Loop-induced and rare processes @ 100 TeV

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based on 1407.1623
1507.00020

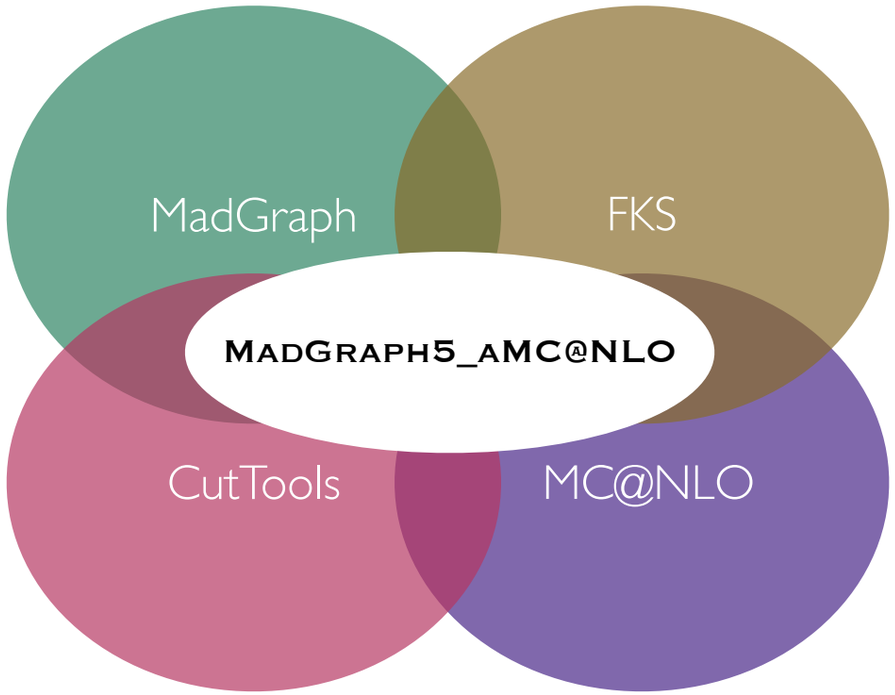
PLAN

- rare processes
  - ➡ enhancement from 8 TeV to 100 TeV
  - ➡ cross-sections @100TeV
- loop-induced processes
  - ➡ method and validation
  - ➡ cross-sections @100TeV
  - ➡ examples

Motivation

- Important to have the cross-section for a large sample of (SM) processes
  - ➡ allow to decide which one can be study
  - ➡ important for BSM searches
- We have the tools (@NLO)

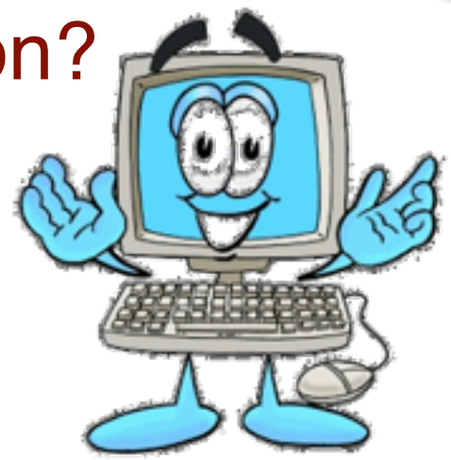
Framework



- automated NLO
- MC@NLO method
- using FKS subtraction
- using OPP method

Why Automation?

