Top cross sections and mass at the luminosity/energy frontiers

P. Ferreira da Silva (CERN)
on behalf of the ATLAS, CMS and LHCb collaborations

Workshop on the physics of HL-LHC and perspectives at HE-LHC
1st November 2017
A HLHE-LHC YR is a unique opportunity to set generic strategies for future top analyses

- the YRs from the LHCHXSWG are a good example of this practice

For what follows, no need for other than fixed-order calculations/generator level studies

- $(m_t, \alpha_s, \text{PDFs}) + \text{search for new physics} (\text{benchmarks, EFTs}) = \text{compelling motivations} \\
  \text{in the first case would be good to quantify the target precision needed for real impact (e.g. on ggH)}$

- choose a couple of benchmark measurements: e.g. $M(tt), p_T(t), \gamma_{t-ch}(t), A_c$, etc.

  - identify dominant systematics and forecast their evolution
  
  - special attention to ratios: quantify impact of HE-LHC/HL-LHC or HL-LHC/Run 1 type of scenarios
  
  - complementarity and combination of ATLAS / CMS / LHCb

Need input from theory and experiment

$\Rightarrow$ a task force within the LHCtopWG is the natural place to align the required inputs
Outlook

**Cross-sections** state of the art and current challenges
probing new physics beyond the systematics barrier

**Top mass** en route to a legacy LHC measurement
Near threshold QCD production modes
JHEP 1009:034, 2010

Pole mass scan
JHEP 0901:047, 2009

\[ \frac{\Delta m_t}{m_t} \sim 1.2 \frac{\Delta m_{t\bar{t}}}{m_{t\bar{t}}} \]

Sensitivity to EW corrections (Z, \gamma, H)
PRD 91, 014020 (2015)

PRD 91, 014020 (2015)

Sensitivity to EW corrections (Z, \gamma, H)
PRD 91, 014020 (2015)

Elusive signs of new physics
PRD 90, 014008 (2014)

10.1007/JHEP01(2015)092

Bump hunting
H \rightarrow tt, Z' \rightarrow tt

Entering the boosted regime
PDFs, \alpha_s at high x

Top mass running?
\[ m_t = m_t(\mu) \]

CMS
Preliminary
e/\mu + jets
parton level

35.8 fb^{-1} (13 TeV)

\[ \frac{d\sigma}{dM(t\bar{t})} \] [pb GeV^{-1}]

\[ \text{Theory/ Data} \]

\[ 0.6 \rightarrow 1.4 \]

many ???
large \( \delta_{syst} \)
Several measurements have been performed at 4 pp centre-of-mass energies, with overall good agreement with NNLO+NNLL QCD prediction.

\[ \frac{\delta \sigma_{th}}{\sigma_{th}} \approx \frac{\delta \sigma_{exp}}{\sigma_{exp}} \]
Main uncertainties

- **Modelling uncertainties non-negligible despite widespread use of NLO MC at 13 TeV**
  - impact of parton shower related uncertainties is non-negligible (main MC is Powheg)
  - partially reducible with ancillary measurements and in-situ profiling

- **Trigger/selection efficiency uncertainties**
  - still potential for improving, but challenging to maintain inclusive triggers with low thresholds

- **Integrated luminosity**
  - uncertainties limited by x-y correlations and length scale determination in VdM scans
  - LHCb has shown capability of achieving 1.2% unc. in luminosity with beam imaging (see backup)
\(\sigma_{t\bar{t}}\) and fundamental parameters

- Individual extraction of \(m_t\) or \(\alpha_s\) (or PDFs)
  - crucial to minimise dependence of acceptance on parameter being extracted
  - extrapolation uncertainties dominated by the impact of the QCD scale choice

\[\Rightarrow\] tendency to prefer dilepton final states which can be triggered with looser requirements

\[\alpha_s\] extracted with \(\approx 2.6\%\) unc.

