Top quark production

LHCP 2014

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Hosted by:
Brookhaven National Laboratory
Columbia University

Mara Senghi Soares

on behalf of
ATLAS,CDF,CMS,D0
Collaborations

Outlook

- Introduction
- Single-top production
  - tW-channel
  - s-channel
  - t-channel
- tt production
  - inclusive cross section
  - differential cross section
  - associated ttV and ttγ production
- Summary and conclusions

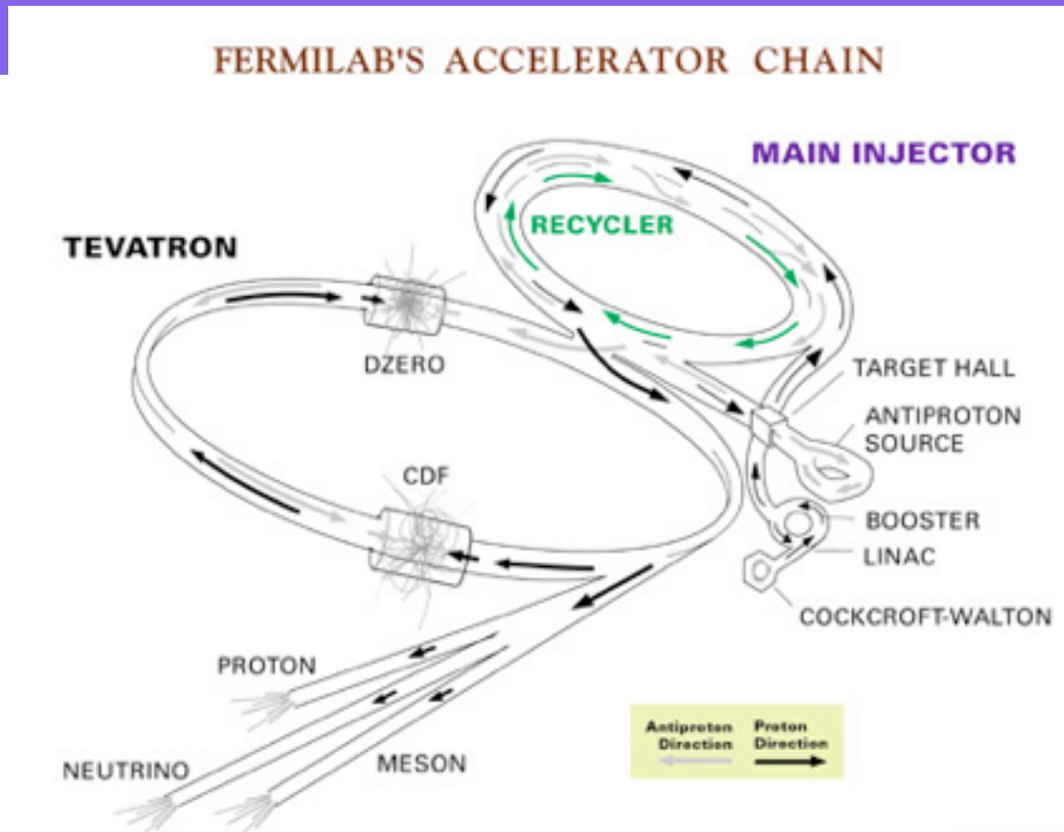
This talk presents a compilation of top production results

For details see also talks from

- Hao Liu: **Top quark production at the Tevatron**
- J.Enrique Garcia Navarro: **Single top quark production cross section in ATLAS**
- Gabriele Benelli: **Top quark production with CMS**
- John Morris: **Top quark pair production cross section in ATLAS**
- Boris Mangano: **Measurements of ttbar events with additional particles in the final state**
- Willian Bell: **W/Z/ttbar+jets**

Introduction

Tevatron and LHC status



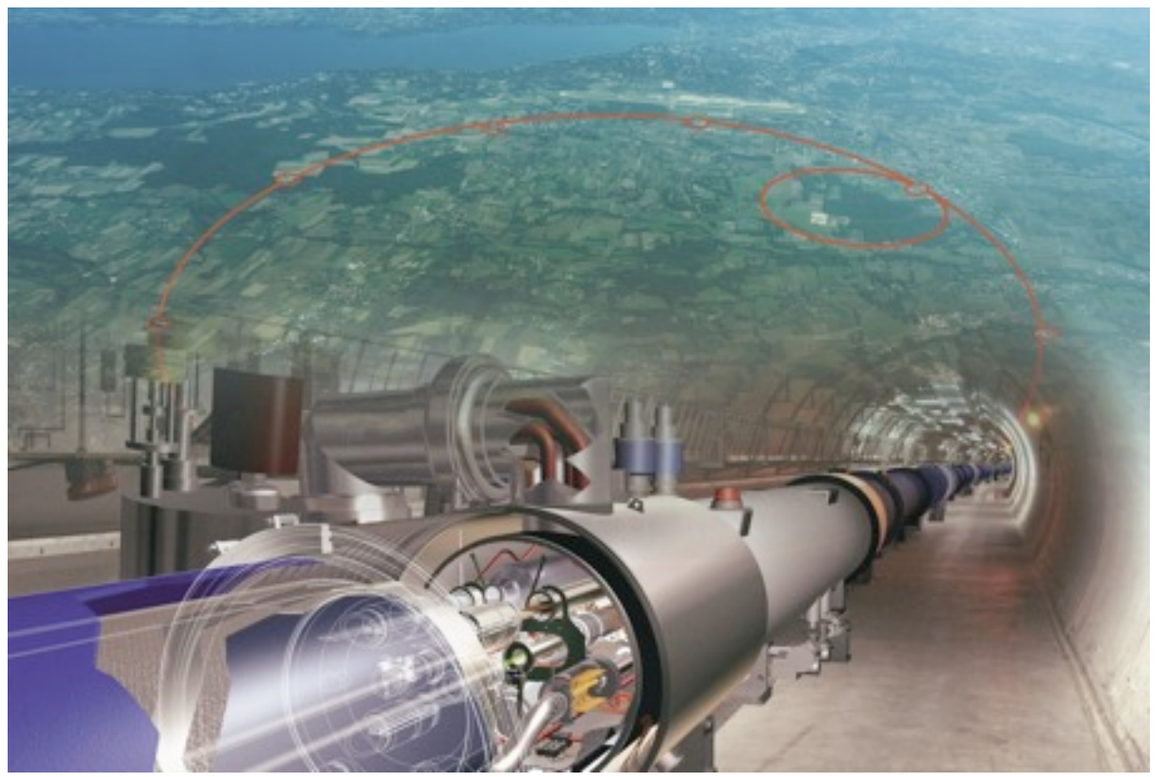
Tevatron (CDF and DO Collab)

$p\bar{p}$ collider at 1.96 TeV

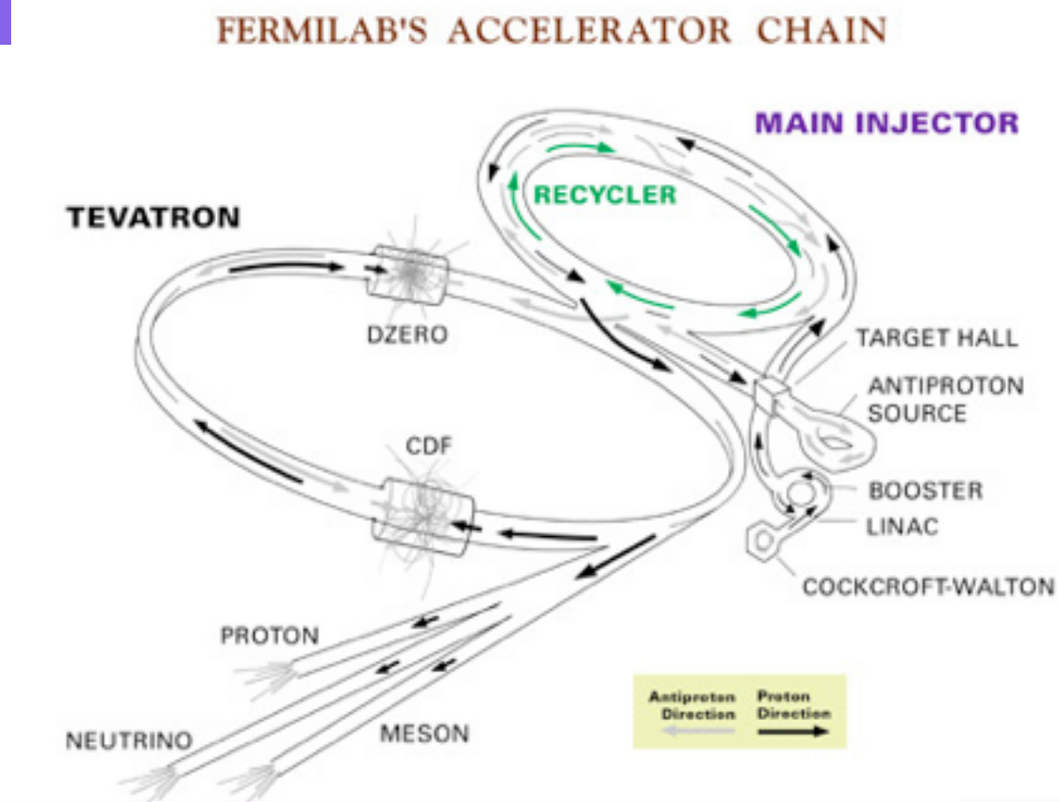
LHC (CMS and ATLAS Collab)

pp collider at 7 TeV

8 TeV



Tevatron and LHC status



Tevatron (CDF and D0 Collab)

$p\bar{p}$ collider at 1.96 TeV

Run II integrated luminosity ~10 fb^{-1}

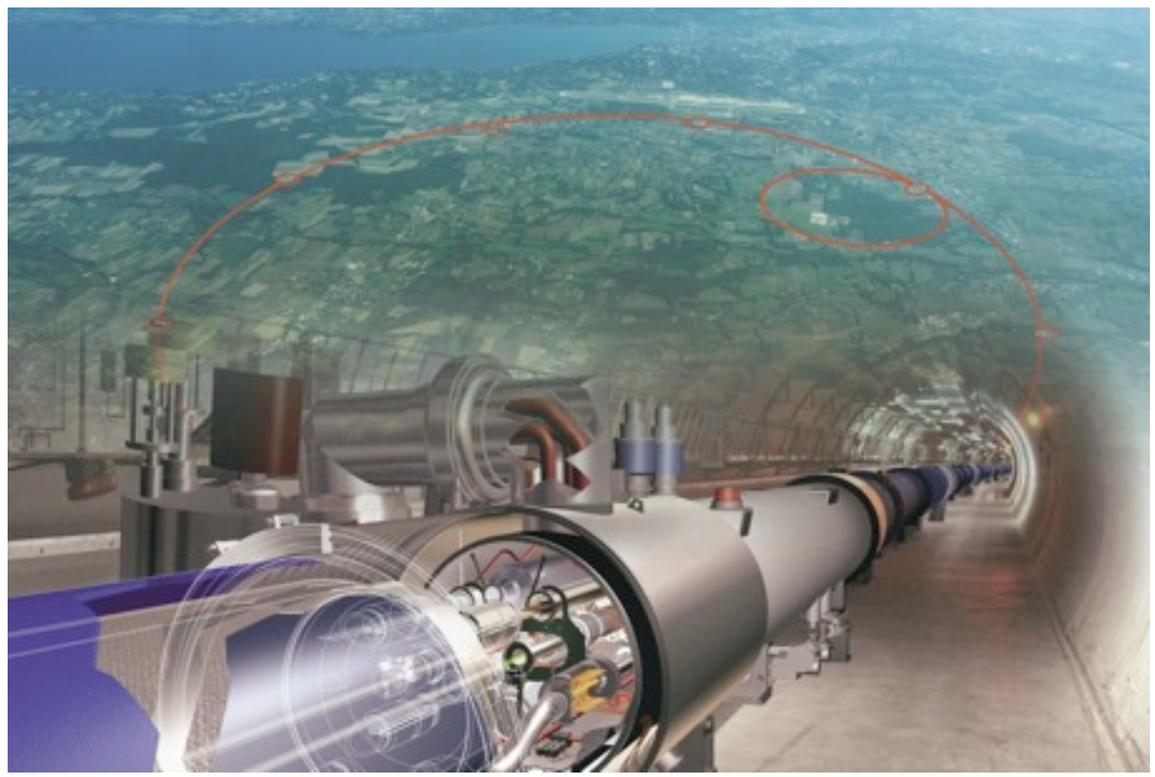
Operations ceased

LHC (CMS and ATLAS Collab)

pp collider at 7 TeV (5 fb^{-1})

8 TeV (20 fb^{-1})

Shutdown for machine upgrade



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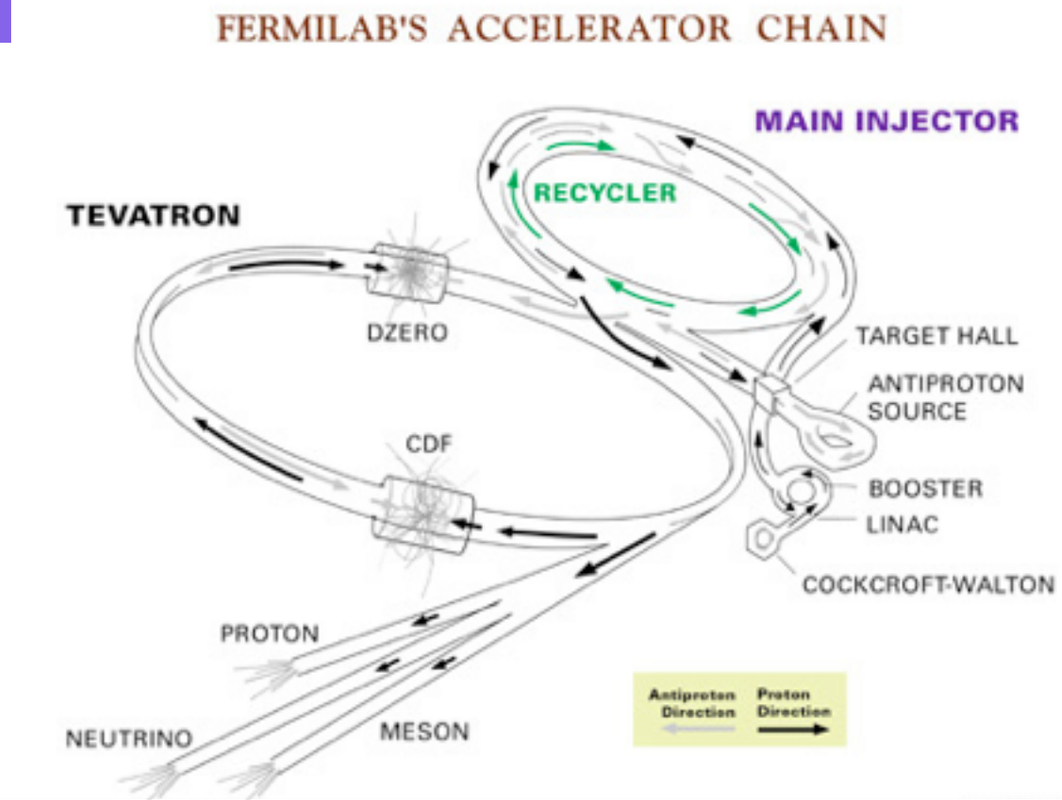


Tevatron (CDF and D0 Collab)

$p\bar{p}$ collider at 1.96 TeV

Run II integrated luminosity ~10 fb^{-1}

Operations ceased

➡ Delivering final results

➡ Improving analysis techniques

LHC (CMS and ATLAS Collab)

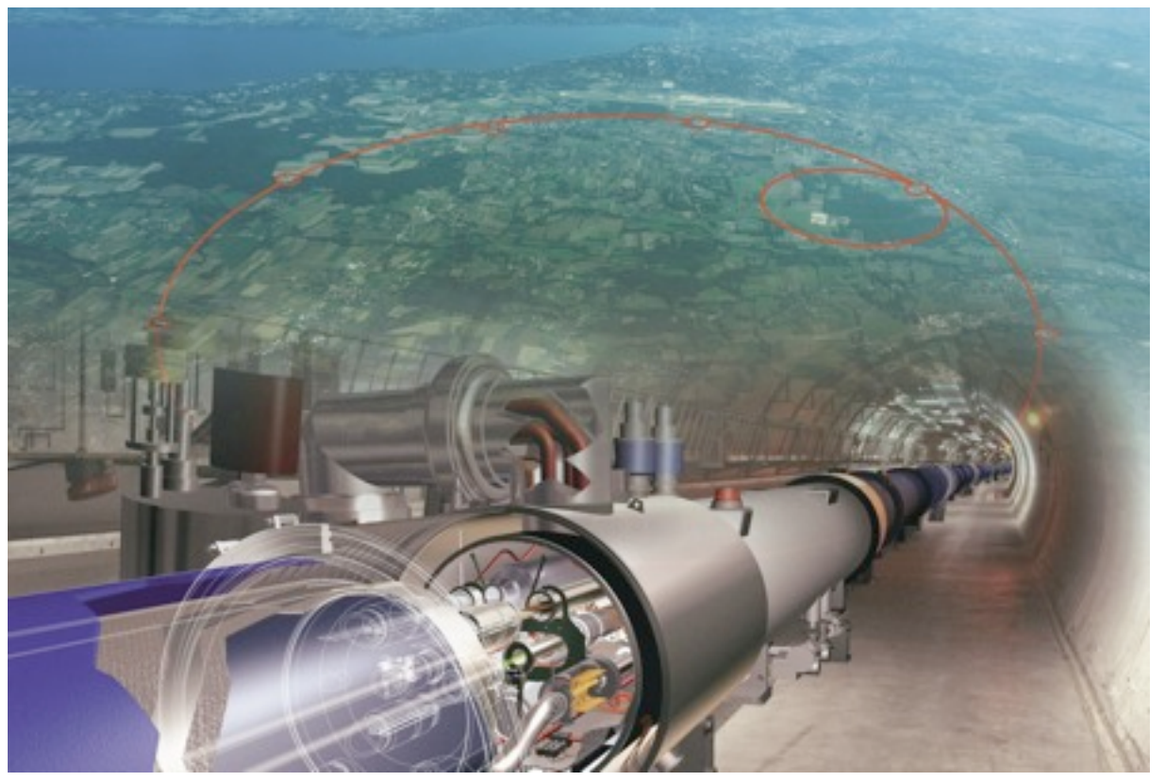
pp collider at 7 TeV (5 fb^{-1})

8 TeV (20 fb^{-1})

Shutdown for machine upgrade

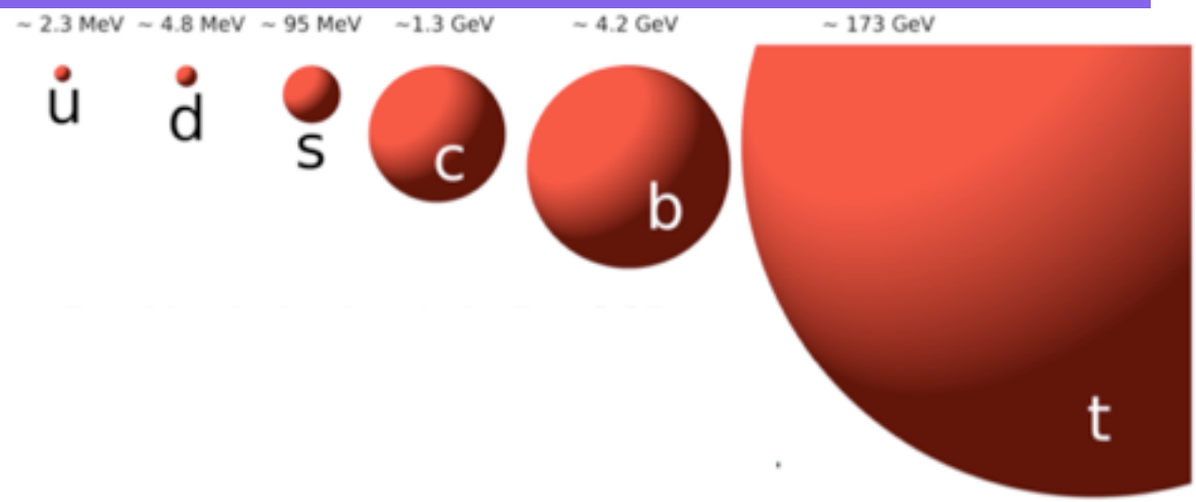
➡ Delivering final results 7 TeV; 8 TeV analyses final/ongoing

➡ Preparing for 13/14 TeV (Run II)



Motivations

- Top production touches major SM issues



… these are a few points of interest, among many others

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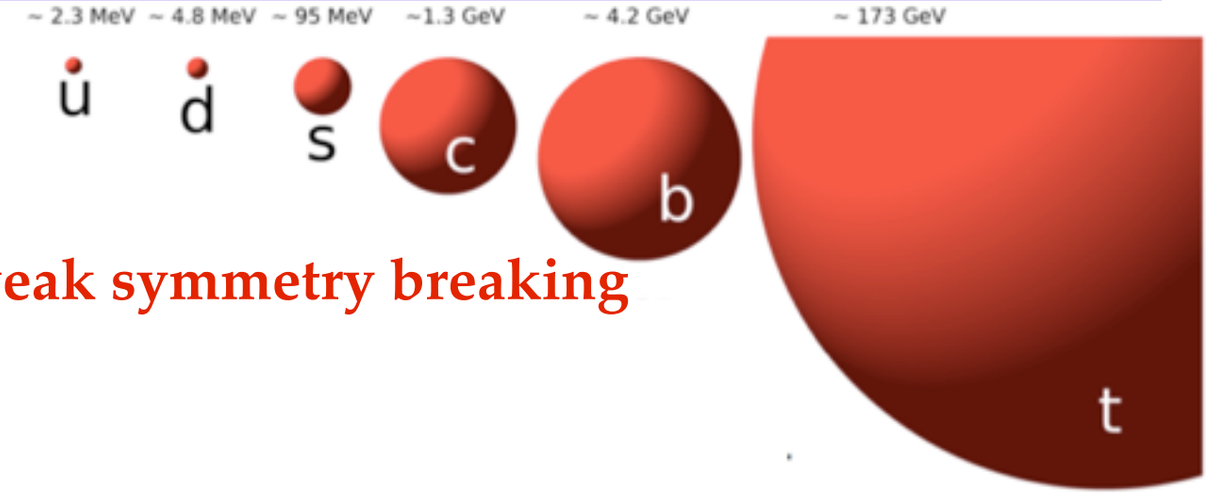
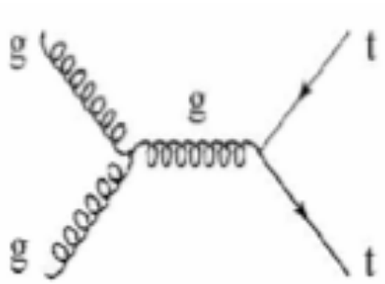
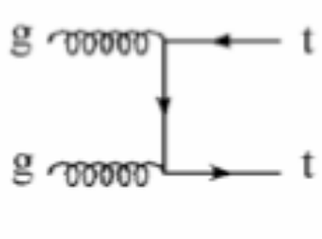


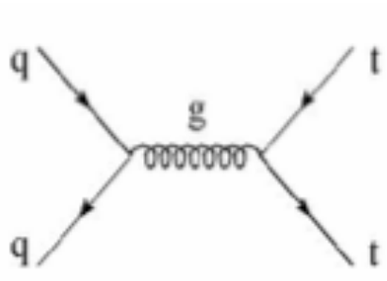
- Top production touches major SM issues
- Top quark coupling to Higgs: **hierarchy/electroweak symmetry breaking**
  - $y_t = \sqrt{2}\, m_t/\text{v.e.v.} \sim 1$
- Largest mass of all elementary particles: **scale**
  - mass-dependent couplings (SM and new physics) are largest
  - heavy BSM particle may choose to decay into SM tops
- Important tests of EWK and QCD: **precise NNLO calculations**
- Access to **electroweak couplings** in associated top production (e.g. ttZ)
  - This and other final states (ttγ, ttW, ttbb...) important backgrounds on the direct measurement of the Yukawa coupling (ttH production)

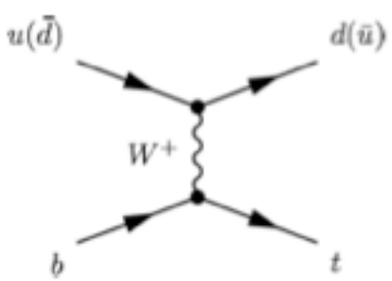
... these are a few points of interest, among many others

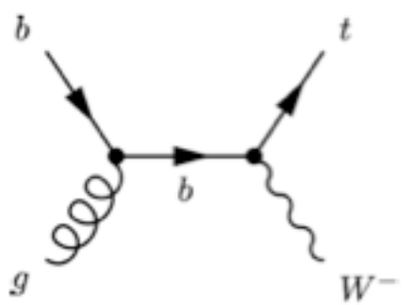
SM top production

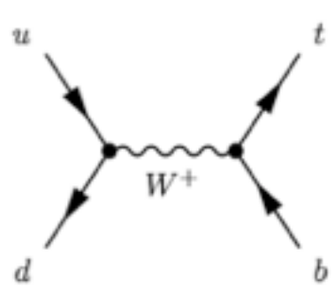












LHC

7, 8 GeV

pp

mostly gg,qg interactions

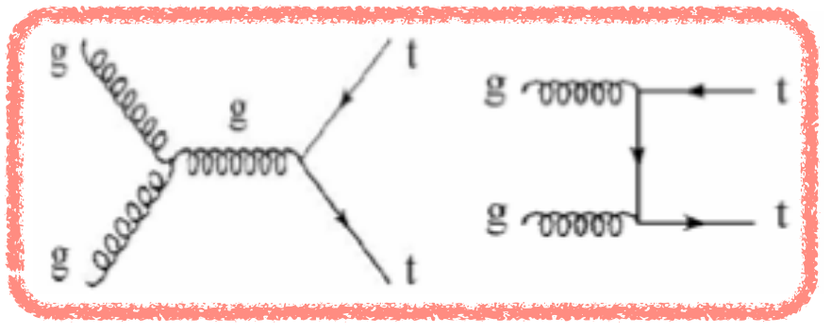
Tevatron

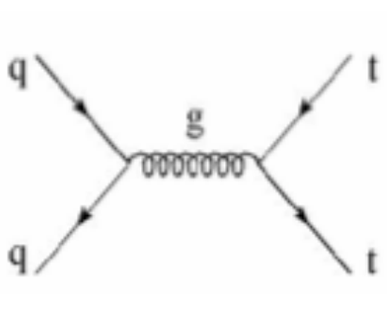
1.96 GeV

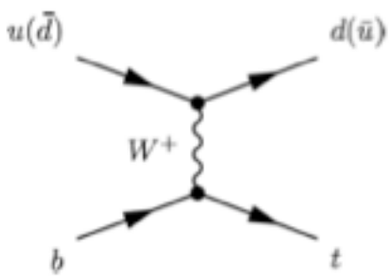
$p\bar{p}$

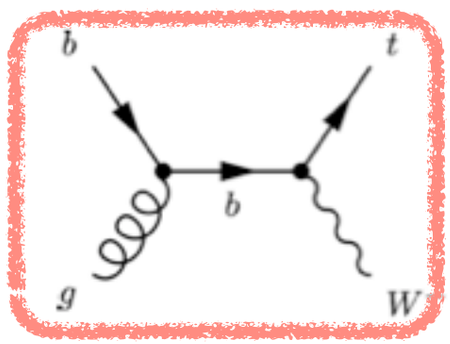
mostly qq

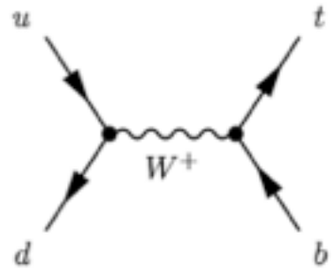
SM top production











LHC

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Tevatron

1.96 GeV

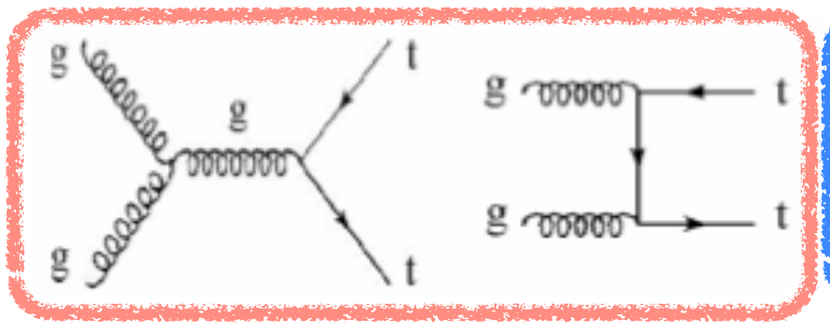
$p\bar{p}$

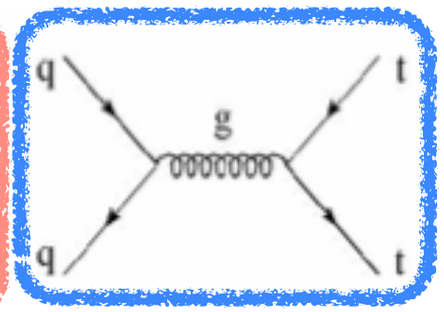
mostly qq

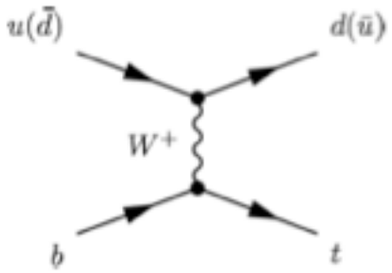
Expected xsec (pb):

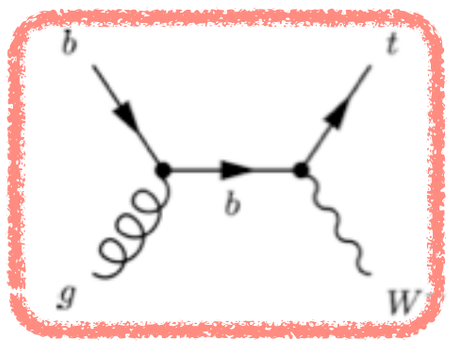
	7TeV	8TeV
$t\bar{t}$:	172.	249.
t-chan:	64.6	87.6
s-chan:	4.59	5.55
tW-chan:	15.6	22.2
$t\bar{t}$+Z/W:	0.318	0.400

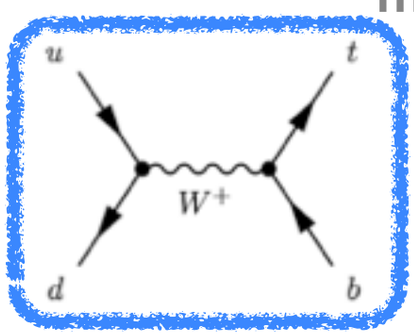
SM top production











LHC

7, 8 GeV

pp

mostly gg,qg interactions

Tevatron

1.96 GeV

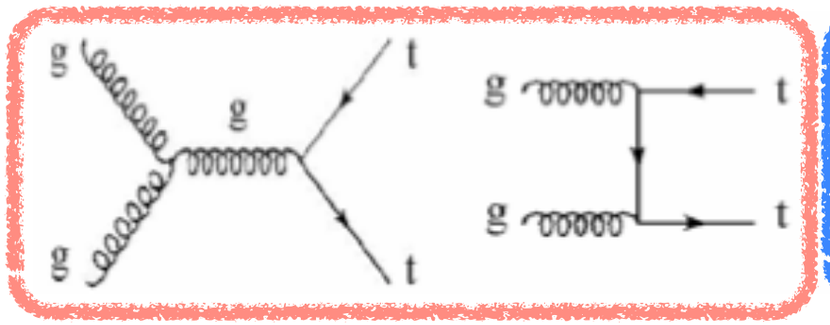
$p\bar{p}$

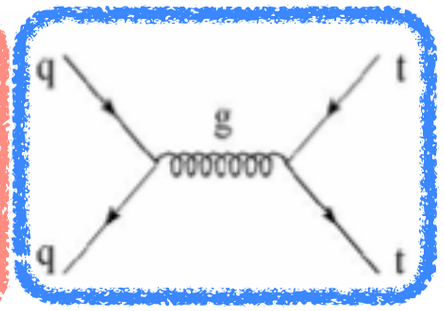
mostly qq

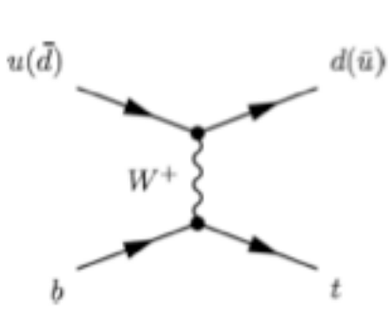
	Expected xsec (pb): 7TeV	**8TeV**	**Expected xsec (pb): 2TeV**
$t\bar{t}$:	172.	249.	$t\bar{t}$: 7.08
t-chan:	64.6	87.6	t-chan: 2.08
s-chan:	4.59	5.55	s-chan: 1.05
tW-chan:	15.6	22.2	tW-ch: 0.22
$t\bar{t}$+Z/W:	0.318	0.400	tt+Z/W

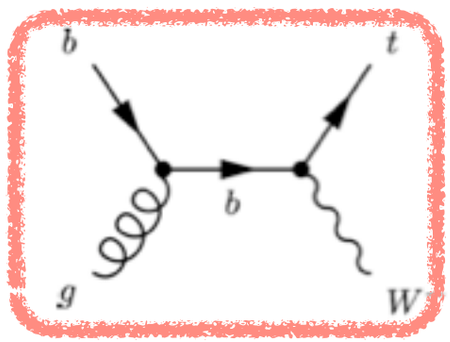
not acessible

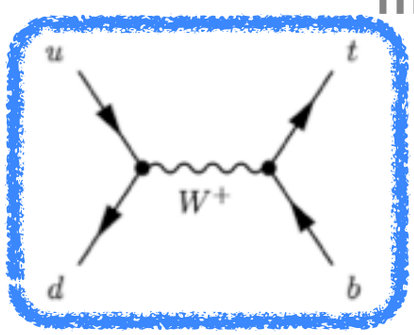
SM top production











5fb^{-1} @7 + 20 fb^{-1} @8 TeV
~5,600,000 top pairs
~2,700,000 single top

10fb^{-1} @1.96TeV
~70,000 top pairs
~3,000 single top

	LHC	Tevatron
Energy	7, 8 GeV	1.96 GeV
Probed partons	pp mostly gg,qg interacti	$p\bar{p}$ mostly qq

