Experimental Summary of Top 2018

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The University of Glasgow

The Top is Special

Maltoni @ LHCP2018

1. It is rich
2. It is strong
3. It is naked
4. It is popular
5. It goes beyond

The top quark is the Ronaldo of elementary particles

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5. It goes beyond

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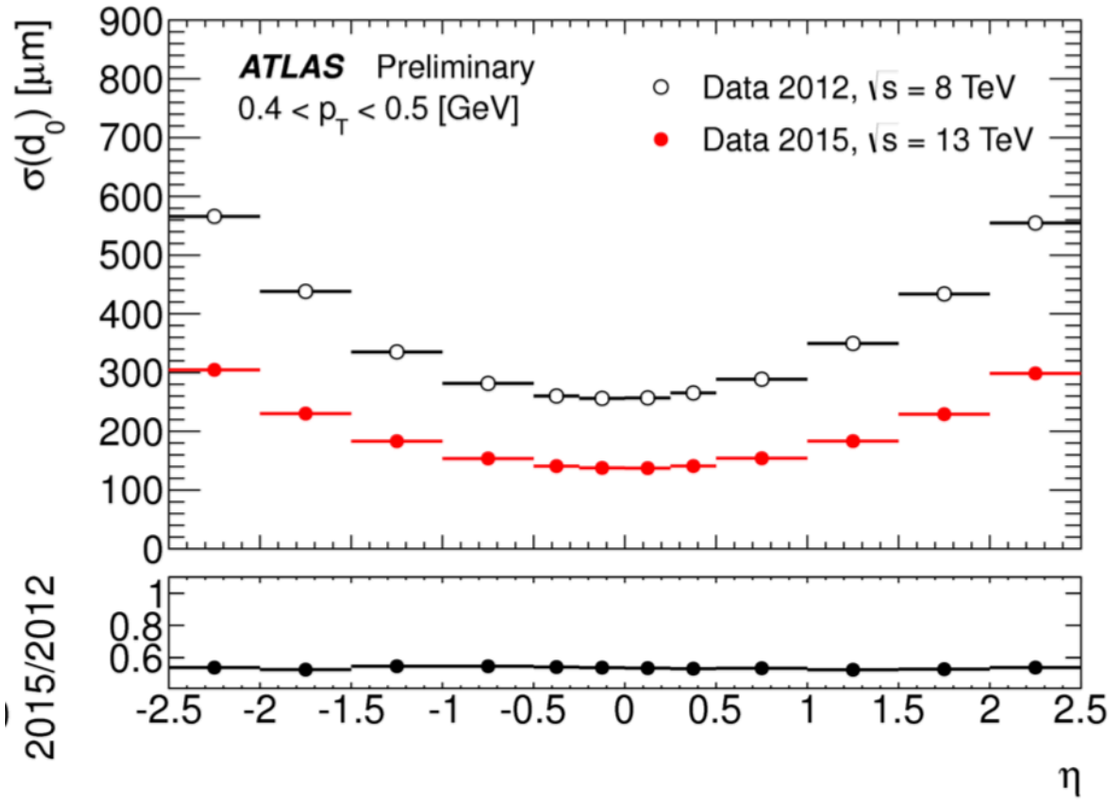
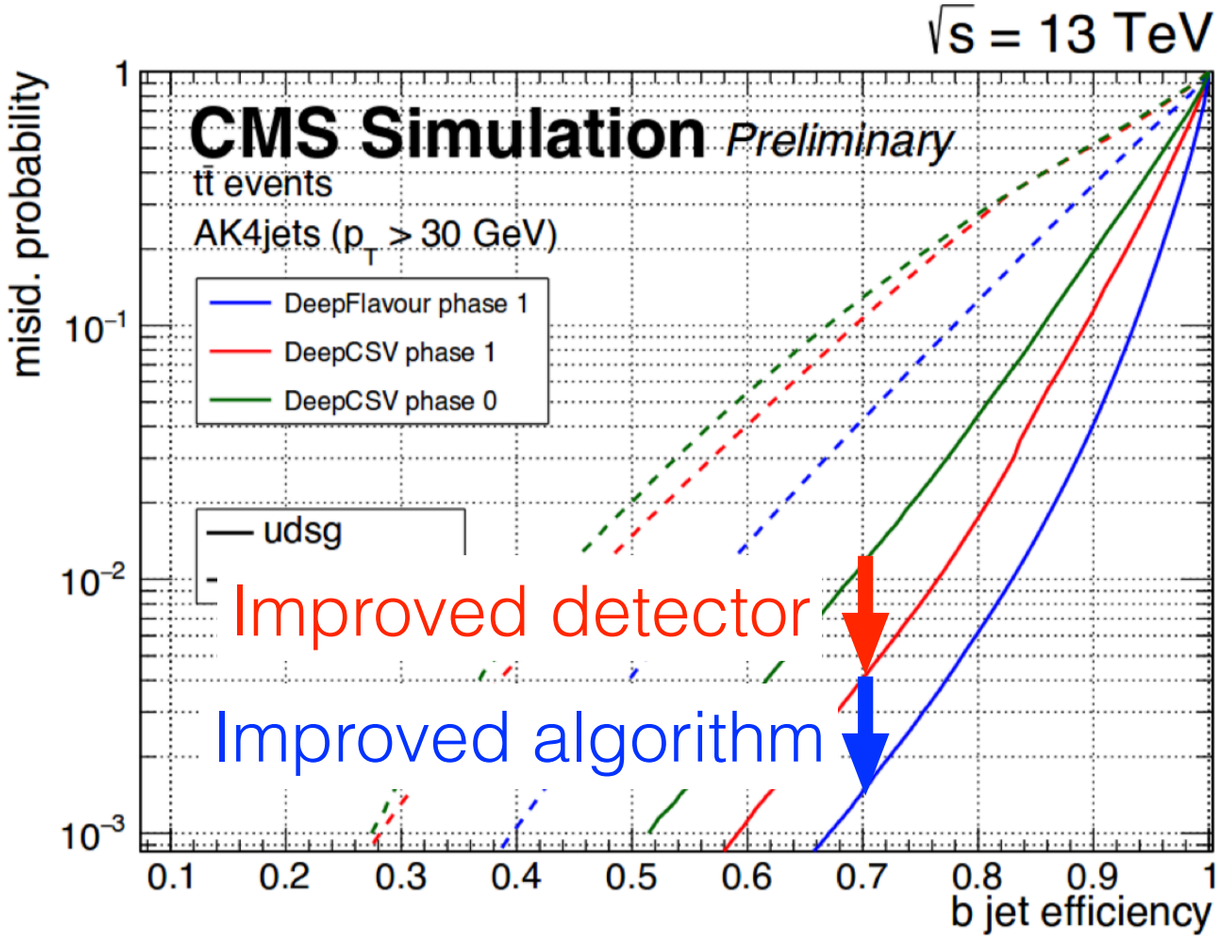
Performance

- Both collaborations continue to improve the detectors - both with hardware upgrade and ‘good ideas’:





Top pair cross-section measurements

- Inclusive cross-section is ‘bread and butter’, but not a simple cut-and-count:

$$\sigma = \frac{(N_d - N_b)}{L\epsilon}$$

Top pair cross-section measurements

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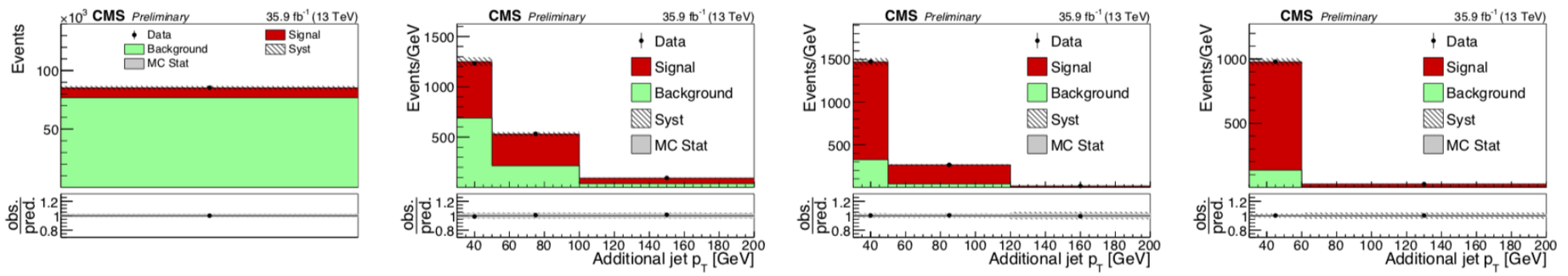
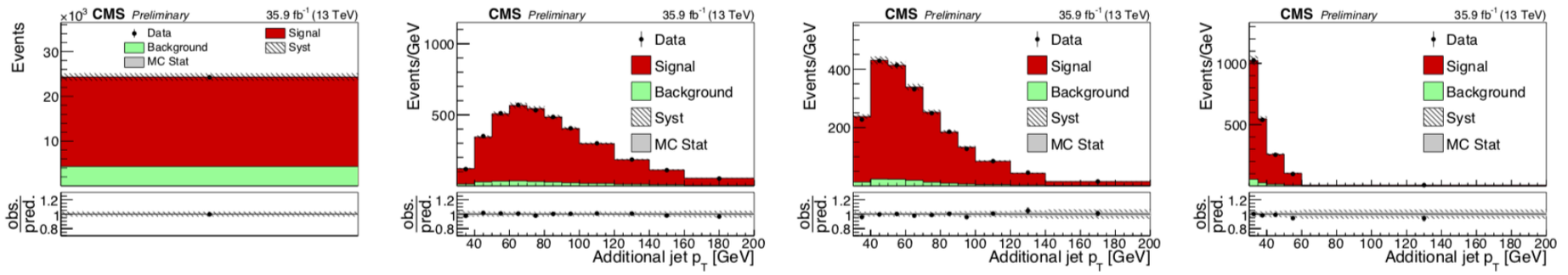
CMS-PAS-TOP-17-001

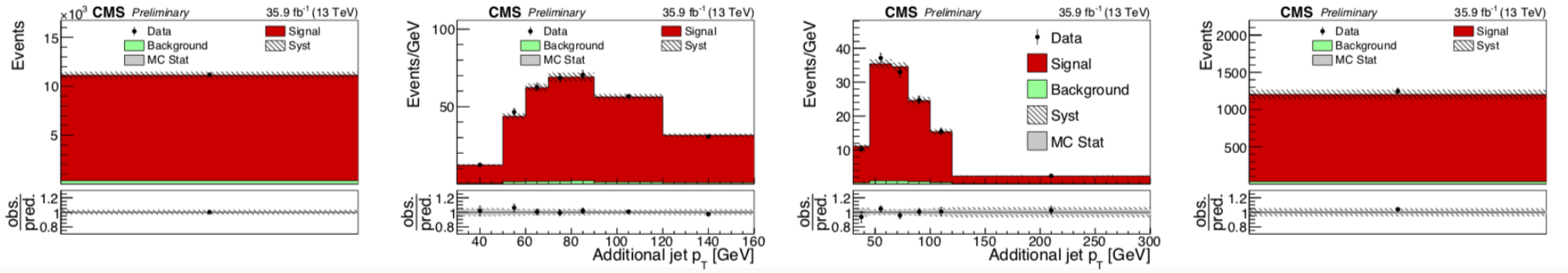
0 b-tags: 0,1,2,3 additional jets



1 b-tag: 0,1,2,3 additional jets



2 b-tags: 0,1,2,3 additional jets



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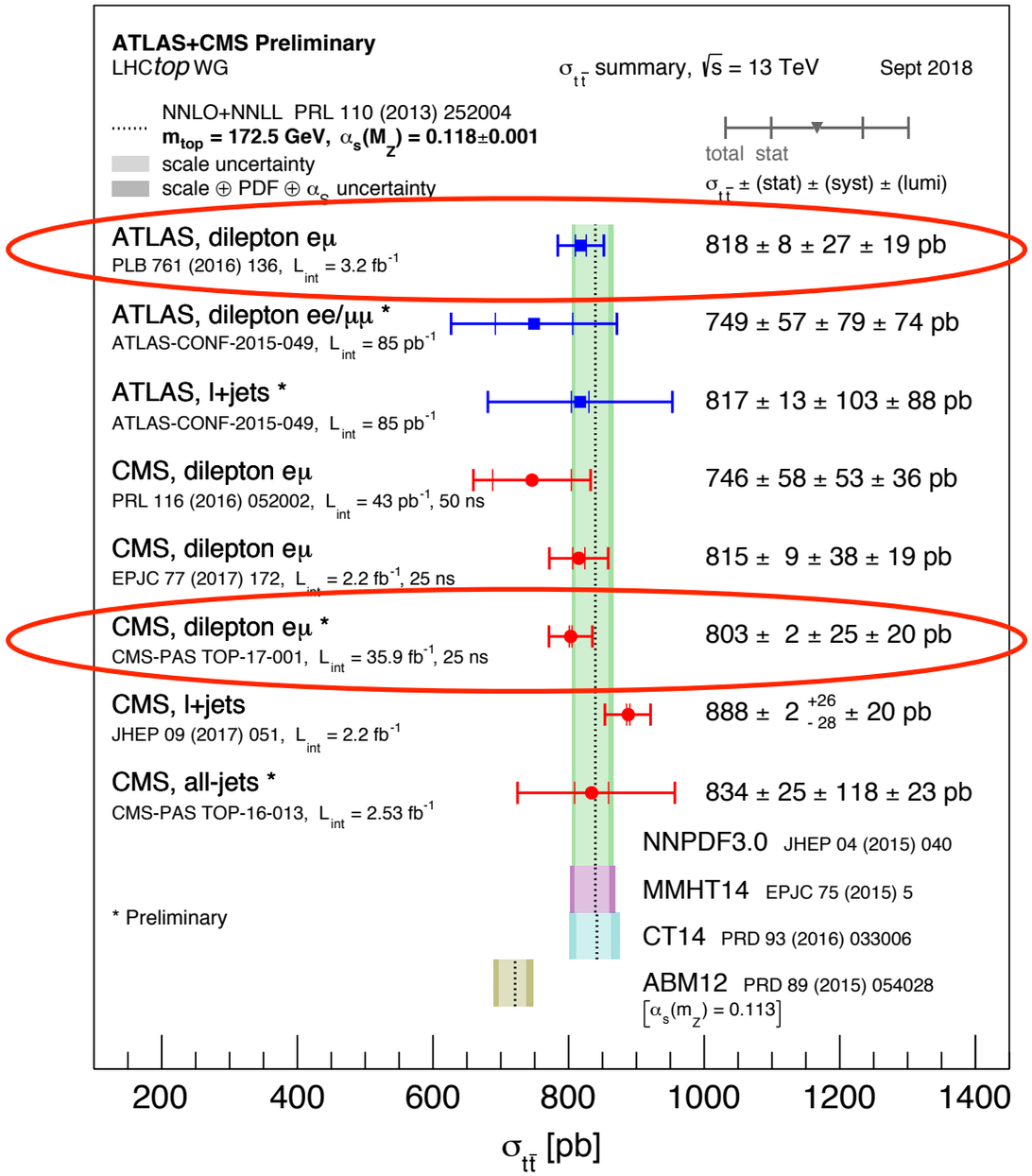
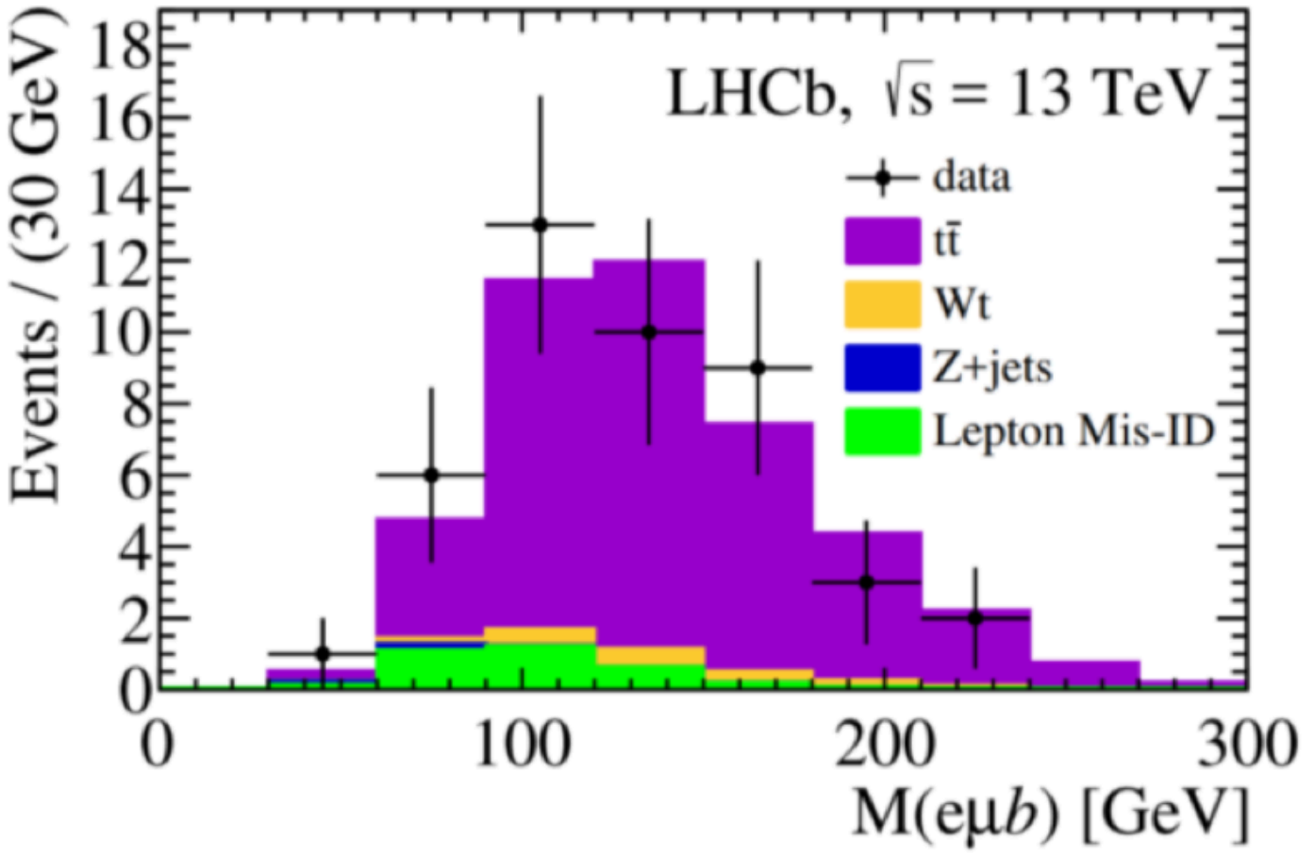
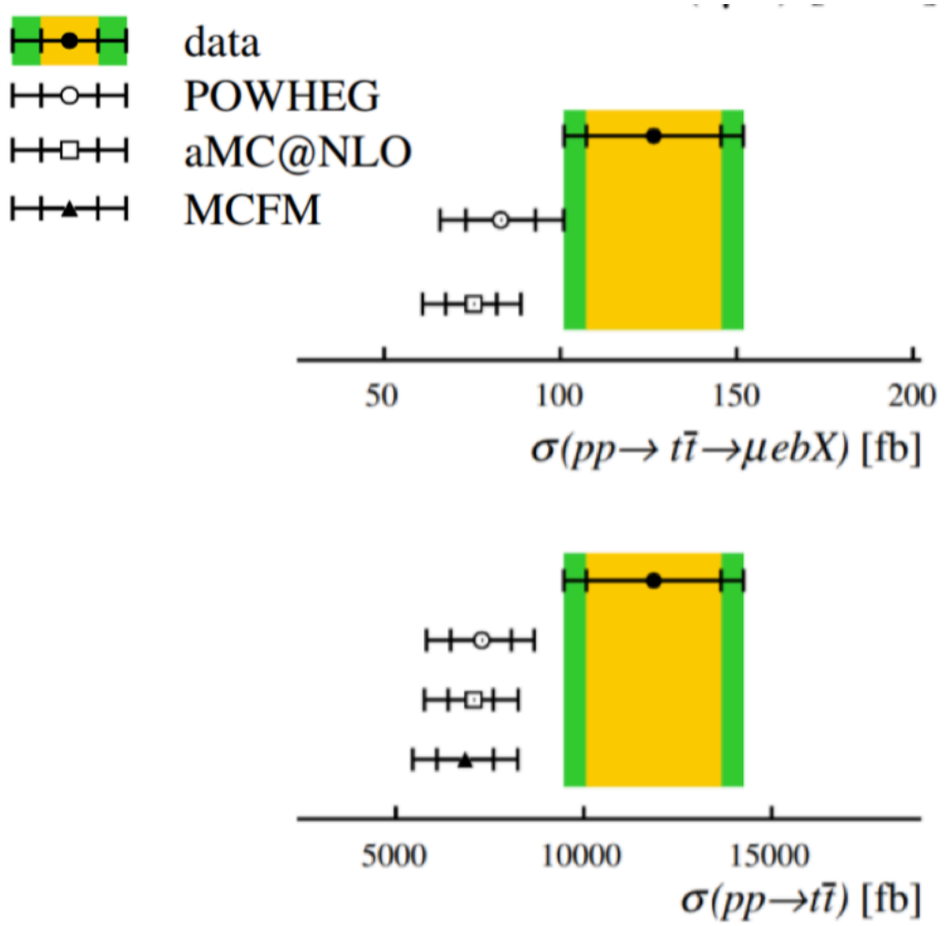


Still room to improve on both sides?

Top pair cross-section measurements

- LHCb measurement of clean top-pair sample:





Top pair cross-section measurements

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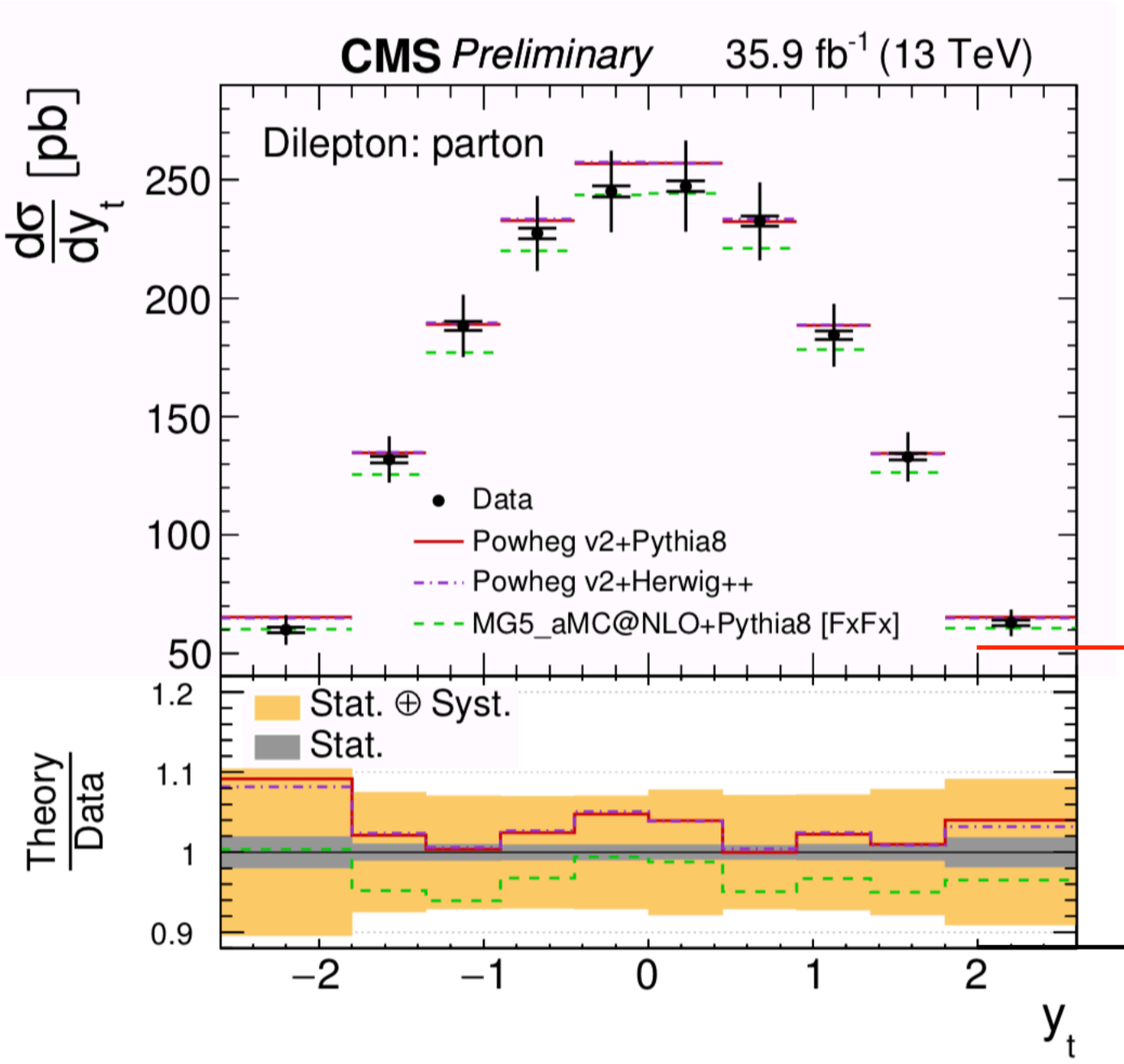
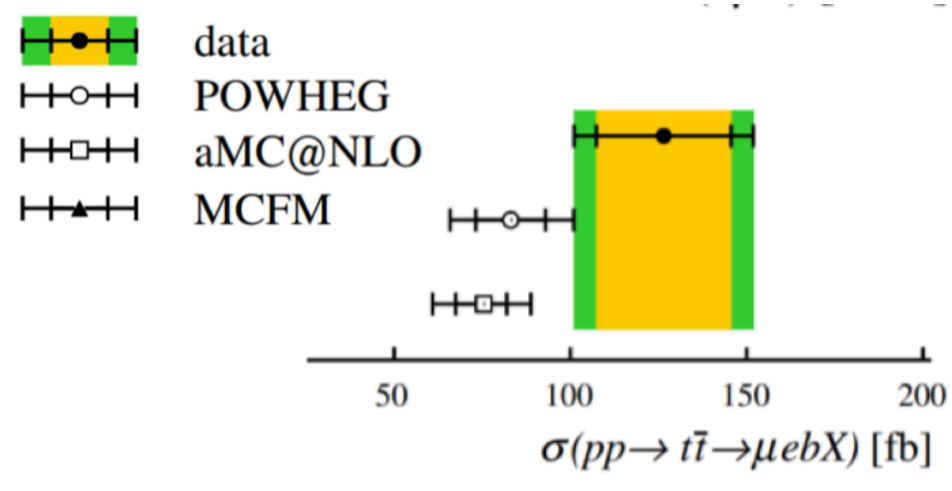
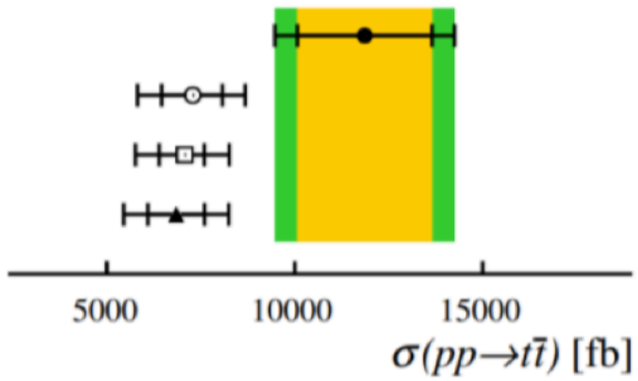




LHCb



Top pair cross-section measurements

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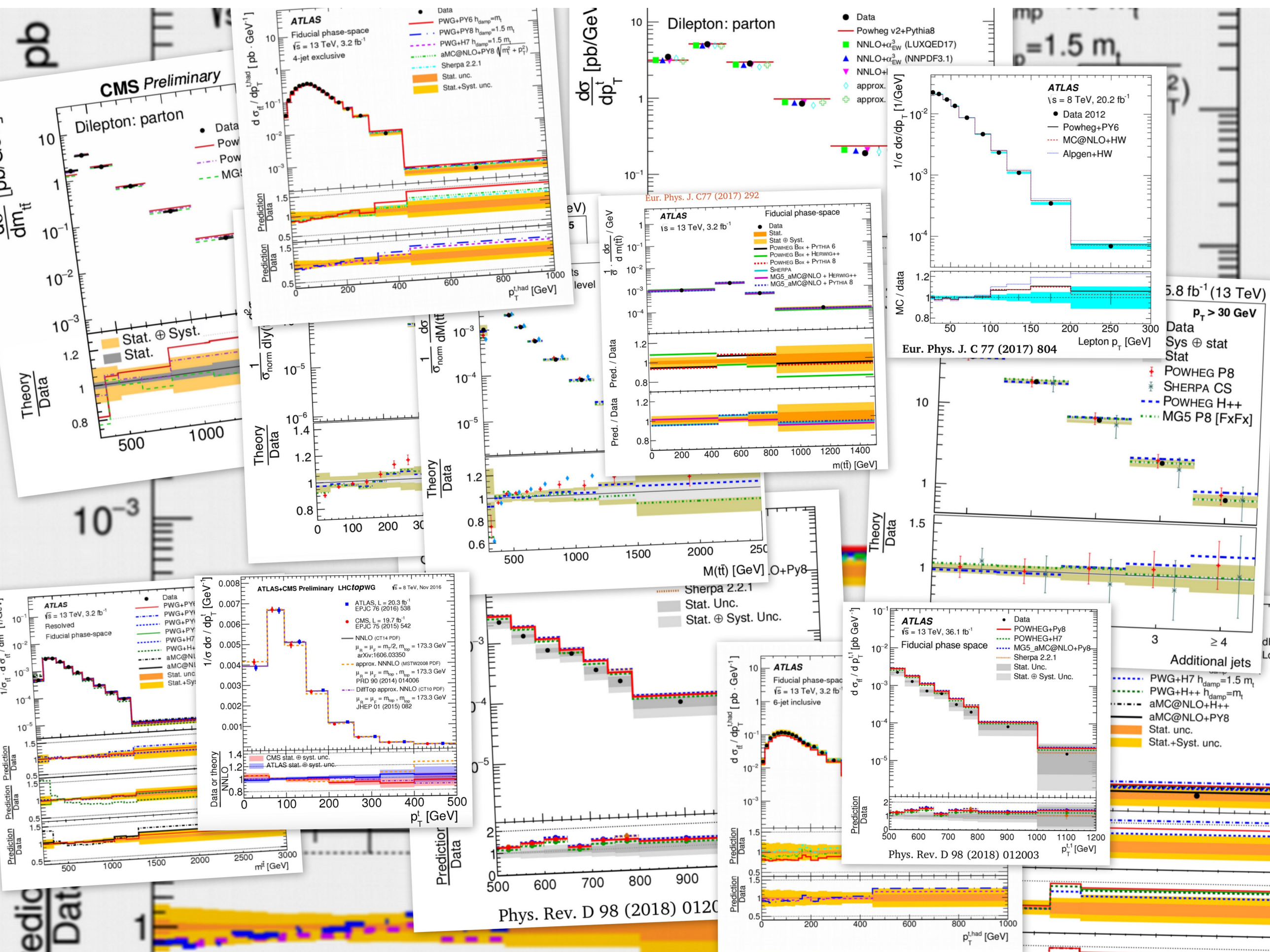
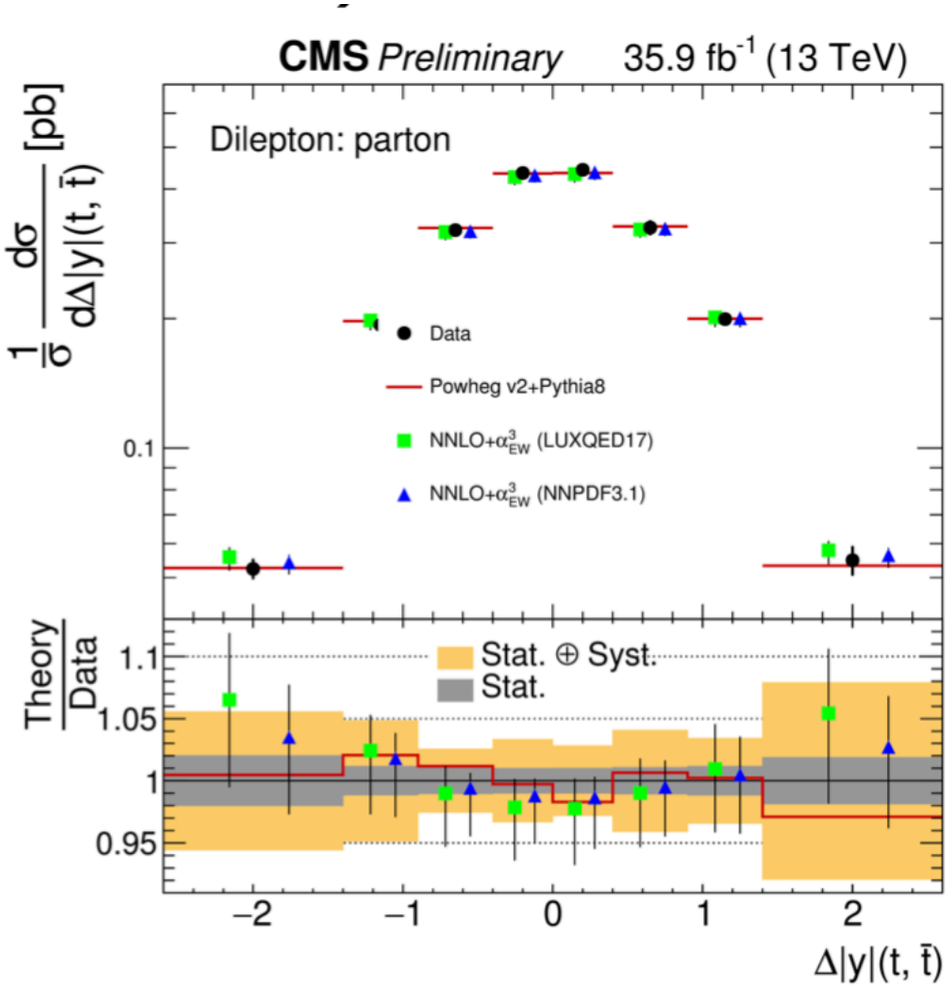

CMS Preliminary
Dilepton: parton
Stat. ⊕ Syst.
Stat.
ATLAS
Fiducial phase-space
√s = 13 TeV, 3.2 fb-1
4-jet exclusive
Data
PWG+PY6 hdamp=mt
PWG+PY8 hdamp=1.5 mt
PWG+H7 hdamp=1.5 mt
aMC@NLO+PY8
Sherpa 2.2.1
Stat. unc.
Stat.+Syst. unc.
Dilepton: parton
Powheg v2+Pythia8
NNLO+αEW3 (LUXQED17)
NNLO+αEW3 (NNPDF3.1)
approx.
ATLAS
√s = 8 TeV, 20.2 fb-1
Data 2012
Powheg+PY6
MC@NLO+HW
Alpgen+HW
Eur. Phys. J. C77 (2017) 292
ATLAS
√s = 13 TeV, 3.2 fb-1
Fiducial phase-space
Powheg Box + Pythia 6
Powheg Box + Herwig++
Powheg Box + Pythia 8
Sherpa
MG5_aMC@NLO + Herwig++
MG5_aMC@NLO + Pythia 8
Eur. Phys. J. C 77 (2017) 804
p_T > 30 GeV
Data
Sys ⊕ stat
Stat
Powheg P8
Sherpa CS
Powheg H++
MG5 P8 [FxFx]
Additional jets
ATLAS
Resolved
Fiducial phase-space
ATLAS+CMS Preliminary LHCtopWG
√s = 8 TeV, Nov 2016
ATLAS, L = 20.3 fb-1
EPJC 76 (2016) 538
CMS, L = 19.7 fb-1
EPJC 75 (2015) 542
NNLO (CT14 PDF)
arXiv:1606.03350
approx. NNNLO (MSTW2008 PDF)
PRD 90 (2014) 014006
DiffTop approx. NNLO (CT10 PDF)
JHEP 01 (2015) 082
CMS stat. ⊕ syst. unc.
ATLAS stat. ⊕ syst. unc.
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Phys. Rev. D 98 (2018) 012
ATLAS
Fiducial phase-space
√s = 13 TeV, 36.1 fb-1
POWHEG+Py8
POWHEG+H7
MG5_aMC@NLO+Py8
Sherpa 2.2.1
Stat. Unc.
Stat. ⊕ Syst. Unc.
Phys. Rev. D 98 (2018) 012003
PWG+H7 hdamp=1.5 mt
PWG+H++ hdamp=mt
aMC@NLO+H++
aMC@NLO+PY8
Stat. unc.
Stat.+Syst. unc.