Impact gluon PDFs at high \((\mu_f, x)\)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>(\sqrt{s})</th>
<th>(m_t) [GeV]</th>
<th>PDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS e(\mu)</td>
<td>7+8</td>
<td>172.9(^{+2.5}_{-2.6})</td>
<td>PDF4LHC I</td>
</tr>
<tr>
<td>CMS e(\mu)</td>
<td>7+8</td>
<td>174.3 (^{+2.1}_{-2.2})</td>
<td>CT14</td>
</tr>
<tr>
<td>CMS (\ell^+\text{+jets})</td>
<td>13</td>
<td>170.6 (\pm 2.7)</td>
<td>CT14</td>
</tr>
</tbody>
</table>
Electroweak production of top quarks

• Production through EWK vertices in agreement with predictions at different $s^{1/2}$

$$\frac{\delta \sigma_{th}}{\sigma_{th}} < \frac{\delta \sigma_{exp}}{\sigma_{exp}}$$ : background, experimental uncertainties typically higher than in $tt$ case
• Extraction of $V_{tb}$ from signal strength

$$
\frac{\delta V_{tb}}{V_{tb}} = \frac{1}{2} \left( \frac{\delta \sigma_{th}}{\sigma_{th}} \oplus \frac{\delta \sigma_{exp}}{\sigma_{exp}} \right)
$$

$+0.9/-0.3\%$

**NNLO QCD**

arXiv:1404.7116

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$</th>
<th>$\sigma_t$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS 8</td>
<td>8</td>
<td>89.6$^{+7.1}_{-6.3}$</td>
</tr>
<tr>
<td>CMS 8</td>
<td>8</td>
<td>83.6 ± 7.7</td>
</tr>
<tr>
<td>ATLAS 13</td>
<td>13</td>
<td>247 ± 46</td>
</tr>
<tr>
<td>CMS 13</td>
<td>13</td>
<td>238 ± 32</td>
</tr>
</tbody>
</table>

$\Delta \sigma / \sigma [%]$

<table>
<thead>
<tr>
<th>ATLAS 13</th>
<th>CMS 13</th>
<th>ATLAS 8</th>
<th>CMS 8</th>
</tr>
</thead>
</table>

$\sigma_{t+\bar{t}}$ impact on $V_{tb}$ and main uncertainties

9

**Experiment**

\[ \sqrt{s} \]

<table>
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<th>$\sigma_t$ [pb]</th>
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<tr>
<th>$\sigma_{t+\bar{t}}$ [pb]</th>
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<table>
<thead>
<tr>
<th>ATLAS 7 TeV$^1$</th>
<th>CMS 7 TeV$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRD 90 (2014) 112006 (4.59 fb$^{-1}$)</td>
<td>JHEP 12 (2012) 035 (1.17 - 1.56 fb$^{-1}$)</td>
</tr>
<tr>
<td>ATLAS 8 TeV$^2$</td>
<td>CMS 8 TeV$^1$</td>
</tr>
<tr>
<td>arXiv:1702.02889 (20.2 fb$^{-1}$)</td>
<td>JHEP 06 (2014) 090 (19.7 fb$^{-1}$)</td>
</tr>
<tr>
<td>CMS 13 TeV$^3$</td>
<td>ATLAS 13 TeV$^1$</td>
</tr>
<tr>
<td>arXiv:1610.00678 (2.3 fb$^{-1}$)</td>
<td>JHEP 04 (2017) 086 (3.2 fb$^{-1}$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\Delta \sigma_{t+\bar{t}} / \sigma_{t+\bar{t}} [%]$</th>
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<tr>
<th>ATLAS 13</th>
<th>CMS 13</th>
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$\Delta \sigma / \sigma [%]$

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<th>CMS 13</th>
<th>ATLAS 8</th>
<th>CMS 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>10.0</td>
<td>15.0</td>
<td>20.0</td>
</tr>
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</table>

$\Delta \sigma / \sigma [%]$

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$|f_{LV_{tb}}| \pm (meas) \pm (theo)$

