Monte Carlo for fm processes (MCFM)

John Campbell and R. Keith Ellis

Radcor 2000, Carmel, September 12, 2000

- Strong radiative corrections to $Wb\bar{b}$ production in $p\bar{p}$ collisions, RKE and S. Veseli, Phys.Rev.D60:011501,1999, hep-ph/9810489
- An update on vector boson pair production at hadron colliders
  JMC and RKE, Phys.Rev.D60:113006,1999, hep-ph/9905386
- Radiative corrections to $Zb\bar{b}$ production
  JMC and RKE, hep-ph/0006304, PRD (in press)

Talk available on the web at
www-theory.fnal.gov/people/ellis/Talks/rad.ps.gz

NLO Monte Carlo development

Campbell, Ellis, Veseli

- The next run at the Tevatron will be sensitive to processes at the femtobarn level
- Particularly interesting are processes involving heavy quarks, leptons, missing energy.
- Standard model processes which result in these final states often include W,Z (or Higgs). Full experimental control of these processes may not be possible. E.g. $\sigma(p\bar{p} \to W(e\nu)Z(\mu^+\mu^-)) = 3$ fb, (after plausible cuts).
- We provide a unified description of many processes at NLO in QCD with a Monte Carlo program, MCFM, which permits the calculation of any infra-red safe variable and the implementation of cuts.
- NLO is the first approximation which gives any indications of the size of the error.

Processes already included in MCFM at NLO
(including vector boson and Higgs decays and pp or $p\bar{p}$)

- $p\bar{p} \to W^{\pm}$
- $p\bar{p} \to W^{\pm} + 1$ jet
- $p\bar{p} \to W^{\pm} + b\bar{b}$, for $m_b = 0$
- $p\bar{p} \to Z/\gamma^* \to (e^-e^+, \mu^-\mu^+, \tau^-\tau^+)$
- $p\bar{p} \to Z/\gamma^* + 1$ jet
- $p\bar{p} \to Z/\gamma^* + b\bar{b}$, for $m_b = 0$
- $p\bar{p} \to W^{\pm} + H$
- $p\bar{p} \to Z + H$
- $p\bar{p} \to W^{\pm} Z/\gamma^*$
- $p\bar{p} \to Z/\gamma^* Z/\gamma^*$
- $p\bar{p} \to W^+ W^-$
- $p\bar{p} \to H \to W^+ W^-$
- $p\bar{p} \to H \to Z^0 Z^0$

Processes included in MCFM at LO (including vector boson and top decays).

- $p\bar{p} \to t\bar{t}$
- $p\bar{p} \to t\bar{t}H$
- $p\bar{p} \to Hg$
- $p\bar{p} \to t\bar{b}$ (single top production)
- $p\bar{p} \to qt\bar{b}$ (single top production, W gluon fusion)

Processes which are under construction at NLO

- $p\bar{p} \to W^{\pm} + 2$ jet
- $p\bar{p} \to Z/\gamma^{*} + 2$ jet

Calculational Method

- we use the general subtraction procedure formulated by ERT and Catani and Seymour [Ellis, Ross, Terrano, NPB178, 421 (1981); Catani, Seymour, NPB485, 291 (1997)]

- at NLO the cross section for two initial partons a and b, and for m outgoing partons, is given by

$$\sigma_{ab} = \sigma_{ab}^{LO} + \sigma_{ab}^{NLO} \ ,$$

where

$$\begin{aligned} \sigma_{ab}^{LO} &= \int_m d\sigma_{ab}^{B} \ , \\ \sigma_{ab}^{NLO} &= \int_{m+1} d\sigma_{ab}^{R} + \int_m d\sigma_{ab}^{V} \end{aligned}$$

- the singular parts of the QCD matrix elements for real emission, corresponding to soft and collinear emission, can be isolated in a process independent manner.

- one can use this observation to construct a set of counter-terms (ct),

$$d\sigma^A = \sum_{ct} d\sigma^B \otimes dV_{ct} \ ,$$

  where $d\sigma^B$ denotes appropriate color and spin projection of the Born-level cross section, while the counter-term factors are *independent* of the details of the process under consideration

- these counter-terms cancel all non-integrable singularities in $d\sigma^R$, so that one can write

$$\begin{aligned} \sigma_{ab}^{NLO} &= \int_{m+1} \left[d\sigma_{ab}^R - d\sigma_{ab}^A \right] \\ &+ \int_{m+1} d\sigma_{ab}^A + \int_m d\sigma_{ab}^V \end{aligned}$$

- the phase space integration in the first term above can be performed numerically in four dimensions

- the counter-terms $d\sigma^A$ have to be integrated analytically in d dimensions over the single-parton subspaces which lead to soft and collinear divergences,

$$\int_{m+1} d\sigma^A = \sum_{ct} \int_m d\sigma^B \otimes \int_1 dV_{ct}$$

- that can be accomplished by suitable definition of the counter-term partonic variables in dV_{ct}

- the poles in $\epsilon = (d-4)/2$ resulting from the above procedure are combined with the ones coming from the virtual graphs

- all divergences cancel and the remaining phase space integration can be carried out numerically

Generation of counter-event

For event

$$q(p_1)+\bar{q}(p_2) \to W(\nu(p_3)+e^+(p_4))+g(p_5), \;\; p_1+p_2 = \sum_{i=3}^{5} p_i$$

generate a counter-event

$$q(x_a p_1)+\bar{q}(p_2) \to W(\nu(\tilde{p}_3)+e^+(\tilde{p}_4)), \;\; x_a p_1+p_2 = \sum_{i=3}^{4} \tilde{p}_i$$

$((1-x_a) = (p_1.p_5 + p_2.p_5)/p_1.p_2)$. A Lorentz tranformation is performed on all j final state momenta

$$\widetilde{p}_j^{\mu} = \Lambda^{\mu}_{\nu} p_j^{\nu}, \;\; j = 3, 4, \; (\widetilde{p}_j^{\mu} \to p_j \text{ for } p_5 \text{ collinear or soft})$$

Energy of emitted gluon is absorbed by p_1, momentum components absorbed by Lorentz transformation of final state.

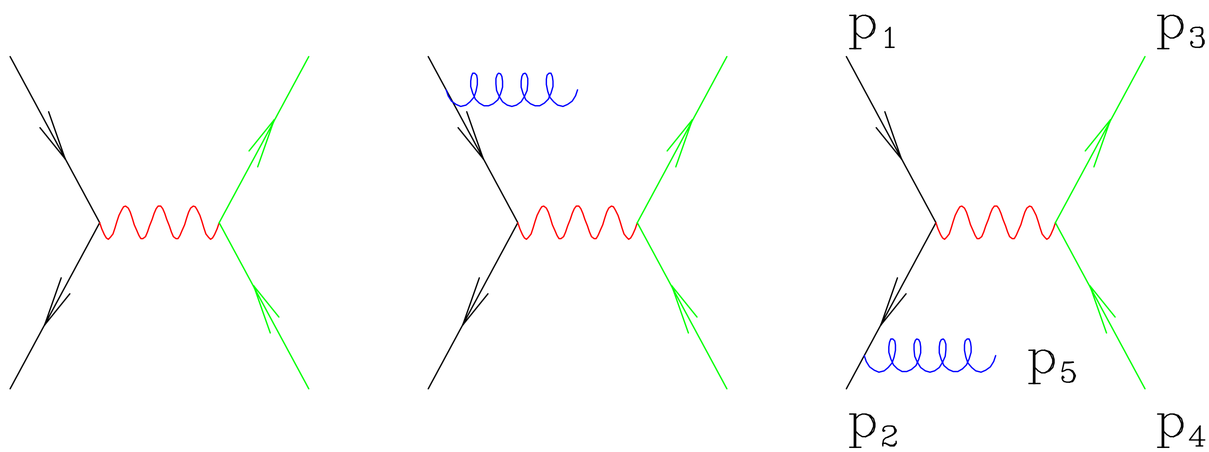
The phase space has a convolution structure:

$$d\phi^{(n)}(p_5, p_4, p_3; p_2, p_1) \quad = \quad \int_0^1 dx \; d\phi^{(n-1)}(\widetilde{p}_4, \widetilde{p}_3; p_2, xp_1)$$
$$[dp_5(p_2, p_1, x)]$$

where

$$[dp_5(p_2, p_1, x)] = \frac{d^d p_5}{(2\pi)^3} \, \delta^+(p_5^2) \; \Theta(x)\Theta(1-x) \; \delta(x - x_a) \quad .$$

Counter-event for W-production



In the soft limit $p_5 \to 0$ we have

$$|M_1(p_1, p_2, p_3, p_4, p_5)|^2 = g^2 \frac{C_F p_1 \cdot p_2}{p_1 \cdot p_5 p_2 \cdot p_5} |M_0(p_1, p_2, p_3, p_4)|^2$$

Eikonal factor is associated with radiation from a given leg by partial fractioning

$$\frac{p_1 \cdot p_2}{p_1 \cdot p_5 \; p_2 \cdot p_5} \to \left[\frac{p_1 \cdot p_2}{p_1 \cdot p_5 + p_2 \cdot p_5}\right]\left[\frac{1}{p_1 \cdot p_5} + \frac{1}{p_2 \cdot p_5}\right]$$

Including the collinear contributions (singular as $p_1.p_5 \to 0$) the matrix element for the counter-event has the structure

$$|M_1(p_1, p_2, p_3, p_4, p_5)|^2 = \frac{g^2}{x_a p_1 \cdot p_5} P_{qq}(x) |M_0(xp_1, p_2, \tilde{p}_3, \tilde{p}_4)|^2$$

