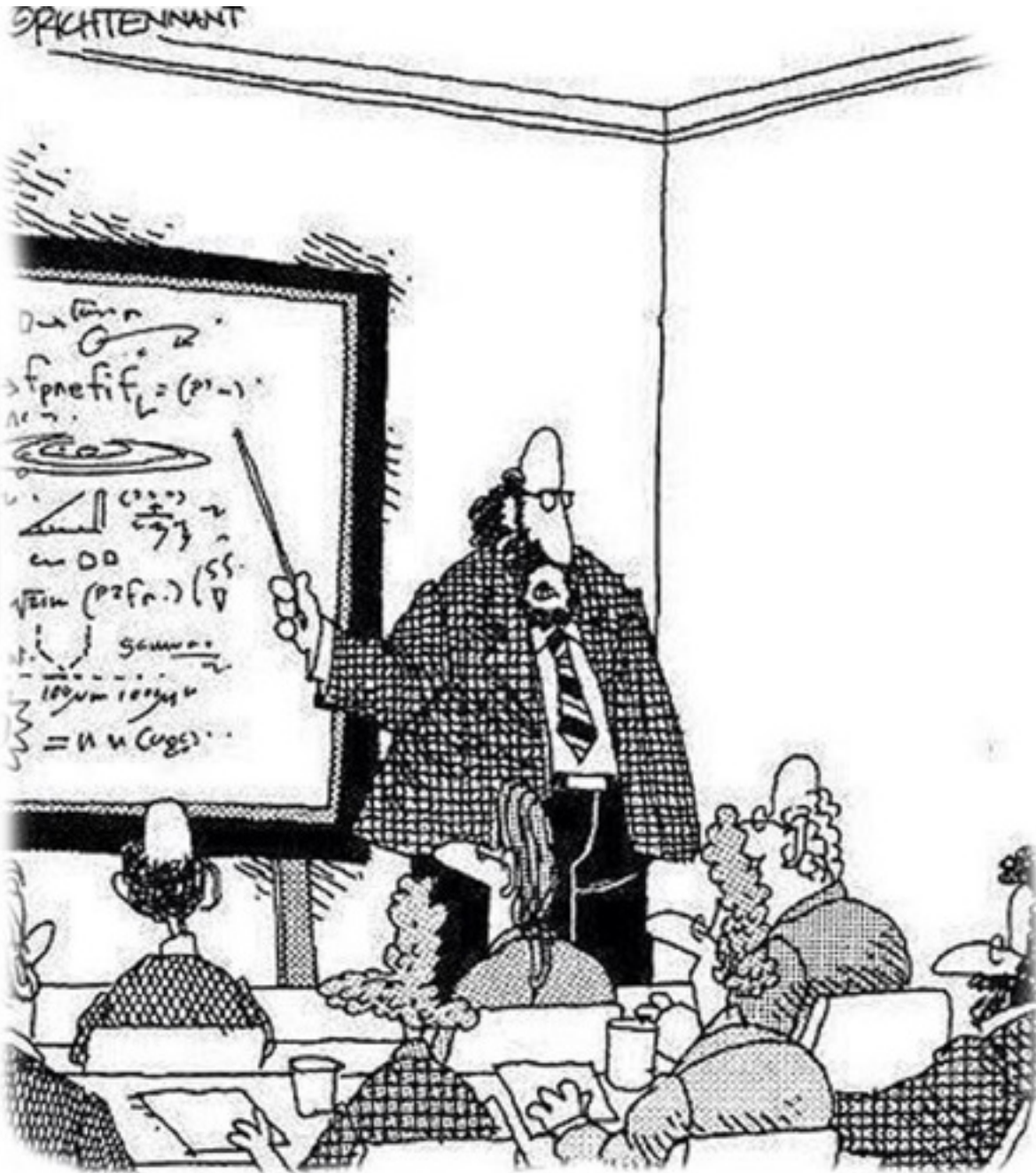




The QCD challenge for precision at colliders

Pier Francesco Monni
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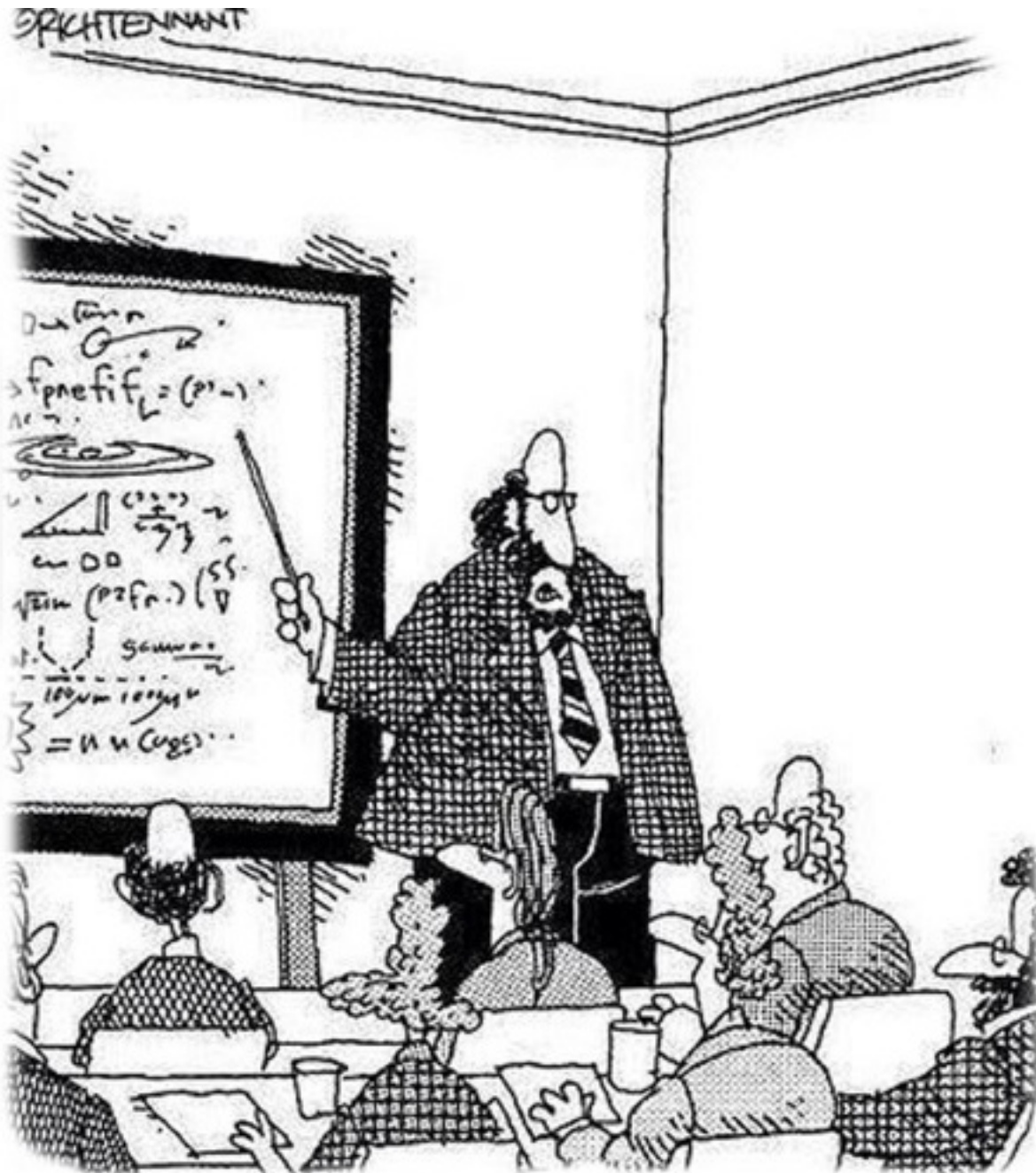
New Physics at the LHC (so far)



New physics constrained to $\sim \text{TeV}$ scales at colliders, may leave elusive small signatures at currently probed energies

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New Physics at the LHC (so far)

ATLAS SUSY Searches* - 95% CL Lower Limits

May 2017

ATLAS Preliminary

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

Model		e, μ, τ, γ	Jets	$E_{\text{T}}^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ 1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.85 TeV	$m(\tilde{q})=m(\tilde{g})$	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{q}$	1.57 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}_1^0) < 5 \text{ GeV}$	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.02 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	$\tilde{g}$	2.01 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}, m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\nu\nu)\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	$\tilde{g}$	1.825 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2017-030
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$	ATLAS-CONF-2017-033
	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	3.2	$\tilde{g}$	1.65 TeV	$c\tau(\text{NLSP}) < 0.1 \text{ mm}$	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 950 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu < 0$	1507.05493
3 rd gen. $\tilde{g}$ med.	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	$\tilde{g}$	1.8 TeV	$m(\tilde{\chi}_1^0) > 680 \text{ GeV}, c\tau(\text{NLSP}) < 0.1 \text{ mm}, \mu > 0$	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e, μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	900 GeV	$m(\text{NLSP}) > 430 \text{ GeV}$	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2} \text{ scale}$	865 GeV	$m(\tilde{G}) > 1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{q})=1.5 \text{ TeV}$	1502.01518
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 b	Yes	36.1	$\tilde{g}$	1.92 TeV	$m(\tilde{\chi}_1^0) < 600 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	$\tilde{g}$	1.97 TeV	$m(\tilde{\chi}_1^0) < 200 \text{ GeV}$	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.37 TeV	$m(\tilde{\chi}_1^0) < 300 \text{ GeV}$	1407.0600

3 rd gen. squarks direct production	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$	0	2 <i>b</i>	Yes	36.1	$\tilde{b}_1$	950 GeV
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{\chi}_1^+$	2 <i>e, μ</i> (SS)	1 <i>b</i>	Yes	36.1	$\tilde{b}_1$	275-700 GeV
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{\chi}_1^+$	0-2 <i>e, μ</i>	1-2 <i>b</i>	Yes	4.7/13.3	$\tilde{t}_1$	117-170 GeV 200-720 GeV
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$	0-2 <i>e, μ</i>	0-2 jets/1-2 <i>b</i>	Yes	20.3/36.1	$\tilde{t}_1$	90-198 GeV 205-950 GeV
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$	0	mono-jet	Yes	3.2	$\tilde{t}_1$	90-323 GeV
	$\tilde{t}_1 \tilde{t}_1$ (natural GMSB)	2 <i>e, μ</i> (Z)	1 <i>b</i>	Yes	20.3	$\tilde{t}_1$	150-600 GeV
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 <i>e, μ</i> (Z)	1 <i>b</i>	Yes	36.1	$\tilde{t}_2$	290-790 GeV
	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 <i>e, μ</i>	4 <i>b</i>	Yes	36.1	$\tilde{t}_2$	320-880 GeV
	EW direct	$\tilde{\ell}_{1L} \tilde{\ell}_{1L}^*, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 <i>e, μ</i>	0	Yes	36.1	$\tilde{\ell}$
$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow \tilde{\ell} \nu(\tau \bar{\nu})$		2 <i>e, μ</i>	0	Yes	36.1	$\tilde{\chi}_1^+$	710 GeV
$\tilde{\chi}_1^+ \tilde{\chi}_1^- / \tilde{\chi}_2^0, \tilde{\chi}_1^+ \rightarrow \tilde{\tau} \nu(\tau \bar{\nu}), \tilde{\chi}_2^0 \rightarrow \tilde{\tau} \tau(\nu \bar{\nu})$		2 τ	-	Yes	36.1	$\tilde{\chi}_1^+$	760 GeV
$\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L \nu \tilde{\ell}_L \ell(\bar{\nu} \nu), \tilde{\ell} \nu \tilde{\ell}_L \ell(\bar{\nu} \nu)$		3 <i>e, μ</i>	0	Yes	36.1	$\tilde{\chi}_1^+, \tilde{\chi}_{2,3}^0$	1.16 TeV
$\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow W \tilde{\ell}^0 Z \tilde{\ell}^0$		2-3 <i>e, μ</i>	0-2 jets	Yes	36.1	$\tilde{\chi}_1^+, \tilde{\chi}_{2,3}^0$	580 GeV
$\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 h \tilde{\chi}_1^0, h \rightarrow b \bar{b} / WW / \tau \tau / \gamma \gamma$		<i>e, μ, γ</i>	0-2 <i>b</i>	Yes	20.3	$\tilde{\chi}_1^+, \tilde{\chi}_2^0$	270 GeV
$\tilde{\chi}_{2,3}^0 \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell} \ell$		4 <i>e, μ</i>	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	635 GeV
GGM (wino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$		1 <i>e, μ + γ</i>	-	Yes	20.3	$\tilde{W}$	115-370 GeV
GGM (bino NLSP) weak prod., $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$		2 γ	-	Yes	20.3	$\tilde{W}$	590 GeV
Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^\pm$	430 GeV
	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
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	850 GeV
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	$\tilde{g}$	
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	440 GeV
	$\tilde{g} \tilde{g}, \tilde{\chi}_1^0 \rightarrow e e \nu / e \mu \nu / \mu \mu \nu$	displ. <i>ee/eμ/μμ</i>	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV
	GGM $\tilde{g} \tilde{g}, \tilde{\chi}_1^0 \rightarrow Z \tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV
RPV	LFV $p p \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e \mu / e \tau / \mu \tau$	<i>eμ, eτ, μτ</i>	-	-	3.2	$\tilde{\nu}_\tau$	
	Bilinear RPV CMSSM	2 <i>e, μ</i> (SS)	0-3 <i>b</i>	Yes	20.3	$\tilde{q}, \tilde{g}$	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e e \nu, e \mu \nu, \mu \mu \nu$	4 <i>e, μ</i>	-	Yes	13.3	$\tilde{\chi}_1^+$	1.14 TeV
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-, \tilde{\chi}_1^+ \rightarrow W \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau \tau \nu_e, e \tau \nu_\tau$	3 <i>e, μ + τ</i>	-	Yes	20.3	$\tilde{\chi}_1^+$	450 GeV
	$\tilde{g} \tilde{g}, \tilde{g} \rightarrow q q q$	0	4-5 large- <i>R</i> jets	-	14.8	$\tilde{g}$	1.08 TeV
	$\tilde{g} \tilde{g}, \tilde{g} \rightarrow q q \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q q q$	0	4-5 large- <i>R</i> jets	-	14.8	$\tilde{g}$	
	$\tilde{g} \tilde{g}, \tilde{g} \rightarrow t \bar{t} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q q q$	1 <i>e, μ</i>	8-10 jets/0-4 <i>b</i>	-	36.1	$\tilde{g}$	
	$\tilde{g} \tilde{g}, \tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b s$	1 <i>e, μ</i>	8-10 jets/0-4 <i>b</i>	-	36.1	$\tilde{g}$	
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b s$	0	2 jets + 2 <i>b</i>	-	15.4	$\tilde{t}_1$	410 GeV 450-510 GeV
$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \ell$	2 <i>e, μ</i>	2 <i>b</i>	-	36.1	$\tilde{t}_1$	0.4 TeV	
Other	Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 <i>c</i>	Yes	20.3	$\tilde{c}$	510 GeV

**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.*

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

 $\sqrt{s} = 8,13 \text{ TeV}$
$$\int \mathcal{L} dt = (3.2 - 37.0) \text{ fb}^{-1}$$

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L} \, dt [\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0 \, e, \mu$	$1-4 \, \text{j}$	Yes	36.1	M_D	7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	$2 \, \gamma$	–	–	36.7	M_S	8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	$2 \, \text{j}$	–	37.0	M_{th}	8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	$\geq 1 \, e, \mu$	$\geq 2 \, \text{j}$	–	3.2	M_{th}	8.2 TeV	$n = 6, M_D = 3 \, \text{TeV}, \text{rot BH}$	1606.02265
	ADD BH multijet	–	$\geq 3 \, \text{j}$	–	3.6	M_{th}	9.55 TeV	$n = 6, M_D = 3 \, \text{TeV}, \text{rot BH}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \, \gamma$	–	–	36.7	$G_{KK} \text{ mass}$	4.1 TeV	$k/\overline{M}_{\text{Pl}} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	$1 \, e, \mu$	$1 \, \text{J}$	Yes	36.1	$G_{KK} \text{ mass}$	1.75 TeV	$k/\overline{M}_{\text{Pl}} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	$1 \, e, \mu$	$\geq 2 \, \text{b}, \geq 3 \, \text{j}$	Yes	13.2	$KK \text{ mass}$	1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \rightarrow t\bar{t}) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 \, e, \mu$	–	–	36.1	$Z' \text{ mass}$	4.5 TeV	$\Gamma/m = 3\%$ $g_V = 3$ $\bar{g}_V = 3$	ATLAS-CONF-2017-027
	SSM $Z' \rightarrow \tau\tau$	$2 \, \tau$	–	–	36.1	$Z' \text{ mass}$	2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \rightarrow b\bar{b}$	–	$2 \, \text{b}$	–	3.2	$Z' \text{ mass}$	1.5 TeV		1603.08791
	Leptophobic $Z' \rightarrow t\bar{t}$	$1 \, e, \mu$	$\geq 1 \, \text{b}, \geq 1\text{J}/2\text{j}$	Yes	3.2	$Z' \text{ mass}$	2.0 TeV		ATLAS-CONF-2016-014
	SSM $W' \rightarrow \ell\nu$	$1 \, e, \mu$	–	Yes	36.1	$W' \text{ mass}$	5.1 TeV		1706.04786
	HVT $V' \rightarrow WW \rightarrow qq\bar{q}q$ model B	$0 \, e, \mu$	$2 \, \text{J}$	–	36.7	$V' \text{ mass}$	3.5 TeV		CERN-EP-2017-147
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	–	–	36.1	$V' \text{ mass}$	2.93 TeV		ATLAS-CONF-2017-055
	LRSM $W'_R \rightarrow t\bar{b}$	$1 \, e, \mu$	$2 \, \text{b}, 0-1 \, \text{j}$	Yes	20.3	$W' \text{ mass}$	1.92 TeV		1410.4103
LRSM $W'_R \rightarrow t\bar{b}$	$0 \, e, \mu$	$\geq 1 \, \text{b}, 1 \, \text{J}$	–	20.3	$W' \text{ mass}$	1.76 TeV	1408.0886		
CI	CI $qqqq$	–	$2 \, \text{j}$	–	37.0	Λ	21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	$2 \, e, \mu$	–	–	36.1	Λ	40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	$2(\text{SS})/\geq 3 \, e, \mu$	$\geq 1 \, \text{b}, \geq 1 \, \text{j}$	Yes	20.3	Λ	4.9 TeV	$ C_{RR} = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	$0 \, e, \mu$	$1-4 \, \text{j}$	Yes	36.1	m_{med}	1.5 TeV	$g_q=0.25, \bar{g}_\gamma=1.0, m(\chi) < 400 \, \text{GeV}$	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	$0 \, e, \mu, 1 \, \gamma$	$\leq 1 \, \text{j}$	Yes	36.1	m_{med}	1.2 TeV	$g_q=0.25, \bar{g}_\gamma=1.0, m(\chi) < 480 \, \text{GeV}$	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	$0 \, e, \mu$	$1 \, \text{J}, \leq 1 \, \text{j}$	Yes	3.2	M_*	700 GeV	$m(\chi) < 150 \, \text{GeV}$	1608.02372
LQ	Scalar LQ 1 st gen	$2 \, e$	$\geq 2 \, \text{j}$	–	3.2	LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2 nd gen	$2 \, \mu$	$\geq 2 \, \text{j}$	–	3.2	LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3 rd gen	$1 \, e, \mu$	$\geq 1 \, \text{b}, \geq 3 \, \text{j}$	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	$0 \text{ or } 1 \, e, \mu$	$\geq 2 \, \text{b}, \geq 3 \, \text{j}$	Yes	13.2	T mass	1.2 TeV	$\mathcal{B}(T \rightarrow Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \rightarrow Zt + X$	$1 \, e, \mu$	$\geq 1 \, \text{b}, \geq 3 \, \text{j}$	Yes	36.1	T mass	1.16 TeV	$\mathcal{B}(T \rightarrow Zt) = 1$	1705.10751
	VLQ $TT \rightarrow Wb + X$	$1 \, e, \mu$	$\geq 1 \, \text{b}, \geq 1\text{J}/2\text{j}$	Yes	36.1	T mass	1.35 TeV	$\mathcal{B}(T \rightarrow Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \rightarrow Hb + X$	$1 \, e, \mu$	$\geq 2 \, \text{b}, \geq 3 \, \text{j}$	Yes	20.3	B mass	700 GeV	$\mathcal{B}(B \rightarrow Hb) = 1$	1505.04306
	VLQ $BB \rightarrow Zb + X$	$2/\geq 3 \, e, \mu$	$\geq 2/\geq 1 \, \text{b}$	–	20.3	B mass	790 GeV	$\mathcal{B}(B \rightarrow Zb) = 1$	1409.5500
	VLQ $BB \rightarrow Wt + X$	$1 \, e, \mu$	$\geq 1 \, \text{b}, \geq 1\text{J}/2\text{j}$	Yes	36.1	B mass	1.25 TeV	$\mathcal{B}(B \rightarrow Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \rightarrow WqWq$	$1 \, e, \mu$	$\geq 4 \, \text{j}$	Yes	20.3	Q mass	690 GeV	1509.04261	
Excited fermions	Excited quark $q^* \rightarrow qg$	–	$2 \, \text{j}$	–	37.0	$q^* \text{ mass}$	6.0 TeV	only u^* and d^* , $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \rightarrow q\gamma$	$1 \, \gamma$	$1 \, \text{j}$	–	36.7	$q^* \text{ mass}$	5.3 TeV	only u^* and d^* , $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \rightarrow bg$	–	$1 \, \text{b}, 1 \, \text{j}$	–	13.3	$b^* \text{ mass}$	2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	$1 \text{ or } 2 \, e, \mu$	$1 \, \text{b}, 2-0 \, \text{j}$	Yes	20.3	$b^* \text{ mass}$	1.5 TeV	$f_\delta = f_t = f_R = 1$	1510.02664
	Excited lepton ℓ^*	$3 \, e, \mu$	–	–	20.3	$\ell^* \text{ mass}$	3.0 TeV	$\Lambda = 3.0 \, \text{TeV}$	1411.2921
	Excited lepton ν^*	$3 \, e, \mu, \tau$	–	–	20.3	$\nu^* \text{ mass}$	1.6 TeV	$\Lambda = 1.6 \, \text{TeV}$	1411.2921
Other	LRSM Majorana ν	$2 \, e, \mu$	$2 \, \text{j}$	–	20.3	$N^0 \text{ mass}$	2.0 TeV	$m(W_R) = 2.4 \, \text{TeV}, \text{no mixing}$	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 \, e, \mu$ (SS)	–	–	36.1	$H^{\pm\pm} \text{ mass}$	870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	$3 \, e, \mu, \tau$	–	–	20.3	$H^{\pm\pm} \text{ mass}$	400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \rightarrow \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	$1 \, e, \mu$	$1 \, \text{b}$	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $ q = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $ g = 1g_D, \text{spin } 1/2$	1509.08059
		$\sqrt{s} = 8 \, \text{TeV}$	$\sqrt{s} = 13 \, \text{TeV}$						
						10^{-1}	1	10	Mass scale [TeV]

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

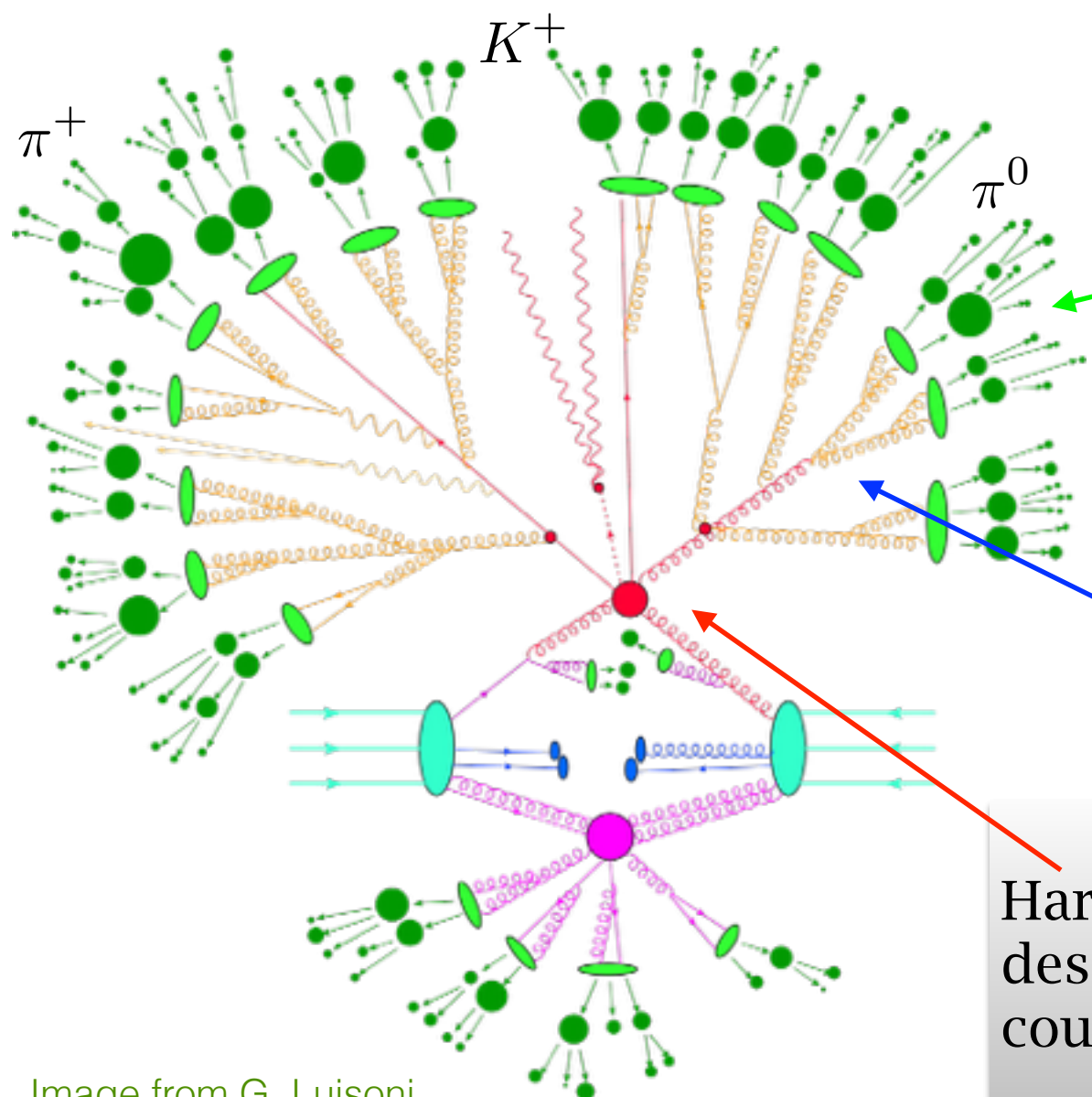
† Small-radius (large-radius) jets are denoted by the letter *j* (*J*).

