Top quark production at CMS

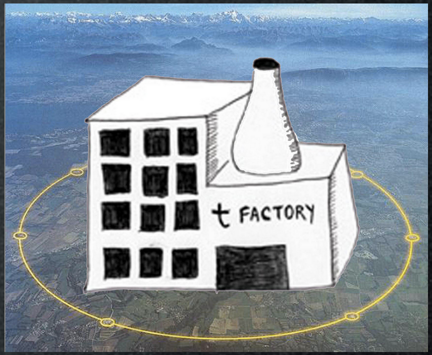
Gabriele Benelli
University of Kansas
On behalf of the CMS Collaboration

LHCP 2014
The Second Annual Conference on Large Hadron Collider Physics

Columbia University, New York City, NY, USA, June 3rd 2014

Top quark at the LHC

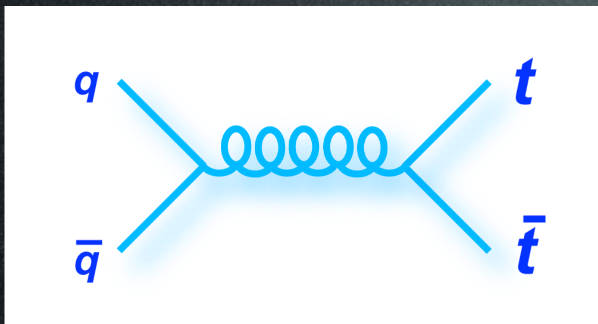
- Heaviest particle
  - Role in EWSB and BSM
- Decays before hadronizing:
  - Access bare quark from decay products (mostly b and W)
  - Measure mass, charge, spin and other properties
- The LHC is a top factory:
  - Precision results
  - Detailed differential measurements
  - Properties

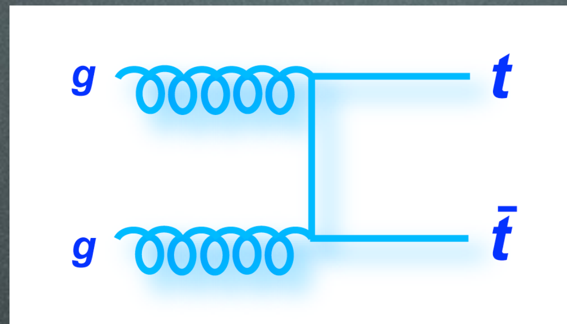


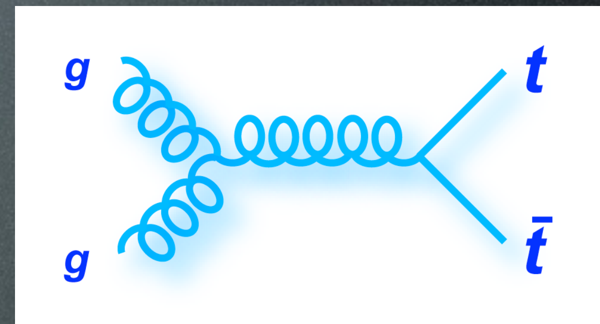
- Top production benchmark for QCD theoretical predictions
- Instrumental for the commissioning of the experiments and for the rest of the LHC physics program
- Sensitive to new physics

Top Production at the LHC

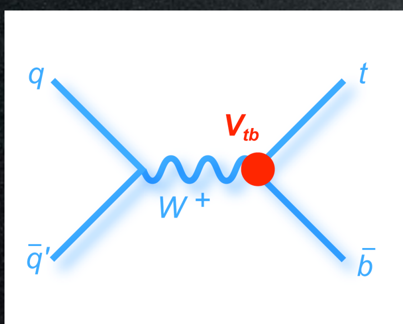
- Top production mainly via strong interaction

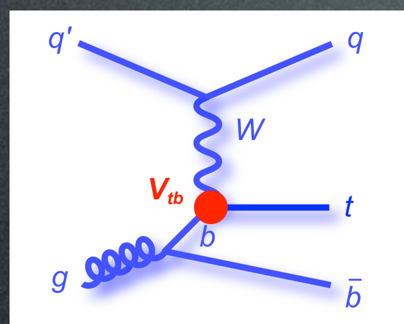


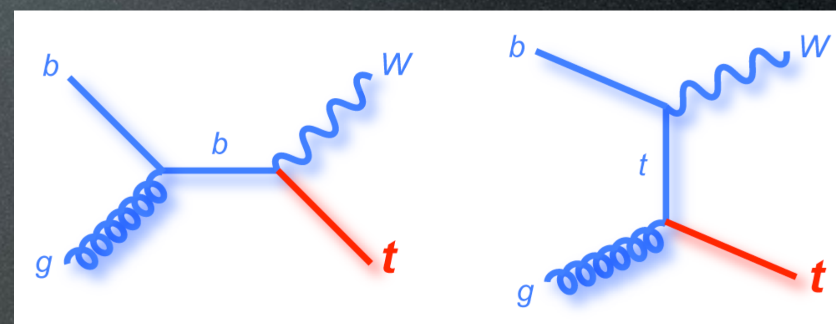




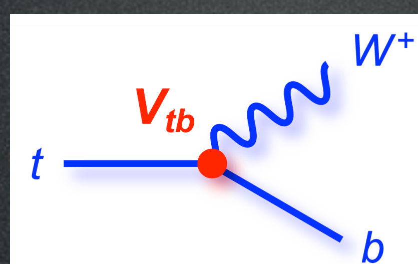
- Electroweak interactions can produce single tops!





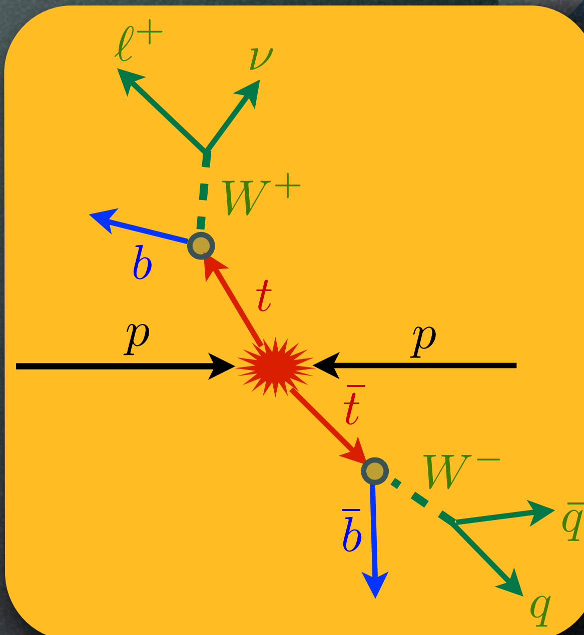


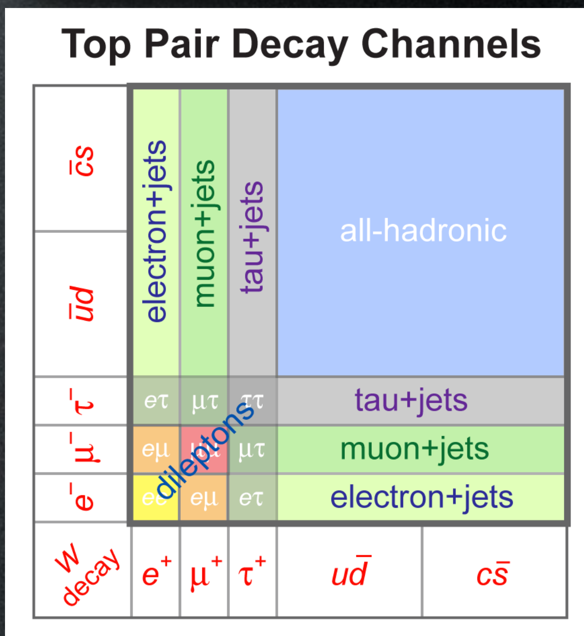
- CKM matrix element V_{tb} is regulating also top decay:



Top quark production at CMS

- Covering a selection of recent top production results from CMS
  - Strong top pair production
    - Total and differential inclusive cross-section results
  - Electroweak single top production
    - Latest CMS results in all single top production channels
- Will not cover:
  - Associated production, mass, properties (see talks by Boris Mangano and Karl Ecklund)
- Summary of the current status

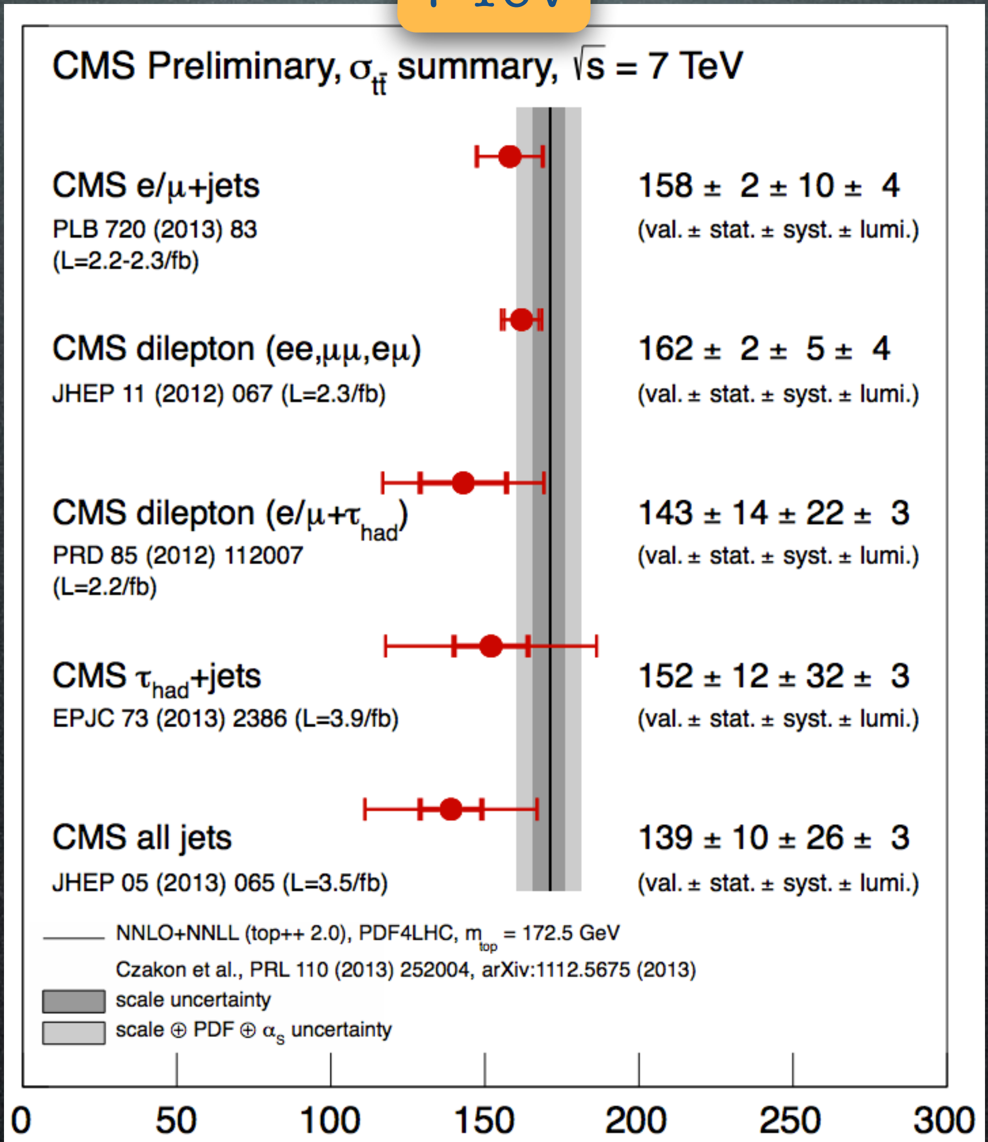




Top pair total x-sect @ 7TeV

- Summary of all CMS 7TeV total pair production cross-section results

7 TeV



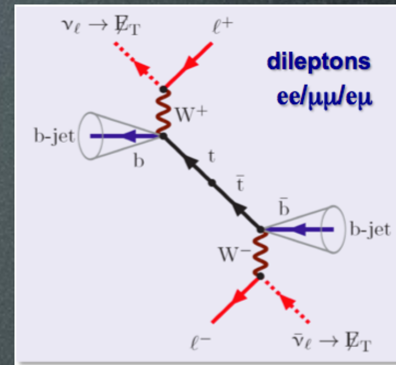
Top pair total production x-sect

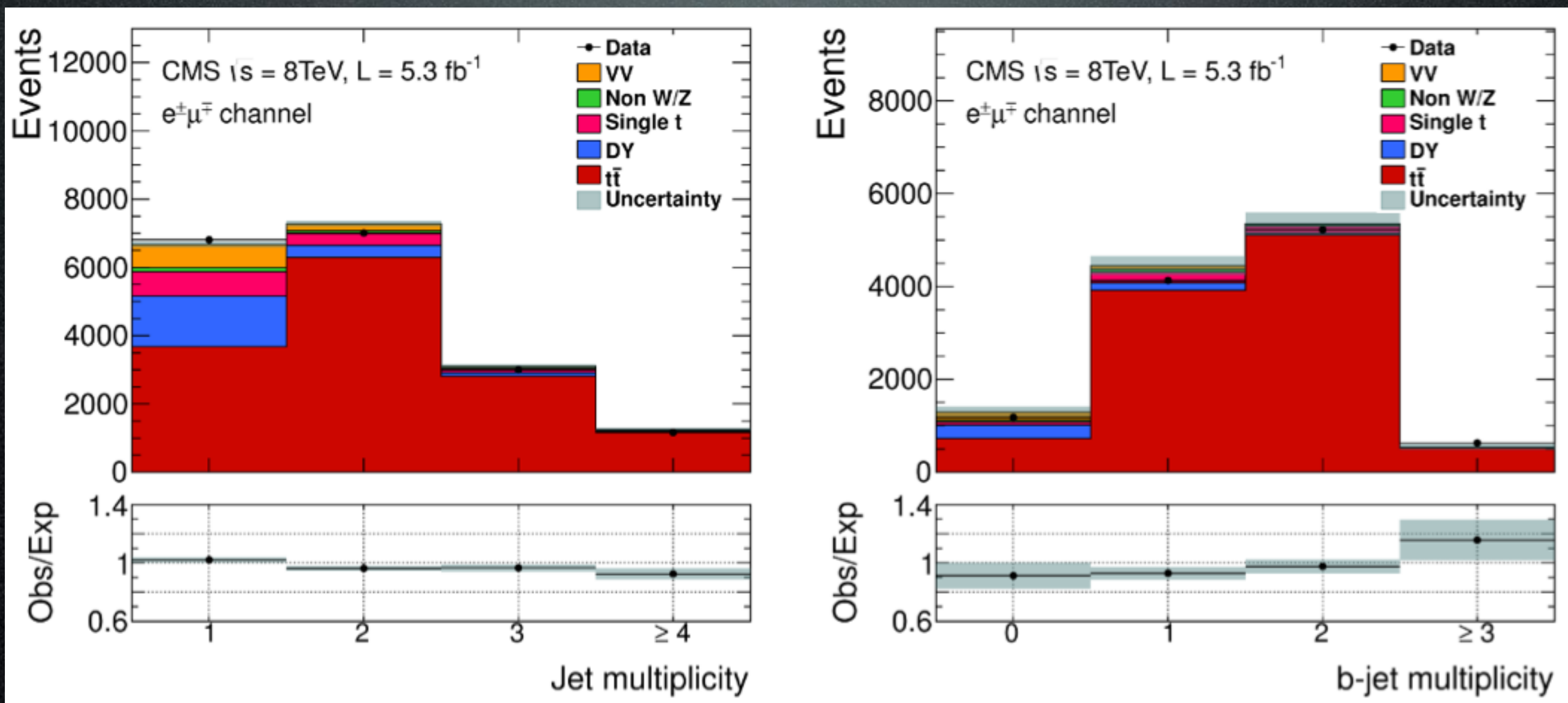
8 TeV

$5.3 fb^{-1}$

Dilepton

- Dilepton channel (ee, μμ, eμ)
- Selection:
  - Two isolated oppositely charged leptons
  - At least two jets, at least one b-tagged