<table>
<thead>
<tr>
<th>t-channel:</th>
<th>W:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.02 ± 0.06 ± 0.02</td>
<td>1.03 ± 0.07 ± 0.02</td>
</tr>
<tr>
<td>1.028 ± 0.042 ± 0.024</td>
<td>1.07 ± 0.09 ± 0.02</td>
</tr>
<tr>
<td>1.020 ± 0.046 ± 0.017</td>
<td>0.998 ± 0.038 ± 0.016</td>
</tr>
<tr>
<td>0.979 ± 0.045 ± 0.016</td>
<td></td>
</tr>
</tbody>
</table>

$|f_{LV_{tb}}|$ including top-quark mass uncertainty

$\sigma_{theo}$: NLO PDF4LHC11 NPPS205 (2010) 10, CPC191 (2015) 74

including beam energy uncertainty
Differential top cross sections

- Maximise the sensitivity to $m_t$, $\alpha_s$, PDFs, pQCD predictions and new physics
  - final state products used to reconstruct top quark candidates, global event properties
  - comparison to theory needs to “un-smear” data for reconstruction, parton shower effects

- Theory-safe definitions when possible
  - particle level top from stable final states
  - mimic reconstruction techniques as in data
  - minimise dependency on parton shower
  - find implementation in RIVET routines
  - direct comparison to NLO+PS (eagerly waiting for particle level NNLO)
$d\sigma_{t(t)}/dX$ status (illustrative examples)

Resolved $tt$: $\gtrless$ 1D

First LHC combination: $A_c$!

Bosted $tt$

Associated productions

$t$-channel production

CMS-PAS-TOP-17-002

PRD 94 (2016) 072002

arXiv:1706.03046

arXiv:1709.05327

arXiv:1706.03046

EPJC 76 (2016) 379

EPJC 77 (2017) 531

CMS-PAS-TOP-17-002

PRD 94 (2016) 072002

arXiv:1706.03046

arXiv:1709.05327

arXiv:1706.03046

EPJC 76 (2016) 379

EPJC 77 (2017) 531
General observation: rates/shapes well reproduced at NLO QCD within uncertainties

- largest discrepancy in top $p_T$ in tt events
- NNLO QCDxNLO EW and alternative recoiling schemes at NLO+PS in better agreement with data
- start to profit from large statistics to unfold in several dimensions simultaneously

First ATLAS+CMS $A_C$ combination in agreement with state-of-the-art predictions

- $t$-channel probing kinematics and polarisation-related variables

Recent progresses in starting to probe rarer processes (so far Run I)

- will benefit from higher integrated luminosity and energies to improve statistical uncertainty
- associated productions: playground for searches but also for improved $y_t$ measurements
Typical dominant uncertainties in $d\sigma_{t(t)}/dX$

- Using as an example $p_T(t)$ measurement in $\ell+\text{jets}$
- Experimental uncertainties are significant at 13 TeV
  - in this case jet energy scale related and b-tagging uncertainties
  - more data: calibrations and scale factors expected to improve
- Total modelling uncertainties are however comparable
  - model assumptions intrinsic to unfolding procedure
    e.g. correcting for events in which at least one ISR jet was used
  - can partially improve with better understanding of MCs
  - but statistical analysis also needs to improve (next slide)
- Relative cross sections (shape only)
  - uncertainty reduced around mode of the distributions (2-5%)
  - however it is still as large as 12-40% in the tails of $p_T(t)$
  - and information on the total rate is lost …
Challenges for $d\sigma_{t(t)}/dX$

- **Binning and correlations** (typically 40-70% between neighbouring bins)
  - resolution-limited: need high purity/stability matrices for stable numerical inversion
  - higher stats doesn’t imply finer binning/smaller correlations keeping same reconstruction
  - include profiling of systematic uncertainties in unfolding? forward folding? ML-based regression?

- **Monte-Carlo driven corrections**
  - statistics in some corners of the phase space is a limiting factor (in particular with neg. weights)
  - data is corrected by simulations available at the time of the analysis
  - particle level definitions allow to factorise better detector effects from model effects
  - reconstruction algorithm: optimise for particle level to follow as close as possible parton level
Looking beyond the systematics wall

• With no striking signs of new physics, we’re looking for subtle effects
Looking beyond the systematics wall

- With no striking signs of new physics, we’re looking for subtle effects.

