Montecarlo and LHC

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Introduction

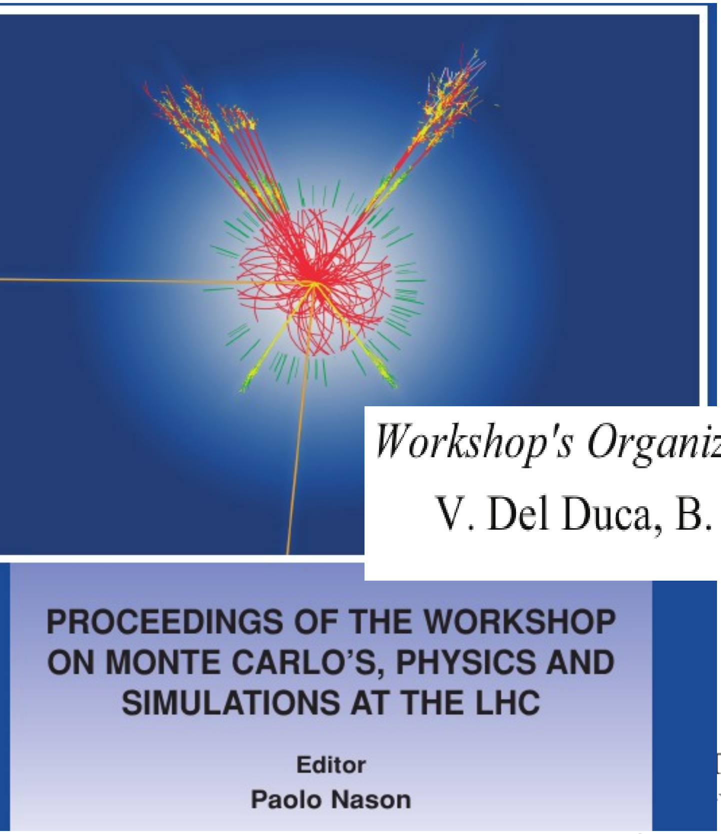
As an experimental LHC physicist I would like to highlight a key contribution of Paolo to the success of the LHC program, his tireless work in trying to bring experimental and theory communities together

- to optimise our usage of Monte Carlos through education of the experimentalist on the features and limits inherent in MonteCarlo generators
- to optimise the lines of generator development giving the theorists a better understanding of the experimental needs.

As a tribute to this work I'll try to give a personal view of how much the results of the LHC experiments depend on work of development on the physics generators which has taken place in the last 25 years

An example

Workshop called by Paolo in 2006 to educate the Italian LHC community to Monte Carlos



Workshop's Organizing Committee

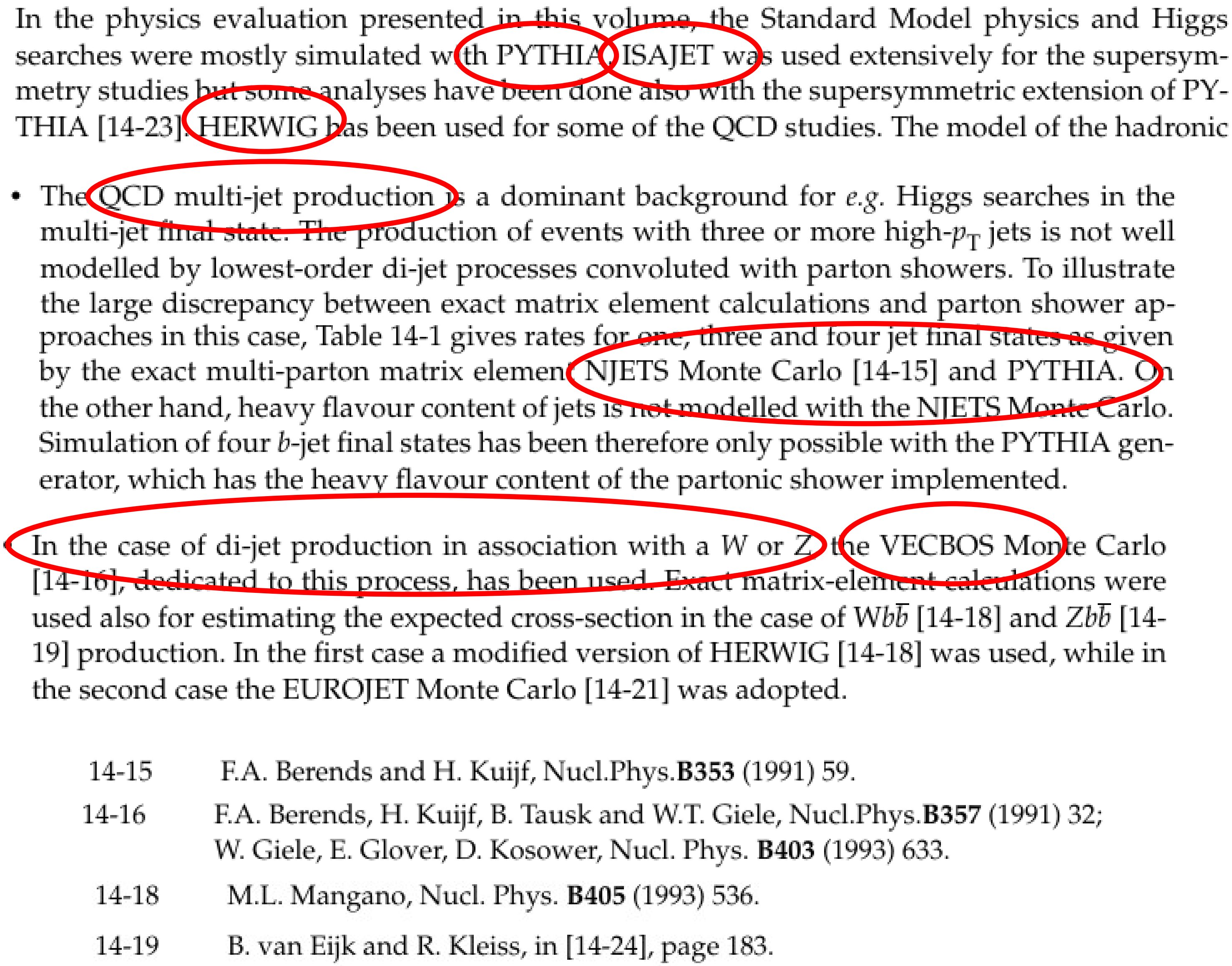
V. Del Duca, B. Mele, P. Nason, G. Polesello (ATLAS), R. Tenchini (CMS)

I normally give to read The intro to shower MCs by Paolo in this volume to my new students

PREFACE

hese proceedings collect the presentations given at the first three meetings Workshop on Monte Carlo's, Physics and Simulations at the LH”, held on February 27-28, May 22-24 and October 23-25 2006 in Frascati (Italy). The purpose of the workshop, sponsored by the INFN, was to bring together all the complementary Italian scientific communities interested into high p_T physics at the LHC. The workshop was thus attended by LHC experimental physicists, theoretical physicists dedicated to the calculation of matrix elements for collider processes and to the implementation of Monte Carlo programs, and theoretical physicists interested into model building and physics beyond the Standard Model. Theoretical Standard Model prediction, as well as physics signals from new models, are made available to the experimental community as Monte Carlo generators, that thus constitute the meeting points of the three communities mentioned above. The aim of the workshop was essentially to start to talk to each other, and to begin to understand the methods, the problems, and the language of the complementary communities.

Archeology: from the ATLAS TDR (1999)



In the physics evaluation presented in this volume, the Standard Model physics and Higgs searches were mostly simulated with PYTHIA. ISAJET was used extensively for the supersymmetry studies but some analyses have been done also with the supersymmetric extension of PYTHIA [14-23]. HERWIG has been used for some of the QCD studies. The model of the hadronic

- The QCD multi-jet production is a dominant background for *e.g.* Higgs searches in the multi-jet final state. The production of events with three or more high-p_T jets is not well modelled by lowest-order di-jet processes convoluted with parton showers. To illustrate the large discrepancy between exact matrix element calculations and parton shower approaches in this case, Table 14-1 gives rates for one, three and four jet final states as given by the exact multi-parton matrix element NJETS Monte Carlo [14-15] and PYTHIA. On the other hand, heavy flavour content of jets is not modelled with the NJETS Monte Carlo. Simulation of four *b*-jet final states has been therefore only possible with the PYTHIA generator, which has the heavy flavour content of the partonic shower implemented.
- In the case of di-jet production in association with a *W* or *Z*, the VECBOS Monte Carlo [14-16], dedicated to this process, has been used. Exact matrix-element calculations were used also for estimating the expected cross-section in the case of $Wb\bar{b}$ [14-18] and $Zb\bar{b}$ [14-19] production. In the first case a modified version of HERWIG [14-18] was used, while in the second case the EUROJET Monte Carlo [14-21] was adopted.

14-15 F.A. Berends and H. Kuijf, Nucl.Phys.**B353** (1991) 59.

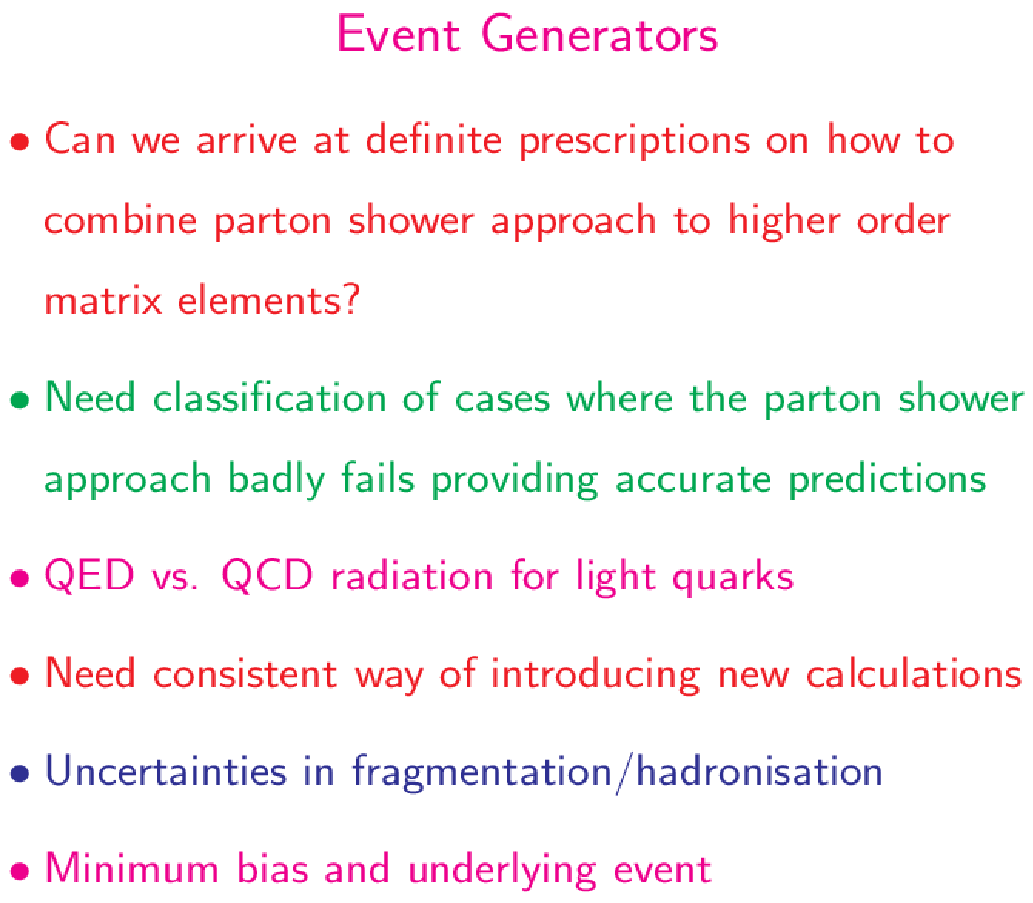
14-16 F.A. Berends, H. Kuijf, B. Tausk and W.T. Giele, Nucl.Phys.**B357** (1991) 32;
W. Giele, E. Glover, D. Kosower, Nucl. Phys. **B403** (1993) 633.

14-18 M.L. Mangano, Nucl. Phys. **B405** (1993) 536.

14-19 B. van Eijk and R. Kleiss, in [14-24], page 183.

But we knew we needed more!

Talk given by GP at Les Houches Workshop 1999, based on talk by D. Denegri and D. Froidevaux the year before



Event Generators

- Can we arrive at definite prescriptions on how to combine parton shower approach to higher order matrix elements?
- Need classification of cases where the parton shower approach badly fails providing accurate predictions
- QED vs. QCD radiation for light quarks
- Need consistent way of introducing new calculations
- Uncertainties in fragmentation/hadronisation
- Minimum bias and underlying event

- Can we arrive at definite prescriptions on how to combine parton shower approach to higher order matrix elements?

1999

Where are we now?

From an inspection of recent papers
of ATLAS and CMS, three different prescriptions
for NLO-PS match are in use as a baseline samples

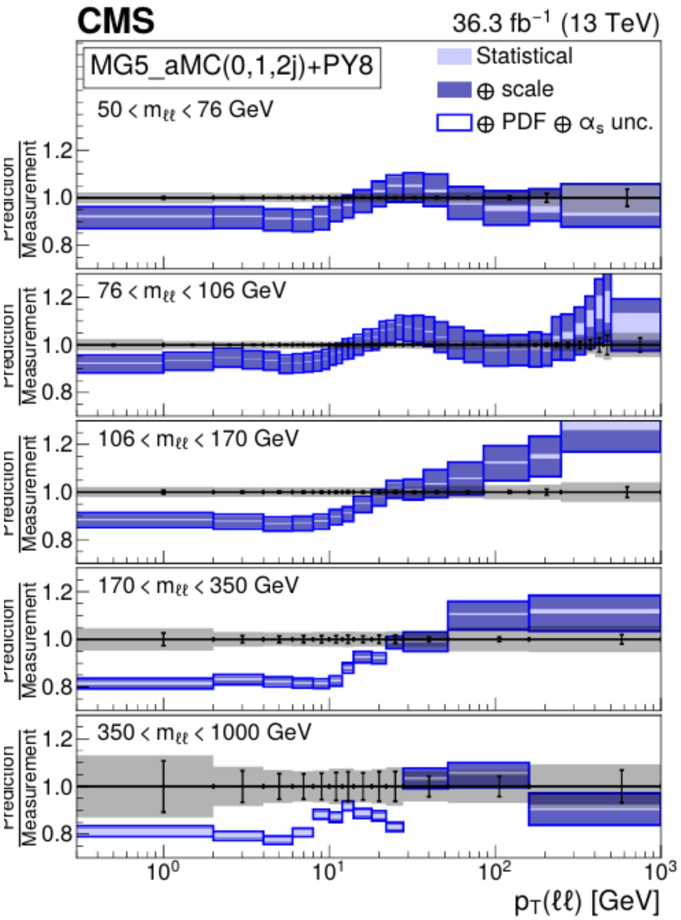
- POWHEG-BOX
  - Higgs Signal: ATLAS + CMS
  - ttbar: ATLAS + CMS
  - single top: ATLAS
  - Diboson: CMS

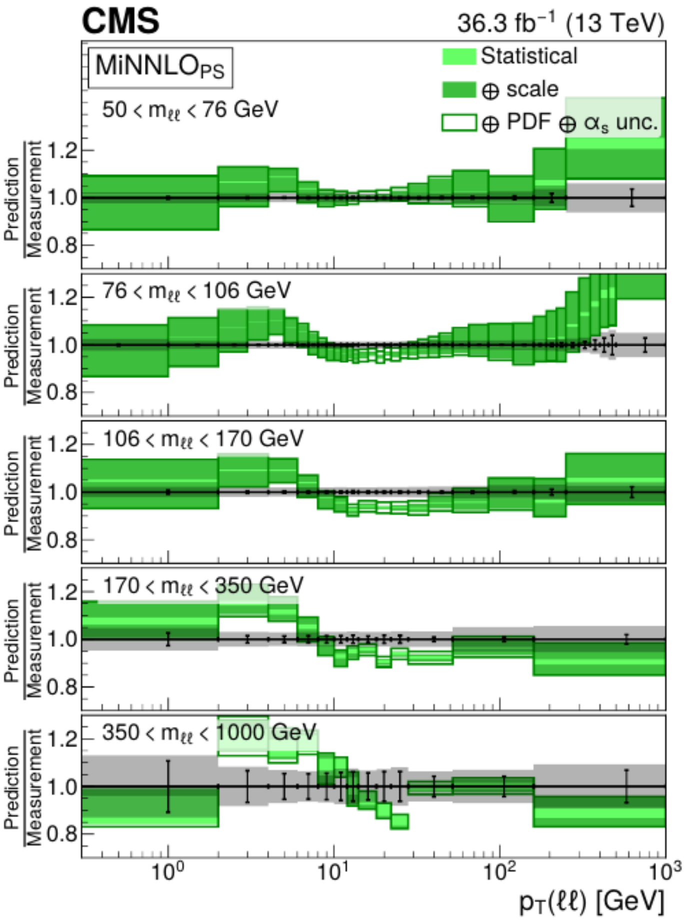
- MG5_McatNLO
  - tt+X: ATLAS + CMS
  - Single top: CMS
  - W/Z+jets: CMS