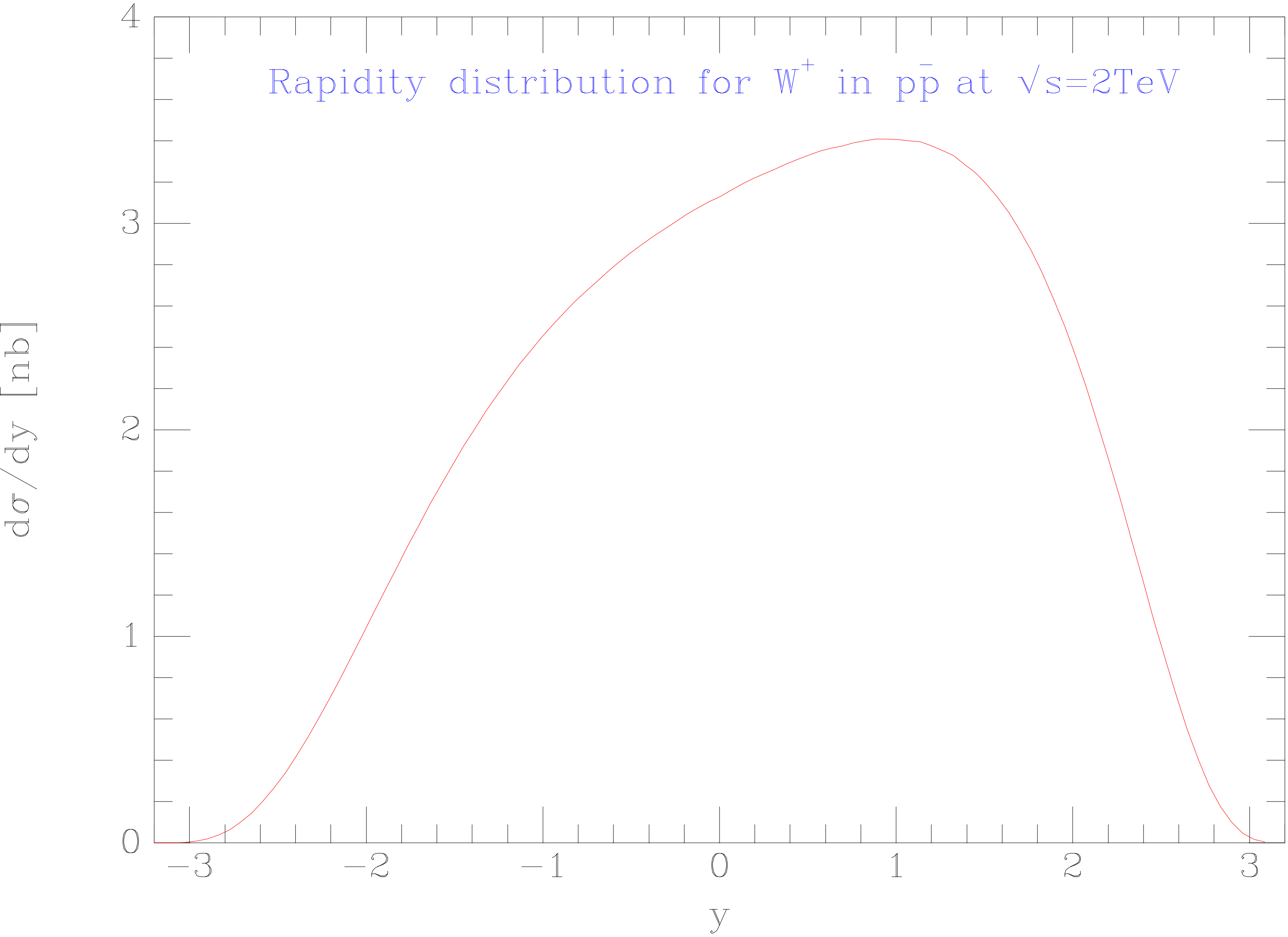
where

$$1 - x = (p_1.p_5 + p_2.p_5)/p_1.p_2$$

and

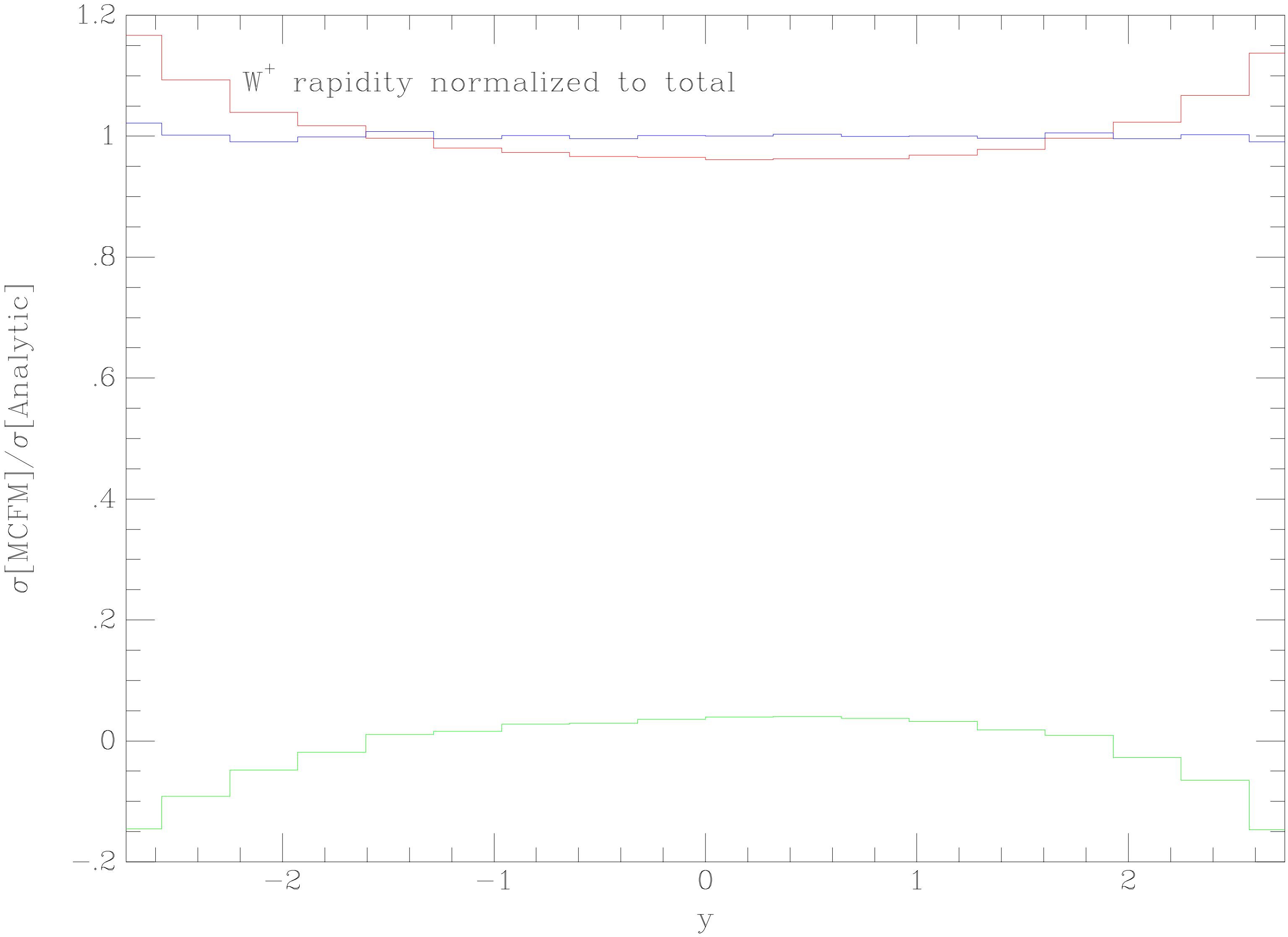
$$P_{qq} = C_F(1 + x^2)/[1 - x]$$

W Rapidity distribution



- For the case of an on-shell W the rapidity distribution at NLO is calculable analytically
- The above is shown calculated in the $\overline{MS}$ scheme.

W Rapidity using MCFM



- LO+Virtual+Counterterm is the dominant contribution to the cross section
- Real-Counterterm is small
- Total/Divided exact analytic result

Example: Vector Boson pair production

- Vector boson production provides a standard model source of charged leptons, missing energy and b-quarks, which are signals for many sorts of new physics.

- Previous calculations of vector boson pair production in $O(\alpha_S)$ were
  a) for on-mass shell bosons without decay

  Mele, Nason and Ridolfi, Nucl. Phys. **B357** (1991) 409

  Frixione, Nason and Ridolfi, Nucl. Phys. **B383** (1992) 3

  Frixione, Nucl. Phys. **B410** (1993) 280

  Ohnemus, PRD 44 (1991) 3477, PRD 44 (1991) 1403

  Ohnemus and Owens, PRD 43 (1991) 3636

  b) for on-mass shell bosons with decay (with only partial inclusion of virtual corrections).

  Ohnemus, PRD 50 (1994) 1931

  Baur, Han and Ohnemus, PRD 51 (1995) 3381, PRD 53 (1996) 1098

- Our calculation includes both the decay and full $O(\alpha_S)$ results[a] implemented into a Monte-Carlo program using the subtraction technique.

- Technically this is the first complete NLO evaluation including the decay, but the major improvement is the updating of parameters. Previous numerical results were given for $\sqrt{s} = 1.8, 16$ or 40 TeV. Collider running will not occur at any of these energies!

- In addition, we use modern values of the gluon distribution and α_S.

- We have checked that our results agree exactly with the earlier results in the literature in the zero width approximation. Results of Dixon, Kunszt and Signer, hep/9907305 are also in agreement with ours.

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[a] Dixon, Kunszt and Signer, Nucl.Phys. **B531**(1998) 3

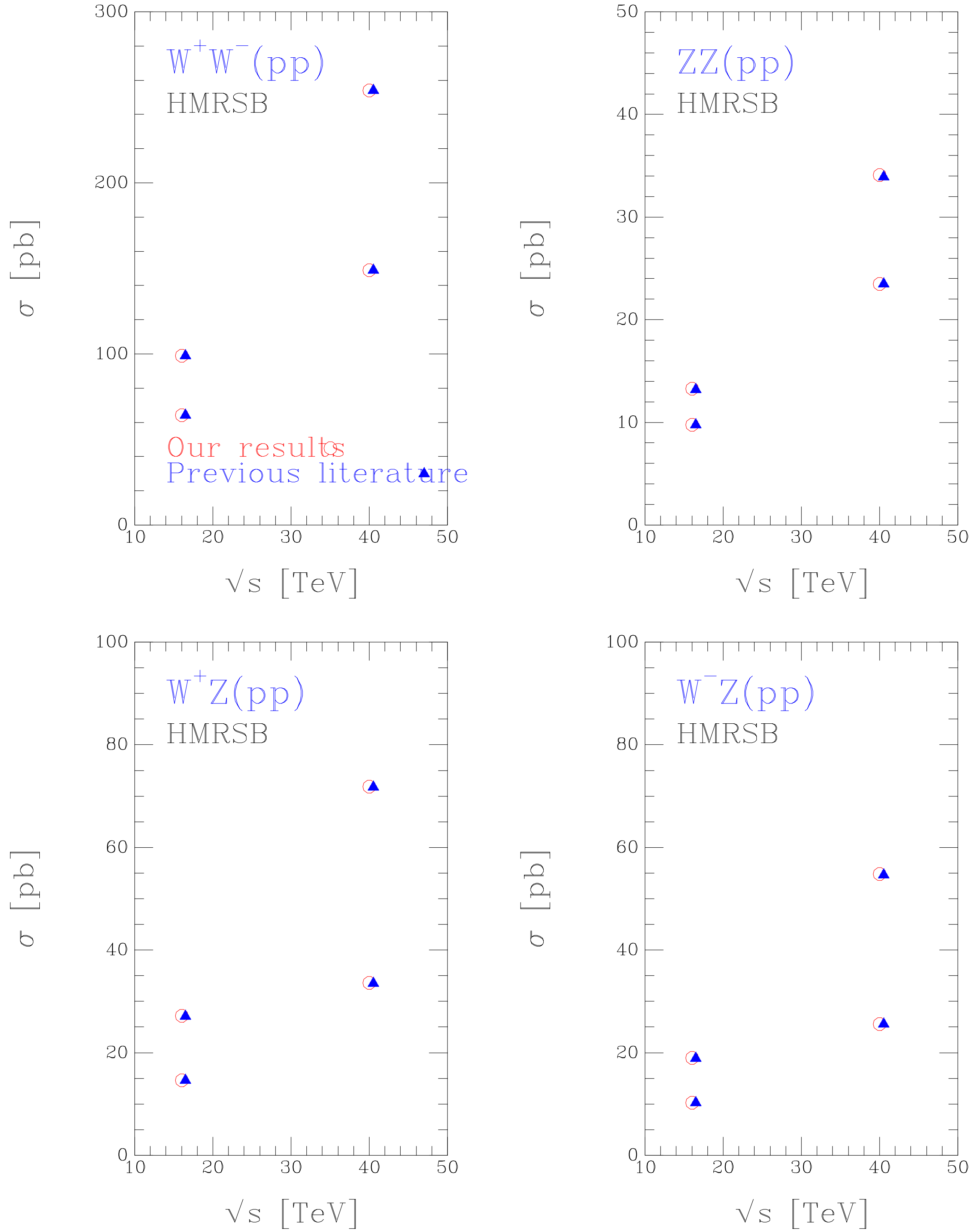


Figure 1: Comparison with results of Frixione, Nason et al, for total X-section using HMRSB with $\alpha_S(M_Z) = 0.10796$ in $O(1)$ and $O(\alpha_S)$ at $\sqrt{s} = 16$ and 40 TeV.