The quest for precision at the LHC

- The need for theory precision is twofold
 - As a precision machine, the LHC is providing us with %-accurate measurements SM parameters/dynamics (couplings, PDFs, masses,...). A full exploitation of these resources requires a deeper understanding of the theory than what we previously had. Also, precision often allows for indirect constraints on NP
 - In order to maximise its discovery reach, sensitive observables have to be conceived. This often requires measurements in extreme regions of phase space where large momentum transfer enhances the effects of new physics (e.g. boosted kinematics)
 - effects of NP could hide behind mild distortions of the kinematics (e.g. differential shapes, broad resonances,...)
 - A careful assessment of the SM background is essential in most cases. This reaches the few-percent level in some scenarios
- Can we get to this level of precision ? What are the limitations of our current understanding ?

Theoretical framework: collinear factorisation

$$d\sigma_{pp \rightarrow X} = \sum_{i,j=q,g} \int dx_1 dx_2 f_i(x_1) f_j(x_2) d\hat{\sigma}_{ij \rightarrow X}(x_1, x_2) O(X) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^n}{Q^n}\right)$$



At scales of the order of Λ_{QCD} hadronisation occurs, causing further (soft) kinematics reshuffling/recombinations

$$\alpha_s(k_t) \sim 1$$

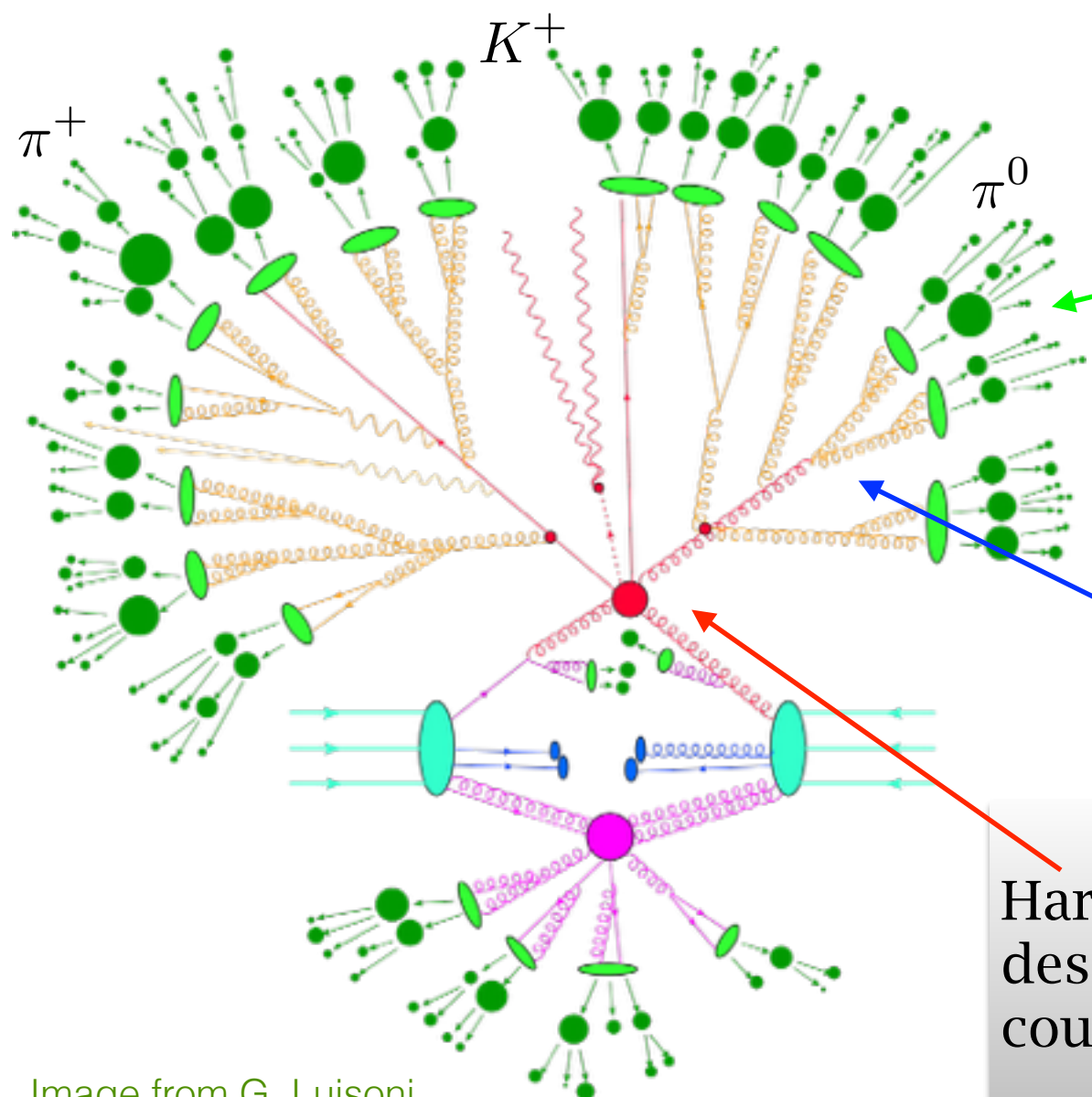
As the coupling grows large, coloured particles are very likely to emit soft and/or collinear radiation (i.e. small k_t) all the way down to hadronisation scales.

$$\alpha_s(Q) \ll \alpha_s(k_t) < 1 \quad \int \frac{dE}{E} \frac{d\theta}{\theta} \alpha_s(k_t) \gg 1$$

Hard scattering between most energetic partons - description relies on perturbation theory as a small-coupling expansion (fixed-order) $\alpha_s(k_t) \sim \alpha_s(Q) \ll 1$

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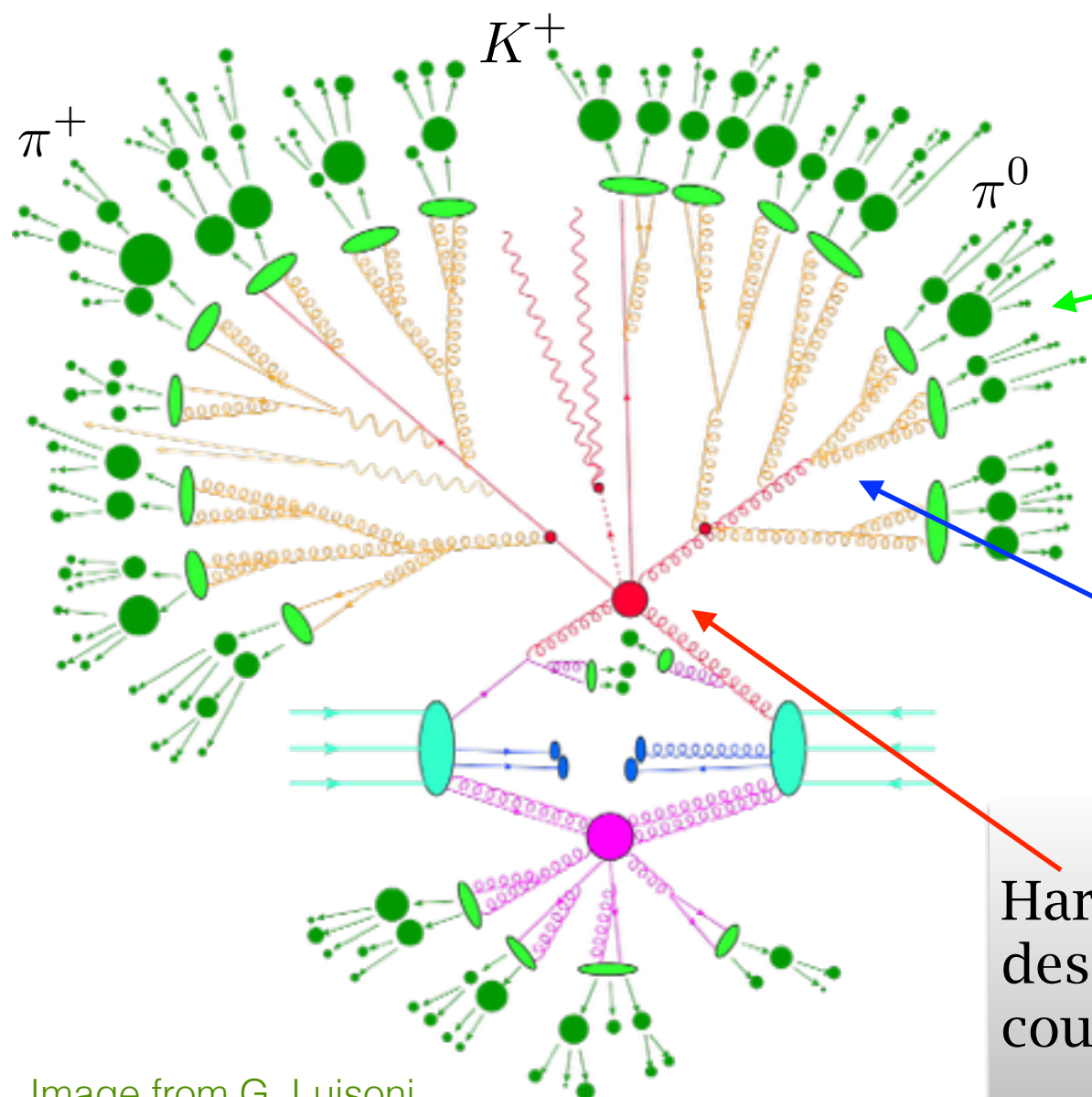
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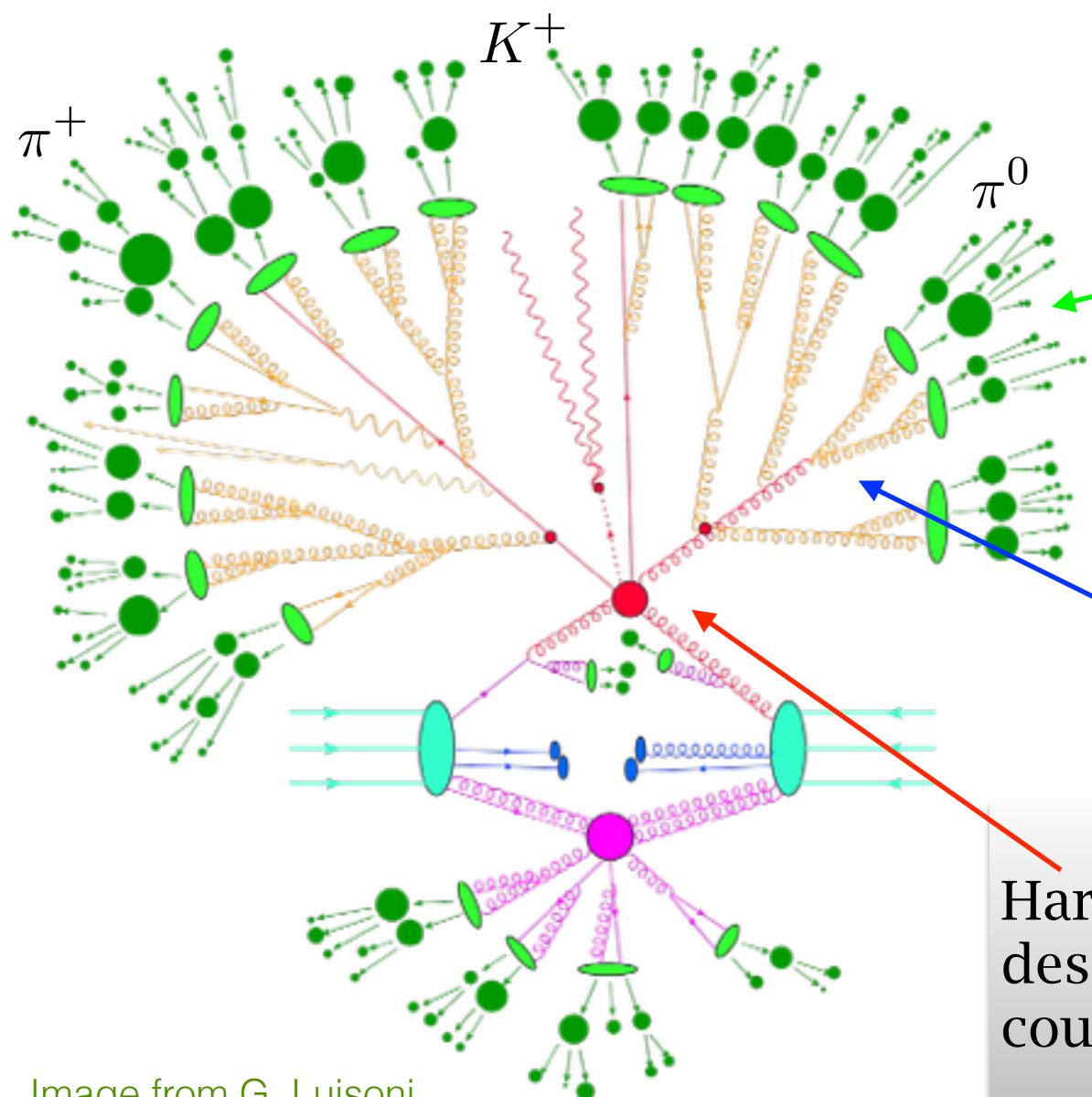
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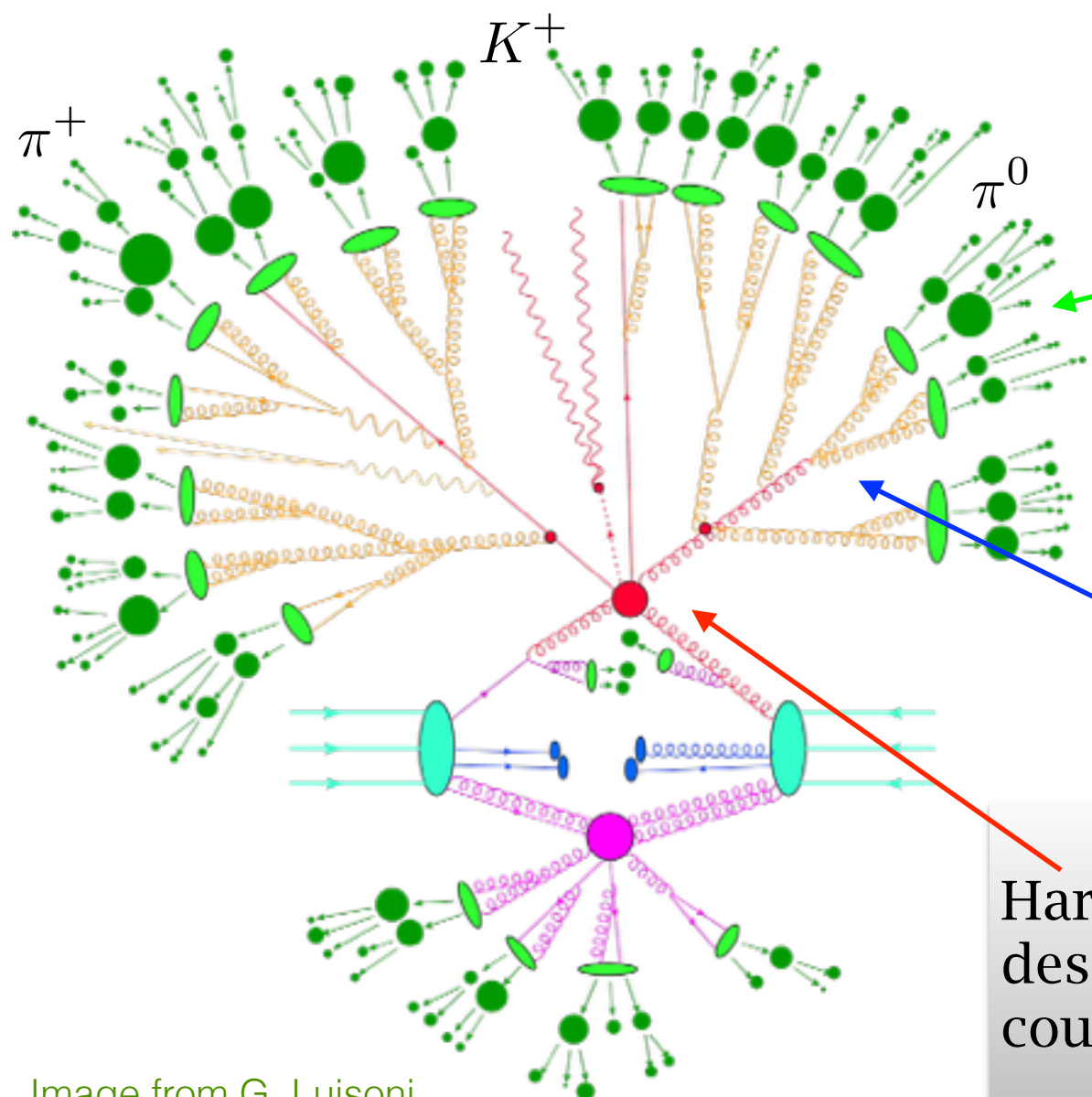
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* factorisation violations at high orders in multi-jet reactions. Few-percent effect expected



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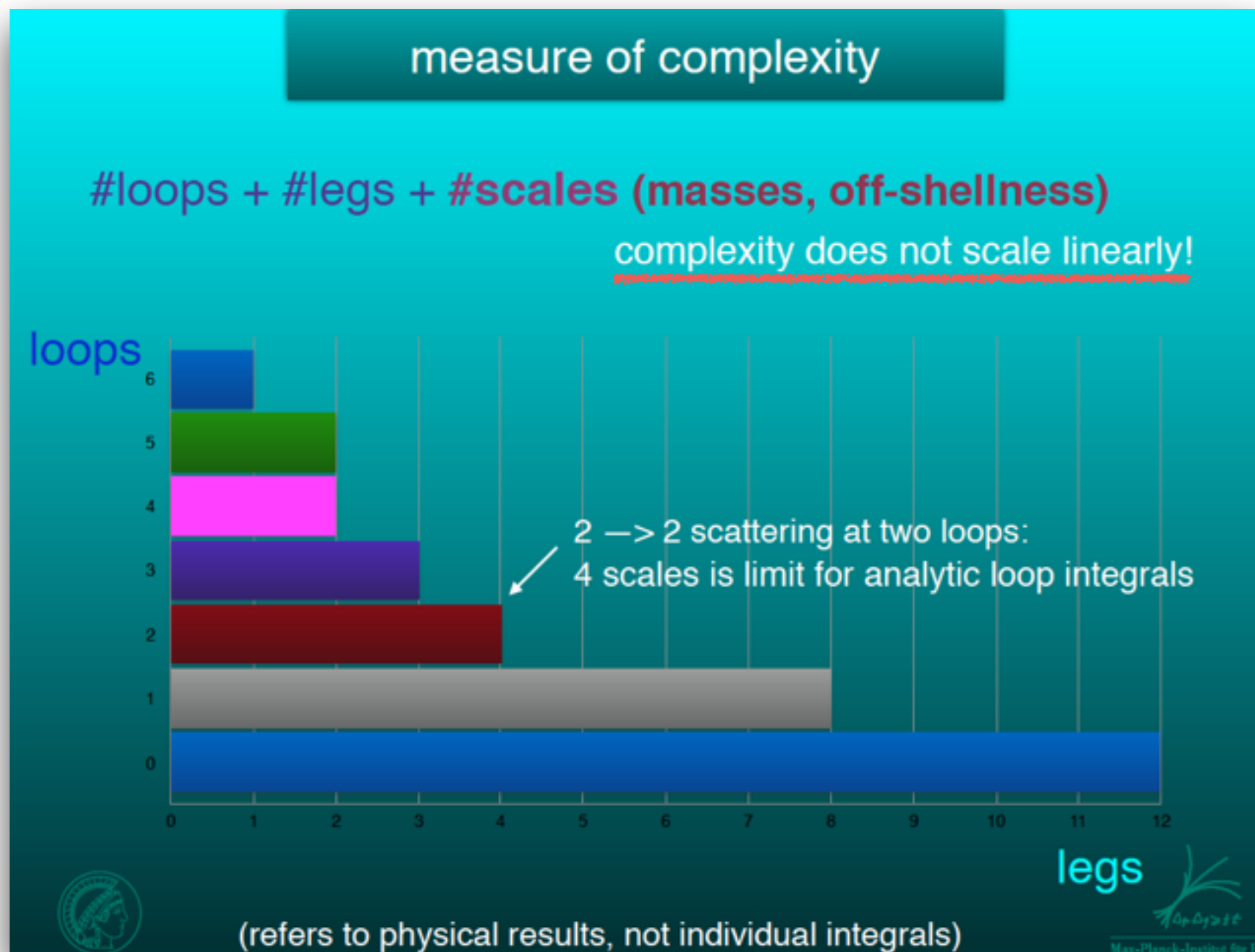
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The hard scattering

- Asymptotic freedom: systematic expansion in powers of small couplings (LO, NLO, NNLO,...)
- Allows for a fully exclusive description of hard partonic final states at a fixed order in the perturbative expansion

