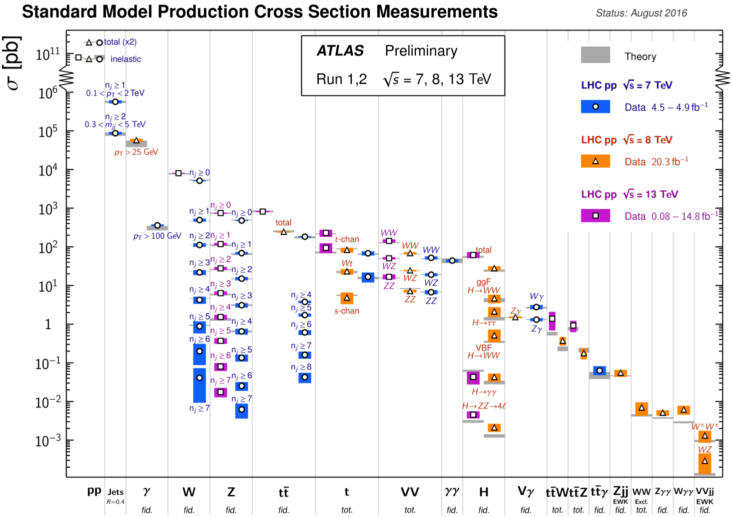
Event generators for the LHC: status and perspectives

Emanuele Re

`CERN & LAPTh Annecy`

LAL Orsay, 22 November 2016

LHC Run I & II, so far



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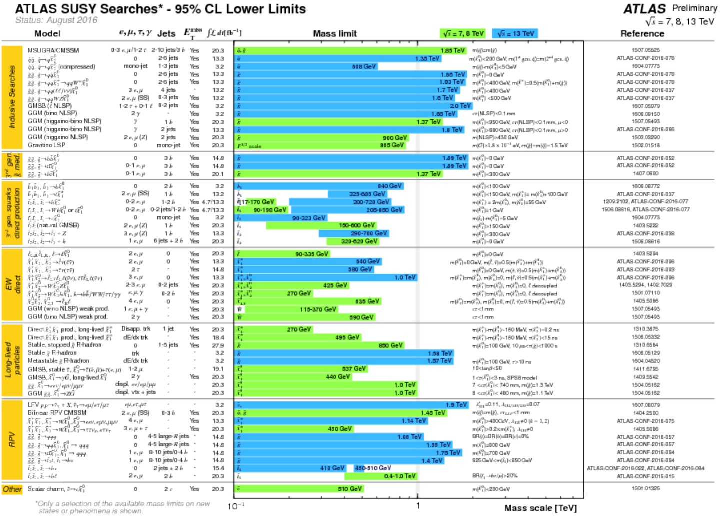


ATLAS SUSY Searches* - 95% CL Lower Limits

Status: August 2016

ATLAS Preliminary

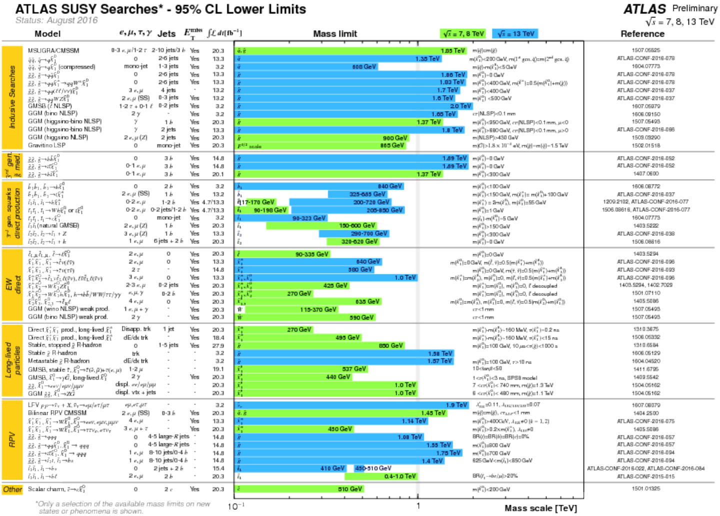
$\sqrt{s}$ = 7, 8, 13 TeV

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[fb^{-1}]$	Mass limit			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
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{q}$	1.35 TeV	$m(\tilde{\chi}^0_1)<200$ GeV, $m(1^{st}$ gen. $\tilde{q})=m(2^{nd}$ gen. $\tilde{q})$	ATLAS-CONF-2016-078
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$	608 GeV	$m(\tilde{q})-m(\tilde{\chi}^0_1)<5$ GeV	1604.07773
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$	1.86 TeV	$m(\tilde{\chi}^0_1)=0$ GeV	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	13.3	🟦 $\tilde{g}$	1.83 TeV	$m(\tilde{\chi}^0_1)<400$ GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}^0_1)+m(\tilde{g}))$	ATLAS-CONF-2016-078
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$	1.7 TeV	$m(\tilde{\chi}^0_1)<400$ GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}^0_1$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$	1.6 TeV	$m(\tilde{\chi}^0_1)$ <500 GeV	ATLAS-CONF-2016-037
	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	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$	1.37 TeV	$m(\tilde{\chi}^0_1)<950$ GeV, $c\tau$(NLSP)<0.1 mm, $\mu<0$	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$	1.8 TeV	$m(\tilde{\chi}^0_1)>680$ GeV, $c\tau$(NLSP)<0.1 mm, $\mu>0$	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$	900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale	865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})=1.5$ TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	14.8	🟦 $\tilde{g}$	1.89 TeV	$m(\tilde{\chi}^0_1)=0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	14.8	🟦 $\tilde{g}$	1.89 TeV	$m(\tilde{\chi}^0_1)=0$ GeV	ATLAS-CONF-2016-052
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$	1.37 TeV	$m(\tilde{\chi}^0_1)<300$ GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$	840 GeV	$m(\tilde{\chi}^0_1)<100$ GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$	325-685 GeV	$m(\tilde{\chi}^0_1)<150$ GeV, $m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_1)+100$ GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 117-170 GeV 🟦 200-720 GeV	$m(\tilde{\chi}^\pm_1)=2m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)=55$ GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	4.7/13.3	$\tilde{t}_1$	🟩 90-198 GeV 🟦 205-850 GeV	$m(\tilde{\chi}^0_1)=1$ GeV	1506.08616, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$	90-323 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}^0_1)=5$ GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$	150-600 GeV	$m(\tilde{\chi}^0_1)>150$ GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	13.3	🟦 $\tilde{t}_2$	290-700 GeV	$m(\tilde{\chi}^0_1)<300$ GeV	ATLAS-CONF-2016-038
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	🟩 $\tilde{t}_2$	320-620 GeV	$m(\tilde{\chi}^0_1)=0$ GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$	90-335 GeV	$m(\tilde{\chi}^0_1)=0$ GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$	640 GeV	$m(\tilde{\chi}^0_1)=0$ GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2016-096
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	🟦 $\tilde{\chi}^\pm_1$	580 GeV	$m(\tilde{\chi}^0_1)=0$ GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2016-093
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	1.0 TeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)=0$, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^\pm_1)+m(\tilde{\chi}^0_1))$	ATLAS-CONF-2016-096
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	425 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)=0$, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$	270 GeV	$m(\tilde{\chi}^\pm_1)=m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)=0$, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3, \tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$	635 GeV	$m(\tilde{\chi}^0_2)=m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)=0$, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}^0_2)+m(\tilde{\chi}^0_1))$	1405.5086
	GGM (wino NLSP) weak prod.	1 e,μ + γ	-	Yes	20.3	🟩 $\tilde{W}$	115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	🟩 $\tilde{W}$	590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$	270 GeV	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)\sim160$ MeV, $\tau(\tilde{\chi}^\pm_1)=0.2$ ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^\pm_1$	495 GeV	$m(\tilde{\chi}^\pm_1)-m(\tilde{\chi}^0_1)\sim160$ MeV, $\tau(\tilde{\chi}^\pm_1)<15$ ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$	850 GeV	$m(\tilde{\chi}^0_1)=100$ GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$	1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$	1.57 TeV	$m(\tilde{\chi}^0_1)=100$ GeV, $\tau>10$ ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$	440 GeV	1<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}^0_1$	1.0 TeV	7 <$c\tau(\tilde{\chi}^0_1)$< 740 mm, $m(\tilde{g})=1.3$ TeV	1504.05162
	GGM $\tilde{g}\tilde{g}, \tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}^0_1$	1.0 TeV	6 <$c\tau(\tilde{\chi}^0_1)$< 480 mm, $m(\tilde{g})=1.1$ TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$	1.9 TeV	$\lambda'_{311}=0.11$, $\lambda_{132/133/233}=0.07$	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$	1.45 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}<1$ mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$	1.14 TeV	$m(\tilde{\chi}^0_1)>400$GeV, $\lambda_{12k}\neq0$ $(k=1,2)$	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1, \tilde{\chi}^+_1\to W\tilde{\chi}^0_1, \tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 e,μ + τ	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$	450 GeV	$m(\tilde{\chi}^0_1)>0.2\times m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$	1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$	1.55 TeV	$m(\tilde{\chi}^0_1)=800$ GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}^0_1, \tilde{\chi}^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	14.8	🟦 $\tilde{g}$	1.75 TeV	$m(\tilde{\chi}^0_1)=700$ GeV	ATLAS-CONF-2016-094
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	14.8	🟦 $\tilde{g}$	1.4 TeV	625 GeV<$m(\tilde{t}_1)$<850 GeV	ATLAS-CONF-2016-094
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	🟦 $\tilde{t}_1$	410 GeV 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$	510 GeV	$m(\tilde{\chi}^0_1)<200$ GeV	1501.01325