- SHERPA MEPSatNLO
  - W/Z+ jets: ATLAS
  - Diboson:ATLAS

NNLO+ parton shower simulations are being phased in:

CMS study of pt(ll) dependence or Z production as a function
 of the m(ll) mass bin



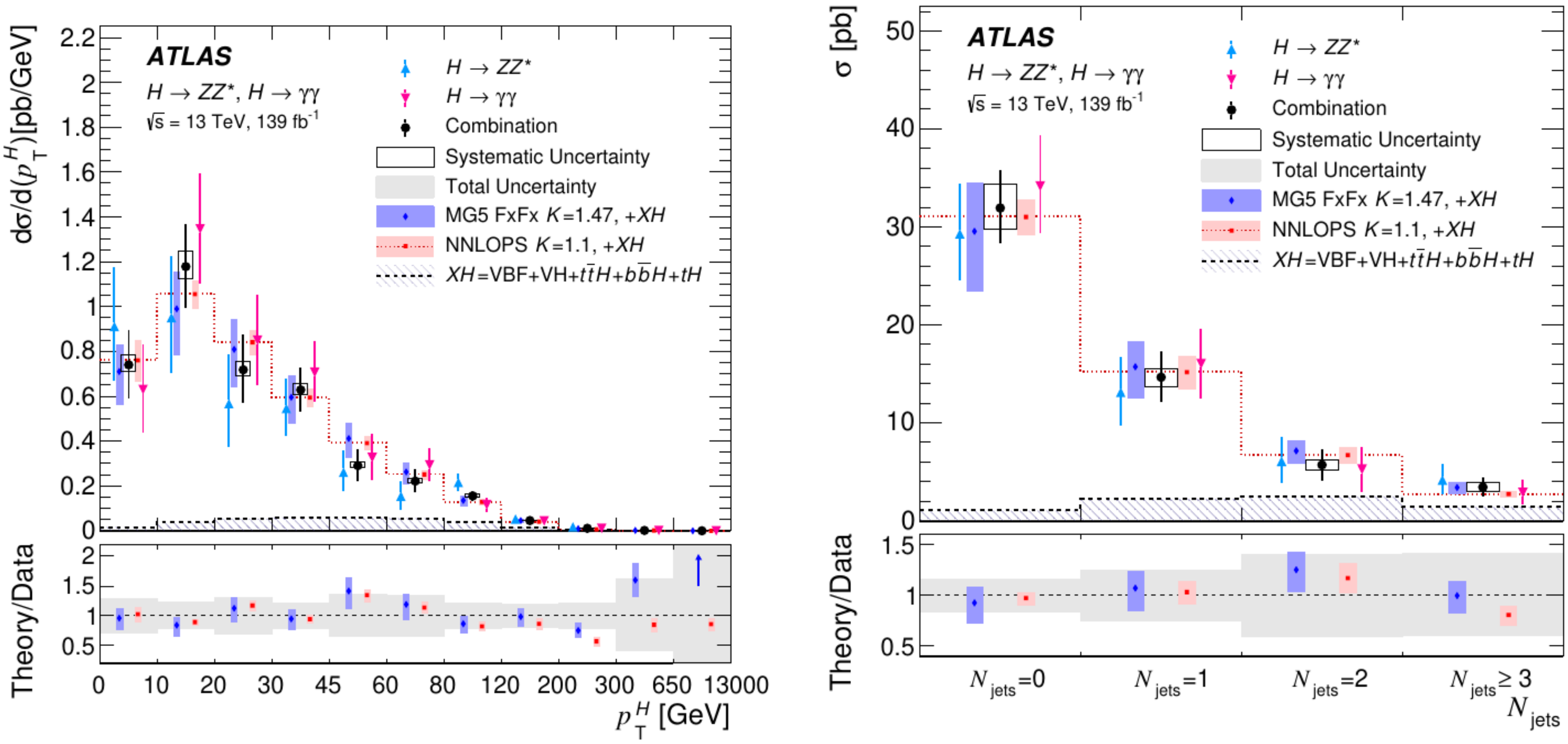


Excellent agreement
off-peak low pt(ll)
for MiNNLOps

arXiv:2205.04897

NLLO+ parton shower simulations are being phased in:

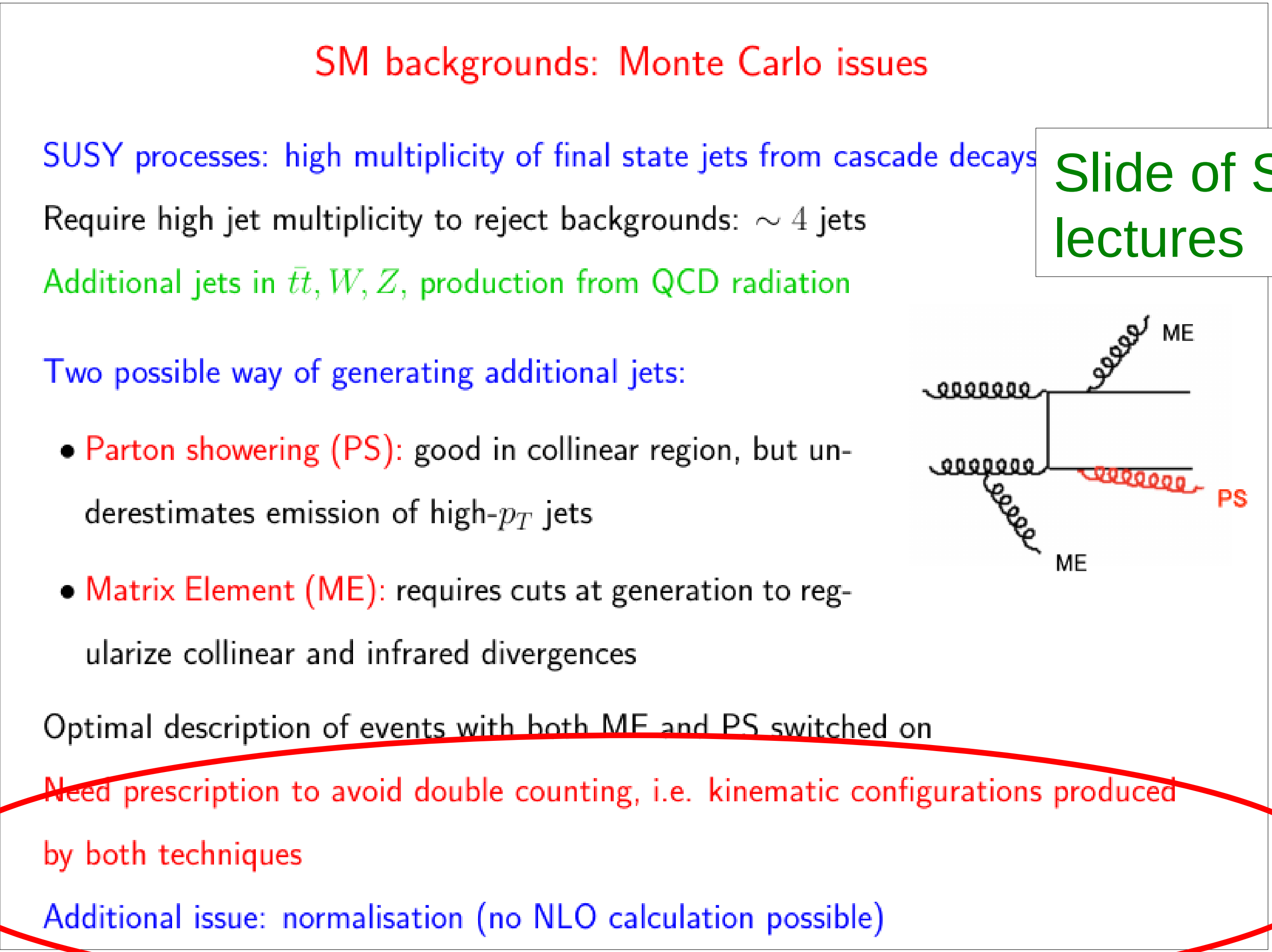
ATLAS measurement of Higgs differential production cross-section
In γγ and 4l channels



arXiv:2207.08615

- Need classification of cases where the parton shower approach badly fails providing accurate predictions

1999



SM backgrounds: Monte Carlo issues

SUSY processes: high multiplicity of final state jets from cascade decays

Require high jet multiplicity to reject backgrounds: ~ 4 jets

Additional jets in $t\bar{t}, W, Z,$ production from QCD radiation

Two possible way of generating additional jets:

- Parton showering (PS): good in collinear region, but underestimates emission of high-p_T jets
- Matrix Element (ME): requires cuts at generation to regularize collinear and infrared divergences

Optimal description of events with both ME and PS switched on

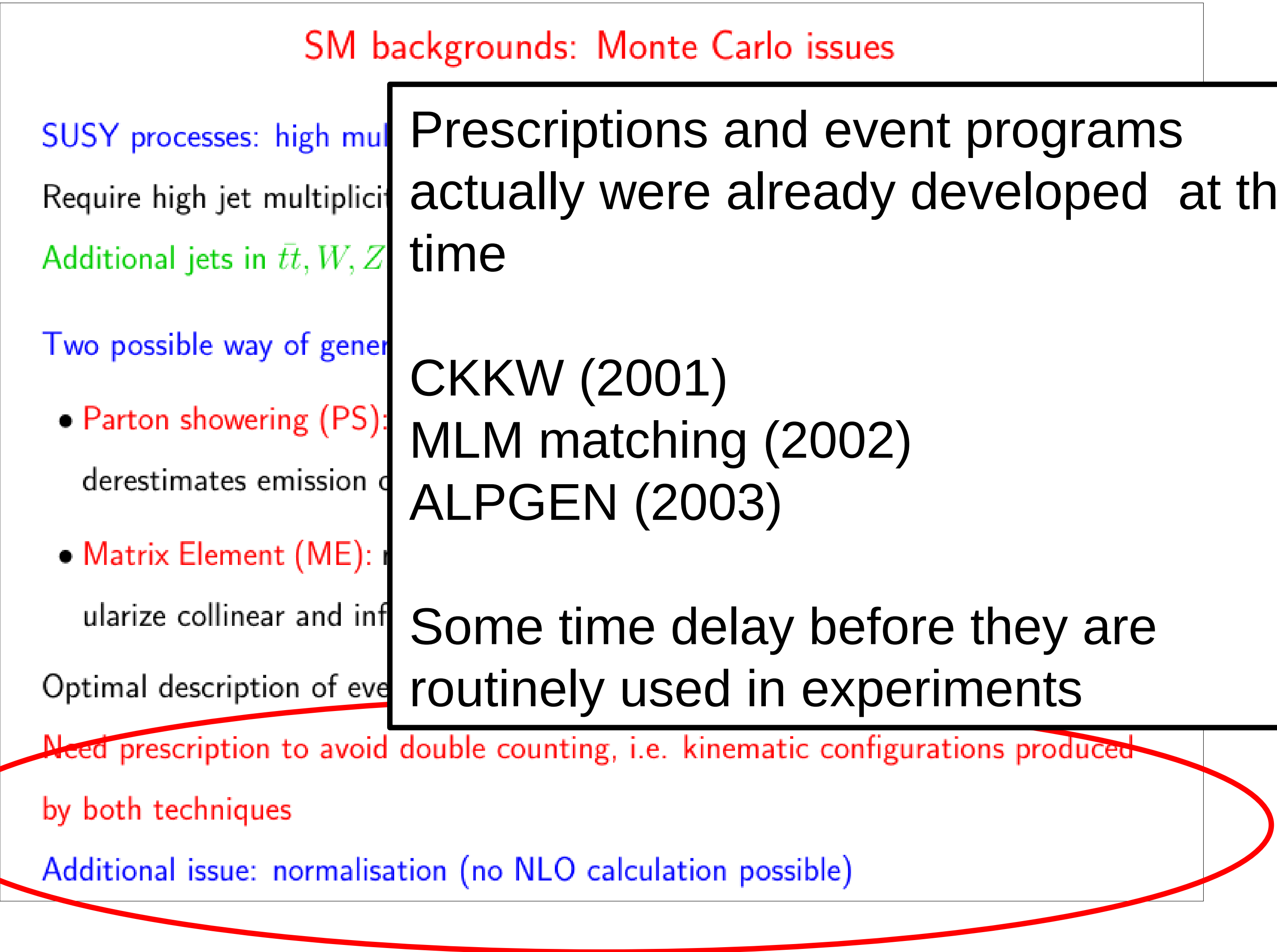
Need prescription to avoid double counting, i.e. kinematic configurations produced by both techniques

Additional issue: normalisation (no NLO calculation possible)

Slide of SUSY lectures I gave circa 2004

- Need classification of cases where the parton shower approach badly fails providing accurate predictions

1999



SM backgrounds: Monte Carlo issues

SUSY processes: high mul

Require high jet multiplici

Additional jets in $t\bar{t}, W, Z$

Two possible way of gener

- Parton showering (PS):

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- Matrix Element (ME): r

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Prescriptions and event programs actually were already developed at the time

CKKW (2001)
MLM matching (2002)
ALPGEN (2003)

Some time delay before they are routinely used in experiments

What do experiments do now for multileg?

ATLAS Multileg configuration of baseline SM samples for Run2 analyses:

W/Z+ jets:

SHERPA 2.2.1 V+0,1,2j NLO, 3,4jLO

Alternate:

MG5_aMC+PY8 V+0-4J LO

Under validation

SHERPA 2.2.11 V+0,1,2j NLO 3,4,5LO

MG5_amC+PY8 FxFx V+0-3JNLO

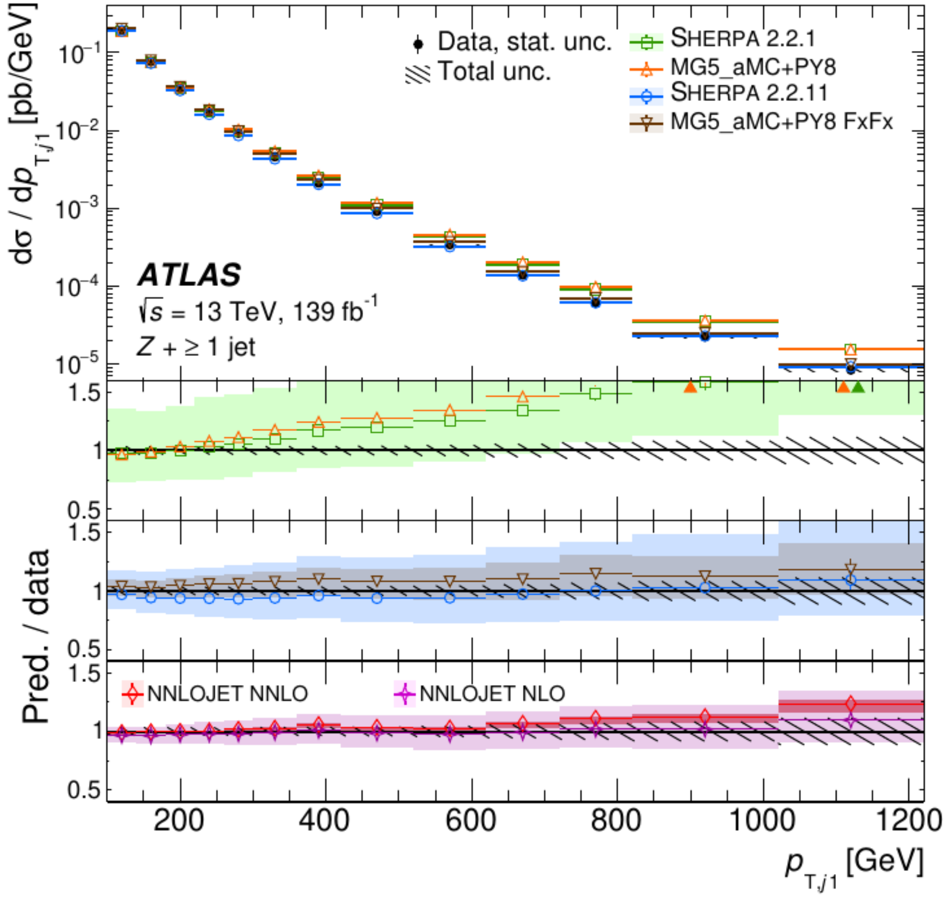
Dibosons:

SHERPA 2.2.2 V+0,1jatNLO, 2,3jLO

ttbb:

NLO ME in 4fs POWHEG-BOX RES

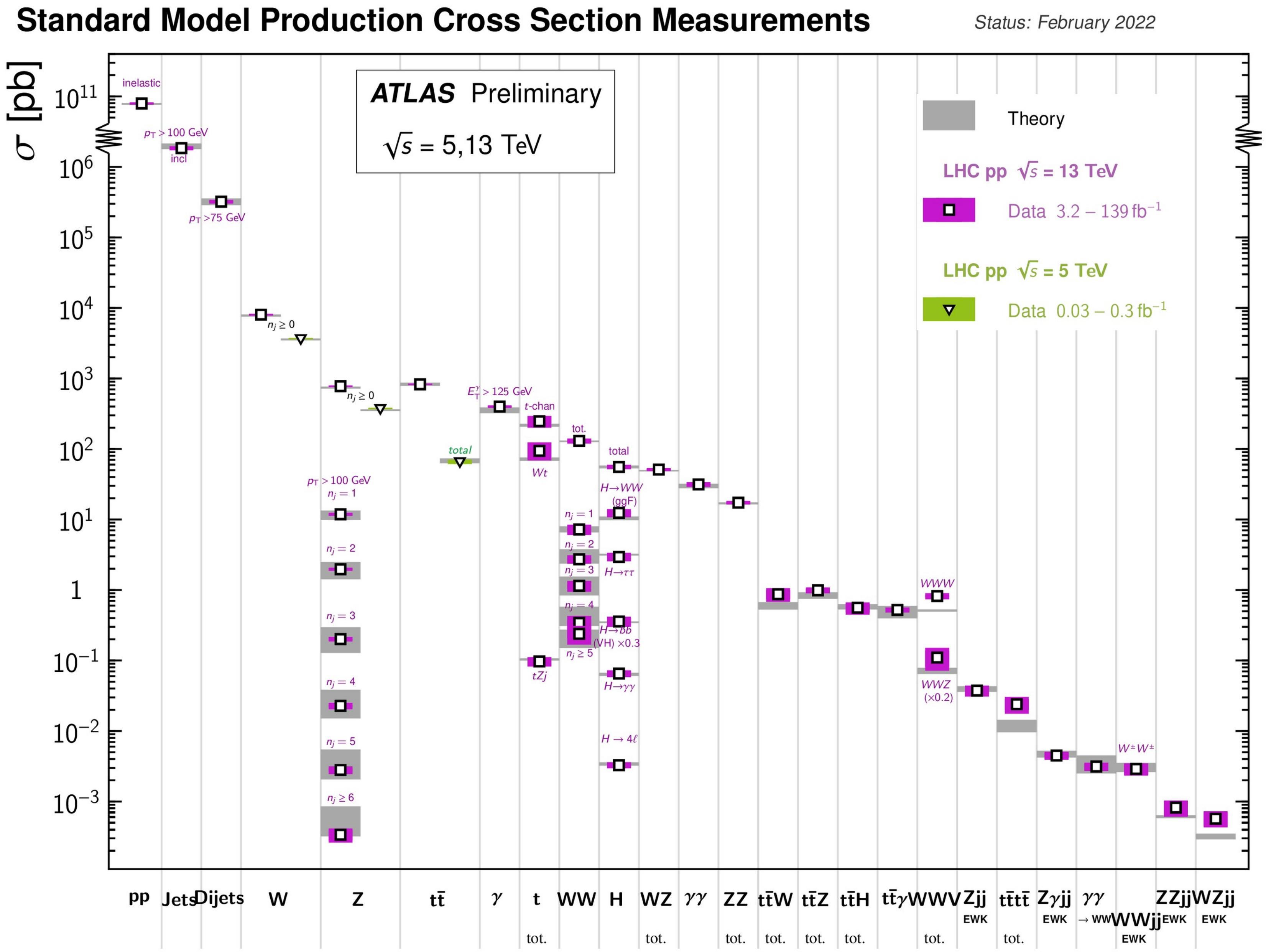
arXiv:2205.02597



Continuing work to improve on Z+jets

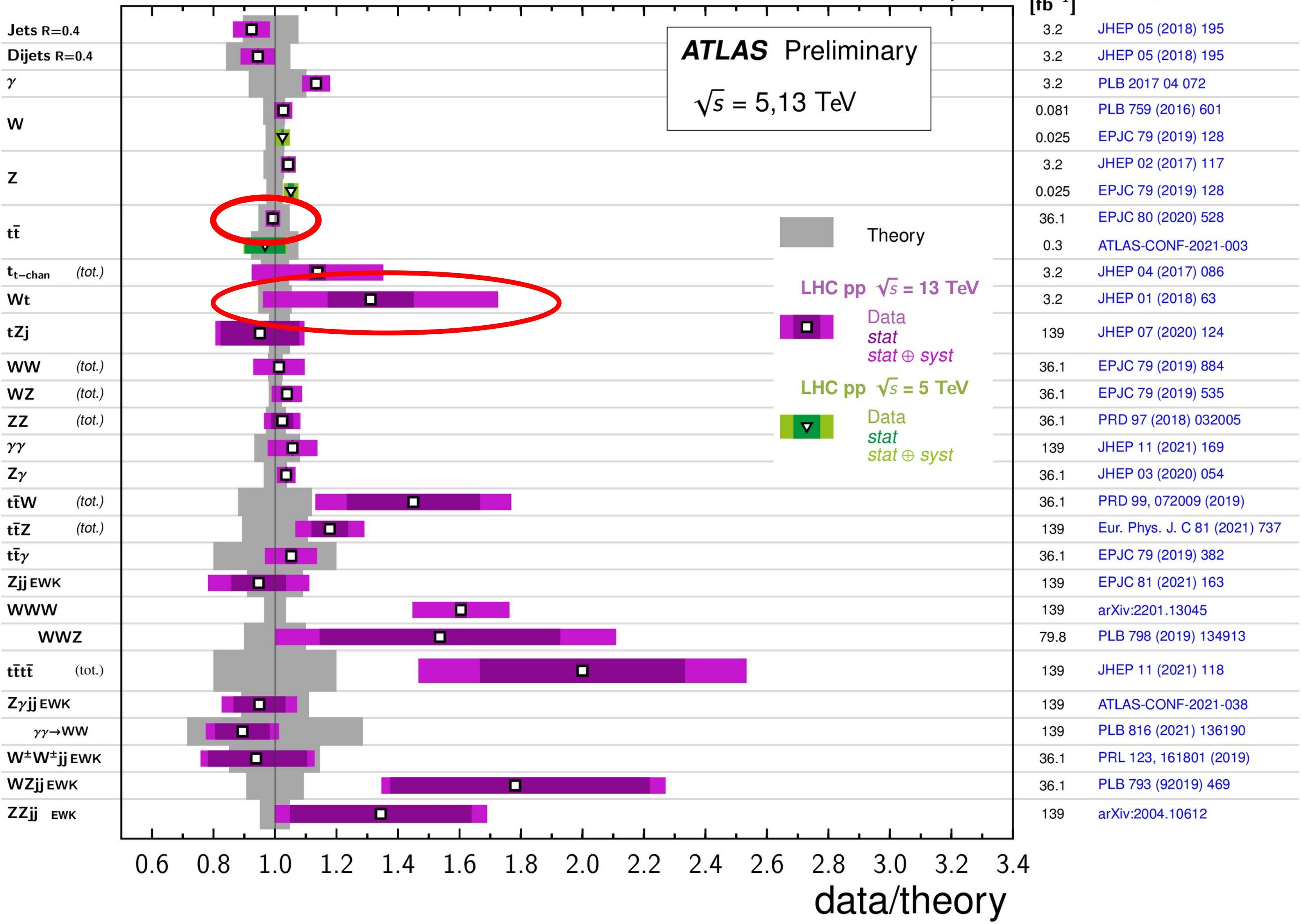
What is the impact of these tools on LHC results?

The glory of SM



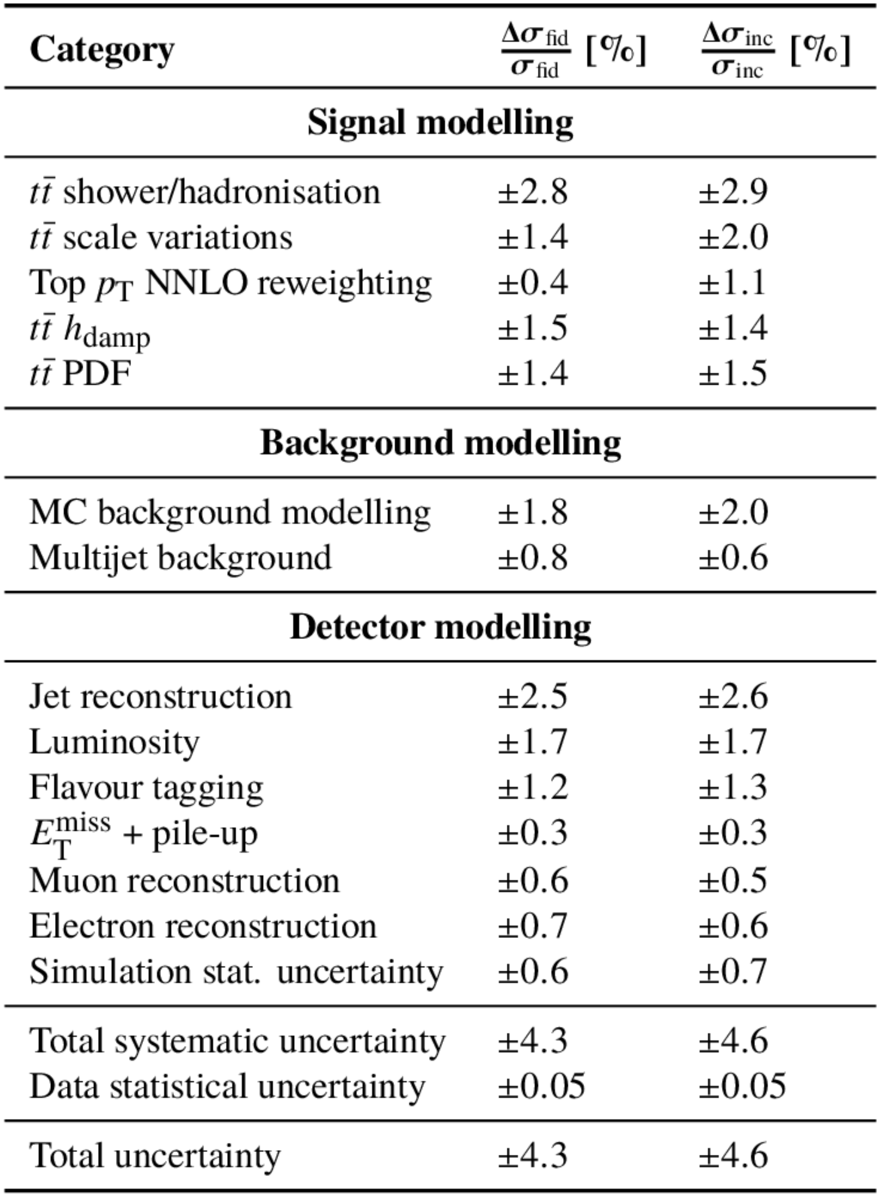
Standard Model Production Cross Section Measurements

Status: February 2022



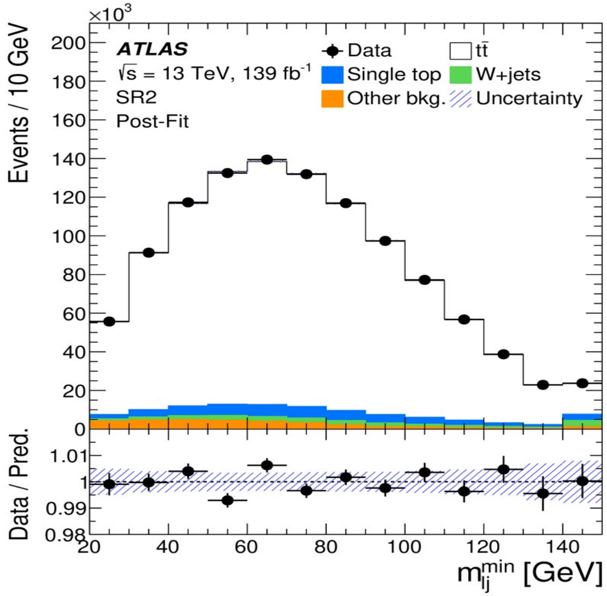
		$\int\mathcal{L}\,dt$ [fb^{-1}]	Reference
Jets R=0.4		3.2	JHEP 05 (2018) 195
Dijets R=0.4		3.2	JHEP 05 (2018) 195
γ		3.2	PLB 2017 04 072
W		0.081	PLB 759 (2016) 601
		0.025	EPJC 79 (2019) 128
Z		3.2	JHEP 02 (2017) 117
		0.025	EPJC 79 (2019) 128
$t\bar{t}$		36.1	EPJC 80 (2020) 528
		0.3	ATLAS-CONF-2021-003
$t_{t\text{-}chan}$	(tot.)	3.2	JHEP 04 (2017) 086
Wt		3.2	JHEP 01 (2018) 63
tZj		139	JHEP 07 (2020) 124
WW	(tot.)	36.1	EPJC 79 (2019) 884
WZ	(tot.)	36.1	EPJC 79 (2019) 535
ZZ	(tot.)	36.1	PRD 97 (2018) 032005
$\gamma\gamma$		139	JHEP 11 (2021) 169
$Z\gamma$		36.1	JHEP 03 (2020) 054
$t\bar{t}W$	(tot.)	36.1	PRD 99, 072009 (2019)
$t\bar{t}Z$	(tot.)	139	Eur. Phys. J. C 81 (2021) 737
$t\bar{t}\gamma$		36.1	EPJC 79 (2019) 382
Zjj EWK		139	EPJC 81 (2021) 163
WWW		139	arXiv:2201.13045
WWZ		79.8	PLB 798 (2019) 134913
$t\bar{t}t\bar{t}$	(tot.)	139	JHEP 11 (2021) 118
$Z\gamma jj$ EWK		139	ATLAS-CONF-2021-038
$\gamma\gamma\to WW$		139	PLB 816 (2021) 136190
$W^{\pm}W^{\pm}jj$ EWK		36.1	PRL 123, 161801 (2019)
WZjj EWK		36.1	PLB 793 (92019) 469
ZZjj EWK		139	arXiv:2004.10612

Example: ATLAS 13 TeV ttbar 1l cross-section



Category	$\frac{\Delta\sigma_{\text{fid}}}{\sigma_{\text{fid}}}$ [%]	$\frac{\Delta\sigma_{\text{inc}}}{\sigma_{\text{inc}}}$ [%]
Signal modelling		
$t\bar{t}$ shower/hadronisation	±2.8	±2.9
$t\bar{t}$ scale variations	±1.4	±2.0
Top p_{T} NNLO reweighting	±0.4	±1.1
$t\bar{t}$ h_{damp}	±1.5	±1.4
$t\bar{t}$ PDF	±1.4	±1.5
Background modelling		
MC background modelling	±1.8	±2.0
Multijet background	±0.8	±0.6
Detector modelling		
Jet reconstruction	±2.5	±2.6
Luminosity	±1.7	±1.7
Flavour tagging	±1.2	±1.3
$E_{\text{T}}^{\text{miss}}$ + pile-up	±0.3	±0.3
Muon reconstruction	±0.6	±0.5
Electron reconstruction	±0.7	±0.6
Simulation stat. uncertainty	±0.6	±0.7
Total systematic uncertainty	±4.3	±4.6
Data statistical uncertainty	±0.05	±0.05
Total uncertainty	±4.3	±4.6