- If BSM evolution as function of energy is different from SM take $\sigma(E_1)/\sigma(E_2)$
  - simplified approach to common fit to two $s^{1/2}$, expect significant cancellation of uncertainties
  - profit from data and expand ratios differentially

$$R_{E_1/E_2}^X \sim \frac{\sigma_{X}^{SM}(E_1)}{\sigma_{X}^{SM}(E_2)} \times \left\{ 1 + \frac{\sigma_{X}^{BSM}(E_1)}{\sigma_{X}^{SM}(E_1)} \Delta_{E_1/E_2} \frac{\sigma_{X}^{BSM}}{\sigma_{X}^{SM}} \right\}$$

HL-LHC or Run2 ratios to Run 1 will provide longer leverage arm with respect to theory uncertainties

usually a double ratio of parton luminosities at different $s^{1/2}$

arXiv:1206.3557
Looking beyond the systematics wall

• With no striking signs of new physics, we’re looking for subtle effects

• If BSM evolution as function of energy is different from SM take $\sigma(E_1)/\sigma(E_2)$
  
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  HL-LHC or Run2 ratios to Run 1 will provide longer leverage arm with respect to theory uncertainties

usual a double ratio of parton luminosities at different $s^{1/2}$

• No need to restrict inclusive ratios to a single process

  • further reduce experimental uncertainties (e.g. efficiencies)
  
  • e.g. theory uncertainties on $W, Z \sim 3-4\%$ at NNLO
  
  • optimisation of the fiducial regions, common selection strategies
  
  • apply to associated productions with top quarks ($\gamma, Z, W, H, bb, 4t$)

arXiv:1206.3557

\[ \frac{\Delta s_2}{s_1} \left[ \frac{L_{q\bar{q}}}{L_{gg}} \right] \]

HL-LHC or Run2 ratios to Run 1 will provide longer leverage arm with respect to theory uncertainties

arXiv:1612.03636

ATLAS
8 TeV, 20.2 fb$^{-1}$

13 TeV, 3.2 fb$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>data ± total uncertainty</td>
<td>green</td>
<td>green</td>
</tr>
<tr>
<td>data ± stat. ± exp. uncertainty</td>
<td>yellow</td>
<td>yellow</td>
</tr>
<tr>
<td>data ± stat. uncertainty</td>
<td>yellow</td>
<td>yellow</td>
</tr>
<tr>
<td>ABM12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NNPDF3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMHT14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS-epWZ12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HERAPDF2.0</td>
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<td></td>
</tr>
</tbody>
</table>

(NNLO QCD, inner unc.: PDF only)
Top quark and PDFs I

- How far can we push to reduce uncertainties on ggH from PDFs and $\alpha_s$?
- Significant impact on PDFs at high $x$ from scanning $M(tt)$ and $y(tt)$
  - Statistical uncertainties still relevant (higher rapidities and masses)
- Charge asymmetry in single top production
  - Interesting to explore differential with higher statistics for q-PDF
Top quark and PDFs II

• Usage of forward region expected to play an important role at HL-LHC
  • LHCb and extended tracker coverage in ATLAS/CMS can probe further qX-enhanced regions
  • unique case for charge asymmetries and resonant productions (see more in F. Deliot’s talk)

\[ x_i = \frac{m_T^2}{\sqrt{s}} \left( e^{\pm y_t} + e^{\pm y_i} \right) \]

ATLAS/CMS probed so far small $\Delta y$

\[ x_1 \sim x_2 \text{ (typically } \sim 0.05) \]

$\Rightarrow$ still g-dominated at high $M_{tt}$ from $\sigma_{gg}^{t-ch} \propto \frac{\log(M_{tt}^2)}{M_{tt}^2}$