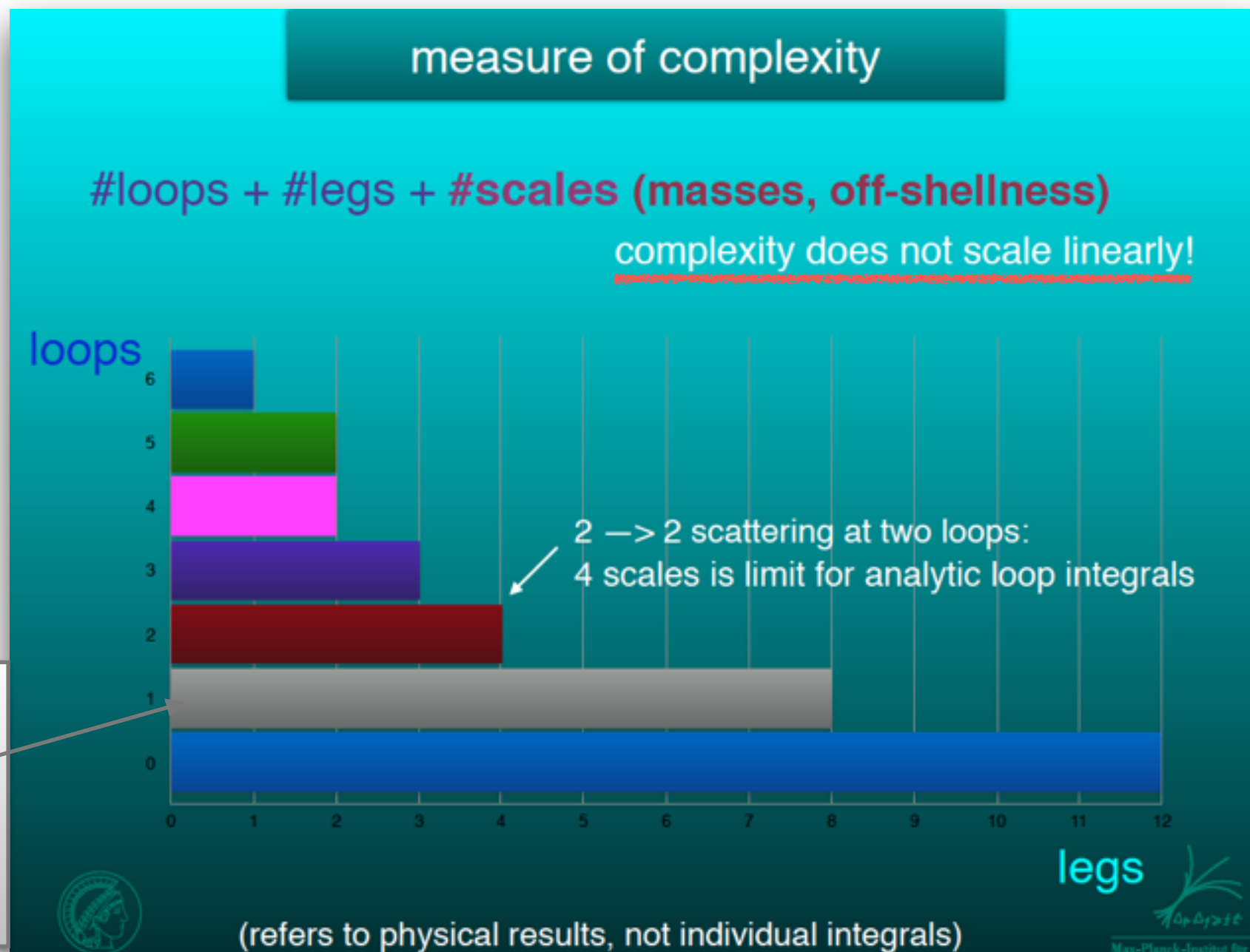
G. Heinrich at CERN colloquium 2017



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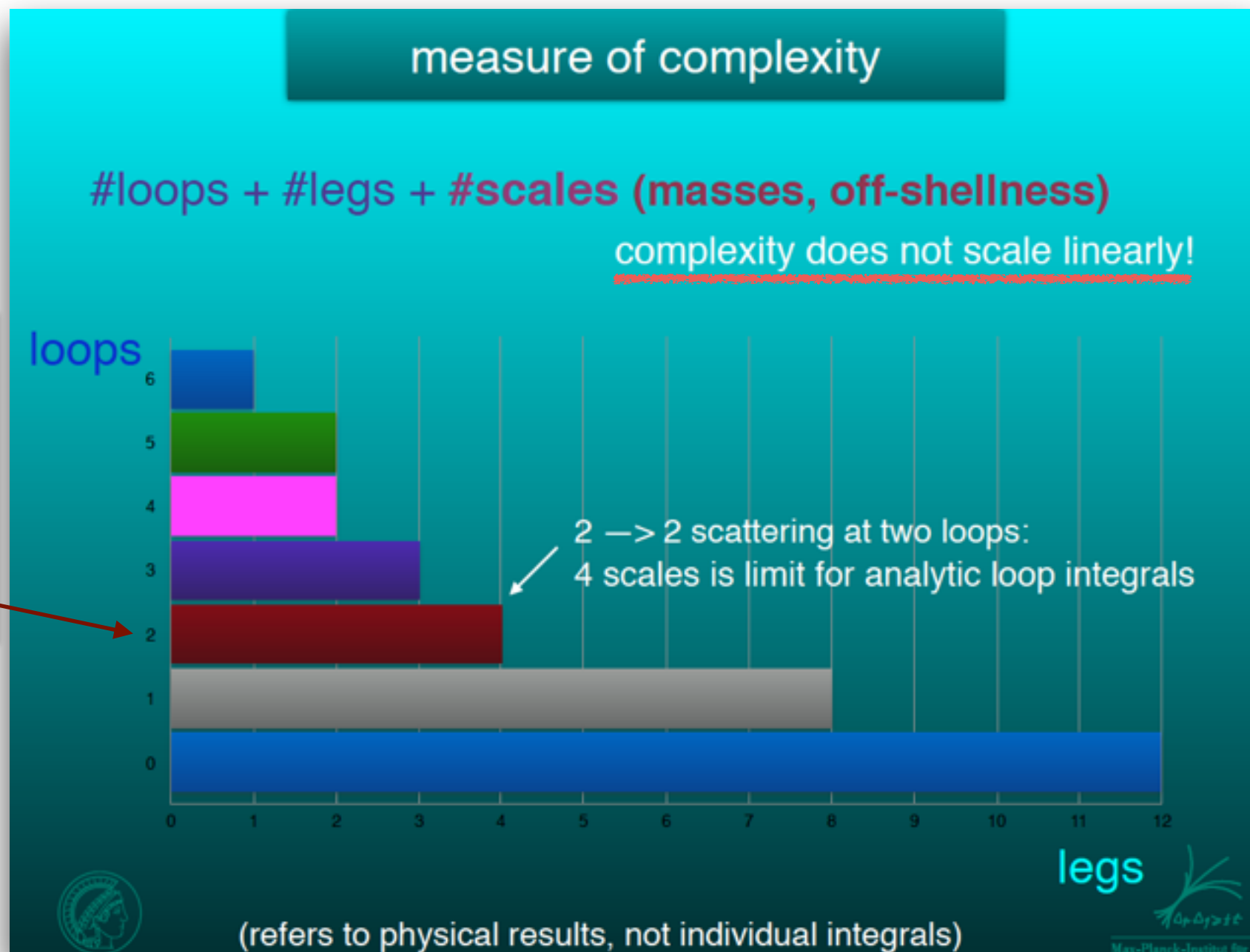
NLO QCD automated to a good extent with up to 5-6 FS particles (proc. dep.). Recent progress on multi-jet processes, off-shell effects, loop induced, EW corrections **and how to combine them with QCD**

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NNLO corrections available for $2 \rightarrow 2$ processes. Typically reach 2-7% accuracy for inclusive XS and 5-10% in kinematic distributions



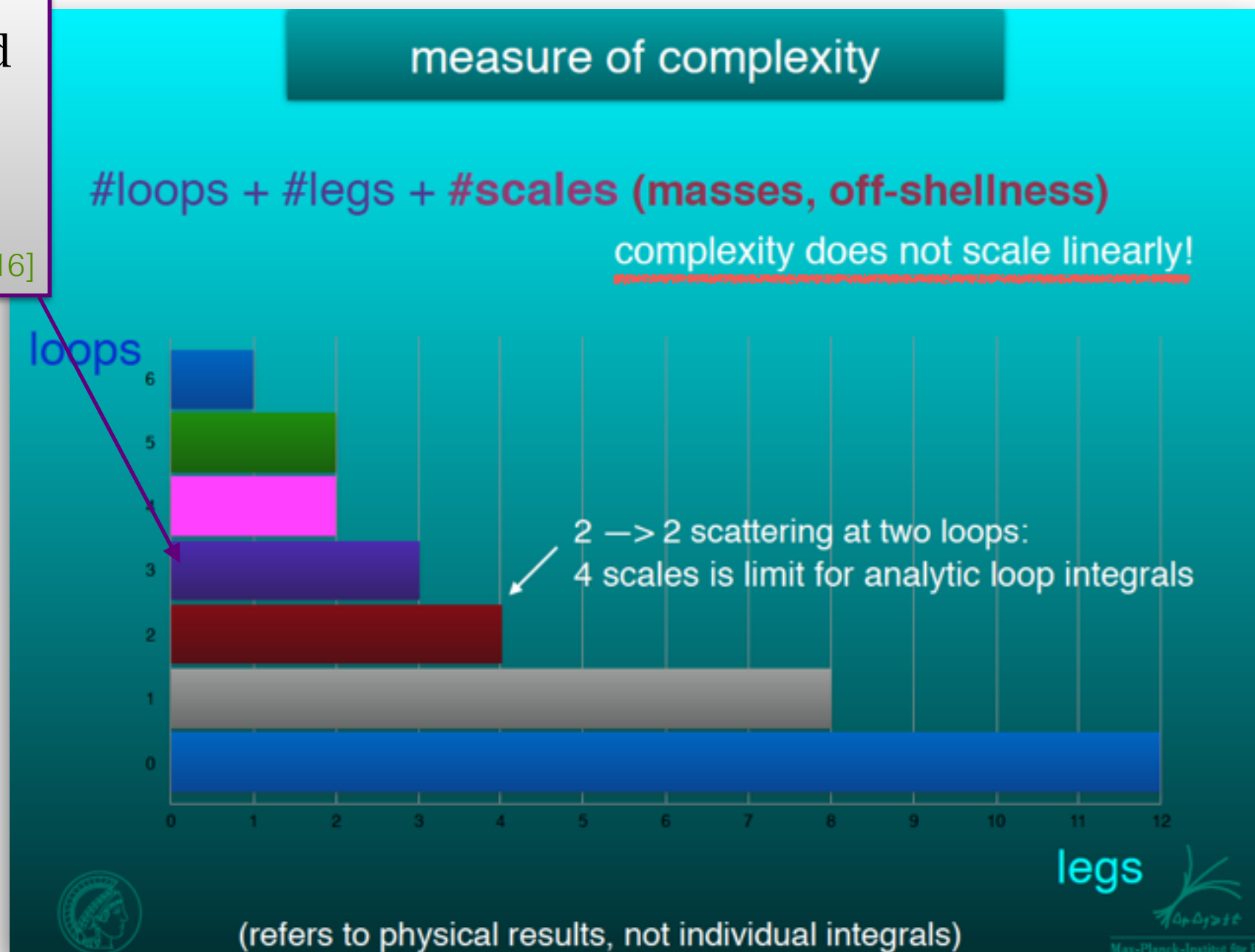
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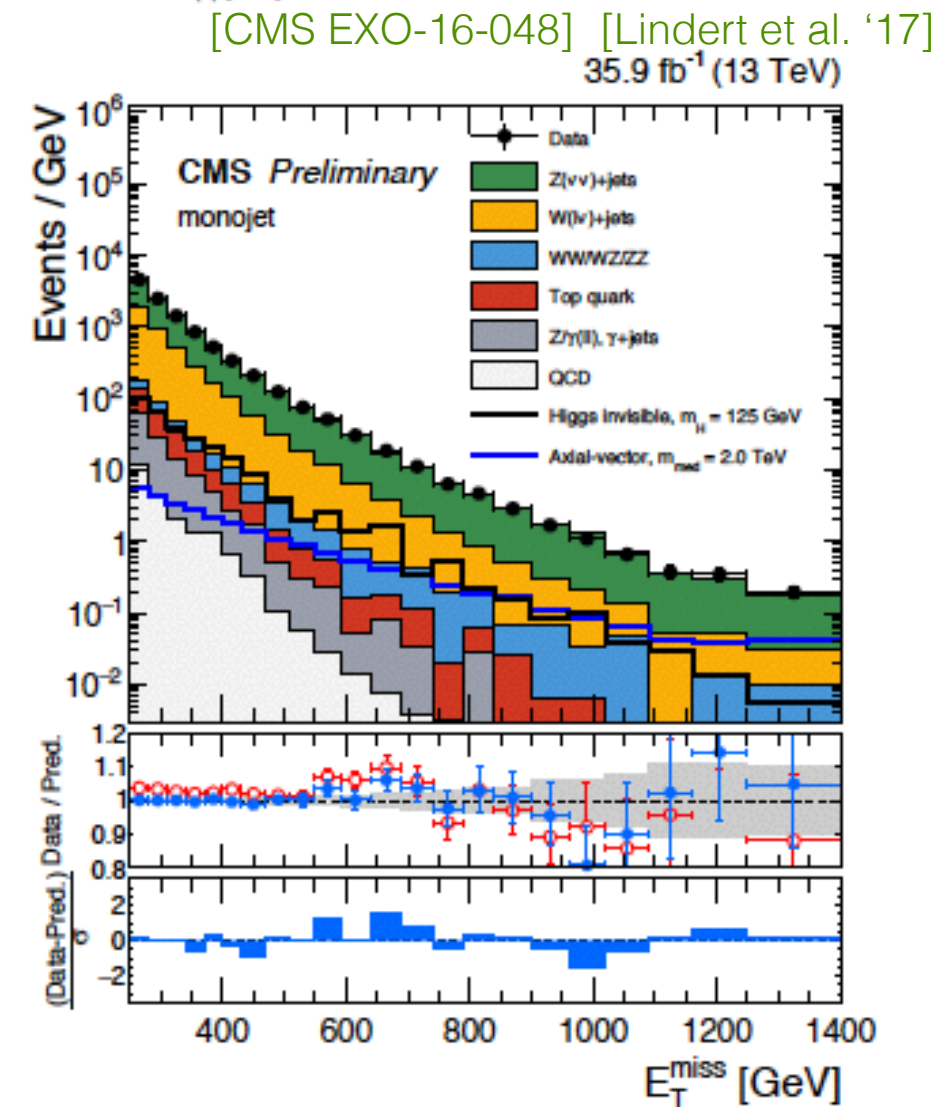
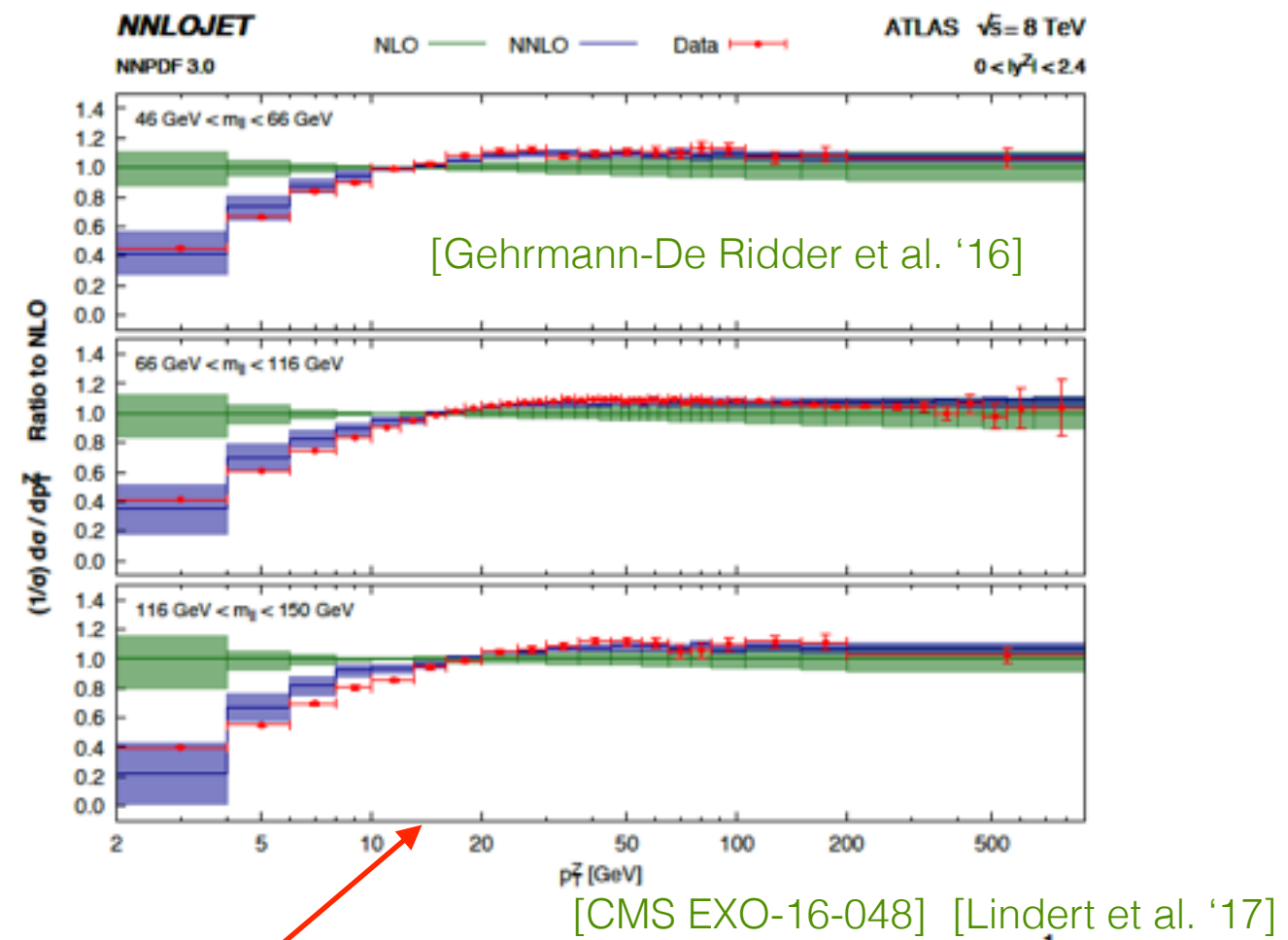
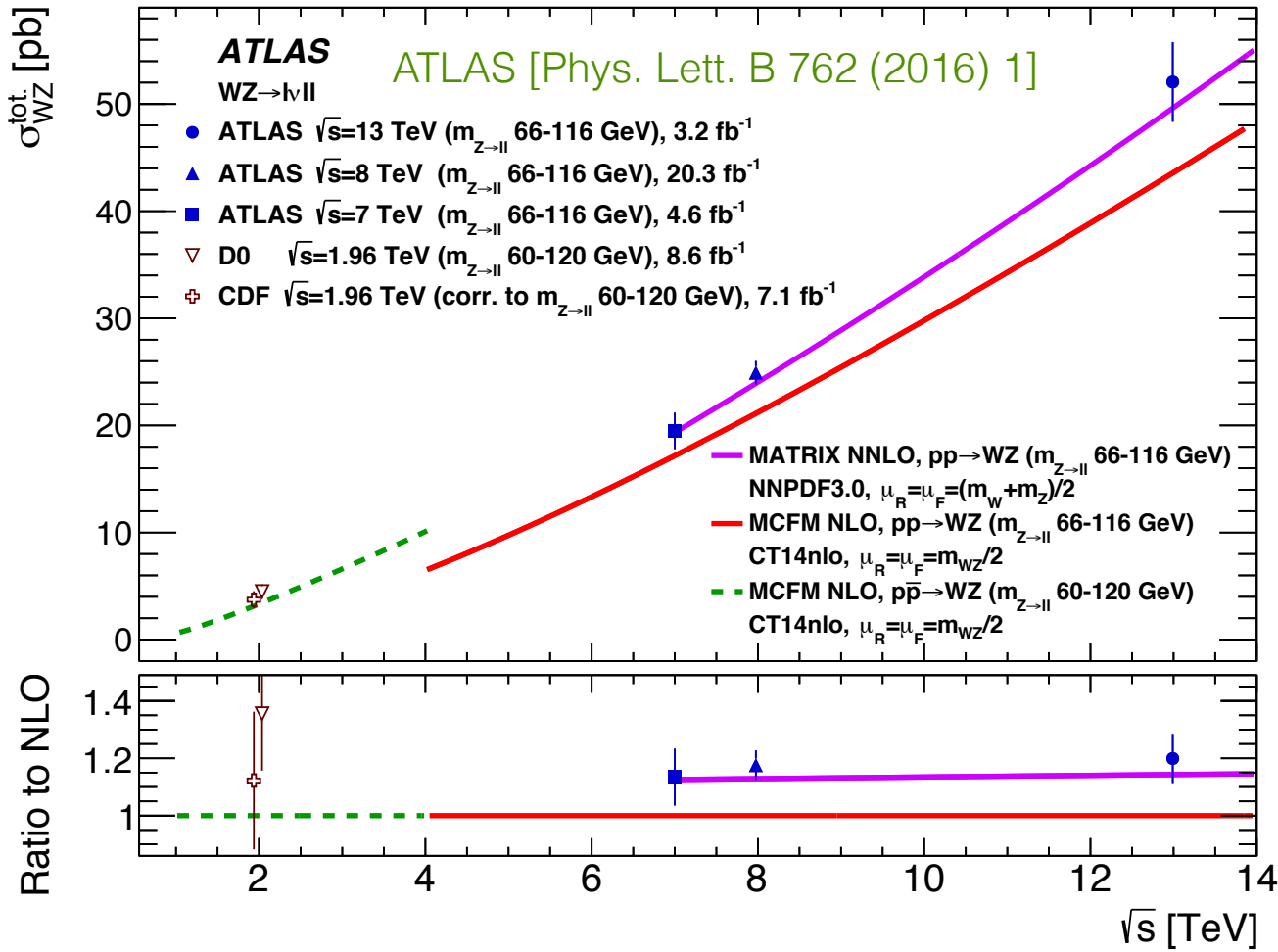
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N3LO corrections may be required for gluonic processes with poor convergence of the series
e.g. Higgs $\rightarrow$ 3-4% error

[Anastasiou et al. '16]



NNLO vs. Data



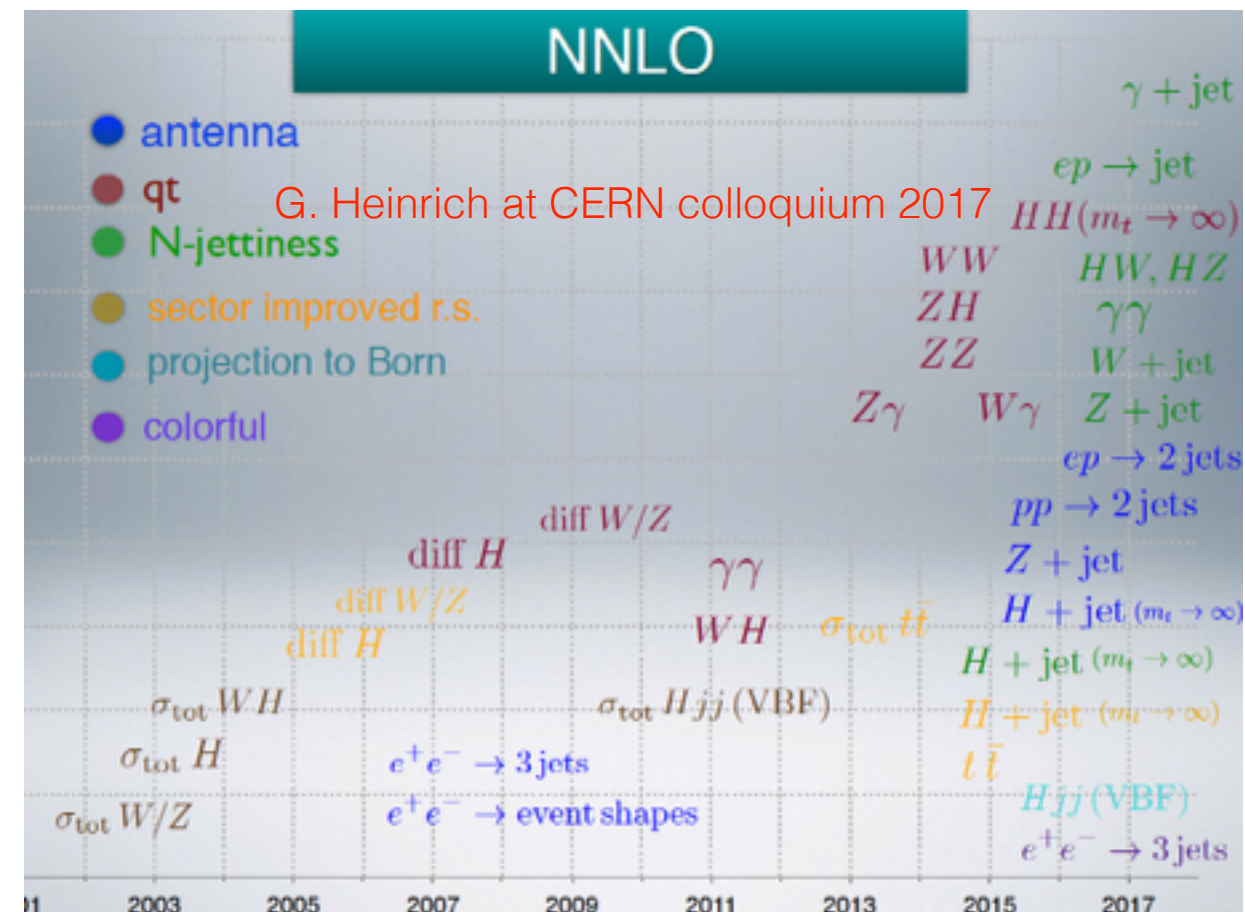
- Data favours NNLO in inclusive XS and differential SM distributions
- Applications in BSM searches
 - background uncertainties for DM in MET+jets at the ~ 4 -10% level in tails (estimate of EW effects crucial)

Amplitudes and subtraction at NNLO

- Amplitudes complexity grows rapidly with the number of scales (legs, masses). Recently progress in two-loop amplitudes for 2->2 processes with new techniques (analytically or numerically). e.g.
 - $p p \rightarrow V V$ (',*) [Gehrmann et al.; Caola et al.]
 - $p p \rightarrow t t$, $p p \rightarrow H H$ [Baernreuther et al.; Bonciani et al.; Borowka et al.]
- Current focus on 2->3 processes and massive amplitudes [Badger et al., Dunbar et al., Gehrmann et al., Papadopoulos et al.; Bonciani et al., Melnikov et al.]
- Cancellation of IRC divergences:
- (local) subtraction

$$\int (|M_R|^2 - \mathcal{S})[dPS_R] + \int \mathcal{S}[dPS_R] + \int |M_V|^2[dPS_V]$$

- Sector decomposition [Anastasiou et al., Binoth et al.]
- Antennae subtraction [Gehrmann et al.]
- Sector-improved residual subtr. [Czakon et al.]
- ColorFul subtraction [Del Duca et al.]
- Projection to Born [Cacciari et al.]
- Nested soft-collinear subtraction [Caola et al.]