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

LHC Run I & II, so far



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but LHC is a discovery machine

LHC Run I & II

- so far no sign of new Physics at the TeV scale from direct searches
- Higgs couplings have started to be measured: SM-like values, within 20-30 %
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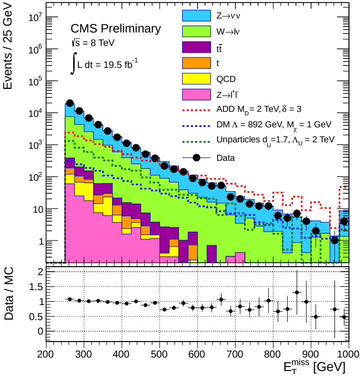

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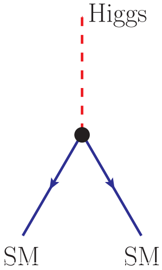

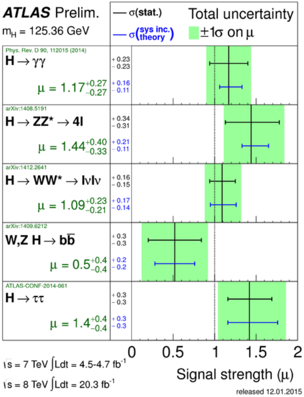

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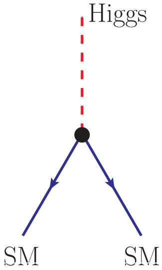

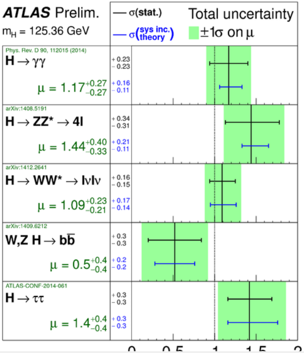

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important also in presence of new discovery

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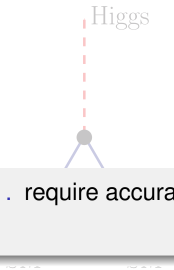

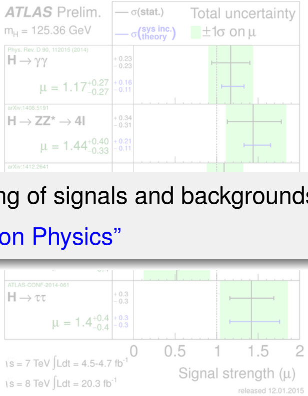

. require accurate understanding of signals and backgrounds:

☞ “precision Physics”

. accurate measurement of Higgs couplings

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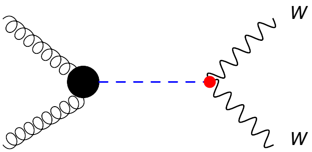
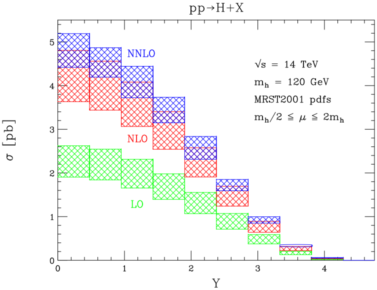
precise predictions and MC: an example

measuring the HWW coupling





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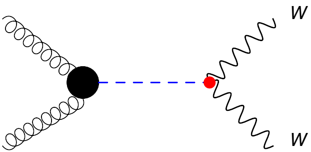

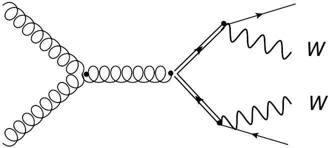

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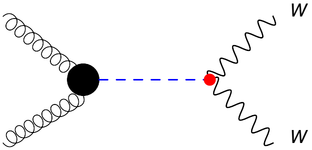

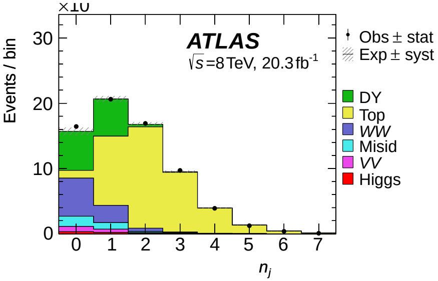

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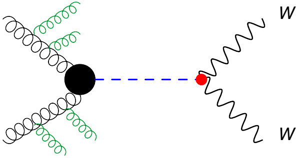

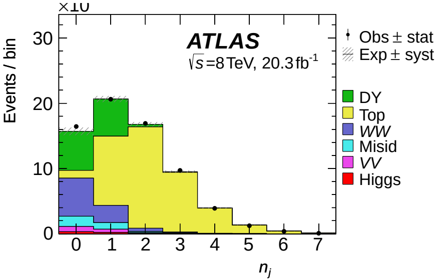

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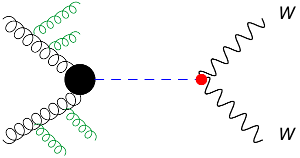

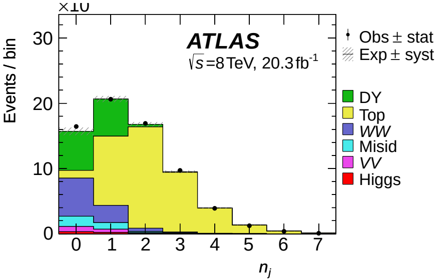

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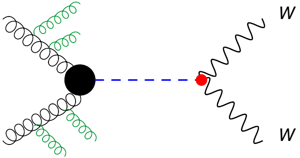
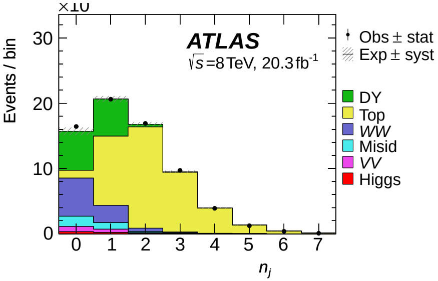
  - jet-binned cross sections: here jet veto at 25-30 GeV
  - widely separated scales: large logs arise, resummation often needed.

precise predictions and MC: an example

measuring the HWW coupling





- higher-order corrections:
  - relevant when they are large or if experimental precision is extremely high.
  - relevant also to have reliable theoretical uncertainties.
- S/B optimized using cuts/BDT
  - jet-binned cross sections: here jet veto at 25-30 GeV
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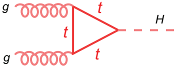
⇒ NLO+PS event generators include both effects and allow for flexible and fully differential simulations.