54 distributions in 3 talks!

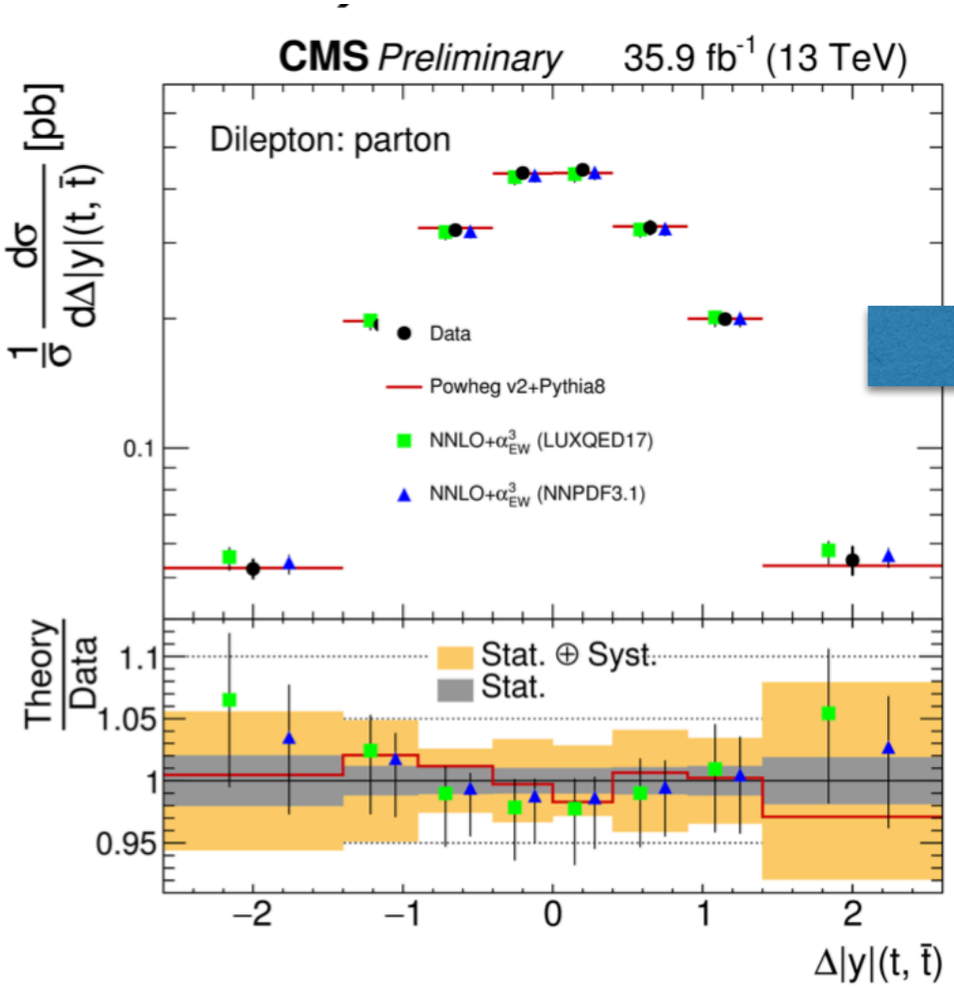
Top pair cross-section measurements

- Differential measurements are now in ‘mass production’ phase.
- Important to answer the physics questions:
  - Does the most precise SM calculation agree with the data?
  - Do the ATLAS & CMS data agree with each other?

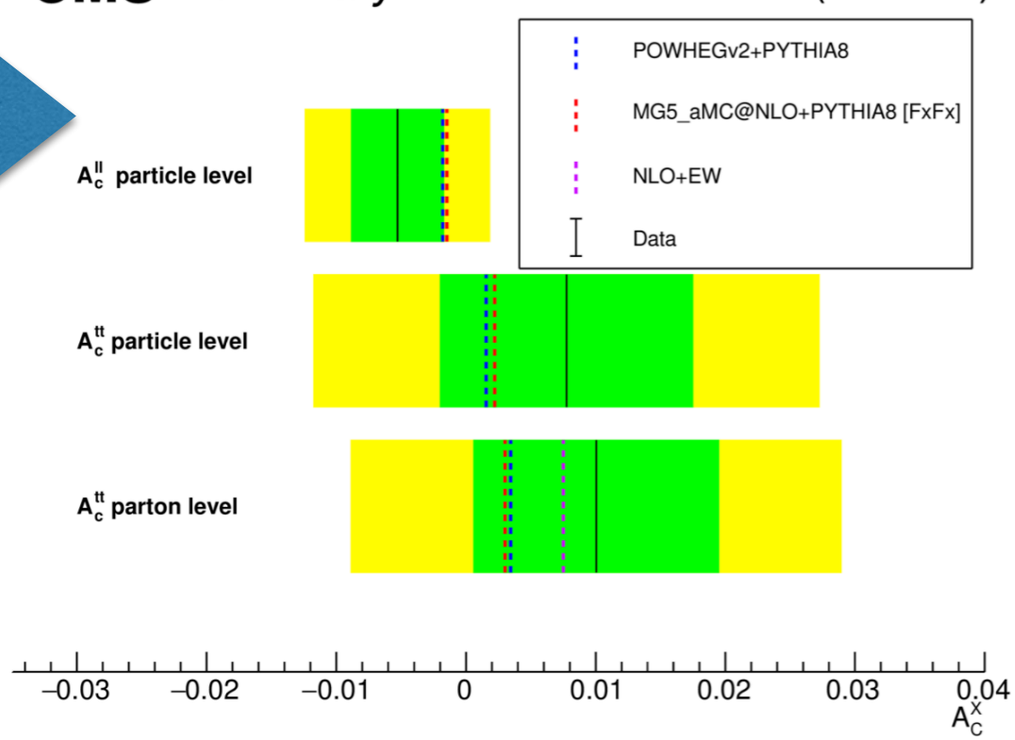
Differential cross-section → top properties



Differential cross-section → top properties

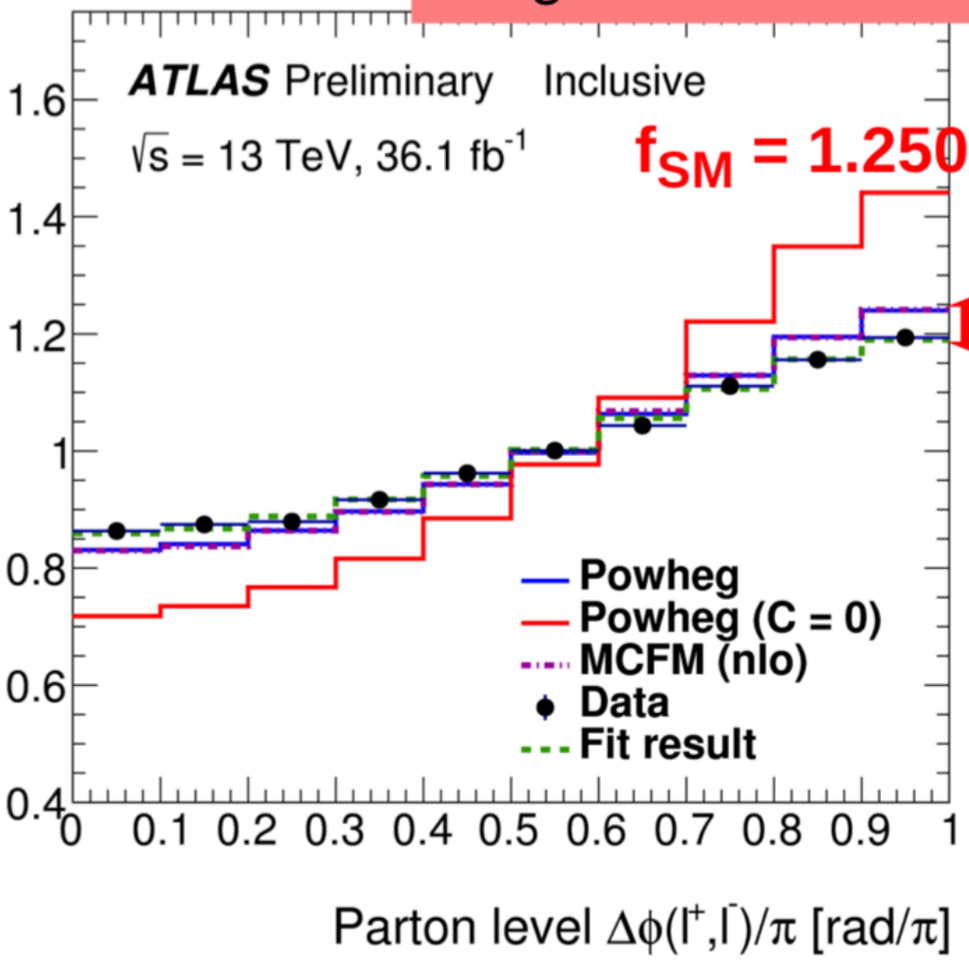


$$A_c^{t\bar{t}} = \frac{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) - \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}{\sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) > 0) + \sigma_{t\bar{t}}(\Delta|y|(t,\bar{t}) < 0)}$$



Differential cross-section → top properties

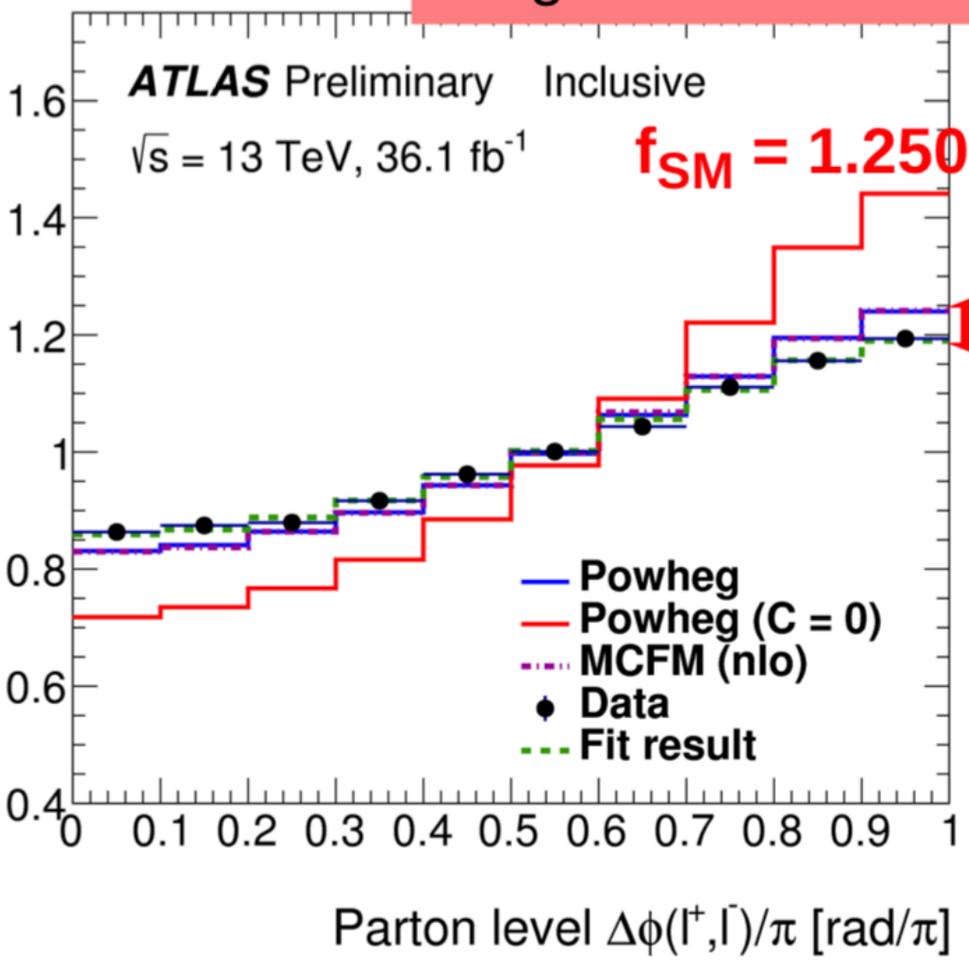
Dominant systematics:
MC generator and scale/radiation



Higher order corrections?
(see talk of Rene yesterday)

Differential cross-section → top properties

Dominant systematics:
MC generator and scale/radiation



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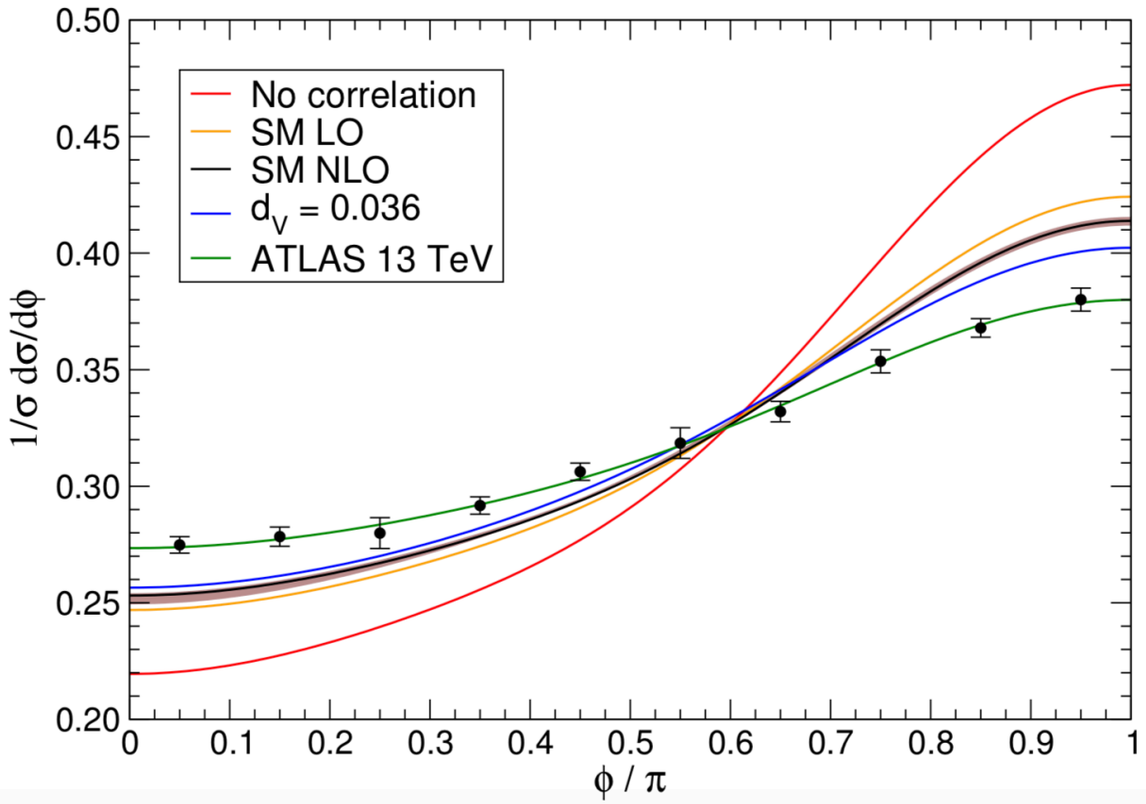

14

Differential cross-section → top properties

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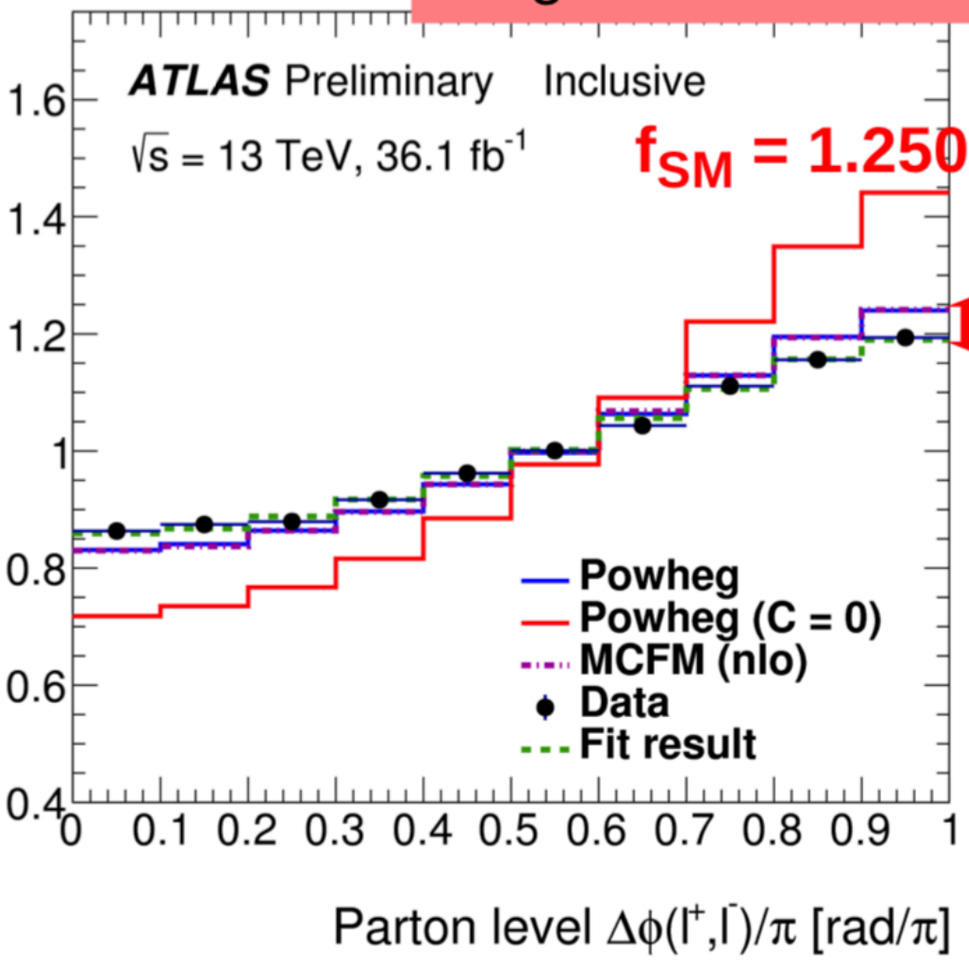

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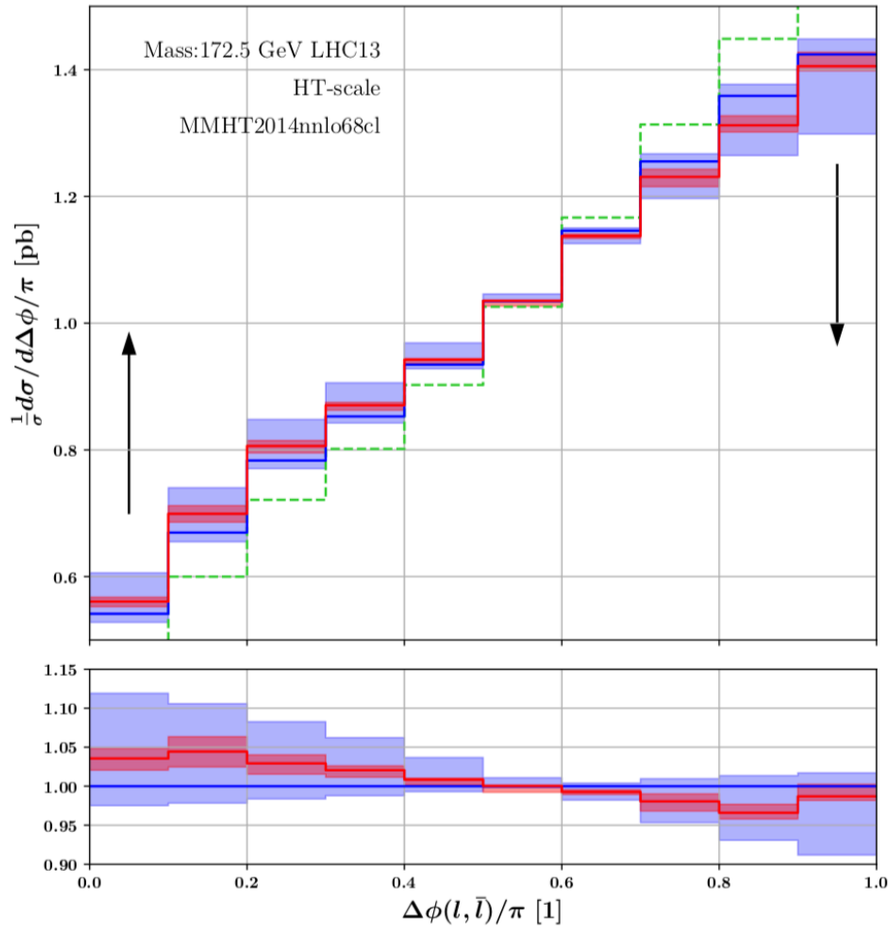
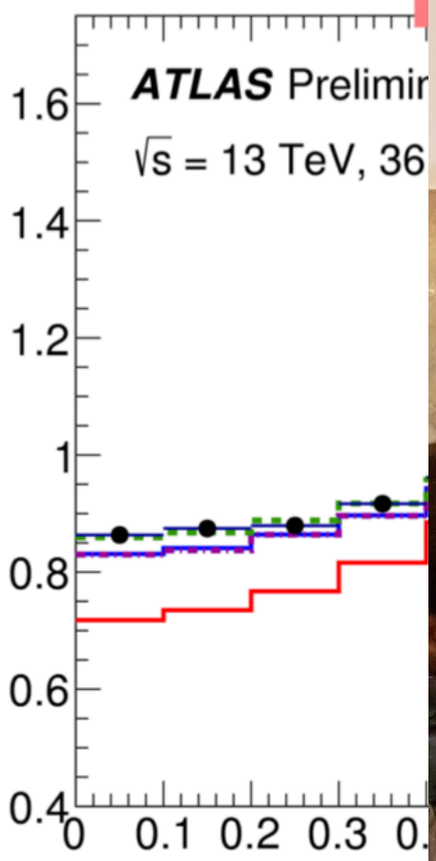
NWA @ NNLO predictions



NB: Different phase space → lets look at comparison in consistent phase space.

Differential cross-section → top properties

Dominant systematics:
MC generator and scale/radiation



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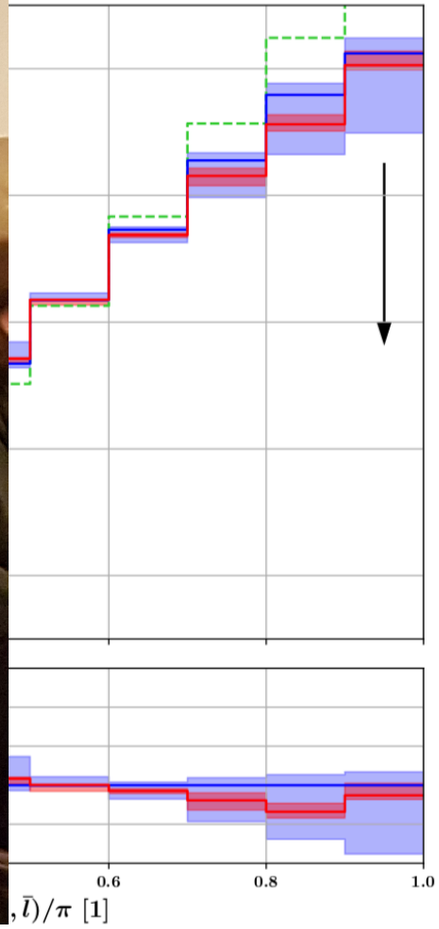
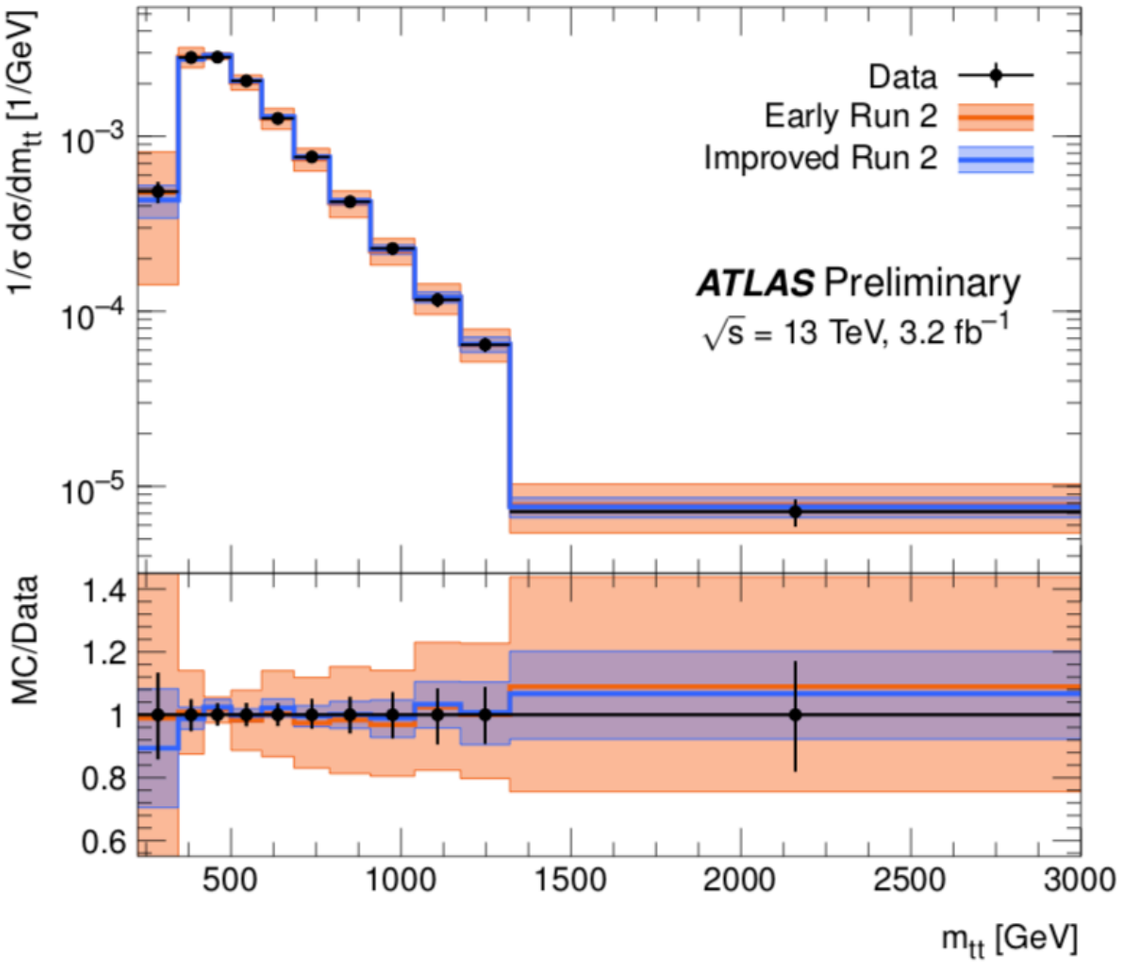


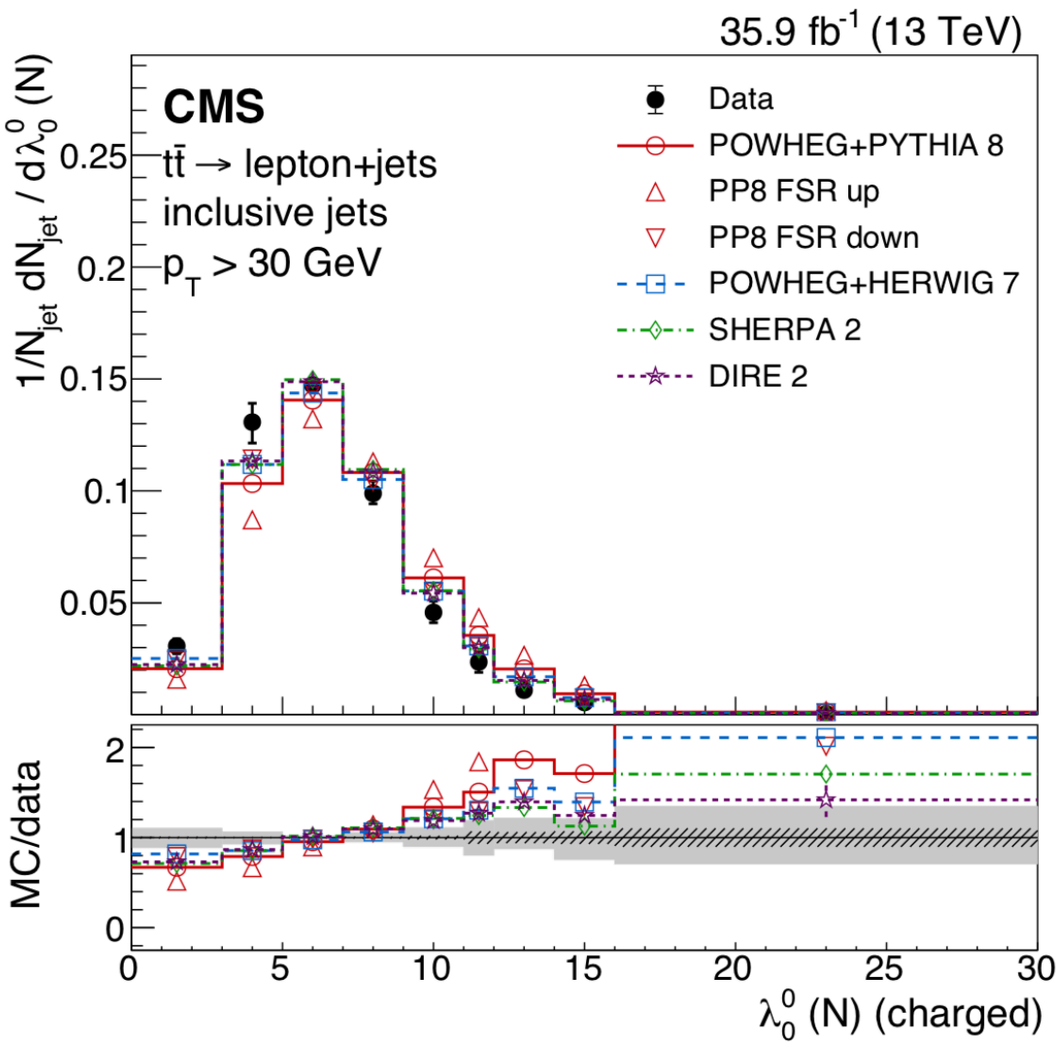
Parton level $\Delta\phi(l^+,l)/\pi$ [rad/π]

14

NB: Different phase space
→ lets look at comparison
in consistent phase space.

MC Tuning





- The unfolded (top) measurements available in Rivet & HepData are invaluable for these kinds of tuning studies - please continue to add to this library!

