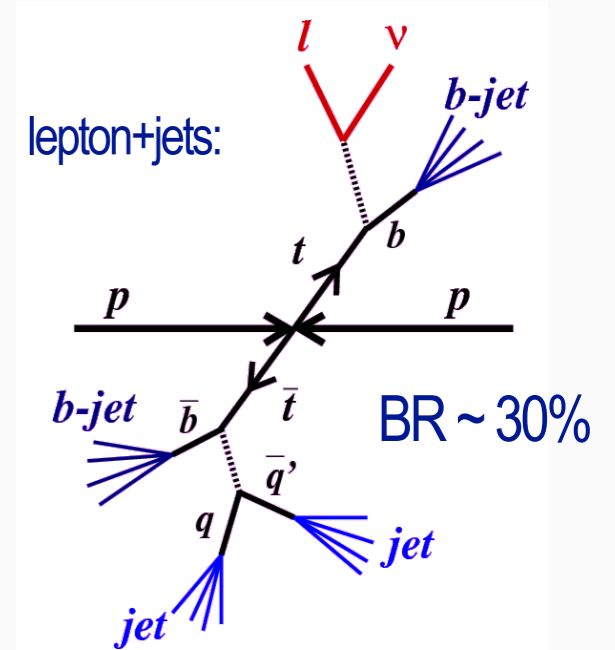
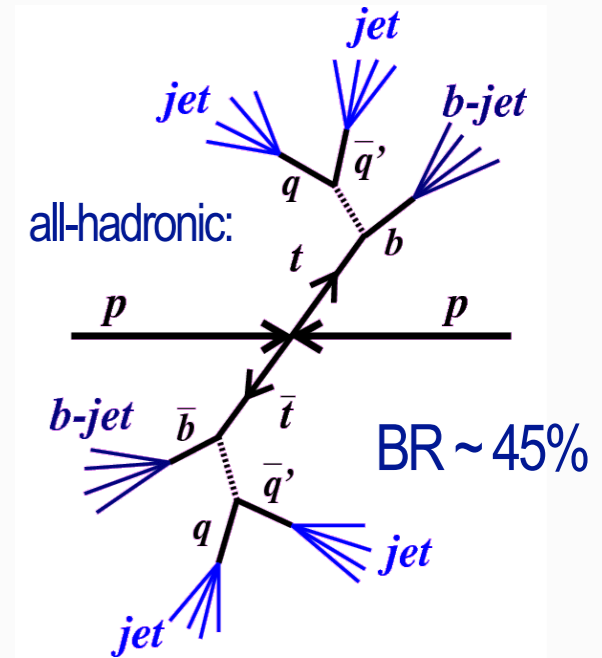
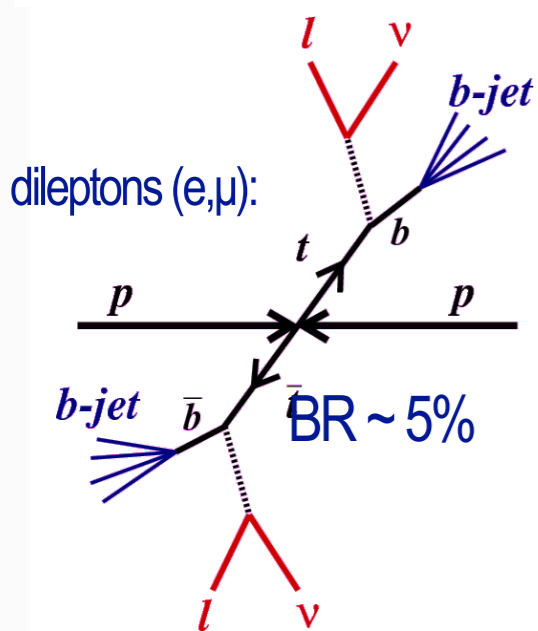
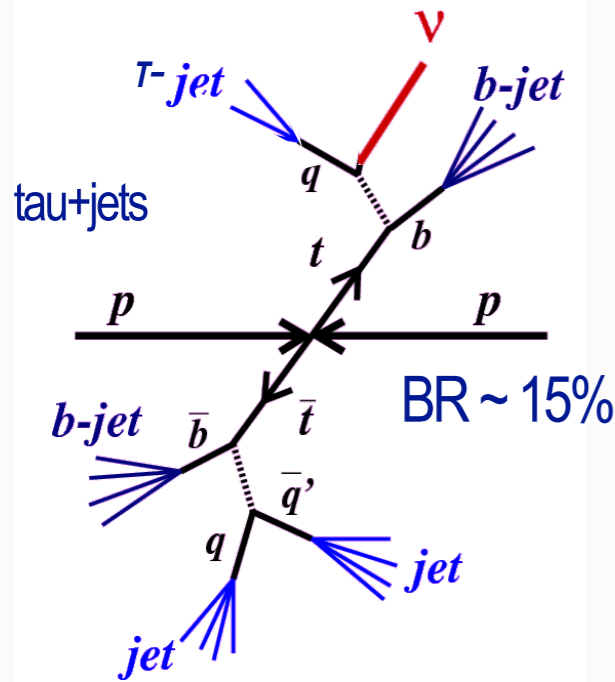
	LHC (7 TeV)	Tevatron
gg	~90%	~15%
qq	~10%	~85%

Beneke et al (TOPIXS), arXiv:1208.5578 [hep-ph], 29 Aug 2012

In SM, $B(t \rightarrow Wb) \sim 100\%$



- presence of b-quark
- final states with complementary S/B ratio

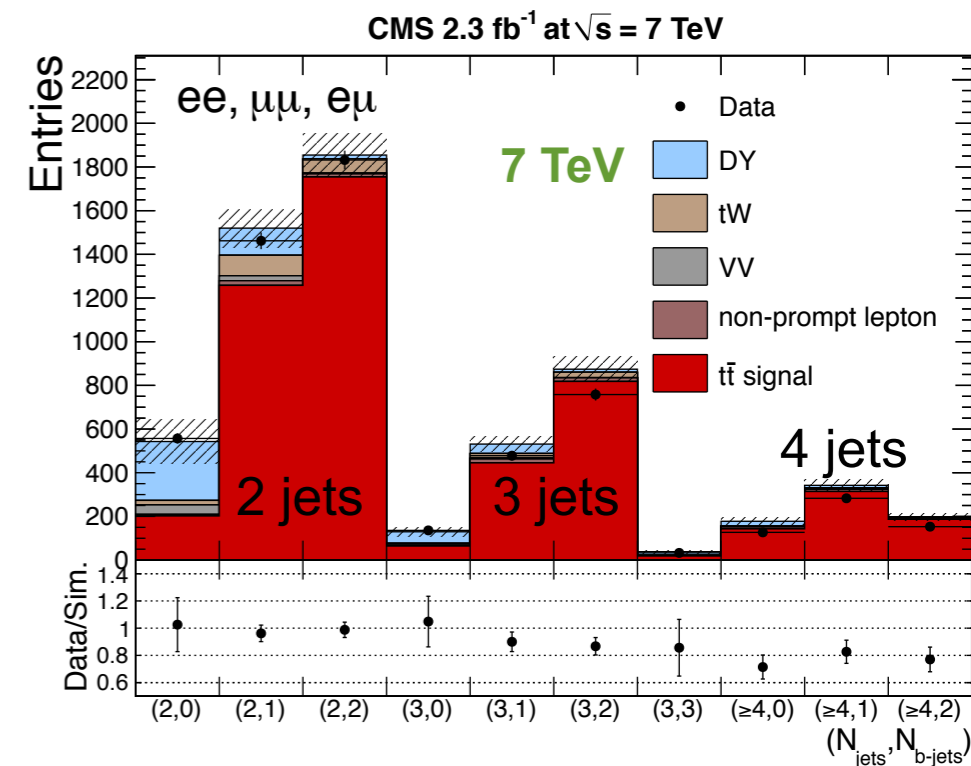


$\bar{c}s$	all-hadronic		
$\bar{u}d$	all-hadronic		
τ^-	eτ	μτ	ττ
μ^-	eμ	μμ	μτ
e^-	ee	eμ	eτ
W decay	e^+	μ^+	τ^+
	$u\bar{d}$	$c\bar{s}$	

All experiments have measured $t\bar{t}$ in all decay channels (except $\tau\tau$)

$t\bar{t} \rightarrow ee/\mu\mu/e\mu$

- Require two opposite sign lepton ($ee, \mu\mu, e\mu$)
- $m_{ll} > 20$ GeV suppresses QCD
- $m_{ll} \notin [76, 106$ GeV] to suppress Z (same fl.)
- Two jets
- $\cancel{E}_T > 40$ GeV in same flavor
- consider events with 0, 1, ≥ 2 b-tagged jets
- background:
 - single-top & diboson from MC
 - DY and non-prompt leptons data based



- 7 TeV:** profile likelihood ratio ($\#jets, \#b-tags$)

$$\sigma_{t\bar{t}} = 161.9 \pm 2.5 \text{ (stat.) } {}^{+5.1}_{-5.0} \text{ (syst.) } \pm 3.6 \text{ (lumi.) pb}$$

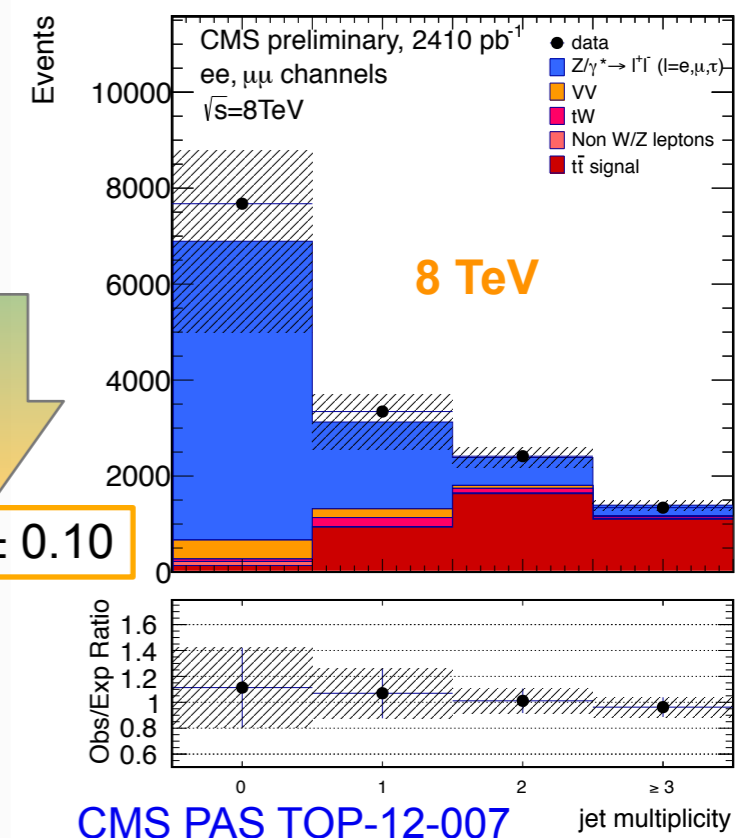
4.2%

- 8 TeV:** counting experiment with ≥ 1 b-tag

$$\sigma_{t\bar{t}} = 227 \pm 3 \text{ (stat.) } \pm 11 \text{ (syst.) } \pm 10 \text{ (lumi.) pb}$$

6.7%

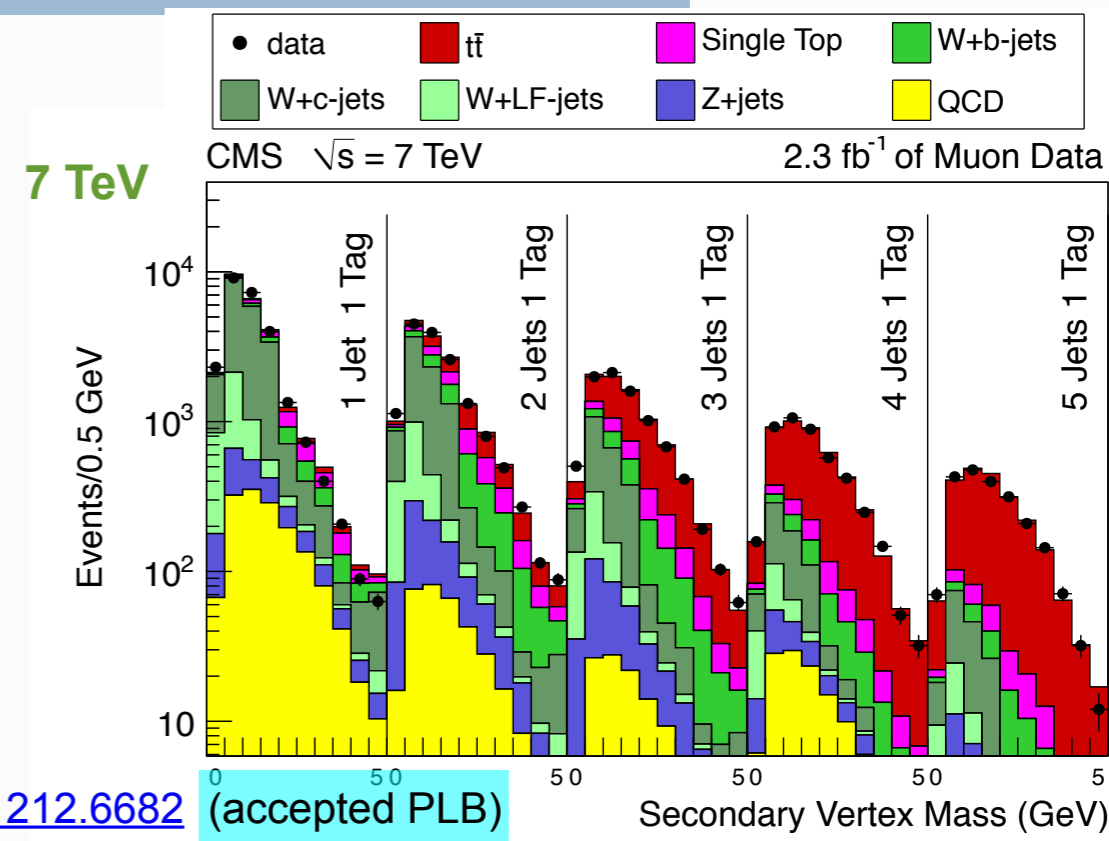
- most precise channel at the LHC



CMS PAS TOP-12-007

$t\bar{t} \rightarrow e/\mu + \text{jets}$

- Require
 - single highly isolated e or μ
 - ≥ 1 jet, 1/2 b-jets
- 7 TeV:** Fit secondary vertex mass in bins of #jets and #tags
- Constrain background rates
- determine major systematics (JES, Wjets Q2) from fit