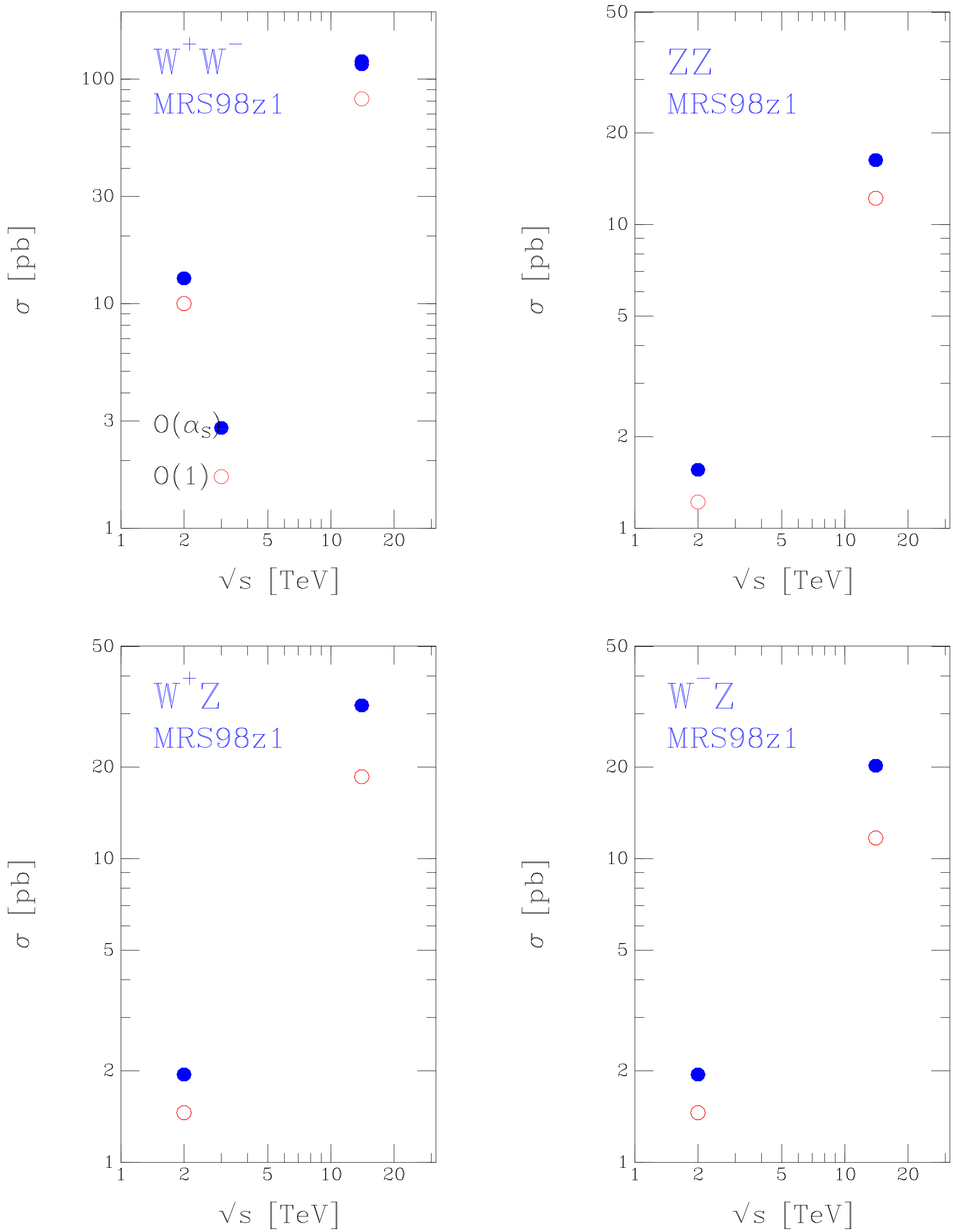


Figure 2: Modern results at $\sqrt{s} = 2$ TeV, $p\bar{p}$ and $\sqrt{s} = 14$ TeV, pp in $O(1)$ and $O(\alpha_S)$, $\mu = (M_{V_1} + M_{V_2})/2$

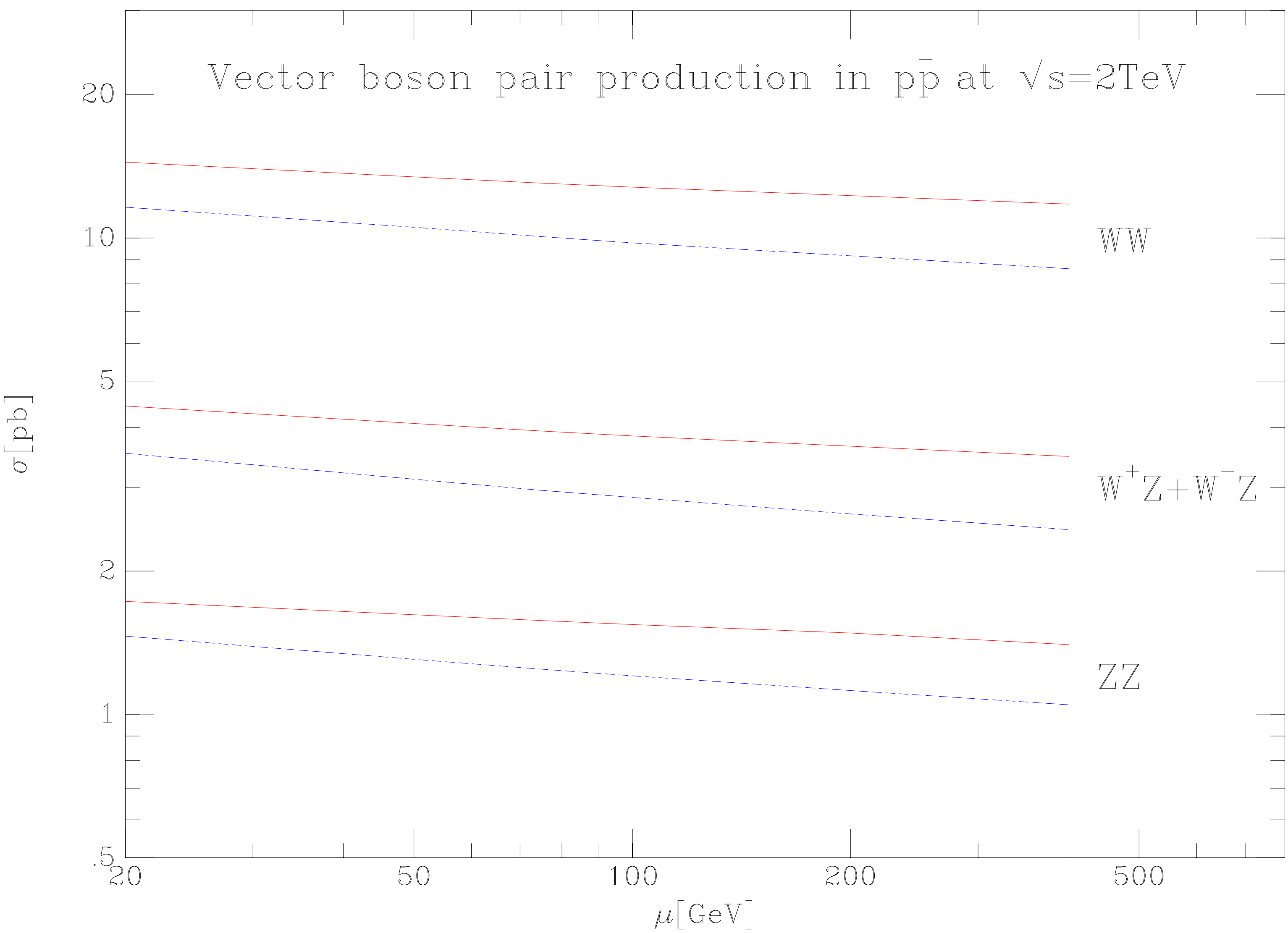
- the NLO corrections to the VV process are significant especially at LHC energies, because of influence of large flux of incoming gluons.

- all distributions are available; for production of W and Z off mass shell there are gauge invariance problems to be solved. (These problems have been extensively considered for $e^+e^- \to W^+W^-$ at LEP).

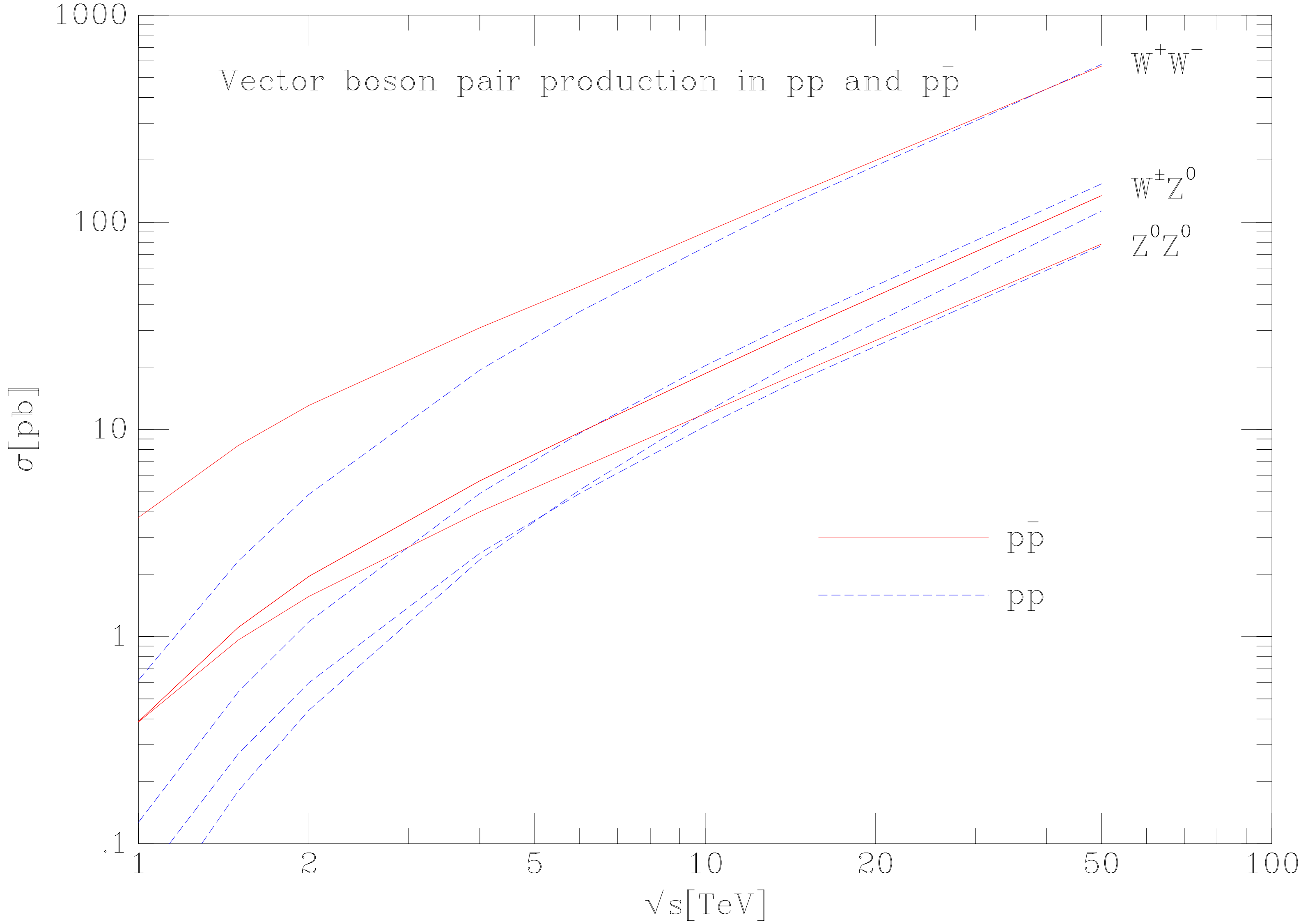
- Including decay, and with plausible cuts, we find (with MRSR1 structure functions at $\sqrt{s} = 2$ TeV.