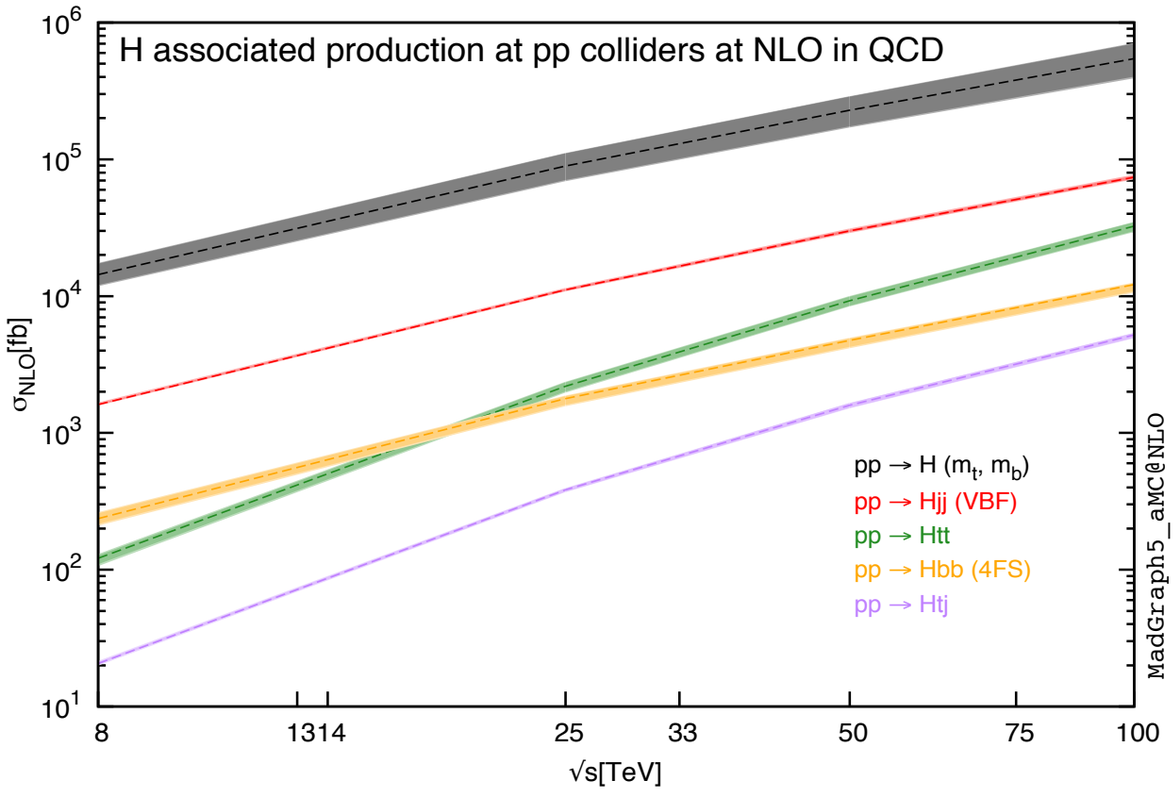
- time
- robust
- easy

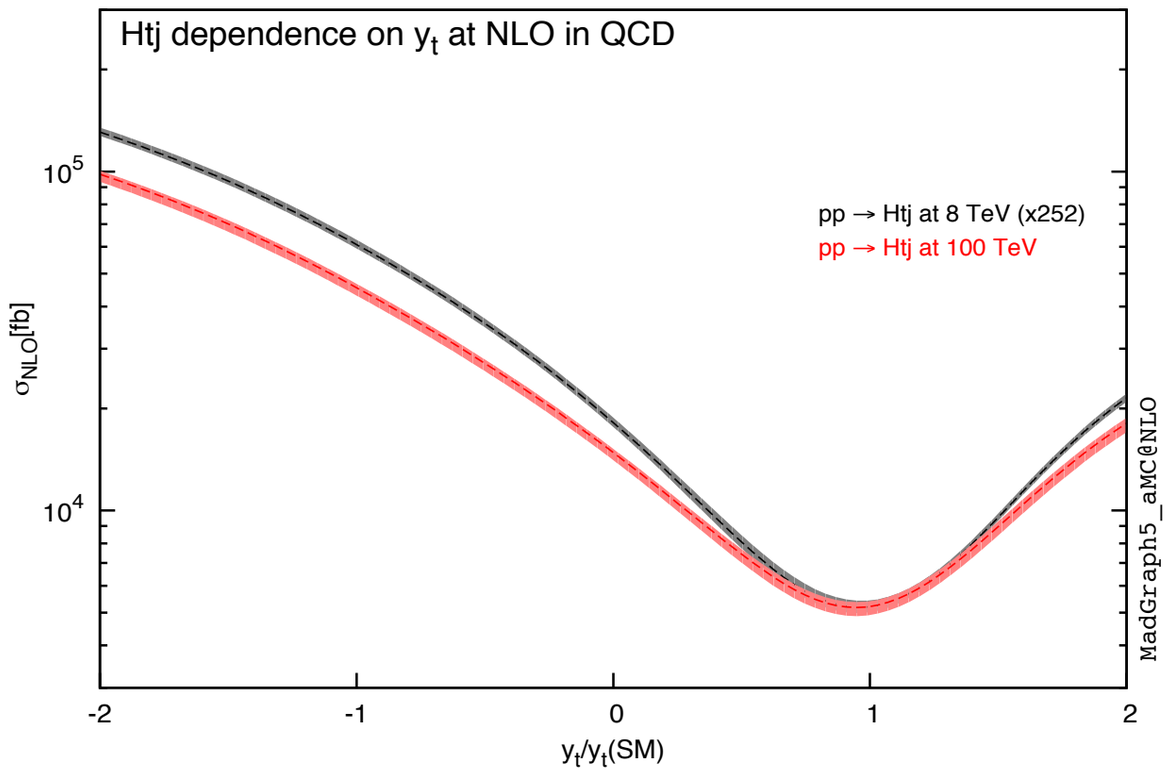


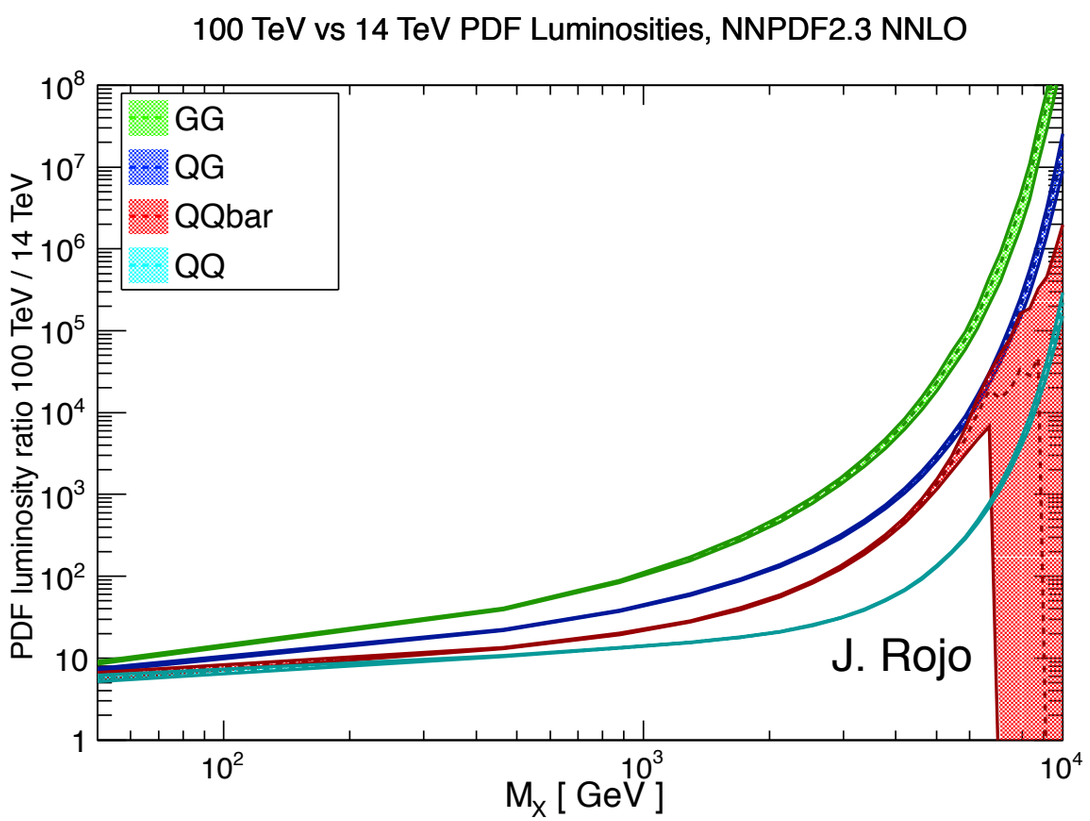
Why NLO?

- reliable prediction of cross-section
- reduction of theoretical uncertainty

Higgs


H associated production at pp colliders at NLO in QCD
σ_{NLO}[fb]
pp → H (m_t, m_b)
pp → Hjj (VBF)
pp → Htt
pp → Hbb (4FS)
pp → Htj
MadGraph5_aMC@NLO
√s[TeV]


Htj dependence on y_t at NLO in QCD
σ_{NLO}[fb]
pp → Htj at 8 TeV (x252)
pp → Htj at 100 TeV
MadGraph5_aMC@NLO
y_t/y_t(SM)


100 TeV vs 14 TeV PDF Luminosities, NNPDF2.3 NNLO
GG
QG
QQbar
QQ
PDF luminosity ratio 100 TeV / 14 TeV
J. Rojo
M_X [GeV]

Higgs

Process	$\sigma_{\rm NLO}(8\ \text{TeV})$ [fb]	$\sigma_{\rm NLO}(100\ \text{TeV})$ [fb]	ρ
$pp \to H\ (m_t, m_b)$	$1.44 \cdot 10^4\ {}^{+20\%}_{-16\%}\ {}^{+1\%}_{-2\%}$	$5.46 \cdot 10^5\ {}^{+28\%}_{-27\%}\ {}^{+2\%}_{-2\%}$	38
$pp \to Hjj$ (VBF)	$1.61 \cdot 10^3\ {}^{+1\%}_{-0\%}\ {}^{+2\%}_{-2\%}$	$7.40 \cdot 10^4\ {}^{+3\%}_{-2\%}\ {}^{+2\%}_{-1\%}$	46
$pp \to Ht\bar{t}$	$1.21 \cdot 10^2\ {}^{+5\%}_{-9\%}\ {}^{+3\%}_{-3\%}$	$3.25 \cdot 10^4\ {}^{+7\%}_{-8\%}\ {}^{+1\%}_{-1\%}$	269
$pp \to Hb\bar{b}$ (4FS)	$2.37 \cdot 10^2\ {}^{+9\%}_{-9\%}\ {}^{+2\%}_{-2\%}$	$1.21 \cdot 10^4\ {}^{+2\%}_{-10\%}\ {}^{+2\%}_{-2\%}$	51
$pp \to Htj$	$2.07 \cdot 10^1\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$5.21 \cdot 10^3\ {}^{+3\%}_{-5\%}\ {}^{+1\%}_{-1\%}$	252
$pp \to HW^{\pm}$	$7.31 \cdot 10^2\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$1.54 \cdot 10^4\ {}^{+5\%}_{-8\%}\ {}^{+2\%}_{-2\%}$	21
$pp \to HZ$	$3.87 \cdot 10^2\ {}^{+2\%}_{-1\%}\ {}^{+2\%}_{-2\%}$	$8.82 \cdot 10^3\ {}^{+4\%}_{-8\%}\ {}^{+2\%}_{-2\%}$	23
$pp \to HW^+W^-$ (4FS)	$4.62 \cdot 10^0\ {}^{+3\%}_{-2\%}\ {}^{+2\%}_{-2\%}$	$1.68 \cdot 10^2\ {}^{+5\%}_{-6\%}\ {}^{+2\%}_{-1\%}$	36
$pp \to HZW^{\pm}$	$2.17 \cdot 10^0\ {}^{+4\%}_{-4\%}\ {}^{+2\%}_{-2\%}$	$9.94 \cdot 10^1\ {}^{+6\%}_{-7\%}\ {}^{+2\%}_{-1\%}$	46
$pp \to HW^{\pm}\gamma$	$2.36 \cdot 10^0\ {}^{+3\%}_{-3\%}\ {}^{+2\%}_{-2\%}$	$7.75 \cdot 10^1\ {}^{+7\%}_{-8\%}\ {}^{+2\%}_{-1\%}$	33
$pp \to HZ\gamma$	$1.54 \cdot 10^0\ {}^{+3\%}_{-2\%}\ {}^{+2\%}_{-2\%}$	$4.29 \cdot 10^1\ {}^{+5\%}_{-7\%}\ {}^{+2\%}_{-2\%}$	28
$pp \to HZZ$	$1.10 \cdot 10^0\ {}^{+2\%}_{-2\%}\ {}^{+2\%}_{-2\%}$	$4.20 \cdot 10^1\ {}^{+4\%}_{-6\%}\ {}^{+2\%}_{-1\%}$	38
$pp \to HW^{\pm}j$	$3.18 \cdot 10^2\ {}^{+4\%}_{-4\%}\ {}^{+2\%}_{-1\%}$	$1.07 \cdot 10^4\ {}^{+2\%}_{-7\%}\ {}^{+2\%}_{-1\%}$	34
$pp \to HW^{\pm}jj$	$6.06 \cdot 10^1\ {}^{+6\%}_{-8\%}\ {}^{+1\%}_{-1\%}$	$4.90 \cdot 10^3\ {}^{+2\%}_{-6\%}\ {}^{+1\%}_{-1\%}$	81
$pp \to HZj$	$1.71 \cdot 10^2\ {}^{+4\%}_{-4\%}\ {}^{+1\%}_{-1\%}$	$6.31 \cdot 10^3\ {}^{+2\%}_{-7\%}\ {}^{+2\%}_{-1\%}$	37
$pp \to HZjj$	$3.50 \cdot 10^1\ {}^{+7\%}_{-10\%}\ {}^{+1\%}_{-1\%}$	$2.81 \cdot 10^3\ {}^{+2\%}_{-5\%}\ {}^{+1\%}_{-1\%}$	80

