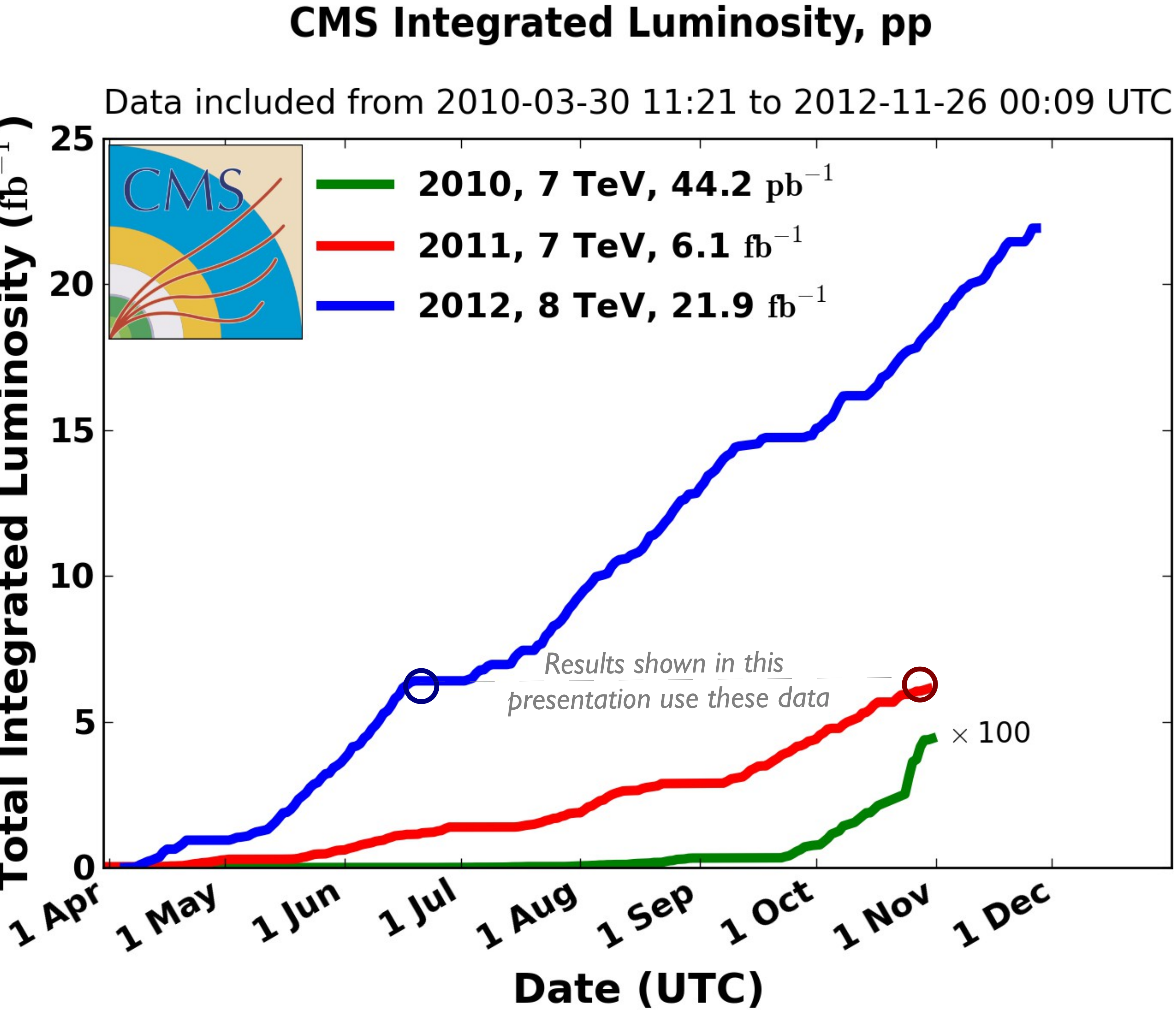
Measurements of the top-quark mass and production cross section at CMS

Pedro Ferreira da Silva (CERN/LIP)

DISCRETE 2012

3rd December 2012

CFTP Instituto Superior Técnico, Lisboa



Results shown in this presentation use these data

Top quark pairs

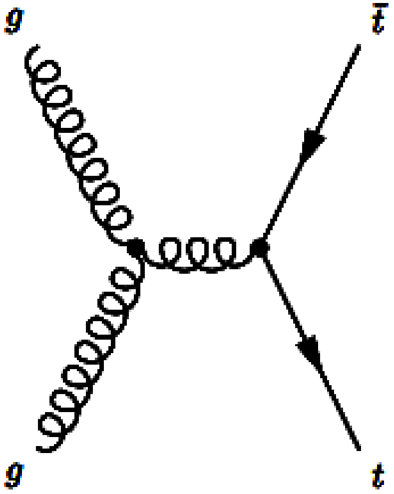
4.3×10^6

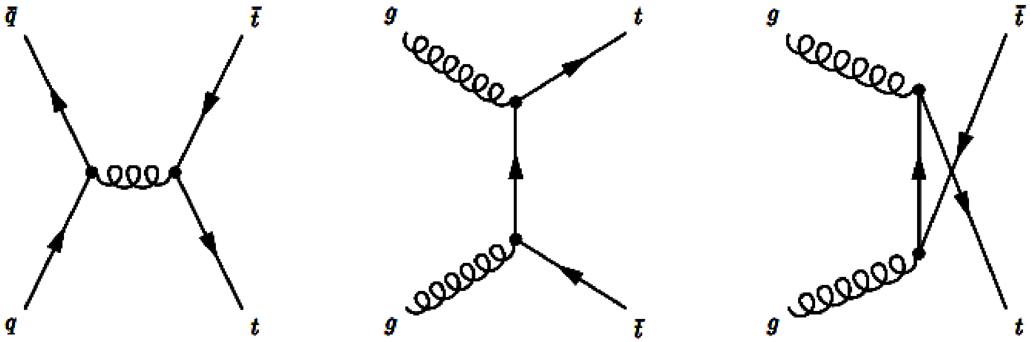
0.99×10^6

5.9×10^3

At the LHC we can learn a lot from the following process

QCD top quark pair production





163^{+11}_{-10} pb @ 7 TeV

$234^{+10}_{-7} \pm 12$ pb @ 8 TeV

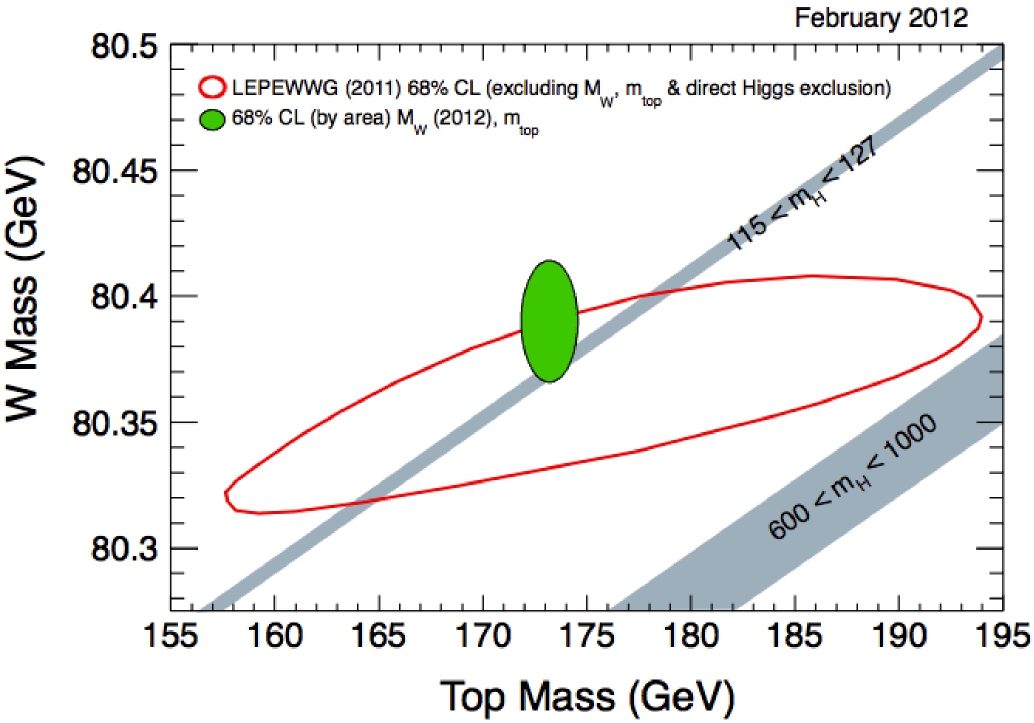
Kidonakis, PRD 82 (2010) 114030
Langenfeld, Moch, Uwer, PRD 80 (2009) 054009
Kidonakis, arXiv:1205.3453.

- Production rate
- Production environment

How precise are top predictions @ the LHC?

- Unique role in EWK symm. breaking ▶
    - measure fundamental th. parameters
    - look for deviations/signs of new physics

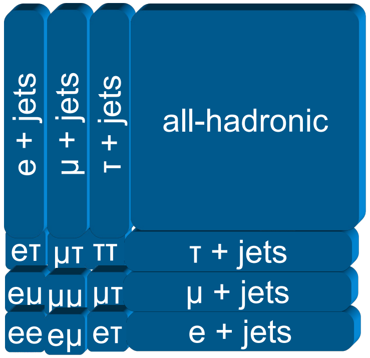
Strong coupling constant, top mass, etc.

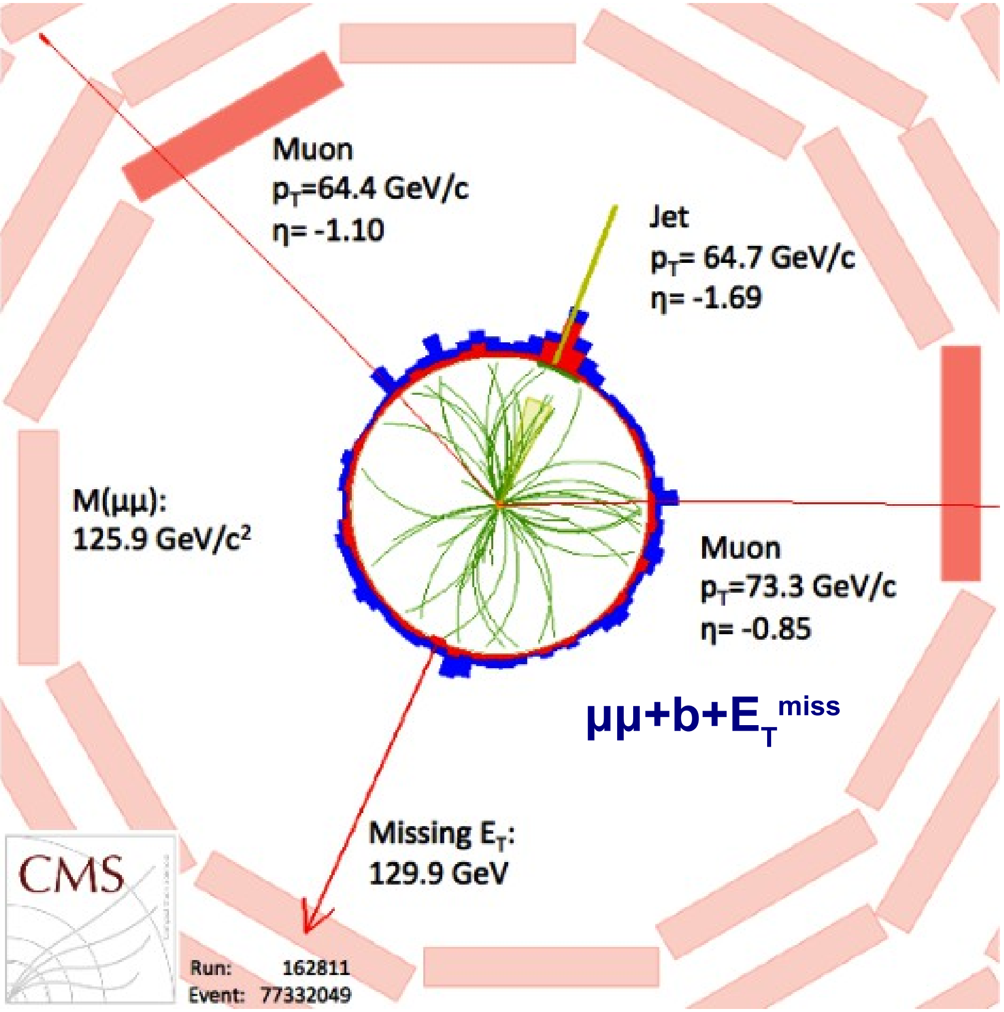


Selecting top quarks at CMS

for an overview of CMS results see J.Varela @ plenary session

We identify top(s) through its main decay: t → Wb ▶





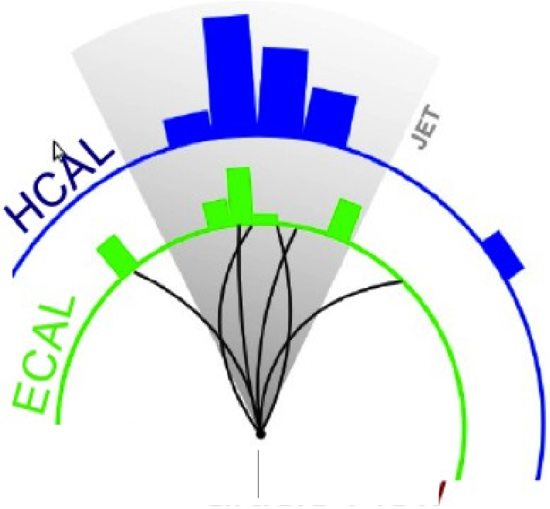
- **Trigger**
  - Single/double (isolated) leptons
  - and/or based on hadronic activity
- **Jets**
  - Anti-k_T algorithm with R=0.5
  - p_T>20 GeV |η|<2.5-4.5 (analysis dependent)
  - b-tagging (optional)
- **Leptons (e,μ,τ) with p_T>20 |η|<2.5**
  - Isolation in tracker and calorimeters
  - Reconstruction quality, i.e. ID
    (number of hits, χ^2, conversion veto, etc.)
- **Missing transverse energy (E_T^{miss})**
  - Requirement is optional
  - Ranging from 20 to 60 GeV

CMS PAS PFT-10-002, JINST 6 (2011) 09001

Global event description approach

- **Charge-based separation** of components making best use of:
  - **field integral** $B \times R = 4.9\ \mathrm{T \cdot m}$
  - **calorimeter granularity** $\Delta\eta \times \Delta\phi|_{\mathrm{ECAL}} \sim 0.017^2$

    $\Delta\eta \times \Delta\phi|_{\mathrm{HCAL}} \sim (5 \cdot \Delta\eta) \times (5 \cdot \Delta\phi)|_{\mathrm{ECAL}}$
  - **iterative tracking** (progressively relaxing constraints/removing hits)
  - After linking sub-detector elements → **particle candidates**

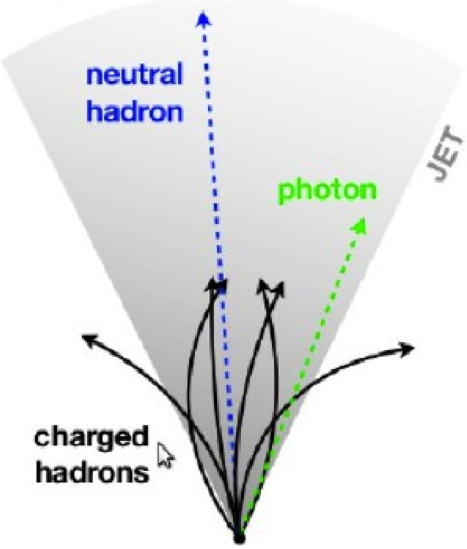


Particle flow

▼

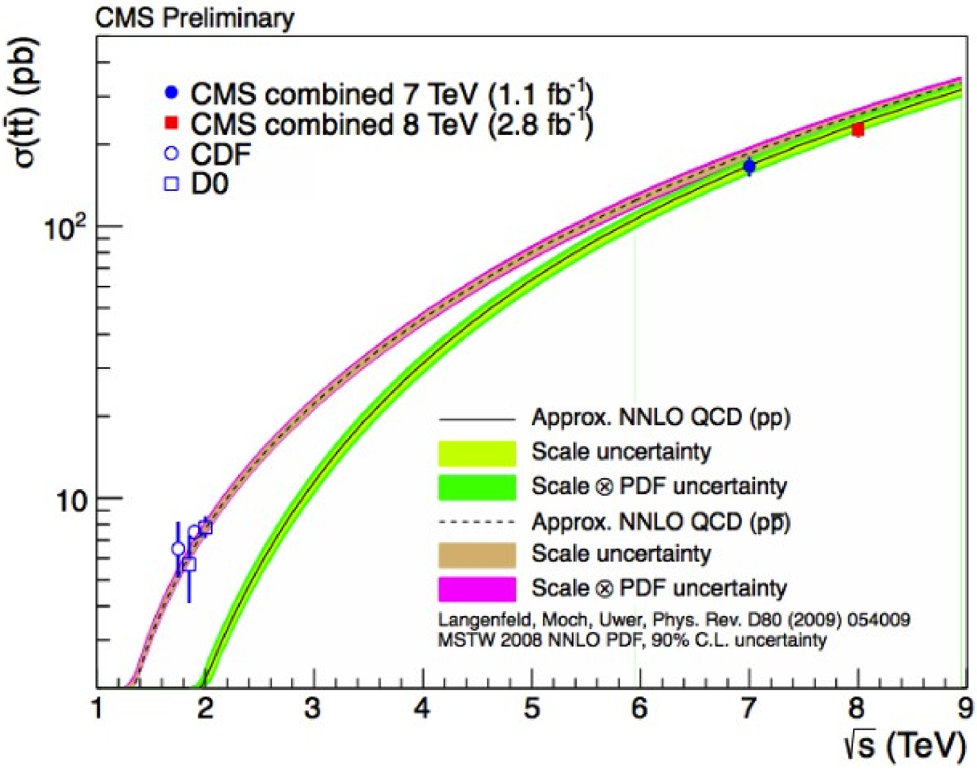
- Particle flow yields a **global description of each event**
- A reconstructed jet is "again" a cluster of particles ▼

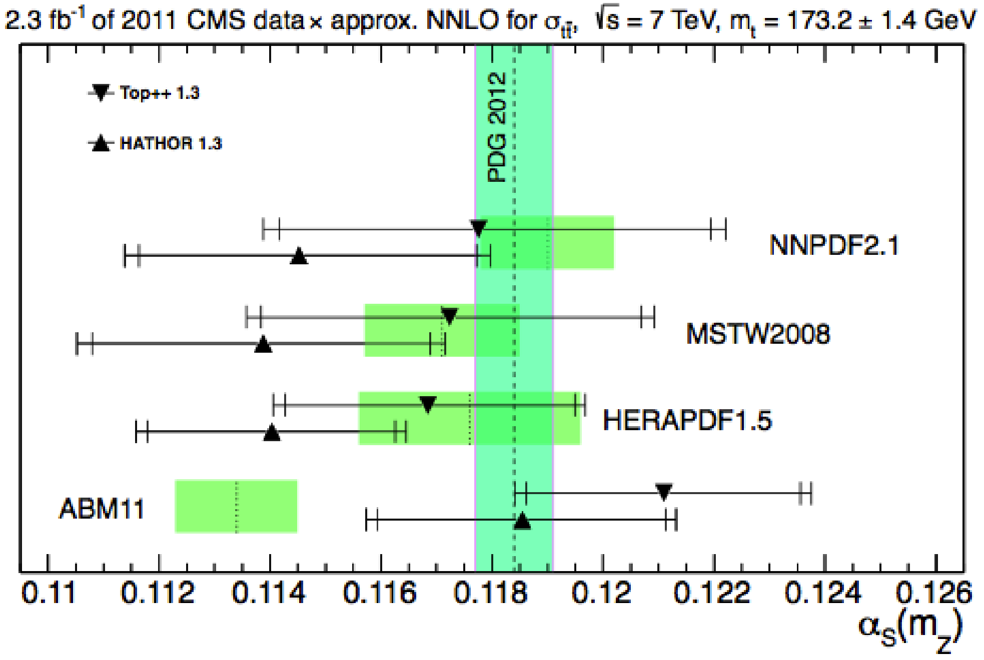
Algorithm	Calorimeter-based	Particle Flow		
Composition	Towers	Charged Hadrons	Photons	Neutral hadrons
Energy fraction	100%	65%	25%	10%
Energy	$E_{HCAL} + E_{ECAL}$		$\sum_{k=h^\pm,h^0,\gamma,\ell} E_k$	
Resolution (σ)	$120\%\ \sqrt{E}$	$1\%\ p_T$	$1\%\ \sqrt{E}$	$120\%\ \sqrt{E}$
Direction	biased by $\vec{B}$	vertex-based	good resolution	-



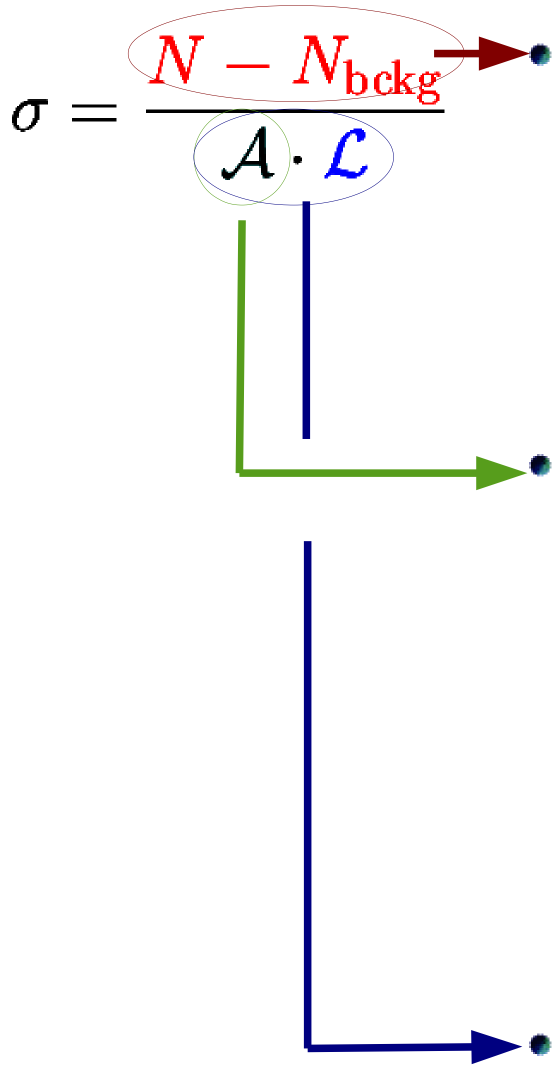
  - **crucial for b-jets** (e.g. reduce material budget uncertainty on energy scale)
  - crucial for **missing transverse energy resolution** ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = -\sum_{k=h^\pm,h^0,\gamma,\ell} \vec{p}_{\mathrm{T},k}$)

Cross section measurements





Ingredients for a precise measurement of the cross section



$$\sigma = \frac{N - N_{\mathrm{bckg}}}{\mathcal{A} \cdot \mathcal{L}}$$

High statistics and low background channels

- Leptons (e or μ) in final state yield efficient rejection of multijets background
- **e/μ+jets**: high statistics, limited backgrounds (W+jets and QCD multijets)
- **ee/eμ/μμ**: low statistics and low background (mostly Drell-Yan and dibosons)
- <u>Establish the cross section in all channels</u>: combination yields ultimate precision

Characterization of our signal

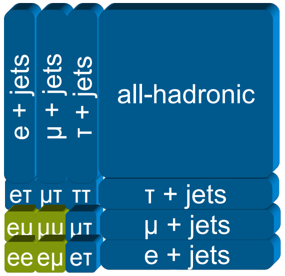
- **Madgraph** (LO) models **top pair** production: matrix element approach for the generation of up to 3 jets interfaced with Pythia for showering. Powheg (NLO) is used for single top. *(Note: Different generators are compared for both)*
- **Main unknowns are:** factorisation/renormalization scale – **Q^2**, **jet-parton matching scale** and **top mass**
  → <u>"educated guesses" are also constrainable from data</u>
  - Hadronization/b-jet uncertainties included in the jet energy uncertainty
  - ISR/FSR variations included in Q^2 uncertainty

Detector uncertainties

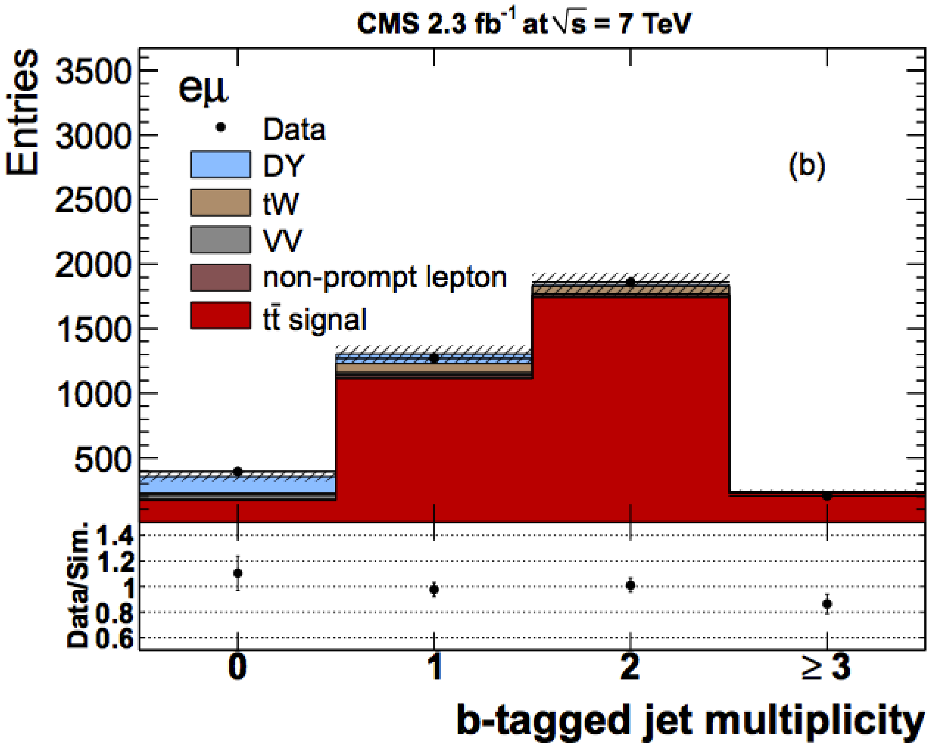
- jet energy scale/resolution, b-tag efficiency, trigger/selection efficiency
- luminosity normalization (2.2% at 7 TeV / 4.4% at 8 TeV)

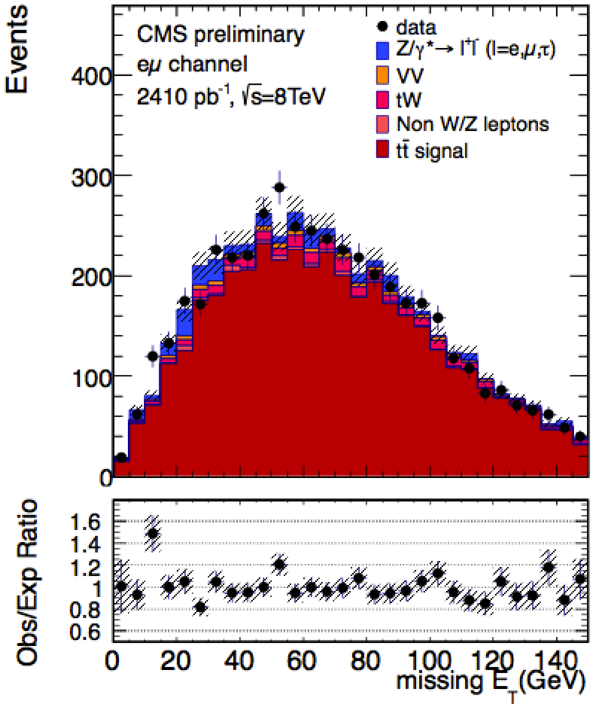
arXiv:1208.2671, *submitted to JHEP*, **TOP-12-007**

Dilepton analysis: most precise



- **Cleanest signature**, main background from:
    - **Drell-Yan** (Z-window is vetoed in ee/μμ and used to rescale DY contribution)
    - **Single top-tW** and dibosons (from MC)
    - Residual **fake leptons** (controlled from sidebands using fake rate/efficiency)
- **Almost background-free even without requiring b-tags or E_T^{miss}**





- Cross section extracted using a profile likelihood ratio method or cut and count

Uncertainties in dilepton analysis

Results

7 TeV

$161.9 \pm 2.5_{\mathrm{stat}} \; {}^{+5.1}_{-5.0}\,_{\mathrm{syst}} \pm 3.6_{\mathrm{lumi}}$ pb

4.2%

8 TeV

$227 \pm 3_{\mathrm{stat}} \pm 11_{\mathrm{syst}} \pm 10_{\mathrm{lumi}}$ pb

6.7%

- Comparing uncertainties for cut and count ▶
  - final unc. at 7 TeV reduced with profile likelihood
- Main uncertainties:
  - **instrumental** (jet energy scale, luminosity)
  - 0.8% uncertainty on **BR(W→lν$_l$)**
  - **Irreducible background** – tW
- **Dependency on top mass** derived at 7 TeV

$$\frac{\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}(m_t = 172.5)} = 1.00 - 0.008 \cdot (m_t - 172.5) - 0.000137 \cdot (m_t - 172.5)^2$$

