Evidence for single top-quark production in the s-channel in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector using the Matrix Element Method

Epiphany 2016 | Cracow • January 9th, 2016

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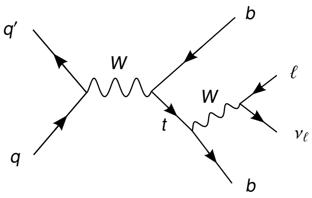
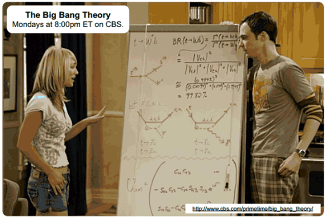
Single top-quark production

- Top-quark: still heaviest known particle – $m_t = 173\,\text{GeV}$
- Dominant production mode: $t\bar{t}$ via strong interactions
- Single top-quark: electroweak production
  - Sensitivity to new phenomena (FCNCs, W', ...)
  - Coupling structure at the Wtq vertex
  - Flavour physics (V_{tq})
- Distinction between s and t-channel (interference negligible)
- Particular rareness of the s-channel process



s-channel single top-quark production



$|V_{tb}|,\ |V_{ts}|,\ |V_{td}|$?

Searches for s-channel single top-quark production

- Fermilab press release Feb. 2014:
  "Scientists complete the top quark puzzle"
  s-channel observation by CDF+D0 (6.3σ)

  [PRL 112, 231803 (2014)]
- Challenge
  - Complex final states
  - Similarity of background events ($t\bar{t}$, t-channel single top, W+jets)
  - Low signal rate, in particular at the LHC due to low anti-quark luminosities (*pp* coll.) (CMS 2013 - 0.7σ, ATLAS 2014 - 1.3σ)

    [CMS-PAS-TOP-13-009, Phys.Lett. B740 (2015) 118]
- Latest result from 2015:
  First evidence for s-channel single top production (3.2σ) by ATLAS

  [arXiv:1511.05980, subm. to PLB]

Fermilab Tevatron
$\sigma_s/(\sigma_t + \sigma_{t\bar{t}}) \approx 10\%$

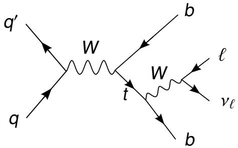
CERN LHC, $\sqrt{s} = 8\,\text{TeV}$
$\sigma_s/(\sigma_t + \sigma_{t\bar{t}}) \approx 1.6\%$

Outline

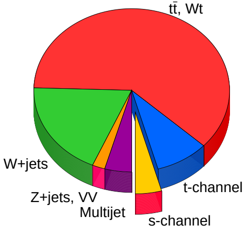
- Collision events
- Matrix Element Method
- Statistical evaluation
- LHC Run 2 prospects

Collision events
Selection

- Data-set recorded in 2012:
  pp coll., $\sqrt{s} = 8\,\mathrm{TeV}$, $\int L dt = 20.3\,\mathrm{fb}^{-1}$
- Selecting events with
  - Two b-tagged jets,
    $p_{\mathrm{T},1} > 40\,\mathrm{GeV}$, $p_{\mathrm{T},2} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
  - One electron or muon,
    $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Missing transverse momentum
    $\not{E}_{\mathrm{T}} > 35\,\mathrm{GeV}$, $m_{\mathrm{T}}^{W} > 30\,\mathrm{GeV}$
  - Veto against $t\bar{t}$ background -
    no additional e or μ (loose object definition)
- In addition: two control regions
  (modelling validation)
  1. W+jets enriched - loosened b-tag req.
  2. $t\bar{t}$ enriched - four jets



s-channel single top-quark production

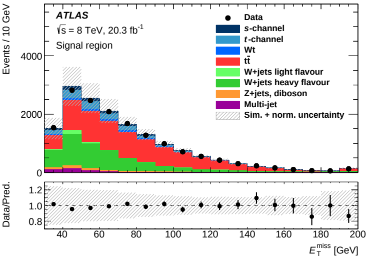


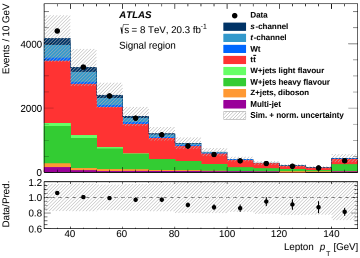
Event yields in the signal region,
$\Sigma = 14.000$

