QCD e fisica di precisione a LHC

Fabio Maltoni

Centre for Cosmology, Particle Physics and Phenomenology (CP3)
UCLouvain Belgium

As of today

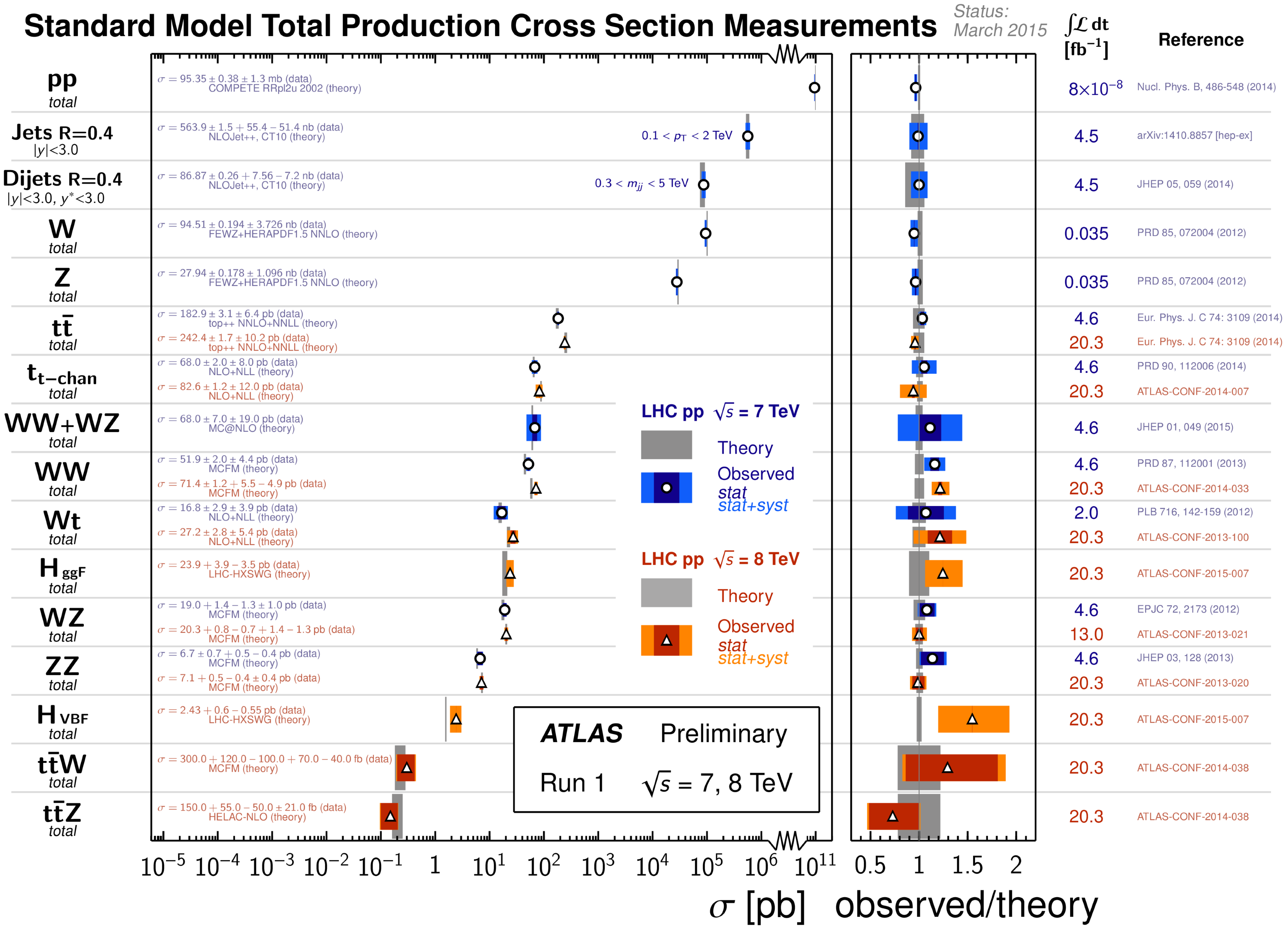
- As predicted in the SM, a new Yukawa force has been discovered, the first ever seen* not mediated by a gauge vector.

- Its mediator behaves a lot like the SM scalar: H-universality of the couplings

- No significant discrepancy with respect to the SM predictions

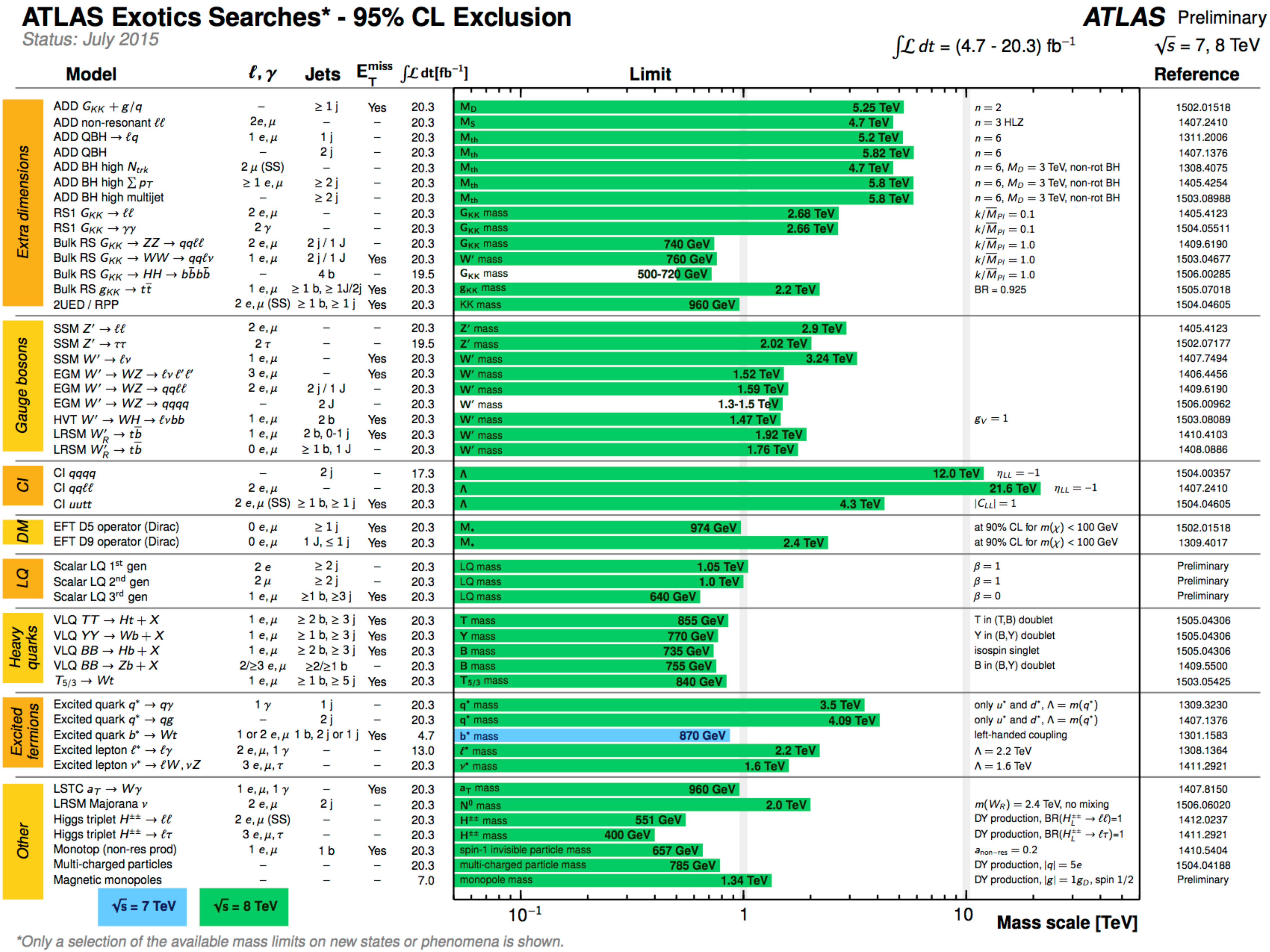
---

*fundamental, ie with elementary mediators.


Standard Model Total Production Cross Section Measurements
Status: March 2015
$\int\mathcal{L}\,dt$ [fb^{-1}]
Reference
pp total
σ = 95.35 ± 0.38 ± 1.3 mb (data)
COMPETE RRpl2u 2002 (theory)
8×10^{-8}
Nucl. Phys. B, 486-548 (2014)
Jets R=0.4 |y|<3.0
σ = 563.9 ± 1.5 + 55.4 − 51.4 nb (data)
NLOJet++, CT10 (theory)
0.1 < p_T < 2 TeV
4.5
arXiv:1410.8857 [hep-ex]
Dijets R=0.4 |y|<3.0, y*<3.0
σ = 86.87 ± 0.26 + 7.56 − 7.2 nb (data)
NLOJet++, CT10 (theory)
0.3 < m_{jj} < 5 TeV
4.5
JHEP 05, 059 (2014)
W total
σ = 94.51 ± 0.194 ± 3.726 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
Z total
σ = 27.94 ± 0.178 ± 1.096 nb (data)
FEWZ+HERAPDF1.5 NNLO (theory)
0.035
PRD 85, 072004 (2012)
$t\bar{t}$ total
σ = 182.9 ± 3.1 ± 6.4 pb (data)
top++ NNLO+NNLL (theory)
4.6
Eur. Phys. J. C 74: 3109 (2014)
σ = 242.4 ± 1.7 ± 10.2 pb (data)
top++ NNLO+NNLL (theory)
20.3
Eur. Phys. J. C 74: 3109 (2014)
$t_{t-\mathrm{chan}}$ total
σ = 68.0 ± 2.0 ± 8.0 pb (data)
NLO+NLL (theory)
4.6
PRD 90, 112006 (2014)
σ = 82.6 ± 1.2 ± 12.0 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2014-007
WW+WZ total
σ = 68.0 ± 7.0 ± 19.0 pb (data)
MC@NLO (theory)
4.6
JHEP 01, 049 (2015)
WW total
σ = 51.9 ± 2.0 ± 4.4 pb (data)
MCFM (theory)
4.6
PRD 87, 112001 (2013)
σ = 71.4 ± 1.2 + 5.5 − 4.9 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-033
Wt total
σ = 16.8 ± 2.9 ± 3.9 pb (data)
NLO+NLL (theory)
2.0
PLB 716, 142-159 (2012)
σ = 27.2 ± 2.8 ± 5.4 pb (data)
NLO+NLL (theory)
20.3
ATLAS-CONF-2013-100
H ggF total
σ = 23.9 + 3.9 − 3.5 pb (data)
LHC-HXSWG (theory)
20.3
ATLAS-CONF-2015-007
WZ total
σ = 19.0 + 1.4 − 1.3 ± 1.0 pb (data)
MCFM (theory)
4.6
EPJC 72, 2173 (2012)
σ = 20.3 + 0.8 − 0.7 + 1.4 − 1.3 pb (data)
MCFM (theory)
13.0
ATLAS-CONF-2013-021
ZZ total
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data)
MCFM (theory)
4.6
JHEP 03, 128 (2013)
σ = 7.1 + 0.5 − 0.4 ± 0.4 pb (data)
MCFM (theory)
20.3
ATLAS-CONF-2013-020
H VBF total
σ = 2.43 + 0.6 − 0.55 pb (data)
LHC-HXSWG (theory)
20.3
ATLAS-CONF-2015-007
$t\bar{t}W$ total
σ = 300.0 + 120.0 − 100.0 + 70.0 − 40.0 fb (data)
MCFM (theory)
20.3
ATLAS-CONF-2014-038
$t\bar{t}Z$ total
σ = 150.0 + 55.0 − 50.0 ± 21.0 fb (data)
HELAC-NLO (theory)
20.3
ATLAS-CONF-2014-038
LHC pp $\sqrt{s}$ = 7 TeV
Theory
Observed
stat
stat+syst
LHC pp $\sqrt{s}$ = 8 TeV
Theory
Observed
stat
stat+syst
ATLAS Preliminary
Run 1 $\sqrt{s}$ = 7, 8 TeV
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{11}
0.5 1 1.5 2
σ [pb]
observed/theory

As of today

- As predicted in the SM, a new Yukawa force has been discovered, the first ever seen* not mediated by a gauge vector.
- Its mediator behaves a lot like the SM scalar: H-universality of the couplings
- No significant discrepancy with the SM predictions
- No convincing sign of resonant new physics found so far



ATLAS Exotics Searches* - 95% CL Exclusion

Status: July 2015

ATLAS Preliminary

$\int \mathcal{L}\,dt = (4.7 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	20.3	M_D 5.25 TeV	$n = 2$	1502.01518
	ADD non-resonant $\ell\ell$	2e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH → ℓq	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	1407.1376
	ADD BH high N_{trk}	2 μ (SS)	–	–	20.3	M_{th} 4.7 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1405.4254
	ADD BH high multijet	–	≥ 2 j	–	20.3	M_{th} 5.8 TeV	$n = 6$, $M_D = 3$ TeV, non-rot BH	1503.08988
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to ZZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	G_{KK} mass 740 GeV	$k/\overline{M}_{Pl} = 1.0$	1409.6190
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	2 j / 1 J	Yes	20.3	W' mass 760 GeV	$k/\overline{M}_{Pl} = 1.0$	1503.04677
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 500-720 GeV	$k/\overline{M}_{Pl} = 1.0$	1506.00285
	Bulk RS $g_{KK} \to t\bar{t}$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	KK mass 960 GeV		1504.04605
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	20.3	W' mass 3.24 TeV		1407.7494
	EGM $W' \to WZ \to \ell\nu\ell'\ell'$	3 e, μ	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	2 e, μ	2 j / 1 J	–	20.3	W' mass 1.59 TeV		1409.6190
	EGM $W' \to WZ \to qqqq$	–	2 J	–	20.3	W' mass 1.3-1.5 TeV		1506.00962
	HVT $W' \to WH \to \ell\nu bb$	1 e, μ	2 b	Yes	20.3	W' mass 1.47 TeV	$g_V = 1$	1503.08089
	LRSM $W'_R \to t\bar{b}$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to t\bar{b}$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	17.3	Λ 12.0 TeV	$\eta_{LL} = -1$	1504.00357
	CI $qq\ell\ell$	2 e, μ	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	1407.2410
	CI $uutt$	2 e, μ (SS)	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	EFT D5 operator (Dirac)	0 e, μ	≥ 1 j	Yes	20.3	M_* 974 GeV	at 90% CL for $m(\chi) < 100$ GeV	1502.01518
	EFT D9 operator (Dirac)	0 e, μ	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	20.3	LQ mass 1.05 TeV	$\beta = 1$	Preliminary
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	20.3	LQ mass 1.0 TeV	$\beta = 1$	Preliminary
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	Preliminary
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	$T_{5/3} \to Wt$	1 e, μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1407.1376
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	2 e, μ, 1 γ	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
	Excited lepton $\nu^* \to \ell W, \nu Z$	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e, μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\mathrm{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	Preliminary

🟦 $\sqrt{s}$ = 7 TeV 🟩 $\sqrt{s}$ = 8 TeV

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

Goals of the SM LHC programme

1. Precise determination of the fundamental parameters of the dim=4 SM lagrangian, such as masses (m_h, m_W, m_t), and couplings:

   - SM measurements of fundamental parameters provide information to be fed to the whole HEP community.

   - Range of validity of the SM

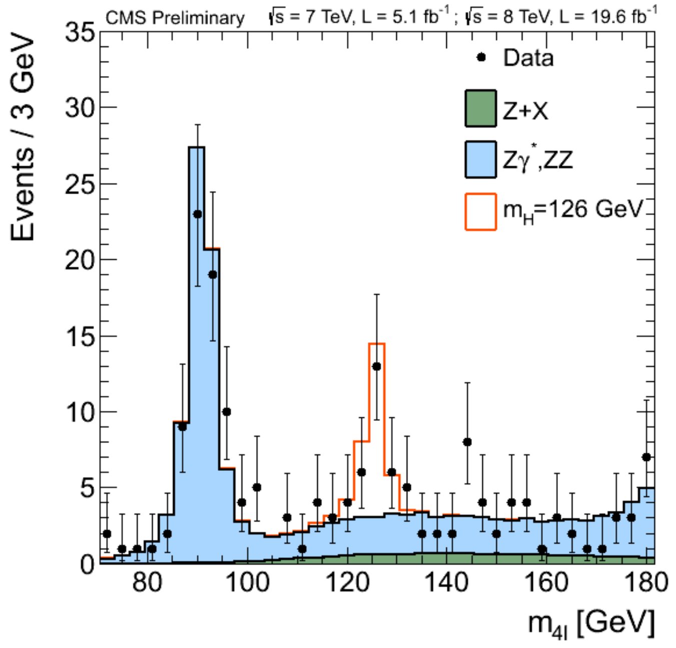
2. Search and quantification of deviations from the SM (New Physics).