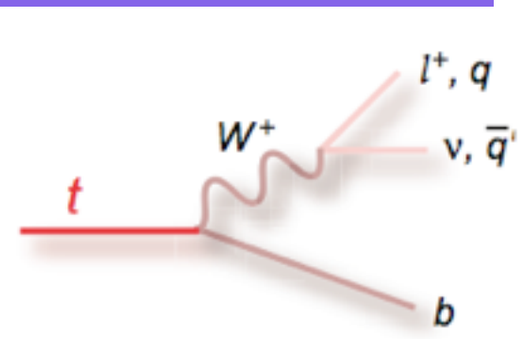
Expected xsec (pb):	7TeV	8TeV	Expected xsec (pb):	2TeV
$t\bar{t}$:	172.	249.	$t\bar{t}$:	7.08
t-chan:	64.6	87.6	t-chan:	2.08
s-chan:	4.59	5.55	s-chan:	1.05
tW-chan:	15.6	22.2	W-ch:	0.22
$t\bar{t}$+Z/W:	0.318	0.4	Z/W	

relative contributions

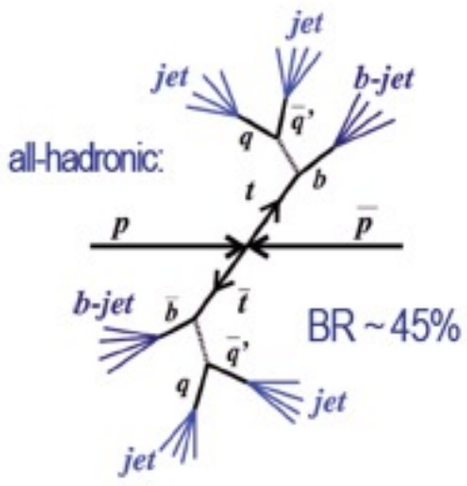
not acessible

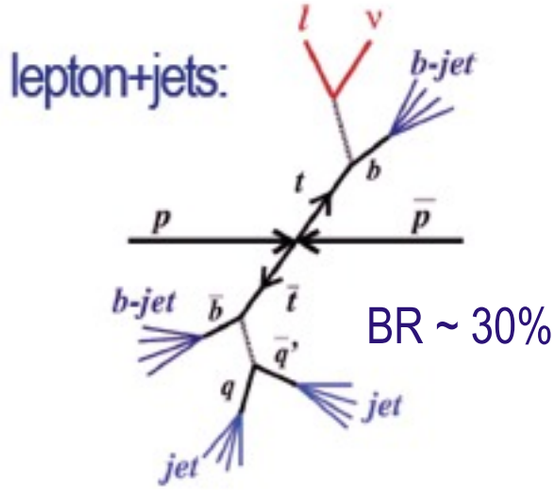
Top production Tevatron vs LHC: complementary information
- testing various/unique aspects of the SM -

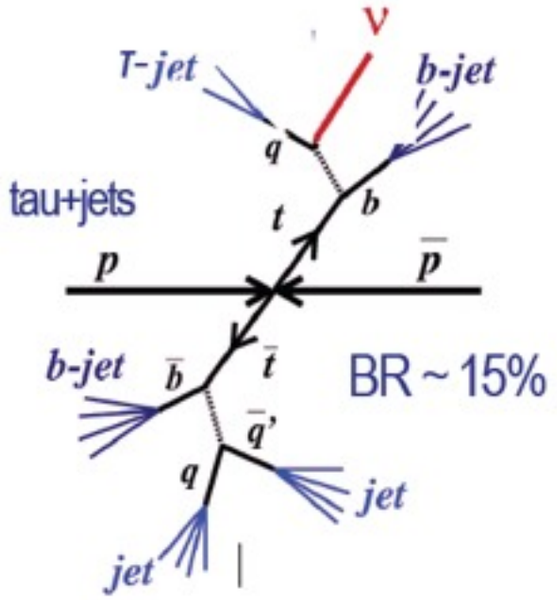
SM top decays

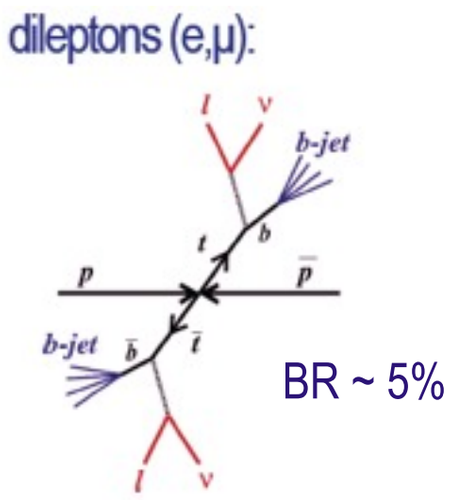


- Top decays: ~100% $t \rightarrow Wb$



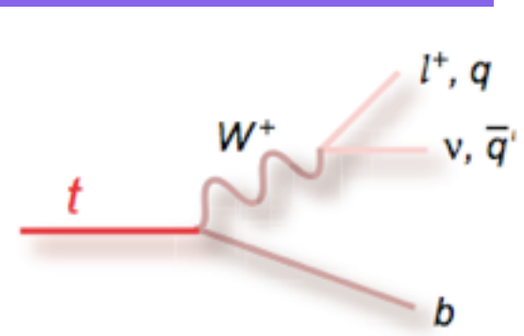






- **Top final states involve all types of particles...**
  - light-quark and b jets, missing transverse energy (ν), electrons, muons, (tau decays products)

SM top decays



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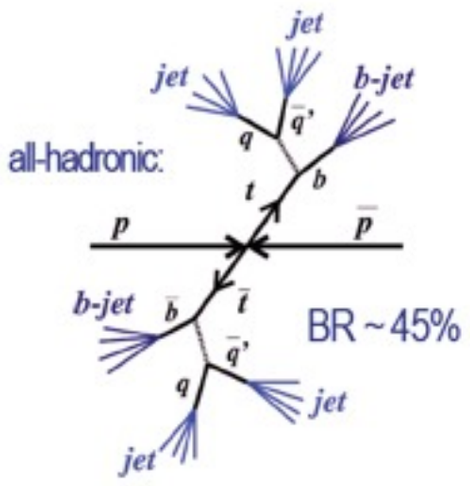
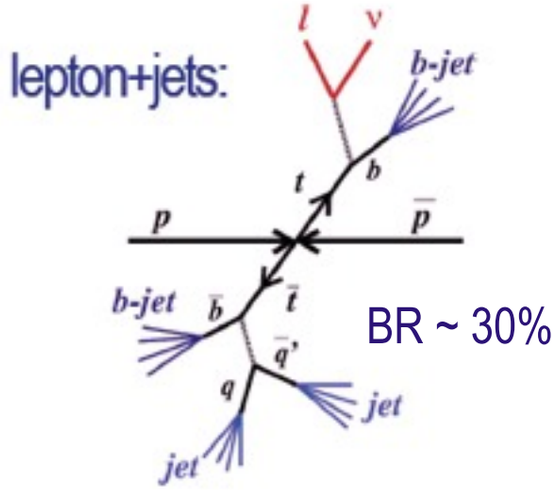
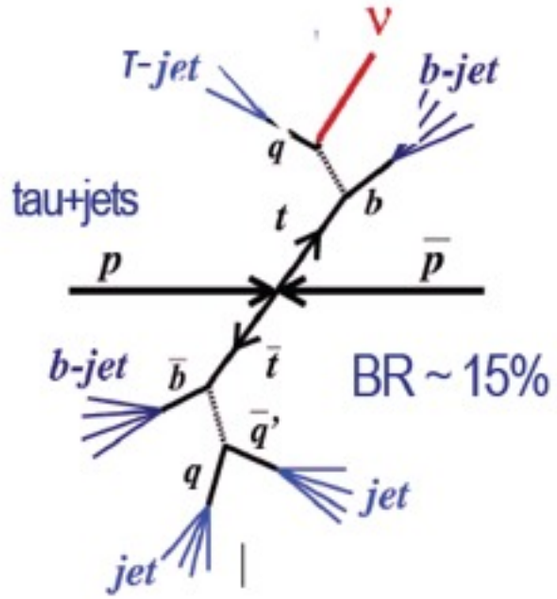
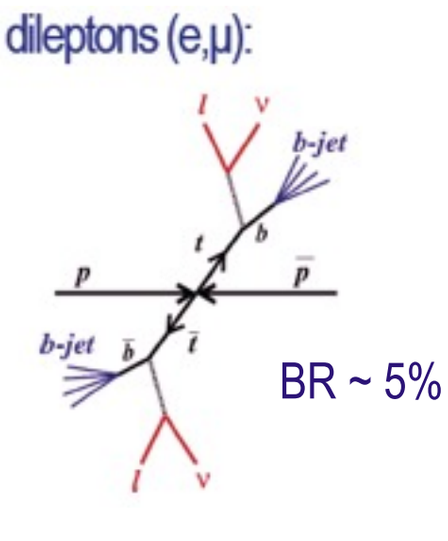
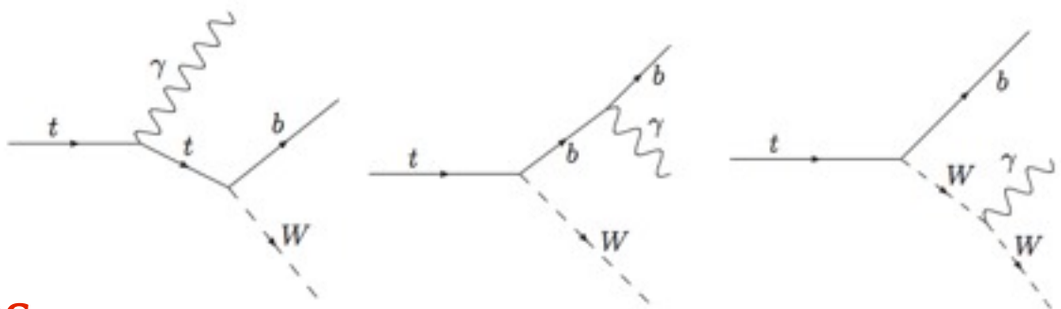






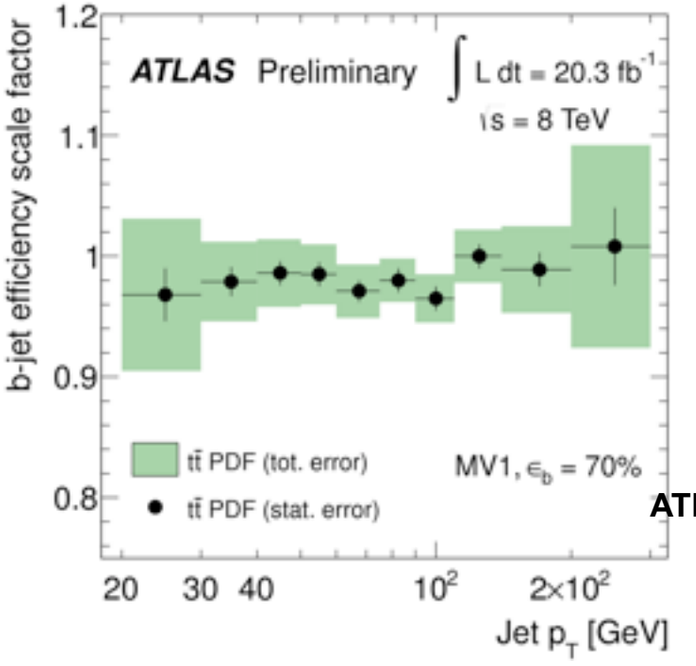




- **Top final states involve all types of particles...**
  - light-quark and b jets, missing transverse energy (ν), electrons, muons, (tau decays products)
    - *+other objects in associated production, e.g, photon*

Motivations

- *The whole detector is involved*: **used for detector commissioning and calibration**



ATLAS-CONF-2014-004

bTag efficiency in dileptonic (eμ) tt events

This yields a cross section measurement in the muon + jets channel of

$$\sigma_{t\bar{t}} = 163.2 \pm 3.4(\text{stat.}) \pm 12.7(\text{syst.}) \pm 7.3(\text{lum.}) \text{ pb.} \quad (6)$$

The fit provides in-situ measurements of the scale factors for both *b*-tagging and the jet energy scale. We obtain a value of 97 ± 1 % for the *b*-tagging scale factor and a value of 100 ± 2% for the jet energy calibration correction (on top of the standard jet corrections). The scale factors

CMS-TOP-11-003

bTag efficiency and jet energy scale in semileptonic (μ+jets) tt events

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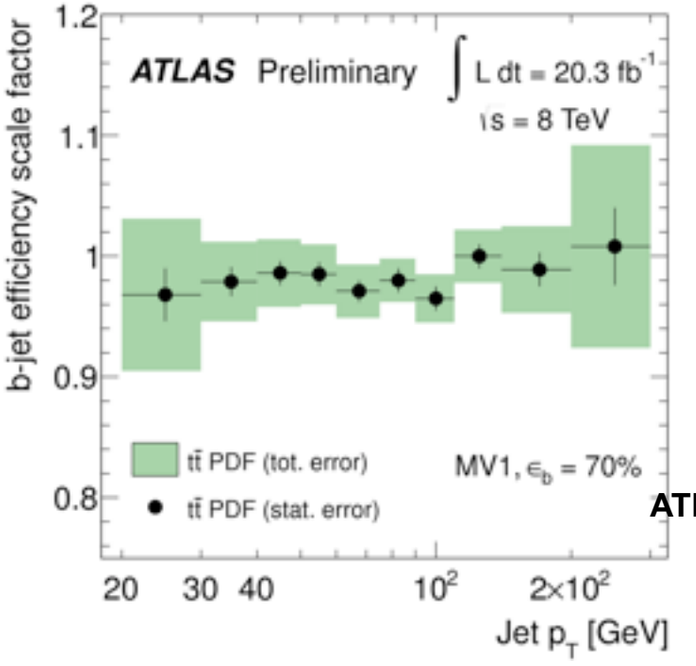

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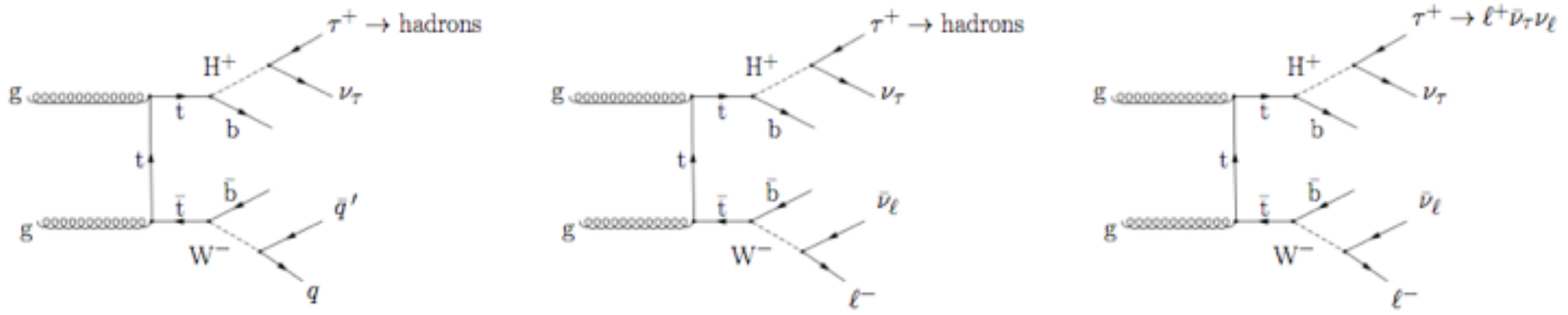
CMS-TOP-11-003

bTag efficiency and jet energy scale in semileptonic (μ+jets) tt events

- All decaying channels are important
- **Competing final states in processes of interest** both in the Standard Model and beyond

e.g. charged Higgs versus $t\bar{t}$ decays into taus:



Single-top: electroweak production

Single top measurements

- Small cross sections: very small yields and overwhelming background
  - 1) $t\bar{t}$ 2) W+jets *(t-channel)* Z+jets *(tW-channel)* 3) QCD multijet, dibosons
  - cut-and-count not sufficient

Best-case example:

CMS t-channel @ 8 TeV muon channel

$t\bar{t}$	17214 ± 49
W/Z+jets	10760 ± 104
QCD multijet	765 ± 5
Diboson	179 ± 4
tW	1914 ± 28
s-channel	343 ± 1
t-channel	6792 ± 25
Total expected	37967 ± 121
Data	38202

bkg: 82% ☹☹☹

signal: 18% ☹

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- Typical analysis techniques:
  - Event selection AND information from event topology / kinematic variables
  - Data-driven background estimation (control regions) when possible
  - Boost Decision Trees, Neural Networks, Multivariate Likelihoods: exploit full event kinematics to separate signal/background

Single top measurements

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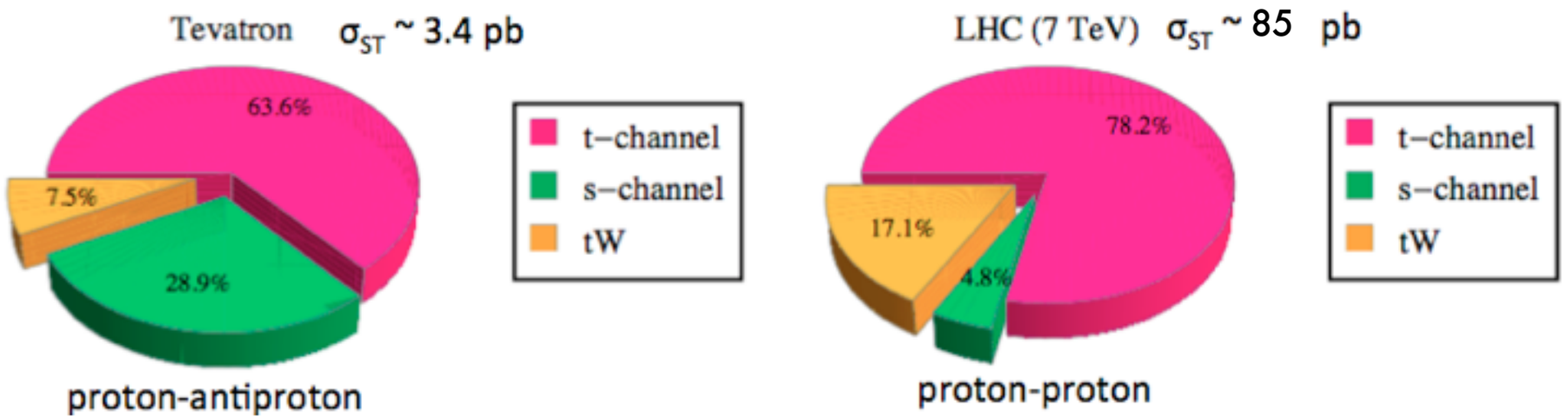
- Typical analysis techniques:
  - Event selection AND information from event topology / kinematic variables
  - Data-driven background estimation (control regions) when possible
  - Boost Decision Trees, Neural Networks, Multivariate Likelihoods: exploit full event kinematics to separate signal/background

Very small cross sections; s-channel slightly favored (in %) at the Tevatron

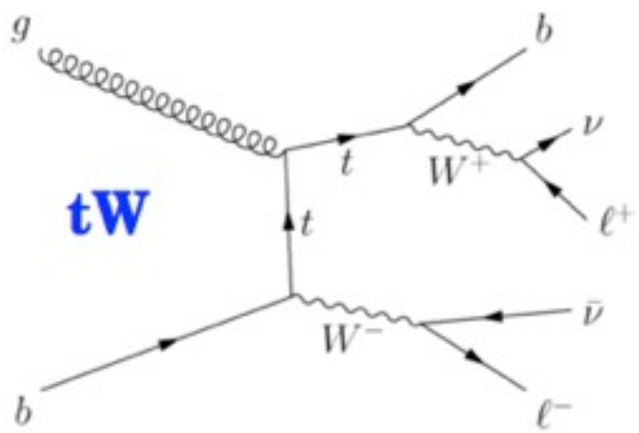


Single-top: tW channel

Too small to be seen at the Tevatron (~0.22 pb)

Signal:

2 leptons+1 jet



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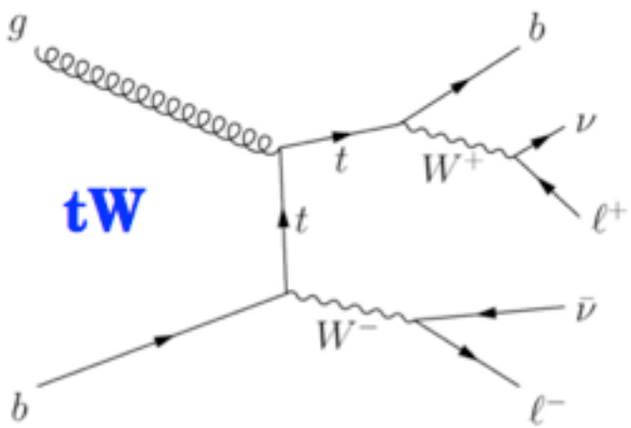
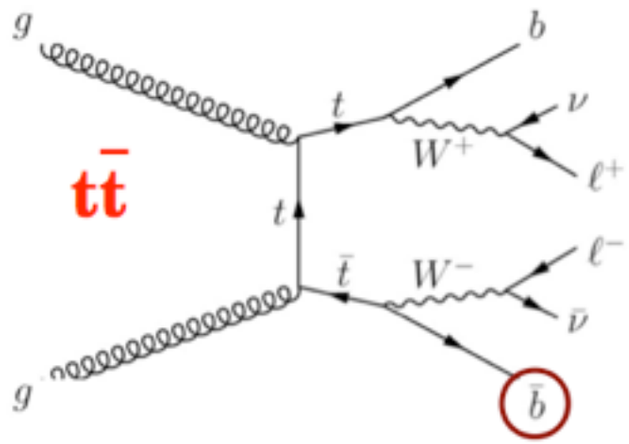


Main bkg:

2 leptons+2 jets



(same final state + 1 b-jet)

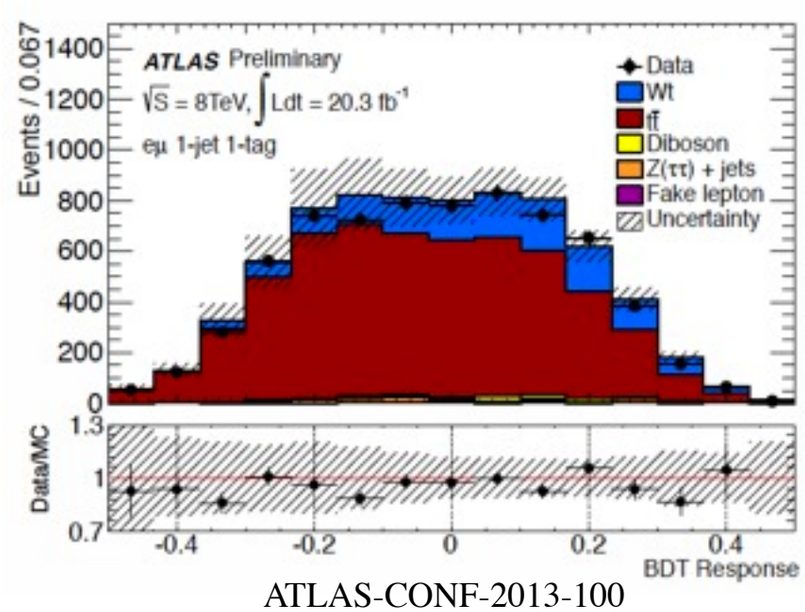
Single top: tW channel at 8 TeV

ATLAS

Two samples: eμ +1 or +2 jets

Separate BDT for 1-jet (2-jets) samples with 19 (20) variables

2-jets: control region for tt determination



ATLAS-CONF-2013-100

Jet-related variables: best discriminants

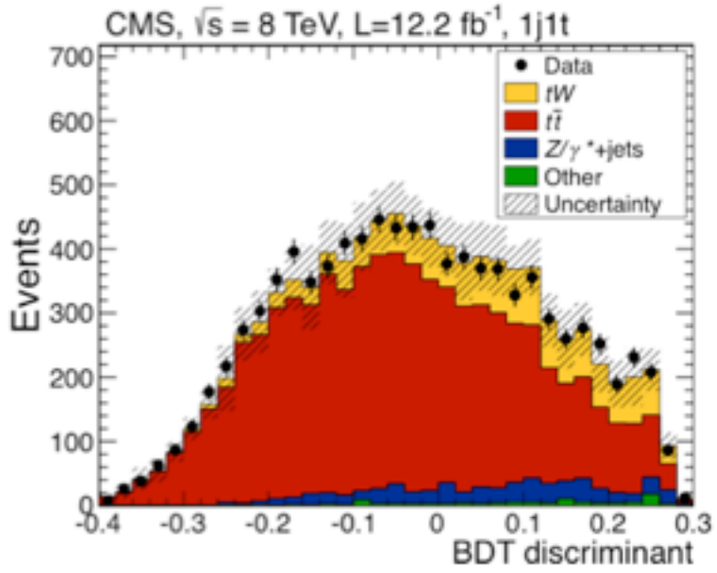
CMS

2 leptons (eμ,μμ,ee), 1 btagged jet

BDT analysis with 13 variables

arXiv:1401.2942, submmited to PRL

2 btagged jets: control regions for tt



Single top: tW channel at 8 TeV

ATLAS: evidence

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Separate BDT for 1-jet (2-jets) samples with 19 (20) variables

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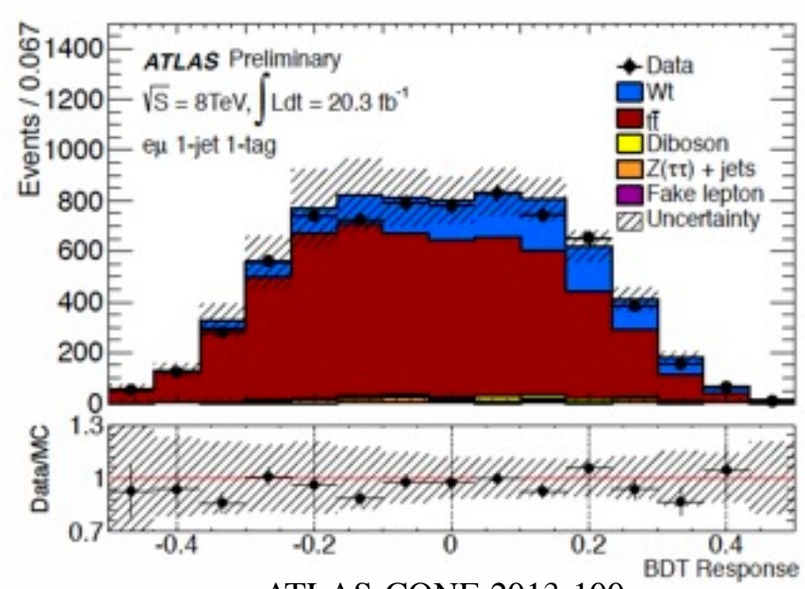


ATLAS-CONF-2013-100

22%

σ_{tW}=27.2±2.8(stat)±5.4(syst) pb

with significance 4.2σ (expected 4.0)

Jet-related variables: best discriminants

prediction approx. NNLO:
σ_{tW}=22.2±0.6(scale) ±1.4(PDF) pb

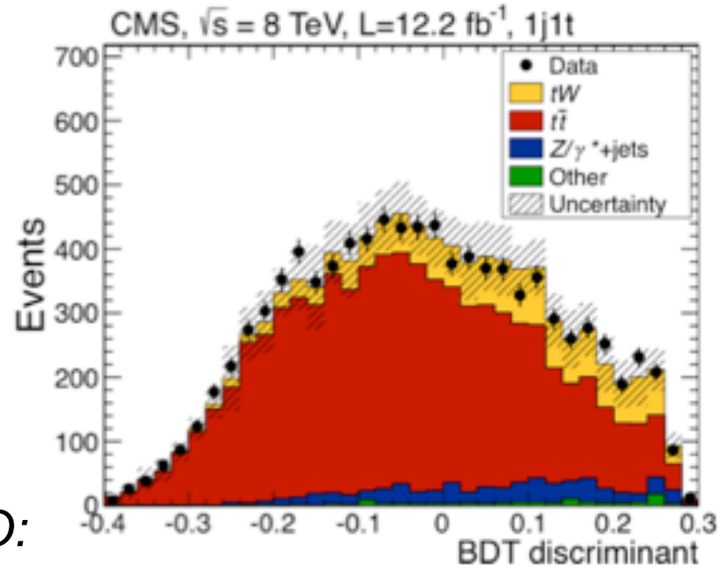
CMS: first observation!

2 leptons (eμ,μμ,ee), 1 btagged jet

BDT analysis with 13 variables

arXiv:1401.2942, submmited to PRL

2 btagged jets: control regions for tt



σ_{tW}=23.4±5.4 pb

tW signal observed

23%

with significance **6.1σ** (exp. 5.4±1.4)

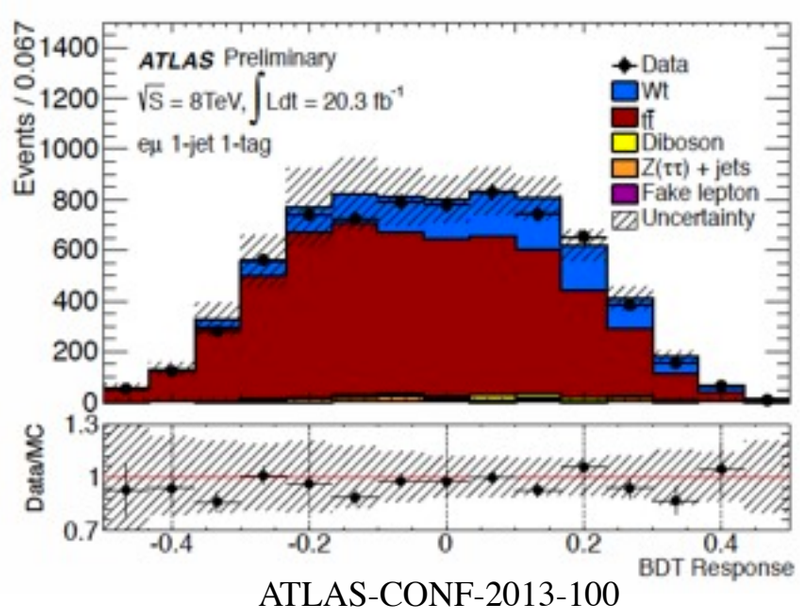
Single top: tW channel at 8 TeV

ATLAS: evidence

Two samples: eμ +1 or +2 jets

Separate BDT for 1-jet (2-jets) samples with 19 (20) variables

2-jets: control region for tt determination



ATLAS-CONF-2013-100

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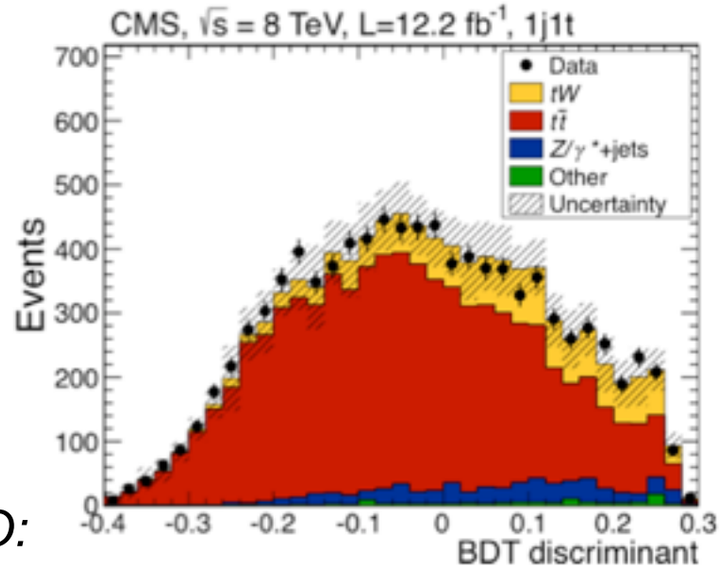
BDT analysis with 13 variables

arXiv:1401.2942, submmited to PRL

2 btagged jets: control regions for tt



σ_{tW}=23.4±5.4 pb

tW signal observed

23%

with significance **6.1σ** (exp. 5.4±1.4)

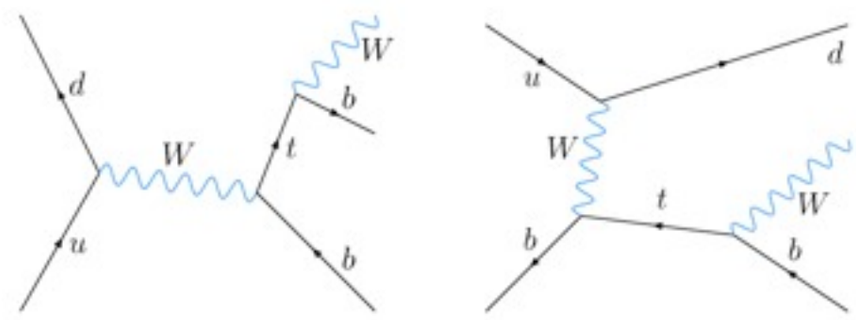
At 7 TeV: first evidence by ATLAS (3.3σ), confirmed by CMS (4σ)

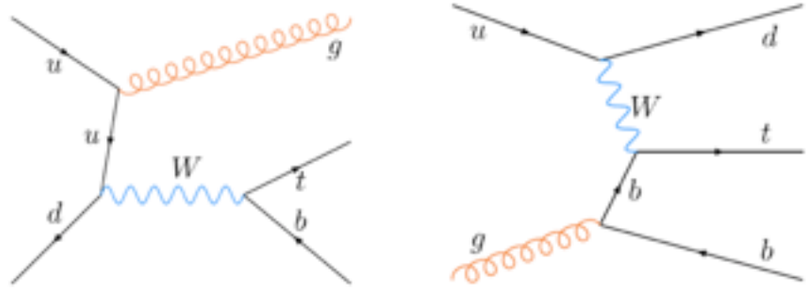
Single-top: s+t channel

1 lepton+2 jets

1 lepton+3 jets

Signal:





Single-top: s+t channel

1 lepton+2 jets

1 lepton+3 jets

Signal:

Bkg:

s+t channel Tevatron

Event selection as generic as possible

1 lepton, MET, >=2 jets (>=1 tagged)

D0

PLB 726, 656 (2013)

three multivariate techniques, with up to 30 variables

$\sigma_{s+t} = 4.11\ ^{+0.60}_{-0.55}$ pb

(SM prediction 3.34 pb)

14%

CDF

Conf. Note 10793

NN with 11-14 variables

$\sigma_{s+t} = 3.04\ ^{+0.57}_{-0.53}$ pb

(SM prediction 3.34 pb)

17%

s+t channel Tevatron

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17%

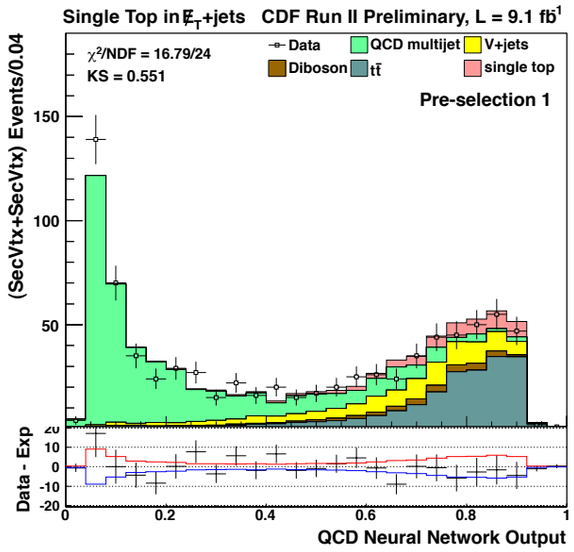
CDF

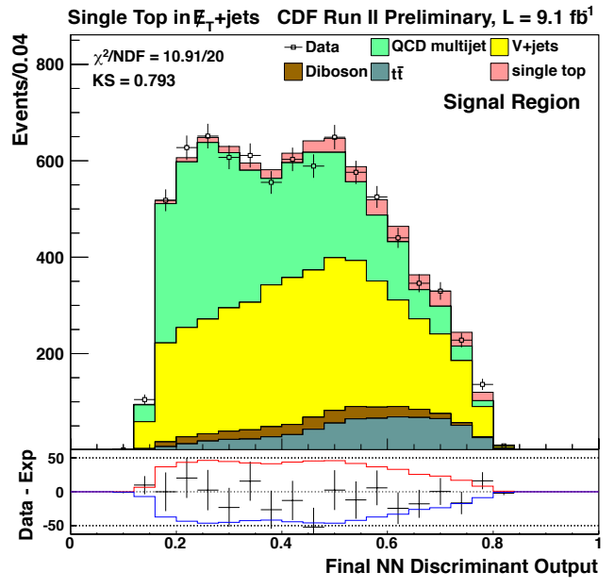
Conf. Note 10979

Select only MET+jets
(recover non-reconstructed leptons)

orthogonal samples MET+jets, l+MET+jets

Train several NN against QCD,tt, then combine with NN



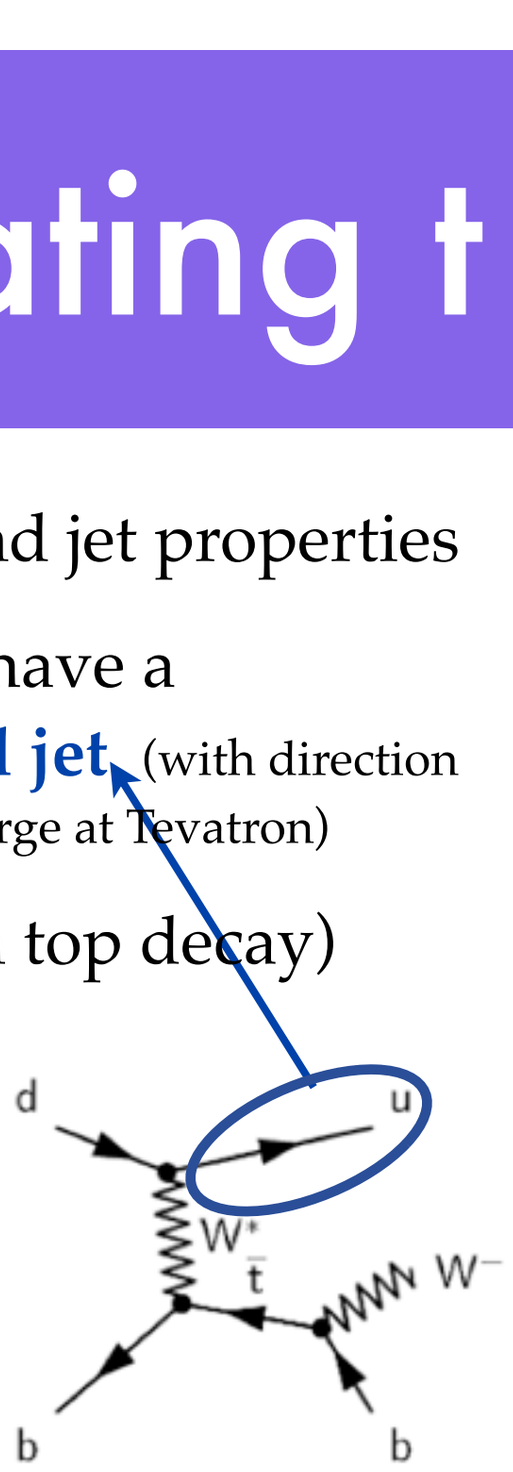


$\sigma_{s+t} = 3.04^{+1.46}_{-1.39}$ pb

48%

Separating t and s channels

- Event kinematic and jet properties
- ***t-channel:*** tend to have a distinctive **forward jet** (with direction correlated with lepton charge at Tevatron)
  - tag: 1 b-jet (from top decay)



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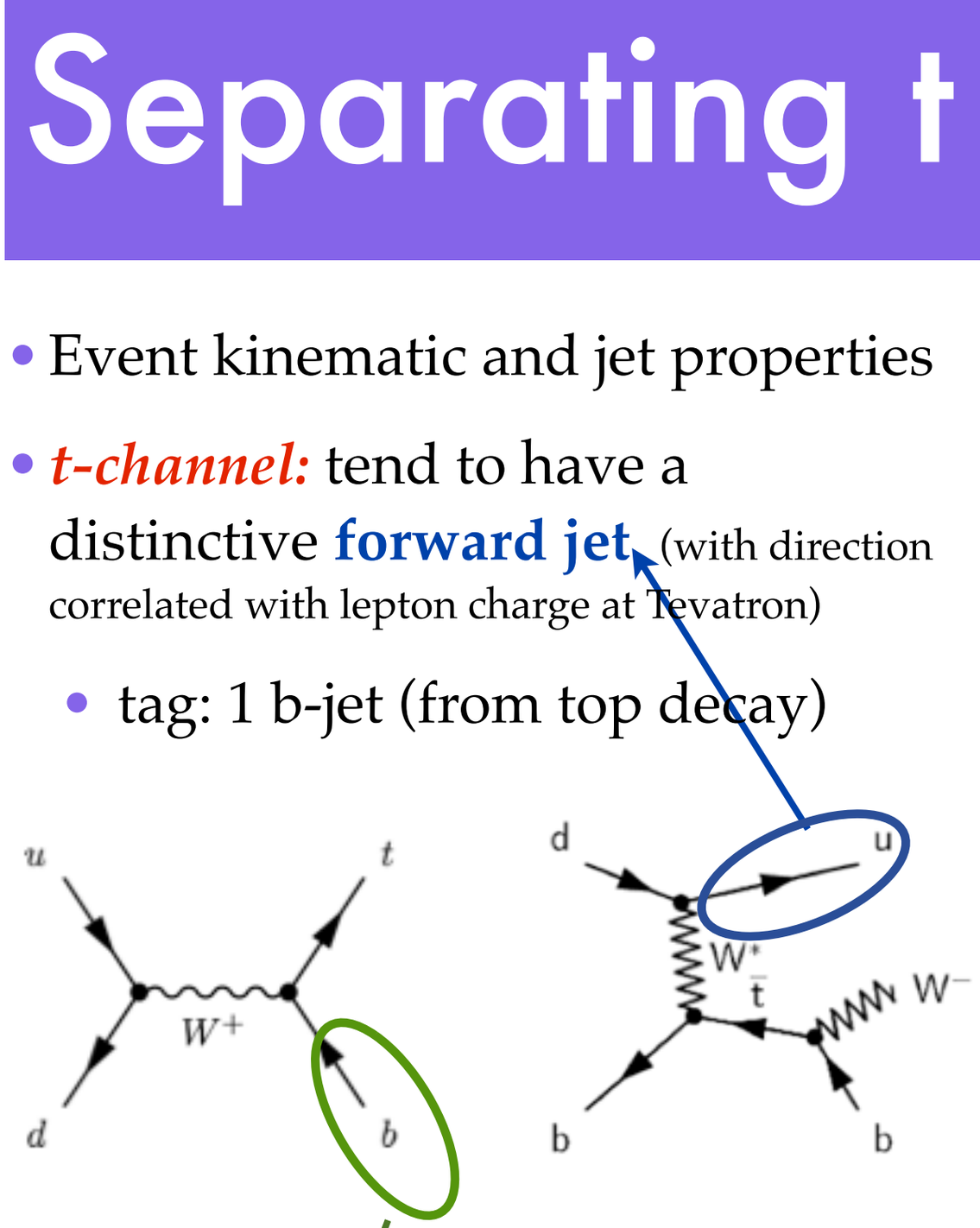

- ***s-channel:*** more likely to have central jets
  - tag: **2 b-jets**

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- Event kinematic and jet properties
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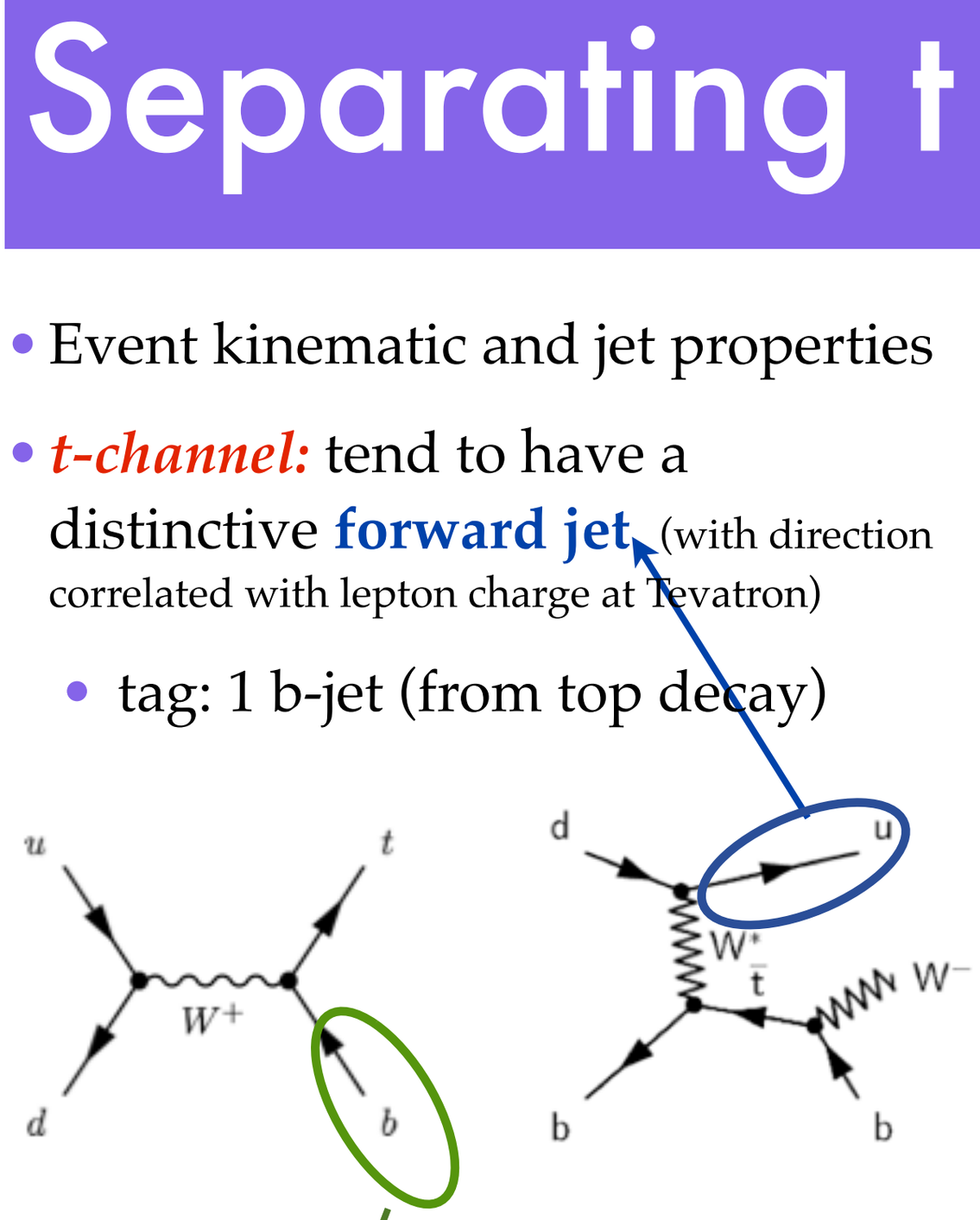
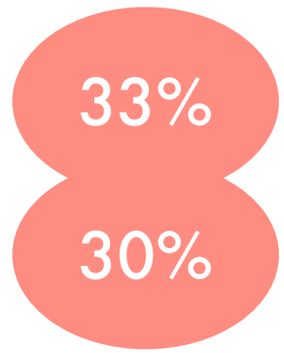


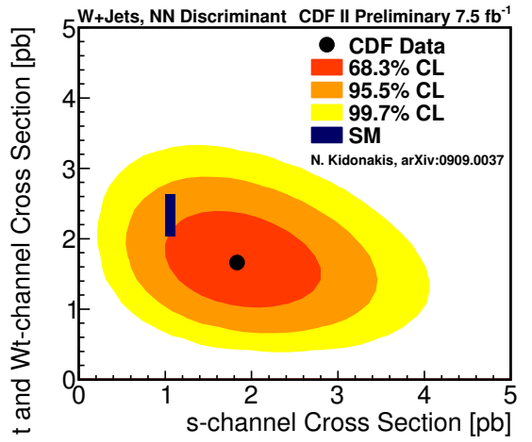
- ***s-channel:*** more likely to have central jets
  - tag: **2 b-jets**

CDF (7.5 fb^{-1})

σ_t=1.49±0.47 pb

σ_s=1.81±0.63 pb





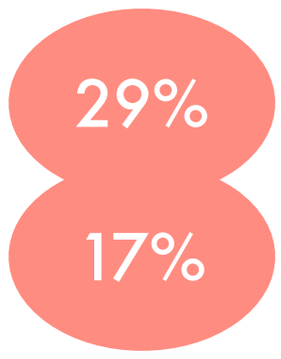
D0 (9.7 fb^{-1})

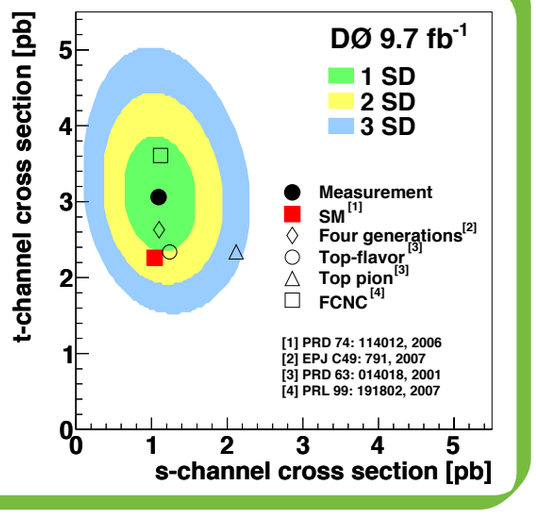
PLB 726, 656 (2013)

σ_t=3.07±0.53 pb

σ_s=1.10±0.33 pb

First evidence: 3.7 σ



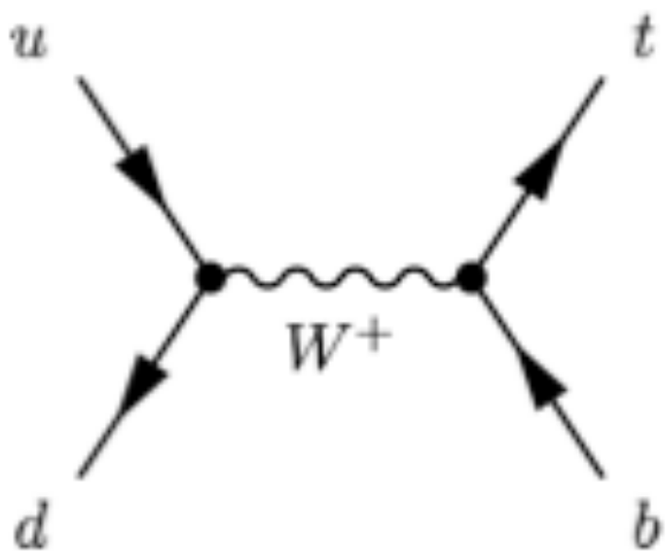


Theory

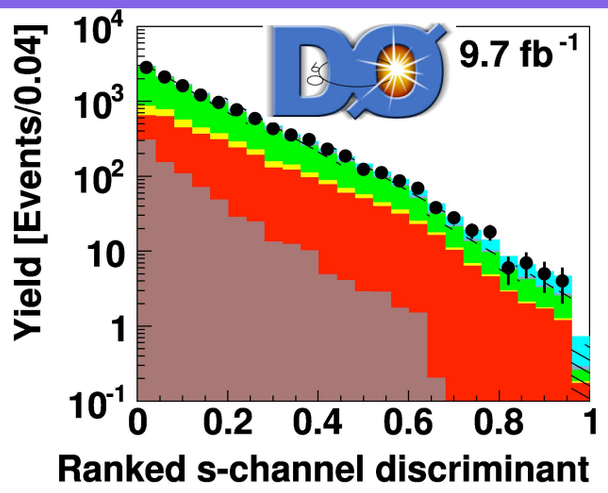
σ_t=2.10±0.06 pb (Kidonakis, arXiv:1001.5034)

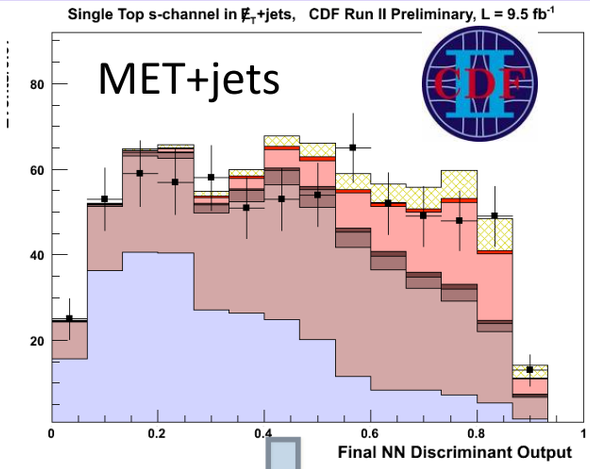
σ_s=1.05±0.05 pb (Kidonakis, arXiv:1103.2792)

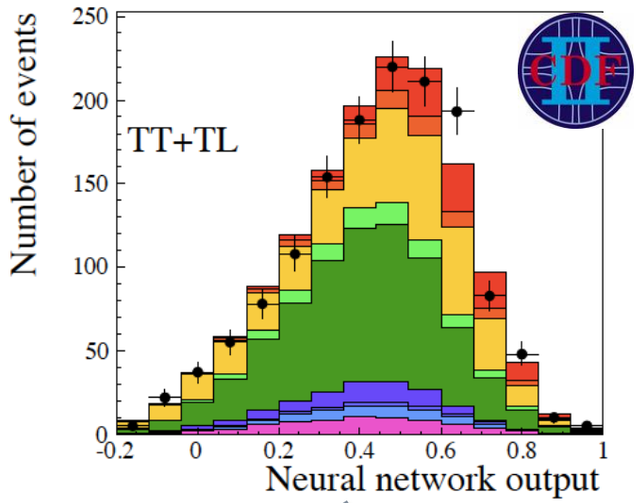
Single-top: *s* channel



s-channel single top at Tevatron

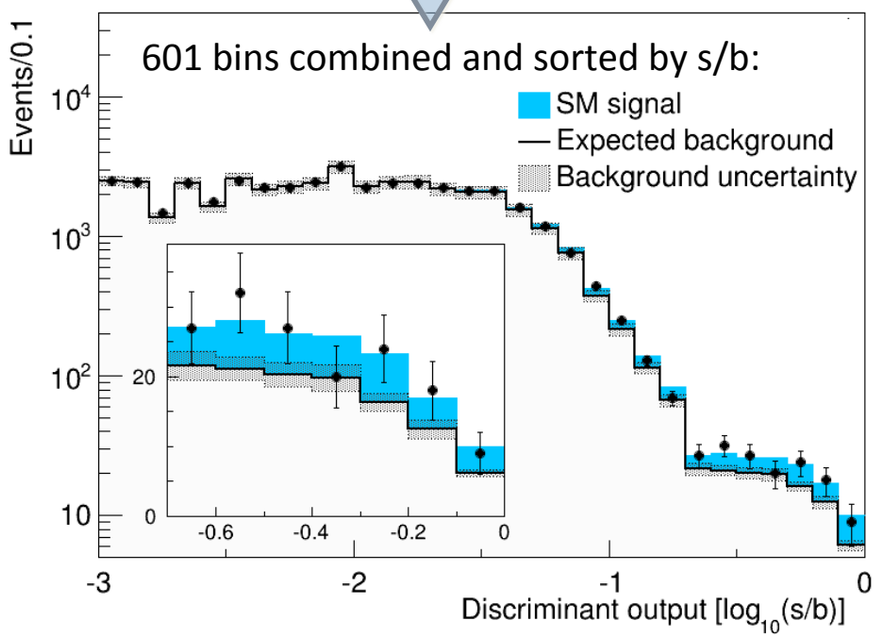


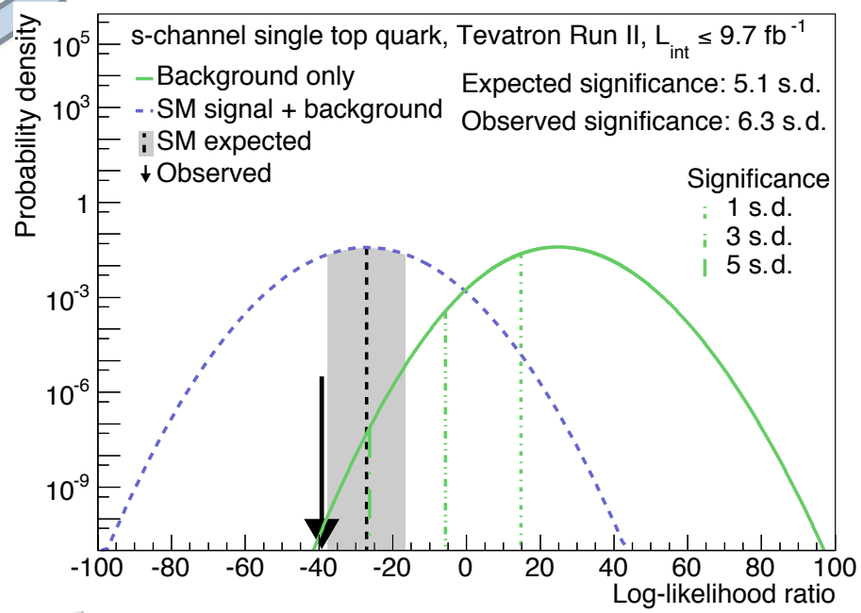




Adding l+jets and MET+jets analyses optimized for s-channel

t-channel fixed at SM prediction





CDF and DO combination

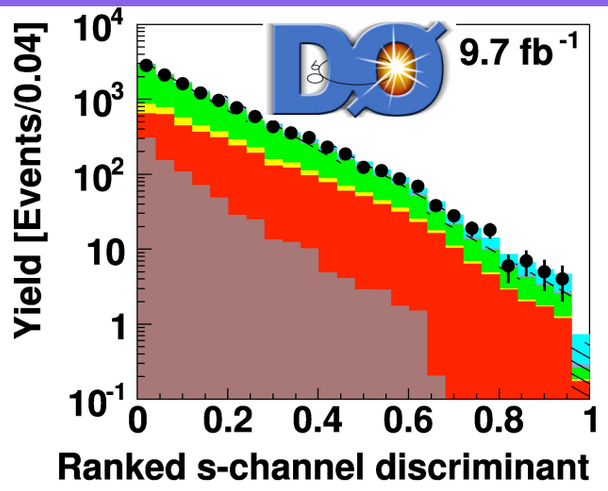
$\sigma_s = 1.29\ ^{+0.26}_{-0.24}$ pb

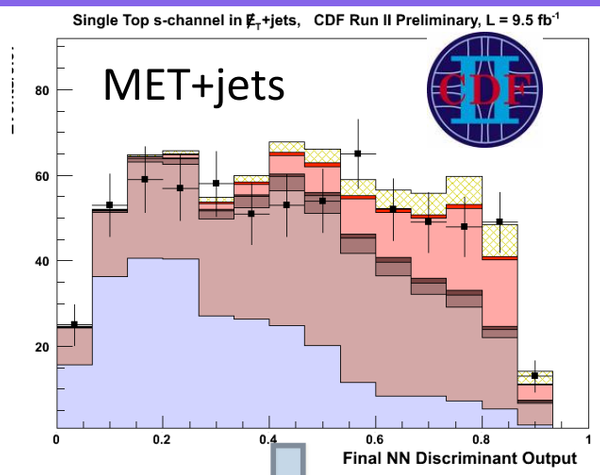
20%

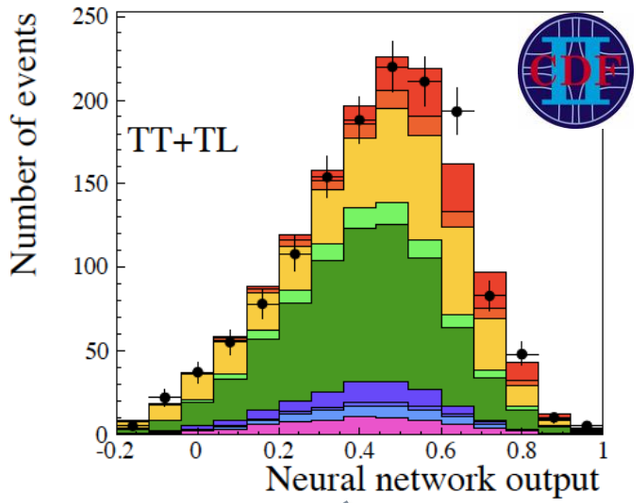
Submitted to PRL

arXiv:1402.5126

s-channel single top at Tevatron

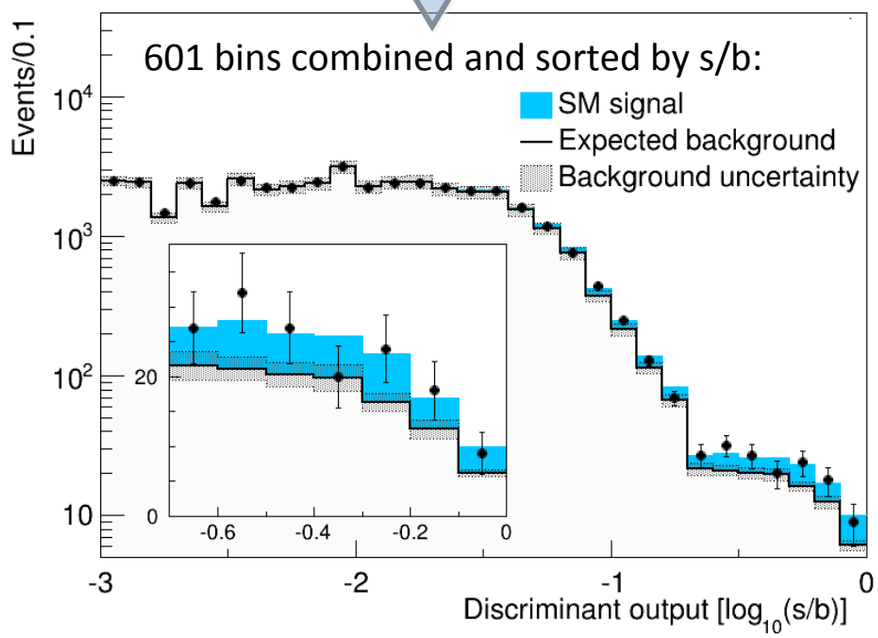


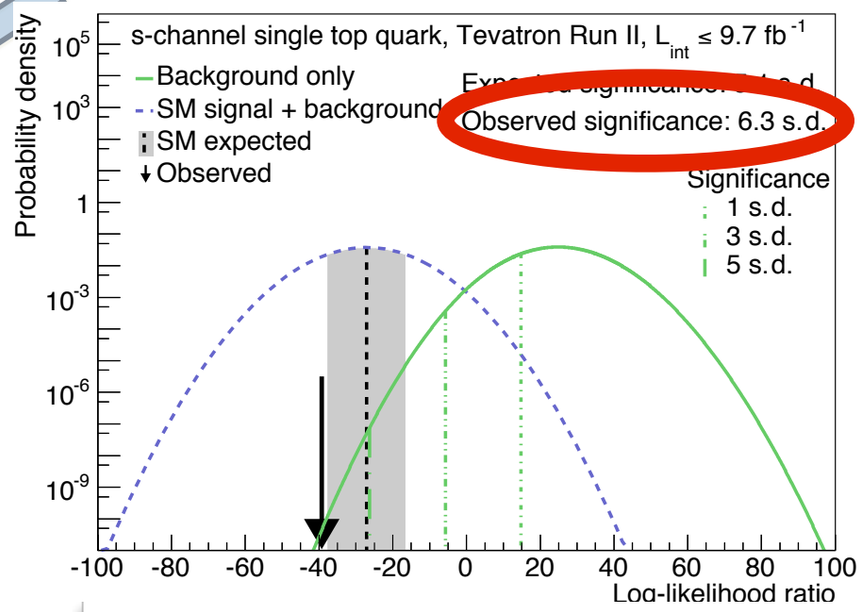




Adding l+jets and MET+jets analyses optimized for s-channel

t-channel fixed at SM prediction





CDF and D0 combination: first observation of single-top s-channel!

$\sigma_s = 1.29\ ^{+0.26}_{-0.24}$ pb

20%

Submitted to PRL
arXiv:1402.5126

s-channel single top @ LHC

ATLAS (7 TeV, 0.7 fb^{-1})

1 lepton, 2 btagged jets

cut-and-count method
QCD & W+jets normalization estimated on data; other backgrounds normal. from theory

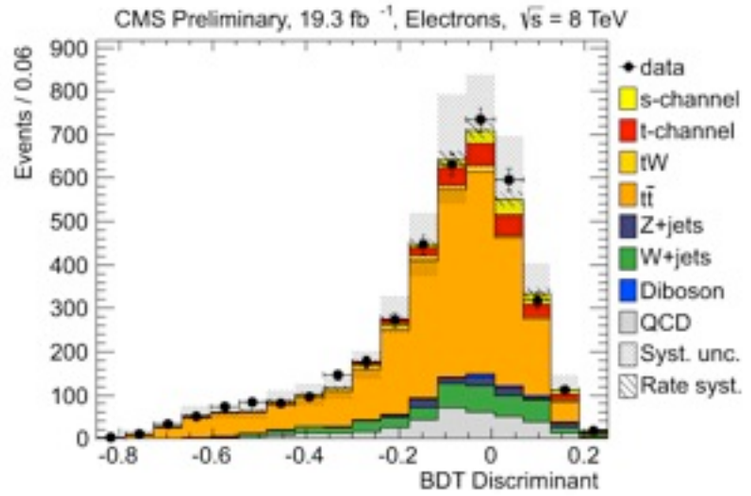
296 events passing full selection

Upper limit: $\sigma_s < 26.5$ pb at 95%C.L.