Phys. Lett. B 810 (2020) 135797



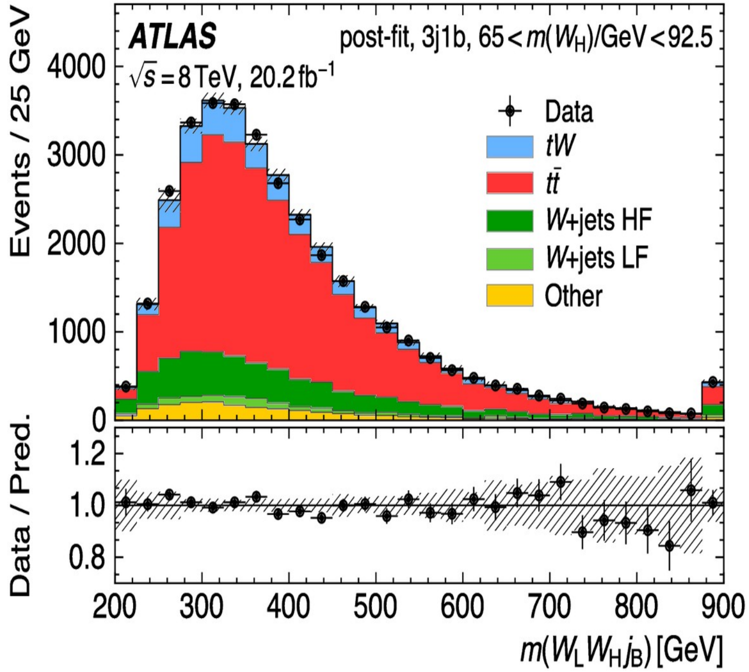
Bulk analysis: desired signal dominates background with very moderate fiducial

Systematics both from signal modelling as from detector modelling small, a few percent

Example: ATLAS Wt cross-section at 8 TeV

Source	Uncertainty [%]
Jet energy scale	10
b-tagging	8
Jet energy resolution	7
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	7
Lepton reconstruction	4
Luminosity	3
Jet vertex fraction	3
$t\bar{t}$ radiation	10
tW radiation	9
tW–$t\bar{t}$ interference	7
$t\bar{t}$ cross-section normalisation	6
Other background cross-section normalisations	5
tW and $t\bar{t}$ parton shower	4
tW and $t\bar{t}$ NLO matching	3
PDF	1
Model statistics	11
Data statistics	4
Total	27

Eur. Phys. J. C 81 (2021) 720



Search-like analysis: fight with much larger background:
Need to apply selections relying on detailed kinematics
→ large modelling errors

Systematic error on modelling

Detector Modelling

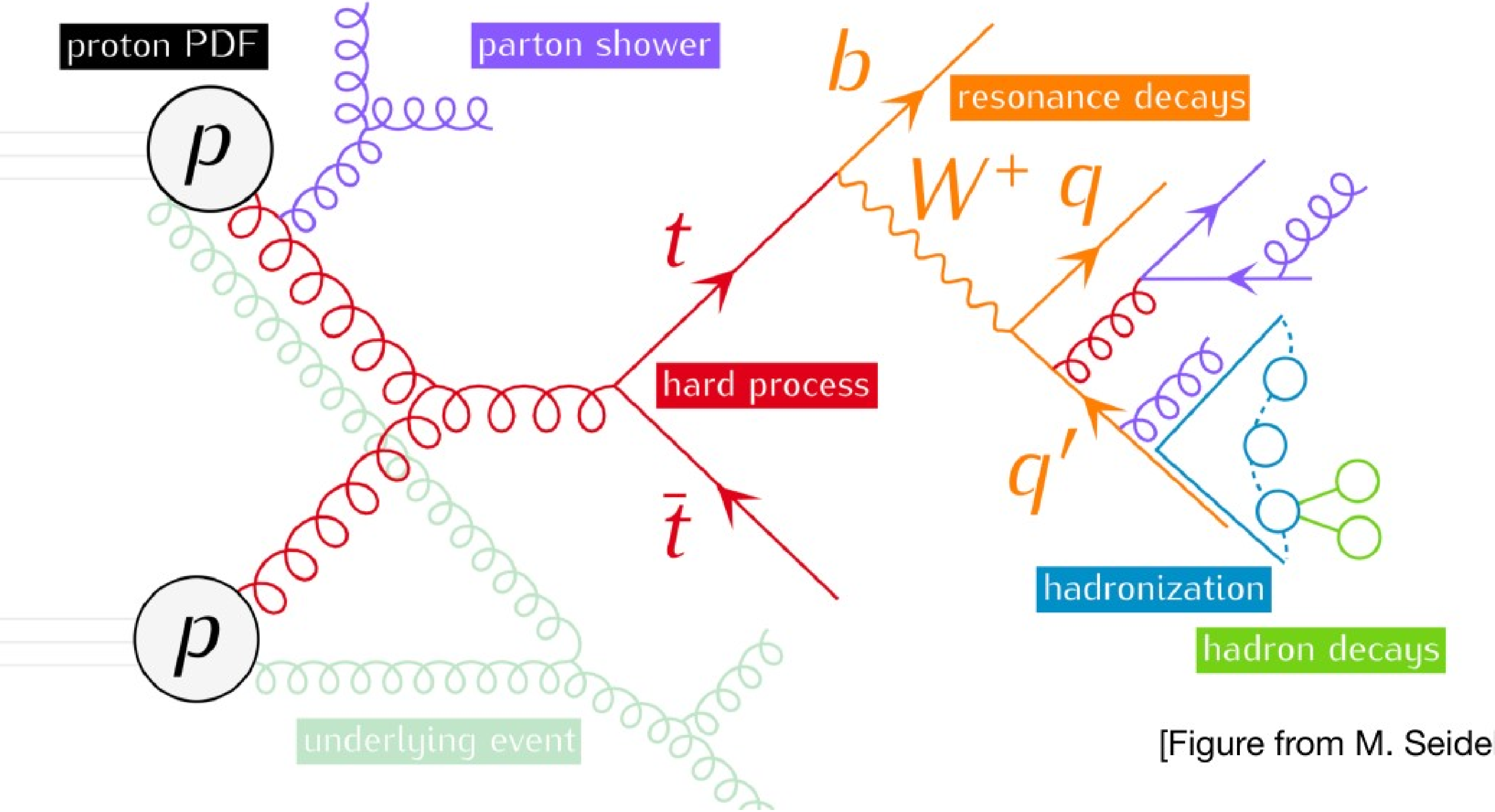
Trigger efficency
Jet energy scale and resolution
Lepton energy scale and efficiency
Etmiss soft component
b-tagging
Luminosity
Pileup modelling

Physics Modelling

Missing Higher orders
(scale variations)
PDFs
NLO matching
Initial State Radiation
Final State Radiation
Underlying Event
B-fragmentation
Fragmentation

Relative impact of the two groups strongly
Depends on the analysis

Physics modelling of top production



[Figure from M. Seidel]

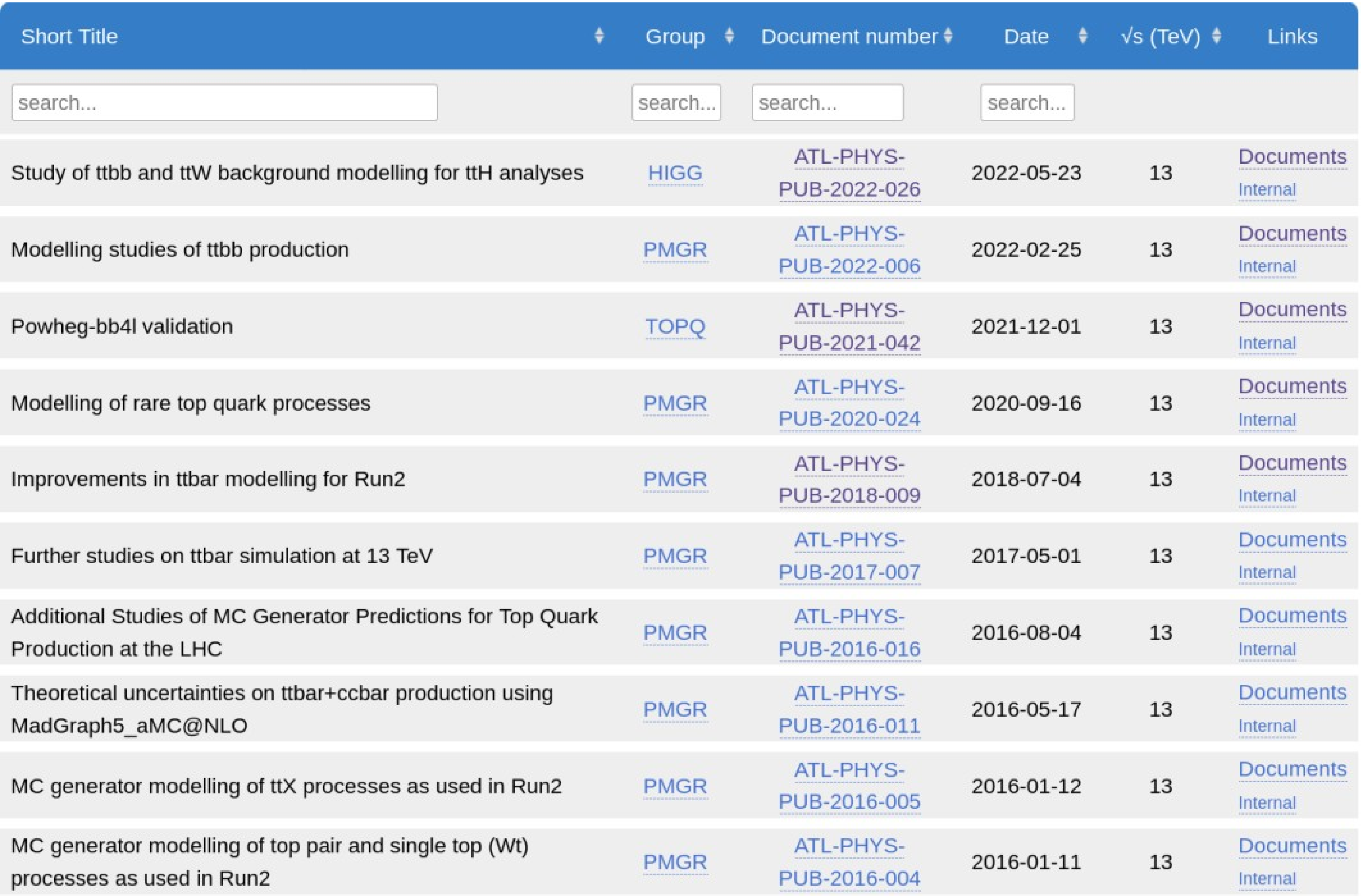
Theoretical uncertainties on MC modelling: ttbar

Systematic	**ATLAS**	**CMS**
Nominal	PowhegPythia8	
PDFs	PDF4LHC recommendations	
NLO matching	Powheg vs MC@NLO	MC@NLO as cross-check but reweights top p_T to NNLO
Initial State Radiation	7-point variations of $\mu_R^{\mathrm{ME}}, \mu_F^{\mathrm{ME}}$ + independent variations of $h_{\mathrm{damp}}, \mu_R^{\mathrm{PS,ISR}}$	
Final State Radiation	Variations of $\mu_R^{\mathrm{PS,FSR}}$	
Underlying Event	Tune variations (*A14*/*CP5*) + different CR models	
B-fragmentation	Variations of r_B parameter in Pythia8 (CMS also compares to Peterson fragmentation)	
Fragmentation/ Hadronisation	Pythia8 vs Herwig7	Pythia6 vs Herwig++ (only impact on jet response)
ttbar/Wt interference	DR vs DS in Powheg	

Study all possible variations of key parameters or compare different implementations

Slide from talk by S.Amoroso at TOP2020

Huge and protracted investment in tuning the parameters of top simulation and evaluating the relative uncertainties

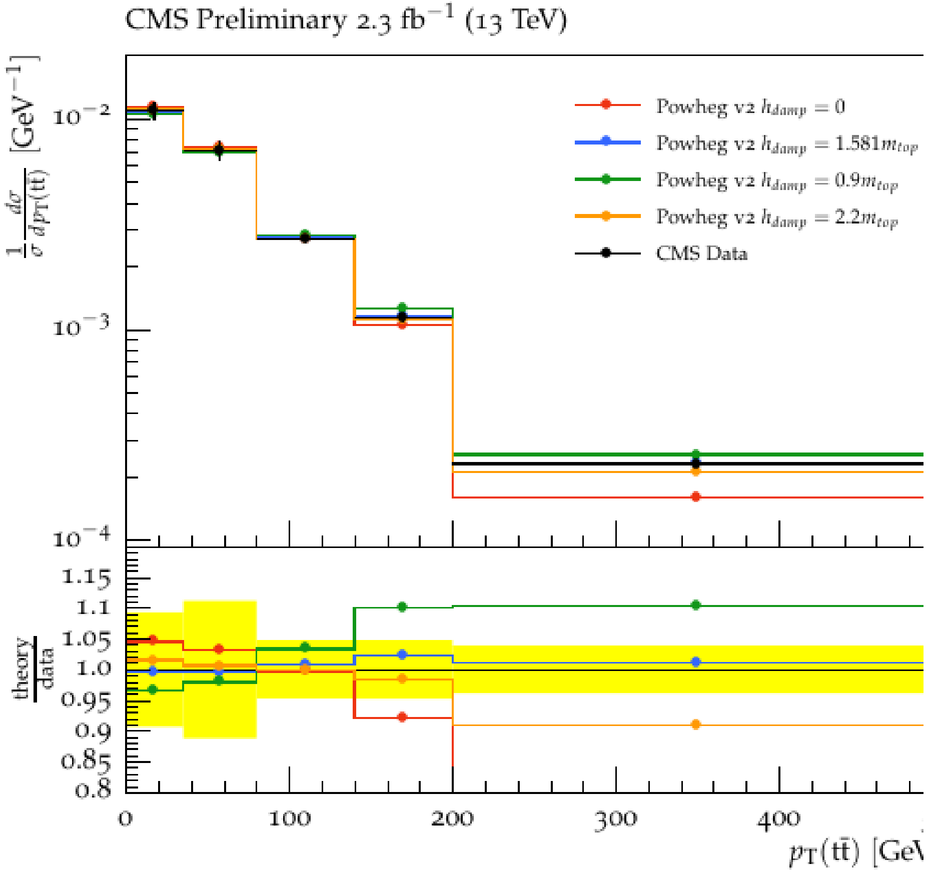


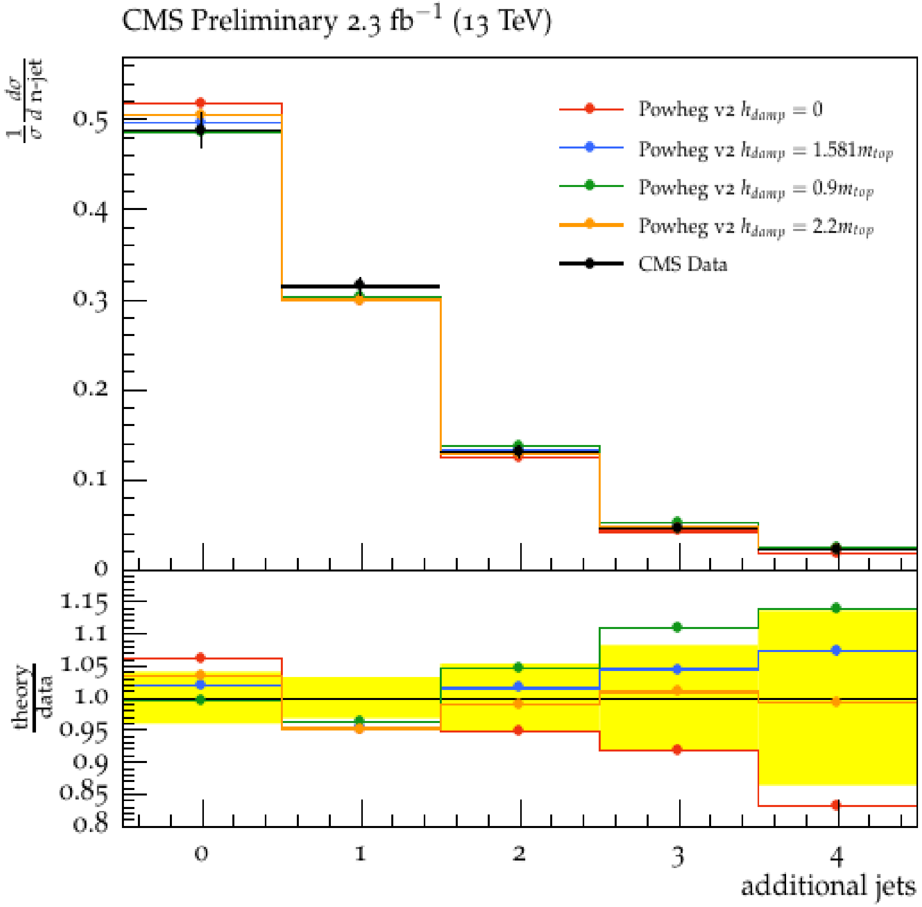
Short Title	Group	Document number	Date	√s (TeV)	Links
search...	search...	search...	search...		
Study of ttbb and ttW background modelling for ttH analyses	HIGG	ATL-PHYS-PUB-2022-026	2022-05-23	13	Documents Internal
Modelling studies of ttbb production	PMGR	ATL-PHYS-PUB-2022-006	2022-02-25	13	Documents Internal
Powheg-bb4l validation	TOPQ	ATL-PHYS-PUB-2021-042	2021-12-01	13	Documents Internal
Modelling of rare top quark processes	PMGR	ATL-PHYS-PUB-2020-024	2020-09-16	13	Documents Internal
Improvements in ttbar modelling for Run2	PMGR	ATL-PHYS-PUB-2018-009	2018-07-04	13	Documents Internal
Further studies on ttbar simulation at 13 TeV	PMGR	ATL-PHYS-PUB-2017-007	2017-05-01	13	Documents Internal
Additional Studies of MC Generator Predictions for Top Quark Production at the LHC	PMGR	ATL-PHYS-PUB-2016-016	2016-08-04	13	Documents Internal
Theoretical uncertainties on ttbar+ccbar production using MadGraph5_aMC@NLO	PMGR	ATL-PHYS-PUB-2016-011	2016-05-17	13	Documents Internal
MC generator modelling of ttX processes as used in Run2	PMGR	ATL-PHYS-PUB-2016-005	2016-01-12	13	Documents Internal
MC generator modelling of top pair and single top (Wt) processes as used in Run2	PMGR	ATL-PHYS-PUB-2016-004	2016-01-11	13	Documents Internal