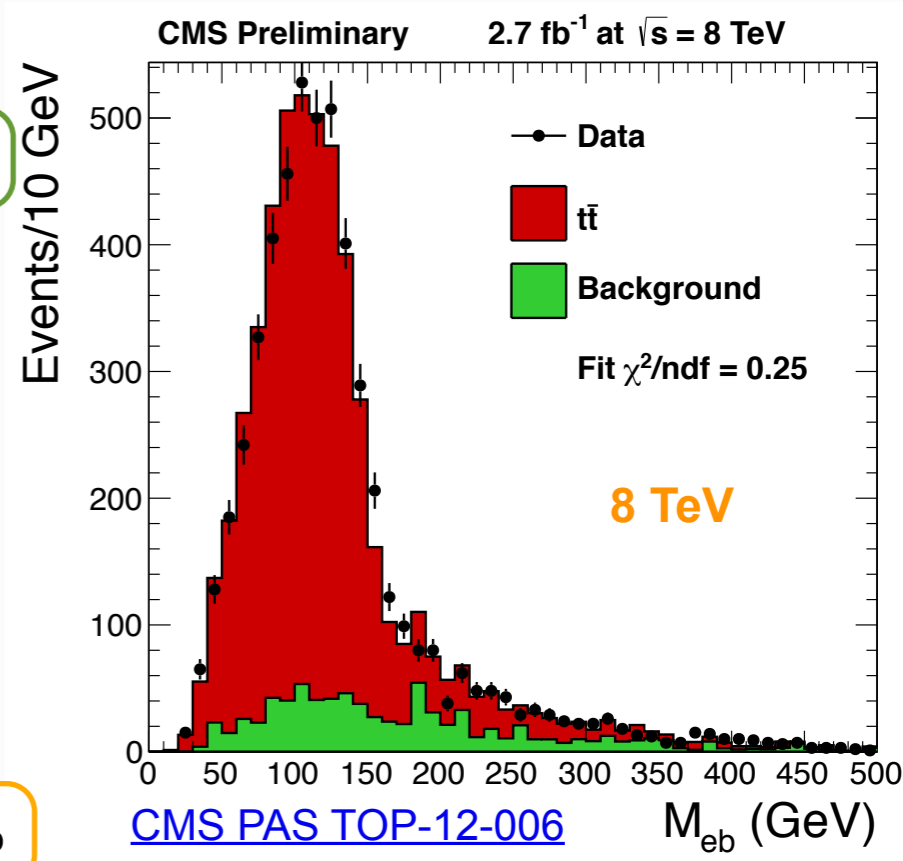
$$\sigma_{t\bar{t}} = 158.1 \pm 2.1 \text{ (stat.)} \pm 10.2 \text{ (syst.)} \pm 3.5 \text{ (lumi.) pb}$$

6.9%

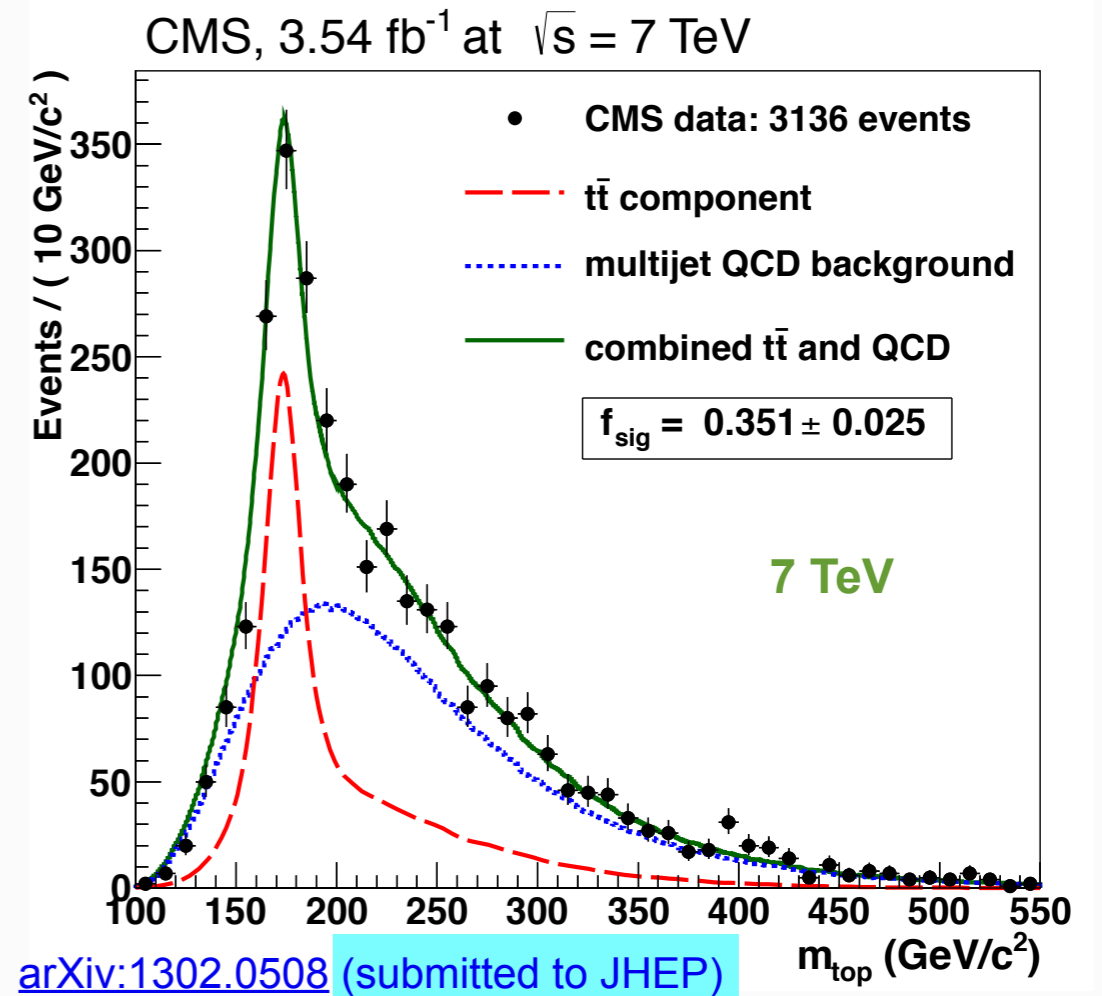
- 8 TeV:** Fit $M(\text{lb})$
- ≥ 4 jets and ≥ 1 bjet
- QCD background determined from non-isolated side band data (with $t\bar{t}$, W-jets, Z-jets leakage removed)

$$\sigma_{t\bar{t}} = 228.4 \pm 9.0 \text{ (stat.)} {}^{+29.0}_{-26.0} \text{ (syst.)} \pm 10.0 \text{ (lumi.) pb}$$

13.4%



- Require 6 jets (2 b-tagged)
- kinematic fit to choose best combination
 - constrain m_W
 - keep m_{top} unconstrained (but equal)
- Unbinned max likelihood fit to reconstructed m_{top}
 - signal from MC
 - multijet background from data using jet-tag rate
- Largest systematic: JES



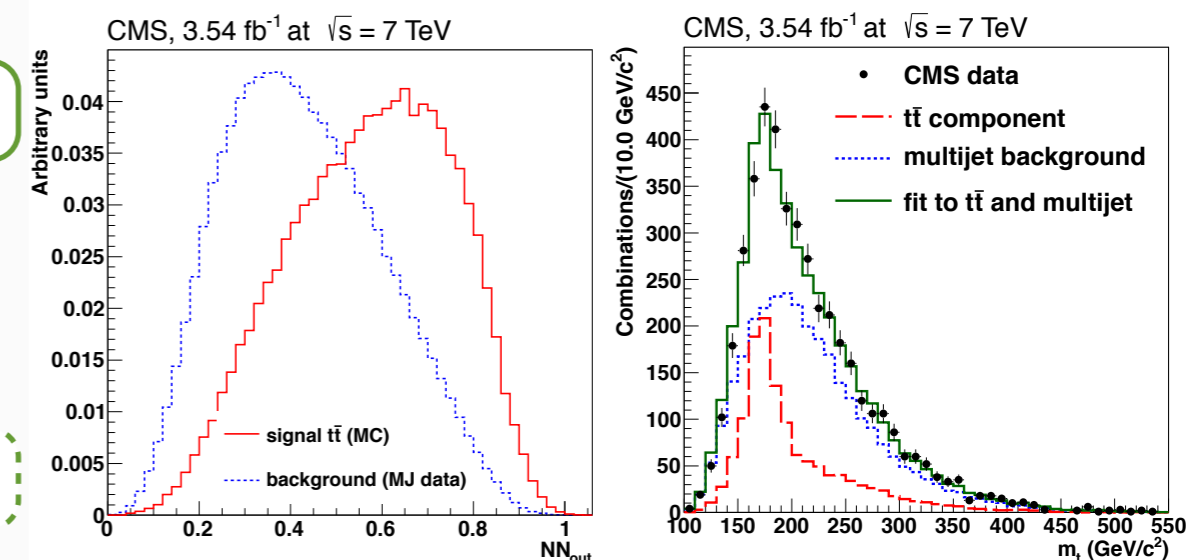
$$\sigma_{t\bar{t}} = 139 \pm 10 \text{ (stat.)} \pm 26 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

20%

- Cross check using NN with 6 variables

$$\sigma_{t\bar{t}} = 114 \pm 15 \text{ (stat.)} \pm 27 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

27%



$t\bar{t} \rightarrow \tau + \text{jets}$ and $\tau + e/\mu$

- final state with taus sensitive $t \rightarrow H^+(\tau, \nu)b$
- $\tau + \text{jets}$** : 4 jets + hadronic τ -candidate + 1 b-jet
 - Dedicated BDT to separate τ from e/μ
- largest background: multi-jet QCD
 - estimated from untagged side-band
 - EWK background from MC
- Fit NN output to to determine cross section

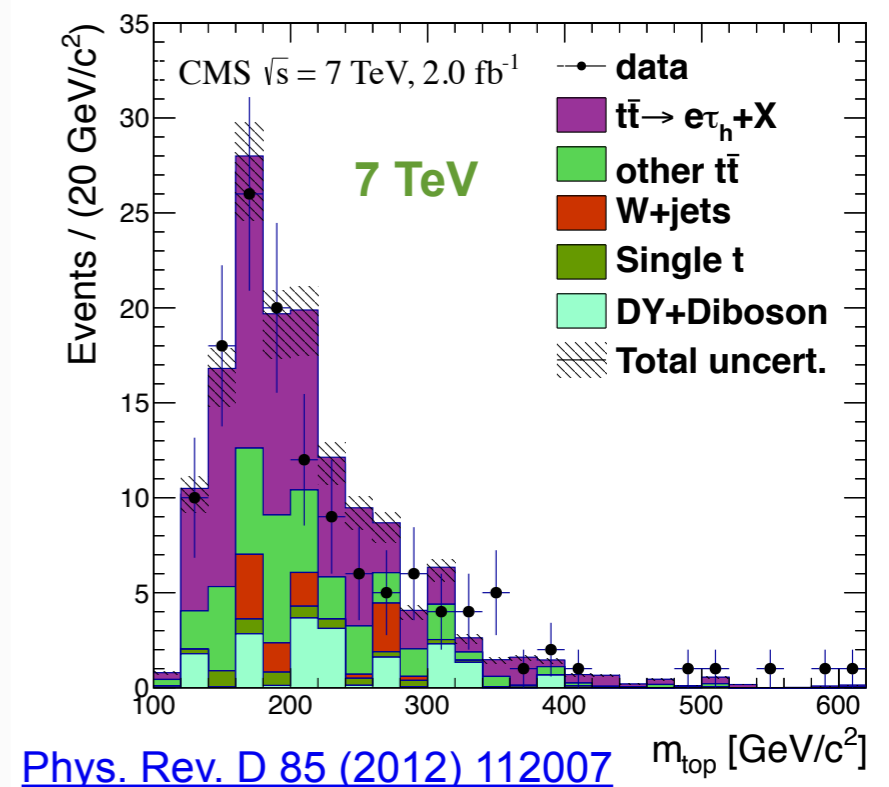
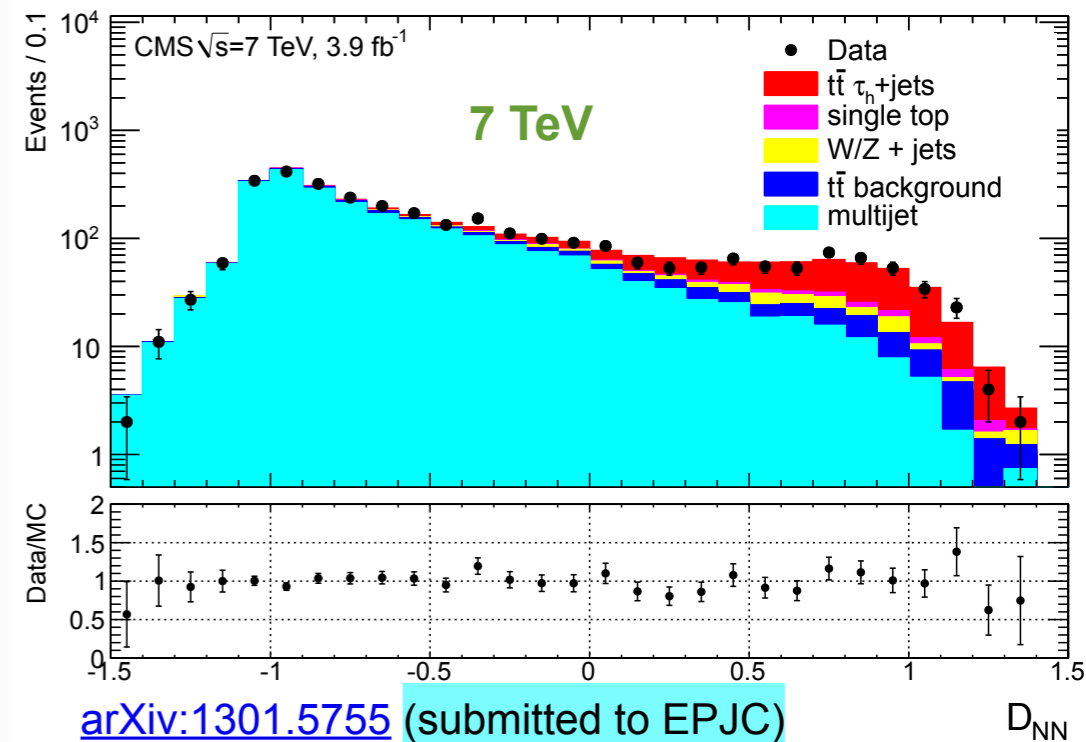
$$\sigma_{t\bar{t}} = 152 \pm 12 \text{ (stat.)} \pm 32 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

