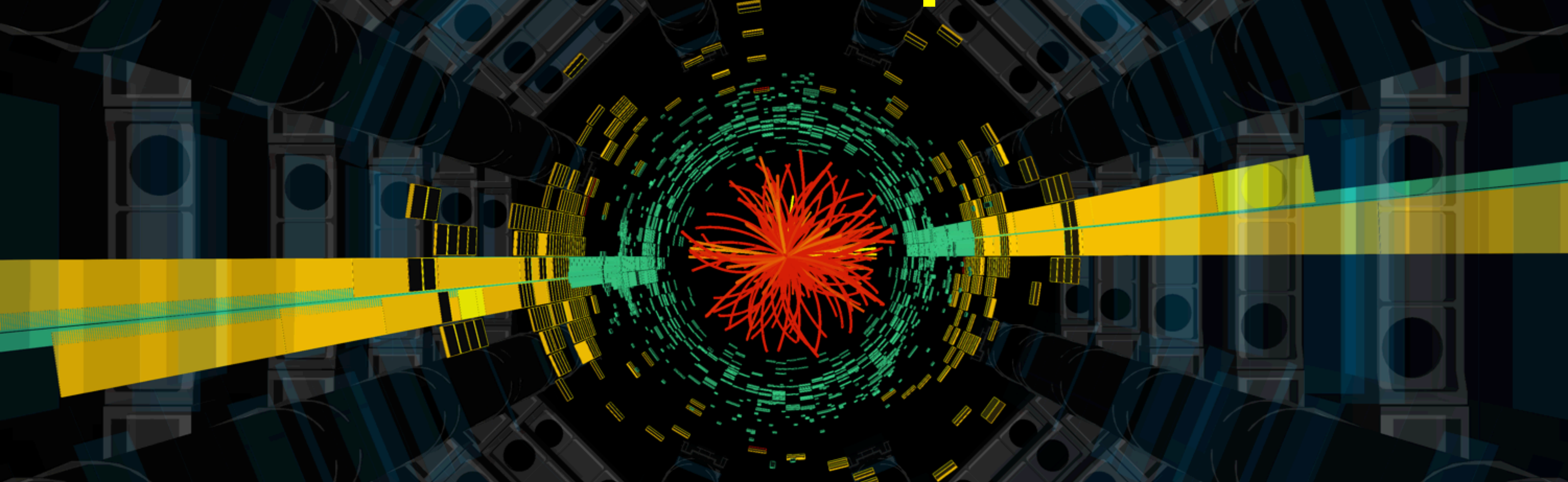
What we have learned so far from the LHC experiments

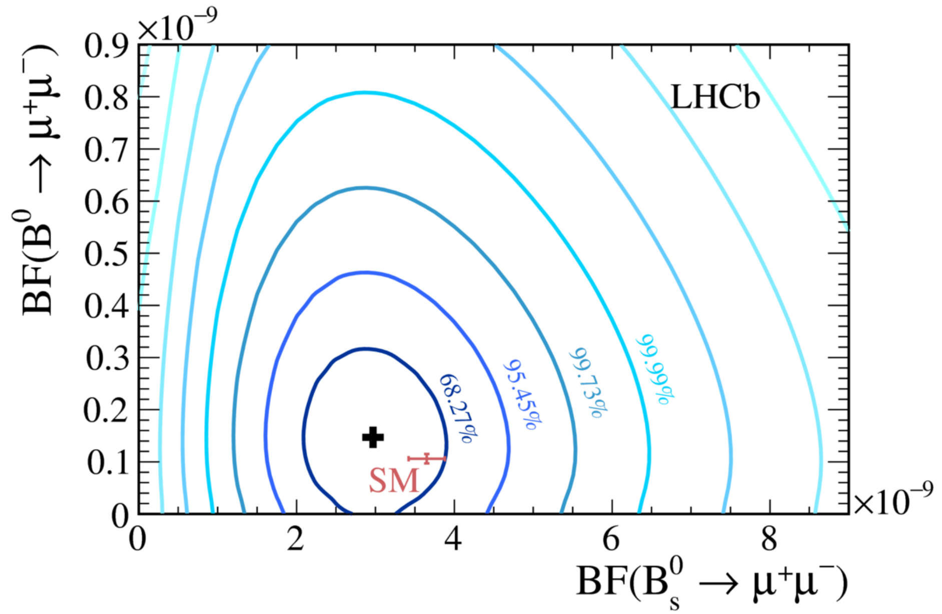


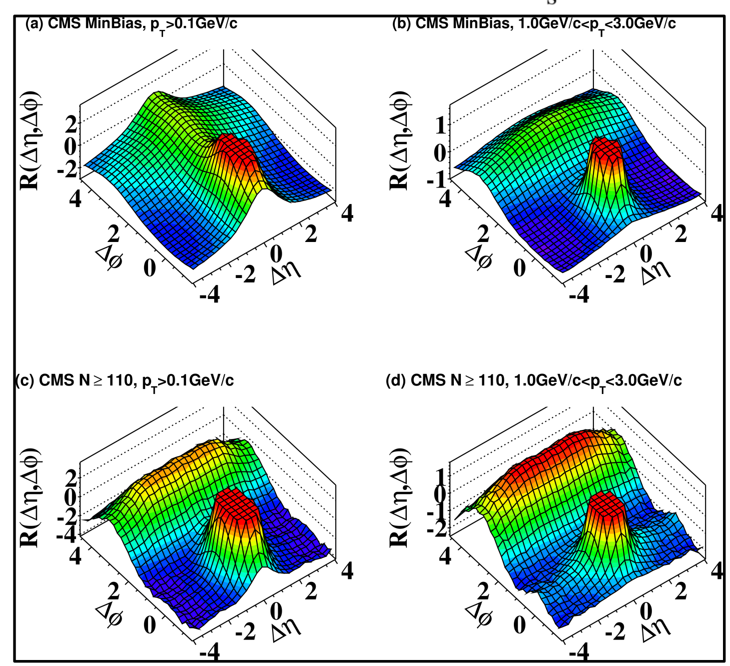
Dan Tovey (University of Sheffield),

Pushing the Boundaries of the Energy and Intensity Frontiers, IPPP Durham, 2-4 July 2018

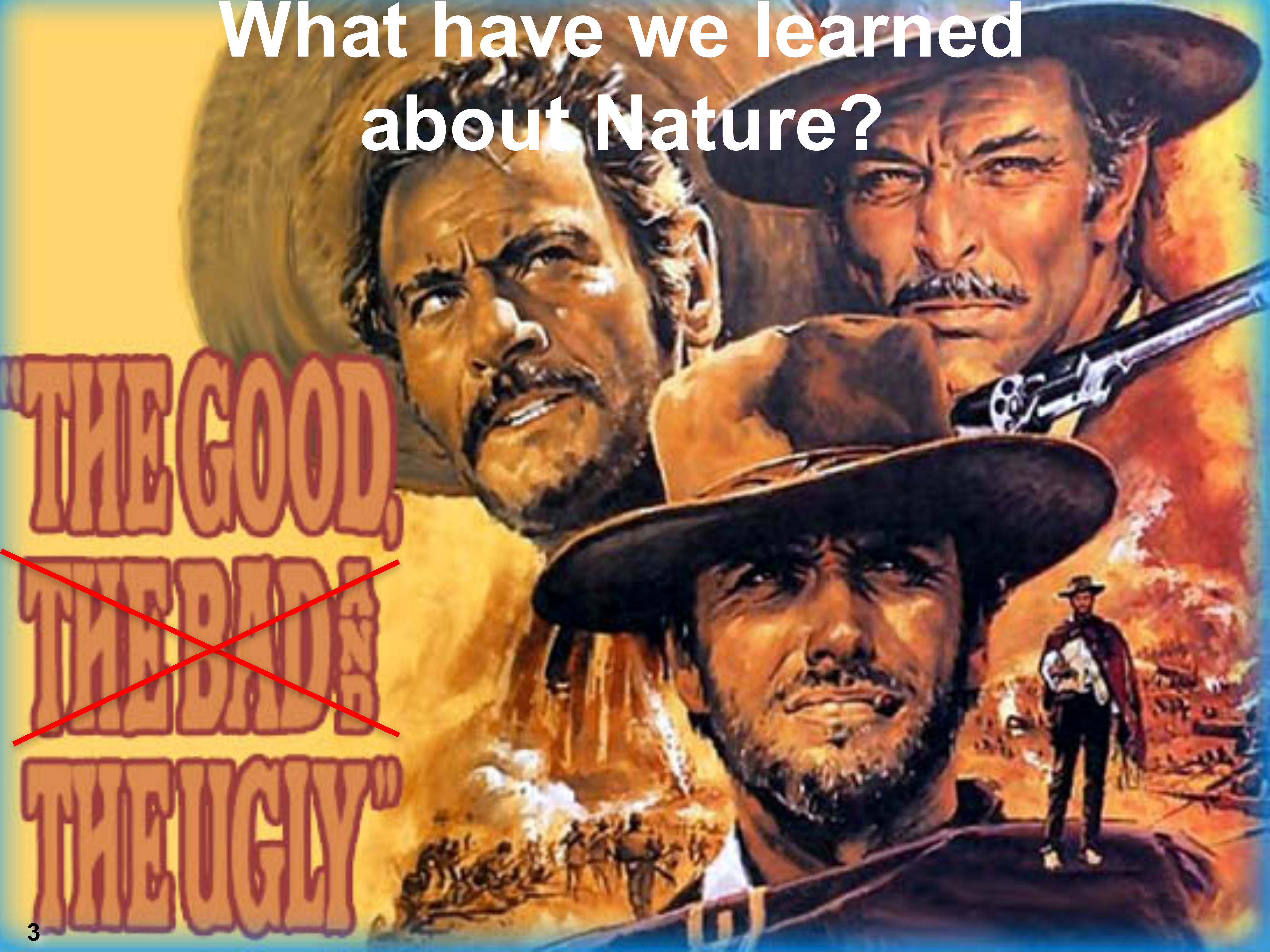
Introduction and Disclaimer

- Outline of this talk:
  - What have we learned about Nature from the high-p_T physics programme?
  - What have we learned about *our ability to learn* about Nature?
  - What lessons can we learn for the future?
- A few personal perspectives – not an exhaustive overview of the field
- Focus on high-p_T results from GPDs
  - LHCb / flavour physics tomorrow.
  - Will not cover highlights such as observation of $B_s \rightarrow \mu\mu$, measurement of γ to 8%, or measurements of ϕ_s and $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\phi$.
  - Will also not cover very highly cited LHC results in soft QCD / HI physics, e.g. collectivity in small (pp) systems ('the ridge')





What have we learned about Nature?

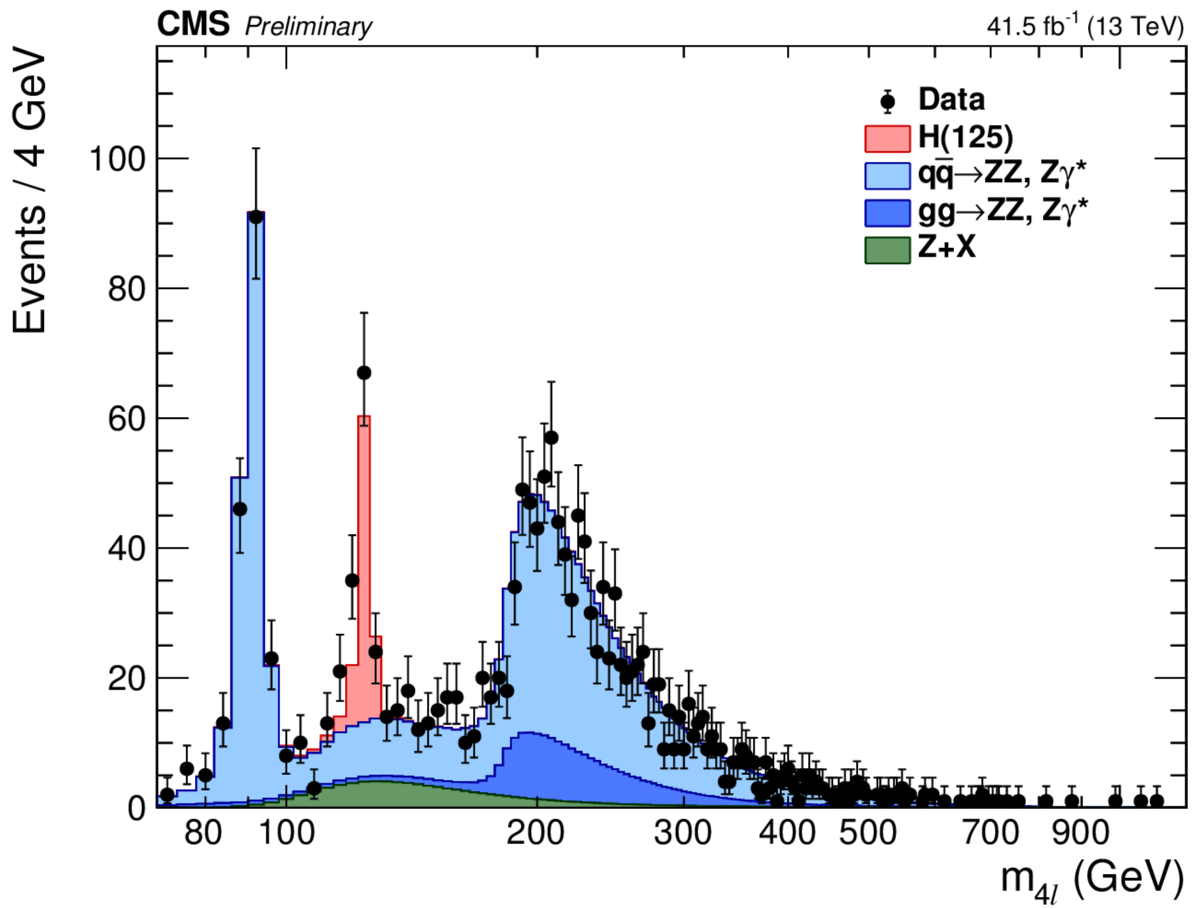


What have we learned about Nature?