➡ Analyses will be available in RIVET and HepData

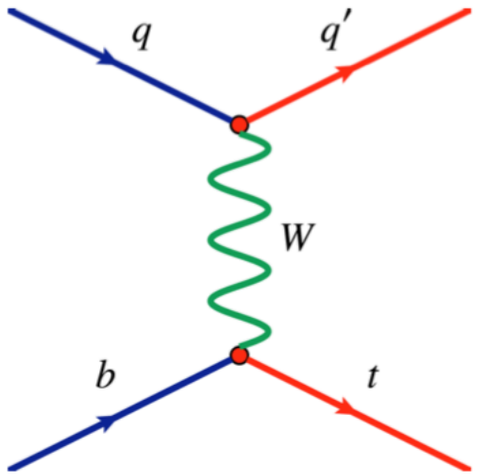
Single top

Cross-sections from LHCTopWG (calculated @NLO)

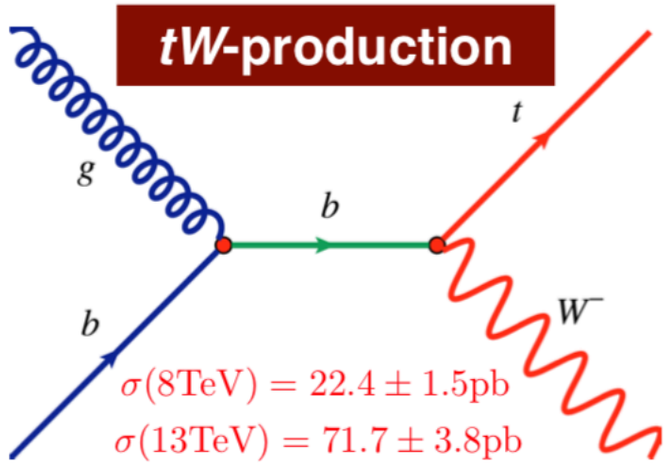
t-channel

$\sigma(8\text{TeV}) = 84.7^{+3.8}_{-3.2}\text{pb}$

$\sigma(13\text{TeV}) = 217.0^{+9.1}_{-7.7}\text{pb}$



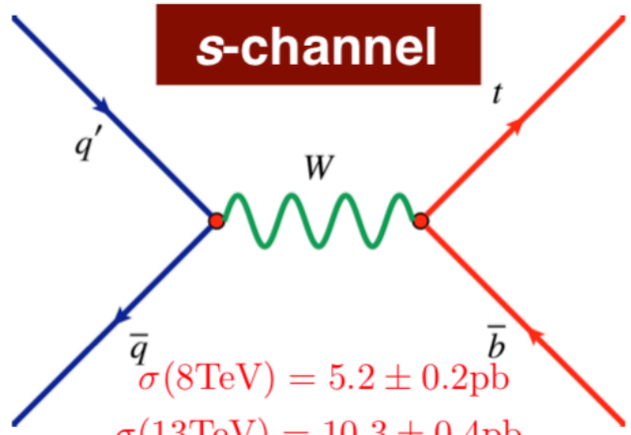
tW-production



$\sigma(8\text{TeV}) = 22.4 \pm 1.5\text{pb}$

$\sigma(13\text{TeV}) = 71.7 \pm 3.8\text{pb}$

s-channel



$\sigma(8\text{TeV}) = 5.2 \pm 0.2\text{pb}$

$\sigma(13\text{TeV}) = 10.3 \pm 0.4\text{pb}$

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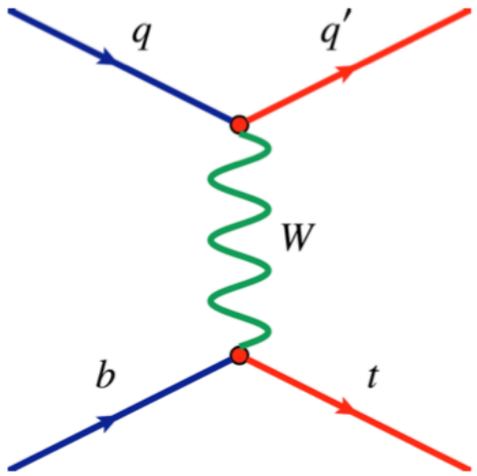

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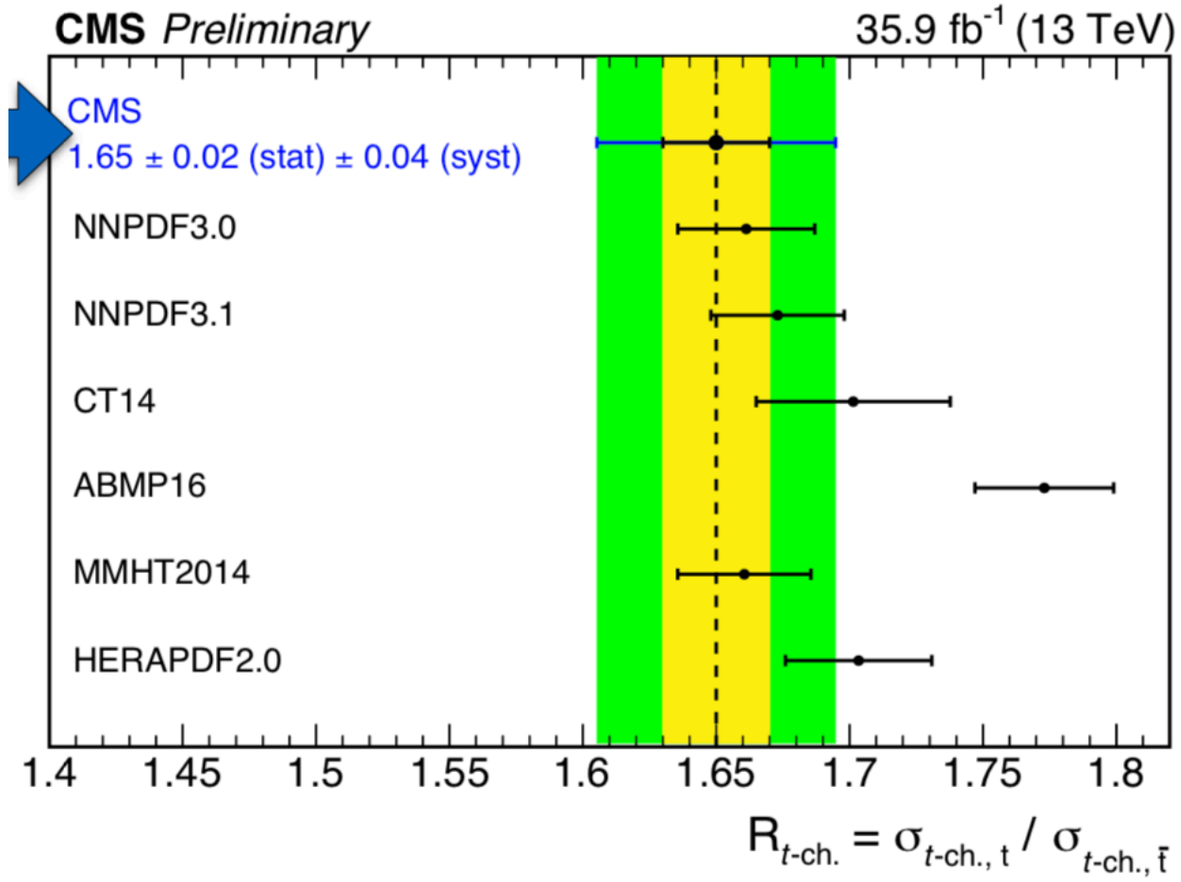

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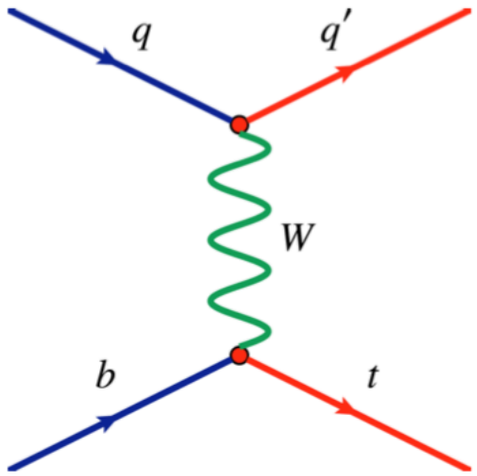

tW-production

$\Delta R/R$	
PDF t channel	1.4
PS-scale t channel	1.1
ME-PS scale matching t channel	0.2
μ_R/μ_F scale t channel	0.1
QCD normalization	2.1
JES	1.9
$t\bar{t}$ modeling and normalization	1.9
Top quark p_T	1.2
MC sample size	0.9

$\sigma(8\text{TeV}) = 5.2 \pm 0.2\text{pb}$

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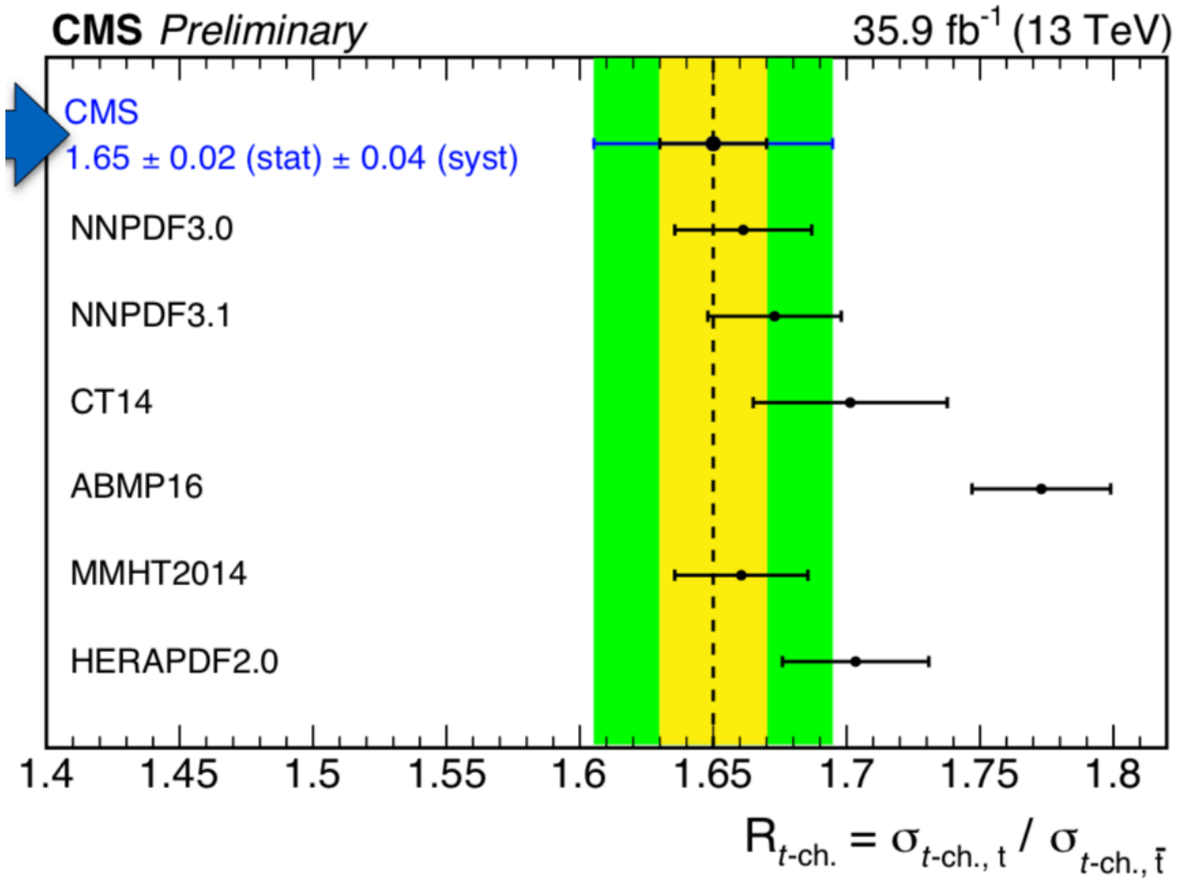

$$R_t = 1.65 \pm 0.02(\text{stat}) \pm 0.03(\text{prof}) \pm 0.03(\text{ext})\text{pb}$$

1.8%

Common way to display components for profiled results?

Single top

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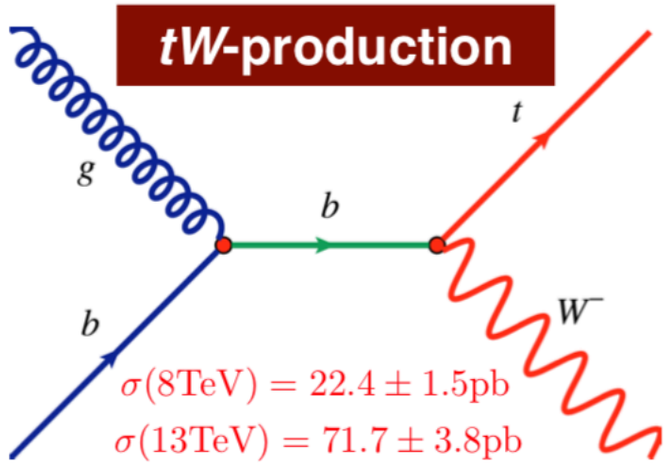

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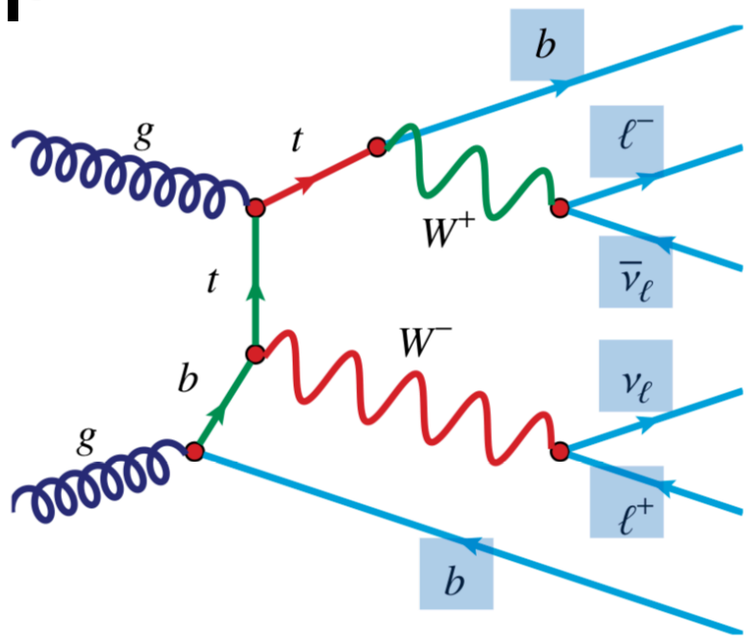
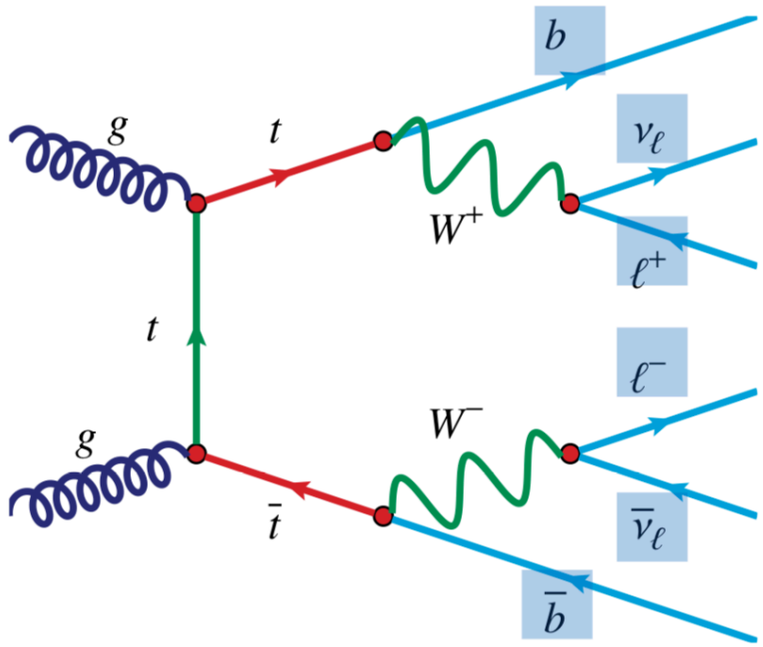


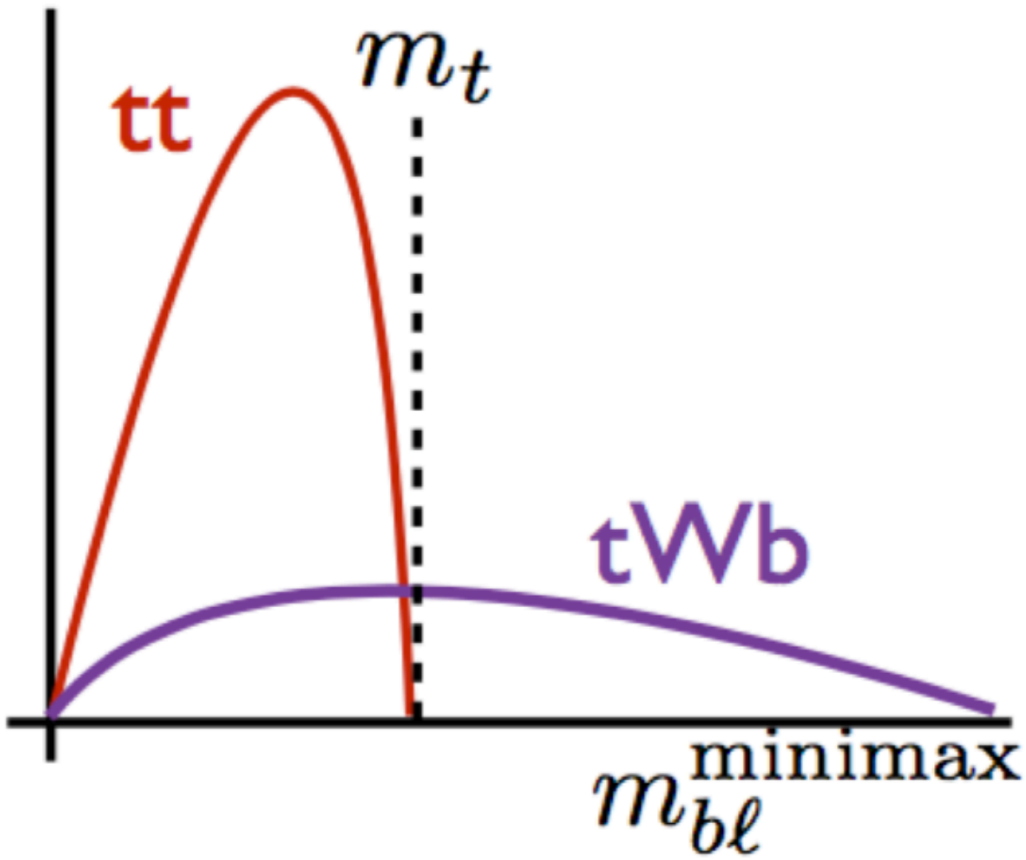
single resonant

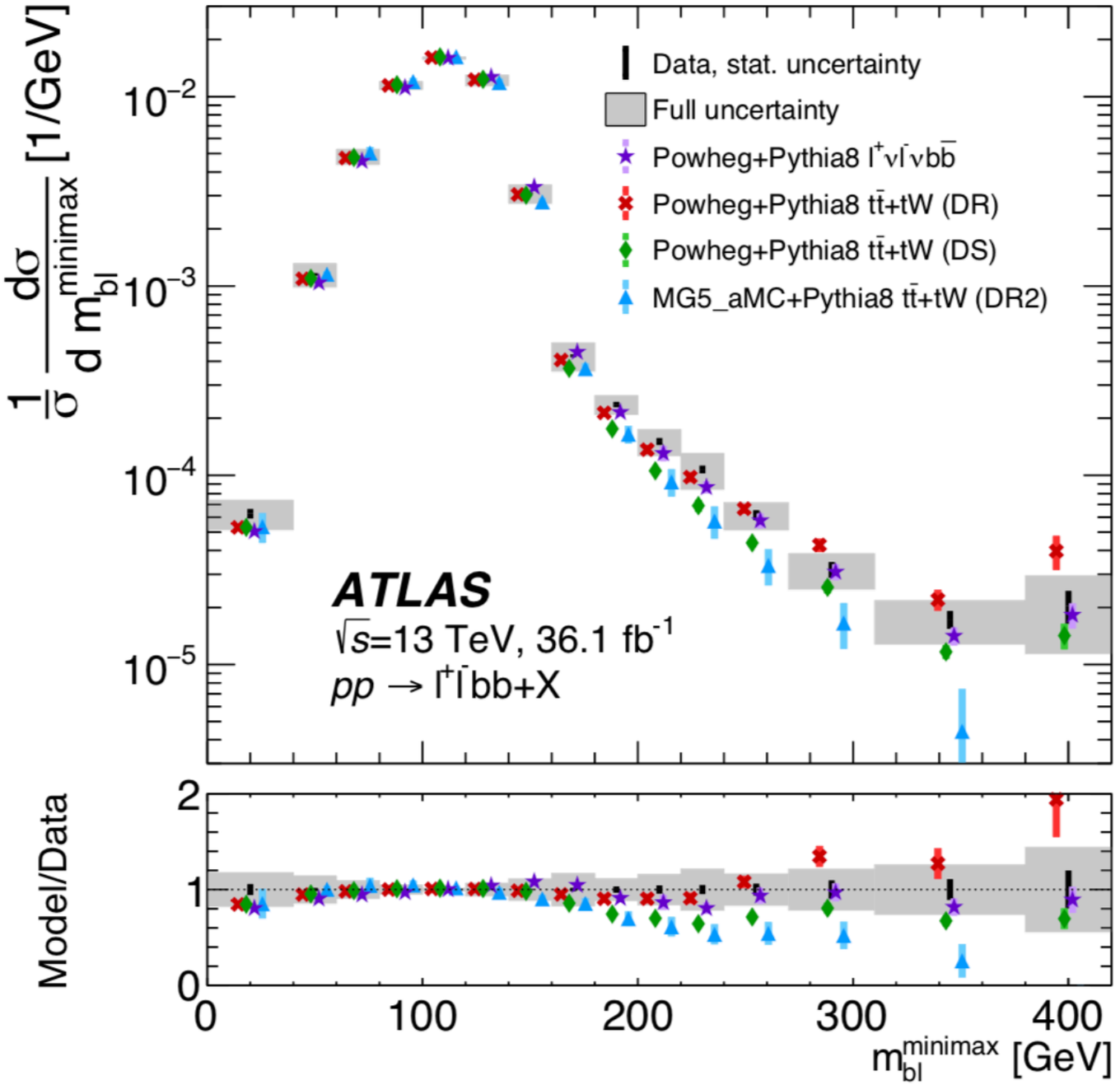


double resonant

Measure WbWb (or lvlvbb)

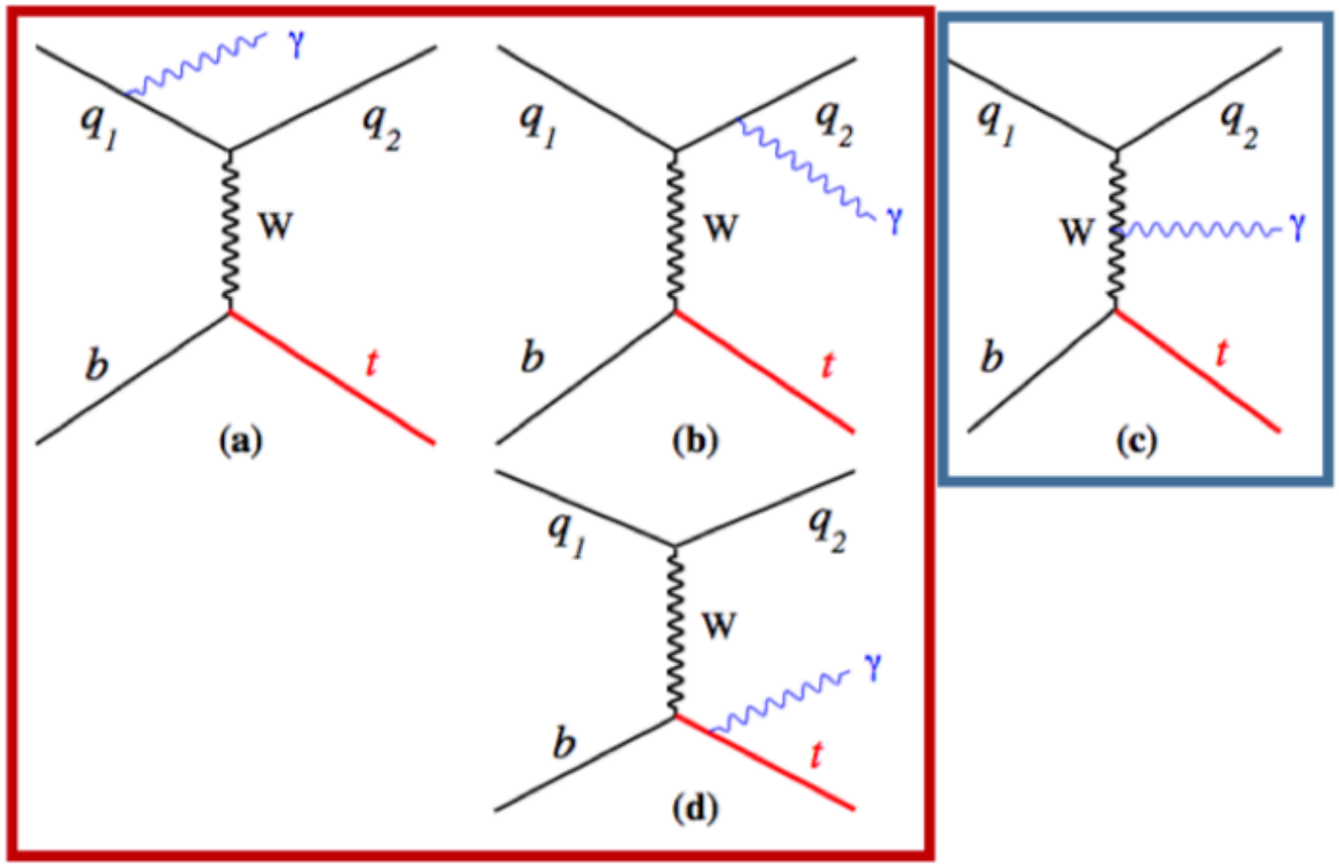
WbWb

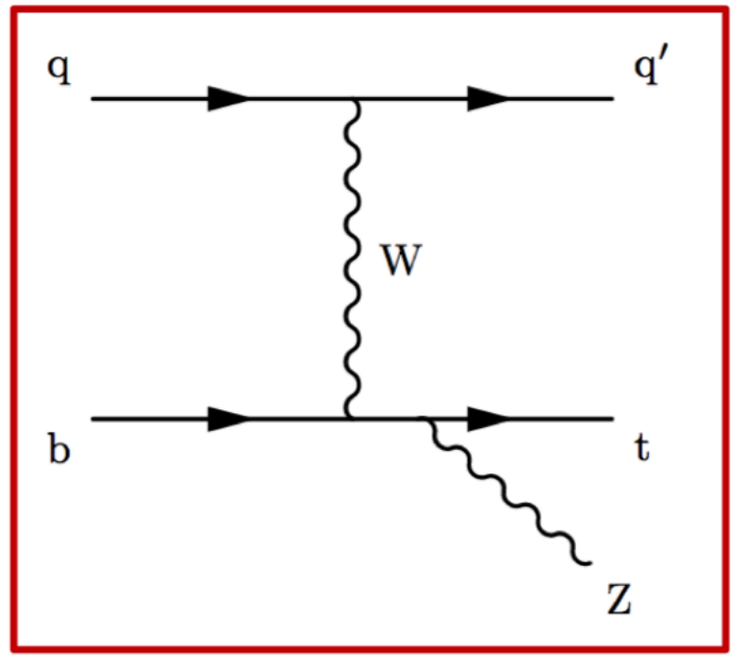




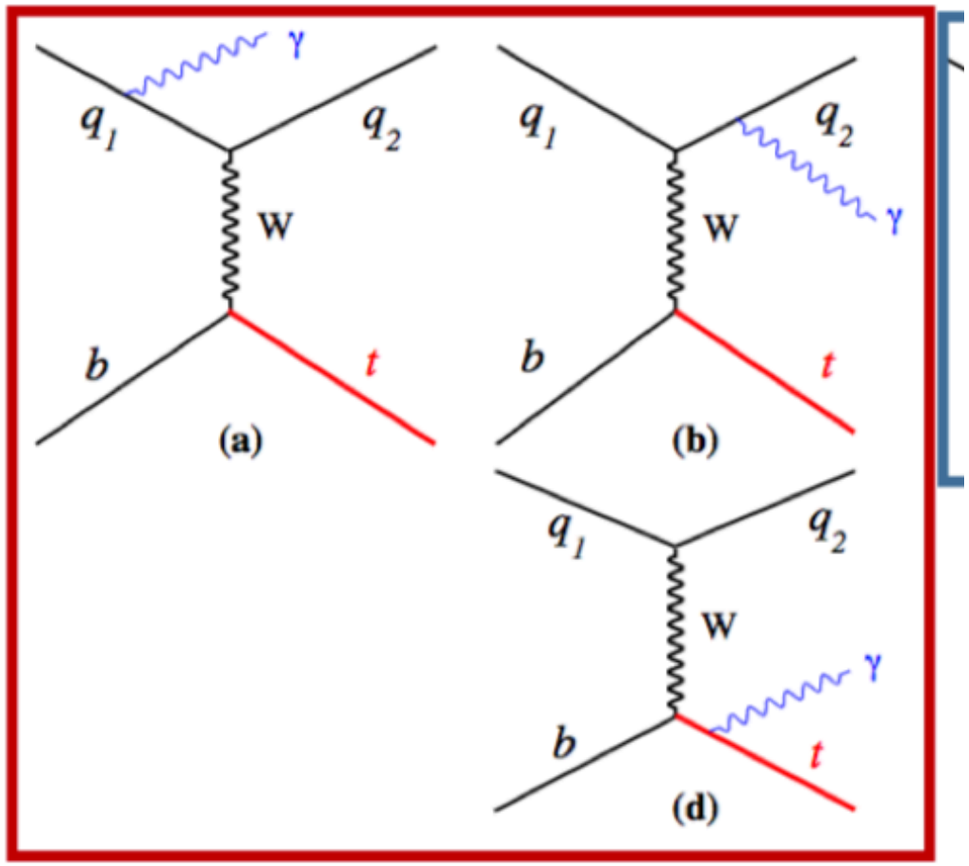
Full WbWb calculation needed to explain the data

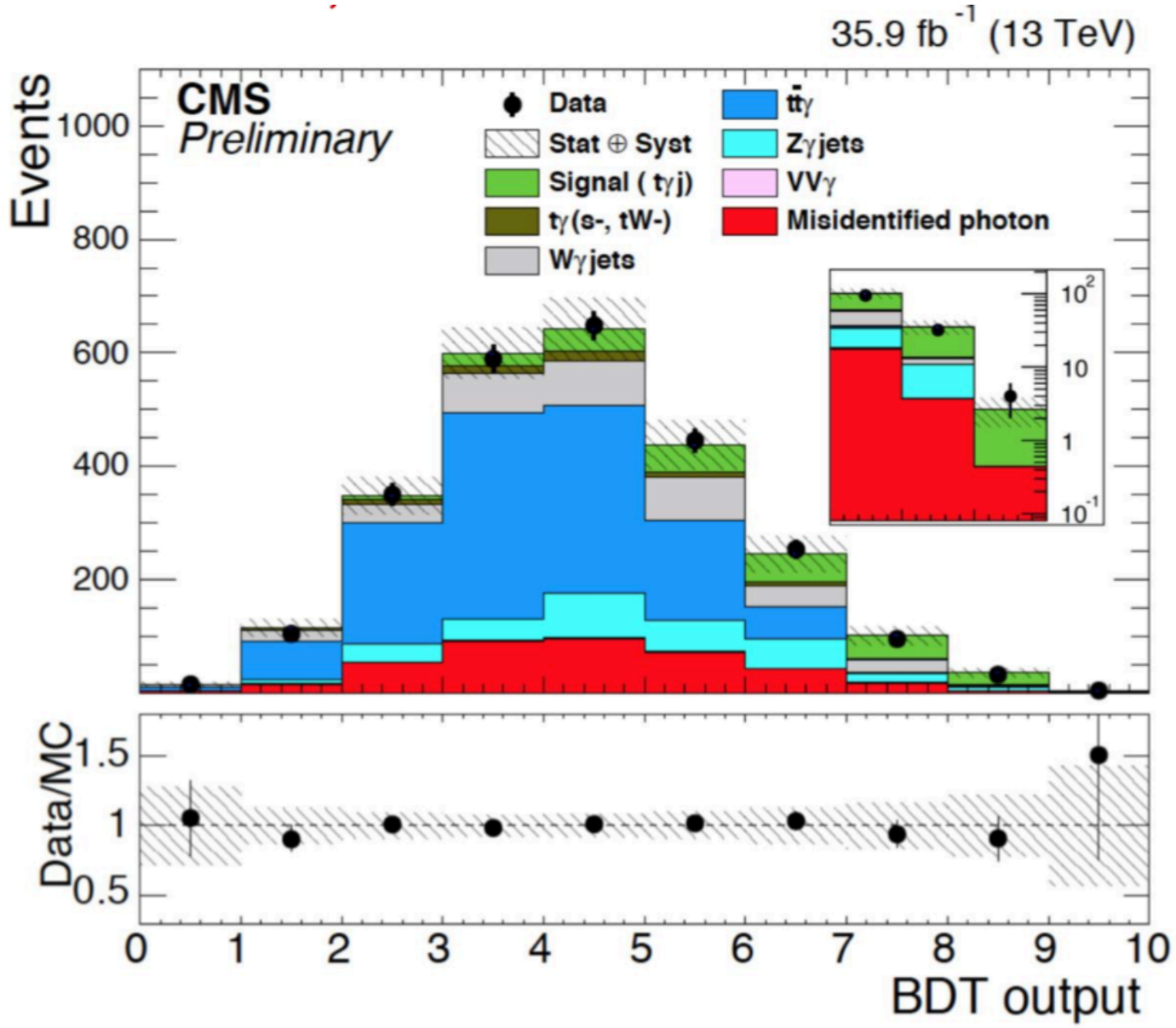
Single top + friends





Single top + friends





$$\sigma(\mathrm{pp} \to \mathrm{t}\gamma\mathrm{j})\mathcal{B}(\mathrm{t} \to \mu\nu\mathrm{b}) = 115 \pm 17\,(\mathrm{stat}) \pm 30\,(\mathrm{syst})\,\mathrm{fb}$$