Event generators: what they are?

ideal world: high-energy collision and detection of elementary particles



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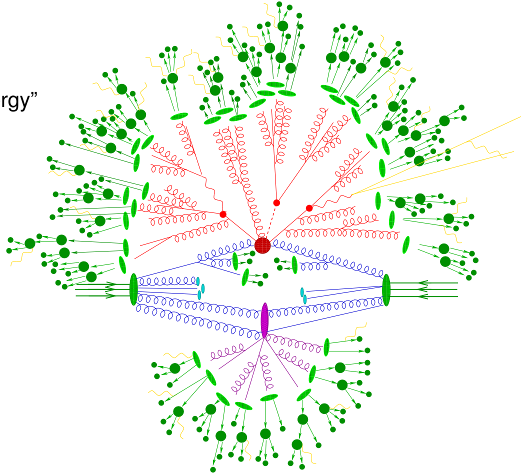
  - realistically
  - precisely
  - from first principles



[sherpa’s artistic view]

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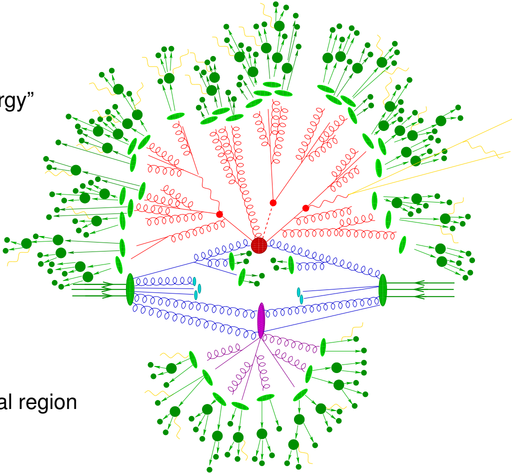
⇒ full event simulation needed to:
- compare theory and data
- estimate how backgrounds affect signal region
- test/build analysis techniques

soner or later, at some point a MC is used...



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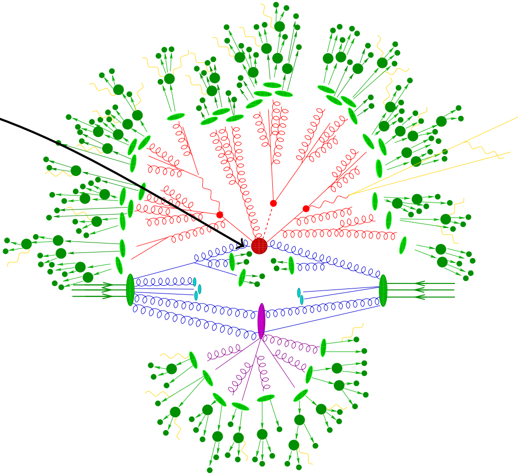

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hard scattering

$\Lambda_{\mathrm{QCD}} \ll \mu \approx Q$

- perturbation theory

parton shower

$\Lambda_{\mathrm{QCD}} < \mu < Q$

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- resummation of large logarithms

hadronisation

$\mu \approx \Lambda_{\mathrm{QCD}}$

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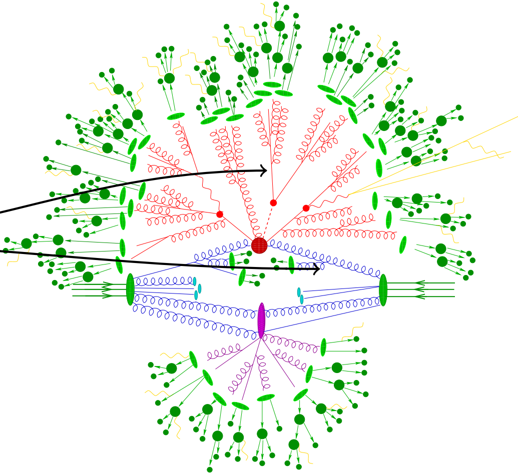

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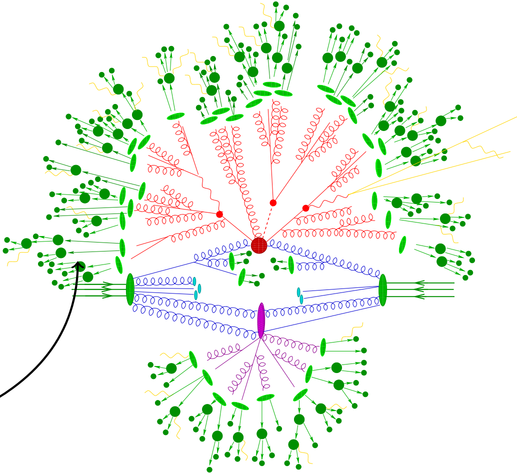


[sherpa's artistic view]

Event generators: what’s the output?

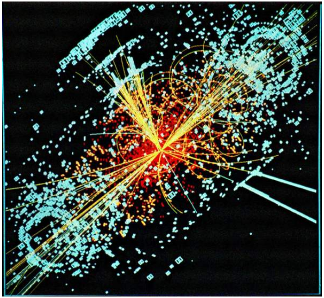
- in practice: momenta of all outgoing leptons and hadrons:

```
IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2   P-X     P-Y     P-Z  ENERGY

  31 NU_E           12   1  29  22   0   0   60.53   37.24-1185.0 1187.1
  32 E+            -11   1  30  22   0   0  -22.80    2.59 -232.4  233.6
 148 K+            321   1 109   9   0   0   -1.66    1.26    1.3    2.5
 151 PI0           111   1 111   9   0   0   -0.01    0.05   11.4   11.4
 152 PI+           211   1 111   9   0   0   -0.19   -0.13    2.0    2.0
 153 PI-          -211   1 112   9   0   0    0.84   -1.07 1626.0 1626.0
 154 K+            321   1 112   9   0   0    0.48   -0.63  945.7  945.7
 155 PI0           111   1 113   9   0   0   -0.37   -1.16   64.8   64.8
 156 PI-          -211   1 113   9   0   0   -0.20   -0.02    3.1    3.1
 158 PI0           111   1 114   9   0   0   -0.17   -0.11    0.2    0.3
 159 PI0           111   1 115  18   0   0    0.18   -0.74 -267.8  267.8
 160 PI-          -211   1 115  18   0   0   -0.21   -0.13 -259.4  259.4
 161 N            2112   1 116  23   0   0   -8.45  -27.55 -394.6  395.7
 162 NBAR        -2112   1 116  23   0   0   -2.49  -11.05 -154.0  154.4
 163 PI0           111   1 117  23   0   0   -0.45   -2.04  -26.6   26.6
 164 PI0           111   1 117  23   0   0    0.00   -3.70  -56.0   56.1
 167 K+            321   1 119  23   0   0   -0.40   -0.19   -8.1    8.1
 186 PBAR        -2212   1 130   9   0   0    0.10    0.17   -0.3    1.0
```

Plan of the talk

1. quickly review how these tools work
2. discuss how their accuracy can be improved
3. show “NNLO matched to parton showers” results (NNLOPS)



parton showers and fixed order

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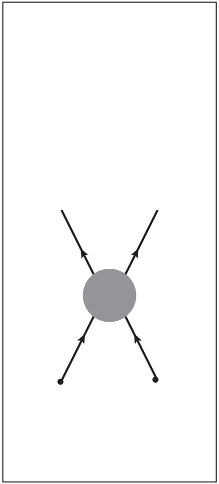

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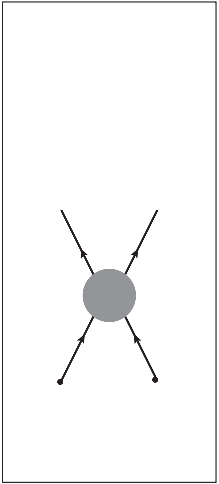