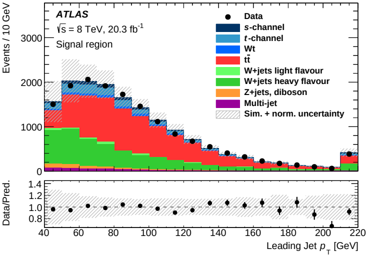
Collision Events
Modelling

- Mostly using MC event generators to model scattering processes
- Fakes of prompt charged leptons - data-driven estimation
- Proper modelling of the data; agreement within uncertainties

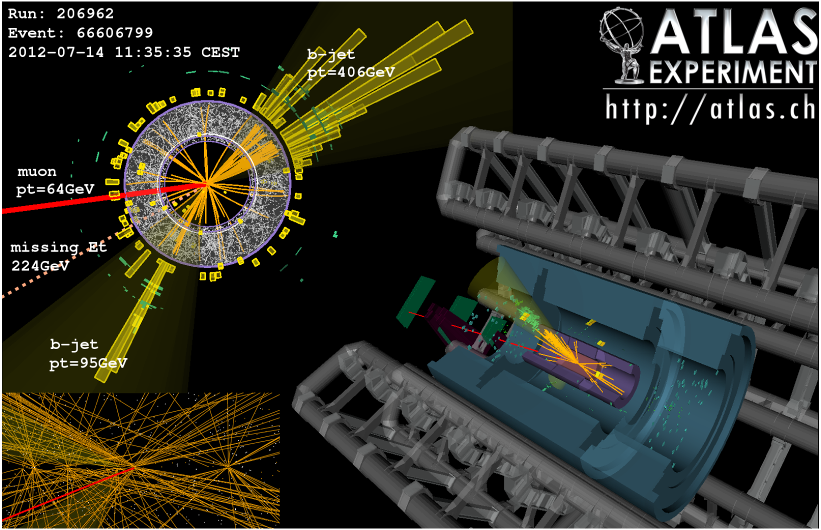
[arXiv:1511.05980, subm. to PLB]







Collision Events
Example

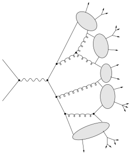


Matrix Element Method (MEM)

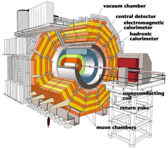
Ansatz and implementation

- $\mathcal{P}(X|H)$: p.d.f. of the event X given the scattering process H
- Approximation of $\mathcal{P}(X|H)$ by means of a factorization
  - Hard scattering - leading order perturbation theory
  - Hadronization, detector effects: parametrizations known as transfer functions

$\mathcal{P}(X|H) =$



$\otimes$



$$\approx \int \mathrm{d}\Phi \frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}\Phi} W(X|\Phi)$$

$$= \frac{1}{\sigma'} \sum_{p \in \{\text{permutations}\}} \int \mathrm{d}x_1 \mathrm{d}x_2 \mathrm{d}\Phi \sum_{i,j} \frac{f_i(x_1) f_j(x_2)}{2 x_1 x_2 s} |\mathcal{M}_{ij}|^2 W_p(X|\Phi)$$

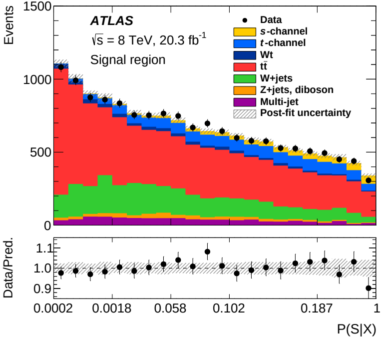
- Development of a comprehensive MEM package from scratch
- Several processes available, easy-to-use
- Not ATLAS specific, shared upon request

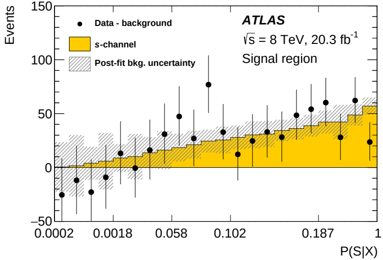
- Signal probability for a given event X:
  (Bayes' theorem)

$$P(S|X) = \frac{\sum_S P(S)\mathcal{P}(X|S)}{\sum_S P(S)\mathcal{P}(X|S) + \sum_B P(B)\mathcal{P}(X|B)}$$