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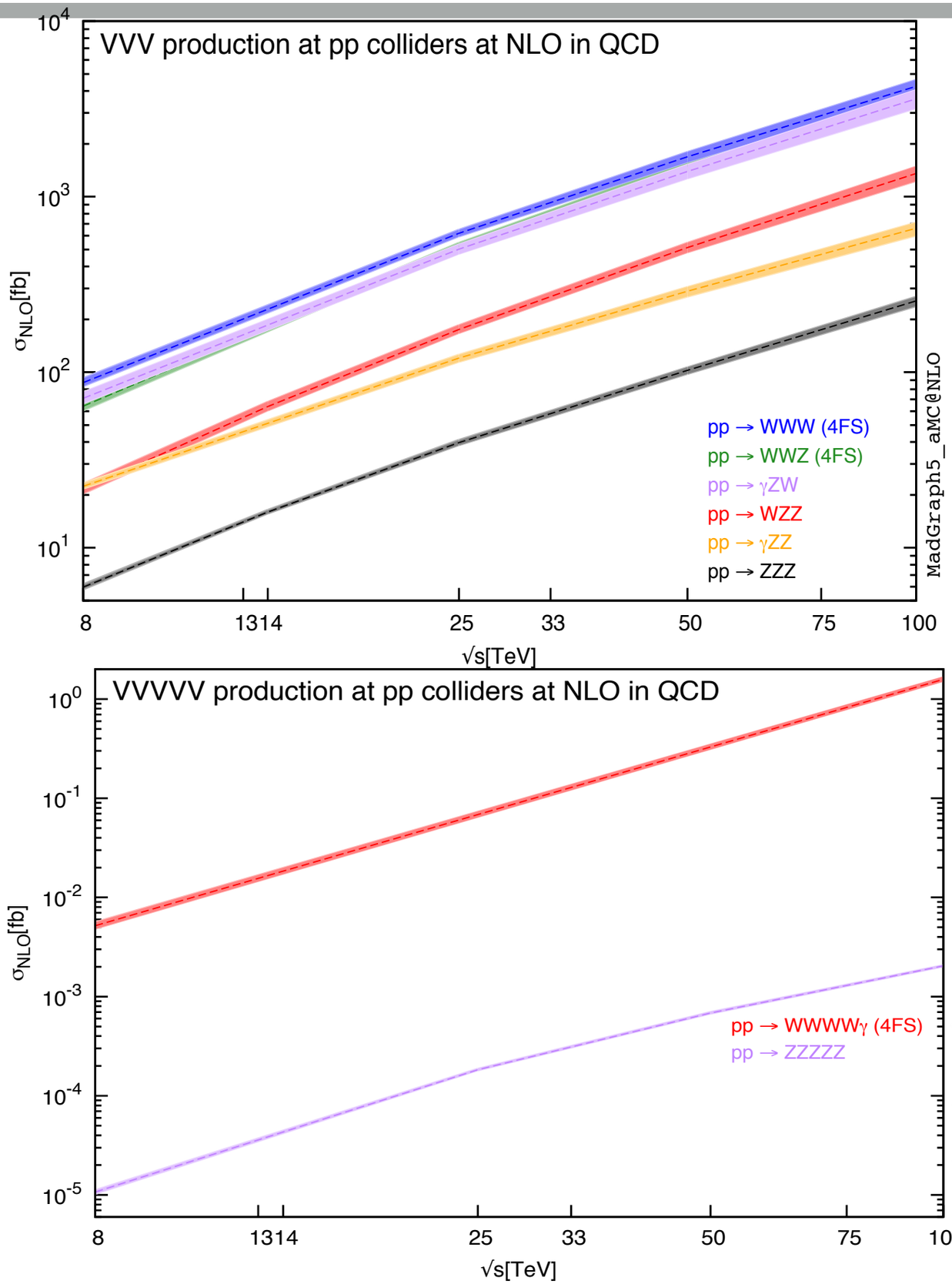
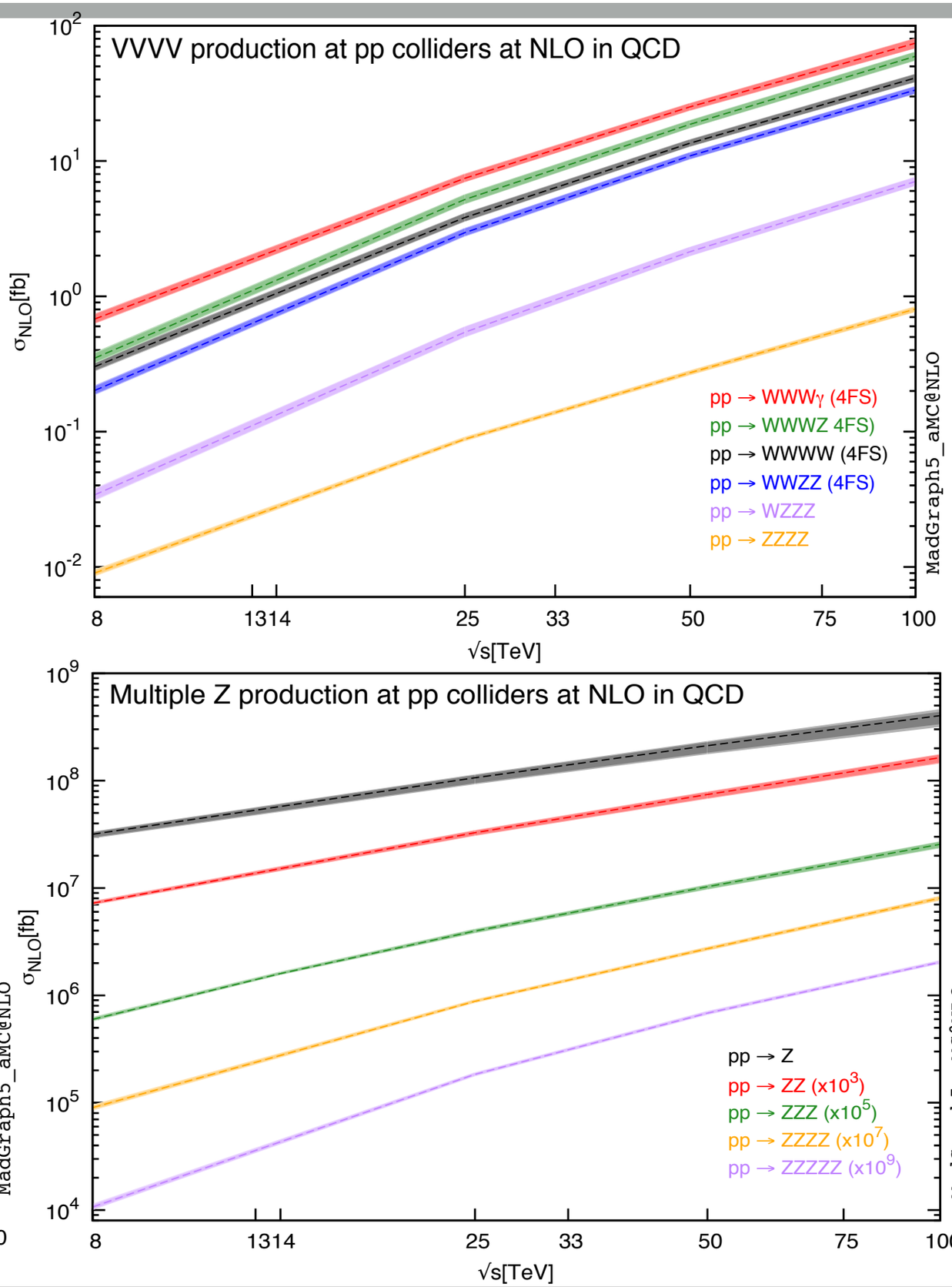
Multi Bosons