ATLAS Physics Modelling public results

An example: the h_{damp} parameter

- In POWHEG matching the amount of real radiation to exponentiate is regulated by the factor $h^2_{damp}/(h^2_{damp}+p_T^2)$, where h_{damp} is to be tuned with data(N_{jets}, p_T(top), p_T(j1), p_T(tt))

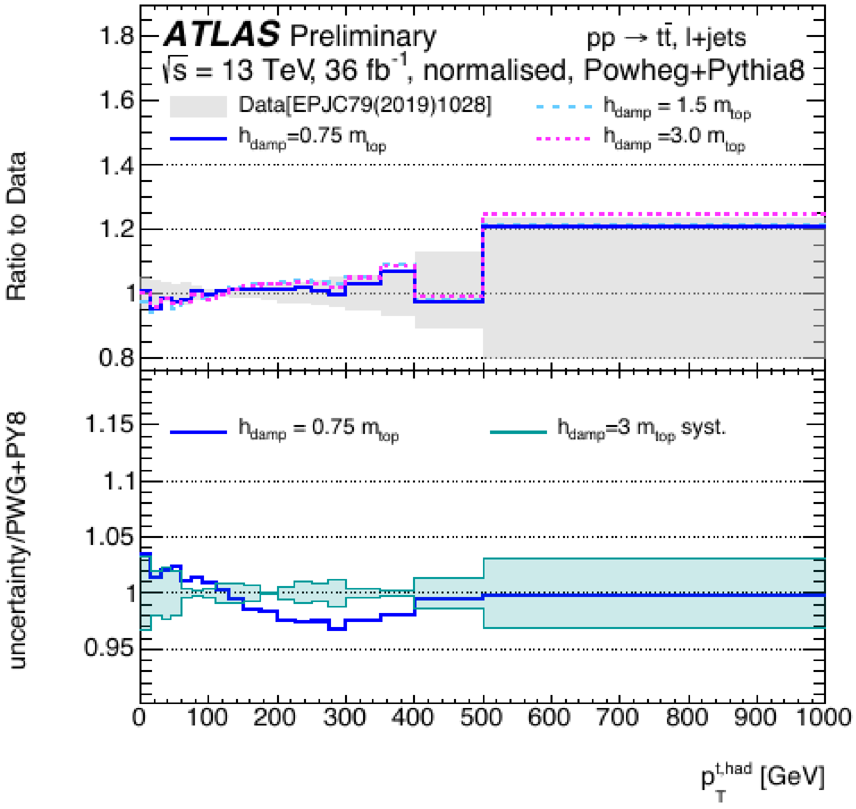


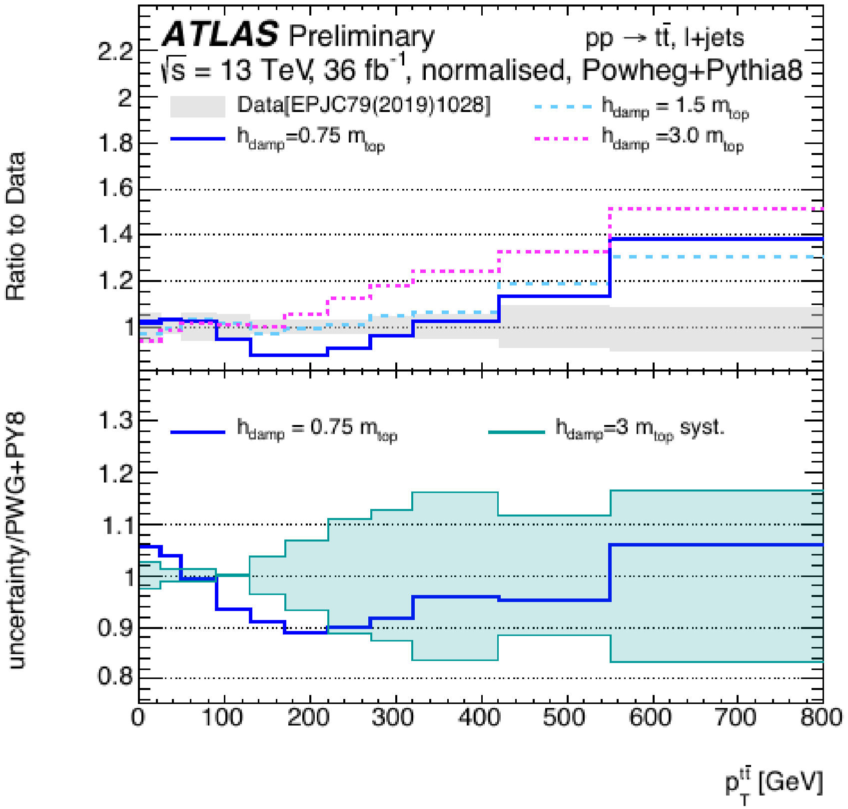


CMS TOP-16-21-PAS

Uncertainty on h_{damp}

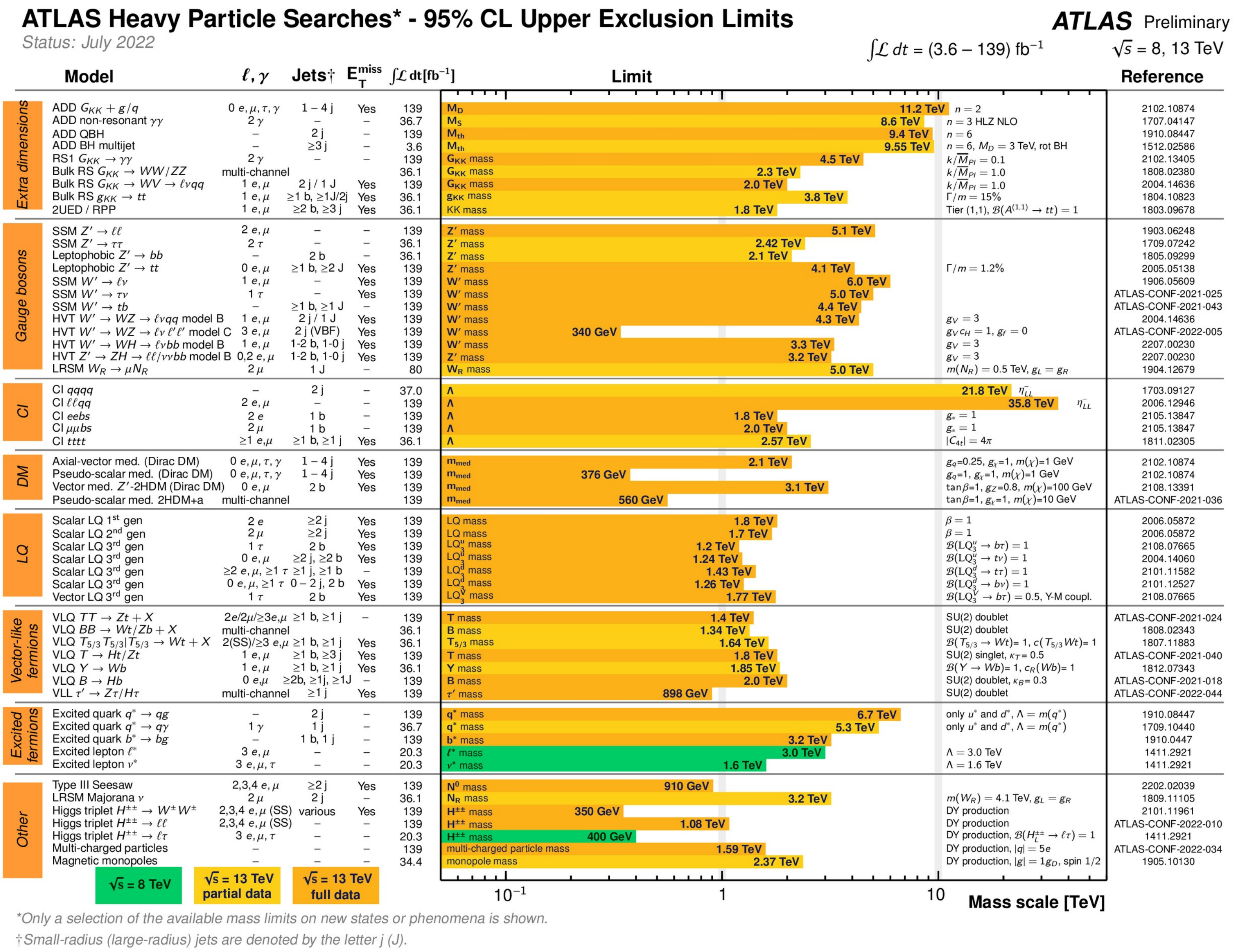
CMS fits h_{damp}1.58+0.66 -0.59, ATLAS uses h_{damp}=1.5 with uncertainty from a symmetrised h_{damp}=3 variation





ATL-PHYS-PUB-2020-023

Searches



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: July 2022

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D	11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th}	9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass	4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass	2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass	2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass	3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass	1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass	5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass	2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass	2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass	4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass	6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass	5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass	4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass	4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass	340 GeV	$g_V c_H = 1$, $g_f = 0$	ATLAS-CONF-2022-005
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e, μ	1-2 b, 1-0 j	Yes	139	W' mass	3.3 TeV	$g_V = 3$	2207.00230
	HVT $Z' \to ZH \to \ell\ell/\nu\nu bb$ model B	0,2 e, μ	1-2 b, 1-0 j	Yes	139	Z' mass	3.2 TeV	$g_V = 3$	2207.00230
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ	35.8 TeV	η_{LL}^-	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ	1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ	2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ	2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med}	2.1 TeV	g_q=0.25, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med}	376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	m_{med}	3.1 TeV	$\tan\beta$=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_{med}	560 GeV	$\tan\beta$=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass	1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass	1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass	1.2 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	2108.07665
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass	1.24 TeV	$\mathcal{B}(LQ_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass	1.43 TeV	$\mathcal{B}(LQ_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass	1.26 TeV	$\mathcal{B}(LQ_3^d \to b\nu) = 1$	2101.12527
	Vector LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^V mass	1.77 TeV	$\mathcal{B}(LQ_3^V \to b\tau) = 0.5$, Y-M coupl.	2108.07665
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass	1.4 TeV	SU(2) doublet	ATLAS-CONF-2021-024
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass	1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \mid T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass	1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass	1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass	1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass	2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass	898 GeV	SU(2) doublet	ATLAS-CONF-2022-044
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass	6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass	5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass	3.2 TeV		1910.0447
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass	910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass	3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass	350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass	1.08 TeV	DY production	ATLAS-CONF-2022-010
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	139	multi-charged particle mass	1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass	2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown.

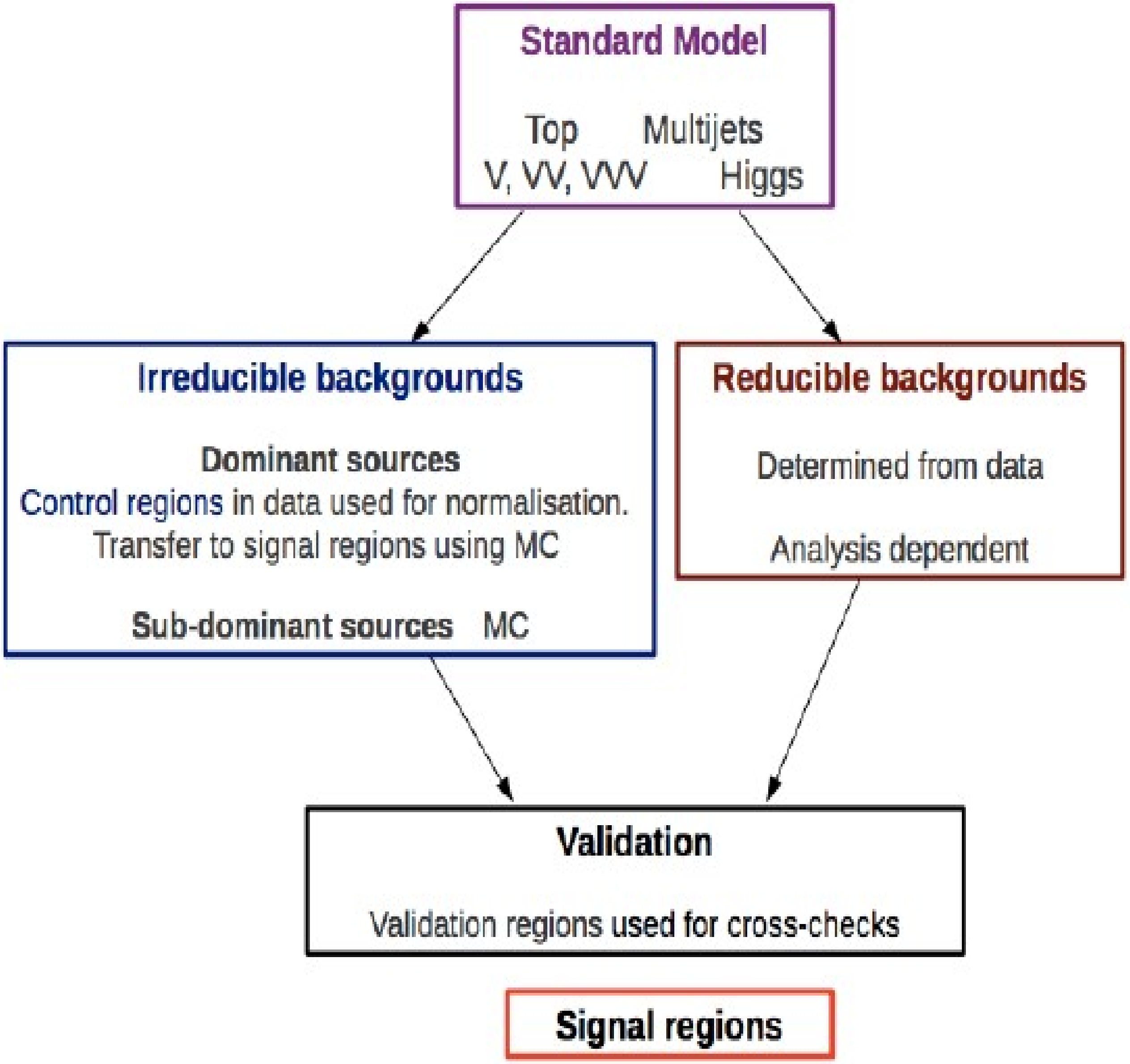
†Small-radius (large-radius) jets are denoted by the letter j (J).