- First footsteps on a new continent – electroweak symmetry breaking, the Higgs mechanism and the masses of fundamental bosons and fermions
- Standard Model measurements at new frontiers of energy and precision
- First observation or evidence of new associated production processes for Standard Model states (e.g. Wt, ttZ, tZq etc.)
- New measurements of the mass of the top quark with improved precision
- First steps towards improved measurements of the W mass
- Where new physics is not to be found, excluding specific BSM models and generic BSM signatures to greatly increased scales and/or reduced cross-sections or branching ratios

The Higgs Boson

- What have we learned?
  - Existence
  - Mass to 0.2%
  - Spin-parity
  - Couplings to SM gauge bosons and (all 3rd generation) fermions
  - Production: total and fiducial cross-sections
  - Production: Differential cross-sections



No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_H uncertainty change	+8.1%	+11%	+21%
Observed m_H (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4\ell})$
Expected m_H uncertainty change		+3.2%	+11%
Observed m_H (GeV)	125.26±0.21	125.30±0.21	125.34±0.23

- HL-LHC will sharpen these measurements considerably

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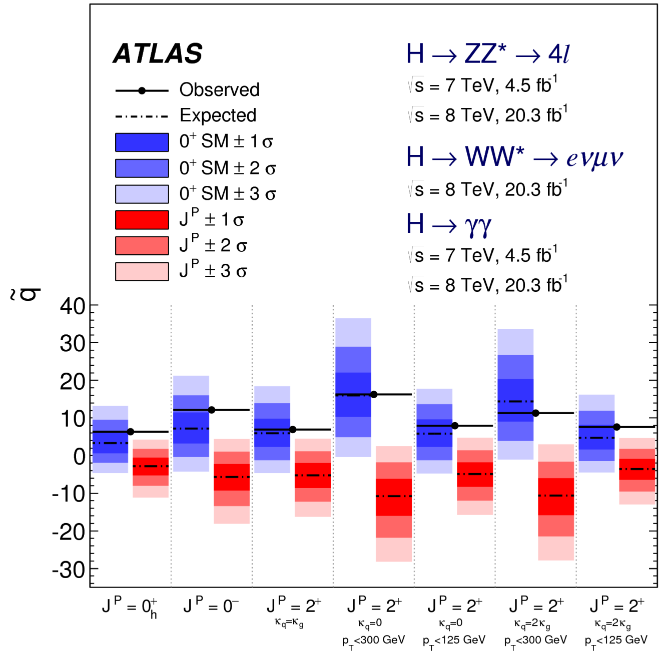

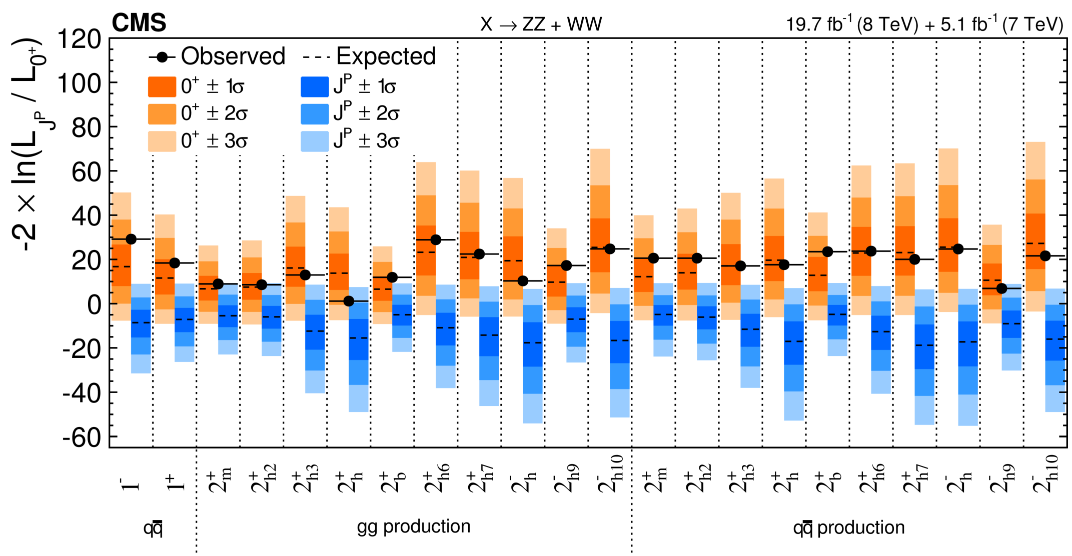

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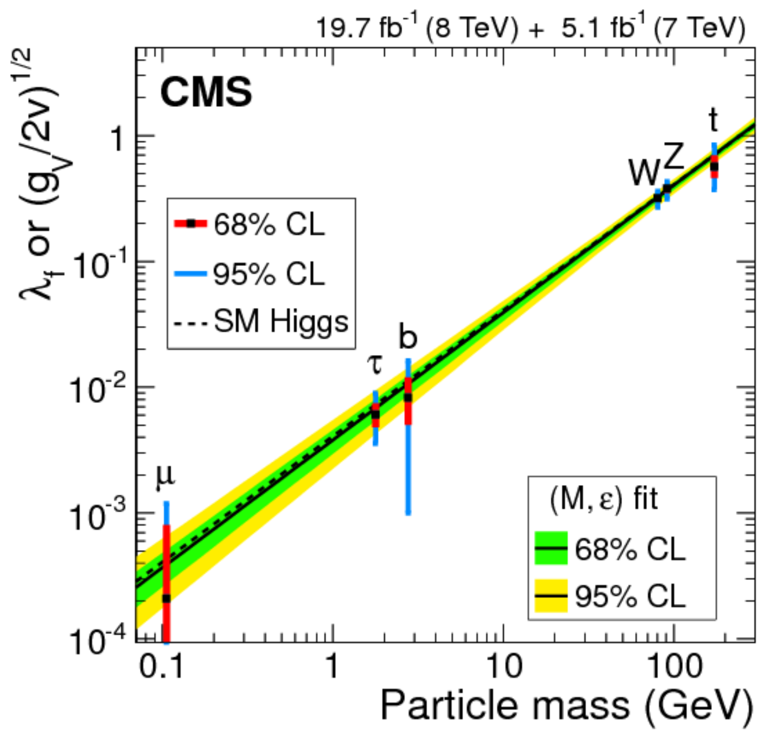

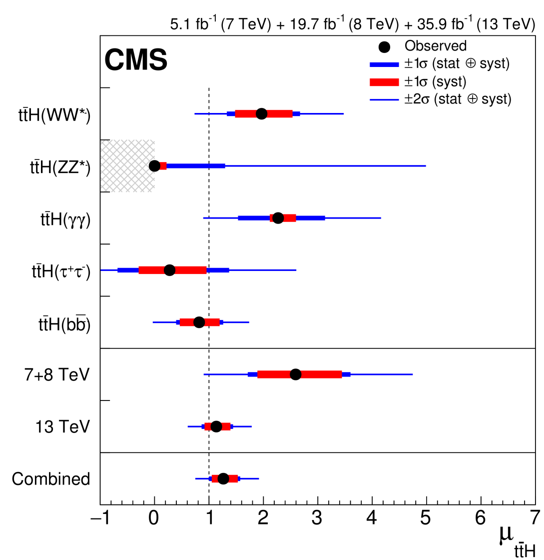

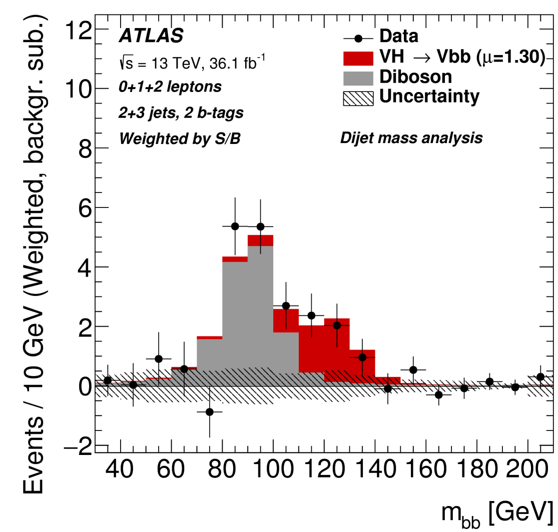

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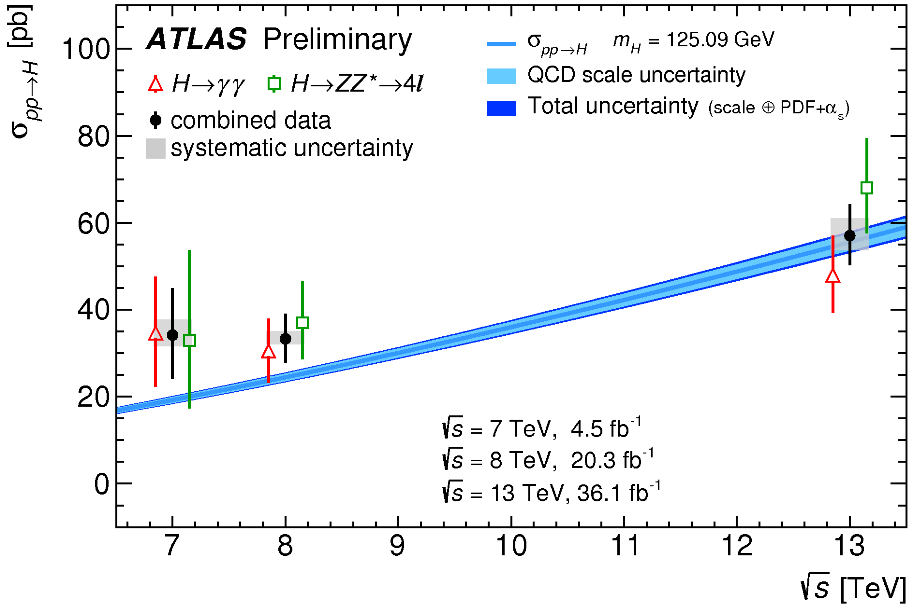

