Top-Quark Mass Measurements: Alternative Techniques (LHC+Tevatron)

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on behalf of the CDF, D0, ATLAS and CMS collaborations

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Standard – Alternative Techinques

Standard measurements:

- ▷ based on the reconstruction of the top quark pair event kinematics
- ▷ mass calibration performed using MC $\leftrightarrow$ $m_t^{measured} = m_t^{MC}$
- ▷ large sensitivity to JES uncertainty unless in-situ constraints are exploited
- ▷ using $t\bar{t}$ final states

Alternative measurements:

- ▷ use observables / final states sensitive to different systematic uncertainties
- ▷ extract top quark mass in well-defined renormalisation scheme ($\leftrightarrow$ comparison with theoretical calculation)

hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\mathrm{MS}}}(m_t) = \frac{M_t}{1 + \frac{4}{3\pi}\alpha_s(M_t)}$$

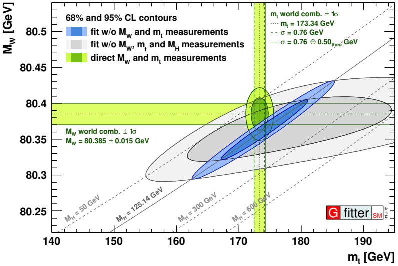
$\overline{\mathrm{MS}}$ scheme

pole mass

$$\frac{1}{p^2 - M_t^2 - i\Gamma_t M_t}$$

$\rightarrow \Delta(m_t^{pole}, m_t^{\overline{MS}}) \approx 10$ GeV

arXiv:1407.3792

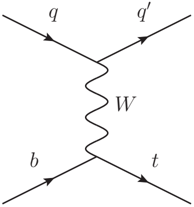


$\rightarrow m_t^{MC} = m_t^{pole}$ within 1 GeV

m_t Using Single Top t-Channel Enhanced Events (ATLAS)

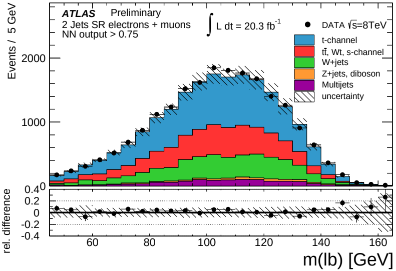
$\sqrt{s} = 8$ TeV (L $= 20.3$ fb^{-1}), single top t-channel ATLAS-CONF-2014-055

- ▷ *measured m_t in a sample enriched by top quarks produced via weak interactions*



- ▷ basic event selection + background estimate similar to single top t-channel x-section measurement (ATLAS-CONF-2014-007), see talk by A. Jafari

- ▷ neural network selection:
  - ▷ training done only against non-top backgrounds
  - ▷ possible bias due to mass dependence of input variables has been checked and excluded



m_t Using Single Top t-Channel Enhanced Events (ATLAS)

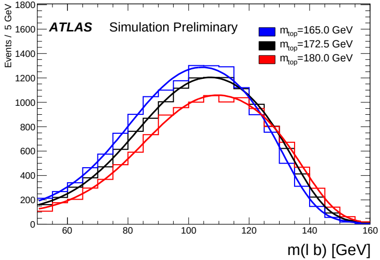
$\sqrt{s} = 8$ TeV (L $= 20.3$ fb^{-1}), single top t-channel ATLAS-CONF-2014-055

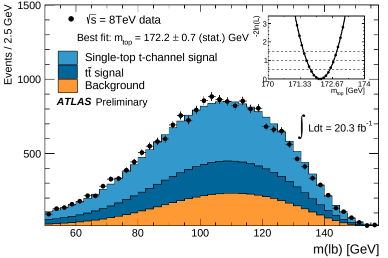
NEW

- final sample composition:
  t-channel $\approx 50\%$, $t\bar{t} \approx 23\%$,
  background $\approx 27\%$
- template method:
  - based on m_{lb} estimator
    (lepton + b-jet invariant mass)
  - signal templates include
    all single top channels + $t\bar{t}$
- binned likelihood fit:

$m_t = 172.2 \pm 0.7\,(\text{stat.}) \pm 2.0\,(\text{syst.})\,\text{GeV}$

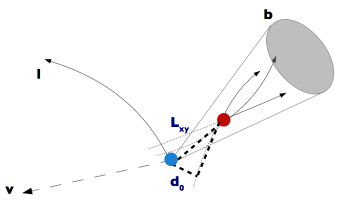
- dominant systematic uncertainties:
  - JES (1.5 GeV)
  - (t-channel) hadronisation (0.7 GeV)
  - background (0.6 GeV)