~30%

$$\sigma_{theo} = 81 \pm 4\,\mathrm{fb}$$

Top quark mass

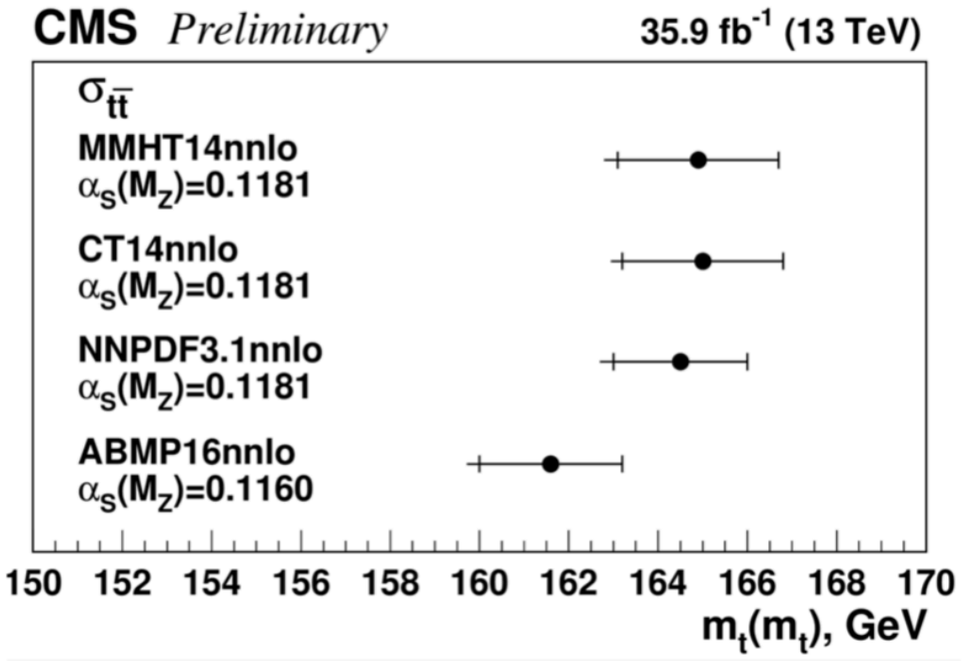
- Pole mass measurement:

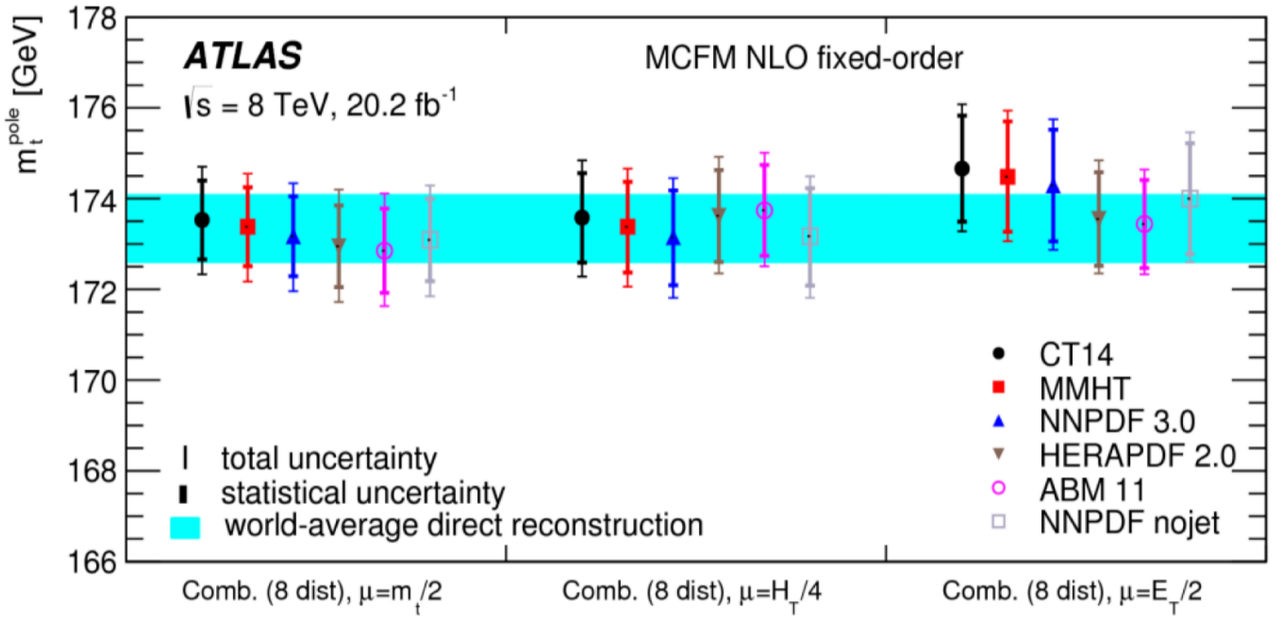
Top quark mass

- Pole mass measurement:

Top quark mass

- Mass measurements from top-pair cross-section:



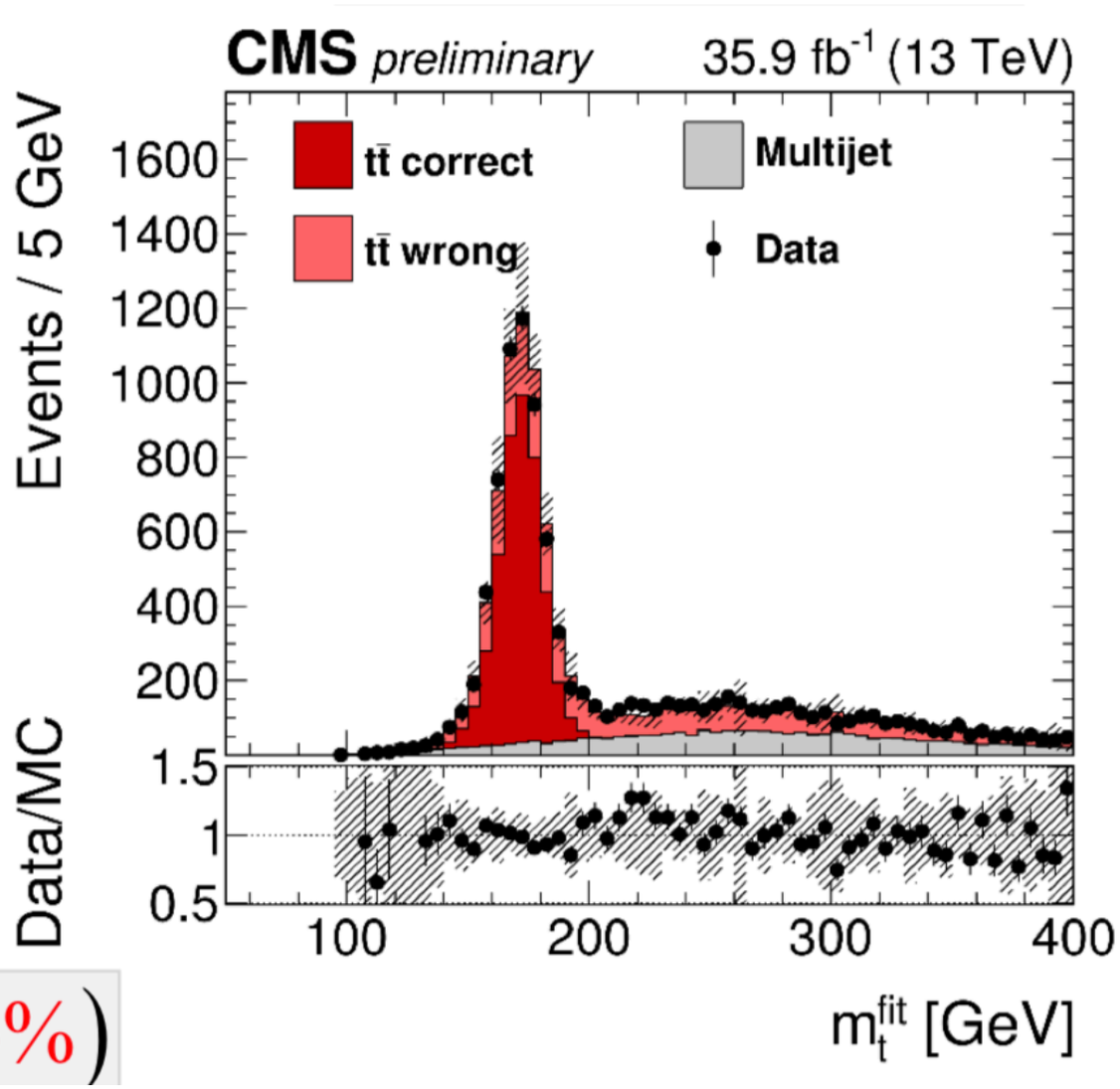


$$m_t^{\text{pole}} = 173.2 \pm 0.9(\text{stat}) \pm 0.8(\text{syst}) \pm 1.2(\text{theo})\,\text{GeV}$$

'Easy' to improve with 13 TeV data

New NNLO calculation should help

Top quark mass



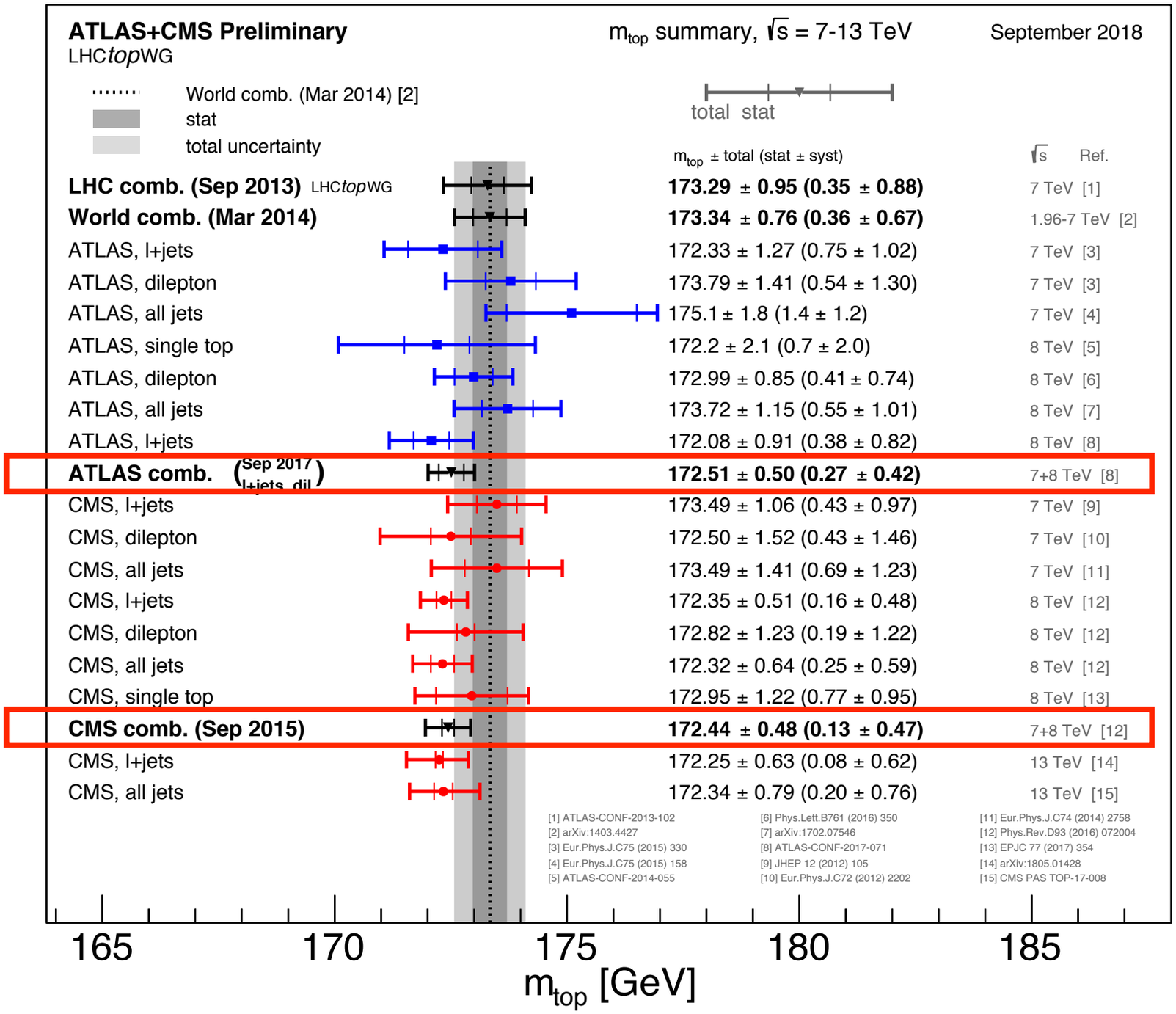
Impressive precision, but not yet at run-1 levels.

A lot of hard work ahead to go below 0.5 GeV.

$$m_t^{\mathrm{hyb}} = 172.34 \pm 0.20(\mathrm{stat+JSF}) \pm 0.76(\mathrm{syst})\,\mathrm{GeV}\ (\Delta = 0.46\%)$$

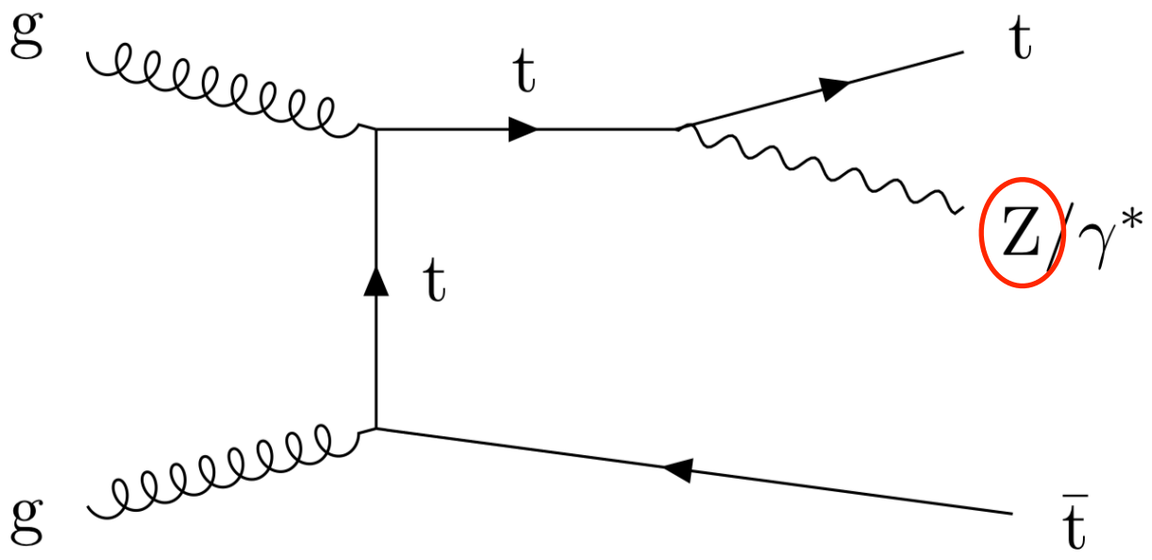
$$\mathrm{JSF}^{\mathrm{hyb}} = 0.997 \pm 0.002(\mathrm{stat}) \pm 0.007\ (\mathrm{syst})\,\mathrm{GeV}.$$

Top quark mass

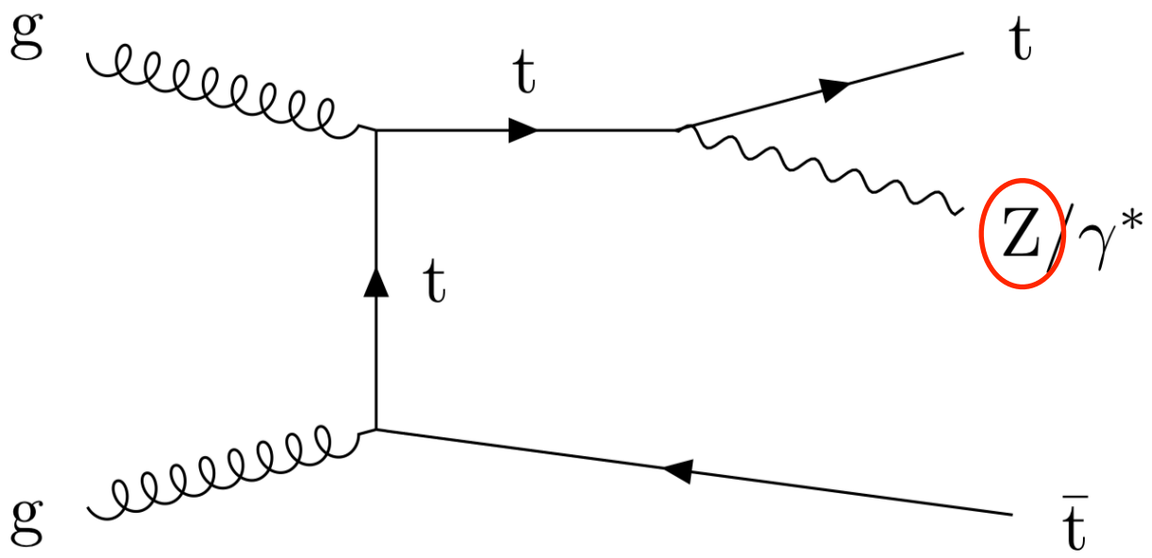


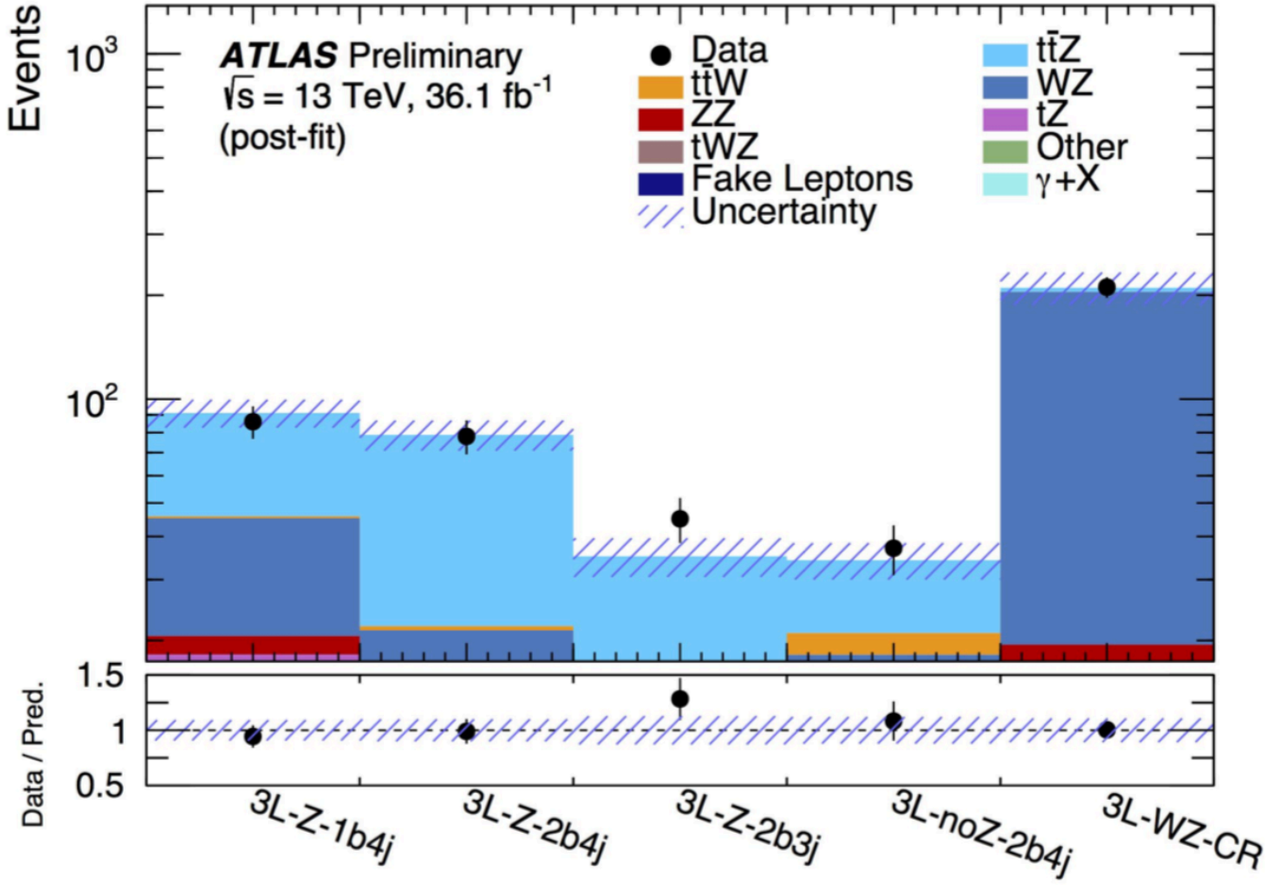
Time for new LHC combination

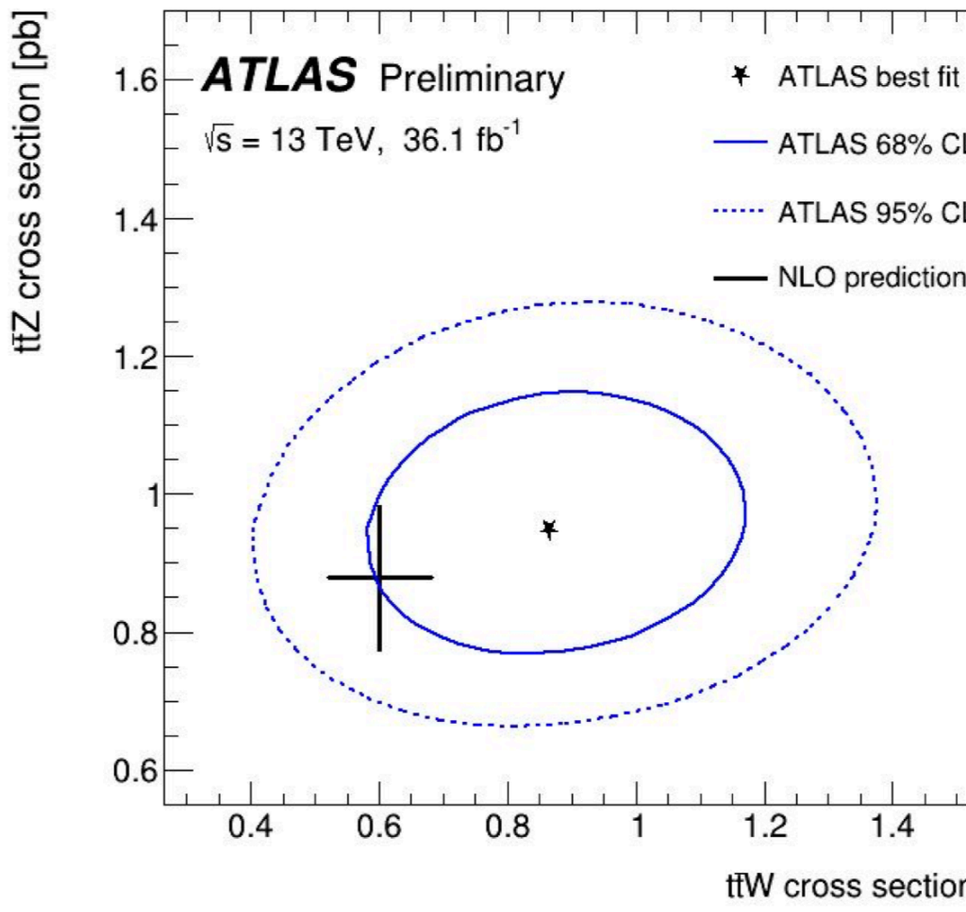
Top + friends



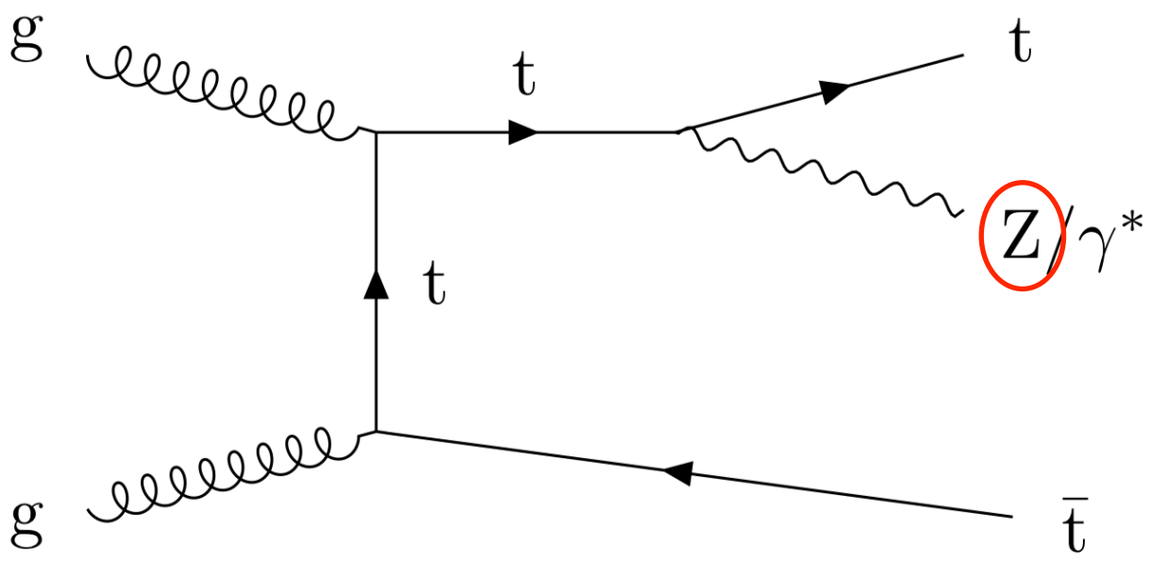
Top + friends

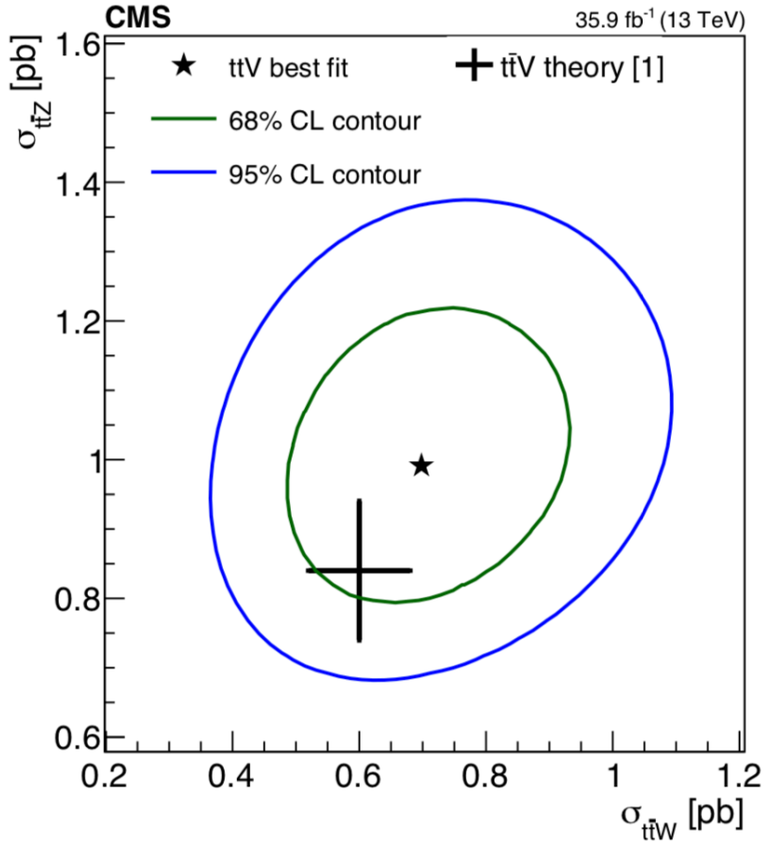

g
g
t
t
t
$\bar{t}$
Z/γ^*

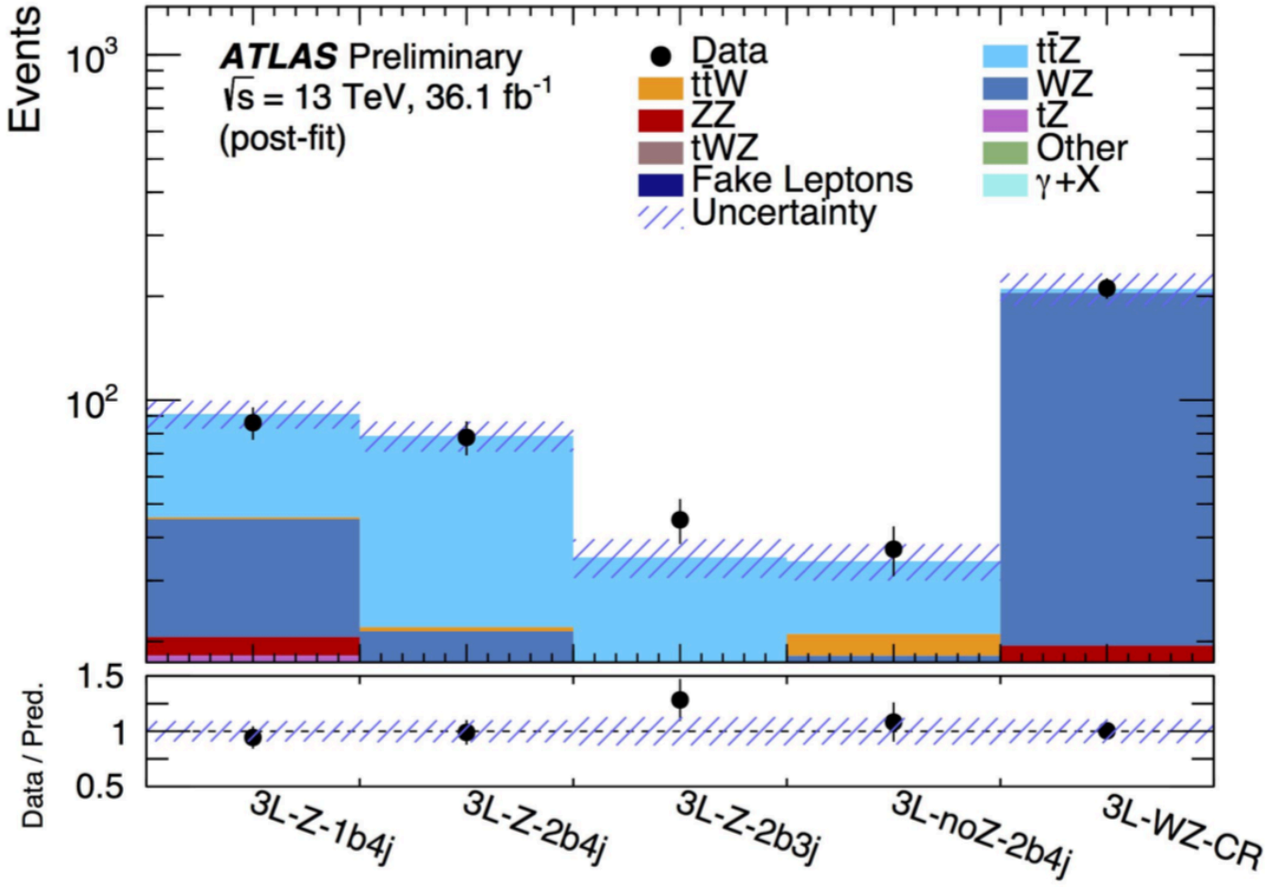

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
(post-fit)
Data
ttW
ZZ
tWZ
Fake Leptons
Uncertainty
ttZ
WZ
tZ
Other
γ+X
Events
Data / Pred.
3L-Z-1b4j
3L-Z-2b4j
3L-Z-2b3j
3L-noZ-2b4j
3L-WZ-CR

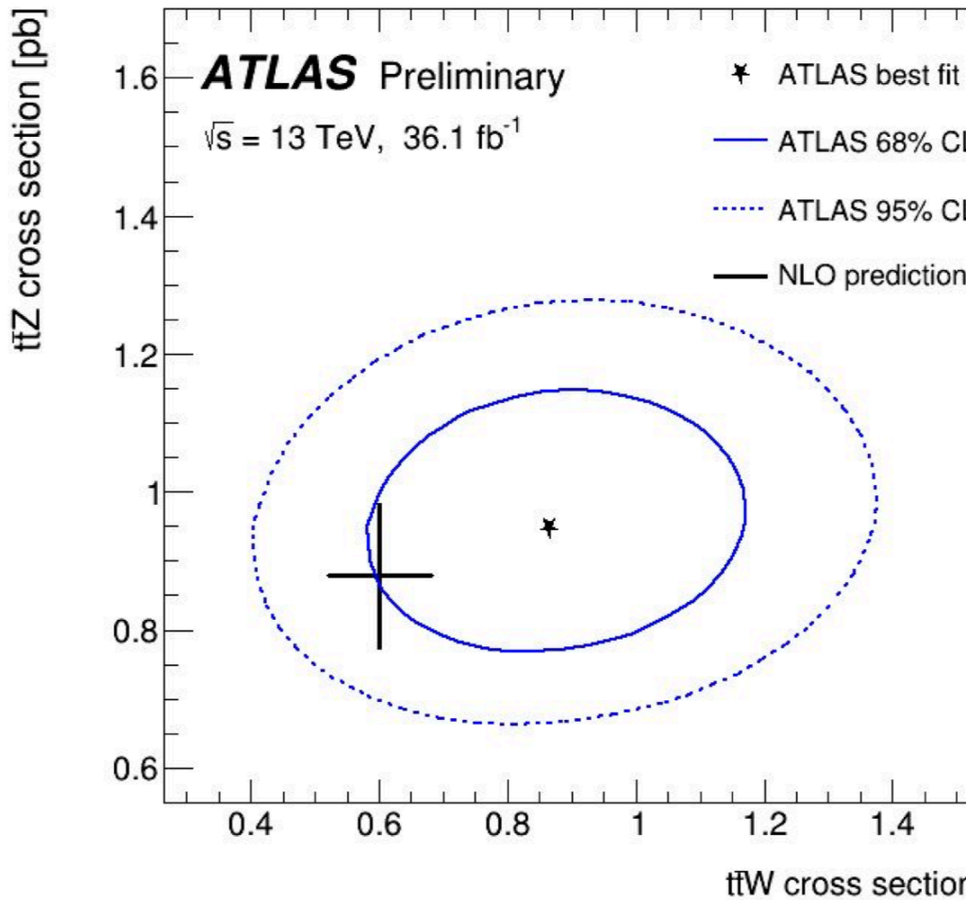

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
ATLAS best fit
ATLAS 68% CI
ATLAS 95% CI
NLO prediction
ttZ cross section [pb]
ttW cross section