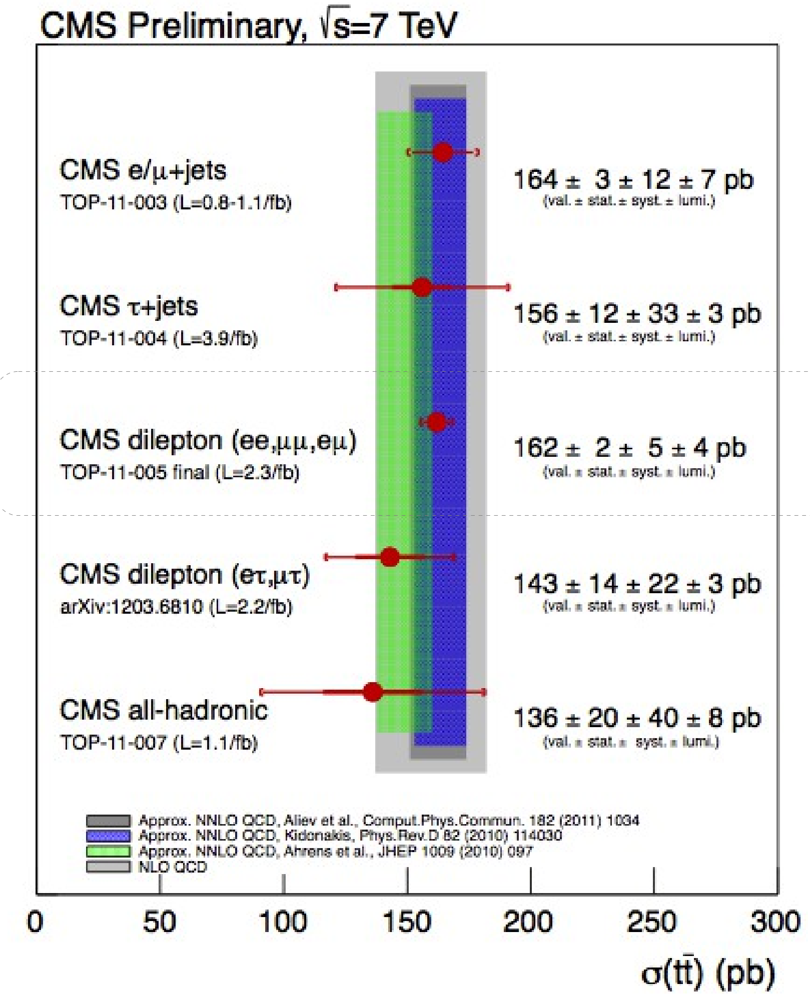
- using the current world average: $161.3 \pm 2.5_{\mathrm{stat}} \; {}^{+5.3}_{-5.2}\,_{\mathrm{syst}} \pm 3.6_{\mathrm{lumi}}$ pb → *4.3% uncertainty*

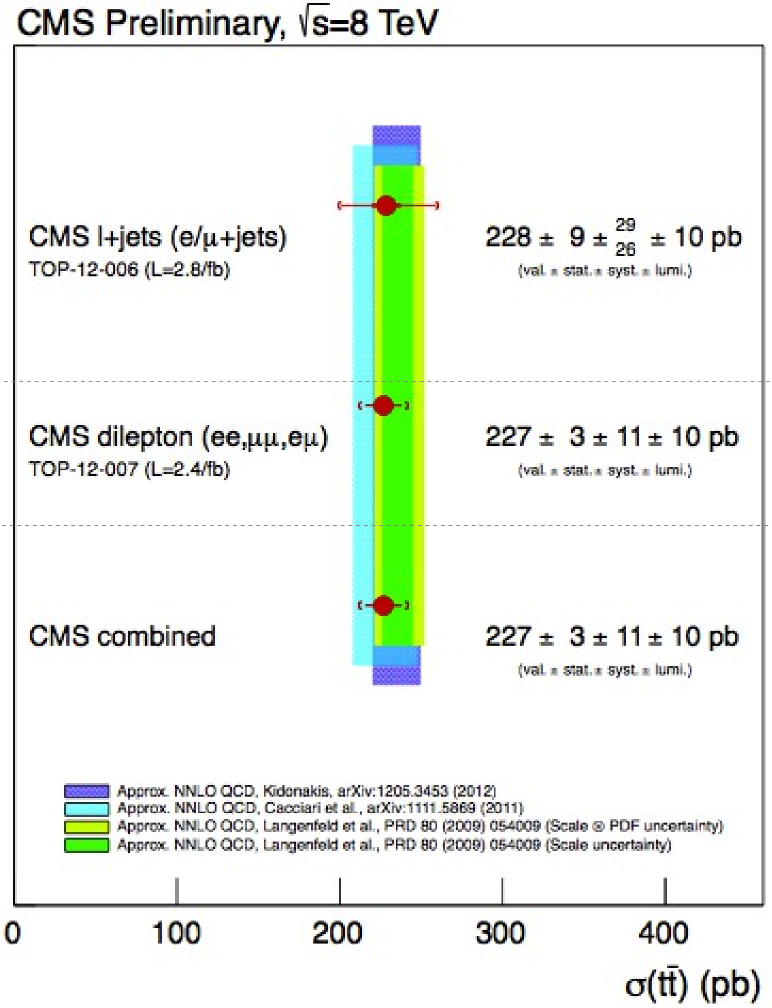
Source	$\Delta\sigma_{t\bar{t}}$ (%) from **7 TeV**	**8 TeV**
Di-bosons	0.4	0.1
Single top - tW	2.3	1.0
Non W/Z leptons	0.6	1.4
Drell–Yan	1.0	0.7
Lepton efficiencies	1.7	1.8
Lepton energy scale	0.5	0.3
Jet energy scale	2.8	2.5
Jet energy resolution	0.5	1.7
E_T^{miss}	1.9	-
b-tagging	1.1	0.9
Pileup	0.7	1.5
Branching ratio	2.7	1.7
Q^2	1.0	0.7
ME-PS scale	1.0	0.7
Total	**5.6**	**4.7**

CMS PAS-TOP-11-024, CMS PAS TOP-12-007

Current word from CMS on σ_{tt}

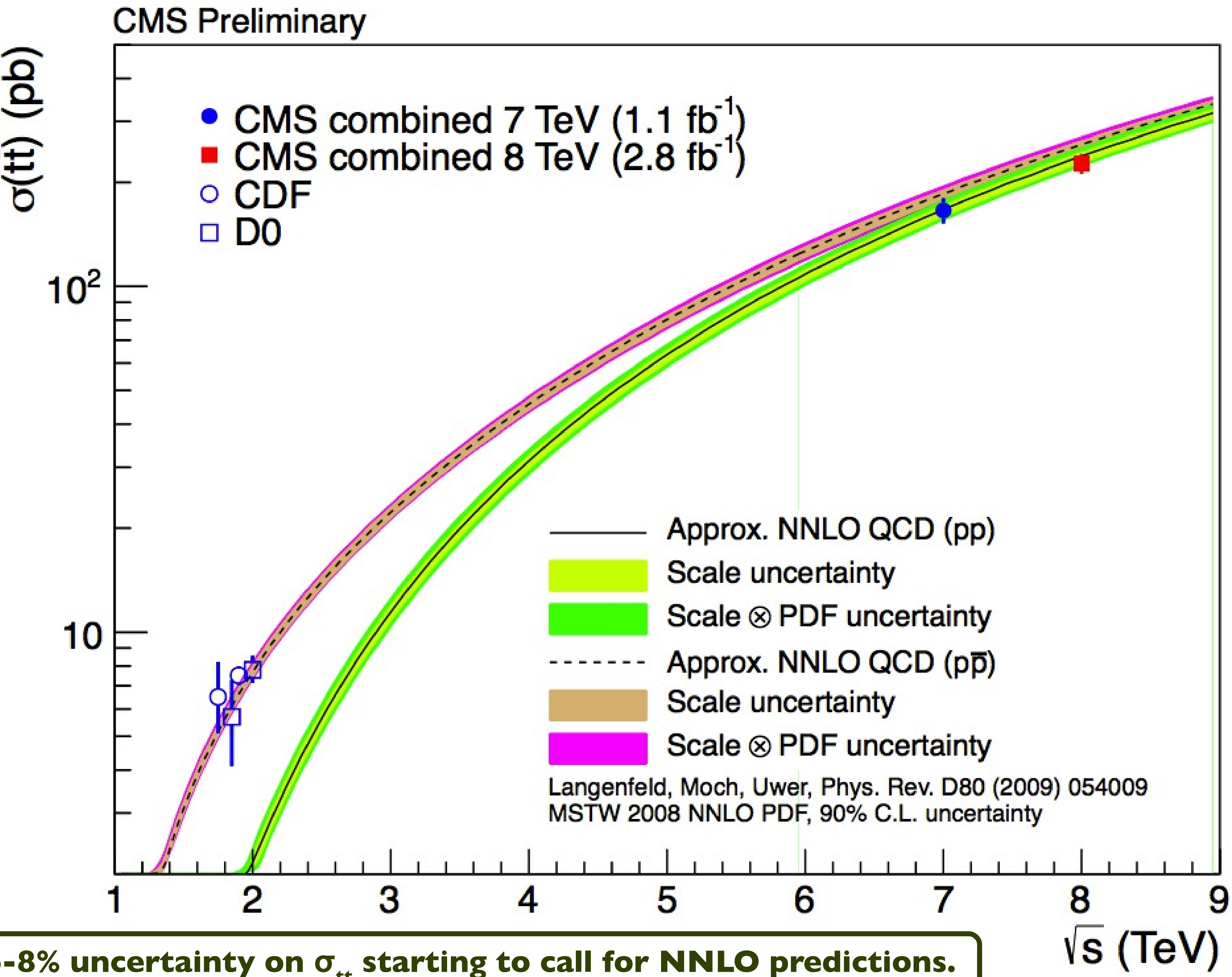
- **Full combination** (@ 8 TeV) is performed using a **binned maximum likelihood fit**
  - Add uncertainties as scale factors affecting rates (nuisance parameters)
  - Link common uncertainties to all channels with the same nuisance (100% correlation)
- **Excellent agreement** between different channels and **with theoretical predictions**





$R_{8/7} = 1.41 \pm 0.10$

assuming fully correlated exp. uncertainties



6-8% uncertainty on σ_{tt} starting to call for NNLO predictions.

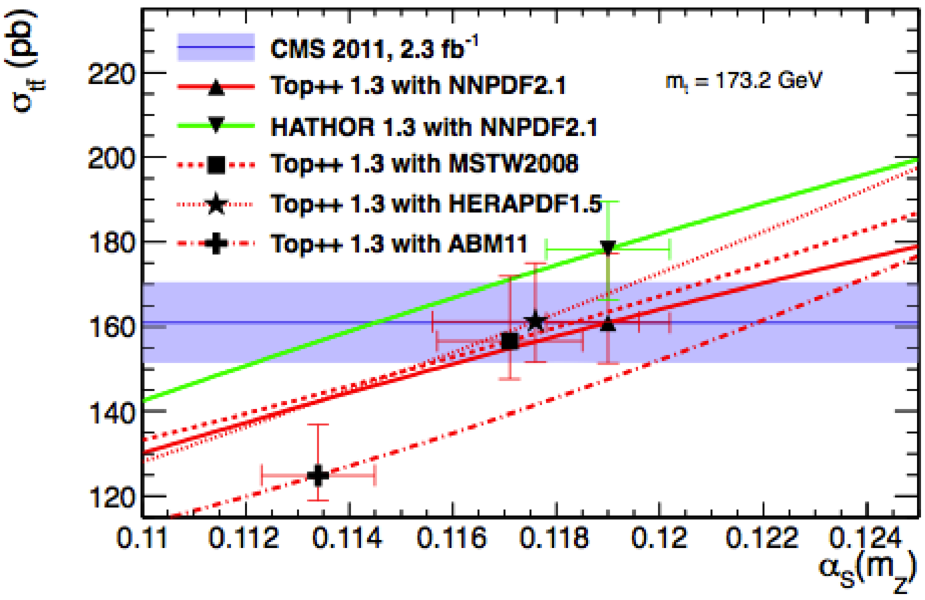
...and current word from CMS-σ_{tt} on

Coupling of strong interactions

m_{top} and α_s can't be determined simultaneously from σ_{tt} → constrain one when measuring the other

$$\mathcal{L}(x) = \int d\sigma \; \underbrace{f_{\mathrm{exp}}(\sigma_{t\bar{t}}|x)}_{\text{Experimental measurement (gaussian)}} \; \underbrace{f_{\mathrm{th}}(\sigma_{t\bar{t}}|x)}_{\text{PDF uncertainty convolved with rectangular “prior” on } Q^2 \text{ scale}} \qquad x = \alpha_S \text{ or } m_t$$

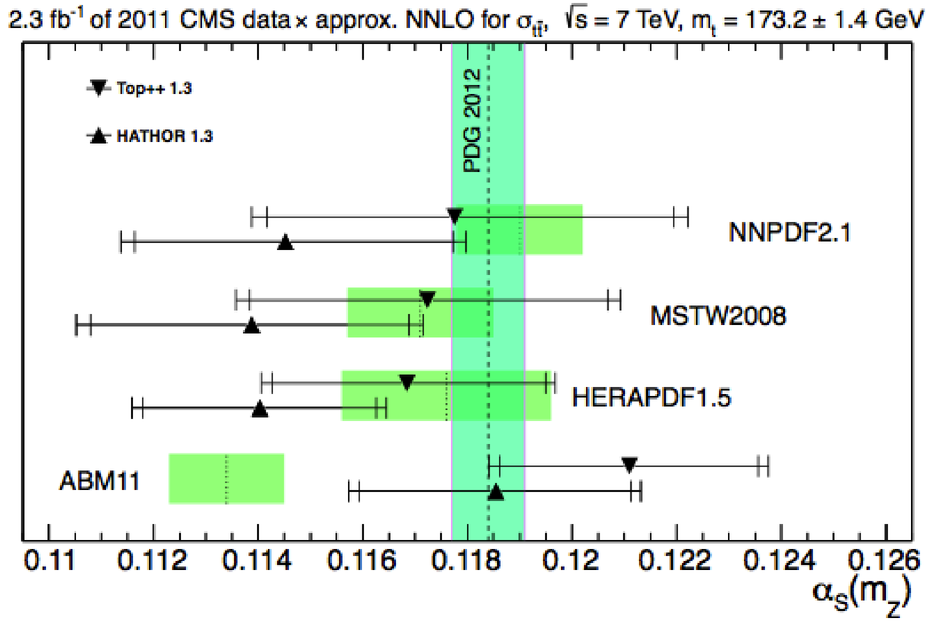
- $\sigma=\sigma(\alpha_s)$ is determined **from Top++** and **HATHOR** with different PDFs



- **Good agreement with world average**

Result

$$\alpha_S(m_Z) = 0.1178^{+0.0046}_{-0.0040}$$ *Top++ with NNPDF2.1*

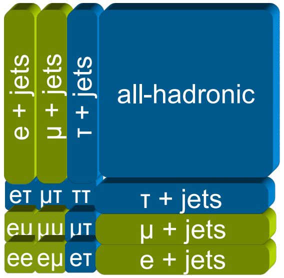


arXiv:1211.2220, *submitted to EPJC*

Testing pQCD differential measurements

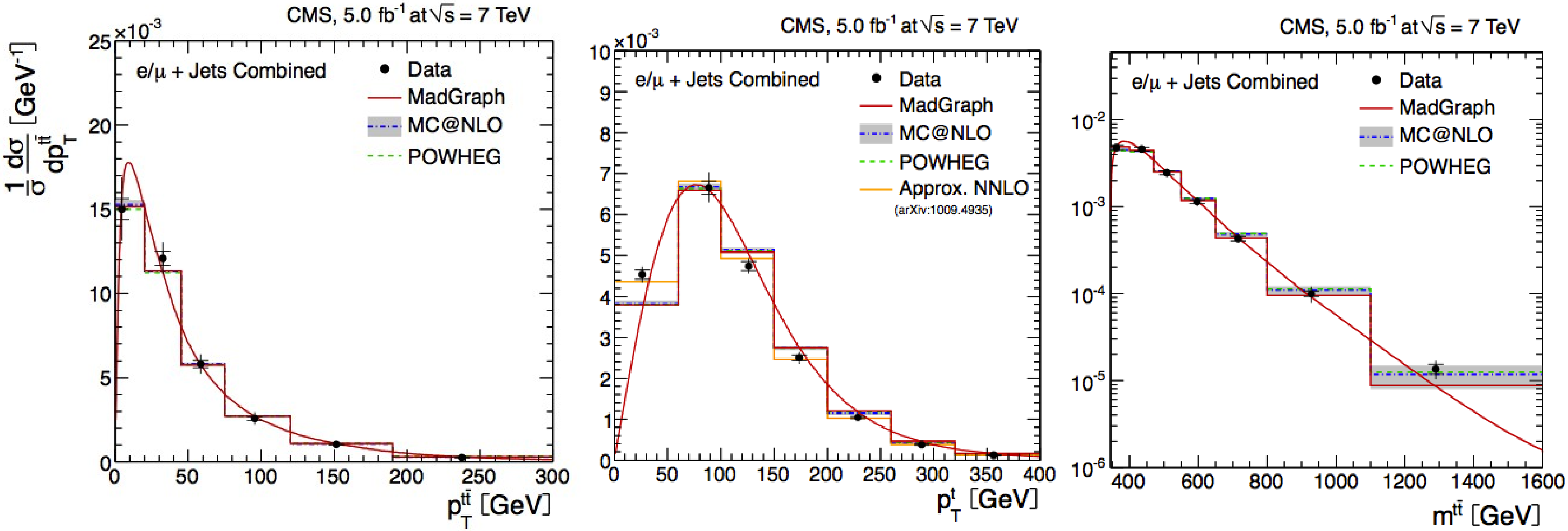
- Measurement of **differential cross-sections**

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



- Kinematics are reconstructed using different methods
  - after constrained fit (l+jets)
  - by prioritizing b-tagged jets and most probable neutrino energies for $100<m_t<300$ GeV/c^2 (dilepton)
  - Unfold after background reconstruction kinematics of: single objects (leptons, jets), top quarks, top pair

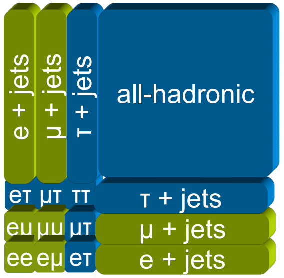
Different generators yield fair description of the data in different channels
Approx. NNLO computation yields best description of top kinematics

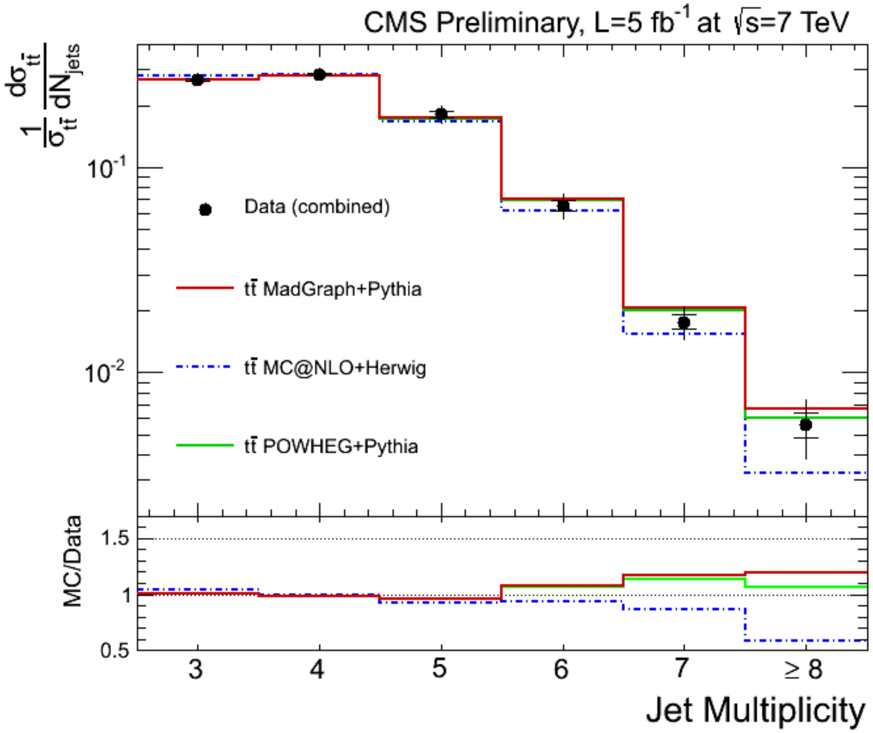


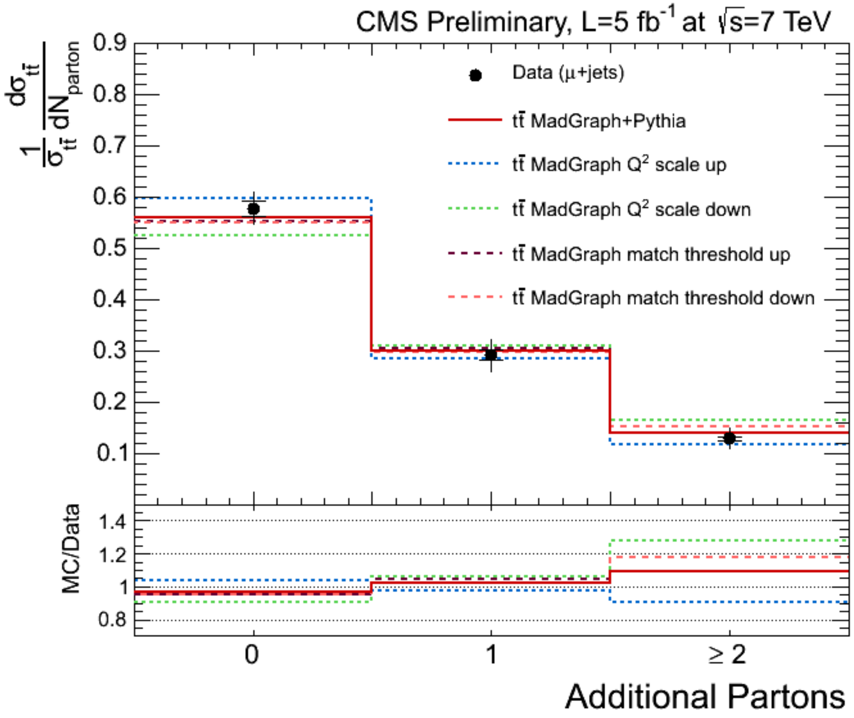
Testing pQCD from jet activity

- How dependent is the signal modeling on pQCD parameters: Q^2, ME-PS matching, generator?
- Obtain **pure distributions for tt**
  - Fit the tt+N partons contributions from the reconstructed kinematics χ^2
  - or subtract the backgrounds to jet multiplicity distributions

  (unfolding is applied for the dilepton case – next slide)







▲ Higher Q^2 tends to describe better multiplicity and gap fraction

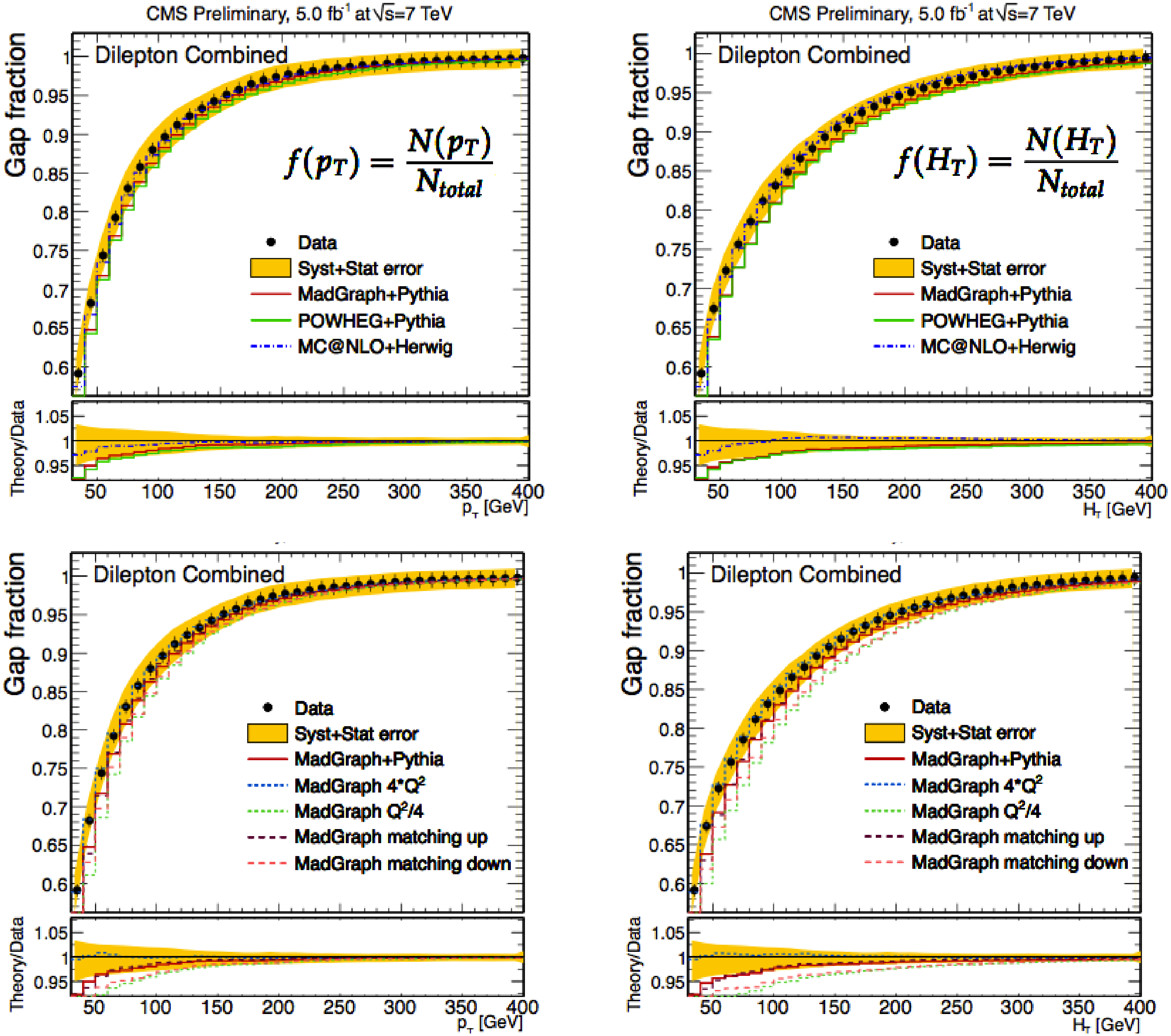
Unc.: 3%-20% (low → high mult.) dominated by jet energy scale / model params.

Madgraph/Powheg+Pythia describe better higher multiplicities rate observed in data

CMS PAS TOP-12-023

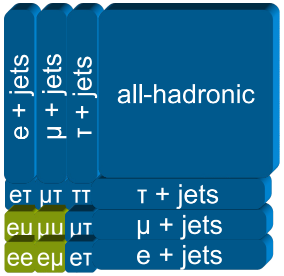
Gap fraction in dilepton events

- Gap fractions vs **different generators**
  - MC@NLO+Herwig better description of gap fractions but poorer description of high jet multiplicities
- Gap fractions vs **different Madgraph parameters**
  - Data tends to indicate prefence for higher Q^2
  - Educated guess for the variation of the parameters in CMS matching exp. uncertainties



Associated production with two b's

NEW



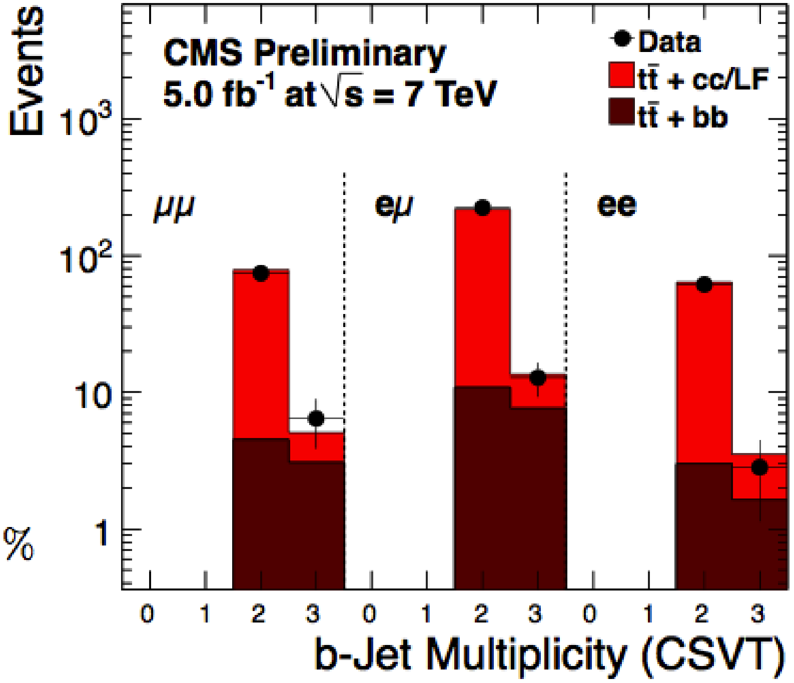
- The **ratio of tt+2 jets to tt+2 b jets** is measured
  - ratio allows for cancellation of many uncertainties
  - **784 dilepton events with two jets and at least two b-tags** are selected in data
  - cleaner environment to study heavy flavor content of top pair sample
- Main challenges:
  - Experimental side: *how well do we know b-tag efficiency and rate for b's from gluon splitting? mistag rate for light?*
  - Theory side: *how important is npQCD? We have defined signal at particle level from jets with* p_T*>20 GeV* ΔR_{jj}*>0.5*
- Mistag rate for light flavours known to ~10% dominates final uncertainty

Source	$\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ (%)	
	Medium b-tagging	*Tight b-tagging*
Pileup	0.5	0.5
Jet energy scale	3.0	2.0
b-tag efficiency	6.0	4.0
mistag efficiency	+23 -19	+18 -15
MC generator	3.0	3.0
Q^2	6.0	6.0
Total	**+25 -21**	**+20 -17**

Results

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

$$\frac{\sigma_{t\bar{t}b\bar{b}}}{\sigma_{t\bar{t}jj}}\Big|^{\mathrm{Madgraph}}_{\mathrm{LO}} = 1.2\%$$



Top quark mass

Measurements which build up on knowledge

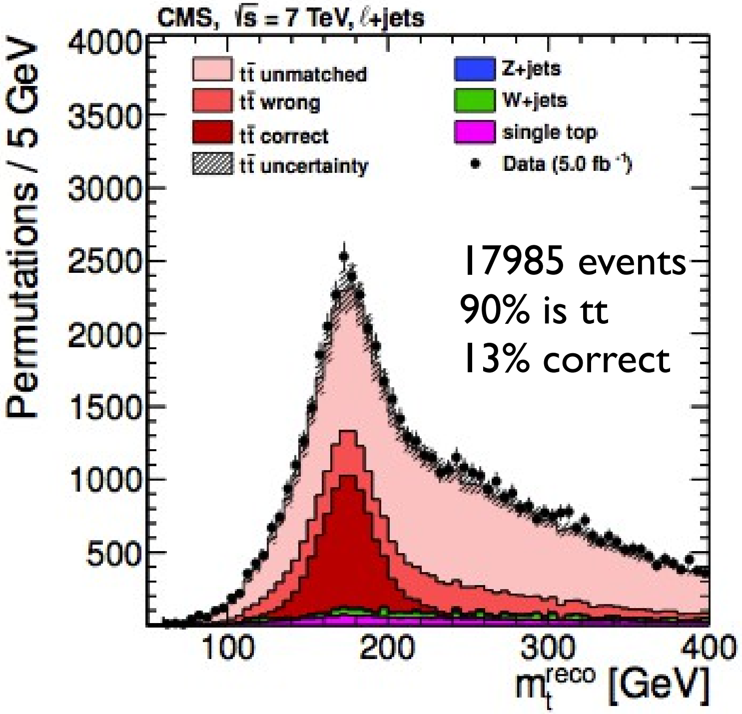
from our detector and top cross section studies.

