University of Sussex

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High-precision for high-energy tails

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UK Research and Innovation





Precision tests of the SM at the quantum level

Remarkable data vs. theory agreement in SM+Higgs measurements



BSM certainly not 'around the corner'

ATLAS SUSY Searches* - 95% CL Lower Limits

C	October 2019		•••	/•••-	•			$\sqrt{s} = 13 \text{ TeV}$	Overview of CMS EXO results
	Model	S	ignatı	ure ∫	<i>L dt</i> [fb	⁻¹] Mass limit		Reference	CMS
	$\tilde{q}\tilde{q}, \tilde{q} ightarrow q \tilde{\chi}_1^0$	0 <i>e</i> , μ mono-jet	2-6 jet 1-3 jet	E_T^{miss} E_T^{miss}	139 36.1	\tilde{q} [10x Degen.] \tilde{q} [1x, 8x Degen.] 0.43	1.9 $m(\tilde{\ell}^0) < 400 \text{ GeV}$ $m(\tilde{\varrho}) - m(\tilde{\chi}^0) = 5 \text{ GeV}$	ATLAS-CONF-2019-040 1711.03301	SSM Z'(<i>ll</i>) M _{Z'} 1803.06292 (2 <i>l</i>) 4.5
rches	$\tilde{g}\tilde{g}, \tilde{g} ightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jet	s E_T^{miss}	139	ğ ğ Forhidden	2.35 $m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2019-040	$SSM 2'(qq) \qquad M_{Z'} = 1806.00843 (2j) \qquad 2.7$ $LFV Z', BR(e\mu) = 10\% \qquad M_{Z'} = 1802.01122 (e\mu) \qquad 4.4$
Sear	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	3 <i>e</i> , μ	4 jets	Emiss	36.1	ğ z	1.85 $m(\tilde{\chi}_1^0) < 800 \text{ GeV}$	1706.03731	SSM W(lv) M_W 1803.11133 ($l + E_T^{mas}$) 5.2 SSM W($q\bar{q}$) M_W 1806.00843 (2) 3.3 CSM W(u) M_W 1806.00843 (2) 3.3
usive	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 <i>e</i> ,μ	7-11 je	ts E_T^{miss}	36.1	e e e	1.2 $m(g) = 50 \text{ GeV}$ 1.8 $m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	1708.02794	$M_{W} = 1807.11421 (\mathbf{T} + \mathbf{E}_{T}^{-MD}) $ $LRSM W_{R}(\ell N_{R}), M_{N_{R}} = 0.5M_{W_{R}} $ $M_{W_{R}} = 1803.11116 (2\ell + 2j) $ 4.4 $HSM W_{L}(TN_{R}), M_{V_{R}} = 0.5M_{V_{R}} $ $M_{W_{R}} = 1811.00806 (2\mathbf{T} + 2j) $ 4.4
Incl	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow tt\tilde{\chi}_1^0$	55 <i>e</i> ,μ 0-1 <i>e</i> ,μ	3 <i>b</i>	$E_T^{\rm miss}$	139 79.8	g 1.1: <i>g</i>	5 $m(\tilde{g})$ - $m(\chi_1^0)$ =200 GeV 2.25 $m(\tilde{\chi}_1^0)$ <200 GeV	1909.08457 ATLAS-CONF-2018-041	$\mathbf{r} = \frac{1}{2} \left[\frac{1}{1000} + \frac{1}{10000} + \frac{1}{1000} + \frac{1}{1000}$
	~ ~ ~ . ~0. ~+	SS <i>e</i> , μ	6 jets		139	ĝ 1	1.25 $m(\tilde{g}) - m(\tilde{\chi}_1^0) = 300 \text{ GeV}$	ATLAS-CONF-2019-015	scalar LQ (pair prod.), coupling to 1 st gen. fermions, $\beta = 1$ M_{LQ} 1811.01197 (2e + 2j) 1.44