Top + friends

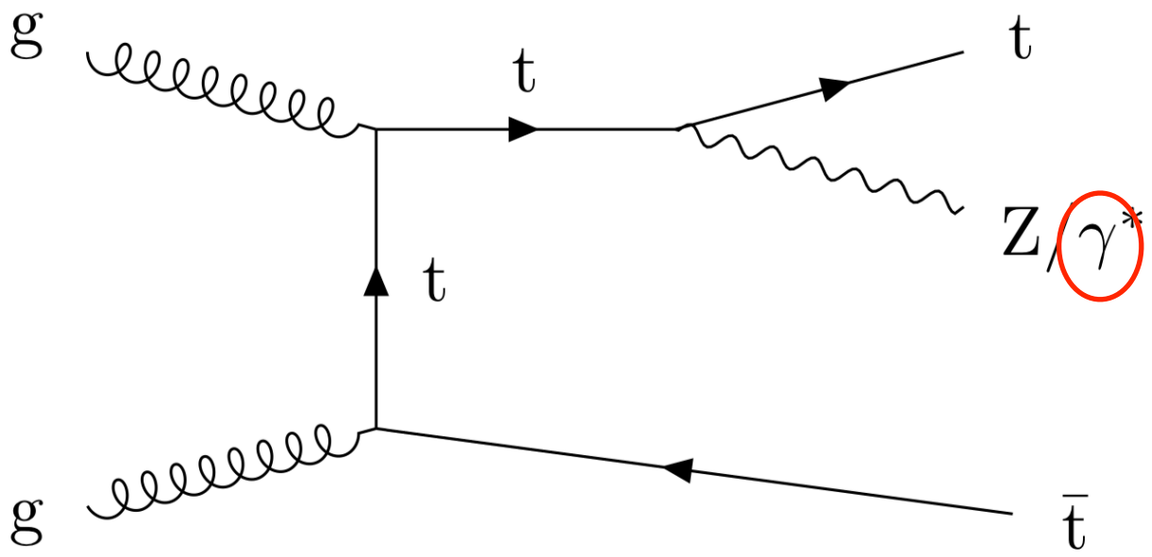

g
g
t
t
t
Z/γ*
t̄

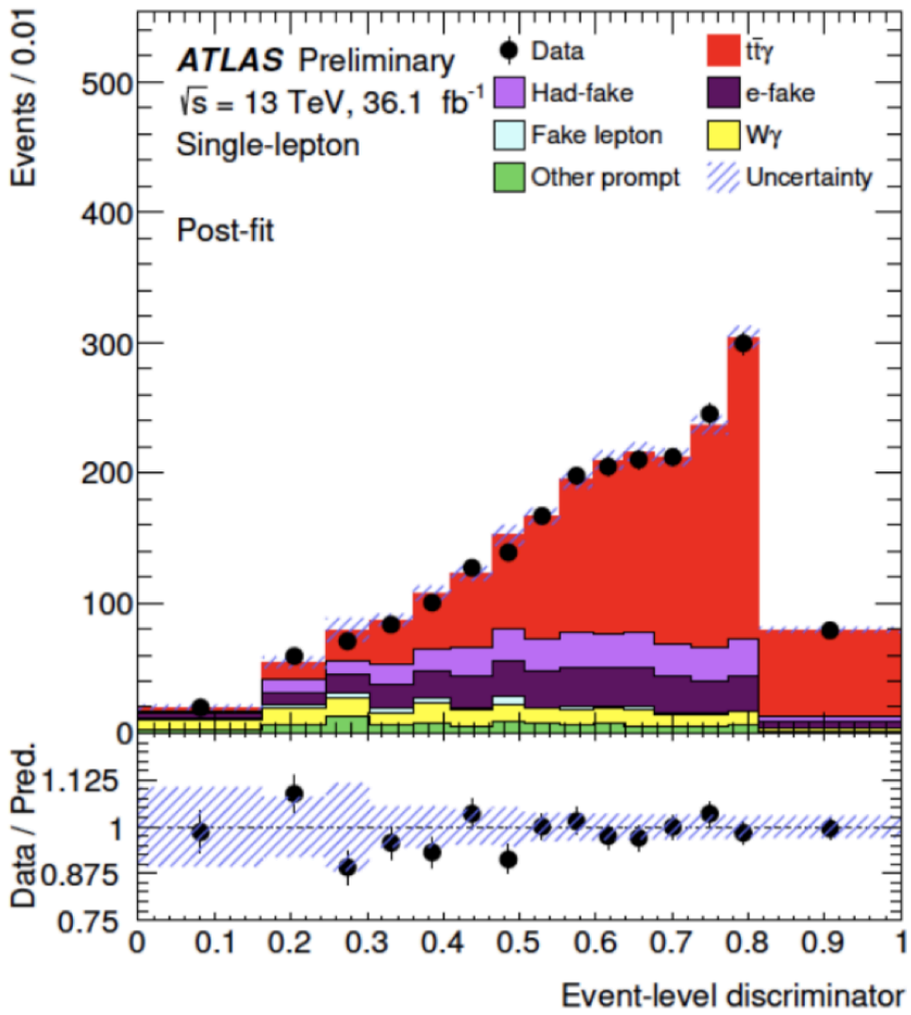

CMS
35.9 fb-1 (13 TeV)
ttV best fit
tt̄V theory [1]
68% CL contour
95% CL contour
σttZ [pb]
σttW [pb]


ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
(post-fit)
Data
ttW
ZZ
tWZ
Fake Leptons
Uncertainty
ttZ
WZ
tZ
Other
γ+X
Events
Data / Pred.
3L-Z-1b4j
3L-Z-2b4j
3L-Z-2b3j
3L-noZ-2b4j
3L-WZ-CR


ATLAS Preliminary
√s = 13 TeV, 36.1 fb-1
ATLAS best fit
ATLAS 68% CI
ATLAS 95% CI
NLO prediction
ttZ cross section [pb]
ttW cross section

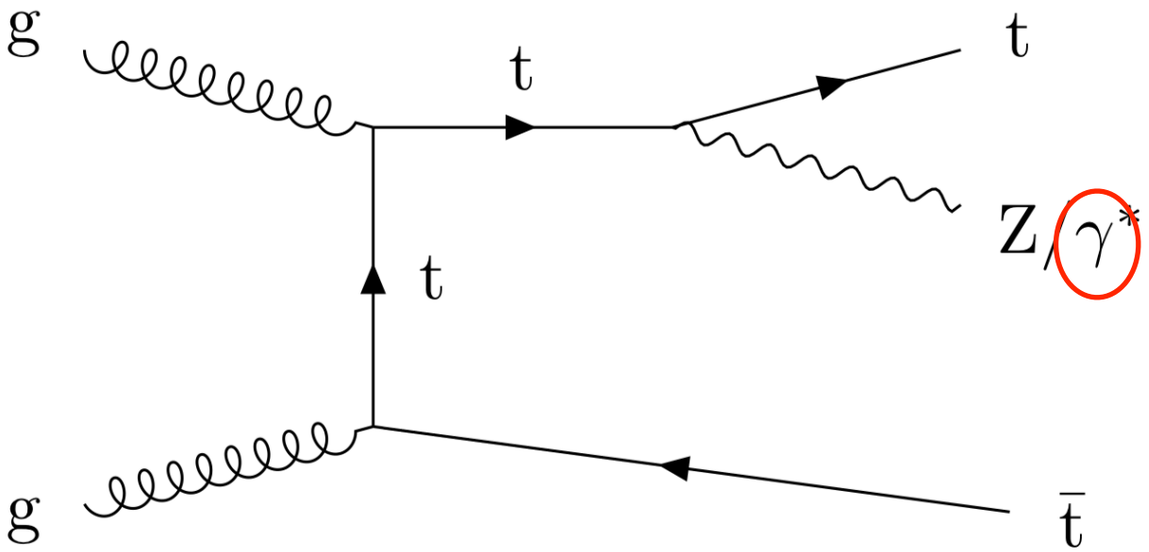
Top + friends

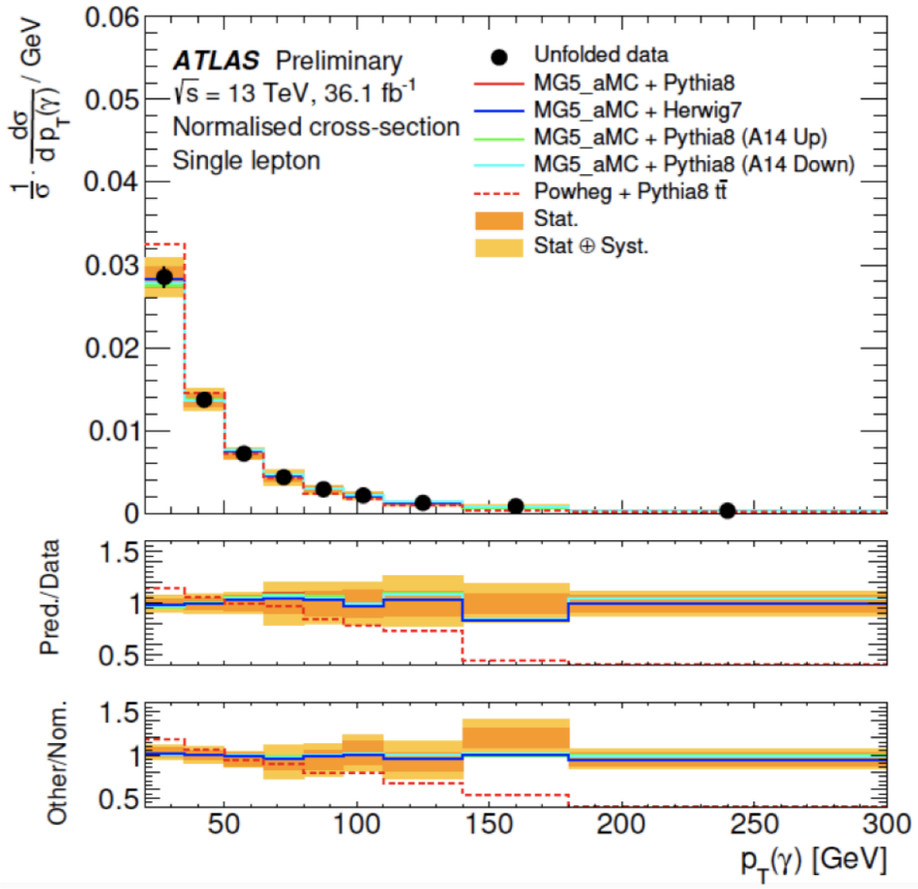


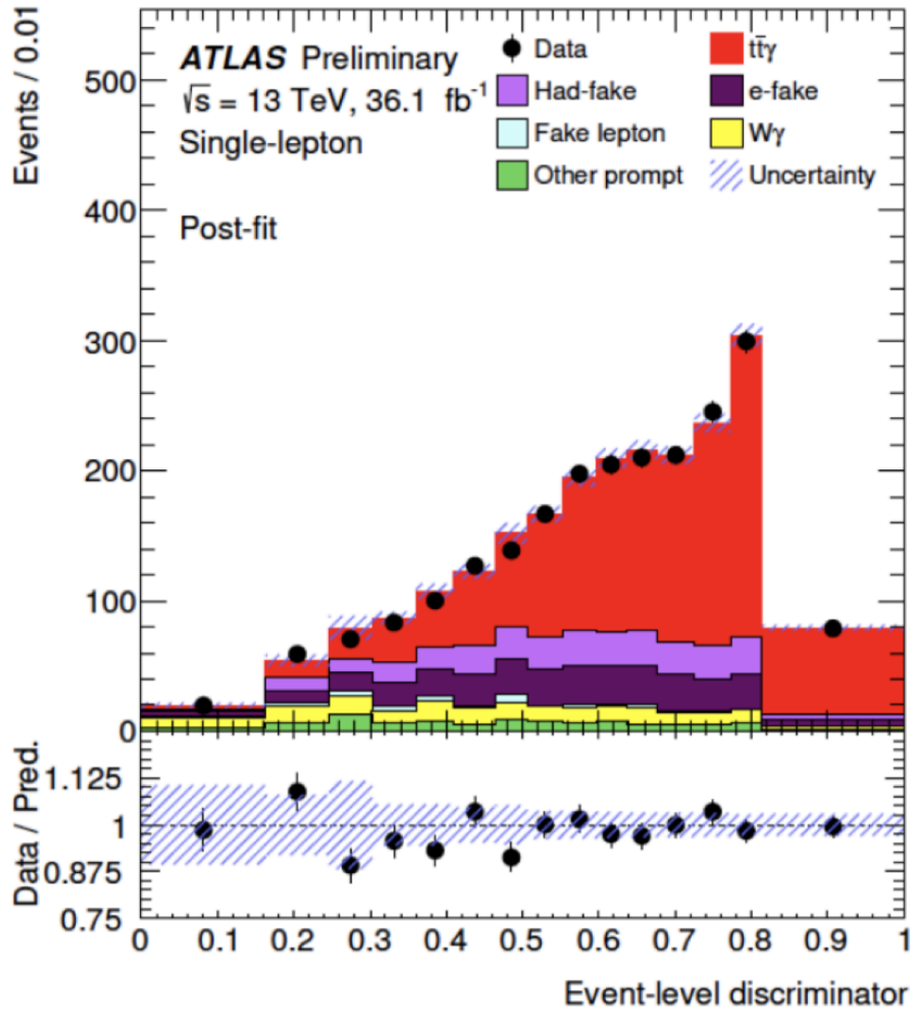


$$\sigma_{\text{fid}}^{\text{SL}} = 521 \pm 9(\text{stat.}) \pm 41(\text{sys.})\ fb \text{ and}$$
$$\sigma_{\text{fid}}^{\text{DL}} = 69 \pm 3(\text{stat.}) \pm 4(\text{sys.})\ fb,$$

Top + friends

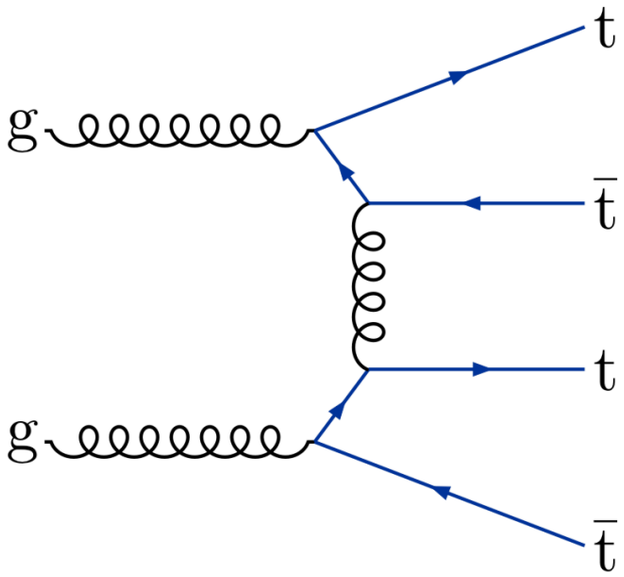






$$\sigma_{\text{fid}}^{\text{SL}} = 521 \pm 9(\text{stat.}) \pm 41(\text{sys.})\ fb \text{ and}$$
$$\sigma_{\text{fid}}^{\text{DL}} = 69 \pm 3(\text{stat.}) \pm 4(\text{sys.})\ fb,$$

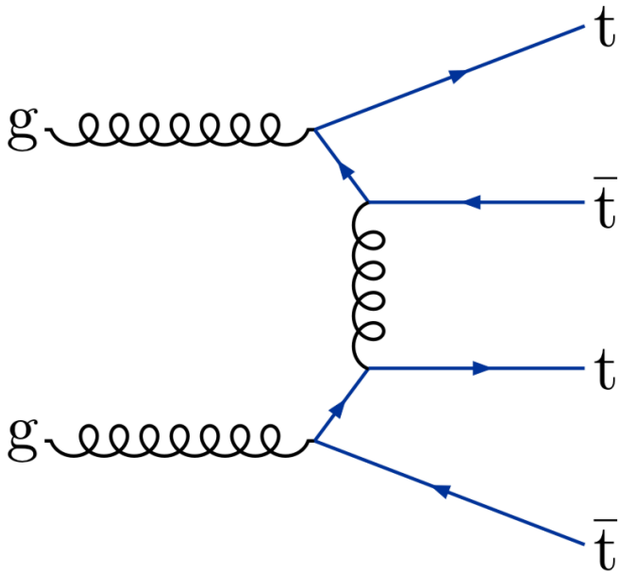
Four Tops



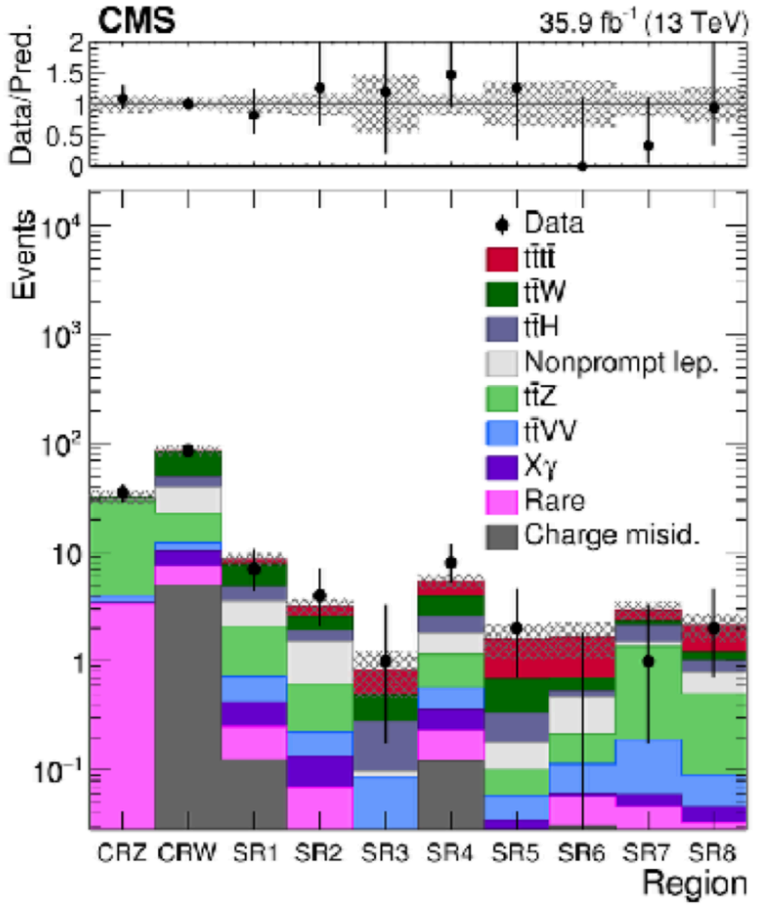
N_ℓ	N_b	N_{jets}	Region
2	2	$\leq$5	CRW
		6	SR1
		7	SR2
		$\geq$8	SR3
	3	5, 6	SR4
		$\geq$7	SR5
	$\geq$4	$\geq$5	SR6
$\geq$3	2	$\geq$5	SR7
	$\geq$3	$\geq$4	SR8
Inverted Z veto			CRZ

High jet multiplicities → tricky background estimates

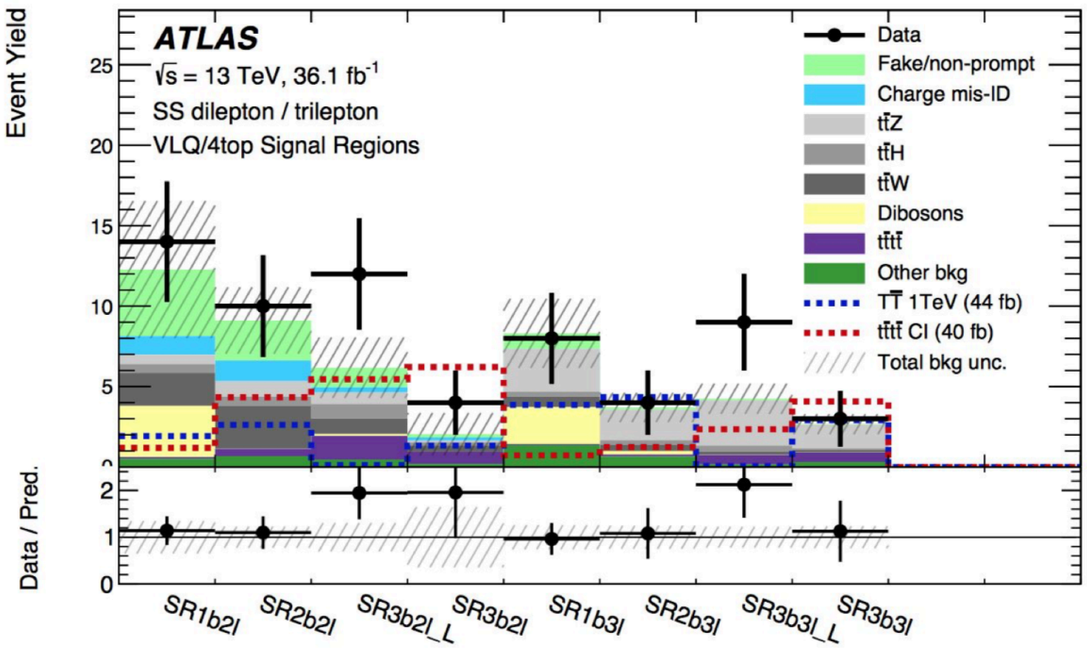
Four Tops



N_ℓ	N_b	N_{jets}	Region
2	2	≤5	CRW
		6	SR1
		7	SR2
		≥8	SR3
	3	5, 6	SR4
		≥7	SR5
	≥4	≥5	SR6
≥3	2	≥5	SR7
	≥3	≥4	SR8
		ted Z veto	CRZ



1.6σ (1.0σ expected)



2.8σ (1.0σ expected)

Searches & top

Bottom line: No discoveries yet….

Searches & top

Harder

Faster

Better

Stronger

(D. Punk 2001)

Searches & top

Harder

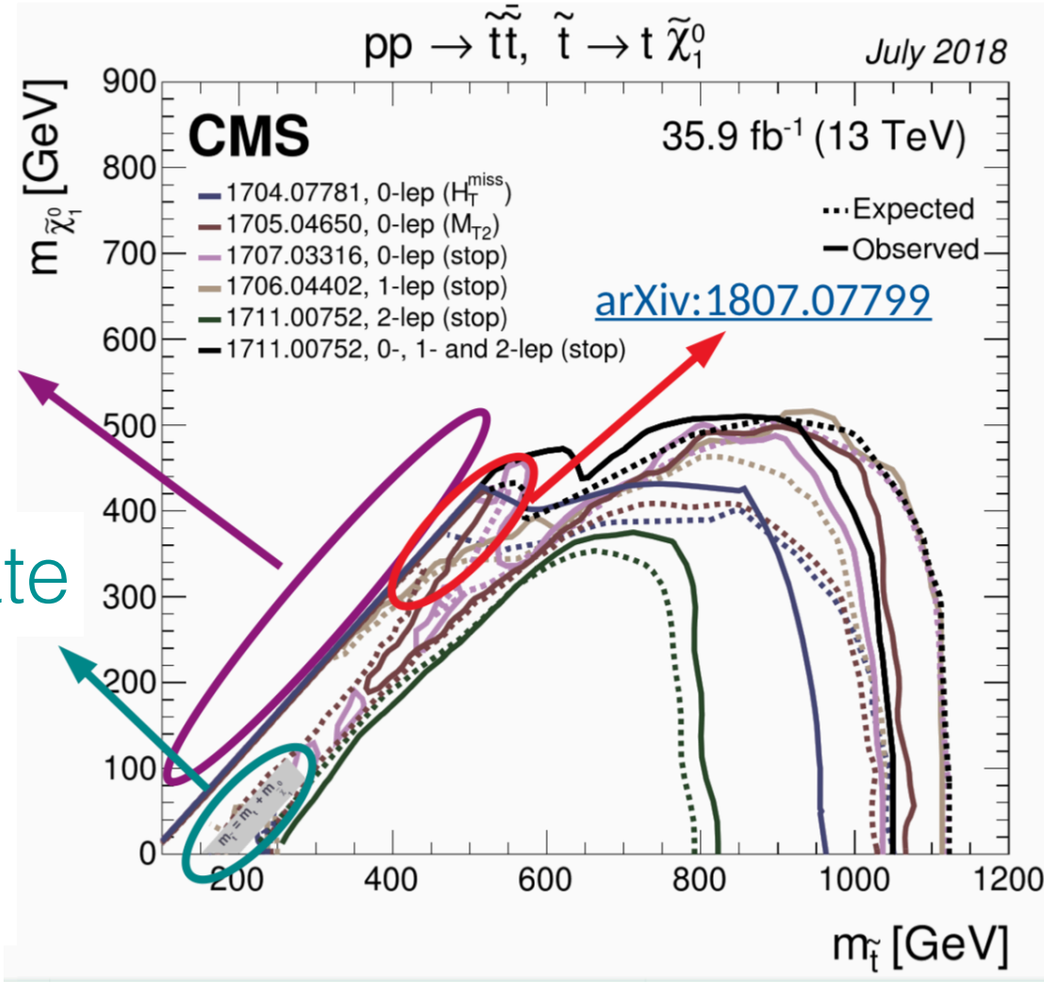
Faster

Better

Stronger

(D. Punk 2001)

Degenerate stops



Searches & top

Harder

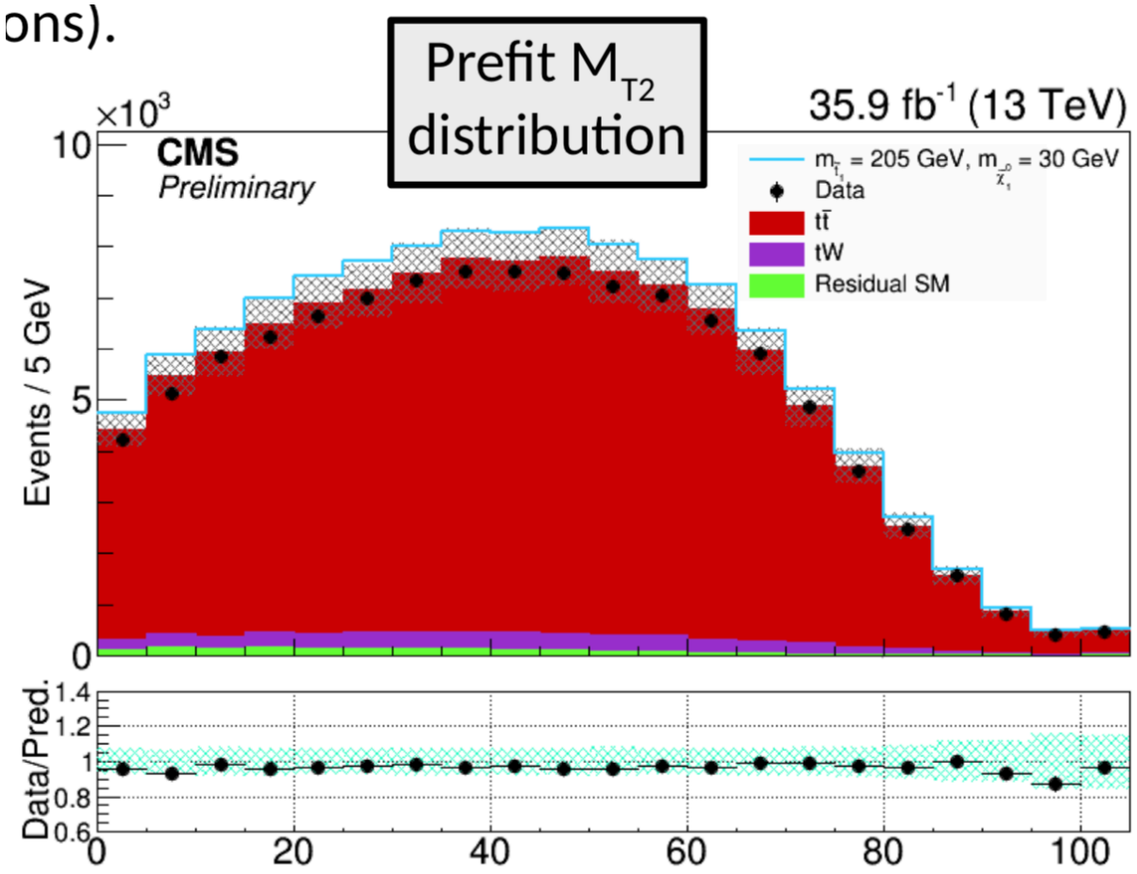
Faster

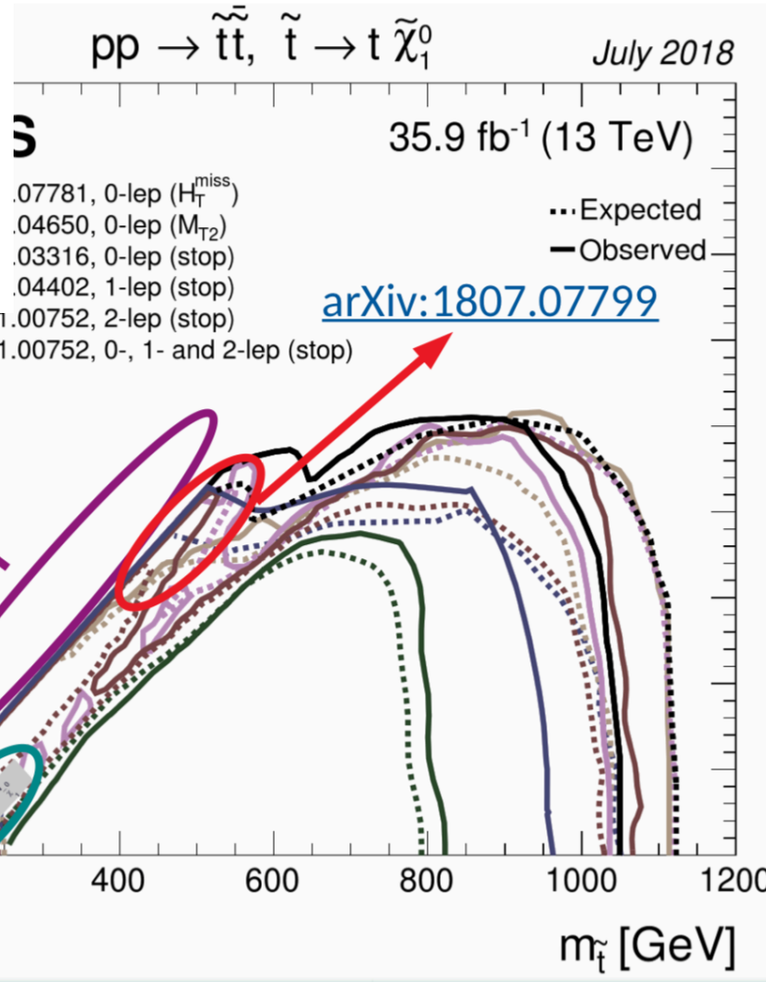
Better

Stronger

(D. Punk 2001)

ons).