The importance of being top or anti-top: mass difference

arXiv:1209.2319, *submitted to JHEP*

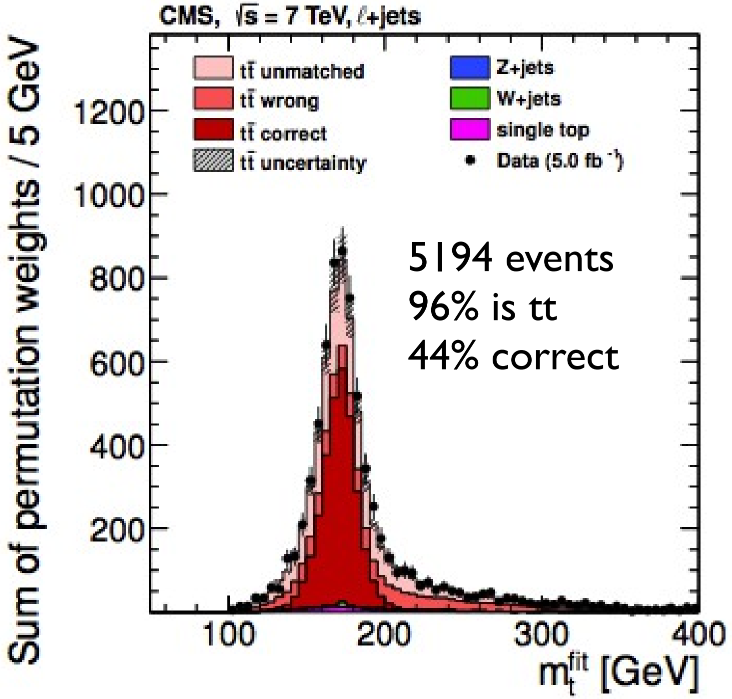
Lepton+jets measurements

- **In-situ calibration of the light quark JES from W→ qq' leg**
- After requiring b-tag the purity of the events is very high
- Kinematics fitter is used to evaluate possible combinations → assign weight $P_{\rm gof}(\chi^2) = \exp\left(-\frac{1}{2}\chi^2\right)$



17985 events
90% is tt
13% correct

$$\xrightarrow[P_{\rm gof}(\chi^2)>0.2]{\text{Kinematic fit}}$$



5194 events
96% is tt
44% correct

Ideogram method

$$\boxed{\mathcal{L}\left(m_t, \mathrm{JES}|\mathrm{sample}\right) \propto \prod_{\mathrm{events}} \left(\sum_{i=1}^{n} c\, P_{\mathrm{gof}}(i)\, P\left(m_{t,i}^{\mathrm{fit}}, m_{W,i}^{\mathrm{reco}} | m_t, \mathrm{JES}\right)\right)^{w_{\mathrm{event}}}}$$

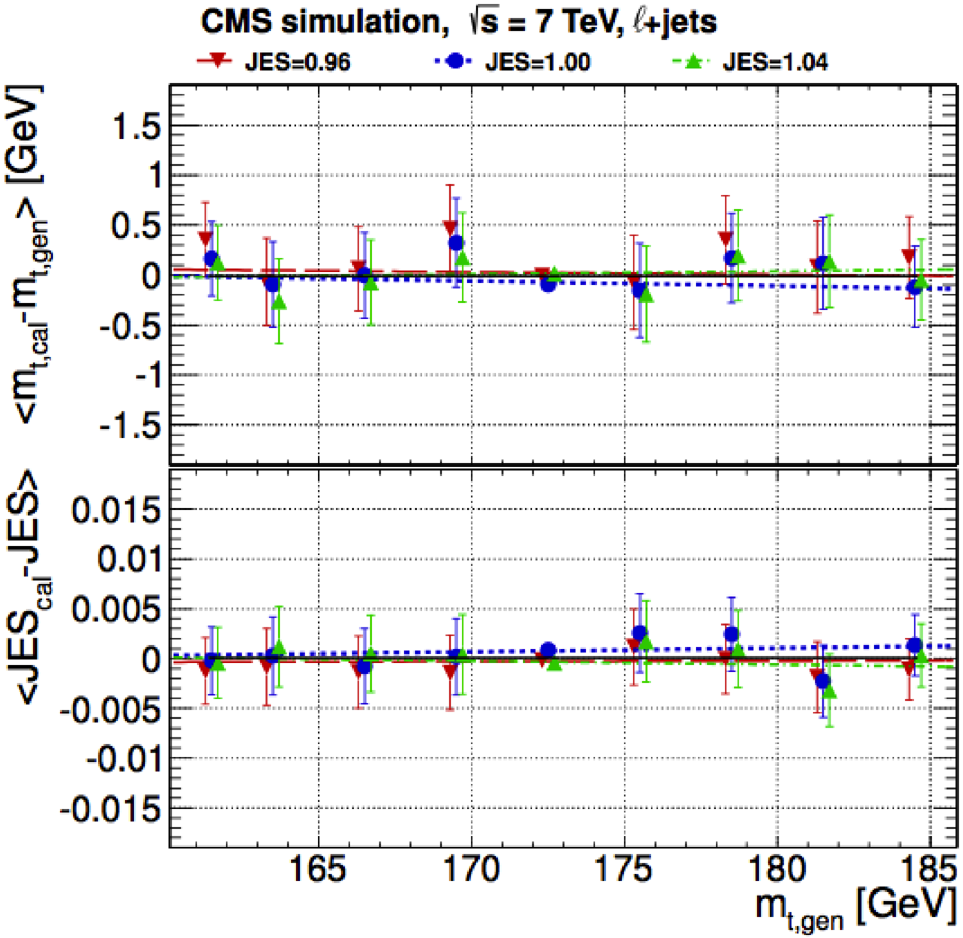
from kinematics fit

composed from correct, wrong,
unmatched and background permutations

left to float
free in the fit

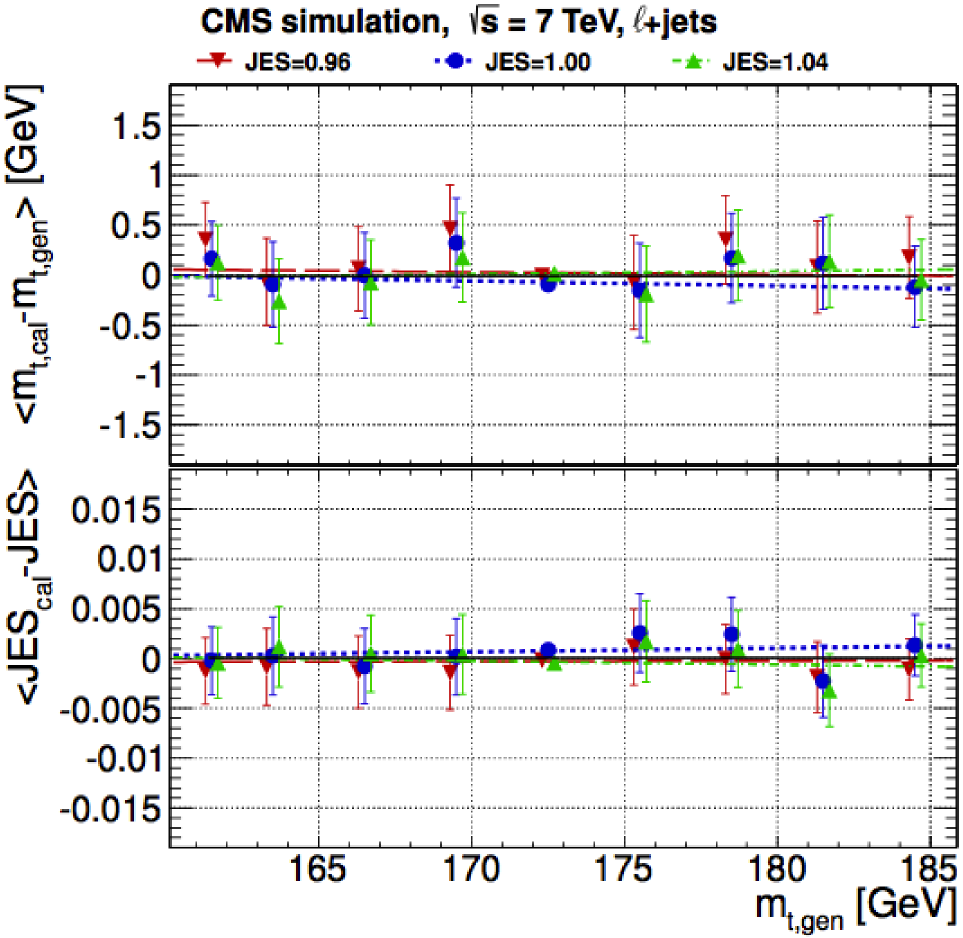
Calibration

- Simulated pseudo-experiments are used:
  - scan m_{top} and JES scenarios (27 points)
  - calibrate / assess the bias and coverage
  - small corrections to nominal fit (<0.5 GeV)



Calibration and results

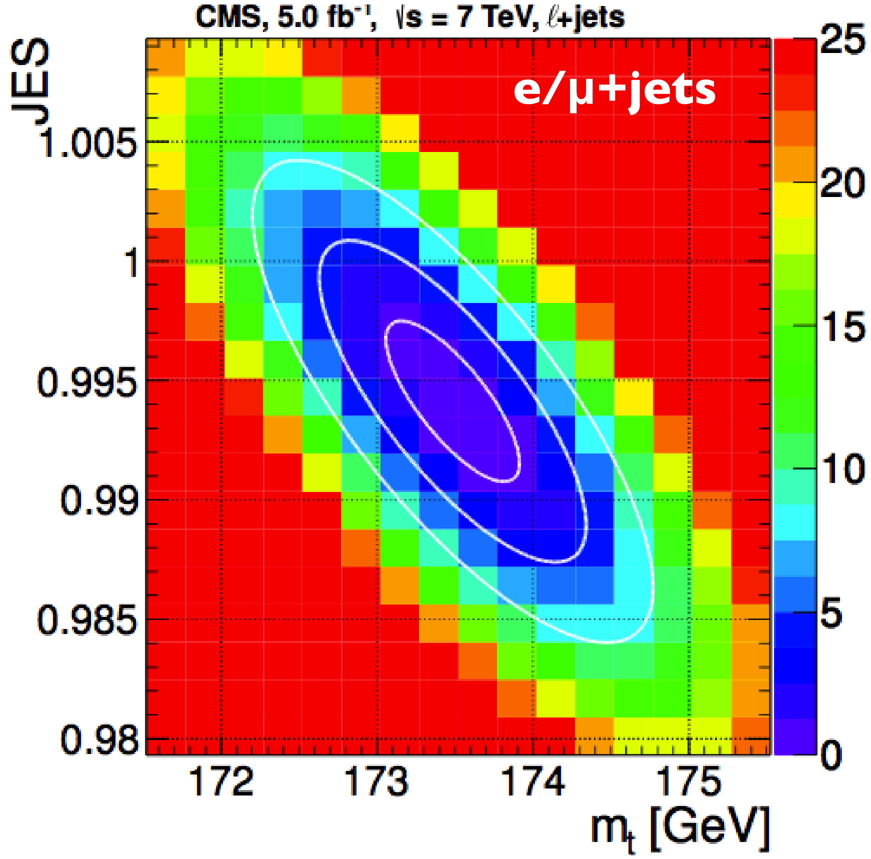
- Simulated pseudo-experiments are used:
  - scan m_{top} and JES scenarios (27 points)
  - calibrate / assess the bias and coverage
  - small corrections to nominal fit (<0.5 GeV)



- Calibration is used to correct the data fit:
  - result self-consistent between channels
  - nominal jet energy scale is validated in-situ

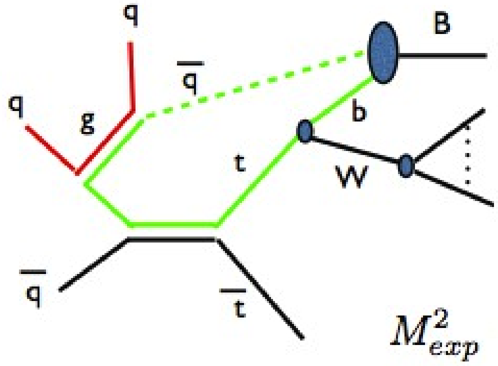
stat. unc. only

Channel	μ+jets	e+jets
m_{top} (GeV)	173.22 ± 0.56	173.72 ± 0.66
JES	0.999 ± 0.005	0.989 ± 0.005



Systematic uncertainties

- **Jet energy scale/resolution**
  - Light JES is calibrated in-situ but expect 2 b-jets in the final state → flavor uncertainty
  - Residual p_T and η dependency to take into account deviations from flat JES fit from data
- **Other instrumental effects**: b-tagging, E_T^{miss} scale, pileup, lepton energy scale
- **Underlying event and colour reconnection**
  - Z2 is the default UE tune for CMS at 7 TeV
  - Perugia2011 tunes are used for variations (direct comparison with ATLAS)
  - CR is compared within Perugia2011 variations (100% variation)
  - Note: tuning in the presence of ME-PS matching is a new field



- **Signal modeling**
  - Q^2 variation addresses two aspects
    - renormalisation & factorisation scale uncertainties - **ME**
    - amount of initial- and final-state radiation - **ISR/FSR**
  - ME-PS tuning: critical parameter for the contribution from soft and collinear showers (Pythia-based)
  - Hadronization related uncertainties are covered by Q^2 and jet energy scale variations
- **Other theoretical uncertainties**: PDF, background contribution

Note: final error is related to the m_{top} measured → careful theoretical interpretation is needed

Results in lepton+jets

Systematic uncertainty	Δm_{top} [GeV]
Calibration	0.06
b-JES	0.61
p_T- and η-dependent JES	0.28
Lepton energy scale	0.02
Missing transverse energy	0.06
Jet energy resolution	0.23
b-tagging	0.12
Pile-up	0.07
Non-$t\bar{t}$ background	0.13
PDF	0.07
μ_R, μ_F	0.24
ME-PS matching threshold	0.18
Underlying event	0.15
Color reconnections	0.54
Total	**0.98**

Results – best in lepton+jets

$$m_{\mathrm{top}} = 173.49 \pm 0.43_{\mathrm{stat+JES}} \pm 0.98_{\mathrm{syst}}\ \mathrm{GeV}$$

EPJC 72 (2012) 2202

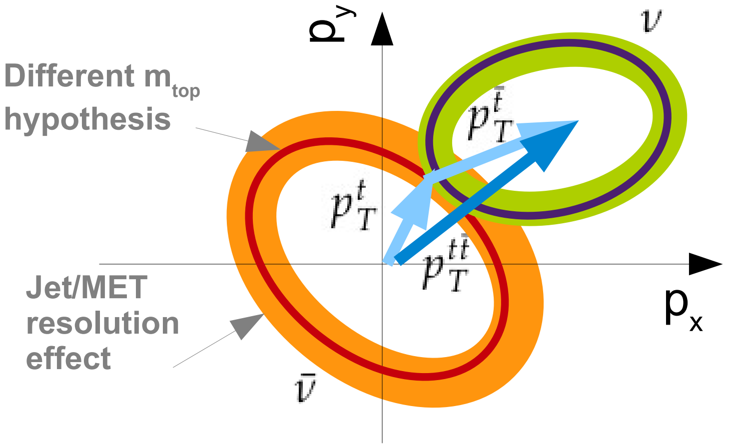
Dilepton mass measurement

- One degree of freedom in the 3D kinematics
  - Up to 8 possible solutions per event ▶
  - Use matrix weighting technique to weight solutions

$$w = \left\{\sum f(x_1)f(x_2)\right\} p(E^*_{\ell^+}|m_t)p(E^*_{\ell^-}|m_t)$$

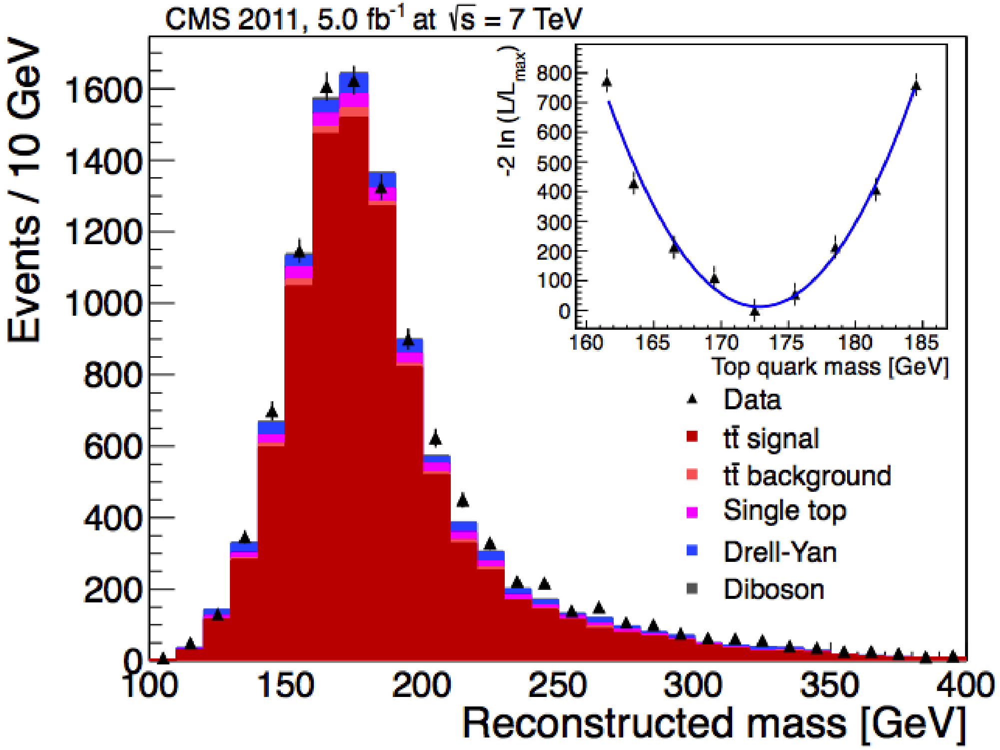
PDF summed over all possible combinations

Probability to observed lepton in top rest frame



Result – best in dilepton channel

$$m_t = 172.5 \pm 0.4\,(\text{stat.}) \pm 1.5\,(\text{syst.})\,\text{GeV}$$

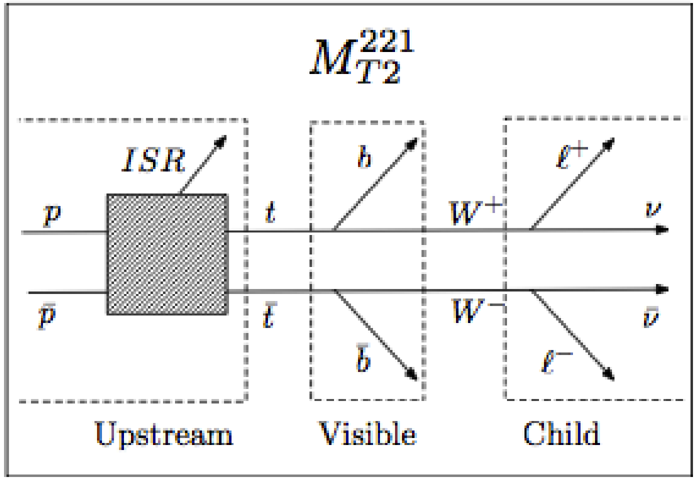


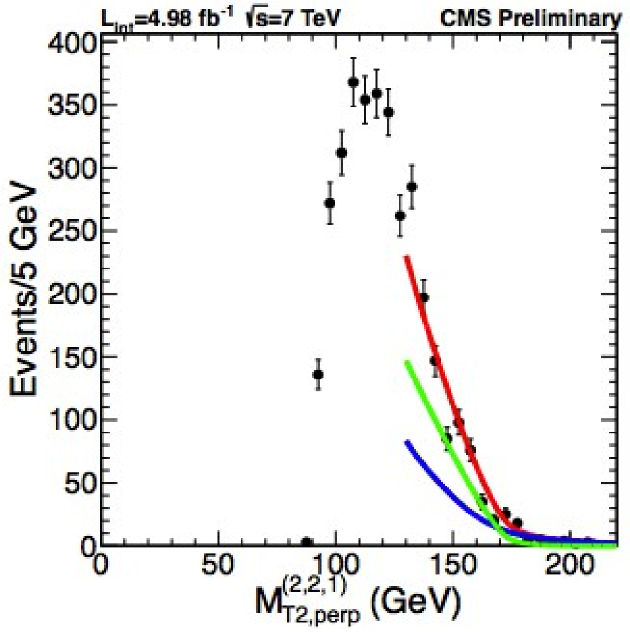
Source	Δm_t (GeV)
Jet energy scale	$^{+0.90}_{-0.97}$
b-jet energy scale	$^{+0.76}_{-0.66}$
Jet energy resolution	±0.14
Lepton energy scale	±0.14
Unclustered E_T^{miss}	±0.12
b-tagging efficiency	±0.05
Mistag rate	±0.08
Fit calibration	±0.40
Background normalization	±0.05
Matching scale	±0.19
Renormalisation and factorisation scale	±0.55
Pileup	±0.11
PDFs	±0.09
Underlying event	±0.26
Colour reconnection	±0.13
Monte Carlo generator	±0.04
Total	±1.48

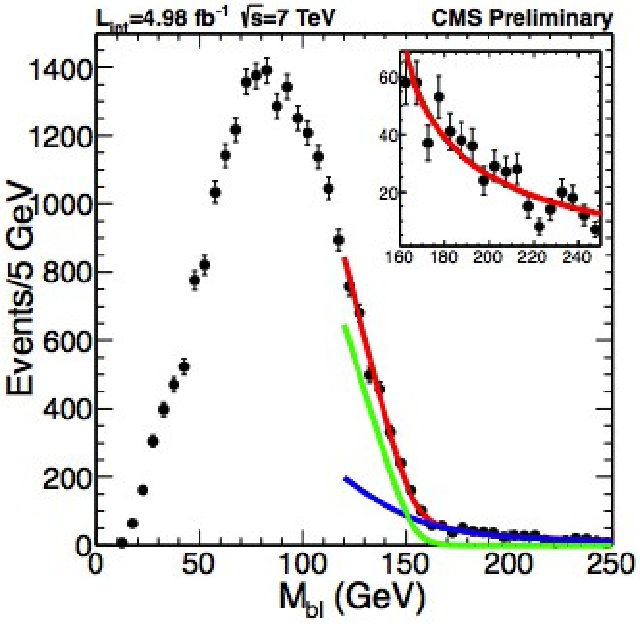
CMS PAS TOP-11-027

m_{top} from kinematic endpoints

- Top **dilepton events resemble** kinematics and topology of **many new physics scenario**
- Explore variables:
  - suited to analyze events with symmetric 3 body decays
    JHEP 0903 (2009) 143, PRL 107 (2011) 061801
  - which factorize event-by-event boost of the tt system ▶







◀ Simultaneous fit of the endpoints

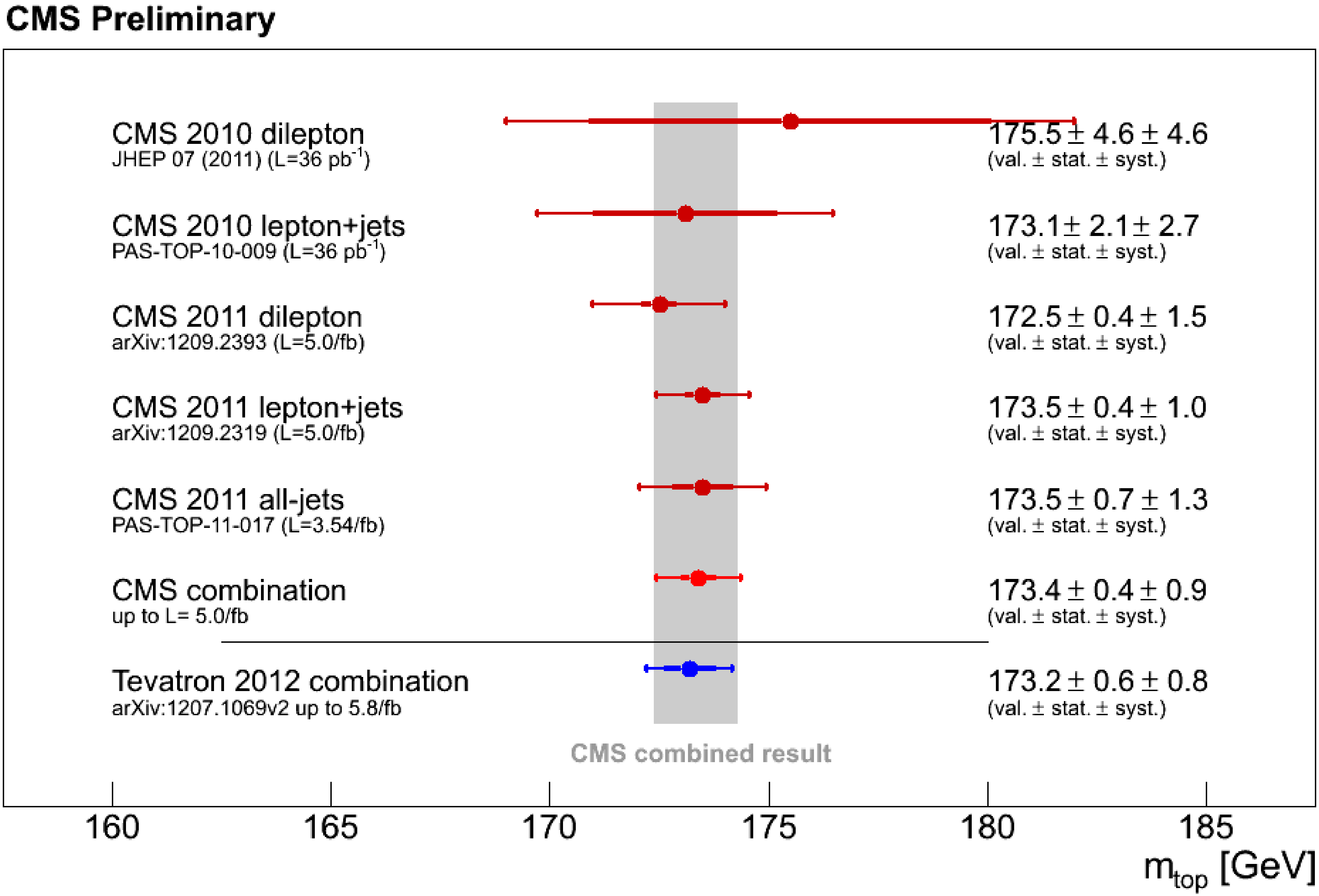
Different systematics with respect to canonical” top mass measurements!