23%

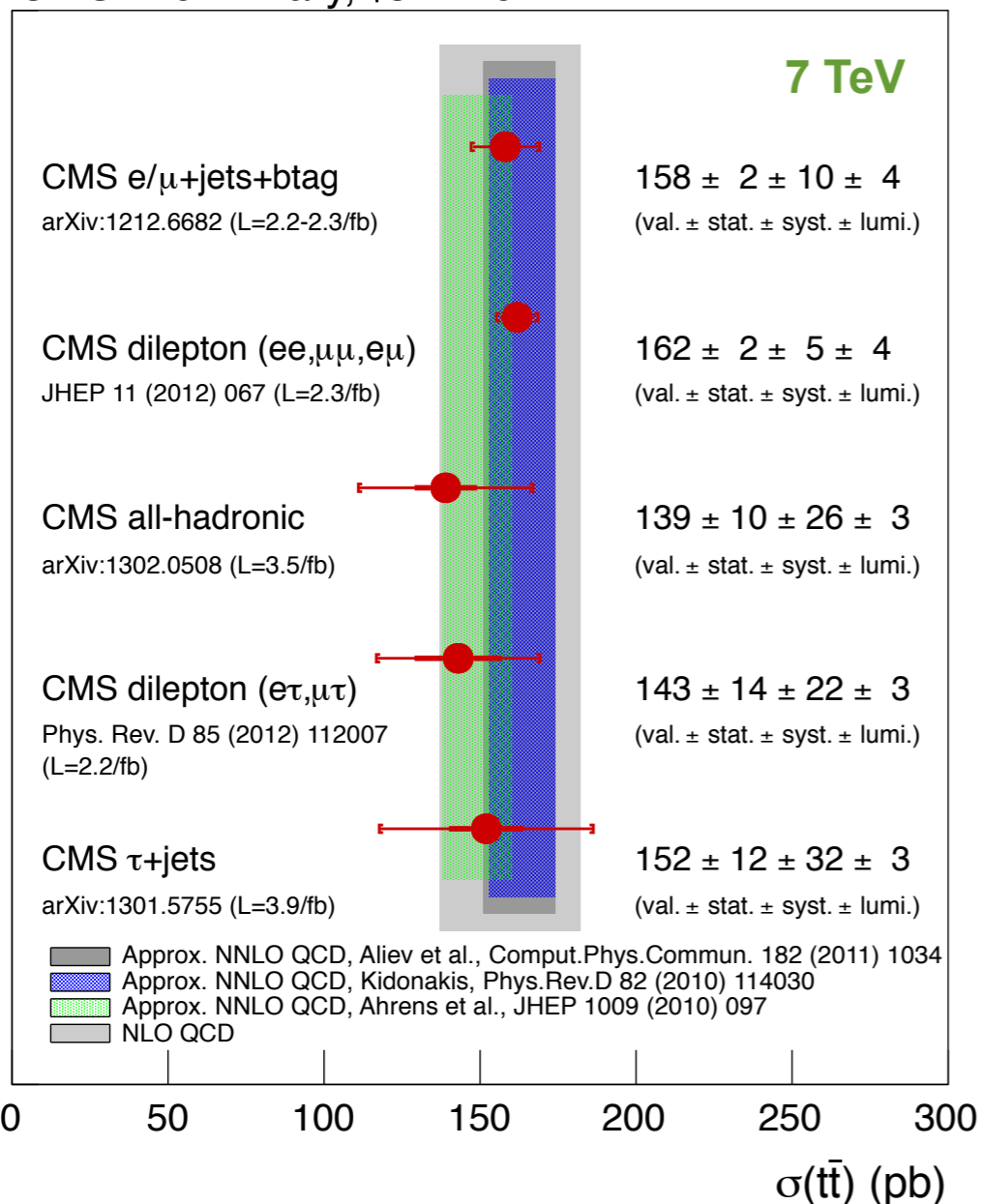
- $\tau + e/\mu$** : isolated e/μ + hadronic τ -candidate + 1 b-jet
- largest background: misreconstructed τ_{had} estimated from data

$$\sigma_{t\bar{t}} = 143 \pm 14 \text{ (stat.)} \pm 22 \text{ (syst.)} \pm 3 \text{ (lumi.) pb}$$

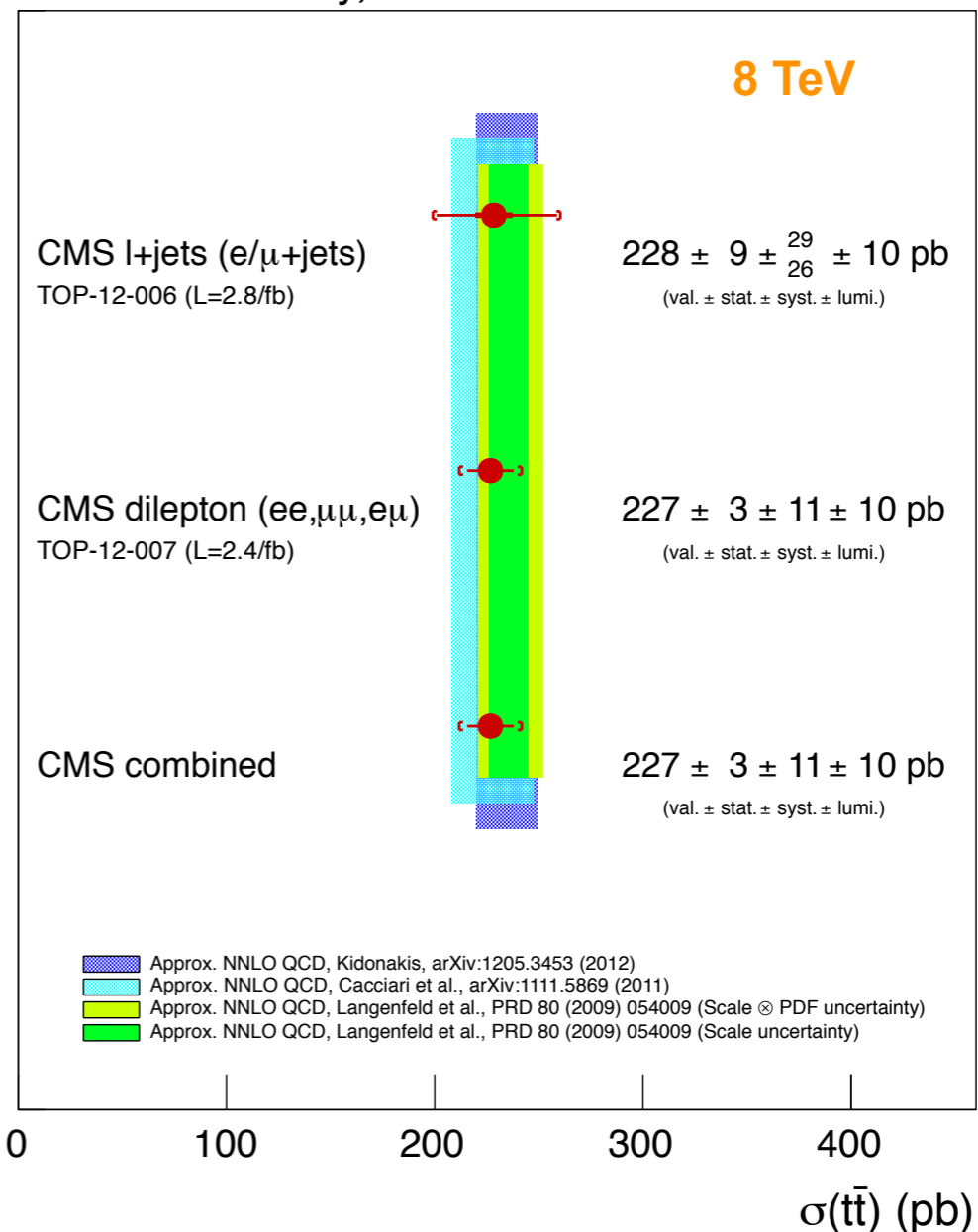
18%



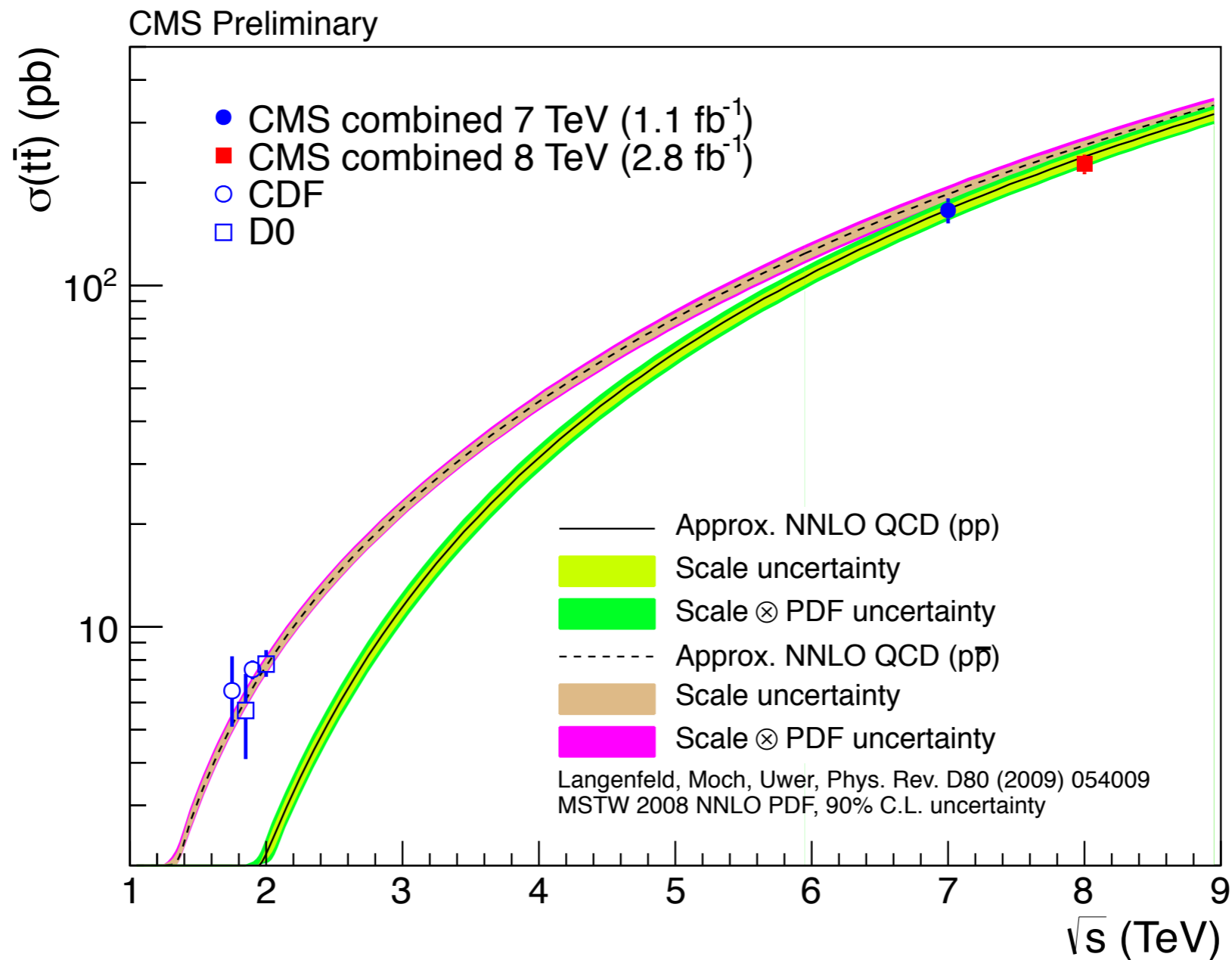
CMS Preliminary, $\sqrt{s}=7$ TeV



CMS Preliminary, $\sqrt{s}=8$ TeV



- Inclusive cross section measurements at 7 and 8 TeV consistent across all channels
- Experimental uncertainties <5-15% \rightarrow approaching/challenging theory precision



- Inclusive cross section measurements at 7 and 8 TeV consistent across all channels
- Experimental uncertainties $<5\text{-}15\%$ \rightarrow approaching/challenging theory precision

- Test pQCD in differential distributions in lepton + jets and dilepton channel

- check dependence on QCD scales, ME-PS matching, generators

- enhance sensitivity to new physics

- sensitive to pdf

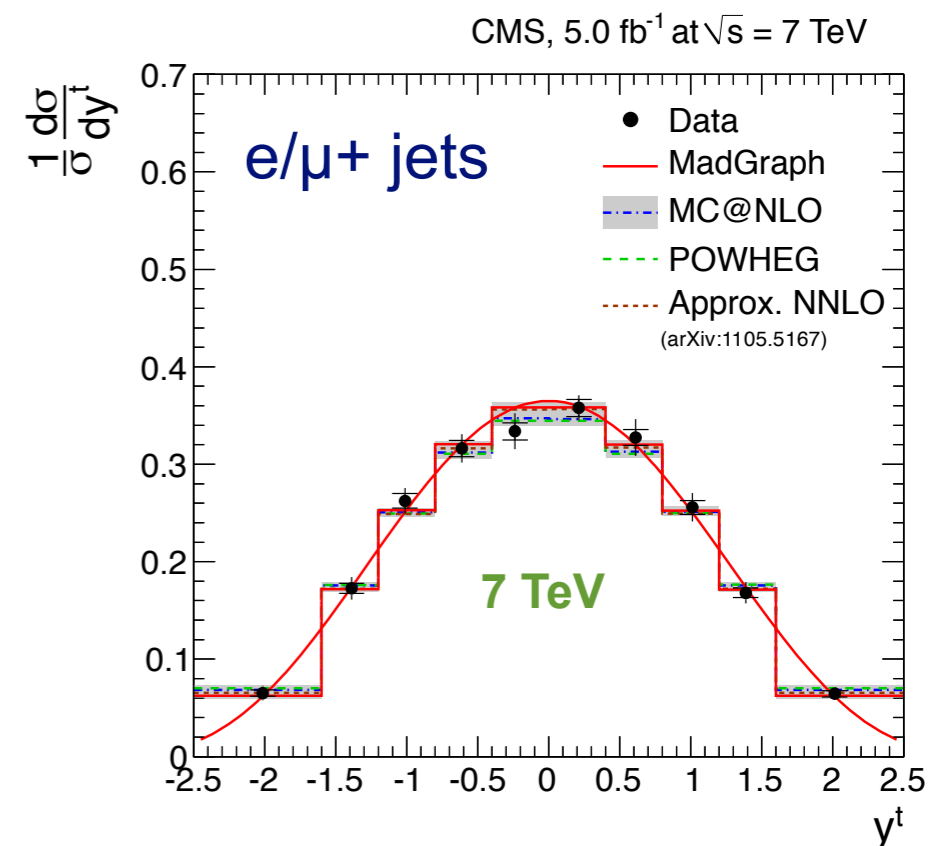
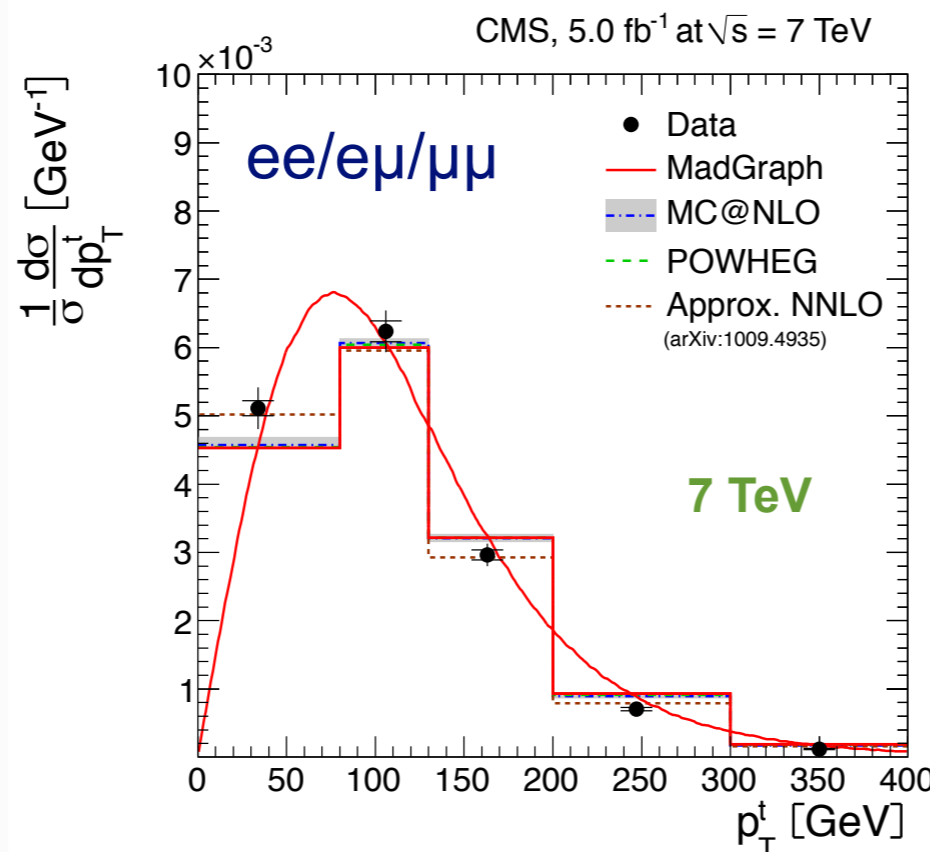
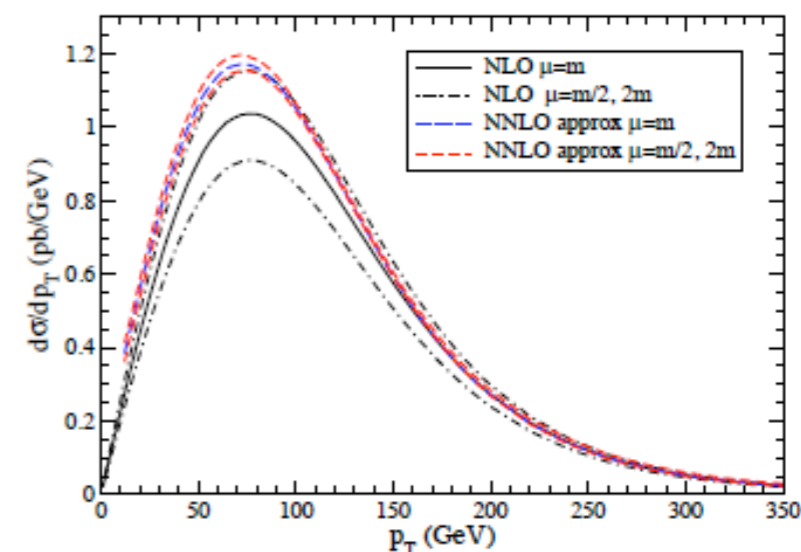
- Analysis ingredients:

- cross section measurement

- kinematic reconstruction

- unfolding (Singular Value Decomposition, NIM A 372 (1996) 469).

Kidonakis, arXiv:1009.4935 [hep-ph]
 $pp \rightarrow t\bar{t}$ at LHC $S^{1/2} = 7 \text{ TeV}$ $m = 173 \text{ GeV}$

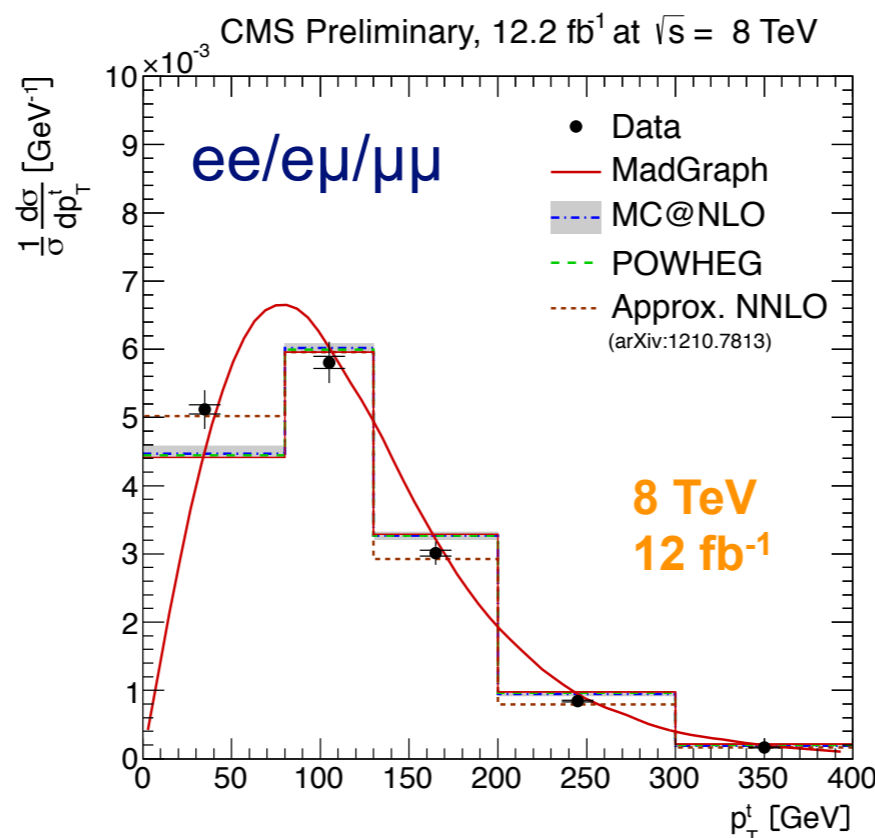
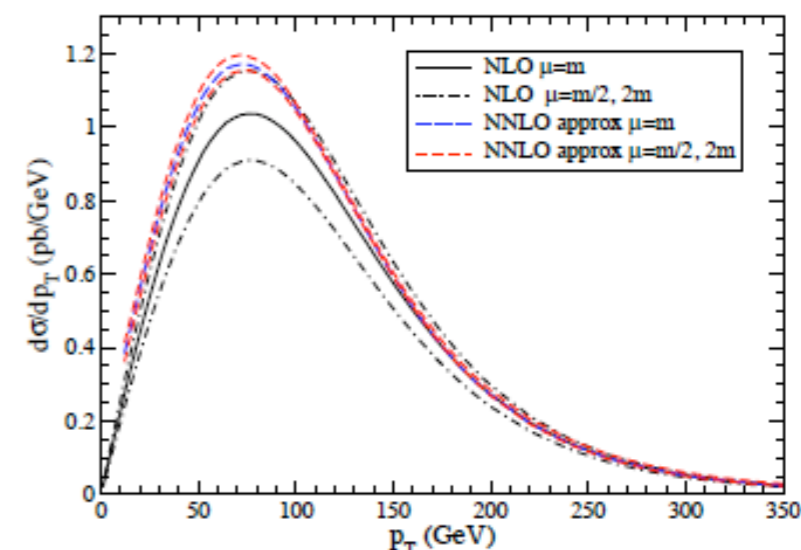


[arXiv:1211.2220](https://arxiv.org/abs/1211.2220)

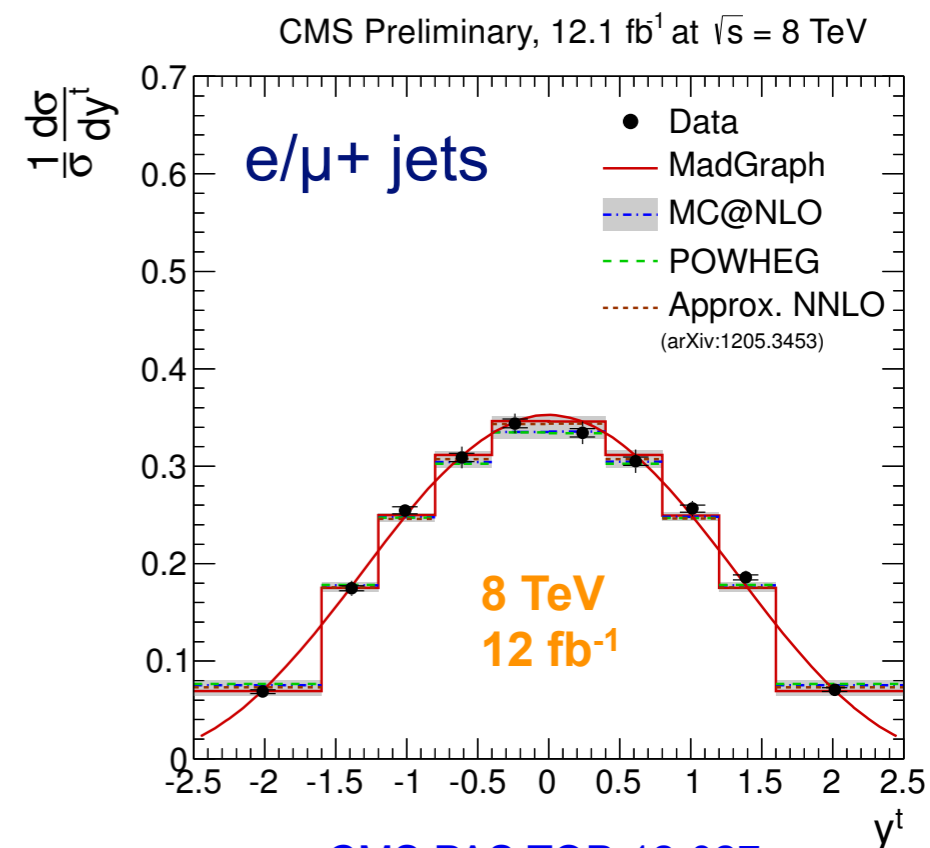
accepted by EPJC

- Test pQCD in differential distributions in lepton + jets and dilepton channel
 - check dependence on QCD scales, ME-PS matching, generators
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- Analysis ingredients:
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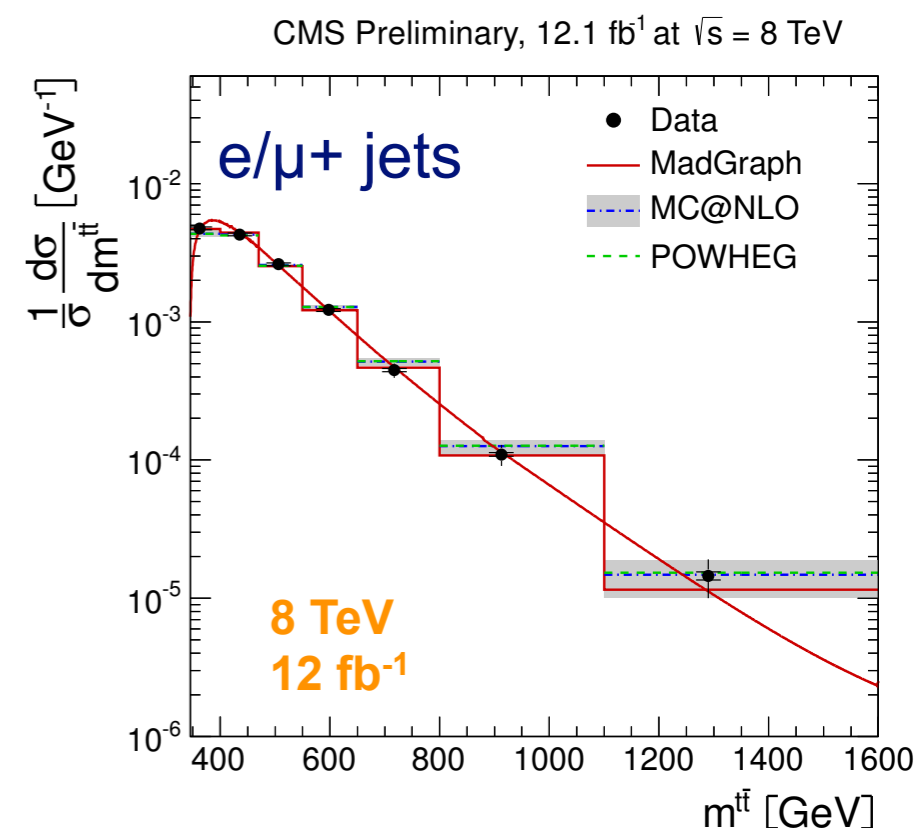
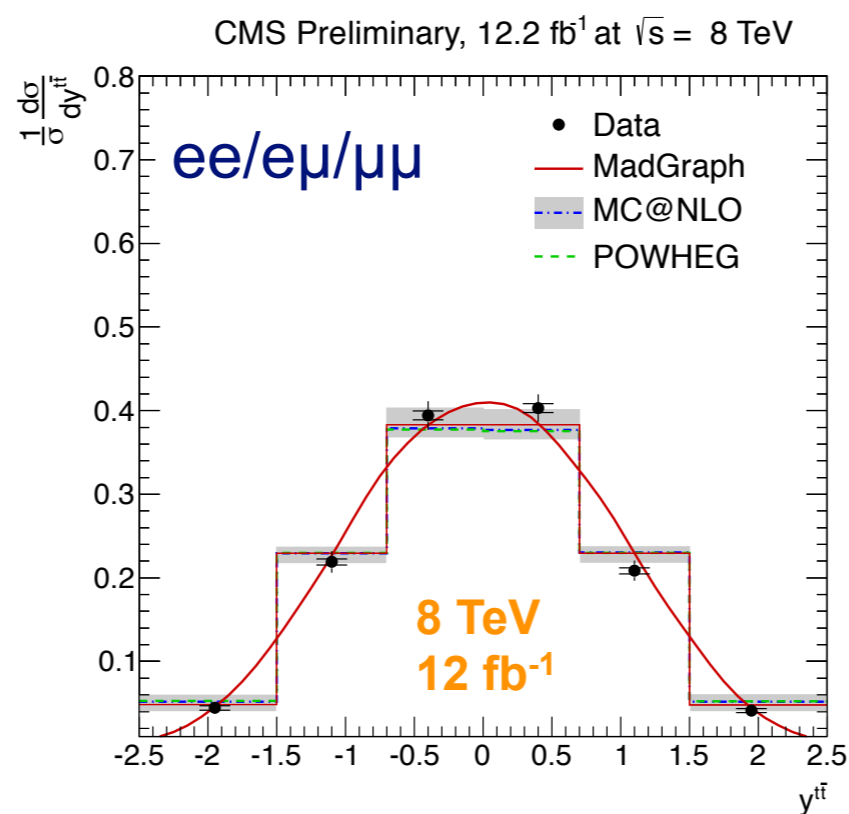
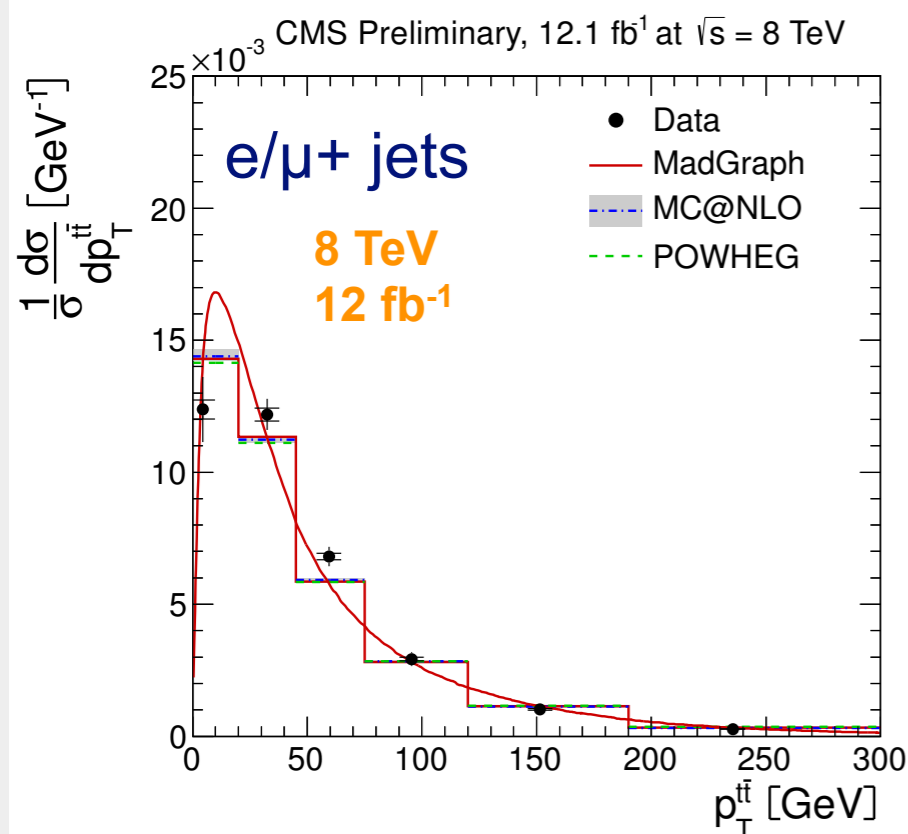