LHCb can probe large $\Delta y$

$\ x_1 > x_2$ enhances valence quark contribution

$\Rightarrow$ slight enhancement of qq/qg

**gluon fraction**

arXiv:1206.3557

**qx-fraction**

arXiv:1311.1810

LHC, pp → t+$\bar{t}$, MNR NLO + MSTW08
Top in the forward region

- LHCb complements “blind” regions of ATLAS/CMS for new physics in $t$ asymmetries
  - e.g. $t$-channel/$u$-channel exchange of light mediator [arXiv:1103.3747]
- Expect significant increase in statistics wrt to early observation of top in forward region
  - assuming current performances: $\varepsilon_\mu \sim 90\%$, $\varepsilon_c \sim 70\%$ and $\varepsilon_b \sim 65\%$ for $\varepsilon_q \sim 0.5\%

<table>
<thead>
<tr>
<th>Final state</th>
<th>Run 2 (5/fb)</th>
<th>Upgrade (300/fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell^+b$</td>
<td>11k</td>
<td>680k</td>
</tr>
<tr>
<td>$\ell^+bj$</td>
<td>6k</td>
<td>360k</td>
</tr>
<tr>
<td>$\ell^+b\bar{b}$</td>
<td>1.4k</td>
<td>90k</td>
</tr>
<tr>
<td>$\ell^+b\bar{b}j$</td>
<td>0.8k</td>
<td>50k</td>
</tr>
<tr>
<td>$\ell\ell$</td>
<td>2k</td>
<td>120k</td>
</tr>
<tr>
<td>$\ell\ell b$</td>
<td>0.8k</td>
<td>50k</td>
</tr>
</tbody>
</table>

arXiv:1311.1810
Top as a probe in heavy ions

- Recently established for the first time in pPb collisions at 8.16 TeV!
- Expect $O(10 \text{ nb}^{-1})$ of PbPb at HL-LHC at $\sqrt{s_{NN}}=5.5$ TeV
  - ~900 dilepton events after typical pp selection cuts
  - impact on nPDFs at uncharted $x$ ▶︎
  - unique to probe QGP with EWK-decaying free quark
- Also, a clear case for higher luminosity pPb runs

$e^+/\mu^+ + \geq 4j (\geq 2b)$
- Data
- $t\bar{t}$ correct
- $t\bar{t}$ wrong
- background
$\chi^2$/dof = 32.1/50

$pPb (174 \text{ nb}^{-1}, \sqrt{s_{NN}} = 8.16 \text{ TeV})$

Potential to probe unexplored anti-shadowing and EMC regions

$R_{gg}(x,Q^2; m_t)$
- Original EPS09 uncert.
- After reweighting with Pb+Pb pseudo data
$E_{cm}=10\text{ pb}^{-1}, \sqrt{s}=5.5\text{ TeV}$
- $x$ range predominantly probed at $\sqrt{s}=5.5\text{ TeV}$

$NLO (A+208) \text{ gluon}$
- $Q^2 = 30000 \text{ GeV}^2$

arXiv:1706.09521
### Top Mass

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$-Quark Mass (Direct Measurements)</td>
<td>$173.1 \pm 0.6$ GeV ($S = 1.6$)</td>
</tr>
<tr>
<td>$t$-Quark Mass from Cross-Section Measurements</td>
<td>$160^{+5}_{-4}$ GeV</td>
</tr>
<tr>
<td>$t$-Quark Pole Mass from Cross-Section Measurements</td>
<td>$173.5 \pm 1.1$ GeV</td>
</tr>
<tr>
<td>$m_t - m_i$</td>
<td>$-0.2 \pm 0.5$ GeV ($S = 1.1$)</td>
</tr>
<tr>
<td>$t$-quark DECAY WIDTH</td>
<td>$1.41^{+0.19}_{-0.15}$ GeV ($S = 1.4$)</td>
</tr>
</tbody>
</table>
**Direct top mass measurements at the LHC**

- Expected to lead in precision
- Achieved <0.3% uncertainty
- Good agreement between LHC experiments
- Good agreement with alternative techniques where $\delta m_t/m_t = 0.4\%$ (CMS-PAS-TOP-15-012)
- Ultimately limited by $\Lambda_{QCD}$ ambiguities