	$b_1b_1, b_1 \rightarrow b\chi_1^\circ/t\chi_1^\circ$		Multipl Multipl Multipl	e e e	36.1 36.1 139	$egin{array}{cccc} b_1 & Forbidden & 0.9 \ eta_1 & Forbidden & 0.58-0.82 \ eta_2 & Forbidden & 0.74 \end{array}$	$m(\tilde{\chi}_1^0)=300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_1^0)=1$ $m(\tilde{\chi}_1^0)=300 \text{ GeV}, \text{ BR}(b\tilde{\chi}_1^0)=\text{BR}(\tilde{\chi}_1^\pm)=0.5$ $m(\tilde{\chi}_1^0)=200 \text{ GeV}, m(\tilde{\chi}_1^\pm)=300 \text{ GeV}, \text{ BR}(\tilde{\chi}_1^\pm)=1$	1708.09266, 1711.03301 1708.09266 ATLAS-CONF-2019-015	scalar LQ (pair prod.), coupling to 2 nd gen. fermions, $\beta = 0.5$ M_{LQ} 1611.0137 (2e + 2), e + 2) + E _T 7 (1.27) scalar LQ (pair prod.), coupling to 2 nd gen. fermions, $\beta = 1$ M_{LQ} 1808.05082 (2µ + 2) (2µ +
S	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	6 <i>b</i>	$E_T^{\rm miss}$	139	Forbidden 0.2	3-1.35 $\Delta m(\tilde{\chi}_{0}^{0},\tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$	1908.03122	scalar LQ (pair prod.), coupling to 3 rd gen. fermions, $\beta = 1$ M_{LQ} scalar LQ (single prod.), coupling to 3 rd gen. ferm. $\beta = 1$, $\lambda = 1$ M_{LQ}
quark	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 <i>e</i> , <i>µ</i>	0-2 jets/1	-2 $b E_T^{\text{miss}}$	36.1	\tilde{t}_1 0.23-0.48 \tilde{t}_1 1.0	$\Delta m(\tilde{x}_2, \tilde{x}_1) = 130 \text{ GeV}, m(\tilde{x}_1) = 0 \text{ GeV}$ $m(\tilde{x}_1^0) = 1 \text{ GeV}$	1506.08616, 1709.04183, 1711.11520	excited light quark (<i>qq</i>), $\Lambda = m_{a}^{*}$ $M_{a^{*}}$ 1806,00843 (2i)
n. s pro	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 <i>e</i> , µ	3 jets/1	$b E_{T_{i}}^{\text{miss}}$	139	<i>ĩ</i> ₁ 0.44-0.59	$m(ilde{\mathcal{X}}_1^0)$ =400 GeV	ATLAS-CONF-2019-017	excited light quark $(q\gamma)$, $f_S = f = f' = 1$, $\Lambda = m_q^*$ M_{q^*} 1711.04652 $(\gamma + j)$ 5.5
ge	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b v, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	$1 \tau + 1 e, \mu, \tau$	2 jets/1	$b E_T^{\text{miss}}$	36.1	<i>t</i> ₁ 1.1	$m(\tilde{\tau}_1) = 800 \text{ GeV}$	1803.10178	excited b quark, $f_S = f = f' = 1, \Lambda = m_q^*$ M_{b^*} 1711.04652 ($\mathbf{\gamma} + \mathbf{j}$) 1.8
3 rd dire	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow c\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2 <i>c</i>	E_T^{mass}	36.1	č 0.85	$m(\tilde{\chi}_1^0) = 0 \text{ GeV}$	1805.01649	M_{e^*} excited electron, $f_S = f = f' = 1, \Lambda = m_e^*$ M_{e^*} 1811.03052 ($\gamma + 2e$) 3.9
		0 <i>e</i> , <i>µ</i>	mono-j	et E_T^{miss}	36.1	\tilde{i}_{1} 0.43	$m(\tilde{t}_1, c) \cdot m(\tilde{t}_1) = 0.000$ $m(\tilde{t}_1, c) \cdot m(\tilde{t}_1^0) = 5 \text{ GeV}$	1711.03301	excited muon, $r_s = r = r = 1$, $\Lambda = m_{\mu}$ M_{μ} . 1811.03052 ($\mathbf{v} + 2\mathbf{\mu}$) 3.8
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 <i>e</i> , μ	4 <i>b</i>	E_T^{miss}	36.1	<i>t</i> ₂ 0.32-0.88	$m(\tilde{\chi}_1^0)$ =0 GeV, $m(\tilde{\iota}_1)$ - $m(\tilde{\chi}_1^0)$ = 180 GeV	1706.03986	quark compositeness $(q\bar{q})$, $\eta_{LL/RR} = 1$ $\Lambda^+_{LL/RR}$ 1803.08030 (2j) 12.
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ	1 <i>b</i>	$E_T^{\rm miss}$	139	Ĩ ₂ Forbidden 0.86	$m(\tilde{\chi}_1^0)$ =360 GeV, $m(\tilde{t}_1)$ - $m(\tilde{\chi}_1^0)$ = 40 GeV	ATLAS-CONF-2019-016	quark compositeness (ll), $\eta_{LL/RR} = 1$ $\Lambda_{LL/RR}^+$ 1812.10443 ($2l$)
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	2-3 e, μ ee, μμ	≥ 1	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 139	$egin{array}{cccc} & \tilde{\chi}_1^{\pm}/ ilde{\chi}_2^0 & 0.6 \ & ilde{\chi}_1^{\pm}/ ilde{\chi}_2^0 & 0.205 \end{array} \end{array}$	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)=5~\mathrm{GeV}$	1403.5294, 1806.02293 ATLAS-CONF-2019-014	$\eta_{\text{uark compositeness (ll), \eta_{\text{LL/RR}}} = -1 \qquad $
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW	2 <i>e</i> , <i>µ</i>		E_T^{miss}	139	$\tilde{\chi}_1^{\pm}$ 0.42	$m(ilde{\mathcal{X}}_1^0)$ =0	1908.08215	ADD (jj) HLZ, $n_{ED} = 3$ M_{S} 1803.08030 (2j) 12
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via Wh	0-1 <i>e</i> , µ	2 <i>b</i> /2 ງ	$V E_T^{\text{miss}}$	139	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ Forbidden 0.74	$m(ilde{\chi}_1^0)$ =70 GeV	ATLAS-CONF-2019-019, 1909.09226	ADD $(\gamma \gamma, \ell \ell)$ HLZ, $n_{ED} = 3$ M_s 1812.10443 $(2\gamma, 2\ell)$ 9.1
W	$ ilde{\chi}_1^{\pm} ilde{\chi}_1^{\mp}$ via $ ilde{\ell}_L / ilde{ u}$	2 e, µ		$E_T^{\rm miss}$	139	$\tilde{\chi}_1^{\pm}$ 1.0	$m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^{0}))$	ATLAS-CONF-2019-008	ADD G_{KK} emission, $n = 2$ $M_D = 1712.02345 (\ge 1j + E_T^{miss})$ 9.9
Ч	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2 τ		E_T^{miss}	139	$\tilde{\tau}$ [$\tilde{\tau}_{L}, \tilde{\tau}_{R,L}$] 0.16-0.3 0.12-0.39	$m(ilde{\chi}_1^0)=0$	ATLAS-CONF-2019-018	ADD QBH (jj), $n_{ED} = 6$ ADD OBH (equ) $n_{ex} = 6$ M (1803.08030 (2j) M (1803.08030 (2j) M (1803.08030 (2j)
	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0 jets	E_T^{miss}	139	Ĩ 0.7	$m(\tilde{\chi}_1^0) = 0$	ATLAS-CONF-2019-008	$\frac{1}{3} = \frac{1}{3} = \frac{1}$
	~~~~~~	2 e, µ	≥ 1	$L_T$	139	1 0.236	$\mathbf{m}(\ell) - \mathbf{m}(\ell) = 10 \text{ GeV}$	ATLAS-CONF-2019-014	$\frac{1}{6} RS G_{KK}(\ell), k/M_{Pl} = 0.1 \qquad M_{G_{KK}} 1803.06292 (2\ell) \qquad 4.25$
	$HH, H \rightarrow hG/ZG$	0 e, μ 4 e μ	$\geq 3 b$ 0 iets	$E_T^{\text{miss}}$ $E^{\text{miss}}$	36.1 36.1	<i>H</i> 0.13-0.23 0.29-0.88	$ BR(\tilde{X}_1^0 \to h\tilde{G}) = 1 $ $ RP(\tilde{X}_1^0 \to Z\tilde{G}) = 1 $	1806.04030	$RS G_{KK}(\gamma\gamma), k/\overline{M}_{Pl} = 0.1 \qquad \qquad$
		ι ε, μ		<i>L_T</i>			$Dr(\mathcal{A}) \to \mathcal{Z}(\mathcal{A}) = T$	1004.00002	<b>K</b> RS QBH (jj), $n_{\text{ED}} = 1$ $M_{\text{QBH}}$ 1803.08030 ( <b>2</b> j) 5.9
be/	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	36.1	$\tilde{\chi}_{1}^{\pm}$ 0.46	Pure Wino	1712.02118	RS QBH ( $e\mu$ ), $n_{ED} = 1$ $m_{QBH}$ 1802.01122 ( $e\mu$ ) $m_{QBH}$ 1802.0122 ( $e\mu$ ) $m_{QBH}$ 1802.0122 ( $e\mu$ ) $m_{QBH}$ 1802.0122 ( $e\mu$ )
g-liv ticle	Ctable ~ D bedren		Multial	-	00.4	<i>x</i> ₁ ⁻ 0.15 ~	Pure Higgsino	ATL-PHYS-PUB-2017-019	split-UED, $\mu \ge 4$ TeV $1/R$ 1803.11133 ( $\ell = E^{\text{miss}}_{\text{miss}}$ 2.9
ong	Stable g R-hadron Metastable $\tilde{g}$ R bedren $\tilde{g} \to \pi e^{\tilde{v}^0}$		Multip	e	36.1	g $\tilde{a} = [\pi(\tilde{a}) - 10 \text{ ns} = 0.2 \text{ ns}]$	2.0	1902.01636,1808.04095	
-	Metastable g R-hadron, $g \rightarrow qqx_1$		wanp		50.1			1710.04301,1000.04033	(axial-)vector mediator ( $\chi\chi$ ), $g_q = 0.25$ , $g_{DM} = 1$ , $m_\chi = 1$ GeV $M_{med}$ 1712.02345 ( $\geq 1j + E_T^{miss}$ ) 1.8
	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$	$e\mu,e au,\mu au$		-mice	3.2	$\tilde{\gamma}_{\tau}$	<b>1.9</b> $\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$	1607.08079	(axiai-)vector mediator (qq), $g_q = 0.25$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV $M_{med}$ [1806.00843 (2]) 2.6
	$\hat{\chi}_1^{\pm}\hat{\chi}_1^{\pm}/\hat{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$	4 <i>e</i> , µ	0 jets	$E_T^{\text{mass}}$	36.1	$\chi_{1}^{+}/\chi_{2}^{*}  [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] $ $0.82$	<b>1.33</b> $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	1804.03602	scalar mediator $(+t/t)$ , $g_q = 1$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV $M_{med}$ [1901.01553 (0, $1t + 23$ ] + $L_T$ $(-2, 23)$ pseudoscalar mediator $(+t/t)$ , $g_q = 1$ , $g_{DM} = 1$ , $m_{\chi} = 1$ GeV $M_{\chi}$ [1901.01553 (0, $1t + 23$ ] + $E_T^{\text{miss}}$ $(-3, 3)$
~	$\tilde{g}\tilde{g},  \tilde{g} \rightarrow qq\chi_1^\circ, \chi_1^\circ \rightarrow qqq$	4	-5 large- <i>I</i> Multinl	r jets e	36.1	$\tilde{g} = [m(\mathcal{X}_1^{\vee}) = 200 \text{ GeV}, 1100 \text{ GeV}]$ $\tilde{g} = [\mathcal{X}_1^{\vee}] = 2e-4, 2e-5]$ 1 05	<b>1.3 1.9</b> Large $\mathcal{X}_{112}^{\circ}$	1804.03568 ATLAS-CONE-2018-003	scalar mediator (fermion portal), $\lambda_u = 1$ , $m_y = 1$ GeV $M_{A_b}$ (1712.02345 ( $\geq 1i + E_{T}^{miss}$ ) 1.4
P	$\tilde{x}$ $\tilde{z}$ $\tilde{v}^0$ $\tilde{v}^0$ .		Multic	~ ^	00.1	φ [/" =2e-4 1e-2]			complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5 \text{ GeV}$ , $c\tau_{X_{DK}} = 25 \text{ mm}$ (1810.10069 (4)) 1.54
L.	$tt, t \to t X_1, X_1 \to tbs$ $\tilde{t}, \tilde{t}, \tilde{t}, \to bs$			с 2 h	30. I 26 7	$\tilde{t} = \begin{bmatrix} aa & bc \end{bmatrix}$ 0.42 0.61	$m(\chi_1)=200$ GeV, bino-like	AILAS-GUNF-2018-003	
	$i_1i_1, i_1 \rightarrow os$ $\tilde{i}_1\tilde{i}_1, \tilde{i}_1 \rightarrow a\ell$	2011	2 jois + 1 0 h	-0	36.1		$RR(\tilde{t}, \underline{\ } b_{\theta} / b_{\theta}) \geq 200/$	1710.05544	Type III Seesaw, $B_e = B_\mu = B_\tau$ $M_{Sigma}$ 1708.07962 ( $\geq 3l$ ) 0.84
	*1*1,*1 ~90	$\frac{2}{1} \frac{e, \mu}{\mu}$	Z U DV		136	$\tilde{t}_1$ [1e-10< $\lambda'_{23k}$ <1e-8, 3e-10< $\lambda'_{23k}$ <3e-9] <b>1.0</b>	<b>1.6</b> BR( $\tilde{t}_1 \rightarrow q\mu$ )=100%, cos $\theta_t$ =1	ATLAS-CONF-2019-006	$M_{\rm s}$ string resonance $M_{\rm s}$ 1806.00843 (2j) 7.7
						200 40A			
									mass scale [TeV]
*				400.00				<b>_</b>	Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).
Univ	' a selection of the available ma	ISS IIMITS ON	new sta	les or		ι -	Mass scale ITeV1		

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.

Mgluino > 2 TeV Msquark > 0.7-2 TeV  $Mstop > 400 \text{ GeV} \dots$ 

### **ATLAS** Preliminary

Z' > 4.5 TeV W' > 5 TeVMleptoquark > 1 TeV ...



17.5



# Timescale of the LHC



Experimental uncertainties will dramatically decrease in the future. Often reaching O(1%).





# Differential SM measurements



# The need for precision in tails: Direct searches



 $\rightarrow$  very good control on large irreducible SM backgrounds necessary!



invisible in detectors







# The need for precision in tails: Direct searches



→very good control on large irreducible SM backgrounds necessary!



# The need for precision in tails: Indirect searches



- many effective BSM operators yield growth with energy
  → expect small deviations in tails of distributions:
- → very good control on SM predictions necessary!





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# The need for precision in tails: Indirect searches





→Theory precision opens the door to the high H-pT laboratory!





## Determine V+jets backgrounds: the DM case



- hardly any systematics (just QED dressing)
- very precise at low pT
- but: limited statistics at large pT

**global fit** of  $Z(\rightarrow II)$ +jets,  $W(\rightarrow IV)$ +jets and  $\gamma$ +jets measurements

- to determine  $Z(\rightarrow \overline{\nu}\nu)$ +jet
- and the visible channels at high-pT

- fairly large data samples at large pT
- systematics from transfer factors: ratios of V+jets processes





QCD uncertainties

[*ML et. al.:* 1705.04664]

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{QCD}}^{(V)} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{LOQCD}}^{(V)} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{NLOQCD}}^{(V)} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{NNLOQCD}}^{(V)}$$

$$\mu_{0} = \frac{1}{2} \left( \sqrt{p_{\mathrm{T},\ell^{+}\ell^{-}}^{2} + m_{\ell^{+}\ell^{-}}^{2}} + \sum_{i \in \{q,g,\gamma\}} |p_{\mathrm{T},i}| \right)$$

this is a 'good' scale for V+jets

- at large pTV:  $HT'/2 \approx pTV$
- modest higher-order corrections
- sufficient convergence

scale uncertainties due to 7-pt variations:

O(20%) uncertainties at LO O(10%) uncertainties at NLO O(5%) uncertainties at NNLO

with minor shape variations

### How to correlate these uncertainties across processes?



| |

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• take scale uncertainties as fully correlated: NLO QCD uncertainties cancel at the <~ | % level







### How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated: NLO QCD uncertainties cancel at the  $<\sim$  1 % level
- introduce **process correlation uncertainty** based on K-factor difference: →effectively degrades precision of last calculated order



δ<2%

$$\delta K_{\rm NLO} = K_{\rm NLO}^V - K_{\rm NLO}^Z$$



δ < 3-4 %



### How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated: NLO QCD uncertainties cancel at the  $<\sim$  1 % level
- introduce **process correlation uncertainty** based on K-factor difference: →effectively degrades precision of last calculated order



$$\delta K_{\rm NLO} = K_{\rm NLO}^V - K_{\rm NLO}^Z$$



check against NNLO QCD!



### How to correlate these uncertainties across processes?

- take scale uncertainties as fully correlated: NLO QCD uncertainties cancel at the <~ 1 % level
- →effectively degrades precision of last calculated order



• introduce process correlation uncertainty based on K-factor difference:  $\delta K_{(N)NLO} = K_{(N)NLO}^V - K_{(N)NLO}^Z$ 



Uncertainty estimates at NNLO QCD



### EW uncertainties

EW corrections become sizeable at large p_{T,V}: -30% @ I TeV

Origin: virtual EW Sudakov logarithms



How to estimate corresponding pure EW uncertainties of relative  $\mathcal{O}(\alpha^2)$  ?







[JML et. al.: 1705.04664]

Large EW corrections dominated by Sudakov logs



17

### Pure EW uncertainties



 $p_{T,V}$  [GeV]

$$\kappa_{\rm NLO\,EW}(\hat{s}, \hat{t}) = \frac{\alpha}{\pi} \left[ \delta_{\rm hard}^{(1)} + \delta_{\rm Sud}^{(1)} \right]$$
$$\kappa_{\rm NNLO\,Sud}(\hat{s}, \hat{t}) = \left(\frac{\alpha}{\pi}\right)^2 \delta_{\rm Sud}^{(2)}$$

[*ML* et. al.: 1705.04664]

Large EW corrections dominated by Sudakov logs



check against two-loop Sudakov²⁰⁰logs^{800 1000 1200}

NNLO/LO - 1 -

[Kühn, Kulesza, Pozzorini, Schulze; 05-07]



+ additional uncertainties for hard non-log NNLO EW effects

(uncorrelated)







# Precise predictions for V+jet DM backgrounds

work in collaboration with: R. Boughezal, J.M. Campell, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, S. Kallweit, M. L. Mangano, P. Maierhöfer, T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam, C. Williams

GeV-TeV range)

one-dimensional reweighting

with  $\frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{TH}}^{(V)} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{QCD}}^{(V)} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{m}}^{(V)}$ 

- Robust uncertainty estimates including
  - I.Pure QCD uncertainties
  - 2. Pure EW uncertainties
  - 3. Mixed QCD-EW uncertainties
  - 4. PDF,  $\chi$ -induced uncertainties ....

### [1705.04664]

• Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred

$$f:=\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}y}\sigma_{\mathrm{MC}}^{(V)}(\vec{\varepsilon}_{\mathrm{MC}}) \begin{bmatrix} \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{TH}}^{(V)}(\vec{\varepsilon}_{\mathrm{TH}}) \\ \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{MC}}^{(V)}(\vec{\varepsilon}_{\mathrm{MC}}) \end{bmatrix}$$

$$g \text{ of MC samples in } x = p_{\mathrm{T}}^{(V)}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\mathrm{mix}}^{(V)} + \frac{\mathrm{d}}{\mathrm{d}x}\Delta\sigma_{\mathrm{EW}}^{(V)} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma_{\gamma-\mathrm{ind.}}^{(V)}$$

- Prescription for **correlation** of these uncertainties
  - within a process (between low-pT and high-pT)
  - ► across processes



19









### Diboson Status







## NNLO QCD + NLO EW for dibosons: pTV2

[M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068]

- ► NNLO/NLO QCD very small at large pTV2
- ► NNLO QCD uncertainty: few percent





## NNLO QCD + NLO EW for dibosons: pTV2

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- ► NNLO/NLO QCD very small at large pTV2
- ► NNLO QCD uncertainty: few percent

$$= d\sigma_{\rm LO} \left( 1 + \delta_{\rm QCD} + \delta_{\rm EW} \right) + d\sigma_{\rm LO}^{gg}$$
$$= d\sigma_{\rm LO} \left( 1 + \delta_{\rm QCD} \right) \left( 1 + \delta_{\rm EW} \right) + d\sigma_{\rm LO}^{gg}$$
$$= d\sigma_{\rm NNLO QCD + EW} + d\sigma_{\rm LO} \delta_{\rm QCD} \delta_{\rm EW}$$

• difference very conservative upper bound on  $\mathcal{O}(\alpha_S \alpha)$ 

•multiplicative/factorised combination clearly superior (EW Sudakov logs x soft QCD) •dominant uncertainty at large pTV2:  $\mathcal{O}(\alpha^2) \sim \alpha_{\rm w}^2 \log^4(Q^2/M_W^2)$ 









•NLO QCD/LO=2-5! (''giant K-factor'' [Rubin, Salam, Sapeta, '10])







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- at large pTVI:VV phase-space is dominated by V+jet (w/ soft V radiation)

$$-\frac{d\sigma_{V(V)j}^{V(V)j}}{d\sigma_{VV}^{LO}} \propto \frac{\sigma_{00}}{\alpha_{\rm S}} \log^2\left(\frac{Q^2}{M_W^2}\right) \simeq 3 \quad \text{at} \quad Q = 17$$

- •NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- •Very large difference  $d\sigma_{
  m NNLO\,QCD+EW}$  vs.  $d\sigma_{
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- . In additive combination dominant V topology does not receive any EVV corrections 2. In multiplicative combination EVV correction for VV is applied to V hard process • Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW 28













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⇒check!





## Giant K-factors and effect of jet veto







• for pTVI > I TeV: hard-Vj topologies dominate over hard-VV

$$_{
m o}~H_{
m T}^{
m lep}$$
 corresponds to

$$=\frac{2}{3}p_{\mathrm{T},V_1}$$
 for  $\xi_{\mathrm{veto}} = 0.2$ 



### Conclusions

- There is no clear scale/signature for new physics effects: Let's explore the unknown leaving no stone unturned!
- ► Tails, tails, tails...!!
- State-of-the art NNLO QCD+NLO EW allows to control important kinematic distributions at the few percent level up to the multiTeV regime.

Let's push the precision frontier!









# With the discovery of the Higgs the SM is 'complete'



### **Standard Model of Elementary Particles**





EW vacuum stability Dark Matter GUT unification Neutrino masses Hierarchy problem





The motivation for BSM searches are as compelling as ever



# inclusive V: MEPS@NLO QCD+EWvirt



[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

- Bases on Sherpa's standard MEPS@NLO
- Stable NLO QCD+EW predictions in all of the phase-space...