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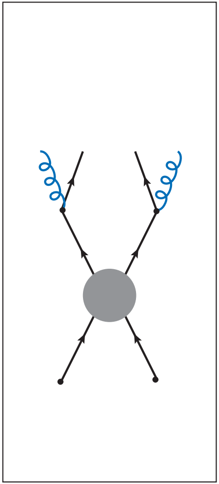

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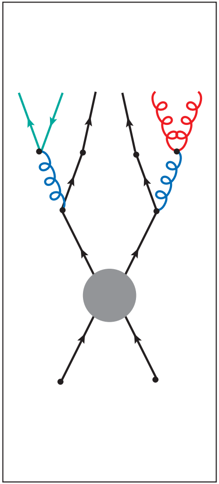

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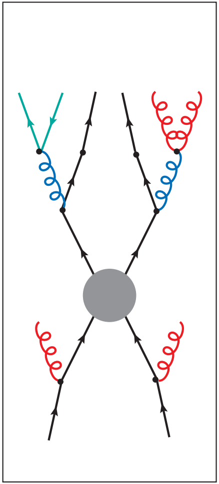

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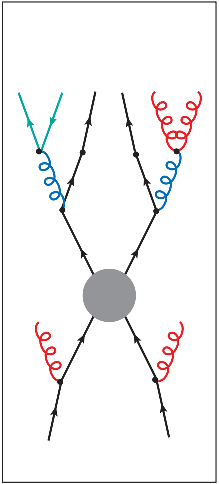
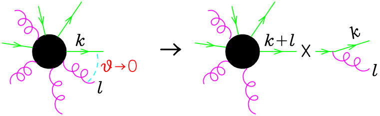
$$\frac{1}{(p_1+p_2)^2} = \frac{1}{2E_1E_2(1-\cos\theta)}$$

4. in soft-collinear limit, factorization properties of QCD amplitudes





$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \to |\mathcal{M}_n|^2 d\Phi_n \, \frac{\alpha_S}{2\pi}\frac{dt}{t} P_{q,qg}(z) dz \frac{d\varphi}{2\pi}$$

$z = k^0/(k^0+l^0)$	quark energy fraction
$t = \left\{(k+l)^2, l_T^2, E^2\theta^2\right\}$	splitting hardness
$P_{q,qg}(z) = C_F \frac{1+z^2}{1-z}$	AP splitting function

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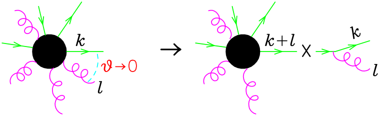

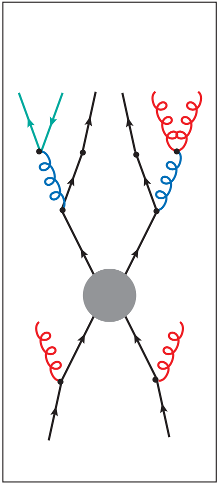

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probabilistic interpretation!

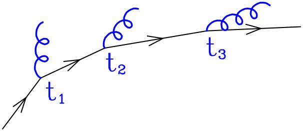
[notice: $\alpha_S L^2$]

Parton showers II

5. dominant contributions for multiparticle production due to strongly ordered emissions

$$t_1 > t_2 > t_3 \ldots$$

6. at any given order, we also have virtual corrections: include them with the same approximation



- LL virtual contributions: Sudakov form factor for each internal line:

$$\Delta_a(t_i, t_{i+1}) = \exp\left[-\sum_{(bc)} \int_{t_{i+1}}^{t_i} \frac{dt'}{t'} \int \frac{\alpha_s(t')}{2\pi} P_{a,bc}(z)\, dz\right]$$

- Δ_a corresponds to the probability of having no resolved emission between t_i and t_{i+1} off a line of flavour a

☞ resummation of collinear logarithms

[very soft/collinear emissions are suppressed - all order effect!]

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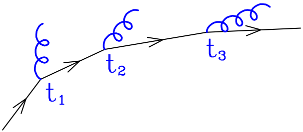

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- PS formulated probabilistically:
  - shapes change, but overall normalization fixed: it stays LO (*unitarity*)
  - they are only LO+LL accurate (whereas we want (N)NLO QCD corrections)

Next-to-Leading Order

$\alpha_S \sim 0.1 \Rightarrow$ to improve the accuracy, use exact perturbative expansion

$$d\sigma = d\sigma_{\text{LO}} + \left(\frac{\alpha_S}{2\pi}\right) d\sigma_{\text{NLO}} + \left(\frac{\alpha_S}{2\pi}\right)^2 d\sigma_{\text{NNLO}} + \ldots$$

LO: *Leading Order*
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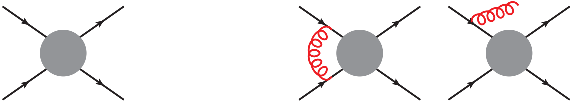

$$d\sigma = d\Phi_n \left\{ \underbrace{B(\Phi_n)}_{\text{LO}} + \frac{\alpha_s}{2\pi}\left[\underbrace{V(\Phi_n) + R(\Phi_{n+1})\, d\Phi_r}_{\text{NLO}}\right] \right\}$$

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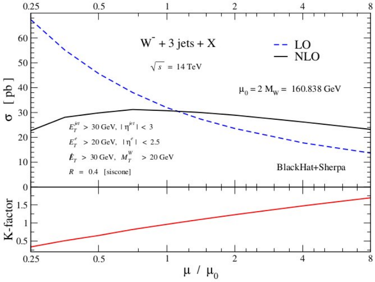
- first order where rates are reliable
- shapes are, in general, better described
- possible to attach sensible theoretical uncertainties [done typically by changing ren. and fac. scales]



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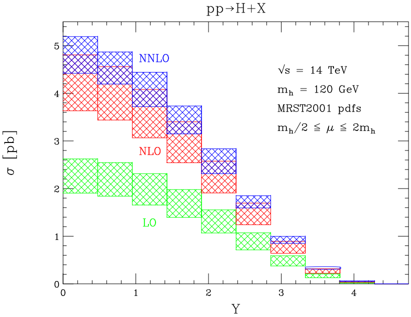
☞ When NNLO is needed?

- NLO corrections large
- very high-precision needed

$\Rightarrow$ Drell-Yan, Higgs, $t\bar{t}$ production



plot from [Anastasiou et al., '03]

PS vs. NLO

NLO

- ✓ precision
- ✓ nowadays this is the standard
- ✗ limited multiplicity
- ✗ (fail when resummation needed)

parton showers

- ✓ realistic + flexible tools
- ✓ widely used by experimental coll's
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Problem:

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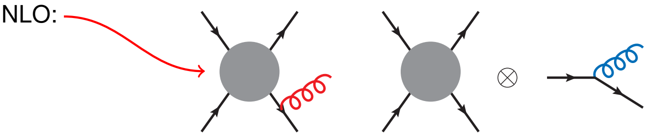

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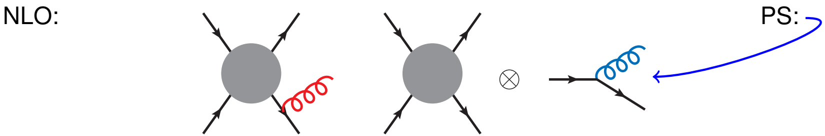

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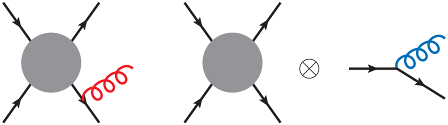


✓ many proposals, 2 well-established methods available to solve this problem: `MC@NLO` and `POWHEG` [Frixione-Webber '03, Nason '04]

matching NLO and PS

- POWHEG (POsitive Weight Hardest Emission Generator)