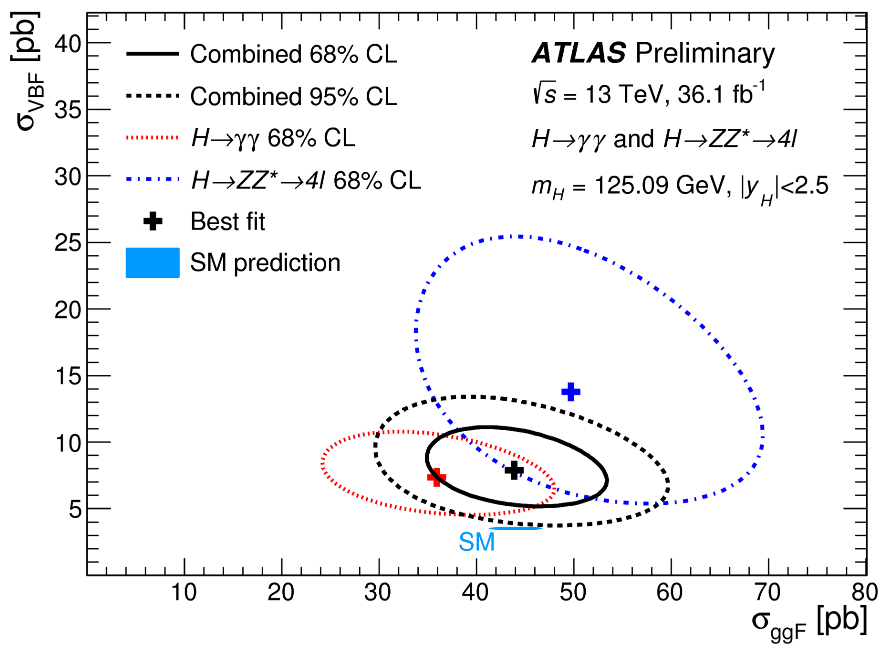

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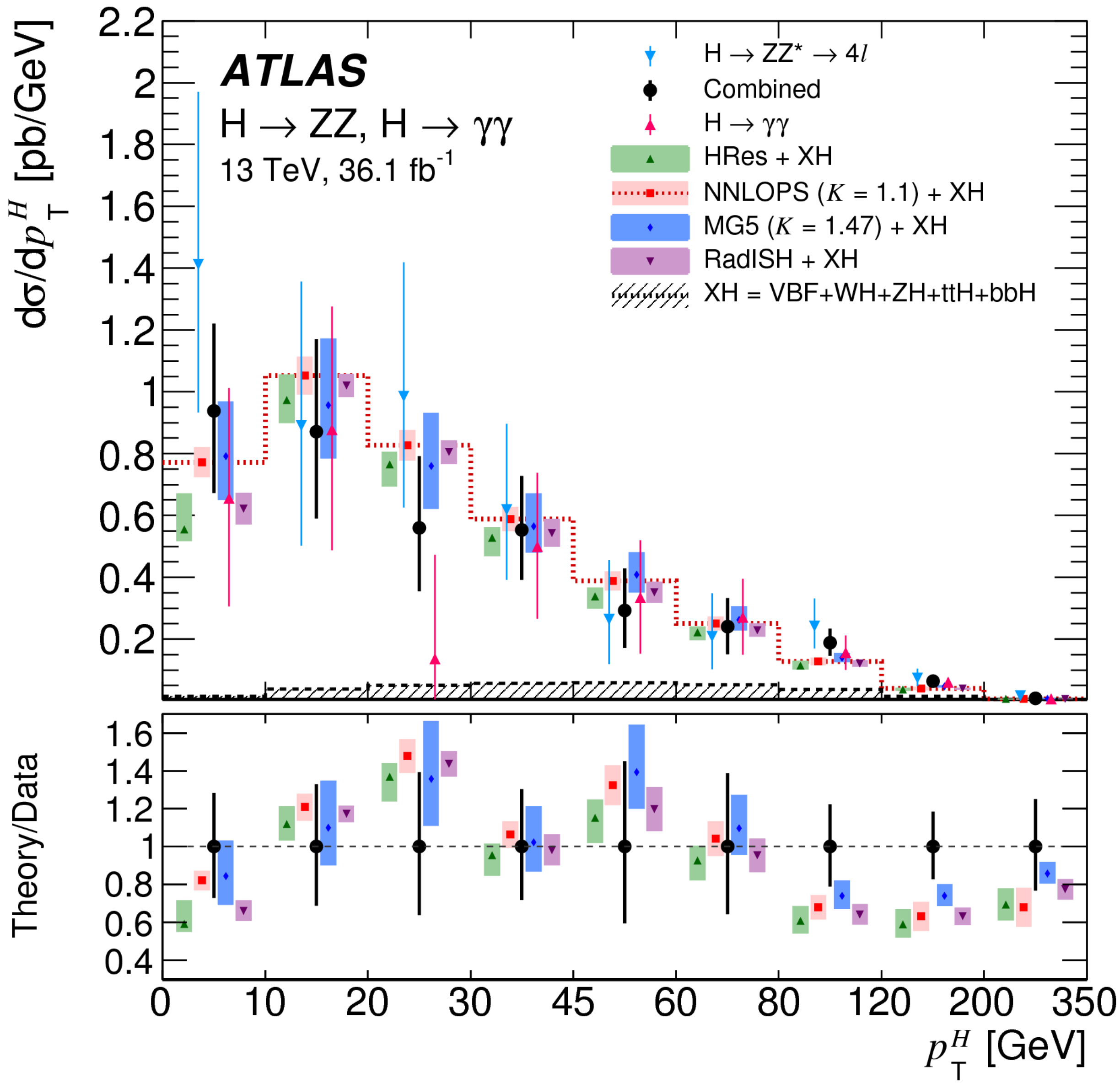
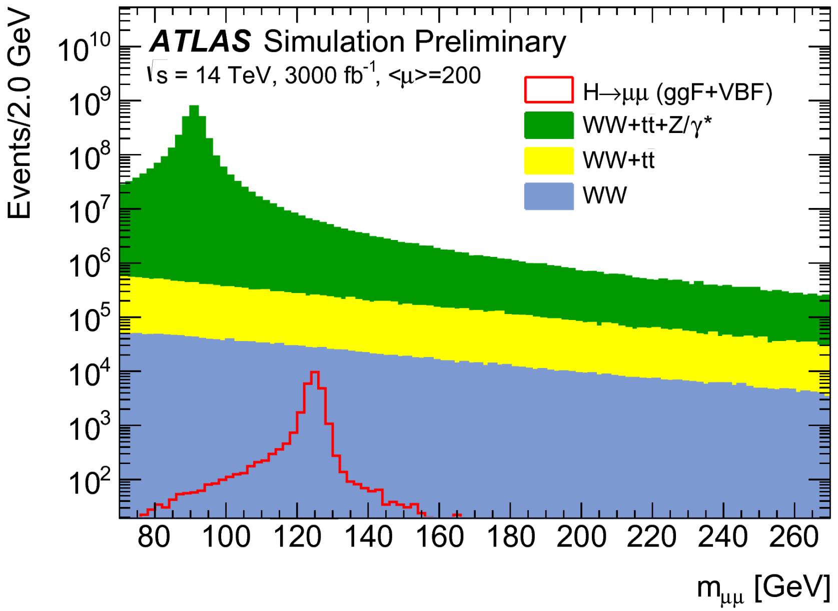
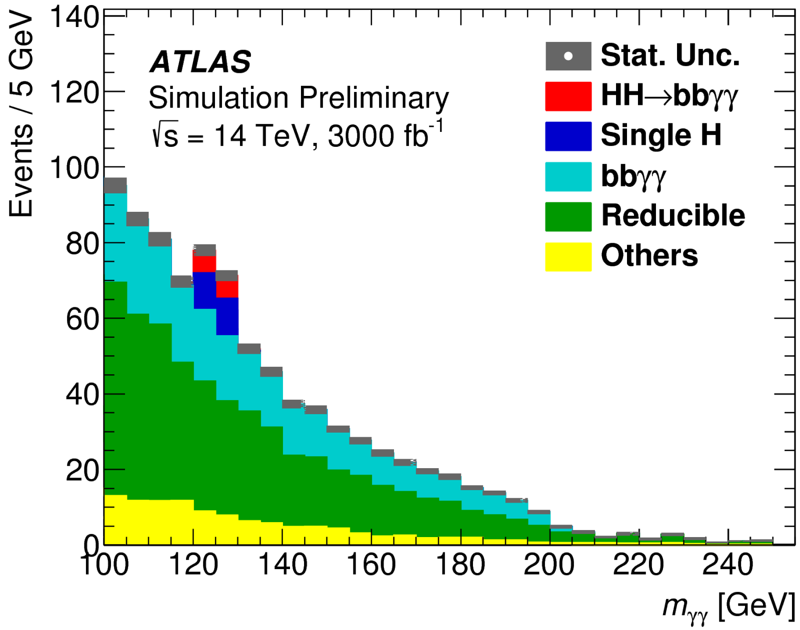


- HL-LHC will sharpen these measurements considerably

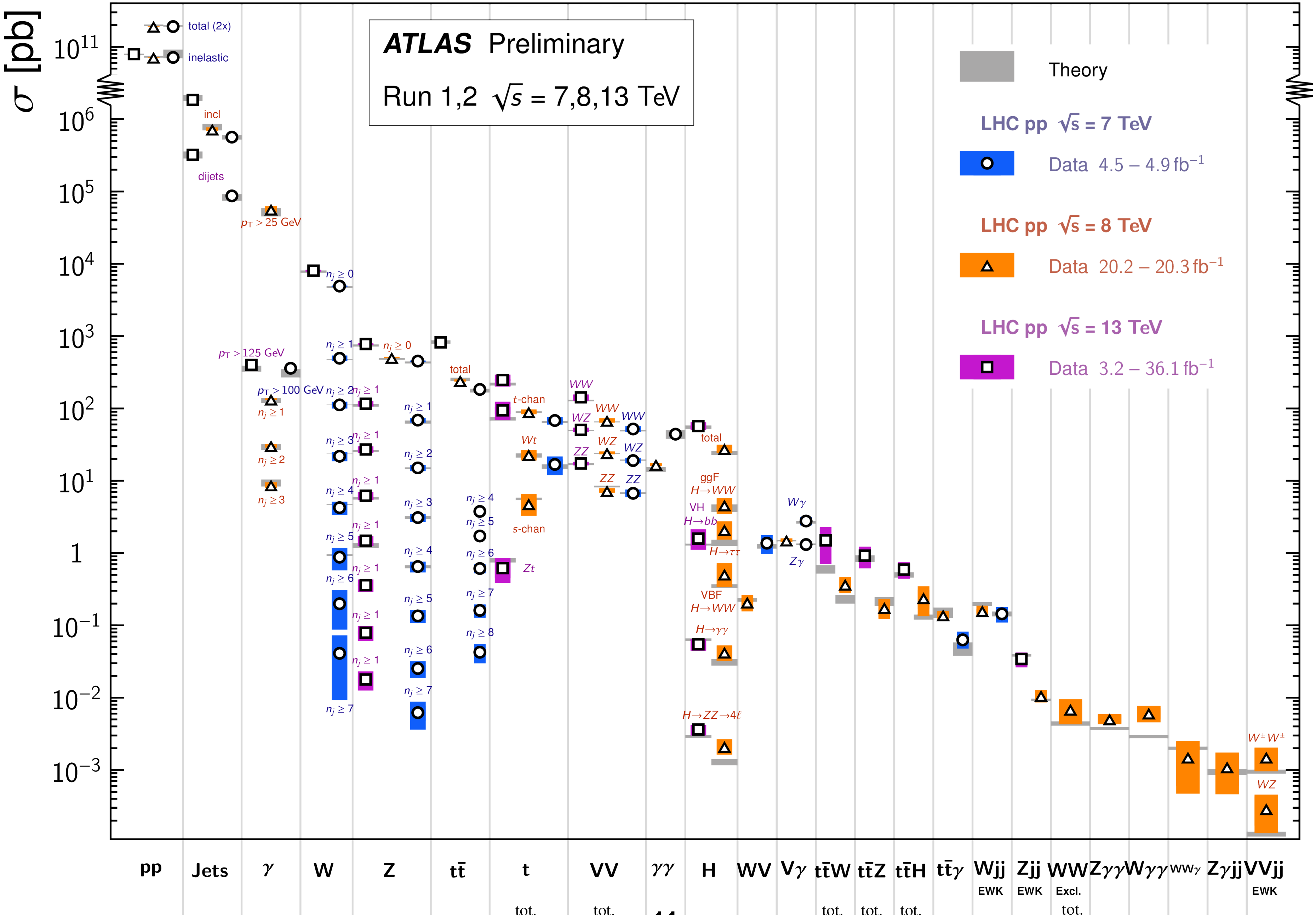
The Higgs Boson

- What haven't we learned?
  - 1st and 2nd generation couplings
  - Rare decay modes
  - Sign of κ_t (directly) – now: $1.25 < \kappa_t < 1.60$ at 95% CL
  - BR(H→inv) constraint <~23%/expt
  - Self-coupling – Higgs potential
- HL-LHC (3 ab^{-1}) will tell us a lot more:
  - H→μμ ~9σ/expt, BR to ~10%/expt
  - H→Zγ ~4σ/expt, BR to ~30%/expt
  - Sign of κ_t via tHq
  - BR(H→inv) <10%/expt with VBF
- Higgs self-coupling measurements appear to be very difficult, even combining all channels and experiments
  - Combined ATLAS+CMS significance for SM HH ~2σ for 3 ab^{-1}?
  - Measure λ_{HHH} to 30% at HE-LHC?