$$\begin{aligned}
\sigma(W^+W^- \to e^+\mu^- + X) &= 70 \text{ fb} \\
\sigma(W^+Z \to e^+\mu^-\mu^+ + X) &= 3 \text{ fb} \\
\sigma(ZZ \to e^+e^-\mu^+\mu^- + X) &= 1.7 \text{ fb} \\
\sigma(ZZ \to e^+e^- + 3[\nu\bar{\nu}] + X) &= 11 \text{ fb}
\end{aligned}$$

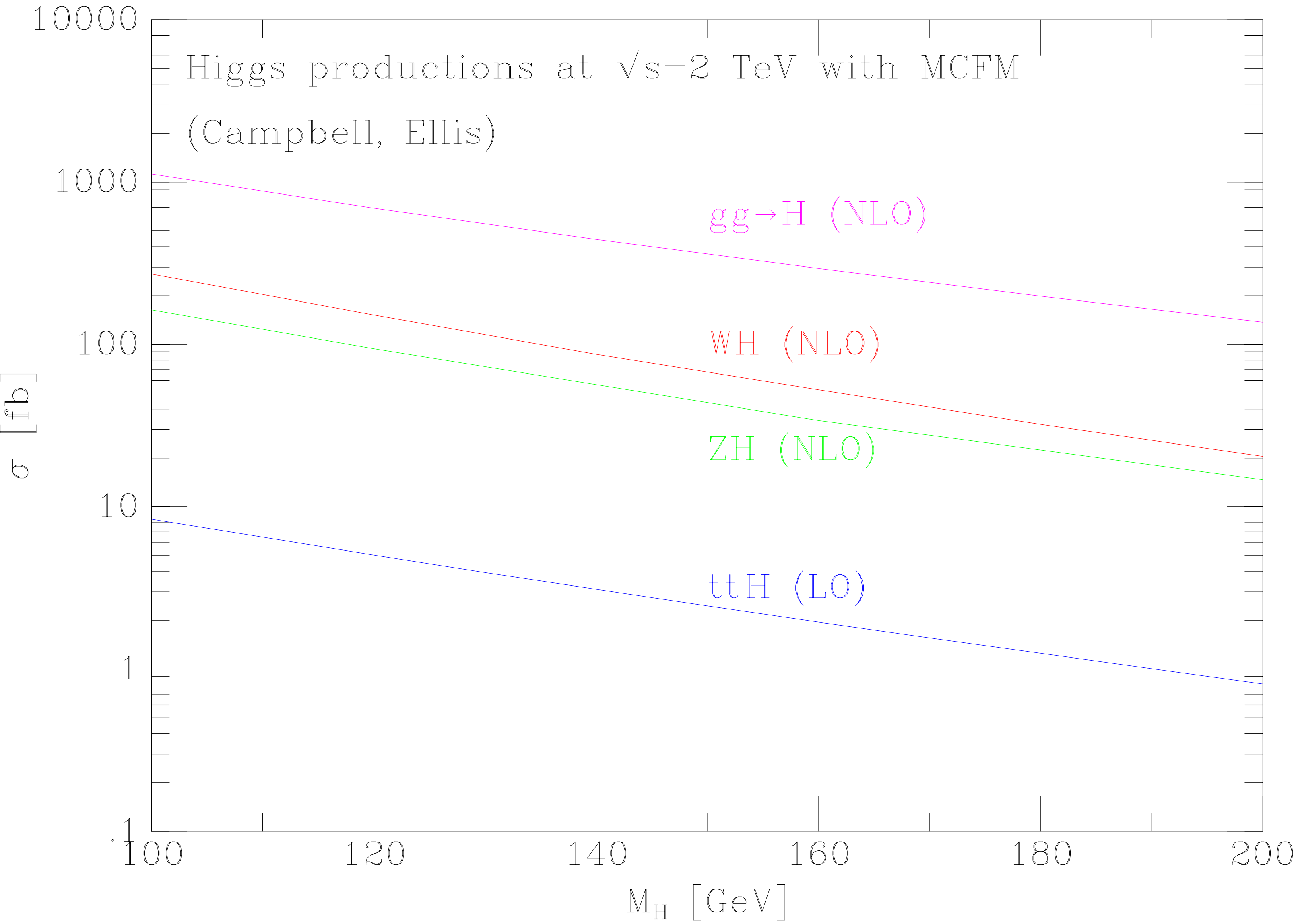
Results for total VV cross sections



Boson pair production vs. Energy

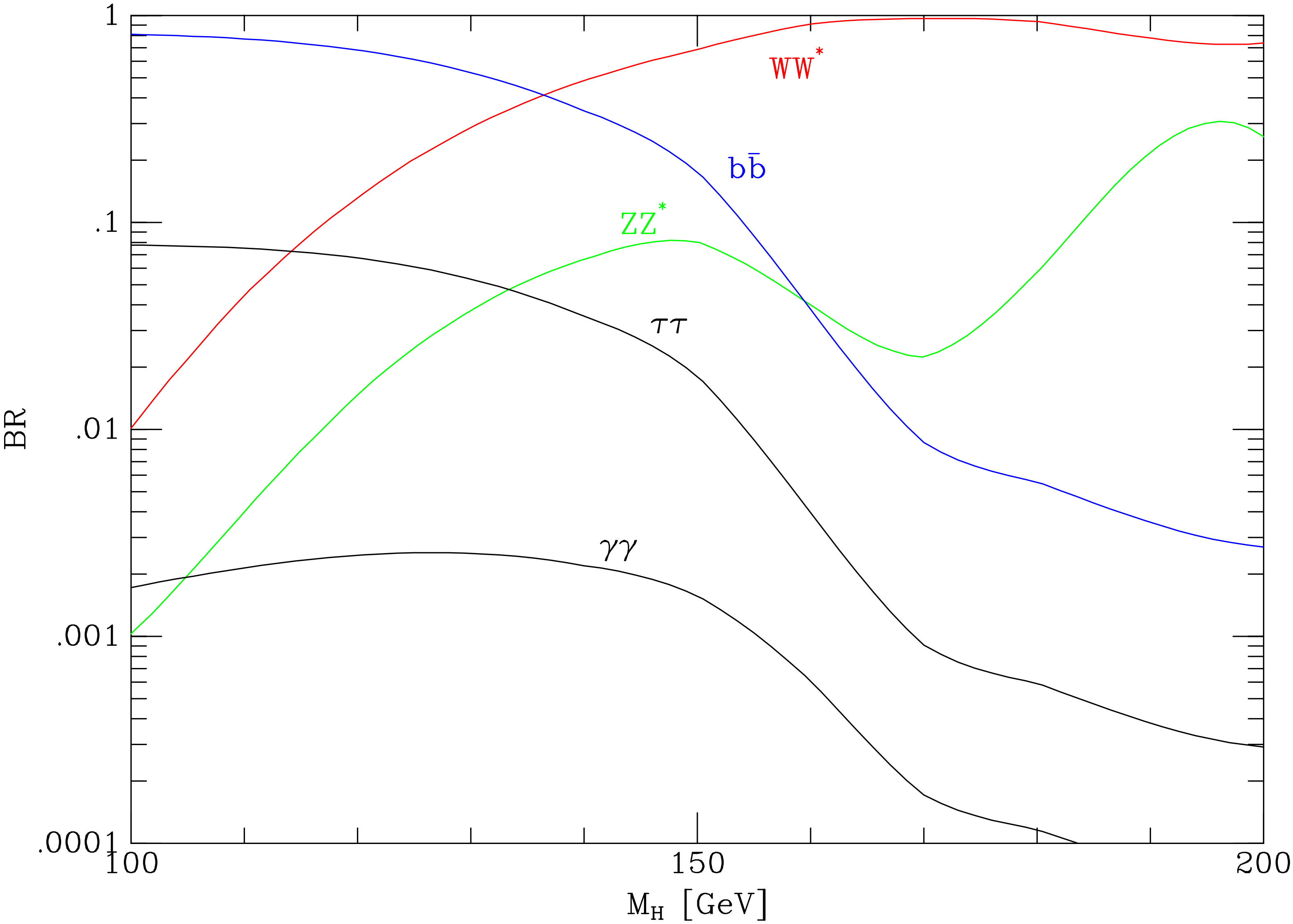


Higgs production at the Tevatron



- $gg \to H$ largest, but has background problems
- $p\bar{p} \to Z + H, W^{\pm} + H$ most promising
- SUSY Higgs cross sections may differ

Standard Model Higgs branching ratios



- $M_H < 130$ GeV, $H \to b\bar{b}$
- $M_H > 130$ GeV, $H \to WW^*$
- $BR(H \to \gamma\gamma) \sim 10^{-3}$, Hence 30fb^{-1} required at LHC

Tevatron Higgs overview

In the low mass region, $m_H < 130\ GeV$

- $p\bar{p} \to W^+(e^+\nu)H(b\bar{b})$
- $p\bar{p} \to Z(l\bar{l})H(b\bar{b}), \quad l = e, \mu, \nu$

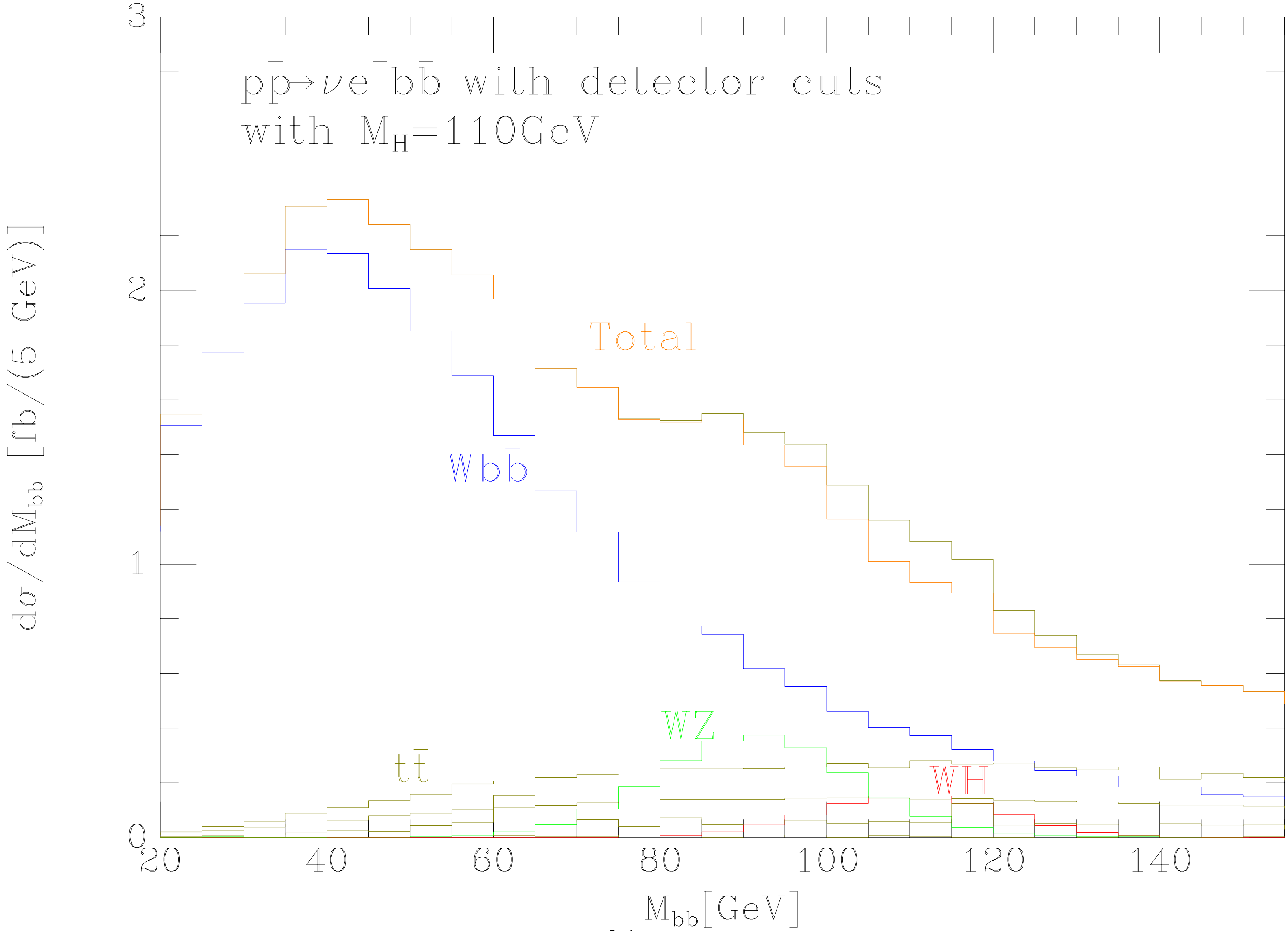
Signatures: lepton(s), missing energy, two b tags