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### ATLAS+CMS Preliminary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$m_{top}$ Summary, $\sqrt{s} = 7-13$ TeV</th>
<th>September 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, 1+jets (*)</td>
<td>$172.31 \pm 1.55 (0.75 \pm 1.35)$</td>
<td>$7$ TeV [1]</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>$173.09 \pm 1.63 (0.64 \pm 1.50)$</td>
<td>$7$ TeV [2]</td>
</tr>
<tr>
<td>CMS, 1+jets</td>
<td>$173.49 \pm 1.06 (0.43 \pm 0.97)$</td>
<td>$7$ TeV [3]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>$172.50 \pm 1.52 (0.43 \pm 1.46)$</td>
<td>$7$ TeV [4]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>$173.49 \pm 1.41 (0.69 \pm 1.23)$</td>
<td>$7$ TeV [5]</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>$173.34 \pm 0.95 (0.35 \pm 0.88)$</td>
<td>$7$ TeV [6]</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>$173.34 \pm 0.76 (0.36 \pm 0.67)$</td>
<td>$1.967$ TeV [7]</td>
</tr>
</tbody>
</table>

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(*) Superseded by results shown below the line

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<td>$172.33 \pm 1.27 (0.75 \pm 1.02)$</td>
<td>$7$ TeV [8]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>$173.79 \pm 1.41 (0.54 \pm 1.30)$</td>
<td>$7$ TeV [9]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>$175.1 \pm 1.8 (1.4 \pm 1.2)$</td>
<td>$7$ TeV [10]</td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>$172.2 \pm 2.1 (0.7 \pm 2.0)$</td>
<td>$8$ TeV [11]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>$172.99 \pm 0.85 (0.41 \pm 0.74)$</td>
<td>$8$ TeV [12]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>$173.72 \pm 1.15 (0.55 \pm 1.01)$</td>
<td>$8$ TeV [13]</td>
</tr>
<tr>
<td>ATLAS, 1+jets</td>
<td>$172.08 \pm 0.91 (0.38 \pm 0.82)$</td>
<td>$8$ TeV [14]</td>
</tr>
<tr>
<td>ATLAS comb. (Sep 2017)</td>
<td>$172.51 \pm 0.50 (0.27 \pm 0.42)$</td>
<td>$7+8$ TeV [15]</td>
</tr>
<tr>
<td>CMS, 1+jets</td>
<td>$172.35 \pm 0.51 (0.16 \pm 0.48)$</td>
<td>$8$ TeV [16]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>$172.82 \pm 1.23 (0.19 \pm 1.22)$</td>
<td>$8$ TeV [17]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>$172.32 \pm 0.64 (0.25 \pm 0.59)$</td>
<td>$8$ TeV [18]</td>
</tr>
<tr>
<td>CMS, single top</td>
<td>$172.95 \pm 1.22 (0.77 \pm 0.95)$</td>
<td>$8$ TeV [19]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>$172.44 \pm 0.48 (0.13 \pm 0.47)$</td>
<td>$7+8$ TeV [20]</td>
</tr>
<tr>
<td>CMS, 1+jets</td>
<td>$172.25 \pm 0.63 (0.08 \pm 0.62)$</td>
<td>$13$ TeV [21]</td>
</tr>
</tbody>
</table>

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### ATLAS+CMS Preliminary

- $m_{top} = \text{total (stat + syst)}$
Dominant uncertainties in $m_t$

- **Using as example single most precise channel**
  - expected to remain the leading one at higher statistics
  - combinations will benefit from different correlations with other measurements

- **Jet energy scale: 3D-fit will probably leverage most of the current unc. on bJES**
  - benefit from integrated jet id with jet energy scale: heavy-flavour, q/g and PU discrimination

- **Non-perturbative effects: moving from CR on/off to new models does increase unc.**
  - differential measurements with profiling will be the next step
  - “easy” to exclude extreme models, profit from statistics to constraint in-situ subtle ones
Rise of alternative methods

- Tracks-only measurements evade the dependency on the JES
  - $M(\ell, J/\Psi)$ and related variations: more prone to b-fragmentation ⇒ constrain in-situ with charmed/bottom mesons
Rise of alternative methods

- Tracks-only measurements evade the dependency on the JES
  - $M(\ell,J/\psi)$ and related variations: more prone to b-fragmentation $\Rightarrow$ constrain in-situ with charmed/bottom mesons
  - dilepton kinematics: rely on excellent lepton calibrations

normalised: no lumi, eff. uncertainties! $\Rightarrow$ benefit from NNLO at particle level for $m_t^{pole}$

CMS Phase-2 Simulation Preliminary 14 TeV, 200 PU

CMS-TDR-17-001

$\psi + J/\psi$ reco $- m_{\psi + J/\psi}$ / $m_{\psi + J/\psi}^{reco}$

Entries (A.U.)

