Production of the *Madala boson* in association with top quarks

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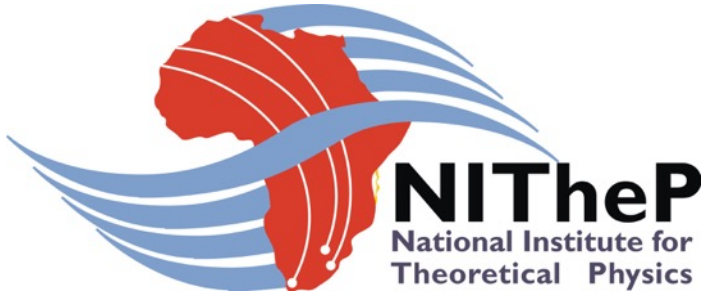
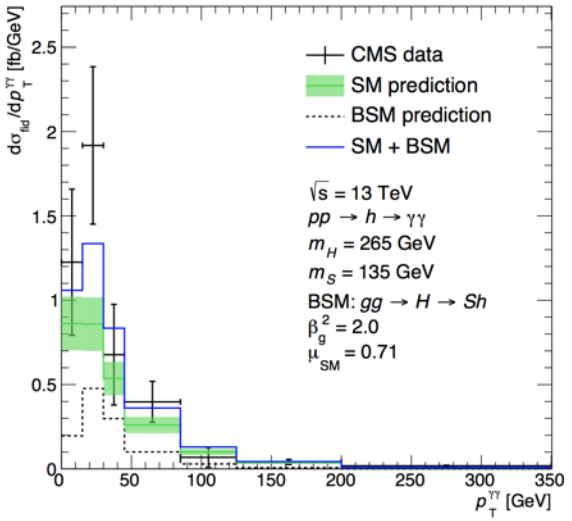
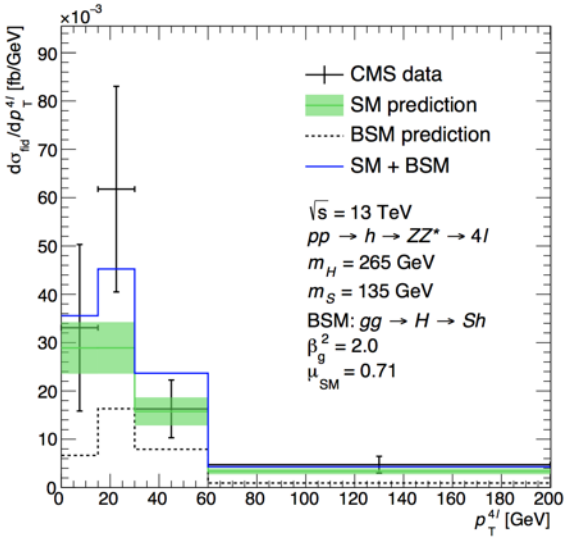
SAIP 2017



The Madala boson?

- A heavy, hypothetical boson, *H*
- Mass around ~270 GeV (arXiv:1506.00612)
- Interacts with the Standard Model Higgs boson, *h*
- Its existence can explain several experimental anomalies, such as
  - Higgs p_T spectrum
  - Multilepton excesses
    - *tth* excesses
- Madala hypothesis
- An effective approach; simplified idea with the intent on studying anomalous LHC data



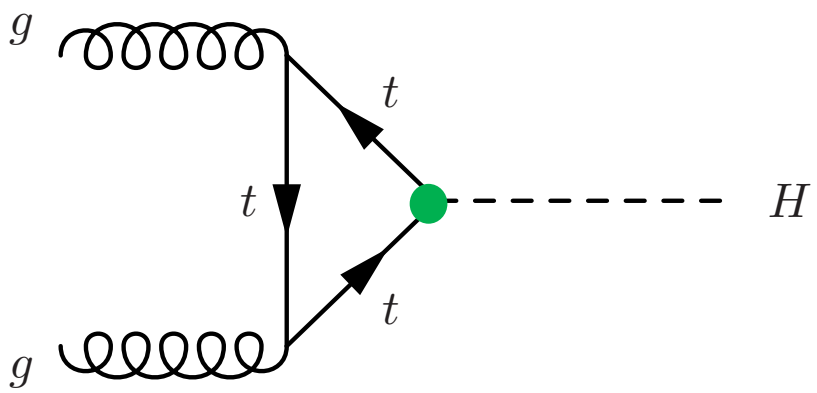


Producing the Madala boson

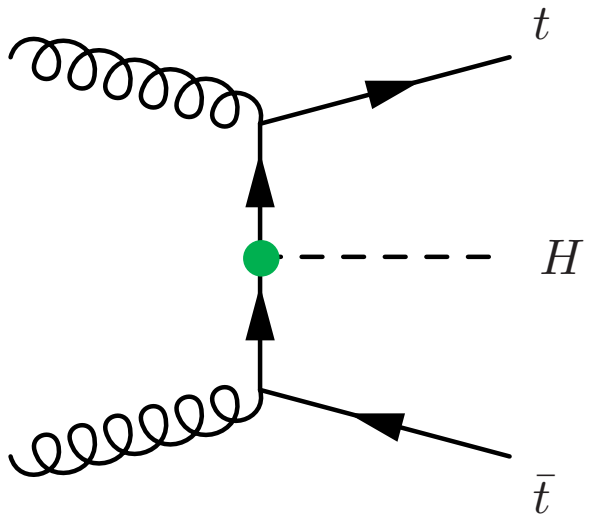
- Initially assumed gluon fusion (*gg*F)
- This assumes a Yukawa coupling:

$$\sim y_t t\bar{t}H$$

  - This coupling in non-negligible (proportional to top mass)
  - what other production modes are possible?
- Top associated production! (*ttH*)
  - Similar to the Higgs boson
- Dominant Feynman diagram contains same vertices as *gg*F
- We scale the Yukawa coupling by $\beta_g \approx 1.5$, so cross section is enhanced



ggF

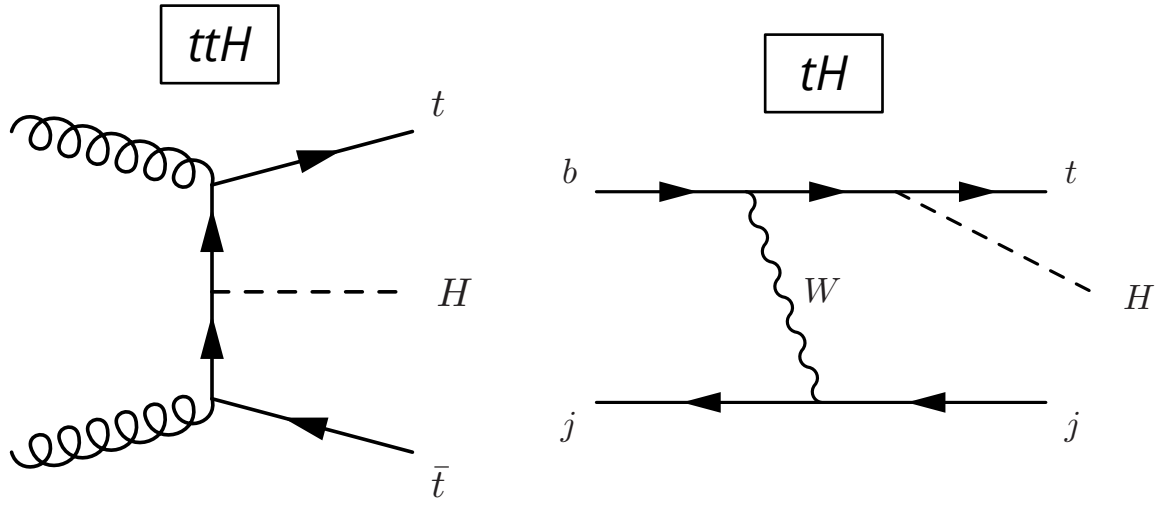


ttH

Cross sections

- For *tth* searches, we need to consider single top (*tH*) AND double top (*ttH*) production
- *ttH* cross sections have been calculated and published
  - What about *tH*?
- We find that in the Madala hypothesis:

$$\sigma_{ttH} \cong \sigma_{tH}$$



For single top production:

$$\mathcal{A} = \frac{g}{2}\left[(c_F - c_V)\frac{m_t\sqrt{s}}{m_W v}A + \left(c_V\frac{2m_W s}{vt} + (2c_F - c_V)\frac{m_t^2}{m_W v}\right)B\right]$$