Multi Bosons

Process	$\sigma_{\text{NLO}}(8\text{ TeV})$ [fb]	$\sigma_{\text{NLO}}(100\text{ TeV})$ [fb]	ρ
$pp \to W^+W^-W^\pm$ (4FS)	$8.73 \cdot 10^{1}\ ^{+6\%}_{-4\%}\ ^{+2\%}_{-2\%}$	$4.25 \cdot 10^{3}\ ^{+9\%}_{-9\%}\ ^{+1\%}_{-1\%}$	49
$pp \to W^+W^-Z$ (4FS)	$6.41 \cdot 10^{1}\ ^{+7\%}_{-5\%}\ ^{+2\%}_{-2\%}$	$4.01 \cdot 10^{3}\ ^{+9\%}_{-9\%}\ ^{+1\%}_{-1\%}$	63
$pp \to \gamma W^\pm Z$	$7.11 \cdot 10^{1}\ ^{+8\%}_{-7\%}\ ^{+2\%}_{-1\%}$	$3.61 \cdot 10^{3}\ ^{+12\%}_{-12\%}\ ^{+1\%}_{-1\%}$	51
$pp \to W^\pm ZZ$	$2.16 \cdot 10^{1}\ ^{+7\%}_{-6\%}\ ^{+2\%}_{-2\%}$	$1.36 \cdot 10^{3}\ ^{+10\%}_{-10\%}\ ^{+1\%}_{-1\%}$	63
$pp \to \gamma ZZ$	$2.24 \cdot 10^{1}\ ^{+4\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$6.62 \cdot 10^{2}\ ^{+8\%}_{-9\%}\ ^{+2\%}_{-1\%}$	30
$pp \to ZZZ$	$5.97 \cdot 10^{0}\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-2\%}$	$2.55 \cdot 10^{2}\ ^{+5\%}_{-7\%}\ ^{+2\%}_{-1\%}$	43
$pp \to W^+W^-W^\pm\gamma$ (4FS)	$6.78 \cdot 10^{-1}\ ^{+8\%}_{-6\%}\ ^{+2\%}_{-2\%}$	$7.42 \cdot 10^{1}\ ^{+8\%}_{-8\%}\ ^{+1\%}_{-1\%}$	109
$pp \to W^+W^-W^\pm Z$ (4FS)	$3.48 \cdot 10^{-1}\ ^{+8\%}_{-7\%}\ ^{+2\%}_{-2\%}$	$5.95 \cdot 10^{1}\ ^{+7\%}_{-7\%}\ ^{+1\%}_{-1\%}$	171
$pp \to W^+W^-W^+W^-$ (4FS)	$3.01 \cdot 10^{-1}\ ^{+7\%}_{-6\%}\ ^{+2\%}_{-2\%}$	$4.11 \cdot 10^{1}\ ^{+7\%}_{-6\%}\ ^{+1\%}_{-1\%}$	137
$pp \to W^+W^-ZZ$ (4FS)	$2.01 \cdot 10^{-1}\ ^{+7\%}_{-6\%}\ ^{+2\%}_{-2\%}$	$3.34 \cdot 10^{1}\ ^{+6\%}_{-6\%}\ ^{+1\%}_{-1\%}$	166
$pp \to W^\pm ZZZ$	$3.40 \cdot 10^{-2}\ ^{+10\%}_{-8\%}\ ^{+2\%}_{-2\%}$	$7.06 \cdot 10^{0}\ ^{+8\%}_{-7\%}\ ^{+1\%}_{-1\%}$	208
$pp \to ZZZZ$	$8.72 \cdot 10^{-3}\ ^{+4\%}_{-4\%}\ ^{+3\%}_{-2\%}$	$8.05 \cdot 10^{-1}\ ^{+4\%}_{-4\%}\ ^{+2\%}_{-1\%}$	92
$pp \to W^+W^-W^+W^-\gamma$ (4FS)	$5.18 \cdot 10^{-3}\ ^{+8\%}_{-7\%}\ ^{+3\%}_{-2\%}$	$1.58 \cdot 10^{0}\ ^{+6\%}_{-5\%}\ ^{+1\%}_{-1\%}$	305
$pp \to ZZZZZ$	$1.07 \cdot 10^{-5}\ ^{+5\%}_{-4\%}\ ^{+3\%}_{-2\%}$	$2.04 \cdot 10^{-3}\ ^{+3\%}_{-3\%}\ ^{+2\%}_{-1\%}$	191

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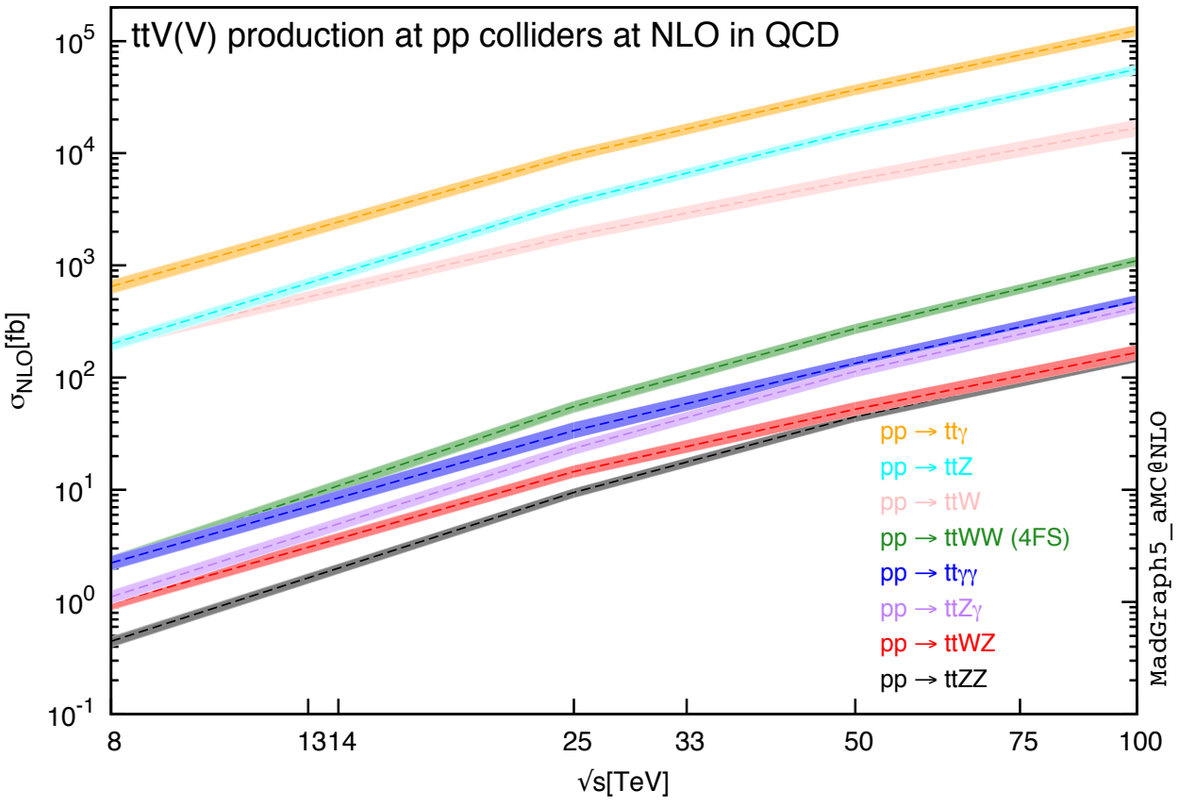
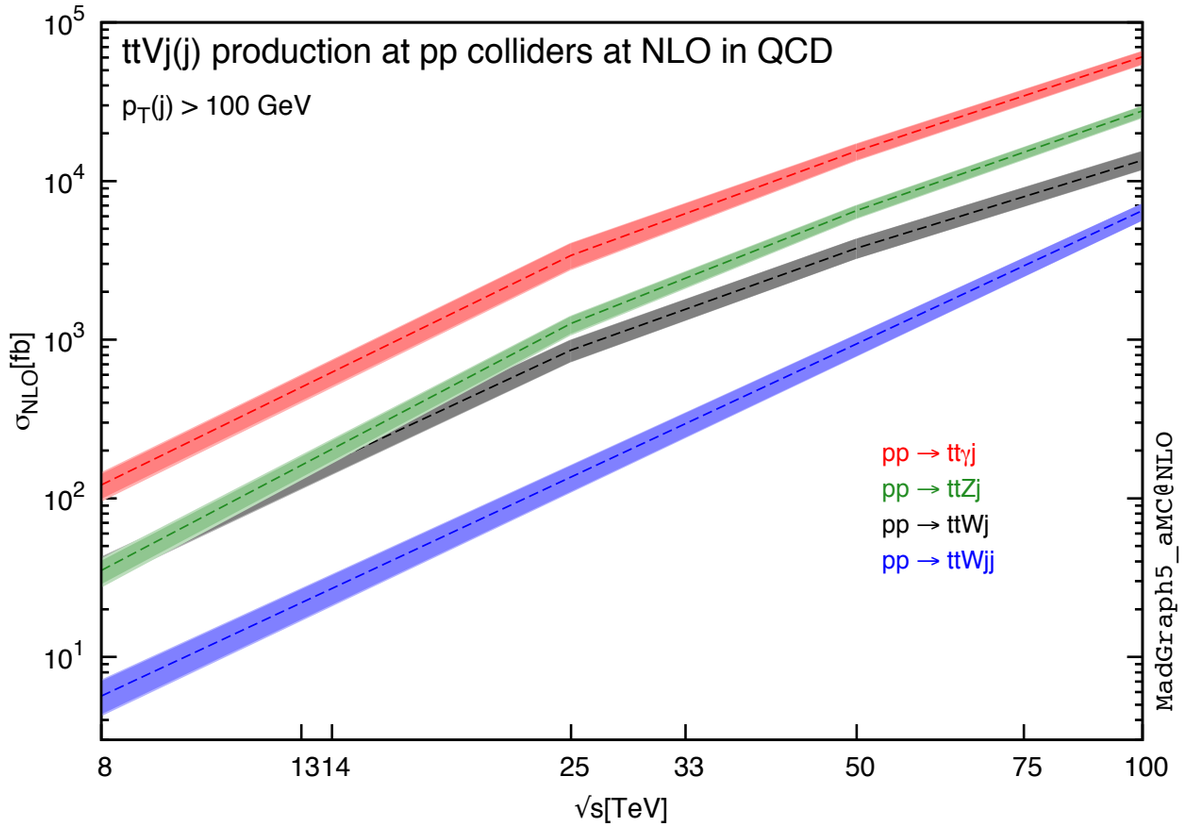
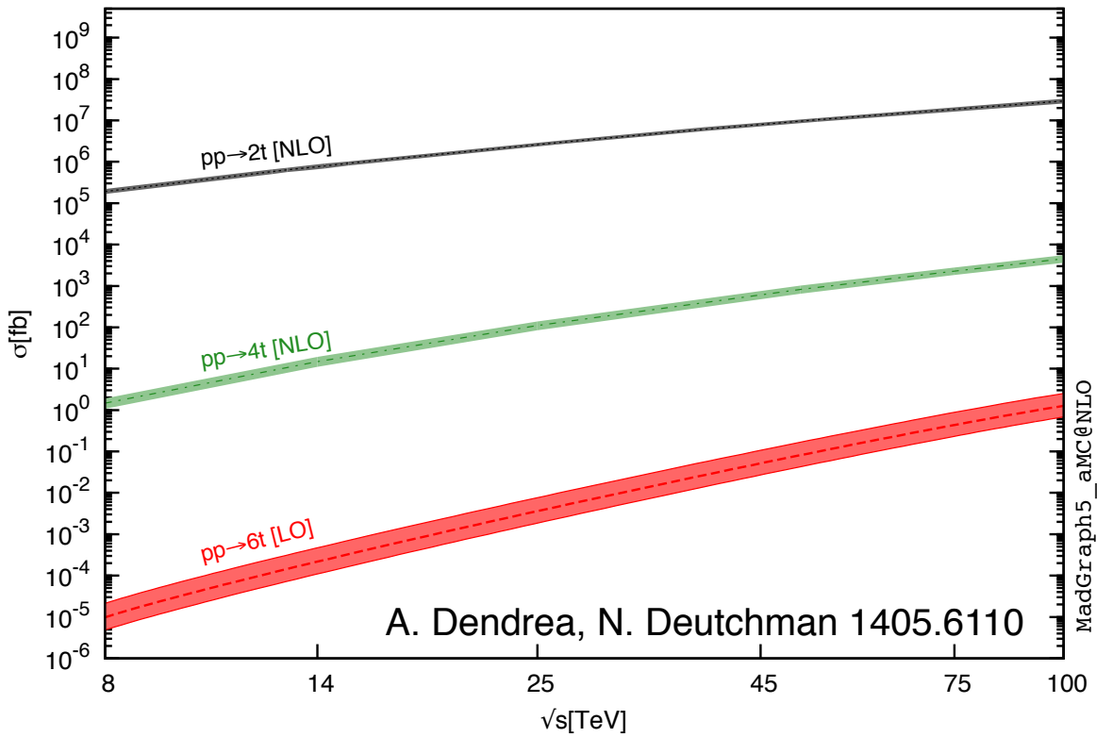
top pair production