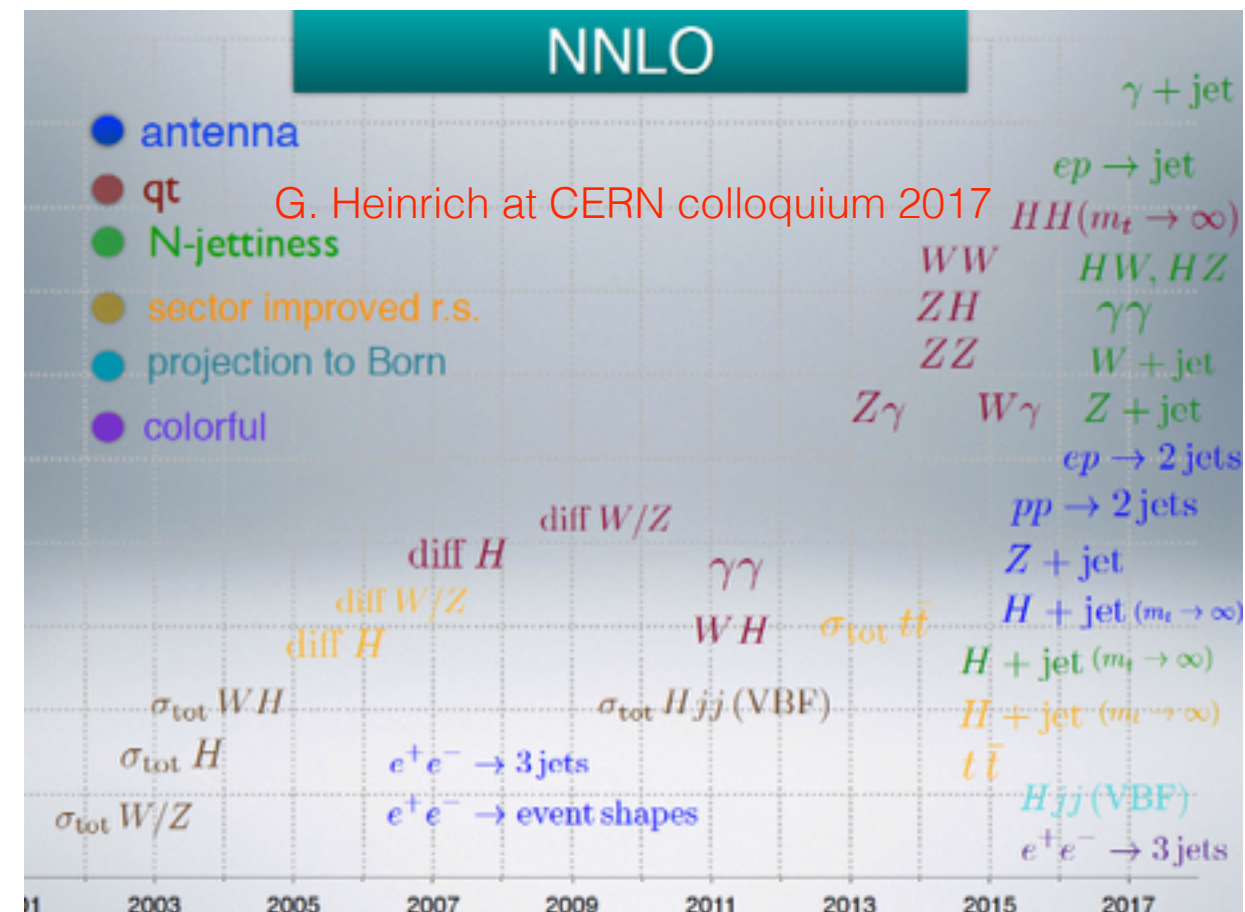


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- Cancellation of IRC divergences:
- slicing

$$\int_{\text{cutoff}} |M_R|^2 [d\text{PS}_R] + \int^{\text{cutoff}} |M_R|^2 [d\text{PS}_R] + \int |M_V|^2 [d\text{PS}_V]$$

- qT subtraction [Catani et al.]
- N-jettiness subtraction [Boughezal et al., Gaunt et al.]
 - power corrections [Boughezal et al., Moulst et al.]



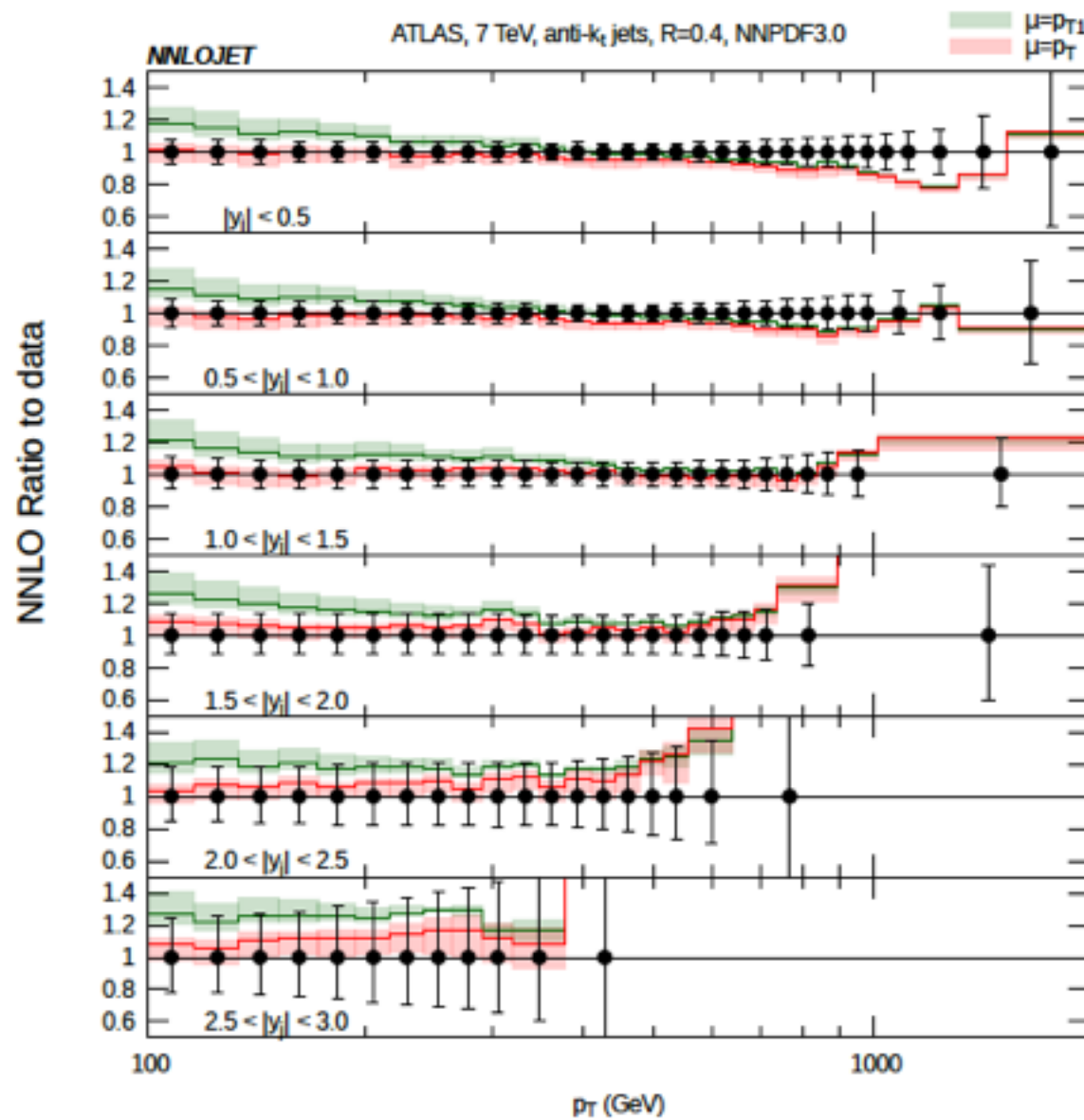
Scale choices

Differential distributions in $t\bar{t}$ production [Czakon et al. '16]

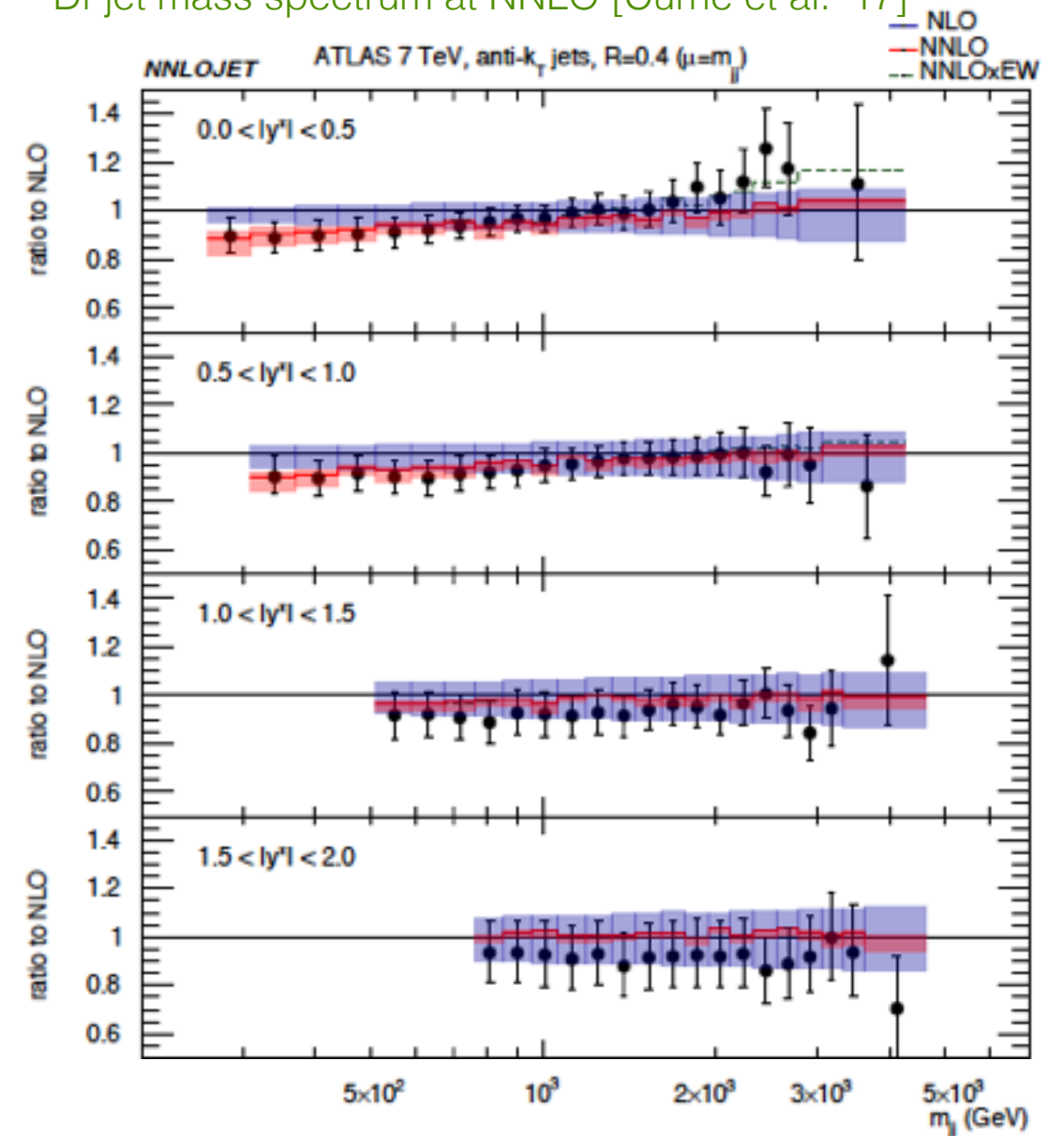
- Scale dependence much reduced at (N)NNLO
- Multijet (i.e. multi-scale) processes make choice of central scale cumbersome (obs. dependent)
 - difference between scales can be large (several criteria-unclear which is best)

$$\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for : } p_{T,t}, p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}, \\ \frac{H_T}{4} & \text{for : all other distributions.} \end{cases}$$

Inclusive jet spectrum at NNLO [Currie et al. '17]



Di-jet mass spectrum at NNLO [Currie et al. '17]



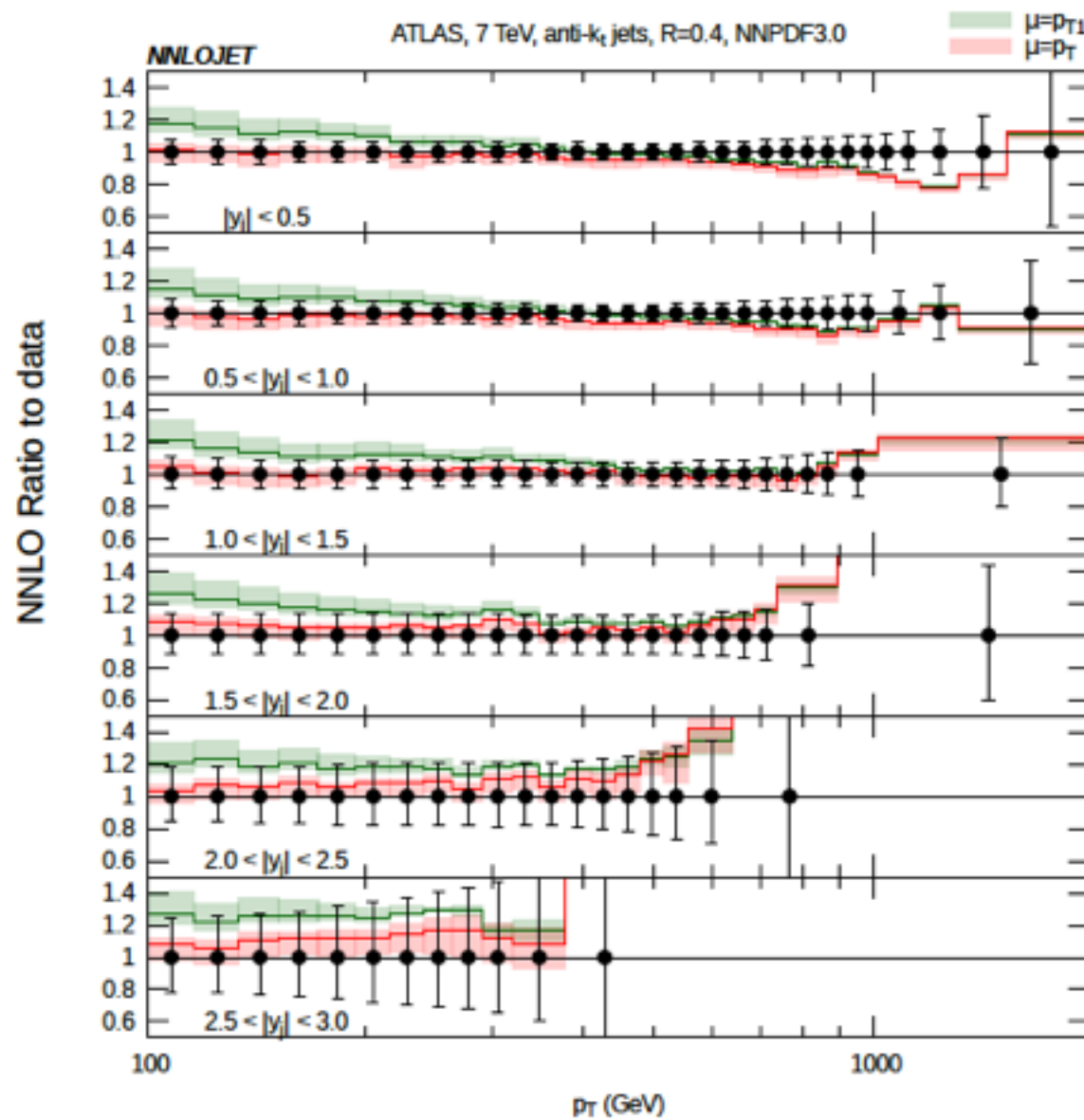
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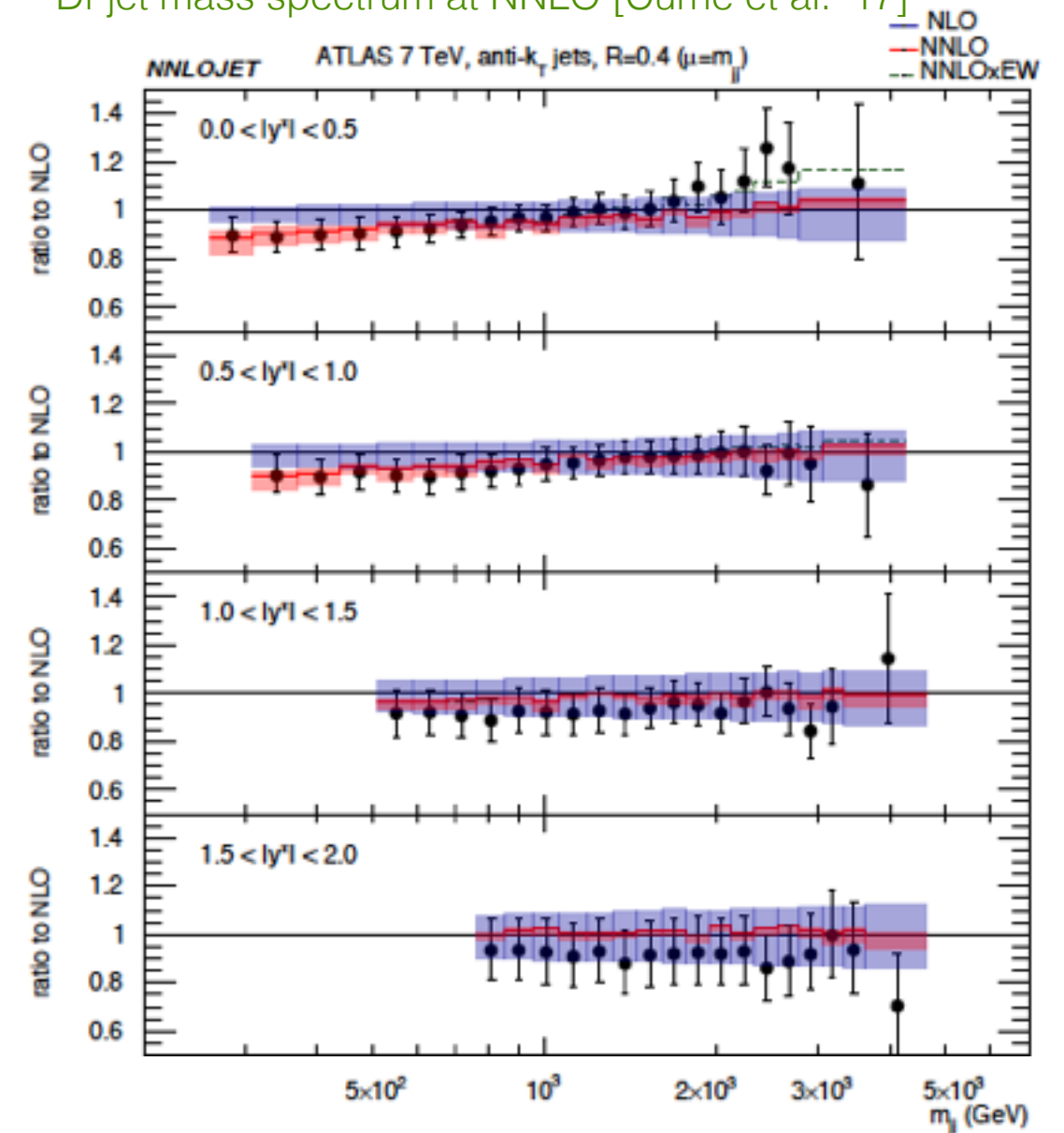
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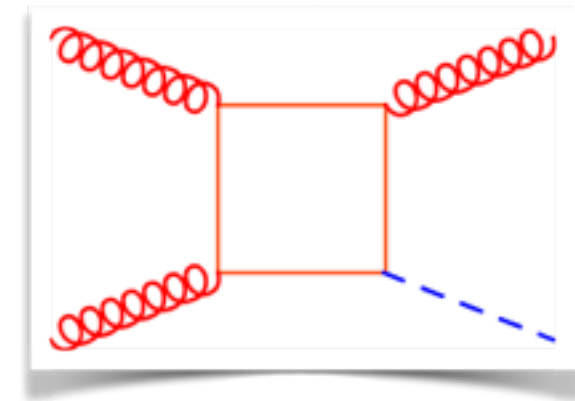
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Di-jet mass spectrum at NNLO [Currie et al. '17]