CMS PAS TOP-12-028



CMS PAS TOP-12-027

- Differential distributions determined in lepton + jets and dilepton channel
- unfolded and extrapolated to full phase space
- kinematic properties (p_T , y , m) of leading (and sub-leading) leptons, lepton pair, b-jets, top quarks, top quark pairs



- Good description between data and theory
- NNLO approx describes softer $p_T(t)$ spectrum in the data better



$t\bar{t} + X (1)$

- $t\bar{t} + \cancel{E}_T$: Verification of models of top production in $e/\mu +$ jets final state
- important background for BSM physics searches

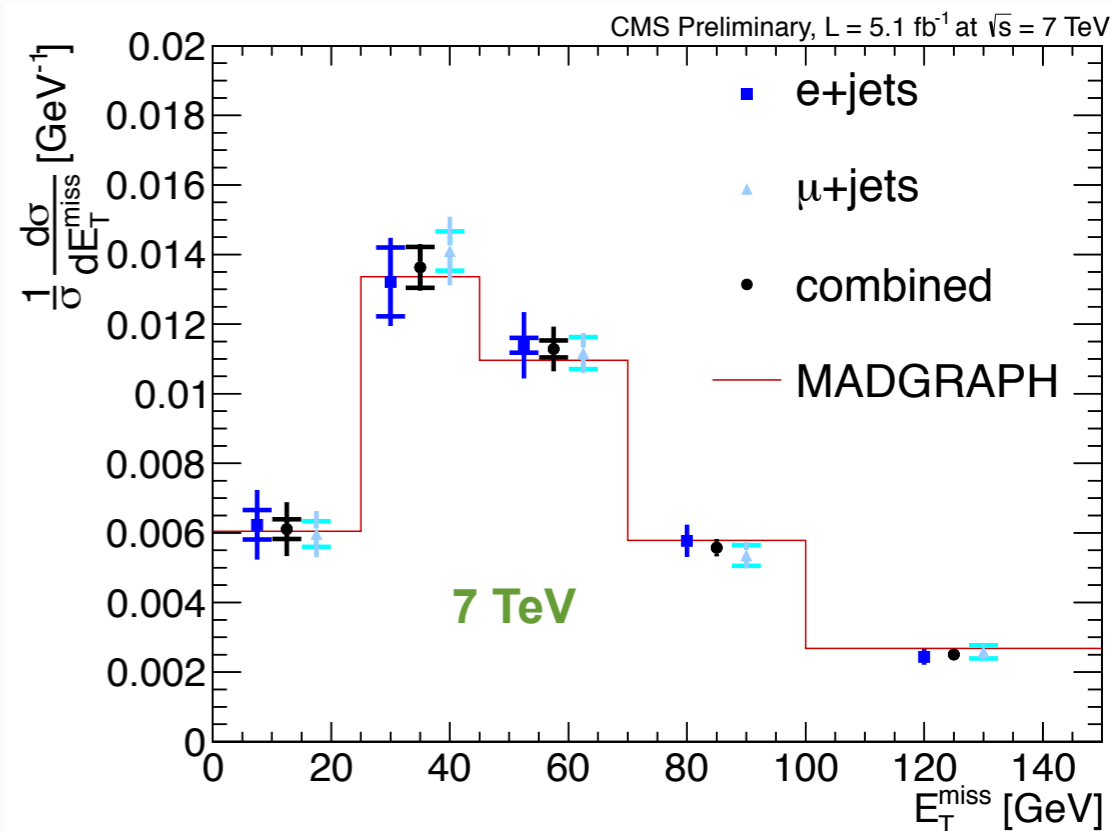
- $t\bar{t} + V$: $t\bar{t} + W$ (same-sign dilepton) & $t\bar{t} + Z$ (trilepton) established (4.7σ)

- access to top-vector-boson coupling
- important background to SUSY and BSM searches

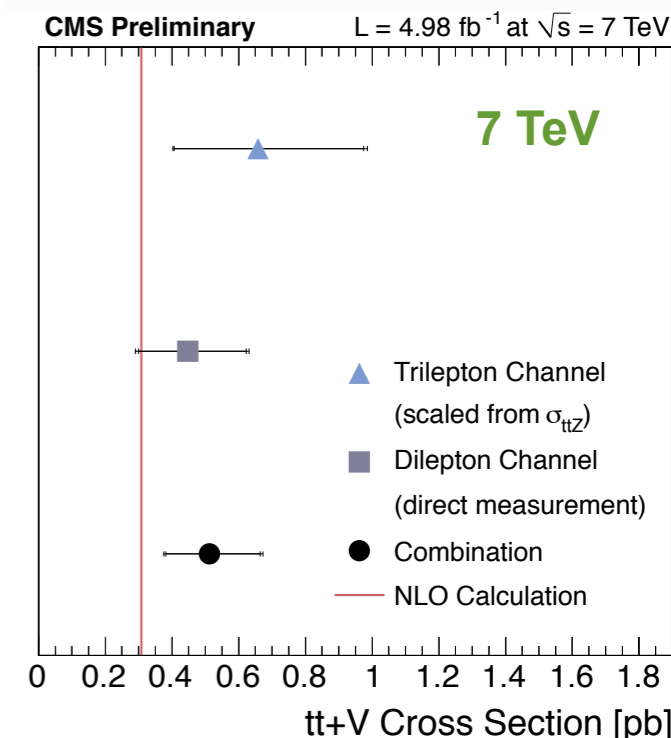
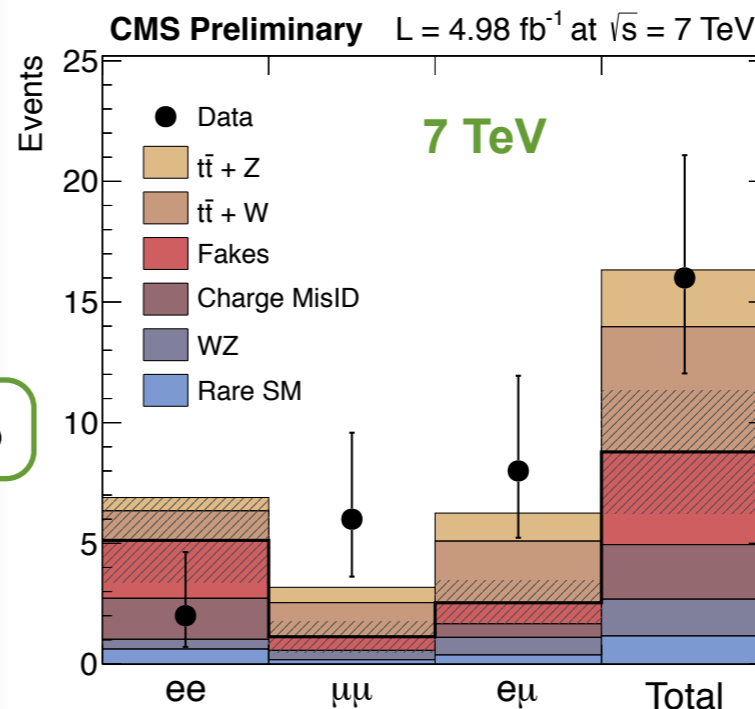
$$\sigma_{t\bar{t}V} = 0.51^{+0.15}_{-0.13} \text{ (stat.) } ^{+0.05}_{-0.04} \text{ (syst.) pb}$$

30%

CMS PAS TOP-12-019



CMS PAS TOP-12-014



- $t\bar{t}$ +jets: jet multiplicity in $t\bar{t}$ dilepton final state

- QCD radiation
- Test of event generator, final state model and QCD scales

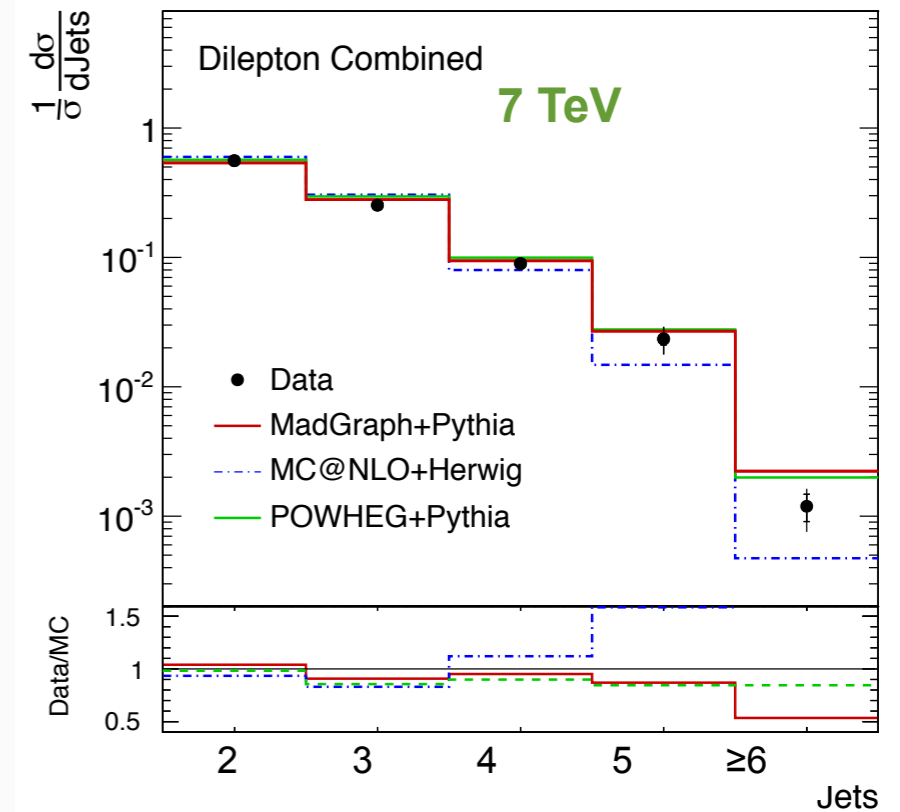
- $t\bar{t}$ + $b\bar{b}$: Ratio of light flavor to b-flavored jets (dilepton final state)

- important background to $t\bar{t}H$ search

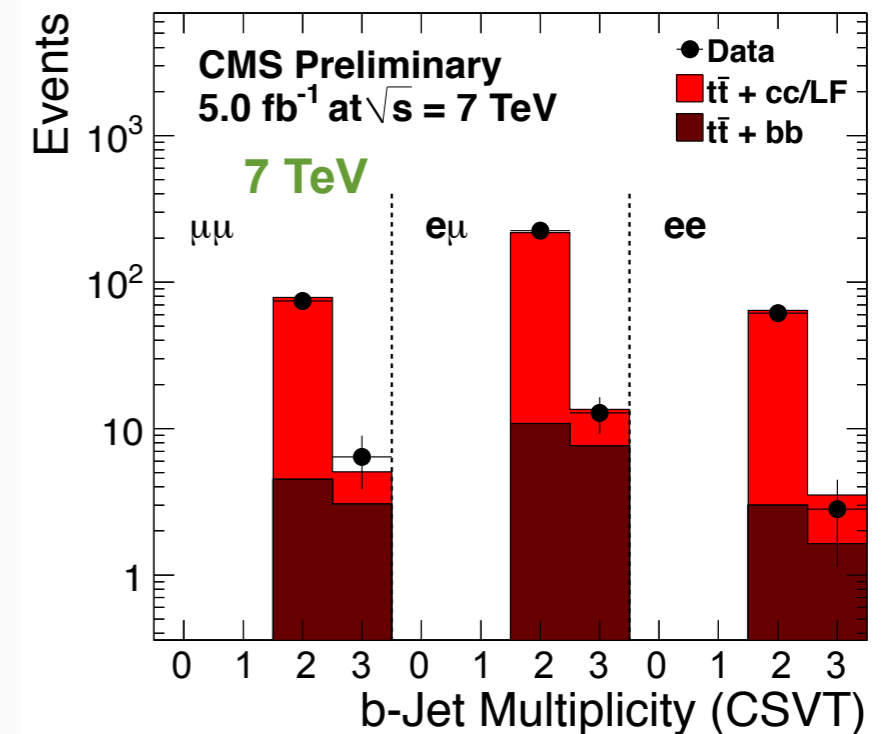
$$\frac{\sigma(t\bar{t}b\bar{b})}{\sigma(t\bar{t}jj)} = 3.6 \pm 1.1_{stat} \pm 0.9_{syst} \%$$

CMS PAS TOP-12-023

CMS Preliminary, 5.0 fb⁻¹ at $\sqrt{s}=7$ TeV



CMS PAS TOP-12-024

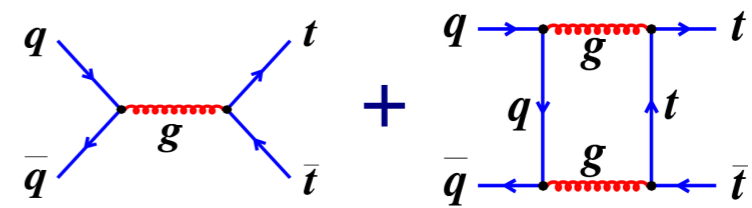


Top Production Charge Asymmetry

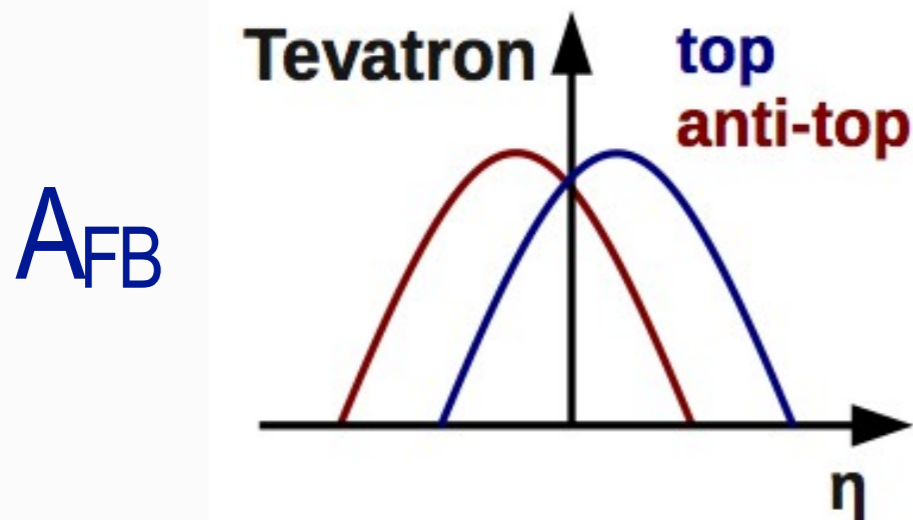
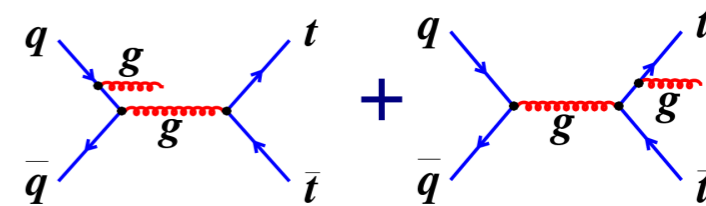
Top production A_{FB}/A_C