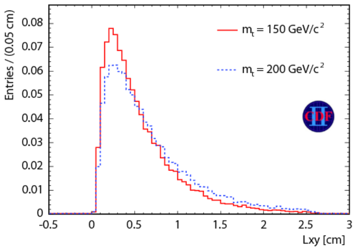
B-hadron Lifetime / Lepton p_T

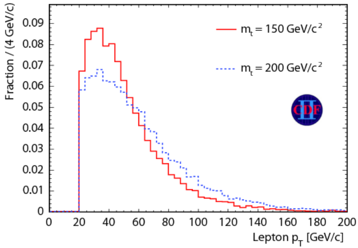
- lifetime and (transverse) decay length (L_{xy}) of B-hadrons from the top decay depend ∼linearly on m_t
- similarly, p_T of the charged leptons from the W boson decay can be used



- L_{xy} and lepton-p_T reconstruction based on the tracking (muon) system(s) and EM calo (for e), largely reduced sensitivity to JES unc., however typically larger statistical uncertainties ($\neq$ standard techniques)

Phys.Rev.D81 032002 (2010)



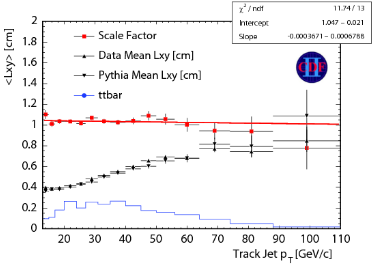


B-hadron Lifetime / Lepton p_T (CDF)

L $= 1.9$ fb^{-1}, ℓ+jets channel

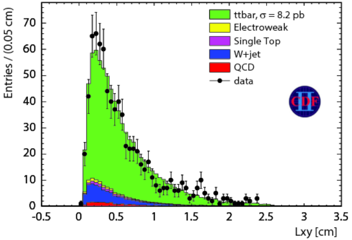
Phys.Rev.D81 032002 (2010)

- ▷ sensitive to:
  - ▷ modelling of top-p_T ($\leftrightarrow$ PDFs)
  - ▷ L_{xy} calibration (b-fragmentation, tracking modelling)
    - $\Rightarrow$ dedicated L_{xy} calibration using $b\bar{b}$ events



- ▷ simultaneous fit to L_{xy} / lepton p_T:

$m_t = 170.7 \pm 6.3\,(\text{stat.}) \pm 2.6\,(\text{syst.})\,\text{GeV}$

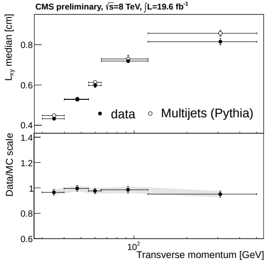


- ▷ systematic uncertainties dominated by:
  - ▷ background shape (1.7 GeV)
  - ▷ lepton p_T scale (1.2 GeV)
  - ▷ L_{xy} calibration (1.1 GeV)
- ▷ calorimeter JES uncertainty: 0.3 GeV

→ Phys.Lett.B698:371-379,2011: $m_t = 176.9 \pm 8.0(\text{stat}) \pm 2.7(\text{syst})$ GeV (lepton p_T only)

$\sqrt{s} = 8$ TeV (L $=$ 19.3-19.6 fb^{-1}),
ℓ+jets and dilepton ($e\mu$) channels

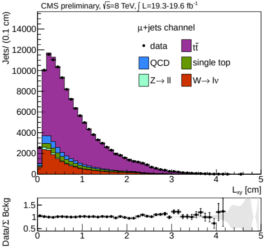
CMS PAS TOP-12-030

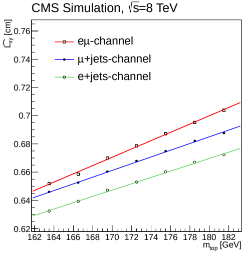


- ▷ L_{xy} calibration checked in dijet sample
  $\rightarrow$ agreement within stat. uncertainties between data and simulation

- ▷ fit to median L_{xy}:

$$m_t = 173.5 \pm 1.5\,(\text{stat.}) \pm 1.3\,(\text{syst.}) \pm 2.6\,(p_T^{\text{top}})\;\text{GeV}$$





- ▷ dominant sources of systematic uncertainty:
  - ▷ top p_T modelling
  - ▷ background in ℓ + jets
  - ▷ hadronisation model