- Main backgrounds Drell-Yan (DY), single top, diboson events
- Single top and diboson from MC, Drell-Yan and fake leptons from data

Top pair total production x-sect

- Cross-section measurement:
  - Event counting
  - Background subtraction

8 TeV

5.3fb^{-1}

Dilepton

Stat. Syst. Lumi.

	e^+e^-	$\mu^+\mu^-$	$e^{\pm}\mu^{\mp}$
ϵ_{total} (%)	0.203 ± 0.012	0.270 ± 0.017	0.717 ± 0.033
$\sigma_{t\bar{t}}$ (pb)	$244.3 \pm 5.2 \pm 18.6 \pm 6.4$	$235.3 \pm 4.5 \pm 18.6 \pm 6.1$	$239.0 \pm 2.6 \pm 11.4 \pm 6.2$

- Main systematics: signal modeling and Jet Energy Scale (JES)
- BLUE combination of three channels (for a 172.5 GeV top mass):

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

JHEP 02 (2014) 024

- Mass dependence quadratic in the range 160-185GeV
- In agreement with NNLO perturbative QCD theoretical prediction:

$$\sigma_{t\bar{t}} = 252.9^{+6.4}_{-8.6}\,(\text{scale}) \pm 11.7\,(\text{PDF}+\alpha_s)\text{ pb}$$

Phys. Rev. Lett. 110 (2013) 252004

Top pair differential cross-sections

- Differential cross-sections as a function of several top and top decay products kinematic variables probe perturbative QCD:
  - Different regions of phase space
  - Test and tune models with measurements
- Increased sensitivity/window to new physics effects
- Helpful to Higgs and Beyond the Standard Model (BSM) analyses
- Full top reconstruction necessary
- Unfolding techniques used:
  - Account for acceptance and detector effects
  - Parton or particle level information to compare with generators

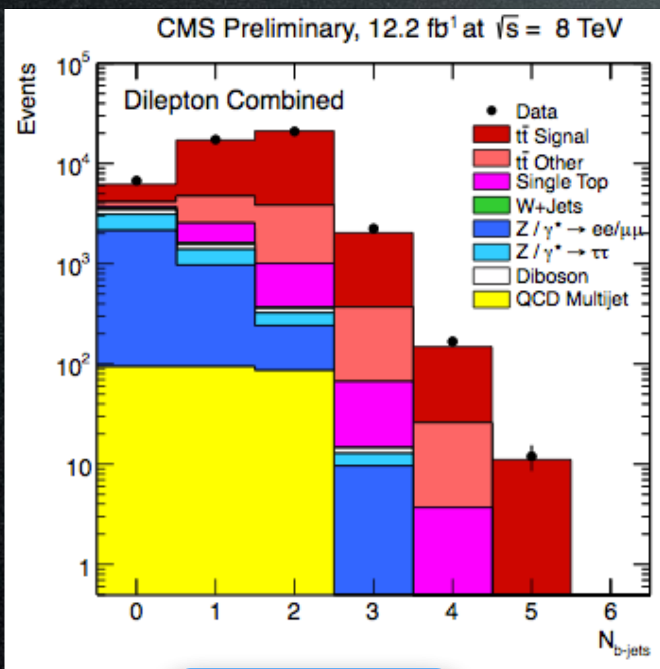
Top pair differential x-sect

8 TeV | $12.2 fb^{-1}$

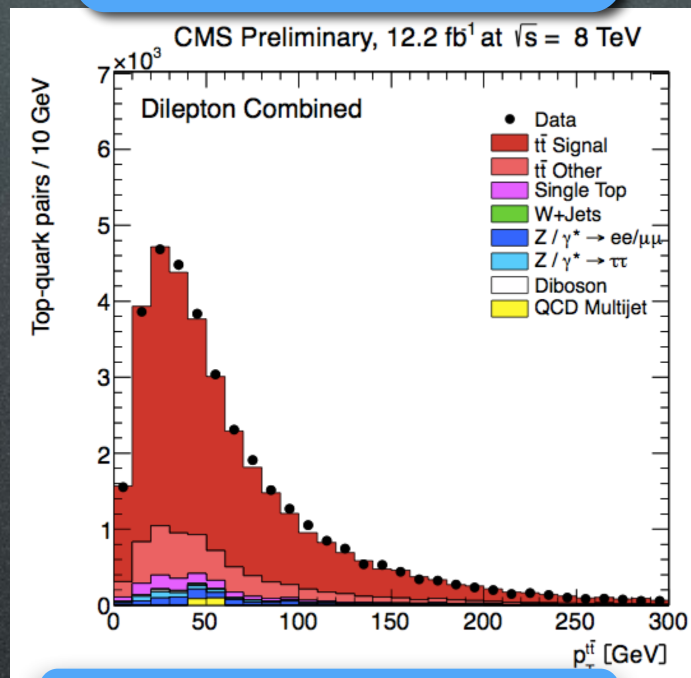
- General strategy:

Dilepton

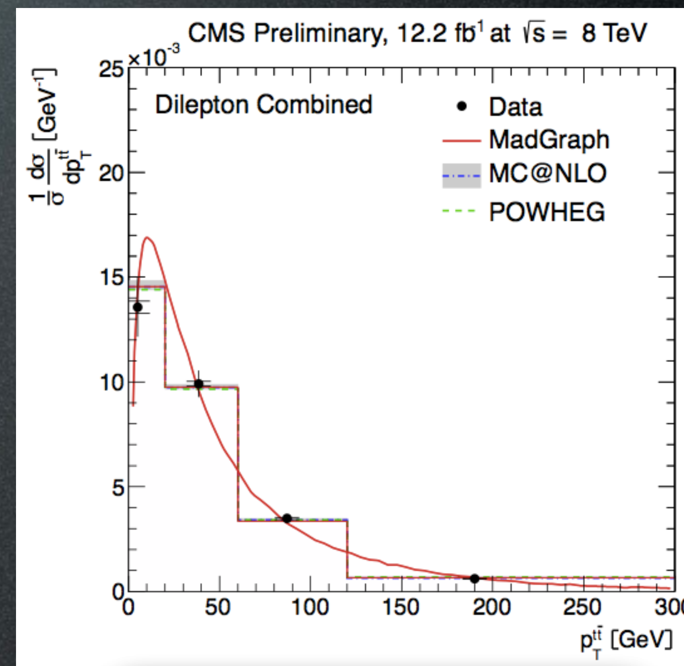
CMS PAS TOP-12-028



Selection



Kin. Reconstruction



Diff. x-section

Bin by bin counting:
- Background subtraction
- Unfolding

$$\frac{1}{\sigma}\frac{d\sigma_i}{dX} = \frac{1}{\sigma}\frac{x_i}{\Delta_i^X \mathcal{L}}$$

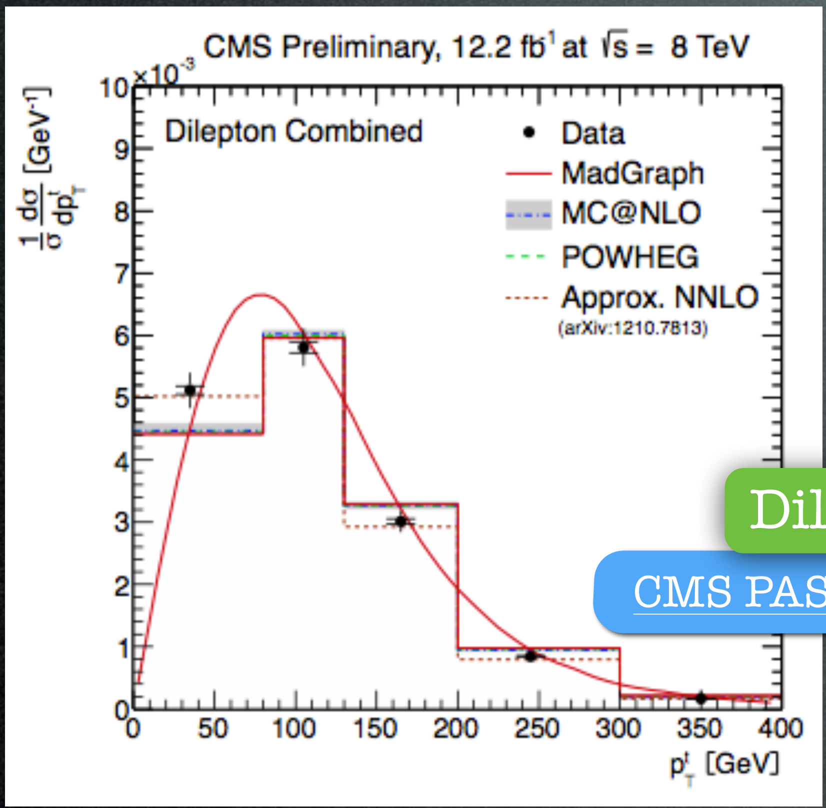
L+Jets

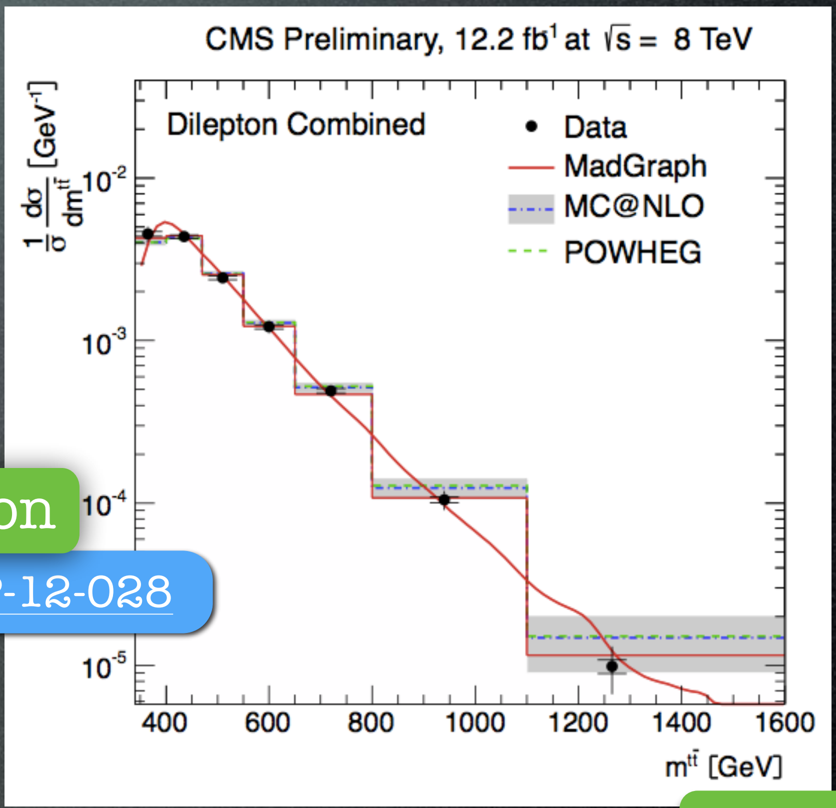
CMS PAS TOP-12-027

Top pair differential x-sect dilepton

8 TeV 12.2fb^{-1}

- Normalized differential cross-sections measured as a function of:
  - $p_T^{Lead.t}$, $y^{Lead.t}$, $p_T^{NLead.t}$, $y^{NLead.t}$, p_T^{t}, y^{t}, $p_T^{t\bar{t}}$, $y^{t\bar{t}}$, $m^{t\bar{t}}$
  - $p_T^{Lead.l}$, $\eta^{Lead.l}$, $p_T^{NLead.l}$, $\eta^{NLead.l}$, $p_T^{Lead.b}$, p_T^{ll}, m^{ll}, $\eta^{Lead.b}$, $p_T^{NLead.b}$, $\eta^{NLead.b}$, m^{lb}
- Tension with theory predictions for top p_T softer in data than MC:





Dilepton

CMS PAS TOP-12-028

- Better agreement with approximate NNLO
- Effect present also in 7TeV data and in lepton+jets final state

L+Jets

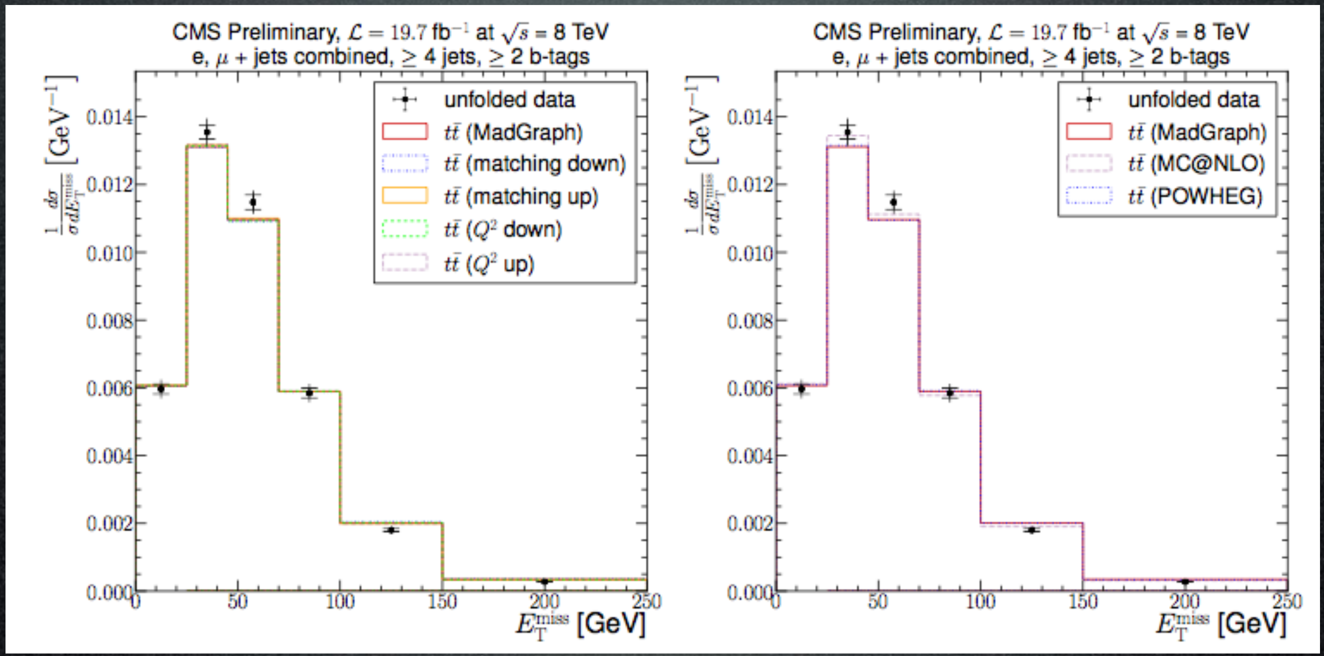
CMS PAS TOP-12-027

Top pair differential cross-sections

- Event level variables in lepton+jets: CMS PAS TOP-12-042
  - Template fit to determine background then unfolding
- Key variables used in SM, rare processes and new physics searches
  - MET, $H_{\mathrm{T}} = \sum_{\mathrm{alljets}} p_{\mathrm{T}}^{\mathrm{jet}}$ $S_{\mathrm{T}} = H_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}} + p_{\mathrm{T}}^{\mathrm{lepton}}$

$$p_T^W = \sqrt{(p_x^{\mathrm{lepton}} + p_x^{\mathrm{miss}})^2 + (p_y^{\mathrm{lepton}} + p_y^{\mathrm{miss}})^2}$$

$$M_T^W = \sqrt{(E_{\mathrm{T}}^{\mathrm{lepton}} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - p_T^{W2}}$$