Fit Quantity	Constraint		
	None	$m_\nu = 0$	$m_\nu = 0$ and $M_W = 80.4$
m_ν^2 (GeV^2)	$-556 \pm 473 \pm 600$	(0)	(0)
M_W (GeV)	$72 \pm 7 \pm 9$	$80.7 \pm 1.1 \pm 1$	(80.4)
M_t (GeV)	$163 \pm 10 \pm 11$	$174.0 \pm 0.9 \pm 2$	$173.9 \pm 0.9^{+1.2}_{-1.8}$

Result

Source	Δm_{top} (GeV)	
Jet energy scale	+0.5	-1.4
Jet energy resolution	0.5	
Fit range	0.6	
Background	0.5	
Efficiency	+0.1	-0.2
Color reconnection	0.6	

Top mass combination

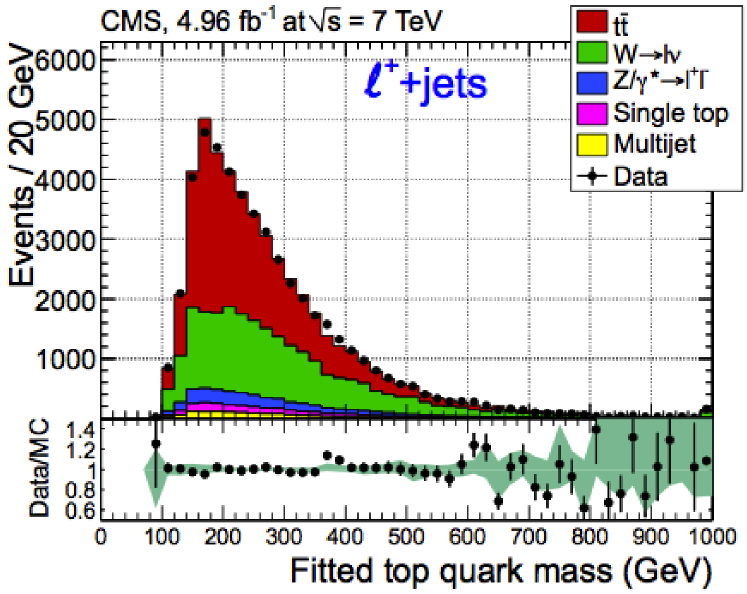


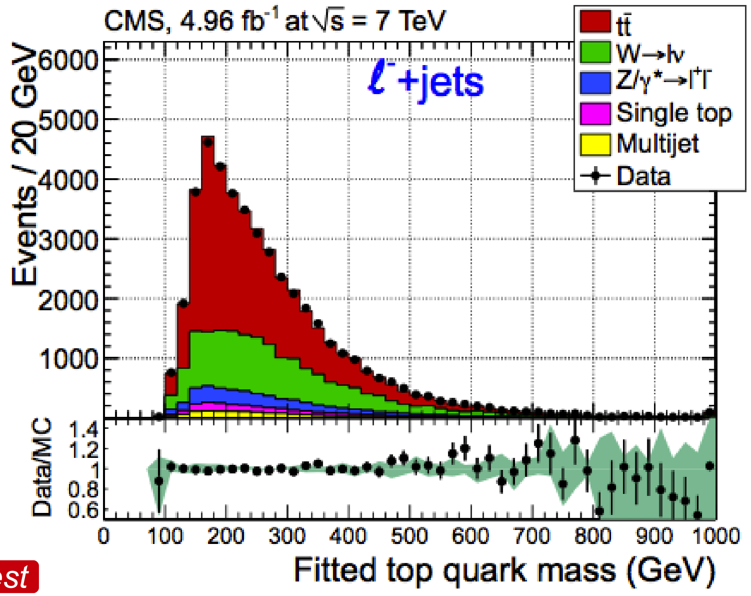
JHEP 06 (2012) 109

Top mass difference

- **Test CPT invariance in the top sector**
- Compare e^-/μ^++jets vs e^-/μ^-+jets samples
- Mass reconstructed from hadronic side
  - Use kinematic fit (including resolutions)
  - Choose combination with lowest χ^2
- Final measurement from **ideogram method** (combine μ^- and μ^+ likelihoods separately)
- **Most systematic effects cancel out**
  - measurement is stat. limited

Source	Estimated effect (GeV)
Jet energy scale	0.04 ± 0.08
Jet energy resolution	0.04 ± 0.06
b vs. $\bar{b}$ jet response	0.10 ± 0.10
Signal fraction	0.02 ± 0.01
Difference in W^+/W^- production	0.014 ± 0.002
Background composition	0.09 ± 0.07
Pileup	0.10 ± 0.05
b-tagging efficiency	0.03 ± 0.02
b vs. $\bar{b}$ tagging efficiency	0.08 ± 0.03
Method calibration	0.11 ± 0.14
Parton distribution functions	0.088
Total	0.27





Results - world's best

$$\boxed{\Delta m_t = -0.44 \pm 0.46\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{GeV}}$$

Conclusions

- **>4x10^6 top pairs collected: great times for top quark physics at the LHC**
  - Potential to provide precision inputs to **QCD** (PDF, α_S,...)
    EWK (m_{top}, V_{tb}, …) *see M. Gallinaro @ Plenary*
    Searches (couplings, top partners, …) *see M. Tosi @ Searches*
- **Focused on precision measurements: production cross section and mass**
  - Precision built on **excellent detector performance**
    careful choice of signal modeling and validation from data
    combination of different, complementary methods
  - Measurements overall consistent with the SM predictions call for next round of theory predictions
- Full collection of public results from CMS @ https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP

Backup

The LHC has already delivered us >10^6 top quarks – what have we been learning?

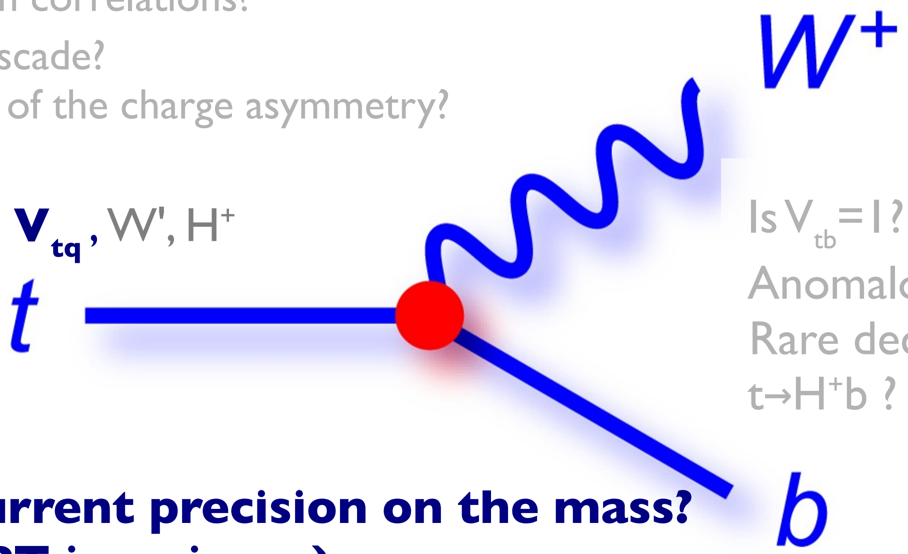
Top pair production: consistent with QCD prediction?

Jet scaling pattern? Associated productions?

Resonant production? Spin correlations?

Production after decay cascade?

Differential measurement of the charge asymmetry?



Single top production: V_{tq}, W', H^+

Is V_{tb}=1?

Anomalous couplings in Wtb vertex?

Rare decays by FCNC to γq, qZ, qg?

$t \to H^+ b$?

Can we improve the current precision on the mass?

$m_{top}=m_{anti-top}$? (CPT invariance)

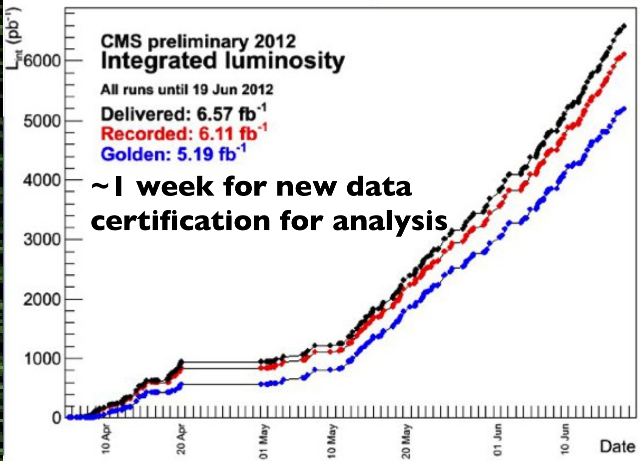
Privileged role in EWSB breaking mechanism (λ_t~1)?

Is the charge of the decay products compatible with 2/3e?

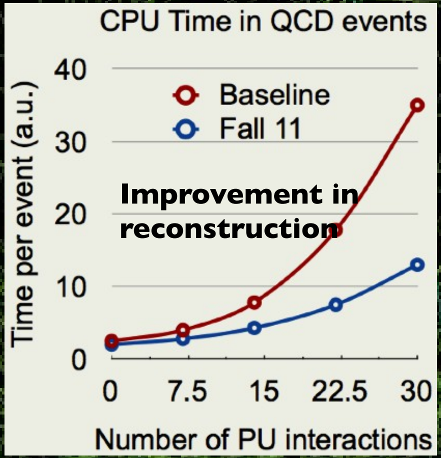
Is the width of the prompt decay compatible with Γ_t~1.3 GeV?

Many unknowns: unique sample for precision measurements and exploration of deviations from the SM at the LHC.

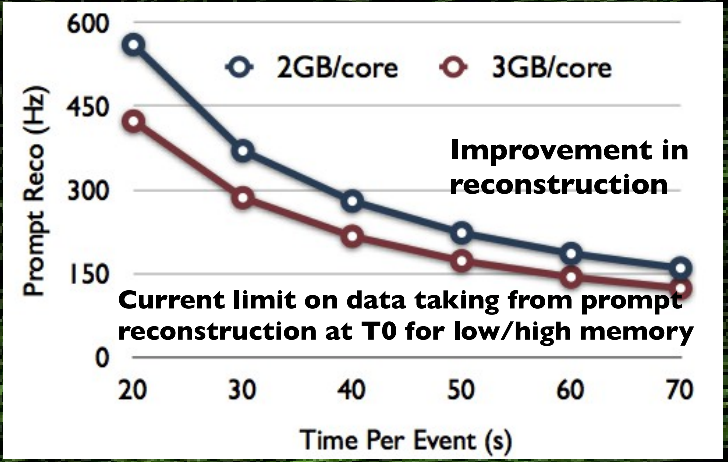
The pileup challenge



~1 week for new data certification for analysis



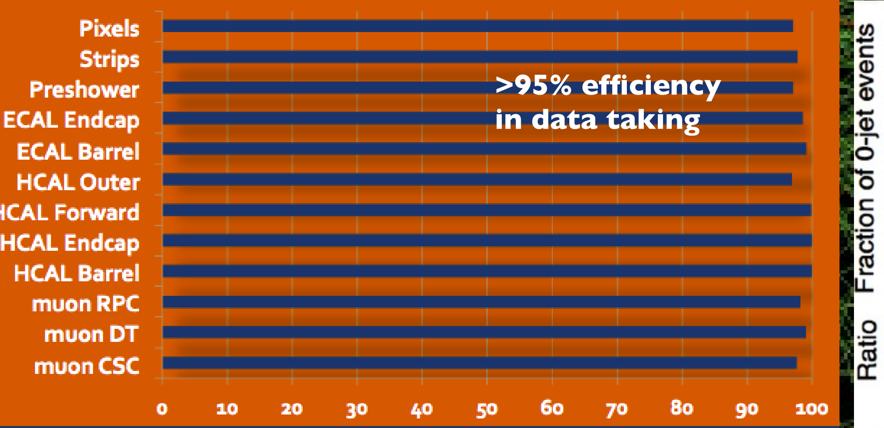
Improvement in reconstruction



Improvement in reconstruction

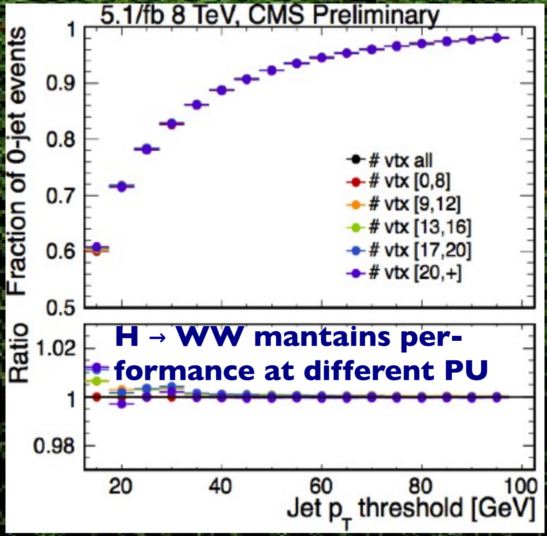
Current limit on data taking from prompt reconstruction at T0 for low/high memory

78 vertices in a single event!

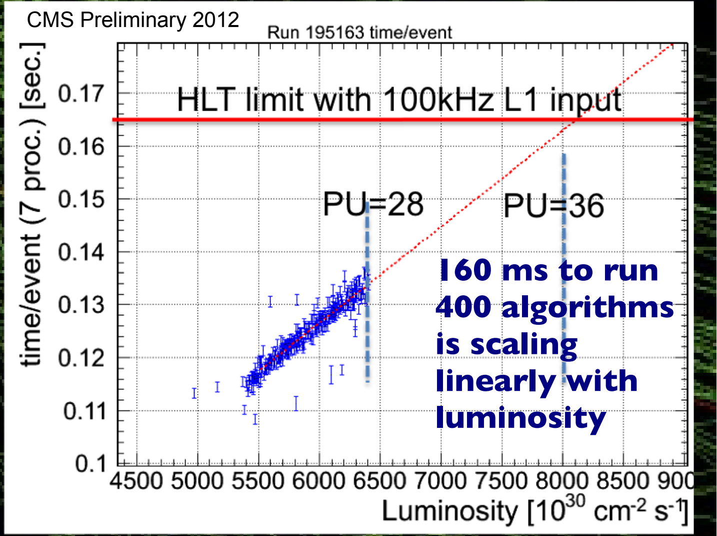


>95% efficiency in data taking

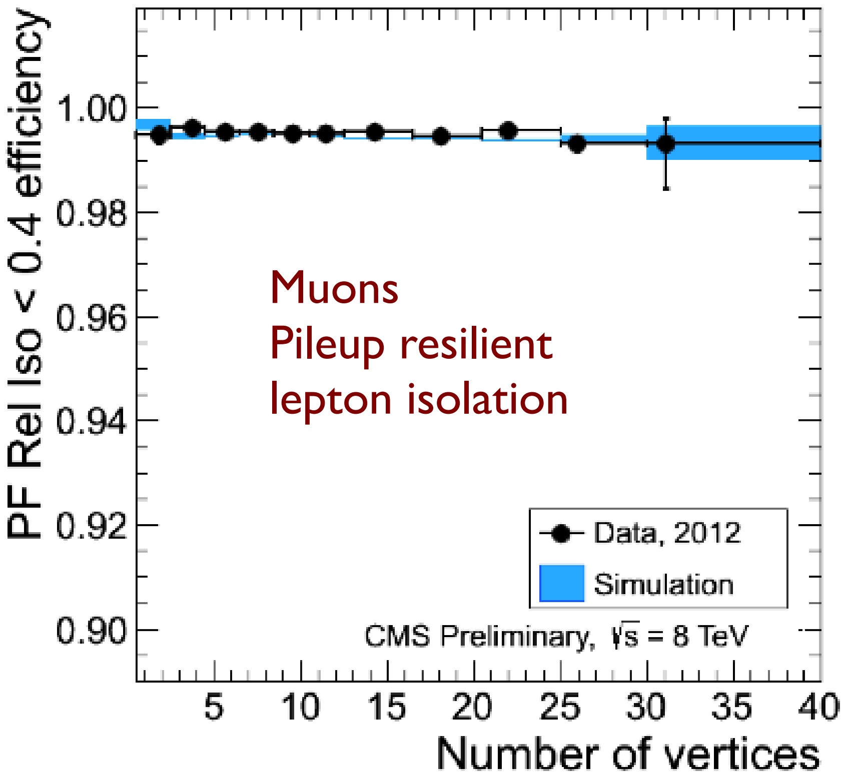
Pixel Tracker	Strip Tracker	Pre shower	ECAL Barrel	ECAL Endcaps	HCAL Barrel	HCAL Endcaps	HCAL Frwrd	HCAL Outer	Muon DT	Muon CSC	Muon RPC
97.1%	97.75%	97.1%	99.16%	98.54%	99.92%	99.96%	99.88%	96.88%	99.1 %	97.67 %	98.2%



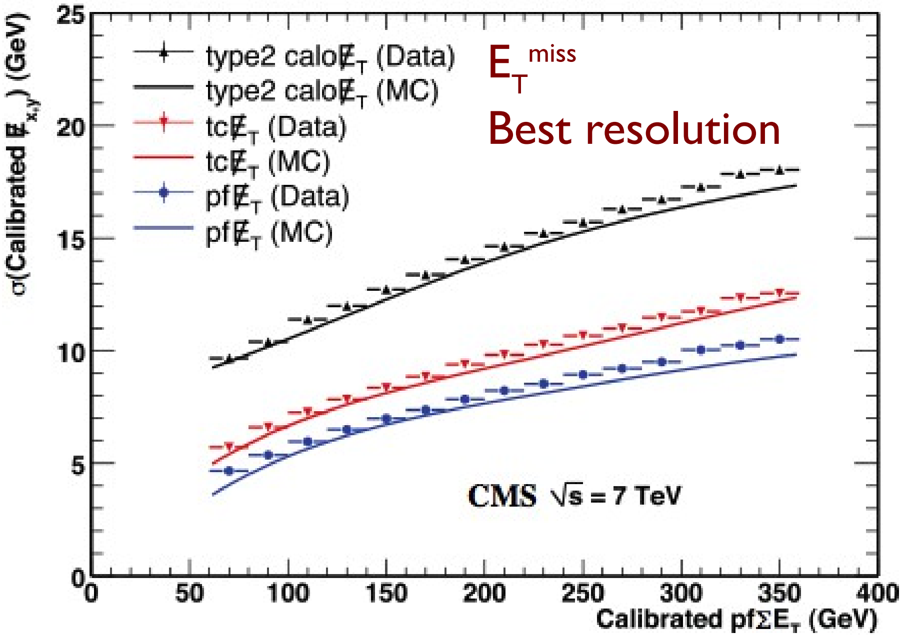
H → WW mantains performance at different PU



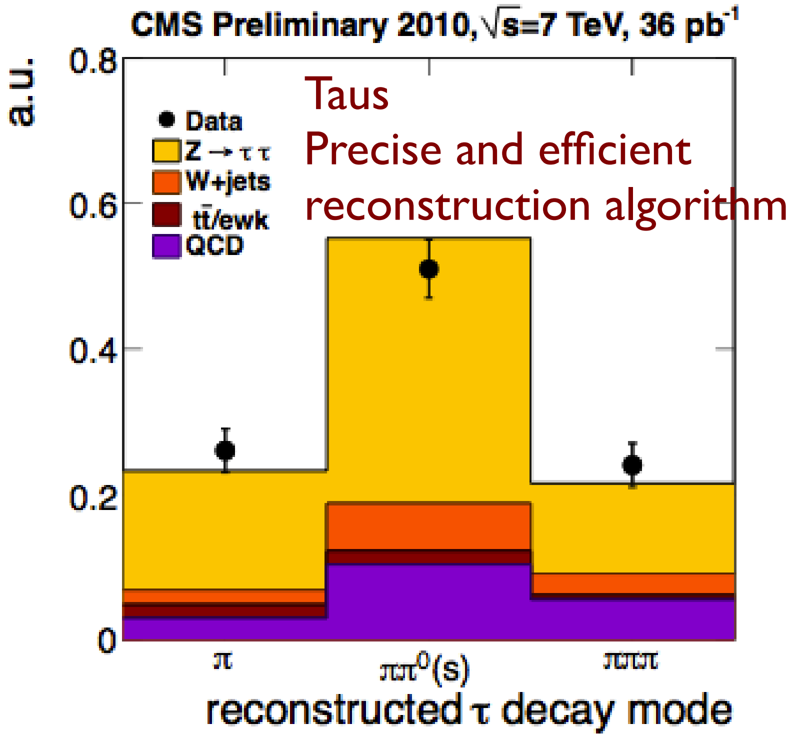
160 ms to run 400 algorithms is scaling linearly with luminosity



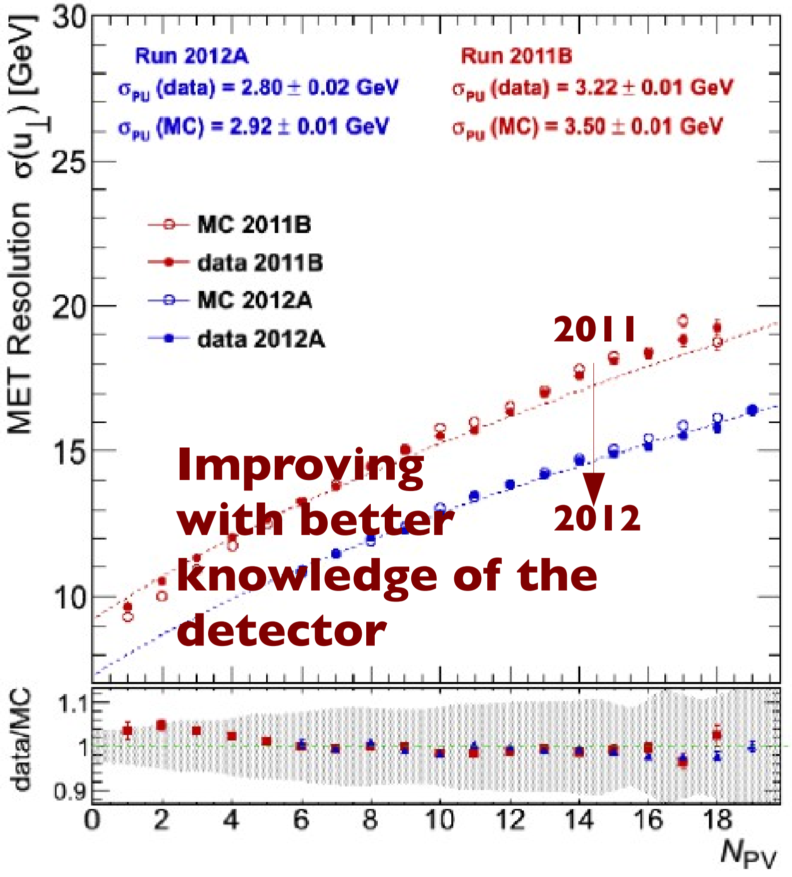
Muons
Pileup resilient
lepton isolation



E_T^{miss}
Best resolution



Taus
Precise and efficient
reconstruction algorithm



2011

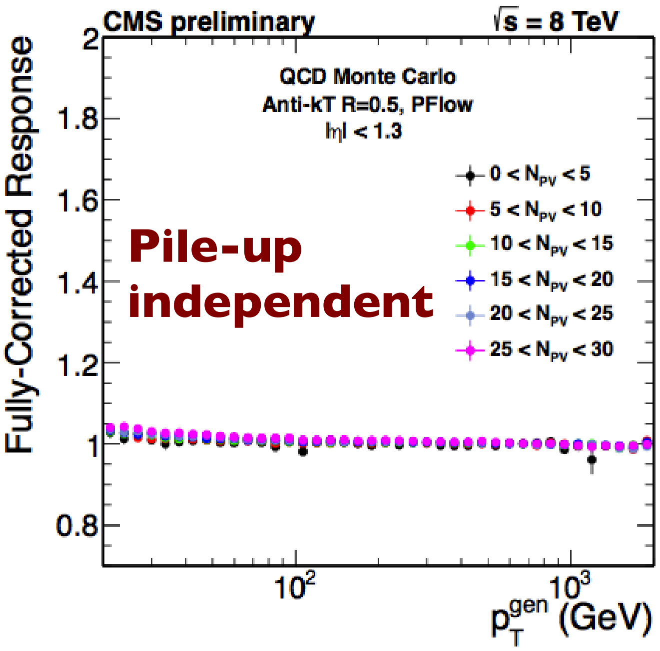
2012

Improving with better knowledge of the detector

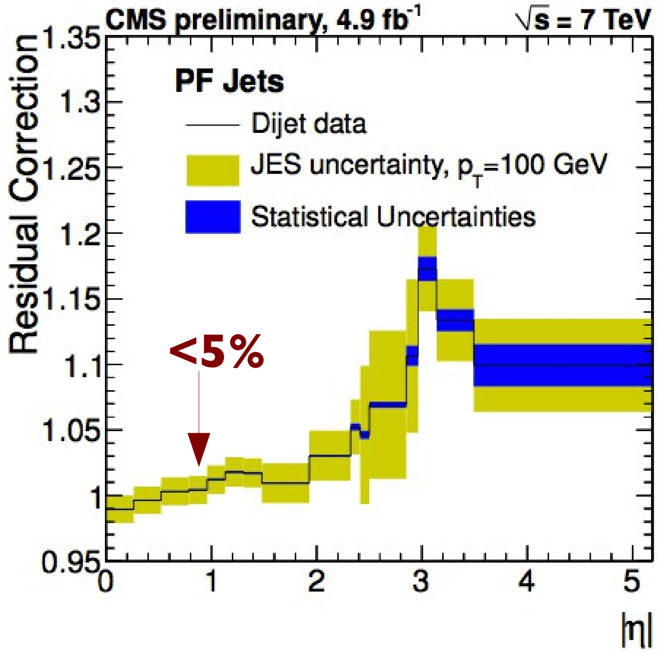
Jet calibration at CMS – I

CMS DP-2012/012
CMS DP-2012/006
2011 JINST 6 P11002

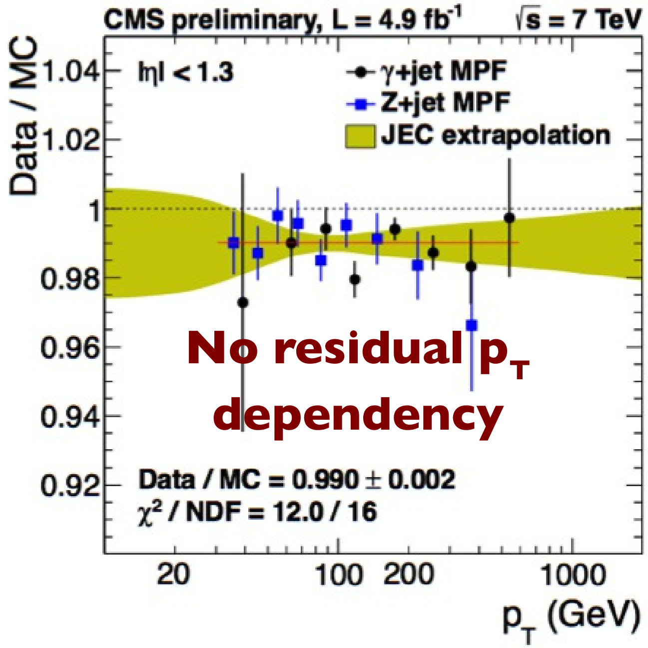
- Factorized approach for jet calibration in CMS
  - **Offset** corrections for pile-up and electronic noise
  - Charged hadron candidates associated to secondary vertices are subtracted
  - Corrections for **detector calibration and reconstruction efficiencies** (MC-based)
  - relative residual **η dependency corrections** (data-based)
  - **absolute and residual p_T** corrections (data-based)