top pair production

	Process	$\sigma_{\rm NLO}(8\ \text{TeV})$ [fb]	$\sigma_{\rm NLO}(100\ \text{TeV})$ [fb]	ρ
$pp \to$	$t\bar{t}\gamma$	$6.50 \cdot 10^{2}\ ^{+12\%}_{-13\%}\ ^{+2\%}_{-2\%}$	$1.24 \cdot 10^{5}\ ^{+11\%}_{-11\%}\ ^{+1\%}_{-1\%}$	192
$pp \to$	$t\bar{t}Z$	$1.99 \cdot 10^{2}\ ^{+10\%}_{-12\%}\ ^{+3\%}_{-3\%}$	$5.63 \cdot 10^{4}\ ^{+9\%}_{-10\%}\ ^{+1\%}_{-1\%}$	282
$pp \to$	$t\bar{t}W^{\pm}$	$2.05 \cdot 10^{2}\ ^{+9\%}_{-10\%}\ ^{+2\%}_{-2\%}$	$1.68 \cdot 10^{4}\ ^{+18\%}_{-16\%}\ ^{+1\%}_{-1\%}$	82
$pp \to$	$t\bar{t}\gamma j$	$1.22 \cdot 10^{2}\ ^{+17\%}_{-18\%}\ ^{+3\%}_{-3\%}$	$6.07 \cdot 10^{4}\ ^{+8\%}_{-10\%}\ ^{+1\%}_{-1\%}$	498
$pp \to$	$t\bar{t}Zj$	$3.51 \cdot 10^{1}\ ^{+15\%}_{-18\%}\ ^{+4\%}_{-4\%}$	$2.77 \cdot 10^{4}\ ^{+7\%}_{-9\%}\ ^{+1\%}_{-1\%}$	789
$pp \to$	$t\bar{t}W^{\pm}j$	$3.59 \cdot 10^{1}\ ^{+18\%}_{-18\%}\ ^{+2\%}_{-2\%}$	$1.36 \cdot 10^{4}\ ^{+14\%}_{-13\%}\ ^{+1\%}_{-1\%}$	379
$pp \to$	$t\bar{t}W^{\pm}jj$	$5.67 \cdot 10^{0}\ ^{+24\%}_{-23\%}\ ^{+3\%}_{-2\%}$	$6.52 \cdot 10^{3}\ ^{+11\%}_{-14\%}\ ^{+1\%}_{-1\%}$	1150
$pp \to$	$t\bar{t}W^{+}W^{-}$ (4FS)	$2.27 \cdot 10^{0}\ ^{+11\%}_{-13\%}\ ^{+3\%}_{-3\%}$	$1.10 \cdot 10^{3}\ ^{+9\%}_{-9\%}\ ^{+1\%}_{-1\%}$	486
$pp \to$	$t\bar{t}\gamma\gamma$	$2.23 \cdot 10^{0}\ ^{+14\%}_{-13\%}\ ^{+2\%}_{-1\%}$	$4.81 \cdot 10^{2}\ ^{+13\%}_{-11\%}\ ^{+1\%}_{-1\%}$	216
$pp \to$	$t\bar{t}Z\gamma$	$1.11 \cdot 10^{0}\ ^{+12\%}_{-13\%}\ ^{+2\%}_{-2\%}$	$4.20 \cdot 10^{2}\ ^{+10\%}_{-9\%}\ ^{+1\%}_{-1\%}$	378
$pp \to$	$t\bar{t}W^{\pm}Z$	$9.71 \cdot 10^{-1}\ ^{+10\%}_{-11\%}\ ^{+3\%}_{-2\%}$	$1.68 \cdot 10^{2}\ ^{+16\%}_{-13\%}\ ^{+1\%}_{-1\%}$	173
$pp \to$	$t\bar{t}ZZ$	$4.47 \cdot 10^{-1}\ ^{+8\%}_{-10\%}\ ^{+3\%}_{-2\%}$	$1.58 \cdot 10^{2}\ ^{+15\%}_{-12\%}\ ^{+1\%}_{-1\%}$	353

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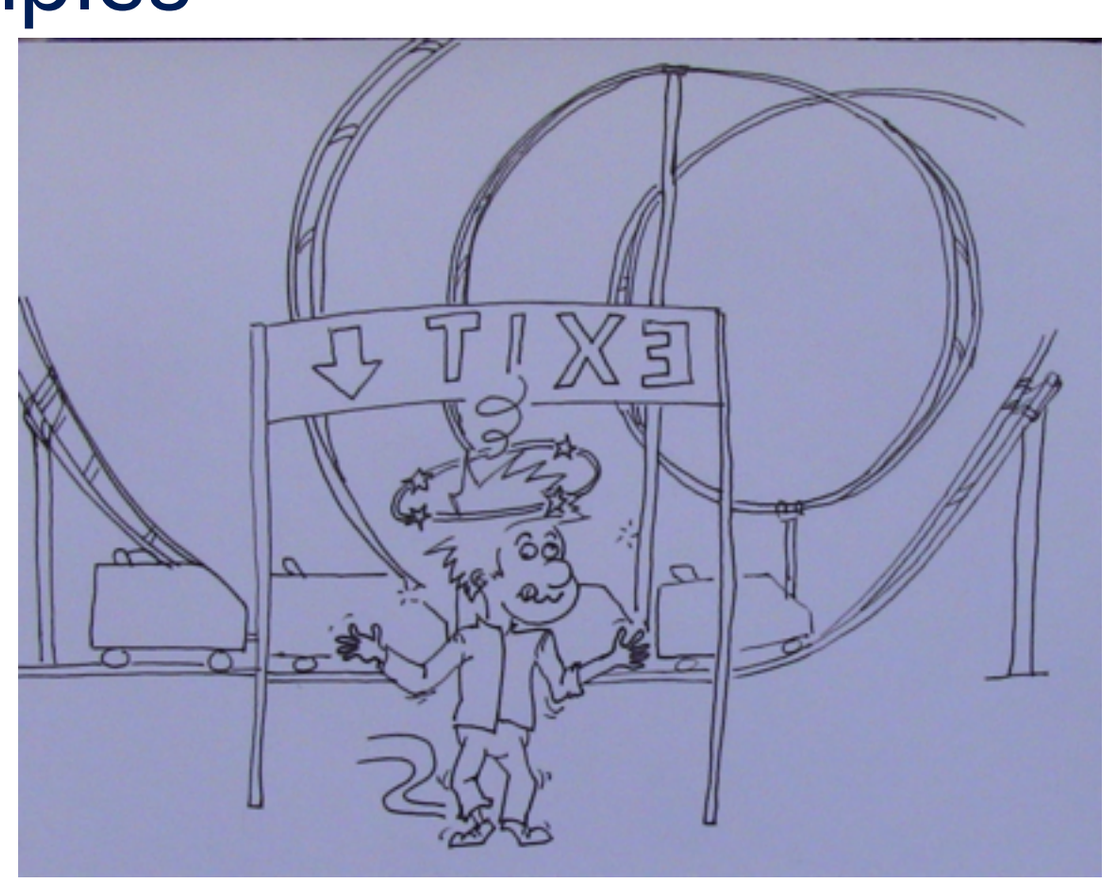
PLAN

- loop-induced processes
  - ➡ method and validation
  - ➡ cross-sections @100TeV
  - ➡ examples



Loop Induced

Why?