Searches

- By construction searches try to define depopulated corners in the kinematics space of the SM.

  A typical search with signal XS at the fb level needs to reduce the ttbar background by 5 orders of magnitude
- The fact that in hundreds of regions considered the number of events predicted is matched by the observation in data is a huge triumph for SM
- The search results are only as good as the prediction of the expected number of events in the signal region
- Generic approach to estimate:
  - Do not believe MonteCarlo normalisation in very small corner of multidimensional parameter space
  - Believe that ratio of predicted events in two contiguous regions in parameter space correctly predicted by MonteCarlo and that the definition of modelling uncertainties provides a reasonable estimate of the uncertainty on this ratio

Background evaluation scheme for searches



Standard Model

Top Multijets
V, VV, VVV Higgs

Irreducible backgrounds

Dominant sources
Control regions in data used for normalisation.
Transfer to signal regions using MC

Sub-dominant sources MC

Reducible backgrounds

Determined from data

Analysis dependent

Validation

Validation regions used for cross-checks

Signal regions

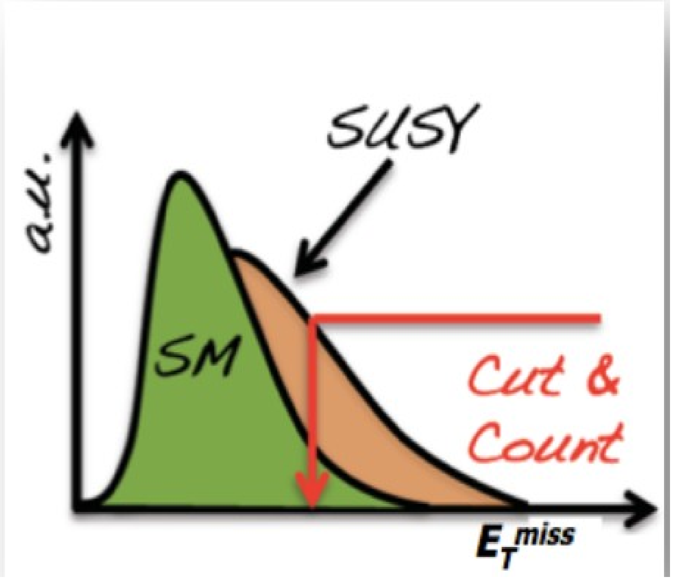
Main examples:

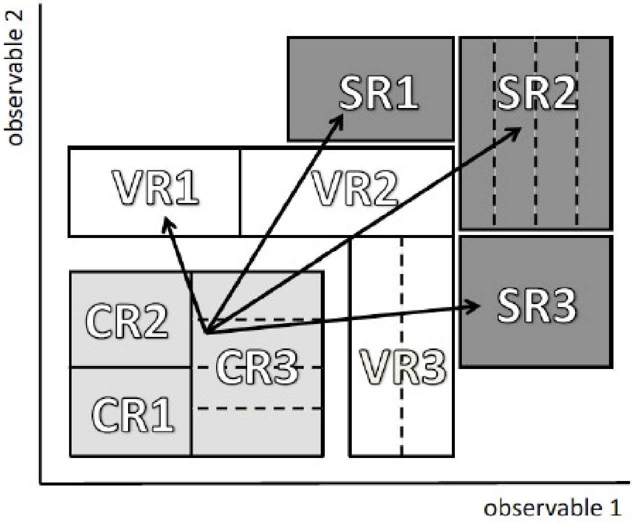
- Non-prompt leptons
- Charge-flip leptons
- E_T^{miss} from multi-jet mismeasurement

Estimate ~independent from simulation, I'll not speak further on it

Background estimate for irreducible backgrounds

- Define a set of observables providing discrimination between signal and backgrounds
- Three type of regions defined:
  - Signal Regions (SR) dominated by signal
  - Control Region (CR) in variable space near SR, with small expected signal contamination.
  - Verify prediction in Validation Regions (VR) typically intermediate





Typically define a CR for each major irreducible background

Master formula

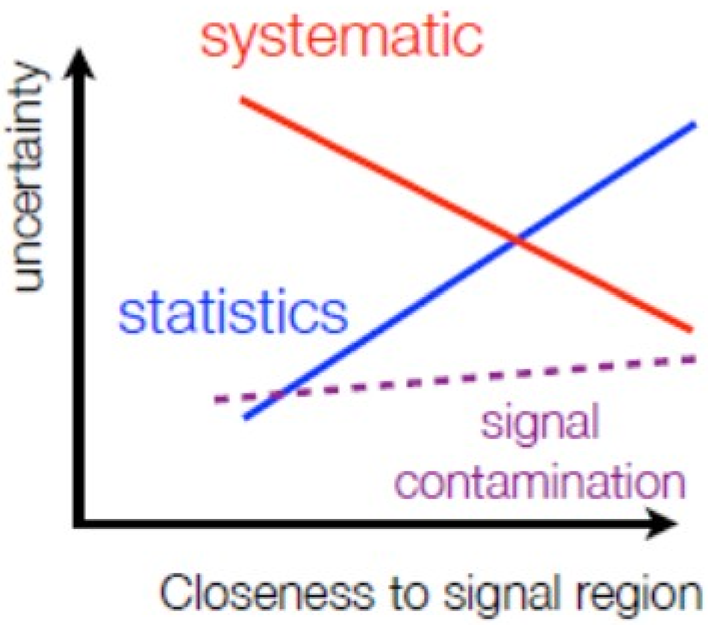
$$N^i_{SR} = \frac{N^{i,MC}_{SR}}{N^{i,MC}_{CR}}\left(N^{i,data}_{CR} - \sum_{j=process} N^{j,MC}_{CR}\right) = \boxed{T}\left(\boxed{N^{i,data}_{CR}} - \boxed{\sum_{j=process} N^{j,MC}_{CR}}\right)$$

Subdominant processes
In CR

Two sources of uncertainty:

- Statistical error on events in CR
- Systematic error on
  - Number of events of subdominant backgrounds
  - Transfer factor T

If CR sufficiently pure, error on T dominant, and error on T is fully a modelling error



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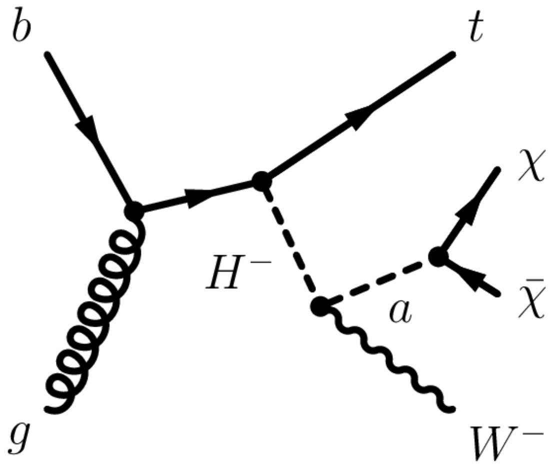
An example: DM+tW analysis



Two lepton final state:

- Two leptons from decays of 2 W
- 1b-tagged jet from top decay
- Etmiss from neutrinos and DM

Main backgrounds: ttbar+tW, ttZ, tWZ

Two main discriminants m_{T2}, and m^{t}_{bl}

$$m_{\mathrm{T2}}(\vec{p}_{\mathrm{T}}^{\,\ell_1}, \vec{p}_{\mathrm{T}}^{\,\ell_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) = \min_{\vec{q}_{\mathrm{T}}} \left[\max \left(m_{\mathrm{T}}^{\mathrm{lep}}(\vec{p}_{\mathrm{T}}^{\,\ell_1}, \vec{q}_{\mathrm{T}}), m_{\mathrm{T}}^{\mathrm{lep}}(\vec{p}_{\mathrm{T}}^{\,\ell_2}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} - \vec{q}_{\mathrm{T}}) \right) \right],$$

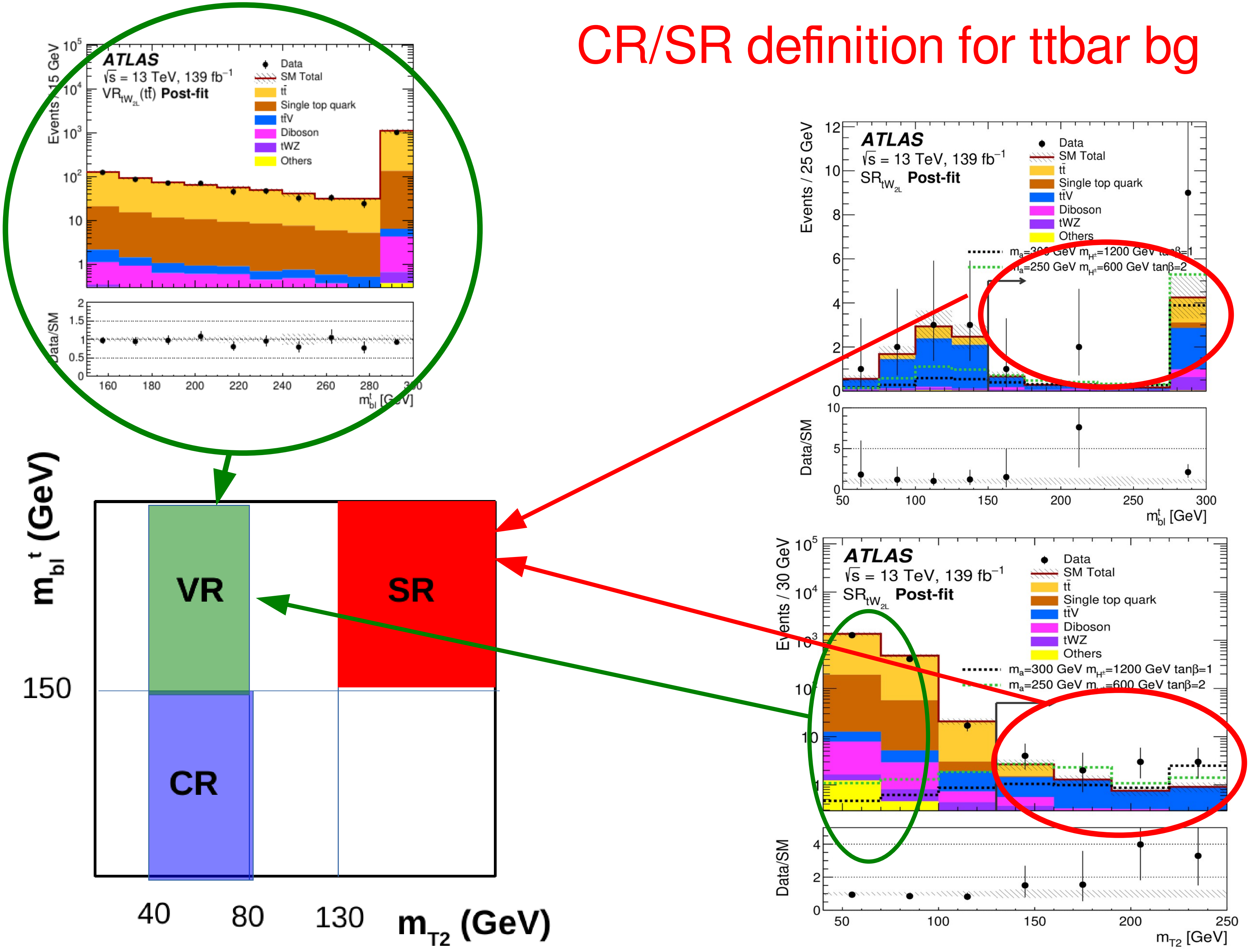
If leptons and all of p_T^{miss} from decay of two W: endpoint at m_W

If event has > 1 jet, build with two leptons all pairs of invariant mass combinations with two most b-like jets in events

$$m^{\mathrm{t}}_{b\ell} = \min[\max(m_{\ell_1 j_1}, m_{\ell_2 j_2}), \max(m_{\ell_1 j_2}, m_{\ell_2 j_1})]$$

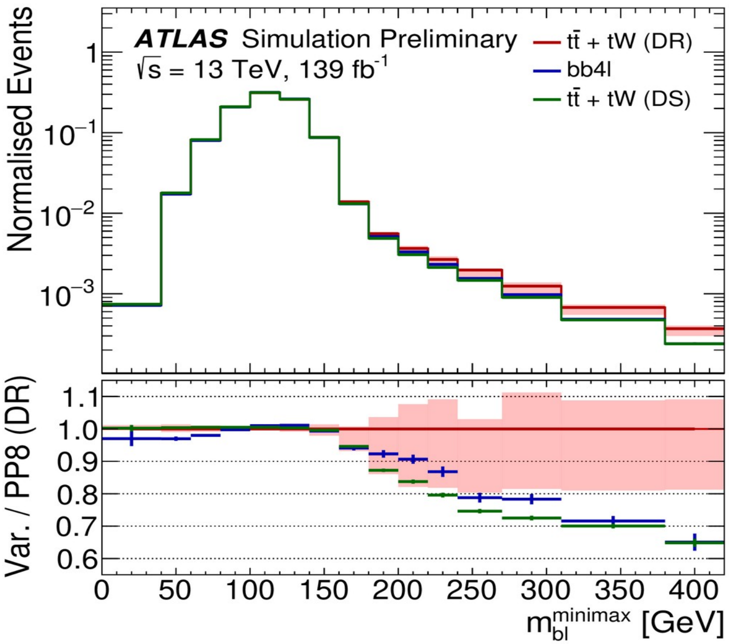
If two lep and two jets from decays of two top quarks m^{t}_{bl}<150 GeV

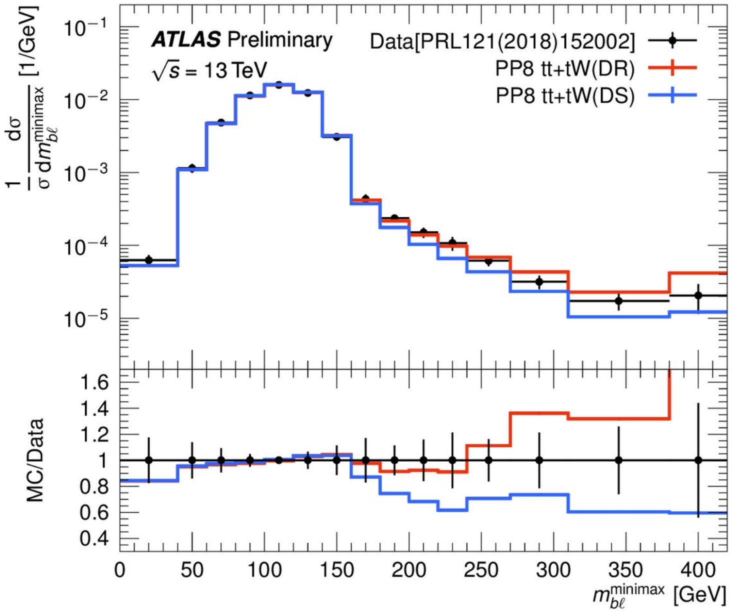
CR/SR definition for ttbar bg

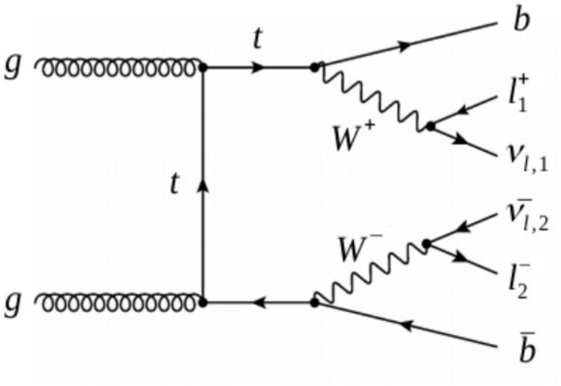


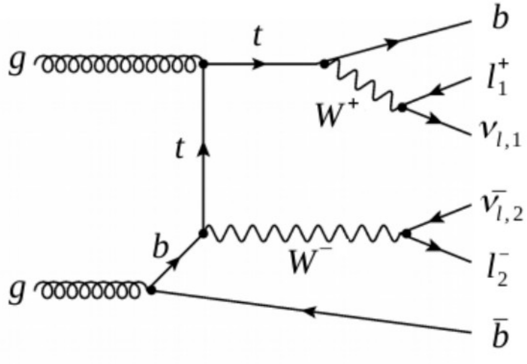
How well do we model m^t_{bl}?