In the high mass region $m_H > 135\ GeV$

- $gg \to H \to WW^*$
- $ZH \to ZWW^*$
- $WH \to WWW^*$

Signatures, di-lepton, trileptons, like sign dilepton+jets.

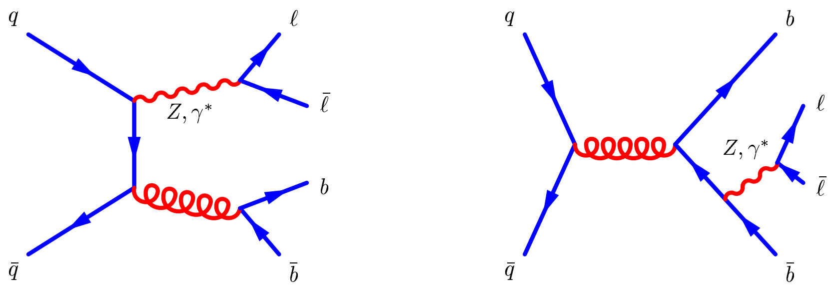
WH channel



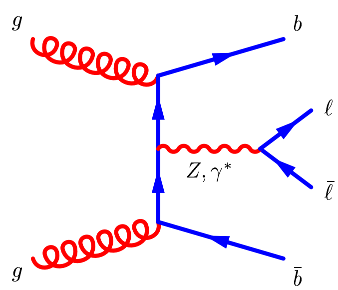
- $M_H = 110$ GeV and 10% resolution, LO only. Resolution testable with $Z \to b\bar{b}$, (seen in Run 1).
- With the simplest cuts, S/B ratio is low.
- Extraction of signal requires detailed knowledge of normalization and kinematic structure of background.

Zbb

New results on the background channel $Zb\bar{b}$ relevant for Higgs search in the channel ZH



(a) (b)

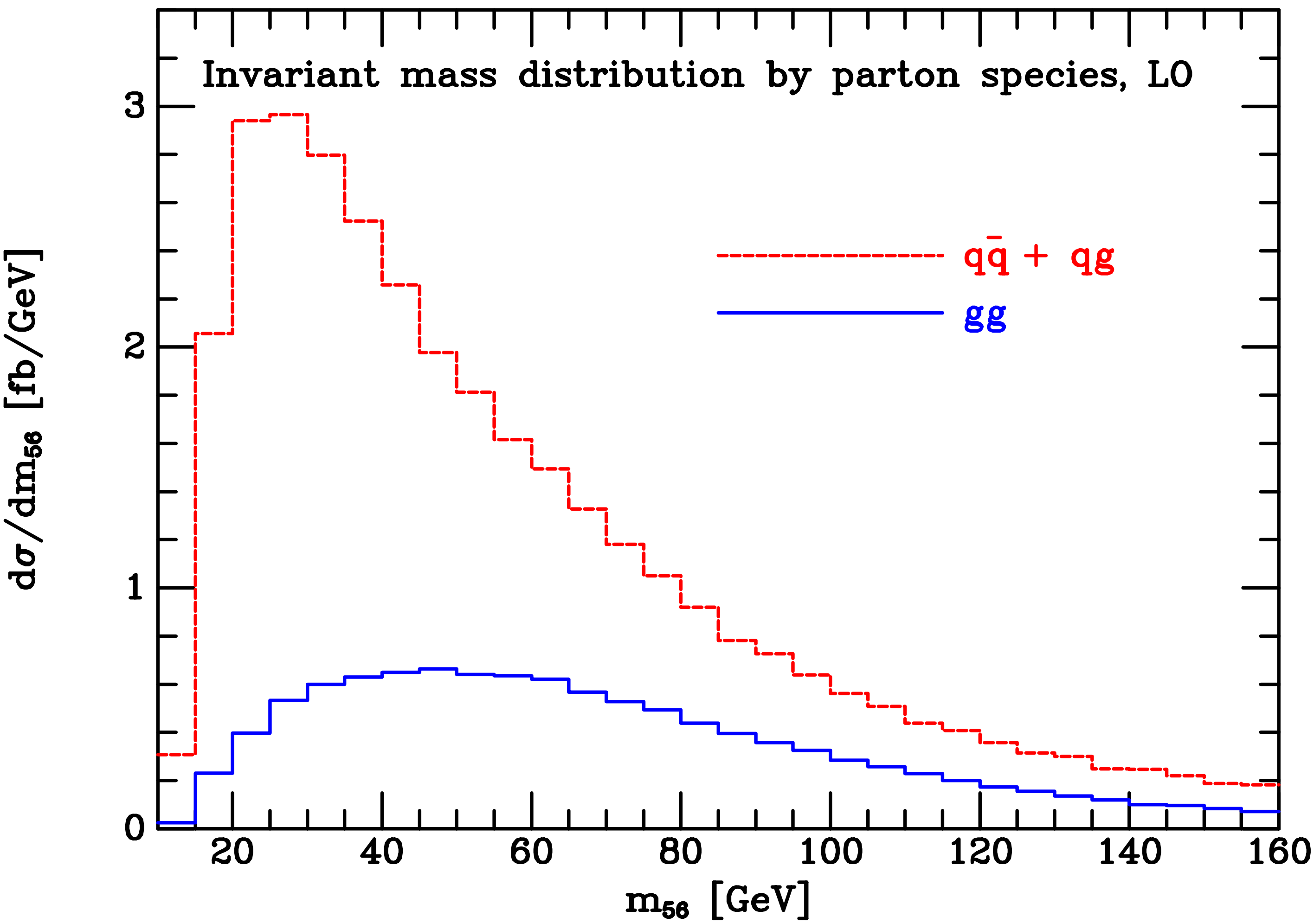


(c)

- Lowest order contribution from gg initial state.
- Complete $O(\alpha_s)$ calculation using virtual matrix elements of Bern, Dixon and Kosower, NPB513,3 (1998). real matrix elements of Trocsanyi and Nagy PRD59:014020(1999)

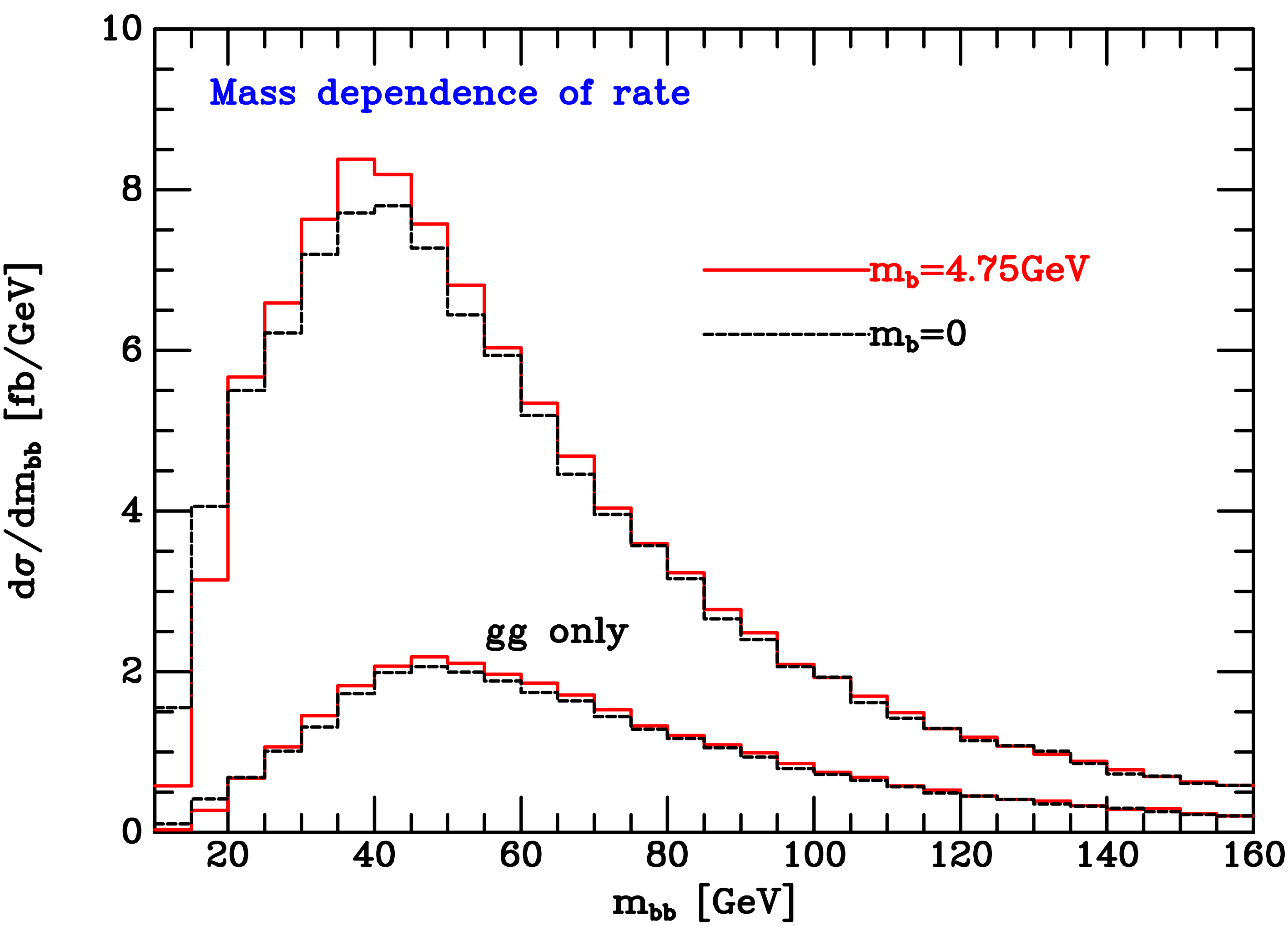
Zbb

The gg initial state gives a large contribution because it can produce a large invariant mass $b\bar{b}$ pair without off-shell propagators