Kinematic Endpoints (CMS)

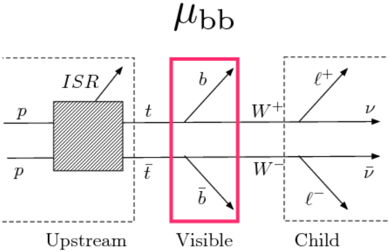
Eur. Phys. J. C 73 (2013) 2494

▷ use transverse mass of $t\bar{t}$ pair:

$$M_{T2} \equiv \min_{\mathbf{p}_T^{\nu a}+\mathbf{p}_T^{\nu b}=\mathbf{p}_T^{miss}} \{\max(m_T^a, m_T^b)\}$$

$\leftrightarrow$ transverse W mass:

$$M_{T,W}^2 \equiv m_\nu^2 + m_\ell^2 + 2(E_T^\nu E_T^\ell - \mathbf{p}_T^\nu \cdot \mathbf{p}_T^\ell)$$



▷ to reduce the sensitivity to the p_T modelling of the $t\bar{t}$ system, use only components perpendicular to the boost of the $t\bar{t}$ pair: $M_{T2} \rightarrow M_{T2\perp} \equiv \mu_{bb}$

▷ endpoint: $\mu_{bb}^{max} = m_t$

▷ ν and W boson masses constrained to their world-average values (method otherwise applicable for BSM searches including undetected particles)

▷ mass measurement based on analytic endpoint formula

$\Rightarrow$ model-independent mass measurement

Kinematic Endpoints (CMS)

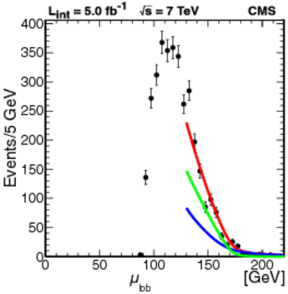
$\sqrt{s} = 7$ TeV (L $= 5.0$ fb^{-1}), dilepton channel

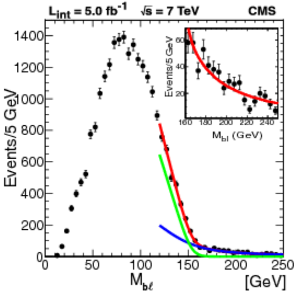
Eur. Phys. J. C 73 (2013) 2494

- ▷ simultaneous, unbinned likelihood fit to endpoints of μ_{bb} and M_{bl}
- ▷ taking resolution into account

$$m_t = 173.9 \pm 0.9\,(\text{stat.})^{+1.7}_{-2.2}\,(\text{syst.})\,\text{GeV}$$

- ▷ dominant source of systematic uncertainty: JES $^{+1.3}_{-1.8}\,\text{GeV}$





M_{bl}: invariant mass of lepton + b-jet pair

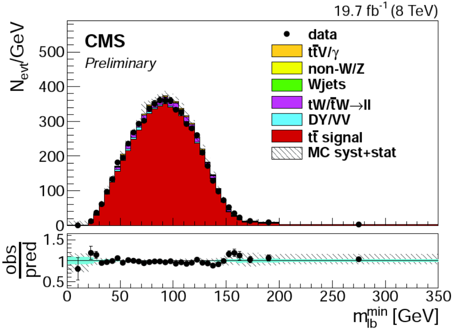
Using m_{lb} and Forward Folding (CMS)

$\sqrt{s} = 8$ TeV (L = 19.7 fb^{-1}),
dilepton channel: $e\mu$, 1 loose b-tag

CMS PAS TOP-14-014

NEW

- $m_{lb,min}$=min($m_{\ell 1,b1}$,$m_{\ell 2,b2}$)
  - 85% correct combinations
- provide $m_{lb,min}$ distribution at reconstruction level, in fiducial volume



Using m_{lb} and Forward Folding (CMS)

- provide response matrix

  $$\mathcal{M}_{ij}^{resp} = N_{ij} / \sum_{j=0}^{n} N_{ij}$$

  NEW

  - computed using MadGraph+Pythia
  - one for each syst. variation and for 7 values m_t

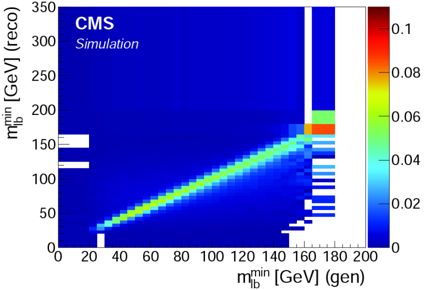
- fold any predicted m_{lb} distribution to reco level: $\vec{x}_{reco} = \mathcal{L}\ \mathcal{M}^{resp} \vec{x}_{pred}$ and extract mass, e.g. using MCFM (NLO):