Degenerate stops

Searches & top

Harder

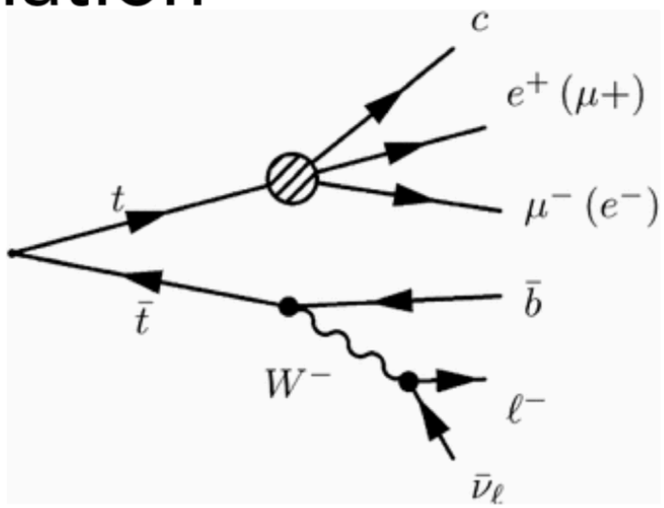
Faster

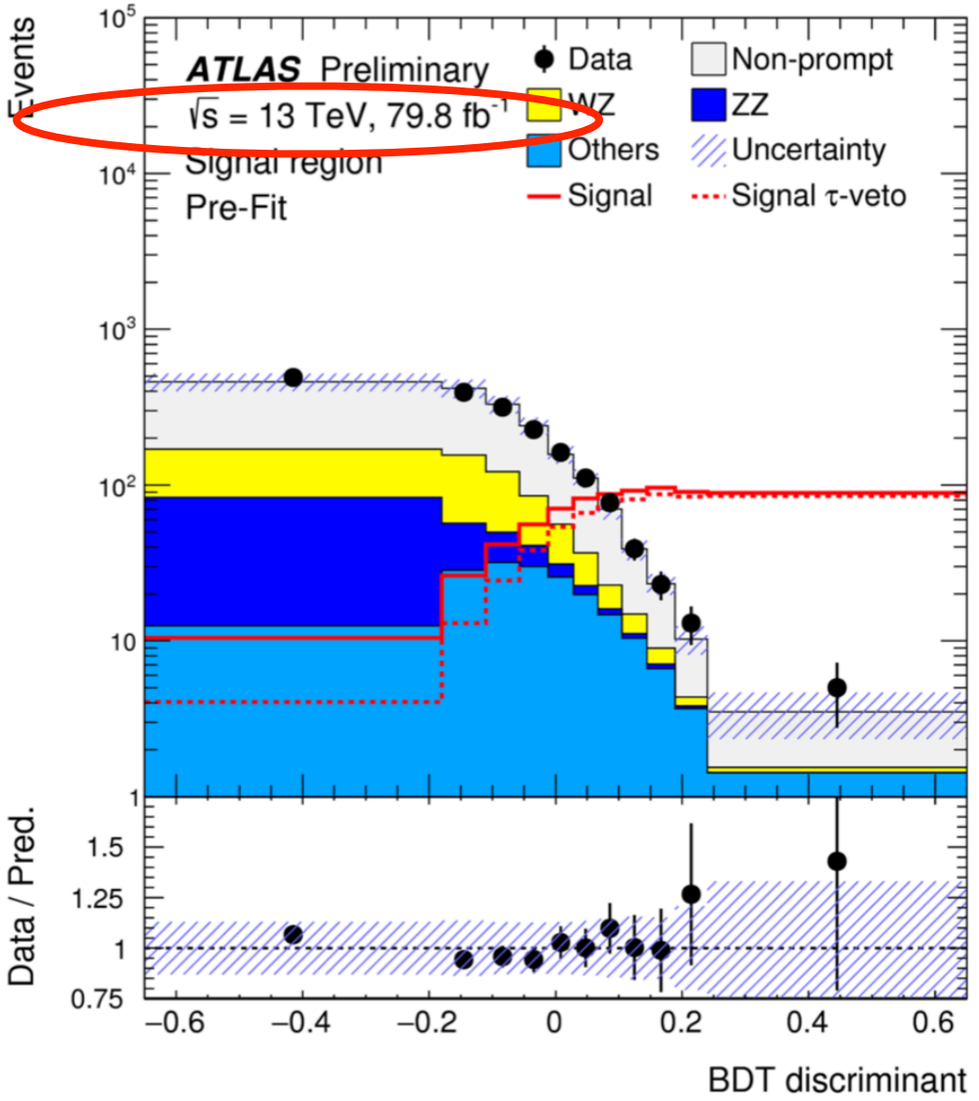
Better

Stronger

(D. Punk 2001)

Charged Lepton Flavor Violation





Searches & top

Harder

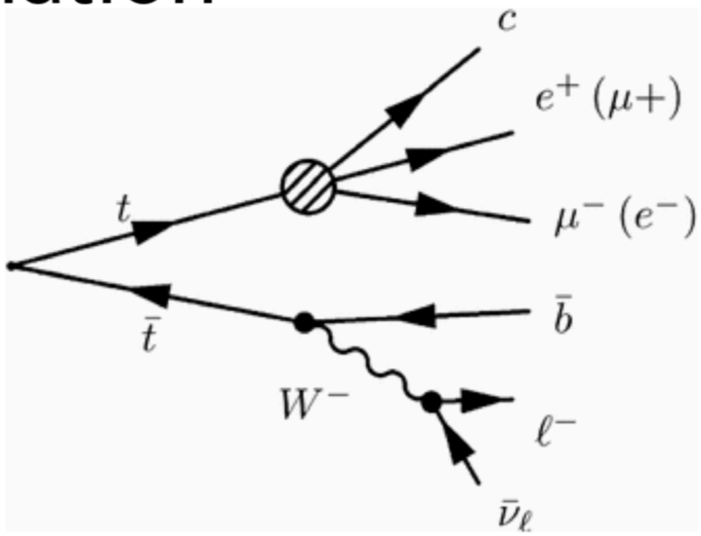
Faster

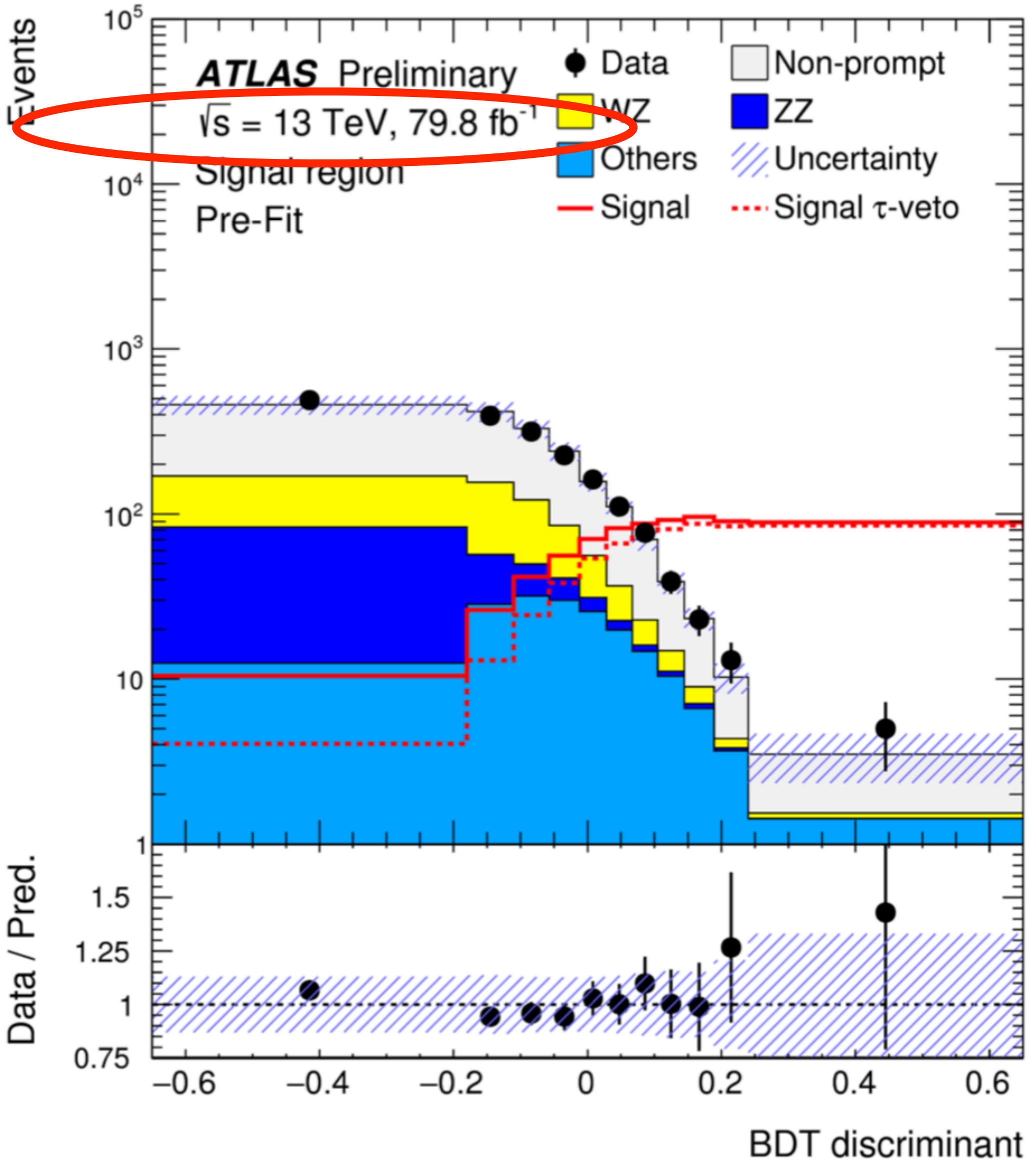
Better

Stronger

(D. Punk 2001)

Charged Lepton Flavor Violation





$B(t\to\ell\ell'q) < 1.86(1.36)\times10^{-5}$ obs (exp)

$B(t\to e\mu q) < 6.6(4.8)\times10^{-6}$ obs (exp)

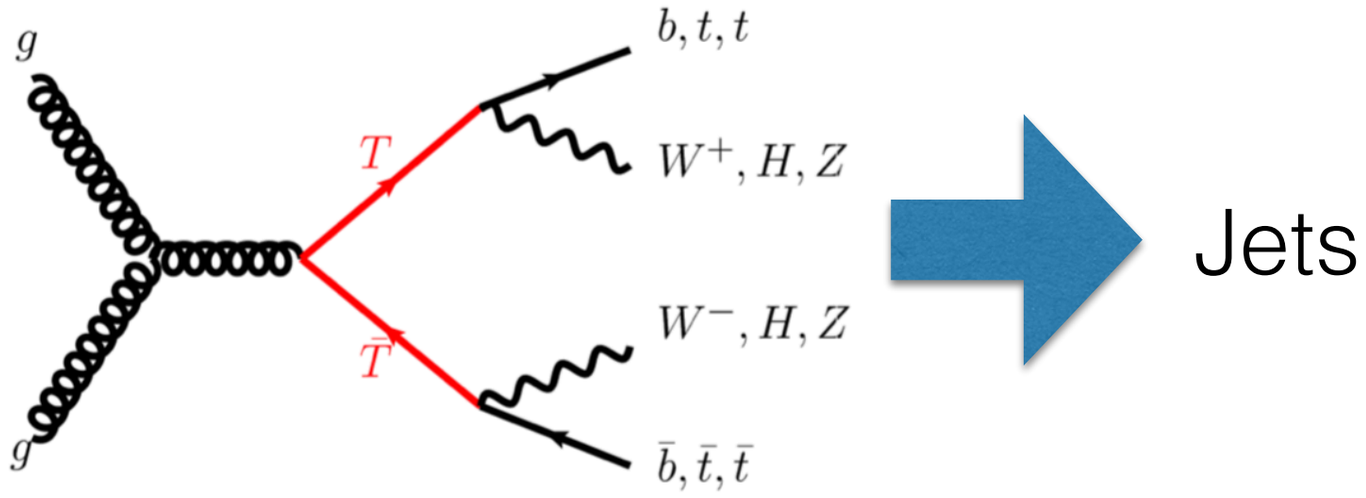
Searches & top

Harder

Faster

Better

Stronger



(D. Punk 2001)

Searches & top

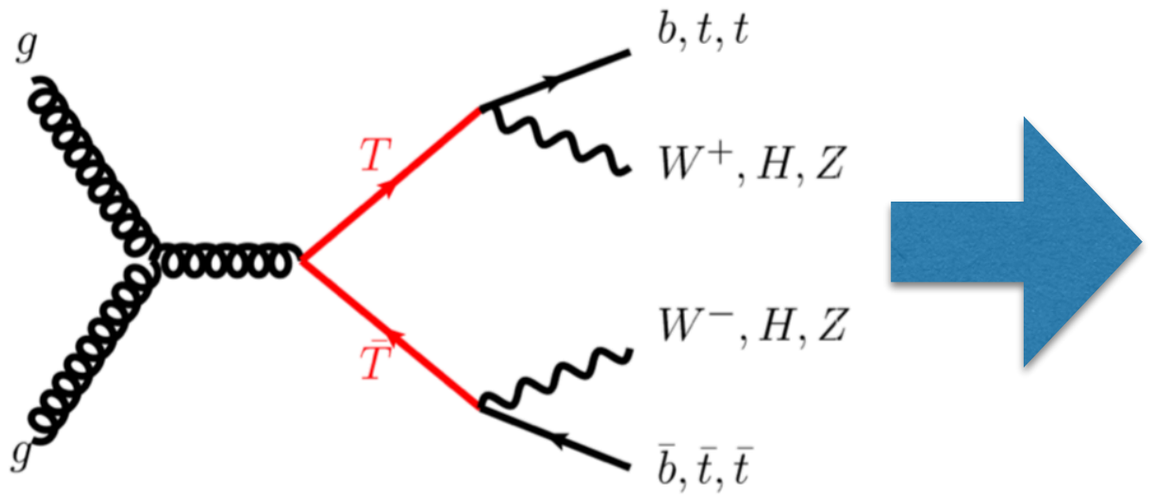
Harder

Faster

Better

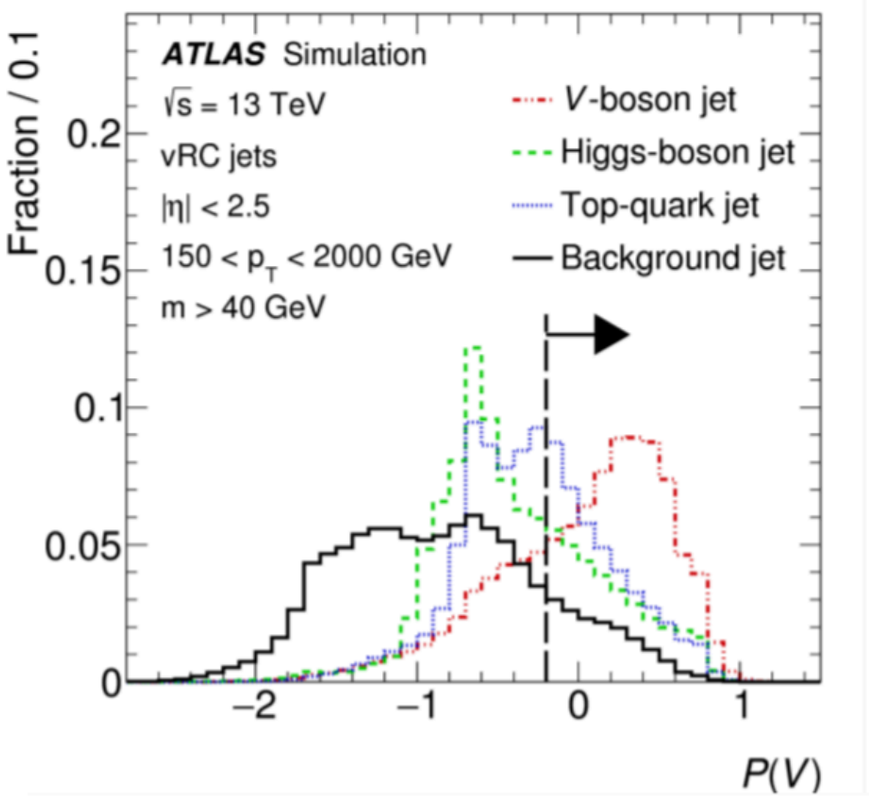
Stronger

(D. Punk 200

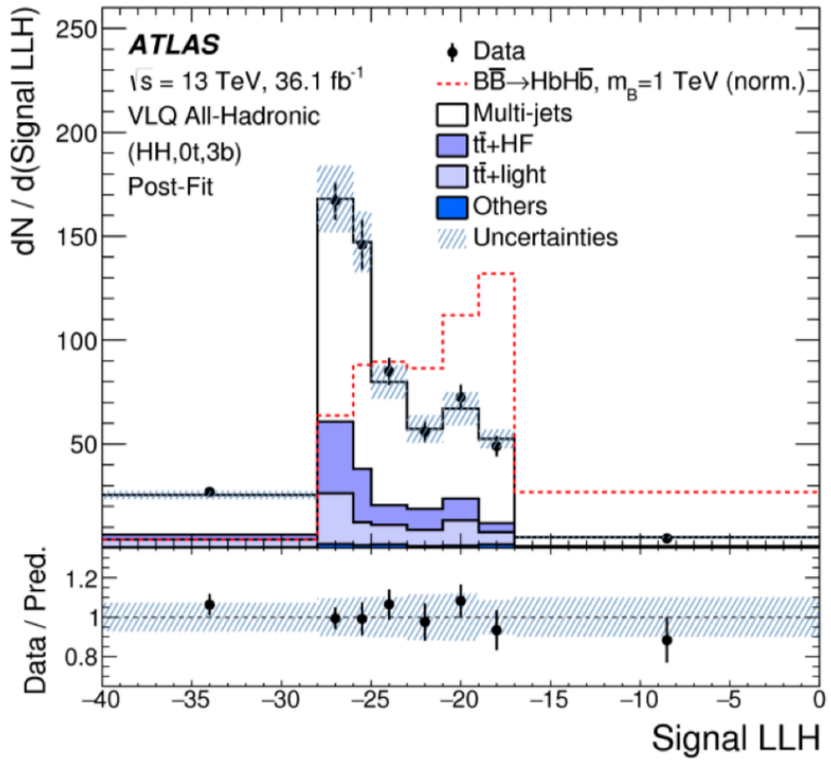


Jets

DNN boosted object tagger:



Matrix element method:



Searches & top

This Letter presents a search for ……

No significant deviation from Standard Model background expectations is observed

Harder

Faster

Better

Stronger

(D. Punk 2001)

Searches & top

This Letter presents a search for ……

No significant deviation from Standard Model background expectations is observed

Surprises do happen:

Harder

Faster

Better

Stronger

(D. Punk 2001)

Searches & top

This Letter presents a search for ……

No significant deviation from Standard Model background expectations is observed

Surprises do happen:

Harder

Faster

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Stronger

(D. Punk 2001)

Country	W	D	L	GD	Pts
SWE	2	0	1	3	**6**
MEX	2	0	1	-1	**6**
KOR	1	0	2	0	**3**
GER	1	0	2	-2	**3**

Searches & top

This Letter presents a search for ……

No significant deviation from Standard Model background expectations is observed

Surprises do happen:

Harder

Faster

Better

Stronger

(D. Punk 2001)

Searches & top

Harder

Faster

Better

Stronger

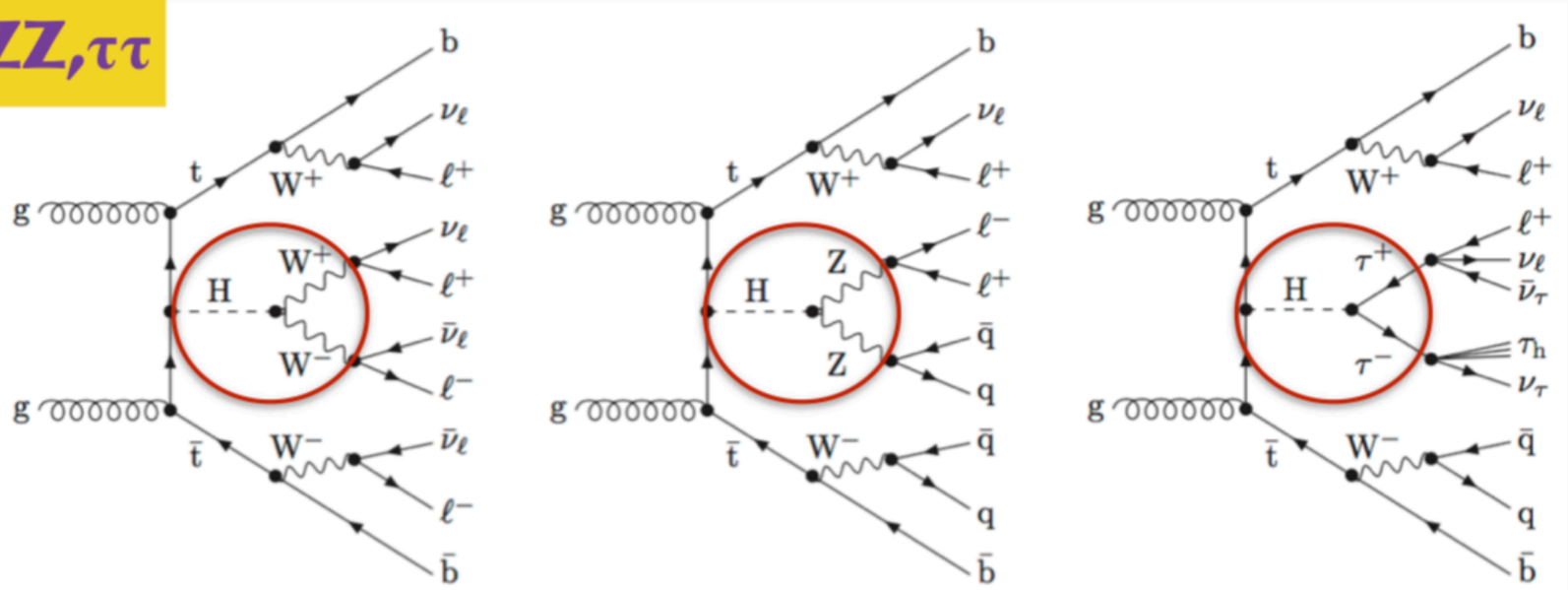
(D. Punk 2001)

Only ~1/10th (100th) of (H)LHC data has been analysed.

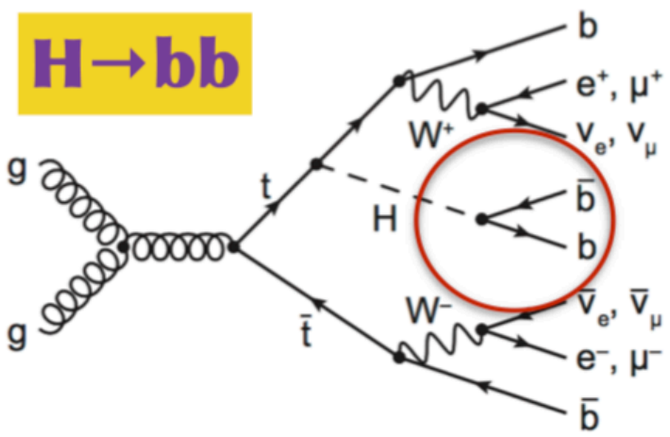
ttH

Golden channel to directly probe y_t but …
a very complex final state !

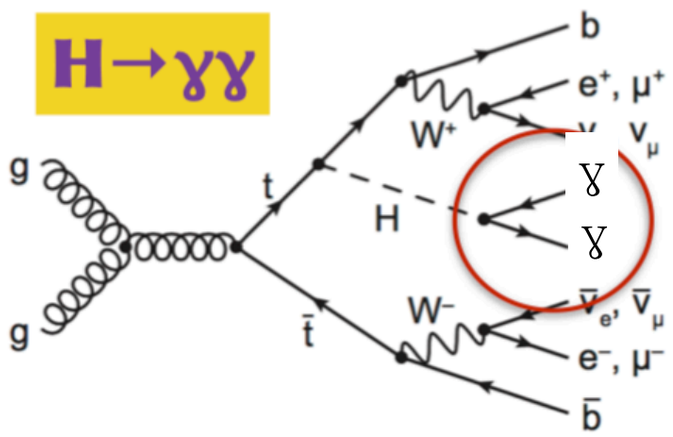
H→WW,ZZ,ττ

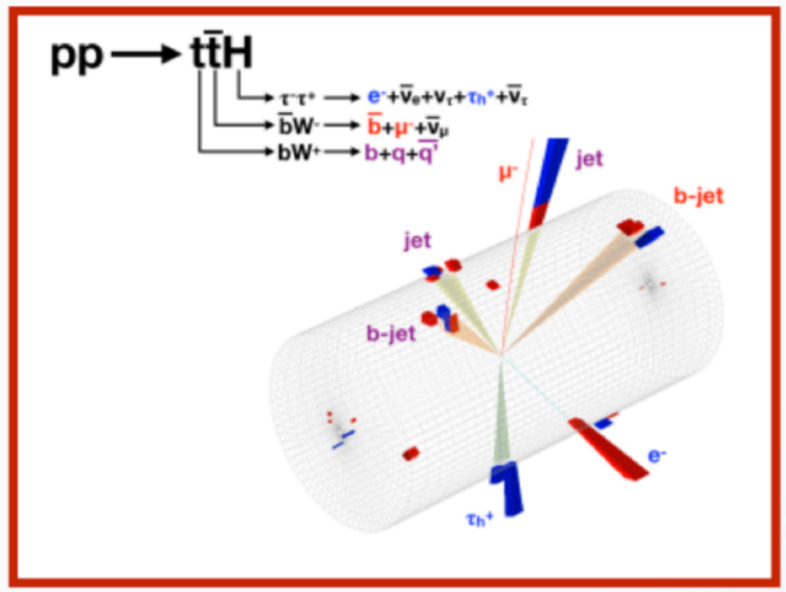


H→bb



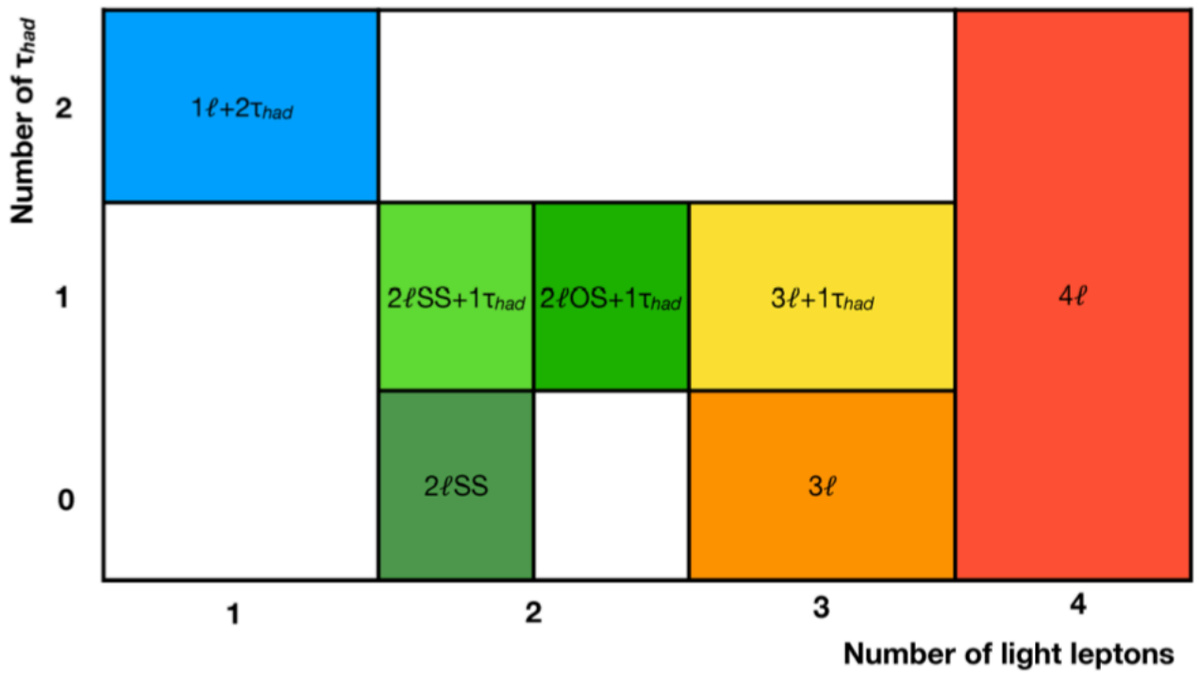
H→γγ

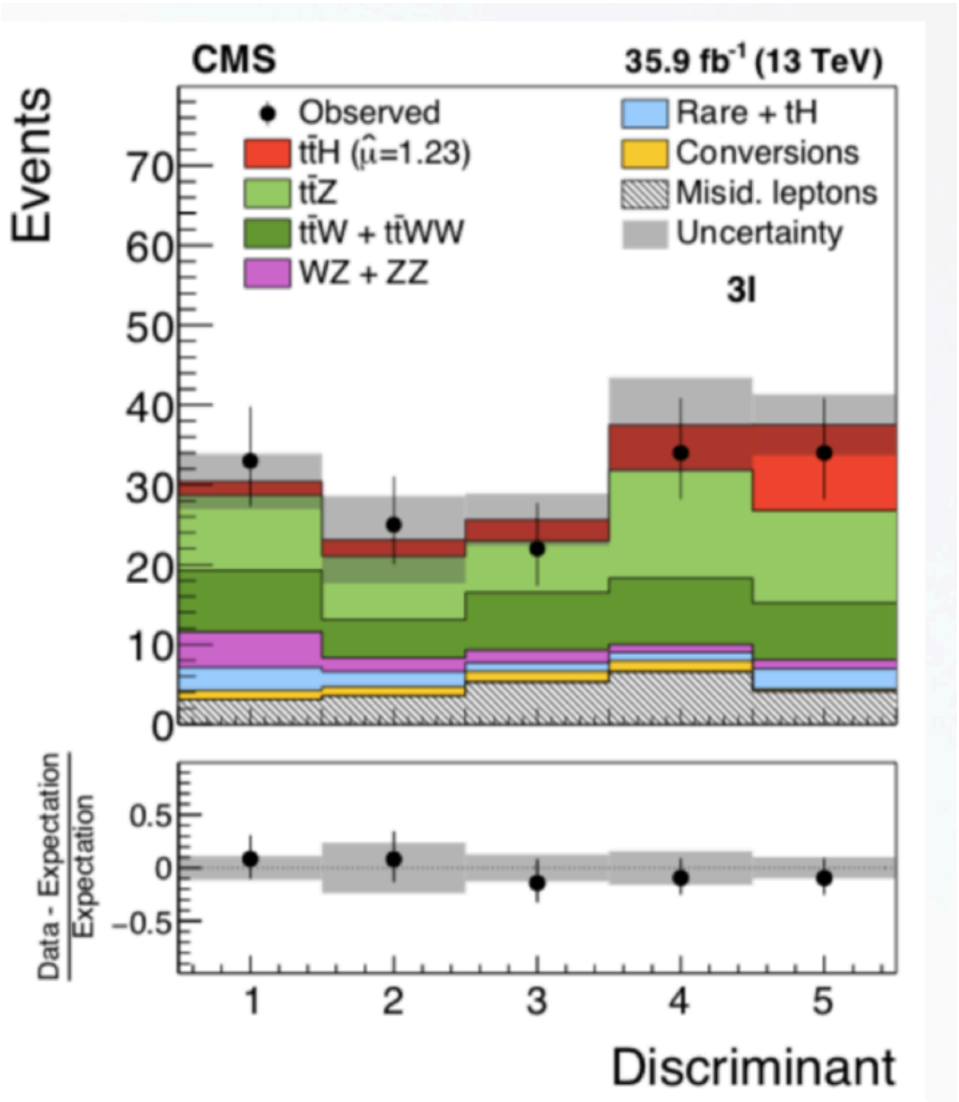




ttH

- Significant use of multiple event categories and multi-variate discriminants:





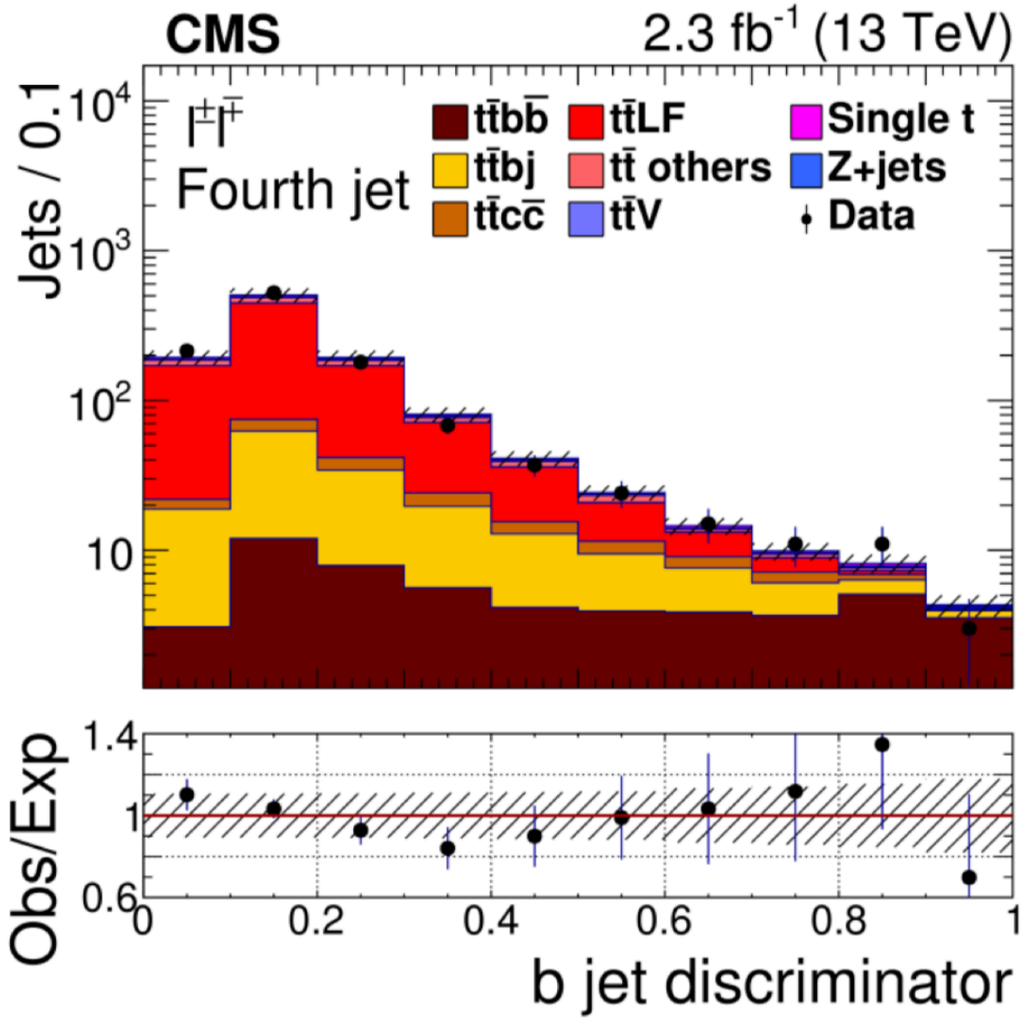
ttH

- Understanding tt+bb background is critical in high-stats bb channel.