- main production mechanism for Higgs & Higgs associated processes
- contribution for NNLO computation
- correction to shape of observables

Difficulties?

- the phase-space integration is based on the born diagram
- loop evaluation are extremely slow
- need Leading Color information for writing Events associated to the loop

Exact Integration

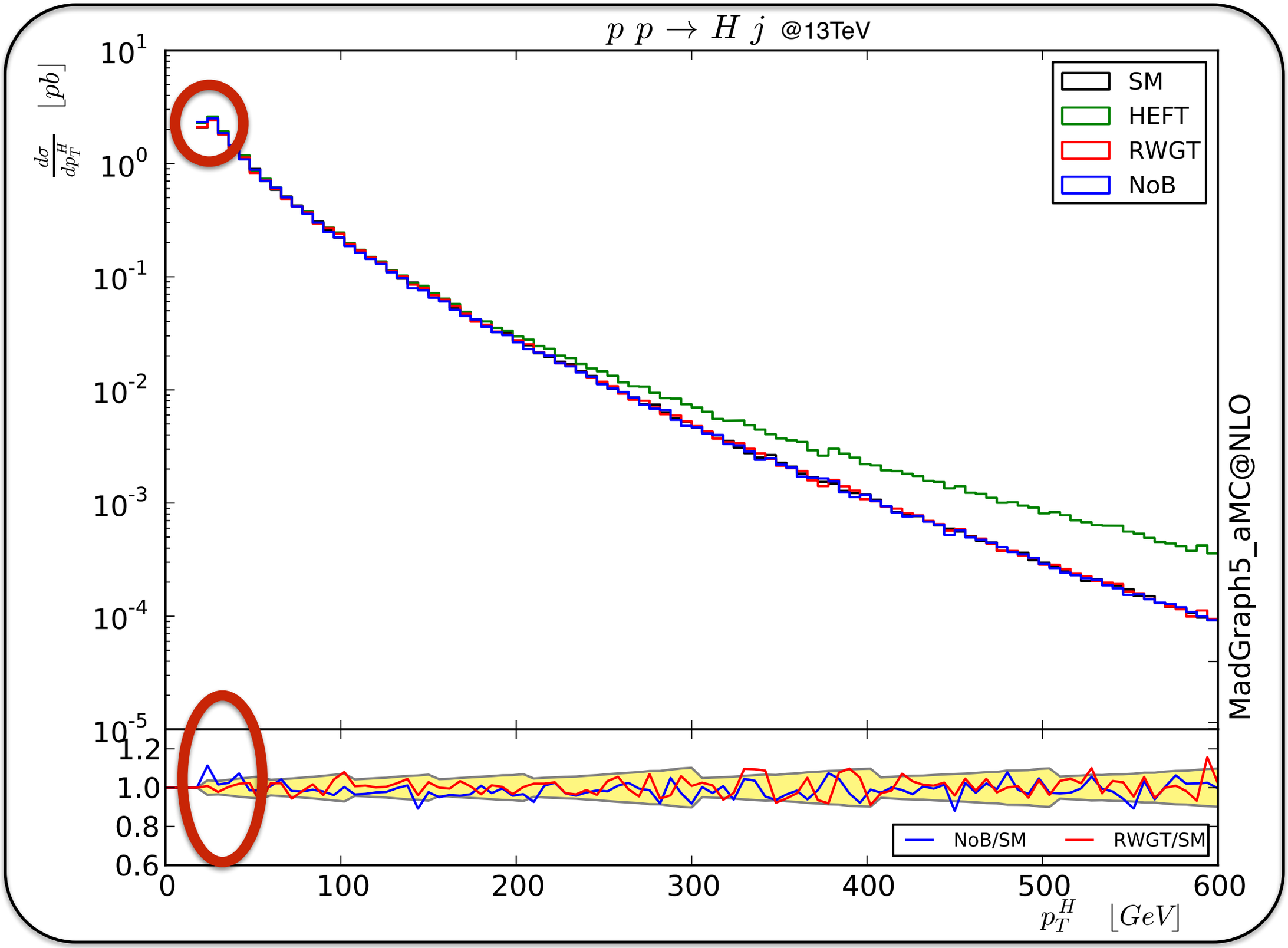
Difficulties?

- the phase-space integration is based on the born diagram
- loop evaluation are extremely slow
- need Leading Color information for writing Events associated to the loop

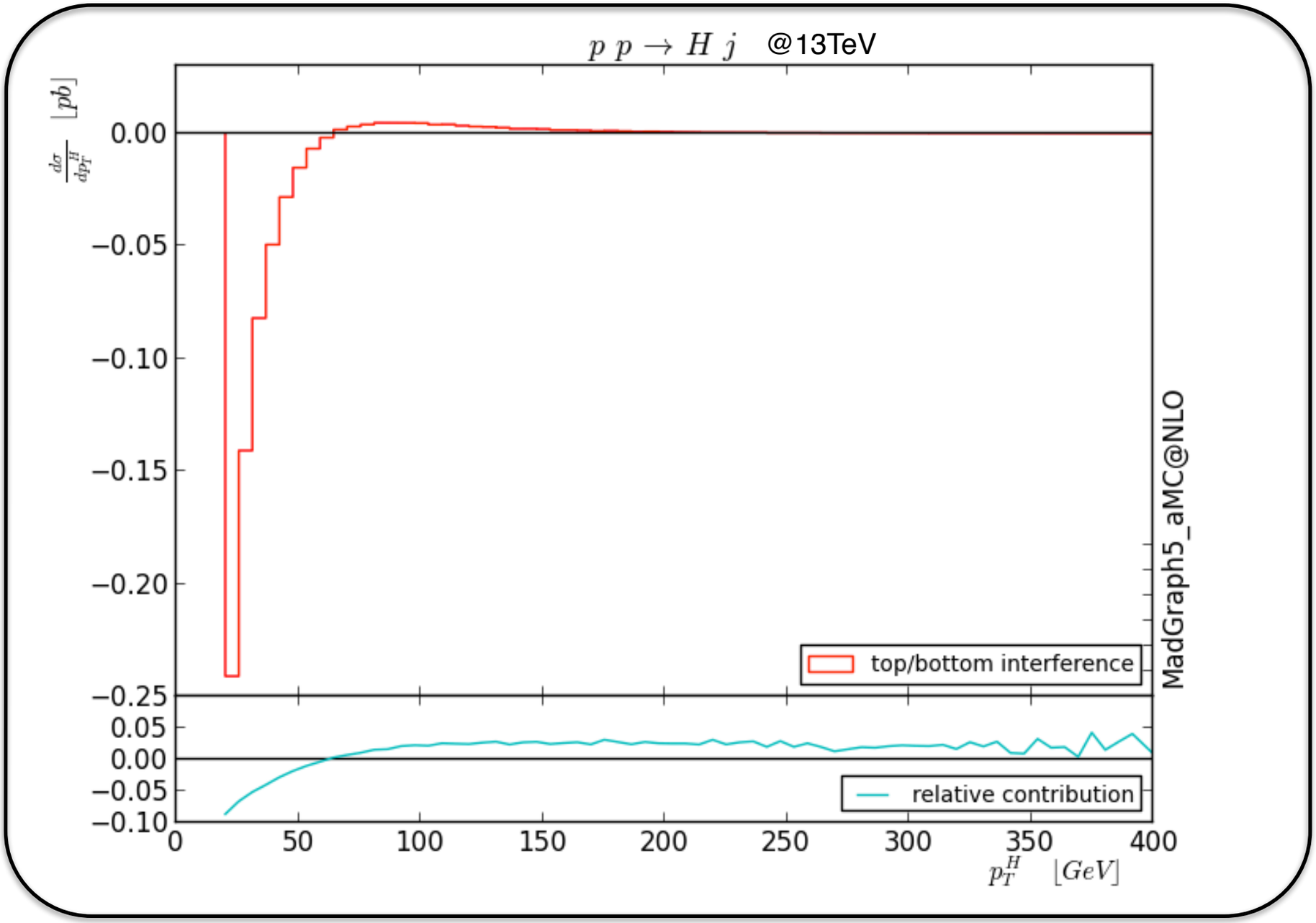
Our Solution

- contract the loop to have tree-level diagrams which drive the integration multi-channel
- use Monte-Carlo over helicity
- compute the loop with the color flow algebra
- increase parallelisation