CMS (8 TeV)

1 lepton, 2 btagged jets

BDT : 11 variables
tt determined on control regions with 3 jets&2 btagged jets



$\sigma_{s\text{-channel}} = 6.2 \pm 5.4(exp.) \pm 5.9(th) pb = 6.2^{+8.0}_{-5.1}$ pb (FC*)

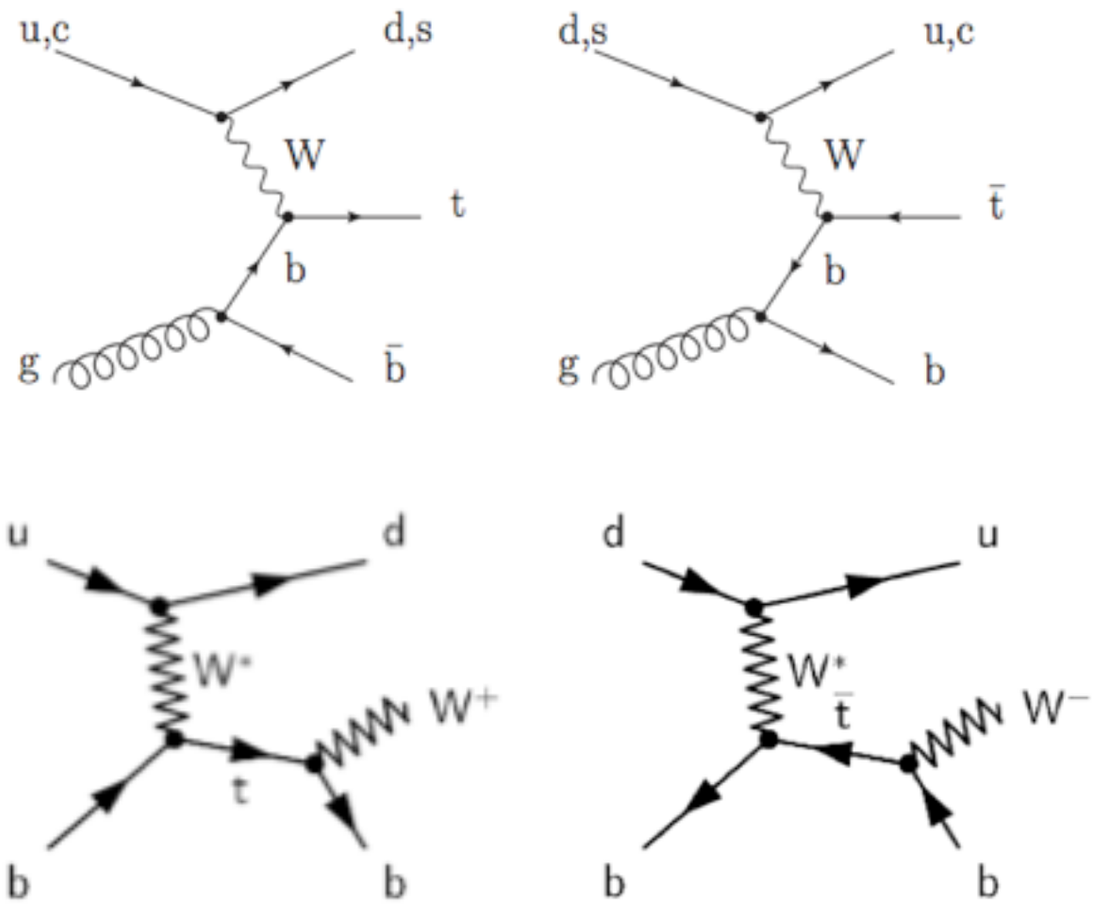
$\sigma^{th}_{s\text{-channel}} = 5.55 \pm 0.08$ (scale) ± 0.21(PDF) pb (NNLL)**

Observed significance of the s-channel signal 0.7σ
Expected significance 0.9σ

Upper limit of 2.1 (3.1,1.6) times the SM → 11.5 (17.0,9.0) pb

*68% interval, Feldman-Cousins unified approach; no negative cross sections

Single-top: t channel



t channel

1.96 TeV

D0 17%

σ_t=3.07±0.53 pb

CDF 30%

σ_t=1.49±0.47 pb

7 TeV

ATLAS 24%

σ_t=83±4(stat.)$^{+20}_{-19}$ (syst.) pb

CMS 9%

σ_t=67.2±6.1 pb

8 TeV

ATLAS 14.5%

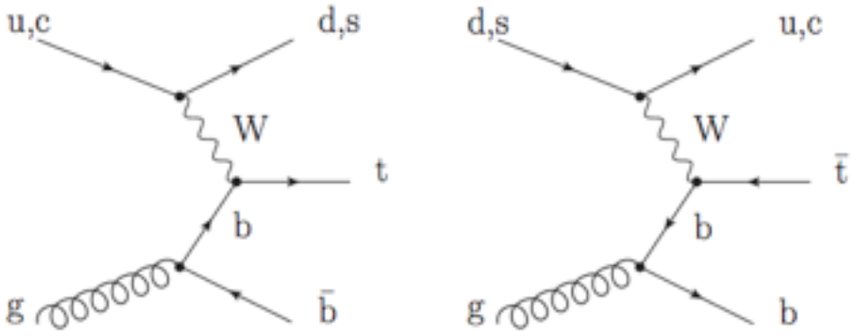
σ_t=82.6±1.2(stat) ±11.4(sys)±3.1(PDF) ±2.3(lumi) pb

CMS 9.3%

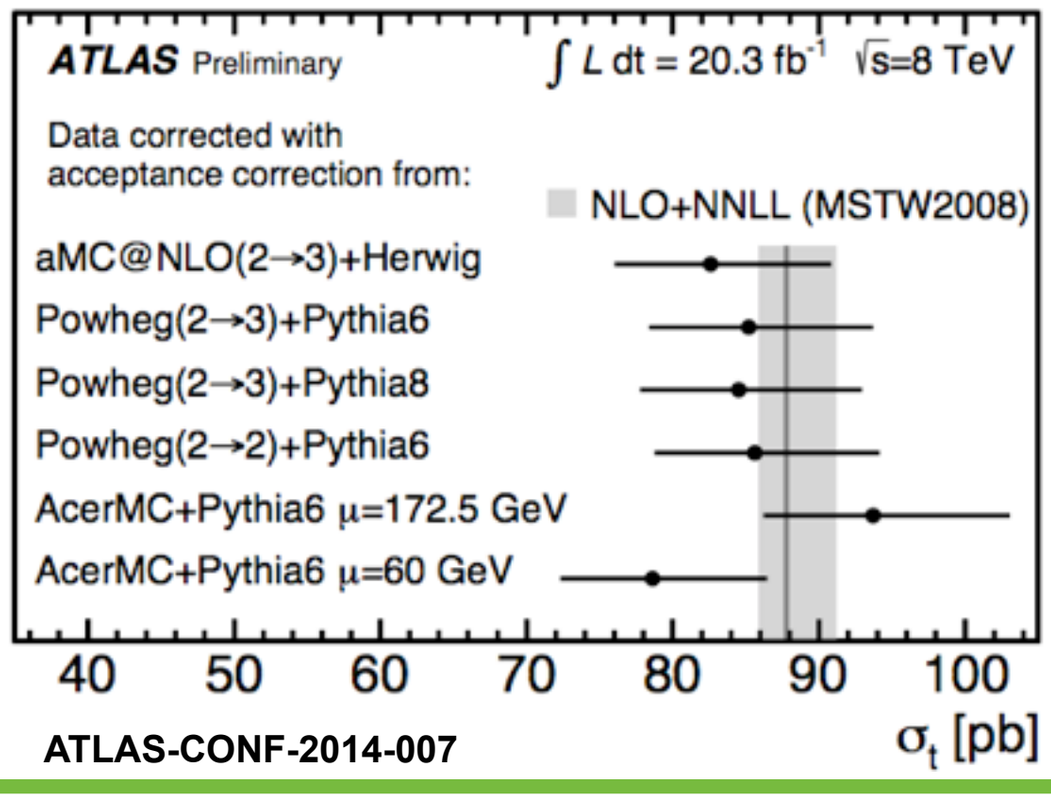
σ_t=83.6±2.3(stat) ±7.4(sys) pb

Higher statistics at LHC: detailed studies on model *(next ➡)*

t channel studies

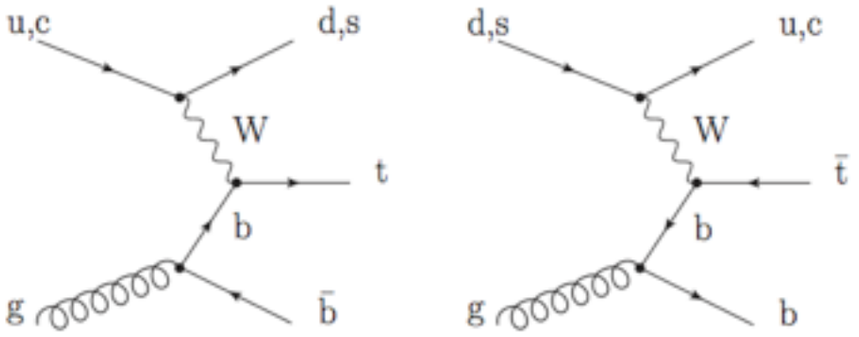


- Measurement fully fiducial
- Model-dependence: acceptance correction
  (but large extrapolation truth ⇔ particle level)



ATLAS-CONF-2014-007

t channel studies



- Measurement fully fiducial
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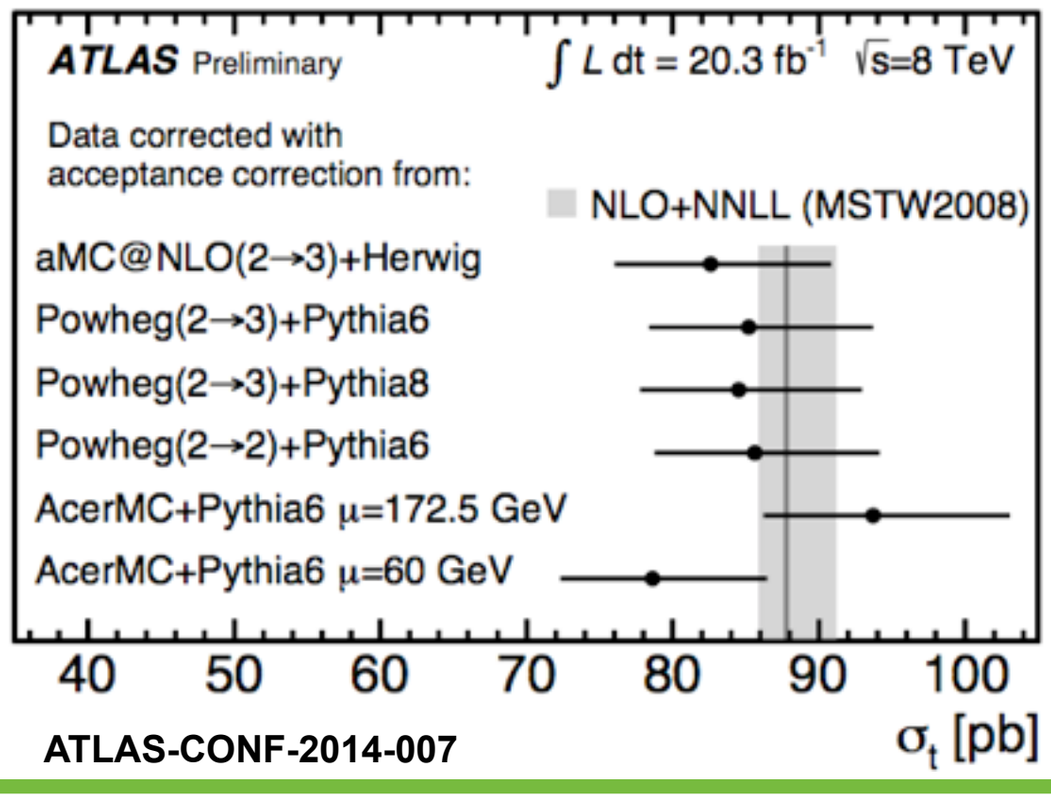
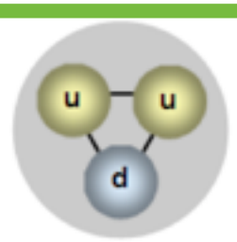


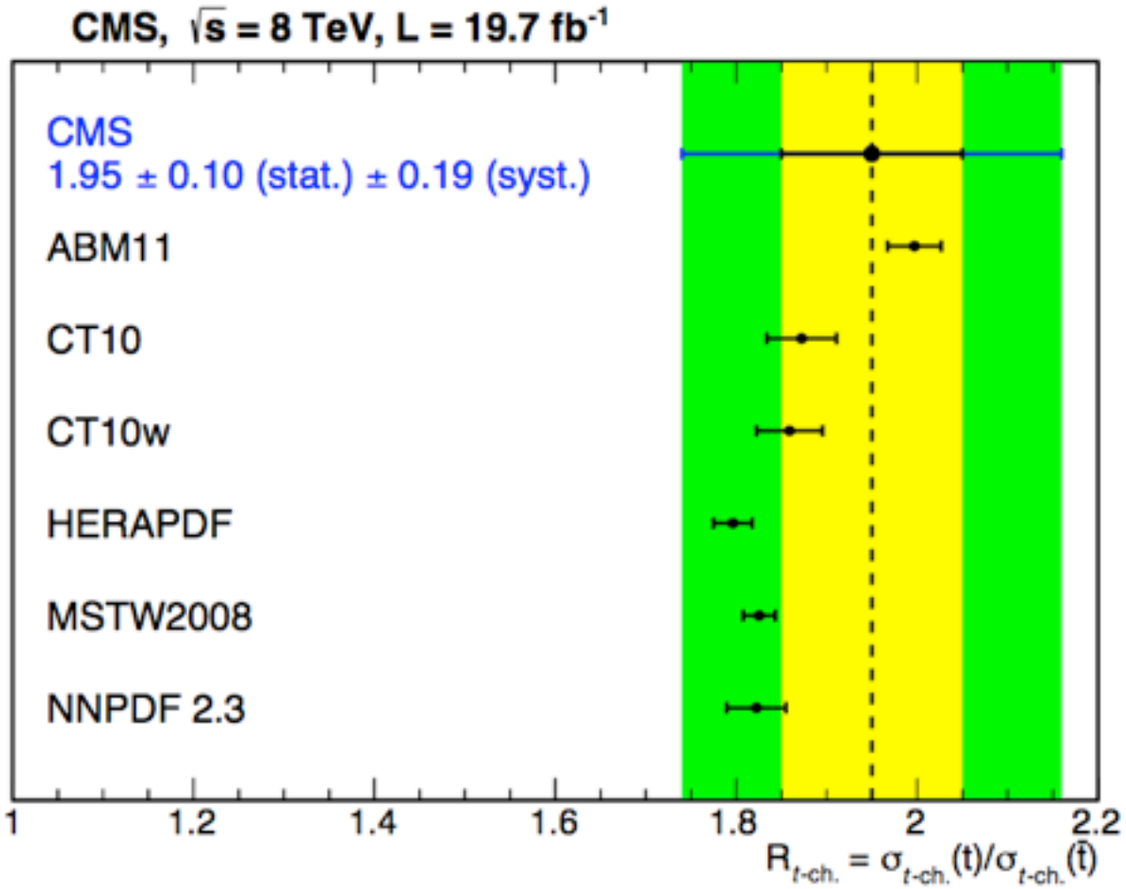
ATLAS-CONF-2014-007



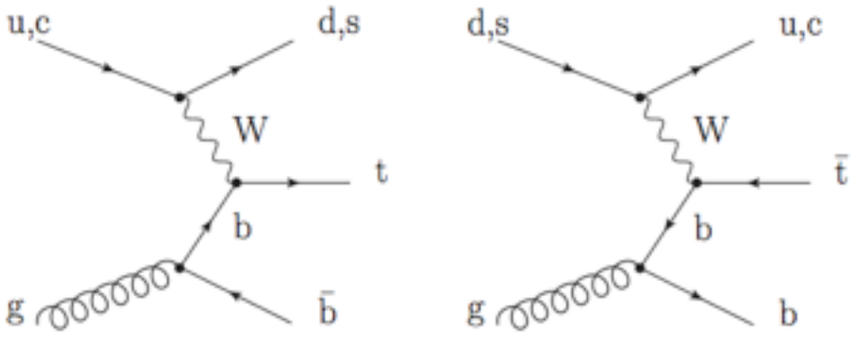
arXiv:14037366
accepted by JHEP

- expected roughly twice tops as compared to anti-tops
- probe proton PDFs

$$R_{t-channel} = 1.95 \pm 0.10(stat.) \pm 0.19(syst.)$$



t channel studies



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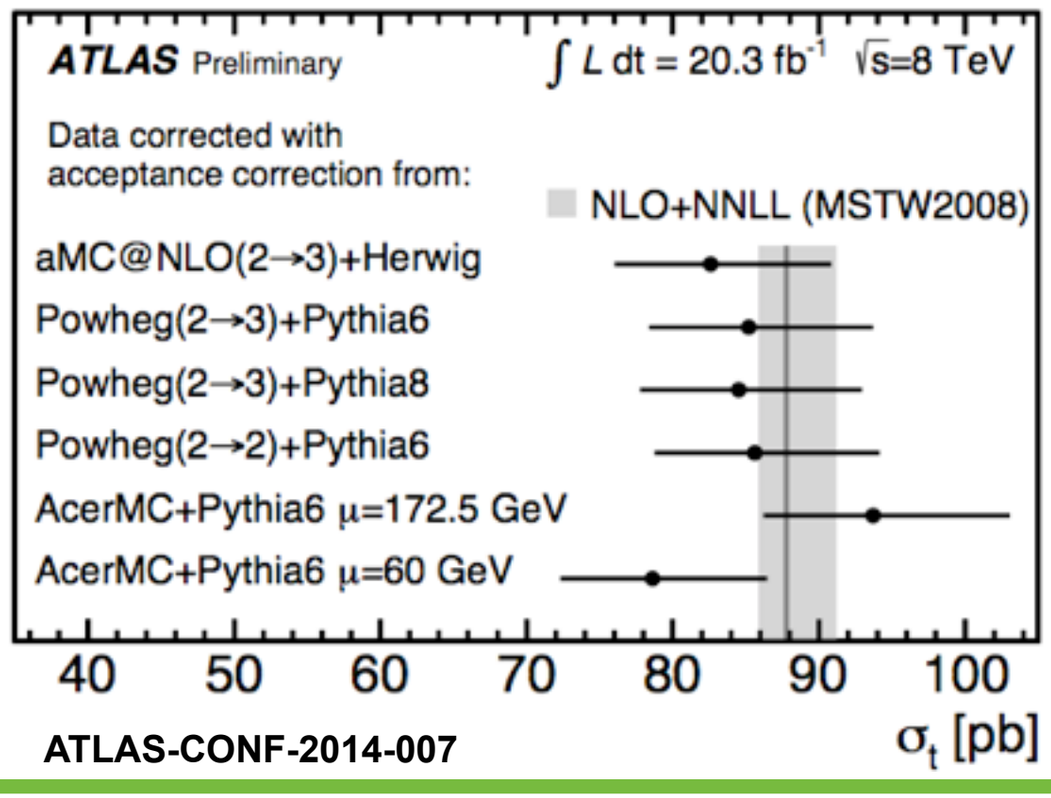
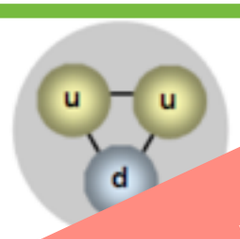


ATLAS-CONF-2014-007

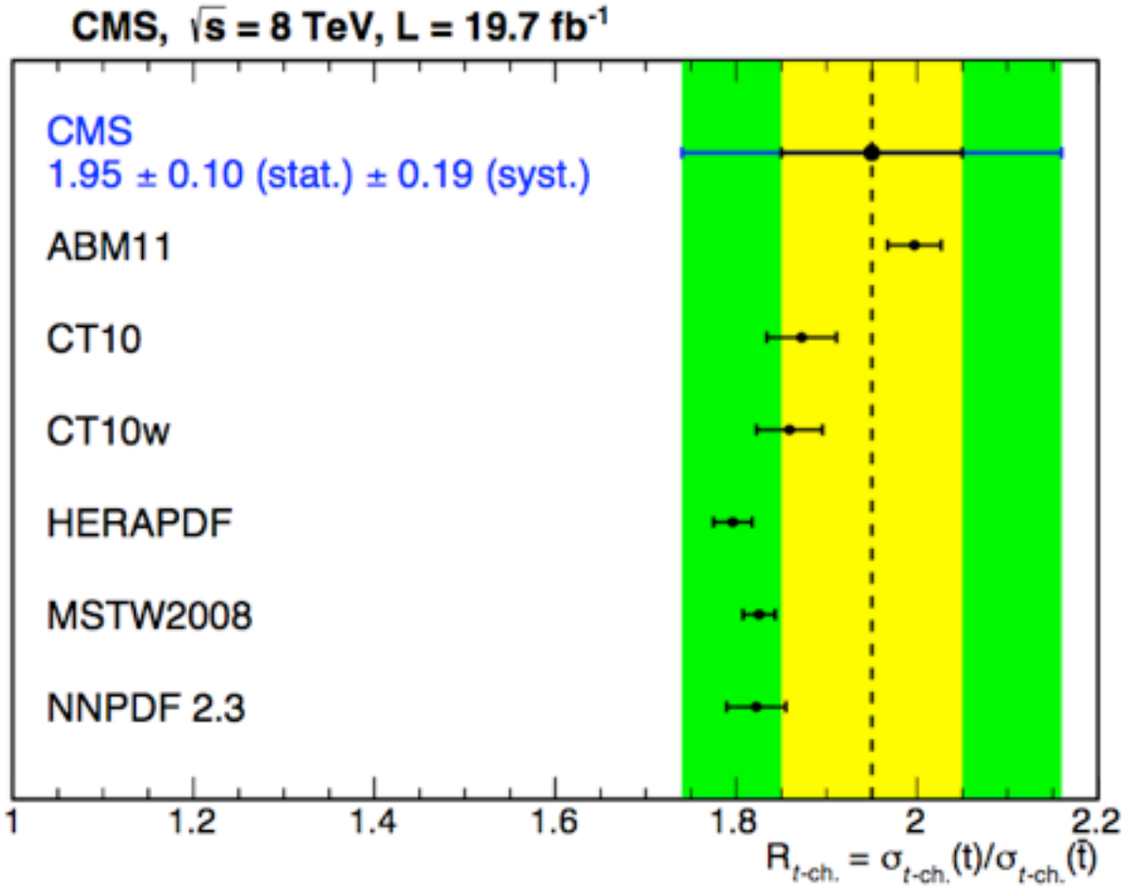


- ex… twice
…o anti-

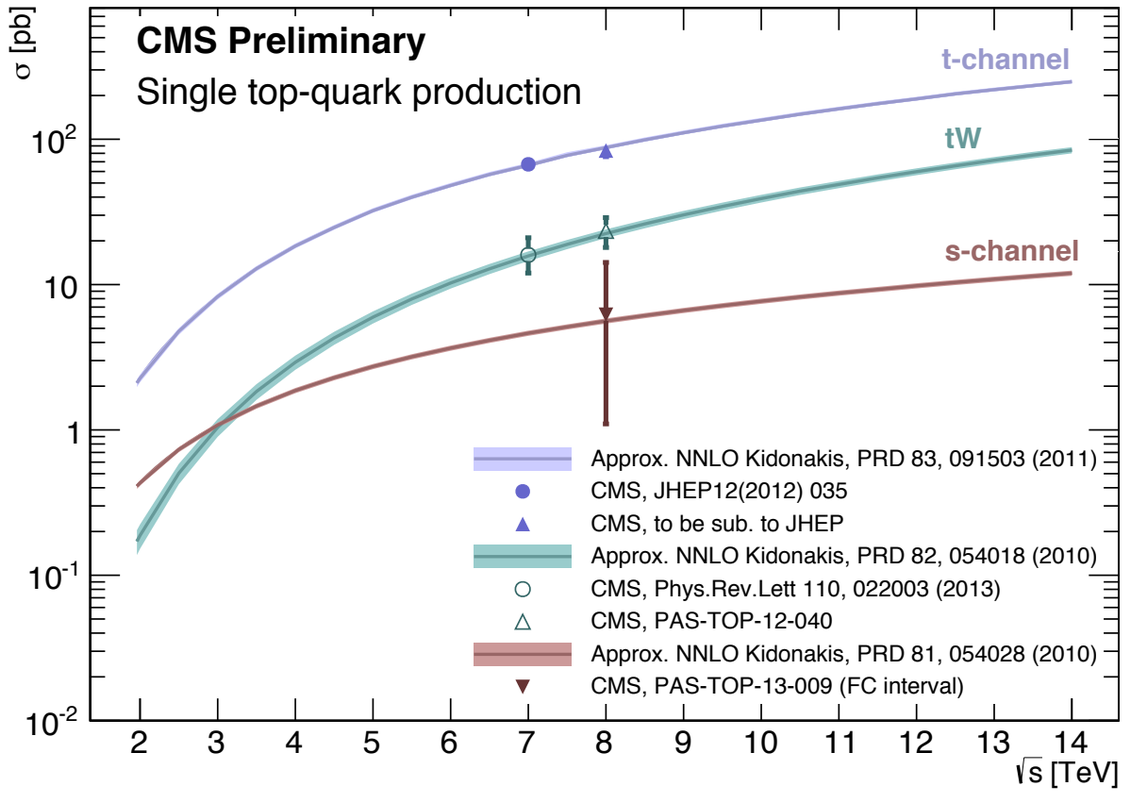
LHC-only measurement (R=1 at Tevatron)

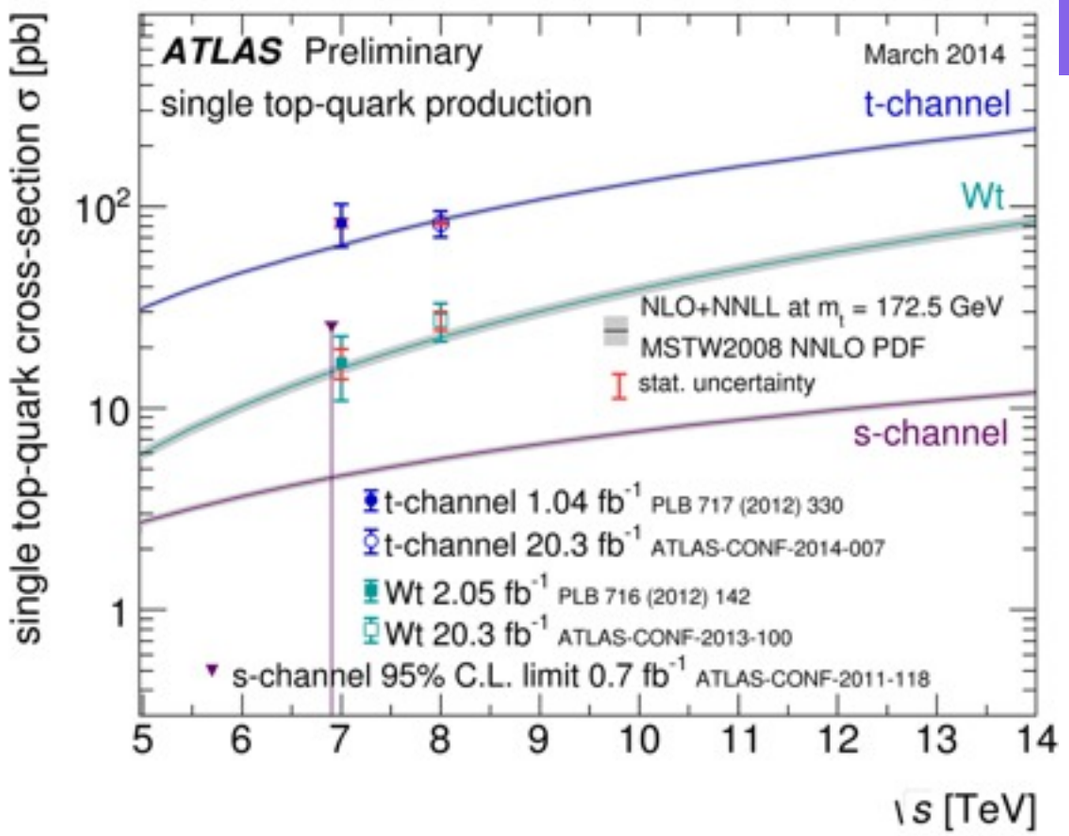
…be proton PDFs

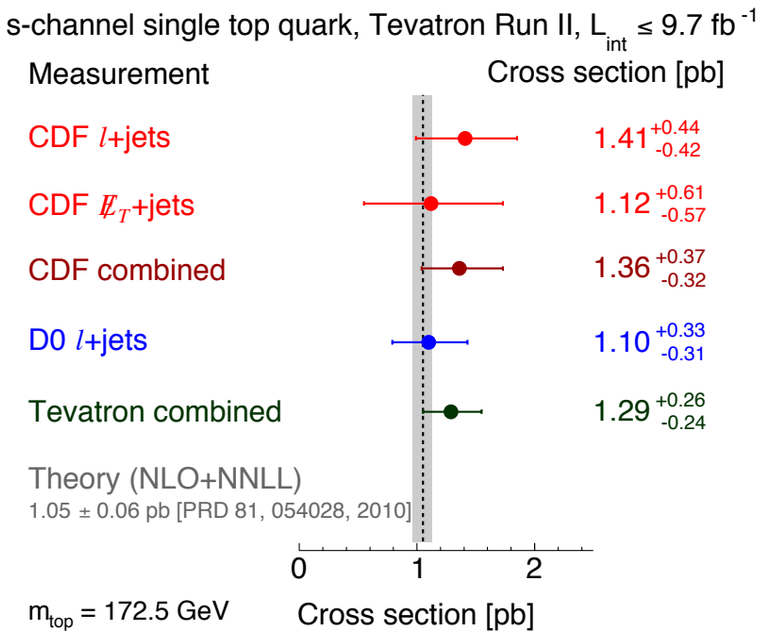
$$\ldots_{t\text{-}channel} = 1.95 \pm 0.10(stat.) \pm 0.19(syst.)$$



Single-top production: summary

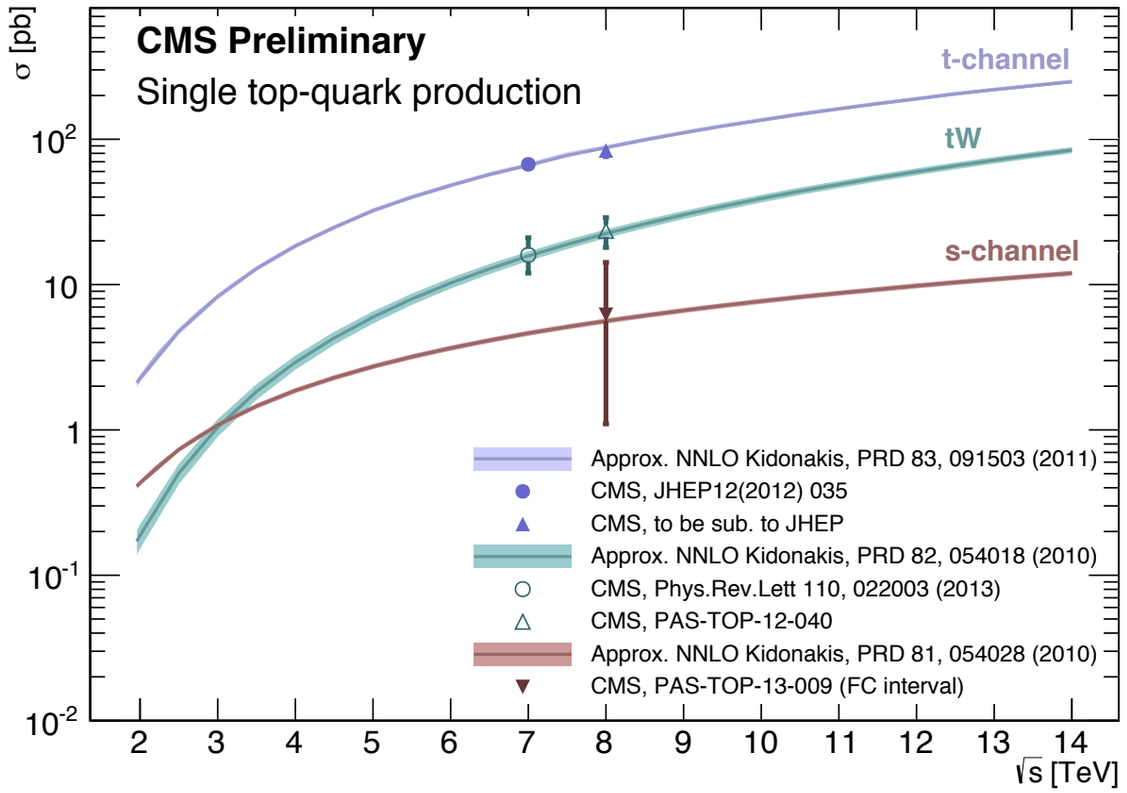


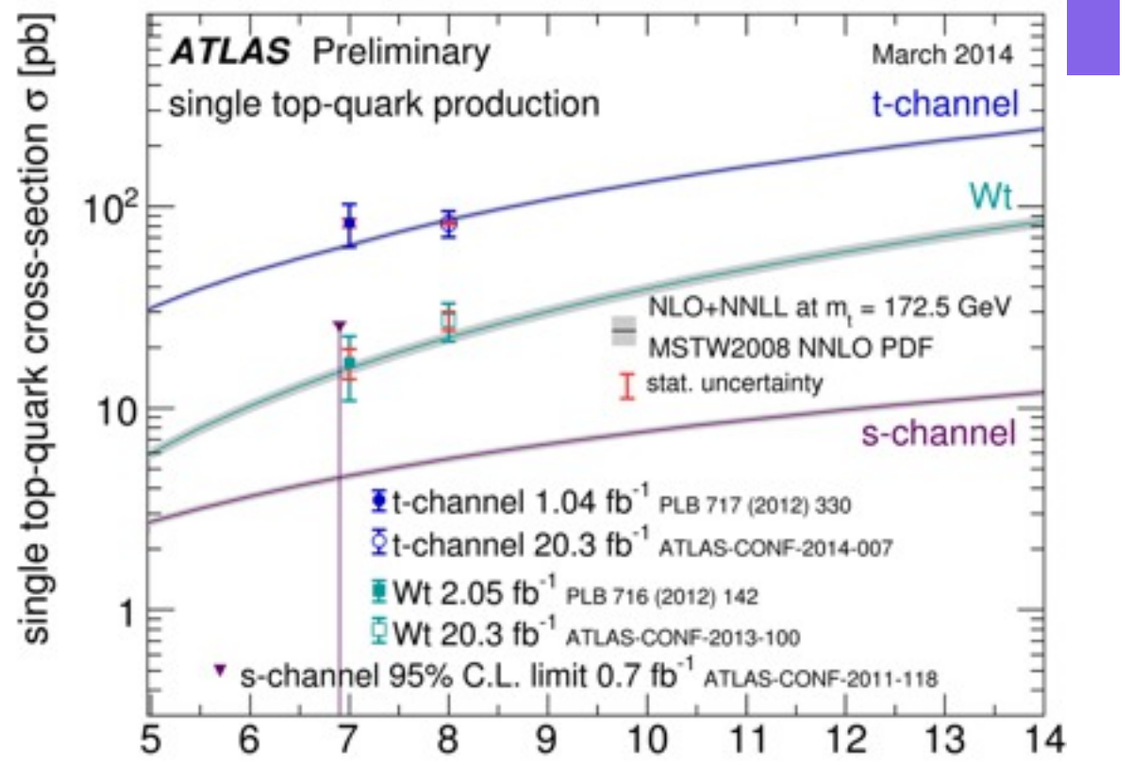


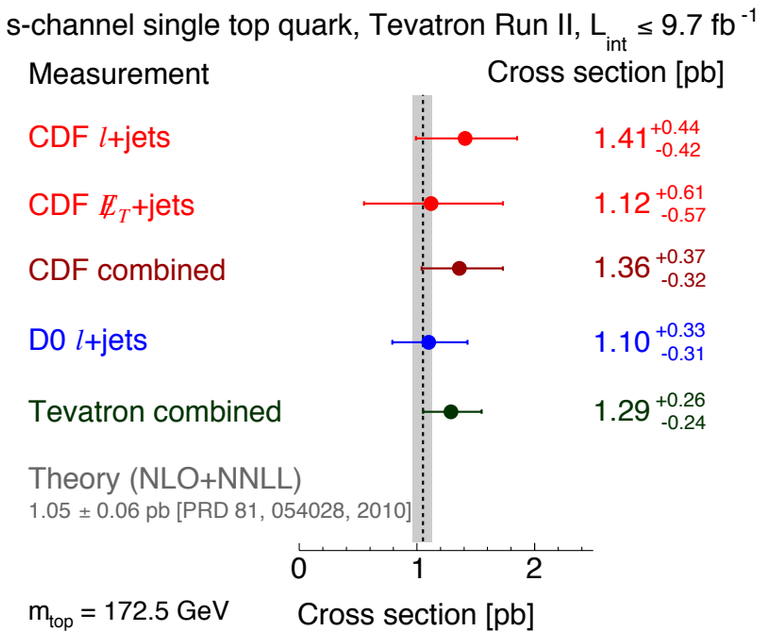


Tevatron and LHC: good agreement with SM expectations

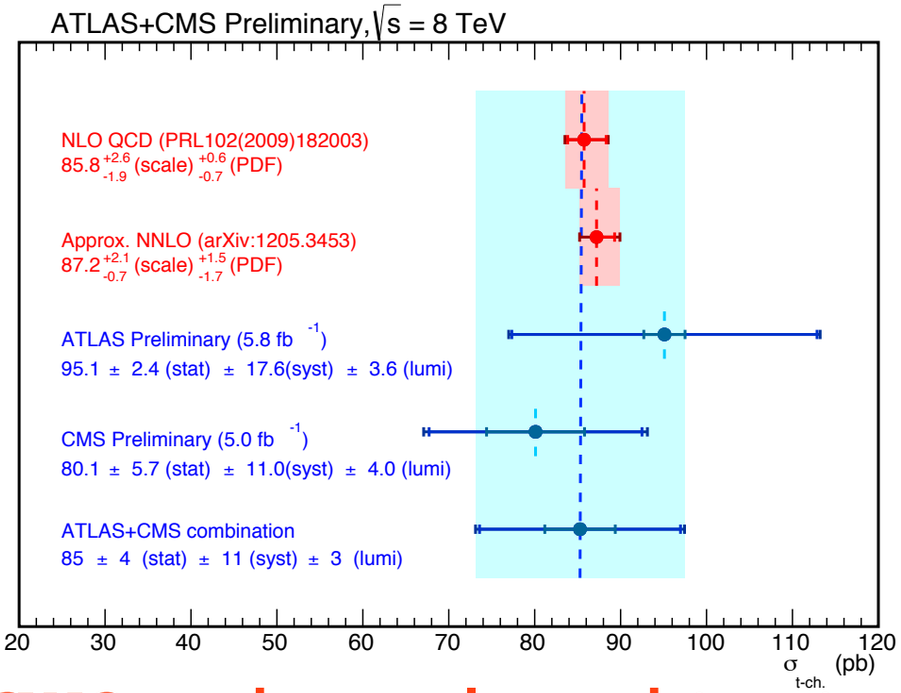
Single-top production: summary







Tevatron and LHC: good agreement with SM expectations

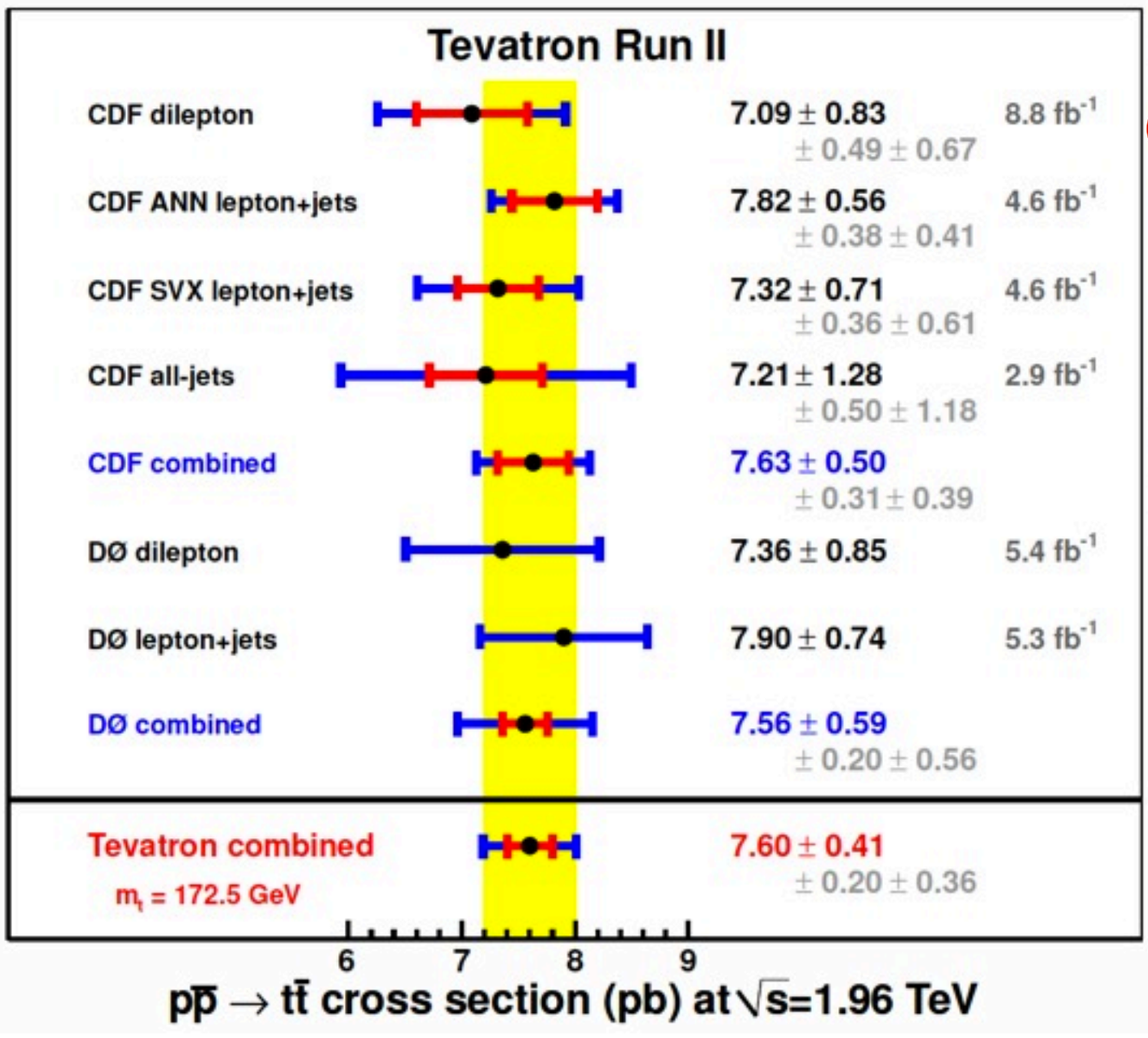


TOPLHCWG: t-channel combination

Inclusive $t\bar{t}$ production

Inclusive tt̄ cross section@ 1.96 TeV

PRD 89, 072001 (2014)

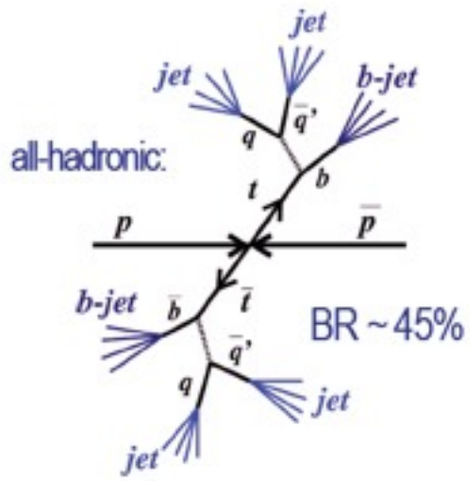


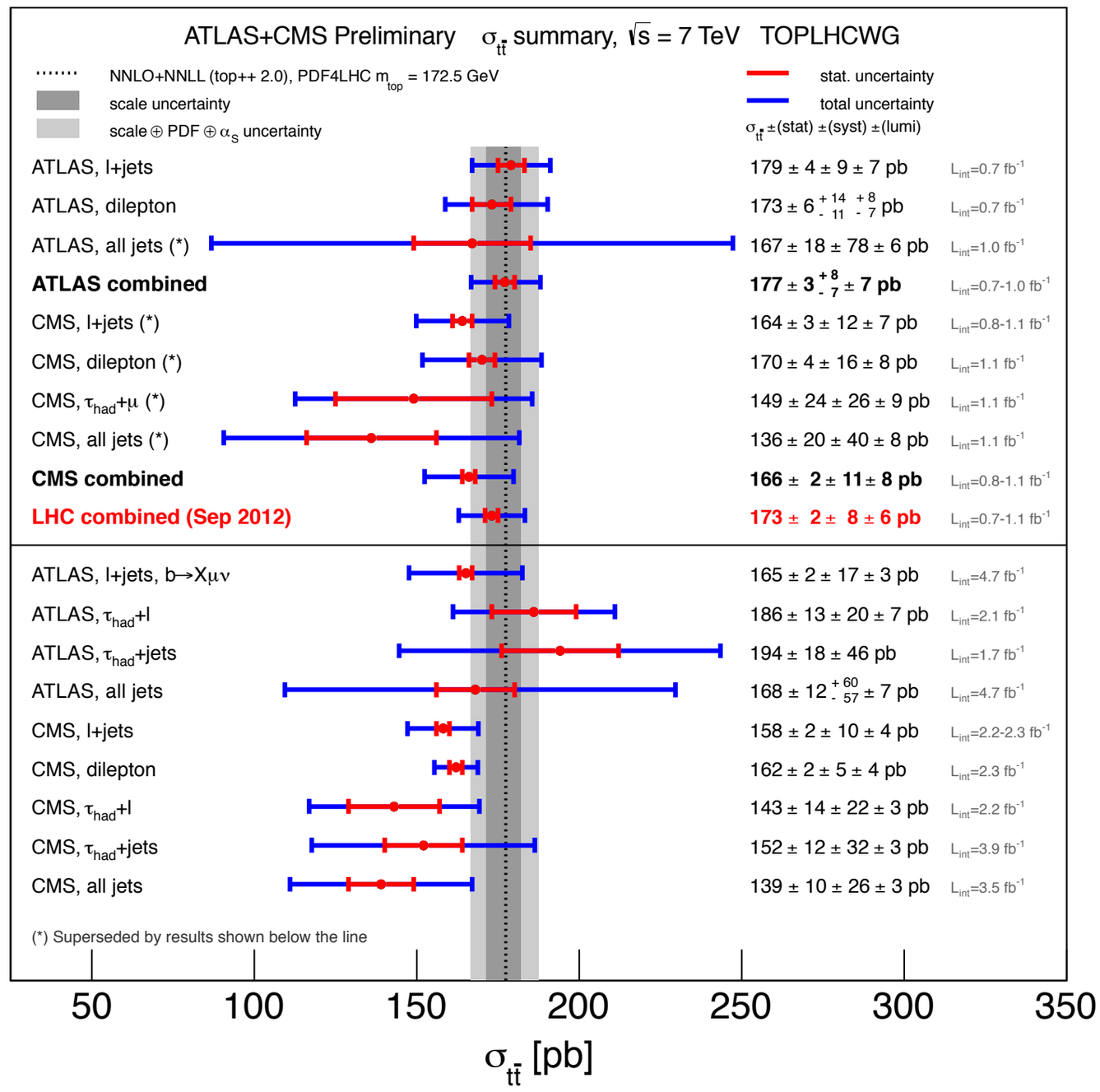
	CDF	D0		Tevatron
Central value of $\sigma_{t\bar{t}}$	7.63	7.56		7.60
Sources of systematic uncertainty			Correlation	
Modeling of the detector	0.17	0.22	NO	0.13
Modeling of signal	0.21	0.13	YES	0.18
Modeling of jets	0.21	0.11	NO	0.13
Method of extracting $\sigma_{t\bar{t}}$	0.01	0.07	NO	0.03
Background modeled from theory	0.10	0.08	YES	0.10
Background based on data	0.08	0.06	NO	0.05
Normalization of Z/γ^* prediction	0.13	–	NO	0.08
Luminosity: inelastic $p\bar{p}$ cross section	0.05	0.30	YES	0.15
Luminosity: detector	0.06	0.35	NO	0.14
Total systematic uncertainty	0.39	0.56		0.36
Statistical uncertainty	0.31	0.20		0.20
Total uncertainty	0.50	0.59		0.41

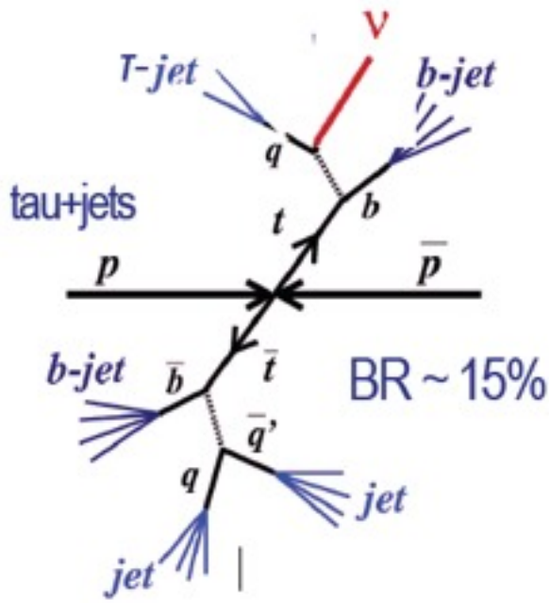
σ_{tt} = 7.6±0.20±0.36 pb 5.4%

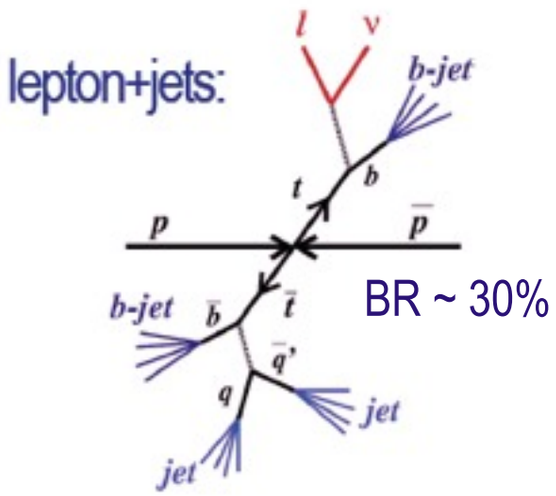
NNLO+NNLL prediction: $7.35\ ^{+0.17}_{-0.12}$ (PDF)$^{+0.11}_{-0.21}$ (QCD scale) pb

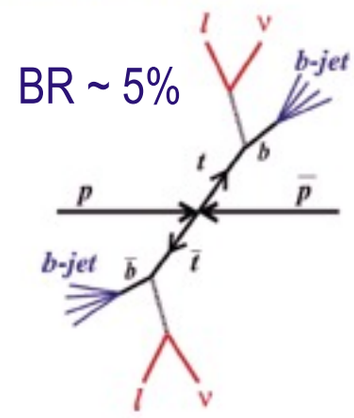
Inclusive $t\bar{t}$ cross section@ 7 TeV











...missing only decays to ττ

Inclusive $t\bar{t}$ cross section@ 8 TeV

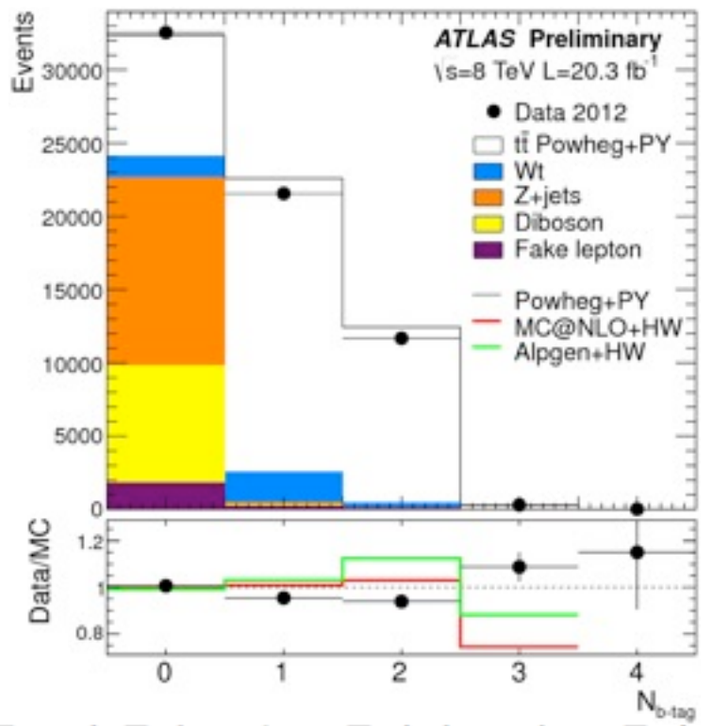
ATLAS (eμ) ATLAS-CONF-2013-097

- 2 equations (number of 1 & 2 tagged jets)
- 2 unknowns: cross section and ε_b (jet reco & b-tag eff.)

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

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

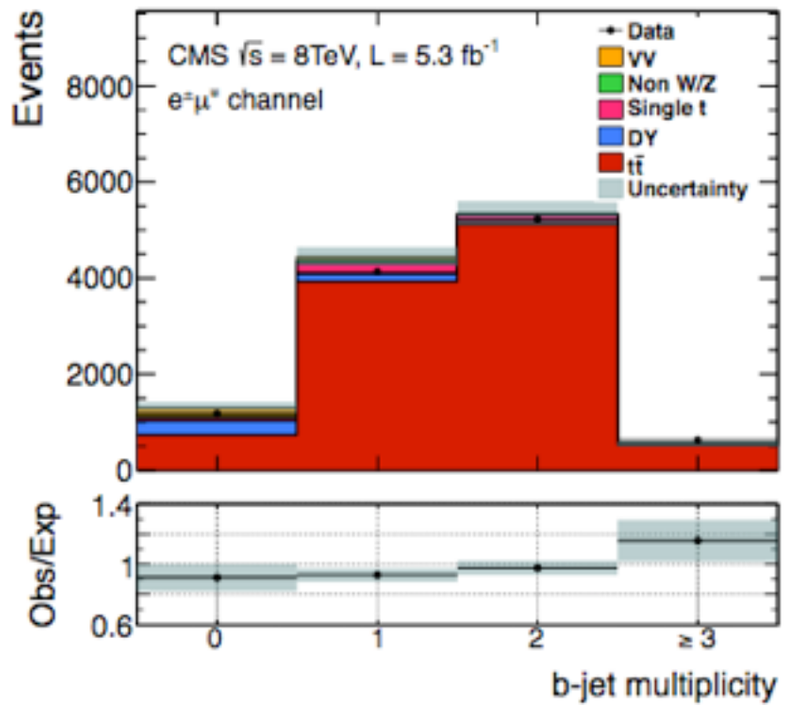
- Single lepton trigger (~fully efficient)
- 20 fb^{-1}



$\sigma_{t\bar{t}} = 237.7 \pm 1.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 7.4\,(\text{lumi})$
$\pm 4.0\,(\text{beam energy})$ pb

CMS (ee, eμ,μμ)

- Cut and count method **JHEP 02 (2014) 024**
- Require 1 btag (2 leptons, 2 jets)
- Dilepton trigger
- Main systematic uncertainties: signal modeling, jet energy scale
- 5.3 fb^{-1} (not yet CMS "final word")



$\sigma_{t\bar{t}} = 239.0 \pm 2.1\,(\text{stat.}) \pm 11.3\,(\text{syst.}) \pm 6.2\,(\text{lum.})$ pb

Inclusive $t\bar{t}$ cross section@ 8 TeV

ATLAS (eμ) ATLAS-CONF-2013-097

- 2 equations (number of 1 & 2 tagged jets)
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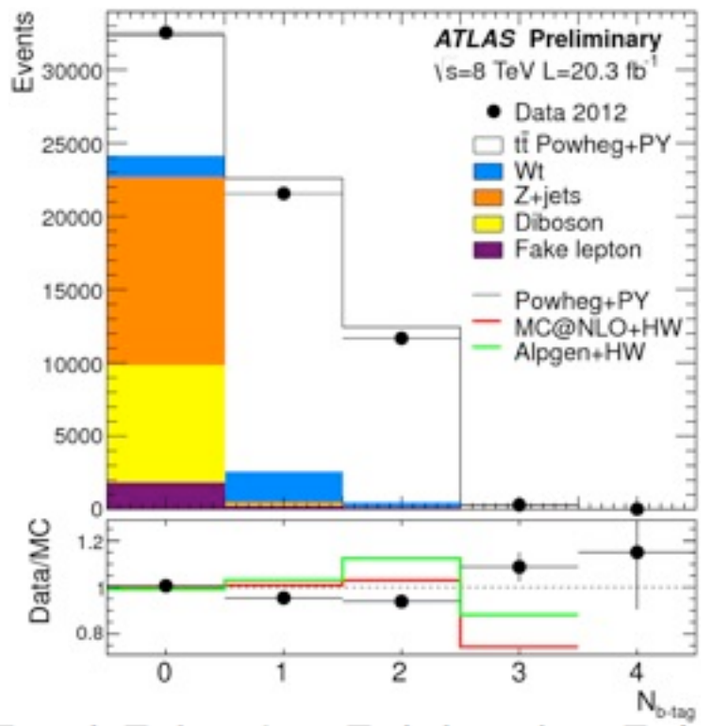

4.5%

$\sigma_{t\bar{t}} = 237.7 \pm 1.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 7.4\,(\text{lumi}) \pm 4.0\,(\text{beam energy})$ pb

CMS (ee, eμ,μμ)

- Cut and count method — JHEP 02 (2014) 024
- Require 1 btag (2 leptons, 2 jets)
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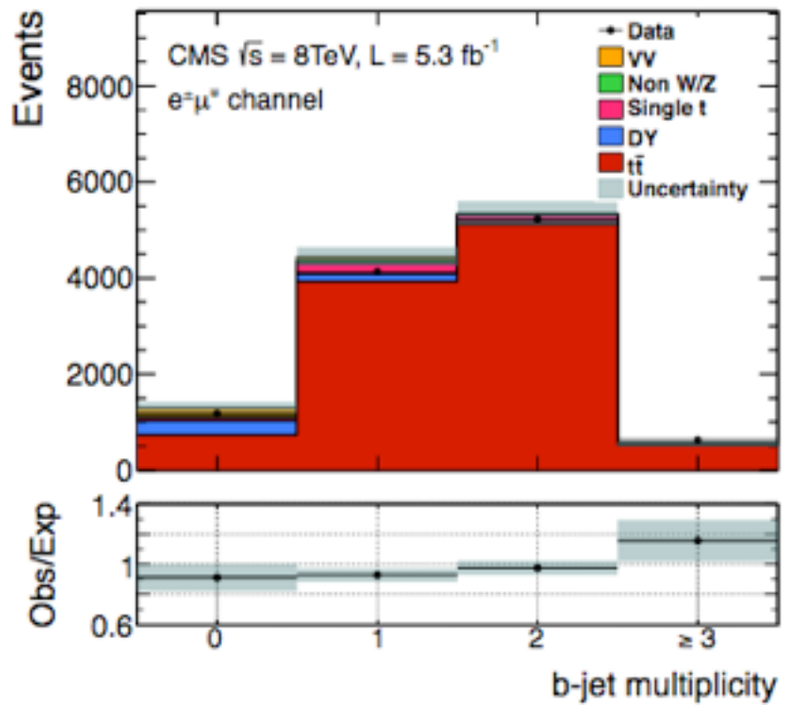


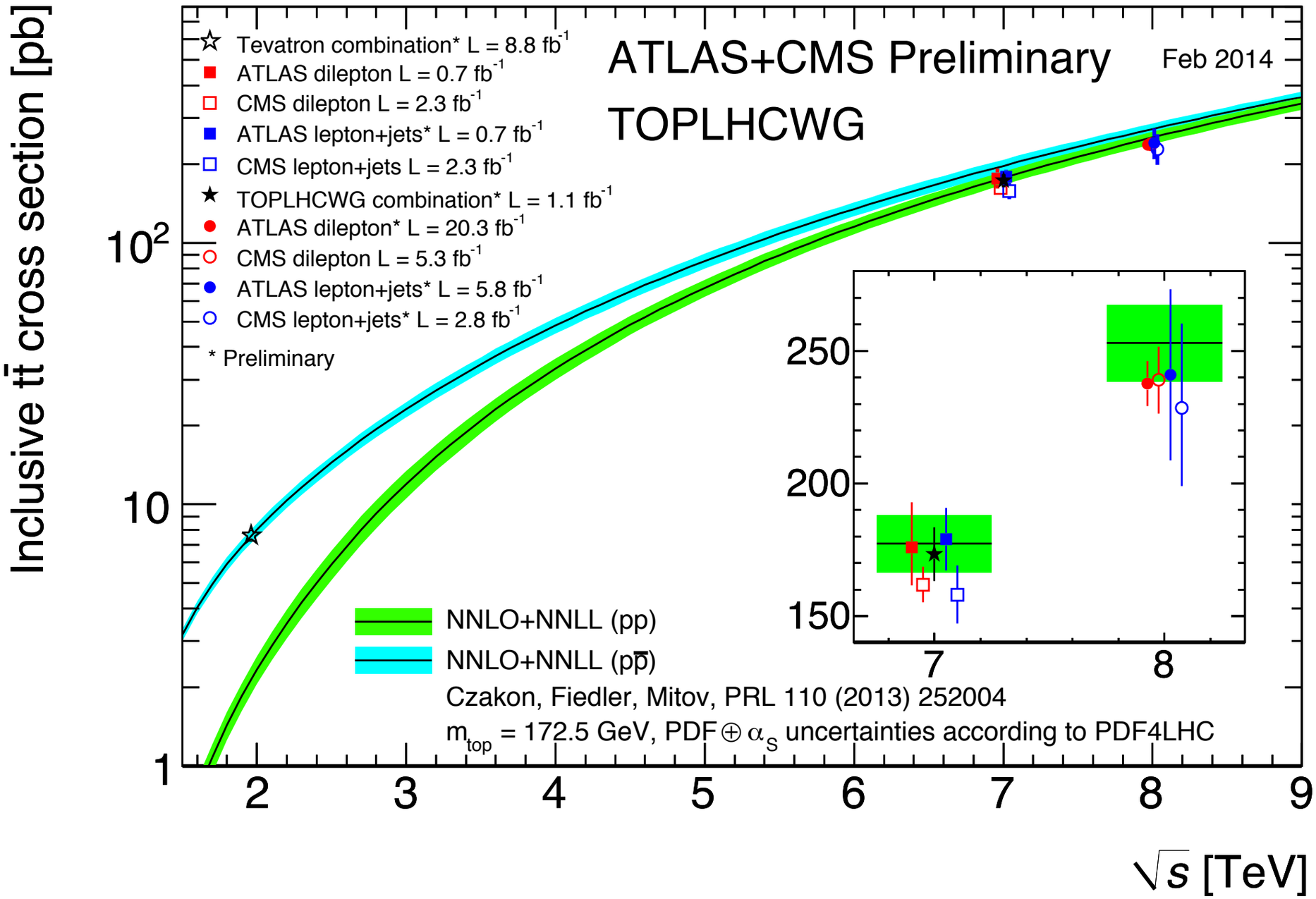
5.5%

$\sigma_{t\bar{t}} = 239.0 \pm 2.1\,(\text{stat.}) \pm 11.3\,(\text{syst.}) \pm 6.2\,(\text{lum.})$ pb

Full NNLO prediction: 252.9±11.7 (PDF and α_s)$^{+6.4}_{-8.6}$ (QCD scale) pb

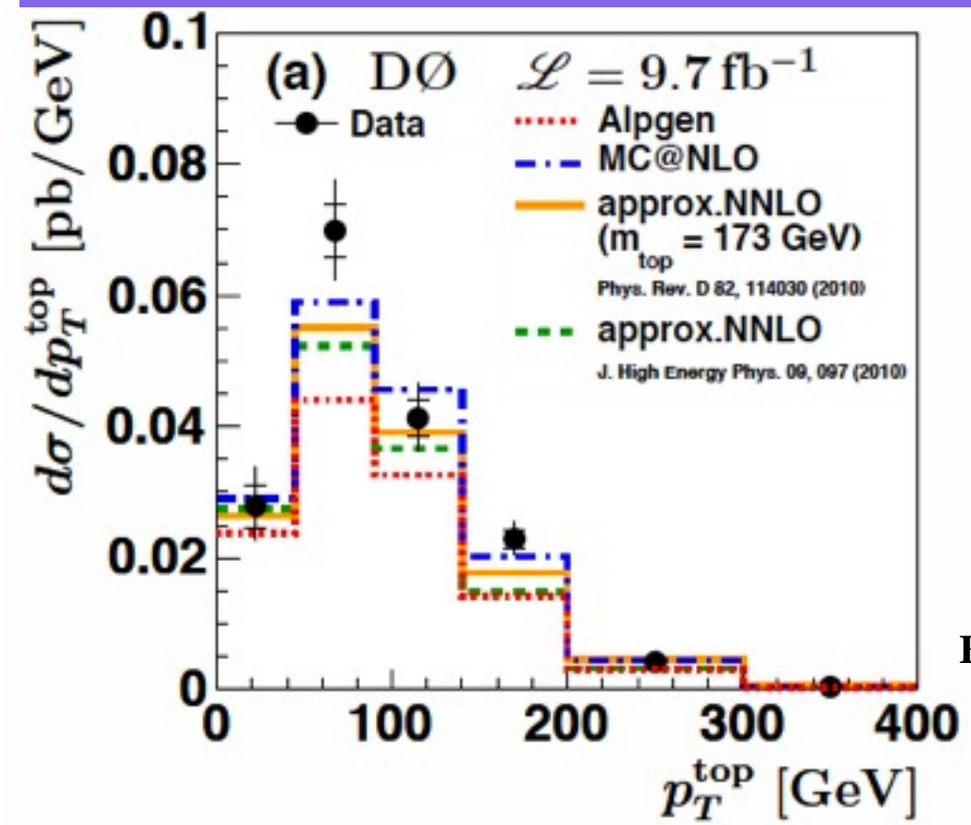
5.7%

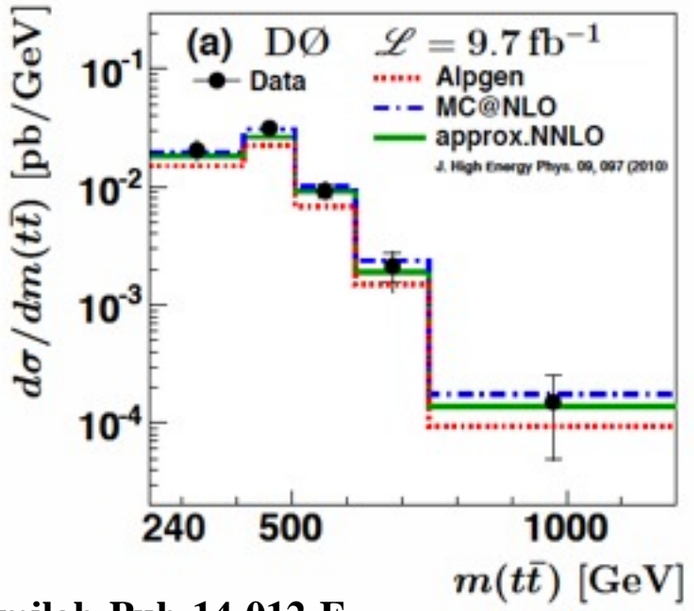
Inclusive tt̄ cross section: summary

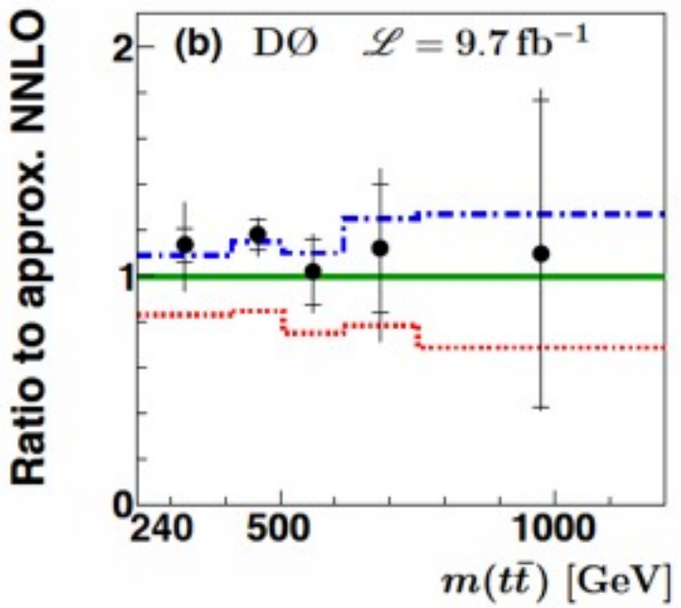


$t\bar{t}$ differential cross section

Differential cross section @ 1.96 TeV





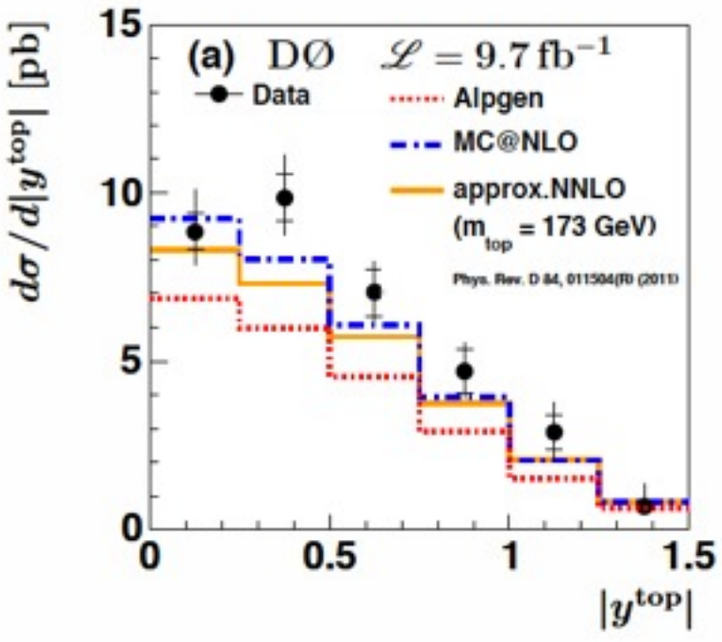


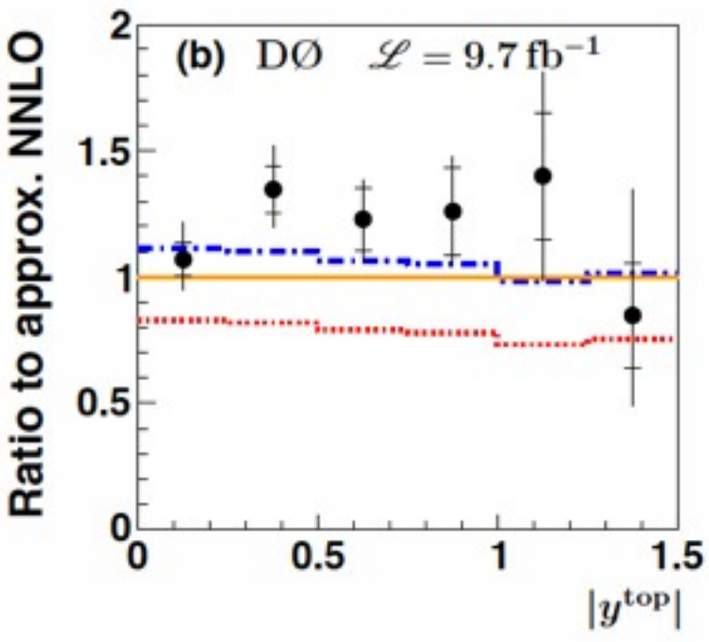
Fermilab-Pub-14-012-E

DØ

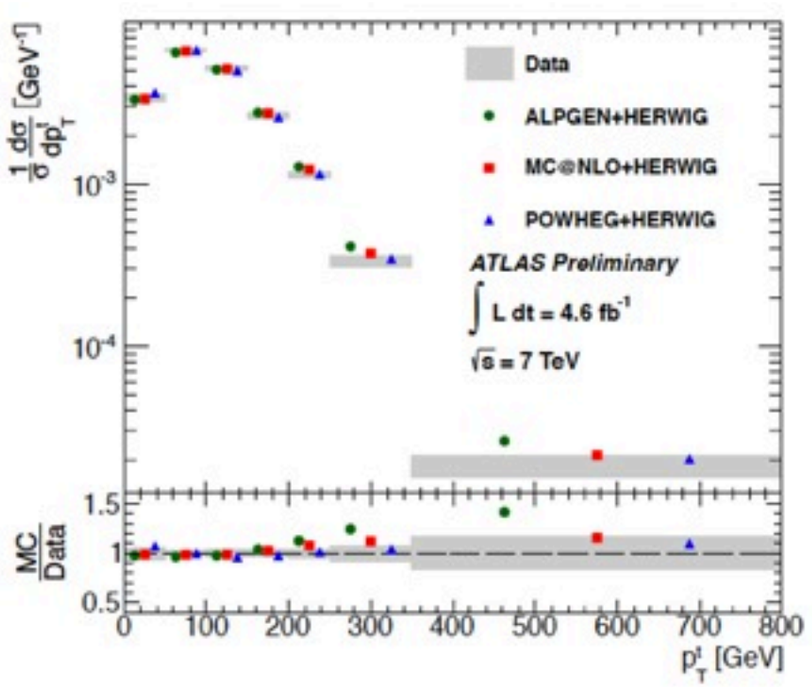
lepton+jets final state

Models generally in good agreement with the data

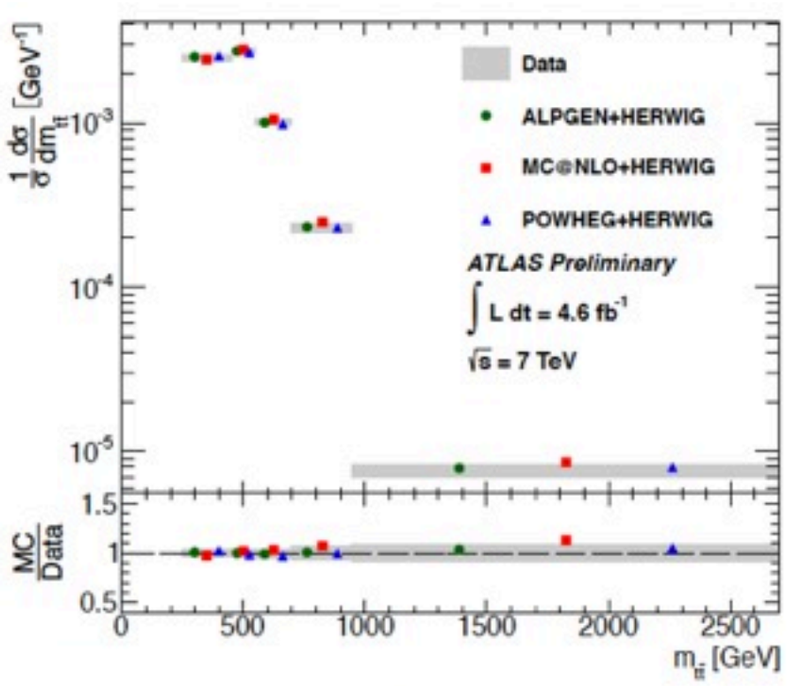




Differential cross section @7 TeV

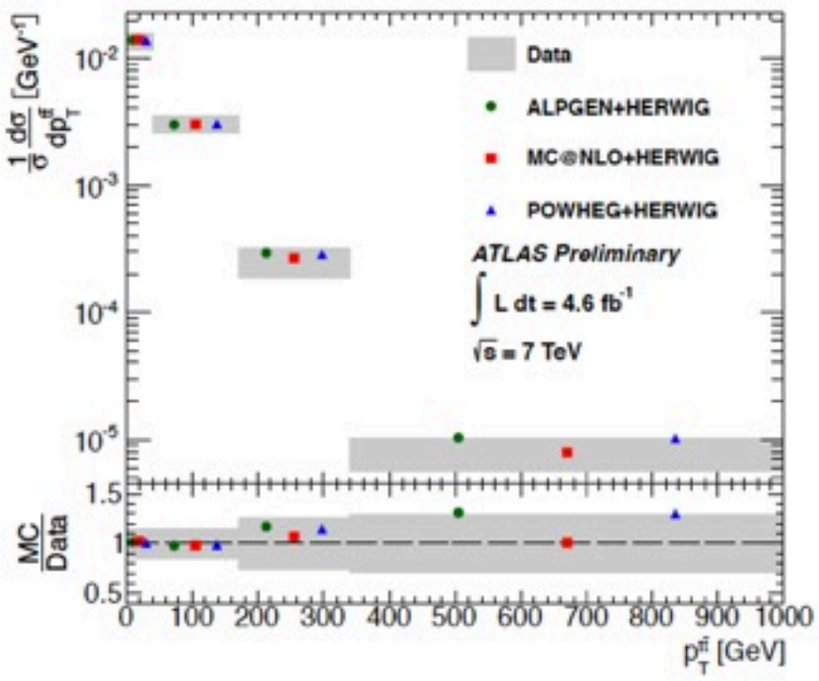


(a)

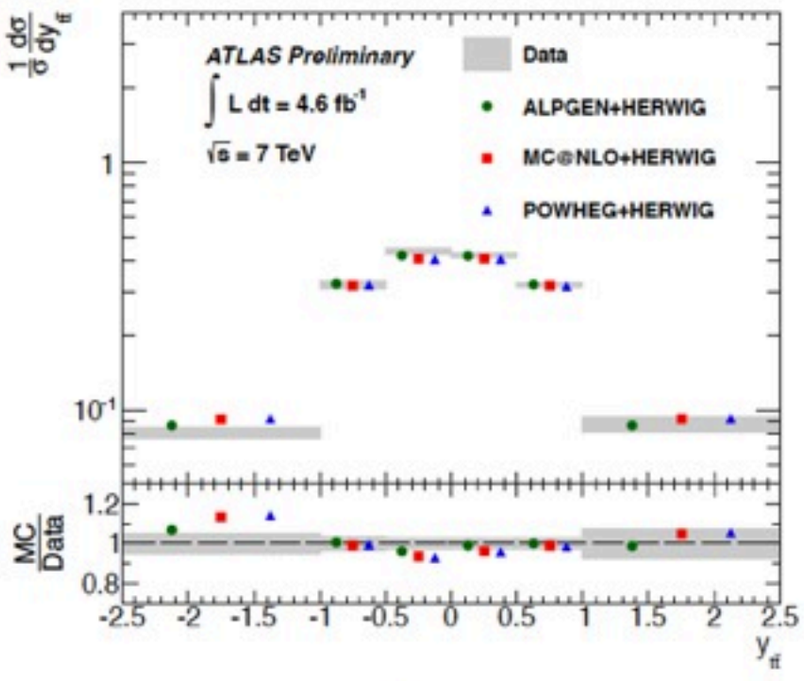


(b)

ATLAS-CONF-2013-099



(c)



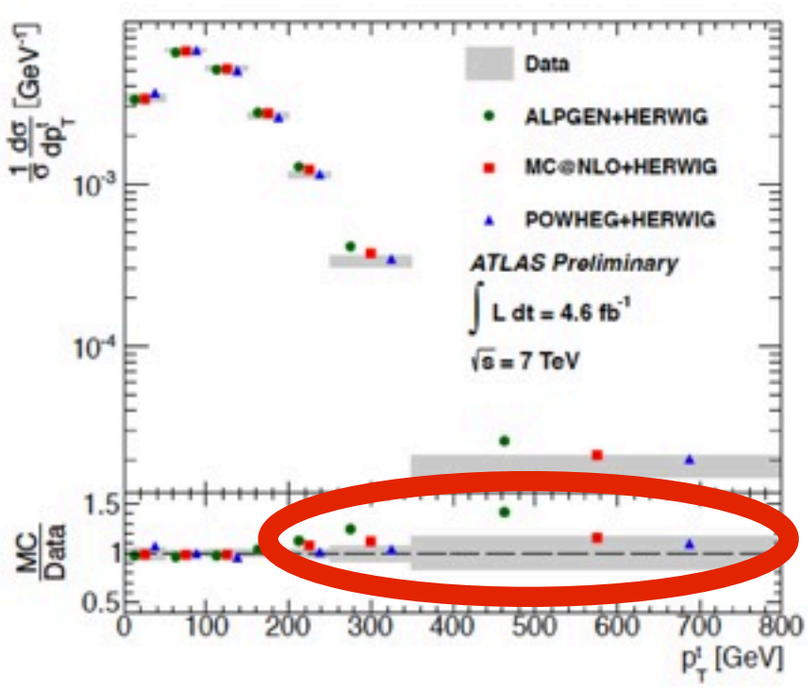
(d)

ATLAS

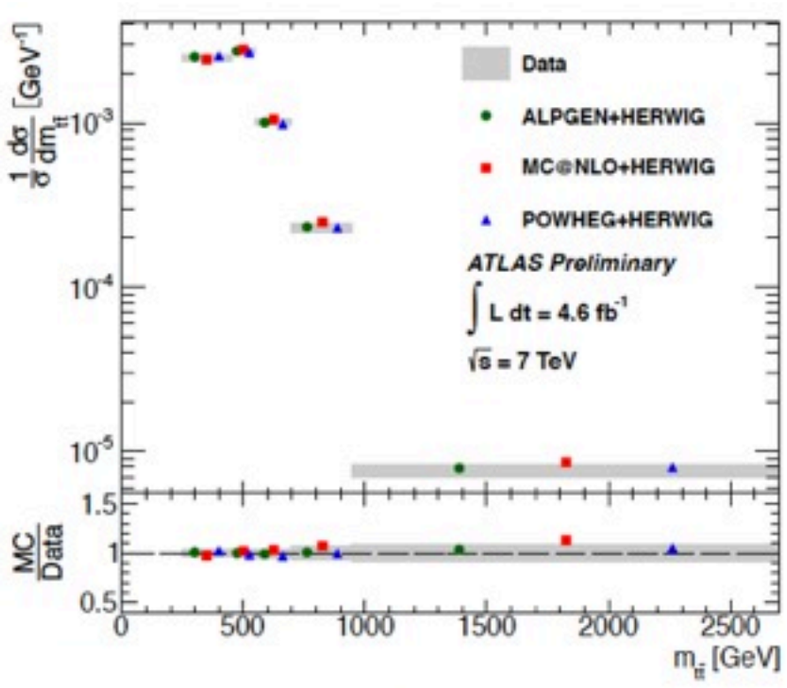
lepton+jets final state

very high-precision

Differential cross section @7 TeV

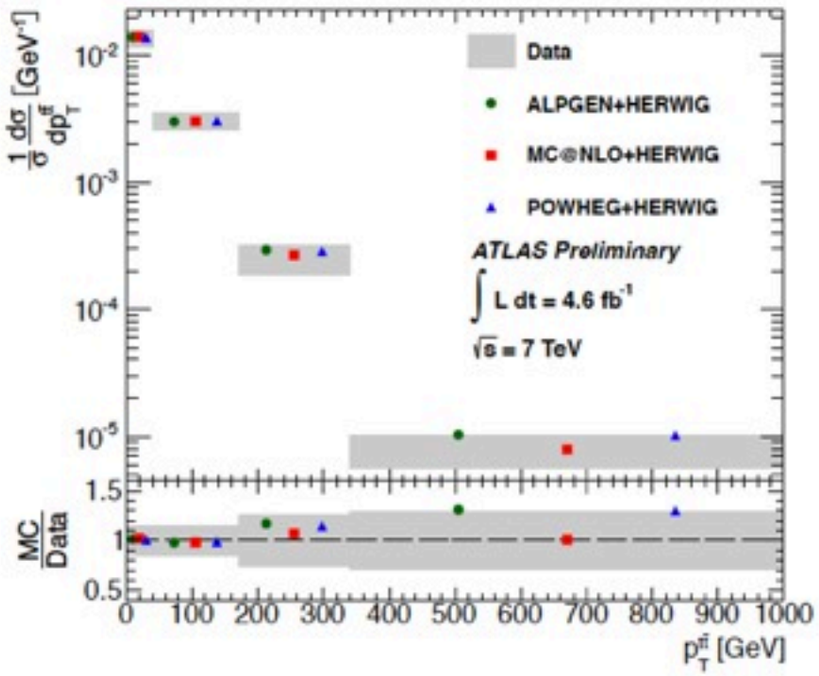


(a)

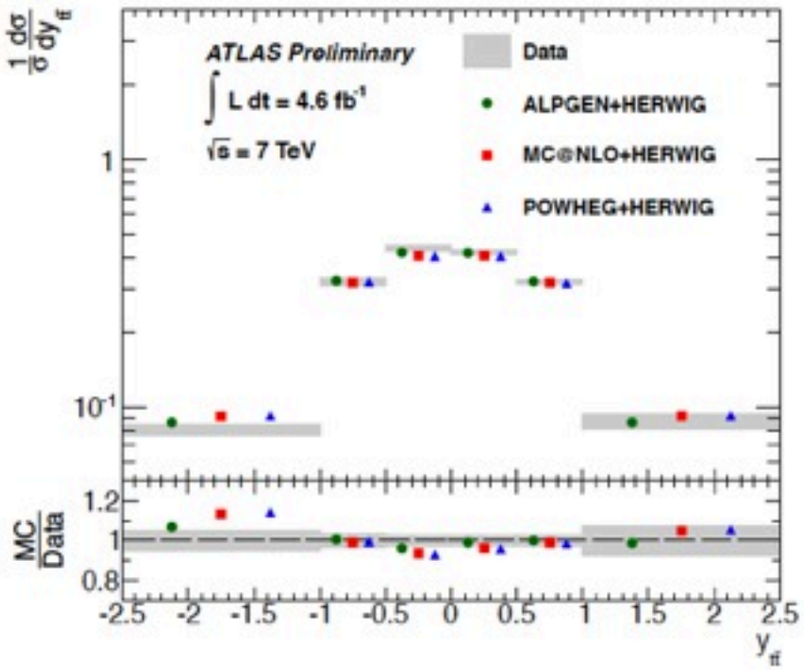


(b)

ATLAS-CONF-2013-099



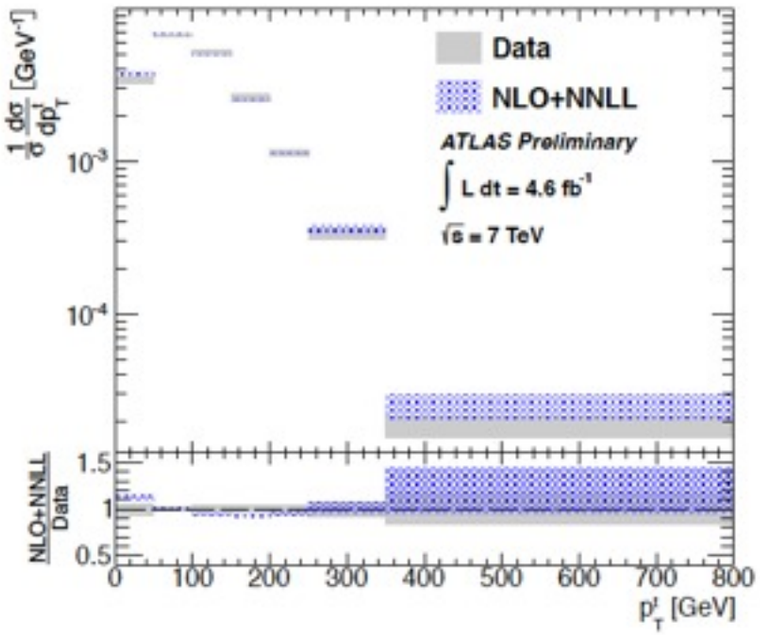
(c)

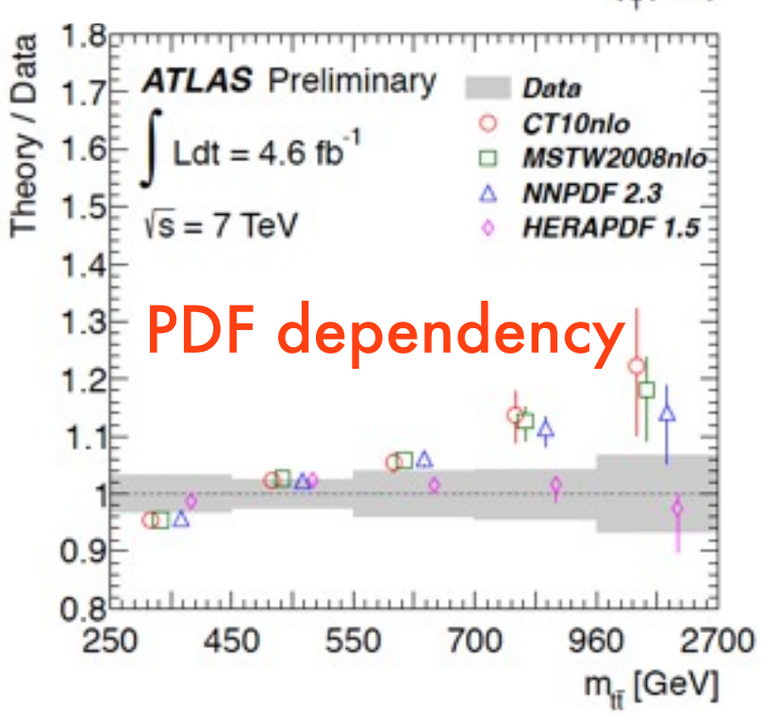


(d)

ATLAS

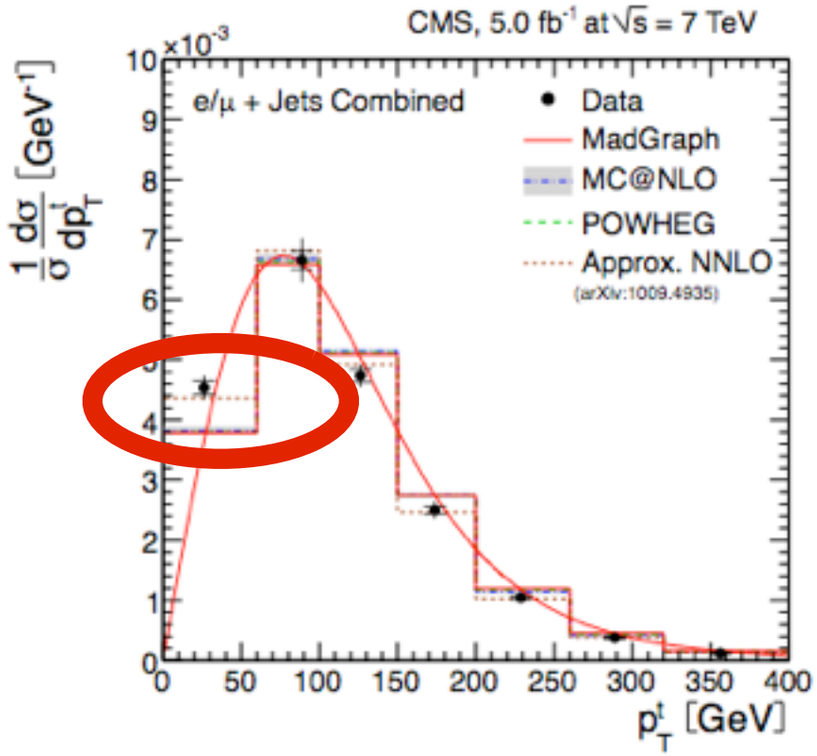
lepton+jets final state

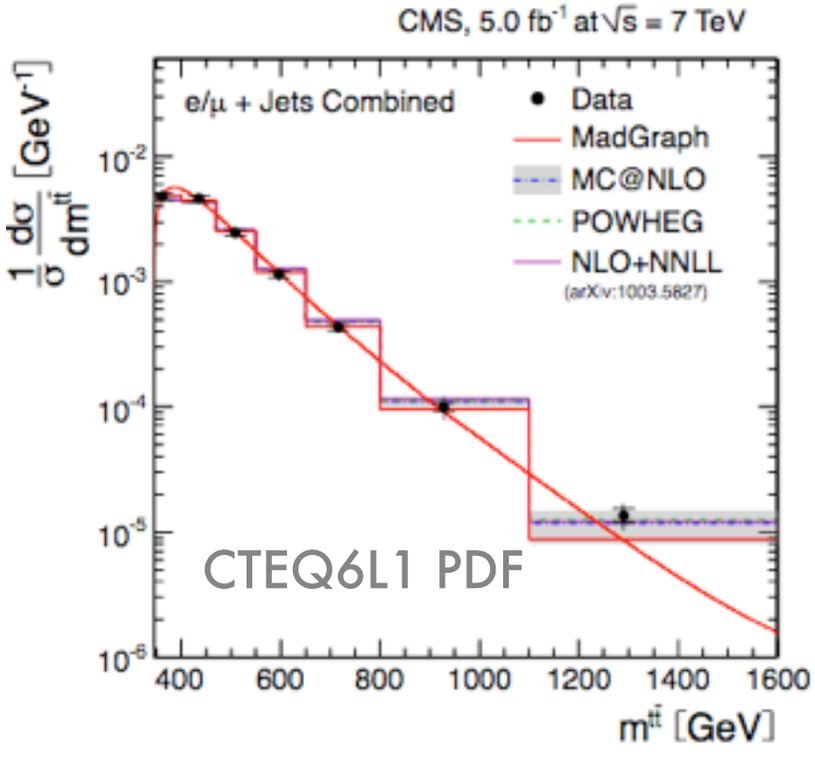


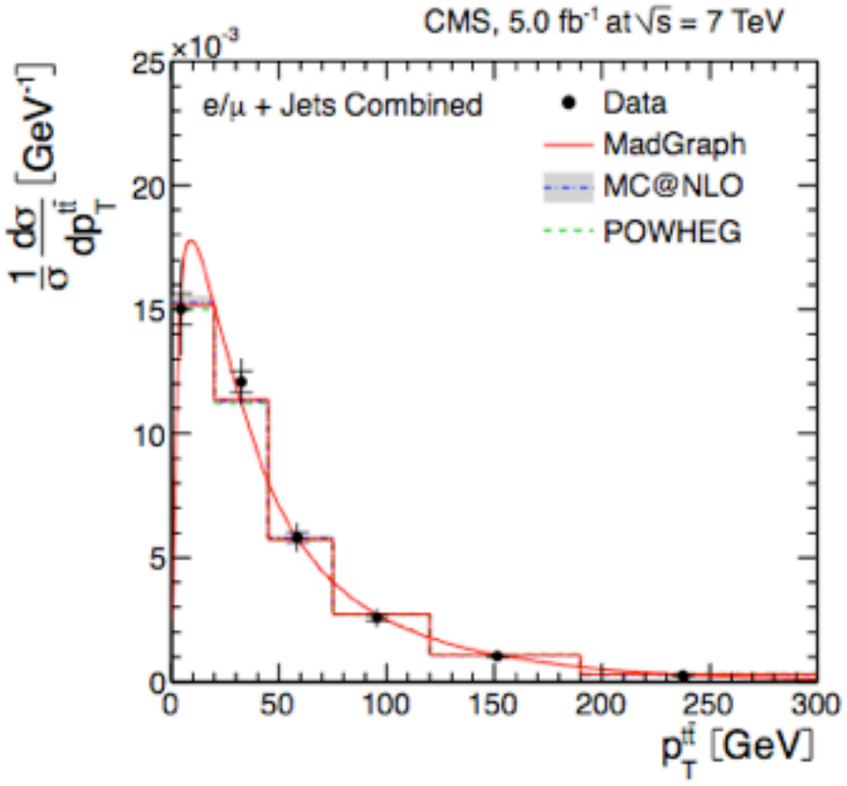


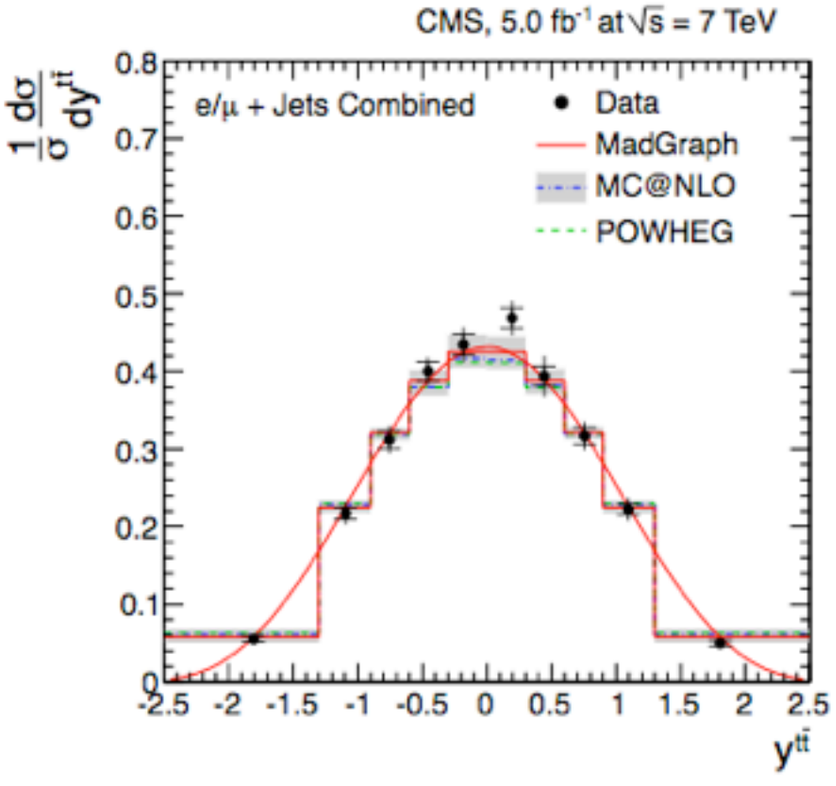
PDF dependency

Differential cross section @7 TeV









CMS

lepton+jets final state

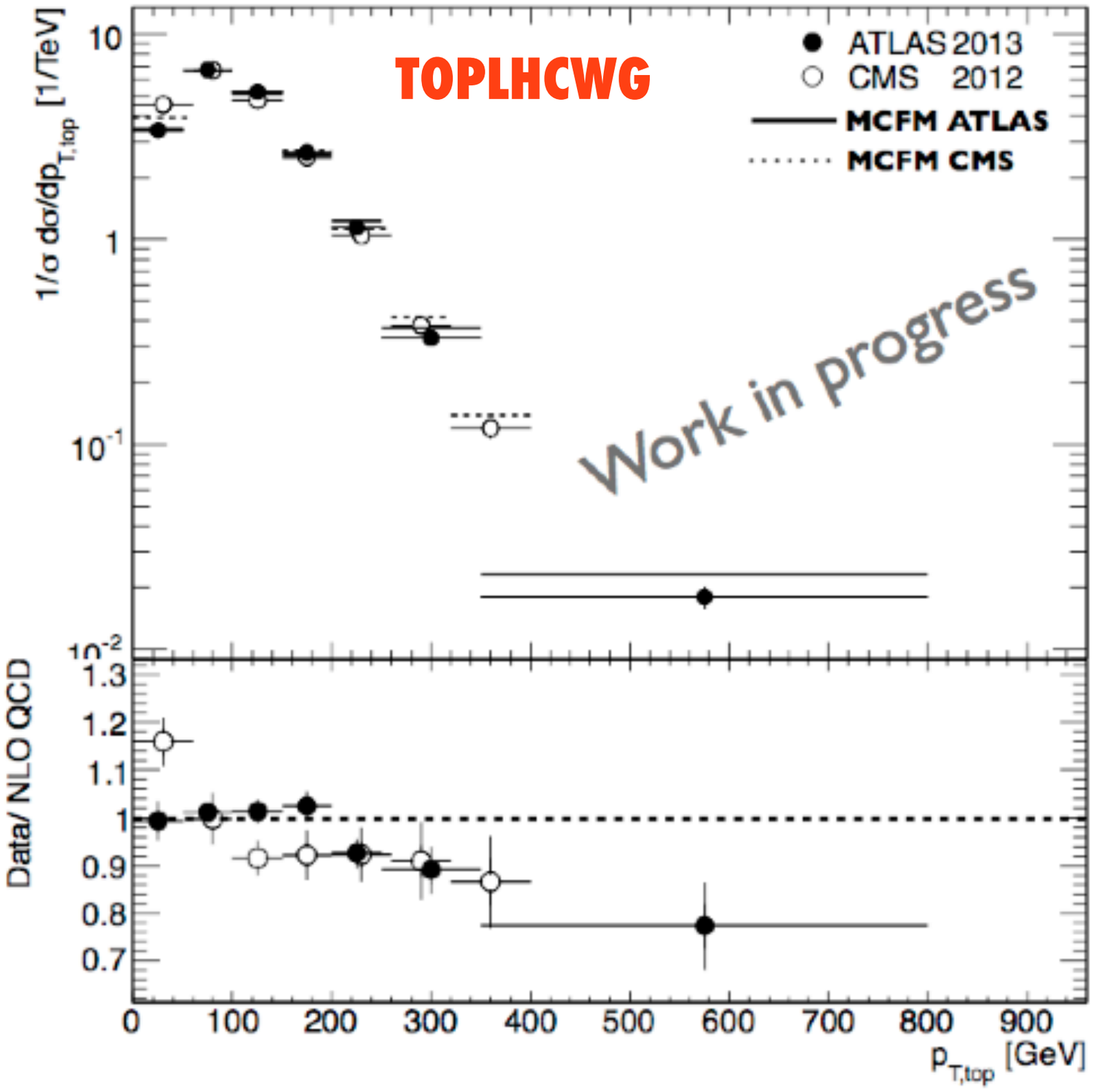
Very similar results for dilepton channel & 8 TeV (not shown)

Eur. Phys. J. C73 (2013) 2339

CMS PAS TOP-12-027

CMS PAS TOP-12-028

Differential cross section @7 TeV



ATLAS&CMS:

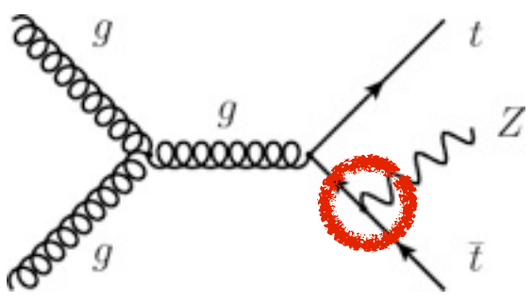
similar results

high-precision:

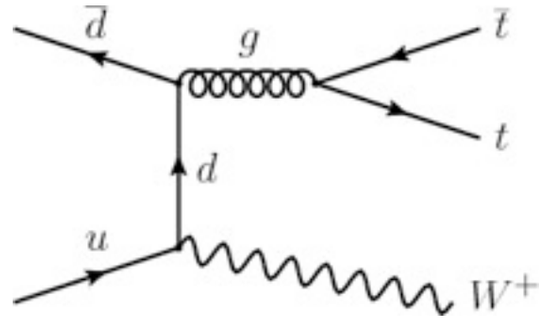
potential to constrain models

Associated production

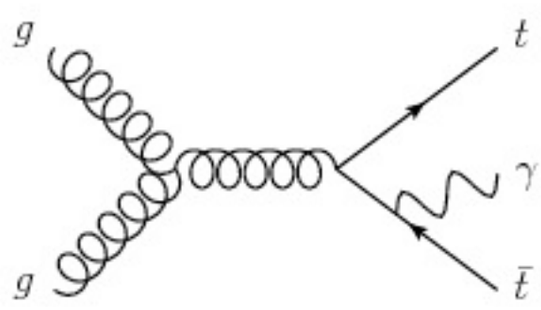
ttZ

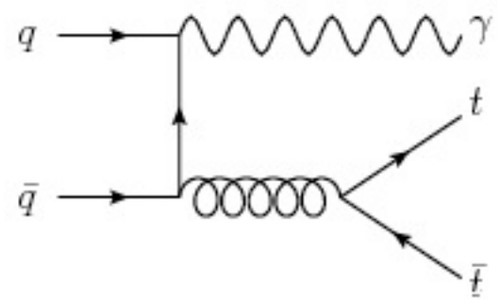


ttW



ttγ





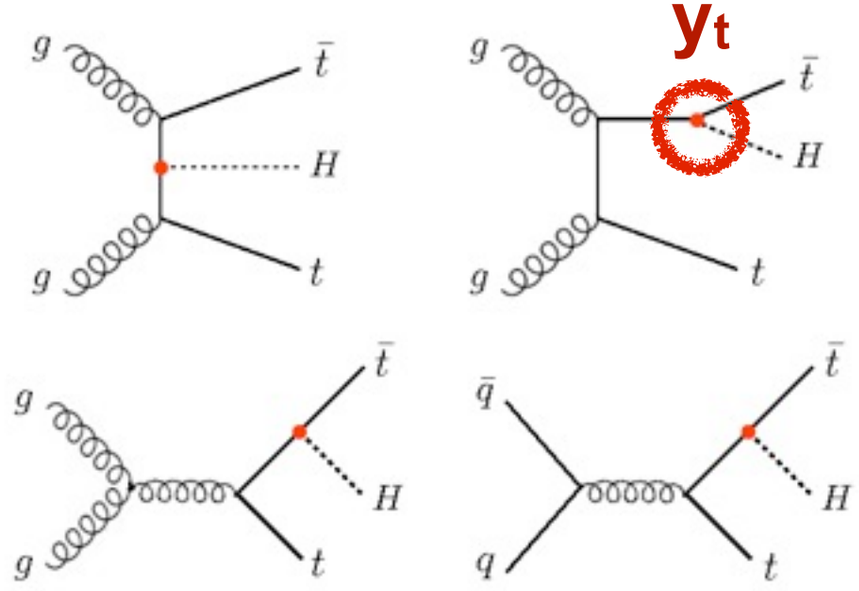
Bkg: mainly instrumental

Direct y_t measurement:

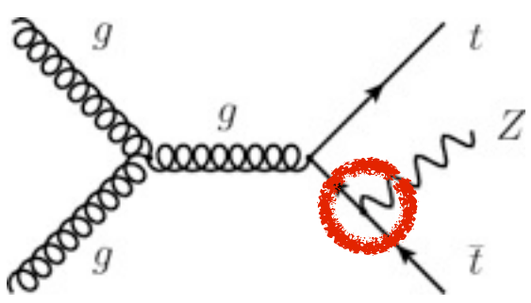
the Cherry on Top of LHC Run II

Associated production

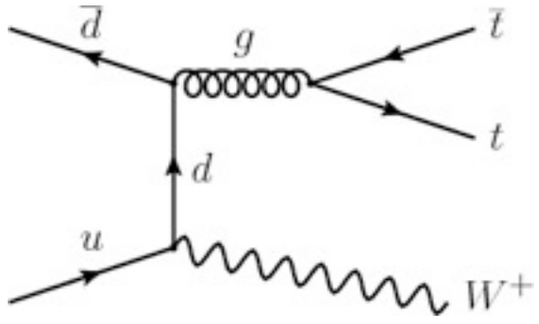
Bkg for ttH:



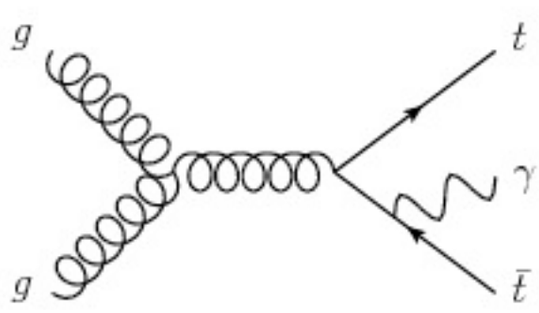
ttZ

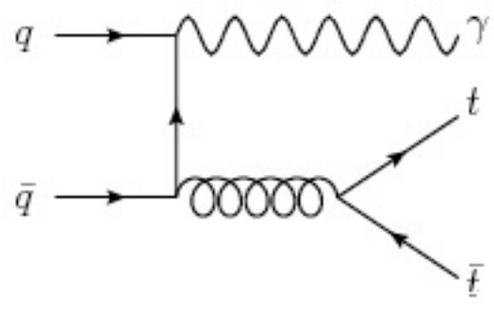


ttW



ttγ

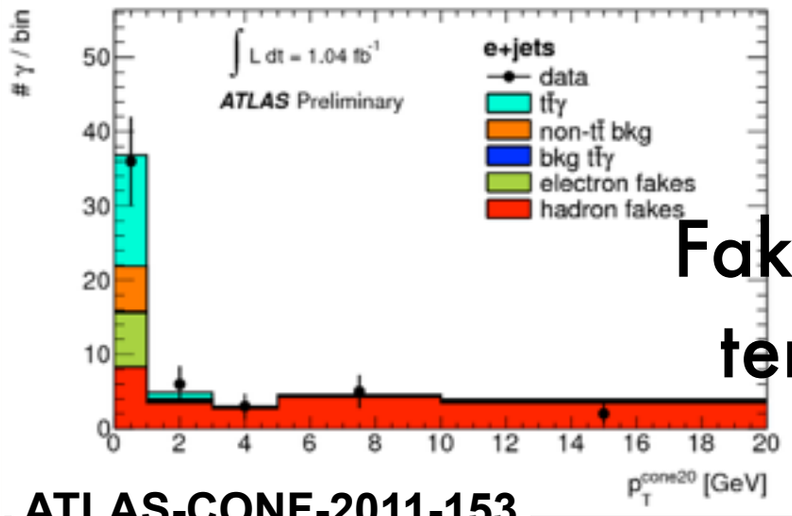




Bkg: mainly instrumental

ttγ, ttV

ttγ



Fakes x signal: template fits

ATLAS-CONF-2011-153

ATLAS (1.fb^{-1}, 7TeV, $p_T(\gamma)$>8 GeV)
$\sigma_{tt\gamma}$.BR= 2.0±0.5(stat)±0.7(sys)
±0.08(lumi) pb

PAS-TOP-13-011

CMS (19fb^{-1}, 8TeV, $p_T(\gamma)$>20 GeV)
$\sigma_{tt\gamma}$.BR= 2.4±0.2(stat)±0.6(sys)

PRD84,031104 (2001)

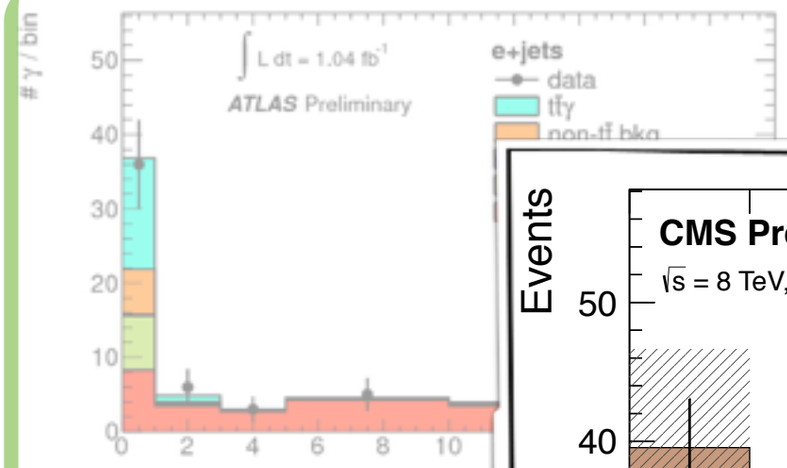
CDF (6.0 fb^{-1})
30 events observed (26.9±3.4 expected)
$\sigma_{tt\gamma}$ = 0.18±0.07(stat)±0.04(sys)±0.41 (lumi) pb

ttV

ATLAS ttZ 7 TeV: σ<0.7 fb @ 95%CL

ttγ, ttV

ttγ



ATLAS-CONF-2011-15

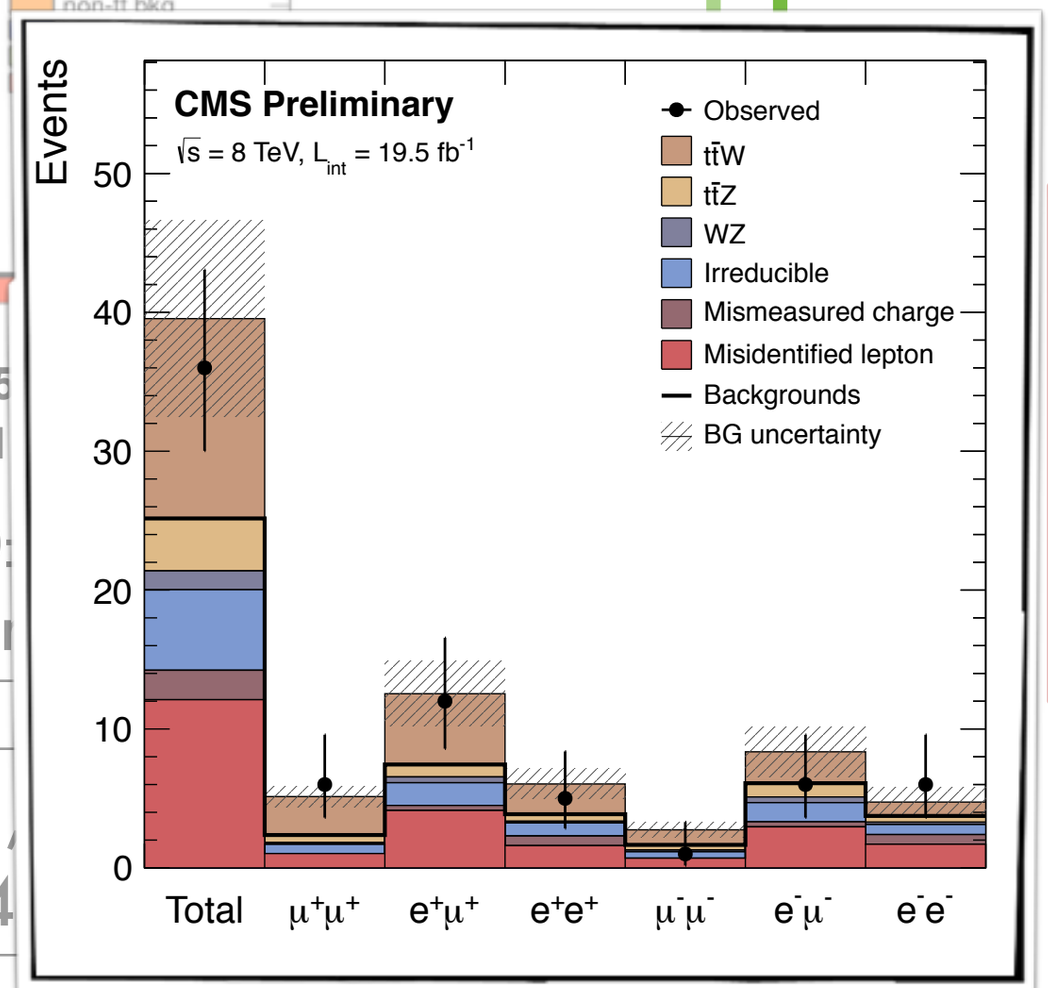
ATLAS (1.fb^{-1}

$\sigma_{tt\gamma}$.BR= 2.0

±0.08(lu

CMS (19fb^{-1})

$\sigma_{tt\gamma}$.BR= 2.4



PRD84,031104 (2001)

CDF (6.0 fb^{-1})

30 events observed (26.9±3.4 expected)

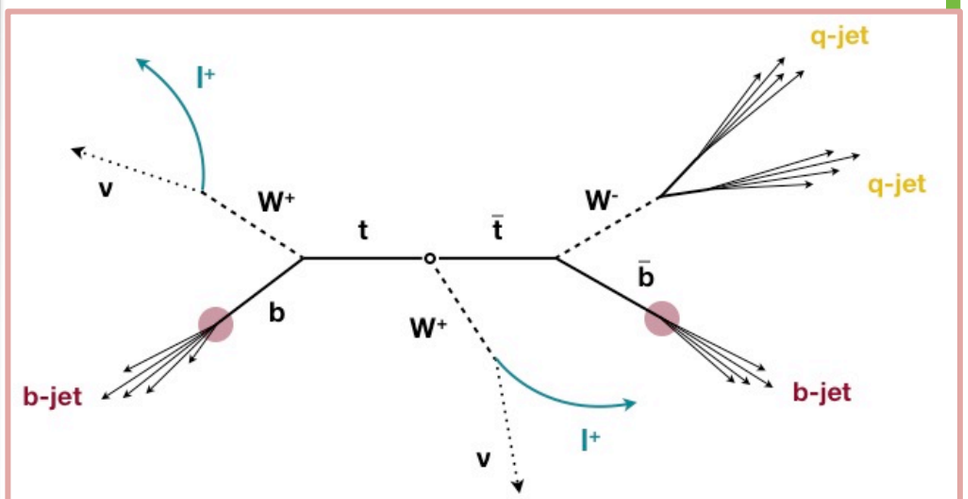
$\sigma_{tt\gamma}$ = 0.18±0.07(stat)±0.04(sys)±0.41 (lumi) pb

ttV

CMS-TOP-12-036

Shown first time @ LHCP14

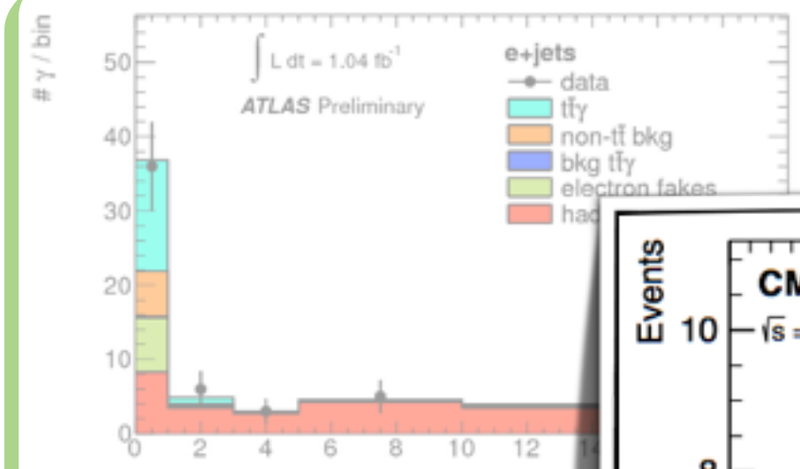
ttW (same sign 2ℓ)



ATLAS ttZ 7 TeV: σ<0.7 fb @ 95%CL

ttγ, ttV

ttγ



ATLAS-CONF-2011-153

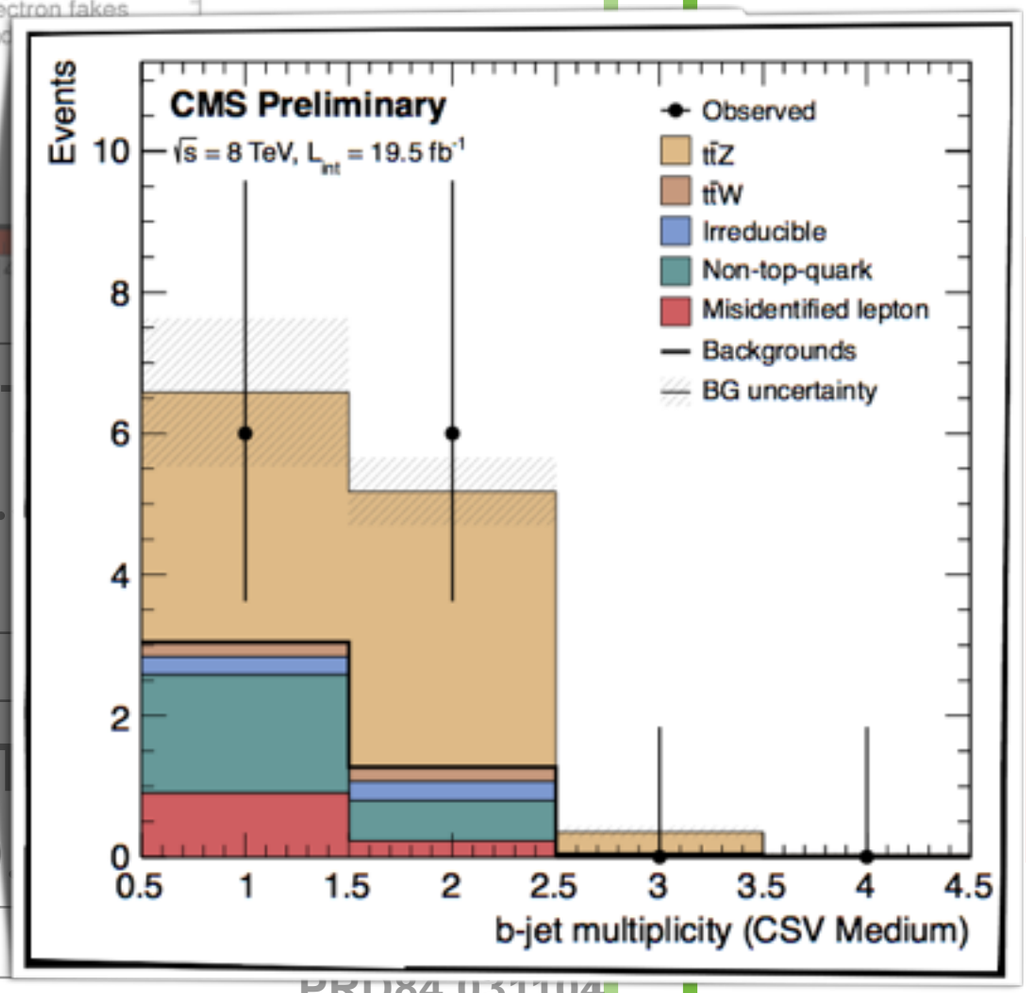
ATLAS (1.fb^{-1}, 7

$\sigma_{tt\gamma}$.BR= 2.0±0.

±0.08(lumi)

CMS (19fb^{-1}, 8T

$\sigma_{tt\gamma}$.BR= 2.4±0



PRD84,031104 (2001)

CDF (6.0 fb^{-1})

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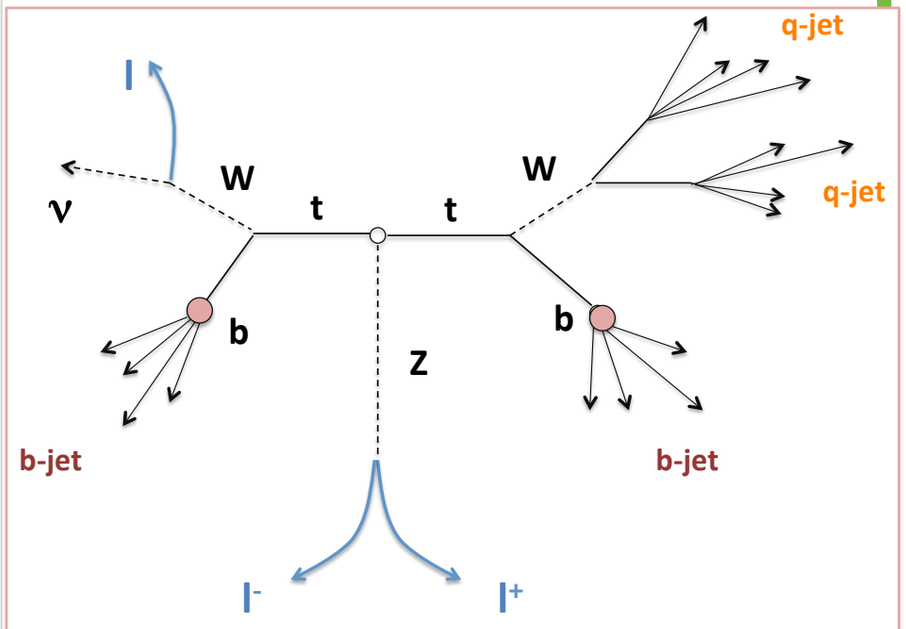
ttV

CMS-TOP-12-036

Shown first time @ LHCP14

ttW (same sign 2ℓ)

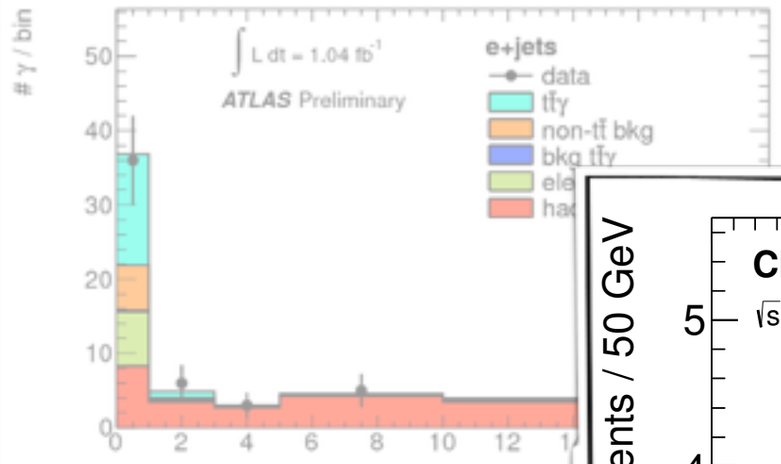
ttZ (3ℓ)



ATLAS ttZ 7 TeV: σ<0.7 fb @ 95%CL

ttγ, ttV

ttγ



ATLAS-CONF-2011-153

ATLAS (1.fb^{-1}, 7

$\sigma_{tt\gamma}$.BR= 2.0±0.

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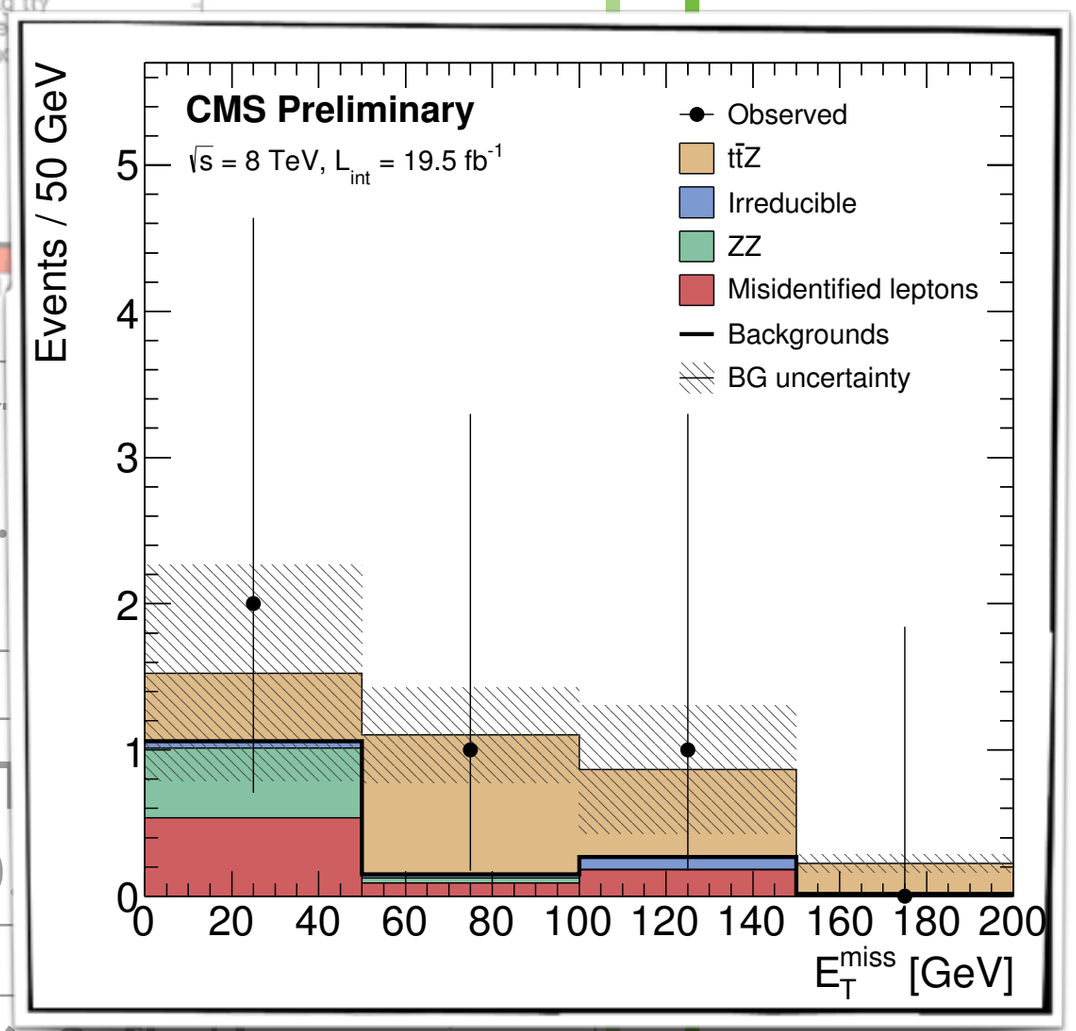
CMS (19fb^{-1}, 8T

$\sigma_{tt\gamma}$.BR= 2.4±0.



CDF (6.0 fb^{-1}) (2001)

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$\sigma_{tt\gamma}$ = 0.18±0.07(stat)±0.04(sys)±0.41 (lumi) pb

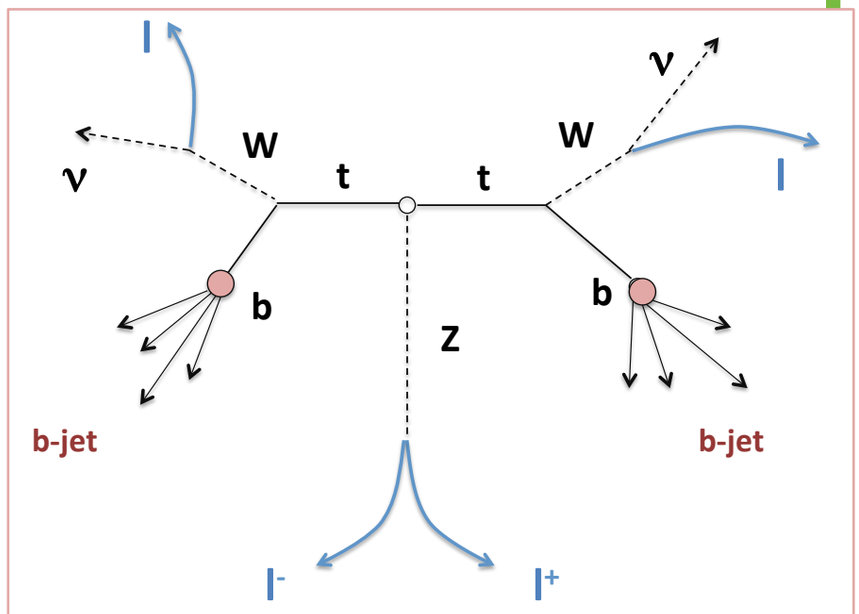
ttV

CMS-TOP-12-036

Shown first time @ LHCP14

ttW (same sign 2ℓ)

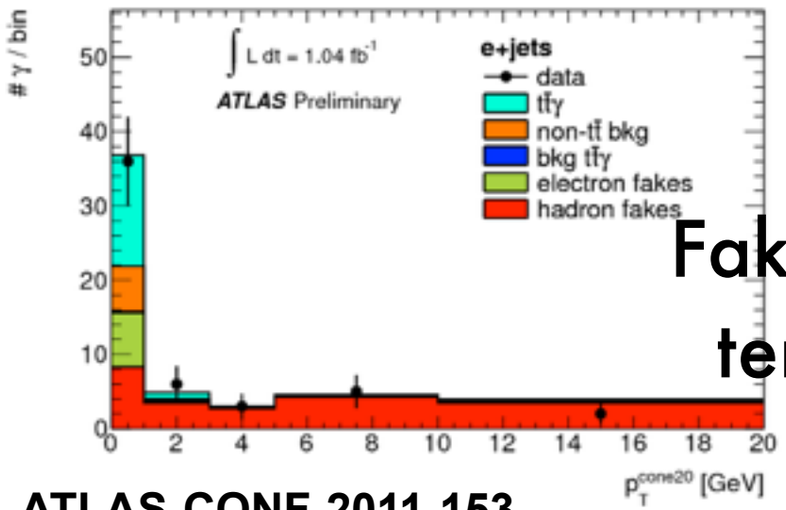
ttZ (3ℓ ,4ℓ)



ATLAS ttZ 7 TeV: σ<0.7 fb @ 95%CL

ttγ, ttV

ttγ



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ttV

CMS-TOP-12-036

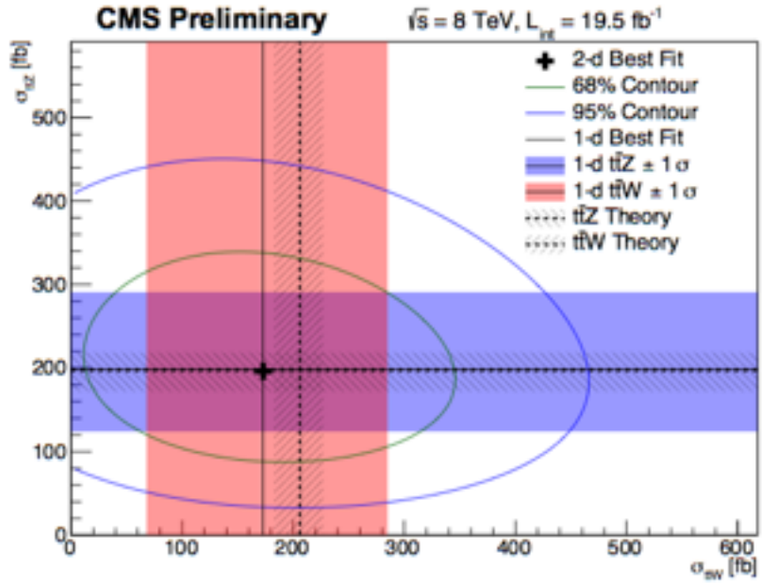
Shown first time @ LHCP14

34%

ttW (same sign 2ℓ)

ttZ (3ℓ ,4ℓ)

Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	$170^{+90}_{-80}(\text{stat.})^{+70}_{-70}(\text{syst.})$ fb	1.6 σ
3ℓ+4ℓ	$t\bar{t}Z$	$200^{+80}_{-70}(\text{stat.})^{+40}_{-30}(\text{syst.})$ fb	3.1 σ
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	$380^{+100}_{-90}(\text{stat.})^{+80}_{-70}(\text{syst.})$ fb	3.7 σ