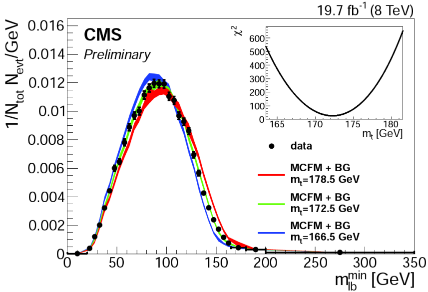
  $$m_t = 171.4^{+1.0}_{-1.1}\ \text{GeV}$$

- in addition to (or instead of) shape can use rate and absolute cross-section only
  - NNLO+MadGraph, rate only:

  $$m_t = 173.7^{+3.5}_{-3.4}\ \text{GeV}$$

CMS PAS TOP-14-014

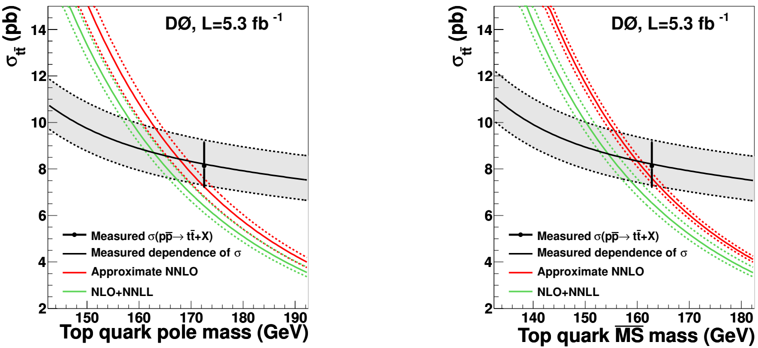




Top-Quark Mass from $t\bar{t}$ x-Section

- *compare experimental $\sigma_{t\bar{t}}$ with theory computation*
  - $\rightarrow$ *measure m_t in well defined renormalisation scheme (m_t^{pole}, $m_t^{\overline{MS}}$)*
  - $\rightarrow$ *m_t^{MC} only enters via top mass dependence of measured $\sigma_{t\bar{t}}$ due to event selection criteria*
- compare measured and predicted cross-section to find most probable m_t ($\leftrightarrow$ likelihood maximisation)

PLB 703 , 422 (2011)



m_t^{pole} and $m_t^{\overline{MS}}$ from $t\bar{t}$ x-Section (D0)

$\sqrt{s} = 1.96$ TeV (L $= 5.3$ fb^{-1}): ℓ + jets channel PLB 703 , 422 (2011)

▷ theory calculation at approximate NNLO

(JHEP 0307 (2003) 001, Comput. Phys. Commun. 135 (2001) 238)

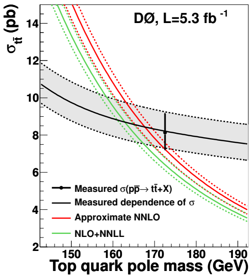
▷ theory uncertainties:

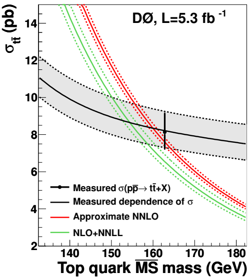
- ▷ renormilisation/factorisation scales (up/down variation by factor 2)
- ▷ PDF uncertainty

▷ assuming $m_t^{MC} = m_t^{\overline{MS}}$ results in shift of

- ▷ $\Delta m_t^{pole} = -2.7\,\mathrm{GeV}$
- ▷ $\Delta m_t^{\overline{MS}} = -2.6\,\mathrm{GeV}$

→ half of shift included in systematic uncertainties





$m_t^{pole} = 167.5^{+5.2}_{-4.7}$ GeV $\quad m_t^{\overline{MS}} = 160.0^{+4.8}_{-4.2}$ GeV

→ PRD 80 , 071102 (2009): $m_t^{pole} = 169.1^{+5.9}_{-5.2}$ (ℓ+jets + dilepton channel)