Pile-up independent



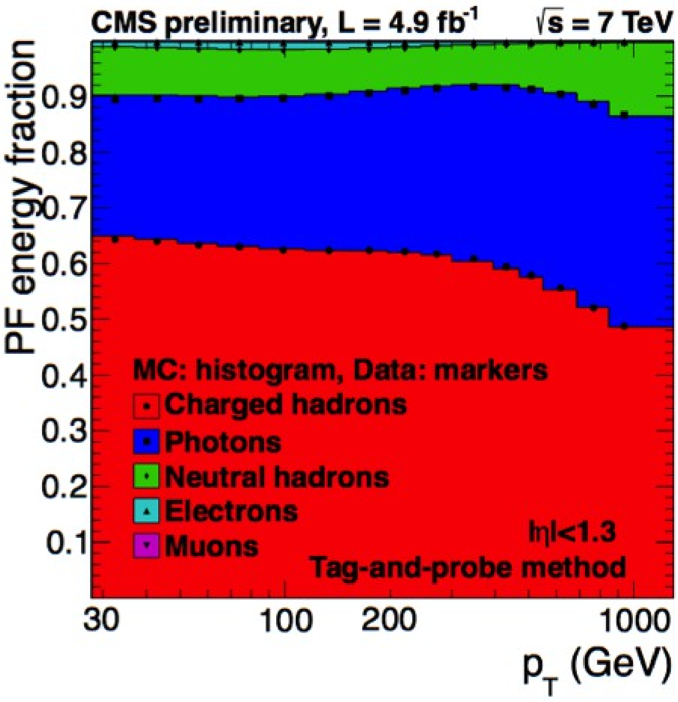
<5%

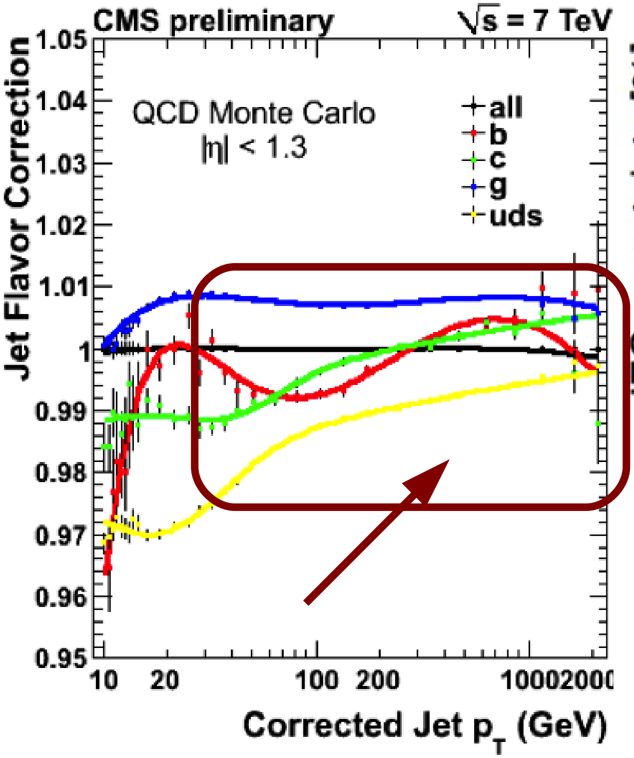


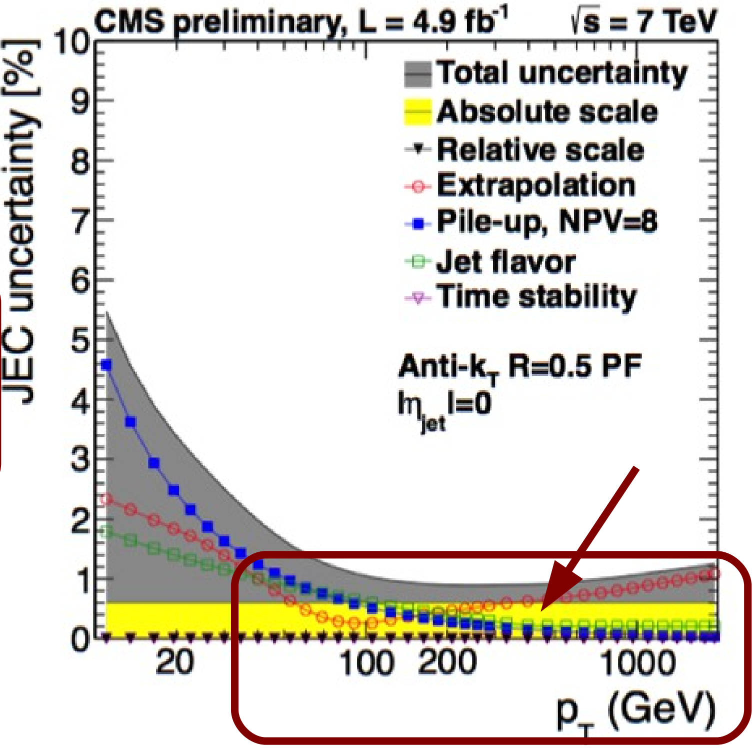
No residual p_T dependency

Achieve <2% uncertainty on energy scale and ~10% on energy resolution

Jet calibration at CMS – II

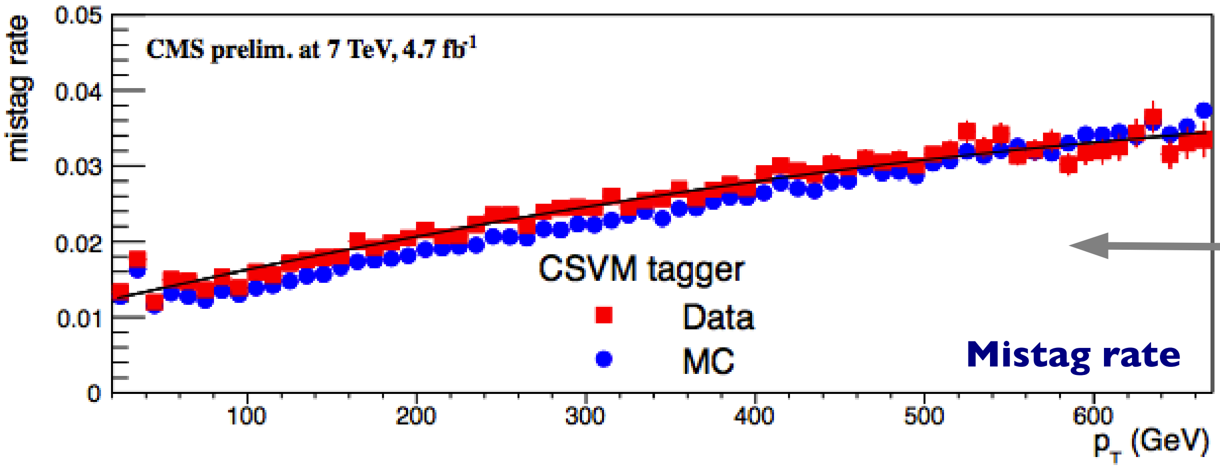


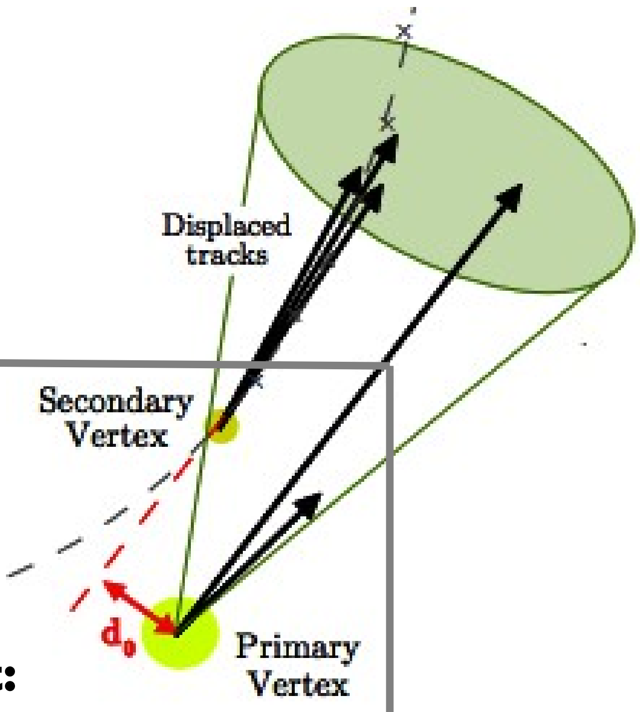




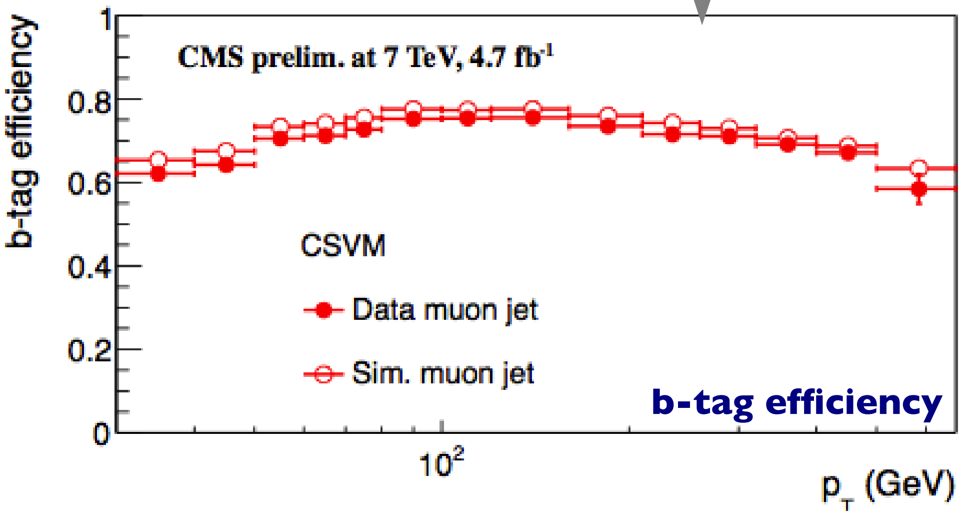
- Contribution of particle flow jet components to jet energy is understood to within <1%
- **Flavor specific differences within 1-3%** of the averaged correction
    - b-jet response is within 1% for p_T>15 GeV
    - pure flavor modeling within 1.5% comparing Pythia6 vs Herwig++
- We factorize **16 independent sources** of jet energy scale uncertainty correlations
    - key feature: sources may cross 0 and produce anti-correlations
    - e.g. extrapolation includes fragmentation (*correlated*) and π response (*anti-correlated*) components

b-jet identification - I

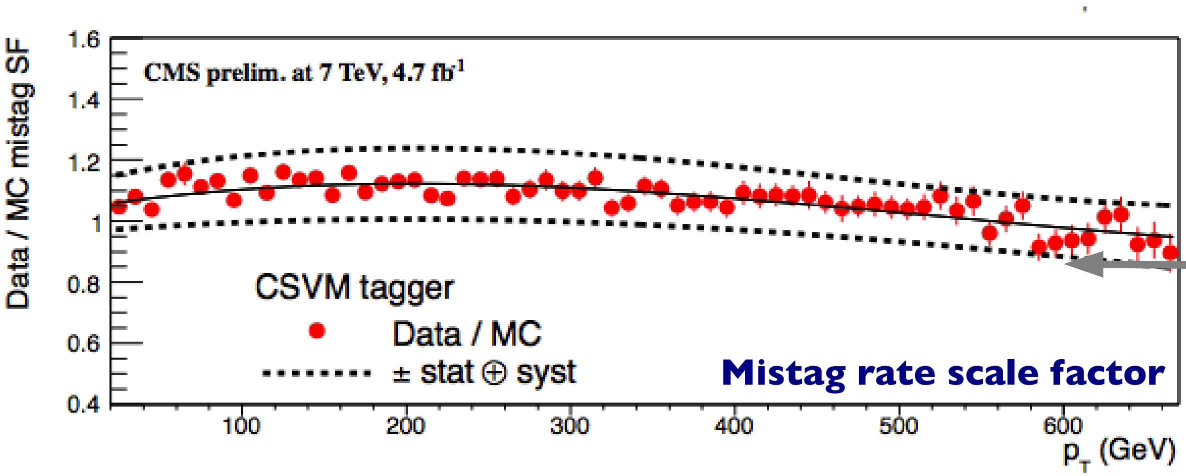




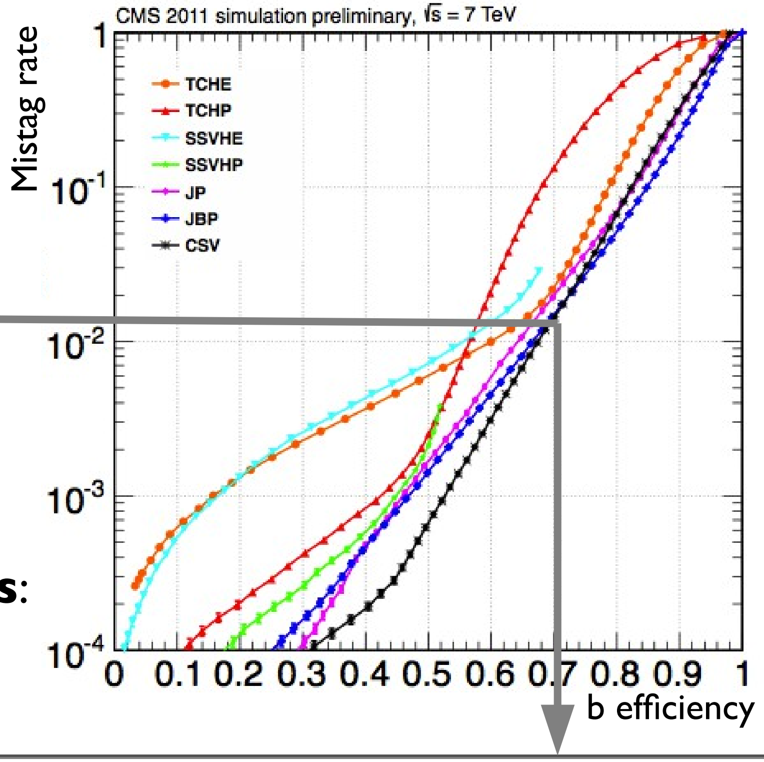
- **Jets stemming from the hadronization of b's are distinct:**
  - Large lifetime of B-hadrons $\tau \sim 1.5$ ps
  - yields displaced decays $c\tau \sim 492\ \mu m$
  - massive secondary vertices $M_{secVtx} \sim 3$ GeV (M_B~5 GeV)
  - may contain soft leptons $BR(B \rightarrow l\nu_l + X) \sim 20\%$
- **Identification algorithms** characterized by **efficiency** and **mistag rate** (probability to mis-identify c- or light flavoured-jets)



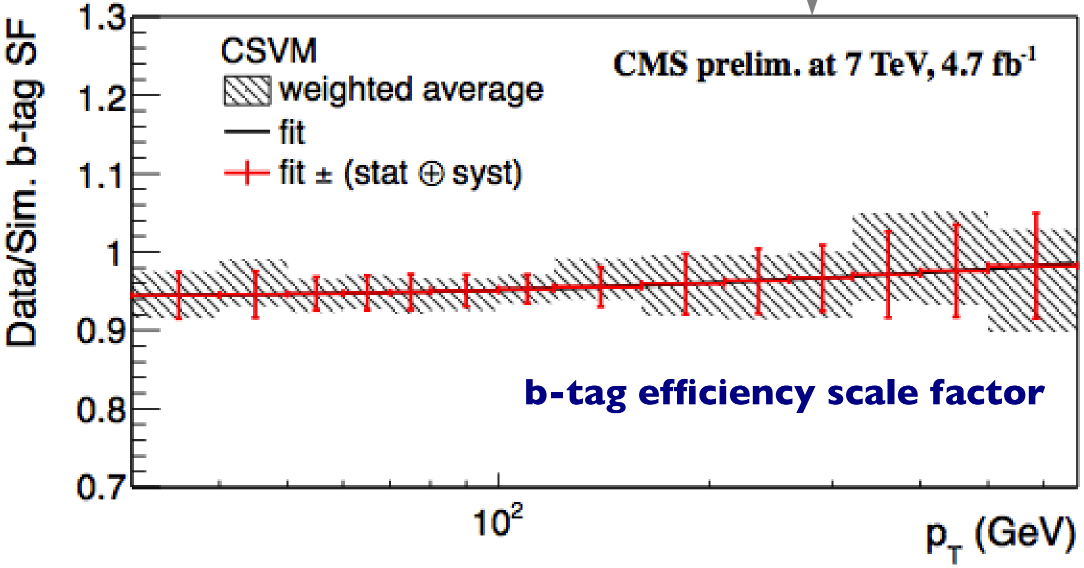
b-jet identification - II



Mistag rate scale factor



- Efficiency measurements affected by different **uncertainties**:
    - Gluon splitting and flavour composition
    - Jet trigger and offline selection
    - Template shapes, pileup, etc.
- **Combine alternative measurements**
    - Different sensitivity to different systematics
    - **2-4%** uncertainty on **b-tagging efficiency**
    - **9-11%** uncertainty on **mistag rate**

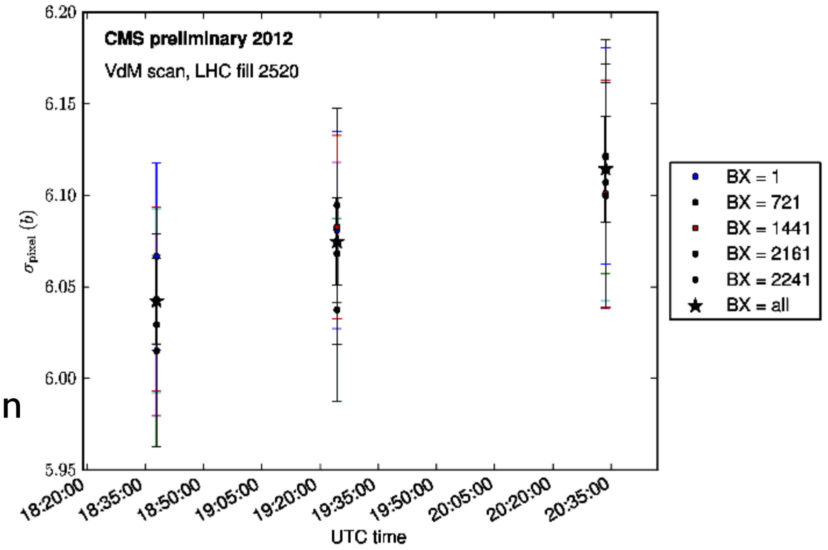


b-tag efficiency scale factor

CMS PAS SMP-12-008, CMS PAS LUM-12-001

Uncertainty on luminosity

- Luminosity measurement is based on pixel cluster counting
  - Use Van der Meer scan to measure $\sigma_{\text{pixel}} = \underbrace{\langle N_{\text{cluster}}\rangle}_{\text{mean number of pixel clusters per zero-bias trigger at the peak of the scan}} \underbrace{f}_{\text{11246 Hz}} \underbrace{\left(\frac{dL}{dt}\right)^{-1}}_{\text{from VdM scan}}$
- At **7 TeV** attain a total uncertainty of **2.2%**
- At **8 TeV** increased uncertainty to **4.4%**
  - Observe larger scan-to-scan variations in the cross section
  - Work in progress to understand variation
  - Assign larger variation (3.7%) as systematic uncertainty



7 TeV

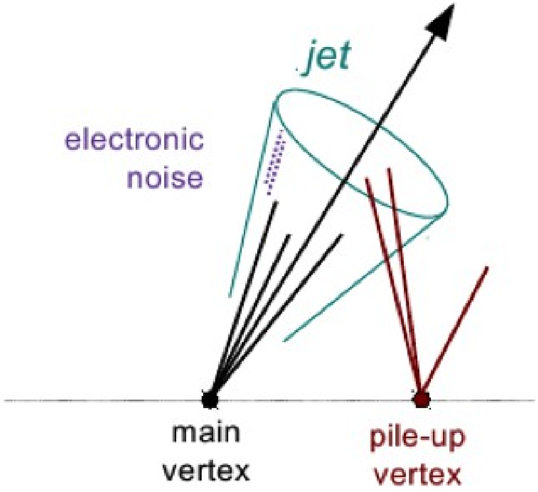
Source	Uncertainty (%)
Stability across pixel detector regions	0.3
Pixel gains and pedestals	0.5
Dynamic inefficiencies	0.4
Length-scale correction	0.5
Beam width evolution	0.6
Beam intensity - DCCT	0.3
Beam intensity - FBCT	0.5
Beam intensity - Ghosts	0.2
Scan-to-scan variations	1.5
Afterglow	1.0
Total	**2.2**

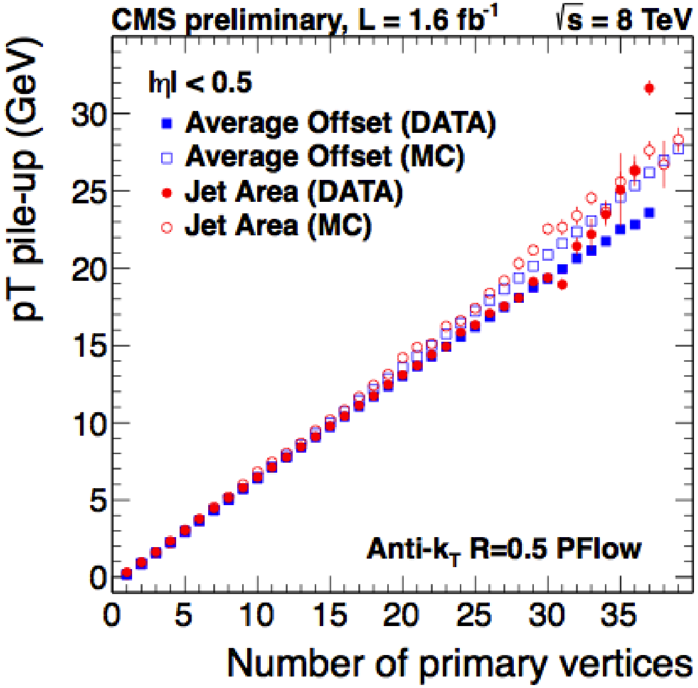
8 TeV

Source	Uncertainty (%)
Stability across pixel detector regions	1.5
Length-scale correction	0.3
Beam intensity - DCCT	0.3
Beam intensity - FBCT	0.5
Beam intensity - Ghosts	0.1
Beam intensity - Satellites	0.2
Dynamic β^* effects	0.5
Scan-to-scan variations	4.0
Afterglow	0.4
Total	**4.4**

Pileup corrections for jets

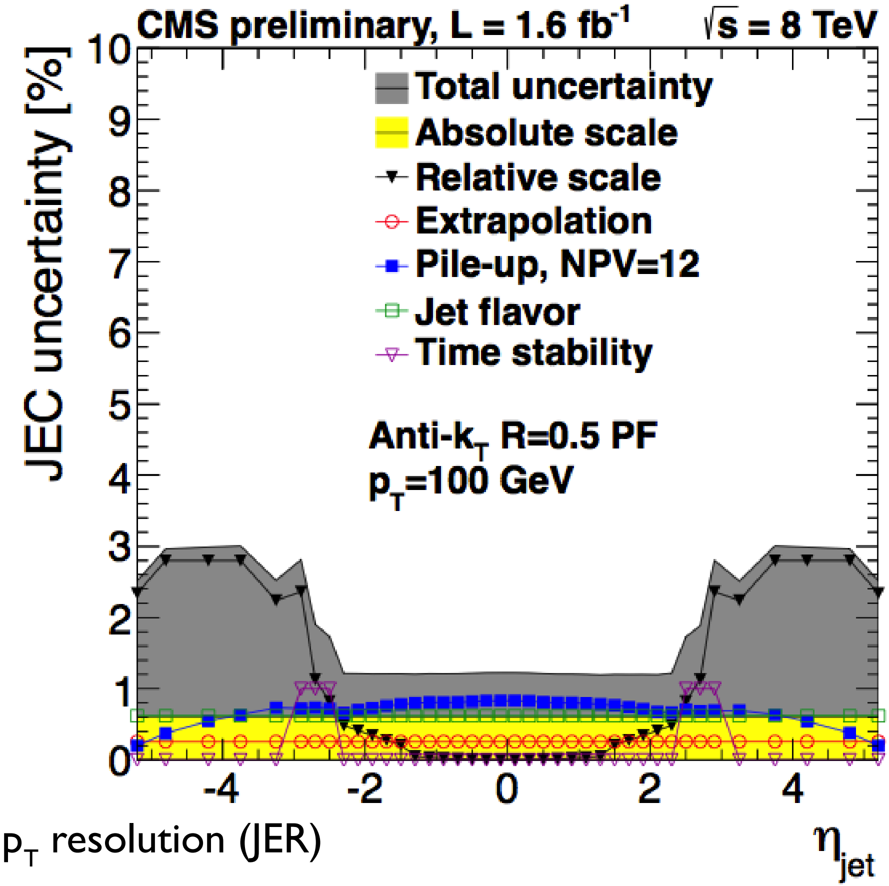
- Corrections are based on two methods:
  - **Average offset** – based on the multiplicity of primary vertices
  - **Jet area –** based on average energy density - ρ - computed with FastJet (Cacciari and Salam, PLB659:119-126,2008)
  - Average offset corrections correctly reproduced by jet area method (as well as η dependency on data)
- Linear dependency as function of pileup (with small quadratic dependency for MC)
- **Charged hadron subtraction** is possible using primary vertex association
  - improve resilience against PU
  - expect to achieve best resolution





Jet energy scale uncertainty components

- **Jet energy scale uncertainties include:**
  - **Absolute** : absolute scale uncertainty derived from Z/γ+jets
  - **High p_T** : extrapolation based on Pythia6 Z2/Herwig++2.3 differences in fragmentation and UE
  - **Single Pion** : high p_T extrapolation after ±3% variation in single particle response
  - **Flavor** : jet flavor based on Pythia6 Z2/Herwig++2.3 differences in quark and gluon responses relative to QCD mixture
  - **Time** : JEC time dependence.
  - **Relative JER** : η-dependence uncertainty from jet p_T resolution (JER)
  - **Relative FSR** :η-dependence uncertainty due to correction for FSR.
  - **Relative Stat** : statistical uncertainty in determination of η-dependence.
  - **Pile Up** : uncertainties for pile-up corrections include data/MC differences in Zero Bias data, out of time residuals, offset on jet pT due to zero suppresion, observed evolution of jet rate with vertex multiplicity



CMS PAS BTV-11-004

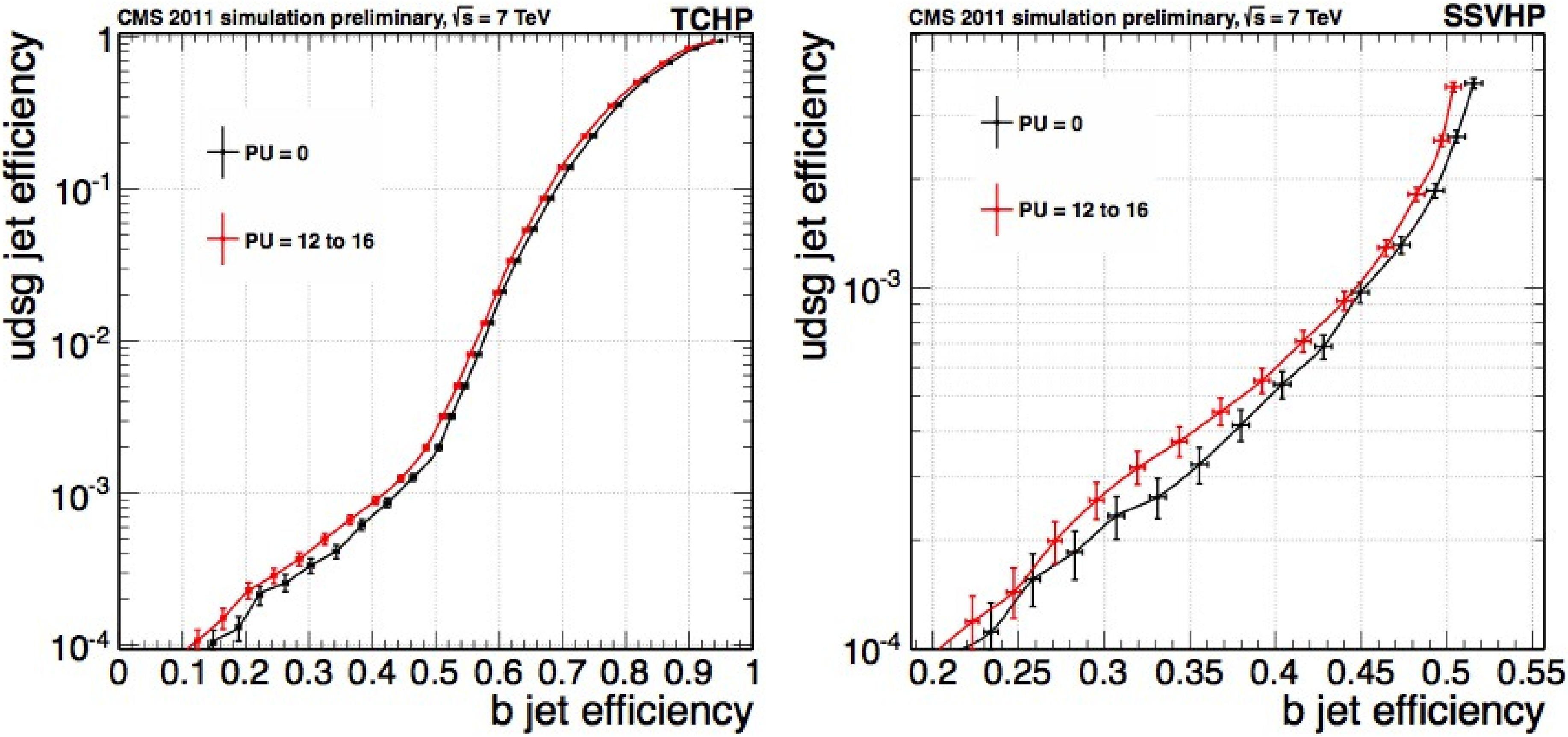
b-tagging and pileup

- Small dependency on pileup for the performance of the algorithms used by top

  (example of the IP-based algorithm used by single top analysis is given in the left figure)

- Larger dependency observed for very high purity algorithms

  (example of SecVtx-based algorithm is given in the right figure)



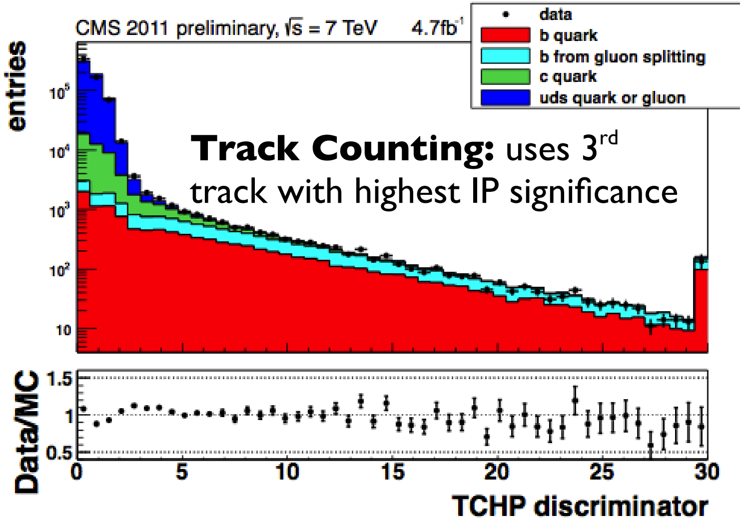
CMS PAS BTV-11-004

b-tagging algorithms at CMS

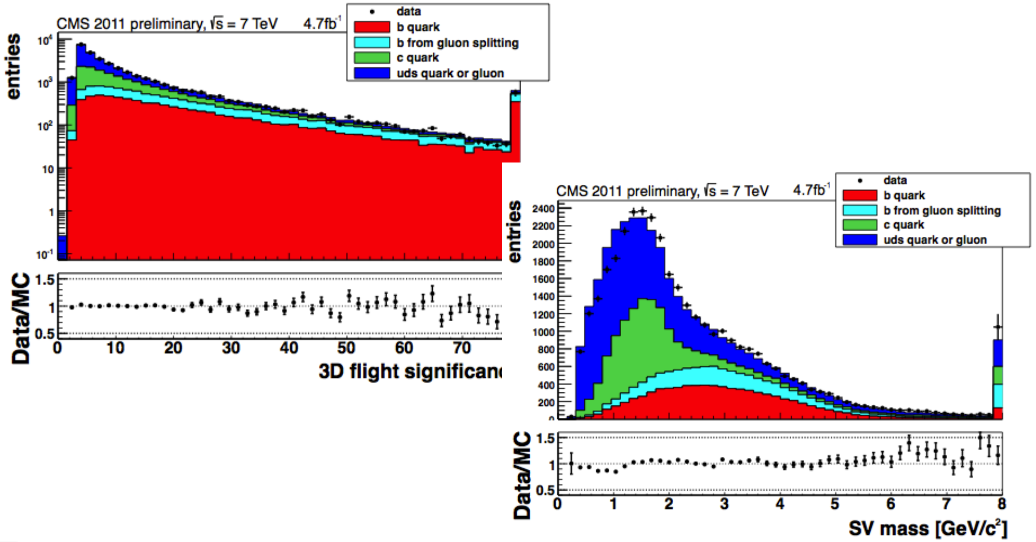
- At CMS b-tagging algorithms can be based on:

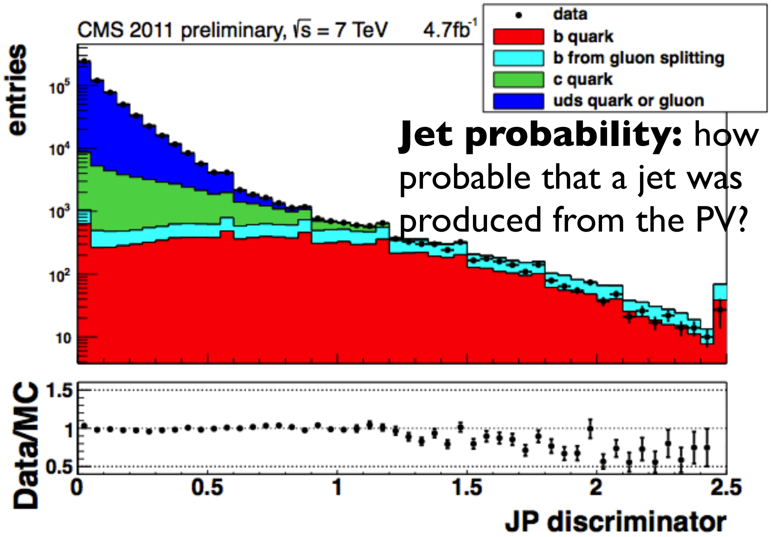
impact parameter

Secondary vertex reconstruction

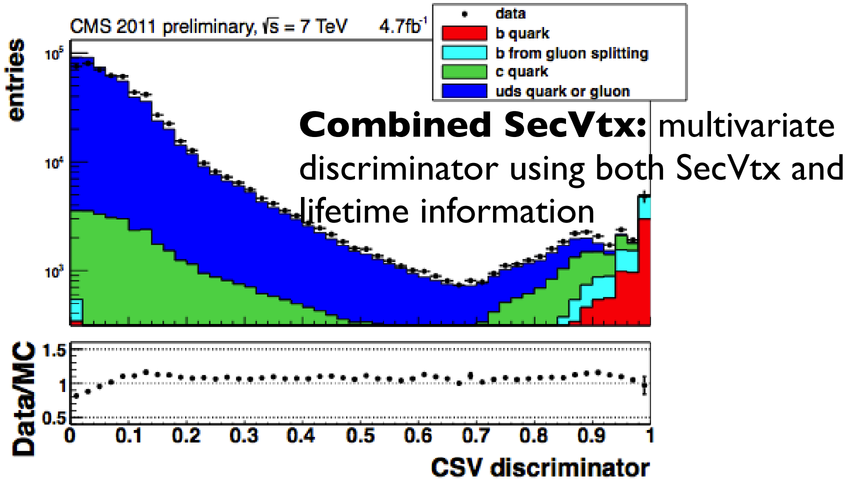


Track Counting: uses 3rd track with highest IP significance





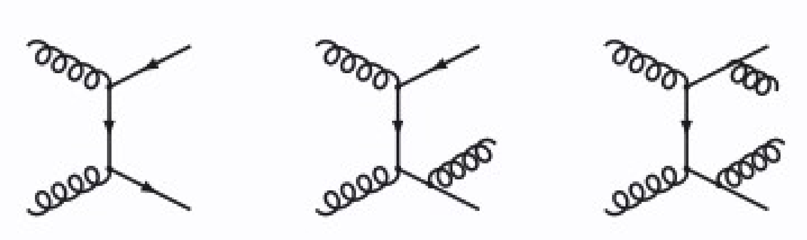
Jet probability: how probable that a jet was produced from the PV?