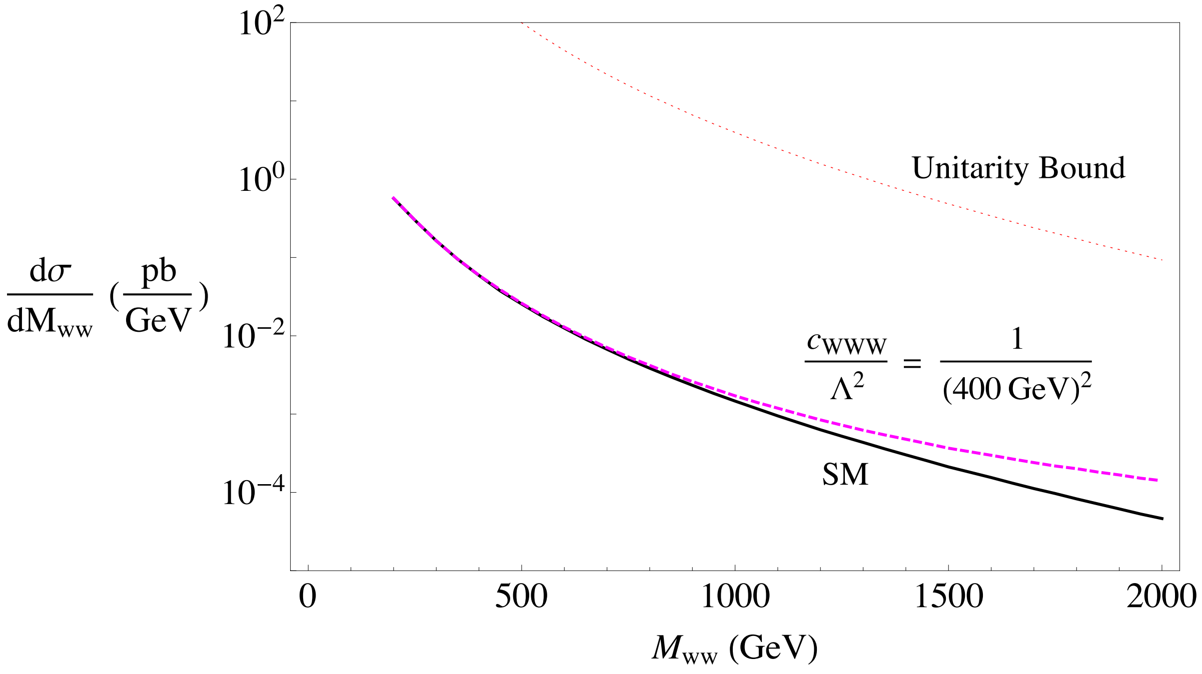
Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states

Search for new interactions





“Peak” or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

BSM goals of the SM LHC programme

Two main strategies for searching new physics

Search for new states ⟷ **Search for new interactions**

SUSY, EXOTICS, BSM HIGGS

SM

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

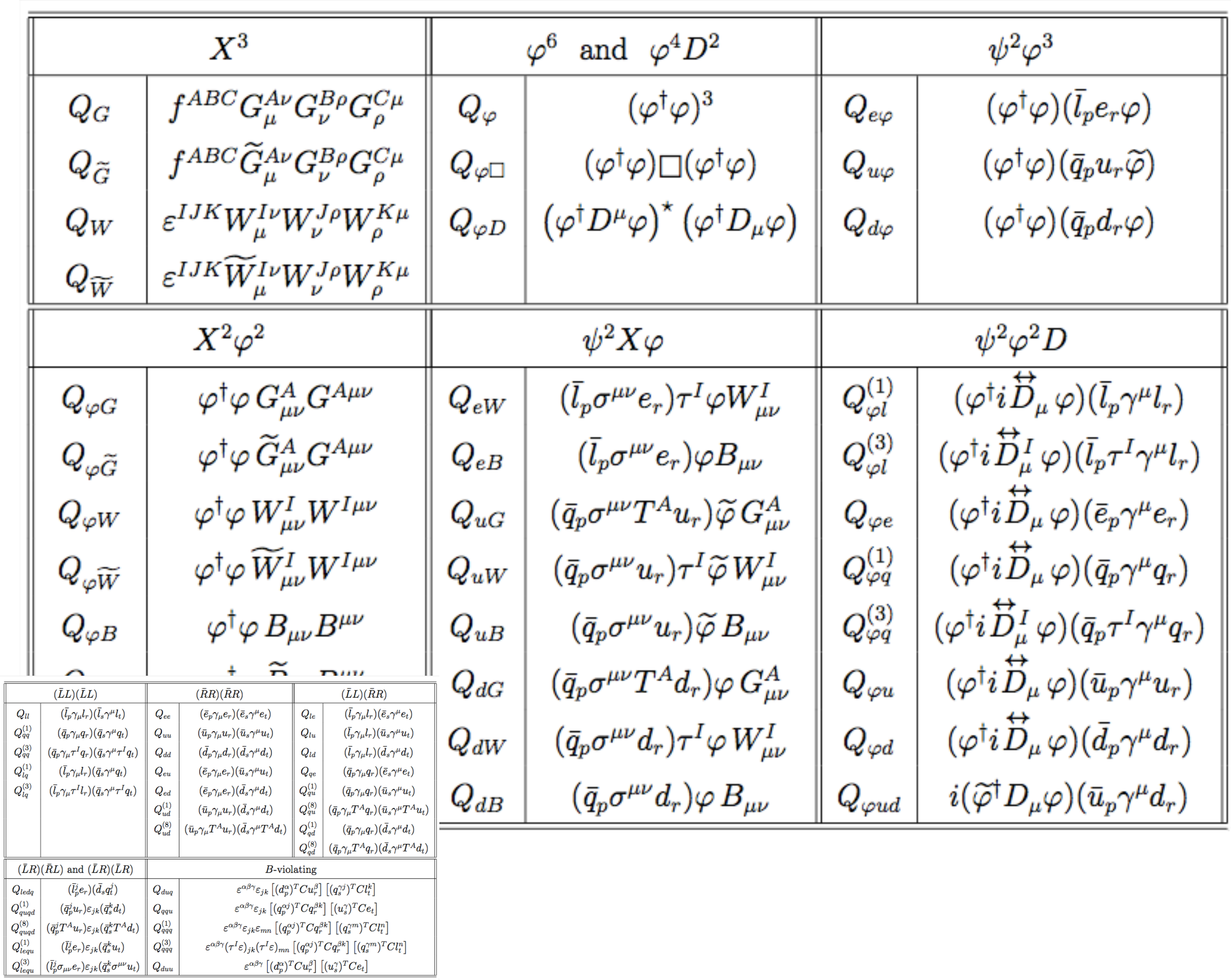
$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6

Dim=6 SM Lagrangian

[Grazdkowski et al, 10]



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
		Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
		Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
		Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

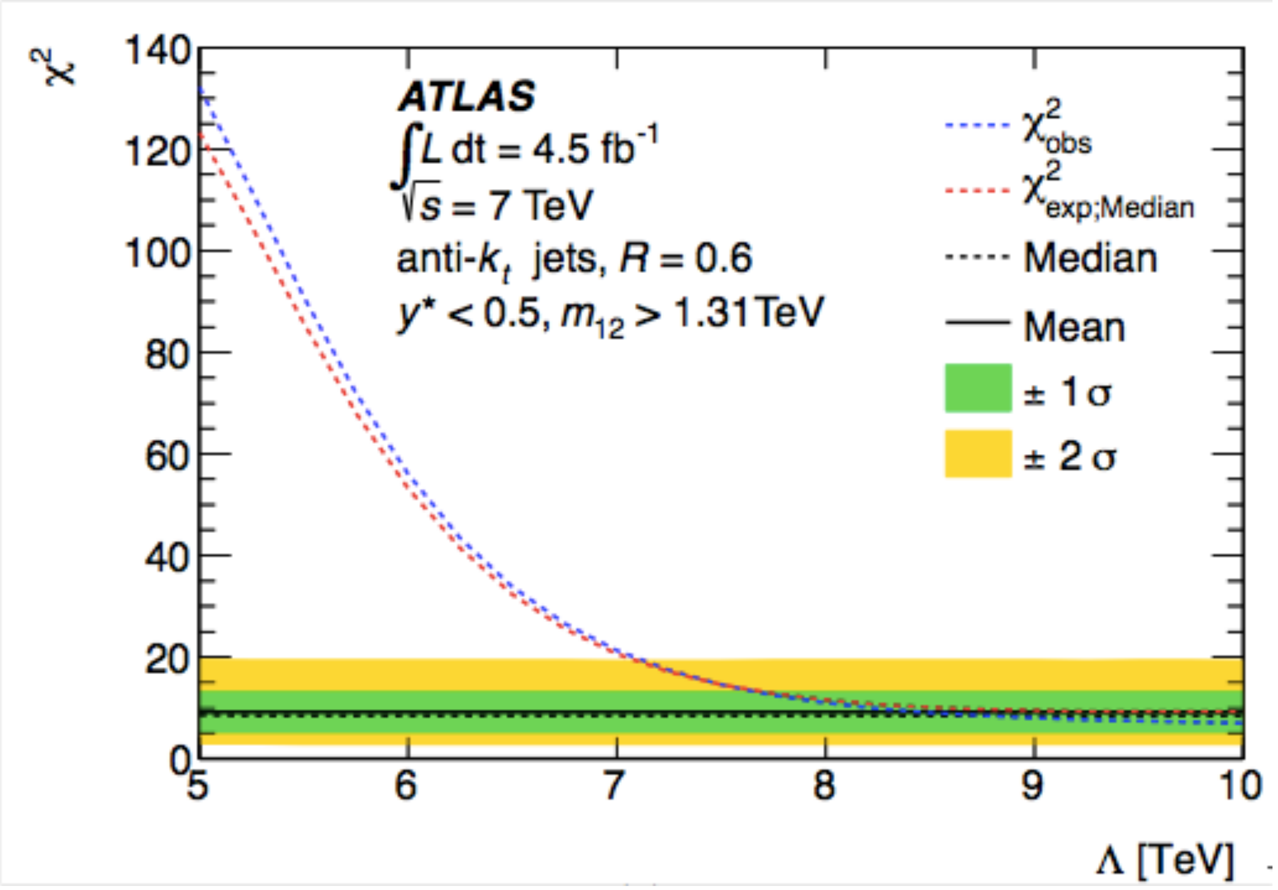
- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

BSM in SM dijets measurements

$$\mathcal{L}_{NP} = \frac{1}{2\Lambda^2}(c_1 O_1 + c_2 O_2)$$

$$\begin{aligned} O_1 &= \delta_{ij}\delta_{kl}\left(\sum_{c=1}^{3}\bar{q}_{Lci}\gamma_\mu q_{Lcj}\sum_{d=1}^{3}\bar{q}_{Ldk}\gamma^\mu q_{Ldl}\right), \\ O_2 &= \mathrm{T}^a_{ij}\mathrm{T}^a_{kl}\left(\sum_{c=1}^{3}\bar{q}_{Lci}\gamma_\mu q_{Lcj}\sum_{d=1}^{3}\bar{q}_{Ldk}\gamma^\mu q_{Ldl}\right), \end{aligned}$$

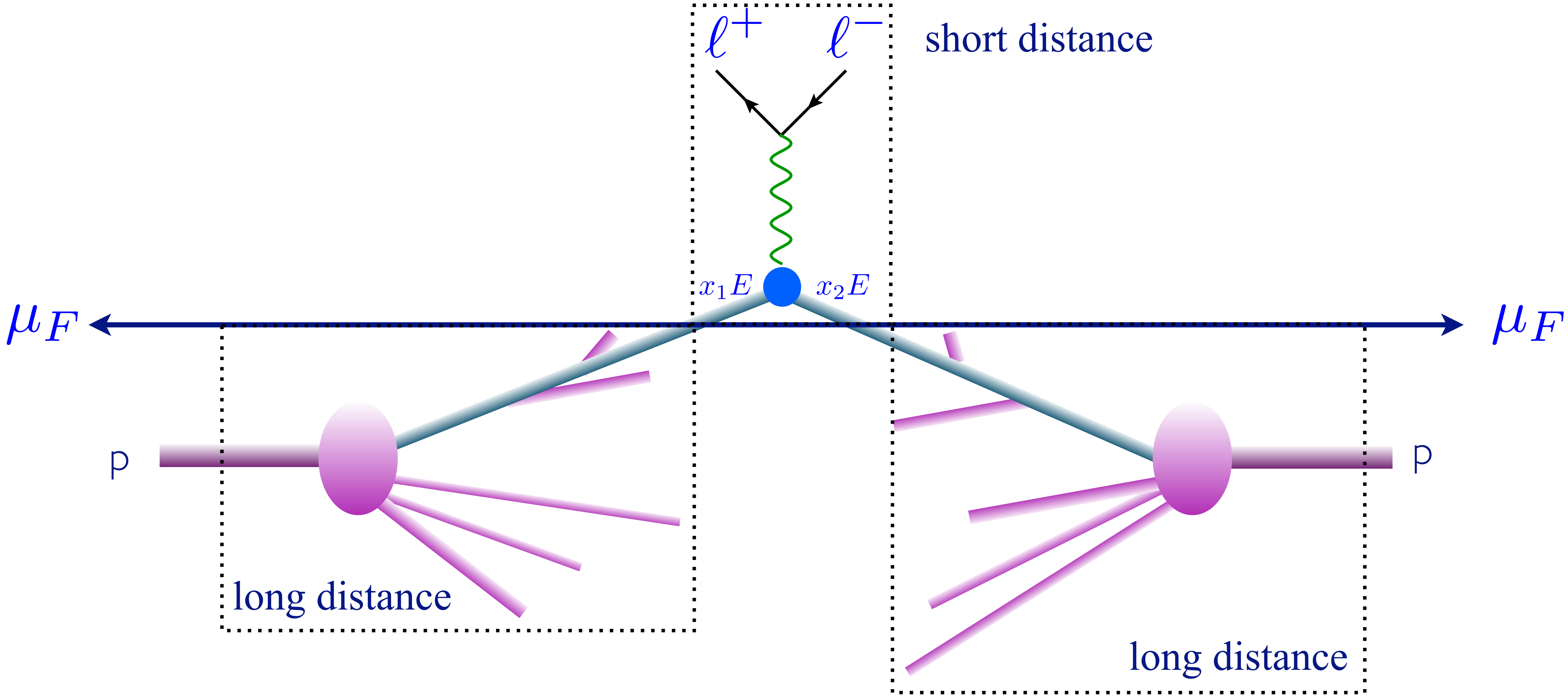
[Gao et al, 2011]



Calculation at NLO accuracy in the EFT. both operators switched on because of mixing. Comparison with SM at NLO consistent.

Many other 4F operators possible, flavour structure to be constrained, NLO+PS. Other observables with quark-gluon tagging.

Master formula for the LHC



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

Accurate predictions for observables in hadronic collisions depend on the knowledge of both parton distribution functions and partonic x sections.

PDFs

Non-perturbative information that is fitted from a wealth of experimental data

- The pdf is parametrised at a given low scale in terms of an analytic or NN function and momentum sum rules are imposed.
- They are evolved through the DGLAP equations:

$$Q^2 \frac{\partial f_a(x,Q^2)}{\partial Q^2} = \int_x^1 \frac{dz}{z} P_{ab}(\alpha_{\rm S}(Q^2), z) f_b(x/z, Q^2)$$

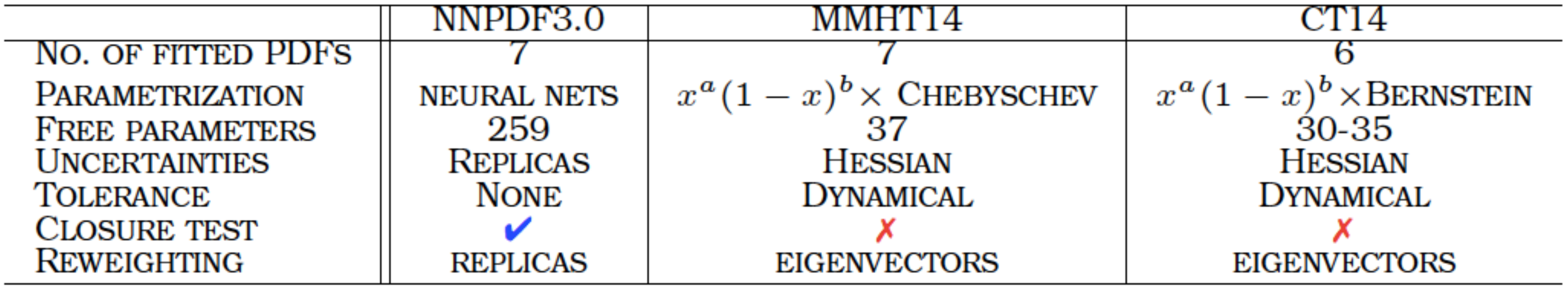
$$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi} \underset{\uparrow}{P_{ab}^{(0)}}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 \underset{\uparrow}{P_{ab}^{(1)}}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 \underset{\uparrow}{P_{ab}^{(2)}}(z) + \ldots\ldots$$

LO (1974) NLO (1980) NNLO (2004)

PDFs

Global fits: recent progress in methodology and data sets:

- NNPDF3.0 1410.8849
- MMHTCT14 1412.3989
- CT14 1506.07443

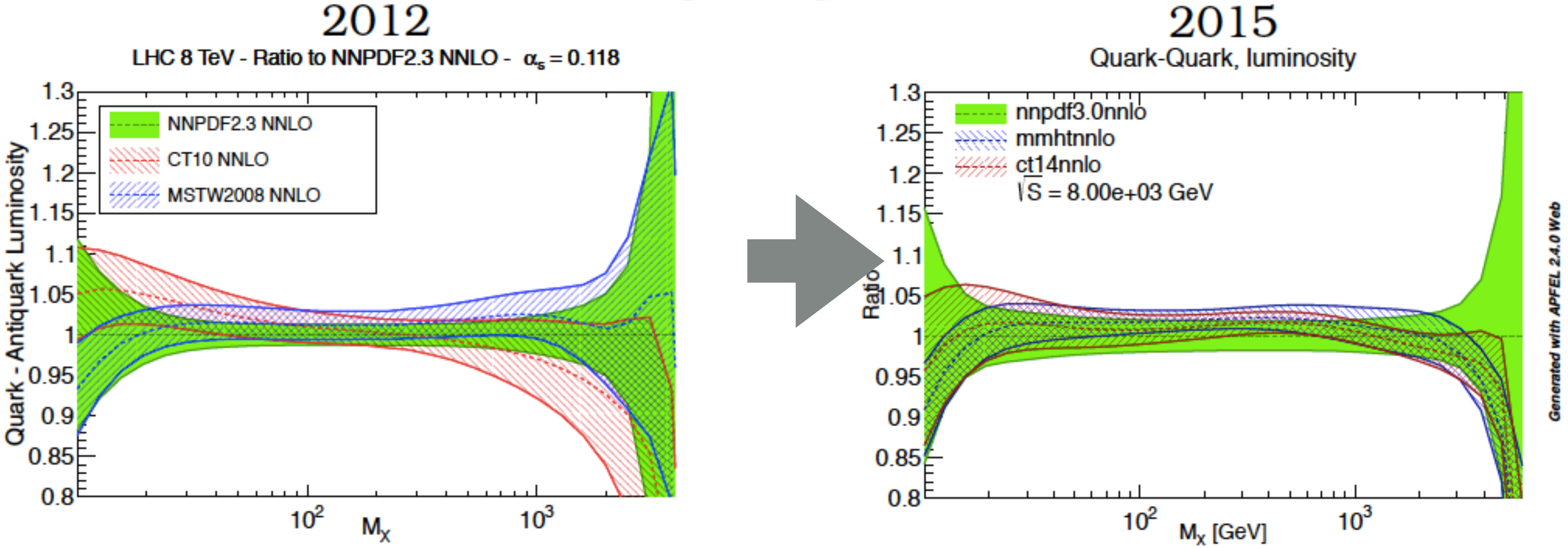


StefanoForte®

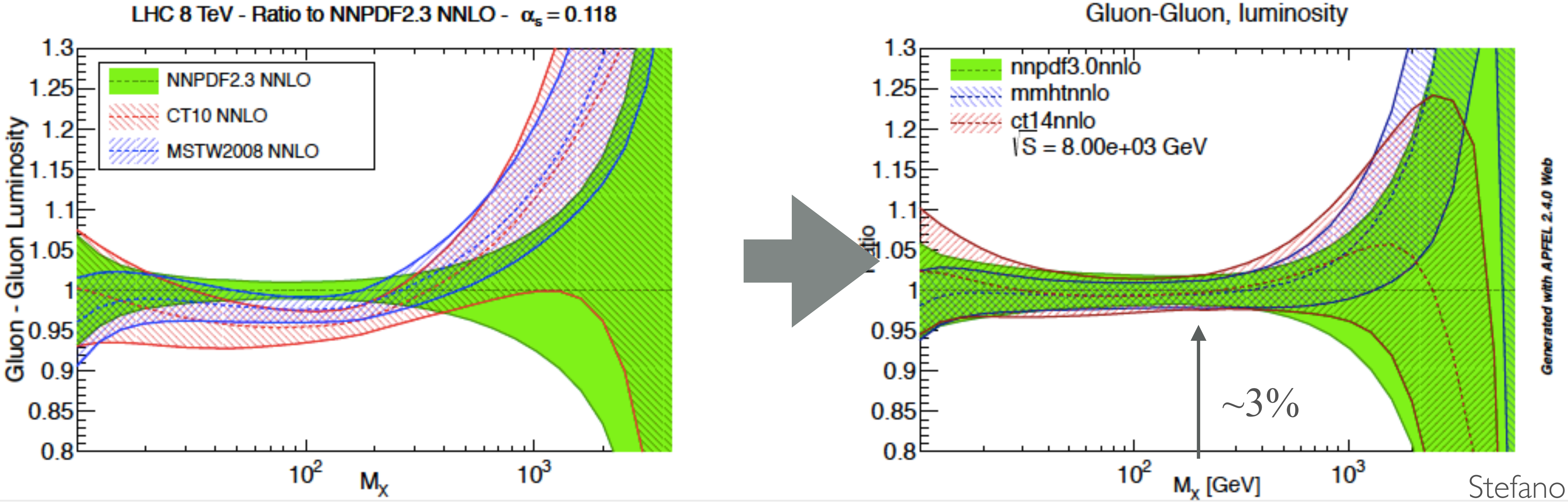
	NNPDF3.0	MMHT14	CT14
NO. OF FITTED PDFS	7	7	6
PARAMETRIZATION	NEURAL NETS	$x^a(1-x)^b\times$ CHEBYSCHEV	$x^a(1-x)^b\times$BERNSTEIN
FREE PARAMETERS	259	37	30-35
UNCERTAINTIES	REPLICAS	HESSIAN	HESSIAN
TOLERANCE	NONE	DYNAMICAL	DYNAMICAL
CLOSURE TEST	✓	✗	✗
REWEIGHTING	REPLICAS	EIGENVECTORS	EIGENVECTORS