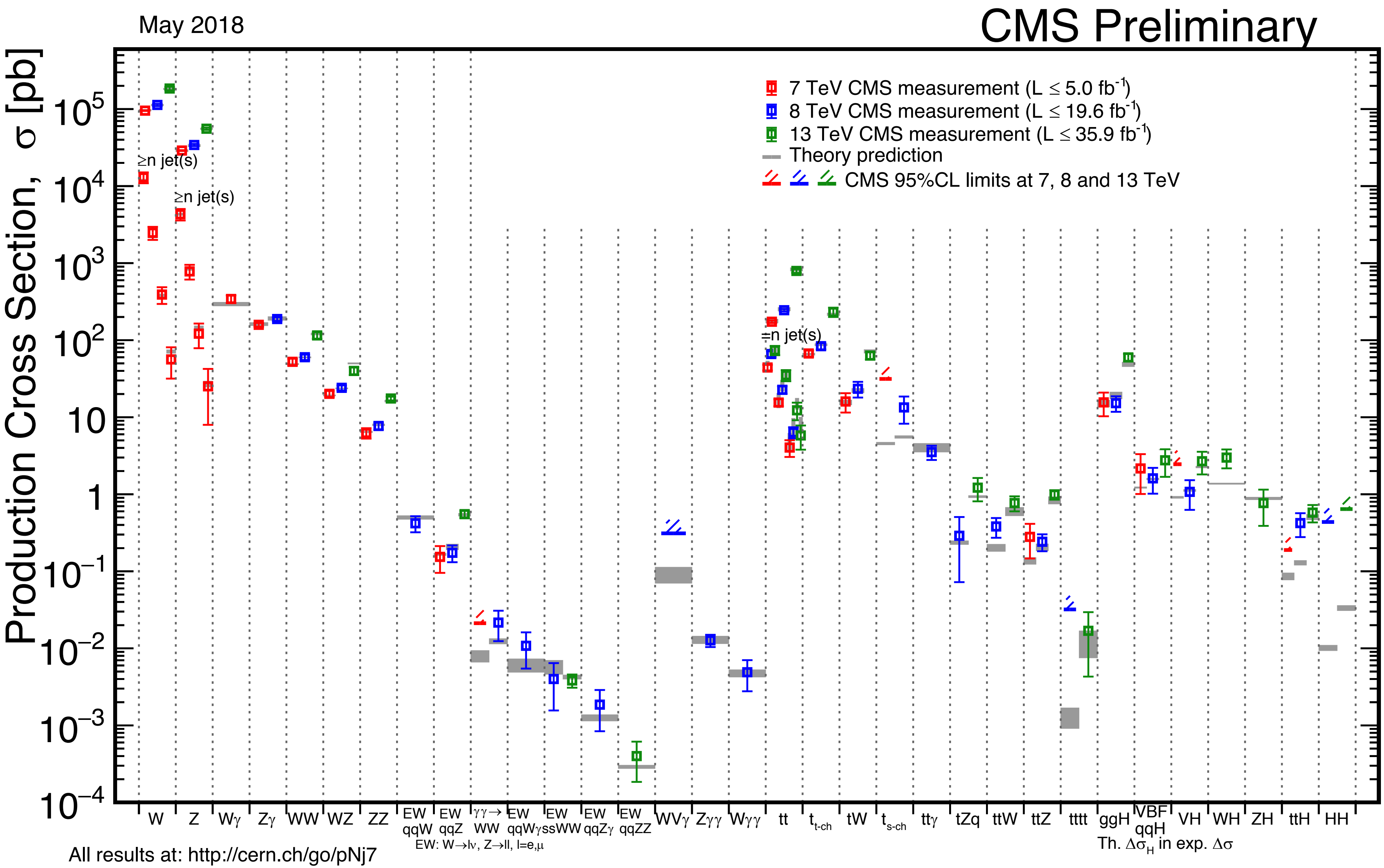




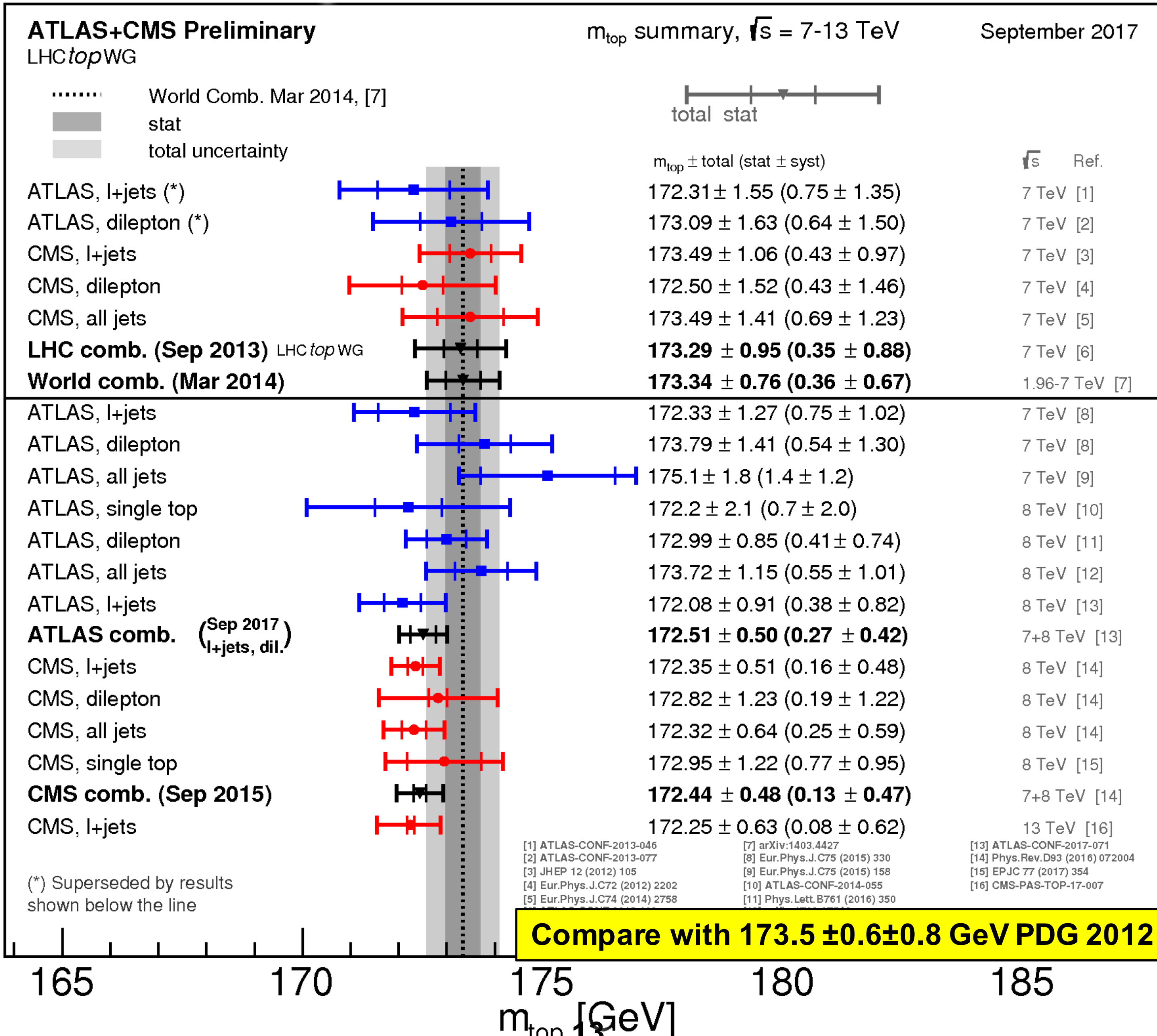
Standard Model Measurements



Standard Model Measurements

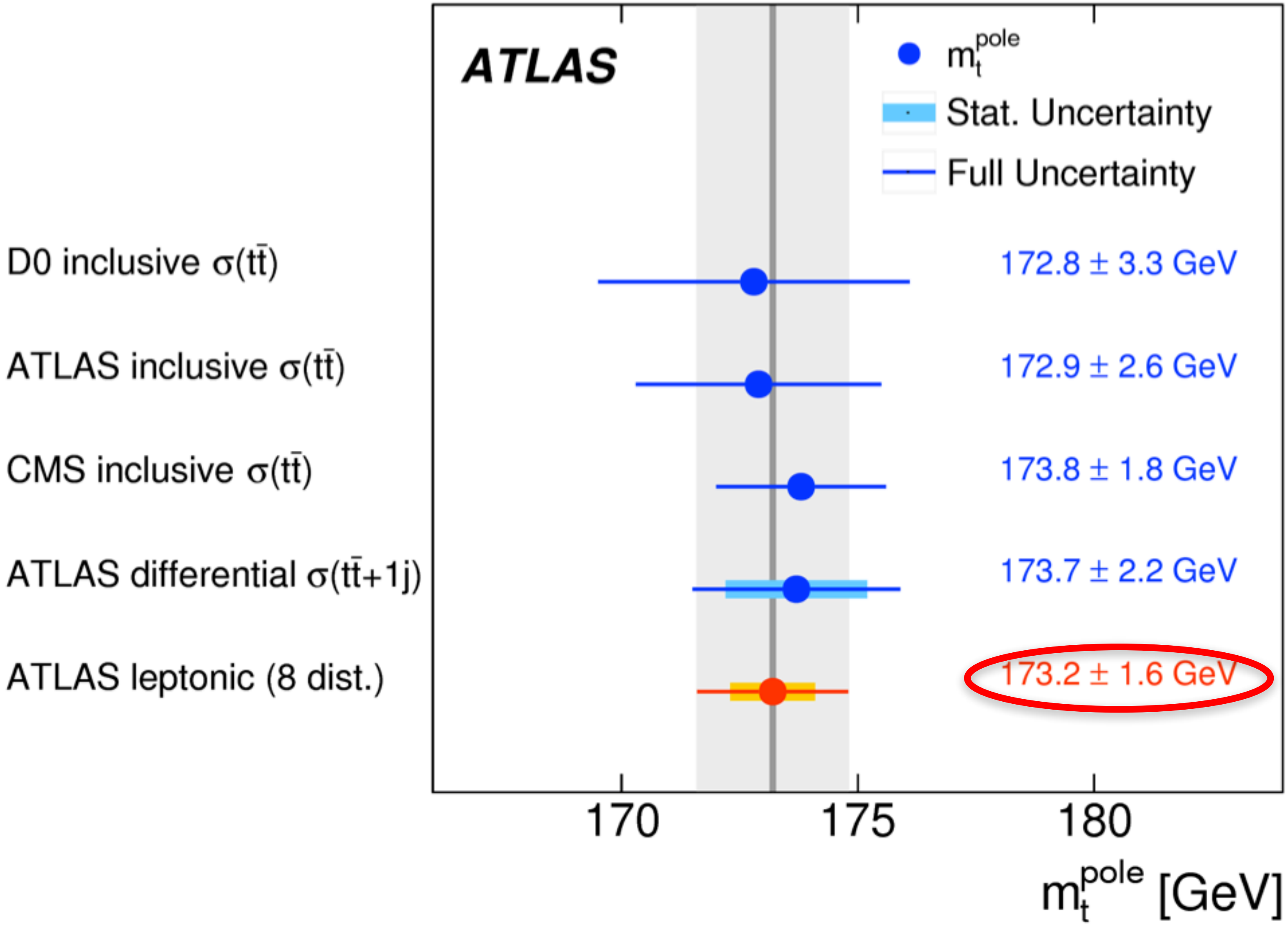


Top Monte Carlo Mass



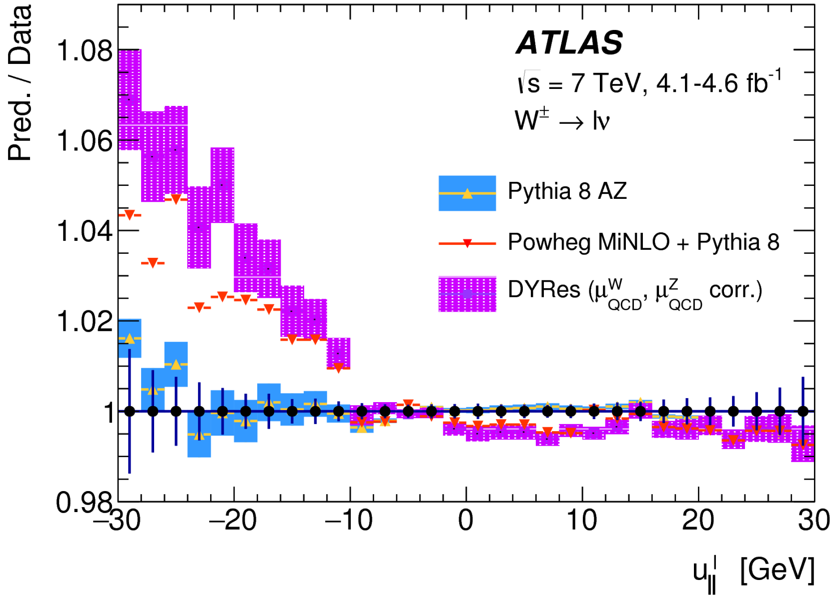
Compare with 173.5 ±0.6±0.8 GeV PDG 2012 (CDF+D0)

Top Pole Mass

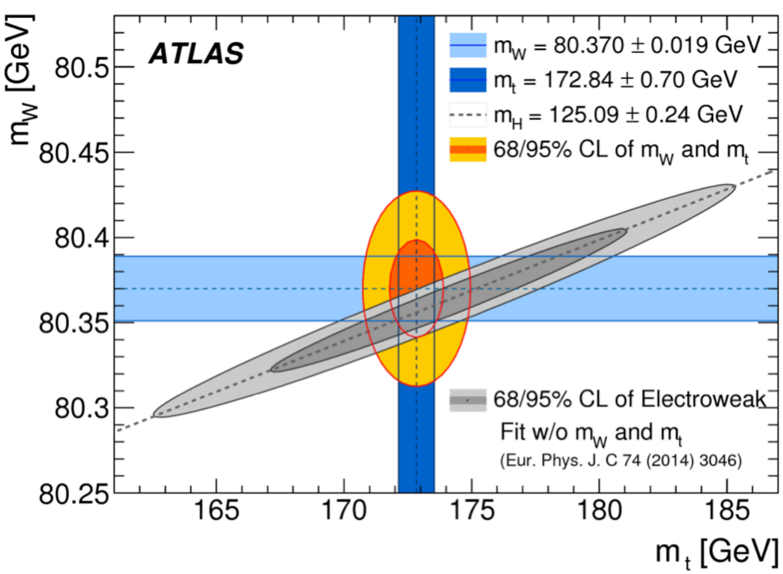


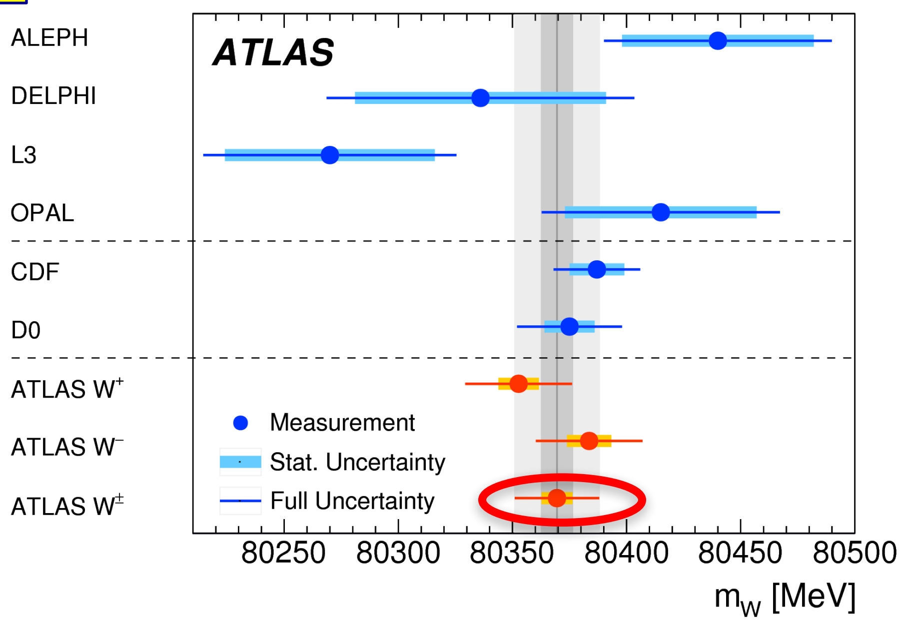
Measurement of the W Boson Mass

- Uses 4.6 fb^{-1} of 7 TeV data ($W \rightarrow e\nu/\mu\nu$)
- Huge amount of work since 2011 to understand detector response and modelling of kinematic quantities, e.g. lepton p_T, E_T^{miss}
- Similar precision to best previous single experiment measurement (from CDF)
- Result consistent with SM expectation
- Further progress requires improved modeling



m_W = 80.370 ± 0.019 GeV
[± 7 MeV (stat.) ± 11 MeV (syst.) ± 14 MeV (modeling)]