Uncertainty source	$\Delta\mu$	
$t\bar{t} + \geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
⋮		
Total systematic uncertainty	+0.57	−0.54

ttH

- Understanding tt+bb background is critical in high-stats bb channel.
- tt+bb can be measured:



ttH

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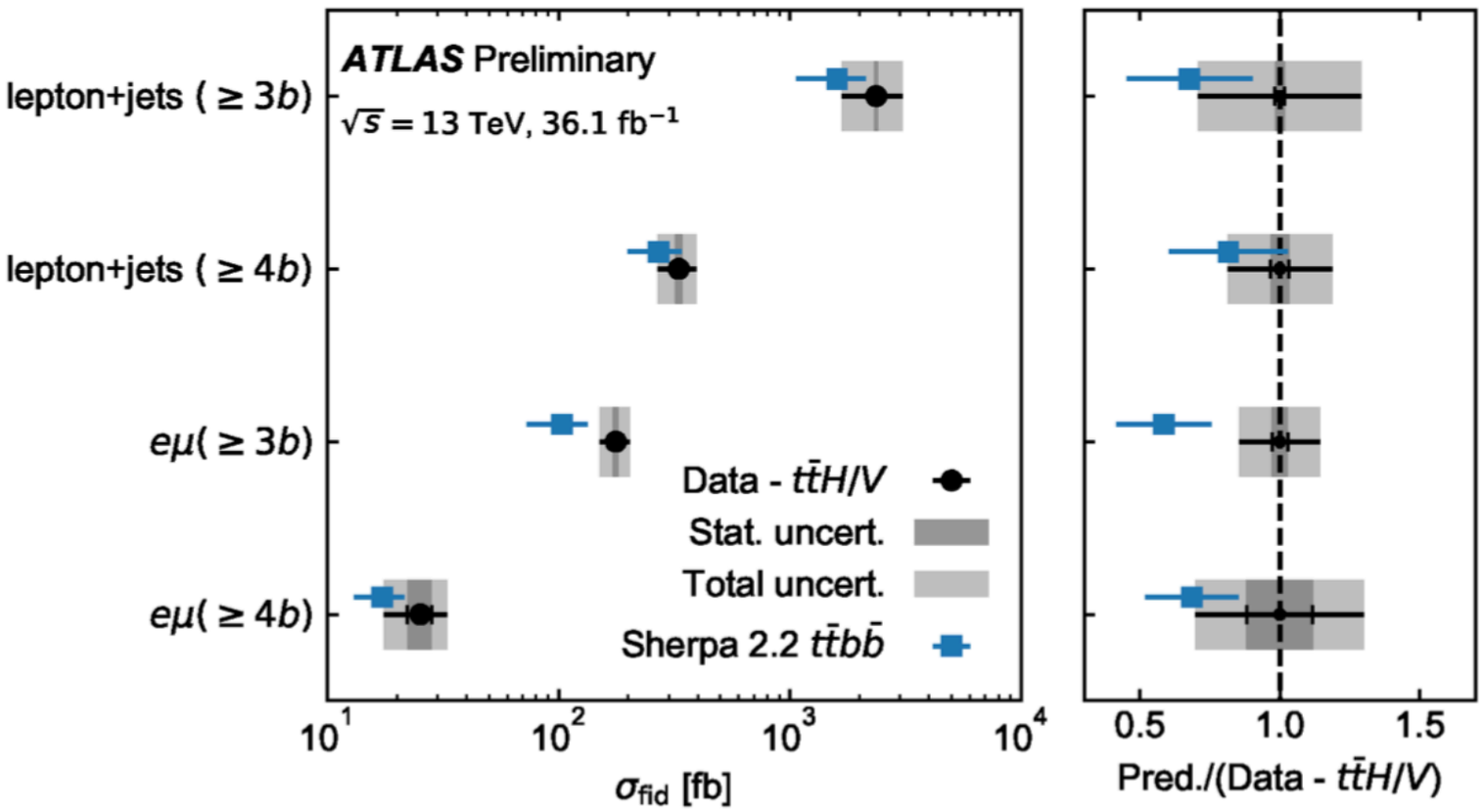
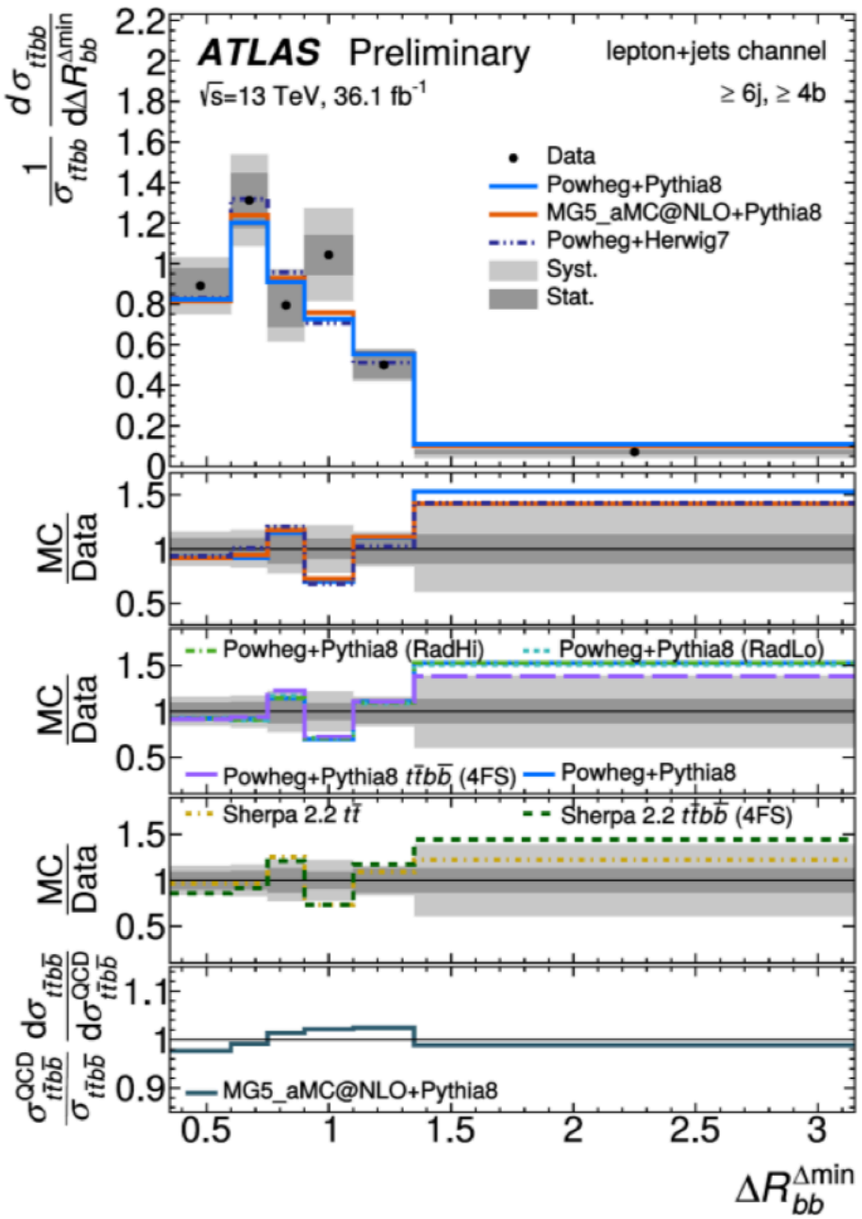
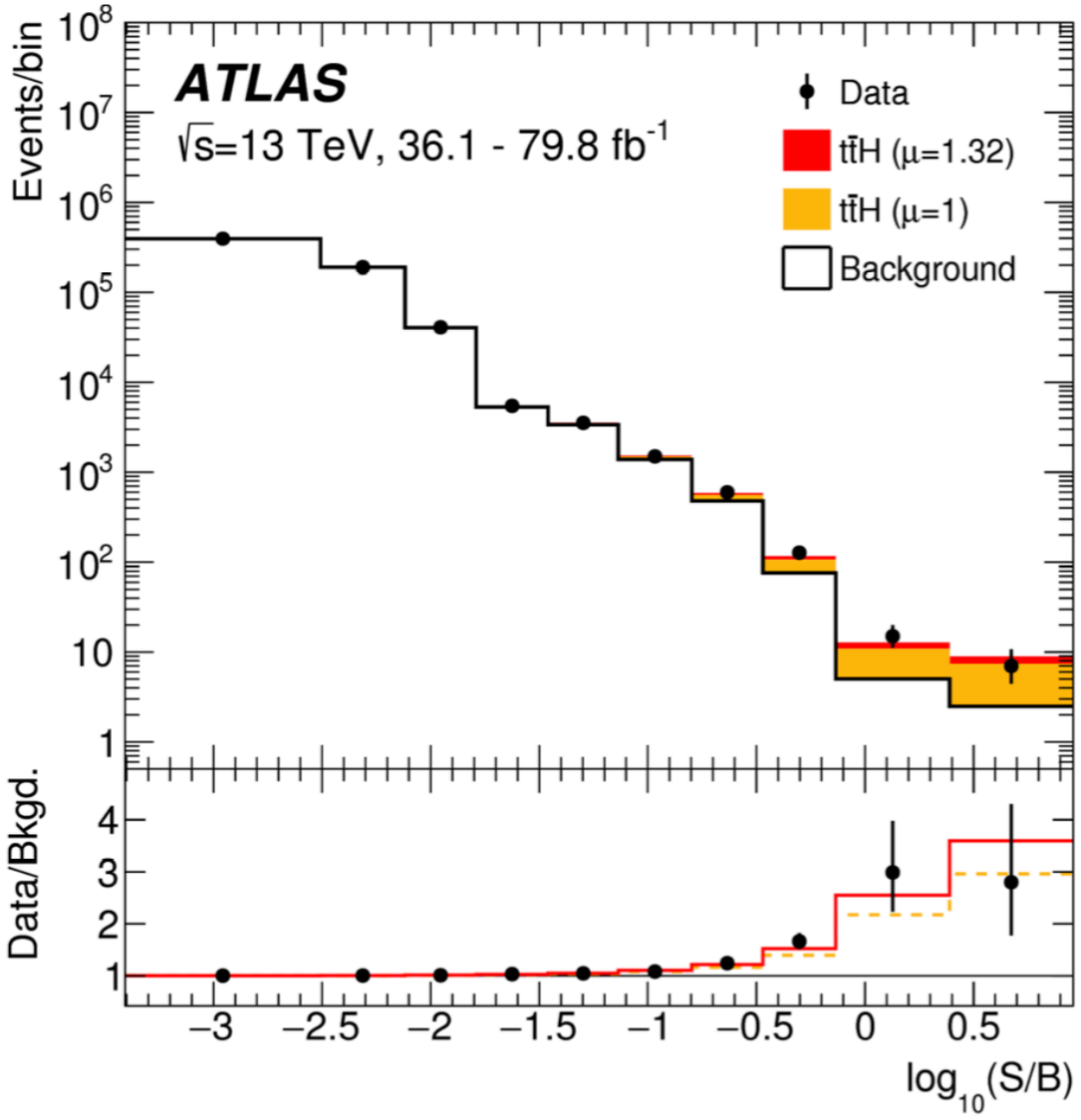
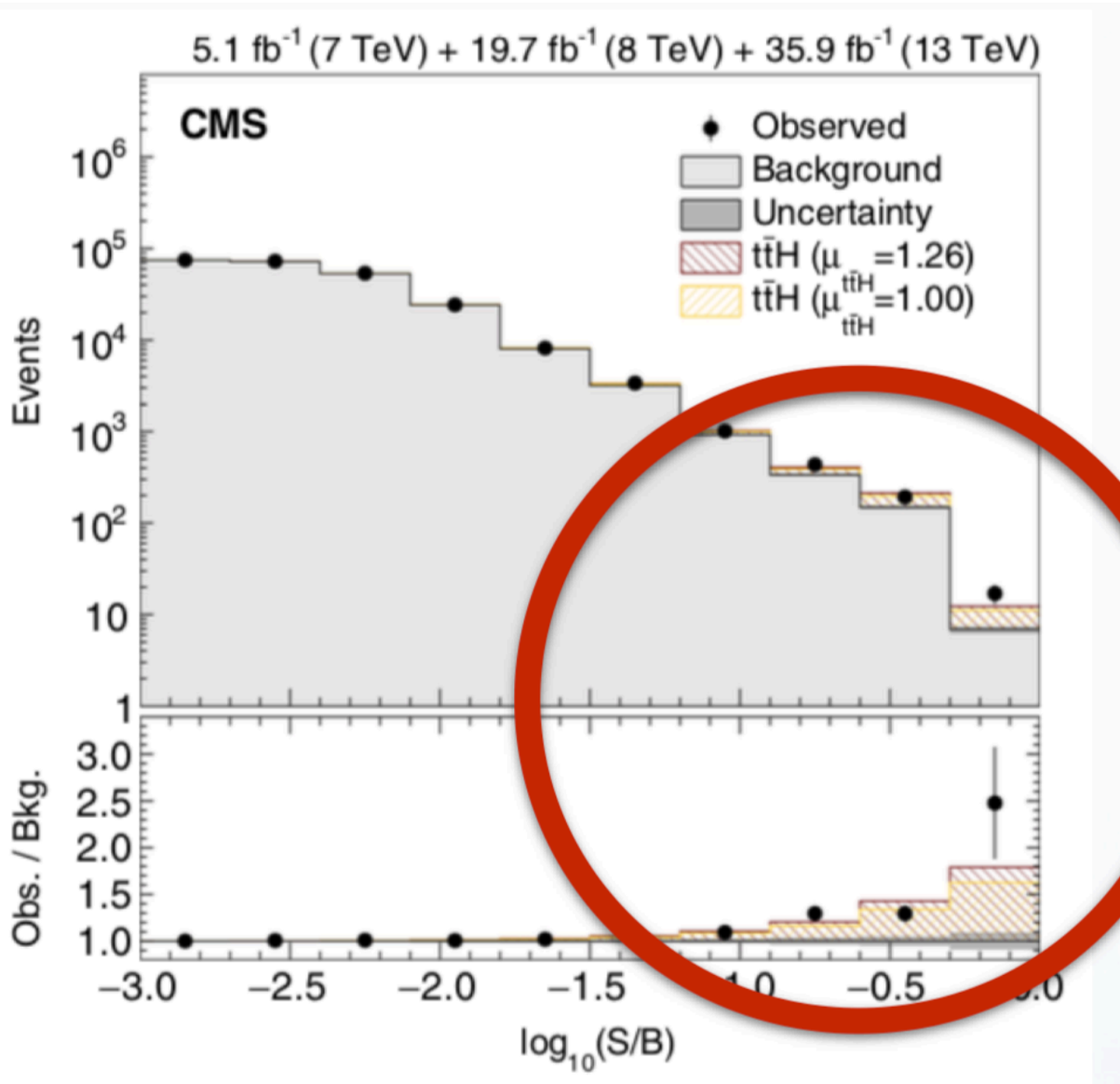




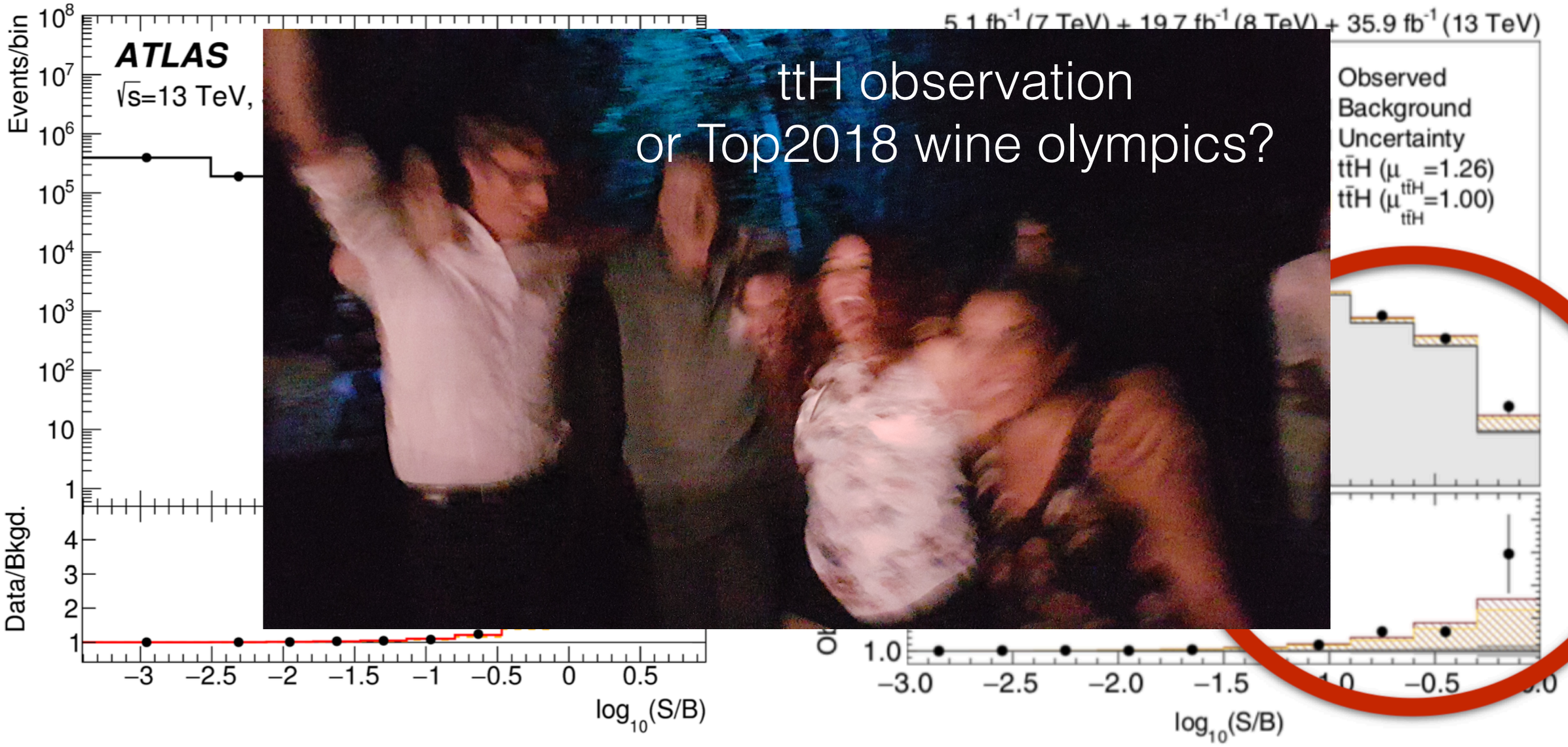
ttH





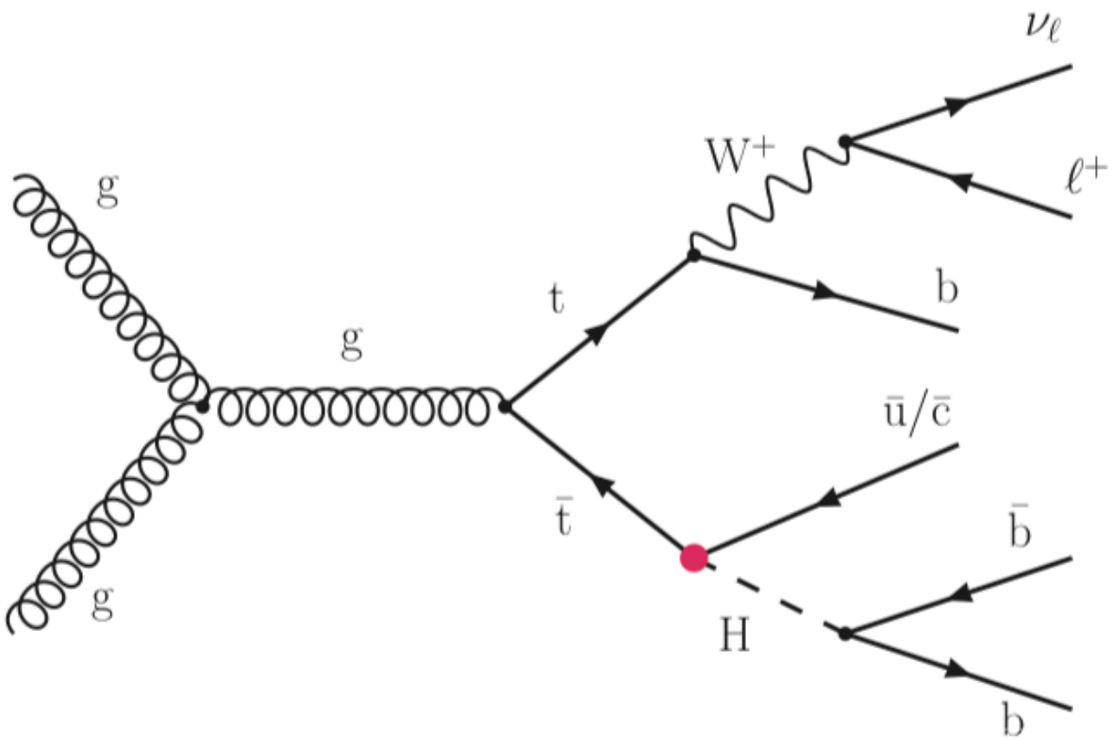
>5σ observation in both experiments!

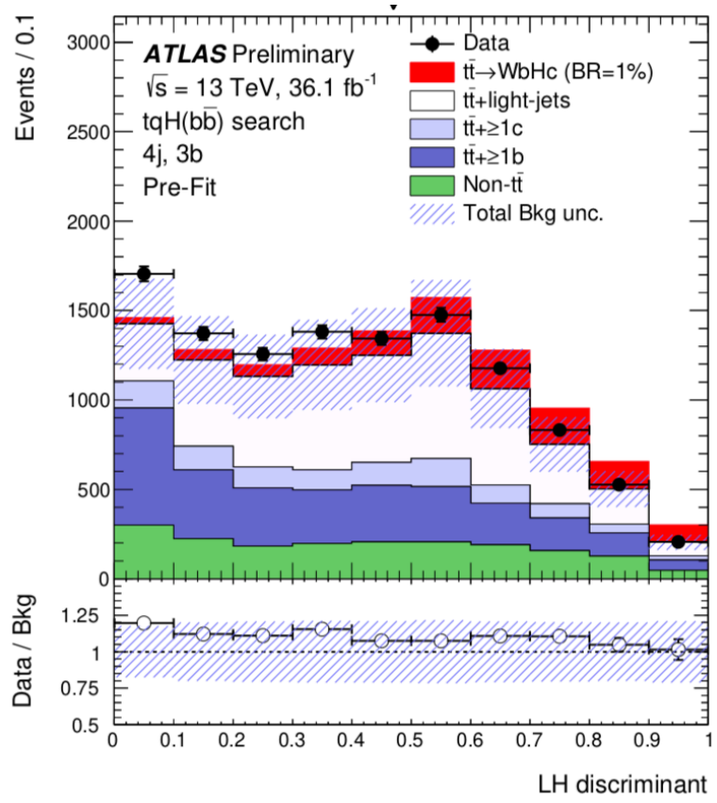
ttH

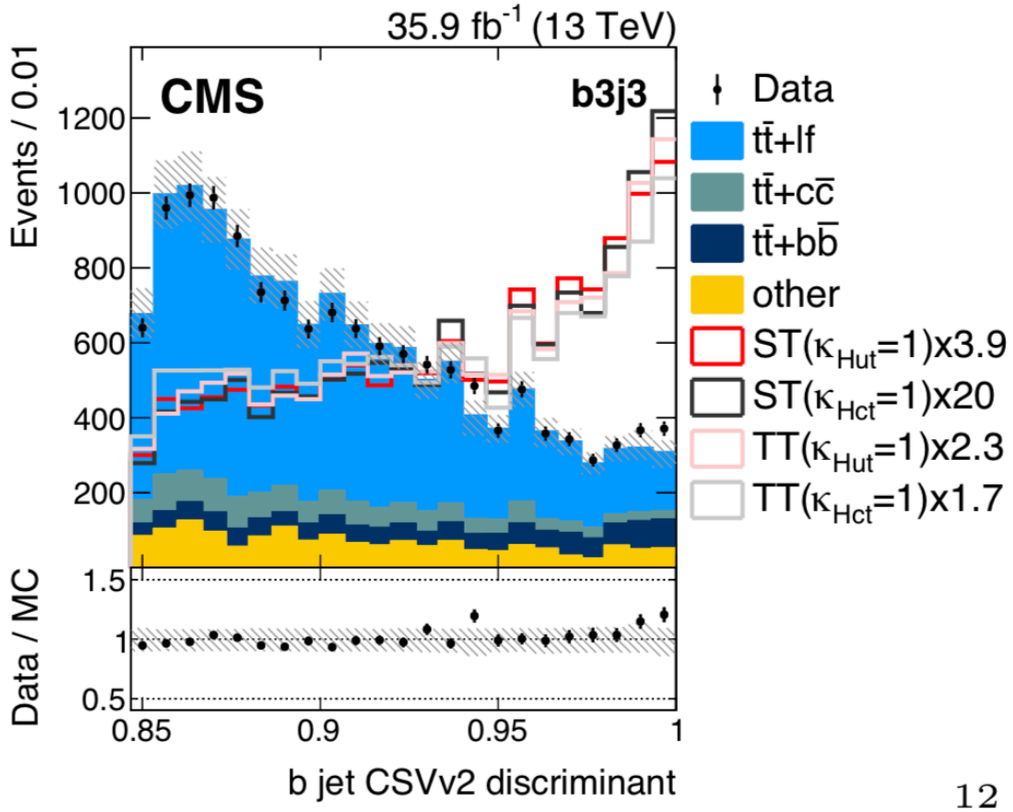


>5σ observation in both experiments!

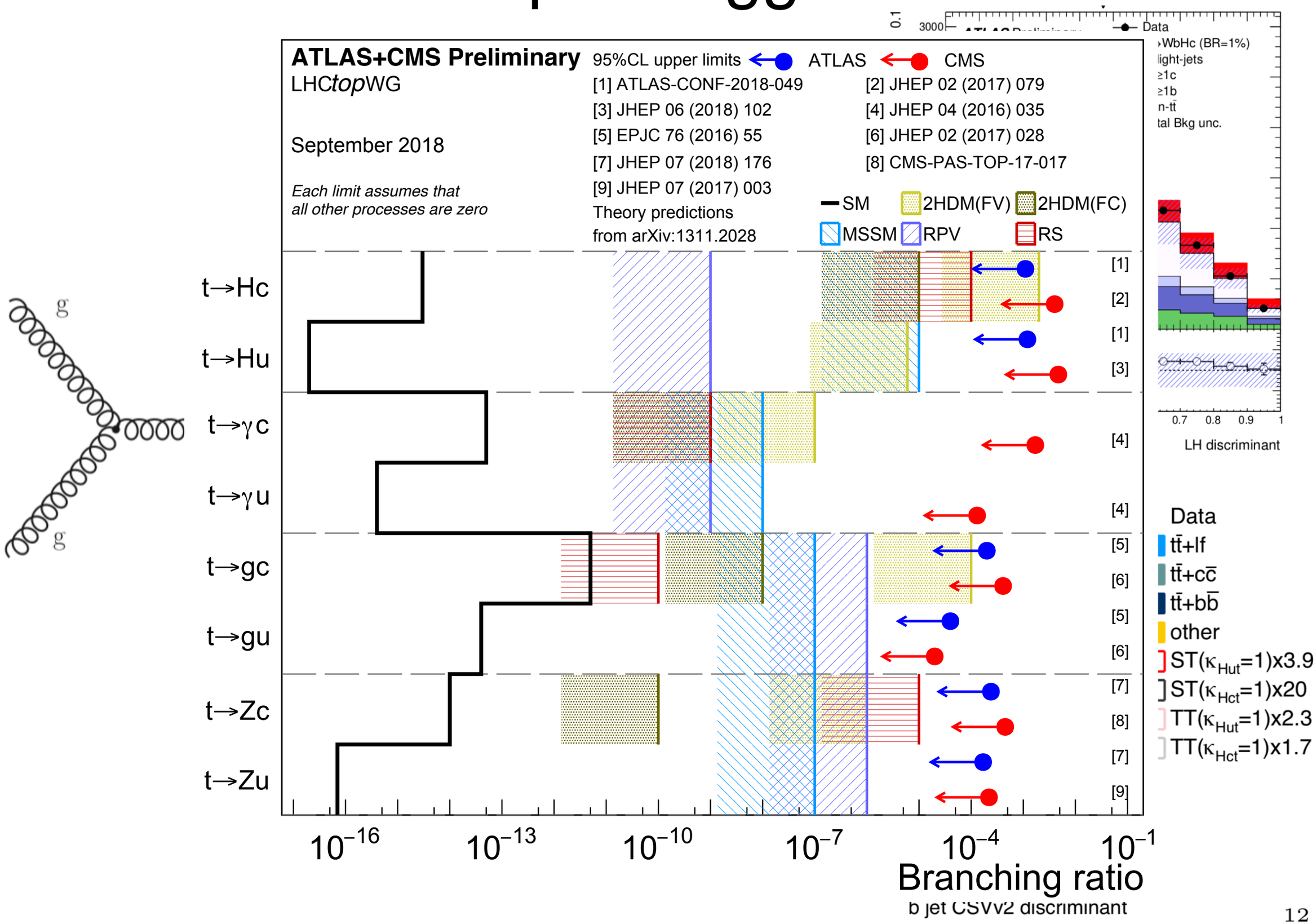
top to Higgs?


g
g
g
t
W+
ν_ℓ
ℓ^+
b
$\bar{u}/\bar{c}$
$\bar{t}$
H
$\bar{b}$
b

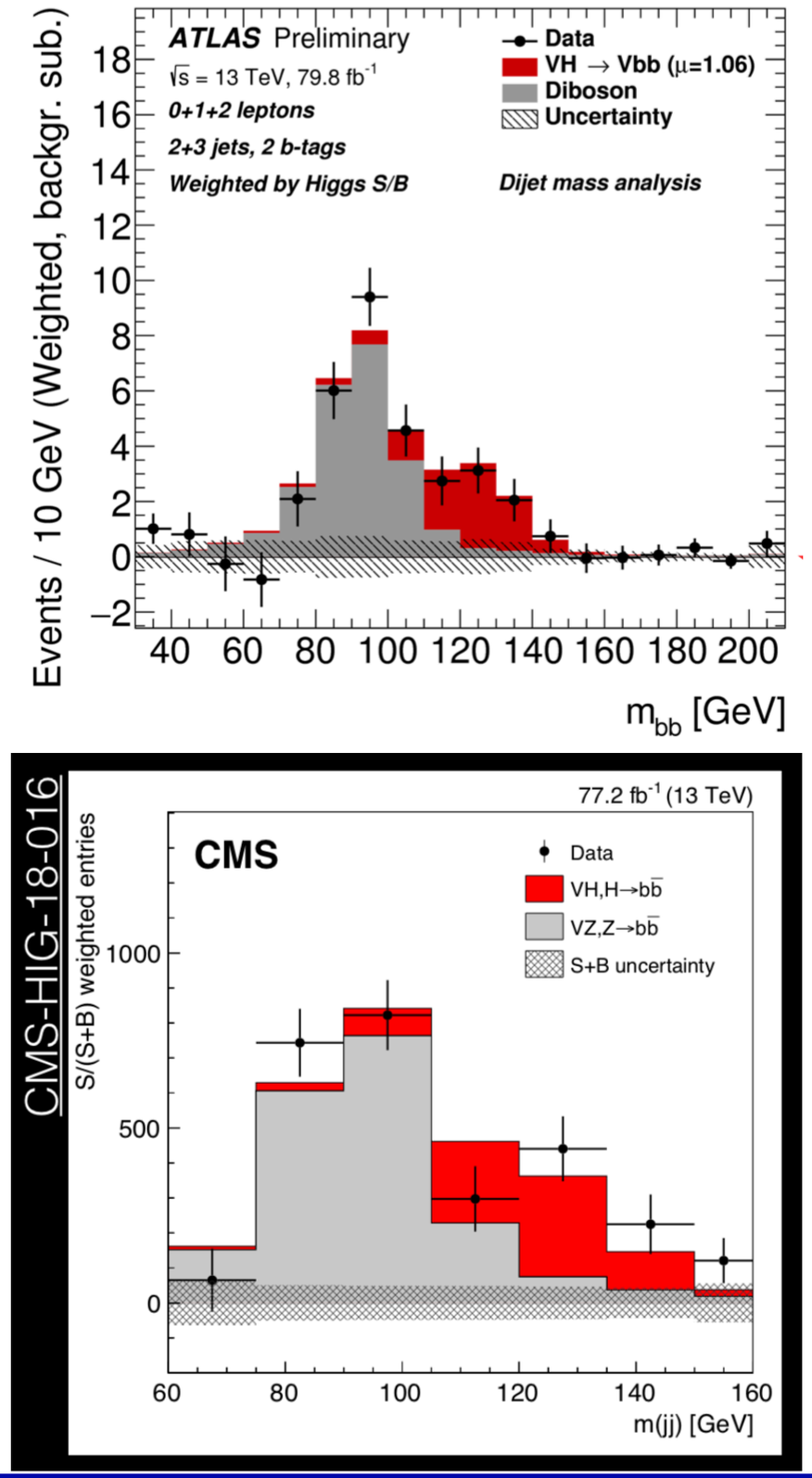

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
tqH(b$\bar{b}$) search
4j, 3b
Pre-Fit
Data
t$\bar{t}$→WbHc (BR=1%)
t$\bar{t}$+light-jets
t$\bar{t}$+≥1c
t$\bar{t}$+≥1b
Non-t$\bar{t}$
Total Bkg unc.
Events / 0.1
Data / Bkg
LH discriminant


35.9 fb^{-1} (13 TeV)
CMS
b3j3
Data
t$\bar{t}$+lf
t$\bar{t}$+c$\bar{c}$
t$\bar{t}$+b$\bar{b}$
other
ST(κ_{Hut}=1)x3.9
ST(κ_{Hct}=1)x20
TT(κ_{Hut}=1)x2.3
TT(κ_{Hct}=1)x1.7
Events / 0.01
Data / MC
b jet CSVv2 discriminant

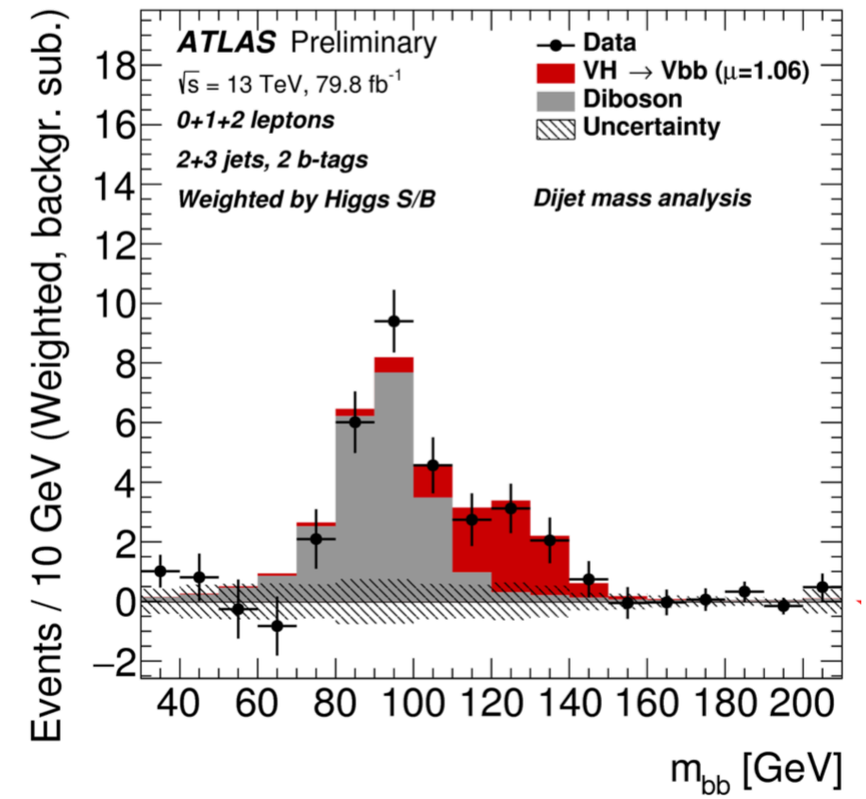
top to Higgs?

