# Non-standard measurements of the top mass

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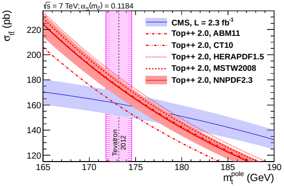
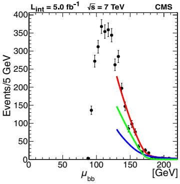
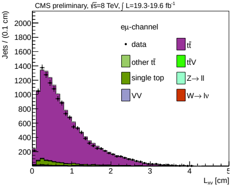
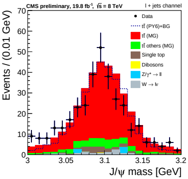
Top-mass mini-workshop of the TOPLHCWG

21st May 2014



# What is a "non-standard" $m_t$ measurement?

Standard measurements:

- mainly via kinematic reconstruction of $m_{qqb}$ or $m_{\ell\nu b}$ (as input to a template, ideogram, or matrix-element method)
- calibrated using relation between reconstructed observable and $m_t$ in (N)LO+PS simulation $\rightarrow$ "$m_t^{\mathrm{MC}}$"
- jet energy scale (JES) typically dominant systematic uncertainty

Alternative measurements:

- different systematic uncertainties

and/or

- access to different $m_t$ definitions, without or with reduced dependence on $m_t^{\mathrm{MC}}$

# Outline

Will go through

a) idea

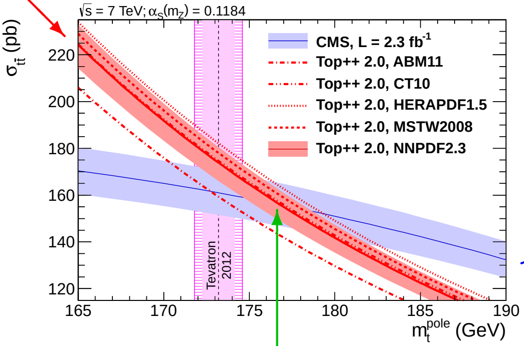
b) status

c) prospects

of $m_t$ measurements from:

1. $t\bar{t}$ cross sections
2. kinematic endpoints
3. B-hadron lifetime
4. J/$\psi$ final states

Predicted $t\bar{t}$ cross section depends on the value of $m_t$




$m_t^{MC}$ only enters via acceptance corrections for measured $\sigma_{t\bar{t}}$

Determine most-probable $m_t$ by comparing measured and predicted $\sigma_{t\bar{t}}$

This yields $m_t$ well defined in the scheme (pole, $\overline{\text{MS}}$, ...) that was used for the cross-section calculation

# Top-mass from cross sections: *Status*

Since March 2013: $\sigma(t\bar{t} + X)$ calculated to full NNLO+NNLL QCD

→ Uncertainties from higher orders ($\mu_R$, $\mu_F$), PDF, and $\alpha_S$ now ≈3% each

Relation between $m_t^{\text{pole}}$ and $m_t^{\overline{\text{MS}}}$ calculated to three-loop level QCD

→ Implications of huge EW corrections? [Jegerlehner/Kalmykov/Kniehl, 2012]

According to its implementation, $m_t^{\text{MC}}$ is assumed to be close to $m_t^{\text{pole}}$

→ Within 1 GeV [Buckley et al., 2011]

or even within 250–500 GeV [discussion at TOP2013]

Most precise $\sigma_{t\bar{t}}$ measurements have uncertainties $\mathcal{O}(4\%)$

# Top-mass from cross sections: *Status*

Latest publications on $m_t$ from $\sigma_{t\bar{t}}$:

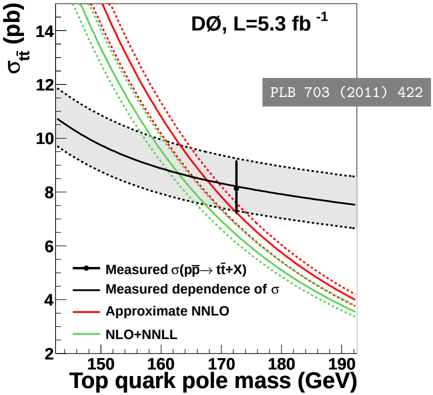
| | $\sqrt{s}$ | $\mathcal{L}$ | |
|---|---|---|---|
| ATLAS | 7 TeV | 35 $pb^{-1}$ | ATLAS-CONF-2011-054 |
| CMS | 7 TeV | 2.3 $fb^{-1}$ | PLB 728 (2014) 496 |
| DØ | 1.96 TeV | 5.3 $fb^{-1}$ | PLB 703 (2011) 422 |
| ABM12 | CDF-DØ combination plus 5 results from ATLAS and CMS (7 and 8 TeV) | | PRD 89 (2014) 054028 |