- Contribution from $q\bar{q}$ only
 - LO: no charge asymmetry expected
 - NLO: Interference between $q\bar{q}$ diagrams
 - correlates (anti-)top quark direction with incoming (anti-) quark direction

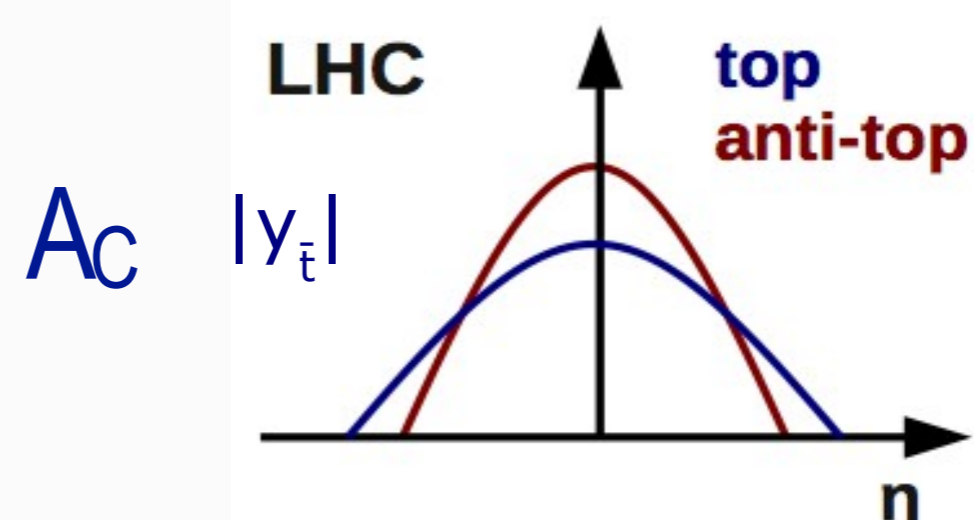
tree-level and box diagrams: positive asymmetry



ISR/FSR: negative asymmetry



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



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

Tevatron: Forward/backward asymmetry

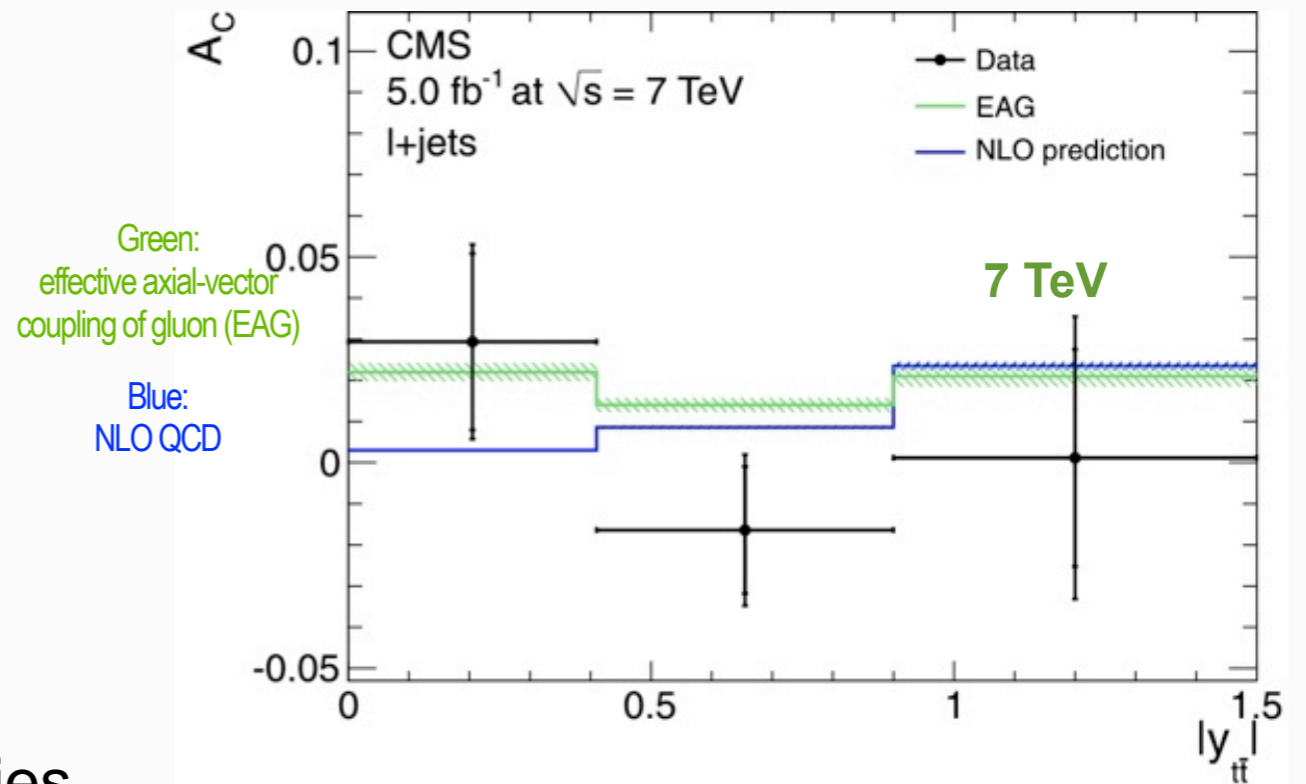
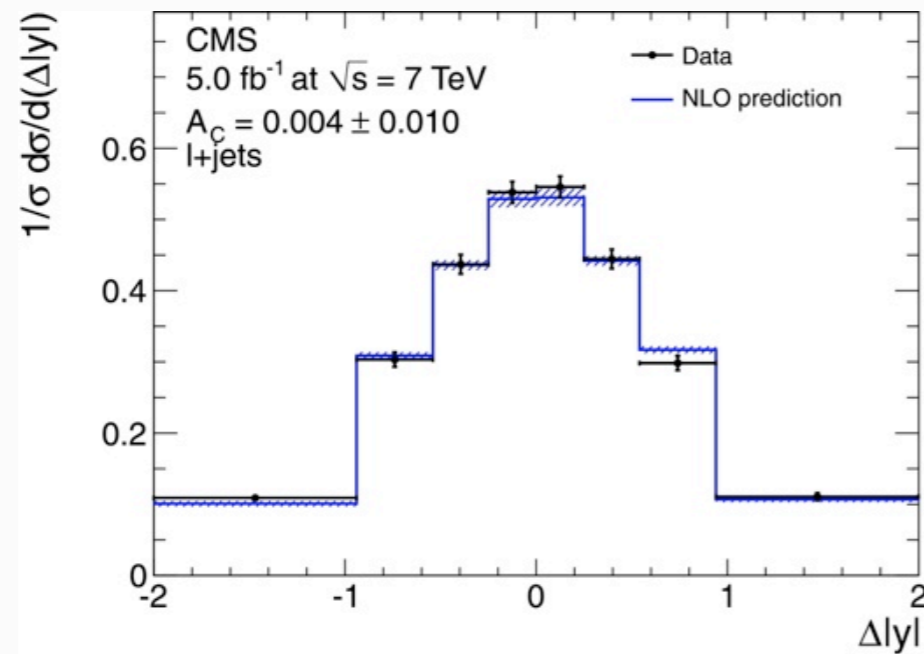
- asymmetric initial state correlates top quark to proton direction

LHC: Charge asymmetry

- top is correlated to valence quark
- A_C diluted due to large gg component

Charge Asymmetry (e/ μ +jets)

Phys. Lett. B717 (2012) 129



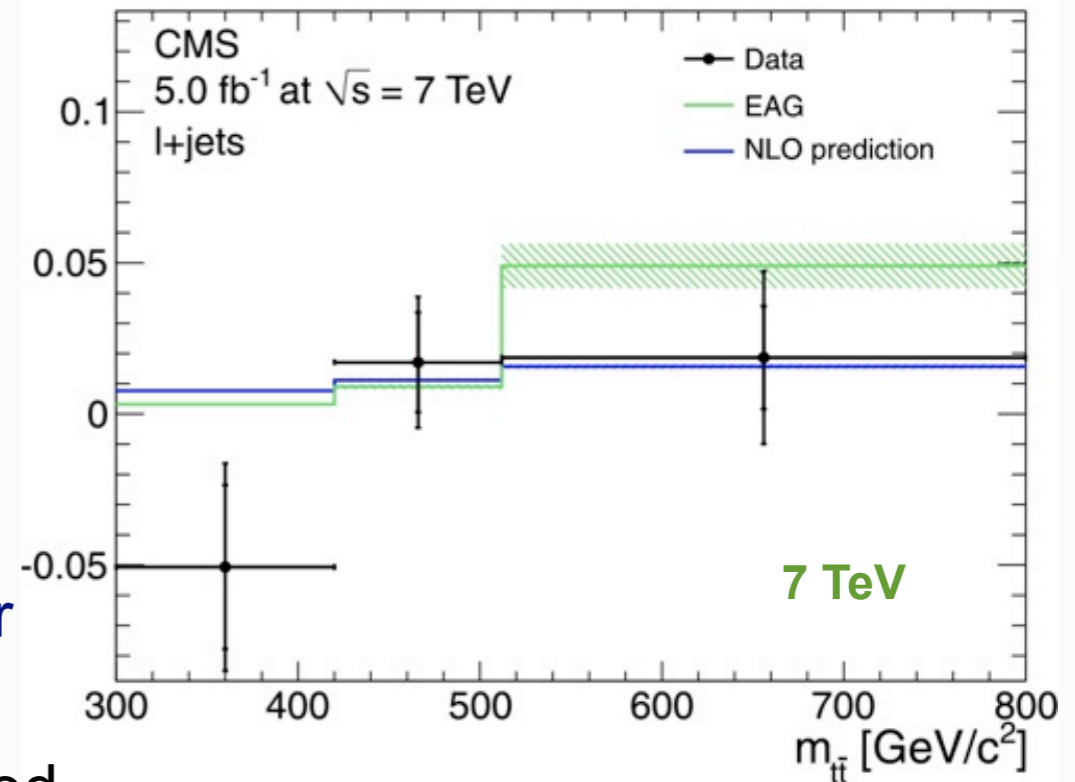
- Inclusive and differential measurement
- careful treatment of intrinsic asymmetries in backgrounds (W+ jets, QCD)

$$A_C = 0.004 \pm 0.010 \text{ (stat.)} \pm 0.011 \text{ (syst.)}$$

- Theory prediction:
 $A_C^{thy} = 0.015 \pm 0.0006$ Kühn, Rodrigo arXiv:1209.6830

- Comparison with NLO and effective axial-vector gluon BSM model
E. Gabrielli et al. PRD 85 (2012) 074021

- No large deviations from SM - more data needed



- Inclusive analysis in the dilepton channel:

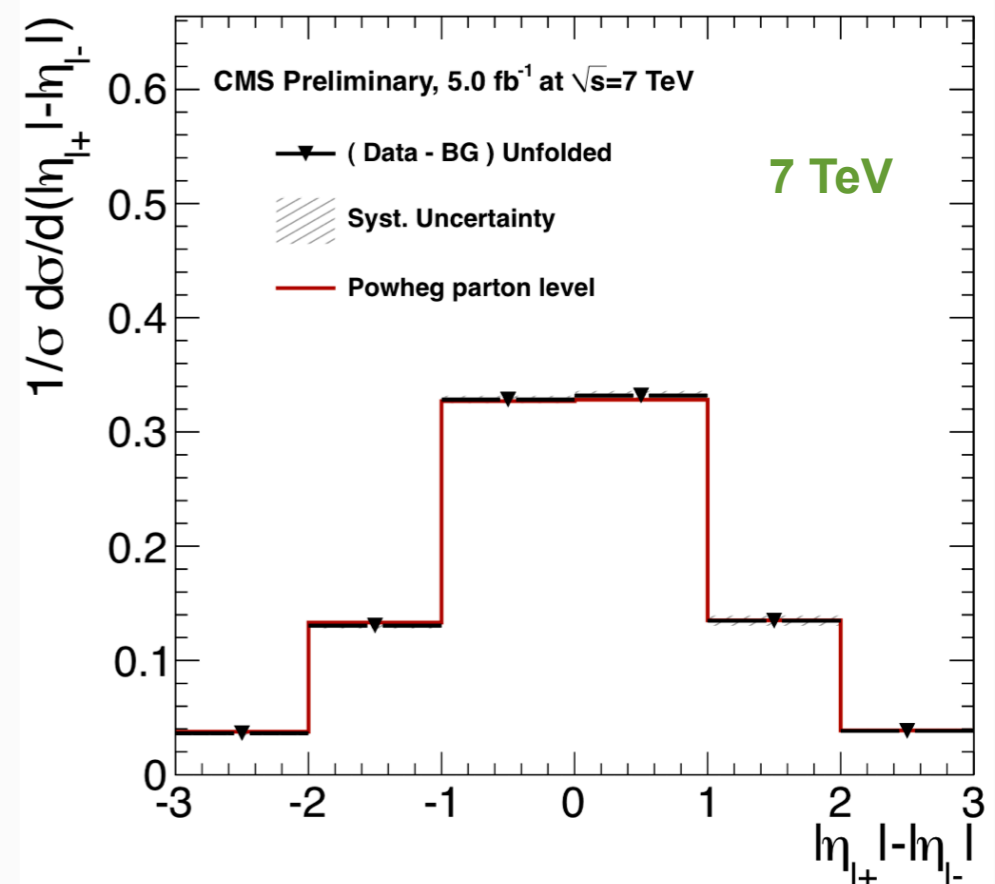
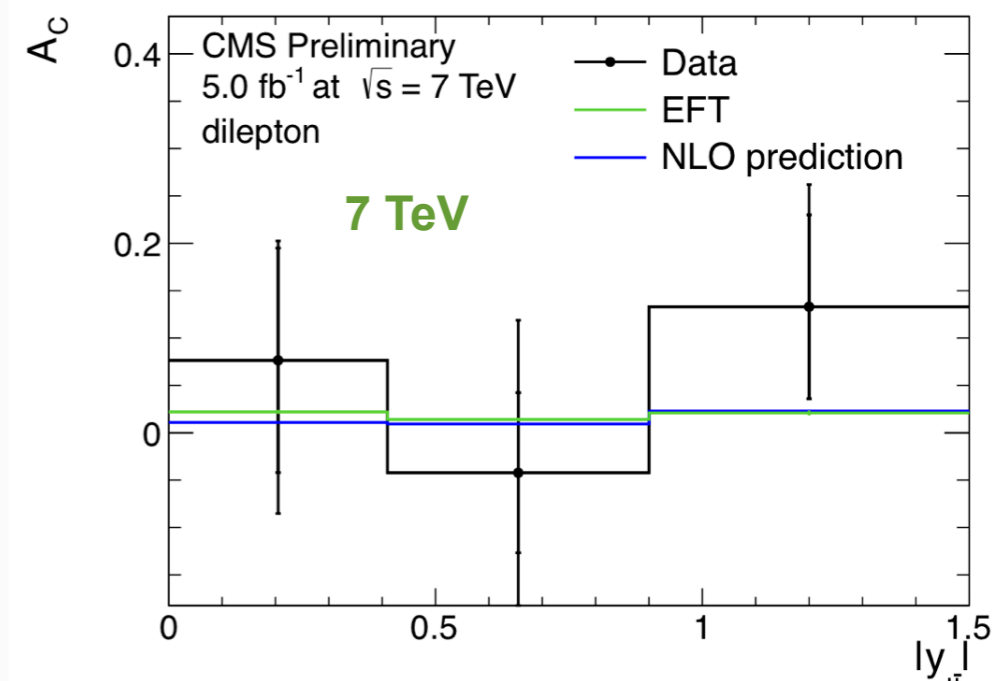
$$A_C = 0.050 \pm 0.043 \text{ (stat.) } {}^{+0.010}_{-0.039} \text{ (syst.)}$$