CMS Phase-2 Simulation Preliminary 14 TeV

200 PU scenario:
RMS = (0.635 ± 0.005) %

0 PU scenario

Phase-0 detector:
RMS = (1.127 ± 0.015) %

$\Lambda_s = 8$ TeV, 20.2 fb$^{-1}$

ATLAS

MCFM NLO fixed-order, $\mu = m_t / 2$

arXiv:1709.09407

Lepton $p_T$  Dilepton $p_T^{\mu\mu}$  Dilepton $m^{\mu\mu}$  Dilepton $p_T^{e+} + p_T^{e-}$  Dilepton $E^e + E^\mu$  Comb. (8 dist)

CT14  MMHT  NNPDF 3.0  HERAPDF 2.0  ABM 11  NNPDF nojet
Rise of alternative methods

- Tracks-only measurements evade the dependency on the JES
  - $M(\mu J/\Psi)$ and related variations: more prone to b-fragmentation $\Rightarrow$ constrain in-situ with charmed/bottom mesons
  - dilepton kinematics: rely on excellent lepton calibrations $\Rightarrow$ benefit from NNLO at particle level for $m_t^{pole}$

• Two-fold goal for alternative methods
  - complement systematics $\Rightarrow$ gain in final combination
  - confirm/calibrate direct $m_t$ measurements to $m_t^{pole}$
Projections

- From "classic" methods
  - 3D fit: mt, JSF, bJSF
  - npQCD, from in-situ and ancillary measurements
  - in-situ b-fragmentation
  - improved top $p_T$ description
  - $m_t^{MC}=m_t^{pole}$

- From tracks
  - Improved PDFs, and $\alpha_S$
  - No acceptance slope
  - No beam energy unc.

- From "classic" methods
  - 3D fit: mt, JSF, bJSF
  - npQCD, from in-situ and ancillary measurements

**Preliminary Projection**

- J/Ψ, JHEP 12(2016)123
- $\sigma(t\bar{t})$, JHEP 08(2016) 029
- sec. vtx, PRD 93(2016)2006
- single $t$, arXiv:1703.02530
- $l+\text{jets}$, PRD 93(2016)2004
Summary

• We are still at the surface of probing the top quark
  • long term programme for top physics at the LHC needs to cope with the systematics
  • in-situ constraints and ancillary measurements expected to improve modelling
  • design measurements such that particle level definition follows closely the parton level
  • long leverage arm in energy to Run I has unique potential to probe BSM using ratios (any gain from a high lumi run at 7 TeV in the future?)
  • complementarity between ATLAS/CMS and LHCb to probe asymmetries in forward region
  • top in heavy ions is just starting: possibility to study much more at the HL-LHC

• The case for the top quark mass - is unification in sight after LHC?
  • experiments have reached an excellent precision with Run I data
  • prospects to attain $\Lambda_{\text{QCD}}$ by the end of HL-LHC are not unrealistic
  • programme needs to be complemented with alternative techniques: make the bridge or confirm direct measurements as pole mass measurements
Backup
Mass reach of HLHE-LHC for 3ab$^{-1}$

http://collider-reach.web.cern.ch/
Reducing x-y dependencies in the luminosity calibration

- LHCb tracking system is able to measure the beams overlap integral very accurately
- direct measurement of the beam profile without need for displacement - complements VdM scan
- x-y dependency is measured in situ, minimising potential bias in the VdM scan
- after combination $\frac{\delta \sigma}{\sigma} \bigg|_{\text{LHCb } 8 \text{ TeV}} = 1.2\%$