Loop-induced processes at NLO



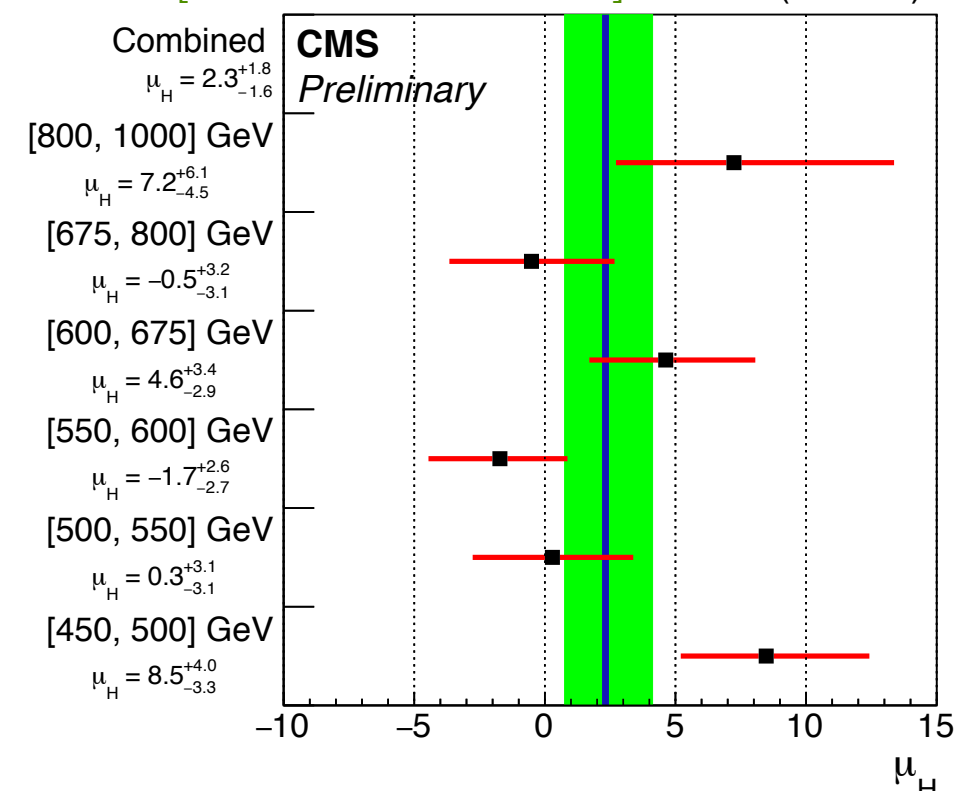
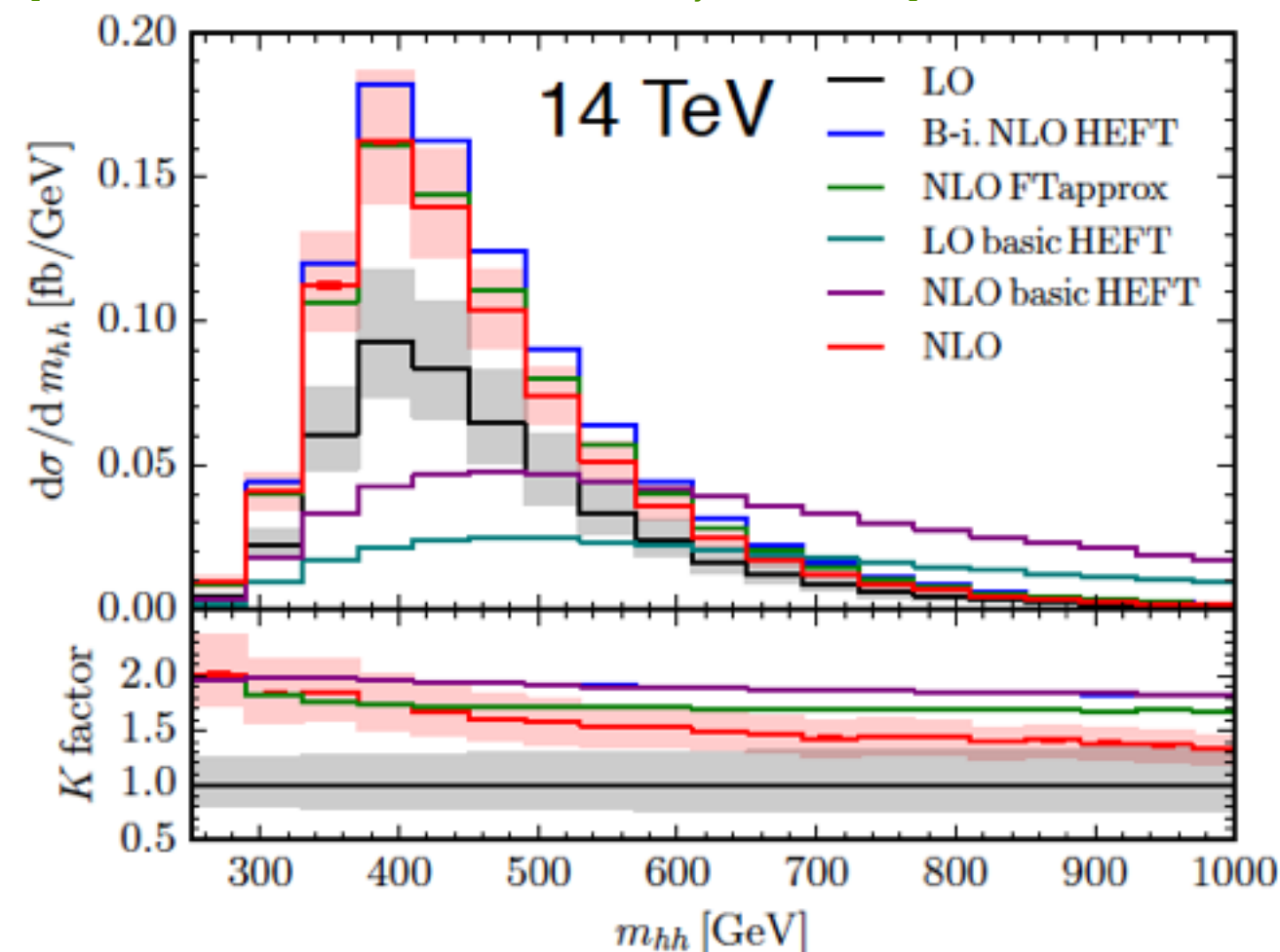
- Formally start at $O(\alpha_s^2)$, but enhanced by gluon densities
 - Recent progresses with light quarks $gg \rightarrow VV$ [Caola, Melnikov, Roentsch, Tancredi '15]
 - top-quark corrections are substantial in the tails (boosted regime very sensitive to NP). Normally described in a EFT where the top is infinitely heavy. Full analytic calculation of two-loop amplitudes highly involved
- Numerical solution for HH production
- Desirable for H+jet

[Borowka, N. Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke '16]
 [Heinrich, Jones, Kerner, Luisoni, Vryonidou '17]

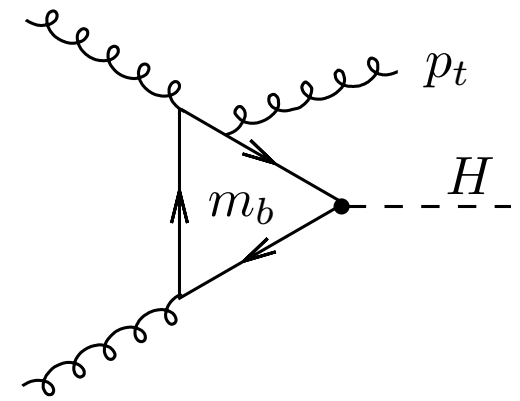
Progress in [Bonciani et al. '17]

- first measurements of tail for $H \rightarrow b\bar{b}$ with substructure

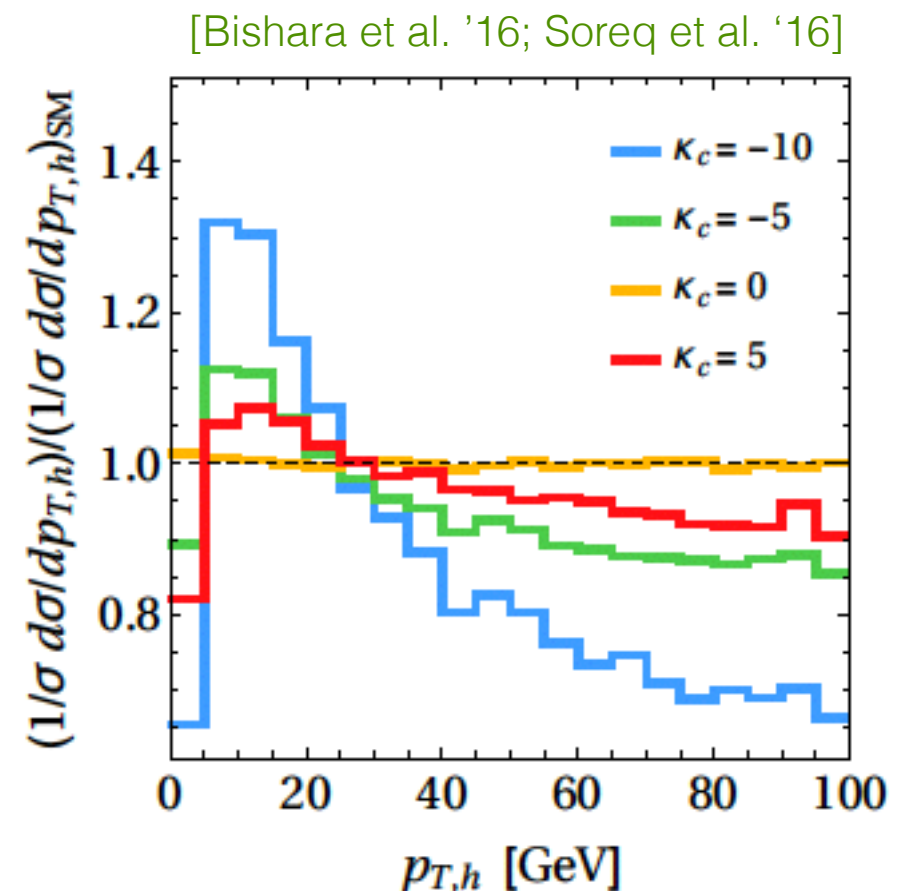
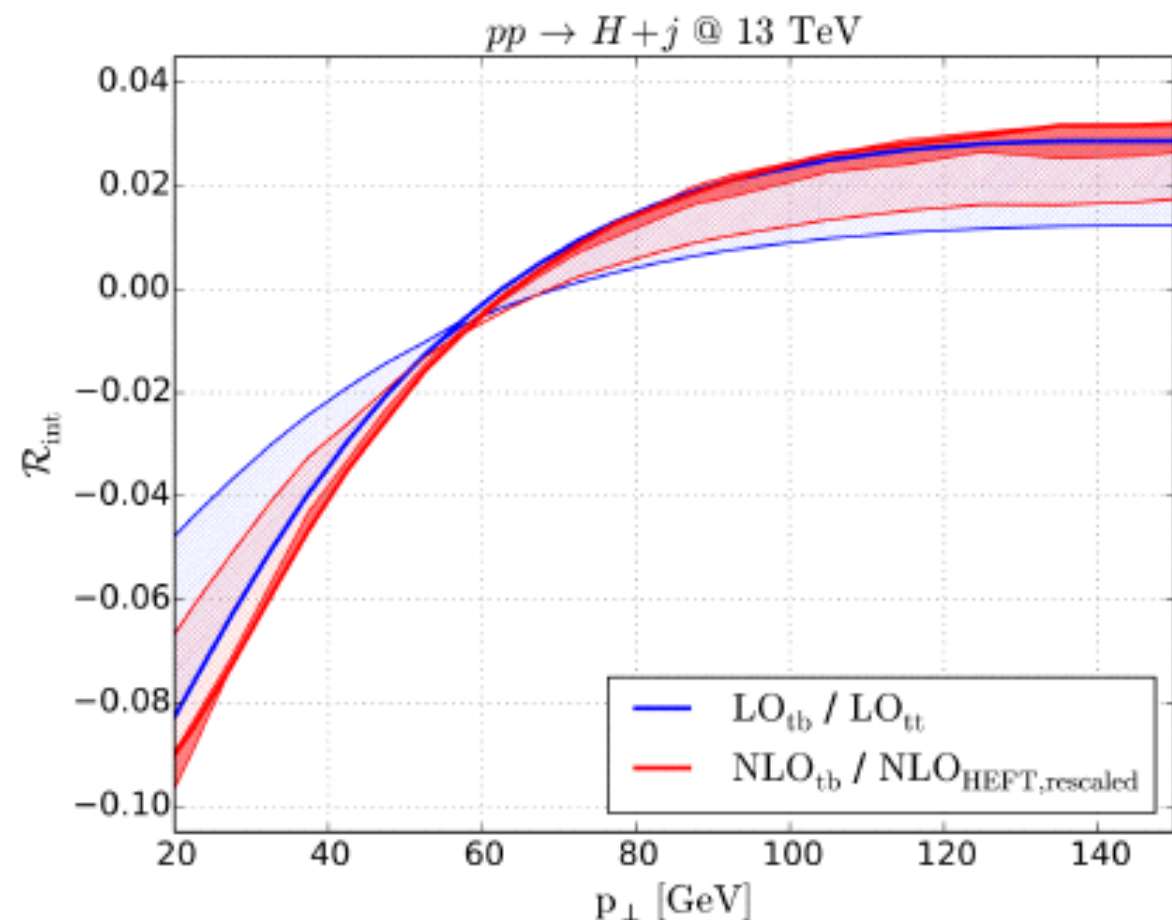
[CMS-PAS-HIG-17-010] 35.9 fb⁻¹ (13 TeV)



An example: bottom quark in H+jet



- Analogous problem for bottom loop in H+jet at $p_T < \sim m_H$
 - NNLO EFT description accurate at $\sim 10\%$ in this region. Heavy-quark (not top) corrections $\sim 5\text{-}6\%$ $\rightarrow$ suppressed by small coupling, but log-enhanced (jet probes the loop structure)
$$A_t A_b^* \sim y_t m_b^2 / m_H^2 \ln^2(p_\perp^2 / m_b^2) \sim 10^{-2}$$
- Recent NLO computation of two-loop virtual amplitudes via small-mass expansion [Lindert, Melnikov, Wever, Tancredi '16-'17]
 - Important to match the exp. systematics in future measurements at the LHC.
 - Sensitivity to charm and bottom couplings



Summing logarithms (in a nutshell)

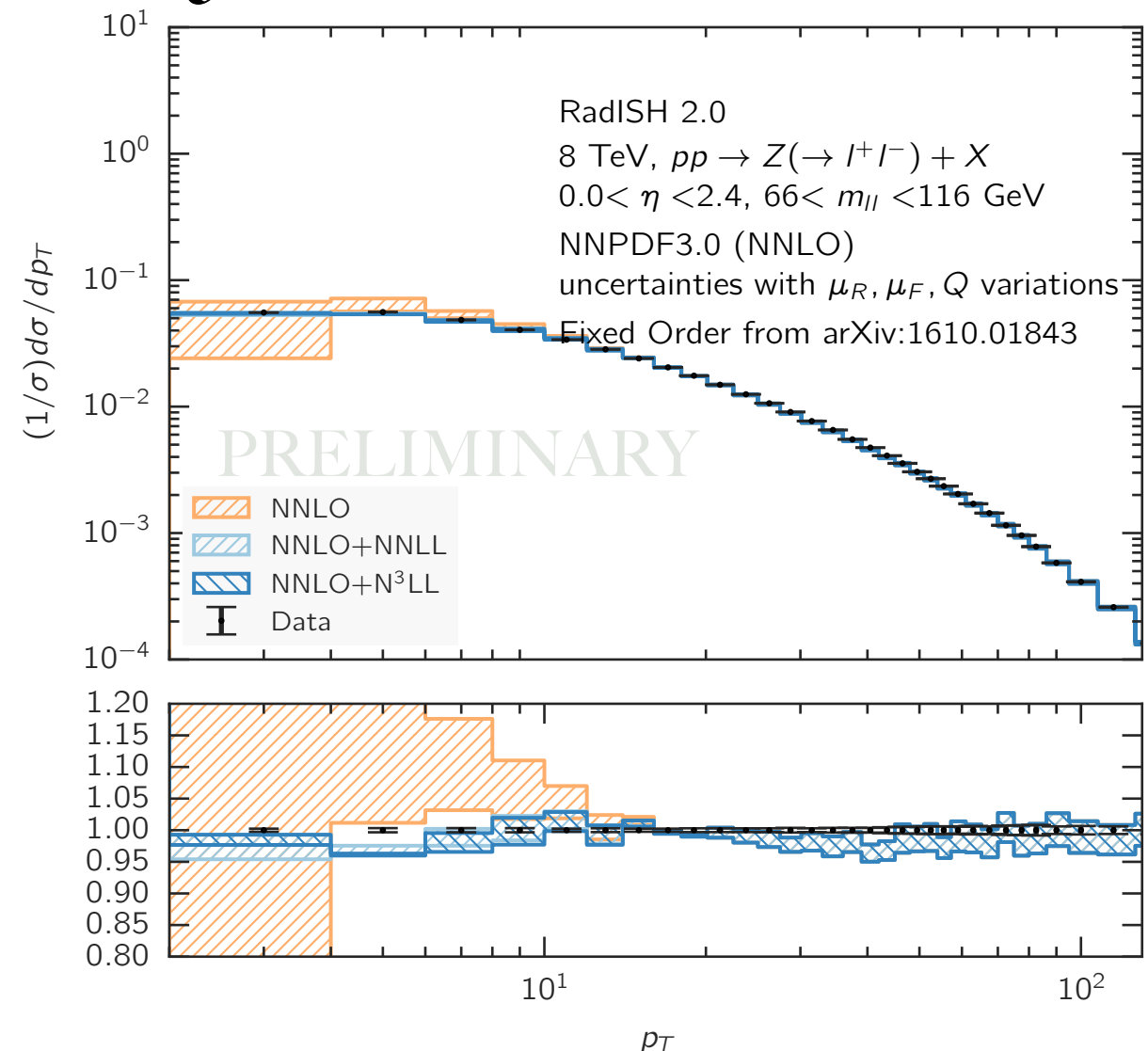
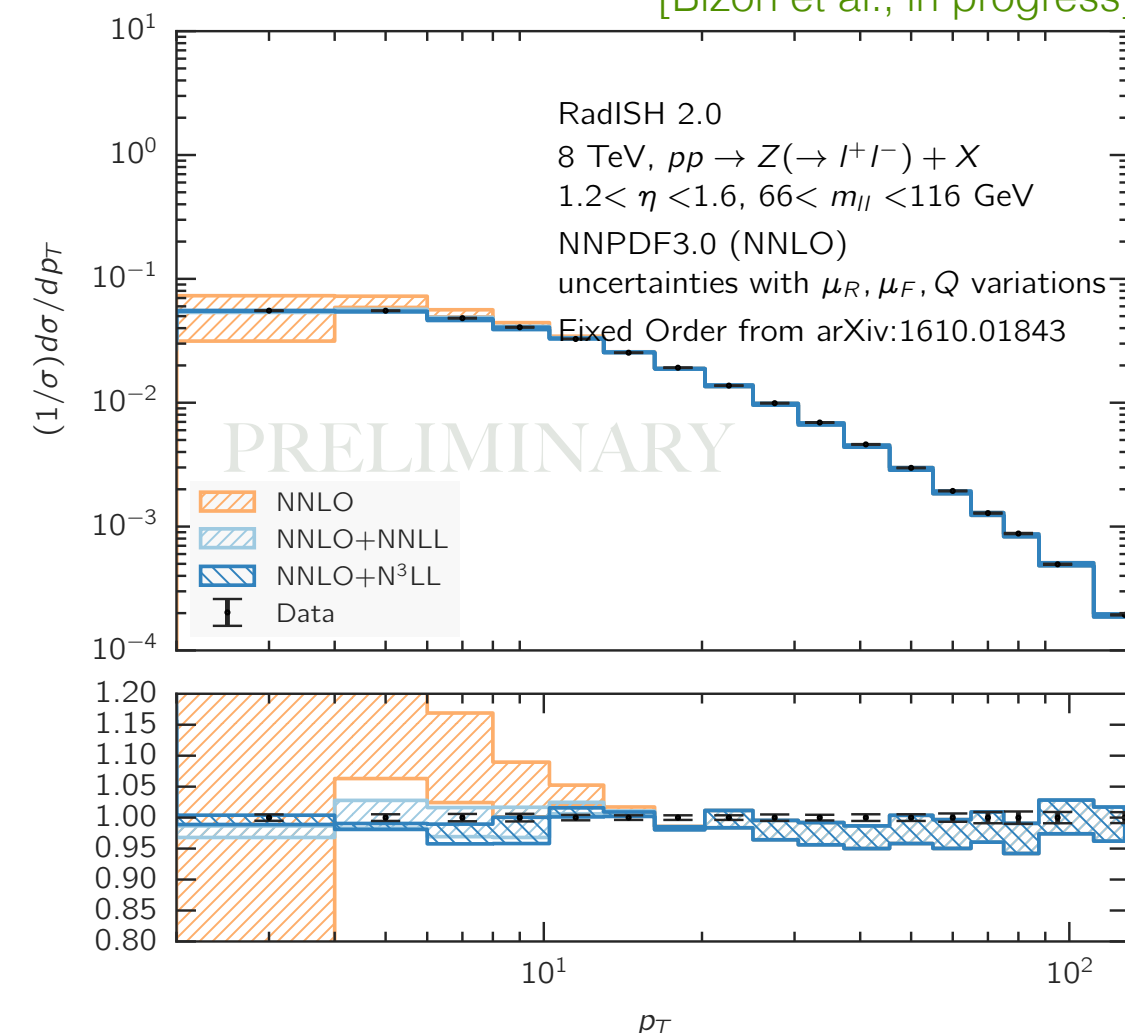
- Logarithms can appear both in amplitudes (e.g. large scale gaps) and cross sections whenever the radiation is constrained to be soft and/or collinear
e.g.
 - production of heavy systems near threshold in hadronic collisions, high-energy scattering, edges of phase space of IRC-safe observables (e.g. exclusive regimes, vetoes, small p_T , ...)
- At the LHC, often is necessary to cut out radiation effects without depleting too much the underlying signal. This operation may develop logarithms that require an all-order treatment
- Resummation aims at answering questions like:
 - Are all sources of all-order corrections under control (multiscale problems) ? Their uncertainties ?
 - Can we start from our knowledge of the radiation dynamics to devise new observables which are predictable at all orders and free of pile-up contamination ? i.e. can we exploit more data ?
 - ...

An example: Z+jets

Astonishing precision in the Z kinematic distributions ($\sim 1\%$ or less)

- distributions relevant for PDFs, M_W ,...
- NNLO+N³LL needed to match exp. precision (not even sufficient at central rapidities)

[Bizon et al., in progress]



Fixed-order obtained with NNLOJET,
computationally demanding

[Gehrmann-De Ridder et al. '16]

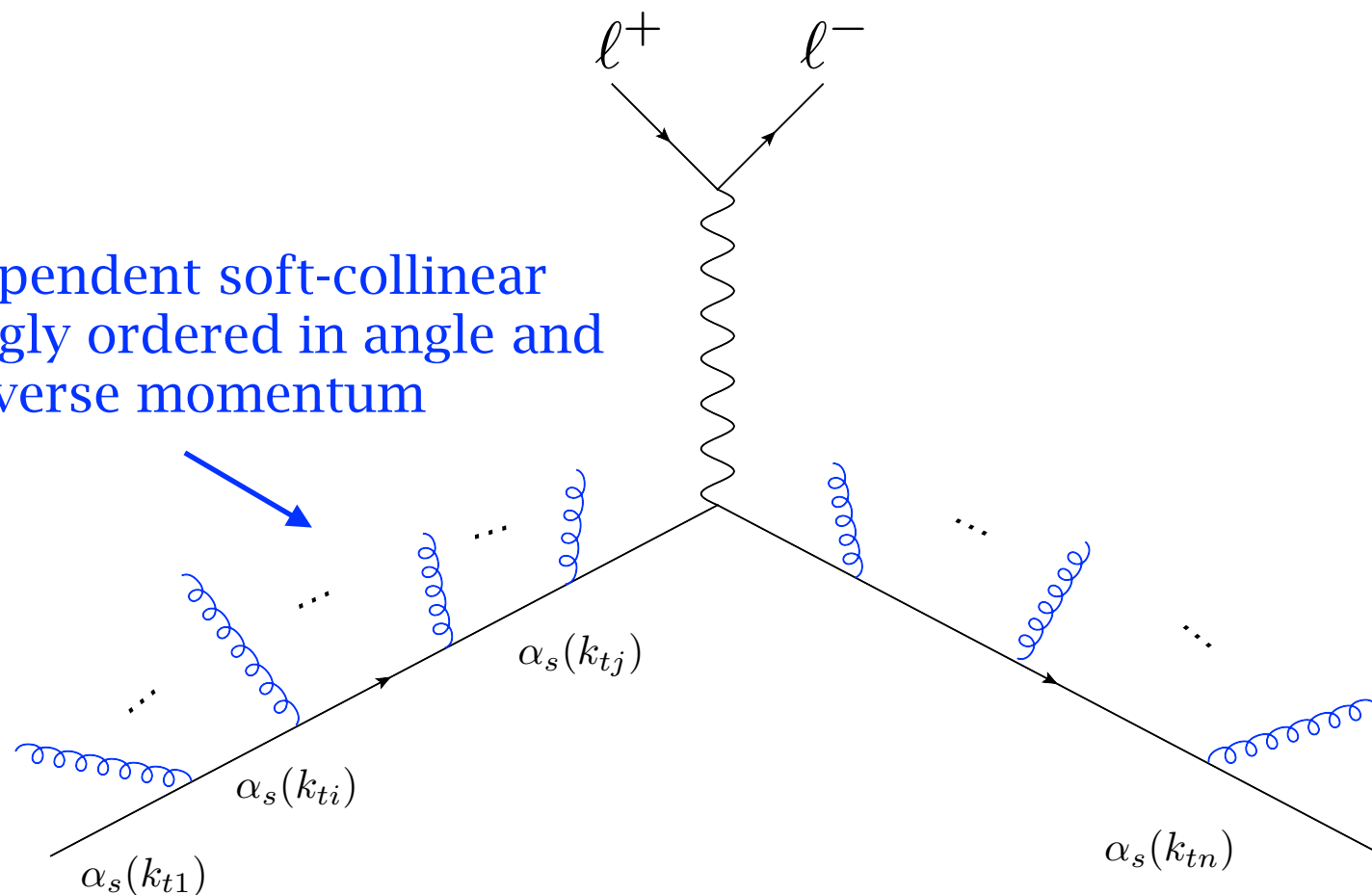
Hit the limits of PT, non-perturbative corrections have comparable size...start worrying about hadronisation. Heavy-quark effects also relevant at this stage

Logarithmic counting: a schematic example

- e.g. measure transverse energy of partonic radiation in colour-singlet production

$$\Sigma(E_{\perp}) \sim e^{\mathcal{O}(\alpha_s^n \ln^{n+1}(M_{\ell\ell}/E_{\perp}))}$$

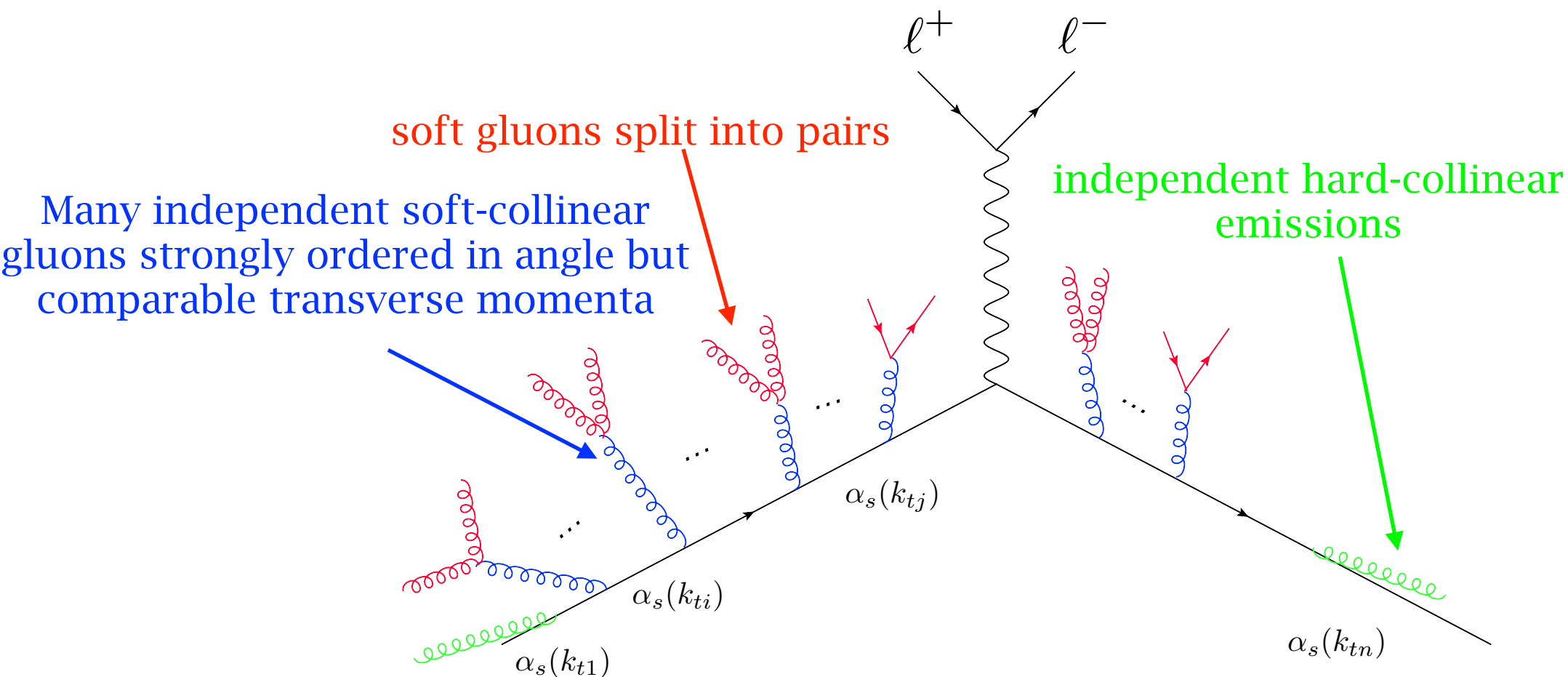
Many independent soft-collinear
gluons strongly ordered in angle and
transverse momentum



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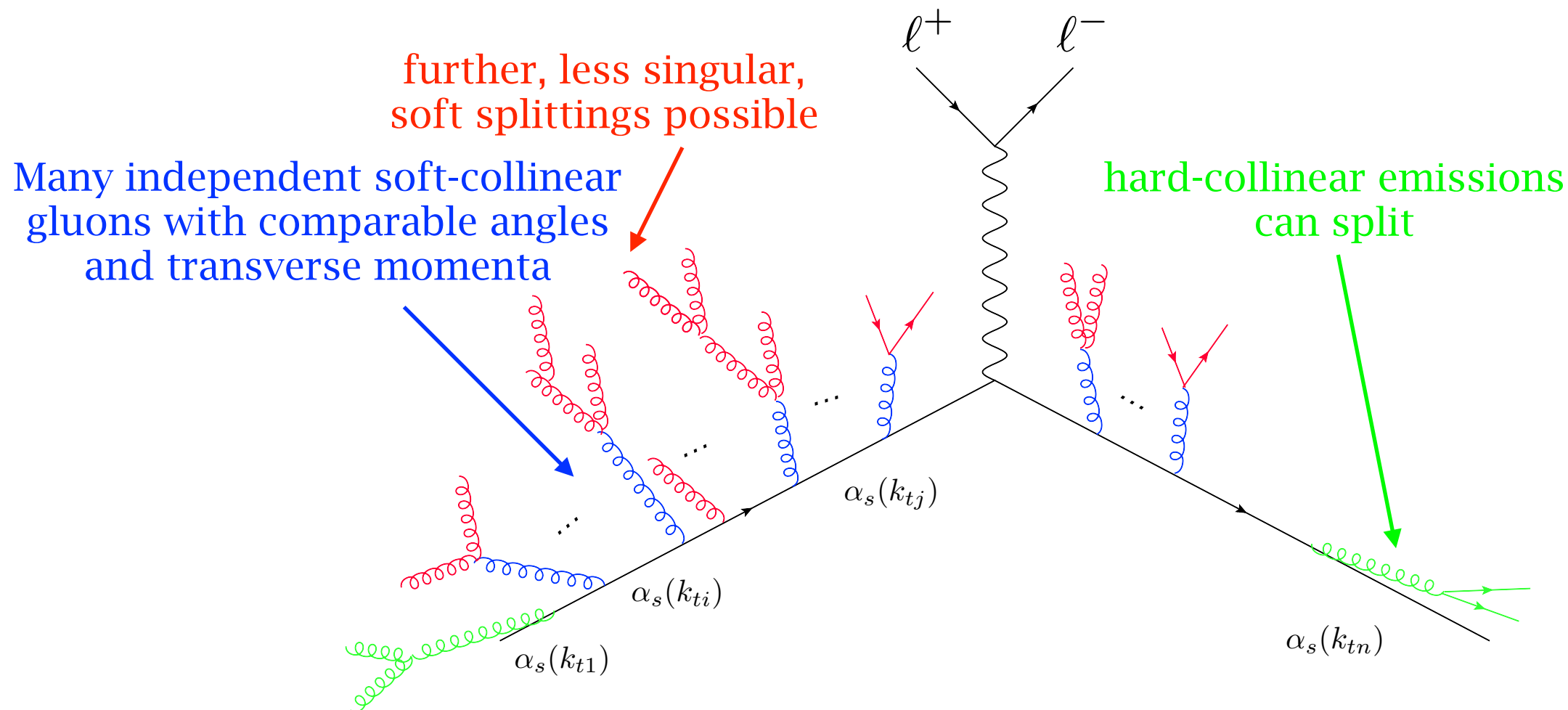
$$\Sigma(E_{\perp}) \sim e^{\mathcal{O}(\alpha_s^n \ln^{n+1}(M_{\ell\ell}/E_{\perp})) + \mathcal{O}(\alpha_s^n \ln^n(M_{\ell\ell}/E_{\perp}))}$$



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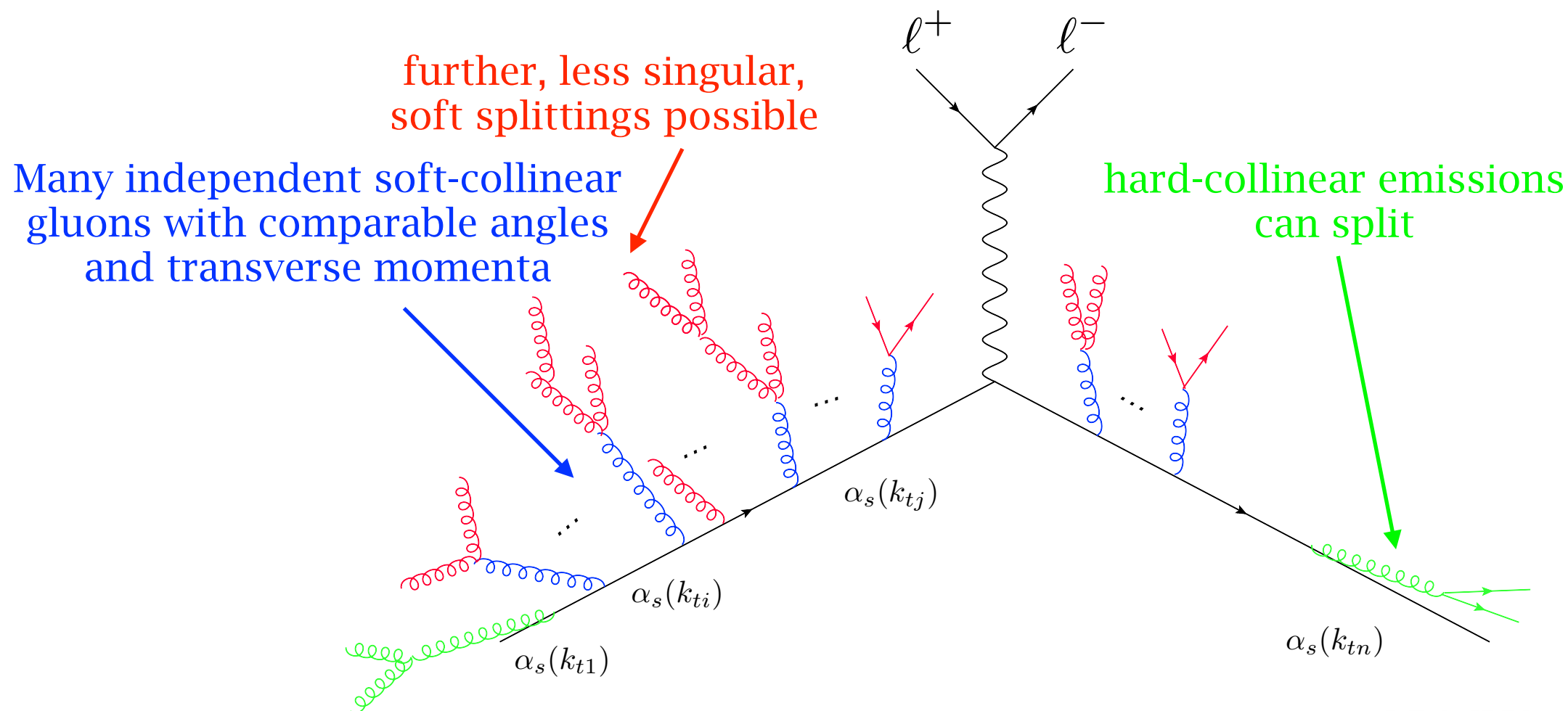
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Higher logarithmic order implies a more accurate description of the radiation dynamics and its kinematics in less singular limits

- Hard to summarize state of the art in a single slide: unlike fixed order (one process, all IRC safe observables), in resummations each observable requires, to some extent, dedicated ingredients (lately progress towards reducing the gap)
- Goal: computation in soft and/or collinear limits at all orders in the coupling. Cancellation of IRC divergences requires computation to be done in $D=4-2\epsilon$ dims.

Large progress in the past decade

Two main concepts:

- Devise a factorisation theorem for a specific observable.
- Factorise singular structure in a conjugate space where the IRC singularities are multiplicatively renormalizable.
- Renormalization $\rightarrow$ anomalous dimensions $\rightarrow$ resummation

e.g. Soft Collinear Effective Theory,
Collins Soper Sterman, Sterman et al.

- Introduce a resolution scale for the real radiation.
- Compute reals below the resolution scale (unresolved) in D dimensions, and cancel virtual singularities (Sudakov FF).
- Compute remaining resolved real radiation in 4 dimensions
 $\rightarrow$ resummation with MC/analytically

e.g. branching algorithm,
CAESAR/ARES, generating
functionals

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- Remaining resolved real emissions in D dimensions
- Comparison with MC/analytically

e.g. branching algorithm, CAESAR/ARES, generating functionals

formal bridge between the two formulations still missing, important to exploit the synergy between them

Non-Global logarithms

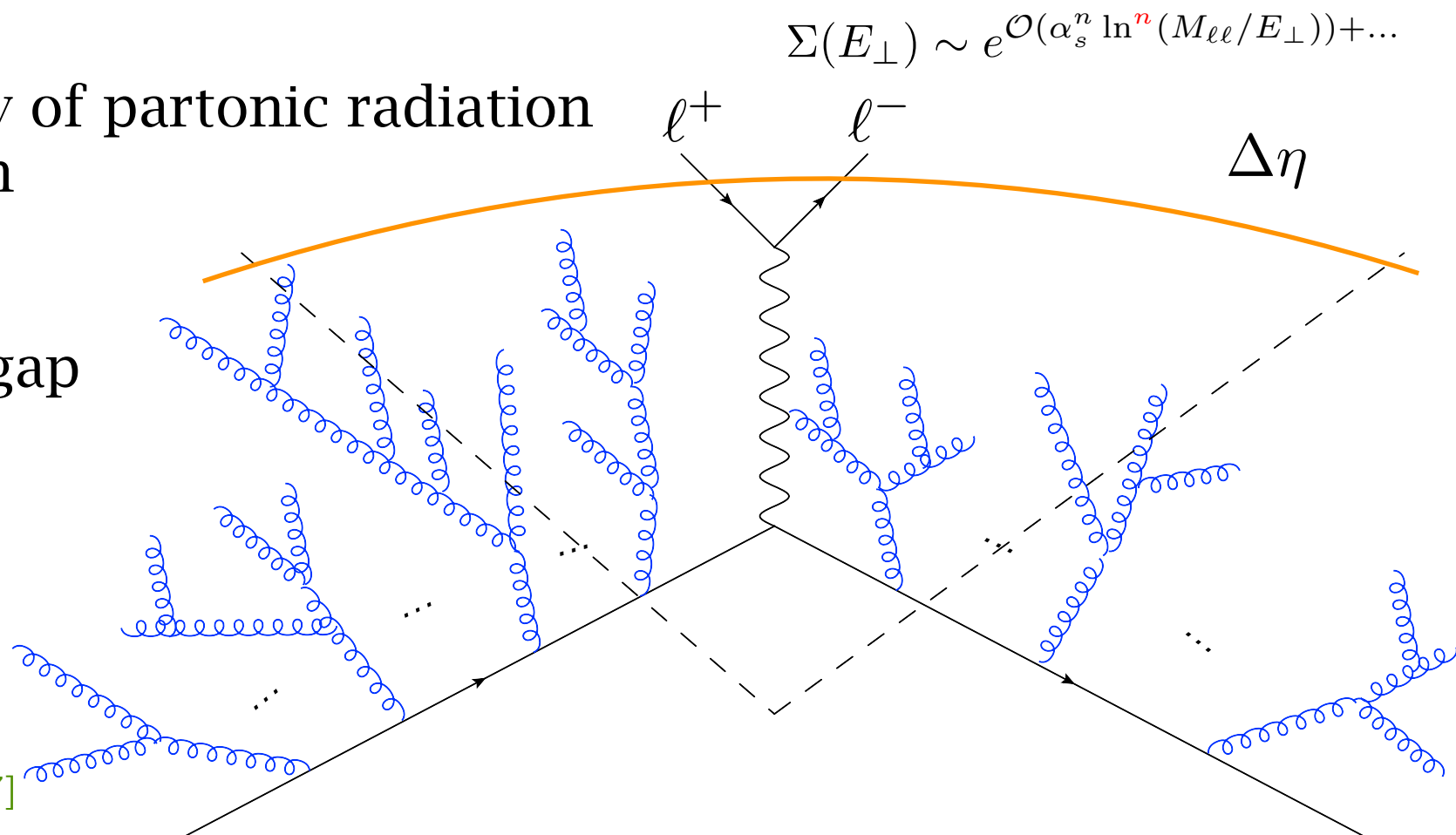
- e.g. measure transverse energy of partonic radiation in an angular phase space patch

- Need to simulate the whole coherent radiation outside the gap to control NGLs (challenging)

- Despite the lot of progress in recent years, no full result beyond LL exists

[Dasgupta, Salam '01; Banfi et al. '02]

[Caron-Huot '15; Larkoski et al. '15; Becher et al. '15-'17]



$$\Sigma(E_{\perp}) \sim e^{\mathcal{O}(\alpha_s^n \ln^n(M_{\ell\ell}/E_{\perp}))} + \dots$$

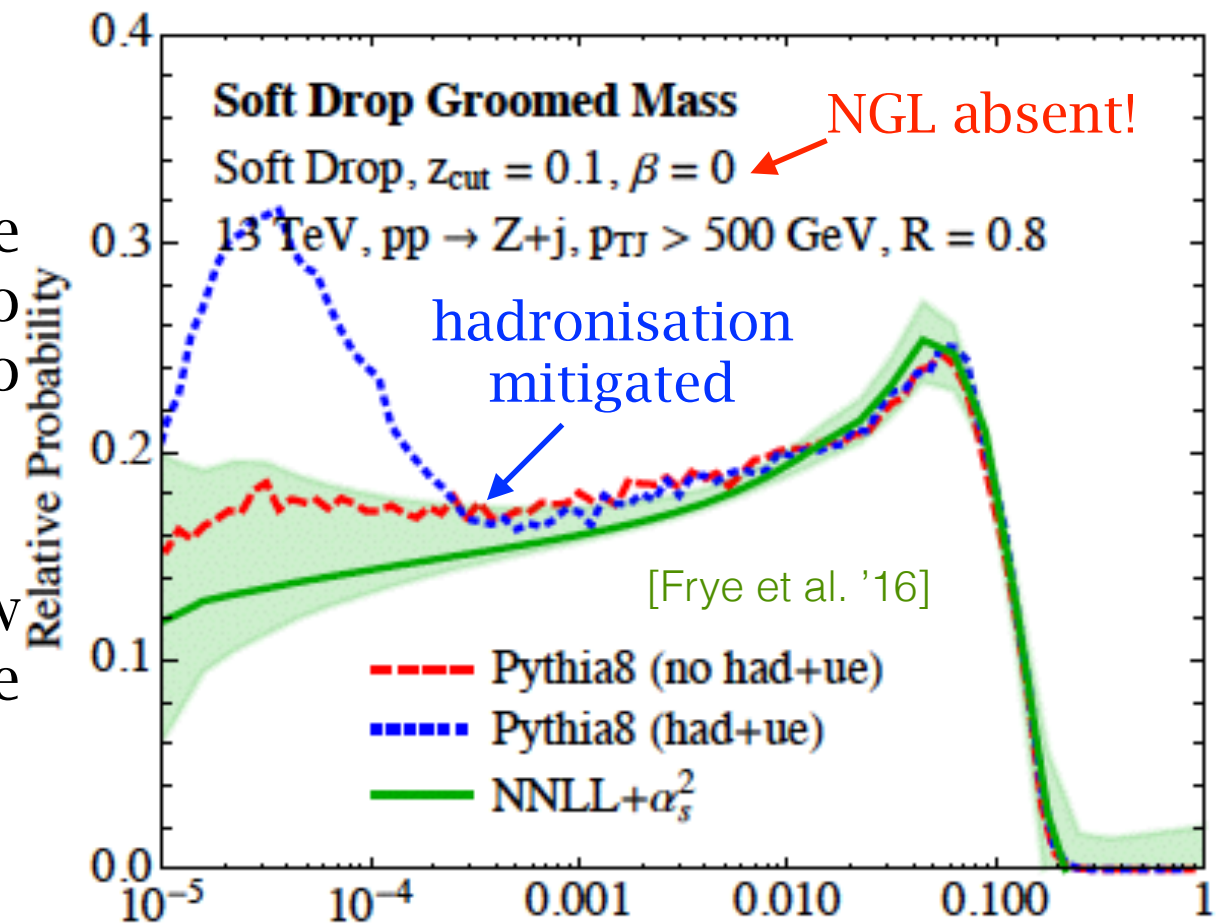
- Their understanding is necessary for precise control of very exclusive obs.
- Non-global logarithms arise from the observable's sensitivity to soft radiation with large angles. Large NGL at the LHC would also imply large PU contamination
 - Define PU-robust observables and reduce impact from NGL -> substructure

Inspecting jets: substructure

- Can these problems be mitigated by grooming jets ?
- An analytic understanding of substructure technology is essential to groom the effect of soft radiation without inducing large perturbative corrections. Moreover, better tools can be devised for which an all-order treatment is possible
 e.g. mMDT/Soft drop groomed jet mass:
 [Dasgupta et al. '13; Larkoski et al. '14]
- This progress made it possible to evolve the substructure concept from a tool to tag boosted objects to a method to groom soft radiation in a controlled way
- Explosion of methods in the past few years with immediate applications at the LHC

e.g. Boost 2017:

<https://indico.cern.ch/event/579660/timetable/>



$\frac{m_J^2}{p_T^2}$

Recursive declustering
until

$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^\beta$$

An alternative approach: PS

- Parton Showers generate collinear radiation from the hard process scale Q down to hadronic scales, in a fully differential way
 - in spirit analogous to resummation, but several very deep conceptual differences in the design/formulation
 - set initial condition for hadronisation (better kinematics -> good tune)
 - matching/merging to the hard process at NLO possible, even NNLO matching for colour singlets. Need higher logarithmic accuracy to match the theory uncertainties in the hard scattering

- Perturbative accuracy of PS currently unknown!

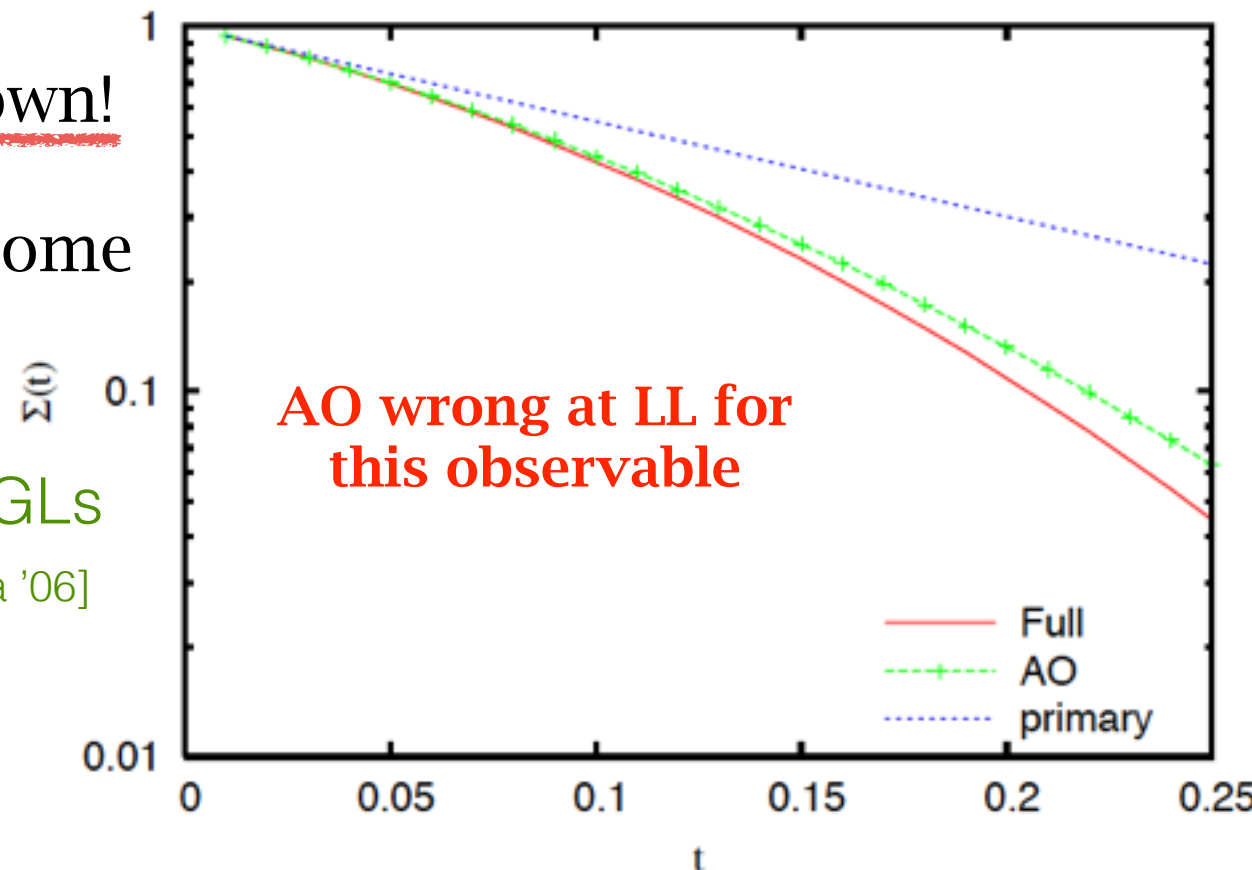
Some designs known to be pathological in some configurations:

e.g.

ET in a rapidity slice: Angular Ordering vs. NGLs

[Banfi, Corcella, Dasgupta '06]

$$E_{\perp} = \sum_{i \in \Omega} E_{ti} < Q_{\Omega}, \quad t = \int_{Q_{\Omega}}^Q \frac{dk_t}{k_t} \frac{\alpha_s(k_t)}{2\pi}$$



angular ordering
kt ordering
antenna shower
CS dipole shower
global recoil
local recoil
virtuality ordering

MC and precision: m_t^{pole}

Tevatron comb.: 174.30 ± 0.65 GeV
 ATLAS comb.: 172.84 ± 0.7 GeV
 CMS comb.: 172.44 ± 0.48 GeV

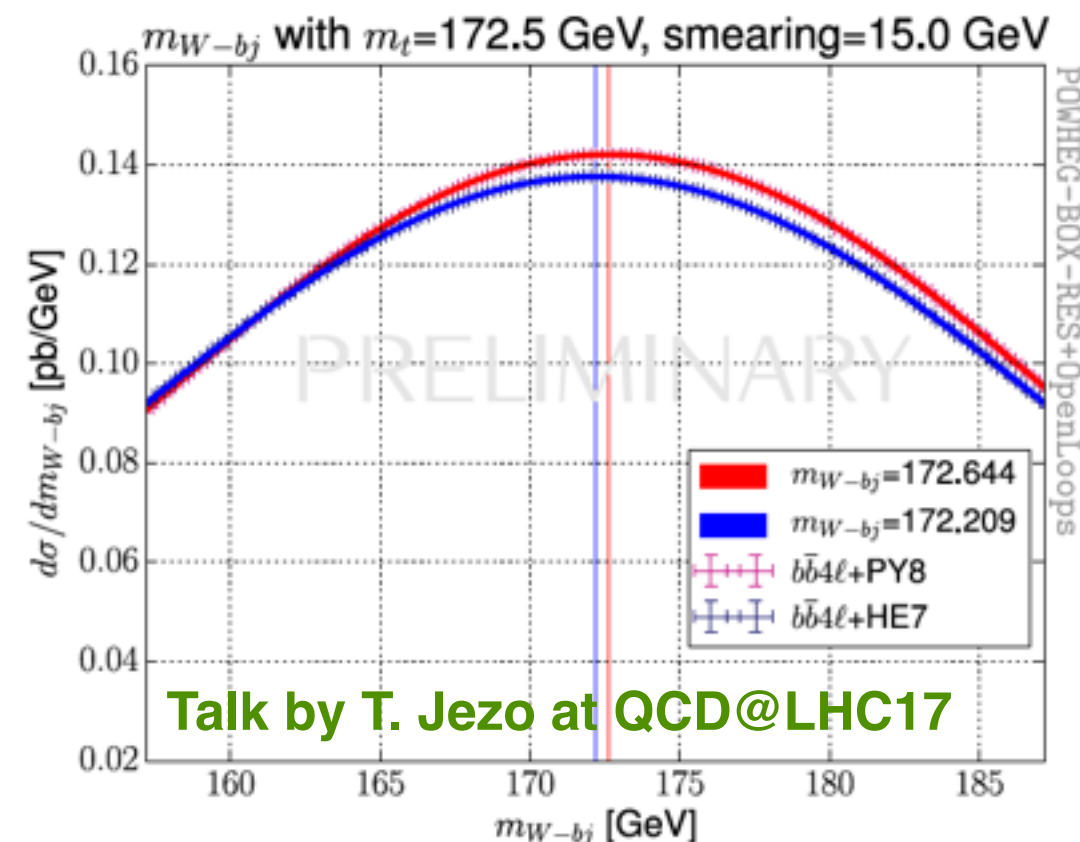
- Although the top pole mass suffers from an intrinsic theoretical ambiguity, this is estimated to be of the order of Λ_{QCD} (hadronisation, renormalon ~ 110 MeV)
- Experimental sensitivity can reach ~ 500 MeV precision (3‰ !) [Beneke et al. '16; Hoang et al. '17]
- e.g. precise extraction from fits of reconstructed $m_{\ell b}^{\text{reco}}$ to MC (template method)

l+jets and dilepton channels in $t\bar{t}$

[ATLAS Phys. Lett. B761 (2016) 350]

- TH uncertainty dominated by PS and hadronisation
- Is this a realistic estimate?
- How well do we control MCs?

	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV
	$m_{\text{top}}^{\ell+\text{jets}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]	$m_{\text{top}}^{\text{dil}}$ [GeV]
Results	172.33	173.79	172.99
Statistics	0.75	0.54	0.41
Method	0.11 ± 0.10	0.09 ± 0.07	0.05 ± 0.07
Signal Monte Carlo generator	0.22 ± 0.21	0.26 ± 0.16	0.09 ± 0.15
Hadronisation	0.18 ± 0.12	0.53 ± 0.09	0.22 ± 0.09
Initial- and final-state QCD radiation	0.32 ± 0.06	0.47 ± 0.05	0.23 ± 0.07
Underlying event	0.15 ± 0.07	0.05 ± 0.05	0.10 ± 0.14
Colour reconnection	0.11 ± 0.07	0.14 ± 0.05	0.03 ± 0.14
Parton distribution function	0.25 ± 0.00	0.11 ± 0.00	0.05 ± 0.00
Background normalisation	0.10 ± 0.00	0.04 ± 0.00	0.03 ± 0.00
W/Z + jets shape	0.29 ± 0.00	0.00 ± 0.00	0
Fake leptons shape	0.05 ± 0.00	0.01 ± 0.00	0.08 ± 0.00
Jet energy scale	0.58 ± 0.11	0.75 ± 0.08	0.54 ± 0.04
Relative b-to-light-jet energy scale	0.06 ± 0.03	0.68 ± 0.02	0.30 ± 0.01
Jet energy resolution	0.22 ± 0.11	0.19 ± 0.04	0.09 ± 0.05
Jet reconstruction efficiency	0.12 ± 0.00	0.07 ± 0.00	0.01 ± 0.00
Jet vertex fraction	0.01 ± 0.00	0.00 ± 0.00	0.02 ± 0.00
b-tagging	0.50 ± 0.00	0.07 ± 0.00	0.03 ± 0.02
Leptons	0.04 ± 0.00	0.13 ± 0.00	0.14 ± 0.01
$E_{\text{T}}^{\text{miss}}$	0.15 ± 0.04	0.04 ± 0.03	0.01 ± 0.01
Pile-up	0.02 ± 0.01	0.01 ± 0.00	0.05 ± 0.01
Total systematic uncertainty	1.03 ± 0.31	1.31 ± 0.23	0.74 ± 0.29
Total	1.27 ± 0.33	1.41 ± 0.24	0.84 ± 0.29



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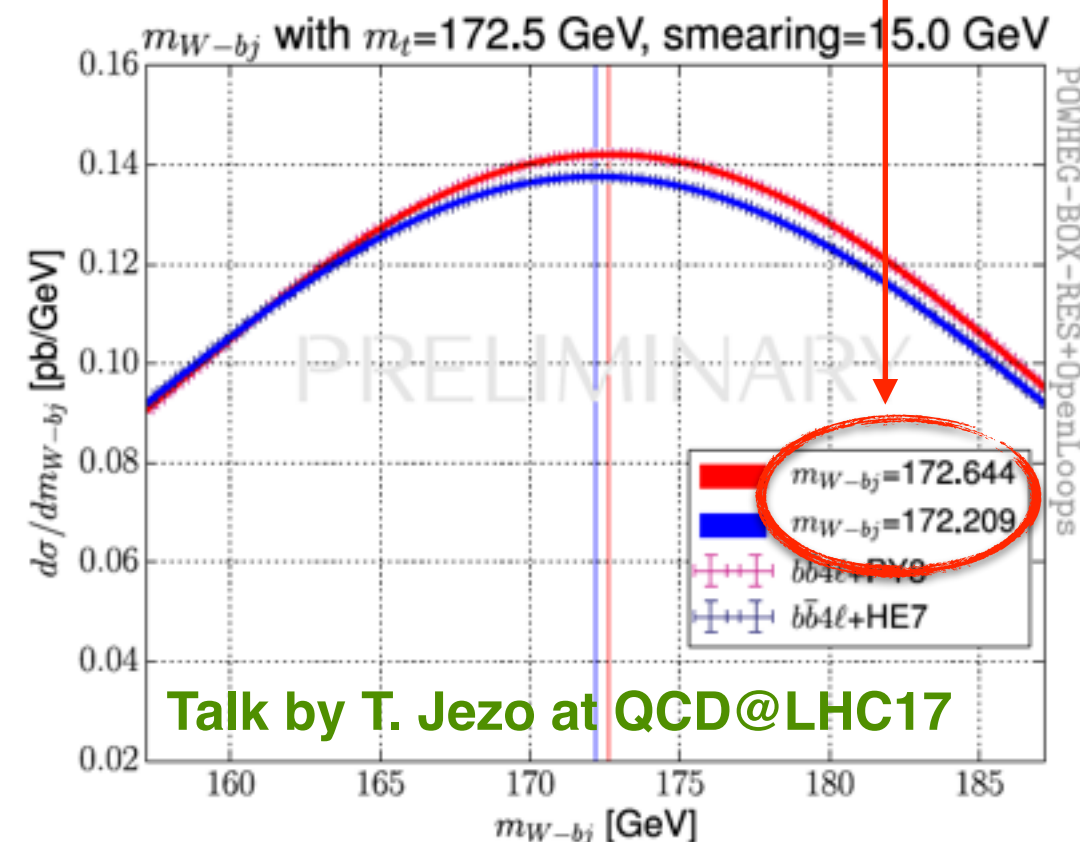
[ATLAS Phys. Lett. B761 (2016) 350]

• TH uncertainty dominated by PS and hadronisation

• Is this a realistic estimate ?

• How well do we control MCs ? 0.5 GeV shift plausible with current tools. Possible to do better ?

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MC and precision: M_W

- Measured using template fits to lepton observ. (small W pT modelling critical)

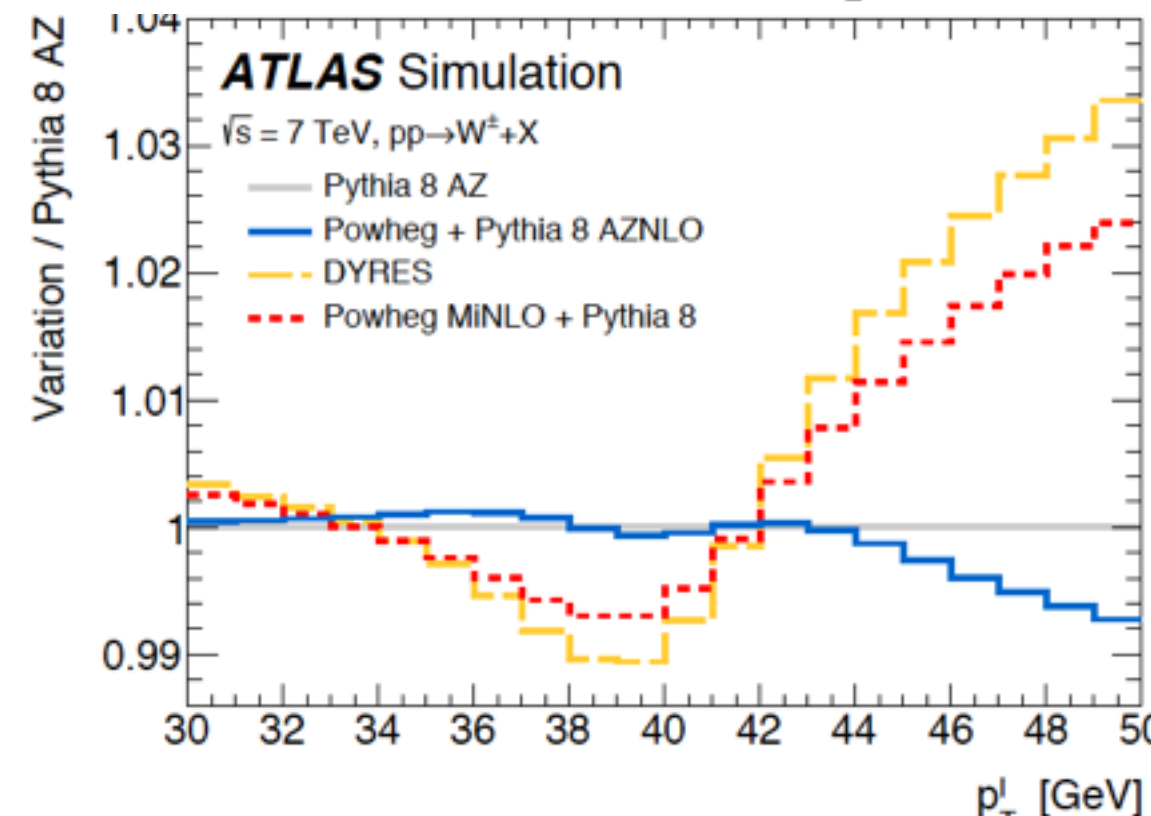
Breit-Wigner parametrisation

Fixed-order QCD (DYNNLO)

$$\frac{d\sigma}{dp_1 dp_2} = \left[\frac{d\sigma(m)}{dm} \right] \left[\frac{d\sigma(y)}{dy} \right] \left[\frac{d\sigma(p_T, y)}{dp_T dy} \left(\frac{d\sigma(y)}{dy} \right)^{-1} \right] \left[(1 + \cos^2 \theta) + \sum_{i=0}^7 A_i(p_T, y) P_i(\cos \theta, \phi) \right]$$

MC generator Pythia 8 (LO !)

- Hard for pQCD to achieve data precision. Use Z to calibrate MC (AZ tune) and then model the W template distributions



$$M_W = 80370 \pm 19 \text{ MeV} \quad [\text{ATLAS 1701.07240}]$$

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

Important to understand the uncorrelated sources of uncertainty.
 New way to perform EW precision measurements

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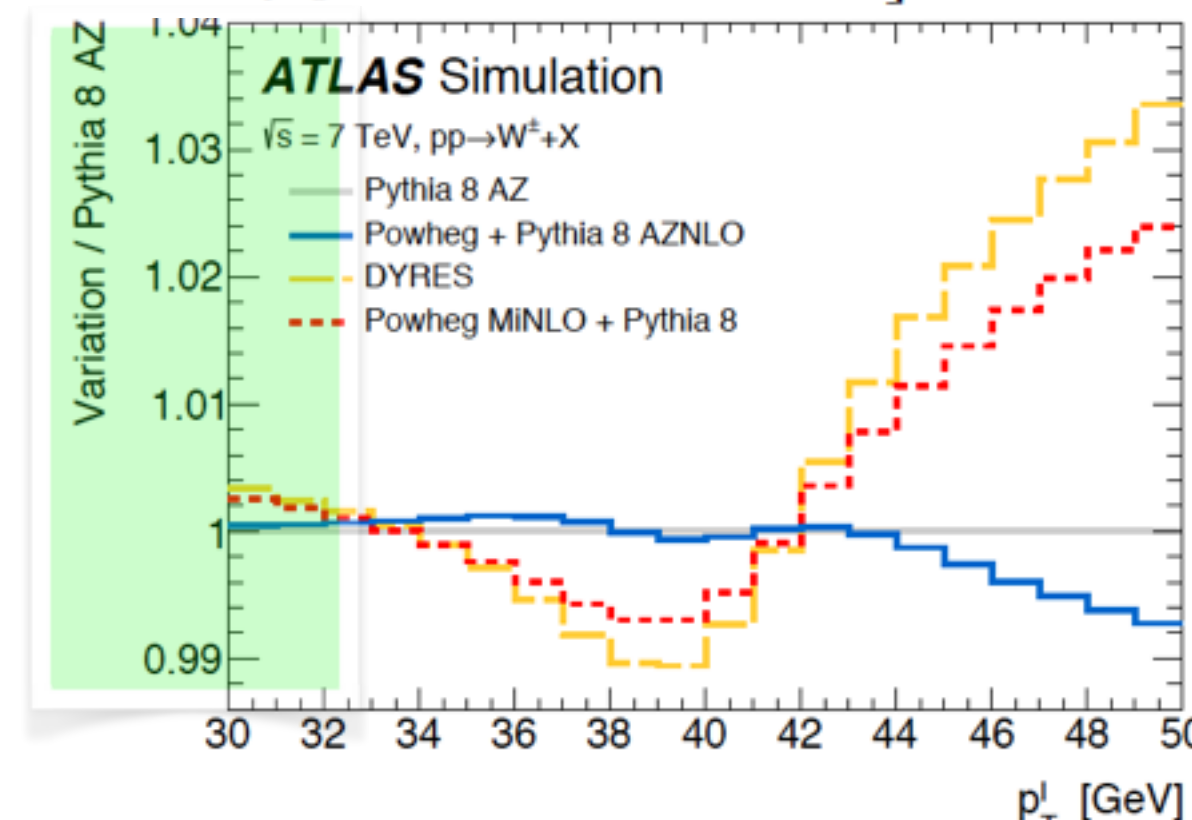
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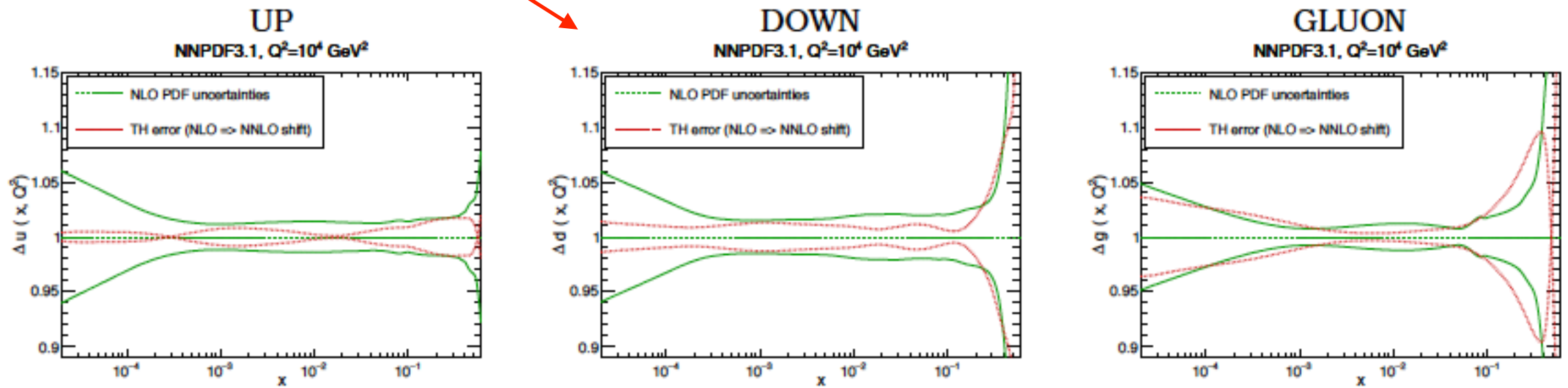
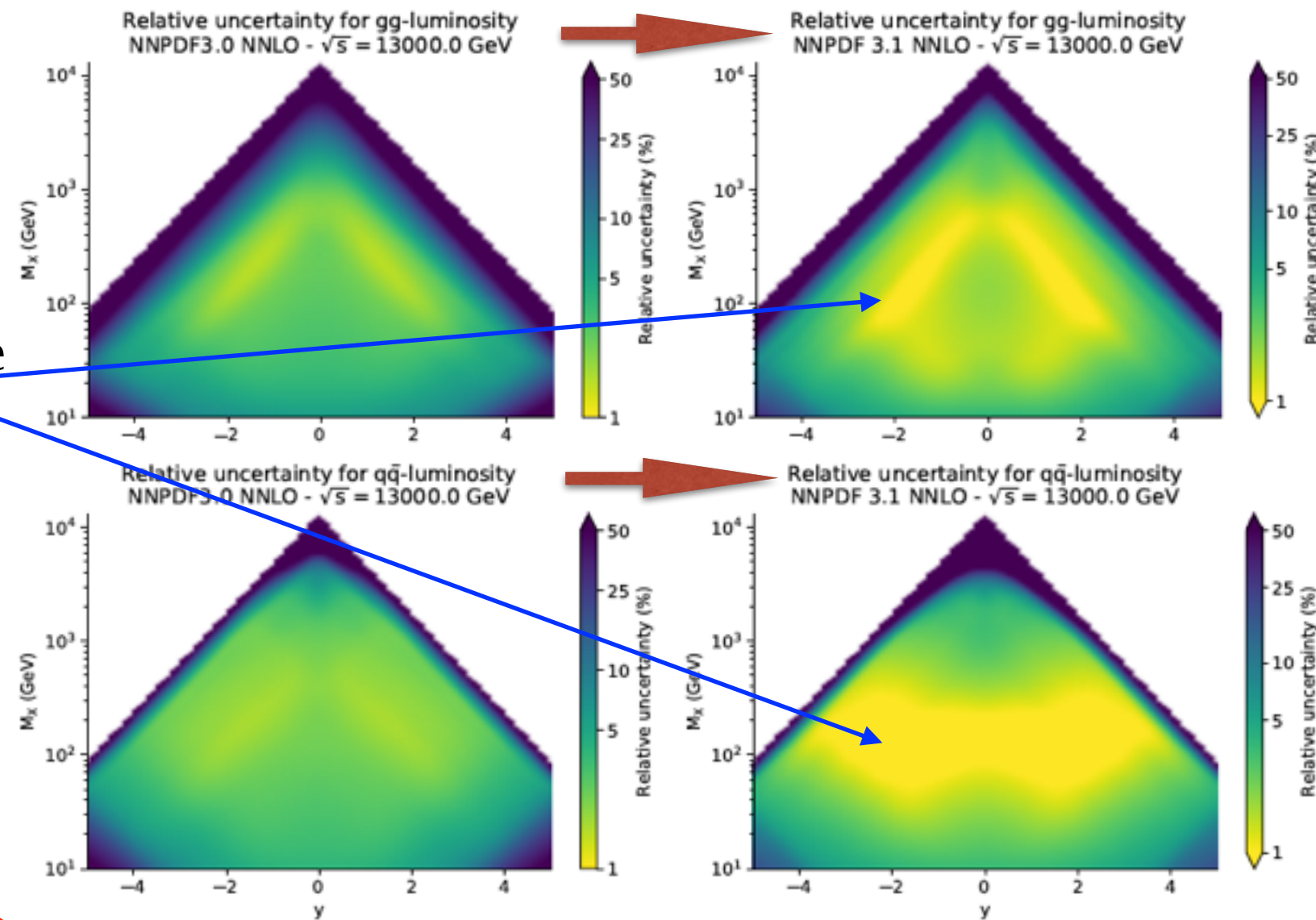
Important to understand the uncorrelated sources of uncertainty.

New way to perform EW precision measurements

Parton densities and LHC data

e.g. [Ball et al. '17]

- Inclusion of LHC data ($t\bar{t}$, jets, EW production) leads to a better determination of PDFs
- %-level errors are achieved in some kinematic configurations
- With these uncertainties, it is important to assess the impact of the errors in the theory used to extract the PDFs
 - TH uncertainties comparable to PDF uncertainties
 - how to include them ?
 - double counting with SV ?



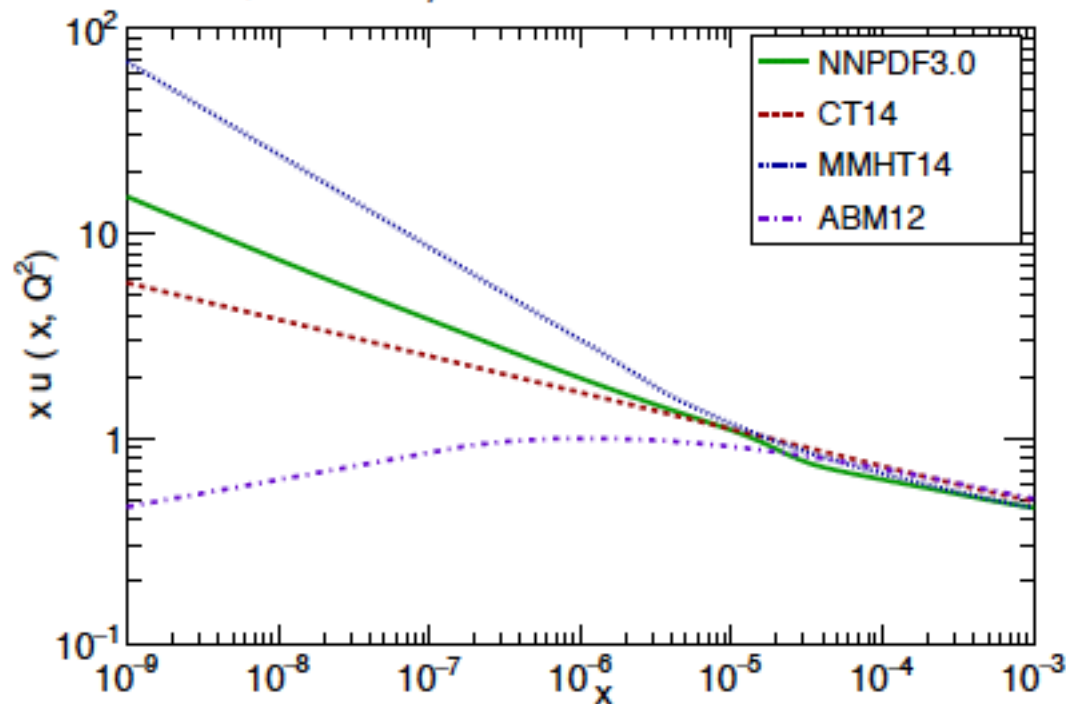
e.g. NLO sets
S. Forte at
SCALES '17
(PRELIMINARY)

PDFs and future colliders

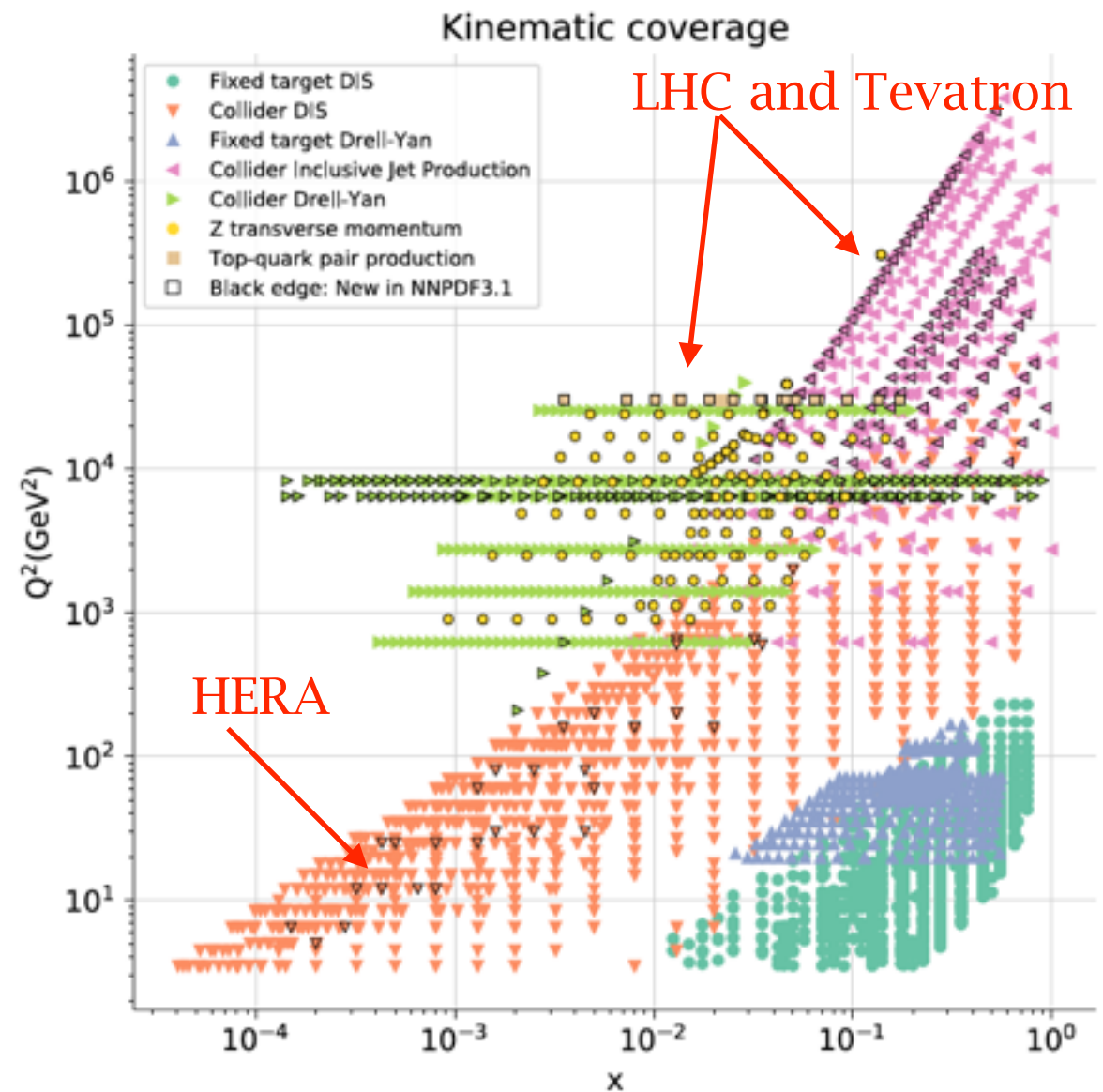
- The kinematic coverage of current (and past) experiments allows for a successful description of PDF evolution in terms of the DGLAP equation
- Higher energies probe smaller x regions, currently unconstrained/extrapolated

[Mangano et al '16: Physics at 100 TeV pp collider]

$Q^2 = 4 \text{ GeV}^2$, small- x PDFs for FCC studies

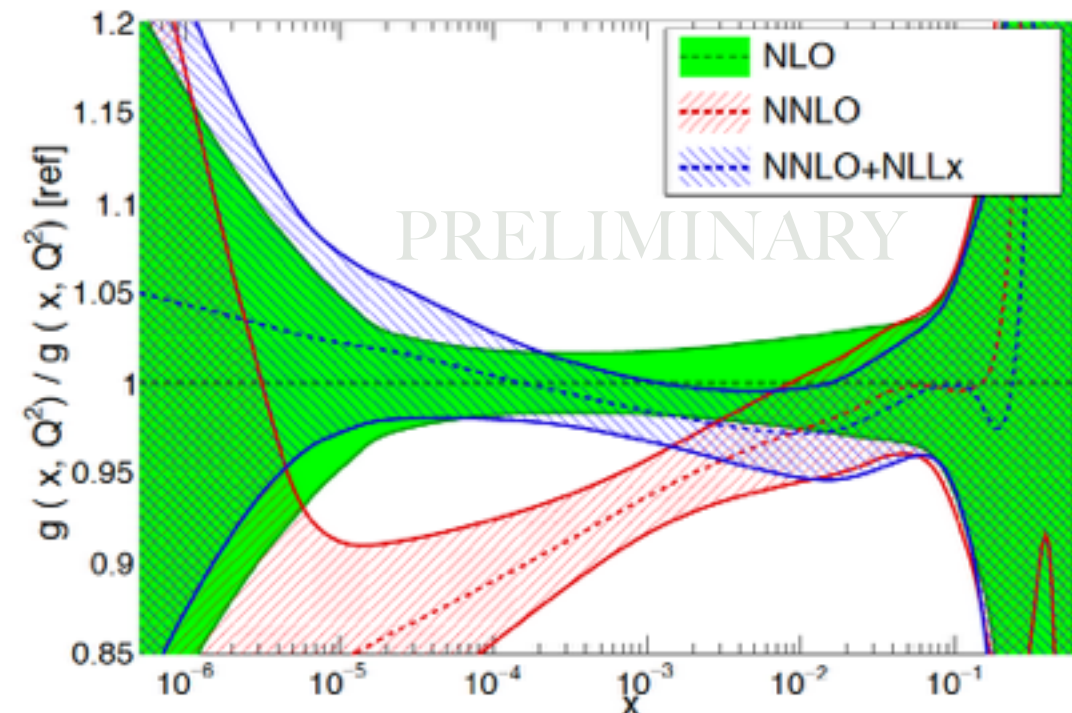


- Besides experimental constraints (e.g. forward production, LHCb,...), it is important to understand whether we have a robust theory understanding of these regions (BFKL effects ? Some effect already at small- x HERA ?)



[J.Rojo at PDF4LHC meeting '17]

NNPDF3.1sx, DIS-only, $Q^2=10^4 \text{ GeV}^2$



What's the uncertainty in alpha_s ?

World average: [Bethke et al. '15]

$$\alpha_s(M_Z) = 0.1177 \pm 0.0013(1.1\%) \text{ weighted}$$

$$\alpha_s(M_Z) = 0.1181 \pm 0.0013(1.1\%) \text{ unweighted}$$

- World Average quotes a $\sim 1\%$ uncertainty
- Some tension with precision extractions from LEP data (event shapes), and some PDFs. Strong hints that these low values are disfavoured (LHC, lattice), but we need to understand what's going on
- Recent determinations agree with WA

[Klijnsma et al. '17]

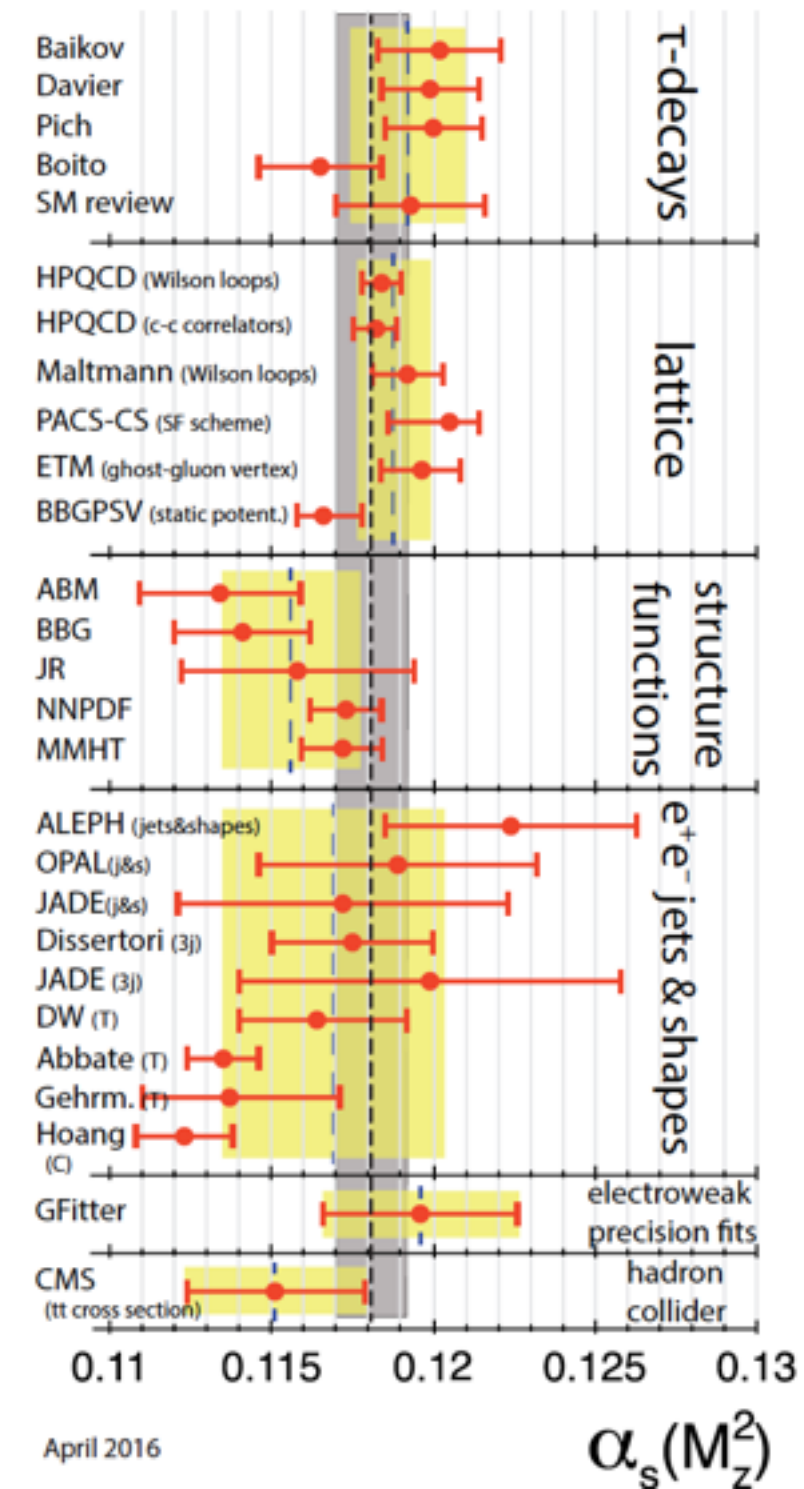
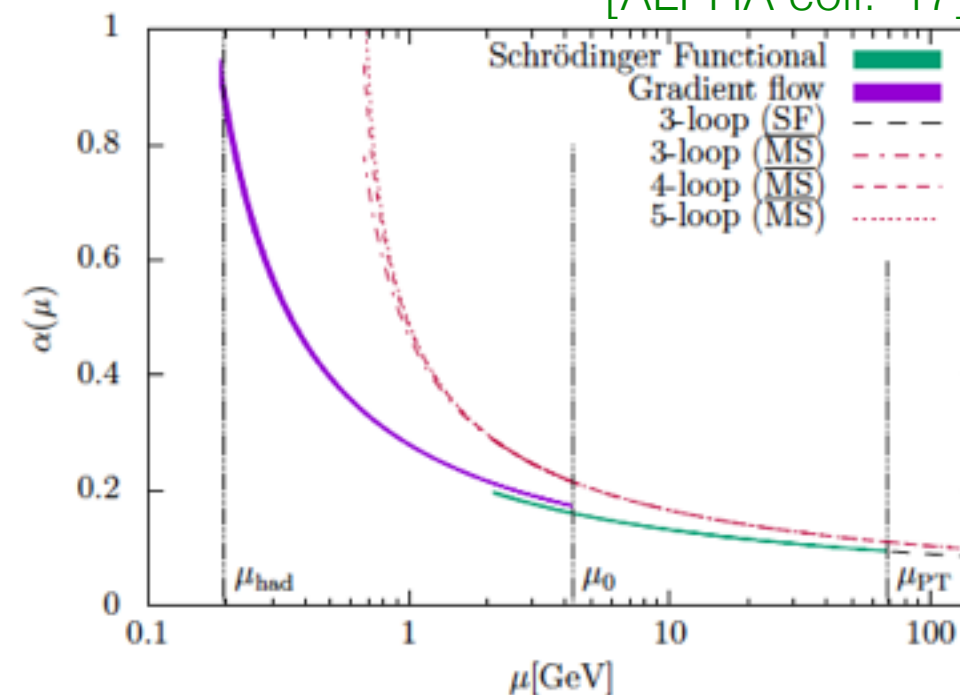
$$t\bar{t} \text{ cross section: } \alpha_s(m_Z) = 0.1177^{+0.0034}_{-0.0036}$$

[ALPHA coll. '17]

- Lattice QCD

finite-size scaling evolution to PT scales
(dominant uncertainty)

$$\alpha_{\overline{\text{MS}}}^{(5)}(m_Z) = 0.11852(84)$$



April 2016

$\alpha_s(M_Z^2)$

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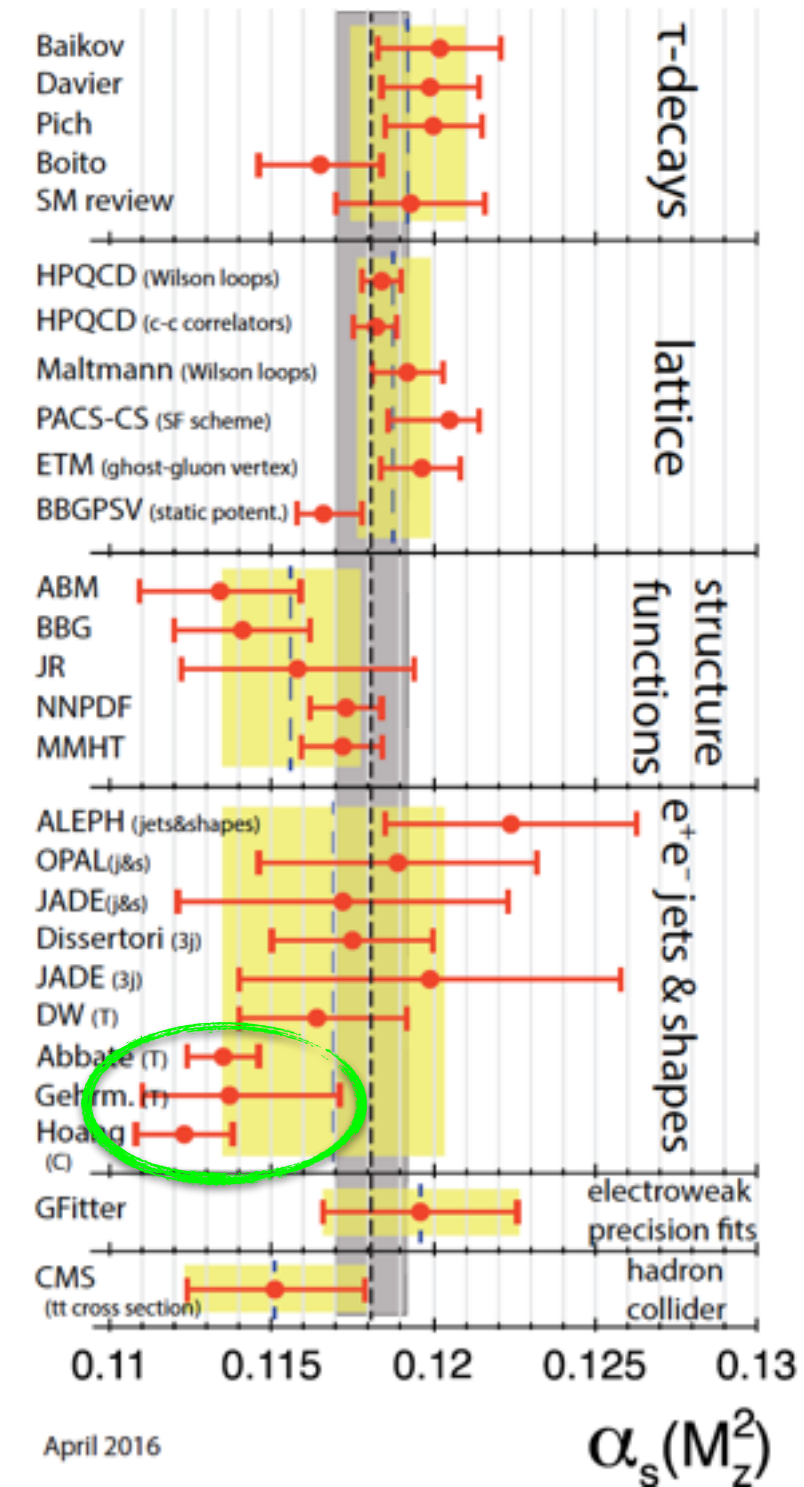
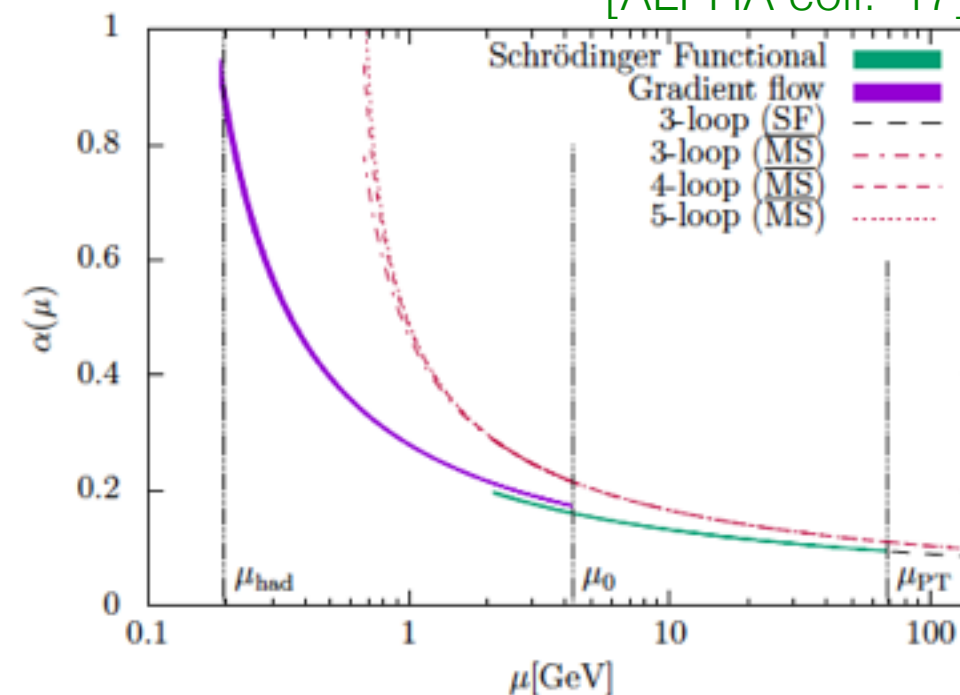
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April 2016

$\alpha_s(M_Z^2)$

Conclusions

- Experimental precision + sensitivity is demanding a huge theoretical progress
- This, in turn, often leads to new ideas for more sensitive measurements and tools
- Recent progress in the understanding of QCD so far has kept up this incredible pace. Few-percent theoretical accuracy is now a reality for many observables, and already not enough for others
- The full exploitation of future data at the (HL-)LHC will require further advances in all directions, that may go beyond PT (better observables, amplitudes, subtraction, resummations, parton showers, parton densities, EW, non-perturbative modelling,...)

Thank you for your attention