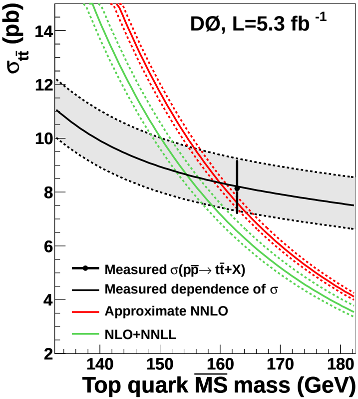
Results:

| | $m_t^{pole}$ / GeV | $m_t^{\overline{MS}}$ / GeV | order QCD |
|---|---|---|---|
| ATLAS | $166.4^{+7.8}_{-7.3}$ | — | approx. NNLO |
| CMS | $176.7^{+3.8}_{-3.4}$ | — | NNLO |
| DØ | $167.5^{+5.2}_{-4.7}$ | $160.0^{+4.8}_{-4.3}$ | approx. NNLO |
| ABM12 | $(171.2 \pm 2.4)^*$ | $162.3 \pm 2.3$ | NNLO |

* obtained by conversion of $m_t^{\overline{MS}}$ result; same QCD analysis in pole scheme yields $169.6 \pm 2.7$ GeV

# Top-mass from cross sections: *Status*




$m_t^{\text{pole}} = 167.5^{+5.2}_{-4.7}$ GeV

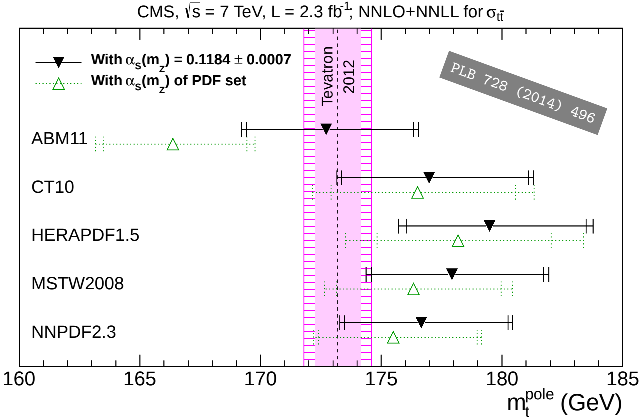
$m_t^{\overline{\text{MS}}} = 160.0^{+4.8}_{-4.3}$ GeV

Assuming $m_t^{\text{MC}} = m_t^{\overline{\text{MS}}}$ (instead of $m_t^{\text{MC}} = m_t^{\text{pole}}$) would shift the results by -2.7 and -2.6 GeV

# Top-mass from cross sections: *Status*

First NNLO determination of the top mass

Correlations between $m_t$, $\alpha_S$ and PDFs taken into account




$m_t^{\text{pole}} = 176.7\ ^{+3.8}_{-3.4}$ GeV with NNPDF2.3

$\approx 176.7\ ^{+3.1}_{-2.8}\ (\sigma^{\text{meas}}_{t\bar{t}}) \pm 1.4\ (\text{PDF}) \pm 0.9\ (\mu_{R,F}) \pm 0.7\ (\alpha_S) \pm 0.9\ (E_{\text{LHC}}) \pm 0.5\ (m_t^{\text{MC}})$ GeV

$\rightarrow$ Variation of $m_t^{\text{MC}} \pm 1$ GeV translates into $m_t^{\text{pole}} \pm 0.5$ GeV

# Top-mass from cross sections: *Status*

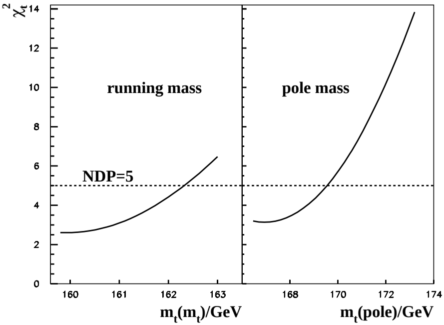
ABM12 QCD fit at NNLO, testing full strength of correlations between PDFs, $\alpha_S$ and $m_t$