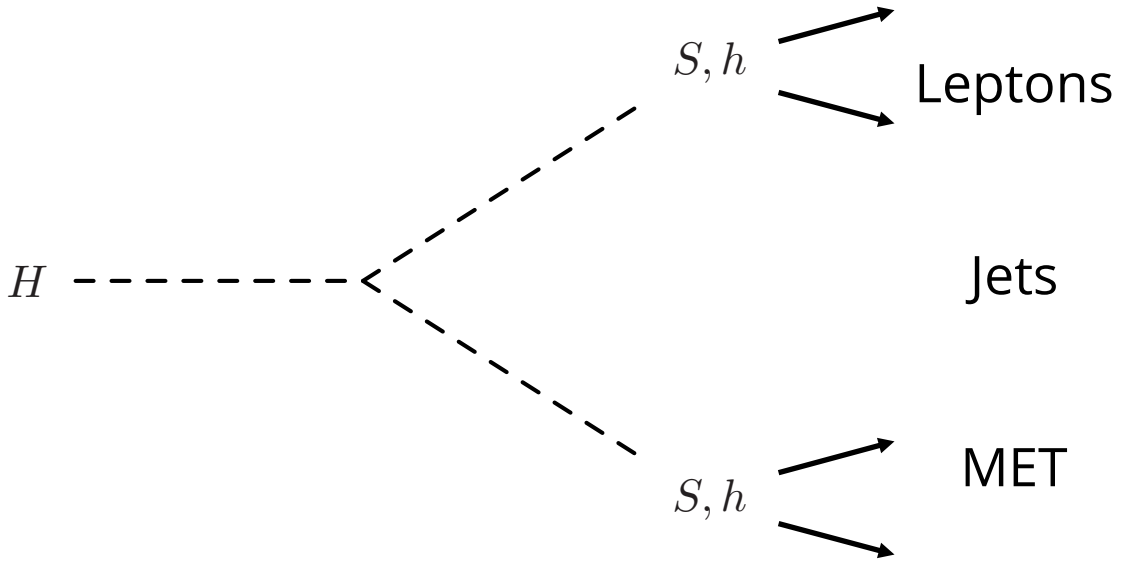
But in our case $c_V \ll c_F$,

$$\therefore \mathcal{A} \cong \frac{g}{2}\left[c_F\frac{m_t\sqrt{s}}{m_W v}A + \left(c_V\frac{2m_W s}{vt} + 2c_F\frac{m_t^2}{m_W v}\right)B\right]$$

(JHEP 1305 (2013) 022)

Decay modes of the Madala boson

- Main decay modes of H:
  - $H \rightarrow Sh, SS, hh$
- Depending on choice of masses, this could be on- or off-shell
- Potential for a Higgs boson in the final state
- So top associated Madala production implies top associated Madala production
- If $S \rightarrow$ leptons, we should look in multilepton searches



The S boson:

- Scalar singlet
- Mass between ~130 and ~180 GeV
- Approximation: make it Higgs-like, to simplify branching ratios
- Potential portal to dark matter

tth -> multileptons

- Experiments make measurements on $$\mu_{tth} = \frac{\sigma_{obs}}{\sigma_{SM}}$$
  - $\mu_{tth} = 1$ is the Standard Model prediction
- Combining all experimental results, we get $\mu_{tth} = 1.92 \pm 0.38$
- Excess of cross section!

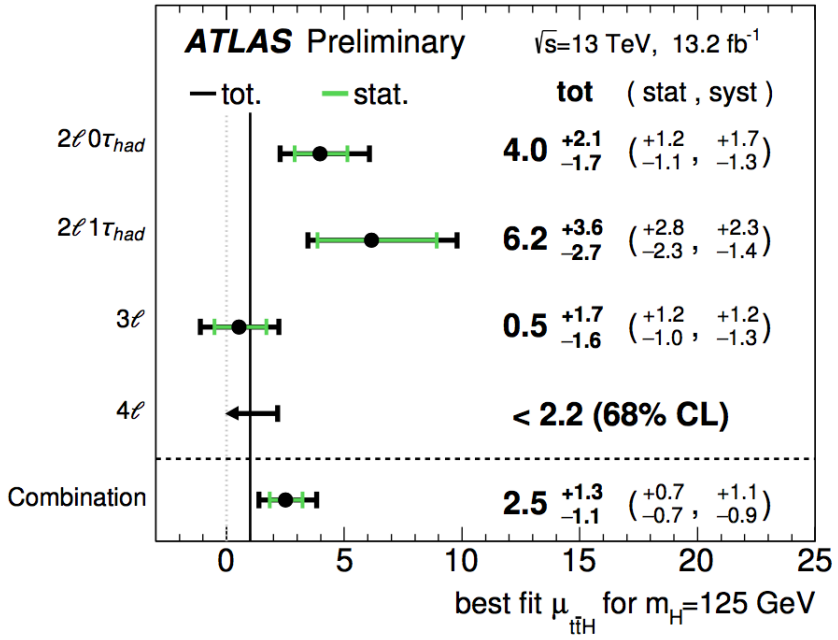
- Table taken from: S von Buddenbrock, 'Exploring LHC Run 1 and 2 data using the Madala hypothesis', arXiv:1706.02477 [hep-ph]

Reference	Channel	Measured μ_{tth}
CMS Run 1 [35]	Same-sign 2ℓ	$5.3^{+2.1}_{-1.8}$
	3ℓ	$3.1^{+2.4}_{-2.0}$
	4ℓ	$-4.7^{+5.0}_{-1.3}$
	Combination	$2.8^{+1.0}_{-0.9}$
ATLAS Run 1 [36]	$2\ell 0\tau_{\text{had}}$	$2.8^{+2.1}_{-1.9}$
	3ℓ	$2.8^{+2.2}_{-1.8}$
	$2\ell 1\tau_{\text{had}}$	$-0.9^{+3.1}_{-2.0}$
	4ℓ	$1.8^{+6.9}_{-2.0}$
	$1\ell 2\tau_{\text{had}}$	$-9.6^{+9.6}_{-9.7}$
	Combination	$2.1^{+1.4}_{-1.2}$
CMS Run 2 [37]	Same-sign 2ℓ	$1.7^{+0.6}_{-0.5}$
	3ℓ	$1.0^{+0.8}_{-0.7}$
	4ℓ	$0.9^{+2.3}_{-1.6}$
	Combination	$1.5^{+0.5}_{-0.5}$
ATLAS Run 2 [38]	$2\ell 0\tau_{\text{had}}$	$4.0^{+2.1}_{-1.7}$
	3ℓ	$0.5^{+1.7}_{-1.6}$
	$2\ell 1\tau_{\text{had}}$	$6.2^{+3.6}_{-2.7}$
	4ℓ	< 2.2
	Combination	$2.5^{+1.3}_{-1.1}$
Error weighted mean		1.92 ± 0.38