Validation p p > h j

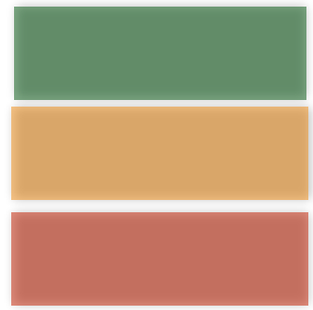


Validation p p > h j

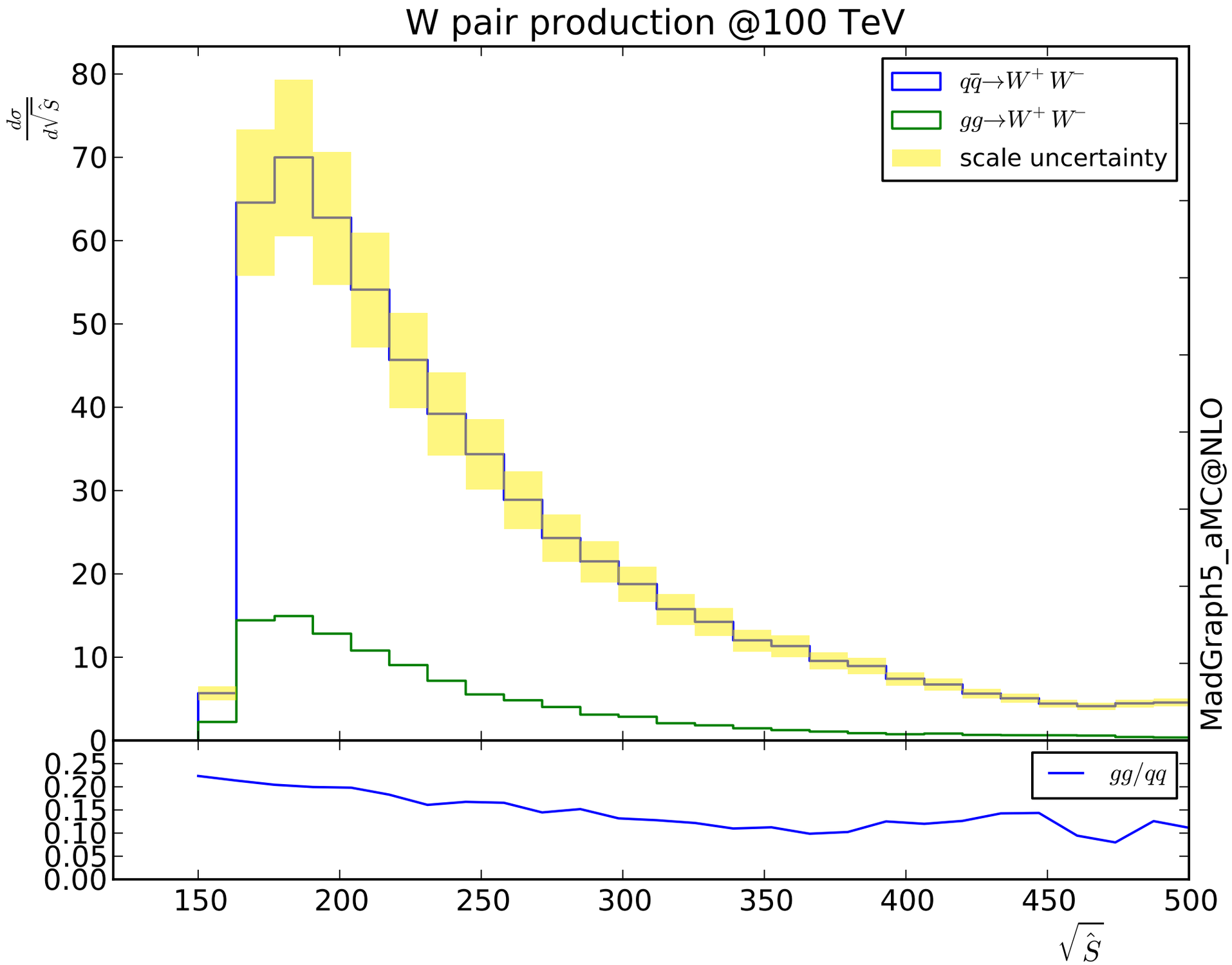


- b effect only important at low pt
- at large pt, this is just a re-scaling

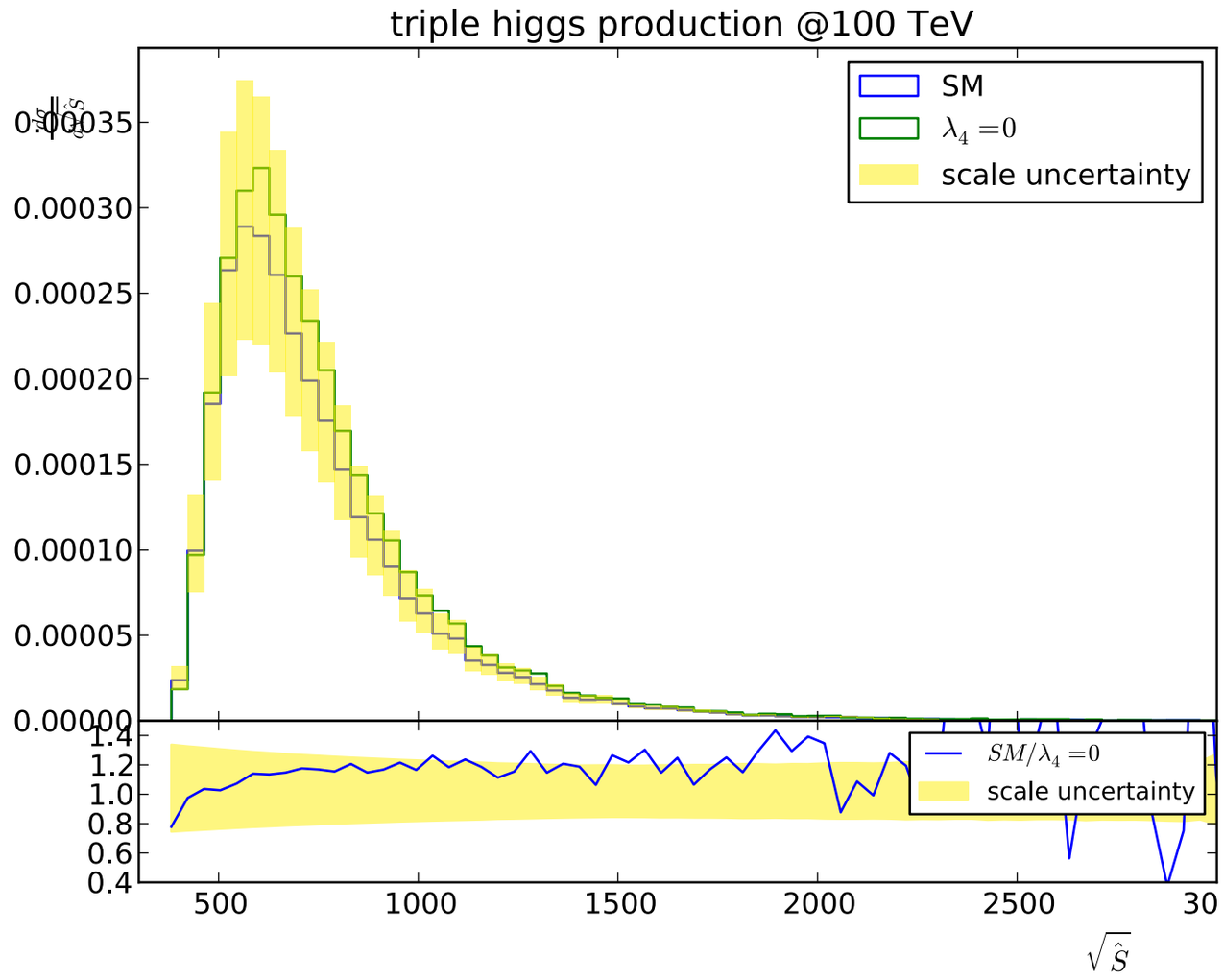
Loop Induced Process	$\sigma_{\rm NLO}(8\ {\rm TeV})$ [fb]	$\sigma_{\rm NLO}(100\ {\rm TeV})$ [fb]	ρ
$gg \to H$	$6.85 \cdot 10^{+3}$ $^{+33\%}_{-24\%}$ $^{+1\%}_{-1\%}$	$2.21 \cdot 10^{+5}$ $^{+58\%}_{-39\%}$ $^{+1\%}_{-1\%}$	32
$pp \to Hjj$	$1.89 \cdot 10^{+3}$ $^{+67\%}_{-37\%}$ $^{+1\%}_{-1\%}$	$2.02 \cdot 10^{+5}$ $^{+66\%}_{-38\%}$ $^{+0\%}_{-1\%}$	107
$gg \to HZ$	22.9 $^{+33\%}_{-23\%}$ $^{+1\%}_{-2\%}$	$2.50 \cdot 10^{+3}$ $^{+35\%}_{-26\%}$ $^{+1\%}_{-1\%}$	109
$gg \to HW^+W^-$	$8.28 \cdot 10^{-2}$ $^{+38\%}_{-26\%}$ $^{-13\%}_{-16\%}$	16.8 $^{+31\%}_{-23\%}$ $^{+8\%}_{+6\%}$	203
$gg \to HZ\gamma$	$2.12 \cdot 10^{-3}$ $^{+34\%}_{-23\%}$ $^{+1\%}_{-2\%}$	0.279 $^{+33\%}_{-25\%}$ $^{+0\%}_{-1\%}$	132
$gg \to HH$	5.46 $^{+34\%}_{-24\%}$ $^{+2\%}_{-2\%}$	$7.74 \cdot 10^{+2}$ $^{+32\%}_{-24\%}$ $^{+0\%}_{-1\%}$	142
$gg \to ZZ$	$4.93 \cdot 10^{+2}$ $^{+30\%}_{-21\%}$ $^{+1\%}_{-1\%}$	$2.92 \cdot 10^{+4}$ $^{+42\%}_{-30\%}$ $^{+1\%}_{-1\%}$	59
$gg \to Z\gamma$	$3.98 \cdot 10^{+2}$ $^{+29\%}_{-21\%}$ $^{+1\%}_{-1\%}$	$1.70 \cdot 10^{+4}$ $^{+52\%}_{-35\%}$ $^{+1\%}_{-1\%}$	43
$gg \to \gamma\gamma$	$2.54 \cdot 10^{+4}$ $^{+56\%}_{-37\%}$ $^{+1\%}_{-1\%}$	$4.59 \cdot 10^{+5}$ $^{+89\%}_{-50\%}$ $^{+3\%}_{-3\%}$	18