Searches for SUSY

ATLAS SUSY Searches* - 95% CL Lower Limits

December 2017

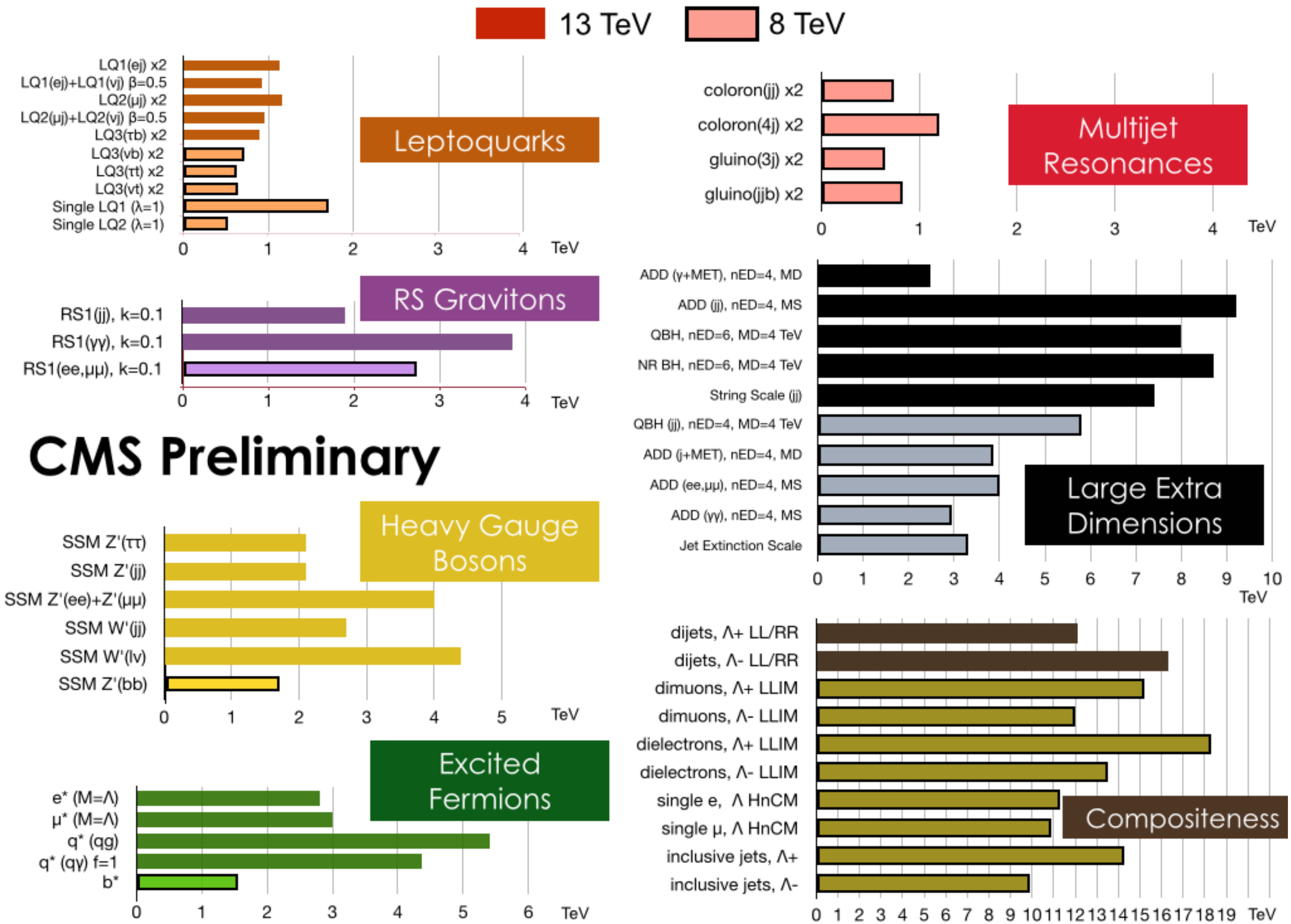
ATLAS Preliminary
$\sqrt{s}$ = 7, 8, 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit ($\sqrt{s}$ = 7, 8 TeV / $\sqrt{s}$ = 13 TeV)		Reference
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$ 1.57 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1712.02332
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	36.1	$\tilde{q}$ 710 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	1711.03301
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.02 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$ 2.01 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1712.02332
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	Yes	14.7	$\tilde{g}$ 1.7 TeV	m($\tilde{\chi}_1^0$)<300 GeV,	1611.05791
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$ 1.87 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03731
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$ 1.8 TeV	m($\tilde{\chi}_1^0$) <400 GeV	1708.02794
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	$\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	36.1	$\tilde{g}$ 2.15 TeV	$c\tau$(NLSP)<0.1 mm	ATLAS-CONF-2017-080
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	36.1	$\tilde{g}$ 2.05 TeV	m($\tilde{\chi}_1^0$)=1700 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2017-080
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$ 1.92 TeV	m($\tilde{\chi}_1^0$)<600 GeV	1711.01901
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$ 1.97 TeV	m($\tilde{\chi}_1^0$)<200 GeV	1711.01901
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	36.1	$\tilde{b}_1$ 950 GeV	m($\tilde{\chi}_1^0$)<420 GeV	1708.09266
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	1 b	Yes	36.1	$\tilde{b}_1$ 275-700 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1706.03731
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0-2 e, μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 117-170 GeV; 200-720 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	20.3/36.1	$\tilde{t}_1$ 90-198 GeV; 0.195-1.0 TeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, 1709.04183, 1711.11520
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet	Yes	36.1	$\tilde{t}_1$ 90-430 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)=5 GeV	1711.03301
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	36.1	$\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1-2 e, μ	4 b	Yes	36.1	$\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1706.03986
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	36.1	$\tilde{\ell}$ 90-500 GeV	m($\tilde{\chi}_1^0$)=0	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 750 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 760 GeV	m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1708.07875
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 1.13 TeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0-2 jets	Yes	36.1	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 580 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	ATLAS-CONF-2017-039
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e, μ, γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	1 $e, \mu + \gamma$	-	Yes	20.3	$\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0\to\gamma\tilde{G}$	2 γ	-	Yes	36.1	$\tilde{W}$ 1.06 TeV	$c\tau$<1 mm	ATLAS-CONF-2017-080
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 460 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1712.02118
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$ 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$ 1.57 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	1604.04520
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	displ. vtx	-	Yes	32.8	$\tilde{g}$ 2.37 TeV	τ($\tilde{g}$)=0.17 ns, m($\tilde{\chi}_1^0$) = 100 GeV	1710.04901
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$ 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to eev/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu, e\tau, \mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e, μ	-	Yes	13.3	$\tilde{\chi}_1^{\pm}$ 1.14 TeV	m($\tilde{\chi}_1^0$)>400GeV, $\lambda_{12k}\neq0$ (k = 1, 2)	ATLAS-CONF-2016-075
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	4-5 large-R jets	-	36.1	$\tilde{g}$ 1.875 TeV	m($\tilde{\chi}_1^0$)=1075 GeV	SUSY-2016-22
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 2.1 TeV	m($\tilde{\chi}_1^0$)= 1 TeV, $\lambda_{112}\neq0$	1704.08493
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e, μ	8-10 jets/0-4 b	-	36.1	$\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	1704.08493
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	36.7	$\tilde{t}_1$ 100-470 GeV; 480-610 GeV		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	36.1	$\tilde{t}_1$ 0.4-1.45 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	1710.05544
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

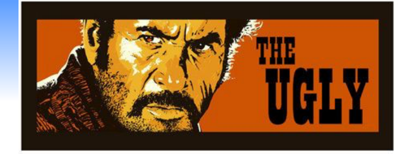
10^{-1} — 1 — Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

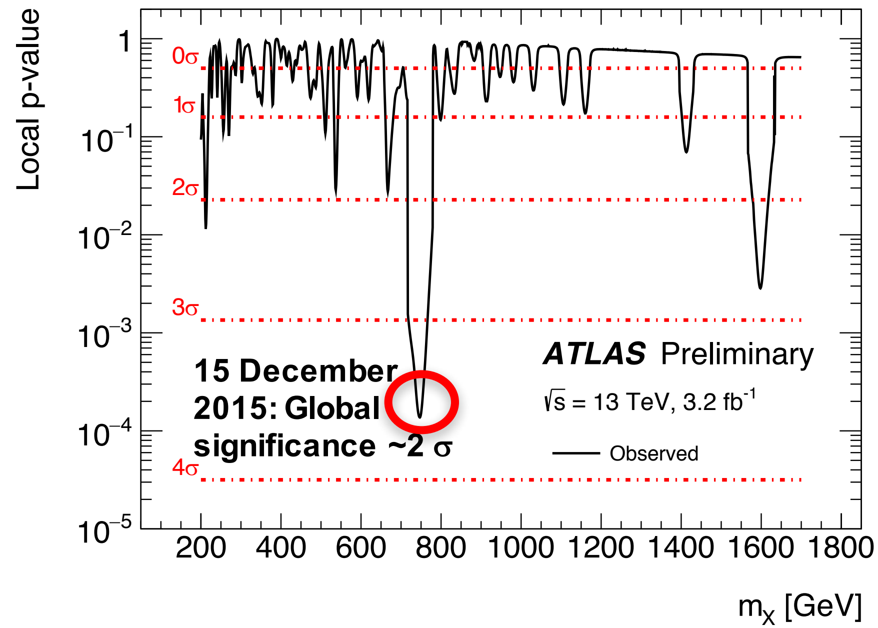
Searches for Other Exotica



A Cautionary Tale ....



- X(750) story (there are others as well) teaches us that our field is not immune to sociological pressures
- Experimentalists and theorists should both shoulder some of the blame
- Excitement is inevitable but scientific objectivity should be paramount



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Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ =
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High Energy Physics – Phenomenology

Di-photon excess illuminates Dark Matter

Mihailo Backovic, Alberto Mariotti, Diego Redigolo

(Submitted on 15 Dec 2015 (v1), last revised 29 Dec 2015 (this version, v2))

We propose a simplified model of dark matter with a scalar mediator to accommodate the di-photon excess recently observed by the ATLAS and CMS collaborations. Decays of the resonance into dark matter can easily account for a relatively large width of the scalar resonance, while the magnitude of the total width combined with the constraint on dark matter relic density lead to sharp predictions on the parameters of the Dark Sector. Under the assumption of a rather large width, the model predicts a signal consistent with ~300 GeV dark matter particle in channels with large missing energy. This prediction is not yet severely bounded by LHC Run I searches and will be accessible at the LHC Run II in the jet plus missing energy channel with more luminosity. Our analysis also considers astrophysical constraints, pointing out that future direct detection experiments will be sensitive to this scenario.