ATL-PHYS-PUB-2021-42









ttbar

tW+b

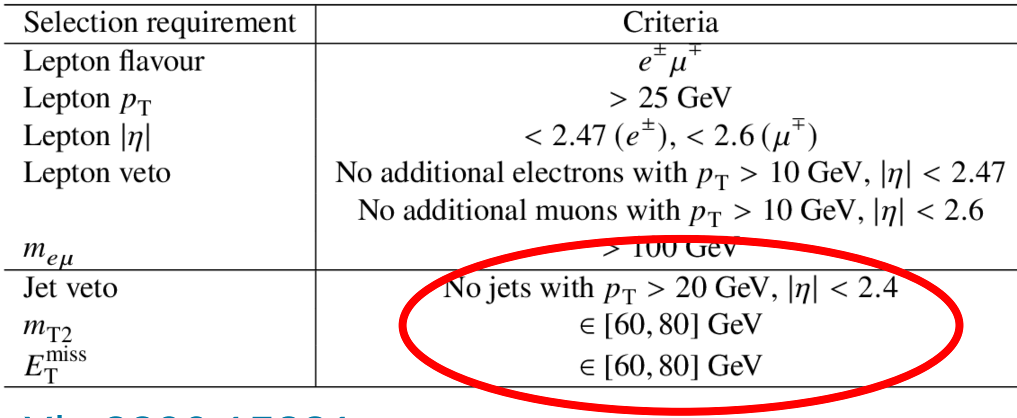
m^t_{bl} extended version of m_{bl}^{minmax}

Sensitive to interference between tt and tW, and to prescriptions to avoid double counting of diagrams

Detailed studies in ATLAS to optimize modelling, and comparison to unfolded ATLAS result

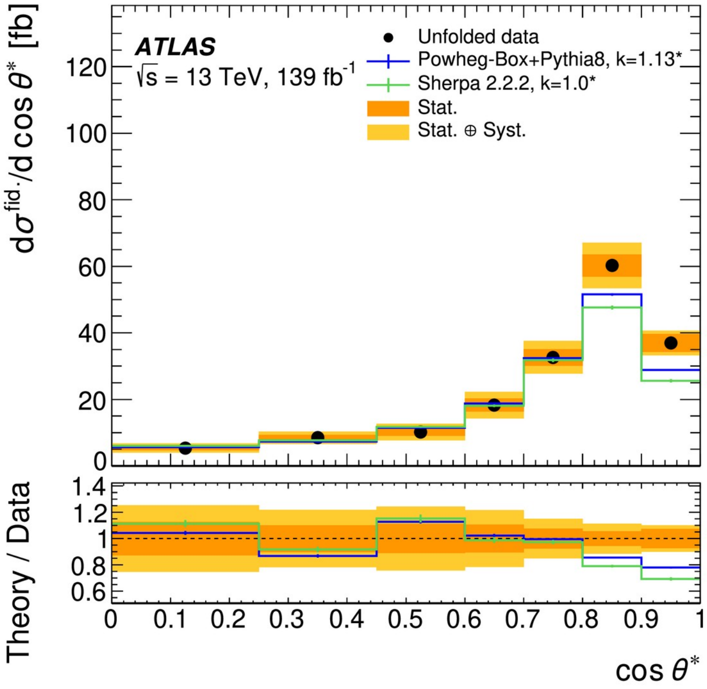
A recent exercise: publish unfolded cross-sections in phase space relevant to searches

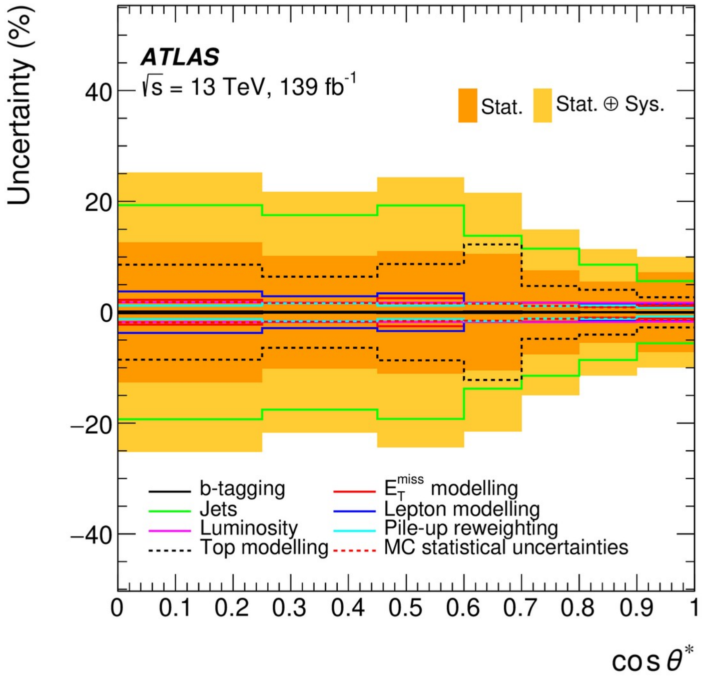
Take WW production, and present unfolded differential cross-section of relevant variables in SR defined by 2l ewkino searches



Selection requirement	Criteria
Lepton flavour	$e^{\pm}\mu^{\mp}$
Lepton p_{T}	> 25 GeV
Lepton $\lvert\eta\rvert$	$< 2.47\,(e^{\pm}), < 2.6\,(\mu^{\mp})$
Lepton veto	No additional electrons with $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.47$ No additional muons with $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.6$
$m_{e\mu}$	> 100 GeV
Jet veto	No jets with $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.4$
m_{T2}	$\in [60, 80]$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\in [60, 80]$ GeV

arXiv:2206.15231





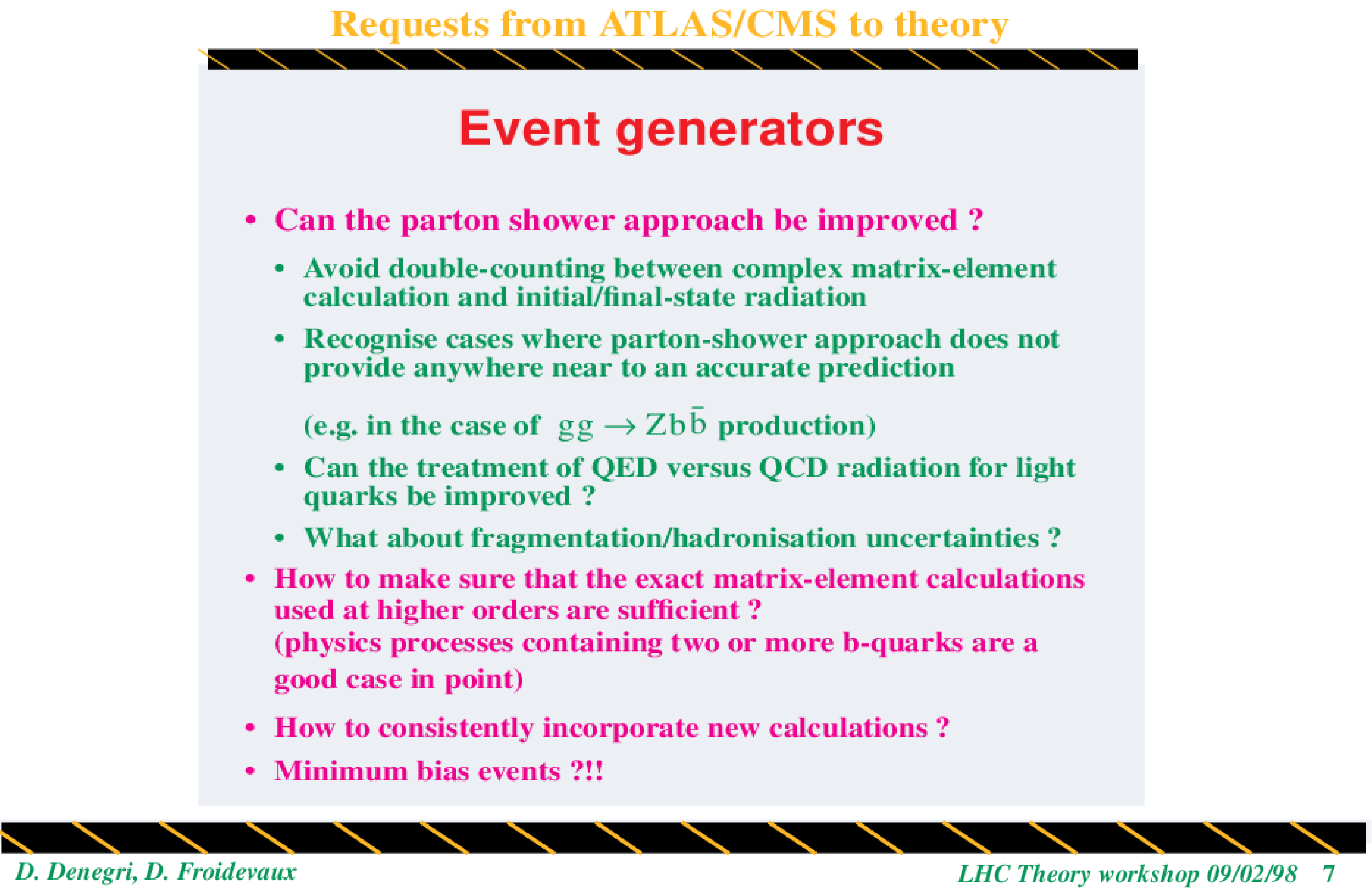
Errorr dominated by JER/JES uncertainty
Significant contribution from modelling of ttbar background

Conclusions

- The LHC has been taking data since 2011, producing thousands of papers, discovering the Higgs and pushing the SM into the farthest retrenchments.
- None of these results possible without close collaboration of the theory community, which has produced tools which have been essential to the achievement of the LHC physics goals.
- The impetuous development of MC modelling tools in parallel with our work on the analysis of LHC data in the last 25 years is a unique achievement of two communities working together towards a common goal
- We are here to celebrate the achievements of Paolo, and he has been and still is a pivotal figure in this process, as well as a somebody from whom I personally have learnt immensely, both from the human and from the professional point of view. Thank you, Paolo!
- Many other key players in this game are sitting in this room today, and I would like to thank all of them for the very long and successful journey together, and for the progress to come with the next ~15 years of LHC data-taking

Backup

But we knew that we needed more!



Requests from ATLAS/CMS to theory

Event generators

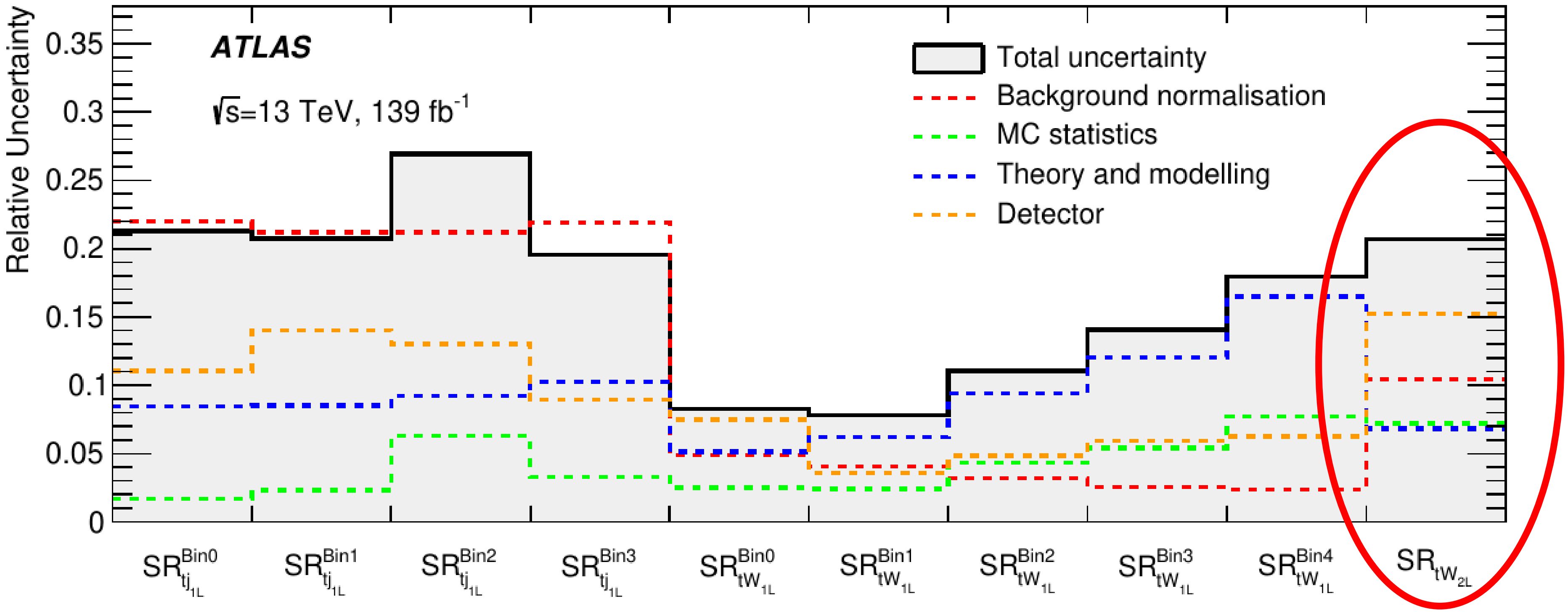
- Can the parton shower approach be improved ?
  - Avoid double-counting between complex matrix-element calculation and initial/final-state radiation
  - Recognise cases where parton-shower approach does not provide anywhere near to an accurate prediction

    (e.g. in the case of $gg \rightarrow Zb\bar{b}$ production)
  - Can the treatment of QED versus QCD radiation for light quarks be improved ?
  - What about fragmentation/hadronisation uncertainties ?
- How to make sure that the exact matrix-element calculations used at higher orders are sufficient ?
  (physics processes containing two or more b-quarks are a good case in point)
- How to consistently incorporate new calculations ?
- Minimum bias events ?!!