NLOPS: POWHEG I

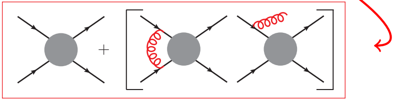
$$d\sigma_{\mathrm{LOPS}} = d\Phi_n \quad B(\Phi_n) \quad \left\{ \Delta(t_{\max}, t_0) + \Delta(t_{\max}, t) \frac{\alpha_s}{2\pi} \, \frac{1}{t} P(z) \, d\Phi_r \right\}$$

NLOPS: POWHEG I

$$d\sigma_{\rm POW} = d\Phi_n \quad \bar{B}(\Phi_n) \quad \left\{ \Delta(\Phi_n; k_{\rm T}^{\rm min}) + \Delta(\Phi_n; k_{\rm T}) \frac{\alpha_s}{2\pi} \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} \, d\Phi_r \right\}$$

NLOPS: POWHEG I

$$B(\Phi_n) \Rightarrow \bar{B}(\Phi_n) = B(\Phi_n) + \frac{\alpha_s}{2\pi}\left[V(\Phi_n) + \int R(\Phi_{n+1})\, d\Phi_r\right]$$



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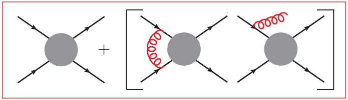

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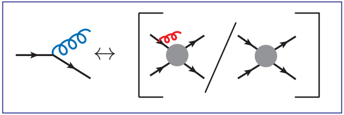

$$\Delta(t_\mathrm{m}, t) \Rightarrow \Delta(\Phi_n; k_\mathrm{T}) = \exp\left\{-\frac{\alpha_s}{2\pi}\int \frac{R(\Phi_n, \Phi_r')}{B(\Phi_n)}\theta(k_\mathrm{T}' - k_\mathrm{T})\, d\Phi_r'\right\}$$

NLOPS: POWHEG II

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[+ p_{T}-*vetoing subsequent emissions*, to avoid double-counting]

- inclusive observables: @NLO
- first hard emission: full tree level ME
- (N)LL resummation of collinear/soft logs
- extra jets in the shower approximation

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POWHEG BOX

[Alioli,Nason,Oleari,ER '10]

- large library of SM processes, (largely) automated
- used by LHC collaborations and other theorists
  [together with similar tools as `MG5_aMC@NLO`, `Herwig7` and `Sherpa`]
- lot achieved, but important developments still happening
  . for instance full $W^+W^-b\bar{b}$ @ NLOPS available only since few months [Jezo et al '16]

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- inclus
- first h
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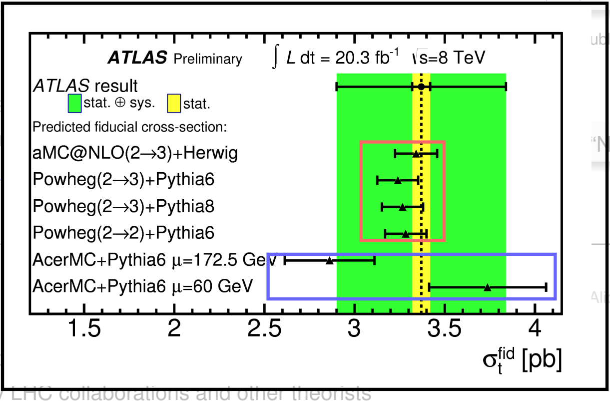
“NLOPS”

NLO+PS

LO+PS

Al li,Nason,Oleari,ER '10]



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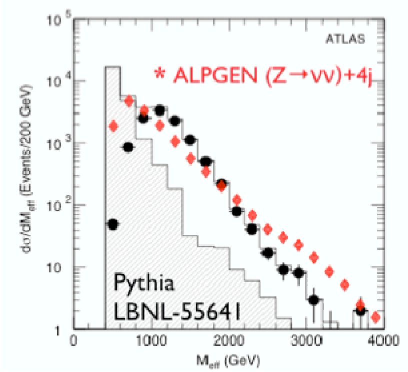
NLO+PS merging and NNLO+PS

NLOPS merging & BSM

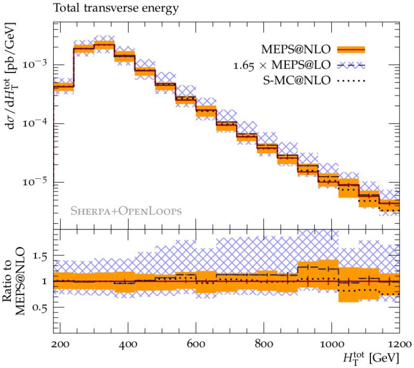
- ME+PS merging is particularly important to model "S+jets" processes, where:
  - S = hard system = $\{\ell,\nu,V,t\}$
  - jets are from QCD emissions (as opposed to jets from SUSY cascades)
- it becomes crucial to model kinematics regions characterized by variable number of jets:
  - cuts on $H_T = ... + \sum_{\text{all jets}} |\vec{p}_{T,j}|$ and/or tails of p_T distributions

LO+PS



plot from [Gianotti,Mangano 0504221]

NLO+PS merging



$t\bar{t}$+jets:Sherpa+OpenLoops [Hoeche,Krauss et al. 1402.6293]

NLOPS merging & BSM

- ME+PS merging is particularly important to model "S+jets" processes, where:

- it becomes crucial to model kinematics regions characterized by variable number of jets:

- rest of the talk: NLO+PS merging is at the core of all approaches aiming for NNLO+PS accuracy

NNLO+PS: why and where?

NLO(+PS) not always enough: NNLO needed when

1. large NLO/LO “K-factor”
   [as in Higgs Physics]

2. very high precision needed
   [e.g. Drell-Yan, top pairs]

- last couple of years:
  huge progress in NNLO

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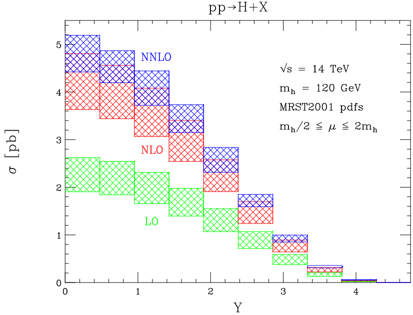

[Anastasiou et al., ’03]

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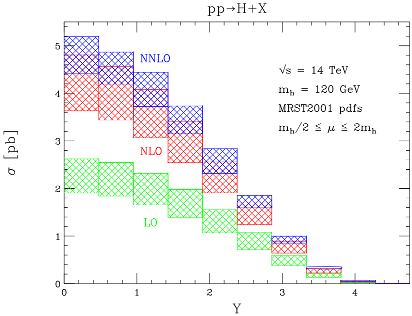

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Q: can we merge NNLO and PS?

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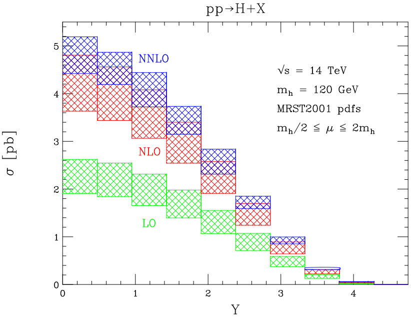

[Anastasiou et al., ’03]

Q: can we merge NNLO and PS?

☞ realistic event generation with state-of-the-art perturbative accuracy !
☞ important for precision studies for several processes

- ▶ method presented here: based on `POWHEG+MiNLO`, used so far for
  - Higgs production [Hamilton,Nason,ER,Zanderighi, 1309.0017]
  - neutral & charged Drell-Yan [Karlberg,ER,Zanderighi, 1407.2940]
  - associated WH production [Astill,Bizon,ER,Zanderighi, 1603.01620]

towards NNLO+PS

- what do we need and what do we already have?