PRD 89 (2014) 054028

Adding Tevatron $\sigma_{t\bar{t}}$ combination and 5 results from ATLAS and CMS (7 and 8 TeV)

$$m_t^{\overline{\mathrm{MS}}} = 162.3 \pm 2.3 \text{ GeV}$$

No changes in gluon PDF and $\alpha_S$, constrained by other data in global fit




Note: mass dependence of measured cross sections neglected

Treatment of correlations between data points and their uncertainties?

# Top-mass from cross sections: *Status*

arXiv:1405.4781

Study by C. Schwinn (MITP Workshop, March 2014, Mainz), using latest cross-section measurements with published parametrization for mass dependence and NNLO prediction with MSTW2008:

| Ref. | $\sqrt{s}$/TeV | $\sigma_{t\bar{t}}(172.5)$/pb | $\frac{1}{\sigma_{t\bar{t}}}\frac{d\sigma_{t\bar{t}}}{dm_t}(172.5)$ | $m_t$/GeV |
|---|---|---|---|---|
| arXiv:1105.5384 (D0) | 1.96 | $7.56^{+0.63}_{-0.56}$ | $-1.1\%\,\mathrm{GeV}^{-1}$ | $170.7^{+5.9}_{-6.8}$ |
| ATLAS - Conf - 2011 - 121 | 7 | $179.0^{+11.8}_{-11.7}$ | $-0.75\%\,\mathrm{GeV}^{-1}$ | $171.4^{+5.5}_{-5.6}$ |
| arXiv:1208.2671 (CMS) | 7 | $161.9^{+6.7}_{-6.7}$ | $-0.80\%\,\mathrm{GeV}^{-1}$ | $175.9^{+6.5}_{-5.5}$ |
| ATLAS - CONF - 2013 - 097 | 8 | $237.7^{+11.3}_{-11.3}$ | $-0.26\%\,\mathrm{GeV}^{-1}$ | $174.0^{+4.1}_{-4.5}$ |
| arXiv:1312.7582 (CMS) | 8 | $239^{+13.1}_{-13.1}$ | $-0.90\%\,\mathrm{GeV}^{-1}$ | $174.76^{+7.1}_{-5.7}$ |

Neglecting mass dependence of measured $\sigma_{t\bar{t}}$ would slightly shift obtained mass and significantly underestimate uncertainty, for example:

$$171.0^{+4.0}_{-4.1}\ \text{GeV (without)} \rightarrow 170.7^{+5.9}_{-6.8}\ \text{GeV (with)}$$

# Top-mass from cross sections: *Status*

arXiv:1405.4781

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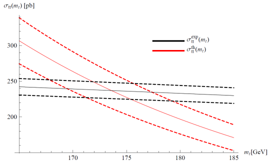
Cross-section measurement with flatter mass dependence
↷ reduction of total uncertainty
↷ reduction of dependence on $m_t^{\mathrm{MC}}$



# Top-mass from cross sections: *Prospects*

From the total cross section:

CMS-PAS-FTR-13-017

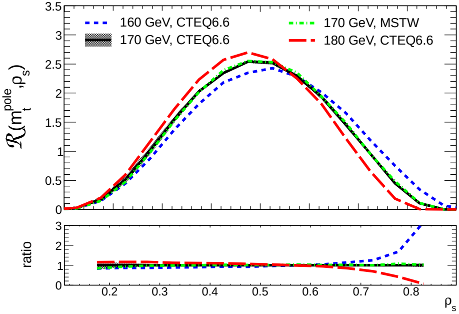
- If uncertainty of measured $\sigma_{t\bar{t}}$ can be further reduced and its mass dependence minimized, uncertainty on $m_t^{\text{pole}}$ of $\mathcal{O}(2\text{ GeV})$ realistic
- Very optimistic scenario, including also further reduction of theory uncertainties on $\sigma_{t\bar{t}}$, yields $\mathcal{O}(1\text{ GeV})$

From differential cross sections:

- Various proposals made for distributions that should be suited for $m_t$ determinations, e.g.: $d\sigma/dm_{\ell b}$
- Dependence of measured cross section on $m_t^{\text{MC}}$ in each bin to be considered
- Precise results will typically require NNLO predictions