tth -> multileptons in the LHC Run 2 data

1) ATLAS *tth*

ATLAS-CONF-2016-058



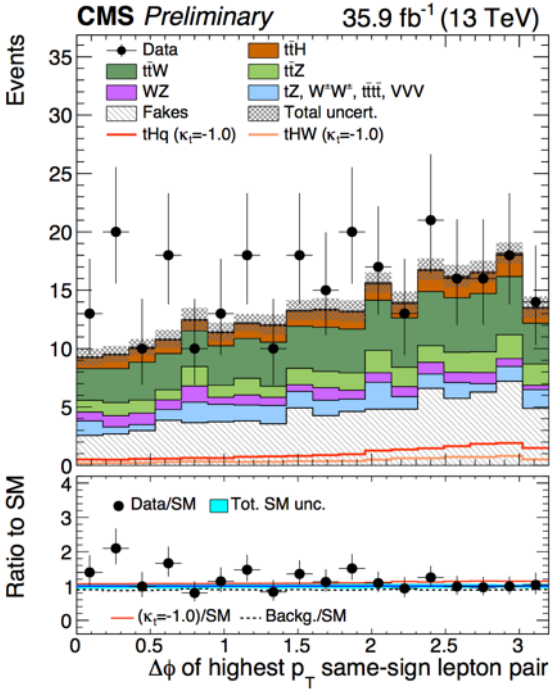
2) CMS *tth*

CMS-PAS-HIG-17-004

Category	Observed μ fit $\pm 1\sigma$
Same-sign di-lepton	$1.7\,(-0.5)\,(+0.6)$
Three lepton	$1.0\,(-0.7)\,(+0.8)$
Four lepton	$0.9\,(-1.6)\,(+2.3)$
Combined (2016 data)	$1.5\,(-0.5)\,(+0.5)$
Combined (2015 data) [42]	$0.6\,(-1.1)\,(+1.4)$
Combined (2015+2016 data)	$1.5\,(-0.5)\,(+0.5)$

3) CMS *single top*

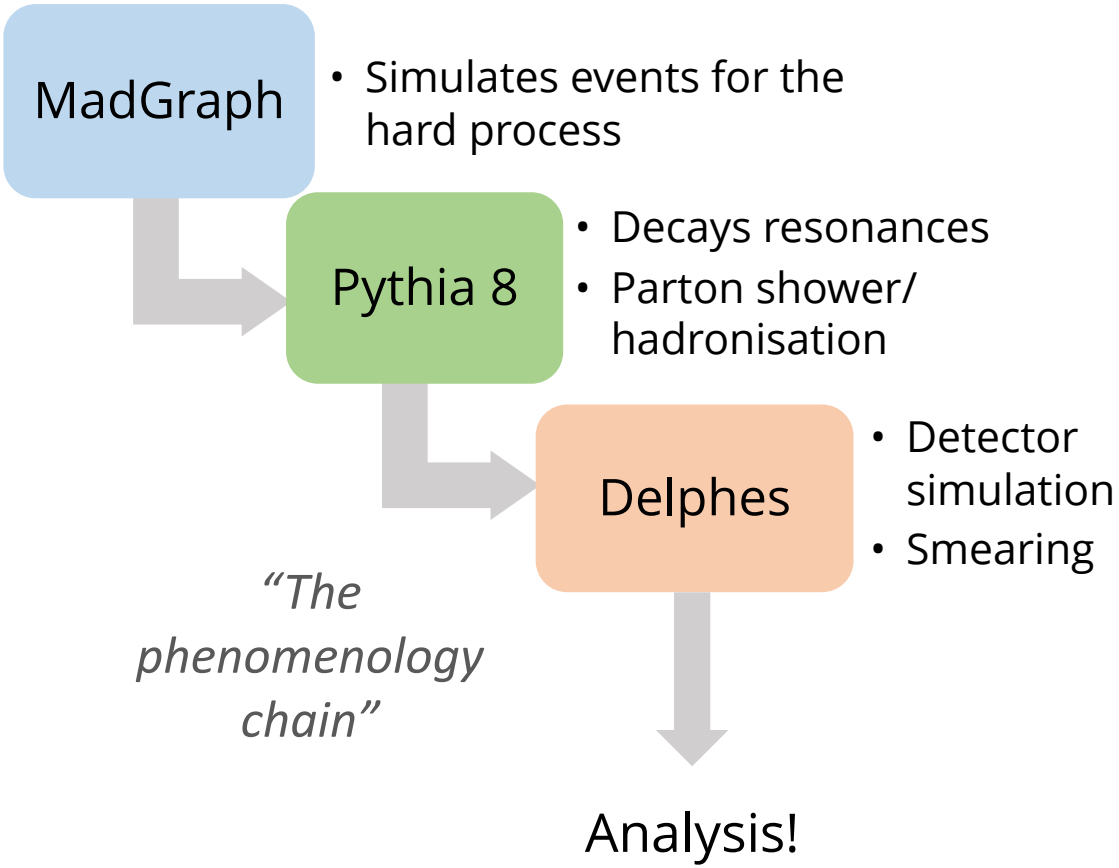
CMS-PAS-HIG-17-005



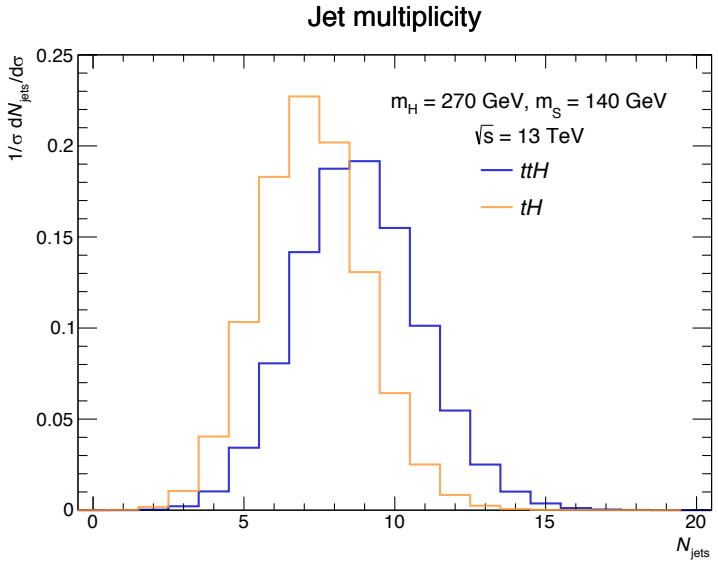
Modeling *ttH* production

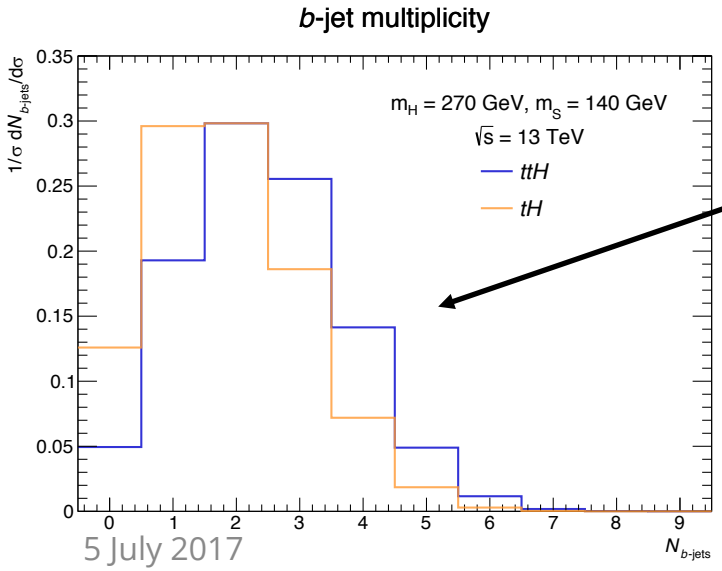
- Three steps required:

1. MadGraph
   - Generate events with the process $pp \to ttH$ and $pp \to tH$
2. Pythia 8
   - Decays $H \to Sh$, and then decays h and S assuming S is Higgs-like
3. Delphes
   - Simulates the detector response
   - Applies experimental efficiencies
   - Outputs data file for analysis