Combined SecVtx: multivariate discriminator using both SecVtx and lifetime information

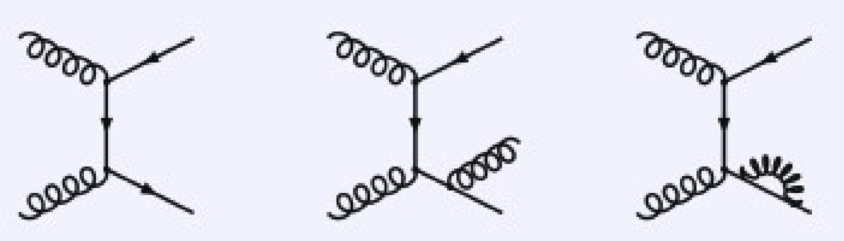
Generator setups for top physics at CMS

- **Matrix Element + Parton shower generators**
  - Better description of high multiplicities
  - ISR/FSR modeling tuned from assumed Q^2
  - PS
  - e.g. Madgraph+Pythia

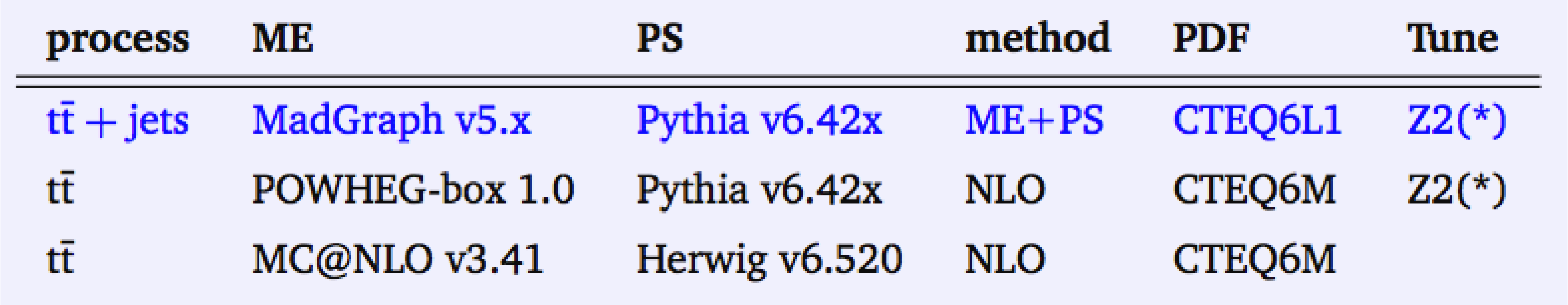


tree level diagrams with up to 3 partons

- **Next Leading Order**
  - More accurate in normalization
  - Smaller uncertainty on the Q^2
  - e.g. MC@NLO+Herwig



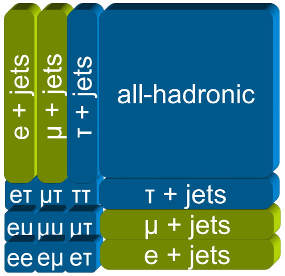
real+virtual corrections



process	ME	PS	method	PDF	Tune
$t\bar{t}+$jets	MadGraph v5.x	Pythia v6.42x	ME+PS	CTEQ6L1	Z2(*)
$t\bar{t}$	POWHEG-box 1.0	Pythia v6.42x	NLO	CTEQ6M	Z2(*)
$t\bar{t}$	MC@NLO v3.41	Herwig v6.520	NLO	CTEQ6M	

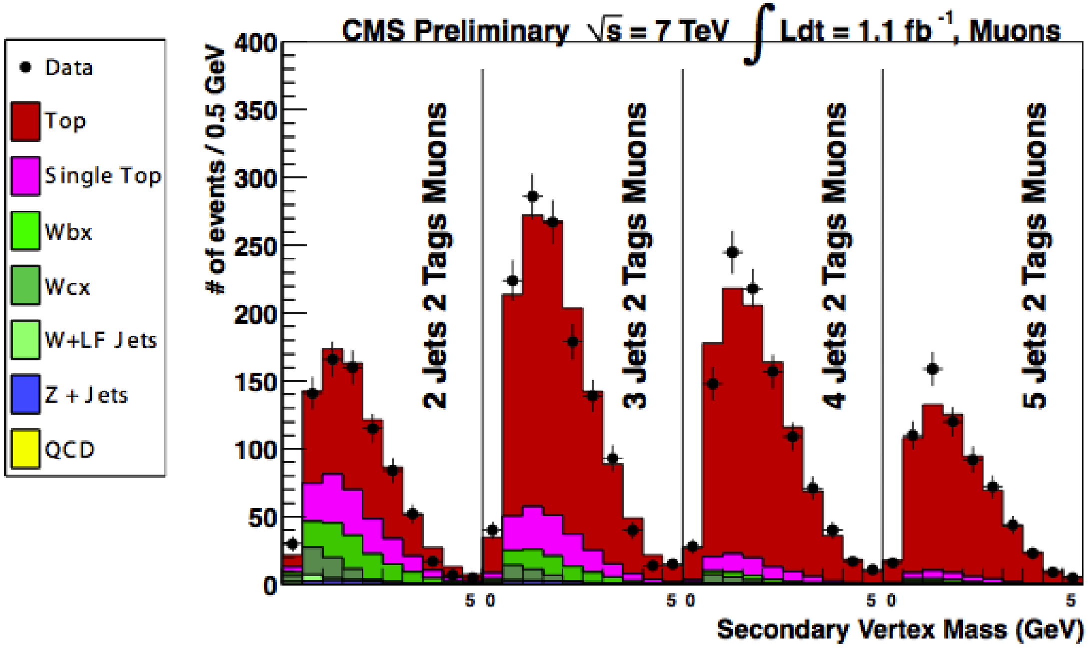
CMS PAS-TOP-11-003,CMS PAS-TOP-12-006

Lepton+jets analysis

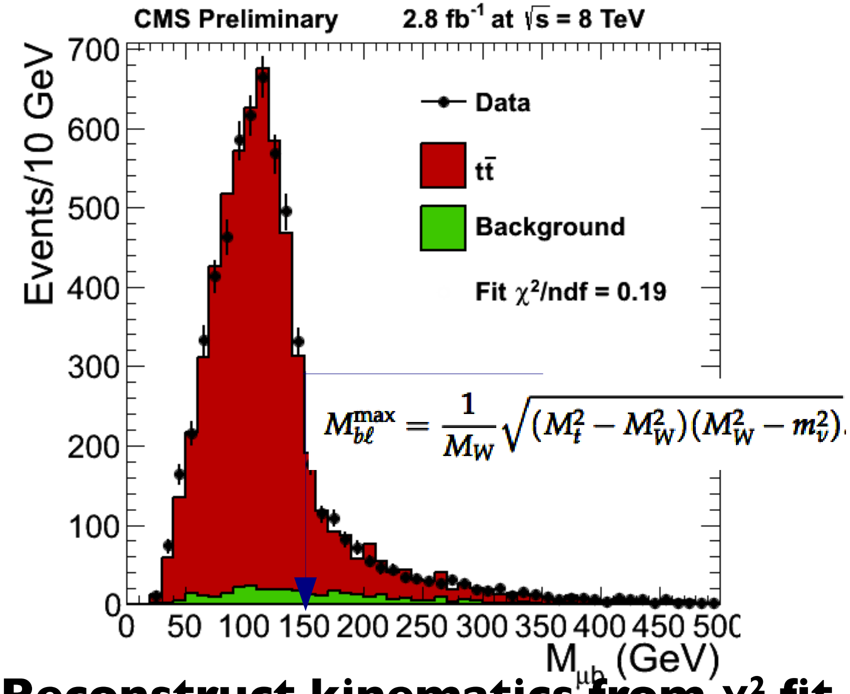


- **Main backgrounds:**
  - QCD multijets (rejected with m_T/MET, can be controlled from sidebands)
  - W+jets (in particular Heavy Flavor, controlled by categorizing or kinematics)
- **Use b-driven kinematics to discriminate top:**

mass of secondary vertex (@7 TeV)



lepton-b invariant mass (@8 TeV)



- **Categorize events and fit σ_{tt}**
  - W+HF normalization included in fit
  - Systematics treated as nuisance parameters (e.g. Q^2, b-tag efficiency)
- **Reconstruct kinematics from χ^2 fit**
  - Assign leptonic top decay
  - Binned fit M_{lb} distribution (data-driven templates for QCD)

Uncertainties in lepton+jets

Results

7 TeV

$164.4 \pm 2.8_{\mathrm{stat}} \pm 11.9_{\mathrm{syst}} \pm 7.4_{\mathrm{lumi}}$ pb

9%

8 TeV

$228.4 \pm 9.0_{\mathrm{stat}} \, {}^{+29.0}_{-26.0}\,{}_{\mathrm{syst}} \pm 10_{\mathrm{lumi}}$ pb

13%

- **Detector related uncertainties**
  jet energy scale/resolution, b-tag
  trigger/selection eff.

- **Signal related uncertainties**
  Q^2, ME-PS matching
  - **reflect directly on top decay products kinematics** (M_{lb}) e.g through modification of the environment (ISR/FSR)
  - **factorize from simple** b **properties** (vertex mass)

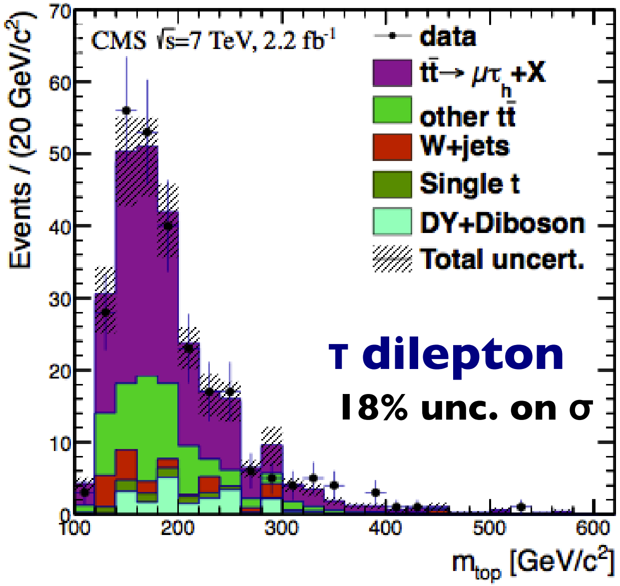
- Results are cross-checked and consistent with alternative measurements

Source	$\Delta\sigma_{t\bar{t}}$ (%) from	
	M_{SecVtx} (7 TeV)	$M_{\ell,\mathrm{b}}$ (8 TeV)
Background composition	-	0.1
Multijet normalization	-	0.9
W+jets Q^2/template	$2^{\dagger}$	0.9
Trigger efficiency	3.4	+3.2 -2.8
Lepton selection		+2.8 -2.4
Jet energy scale	$3.1^{\dagger}$	+4.3 -5.0
Jet energy resolution		+0.5 -1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	<1	-
b-tagging	$2.4^{\dagger}$	8.0
Pileup	2.6	0.7
Q^2	2	+6.2 -2.1
ISR/FSR	2	-
ME-PS scale	2	+4.6 -3.1
PDF	3.4	+1.6 -2.0
Top mass	-	+0.3 -1.4
Total	**7.3**	**+12.7 -11.4**

Challenging channels

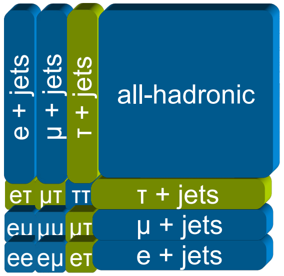
Phys. Rev. D85 (2012) 112007
CMS PAS TOP-11-004
CMS PAS TOP-11-005

3rd generation only



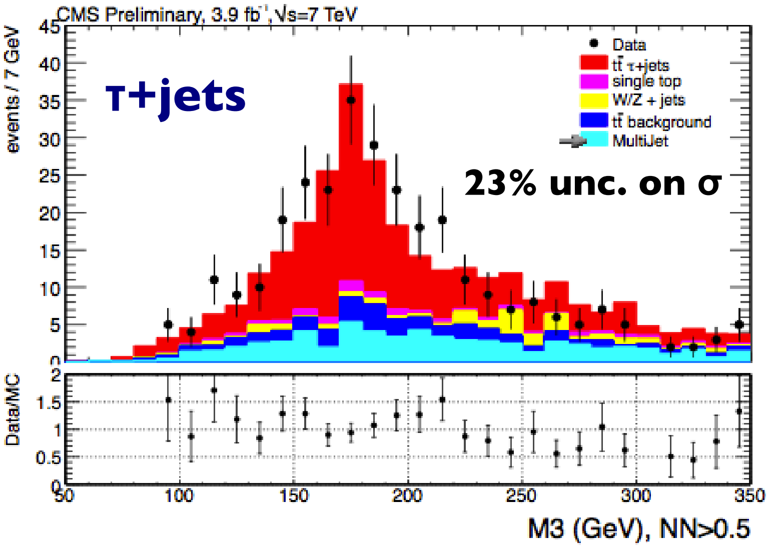
τ dilepton

18% unc. on σ



◀ Main uncertainty due to **τ fake rate** estimated from W+jets sample

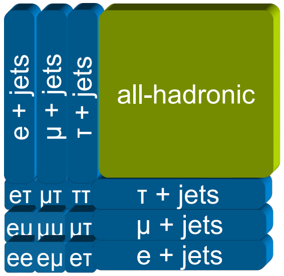
Multivariate analysis (fakes modeled from 0 b-tags sideband) → main uncertainty is jet energy scale ▼



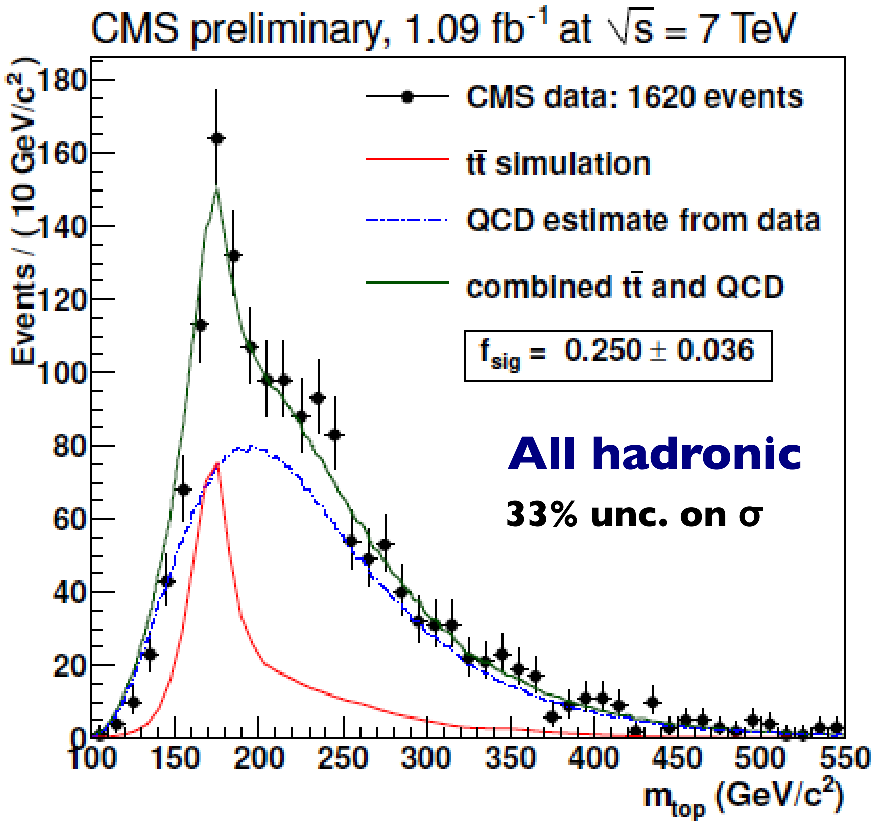
τ+jets

23% unc. on σ

Fully hadronic



- kinematic fit sorts combination which reconstruct m_{top}
- Multijets re-weighted from 0 b-tags control region
- **Uncertainties: instrumental/ background** are dominant over other contributions



All hadronic

33% unc. on σ

CMS PAS TOP-12-022, CMS PAS TOP-11-008

...and current word from CMS-σ_{tt} on

Coupling of strong interactions

Top quark mass

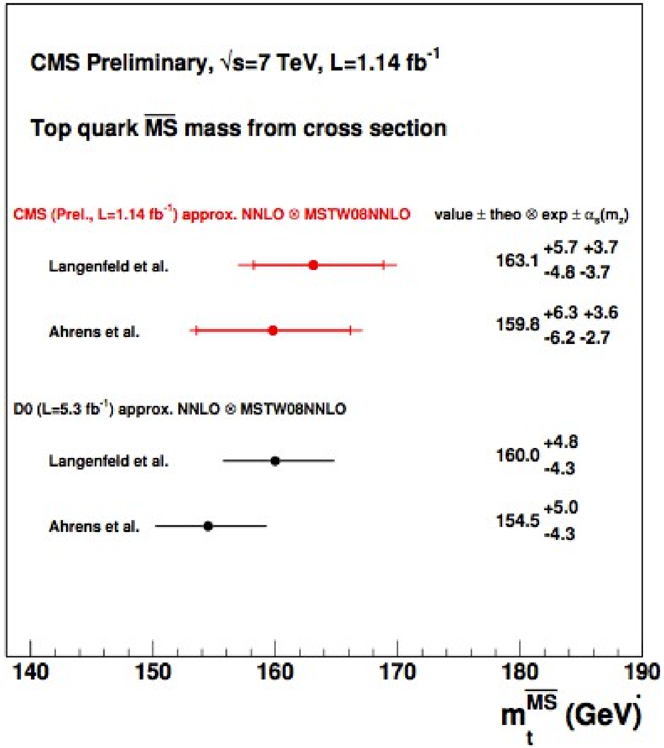
m_{top} and α_s can't be determined simultaneously from σ_{tt} → constrain one when measuring the other

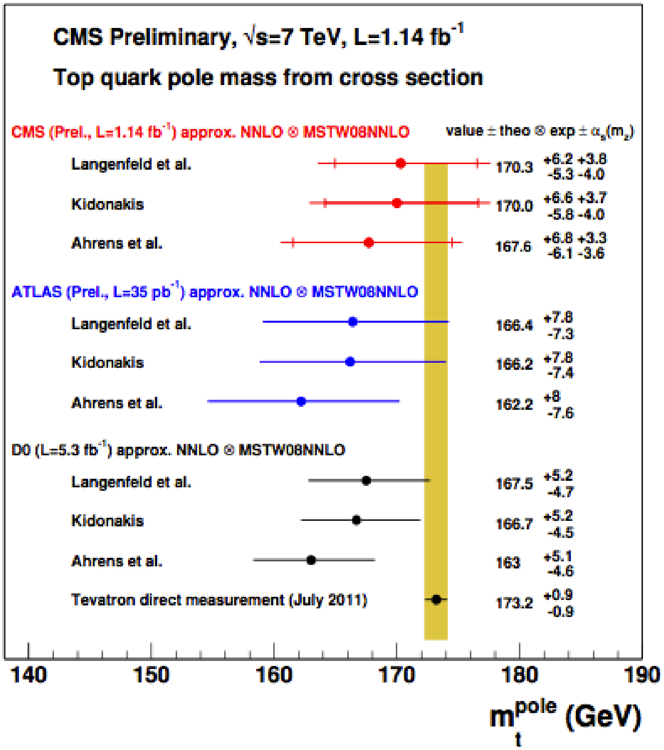
$$\mathcal{L}(x) = \int d\sigma \; \underbrace{f_{\mathrm{exp}}(\sigma_{t\bar{t}}|x)}_{\text{Experimental measurement (gaussian)}} \; \underbrace{f_{\mathrm{th}}(\sigma_{t\bar{t}}|x)}_{\text{PDF uncertainty}} \qquad x = \alpha_S \text{ or } m_t$$

- **Parametrize** measured and predicted **dependency on m_{top}:**

$$\sigma_{t\bar{t}}(m_t) = \frac{1}{m_t^4}\left(a + b \cdot m_t + c \cdot m_t^2 + d \cdot m_t^3\right)$$

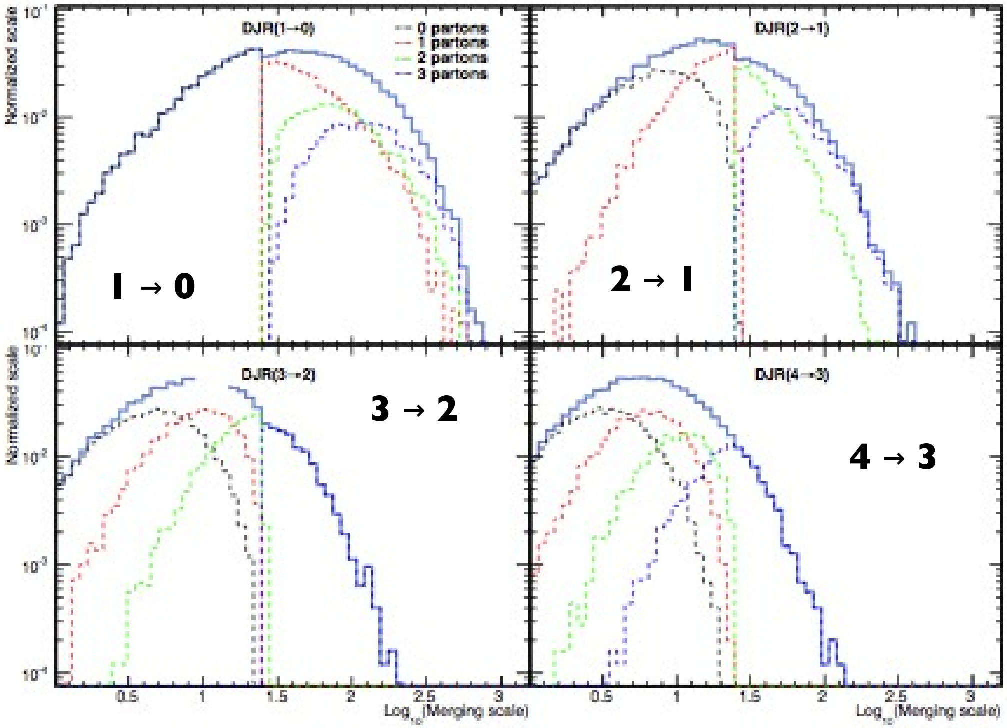
- Uncertainties: experimental measurement, PDF, Q^2 scale, α_s

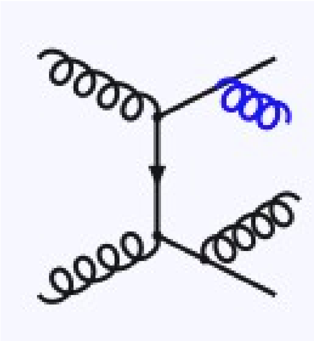




More on the Q^2 and ME-PS parameters and choices

- Parton showering (e.g. Pythia) describes the soft and collinear region
  - ME-PS matching is done via k_TMLM
  - ensure smoothness of N → N+1 jet rates
  - matching thresholds (xqcut=20) drives optimal scale (qcut=40)
  - Choice is varied by factors of 2 or ½



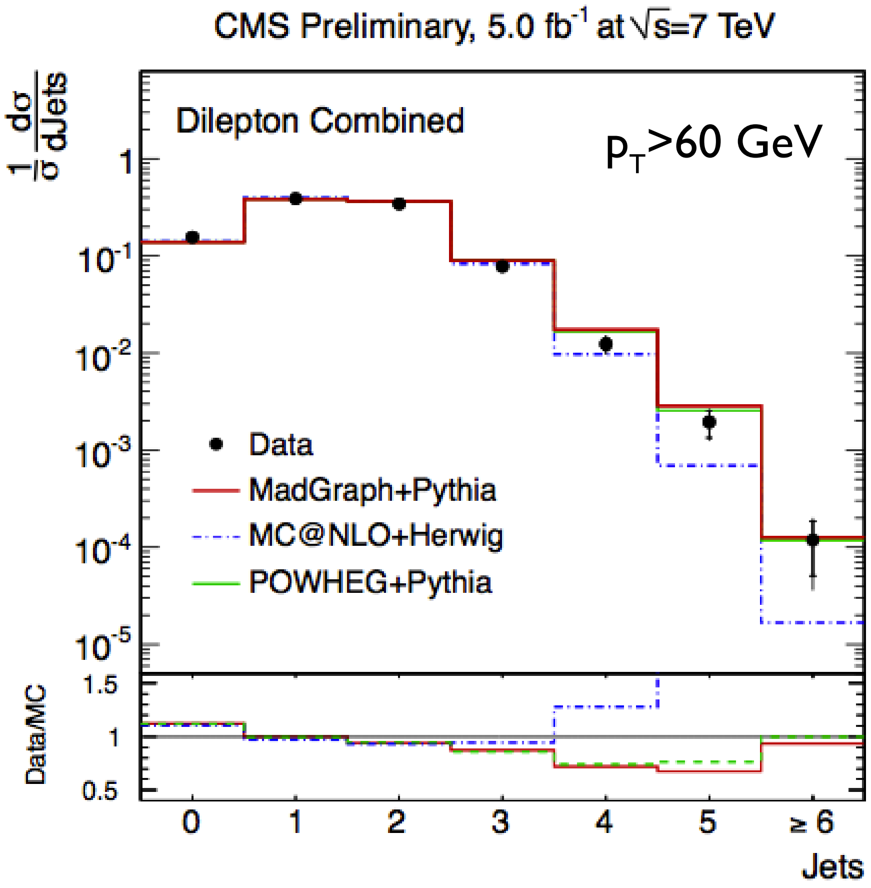


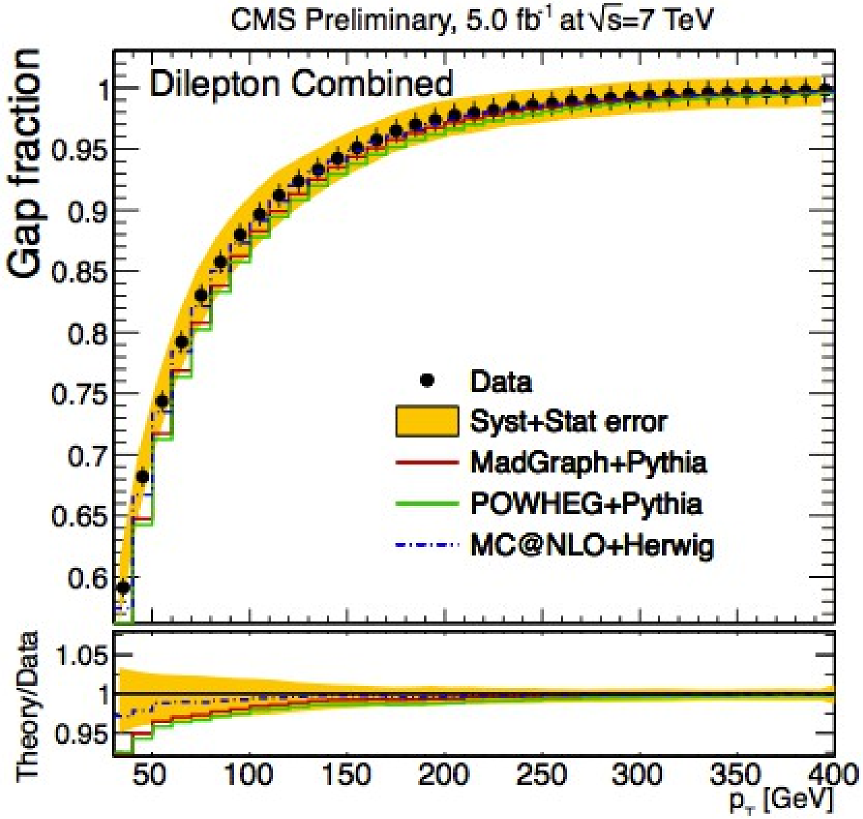
- For each event the Q^2 is defined as:

$$\boxed{Q^2 = m_{\text{top}}^2 + \sum_{\text{partons}} p_{\text{T}}^2}$$

  - Alternative settings vary by $4Q^2$ and $\frac{1}{4}Q^2$
- Parton showering:
  - α_s-based evolution scale of ISR/FSR
  - shares Q^2 factor α_s scale with ME
  - implicitly: starting scale changes with ΔQ^2
- *Note: scales in different processes are varied independently (tt, single top, W/Z+jets, etc.)*