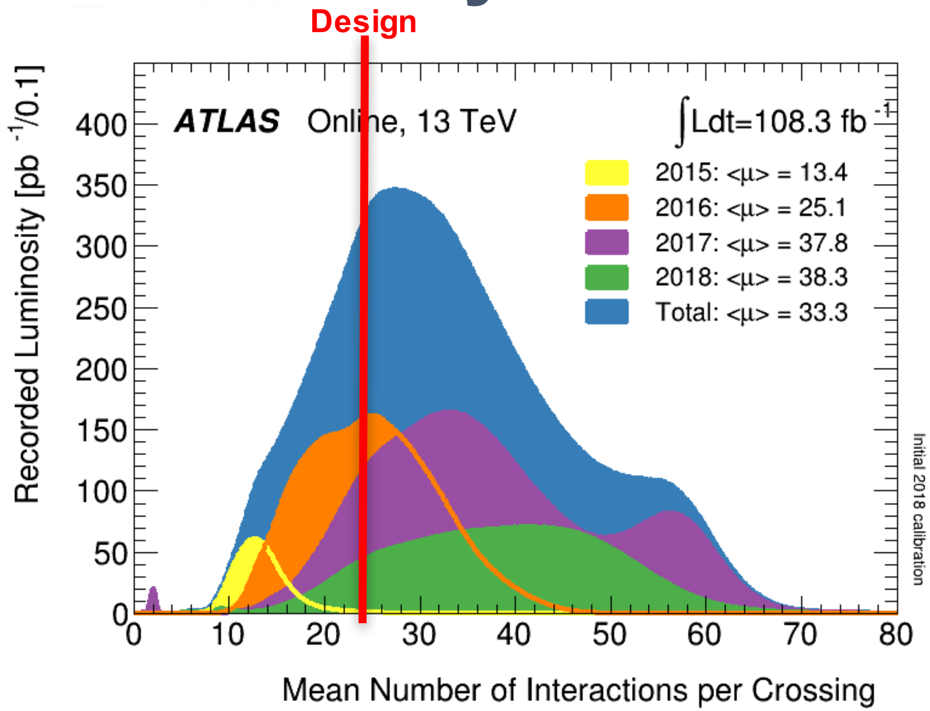
Comments: 23 pages, 8 figures. Added 2 figures and more discussions
Subjects: High Energy Physics – Phenomenology (hep-ph); High Energy Physics – Experiment (hep-ex)
Cite as: arXiv:1512.04917 [hep-ph]
(or arXiv:1512.04917v2 [hep-ph] for this version)

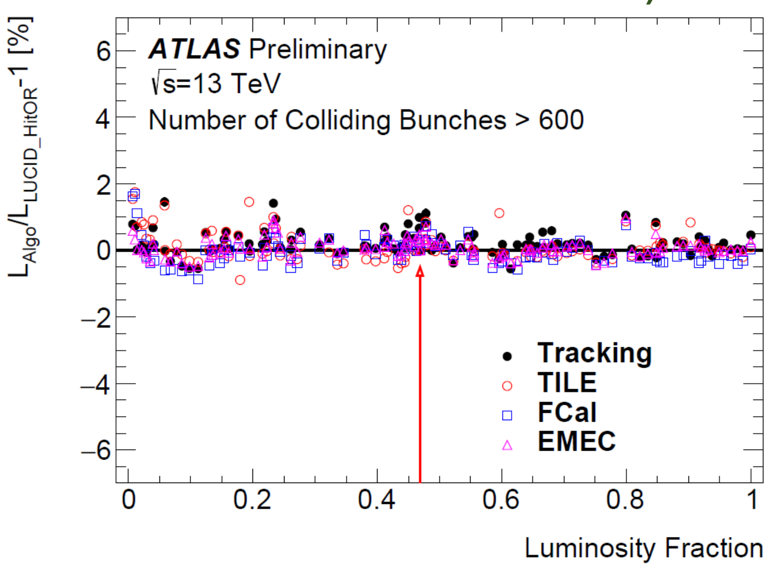
Submission history
From: Diego Redigolo [view email]
[v1] Tue, 15 Dec 2015 20:26:16 GMT (403kb,D)
[v2] Tue, 29 Dec 2015 20:05:44 GMT

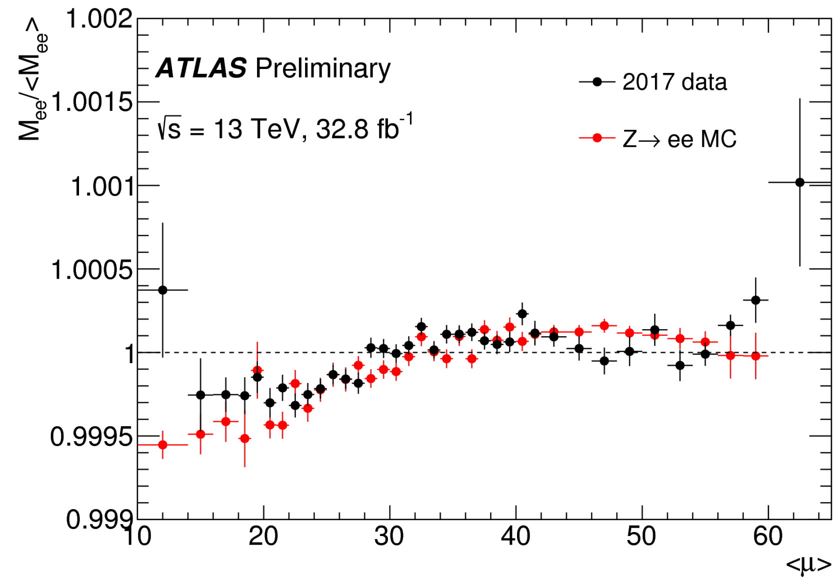
What have we learned about our ability to learn about nature?

Pile-Up and Luminosity

- Pile-up conditions have been much more challenging in Run-2 than foreseen before data-taking.
- Experiments have been up to the challenge however!
- Detailed understanding of machine and detector performance has enabled exquisite precision for luminosity measurement <2% (10% was often assumed in the 90's).



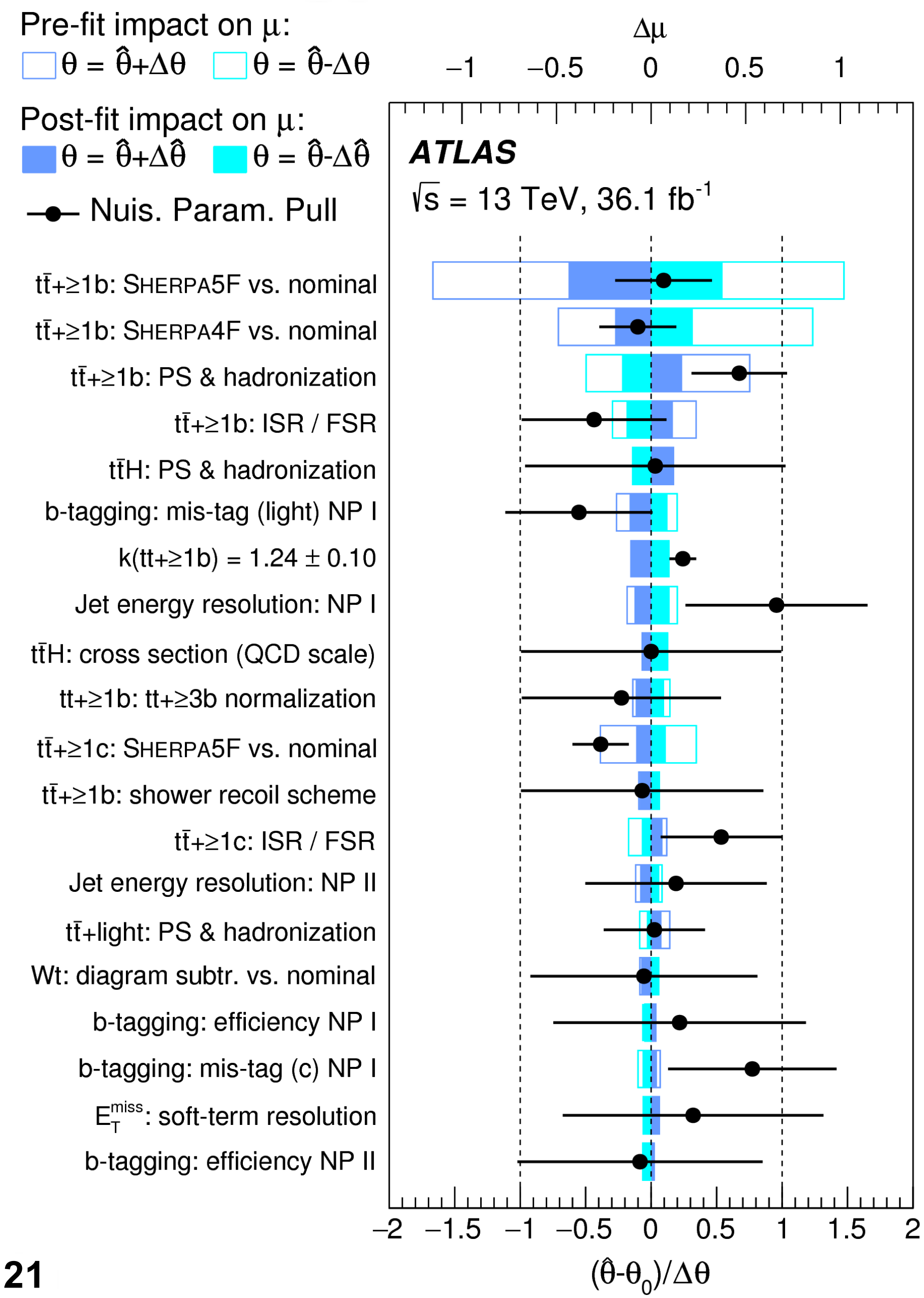




Analysis Strategy

- Techniques for statistical interpretation of data have advanced hugely, partly as a result of increased computing resources
  - Profile likelihood ratio fits with many nuisance parameters
  - Proper treatment of profiling
  - Toys or asymptotics for limits

- Standardisation of analysis strategy for both searches and measurements
  - Data-driven background estimates
  - Careful design and use of signal, control and validation regions
  - Careful scrutiny of pulled nuisance parameters, e.g. background scale factors

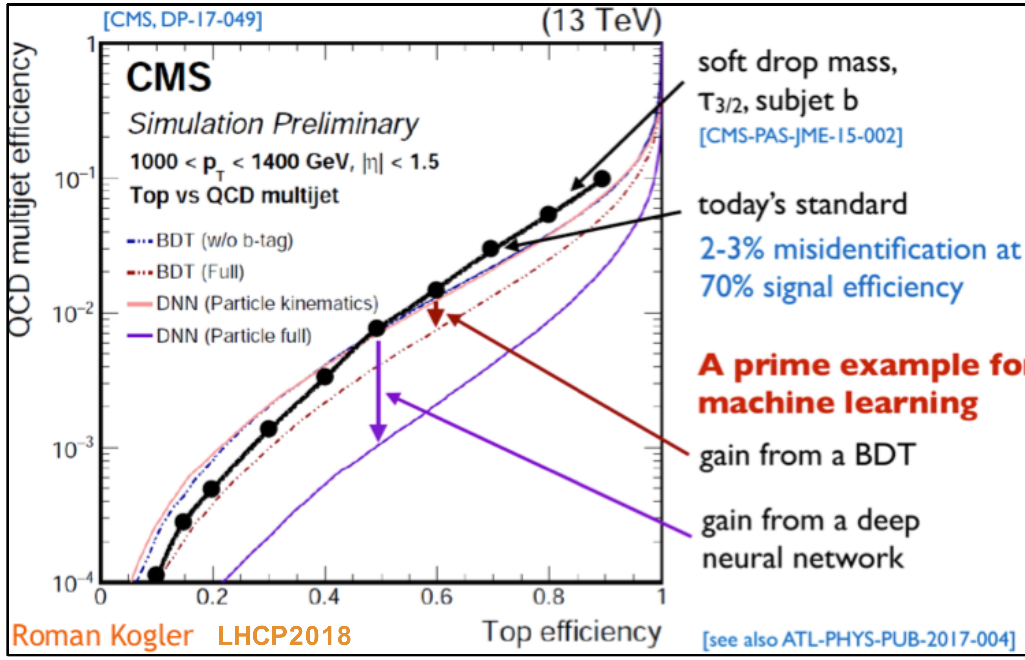


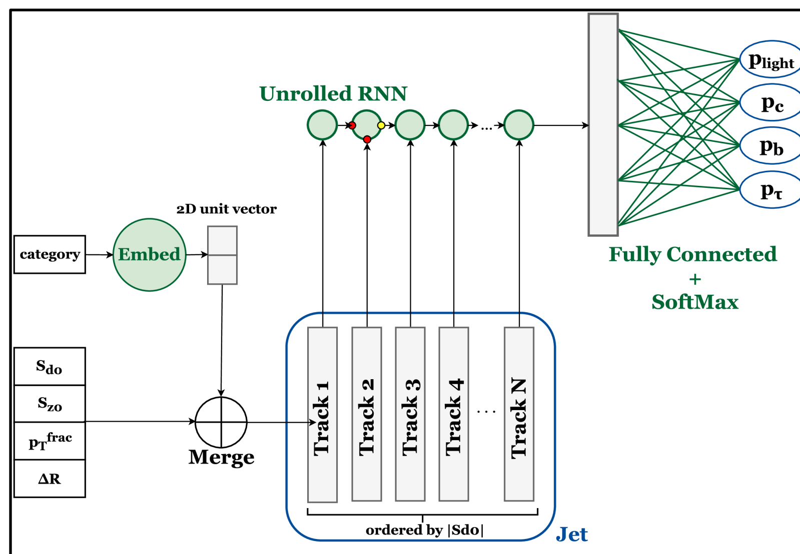
Multivariate and ML Techniques

- Multivariate LLRs, neural networks, and BDTs used extensively throughout object reconstruction. Dramatic improvements in performance

- BDTs have become standard analysis tools in SM measurements and searches. Now extending increasingly into BSM searches (is this a good thing?)

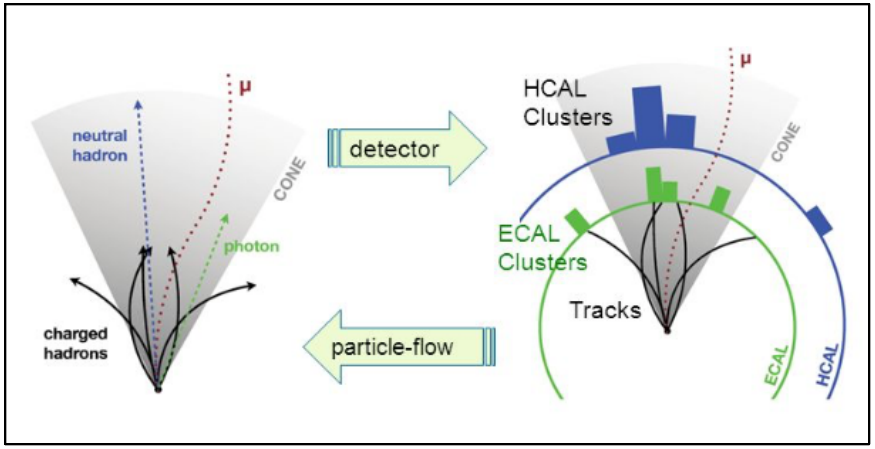
- More sophisticated ML techniques now being used for object reconstruction, e.g. RNN for b-tagging. Riding wave of excitement throughout science.