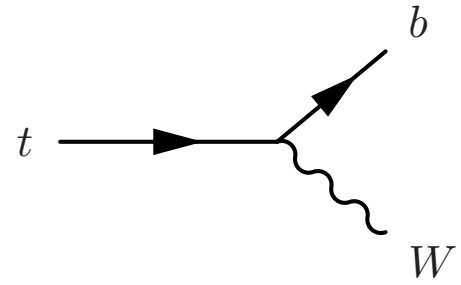


ttH and *tH* kinematics



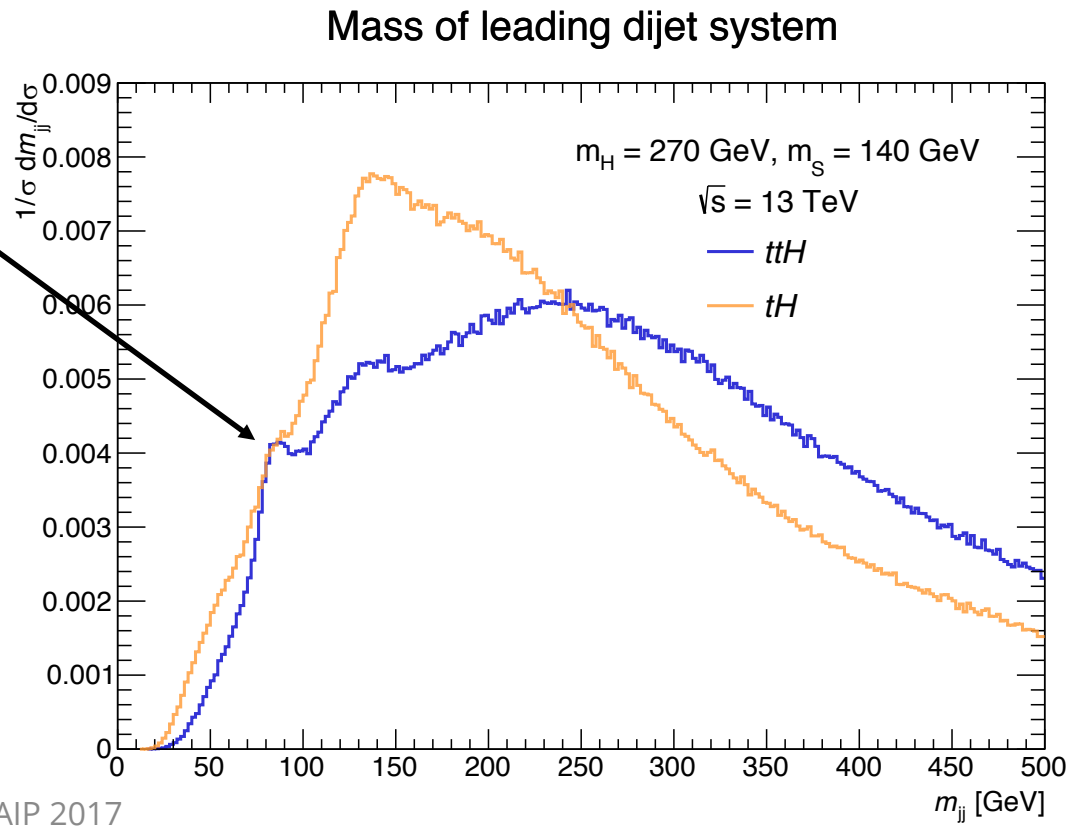


- The top quark *always* decays to *Wb*
  - 99.8% branching ratio



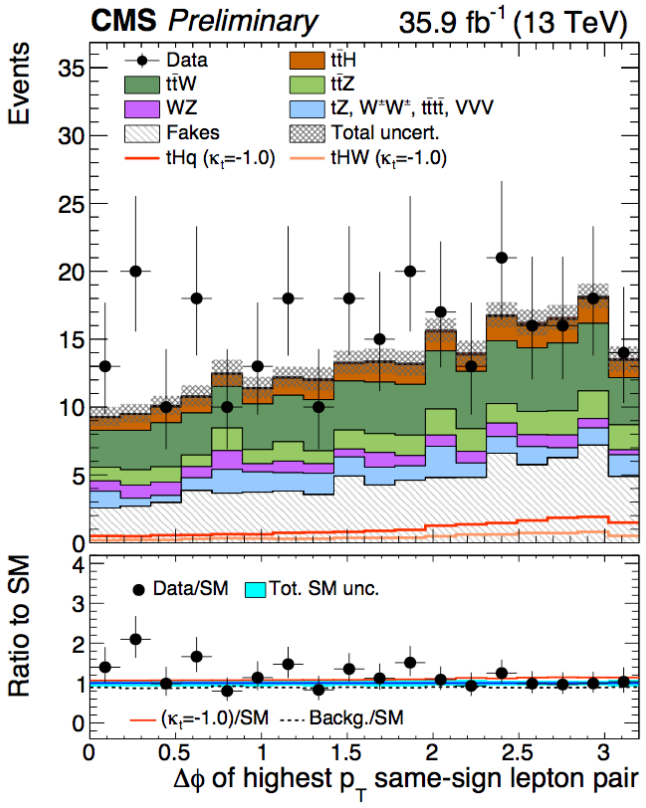
More *W* bosons

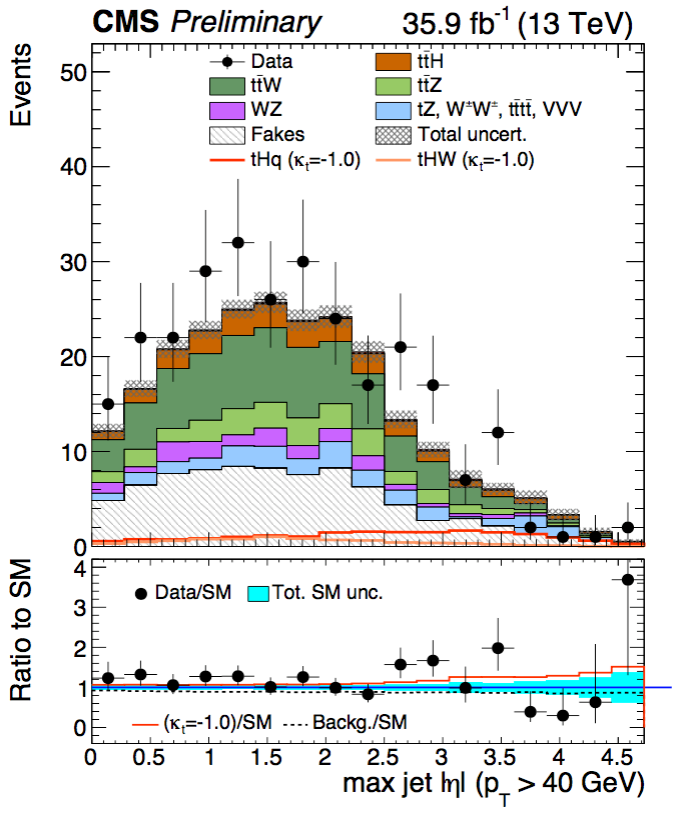
More *b*-jets

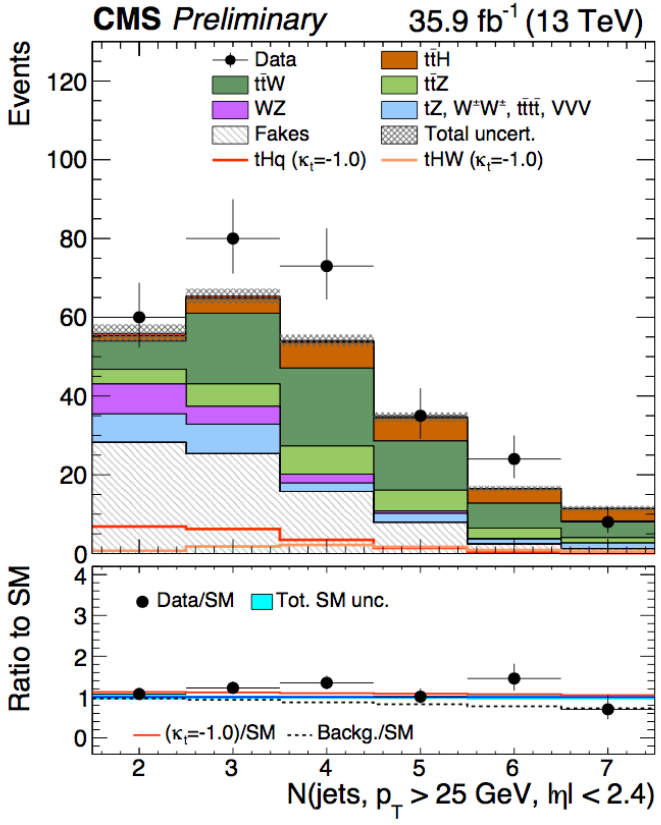