8 TeV

20fb^{-1}

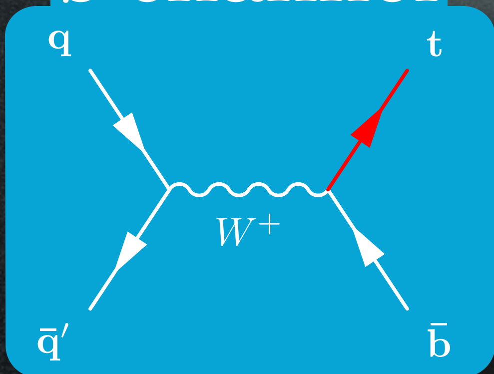
L+Jets

- Overall good agreement with theoretical predictions (similar to 7TeV)
- Main systematics: model uncertainties, JES and fit/unfolding

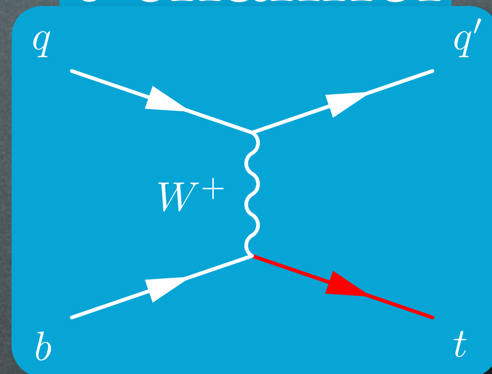
Single top at the LHC

- Three single top production modes:

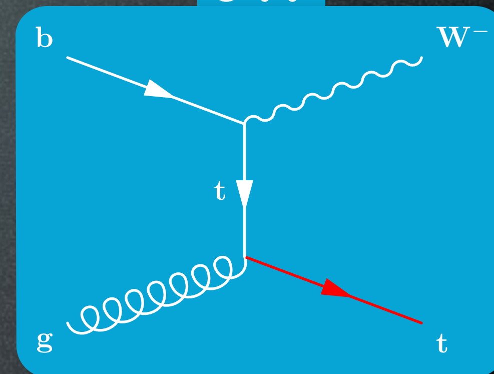
s-channel



t-channel



tW



tW not accessible at Tevatron

- Electroweak interaction production and decay
- Access to CKM element V_{tb}
- Sensitive to new physics, backgrounds to several analyses
- Top cross-sections at Tevatron and the LHC

Top mass = 173 GeV

Cross sections (pb)	s-channel	t-channel	tW channel	top pairs
Tevatron: ppbar@1.96TeV	1.05	2.08	0.22* *arxiv.org/pdf/0909.0037	7.08
LHC: pp @ 7 TeV	4.56	65.9	15.6	163
LHC: pp @ 8 TeV	5.55	87.2	**22.2**	**234**

N. Kidonakis arxiv.org/pdf/1205.3453v1 (2012)

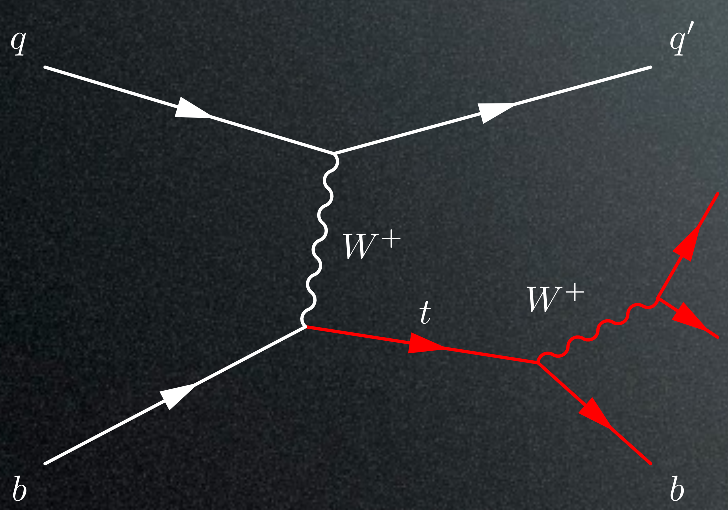
Single top t-channel

8 TeV

$19.7 fb^{-1}$

L+Jets

- Highest single top production cross-section
- Systematics dominated measurement
- Only leptonic W decays considered (e, μ final states):
  - **Lepton + jets** topology:



Light quark jet (large $|\eta_{j'}|$)

Isolated lepton (μ or e)

Missing Transverse Energy (ν_e or ν_μ)

Central high p_t b-jet

  - Potential extra b-jet, broad **$|\eta|$** and low p_t
- Main backgrounds W+jets, top pairs, QCD multi-jets
- Strategy:
  - Fit pseudorapidity of light recoil jet $|\eta_{j'}|$
  - Shape of W+jets and top pairs from data control regions

Accepted by JHEP
arXiv:1403.7366

Single top t-channel

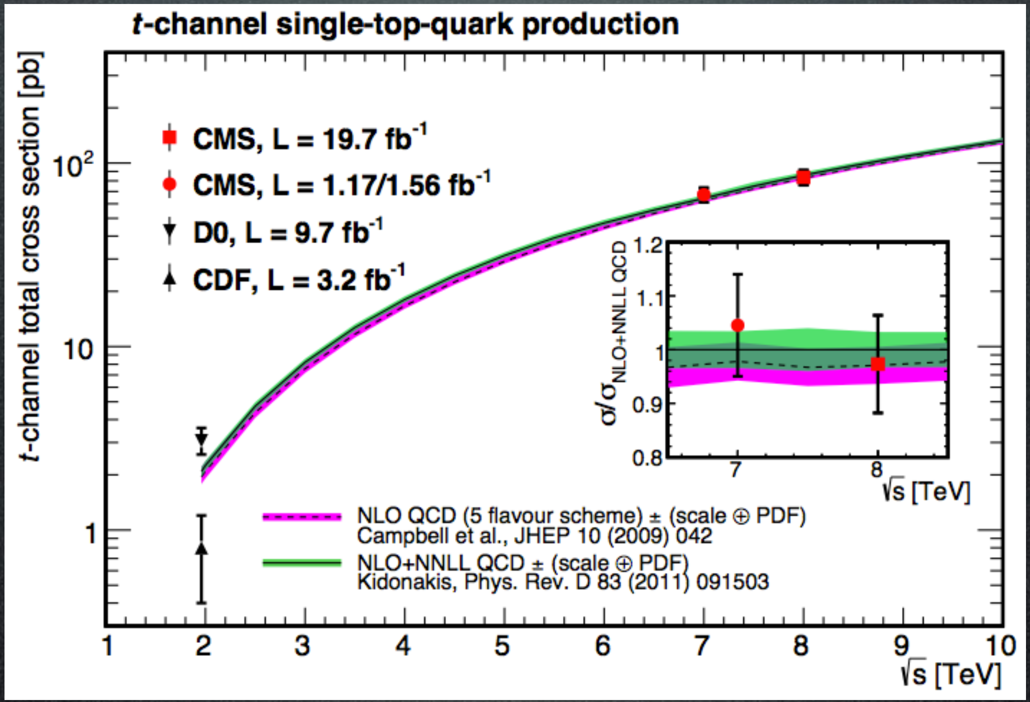
- Inclusive single top t-channel cross-section:

$$\sigma_{t\text{-ch.}} = 83.6 \pm 2.3\,(\text{stat.}) \pm 7.4\,(\text{syst.})\,\text{pb}$$

- Single t quark and antiquark t-channel cross-sections also obtained:

$$\sigma_{t\text{-ch.}}(\text{t}) = 53.8 \pm 1.5\,(\text{stat.}) \pm 4.4\,(\text{syst.})\,\text{pb}, \quad \sigma_{t\text{-ch.}}(\bar{\text{t}}) = 27.6 \pm 1.3\,(\text{stat.}) \pm 3.7\,(\text{syst.})\,\text{pb}$$

- All three results in agreement with theoretical predictions



8 TeV

19.7fb^{-1}

L+Jets

Accepted by JHEP
arXiv:1403.7366

- Largest uncertainties: signal modeling and JES

Single top t-channel

8 TeV

19.7fb^{-1}

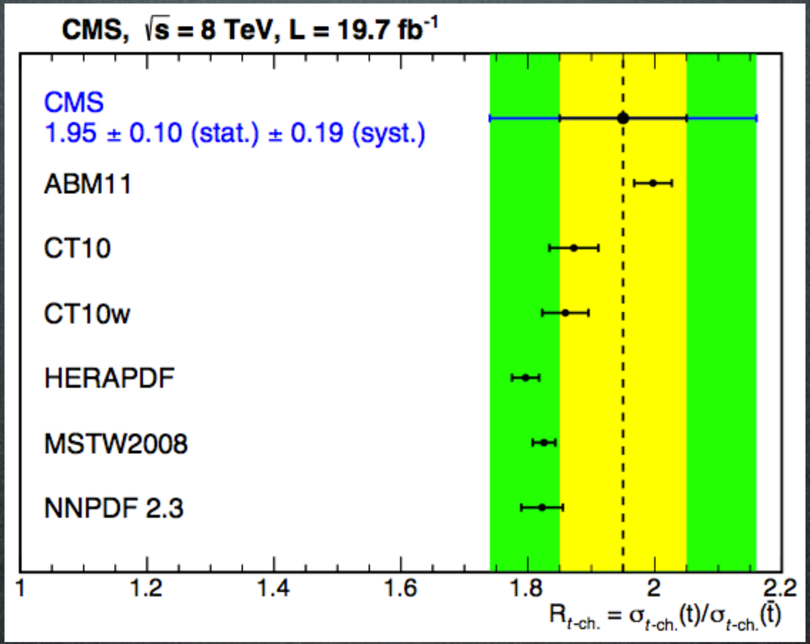
L+Jets

- Cross-section ratios (top quark/antiquark, and 8/7TeV)

$$R_{8/7} = \sigma_{t\text{-ch.}}(8\,\text{TeV})/\sigma_{t\text{-ch.}}(7\,\text{TeV}) = 1.24 \pm 0.08\,(\text{stat.}) \pm 0.12\,(\text{syst.})$$

$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(\text{t})/\sigma_{t\text{-ch.}}(\bar{\text{t}}) = 1.95 \pm 0.10\,(\text{stat.}) \pm 0.19\,(\text{syst.})$$

- From the latter it is possible to compare the predictions of several PDF sets:



Accepted by JHEP
arXiv:1403.7366

- High statistics of t-channel:
  - Differential cross-section studies (top/W polarization)
  - Gives best $|V_{tb}|$ estimates:

See Karl Ecklund talk

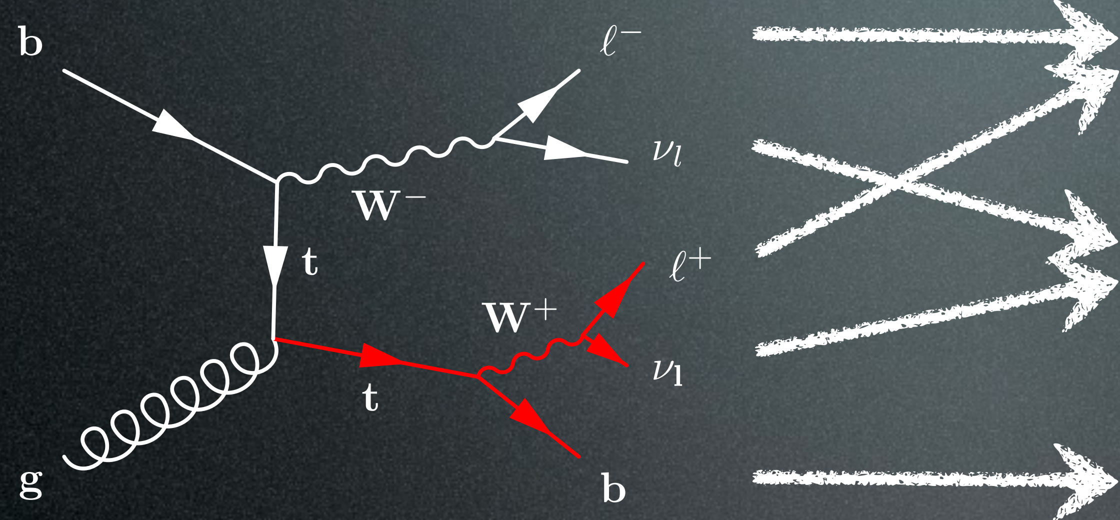
$$|f_{\text{Lv}}V_{\text{tb}}| = 0.979 \pm 0.045\,(\text{exp.}) \pm 0.016\,(\text{theo.})$$ 8 TeV

$$|f_{\text{Lv}}V_{\text{tb}}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{theo.})$$ 7+8 TeV

$|V_{tb}|>0.92$ at 95% C.L. ($0 \le |V_{tb}|^2 \le 1$)

Single top tW

- tW associated production observable at LHC for the first time!
- **Di-lepton** topology:



Two isolated leptons (ee, μμ, eμ)

E_t^{miss} from the two neutrinos

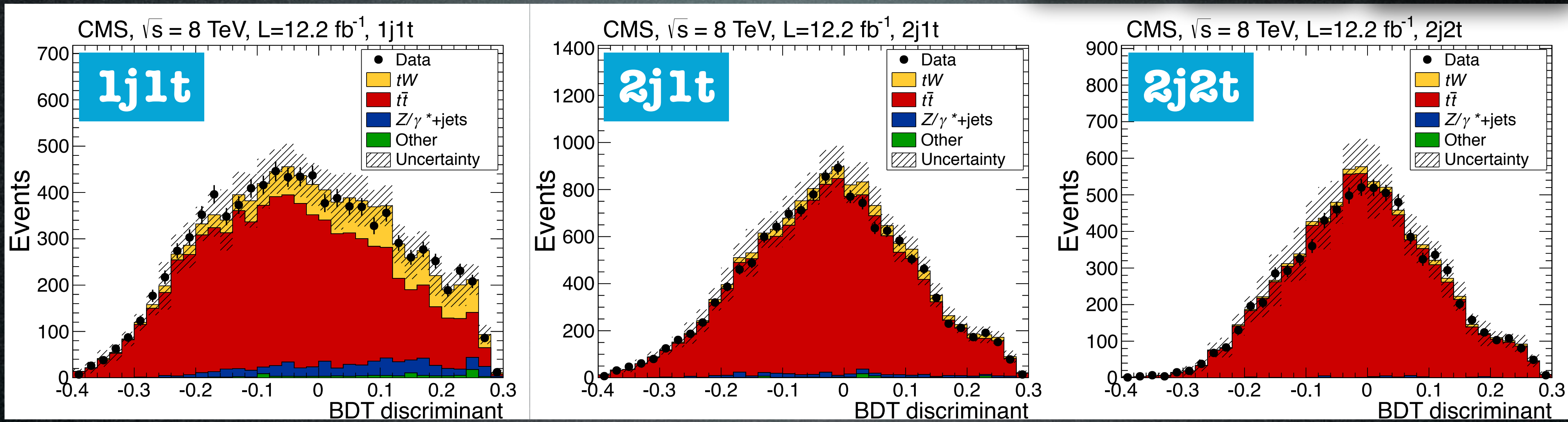
One b-jet from top decay b quark

- Main backgrounds top pairs, Z+jets
- Signal and control regions to constrain top pair and b-tagging uncertainty:
  - 1 jet 1 b-tag (**1j1t**): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag (**2j1t**) and 2 jets 2 b-tags (**2j2t**) control regions
- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal

Single top tW

8 TeV | $12.2 fb^{-1}$ | dilepton

- Likelihood fit to BDT discriminant



- Expected significance from MC: **5.4 ± 1.4σ**, observed: **6.1 σ**
- Cross-section estimated using profile likelihood:
  - **σ_{tW} = 23.4 ± 5.4 pb at 8TeV**
  - Theoretical value (m_{top}=173GeV): σ_{tW} = 22.2 ± 0.6(scale) ±1.4(PDF) pb

(Approximate NNLO) N. Kidonakis arxiv.org/pdf/1210.7813 (2012)

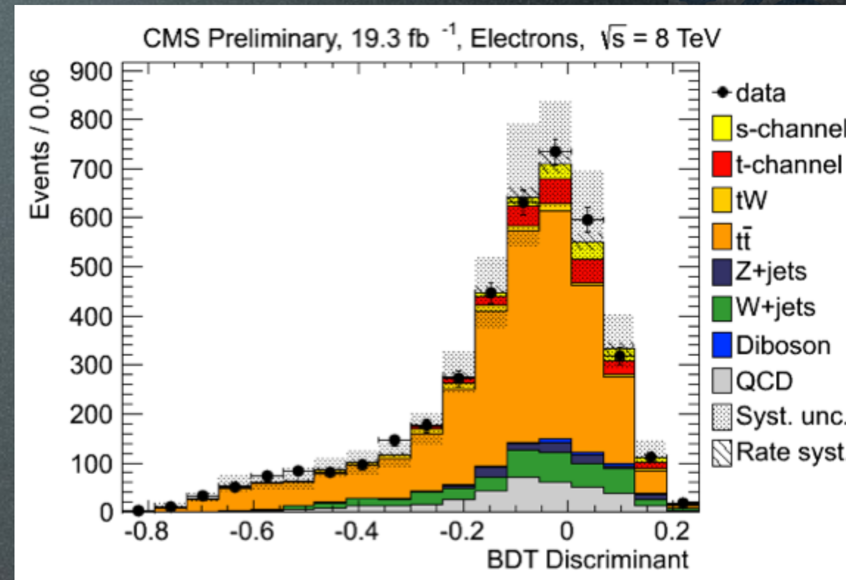
- V_{tb} matrix element estimate ($|V_{tb}|>>|V_{td}|,|V_{ts}|$ and $f_{Lv}=1$):
  - $$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$
  - $|V_{tb}|>0.78$ at 95% C.L. ($0\leq|V_{tb}|^2\leq1$)

Accepted by PRL
arXiv:1401.2942

Single top s-channel

CMS PAS TOP-13-009

- Very sensitive to new physics
- Lowest cross-section, irreducible large backgrounds (W+jets, top pairs, multijet QCD)
- Analysis strategy:
  - Multivariate analysis based on BDTs
  - Data-driven QCD background estimate
  - Top pair control region (3j2b-tags) used in the fit
  - Binned maximum likelihood fit of BDT



- Expected significance: 0.9σ, observed 0.7σ
- Cross-section measurement:

$$\sigma_{\text{s-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.})\ \text{pb} = 6.2 \pm 8.0\ \text{pb}$$

- Theory prediction (NLO+NNLL order) at 8Tev:

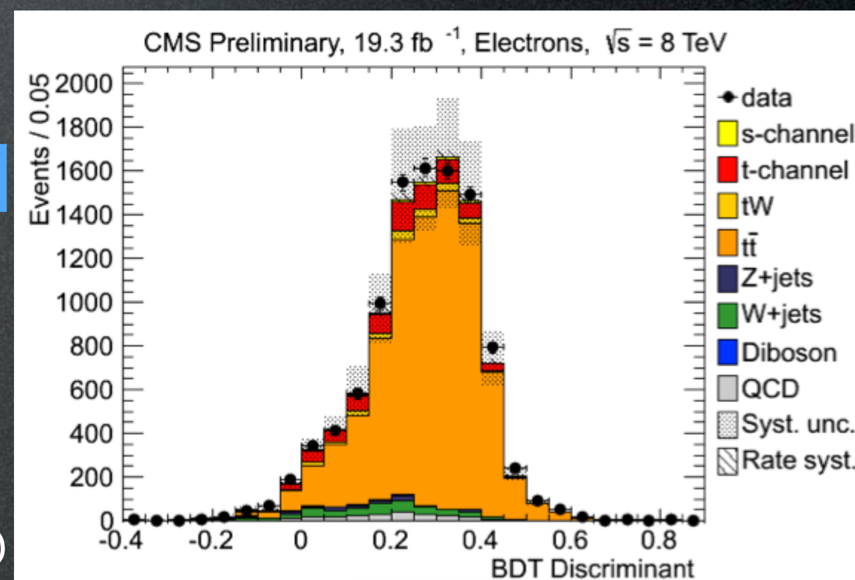
$$\sigma_{s-\text{ch.}} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF})\ \text{pb}$$

arXiv:1205.3453

- Assuming Standard Model signal FC 68%C.L.:

$$\sigma_{\text{s-ch.}} = 6.2^{+8.0}_{-5.1}\ \text{pb}$$

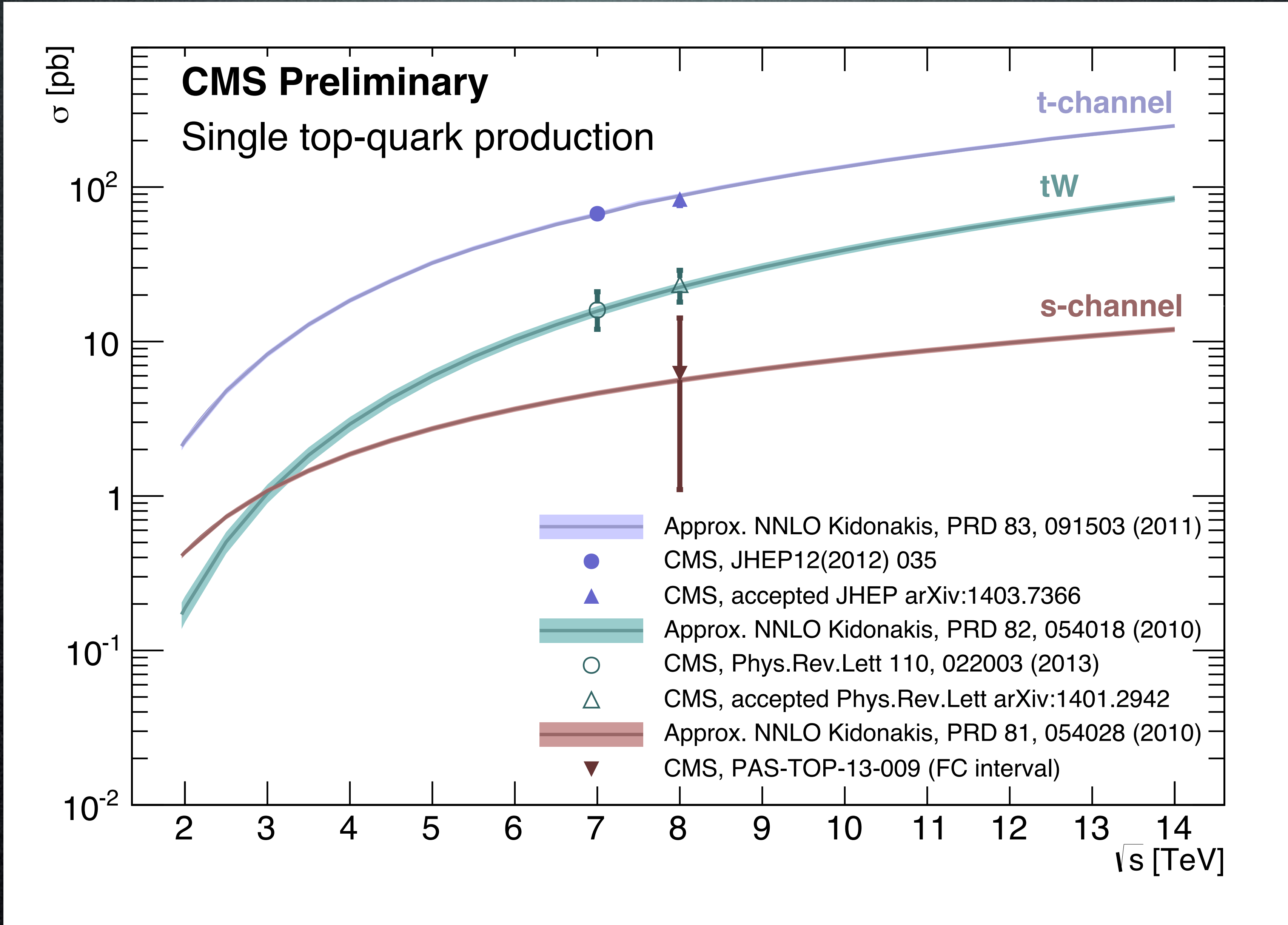
- Upper limit on s-channel x-sect 11.5pb (95%C.L.)



L+jets | 8 TeV | 19.7fb^{-1}

Single top cross-sections

- Summary from CMS single top production analyses:



Conclusions

- Top pair production cross-section measurements testing theoretical predictions
- Top pair differential cross-section challenging models
- Single top:
  - t-channel: precise new result, statistics allows for differential cross-section and properties studies
  - tW: first observation
  - s-channel: upper limit set
- No significant deviation from SM
- Analyses preparing for 13/14TeV LHC data

Thank you!

All results are public

- You can find all the CMS results with much more details at:

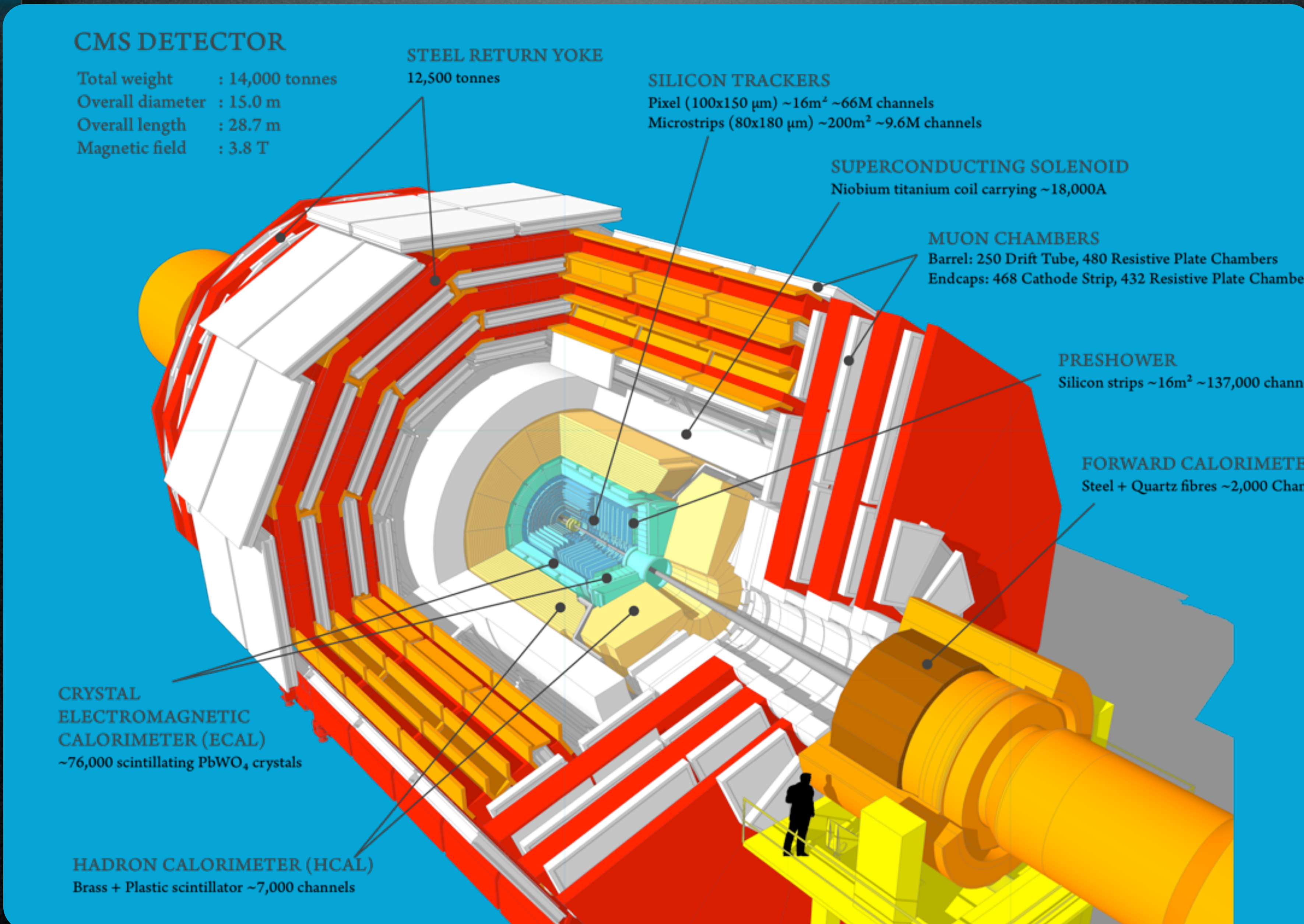
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Back-up