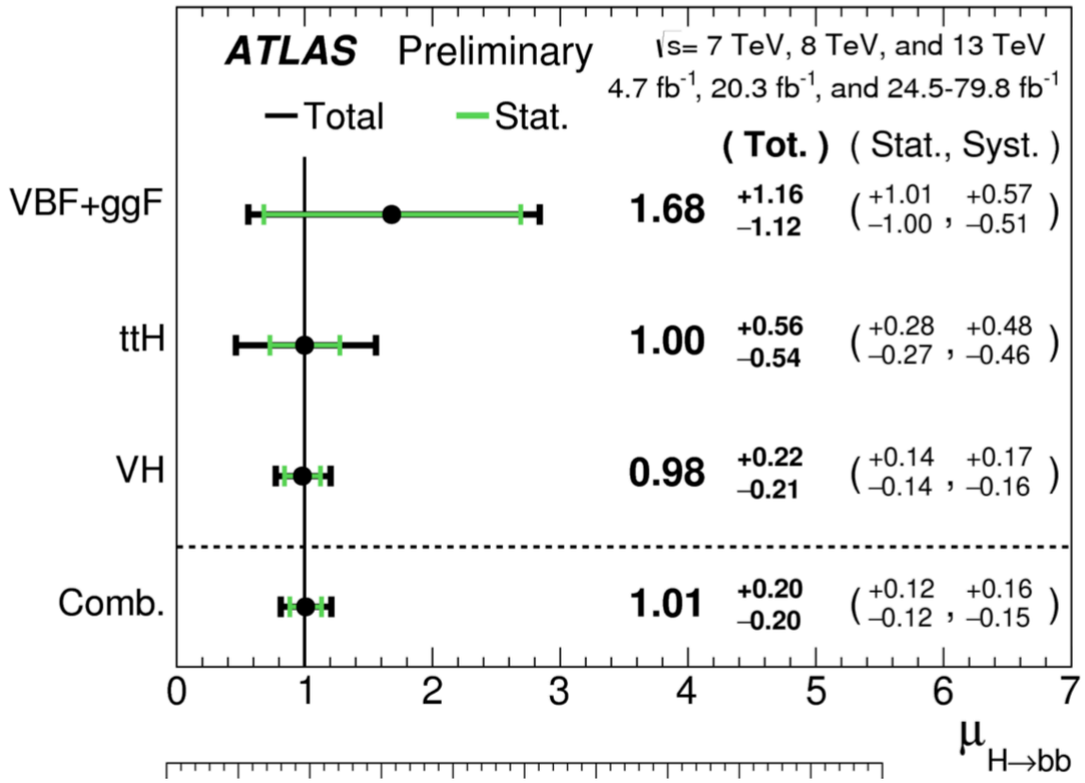

ATLAS+CMS Preliminary
LHCtopWG
September 2018
Each limit assumes that all other processes are zero
95%CL upper limits
ATLAS
CMS
[1] ATLAS-CONF-2018-049
[2] JHEP 02 (2017) 079
[3] JHEP 06 (2018) 102
[4] JHEP 04 (2016) 035
[5] EPJC 76 (2016) 55
[6] JHEP 02 (2017) 028
[7] JHEP 07 (2018) 176
[8] CMS-PAS-TOP-17-017
[9] JHEP 07 (2017) 003
Theory predictions from arXiv:1311.2028
SM
2HDM(FV)
2HDM(FC)
MSSM
RPV
RS
t→Hc
t→Hu
t→γc
t→γu
t→gc
t→gu
t→Zc
t→Zu
g
g
[1]
[2]
[1]
[3]
[4]
[4]
[5]
[6]
[5]
[6]
[7]
[8]
[7]
[9]
10^{-16}
10^{-13}
10^{-10}
10^{-7}
10^{-4}
10^{-1}
Branching ratio
b jet CSVv2 discriminant
Data
$t\bar{t}$+lf
$t\bar{t}$+c$\bar{c}$
$t\bar{t}$+b$\bar{b}$
other
ST(κ_{Hut}=1)x3.9
ST(κ_{Hct}=1)x20
TT(κ_{Hut}=1)x2.3
TT(κ_{Hct}=1)x1.7
Data
›WbHc (BR=1%)
light-jets
≥1c
≥1b
n-$t\bar{t}$
tal Bkg unc.
0.7
0.8
0.9
1
LH discriminant

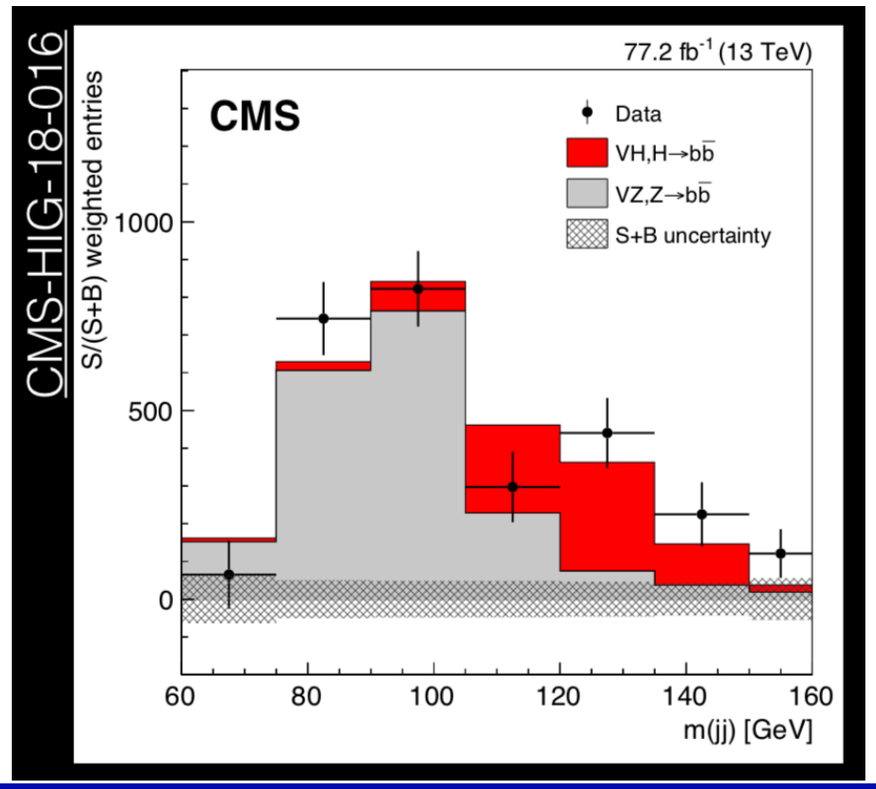
Higgs using top

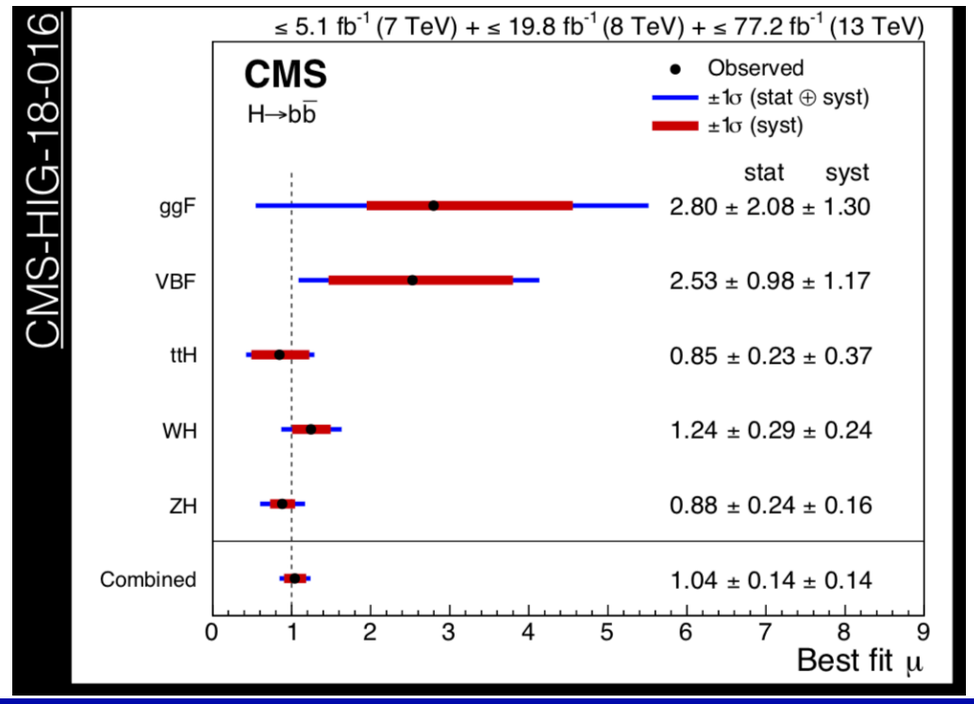


Higgs using top



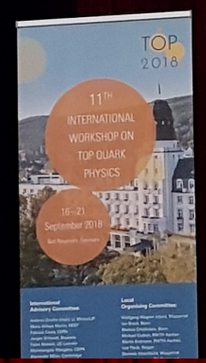






Future


event variables at 13 TeV at CMS
BRISTOL


TOP 2018
11TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS
16–21 September 2018


TOP 2018
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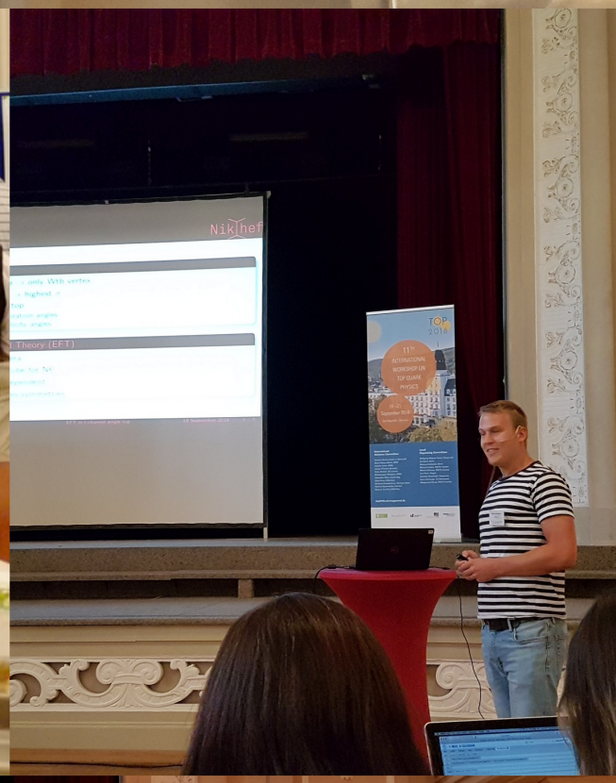
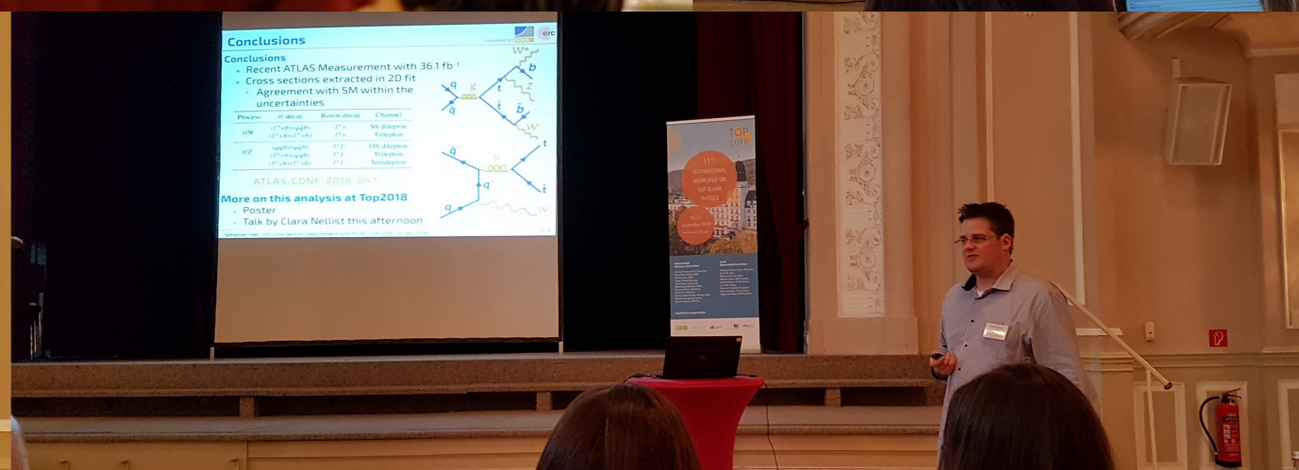
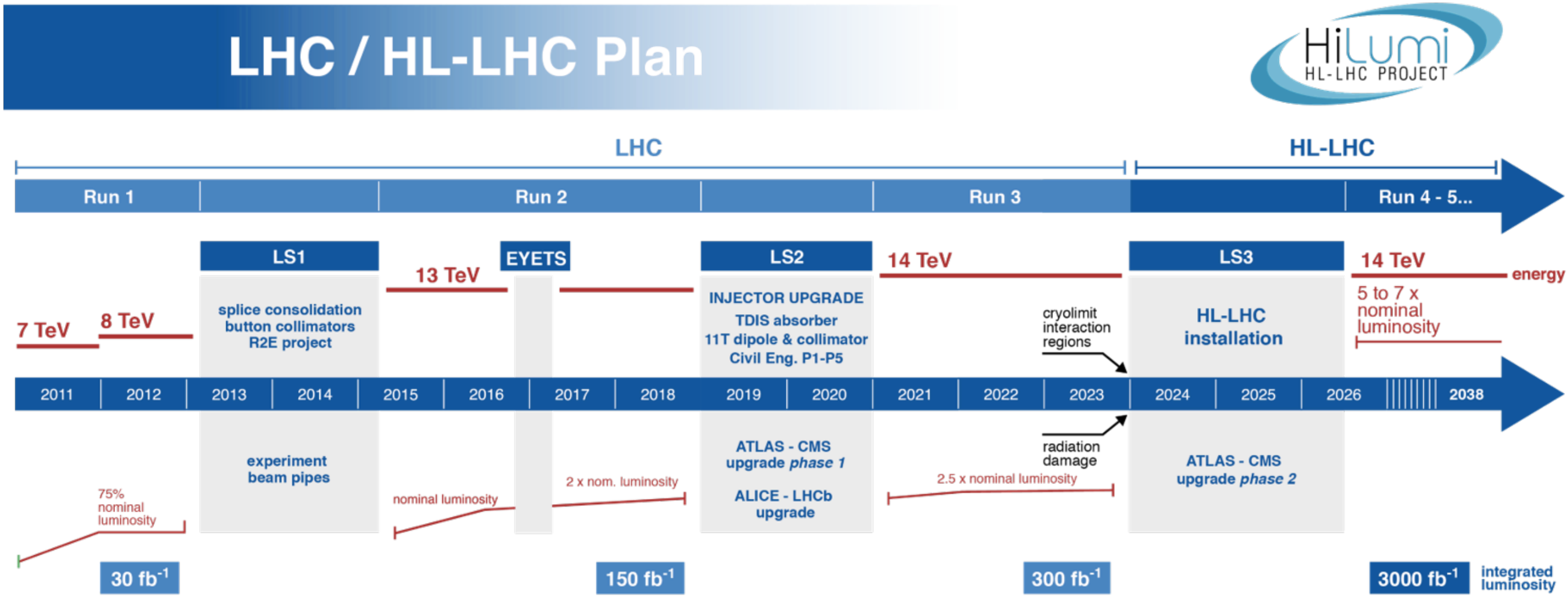
16–21 September 2018

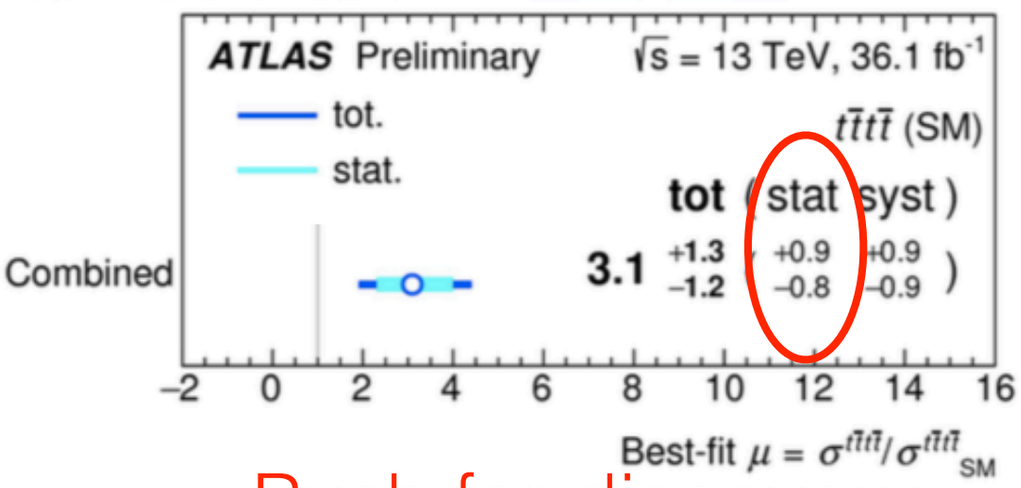

Nikhef
TOP 2018
11TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS

TOP 2018
11TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS
16–21 September 2018


Conclusions
Conclusions
Recent ATLAS Measurement with 36.1 fb-1
Cross sections extracted in 2D fit
Agreement with SM within the uncertainties
Process
tt decays
Boson decays
Channel
ATLAS-CONF-2018-047
More on this analysis at Top2018
Poster
Talk by Clara Nellist this afternoon
TOP 2018
11TH INTERNATIONAL WORKSHOP ON TOP QUARK PHYSICS

Run 3 / HL-LHC





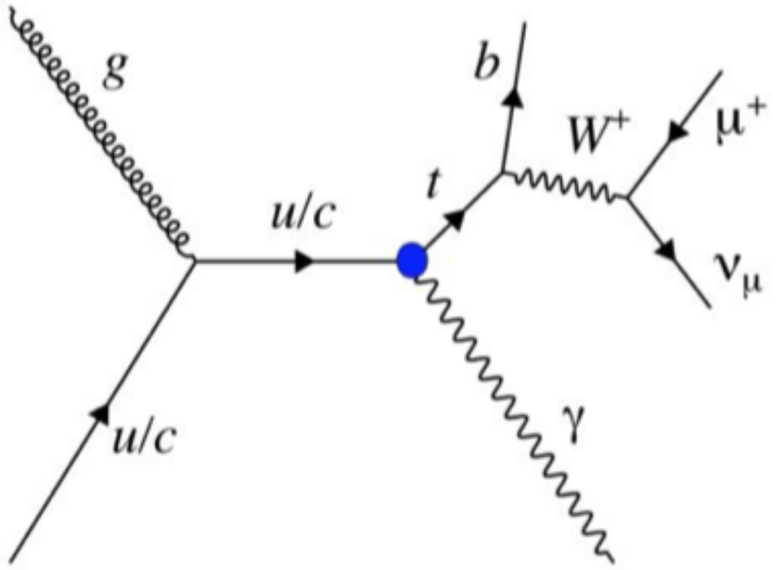
Push for discovery

- Likely even more analyses techniques become available not covered here
- Crucial to adapt analysis techniques to higher statistics

Will need good ideas & hard work!

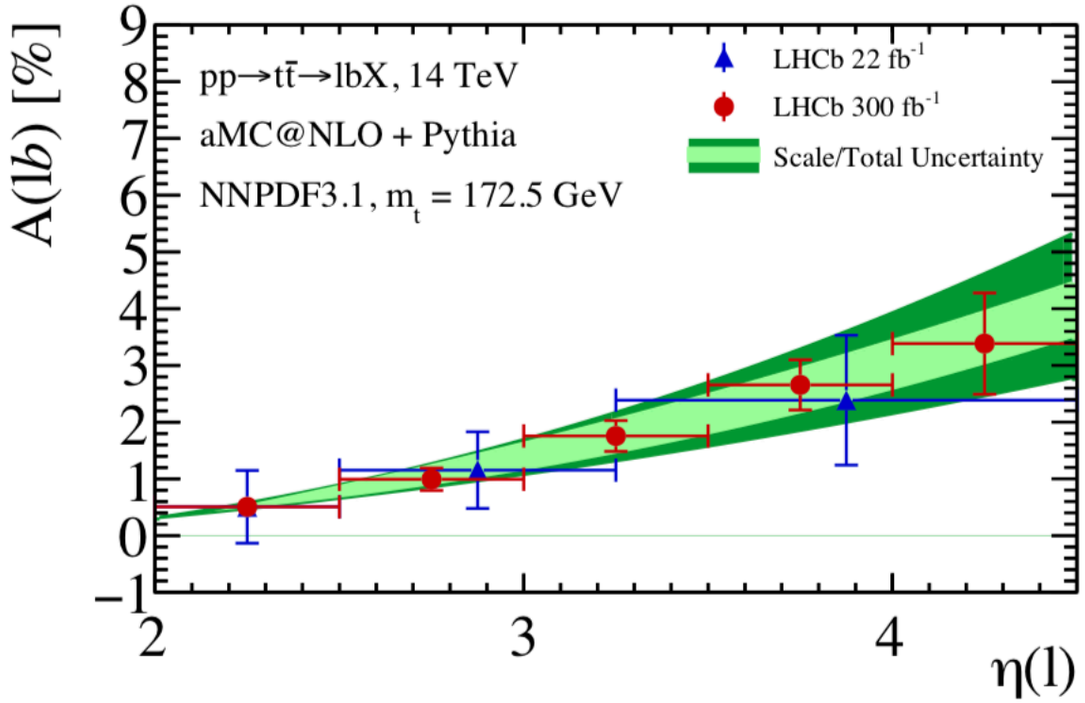
HL-LHC

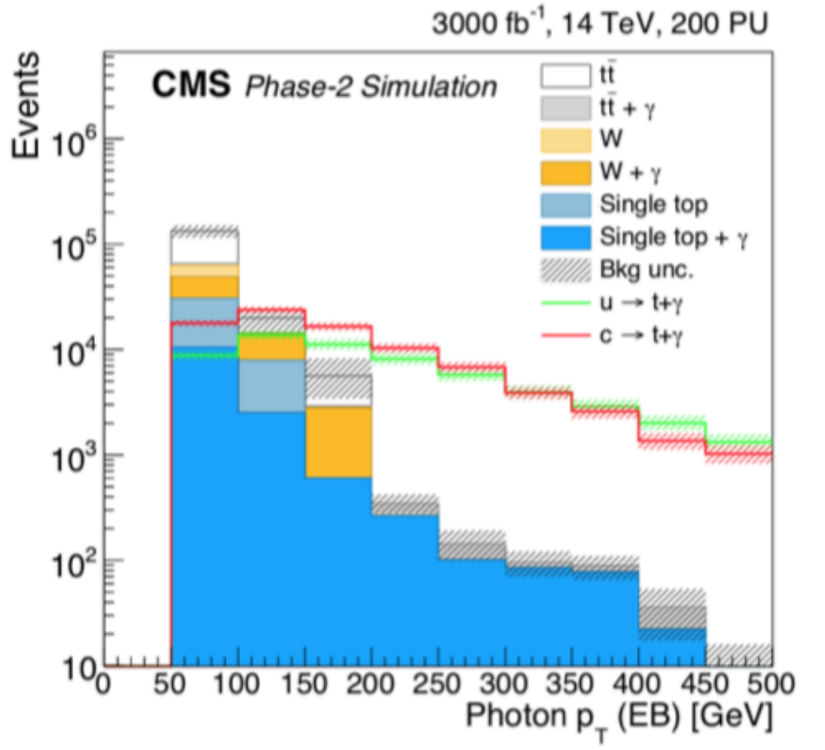
- Yellow report efforts in full swing:



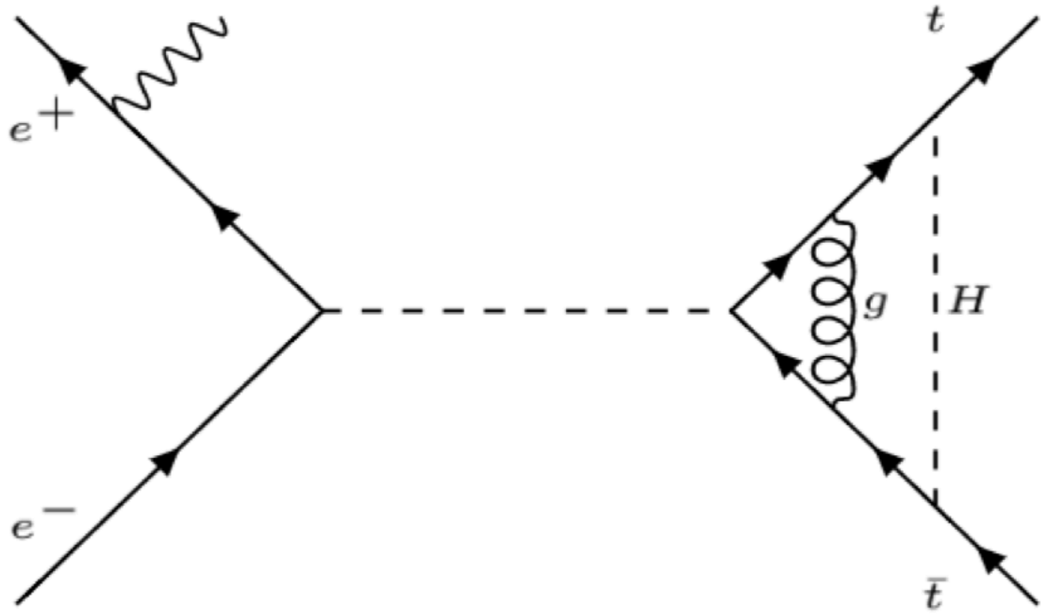
- For 3000 fb^{-1} : 8.6(74) x 10^{-6} u(c)

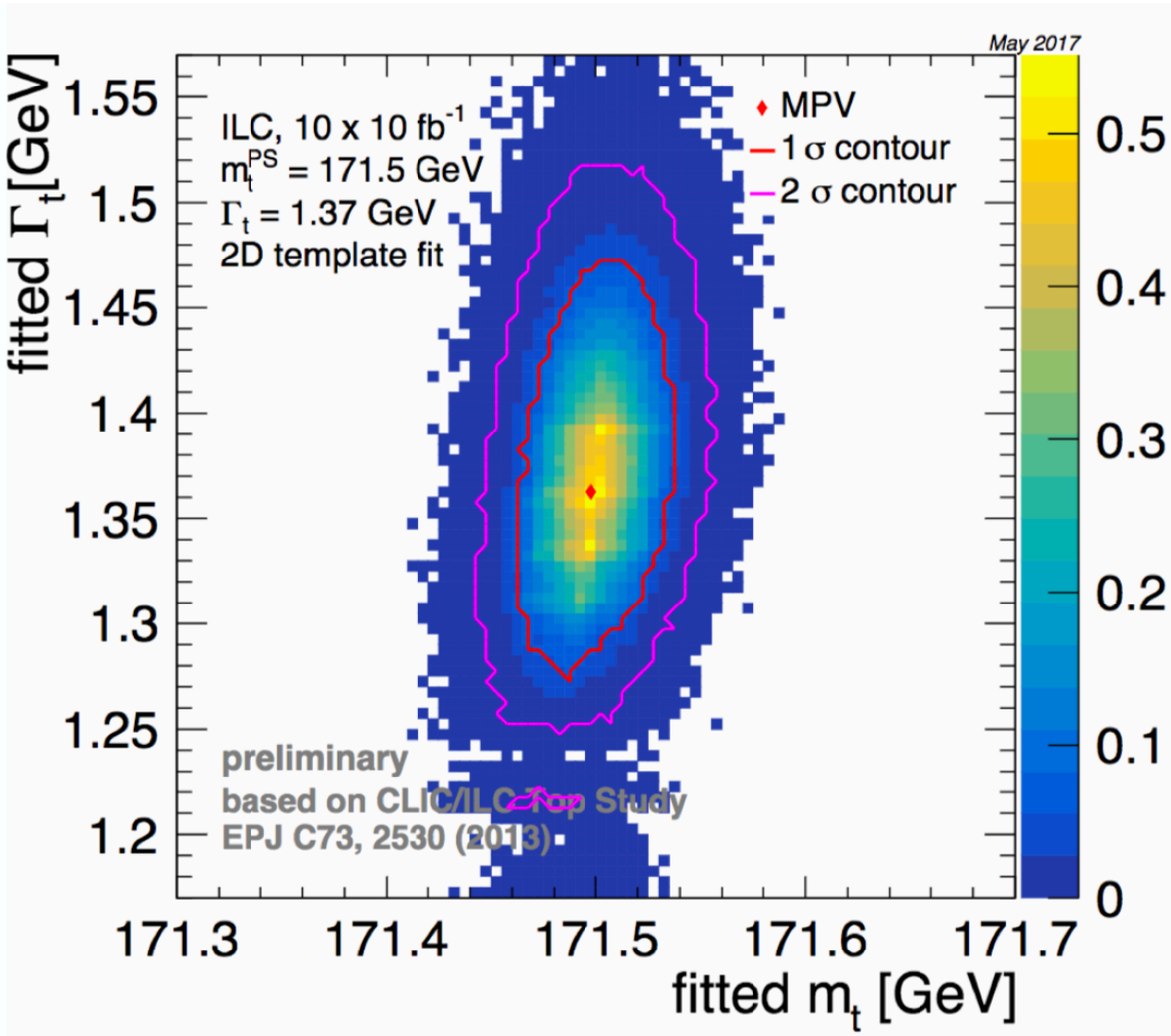
An actually approved plot!





e+ e-



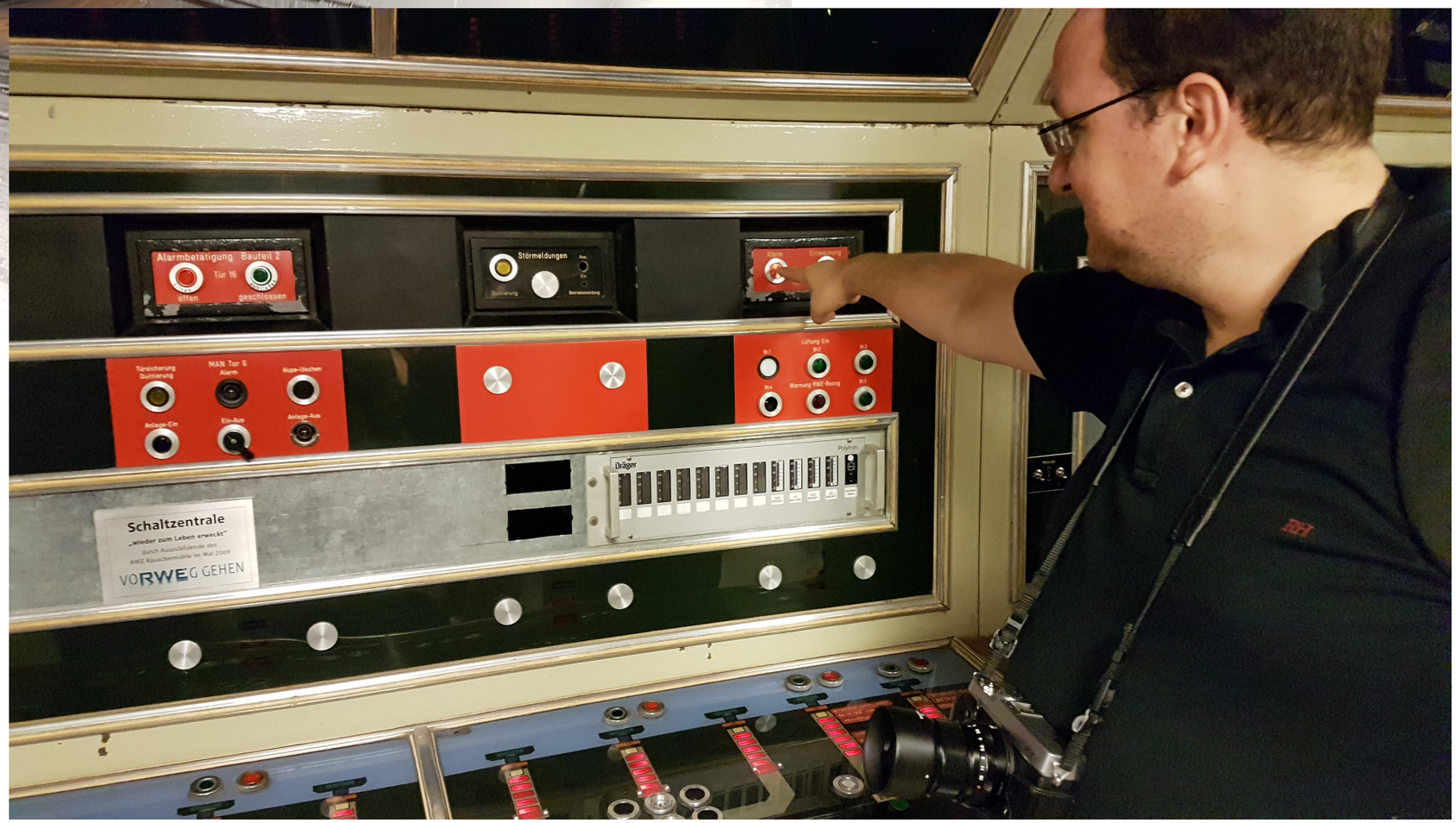


Four potential ee machines – physics input/studies ongoing

- CLIC and FCC-ee have ttbar in their 'standard' programme, for CPEC and ILC it is part of the upgrade planning

Future colliders

Future colliders



Summary

- “Don’t summarise a summary”.
- Thanks to the speakers for the great talks.
  - Thanks for patience to answer (my) questions!
- Thanks to the organisers for a great workshop.