- Alternative approach using lepton charge asymmetry: Krohn et al. PRD D84 (2011) 074034

$$A_{lepC} = \frac{N(|\eta_{l+}| > |\eta_{l-}|) - N(|\eta_{l+}| < |\eta_{l-}|)}{N(|\eta_{l+}| > |\eta_{l-}|) + N(|\eta_{l+}| < |\eta_{l-}|)}$$

$$A_{lepC} = 0.010 \pm 0.015 \text{ (stat.) } \pm 0.006 \text{ (syst.)}$$

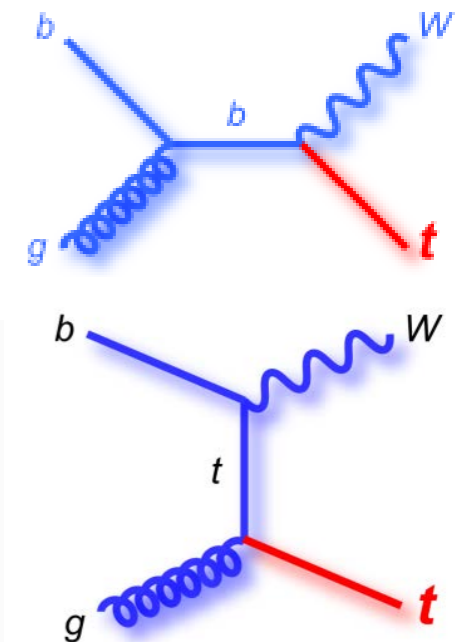
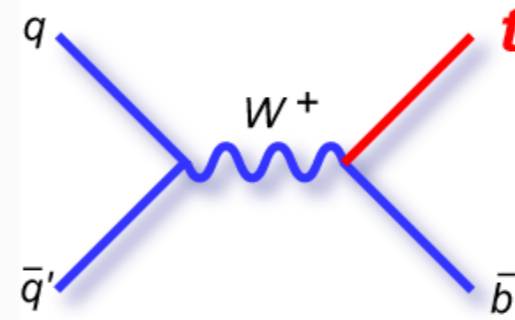
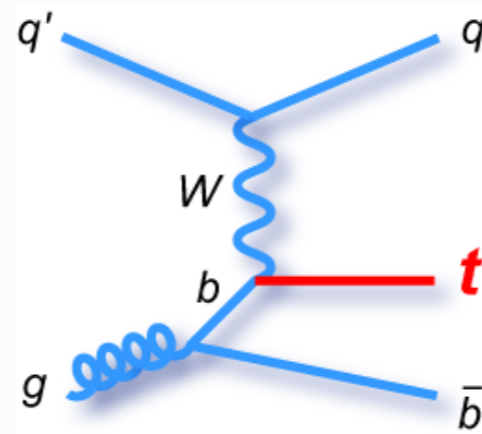
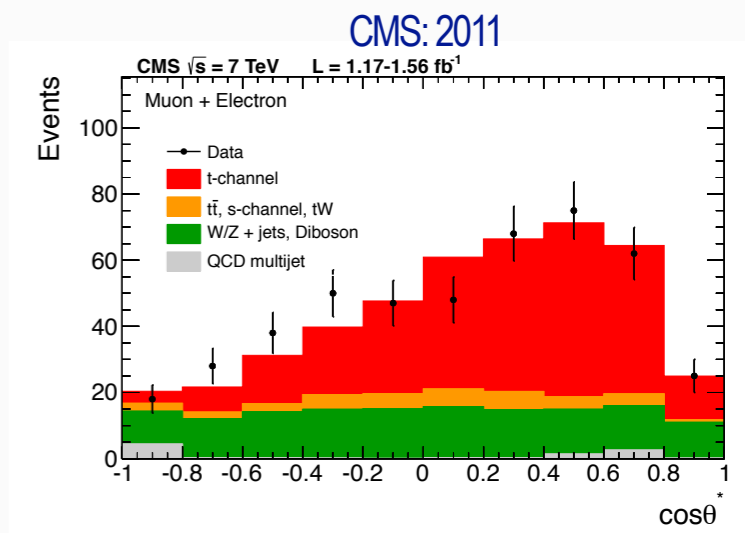
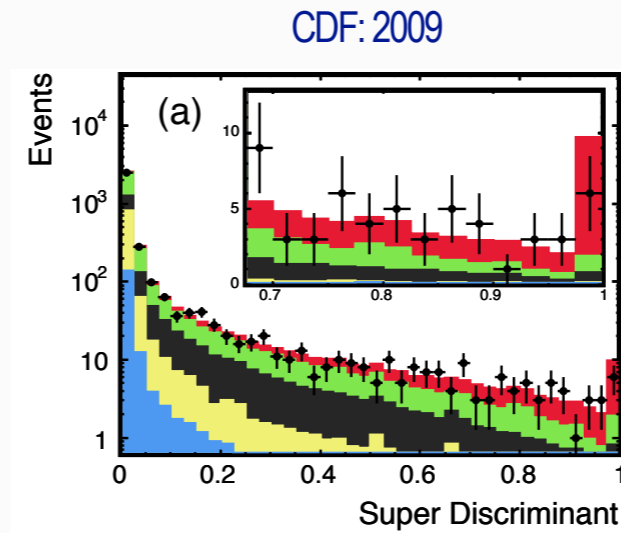
- Compatible with SM - more data needed.



[CMS PAS TOP-12-010](#)

Single Top Cross Section

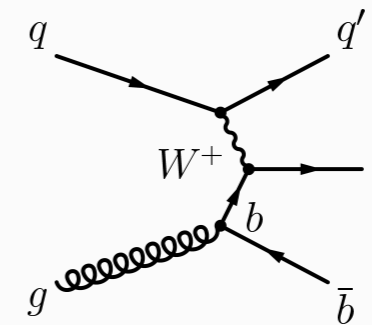
- Test of EW interactions
- Probe for new physics
- measure V_{tb}
- 4th generation
- FCNC
- sensitivity to b-PDF and u/d-PDF
- t and Wt channel
- Main backgrounds
 - W+jets background
 - top pair production
 - QCD multi-jet production



Predictions	t-channel (σ_{tqb})	s-channel (σ_{tb})	tW-channel
Tevatron	2.26 pb	1.04 pb	0.28 pb
LHC (7 TeV)	64.6 pb	4.6 pb	15.7 pb

N. Kidonakis, Phys. Rev. D 83, 091503(R) (2011); Phys. Rev. D 81, 054028 (2010); Phys. Rev. D 82, 054018 (2010)

- Signature: (b,l,v)+1 forward jet
- Analysis performed in #jet (2-4)/#b-tag (0-2) bins
- Three analysis approaches:

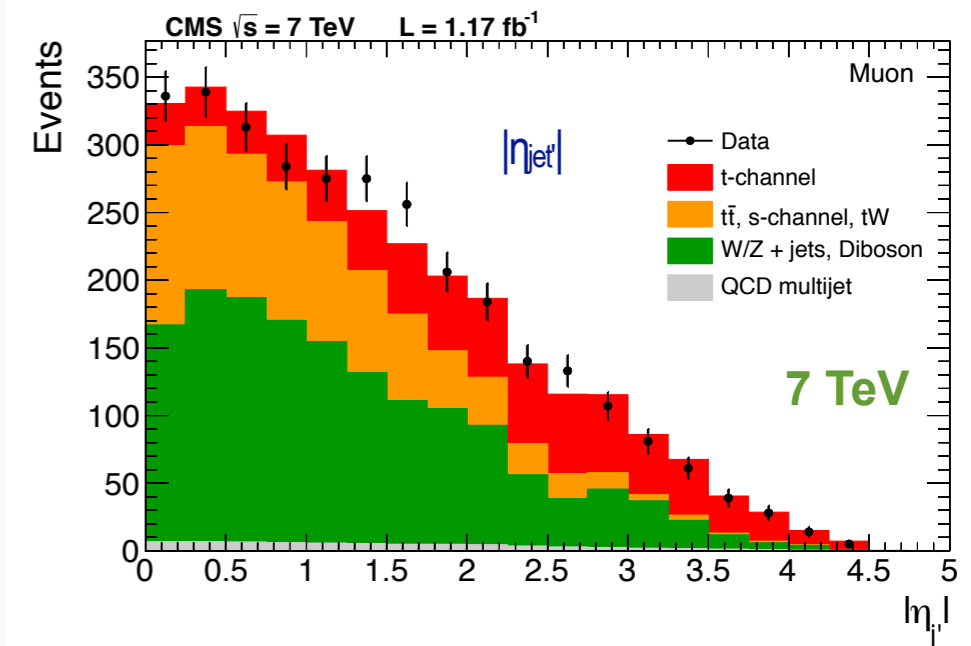


[JHEP 12 \(2012\) 035](#)

- $|\eta_j|$: maximum likelihood fit to the pseudorapidity of forward jet
- multivariate discriminants (NN, BDT)

Dominant backgrounds:

- suppress EWK background
 - $M_T(W) > 40$ GeV for $W \rightarrow \mu\nu$
 - $\cancel{E}_T > 35$ GeV for $W \rightarrow e\nu$
- Determine $W+$ jets from $M(lvb)$ sideband
- QCD from fits to $M_T(W)[\mu]$ and $\cancel{E}_T[e]$



Combination of three analyses with BLUE:

$$\sigma_{t-ch.} = 67.2 \pm 6.1 \text{ pb}$$

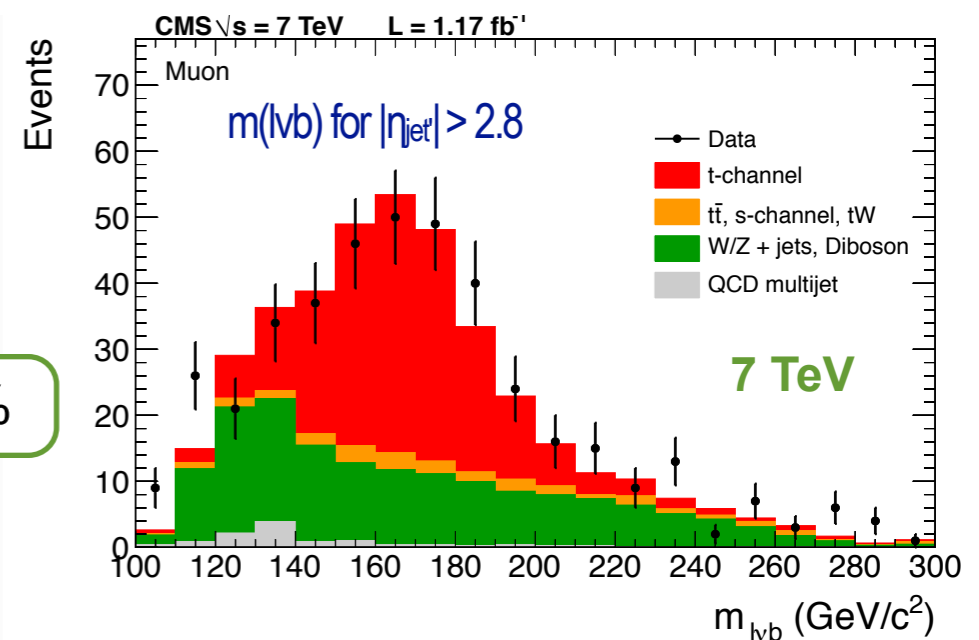
9%

Extraction of V_{tb} :

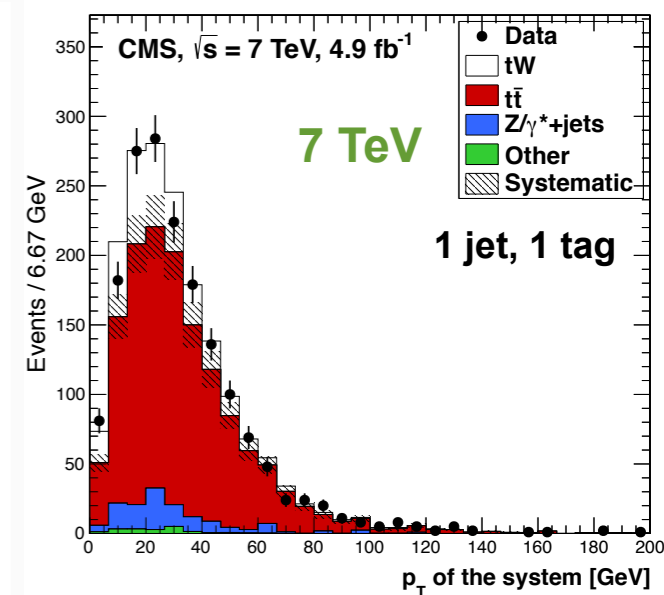
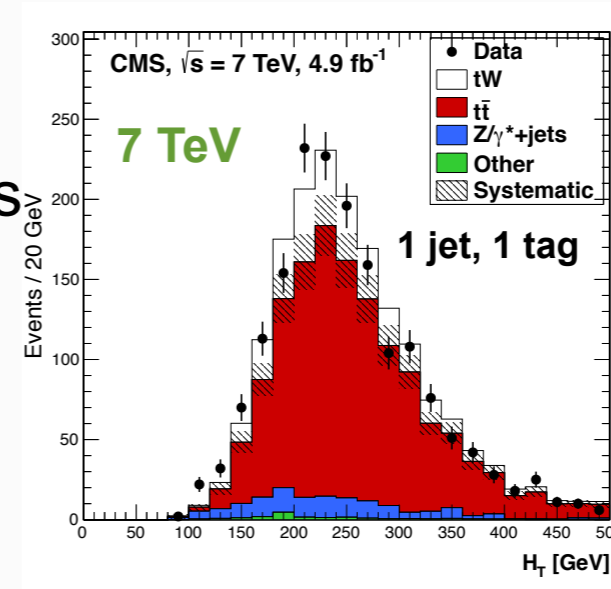
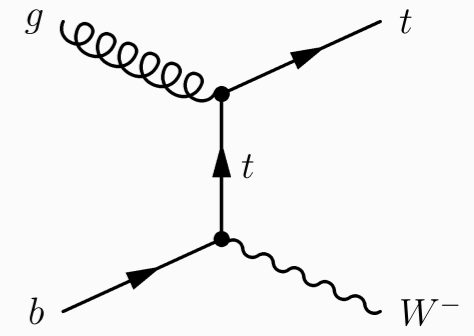
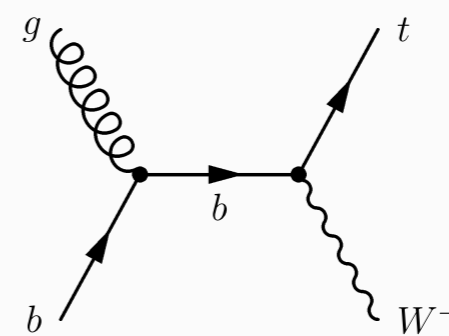
$$|V_{tb}| = 1.020 \pm 0.046 \text{ (meas.)} \pm 0.017 \text{ (theor.)}$$

$$0.92 < |V_{tb}| \leq 1, \text{ at 95\% confidence level}$$

5%



- significant production mode at the LHC
- dilepton ee/μμ/εμ
- opposite charge from 2 Ws
- signal: exactly one b-tagged jet
background (tt): 2 jets, 1 or 2 b-tags
- major background tt̄
- estimated from background side bands
- simultaneous fit of BDT discriminant in signal region for 3 flavor combinations and event yields of control regions