# Top-mass from cross sections: *Prospects*

Alioli et al. EPJC 73 (2013) 2438




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

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

Proposal to employ $t\bar{t}$+jet rate

NLO corrections available and small; small residual scale uncertainties in NLO

Method similar to $m_b$ measurements at LEP via 3-jet rate

Feasibility study:

total uncertainty $\mathcal{O}(1\text{ GeV})$

# Outline

Will go through

a) idea

b) status

c) prospects

of $m_t$ measurements from:

1. $t\bar{t}$ cross sections
2. kinematic endpoints
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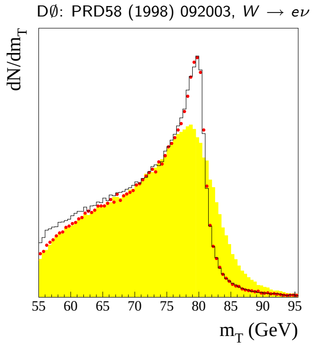
# Top-mass from endpoints: *Idea*

Use transverse mass, famous from $W \to \ell\nu$, where

$$m_T = \sqrt{(E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2}$$
$$\approx \sqrt{2E_T^\ell E_T^\nu (1 - \cos\phi_{\ell\nu})}$$

Upper edge $m_T^{\text{max}} = m_W$ diluted by finite W width, boost of the W, and detector resolution




Extend it to a pair $(a, b)$ of identically particles with two-body decay and two unmeasured particles $(\nu_a, \nu_b)$:

$$m_{T2} \equiv \min_{p_T^{\nu_a} + p_T^{\nu_b} = p_T^{\text{miss}}} \left\{ \max\left( m_T^a, m_T^b \right) \right\}$$

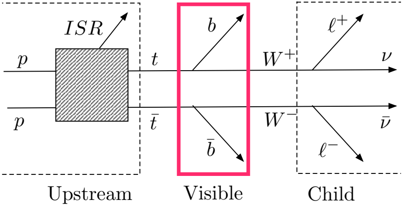
Remove sensitivity to "upstream" $p_T$ (ISR) by using only components perpendicular to boost of the (a+b) system: projected variable $m_{T2\perp}$

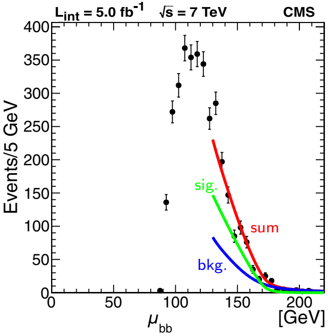
# Top-mass from endpoints: *Idea*

To determine $m_t$ from top-pair decays, can use

$$\mu_{bb} \equiv m_{T2\perp}(t \to bW)$$

Endpoint: $\mu_{bb}^{\max} = m_t$




Interpretation: pole mass in a narrow-width approximation?

No QCD effects involved in this mass calculation

In event-wise likelihood fit, convolution of kinked-line shape for signal with resolution function based on known jet resolutions

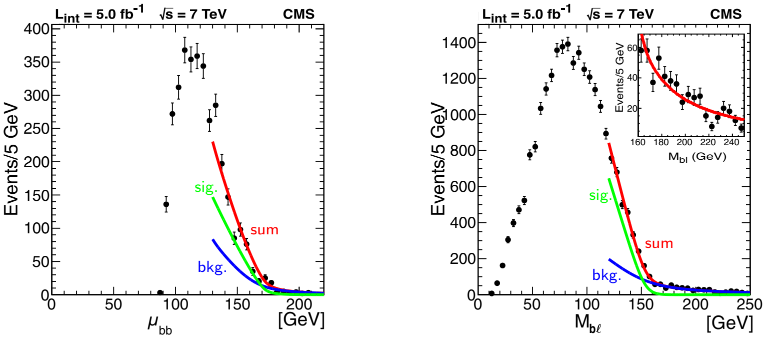
# Top-mass from endpoints: *Status*

CMS, 2011 data, dilepton channel:

EPJC 73 (2013) 2494

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

From simultaneous, unbinned fit to $\mu_{bb}$ and $m_{b\ell}$, based on analytic endpoint formulas for both



# Top-mass from endpoints: *Status*

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EPJC 73 (2013) 2494

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

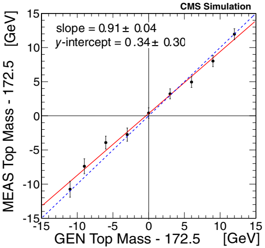
From simultaneous, unbinned fit to $\mu_{bb}$ and $m_{b\ell}$, based on analytic endpoint formulas for both

Almost as precise as standard measurements in dileptonic channel

Dominant systematic uncertainty: JES ($^{+1.3}_{-1.8}$ GeV)

Not employing MC top-mass definition for analysis calibration!

As cross-check: agreement between fit result in simulation and MC mass within 0.3 GeV



# Top-mass from endpoints: *Prospects*

Technique applicable to mass measurements from decay cascades involving new particles

To yield a more precise $m_t$, a better knowledge of the b-JES is needed

Two other significant systematic uncertainties can be expected to directly decrease with higher statistics: fit range (currently: 0.6 GeV)
bkg. shape (currently: 0.5 GeV)

CMS-PAS-FTR-13-017

Very optimistic extrapolation for total uncertainty at end of LHC running: 0.5 GeV

With such precision, it would not only be valuable input for $m_t$ combinations but also an interesting cross-check for the mass definition

# Outline

Will go through of $m_t$ measurements from:

a) idea
b) status
c) prospects

1. $t\bar{t}$ cross sections
2. kinematic endpoints
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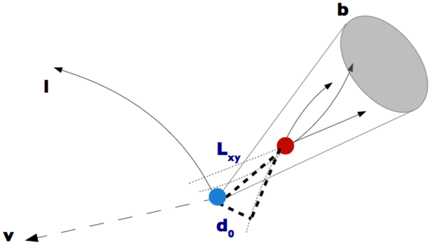
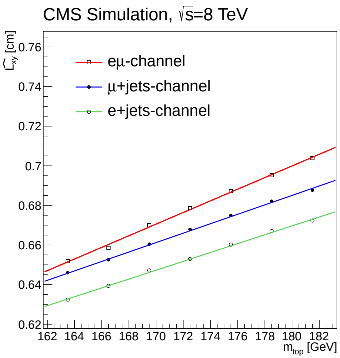
4. J/$\psi$ final states

# Top-mass from B-hadron lifetime: *Idea*




Transverse decay length of B-hadrons in top events depends ∼linearly on $m_t$

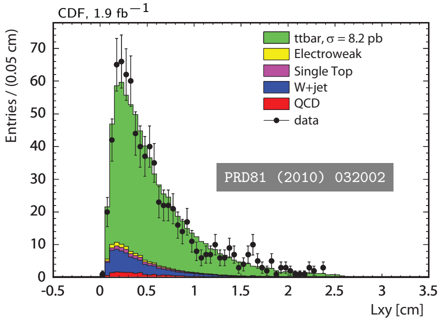


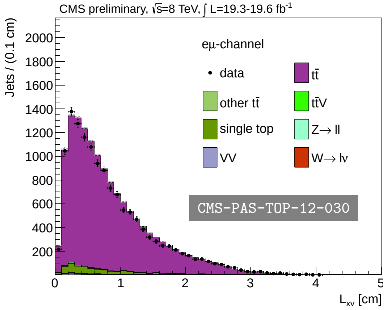

Reconstruction of $L_{xy}$ from tracks

↷ no direct sensitivity to calorimetry and JES

Another approach that is also based on tracking: lepton $p_T \propto m_t$

# Top-mass from B-hadron lifetime: *Status*




Using mean $L_{xy}$ in l+jets:

$m_t = 166.9^{+9.5}_{-8.5}$ (stat) $\pm 2.9$ (syst) GeV

From mean lepton $p_T$:

$m_t = 173.5^{+8.8}_{-8.9}$ (stat) $\pm 3.8$ (syst) GeV

And simultaneous fit to both:

$m_t = 170.7 \pm 6.3$ (stat) $\pm 2.6$ (syst) GeV

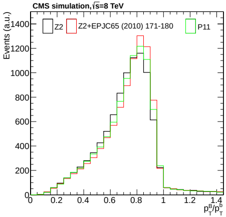
Using median $L_{xy}$ in l+jets and dileptons:

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

Main systematic uncertainties:

- backgrounds in l+jets
- the hadronization model
- the $p_T^{top}$ spectrum

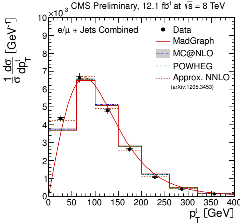
# Top-mass from B-hadron lifetime: *Prospects*




Impact of hadronization model tested by comparing three Pythia tunes that yield different B-hadron distributions

As cross-check: same order of uncertainty when comparing Pythia to Herwig

Optimistic assumption: these uncertainties will be reduced with more data and improved MC tunes




MC generators fail to describe $p_T^{top}$ spectrum

Reweighting simulated to observed spectrum has huge impact on $m_t$ obtained from $L_{xy}$ since it is not a Lorentz-invariant quantity

Hoping that this will be understood soon (eager to compare to full NNLO) and uncertainty vanishes

Very optimistic extrapolation for total uncertainty at end of LHC running: 0.4 GeV

CMS-PAS-FTR-13-017

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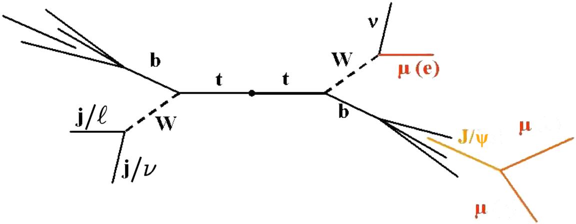
# Top-mass from J/$\psi$ final states: *Idea*



