Outline:

- **Motivation**
- **Individual results for t-channel and tW @ 13 TeV**
- **ATLAS+CMS combination @ 7 and 8 TeV**
- **Conclusions**
**Why study single top production?**

- study interplay of EW physics and QCD
- sensitivity to flavour couplings and parton densities

- $t$-channel virtual $W$ exchange
  $\sigma \sim O(100) \text{ pb}$

- $s$-channel virtual $W$ exchange
  $\sigma \sim O(5) \text{ pb}$

- real $W$ emission
  $\sigma \sim O(20) \text{ pb}$

- different initial/final states and/or different colour structure
  -> the three channels do not interfere
t-channel single top production

- 5 flavour scheme (5FS) LO:

- 4-flavour scheme (4FS) LO:

- t and tbar cross sections differ (u and d valence PDFs in p differ) and give different information on proton flavour structure and flavour couplings

(or NLO correction to 5FS) -> interplay with QCD
t-channel single top measurements

- e.g. 4-flavour scheme

\[ q \rightarrow q', \quad W^+ \rightarrow t, \quad W \rightarrow \ell^- v (\text{MET}) \]
\[ \ell^- \text{ (lepton)}, \ b\text{-tagged jet}, \ \text{untagged jet}, \ \text{MET} + \text{potentially further jets} \]
\[ \ell^- \text{ charge determines whether } t \text{ or } t\bar{t} \]

- latest inclusive result @ 13 TeV: \text{arXiv:1812.10514}

\[ (CMS, \text{data 2016, 36 fb}^{-1}) \]

define categories
(similar for e)

see also: \text{arXiv:1609.03920} (ATLAS, data 2015, 3.2 fb^{-1})
\text{arXiv:1610.00678} (CMS, data 2015, 2.2 fb^{-1})
input variables (examples)

BDT output (examples)

(separately for each lepton/category -> fit all)

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arXiv:1812.10514
Total cross section results

**measurement:**

\[ \sigma_{t-ch,t} = 136 \pm 1 \text{ (stat)} \pm 22 \text{ (syst)} \text{ pb} \]
\[ \sigma_{t-ch,t} = 136.0^{+4.1}_{-2.9} \text{ (scale)} \pm 3.5 \text{ (PDF+\(\alpha_s\)) pb}, \]
\[ \sigma_{t-ch,\bar{t}} = 82 \pm 1 \text{ (stat)} \pm 14 \text{ (syst)} \text{ pb} \]
\[ \sigma_{t-ch,\bar{t}} = 81.0^{+2.5}_{-1.7} \text{ (scale)} \pm 3.2 \text{ (PDF+\(\alpha_s\)) pb}, \]
\[ \sigma_{t-ch,t+\bar{t}} = 219 \pm 2 \text{ (stat)} \pm 36 \text{ (syst)} \text{ pb} \]
\[ \sigma_{t-ch,t+\bar{t}} = 217.0^{+6.6}_{-4.6} \text{ (scale)} \pm 6.2 \text{ (PDF+\(\alpha_s\)) pb}, \]

**prediction:**

HATHOR, NLO QCD + LO EW

**main systematic uncertainty:** signal modelling \((\mu_F, \mu_R, \text{PS scales}; \text{PDF}; \ldots)\)

**very good agreement** with small uncertainty, **SM works!**
Single $t/t\bar{t}$ cross section ratio

$R = \frac{\sigma_t}{\sigma_{t\bar{t}}}$

reasonable agreement with all NLO QCD PDF predictions, some PDF discrimination power
Measurement of $V_{tb}$ CKM coupling

$f_{LV}$: potential BSM lepton flavour violation factor

$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t-ch,t+\bar{t}}}{\sigma_{t-ch,t+\bar{t}}^\text{theo}}}$$

result:

$$|f_{LV} V_{tb}| = 1.00 \pm 0.08 \text{ (exp)} \pm 0.02 \text{ (theo)}$$

very good agreement with SM (expect 1.00)
Differential $t$ channel cross sections

example distributions: particle level, similar plots also available at parton level

reasonable agreement with NLO+PS QCD theory

differences 4FS/5FS of similar order as differences data/theory

charge ratio and impact on PDFs -> talk O. Behnke WG1

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Normalized cross sections

lowest $t \ p_T$ bin overestimated by theory
(improve PS matching?)

$4FS \ W \ p_T$ slope better than $5FS$
(better description of 'spectator' $b$?)

9. 4. 19

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Top quark polarisation

expect spin asymmetry:

\[
\frac{\text{d}\sigma}{\sigma \cdot \text{d} \cos \theta^*_\text{pol.}} = \frac{1}{2} \left( 1 + 2 A_\ell \cos \theta^*_\text{pol.} \right)
\]

\[
A_\ell = \frac{1}{2} P \cdot \alpha_\ell
\]

lepton analysing power

top quark polarisation

fit result:

\[
A_e = 0.443 \pm 0.048 \text{ (stat+exp)} \pm 0.068 \text{ (syst)} = 0.443 \pm 0.083
\]

\[
A_\mu = 0.398 \pm 0.042 \text{ (stat+exp)} \pm 0.047 \text{ (syst)} = 0.398 \pm 0.063
\]

\[
A_{e+\mu} = 0.439 \pm 0.032 \text{ (stat+exp)} \pm 0.053 \text{ (syst)} = 0.439 \pm 0.062
\]

good agreement with SM V-A (POWHEG): 0.436
Associated $tW$ production

- Study interplay of EW physics and QCD
- Real $W$ emission, LO 5FS
- Interference with inclusive $gg \rightarrow t\bar{t}b\bar{b}$, LO 4FS or NLO 5FS

see also talk Poncelet this morning
tW total cross section @ 13 TeV

Use dilepton (e+μ) channel: one from W, one from t accompanied by b jet and MET (two neutrinos)

categories:
**tW total cross section @ 13 TeV**

Example of BDT input variable  

BDT output

\[
\sigma(tW) = 63.1 \pm 1.8_{\text{stat}} \pm 6.4_{\text{sys}} \pm 2.1_{\text{lumi}} \text{ pb}
\]

approx. NNLO QCD: \(71.7 \pm 1.8_{\text{scale}} \pm 3.4_{\text{PDF}} \text{ pb}\)

see also arXiv:1612.07231 (ATLAS, 2015 data, 3.2 fb\(^{-1}\))
Inclusive cross section summary plot

Single top-quark production

Inclusive cross sections

March 2019

$\sigma$ [pb]

$\sqrt{s}$ [TeV]

$10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$

$t$-channel

CDF & D0, PRL 115, 152003 (2015)

CMS, JHEP 12, 035 (2012)

CMS, JHEP 06, 090 (2014)


$W$-associated

CMS, PRL 110, 022003 (2013)

CMS, PRL 112, 231802 (2014)

CMS, JHEP 10, 117 (2018)

$Z$-associated

CMS, JHEP 07, 003 (2017)


s-channel

CDF & D0, PRL 112, 231803 (2014)

CMS, JHEP 09 (2016) 027

ATLAS results see below
tWb - ttbar interference

analogy: $Z/\gamma^*$ interference,

Drell-Yan, $qqbar \rightarrow Z/\gamma^* \rightarrow$ leptons

adapted from plot by U.Klein
**tt/tWb differential cross section**

**test tWb - ttbar interference**

Similar signature as for inclusive measurement, use 'best' $m(b+\text{lepton})$ to discriminate resonant and nonresonant states.

$$m_{b\ell}^{\text{minmax}} = \min\{\max(m_{b_1\ell_1}, m_{b_2\ell_2}), \max(m_{b_1\ell_2}, m_{b_2\ell_1})\}$$

3 b tags: $\rightarrow$ normalize bg from tt + bb ($= \text{tt+HF}$) including tWb \(\ell^+\) interference}

**ATLAS**

$\sqrt{s}=13\ \text{TeV}, \ 36.1\ \text{fb}^{-1}$

**3 b-tag region**

**Signal region**

(doubly resonant) tt only
tt/tWb differential cross section

interference is important

direct full interference implementation best

interference:
4FS full treatment at ME level
diagram removal
diagram subtraction
Combination of single top cross sections @ 7 and 8 TeV

- Run 1 combination of 11 ATLAS and CMS results (references see backup)
  - major milestone! arXiv:1902.07158

- Challenge: properly deal with correlations of systematic uncertainties
- All results in good agreement with each other and with NNLO or NLO (+NNLL) QCD + LO EW theory
Example: t-channel

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<tr>
<th>Uncertainty category</th>
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<td>5.5</td>
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<tr>
<td>Total uncertainty</td>
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significant correlation between ATLAS and CMS results (theory modelling, also see backup) 
-> total uncertainty improvement < \sqrt{2}
comparison to 13 TeV