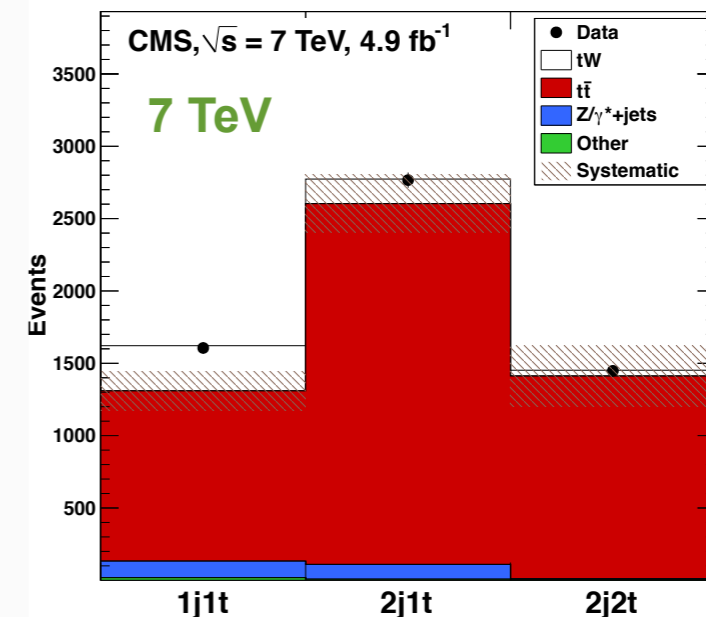


Phys. Rev. Lett. 110 (2013) 022003

- signal firmly established (4σ):

$$\sigma_{tW} = 16^{+5}_{-4} \text{ pb} \quad 30\%$$

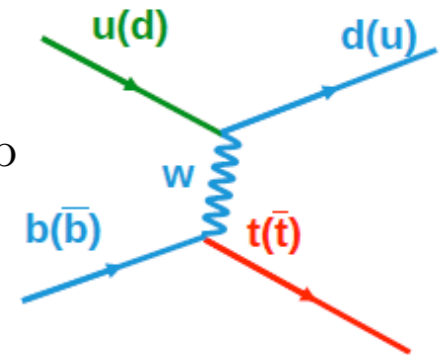
- compatible with Standard Model



Single Top t-channel (8 TeV)

- single top/anti-top t-channel production depends on u/d pdf
- lepton charge (+/-) correlated with u(d) pdf
- Theoretical prediction: $\sigma_{t\text{-ch, theory}} = 56.4 \text{ pb (top)} + 30.7 \text{ pb (anti-top)} = 87.1 \text{ pb}$

N. Kidonakis, arXiv:1205.3453



$$\sigma_{t\text{-ch}} = 80.1 \pm 5.7 \text{ (stat.)} \pm 11.0 \text{ (syst.)} \pm 4.0 \text{ (lumi.) pb}$$

16%

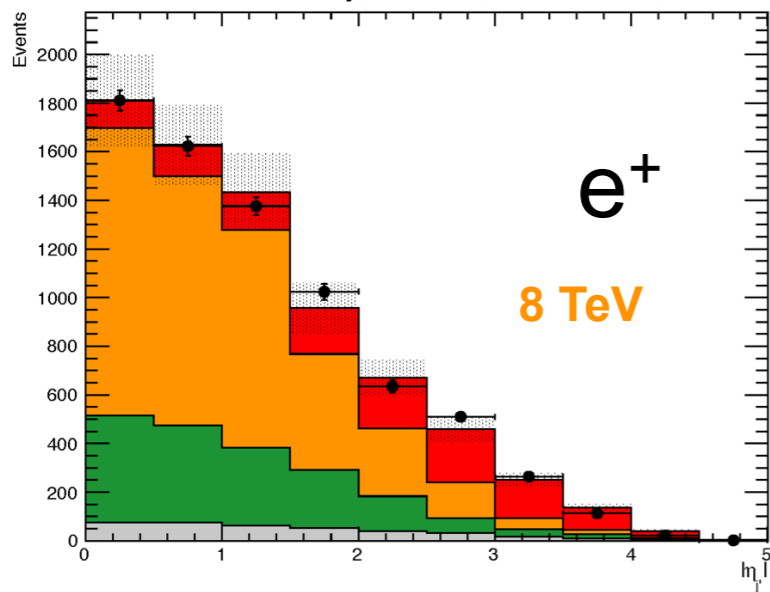
[CMS PAS TOP-12-011](#)

- perform $|\eta_j|$ analysis separately by lepton charge

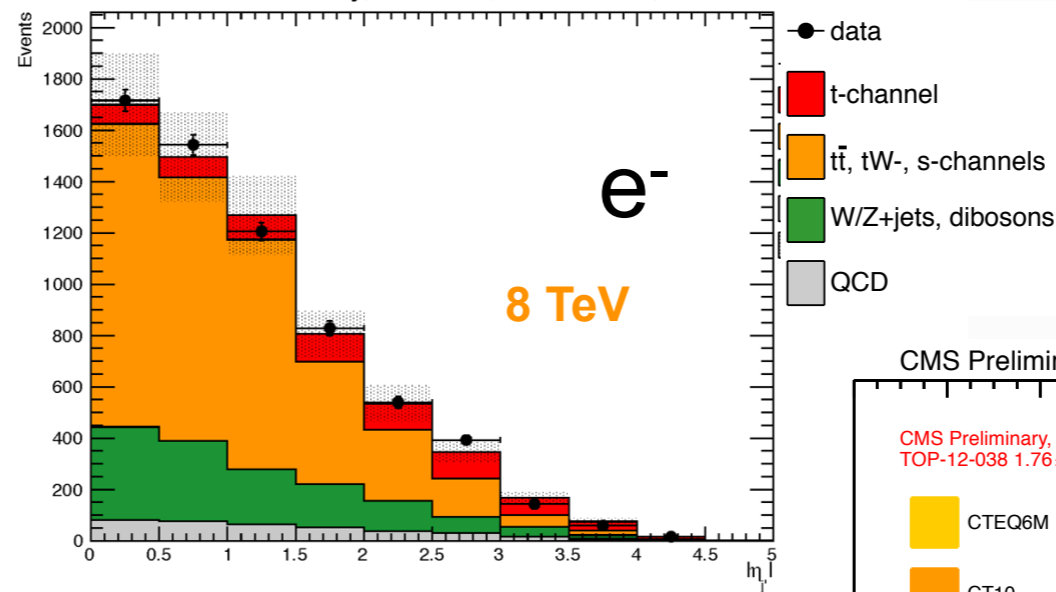
[CMS PAS TOP-12-038](#)



CMS Preliminary, 12.2 fb⁻¹, Electrons +, $\sqrt{s} = 8 \text{ TeV}$



CMS Preliminary, 12.2 fb⁻¹, Electrons -, $\sqrt{s} = 8 \text{ TeV}$



$$\sigma_{t\text{-ch, t}} = 49.6 \pm 2.0 \text{ (stat.)} \pm 8.8 \text{ (syst.) pb}$$

28%

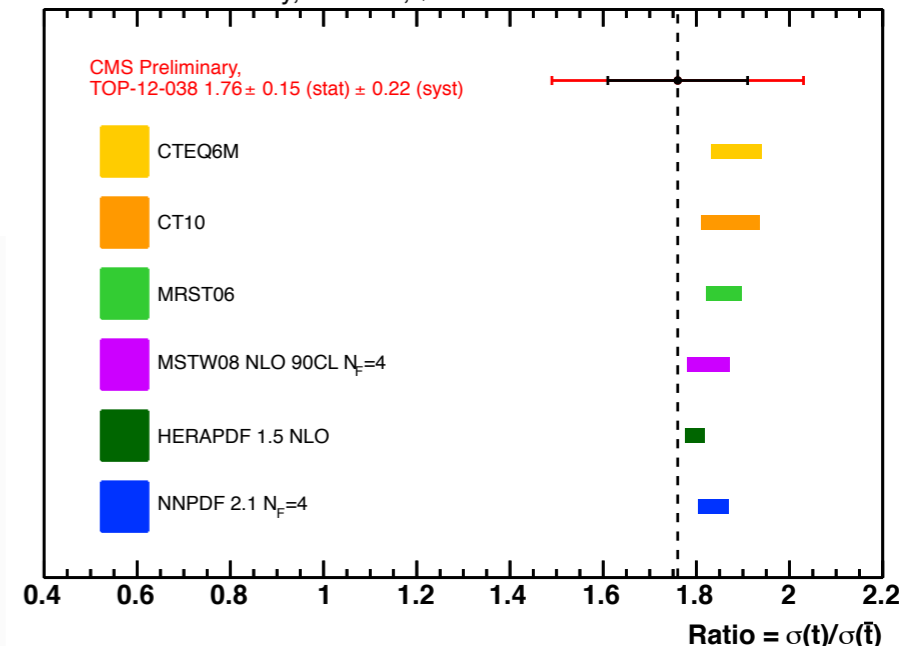
$$\sigma_{t\text{-ch, t-bar}} = 28.2 \pm 2.2 \text{ (stat.)} \pm 4.8 \text{ (syst.) pb}$$

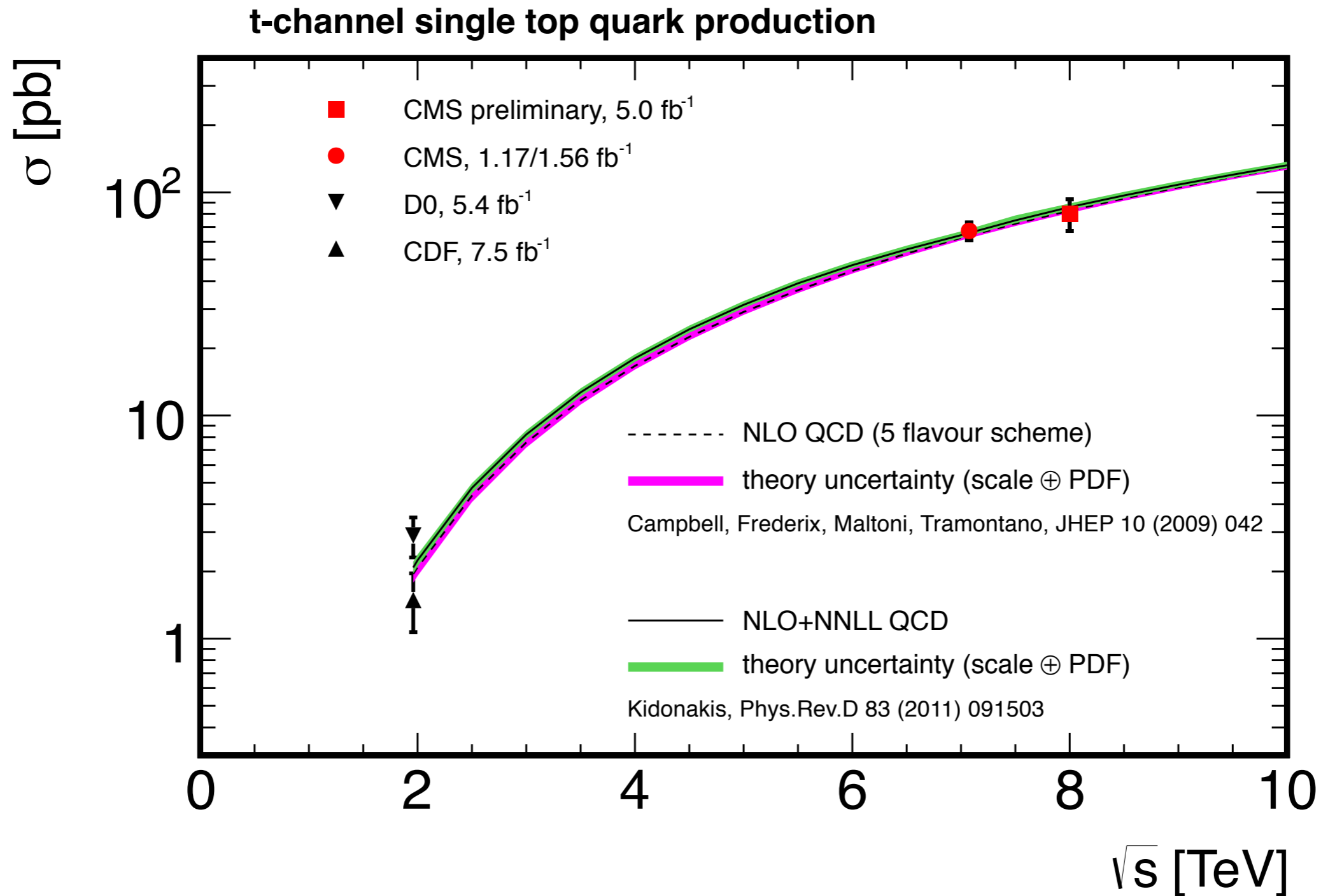
18%

$$R_{t\text{-ch}} = 1.76 \pm 0.14 \text{ (stat.)} \pm 0.21 \text{ (syst.)}$$

19%

CMS Preliminary, 12.2 fb⁻¹, $\sqrt{s} = 8 \text{ TeV}$





Good agreement with NNLO (approx) theory

- Precision era of top physics at the LHC in full swing**
 - inclusive cross section measurements (CMS dilepton 5%) compete with theory precision
 - Differential cross section measurements probe pQCD further
 - new results at $\sqrt{s} = 8$ TeV
 - Measurements of $t\bar{t}+X$ (jets, b-jets, \cancel{E}_T , W/Z) at 7 TeV
 - important SM backgrounds, access to couplings, SM test
 - Top charge asymmetry A_C complementary to A_{FB} at Tevatron
 - no large deviation from SM observed
 - Single top production measurements enter precision regime
 - new charge dependent t-channel result at $\sqrt{s} = 8$ TeV

- Many more measurements to come @ $\sqrt{s} = 8$ TeV!**