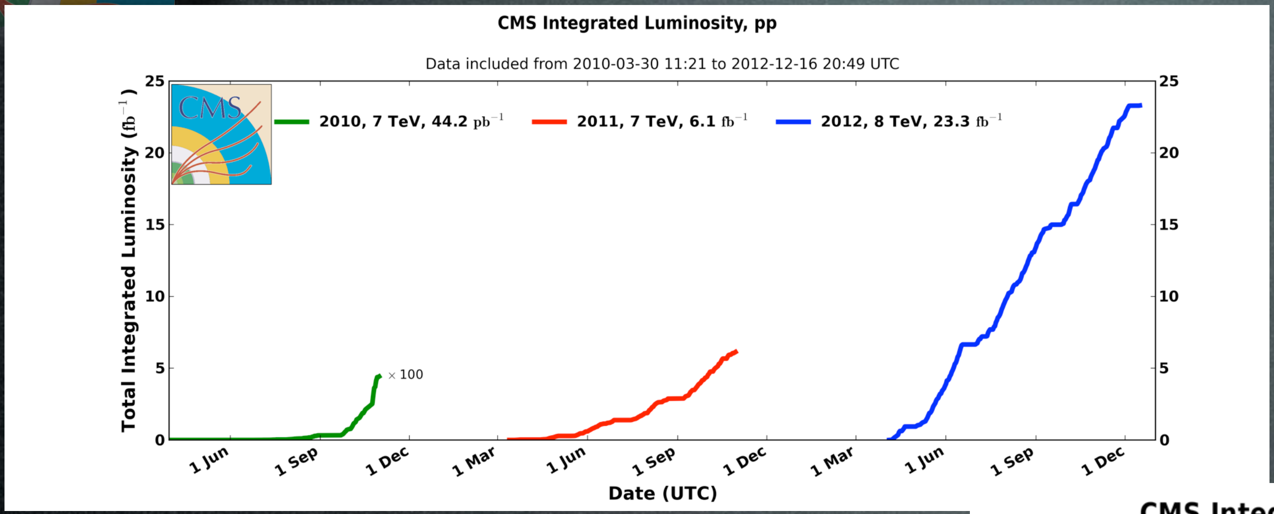
Top quark at the LHC

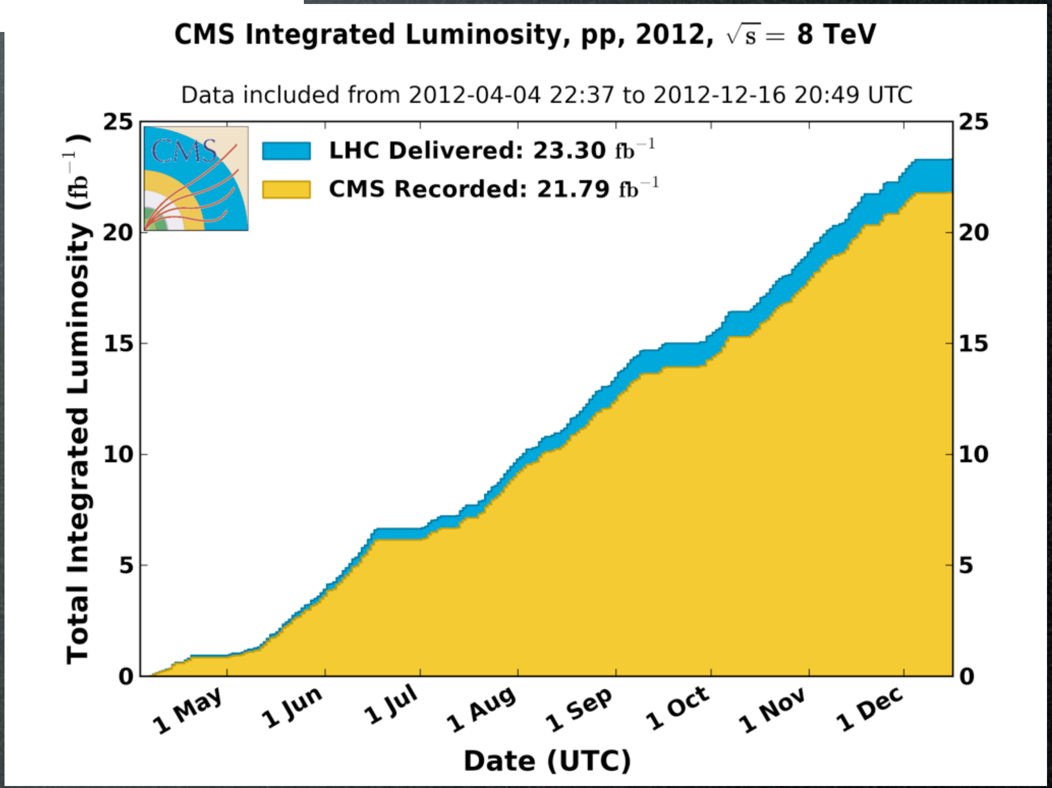
- While the LHC is preparing for Run II 13/14TeV pp collisions:
  - Final/ongoing Run I analysis completing:
    - 5 fb^{-1}@7TeV
    - 20fb^{-1}@8TeV
  - New analyses preparing for Run II
  - Detectors completing upgrades to cope with increased luminosity and pileup

The Compact Muon Solenoid



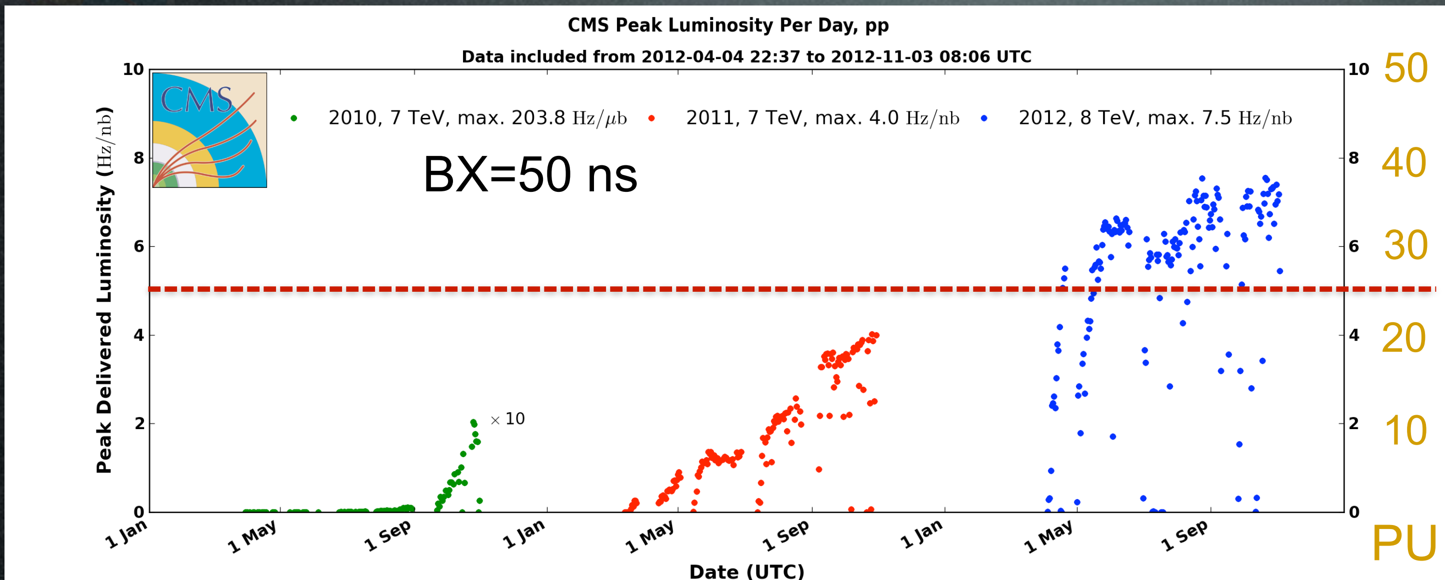
Dataset(s)





- Excellent LHC performance
- Two large datasets exploited
- High recording efficiency
- Event pile-up challenge

Event pile-up

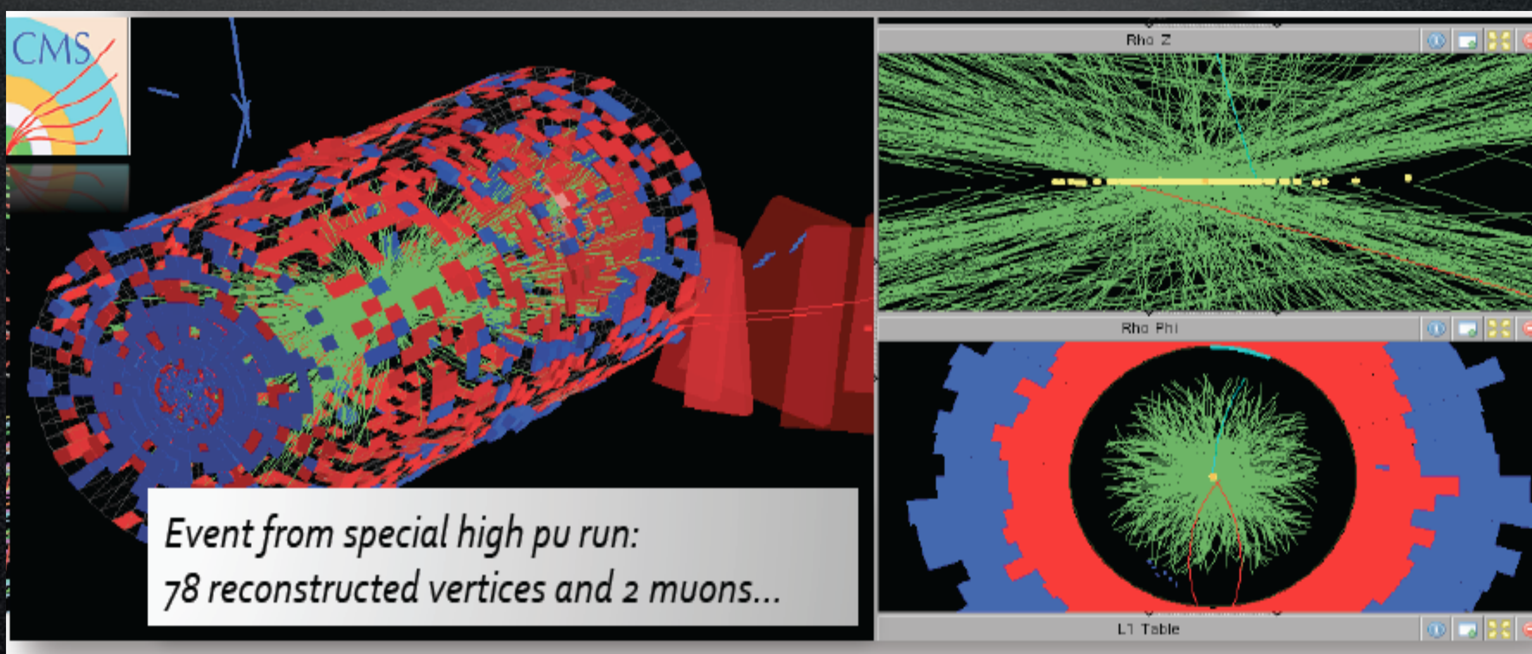


Peak: 37 pileup events

Design value

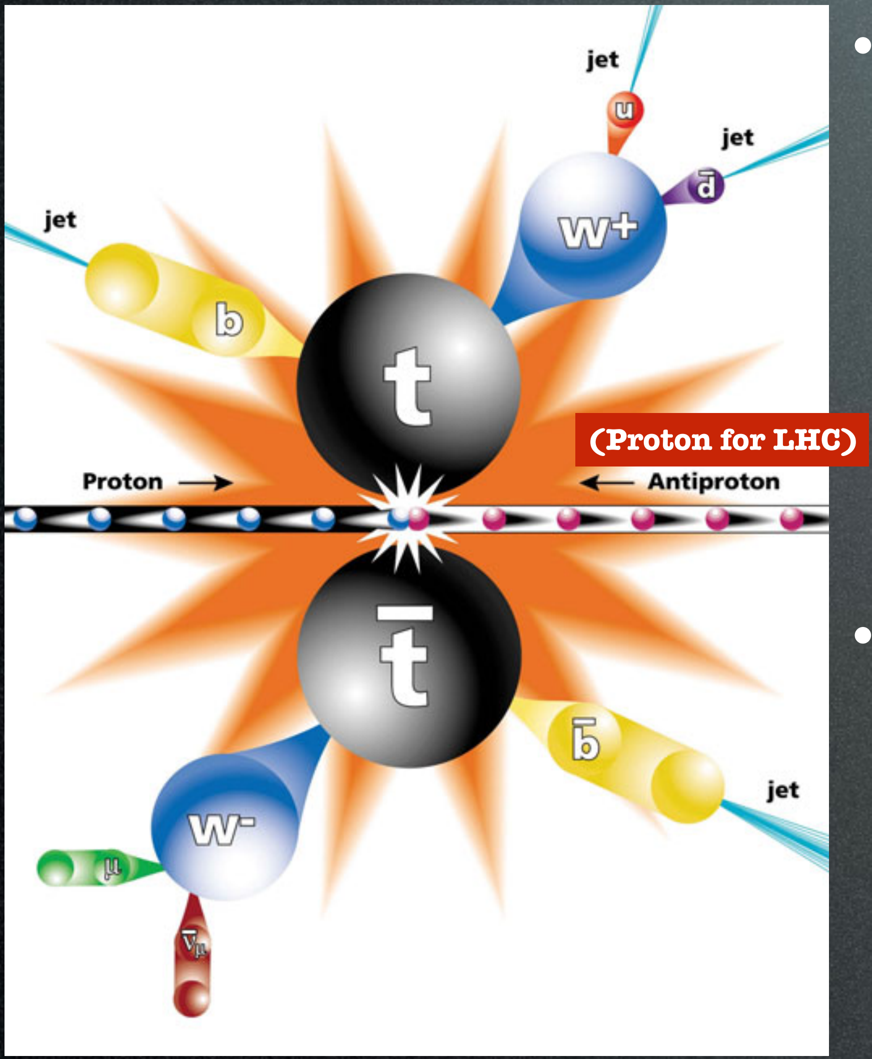
25 pileup events

($L=10^{34}$, BX=25 ns)



Top Quark Signature

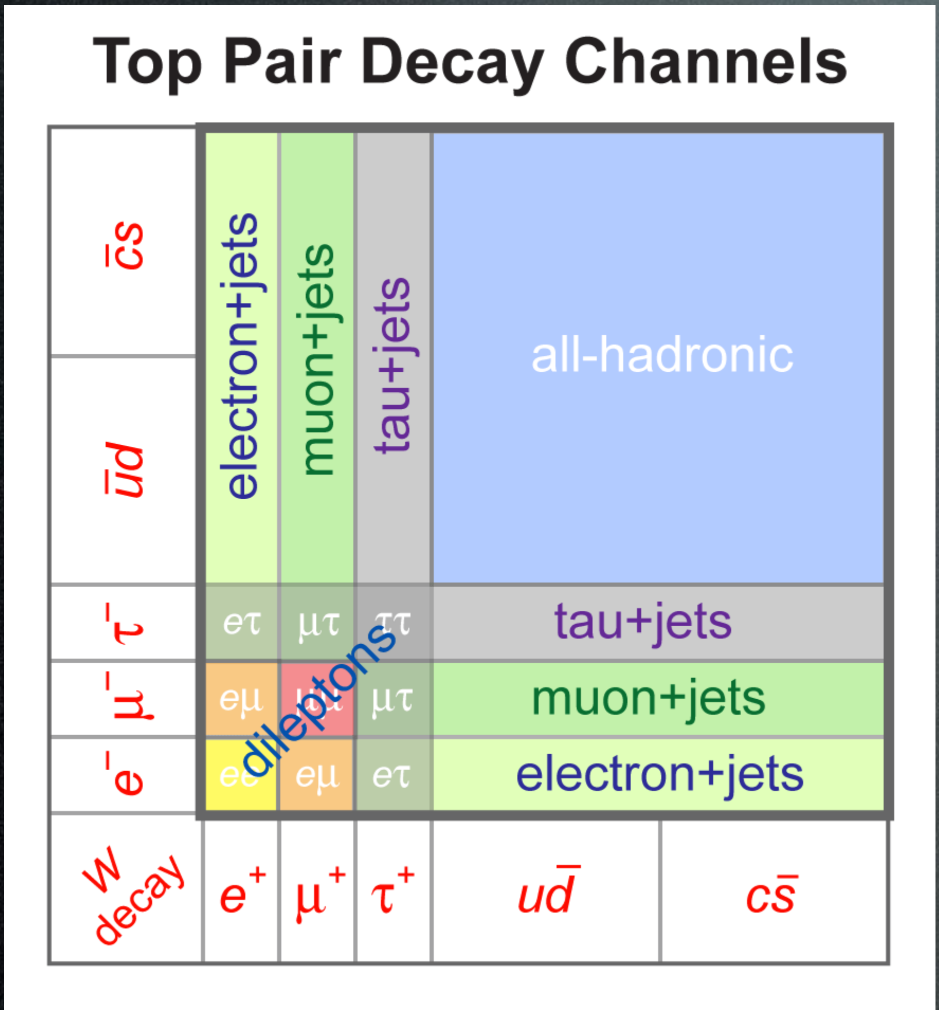
- Experimental challenges:
  - Detection in hadron collider environments:



- Top decays almost always into Wb:
  - Topology driven by W decay
  - Signatures are named after final states:
    - Di-lepton (both Ws leptonic decay)
    - Lepton+jets (1 leptonic, 1 hadronic)
    - Fully hadronic (both Ws hadronic decay)
- Whole detector capabilities are crucial:
  - Lepton Identification
  - Light and B jets reconstruction
  - B-tagging
  - Missing transverse energy

Top-ology

- Top decay signatures based on the fact top decay almost always into a W boson and a b quark:



- Dilepton:
  - High S/B
  - Lower statistics
  - Two neutrinos
- Lepton plus jets:
  - Highest statistics
  - Good S/B
- All hadronic:
  - Full top reconstruction
  - Toughest background
- B-tagging efficiency typically 70%

Total production cross-section

- Event counts:

8 TeV

5.3fb^{-1}

Dilepton

	Number of events		
Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Drell-Yan	386 ± 116	492 ± 148	194 ± 58
Non-W/Z leptons	25 ± 10	114 ± 46	185 ± 72
Single top quark	127 ± 28	157 ± 34	413 ± 88
VV	30 ± 8	39 ± 10	94 ± 21
Total background	569 ± 120	802 ± 159	886 ± 130
$t\bar{t}$ dilepton signal	2728 ± 182	3630 ± 250	9624 ± 504
Data	3204	4180	9982

JHEP 02 (2014) 024

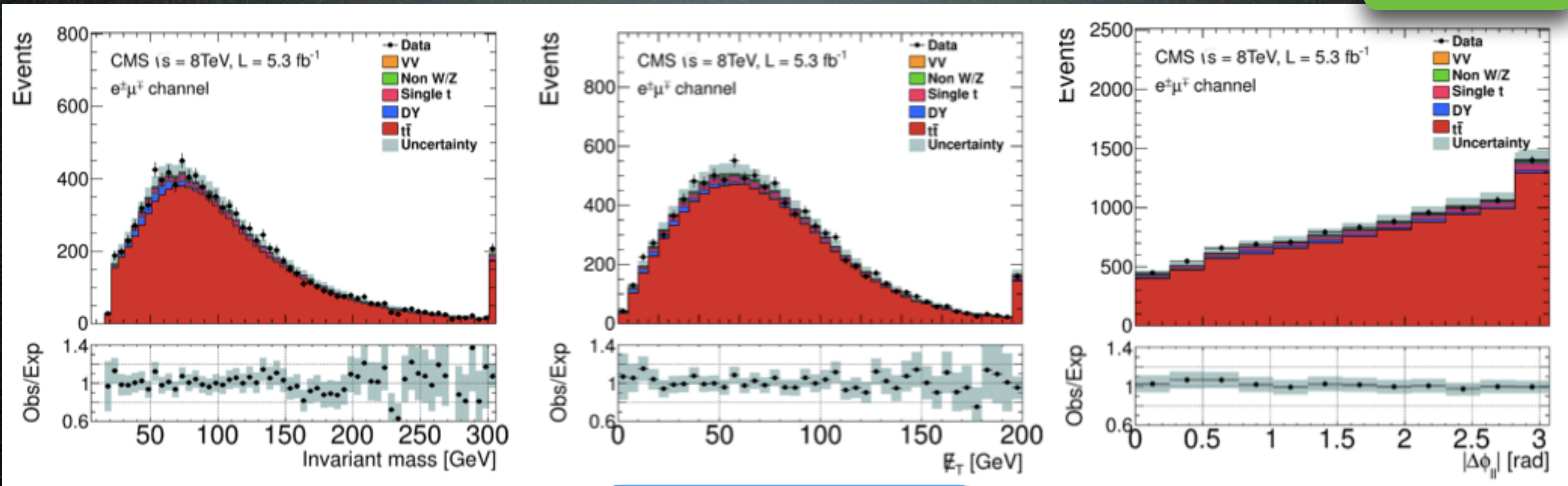
Total top pair x-sect 8TeV

8 TeV

$5.3 fb^{-1}$

Dilepton

- Data/MC agreement scaling top pair MC to measured x-sect:



JHEP 02 (2014) 024

Top pair total x-section

8 TeV

5.3fb^{-1}

Dilepton

- Systematic uncertainties to top pair total cross-section (in pb)

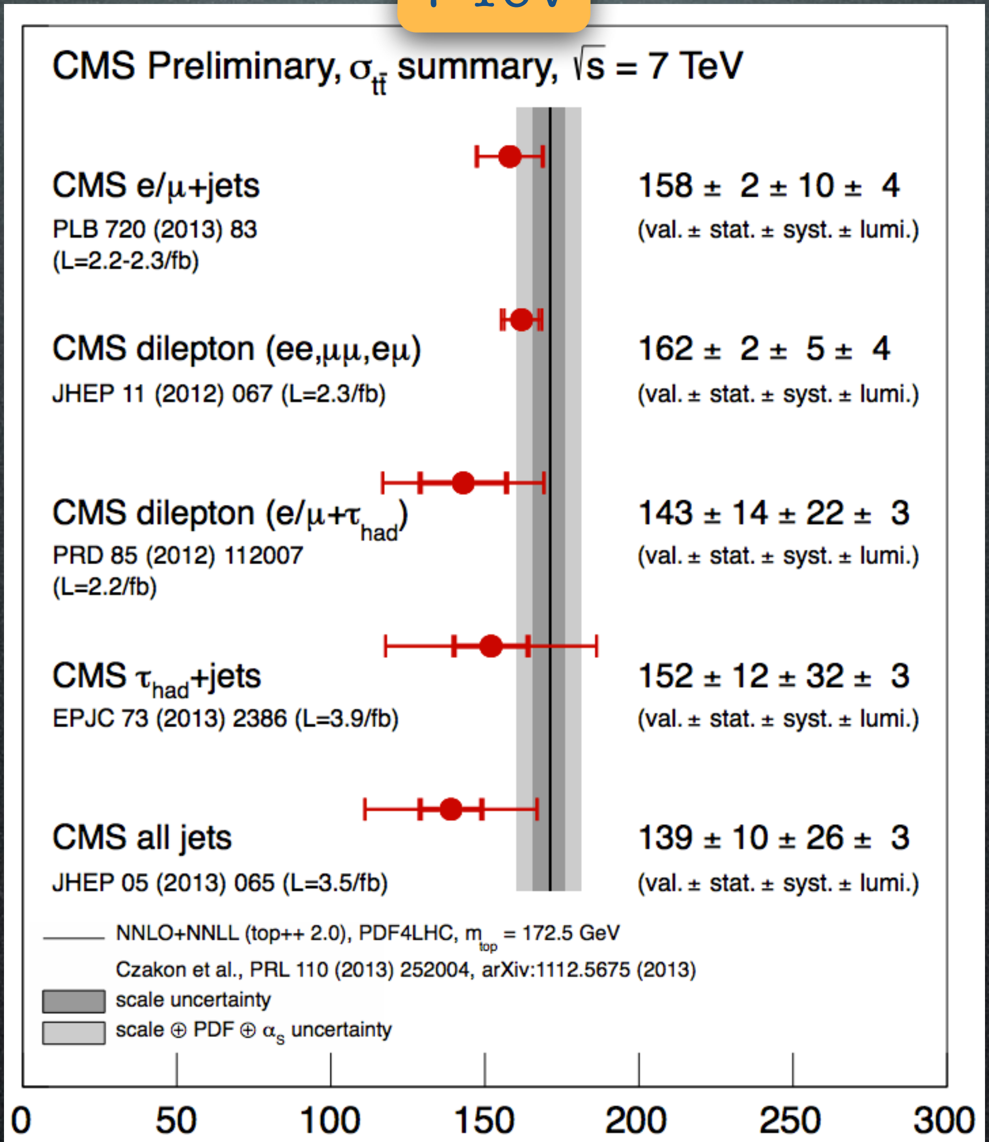
Source	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
Trigger efficiencies	4.1	3.0	3.6
Lepton efficiencies	5.8	5.6	4.0
Lepton energy scale	0.6	0.3	0.2
Jet energy scale	10.3	10.8	5.2
Jet energy resolution	3.2	4.0	3.0
b-jet tagging	1.9	1.9	1.7
Pileup	1.7	1.5	2.0
Scale (μ_F and μ_R)	5.7	5.5	5.6
Matching partons to 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

JHEP 02 (2014) 024

Total pair total x-sect @ 7TeV

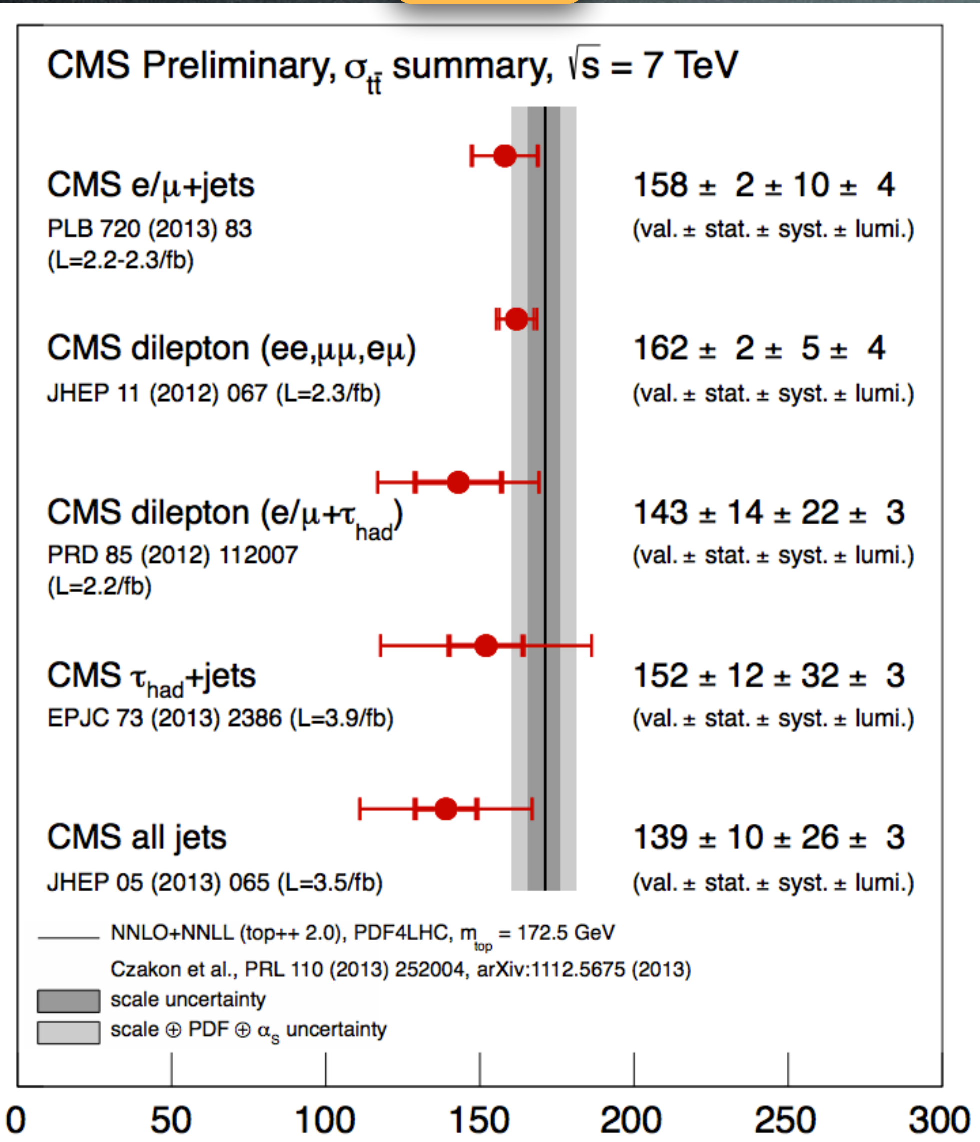
- Summary of all CMS 7TeV total pair production cross-section results

7 TeV

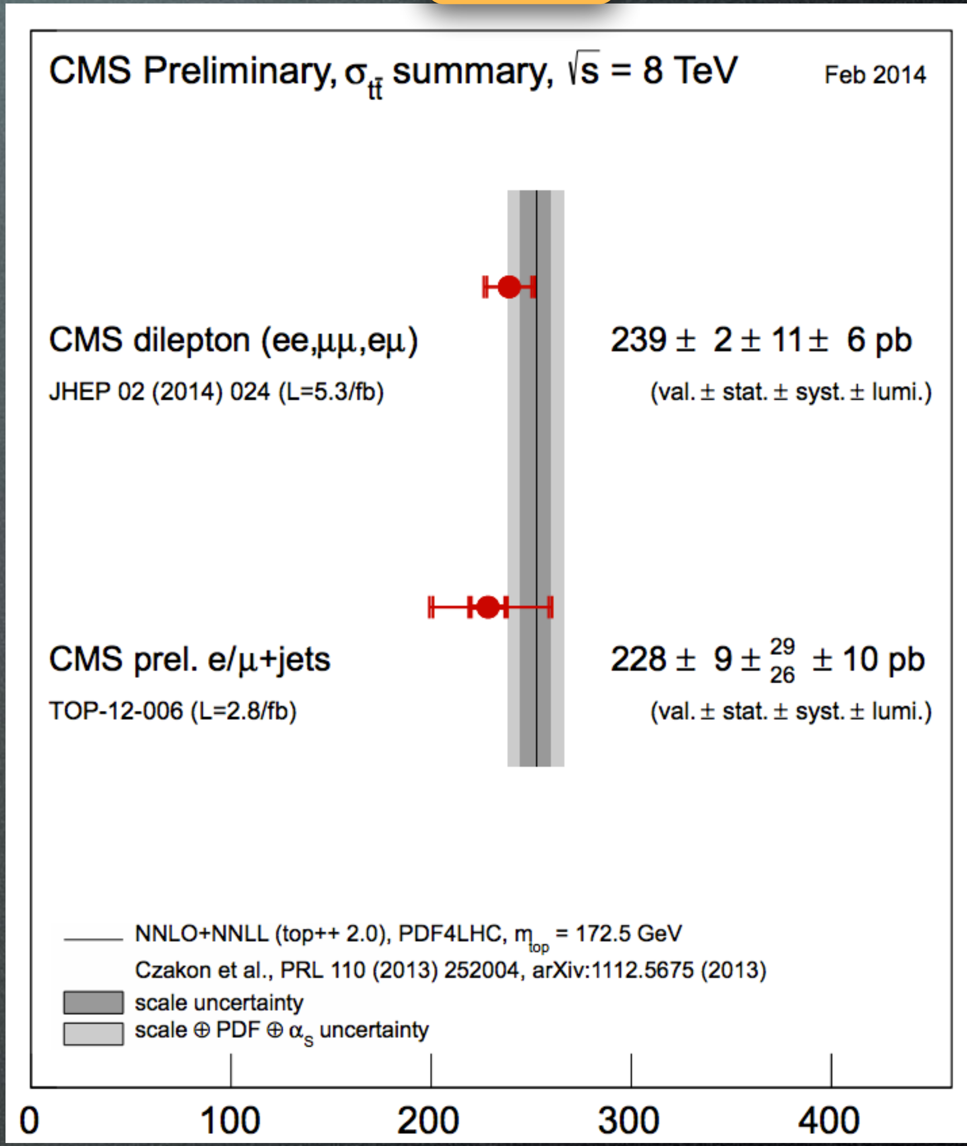


Total pair total x-sect summary

7 TeV



8 TeV



Top pair production x-sect

8 TeV

$5.3 fb^{-1}$

Dilepton

- Mass dependence in the range 160-185GeV:

$$\sigma_{t\bar{t}}/\sigma_{t\bar{t}}\,(m_t = 172.5) = 1.00 - 0.009 \times (m_t - 172.5) - 0.000168 \times (m_t - 172.5)^2$$