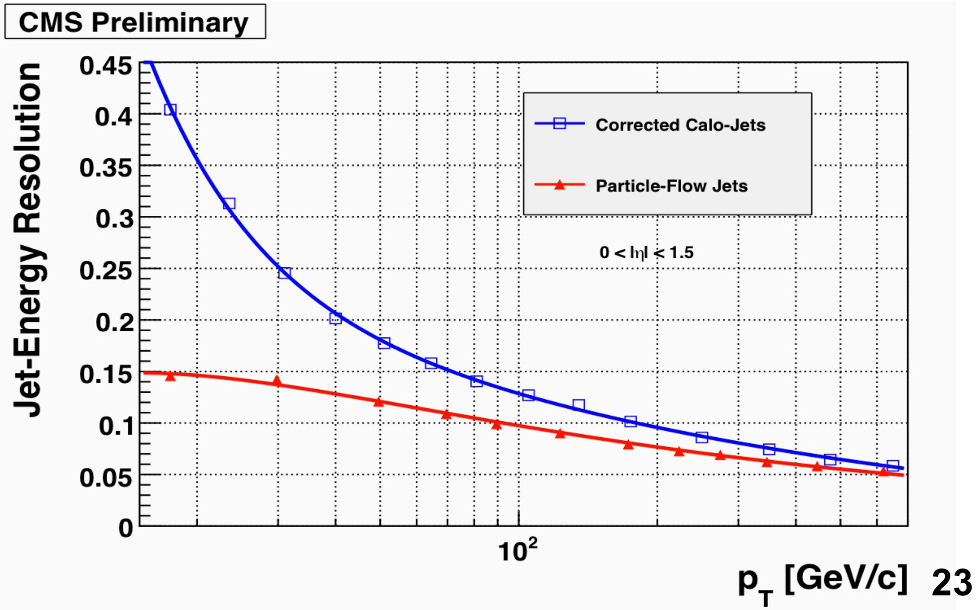


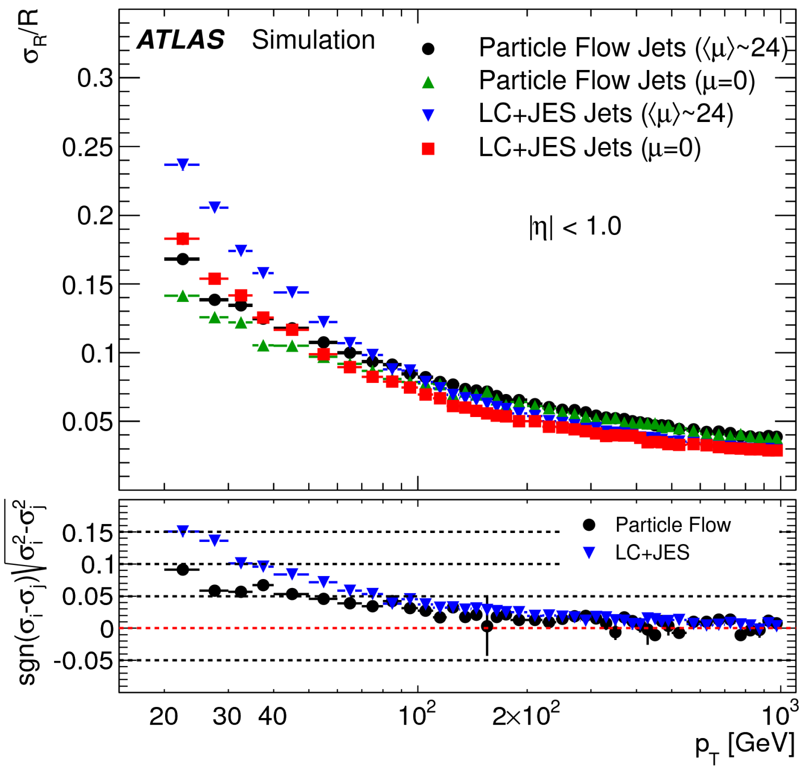


Particle Flow Reconstruction

- Particle flow reconstruction was once a peripheral interest at hadron colliders. No more!
- Particle flow is at the heart of CMS. ATLAS is catching up.
- Simplifies analysis and enables coherent treatment of physics objects
- Critical for pileup suppression / maintaining performance of low p_T reconstruction at very high mu

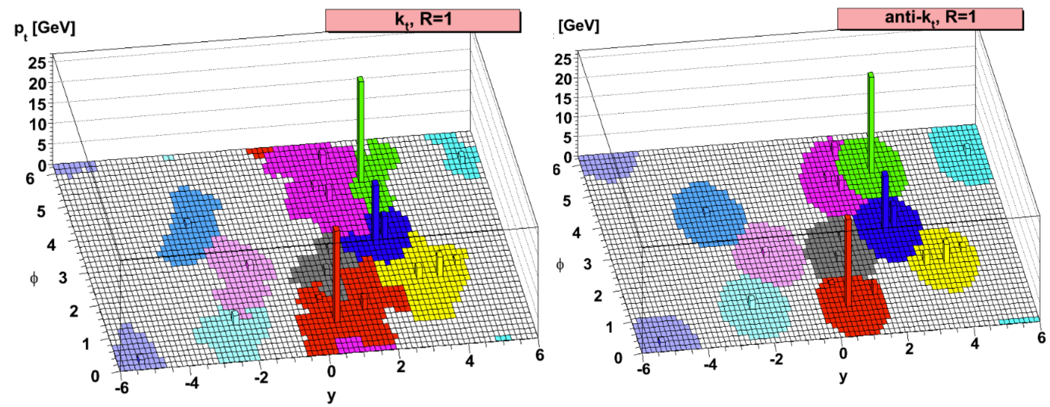




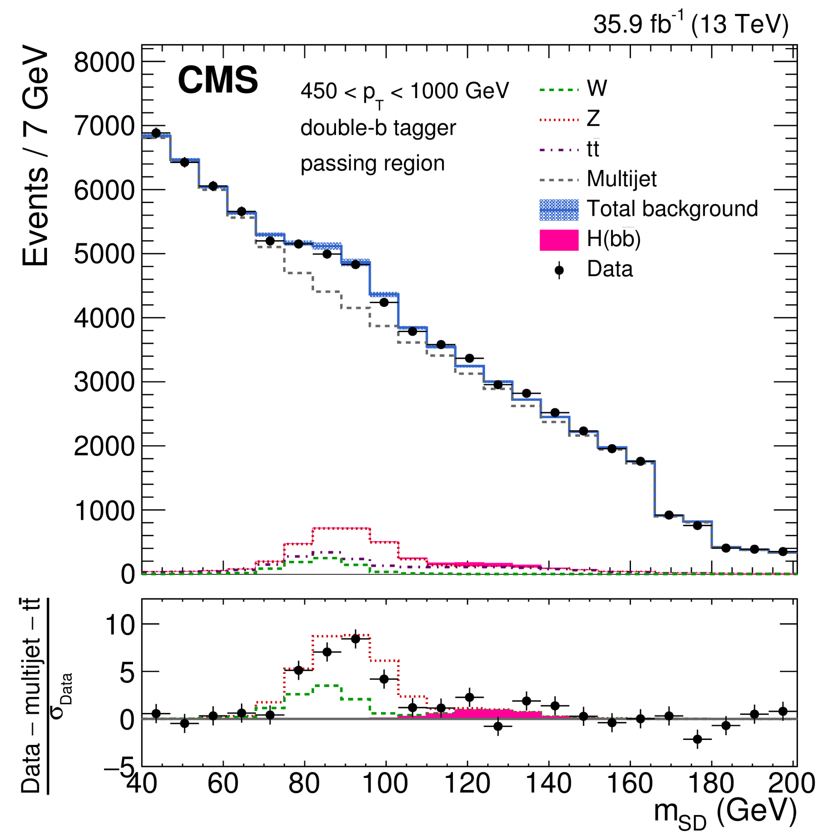


Jet Algorithms and Substructure

- IR safety in jet reconstruction was a major concern and source of disagreement for many years.
  - Anti-k_t (Cacciari, Salam and Soyuz 2008) solved the problem almost overnight …

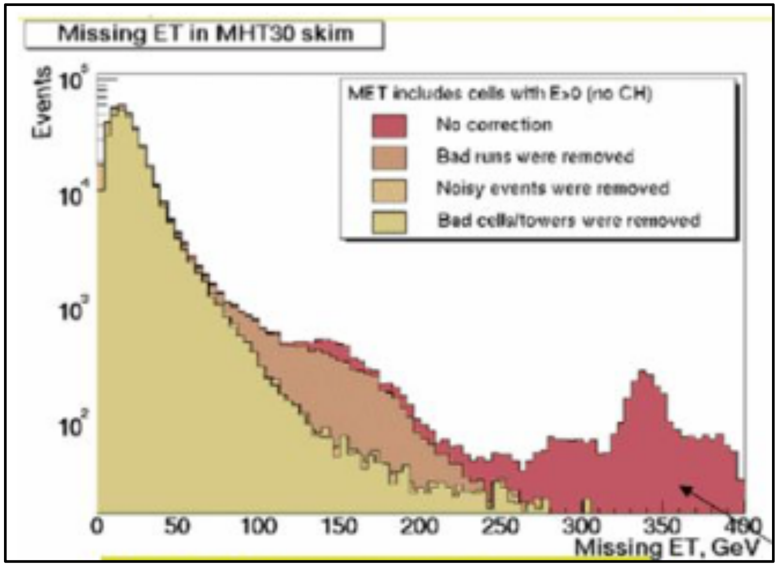


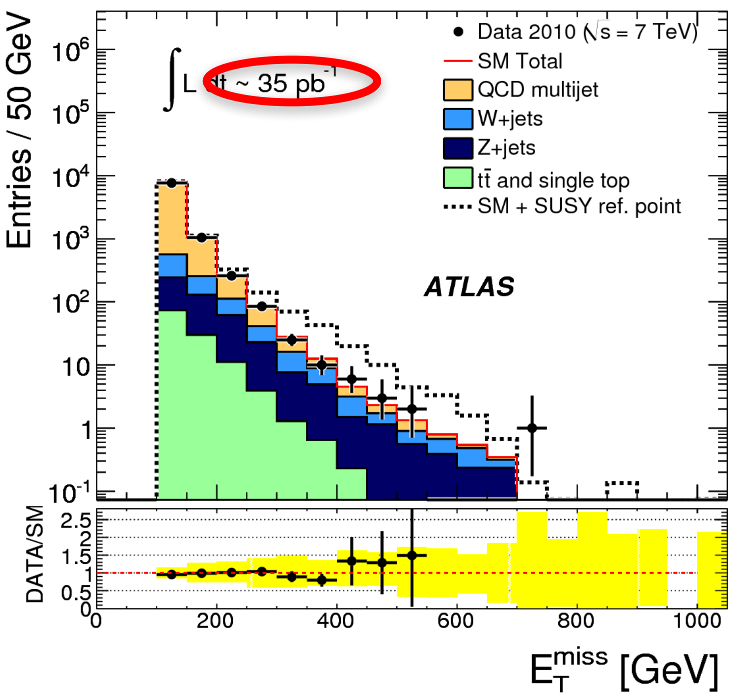
- Jet substructure techniques have revolutionised high-p_T searches and measurements
  - e.g. Observation of boosted Z→bb and search for H→bb by CMS following Butterworth et al. (2008)
  - New ideas (e.g. soft-drop) now finding first application in analyses



Missing Transverse Energy

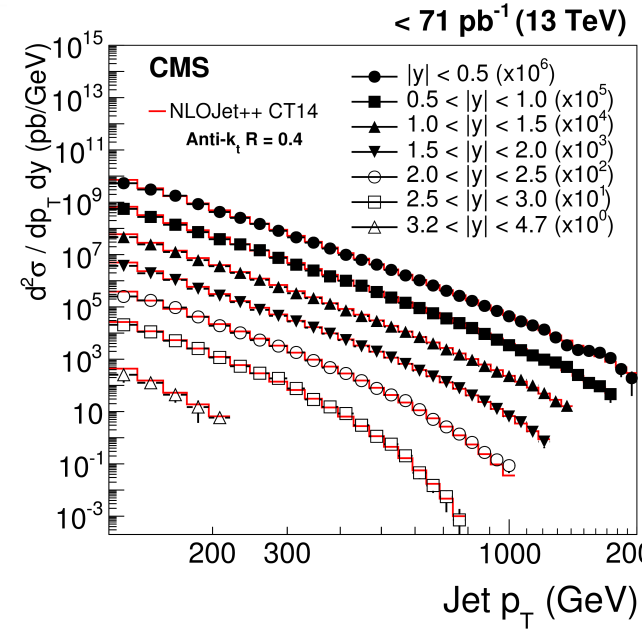
- 'Fake' missing transverse energy was a crucial concern prior to data-taking.
- Earlier experience from Tevatron showed that this could generate huge multijet backgrounds to BSM searches (e.g. SUSY)
- Benefiting from careful hermetic design of the experiments and Tevatron experience with event cleaning this fear was not realised.