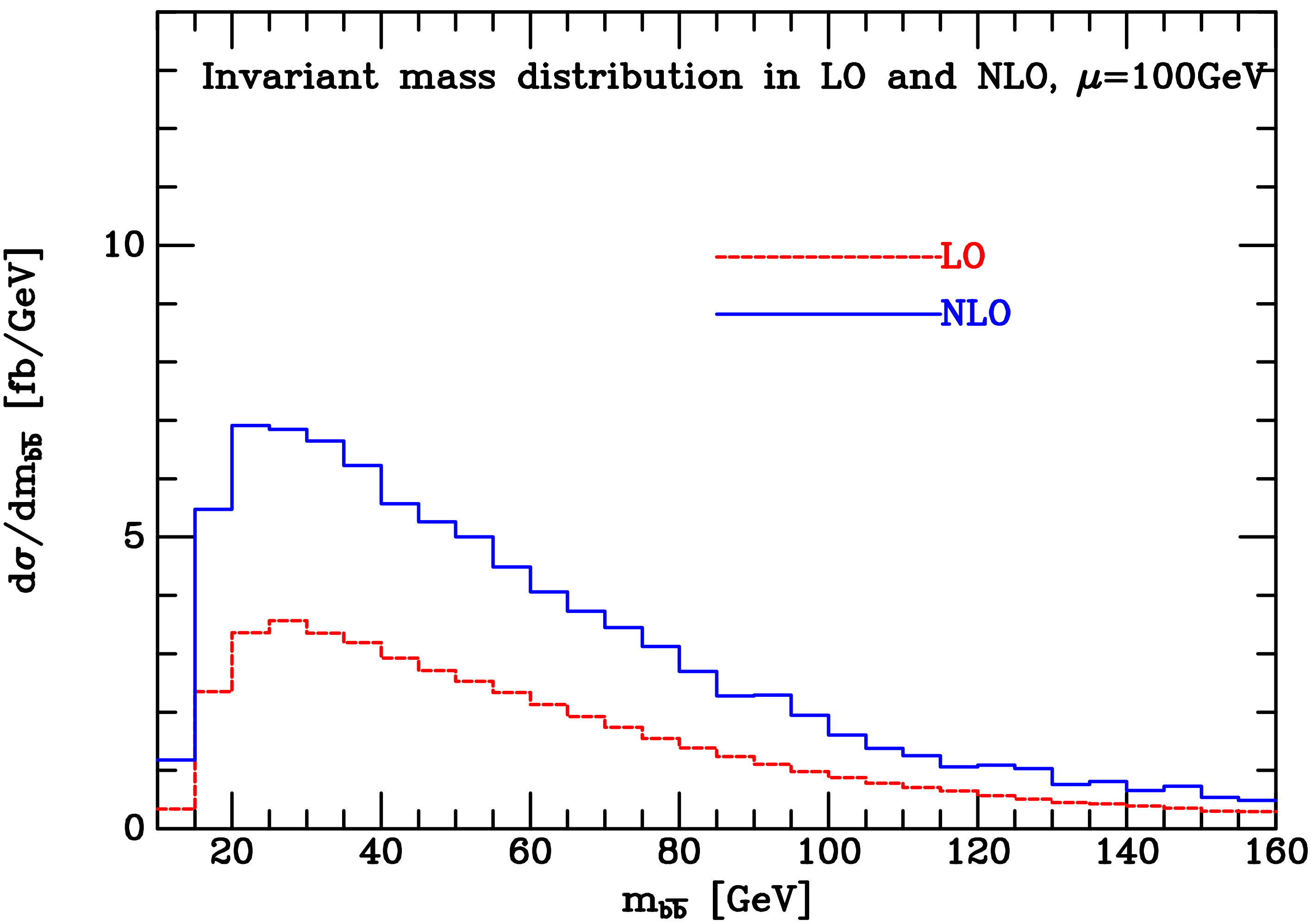
Zbb calculation, neglect of m_b

Mass of the b quark is set to zero - appropriate at high $b\bar{b}$ masses. We can estimate the validity of this approximation using the lowest order calculation.



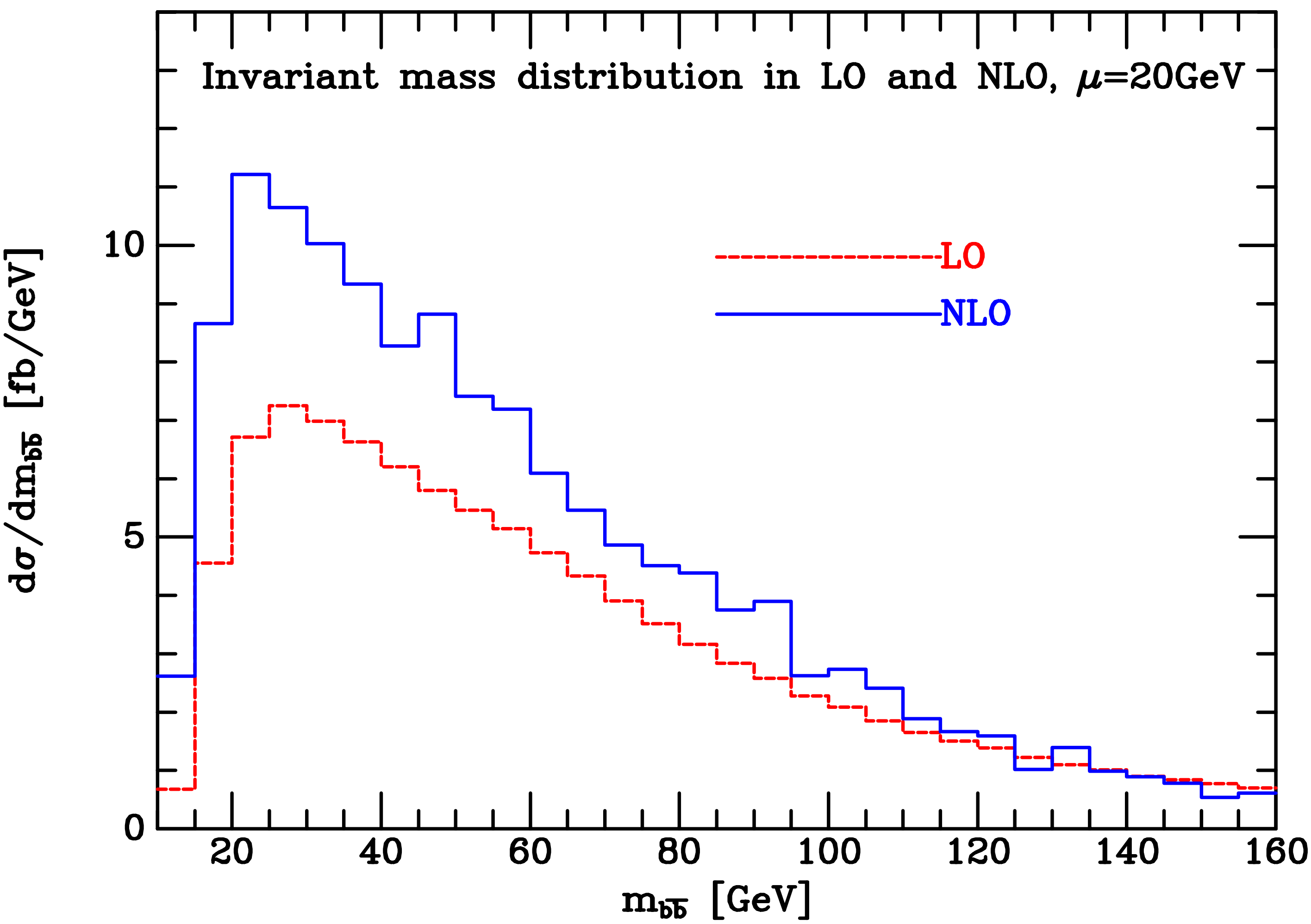
- Mass corrections are of order $4m_b^2/m_{b\bar{b}}$

$Zbb, \mu = 100$ GeV



- $m_{b\bar{b}}$ distribution changed both in shape and normalization

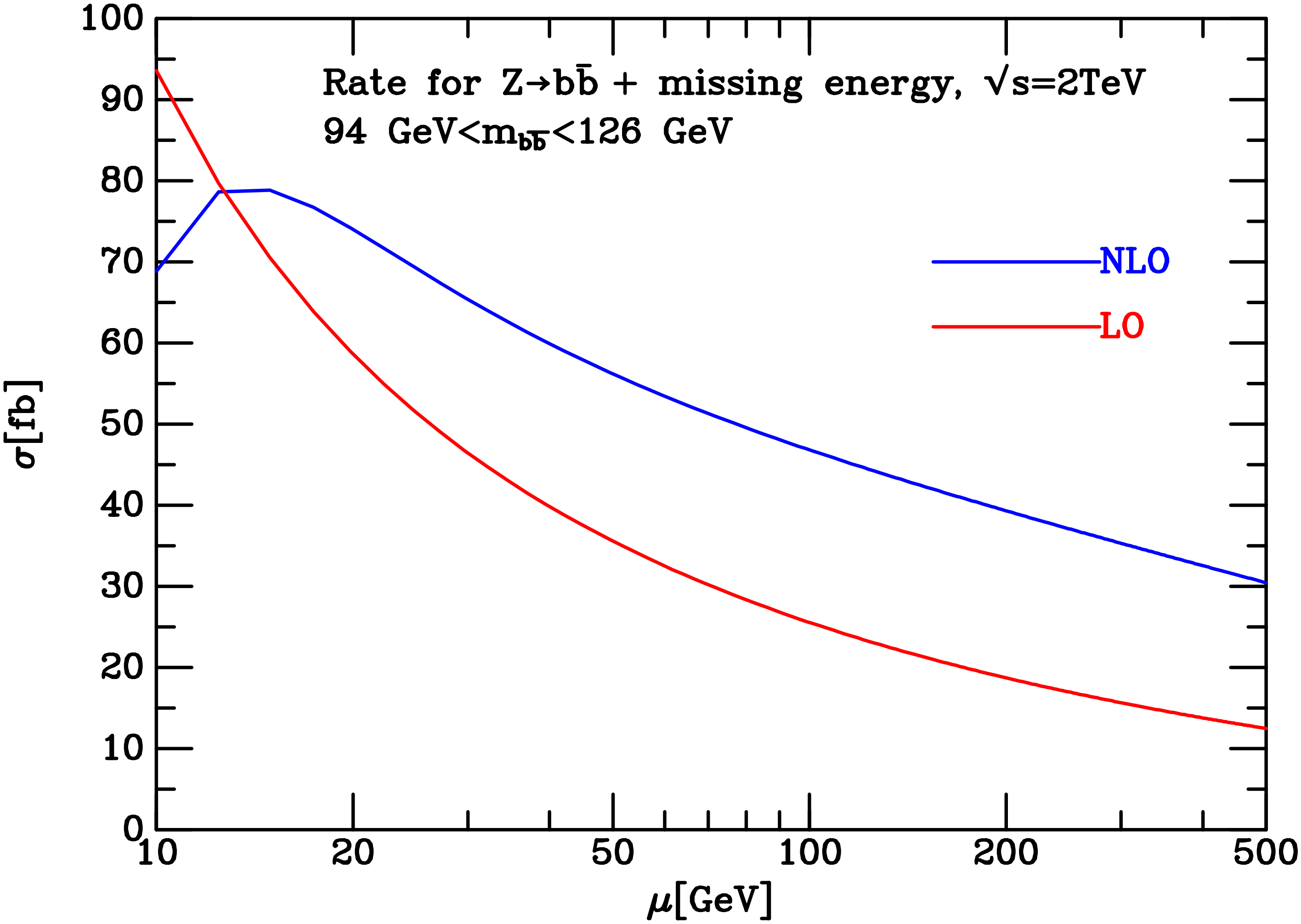
$Zbb, \mu = 20$ GeV



- Corrections small at large mass, but shape change at small mass

Zbb

Both leading order and NLO are dependent on the renormalization and factorization scale