(status fall 2018)
Combination of $|f_{LV} V_{tb}|$

$t$-channel, $\sqrt{s} = 7, 8$ TeV

\[ |f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{t-ch,t+t}}{\sigma_{t-ch,t+t}}} \]

\[ \frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}} \]

From single-top-quark production

- NLO (t- and s-channel)
- NLO+NNLL (tW)

\[ \delta \sigma_{\text{theo.}}: \text{scale } \oplus \text{PDF } \oplus \alpha_s \oplus m_t \oplus E_{\text{beam}} \]

- $m_t = 172.5$ GeV

\[ |f_{LV} V_{tb}| \pm (\text{meas.}) \pm (\text{theo.}) \]

- 1.02 ± 0.04 ± 0.02
- 1.02 ± 0.09 ± 0.04
- 0.97 ± 0.15 ± 0.02
- 1.02 ± 0.04 ± 0.02

Treat all correlations

Best direct measurement of $V_{tb}$ so far
$|f_{LV} V_{tb}|$, treatment of systematic uncertainties

Correlation treatment:

Stability tests:

$\rightarrow$ change of correlation assumptions has negligible impact
**| $f_{LV} V_{tb}$ |, comparison to earlier results**

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**ATLAS+CMS Preliminary**

LHCtopWG

May 2018

| $|f_{LV} V_{tb}|$ | $\pm$ (meas) $\pm$ (theo) |
|-----------------|-----------------|
| 1.02 $\pm$ 0.06 $\pm$ 0.02 |

**t-channel:**

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<th>Experiment</th>
<th>Events</th>
<th>$\sigma_{\text{theo}}$ (fb)</th>
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<td>112006</td>
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<td>ATLAS 8 TeV</td>
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<td>20.2 fb$^{-1}$</td>
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<tr>
<td>CMS 7 TeV</td>
<td>035</td>
<td>1.17 - 1.56 fb$^{-1}$</td>
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<td>CMS 8 TeV</td>
<td>090</td>
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<td>CMS combination 7+8 TeV</td>
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<td>0.998 $\pm$ 0.038 $\pm$ 0.016</td>
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<td>CMS 13 TeV</td>
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<tr>
<td>ATLAS 13 TeV</td>
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**Wt:**

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<tr>
<td>CMS 7 TeV</td>
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<td>ATLAS 8 TeV</td>
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<td>LHC combination 8 TeV</td>
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**s-channel:**

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**best direct measurement of $V_{tb}$ so far**
Conclusions

- Measurements of single top quark production at LHC are great tool to test EW theory, QCD and their interference, constrain PDFs (see talk O. Behnke in WG1 session) and measure $V_{tb}$ (check for deviations coming from new physics).

- Single top production has been measured by both ATLAS and CMS at 7, 8, and 13 TeV in the t-, tW-, and s-channel processes.

- Latest differential measurements of t channel at 13 TeV show slight preference for 4-flavour scheme calculations ($W p_T$), and further theory optimisation potential for low $p_T$ end of single t spectrum. Spin correlations agree with V-A.

- Latest measurements of associated tW production at 13 TeV show good agreement for total cross section.

- Measurement of tWb-ttbar interference in differential tW cross section shows preference for direct implementation of interference at matrix element level.

- Combination of t-, s-channel and tW total cross sections from ATLAS and CMS at 7 and 8 TeV show good consistency, yield (slightly) improved precision and show no deviations from Standard Model expectations. Achieve so far best direct measurement of $V_{tb}$. 

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Backup
ATLAS and CMS single top combination

References for input data sets:


treatment of systematic uncertainties

Table 10: Measured cross-sections, uncertainty components, their magnitudes (relative to the individual measurements) and the correlation ($\rho$) between the ATLAS and CMS $\sigma_{t\text{-chan.}}$ measurements at $\sqrt{s} = 8$ TeV. Uncertainties in the same row can be compared between experiments, as detailed in the text. The naming conventions follow those of the corresponding experiments.

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<th>ATLAS ($\sigma_{t\text{-chan.}}$, $\sqrt{s} = 8$ TeV)</th>
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<td>$t\bar{t}$, $tW$ and $s$-chan. norm.</td>
<td>$t\bar{t}$ and $W$+jets norm.</td>
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