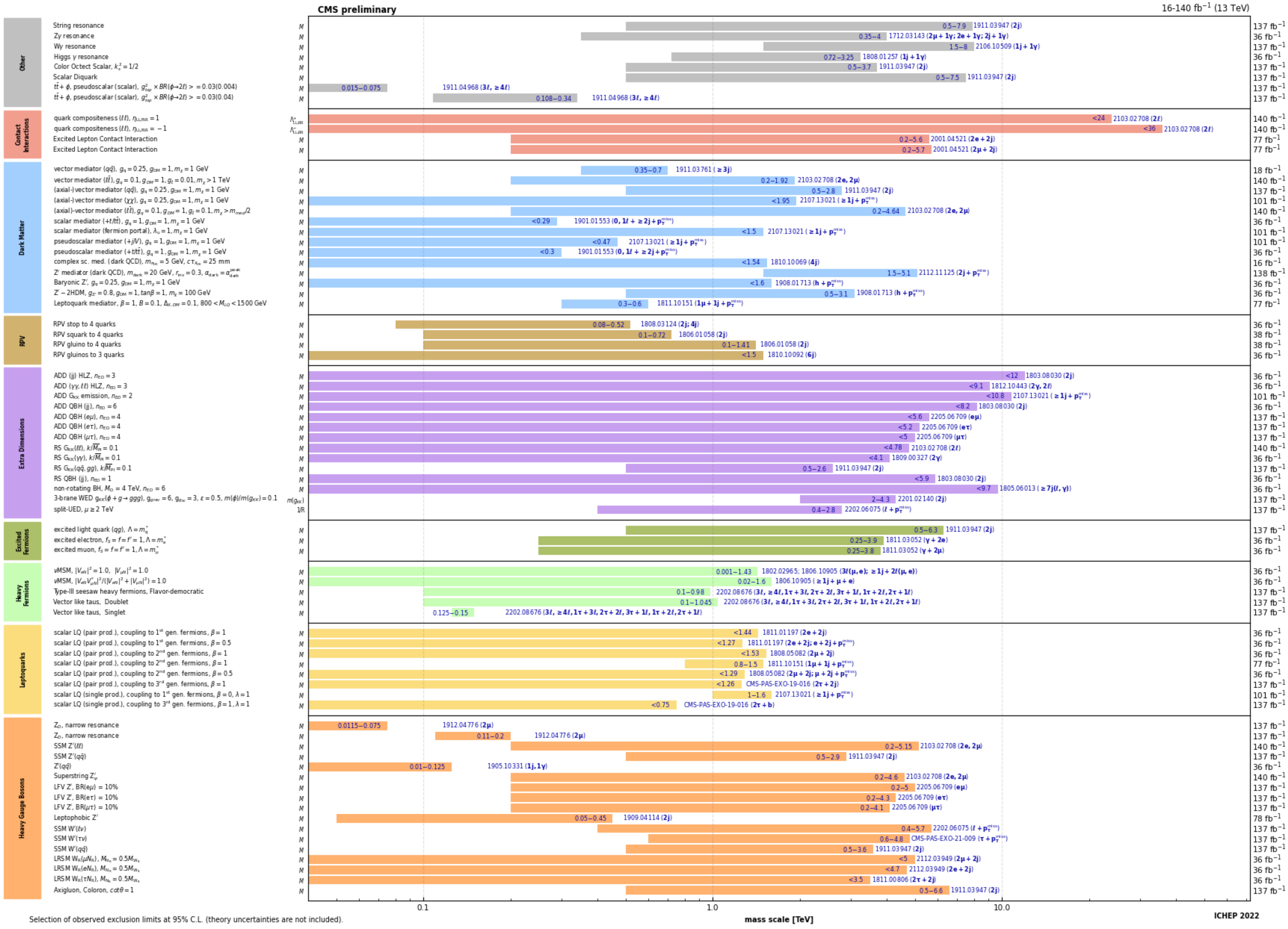
D. Denegri, D. Froidevaux

LHC Theory workshop 09/02/98 7

Split of systematic errors for tWDM

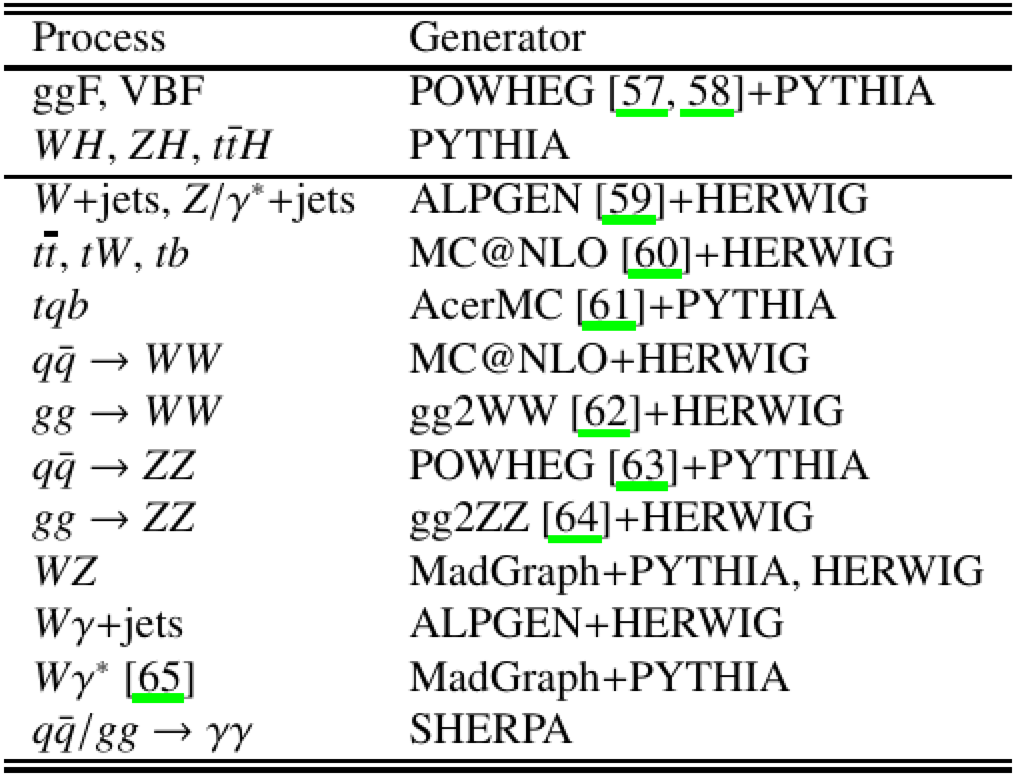


Overview of CMS EXO results



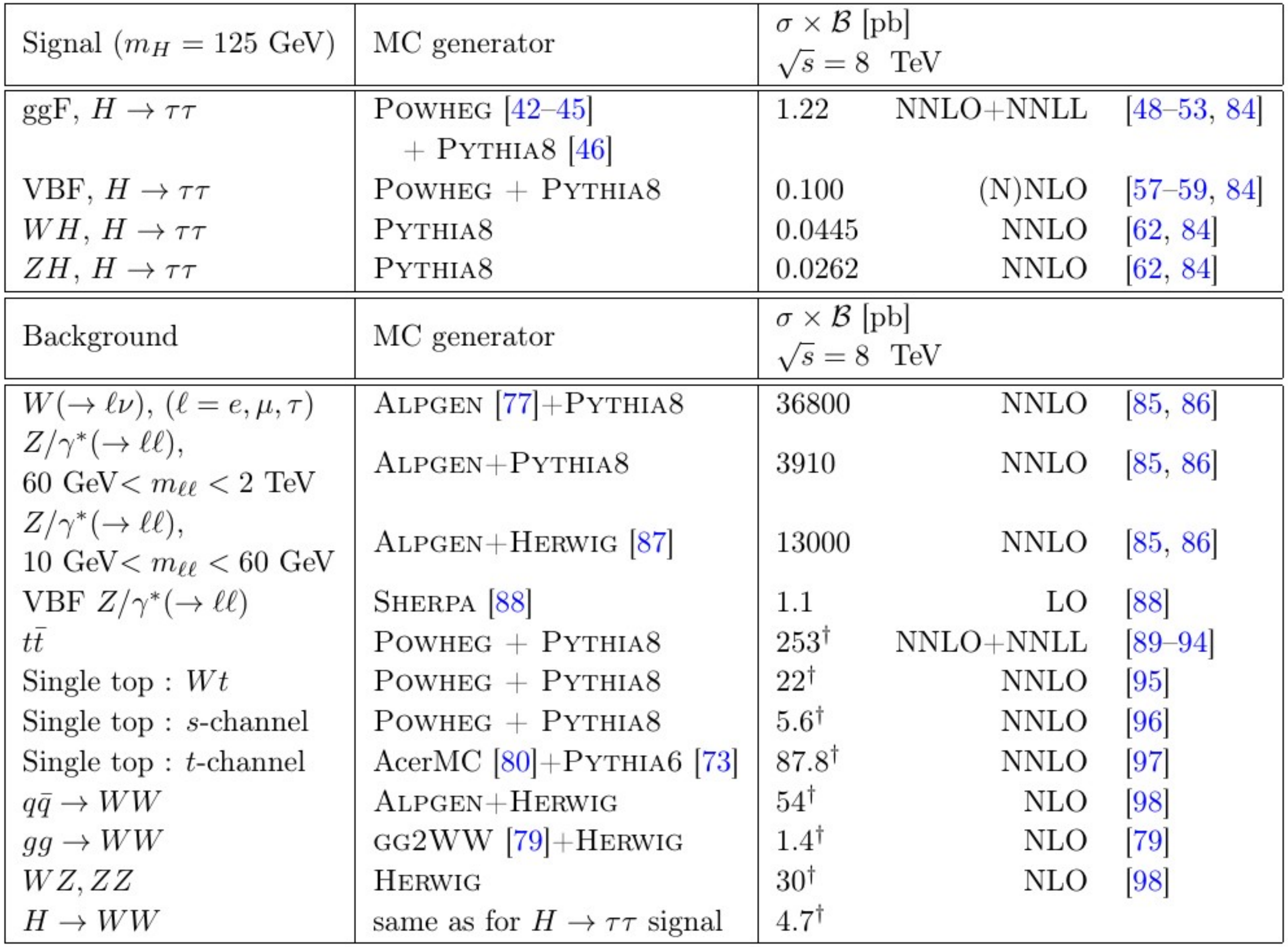
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Tools fror Higgs discovery paper (2012)



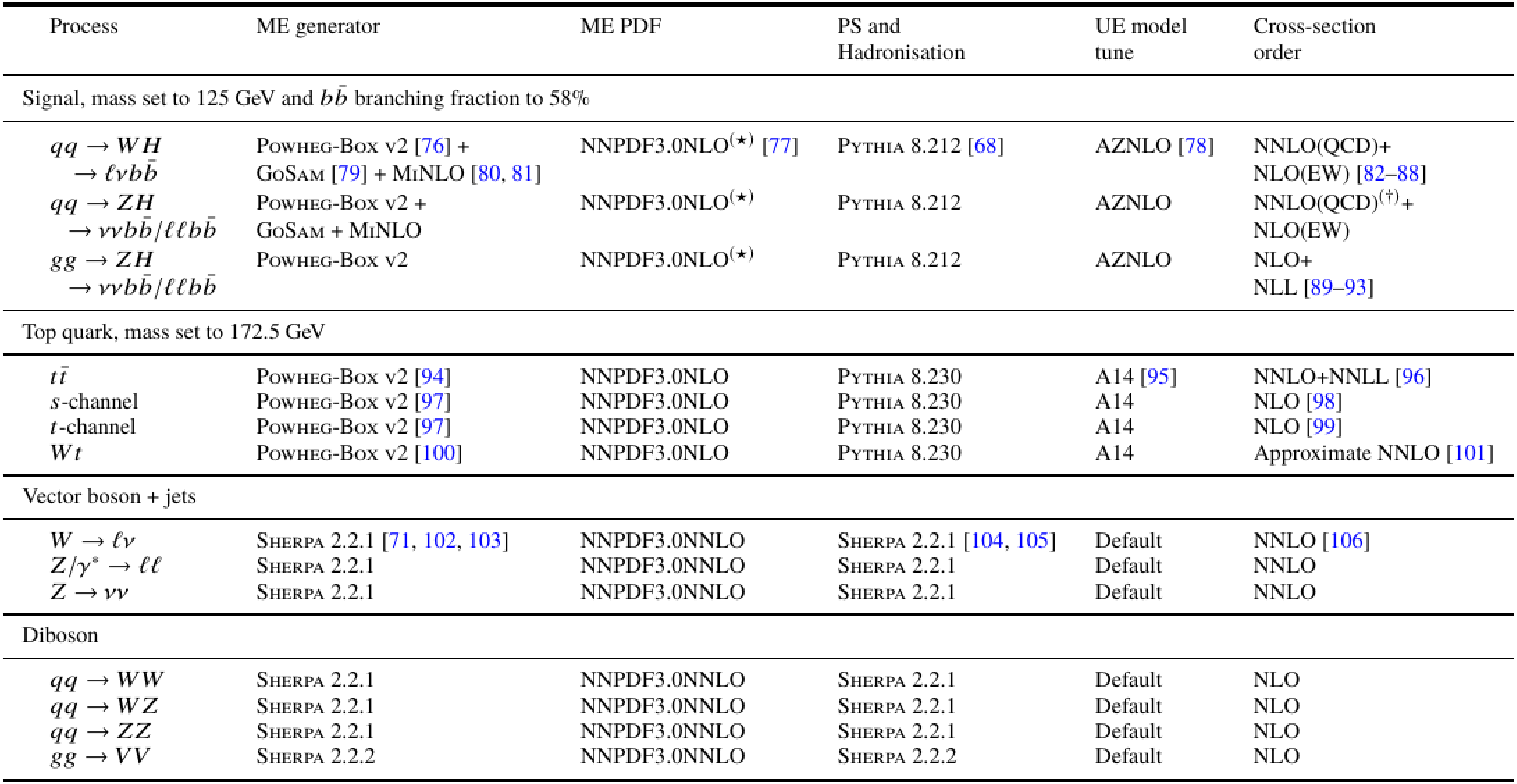
Process	Generator
ggF, VBF	POWHEG [57, 58]+PYTHIA
WH, ZH, $t\bar{t}H$	PYTHIA
W+jets, Z/γ^*+jets	ALPGEN [59]+HERWIG
$t\bar{t}$, tW, tb	MC@NLO [60]+HERWIG
tqb	AcerMC [61]+PYTHIA
$q\bar{q} \to WW$	MC@NLO+HERWIG
$gg \to WW$	gg2WW [62]+HERWIG
$q\bar{q} \to ZZ$	POWHEG [63]+PYTHIA
$gg \to ZZ$	gg2ZZ [64]+HERWIG
WZ	MadGraph+PYTHIA, HERWIG
$W\gamma$+jets	ALPGEN+HERWIG
$W\gamma^*$ [65]	MadGraph+PYTHIA
$q\bar{q}/gg \to \gamma\gamma$	SHERPA

Observation of h→tautau (2014)



Signal ($m_H = 125$ GeV)	MC generator	$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV		
ggF, $H \to \tau\tau$	Powheg [42–45] + Pythia8 [46]	1.22	NNLO+NNLL	[48–53, 84]
VBF, $H \to \tau\tau$	Powheg + Pythia8	0.100	(N)NLO	[57–59, 84]
WH, $H \to \tau\tau$	Pythia8	0.0445	NNLO	[62, 84]
ZH, $H \to \tau\tau$	Pythia8	0.0262	NNLO	[62, 84]
Background	MC generator	$\sigma \times \mathcal{B}$ [pb] $\sqrt{s} = 8$ TeV		
$W(\to \ell\nu)$, $(\ell = e, \mu, \tau)$	Alpgen [77]+Pythia8	36800	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 60 GeV$< m_{\ell\ell} <$ 2 TeV	Alpgen+Pythia8	3910	NNLO	[85, 86]
$Z/\gamma^*(\to \ell\ell)$, 10 GeV$< m_{\ell\ell} <$ 60 GeV	Alpgen+Herwig [87]	13000	NNLO	[85, 86]
VBF $Z/\gamma^*(\to \ell\ell)$	Sherpa [88]	1.1	LO	[88]
$t\bar{t}$	Powheg + Pythia8	$253^{\dagger}$	NNLO+NNLL	[89–94]
Single top : Wt	Powheg + Pythia8	$22^{\dagger}$	NNLO	[95]
Single top : s-channel	Powheg + Pythia8	$5.6^{\dagger}$	NNLO	[96]
Single top : t-channel	AcerMC [80]+Pythia6 [73]	$87.8^{\dagger}$	NNLO	[97]
$q\bar{q} \to WW$	Alpgen+Herwig	$54^{\dagger}$	NLO	[98]
$gg \to WW$	gg2WW [79]+Herwig	$1.4^{\dagger}$	NLO	[79]
WZ, ZZ	Herwig	$30^{\dagger}$	NLO	[98]
$H \to WW$	same as for $H \to \tau\tau$ signal	$4.7^{\dagger}$		

VH observation (2018)



Process	ME generator	ME PDF	PS and Hadronisation	UE model tune	Cross-section order
Signal, mass set to 125 GeV and $b\bar{b}$ branching fraction to 58%					
$qq \to WH \to \ell\nu b\bar{b}$	Powheg-Box v2 [76] + GoSam [79] + MiNLO [80, 81]	NNPDF3.0NLO$^{(\star)}$ [77]	Pythia 8.212 [68]	AZNLO [78]	NNLO(QCD)+ NLO(EW) [82–88]
$qq \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2 + GoSam + MiNLO	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NNLO(QCD)$^{(\dagger)}$+ NLO(EW)
$gg \to ZH \to \nu\nu b\bar{b}/\ell\ell b\bar{b}$	Powheg-Box v2	NNPDF3.0NLO$^{(\star)}$	Pythia 8.212	AZNLO	NLO+ NLL [89–93]
Top quark, mass set to 172.5 GeV					
$t\bar{t}$	Powheg-Box v2 [94]	NNPDF3.0NLO	Pythia 8.230	A14 [95]	NNLO+NNLL [96]
s-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [98]
t-channel	Powheg-Box v2 [97]	NNPDF3.0NLO	Pythia 8.230	A14	NLO [99]
Wt	Powheg-Box v2 [100]	NNPDF3.0NLO	Pythia 8.230	A14	Approximate NNLO [101]
Vector boson + jets					
$W \to \ell\nu$	Sherpa 2.2.1 [71, 102, 103]	NNPDF3.0NNLO	Sherpa 2.2.1 [104, 105]	Default	NNLO [106]
$Z/\gamma^* \to \ell\ell$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
$Z \to \nu\nu$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
$qq \to WW$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to WZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$qq \to ZZ$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO
$gg \to VV$	Sherpa 2.2.2	NNPDF3.0NNLO	Sherpa 2.2.2	Default	NLO