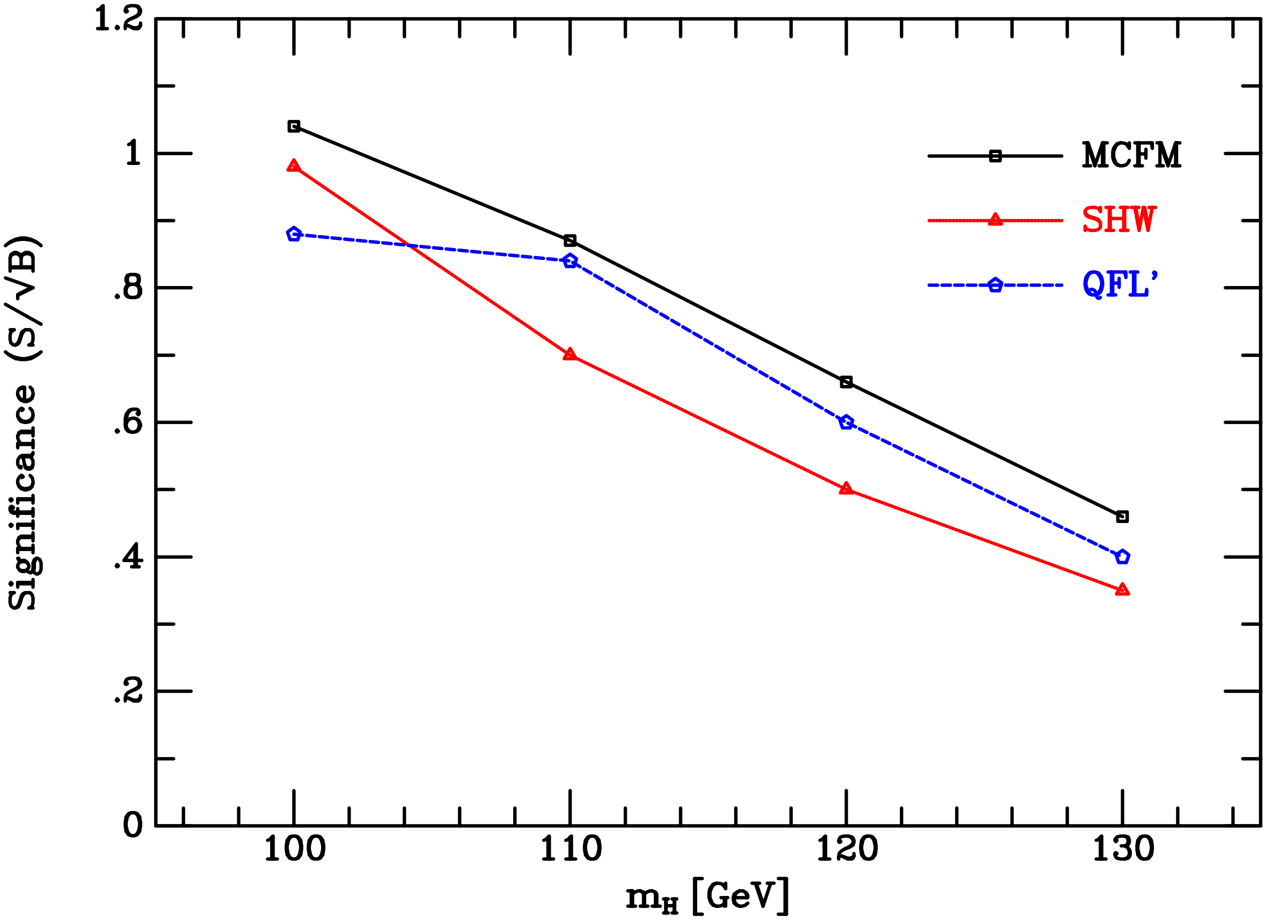


MCFM analysis of Higgs signal

m_H [GeV]	100	110	120	130
$Z^0(\to \nu\bar{\nu})H(\to b\bar{b})$	5.8	4.4	2.9	1.8
$W(\to \ell\nu)H(\to b\bar{b})$	0.7	0.5	0.3	0.2
Total S	6.5	4.9	3.2	2.0
$Z^0(\to \nu\bar{\nu})g^*(\to b\bar{b})$	23.3	21.0	17.5	15.8
$Z^0(\to \nu\bar{\nu})Z(\to b\bar{b})$	10.8	6.9	3.3	1.4
$W^\pm(\to \ell\bar{\nu})g^*(\to b\bar{b})$	2.7	2.4	1.6	1.1
$W^\pm(\to \ell\bar{\nu})Z(\to b\bar{b})$	1.4	0.8	0.4	0.2
$W^{\pm *}(\to t(\to bW^+)\bar{b})$	0.6	0.6	0.6	0.6
$q't(\to bW^+)\bar{b}$	0.2	0.2	0.2	0.2
Total B	39.0	31.9	23.6	19.3
S/B	0.17	0.15	0.14	0.11
$S/\sqrt{B}$	1.04	0.87	0.66	0.46

Table 1: Signal, backgrounds and significance per fb^{-1} for the $b\bar{b}$ +missing energy channel at $\sqrt{s} = 2$ TeV

Comparision with other $b\bar{b} + \not{E}_T$ analyses



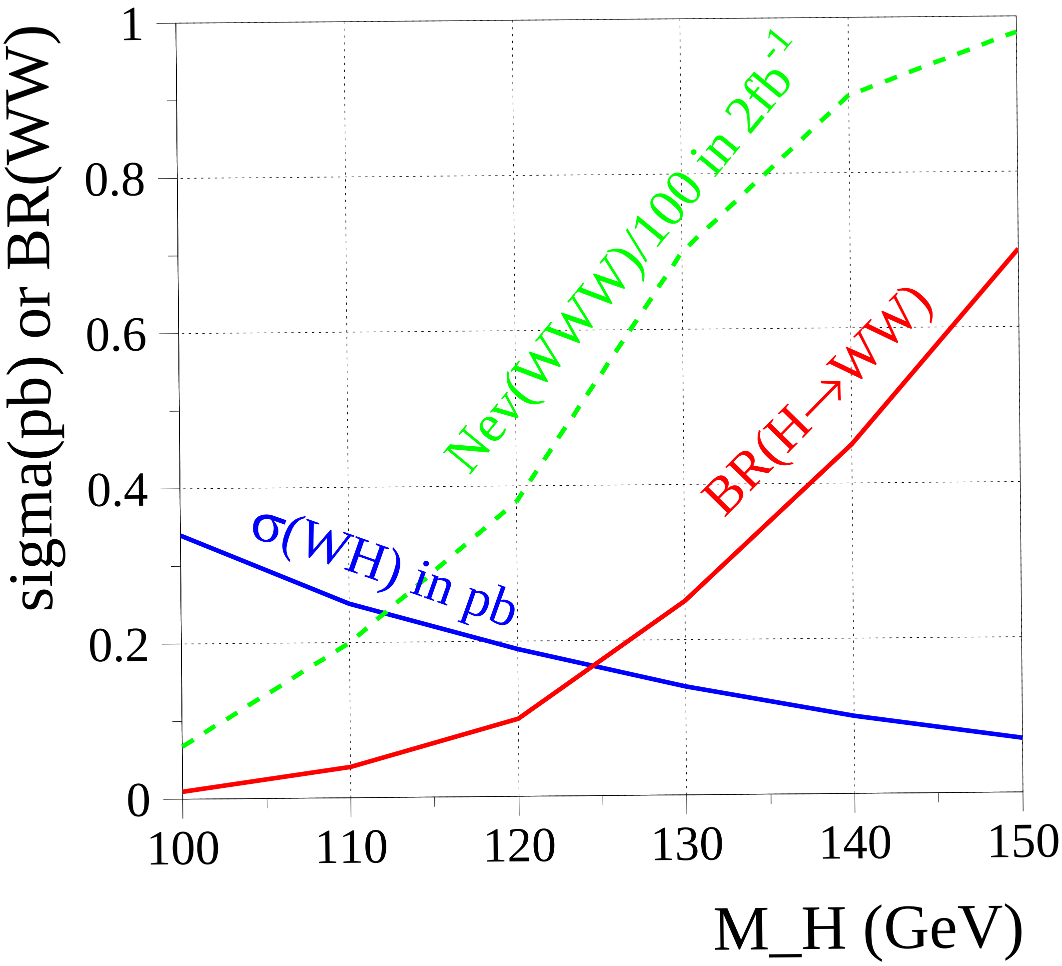
- MCFM and SHW-results differ
- MCFM results do not include detector effects
  SHW results do not include higher order effects.
- $b\bar{b}$ + missing energy production process needs to be included from data

SM Higgs in WW^*, WWW^*, ZWW^* modes

T. Han, A. Lucotte, M. Schmitt, A. Turcot, R. Zhang

idea: exploit $H \to WW^*$ decays at higher masses

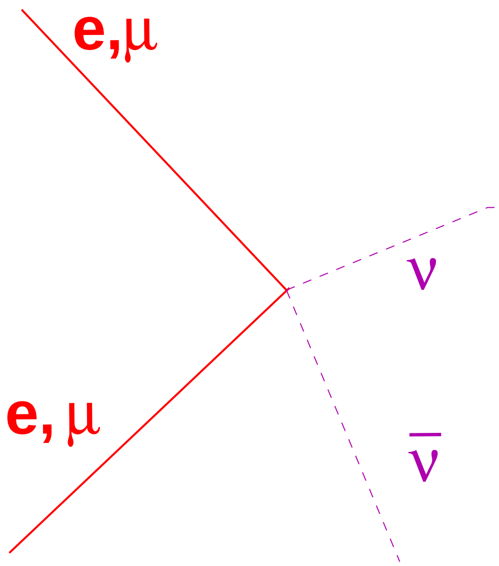
- $gg \to H \to WW^*$
- $ZH \to ZWW^*$
- $WH \to WWW^*$



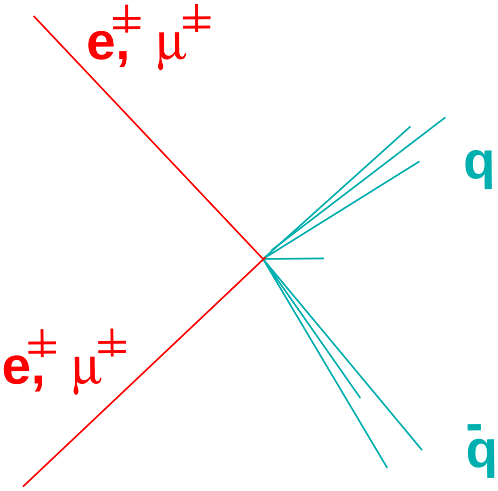
→ dilepton, trilepton, like-sign dilepton plus jets

High-mass SM Higgs channels

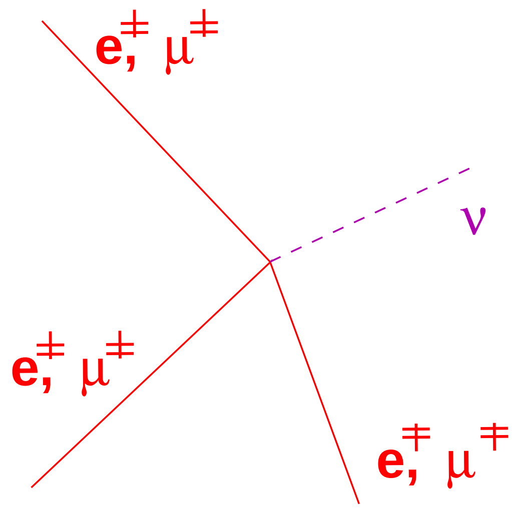
$\ell^+\ell^-\nu\bar{\nu}$



$\ell^\pm\ell^\pm jj$



$\ell^\pm\ell'^\pm\ell^\mp$



main backgrounds: WW, WZ, ZZ, $t\bar{t}$

→ most powerful channel at high masses: $\ell^\pm\ell^\pm jj$

→ published in PRD 59:093001 (Han, Turcot, Zhang)

