Accurate backgrounds to Higgs production at the LHC

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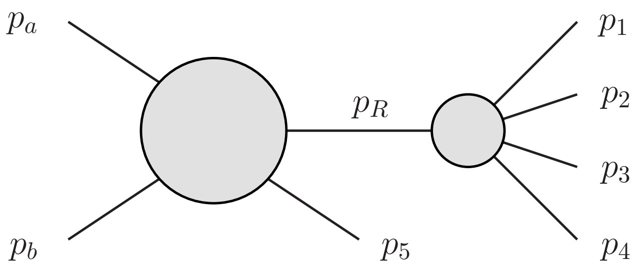
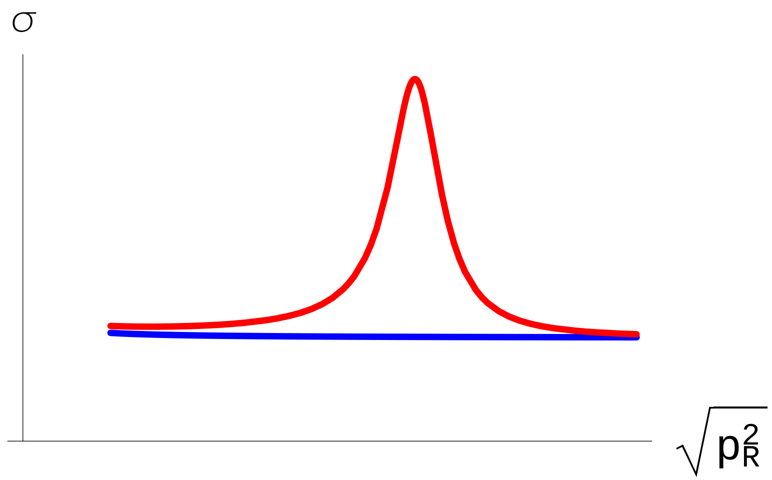
Overview

- LHC SM Higgs discovery potential: $H \to WW \to \ell^+\ell^- \not{p}_T$
  $\longrightarrow$ talks by Anne-Sylvie Giolo-Nicollerat and Barbara Jäger
- Top background
- Gluon fusion WW background
- Outlook: BSM backgrounds

Particle discovery: the ideal experimental case



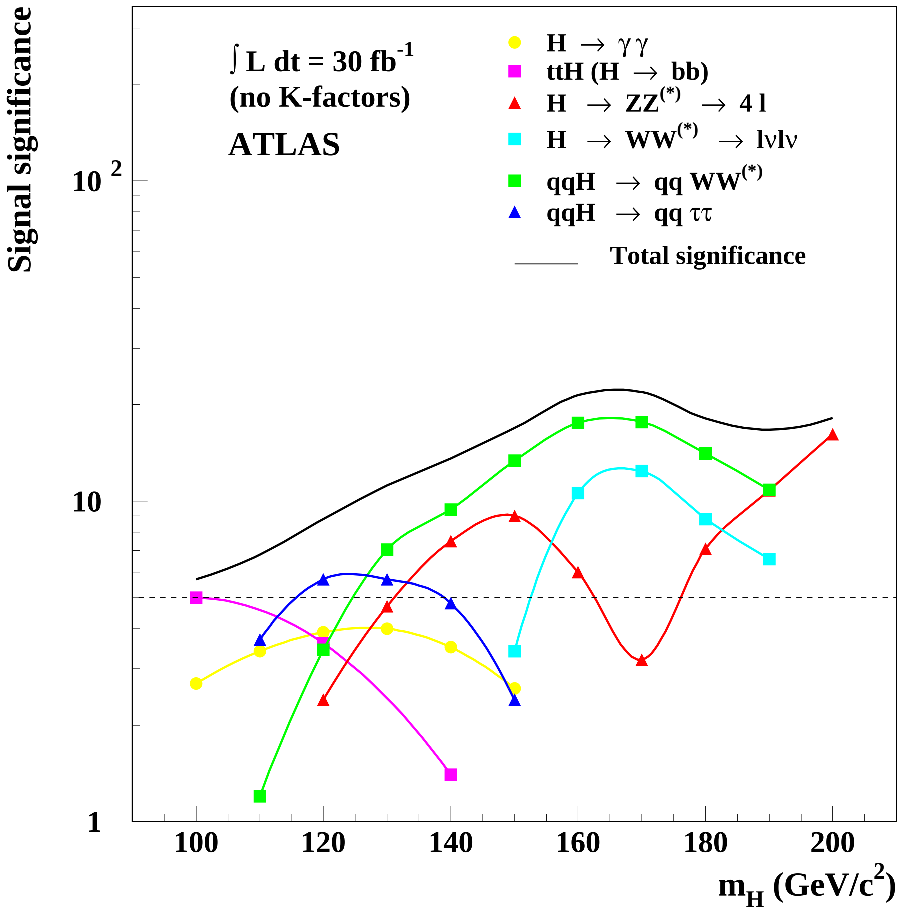
new resonance: can measure $p_1, p_2, p_3, p_4 \longrightarrow p_R = p_1 + p_2 + p_3 + p_4$



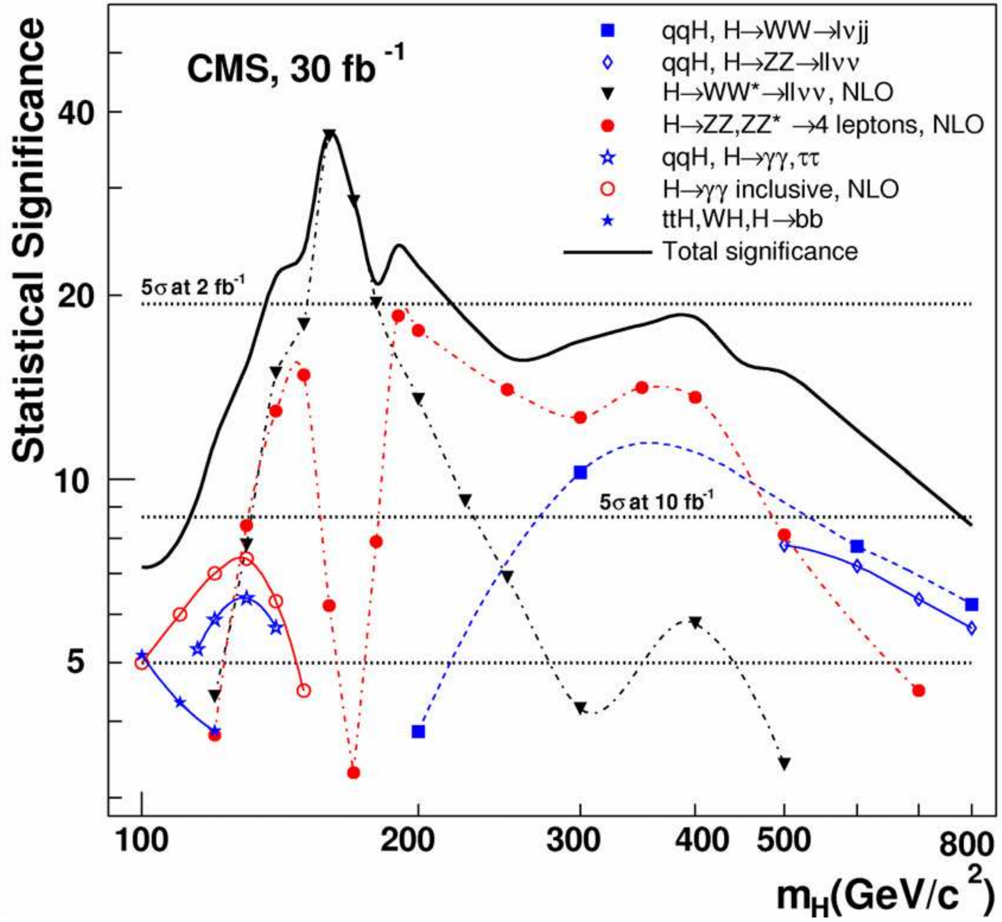
$\longrightarrow$ Invariant mass distribution from data ($\longrightarrow$ particle mass and width)