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
H @ NLOPS	NLO	LO	shower
HJ @ NLOPS	/	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

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☞ a merged H-HJ@NLOPS generator is “almost” OK

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- many of the multijet NLO+PS merging approaches work by combining 2 (or more) NLO+PS generators, introducing a merging scale (except `Geneva`)*
- `POWHEG` + `MiNLO` [Multiscale Improved NLO]. [Hamilton et al. ’12]

  No need of merging scale: it extends the validity of a NLO+PS computation with jets in the final state to phase-space regions where jets become unresolved

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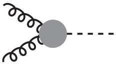
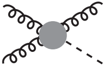
* [Hoeche,Krauss, et al.,1207.5030] [Frederix,Frixione,1209.6215] [Lonnblad,Prestel,1211.7278] [Platzer,1211.5467] [Alioli,Bauer, et al.,1211.7049] ...

POWHEG → MiNLO → NNLO+PS

Higgs at NNLO:



loops: 0 1 2



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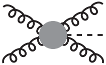

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POWHEG → MiNLO → NNLO+PS

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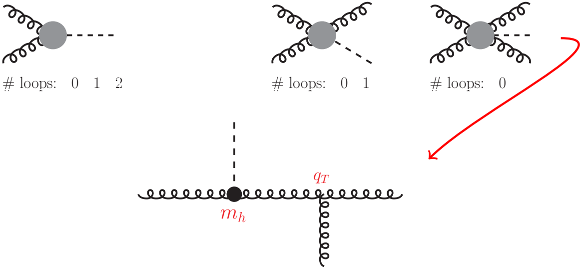
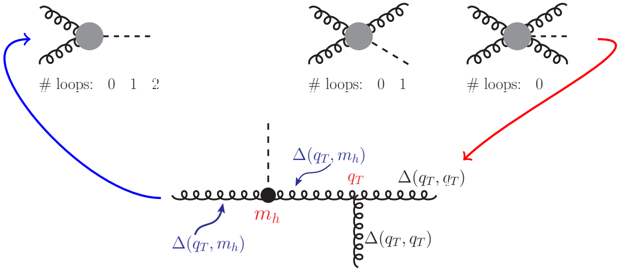


(a) 1 and 2 jets: POWHEG H+1j

POWHEG → MiNLO → NNLO+PS

Higgs at NNLO:



(b) - integrate down to $q_T = 0$ with MiNLO
- "Improved MiNLO" allows to build a H-HJ @ NLOPS generator

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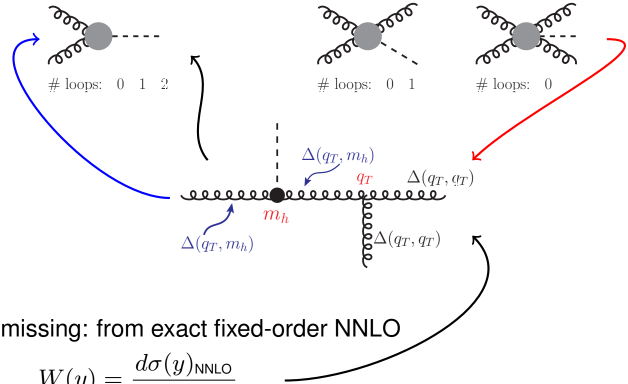

(c) 2 loops missing: from exact fixed-order NNLO

$$W(y) = \frac{d\sigma(y)_{\text{NNLO}}}{d\sigma(y)_{\text{MiNLO}}}$$

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MiNLO (Multiscale Improved NLO)

[Hamilton,Nason,Zanderighi, 1206.3572]

- original goal: method to a-priori choose scales in multijet NLO computation
- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)

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- how: correct weights of different NLO terms with CKKW-inspired approach (without spoiling formal NLO accuracy)
  - for each point sampled, build the “more-likely” shower history that would have produced that kinematics (can be done by clustering kinematics with k_T-algo, then, by undoing the clustering, build “skeleton”)
  - “correct” original NLO à la CKKW:

    $\rightarrow$ α_{S} evaluated at nodal scales

    $\rightarrow$ Sudakov FFs

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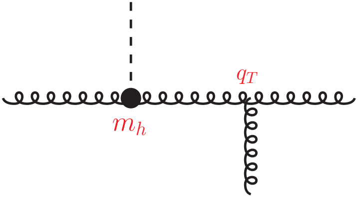
$$\bar{B}_{\mathrm{NLO}} = \alpha_{\mathrm{S}}^{3}(\mu_R)\Big[B + \alpha_{\mathrm{S}} V(\mu_R) + \alpha_{\mathrm{S}} \int d\Phi_{\mathrm{r}} R\Big]$$



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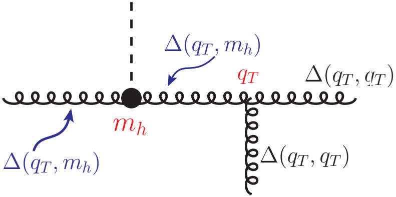
$$\bar{B}_{\mathrm{MiNLO}} = \alpha_{\mathrm{S}}^2(m_h)\alpha_{\mathrm{S}}(q_T)\Delta_g^2(q_T, m_h)\Big[B\left(1 - 2\Delta_g^{(1)}(q_T, m_h)\right) + \alpha_{\mathrm{S}}\, V(\bar{\mu}_R) + \alpha_{\mathrm{S}} \int d\Phi_{\mathrm{r}} R\Big]$$



- $\bar{\mu}_R = (m_h^2 q_T)^{1/3}$
- $\log \Delta_{\mathrm{f}}(q_T, m_h) = -\int_{q_T^2}^{m_h^2} \frac{dq^2}{q^2} \frac{\alpha_{\mathrm{S}}(q^2)}{2\pi}\Big[A_f \log \frac{m_h^2}{q^2} + B_f\Big]$
- $\Delta_{\mathrm{f}}^{(1)}(q_T, m_h) = -\frac{\alpha_{\mathrm{S}}}{2\pi}\Big[\frac{1}{2} A_{1,\mathrm{f}} \log^2 \frac{m_h^2}{q_T^2} + B_{1,\mathrm{f}} \log \frac{m_h^2}{q_T^2}\Big]$
- $\mu_F = q_T$

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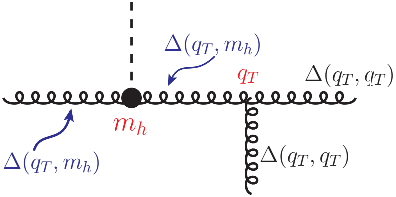

☞ Sudakov FF included on $H+j$ Born kinematics

- `MiNLO`-improved HJ yields finite results also when 1st jet is unresolved ($q_T \to 0$)
- $\bar{B}_{\rm MiNLO}$ ideal to extend validity of `HJ-POWHEG` [called "`HJ-MiNLO`" hereafter]

“Improved” MiNLO & NLOPS merging

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- formal accuracy of `HJ-MiNLO` for inclusive observables carefully investigated

  [Hamilton et al., 1212.4504]
- `HJ-MiNLO` describes inclusive observables at order α_{S}
- to reach genuine NLO when fully inclusive (NLO$^{(0)}$), “spurious” terms must be of relative order α_{S}^2, *i.e.*

$$O_{\mathrm{HJ-MiNLO}} = O_{\mathrm{H@NLO}} + \mathcal{O}(\alpha_{\mathrm{S}}^{2+2}) \qquad \text{if } O \text{ is inclusive}$$

- “Original `MiNLO`” contains ambiguous “$\mathcal{O}(\alpha_{\mathrm{S}}^{2+1.5})$” terms

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- Possible to improve `HJ-MiNLO` such that inclusive NLO is recovered (NLO$^{(0)}$), without spoiling NLO accuracy of H+j (NLO$^{(1)}$).
- accurate control of subleading small-p_T logarithms is needed (scaling in low-p_T region is $\alpha_S L^2 \sim 1$, *i.e.* $L \sim 1/\sqrt{\alpha_S}$!)

Effectively as if we merged NLO$^{(0)}$ and NLO$^{(1)}$ samples, without merging different samples (no merging scale used: there is just one sample).