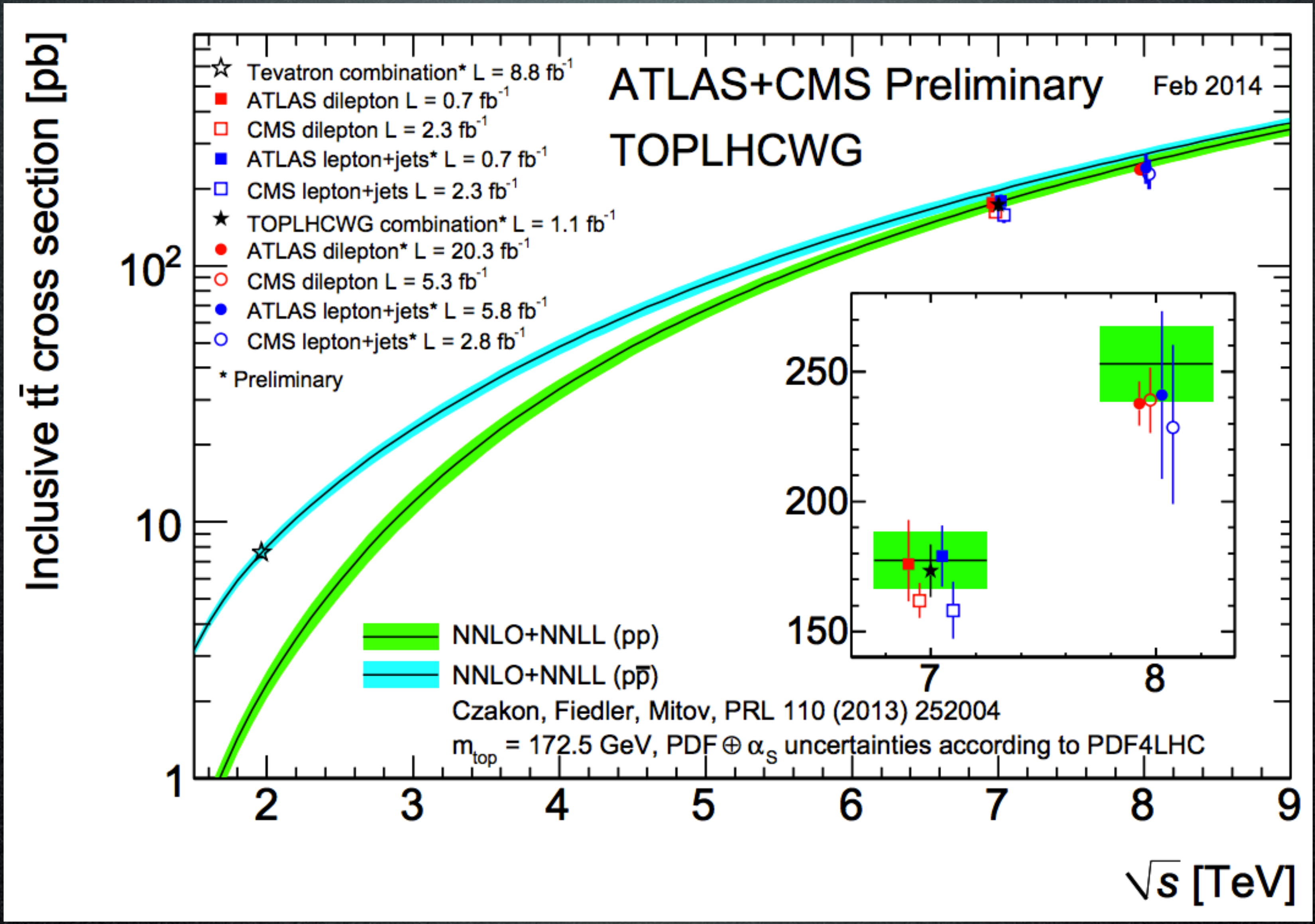
JHEP 02 (2014) 024

- Using m_t=173.2GeV:

$$\sigma_{t\bar{t}} = 237.5 \pm 13.1\,\text{pb}$$

Top pair total x-sect summary

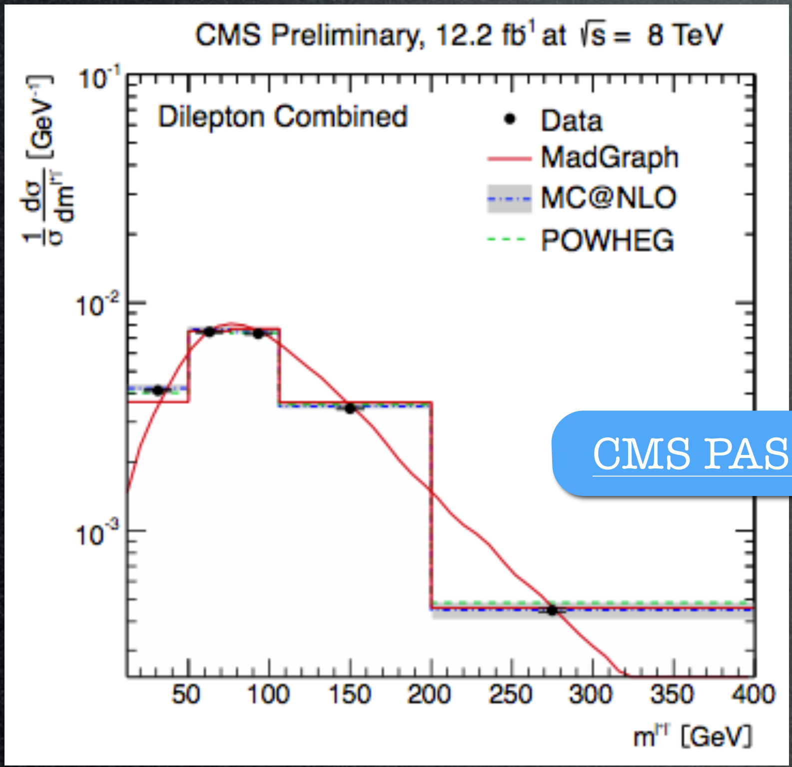
- TOPLHCWG combination, individual measurement, NNLO prediction

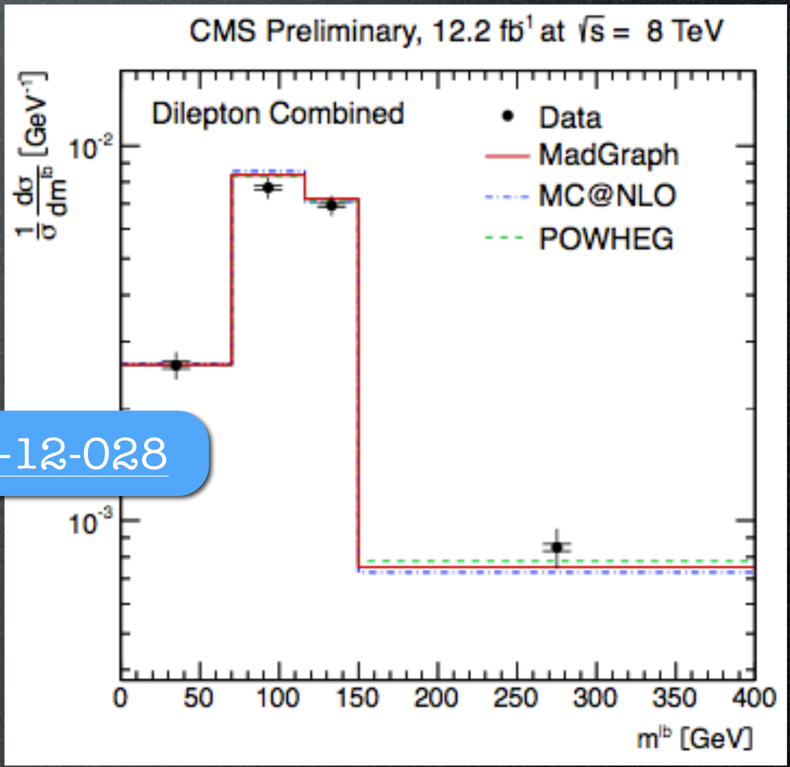


Top pair differential x-sect dilepton

Dilepton | 8 TeV | $12.2 fb^{-1}$

- Normalized differential cross-sections measured as a function of:
  - Lepton: p_T, pseudorapidity separately for leading and next to leading lepton
  - Lepton pair: p_T, mass
  - b-jet: p_T, pseudorapidity separately for leading and next to leading b-jet
  - Invariant Lepton+b-jet pair mass
- Good agreement with predictions within experimental uncertainties





CMS PAS TOP-12-028

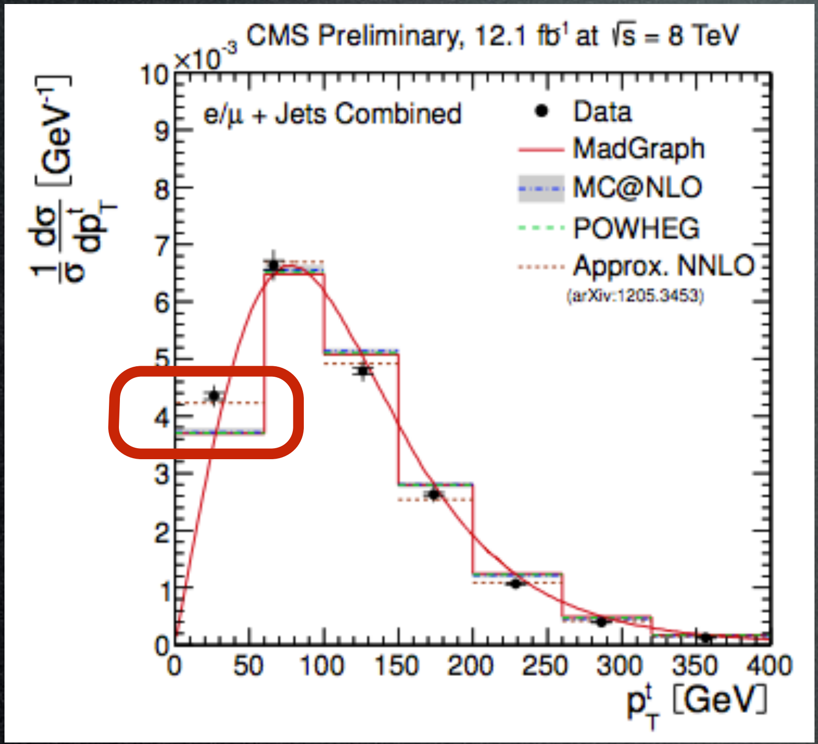
Top pair differential cross-sections

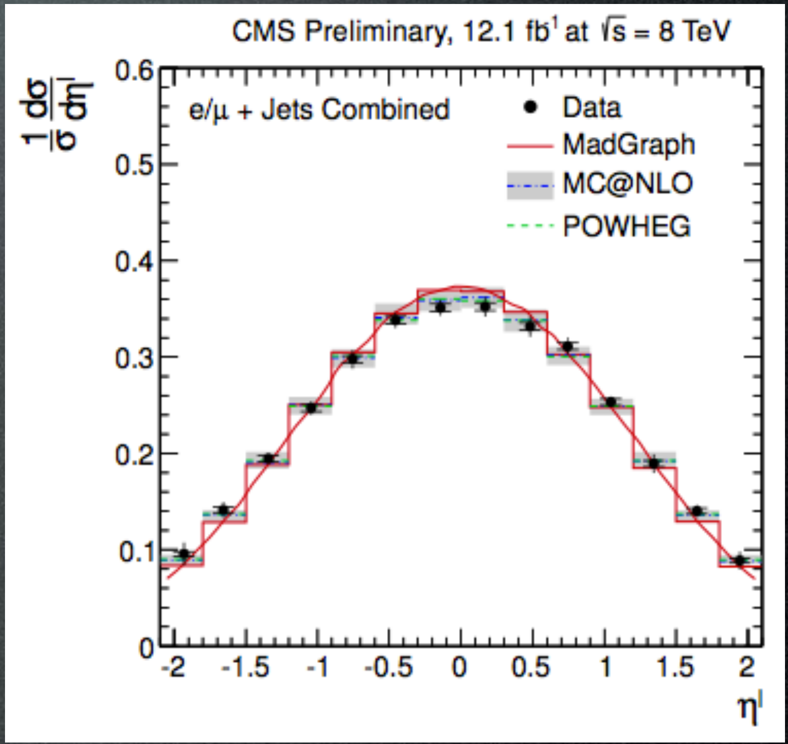
8 TeV

$12.1 fb^{-1}$

L+Jets

- Lepton+jets final state [CMS PAS TOP-12-027]
  - Main backgrounds: W+jets, QCD multijet
  - Similar kinematic reconstruction and unfolding technique
  - Dominant systematics: JES and model uncertainties
  - “Same” differential cross-sections (one lepton only)
  - Similar top p_T behavior observed





  - Good agreement with predictions within experimental uncertainty

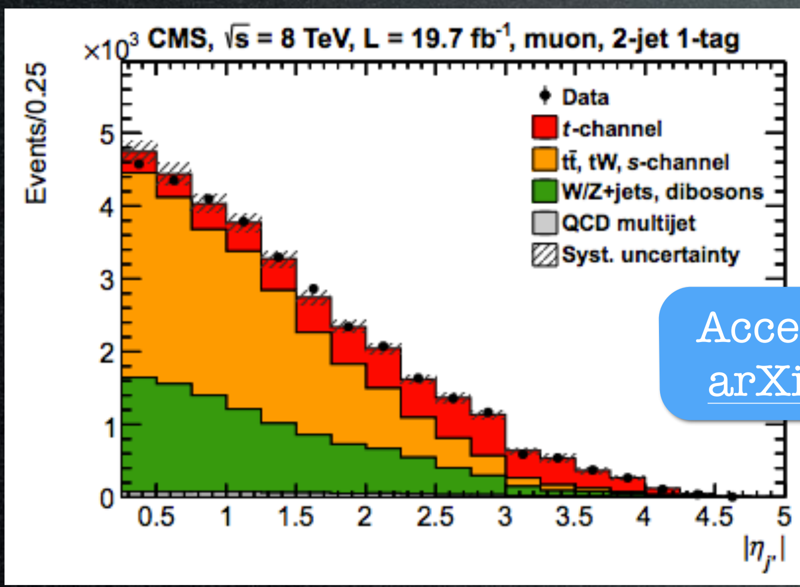
Single top t-channel

8 TeV

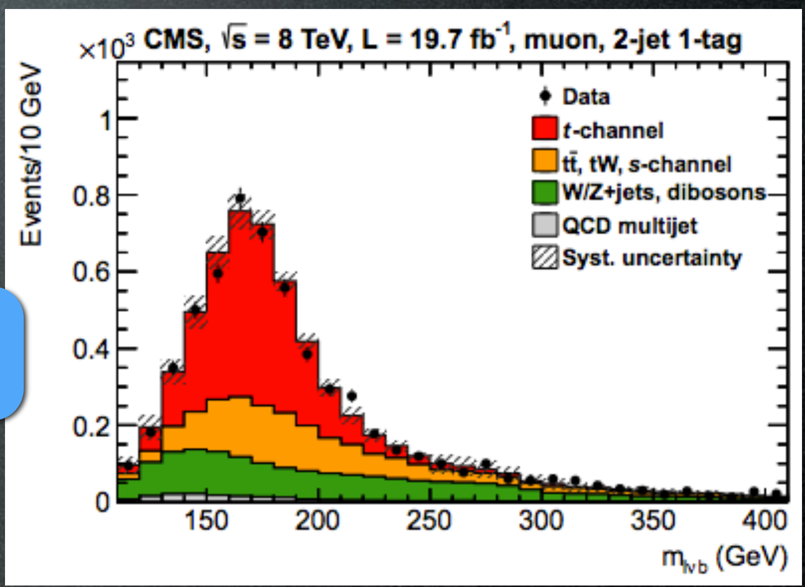
$19.7 fb^{-1}$

L+Jets

- Signal region:
  - Single isolated lepton (e/μ), MET
  - 2 jets, 1b-tag in top mass window ($130 < m_{l\nu b} < 220$GeV)
- Fit pseudorapidity of light recoil jet $|\eta_{j'}|$
- Shape of W+jets and top pairs from data control regions:
  - $m_{l\nu b}$ sidebands, 3jets2b-tags



Accepted by JHEP
arXiv:1403.7366



tW channel Event Selection

- Selection (3 final states ee, μμ, eμ):
  - Exactly 2 isolated, oppositely charged leptons,
  - Leptons invariant mass m_{ll} >20 GeV