$\longrightarrow$ interpolate background from sidebands ($\longrightarrow$ σ_{signal})

LHC SM Higgs discovery potential



ATLAS (2003)



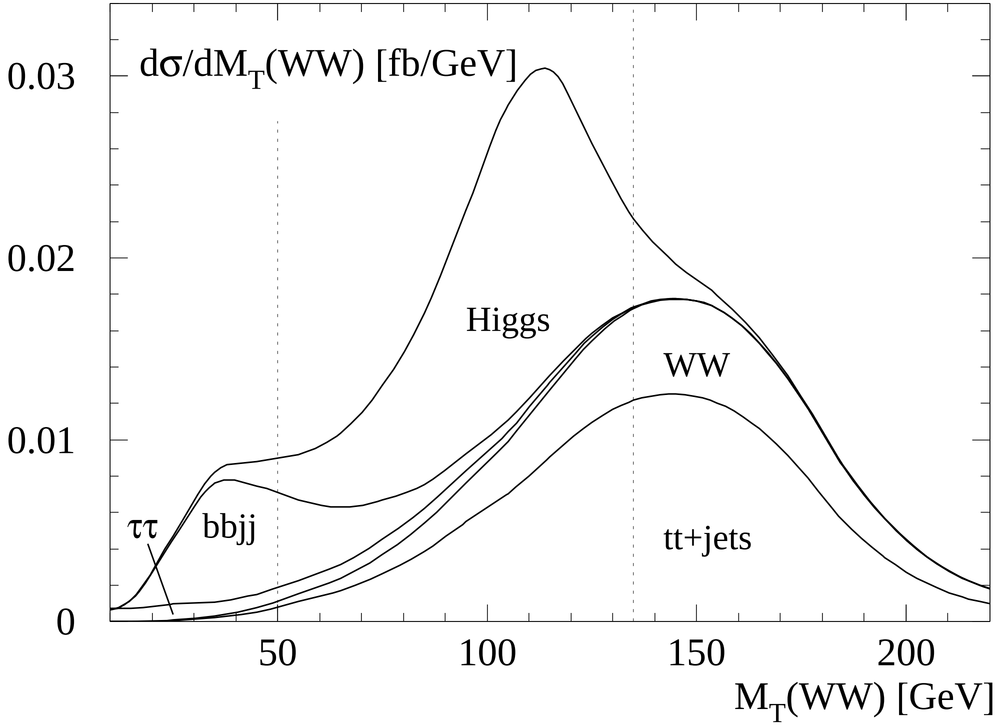
CMS (2003)

Backgrounds to $H \to WW \to \ell^+\ell^-\not{p}_T$ search

$H \to WW \to \ell\ell\nu\nu \; (p_3 =?,\, p_4 =?)$ $\longrightarrow$ Higgs momentum cannot be reconstructed

$$M_T := \sqrt{(E_{T,\ell\ell} + \not{E}_T)^2 - (\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T)^2}\,, \quad E_{T,\ell\ell} := \sqrt{p^2_{T,\ell\ell} + m^2_{\ell\ell}}\,, \quad \not{E}_T := \sqrt{\not{p}^2_T + m^2_{\ell\ell}}$$

e.g. Higgs search in **vector boson fusion**:

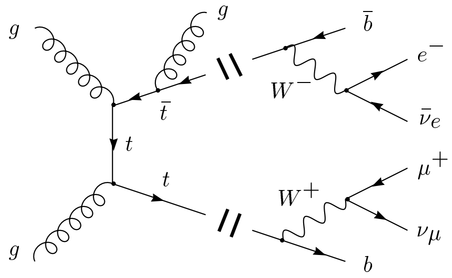


NK, Plehn, Rainwater, Zeppenfeld (2001)

WW and top background also dominant in **gluon fusion**

Top background corrections

in ***narrow width approximation***: $p\overset{(-)}{p} \to t\,(\to b\bar{\ell}'\nu')\ \ \bar{t}\,(\to \bar{b}\ell\bar{\nu})$ (+ jets)



with **complete LO matrix elements**: $p\overset{(-)}{p} \to b\bar{b}\ell\bar{\nu}\bar{\ell}'\nu'$ (+ jets) NK, Zeppenfeld (2002), NK (2003)

number of Feynman diagrams: $gg \to X$ (87), $gg \to Xg$ (600), $gg \to Xgg$ (5820) with $X = b\bar{b}\ell\bar{\nu}\bar{\ell}'\nu'$

`AcerMC`: complete WW-contribution (+ 0 jets) Kersevan, Richter-Was

vector boson fusion

$H \to WW \to \ell^\pm\ell^\mp \not{E}_T$

$H \to \tau\tau \to \ell^\pm\ell^\mp \not{E}_T$

$\sigma_{\text{LO,complete}}/\sigma_{\text{NWA}} - 1 \approx$ 10-25%

gluon fusion

$H \to WW \to \ell^\pm\ell^\mp \not{E}_T$

$\sigma_{\text{LO,complete}}/\sigma_{t\bar{t}\text{-NWA}} - 1 \approx 50\%$ $(\sigma_{t\bar{t}+Wt\text{-NWA}}/\sigma_{t\bar{t}\text{-NWA}} \approx 2)$

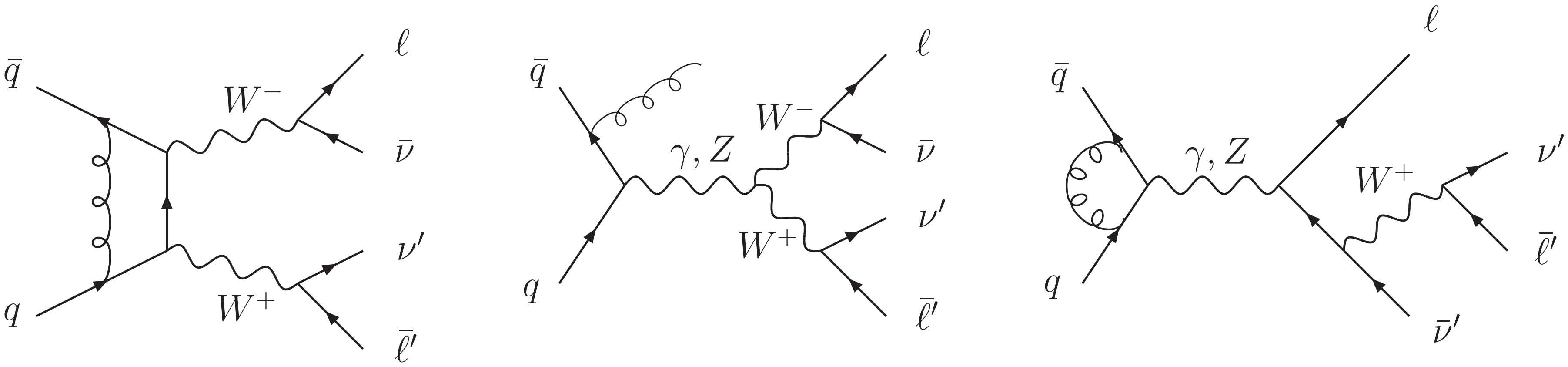
central jet veto: $p_{Tj} > 15$ GeV , $|\eta_j| < 3.2$

$\longrightarrow$ single- $\approx$ double-resonant contribution (90%)

single top via W-gluon fusion background M. Bähr, Zeppenfeld

Gluon fusion WW background corrections

$$p(\bar{p}) \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu' \text{ at } \mathcal{O}(\alpha_s)$$



$q\bar{q} \to W^+W^-$ *NLO QCD*, $\quad g(\bar{q}) \to W^+W^-(\bar{q})$

Ohnemus (1991); Frixione (1993)

$q\bar{q} \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$ *NLO QCD*, $\quad g(\bar{q}) \to \ell\bar{\nu}\bar{\ell}'\nu'(\bar{q})$

Ohnemus (1994); Dixon, Kunszt, Signer (1998, 1999)

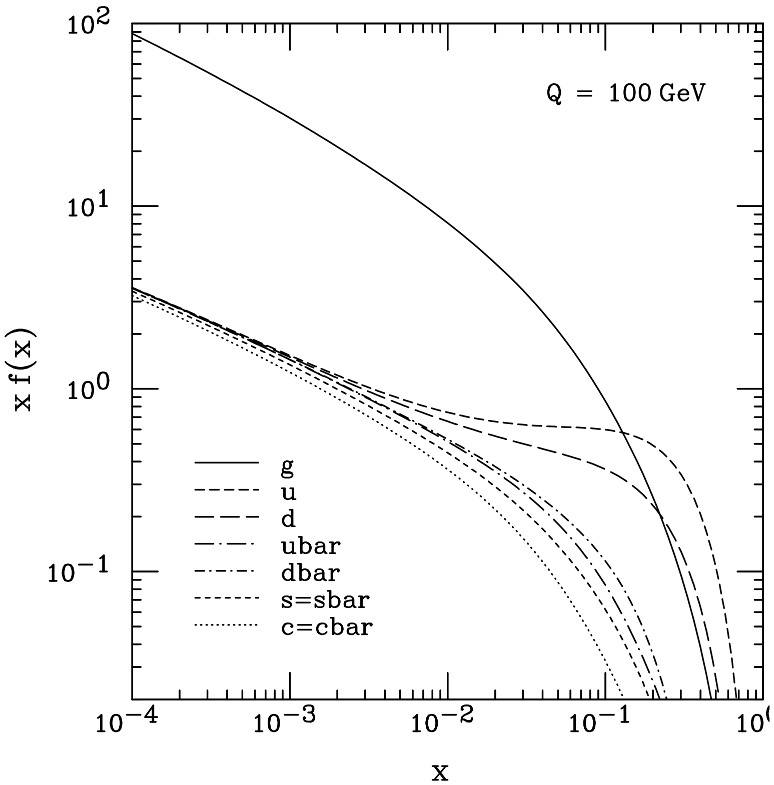
$p(\bar{p}) \to \ell\bar{\nu}\bar{\ell}'\nu'$ *at* $\mathcal{O}(\alpha_s)$

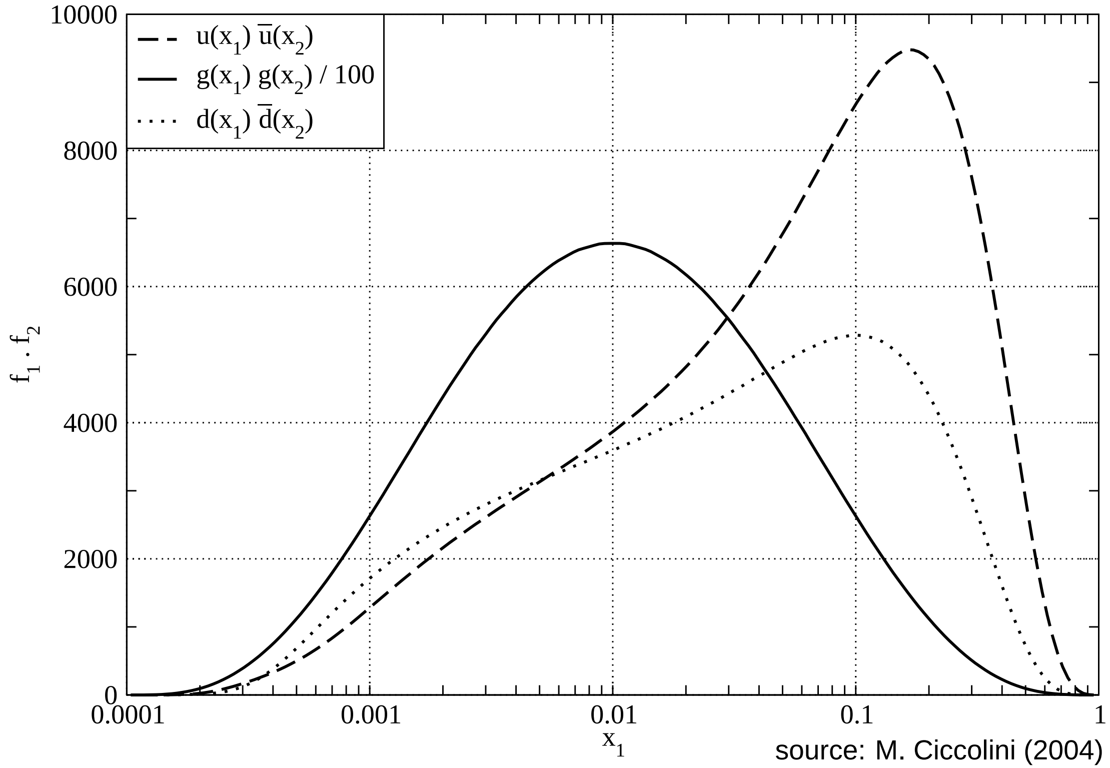
Campbell, K. Ellis (1999) **($\to$ MCFM)**

$p\text{`}\bar{p}\text{'} \rightarrow W^+W^-$ at $\mathcal{O}(\alpha_s^2)$

Why (partial) NNLO calc.? new subprocess: $gg \rightarrow W^+W^-$

- enhanced by large gluon-gluon flux at the LHC
- more similar to $gg \rightarrow H \rightarrow W^+W^-$ signal
- boost of W^+W^- system only in $q\bar{q}$ scattering

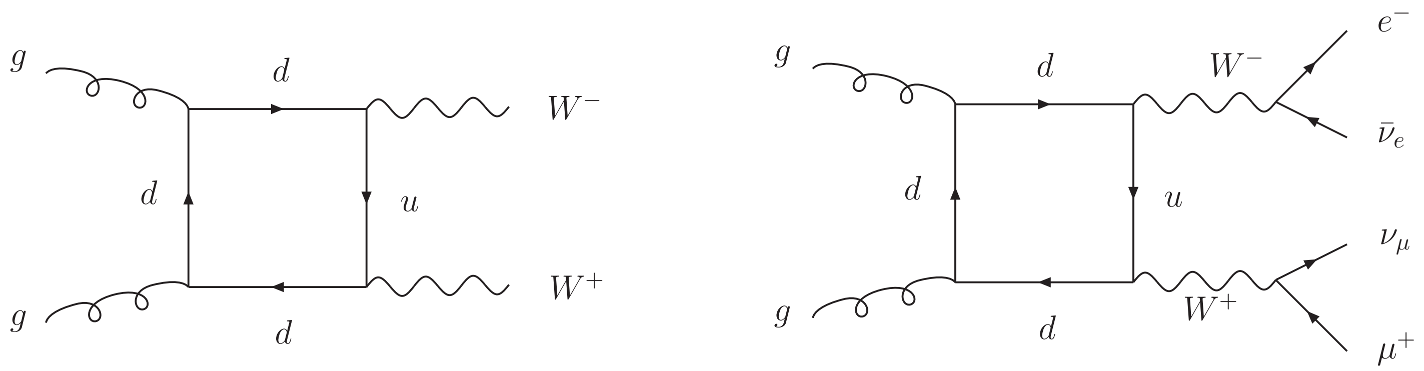




source: M. Ciccolini (2004)

CTEQ6M, $x_1 \cdot x_2 = \hat{s}/s = m_{WW}^2/s \approx 10^{-4} = 0.01^2$, (cut: $\cos\theta_{\ell\ell,\text{beam}} < 0.8$)

$gg \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$



$\mathcal{O}(\alpha_s^2)$, *LO, loop-induced*

$$gg \to W^+W^-$$

Glover, van der Bij (1989) massless quarks in loop

Kao, Dicus (1991) + massive loop

$$gg \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$$

Binoth, Ciccolini, NK, Krämer (2005) massless quarks in loop, off-shell effects

Dührssen, Jakobs, Marquard, van der Bij (2005) + massive loop, NWA

Binoth, Ciccolini, NK, Krämer (2006) + massive loop, off-shell effects & H interference

Calculation

$$g(p_1,\lambda_1) + g(p_2,\lambda_2) \to W^{+*}(p_3) + W^{-*}(p_4) \to \bar{\ell}'(p_5,+) + \nu'(p_6,-) + \bar{\nu}(p_7,+) + \ell(p_8,-)$$

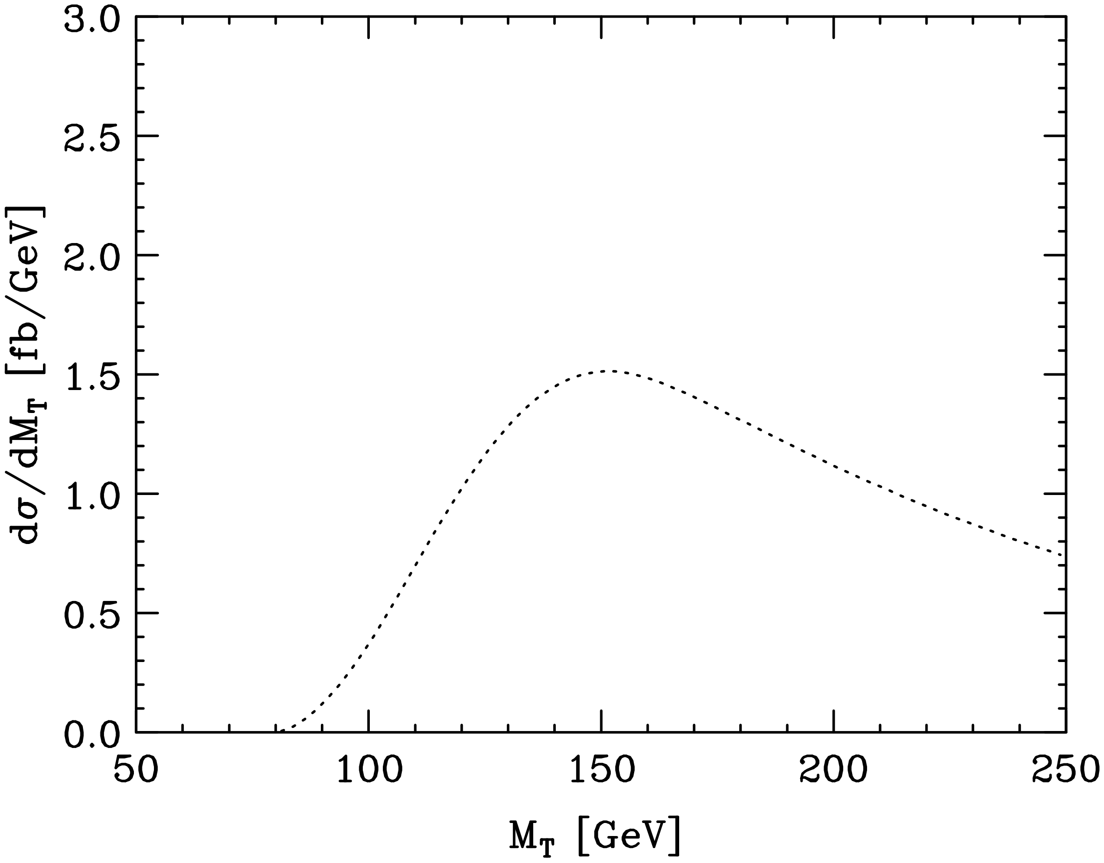
$$\mathcal{M}_{DR} = \varepsilon_{1,\mu_1}\varepsilon_{2,\mu_2}\mathcal{M}^{\mu_1\mu_2\mu_3\mu_4} P_{\mu_3\nu_3}(p_3, M_W) P_{\mu_4\nu_4}(p_4, M_W) J_3^{\nu_3} J_4^{\nu_4}$$

$$J_3^{\mu_3} = \bar{u}(p_6)\gamma^{\mu_3}\tfrac{1}{2}(1-\gamma_5)v(p_5)\,,\ J_4^{\mu_4} = \bar{u}(p_8)\gamma^{\mu_4}\tfrac{1}{2}(1-\gamma_5)v(p_7)$$

$$P^{\mu\nu}(p, M_W) = g^{\mu\nu}/(p^2 - M_W^2 + i\,M_W\Gamma_W)$$

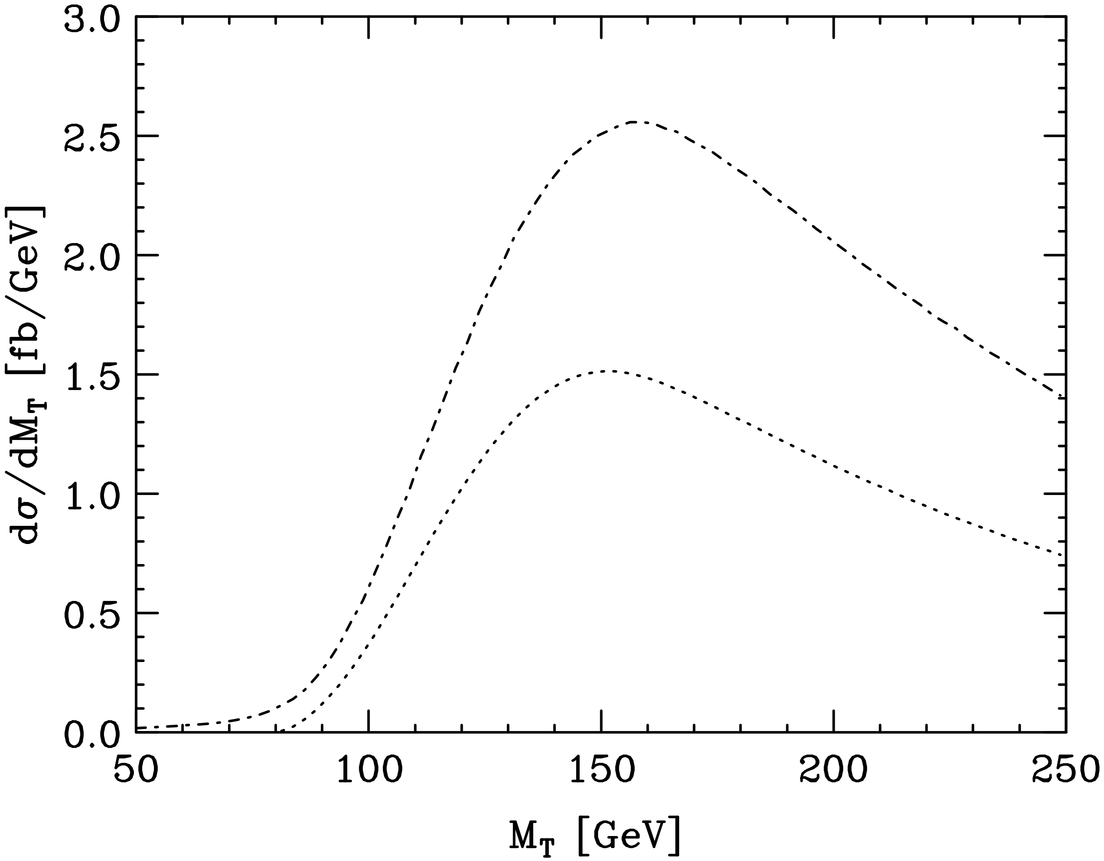
- external leptons: massless
- internal quarks: massless + massive (t, b)
- arbitrary invariant masses for W bosons (off-shell effects)
- gauge-invariant amplitude
- $gg \to H \to WW$ amplitude included (signal-background interference)
- $\mu_{ren,fac} = M_W$, CTEQ6M, G_μ scheme ($\alpha(0), \alpha(M_Z)$: $\mp$ 10%)
- Passarino, Veltman (1979) / Binoth, Guillet, Heinrich (2000) reduction
- two independent calculations
- checked with results in literature
- tools: FeynArts, LoopTools Hahn, FORM Vermaseren

Transverse mass distribution



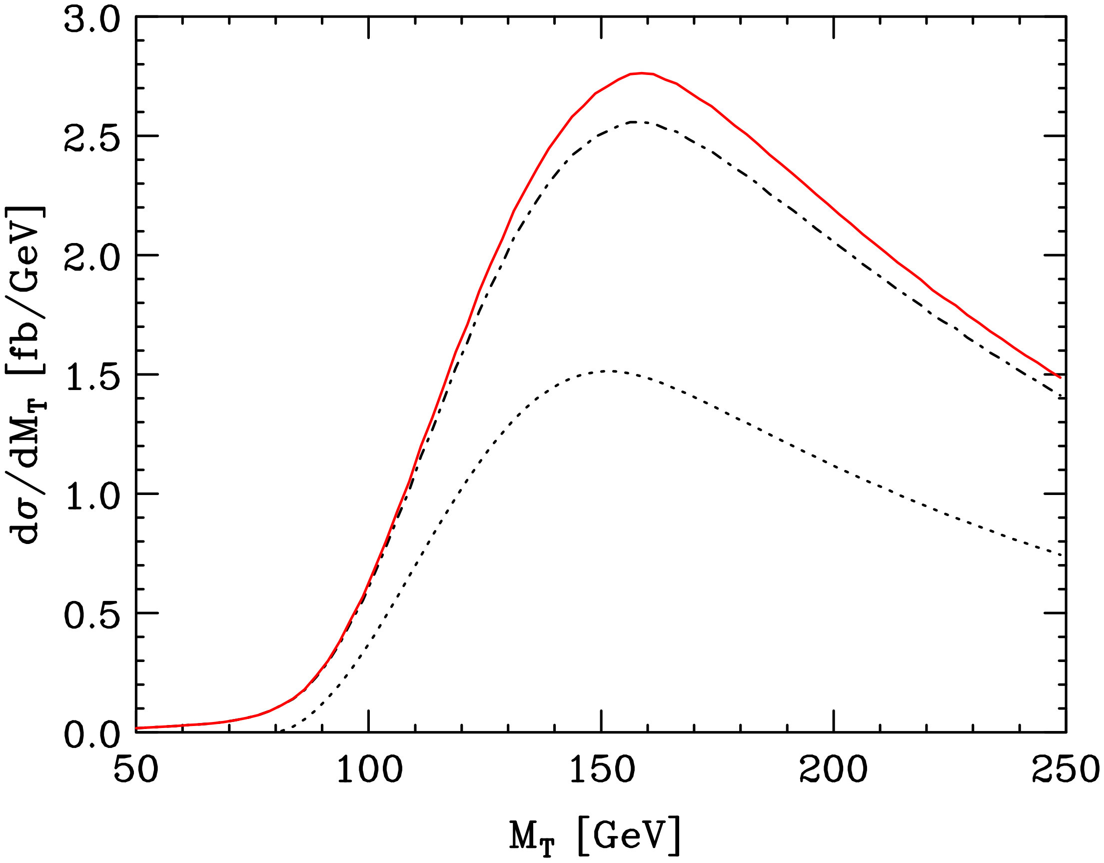
$q\bar{q} \longrightarrow \ell\bar{\nu}\bar{\ell}'\nu'$ (LO)

standard LHC cuts (*std cuts*): $p_{T,\ell} > 20$ GeV, $|\eta_\ell| < 2.5, \not{p}_T > 25$ GeV



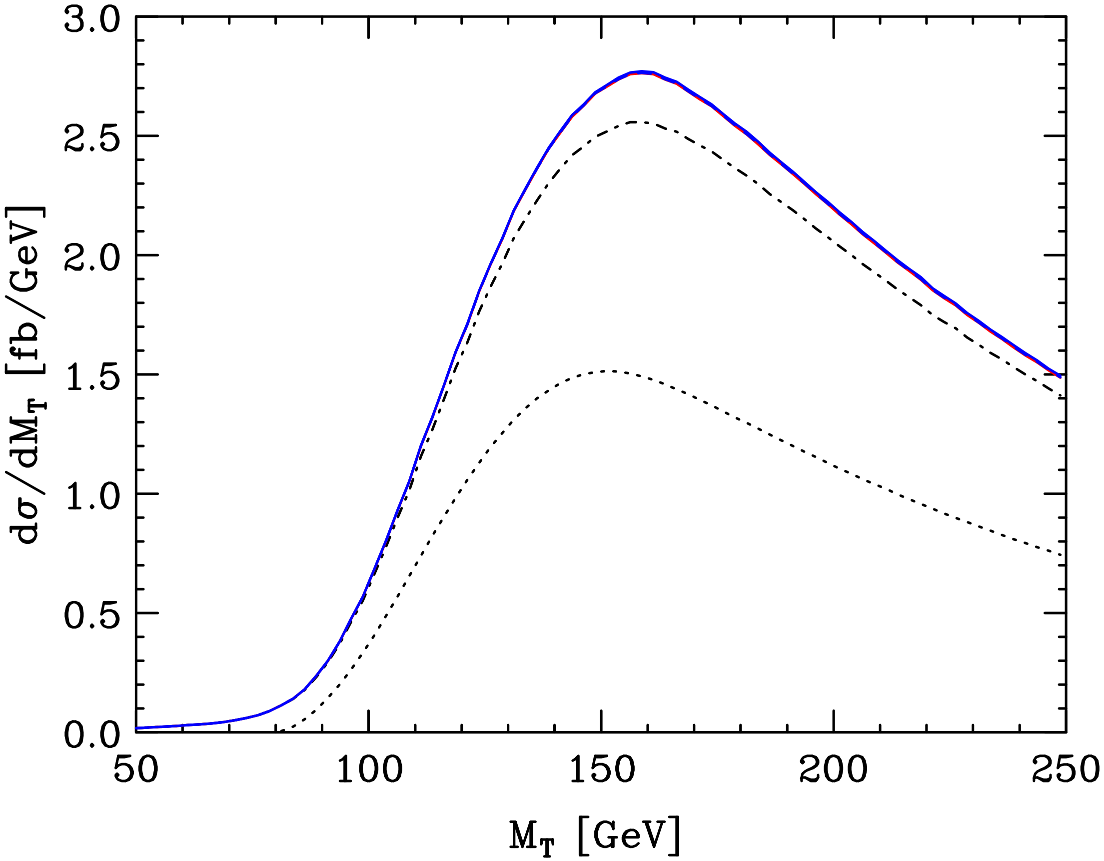
+ $p\,\overset{(}{\bar{p}}{}^{)} \rightarrow \ell\bar{\nu}\bar{\ell}'\nu'$ $\mathcal{O}(\alpha_s)$ corrections

std cuts



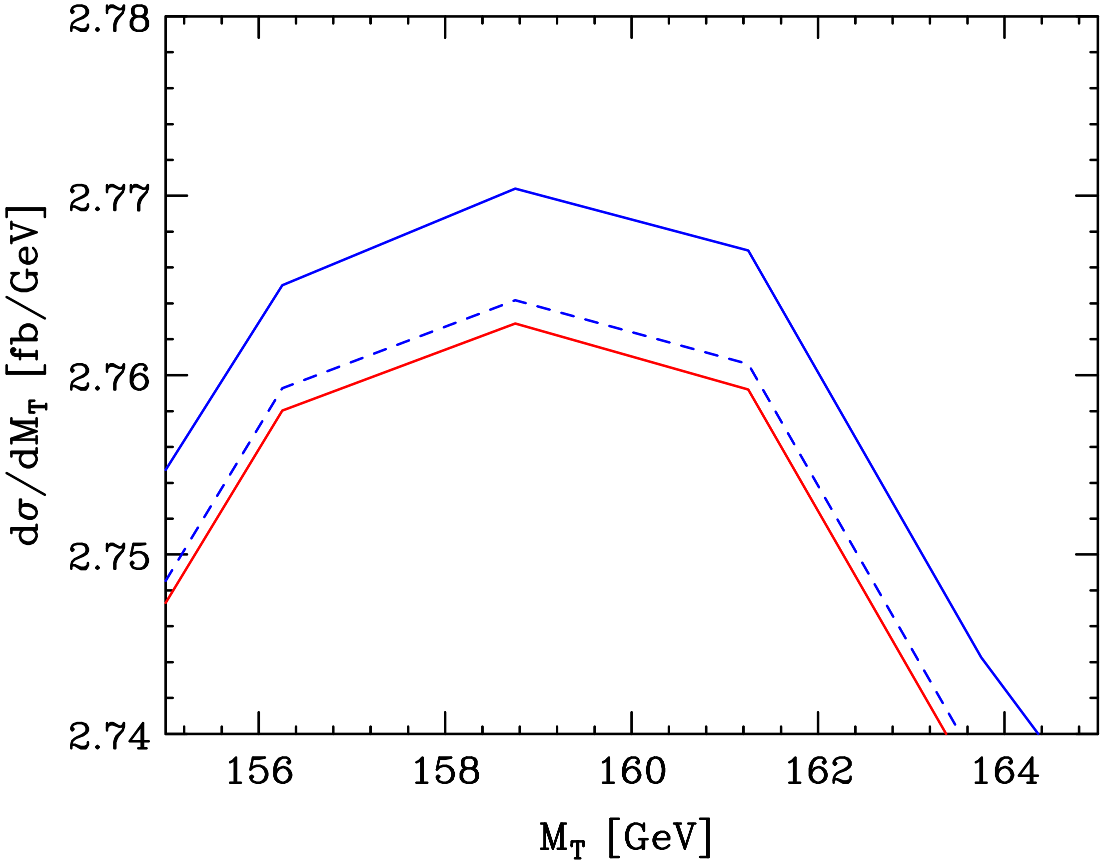
\+ $gg \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$ (2 massless generations)

std cuts



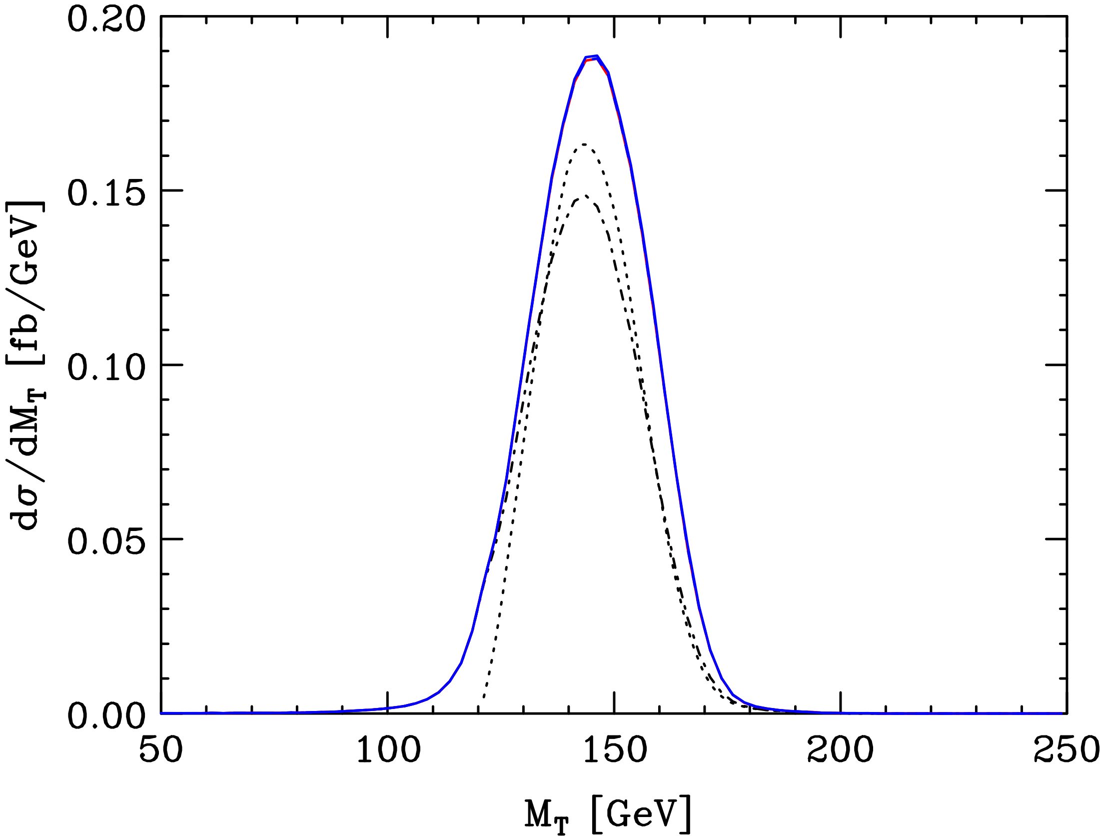
+ $gg \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$ (3rd generation)

std cuts



dashed: without massless-massive quark interference

std cuts

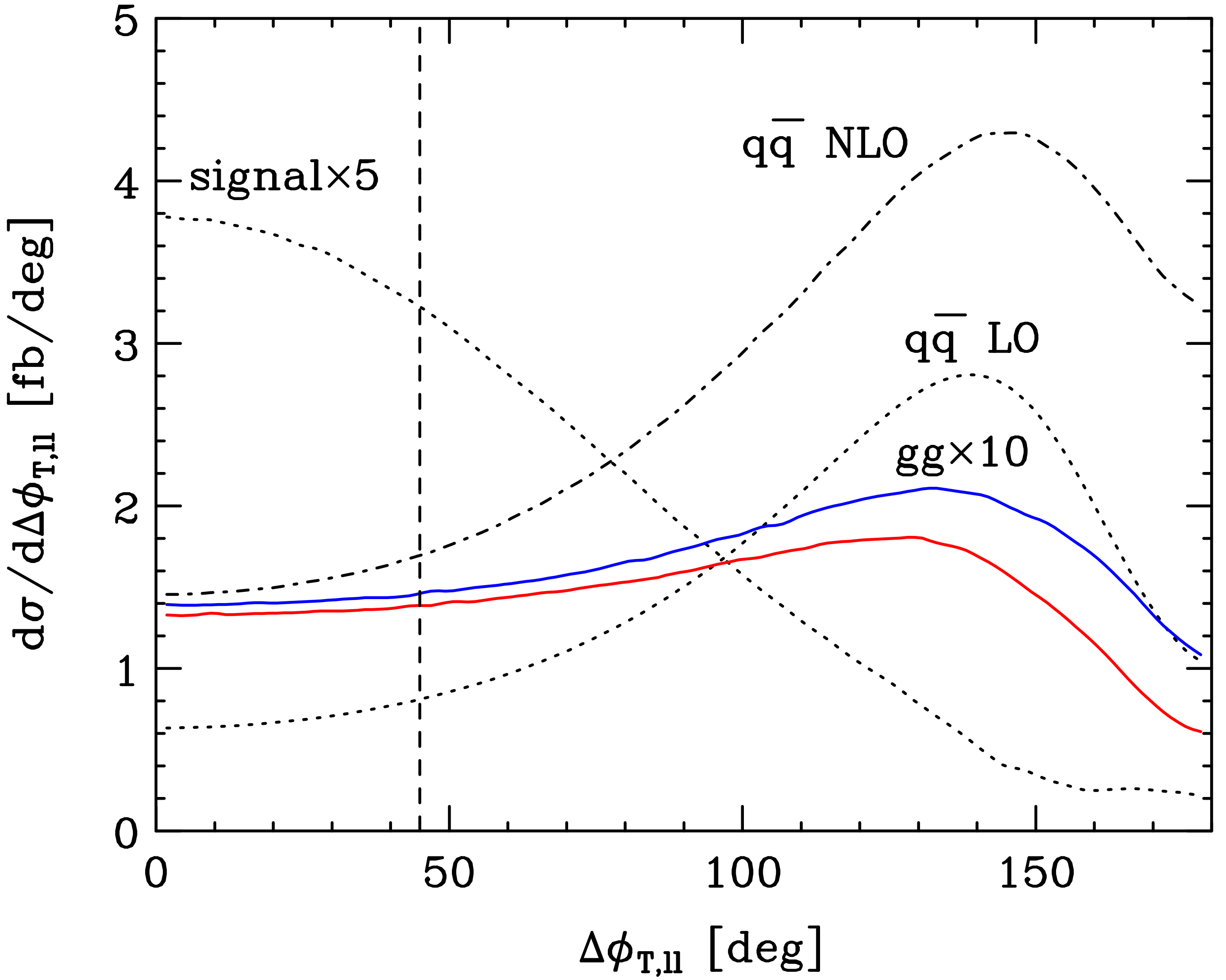


bkg cuts: *std cuts* & Higgs search cuts:

$\Delta\phi_{T,\ell\ell} < 45°$, $m_{\ell\ell} < 35$ GeV, jet veto: $p_{Tj} > 20$ GeV and $|\eta_j| < 3$,
35 GeV $< p_{T\ell,\text{max}} < 50$ GeV, 25 GeV $< p_{T\ell,\text{min}}$

Davatz, Dissertori, Dittmar, Grazzini, Pauss (2004)

Charged-lepton azimuthal opening angle



$M_H = 165$ GeV, *std cuts*

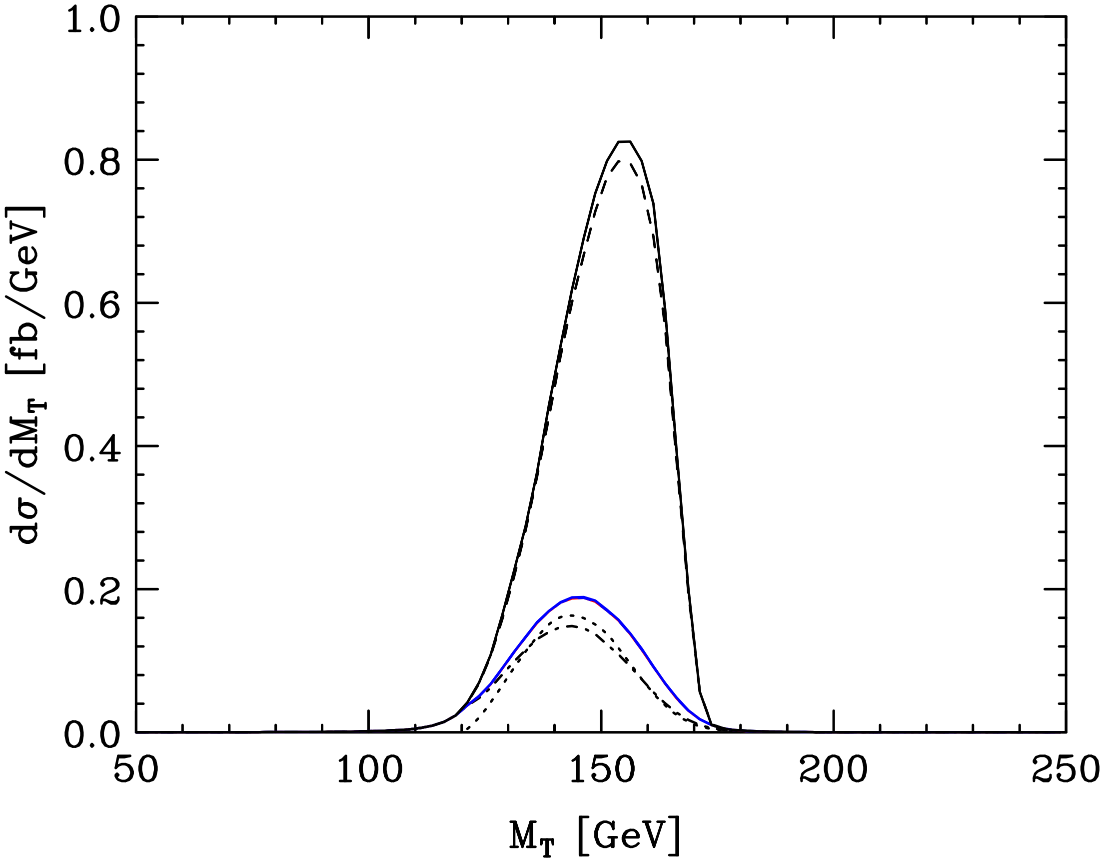
Results overview

2 massless generations, 3 generations

	$q\bar{q}$		gg	$\frac{\sigma_{gg,3gen}}{\sigma_{gg,2gen}}$	$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{{\rm NLO}+gg}}{\sigma_{\rm NLO}}$
$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu')$ [fb], LHC, $M_W/2 \le \mu_{\rm ren,fac} \le 2M_W$	LO	NLO	NNLO			
σ_{tot}	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	$60.12(7)$ $53.61(2)^{+14.0}_{-10.8}$	1.12	1.57	1.04 1.04
σ_{std}	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	$29.79(2)$ $25.89(1)^{+6.85}_{-5.29}$	1.15	1.82	1.06 1.05
σ_{bkg}	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	$1.416(3)$ $1.385(1)^{+0.40}_{-0.31}$	1.02	1.05	**1.30** **1.29**

$gg \to WW$ **is important for extraction of Higgs couplings**

Signal-background interference



+ $gg \to H \to W^+W^- \to \ell\bar{\nu}\bar{\ell}'\nu'$

$gg(\to H) \to \gamma\gamma$: $\sim 5\%$ Dicus, Willenbrock (1988); Dixon, Siu (2003)

$M_H = 165$ GeV, *bkg cuts*

GG2WW event generator & parton-level program

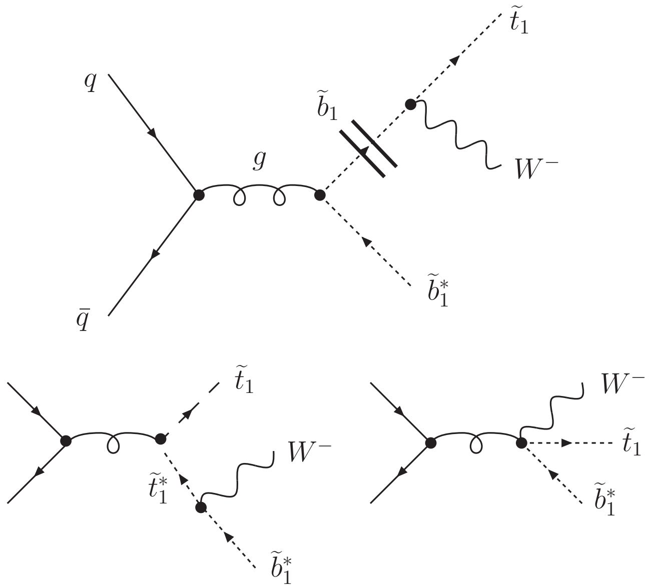
`http://hepsource.sf.net/GG2WW/`

- includes full spin correlations, off-shell & interference effects
- generates weighted and unweighted events
- events in LHA format, compatible with PYTHIA etc.
- LHAPDF interface
- user-friendly specification of selection cuts and histograms
- adaptive MC integration (Dvegas)
- OmniComp-based parallel mode (incl. histogram filling)

used by ATLAS and CMS for $H \to WW$ studies

Outlook: SUSY/2HDM NWA corrections

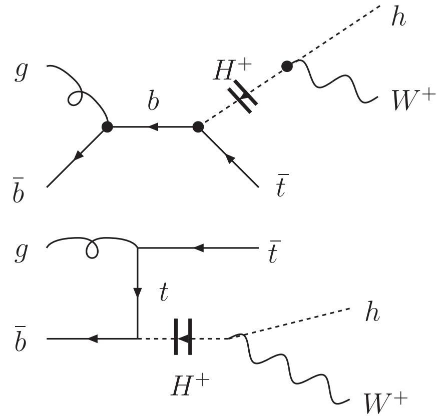
$q\bar{q} \to g \to (\tilde{b}_1 \to W^- \tilde{t}_1)\, \tilde{b}_1^*$



E_{PCMS} [TeV]	σ [fb]		
	NWA	$\mathcal{M}_{\text{res}}$	complete
2	33.4	41.7 (1.2)	35.3 (1.06)
4	12.0	26.3 (2.2)	13.5 (1.13)
10	2.10	18.2 (8.7)	2.56 (1.22)

$m_{\tilde{b}_1} = 517$ GeV, $\Gamma_{\tilde{b}_1} = 3.9$ GeV

$g\bar{b} \to g \to (H^+ \to h\, W^+)\, \bar{t}$



+ 8 nonresonant graphs

E_{PCMS} [TeV]	σ [fb]	
	NWA, $\mathcal{M}_{\text{res}}$	complete
0.65	0.236	12.4 (53)
2	0.130	16.7 (128)
LHC	0.112	12.2 (108)

$m_{H^+} = 414$ GeV, $\Gamma_{H^+} = 0.9$ GeV,
$m_h = 112$ GeV

$\mathbf{BR_{H^+ \to hW^+}} = 2 \cdot 10^{-3}$ ($\to$ NMSSM,2HDM)

MSSM (SPS1a, no selection cuts) Berdine, NK, Orr, Rainwater (in preparation)

Summary

- theory $\longrightarrow$ new particles/mechanisms exist
- discoveries at the LHC expected
- important background effects and corrections
- accurate predictions: improvements necessary and feasible
- more work ahead ...