$gg \to W^+W^-$	$1.37 \cdot 10^{+3}$ $^{+32\%}_{-23\%}$ $^{-8\%}_{-10\%}$	$8.06 \cdot 10^{+4}$ $^{+48\%}_{-33\%}$ $^{+31\%}_{+29\%}$	59
$gg \to HZZ$	$3.56 \cdot 10^{-2}$ $^{+35\%}_{-24\%}$ $^{+2\%}_{-2\%}$	7.29 $^{+28\%}_{-22\%}$ $^{+0\%}_{-1\%}$	205
$gg \to H\gamma\gamma$	$2.23 \cdot 10^{-3}$ $^{+38\%}_{-26\%}$ $^{-13\%}_{-16\%}$	0.374 $^{+33\%}_{-25\%}$ $^{+10\%}_{+9\%}$	167
$gg \to W^+W^-Z$	2.82 $^{+38\%}_{-26\%}$ $^{-13\%}_{-16\%}$	$4.72 \cdot 10^{+2}$ $^{-100\%}_{-100\%}$ $^{+0\%}_{+0\%}$	167
$gg \to Z\gamma\gamma$	$5.58 \cdot 10^{-2}$ $^{+28\%}_{-21\%}$ $^{+1\%}_{-1\%}$	3.42 $^{+44\%}_{-31\%}$ $^{+1\%}_{-1\%}$	61
$gg \to \gamma ZZ$	$1.13 \cdot 10^{-3}$ $^{+33\%}_{-23\%}$ $^{+1\%}_{-2\%}$	0.13 $^{+34\%}_{-25\%}$ $^{+1\%}_{-1\%}$	115
$gg \to HHH$	$1.16 \cdot 10^{-2}$ $^{+39\%}_{-26\%}$ $^{-14\%}_{-17\%}$	2.99 $^{+29\%}_{-22\%}$ $^{+5\%}_{+4\%}$	258
$gg \to HHHH$	$2.63 \cdot 10^{-5}$ $^{+39\%}_{-26\%}$ $^{+3\%}_{-3\%}$	$1.30 \cdot 10^{-2}$ $^{+23\%}_{-18\%}$ $^{+1\%}_{-1\%}$	494
$gg \to HHZ$	$1.60 \cdot 10^{-2}$ $^{+36\%}_{-24\%}$ $^{+2\%}_{-2\%}$	3.35 $^{+29\%}_{-22\%}$ $^{+0\%}_{-1\%}$	209

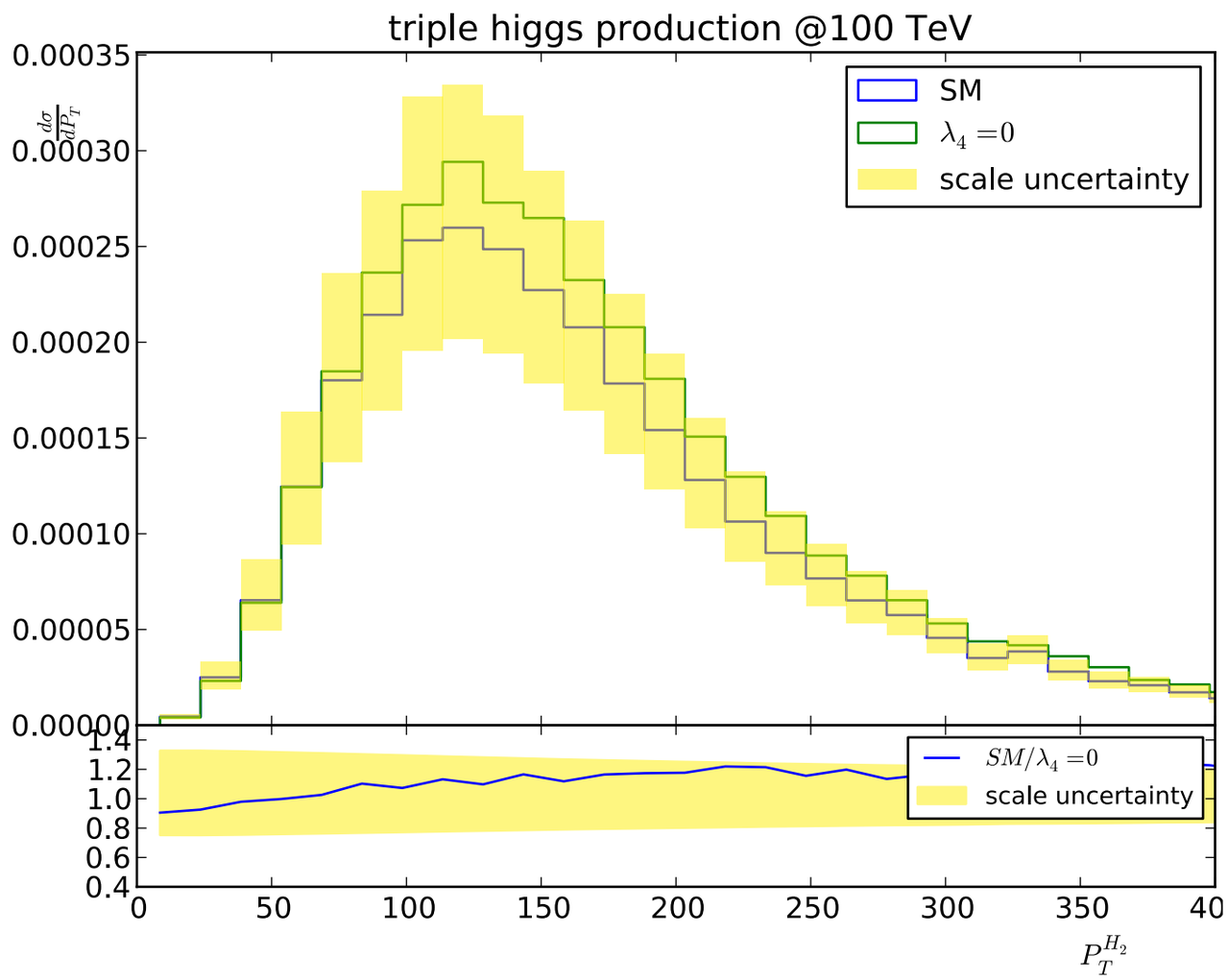


gg > w+w-


W pair production @100 TeV
$\frac{d\sigma}{d\sqrt{\hat{S}}}$
$q\bar{q}\to W^+W^-$
$gg\to W^+W^-$
scale uncertainty
MadGraph5_aMC@NLO
gg/qq
$\sqrt{\hat{S}}$

triple Higgs





Conclusion

- cross-section @NLO for 100TeV collision
  - ➡ Huge enhancement of rare processes at 100TeV compare to 8/13 TeV
- cross-section for loop-induced process @LO
  - ➡ Huge enhancement as well