All states

  - Z mass veto (m_{ll} < 81GeV, m_{ll} > 101 GeV)
  - E_T^{miss} > 50 GeV

ee/μμ

- Signal and control regions defined by jet multiplicity and b-tagging:
  - 1 jet 1 b-tag (**1j1t**): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag (**2j1t**) and 2 jets 2 b-tags (**2j2t**) control regions to constrain top pair cross-section and b-tagging efficiency uncertainty
- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal

tW channel Event Selection Objects

- Dileptonic Triggers:
  - Two leptons (e or μ: ee, eμ, μμ)
  - Leading lepton p_t > 17GeV, second lepton p_t > 8GeV
- Object selection:
  - Electrons:
    - p_t>20GeV
    - $|\eta|$<2.5
    - IP<0.04cm from beamspot
    - RelIso<0.15 in a cone of ΔR<0.3
  - Loose Electrons:
    - p_t>10GeV
    - $|\eta|$<2.5GeV
  - Muons:
    - p_t>20GeV
    - $|\eta|$<2.4
    - RelIso<0.20 in a cone of ΔR<0.4
  - Loose Muons:
    - p_t>10GeV
    - $|\eta|$<2.5GeV
  - Jets:
    - Anti-k_t
    - p_t>30GeV
    - $|\eta|$<2.4
    - Energy and p_t corrected
  - Loose Jets:
    - Not "tight"
    - p_t>20GeV
    - $|\eta|$<4.9GeV
    - $|\eta|$<2.4GeV (central)
- Particle Flow corrected missing transverse energy (E_t^{miss}) used
- B tagging information:
  - Tracking-based multivariate tagging algorithm
  - Data-driven pt dependent b-tagging scale factors applied

tW channel Event Selection

- Selection (3 final states ee, μμ, eμ):
  - Exactly 2 isolated, oppositely charged leptons,
  - Leptons invariant mass m_{ll} >20 GeV

All states

  - Z mass veto (m_{ll} < 81GeV, m_{ll} > 101 GeV)
  - E_T^{miss} > 50 GeV

ee/μμ

- Signal and control regions defined by jet multiplicity and b-tagging:
  - 1 jet 1 b-tag (**1j1t**): signal region (15-20% tW, 75% top pairs, 5% Z+Jets)
  - 2 jets 1 b-tag (**2j1t**) and 2 jets 2 b-tags (**2j2t**) control regions to constrain top pair cross-section
- Analysis strategy:
  - Data-driven normalization of Z+jets MC (reverse Z mass veto control region)
  - Kinematic variables used to disentangle tW from top pairs
  - Multivariate Boosted Decision Tree (BDT) analysis to extract signal

tW Boosted Decision Trees

- Training on 200k exclusive tW and top pair dilepton events (after selection and in the 1j1t region)
  - MC generators:
    - Single Top: POWHEG
    - Top pairs/V+jets: MadGraph
    - VV et al: Pythia
- 13 kinematic input variables chosen based on:
  - signal/background separation
  - data/MC agreement in several control regions (2j1t, 2j2t, 2j0t,1j0t)

Variable	Description
Nloosejets	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 4.9$
NloosejetsCentral	Number of loose jets, $p_T > 20$ GeV, $\|\eta\| < 2.4$
NbtaggedLoosejets	Number of loose jets, $p_T > 20$ GeV, CSVM btagged
$p_{T,sys}$	Vector sum of p_T of leptons, jet, and E_T^{miss}
H_T	Scalar sum of p_T of leptons, jet, and E_T^{miss}
Jet p_T	p_T of the leading, tight, b-tagged jet
Loose jet p_T	p_T of leading loose jet, defined as 0 for events with no loose jet present
$p_{T,sys}/H_T$	Ratio of $p_{T,sys}$ to H_T for the event
Msys	Invariant mass of the combination of the leptons, jet, and E_T^{miss}
centralityJLL	Centrality of jet and leptons
$H_{T,leptons}/H_T$	Ratio of scalar sum of p_T of the leptons to the H_T of full system
p_T-jll	Vector sum of p_T of jet and leptons
E_T^{miss}	Missing transverse energy in the event

tW BDT Input Variables

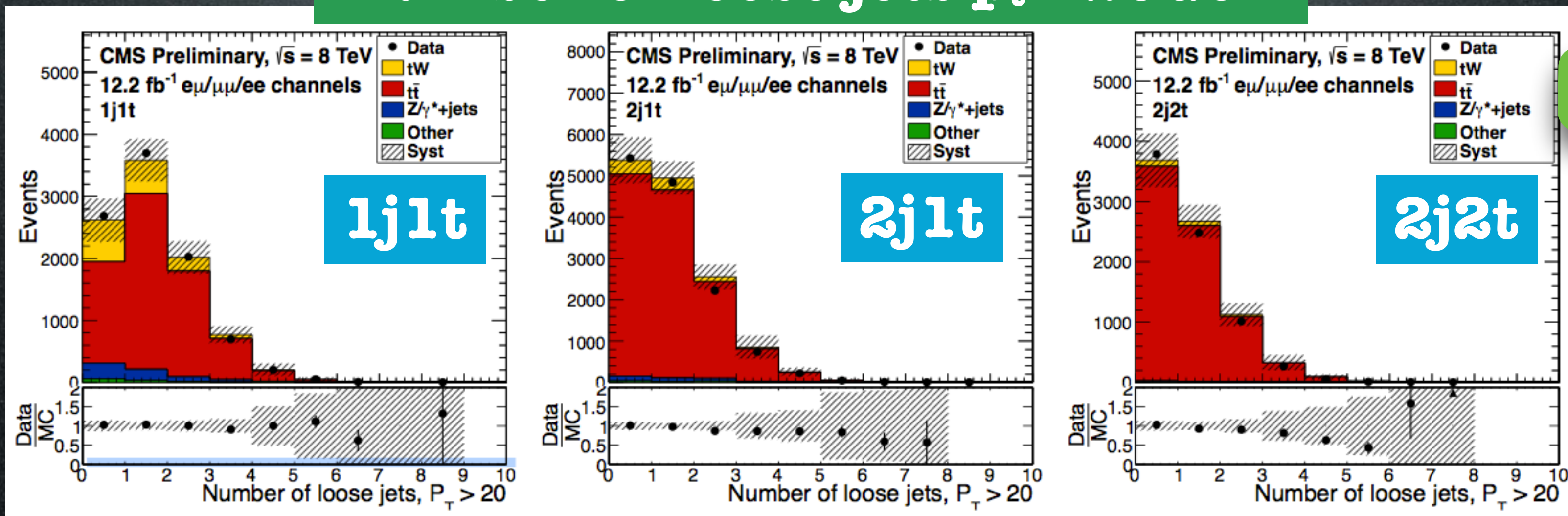
8 TeV

12.2fb^{-1}

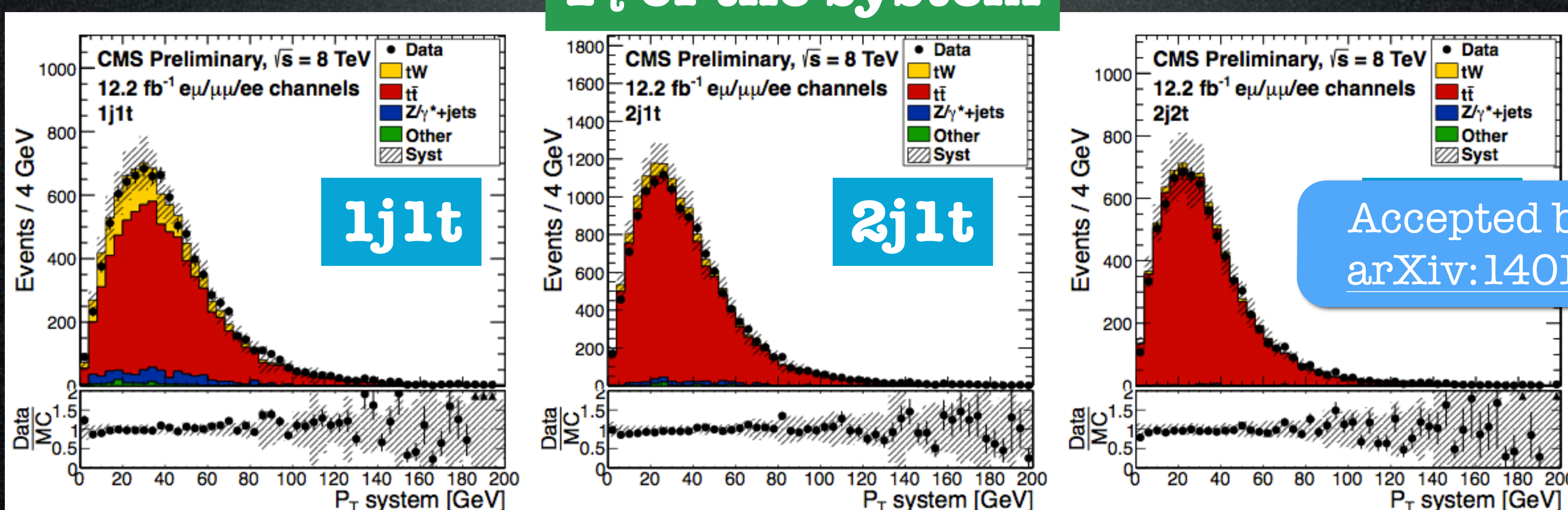
dilepton

- Sample input variable distributions in the control and signal regions:

Number of loose jets p_t > 20GeV



P_t of the system



Accepted by PRL
arXiv:1401.2942

tW Systematic Uncertainties

dilepton | 8 TeV | $12.2 fb^{-1}$

- Several sources of systematic uncertainties considered in both significance and cross-section estimate
- The 68%C.L. interval evaluated using profile likelihood
- Theory shape uncertainties estimated as the central value difference from value obtained setting nuisance parameters to +/-1σ
- Externalized in the significance calculation
- For other sources nuisance parameters fixed to central value and confidence level interval change used as estimate
- "Statistical" uncertainty from fixing all other sources to central value

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
ME/PS matching thresholds	3.25	14%
Q^2 scale	2.68	11%
Top quark mass	2.28	10%
Statistical	2.13	9%
Luminosity	1.13	5%
JES	0.91	4%
$t\bar{t}$ cross section	0.87	4%
Z+jet data/MC scale factor	0.56	2%
tW DR/DS scheme	0.45	2%
PDF	0.33	1%
Lepton identification	0.31	1%
JER	0.27	1%
B-tagging data/MC scale factor	0.20	$< 1\%$
$t\bar{t}$ Spin Correlations	0.12	$< 1\%$
Top Pt Reweighting	0.12	$< 1\%$
Event pile up	0.11	$< 1\%$
E_T^{miss} modeling	0.07	$< 1\%$
Lepton energy scale	0.02	$< 1\%$
Total	5.58	24%

Accepted by PRL
arXiv:1401.2942

tW Cross-check analyses

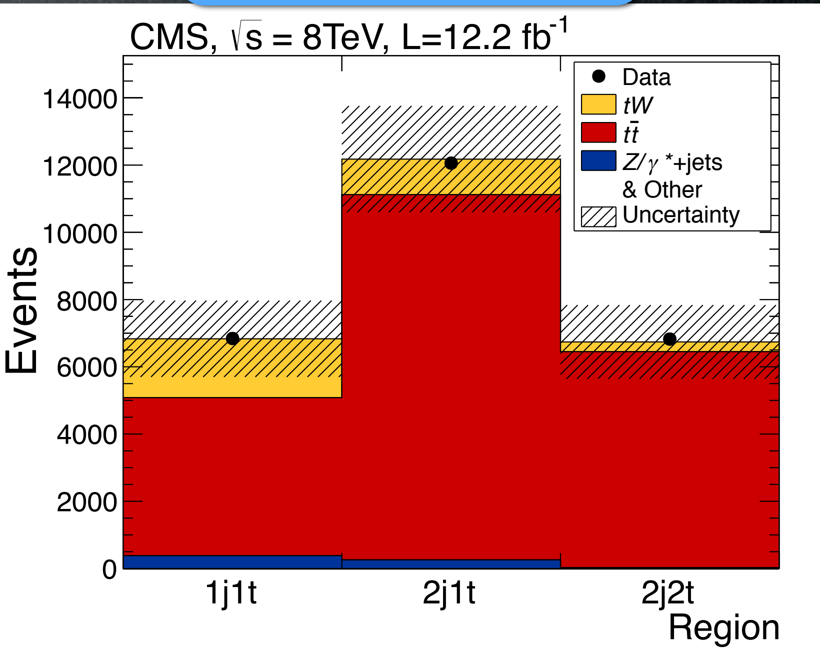
8 TeV

$12.2fb^{-1}$

dilepton

- Two cross-check analyses performed, using the same event selection and the same signal and control regions with the following exceptions:
- $p_{T,sys}$ Fit:
  - Veto extra btagged loose jets events
  - Cut on H_t in eμ channel (H_t>160GeV)
  - Same fit as BDT but to the $p_{T,sys}$ distribution
  - Results:
    - Observed significance **4.0** sigma
    - Expected significance $\mathbf{3.2^{+0.4}_{-0.9}}$ sigma
    - Cross section: **24.3 ± 8.6** pb
- Cut and Count:
  - Veto extra btagged loose jets events
  - Cut on H_t in eμ channel (H_t>160GeV)
  - Fit to the event counts only in each region
  - Results:
    - Observed significance **3.6** sigma
    - Expected significance **2.8 ± 0.9** sigma
    - Cross section: **33.9 ± 8.6** pb

Accepted by PRL
arXiv:1401.2942



tW Results

8 TeV

$12.2 fb^{-1}$

dilepton

- Significance estimated using binned likelihood fit with pseudo-experiments (lots of them!):
  - Excess of events with respect to the background-only hypothesis
  - Observed significance in $12.2\ fb^{-1}$ of 8 TeV data: **6.1 σ**
  - Expected significance from MC: **5.4 ± 1.4σ**
- Cross-section estimated using profile likelihood:
  - **σ_{tW} = 23.4 ± 5.4 pb at 8TeV**
  - Theoretical value (m_{top}=173GeV):
    - σ_{tW} = 22.2 ± 0.6(scale) ±1.4(PDF) pb

Accepted by PRL arXiv:1401.2942

(Approximate NNLO) N. Kidonakis arxiv.org/pdf/1210.7813 (2012)

- V_{tb} matrix element estimate ($|V_{tb}|>>|V_{td}|,|V_{ts}|$ and $f_{Lv}=1$):
  - $$|V_{tb}| = \sqrt{\frac{\sigma_{tW}}{\sigma_{tW}^{th}}} = 1.03 \pm 0.12(exp.) \pm 0.04(th.)$$
  - $|V_{tb}|>0.78$ at 95% C.L. ($0\leq|V_{tb}|^2\leq1$)

Single top s-channel

L+jets | 8 TeV | 19.7fb^{-1}

- BDT analysis still not very sensitive (main systematics model uncertainties):
  - Expected significance: 0.9 sigma
  - Observed significance: 0.7 sigma
- Cross-section measurement:

CMS PAS TOP-13-009

$$\sigma_{\text{s-ch.}} = 6.2 \pm 5.4(\text{exp.}) \pm 5.9(\text{th.}) \text{ pb} = 6.2 \pm 8.0 \text{ pb}$$

- Theory prediction (NLO+NNLL order) at 8Tev:

$$\sigma_{s-\text{ch.}} = 5.55 \pm 0.08(\text{scale}) \pm 0.21(\text{PDF}) \text{ pb}$$

arXiv: 1205.3453

- Assuming Standard Model signal, Feldmann-Cousin confidence level interval is derived:

$$\sigma_{\text{s-ch.}} = 6.2^{+8.0}_{-5.1} \text{ pb}$$

- Upper limit on s-channel cross-section calculated with Bayesian approach 11.5 pb (95%C.L.)

Single top cross-sections

- Summary from CMS single top production analyses: