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Measurement of the production of highly boosted W-associated single top quarks

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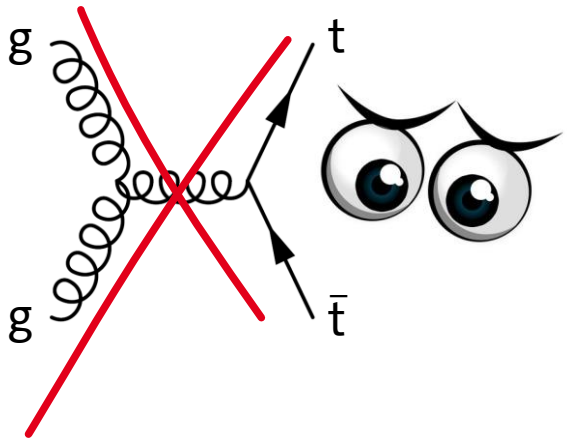
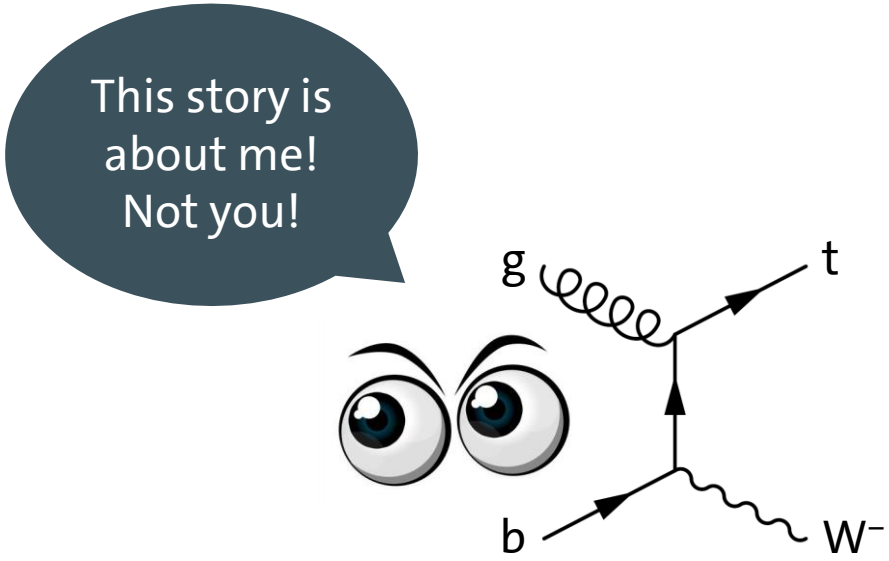


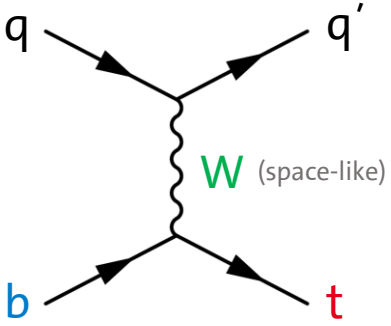


A quick introduction …

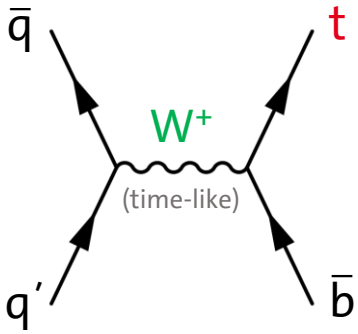
… to single top quark physics

Single top quark processes

- There are 3 canonical production processes of single top quarks
- Distinguished by the virtuality of the involved W boson
- $\sqrt{\hat{s}}_{min}(t\bar{t})$ higher, but single t suppressed by weak force and b PDFs



***t*-channel**



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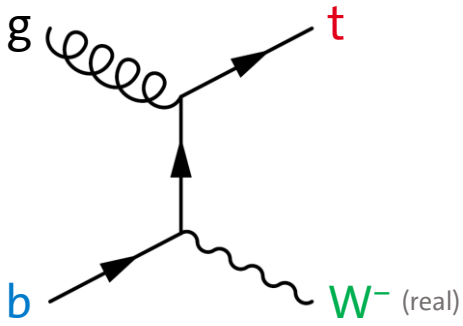


W-associated

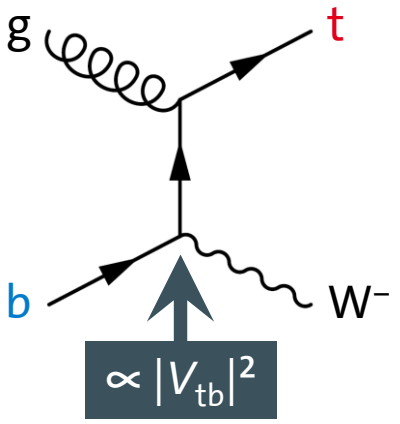
σ_{incl}(pp @ 13 TeV):	217 pb	10 pb	72 pb	$t\bar{t}$: 832 pb
Single t fraction:	73 %	3 %	24 %	$\sigma(t\bar{t})/\sigma(t)$ = 2.78

Predictions taken from: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/<SingleTopRefXsec|TtbarNNLO>

… and why their study is important!

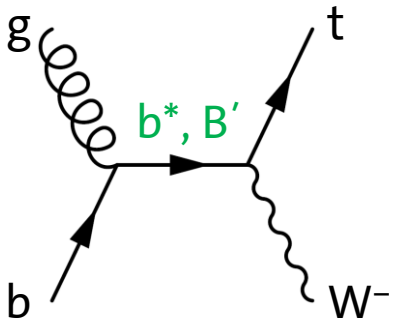
Standard Model:

- Top quark mass and spin polarization
  ($t\bar{t}$: only spin correlations accessible at LO)
- $|V_{tb}|$ from single t production x-section
  ($t\bar{t}$: only accessible via top quark decay)
- b PDFs and b quark/antiquark ratio



New physics:

- Important background in many searches
- BSM single t processes: b*, B′, H±, FCNC, …
- Effective field theory (EFT) sensitivity

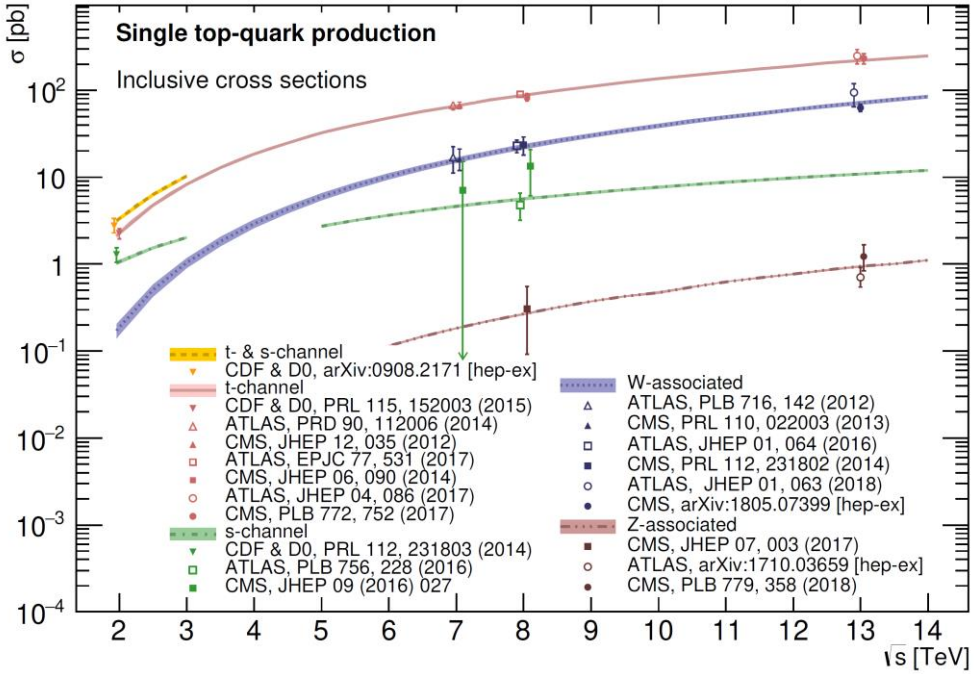


cf. talk by A. Fröhlich
on 2nd October 2019

Further reading: arXiv:1710.10699 (experimental review), arXiv:1211.7146 (theoretical review)

“Boom” in single top quark physics

- 2009: First observation in the combined *t*- & *s*-channel at CDF & DØ
- Today: Measurements of rare single t processes (e.g. tZq) at the LHC

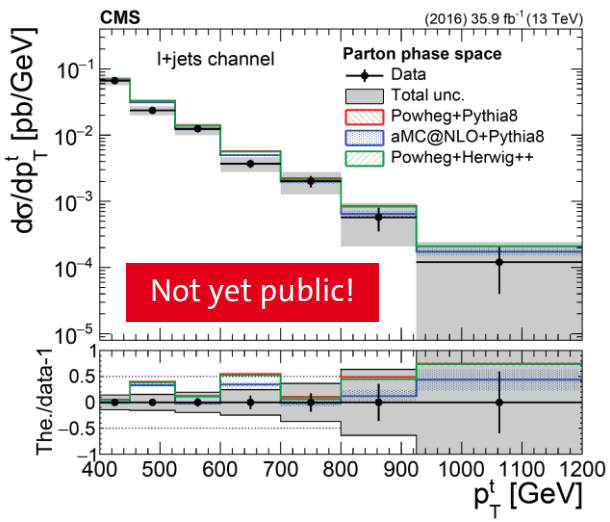


Single top quark physics entering its precision era ***NOW!***

Figure taken from: arXiv:1710.10699 (last update in spring 2018)

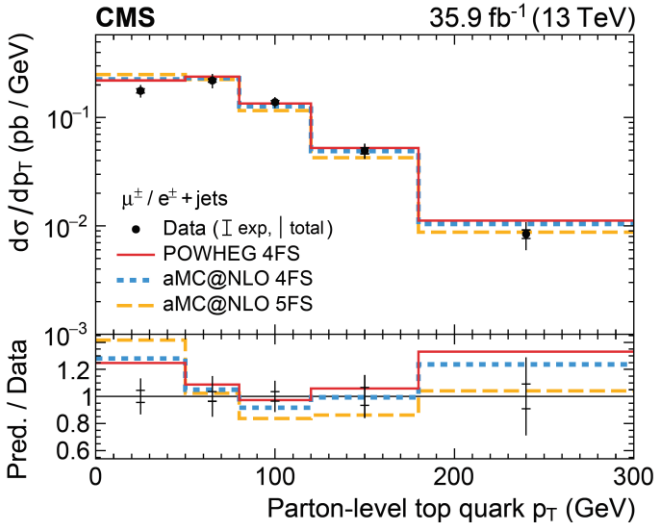
Differential x-section measurements

- Various measurements for $t\bar{t}$ and some for single t by ATLAS & CMS
- High-p_T ("boosted") sector completely untouched in case of single t



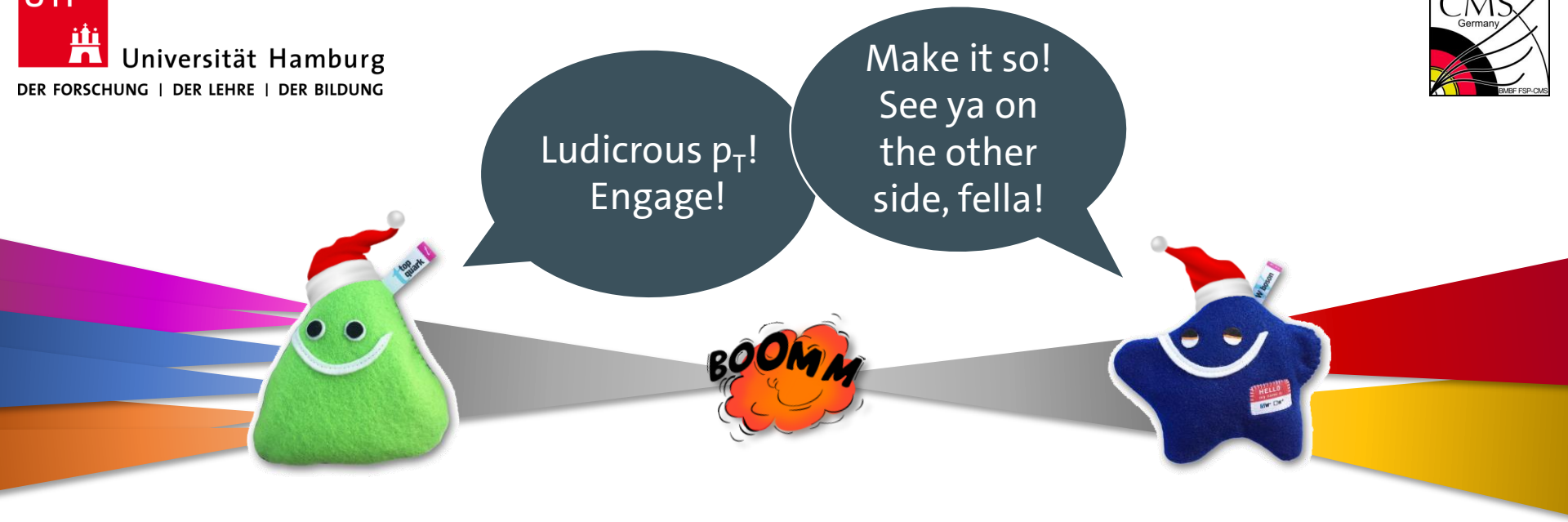
pair production

Taken from CMS-TOP-18-013
AN-2016/174 version no. 7



t-channel single t

Taken from CMS-TOP-17-023
Publication: arXiv:1907.08330



With the “boom” comes the “boost”

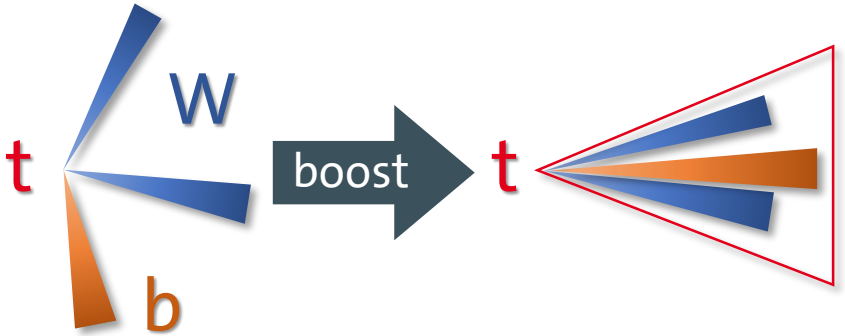
Or: How to reconstruct highly boosted single top quarks

Boosted (hadronic) top quark decays

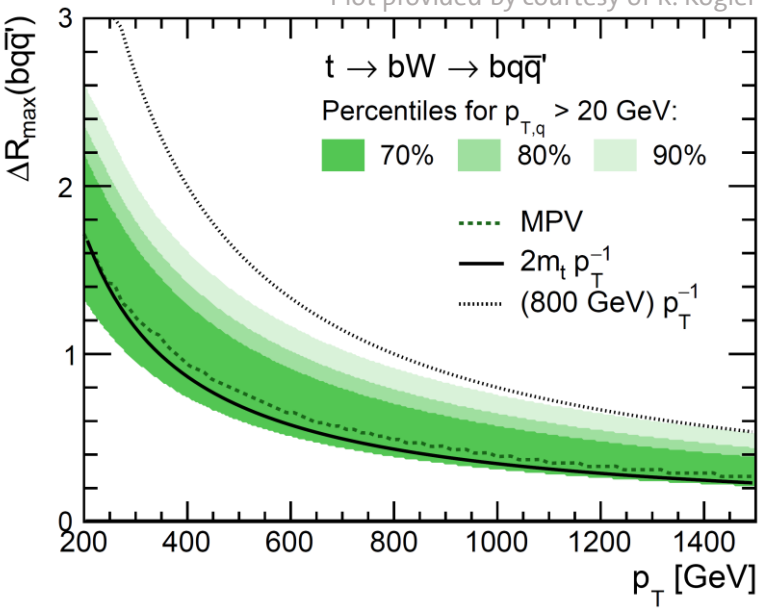
- Large γ factor, $p \gg m \simeq 173$ GeV
- Decay products cannot be reconstructed individually
- Top quark must be reconstructed as one, **merged large-radius jet**
- Collimation **p_T-dependent**, rule of thumb for *two-body* decays:

$$\Delta R_{min} \approx \frac{2m}{p_T} \quad \Rightarrow \quad p_T \propto R^{-1}$$

- Intuitive approach:
  Use of **variable-R** jet algorithm



Plot provided by courtesy of R. Kogler

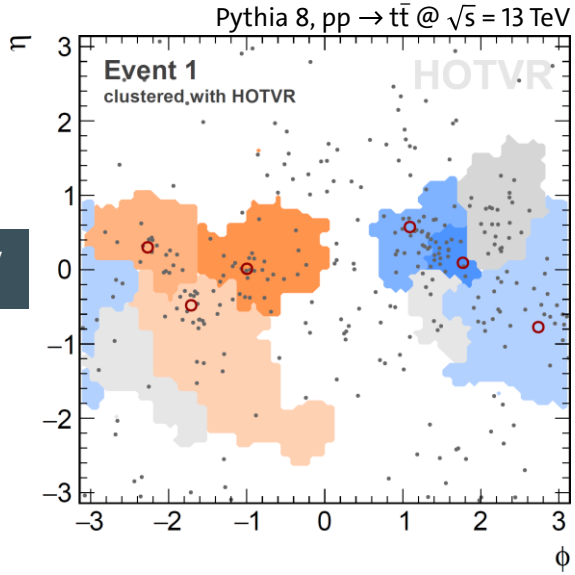


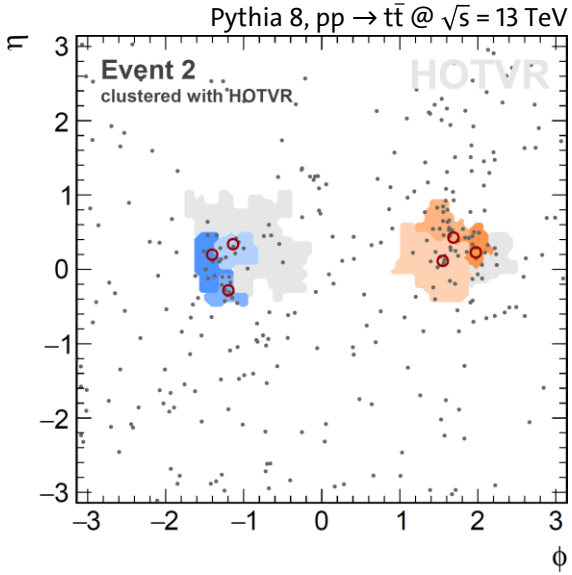
Further reading: arXiv:0903.0392

Heavy Object Tagger with Variable R

- Based on C/A algorithm
- Adaptive jet radius:
  $R \propto 1/p_T(\text{jet})$, $R \in [0.1, 1.5]$
- Stable perform. in wide p_T range
- Mass-jump criterion to reject soft/wide-angle radiation
- Implements subjet finding
- t-tagging possible (later slides)

p_T ~ 240 GeV

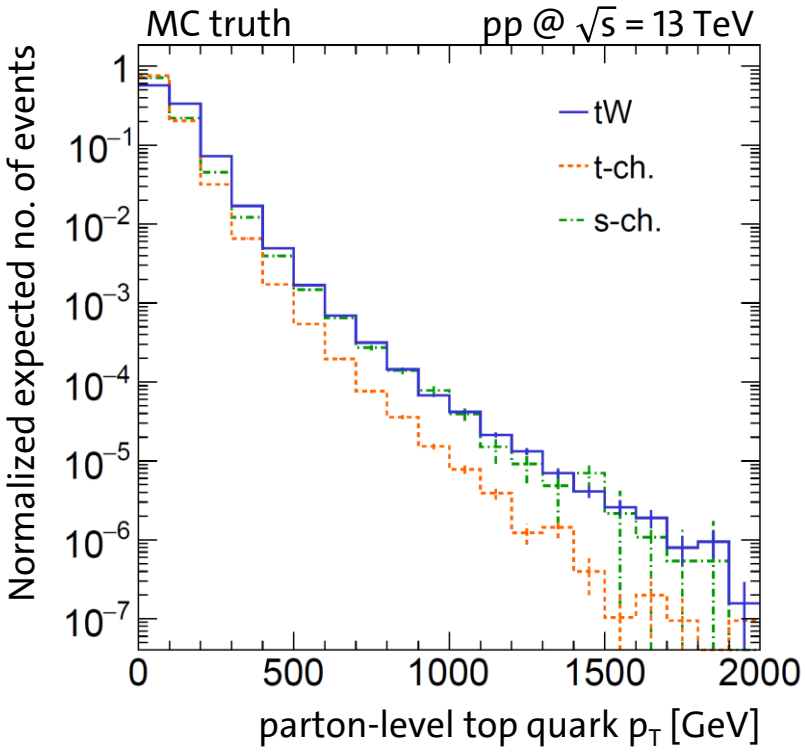




p_T ~ 850 GeV

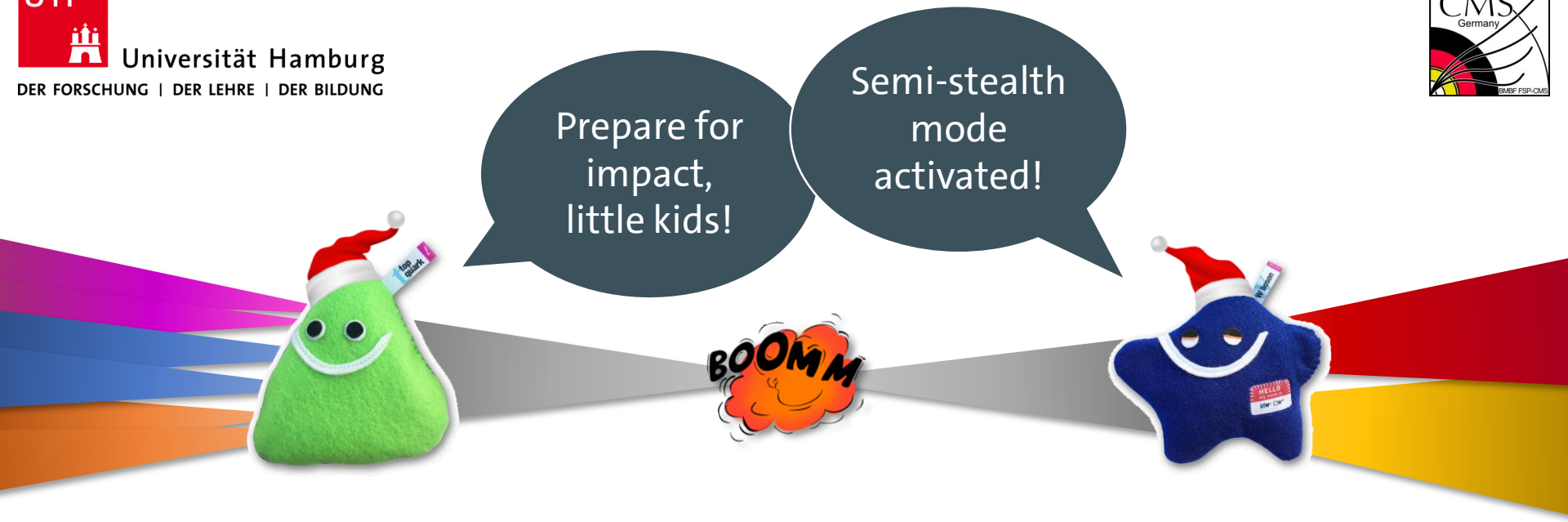
Event displays taken from HOTVR publication: **T. Lapsien et al.**, Eur. Phys. J. C 76, 600 (2016), arXiv:1606.04961

Which single t process to go for?



- σ_{incl}(*t*-ch.) ≃ 217 pb largest, but harder spectrum for *s*-ch. & tW
- σ_{incl}(*s*-ch.) ≃ 10 pb very low, σ_{incl}(tW) ≃ 72 pb good compromise
- Considering **hadronic t decay**, all-jets final states for *t*- & *s*-ch. ⇒ Separation from background (mainly QCD & $t\bar{t}$) not feasible
- Leptonic component beneficial

$t_{had}W_{lep}$ most promising!



Analysis

Measurement of W-associated single top quark production in the highly boosted sector using the $t_{had}W_{lep}$ final state

Analysis goal & strategy

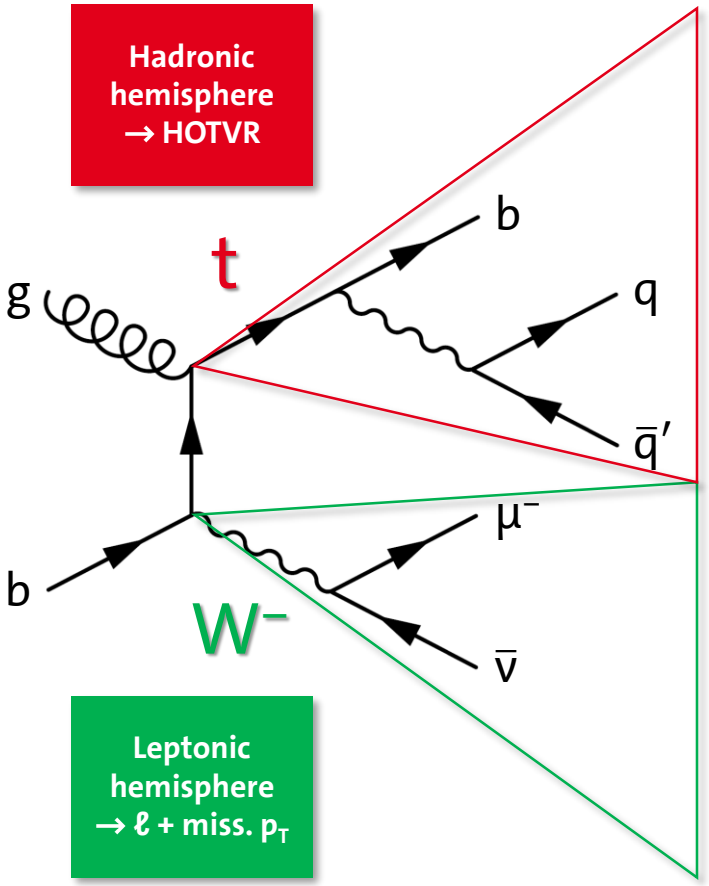
Measure tW properties on parton & particle level: top quark p_T main target

- Event selection
- Top quark reconstruction
- Event classification using neural nets
- Fits on NN outputs per p_T bin
- Unfolding using fit results

We are here

Selection of tW → ℓ+jets events

- Working on 2016 μ+jets for now
- Single muon trigger
- Exactly one isolated, tight muon
  (rel. iso. < 0.15, p_T > 50 GeV, $|\eta|$ < 2.4)
- Veto on additional loose leptons
- Missing p_T > 50 GeV
- At least one AK4 jet
- At least one HOTVR jet
  (p_T > 200 GeV, $|\eta|$ < 2.5, $\Delta R(\ell, \text{jet})$ > 1.5)
- Exactly **one HOTVR t-tag**

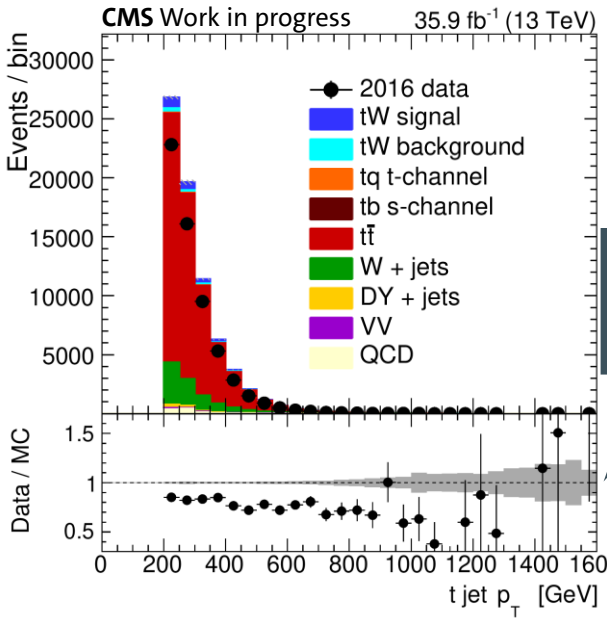


Tagging of t jets

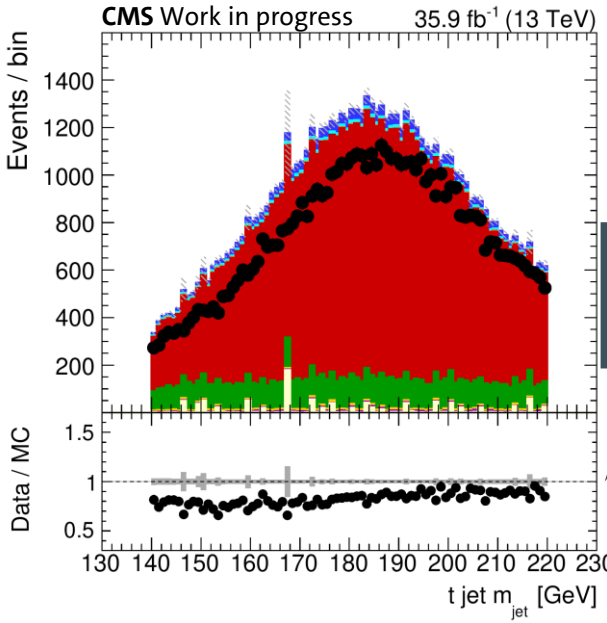
A HOTVR jet is considered t-tagged if:

- 140 GeV < jet mass < 220 GeV
- Number of subjets ≥ 3
- p_T fraction of leading subjet < 80 %
- Minimum pairwise mass of leading 3 subjets: m_{ij} > 50 GeV
- N-subjettiness ratio τ_3/τ_2 < 0.56

τ_N: figure of merit for likelihood that jet consists of up to N subjets
1 = unlikely, 0 = likely



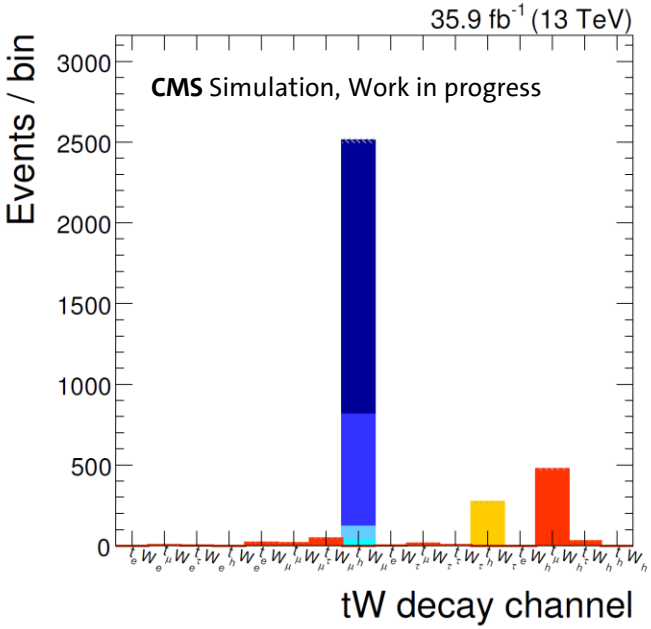
Slope in ratio: top p_T in $t\bar{t}$ mis-modelled

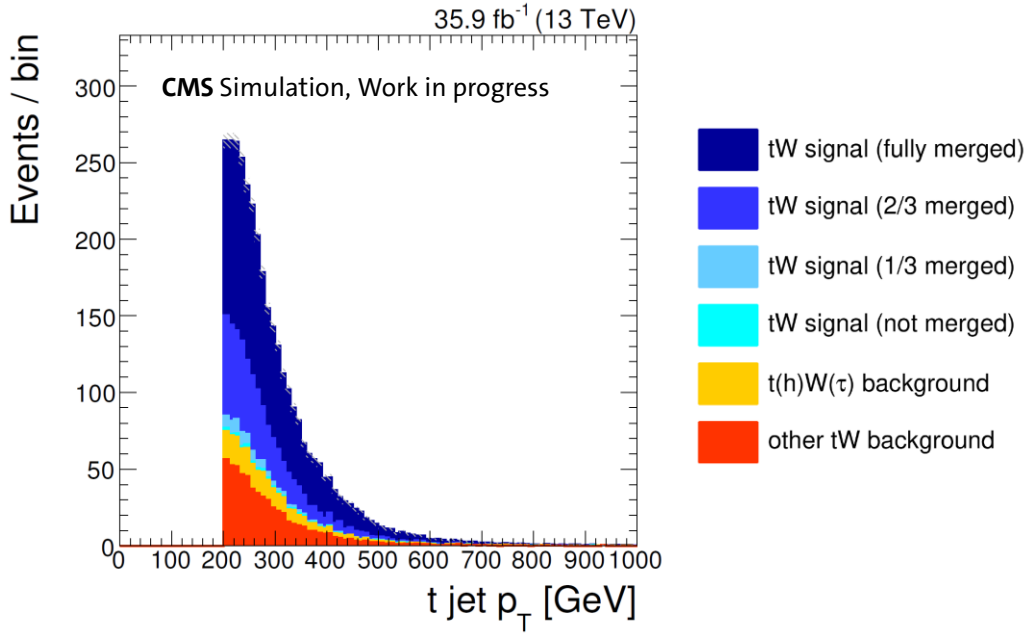


Offset in ratio: top p_T in $t\bar{t}$ mis-modelled

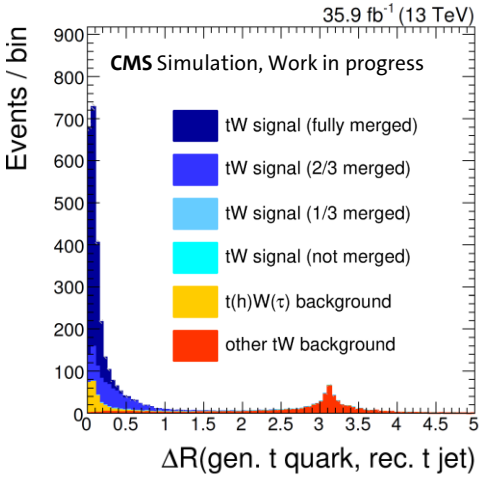
Composition of tW Monte Carlo (I)

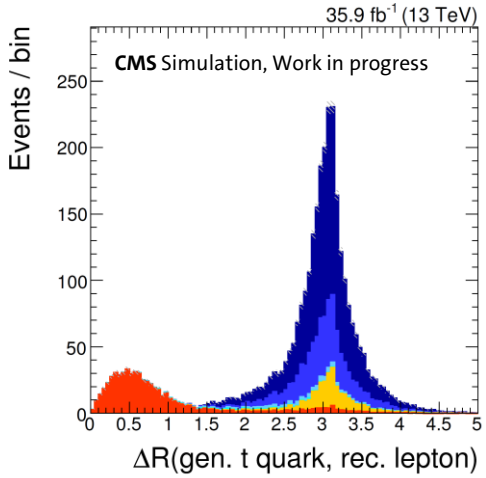
- After full selection, ca. 70 % of all tW is actual signal ($t_{had}W_{\mu}$)
  (95 % thereof feature a t jet merging 2 or 3 quarks from t decay)
- HOTVR t-tagging allows for discrimination of $t_{had}W_{lep}$ and $t_{lep}W_{had}$

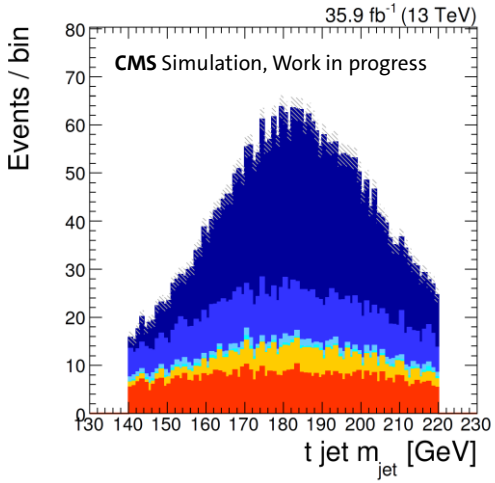


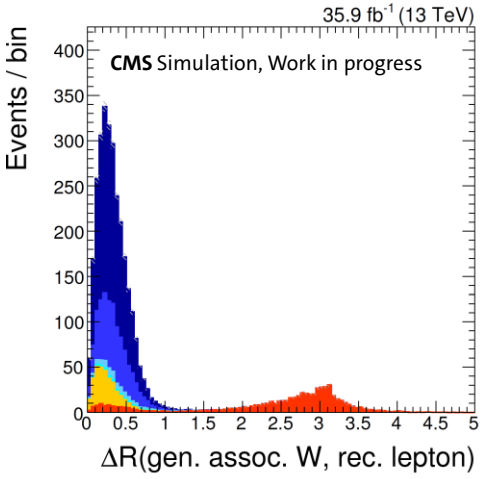


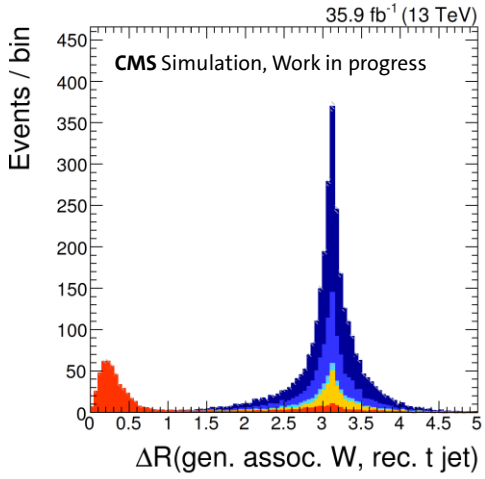
Composition of tW Monte Carlo (II)