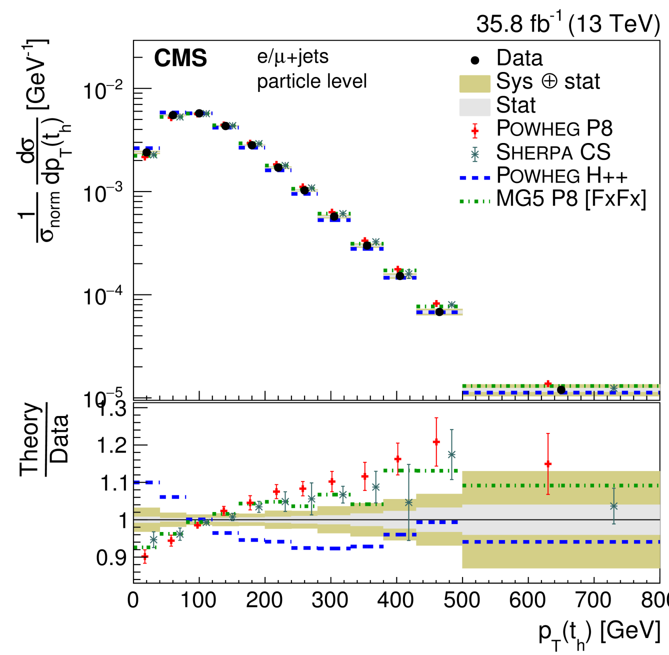




Modeling

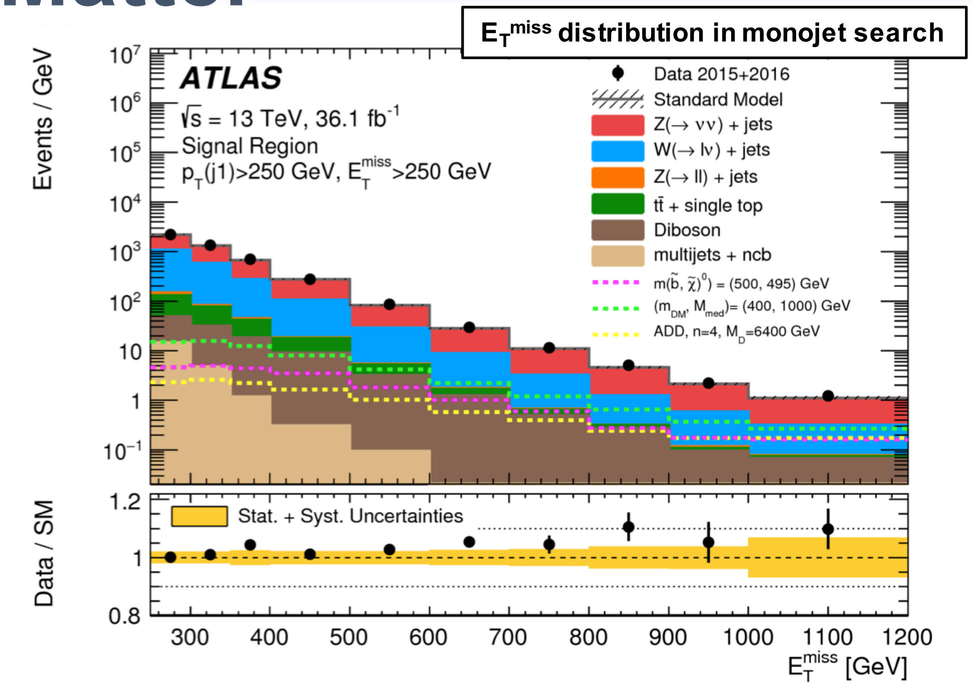
- Theoretical models (fixed order ME, resummation, ME+PS matching) and improved PDF sets (benefiting from LHC measurements) have been supremely successful at accurately representing data.
  - Use of NLO and/or multi-leg ME with PS matching MC is now routine.
  - NNLO ME+PS now becoming available
  - Automated one-loop QCD and EW corrections
  - NNLO fixed-order calculations common, N^3LO available for Higgs
  - 50% discrepancies between data and background model now rare in any systematics-dominated region of any observable
- Compare to 90’s when stand-alone Pythia and Herwig 2→2 were standard MC tools. Isajet for SUSY events.

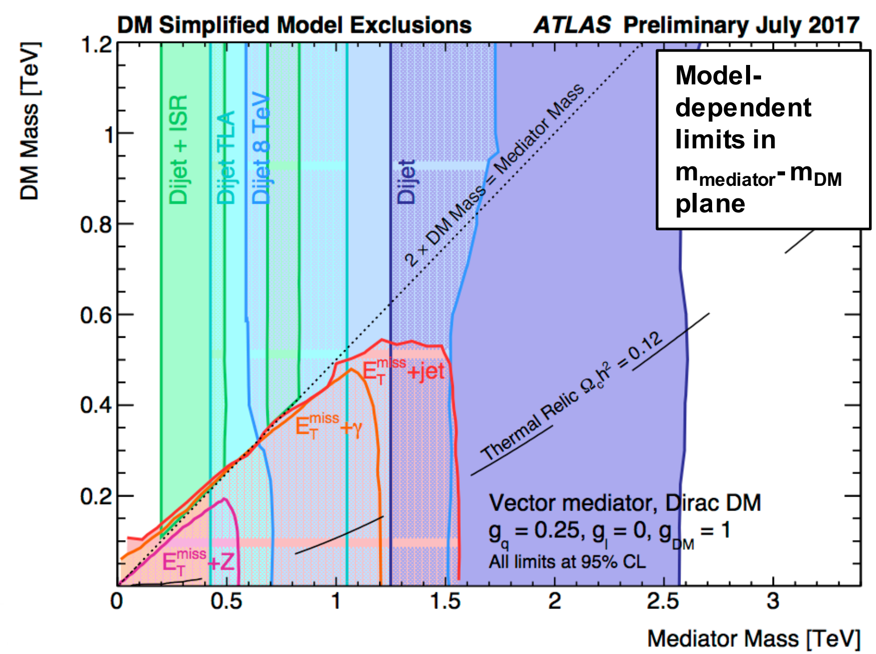




Dark Matter

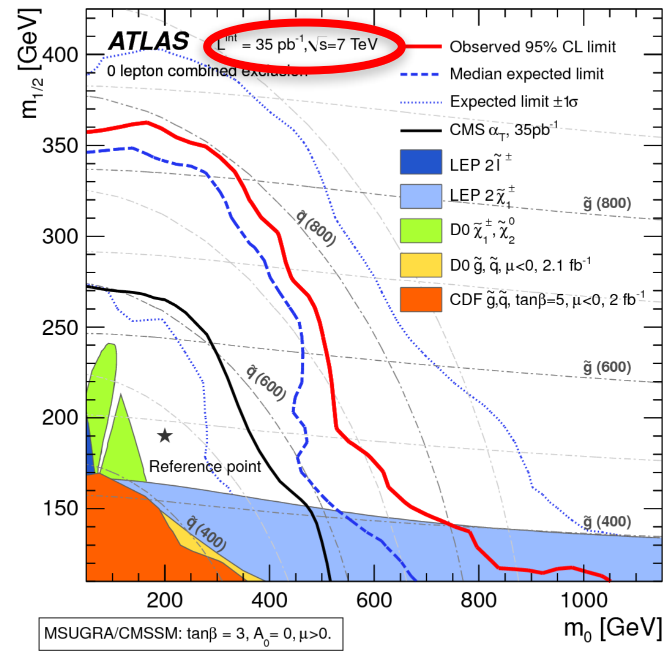
- Prior to data-taking ‘mono-object’ searches (especially mono-jet) were focused on searches for extra dimensions via ‘graviton-sstrahlung’
- Interest in dark matter searches propelled by new EFT models and subsequent simplified (mediator+DM) models
- Important limits on generic DM models – competitive with direct searches. Less competitive in specific context of SUSY.
- Complementary to dijet searches for mediators
- Systematics in background modelling a key concern (e.g. mono-jet)

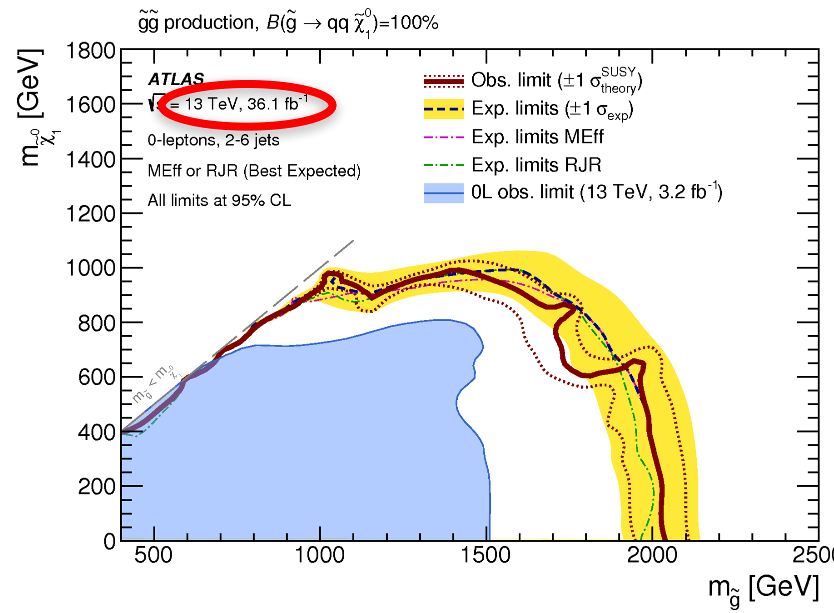




(Re-)Interpretation and Analysis Preservation

- Prior to data-taking little thought went into how to best enable interpretation of (negative) search results by theorists. This is now a hot topic (and rightly so).
  - New physics would appear quickly. Main focus would be measuring properties of new states. Limits were not a priority!
- Early steps to improve the situation, e.g. move from mSUGRA limits to SUSY simplified models
- ATLAS now provides detailed efficiency and acceptance information for models
- CMS now providing simplified likelihood information for some analyses
- Analysis preservation with new software tools such as Docker and Recast strongly encouraged/developed





What lessons can we learn for the future?

Some lessons for the future

- We are now entering a regime where statistics are no longer the limiting factor for many/most measurements (e.g. masses of W, top and Higgs)
  - Huge data samples, but size increasing more slowly
  - Presents challenges (experimentalists and theorists need to work harder) but also opportunities (e.g. clever selections or categorisation – sacrifice some stats to reduce systematics)

- Never underestimate the ingenuity of experimentalists for improving the performance of their experiments and understanding related systematics
  - Example: potential further gains from deep machine learning

- Never underestimate the ingenuity of theorists for improving the precision of calculations and developing clever tricks to enable efficient use in MC

Some lessons for the future

- Maintaining or improving performance in the presence of pileup is **<u>THE</u>** challenge for the future LHC experimental programme
  - New hardware and increased computing resources will be critical
  - So will improved reconstruction - new ideas in e.g. machine learning and particle flow reconstruction vital
  - The status quo is not an option!

- Improved measurement precision and search sensitivity crucially rely upon control of systematics. Monte Carlo modelling (and inputs from new PDF fits) of the highest precision is a vital ingredient. Close contact between theorists and experimentalists must be maintained, e.g.
  - W mass measurement where PDF and hadronic recoil modelling uncertainties are currently limiting factors.
  - EW corrections to background models for monojet DM search
  - Improved understanding of relationship between top ‘MC mass’ and pole mass

Some lessons for the future

- Searches will inevitably increasingly focus on models with challenging signatures, e.g. long-lived states and events requiring multi-object and/or low threshold triggers.
  - Models with compressed spectra with soft decay products in which the NP signal underlies large SM backgrounds are a particular target. Multi-bin shape-fits rather than cut/count for model-dependent BSM searches.

- Enabling analysis preservation and reinterpretation is an important duty for the experimental collaborations. It maximises the use of our results (citations!) and enables a broad and vibrant theory programme
  - Limitations to amount of information experimentalists can provide in short time
  - With longer gaps between results possibly more scope for more information
  - Communication and compromise between experimentalists and theorists is vital

- Need to retain perspective when unblinding searches in new energy regime, even if modest increment (e.g. 13→14 TeV)
  - If combination with earlier data takes place at 'interpretation-stage' rather than with histograms, there is scope for large fluctuations without trivial/immediate exclusion with earlier data

Some Final Thoughts ….

- HL-LHC will be a Higgs factory and will enable us to set out inland from the shores of this new territory with greatly improved precision and new opportunities for measurements.

- Measurements of the Higgs trilinear self-coupling will be more challenging but are crucial for us to understand the nature of EWSB. How we illuminate this sector of the theory experimentally should be a key consideration when planning future facilities (c.f. ESPP).

- We must not forget the argument that exploration of unknown territory offers the promise of undreamt-of rewards.

- If we see clear evidence for (scale of) BSM physics anywhere in Run-2 data or beyond (e.g. flavour anomalies in LHCb → LFV?) this will be a game-changer ….

Backup

Higgs Self-Coupling Prospects

HH final state	ATLAS Significance Coupling limit (95 % C.L.)	CMS Significance
$HH \to b b\gamma\gamma$	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$	1.43 σ
$HH \to bb\tau\tau$	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$	0.39 σ
$HH \to bbbb$	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$	0.39 σ
$HH \to bbVV$		0.45 σ
ttHH, HH-> bbbb	0.35 σ	

S. Jezequel, HL-LHC yellow report workshop, CERN, Nov 2017