“Improved” MiNLO & NLOPS merging: details

- Resumption formula can be written as

$$\frac{d\sigma}{dq_T^2 dy} = \sigma_0 \frac{d}{dq_T^2}\left\{[C_{ga}\otimes f_a](x_A,q_T)\times[C_{gb}\otimes f_b](x_B,q_T)\times \exp S(q_T,Q)\right\} + R_f$$

$$S(q_T,Q) = -2\int_{q_T^2}^{Q^2}\frac{dq^2}{q^2}\frac{\alpha_S(q^2)}{2\pi}\left[A_f\log\frac{Q^2}{q^2}+B_f\right]$$

- If $C_{ij}^{(1)}$ included and R_f is LO$^{(1)}$, then upon integration we get NLO$^{(0)}$
- `MiNLO` formula is not written as a total derivative: “expand” the above expression, then compare with `MiNLO` :

$$\sim \sigma_0\frac{1}{q_T^2}[\alpha_S, \boxed{\alpha_S^2}, \alpha_S^3, \alpha_S^4, \alpha_S L, \alpha_S^2 L, \alpha_S^3 L, \alpha_S^4 L]\exp S(q_T,Q) + R_f \qquad L=\log(Q^2/q_T^2)$$

- highlighted terms are needed to reach NLO$^{(0)}$:

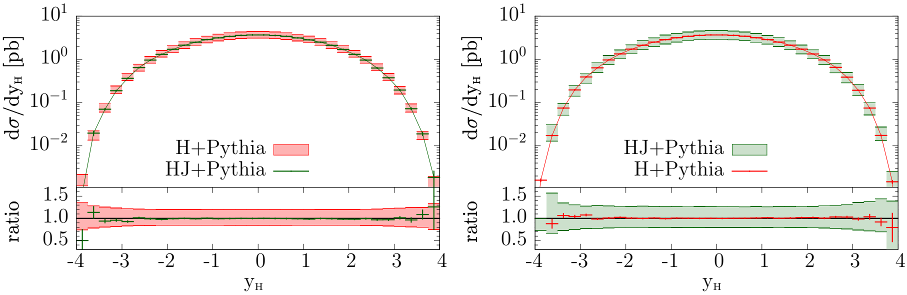
$$\int^{Q^2}\frac{dq_T^2}{q_T^2}L^m {\alpha_S}^n(q_T)\exp S \sim \left(\alpha_S(Q^2)\right)^{n-(m+1)/2}$$

(scaling in low-p_T region is $\alpha_S L^2 \sim 1$!)

- if I don’t include B_2 in `MiNLO` Δ_g, I miss a term $(1/q_T^2)\ \boxed{\alpha_S^2}\ B_2\exp S$
- upon integration, violate NLO$^{(0)}$ by a term of relative $\mathcal{O}(\alpha_S^{3/2})$

MiNLO merging: results

[Hamilton et al., 1212.4504]



- "H+Pythia": standalone `POWHEG` $(gg \to H)$ + `PYTHIA` (PS level) [7pts band, $\mu = m_H$]
- "HJ+Pythia": `HJ-MiNLO`* + `PYTHIA` (PS level) [7pts band, μ from `MiNLO`]

- very good agreement (both value and band) [✓]

☞ Notice: band is $\sim 20 - 30\%$

Higgs at NNLO+PS: details

- `HJ−MiNLO+POWHEG` generator gives H-HJ @ NLOPS

	H (inclusive)	H+j (inclusive)	H+2j (inclusive)
✓ H-HJ @ NLOPS	NLO	NLO	LO
H @ NNLOPS	NNLO	NLO	LO

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- reweighting (differential on Φ_B) of “`MiNLO`-generated” events:

$$W(\Phi_B) = \frac{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{NNLO}}}{\left(\frac{d\sigma}{d\Phi_B}\right)_{\mathrm{HJ-MiNLO*}}}$$

  - by construction NNLO accuracy on fully inclusive observables $(\sigma_{\mathrm{tot}}, y_H; m_{\ell\ell}, ...)$ [✓]
  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn't spoil the NLO accuracy of `HJ−MiNLO` in 1-jet region [ ]

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  - to reach NNLOPS accuracy, need to be sure that the reweighting doesn’t spoil the NLO accuracy of `HJ−MiNLO` in 1-jet region [✓]
  - notice: formally works because no spurious $\mathcal{O}(\alpha_S^{2+1.5})$ terms in H-HJ @ NLOPS

Higgs at NNLO+PS: details II

- Variants for reweighting ($W(y_H)$, $W(\Phi_B)$) are also possible:

$$W(y,p_T)=h(p_T)\frac{\int d\sigma_A^{\rm NNLO}\delta(y-y(\mathbf{\Phi}))}{\int d\sigma_A^{\rm MiNLO}\delta(y-y(\mathbf{\Phi}))}+(1-h(p_T))$$

$$d\sigma_A=d\sigma\; h(p_T),\qquad d\sigma_B=d\sigma\;(1-h(p_T)),\qquad h=\frac{(\beta m_H)^2}{(\beta m_H)^2+p_T^2}$$

- freedom to distribute "NNLO/NLO K-factor" only over medium-small p_T region
  - $h(p_T)$ controls where the NNLO/NLO K-factor is distributed
    (in the high-p_T region, there is no improvement in including it)
  - β cannot be too small, otherwise resummation spoiled:
    for Higgs, chosen $\beta=1/2$; for DY, $\beta=1$

- in practice, we used

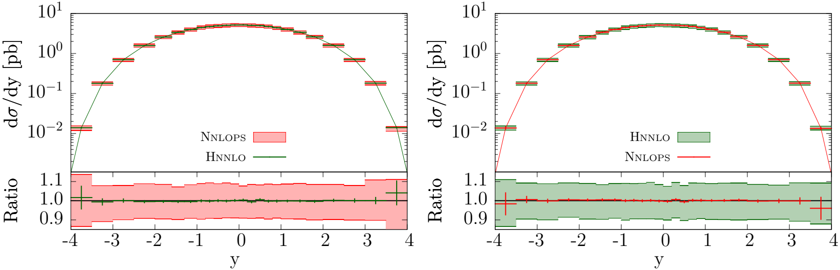
$$W(y,p_T)=h(p_T)\frac{\int d\sigma^{\rm NNLO}\delta(y-y(\mathbf{\Phi}))-\int d\sigma_B^{\rm MiNLO}\delta(y-y(\mathbf{\Phi}))}{\int d\sigma_A^{\rm MiNLO}\delta(y-y(\mathbf{\Phi}))}+(1-h(p_T))$$

- one gets exactly $(d\sigma/dy)_{\rm NNLOPS}=(d\sigma/dy)_{\rm NNLO}$ (no α_S^5 terms)
- chosen $h(p_T^{j_1})$

H@NNLOPS (fully incl.)

To reweight, use y_H

- NNLO with $\mu = m_H/2$, `HJ-MiNLO` "core scale" m_H [NNLO from HNNLO, Catani,Grazzini]
- $(7_{\rm Mi} \times 3_{\rm NN})$ pts scale var. in `NNLOPS`, 7pts in NNLO

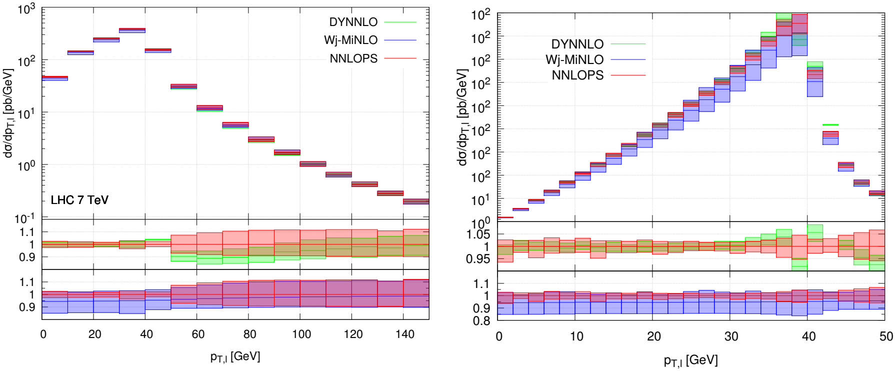


☞ Notice: band is 10% (at NLO would be $\sim$ 20-30%) [✓]