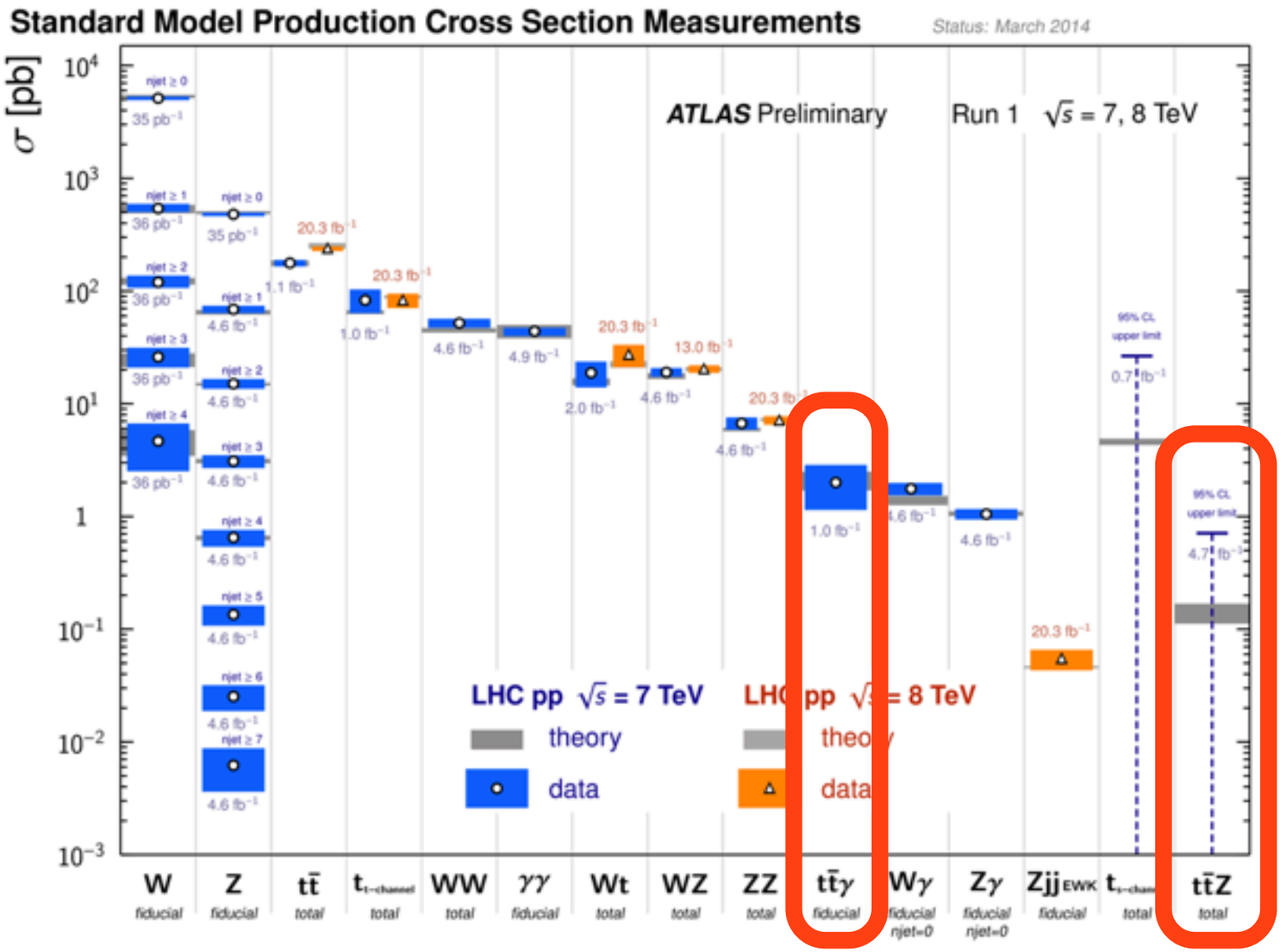


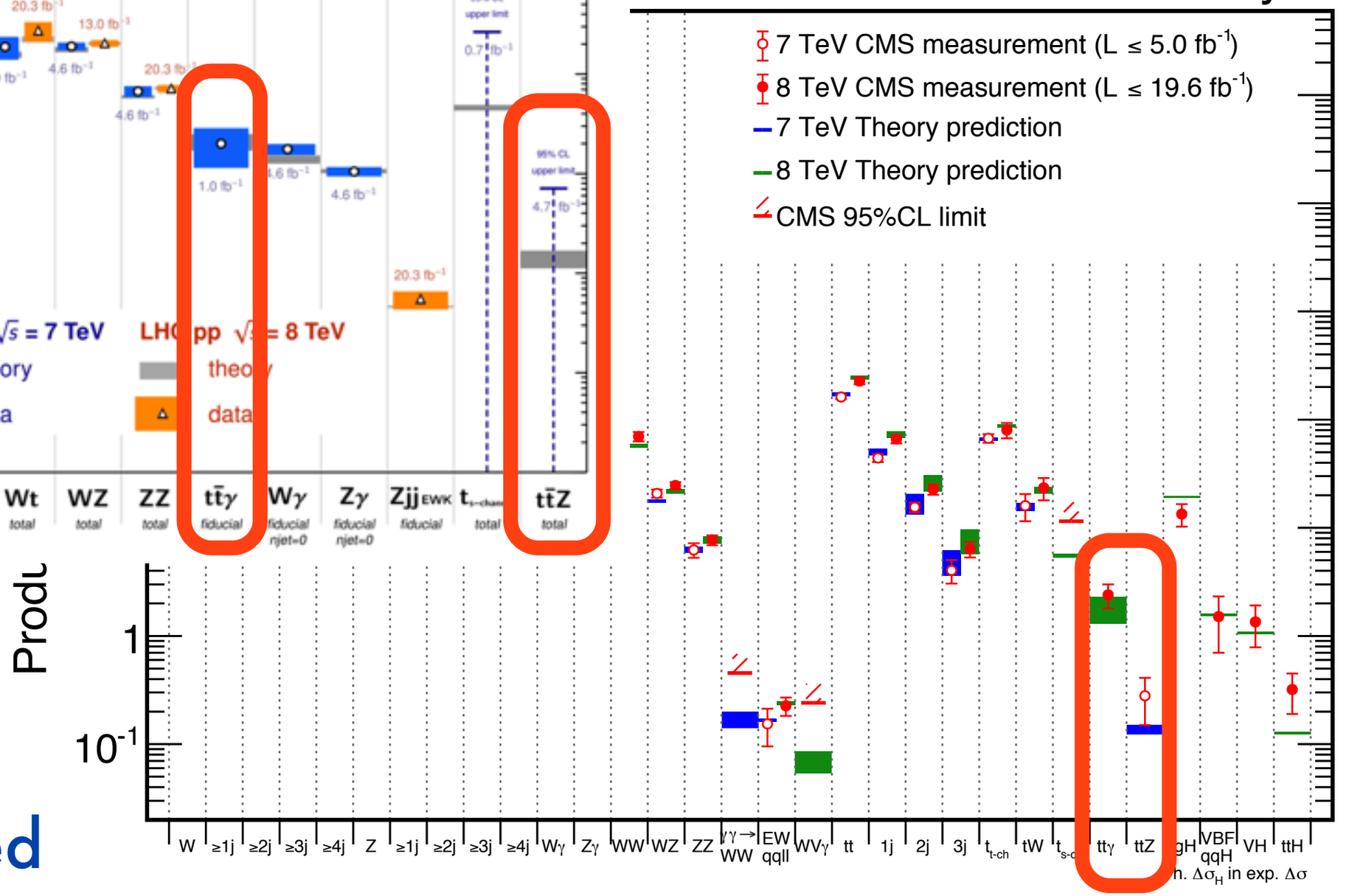
Channels used	$t\bar{t}W$ cross section	$t\bar{t}Z$ cross section
2ℓ+3ℓ+4ℓ	170^{+110}_{-100}(total) fb	200^{+90}_{-90}(total) fb

ATLAS ttZ 7 TeV: σ<0.7 fb @ 95%CL

ttV, ttγ

Remarkable detector perfomance reaching very low cross sections





At 7,8 TeV still statistically limited

Summary and conclusions

20 years of top quark production:
a thrilling journey

Tevatron

1995 Top quarks observed first time on a couple dozen of events

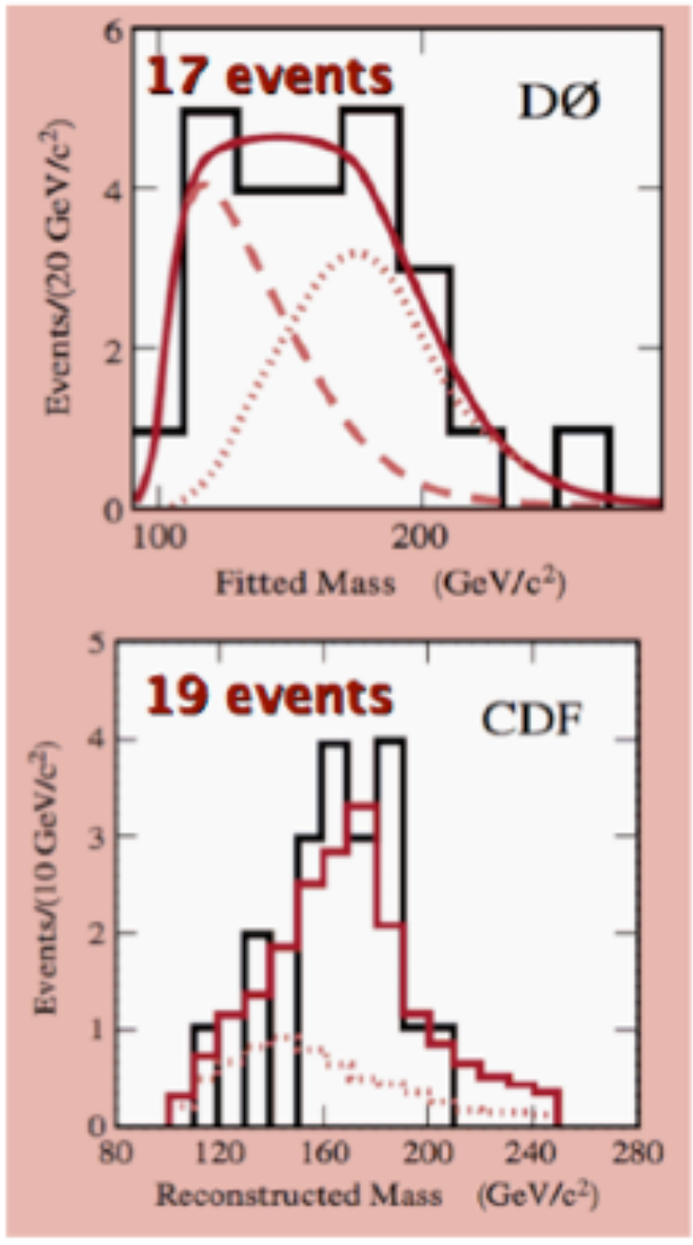
2009 First single-top quark production observation

2012

Observations
Evidences

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

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LHC

2012 Single-top evidence

First measurements of associated ttV, ttγ, tt+bb

Observations
Evidences

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Precision era

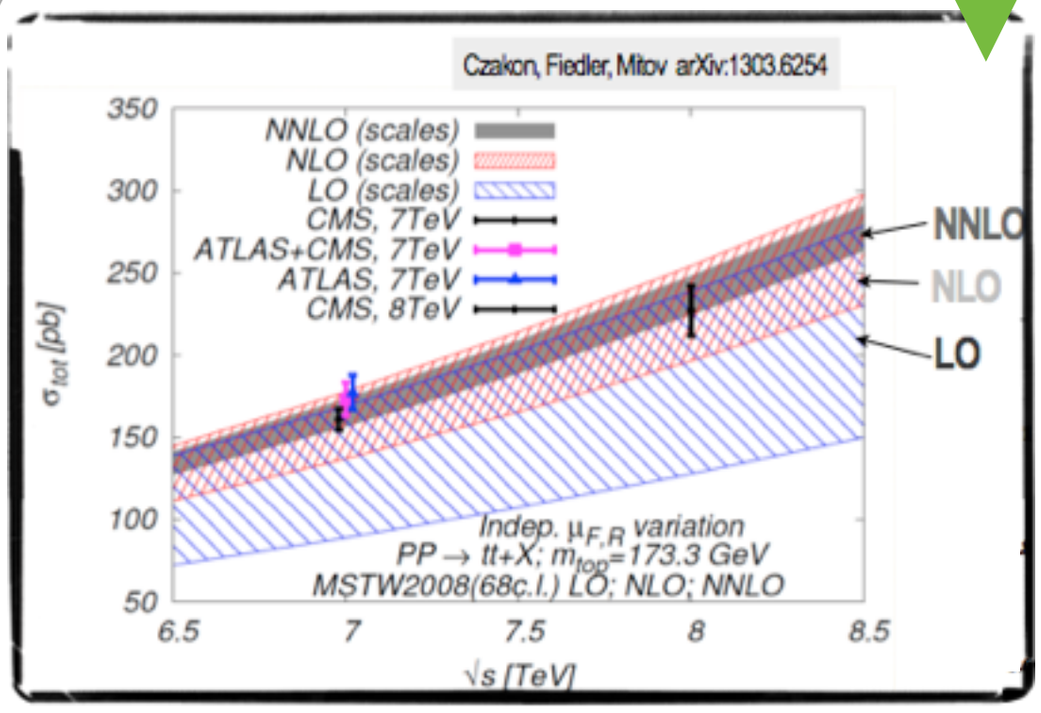
Tevatron **LHC**

2010 End of Tevatron, millions of top quarks produced at LHC

Differential x-sec, jet multiplicity

1.96 TeV precision: σ(tt) ~5% σ(t) ~20-30%
7 TeV precision: σ(tt) ~4% σ(t) ~9-30%
8 TeV precision: σ(tt) ~5% σ(t) ~8-20%

we are here!



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we are here!

Run II: important step on beam intensity and energy

LHC

2015

14 TeV: $\sigma(tt) = 953.6^{+16.2}_{-17.8}\ (\text{PDF})^{+22.7}_{-33.9}\ (\text{QCD scales})$ pb

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we are here!

High precision in Run II top measurements will test SM further & may reveal new physics!

Run II: important step on beam intensity and energy

LHC

2015 Challenging running conditions (trigger rates, pileup)

New analyses/improved techniques, top-Higgs coupling

Exciting time for top production

14 TeV: $\sigma(tt) = 953.6^{+16.2}_{-17.8}$ (PDF)$^{+22.7}_{-33.9}$ (QCD scales) pb

Conclusions

- Tevatron: finalizing top production measurements at 1.96 TeV, more & more precise (improved techniques) to come
- LHC: precision era with millions of tops produced at 7 and 8 TeV
- No deviation from SM observed so far

- **Synergy: precision of theory and experimental efforts challenging each other**
- PDFs constrained (e.g. ratios single top/anti-top, differential cross sections)
- Limits of best predictions tested (e.g. few discrepancies on differential cross-sections, need higher orders?)
- MC models and tuning parameters constrained (jet multiplicity, gap fractions)

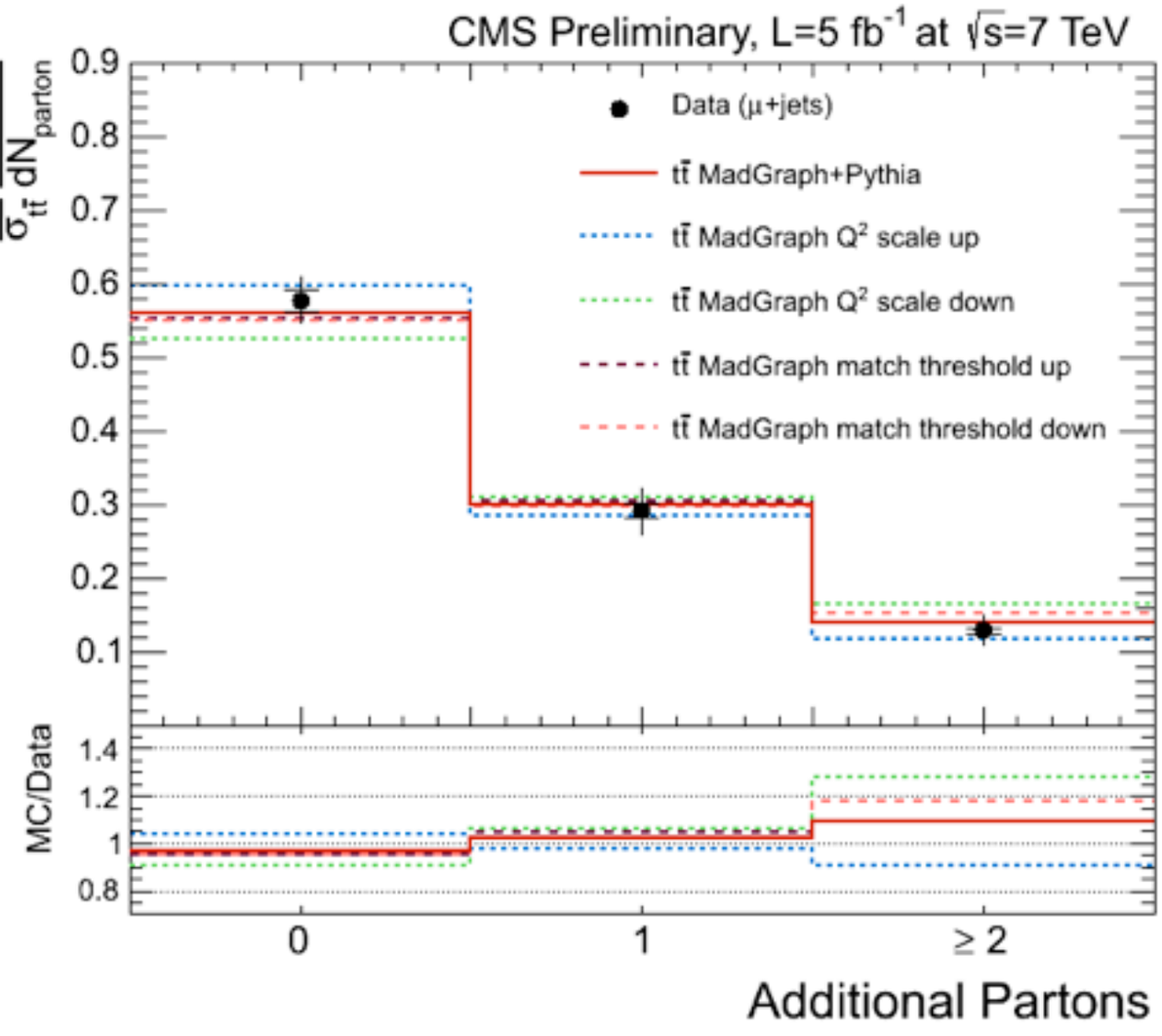
- Associated top production: interesting by itself + necessary step for ttH measurement

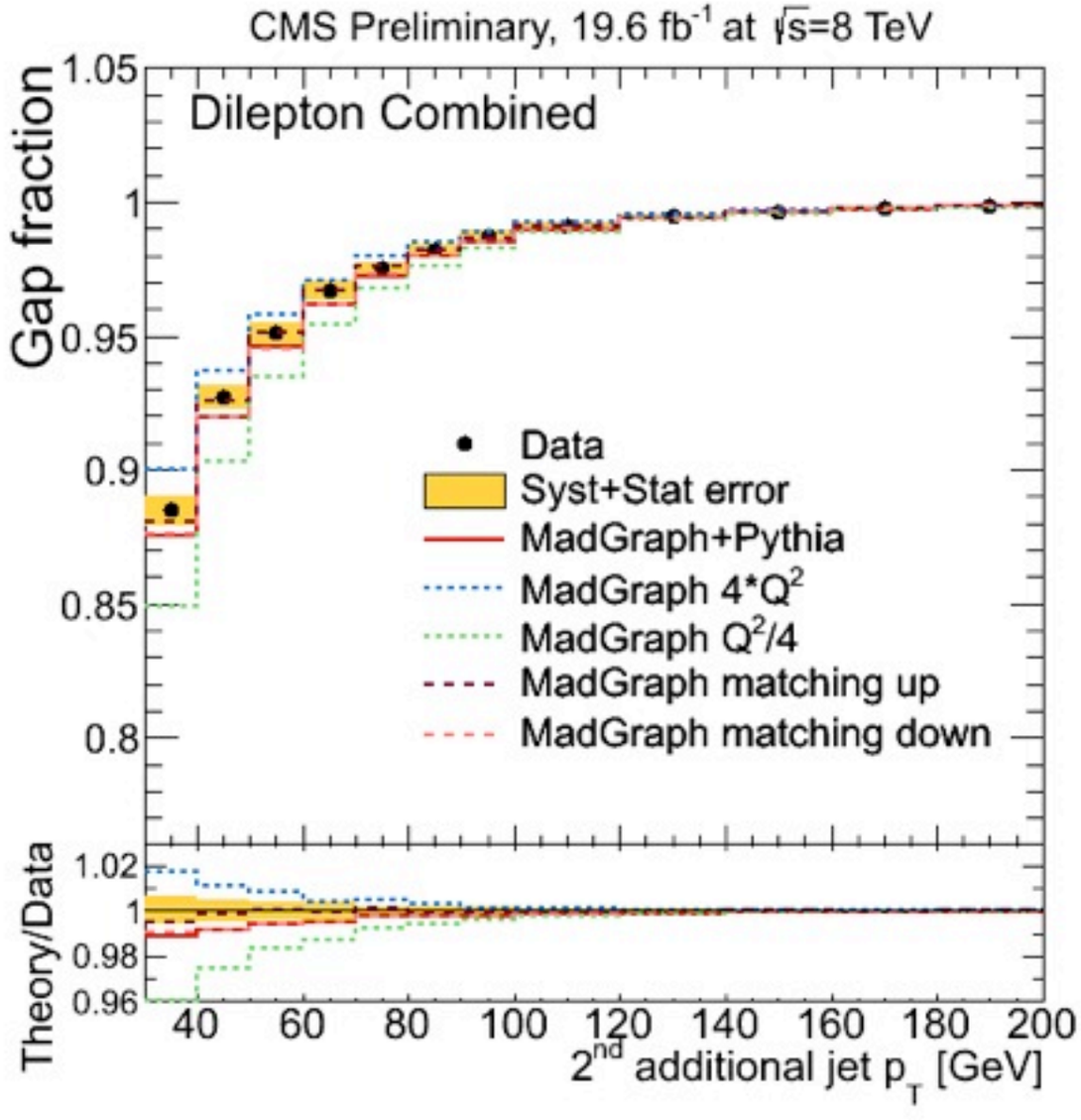
- Future: exciting new measurements at LHC Run II -- 13-14 TeV
- high precision @ higher beam energy and higher beam intensity

- Top production:
- promising ground for discovery beyond the Standard Model
- a path to better understand Higgs sector

Extras

Constraining ISR/FSR





Inclusive top pair xsec

CMS

Cross-check higher order emissions:
MADGRAPH versus POWHEG, both with Pythia (2.3%)

Hadronization:
Pythia versus Herwig, in both cases POWHEG (1.4%)

Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to showers	3.9	3.8	3.8
Single top quark	2.6	2.4	2.3
VV	0.7	0.7	0.5
Drell–Yan	10.8	10.3	1.5
Non-W/Z leptons	0.9	3.2	1.9
Total systematic	18.6	18.6	11.4
Integrated luminosity	6.4	6.1	6.2
Statistical	5.2	4.5	2.6

Inclusive top pair xsec

ATLAS

- Count number of opposite-sign $e\mu$ events with:

$$1\,b\text{−tagged jet} : N_1 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\left(1 - C_b\epsilon_b\right) + N_1^{bkg}$$

$$2\,b\text{−tagged jets} : N_2 = \mathcal{L}\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{bkg}$$

$\mathcal{L}$	: Integrated luminosity of sample
$\epsilon_{e\mu}$	: Event selection efficiency
ϵ_b	: Jet reconstruction & b-tagging efficiency
C_b	: Tagging correlation $C_b = \epsilon_{bb}/\epsilon_b^2 = 1.007 \pm 0.002$
$N_{1,2}^{bkg}$	: Observed background events

- Solve equations for ϵ_b and $\sigma_{t\bar{t}}$
- Benefit from reduction in systematic uncertainties
- Measurement uses $\mathcal{L} = 20.3\text{fb}^{-1}$ of $\sqrt{s} = 8$ TeV data

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\epsilon_b/\epsilon_b$ (%)
Data statistics	-	-	0.72	1.7	0.57
$t\bar{t}$ modelling	0.91	-0.61	1.52	3.6	0.61
Initial/final state radiation	-0.76	0.26	1.23	2.9	0.37
Parton density functions	1.08	-	1.09	2.6	0.06
QCD scale choices	0.30	-	0.30	0.7	0.00
Single-top modelling	-	-	0.38	0.9	0.56
Single-top/$t\bar{t}$ interference	-	-	0.15	0.4	0.25
Single-top Wt cross-section	-	-	0.70	1.7	0.24
Diboson modelling	-	-	0.42	1.0	0.19
Diboson cross-sections	-	-	0.03	0.1	0.01
Z+jets extrapolation	-	-	0.05	0.1	0.02
Electron energy scale/resolution	0.43	0.01	0.48	1.1	0.03
Electron identification/isolation	1.28	0.00	1.42	3.4	0.05
Muon momentum scale/resolution	0.01	0.01	0.05	0.1	0.02
Muon identification/isolation	0.50	0.00	0.52	1.2	0.01
Lepton trigger	0.15	0.00	0.16	0.4	0.01
Jet energy scale	0.46	0.07	0.49	1.2	0.11
Jet energy resolution	-0.44	0.04	0.59	1.4	0.08
Jet reconstruction/vertex fraction	0.02	0.01	0.04	0.1	0.01
b-tagging	-	0.13	0.42	1.0	0.09
Pileup modelling	-0.30	0.05	0.28	0.7	0.05
Misidentified leptons	-	-	0.38	0.9	0.12
Total systematic	2.29	0.69	3.12	7.4	1.02
Integrated luminosity	-	-	3.11	7.4	0.11
LHC beam energy	-	-	1.70	4.0	0.00
Total uncertainty	2.29	0.69	4.77	11.3	1.17

Single top t channel

CMS

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	$\pm$ 2.7
JES, JER, MET, and pileup	$\pm$ 4.3
b-tagging and mis-tag	$\pm$ 2.5
Lepton reconstruction/trig.	$\pm$ 0.6
QCD multijet estimation	$\pm$ 2.3
W+jets, $t\bar{t}$ estimation	$\pm$ 2.2
Other backgrounds ratio	$\pm$ 0.3
Signal modeling	$\pm$ 5.7
PDF uncertainty	$\pm$ 1.9
Simulation sample size	$\pm$ 0.7
Luminosity	$\pm$ 2.6
Total systematic	$\pm$ 8.9
Total uncertainty	$\pm$ 9.3
Measured cross section	83.6 ± 7.8 pb

ATLAS fiducial xsec

Source	$\Delta\sigma_{\text{fid}}/\sigma_{\text{fid}}$ [%]
Data statistics	±1.5
MC statistics	±1.1
Multijet normalisation	+2.3 -1.4
Other background normalization	±0.8
JES η intercalibration	±7.9
JES physics modelling	±3.0
JES detector	< 0.5
JES statistical	< 0.5
JES mixed detector and modelling	< 0.5
JES single particle	< 0.5
JES pile-up	< 0.5
JES flavor composition	±0.8
JES flavor response	±0.5
b-JES	< 0.5
Lepton uncertainties	±2.9
$E_{\text{T}}^{\text{miss}}$ modelling	±3.0
b-tagging efficiency	±3.5
c-tagging efficiency	< 0.5
Mistag efficiency	< 0.5
Jet energy resolution	±1.7
Jet reconstruction eff.	< 0.5
Jet vertex fraction	< 0.5
t-channel generator	±7.9
W+jets generator	±1.4
PDF	±1.1
$t\bar{t}$,*Wt* and *s*-channel generator	< 0.5
ISR / FSR ($t\bar{t}$)	< 0.5
Total Systematic	±14
Total	±14

single top tW channel

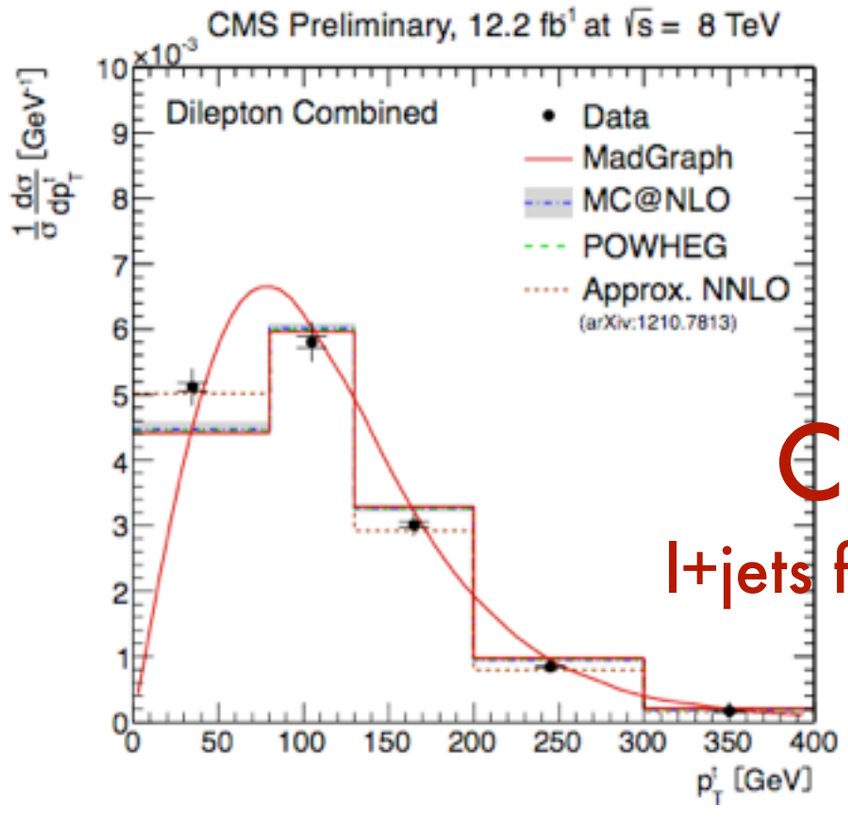
CMS

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$
ME/PS matching thresholds	3.3	14%
Renormalization/factorization scale	2.9	12%
Top-quark mass	2.2	9%
Fit statistical	1.9	8%
Jet energy scale	0.9	4%
Luminosity	0.7	3%
Z+jets data/simulation scale factor	0.6	3%
tW DR/DS scheme	0.5	2%
$t\bar{t}$ cross section	0.4	2%
Lepton identification	0.4	2%
PDF	0.4	2%
Jet energy resolution	0.2	1%
b-tagging data/simulation scale factor	0.2	<1%
$t\bar{t}$ spin correlations	0.1	<1%
Pileup	0.1	<1%
Top-quark p_T reweighting	0.1	<1%
E_T^{miss} modeling	0.1	<1%
Lepton energy scale	0.1	<1%
Total	5.5	24%

ATLAS

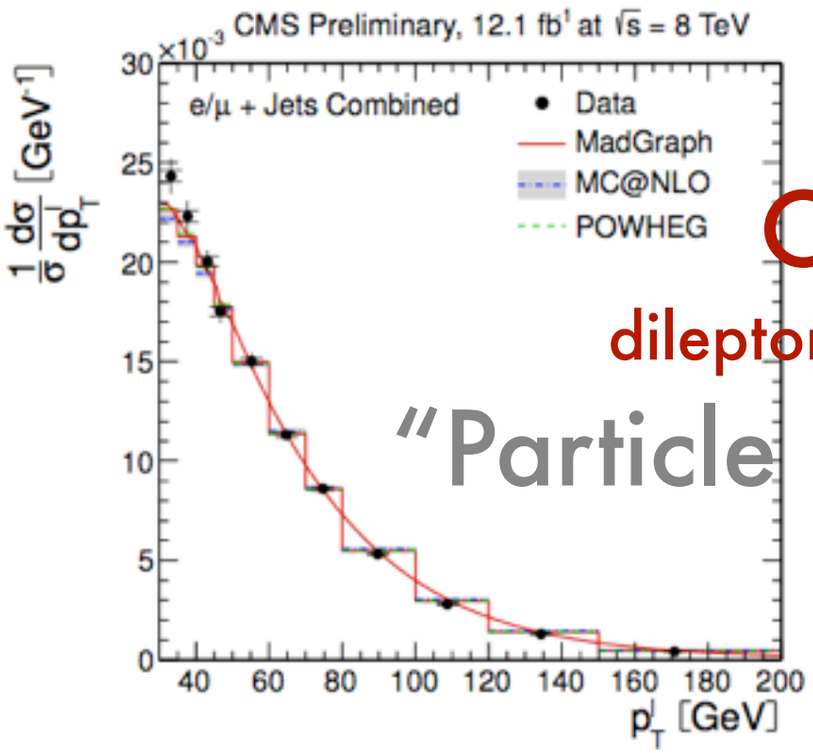
Source	$\Delta\sigma/\sigma$ [%]	
	observed	**expected**
Data statistics	7.1	8.6
MC statistics	2.8	3.5
Experimental uncertainties		
Lepton modeling	2.4	2.4
Jet identification	0.2	0.6
Jet energy scale	10	12
b-jet energy scale	5.0	6.3
Jet energy resolution	0.7	0.2
E_T^{miss} scale	4.1	5.0
E_T^{miss} resolution	4.5	5.3
Flavor tagging	8.4	9.4
Theory uncertainties		
$Wt/t\bar{t}$ overlap modeling	1.4	1.6
PDF	2.5	3.2
Background normalization	3.6	4.4
ISR/FSR	5.9	6.0
Wt generator and PS	11	11
$t\bar{t}$ generator and PS	7.5	9.2
Luminosity	3.7	3.9
Total (syst)	20	23

Differential cross section @ 8 TeV



CMS

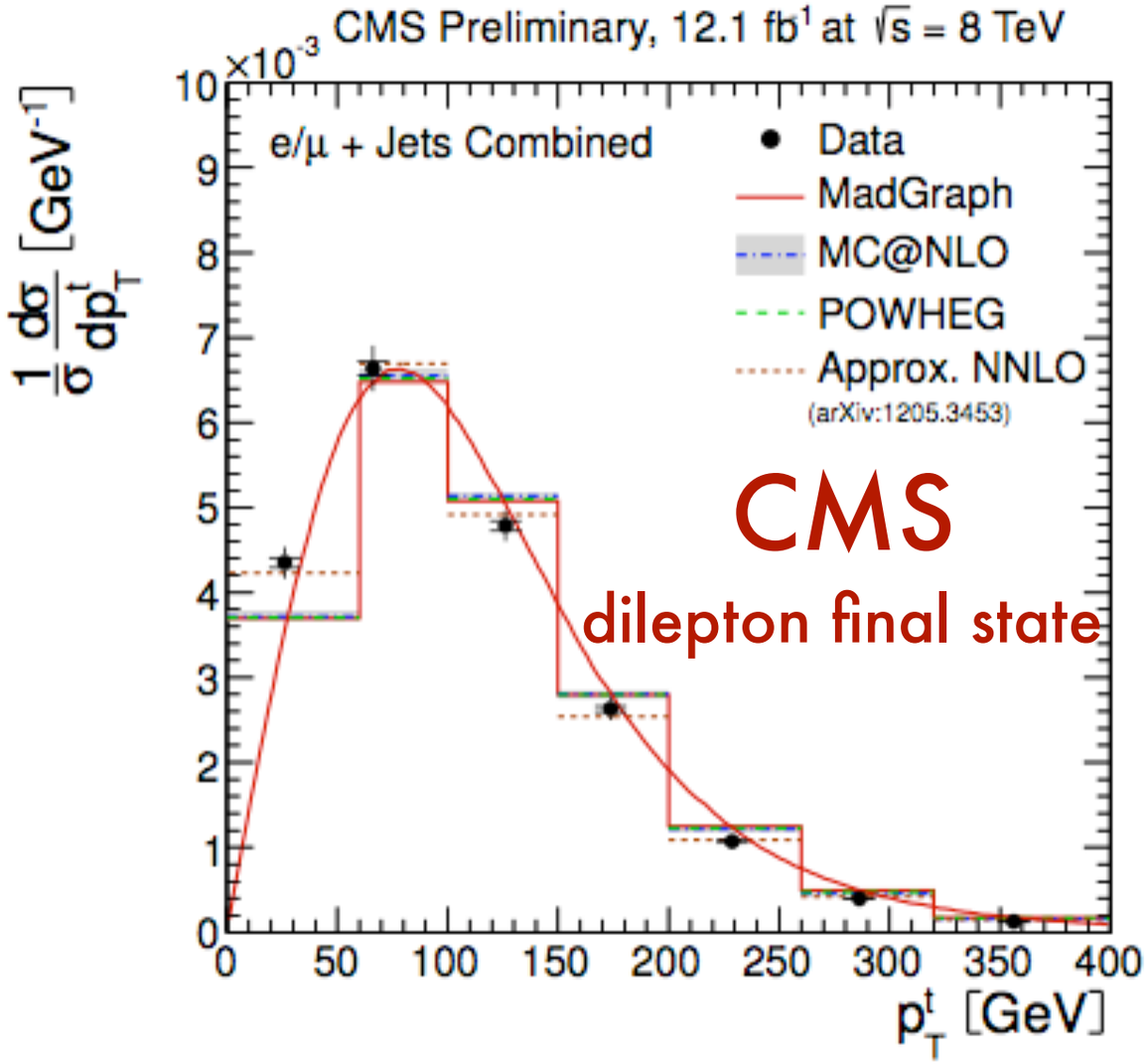
l+jets final state



CMS

dilepton final state

"Particle level"



CMS

dilepton final state