Comparing to data: CMS Run 2 single top

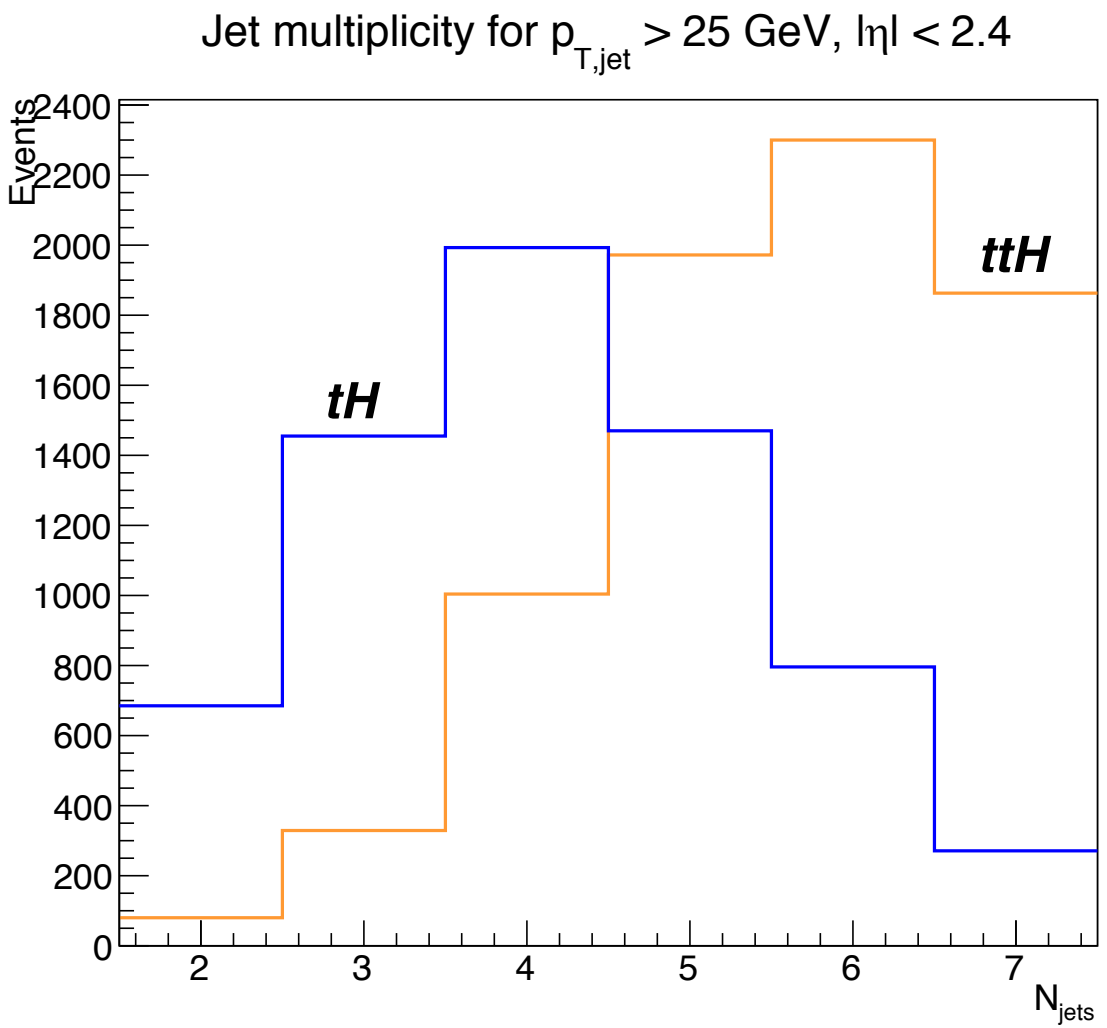
- CMS do a search for a Higgs boson with an additional top quark
- The analysis is an MVA, but they also give results for their pre-selection (below)
  - For the Madala hypothesis, both *ttH* and *tH* production contribute a signal

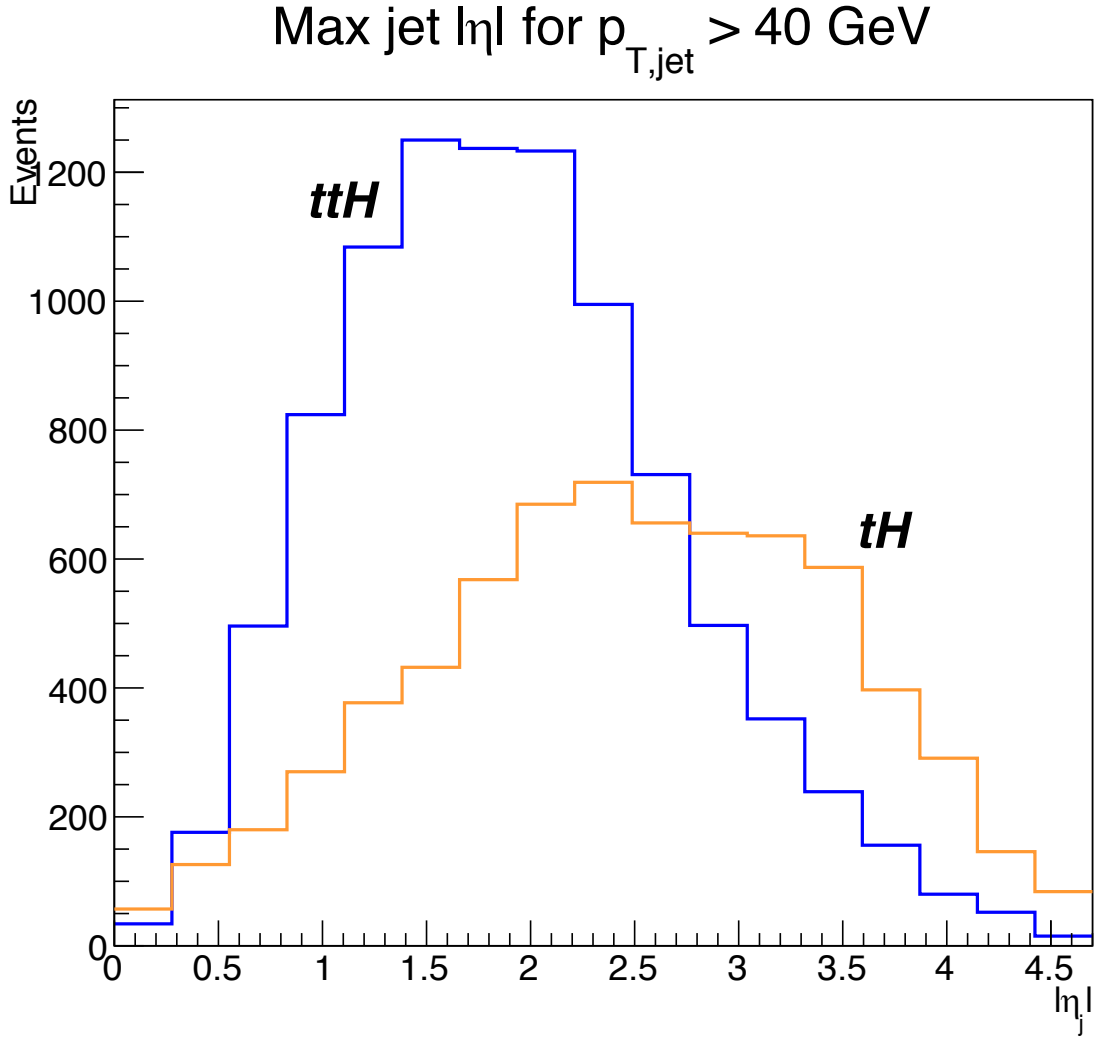






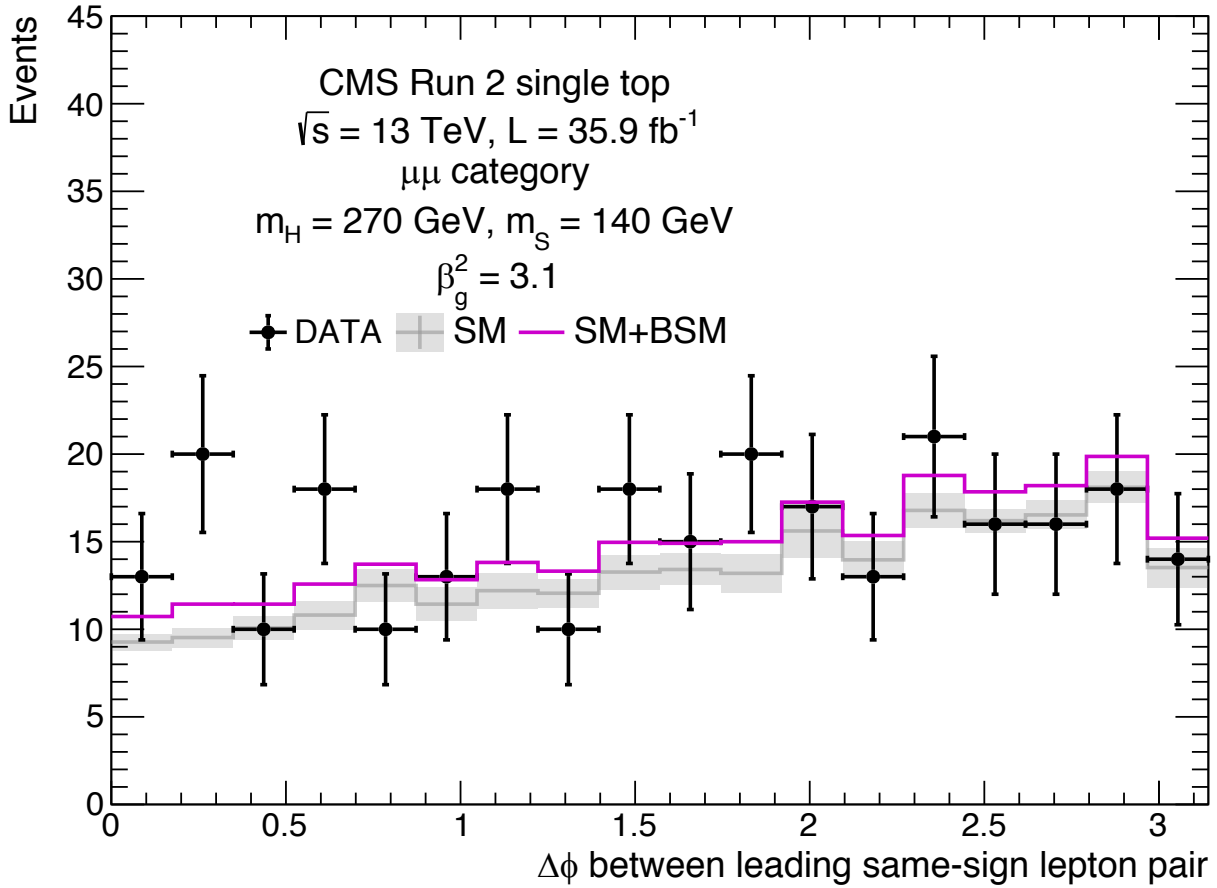
Comparing *tH* and *ttH*



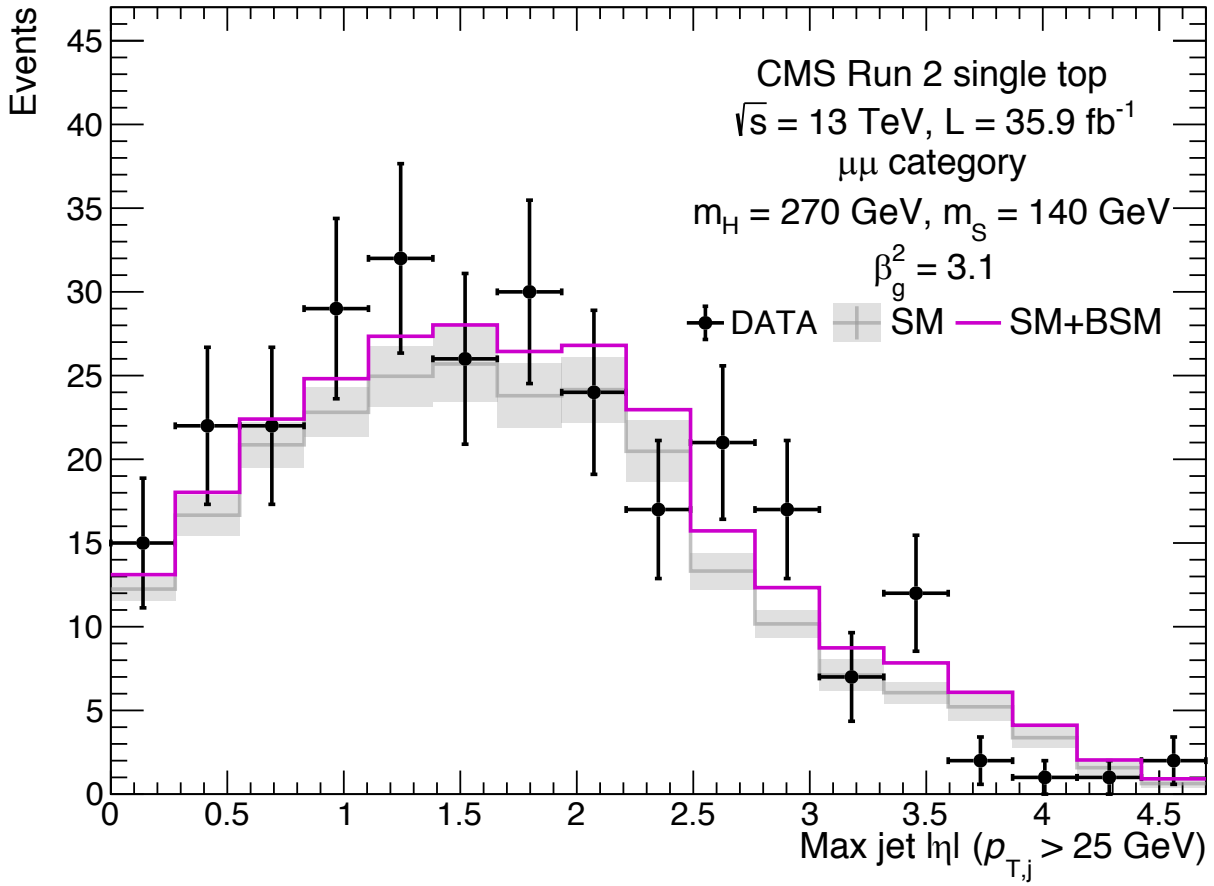


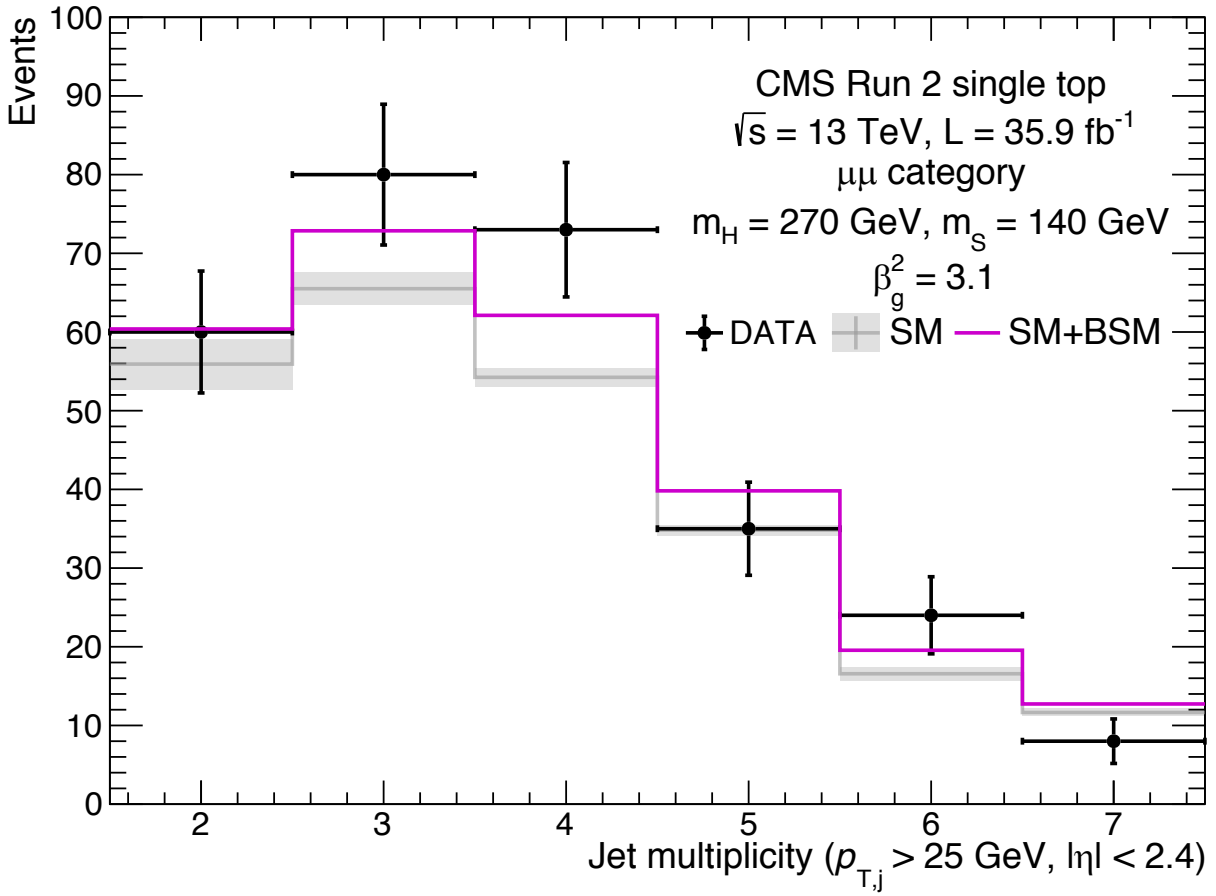
Results: CMS Run 2 single top search

- In this search the same sign di-muon channel has an enhanced rate
- Adding the Madala hypothesis (purple) and scaling $\beta_g^2 = 3.1 \pm 1.02$ gives the best fit to di-muon data
- This value is consistent with our previous studies (arXiv:1506.00612)
- Errors are large



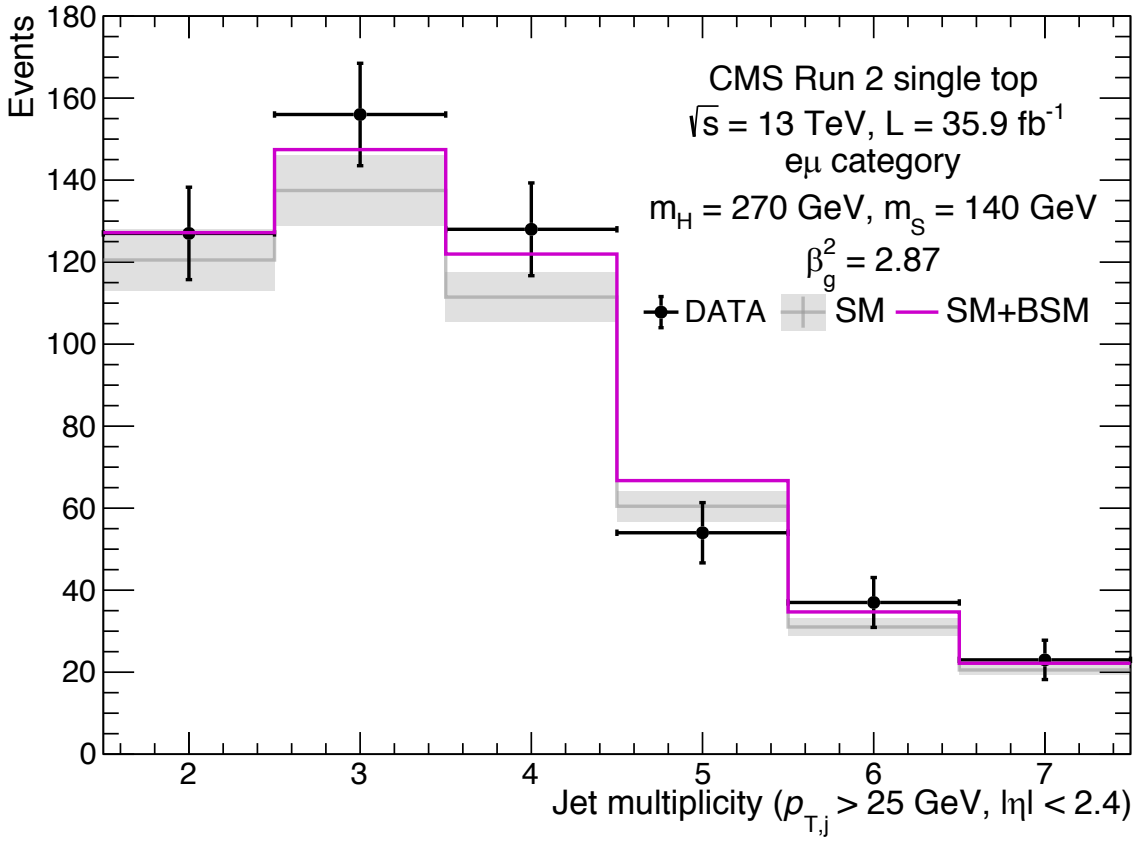
Results: CMS Run 2 single top search

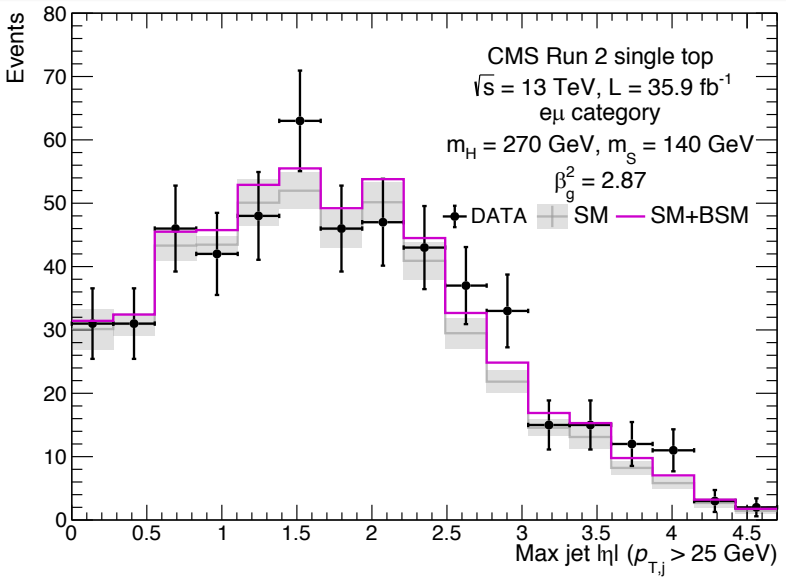


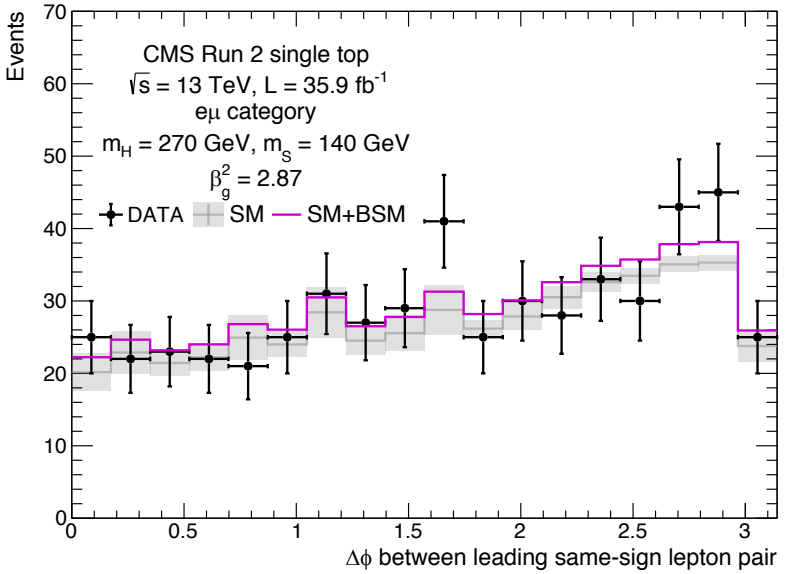


Results: CMS Run 2 single top search

$e\mu$ channel

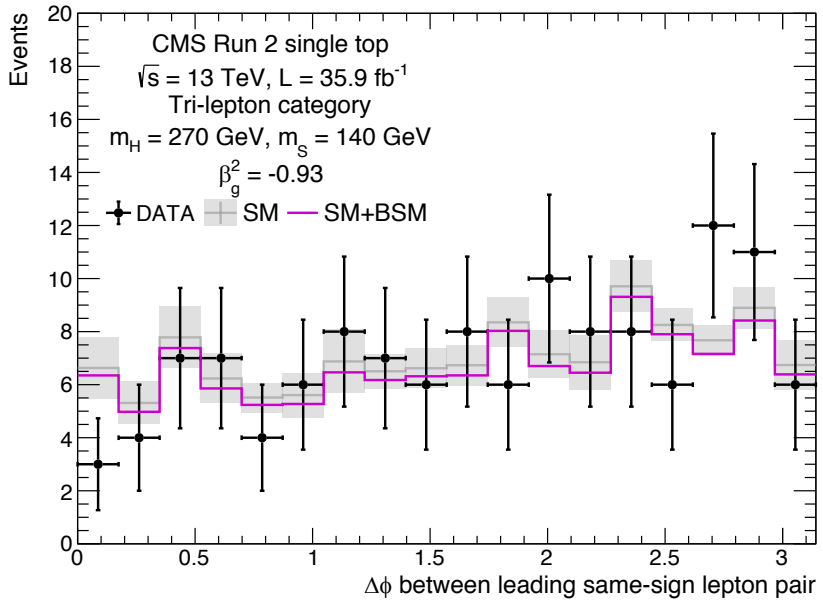


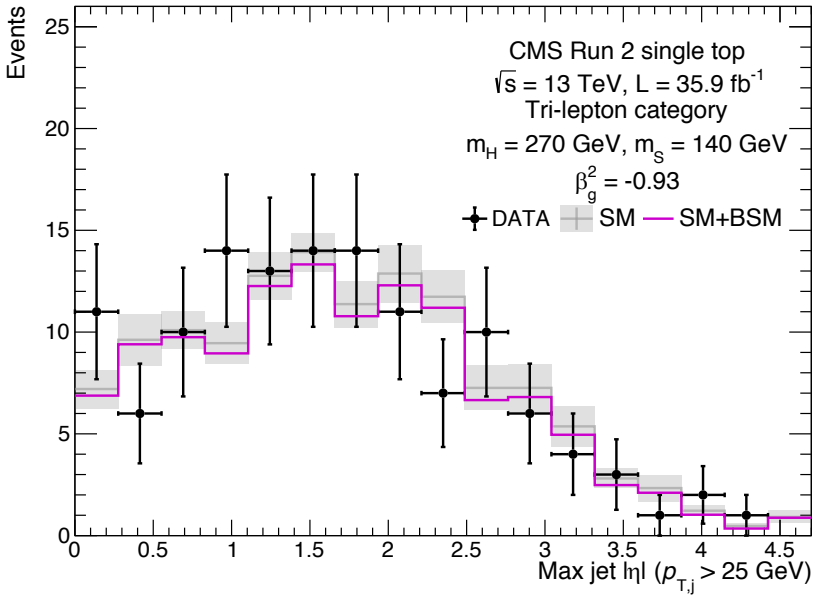


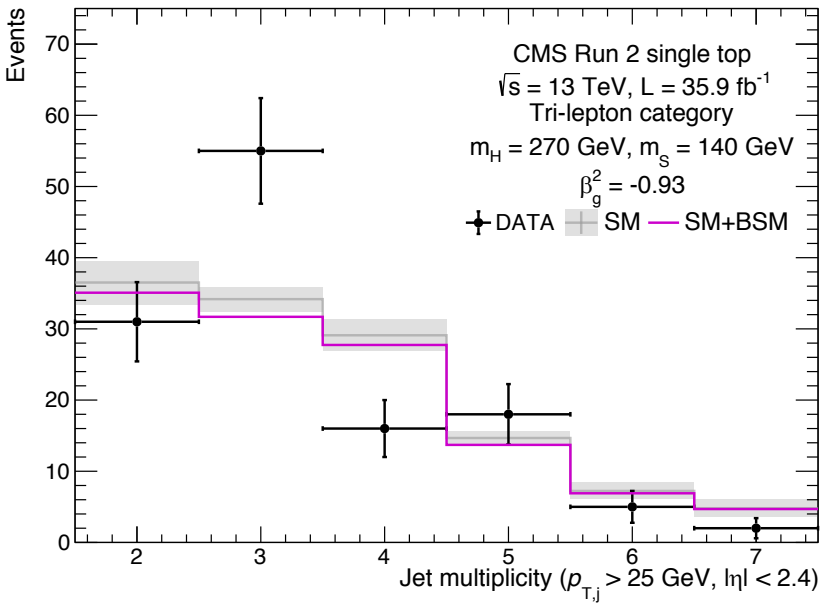


Results: CMS Run 2 single top search

Tri-lepton channel







- Negative fluctuation
- Statistics are lower → errors are larger

Results: CMS Run 2 single top search

- Using the cross section scaling β_g^2, we can determine whether the results are compatible with each other
- The di-lepton results are compatible with our previous result
- This may have to do with the way we model *S*, other ideas are being investigated (see Mukesh's talks)

Channel	**Value of β_g^2**
Same sign $\mu\mu$	3.10 ± 1.02
Same sign eμ	2.87 ± 1.04
Tri-lepton	-0.93 ± 0.92
Combined	1.48 ± 0.57
Old fit result	2.25 ± 1.80

Conclusions

- The Madala hypothesis has been investigated in the context of top associated production
- When making fits to the CMS Run 2 single top search:
  - The di-lepton search channels are compatible with our previous results
  - Combined fit significance: $\sim 2.6\sigma$
- Combining this with other results: $\sim 3.5\sigma$
- More investigation has to be done into the modelling of the *S* boson
- With more data, we could make fits to additional distributions and come up with stronger results

Thank you!

Le Peintre et son Modèle (The Artist and his Model) **– Pablo Picasso (1926)**