- ...including Parton-Shower effects.
- Can directly be used by the experimental collaborations
- pT,V: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)

▶ P⊤, j I :

- merging ensures stable results (dijet topology at LO)
- compensation between negative Sudakov and LO mix





10

### QCD uncertainties

$$\frac{\mathrm{d}}{\mathrm{dx}}\sigma_{\mathrm{N}^{k}\mathrm{LO}\,\mathrm{QCD}}^{(V)}(\vec{\varepsilon}_{\mathrm{QCD}}) = \begin{bmatrix} K_{\mathrm{N}^{k}\mathrm{LO}}^{(V)}(x) + \sum_{i=1}^{3} \varepsilon_{\mathrm{QCD},i} \, \delta^{(i)} K_{\mathrm{N}^{k}\mathrm{LO}}^{(V)}(x) \\ \times \frac{\mathrm{d}}{\mathrm{dx}}\sigma_{\mathrm{LO}\,\mathrm{QCD}}^{(V)}(\vec{\mu}_{0}). \end{bmatrix}$$

$$\times \frac{\mathrm{d}}{\mathrm{dx}}\sigma_{\mathrm{LO}\,\mathrm{QCD}}^{(V)}(\vec{\mu}_{0}).$$

$$R_{\mathrm{D},i} = \epsilon_{\mathrm{QCD},i}^{(W^{\pm})} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} = \epsilon_{\mathrm{QCD},i}^{(V)} = \epsilon_{\mathrm{QCD},i}^{(\gamma)} =$$

(important for extrapolation from low-pT to high-pT)

$$S^{(3)}K^{V}_{N^{k}LO} = \frac{K^{V}_{N^{k}LO}}{K^{V}_{N^{k-1}LO}} - \frac{K^{Z}_{N^{k}LO}}{K^{Z}_{N^{k-1}LO}}$$

(correlated)

Difference of (N)NLO corrections as **process correlation uncertainty** 

### Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative  $O(\alpha \alpha_s)$  have to be considered.

### Additive combination

 $\sigma_{\rm QCD+EW}^{\rm NLO} = \sigma^{\rm LO} + \delta \sigma_{\rm QCD}^{\rm NLO} + \delta \sigma_{\rm EW}^{\rm NLO}$ 

### Multiplicative combination

 $\sigma_{\rm QCD\times EW}^{\rm NLO} = \sigma_{\rm QCD}^{\rm NLO} \left(1 + \frac{\delta \sigma_{\rm EW}^{\rm NLO}}{\sigma^{\rm LO}}\right)$ 

(try to capture some  $\mathcal{O}(\alpha \alpha_s)$  contributions, e.g. EW Sudakov logs × soft QCD)

Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

 $K_{\rm QCD\otimes EW} - K_{\rm QCD\oplus EW} \sim 10\%$  at 1 TeV

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

### Mixed QCD-EW uncertainties



 $pT_{j,2} > 30 \text{ GeV}$ 

Bold estimate:

Consider real  $\mathcal{O}(\alpha \alpha_s)$  correction to V+jet  $\simeq$  NLO EW to V+2jets

and we observe

 $\frac{\mathrm{d}\sigma_{\mathrm{NLO}\,\mathrm{EW}}}{\mathrm{d}\sigma_{\mathrm{LO}}}\Big|_{V+2\mathrm{jet}} - \frac{\mathrm{d}\sigma_{\mathrm{NLO}\,\mathrm{EW}}}{\mathrm{d}\sigma_{\mathrm{LO}}}\Big|_{V+1\mathrm{jet}} \lesssim 1\%$ 

strong support for

- factorization
- multiplicative QCD x EW combination

### Mixed QCD-EW uncertainties



N-jettiness cut ensures approx. constant ratio V+2jets/V+jet

$$\tau_1 = \sum_k \min_i \left\{ \frac{2p_i \cdot q_k}{Q_i \sqrt{\hat{s}}} \right\}$$

### Estimate of non-factorising contributions



(tuned to cover above difference of EW K-factors)