[Until and including $\mathcal{O}(\alpha_S^4)$, PS effects don't affect y_H (first 2 emissions controlled properly at $\mathcal{O}(\alpha_S^4)$ by MiNLO+POWHEG)]

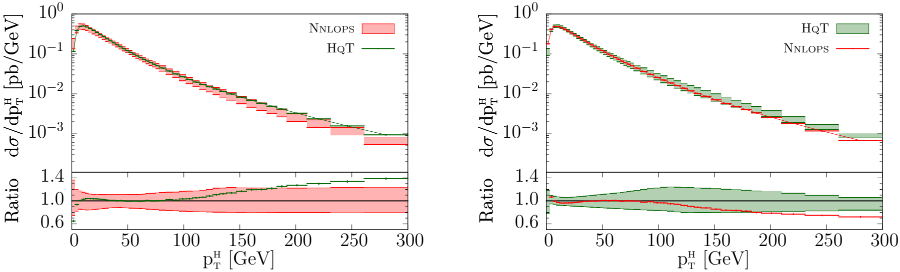
W@NNLOPS, PS level

To reweight, use $(y_{\ell\ell}, m_{\ell\ell}, \cos\theta_\ell)$



- not the observables we are using to do the NNLO reweighting
  - observe exactly what we expect: $p_{T,\ell}$ has NNLO uncertainty if $p_T < M_W/2$, NLO if $p_T > M_W/2$
  - smooth behaviour when close to Jacobian peak (also with small bins) (due to resummation of logs at small $p_{T,V}$)
- just above peak, `DYNNLO` uses $\mu = M_W$, `WJ-MiNLO` uses $\mu = p_{T,W}$
  - here $0 \lesssim p_{T,W} \lesssim M_W$ (so resummation region does contribute)

H@NNLOPS (p_T^H)



- HqT: NNLL+NNLO, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$ [HqT, Bozzi et al.]

✓ uncertainty bands of HqT contain NNLOPS at low-/moderate p_T

- very good agreement with HqT resummation at low p_T ["∼ expected", since $Q_{\rm res} \equiv m_H/2$, and $\beta = 1/2$]

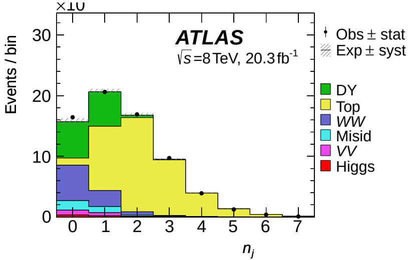
- HqT tail harder than NNLOPS tail

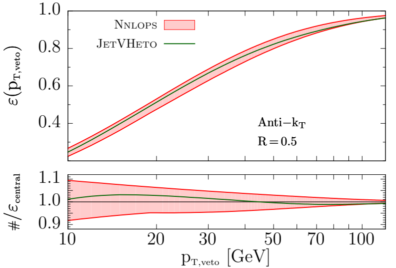
  \- understood: $\mu_{\rm HqT} < "\mu_{\rm MiNLO}"$

H@NNLOPS ($p_T^{j_1}$)

☞ Separation of $H \to WW$ from $t\bar{t}$ bkg: x-sec binned in $N_{\rm jet}$

0-jet bin ⇔ jet-veto accurate predictions needed !





$$\varepsilon\left(p_{\rm T,veto}\right) = \frac{\Sigma(p_{\rm T,veto})}{\sigma^{\rm tot}} = \frac{1}{\sigma^{\rm tot}} \int d\sigma\ \theta\left(p_{\rm T,veto} - p_{\rm T}^{\rm j_1}\right)$$

- `JetVHeto`: NNLL resum, $\mu_R = \mu_F = m_H/2$ [7pts], $Q_{\rm res} \equiv m_H/2$, (a)-scheme only

  [`JetVHeto`, Banfi et al.]

- nice agreement, differences never more than 5-6 %

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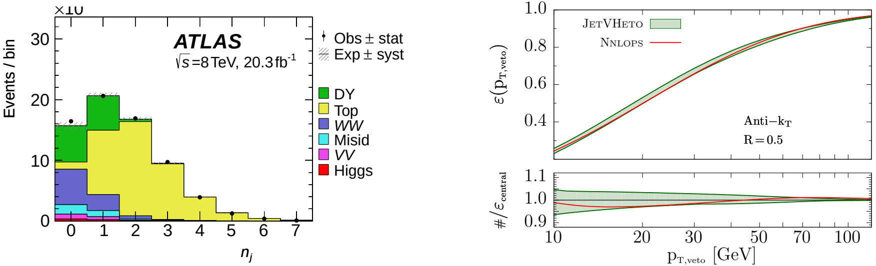

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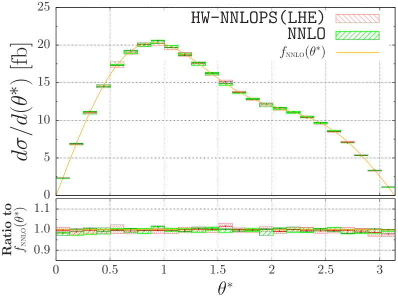
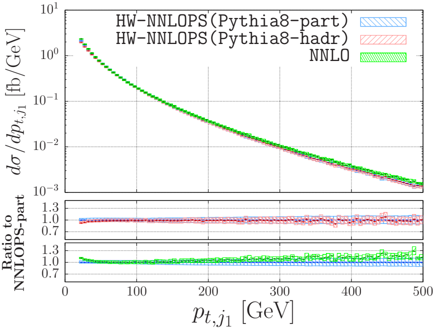
WH@NNLOPS

To reweight, use $(y_{\rm HW}, \Delta y_{\rm HW}, p_{t,\rm H})$ + Collins-Soper angles

$$\frac{d\sigma}{d\Phi_B} = \frac{d\sigma}{dy_{\rm HW}\, d\Delta y_{\rm HW}\, dp_{t,\rm H}\, d\cos\theta^*\, d\phi^*}$$

$$= \frac{3}{16\pi}\left(\frac{d\sigma}{d\Phi_{\rm HW^*}}(1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(\Phi_{\rm HW^*})\, f_i(\theta^*,\phi^*)\right)$$





- left plot: angular dependence in slice of $y_{\rm HW}$
- right plot: hardest-jet spectrum

conclusions

- Monte Carlo tools play a major role for LHC searches
- especially if no “smoking gun” new-Physics around the corner, precision will be the key to maximise impact of LHC results
- huge amount of improvements over the last few years

- NLO+PS tools are now well established and very mature

  \- by now they are basically automated also for BSM processes
- major developments in last 3-4 years: NLOPS multijet merging

  \- it might play a very important role in absence of smoking-gun BSM signal
- NNLO+PS is doable, at least for color-singlet production.

Outlook

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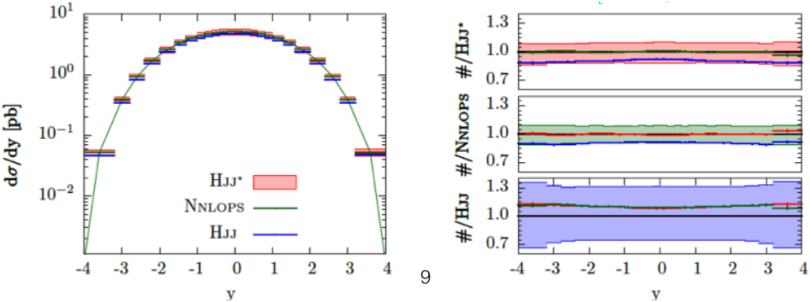
- “proof of principle” results for NLOPS merging for higher multiplicity, using MiNLO
  - H+jj @ NLO, H+j @ NLO and H @ NNLO

[Frederix,Hamilton ’15]



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Thank you for your attention!