Other non-global sets: HeraPDF, ABM14, GJR

QUARK-QUARK



GLUON-GLUON



StefanoForte

Perturbative expansion

$\hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$ Parton-level cross section

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter

$$\hat{\sigma} = \sigma^{\mathrm{Born}}\left(1+\frac{\alpha_s}{2\pi}\sigma^{(1)}+\left(\frac{\alpha_s}{2\pi}\right)^2\sigma^{(2)}+\left(\frac{\alpha_s}{2\pi}\right)^3\sigma^{(3)}+\ldots\right)$$

LO predictions

NLO corrections

NNLO corrections

NNNLO corrections

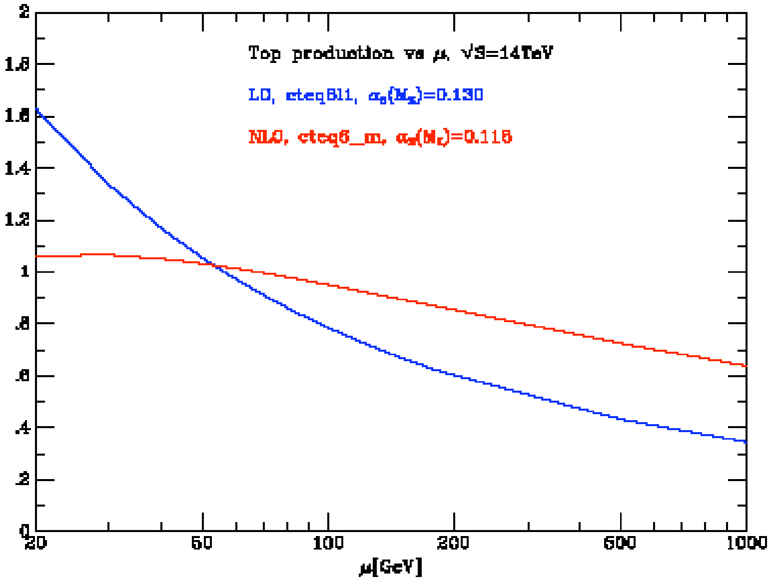
- Including higher corrections improves predictions and reduces theoretical uncertainties: improvement in accuracy and precision.

Perturbative expansion

- Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions
  - the scale of αs is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC

- To obtain reliable predictions at least NLO is needed

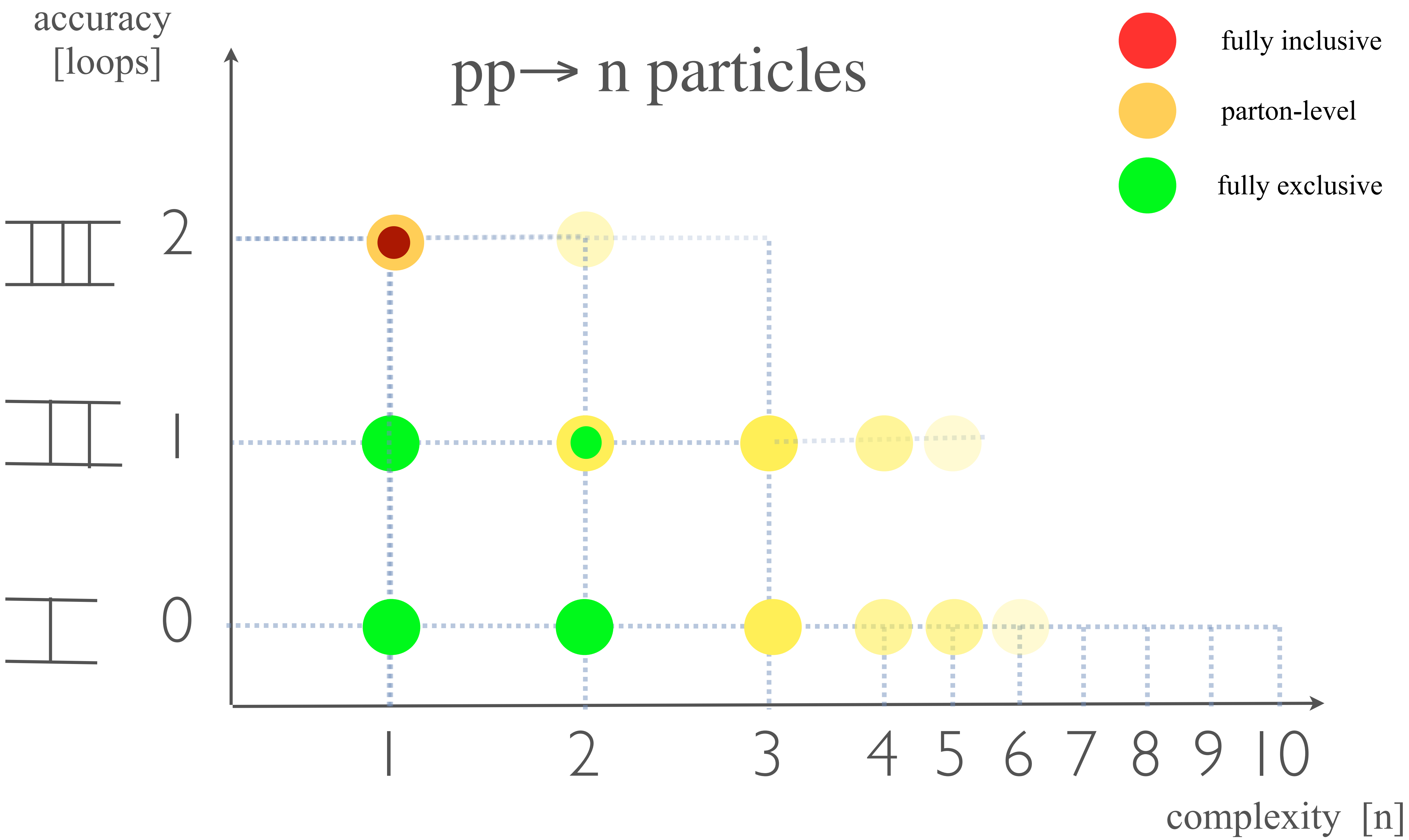
- NNLO allows to quantify uncertainties



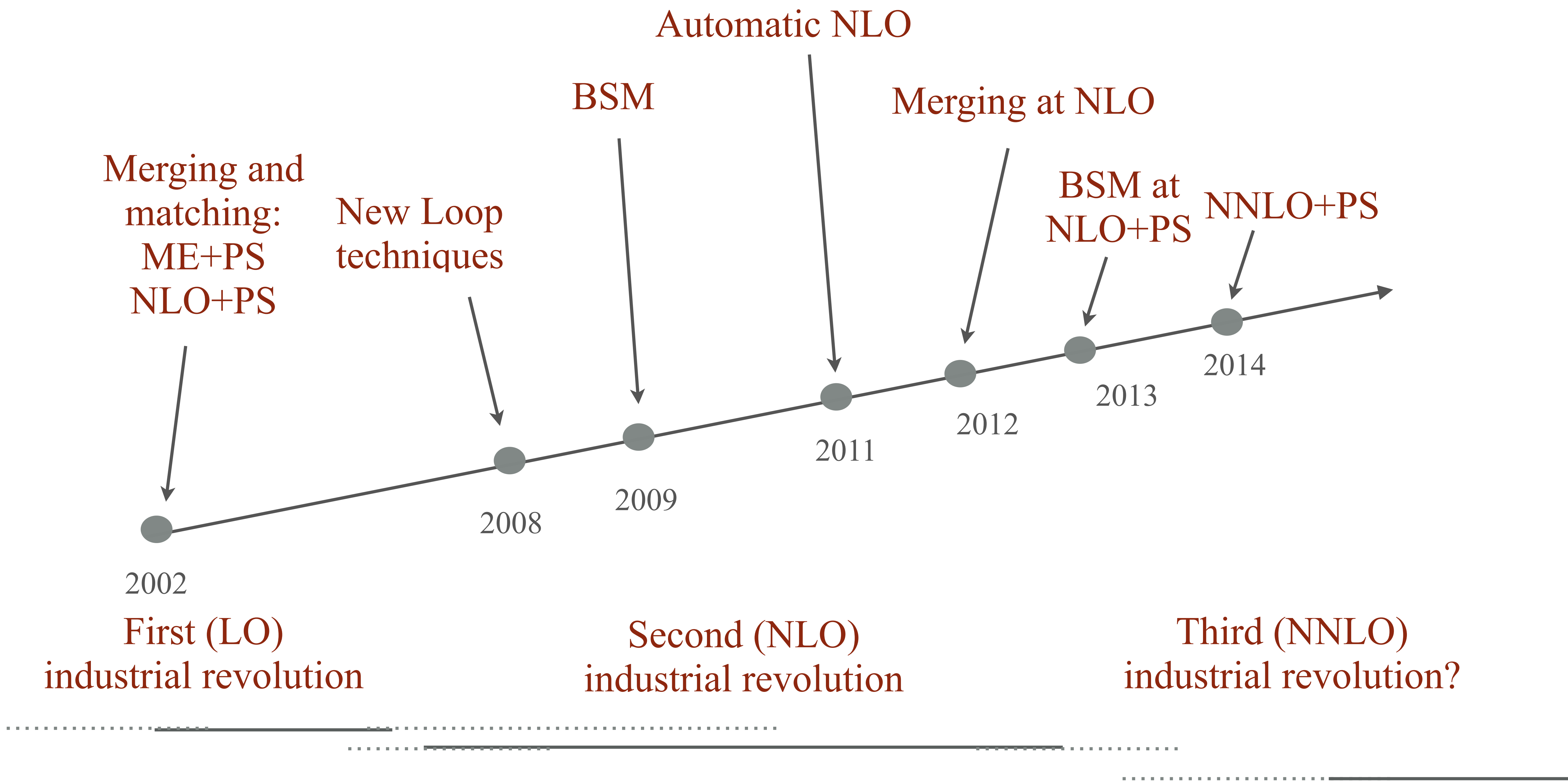
Furthermore:

- Resummation of the large logarithmic terms at phase space boundaries
- NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
- Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis

Predictions in QCD: before the LHC



Predictive MC (simplified) progress



Merging and matching: ME+PS NLO+PS

2002

New Loop techniques

2008

BSM

2009

Automatic NLO

2011

Merging at NLO

2012

BSM at NLO+PS

2013

NNLO+PS

2014

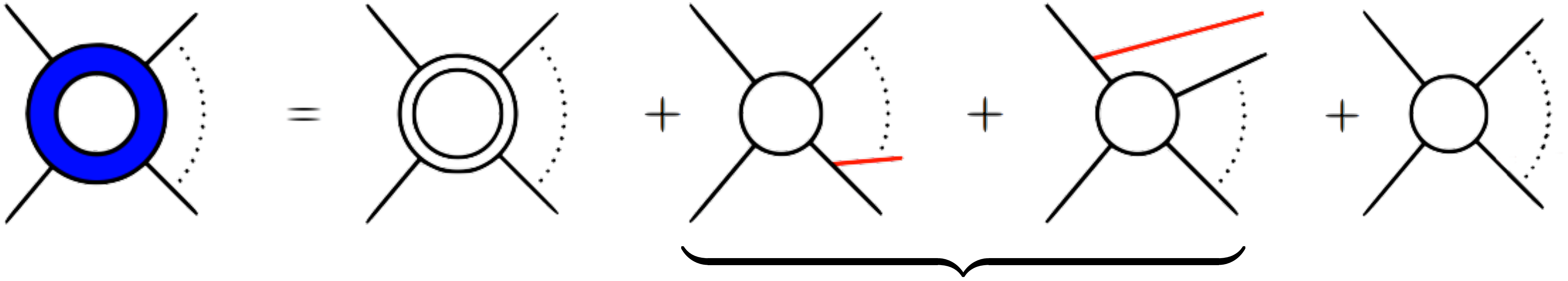
First (LO) industrial revolution

Second (NLO) industrial revolution

Third (NNLO) industrial revolution?

NLO Basics

NLO contributions have three parts



$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

Virtual part

Real emission part

Born

- Loops have been for long the bottleneck of NLO computations
- Virtuals and Reals are each divergent and subtraction scheme need to be used (Dipoles, FKS, Antenna's)
- A lot of work is necessary for each computation

The cost of a new prediction at NLO used to exceed 100k€.

New Loop techniques

For the calculation of one-loop matrix elements, several methods have been established and public tools released:

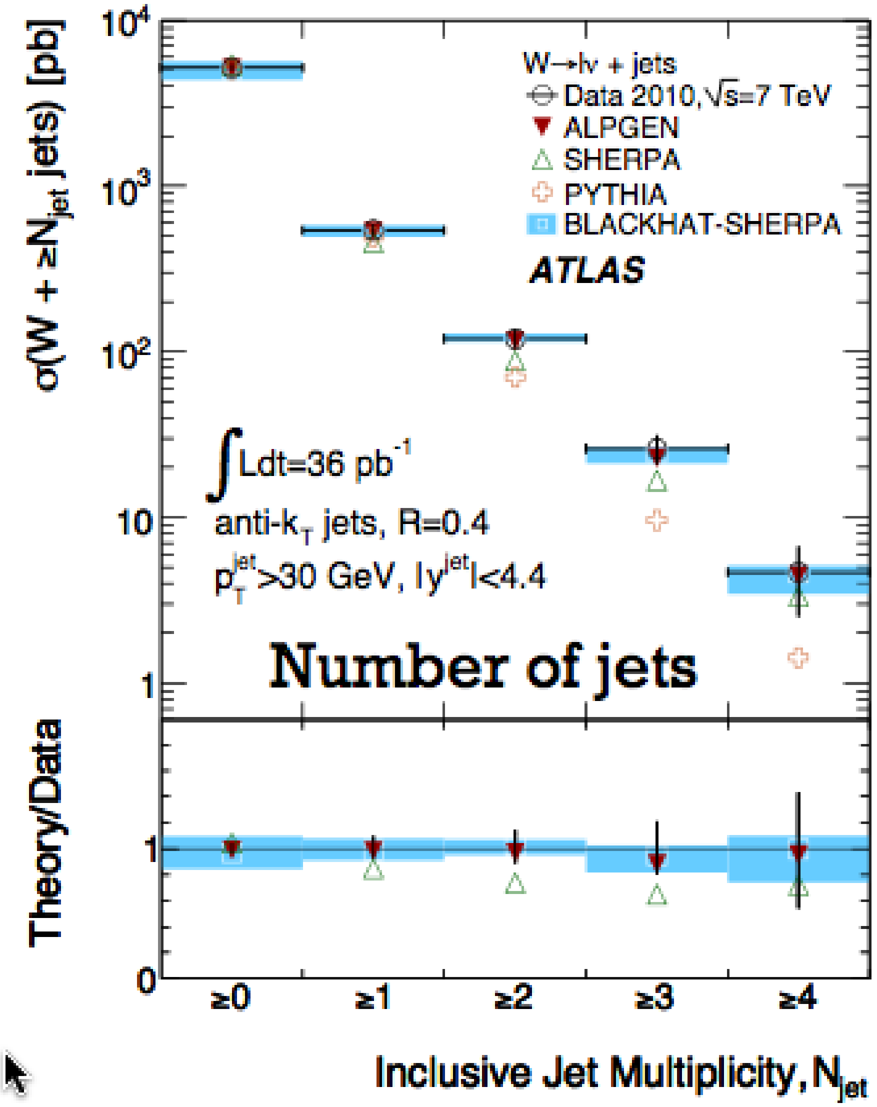
•Generalized Unitarity (ex. BlackHat, Rocket,...)
[Bern, Dixon, Dunbar, Kosower, hep-ph/9403226 + ...; Ellis, Giele, Kunszt 0708.2398, +Melnikov 0806.3467]

•Integrand Reduction (ex. CutTools, Samurai)
[Ossola, Papadopolulos, Pittau, hep-ph/0609007; del Aguila, Pittau, hep-ph/0404120; Mastrolia, Ossola, Reiter, Tramontano, 1006.0710]

•Tensor Reduction (ex. Golem, GoSam, MadLoop)
[Passarino, Veltman, 1979; Denner, Dittmaier, hep-ph/0509141, Binoth, Guillet, Heinrivh, Pilon, Reiter 0810.0092]

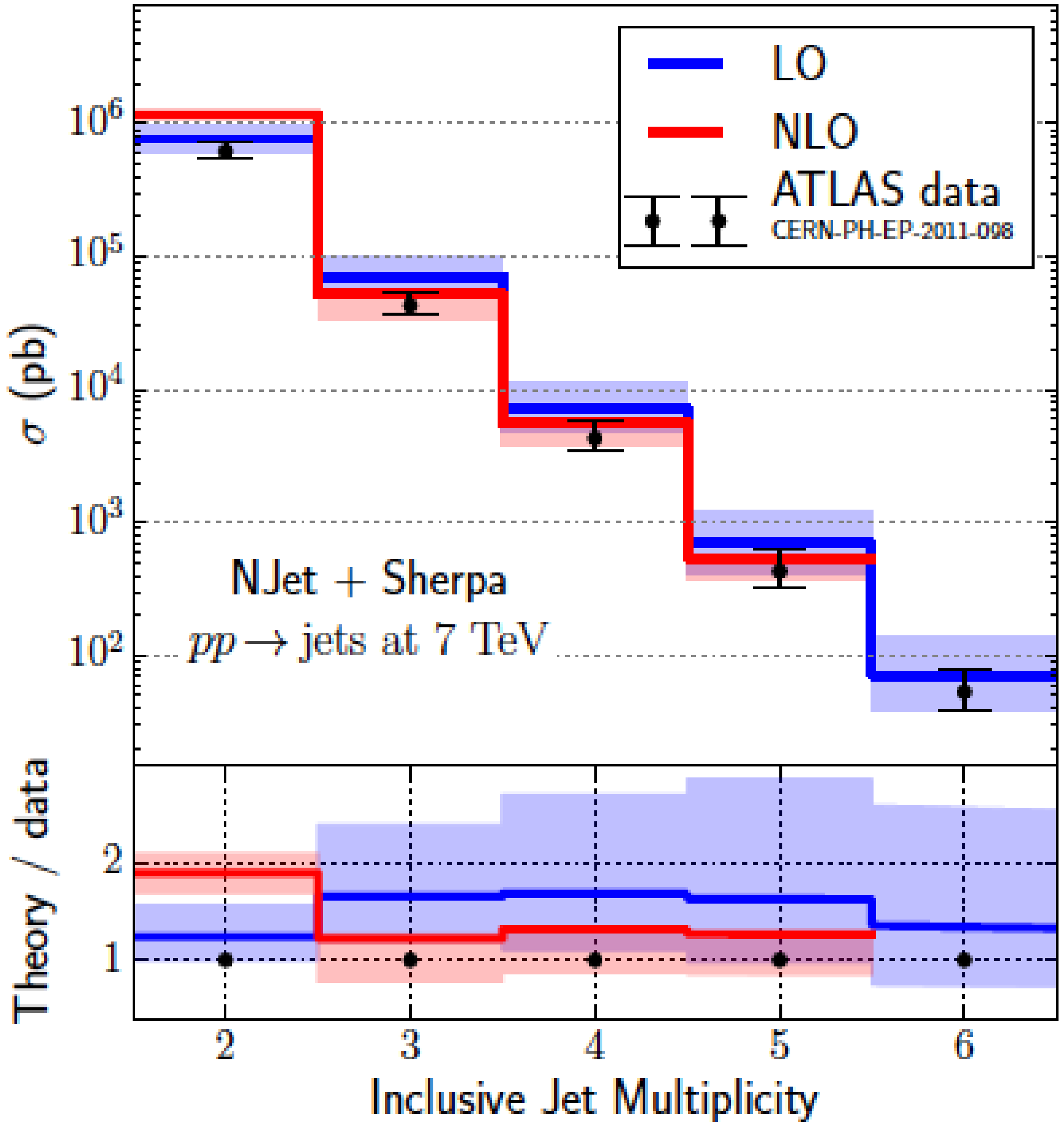
The NLO Guinness World Records

p p →W + 5 jets



[Bern et al., 1304.1253]

p p →5 jets



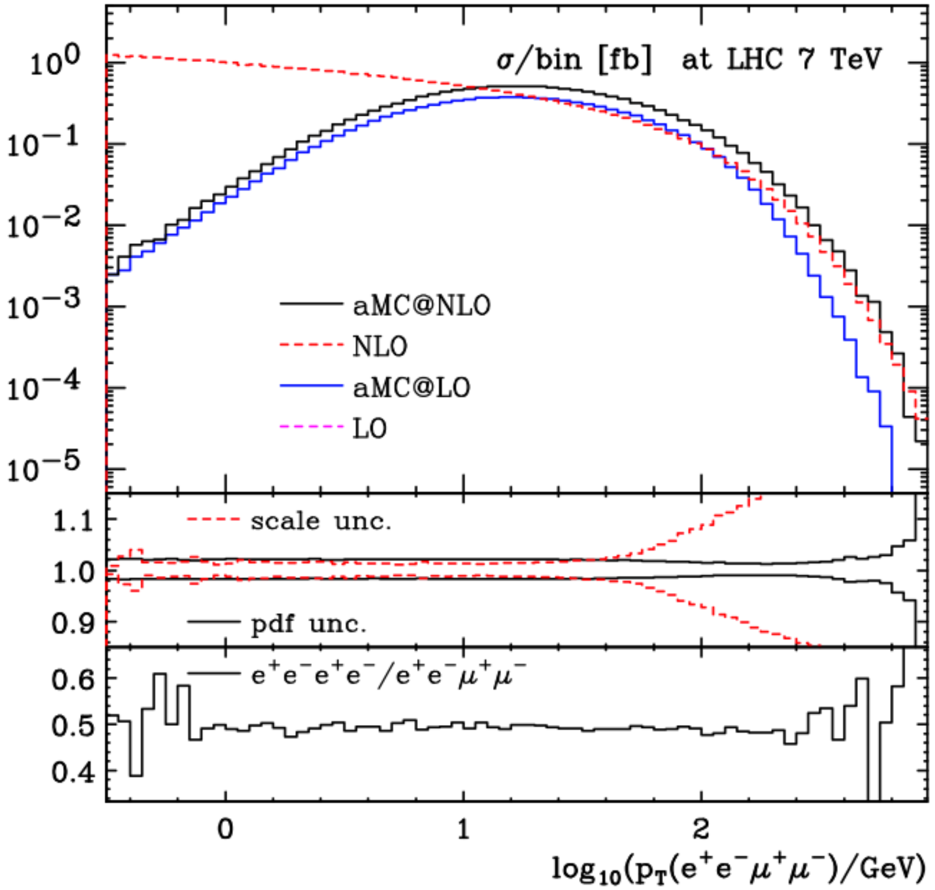
[Badger et al. 1309.6585]

NLO+PS matching

Parton Shower Monte Carlo provide a simulation of all the stages of the hadronic collision: merge QCD matrix element + shower in the soft collinear approximation +hadronization model

The **MC@NLO** and **POWHEG** methods allow to combine NLO calculations with existing shower/hadronisation programs such as PYTHIA8, HERWIG++, SHERPA….

POWHEG and MC@NLO implementations have same formal accuracy but differ in the amount of radiation that is exponentiated.



The MC@NLO method has been extended to deal with samples of different jet multiplicity (merging) keeping NLO accuracy (FxFx in MG5aMC, ME@NLOPS in SHERPA)

The POWHEG method has been extended via the MINLO technique to obtain inclusive samples without merging scales.

Automation of NLO+PS

- **MadGraph5_aMC@NLO** Alwall, Frederix, Frixione, FM, Mattelaer, Shao, Stelzer, Torrielli, Zaro et al, 0908.4272, 1103.062, 1104.5613, 1110.4738, 1110.5502, 1304.7927, 1305.7088, 1306.6464,1311.1829, 1401.7340,1405.0301, 1407.5089,1409.5301,1504.00611, 1507.05640, 1507.02549, 1508.05327…

  Fully automatic framework, where all the elements of a NLO+PS computation in the SM and (BSM) are automatically generated.

- **POWHEG-BOX** and applications: Alioli, Nason, Oleari, Re et al, 1002.2581, 1009.2450, 1009.5594, 1012.3380, 1102.4846, 1105.4488, 1107.5051, 1108.0909, 1310.4491, 1306.2442, 1311.1365, 1402.4001:

  Framework which allows to promote a standard NLO calculation into a MC at NLO generator. Very popular choice. More than ~30 processes implemented. Similar in spirit to MCFM.

- **SHERPA** Hoeche et al, 1008.5399, 1009.1127, 1111.1220, 1402.6293,1403.7516

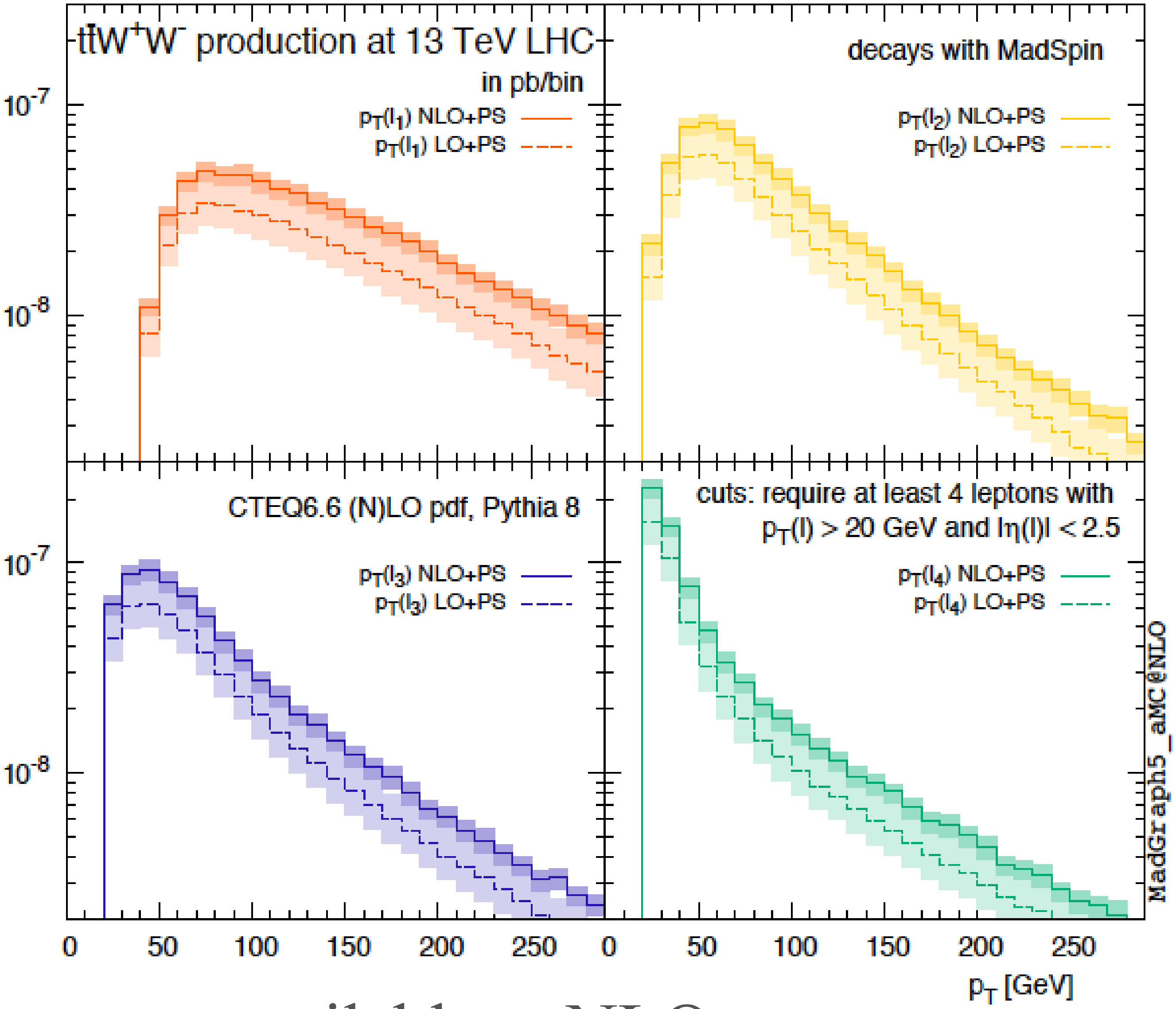
  Flexible framework having both MC@NLO and POWHEG methods based on CS dipoles, needs virtuals. Fully automatic except for virtuals which are taken from BlackHAT, OpenLoops,GoSam..

NLO+PS Automation

For example, the level of automation in MadGraph5_aMC@NLO is as follows:

```
./bin/mg5_aMC
> generate p p > t t~ W+ W- [QCD]
> output ttww
> launch
```

Uncertainties from scale variation and pdfs are automatically computed (at no extra cost) and associated to each of the unweighted events (=any distribution will have the corresponding uncertainty band). Short-distance events ready to be “dressed” by PS and hadronisation.



[Alwall, et al. 1505.0301]

Virtually unlimited set of LHC processes available at NLO

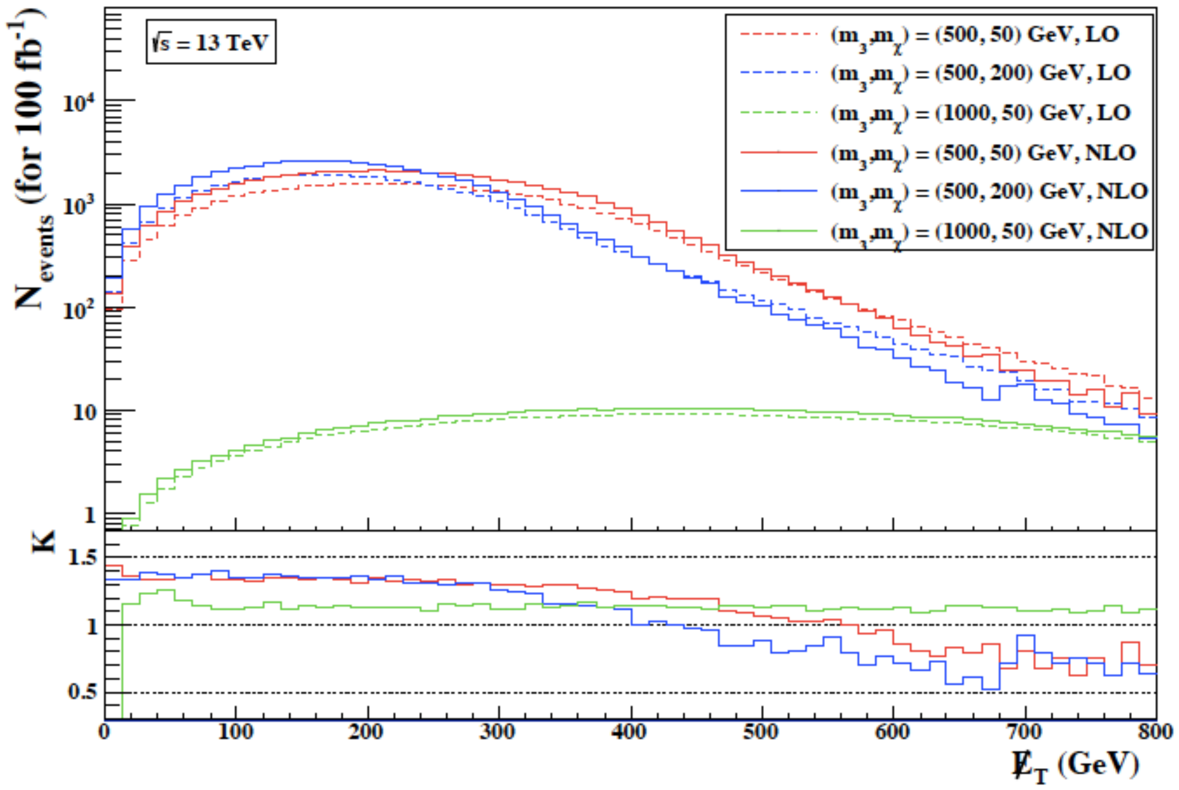
NLO+PS Automation

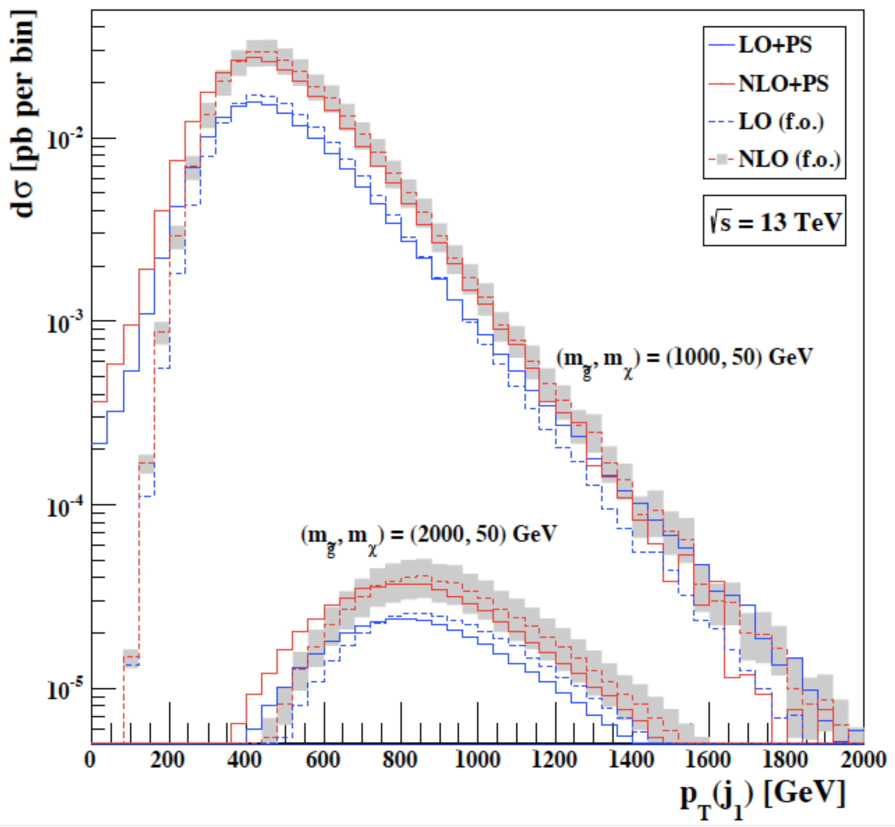
The same level of automation is being achieved for BSM:

[Degrande, Fuks, Hirschi,Proudom, Shao, 1412.5589, 1509.XXXX]

```
./bin/mg5_aMC
> import model SUSYQCD
> generate p p > t1 t1~ [QCD]
> output StopPair
> launch
```

```
./bin/mg5_aMC
> import model SUSYQCD
> generate p p > gl gl [QCD]
> output GluinoPair
> launch
```





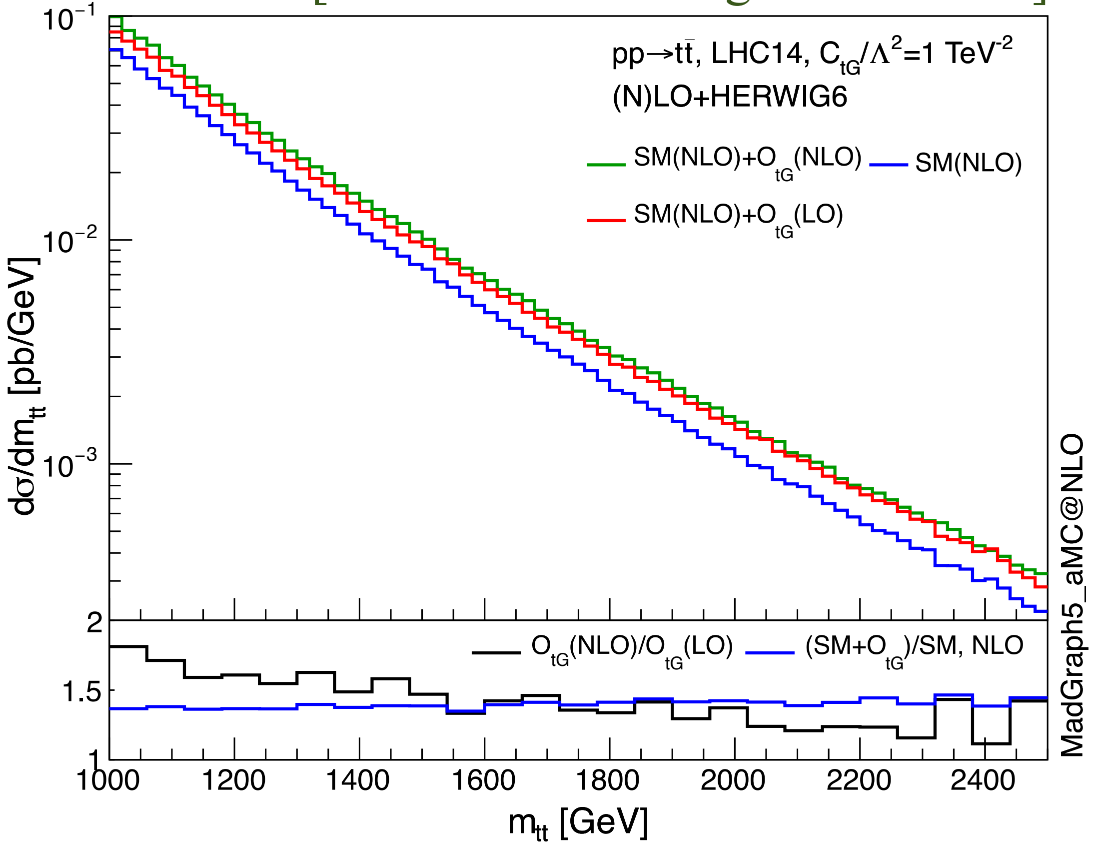
NLO+PS Automation

The same level of automation is being achieved for EFT’s:

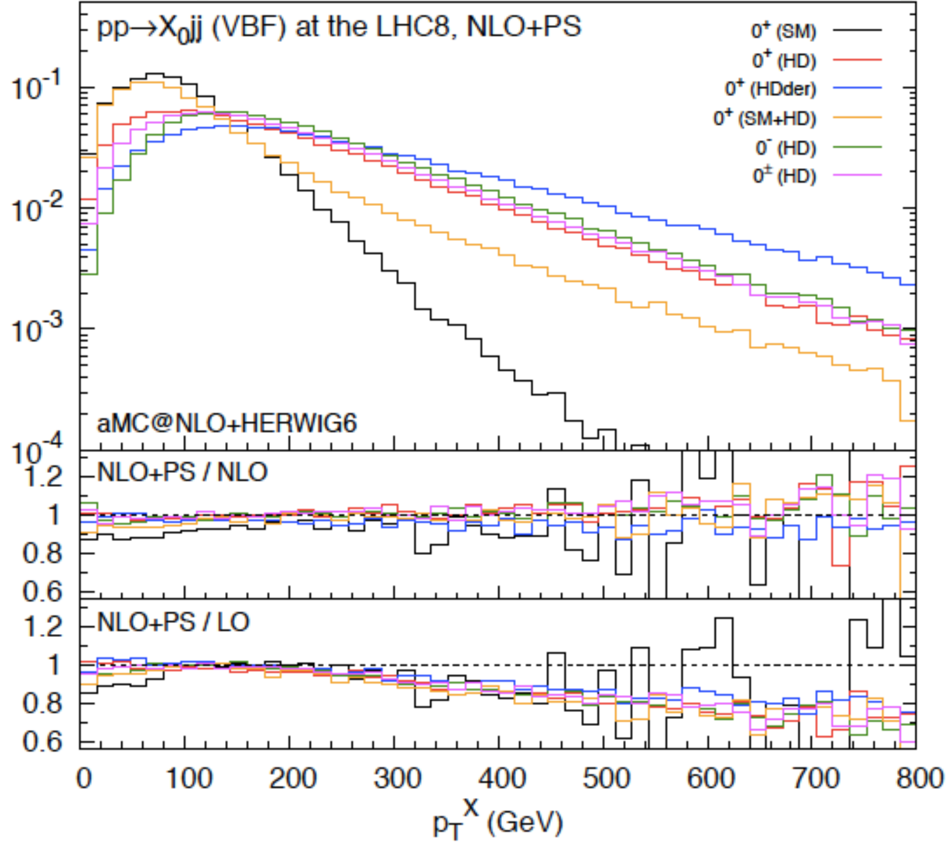
```
./bin/mg5_aMC
> import model TopEFT
> generate p p > t t~ , NP=1 [QCD]
> output Chromott
> launch
```

```
./bin/mg5_aMC
> import model HC
> generate p p > X0 j j [QCD]
> output VBFdim6
> launch
```

[Franzosi and Zhang. 1503.08841]



[Mawatari, Zaro, FM: 1311.1829]



The NNLO era

NNLO calculations important at least for the following cases:

1) Benchmark processes measured with high precision	$e^+e^- \to$ 3 jets	✓
	pp $\to$ W, Z	✓
	pp $\to$ 2 jets	partial
	pp $\to$ t tbar	✓
2) Processes with large NLO corrections (eg, new channels)	pp$\to$H (EFT)	✓
	pp$\to$H+jet (EFT)	✓
	pp$\to$HH (EFT)	✓
3) Important/Irreducible backgrounds for Higgs or NP searches	pp $\to$ t tbar	✓
	pp$\to$VV' (W,γ,Z)	✓
	pp$\to$W/Z j	✓

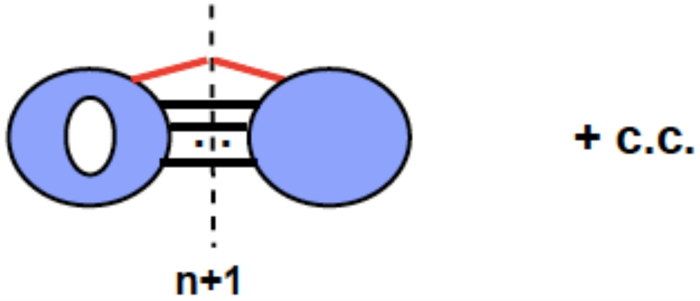
In addition it is essential to provide codes that are able to deal with final state selections (at the parton level) so that fiducial cross sections and distributions can be directly compared with data.

MGrazzini®

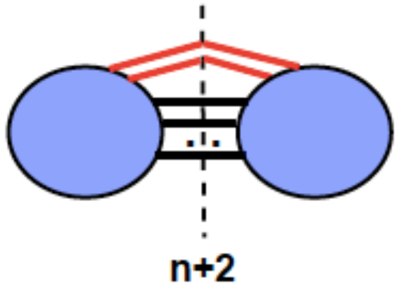
Ingredients of NNLO calculations

Double virtual contribution
with n resolved partons

Real-virtual contribution with 1 unresolved parton



Double-real contribution with 2 unresolved patrons



Each of the three contributions is divergent, yet the sum is finite (KLN theorem).
How to deal with IR singularities ?

NNLO methods

There are two main approaches available in the literature:

1. Organise the calculation from scratch so as to cancel all the singularities

- sector decomposition
- antenna subtraction
- “colourful” subtraction
- joint use of subtraction and sector decomposition

T. Binoth, G.Heinrich (2000,2004)
C.Anastasiou, K.Melnikov, F.Petriello (2004)

A. & T. Gehrmann, N. Glover (2005)

G, Somogyi, Z. Trocsanyi, V. Del Duca (2005, 2007)

M.Czakon (2010,2011)$
R.Boughezal, K.Melnikov, F.Petriello (2011)

2. Start from an inclusive NNLO calculation and combine it with an NLO calculation for n+1 parton process

- q_T subtraction
- “N-jettiness” method
- “Born projection” method for VBF

S.Catani, M.Grazzini (2007)
R.Boughezal, C.Focke,X.Liu, F.Petriello (2015)
F.Tackmann et al. (2015)
M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)

…and then of course the (sometimes extremely hard) two-loop amplitudes !

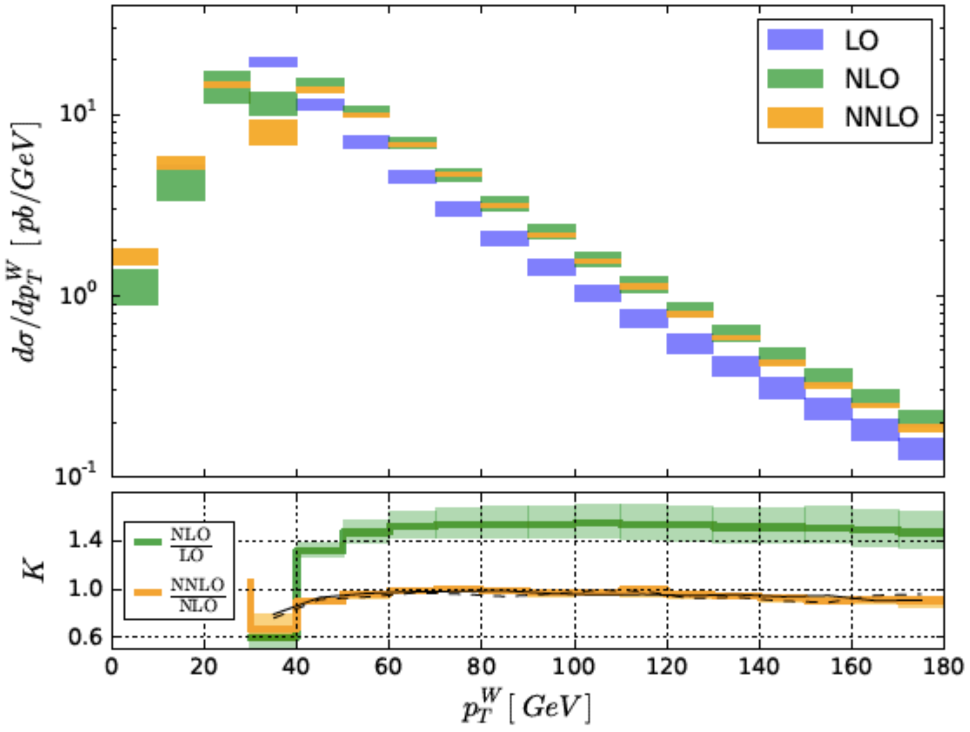
C.Anastasiou, F.Caola, M.Czakon, T.Gehrmann, N.Glover, M.Jaquier, A. Koukoutsakis
C.Oleari, K.Melnikov, L.Tancredi, M.E. Tejeda-Yeomans, A. von Manteuffel and many others

MGrazzini®

V+jet at NNLO

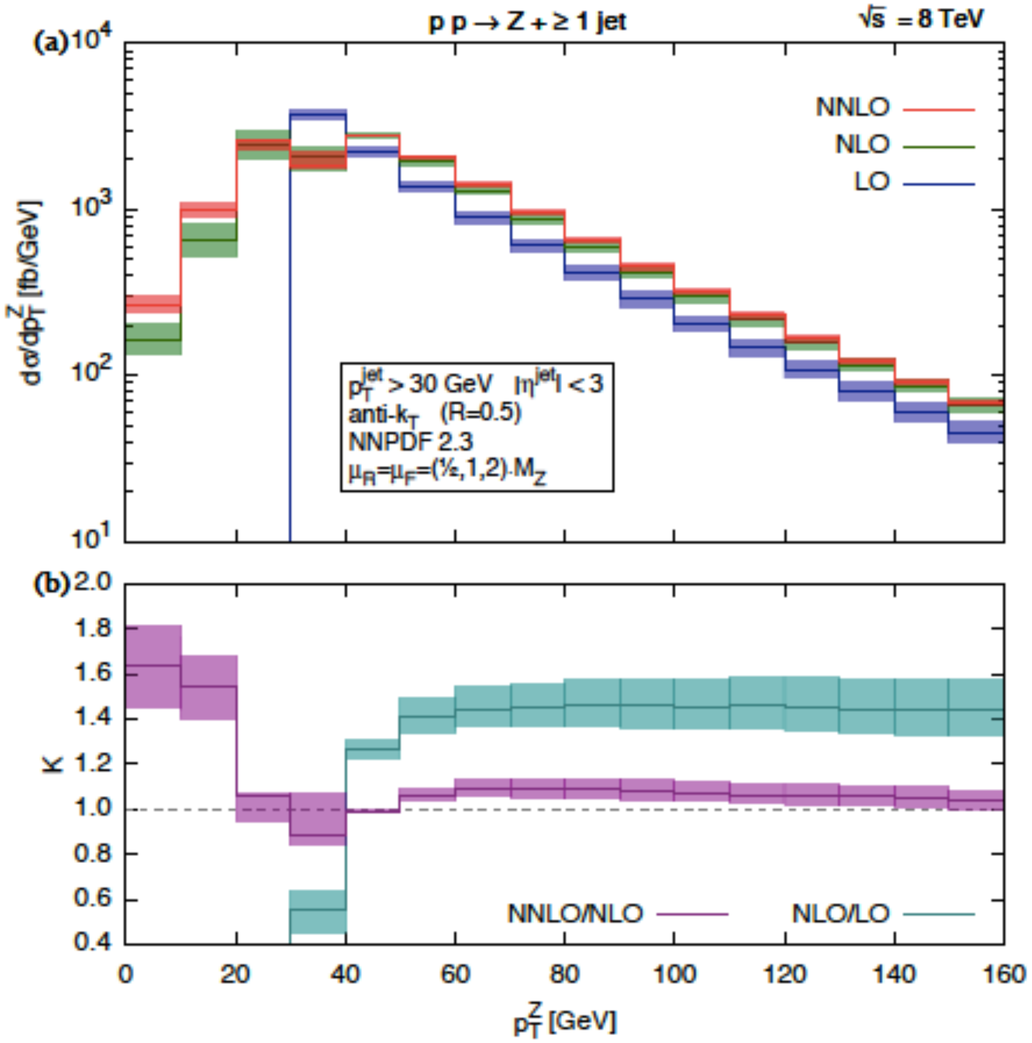
[R.Boughezal, C.Focke,X.Liu, F.Petriello (2015)]

W+jet



Small NNLO effect and significant reduction of scale uncertainties. First application of new "N-jettiness" method: relatively flat NNLO correction.

[A and T. Gehrmann, N. Glover, T.Morgan, A.Huss (2015)]

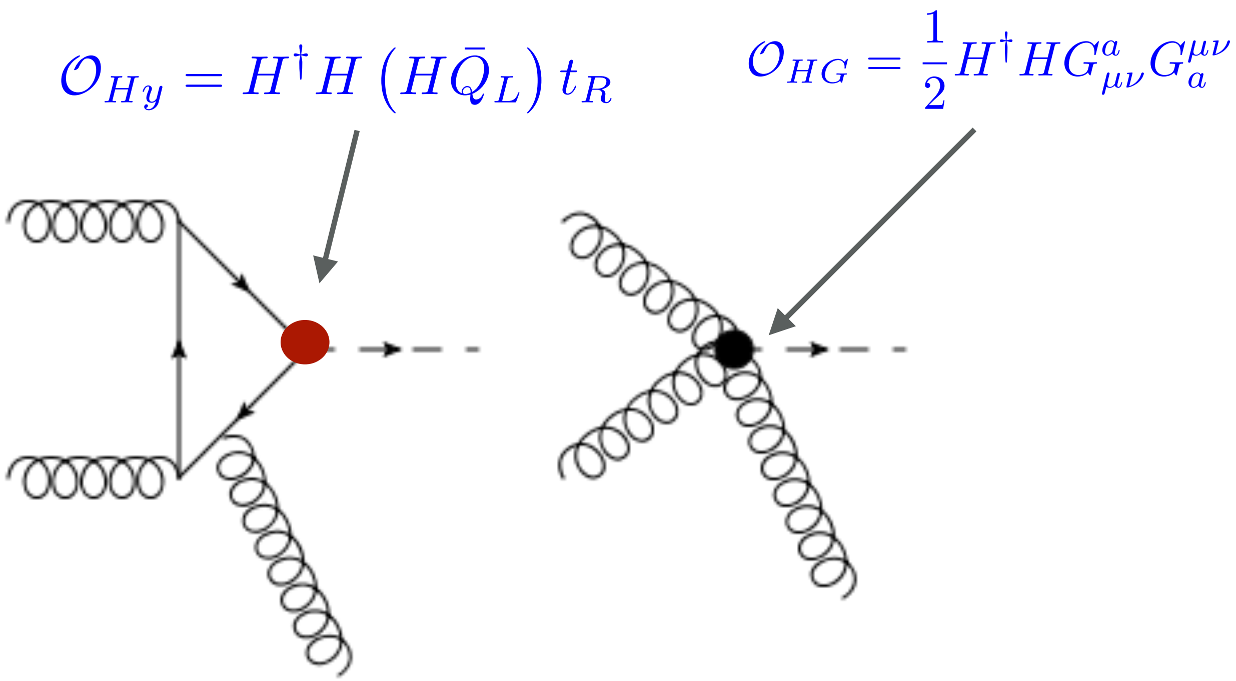


Similar effects for Z+jet: antenna subtraction (large Nc approximation for the dominant channels)

H+jet

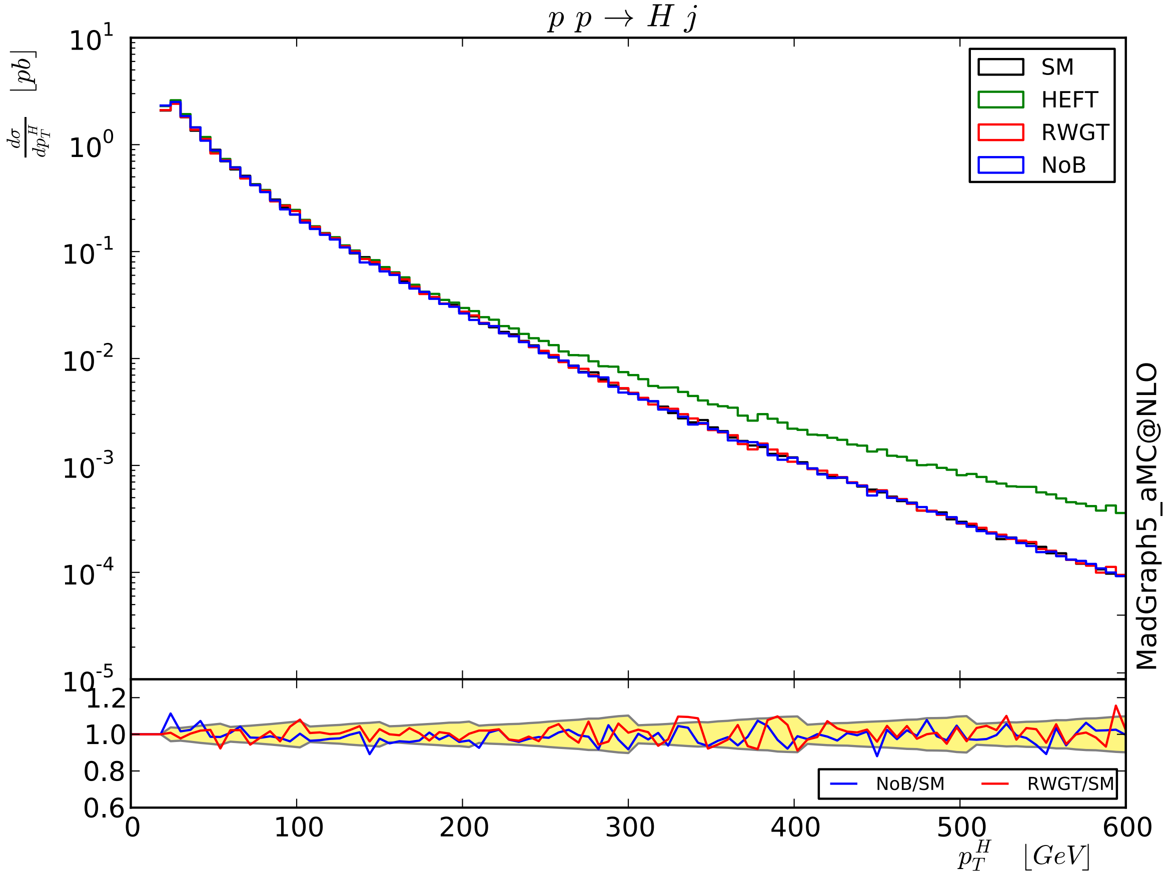
From a global fit the coupling of the higgs to the top is poorly determined: the loop could still be dominated by np.

[Grojean et al., 2013][Banfi et al. 2014] [Buschmann, et al. 2014]



$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$$

$$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision. NLO prediction for H+1jet with top loops not yet available.

H+jet at NNLO (in the EFT)

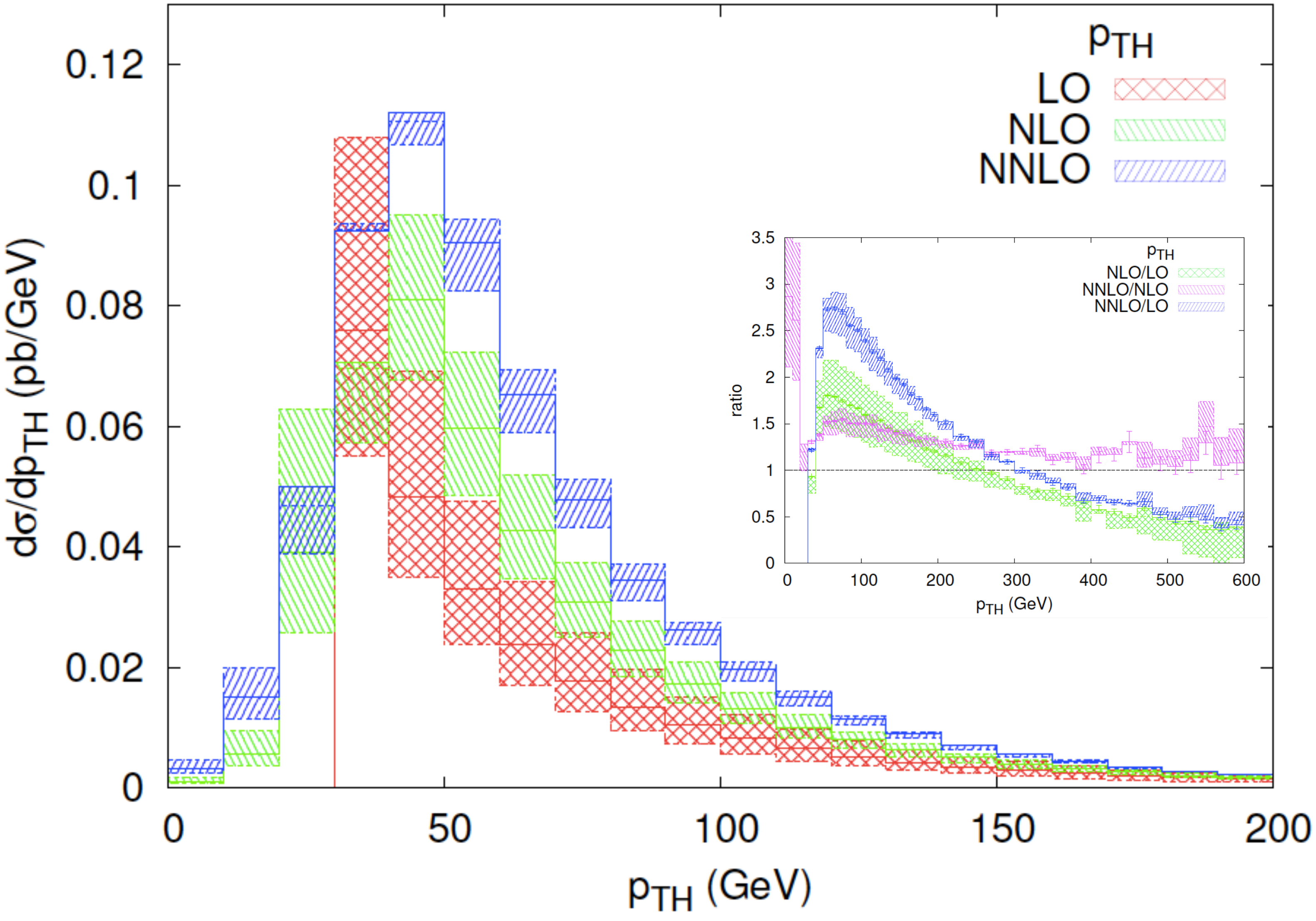
NNLO calculation carried out with three independent methods (antenna subtraction, subtraction+sector, N-jettiness)

X. Chen, T. Gehrmann, N. Glover, M. Jaquier (2014)

R.Boughezal, F.Caola, K.Melnikov, ,F.Petriello, M.Schulze (2015)

R.Boughezal, C.Focke, W.Giele ,X.Liu, F.Petriello (2015)

Quantitative effect smaller than previously anticipated from gg only: at the 20% level (μ=mH)



VBF at NNLO

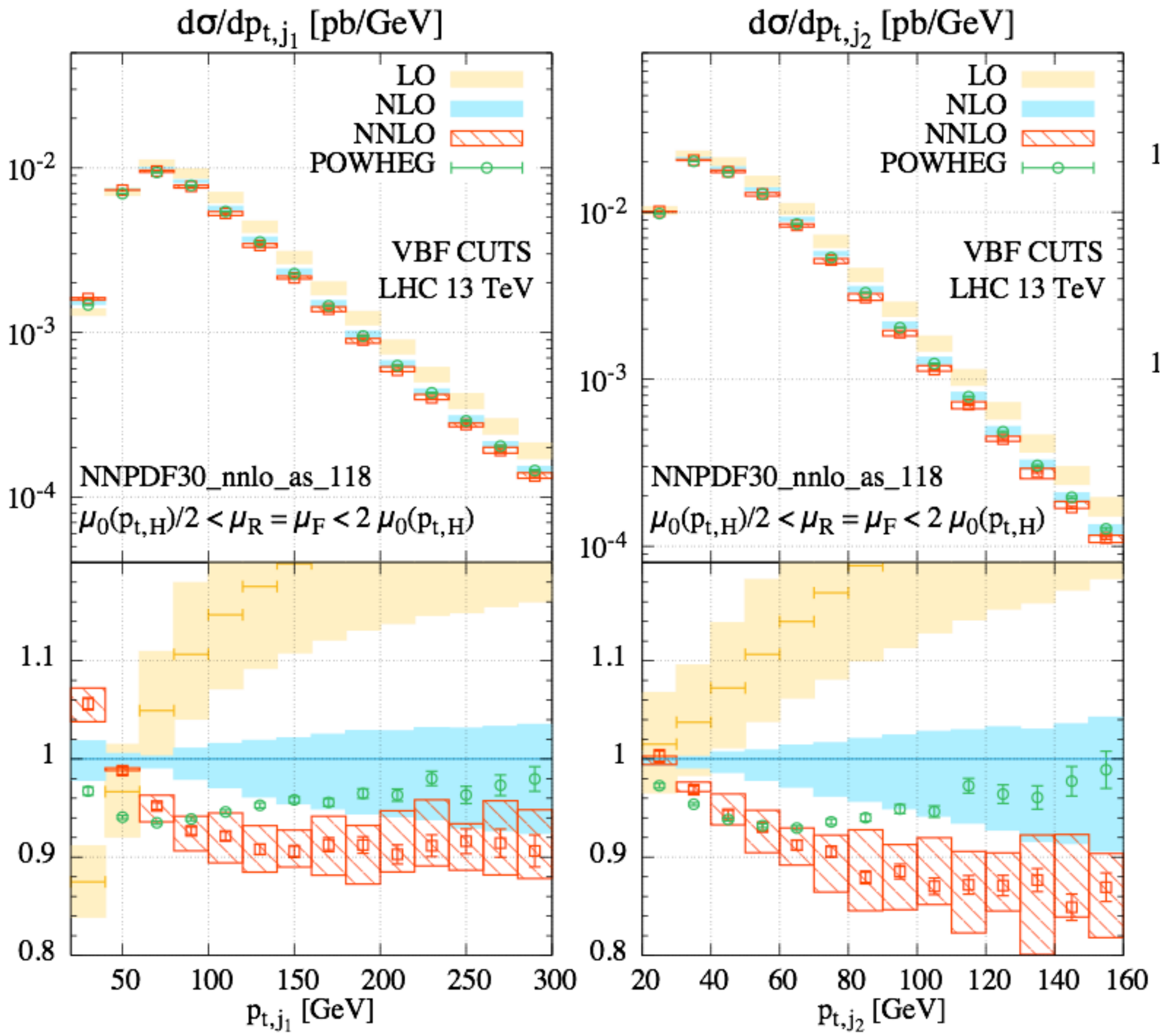
Vector boson fusion (VBF) is an important production channel for the Higgs boson: distinctive signature with little hadronic activity in the central rapidity region.

Fully inclusive NNLO corrections known since quite some time [P.Bolzoni, F.M,S.Moch,M.Zaro (2010)] in the structure function approach: O(1%) effect.

Fully exclusive NNLO computation recently completed (still neglecting color exchanges between quark lines) [M.Cacciari, F.Dreyer, A.Karlberg, G.Salam,G.Zanderighi (2015)]

NNLO corrections make p_T spectra softer larger impact when VBF cuts are applied

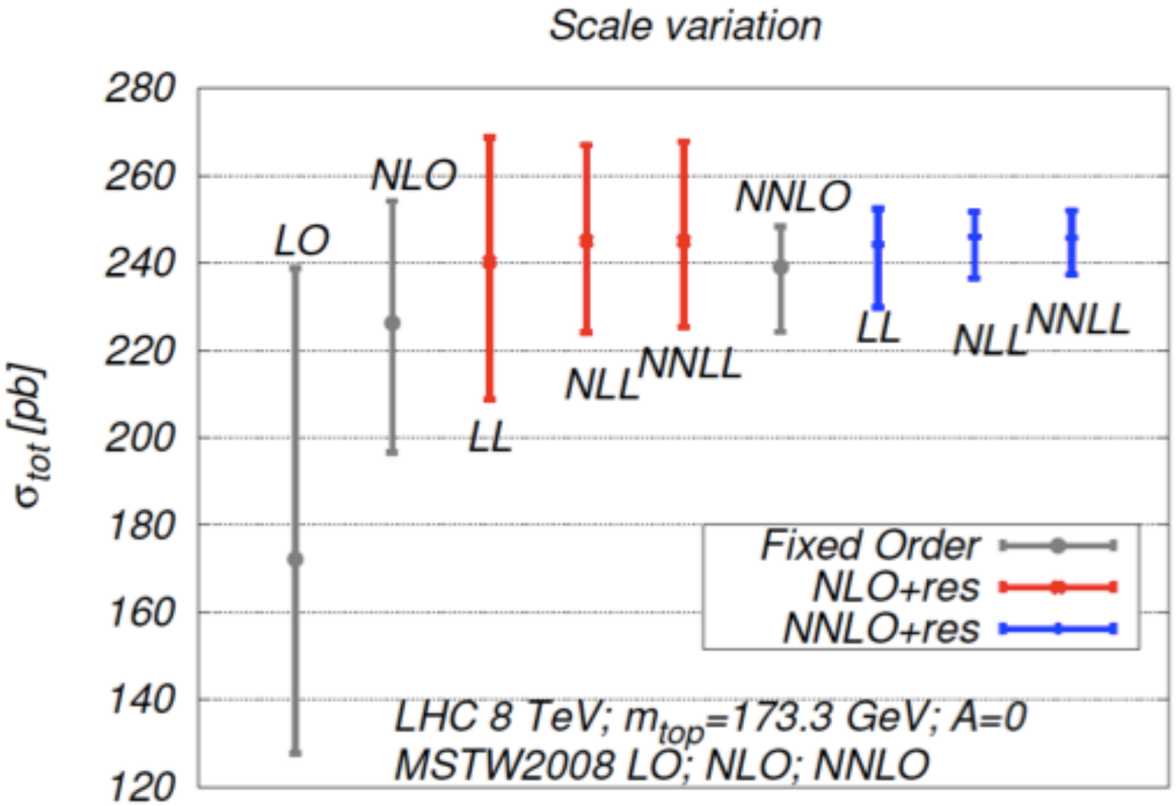
	$\sigma^{(\text{no cuts})}$ [pb]	$\sigma^{(\text{VBF cuts})}$ [pb]
LO	$4.032\,^{+0.057}_{-0.069}$	$0.957\,^{+0.066}_{-0.059}$
NLO	$3.929\,^{+0.024}_{-0.023}$	$0.876\,^{+0.008}_{-0.018}$
NNLO	$3.888\,^{+0.016}_{-0.012}$	$0.826\,^{+0.013}_{-0.014}$

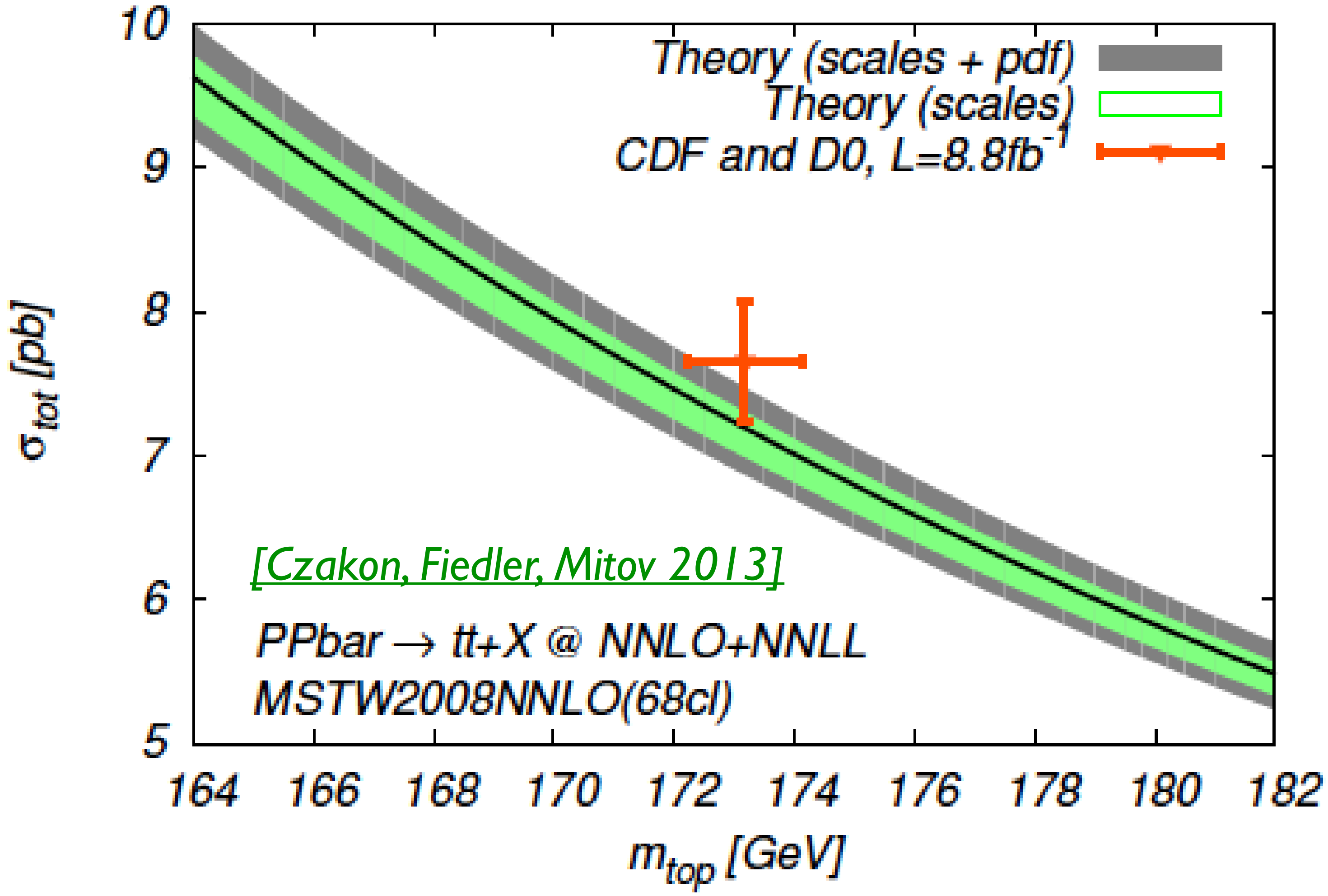


$t\bar{t}$ cross section at NNLO

Monumental MILESTONE in perturbative QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]





[Czakon, Fiedler, Mitov 2013]

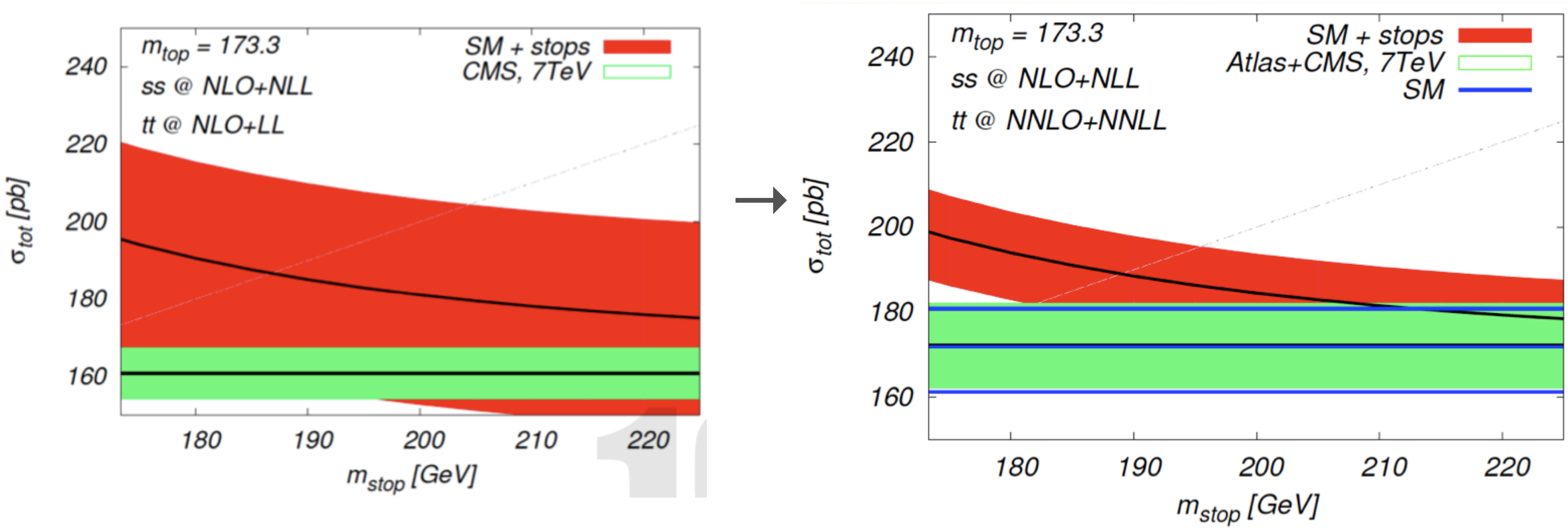
- Two loop hard matching coefficient extracted and included
- Very weak dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~ 50% scales reduction compared to the NLO+NNLL analysis

$t\bar{t}$ cross section at NNLO

Having a NNLO prediction opens the door to new possibilities.

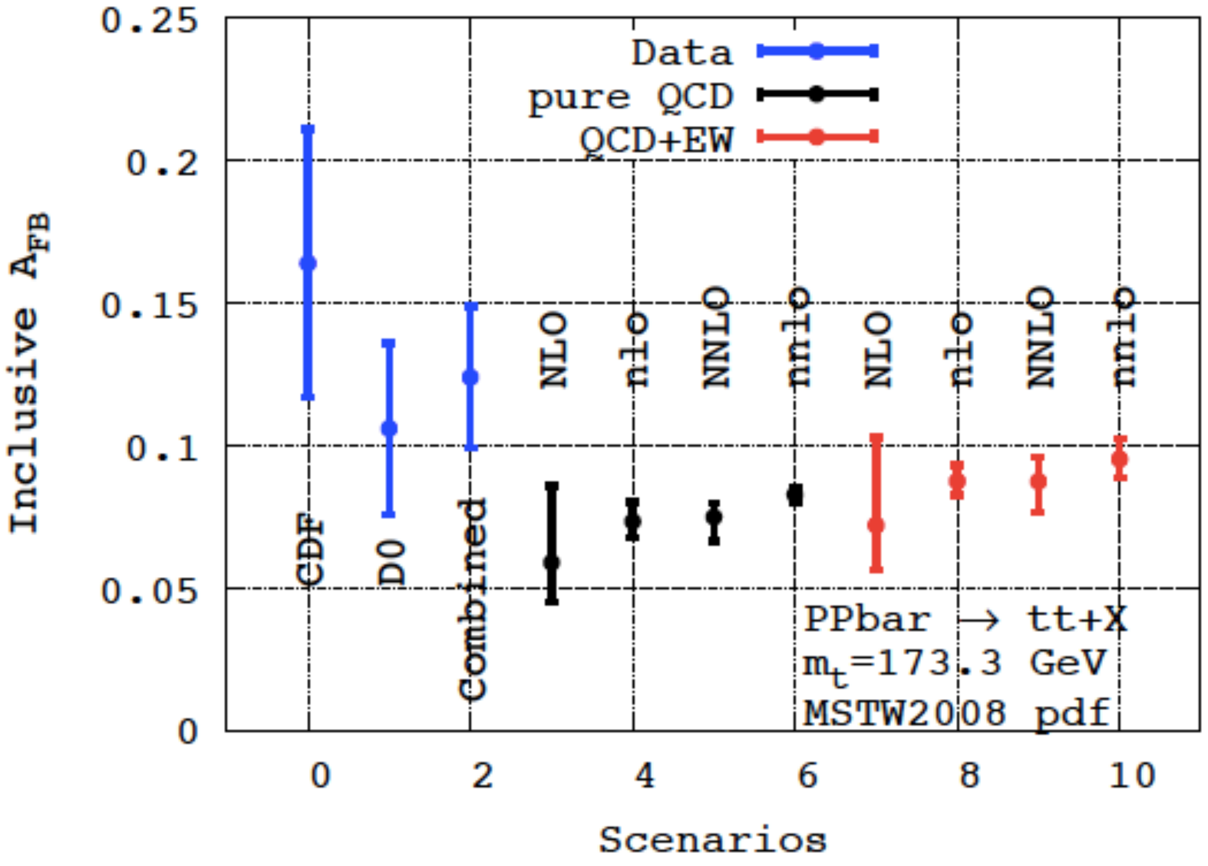
Consider the light stop window in a compressed spectrum, that mimicks the normal ttbar production:

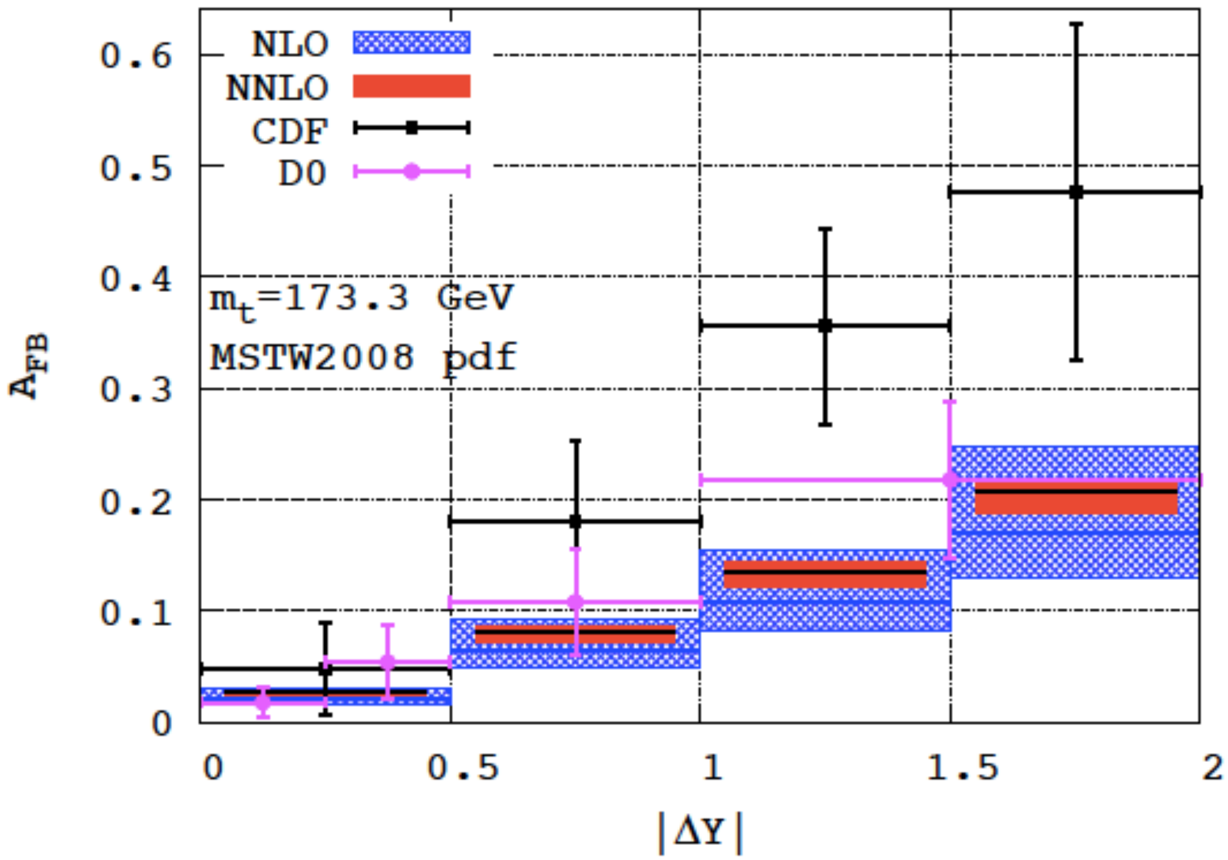
[Czakon, Mitov, Papucci, Ruderman, Weiler,2014]



$t\bar{t}$ forward-backward asymmetry

[Czakon, Fiedler, Mitov,2014]



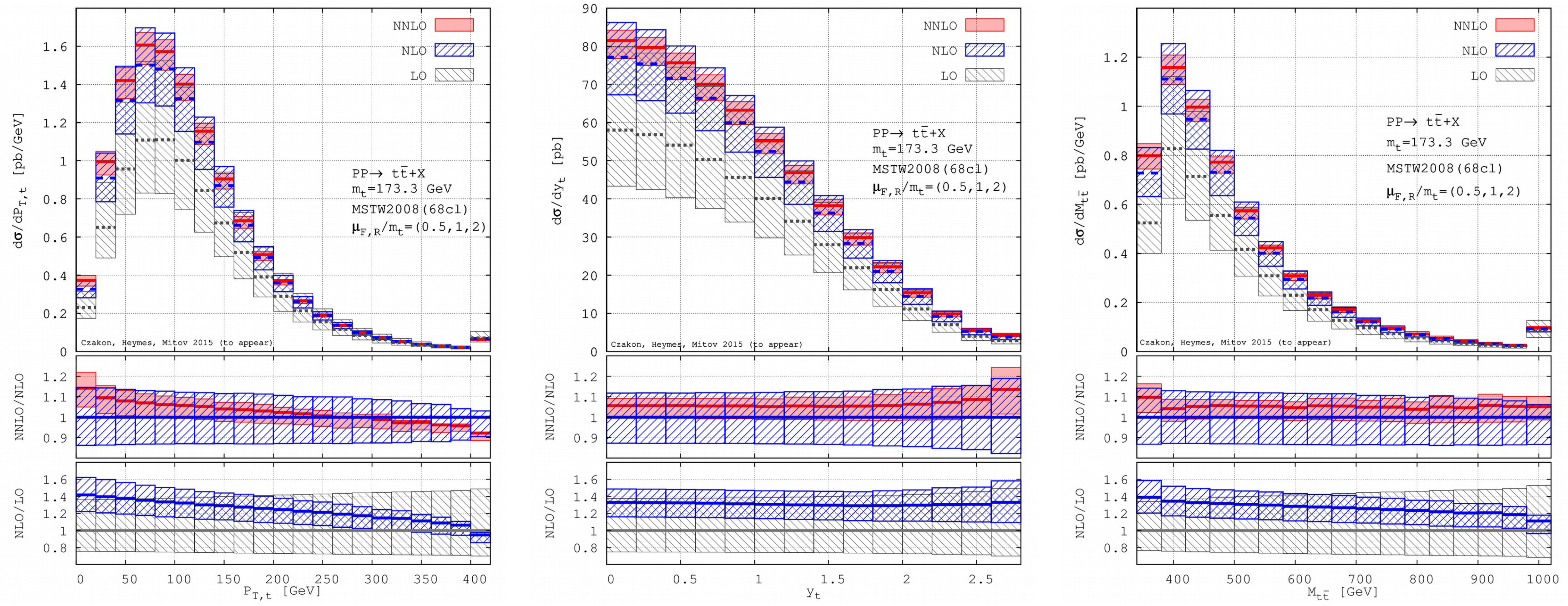


The asymmetry at NLO accuracy (from the NNLO total cross section calculation) is sizeably larger and much more precise than the LO result.

$t\bar{t}$ at NNLO : differential distributions

The first differential distributions at NNLO for the p_T (top), y(top), m(ttbar):

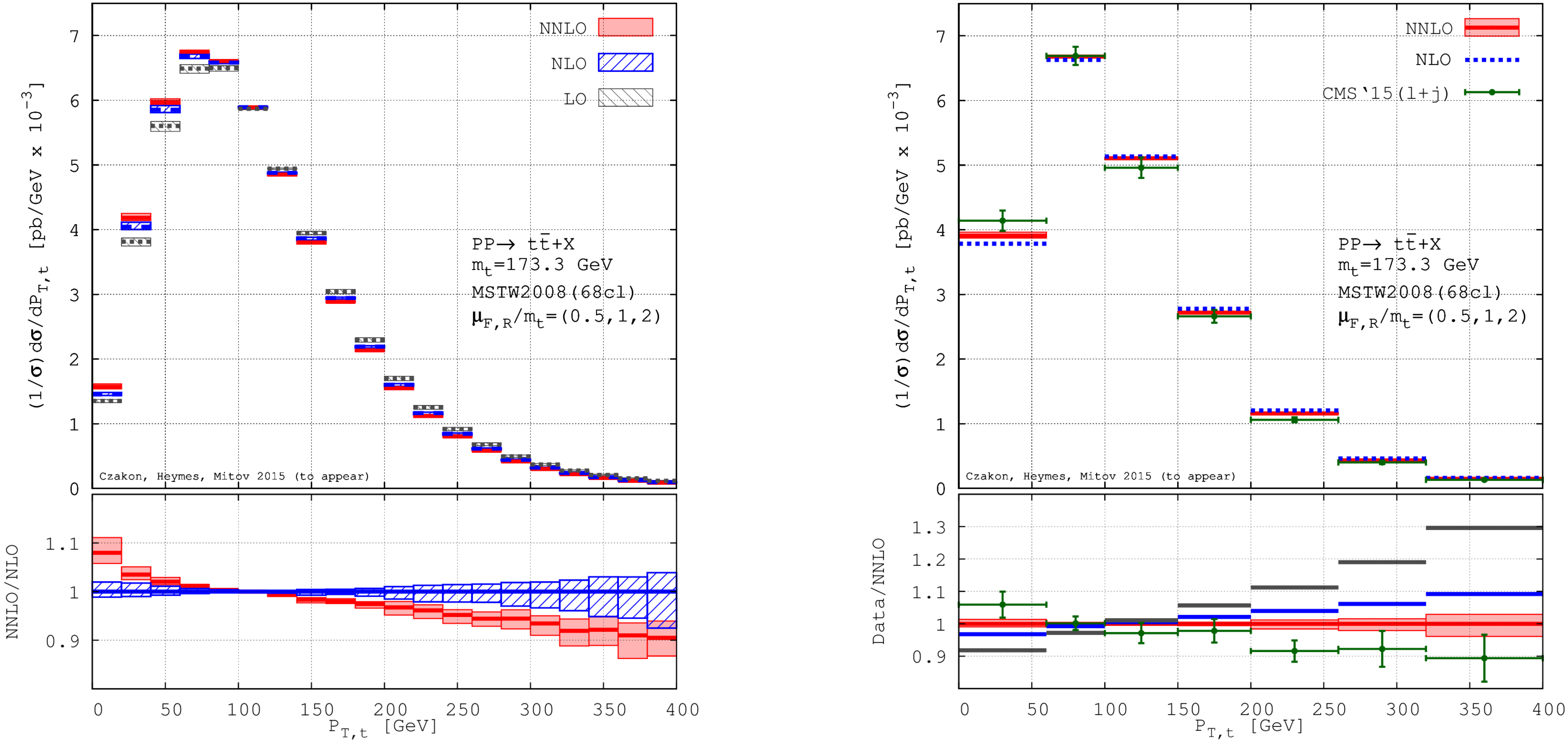
[Czakon, Fiedler, Heymes, Mitov.; in preperation]



Good perturbative convergence. Improved precision.

$t\bar{t}$ at NNLO : differential distributions

For the first time the issue of “a softer than NLO” p_T (top) has been seen in data can be studied. NNLO predictions seem to go in the direction of data.



[Czakon, Fiedler, Heymes, Mitov.; in preperation]

NNLO + PS

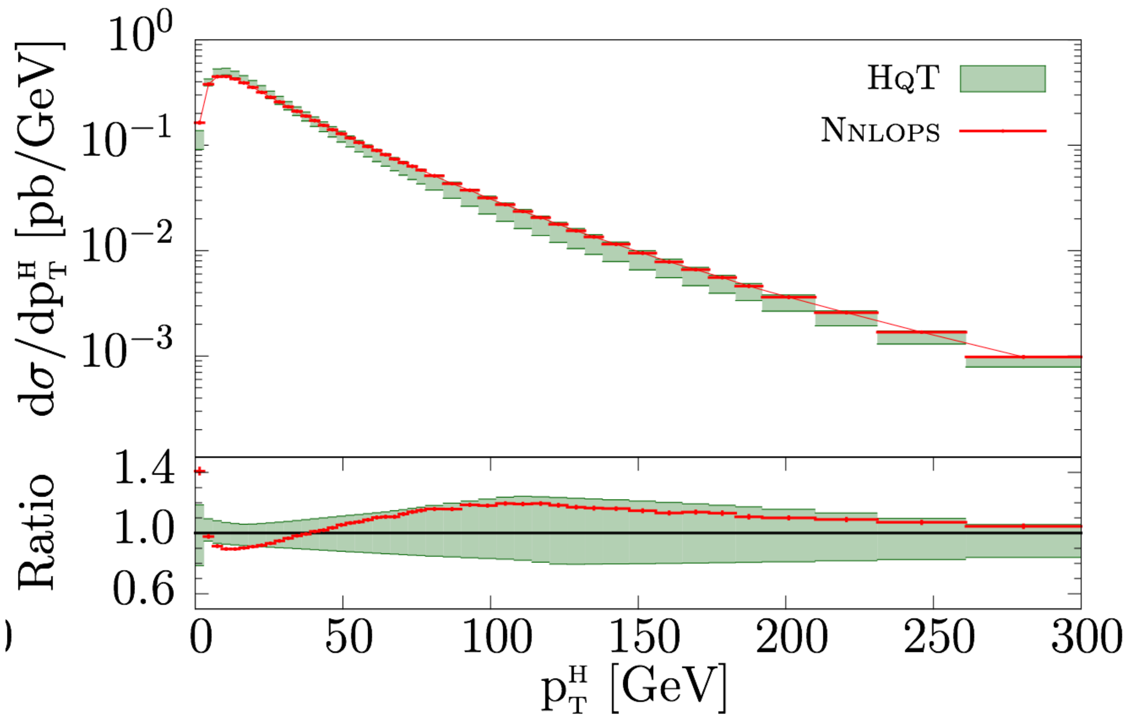
NLO matching well established, while NNLO matching still in its infancy

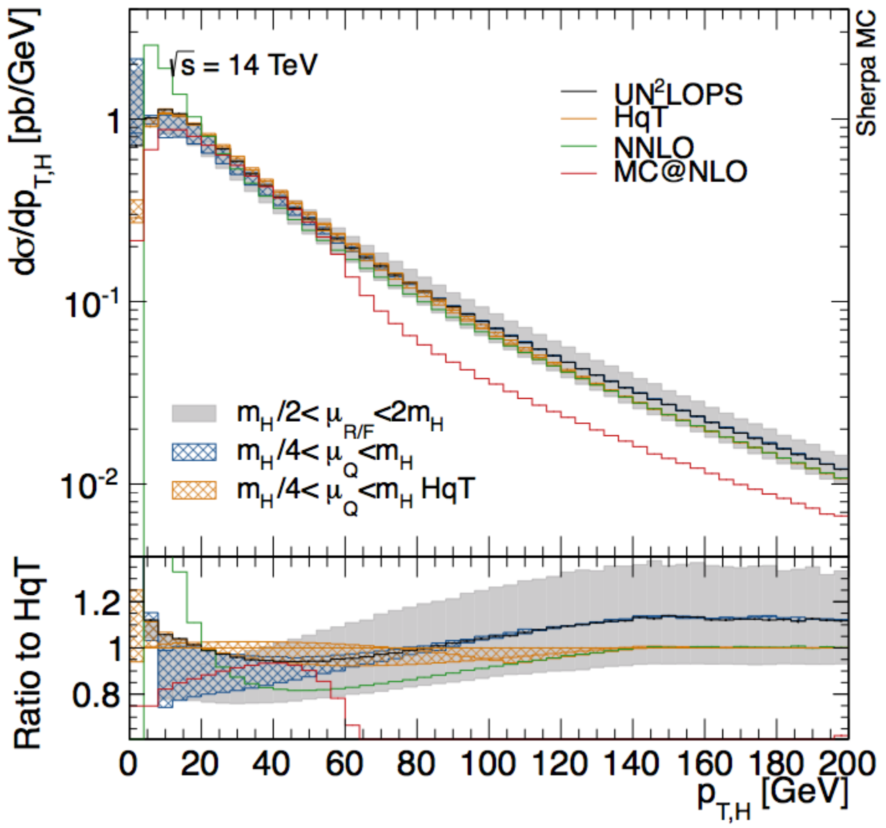
1) NNLOPS: use MINLO to obtain a NLO generator for both H and H+jet(s)

[K.Hamilton, P.Nason,G.Zanderighi (2014,2015)]

2) UN2LOPS: use S-MC@NLO + UNLOPS + q_T slicing

[N.Lavesson, L.Lonnblad (2008), S.Hoeche,Y.Li, S.Prestel (2014)]





Enforce correct NNLO normalisation by reweighing the inclusive rapidity distribution to the NNLO calculation

NNLO virtual corrections confined in the low pT region while in the POWHEG-MINLO approach they are spread over the whole pT region

The frontier: N3LO

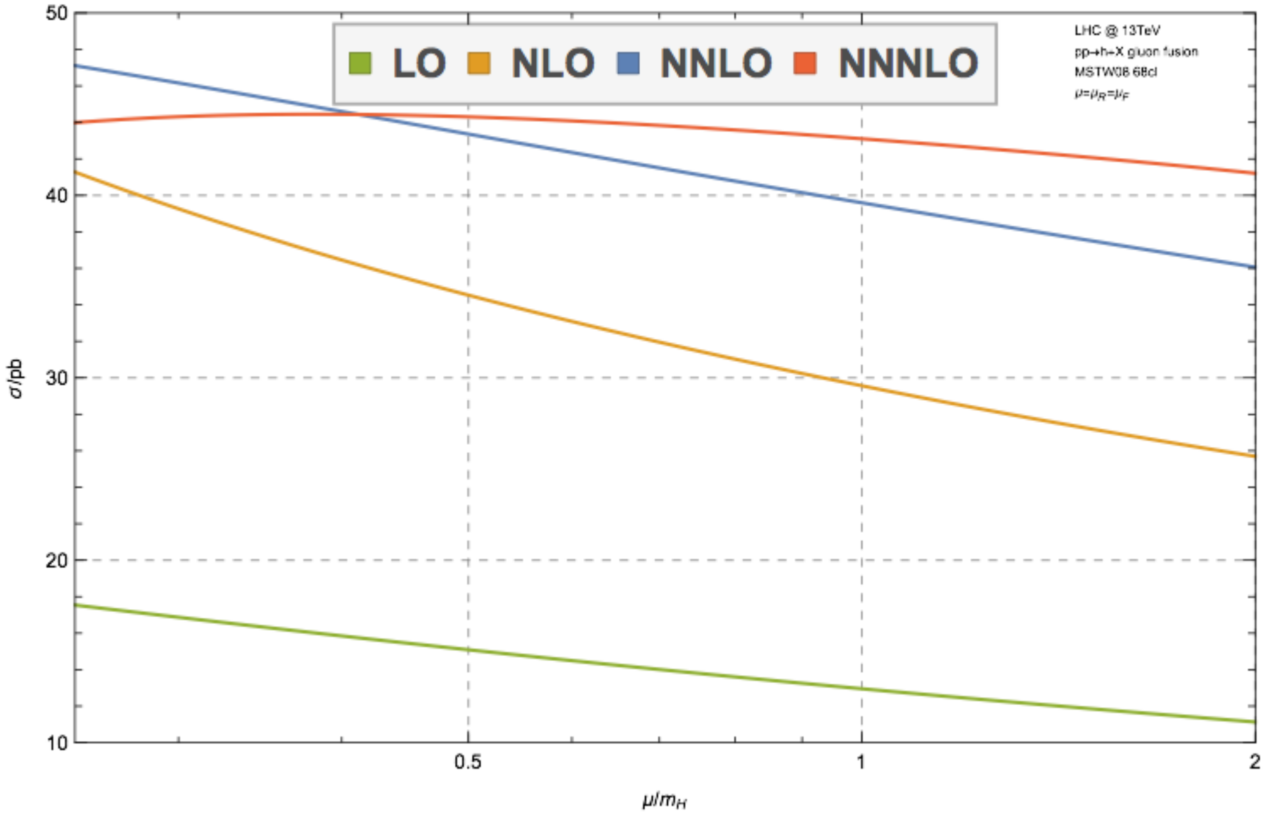
[C.Anastasiou, C.Duhr, F.Dulat, F.Herzog, B.Mistlberger (2015)]

Full calculation for the gg →H completed through the evaluation of 30 terms in the soft-expansion: first ever complete calculation at N3LO in hadronic collisions.

Significant reduction of uncertainties from missing higher orders and PDF+αs

Scale dep. stabilizes around $\mu=m_H/2$

N3LO effect +2.2% at $\mu=m_H/2$

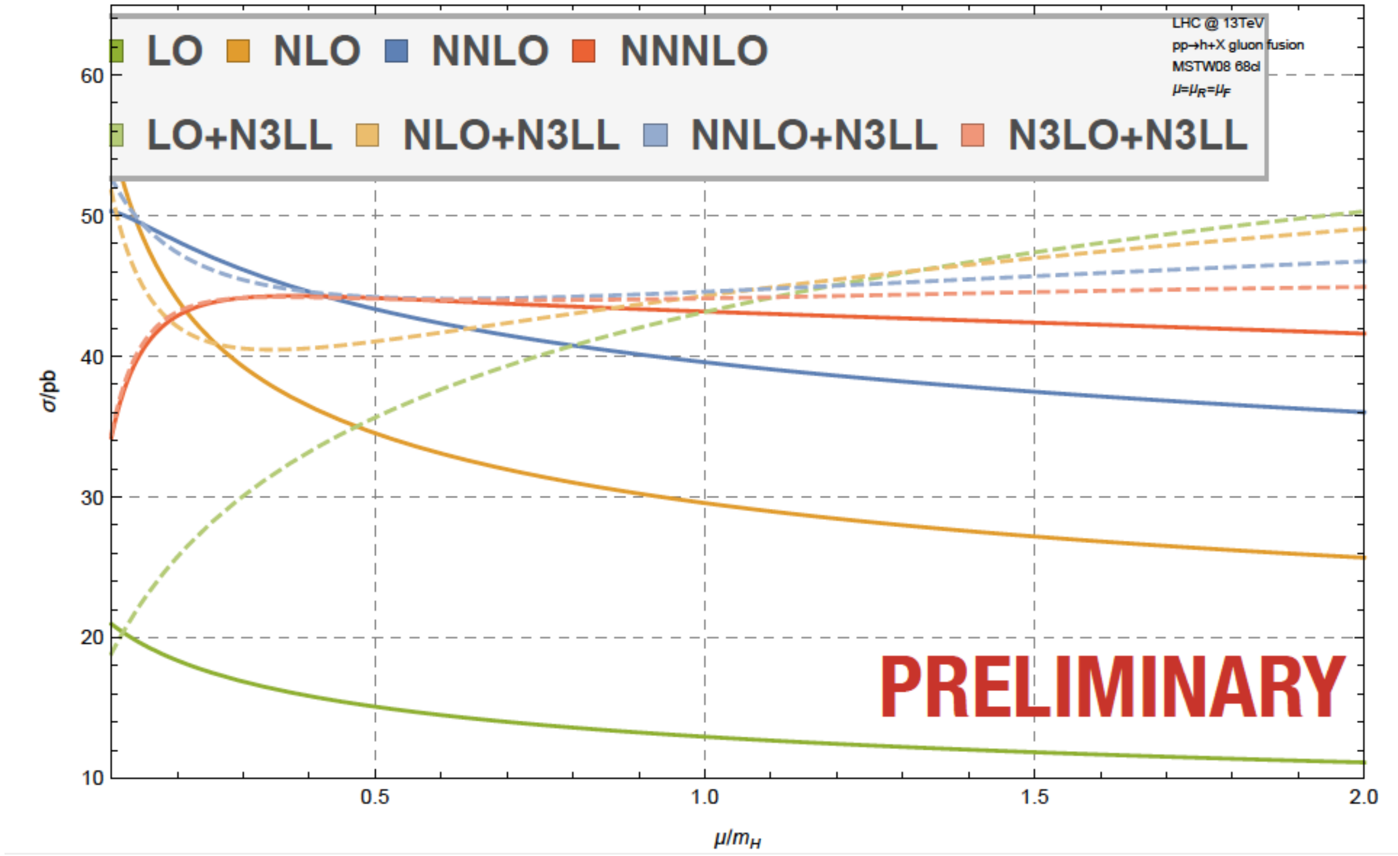


Corresponding new results for the Higgs cross section including mass effects at NLO and the other known corrections at 13 TeV expected soon.

The frontier: N3LO

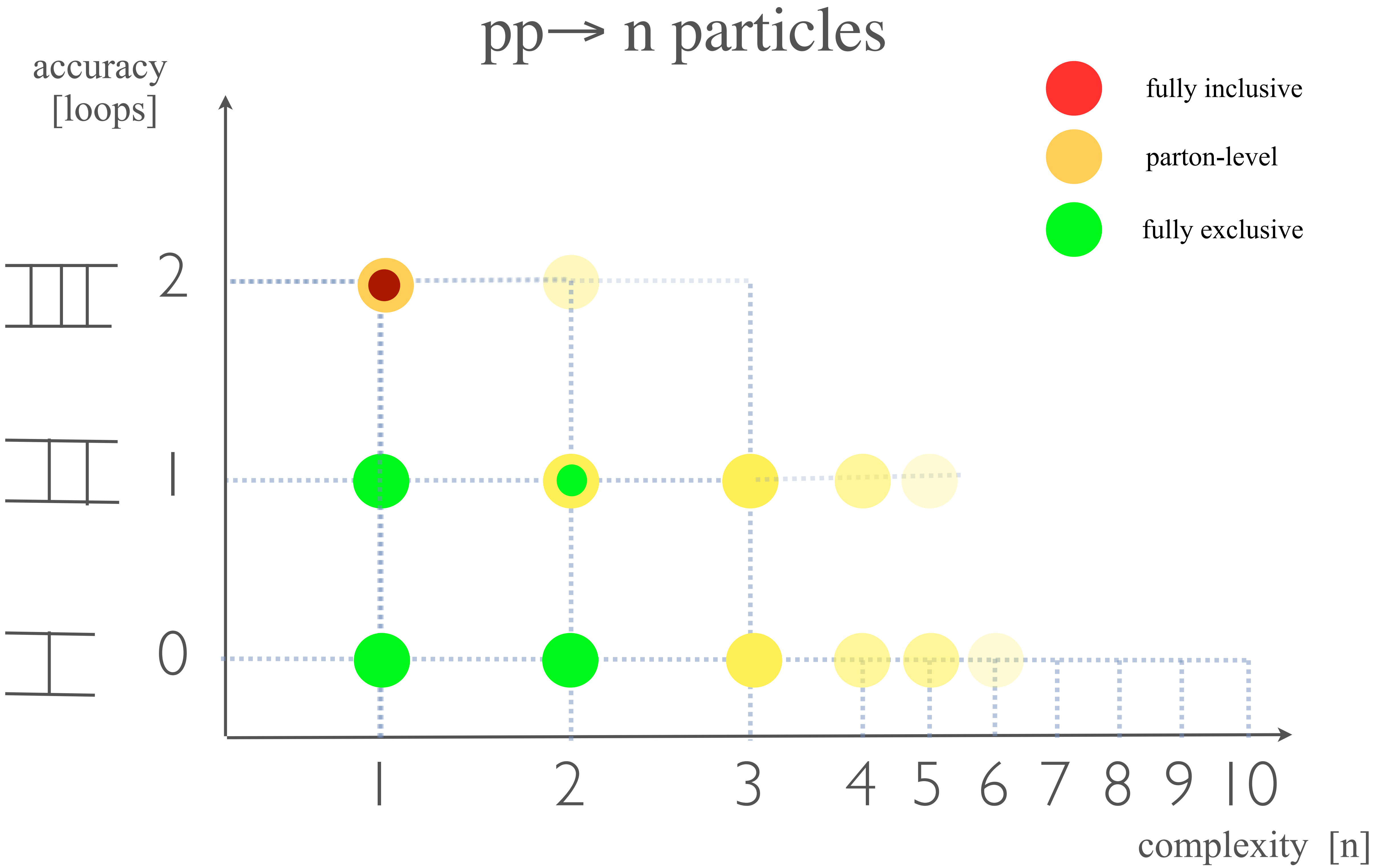
The best predictions for Higgs production include threshold resummation effects.

Results of systematically including the resummation of the threshold logs points towards a stabilisation of the scale dependence.



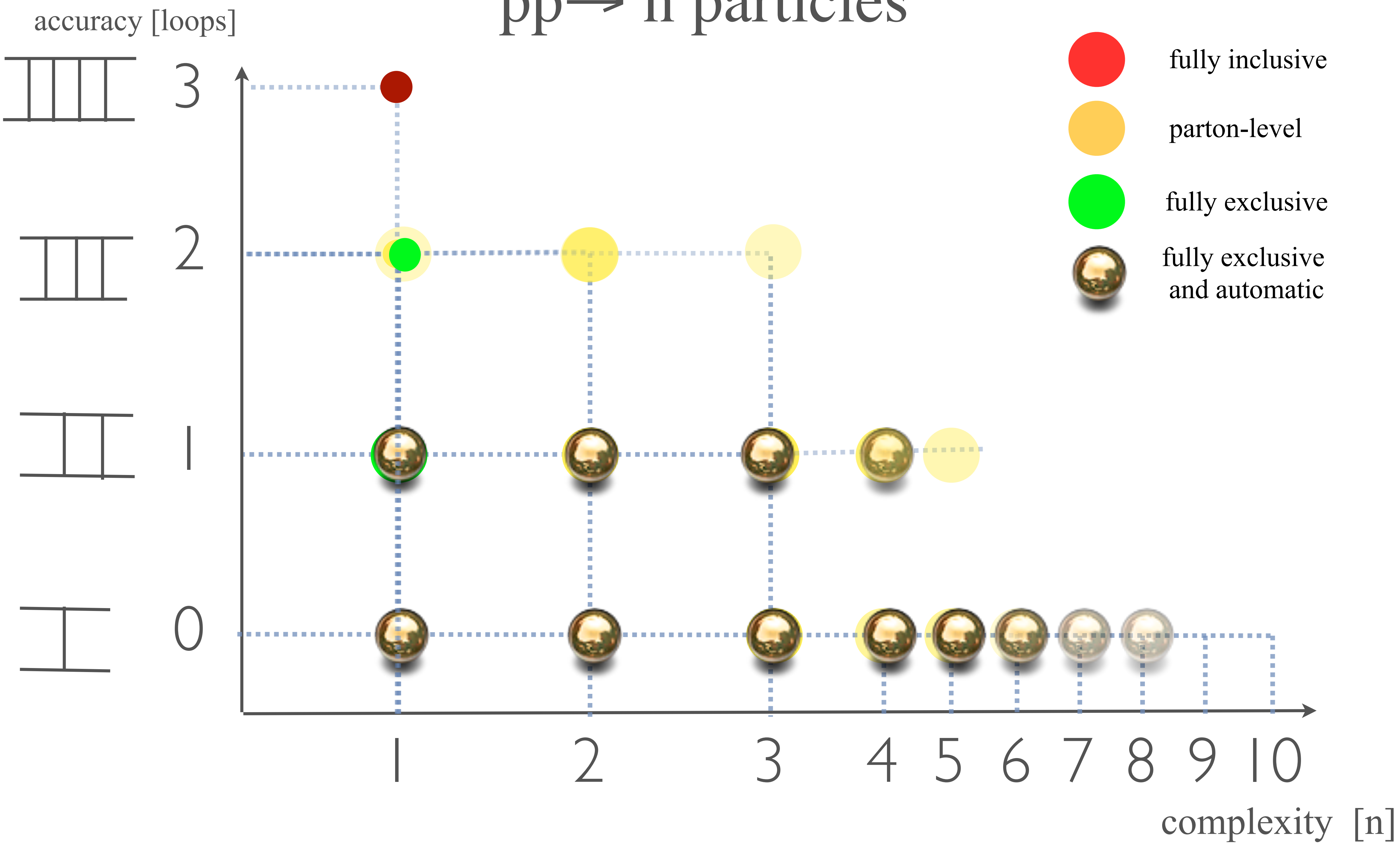
Such a flat behaviour puts into question the reliability of very method that we use to evaluate the effects of unknown higher-order contributions through scale variation.

Predictions in QCD: before the LHC



Predictions in QCD for the LHC: status 2015

pp→ n particles



Summary

- The LHC physics program demands predictions at an unprecedented level of accuracy and precision.
- Rapid and impressive progress in techniques in the last few years has lead to:
  - Full automation of the computation of NLO QCD corrections and their matching/merging with parton shower program: experimental grade predictions are now available for SM and BSM (resonant and in EFTs). Automatic NLO EW is being achieved now.
  - The new era of differential predictions at NNLO in QCD for a every-day increasing set of important SM processes 2→2, such as H+jet, V+jet, VV, t tbar production. In addition first exploration of NNLO+PS for 2→1 process has started.
  - Moving the frontier to N3LO.
- Main outcomes:
  - Progress in understanding of QCD and pp collisions at high Q^2
  - TH Ready for Run II LHC

Credits

A special thank to the italian TH QCD/MC at LHC community, currently working in Italy or **abroad,** great collaborators and precision passionates (rnd order):

Francesco Tramontano, **Michelangelo Mangano**, **Andrea Banfi**, Paolo Nason, **Marco Bonvini**, Giovanni Ridolfi, Stefano Frixione, **Giulia Zanderighi,** Stefano Catani, Carlo Oleari, **Giovanni Ossola,** Pierpaolo Mastrolia, Giancarlo Ferrera, **Emanuale Re**, Paolo Torrielli, **Roberto Pittau,** Stefano Forte, Alessandro Vicini, **Simone Alioli**, **Alberto Guffanti, Fabrizio Caola**, Gennaro Corcella**, Massimiliano Grazzini**, Fulvio Piccinini,**Matteo Cacciari**, **Maria Ubiali, Vittorio del Duca**, **Simone Marzani,** Stefano Forte, **Laura Reina**, **Marco Zaro, Davide Pagani, …**

Thanks to Massimiliano Grazzini for his great talk at EPS 2015, that was extensively used in this seminar.