High-mass SM Higgs Channel Sensitivities

expected events and sensitivity in 1 fb^{-1}

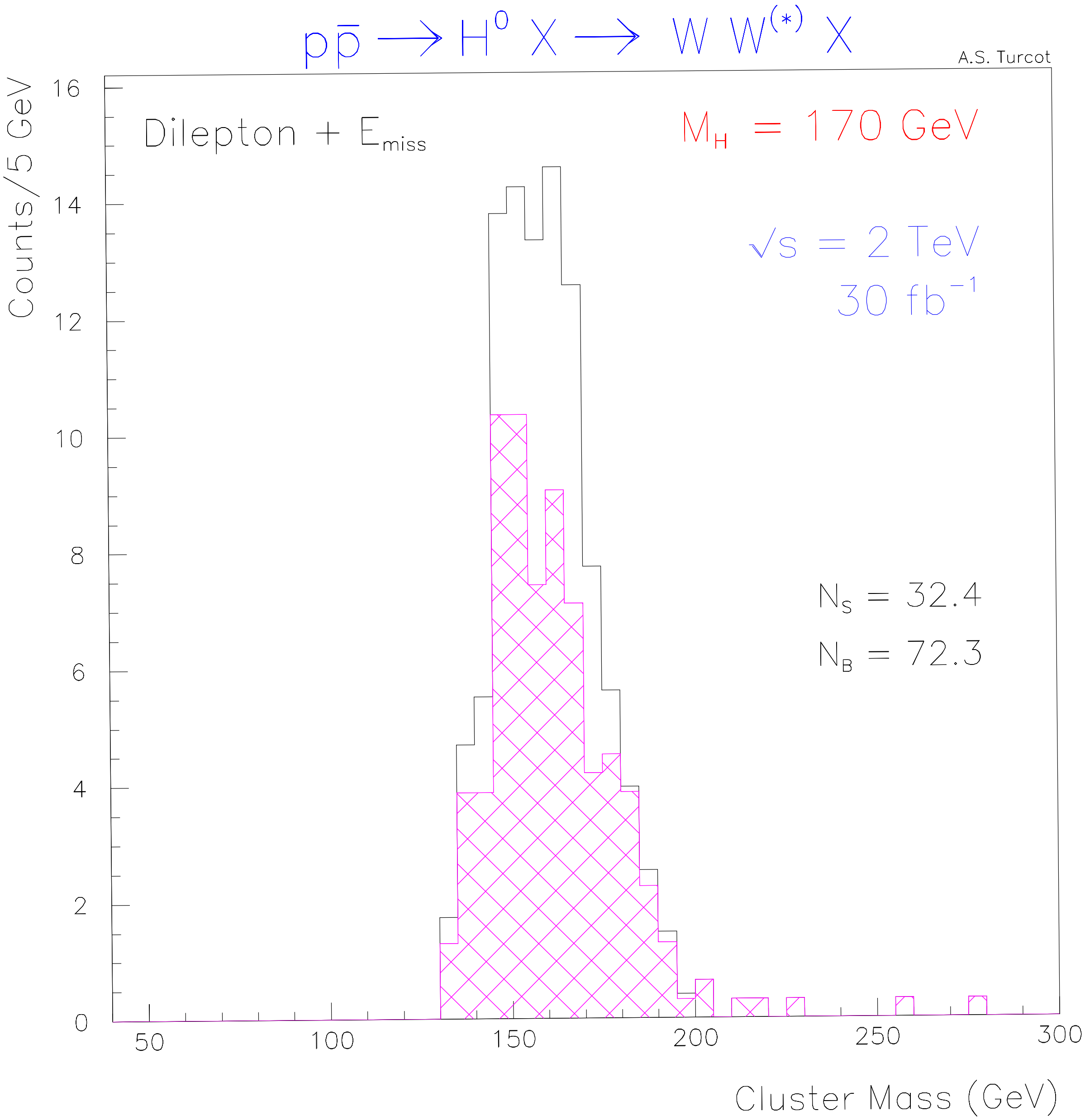
channel	rate	Higgs mass (GeV/c^2) 130	140	150	160	170	180
$\ell^\pm\ell'^\pm\ell^\mp$	S	0.025	0.039	0.050	0.057	0.033	0.033
	B	0.025	0.025	0.025	0.025	0.025	0.025
	$S/\sqrt{B}$	0.16	0.25	0.32	0.36	0.21	0.21
$\ell^+\ell^-\nu\bar{\nu}$	S	-	2.6	2.8	1.5	1.1	1.0
	B	-	44	30	4.4	2.4	3.8
	$S/\sqrt{B}$	-	0.39	0.51	0.71	0.71	0.51
$\ell^\pm\ell^\pm jj$	S	0.15	0.29	0.36	0.41	0.38	0.26
	B	0.58	0.58	0.58	0.58	0.58	0.58
	$S/\sqrt{B}$	0.20	0.38	0.47	0.54	0.50	0.34

- trileptons need very large data samples
- $gg \to H \to WW$ most sensitive!

$\ell^+\ell^-\nu\bar{\nu}$ channel

$\rightarrow$ lots of finely tuned cuts

$\rightarrow$ use "cluster transverse mass" to sharpen mass



$$M_C \equiv \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$$

Results on High-mass Higgs from MCFM

Signal (m_H)	140	150	160	170	180	190
σ_{cuts} (fb)	4.36	5.32	6.12	5.15	3.90	2.47
σ_{total} (pb)	0.181	0.206	0.215	0.180	0.143	0.097

Background	WW	$t\bar{t}$	ZZ	WZ
σ_{cuts} (fb)	185	9.55	2.48	10.4
σ_{total} (pb)	13.0	6.82	1.56	3.96

Table 2: Signal and background cross-sections for a Higgs search with di-lepton final states. The total cross sections (without leptonic decays from the vector bosons) are also shown.

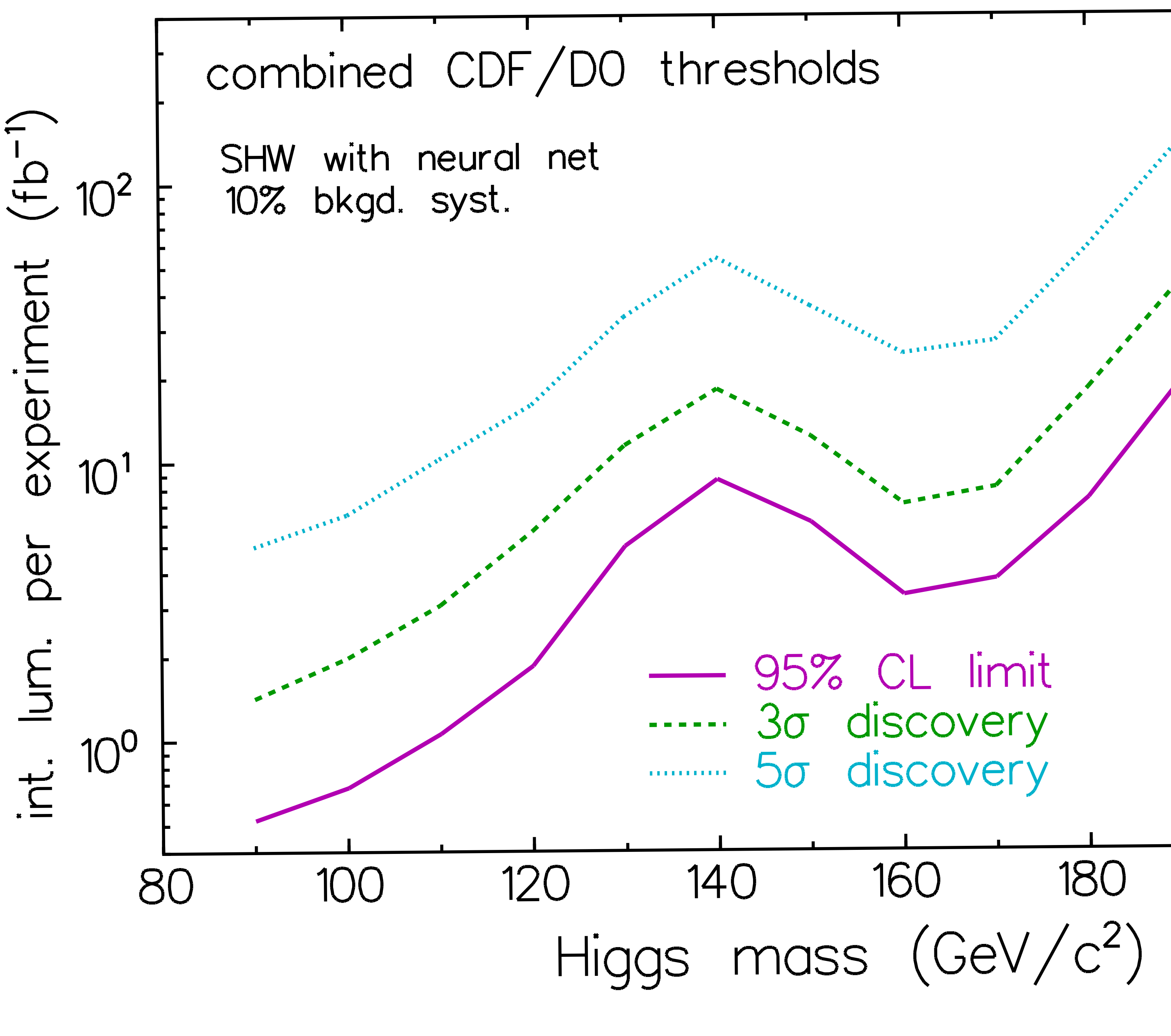
- We find that all the backgrounds due to the di-boson processes are larger than in Han,Turcot and Zhang (HTZ) because we have normalized to the $O(\alpha_s)$ cross-sections which are about 30% bigger than the Born cross-sections..
- Our signal cross sections are also larger than HTZ

by about 20%; the net effect on $S/\sqrt{B}$ may be small.

- The background from the WZ-class of events is twice as big as in HTZ because of our inclusion of the $W\gamma^*$ contribution.

SM Higgs combined channel thresholds

- → Bayesian combination method - two experim
- → 30% better $m_{b\bar{b}}$ resolution than Run 1
- → SHW acceptance, neural network selection
- → nominal systematic errors: 10% or $1/\sqrt{LB}$



Conclusions

- I have presented new results from the NLO MC program, MCFM for the process $p\bar{p} \to Zb\bar{b}$. $Zb\bar{b}$ background is larger than at LO.

- Large radiative corrections can significantly change the estimates of the backgrounds to the process $p\bar{p} \to ZH$ at the Tevatron.

- Our calculation underscores the importance of having an experimental determination of the $Zb\bar{b}$ background, either by relating it to observed $Zb\bar{b}$ events at lower $m_{b\bar{b}}$ or by relating it to Z+two jet events.

- Many of the measurements to be attempted at run II are extremely challenging and will rely on detailed understanding of the backgrounds. This will require improvements both in the NLO Monte Carlos, (described here) and also in the parton shower Monte Carlos.