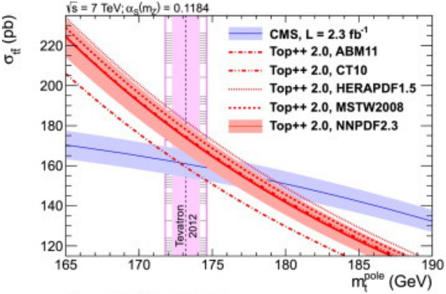
Top-Quark Pole Mass from $t\bar{t}$ x-Section (CMS)

$\sqrt{s} = 7$ TeV (L $= 2.3$ fb^{-1}), dilepton channel

- ▷ theory calculation using Top++ (PDF: NNPDF2.3)
- ▷ uncertainties:
  - ▷ $\sigma_{t\bar{t}}^{meas}$: $^{+2.1}_{-2.0}$
  - ▷ LHC beam energy: $^{+0.9}_{-0.9}$
  - ▷ PDF: $^{+1.5}_{-1.3}$, $\mu_{R,F}$: $^{+0.9}_{-0.9}$, α_S: $^{+0.7}_{-0.7}$
  - ▷ m_t^{MC}: $^{+0.5}_{-0.4}$

→ dominated by experimental uncertainties

Phys. Lett. B 728 (2014) 496



- ▷ fixed $\alpha_S(m_Z) = 0.1184 \pm 0.0007$:
  $m_t^{\mathrm{pole}} = 176.7^{+3.0}_{-2.8}\,\mathrm{GeV}$
- ▷ fixed $m_t = 173.2 \pm 1.4$ GeV:
  $\alpha_S(m_Z) = 0.1151^{+0.0028}_{-0.0027}$

Top-Quark Pole Mass from $t\bar{t}$ x-Section (ATLAS)

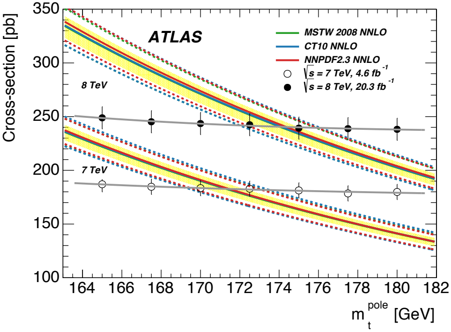
$\sqrt{s} = 7/8$ TeV (L $= 4.6/20.3$ fb^{-1}).
dilepton (e/μ) channel

- ▷ theory calculation using Top++ (PDF4LHC)
- ▷ small m_t^{MC}-dependence of measured $\sigma_{t\bar{t}}$

Theoretical uncertainties:

- ▷ including PDF / α_s / QCD scale uncertainties
- ▷ slightly larger compared to exp. uncertainties from meas. $\sigma_{t\bar{t}}$

arXiv:1406.5375



$$m_t^{\text{pole}} = 171.4 \pm 2.6\,\text{GeV} \;(\sqrt{s} = 7\,\text{TeV})$$

$$m_t^{\text{pole}} = 174.1 \pm 2.6\,\text{GeV} \;(\sqrt{s} = 8\,\text{TeV})$$

$$m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}\,\text{GeV} \;(\sqrt{s} = 7/8\,\text{TeV})$$

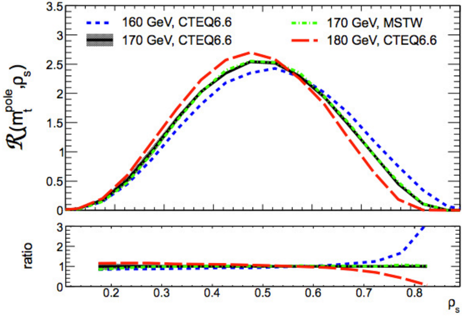
Top-Quark Pole Mass Using $t\bar{t}$+1-jet Events (ATLAS)

⇒ *exploit m_t^{pole} dependence of normalised $t\bar{t}$+1-jet differential cross-section, as a function of the inverse of the invariant mass of the $t\bar{t}$+1-jet system*

$$\mathcal{R}(m_t^{pole}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1-\mathrm{jet}}} \frac{d\sigma_{t\bar{t}+1-\mathrm{jet}}}{\rho_s}(m_t^{pole}, \rho_s)$$

with $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}j}}}$ and $m_0 = 170\ GeV$

Eur.Phys.J C73 (2013) 2438



▷ enhanced m_t-sensitivity w.r.t. $\sigma_{t\bar{t}}$ through usage of differential distribution

▷ theoretical calculations performed at NLO+PS accuracy

▷ compared to measured differential cross-section, corrected for detector and resolution effects