Modeling jet activity in dilepton events





- Best agreement is observed for generators interfaced with Pythia (Madgraph, Powheg)
- MC@NLO+Herwig describes better the jet gap fraction due to the fact that it fails to reproduce correctly events with emission of several hard jets
- Distributions are overall better described with Madgraph with increased Q^2 (see slide 27)

CMS PAS TOP-12-014

Associated production with bosons

- Search is carried in two different channels
  - **Trilepton:** Z → ll + l at least 3 jets (2 b-tagged), H_T>120 GeV
  - **Same sign dilepton:** $l^\pm l^\pm$ with high p_T, at least 3 jets (2 b-tagged) HT>100 GeV
- Dominant systematic uncertainties due to background estimation

Result

$$\sigma_{t\bar{t}V} = 0.51\ ^{+0.15}_{-0.13}\ \mathrm{stat}\ ^{+0.05}_{-0.04}\ \mathrm{syst}\quad \mathrm{pb}$$

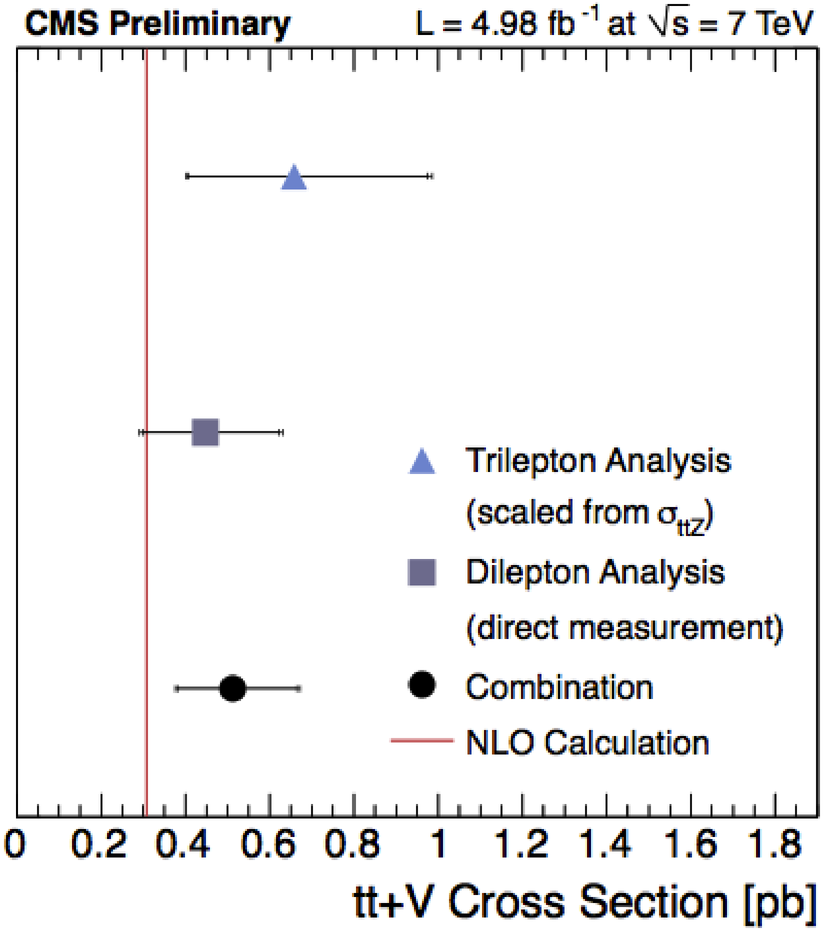
4.67σ significance

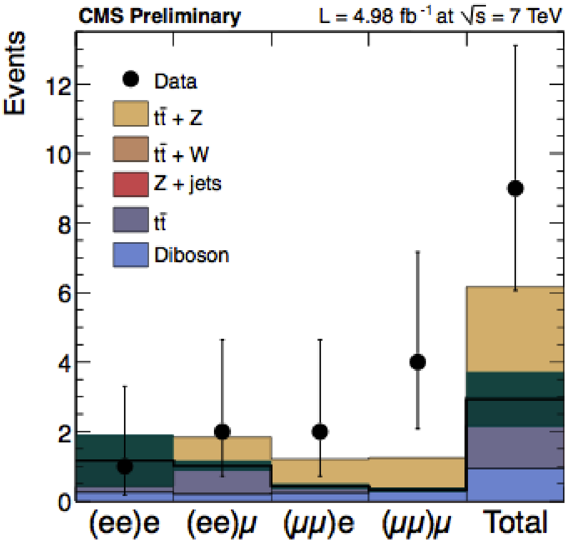
$$\sigma_{t\bar{t}Z} = 0.28\ ^{+0.14}_{-0.12}\ \mathrm{stat} \pm 0.04_{\mathrm{syst}}\quad \mathrm{pb}$$

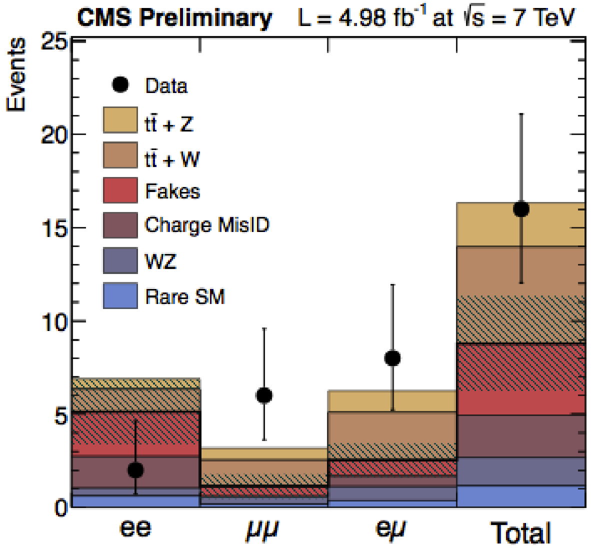
3.66σ significance

$$\sigma_{t\bar{t}W} = 0.30\ ^{+0.14}_{-0.11}\ \mathrm{stat}\ ^{+0.04}_{-0.02}\ \mathrm{syst}\quad \mathrm{pb}$$

2.44σ significance

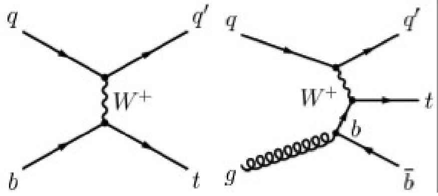






arXiv:1209.4533, *submitted to JHEP,* **CMS PAS TOP-12-011**

Single top: t-channel

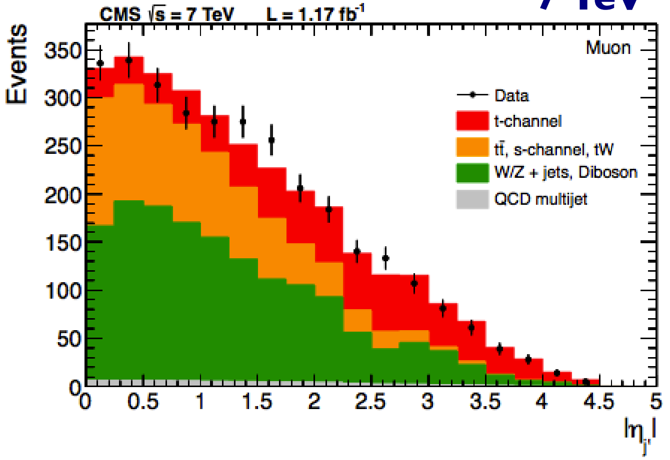


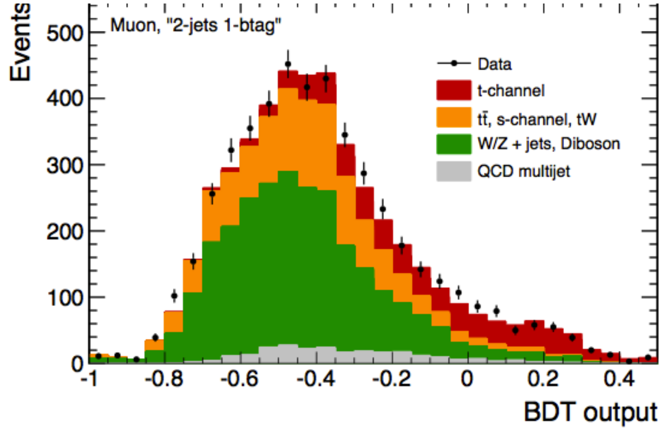
- **Dominant production channel**
  - **1 central, isolated lepton** + E_t^{miss}
  - expect **N(l^+) ≈ 1.9 N(l^-)**, i.e. N(t) ≈ 1.9 N(anti-t)
  - Main signal contribution in **1 b jet+1 forward recoil jet -** |η|<4.5

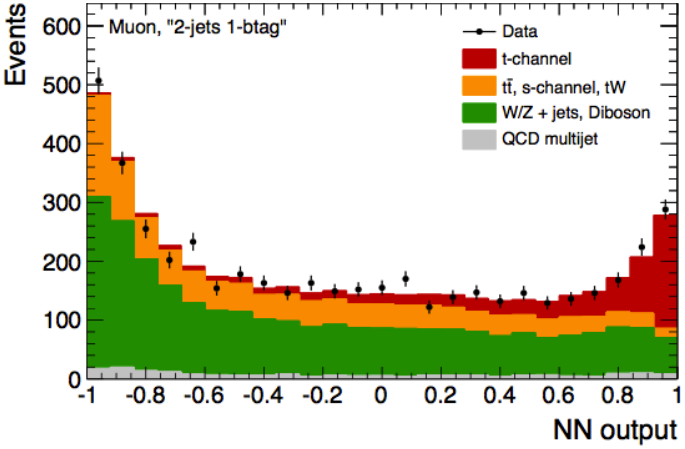
    (analysis may use however N_{jets}, N_{tags} categories)
- Main backgrounds:
  - **Top pair production**: assumed from simulation
  - **W+jets**: fit from the discriminator output or re-scaled from selection sideband (e.g. failing m_{lvb} requirement)
  - **Multijets**: fit to E_T^{miss}, or m_T spectrum with template from lepton selection side-band
- Measurement stems from 2 approaches:
  - **fit to angular variable - $\eta_{j'}$** – robust approach (7 and 8 TeV)
  - **multivariate analysis** (neural network and boosted decision tree) exploiting fully signal topology and maximizing significance (7 TeV only)

Combine individual to produce the final measurement

7 TeV







Results and V_{tb} extraction

Results

7 TeV

$$67.2 \pm 3.7_{\text{stat}} \pm 3.0_{\text{syst}} \pm 3.5_{\text{theor}} \pm 1.5_{\text{lum}} \text{ pb}$$

8 TeV

$$80.1 \pm 5.7_{\text{stat}} \pm 11.0_{\text{syst}} \pm 4.0_{\text{lum}} \text{ pb}$$

$$R_{8/7} = 1.14 \pm 0.12_{\text{stat}} \pm 0.14_{\text{syst}}^{*}$$

Notes: * - $R_{8/7}$ *using the* $\eta_{j'}$ *based cross section only*

Main uncertainties

- ***Experimental/background uncertainties*** :W+jets background, b-tagging
- ***Theoretical inputs for signal modeling*** as well as Q^2 for W+jets and top pairs

V_{tb} is (≈) the signal strength

$$|\underbrace{f_{L_V}}_{\textit{Anomalous form factor}} \underbrace{V_{\text{tb}}}_{\textit{Is it really 1?}}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{\text{th}}_{t\text{-ch.}}}}$$

or $|V_{\text{tb}}| = \sqrt{\frac{\sigma_{\text{tW}}}{\sigma^{\text{th}}_{\text{tW}}}}$

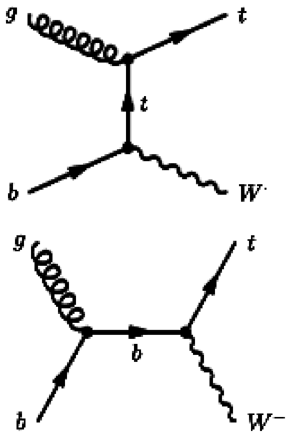
Results

t-channel, 7 TeV **best from single top**	*t-channel, 8 TeV*	*tW-channel, 7TeV*
$1.020 \pm 0.046_{\text{exp}} \pm 0.017_{th}$	$0.96 \pm 0.08_{\text{exp}} \pm 0.02_{th}$	$1.01 \,^{+0.16}_{-0.13}\text{ exp} \,^{+0.03}_{-0.04}\text{ th}$
$|V_{\text{tb}}| > 0.92$ @ 95%CL	$|V_{\text{tb}}| > 0.81$ @ 95%CL	$|V_{\text{tb}}| > 0.79$ @ 90%CL

arXiv:1209.3489, *submitted to PRL*

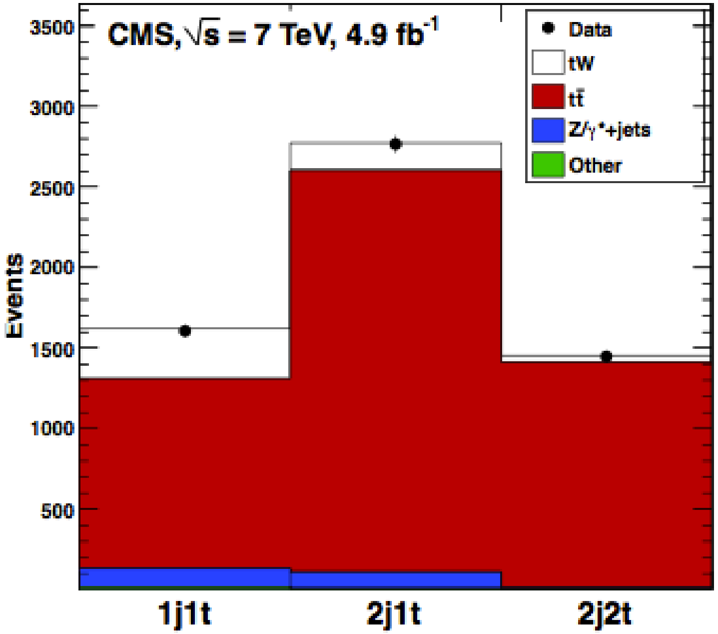
Single top: tW-channel

NEW

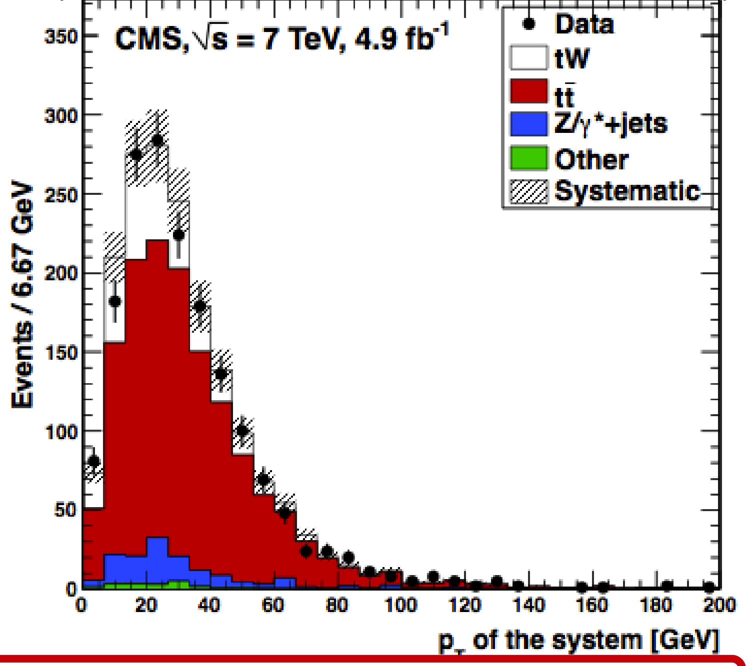


- **Final state: 2 leptons+1 b-jet+E_T^{miss}**
- At LO similar to top pair event with dilepton and only 1 b-jet in final state
  - 2nd b-jet veto is applied for signal region
  - **Balance** (p_T of the system): $\sum_{\text{leptons}} \vec{p}_T + \vec{p}_T^{\,\text{b-jet}} + \vec{p}_T^{\,\text{miss}}$
- **Categorize events** according to number of jets and b-tagging multiplicity
- Compare fit from **cut and count** to fit to **multivariate discriminator**

Cut and count events with H_T>60 GeV



H_T, balance, leading jet p_T, min $\Delta\varphi$(lepton,E_T^{miss})



Results

Cut and count
3.2σ significance
$15 \pm 5\,\text{pb}$

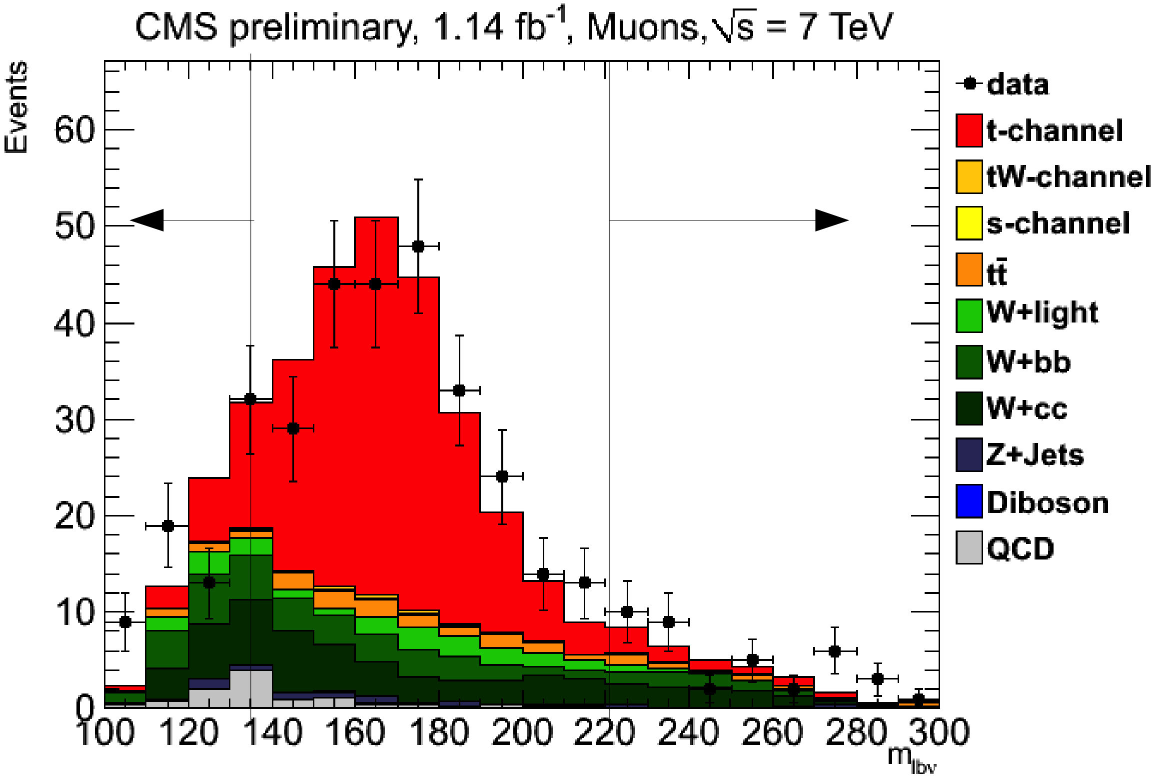
BDT
4σ significance
$16^{+5}_{-4}\,\text{pb}$

Background control for t-channel

- **QCD multijets** is controlled in the 2 jet 1 tag sample after fitting the low M_T region for the muon channel (low E_T^{miss} region for the electron channel)

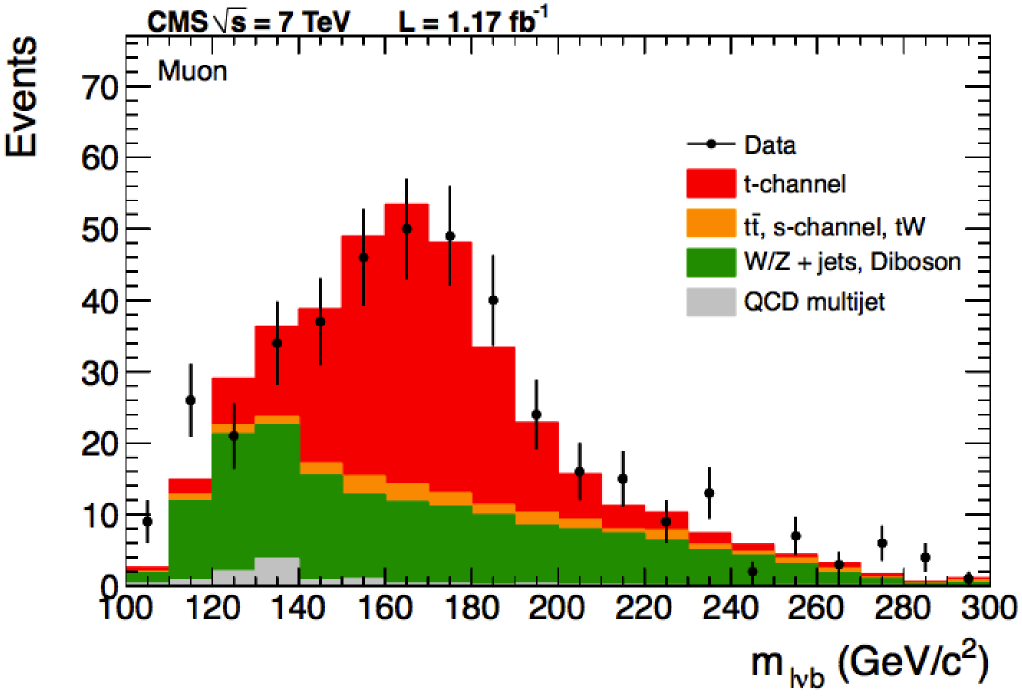
- Check shape and normalization of $|\eta_j|$ and m_{lvb} in 2 control regions:
  - 2 jets 0 tags: **W+light**
  - 3 jets 2 tags: **Ttbar**

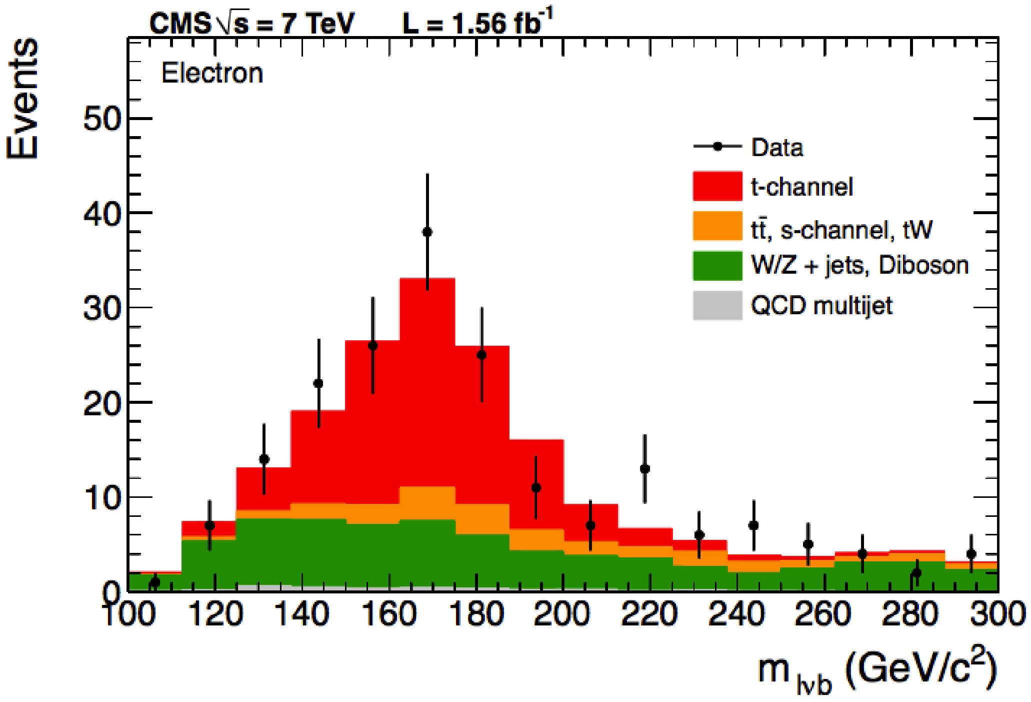
- **W+ jets** cross-checks
  - From EWK/ Ttbar cross section measurement it is expected to be 1.2 (W+b) / 1.7x (W+c) larger with respect to MC prediction
  - Control $|\eta_j|$ in the m_{lvb} sidebands ▶
  - Subtract TTbar, single top-s, -tW and dibosons from prediction
  - Derive the template for the W+heavy flavor contribution to be fit in the signal region



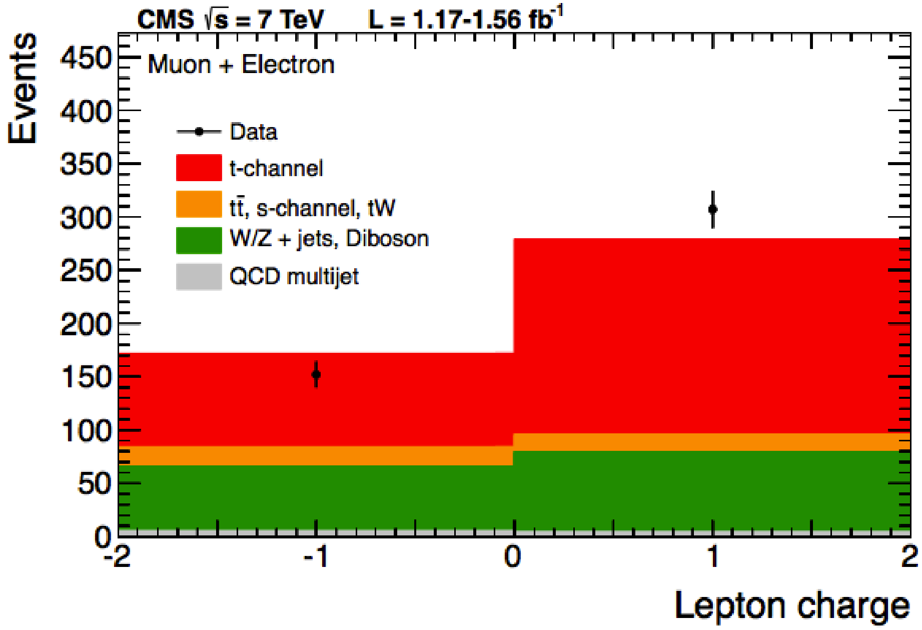
arXiv:1209.4533, *submitted to JHEP*

Further control distributions for single top t-channel





- Distributions obtained in the signal region
  - Using result of the fit to $\eta_{j'}$
  - For $|\eta_{j'}|$>2.8



Results for the t-channel

Results

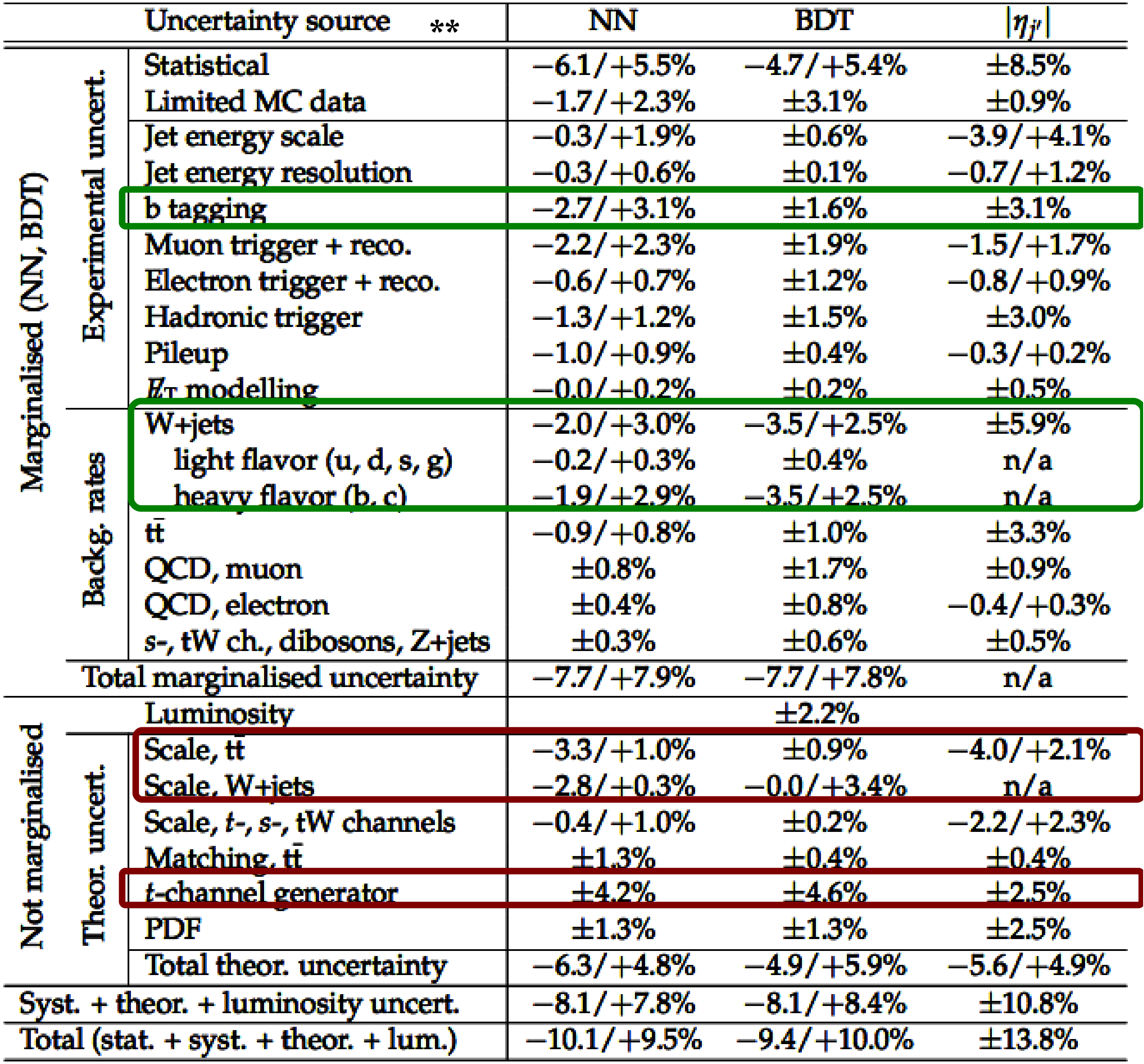
$$67.2 \pm 3.7_{\mathrm{stat}} \pm 3.0_{\mathrm{syst}} \pm 3.5_{\mathrm{theor}} \pm 1.5_{\mathrm{lum}}\ \mathrm{pb}$$

7 TeV

$$80.1 \pm 5.7_{\mathrm{stat}} \pm 11.0_{\mathrm{syst}} \pm 4.0_{\mathrm{lum}}\ \mathrm{pb}$$

8 TeV

$$R_{8/7} = 1.14 \pm 0.12_{\mathrm{stat}} \pm 0.14_{\mathrm{syst}}^{*}$$



		Uncertainty source **	NN	BDT	$\lvert\eta_{j'}\rvert$
Marginalised (NN, BDT)	Experimental uncert.	Statistical	−6.1/+5.5%	−4.7/+5.4%	±8.5%
		Limited MC data	−1.7/+2.3%	±3.1%	±0.9%
		Jet energy scale	−0.3/+1.9%	±0.6%	−3.9/+4.1%
		Jet energy resolution	−0.3/+0.6%	±0.1%	−0.7/+1.2%
		b tagging	−2.7/+3.1%	±1.6%	±3.1%
		Muon trigger + reco.	−2.2/+2.3%	±1.9%	−1.5/+1.7%
		Electron trigger + reco.	−0.6/+0.7%	±1.2%	−0.8/+0.9%
		Hadronic trigger	−1.3/+1.2%	±1.5%	±3.0%
		Pileup	−1.0/+0.9%	±0.4%	−0.3/+0.2%
		$\not{E}_T$ modelling	−0.0/+0.2%	±0.2%	±0.5%
	Backg. rates	W+jets	−2.0/+3.0%	−3.5/+2.5%	±5.9%
		light flavor (u, d, s, g)	−0.2/+0.3%	±0.4%	n/a
		heavy flavor (b, c)	−1.9/+2.9%	−3.5/+2.5%	n/a
		tt̄	−0.9/+0.8%	±1.0%	±3.3%
		QCD, muon	±0.8%	±1.7%	±0.9%
		QCD, electron	±0.4%	±0.8%	−0.4/+0.3%
		s-, tW ch., dibosons, Z+jets	±0.3%	±0.6%	±0.5%
	Total marginalised uncertainty		−7.7/+7.9%	−7.7/+7.8%	n/a
Not marginalised		Luminosity	±2.2%		
	Theor. uncert.	Scale, tt̄	−3.3/+1.0%	±0.9%	−4.0/+2.1%
		Scale, W+jets	−2.8/+0.3%	−0.0/+3.4%	n/a
		Scale, *t*-, *s*-, tW channels	−0.4/+1.0%	±0.2%	−2.2/+2.3%
		Matching, tt̄	±1.3%	±0.4%	±0.4%
		t-channel generator	±4.2%	±4.6%	±2.5%
		PDF	±1.3%	±1.3%	±2.5%
		Total theor. uncertainty	−6.3/+4.8%	−4.9/+5.9%	−5.6/+4.9%
Syst. + theor. + luminosity uncert.			−8.1/+7.8%	−8.1/+8.4%	±10.8%
Total (stat. + syst. + theor. + lum.)			−10.1/+9.5%	−9.4/+10.0%	±13.8%

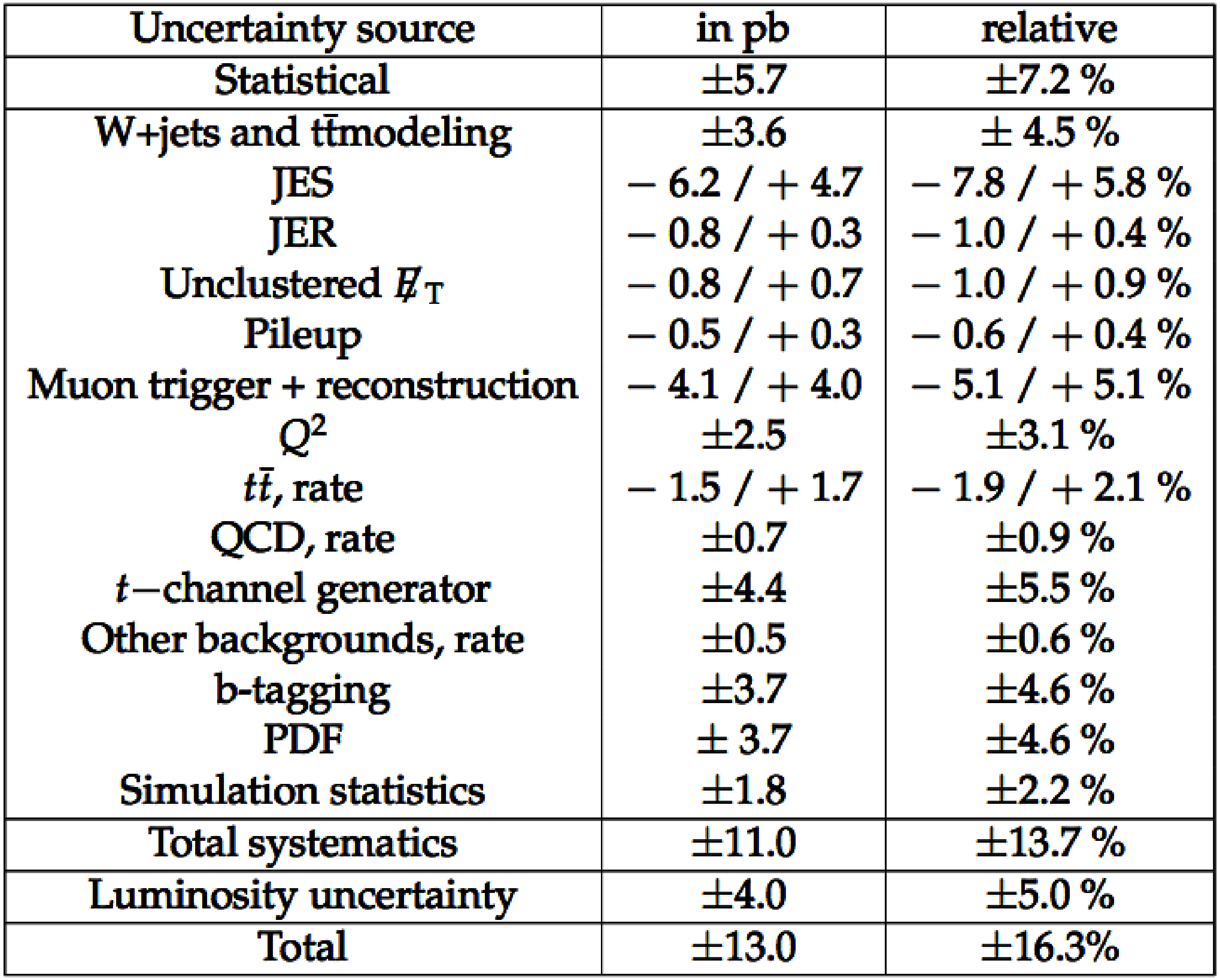
Main uncertainties

- ***Experimental/background uncertainties*** : W+jets background, b-tagging
- ***Theoretical inputs for signal modeling*** as well as Q^2 for W+jets and top pairs

Notes: * - $R_{8/7}$ using the $\eta_{j'}$ based cross section only / ** - table corresponds to the 7 TeV analysis

CMS PAS TOP-12-011

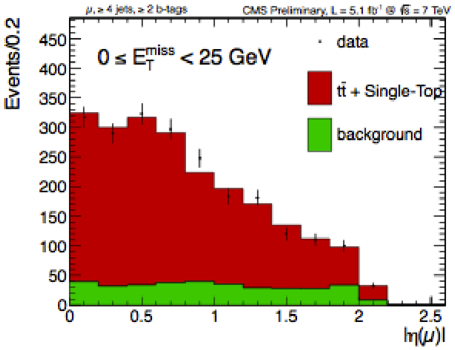
Uncertainties in the t-channel at 8 TeV

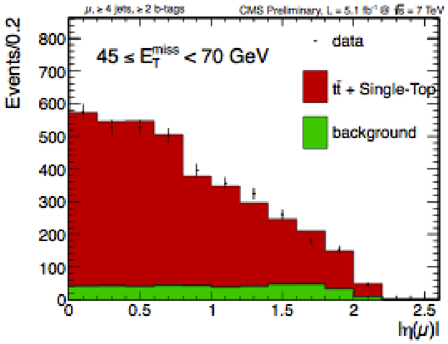


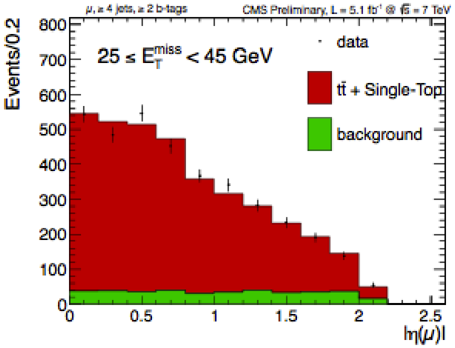
Uncertainty source	in pb	relative
Statistical	±5.7	±7.2 %
W+jets and $t\bar{t}$modeling	±3.6	± 4.5 %
JES	− 6.2 / + 4.7	− 7.8 / + 5.8 %
JER	− 0.8 / + 0.3	− 1.0 / + 0.4 %
Unclustered $\not{E}_T$	− 0.8 / + 0.7	− 1.0 / + 0.9 %
Pileup	− 0.5 / + 0.3	− 0.6 / + 0.4 %
Muon trigger + reconstruction	− 4.1 / + 4.0	− 5.1 / + 5.1 %
Q^2	±2.5	±3.1 %
$t\bar{t}$, rate	− 1.5 / + 1.7	− 1.9 / + 2.1 %
QCD, rate	±0.7	±0.9 %
$t-$channel generator	±4.4	±5.5 %
Other backgrounds, rate	±0.5	±0.6 %
b-tagging	±3.7	±4.6 %
PDF	± 3.7	±4.6 %
Simulation statistics	±1.8	±2.2 %
Total systematics	±11.0	±13.7 %
Luminosity uncertainty	±4.0	±5.0 %
Total	±13.0	±16.3%

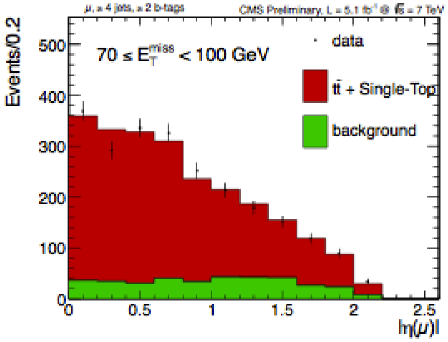
$t\bar{t}$+MET

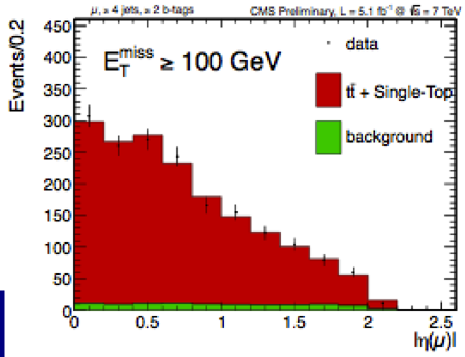
- High purity after requiring 2 b-tags
- Distinctive feature: *leptons from tt are central*
- Fit signal contribution in E_T^{miss} bins



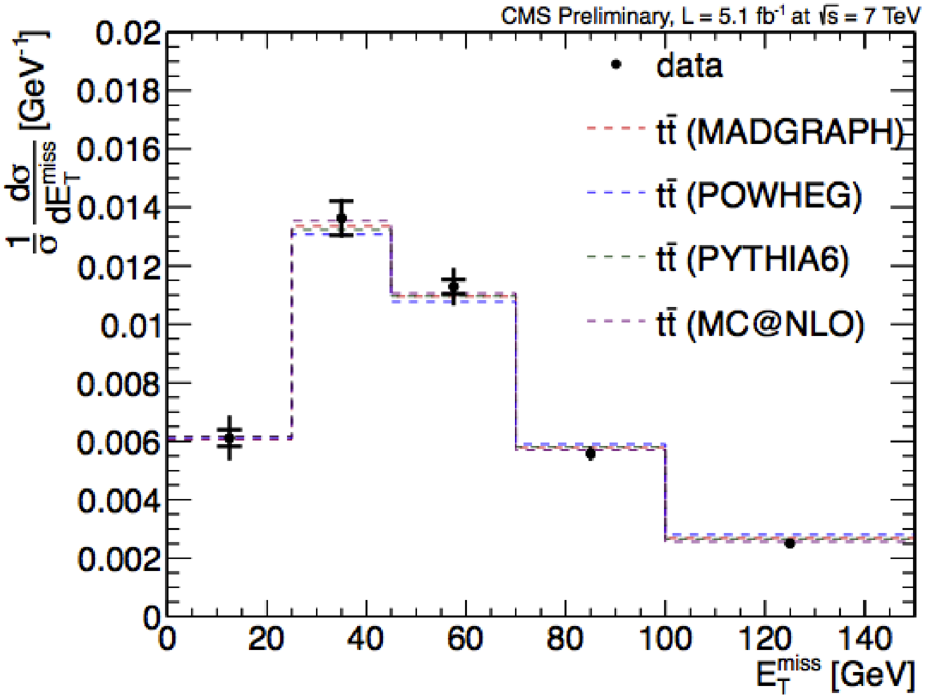








- Comparison with different generators
- **LO**
  - Madgraph interfaced with PYTHIA: ME+PS
  - PYTHIA only PS
- **NLO**
  - MC@NLO Is interfaced with Herwig
  - Powheg is interfaced with PYTHIA



More on m_{top} from kinematic endpoints

- Unbinned likelihood fit
  - 3 variables: $M_{T2\perp}^{210}$ $M_{T2\perp}^{221}$ and M_{bl}
  - The likelihood component for each observable expressed in terms of the observable and endpoint

$$\mathcal{L}(\mathbf{M}) = \prod_{i=1}^{N} \mathcal{L}_i^{210}(\mathbf{u}_i|\mathbf{M}) \cdot \mathcal{L}_i^{221}(\mathbf{u}_i|\mathbf{M}) \cdot \mathcal{L}_i^{M_{b\ell}}(\mathbf{u}_i|\mathbf{M})$$

$$M_{T2\perp}^{\max}(210) \equiv x_{\max} = \frac{M_W}{2}\left(1-\frac{m_\nu^2}{M_W^2}\right) + \sqrt{\frac{M_W^2}{4}\left(1-\frac{m_\nu^2}{M_W^2}\right)^2 + \tilde{M}_C^2}.$$

$$M_{T2\perp}^{\max}(221) = \frac{M_t}{2}\left(1-\frac{M_W^2}{M_t^2}\right) + \sqrt{\frac{M_t^2}{4}\left(1-\frac{M_W^2}{M_t^2}\right)^2 + \tilde{M}_C^2}$$

$$M_{b\ell}^{\max} = \frac{1}{M_W}\sqrt{(M_t^2 - M_W^2)(M_W^2 - m_\nu^2)}.$$

- Low correlation
- Distinct signal shapes
- LO-based parameterizations

- For each variable the individual likelihood is

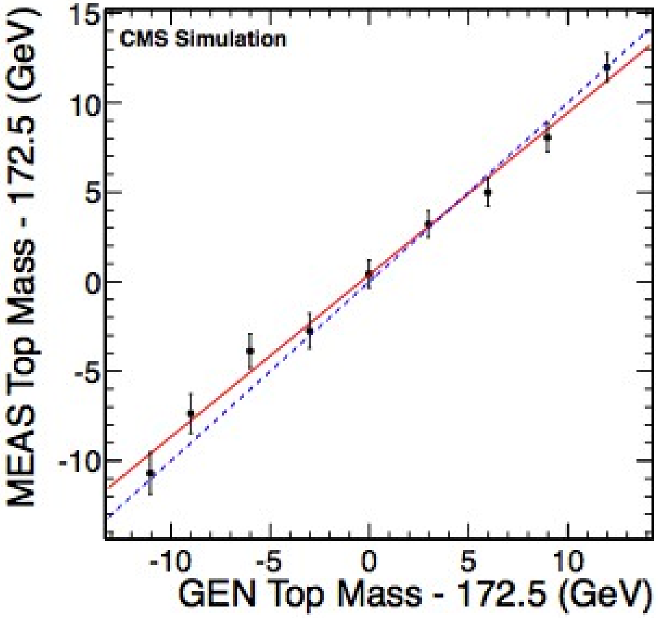
$$\mathcal{L}_i^a(x_i|x_{\max}) = \alpha \int \underline{S^a(y|x_{\max})}\,\underline{\mathcal{R}_i^a(x_i-y)}\,dy + \underline{(1-\alpha)B^a(x_i)}$$

Signal is parametrized as a kinked-line shape

$$S(x|x_{\max}) \equiv \begin{cases} \mathcal{N}(x_{\max}-x) & x_{lo} \le x \le x_{\max} \\ 0 & x_{\max} \le x \le x_{hi} \end{cases}$$

Parametrizes the resolution

Background shape

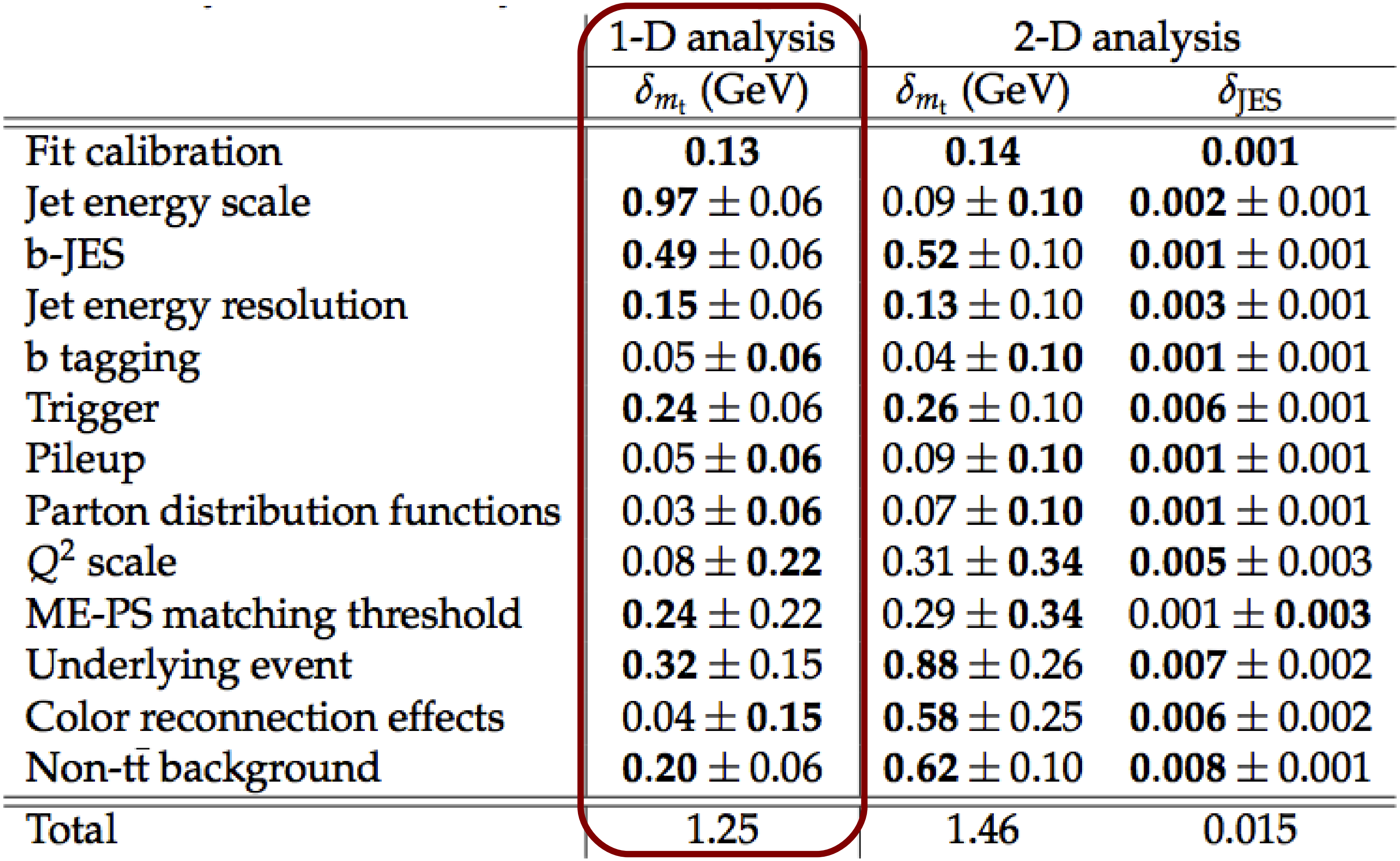


- Fit range is chosen to minimize the dependency of the fit result

CMS PAS TOP-11-017

Uncertainties in full hadronic m_{top}

- **1-D analysis** yields **the best uncertainty** in the determination of mtop
- **If stat. uncertainty** associated to the determination of syst. uncertainty **is larger it is conservatively taken as the systematic uncertainty**

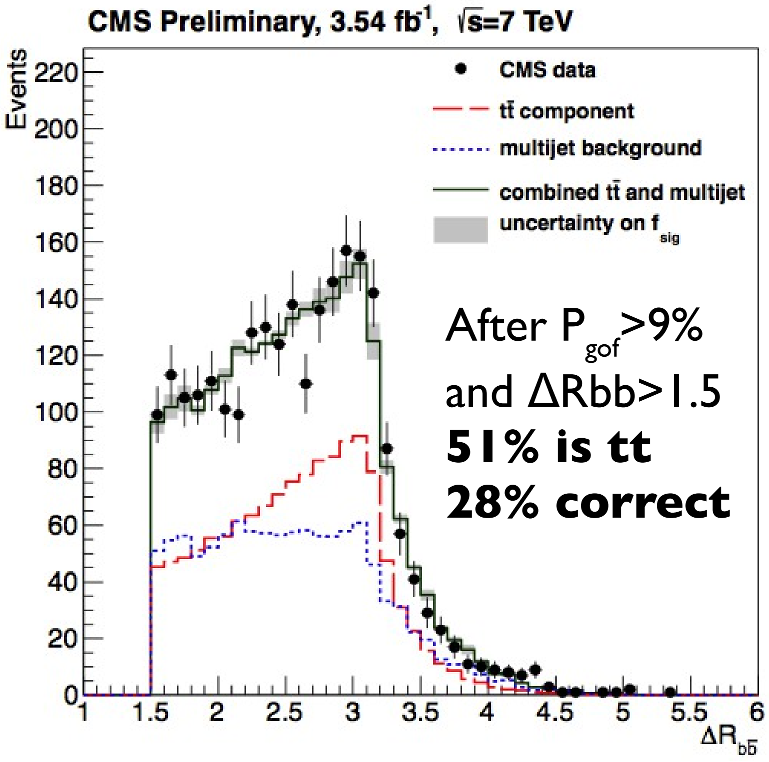


	1-D analysis	2-D analysis	
	δ_{m_t} (GeV)	δ_{m_t} (GeV)	δ_JES
Fit calibration	**0.13**	**0.14**	**0.001**
Jet energy scale	**0.97** ± 0.06	0.09 ± **0.10**	**0.002** ± 0.001
b-JES	**0.49** ± 0.06	**0.52** ± 0.10	**0.001** ± 0.001
Jet energy resolution	**0.15** ± 0.06	**0.13** ± 0.10	**0.003** ± 0.001
b tagging	0.05 ± **0.06**	0.04 ± **0.10**	**0.001** ± 0.001
Trigger	**0.24** ± 0.06	**0.26** ± 0.10	**0.006** ± 0.001
Pileup	0.05 ± **0.06**	0.09 ± **0.10**	**0.001** ± 0.001
Parton distribution functions	0.03 ± **0.06**	0.07 ± **0.10**	**0.001** ± 0.001
Q^2 scale	0.08 ± **0.22**	0.31 ± **0.34**	**0.005** ± 0.003
ME-PS matching threshold	**0.24** ± 0.22	0.29 ± **0.34**	0.001 ± **0.003**
Underlying event	**0.32** ± 0.15	**0.88** ± 0.26	**0.007** ± 0.002
Color reconnection effects	0.04 ± **0.15**	**0.58** ± 0.25	**0.006** ± 0.002
Non-$t\bar{t}$ background	**0.20** ± 0.06	**0.62** ± 0.10	**0.008** ± 0.001
Total	1.25	1.46	0.015

CMS PAS TOP-11-017

Top mass from jets only

- At least 6 jets (2 b-tagged with p_T>30 GeV)
- Choose permutation with lowest χ^2 after kinematics fit
- **Multijets background modeled from data** using event mixing from pre-selected sample

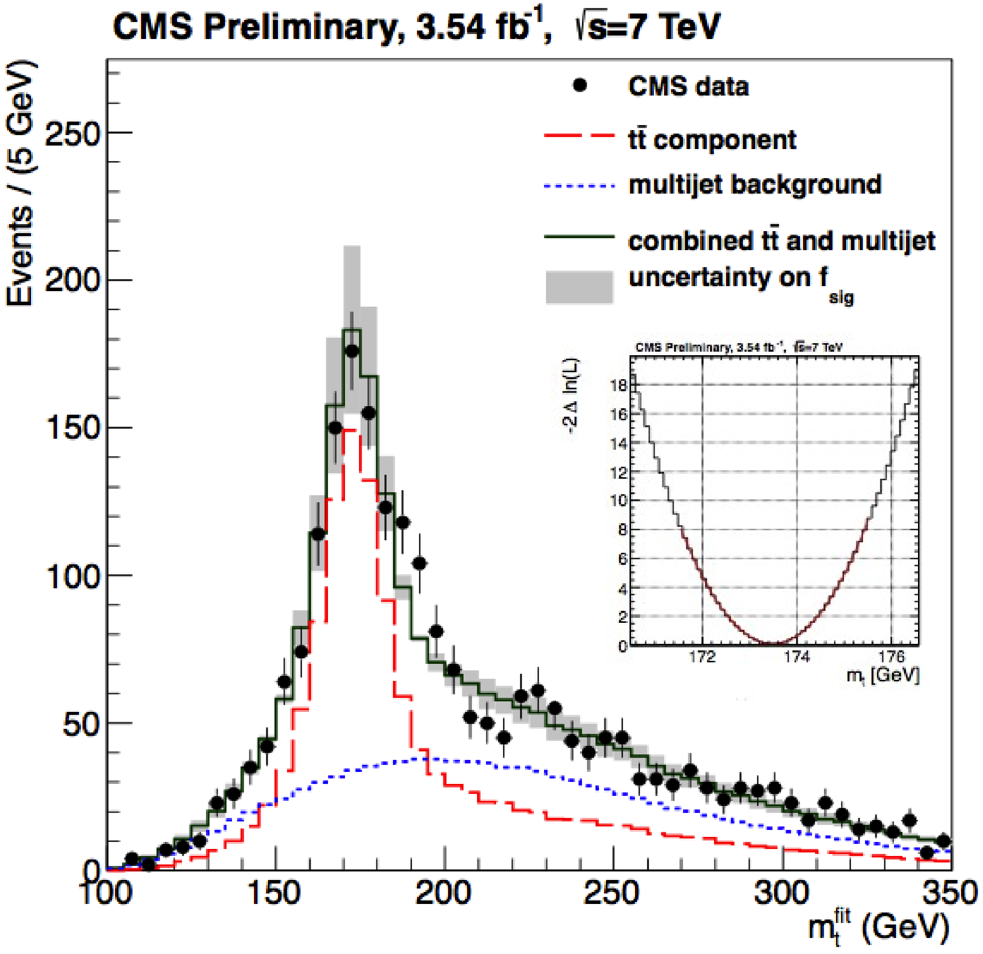


After P_{gof}>9%

and ΔRbb>1.5

51% is tt

28% correct



- Ideogram method is applied (similar to l+jets)
- Best result attained assuming nominal JES

(JES is dominant uncertainty 1.09 GeV)

Result – best in all hadronic

$$173.49 \pm 0.69\ (\text{stat.}) \pm 1.25\ (\text{syst.})\ \text{GeV}$$