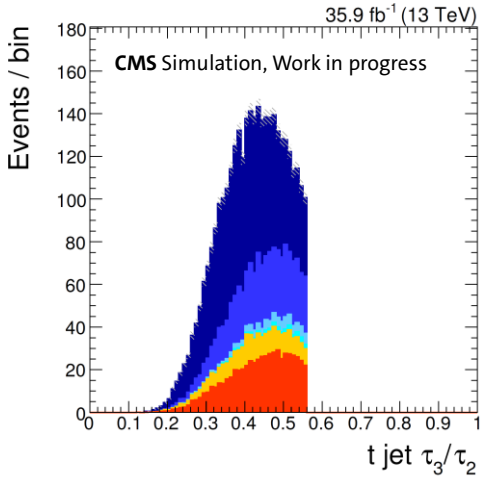






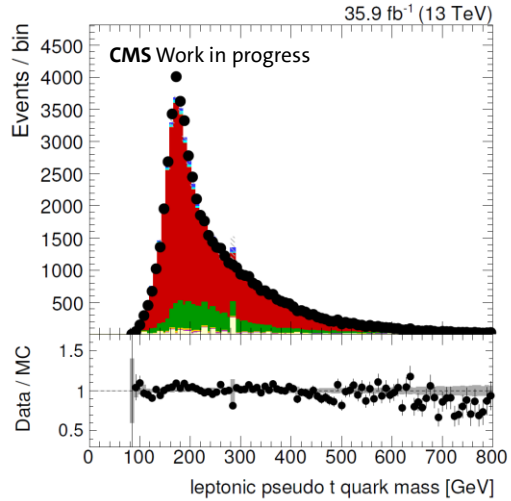


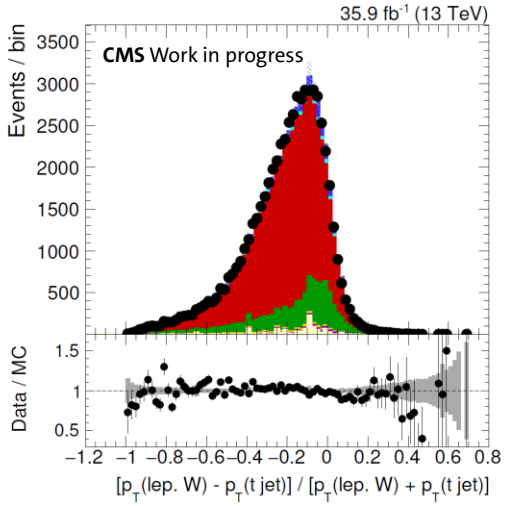


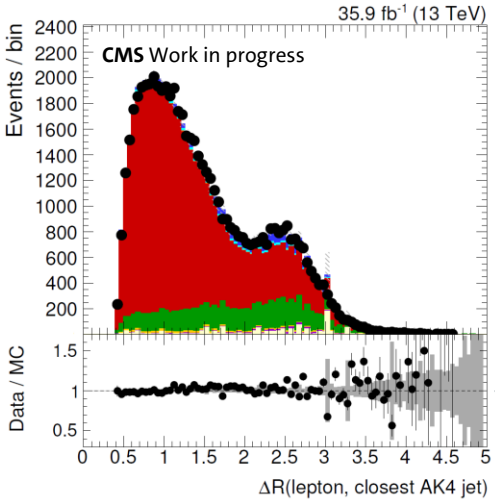


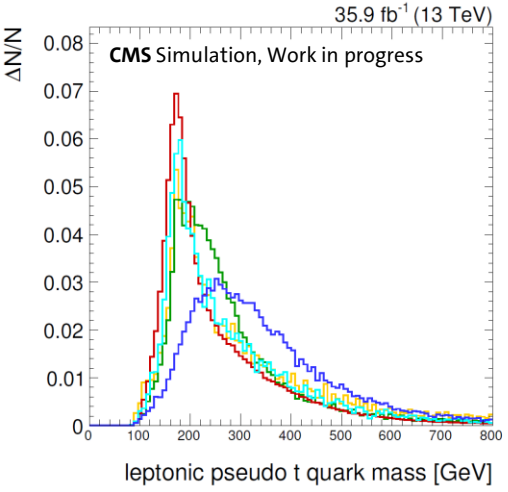
Leptonic top quark in $t\bar{t}$ and tW background reconstructed from lepton, miss. p_T, (b) jet(s)

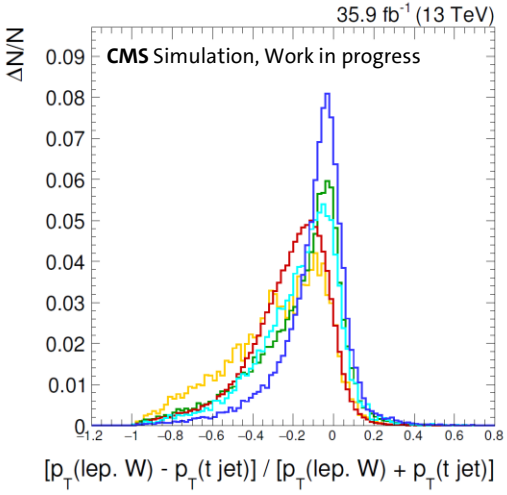
Exemplary discriminants

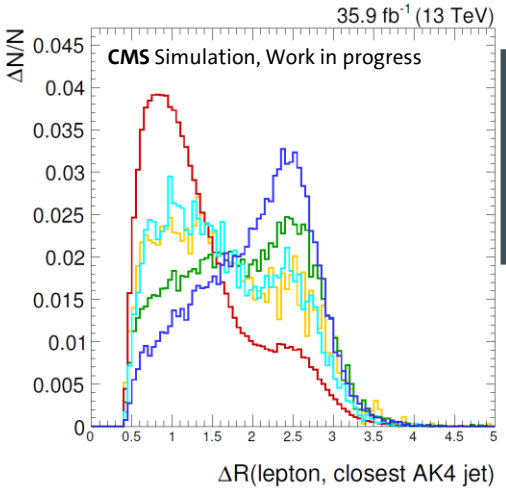












$t\bar{t}$ scaled to match data in fiducial phase space (factor ~0.78)