- Several Signal and background p.d.f.s $\mathcal{P}(X|H)$
- $P(H)$: *a priori* probabilities given by relative event yields
- Computation of $P(S|X)$ for each event
  $\Rightarrow$ Accumulation of signal / bkg at high / low values

Matrix Element Method
Application





- Clear separation between signal and background processes

  ⇒ Possibility to measure the signal cross section [arXiv:1511.05980, subm. to PLB]

Statistical evaluation

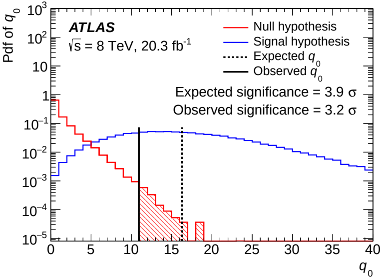
- Profile likelihood fit of signal and background templates of $P(S|X)$ to the data
- Test of B vs S+B hypothesis
  $\Rightarrow$ observe 3.2 σ signal significance

First evidence for s-channel single top-quark production in *pp* collisions

- Cross section measurement

$$\sigma_s = 4.8^{+1.8}_{-1.6}\ \text{pb} = 0.86^{+0.31}_{-0.28} \cdot \sigma_s^{\text{SM, approx. NNLO}}$$

- Agreement with the standard model
- Precision limited by data statistics



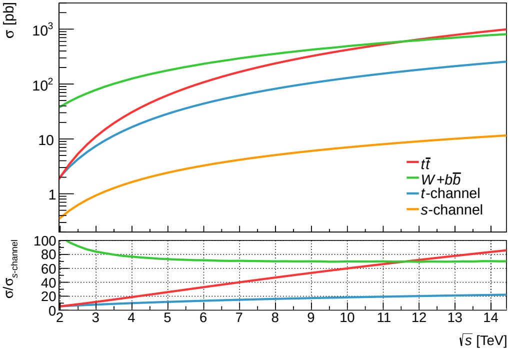
Source	$\frac{\Delta\sigma_s}{\sigma_s}$ [%]
Data stat.	16
MC stat.	12
Jet energy res.	12
t-channel generator	11
Others	< 10 each
Total	34

LHC Run 2 prospects

- Unlikely to substantially improve the Run 1 analysis (apart from a combination with CMS?)

Run 2 : $\sqrt{s} = 13\,\text{TeV}$, more data

- Disadvantage:
  S/B even worse,
  $\sigma_s/(\sigma_{t\bar{t}} + \sigma_t)$: 1.6% → 1.0%
- Advantage:
  surpassing statistical limitation
- Overall:
  improvement feasible



Summary

- Valuable to measure single / electroweak production of top-quarks
- Most challenging: s-channel single top-quark production
- ATLAS analysis, $\int L\mathrm{d}t = 20.3\,\mathrm{fb}^{-1}$, $\sqrt{s} = 8\,\mathrm{TeV}$:
  - First evidence for s-channel single top-quark prod. in *pp* collisions
  - Agreement with the standard model prediction
  - Earlier approaches significantly improved,
    in particular due to the MEM
- Potential to improve the analysis in LHC Run 2

Backup

Run Script:

```
MemMgr *mgr = new MemMgr;
mgr->SetCollider(MemMgr::kPP, 8000.);
mgr->SetPdfMgr("cteq66");

MemTFcnSet *tfcnATLAS = new MemTFcnSet(MemTFcnAtlasBase::kMC12);

MemProcSgTop_tChannel_2jets *procSgTop =
      new MemProcSgTop_tChannel_2jets("tChannel", "SgTop t-channel", 172.5);
procSgTop->GetMCMgr()->SetEpsRel(0.05);
procSgTop->SetTFcnSet(tfcnATLAS);
mgr->AddProcess(procSgTop_tChannel);

mgr->SetEvtReader(new MemEvtReaderGeneric);
mgr->SetInputTreeName("t_mem");
mgr->AddInputFile("myMemInput.root");

mgr->SetEvtWriter(new MemEvtWriterGeneric);
mgr->SetOutputFile("MyMemOutput.root");
mgr->SetOutputTree("t_llh", "MEM Likelihodd Tree");

mgr->Run();
```

- Easy-to-use MEM package, currently shared upon request