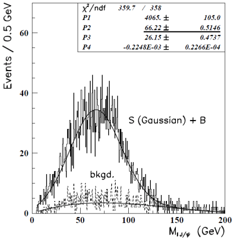

Select $t\bar{t}$ events with $b \to J/\psi + X$ and $J/\psi \to \ell\ell$

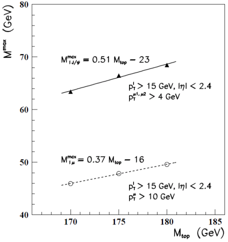
Rare but

experimentally very clean

Obtain $m_t$ via $m(J/\psi, \ell)$

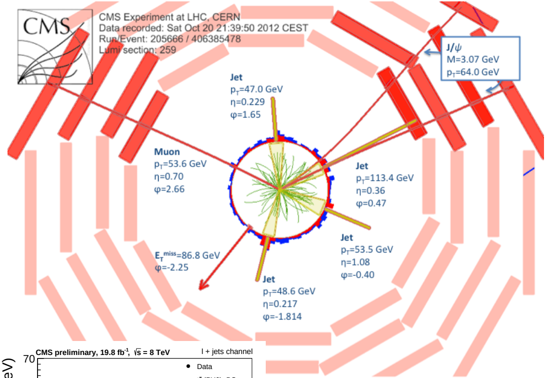
A. Kharchilava, 1999

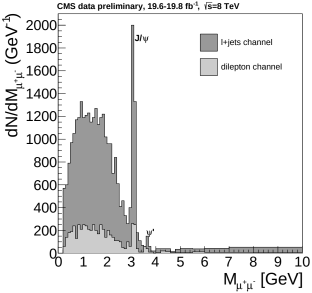


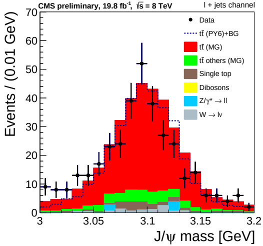



# Top-mass from $J/\psi$ final states: *Status*

CMS-PAS-TOP-13-007



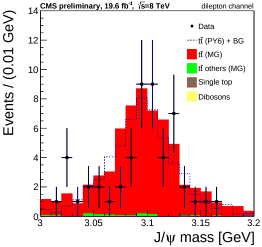




Clear signal of
$b \to J/\psi + X$ in $t\bar{t}$

354 and 60 candidate events in l+jets and dilepton channel

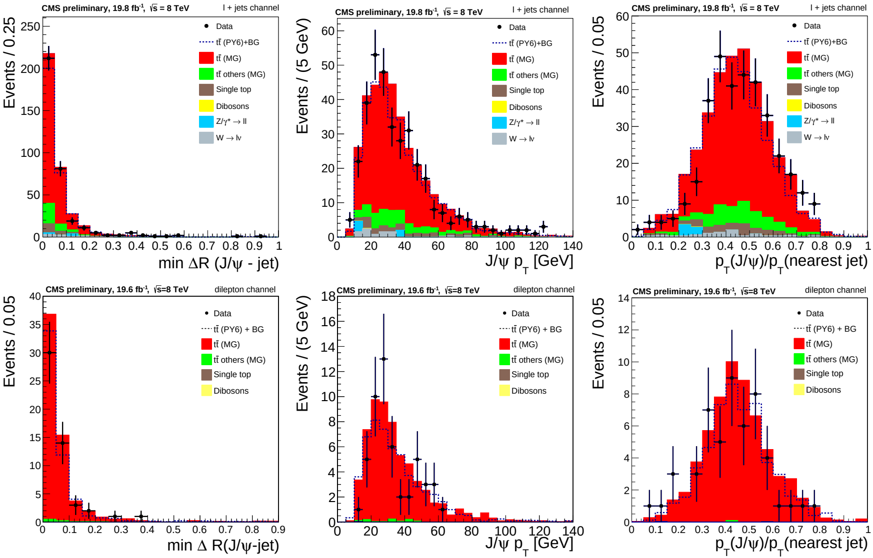
(full 2012 data but only $J/\psi \to \mu\mu$)



# Top-mass from $J/\psi$ final states: *Status*

CMS-PAS-TOP-13-007

Overall rate and kinematic distributions reasonably well modeled



# Top-mass from J/$\psi$ final states: *Prospects*

Exploratory study at 8 TeV suggests that the yield of 800 evts / 10 $\mathrm{fb}^{-1}$, expected in the CMS TDR, could be realistic and actually achievable with $J/\psi \to \mu\mu$ alone

However, LHC jet performance was expected to be relatively poor when the $J/\psi$ approach was suggested: still interesting? with higher pileup?

Required for this approach to become competitive:

- large statistics from LHC Run-2 ($>$ 100 $\mathrm{fb}^{-1}$)
- improved understanding of the hadronization models and their uncertainties, also via fragmentation studies with LHC data
- NNLO for $m_{\ell B}$?

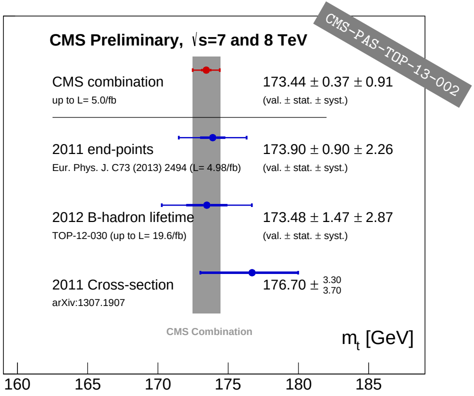
CMS-PAS-FTR-13-017

Very optimistic extrapolation for total uncertainty at end of LHC running: 0.6 GeV

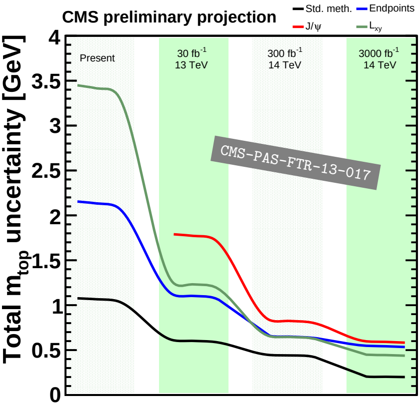
# Summary & Conclusions

So far, results from "alternative" measurements compatible with results from standard methods

Not (yet) precise enough to contribute to combinations or to allow for strong conclusions about mass definitions



# Summary & Conclusions & Open Questions




With very optimistic assumptions, uncertainties $\mathcal{O}(0.5\text{ GeV})$ expected for endpoint, $L_{xy}$, $J/\psi$ methods at the of LHC running

However, given current performance and projections for the standard approach: will non-standard results ever contribute significantly to combinations?

$L_{xy}$ and $J/\psi$ also yield $m_t^{\mathrm{MC}}$

Can the mass from (differential) cross sections ($m_t^{\mathrm{pole}}$, $m_t^{\overline{\mathrm{MS}}}$, ...) really be brought to a precision $\mathcal{O}(1\text{ GeV})$ or even better?

What is the interpretation of the endpoint mass?