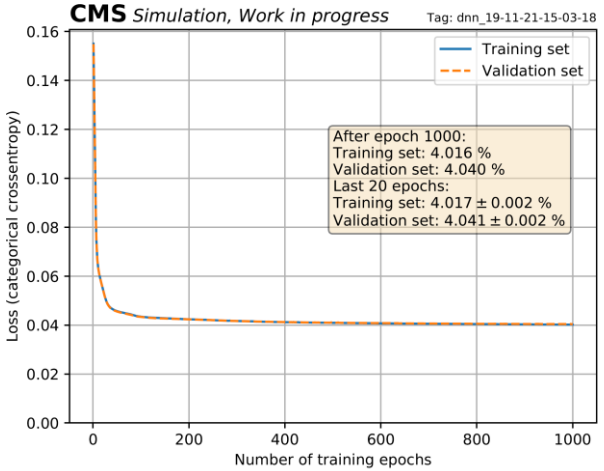
DNN-based event classification (I)

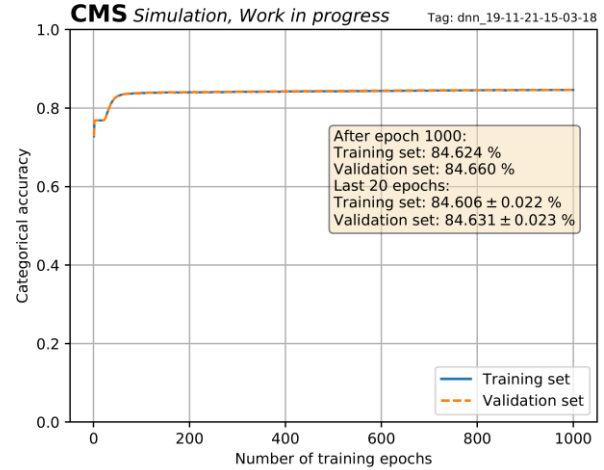
Architecture:

- 68 inputs (jet, lepton, event quantities)
- 2 x 16 hidden nodes (ReLU activation)
- 6 output classes: $t_{had}W_{\mu}$ signal, $t_{had}W_{\tau}$ bkg., other tW bkg., $t\bar{t}$, W + jets, Drell–Yan + jets

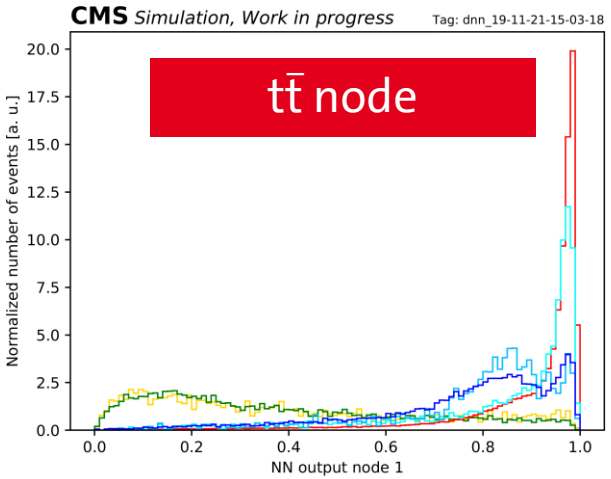
Training:

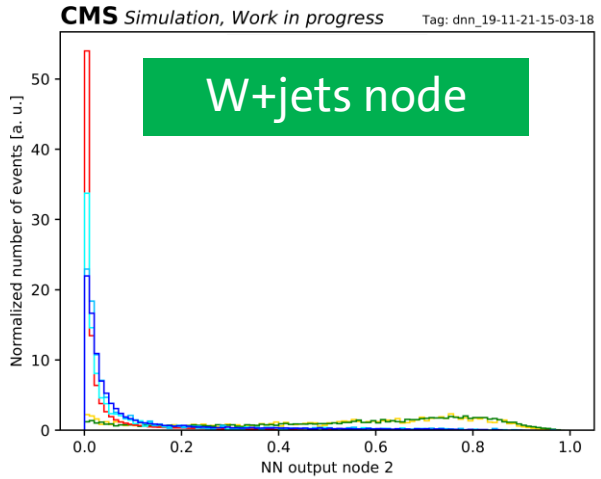
- 500k MC events in training set
- Minimize categorical crossentropy
- Loss saturates quickly for training and validation set; overfitting almost null
- Ca. 84 % of events classified correctly

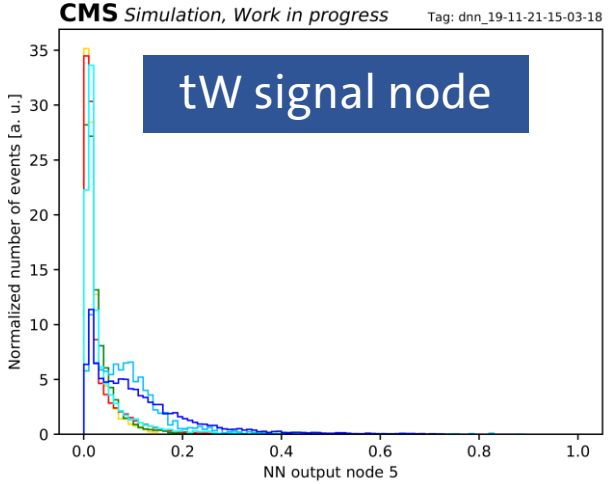


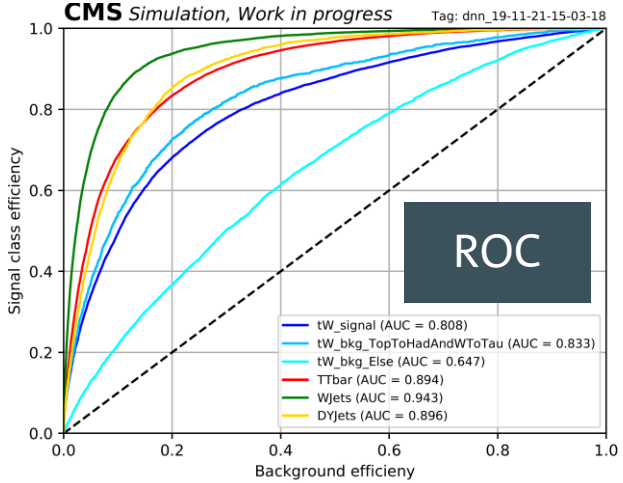


DNN-based event classification (II)









Summary & outlook

Single top quark phyiscs overview:

- Exciting field of research
- Pioneering times are over, precision era begins → boosted sector!

Measurement of highly boosted tW production:

- Event selection, using HOTVR to identify top quark
- DNN to discriminate tW from large backgrounds
- Next steps: Fits on DNN output to extract tW, then unfold fit results

Far outlook:

- Interpretation of results in context of EFT
- Measurement of b PDFs at high x