Top-Quark Pole Mass Using $t\bar{t}$+1-jet Events (ATLAS)

$\sqrt{s} = 7$ TeV (L $= 4.6$ fb^{-1}), ℓ+jets channel ATLAS-CONF-2014-053

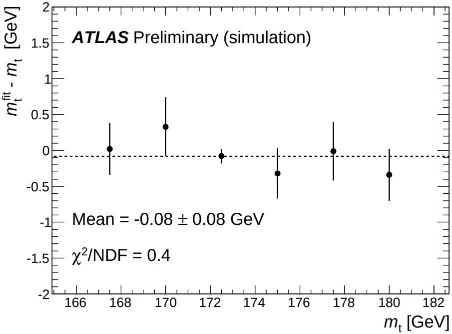
NEW

▷ kinematical event reconstruction to identify W- and t-candidates, "additional jet" with $p_T > 50\,\mathrm{GeV}$

▷ regularised matrix unfolding to correct for detector effects

▷ compare data to NLO+PS prediction at parton-level

▷ no m_t^{MC} dependence due to MC based correction observed



Top-Quark Pole Mass Using $t\bar{t}$+1-jet Events (ATLAS)

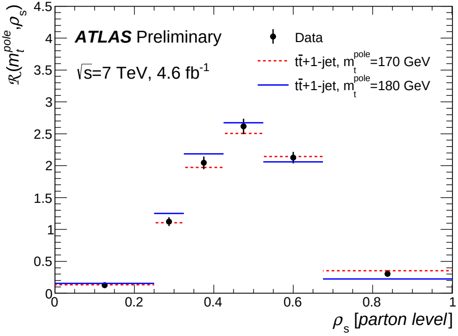
$\sqrt{s} = 7$ TeV (L = 4.6 fb^{-1}), ℓ+jets channel — ATLAS-CONF-2014-053

NEW

- fit with NLO+PS prediction:

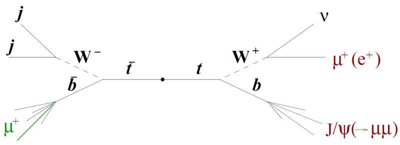
$$m_t^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat.}) \pm 1.4\,(\text{syst.})\,^{+1.0}_{-0.5}(\text{theo.})\,\text{GeV}$$

- dominant sources of systematic uncertainty:
  - JES: 0.94 GeV
  - ISR/FSR: 0.72 GeV
  - proton PDF: 0.54 GeV
- theorie uncertainties (on NLO+PS prediction):
  - scale uncertainty: $^{+0.93}_{-0.44}$ GeV
  - PDF uncertainty: 0.21 GeV
  - (α_S: 0.01 GeV)



J/Ψ Peak: Prospects

- select $t\bar{t}$ events with $b \to J/\Psi$ $(+J/\Psi \to \ell\ell)$
- rare but experimentally very clean

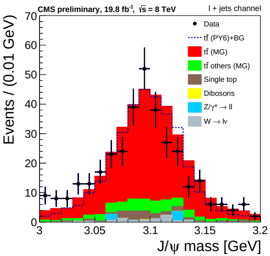


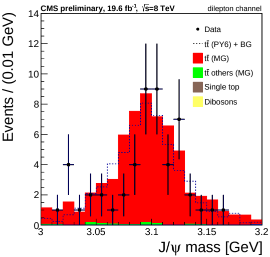
- exploit m_t dependence of $M_{J/\Psi+\ell}$ (Phys. Lett. B 476 (2000) 73)

- $\sqrt{s} = 8$ TeV (L $= 19.6/19.8$ fb^{-1})

CMS PAS TOP-13-007

  - $b \to J/\Psi + X$ signal in ℓ+jets and dilepton $t\bar{t}$ events
  - competitive using higher statistics in RunII?
  - might be difficult due to large sensitivity to details of b-fragmentation





Alternative Top-Quark Mass Measurements - Summary

- for the first time, m_t has been extracted in single top events
- exploited new techniques: compare data to theoretical calculation (MCFM), folded to reconstruction level
- alternative methods are approaching precision of standard measurements
- m_t^{pole} has been measured with
  - $\Delta m_t^{pole} =^{+2.5}_{-2.6}$ from $\sigma_{t\bar{t}}$ with minimum m_t^{MC}- dependence
  - $\Delta m_t^{pole} =^{+2.3}_{-2.1}$ GeV using differential $t\bar{t} + 1$ jet x-section